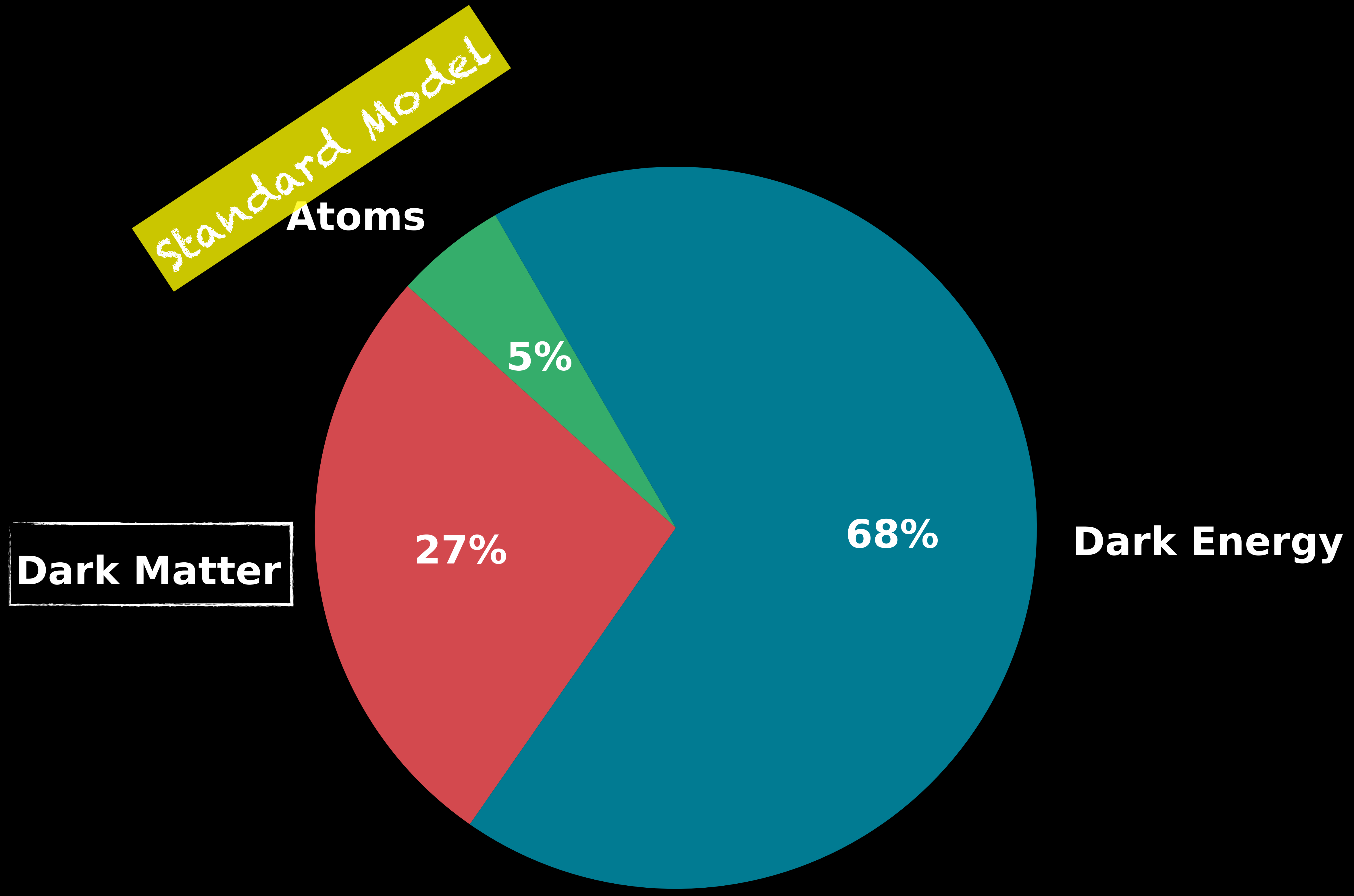
Searches for light Dark Matter with Spherical Proportional Counters

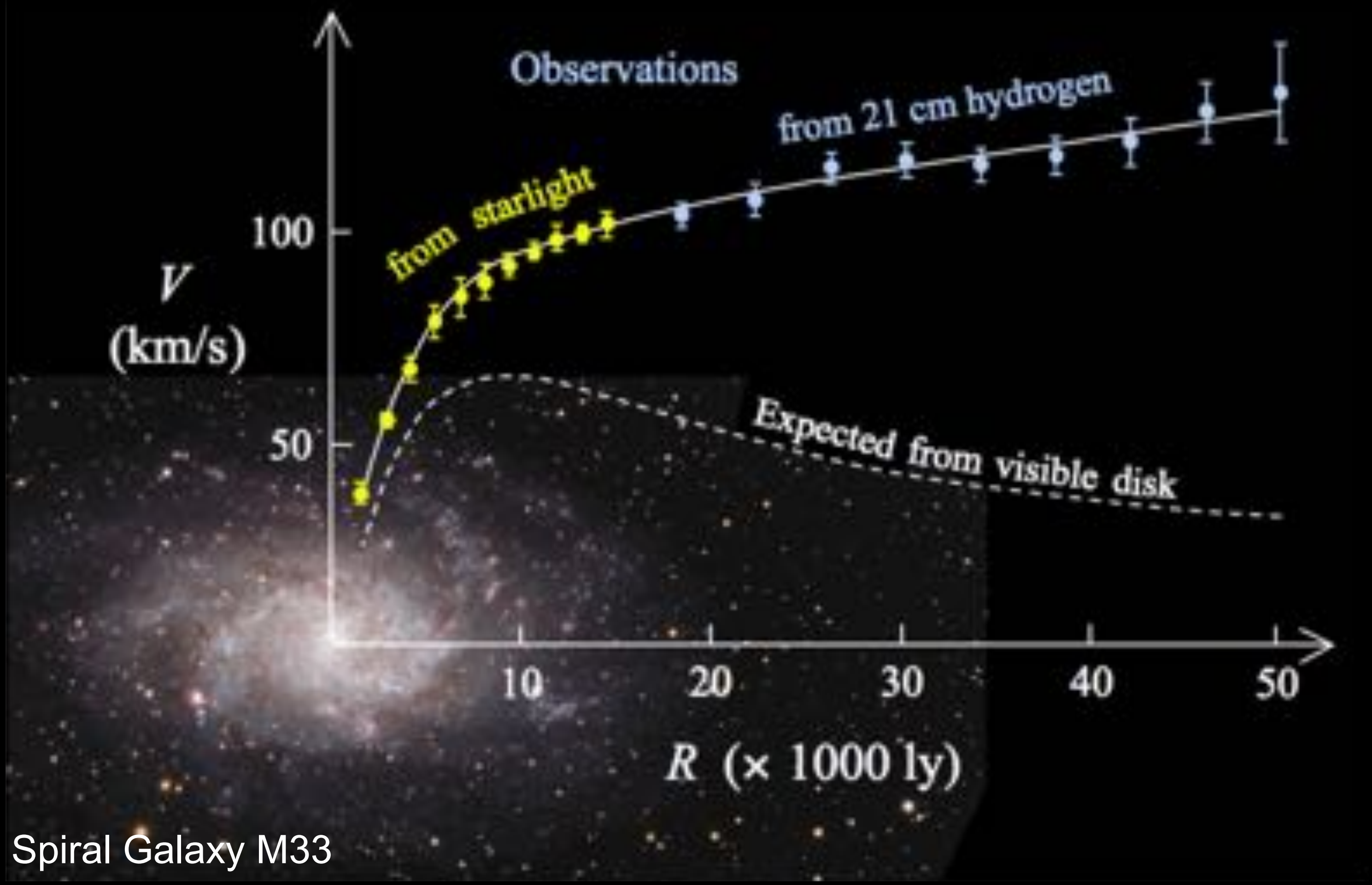
Konstantinos Nikolopoulos
