Searching for Light-Dark Matter with NEWS-G

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University of Warwick Seminar
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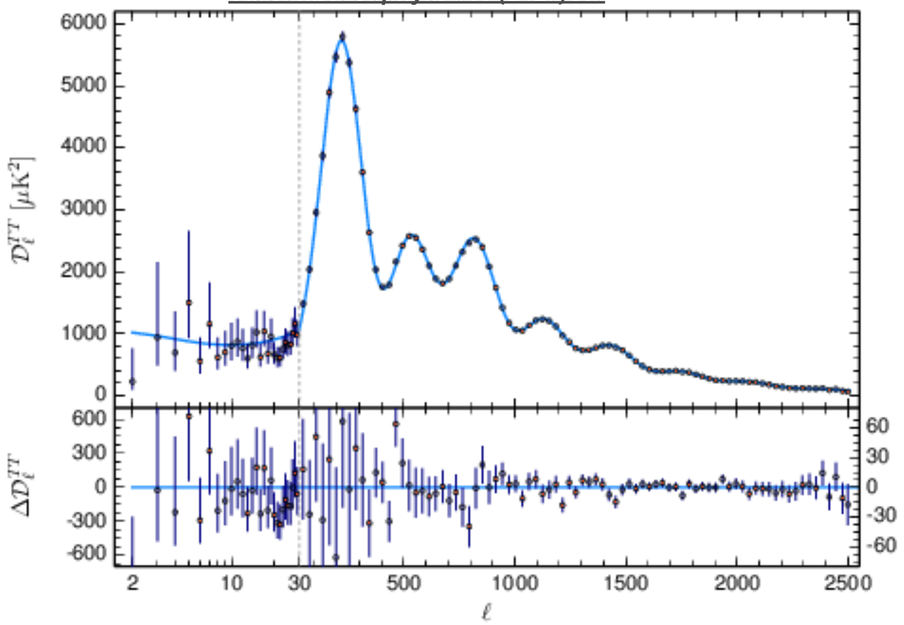
The Dark Matter Puzzle

One of the greatest mysteries of modern physics:

'What makes up 84% of matter?'

➡Leading explanation is **Dark Matter**

Astron.Astrophys. 641 (2020) A6



Cosmic Microwave Background

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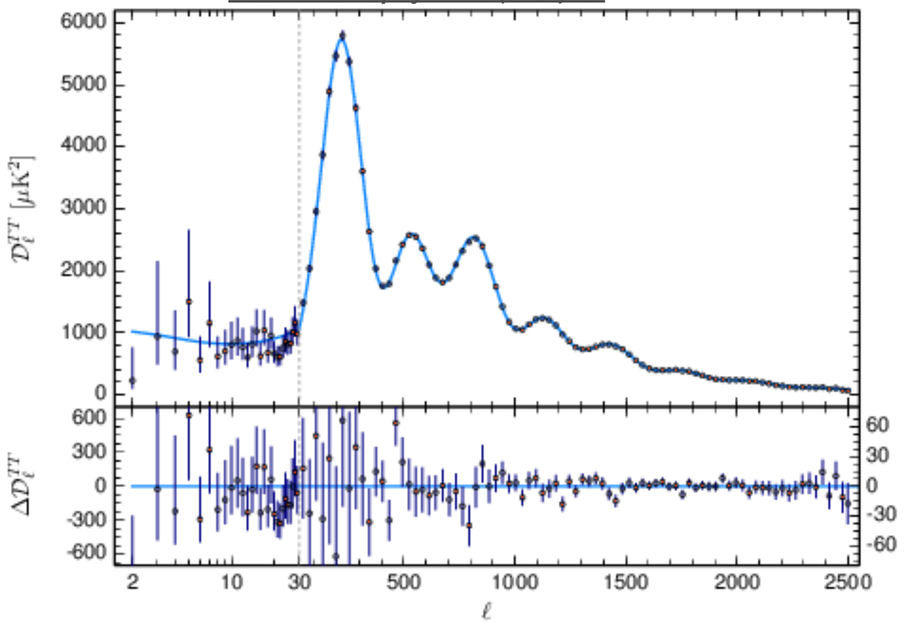

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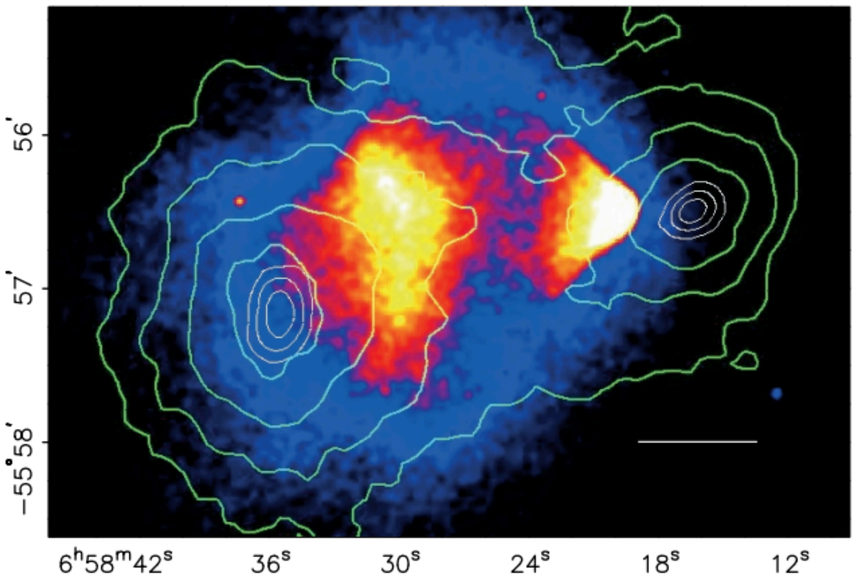
Astrophys.J.Lett. 648 (2006) L109-L113



Gravitational lensing

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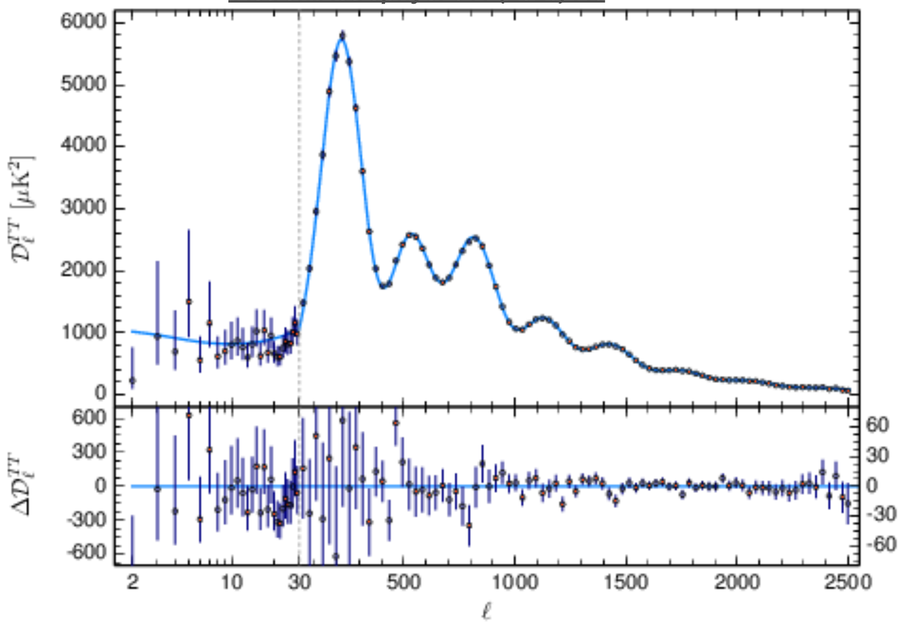

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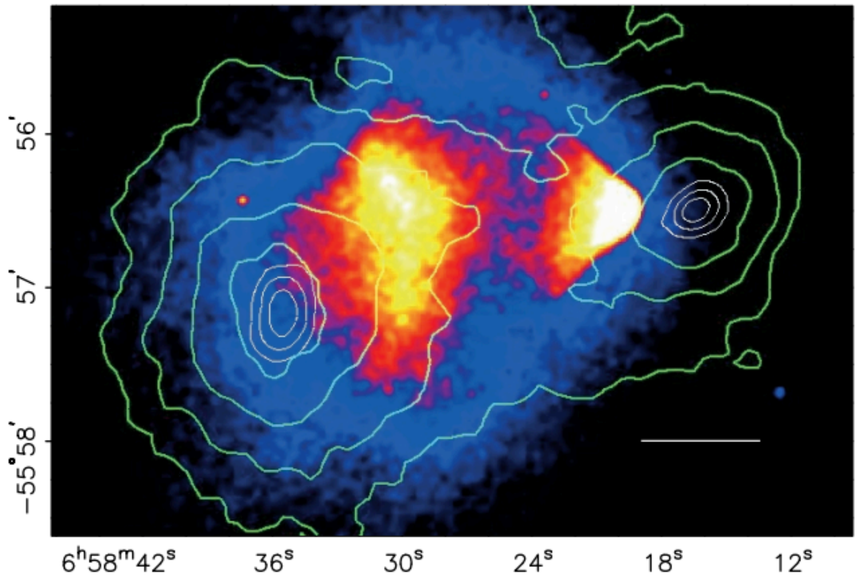

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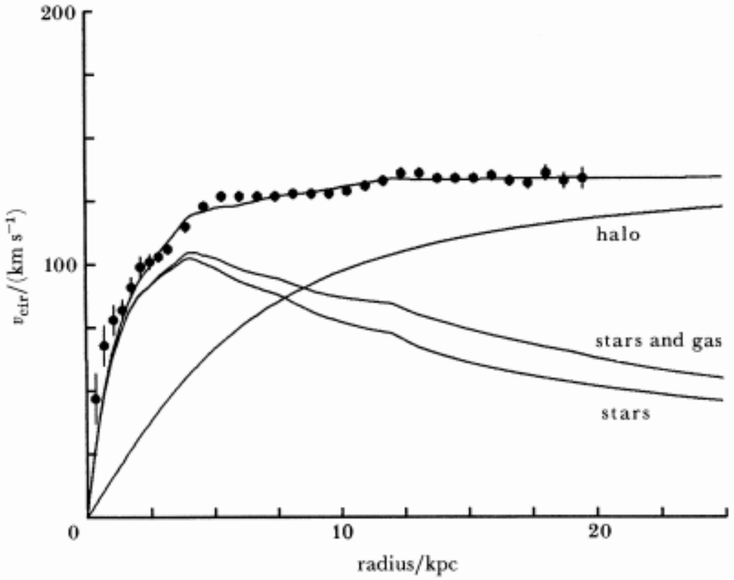

Galactic rotation curves

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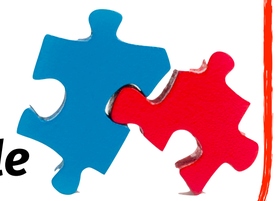
DM properties:

- 'Weakly' interacting
- Non-baryonic
- Electrically neutral
- Non-relativistic
- Long-lived

No known particle solves the puzzle!



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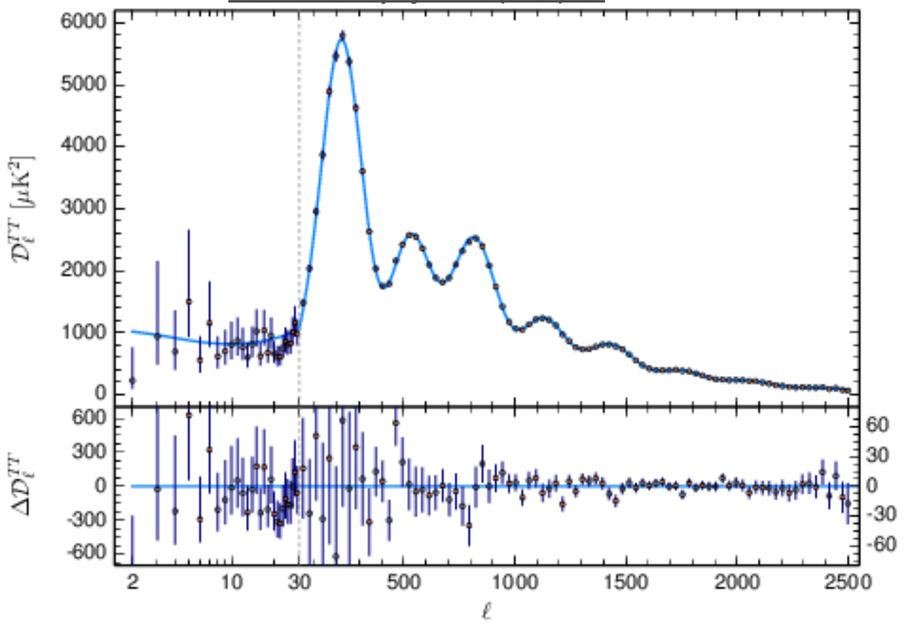

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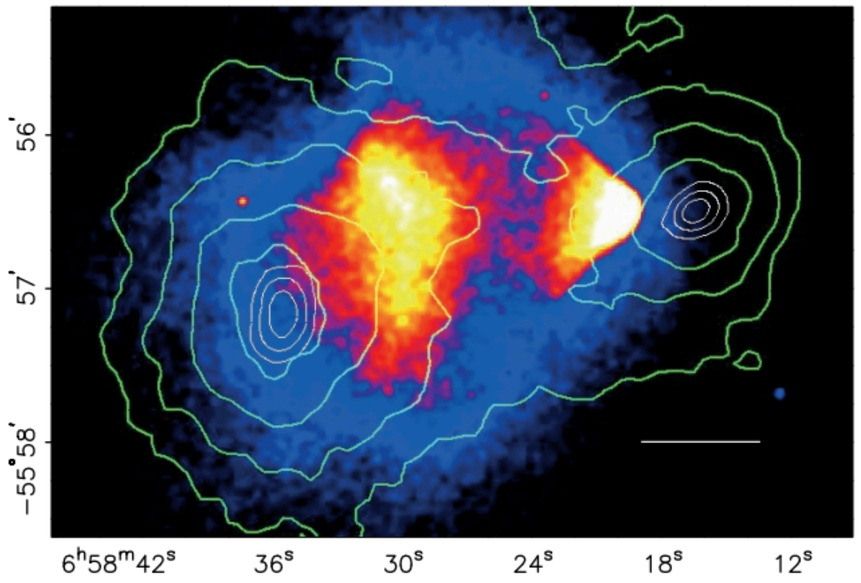

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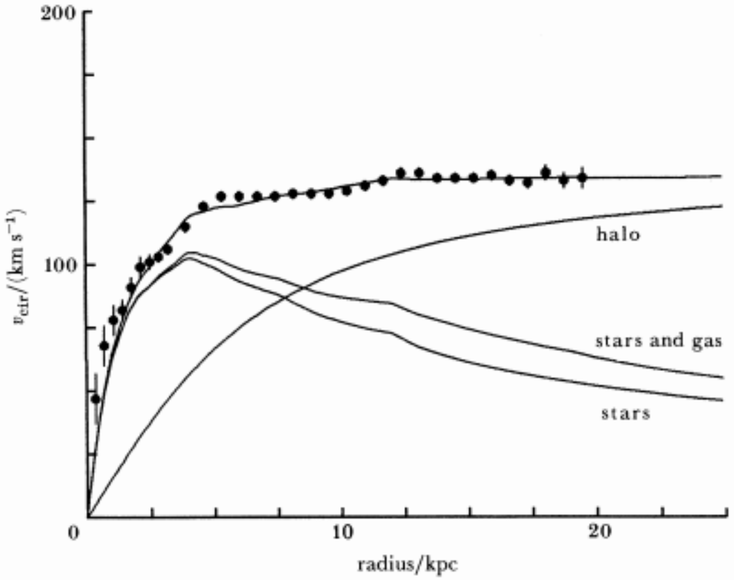

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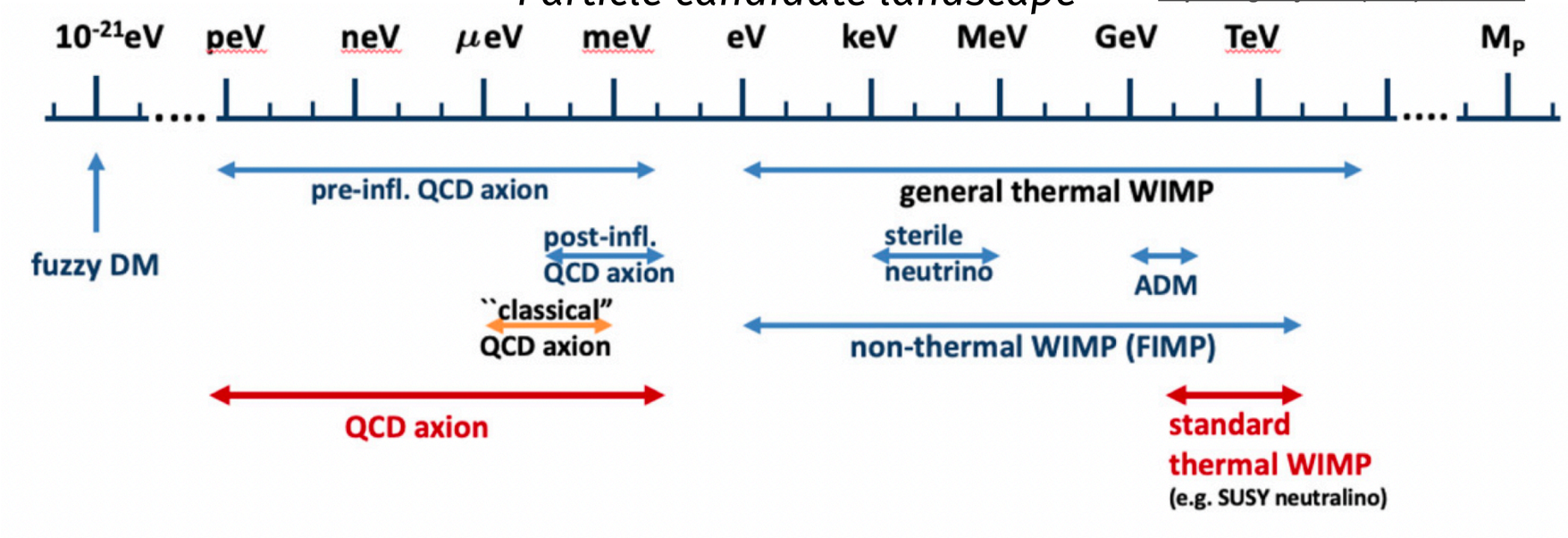
Dark Matter Detection

Particle candidate landscape

Rept.Prog.Phys. 85 (2022) 5, 056201



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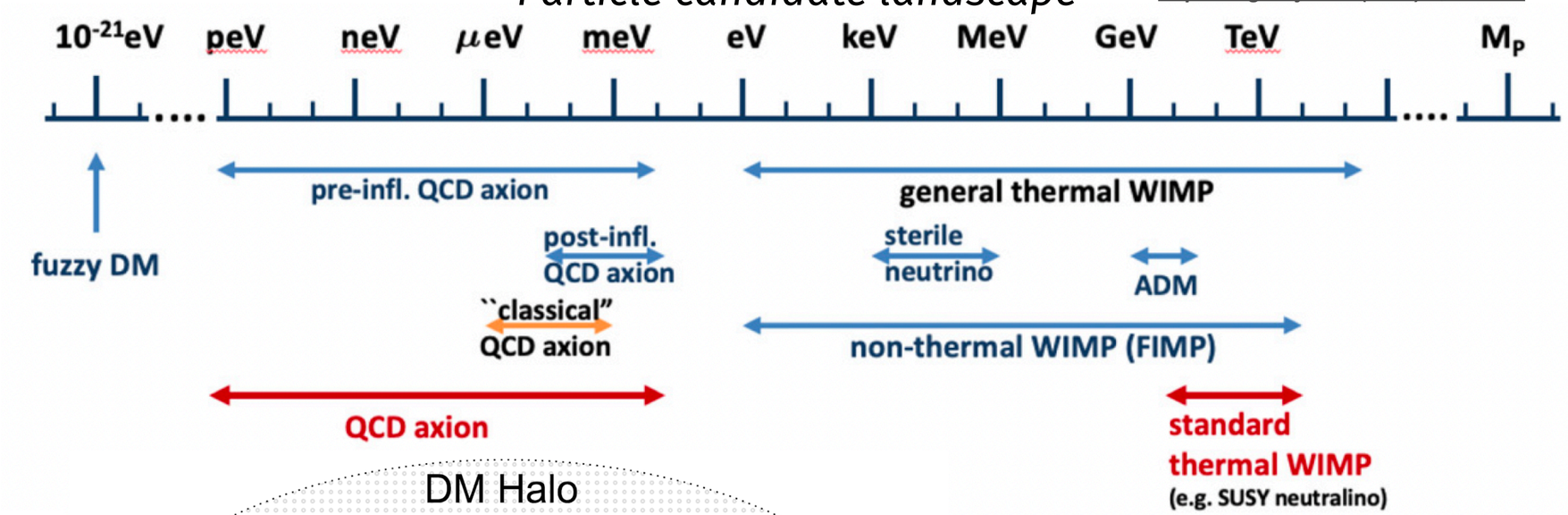

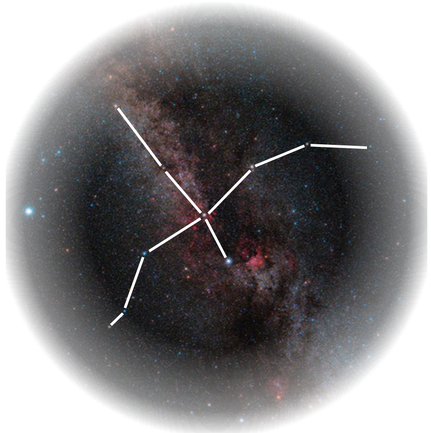

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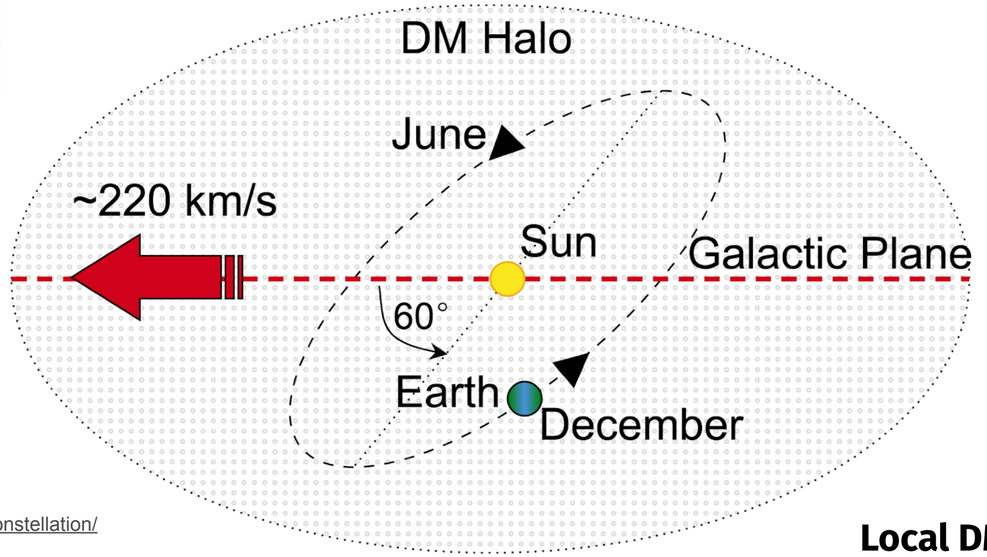

Local DM density, ρ~0.3-0.4 GeV cm^{-3} J.Phys. G41 (2014) 063101

Local flux φ~(10^7/m_χ[GeV]) cm^{-2} s^{-1} JCAP 1008 (2010) 004

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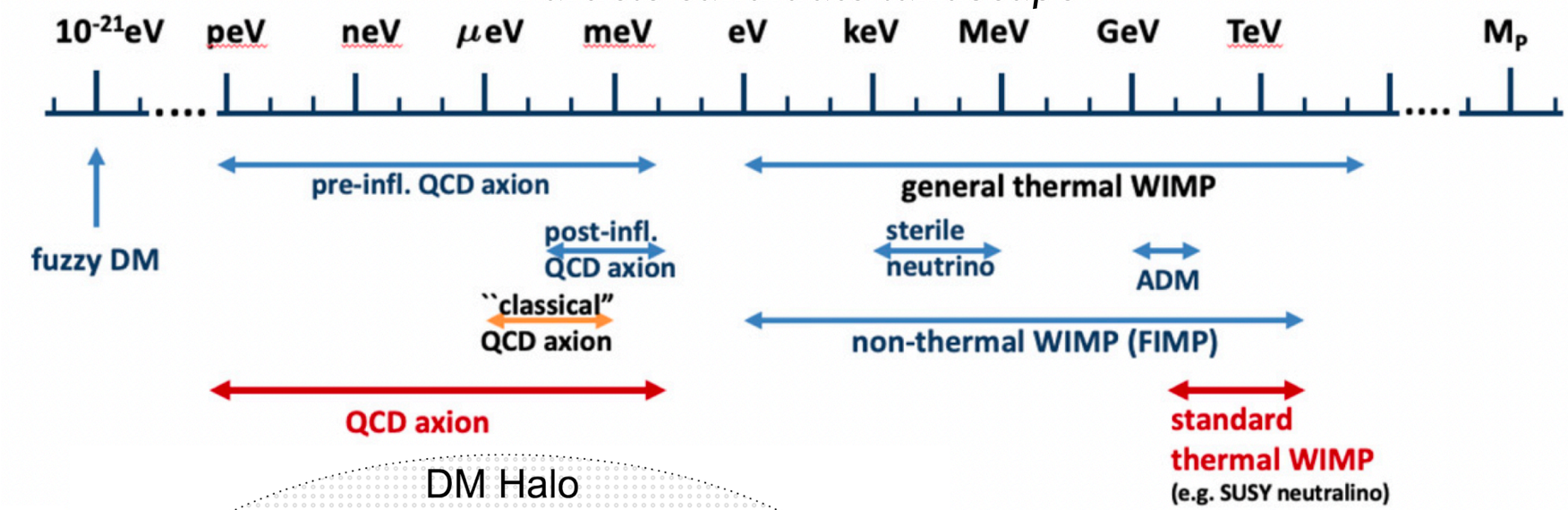

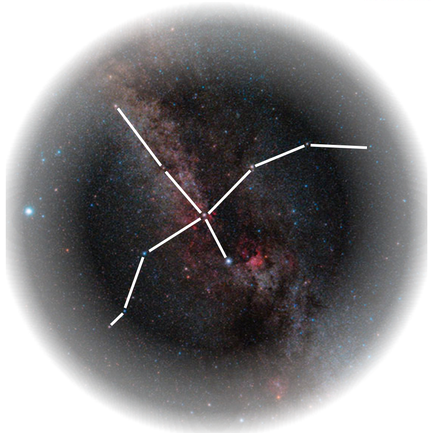

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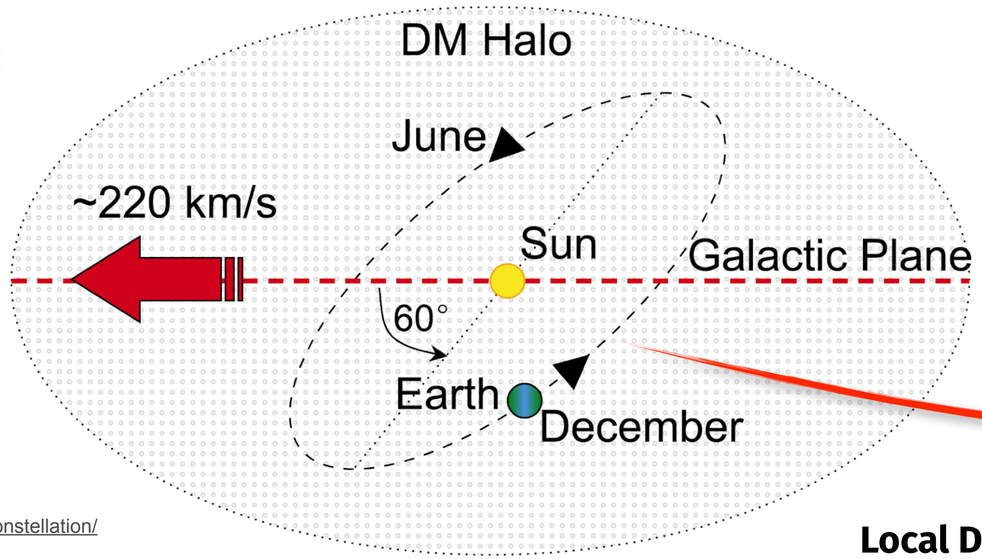

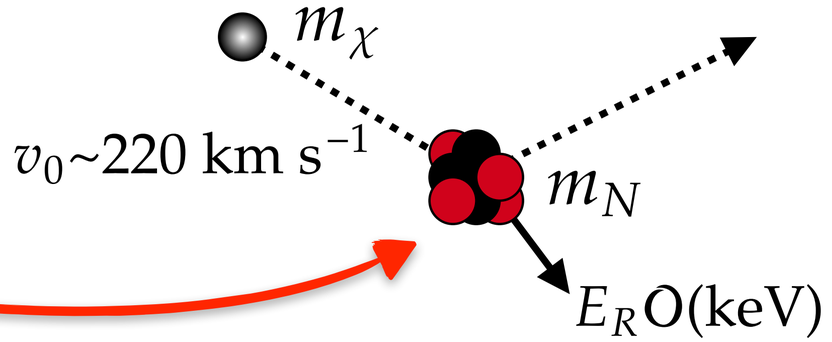

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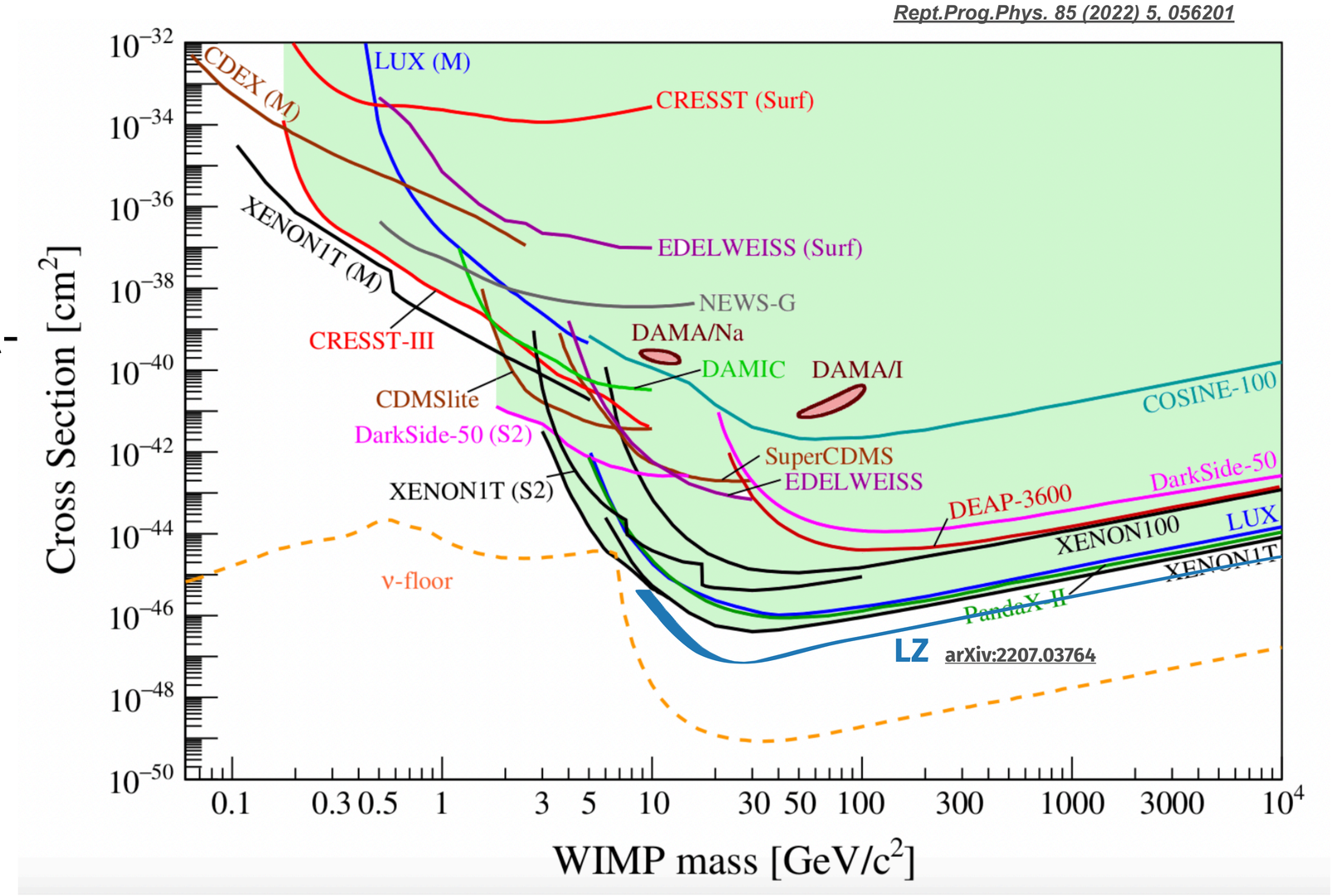
Landscape of Direct DM Searches

- **World-leading sensitivities** from dual-phase **liquid noble gas experiments**
- LZ, XENON-1T, PANDA-X…
- **Lower-masses** less well constrained



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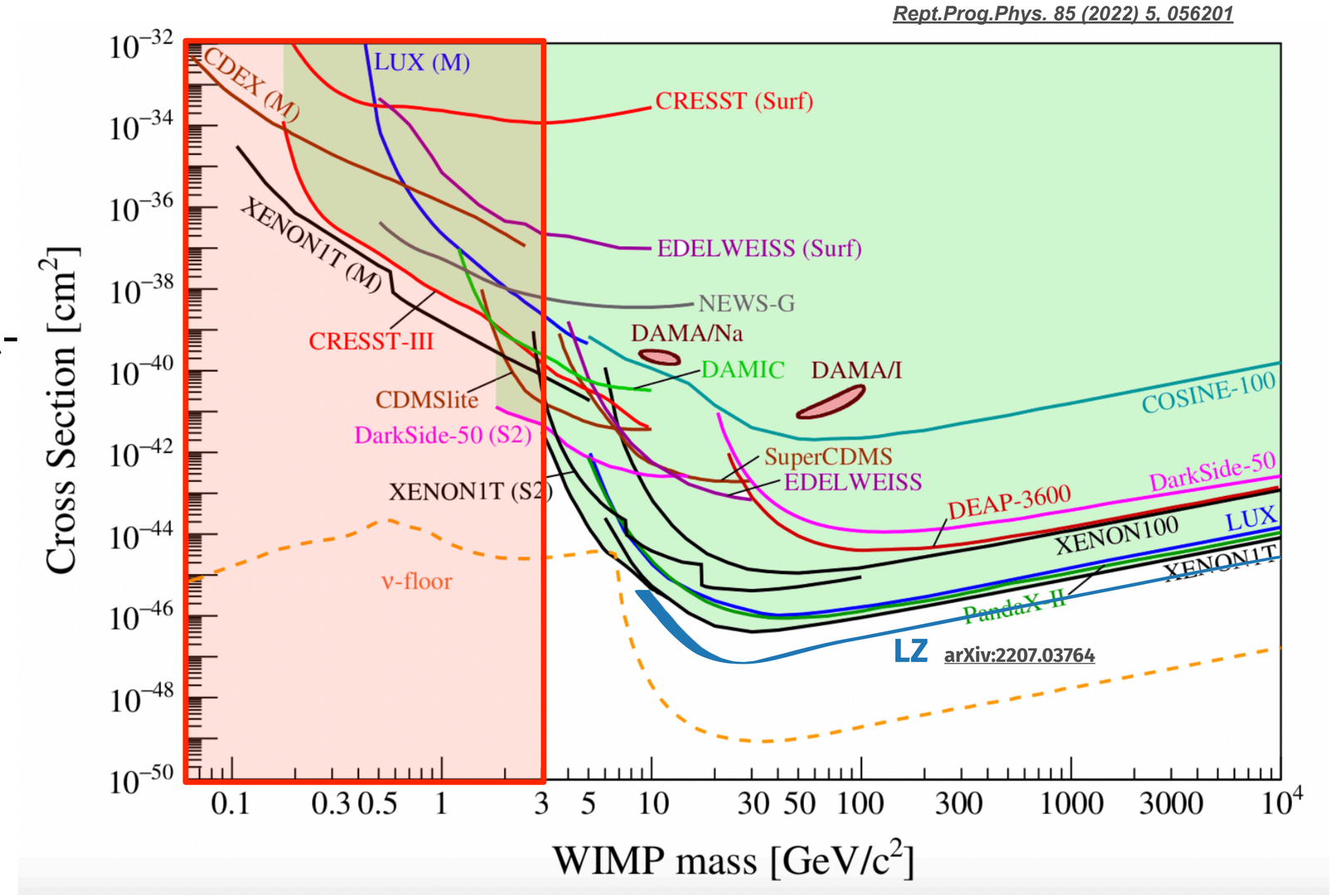
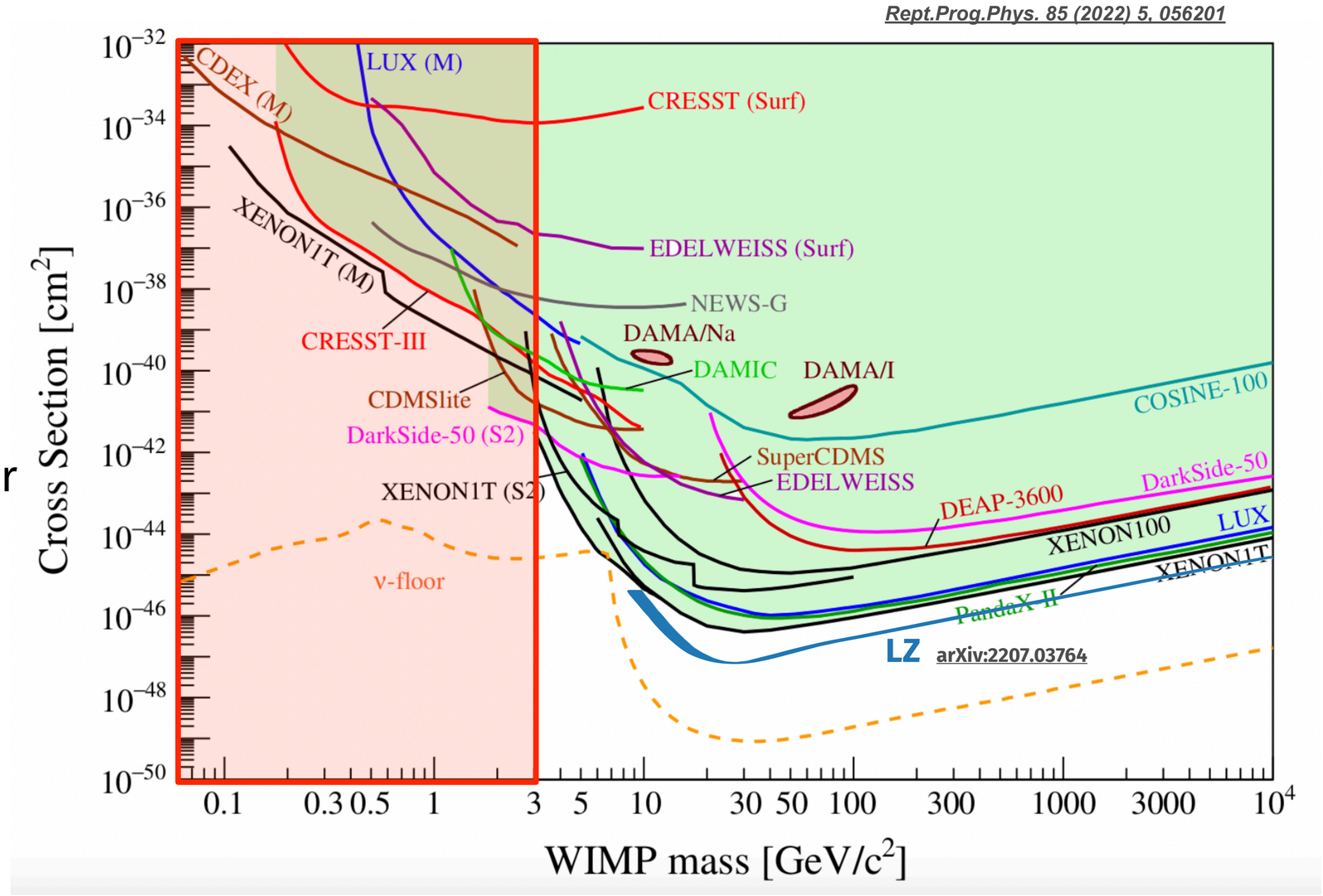


Landscape of Direct DM Searches

- Region has **attracted theoretical** interest
  - ➡Asymmetric DM
  - ➡Dark sectors
- **Exploring light-DM region** with nuclear recoils **requires**:
  - ➡Low energy threshold
  - ➡Low mass nuclei
  - ➡Novel approaches



Exploring Uncharted Territory

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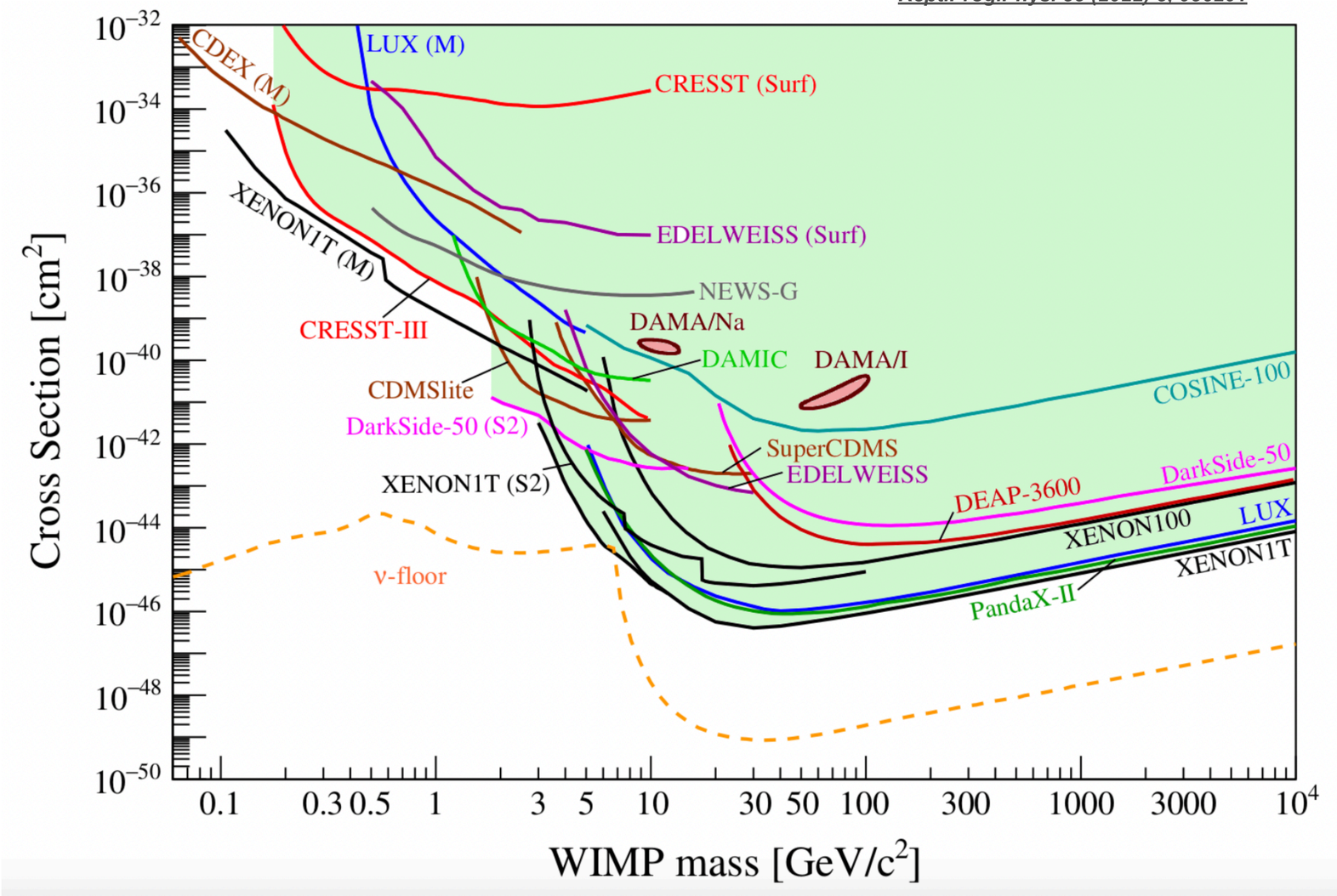

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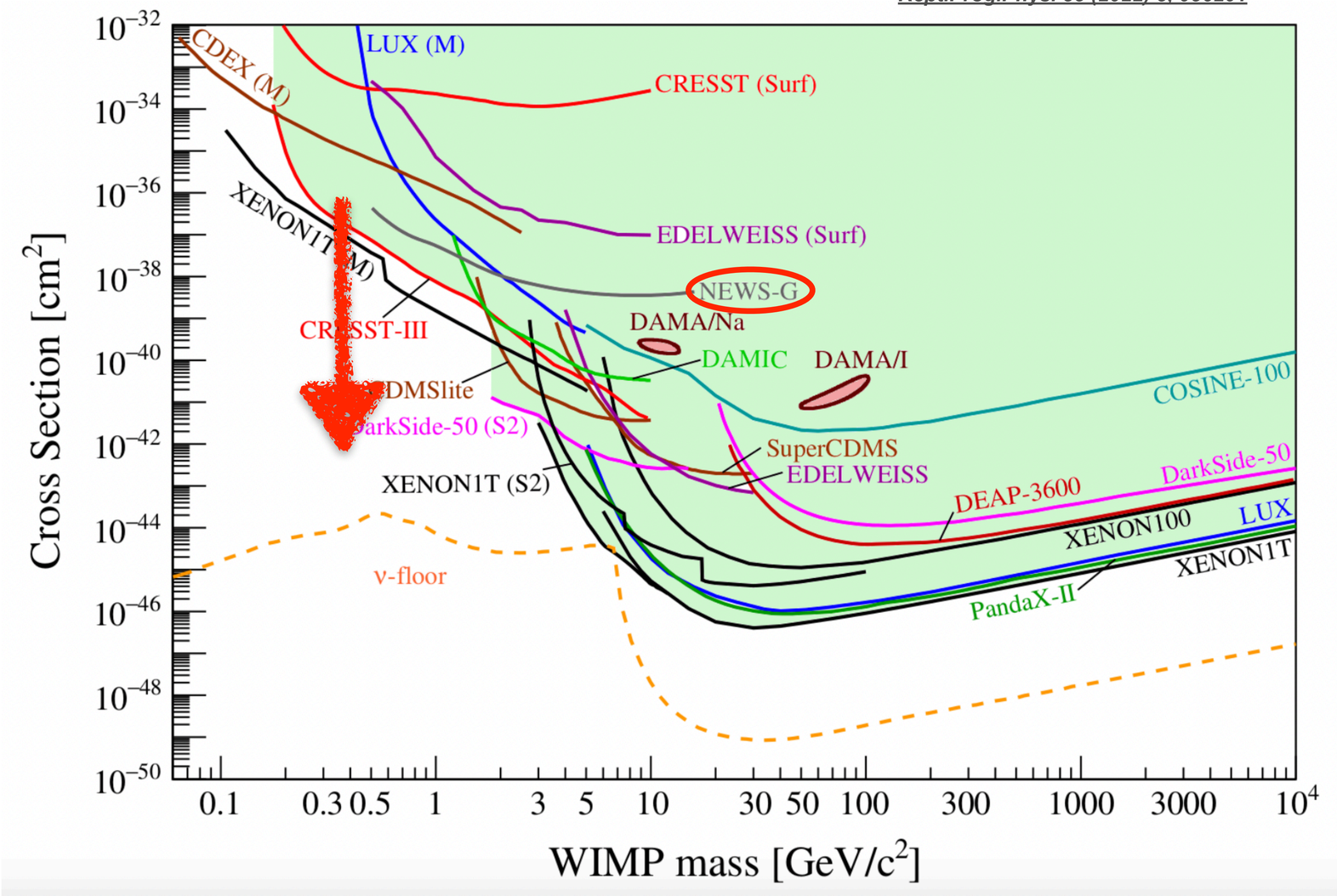
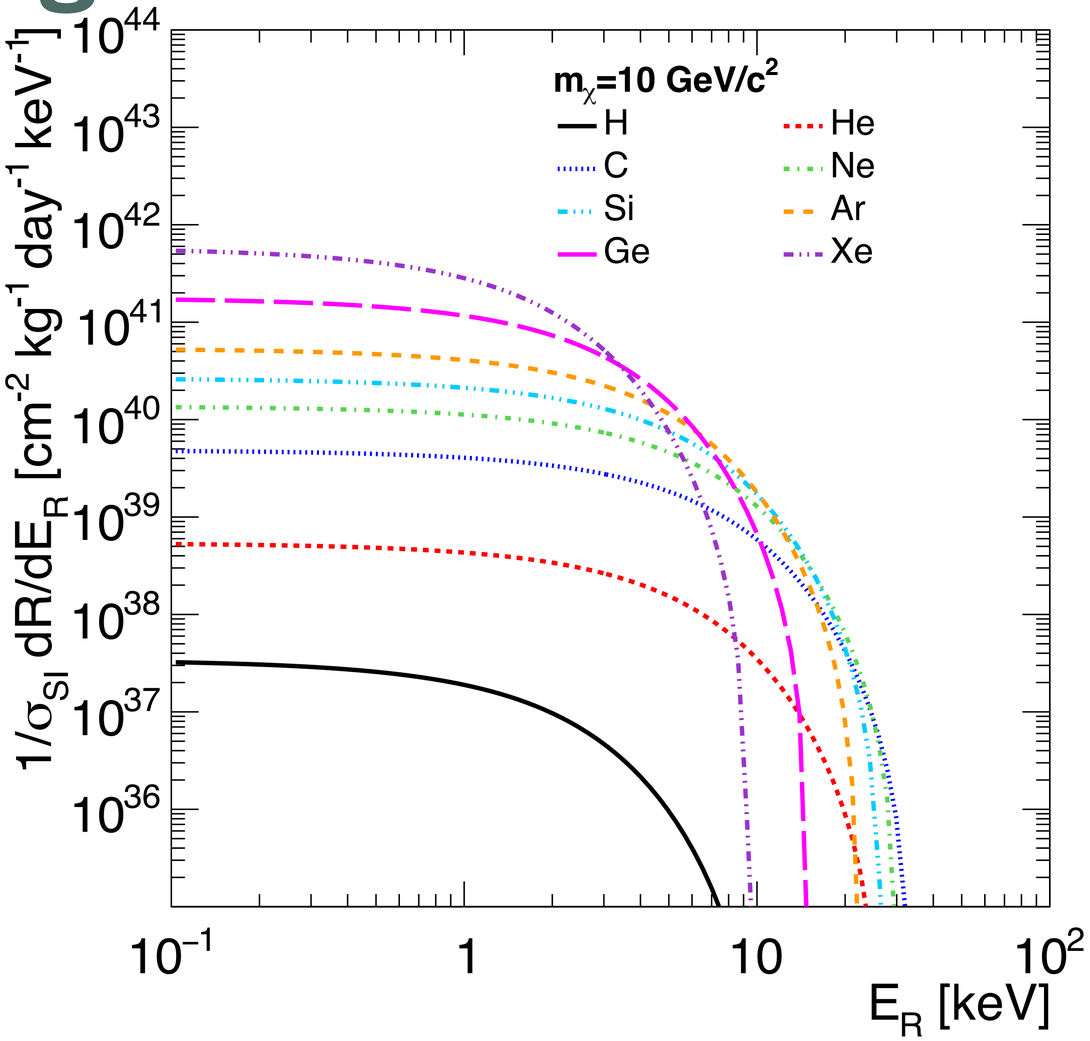


NEWS-G

Light DM searches with a novel gaseous detector, the spherical proportional counter

Light Dark Matter Detection - Kinematics



- **Kinematic matching**: **low-mass targets** are **favourable for light-DM** detection by nuclear recoils
- Require low energy thresholds to see recoil energy

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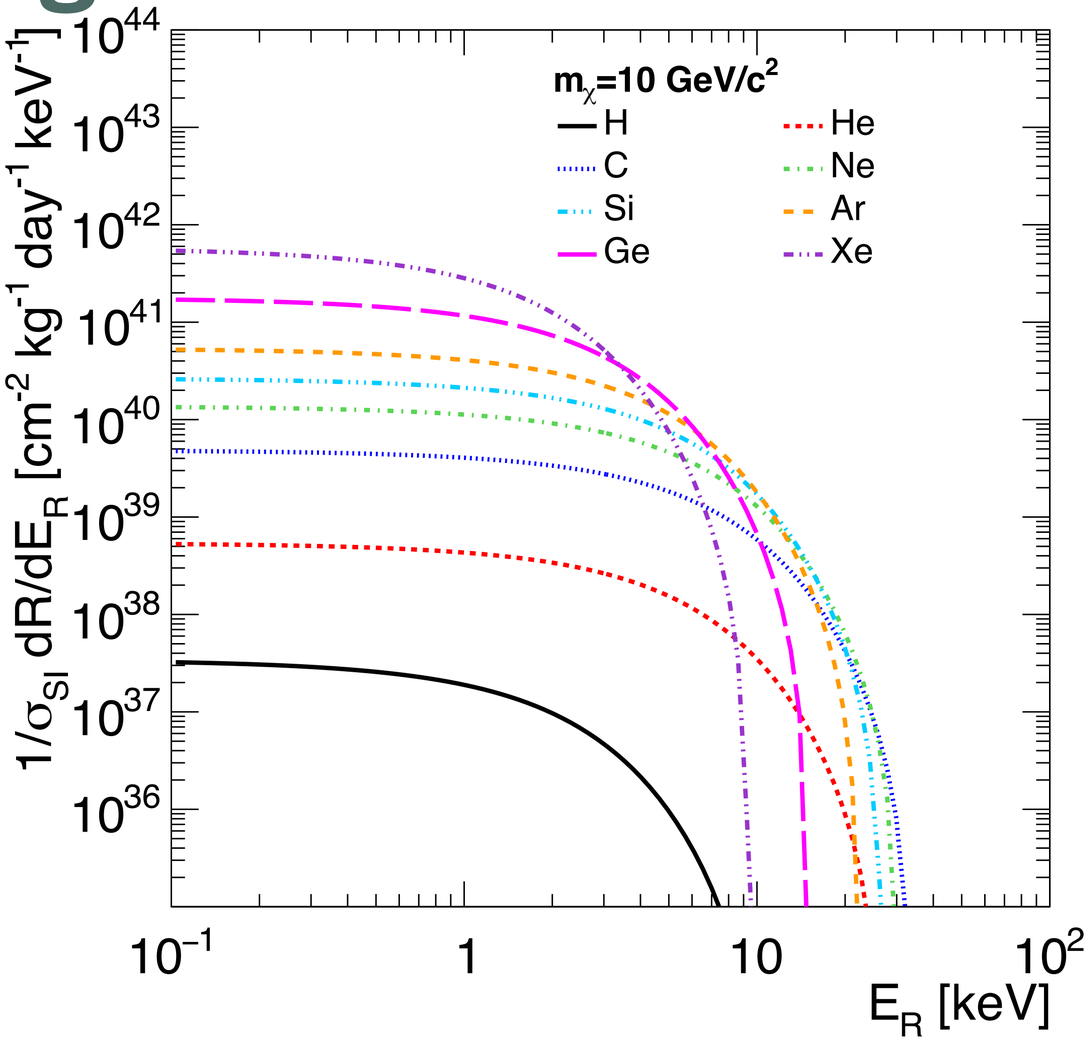

