Some recent developments in planet formation theory

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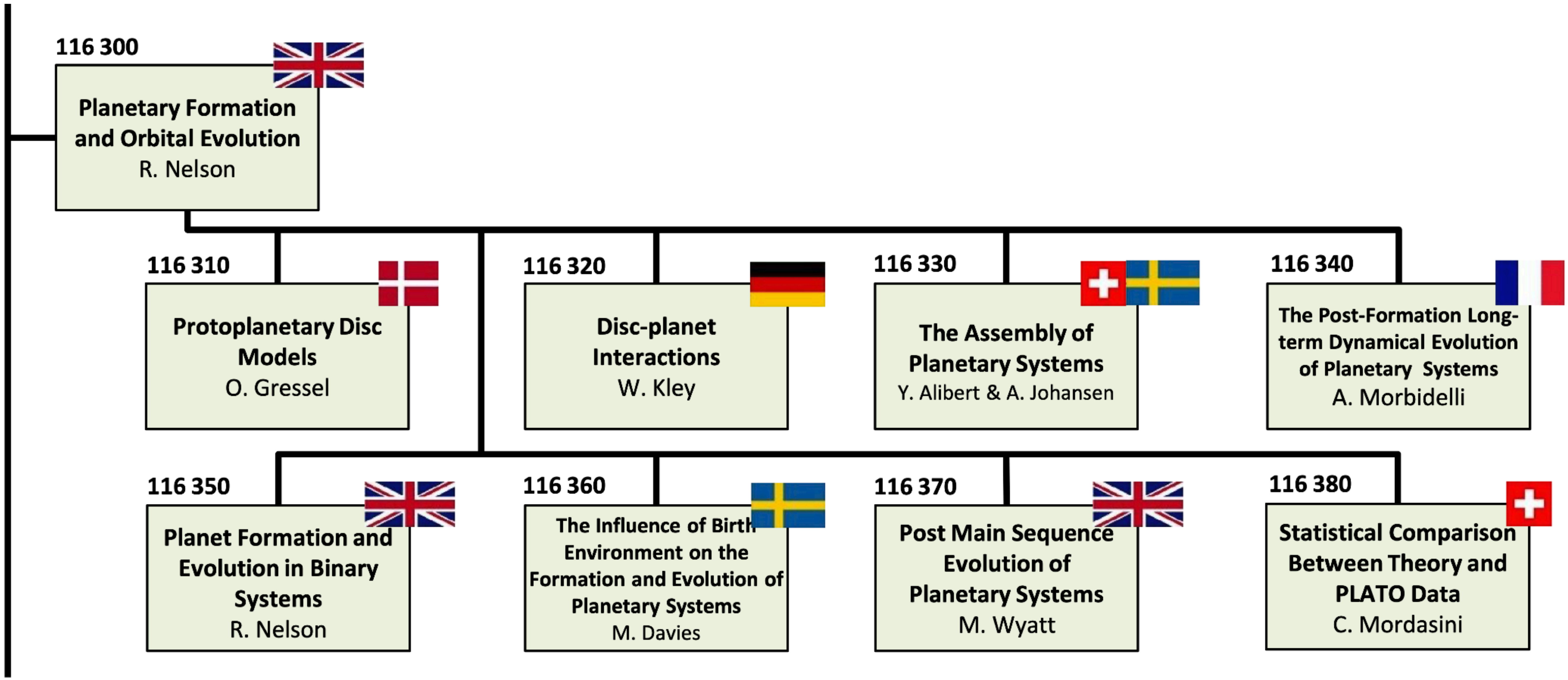
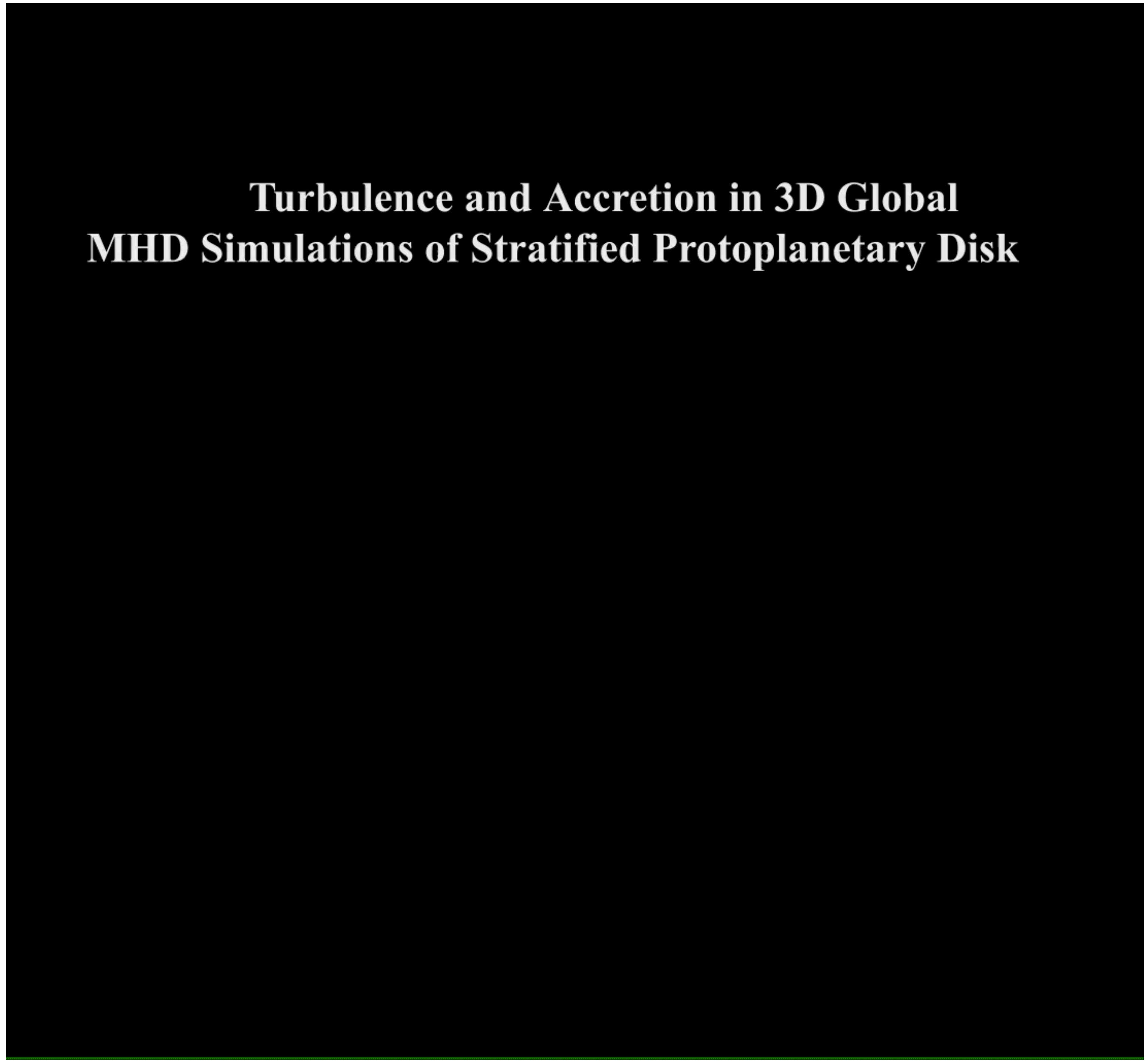


The role of theory:

(i) To understand how planetary systems in their full diversity form and evolve by comparing theoretical models with the observed planet population

(ii) To help identify high-value targets for intensive follow-up that can provide unique insights into formation and evolutionary processes

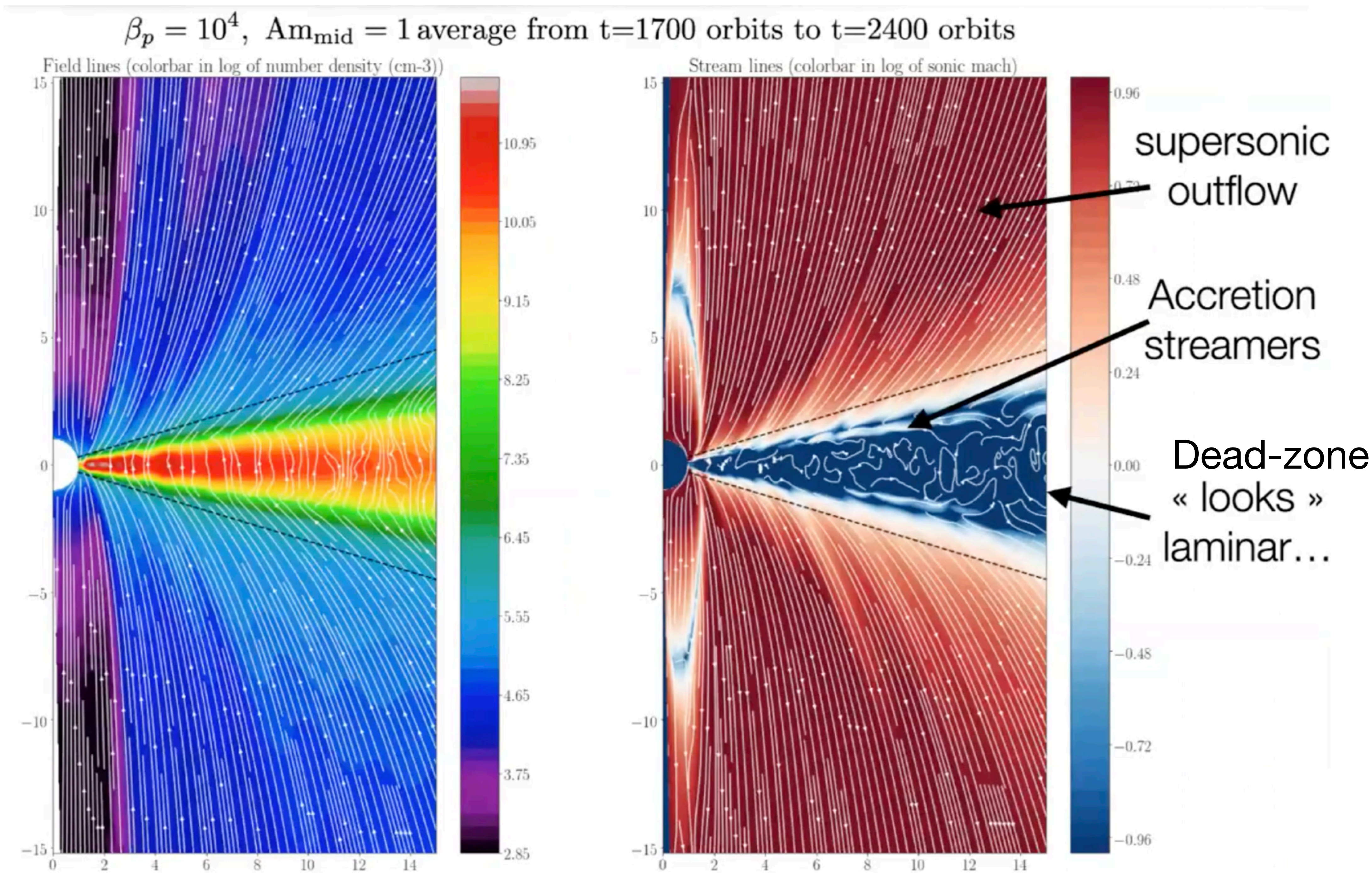
Protoplanetary disc models



Flock et al (2011)

In a traditional disc model angular momentum transport and accretion driven by turbulent viscosity

A highly turbulent disc can create a hostile environment for planet formation
(Nelson & Gressel 2010)



