SCIENTISTS, SANCTIONS, AND SPILLOVERS

JAMES FENSKE, MUHAMMAD HASEEB, NAMRATA KALA, AND JUNXI LIU

ABSTRACT. Whether targeted sanctions remain targeted depends on their spillovers. We study the 1998 US sanctions imposed on selected Indian scientific institutions after India's nuclear tests. Using an event-study design, we find large and persistent effects on both sanctioned institutions and their pre-1998 collaborators. After a decade, scientific output was more than 40% lower relative to the estimated no-sanctions counterfactual. Research impact and nuclear-related work also declined, while affected institutions attracted fewer new scientists and collaborated with fewer other institutions. The results show that sanctions can propagate through scientific networks, generating substantial indirect costs.

1. INTRODUCTION

Targeted sanctions are defined by the entities named on a legal list, but their economic incidence need not end at those entities. This distinction is especially important in science, where research is produced within institutions and through collaboration networks. Cross-institutional collaboration is widespread and growing (Laband and Tollison, 2000; Lin, Huang and Chen, 2025; Sonnenwald et al., 2007), and institutional environments can account for a large share of individual scientists' output (Chandra and Xu, 2025). Collaboration ties may also embody complementary knowledge and team-specific capital that are costly to replace (Jaravel, Petkova and Bell, 2018; Poege et al., 2026). The United States has repeatedly subjected universities and research centers to Entity List restrictions, including institutions in Iran, Russia, and China. The relevant policy question is therefore not only whether sanctions reduce output at listed institutions, but whether they propagate to unlisted institutions connected to them. The case for describing entity-based sanctions as "smart" depends in part on the magnitude of these indirect costs (Ahn and Ludema, 2020; Nigmatulina, 2025).

Existing evidence that spillovers matter in science does not determine the sign, magnitude, or persistence of this effect. A shock to another institution can reduce access to complementary knowledge, equipment, and established research relationships. But

UNIVERSITY OF WARWICK
UNIVERSITY OF BRISTOL
MIT SLOAN SCHOOL OF MANAGEMENT
UNIVERSITY OF WARWICK
E-mail addresses: J.Fenske@warwick.ac.uk, m.haseeb@bristol.ac.uk, kala@mit.edu, junxi.liu@warwick.ac.uk.
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it may also reduce competition for funding, scientists, or scientific attention (Borjas and Doran, 2012). The net effect depends on whether institutions can replace the lost inputs and relationships. Organizations appear better able to absorb the loss of internal collaborators than external collaborators (Poege et al., 2026), while experimental evidence indicates that forming new scientific collaborations is subject to substantial search frictions (Boudreau et al., 2017). Restrictions on access to scientific inputs can also reduce follow-on research and create persistent gaps in cumulative knowledge (Murray et al., 2016; Williams, 2013). Most of this evidence, however, concerns shocks to individual scientists or access to particular research tools. It does not establish how a policy shock directed at whole institutions—simultaneously affecting imported inputs, scientific exchange, and many researchers—propagates through a pre-existing institutional network.

We address this question using the US Entity List restrictions imposed on selected Indian scientific institutions following India's 1998 nuclear tests. We construct a balanced panel of Indian scientific institutions from 1990 to 2009 using OpenAlex data (Priem, Piwowar and Orr, 2022). We classify institutions into three groups: those named in the sanctions, unsanctioned institutions that had coauthored research with a sanctioned institution before 1998, and institutions in neither group. Defining collaboration before the sanctions ensures that subsequent changes in the network do not determine exposure.

We estimate difference-in-differences and event-study specifications with institution and year fixed effects. The direct-effect specifications compare sanctioned institutions with non-sanctioned institutions. The spillover specifications exclude sanctioned institutions and compare their pre-1998 collaborators with other non-sanctioned institutions. More demanding specifications allow common shocks to differ by institution type and by pre-sanction research specialization. The event studies examine pre-sanction trends and trace the evolution of the effects through 2009.

Our analysis proceeds in three stages. We first estimate effects on scientific output, citation-based impact, and the direction of research, and assess the robustness of these results. We then develop a conceptual framework and examine changes in author entry and mobility, how spillover effects vary with distance in the pre-1998 network, and changes in institutional collaboration as evidence on its proposed channels. Finally, we consider alternative explanations for the results.

The estimates show large and increasingly negative effects on scientific output. Output at sanctioned institutions was 20% lower by 2001 and 45% lower by 2009. At institutions that had collaborated with sanctioned institutions before 1998, output was 23% lower by 2001 and 43% lower by 2009. Citation-based measures of research impact and the

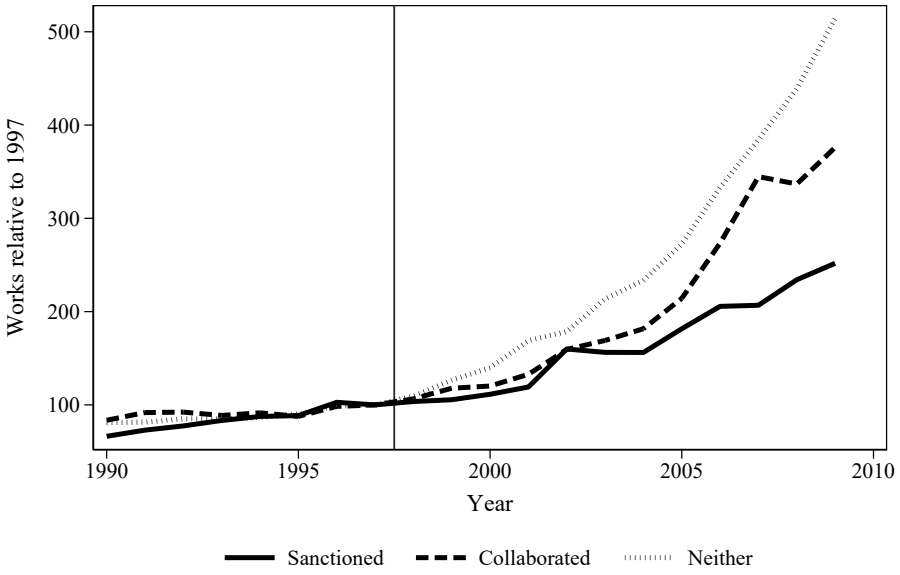
production of highly cited work also declined. Both nuclear and non-nuclear output fell, and affected institutions reallocated less toward new research topics.

These estimates describe relative rather than absolute declines. Figure 1 shows that output continued to increase in all three groups, but grew much more slowly at sanctioned institutions and their pre-1998 collaborators. The gaps widened after 1998 and continued to widen following the major relaxation of the Entity List in 2000–01.

We interpret these results using a framework in which scientific production depends on physical inputs, scientists, and access to existing knowledge. Current research expands the stock of knowledge available for future work, both within an institution and among its collaborators. Restrictions on imported inputs and scientific exchange can therefore reduce current productivity and, through cumulative knowledge production and disruption of established relationships, generate effects that grow over time and spread to connected institutions.

Several additional patterns are consistent with this interpretation. After 1998, sanctioned institutions and their collaborators had fewer authors appearing with them for the first time. Author moves and exits also declined, a pattern consistent with weaker recruitment and less observed reallocation within the Indian research system. Both groups also collaborated with fewer other institutions, including Indian and US institutions.

FIGURE 1. Works by Institution Status



This figure shows total works by year, summed across Indian institutions separately for sanctioned institutions, institutions that collaborated with a sanctioned institution before 1998, and institutions in neither group. Each series is normalized to 100 in 1997. The vertical line marks 1997.5.

We consider two alternative explanations. The estimates are not explained by a general decline in nuclear research: output also fell outside nuclear topics, and allowing trends to vary flexibly with pre-sanction nuclear and field specialization leaves the main results largely unchanged. Nor do we find evidence that affected institutions replaced US and domestic partners with collaborators elsewhere.

The results are robust to alternative comparison groups, richer controls for pre-sanction research specialization, and city-by-year fixed effects. The estimates are also similar when exposure is measured using the intensity of prior coauthorship or citations to sanctioned institutions, and when government, defence, or major nuclear institutions are excluded.

1.1. **Contribution.** We contribute primarily to three literatures in economics. The first studies the organization of scientific production and the formation and consequences of scientific collaboration. Existing work examines how advisers and local colleagues shape scientific careers and productivity (Waldinger, 2010, 2012), how the arrival of potential collaborators affects entry into research fields (Moser, Voena and Waldinger, 2014), and how advisers influence job placement (Fry and Glennon, 2025). Other work studies the search frictions involved in forming scientific teams (Boudreau et al., 2017), the importance of researchers' positions within collaboration networks (Burkhauser and Ma, 2025), and the effects of losing important collaborators (Azoulay, Graff Zivin and Wang, 2010; Jaravel, Petkova and Bell, 2018; Poege et al., 2026). Political barriers can also disrupt international scientific exchange. The collapse of international cooperation during and after the First World War reduced the productivity of researchers who had relied on foreign frontier knowledge (Iaria, Schwarz and Waldinger, 2018), while recent work shows that US–China tensions have reduced scientific collaboration and support for proposals involving China-based partners (Furnas et al., 2026; Jia et al., 2024).

We add to this literature by studying an adverse shock whose unit of treatment is the scientific institution rather than an individual researcher, adviser, or research team. Institution-level sanctions can simultaneously affect equipment and other physical inputs, the work of many scientists, and an organization's relationships with external partners. Our data allow us to trace several corresponding margins of adjustment. We study not only institutional output and research impact, but also the arrival of new scientists, the movement and exit of incumbent scientists, and the formation of new institutional collaborations. The results therefore provide evidence on how scientific organizations adjust when both their own productive capacity and the capacity of their established partners are disrupted. They also extend evidence on the organization of science to a developing-country setting in which scientific resources and opportunities for institutional substitution may be more limited.

The second literature studies the economic effects and incidence of sanctions. At the aggregate level, sanctions often fail to achieve their stated objectives and can have large, persistent, and heterogeneous economic effects, including changes in the direction of trade (Broadberry and Harrison, 2025; Felbermayr et al., 2025; Hufbauer, Schott and Elliott, 1990). Firm-level research shows that targeted entities can suffer substantial losses, but also that governments may protect strategically important firms or redirect resources towards them (Ahn and Ludema, 2020; Egorov et al., 2025*a*,*b*; Lin et al., 2025; Nigmatulina, 2025). Sanctions may also induce circumvention, import substitution, and changes in domestic production networks (Egorov et al., 2025*a*; Felbermayr et al., 2025). Recent work on export controls finds contrasting innovation responses. Targeted Chinese firms may increase their innovation efforts (Lin et al., 2025; Liu et al., 2025), whereas US firms supplying sanctioned foreign entities reduce R&D, patenting, and innovative hiring (Gao, Shroff and Zhang, 2026).

Our contribution to this literature concerns the difference between the legal target of sanctions and their economic incidence. Existing firm-level work documents indirect effects through ownership links, sectors, supply chains, and supplier–customer relationships (Ahn and Ludema, 2020; Egorov et al., 2025*a*; Gao, Shroff and Zhang, 2026). We instead measure indirect exposure through scientific collaboration ties within the target country. We separately estimate the effects on institutions named on the Entity List and on unlisted Indian institutions that had collaborated with them before 1998. By the end of our sample, the estimated output losses among these collaborators are nearly as large as the losses among sanctioned institutions. The list of formally targeted entities can therefore substantially understate the incidence of sanctions when the production being restricted is organized through scientific networks. This result bears directly on the rationale for "smart" sanctions: concentrating legal restrictions on selected entities does not ensure that their economic costs remain similarly concentrated.

The third literature studies innovation spillovers and the propagation of shocks through knowledge networks. Existing research documents large knowledge spillovers across firms, technologies, and research fields (Acemoglu, Akcigit and Kerr, 2016; Myers and Lanahan, 2022; Zacchia, 2020). These positive technology spillovers can outweigh negative effects arising from product-market competition (Bloom, Schankerman and Van Reenen, 2013). A related literature finds substantial geographic concentration and agglomeration in innovation (Abou El-Komboz, Fackler and Goldbeck, 2024; Jaffe, Shupp and Tartari, 2026; Jaffe, Trajtenberg and Henderson, 1993; Moretti, 2021). Access to scientific inputs and prior discoveries also affects the amount and direction of subsequent research (Murray et al., 2016; Williams, 2013). Together, this work shows that innovative

production depends on access to ideas, people, and research tools located outside the innovating organization itself.

We add to this literature by documenting the dynamic propagation of an institution-level shock through a pre-existing knowledge network. The effects we estimate do not resemble a short-lived interruption followed by catch-up. Output gaps instead widen over time and remain large through 2009, despite the removal of most Indian entities from the Entity List in 2000–01. Affected institutions also produce less highly cited work, undertake less research on both nuclear and non-nuclear topics, and reallocate less towards new research areas. These results connect network spillovers to cumulative knowledge production: when current research and research relationships are inputs into future scientific work, the effects of a policy shock can persist even after the restrictions are substantially relaxed. These results also show that innovation networks transmit not only knowledge and positive productivity spillovers, but persistent losses following adverse shocks.

The remainder of the paper is organized as follows. Section 2 describes the historical context and empirical strategy. Section 3 introduces the data. Section 4 presents the main results and robustness checks. Section 5 develops the conceptual framework, presents evidence consistent with its proposed channels, and considers alternative explanations. Section 6 concludes.

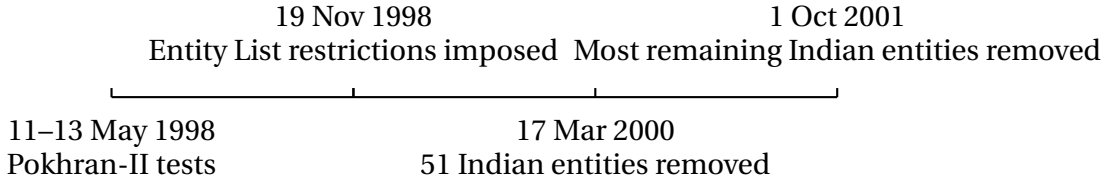
2. Context and Empirical Strategy

This section describes the historical context and empirical strategy. Subsection 2.1 traces the development of India's nuclear programme, the 1998 Pokhran-II tests, the international response, and the imposition and subsequent relaxation of the US Entity List restrictions. Subsection 2.2 presents the difference-in-differences and event-study specifications used to estimate the direct effects on sanctioned institutions and the spillover effects on their pre-1998 collaborators.

2.1. **Context.**

2.1.1. *India's Nuclear Programme Before 1998.* The institutional foundations of India's nuclear programme predated independence. The Tata Institute of Fundamental Research was established in 1945 under the directorship of Homi Bhabha (Gopalakrishnan, 2002, p. 371). After independence, the Indian government created the Atomic Energy Commission in 1948 and the Department of Atomic Energy in 1954 (Anderson, 2010, pp. 120 and 170). The Apsara research reactor began operation at Trombay in 1956, at the site that later became the Bhabha Atomic Research Centre (BARC) (Gopalakrishnan, 2002, p. 374). The CIRUS reactor began operation there in 1960 (Mistry, 2017, p. 118).

FIGURE 2. Timeline of Pokhran-II and Entity List Restrictions



India's security environment changed during the 1960s. It fought a war with China in 1962, and China became a nuclear power in 1964 (Subrahmanyam, 2018). During the remainder of the decade, India worked towards acquiring a nuclear-weapons capability (Sarkar, 2015). In 1974, it conducted an underground nuclear explosion at the Pokhran Test Range in Rajasthan, commonly known as "Smiling Buddha" or Pokhran-I. The test prompted tighter US-led restrictions on nuclear cooperation and technology transfer (Gopalakrishnan, 2002, p. 376).

India continued to expand its nuclear and missile capabilities during the 1980s and 1990s despite these restrictions. It prepared a new test site after receiving reports that Pakistan was excavating one of its own (Mistry, 2017, p. 119). In 1986, India opened the Dhruva reactor, which could produce enough plutonium for approximately five nuclear weapons annually (Mistry, 2017, p. 117). At the same time, the Defence Research and Development Organisation (DRDO) developed short- and medium-range guided missiles (Mistry, 2017, p. 121). Tensions with Pakistan increased, including through military conflict over the Siachen Glacier (Nair, 2009), while the collapse of the Soviet Union heightened India's security concerns (Mistry, 2017, p. 120). By the mid-1990s, India remained outside the Treaty on the Non-Proliferation of Nuclear Weapons and resisted US pressure to support an emerging comprehensive nuclear test ban. In late 1995, US intelligence detected apparent preparations at Pokhran and feared that India might conduct another test, although officials remained uncertain whether Prime Minister Narasimha Rao had authorized one (Burr, 2013).

2.1.2. *India's 1998 Nuclear Tests and US Sanctions.* We study the US sanctions imposed following India's Pokhran-II nuclear tests in May 1998. Figure 2 summarizes the principal events. In March 1998, Atal Bihari Vajpayee became prime minister at the head of a Bharatiya Janata Party-led government. The BJP had expressed greater public support for nuclear testing than the outgoing Congress-led government, and preparations at the Pokhran Test Range were conducted in secrecy to avoid US detection (Chengappa, 2000). India conducted three underground tests on 11 May and two further tests on 13 May, completing its planned series. The tests culminated more than two decades of collaboration between the Defence Research and Development Organisation (DRDO)

and the Department of Atomic Energy (DAE) (Jayaraman, 1998*c*). The government announced the first tests on 11 May and the completion of the series two days later. The tests met with both domestic praise and protest (Jayaraman, 1998*b*). Pakistan conducted its own nuclear tests later that month (Hufbauer et al., 2008).

The initial US response was immediate and applied to India at the country level. Under the Glenn Amendment, India's tests triggered statutory restrictions on foreign assistance, defence sales, military financing, US government credit, technical assistance, and specified exports (Hufbauer et al., 2008). Humanitarian assistance was exempted. These country-level sanctions are not the treatment on which our empirical analysis focuses. Their effects that were common across Indian scientific institutions are absorbed by year fixed effects. They could nevertheless have affected some institutions more than others, particularly institutions such as BARC and DRDO that depended heavily on restricted technologies or credit. We address this concern below by showing that the results are not driven by these major government and defence institutions.

Our treatment of interest is the institution-specific restrictions imposed through the Entity List in November 1998. In June, the Clinton administration announced that it would identify entities involved in India's nuclear and missile programmes (Hufbauer et al., 2008). On 19 November, the Bureau of Export Administration added a large set of Indian and Pakistani government, parastatal, private, and military entities to the Entity List. The rule required licenses for exports and reexports of covered US goods and technologies to listed entities, with applications generally subject to a presumption of denial.[1]

Entities placed on the Entity List faced extensive licensing requirements under the Export Administration Regulations (EAR). For listed government, parastatal, and private entities, exports and reexports of all items subject to the EAR generally required a licence; for certain military entities, the requirement covered all such items except those classified as EAR99.[2] Applications were normally reviewed under a presumption of denial. The restrictions therefore extended beyond explicitly military or nuclear goods to commercial equipment, software, technology, and certain foreign-produced items subject to the EAR.[3] The measures also disrupted scientific exchange. For example, eight US scientists

[1]Federal Register, Vol. 63, No. 223, 19 November 1998, pp. 64322–64324.

[2]EAR99 is the residual designation for commodities, software, and technology that are subject to the Export Administration Regulations but are not specifically listed on the Commerce Control List. Such items ordinarily do not require an export licence, although licensing requirements may arise because of the destination, end use, or end user.

[3]Federal Register, Vol. 63, No. 223, 19 November 1998, Supplement No. 4 to Part 744. Details of the scope of the EAR are provided in Part 734: `https://www.bis.gov/regulations/ear/734`.

were reportedly prevented from attending a physics seminar at the Tata Institute of Fundamental Research.[4]

Selection onto the Entity List was purposeful. Core targets included organizations directly involved in India's nuclear-weapons and missile programmes, particularly BARC, DRDO, and DAE (Chakma, 2005). The list also extended beyond these agencies to organizations associated with dual-use capabilities, including advanced electronics, aerospace engineering, and high-performance computing.[5] The stated aim was to restrict specific "government, parastatal, and private entities determined to be involved in nuclear or missile activities," rather than the Indian higher-education sector as a whole.[6] The boundary of this involvement was not always transparent. Contemporary scientists argued that it was difficult to identify the particular departments within larger institutions that had participated in defence research.[7]

This selective assignment shapes our empirical strategy. We do not assume that placement on the Entity List was random. Instead, our difference-in-differences and event-study specifications compare changes in outcomes after 1998 and examine whether sanctioned institutions and their pre-sanction collaborators exhibited differential trends beforehand. More demanding specifications make comparisons among institutions of similar types and with similar pre-sanction research specializations. Uncertainty about the eventual contents of the Entity List may have limited precise anticipation, especially among collaborating institutions, but does not rule it out. Because almost all institutions in our direct-treatment group were added during 1998, treatment onset is effectively common at the annual frequency of our data. We do not use the later staggered removal of entities for identification.

Other governments also responded to the tests. In June 1998, the United Nations Security Council condemned the tests by both India and Pakistan.[8] Japan suspended non-humanitarian aid and yen loans.[9] Britain condemned the tests and recalled its High Commissioner, while China announced that it would no longer supply India with enriched uranium fuel (Gopalakrishnan, 2002, p. 376). Russia condemned the tests

[4]Pallava Bagla, "Washington Blocks 8 US Scientists from TIFR Physics Seminar," *Indian Express* (Mumbai), 15 January 1999, quoted in the Nuclear Threat Initiative, "India Nuclear Chronology," 2010, p. 148, `https://media.nti.org/pdfs/india_nuclear.pdf`.

[5]Federal Register, Vol. 63, No. 223, 19 November 1998, Supplement No. 4 to Part 744.

[6]Federal Register, Vol. 63, No. 223, 19 November 1998, p. 64322.

[7]"IISc, NAL now in US sanction list," *The Asian Age* (Bangalore edition), 23 November 1998.

[8]United Nations Security Council Resolution 1172 (1998).

[9]"Japan suspends India aid," BBC News, 13 May 1998, `http://news.bbc.co.uk/1/hi/special_report/1998/05/98/india_nuclear_testing/92842.stm`. See also the Japanese Ministry of Foreign Affairs, *Diplomatic Bluebook 1999*, `https://www.mofa.go.jp/policy/other/bluebook/1999/I-b.html#1`.

but continued its nuclear relationship with India, signing an agreement in July for the construction of two reactors in Tamil Nadu.[10]

Most of these responses operated at the country level, so their effects that were common across Indian institutions are absorbed by year fixed effects. Differential exposure remains possible, however. Japan, for example, also maintained a much smaller list of restricted Indian entities.[11] Institutions at the centre of India's nuclear and defence programmes may also have been especially exposed to several countries' responses. We therefore show that the results survive the exclusion of government institutions, defence institutions, and the principal nuclear, defence, and space agencies.

The generalized sanctions were relaxed more quickly than the institution-specific Entity List restrictions. In October 1998, Congress passed the Brownback Amendment, authorizing the president to waive parts of the sanctions triggered by the nuclear tests. President Clinton exercised this authority the following month (Morrow and Carriere, 1999). The Entity List restrictions imposed in November 1998, however, initially remained in place. Although the 1999 Kargil War heightened US concerns about regional instability, continued diplomacy between the United States and India contributed to their gradual relaxation (Talbott, 2010). In December 1999, the Clinton administration announced that 51 Indian entities would be removed from the Entity List, a change that took effect on 17 March 2000, shortly before Clinton's visit to India (Muro et al., 1999).[12] Following President Bush's waiver of the remaining nuclear-test sanctions in September 2001, the Department of Commerce removed most remaining Indian entities from the list and relaxed the licensing policy applying to those that remained. These changes took effect on 1 October 2001.[13]

US–India relations continued to normalize during the 2000s. In September 2004, the United States removed the headquarters of the Indian Space Research Organisation (ISRO) from the Entity List, with additional ISRO subordinates removed in 2005.[14] In 2005,

[10]"NATO and Russia condemn nuclear tests conducted by India and Pakistan," 28 May 1998, https://www.nato.int/en/news-and-events/articles/news/1998/05/28/nato-and-russia-condemn-nuclear-tests-conducted-by-india-and-pakistan?selectedLocale=en; Howard Diamond, "Russia, India Move Forward With Deals on Arms, Nuclear Power," *Arms Control Today*, 1998, https://www.armscontrol.org/act/1998-06/news/russia-india-move-forward-deals-arms-nuclear-power.

[11]"ISRO, Godrej, BEL off Japan's blacklist," *The Economic Times*, 2 June 2010, https://economictimes.indiatimes.com/news/economy/foreign-trade/isro-godrej-bel-off-japans-blacklist/articleshow/6000880.cms.

[12]Federal Register, Vol. 65, No. 53, 17 March 2000, pp. 14444–14455.

[13]Federal Register, Vol. 66, No. 190, 1 October 2001, pp. 50090–50093.

[14]See "Joint Statement Between the United States of America and India," Office of the Press Secretary, The White House, 21 September 2004, https://georgewbush-whitehouse.archives.gov/news/releases/2004/09/20040921-12.html.

President Bush and Prime Minister Manmohan Singh announced that the two countries would work towards full civilian nuclear cooperation.[15] In 2008, the International Atomic Energy Agency approved a safeguards agreement covering India's declared civilian nuclear facilities, and the Nuclear Suppliers Group granted India a waiver permitting civilian nuclear trade despite its remaining outside the Treaty on the Non-Proliferation of Nuclear Weapons.[16]

These developments did not eliminate all institution-specific restrictions. A smaller set of Indian entries remained on the Entity List through the end of our sample in 2009, including BARC and several subordinate organizations of DRDO and ISRO. Most of the remaining defence and space entities were not removed until 2011.[17] We define treatment by inclusion on the Entity List in 1998 and do not reclassify institutions when they were subsequently removed. Consequently, our later estimates capture the persistence of the initial sanctions shock following a substantial relaxation of the regime, but they should not be interpreted as effects after sanctions had ended for every treated institution. We show that the results are not driven by the institutions that remained listed longest: they survive the exclusion of government institutions as a whole and of BARC, DRDO, and ISRO specifically.

2.1.3. *Indian Science circa 1998.* At the time of the sanctions, India's scientific system was growing but remained small relative to its population and to the scientific systems of several major economies. From the 1980s through the late 1990s, the growth of Indian output in indexed scientific publications lagged behind global growth and was substantially slower than growth in either the United States or China (Kademani et al., 2007). In 1999, India ranked fourteenth globally in the number of publications in medicine (Gupta and Bala, 2011). According to the World Development Indicators, India produced approximately 19 scientific and technical journal articles per million people in 1998, compared with 170 globally and 1,097 in the United States.[18] A scientific system with

[15]"Joint Statement Between President George W. Bush and Prime Minister Manmohan Singh," Office of the Press Secretary, The White House, 18 July 2005, https://georgewbush-whitehouse.archives.gov/news/releases/2005/07/20050718-6.html. See also H.R. 5682, the Henry J. Hyde United States–India Peaceful Atomic Energy Cooperation Act of 2006.

