Gaseous detectors in light DM searches: The NEWS-G and MIGDAL experiments

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University of Hamburg and
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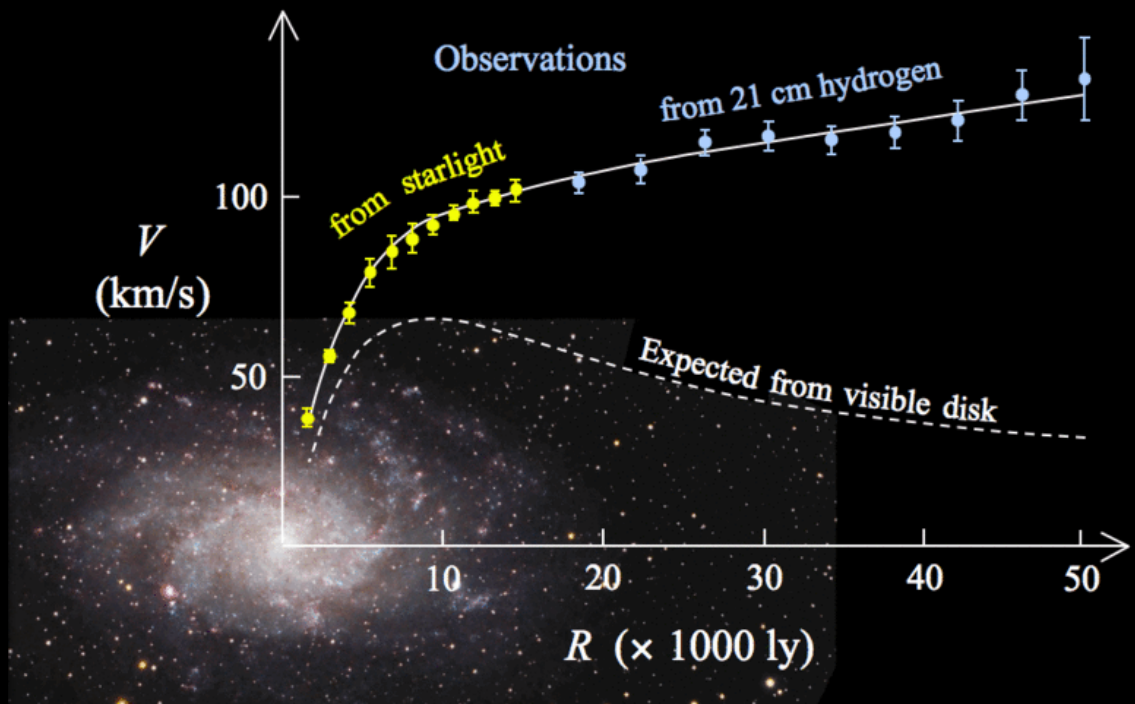
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

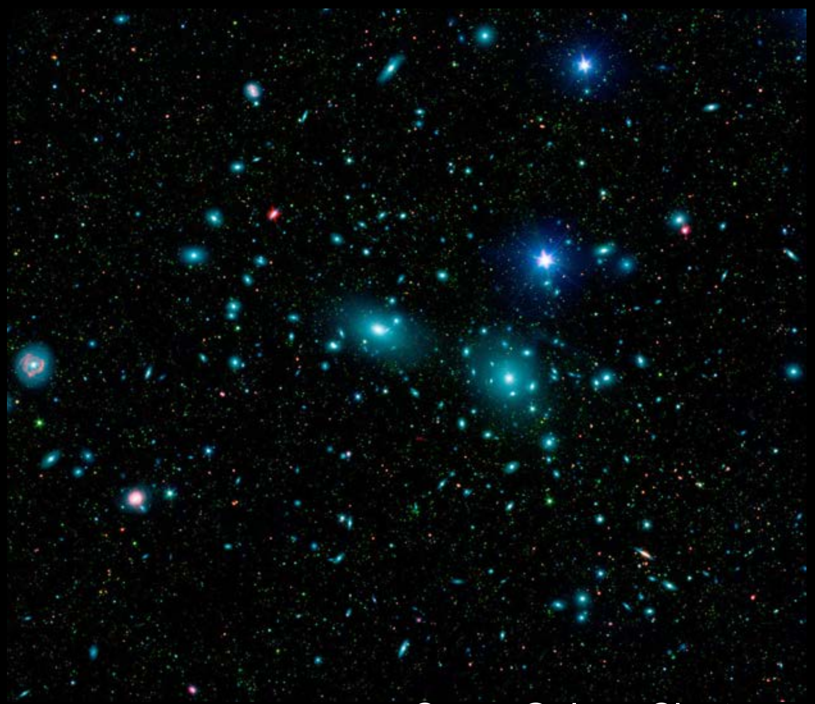
UNIVERSITY OF BIRMINGHAM

MIGDAL
Migdal In Galactic Dark mAtter expLoration

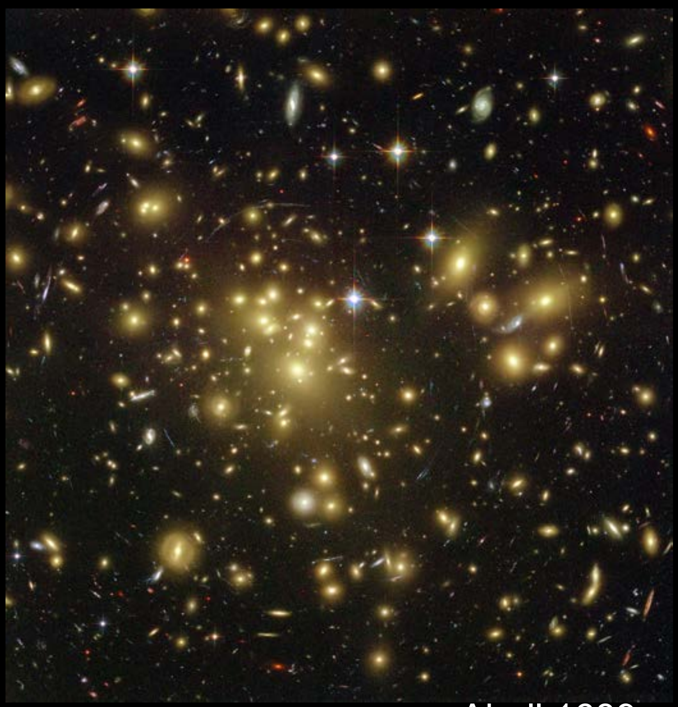
Exploring the Dark Side of the Universe - Tools
June 7th, 2024, Île de Noirmoutier, France



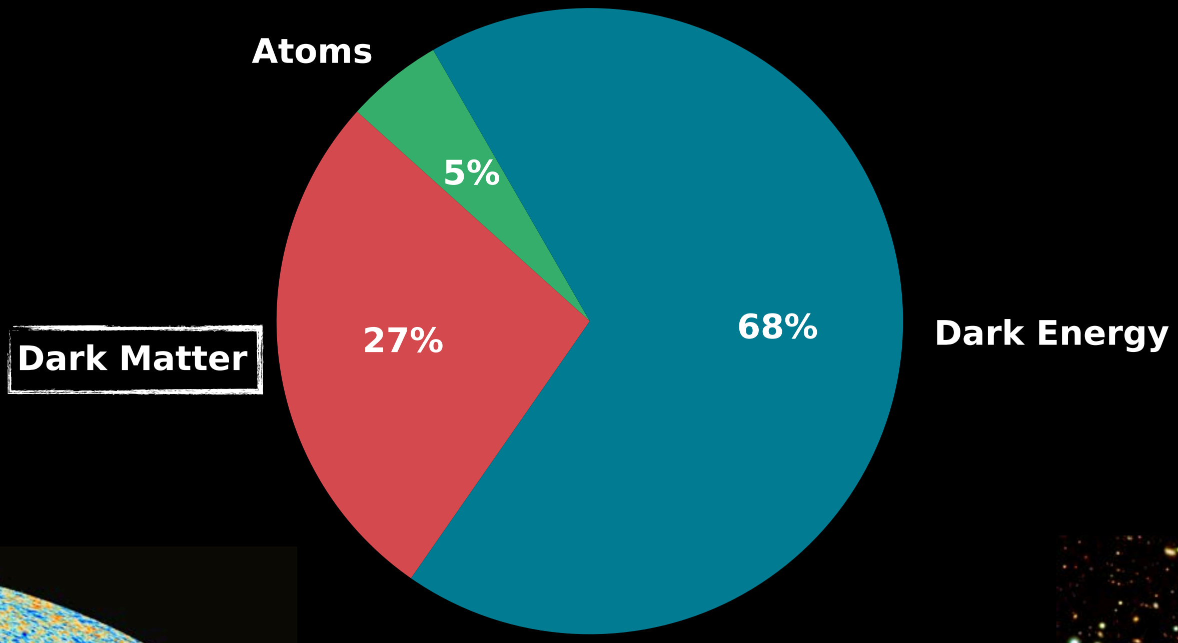
Spiral Galaxy M33

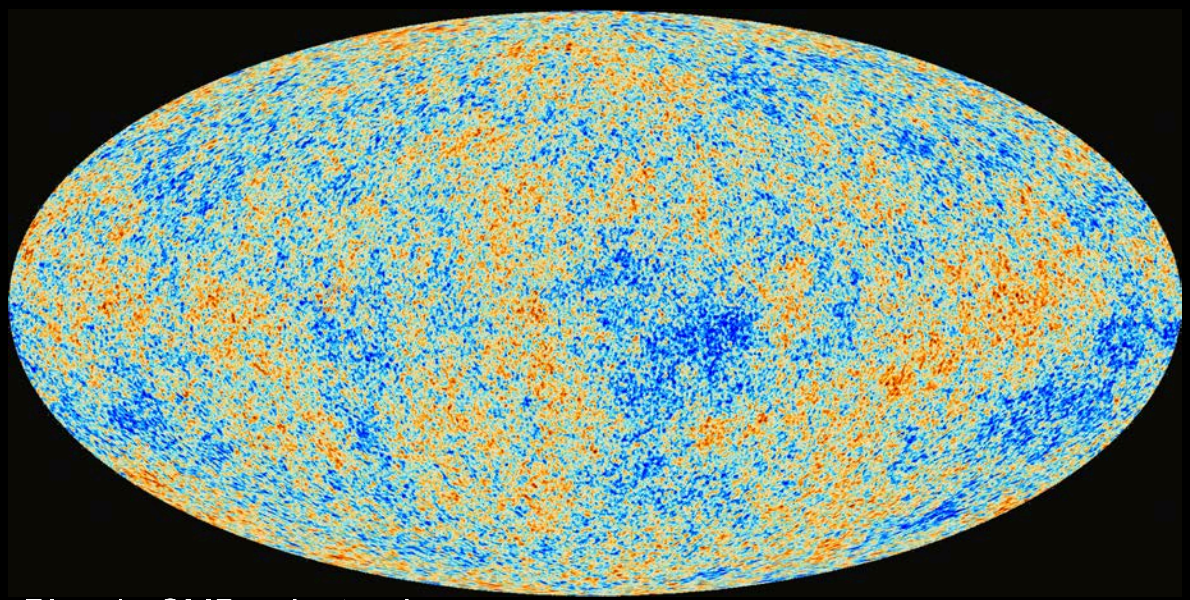


Coma Galaxy Cluster



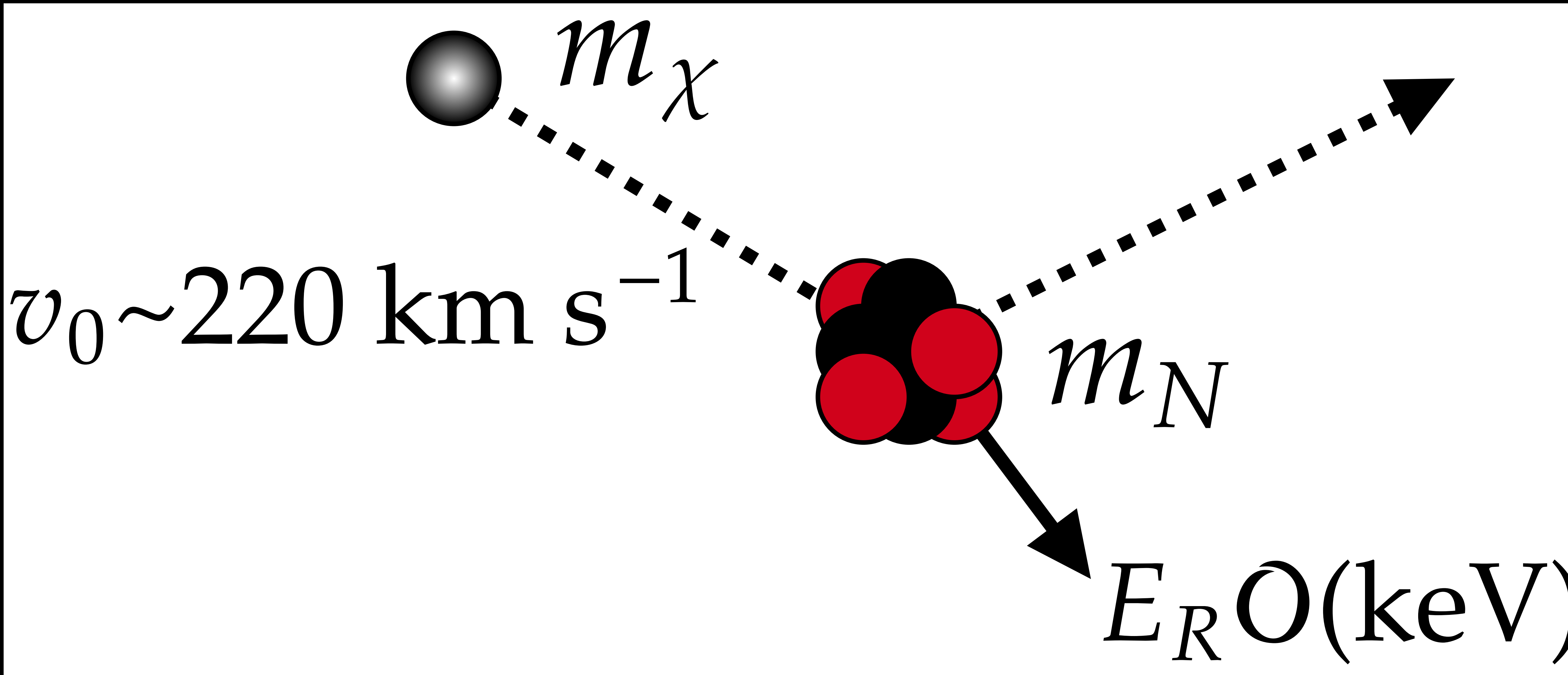
Abell 1689

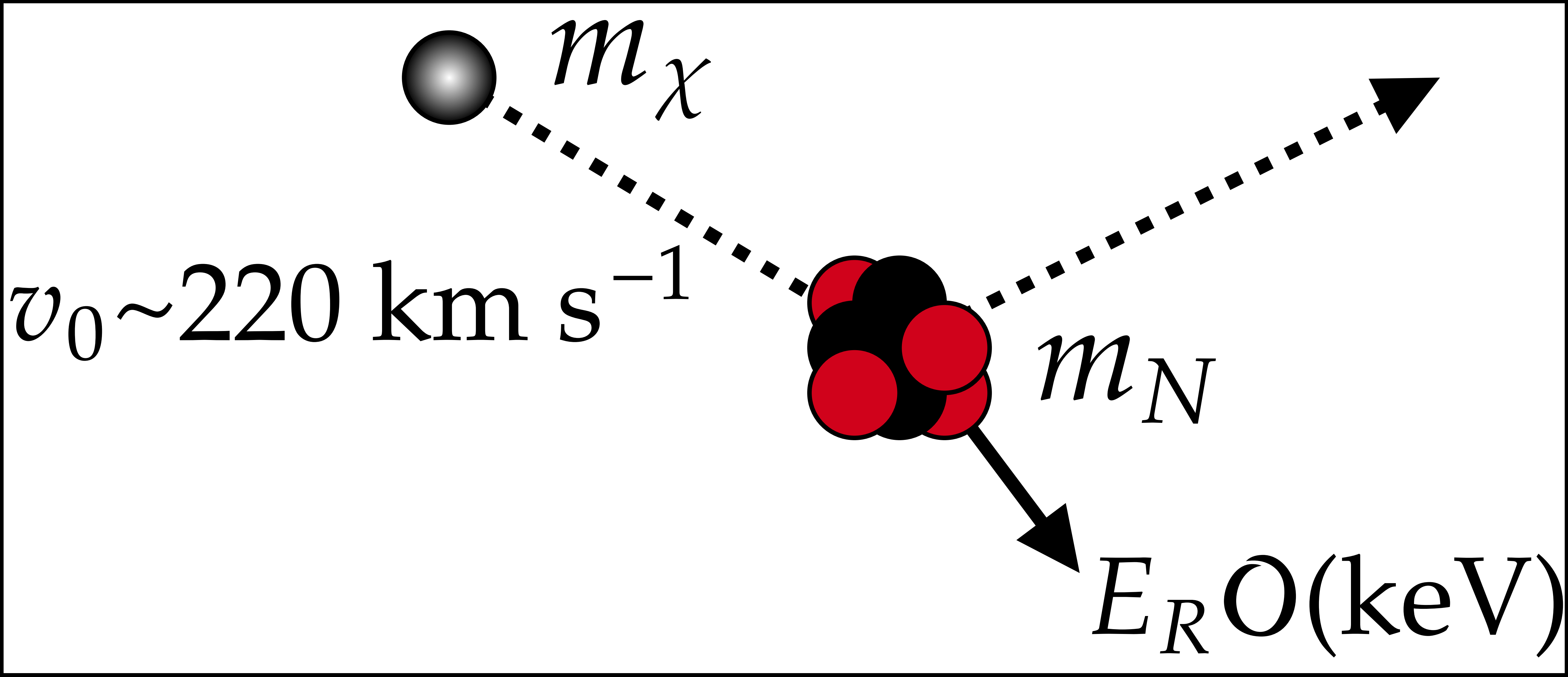




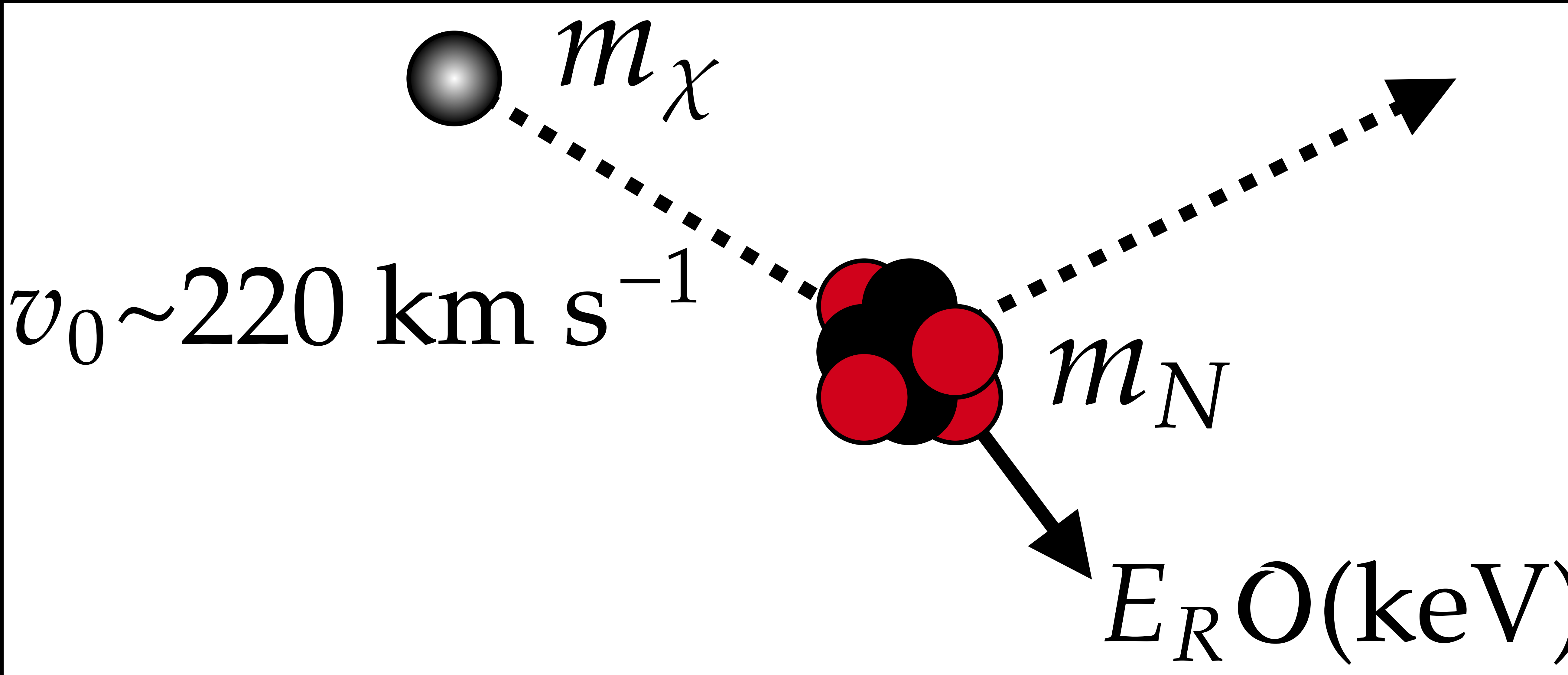
Planck: CMB anisotropies

Bullet Cluster


m_χ
$v_0 \sim 220$ km s^{-1}
m_N
E_R O(keV)



- **Standard Halo Model**
  - Isothermal sphere with isotropic Maxwell-Boltzmann velocity distribution
  - No substructure
- **Locally**
  - DM density is $\rho \sim 0.3$ GeV cm^{-3}
  - Solar system travelling through “DM Wind”
  - Flux: $10^7/m_\chi$ GeV cm^{-2}s^{-1}



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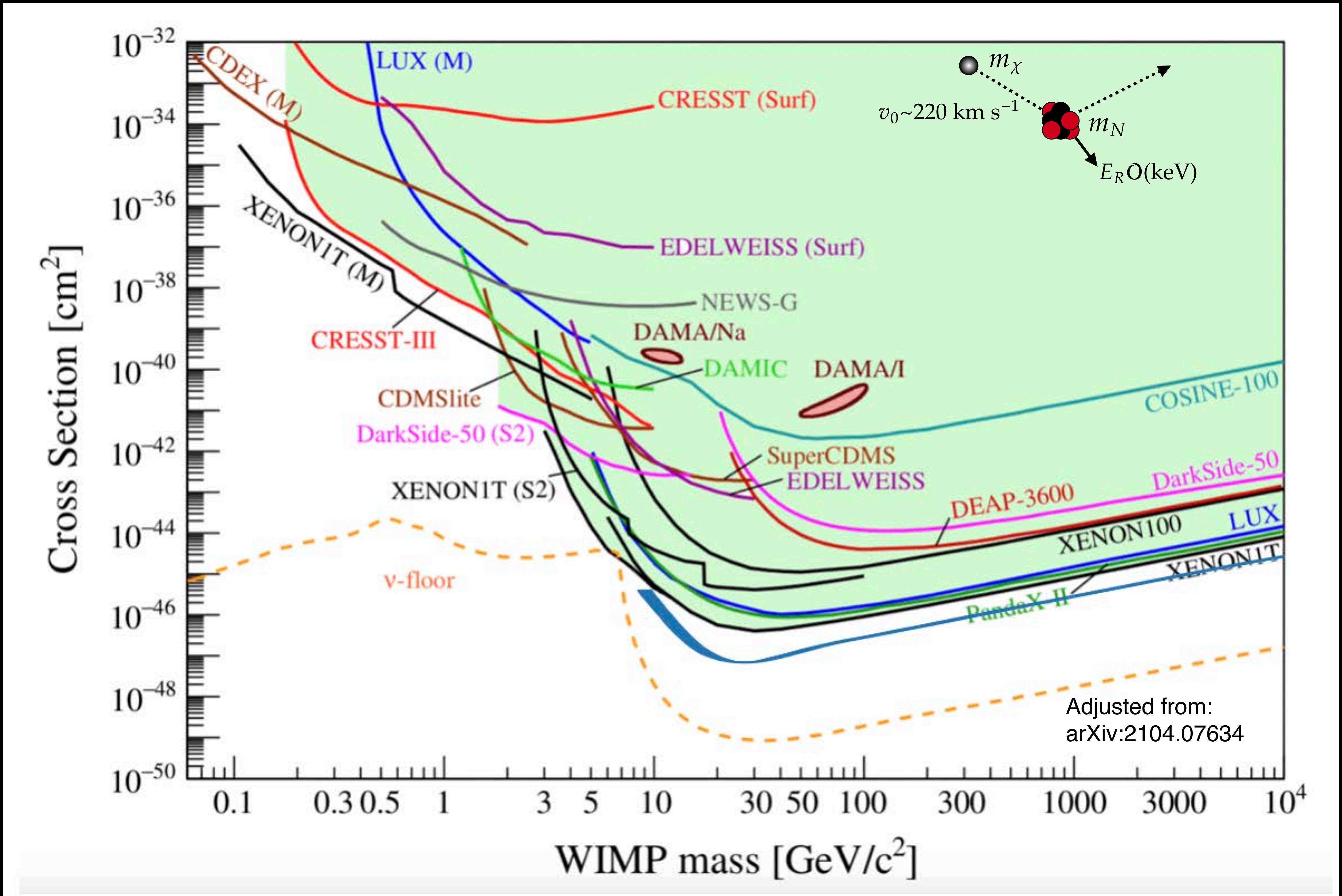
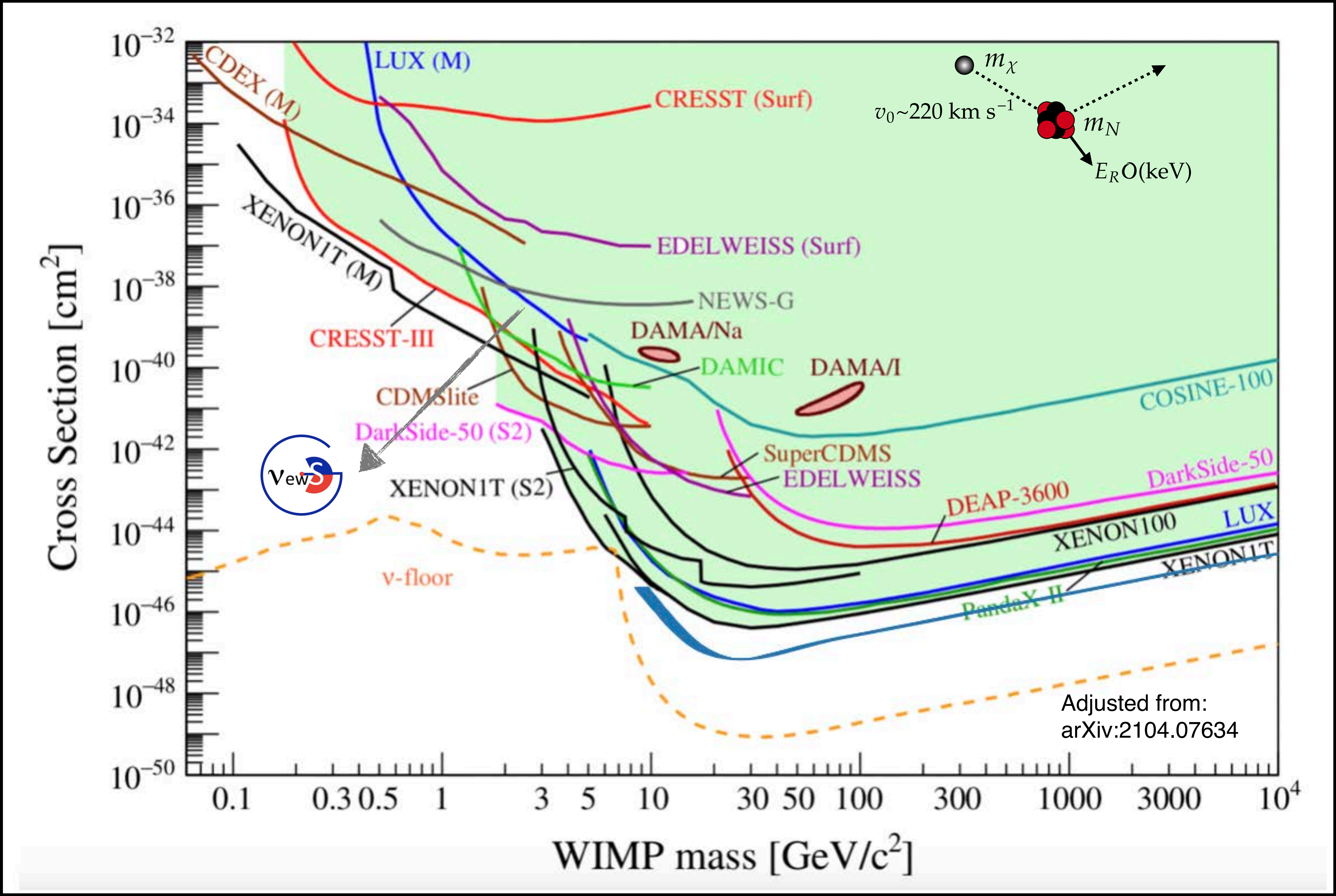


- Also constraints on spin-dependent proton/neutron-DM interactions



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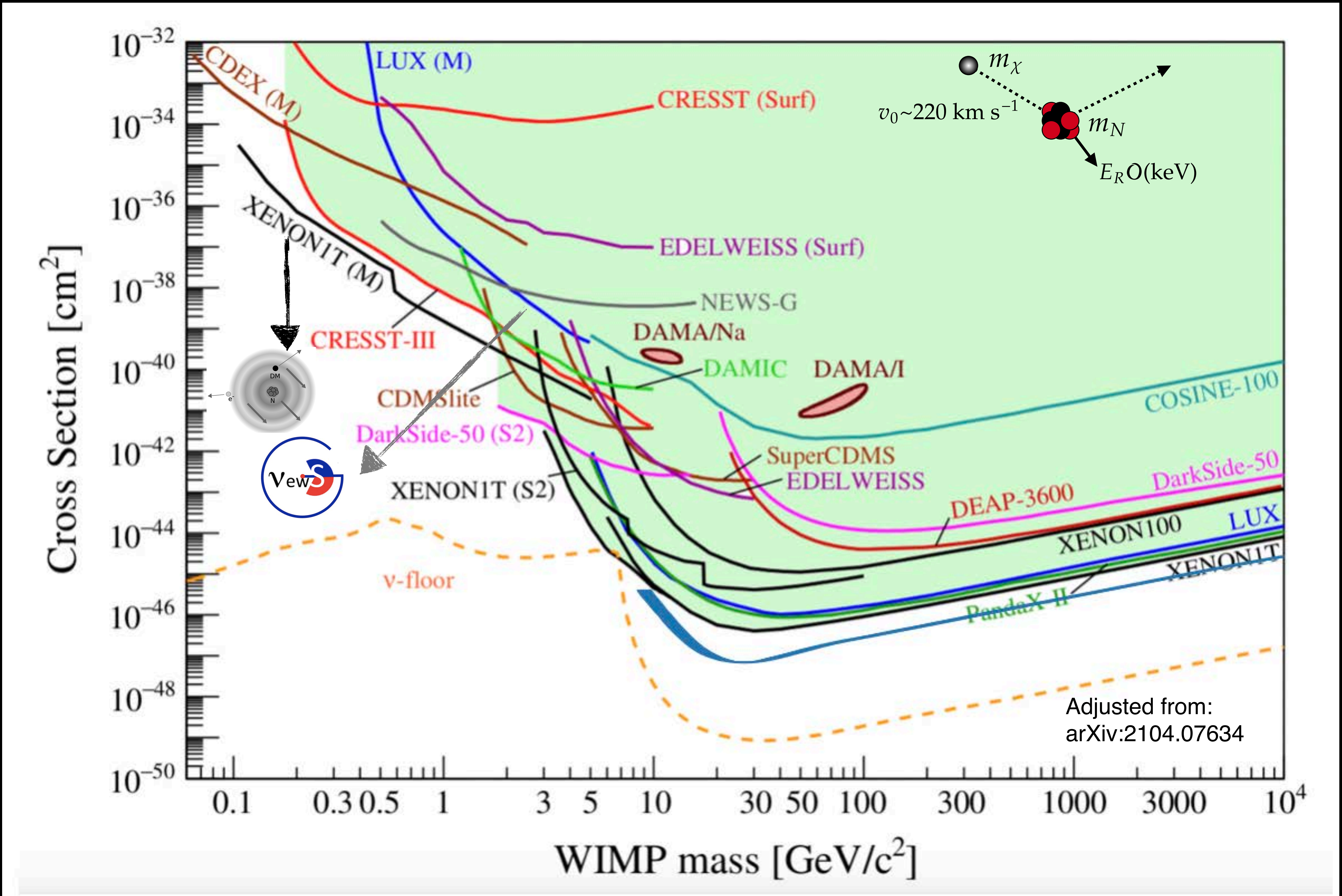


Also constraints on spin-dependent proton/neutron-DM interactions

NEWS-G

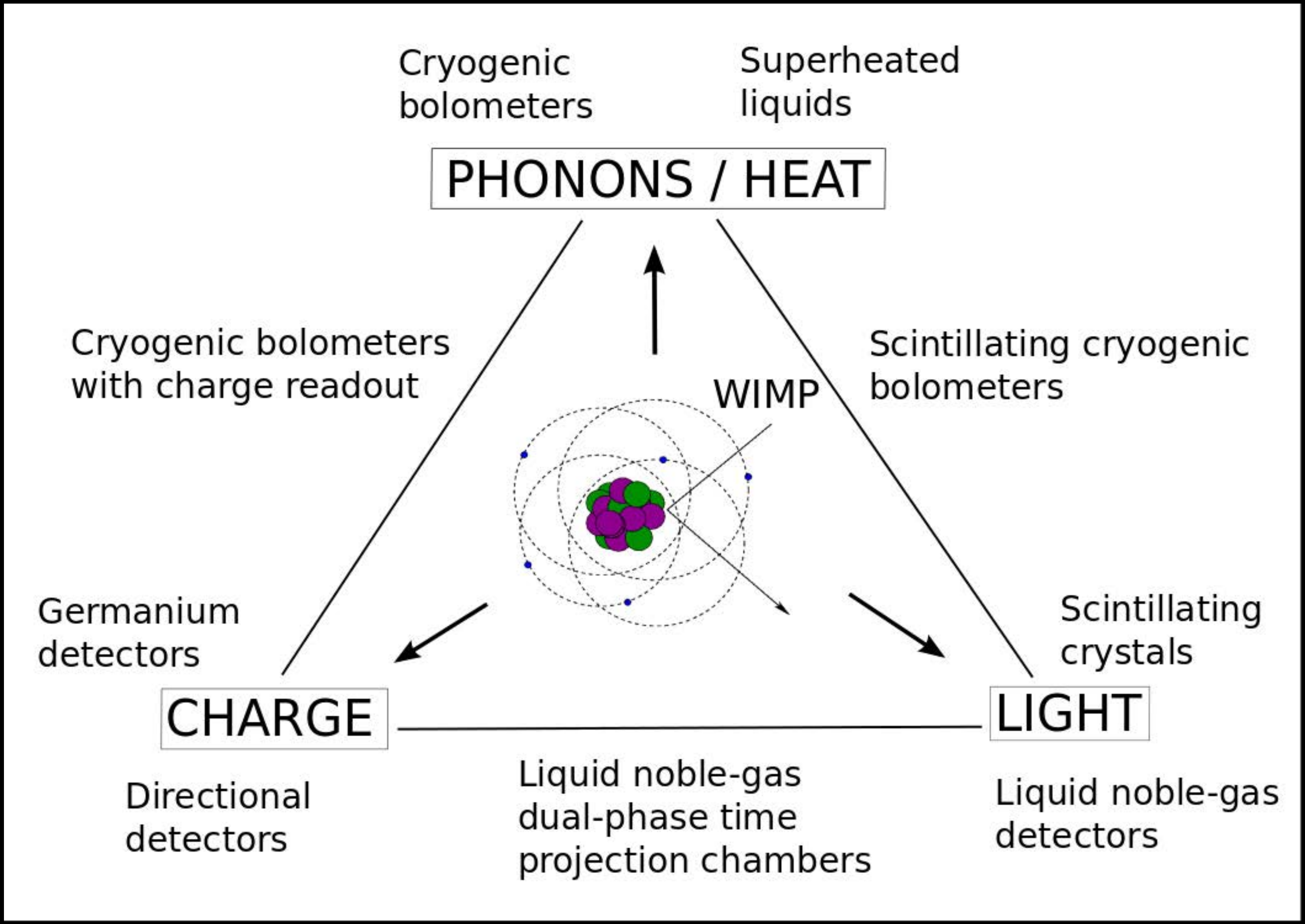
Light Dark Matter searches with Spherical Proportional Counters

New Experiment With Spheres - Gas

- NEWS-G Collaboration
  - 5 countries
  - 10 institutes
  - ~40 collaborators
- Three underground laboratories
  - SNOLAB
  - Laboratoire Souterrain de Modane
  - Boulby Underground Laboratory

13th collaboration meeting, May 2023

Direct Detection: Signal



J.Phys. G43 (2016) 013001

- Recoiling nucleus can deposit energy in several forms
- Sensitivity to multiple signals for background suppression

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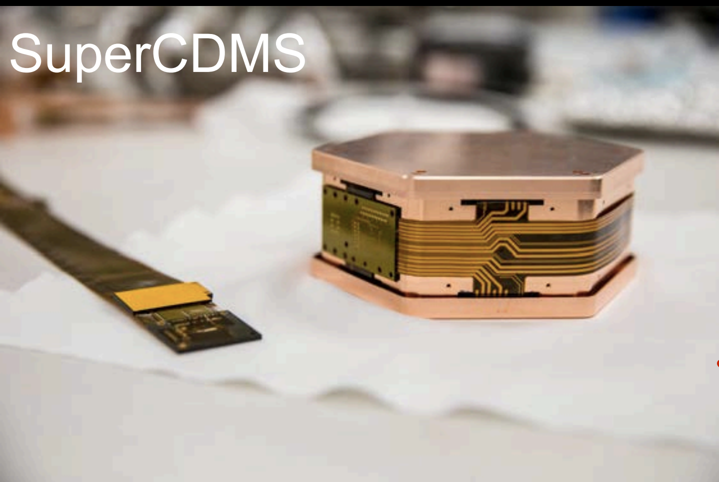
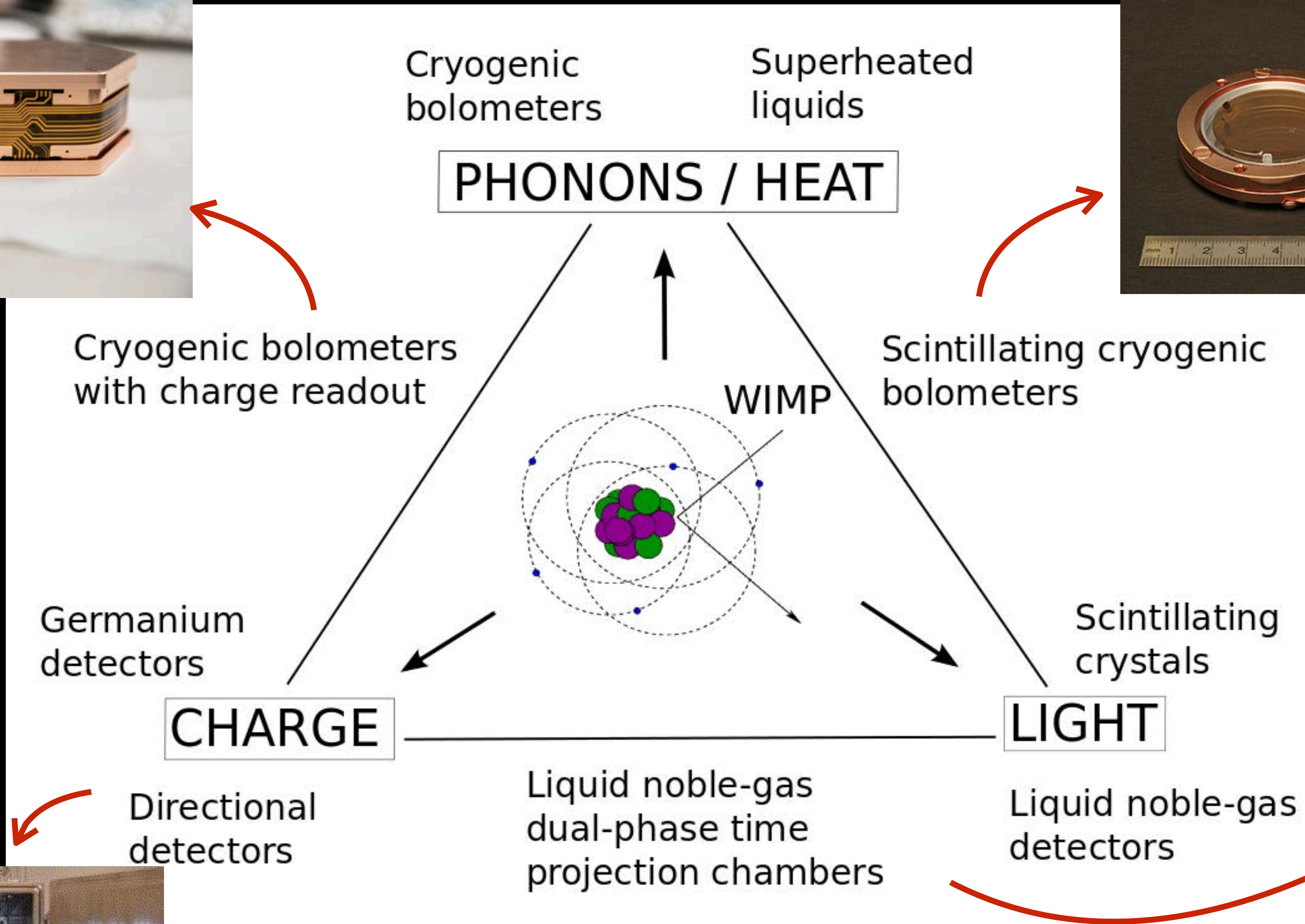
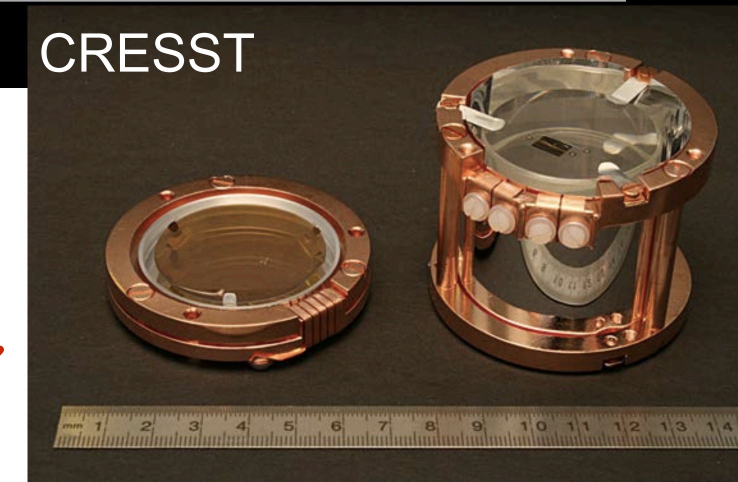
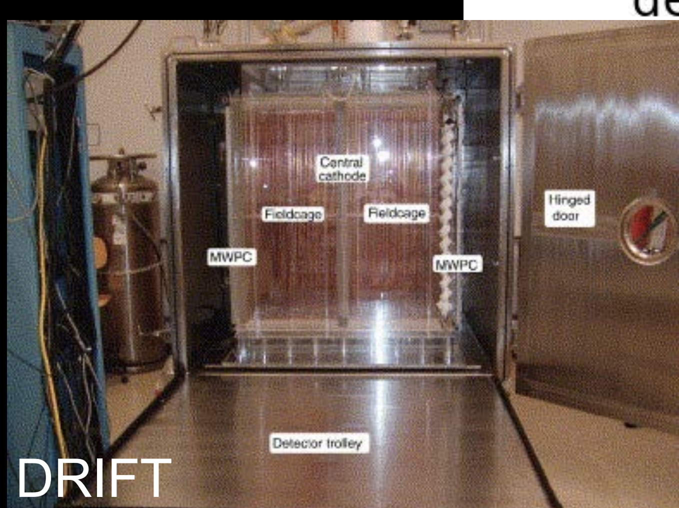