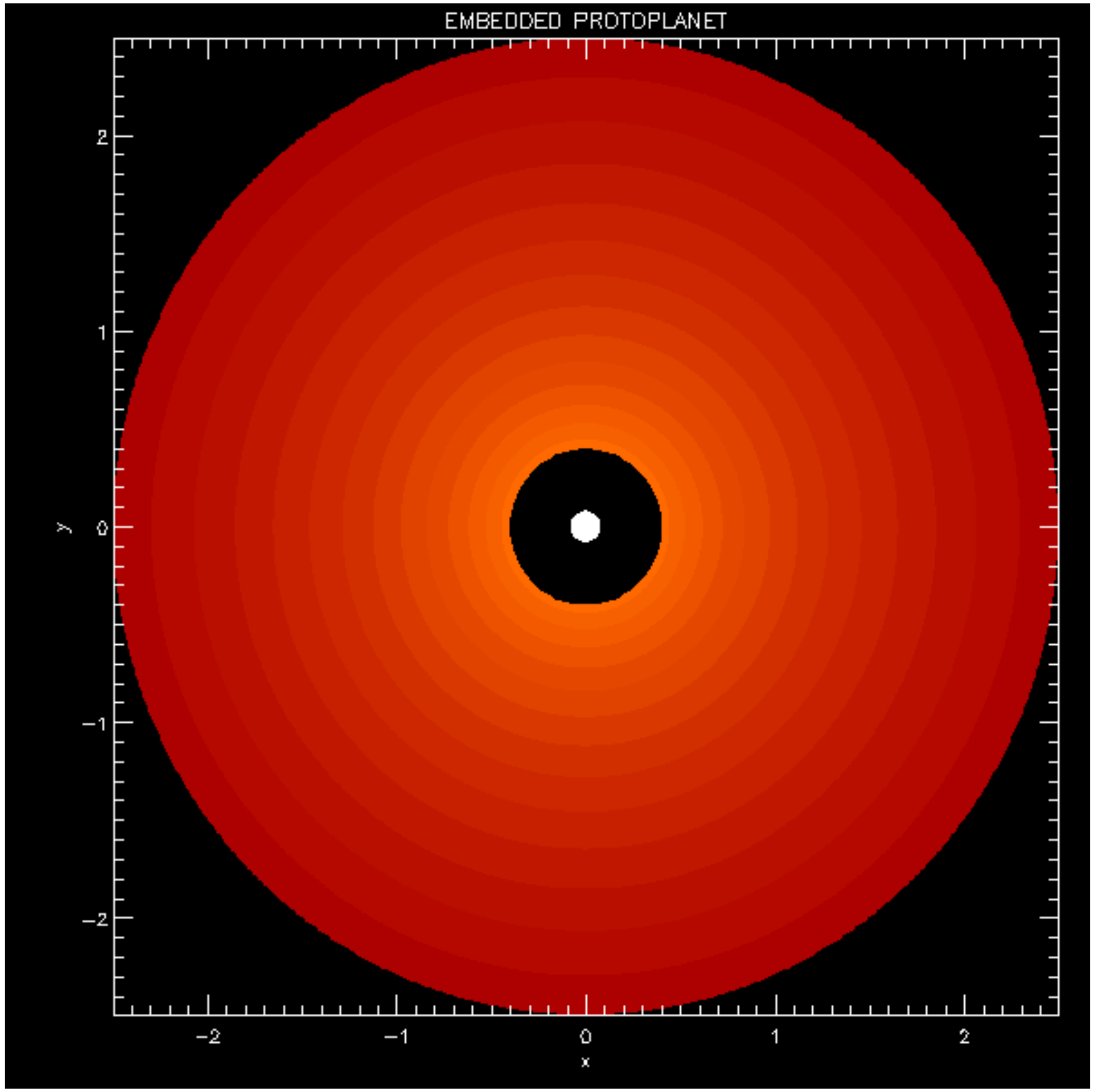
Bethune et al (2017)

Protoplanetary discs have very low levels of ionisation except in their surface layers

Non-ideal MHD effects combined with a vertical magnetic field generate a magnetised wind and accretion through narrow surface layers

The midplane regions are essentially laminar - planet formation friendly dead-zone

Planet migration

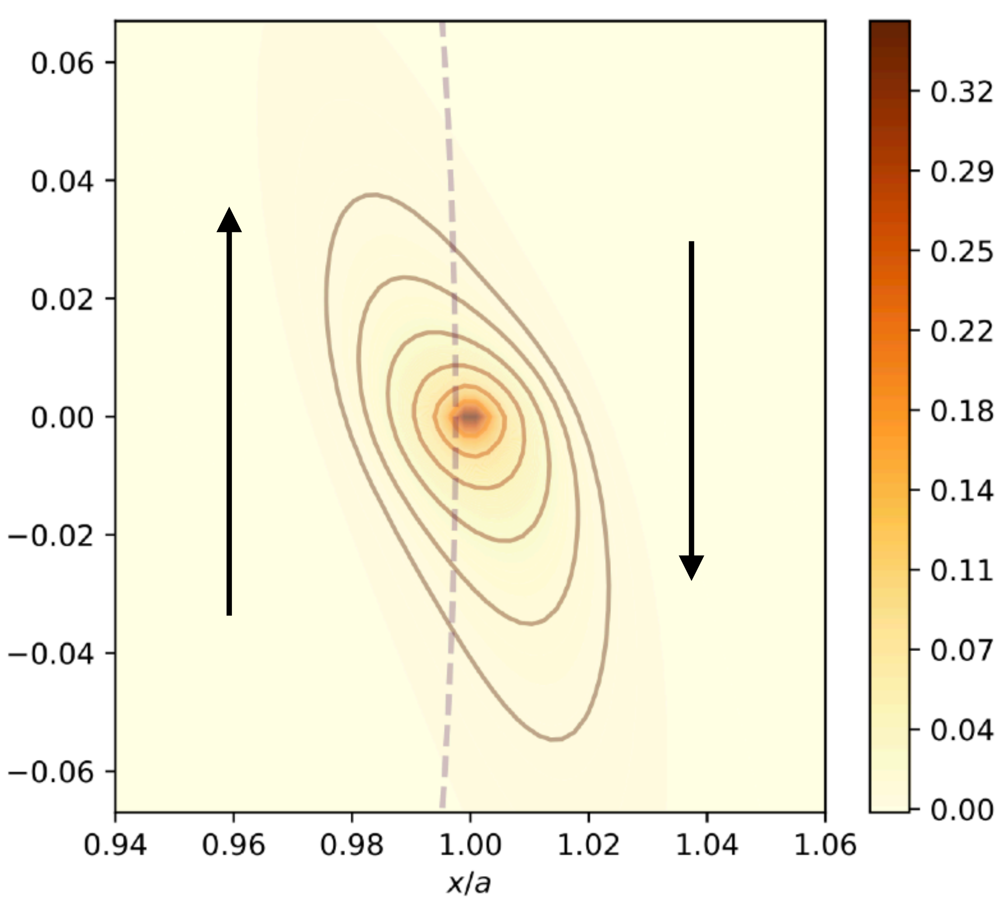


In most situations migration is mainly driven by spiral waves (+ coronation torque)

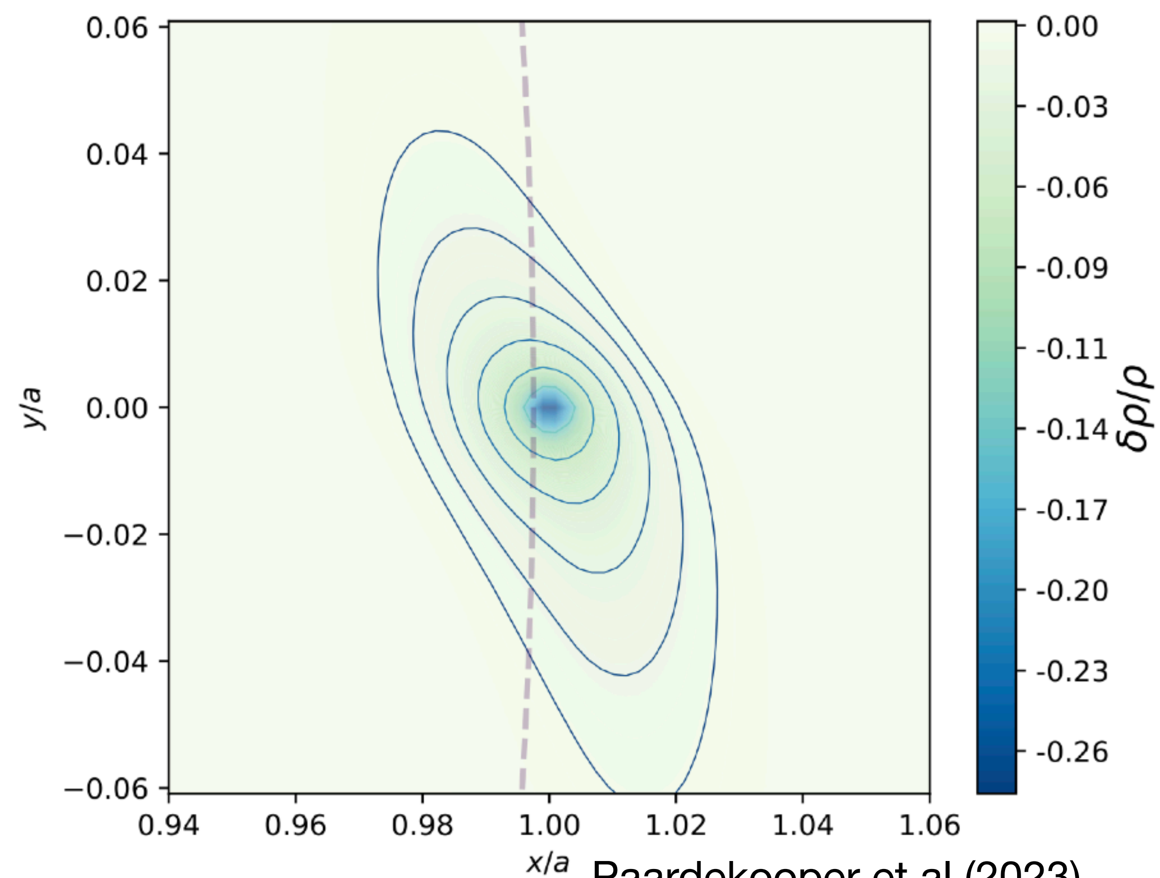
Typical migration times are ~ 10^5 years for an Earth-mass planet

Thermal torques

Temperature perturbation



Density perturbation



Paardekooper et al (2023)

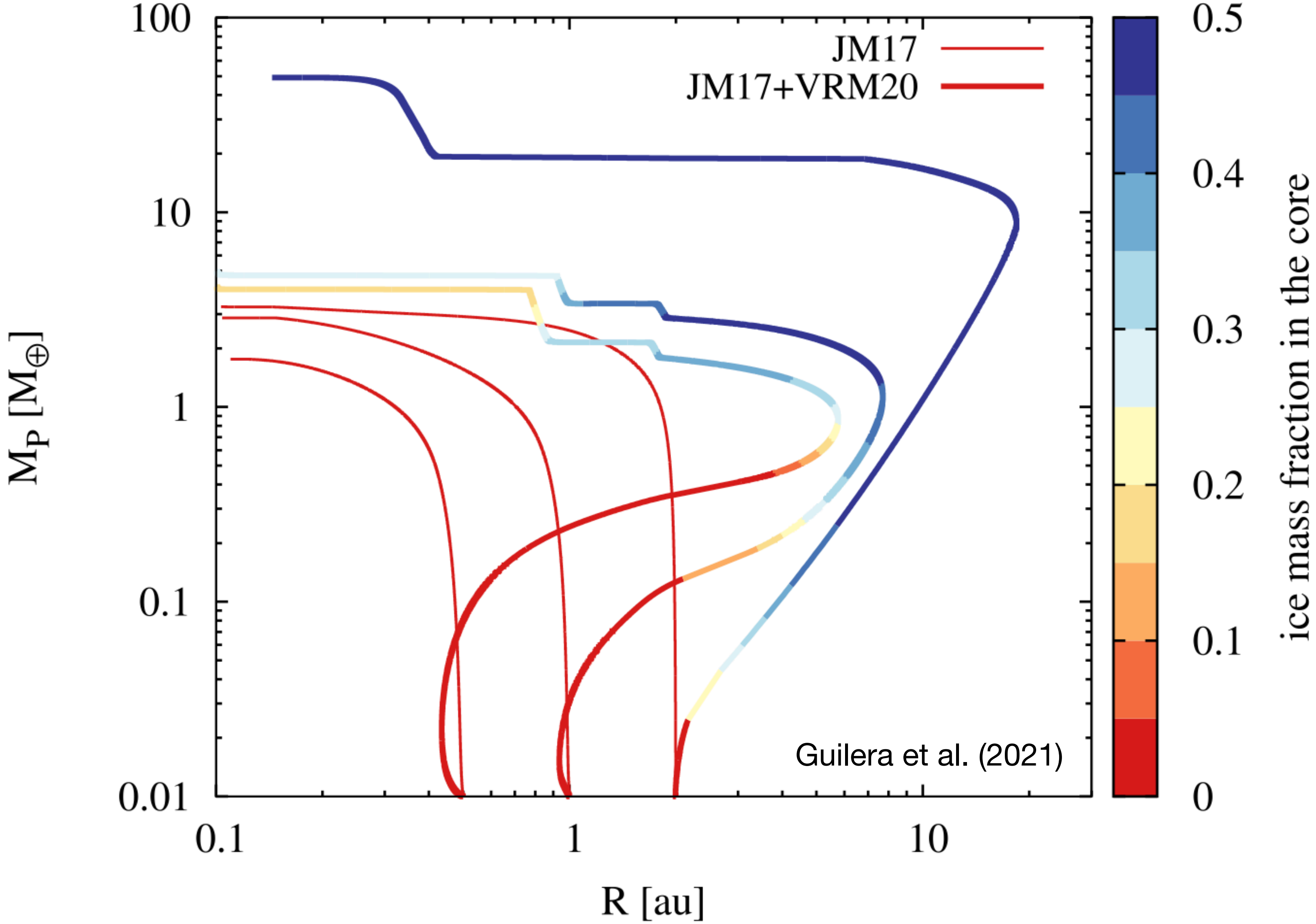
A hot pebble-accreting planet in a disc perturbs the temperature and density near the planet

The background sub-Keplerian shear causes a spatial asymmetry

Obtain a net torque and outwards migration (Benitez-Llambay et al 2015)

Depends on planet mass, luminosity and disc opacity (Masset 2017)