[16]"Board Approves India-Safeguards Agreement," International Atomic Energy Agency, 1 August 2008, https://www.iaea.org/newscenter/news/iaea-board-approves-india-safeguards-agreement; Sharon Squassoni, "Frequently Asked Questions about India, the Nuclear Suppliers Group, and Next Steps," Carnegie Endowment for International Peace, 10 September 2008, https://carnegieendowment.org/russia-eurasia/research/2008/09/frequently-asked-questions-about-india-the-nuclear-suppliers-group-and-next-steps.

[17]"US removes ISRO and DRDO from entities list," *The Indian Express*, 25 January 2011, https://indianexpress.com/article/news-archive/print/us-removes-isro-and-drdo-from-entities-list/.

[18]Computed using https://data.worldbank.org/indicator/IP.JRN.ARTC.SC and https://data.worldbank.org/indicator/SP.POP.TOTL.

fewer institutions and resources may have had fewer domestic substitutes for equipment, knowledge, and research relationships restricted by the sanctions, although this possibility is ultimately an empirical question.

Collaboration among Indian scientists was predominantly domestic, but international links were becoming increasingly important. The number of international collaborative links rose from 13.2 per 100 Indian papers in 1990 to 18.7 in 1994. More than one third of these links involved the United States, making it India's most important foreign scientific partner; Germany, the United Kingdom, Japan, Canada, and France were the next most common partners (Basu and Kumar, 2000, p. 384). International collaboration was particularly prevalent in physics, chemistry, and medicine (Anuradha and Urs, 2007; Dua, Singh and Lathabai, 2023), while collaboration with other South Asian countries remained limited (Gupta, Munshi and Mishra, 2002). Thus, the US restrictions affected a scientific system in which most research links were domestic, but in which the United States occupied an especially important position among foreign partners.

Evidence on the mobility of scientists within India around 1998 is more limited. The existing literature has focused primarily on the international "brain drain" rather than movement between Indian institutions (Khadria, 2004; Mashelkar, 2005). Later bibliometric evidence indicates that international mobility among Indian scientists is substantial and that many scientists who move abroad do not return (TM et al., 2025, p. 1). Descriptive evidence from our OpenAlex data suggests that institutional mobility was comparatively limited in India before the sanctions. Among authors first observed during 1990–1997 with a single Indian institutional affiliation and whom we subsequently observe publishing again, 32.5% later publish without that original institution, compared with 40–47% in China, Germany, Japan, the United Kingdom, and the United States.

2.1.4. *Existing Assessments of the Sanctions.* Contemporaneous assessments of the sanctions were sharply divided. Some Indian scientists expected serious harm because research in areas such as nanotechnology, superconductivity, aerospace, and military technology depended on foreign equipment, services, and scientific cooperation (Jayaraman, 1998*b*). Scientists at the Tata Institute of Fundamental Research, for example, reported losing access to both equipment and services provided by US firms (Jayaraman, 1999). Others expected Indian institutions to adapt. The government announced plans to expand partnerships with private firms in defence research (Jayaraman, 1998*a*). Raghunath Mashelkar, then head of the Council of Scientific and Industrial Research, argued that India "seems to excel precisely in those areas in which technology is denied" (Jayaraman, 1998*b*). H. S. Mukunda of the Indian Institute of Science and the National

Aerospace Laboratories similarly predicted that the effects on his department would be limited.[19]

Retrospective assessments have remained similarly mixed. In 2000, Defence Minister George Fernandes attributed delays in several military programmes partly to the sanctions (Rajiv, 2023, p. 19). Later technological advances were sometimes presented as evidence that India had overcome the US policy of technology denial. Progress on the Agni-V missile, for example, led the head of DRDO to claim in 2012 that India had made "mincemeat" of that policy.[20] Yet subsequent officials continued to attribute delays in major programmes to the restrictions. In 2018, the head of DRDO argued that sanctions had slowed the development of the Tejas Light Combat Aircraft.[21]

The academic literature has concentrated primarily on the sanctions' macroeconomic consequences and their influence on Indian nuclear policy, rather than estimating their effects on the institutions placed on the Entity List or on connected scientific institutions (Hufbauer et al., 2008; Morrow and Carriere, 1999). The disagreement among contemporary observers and later policymakers therefore remains difficult to resolve from existing evidence. Our analysis provides an institution-level assessment of both the direct and network effects of the restrictions.

2.2. **Empirical Strategy.** We use the 1998 expansion of the US Entity List to estimate the direct and indirect effects of sanctions on Indian scientific institutions. Direct treatment is defined by an institution's inclusion on the Entity List in 1998. The restrictions limited listed institutions' access to covered goods, software, technology, and scientific exchange. We measure indirect exposure using collaboration with a sanctioned institution before 1998 and analyze these spillover effects separately below.

Placement on the Entity List was targeted rather than random. Our causal interpretation therefore rests on the assumption that, conditional on the fixed effects and controls described below, sanctioned and non-sanctioned institutions would have followed parallel trends in the absence of the sanctions. The Entity List nevertheless contains treated and untreated institutions within the same broad institution types and research specializations, allowing us to make progressively narrower comparisons. Event-study specifications allow us to examine differential pre-sanction trends and trace the evolution of the estimated effects after 1998.

[19] "IISc, NAL now in US sanction list," *The Asian Age* (Bangalore edition), 23 November 1998.

[20] "Whom does the US sanctions hurt?," Centre for Land Warfare Studies, 5 July 2012, https://archive.claws.co.in/863/whom-does-the-us-sanctions-hurt-radhakrishna-rao.html.

[21] "As Tejas inches towards final clearance, DRDO chairman explains why the fighter jet programme was delayed," *India Today*, 29 April 2018, https://www.indiatoday.in/india/story/as-tejas-inches-towards-final-clearance-drdo-chairman-explains-why-the-fighter-jet-programme-was-delayed-1222844-2018-04-29.

Treatment began at effectively the same time across institutions at the annual frequency of our data. We define treatment according to inclusion on the Entity List in 1998 and do not reclassify institutions following their later, staggered removal. Our estimates should therefore be interpreted as the effects associated with initial inclusion in the 1998 sanctions, rather than as the effect of being listed in each particular year. The pre-treatment coefficients also allow us to assess whether outcomes began to diverge before the sanctions, including because of anticipation.

We construct a balanced annual panel of 1,619 Indian institutions covering 1990 through 2009. The sample consists of institutions recorded in OpenAlex that published at least one work between 1990 and 1997, the last full year before the sanctions. A balanced panel here means that we retain every institution-year observation, including years in which an institution published no work. Our institution definitions and identifiers follow OpenAlex and its links to the Research Organization Registry.[22] Consequently, we treat a multidivisional organization such as DRDO as one institution when OpenAlex assigns it a single institutional identifier. Of the 1,619 institutions in the panel, 66 were included on the Entity List in 1998. In the baseline direct-effect specification, the comparison group contains all institutions not listed in 1998, including institutions that may have been indirectly exposed through prior collaboration.

To estimate the direct effects of sanctions, we use the following event-study specification:

$$E[Y_{it} \mid \cdot] = \exp\left\{ \sum_{\tau \neq 1997} \beta_\tau \left(Sanctioned_i \times \mathbf{1}\{t = \tau\} \right) + \delta_i + \eta_t + \mathbf{X}_{i0}' \boldsymbol{\gamma}_t \right\}. \tag{1}$$

Here, Y_{it} is an outcome for institution i in year t, such as the number of works published. $Sanctioned_i$ indicates that institution i was included on the Entity List in 1998. The coefficients β_τ measure the difference between sanctioned and non-sanctioned institutions in year τ, relative to the omitted year 1997. Institution fixed effects δ_i absorb time-invariant differences across institutions, while year fixed effects η_t absorb shocks common to all institutions in a given year. The vector $\mathbf{X}_{i0}$ contains characteristics measured before the sanctions, and $\boldsymbol{\gamma}_t$ allows their coefficients to vary flexibly by year. In the baseline specification, these terms are institution type-by-year fixed effects. Standard errors are clustered by institution.

Because most of our principal outcomes are non-negative, highly skewed, and contain many zeroes, we estimate equation (1) using pseudo-Poisson maximum likelihood. PPML does not require the dependent variable to be integer-valued or to follow a Poisson distribution. We also estimate a conventional difference-in-differences specification, replacing the year-specific treatment interactions with $Sanctioned_i \times Post_t$, where $Post_t$

[22] `https://ror.org/`

equals one from 1998 onwards. The corresponding coefficient β measures the average proportional difference in the post-sanction period. We report percentage effects as $100[\exp(\hat{\beta}) - 1]$.

The coefficients in equation (1) are identified from differences in the evolution of outcomes at sanctioned and non-sanctioned institutions, after absorbing time-invariant institution characteristics, common year shocks, and the year-specific effects of pre-sanction characteristics. Because we use a log-link specification, causal interpretation requires a conditional parallel-trends assumption: absent the sanctions, the expected outcomes of sanctioned and comparison institutions would have experienced the same proportional changes, conditional on the included fixed effects and controls. Identification also requires that institutions did not adjust their outcomes in anticipation of being listed and that no other post-1998 shock differentially affected sanctioned institutions for reasons unrelated to the US sanctions.

For example, sanctions imposed independently by another country on the same institutions would constitute a confounding shock. By contrast, assistance provided by the Indian government in response to the US sanctions would form part of the total effect of the sanctions rather than a confounder. Our estimates therefore incorporate any government mitigation or other institutional responses induced by initial placement on the Entity List.

Interference across institutions requires particular attention in this setting. The baseline direct-effect comparison group includes all institutions not placed on the Entity List in 1998, including institutions that had previously collaborated with sanctioned institutions. If sanctions affected these collaborators, the direct-effect estimates compare sanctioned institutions with a partly exposed comparison group and may therefore understate the effect relative to a wholly unexposed counterfactual. We address this issue by estimating spillover effects separately. In the spillover analysis, the comparison group consists of institutions without a direct pre-1998 collaboration tie to a sanctioned institution. More distant network exposure could nevertheless attenuate the estimated spillover effects.

Treatment onset is effectively common across institutions at the annual frequency of our data, since the institutions in our treatment group were placed on the Entity List in 1998. We therefore do not face the staggered-adoption problems that arise when institutions begin treatment at different times (De Chaisemartin and d'Haultfoeuille, 2020; Goodman-Bacon, 2021). Removal from the Entity List was staggered, however, and we do not use that variation for identification. The post-1998 coefficients should consequently be interpreted as the effects associated with initial inclusion on the 1998 Entity List, rather than the effect of being listed in each particular year.

The identifying assumptions cannot be tested directly (Baker et al., 2026). We use the coefficients for 1990–1996, relative to the omitted year 1997, to assess whether sanctioned and comparison institutions exhibited differential trends before treatment. Coefficients close to zero are consistent with conditional parallel trends and limited anticipation, but do not prove either assumption. We further assess robustness by allowing trends to vary with institution type and pre-sanction research specialization, and using alternative comparison groups.

To estimate spillover effects, we exclude the 66 institutions placed on the Entity List in 1998 and retain a balanced panel of 1,553 unsanctioned institutions from 1990 through 2009. We define an institution as exposed if it coauthored at least one work with a subsequently sanctioned institution between 1990 and 1997. We define an institutional coauthorship link when both institutions appear among the affiliations attached to the same work. In the full sample, 442 institutions had such a link to a sanctioned institution. Of these, 61 were themselves sanctioned, leaving 381 exposed institutions in the spillover sample. In robustness checks, we use the intensity of prior coauthorship and prior citations to sanctioned institutions as alternative measures of exposure.

We estimate the following event-study specification:

$$E[Y_{it} \mid \cdot] = \exp\left\{ \sum_{\tau \neq 1997} \beta_\tau \left(Collaborated_i \times \mathbf{1}\{t = \tau\} \right) + \delta_i + \eta_t + \mathbf{X}'_{i0}\boldsymbol{\gamma}_t \right\}. \tag{2}$$

The outcome Y_{it} and the fixed effects and controls are defined as in equation (1). The indicator $Collaborated_i$ equals one if institution i coauthored at least one work with a sanctioned institution between 1990 and 1997. The coefficients β_τ compare the evolution of outcomes at these pre-1998 collaborators with the evolution of outcomes at other unsanctioned institutions, relative to the omitted year 1997. Standard errors are clustered by institution, and we estimate the model by pseudo-Poisson maximum likelihood using PPMLHDFE (Correia, Guimarães and Zylkin, 2020). We also estimate a difference-in-differences specification that replaces the year-specific interactions with $Collaborated_i \times Post_t$.

A causal interpretation requires that, conditional on the included fixed effects and controls, collaborating and other unsanctioned institutions would have experienced the same proportional changes in outcomes absent the sanctions. This assumption could fail if institutions connected to sanctioned organizations were differentially exposed after 1998 to other shocks, policies, or changes in the returns to their pre-sanction research specializations. We assess this concern using the pre-treatment event-study coefficients, institution type-by-year fixed effects, controls for pre-sanction research specialization interacted with year, and alternative comparison groups.

The spillover specification also requires an exposure-mapping assumption. We classify institutions according to whether they had a direct coauthorship link to a sanctioned institution before 1998. Institutions in the comparison group may nevertheless have been indirectly connected through longer network paths, citations, shared scientists, or common research inputs. Such broader exposure would tend to reduce the contrast between the two groups and could attenuate the estimated effect of direct pre-sanction collaboration. We therefore interpret β_τ as the effect associated with having a direct pre-1998 collaboration tie, relative to institutions without such a tie, rather than as the effect of all possible exposure to the sanctions. Alternative measures based on citation links and the intensity of prior connections assess the sensitivity of this exposure definition.

3. DATA

Subsection 3.1 describes the OpenAlex data and the construction of our principal outcomes. Subsection 3.2 describes the Entity List, our matching of listed entities to scientific institutions, and our measures of pre-sanction collaboration. Subsection 3.3 introduces the data used to classify research topics, identify nuclear-related work, and locate and categorize institutions.

3.1. **Science.**

We obtain data on Indian scientific production from OpenAlex, an open-access database of scholarly works, authors, institutions, and citations (Priem, Piwowar and Orr, 2022). Our extract, using the February 27, 2025 snapshot, contains more than 500,000 works published between 1990 and 2009, written by more than 350,000 authors with affiliations to 2,505 Indian institutions. We restrict the analysis to the 1,619 institutions that published at least one work between 1990 and 1997, the last full year before the sanctions. We then retain every institution-year observation between 1990 and 2009, including years in which an institution published no work. Institutions that first appear after 1997 are therefore not included in the estimation sample.

OpenAlex combines bibliographic records with persistent identifiers for works, authors, publication sources, and institutions. Where available, it links works to Digital Object Identifiers, authors to ORCID identifiers, publication sources to International Standard Serial Numbers, and institutions to the Research Organization Registry. These identifiers allow us to aggregate works and citations consistently to the institution-year level. We follow OpenAlex's institutional definitions throughout. Thus, a multidivisional organization such as the Defence Research and Development Organisation is treated as one institution when its constituent units share a single OpenAlex institutional identifier.

OpenAlex is particularly well suited to our application for three reasons. First, it provides historical coverage extending throughout our pre-sanction period. Second, it has relatively broad coverage of non-Western and non-English-language research

(Culbert et al., 2025; Maddi, Maisonobe and Boukacem-Zeghmouri, 2025; Mezquita et al., 2025). Third, its open bulk access allows us to retrieve publication-level records and construct a reproducible institution-level panel. Its overall coverage is comparable to that of Web of Science and Scopus (Alperin et al., 2024; Culbert et al., 2025), while avoiding the bulk-access restrictions of commercial databases. OpenAlex has also been used in recent economic research on scientific institutions, international knowledge flows, and researchers' careers (Burkhauser and Ma, 2025; Chandra and Xu, 2025; Fry and Glennon, 2025; Huang and Lin, 2026).

We construct several outcomes Y_{it} for institution i in year t. Our principal outcomes are *Works*, *Citations*, and *New Authors*. *Works* is the number of OpenAlex-indexed works published in year t on which at least one author reports an affiliation with institution i. Our baseline measure includes all types of work in the OpenAlex data.[23] Because a work may contain authors affiliated with several institutions, we use full counting: the same work is assigned to every institution represented among its authors.

Citations is the total number of citations, measured through the date of our OpenAlex snapshot, received by works published by institution i in year t. Citations are assigned to the publication year of the cited work, not to the year in which the citation occurs. Thus, a citation received in year $t+s$ by a work published in year t contributes to $Citations_{it}$. Differences in the time available to accumulate citations across publication years are absorbed by year fixed effects.

New Authors counts authors observed with institution i for the first time in year t. These authors need not be new to scientific publishing: they may have previously published with another affiliation. The variable therefore measures authors who are new to the institution in our data, rather than first-time authors generally. As with works, an author may be assigned to more than one institution in the same year when multiple affiliations are reported.

The institution-year distributions of these outcomes are highly right-skewed, and extreme observations may also reflect errors in author or institution disambiguation. In the baseline analysis, we top-code each outcome at its 99th percentile. We report robustness to alternative thresholds and to using the raw variables. Additional outcomes are defined in the sections in which they are introduced.

Table 1 reports summary statistics for our principal outcomes. Their institution-year distributions are highly right-skewed. The raw number of works has a mean of 20.90, a median of 3, and a maximum of 4,923; more than 25% of institution-year observations

[23] In particular, our data on Indian science contain nineteen distinct types of work. In descending order of frequency, these are: article, book chapter, review, preprint, letter, paratext, other, book, editorial, dataset, erratum, peer review, dissertation, report, retraction, reference entry, standard, supplementary materials, and grant.

contain no works. After top-coding at the 99th percentile, the mean falls to 17.84 and the maximum to 321. Table 1 reports statistics for this top-coded measure.

Citations are similarly concentrated. The raw variable has a mean of 559.53, a median of 28, and a maximum of 72,951. Top-coding at the 99th percentile reduces the mean to 464.22 and the maximum to 9,567. In 32.0% of institution-year observations, works published in that year receive no citations through the date of our OpenAlex snapshot. The raw number of new authors has a mean of 13.71, a median of 3, and a maximum of 1,081; 31.2% of institution-year observations contain no new authors. After top-coding, the mean falls to 12.44 and the maximum to 174.

The combination of non-negative outcomes, many zeroes, and highly right-skewed distributions motivates our use of a Poisson pseudo-maximum-likelihood specification. We show below that the results are robust to alternative top-coding thresholds and to using the unadjusted variables.

3.2. **Sanctions.** We construct our measure of direct treatment from the final rule published in the *Federal Register* on 19 November 1998, which added Indian and Pakistani entities associated with nuclear and missile activities to the US Entity List.[24] Appendix Figure B.1 reproduces an example page from the rule.

The listed entries do not map one-for-one into institutions in our estimation sample. The rule covered both India and Pakistan, included many industrial and military entities that did not publish scientific work, and often listed individual facilities or organizational subdivisions separately. Several listed units therefore map to the same parent institution in OpenAlex. We manually match Indian Entity List entries to OpenAlex institutions using names, aliases, locations, and organizational relationships. Some matches are exact or nearly exact, such as Bharat Heavy Electrical Limited in the Entity List and Bharat Heavy Electricals in OpenAlex. In other cases, a listed facility belongs to a larger organization for which OpenAlex provides only a parent-level identifier. For example, the Beryllium Machining Facility is listed as part of the Indian Space Research Organisation (ISRO), while OpenAlex records scientific output at the level of ISRO. In such cases, we code the OpenAlex parent institution as sanctioned. This procedure identifies 66 sanctioned institutions among the 1,619 institutions in our estimation sample.

We classify institutions using two potentially overlapping indicators. *Sanctioned* equals one for the 66 institutions that we match to an Indian entry on the Entity List in 1998. *Collaborated* equals one if an institution coauthored at least one work with an institution sanctioned in 1998 during the period 1990–1997. We measure institutional coauthorship using the institutional affiliations attached to each work: two institutions are linked if

[24]Federal Register, Vol. 63, No. 223, 19 November 1998, pp. 64322–64340, `https://www.govinfo.gov/content/pkg/FR-1998-11-19/pdf/98-30877.pdf`.

TABLE 1. Summary Statistics

VARIABLES	(1) mean	(2) sd	(3) min	(4) max	(5) N
Year	2,000	5.77	1,990	2,009	32,380
Sanctioned	0.041	0.20	0	1	32,380
Collaborated	0.27	0.45	0	1	32,380
Works	17.8	45.6	0	321	32,380
Works on Nuclear Topics	0.34	1.46	0	11	32,380
Citations	464	1,356	0	9,567	32,380
New Authors	12.4	27.0	0	174	32,380

Works, Works on Nuclear Topics, Citations, and *New Authors* are top-coded at their 99th percentiles. *Collaborated* is an overlapping indicator and includes sanctioned institutions that collaborated with another sanctioned institution before 1998.

both appear among the affiliations on the same work. Because sanctioned institutions could collaborate with one another before 1998, the two indicators overlap. In our main spillover analysis, we exclude sanctioned institutions, leaving only unsanctioned institutions with pre-1998 links to sanctioned institutions in the exposed group. We classify institutions for which both indicators equal zero as *Neither*.

In the full sample, 442 institutions had at least one pre-1998 coauthorship link to a subsequently sanctioned institution. Of these, 61 were themselves sanctioned. Our classification therefore contains 66 sanctioned institutions, 381 unsanctioned collaborators, and 1,172 institutions in the *Neither* category. Collaborators constitute 24.5% of the unsanctioned sample, or 23.5% of the full sample. In robustness checks, we replace the binary collaboration measure with measures based on the number of jointly authored works and on pre-sanction citations to sanctioned institutions.

Pre-sanction collaborations with subsequently sanctioned institutions covered a wide range of fields and team structures. Some occurred within large international collaborations. For example, Abachi et al. (1995) reported the observation of the top quark in a paper whose authors included B. S. Acharya of the subsequently sanctioned Tata Institute of Fundamental Research and V. Bhatnagar of the unsanctioned Panjab University. Other links involved much smaller teams. Mohan et al. (1997) brought together researchers from the unsanctioned International Centre for Genetic Engineering and Biotechnology and BARC's sanctioned Nuclear Agricultural Division. In Devi, Bhagawan and Thomas (1997), researchers at the unsanctioned Mahatma Gandhi University collaborated with a scientist at the sanctioned Vikram Sarabhai Space Centre on the use of pineapple-leaf

fibre in polyester composites. These examples illustrate both the breadth of the network and the potential importance of distinguishing isolated coauthorships from more intensive relationships.

To describe pre-sanction collaboration quantitatively, we count the distinct works published by each institution between 1990 and 1997 and calculate the share that included affiliations from at least two Indian institutions. We use full counting, so a work involving several institutions contributes once to the publication count of each institution represented on it. The mean share of works involving another Indian institution was 35% among subsequently sanctioned institutions and 35% among their unsanctioned collaborators, compared with 26% among institutions in neither group.

Collaboration was highly uneven across institutions. In the average institution-year, an institution collaborated with 10.6 distinct partners, of which 4.4 were Indian and 6.2 were foreign. The median institution, however, collaborated with only one partner: one Indian institution and no foreign institutions.

To describe the domestic network, we use a stricter definition of collaboration that requires the two institutions to be represented by different authors on the same work. We define an undirected edge between two Indian institutions if they satisfy this criterion on at least one work between 1990 and 1997. The resulting network contains 1,619 nodes and 6,831 edges, implying an average degree of 8.4 and a density of 0.52%.[25] Figure 3 displays the components of the pre-sanction domestic network that contain at least one sanctioned institution. Nearly 70% of institutions belong to a single large connected component, while 29% are isolates.

Sanctioned institutions and their unsanctioned first-order neighbours were much more connected than other institutions. Their mean degrees were 24.0 and 22.5, respectively, compared with 3.1 among institutions in neither group. The network also exhibits positive assortative mixing by sanction status, with an assortativity coefficient of 0.164.[26] Of the 66 sanctioned institutions, 60, or 90.9%, had collaborated with at least one other sanctioned institution before 1998 under this stricter definition. Similarly, 376 of the 1,553 unsanctioned institutions, or 24.2%, had collaborated with a sanctioned institution.[27]

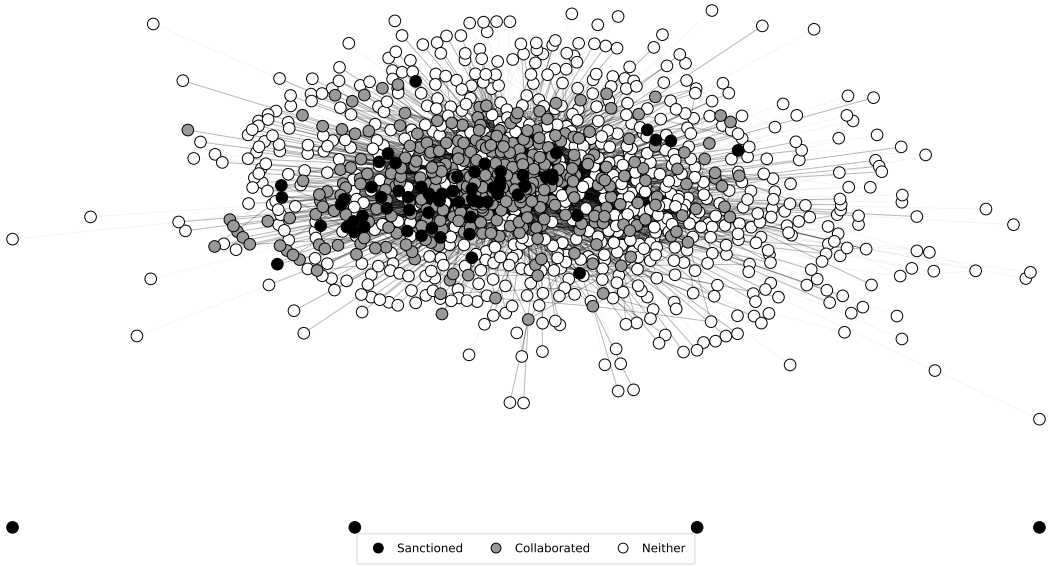
3.3. **Other Data.** We supplement the publication data with measures of research specialization, nuclear-related research, institutional location, and institution type.

[25]For an undirected network with N nodes and E edges, average degree is $2E/N$, while density is $2E/[N(N-1)]$.

[26]We measure assortativity as the Pearson correlation between the *Sanctioned* indicators at the two ends of each edge.

[27]The latter figure is slightly smaller than the 381 institutions classified as collaborators under our broader treatment definition, which also includes links arising from authors with multiple institutional affiliations.

FIGURE 3. Pre-Sanction Collaboration Network around Sanctioned Institutions



Nodes are Indian institutions active between 1990 and 1997, and edges indicate at least one jointly authored work during this period. The figure displays all connected components containing at least one institution sanctioned in 1998, including isolated sanctioned institutions, and omits components containing no sanctioned institution. Black nodes are sanctioned institutions, grey nodes are their first-order neighbours, and white nodes are other institutions in these components.