LZ



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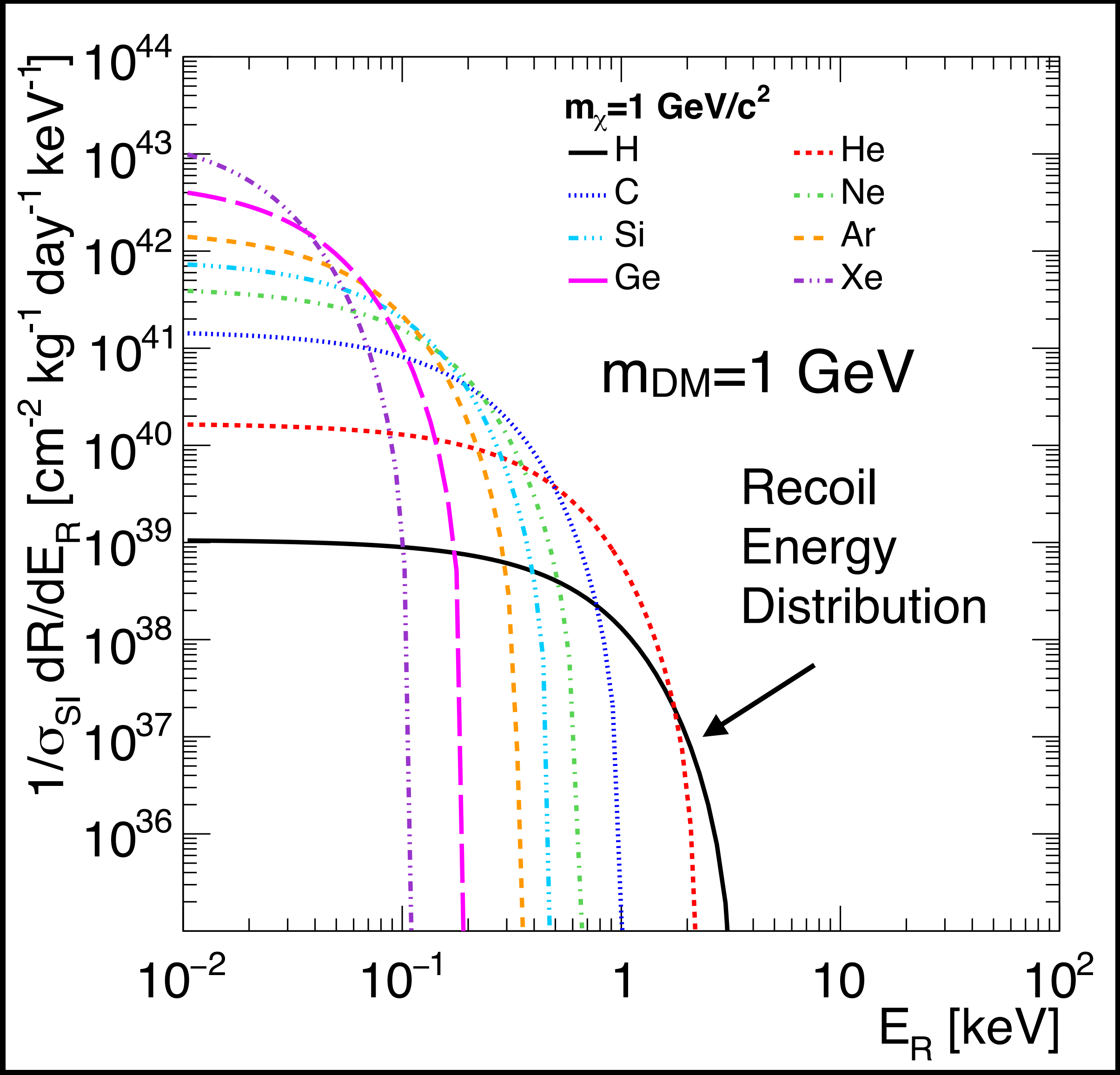
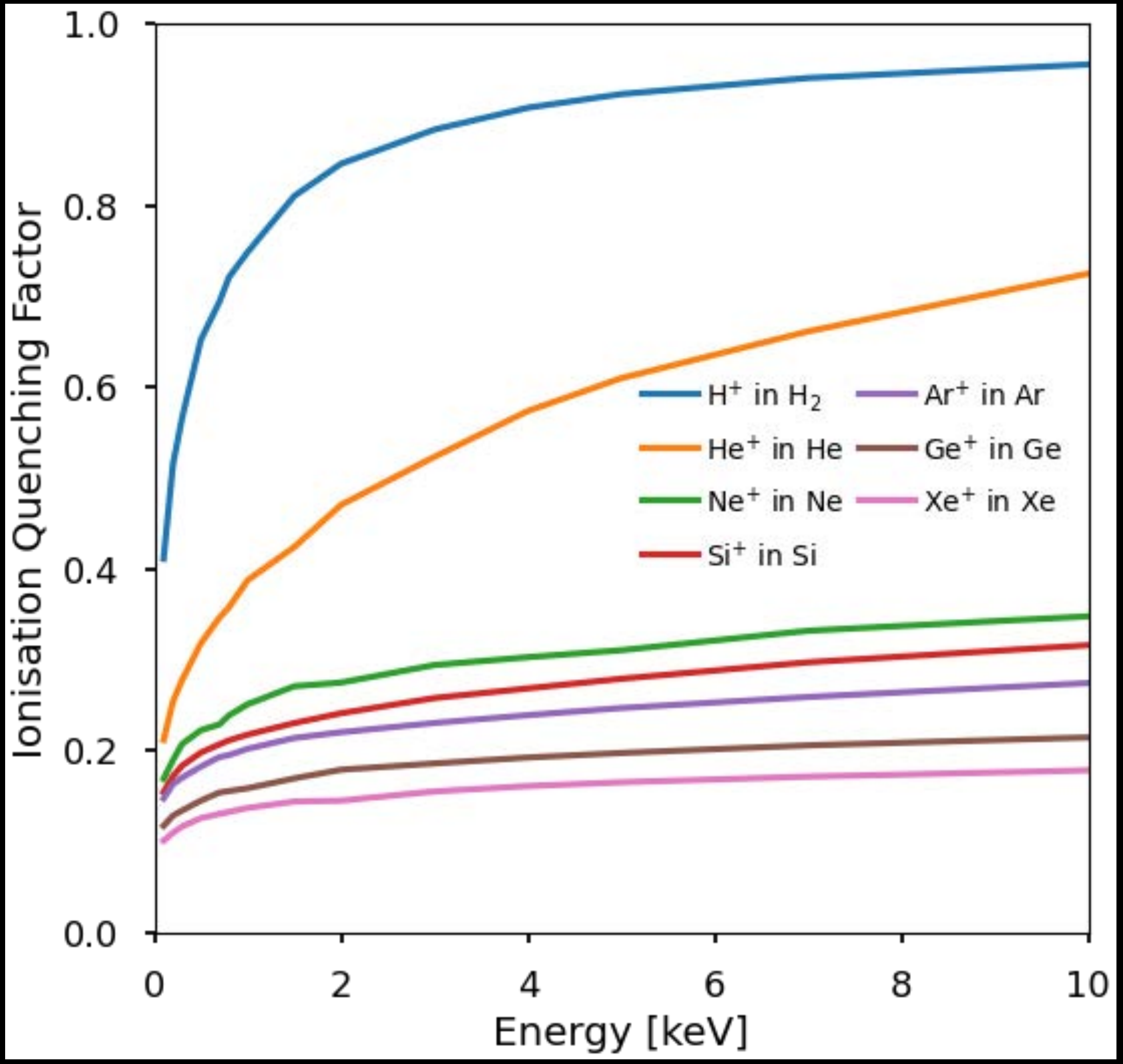
Direct Detection: Light Dark Matter



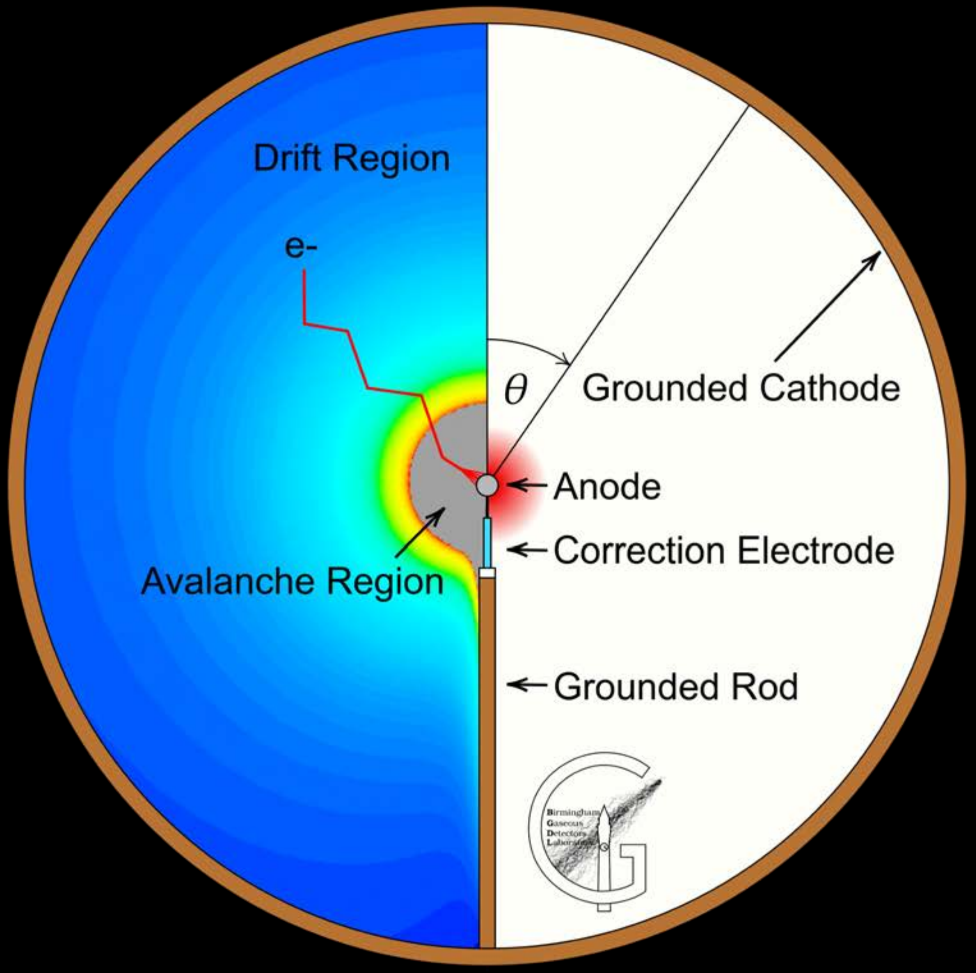


- Favourable recoil energy distribution for lighter targets
- Fraction of energy dissipated as ionisation higher for lighter elements
  - Larger part of recoil nucleus energy “visible” to detector

Spherical Proportional Counter

Electric field scales as $1/r^2$, volume divided in: “drift” and “amplification” regions

Capacitance independent of size: low electronic noise



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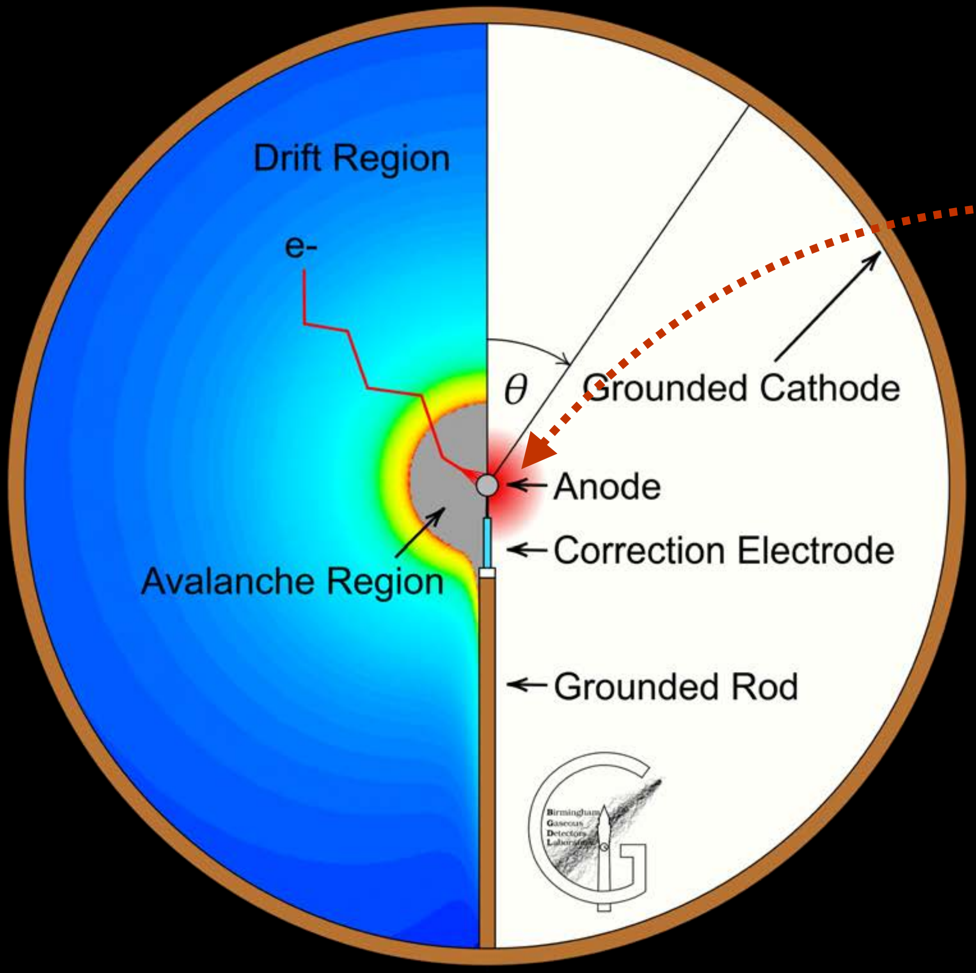

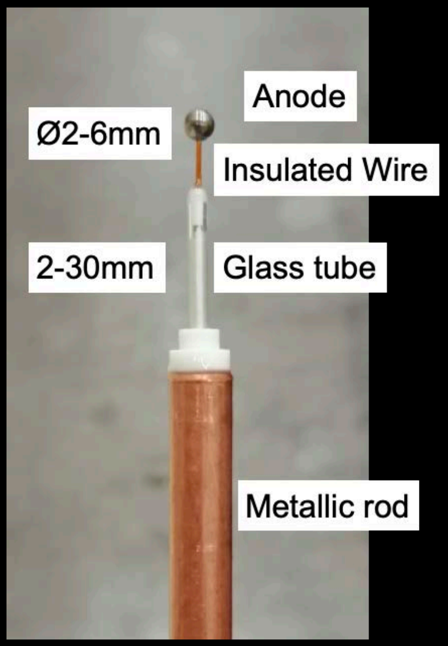

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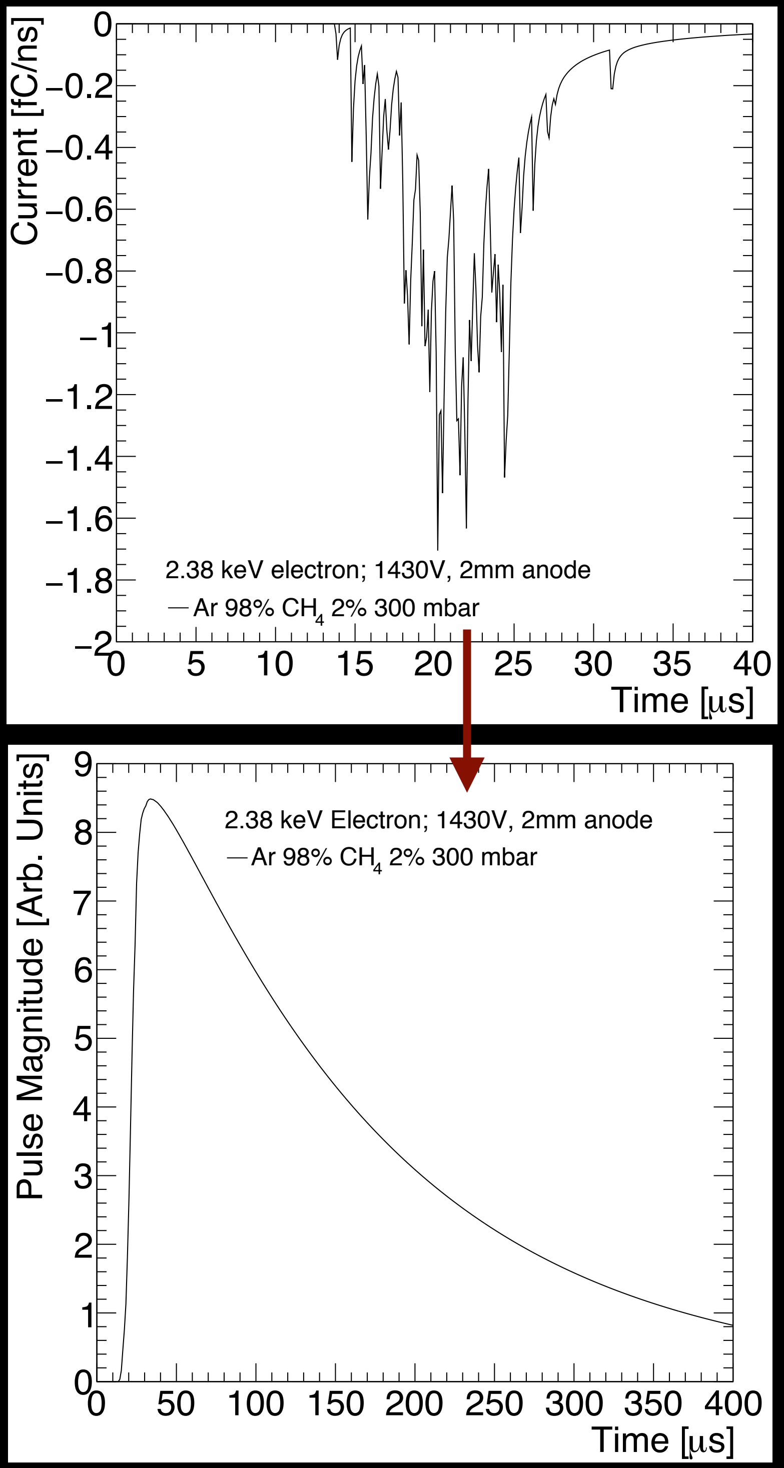

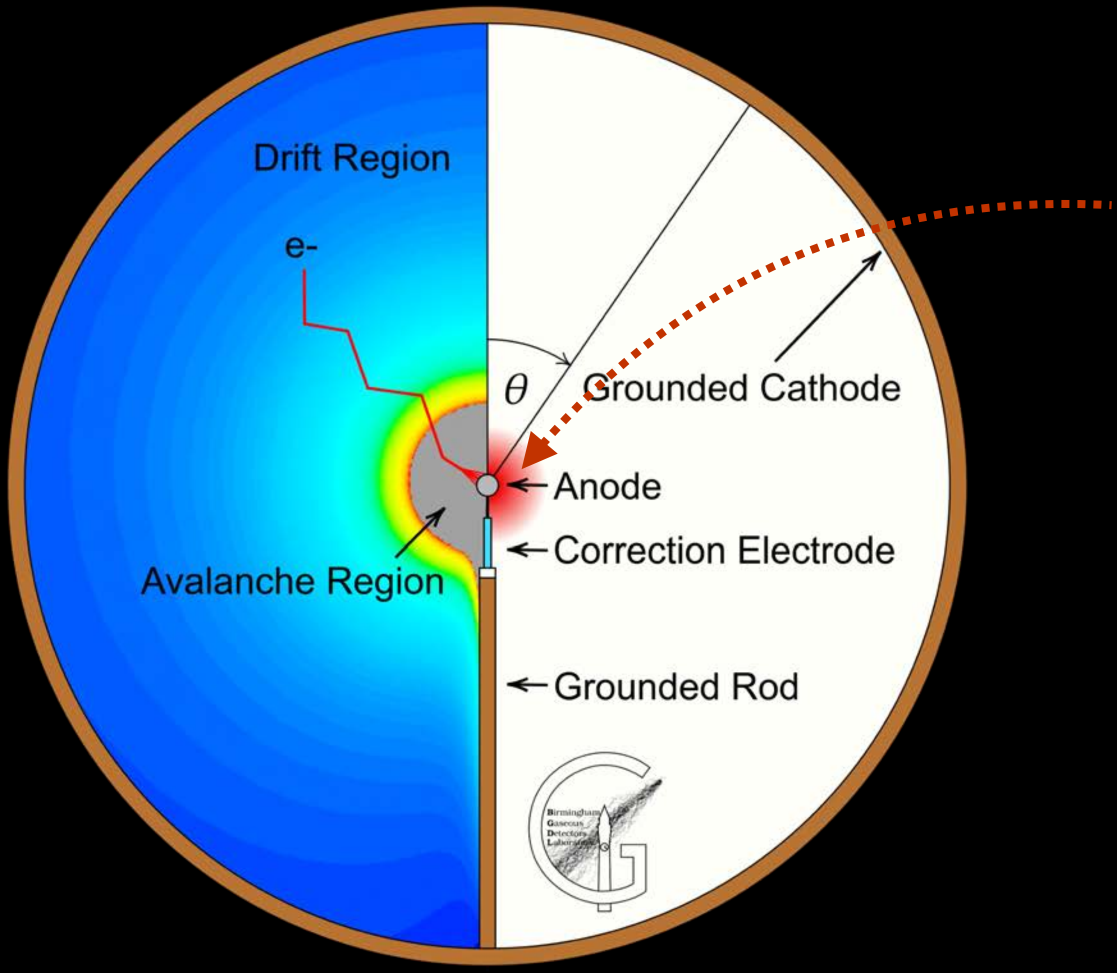

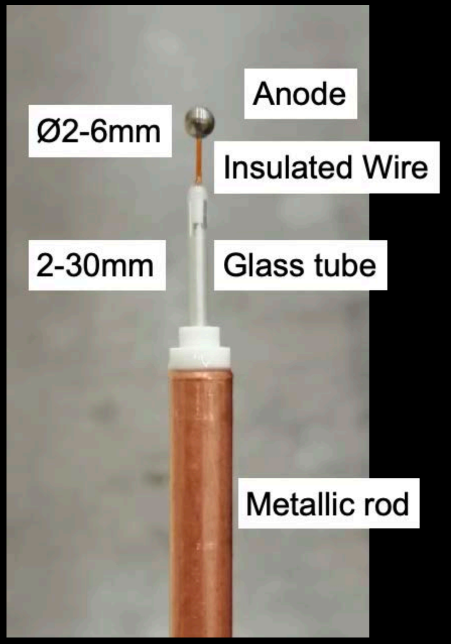

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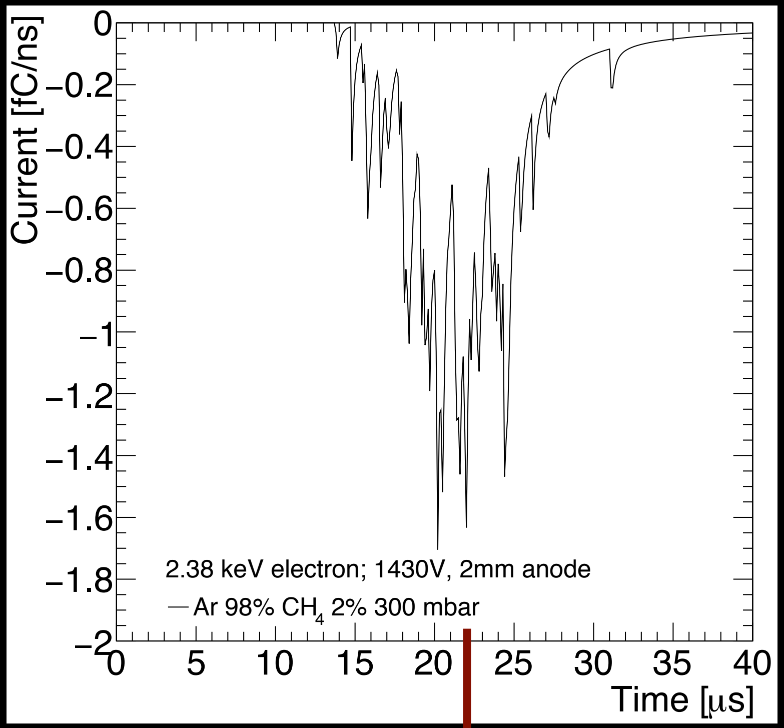

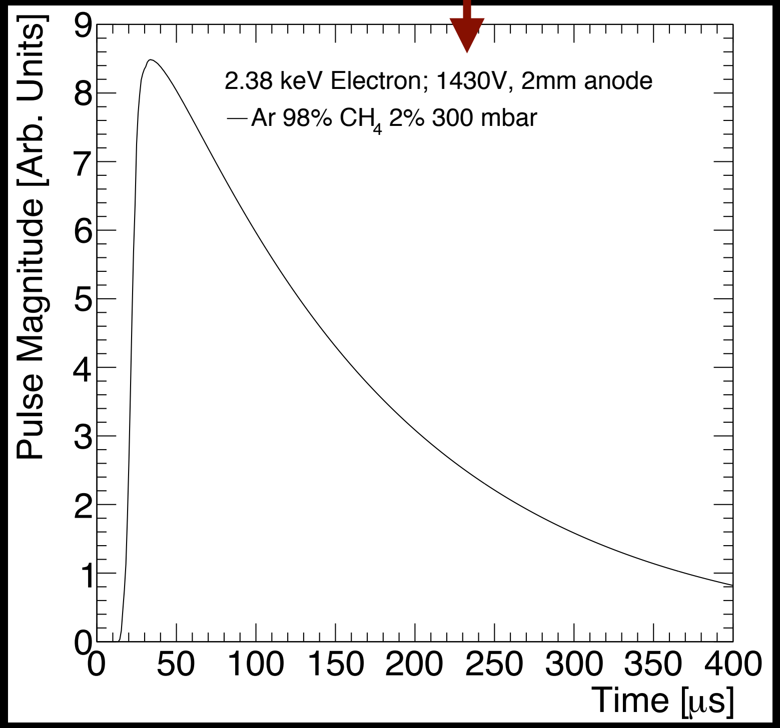

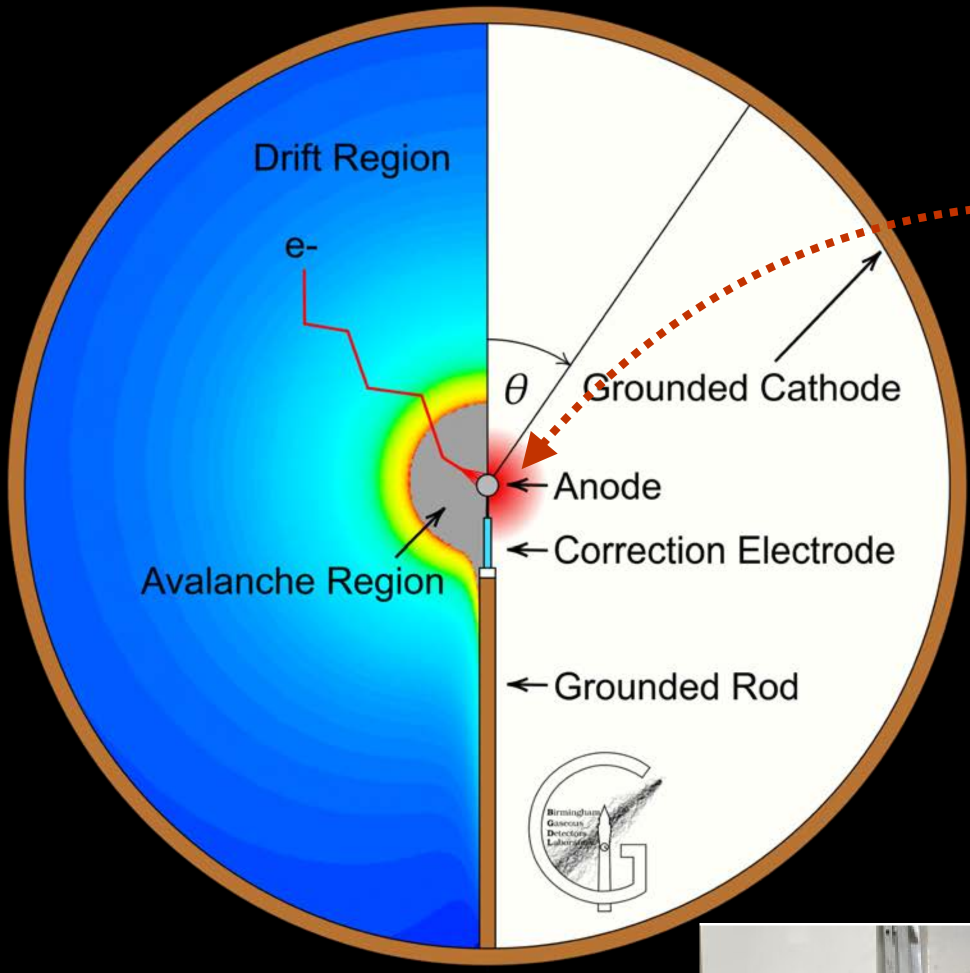

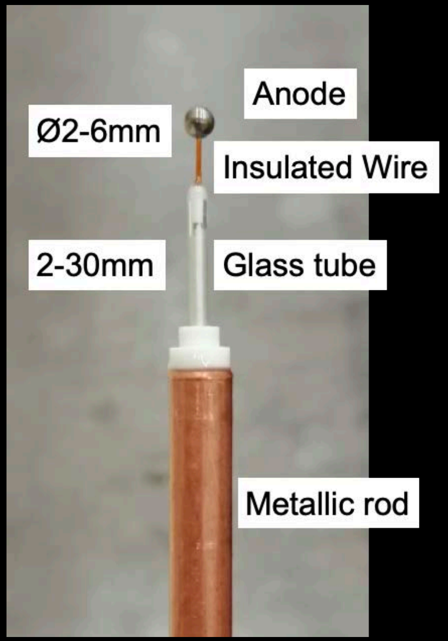

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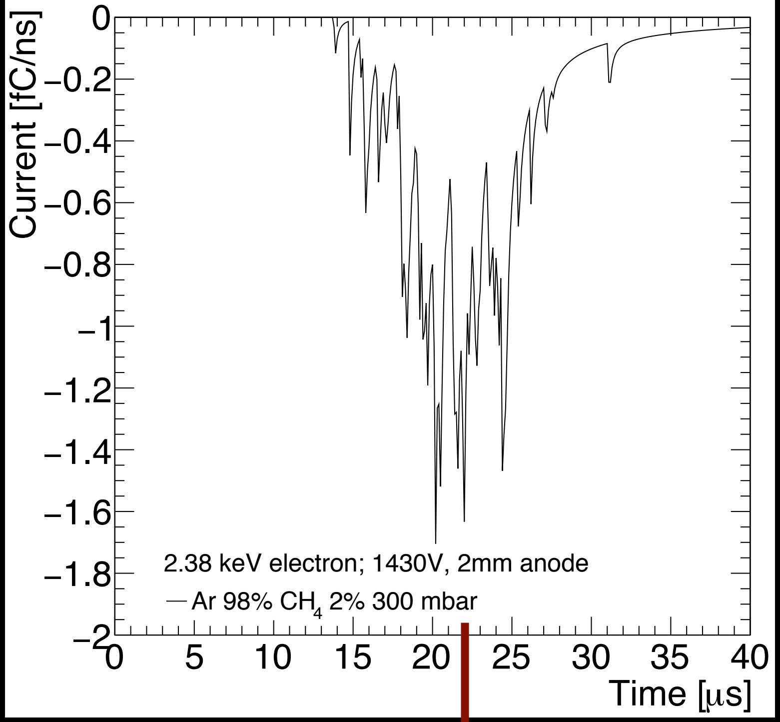

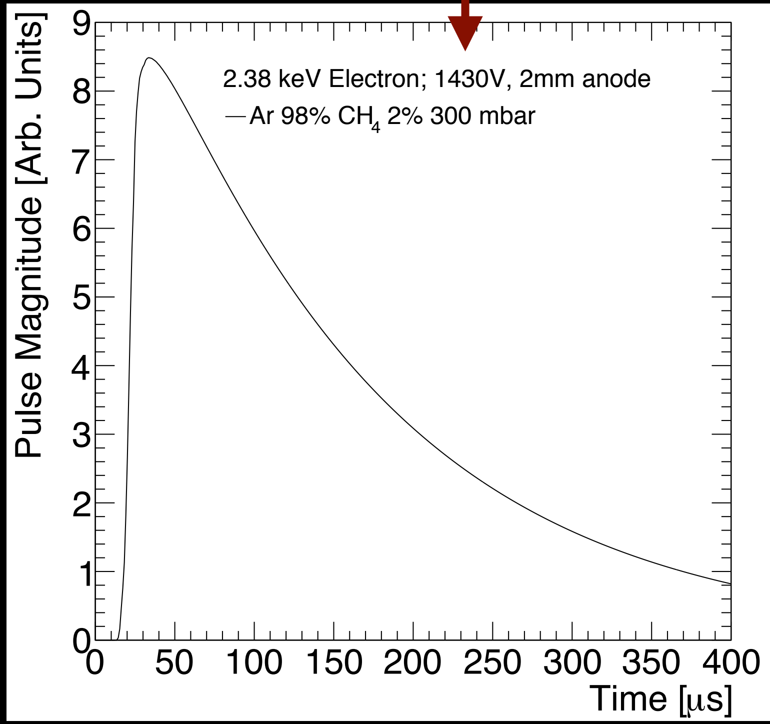

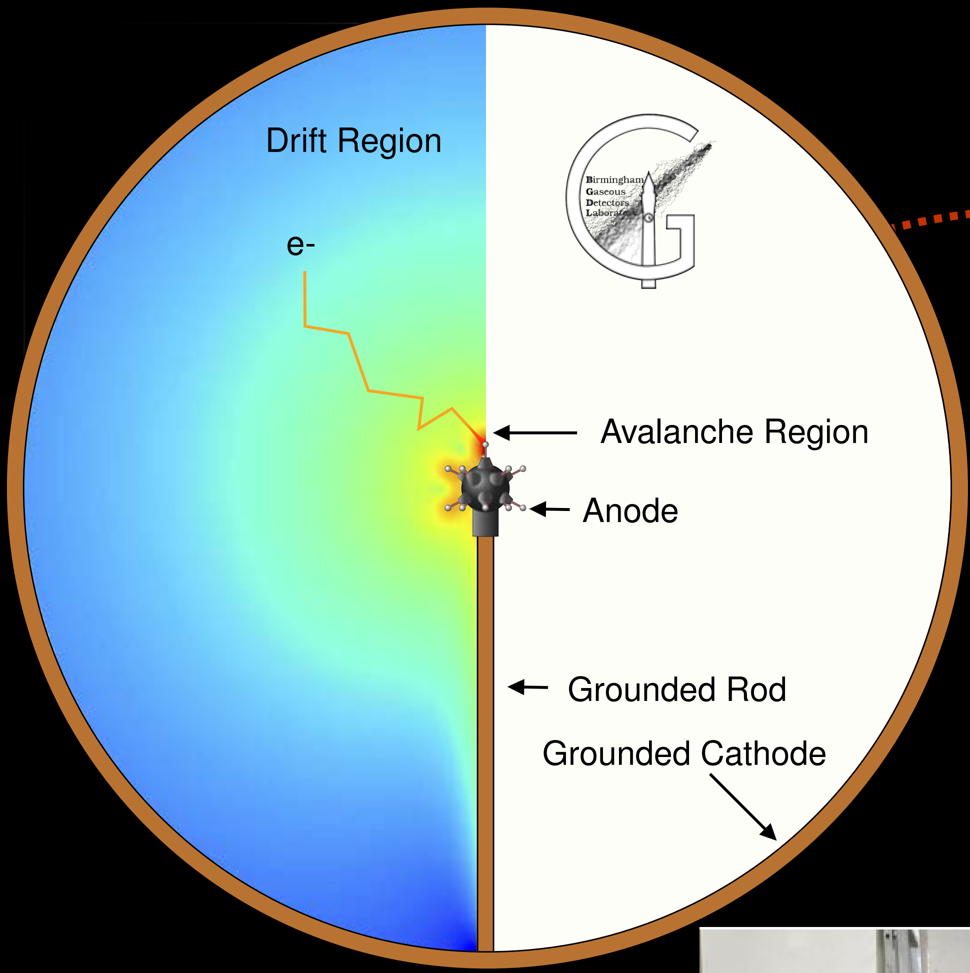

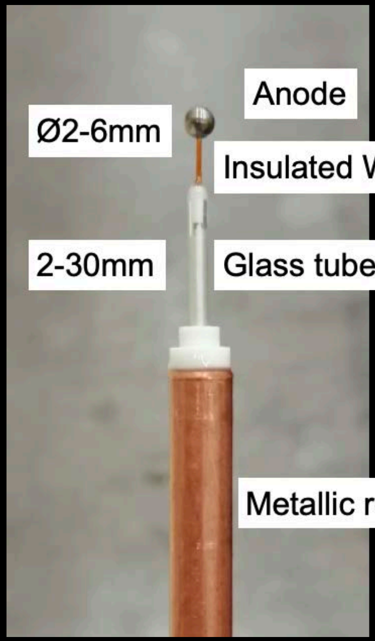

Increasing Target Mass

Single anode: Drift and Amplification fields are connected $E = \frac{V_a}{r^2}\frac{r_a r_c}{r_c - r_a} \approx \frac{V_a r_a}{r^2}$

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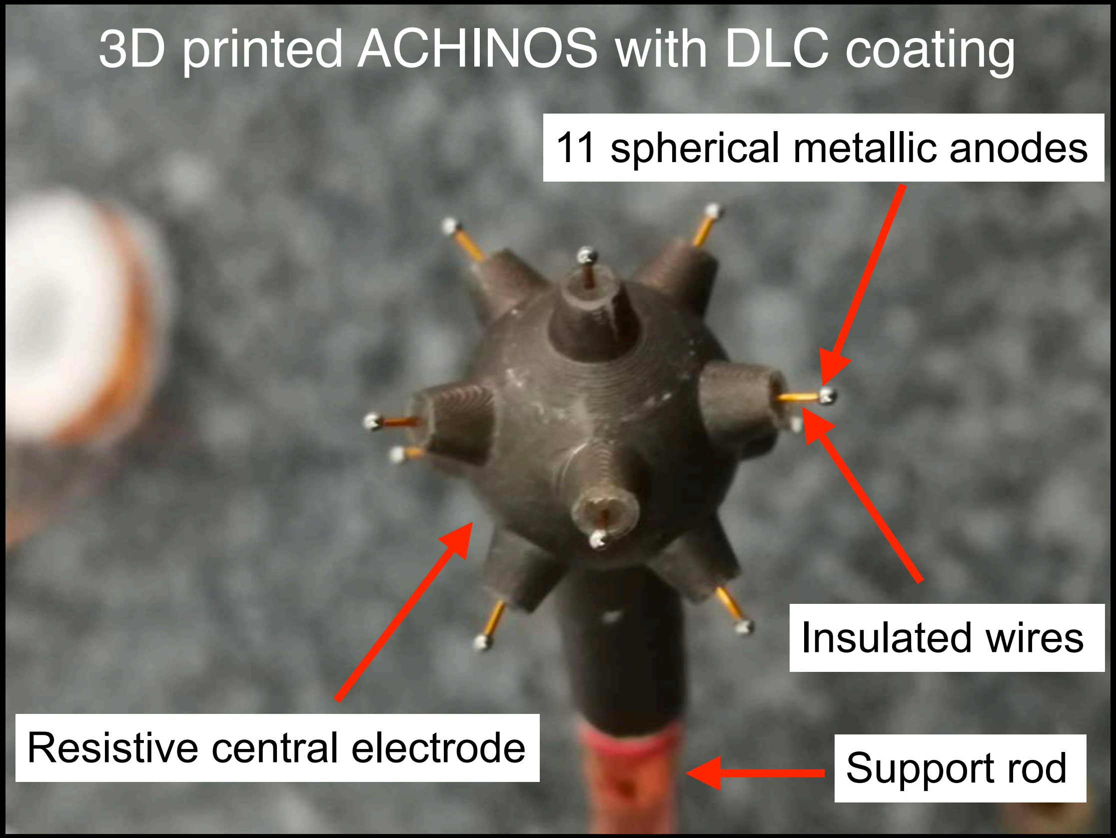

JINST 15 (2020) 11, 11

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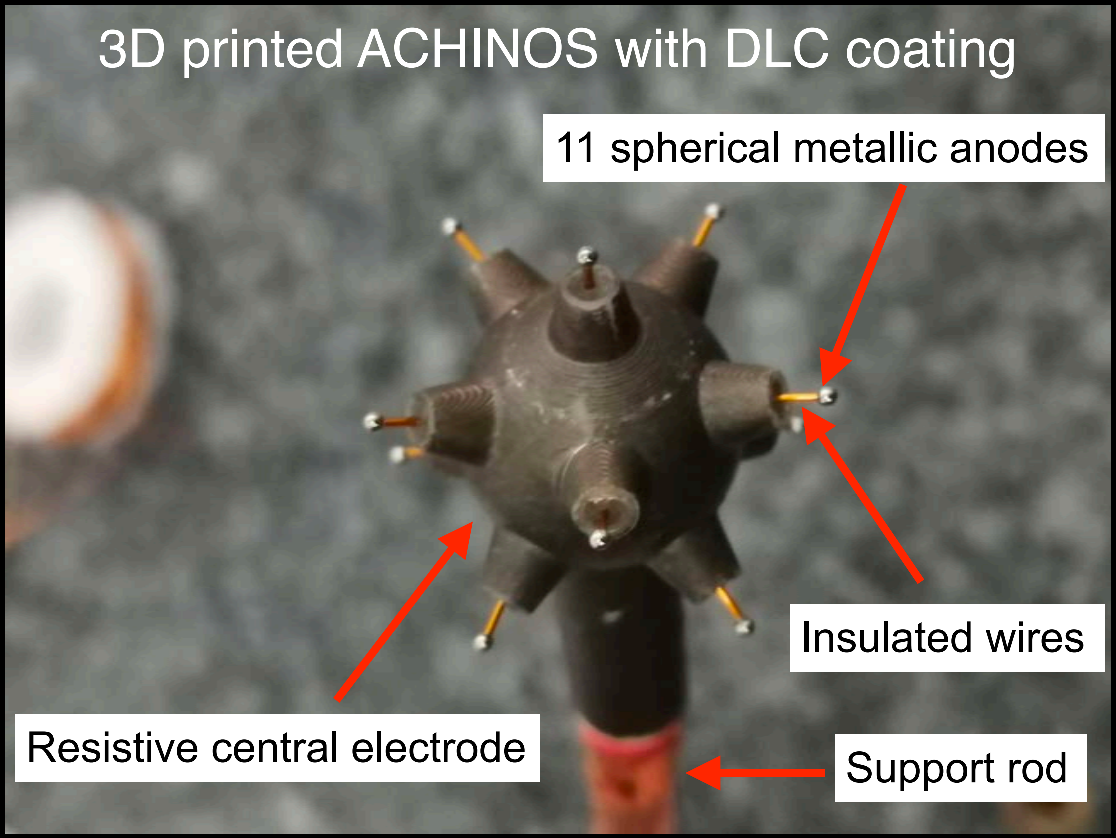