Evolution of pebble accreting embryos + heating torque



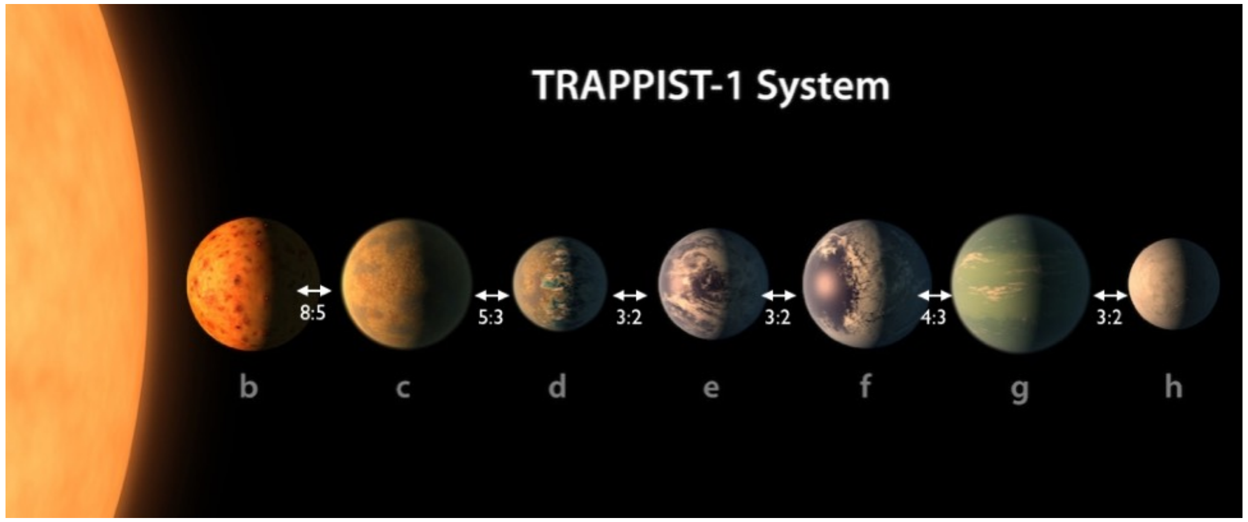
Planetary embryos undergoing pebble accretion show very different growth and migration tracks when heating torque is included (Guilera et al. 2021)

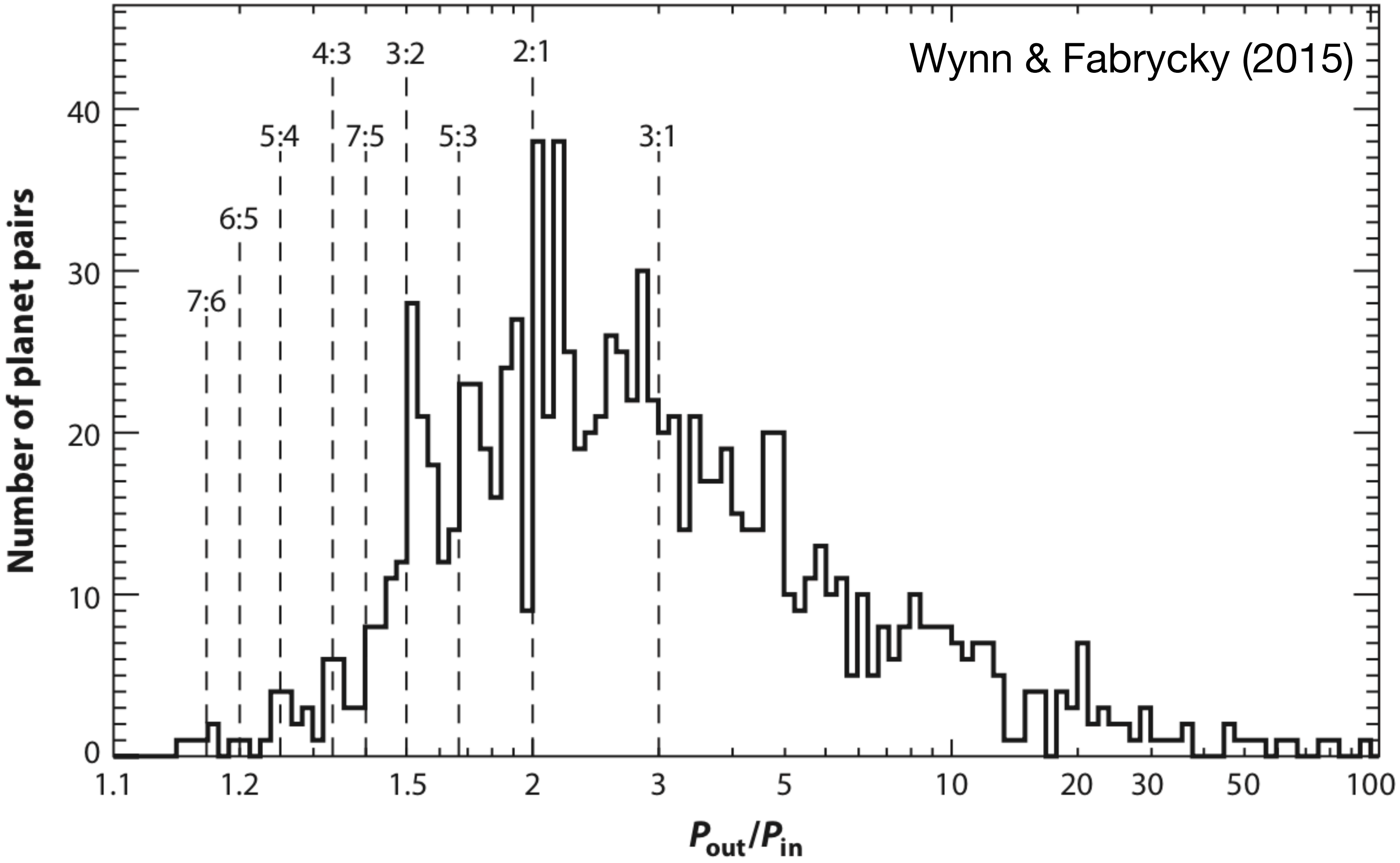
Heating torque can also lead to growth of eccentricity & inclination impacting on pebble accretion efficiency (Liu & Ormel 2018)

Resonant chains in multiplanet systems

Multiplanet systems are found in resonant chains e.g. Kepler-233 (Mills et al 2016) and Trappist-1 (Gillon et al 2017)

Kepler data shows multiplanet systems are rarely in resonance (Fabrycky et al 2014)



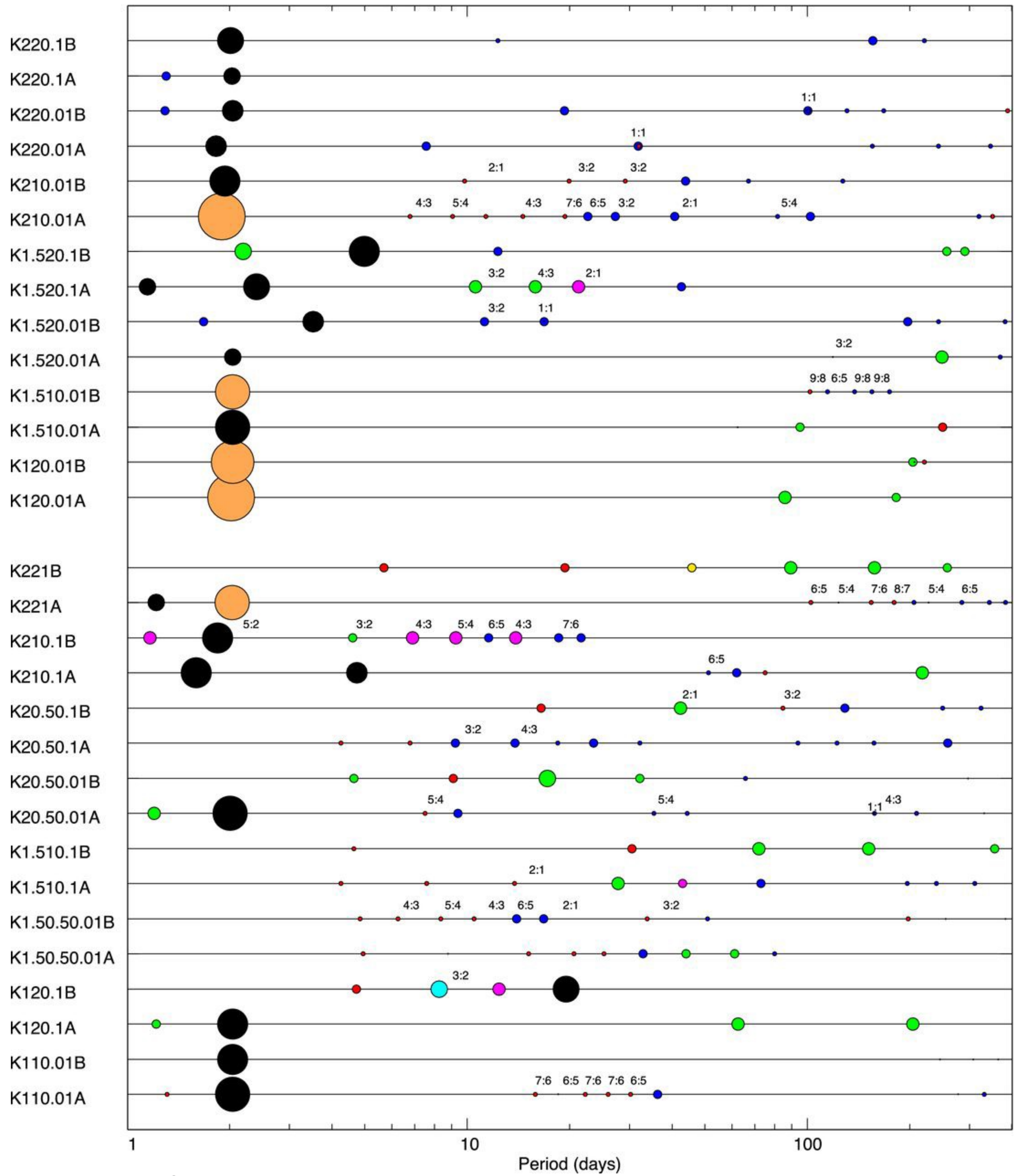


N-body simulations of planet formation predict that resonant chains should be common (e.g. Coleman & Nelson 2014, 2016)

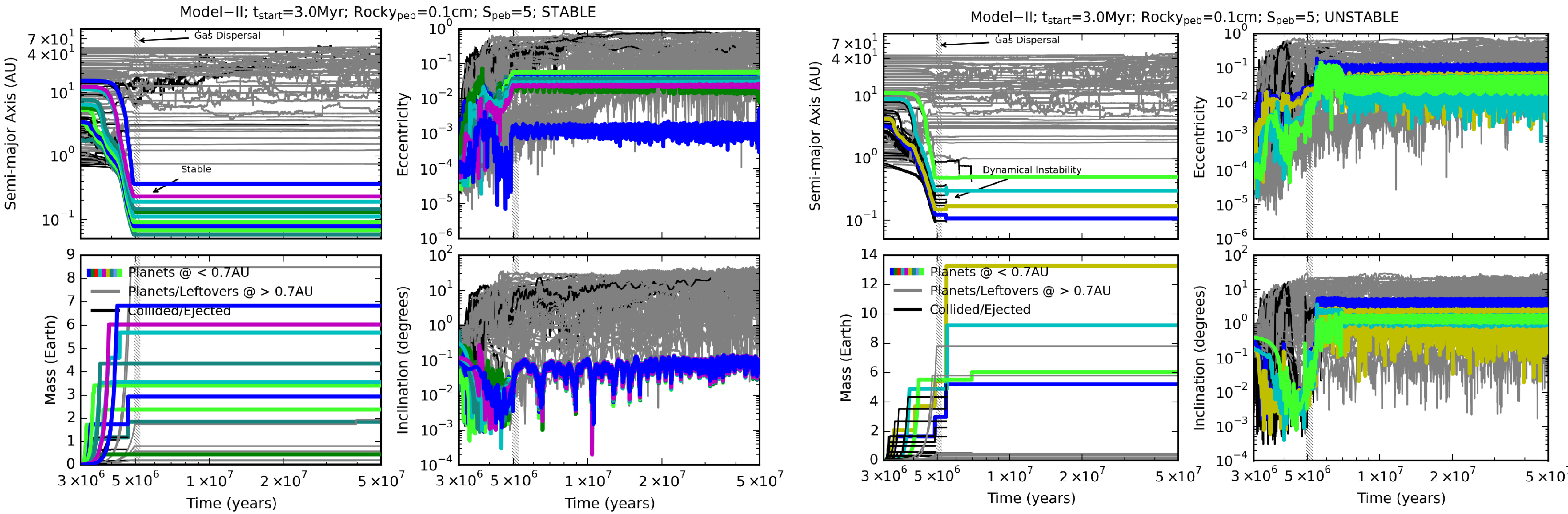
How to explain the lack of resonances?