OpenAlex assigns one or more topics to each work using a machine-learning model.[28] Our data contain 4,228 topics, which OpenAlex organizes into 252 subfields, 26 fields, and four broad domains. For example, OpenAlex places the topic "Cold Fusion and Nuclear Reactions" within the subfield "Geochemistry and Petrology," the field "Earth and Planetary Sciences," and the domain "Physical Sciences." OpenAlex also assigns each work–topic pair a score between zero and one. We classify a work as belonging to a topic when this score is at least 0.9. Because OpenAlex can assign several topics to the same work and the topic scores need not sum to one, a single work may contribute to more than one topic-specific count. We use these counts to construct each topic's share of an institution-year's qualifying topic assignments.

We use these assignments to construct *Works on Nuclear Topics*, the number of works published by institution i in year t that OpenAlex links to at least one topic that we classify as nuclear. For our baseline measure, we use ChatGPT 5.2 to classify the OpenAlex topic list and apply these classifications to the 4,228 topics appearing in our data. We use the following criterion: a topic is nuclear if "the scientific knowledge represented by the topic has a specific, technically meaningful, and reasonably proximate connection to nuclear

[28] `https://help.openalex.org/hc/en-us/articles/24736129405719-Topics`

weapons capability." The full prompt is in Appendix A. This classification identifies 20 nuclear topics.[29] We apply the classification at the topic level, rather than asking the model to classify individual works, and retain the resulting topic list throughout the analysis.

Because the boundary of nuclear-related research is inherently uncertain, we also construct several alternative measures. As an alternative keyword-based measure, we code a topic as nuclear if its lowercase name contains "nuclear" or "atomic," identifying 16 topics. We introduce further alternative approaches below, for robustness. These use related topics identified by OpenAlex or, alternatively, a continuous score based on the rate at which each topic appears alongside keyword-defined nuclear topics in pre-sanction publications. These alternatives allow us to assess whether the results depend on the breadth of our baseline LLM classification.

OpenAlex assigns each institution to a city based on the headquarters or principal location associated with each institution. These cities have GeoNames identifiers and latitude-longitude coordinates. These locations allow us to include city-by-year fixed effects, which absorb shocks that affect all institutions in the same city in a given year.

Finally, OpenAlex classifies institutions by type. The nine categories in our sample are education, healthcare, facility, funder, government, company, nonprofit, archive, and other. We use these classifications in several ways. Our baseline specifications include institution type-by-year fixed effects, allowing institutions of different types to follow different time paths. In robustness checks, we restrict the comparison group to institution types that include at least one sanctioned institution and exclude government institutions to determine whether public research agencies drive the results.[30]

4. RESULTS

This section presents our results in three parts. In subsection 4.1, we estimate the effects of sanctions on scientific output. The event-study estimates show that, relative to their respective comparison groups, output at sanctioned institutions was 20% lower by 2001 and 45% lower by 2009. Output at their pre-1998 collaborators was 23% lower

[29]These are: Nuclear physics research studies; Radioactive element chemistry and processing; Nuclear Physics and Applications; Laser-Plasma Interactions and Diagnostics; Nuclear Materials and Properties; Combustion and Detonation Processes; Radiation Detection and Scintillator Technologies; Nuclear reactor physics and engineering; Graphite, nuclear technology, radiation studies; Particle accelerators and beam dynamics; Nuclear materials and radiation effects; Radiation Effects in Electronics; Particle Accelerators and Free-Electron Lasers; Particle Detector Development and Performance; Radioactive Decay and Measurement Techniques; Nuclear Engineering Thermal-Hydraulics; Molten salt chemistry and electrochemical processes; Pulsed Power Technology Applications; Cold Fusion and Nuclear Reactions; and Fusion and Plasma Physics Studies.

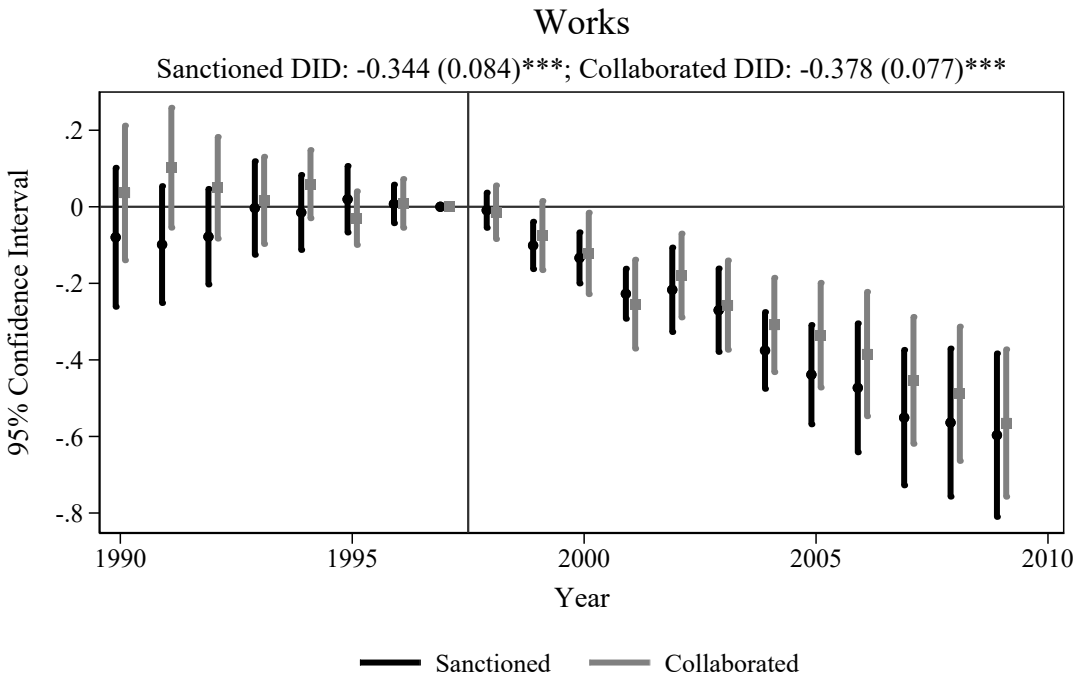
[30]The shares of institutions in each category are education (31.25%), healthcare (17.36%), facility (14.82%), funder (13.22%), government (8.59%), company (6.86%), nonprofit (5.31%), archive (0.37%), and other (2.22%).

by 2001 and 43% lower by 2009. Thus, the indirect effects grew over time and became similar in magnitude to the direct effects.

In subsection 4.2, we examine citation-based measures of research impact and the direction of research. Sanctioned institutions and their collaborators produced relatively fewer highly cited works and less research on both nuclear and non-nuclear topics. They also reallocated less toward new research areas than did their comparison institutions. In subsection 4.3, we show that the main results are robust to alternative comparison groups, alternative measures of exposure to sanctioned institutions, richer controls for pre-sanction characteristics, and other changes to the sample and estimation procedure.

4.1. **Main Results.** Our main result is that scientific output at both sanctioned institutions and their pre-1998 collaborators grew substantially more slowly after 1998 than output in their respective comparison groups. Figure 4 plots the event-study coefficients. The black estimates compare sanctioned institutions with non-sanctioned institutions, while the grey estimates compare unsanctioned pre-1998 collaborators with other unsanctioned institutions. The bars show 95% confidence intervals, and 1997 is the omitted

FIGURE 4. Dynamic Effects of Sanctions on Scientific Output



***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

TABLE 2. Average Post-1998 Effects on Scientific Output

VARIABLES	(1) Works	(2) Works	(3) Works	(4) Works
Sanctioned × Post	-0.396***	-0.344***		
	(0.095)	(0.084)		
Collaborated × Post			-0.421***	-0.378***
			(0.070)	(0.077)
Observations	32,380	32,380	31,060	31,060
Institution and Year FE	Yes	Yes	Yes	Yes
Controls	No	Yes	No	Yes

***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. Controls are institution type × year fixed effects. Standard errors clustered by institution.

year. The pre-sanction coefficients show no clear differential trend in the baseline specification.

The estimated output gaps grow over time. By 2001, output at sanctioned institutions was 20.3% lower than its estimated counterfactual. By 2009, the gap had widened to 44.9%. For pre-1998 collaborators, the corresponding estimates are 22.5% in 2001 and 43.2% in 2009. These estimates represent relative shortfalls rather than absolute declines. As Figure 1 shows, raw output continued to rise in both groups after 1998, but it failed to keep pace with output at the comparison institutions.

Table 2 reports the corresponding difference-in-differences estimates. Columns (1) and (2) estimate the direct effect of inclusion on the Entity List. Columns (3) and (4) exclude sanctioned institutions and estimate spillover effects on their pre-1998 collaborators. Columns (1) and (3) include institution and year fixed effects, while columns (2) and (4) additionally include institution type-by-year fixed effects. In our preferred specifications, in columns (2) and (4), the coefficients are -0.344 for sanctioned institutions and -0.378 for collaborating institutions. These estimates imply average post-1998 output shortfalls of 29.1% and 31.5%, respectively.[31] The DID estimates summarize average differences over the post-sanction period, while the event studies show that these differences became progressively larger.

These effects are large relative to many shocks studied in the economics of science. The death of a superstar collaborator reduces coauthors' publication rates by approximately 5–8% (Azoulay, Graff Zivin and Wang, 2010), while the death of a co-inventor reduces

[31]We convert coefficients into percentage effects using $100[\exp(\hat{\beta}) - 1]$, unless otherwise indicated.

citation-weighted patenting by roughly 15% (Jaravel, Petkova and Bell, 2018). US scientists with Chinese collaborators experienced a 2.1% relative decline in publications after 2018 (Jia et al., 2024). Our estimates are closer to those associated with broader disruptions to scientific systems. The collapse of international scientific cooperation during the First World War reduced the productivity of exposed US biochemists by approximately 30% (Iaria, Schwarz and Waldinger, 2018), while the arrival of Soviet mathematicians reduced the productivity of more exposed American mathematicians by roughly one third (Borjas and Doran, 2012).

The magnitudes are also large relative to several firm-level estimates of sanctions. Russian firms that depended on subsequently restricted imports experienced an output decline of approximately 14% (Egorov et al., 2025*a*), while US suppliers of sanctioned foreign entities reduced R&D expenditure by approximately 11% (Gao, Shroff and Zhang, 2026). By comparison, imports by directly targeted Russian firms fell by approximately 44% (Nigmatulina, 2025). These comparisons are necessarily approximate because the studies examine different outcomes, treatment intensities, and units of observation, but they place our estimates toward the upper end of the existing evidence.

Two features of the results stand out. First, the estimated gaps widen over time and remain large through 2009, despite the substantial relaxation of the Entity List restrictions in 2000–01. Because some institutions remained listed through the end of our sample, the later coefficients do not identify effects after sanctions had ended for every treated institution. They do, however, show that the effects associated with initial listing did not quickly disappear as the broader sanctions regime was relaxed. Second, the estimated output shortfall among pre-1998 collaborators becomes numerically similar to the direct-effect estimate by 2009. The indirect incidence of the sanctions was economically substantial.

4.2. **Additional Results.** We next examine how the sanctions affected research impact and the direction of research. Citation-based measures show that sanctioned institutions and their pre-1998 collaborators produced less influential work after 1998. The results using Kelly et al. (2021) (KPST) scores are more nuanced: affected institutions published less, but the works they continued to publish had higher average KPST scores. We then show that affected institutions produced less research on both nuclear and non-nuclear topics and reallocated less towards new research areas.

4.2.1. *Research Impact.* We measure research impact using citations, counts of highly cited works, and title-based KPST scores. Our citation outcome assigns to each institution-year the total citations, measured over our observation window, received by works published in that year. Thus, citations received in year $t + s$ by a work published in year t contribute to the outcome in year t. The estimates therefore capture the

subsequent impact of newly published research, not changes in citations to work published before the sanctions.

Appendix Figure B.2 shows that works published after 1998 by both sanctioned and collaborating institutions received fewer citations than works published by their respective comparison institutions. The DID coefficients imply average citation shortfalls of approximately 42% for sanctioned institutions and 30% for collaborating institutions. The event-study estimates remain negative through 2009.

We find similar results when we count highly cited works. We use as outcomes the numbers of works that subsequently receive at least 10, 50, or 100 citations. Appendix Figures B.3, B.4, and B.5 show declines for both sanctioned institutions and their pre-1998 collaborators at all three thresholds. Thus, the fall in total citations does not arise solely from small reductions spread across many publications; affected institutions also produced substantially fewer works in the upper tail of the citation distribution.

We also construct title-based KPST scores (Kelly et al., 2021). The score compares a work's similarity to later research with its similarity to earlier research.[32] A higher score therefore identifies work that is relatively dissimilar from prior research but more closely related to subsequent work. We use a five-year window on either side of publication and calculate textual similarity using titles rather than abstracts. For computational feasibility, we construct the comparison corpus using works with at least one Indian-affiliated author. The resulting measure should therefore be interpreted as influence relative to subsequent research in our Indian publication corpus. We average the work-level scores within each institution-year.

The KPST estimates depend on how we treat institution-years with no publications. Appendix Figure B.6 restricts the sample to institution-years for which we can compute an average KPST score. Conditional on publishing, both sanctioned and collaborating institutions produced works with higher average KPST scores after 1998. This result does not imply that their overall scientific influence increased, because the sanctions also made these institutions substantially less likely to publish. In Figure B.7, we assign a score of zero to institution-years in which the institution publishes no works. We leave institution-years with publications but no defined KPST score as missing. Under this measure, KPST influence declines for both groups.

The contrast between the two KPST measures suggests a compositional effect: the sanctions may have reduced output disproportionately among institutions whose pre-sanction research was less influential, raising average KPST scores among the works that remained. To examine this possibility, we divide collaborating institutions according

[32] For work j, the KPST score is FS_j^τ / BS_j^τ, where FS_j^τ measures similarity to works published during the following τ years and BS_j^τ measures similarity to works published during the preceding τ years. We set $\tau = 5$. A full description of the measure is in Kelly et al. (2021).

to whether their average KPST score during 1990–1997 was above or below the median and re-estimate equation (2). Figure B.8 shows substantially larger output losses among institutions with below-median pre-sanction KPST scores. This heterogeneity is consistent with the increase in average KPST scores conditional on publishing: lower-influence institutions account for a disproportionate share of the decline in output. We do not conduct the corresponding split for sanctioned institutions because the number of treated institutions is small.

4.2.2. *The Direction of Research.* We next examine whether sanctions changed the direction as well as the level of scientific output. We first ask whether the decline documented in Figure 4 was confined to nuclear-related research. It was not. Appendix Figures B.9 and B.10 show that both sanctioned institutions and their pre-1998 collaborators produced less nuclear and non-nuclear research after 1998.

A decline in nuclear research need not imply that affected institutions successfully redirected their activity towards new fields. We examine changes in research composition using two measures that compare each institution's topic profile in year t with its average profile during 1990–1997.

Our first measure captures overlap with the pre-sanction topic profile. Let s_{ikt} denote the share of institution i's topic assignments in year t that belong to topic k, and let s_{ik0} denote the corresponding share during 1990–1997. We define *Topic Profile Overlap* as

$$TopicProfileOverlap_{it} = \sum_k s_{ikt} s_{ik0}. \tag{3}$$

Higher values indicate that an institution places more weight on topics that were prominent in its pre-sanction research.[33] We define both measures only for institution-years with at least one qualifying topic assignment.

Figure B.11 shows that this overlap measure increases for both sanctioned and collaborating institutions: their post-1998 research remained more closely concentrated in the topics that had characterized their pre-sanction work than did research at their respective comparison institutions.

Our second measure is the total variation distance between the current and pre-sanction topic profiles:

$$TopicReallocation_{it} = \frac{1}{2} \sum_k \left| s_{ikt} - s_{ik0} \right|. \tag{4}$$

[33] Let n_{ikt} denote the number of works published by institution i in year t that OpenAlex assigns to topic k with a score of at least 0.9. We define $s_{ikt} = n_{ikt} / \sum_{k'} n_{ik't}$ and define s_{ik0} analogously using works published during 1990–1997. Because OpenAlex may assign more than one qualifying topic to the same work, these quantities are shares of topic assignments rather than shares of distinct works.

This measure equals zero when the two topic profiles are identical and increases as an institution reallocates research across topics.[34] Figure B.12 shows negative effects for both sanctioned and collaborating institutions. Relative to their respective comparison groups, affected institutions reallocated less of their research towards topics outside their pre-sanction portfolios. Taken together, the results show that the sanctions reduced output in both nuclear and non-nuclear fields and did not induce compensating movement into new research areas.

4.3. **Robustness.** We assess the robustness of our results along three dimensions. First, we use alternative comparison groups and allow outcomes to evolve flexibly with institutions' pre-sanction characteristics. Second, we vary how we define exposure to sanctioned institutions. Third, we examine whether particular institutions, local shocks, or features of our estimator drive the results.

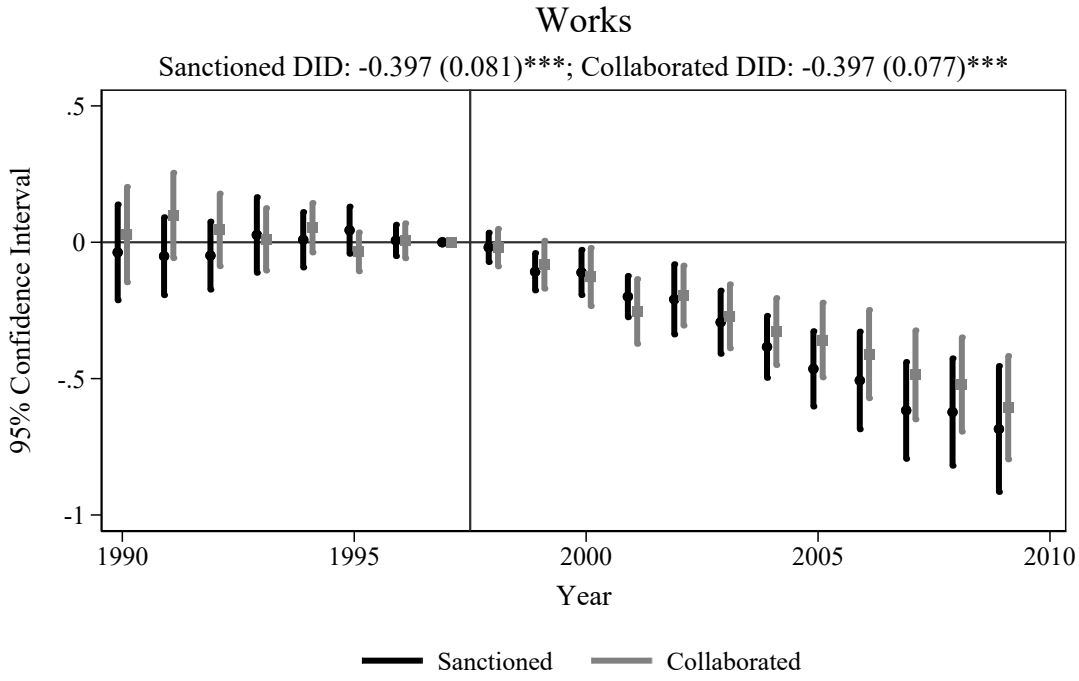
4.3.1. *Comparison Groups and Pre-Sanction Characteristics.* Our baseline direct-effect specification compares sanctioned institutions with all non-sanctioned institutions, including institutions that had previously collaborated with sanctioned institutions. Our baseline spillover specification excludes sanctioned institutions and compares their pre-1998 collaborators with other unsanctioned institutions. A causal interpretation requires that, conditional on our controls, each comparison group would have experienced the same proportional changes as the corresponding treated group in the absence of the sanctions. We assess this assumption by allowing outcomes to evolve with pre-sanction research specialization and restricting the sample in several ways.

One concern is that the returns to nuclear-related research changed after India completed the tests for reasons unrelated to the sanctions. Because sanctioned institutions and their collaborators were more specialized in nuclear research before 1998, such a change could generate differential post-1998 trends even in the absence of the Entity List restrictions. In Figure 5, we interact year indicators with each institution's share of works on nuclear topics during 1990–1997. This specification allows the association between pre-sanction nuclear specialization and research output to vary in every year. The estimated effects on sanctioned institutions and their collaborators remain close to, and slightly larger than, the baseline estimates in Figure 4.

Changing returns to other fields could create a similar concern. We therefore interact year indicators with each institution's pre-sanction shares of research in OpenAlex's four broad domains: Health Sciences, Life Sciences, Physical Sciences, and Social Sciences. Figure B.13 again shows estimates that are somewhat larger than the baseline results.

[34] The shares s_{ikt} and s_{ik0} are defined in Footnote 33.

FIGURE 5. Controlling for Pre-Sanction Nuclear Specialization



***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution. All specifications additionally interact year indicators with the share of works published on nuclear topics during 1990–1997.

We next examine the sensitivity of the estimates to sample composition. Figure B.14 restricts the sample to institution types that contain at least one sanctioned institution, excluding archives, healthcare institutions, nonprofits, and institutions classified as "other." Because sanctioned institutions were generally larger than other institutions, we also progressively remove institutions in the bottom 10%, 25%, and 50% of the pre-sanction output distribution in Figures B.15, B.16, and B.17. These restrictions compare treated institutions with increasingly large and research-active institutions.

We conduct two further checks for influential observations. Figure B.18 excludes institutions that published 3,000 or more works during 1990–1997, ensuring that the largest research organizations do not drive the estimates. Figure B.19 reports the distribution of direct-effect estimates obtained by excluding each sanctioned institution in turn.

Finally, we vary the composition of the estimation samples. Because the baseline direct-effect comparison group includes institutions that may themselves experience spillovers, Figure B.20 re-estimates the direct effect after excluding pre-1998 collaborators. This specification compares sanctioned institutions only with institutions in the *Neither* group.

Figure B.21, similarly, includes sanctioned institutions in the spillover sample, rather than excluding them. Figure B.22 restricts the sample to institutions that published at least one work in every year from 1990 through 2009. Across these specifications, the estimates remain negative. Most remain statistically significant, although their magnitudes vary: the spillover estimate becomes smaller when we restrict the sample to continuously publishing institutions.

4.3.2. *Alternative Measures of Spillover Exposure.* Our baseline spillover measure classifies an unsanctioned institution as exposed if it coauthored at least one work with a subsequently sanctioned institution between 1990 and 1997. A single coauthorship may represent only a weak relationship. We therefore construct two measures of more intensive pre-sanction collaboration. We classify institutions according to whether their number of jointly authored works with sanctioned institutions was at or above the 75th or 90th percentile of the pre-sanction distribution. Figure B.23 shows that the estimated output losses remain negative, statistically significant, and similar in magnitude to our baseline spillover estimate. The results therefore do not depend on treating every pre-sanction coauthorship as equally informative about exposure.

Coauthorship is not the only channel through which institutions may depend on research produced elsewhere. An institution may use knowledge generated by a sanctioned institution without publishing jointly with it. We therefore construct citation-based measures of exposure. First, we classify an unsanctioned institution as exposed if its pre-1998 works cited at least one work associated with a subsequently sanctioned institution. Figure B.24 compares estimates based on this citation link with those based on our baseline coauthorship measure. The citation-based estimates show the same declining post-1998 pattern and are somewhat larger in magnitude.

We then define more intensive citation exposure using the 75th and 90th percentiles of the number of pre-sanction citations to sanctioned institutions. Figure B.25 again shows large and persistent output losses. Taken together, these exercises show that the spillover results do not depend on defining exposure through a single coauthored work: they also appear when we require stronger coauthorship ties and when we measure links through the prior use of sanctioned institutions' research.

4.3.3. *Other Robustness Checks.* We first examine whether a small number of government and defence institutions drive the results. Figure B.26 excludes all institutions that OpenAlex classifies as government institutions. Figure B.27 instead excludes the principal agencies associated with India's nuclear, defence, and space programmes: the Indian Space Research Organisation, Bhabha Atomic Research Centre, Department of Atomic Energy, Indira Gandhi Centre for Atomic Research, and Defence Research and Development Organisation. Similarly, Figure B.28 excludes every institution whose name

contains either "defence" or "defense." The estimated direct and spillover effects remain negative and similar to the baseline across these restrictions. Finally, Figure B.29 excludes four institutions that the Federal Register of 19 November 1998 identifies as having been added in 1997 – the Bhabha Atomic Research Centre, Bharat Electronics, the Indira Gandhi Centre for Atomic Research, and the Department of Atomic Energy. Results again are almost unchanged.

We next assess whether our results for nuclear-related output depend on the LLM classification of OpenAlex topics. Our first alternative defines a topic as nuclear when its name contains either "nuclear" or "atomic." Figure B.30 shows that nuclear-related output again declines at both sanctioned institutions and their pre-1998 collaborators. Our second alternative expands this keyword-defined set to include topics that OpenAlex identifies as siblings of the keyword-defined nuclear topics. Figure B.31 produces similar results.

Our third alternative constructs a continuous measure of nuclear intensity using pre-sanction co-publication patterns. For each topic, we calculate the share of works assigned to that topic during 1990–1997 that OpenAlex also assigns to a keyword-defined nuclear topic. We then calculate each work's nuclear intensity as the OpenAlex-score-weighted average of these topic-specific shares and sum the work-level scores within each institution-year.[35] Figure B.32 again shows relative declines for both sanctioned institutions and their collaborators. The conclusion that sanctions reduced nuclear-related research therefore survives alternative measures of nuclear content.

We also test whether local shocks account for the estimates. Figure B.33 adds city-by-year fixed effects, which absorb shocks common to all institutions located in the same city in a given year. The estimates remain close to the baseline results. Thus, differential city-level changes do not explain the estimated direct or spillover effects.

Finally, we vary the estimator and the treatment of extreme observations. Figure B.34 estimates the specifications by ordinary least squares using the inverse hyperbolic sine of the top-coded number of works. The coefficients remain negative for both sanctioned and collaborating institutions, although they are smaller and less precisely estimated than the PPML coefficients. Figure B.35 instead uses an indicator for whether an institution publishes any work in a given year. Both groups become significantly less likely to publish, showing that the results also appear on the extensive margin.

[35] Let n_k denote the share of Indian works assigned to topic k during 1990–1997 that are also assigned to a topic whose name contains "nuclear" or "atomic." We include a work–topic assignment when its OpenAlex score s_{wk} is at least 0.9. For work w, we define

$$n_w = \frac{\sum_{k:s_{wk}\geq 0.9} n_k s_{wk}}{\sum_{k:s_{wk}\geq 0.9} s_{wk}}.$$

Our institution-year outcome is the sum of n_w across works associated with that institution in that year.