JINST 15 (2020) 11, 11

JINST 12 (2017) 12, P12031

- ACHINOS: Multi-anode sensor
  - Multiple anodes placed at equal radii
    - Sensors with 5, 11, 33 anodes operated
  - Decoupling drift and amplification fields
  - Individual anode read-out; TPC-like capabilities

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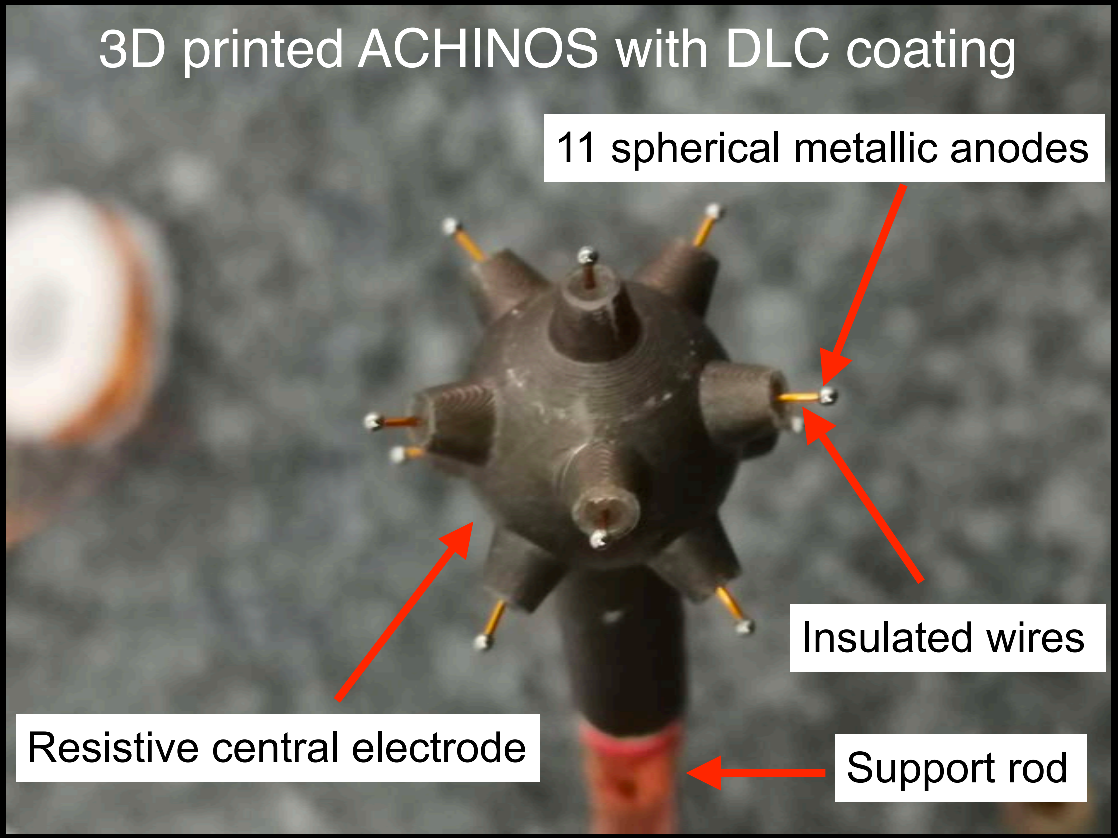

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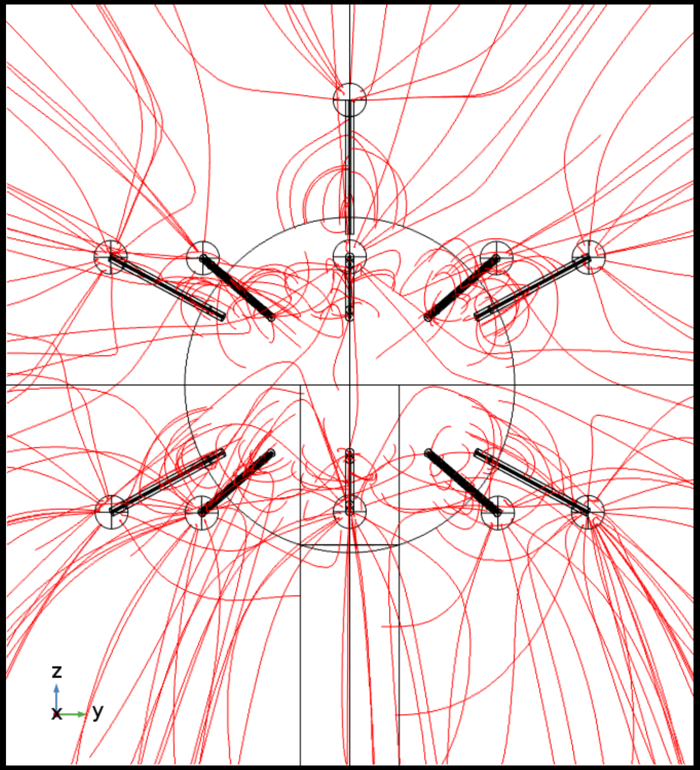
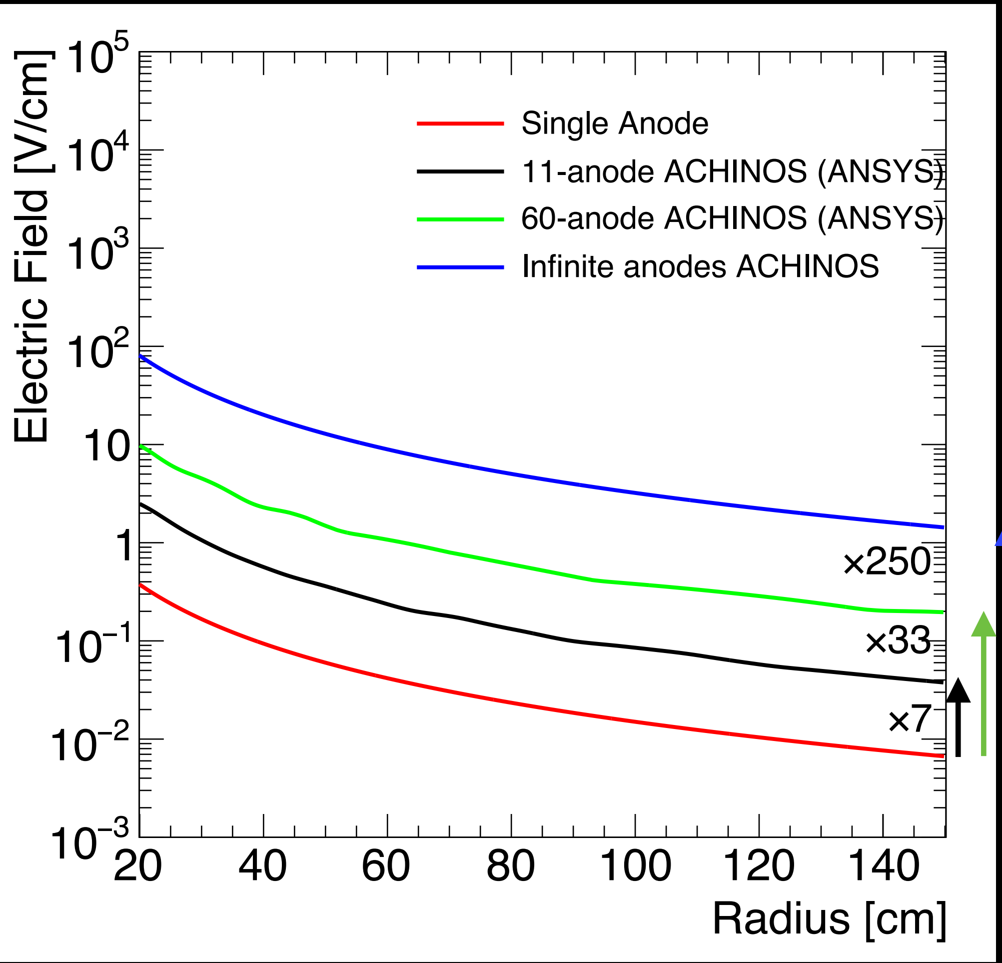
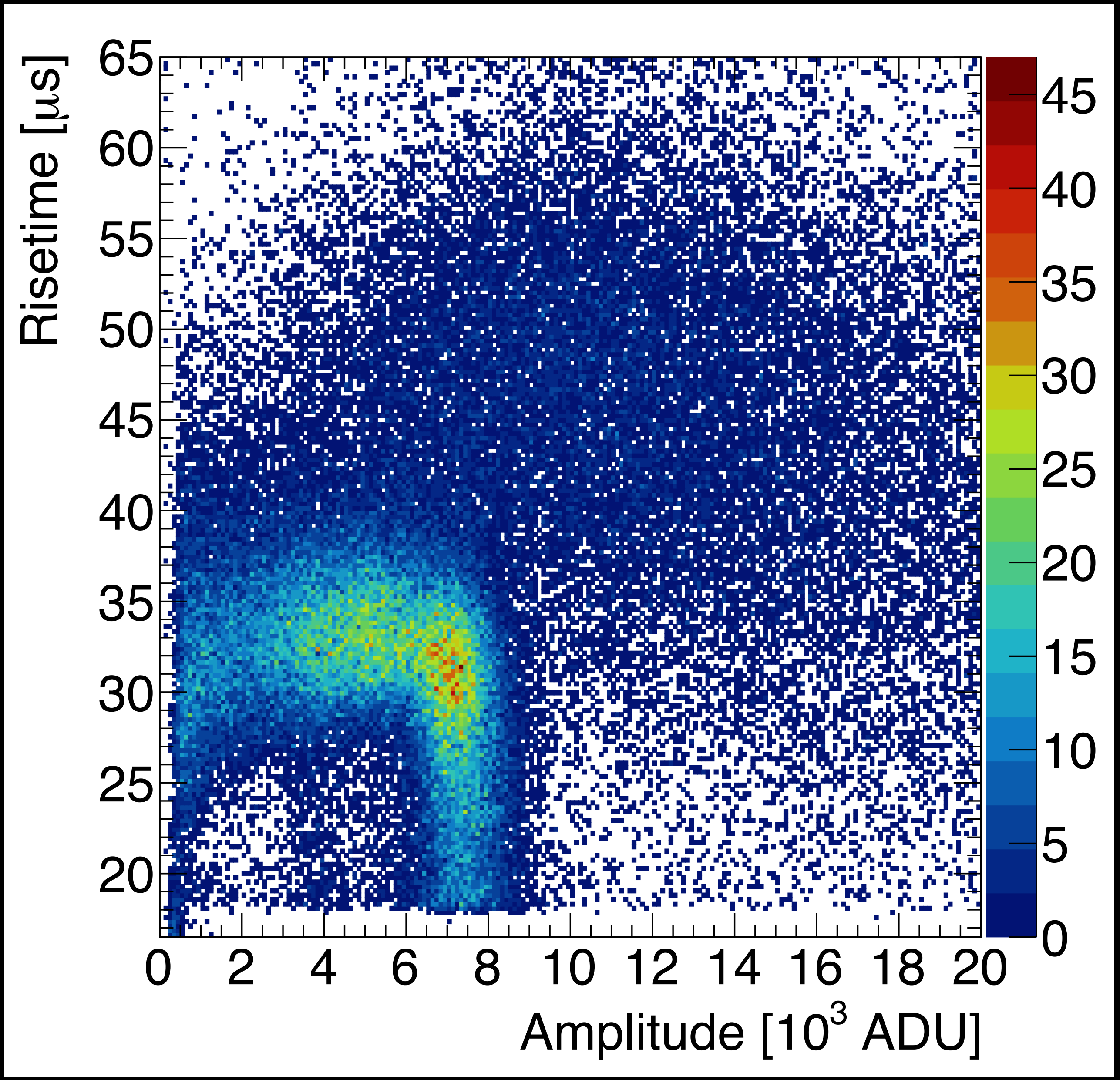




Detector Fiducialisation



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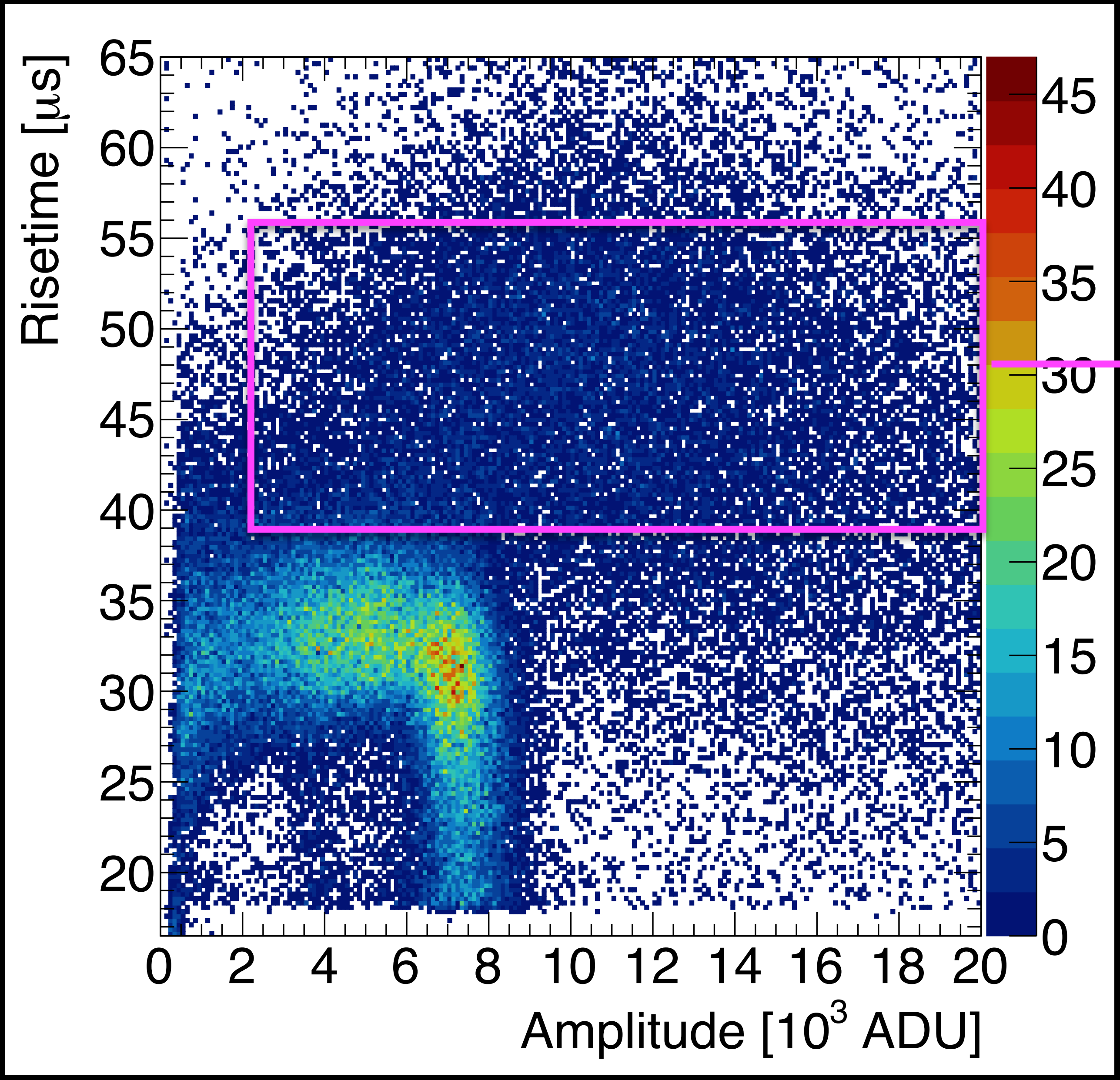

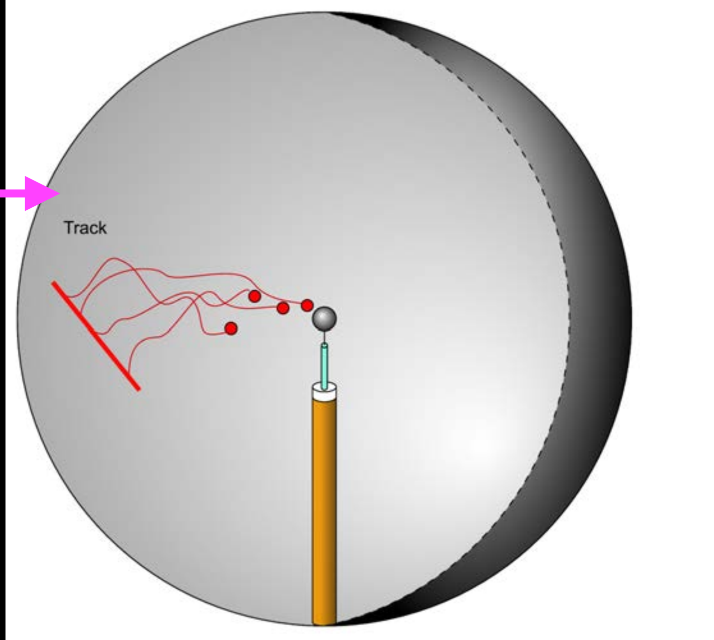

"Muon"-like events

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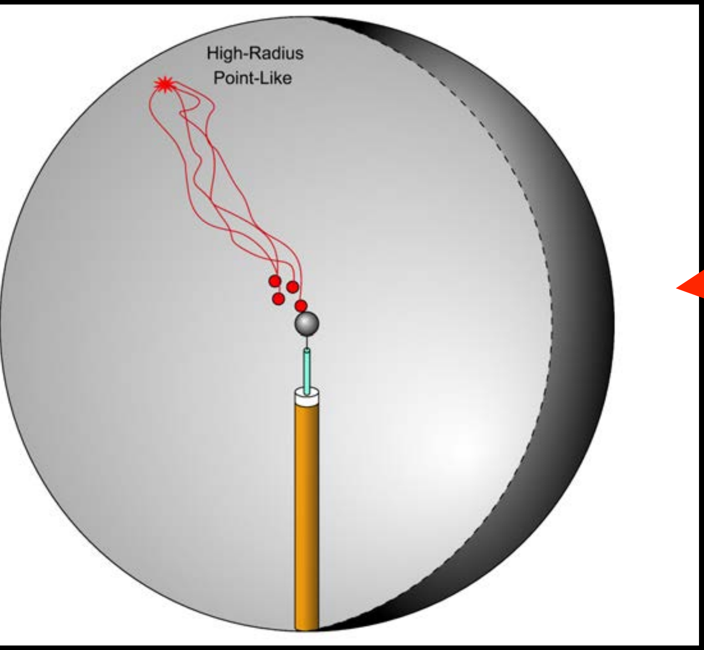
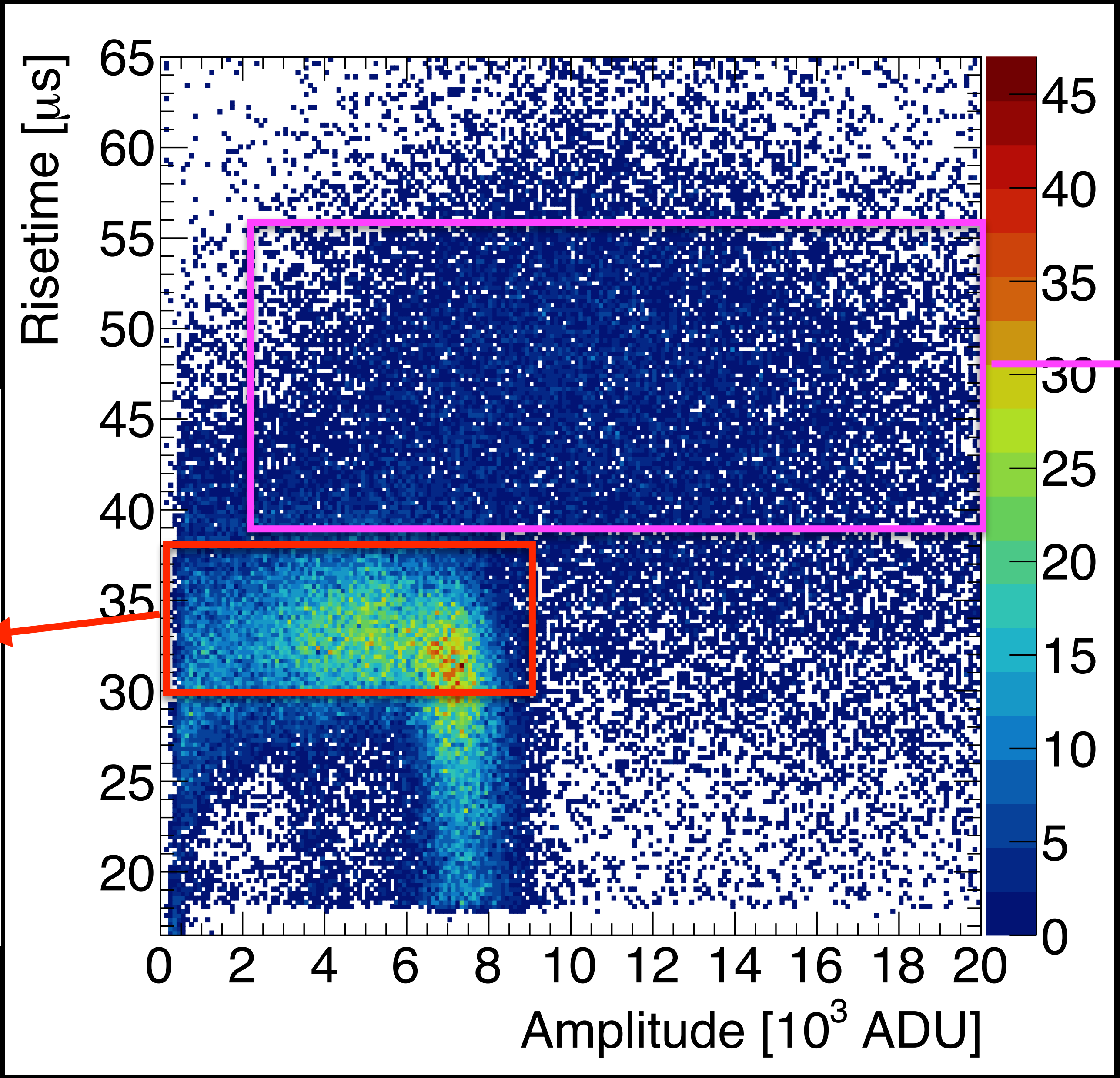
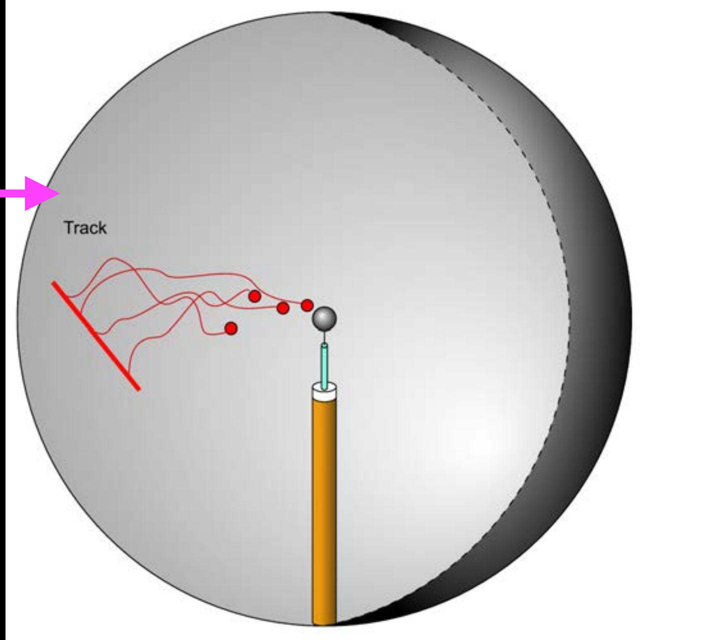


“Surface”-like events





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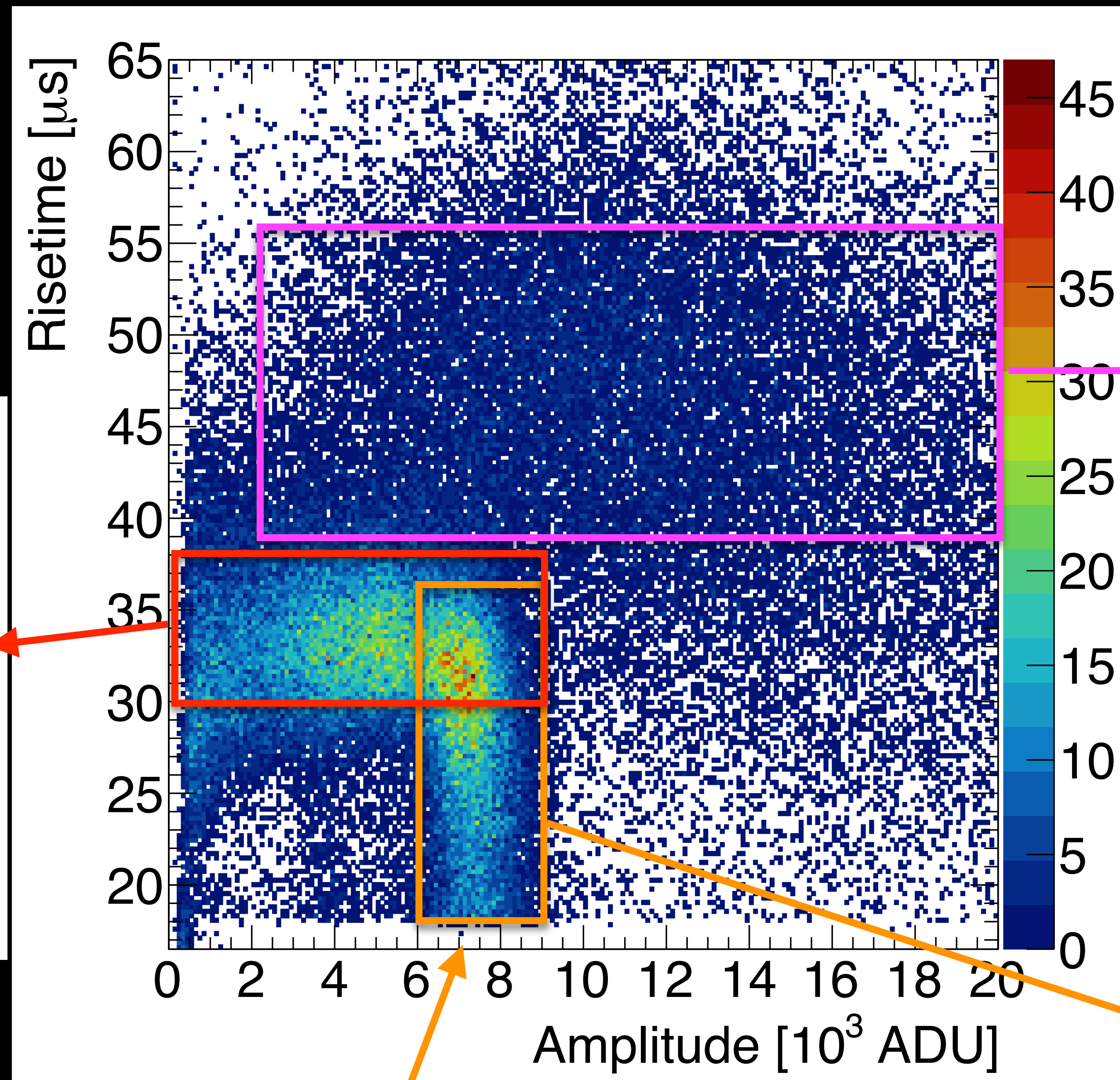

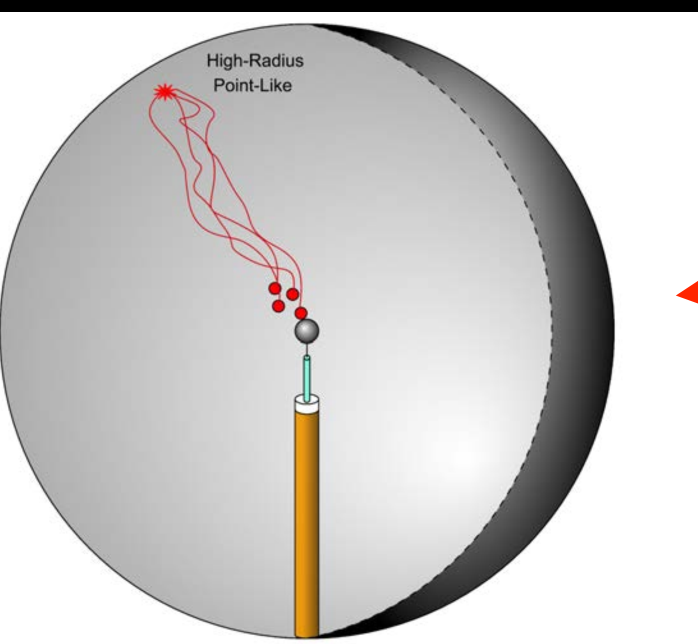

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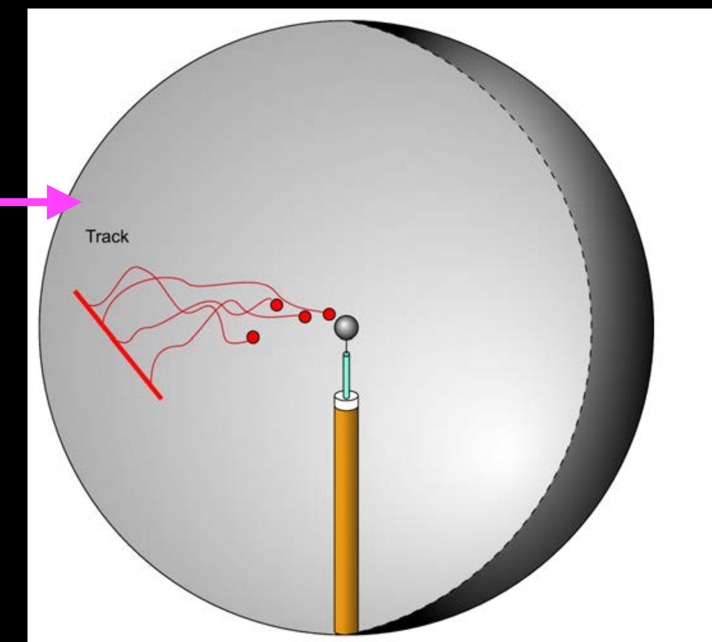
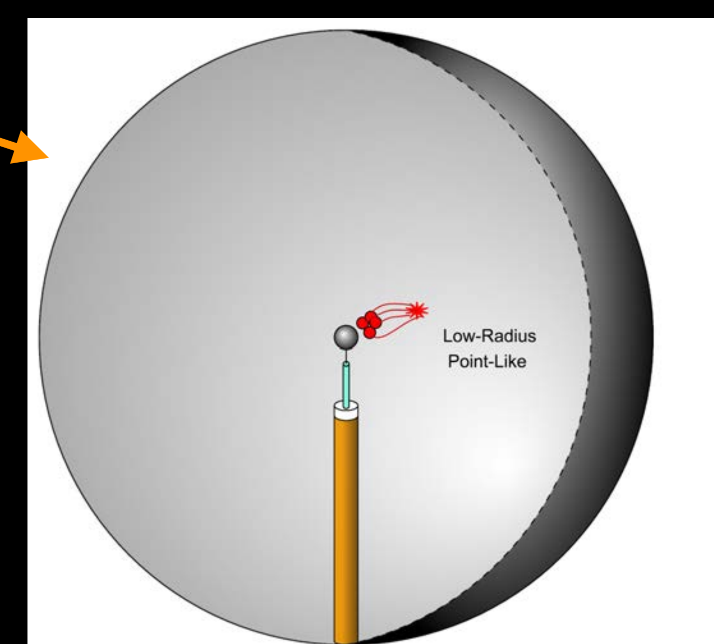


"Muon"-like events

5.9 keV X-rays
from ^{55}Fe decays



"Signal"-like events

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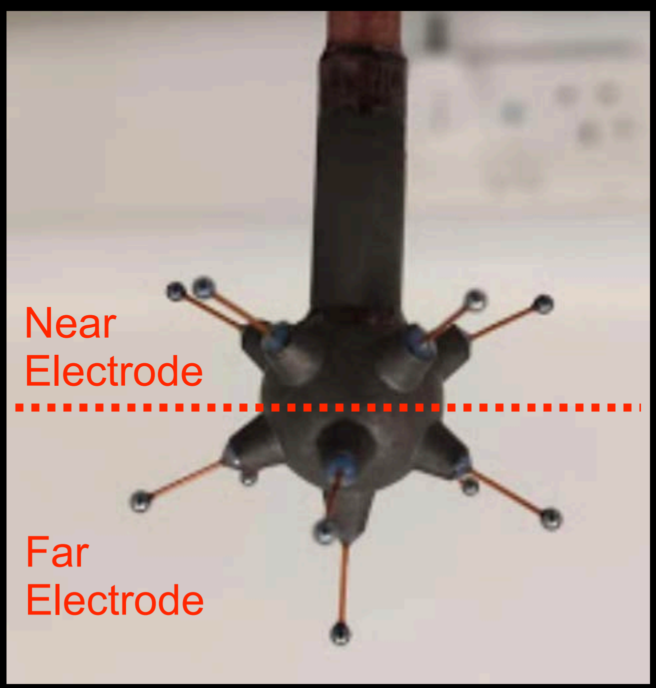

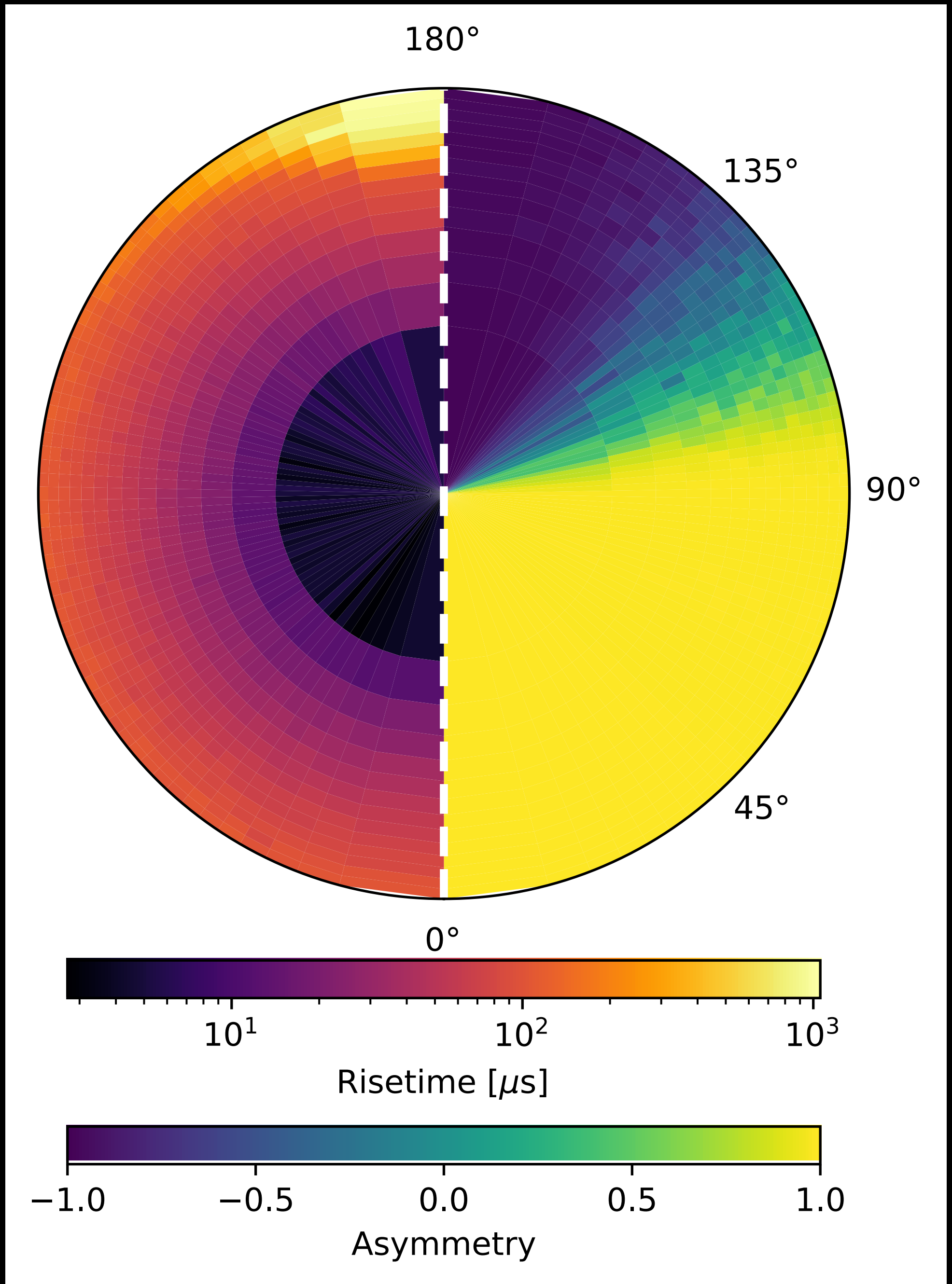

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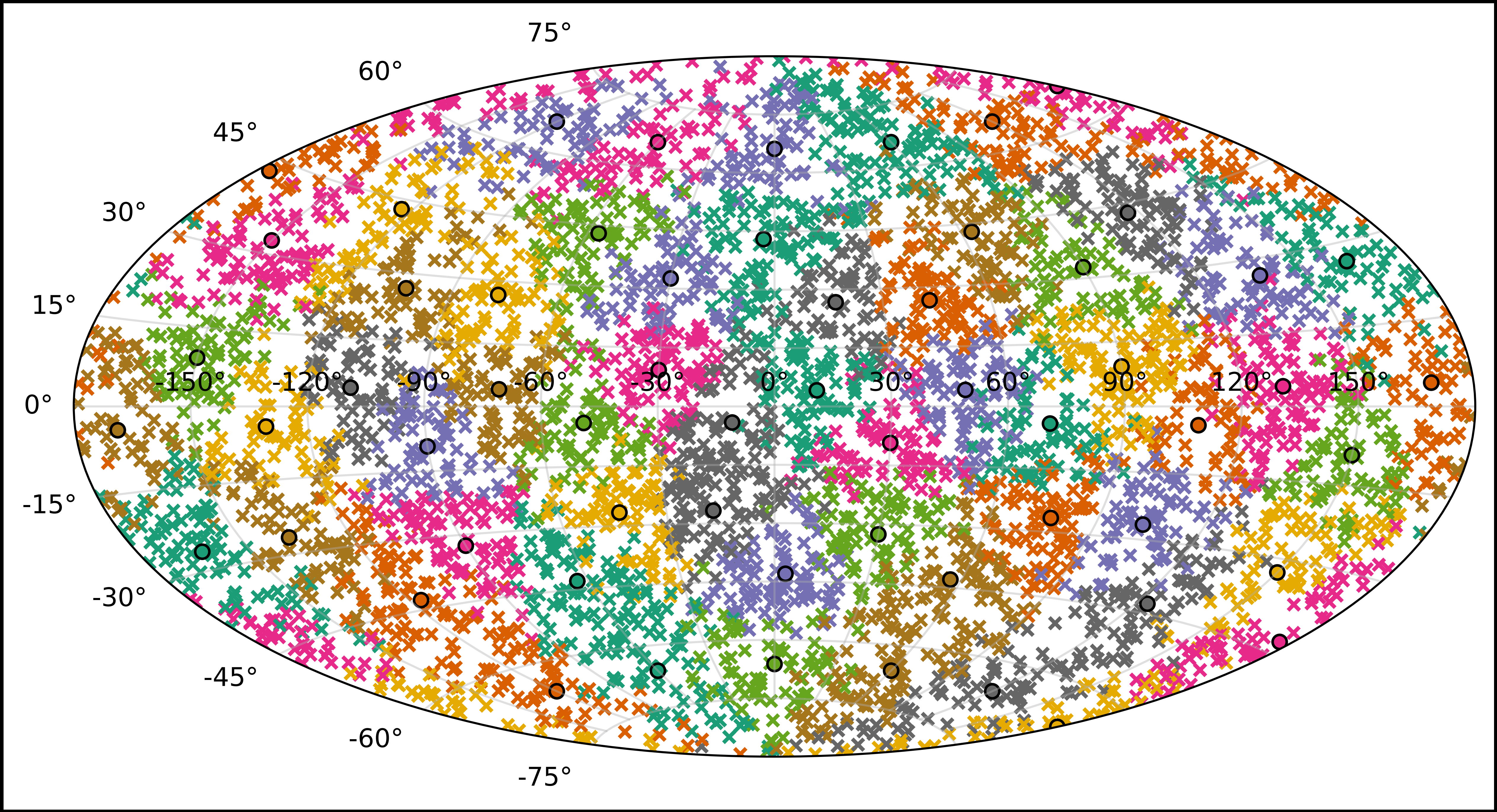
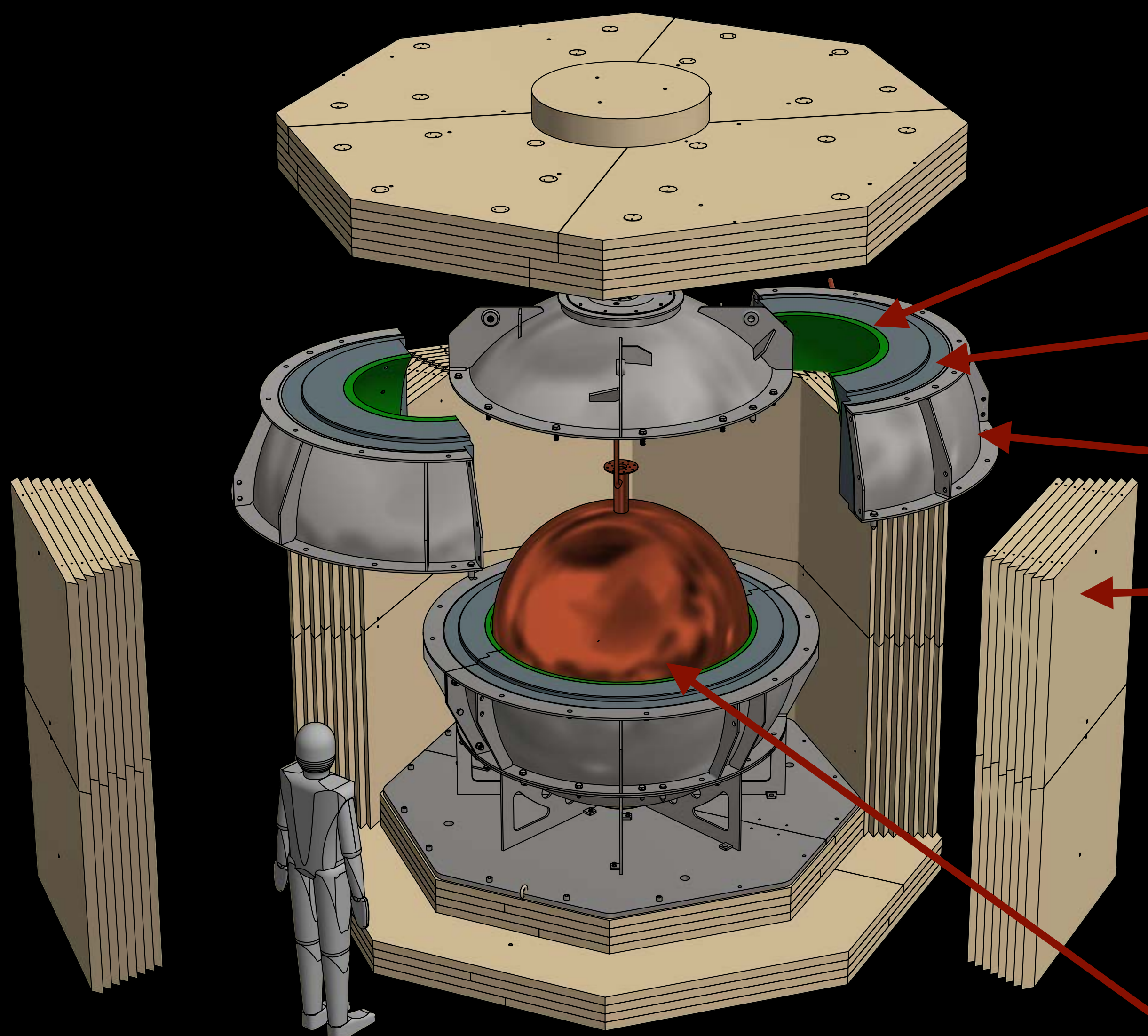