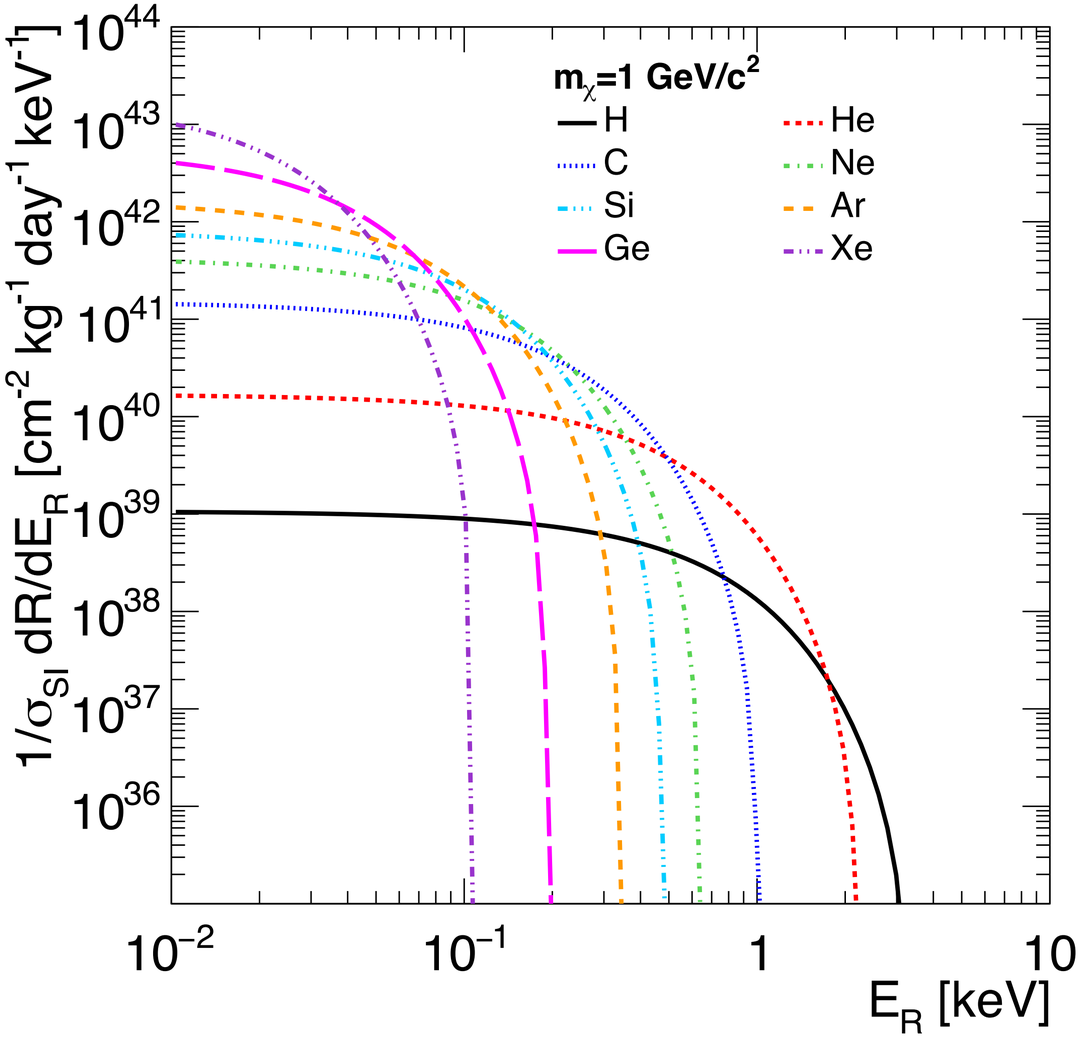

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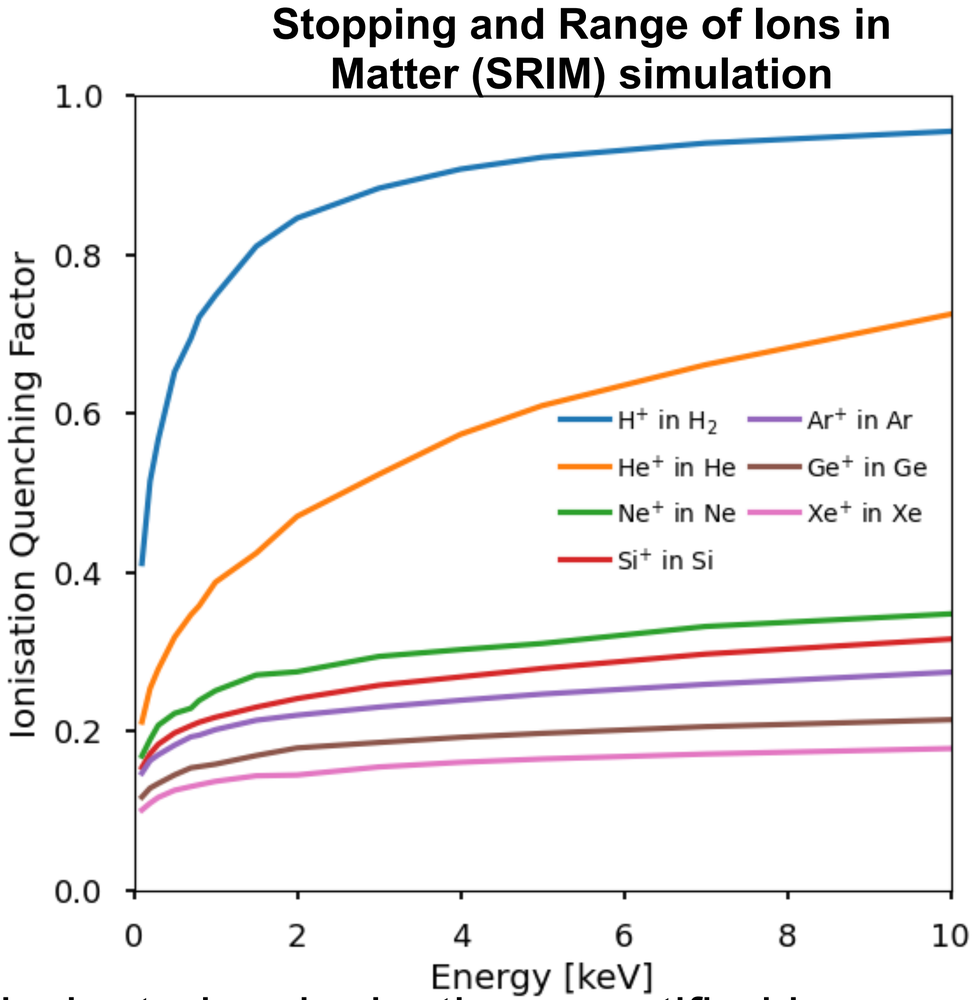
Light Dark Matter Detection - Quenching Factor

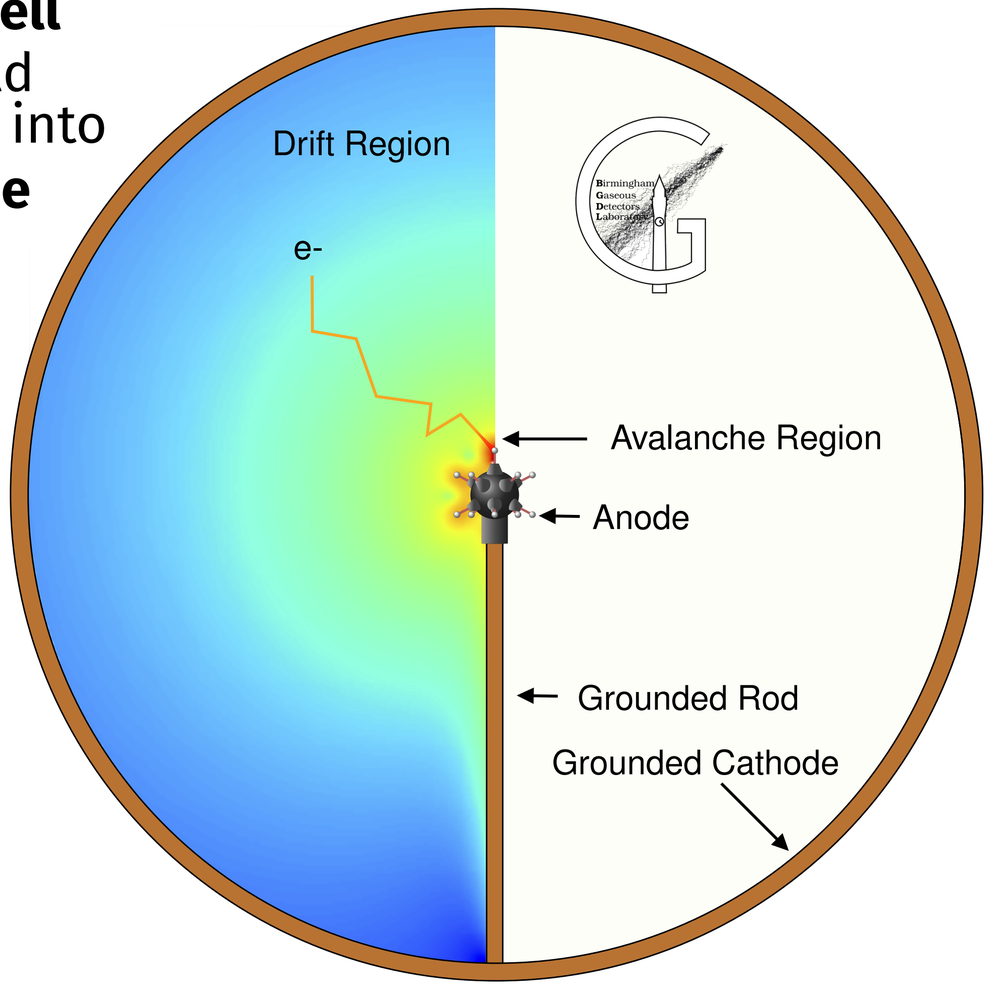


- Portion of deposited energy dissipated as ionisation quantified by quenching factor
- **Light targets** have **favourable quenching factors**
  - Greater fraction of energy deposited by recoil nucleus is visible to detector

Spherical Proportional Counters

The detector:

- **~1 mm anodes** inside **~0.1-1 m radius spherical shell**
- Radial electric field
  - ➡Divides detector into **drift** and **avalanche**



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$$C \approx 4\pi\varepsilon_0 r_a$$

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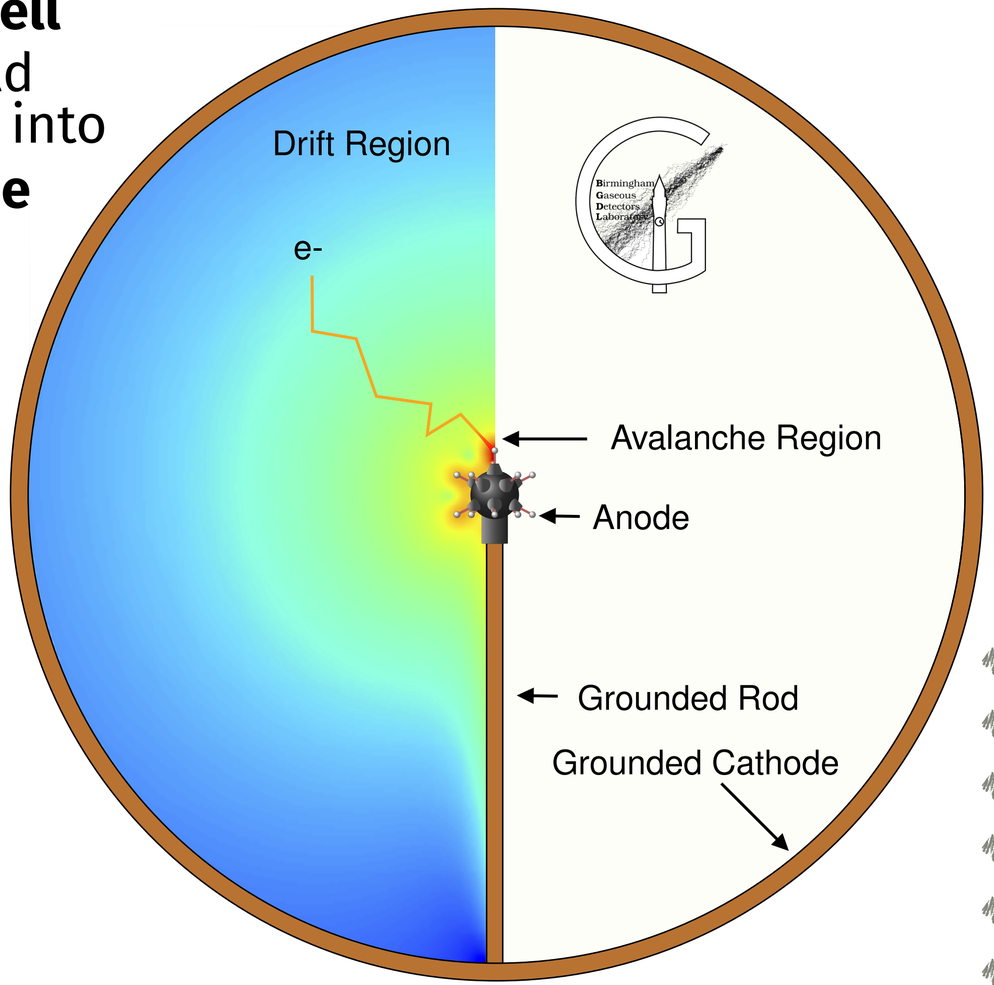

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Strengths in Direct DM Searches:

- **Choice of gas targets and pressures**
- **Low capacitance,** single-electron detection
- **Lowest surface area to volume ratio**
- **Fiducialisation**
- **Simple, few-channel read-out**
- **Radiopure construction**

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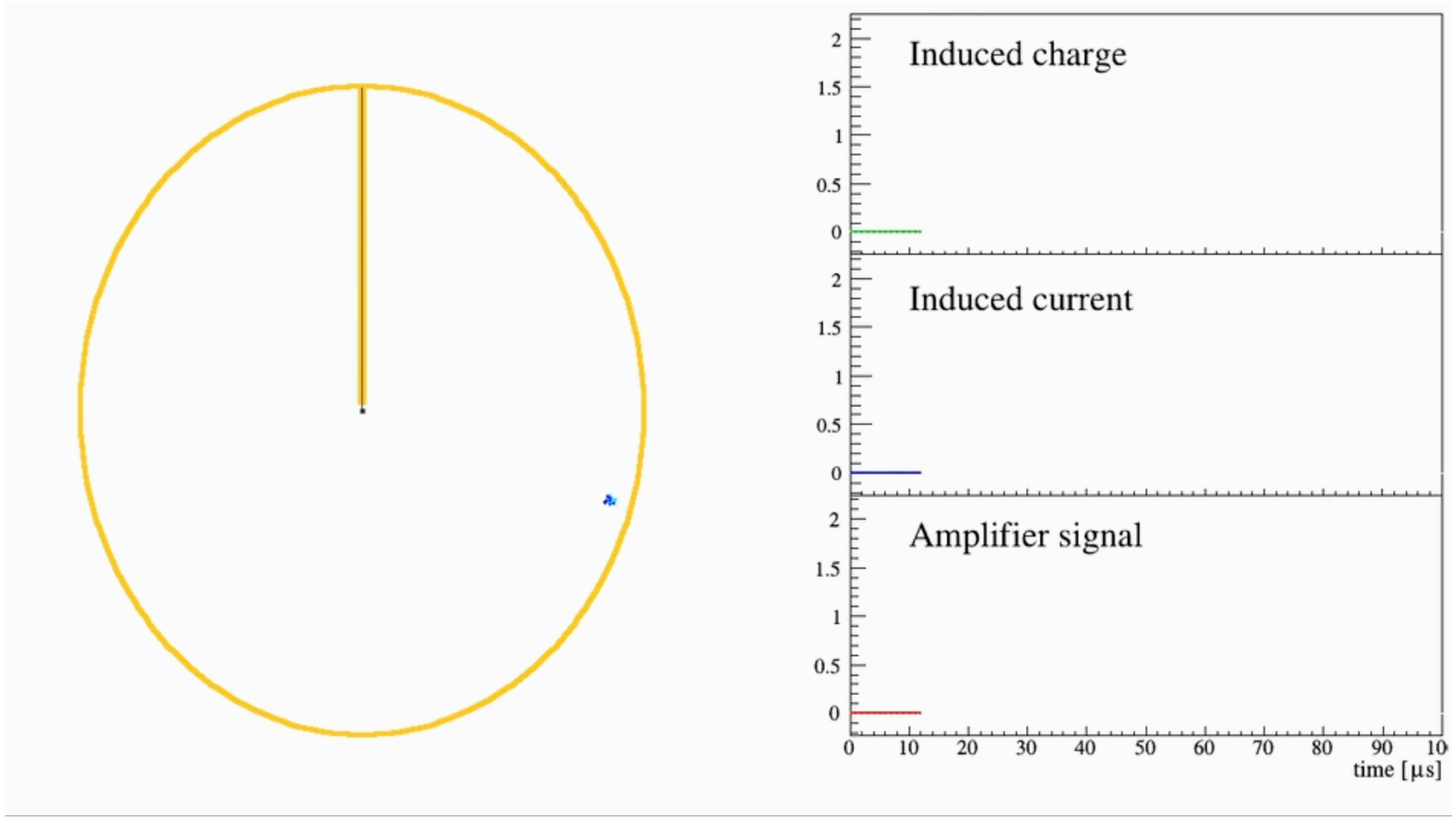

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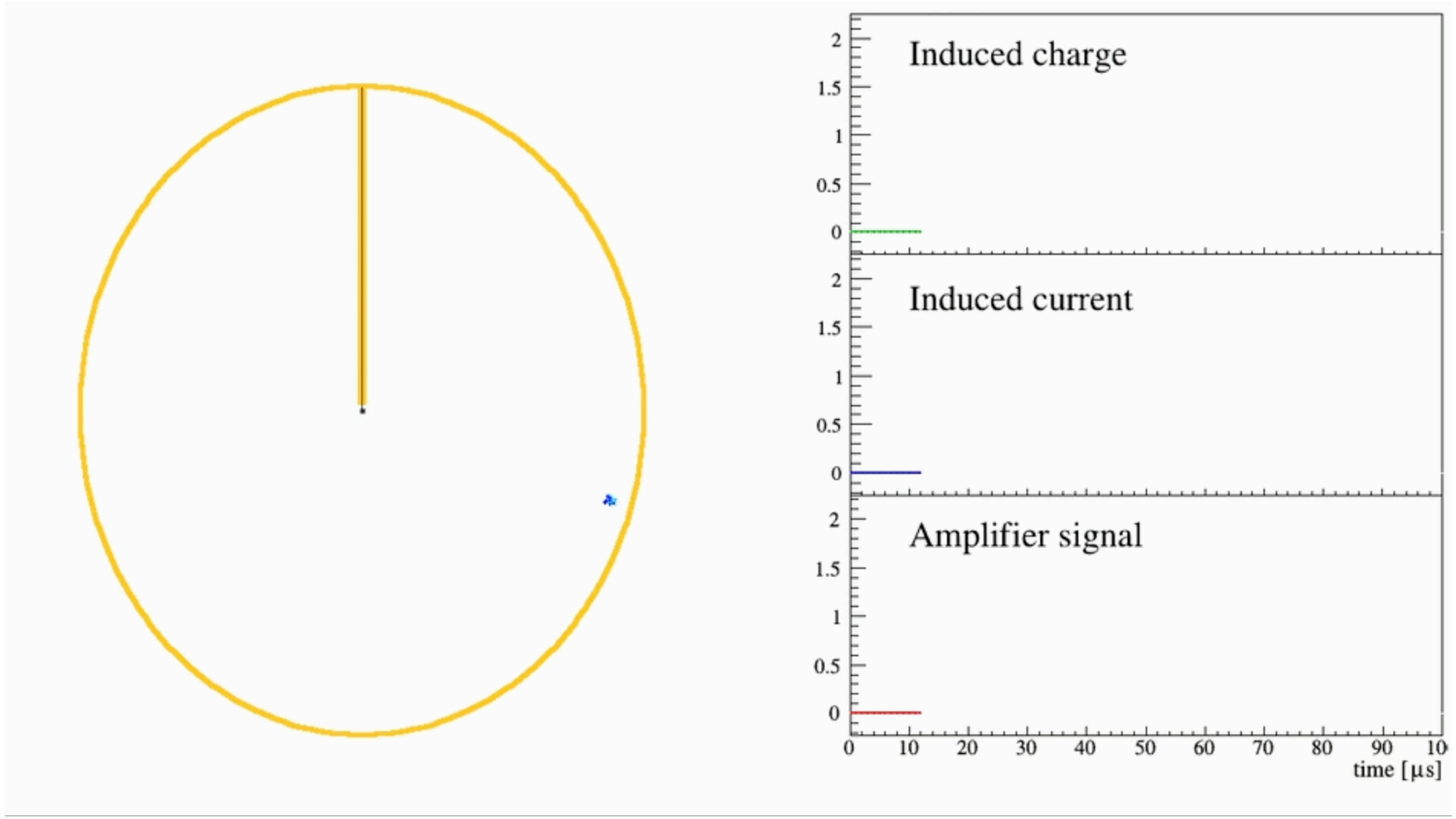
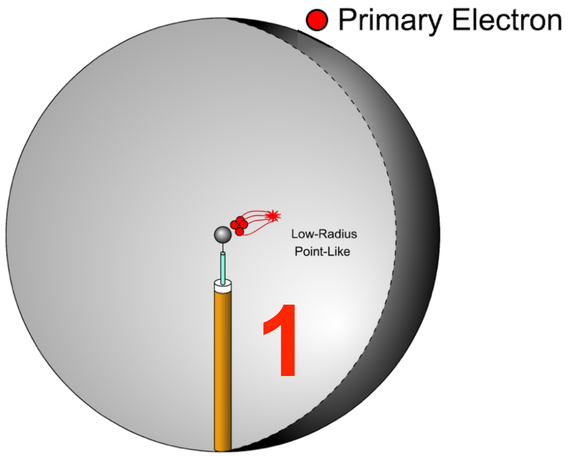
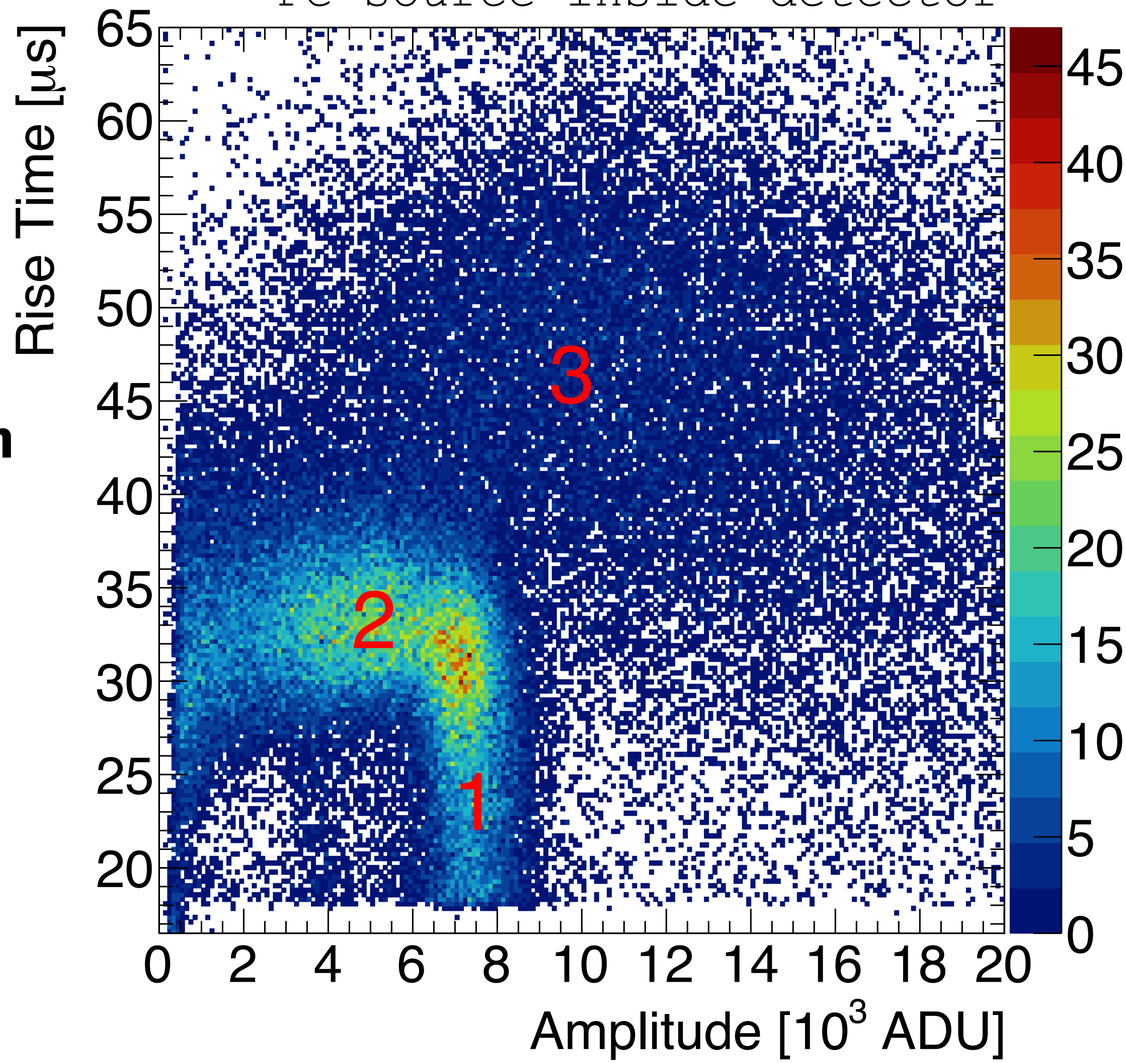


Pulse-Shape Discrimination

- Lots of information in a pulse. e.g. in rise time
- Electron from **larger radii diffuse more**
  - ➡Larger spread in arrival → higher pulse rise time/width
- Spatially extended primary ionisation results in higher rise time/width
- **Fiducialisation/Particle ID by pulse-shape discrimination**





(1) X-rays in volume, (2) X-rays near shell, (3) Cosmic muons

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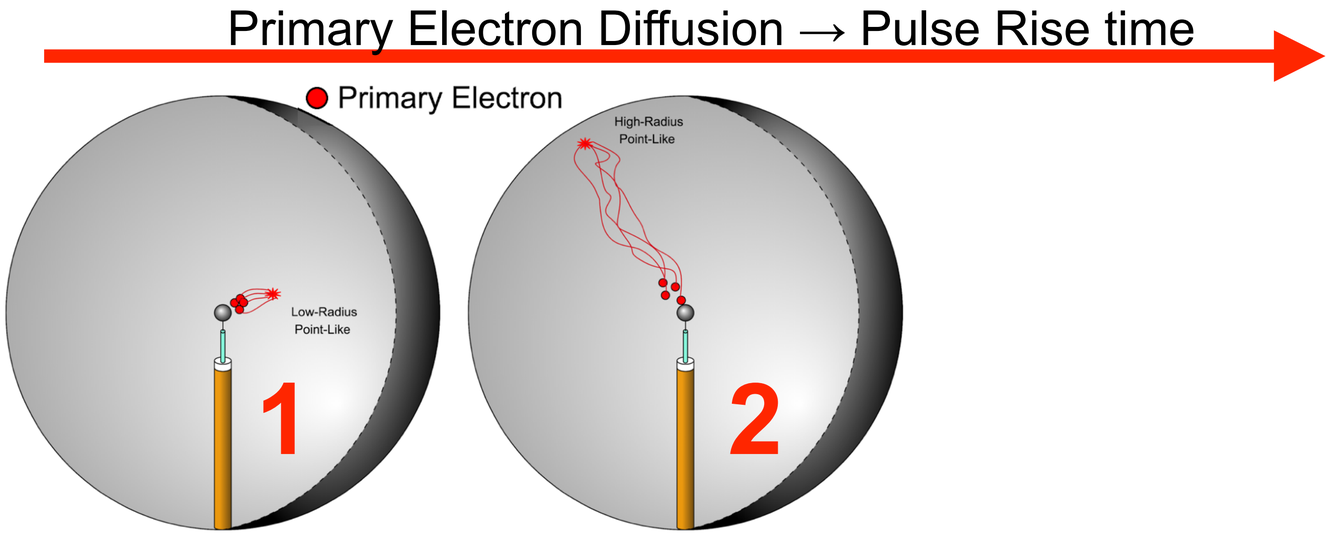

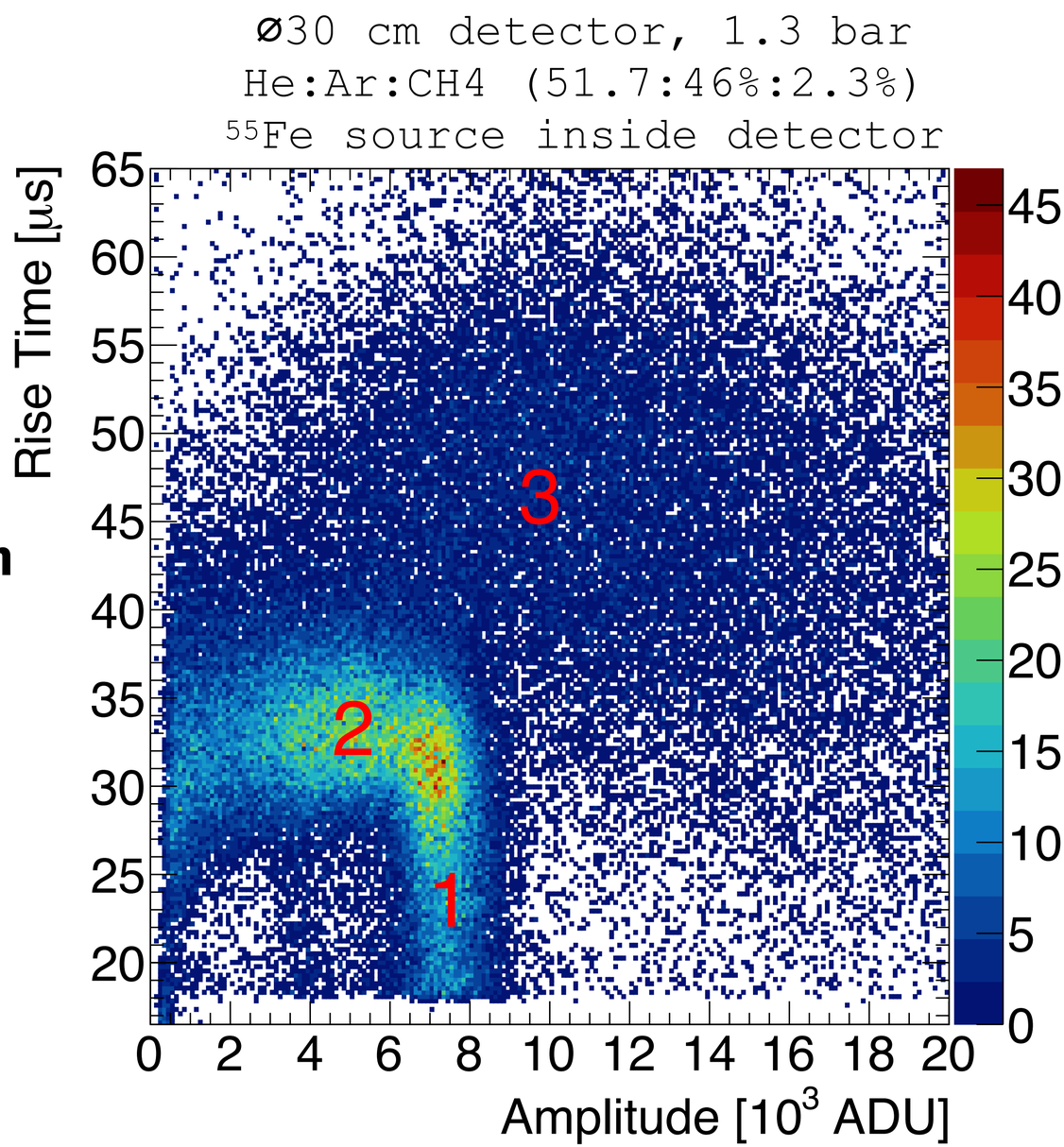

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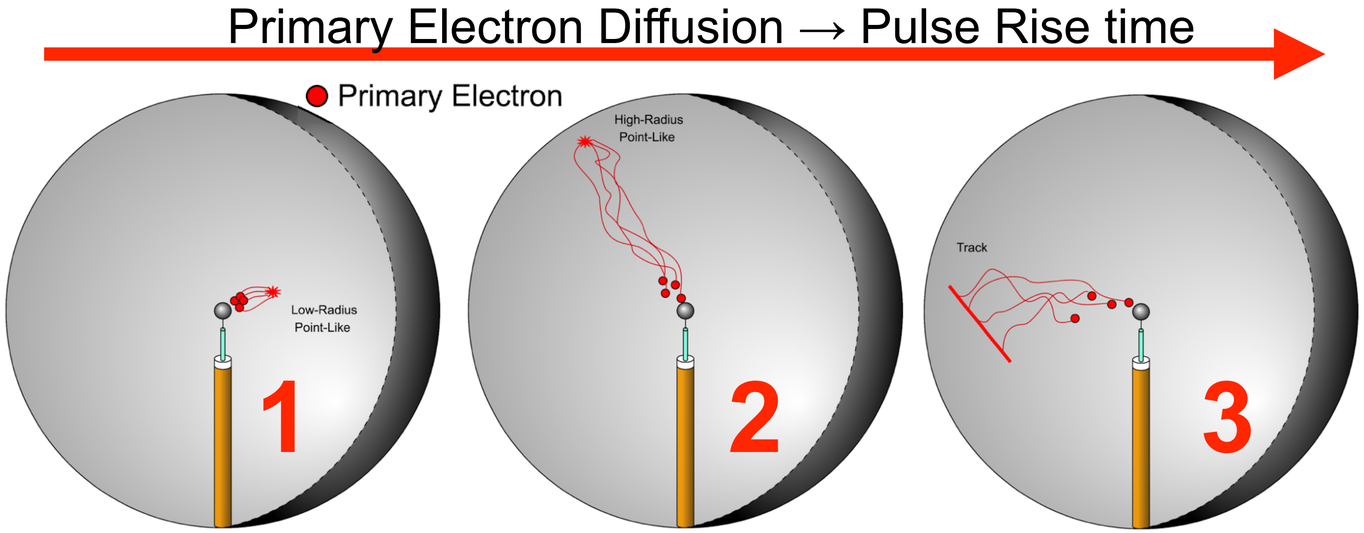

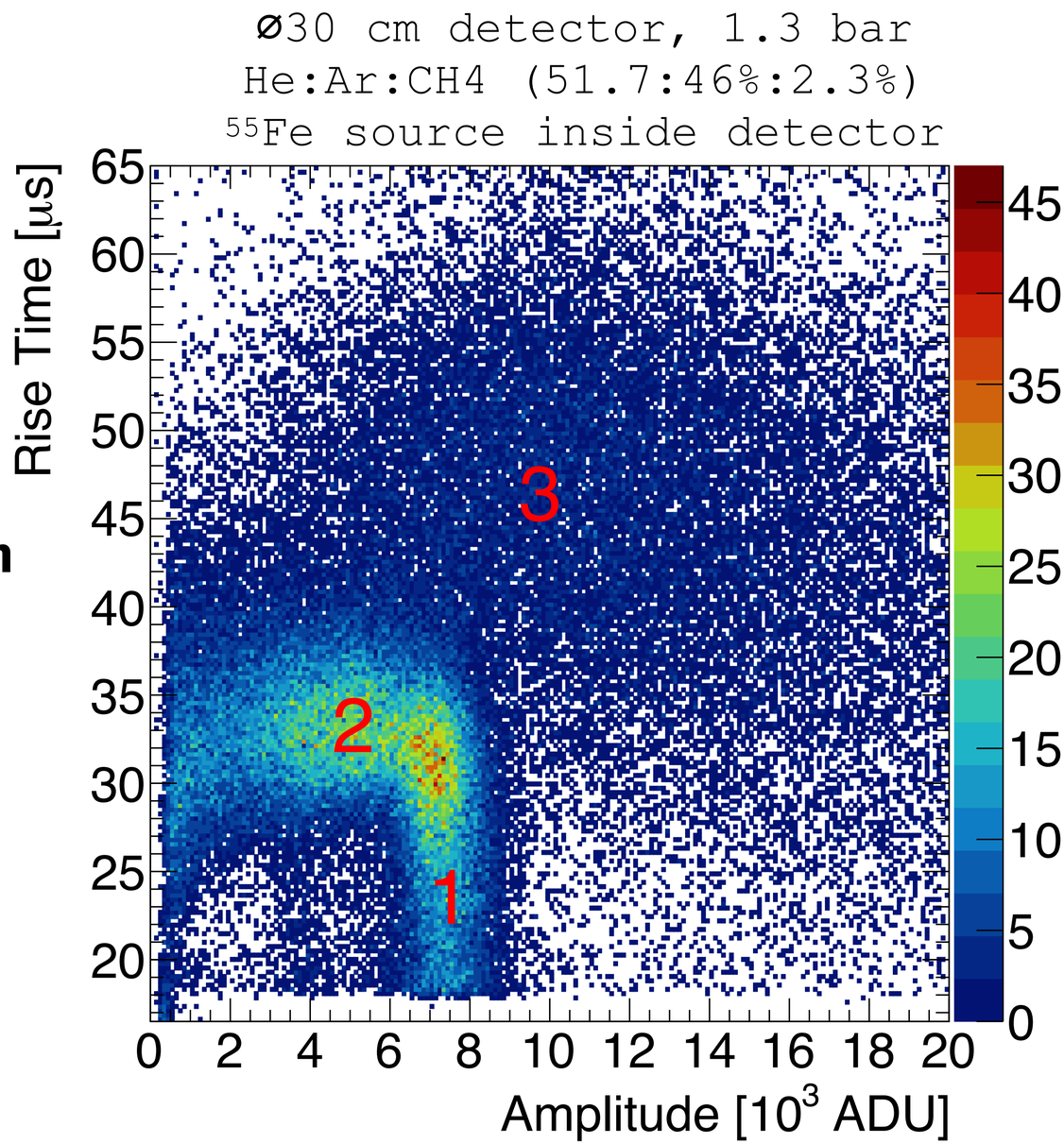

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- First NEWS-G results in 2018: ⌀60 cm prototype in LSM, France
- Ne:CH_4 (99.3%:0.7%) 9.6 kg day exposure
- **Strongest SI limit at time (2017)** on 0.5 GeV candidate
- *More physics with this data?*

Astropart.Phys. 97 (2018) 54-62

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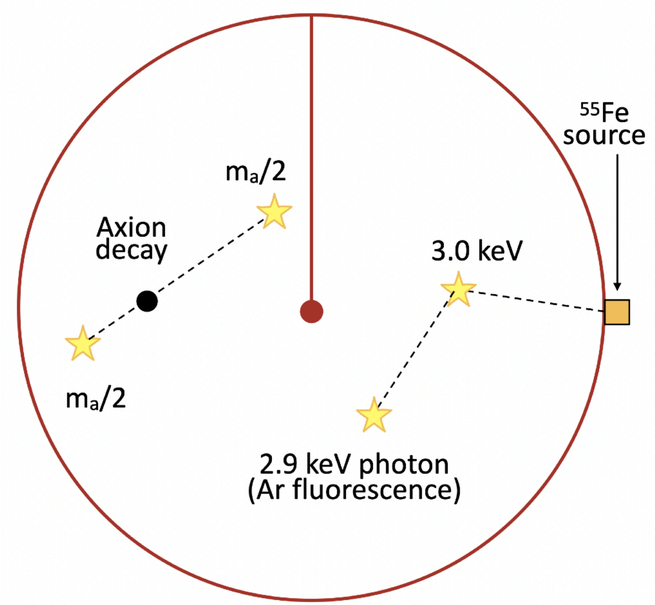

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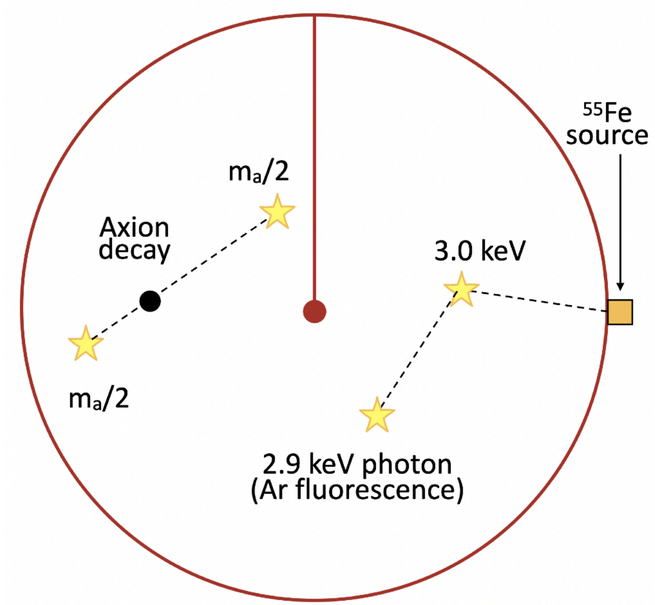

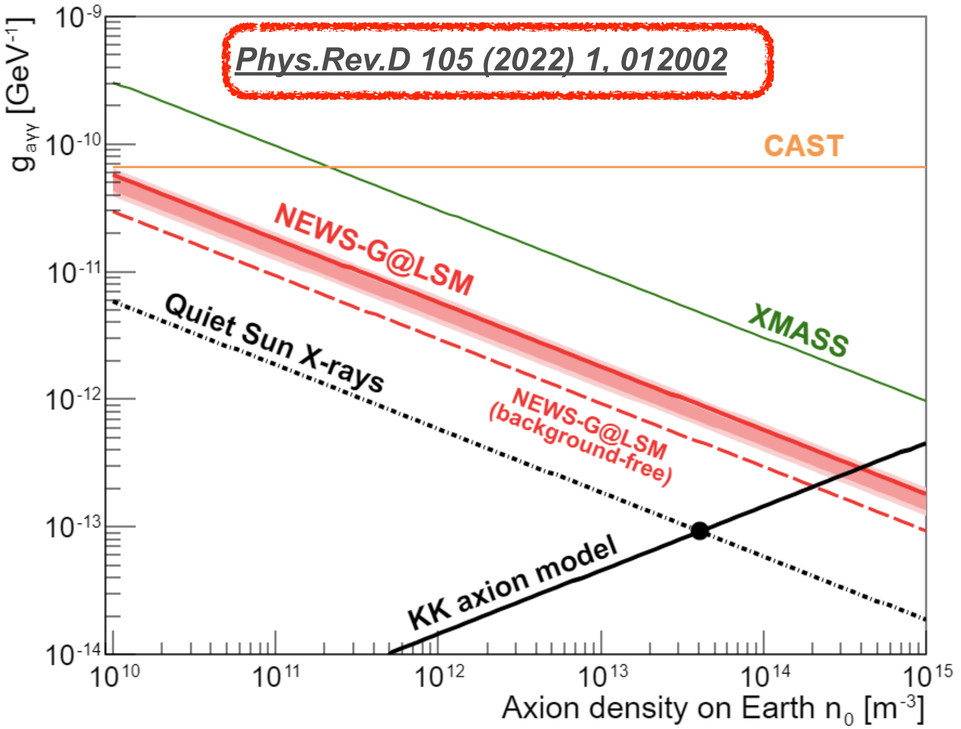

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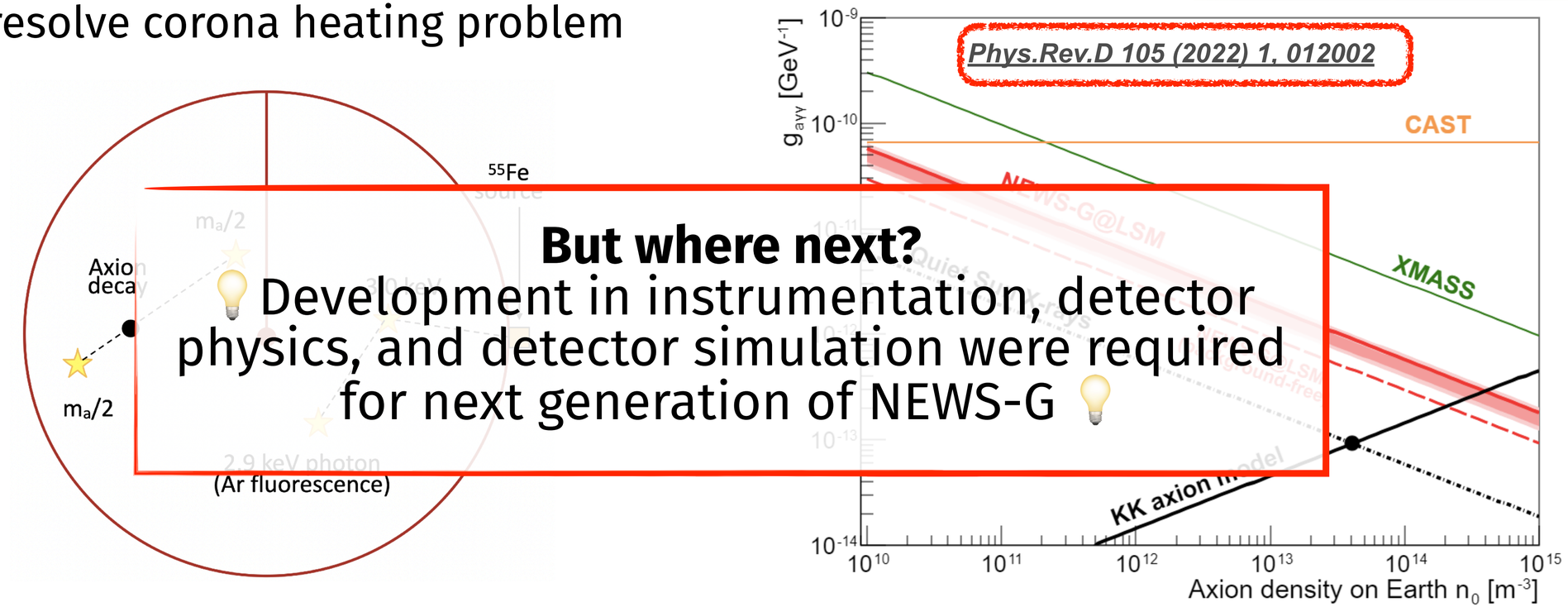


But where next?

💡 Development in instrumentation, detector physics, and detector simulation were required for next generation of NEWS-G 💡

Simulation Framework

- Many packages available for detector simulation:
- **Geant4**: for simulation particle interactions with matter
- **ANSYS**: finite-element methods software for electric field calculations
- **Garfield++**: For simulating electron-ion drift and signal calculations
  - ✓Interfaces with Magboltz, SRIM and HEED
- **Simulation framework combines these** with custom calculations to form complete simulation
- In use by NEWS-G, R2D2 and for detector R&D

Development of a simulation framework for spherical proportional counters

I. Katsioulas,[a] P. Knights,[a,b] J. Matthews,[a] T. Neep,[a] K. Nikolopoulos,[a] R. Owen[a] and R. Ward[a,1]

[a]*School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*
[b]*IRFU, CEA, Universite Paris-Saclay, F-91191 Gif-sur-Yvette, France*

E-mail: rjw439@bham.ac.uk

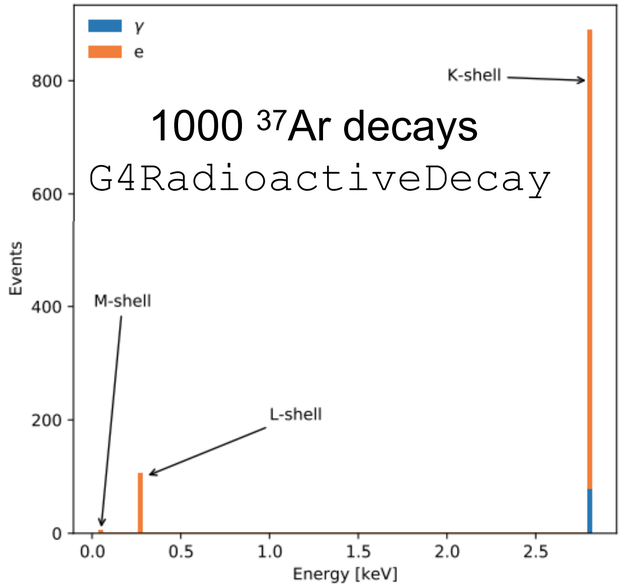
Abstract: The spherical proportional counter is a novel gaseous detector with numerous applications, including direct dark matter searches and neutron spectroscopy. The strengths of the Geant4 and Garfield++ toolkits are combined to create a simulation framework for spherical proportional counters. The interface is implemented by introducing Garfield++ classes within a Geant4 application. Simulated muon, electron, and photon signals are presented, and the effects of gas mixture composition and anode support structure on detector response are discussed.