- breaking-the-chains
  (Matsumoto et al 2012; Izidoro et al 2017, 2021)

- vortex-induced stochastic migration
  (McNally et al 2019)



Breaking-the-chains



Izidoro et al (2021)

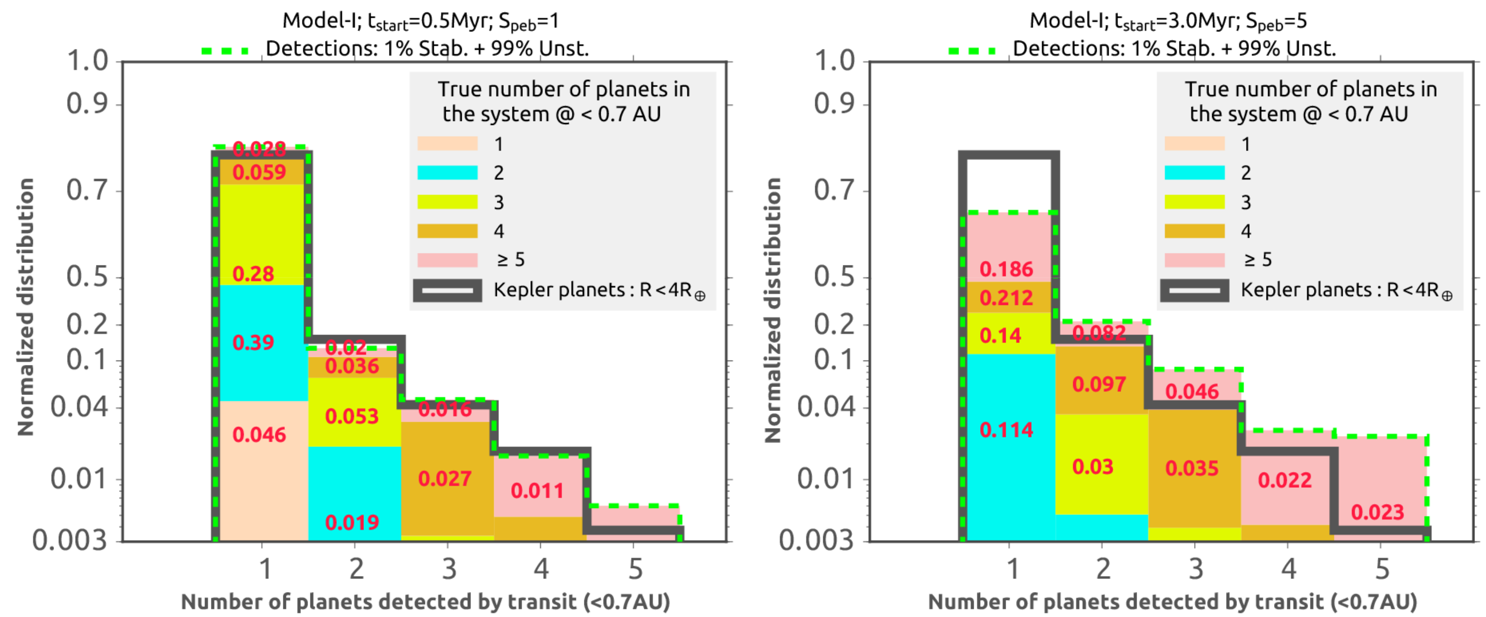
N-body simulations that follow long-term evolution show resonant systems can be dynamically unstable - leading to breaking-the-chains scenario

Depends on planet masses, which resonances are occupied, how deeply planets are in resonance

No simulation suite gives automatic agreement with observed multiplicity of planetary systems after synthetic transit survey

But can obtain agreement:
- use mixture model containing 1% stable systems and 99% unstable systems

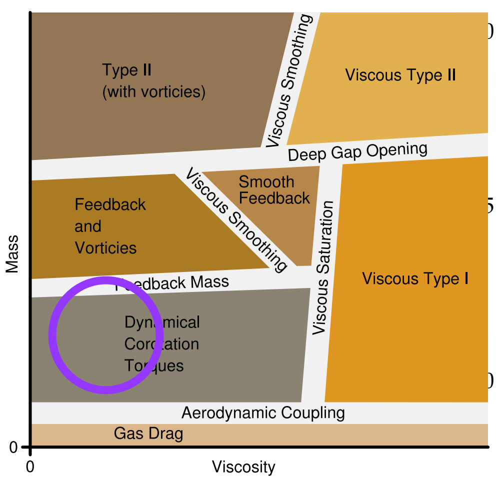
Need to see if such a scenarios can arise naturally from a population synthesis

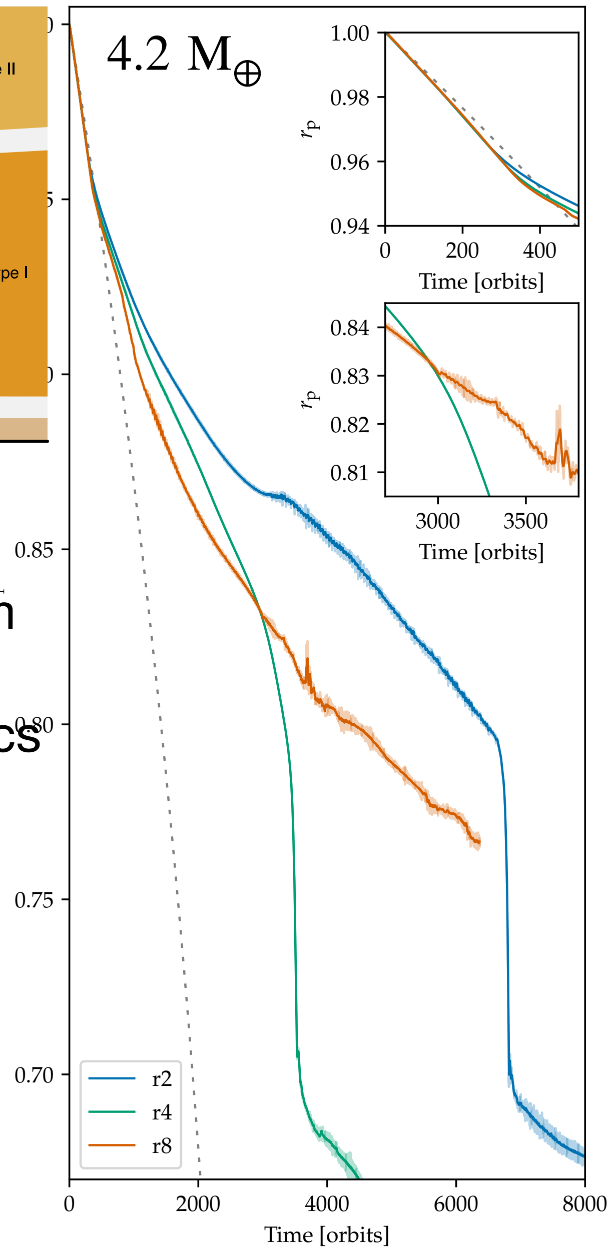


Izidoro et al (2021)

Knowing the planet masses is crucial for testing the theory - this is where PLATO can make a big difference!

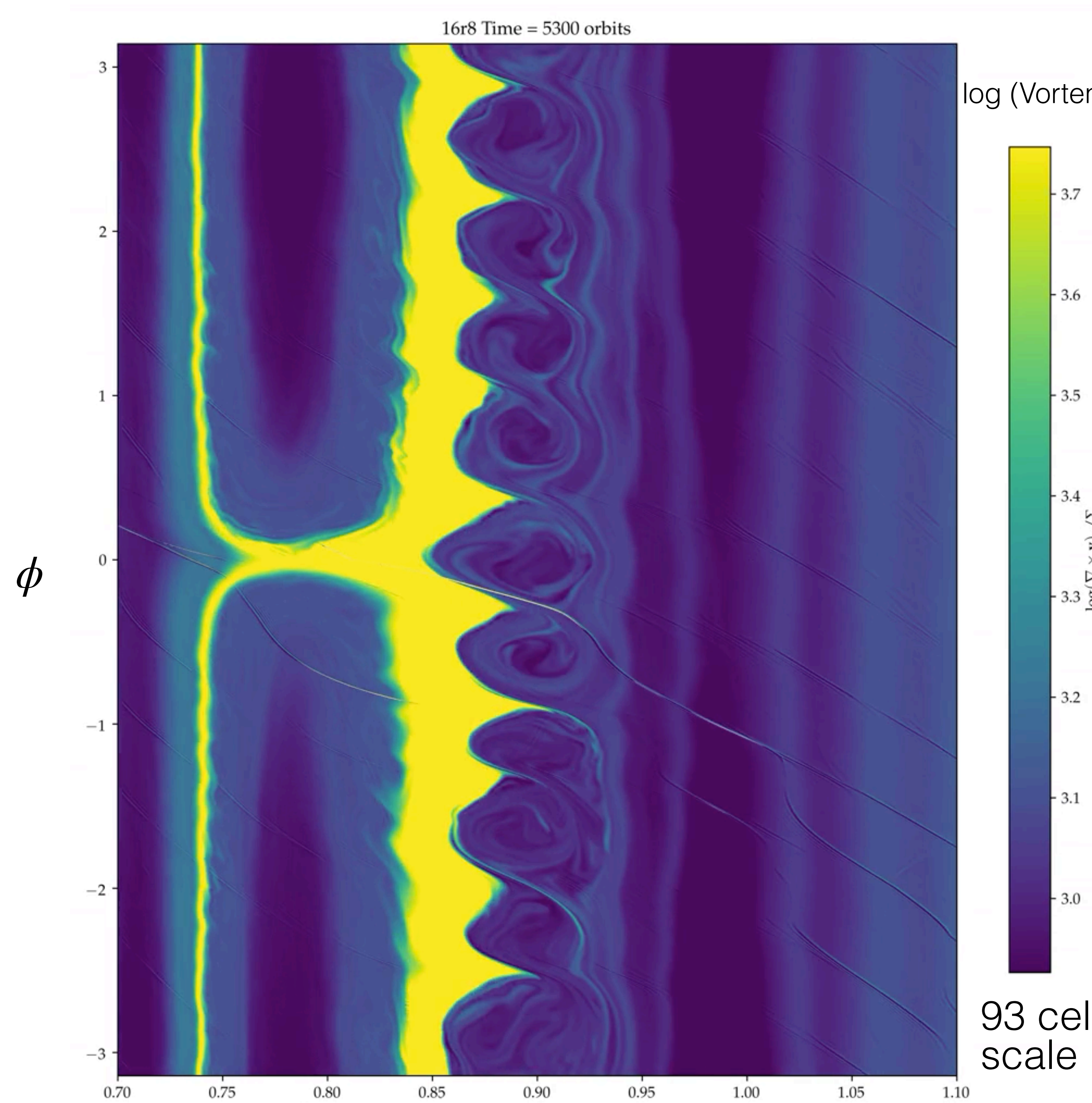
Super-Earths and vortices in laminar discs





Super-Earths form vortices in non-turbulent discs

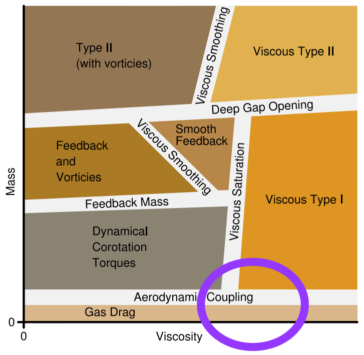
These induce stochastic migration



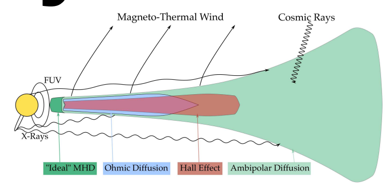
log (Vortensity)