NEWS-G at SNOLAB



3 cm archaeological lead

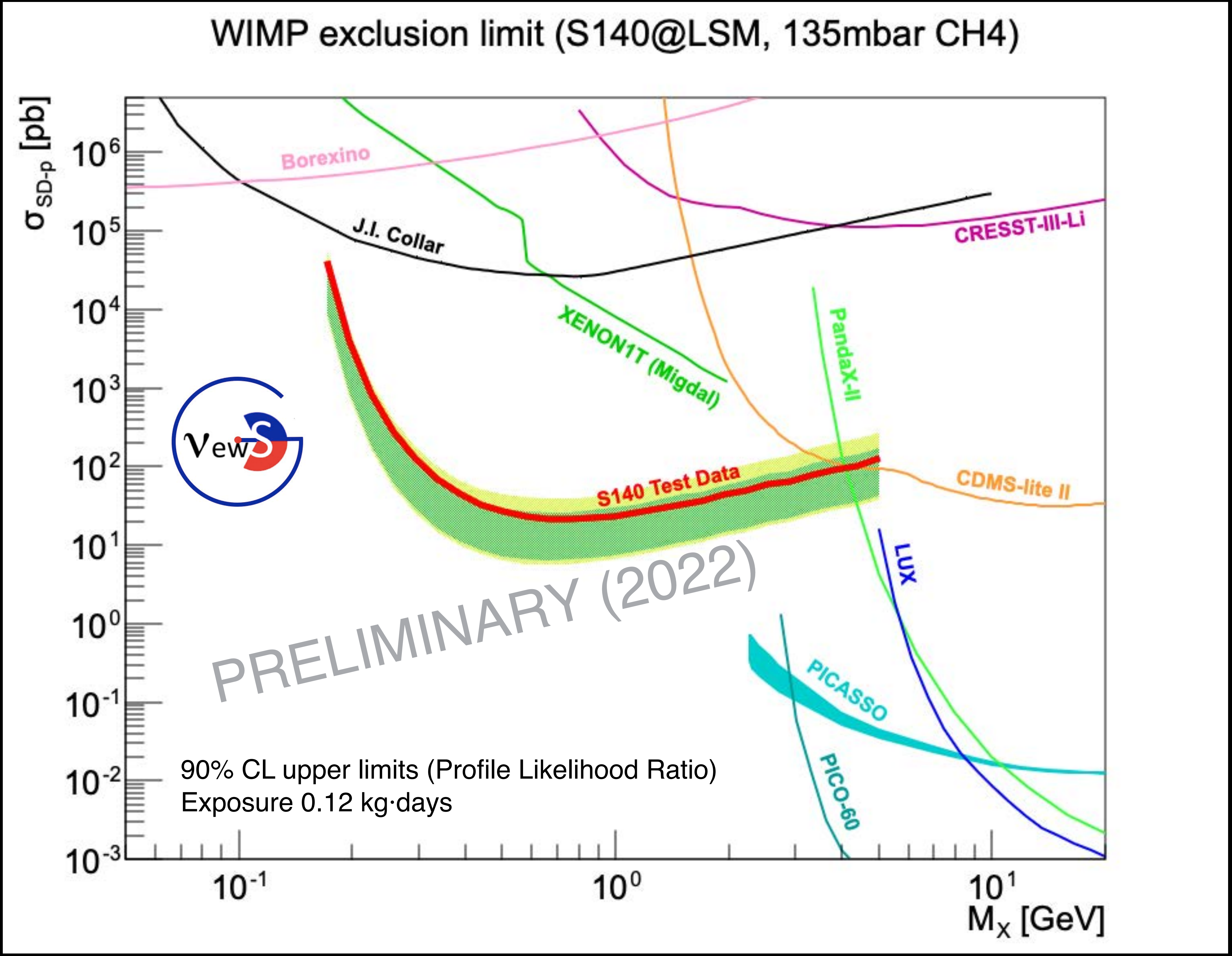
22 cm of Very Low Activity lead

Stainless steel skin

40 cm high density polyethylene

Ø140 cm
4N Copper (99.99% pure)
Assembled at LSM

Results with LSM data



Higher purity materials

- Copper common material for rare event experiments
  - Strong enough to build gas vessels
  - No long-lived isotopes (^{67}Cu $t_{1/2}$=62h)
  - Low cost/commercially available at high purity
- Backgrounds
  - Cosmogenic: ^{63}Cu(n,α)^{60}Co from fast neutrons
  - Contaminants: ^{238}U/^{232}Th decay chains

4N Aurubis AG Oxygen Free Copper (99.99% pure)

Spun into two hemispheres
Electron-beam welded together

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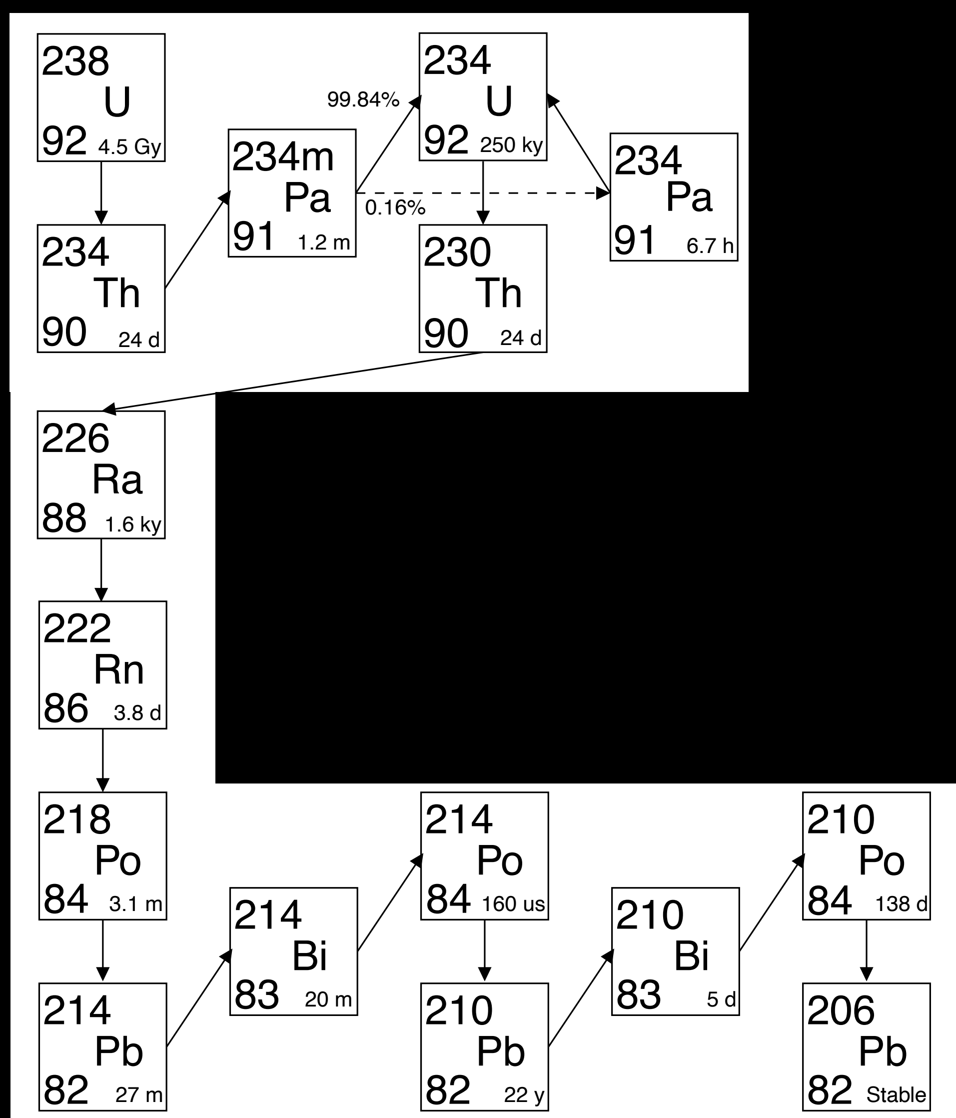

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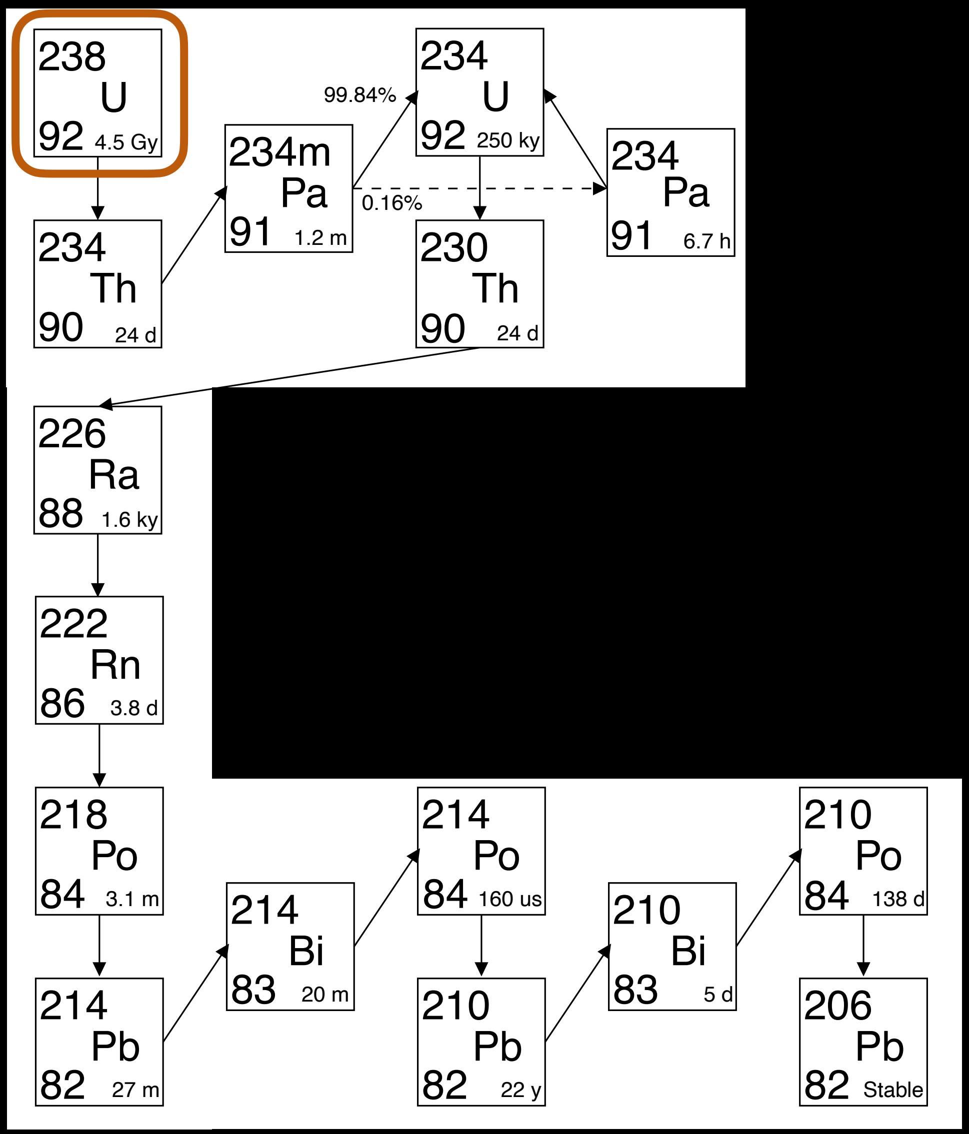
directly measured with mass spectrometers ~10 µBq/kg



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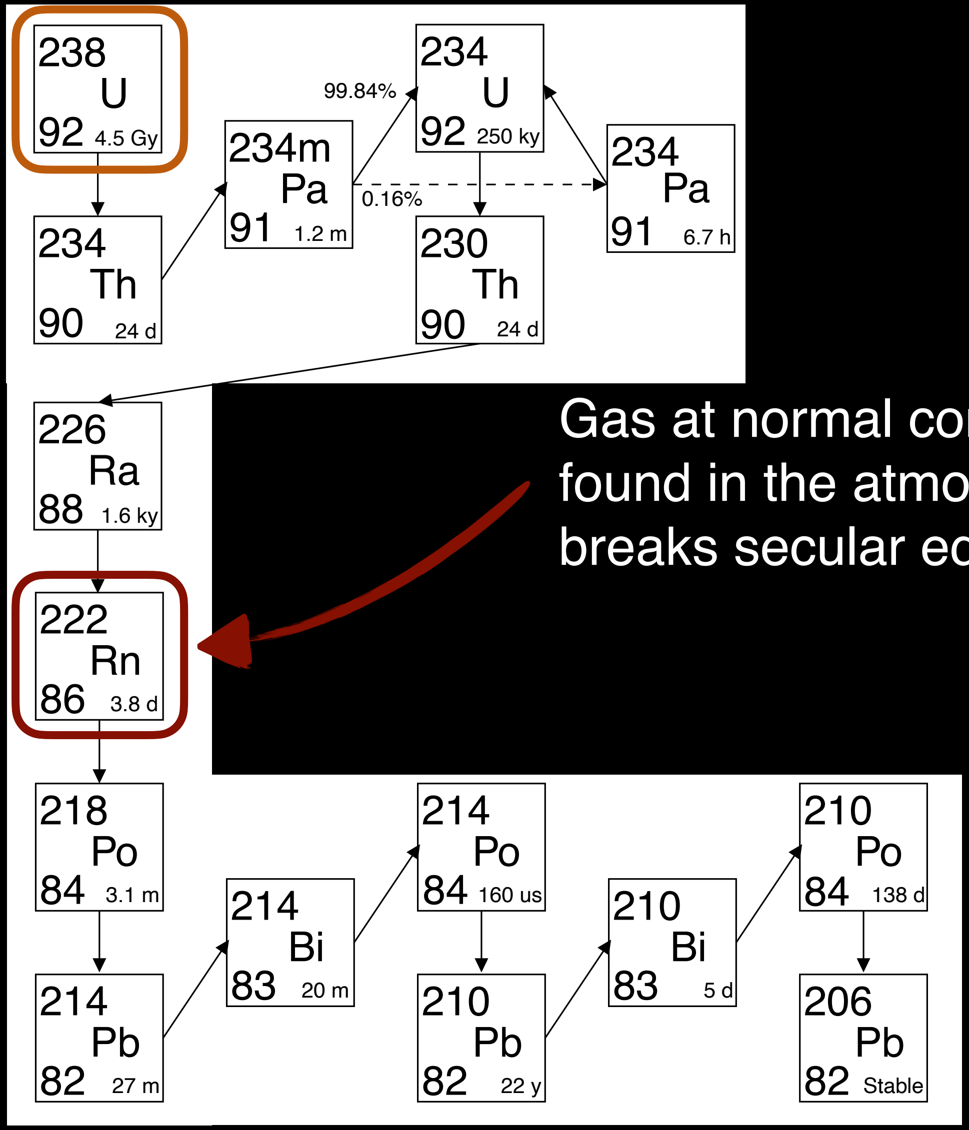

Gas at normal conditions: found in the atmosphere breaks secular equilibrium

4N Aurubis AG Oxygen Free Copper (99.99% pure)

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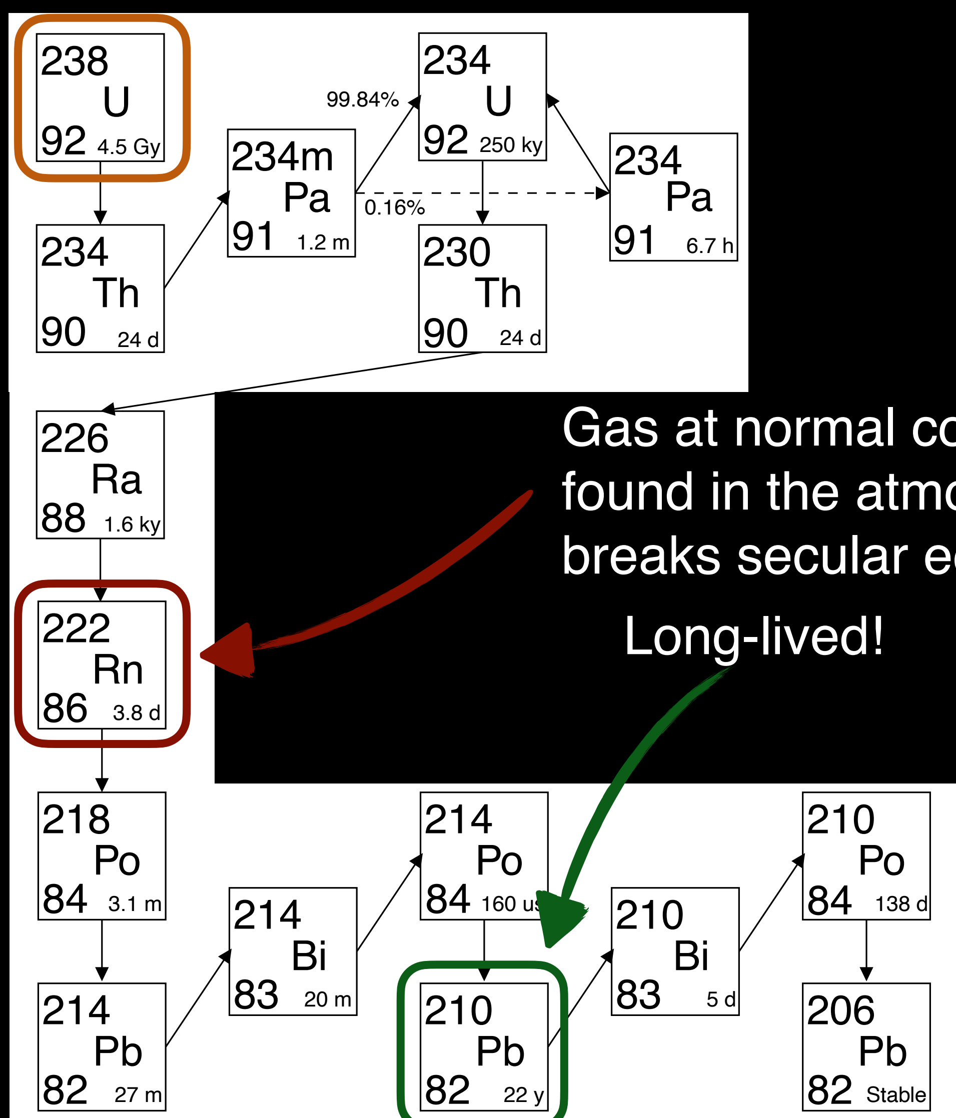

Gas at normal conditions: found in the atmosphere breaks secular equilibrium

Long-lived!

4N Aurubis AG Oxygen Free Copper (99.99% pure)

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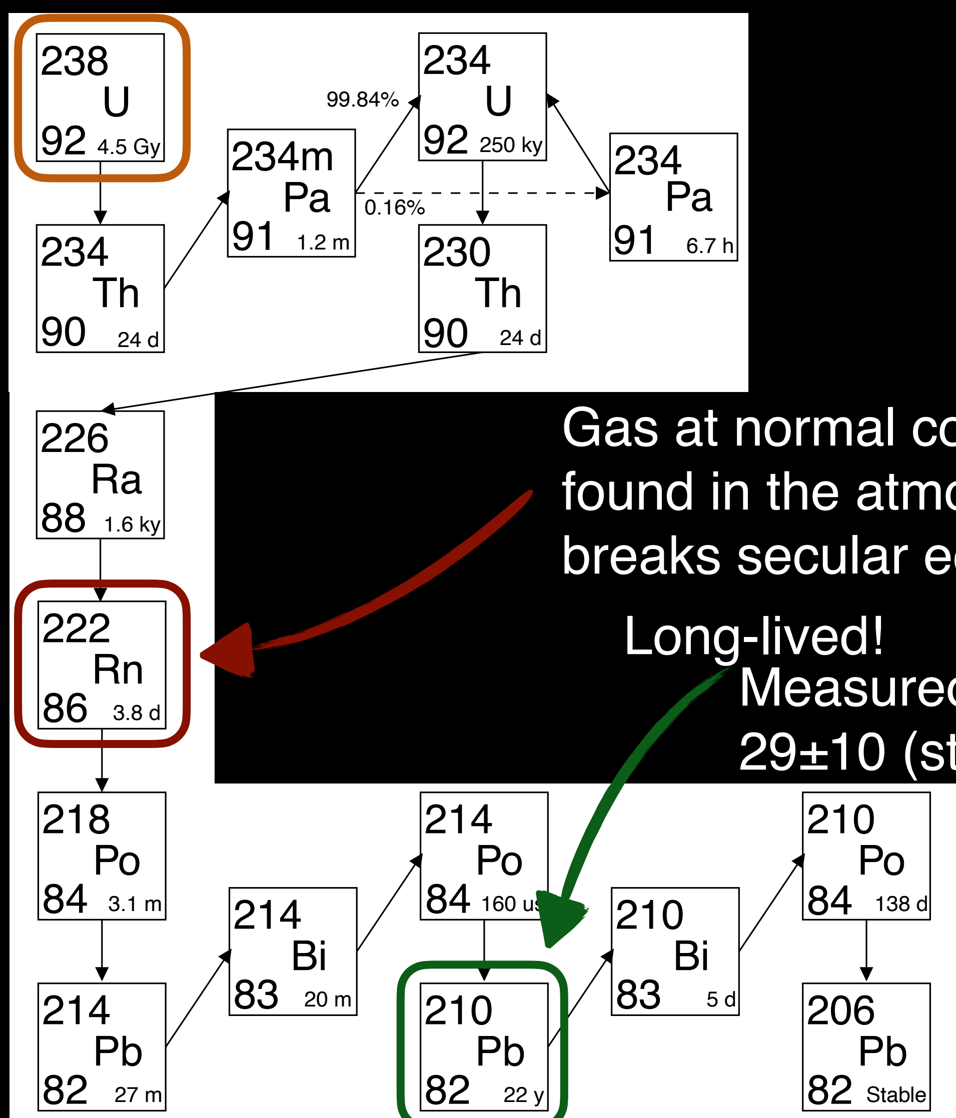
Electron-beam welded together

Higher purity materials

- Copper common material for rare event experiments
  - Strong enough to build gas vessels
  - No long-lived isotopes (^{67}Cu $t_{1/2}$=62h)
  - Low cost/commercially available at high purity
- Backgrounds
  - Cosmogenic: ^{63}Cu(n,α)^{60}Co from fast neutrons
  - Contaminants: ^{238}U/^{232}Th decay chains

directly measured with mass spectrometers ~10 µBq/kg



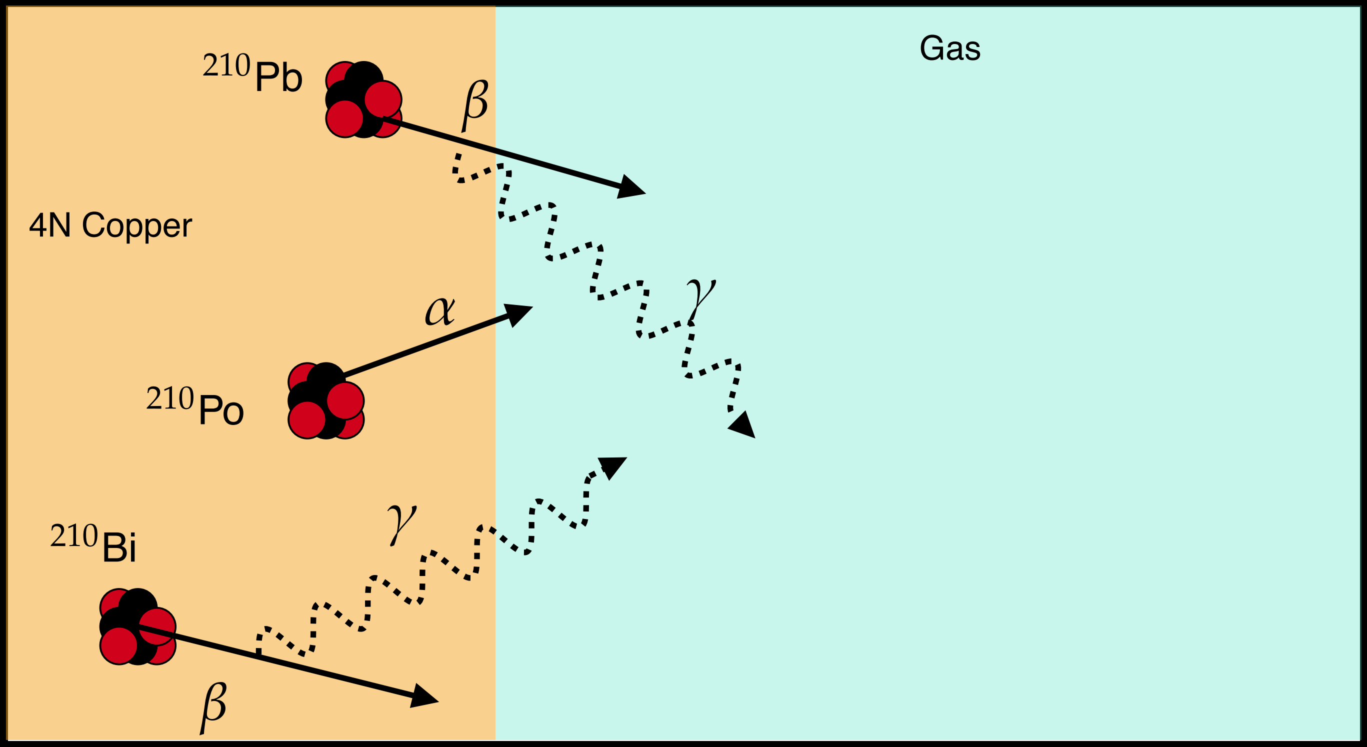
Gas at normal conditions: found in the atmosphere breaks secular equilibrium

Long-lived!
Measured:
29±10 (stat)$^{+9}_{-3}$ mBq/kg

4N Aurubis AG Oxygen Free Copper (99.99% pure)

Spun into two hemispheres
Electron-beam welded together

Suppressing backgrounds



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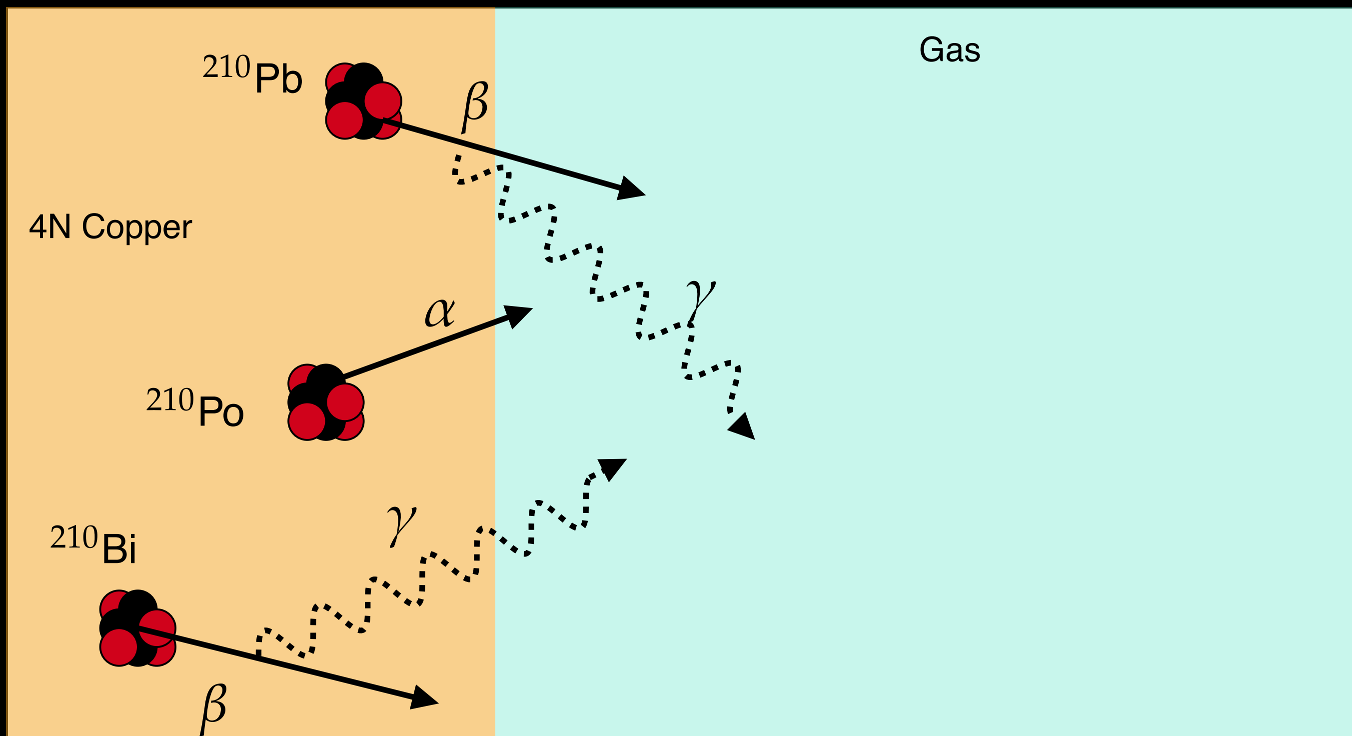

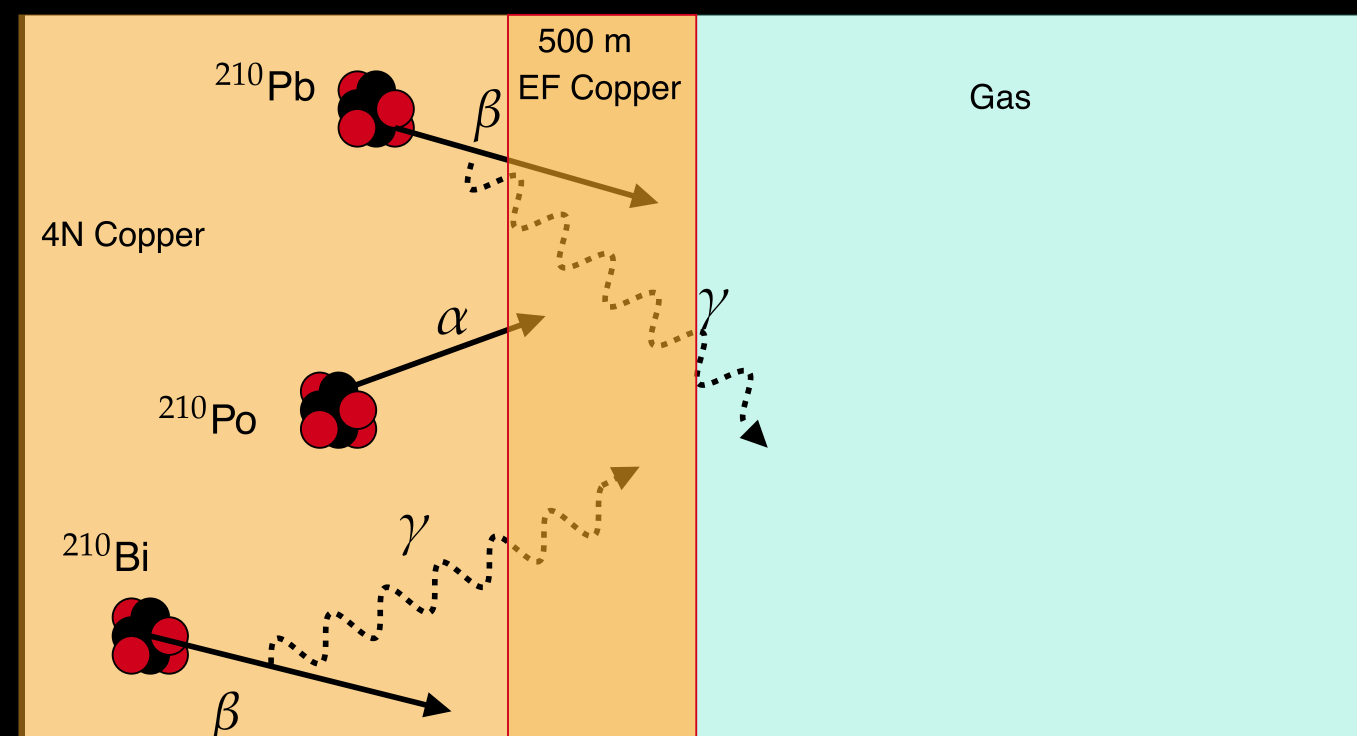

Copper Electroplating

Internal shield: add a layer of extremely radio-pure copper

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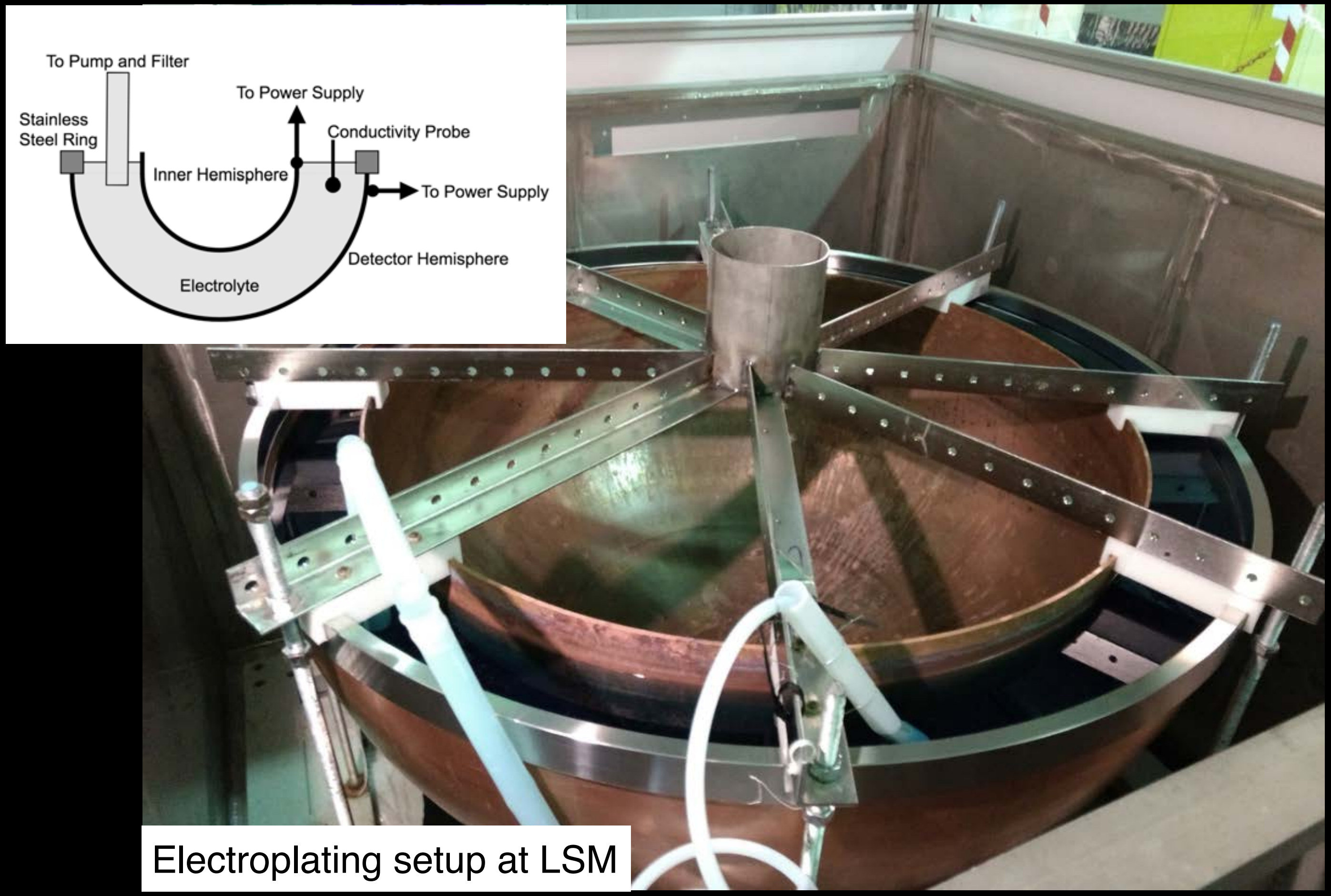

Electroplating setup at LSM

Copper Electroplating

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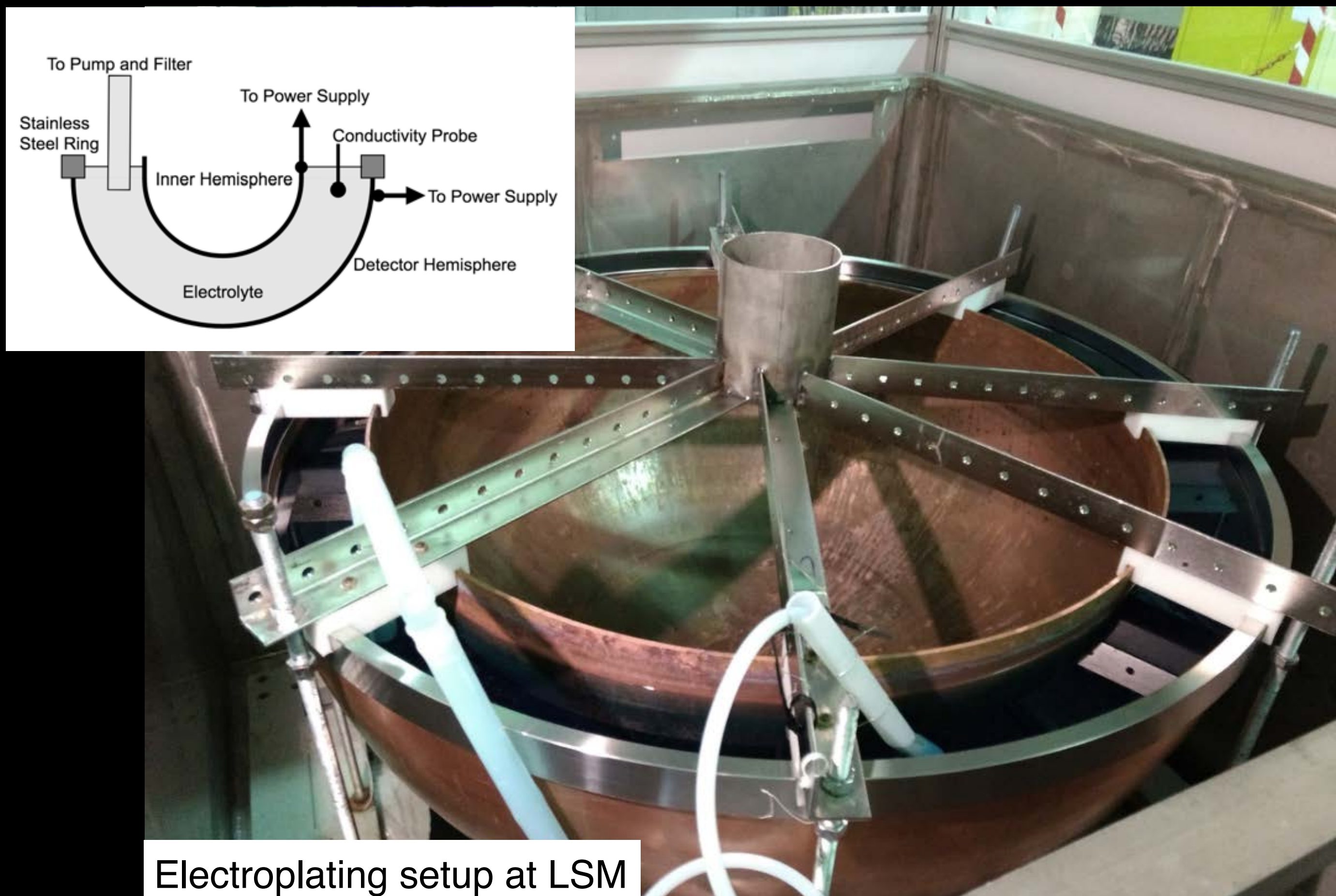