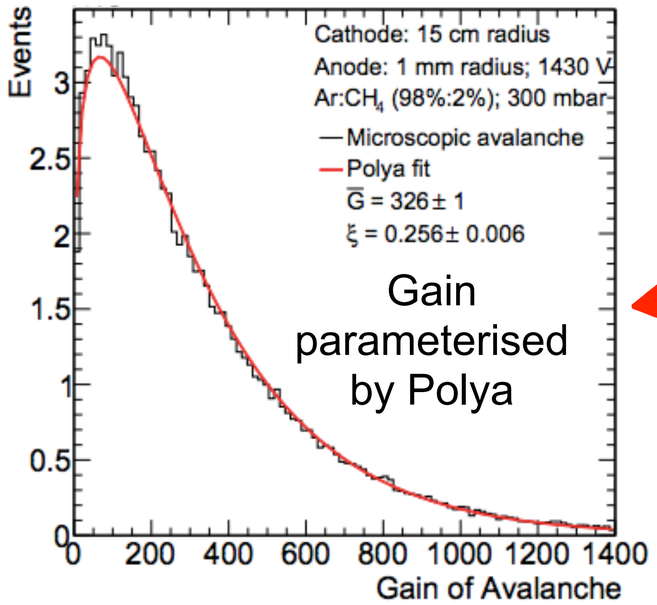
Keywords: Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Detector modelling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc); Gaseous detectors; Simulation methods and programs

JINST 15 (2020) 06, C06013

2020 JINST 15 C06013

Simulation Chain





Detector is initialised and initial particle is generated in Geant4

Geant4 tracks particles and interactions

Electrons with kinetic energy <2 keV are passed to Garfield++

Heed calculates further ionisation

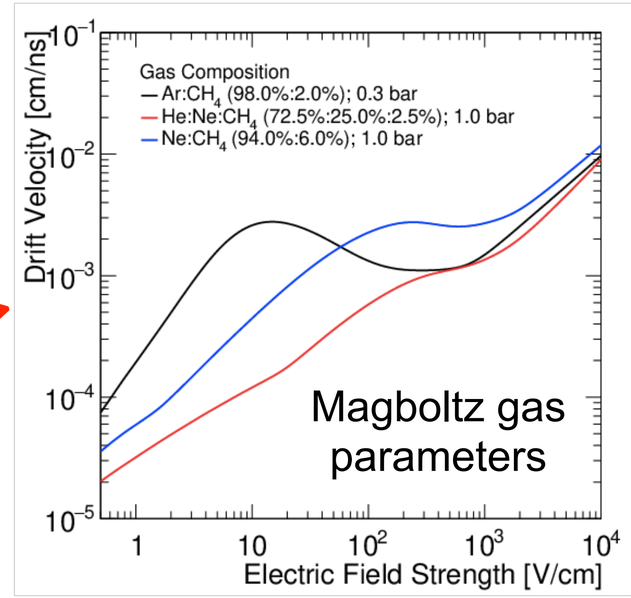
Using the electron transport parameters, ionisation electrons are transported up to the avalanche region

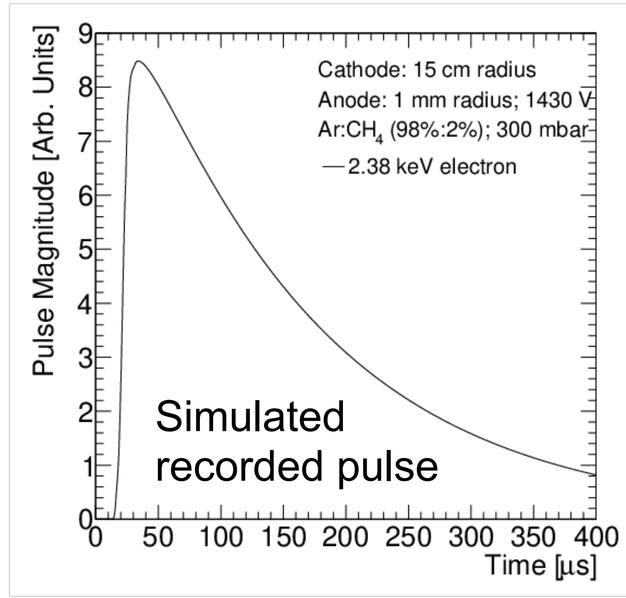
Electron multiplication is simulated

Ions and electrons produced in avalanche drift in electric field, and induced electric current is calculated

Signal is processed through electronics module to form pulse

JINST 15 (2020) 06, C06013

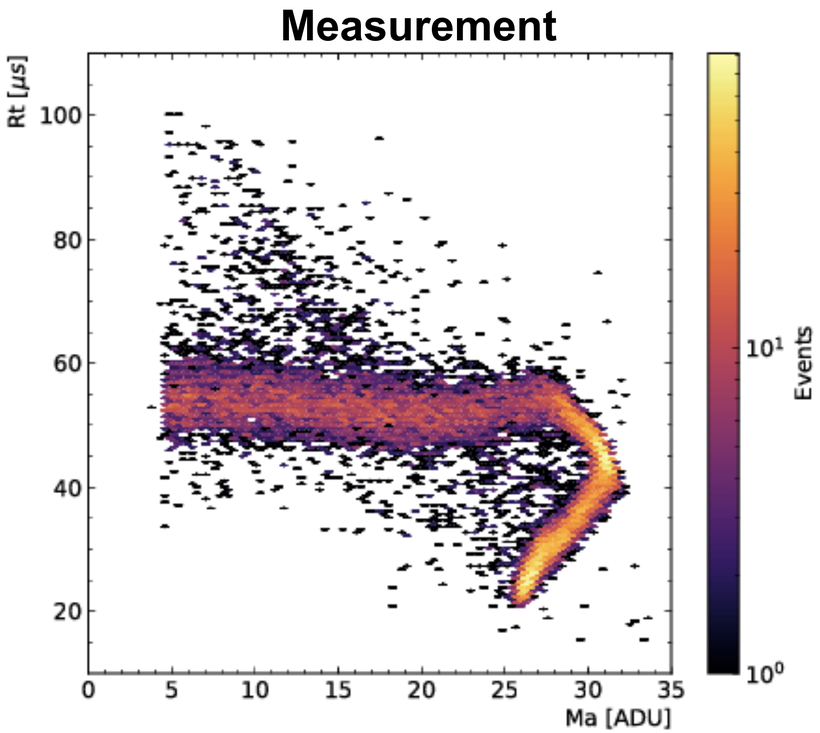




Example Simulation Application: Alpha Particles

- R2D2 0νββ experiment investigating energy resolution
- Simulation used to understand distribution of pulse-shape parameters

JINST 16 (2021) 03, P03012



Rt = pulse rise time
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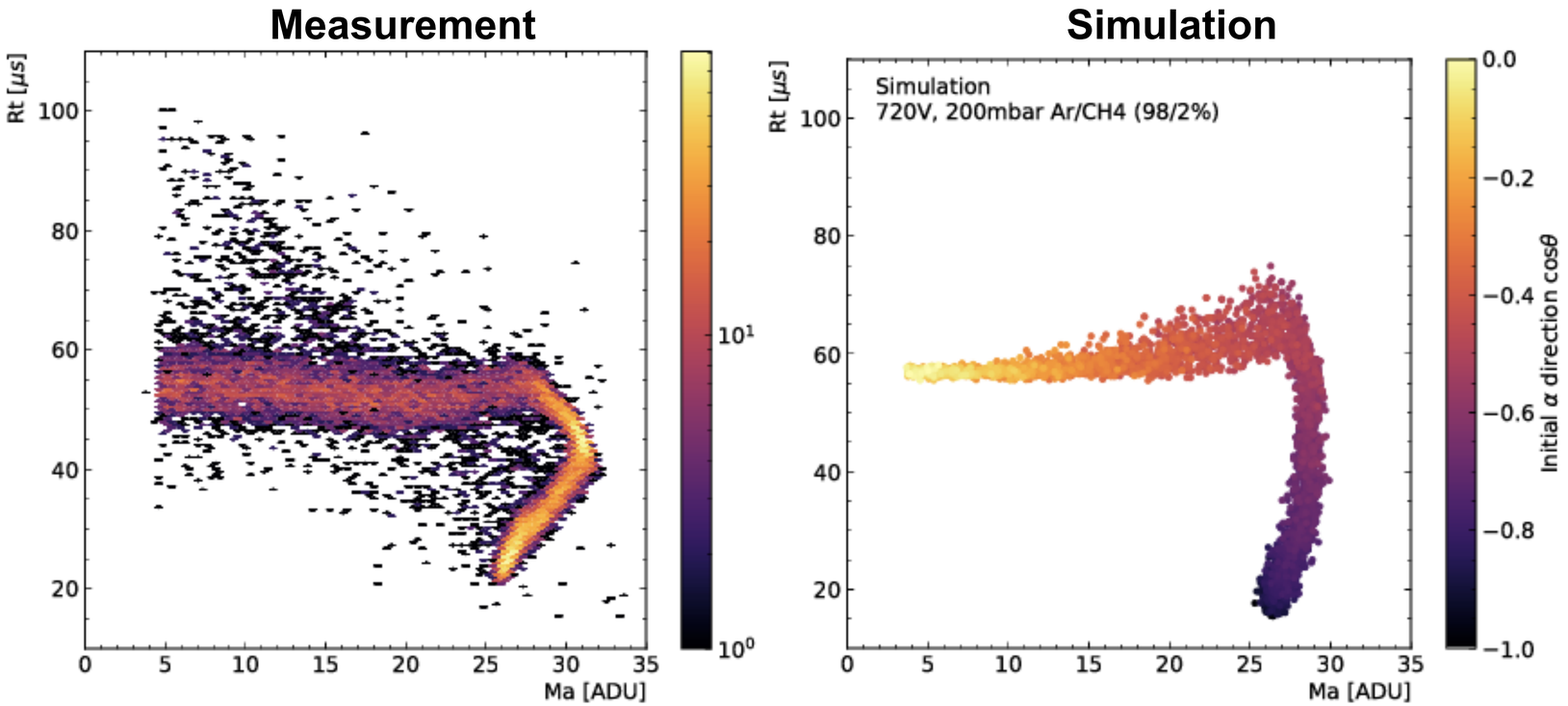

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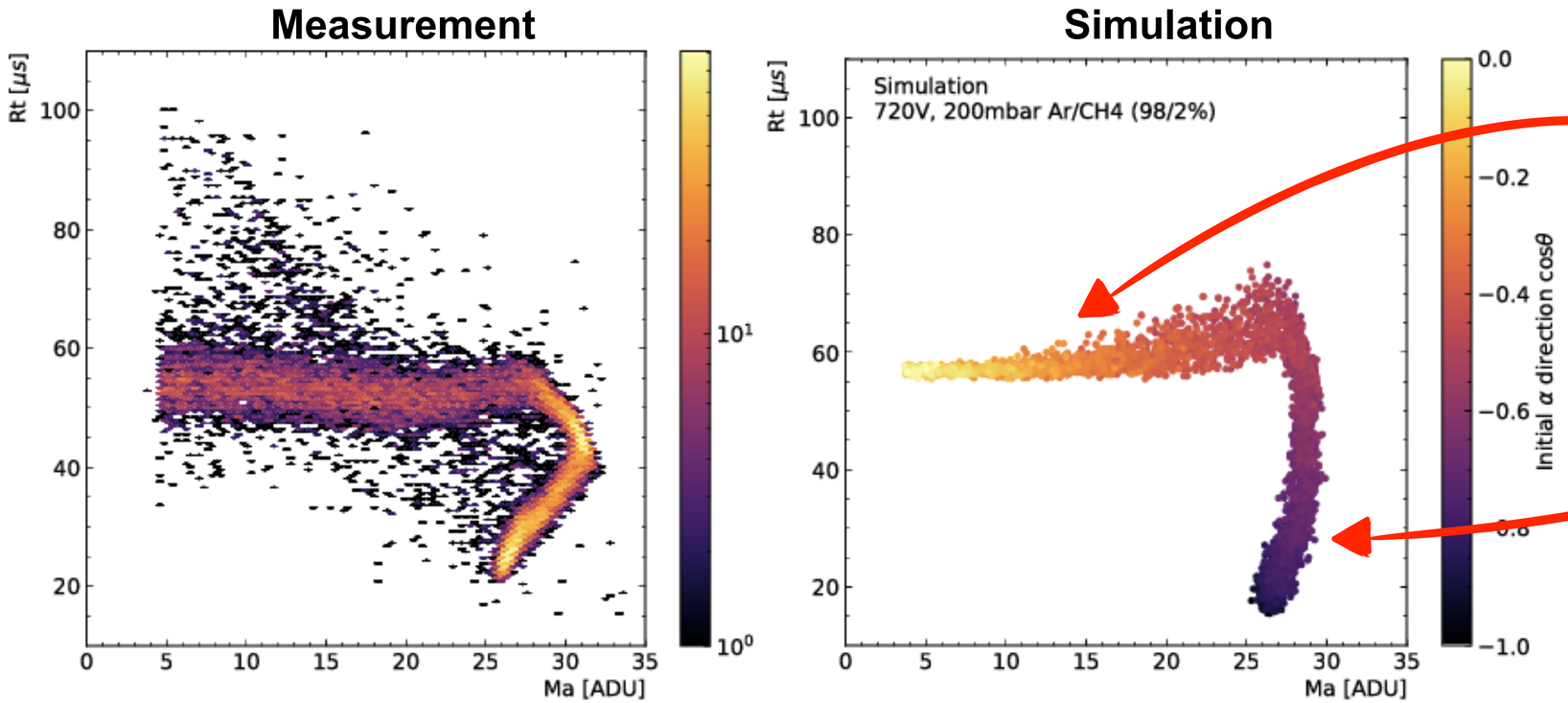

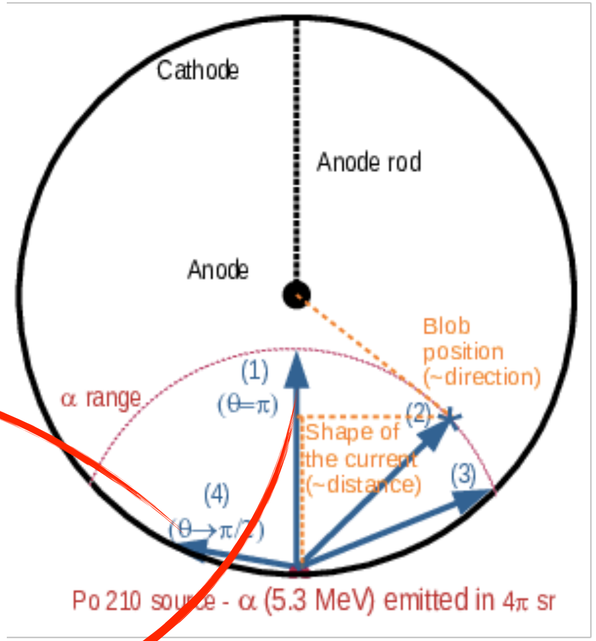

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Multi-Anode Readout: ACHINOS

- Single anode: drift and avalanche fields coupled
  - ➡ $E \simeq V \cdot r_a / r^2$ → **higher voltage** for same field at high r
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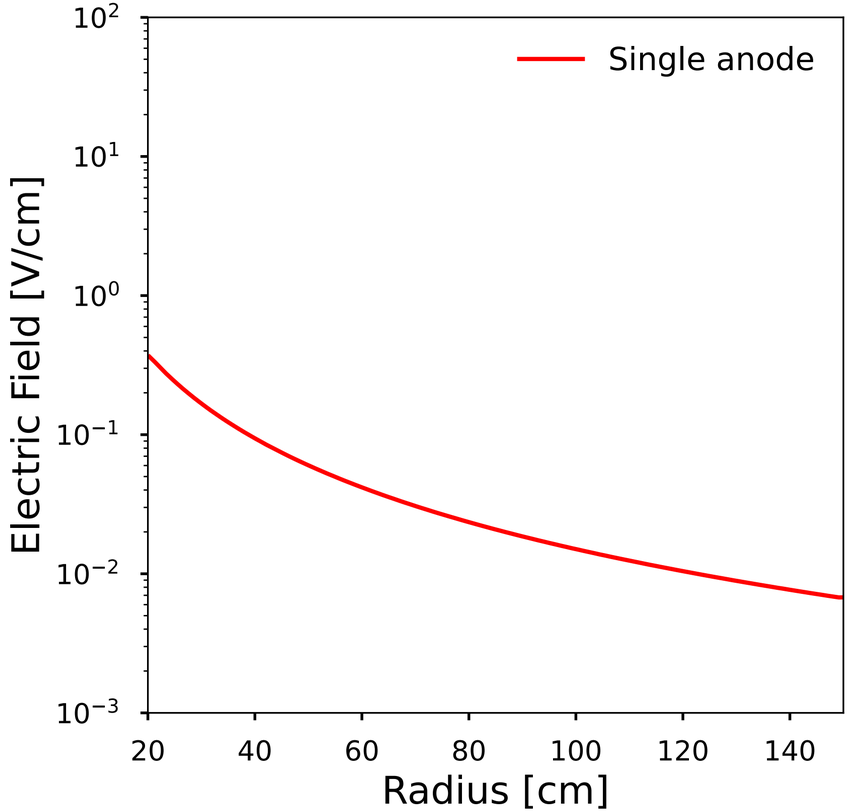
Individual anode: ***JINST 13 (2018) 11, P11006***

Simulation framework: ***JINST 15 (2020) 06, C06013***



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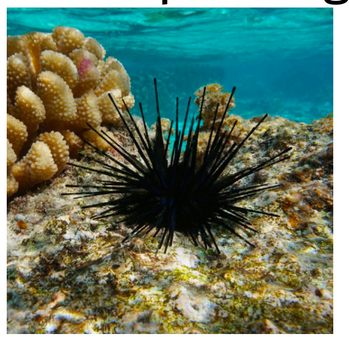

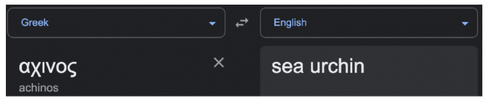

JINST 15 (2020) 11, 11

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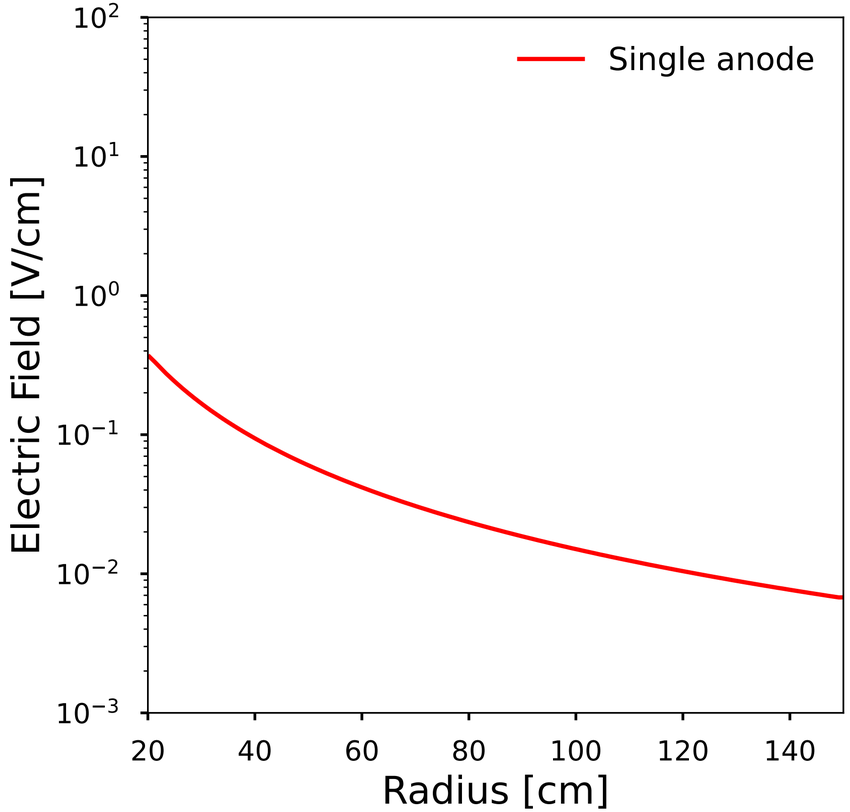

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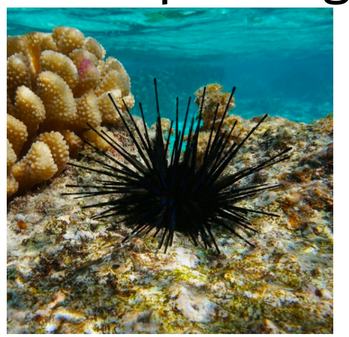

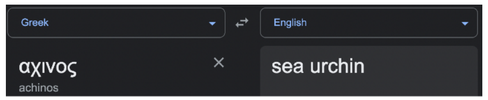

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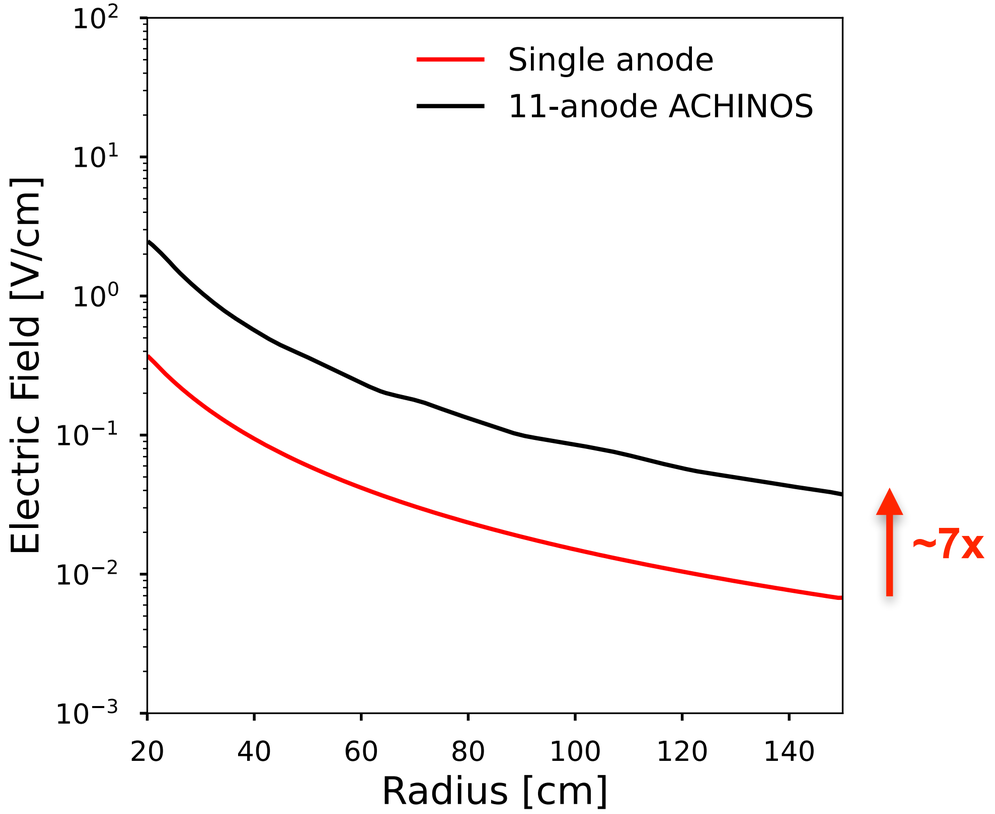

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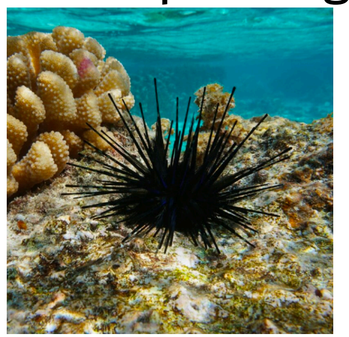
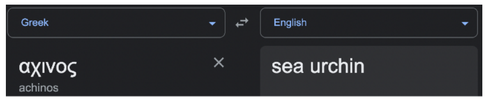
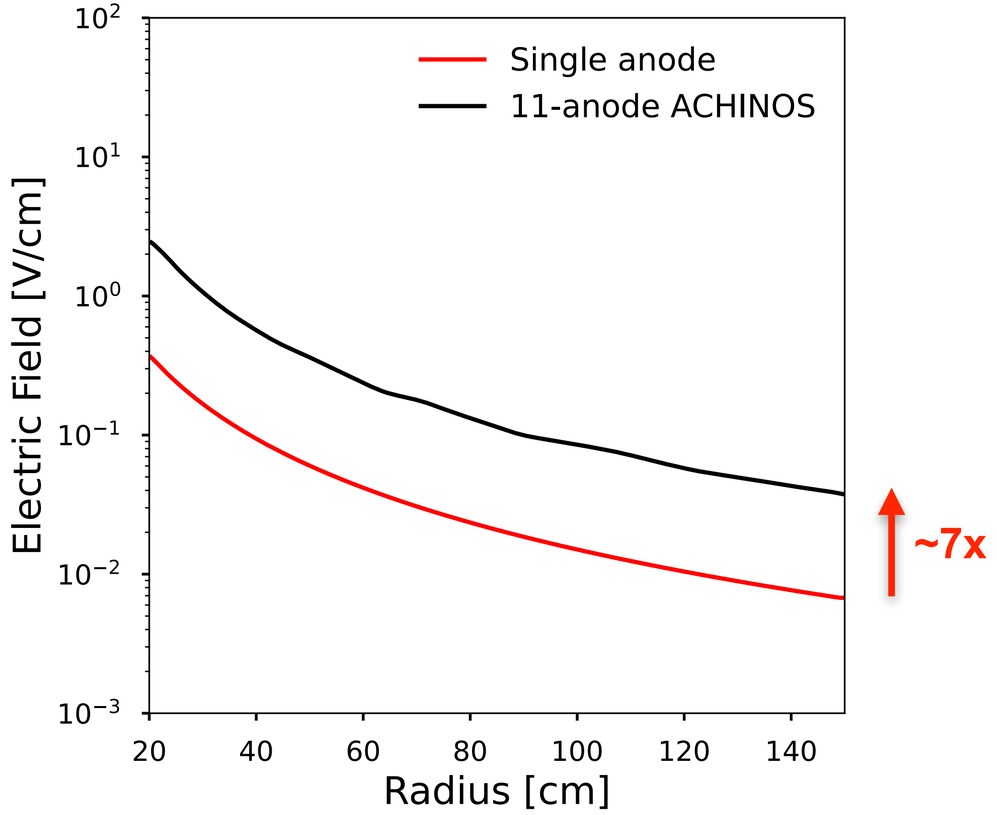




JINST 15 (2020) 11, 11



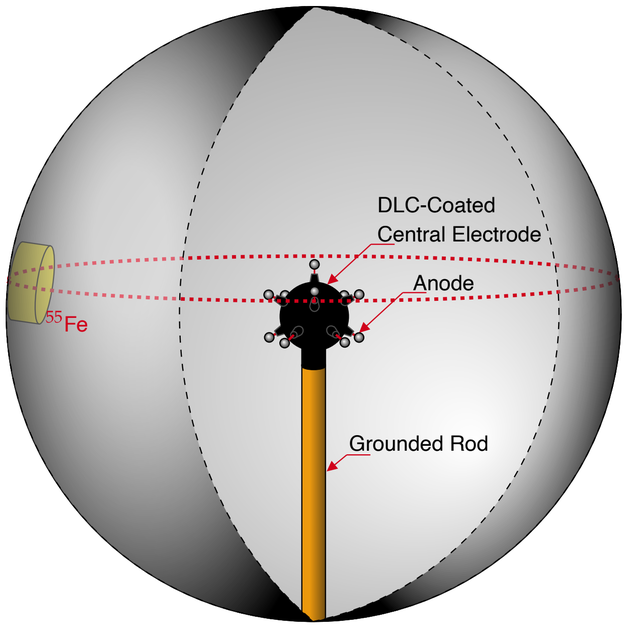
Enabled larger detectors, higher pressures

- ☑ Key for NEWS-G **DM searches**
- ☑ **Energy resolution** key to **0νββ searches**: R2D2
- ☑ **Exploring application to liquid Xe** for S2

JINST 16 (2021) 03, P03012

ACHINOS Response: 2-Channel Read-Out

- Early ACHINOS read out all anodes together
- Experimentally observed **amplitude dependance** on source azimuthal position
- Investigated with simulation



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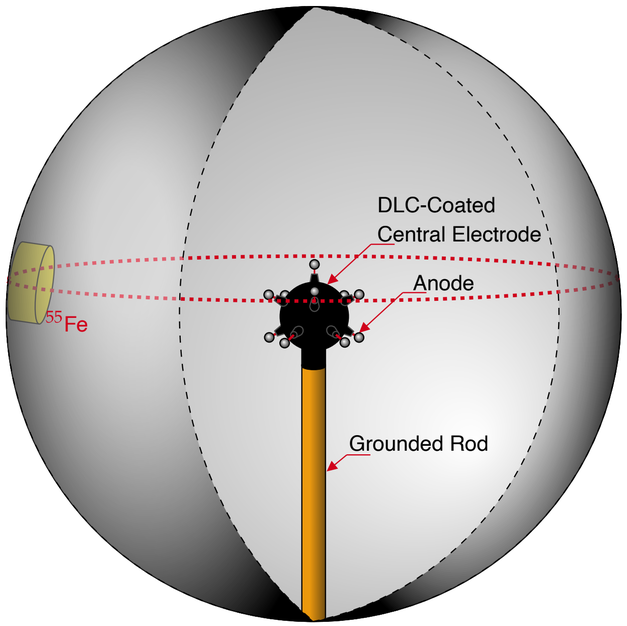

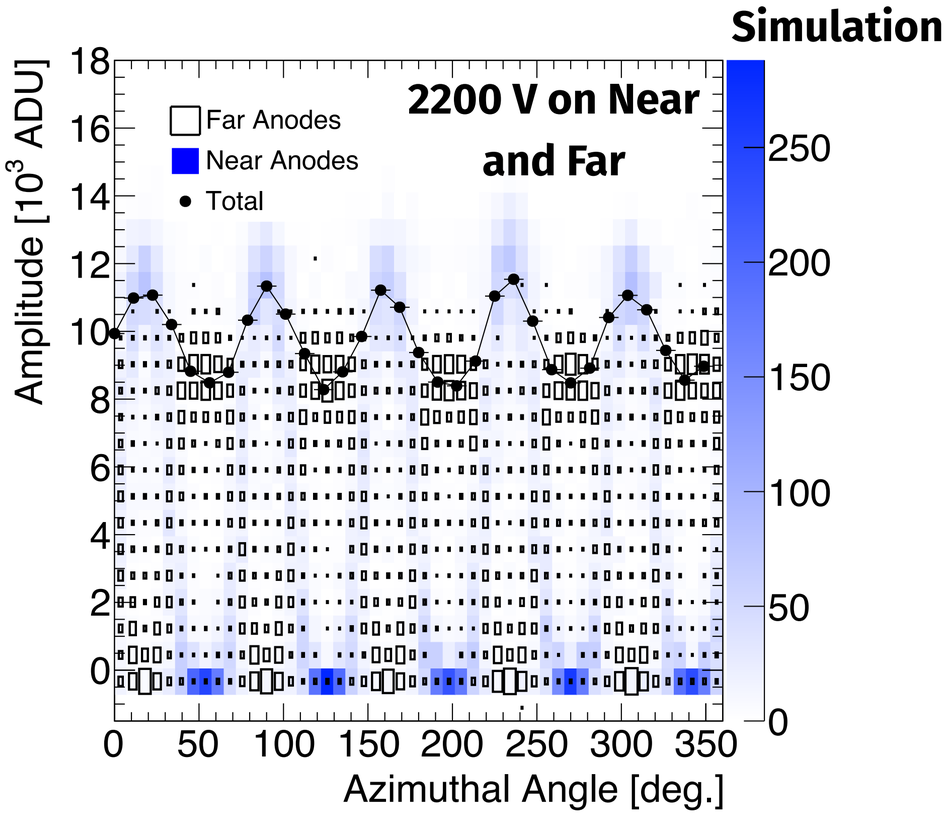

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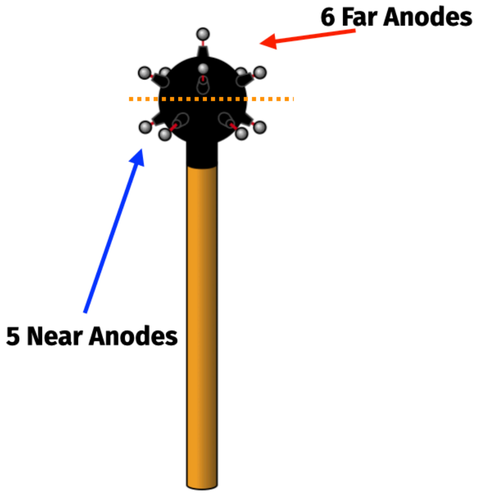

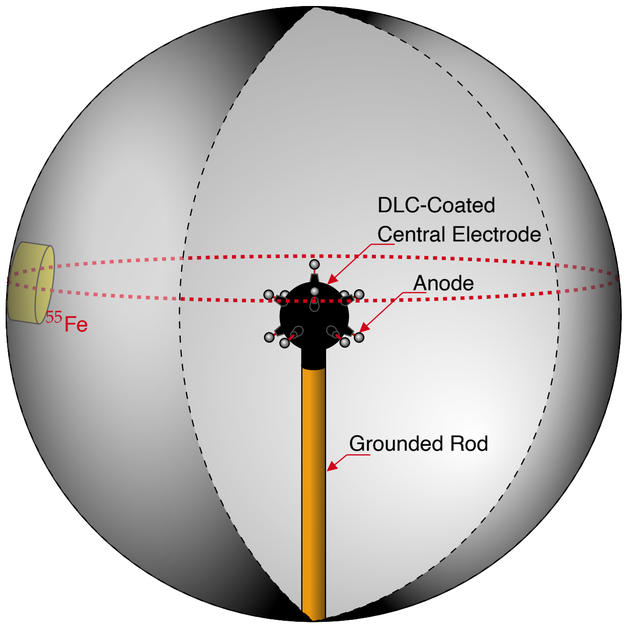

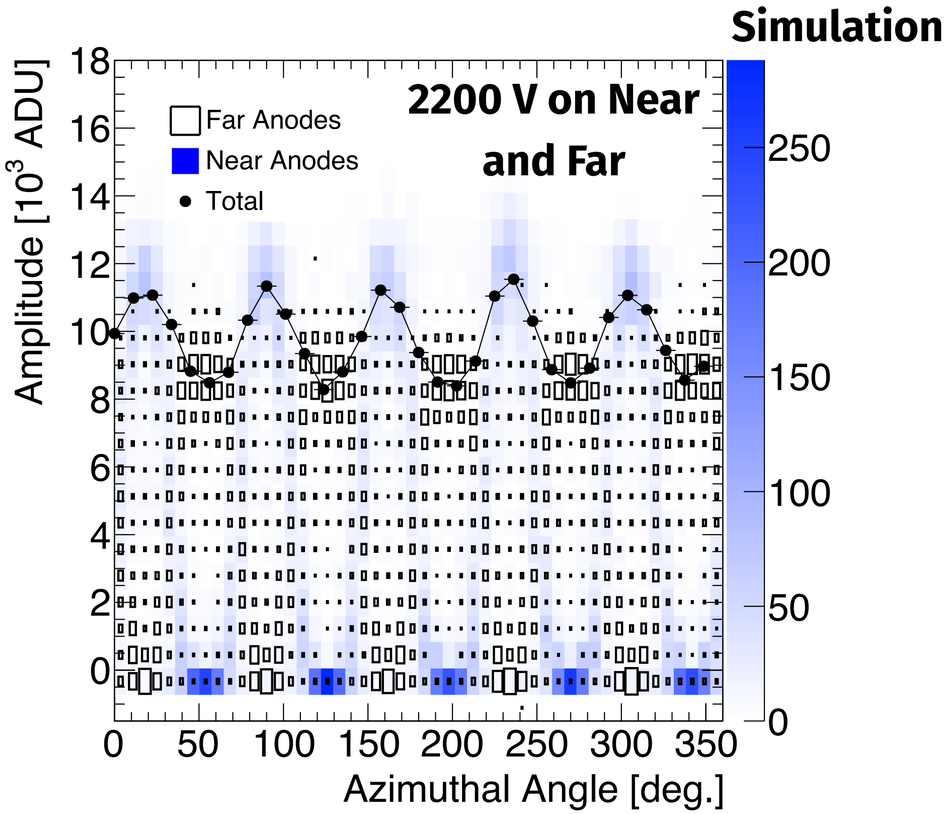

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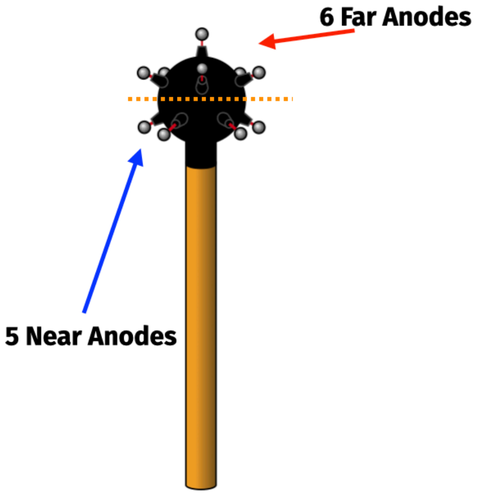

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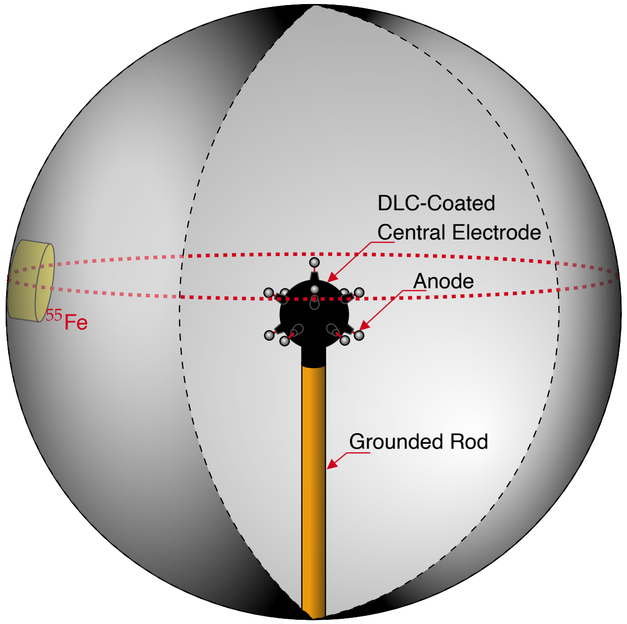
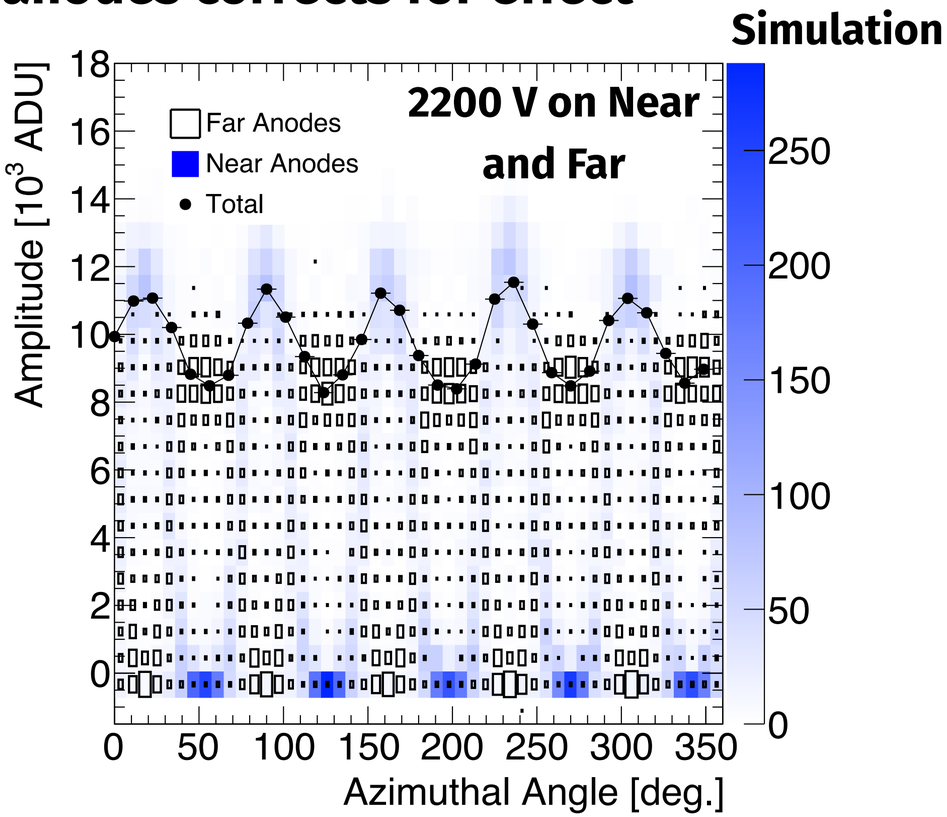
- Now standard practise for bias on 2 ACHINOS channels





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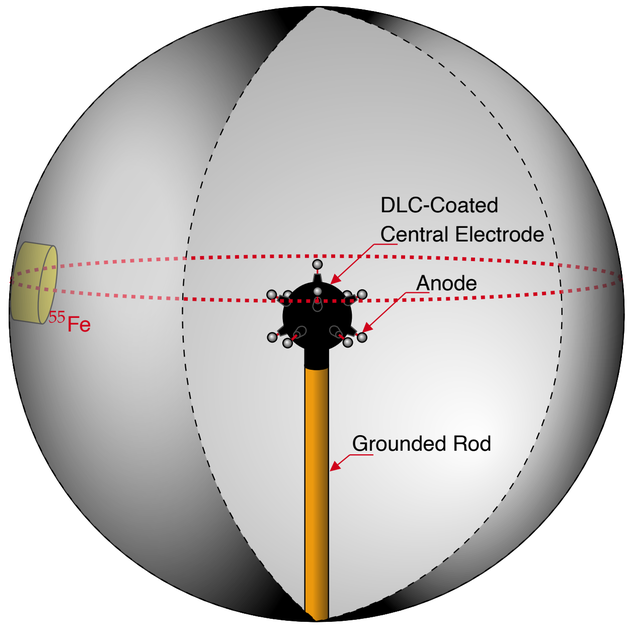
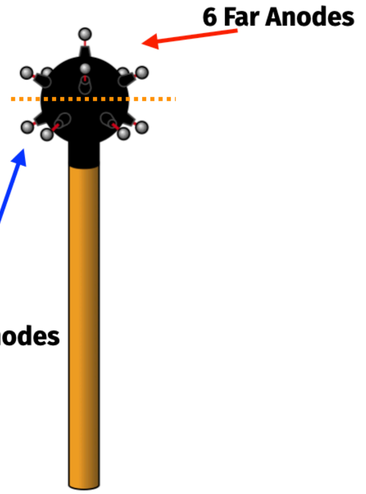
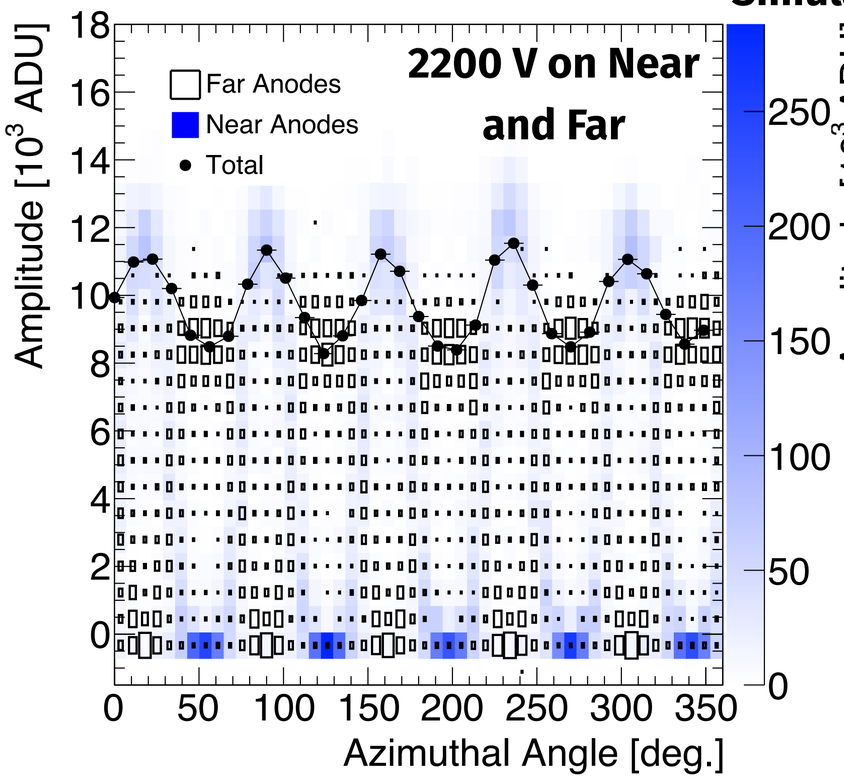
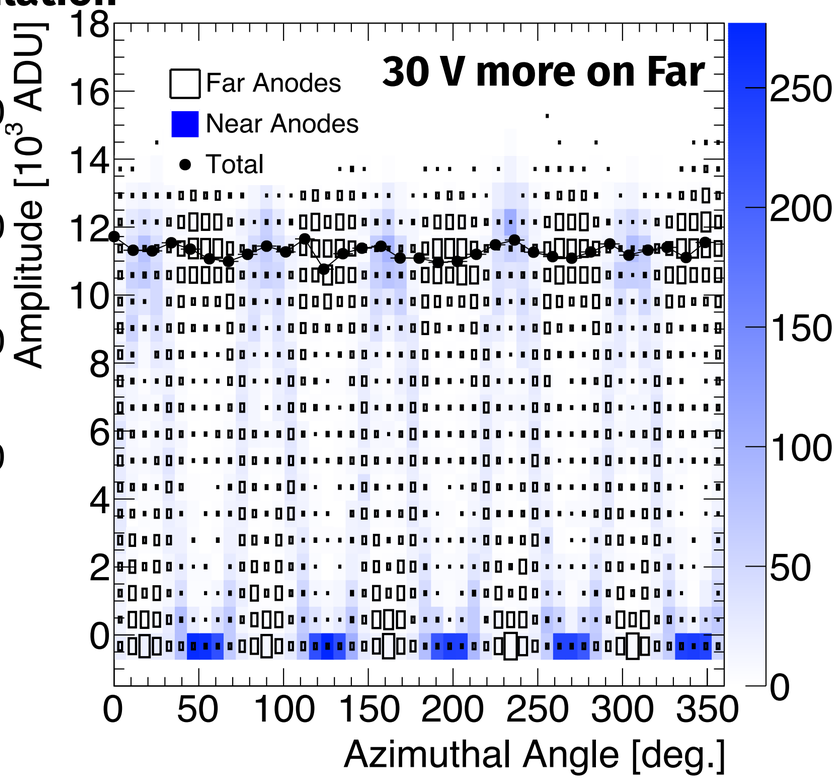




Simulation





Individual Anode Read-Out

- Developed electronics and read-out to instrument all **11 anodes individually**
- Improved energy resolution, fiducialisation, track reconstruction, …

NEW: *JINST 19 (2024) 01, P01018*

First operation of an ACHINOS-equipped Spherical Proportional Counter with individual anode read-out

D. Herd,[a] I. Katsioulas,[a,b] P. Knights,[a,1] I. Manthos,[a] J. Matthews,[a] L. Millins,[a,c] T. Neep,[a] K. Nikolopoulos,[a,d] G. Rogers[a]

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[c] *Particle Physics Department, STFC Rutherford Appleton Laboratory, UK*
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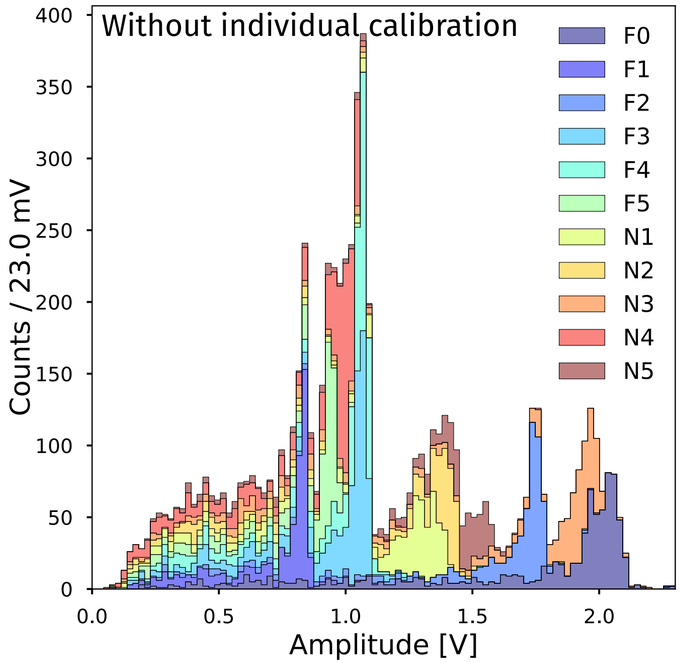

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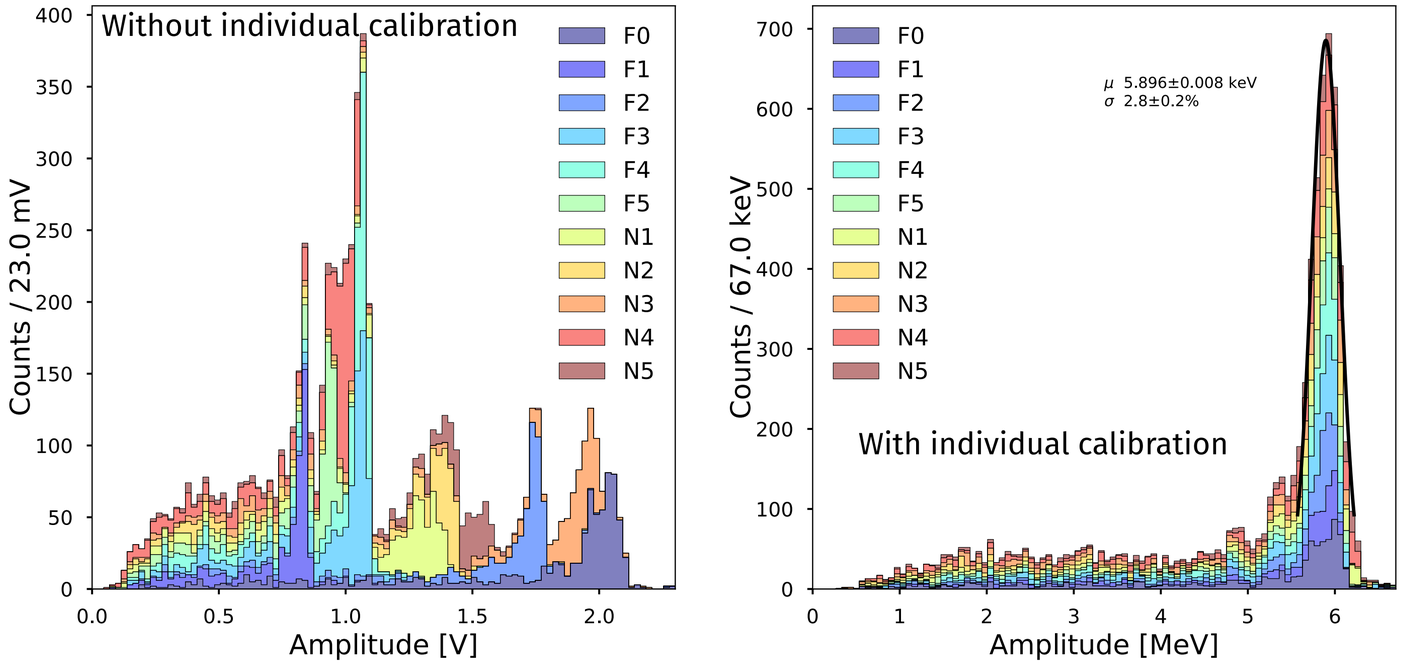

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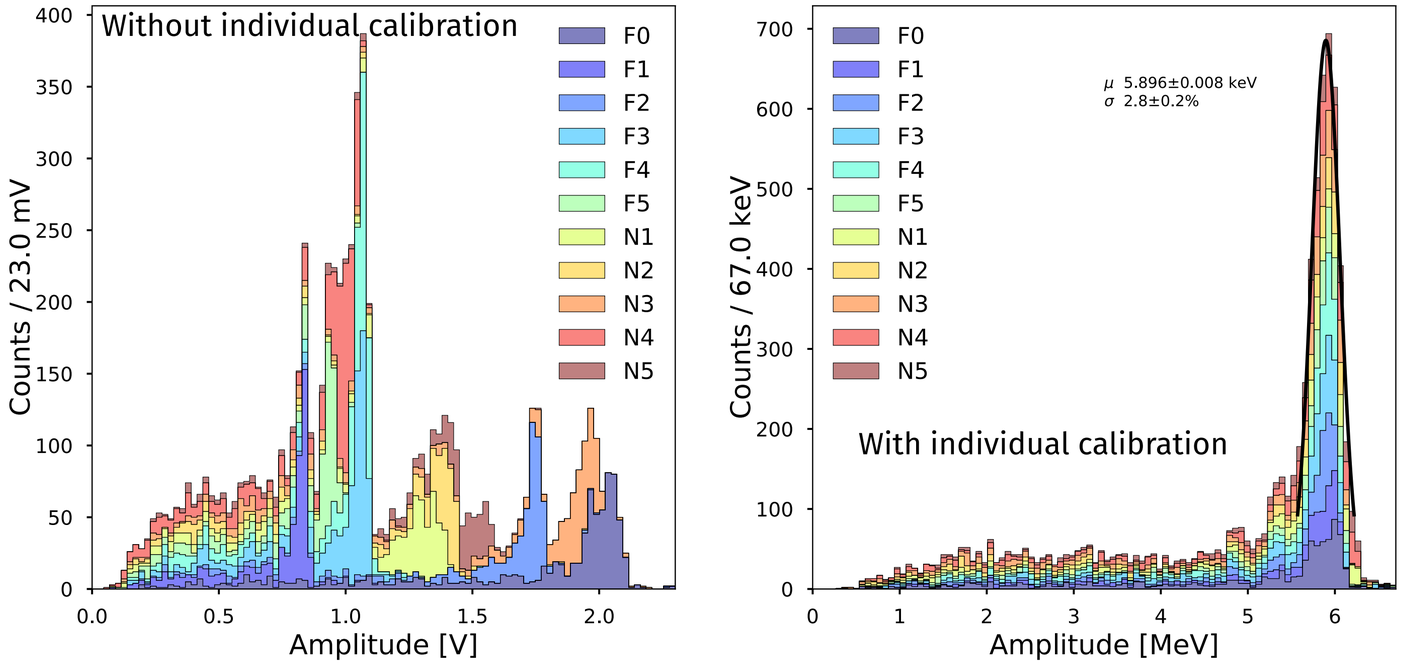

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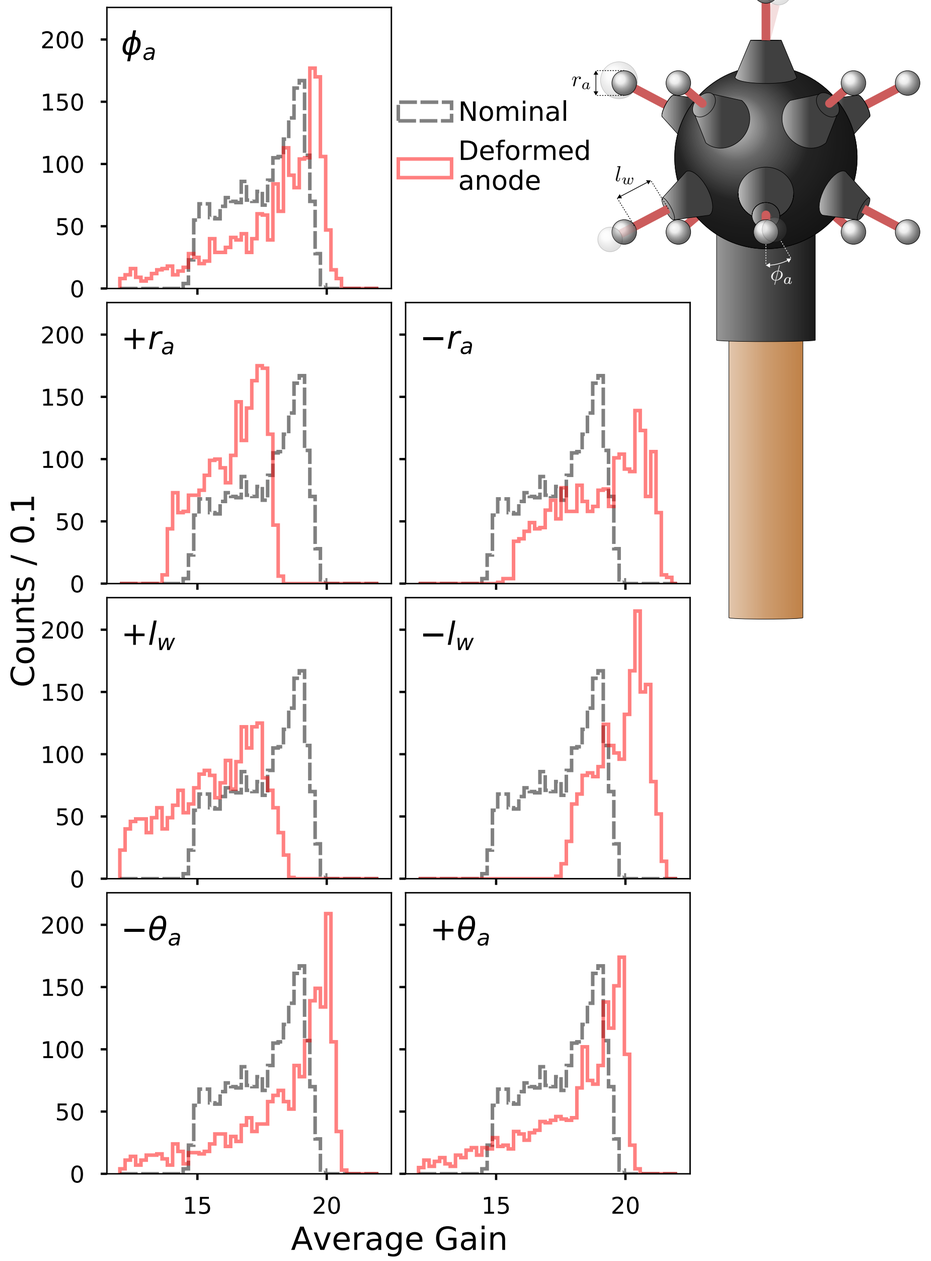

Event Localisation

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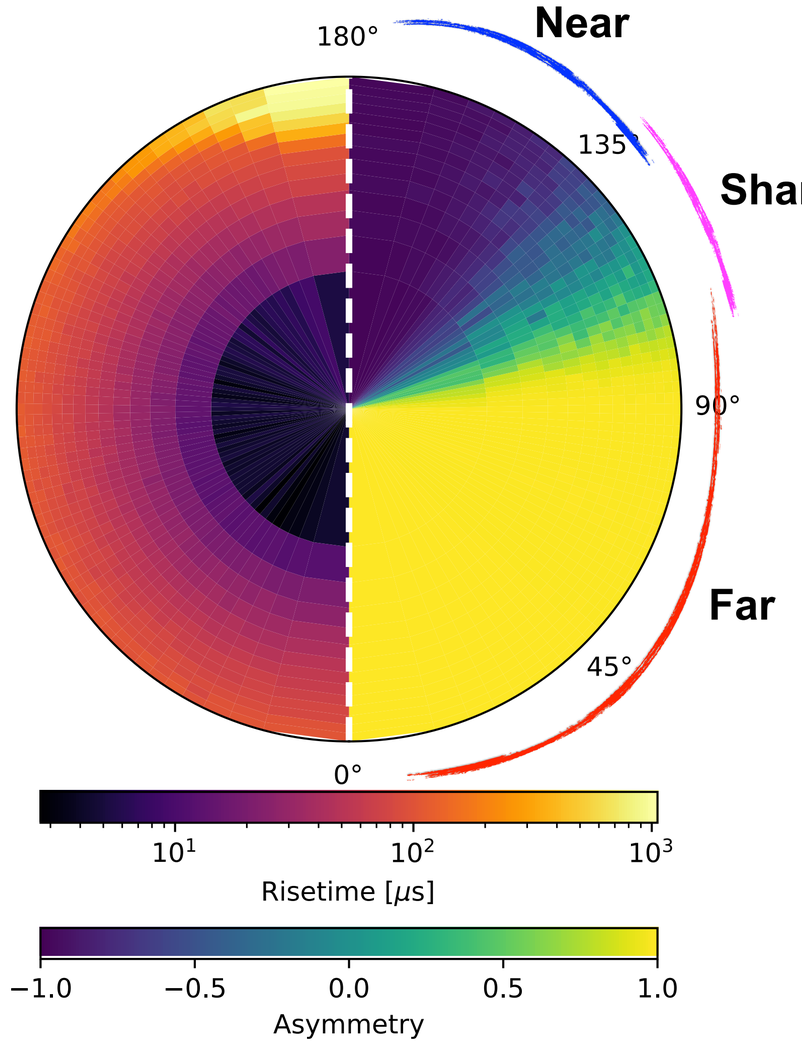
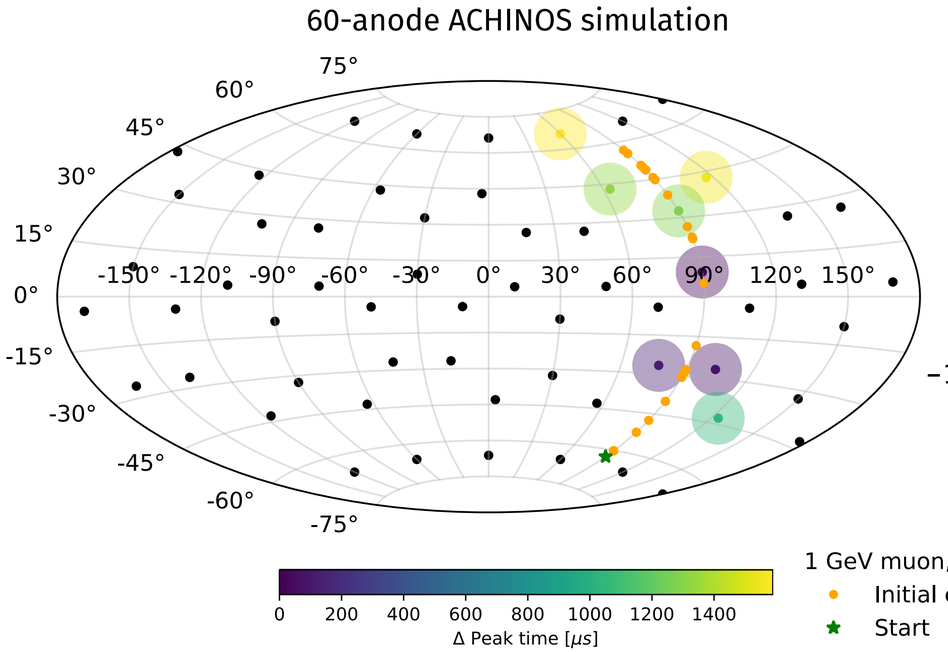
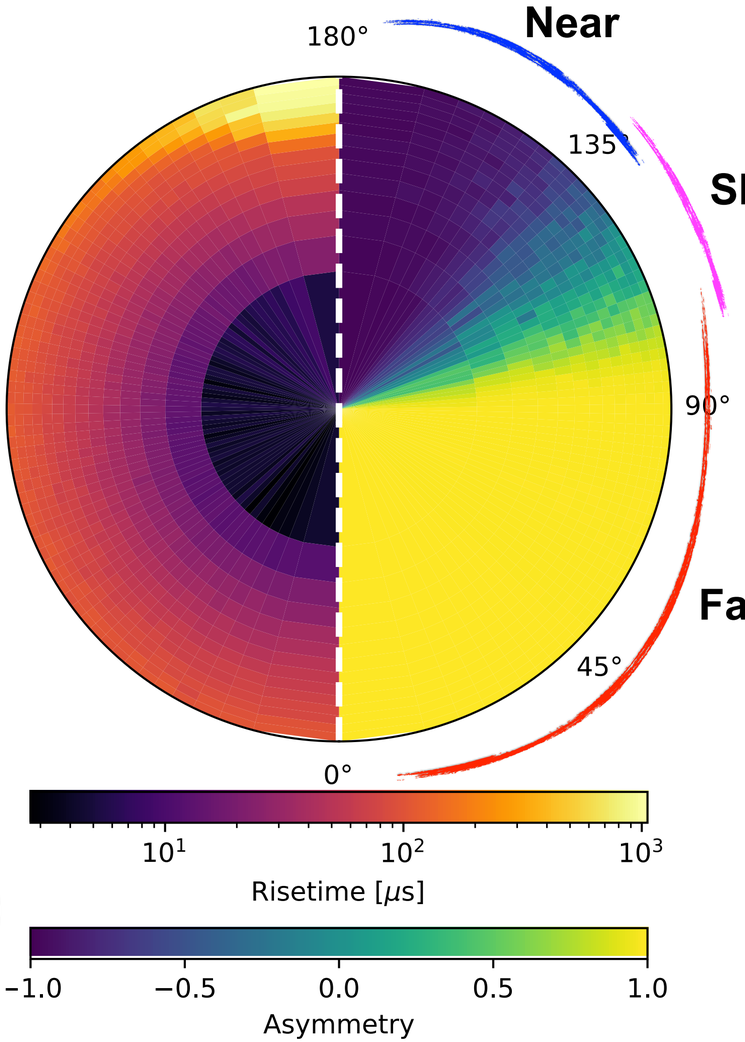