Our baseline outcome is top-coded at the 99th percentile. We instead top-code at the 95th percentile in Figure B.36, at the 99.9th percentile in Figure B.37, and do not top-code in Figure B.38. The estimated post-sanction effects remain negative and statistically significant under each treatment of the upper tail, although their magnitudes vary. The treatment of extreme observations matters more for the pre-sanction coefficients among sanctioned institutions. When some of these coefficients are significant, they are negative in the earlier pre-sanction years and move towards zero by 1997. This pattern indicates relative improvement before the sanctions, rather than continuation of the subsequent decline, and therefore does not explain the negative post-sanction estimates.

5. MECHANISMS

This section develops a conceptual framework and presents evidence consistent with its proposed channels. Subsection 5.1 explains how restrictions on research inputs and scientific exchange can affect both sanctioned institutions and institutions connected to them through prior collaboration. Subsection 5.2 examines the corresponding changes in author entry and mobility, spillovers by network distance, and impacts on institutional collaboration. Subsection 5.3 considers two alternative explanations: a general decline in the returns to nuclear research and substitution towards foreign collaborators outside the United States.

The framework emphasizes two immediate effects of the Entity List restrictions. First, they raised the cost or reduced the availability of covered equipment, materials, software, maintenance, and other imported research inputs. Second, they impeded scientific exchange with US institutions and researchers. Because scientific production is cumulative and collaboration provides access to complementary knowledge, these disruptions can reduce both current and future output and can propagate to institutions that had previously collaborated with sanctioned institutions.

Several patterns in the data are consistent with this interpretation. Sanctioned institutions and their pre-1998 collaborators attracted fewer new authors and collaborated with fewer other institutions, including Indian and US institutions. Author moves and exits also declined. We find little evidence that a general decline in nuclear research or substitution towards other foreign partners explains the main results.

5.1. **Conceptual Framework.**

Scientific production at an institution depends on scientists, physical inputs, and access to existing knowledge. Existing research matters because ideas are inputs into the production of new ideas. Innovation is cumulative and often recombinant, so current research contributes to the knowledge on which future research can build (Jones, 1995; Klette and Kortum, 2004; Weitzman, 1998). As the stock

of knowledge expands, scientific production may also require greater specialization and larger teams (Jones, 2009).

Institutions differ in their access to this knowledge. Some knowledge is codified in publications and can diffuse widely, while tacit knowledge is transmitted through interaction among researchers. Collaboration can therefore provide access to complementary knowledge and capabilities that an institution does not possess internally. This interpretation is consistent with the growing importance of teams in scientific production and with evidence that knowledge flows through collaboration networks (Wuchty, Jones and Uzzi, 2007; Zacchia, 2020). Geographic proximity can facilitate such exchanges (Jaffe, Trajtenberg and Henderson, 1993; Keller, 2002), but collaboration links can also transmit knowledge across locations.

The Entity List restrictions disrupted scientific production at targeted institutions through two immediate channels. First, export controls raised the cost or reduced the availability of covered equipment, materials, software, maintenance services, and other imported inputs. Second, restrictions on scientific exchange impeded access to US researchers and to knowledge transmitted through collaboration. Both channels can reduce current productivity and make sanctioned institutions less attractive to prospective scientists and collaborators. Some physical inputs may eventually be replaced, but scientific teams, specialized human capital, and institutional research capacity may take longer to rebuild (Waldinger, 2016).

The same channels can generate spillovers. Research produced by a sanctioned institution may serve as an input into research at other institutions, particularly those connected to it through prior collaboration. If sanctions reduce the institution's output or disrupt established relationships, its partners lose access to both a source of knowledge and a complementary research relationship. Institutions that collaborated with sanctioned institutions before 1998 should therefore be particularly exposed. More generally, innovation shocks can propagate through technological and collaboration networks, with the size of the resulting effects depending on technological proximity and network position (Acemoglu, Akcigit and Kerr, 2016; Fleming, King III and Juda, 2007; Fons-Rosen and Pu, 2023; Huang, 2021, 2018).

These effects may persist after the restrictions are relaxed. Lower current output reduces the stock of research available for subsequent work, while disrupted teams and collaboration links may be costly to reconstruct. An initial restriction on inputs and scientific exchange can therefore reduce future output, recruitment, and collaboration even after the immediate constraints have eased. Frictions in scientific labour markets may reinforce this persistence by slowing the movement of researchers across institutions and

fields (Lissoni and Miguelez, 2024). The predicted effect on incumbent mobility is nevertheless ambiguous. Deteriorating research conditions may encourage scientists to leave, while institution- or topic-specific human capital and limited outside opportunities may discourage movement.

The framework has four implications that organize our empirical evidence. First, output and research impact should decline at sanctioned institutions. Second, output and impact should also decline at institutions connected to sanctioned institutions through the pre-sanction collaboration network. If these spillovers propagate through successive collaboration links, their magnitude should attenuate with network distance: immediate neighbours should be most exposed, institutions two links away less exposed, and more distant connected institutions less exposed still. Third, both direct and spillover effects may grow over time and remain after the sanctions are substantially relaxed, because lower current output weakens subsequent knowledge accumulation and the formation of scientific teams. Fourth, sanctioned institutions and their collaborators should attract fewer new scientists and form fewer new collaborations, particularly with US institutions.

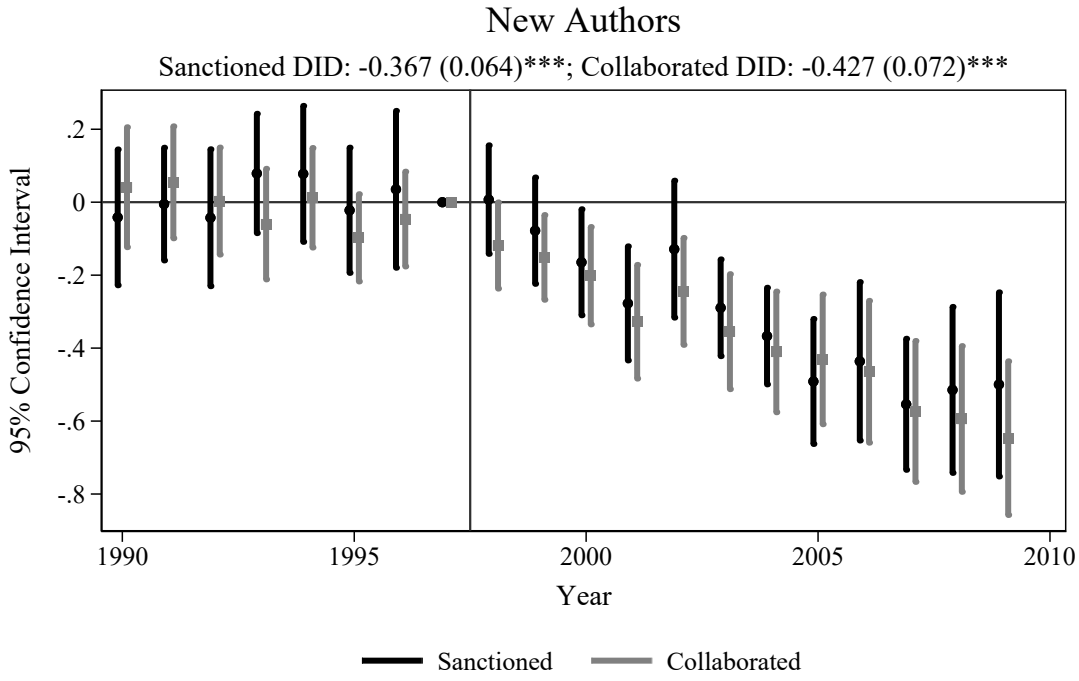
5.2. **Evidence.** We examine three patterns that bear on the channels highlighted by the conceptual framework. First, we study the entry and subsequent movement of scientists associated with sanctioned institutions and their pre-1998 collaborators. Second, we show that spillovers attenuate with network distance. Third, we examine changes in their institutional collaborations.

5.2.1. *Scientist Entry and Mobility.* We first examine whether affected institutions attracted fewer scientists. Our measure of *New Authors* counts authors who appear with institution i for the first time in year t. These authors need not be new to scientific publishing and need not represent permanent hires: they may have previously published with another institution or may be temporarily affiliated with institution i. The measure therefore captures entry into the institution's observed pool of authors rather than employment directly.

Figure 6 shows substantial relative declines in new authors at both sanctioned institutions and their pre-1998 collaborators. The DID coefficients imply shortfalls of approximately 31% and 35%, respectively. The total number of authors associated with both groups also declines, as shown in Figure B.39. These patterns are consistent with weaker recruitment or reduced attractiveness to prospective collaborators, although the publication data do not allow us to distinguish formal hiring from other forms of institutional affiliation.

This decline in new authors is broad-based across entrants from different prior positions. Figure B.40 shows a relative decline in authors who are new to publishing, whom

FIGURE 6. New Authors



***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

we define as having no OpenAlex publication in an earlier year. Figure B.41 shows a similar decline in authors who are new to the institution but whose most recent identifiable pre-entry affiliation was Indian. The fall also extends to international inflows. Figures B.42 and B.43 show relative declines in new authors whose most recent identifiable pre-entry affiliations were in the US and other foreign countries, respectively. The proportional reductions are broadly similar across these sources, indicating that the overall decline in new authors reflects both reduced entry into publishing and reduced movement of previously active scientists across institutions and countries.

We next examine the departure of incumbent authors. For each author–institution pair, we identify the last year in which the author publishes with that institution and assign the departure to the following year. We classify the departure as a *move* if the author subsequently publishes with another Indian institution, and as an *exit* if the author is not subsequently observed publishing with any Indian institution. The latter category may include researchers who continue publishing abroad.

Figures B.44 and B.45 show that both moves and exits decline at sanctioned institutions and their pre-1998 collaborators. Together with the decline in new authors, these patterns

are consistent with reduced entry and reallocation within the Indian research system. However, our measures cannot distinguish researchers who cease publishing from those who continue publishing abroad.

5.2.2. *Network Propagation.* We test whether the spillover effects attenuate with distance from sanctioned institutions in the pre-sanction collaboration network. We exclude sanctioned institutions and classify the remaining institutions by their shortest path to any sanctioned institution in the 1990–1997 domestic collaboration network: first-order connections, second-order connections, and institutions three or more links away. Institutions with no path to a sanctioned institution form the comparison group. Figure 7 shows a clear post-1998 gradient. The DID coefficients are -0.976 for first-order connections, -0.692 for second-order connections, and -0.414 for institutions three or more links away. Thus, the estimated output loss is largest among immediate neighbours of sanctioned institutions and progressively smaller at greater network distance. This pattern is consistent with the sanctions propagating through pre-existing scientific networks rather than affecting only institutions that collaborated directly with a sanctioned institution.

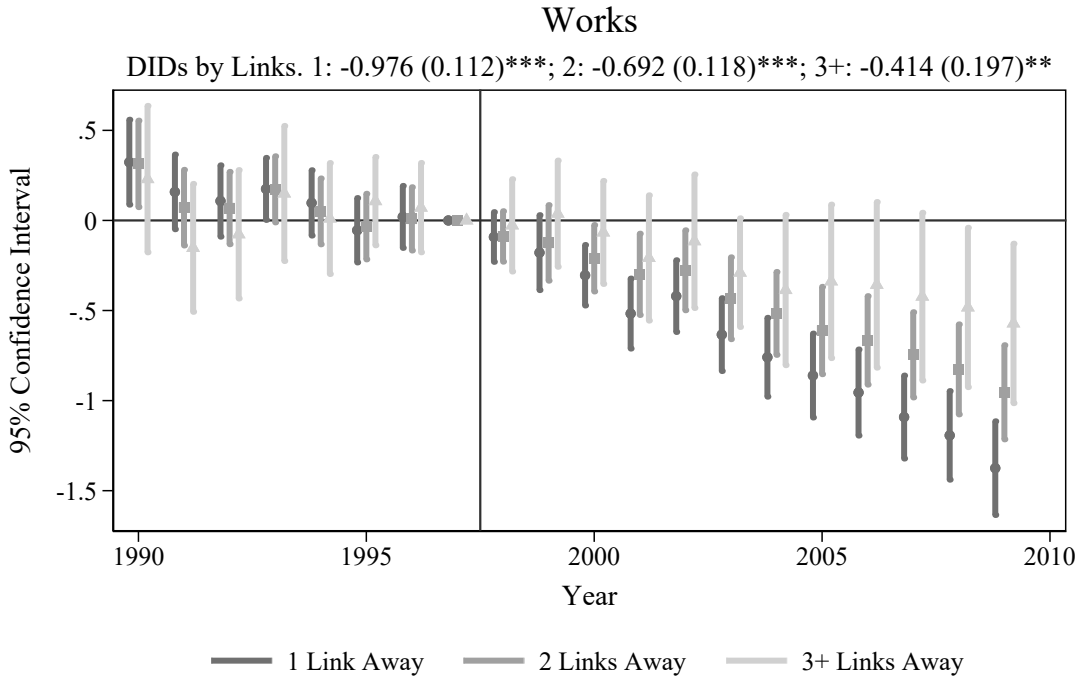
5.2.3. *Institutional Collaboration.* The framework also predicts that sanctions may disrupt established collaboration relationships and make affected institutions less attractive as research partners. We therefore examine changes in overall institutional collaboration, followed by collaboration with Indian institutions, US institutions, other sanctioned institutions, and leading Indian research institutions.

For each institution-year, we count the number of distinct institutions that appear alongside institution i among the affiliations attached to at least one work. Figure 8 shows that the total number of collaborating institutions falls at both sanctioned institutions and their pre-1998 collaborators. The DID coefficients imply reductions of approximately 26% and 35%, respectively. We then examine the composition of this decline by partner location and characteristics.

We construct the corresponding measure for domestic (Indian) institutions in the same way. Figure B.46 shows that the number of domestic partners falls by roughly 30% for sanctioned institutions and 43% for their collaborators. For US collaborators, Figure B.47 shows declines of approximately 24% for sanctioned institutions and 28% for their collaborators. The effects are somewhat smaller than those for domestic partners, but they indicate that affected institutions did not replace disrupted domestic links by maintaining their US collaborations.

We also examine collaboration among sanctioned institutions. Because the number of possible sanctioned partners is small, we measure the intensity of these links using the number of works on which institution i appears together with a different sanctioned

FIGURE 7. Network Propagation



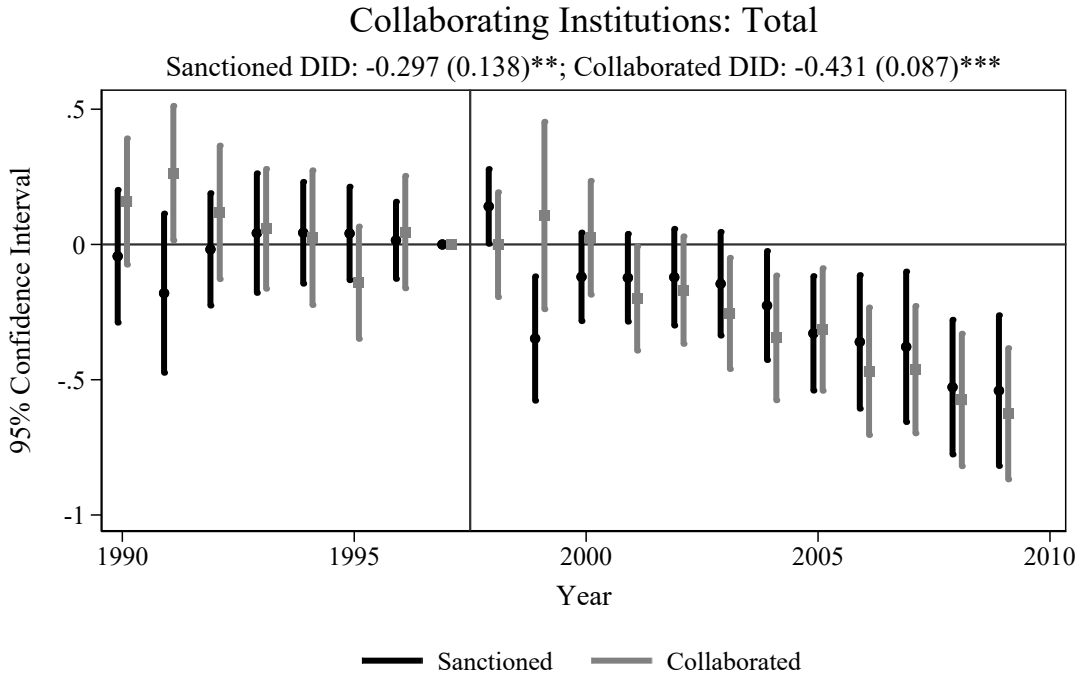
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. All specifications include institution fixed effects and institution type $\times$ year fixed effects. Standard errors clustered by institution. Sanctioned institutions are excluded.

institution. Figure B.48 shows a marked decline in collaboration among sanctioned institutions after 1998.[36]

We next examine whether affected institutions lost access to leading domestic research organizations. We rank Indian institutions by their total output during 1990–1997 and identify those in the top 1%, 5%, and 10% of the distribution. For each institution-year, we then count the number of institutions in each group with which institution i coauthors at least one work. For these measures of collaboration, we require the two institutions to be represented by different authors on the same work, to ensure they are not driven by joint affiliations. Figures B.49, B.50, and B.51 show declines at all three thresholds. Thus, the contraction in collaboration was not confined to peripheral partners; affected institutions also collaborated with fewer of the most research-intensive Indian institutions.

[36]The figure also reports the corresponding series for pre-1998 collaborators. This series is not an event study, because collaborator status is defined by having coauthored with a sanctioned institution before 1998. Institutions in the comparison group have zero pre-1998 values of this outcome by construction, so pre-treatment coefficients cannot be estimated. The post-1998 coefficients show a progressive closing of the initial gap in collaboration with sanctioned institutions.

FIGURE 8. Number of Collaborating Institutions



***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

Finally, we examine the evolution of collaboration relationships established before the sanctions. We fix each institution's set of Indian collaborators observed during 1990–1994 and identify the last year in which each pair is observed publishing together during 1990–2009. Appendix Figure B.52 shows that the cumulative share of relationships whose last observed collaboration has occurred rises significantly for pre-1998 collaborators of sanctioned institutions, but not for sanctioned institutions themselves. Figure B.53 shows that the number of pre-1995 partners with whom an institution continues to publish declines for both groups, while Figure B.54 shows that, among institution-years with collaboration activity, post-1994 partners account for a larger share of subsequent collaboration activity. These patterns are consistent with reduced activity with established partners and reallocation towards newer relationships.

5.3. **Alternative Mechanisms.** We consider two additional interpretations of the results. First, the estimated effects might reflect a general decline in the returns to nuclear-related research after the completion of the 1998 tests, rather than the Entity List restrictions.

Second, affected institutions might have responded to the loss of US research relationships by forming new collaborations elsewhere. The evidence does not support either interpretation.

One possibility is that the Indian government reduced its support for nuclear-related research after the tests, causing institutions initially specialized in this area to grow more slowly for reasons unrelated to the sanctions. Three findings weigh against this explanation. First, Figure B.10 shows that output also declined in non-nuclear fields. Second, Figure 5 allows the evolution of output to vary flexibly with each institution's pre-sanction share of nuclear research; the estimated direct and spillover effects remain close to the baseline results. Thus, the estimates are not explained by a change common to institutions with similar initial nuclear specialization.

Third, nuclear-related research was not confined to sanctioned institutions. Figure B.55 shows that unsanctioned institutions produced a substantial share of nuclear-related work both before and after 1998. Figure B.56 reports the share of each institution group's output classified as nuclear. During 1990–1997, the share of aggregate output classified as nuclear was higher among sanctioned institutions than among their unsanctioned collaborators, while those in neither group did little nuclear research. Sanctioned and collaborating institutions were therefore more specialized in nuclear research, but neither group was devoted exclusively to it. Taken together, these results indicate that a general decline in nuclear-related research cannot account for the broad output losses that we estimate.

A possible adaptive response was to replace disrupted US relationships with collaborators in other countries. Figure B.57 first examines the number of distinct foreign institutions with which each Indian institution collaborated. Foreign collaboration does not increase after 1998: the estimated effect is statistically insignificant for sanctioned institutions and negative for their pre-1998 collaborators. Excluding US institutions from the set of foreign institutions, in Figure B.58, gives similar results.

Figure B.59 provides more direct evidence by reporting separate DID estimates for each partner country represented in the pre-sanction data. It also reports estimates for all foreign partners combined, the European Union, and the European Union together with the United States. Hollow markers denote estimates that are not statistically significant at the 5% level, while solid markers denote statistically significant estimates. We label a country when either the direct- or spillover-effect estimate is statistically significant.[37]

[37]The figure omits the collaborator estimate for Romania, which is an extreme negative outlier.

Few countries exhibit a statistically significant increase in collaboration, and most of the point estimates are negative. We therefore find little evidence that affected institutions offset the loss of existing research relationships by forming partnerships elsewhere. This pattern is consistent with collaboration links being costly to replace.

6. Conclusion

We study whether sanctions directed at selected scientific institutions remain confined to their formal targets or propagate through scientific networks. Following the 1998 US Entity List restrictions, research output at sanctioned Indian institutions grew substantially more slowly than at comparison institutions. Similar relative shortfalls emerged among unsanctioned institutions that had collaborated with sanctioned institutions before 1998. By the end of our sample, the estimated output gaps for the two groups were both greater than 40%.

The effects extended beyond publication counts. Sanctioned institutions and their pre-1998 collaborators produced relatively fewer highly cited works and experienced declines in citation-based measures of research impact. Output fell relative to comparison institutions in both nuclear and non-nuclear fields. Among the research they continued to produce, affected institutions also reallocated less towards topics outside their pre-sanction research portfolios. The output gaps widened over time and remained large through 2009, despite the substantial relaxation of the Entity List restrictions in 2000–01.

We interpret these findings using a framework in which scientific production depends on physical inputs, scientists, and access to existing knowledge. Because current research contributes to the knowledge available for future work, disruptions to research inputs and established collaboration relationships can have cumulative effects. These disruptions can also propagate to institutions that rely on sanctioned organizations as sources of knowledge and complementary research capacity. Several additional patterns are consistent with this interpretation. Sanctioned institutions and their collaborators attracted fewer new authors and collaborated with fewer other institutions. Author moves and exits also declined, consistent with reduced observed reallocation within the Indian research system.

The results contribute to research on the organization of science, innovation networks, and economic sanctions. Scientific collaboration gives institutions access to knowledge and capabilities outside their own boundaries (Partha and David, 1994; Powell, Koput and Smith-Doerr, 1996). Our findings show that these links can transmit adverse shocks as well as positive knowledge spillovers. They also illustrate how an initial disruption can produce long-lasting relative gaps when scientific production is cumulative (Akcigit and

Kerr, 2018; Love, Roper and Vahter, 2014; Romer, 1986). The decline in author movement further suggests that the reallocation of scientific human capital is subject to important frictions (Becker et al., 2024).

The policy implications concern the difference between the legal target of a sanction and its economic incidence. Restricting a selected set of institutions does not ensure that the resulting costs remain concentrated among those institutions. In our setting, indirect output losses among pre-existing collaborators eventually became similar in magnitude to the losses among the institutions named on the Entity List. Evaluations of targeted or "smart" sanctions should therefore account for the networks through which affected organizations obtain knowledge and other productive inputs (Hufbauer, Schott and Elliott, 1990). The persistence of the estimated gaps also suggests that relaxing restrictions need not produce an immediate recovery in scientific capacity.

Our analysis has several limitations. First, we study a single episode of sanctions on scientific institutions. Assessing external validity will require evidence from other cases in which sanctions have targeted universities, research institutes, and public scientific agencies. Second, limitations in the available Indian patent data prevent us from examining patented innovation as an outcome (Kala, Lerner and Liu, 2026). Third, without institution-level budget data, we cannot determine whether the Indian government systematically compensated affected institutions, as governments have done in other sanctions settings (Nigmatulina, 2025). Finally, we do not observe links between scientific institutions and firms that produce no indexed scientific publications. We therefore cannot measure the extent to which the effects propagated from scientific institutions into private industry.

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APPENDIX A. PROMPT DEFINING NUCLEAR

```
You are classifying one scientific research topic for an academic study of the
effect of nuclear-related export sanctions on scientific research.

Your task is to assess the semantic scientific content of this particular topic,
not to perform keyword matching.

A topic is nuclear-weapons-relevant when the scientific knowledge represented by
the topic has a specific, technically meaningful, and reasonably proximate
connection to nuclear weapons capability. Relevance can be direct or foundational,
but it must be characteristic of the topic rather than merely a conceivable
application of generic scientific knowledge.

Consider:

3 | Direct/core relevance: nuclear weapons, nuclear explosions and effects,
fissile materials, uranium enrichment, plutonium production or reprocessing,
nuclear reactors or fuel cycles with clear weapons relevance, neutron physics,
nuclear testing and diagnostics, or technologies specifically associated with
nuclear weapon delivery.

2 | Meaningful enabling/foundational relevance: fields whose scientific content
has a substantial and technically specific connection to nuclear weapons
capability, such as relevant nuclear physics, radiation transport,
high-energy-density physics, shock/detonation physics, relevant plasma physics,
radiation hardening/effects, or missile guidance and propulsion.

1 | Remote/general dual use: knowledge that could contribute to nuclear weapons
only through broad or generic applications, such as general materials science,
generic metallurgy, ordinary ceramics, general aerospace engineering, generic
computing, general high-temperature research, or broad mathematical methods.

0 | Unrelated: no meaningful technical pathway to nuclear weapons capability.

Set nuclearbygpt = 1 only for scores 2 or 3. Set it to 0 for scores 0 or 1.

Important safeguards against false positives:
```

Do not classify a topic as relevant merely because one of its hierarchy fields contains words such as "nuclear," "materials science," "radiation," "aerospace," "shock," or similar terms.
Treat display_name as the primary evidence. Use subfield, field and domain only to interpret the topic, not as sufficient evidence by themselves.
Clinical nuclear medicine, diagnostic imaging, radiotherapy, biological radiation effects, and other medical topics are 0 unless the specific topic concerns physical principles or technologies with a meaningful weapons-relevant application.
Generic materials science, metallurgy, ceramics, composites, electronics, computing, aerospace, high-temperature research and similar broad enabling sciences are normally 0 or 1 unless the specific topic identifies a weapons-relevant mechanism or application.
Ignore superficial word overlap. For example, "heat shock proteins" is unrelated to shock physics.
Social science, geopolitics, history and policy concerning nuclear weapons are not part of the scientific knowledge base being measured and should be coded 0.

Important safeguards against false negatives:

A topic need not contain the words "nuclear" or "atomic" to be relevant. Technologies such as uranium enrichment, plutonium processing, neutron transport, detonation physics, high-energy-density physics, radiation hardening, missile guidance, and relevant propulsion may qualify even without explicit nuclear terminology.

Return a judgement about the topic supplied below. Give a short explanation identifying the specific technical pathway that justifies the score, or explaining why the apparent connection is too remote.