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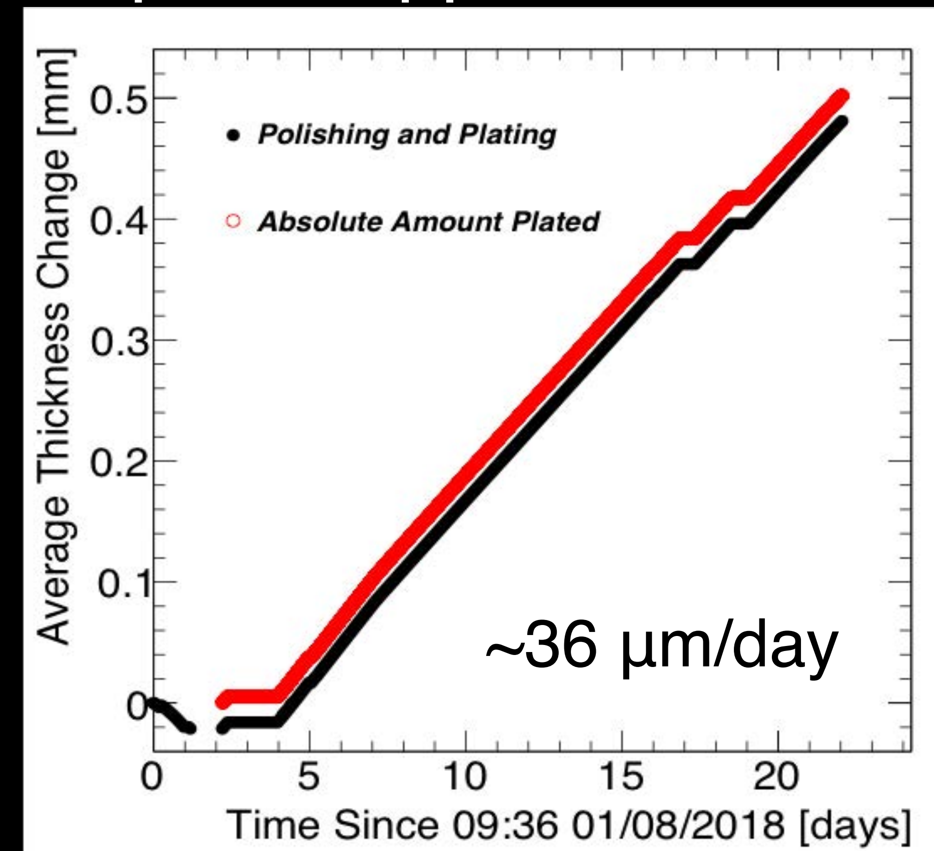

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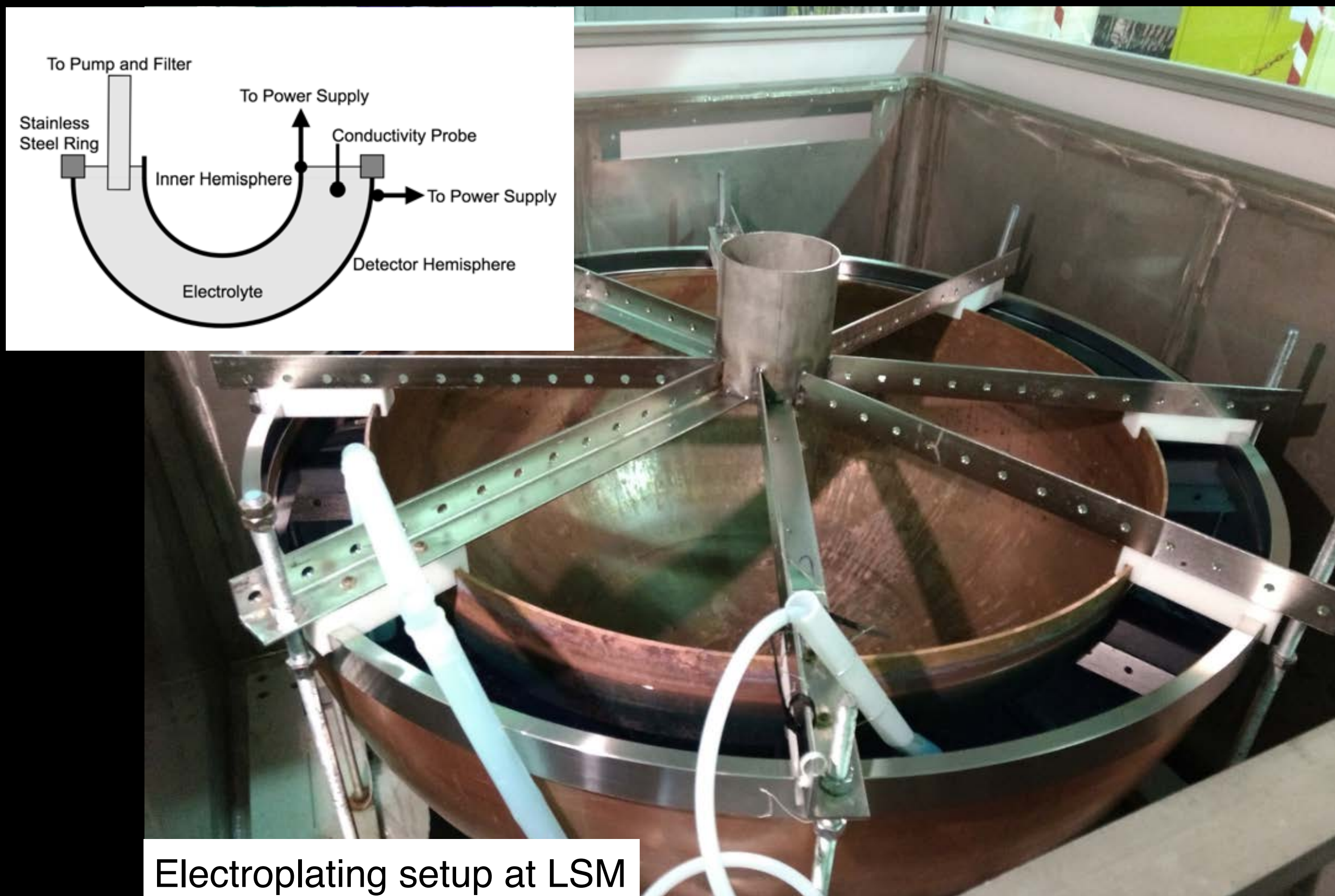
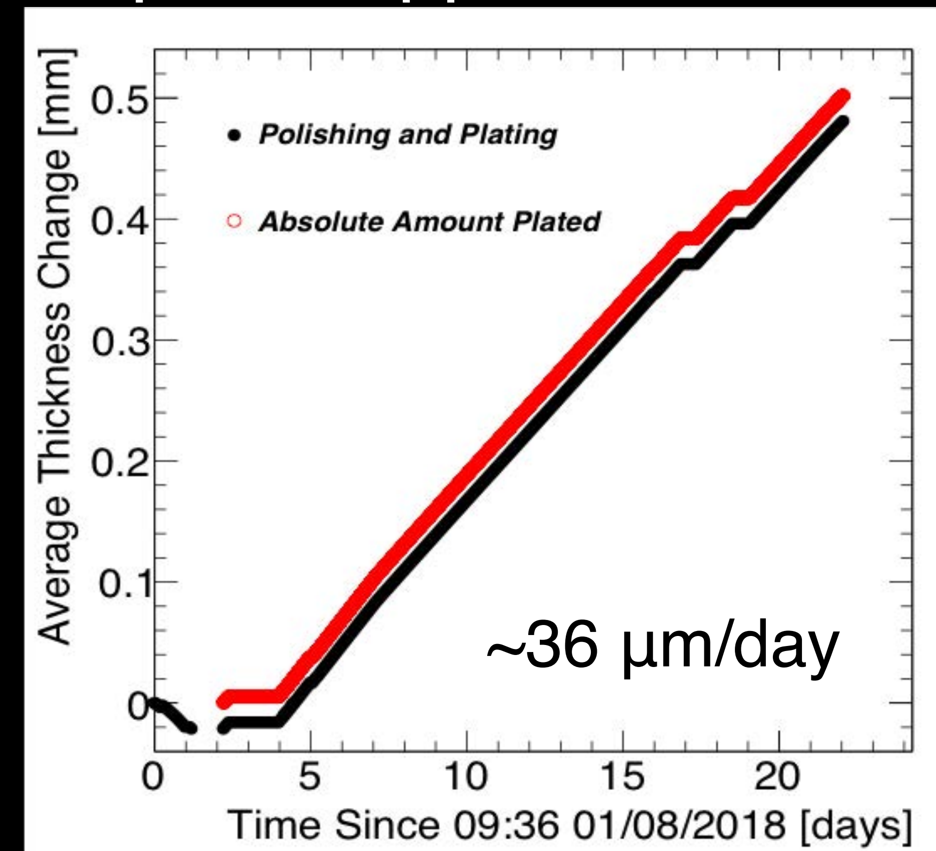
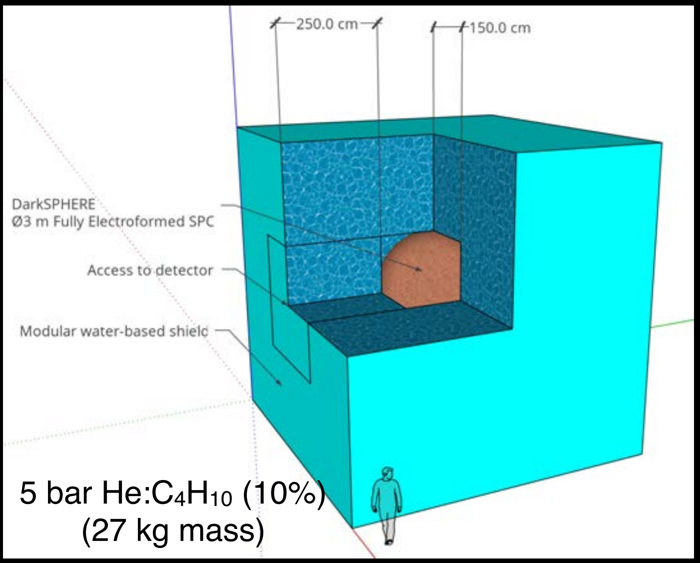


Electroplating setup at LSM



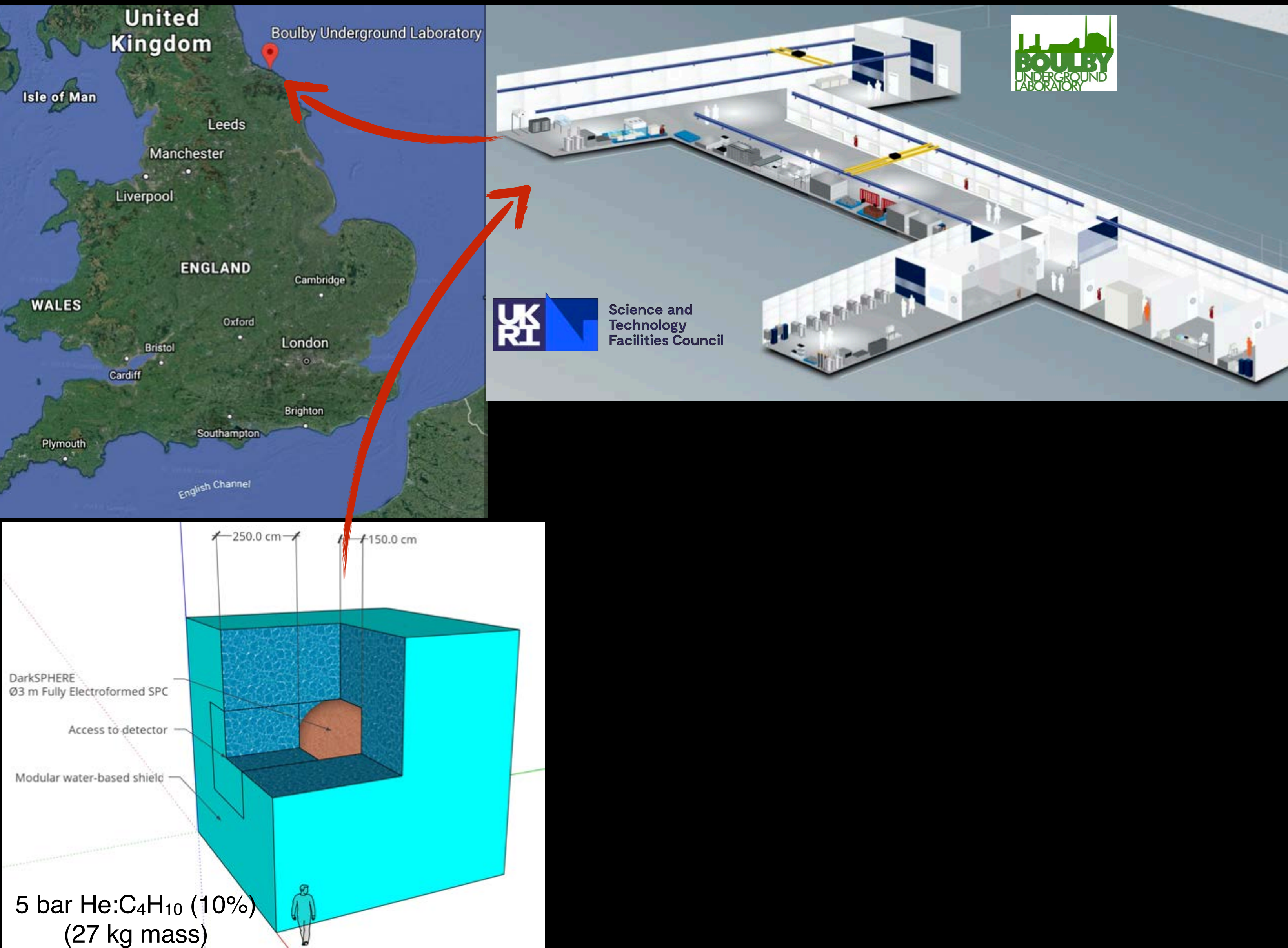
- 36 µm/day → ~1 mm/month
- Possibility to directly grow the sphere
  - No machining or welding
- ECuME: ⌀30 cm prototype at PNNL
  - Bath designed and assembled
  - Tests on electrolyte quality successful
- R&D on EF CuCr alloys (PureAlloys project)

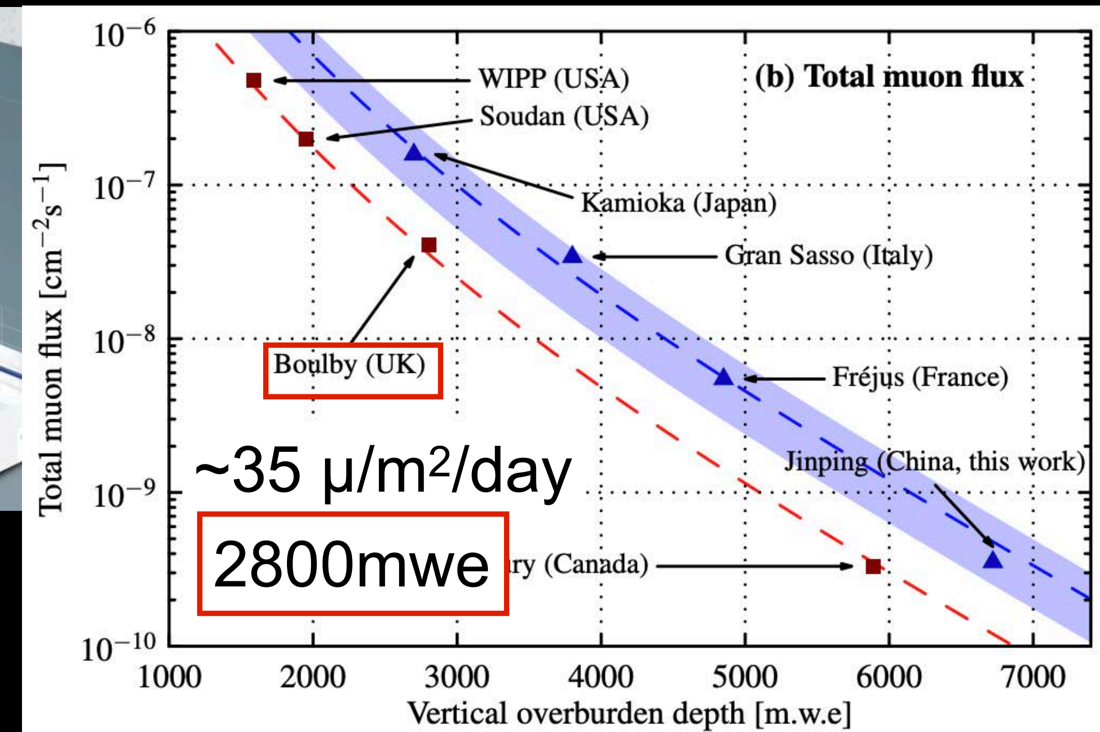
DarkSPHERE



- A ⌀300cm intact underground electroformed spherical proportional counter with water-based shield

DarkSPHERE





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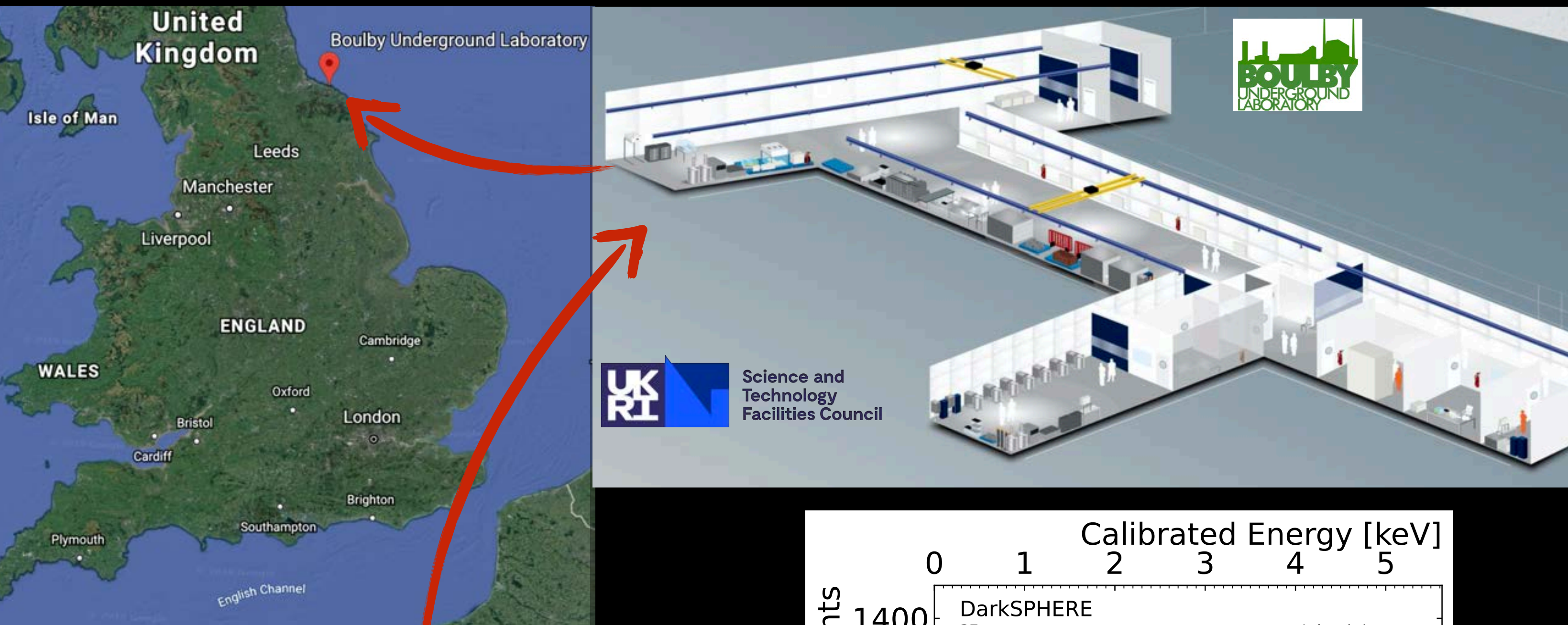

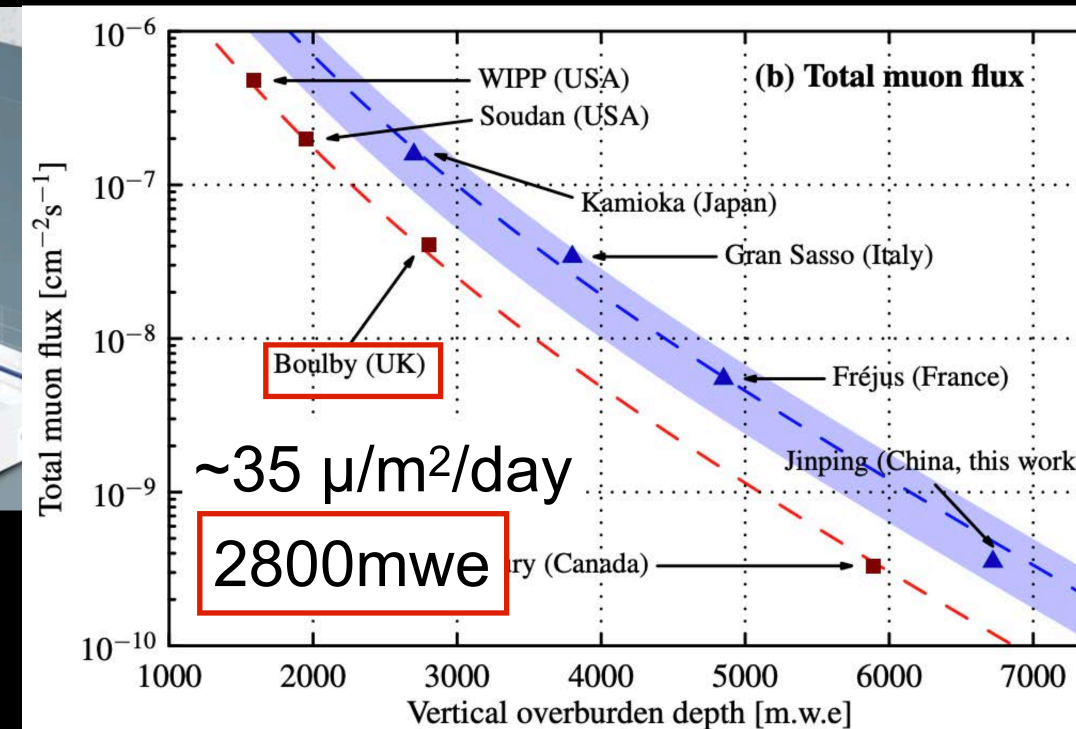

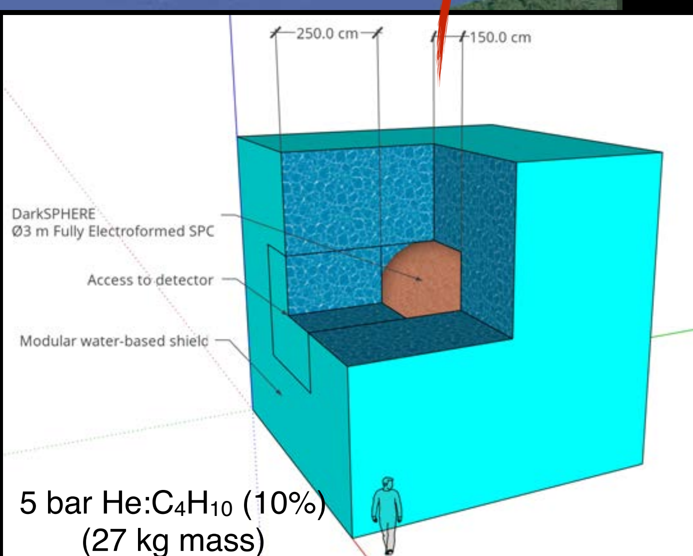

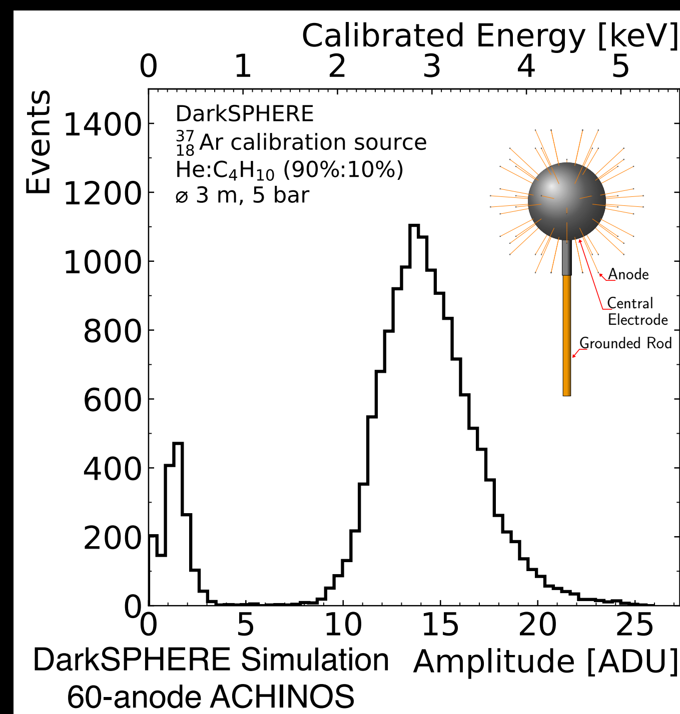

Shielding Configuration	Environmental background rate $\leq 1\,\mathrm{keV}$ [dru] Photon-induced: Photon	Neutron-induced: Neutron	Neutron-induced: Photon	Muon-induced
2.5 m water	4.2×10^{-3} (0.3)	9×10^{-5} (5)	1.3×10^{-4} (0.4)	5×10^{-3} (4)

- A ⌀300cm intact underground electroformed spherical proportional counter with water-based shield

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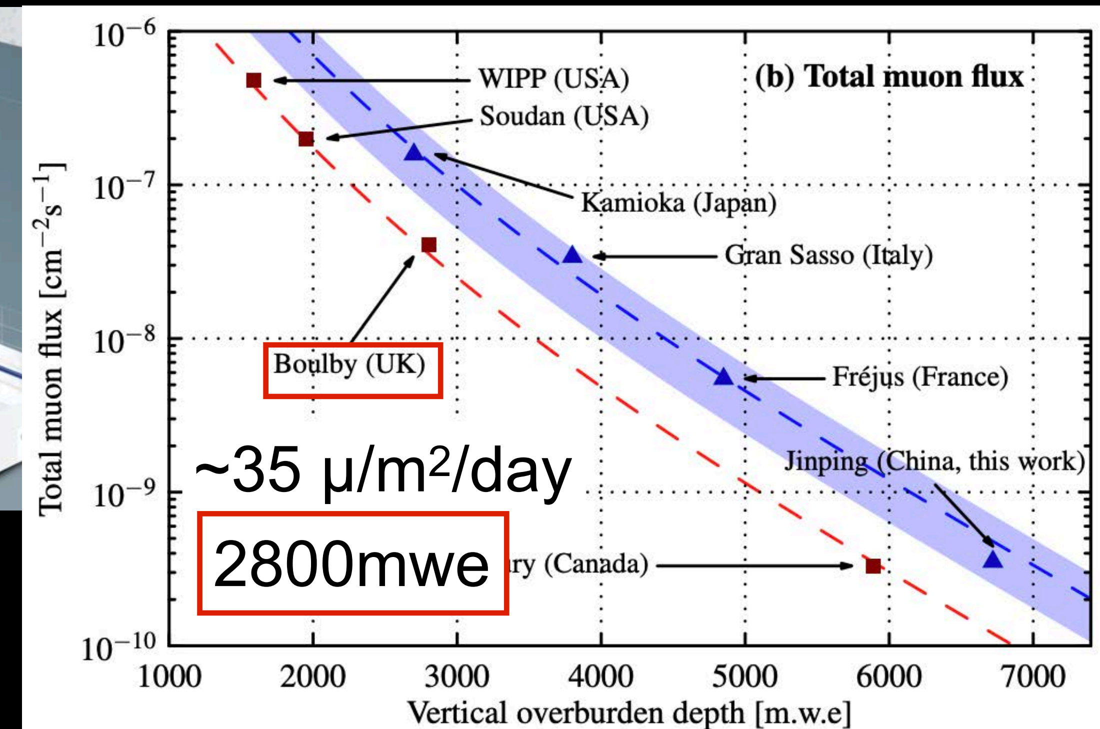

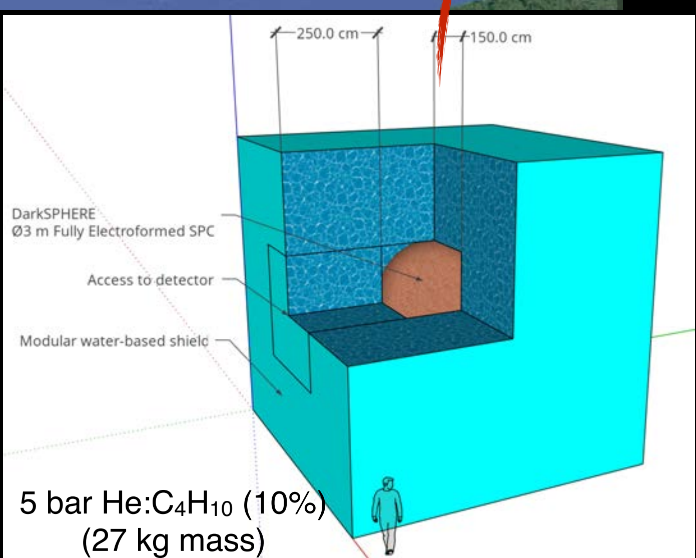

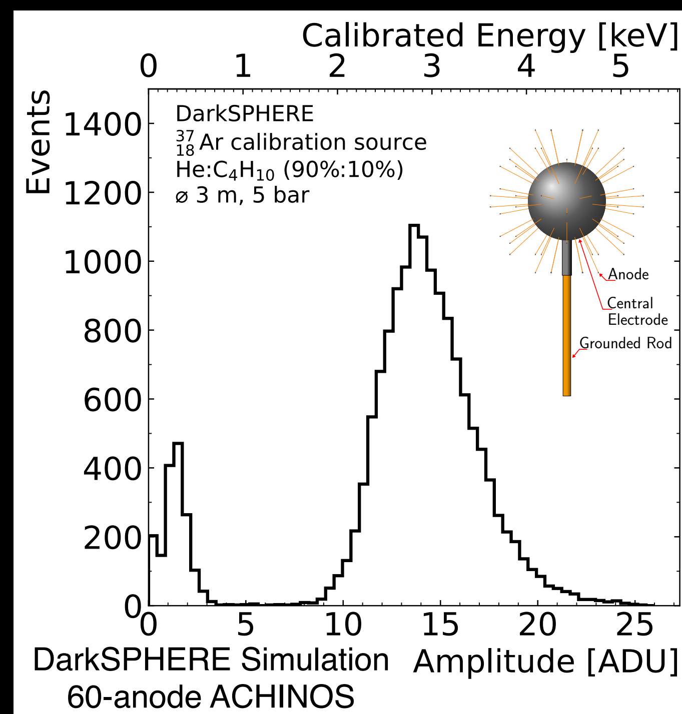

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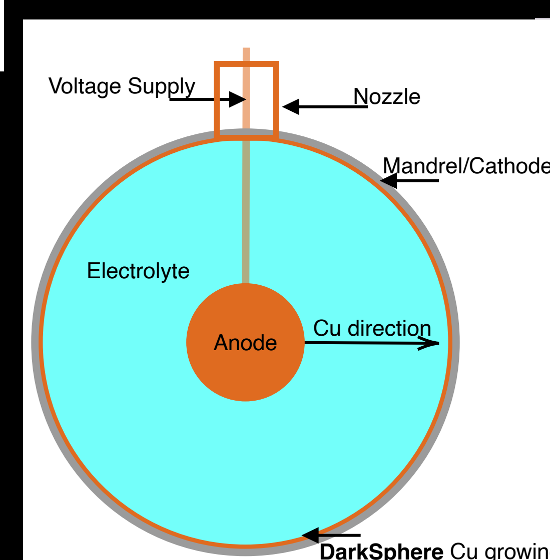


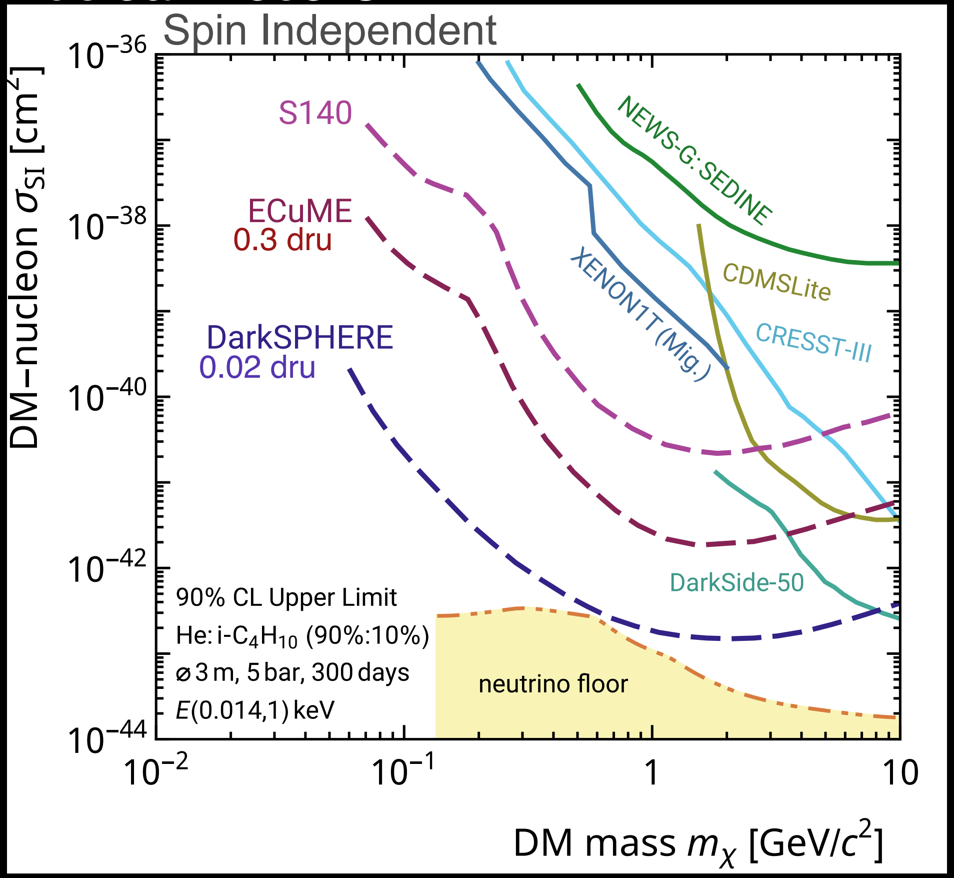
DarkSPHERE: Physics Potential

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

DarkSPHERE: Physics Potential

Nuclear Recoils

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



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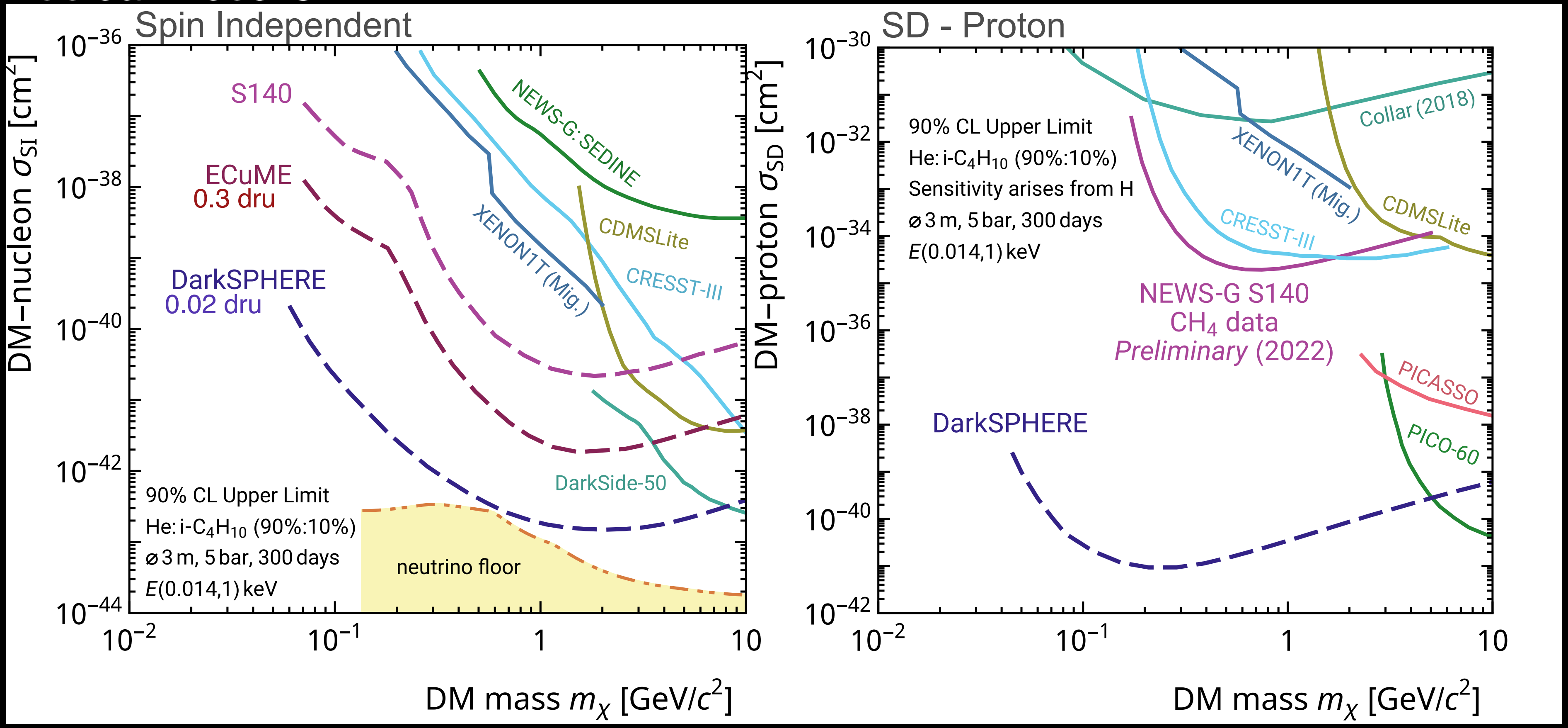

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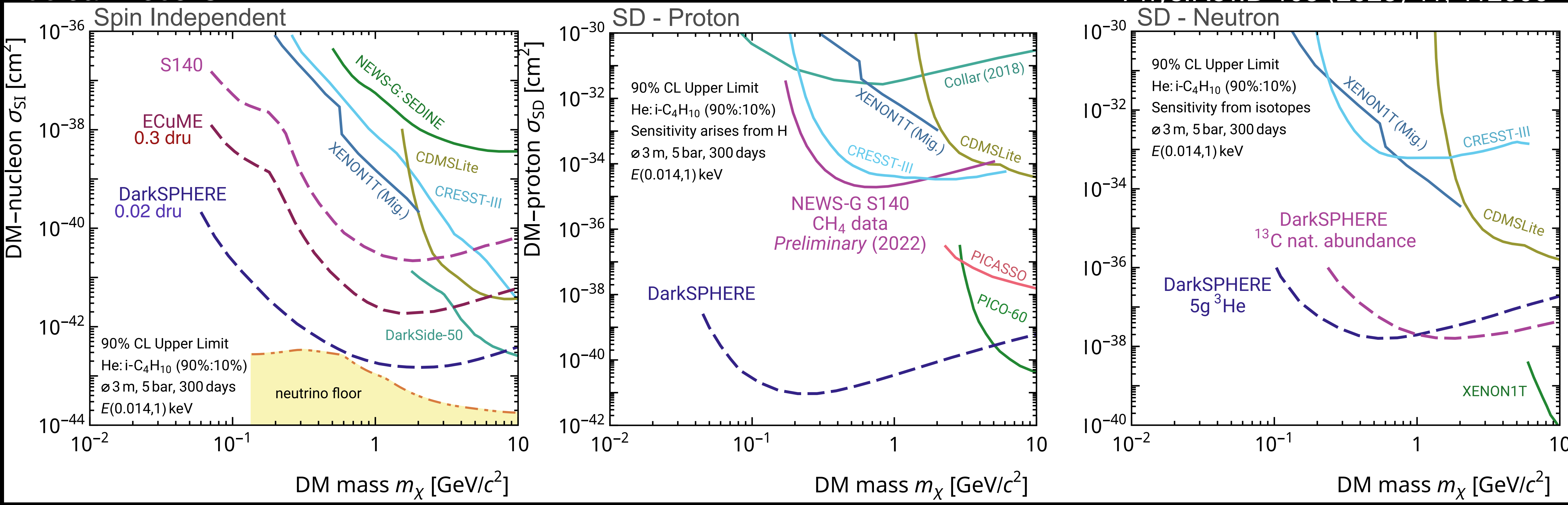

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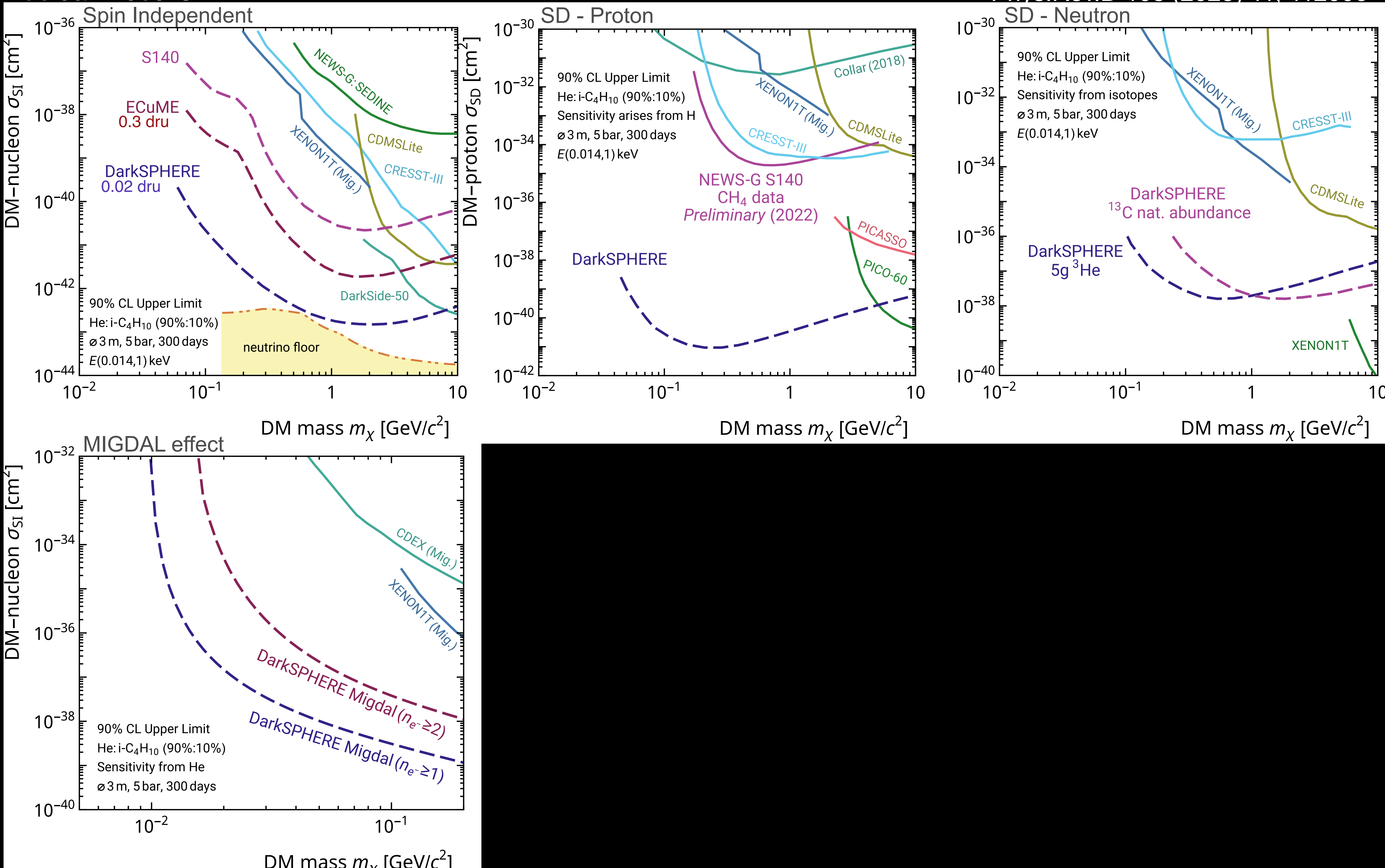