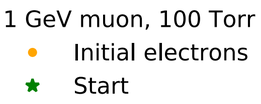
11-anode ACHINOS simulation

Event Localisation

- Single-anode(channel) → Radial information from rise time
  - ➡Also track vs point-like from rise time
- 2-channel → +Near/Far information from amplitude asymmetry
- **11-channel** → +potential for event localisation
  - ➡Potential to reconstruct tracks in detector volume
- **60 anodes** → higher field and improved position resolution



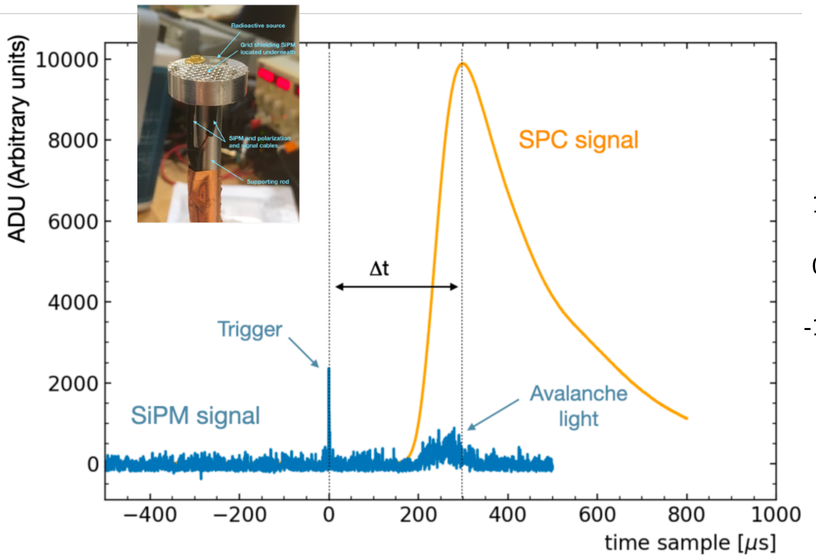




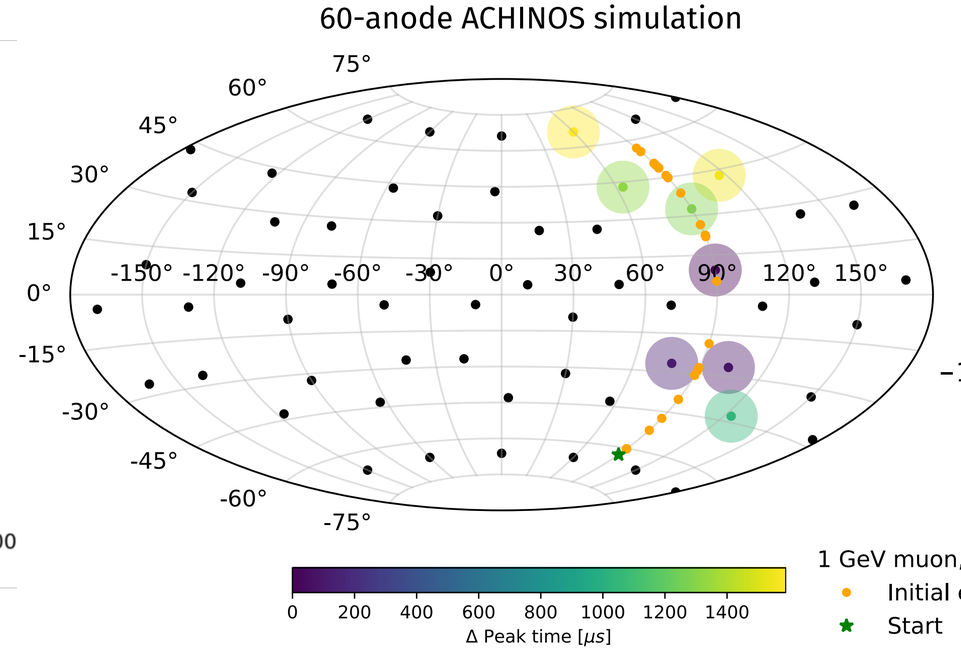
11-anode ACHINOS simulation

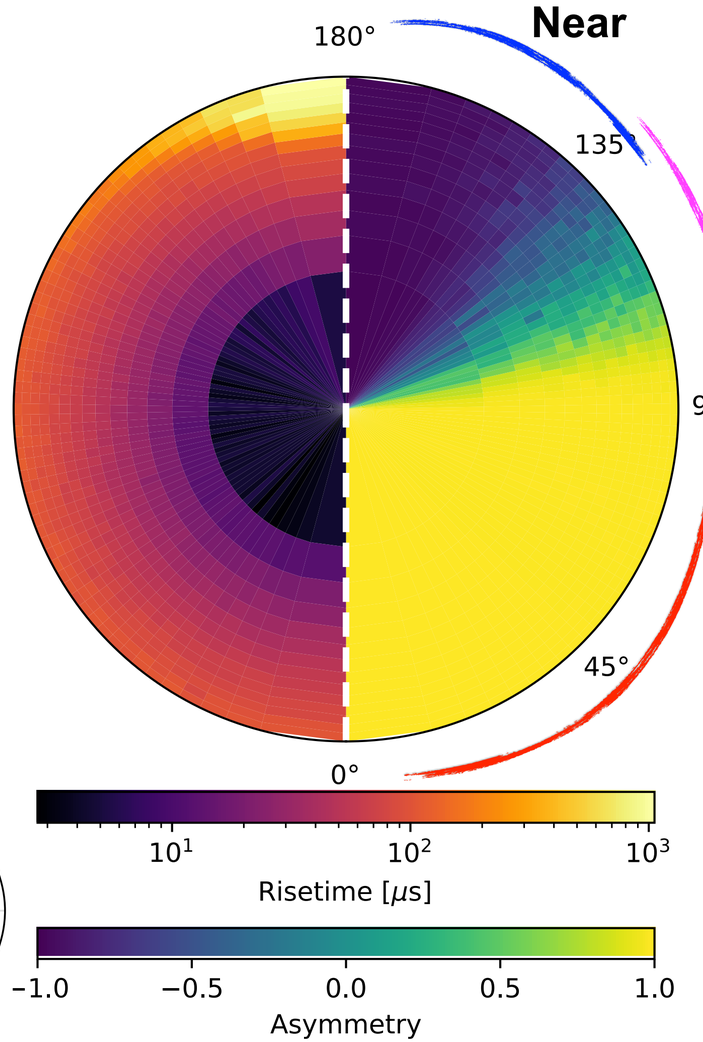
Event Localisation

- Single-anode(channel) → Radial information from rise time
  - ➡Also track vs point-like from rise time
- 2-channel → +Near/Far information from amplitude asymmetry
- **11-channel** → +potential for event localisation
  - ➡Potential to reconstruct tracks in detector volume
- **60 anodes** → higher field and improved position resolution
- **Light read-out** → event t_0



Nucl.Instrum.Meth.A 1028 (2022) 166382





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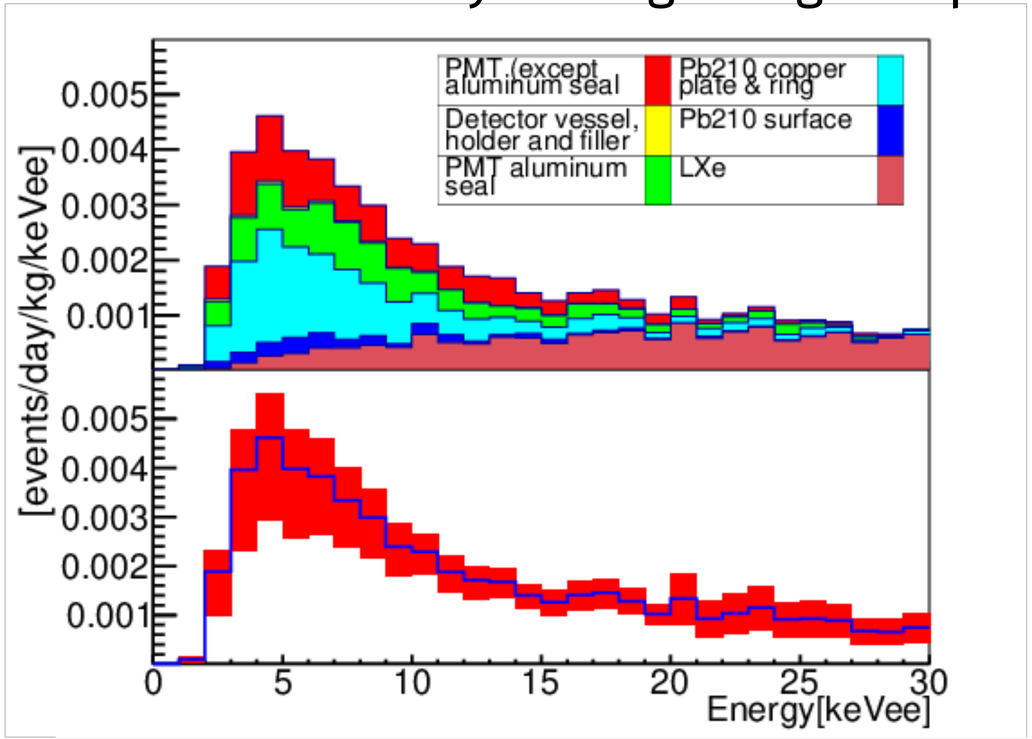
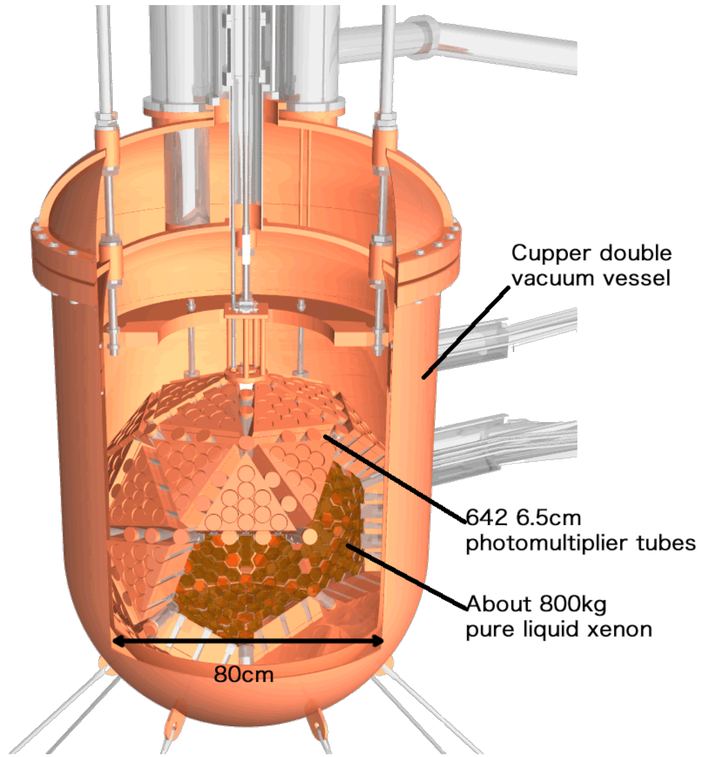
ACHINOS in other spherical detectors

- XMASS recently published results of full data set
- **Similarities** between the spherical proportional counter and XMASS are striking
  - **SPC**: Charge-only, and gas. **XMASS**: Light-only, liquid Xenon
- **Question**: Could XMASS sensitivity be improved with fiducialisation/background rejection?
  - Can this be done by adding charge-amplification to get S2 signal?



Phys.Rev.D 108 (2023) 8, 083022



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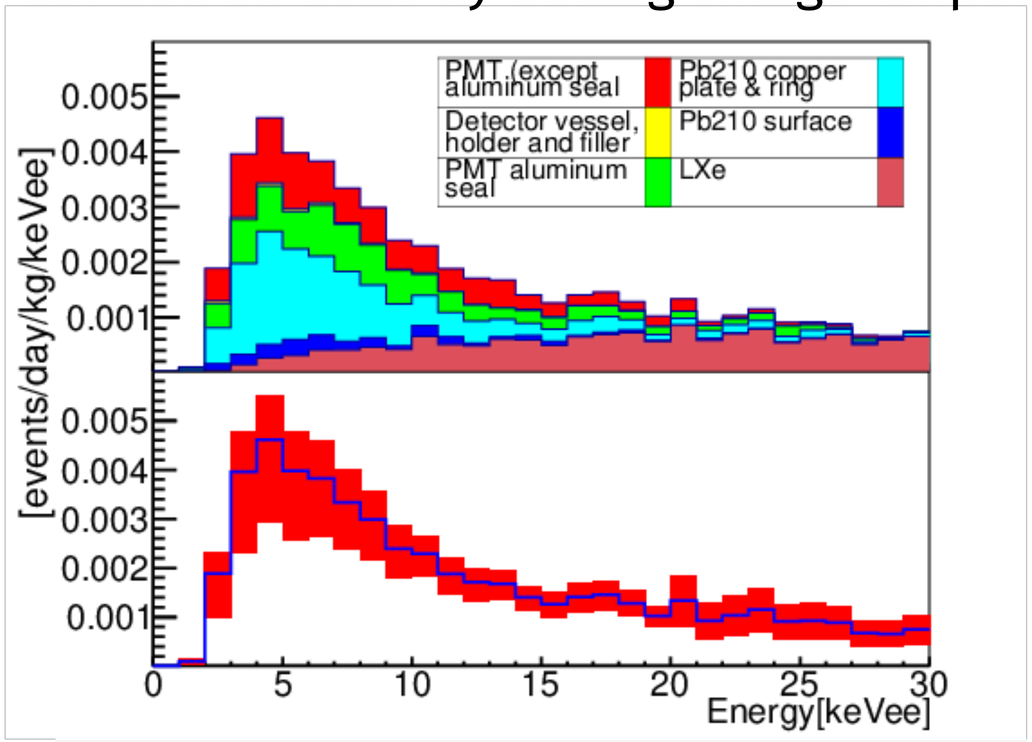

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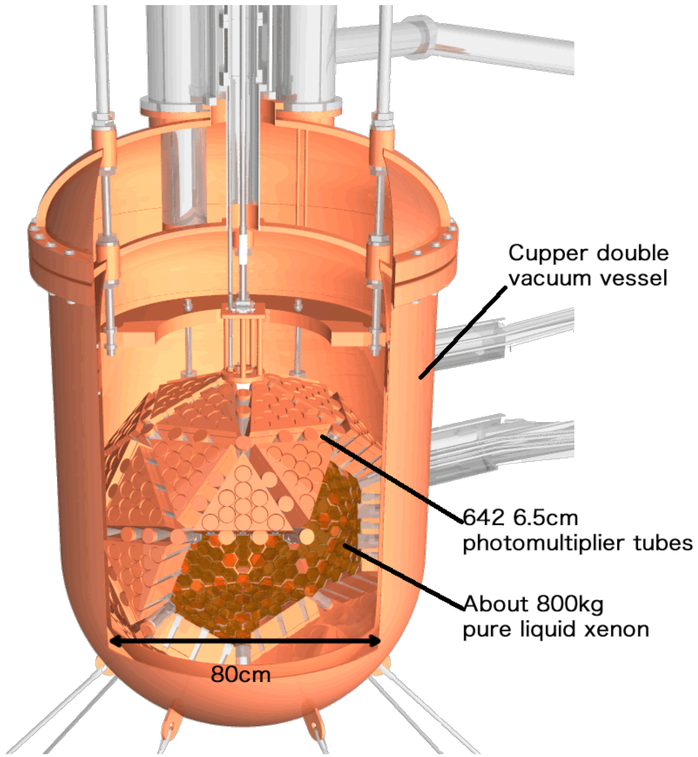

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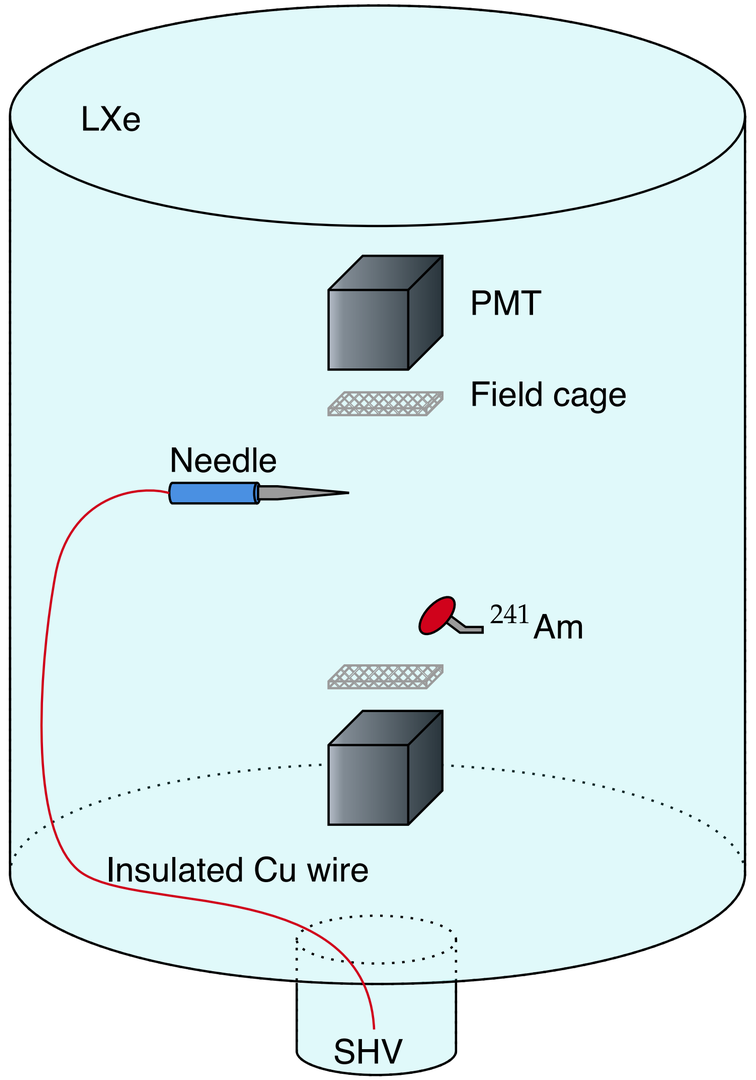
+

Towards Scalable Amplification in LXe

- Amplification directly in LXe demonstrated previously → challenge is scalability
  - ➡Idea: an ACHINOS-like structure
- First tests with ⌀**50µm-tip needle** mounted inside test vessel
  - ➡Installed with ^{241}Am source, and volume observed by 2 PMTs



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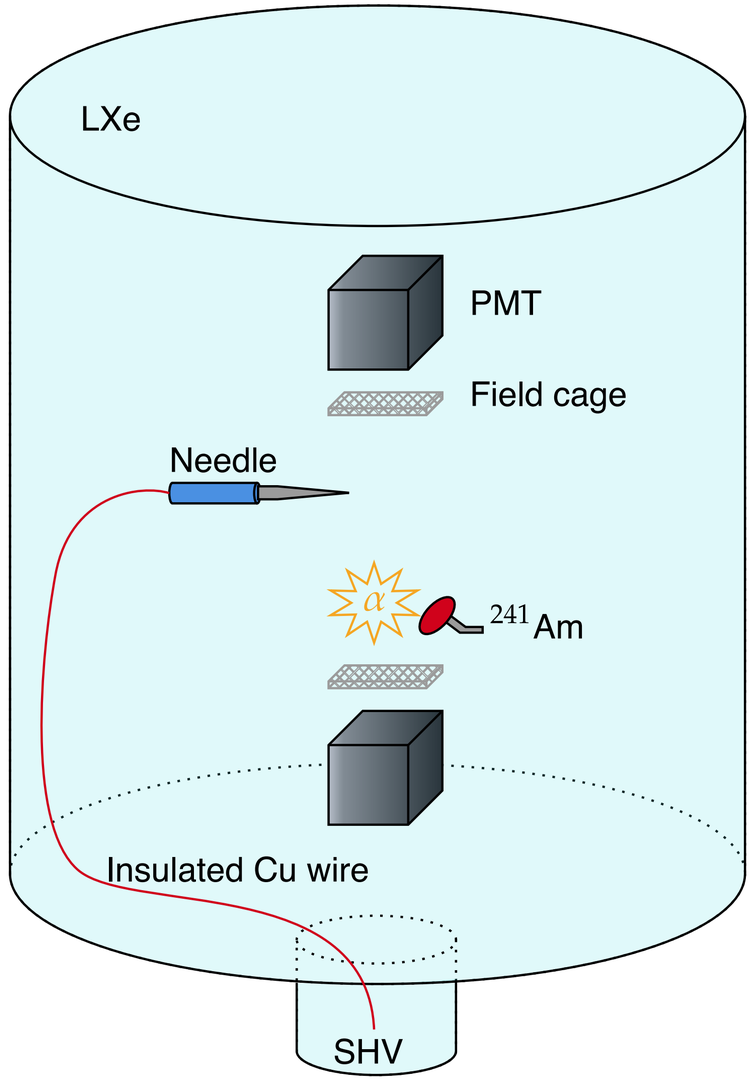

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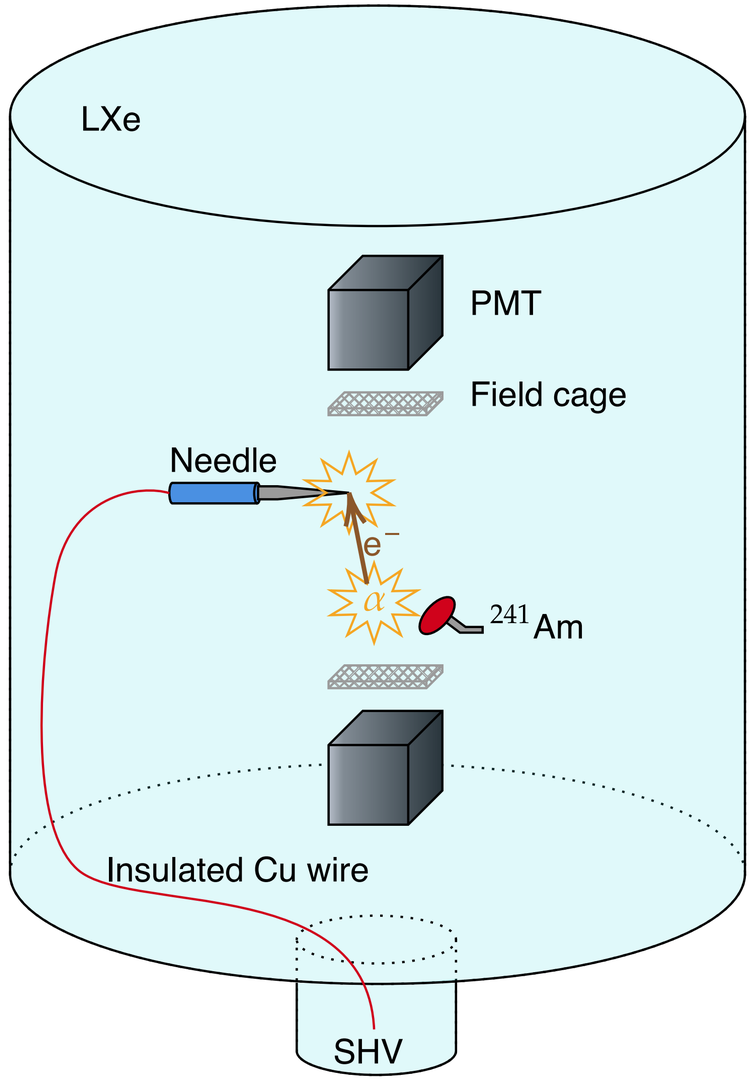

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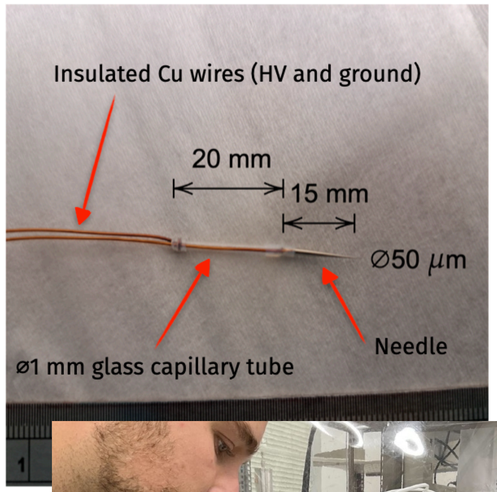

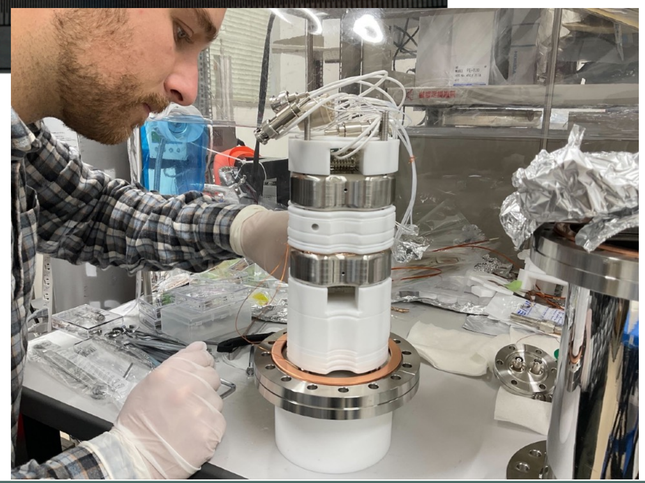

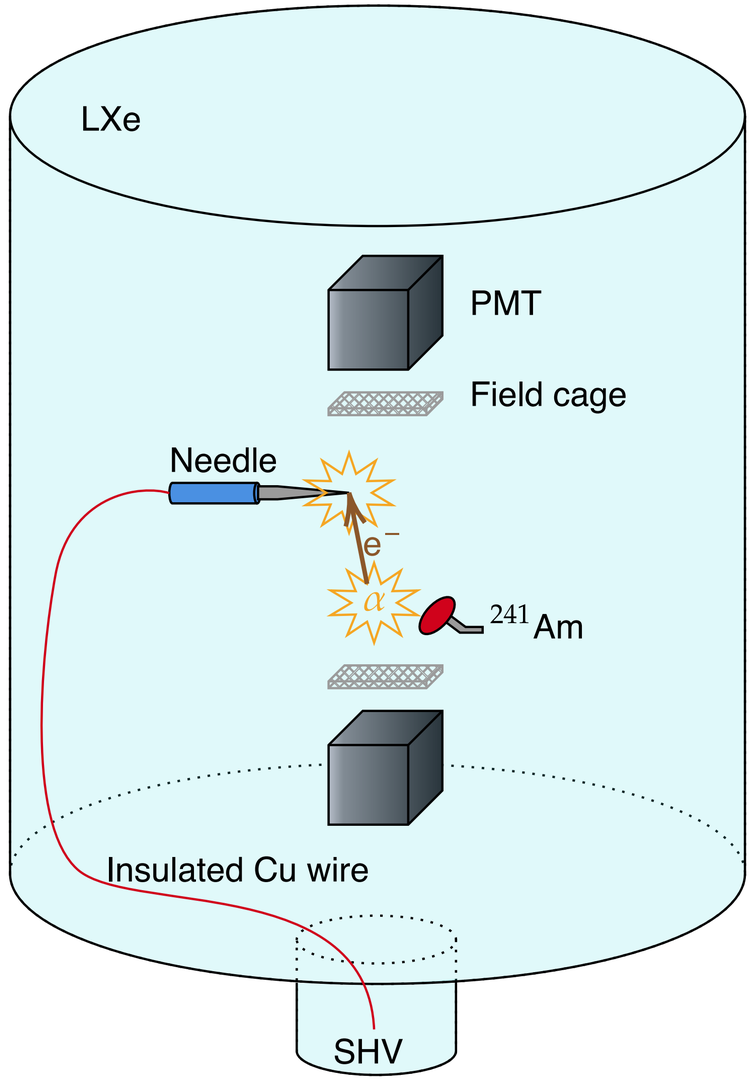

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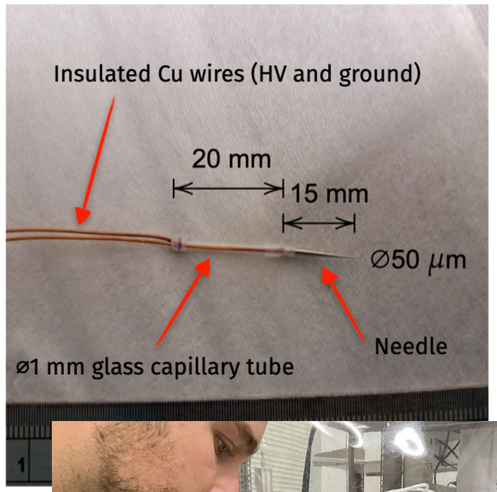
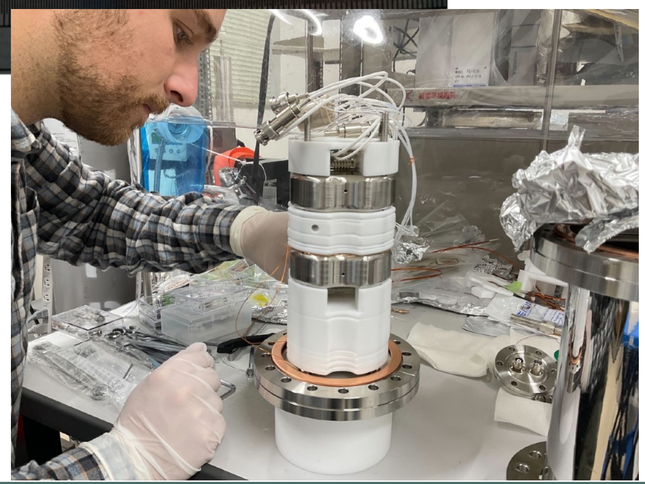
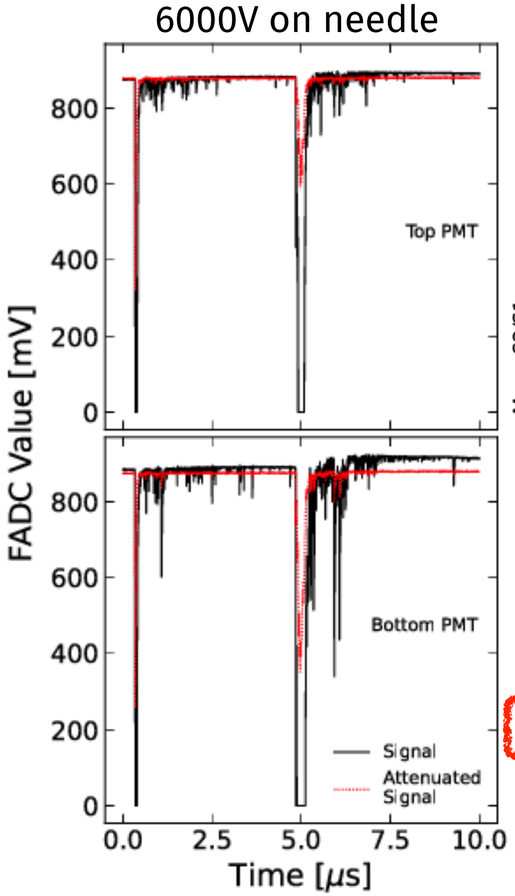
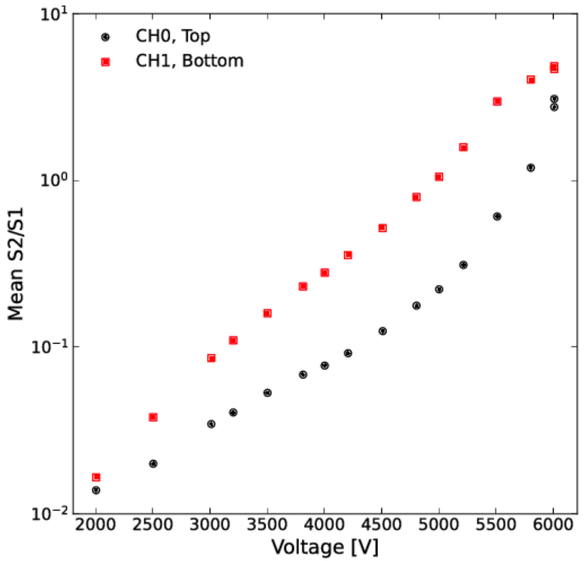
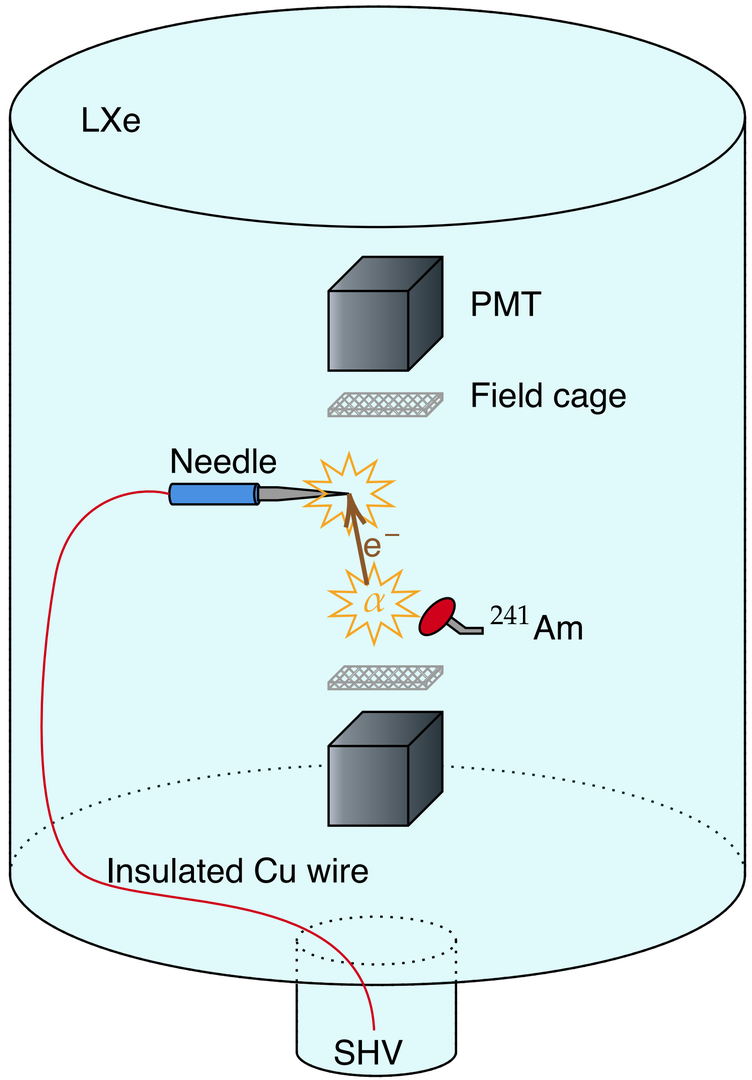








arXiv:2401.02327



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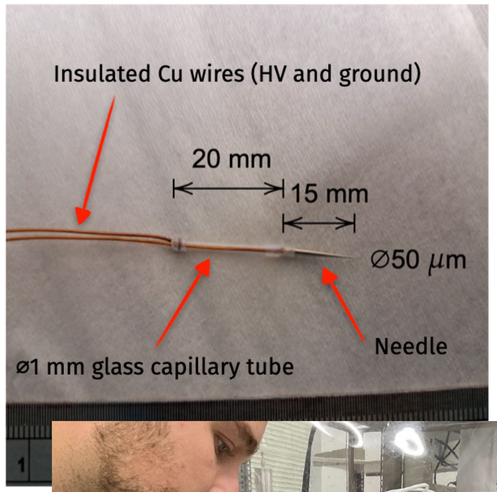

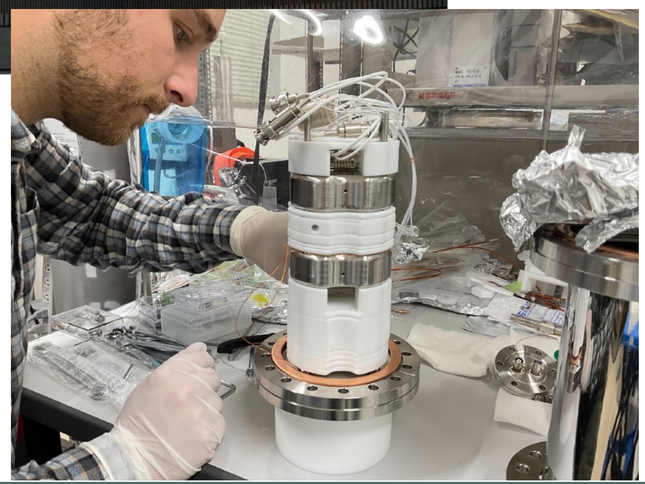

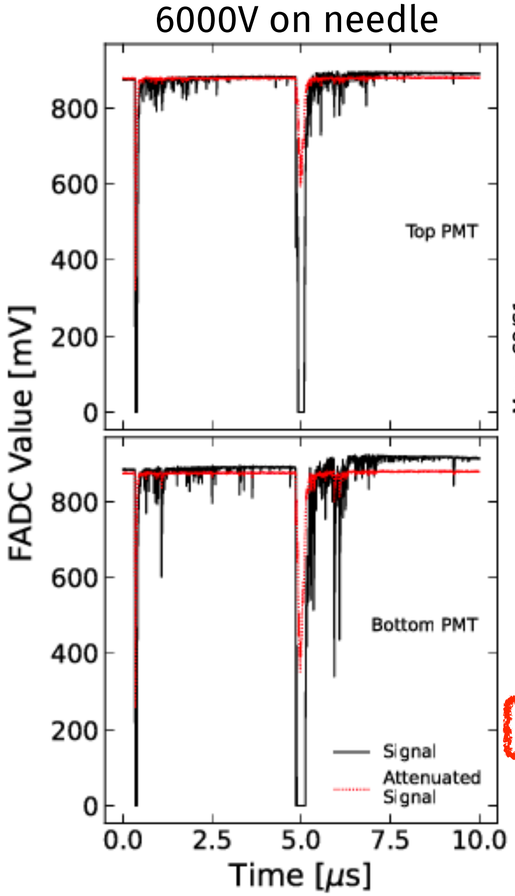

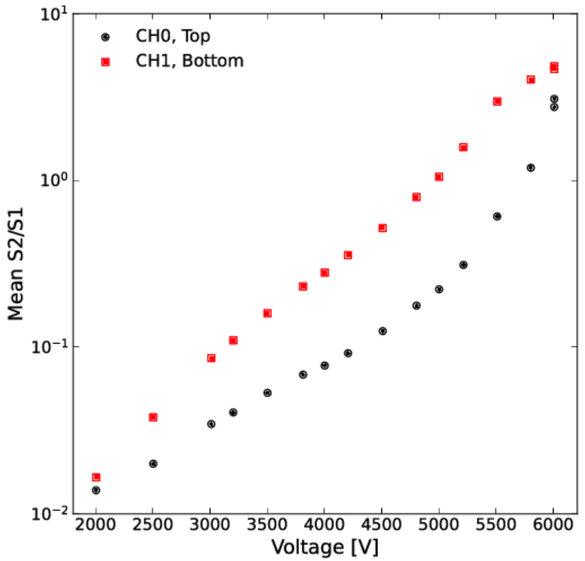

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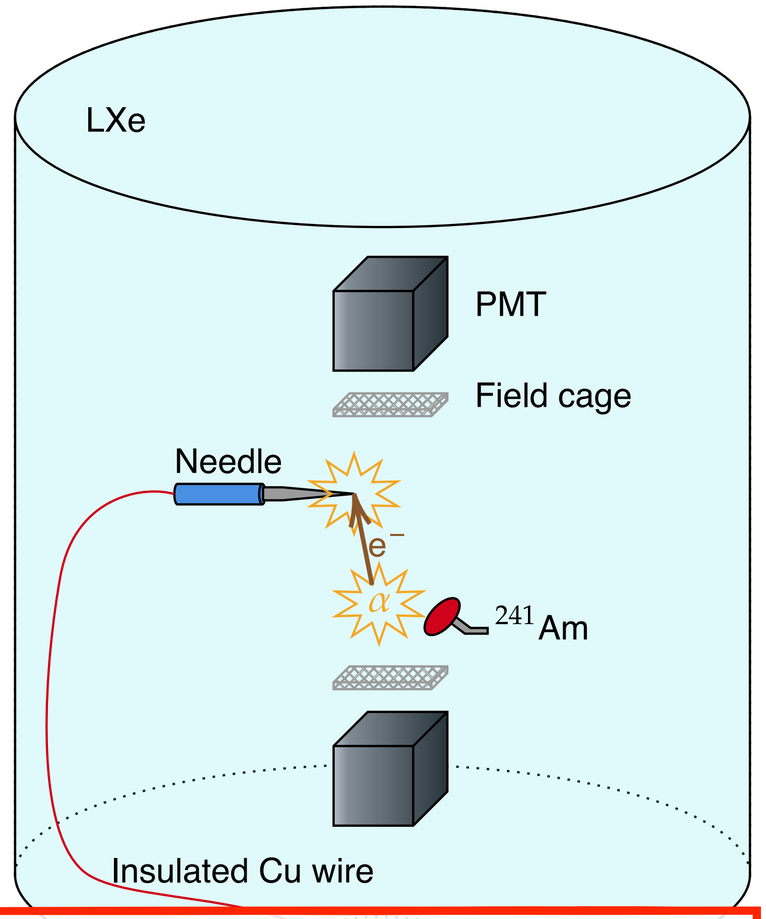
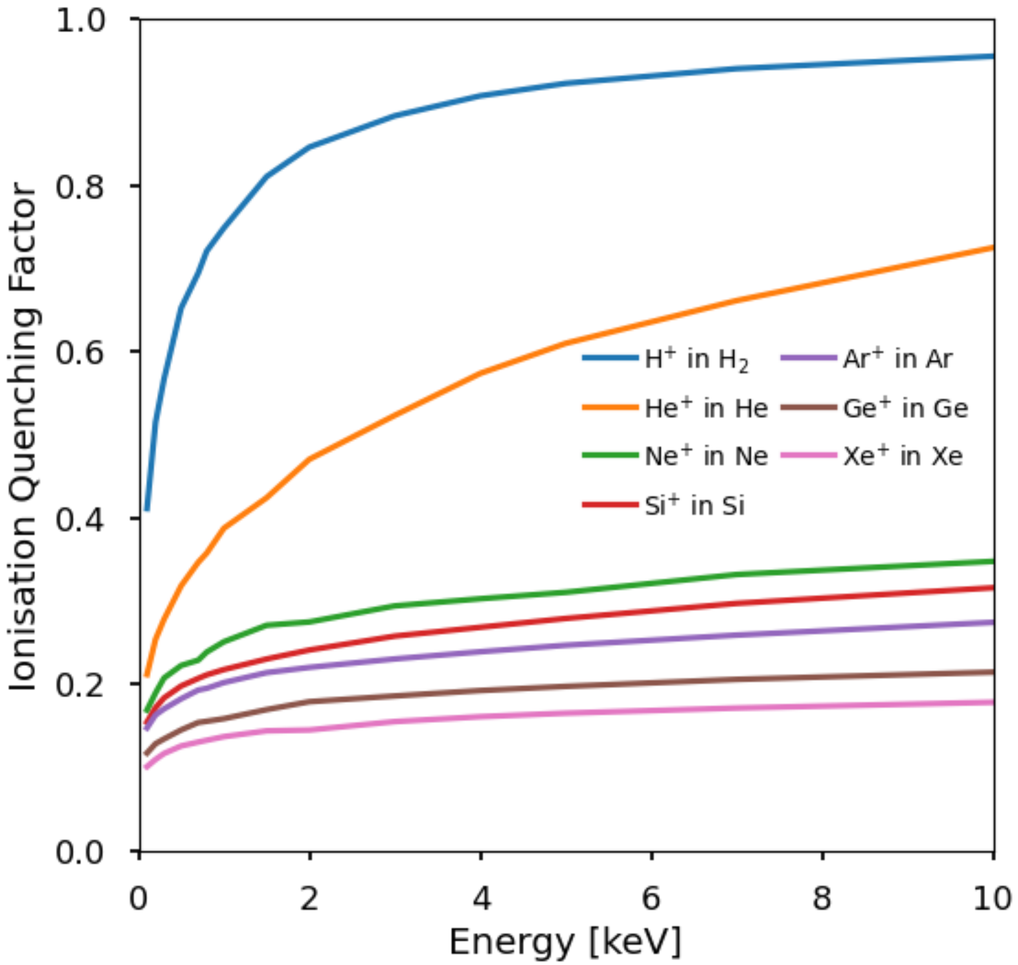


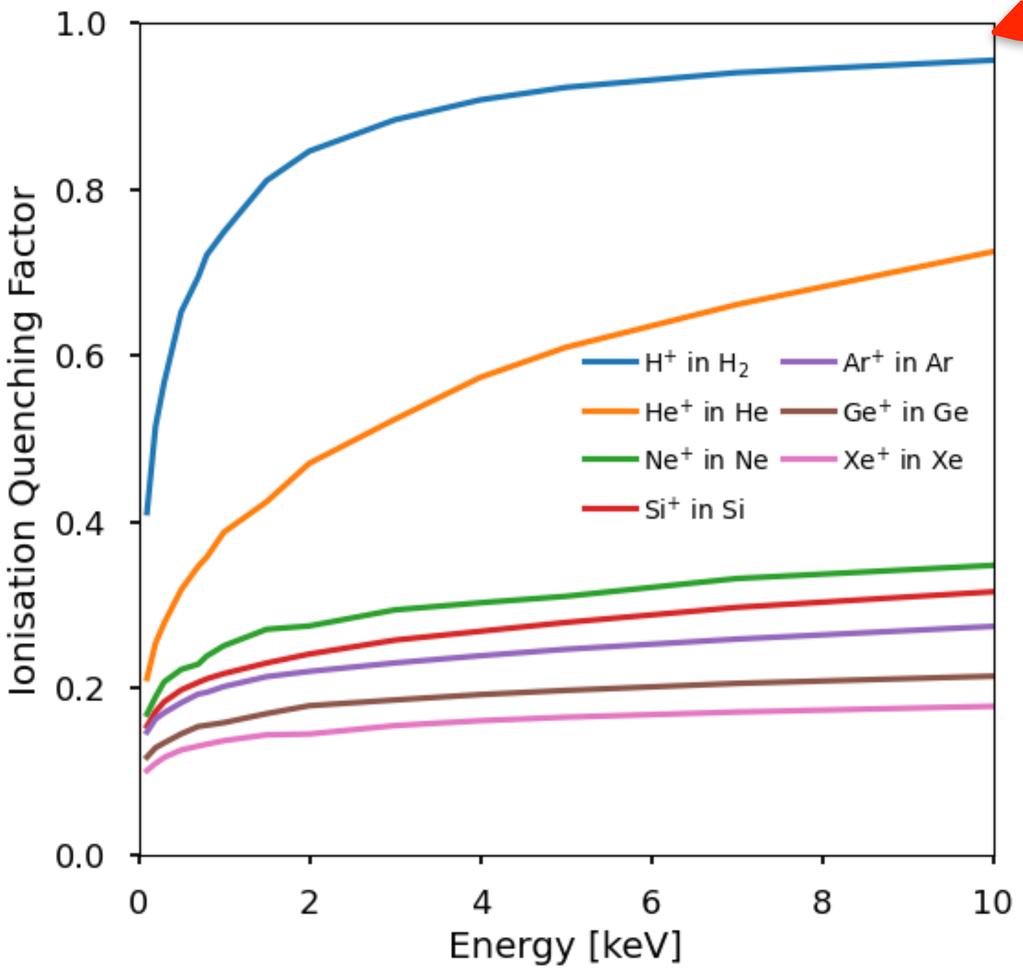
First demonstration of principle!
Moving to using ACHINOS

Ionisation Quenching Factor

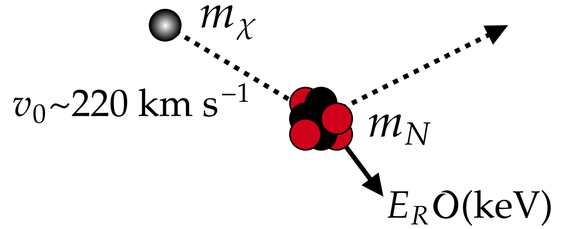


- **Kinematic matching**: **low-mass targets** are **favourable for light-DM** detection by nuclear recoils
- **Light targets** have **favourable quenching factors**

Ionisation Quenching Factor



Stopping and Range of Ions in Matter (SRIM) simulation



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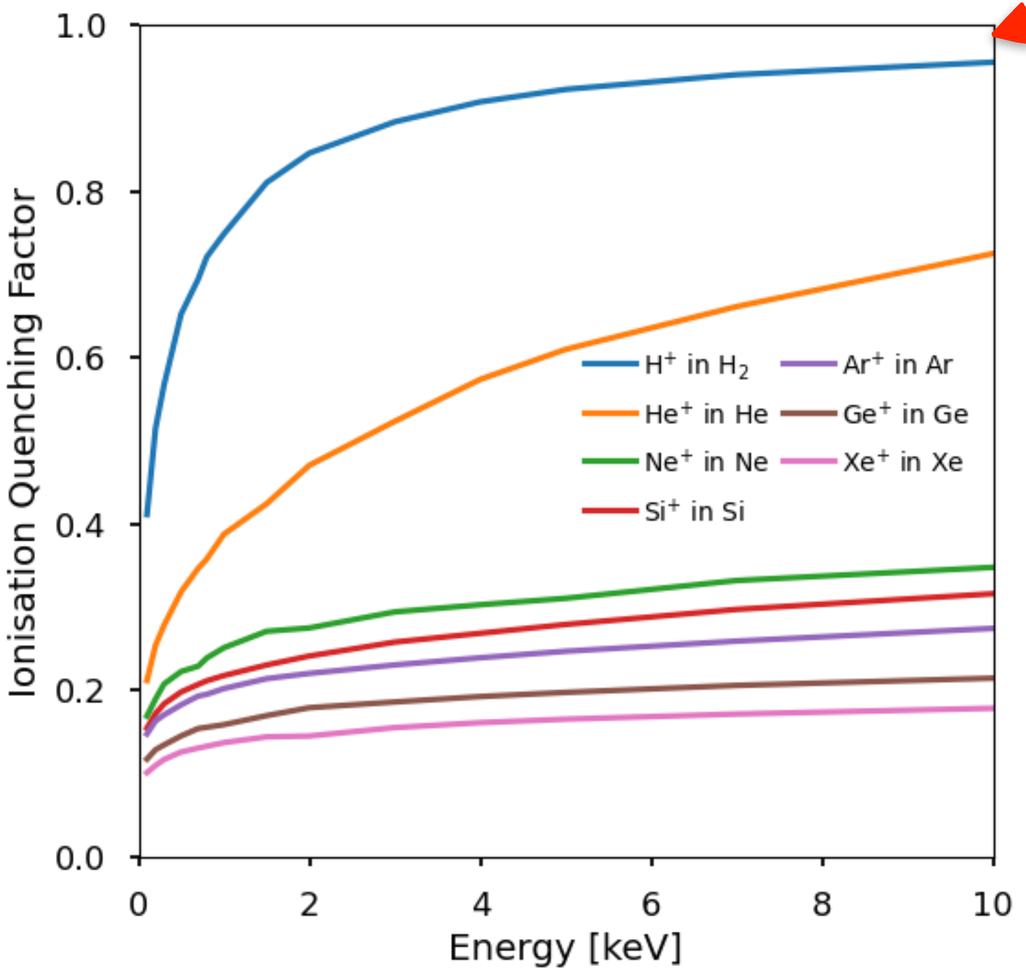

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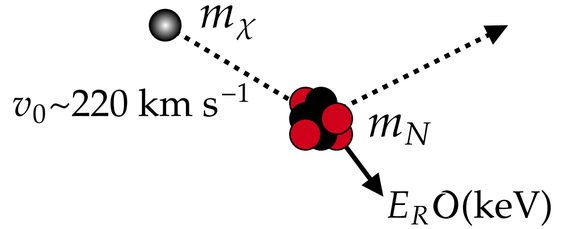

- **2 measurement approaches** in NEWS-G
  - Neutron scattering at TUNL — *Phys.Rev.D 105 (2022) 5, 052004*
  - Electron/Ion beam, COMIMAC, Grenoble — *Eur.Phys.J.C 82 (2022) 12, 1114*
- **Innovative approach** using literature measurements — *Astropart.Phys. 141 (2022) 102707*

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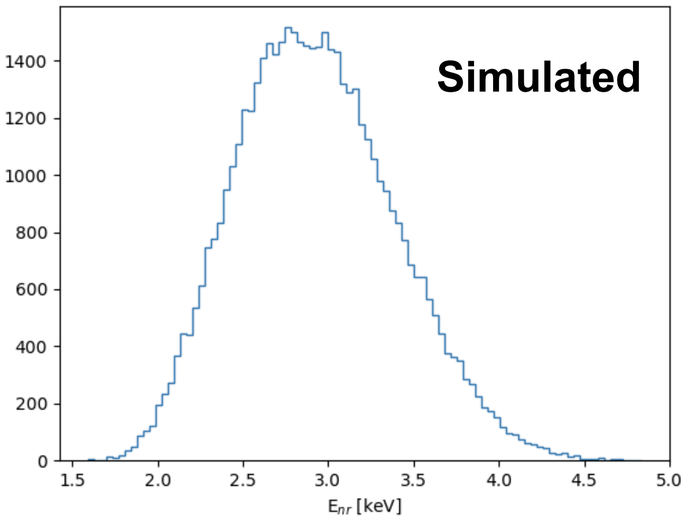
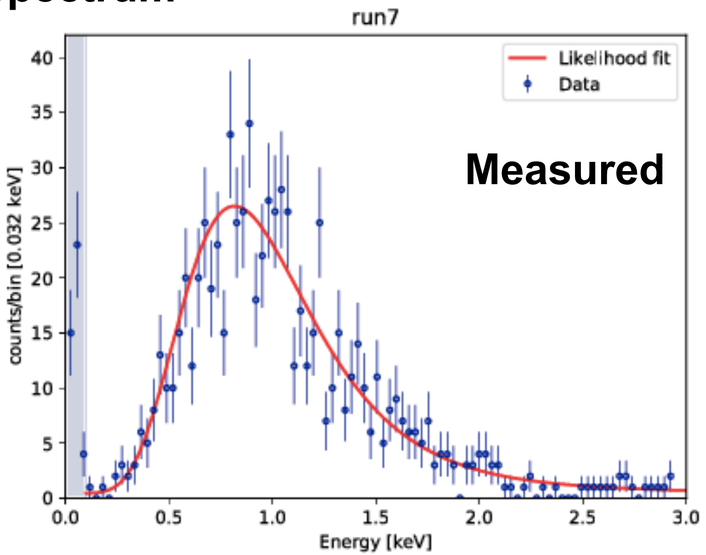
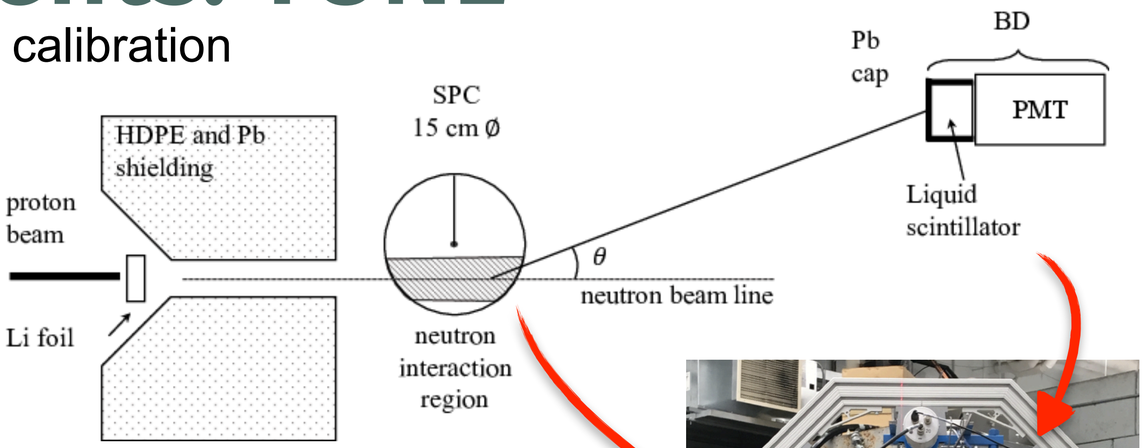
Quenching Factor Measurements: TUNL