APPENDIX B. ADDITIONAL FIGURES

FIGURE B.1. Entity List: Example Page

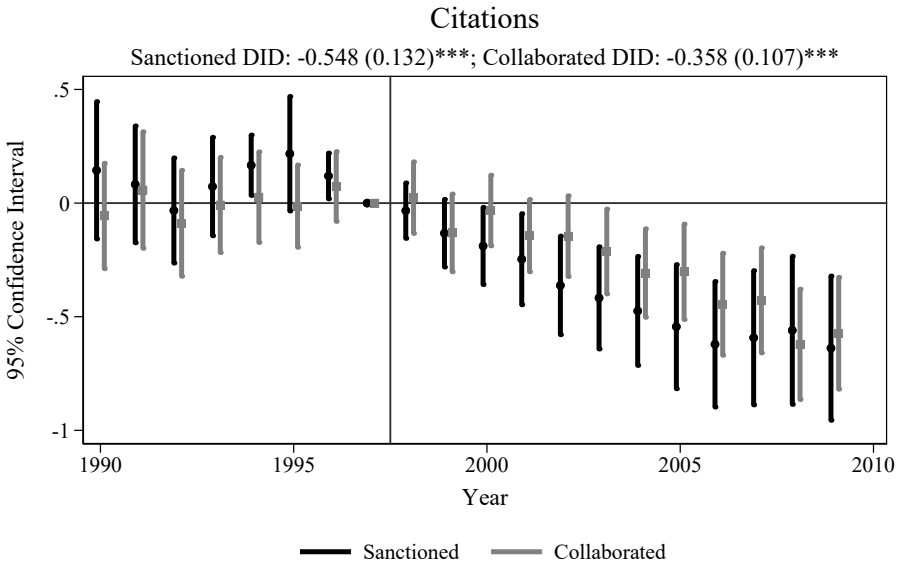
Federal Register / Vol. 63, No. 223 / Thursday, November 19, 1998 / Rules and Regulations **64327**

SUPPLEMENT NO. 4 TO PART 744—ENTITY LIST—Continued

Country	Entity	License requirement	License review policy	Federal Register citation
	AURO Engineering, Pondicherry	For all items subject to the EAR.	See § 744.11(c)(2) of this part.	[Insert: Federal Register Cite and date of publication].
	Avadi Combine Engine Plant, Ordnance Factory Board, Department of Defense Production and Supplies, Ministry of Defense.	For all items subject to the EAR having a classification other than EAR99.	See § 744.12(c) of this part.	[Insert: Federal Register Cite and date of publication].
	Avadi Heavy Vehicle Factory, Ordnance Factory Board, Department of Defense Production and Supplies, Ministry of Defense.	For all items subject to the EAR having a classification other than EAR99.	See § 744.12(c) of this part.	[Insert: Federal Register Cite and date of publication].
	Avadi Ordnance Clothing Factory, Ordnance Factory Board, Department of Defense Production and Supplies, Ministry of Defense.	For all items subject to the EAR having a classification other than EAR99.	See § 744.12(c) of this part.	[Insert: Federal Register Cite and date of publication].
	Baroda Ammonia Plant, (collocated with the Baroda Heavy Water Production Facility), Gujarat Fertilizers, Baroda.	For all items subject to the EAR.	See § 744.11(c)(2) of this part.	[Insert: Federal Register Cite and date of publication].
	Baroda Heavy Water Production Facility, Heavy Water Board, Department of Atomic Energy (DAE), Baroda.	For all items subject to the EAR.	See § 744.11(c)(1) of this part.	[Insert: Federal Register Cite and date of publication].
	Beryllium Machining Facility, Indian Space Research Organization (ISRO), and Department of Atomic Energy (DAE), Mumbai (formerly Bombay).	For all items subject to the EAR.	See § 744.11(c)(1) of this part.	[Insert: Federal Register Cite and date of publication].
	Bhabha Atomic Research Center (BARC), Department of Atomic Energy (DAE), Trombay, suburban city of Mumbai (formerly Bombay).	For all items subject to the EAR.	See § 744.11(c)(1) of this part.	62 FR 35334, 6/30/97. [Insert: Federal Register Cite and date of publication].
	Bharat Dynamics Limited, Bhanur and Hyderabad.	For all items subject to the EAR.	See § 744.11(c)(2) of this part.	[Insert: Federal Register Cite and date of publication].
	Bharat Earth Movers Limited (BEML), Bangalore.	For all items subject to the EAR.	See § 744.11(c)(2) of this part.	[Insert: Federal Register Cite and date of publication].
	Bharat Electronics Limited (BEL), Bangalore, Ghaziabad, and Hyderabad.	For all items subject to the EAR.	See § 744.11(c)(2) of this part.	62 FR 26922, 5/16/97, 62 FR 51369, 10/1/97. [Insert: Federal Register Cite and date of publication].
	Bharat Heavy Electrical Limited (BHEL), Trichy (Tiruchirapalli), Hyderabad, Hardwar, New Delhi, and Ranipet.	For all items subject to the EAR.	See § 744.11(c)(2) of this part.	[Insert: Federal Register Cite and date of publication].
	Bhatin Uranium Mine and Mill, Uranium Corporation of India, Ltd. (UCIL), Bhatin.	For all items subject to the EAR.	See § 744.11(c)(2) of this part.	[Insert: Federal Register Cite and date of publication].
	Bhusawal Ordnance Factory, Avadi Com-	For all items subject	See § 744.12(c) of	[Insert: Federal Register Cite

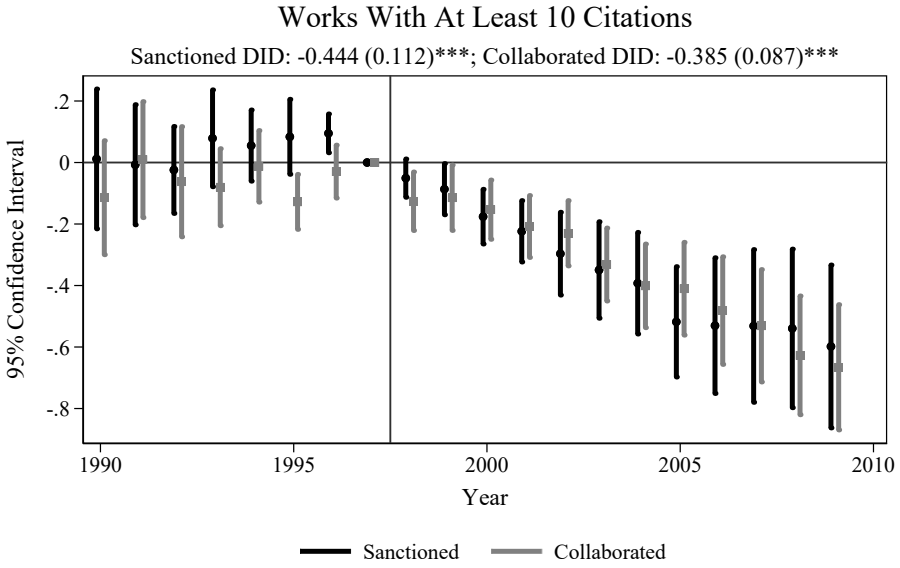
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FIGURE B.2. Citations



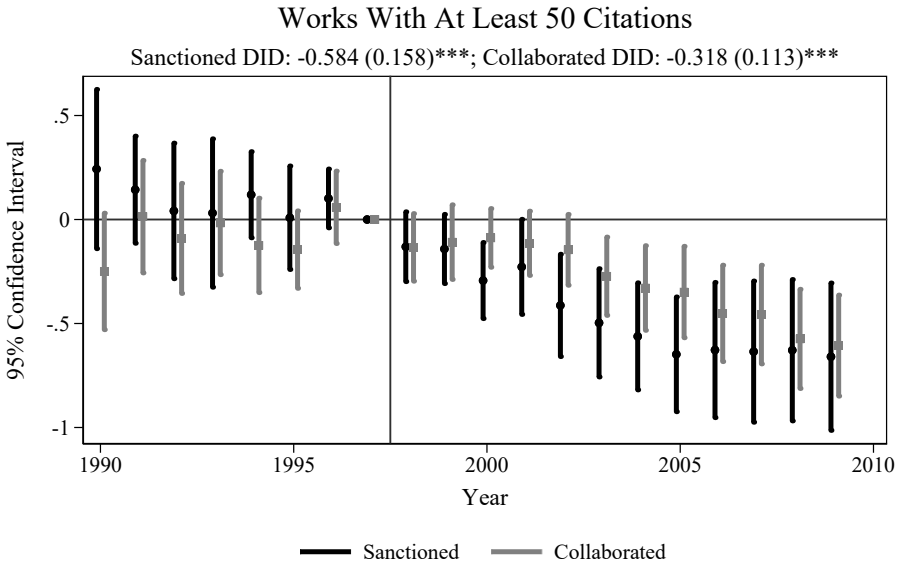
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FIGURE B.3. Highly Cited Works: 10 Citations



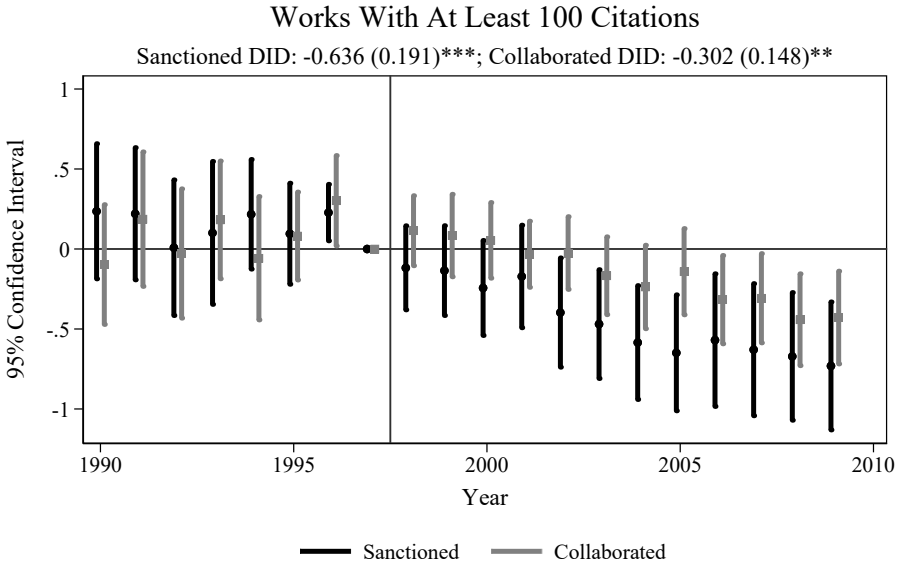
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.4. Highly Cited Works: 50 Citations



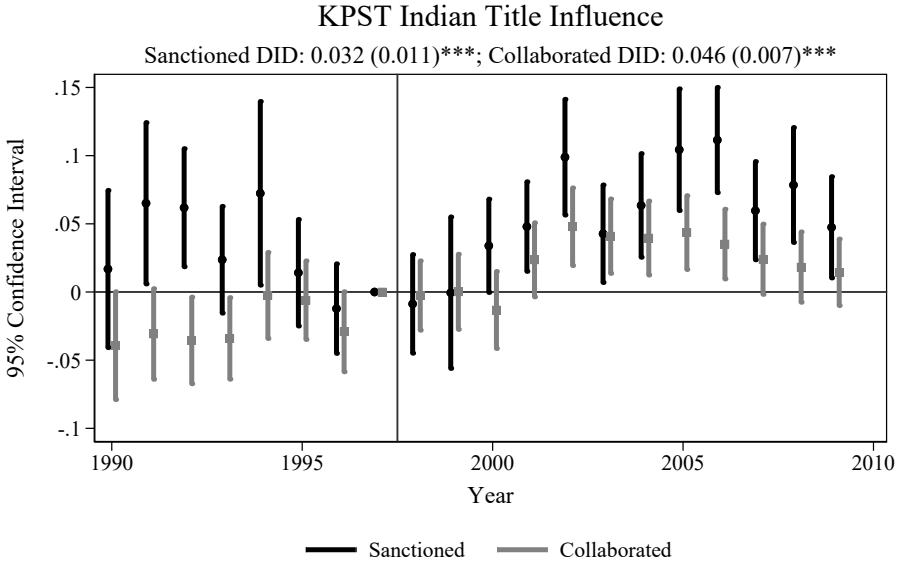
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.5. Highly Cited Works: 100 Citations



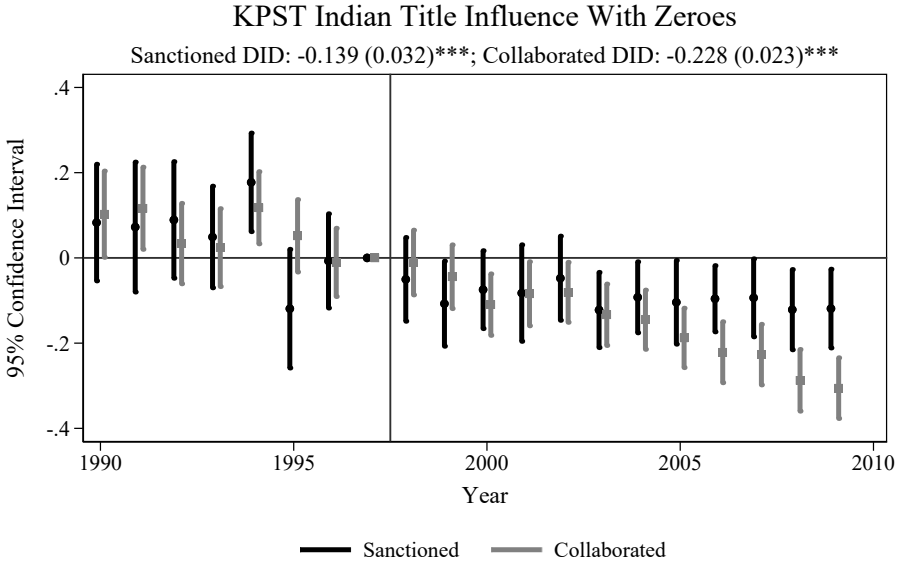
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FIGURE B.6. Article Influence: KPST



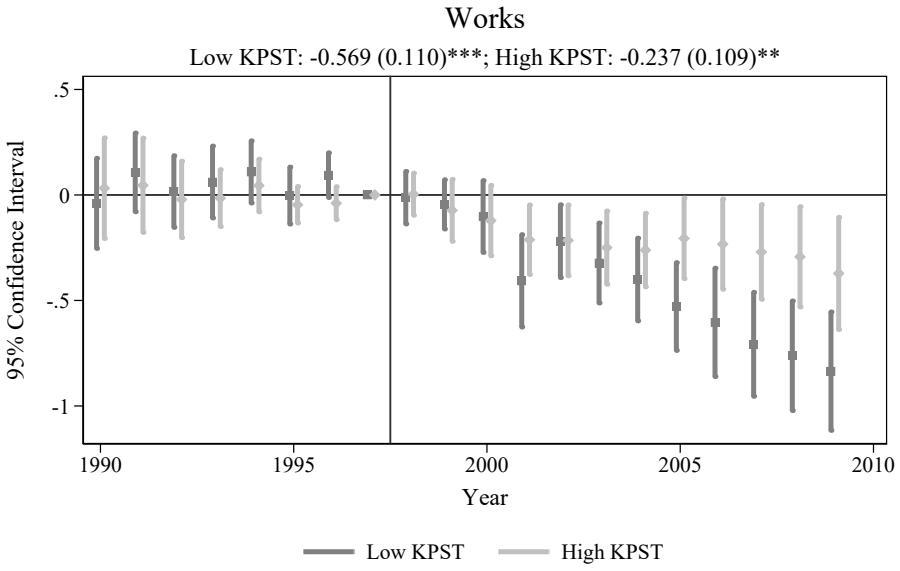
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution. The sample includes only institution-years for which an average KPST score is defined.

FIGURE B.7. Article Influence: KPST with Zeroes



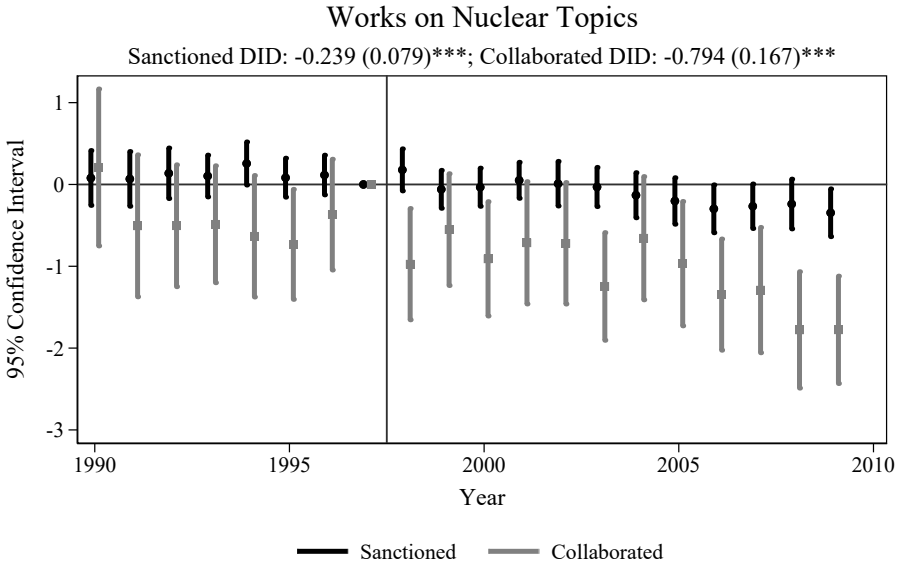
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type $\times$ year fixed effects. Standard errors clustered by institution. Institution-years with no publications are assigned a KPST score of zero.

FIGURE B.8. Results by KPST Score, 1990-97



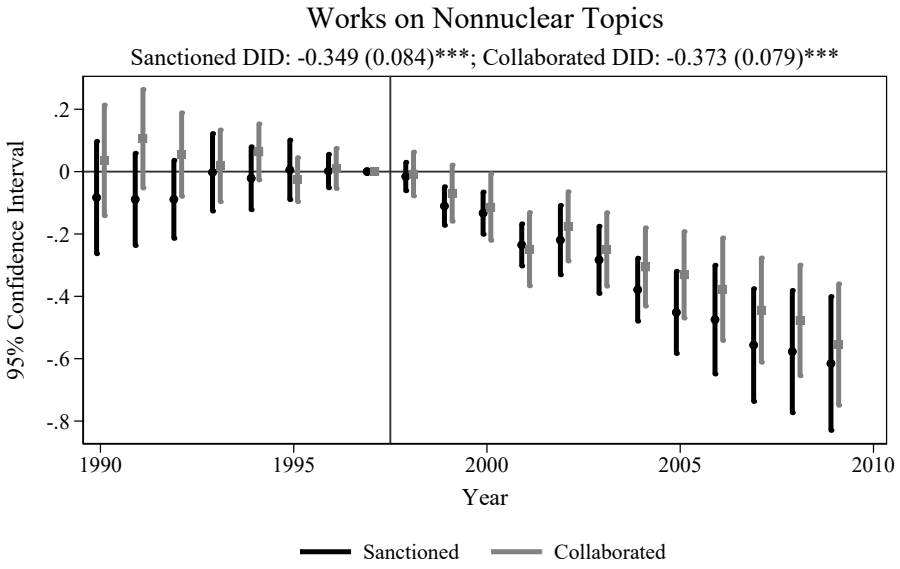
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.9. Works on Nuclear Topics



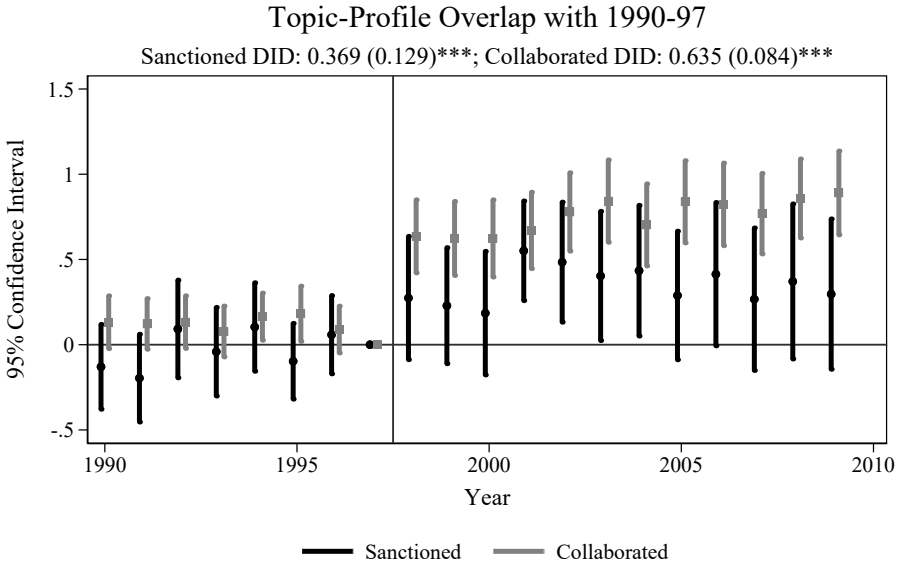
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.10. Works on Non-nuclear Topics



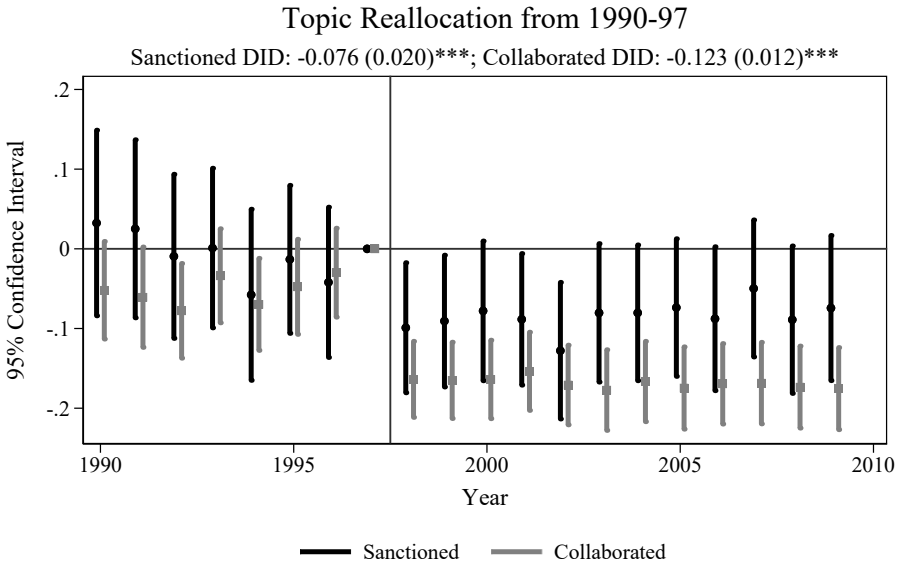
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.11. Topic Similarity to 1990-97



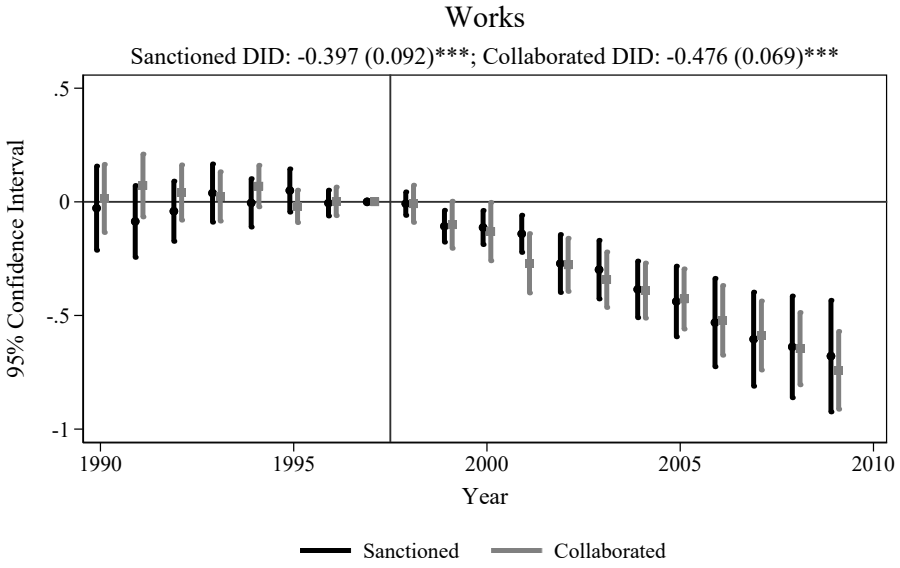
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.12. Topic Reallocation from 1990-97



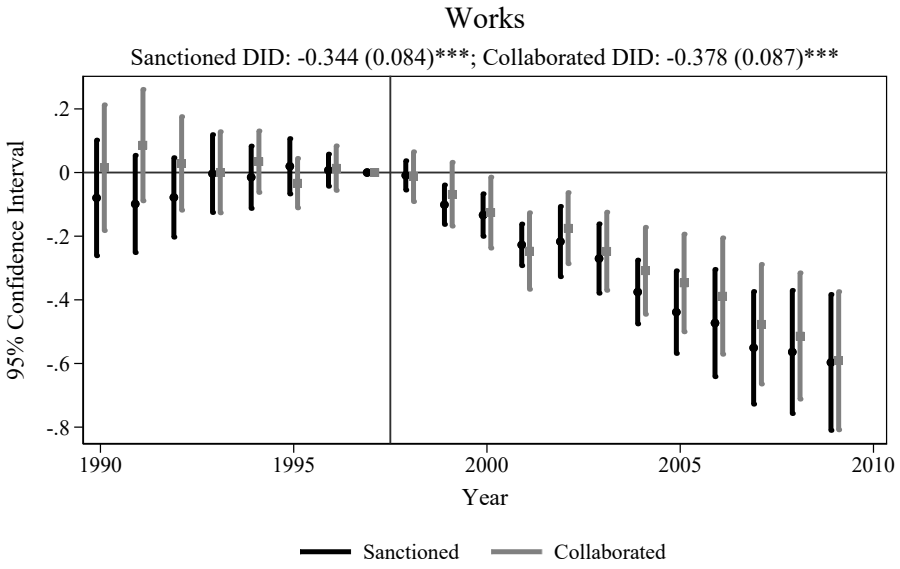
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.13. Control for Shares of Work by Domain, 1990-97, × Year Fixed Effects



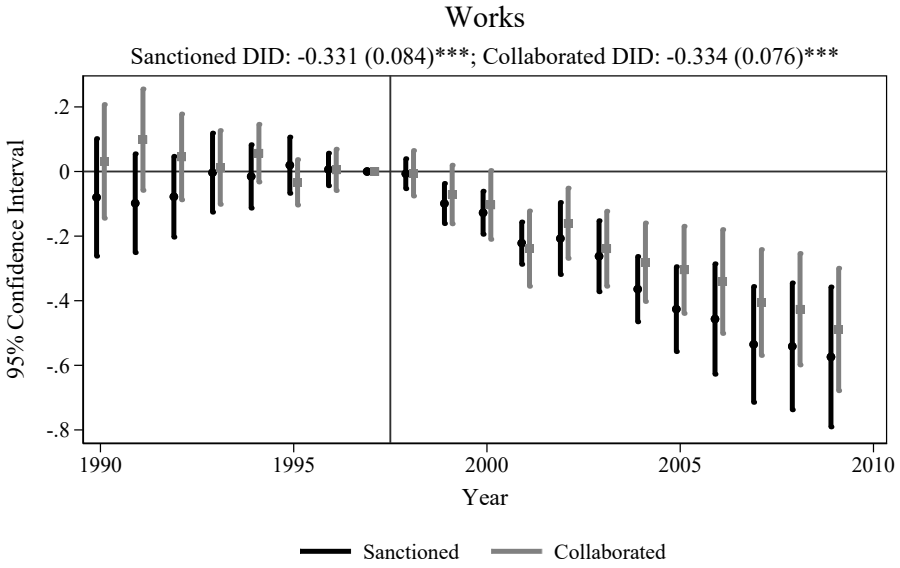
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. The "collaborating" sample excludes sanctioned institutions. Outcome variable top-coded at the 99th percentile. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution. Each specification also controls for shares of work by domain, 1990-97, × year fixed effects.