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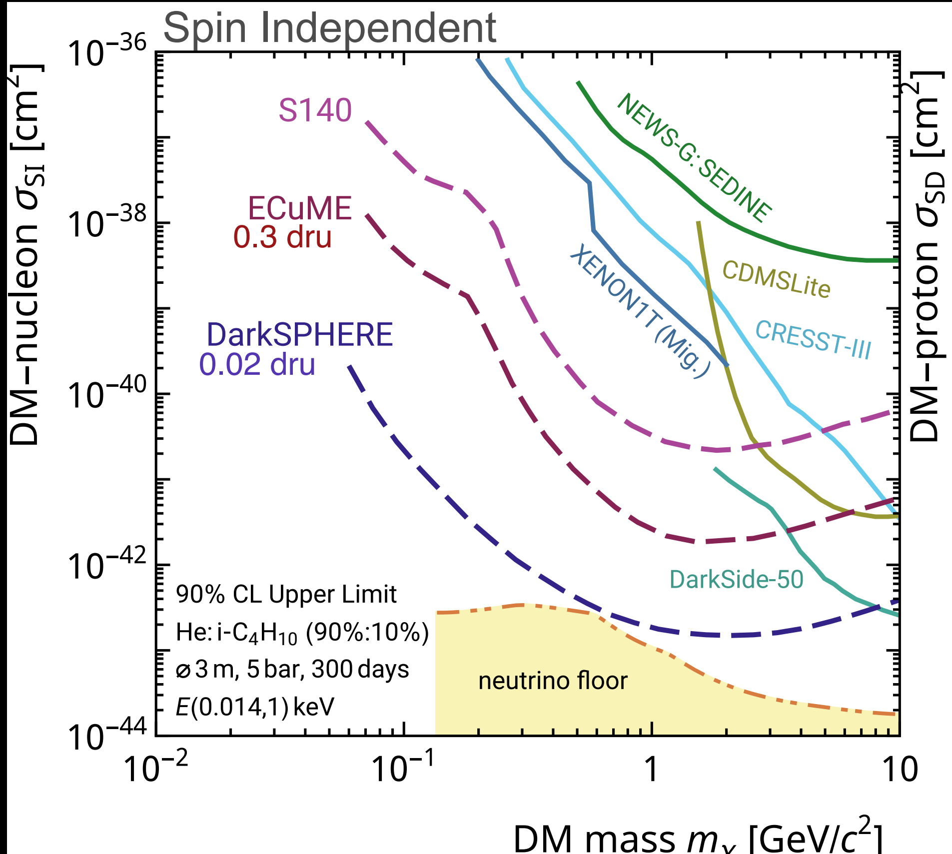

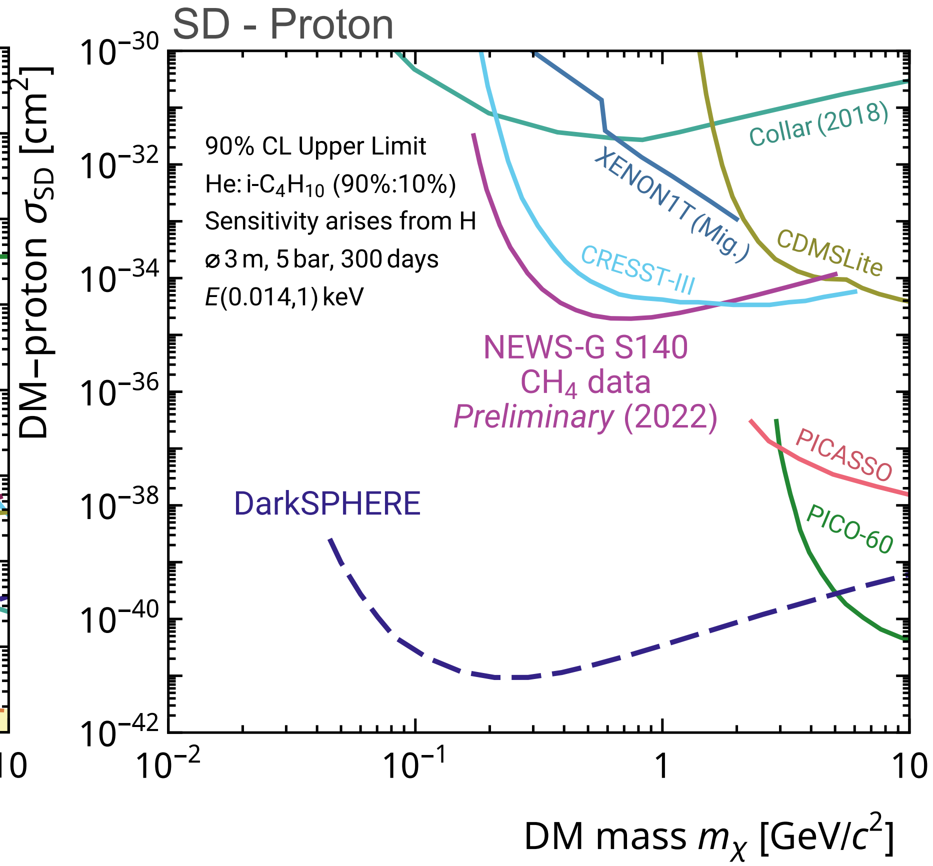

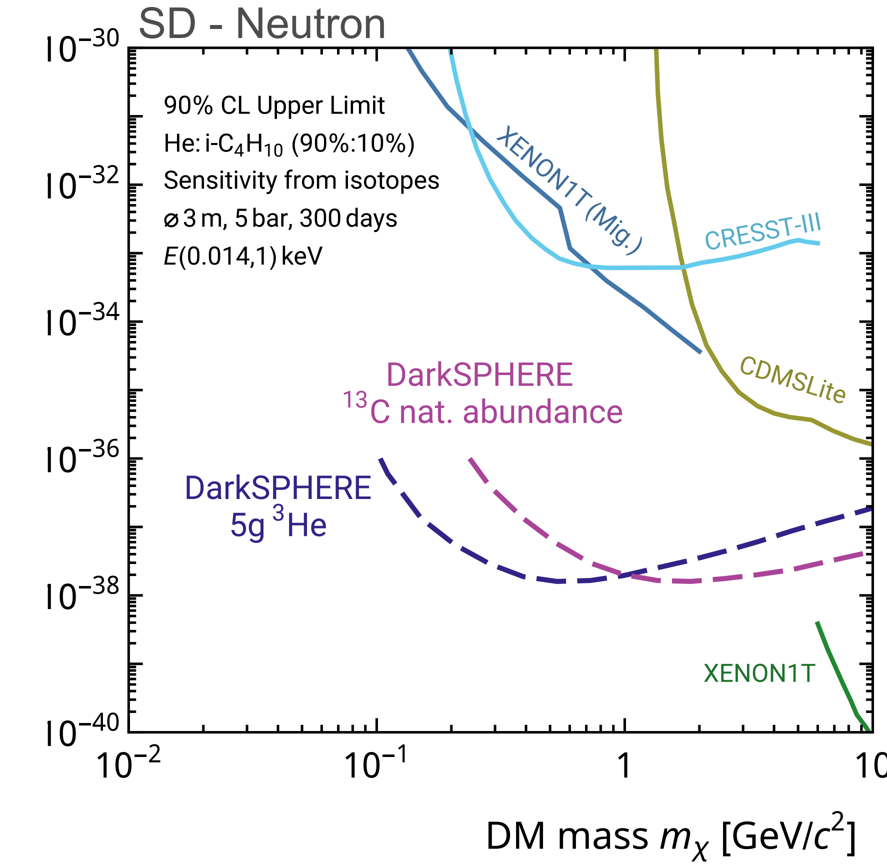

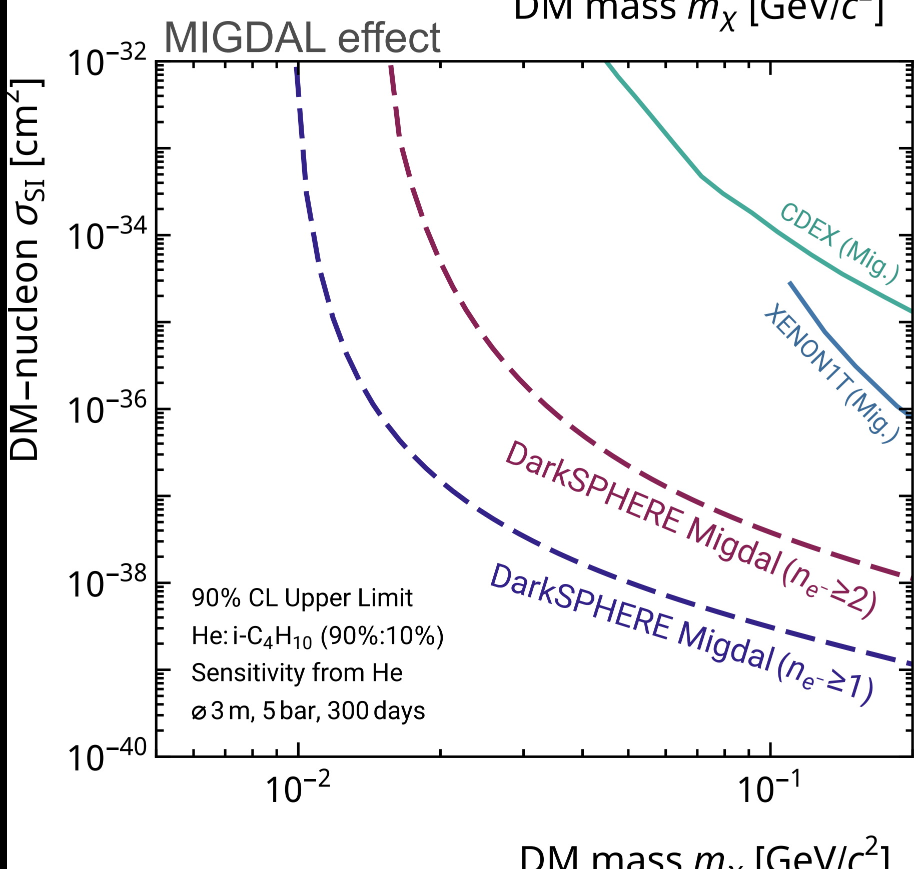

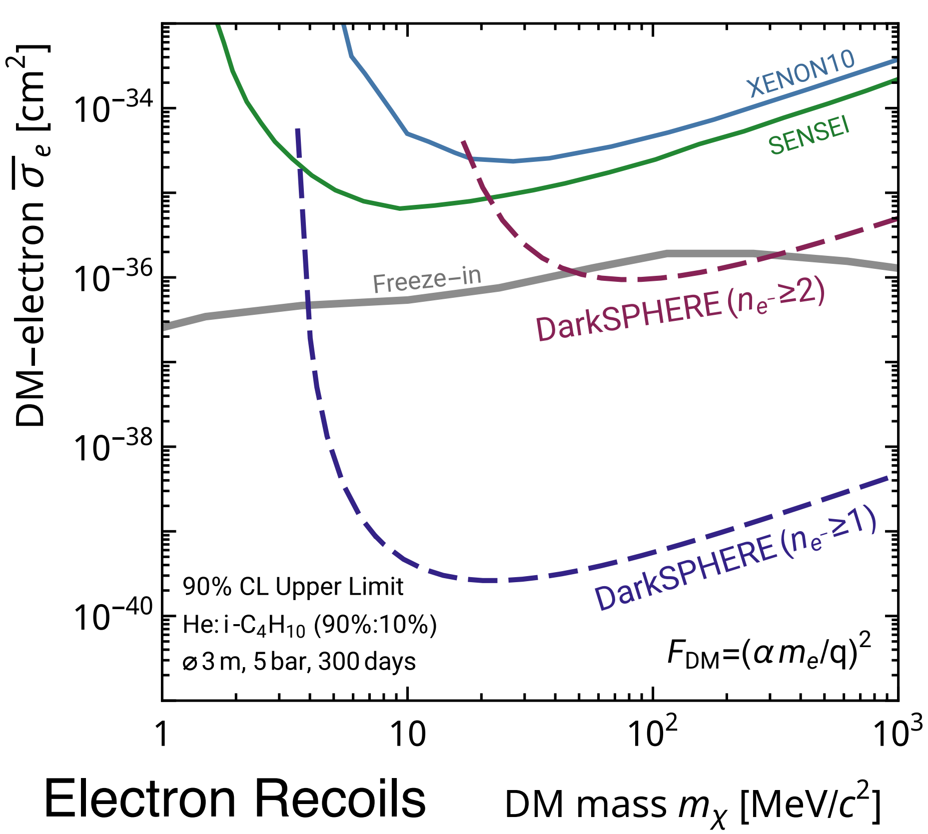

Electron Recoils

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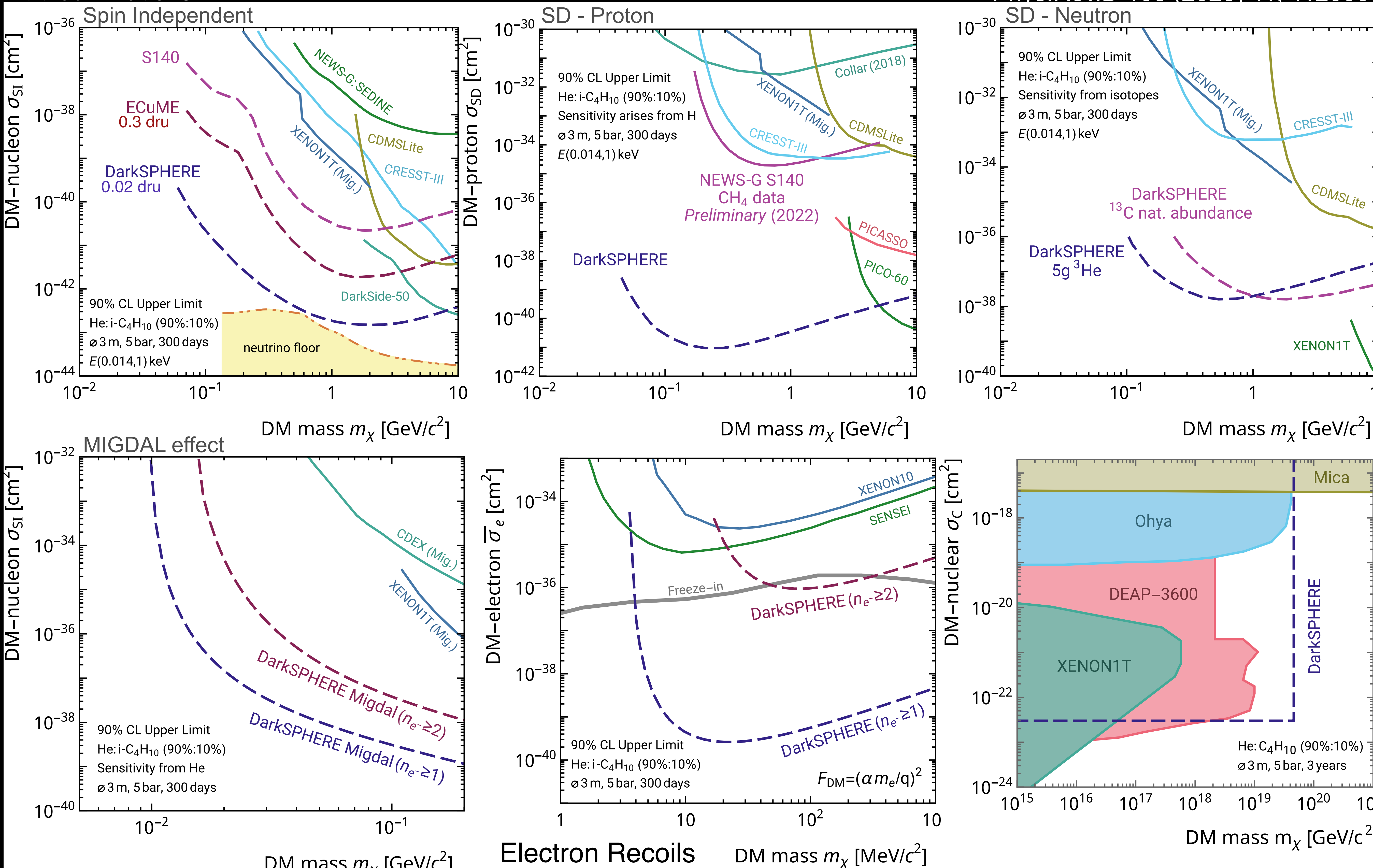
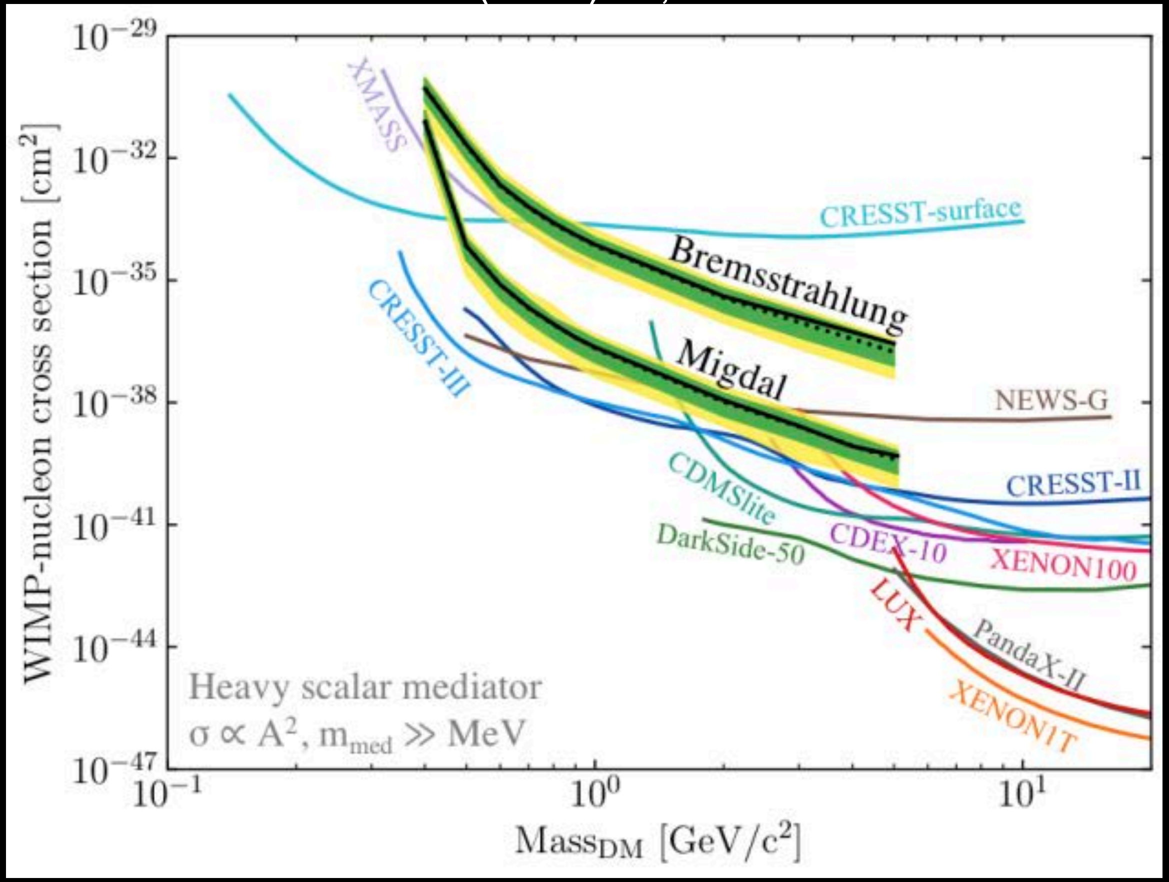


MIGDAL

Unambiguous Migdal effect observation and measurement

Migdal effect: Light DM with heavy targets

LUX: PRL 122 (2019) 13, 131301
Also Xenon1T: PRL 123 (2019) 24, 241803



UNIVERSITY OF BIRMINGHAM
Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG

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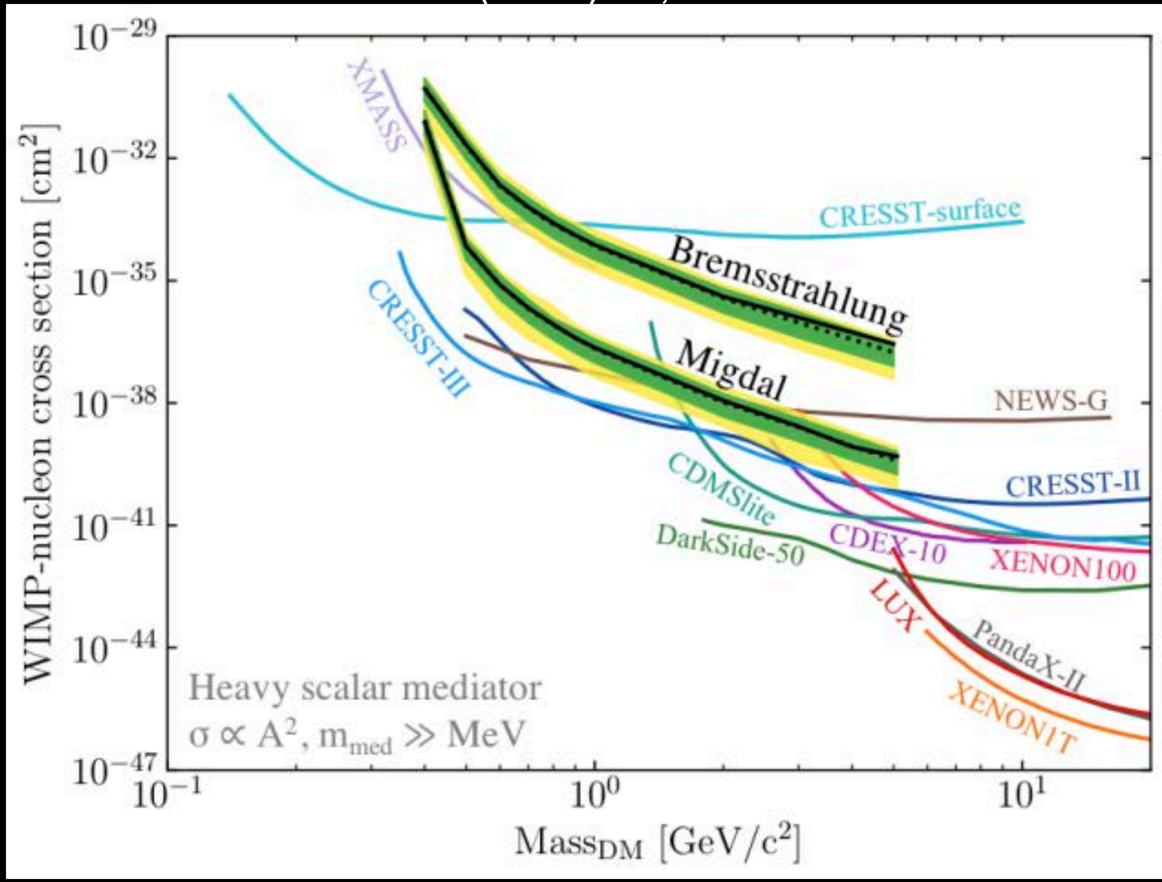

- Analysed theoretically by Arkady Migdal
  - Nuclear scattering (1939)
  - α and β± decays (1941)
- Relevance for DM searches
  - Nucl. Phys. B727 (2005) 406, PLB 606 (2005) 313, IJMPA 22 (2007) 3155, JHEP03(2018)194, …

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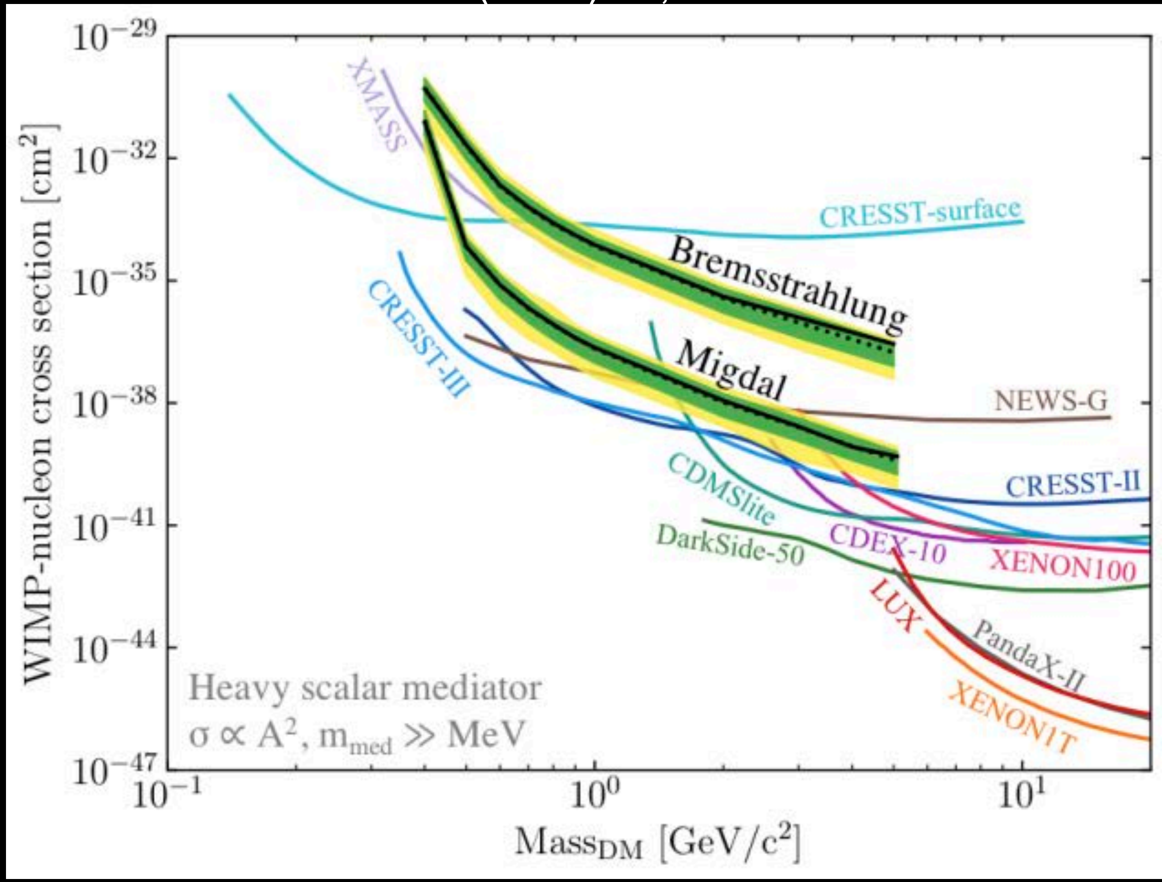

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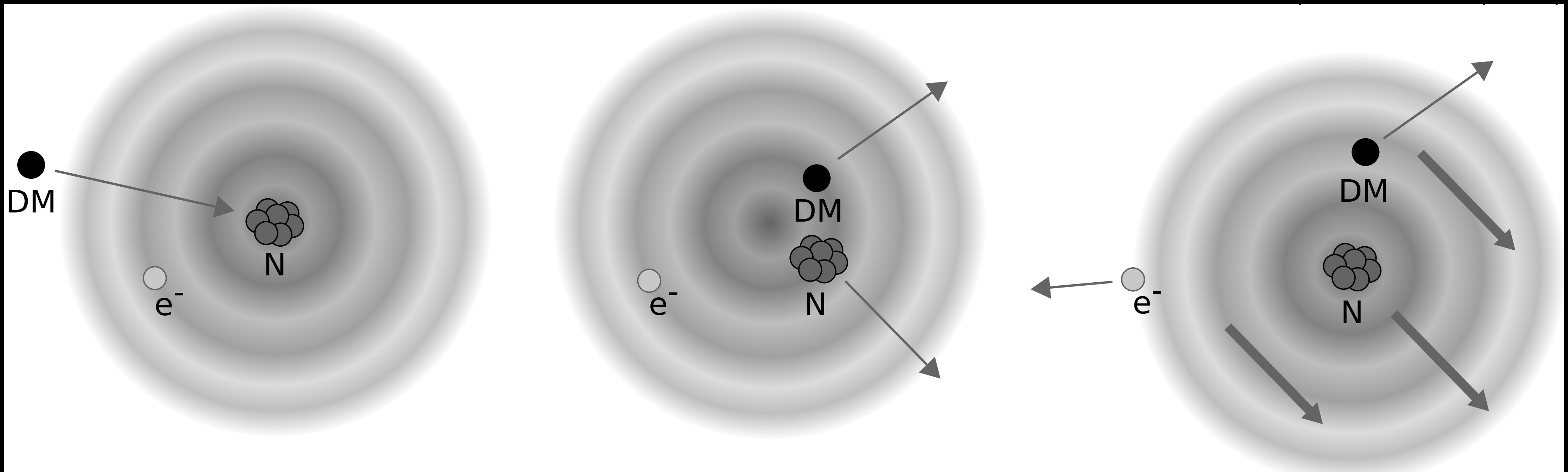

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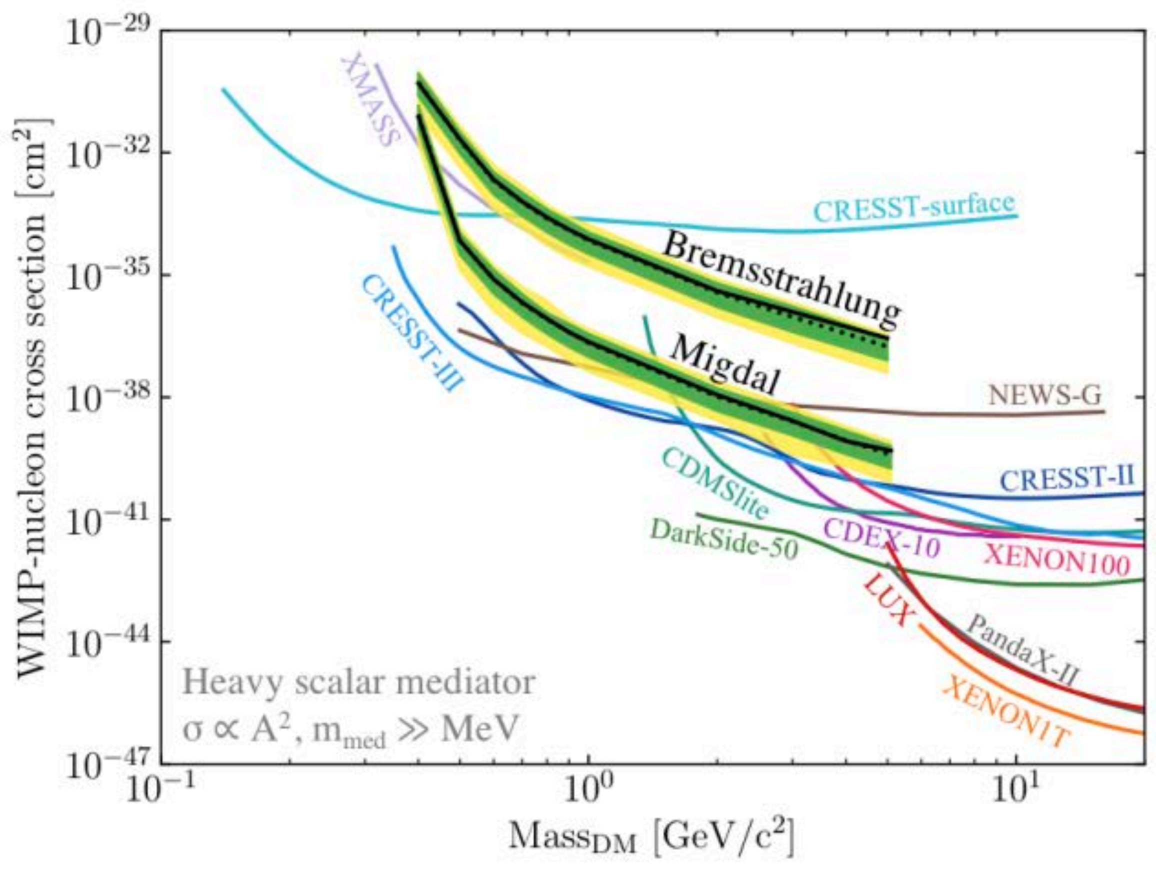

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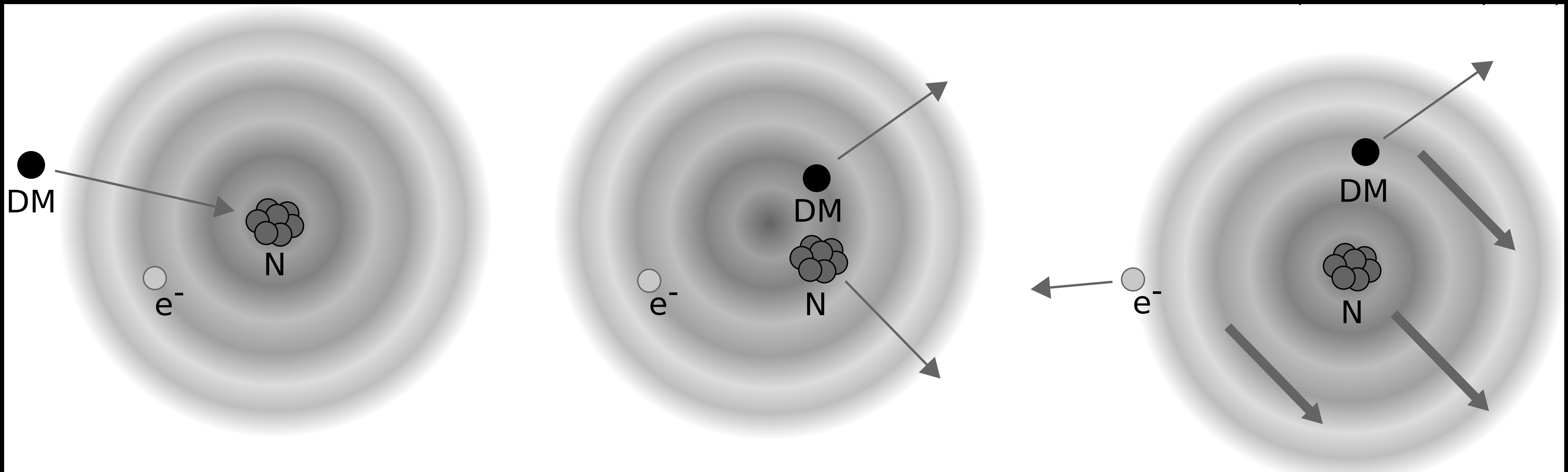
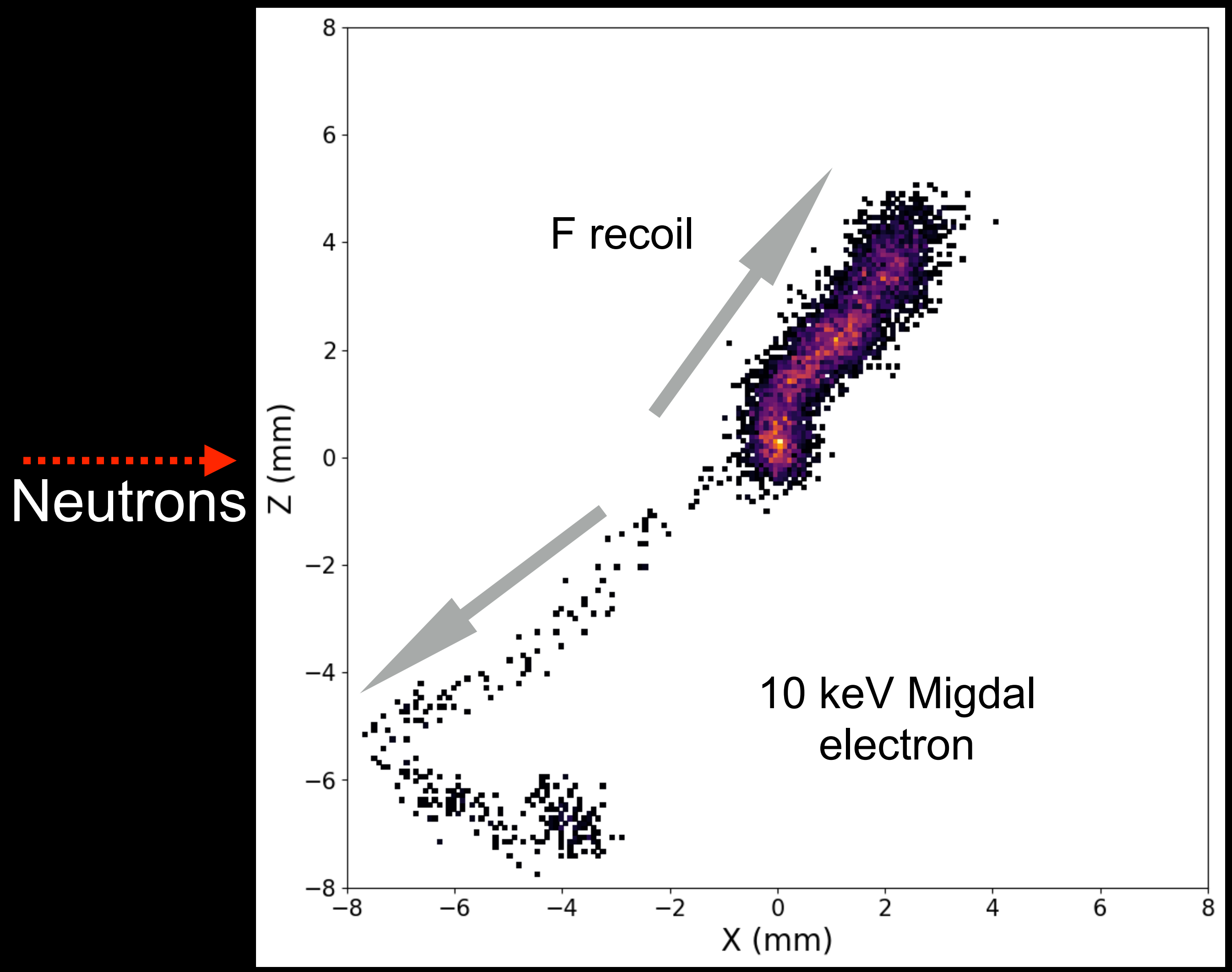
  - α and β± decays (1941)
- Relevance for DM searches
  - Nucl. Phys. B727 (2005) 406, PLB 606 (2005) 313, IJMPA 22 (2007) 3155, JHEP03(2018)194, …
- Effect observed in α and β± decays
- Not observed (yet) in nuclear scattering
  - Recent attempts inconclusive (PRD109 (2024) L051101, J.Bang UCLA DM'23)



MIGDAL Experiment

- Aim: unambiguous Migdal effect observation and measurement in nuclear scattering
  - Observe both electron and ion recoil
  - 12 institutes and ~40 participants

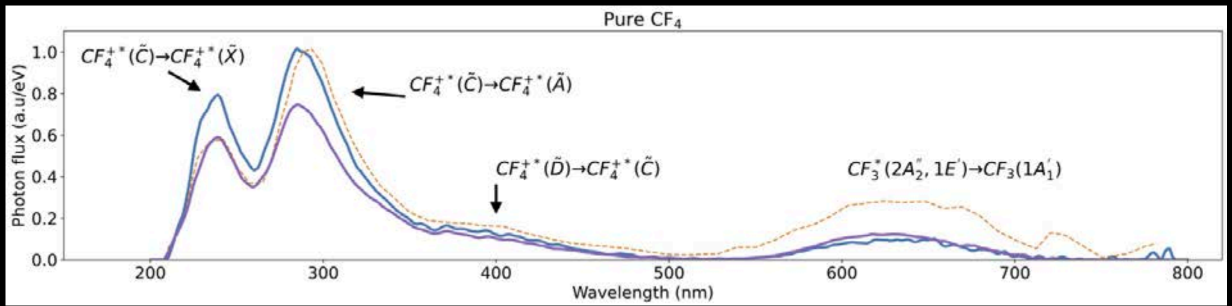
Astropart.Phys. 151 (2023) 102853



MIGDAL Experiment

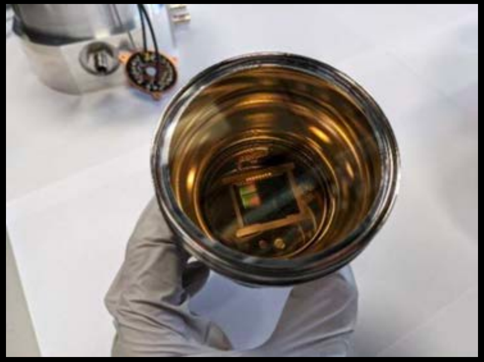
- Low Pressure Optical Time Projection Chamber
  - Neutrons interacting in 50 Torr CF_4
  - Extended particle tracks
  - Avoid photon interactions
- Detailed simulation (Degrad, SRIM/TRIM, Garfield++, Magboltz, Gmsh/Elmer & ANSYS)

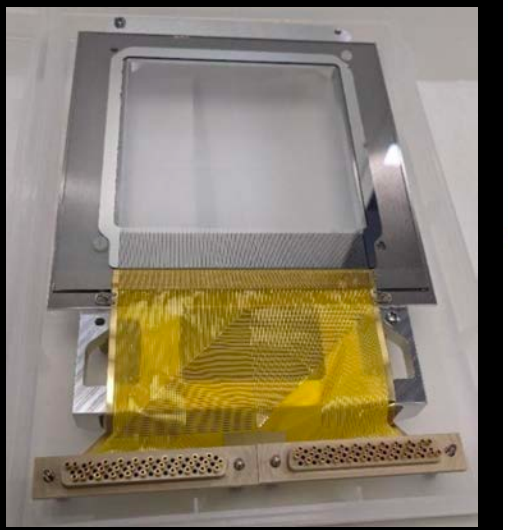
arXiv:2306.09919



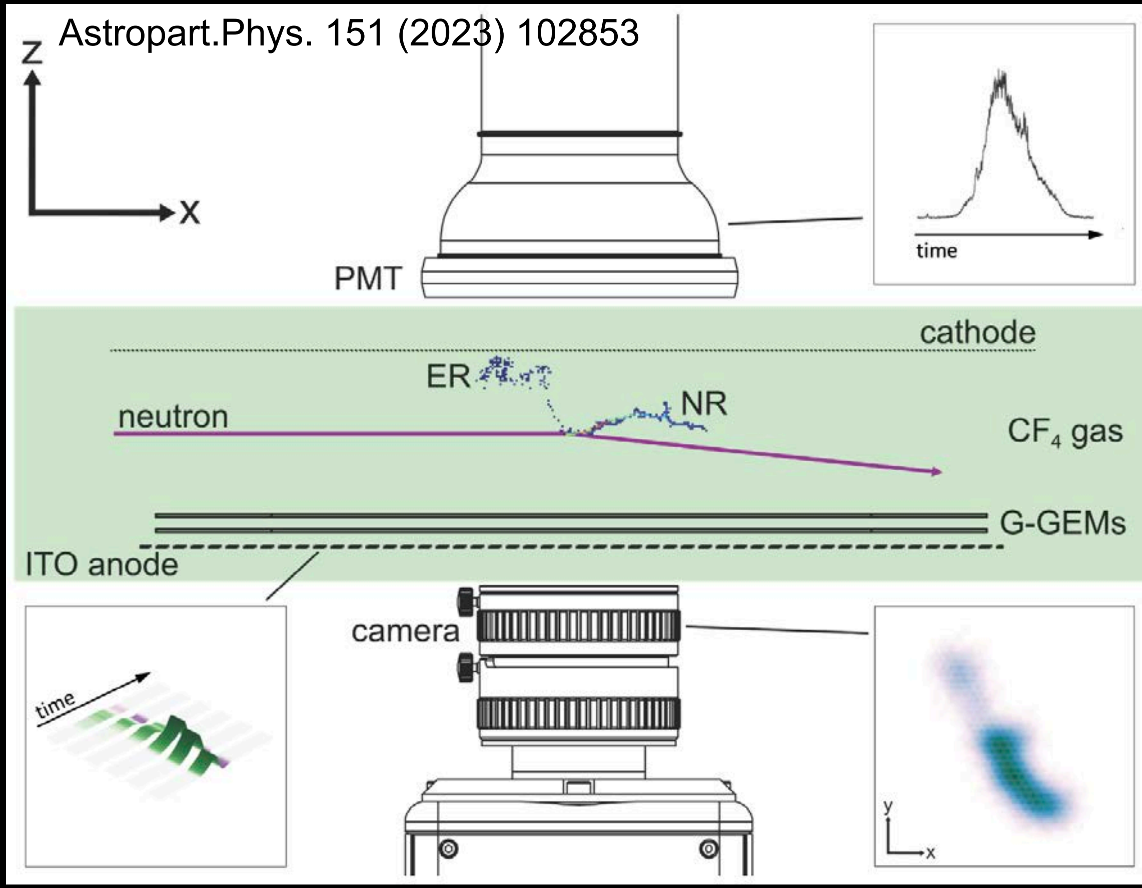
Double Glass-GEM
Hole/pitch: 170/280 µm
Gain: ~10^5