Neutron scattering-induced nuclear recoils in SPC → compare to calibration

Recoil Spectrum







Run	E_{nr} [keV$_{nr}$]	$\sigma_{E_{nr}}$ [keV$_{nr}$]	θ [°]	σ_θ [°]
8	6.80	1.15	29.02 ± 0.4	2.45
7	2.93	0.46	18.84 ± 0.1	1.47
14	2.02	0.29	15.63 ± 0.3	1.12
9	1.70	0.26	14.33 ± 0.06	1.1
10	1.30	0.2	12.48 ± 0.05	0.94
14	1.03	0.2	11.13 ± 0.3	1.1
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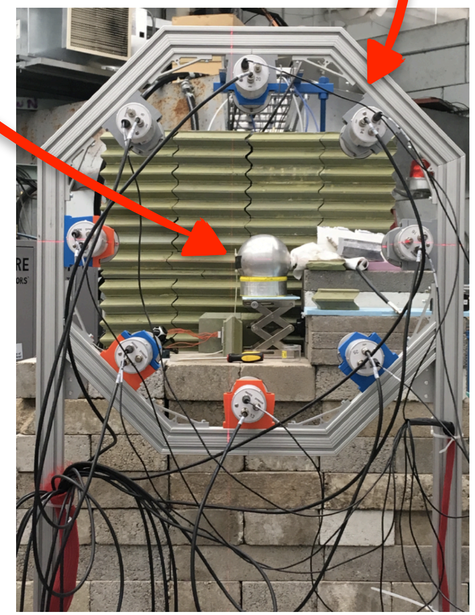
14	0.34	0.11	6.33 ± 0.26	1.1



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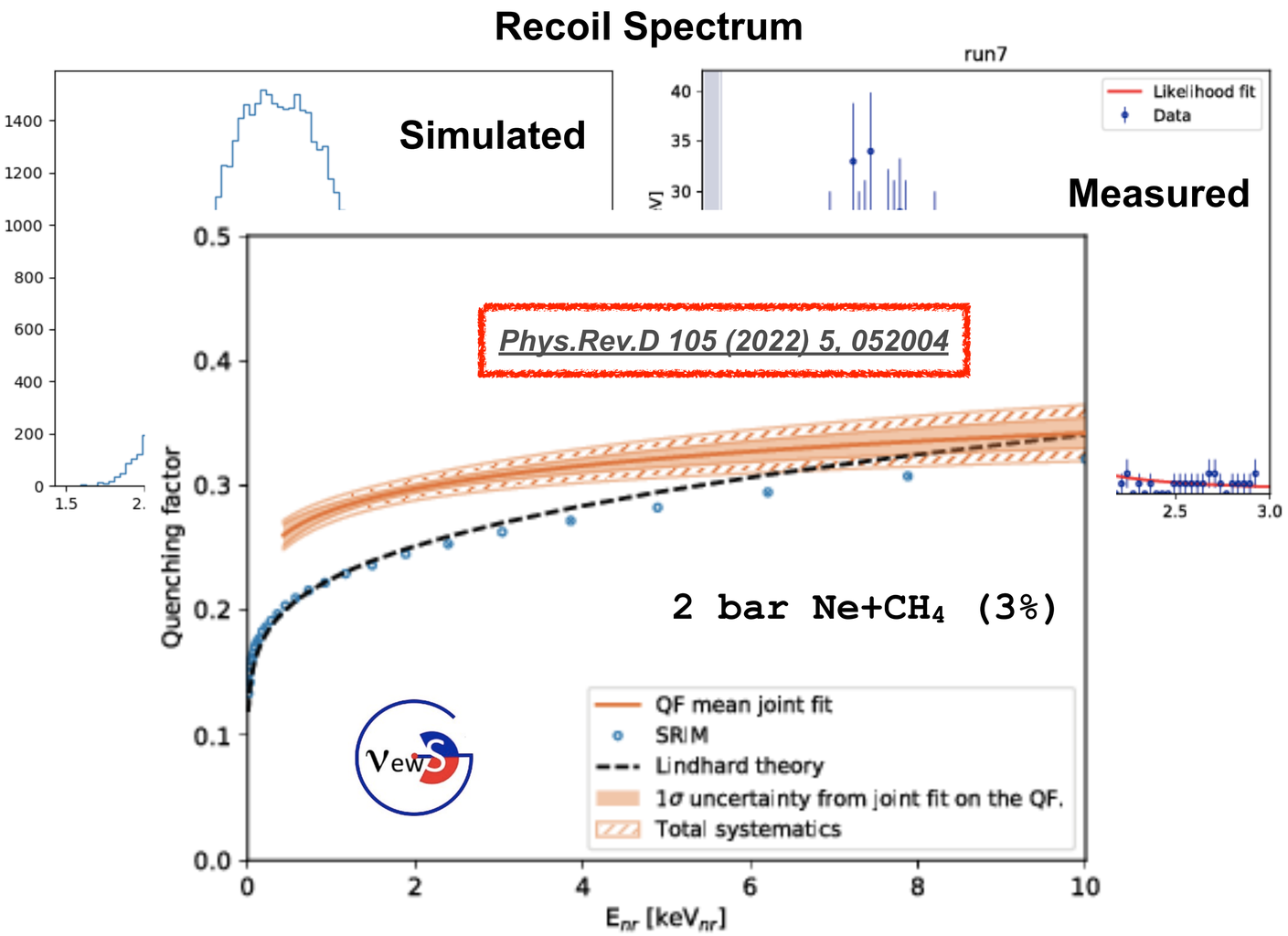

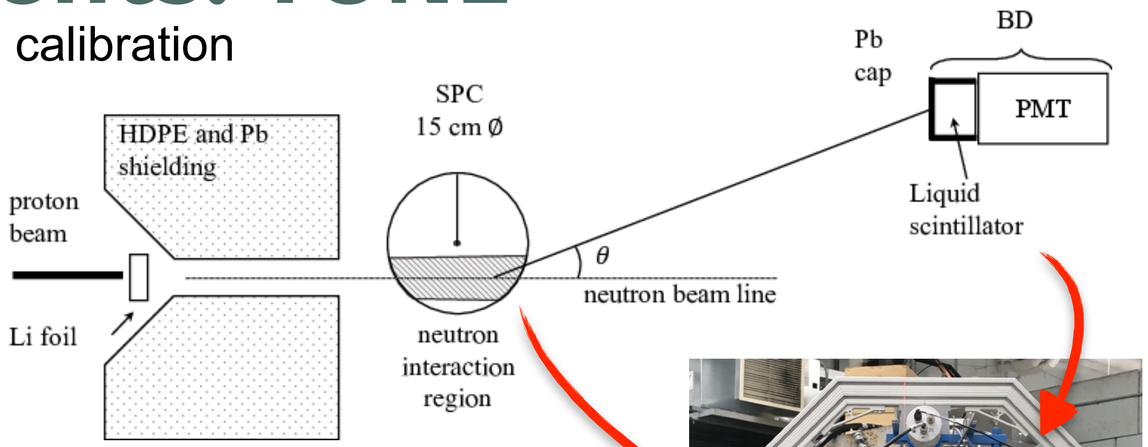

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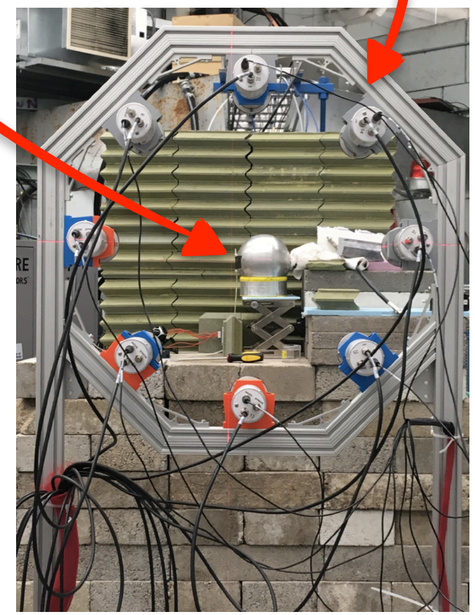
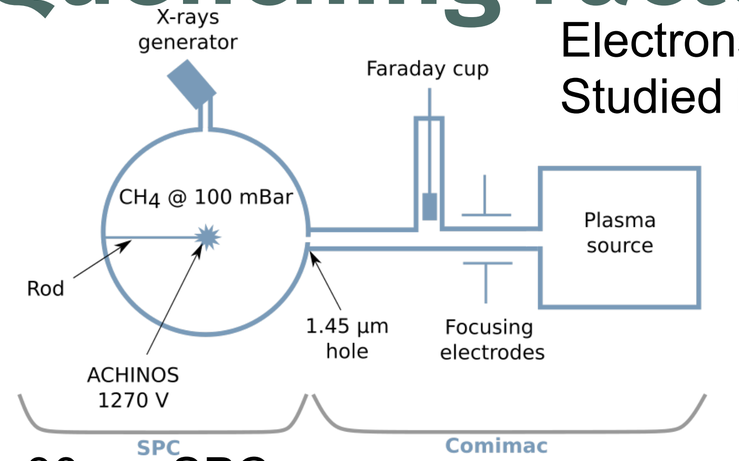


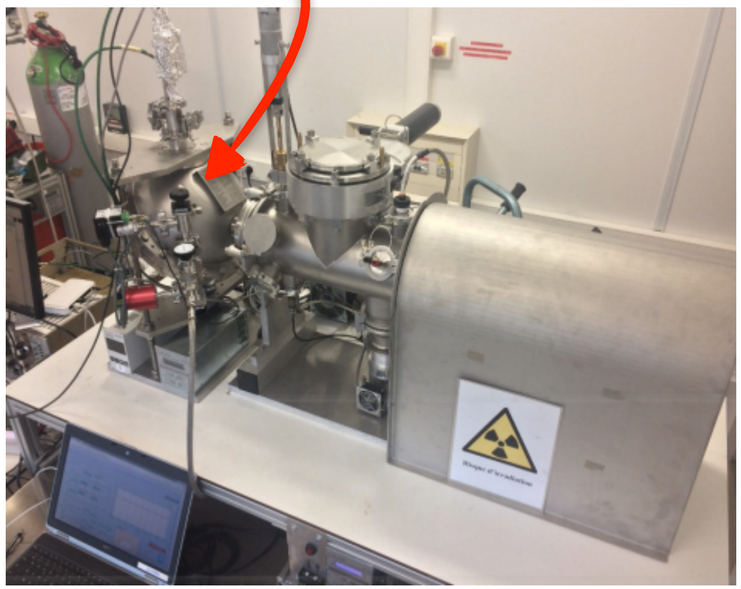
Quenching Factor Measurements: COMIMAC

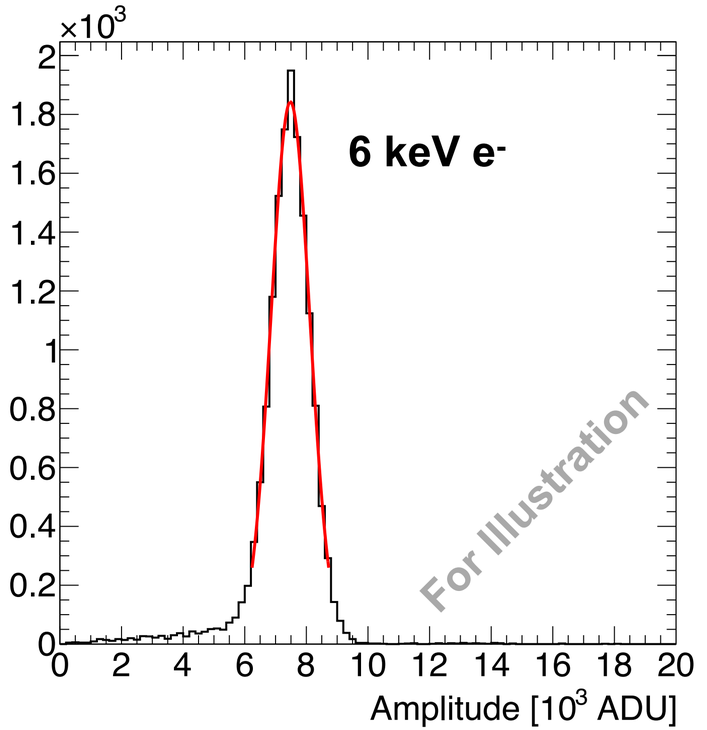


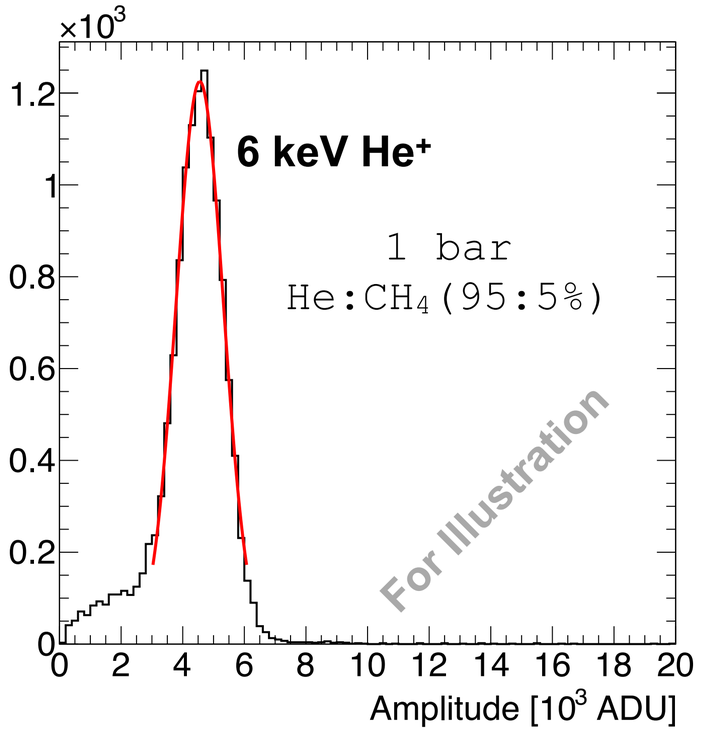
Electrons and ions directed into SPC → compare response

Studied ions 2 - 13 keV, calibrated with e^- 1.5 - 13 keV

⌀30 cm SPC







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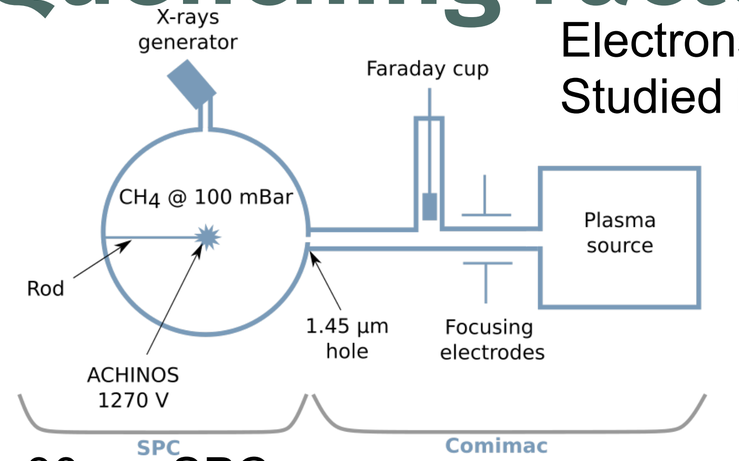

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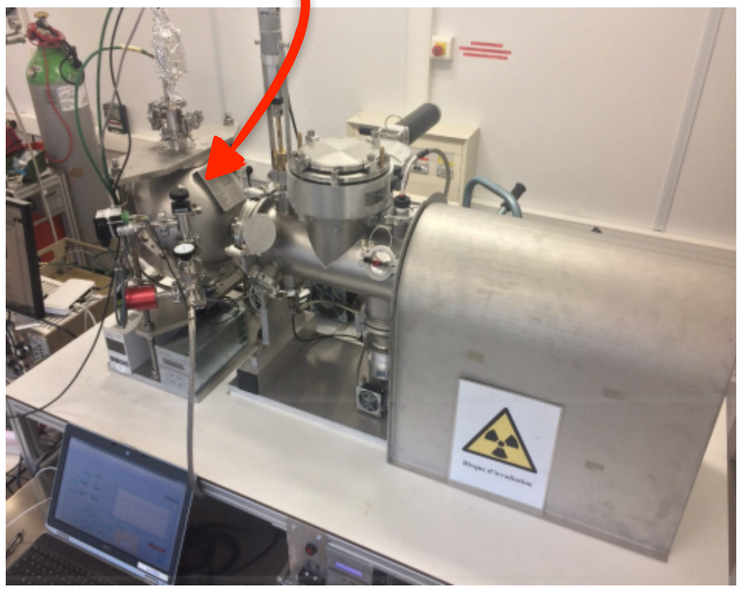
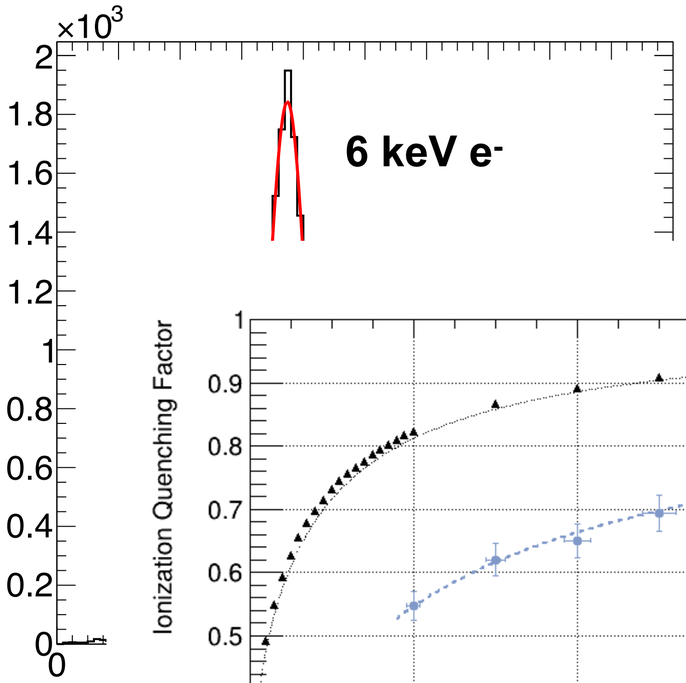
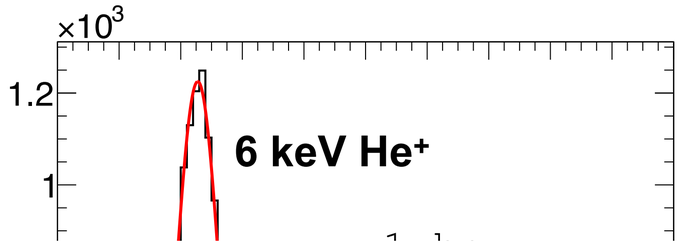
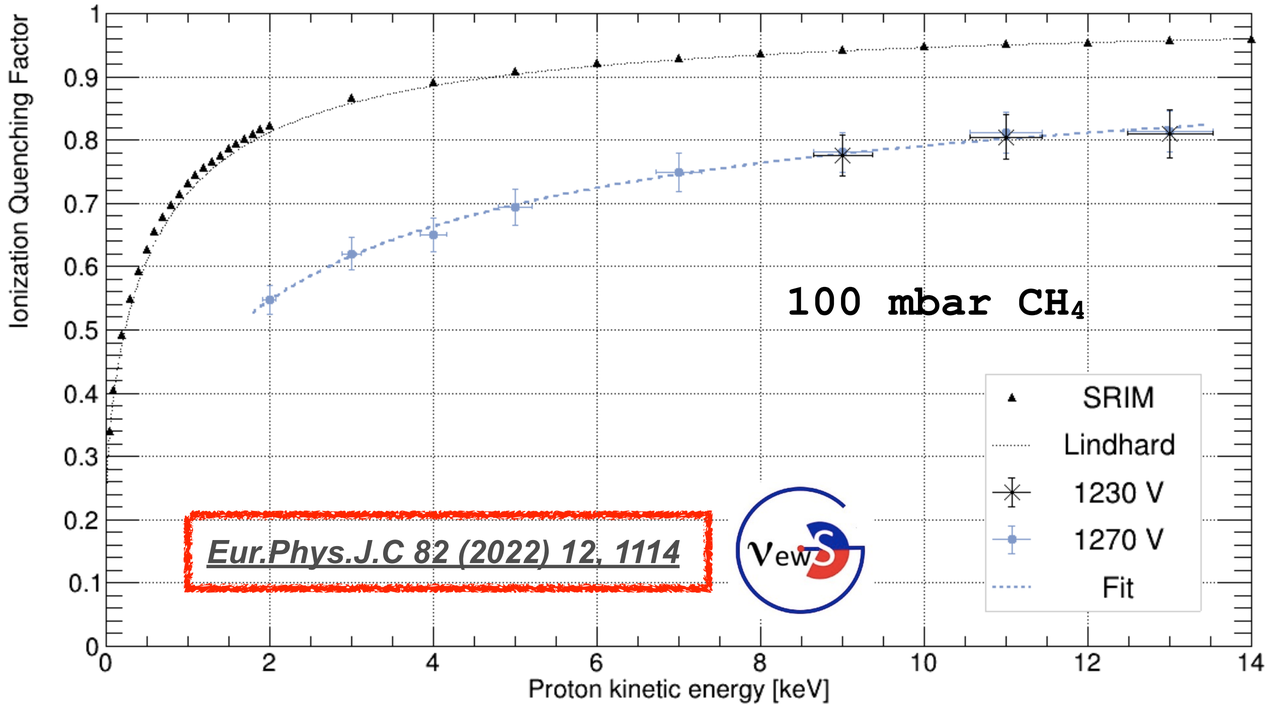


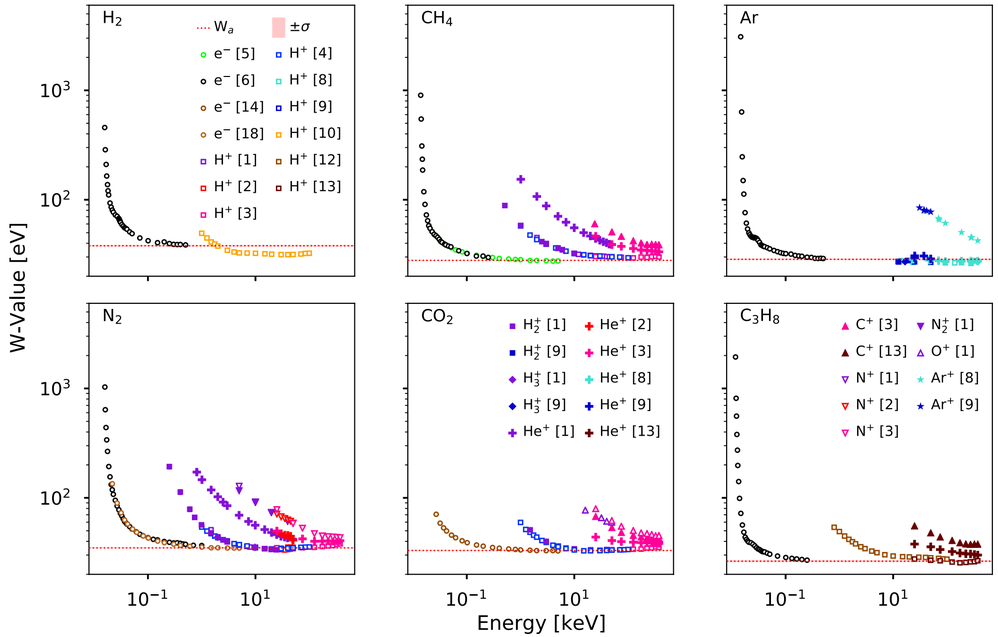






Quenching Factor Estimates: W-Values

- W-value: **Average energy** required to produce **electron-ion pair**
- W different for electrons and ions, and varies with energy
  - ➡Difference is quantified by QF
- W of electrons and ions in gases prev. studied for dosimetry
  - ➡Comparing asymptotic electron W-value and W(E) for ions, get QF



[Astropart.Phys. 141 (2022) 102707]

Quenching Factor Estimates: W-Values

- W-value: **Average energy** required to produce **electron-ion pair**
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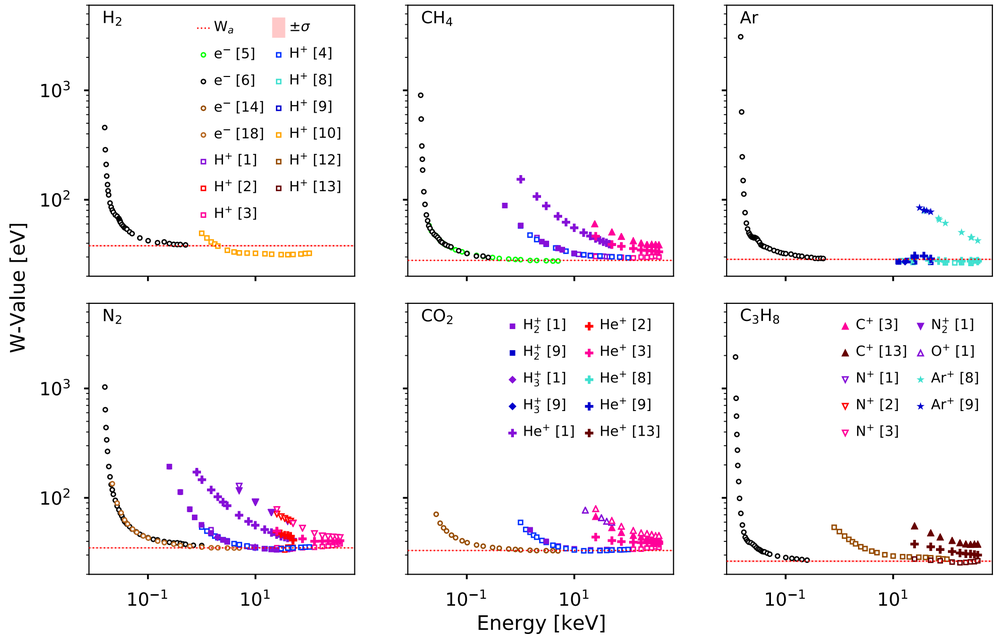

Astropart.Phys. 141 (2022) 102707

Gas	W [eV]	
	ICRU	Asymptotic
H_2	36.5±0.7	38.0±0.8
CH_4	27.3±0.6	27.90± 0.01
N_2	34.8±0.7	34.91±0.17
Ar	26.4±0.5	28.5±0.6
CO_2	33.0±0.7	33.02±0.12
C_3H_8	24.0±0.5	26.4±0.5

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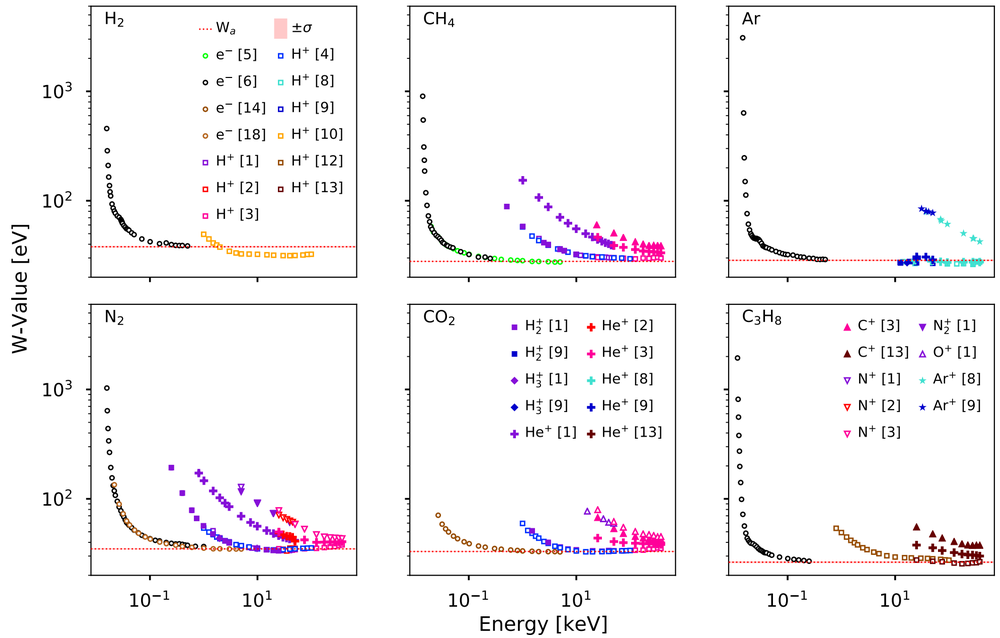
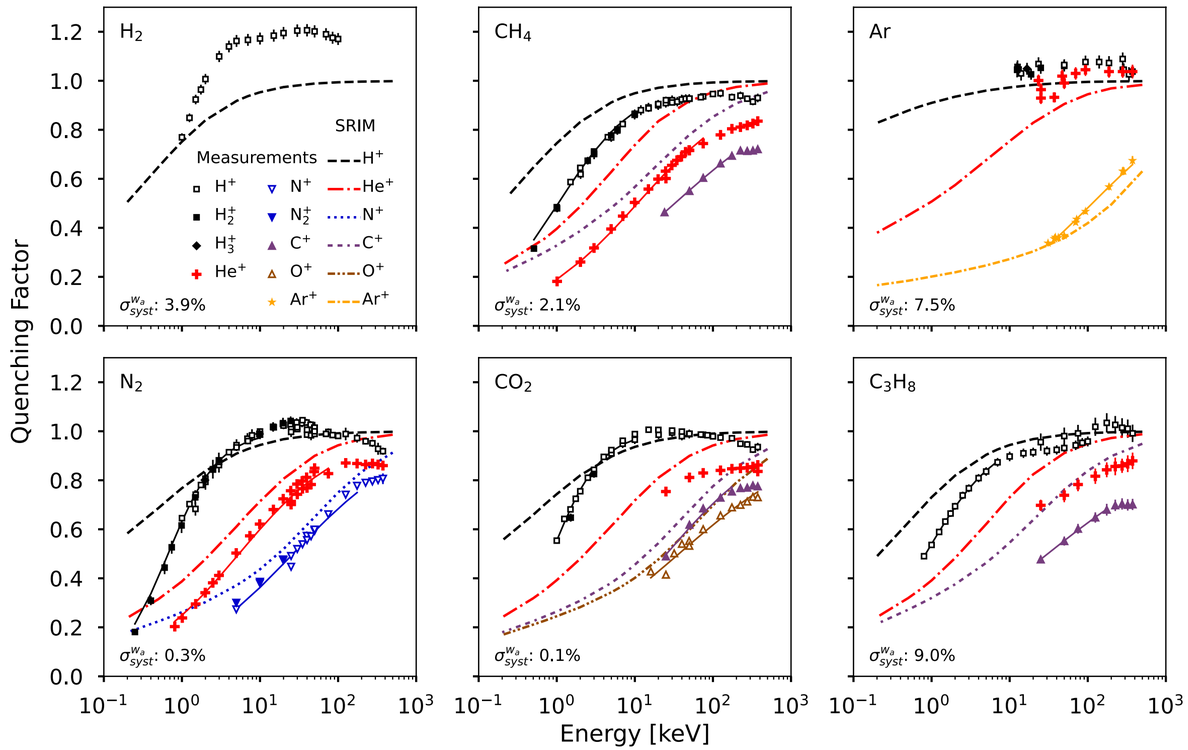
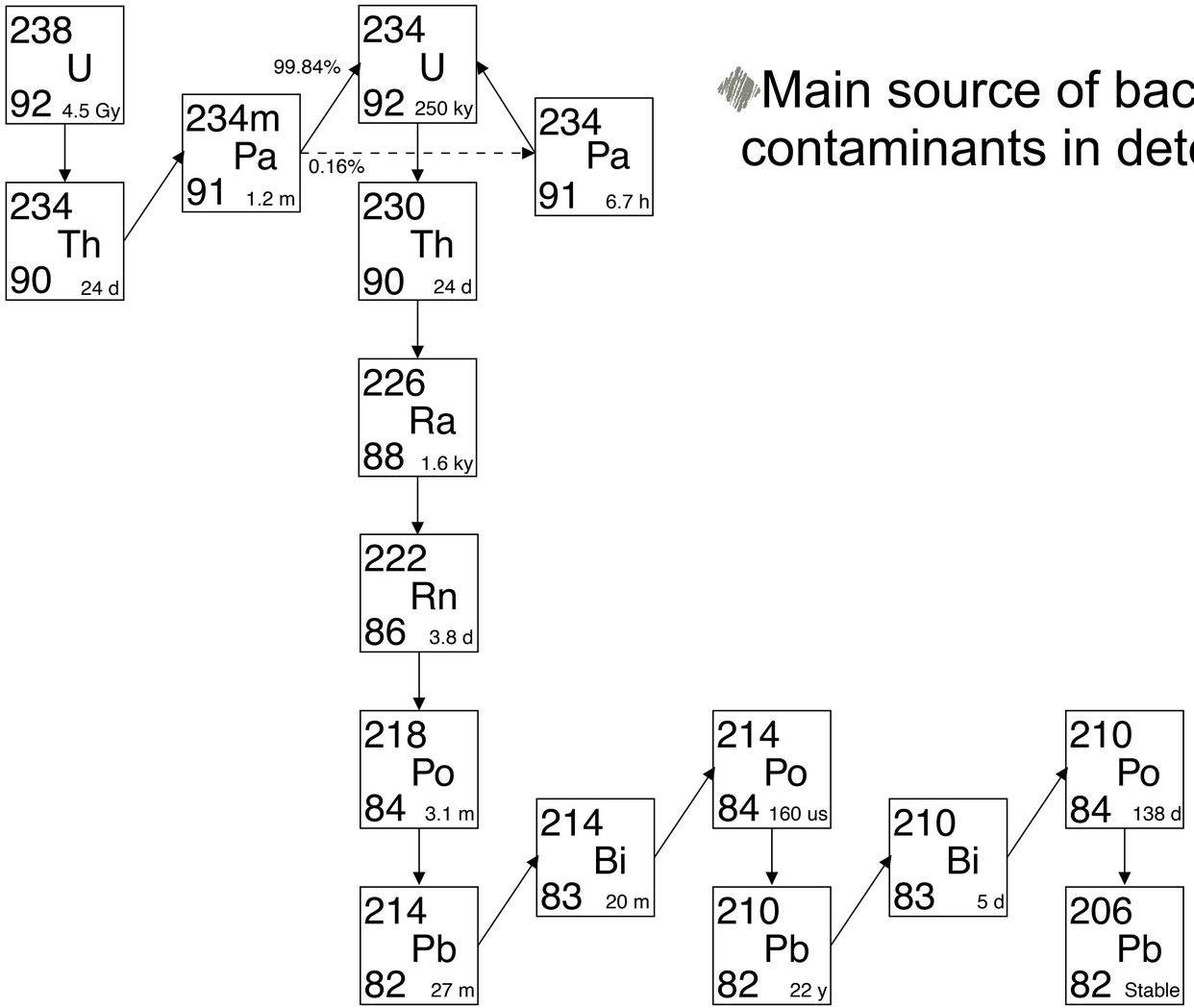


Extends QF knowledge in NEWS-G gases beyond current measurements!

Astropart.Phys. 141 (2022) 102707



Overcoming Backgrounds in Copper



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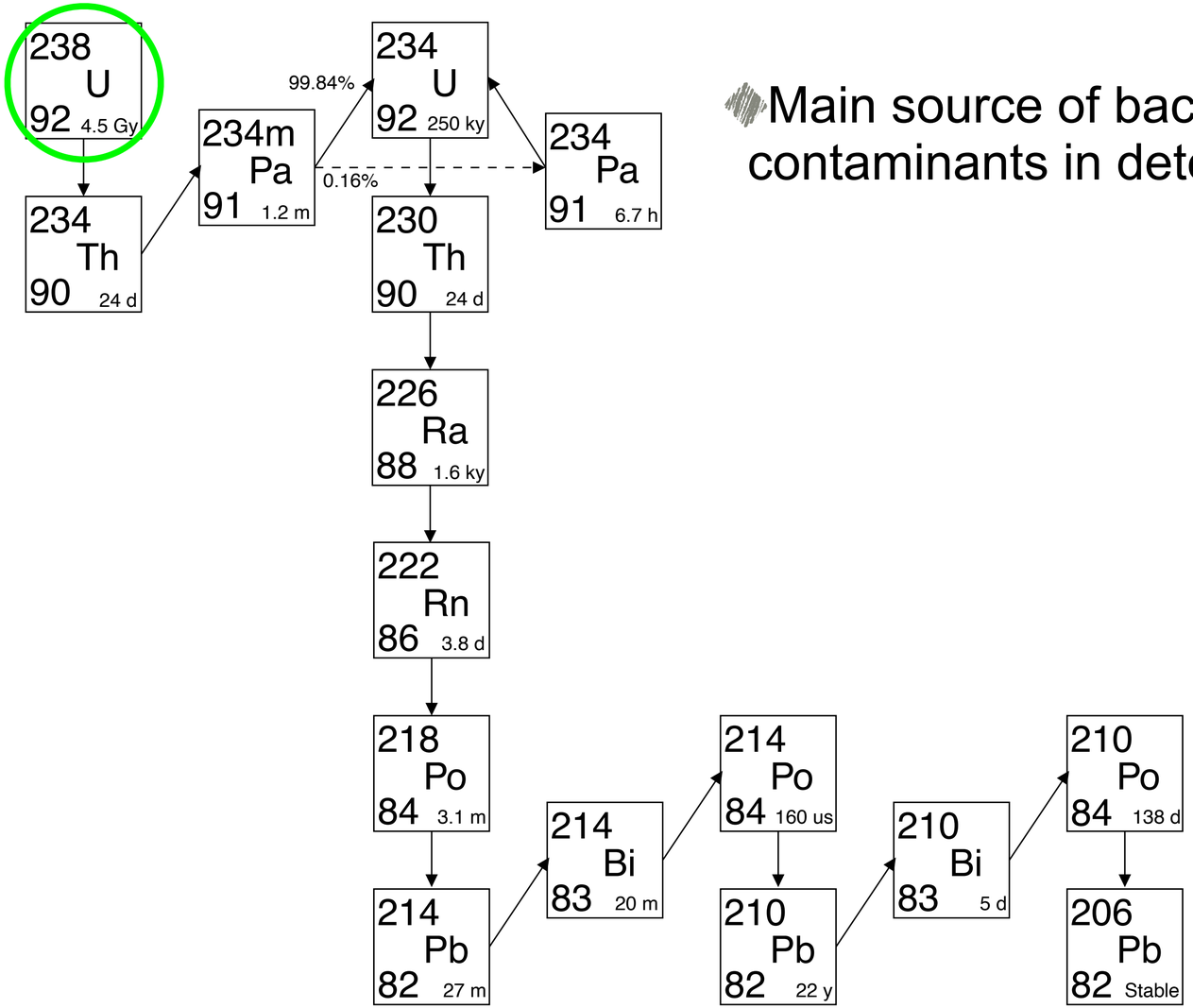

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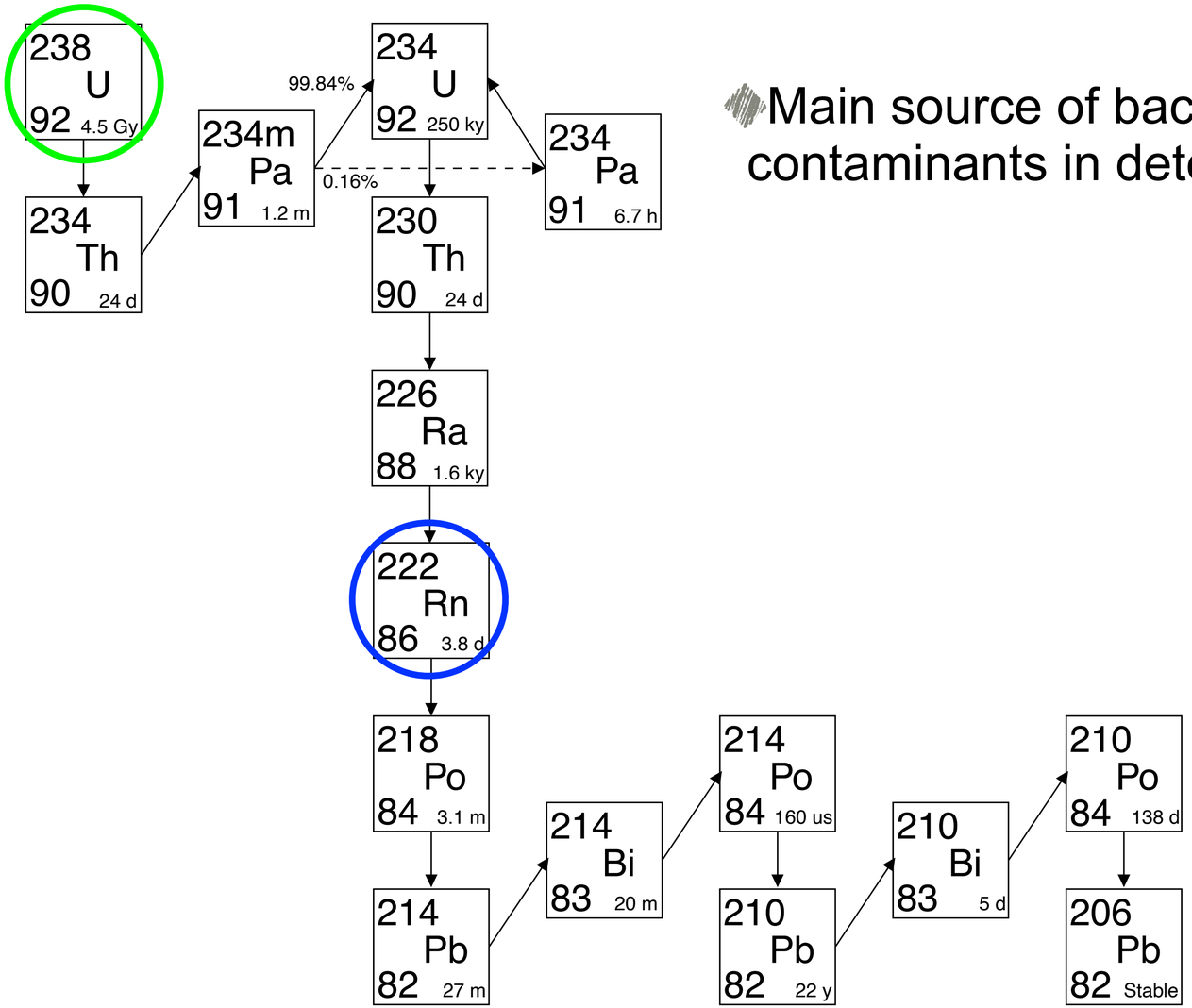

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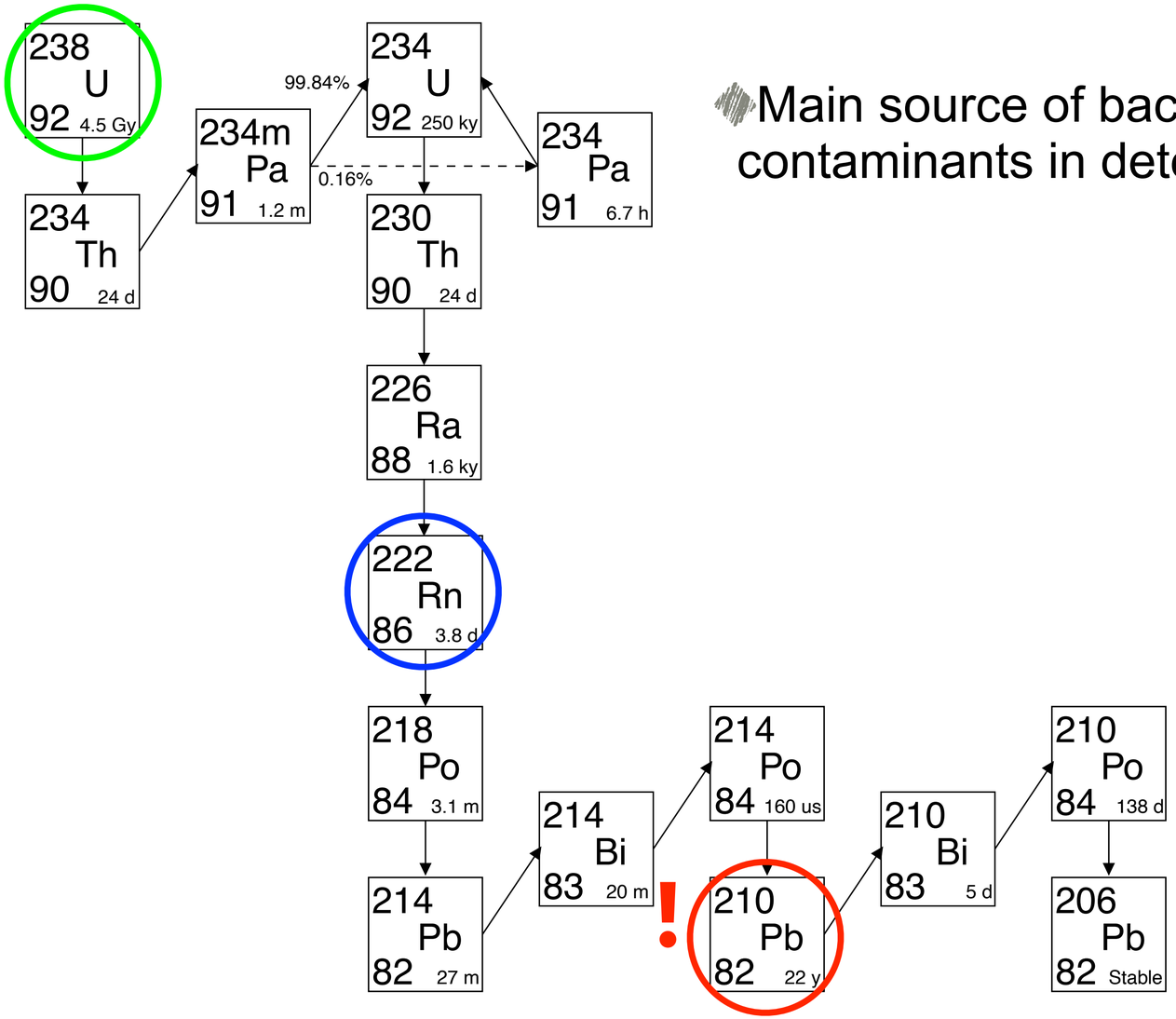

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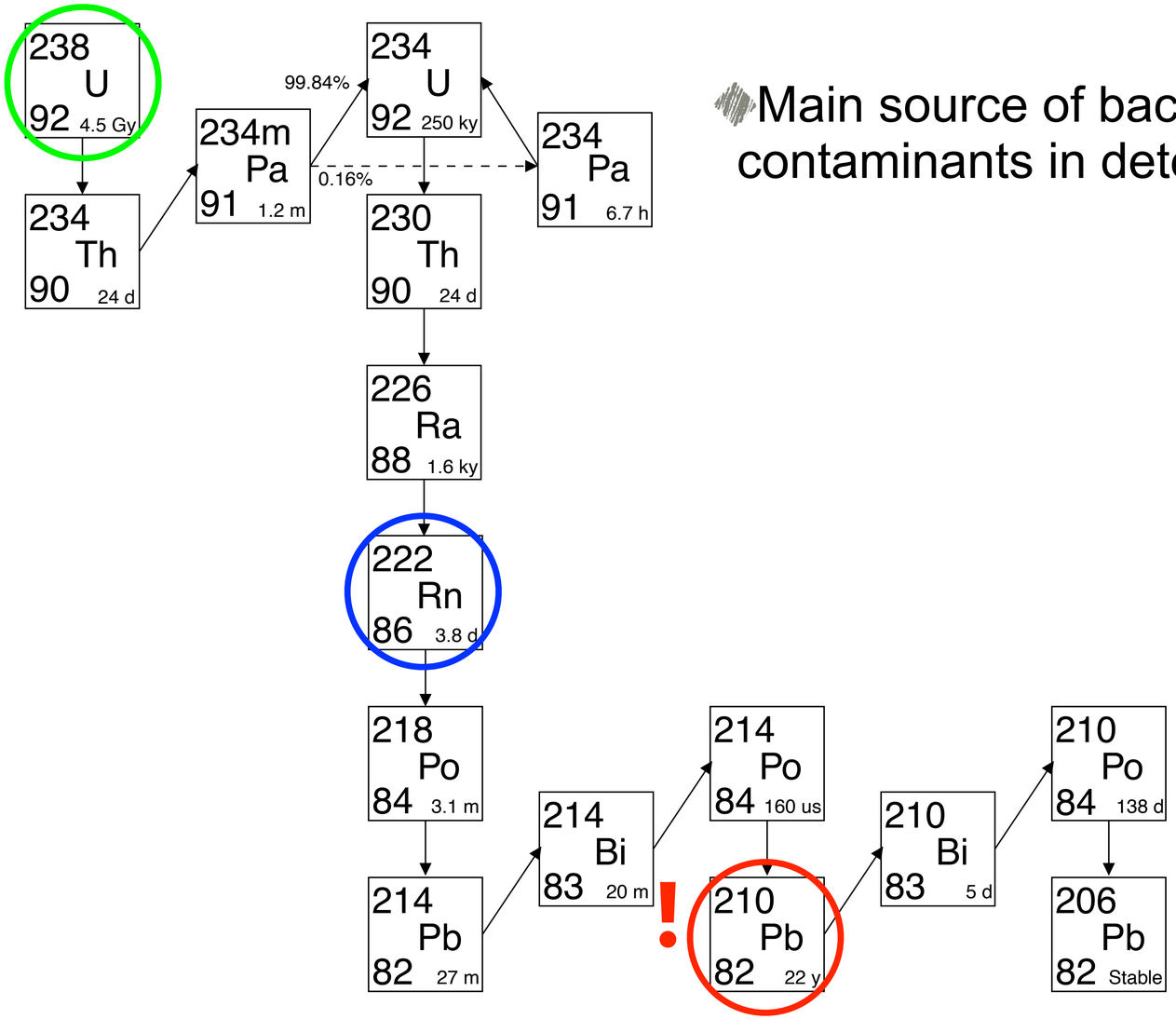

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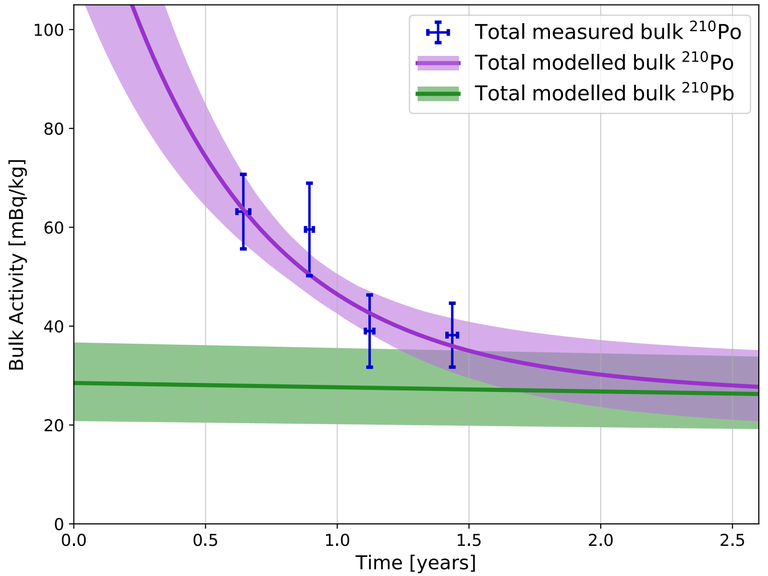