FIGURE B.14. Drop Unsanctioned Institution Types



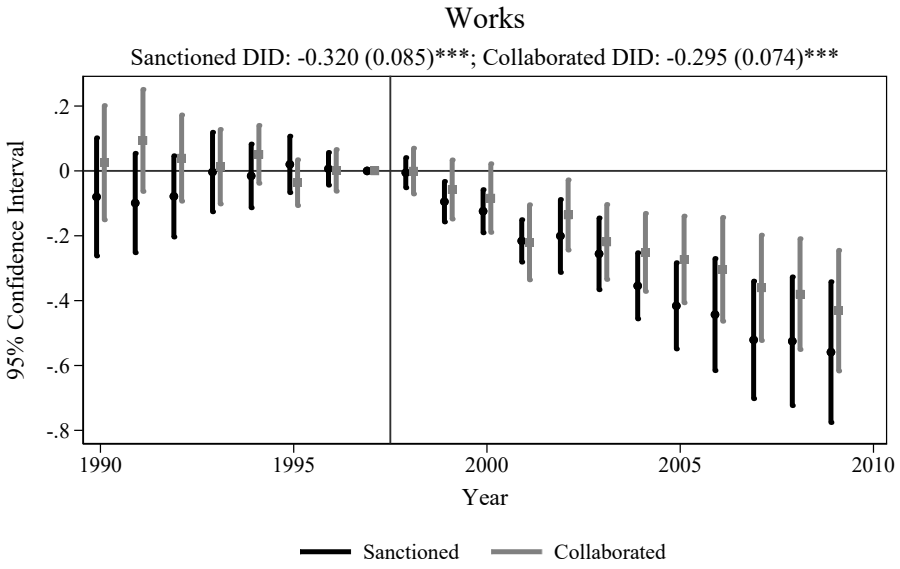
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.15. Drop Bottom 10% by Works, 1990-97



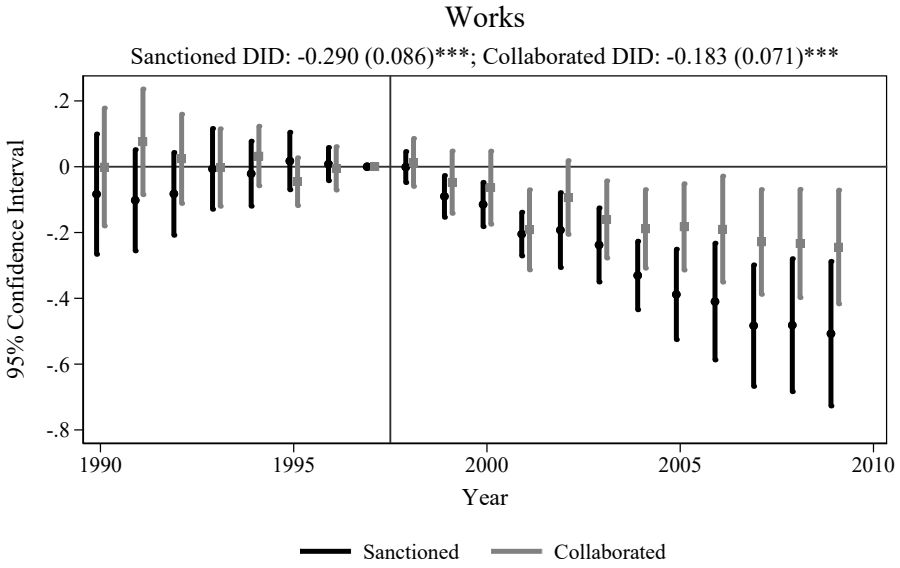
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.16. Drop Bottom 25% by Works, 1990-97



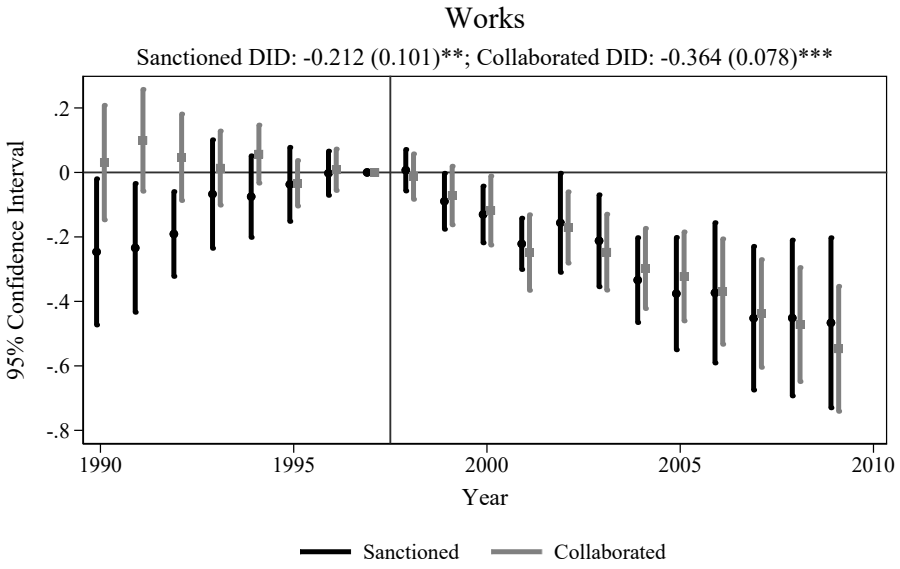
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.17. Drop Bottom 50% by Works, 1990-97



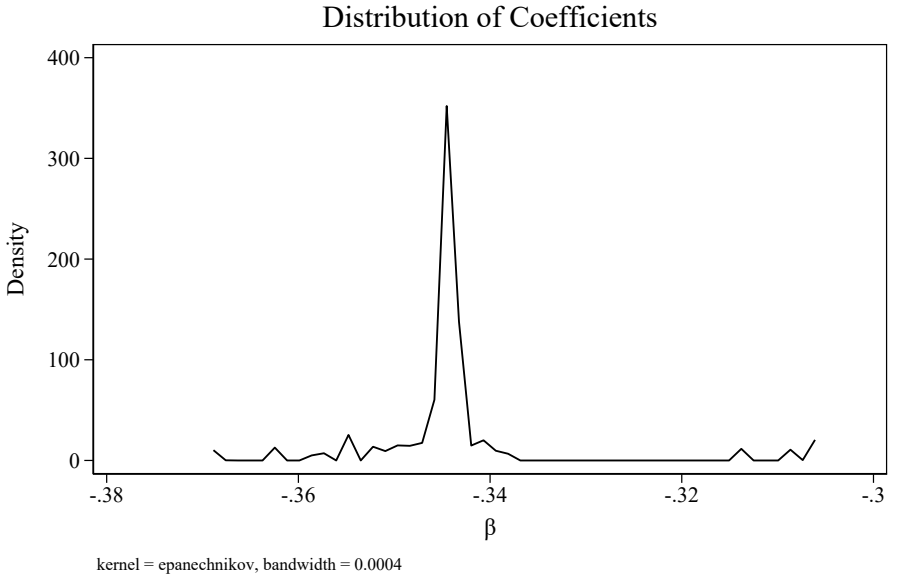
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.18. Drop Institutions with 3,000 or more Works, 1990-97



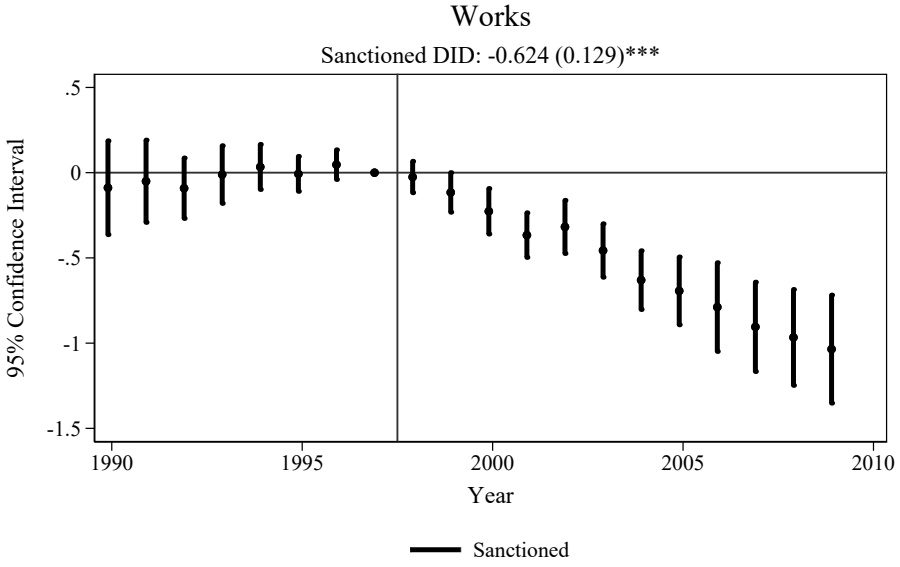
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.19. Drop Sanctioned Institutions One at a Time



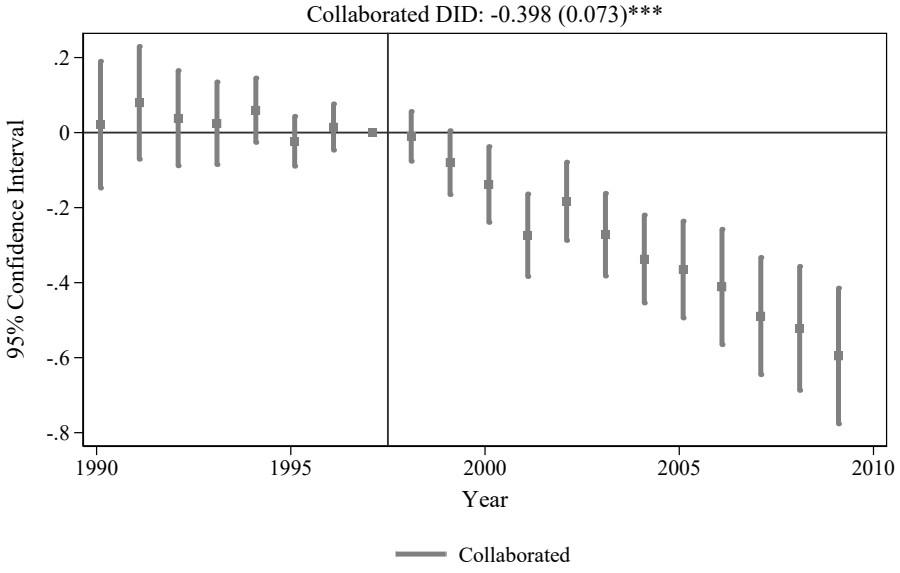
The figure shows the distribution of direct-effect DID coefficients obtained by excluding each sanctioned institution in turn. Each specification is estimated using pseudo-Poisson maximum likelihood and includes institution fixed effects and institution type × year fixed effects.

FIGURE B.20. Drop Collaborating Institutions in the Direct Effect Sample



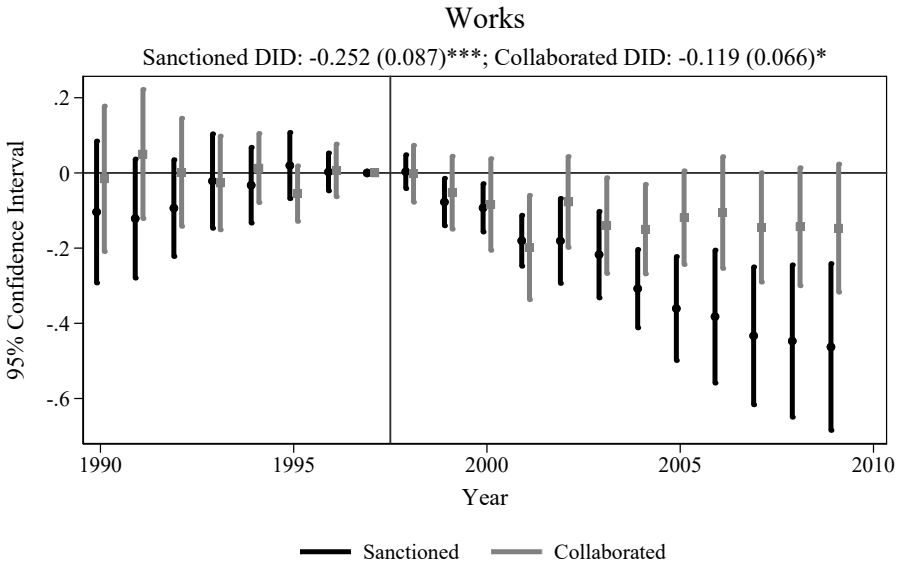
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.21. Keep Sanctioned Institutions in the Spillover Sample



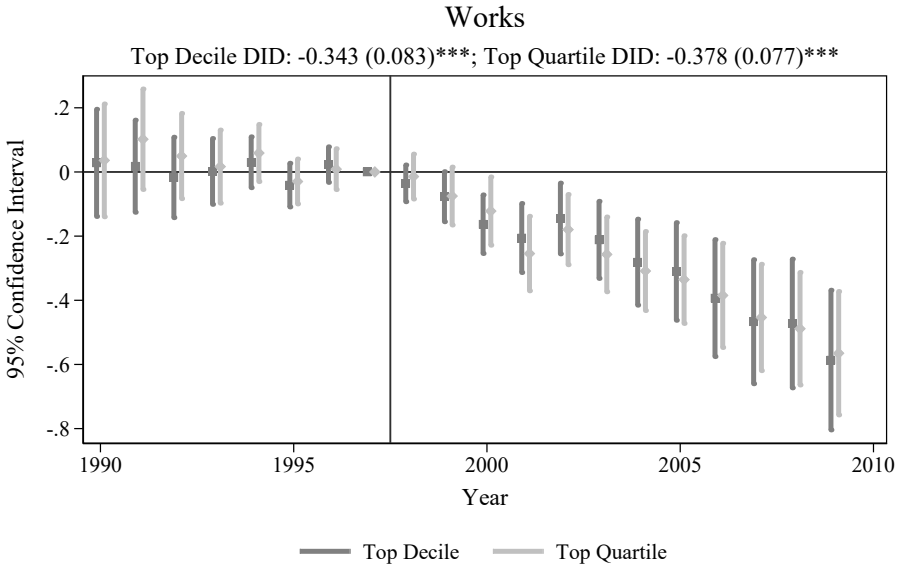
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.22. Keep Only Institutions Publishing in All Years



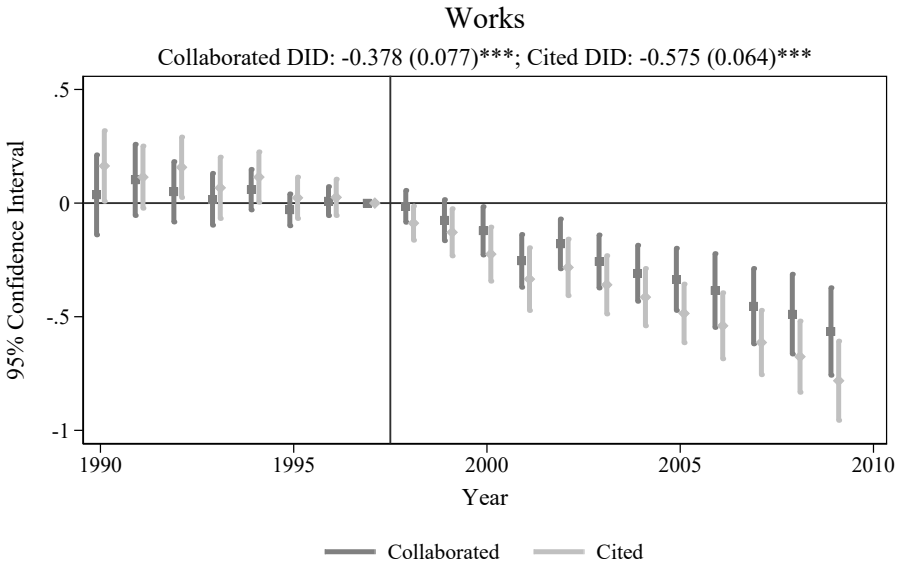
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.23. High Levels of Coauthorship with Sanctioned Institutions



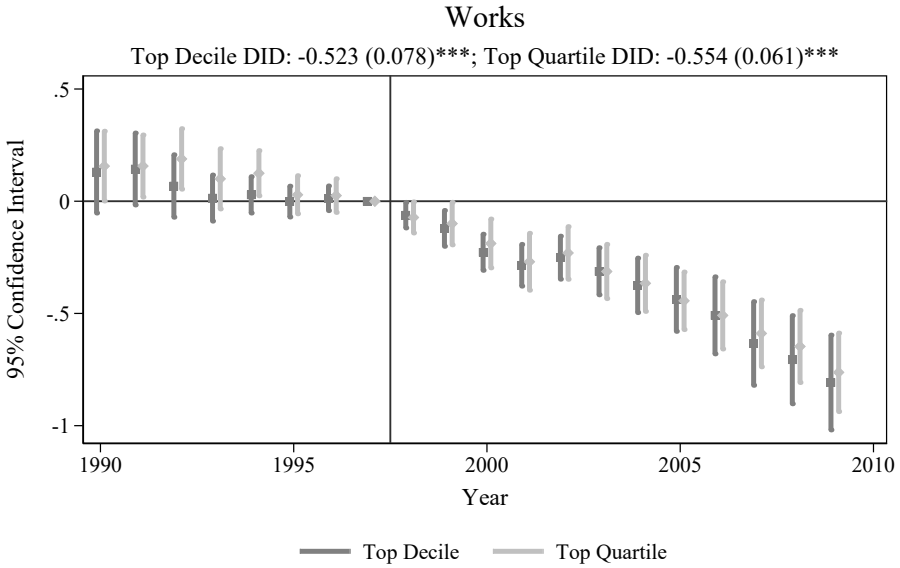
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.24. Collaboration vs. Citation



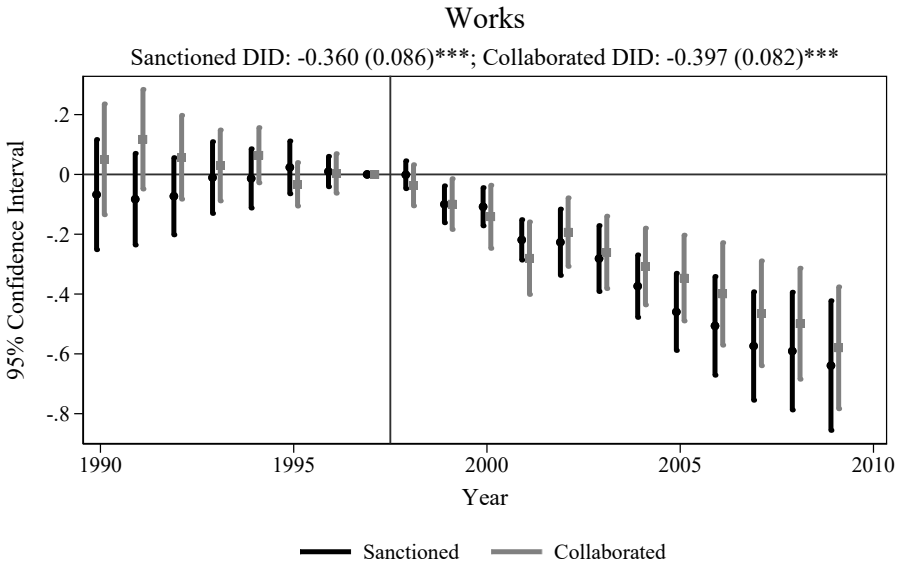
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.25. High Levels of Citation to Sanctioned Institutions



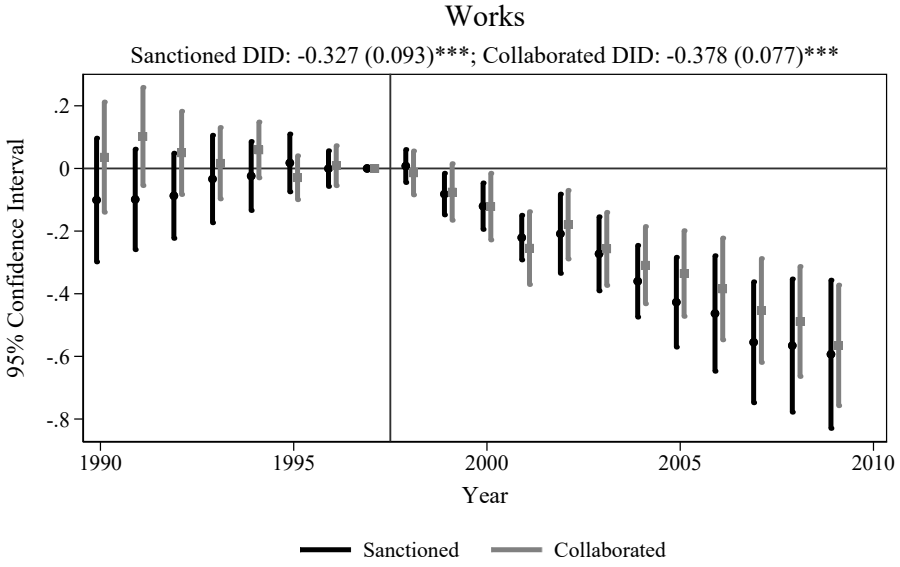
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.26. Drop Government Institutions



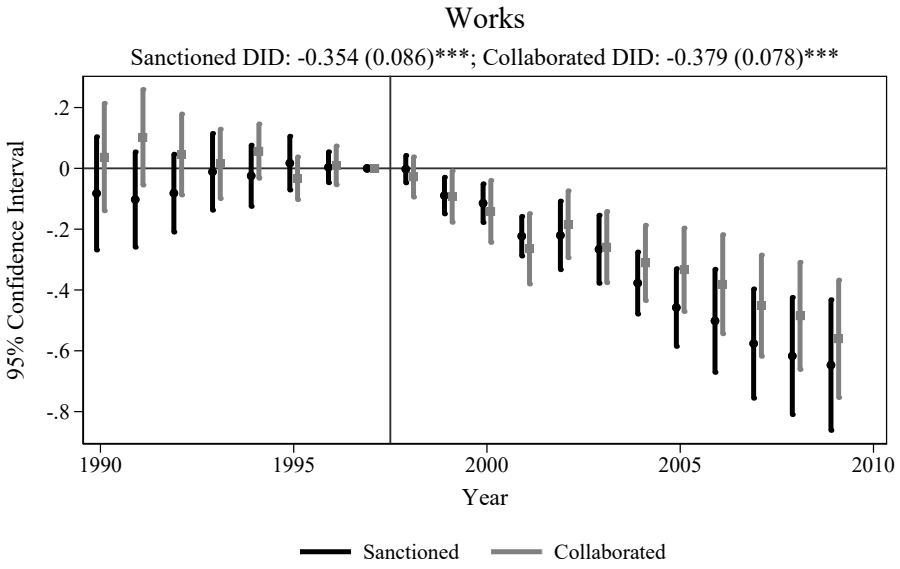
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type $\times$ year fixed effects. Standard errors clustered by institution.

FIGURE B.27. Drop Major Government Institutions



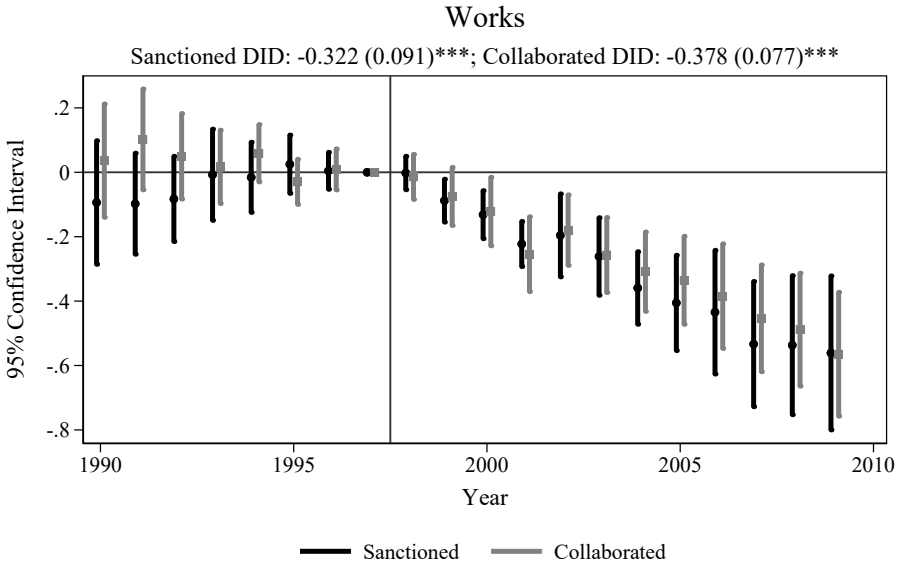
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution. The specific institutions removed are the Indian Space Research Organisation, Bhabha Atomic Research Centre, Department of Atomic Energy, Indira Gandhi Centre for Atomic Research, and Defence Research and Development Organization.