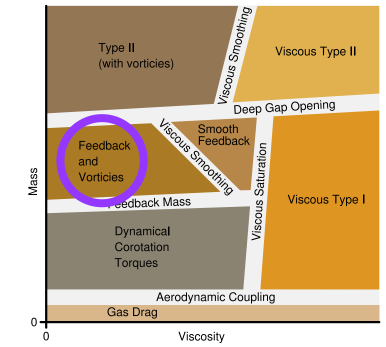
93 cells per scale height

McNally, Nelson, Paardekooper, Benitez-Llambay 2019

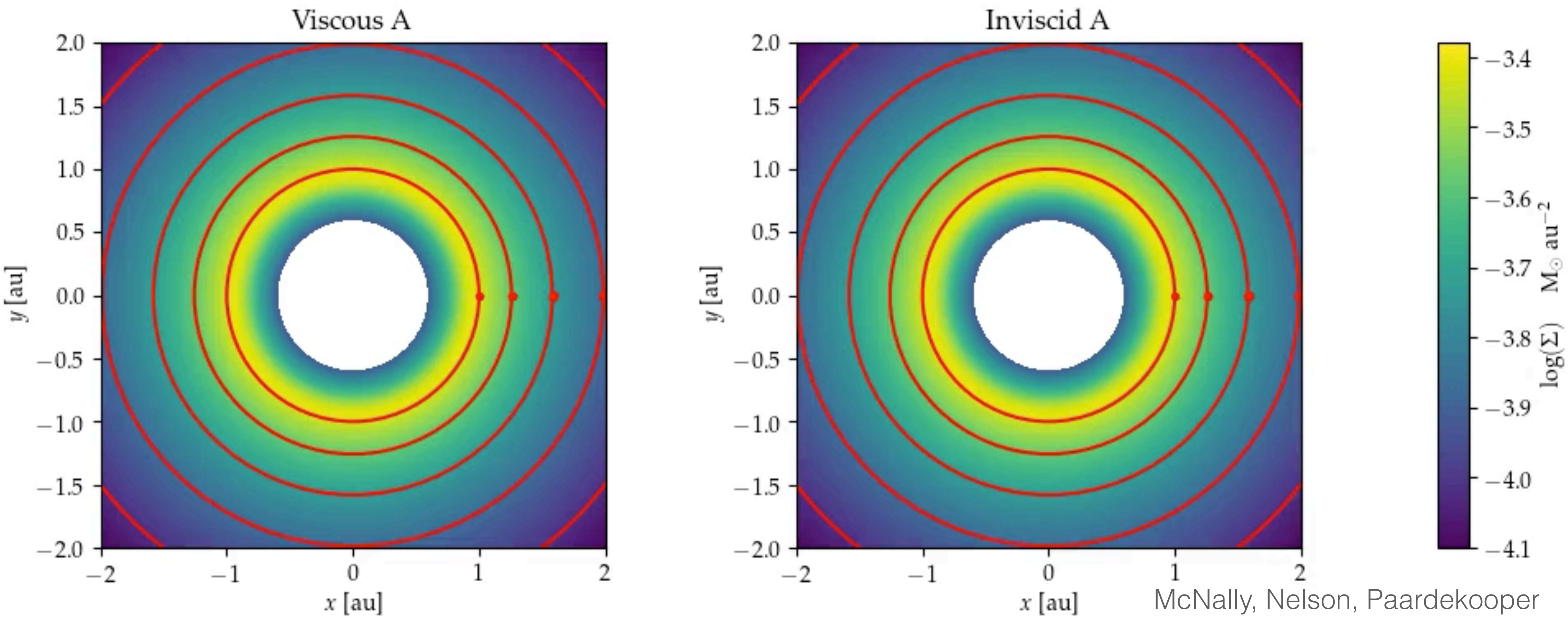


Planetary systems in gas discs





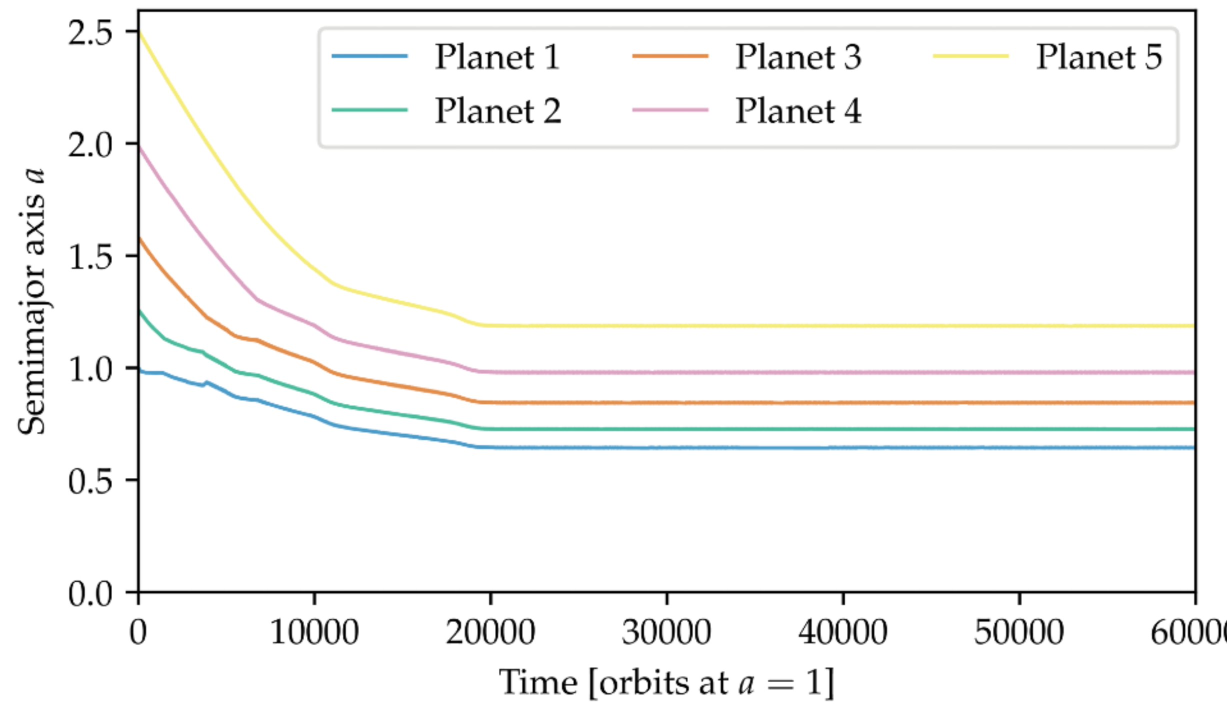
Turbulent (viscous) discs and inviscid discs produce different planetary systems



McNally, Nelson, Paardekooper (2019 MNRAS)

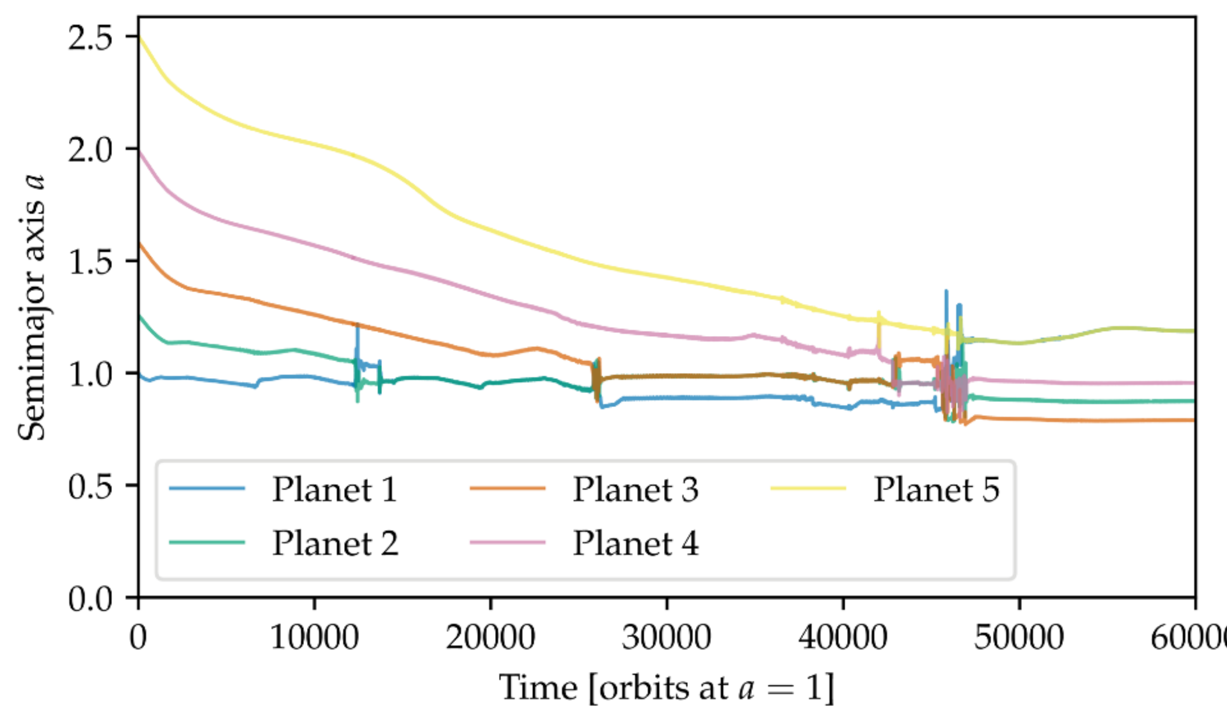
Viscous disc

Smooth convergence into a resonant chain



Inviscid disc

Chaotic compression into an unstable system with some planets pairs out of resonance.



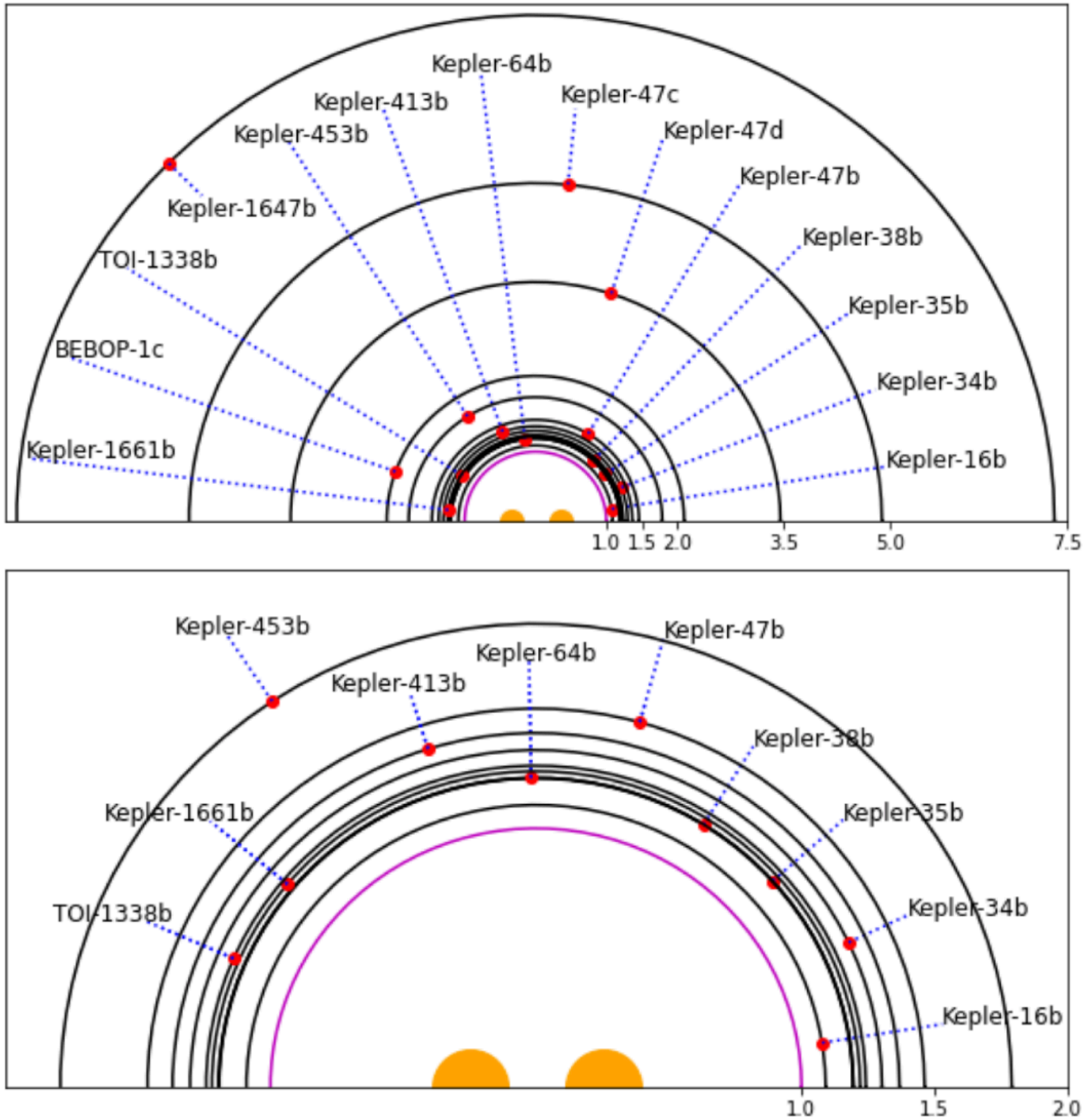
McNally, Nelson, Paardekooper (2019, MNRAS)

Breaking-the-chains and stochastic migration scenarios have different mass dependencies

Circumbinary discs and planets

Total of 15 circumbinary planets (CBPs) have been detected by Kepler, TESS and the BEBOP RV survey around main sequence eclipsing binaries

Many orbit just outside the Holman-Wiegert instability zone (Holman & Wiegert 1999)