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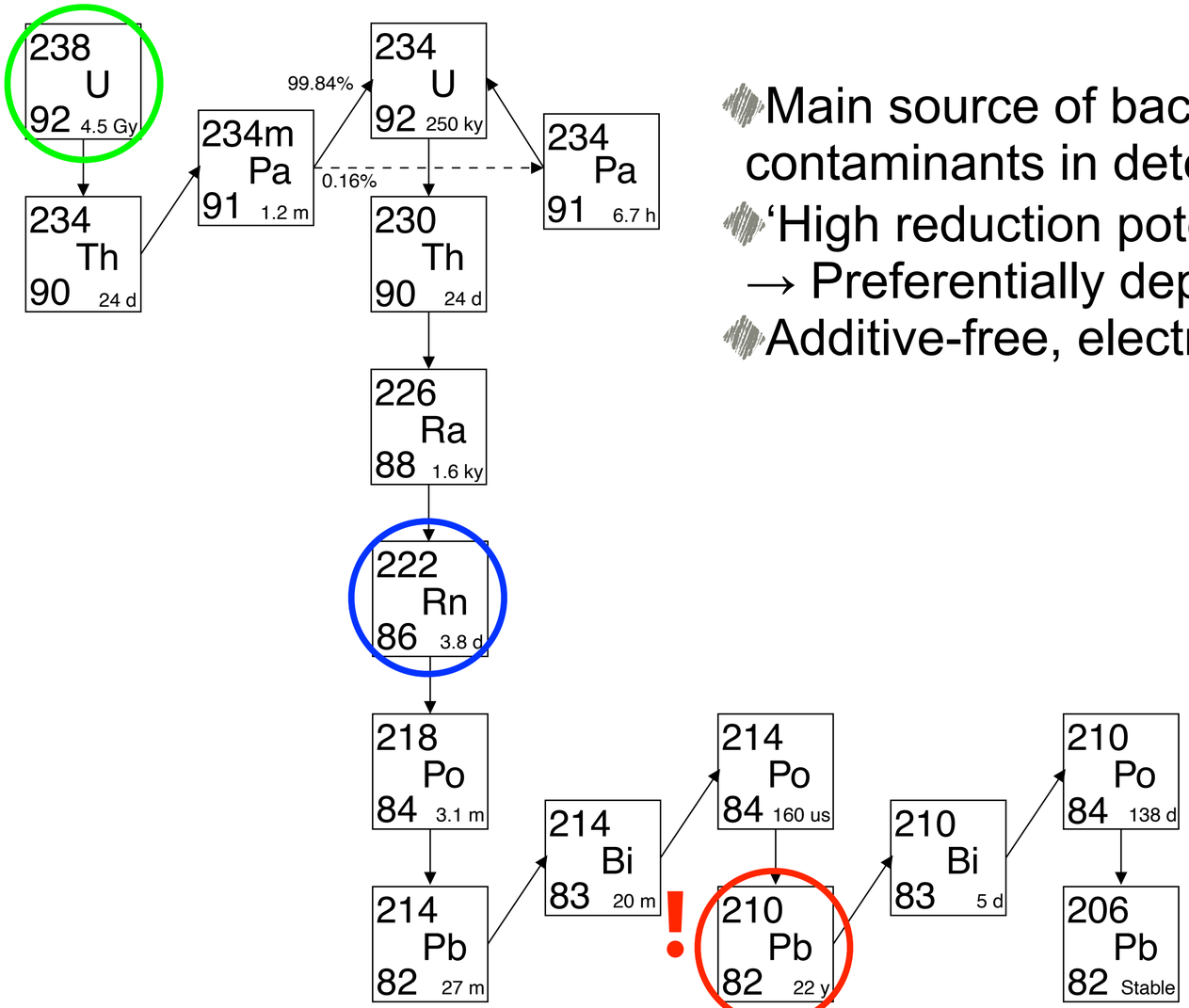
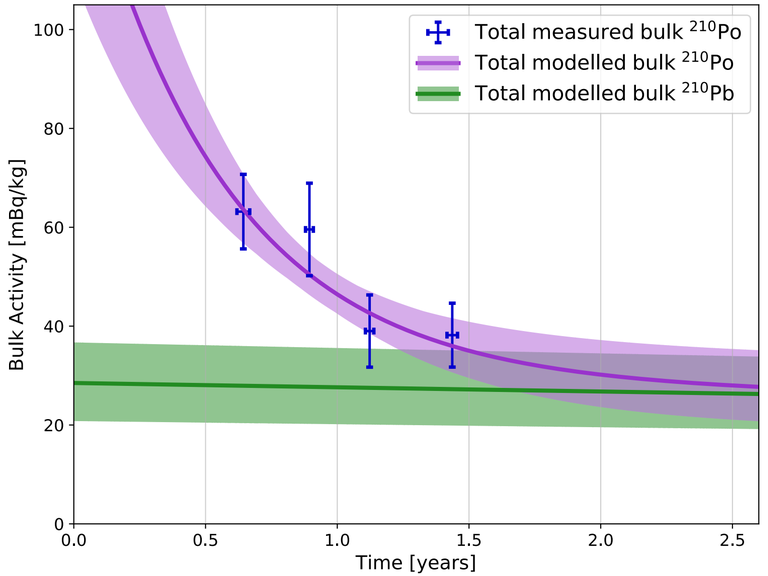
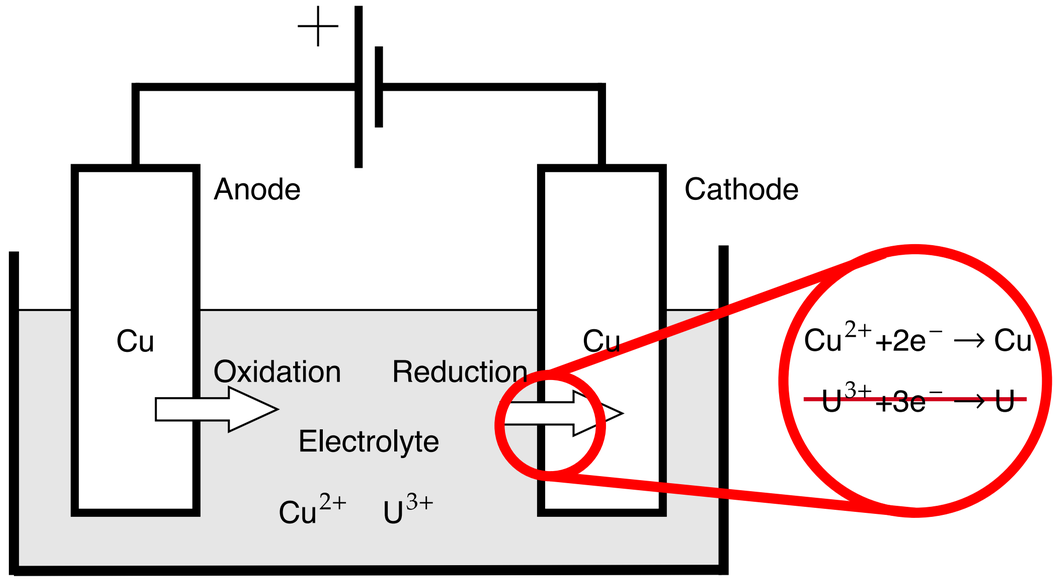


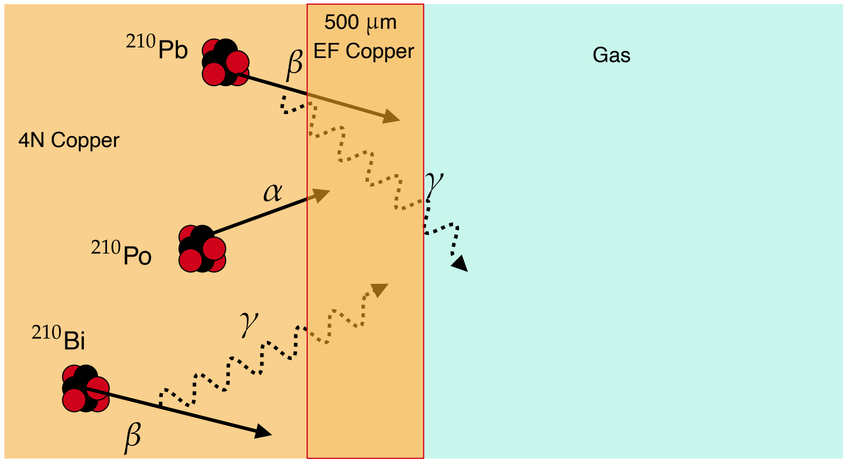
- Main source of background is contaminants in detector copper
- 'High reduction potential' of copper → Preferentially deposited
- Additive-free, electroforming





Ultra-Pure Copper Electroforming

- **500 µm electroplated layer** to NEWS-G detector inner surface
- Demonstrated potential to electroform full detector on feasible time scale



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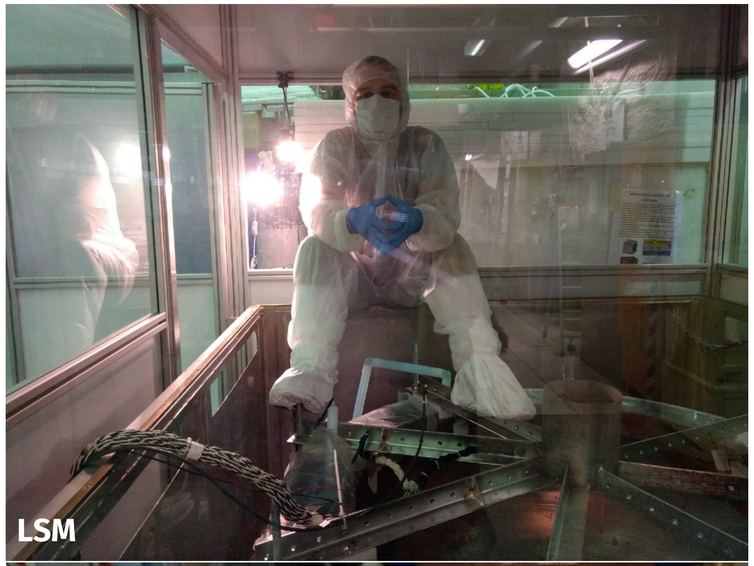

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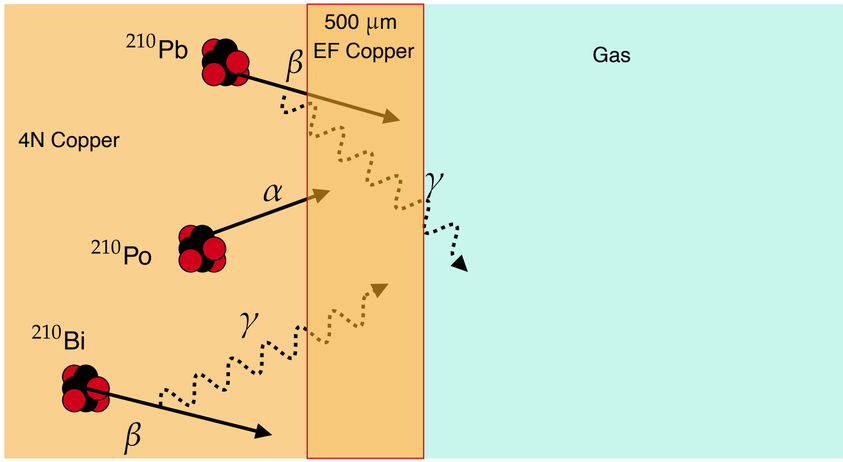

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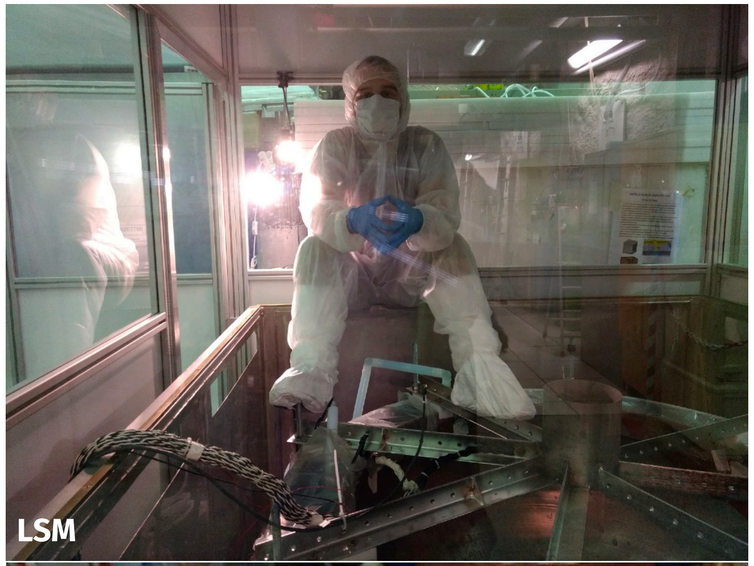

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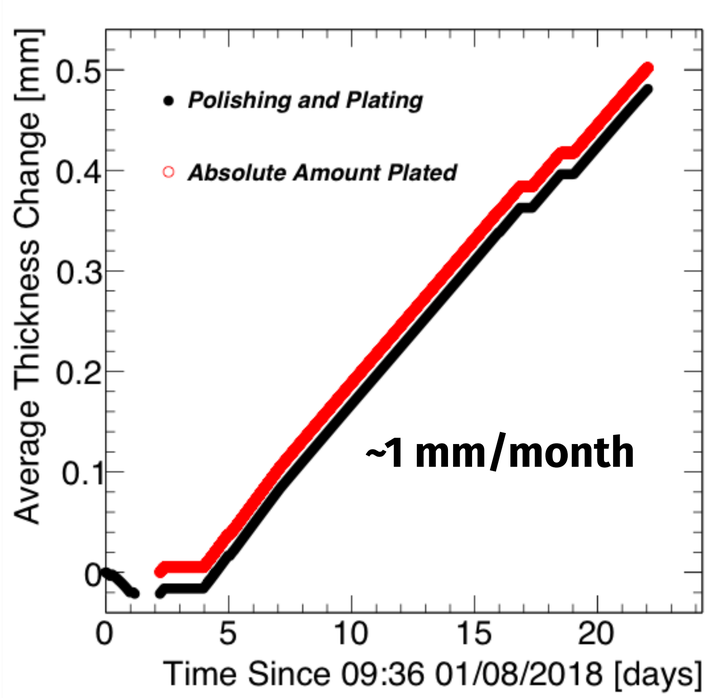
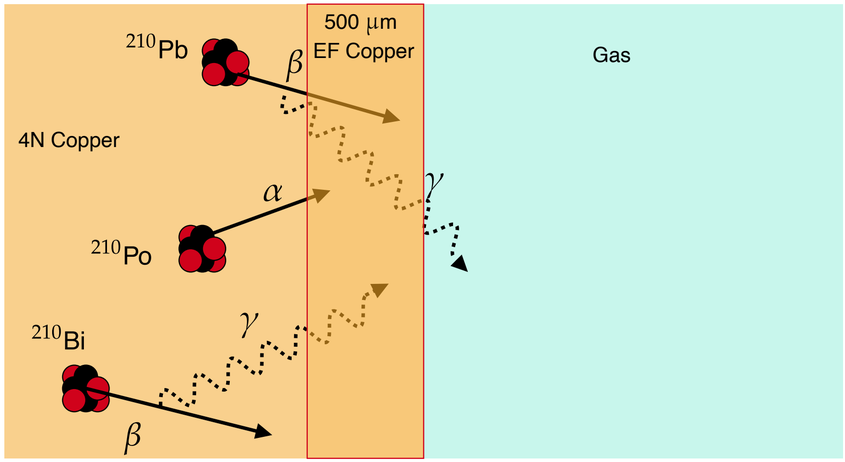




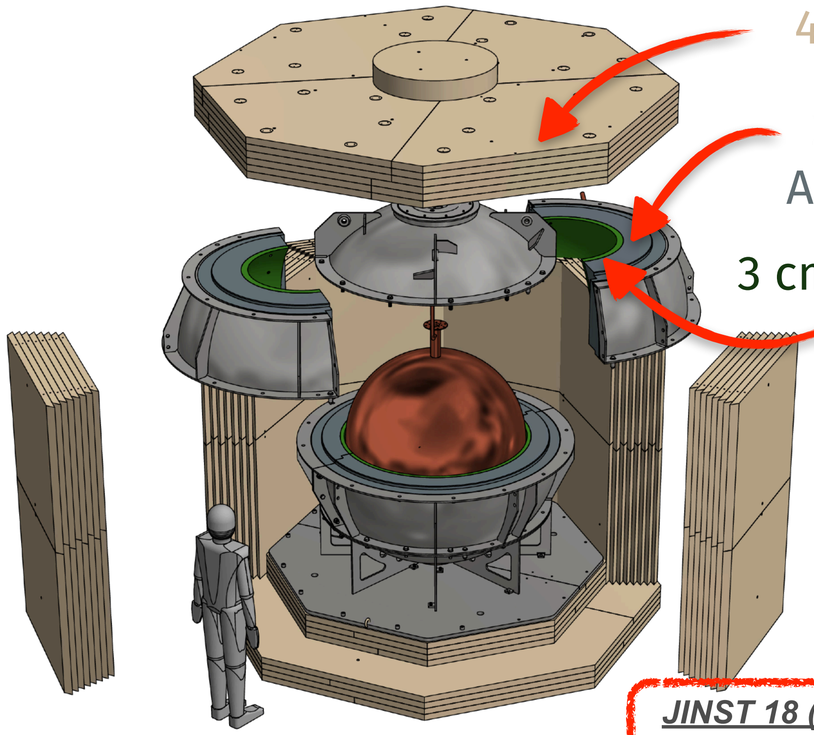
ICP-MS Assay

Sample	Weight [g]	^{232}Th [µBq kg^{-1}]	^{238}U [µBq kg^{-1}]
C10100 Cu (Machined)	-	8.7 ± 1.6	27.9 ± 1.9
Cu Electroformed	-	<0.119	<0.099
Hemisphere 1	0.256	<0.58	<0.26
Hemisphere 2	0.614	<0.24	<0.11

NIMA 988 (2021) 164844

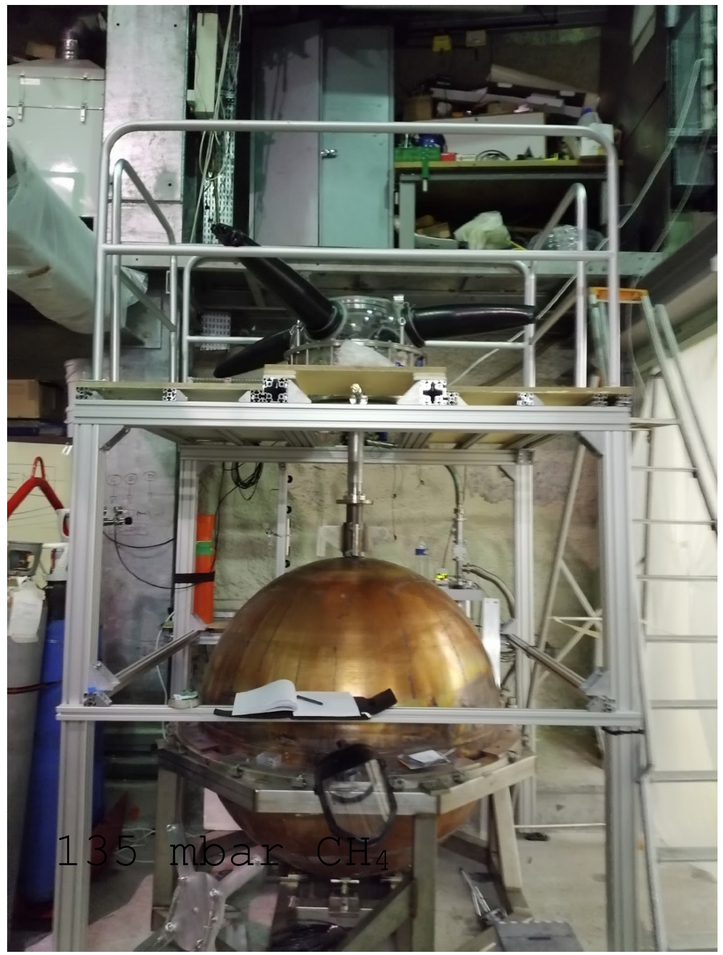
SNOGLOBE in SNOLAB

- ⌀140 cm detector **4N (99.99% pure)** Aurubis copper
  - ➡Electroplated internal layer
- Constructed and tested in LSM, France
  - ✓Commissioning data analysis finalising (CH_4)



JINST 18 (2023) 02, T02005

S140 in LSM



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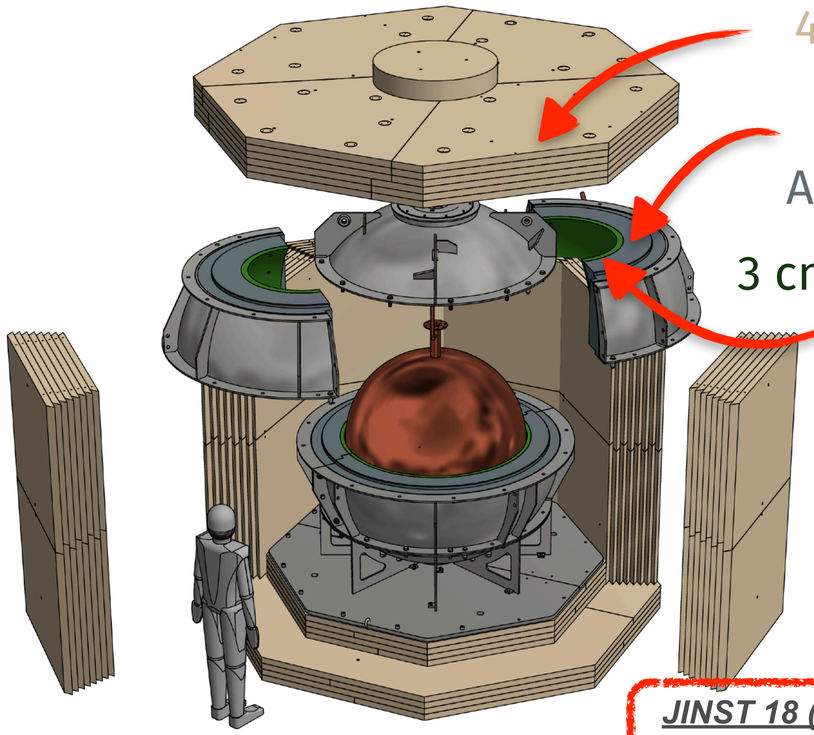
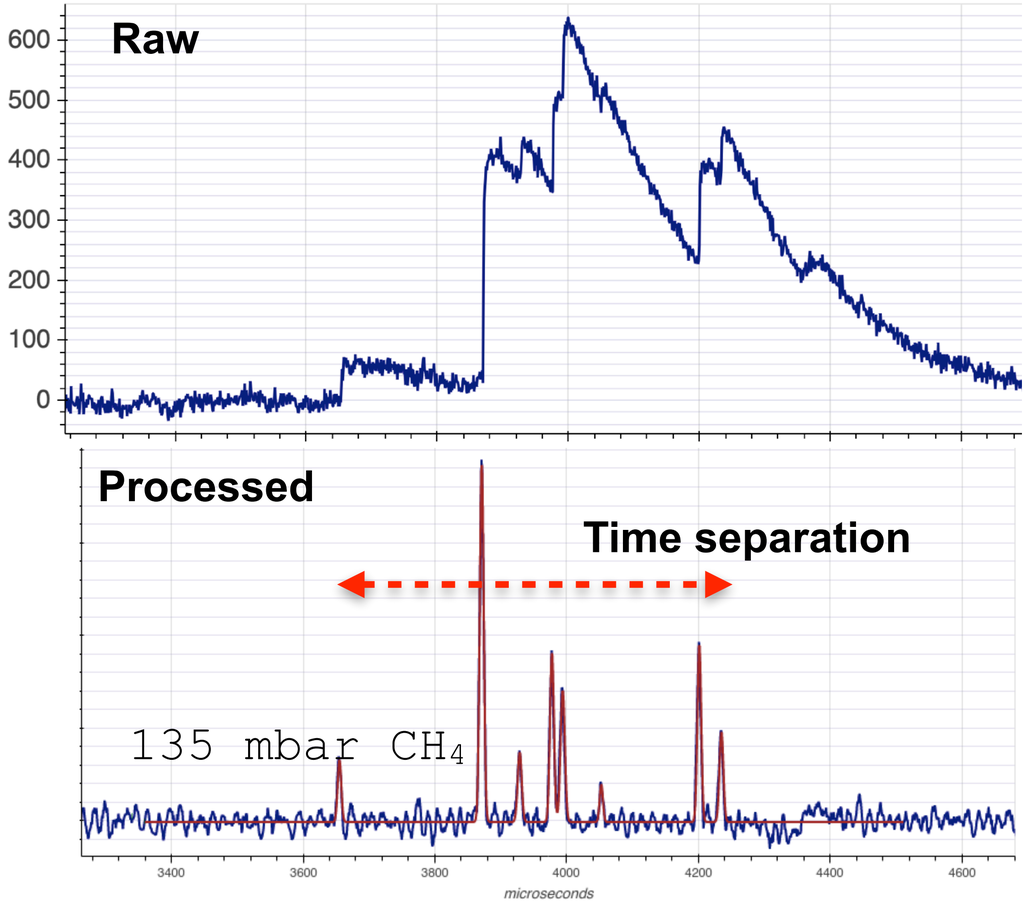


JINST 18 (2023) 02, T02005

- Discriminating variable: time separation
- Surface/volume and coincidence discrimination



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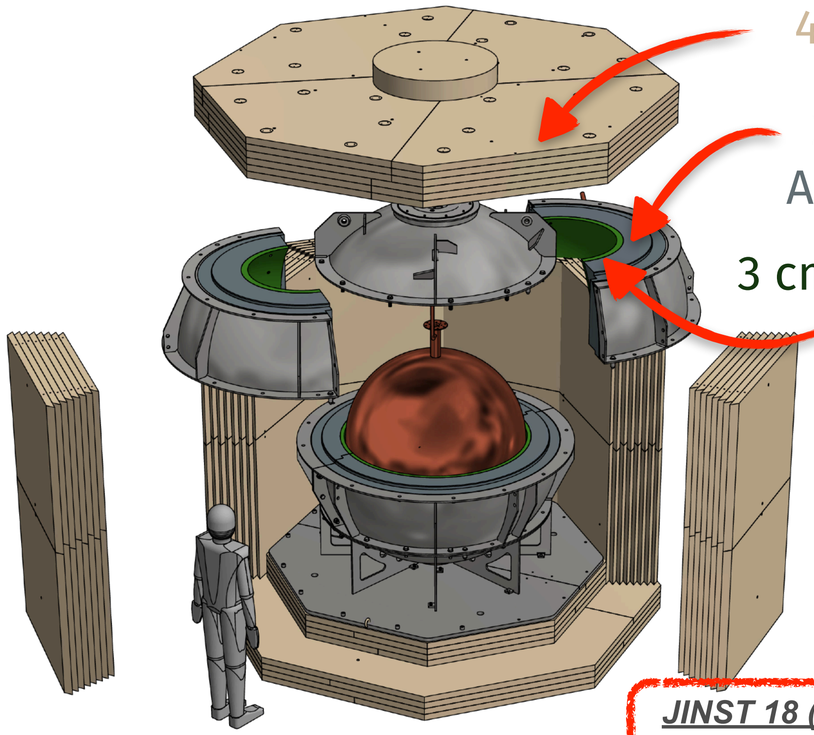

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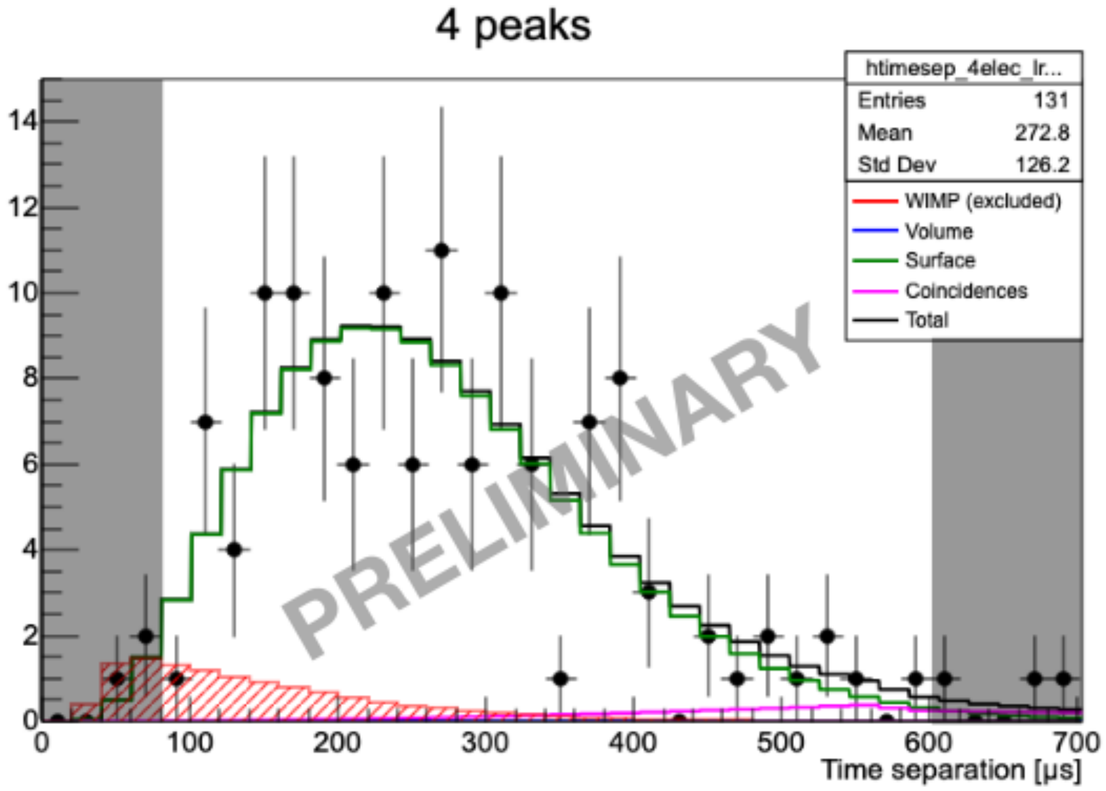

135 mbar CH_4

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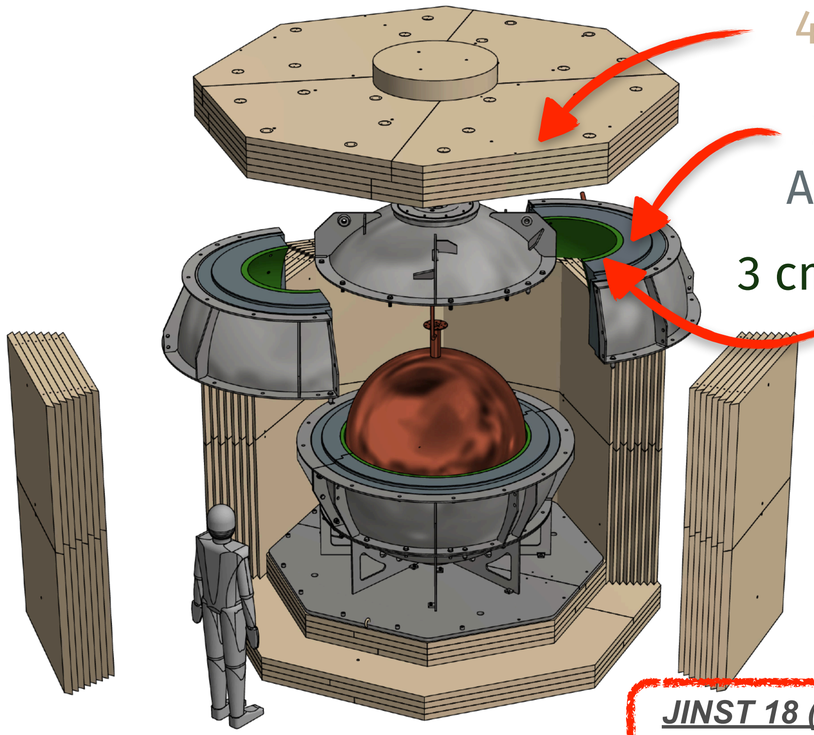

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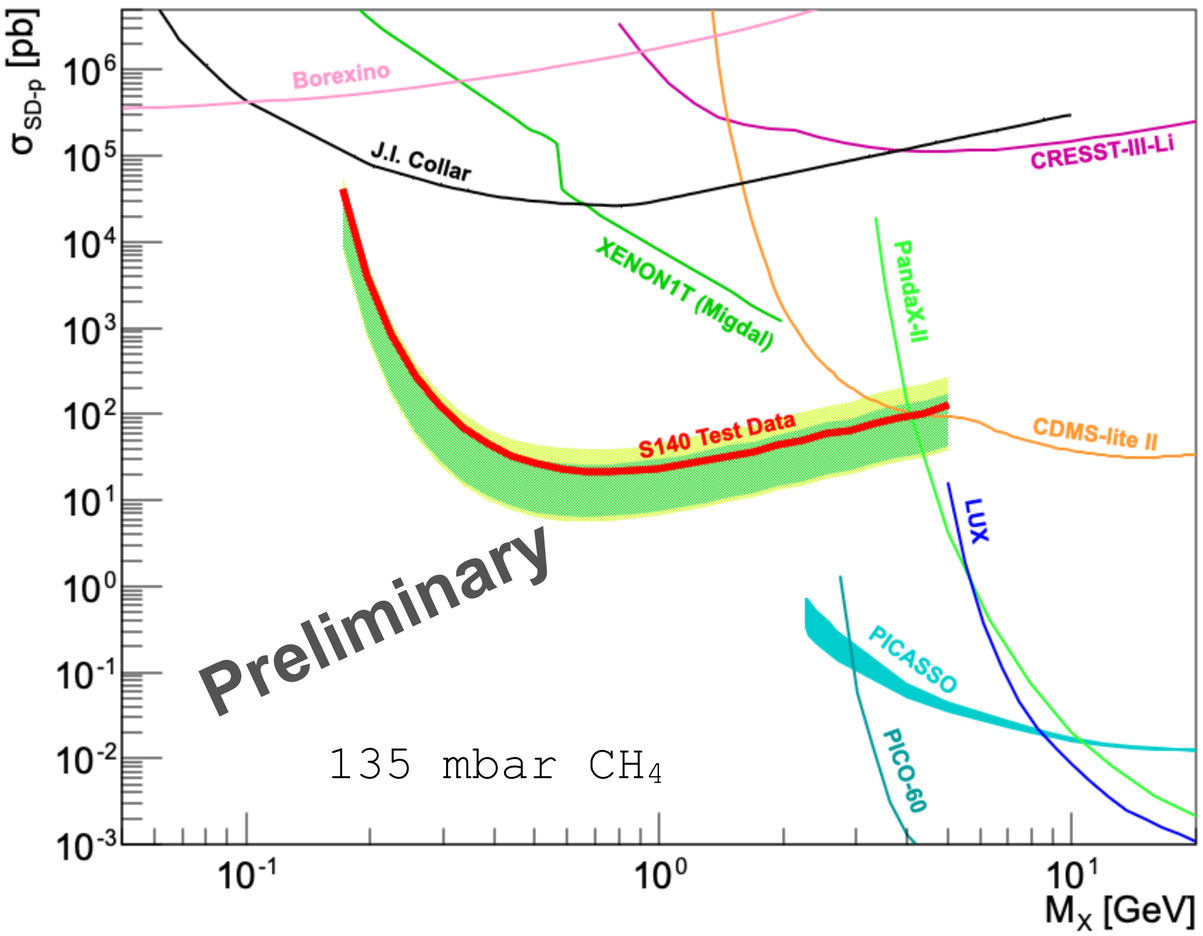

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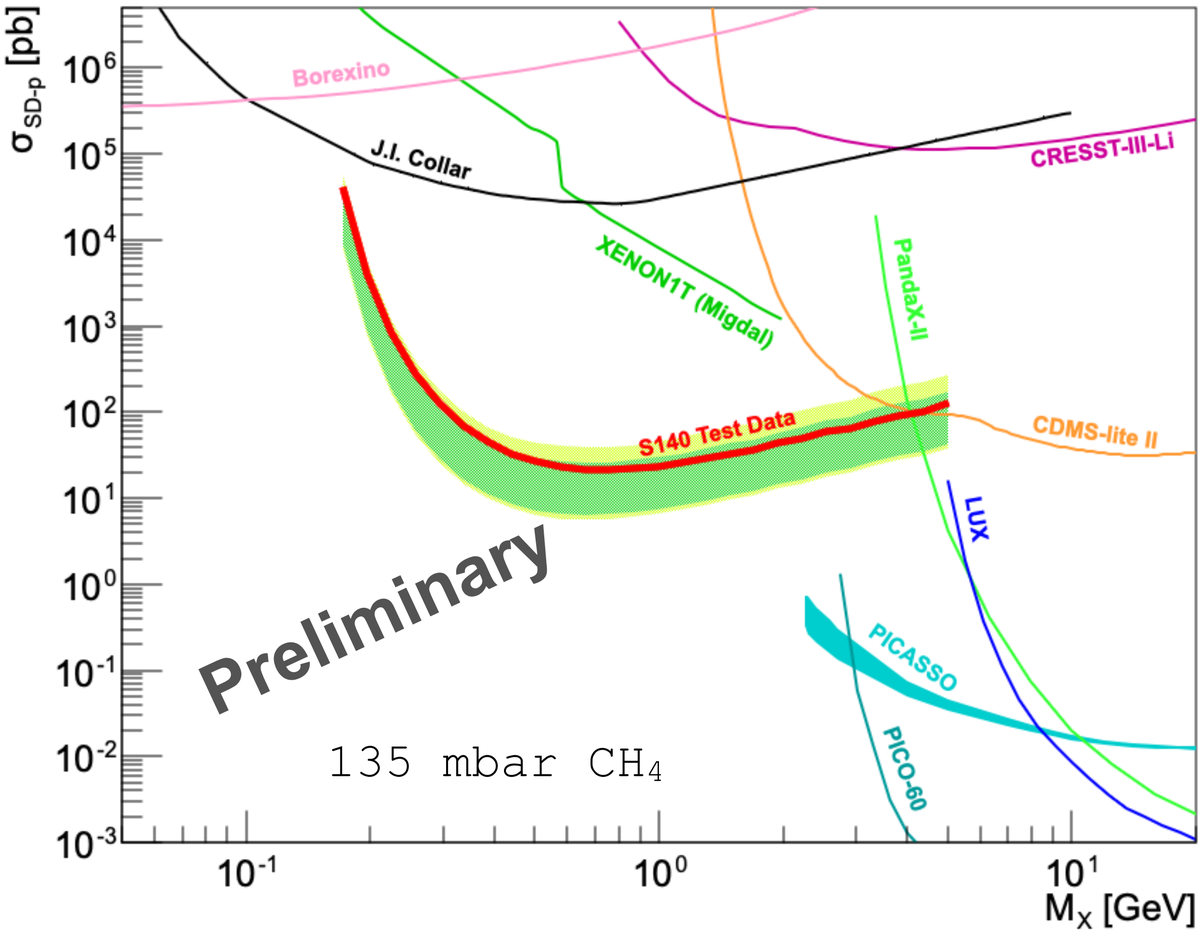
  - ✓Commissioning data analysis finalising (CH_4)
- **First physics run in SNOLAB** in 2023
  - ✓~20 kg·days exposure with Ne:CH_4



SPC Applications: Neutron Spectroscopy

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- Medical and industrial applications

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$^{14}N + n \rightarrow {}^{14}C + p$ **+ 625 keV**

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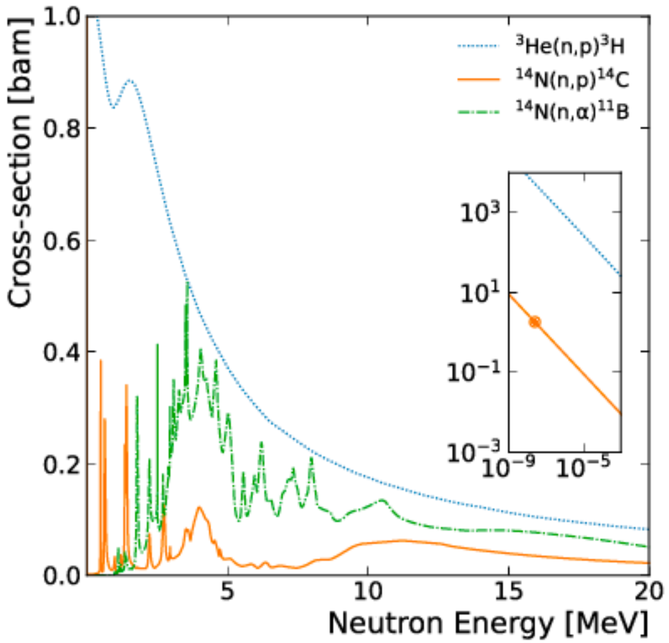

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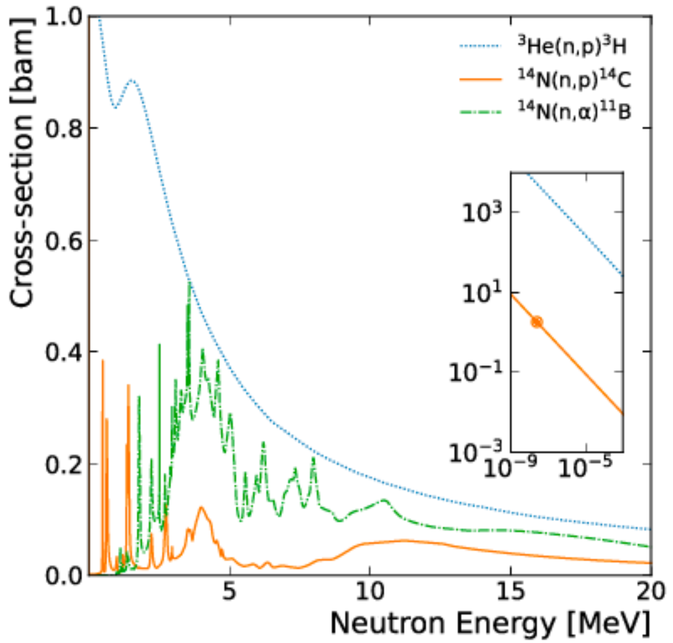

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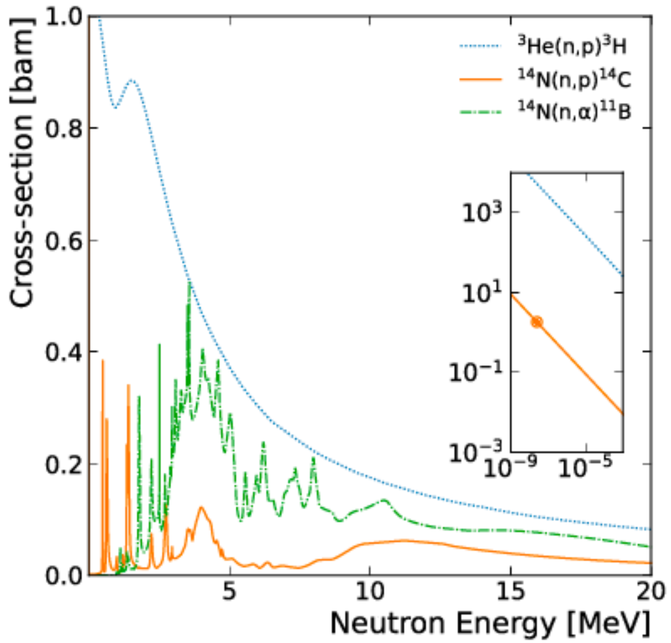
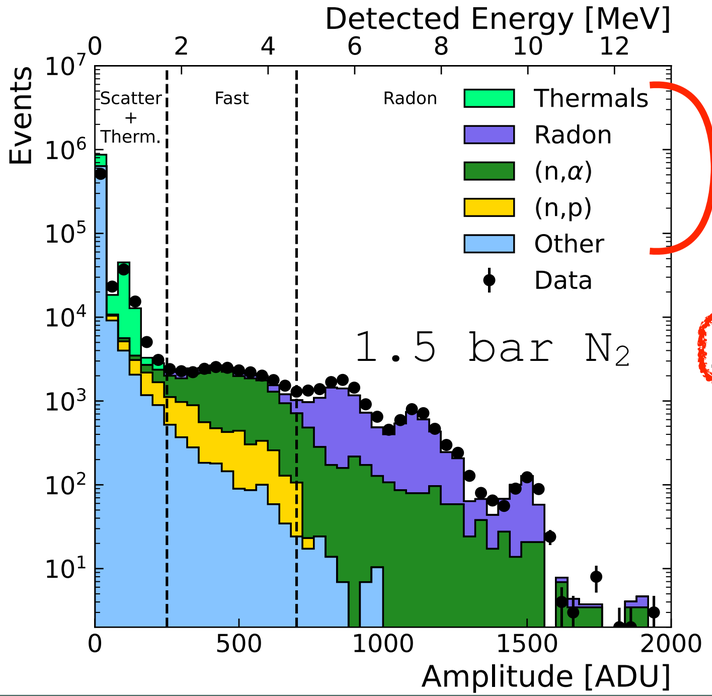
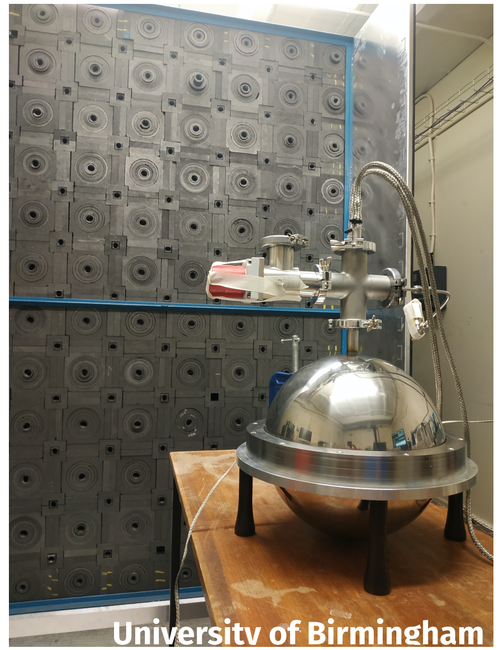




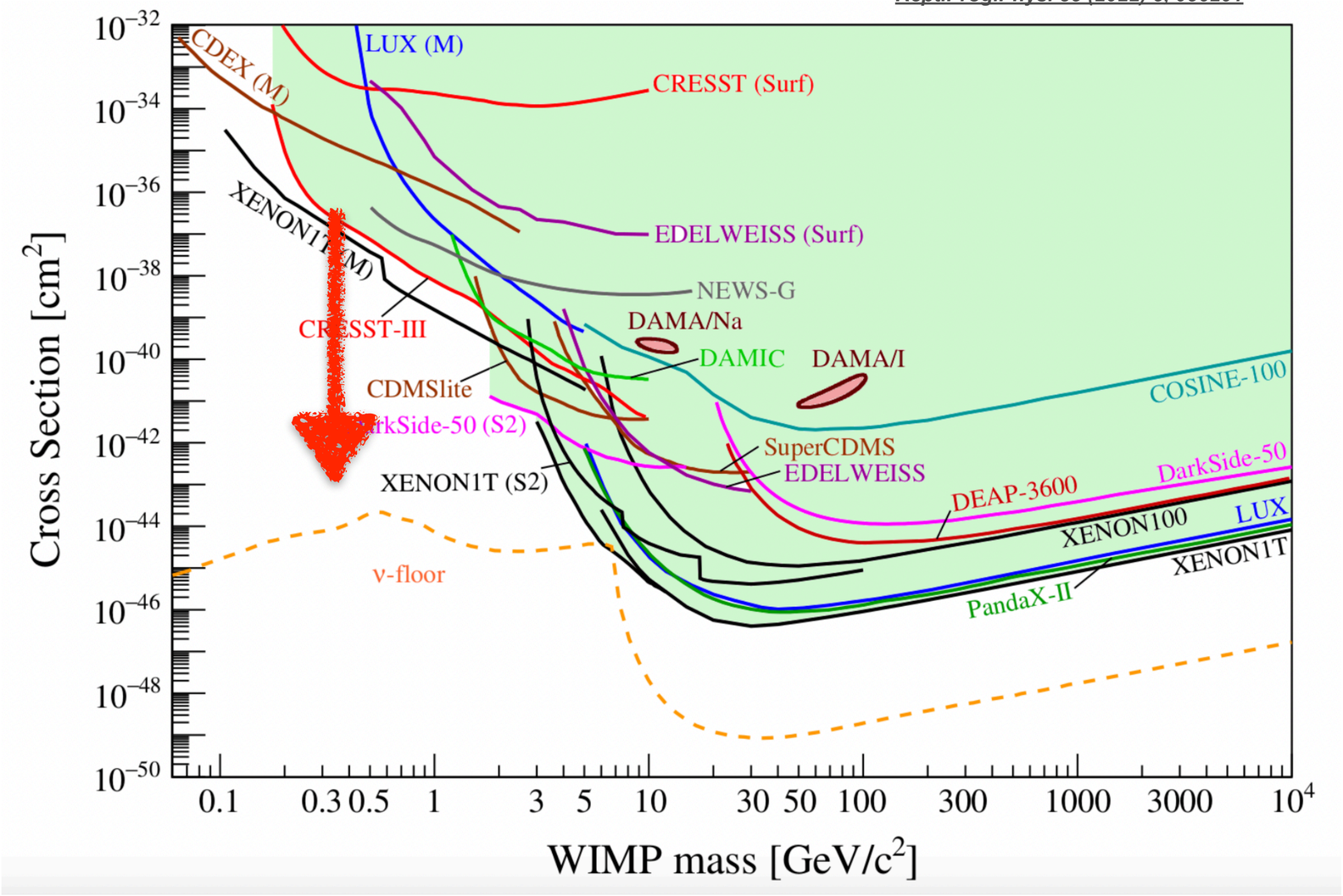
Simulation

NIMA 1049 (2023) 168124



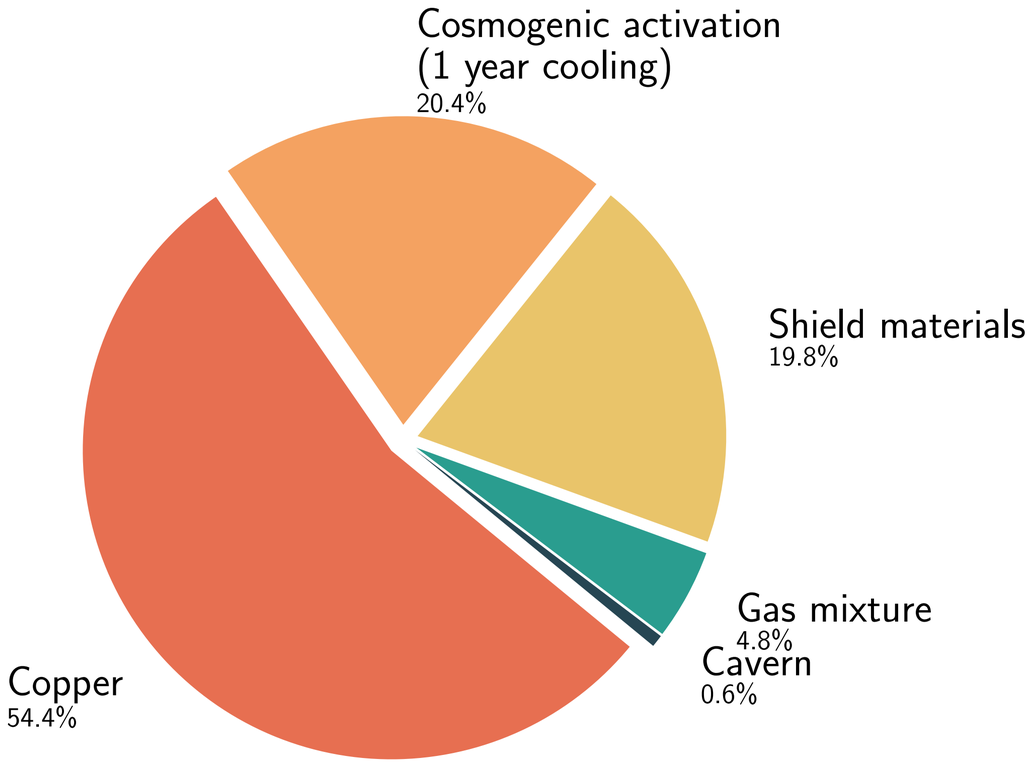
Exploring Uncharted Territory

Rept.Prog.Phys. 85 (2022) 5, 056201



Towards the Neutrino Floor with NEWS-G

Simulated backgrounds in SNOGLOBE

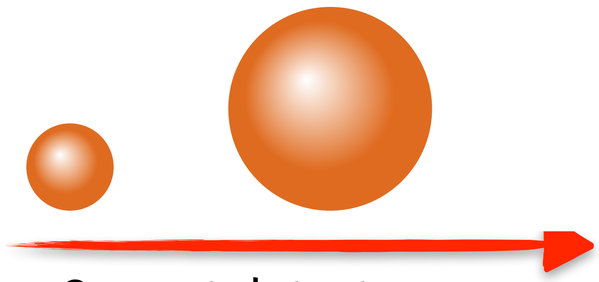


SEDINE

∅60cm
NOSV Cu

SNOGLOBE

∅140cm
99.99% Cu
500 μm EFCu Layer



Current detectors

Towards the Neutrino Floor with NEWS-G

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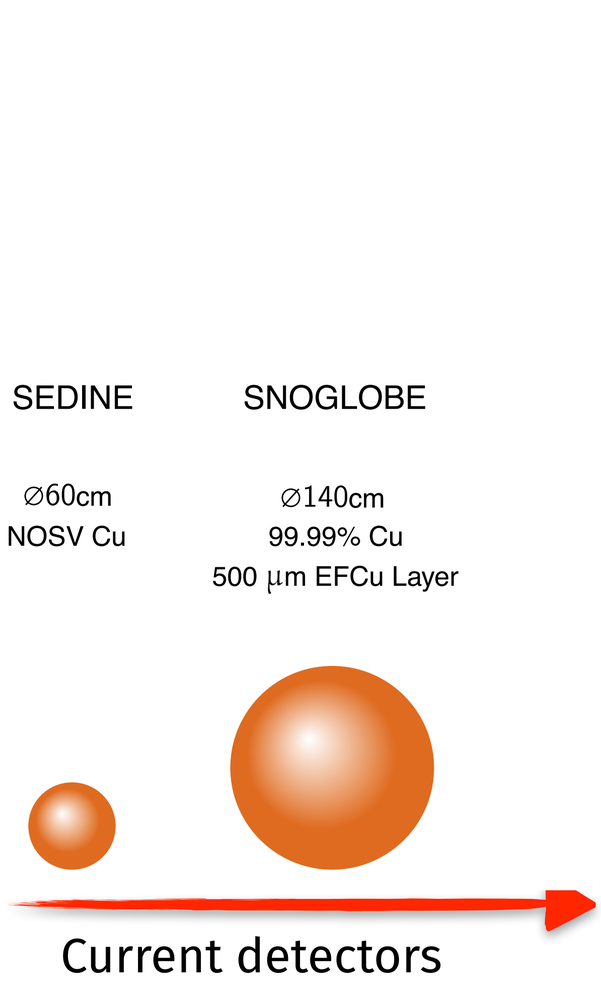

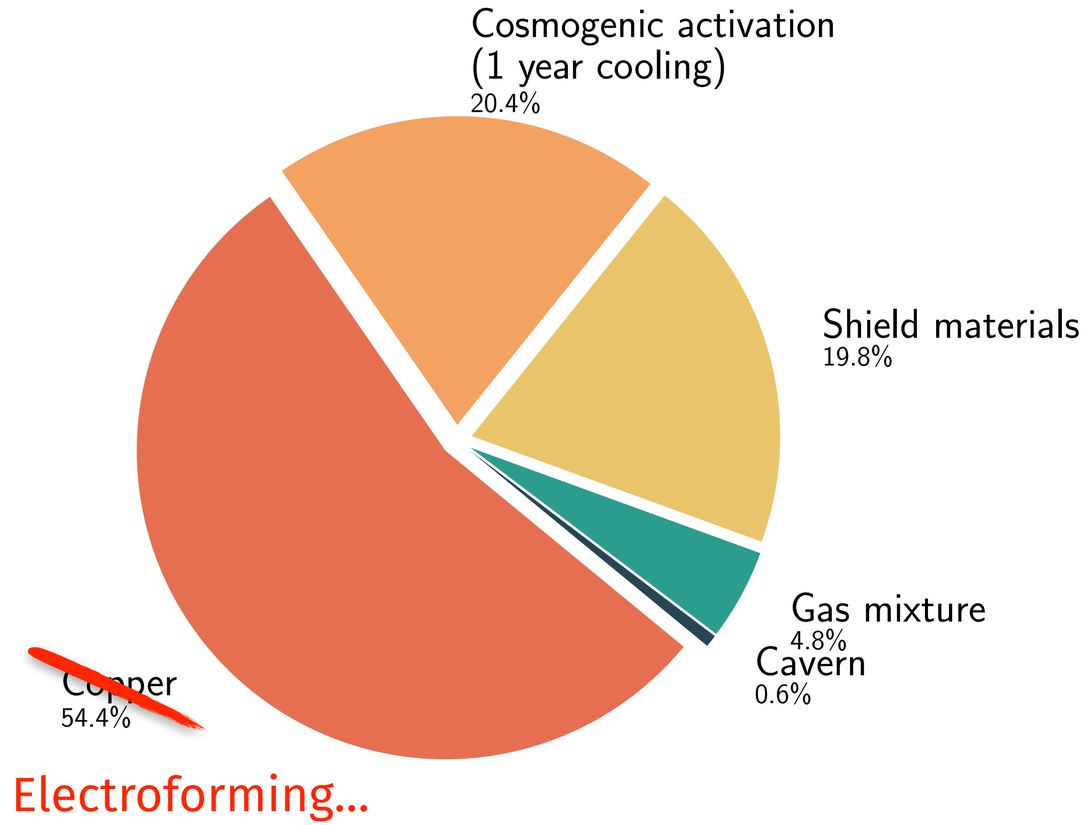

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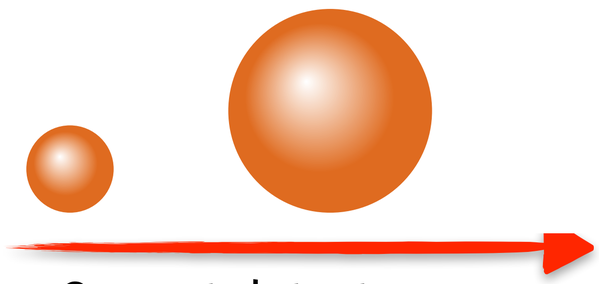
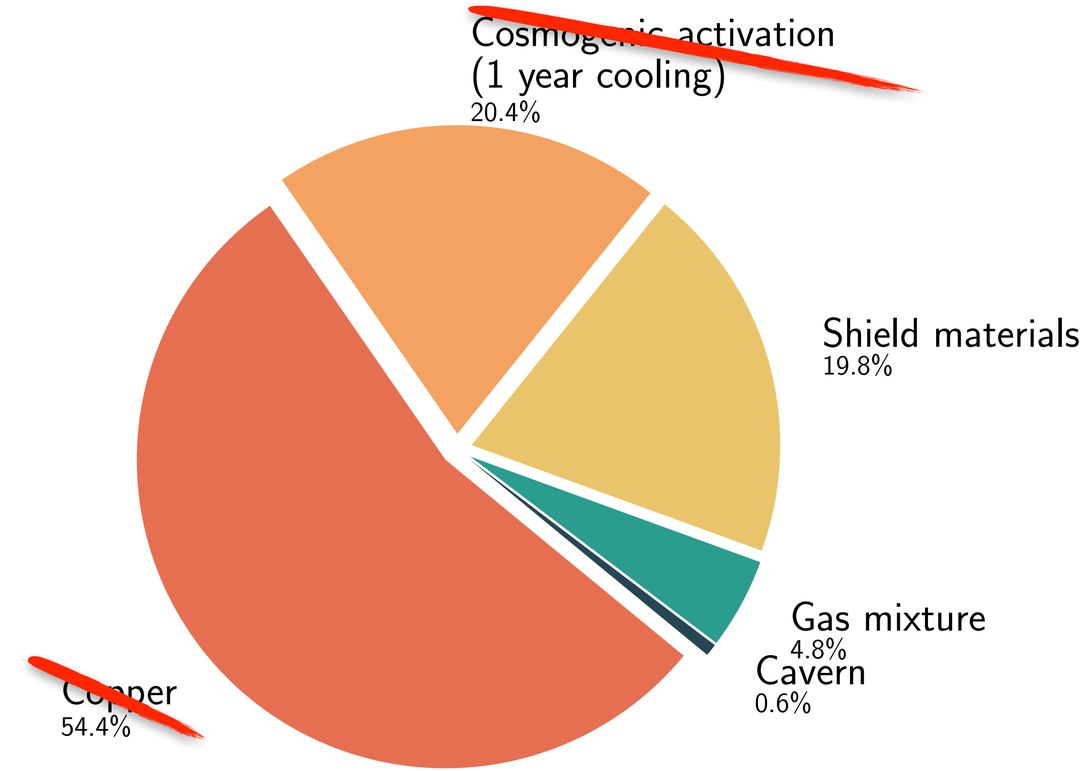


Current detectors

Simulated backgrounds in SNOGLOBE

...underground



Electroforming...