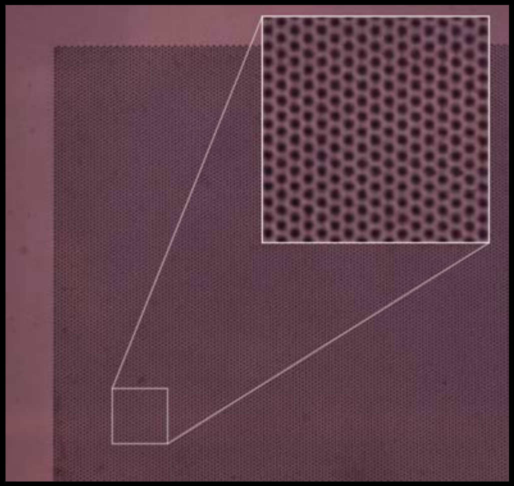
VUV PMT

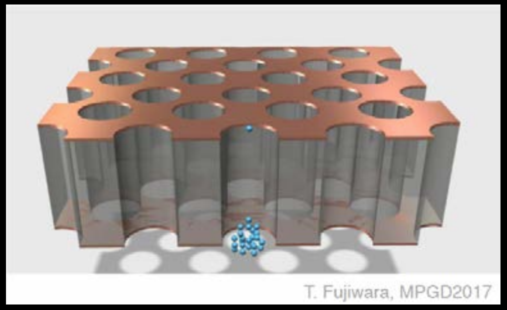


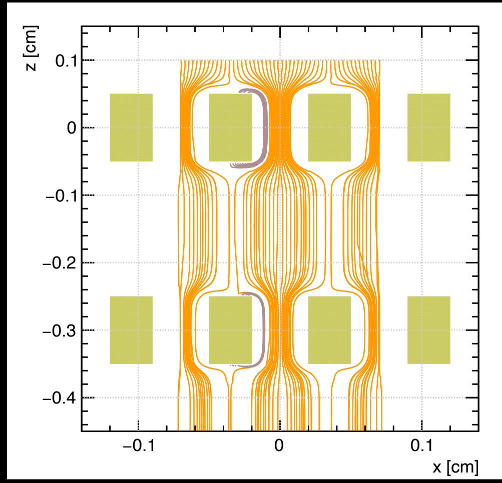


ITO Anode Strips (xz)





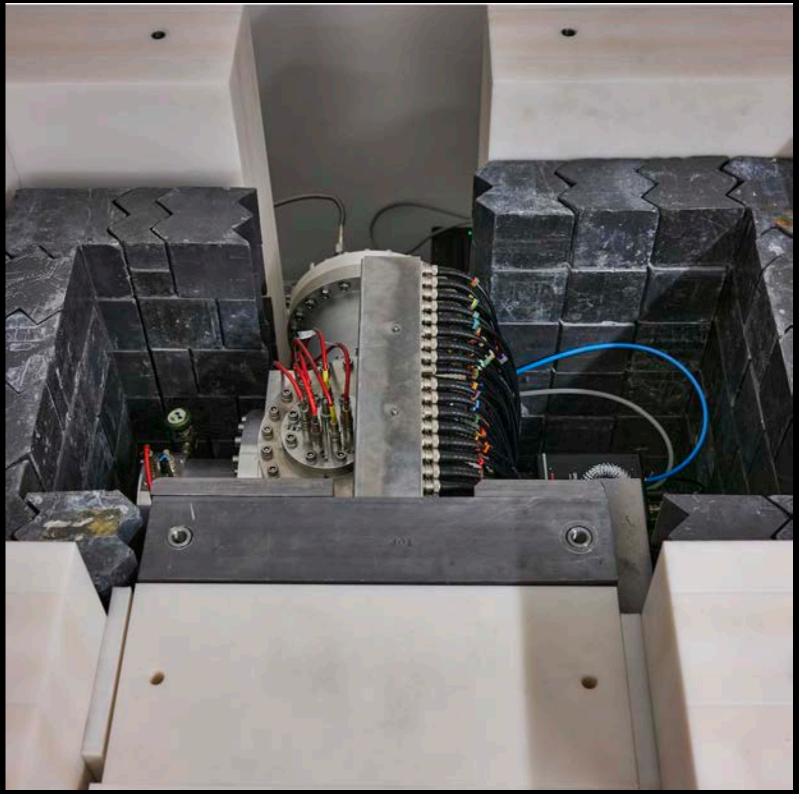


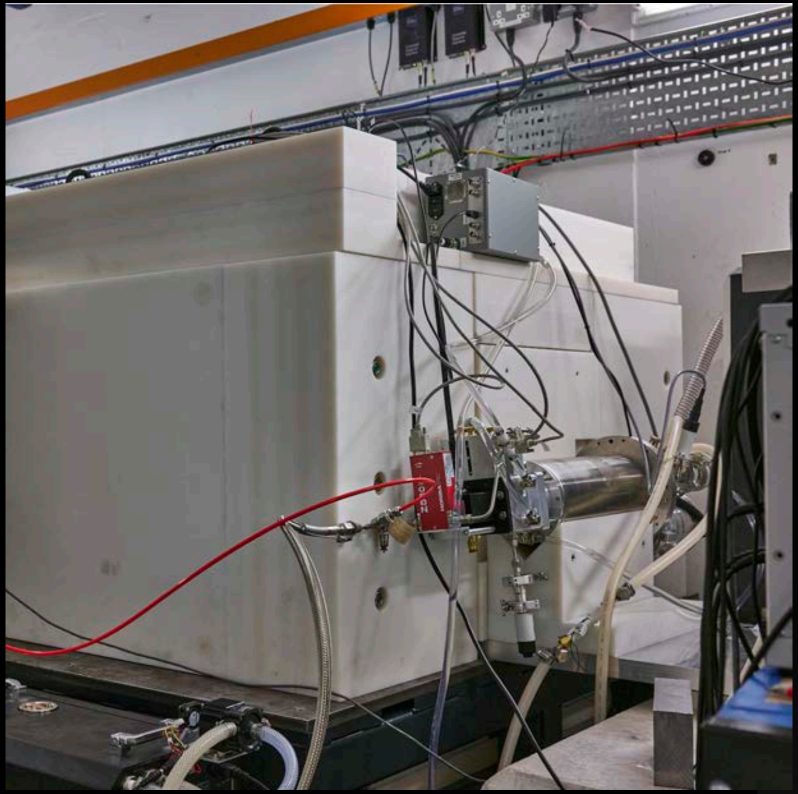


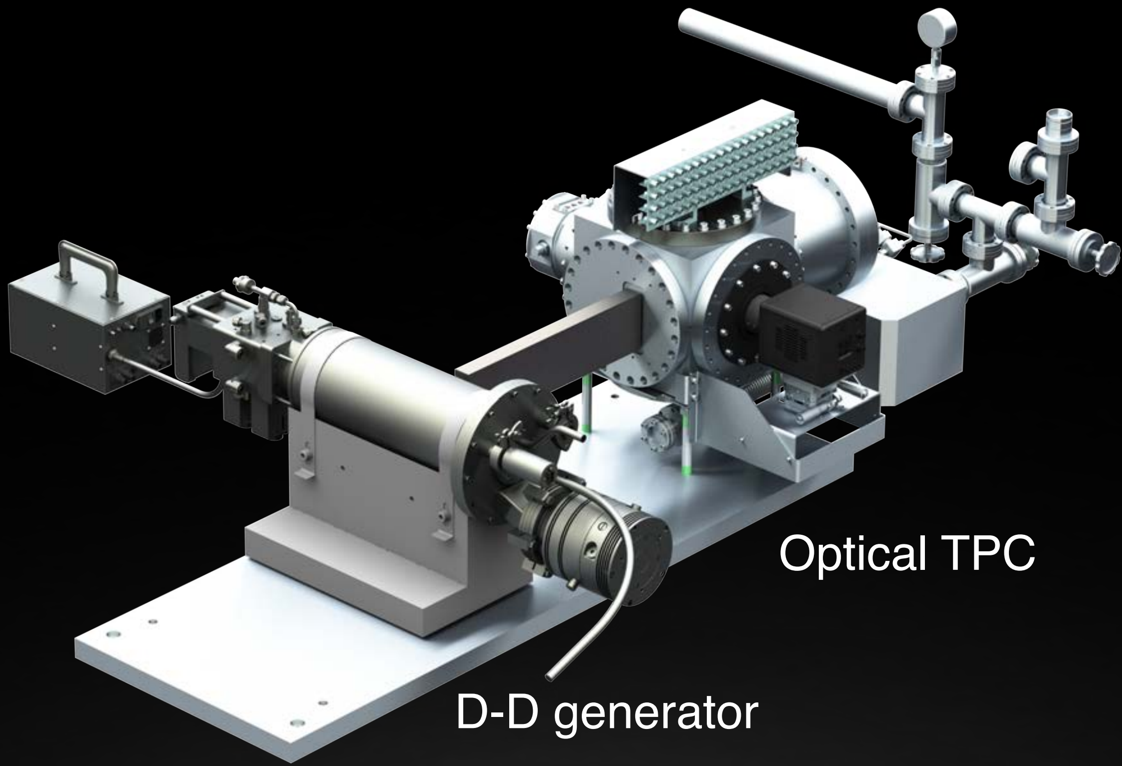
qCMOS camera

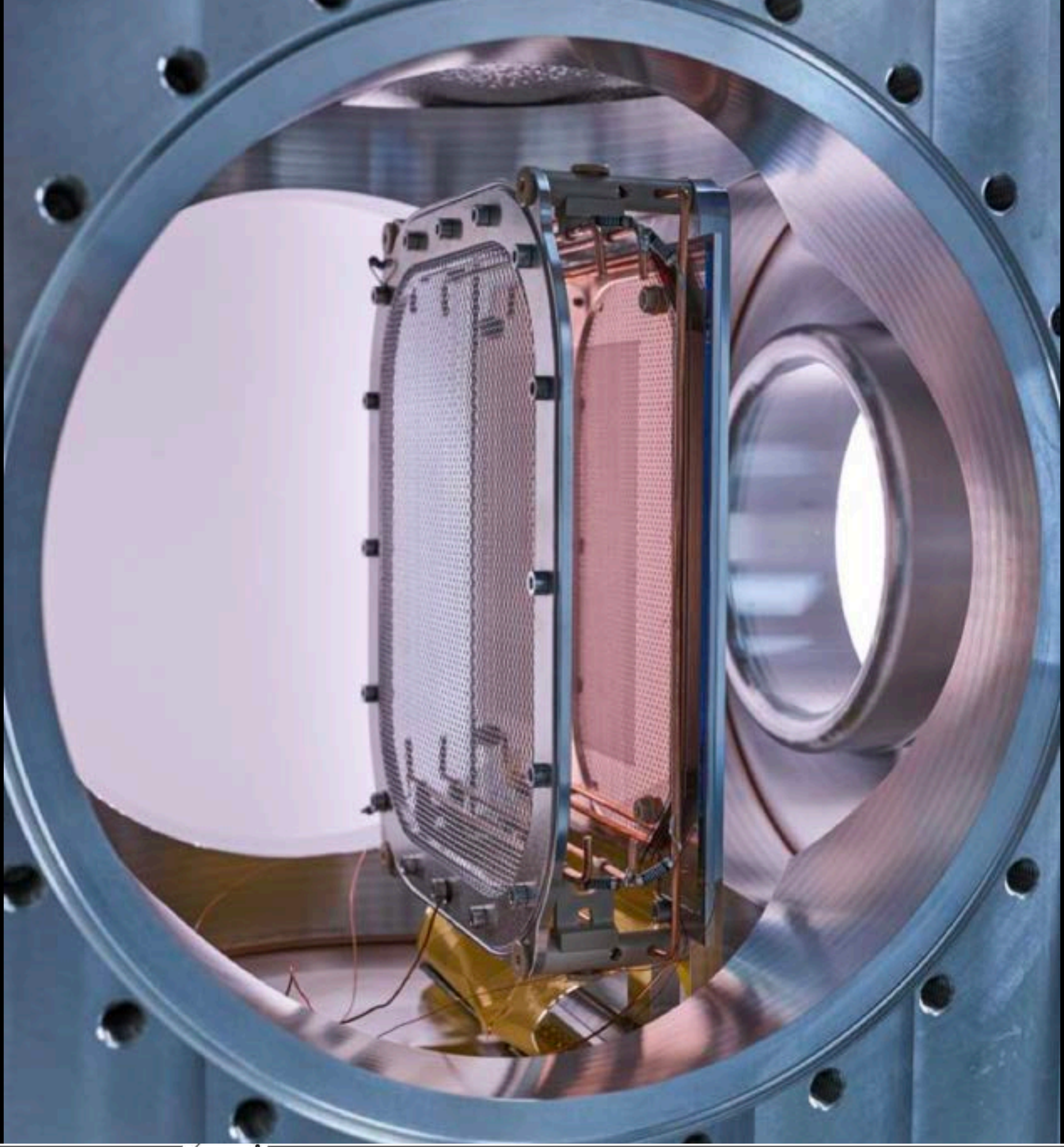
NILE Facility at Rutherford Appleton Lab

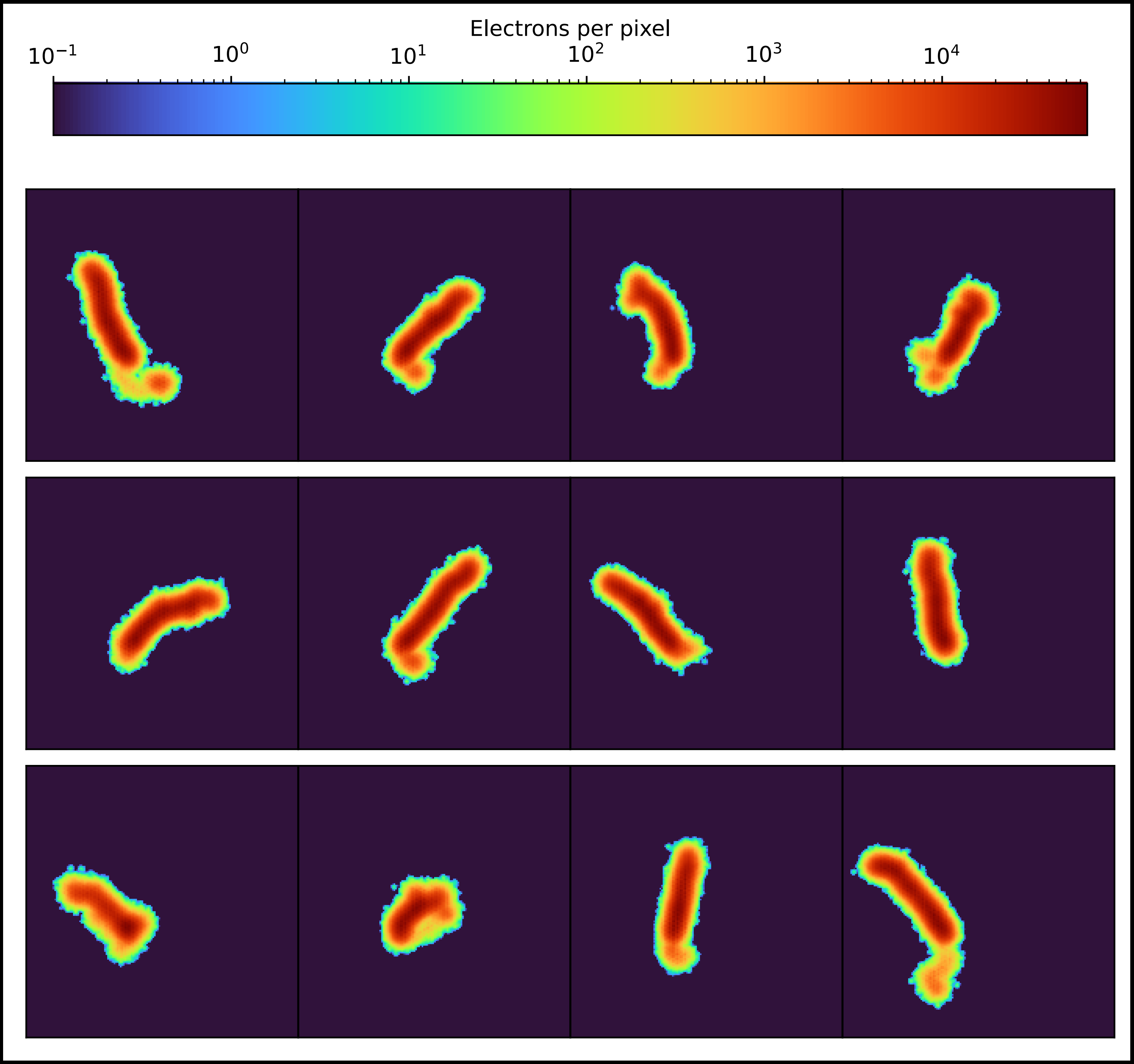
- ISIS facility: High-yield neutron generators
  - Installed in "shielding bunker"
    - D-D: 2.47 MeV (10^{9} n/s)
    - D-T: 14.1 MeV (10^{10} n/s)
  - Collimators: Defined beam through TPC
    - e.g. D-D collimator 30 cm in length



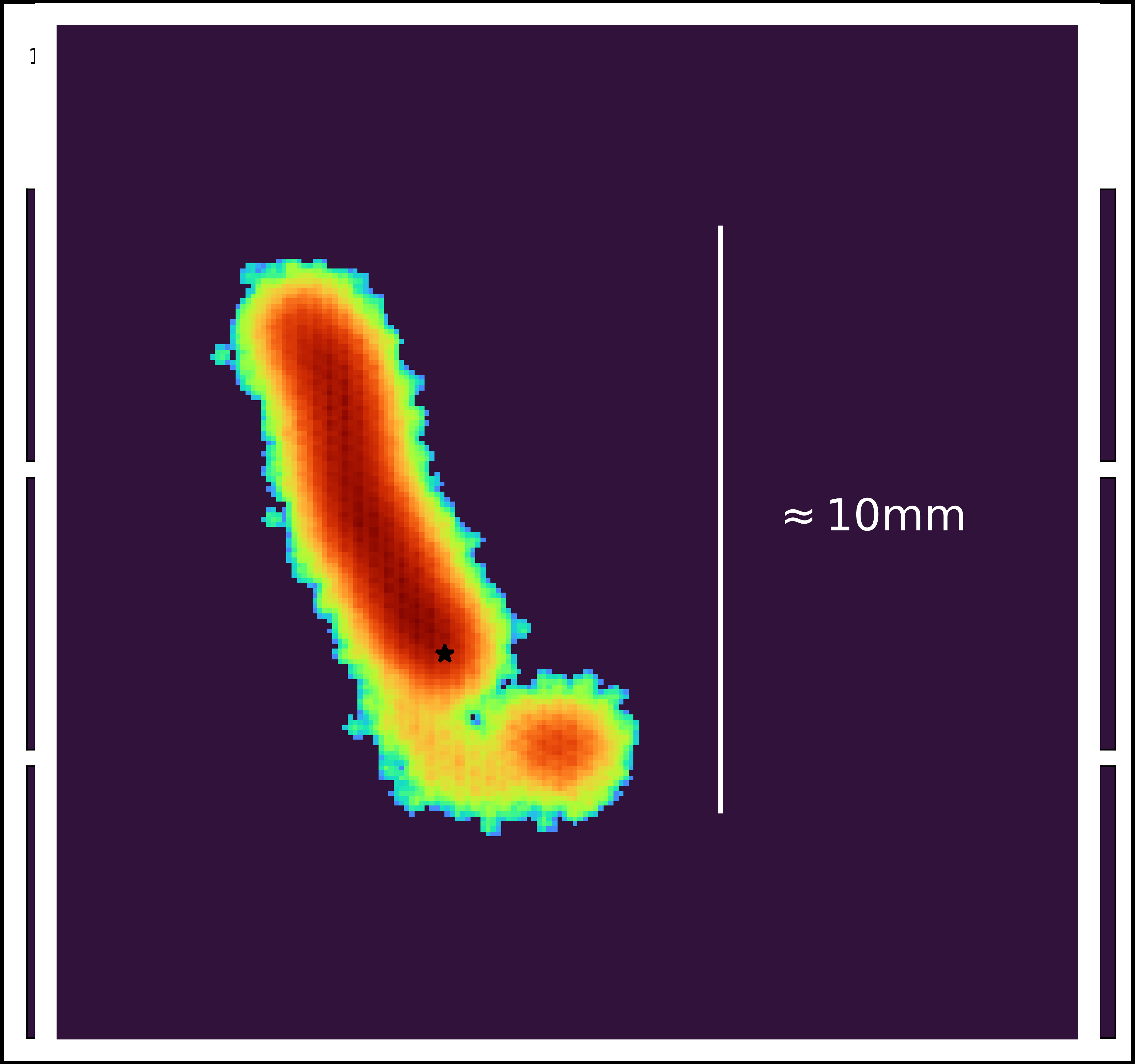








- Simulated Migdal-like events with a 250 keV NR and a 5 keV ER



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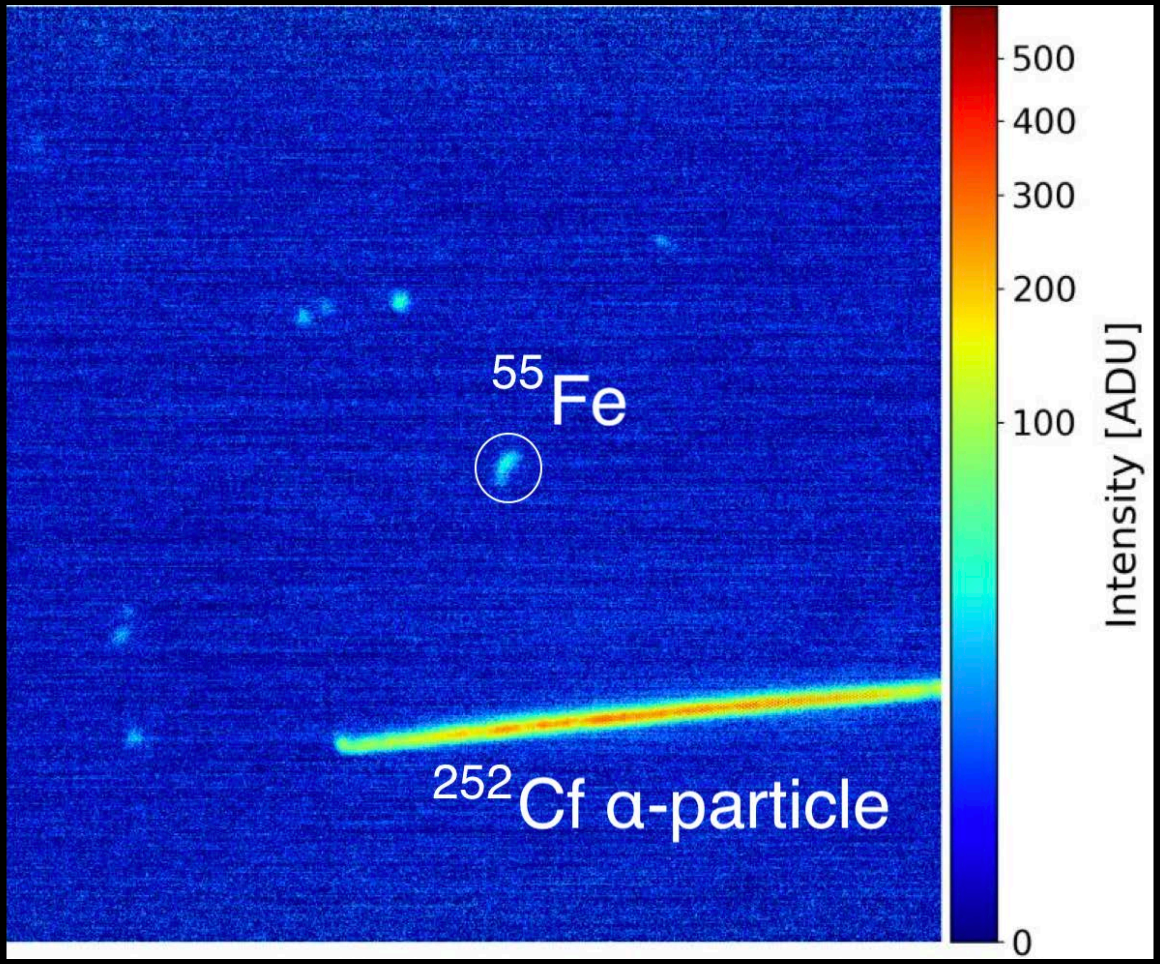
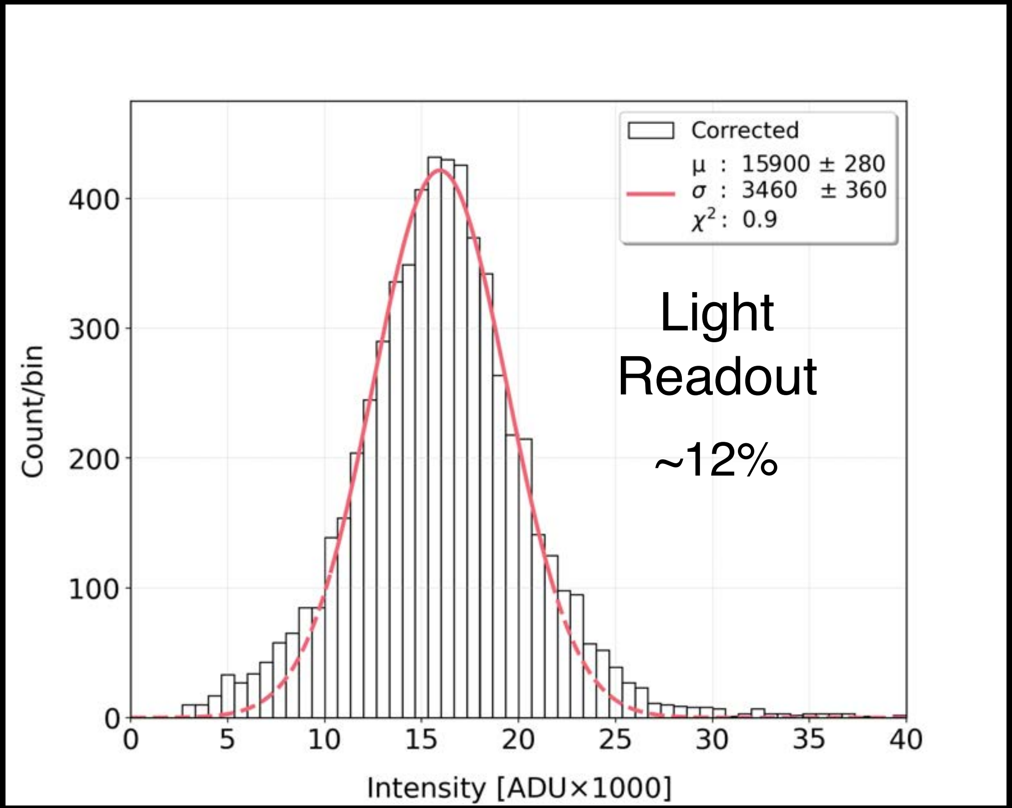
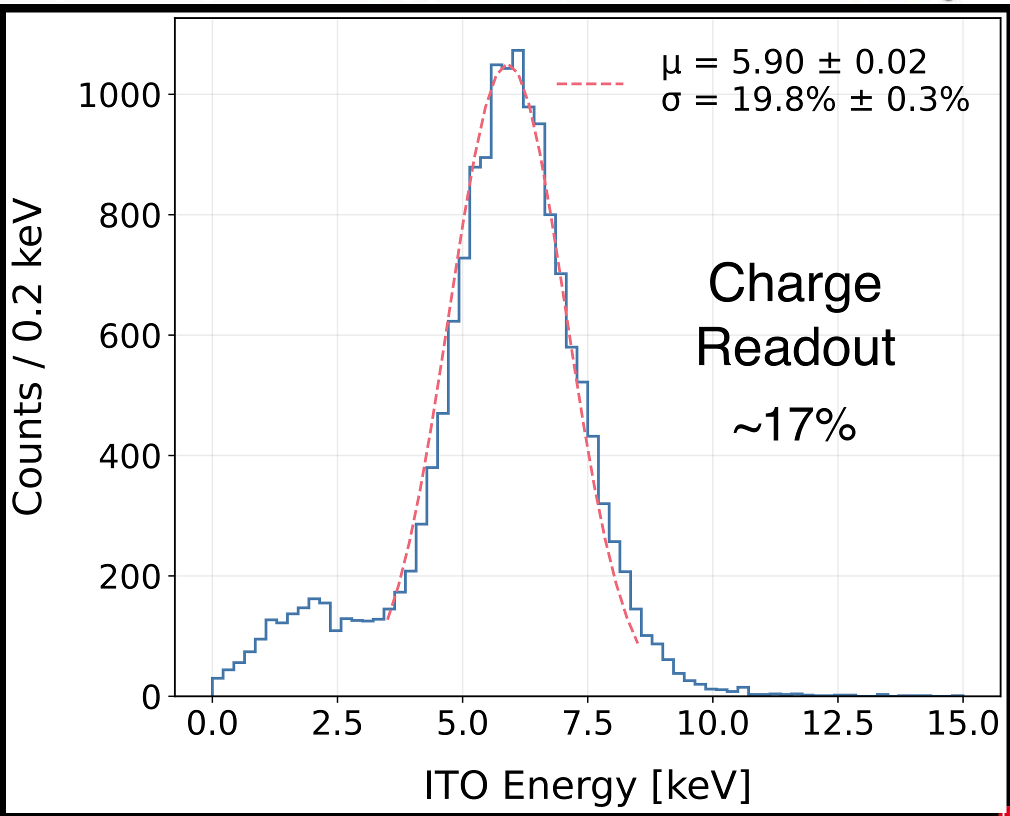
Detector Commissioning

- Commissioning with radioactive sources
- ^{55}Fe calibrations throughout data-taking