Circumbinary discs and planets

Kepler-16 analogue

Kepler-34 analogue

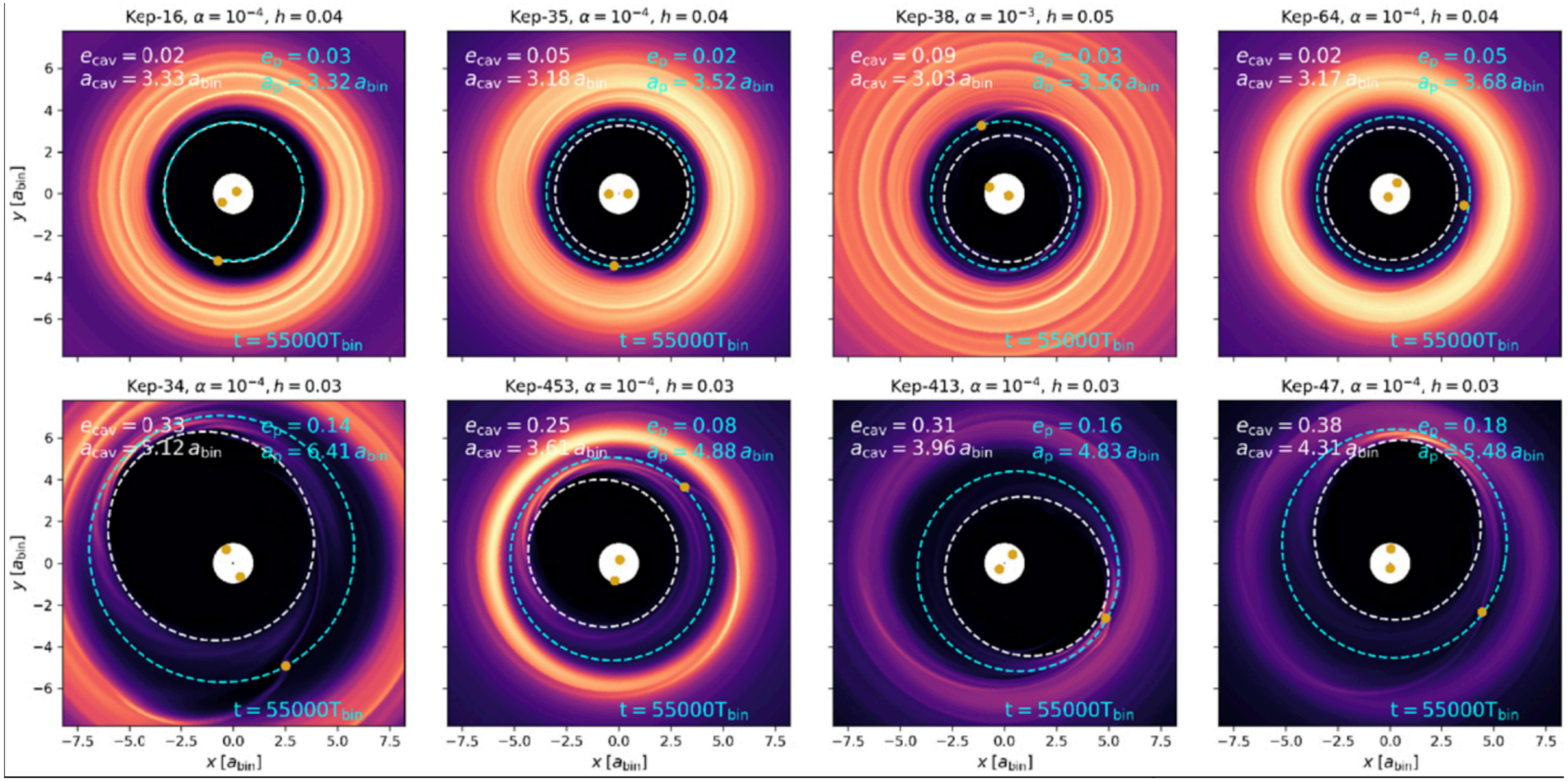
A tidally-truncated, eccentric and precessing cavity always forms
- depends on binary and disc parameters

Planets migrating through the disc become trapped at the cavity edge

(Nelson 2003; Pierens & Nelson 2008)

Fitting the observed systems

Penzlin, Kley & Nelson (2021)



6 out of 10 close-orbiting CBPs can be explained by 2D hydrodynamical simulations of viscous CBDs

CBPs forming in CBDs with highly eccentric cavities such as Kepler-34 and -413 are difficult to explain
Penzlin, Kley & Nelson (2021)

Need to test if results are the same when using 3D simulations - recent work suggests 2D & 3D differ

PLATO will discover new systems showing how planet and binary properties correlate

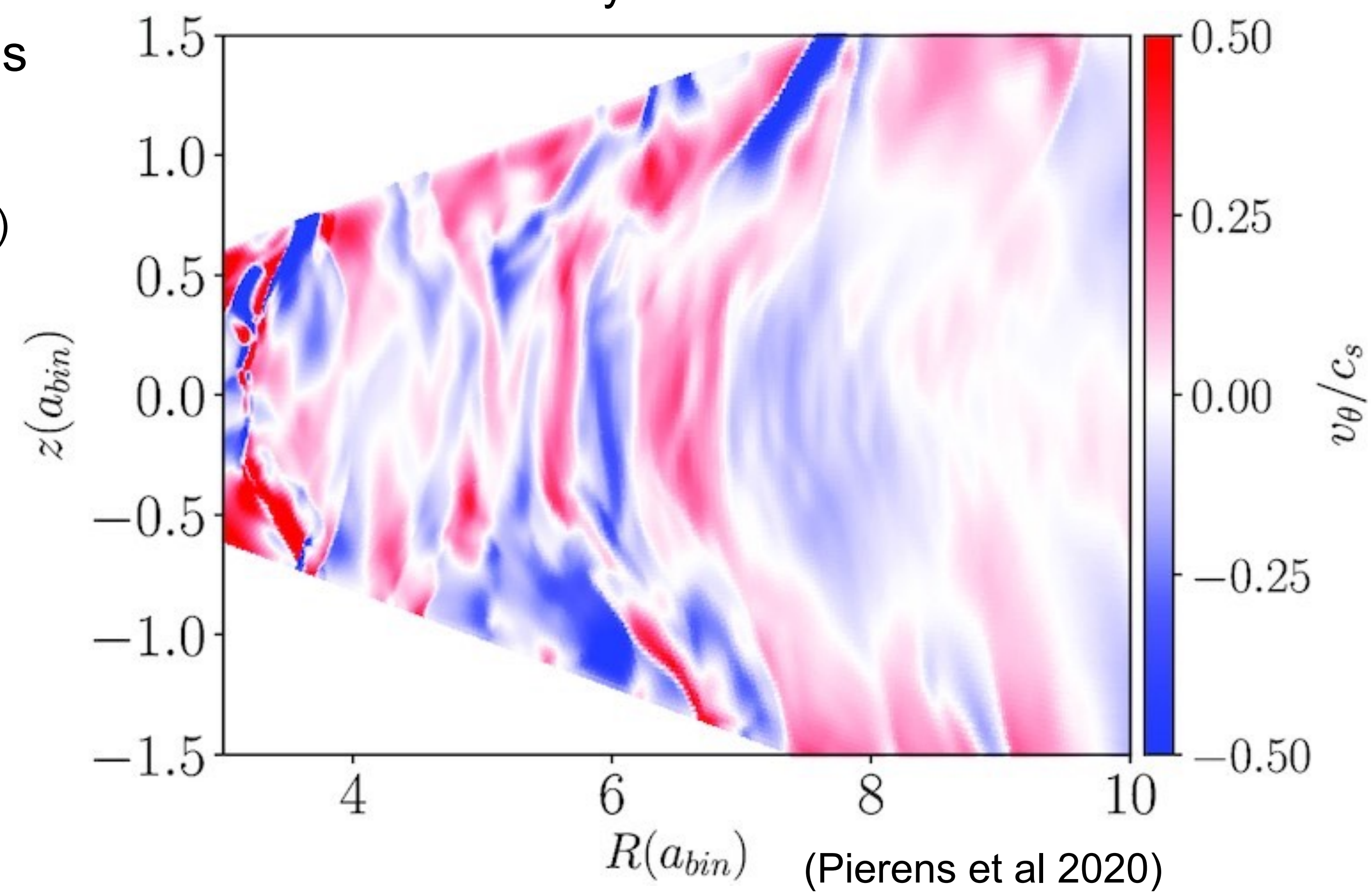
Hydrodynamical turbulence and in situ formation of CBPs

3D hydro simulations of inviscid eccentric CBDs show they become turbulent near cavity

(Pierens et al 2020, 2021)

(see also Papaloizou 2005, Barker & Ogilvie 2014)

Vertical velocity fluctuations

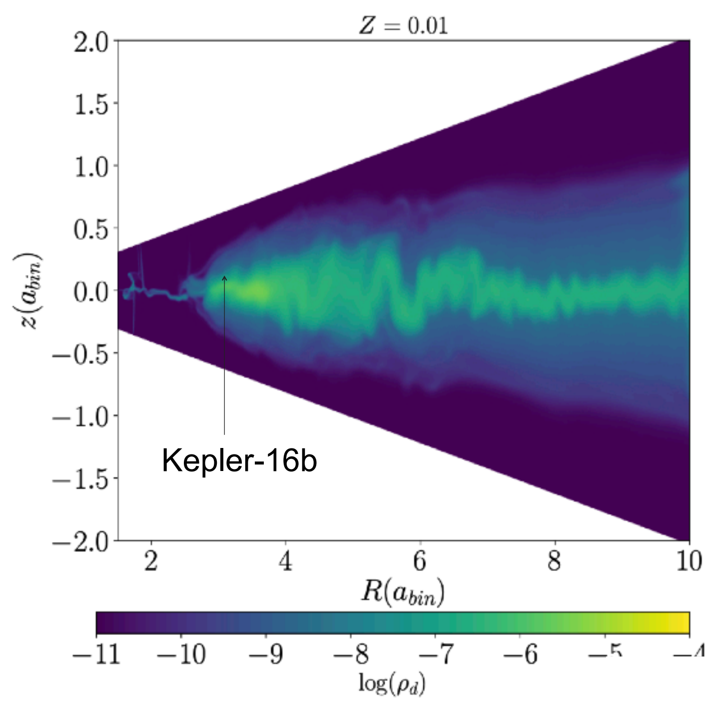


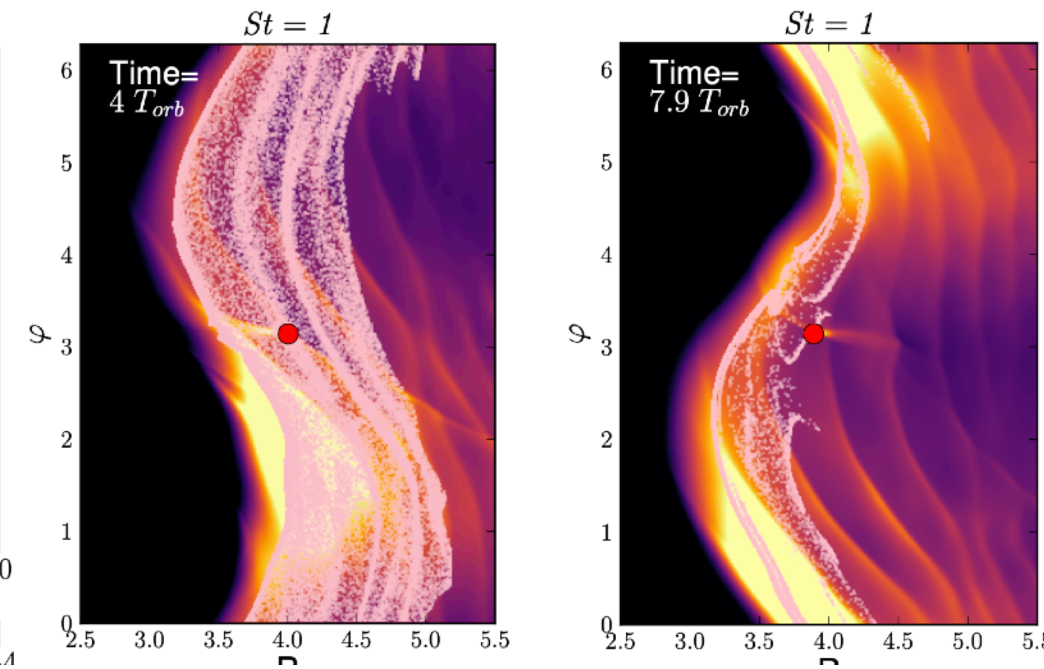
(Pierens et al 2020)

Turbulence stirs up dust grains and pebbles

Increases the thickness of the pebble layer

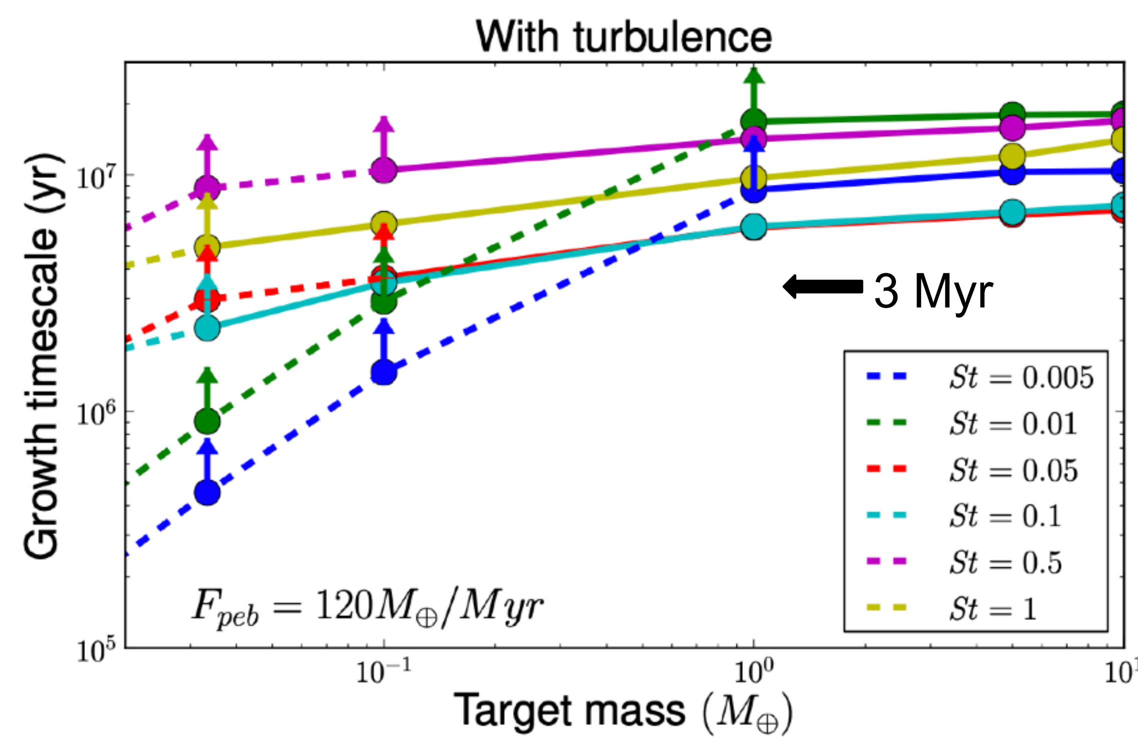
Pebble accretion becomes inefficient when $H_{dust} > R_{hill}$
(Lambrechts & Johansen 2012)