Towards the Neutrino Floor with NEWS-G

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∅60cm	∅140cm
NOSV Cu	99.99% Cu
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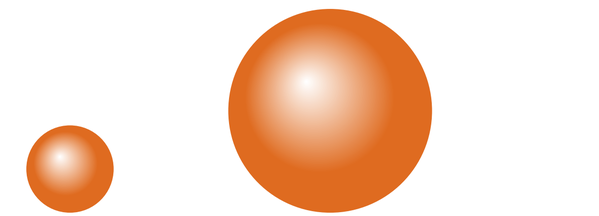

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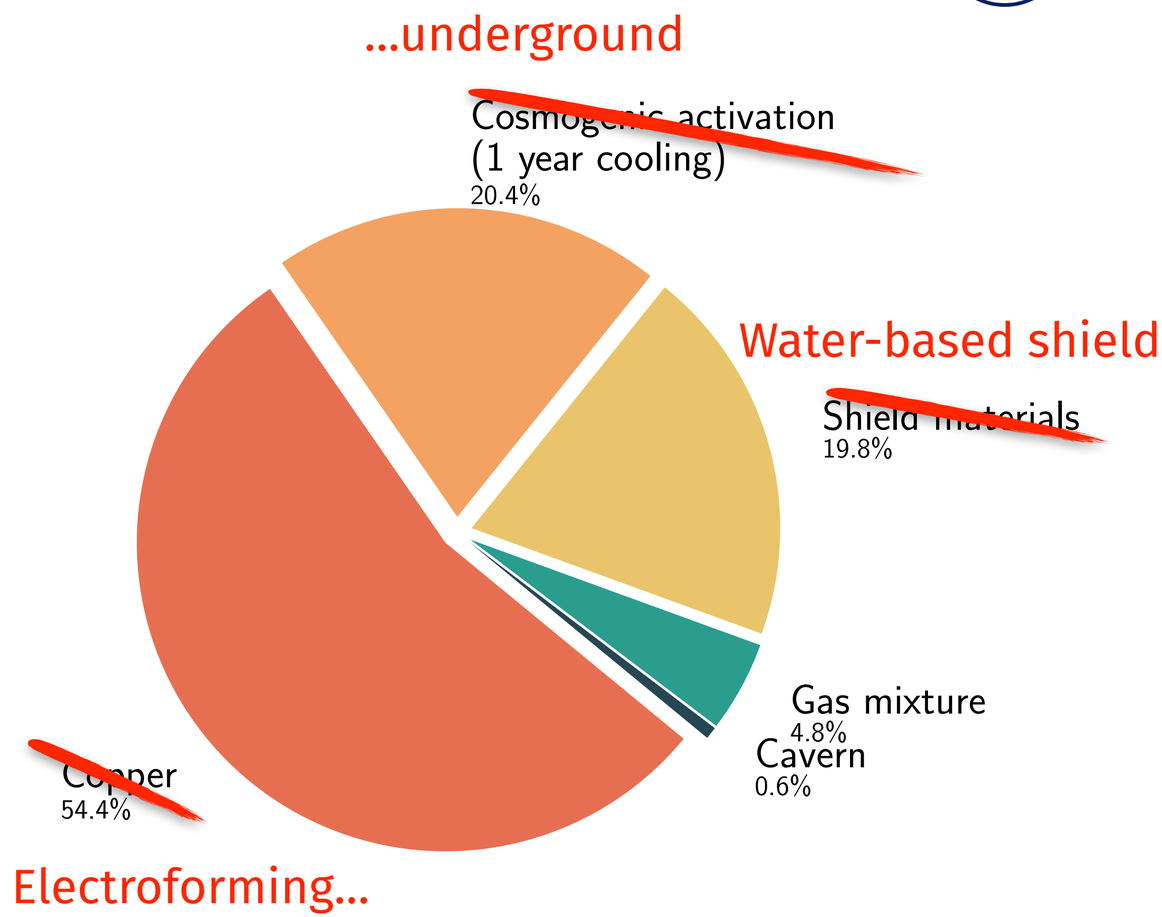
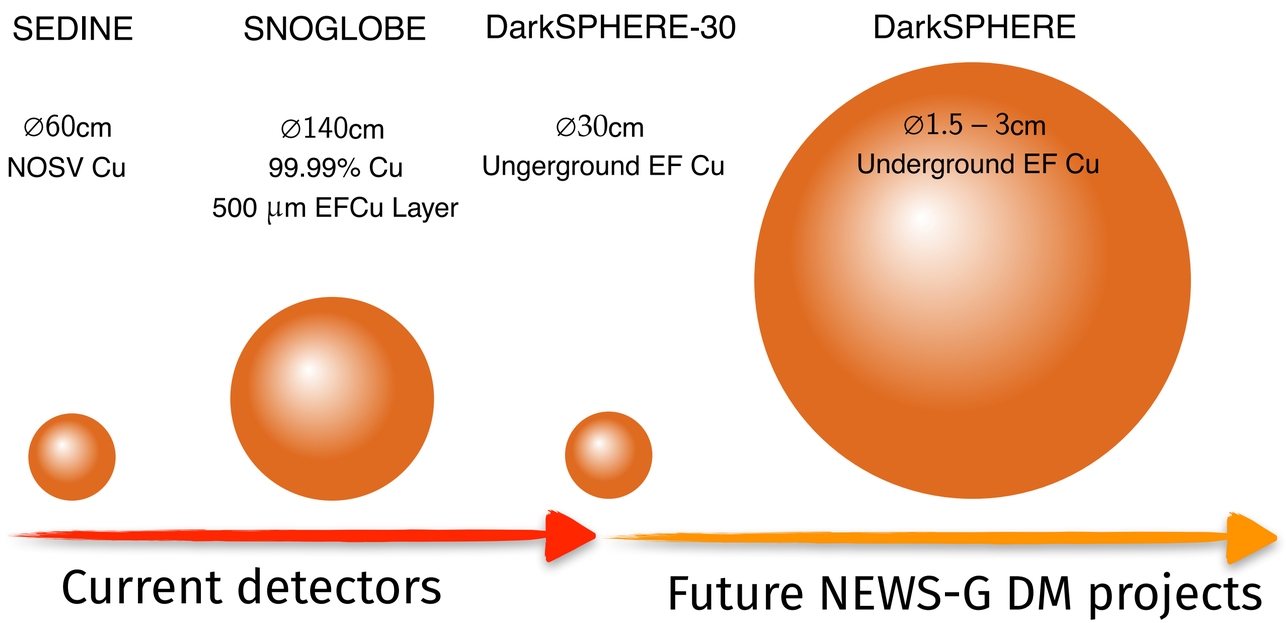
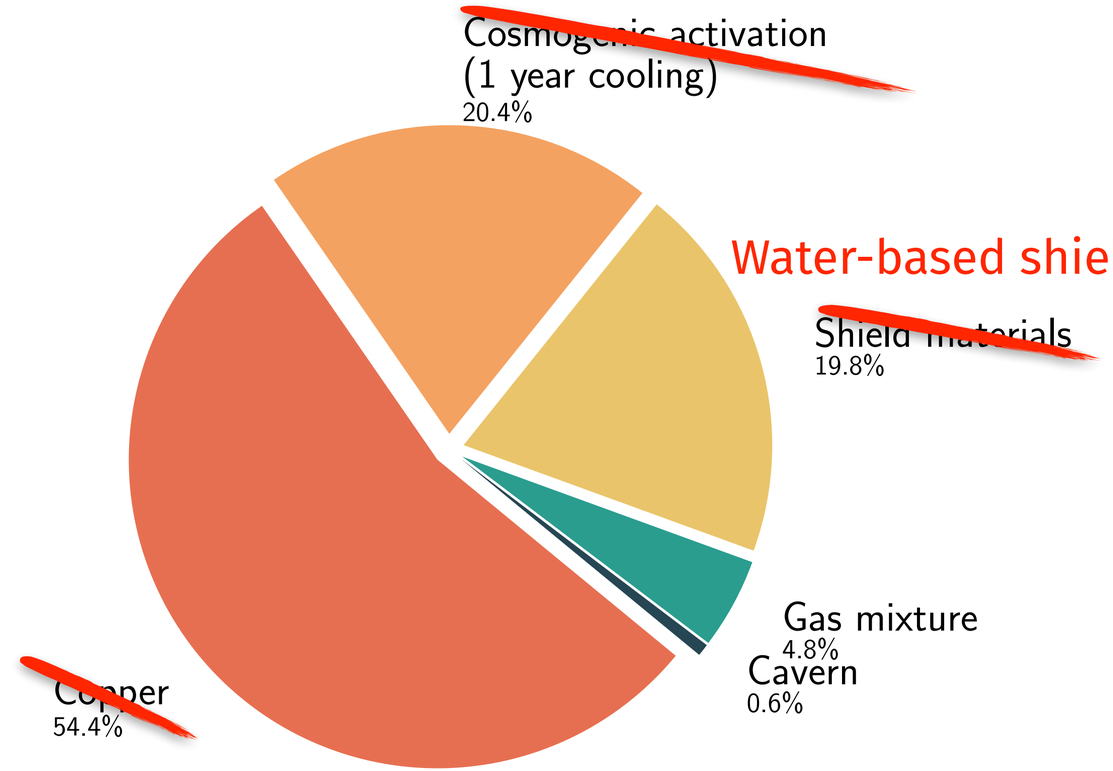


Towards the Neutrino Floor with NEWS-G



Simulated backgrounds in SNOGLOBE

...underground



Electroforming...

Towards the Neutrino Floor with NEWS-G

PHYSICAL REVIEW D **108,** 112006 (2023)

Phys.Rev.D 108 (2023) 11, 112006

Exploring light dark matter with the DarkSPHERE spherical proportional counter electroformed underground at the Boulby Underground Laboratory

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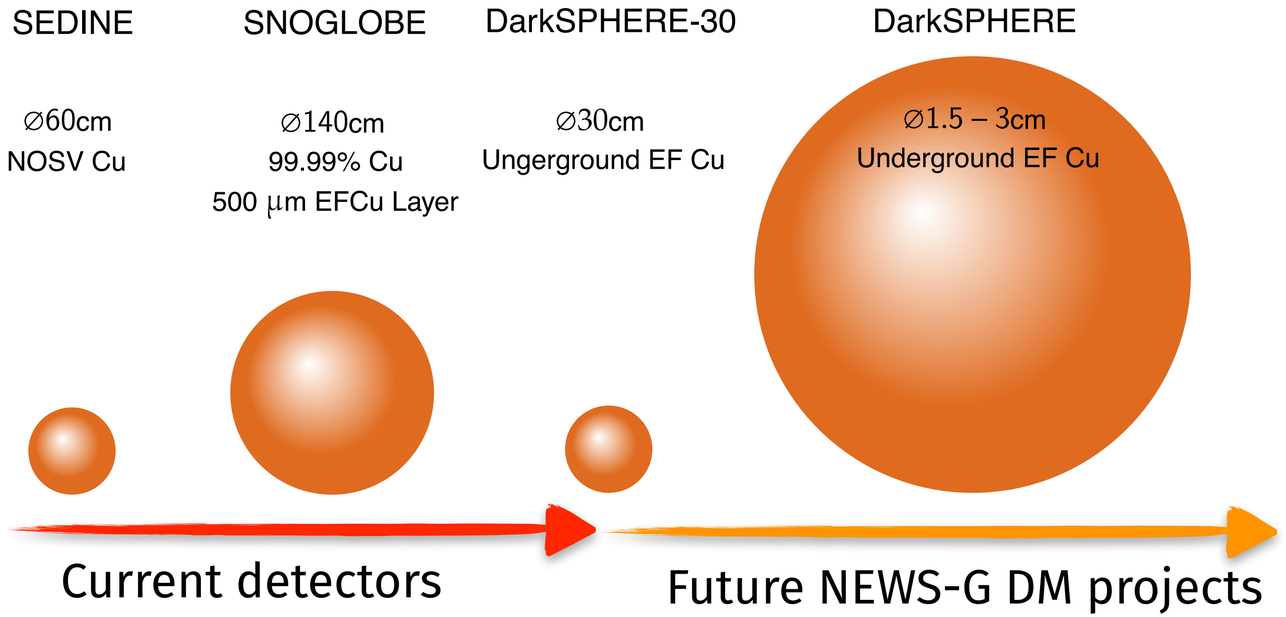
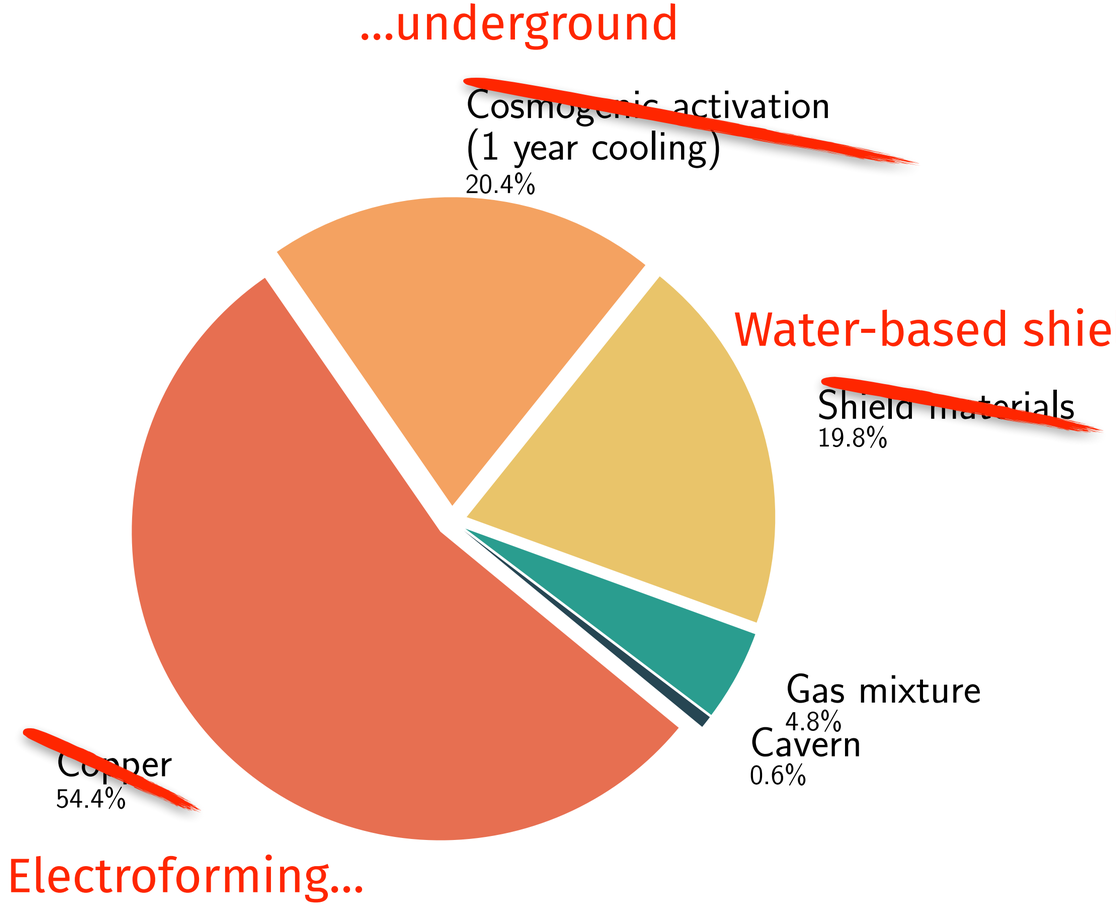
(NEWS-G Collaboration)

E. Banks,[12] L. Hamaide,[13] C. McCabe,[13] K. Mimasu,[13] and S. Paling[12]



Simulated backgrounds in SNOGLOBE

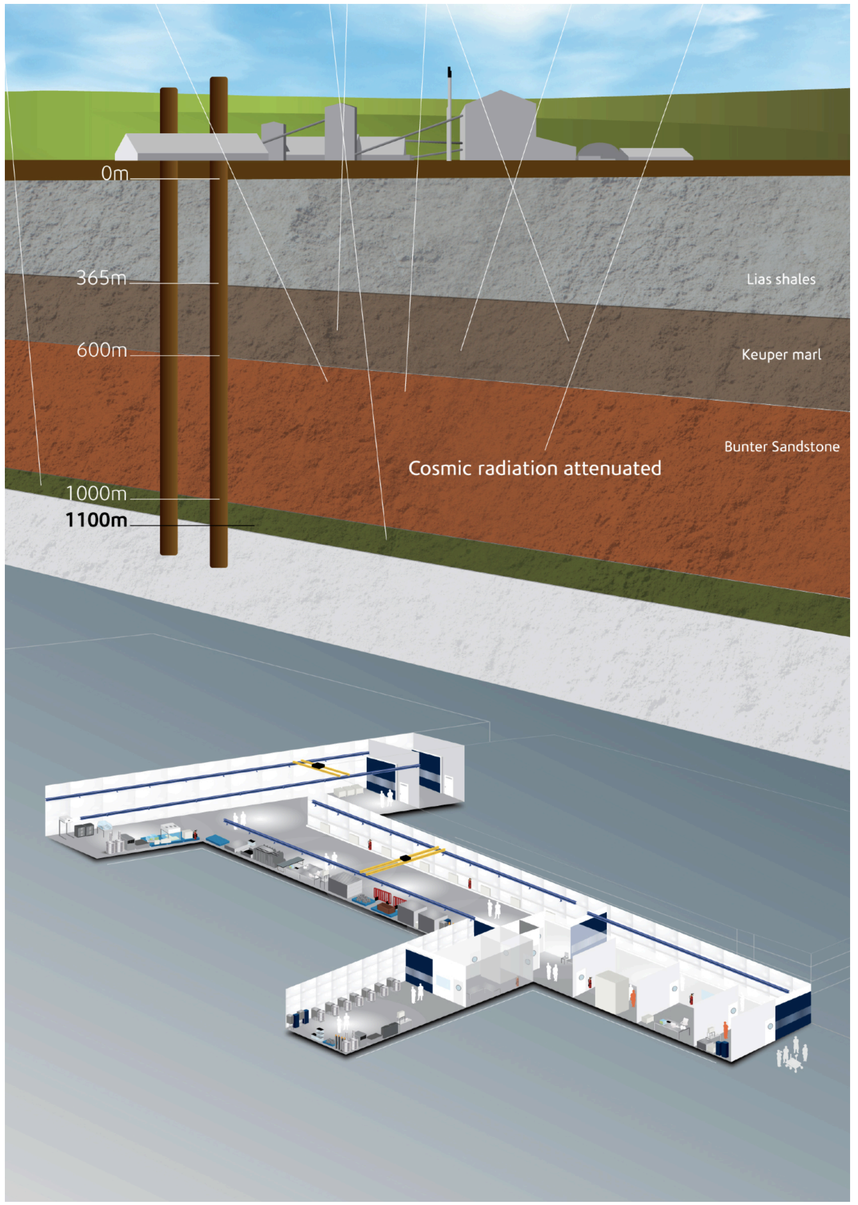


DarkSPHERE in Boulby

Science and Technology Facilities Council
Boulby Underground Laboratory

- DarkSPHERE will use a modular water-based shield
- A pure water shield is sufficient for background goal of **0.01 event/keV/kg/day** in ROI
- Boulby as potential host - UK's deep-underground science facility

^{222}Rn ~3 Bq/m^3 *P. Scovell, DMUK 2019*
μ ~4×10^{-8} /cm^2/s *NIMA 511 (2003) 347-353*



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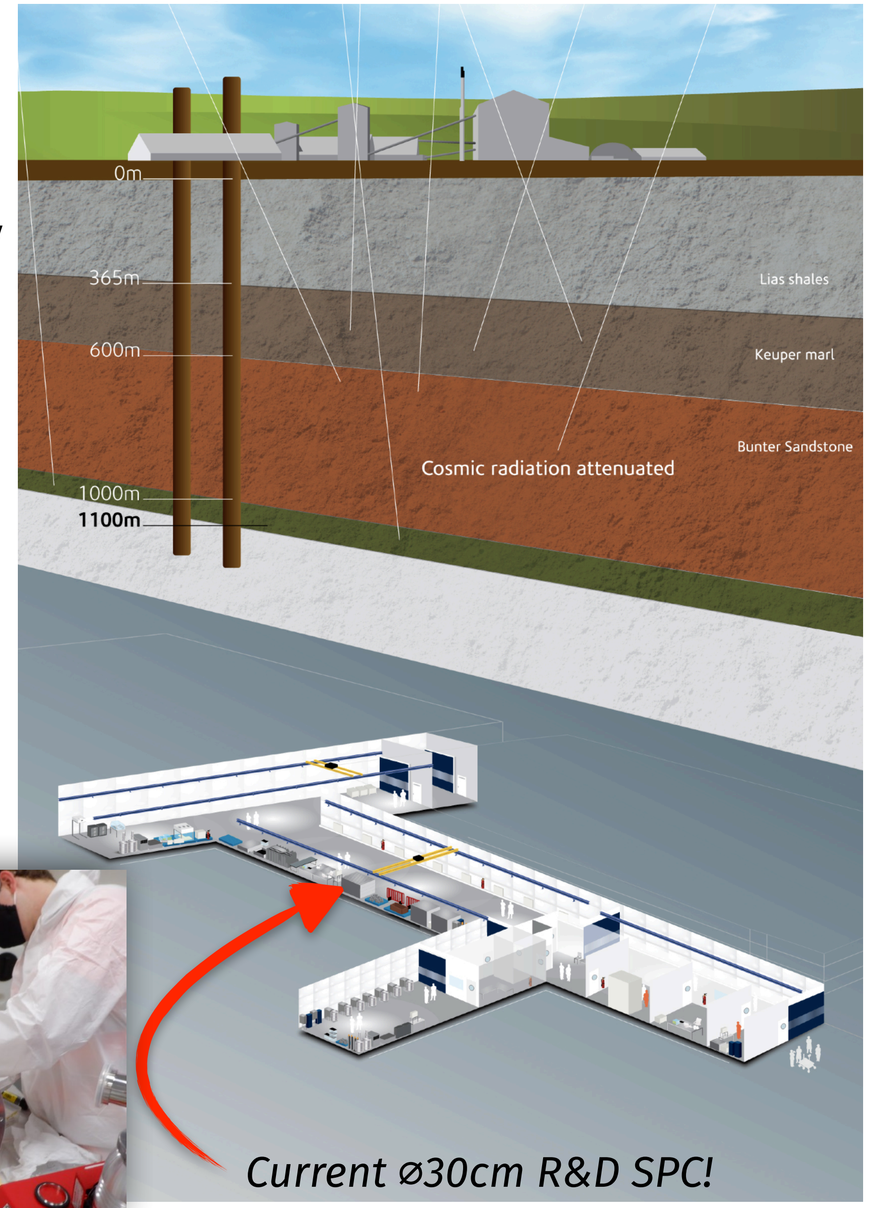

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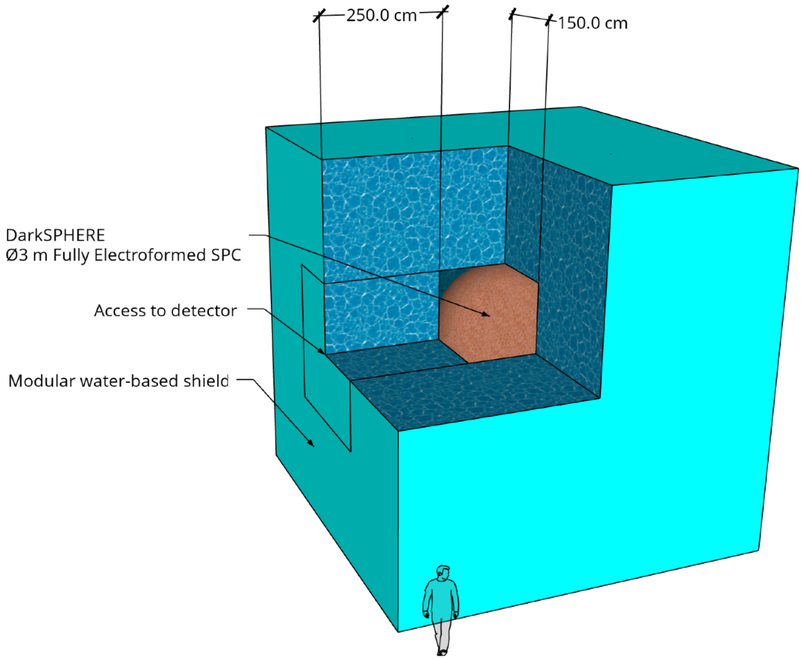
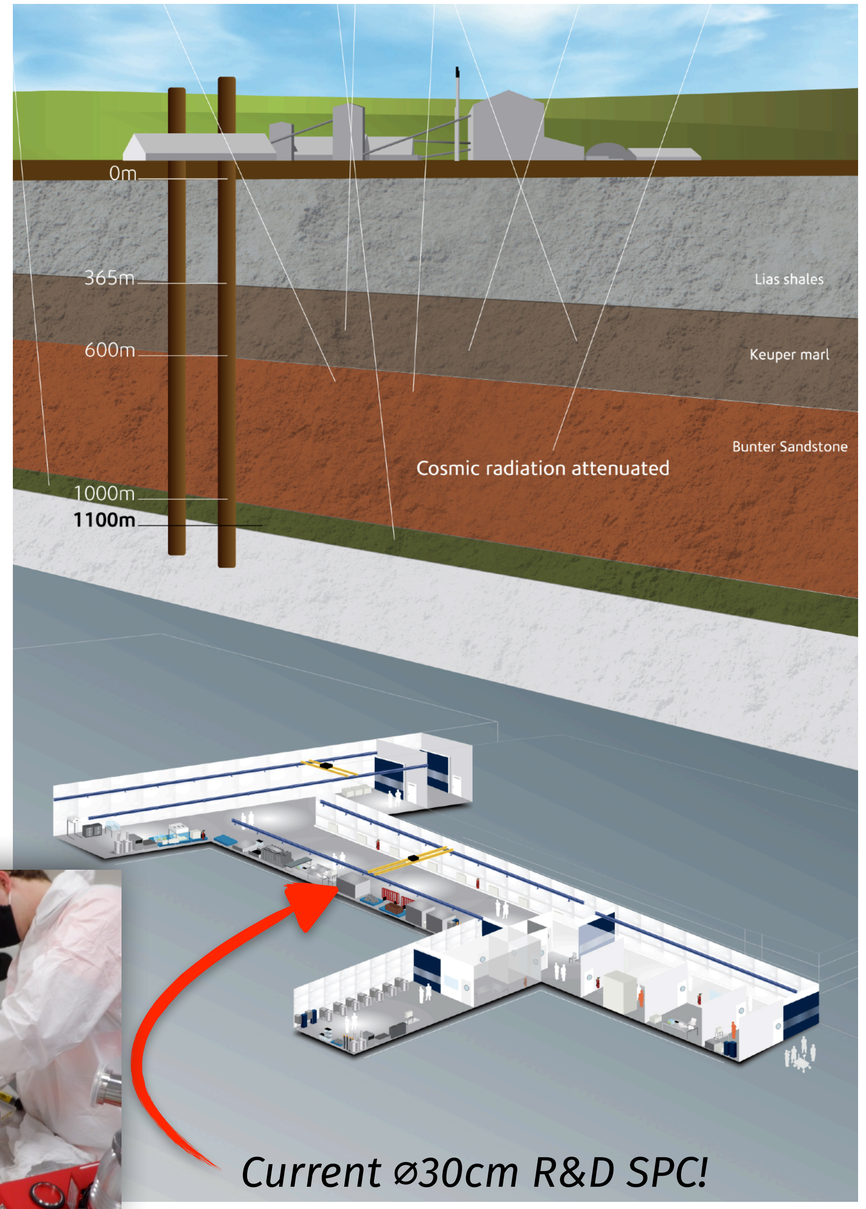
2.5 m water	4.2×10^{-3} (0.3)	9×10^{-5} (5)	1.3×10^{-4} (0.4)	5×10^{-3} (4)





Current ø30cm R&D SPC!

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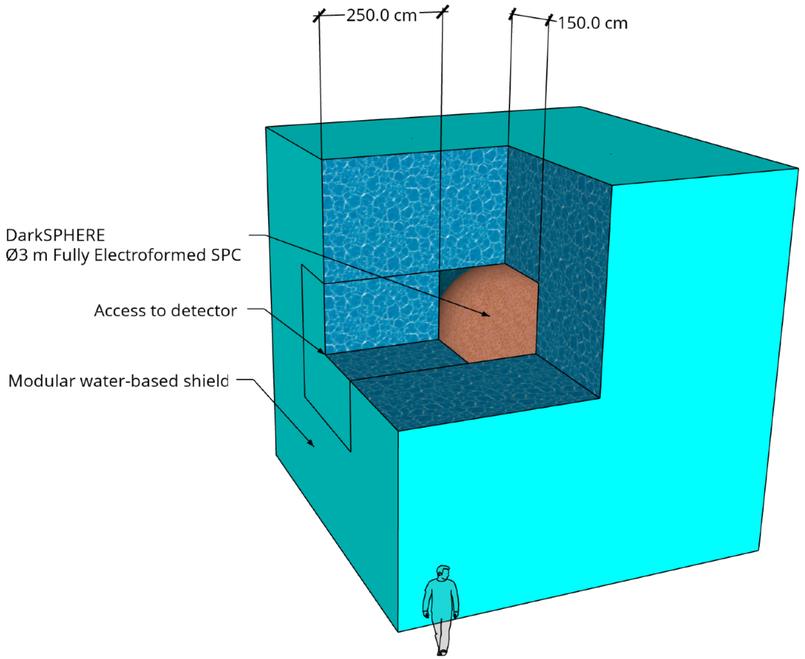
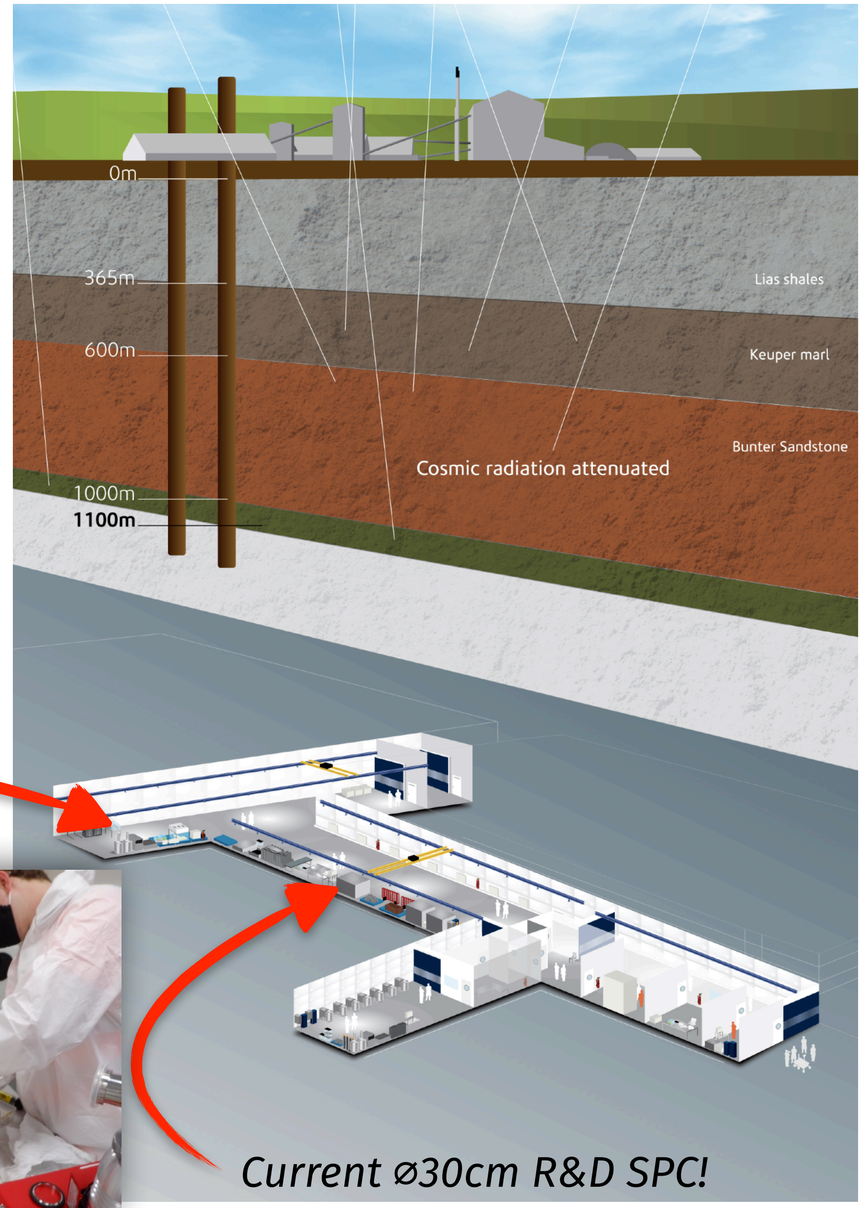


Conceptual design fits in Large Experiment Cavern



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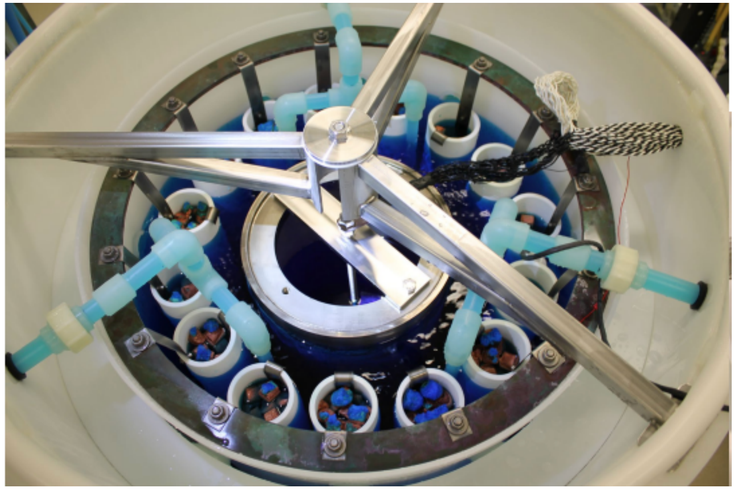
EFCu in Boulby

- ECuME project, SNOLAB, of ⌀140cm detector + scale model in PNNL
- STFC funding for an ultra-pure EFCu facility underground in Boulby
  - ➡Currently under construction

Example electroforming bath
at Pacific Northwest National Laboratory



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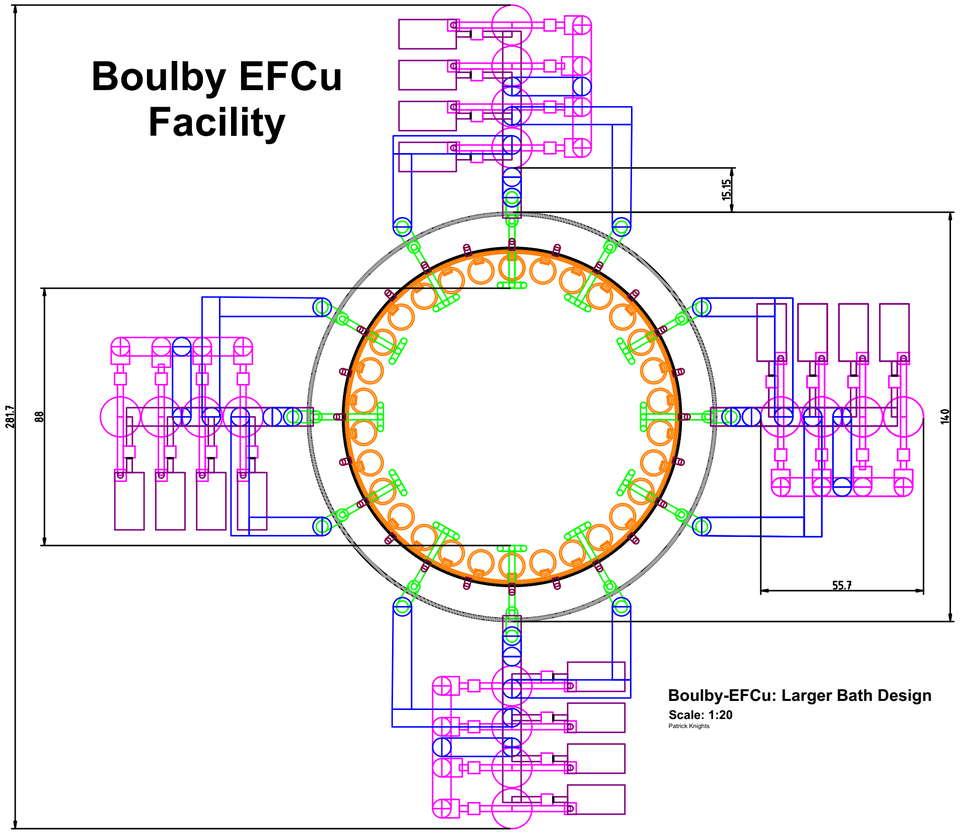

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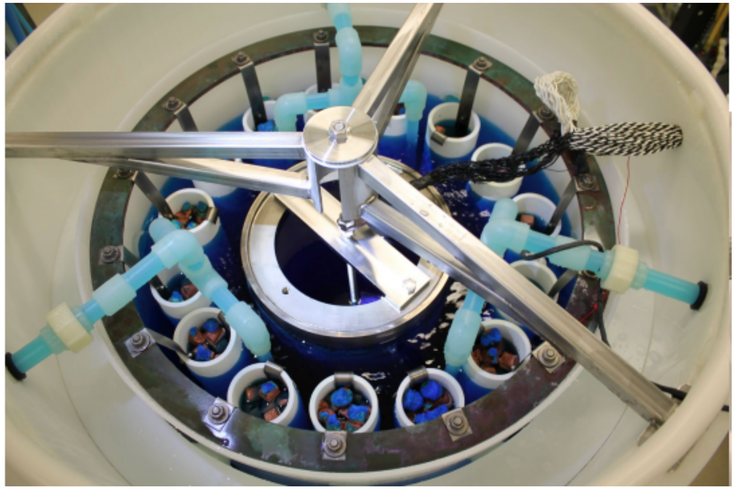

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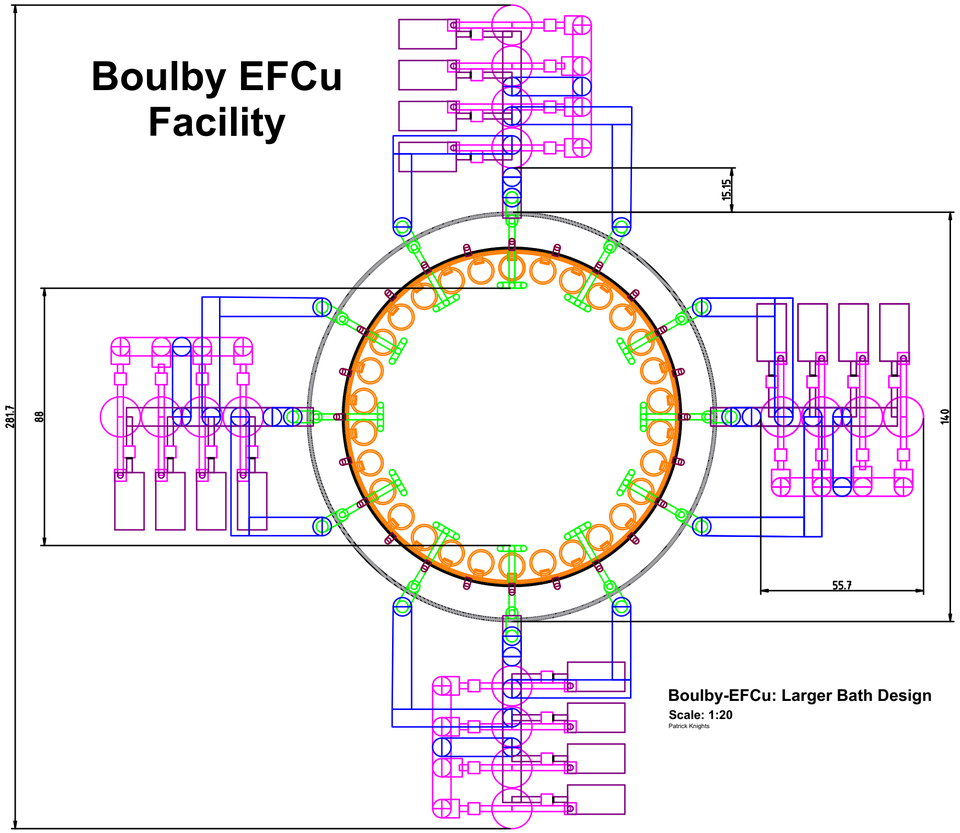

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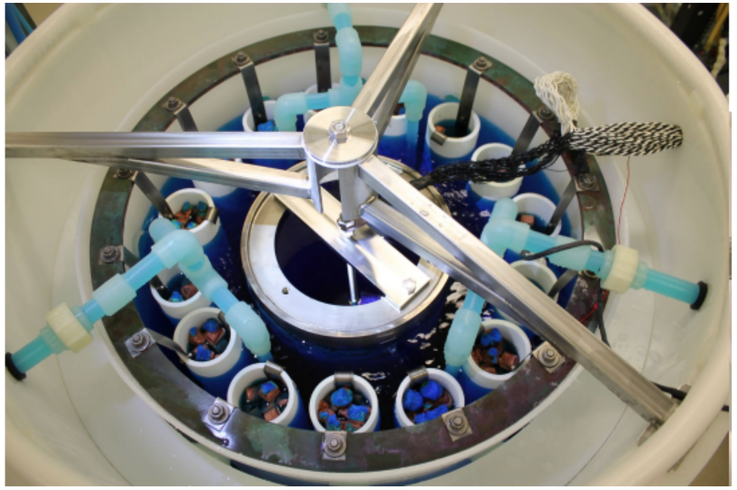

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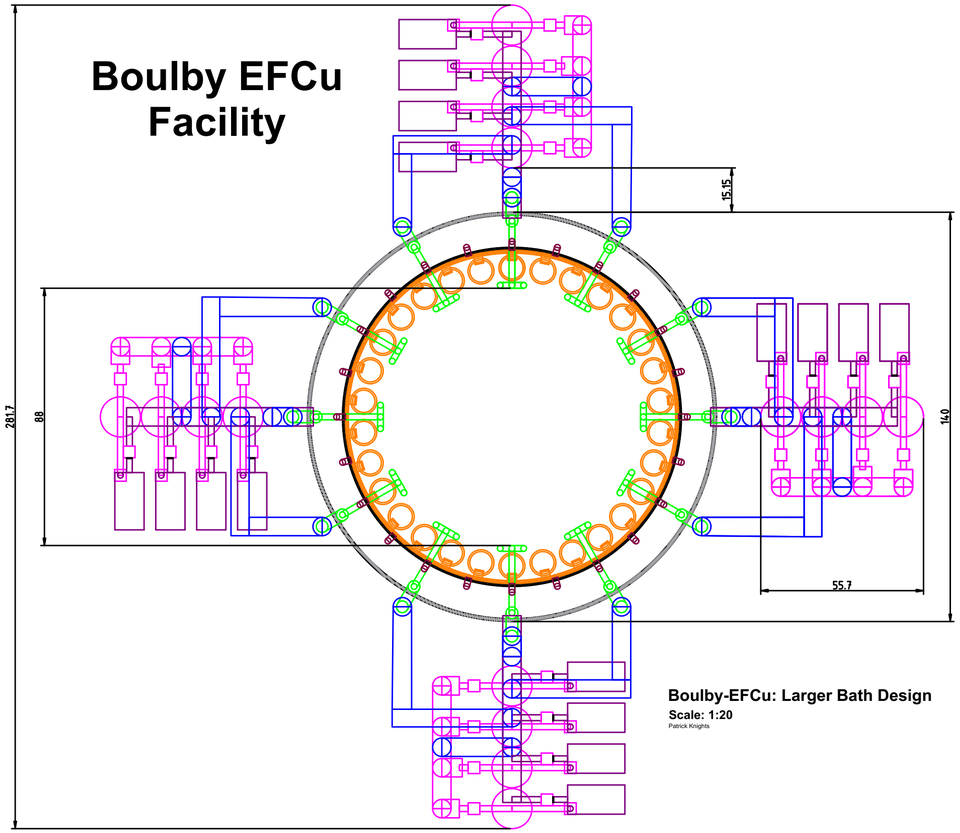

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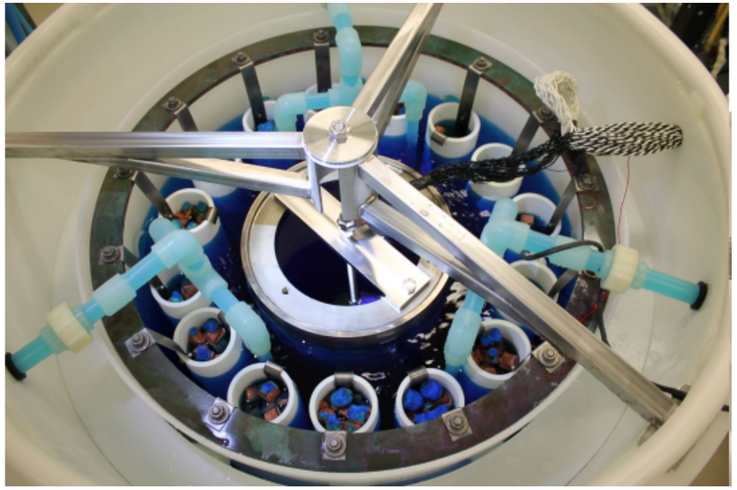

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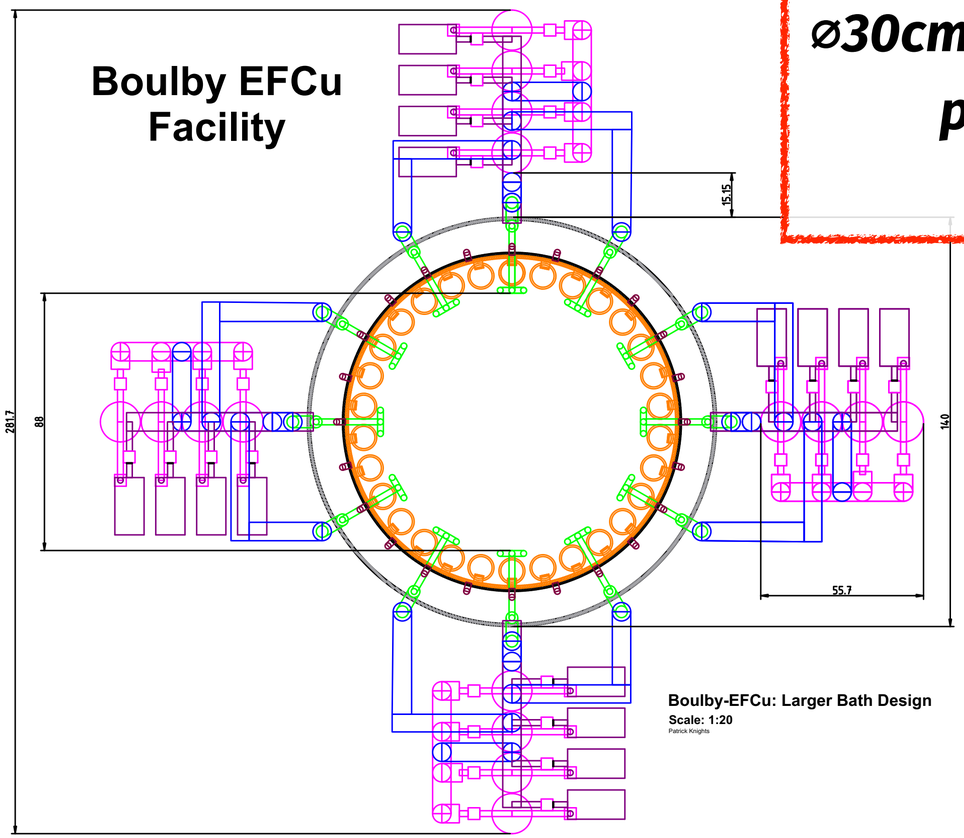
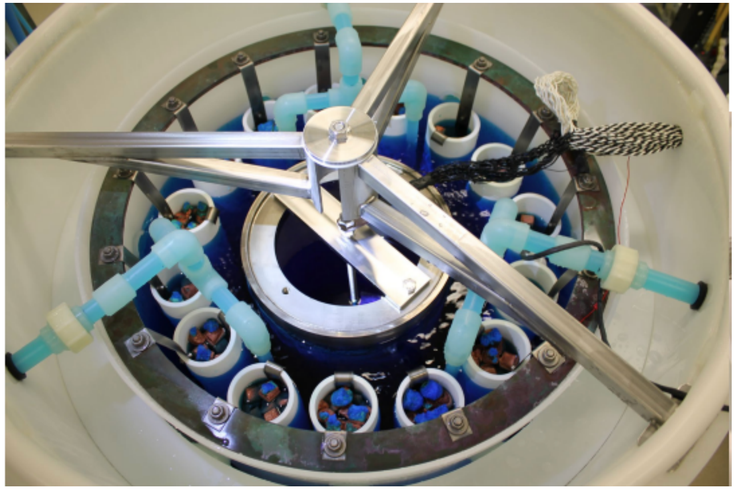


⌀30cm prototype with world-leading physics potential to begin construction this year!