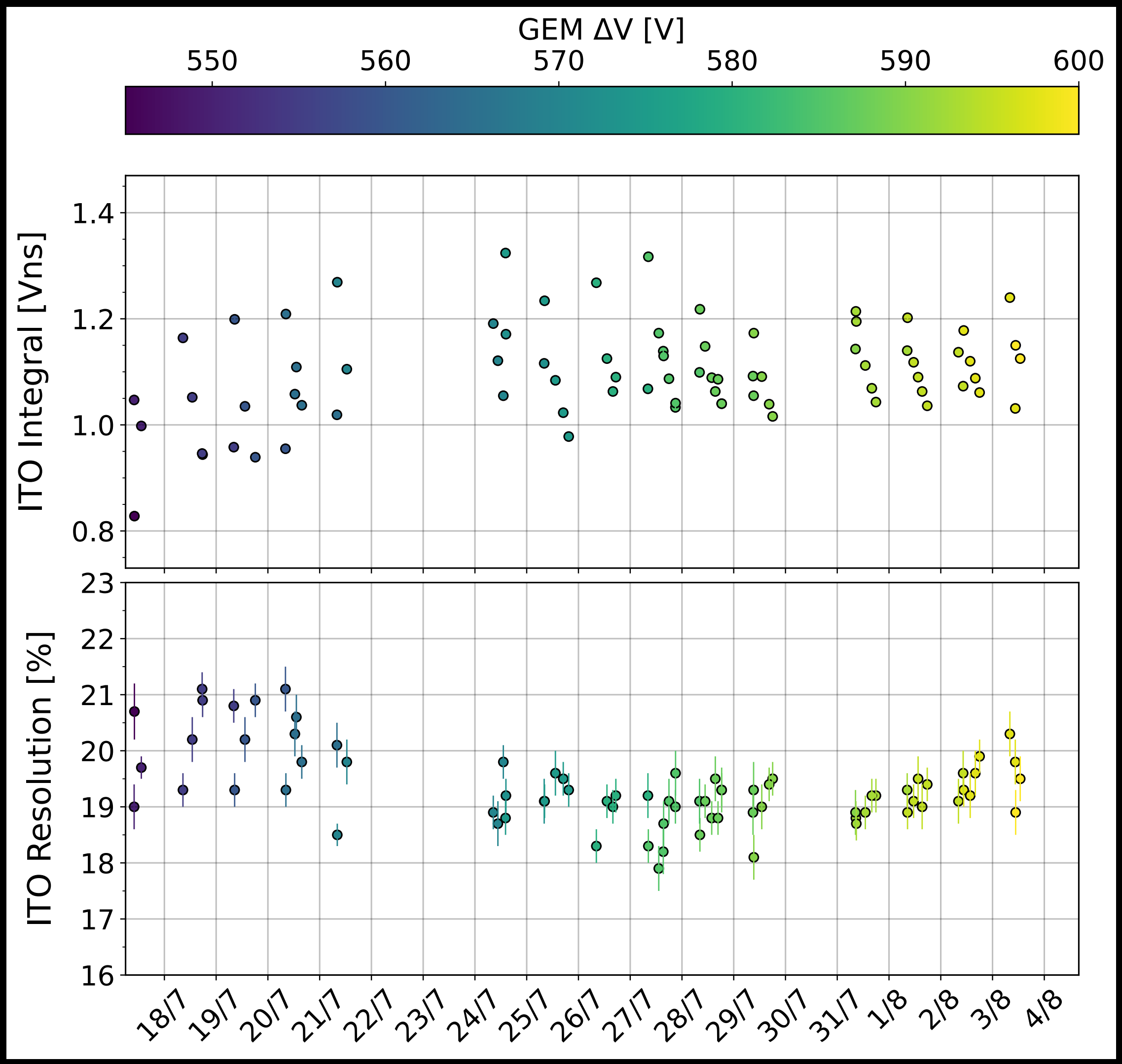




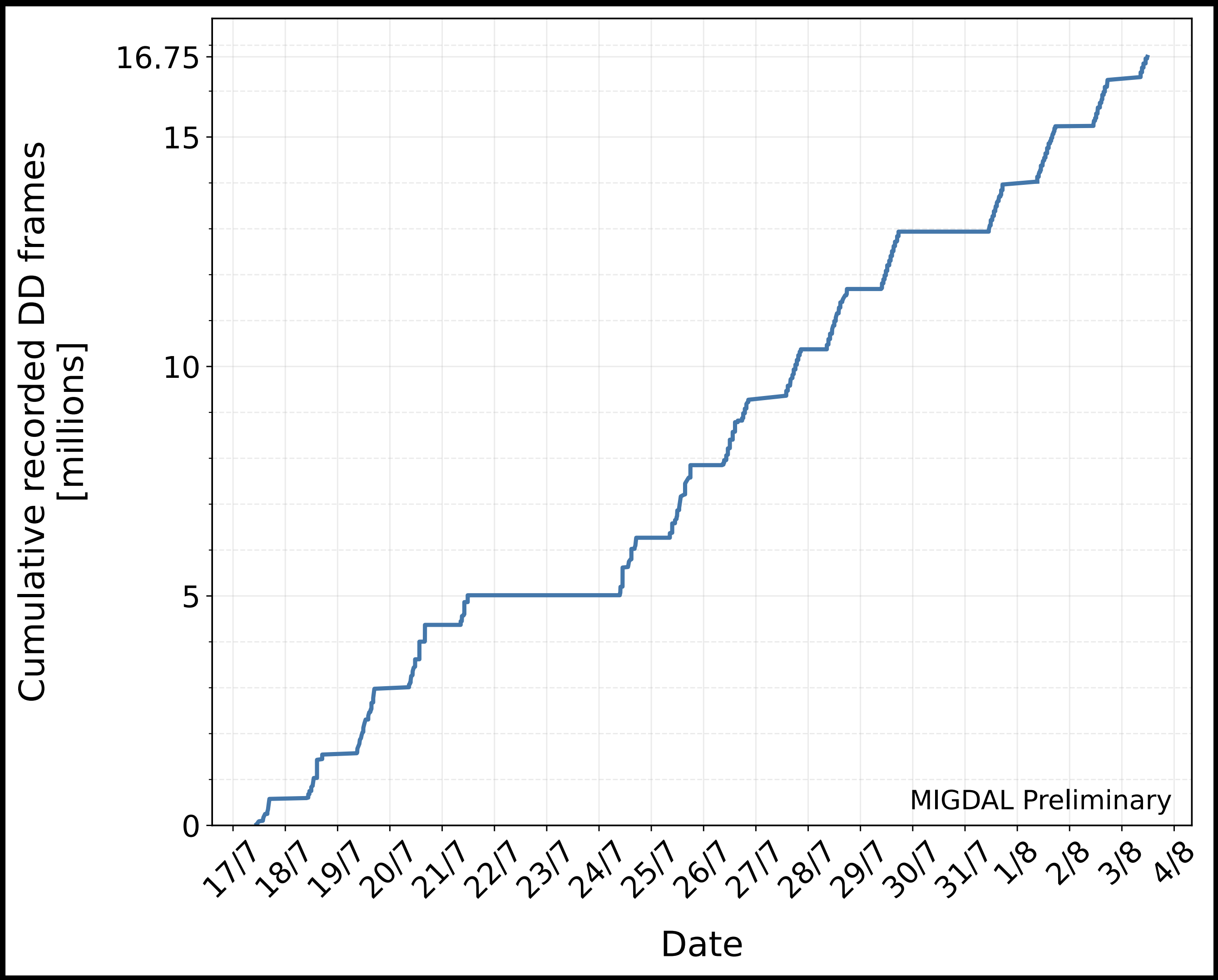


Data collection

Detector stability vs time.
Voltage adjusted by 2V/day

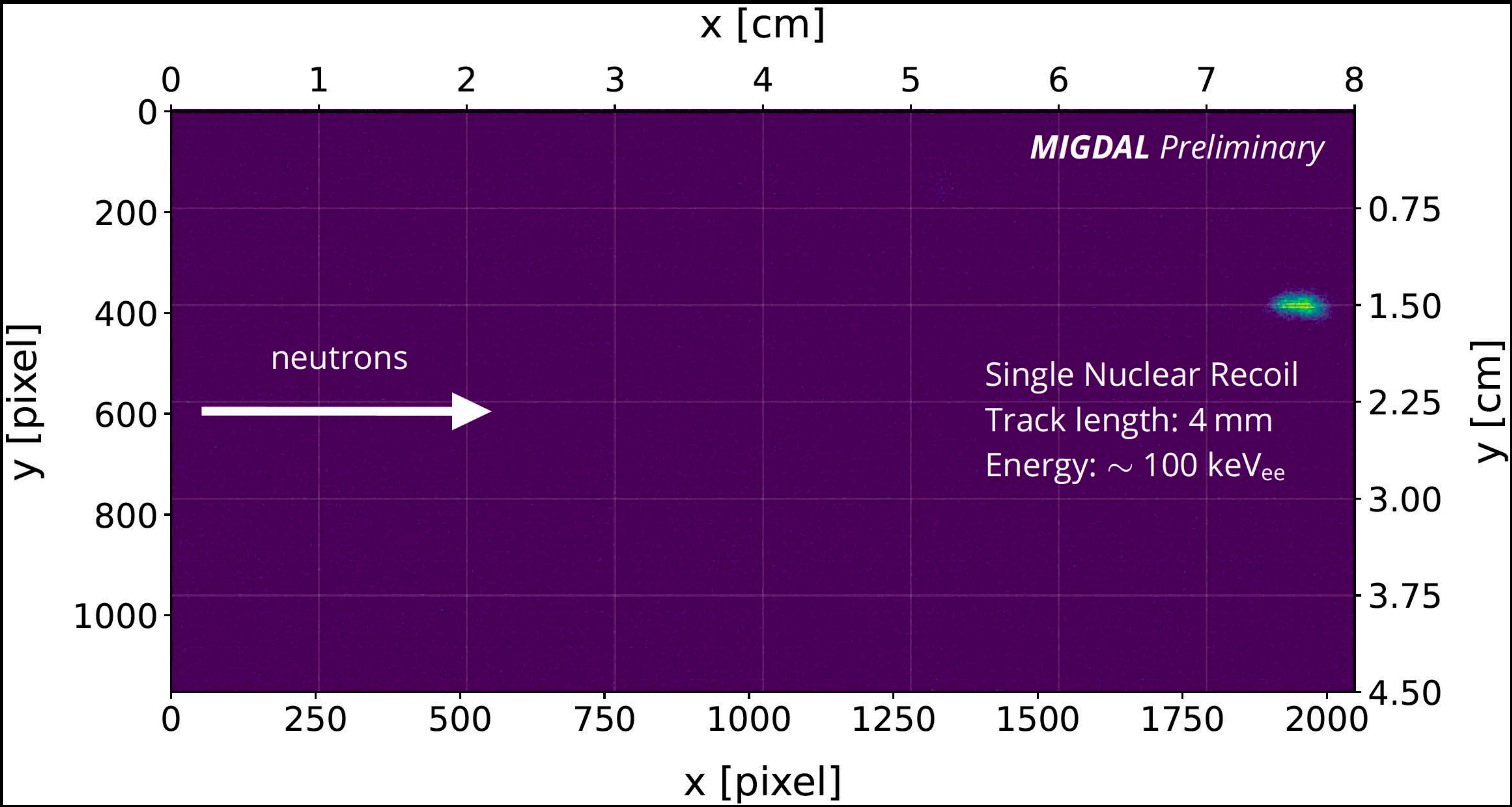


Science Run 1

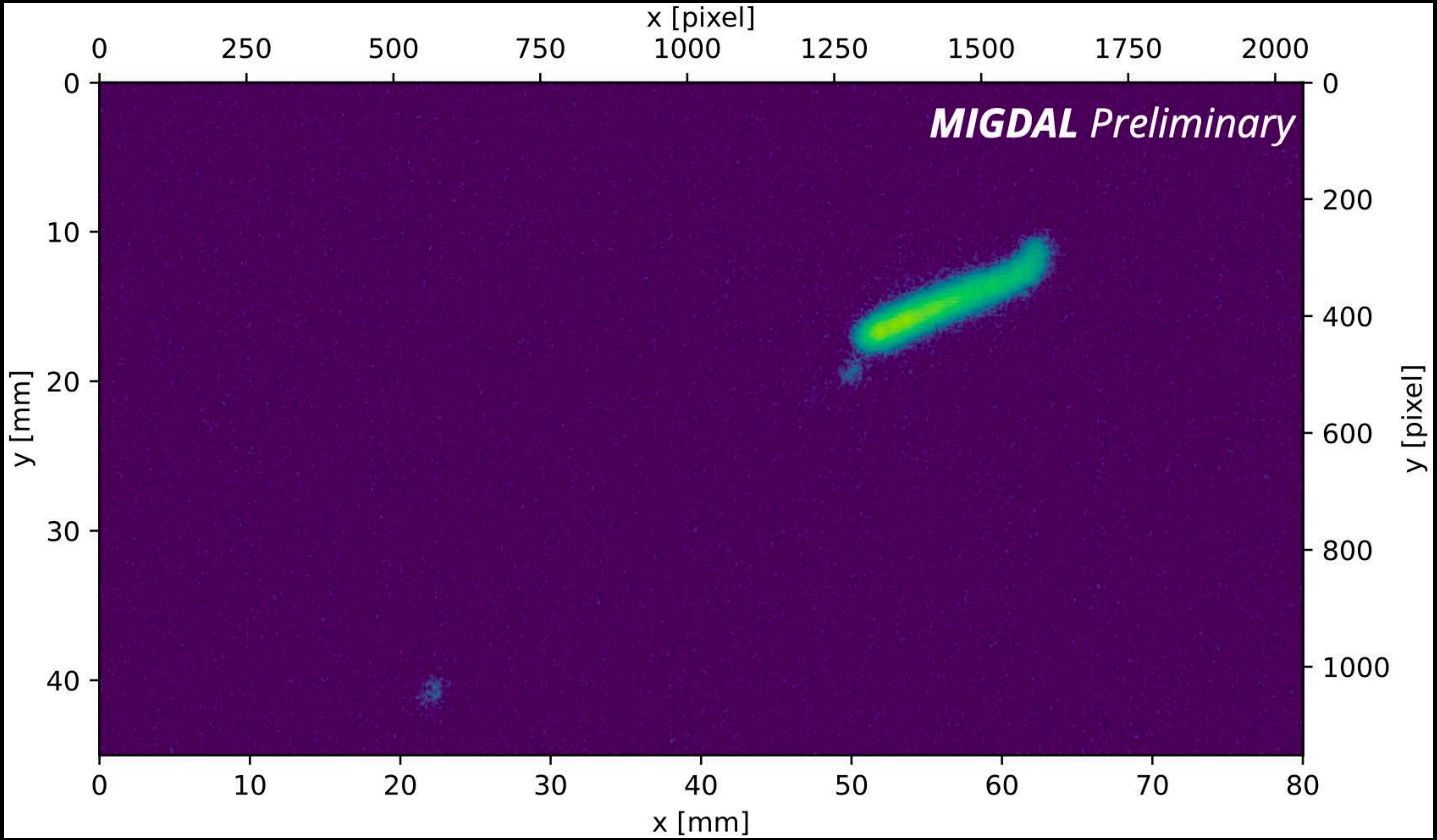


- Two science runs completed
- Data analysis on-going

Example event with 100 keV_{ee} NR

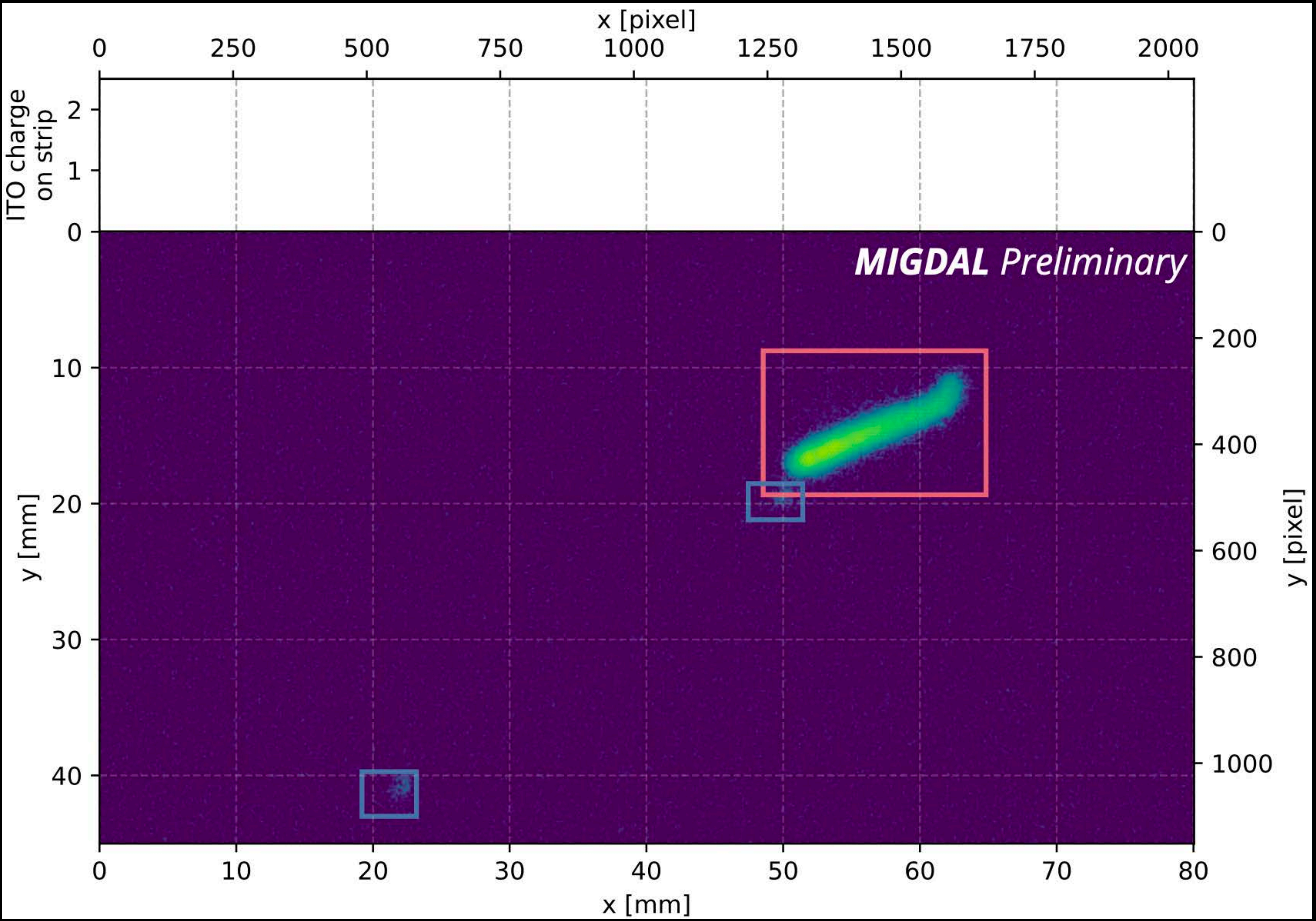


DD-neutrons + ^{55}Fe



MIGDAL-like topology: High energy NR candidate with ER candidate

DD-neutrons + ^{55}Fe



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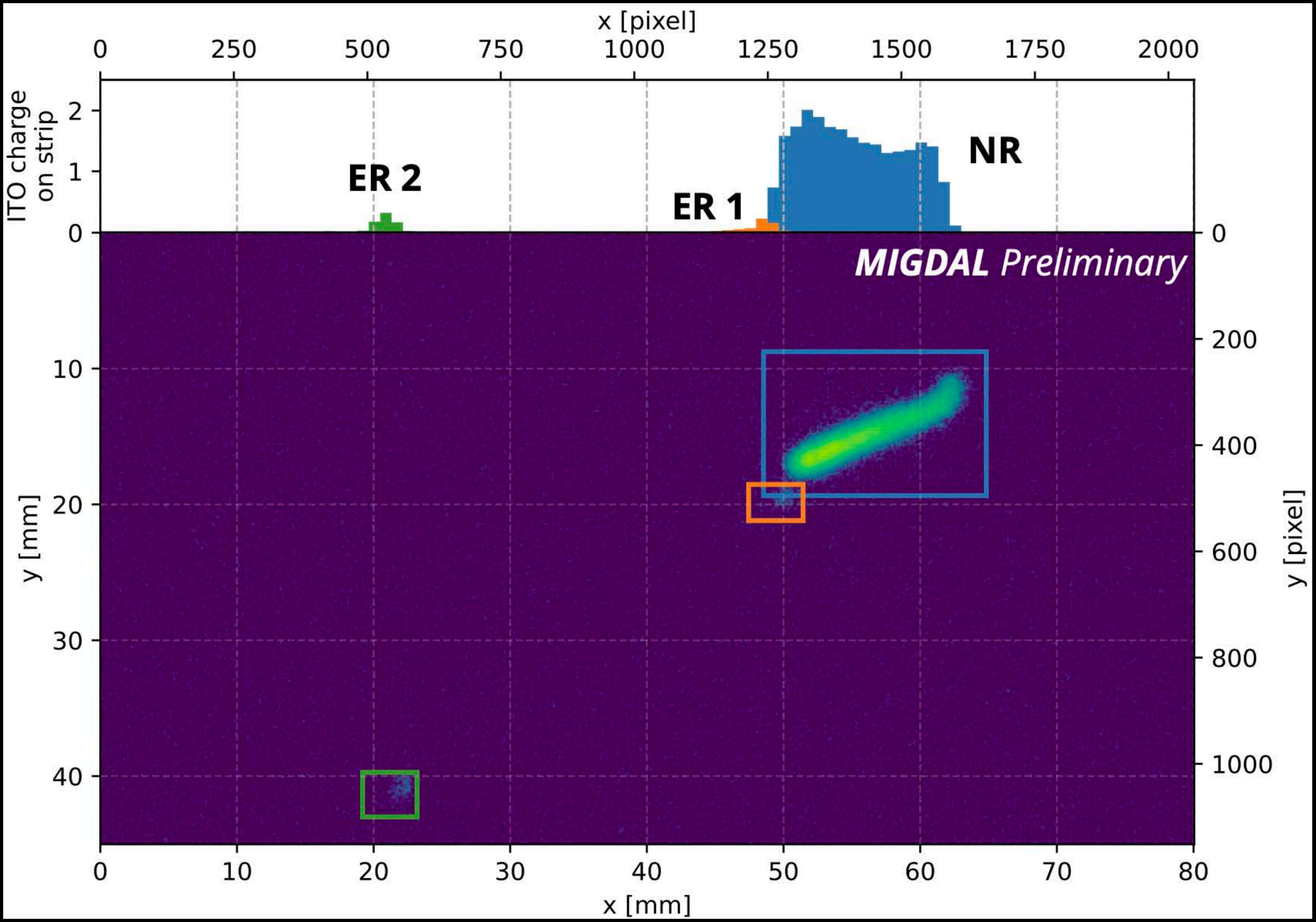
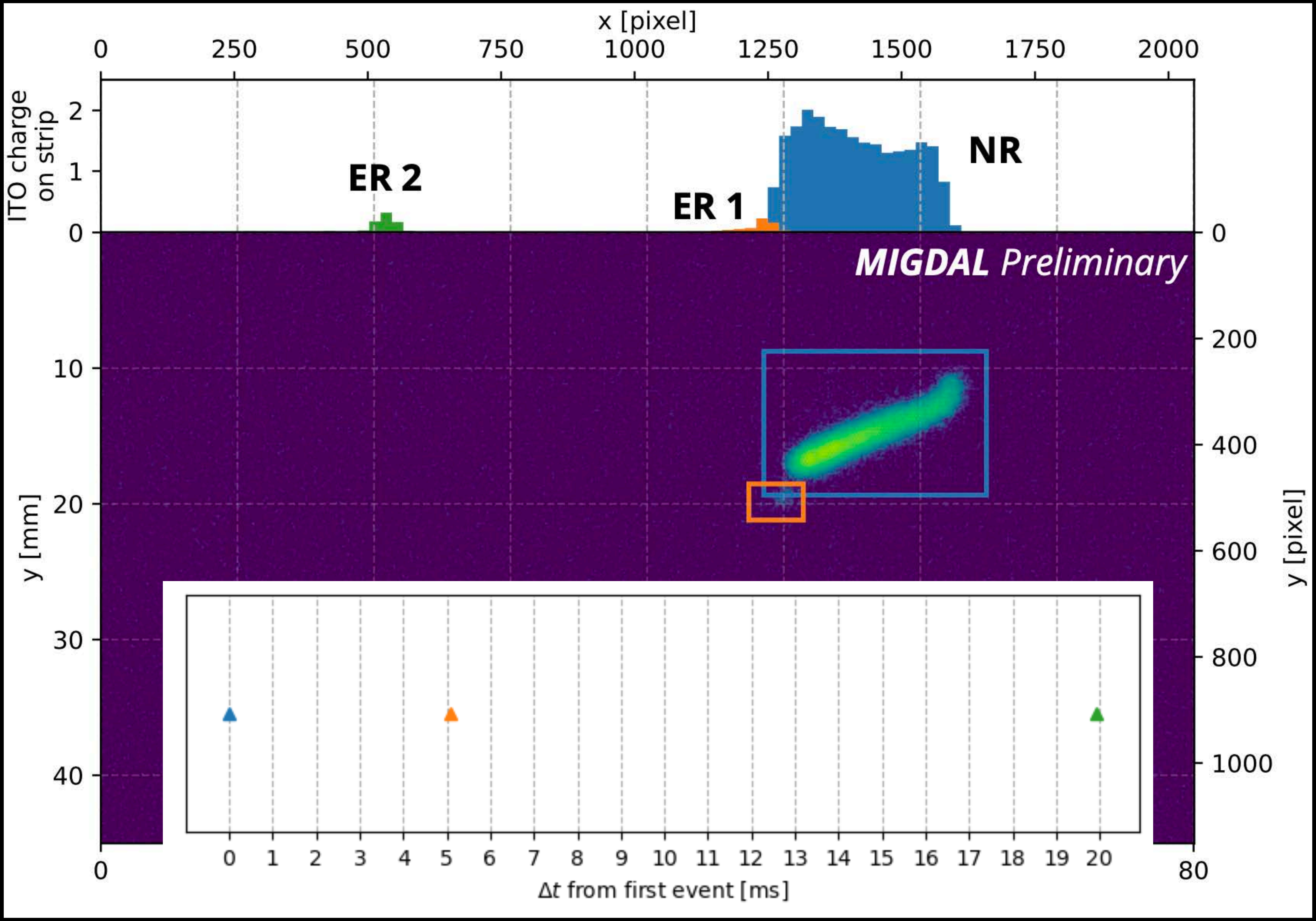


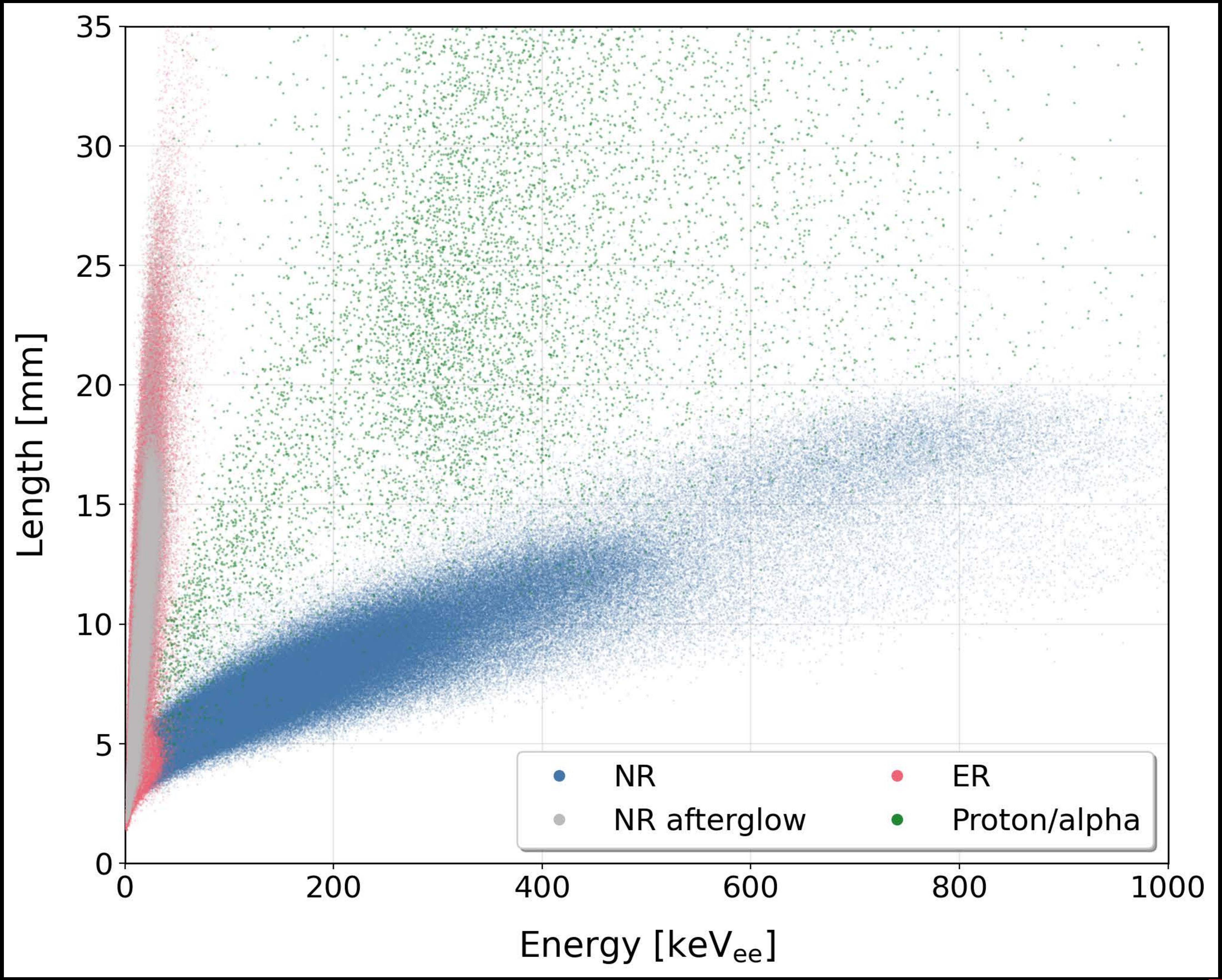
MIGDAL-like topology: High energy NR candidate with ER candidate

DD-neutrons + ^{55}Fe



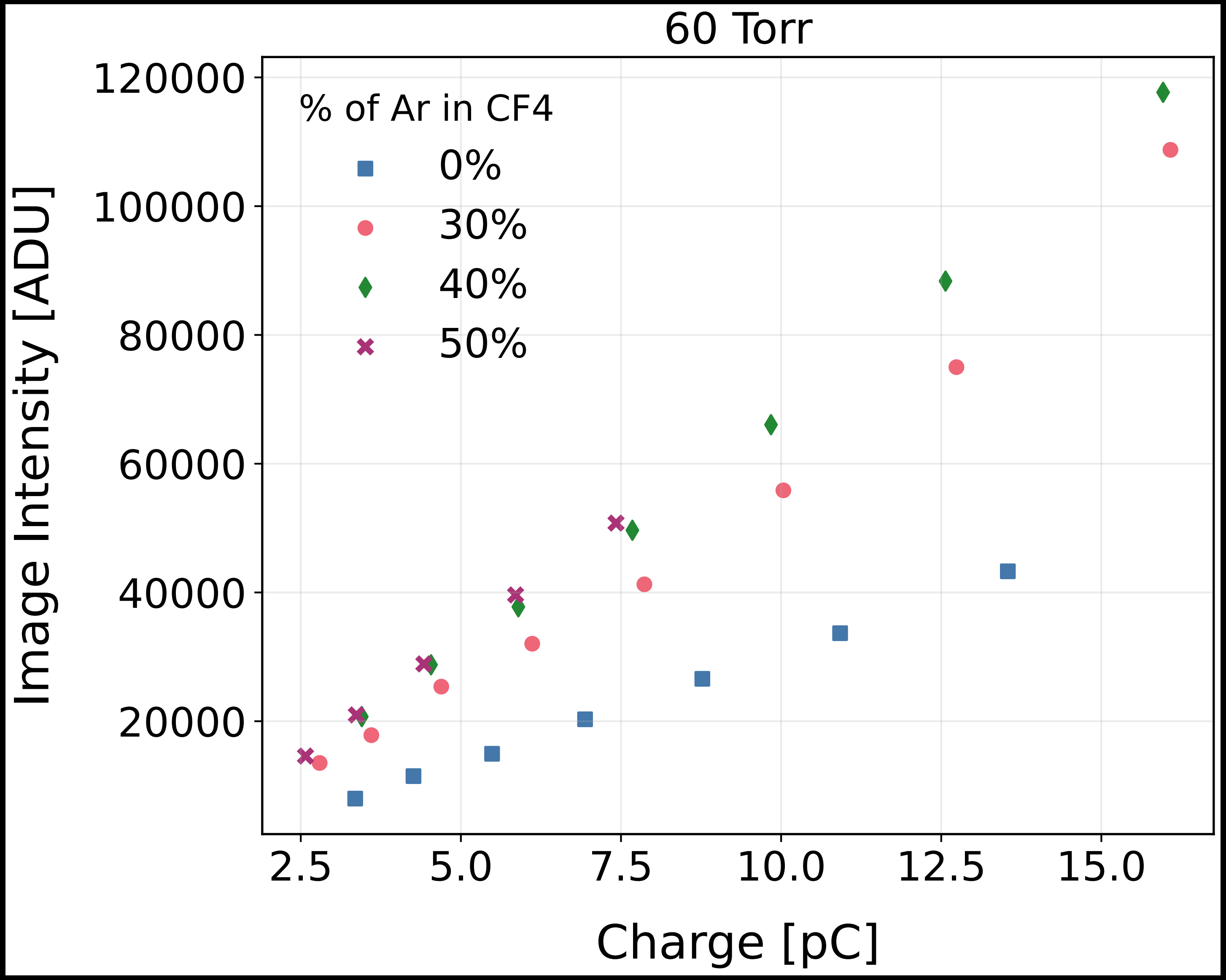
MIGDAL-like topology: High energy NR candidate with ER candidate

Particle identification



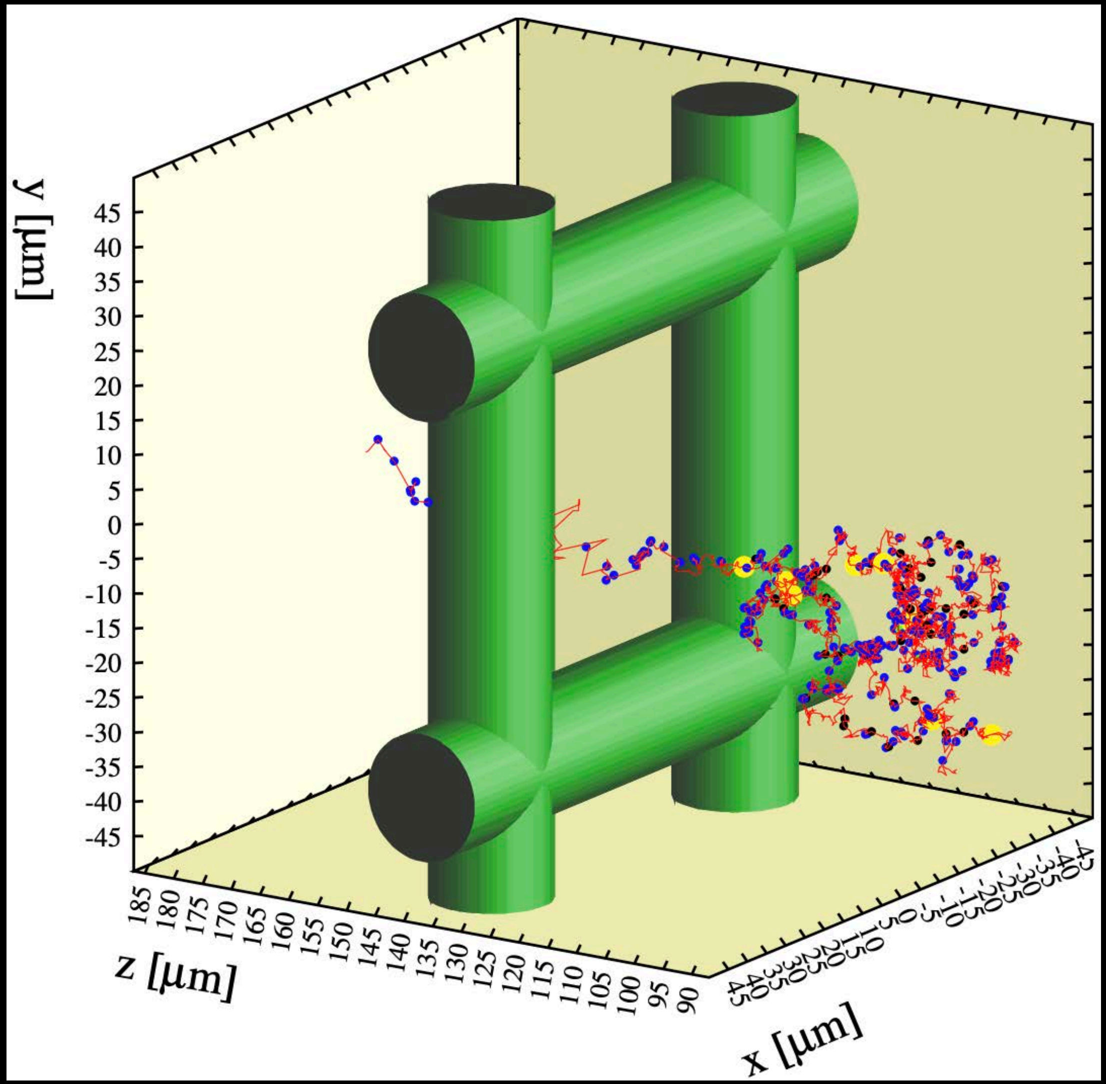
Tests with noble gas mixtures

- As the next step, investigations of the Migdal effect in noble gases will be pursued
- Preliminary results from detector tests with ^{55}Fe in Argon + CF_4 mixtures
  - Enhancement in light yield with Argon
- Operation with exposure to AmBe neutrons

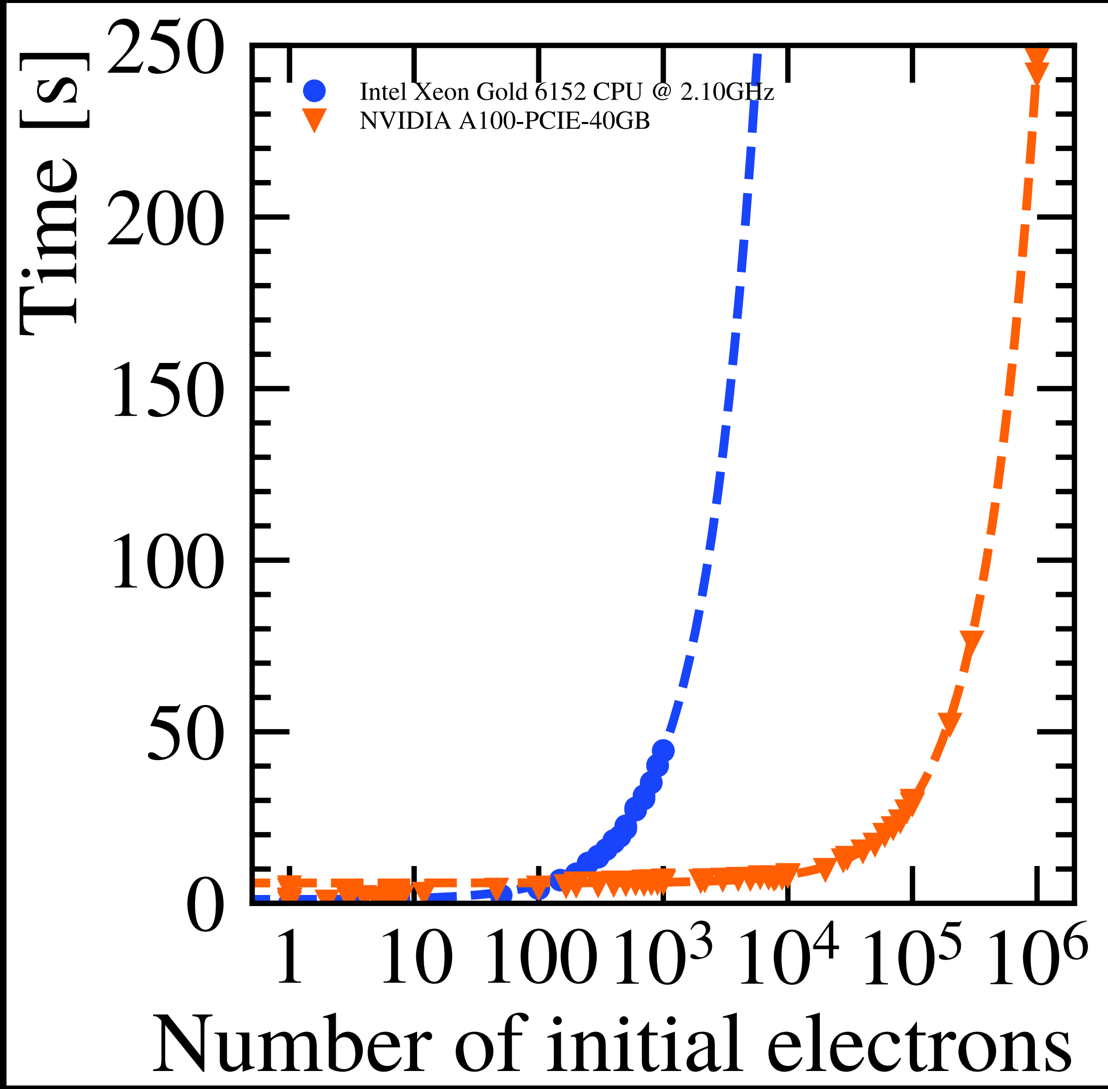


Garfield++ on GPUs

- Garfield++ is industry standard for gaseous detector simulation
- Modern detectors require “microscopic electron tracking” to reproduce observations
- We have now developed a GPU version of the main algorithms of Garfield++
  - Incorporated in the Garfield++ codebase.
- Change between CPU and GPU with a single switch!
  - Available in the Garfield++ repository.



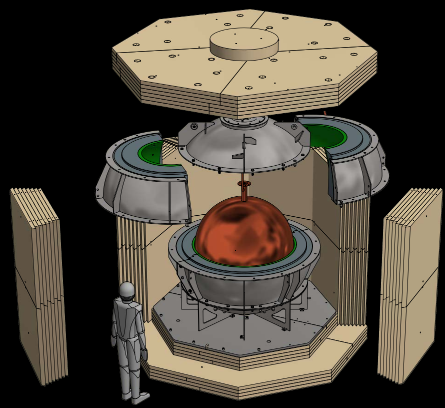
JINST 6 (2011) P06011

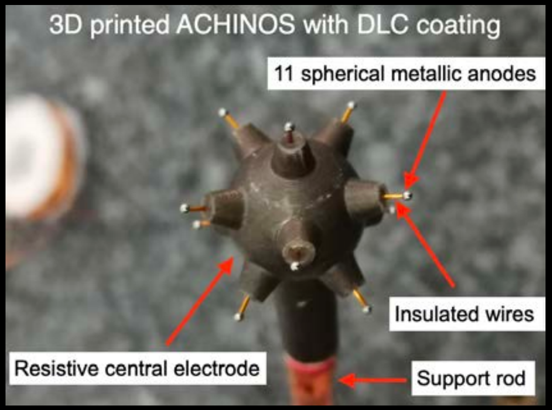


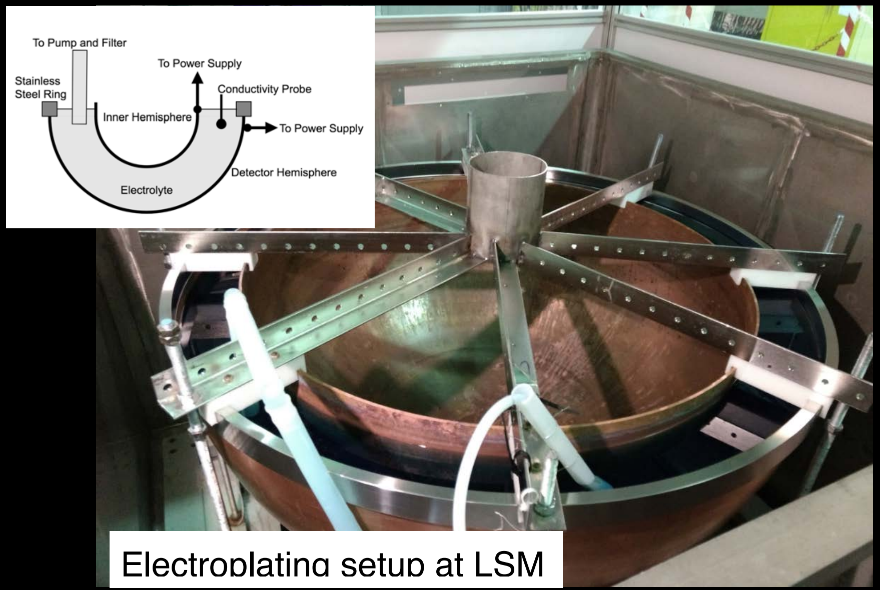
Neep, Nikolopoulos, Slater in preparation

Summary

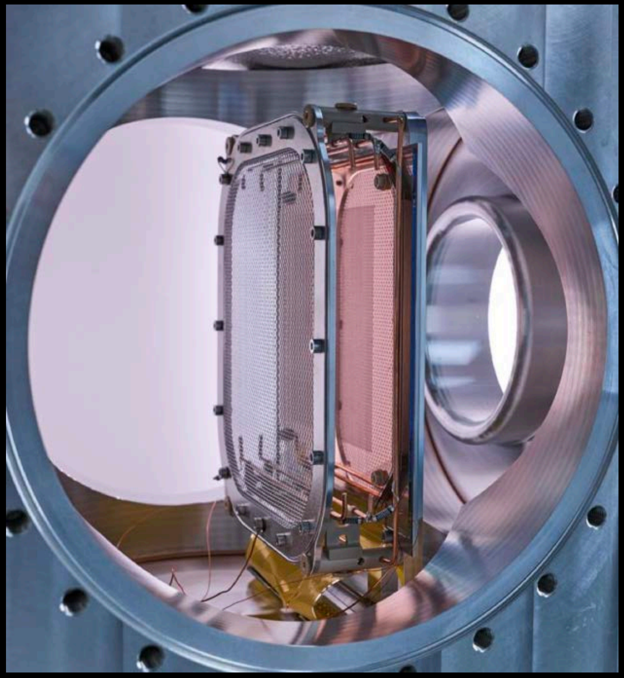
- Particle nature of Dark Matter remains unknown!
  - Sub-GeV mass range is uncharted territory
- Novel methods for light DM searches are pursued
- NEWS-G probes this key mass range
  - Data-taking in SNOLab on-going
  - New detectors planned for the coming years
  - Many physics opportunities
- MIGDAL is aiming to demonstrate/measure the Migdal effect
  - Two science-runs completed
  - Analysis of collected data on-going
- Exciting physics programme ahead!

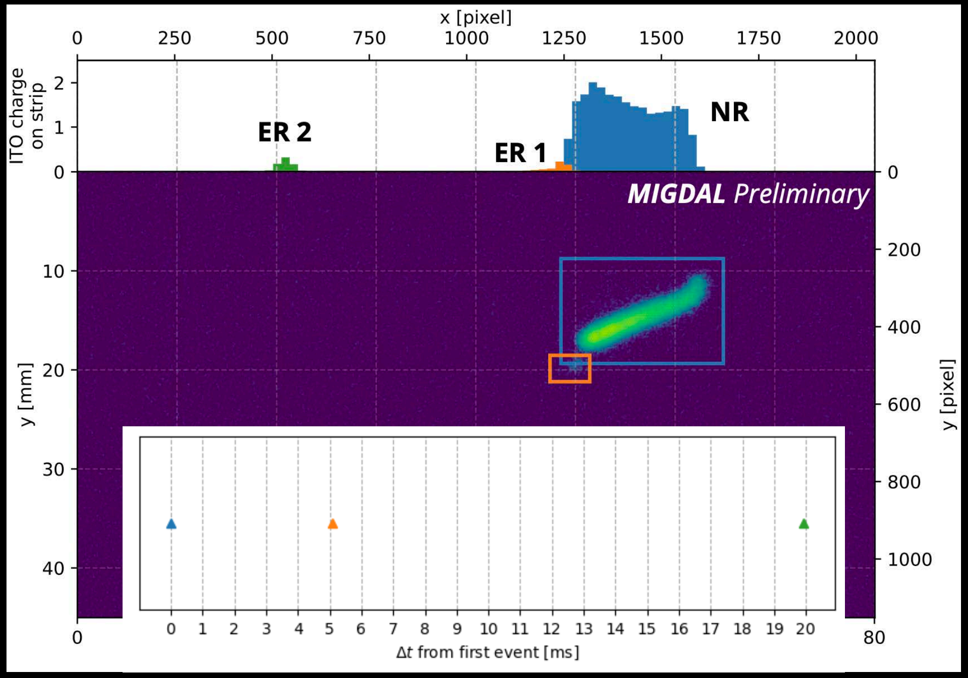


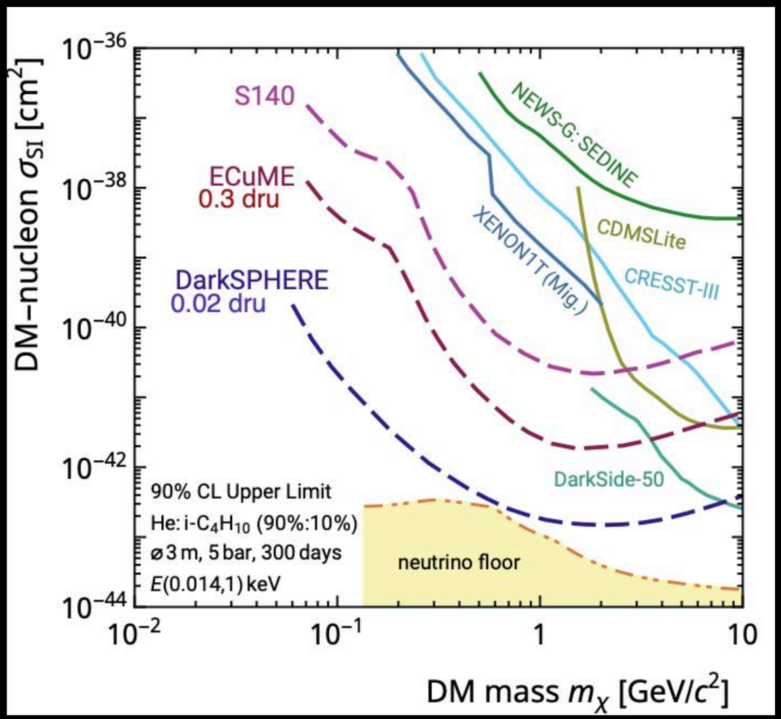


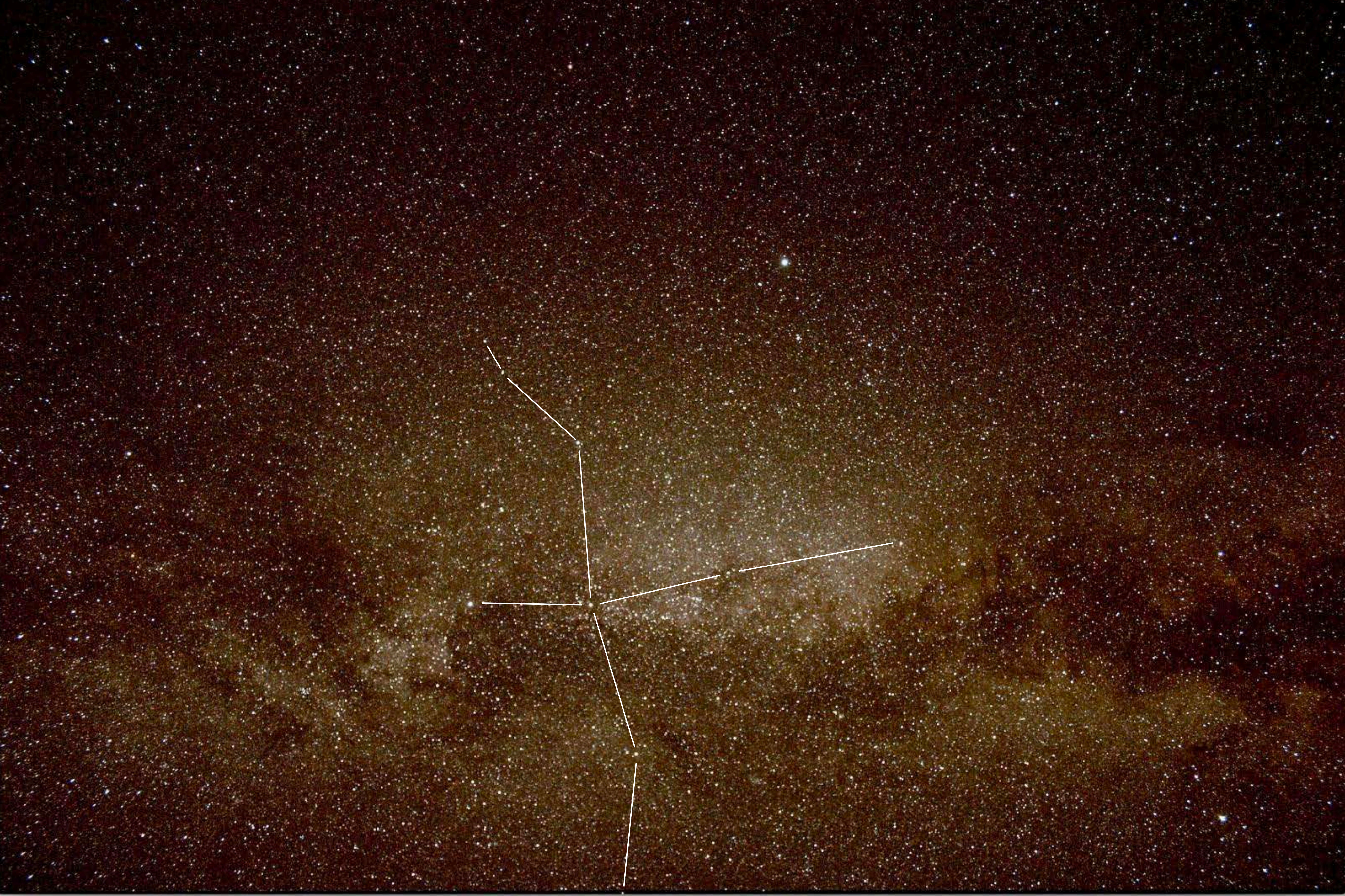


Electroplating setup at LSM









Additional Slides