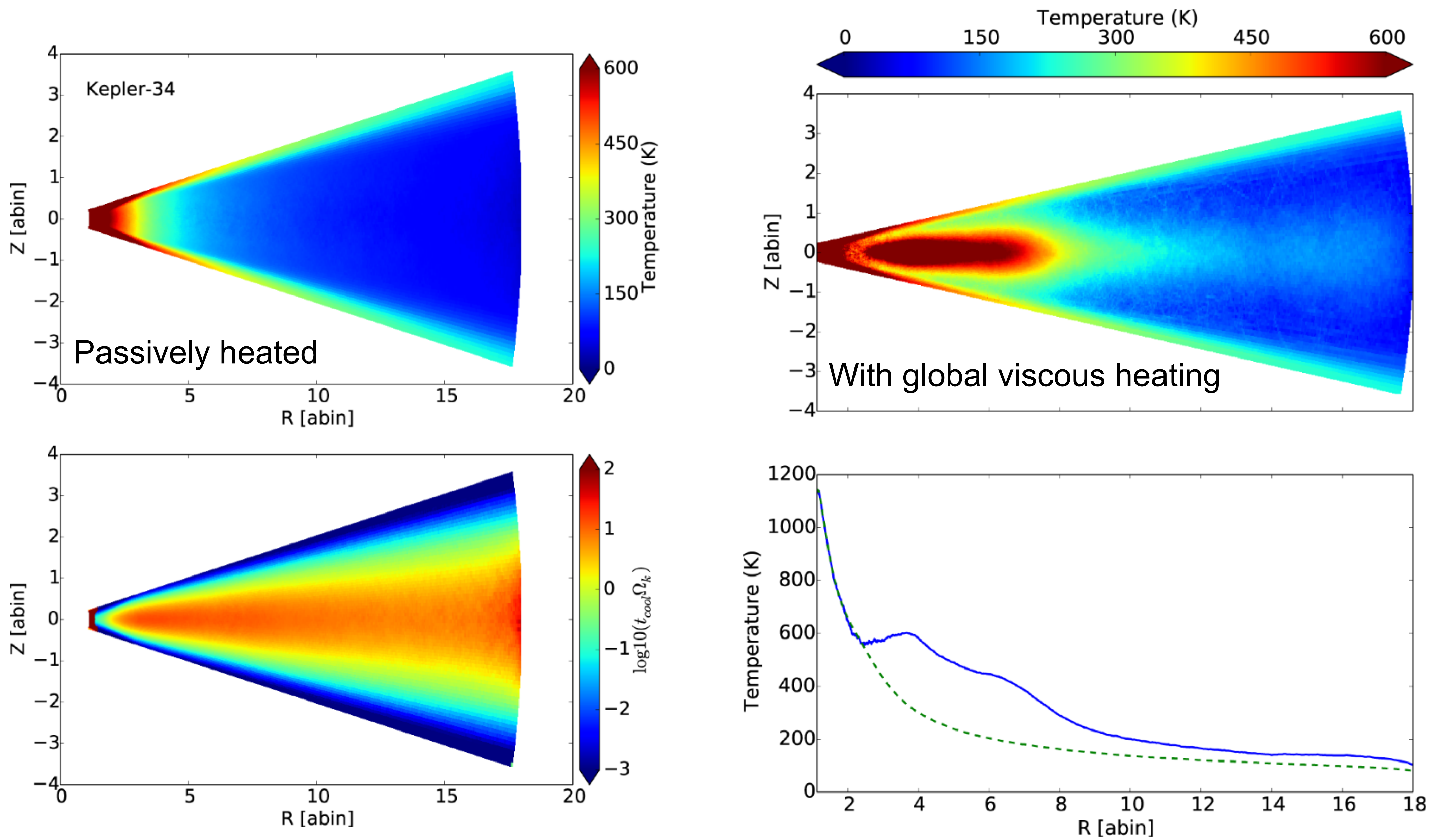
3D hydro simulations of pebble accretion in Kepler-16 analogues show that in situ planet formation timescales significantly exceed disc lifetimes

(Pierens, McNally & Nelson 2020)
(Pierens, Nelson & McNally 2021)



Pierens, McNally & Nelson (2020)

Snowline locations in CPDs: CBPs should be icy not rocky!

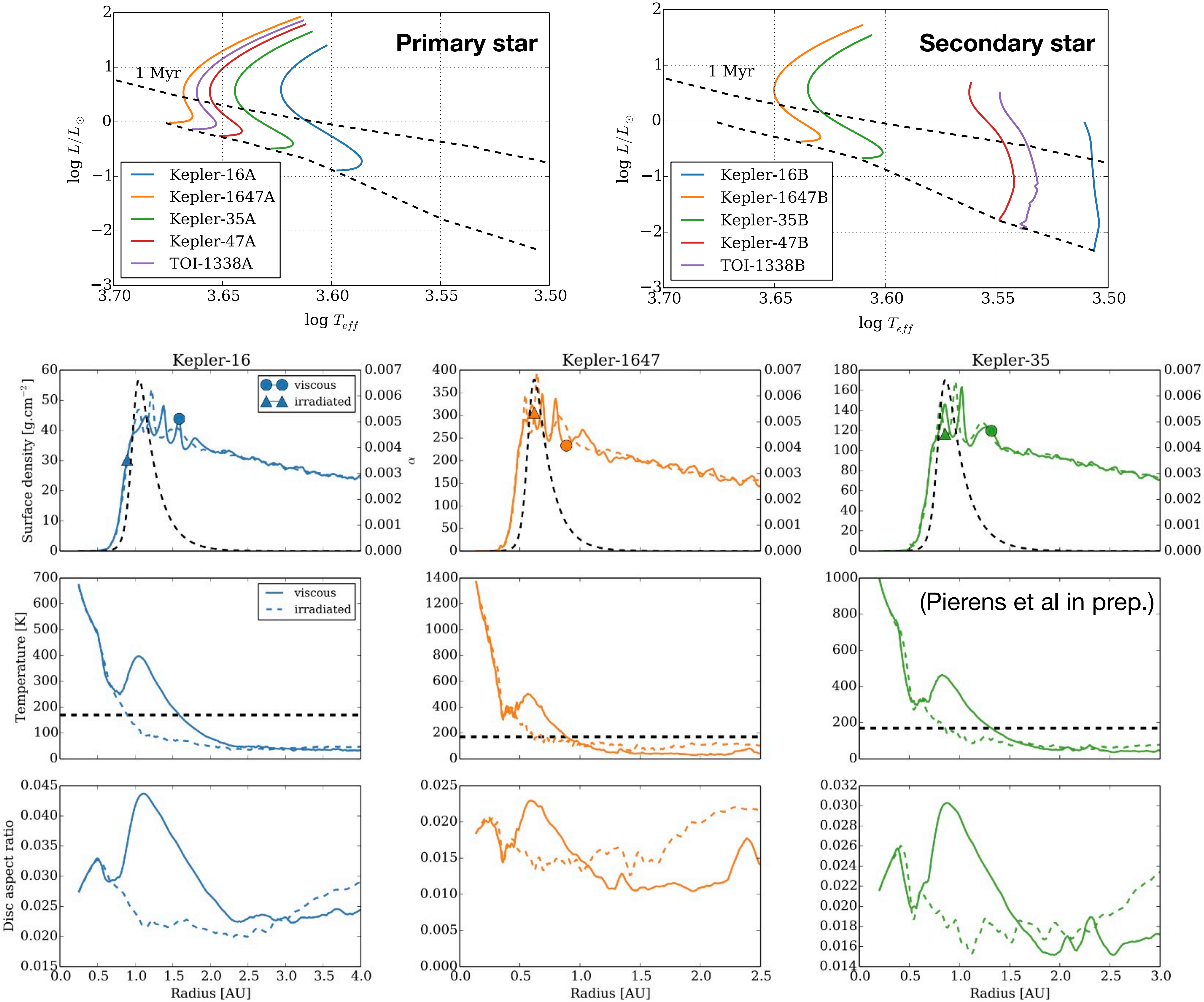


RADMC-3D radiative transfer simulations of CBDs show most of stellar flux is absorbed at the cavity edge

Temperatures deep inside the CBD are < 160 K - the ice-condensation temperature

3D hydro + RADMC-3D simulations of CBDs show snowline is always close to cavity edge

(Pierens et al in prep.)



The snowline is always close to the cavity edge - CBPs should be icy not rocky…

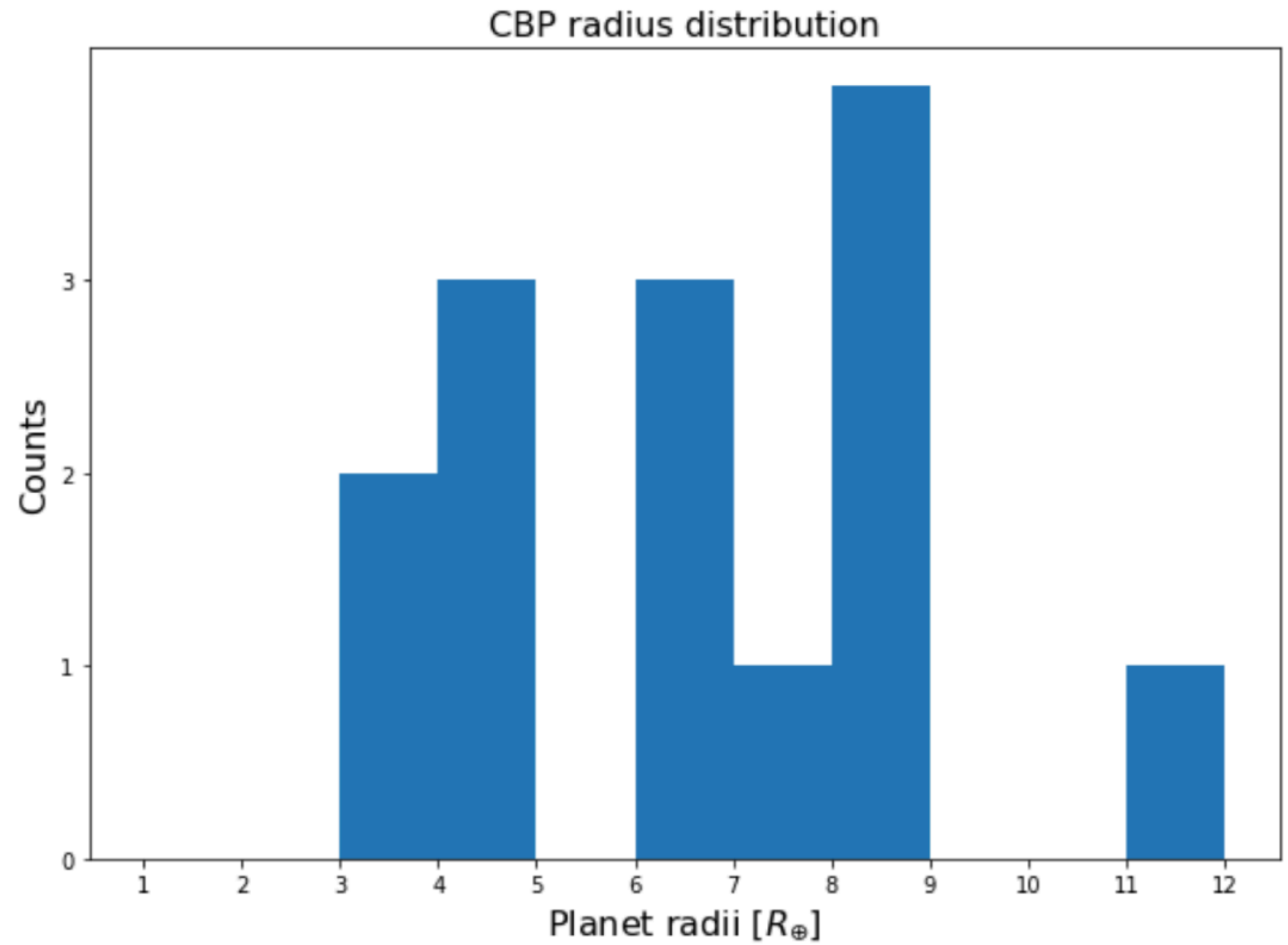
CBPs appear to be in the sub-Neptune-Saturn size and mass range.