Construction of bath underway

Example electroforming bath at Pacific Northwest National Laboratory

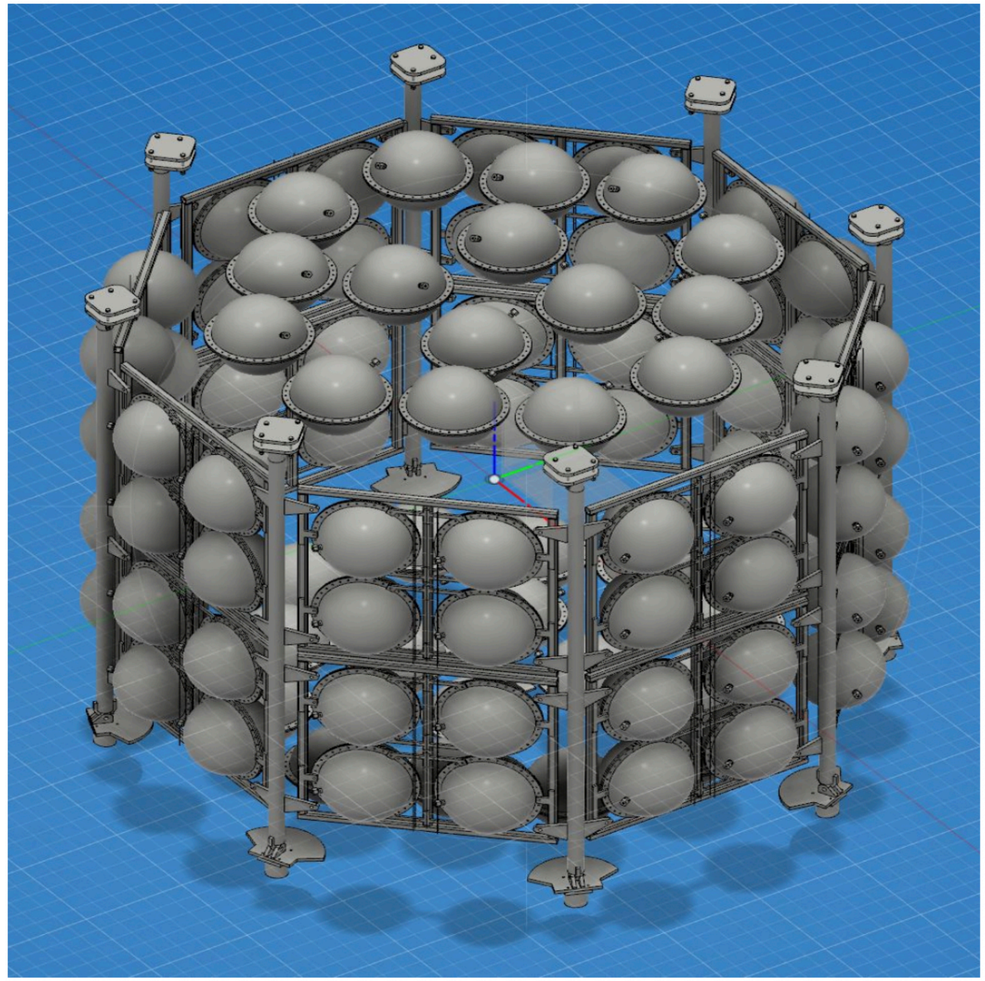


Credit: E W Hoppe, PNNL

First EFCu test in Boulby

BUTTON-30

- **BUTTON** experiment - a technology testbed for neutrino detector hardware and active media
- Hosted in Boulby, with BUTTON-30 **under construction**
  - ➡~30 tonne first stage instrumented by ~100 10” PMTs
  - ➡Fill media: water and water-based liquid scintillators (+Gd doping)
- Exploring synergies as **active veto** for DarkSPHERE



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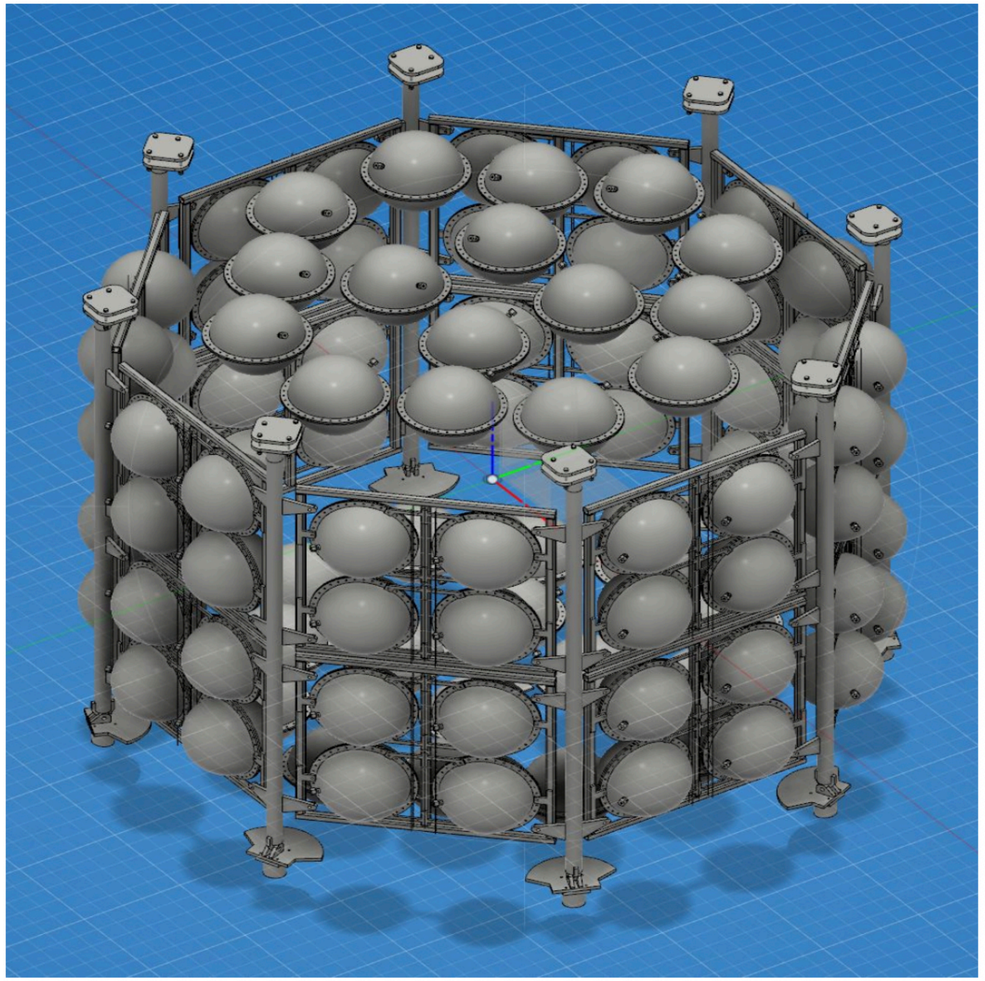

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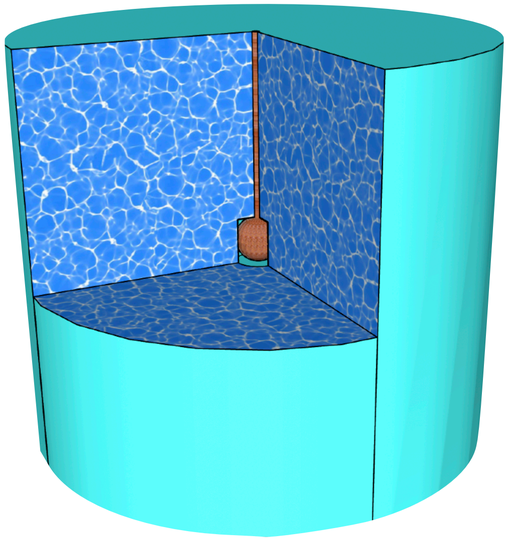
Rough schematic for scale with ⌀30 cm detector



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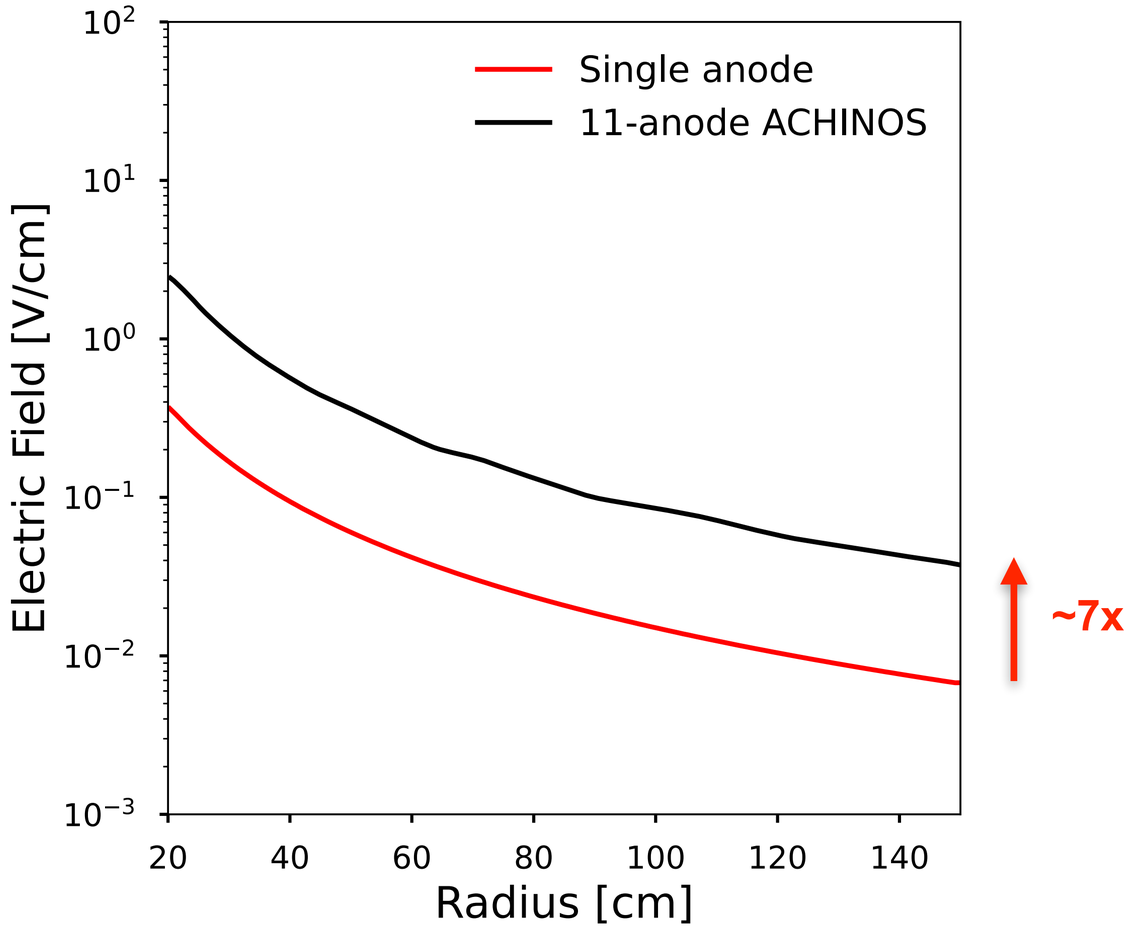

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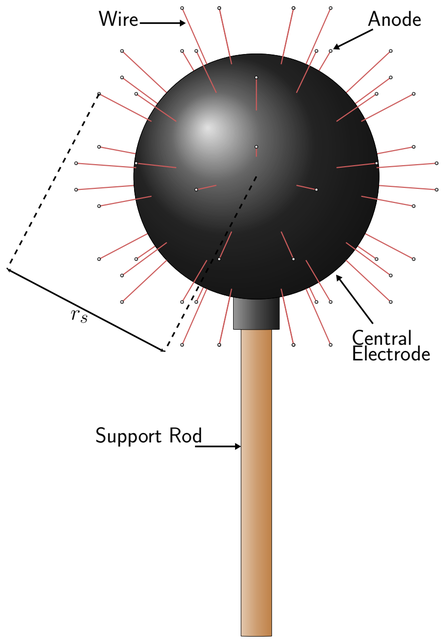
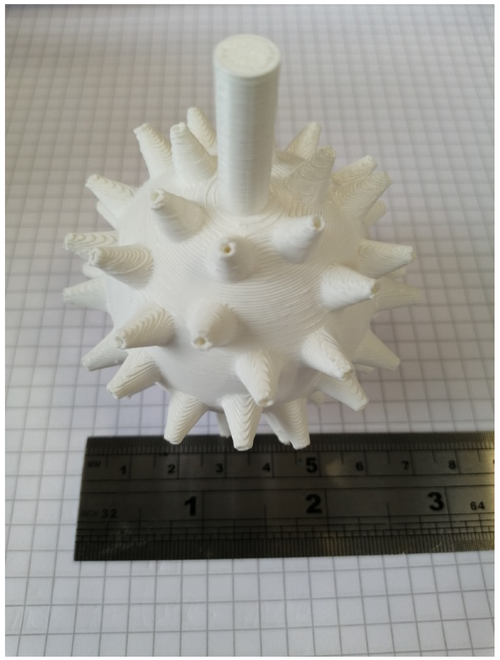
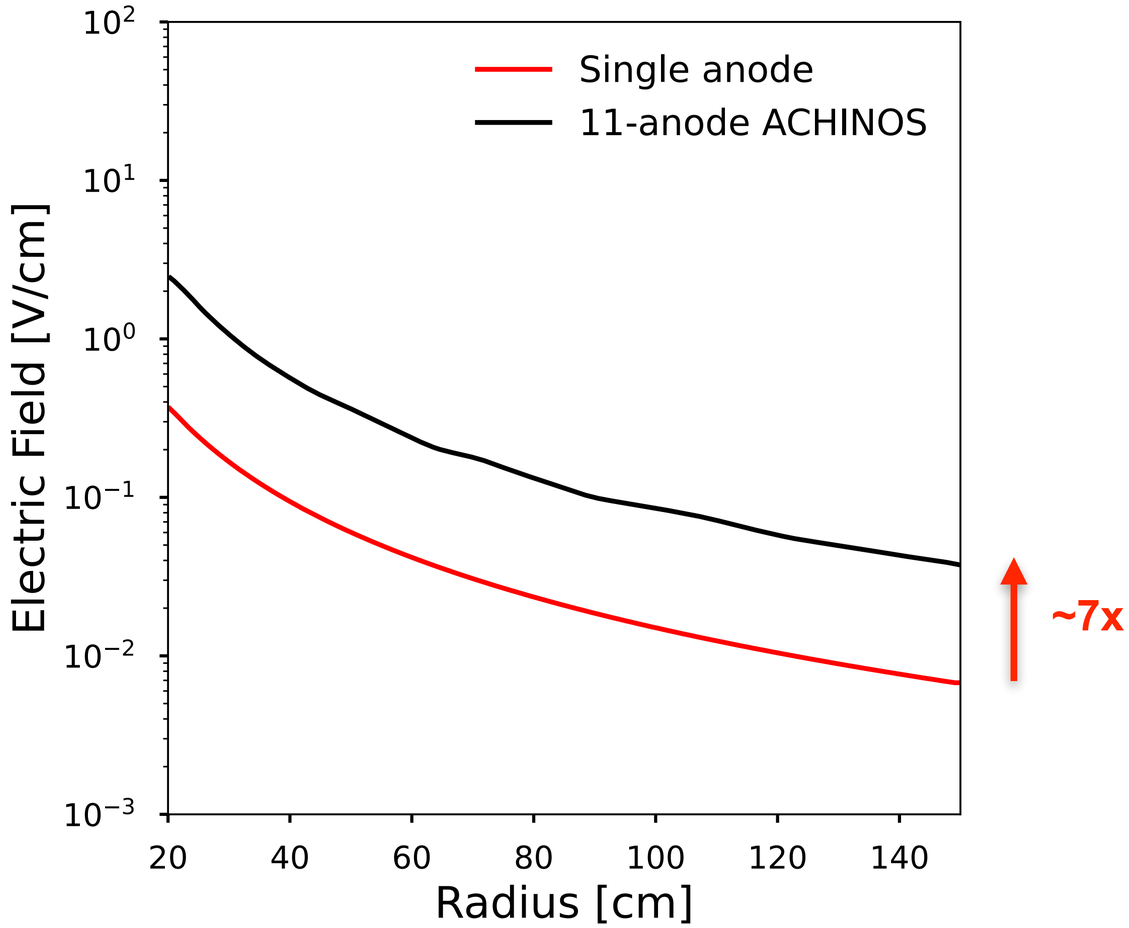




25%-scale 3D-printed prototype based on the truncated icosahedron



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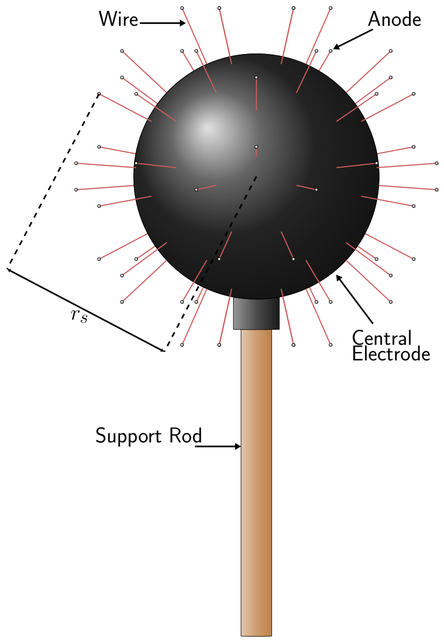

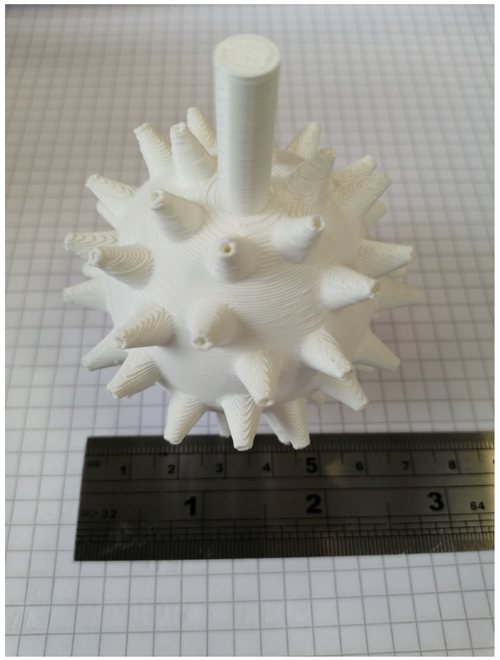

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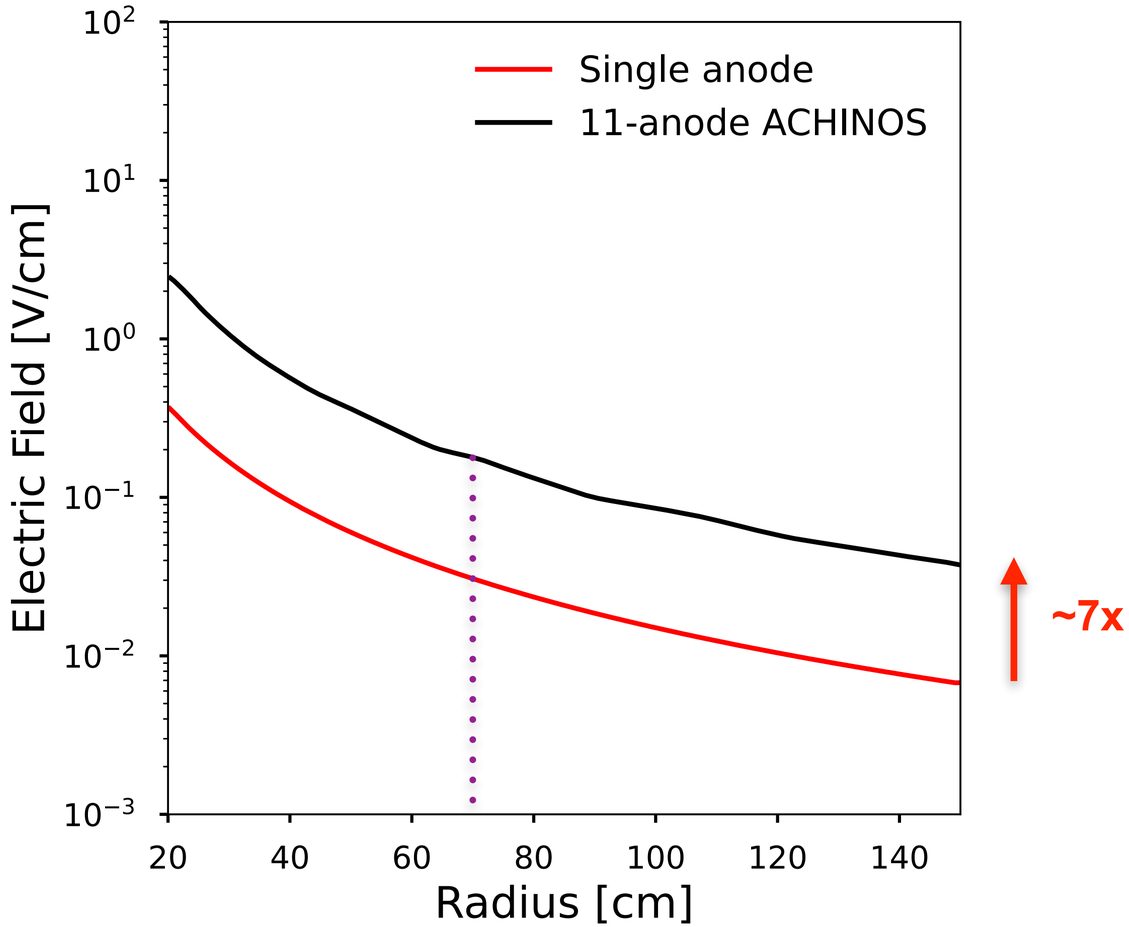

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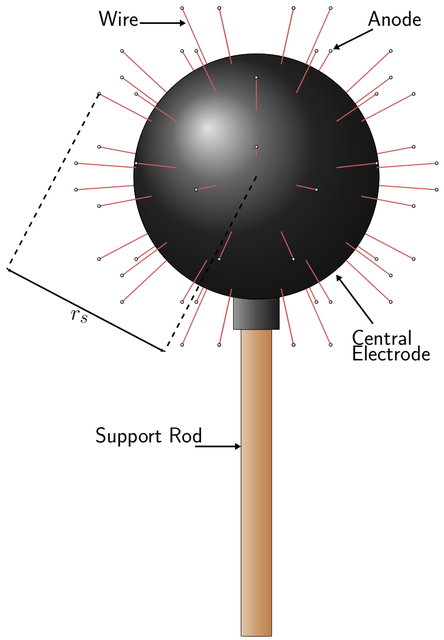

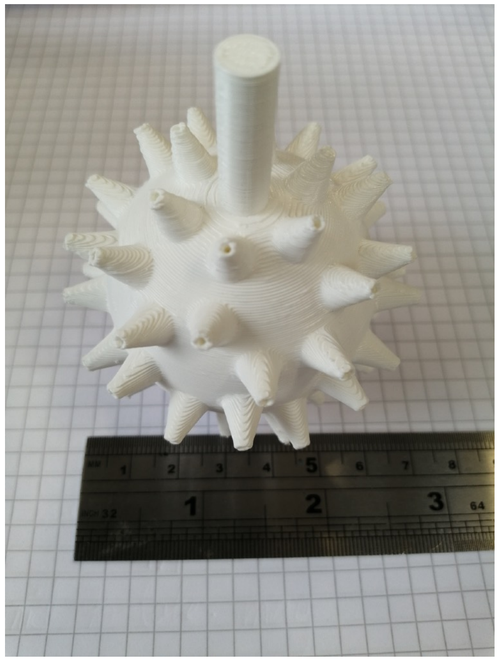

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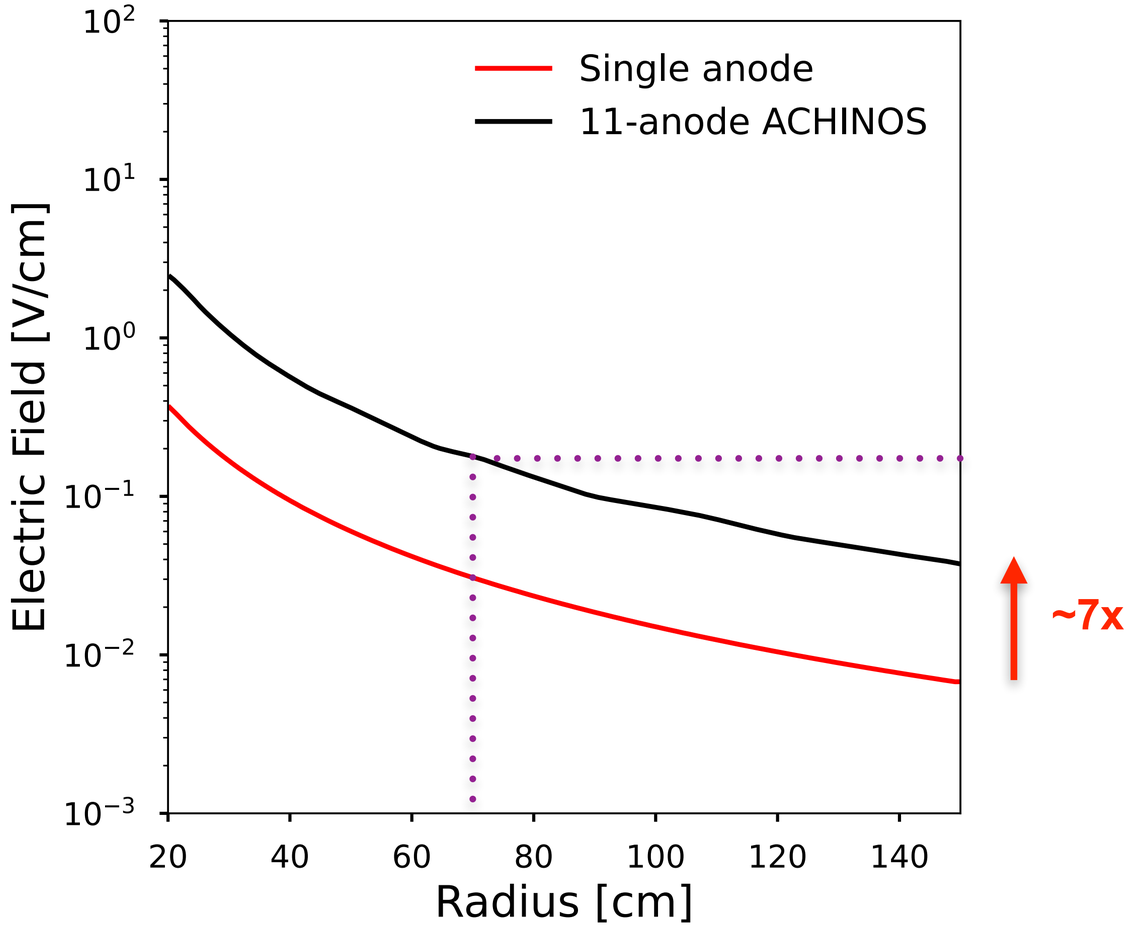

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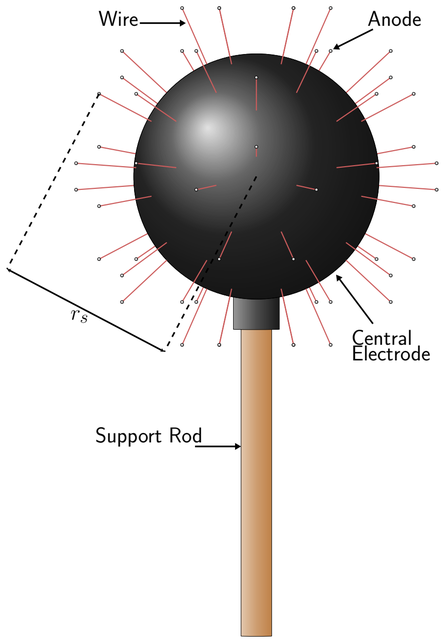

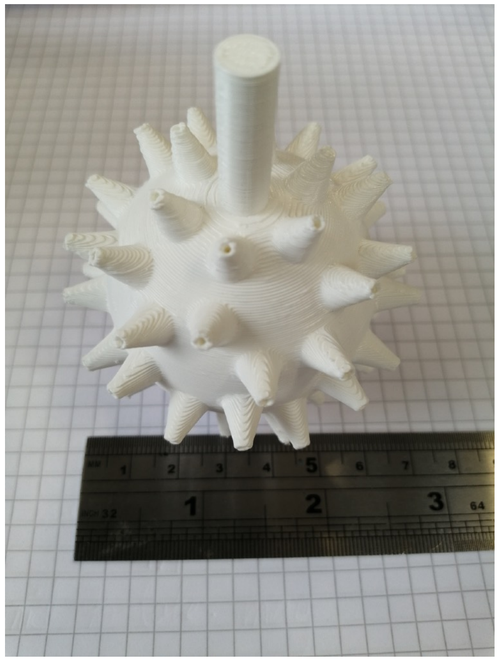

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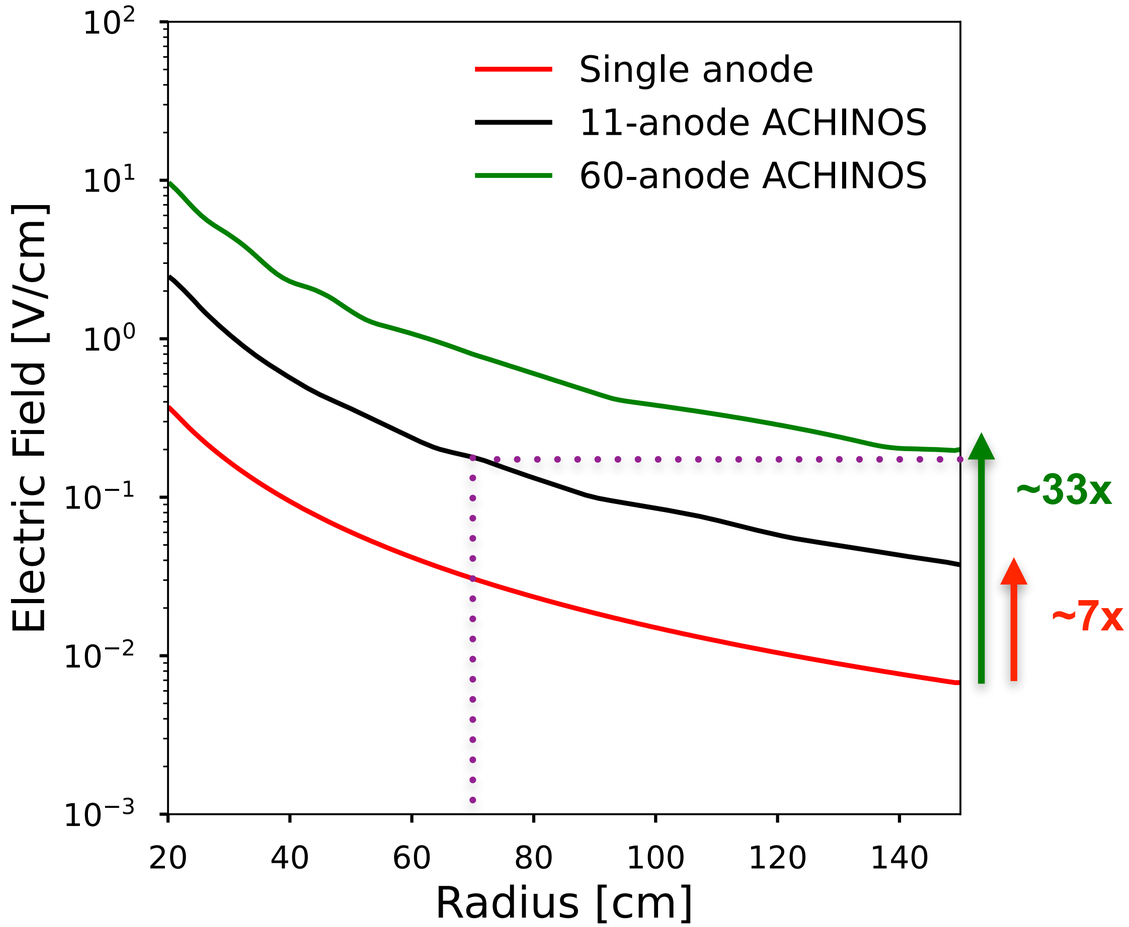

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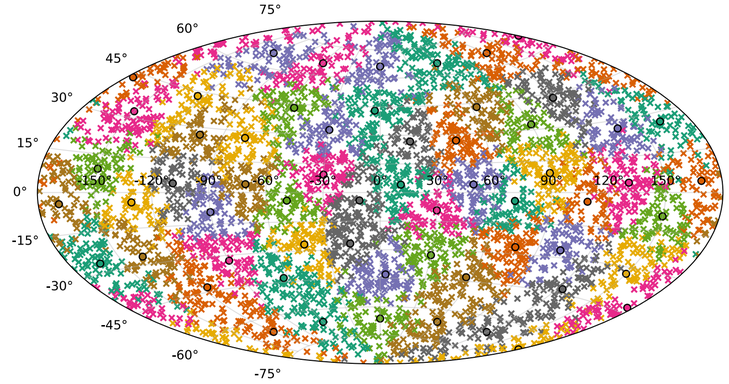

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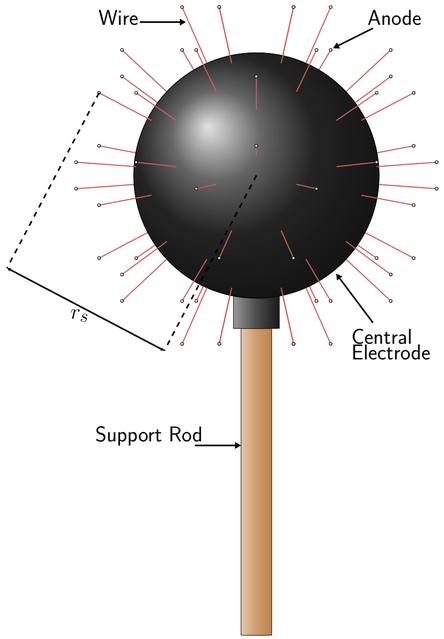

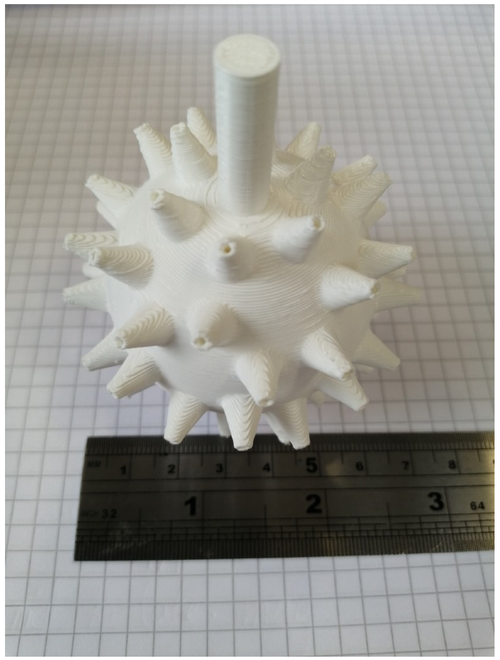

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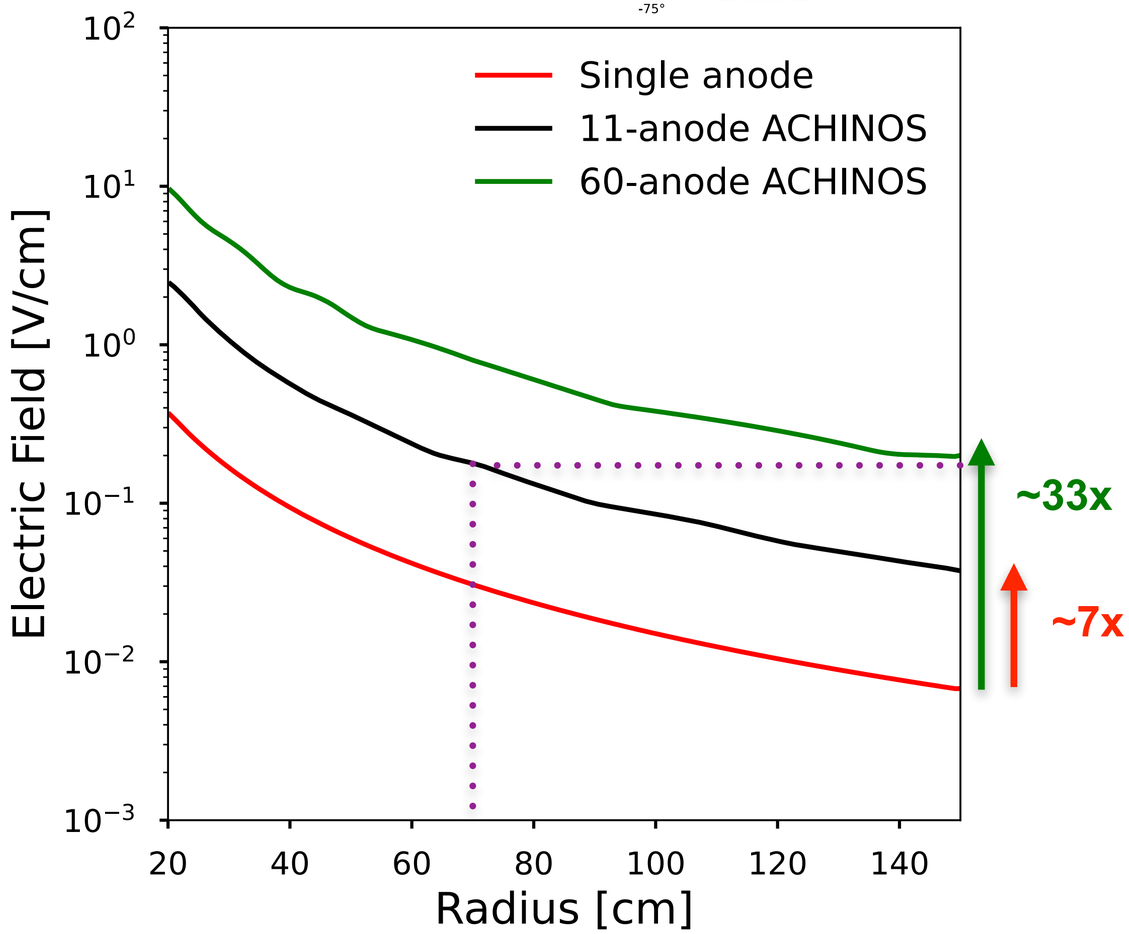
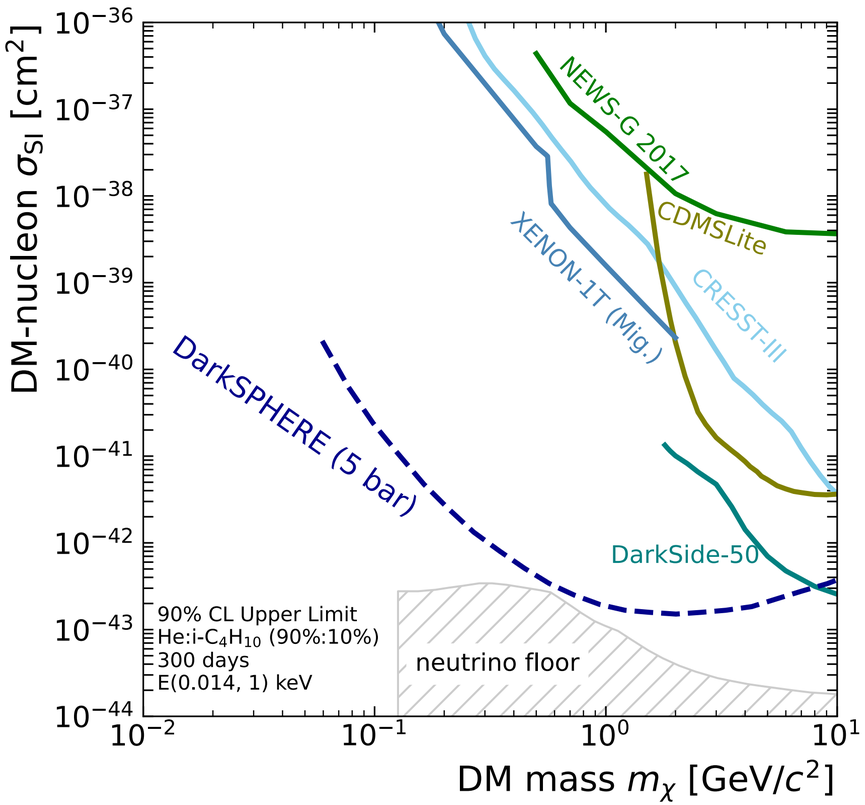


DarkSPHERE Physics Potential



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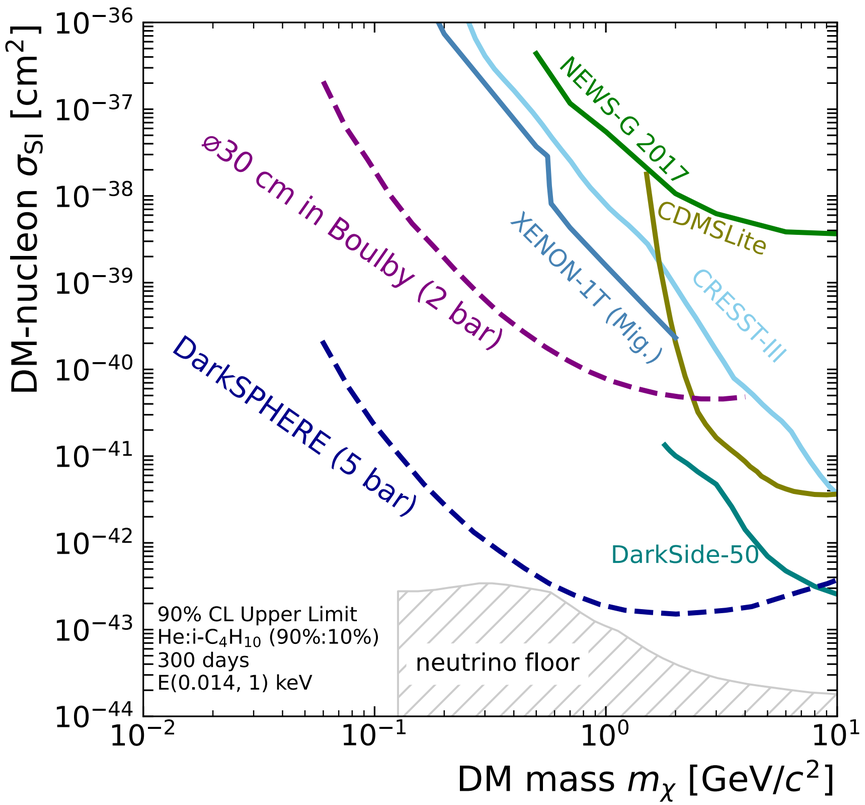

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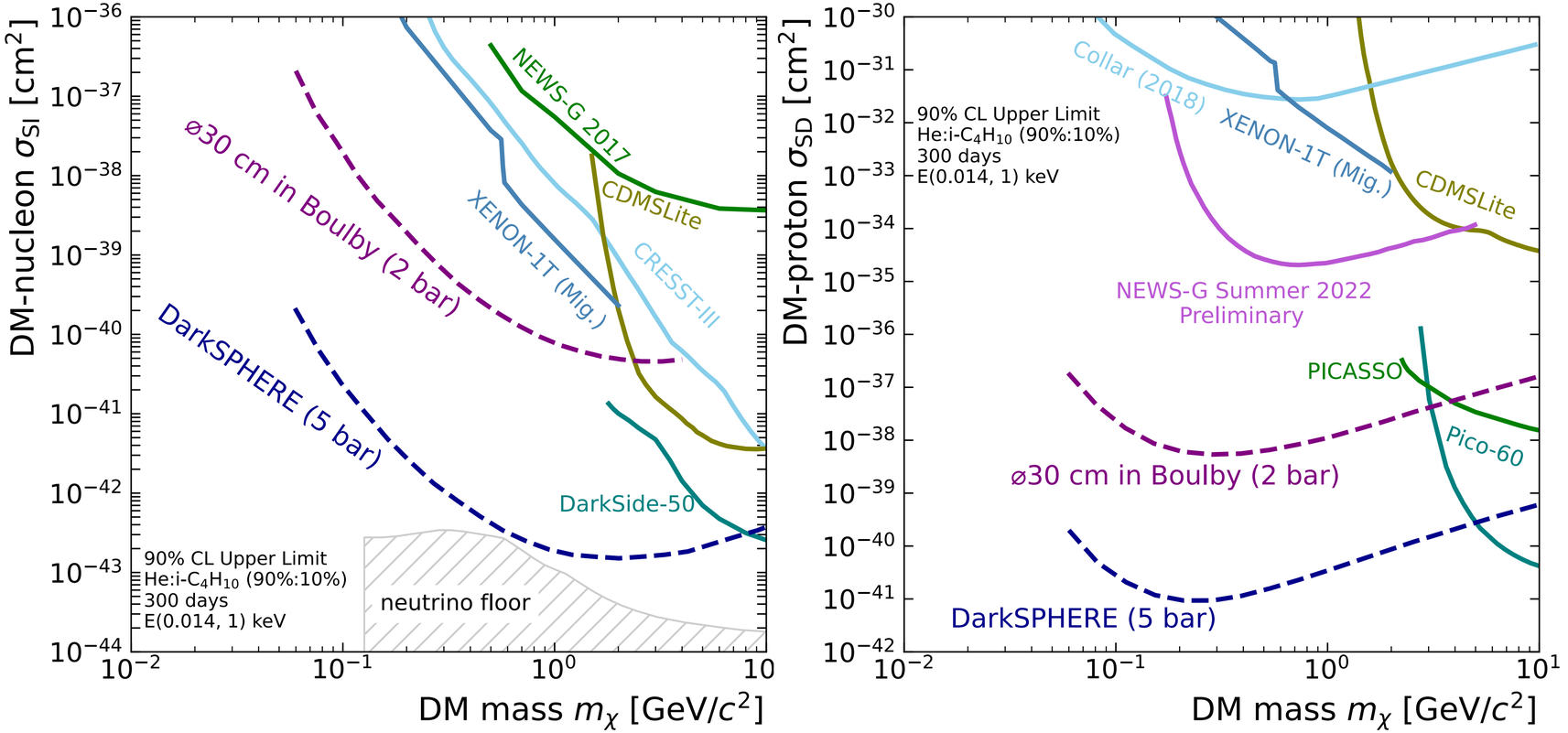

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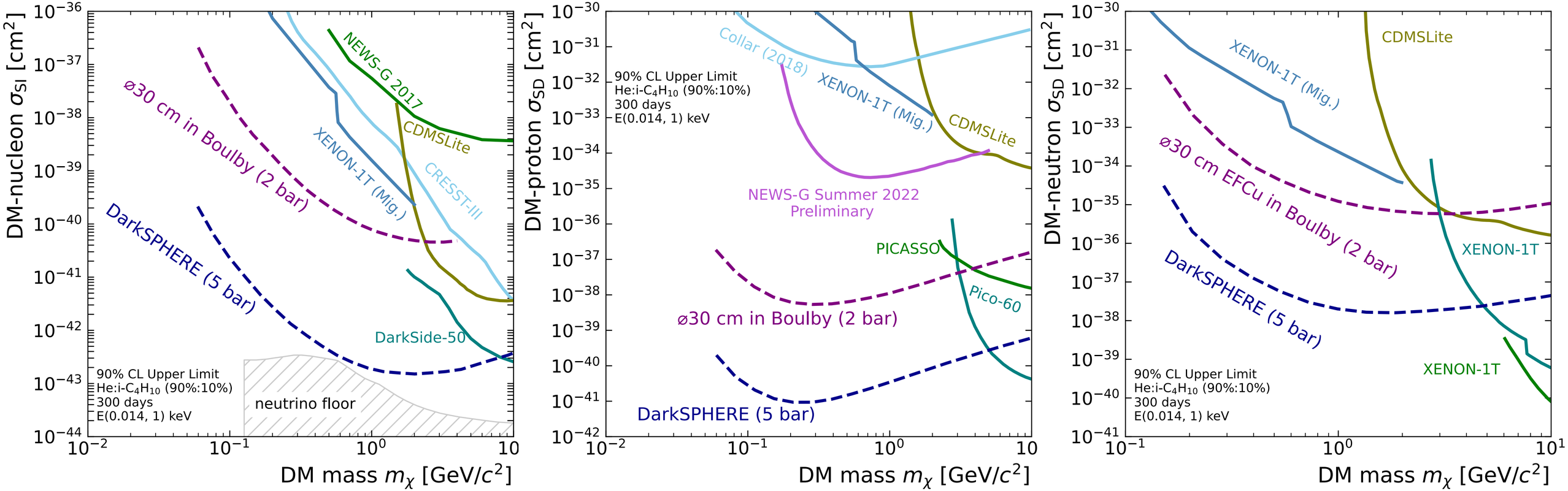

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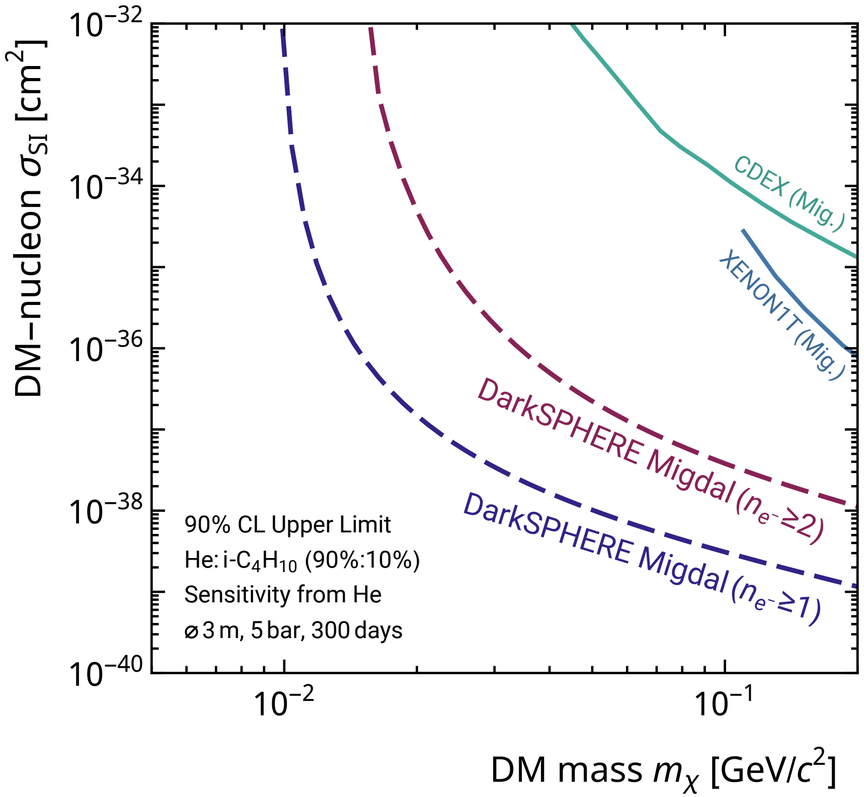

- Enhanced sensitivity through **MIGDAL effect** in nuclear scattering
- Sensitivity to electron scattering through low threshold
- Large sphere is also ideal shape to study more **exotic candidates**

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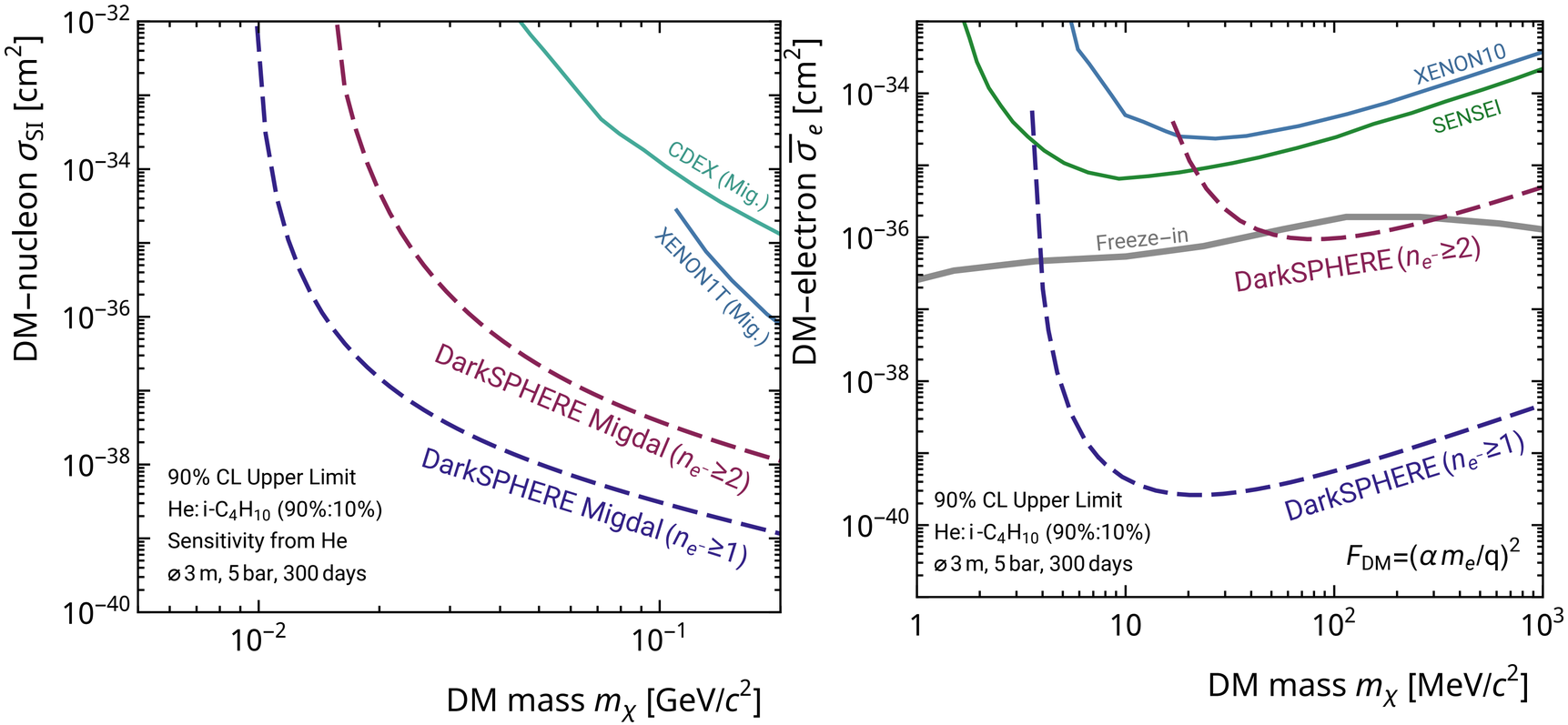

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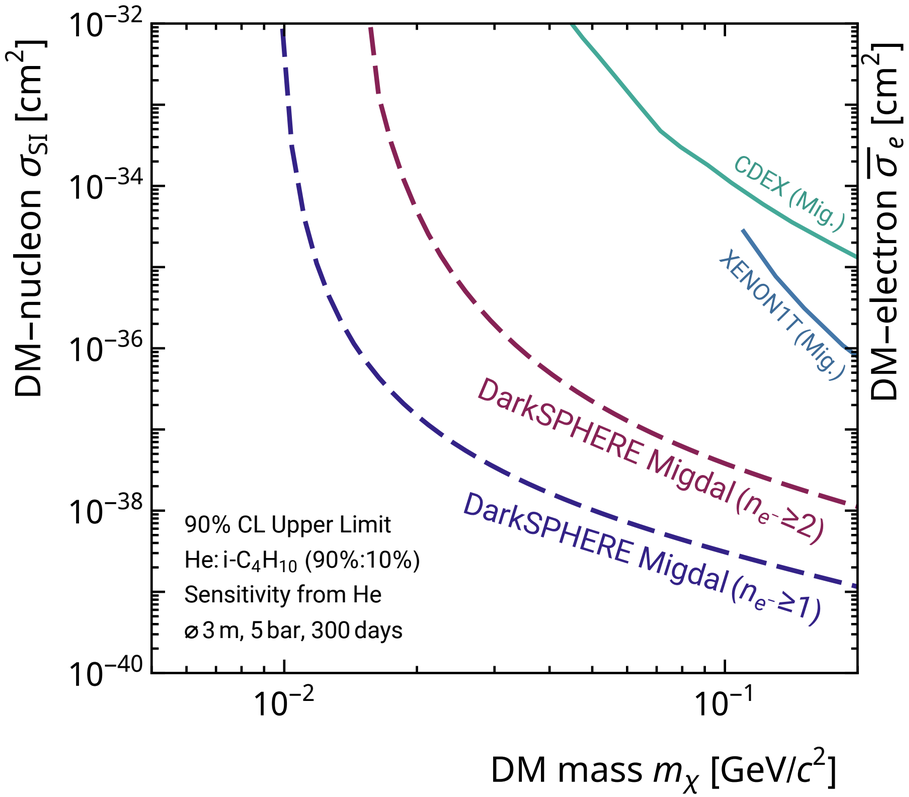

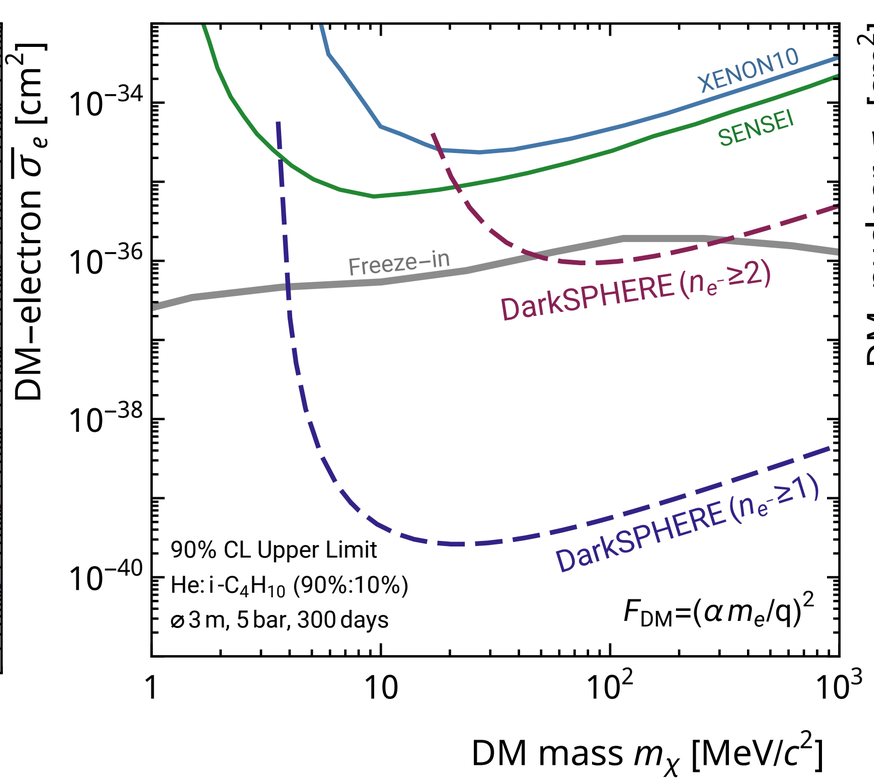

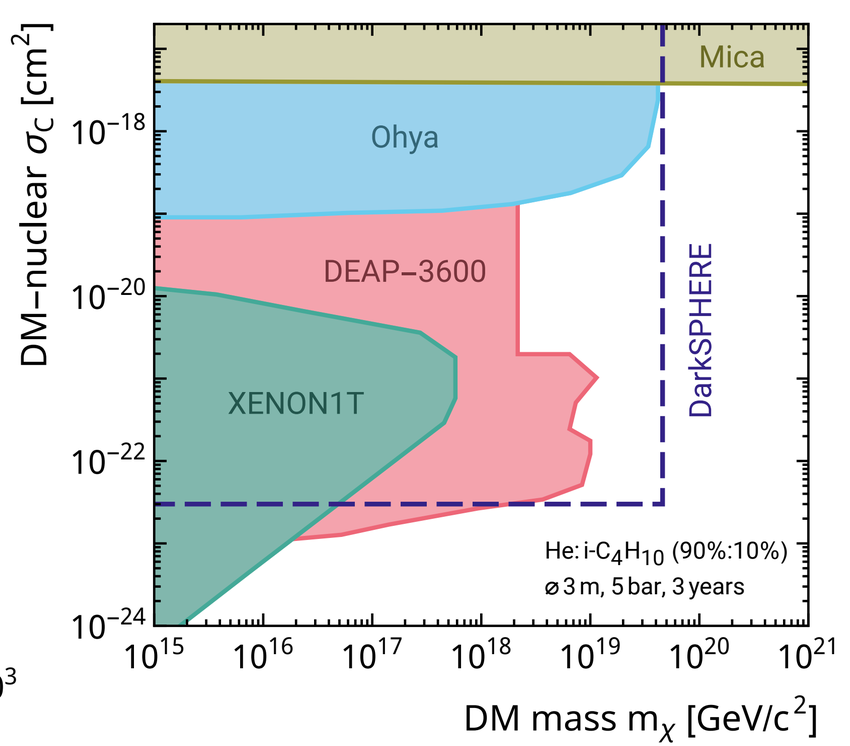

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Summary

- Spherical proportional counters have a number of strengths in probing light DM candidates
- **NEWS-G** first physics campaign in SNOLAB, analysis ongoing
- Fully electroformed SPCs will overcome main background
  - ➡ **DarkSPHERE** proposed for current Boulby lab space
  - ➡ 30cm scale detector to begin in next weeks
  - ➡ World-leading **DM search in Boulby**