FIGURE B.28. Drop Defence Institutions



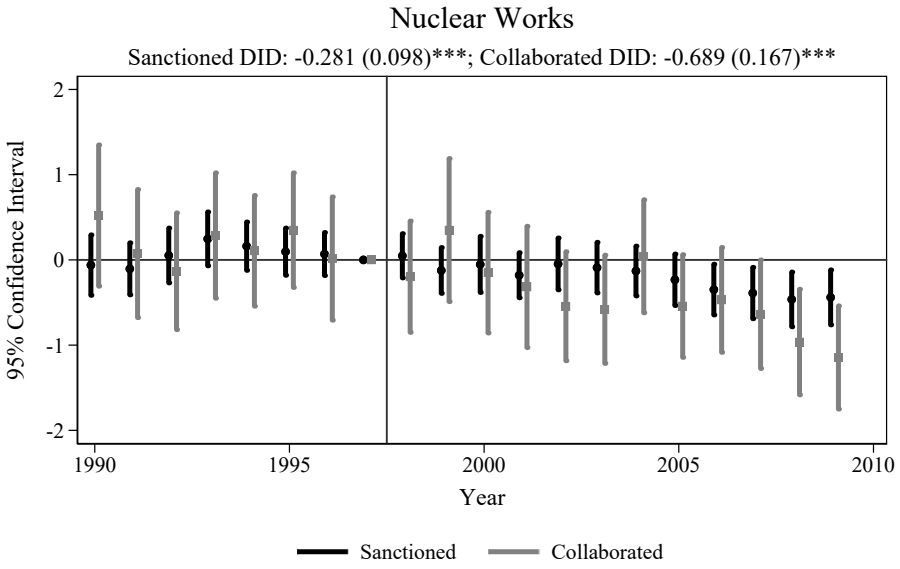
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.29. Drop Institutions Sanctioned in 1997



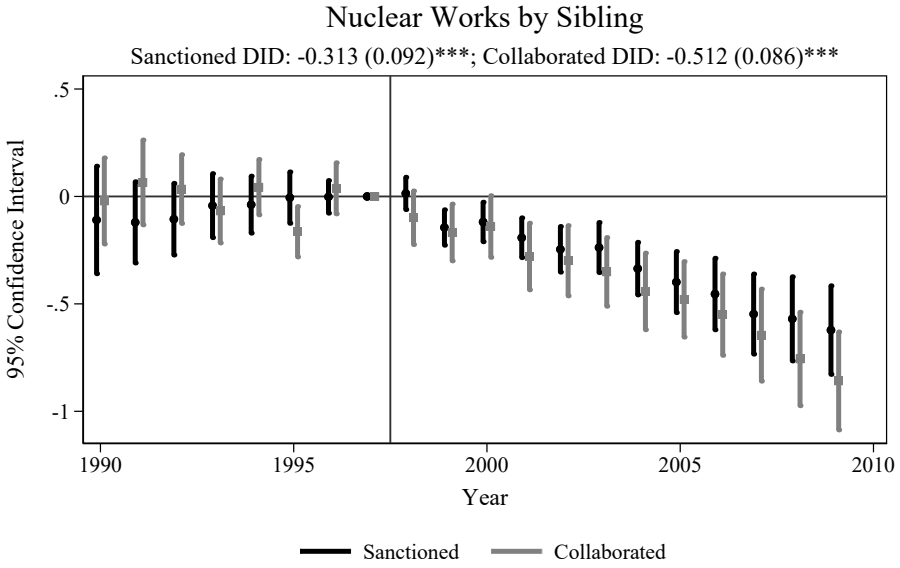
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.30. Define Nuclear Topics Using Keywords



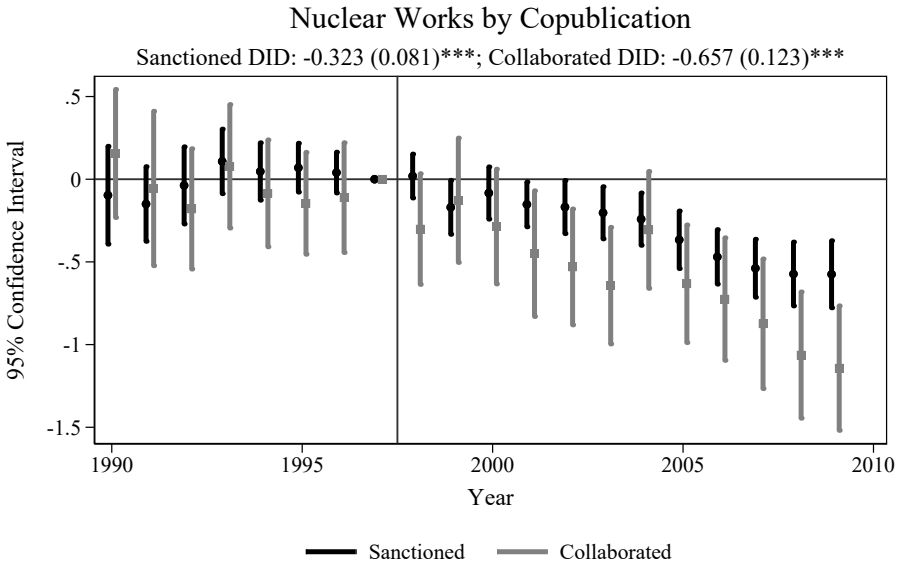
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.31. Define Nuclear Topics Using Siblings



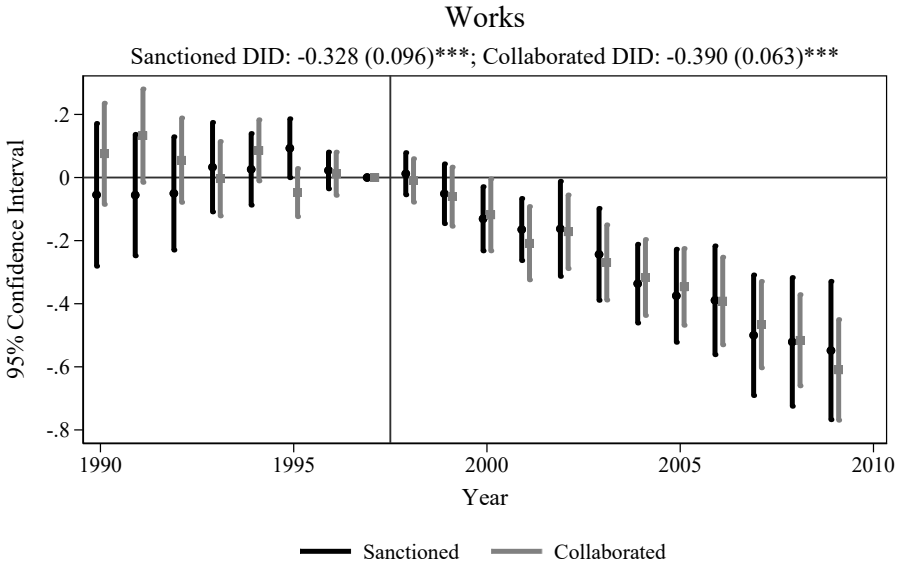
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.32. Define Nuclear Topics Using Co-Publication



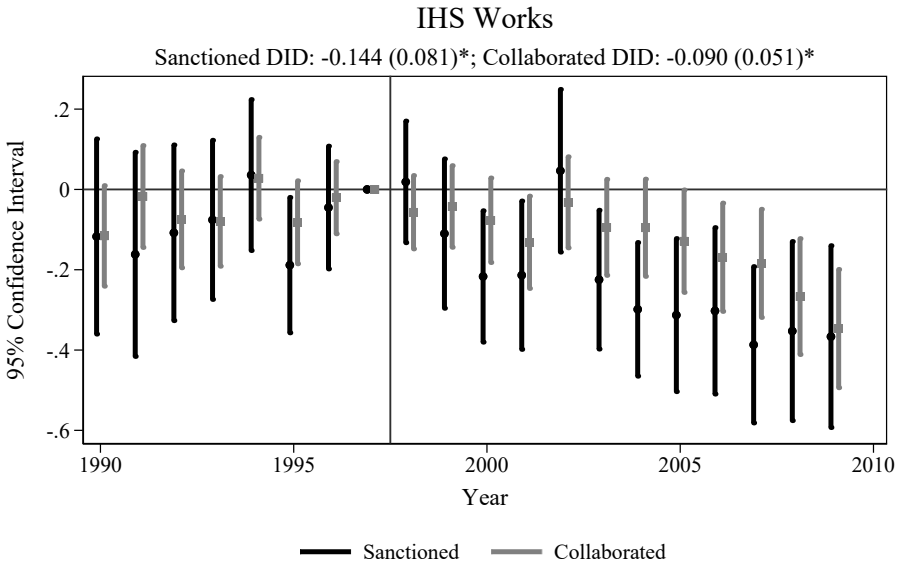
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.33. Control for City × Year Fixed Effects



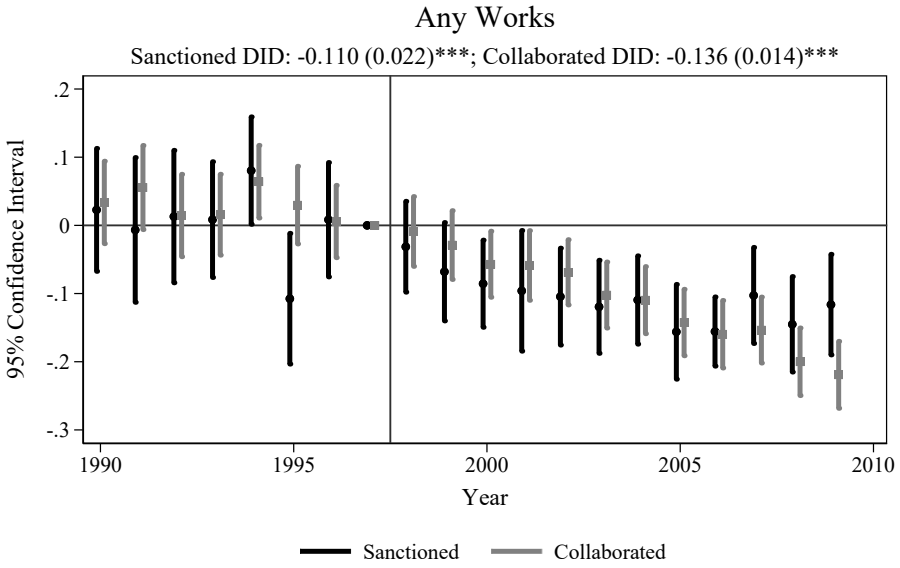
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution. All specifications additionally control for city × year fixed effects.

FIGURE B.34. Ordinary Least Squares: Inverse Hyperbolic Sine



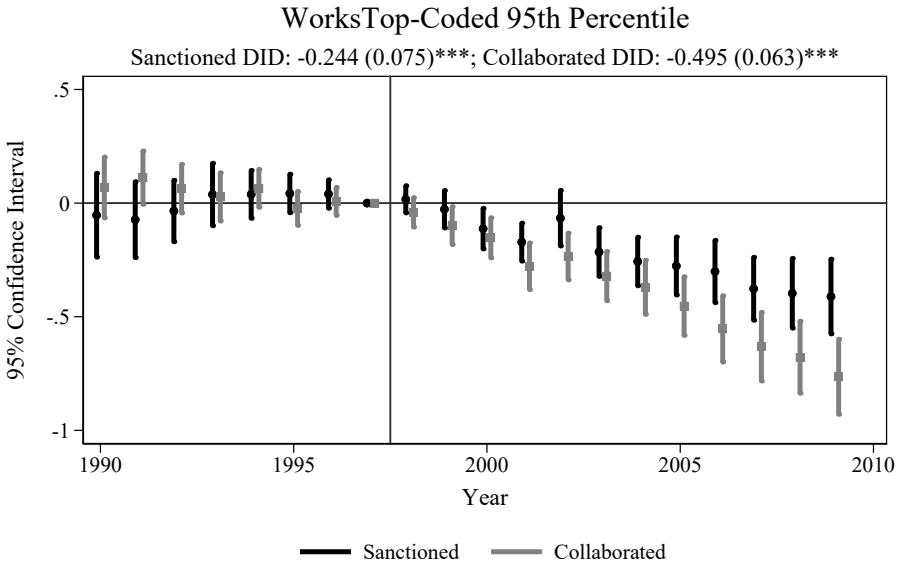
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using ordinary least squares. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.35. Ordinary Least Squares: Any Work



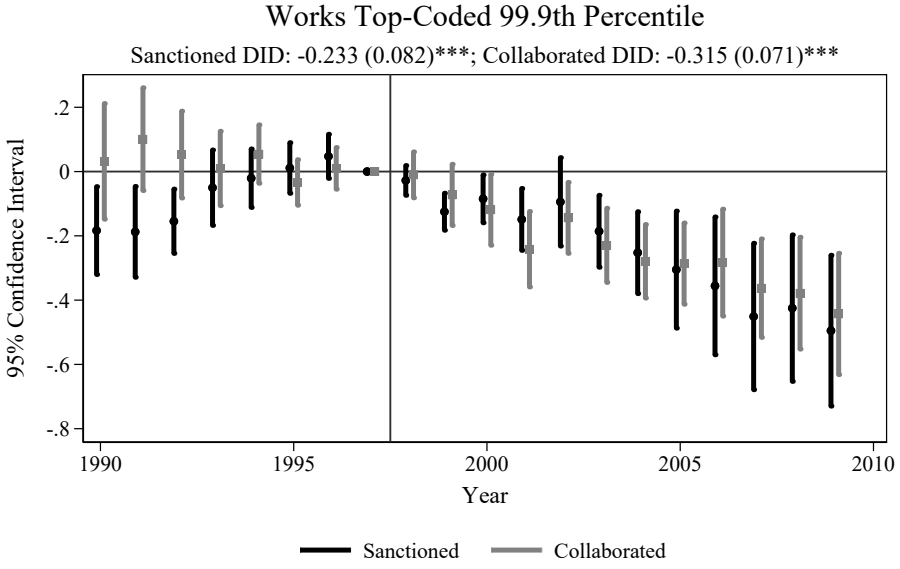
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using ordinary least squares. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.36. Top-code at the 95th percentile



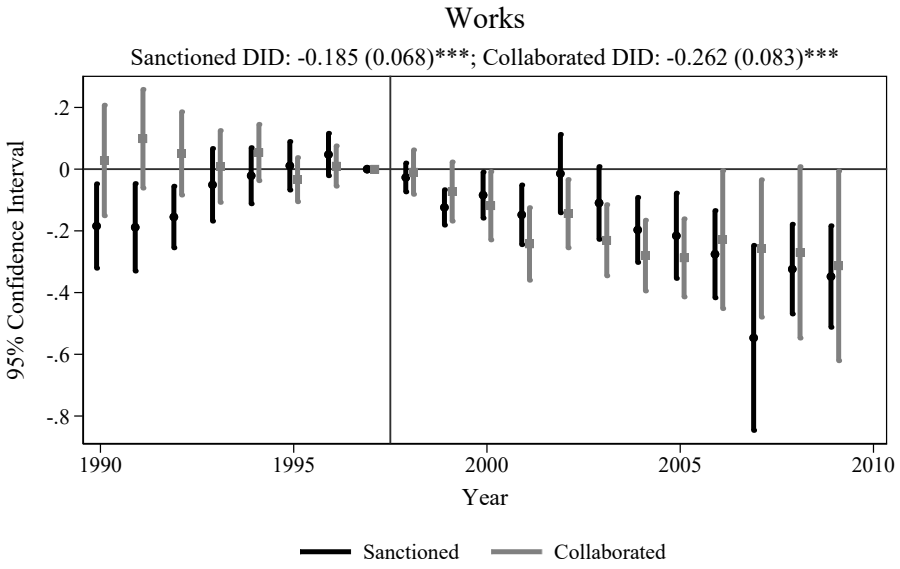
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.37. Top-code at 99.9th percentile



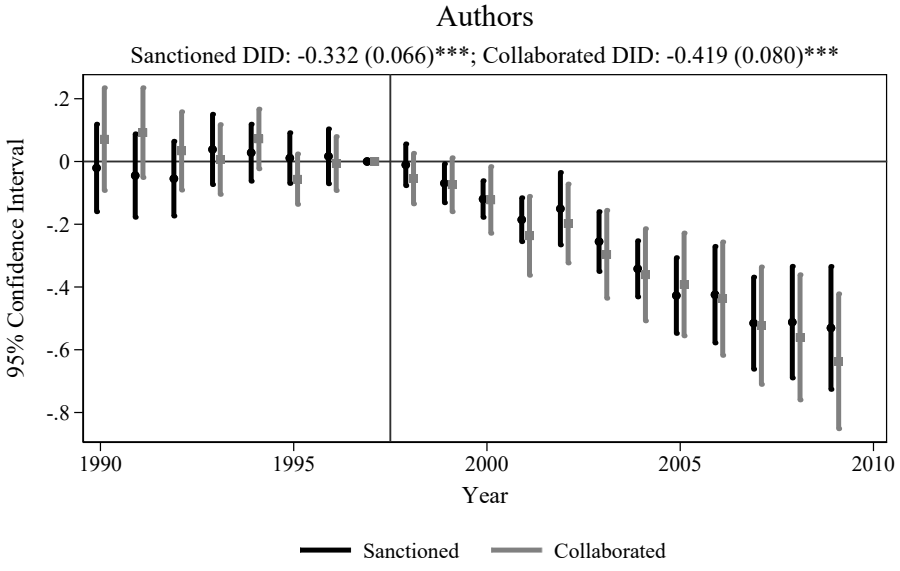
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.38. Do Not Top-Code



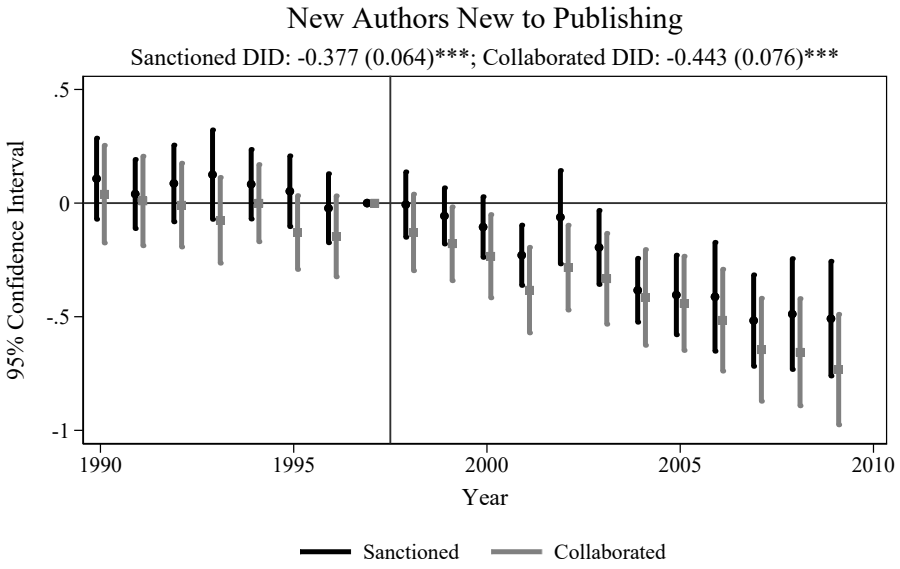
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.39. Authors



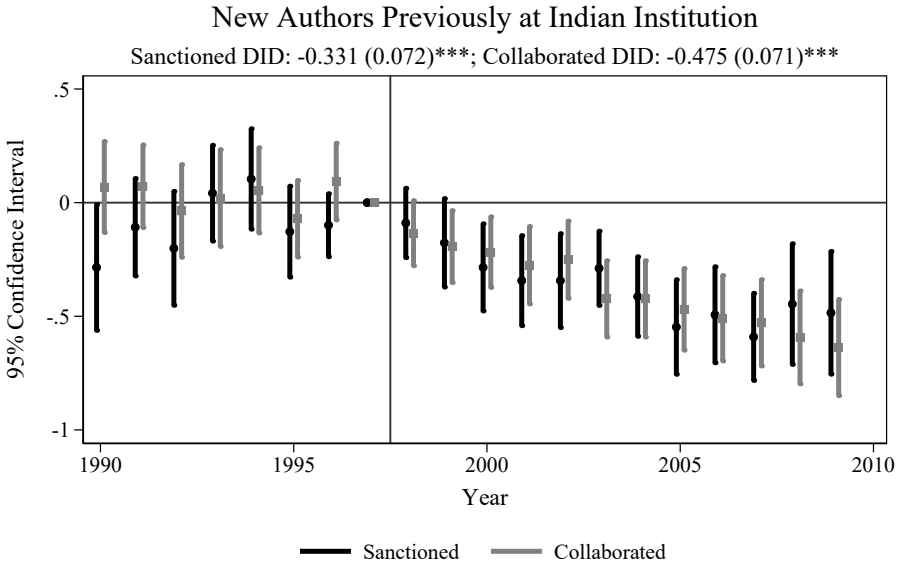
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.40. New Authors New to Publishing



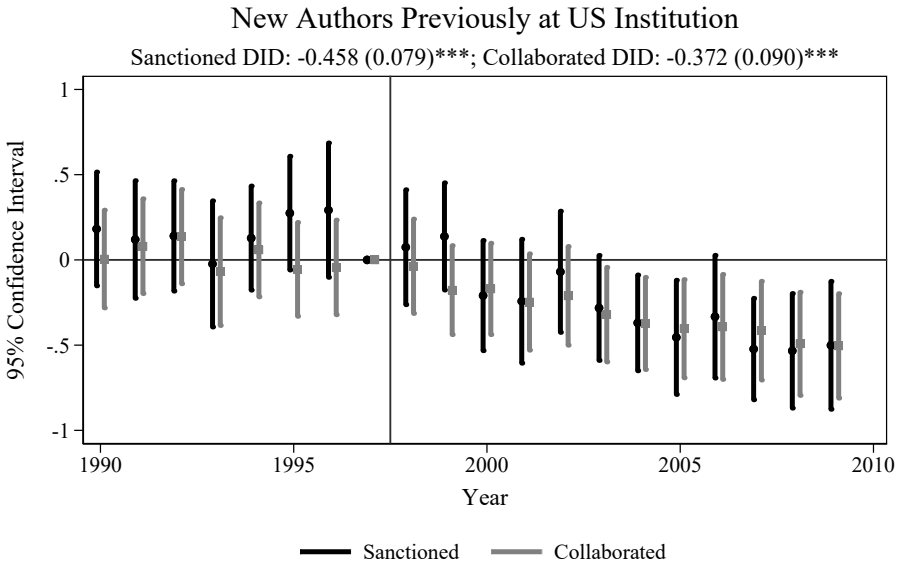
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.41. New Authors Previously at Indian Institution



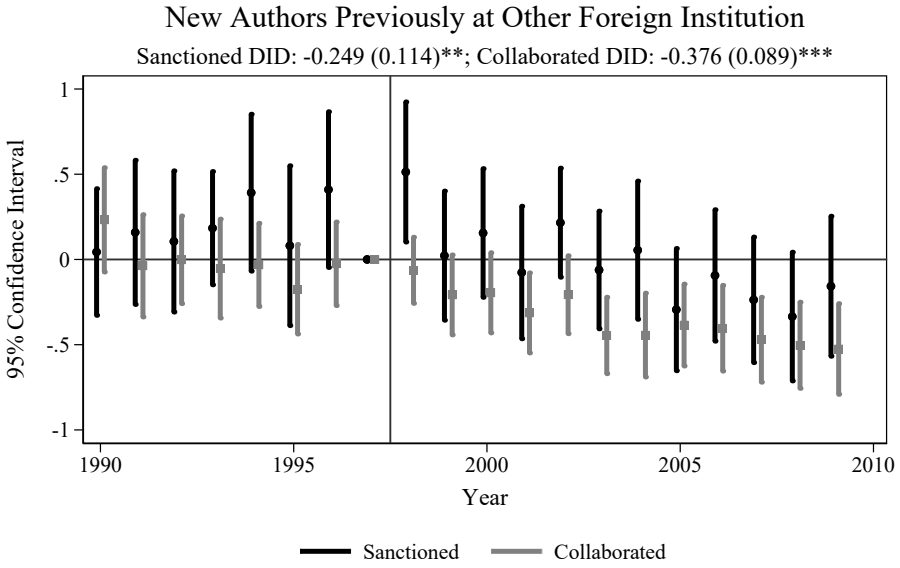
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.42. New Authors Previously at US Institution



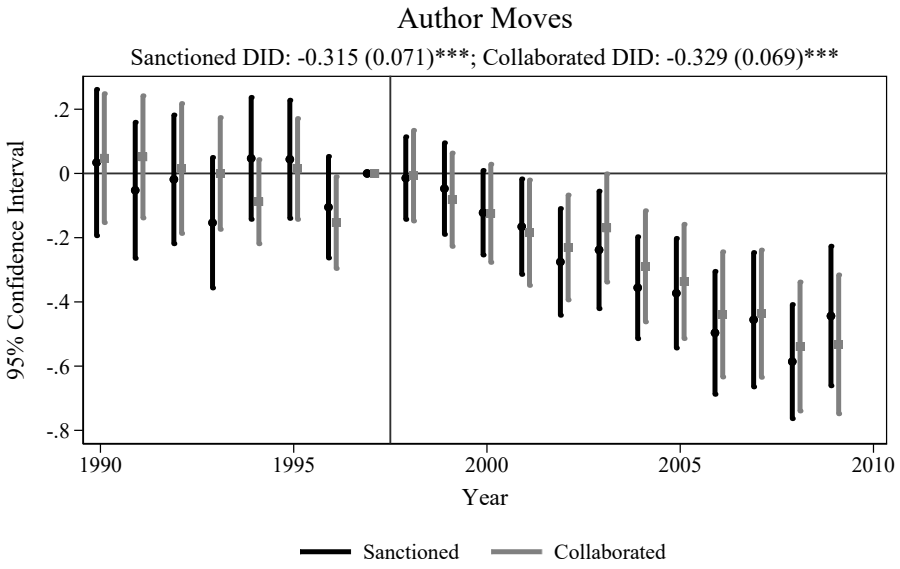
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.43. New Authors Previously at Other Foreign Institution



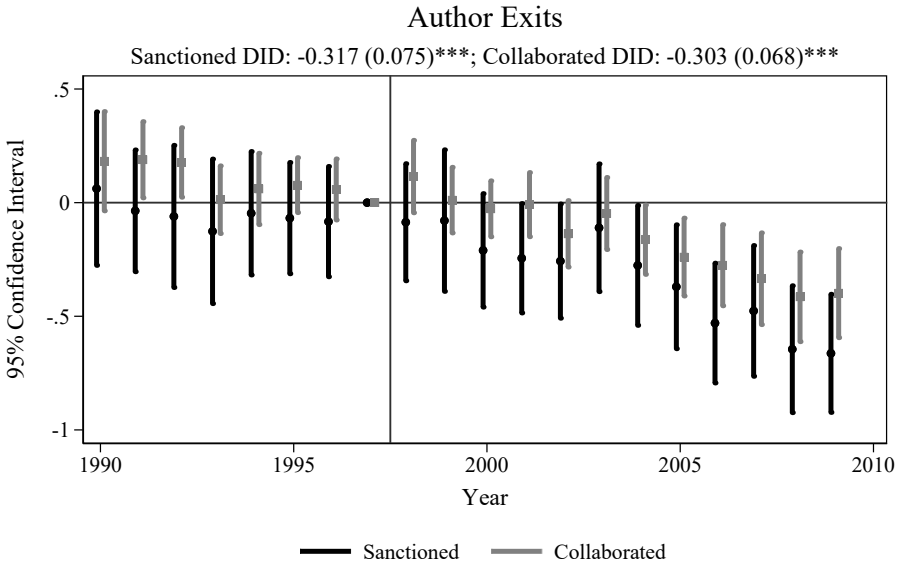
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.44. Authors Moving to Other Indian Institutions