No small rocky CBPs have been discovered in Kepler data (David Martin - Private Comm.)

- consistent with predicted snowline locations

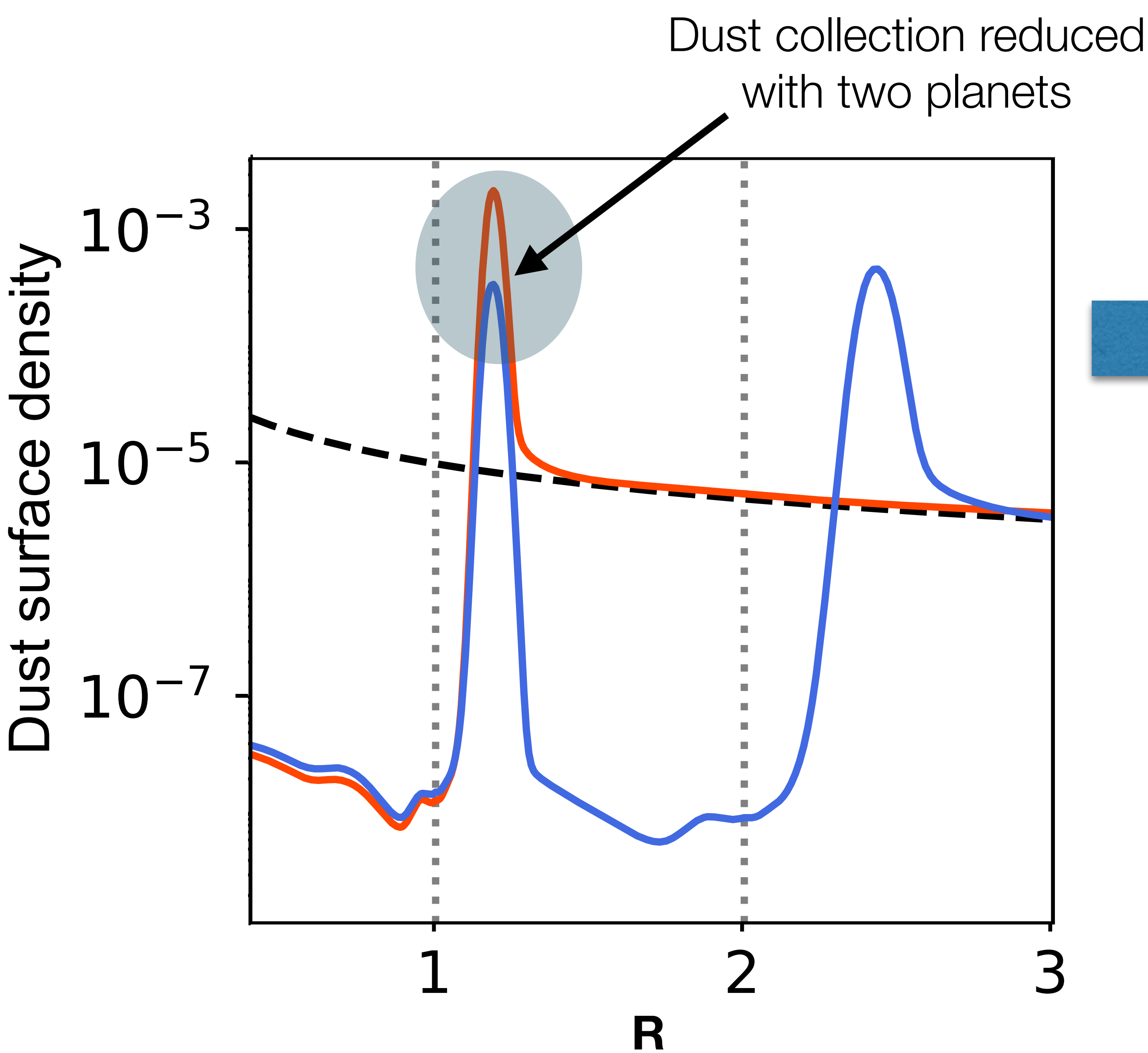
CBPs discovered by PLATO will confirm or contradict this finding

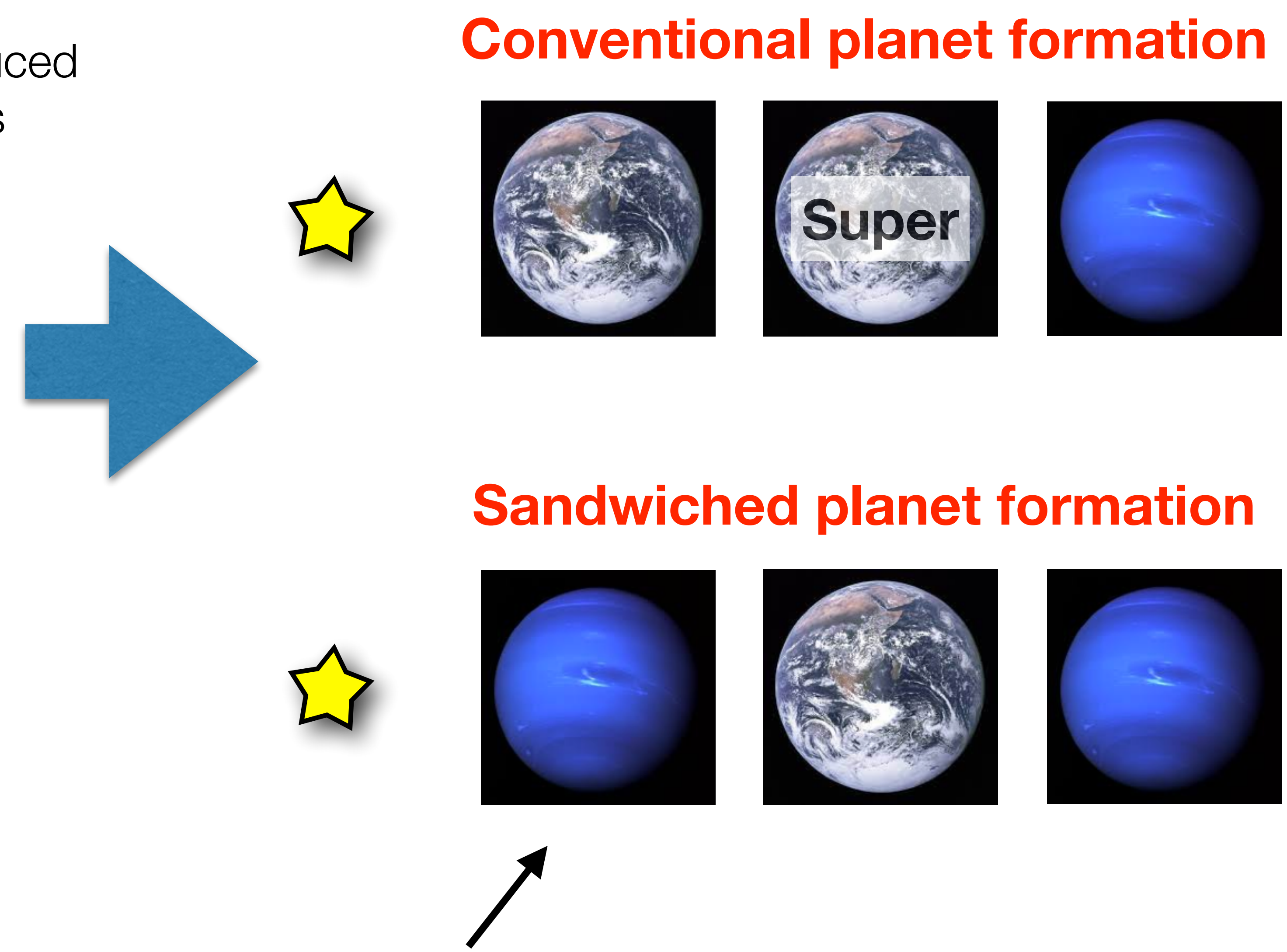
- demonstrating that either migration or in situ formation is important



Can PLATO observe more “sandwiched planet” systems?

Simulations of dust flow in the presence of one and two planets



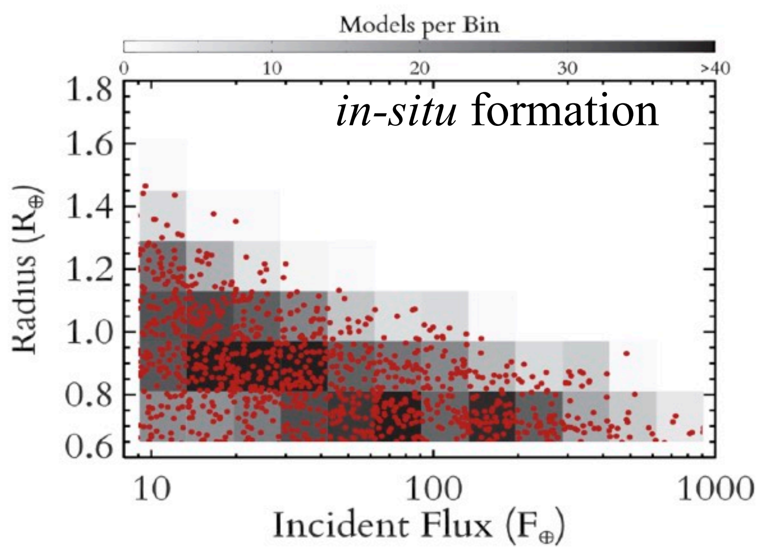


The sandwiched architecture is already seen in observations

Red = single planet simulation
Blue = two planet simulation

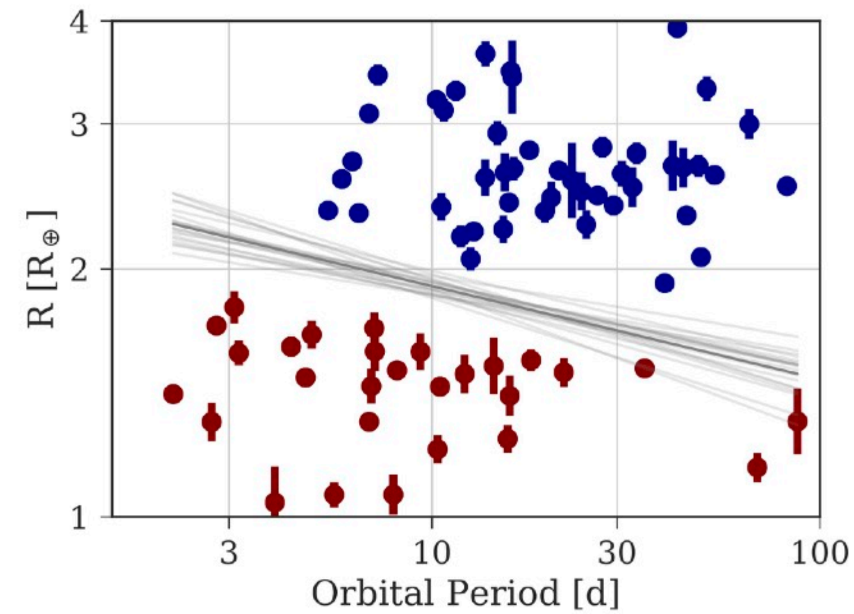
Pritchard, Meru et al submitted

Understanding the radius gap



Lopez & Rice 2018

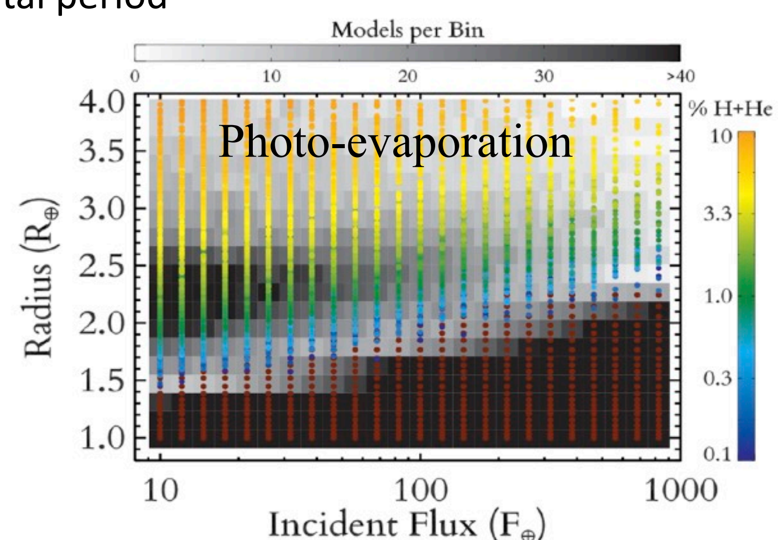
Orbital period



Van Eylen et al. 2018

Radial size distribution depends on origin.

- Born rocky – planet radius increases with orbital period.
- Photo-evaporation – planet radius decreases with orbital period.



Orbital period

- Radius valley consistent with photoevaporation for FGK host stars.
- Origin may differ for M-star hosts (e.g., Cloutier et al. 2021).

The inaugural PLATO theory meeting was held in London in September 2014

In September 2024 we will host a PLATO theory meeting to mark this 10th anniversary and to coordinate theory efforts ahead of the launch in 2026… more details to follow…