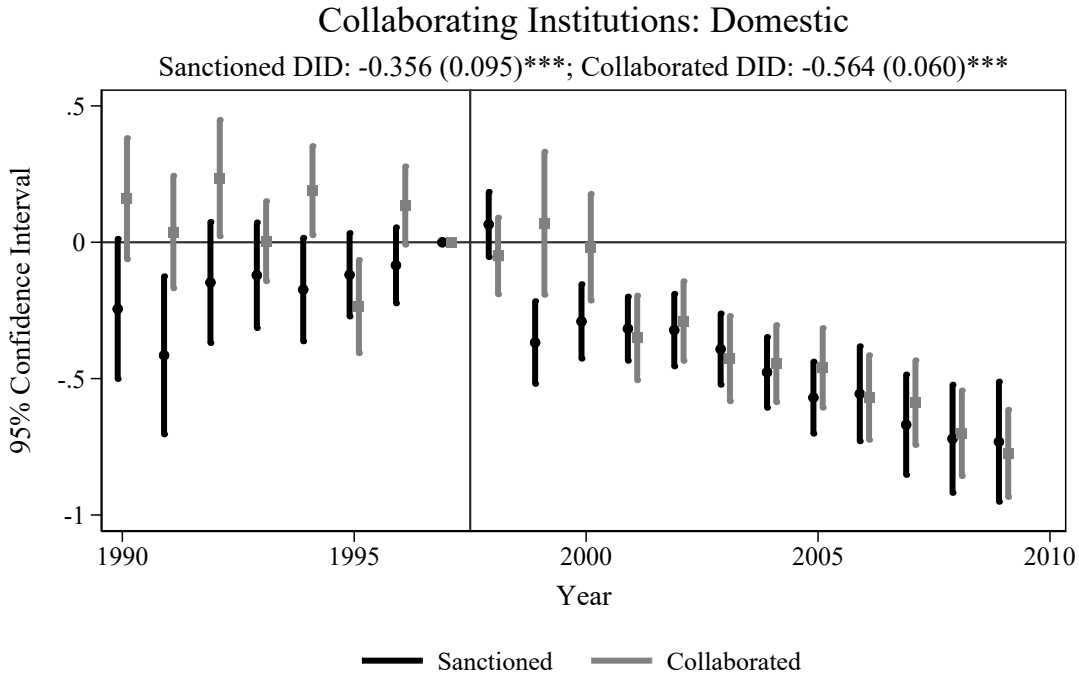
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.45. Authors No Longer Publishing in India



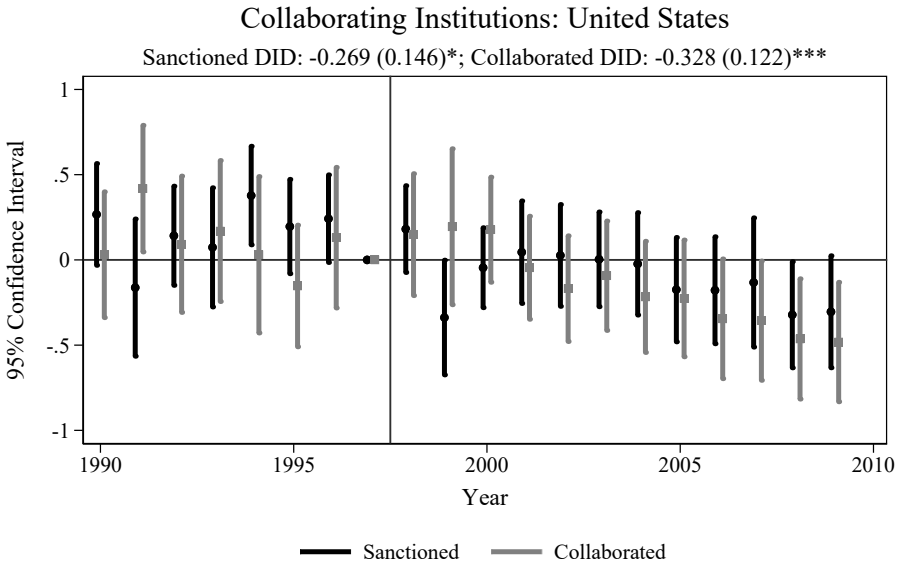
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.46. Collaboration with Domestic Institutions



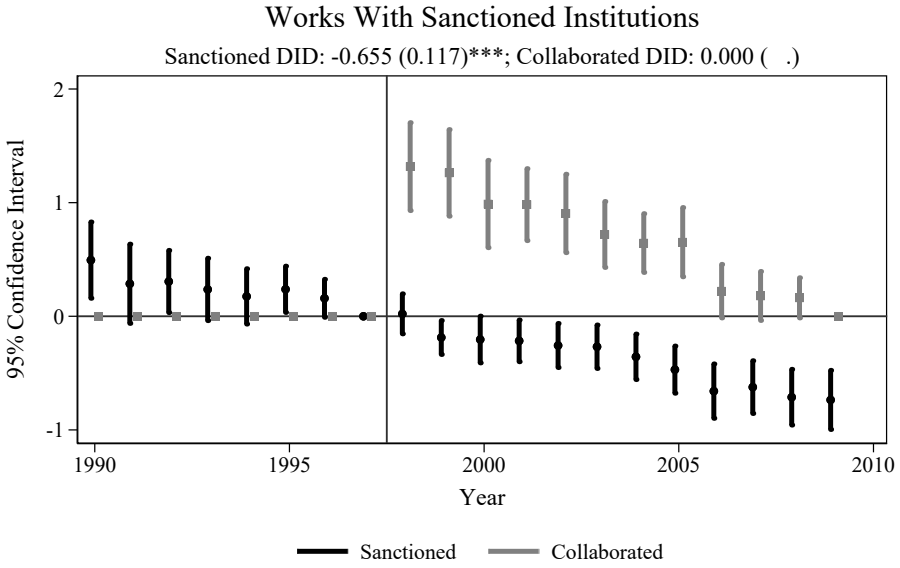
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.47. Collaboration with US Institutions



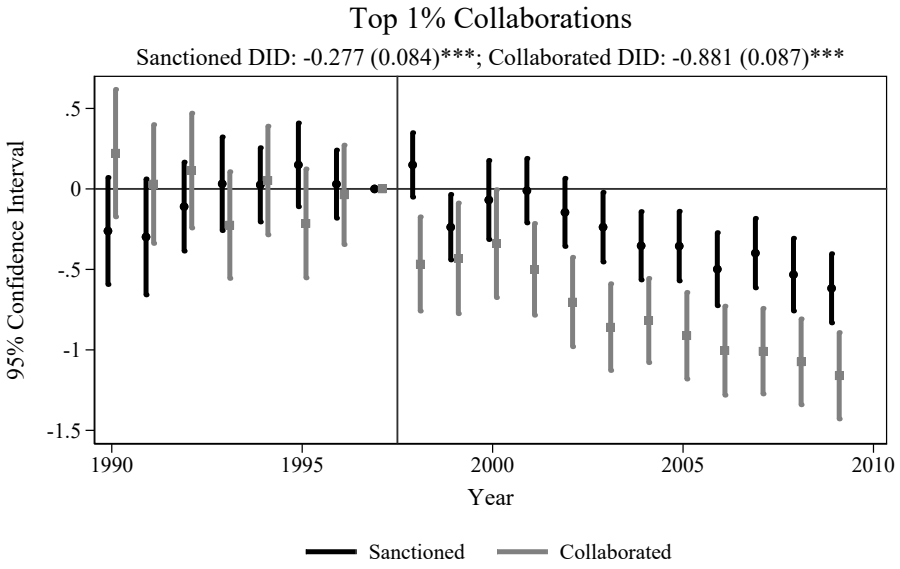
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.48. Collaboration with Sanctioned Institutions



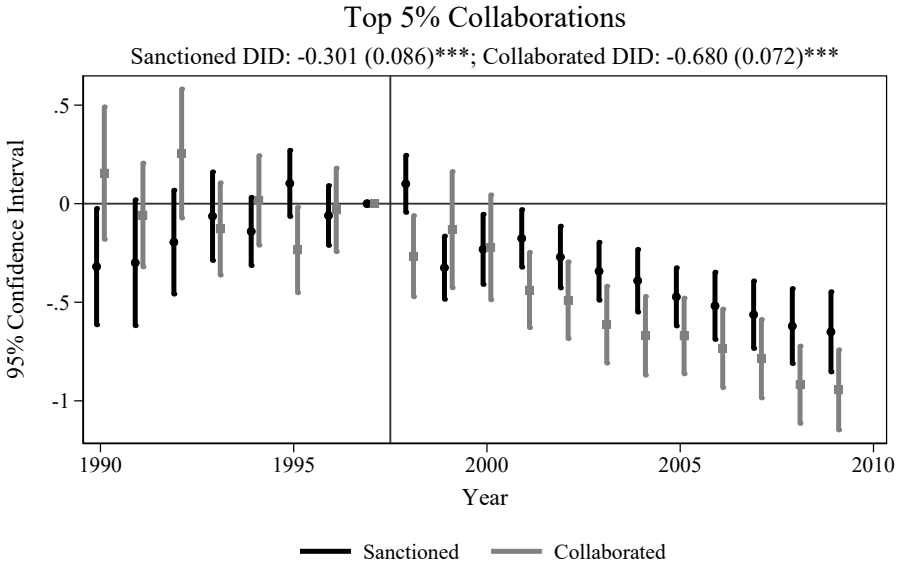
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.49. Collaboration with Top 1% Institutions



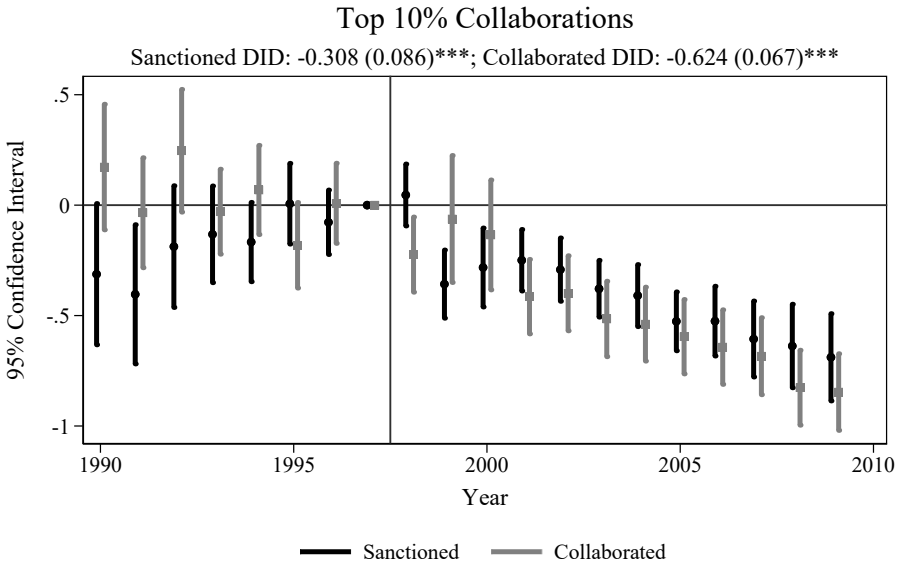
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.50. Collaboration with Top 5% Institutions



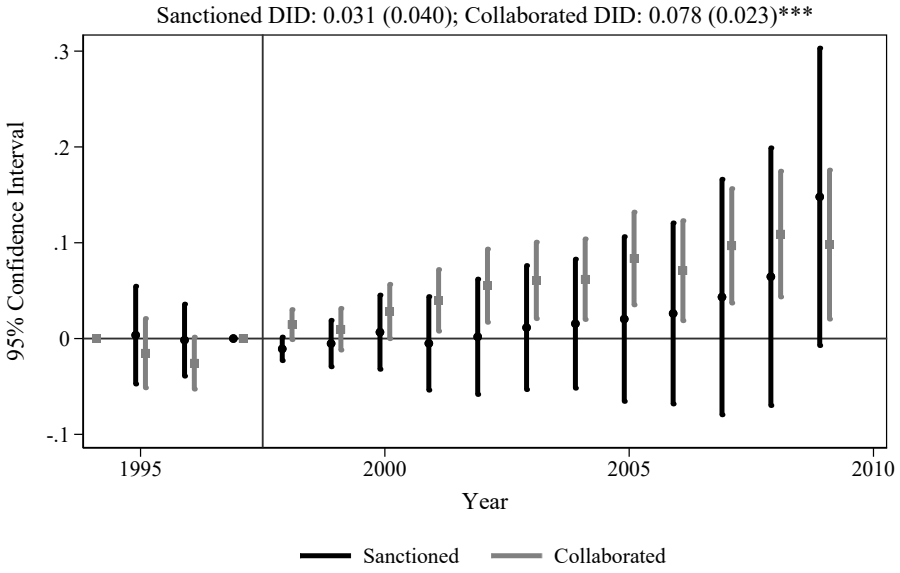
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.51. Collaboration with Top 10% Institutions



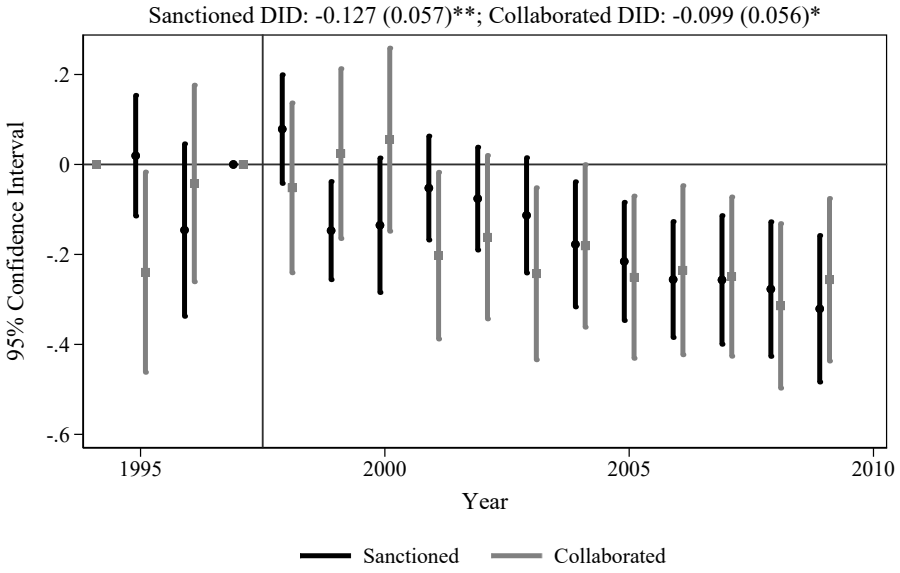
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type $\times$ year fixed effects. Standard errors clustered by institution.

FIGURE B.52. Share of Pre-1995 Ties After Last Observed Collaboration



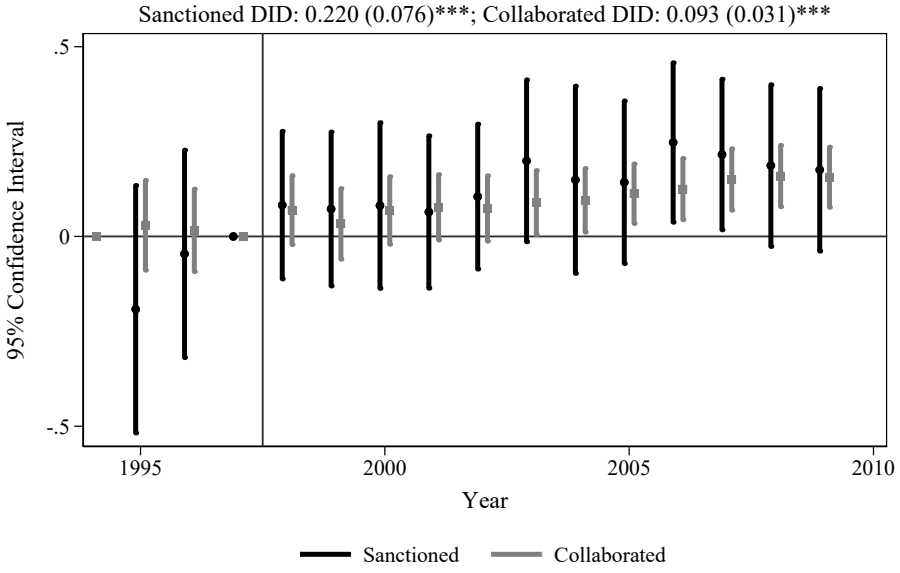
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution. For each pair of Indian institutions that collaborated during 1990–1994, the measure equals one beginning in the year following their last observed joint publication during 1990–2009. Publications after 2009 are not used.

FIGURE B.53. Active Pre-1995 Partners



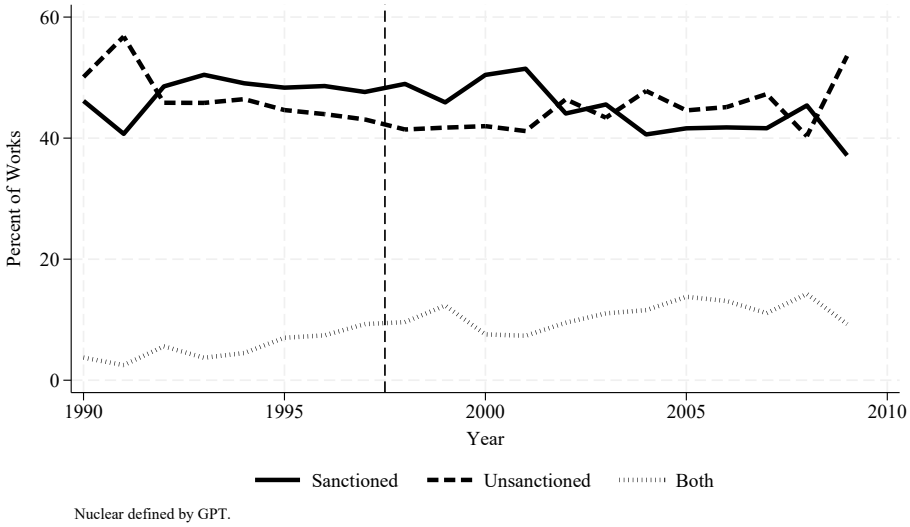
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.54. Share of Activity with New Partners



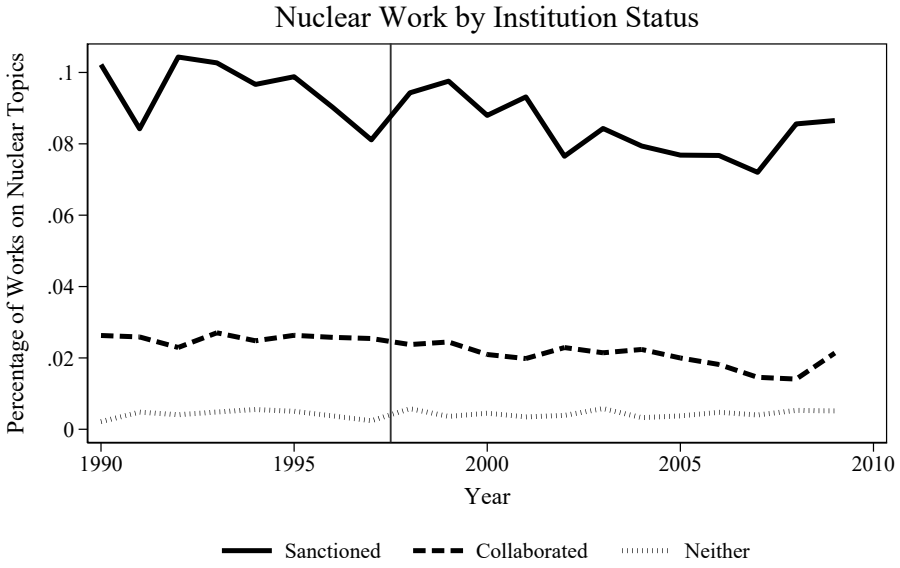
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.55. Nuclear Work by Sanctioned and Unsanctioned Institutions



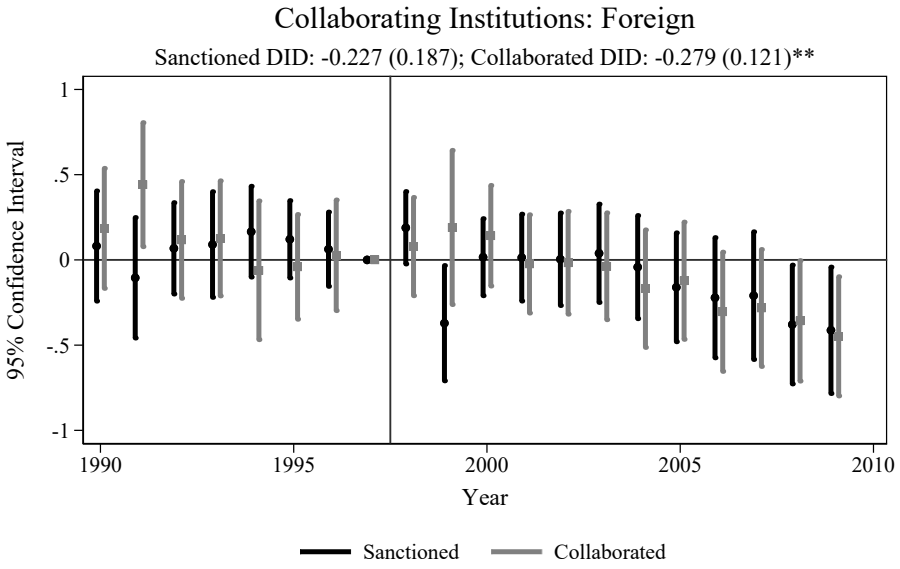
"Sanctioned" is the percentage of works for which all institutions are sanctioned. "Unsanctioned" is the percentage of works for which all institutions are unsanctioned. "Both" is the percentage of works on which both sanctioned and unsanctioned institutions are represented.

FIGURE B.56. Percentage of Works on Nuclear Topics by Status



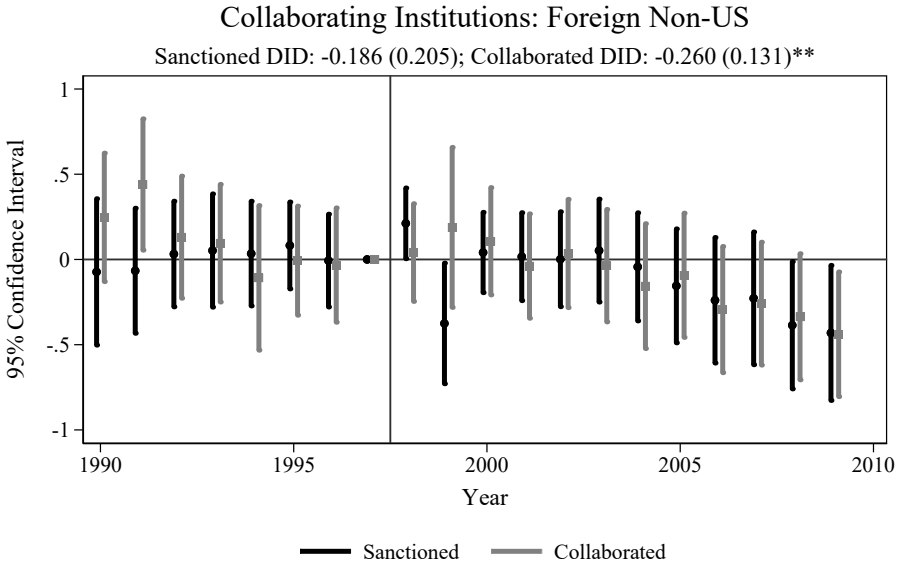
"Sanctioned" is the percentage of works at sanctioned institutions that are on nuclear topics. "Collaborated" and "Neither" are defined analogously.

FIGURE B.57. Collaboration with Foreign Institutions



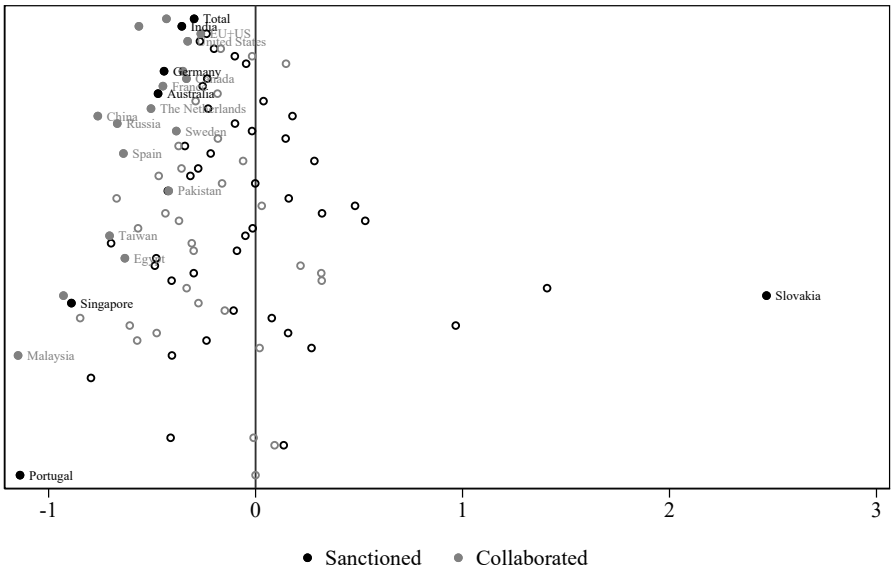
***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.58. Collaboration with Non-US Foreign Institutions



***Significant at 1%, **Significant at 5%, *Significant at 10%. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type × year fixed effects. Standard errors clustered by institution.

FIGURE B.59. Collaboration by Partner Country



Each circle is a partner-country or aggregate estimate corresponding to equation (1) (dark dots) or (2) (light dots). Statistically insignificant results (at the 5% level) are shown with hollow dots, and statistically significant results are shown with solid dots. Results estimated using pseudo-Poisson maximum likelihood. Outcome variable top-coded at the 99th percentile. The "collaborating" sample excludes sanctioned institutions. All specifications include institution fixed effects and institution type $\times$ year fixed effects. Standard errors clustered by institution. The figure includes only countries for which there was collaboration with Indian institutions between 1990 and 1997, and excludes Romania (an outlier). We include "Total," "EU+US," and "EU" as additional aggregates. We label estimates only if either coefficient is significant for a given country. We sort countries by the mean number of partner institutions per institution-year during 1990–1997.