University of Birmingham

ATLAS experiment at CERN

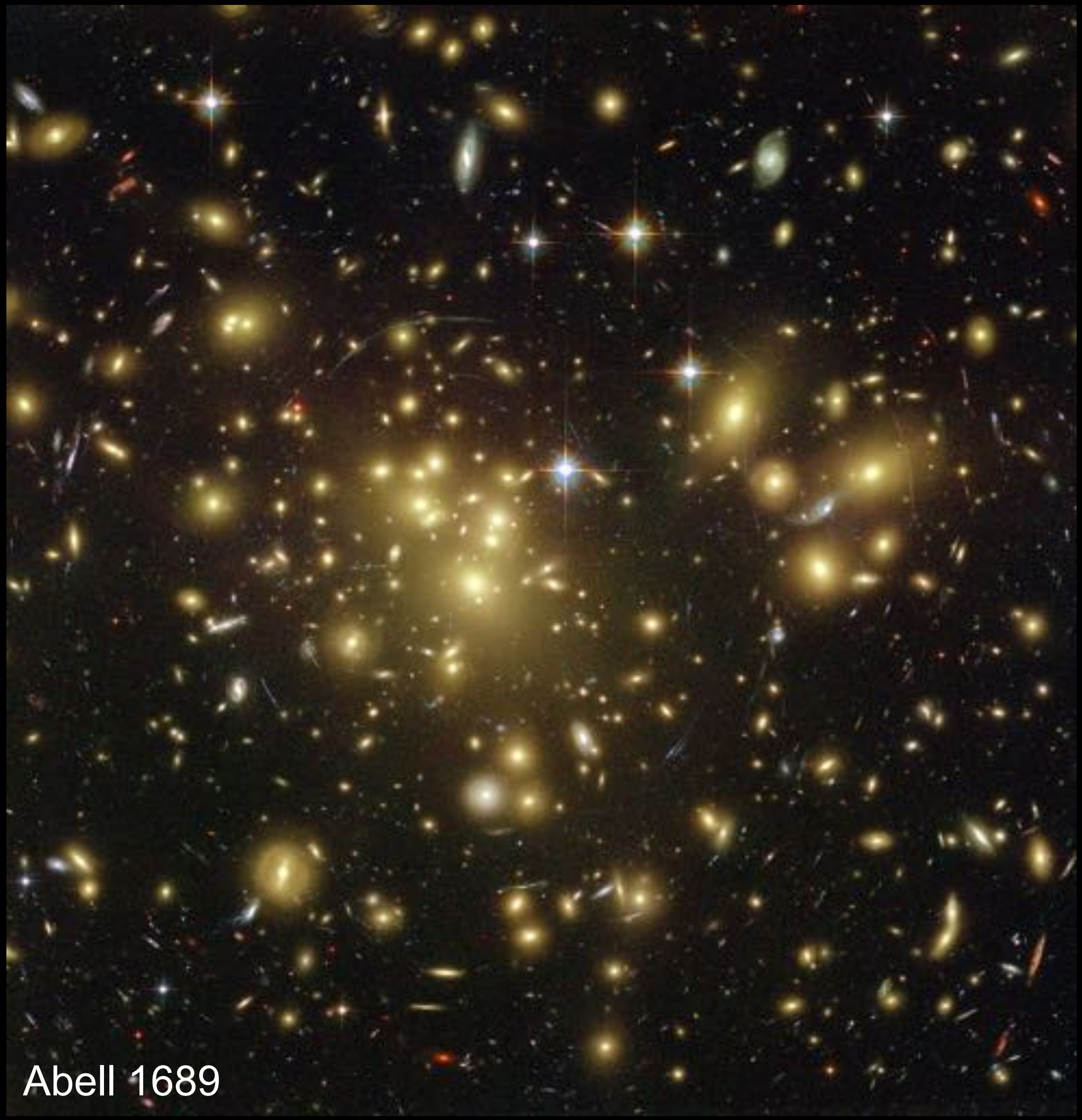
Particle Physics Seminar
March 13th, 2023, IJCLab, Orsay, Paris

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement 714893-ExclusiveHiggs and under Marie Skłodowska-Curie agreement 841261-DarkSphere, 895168-neutronSPHERE, 101026519-GaGARin

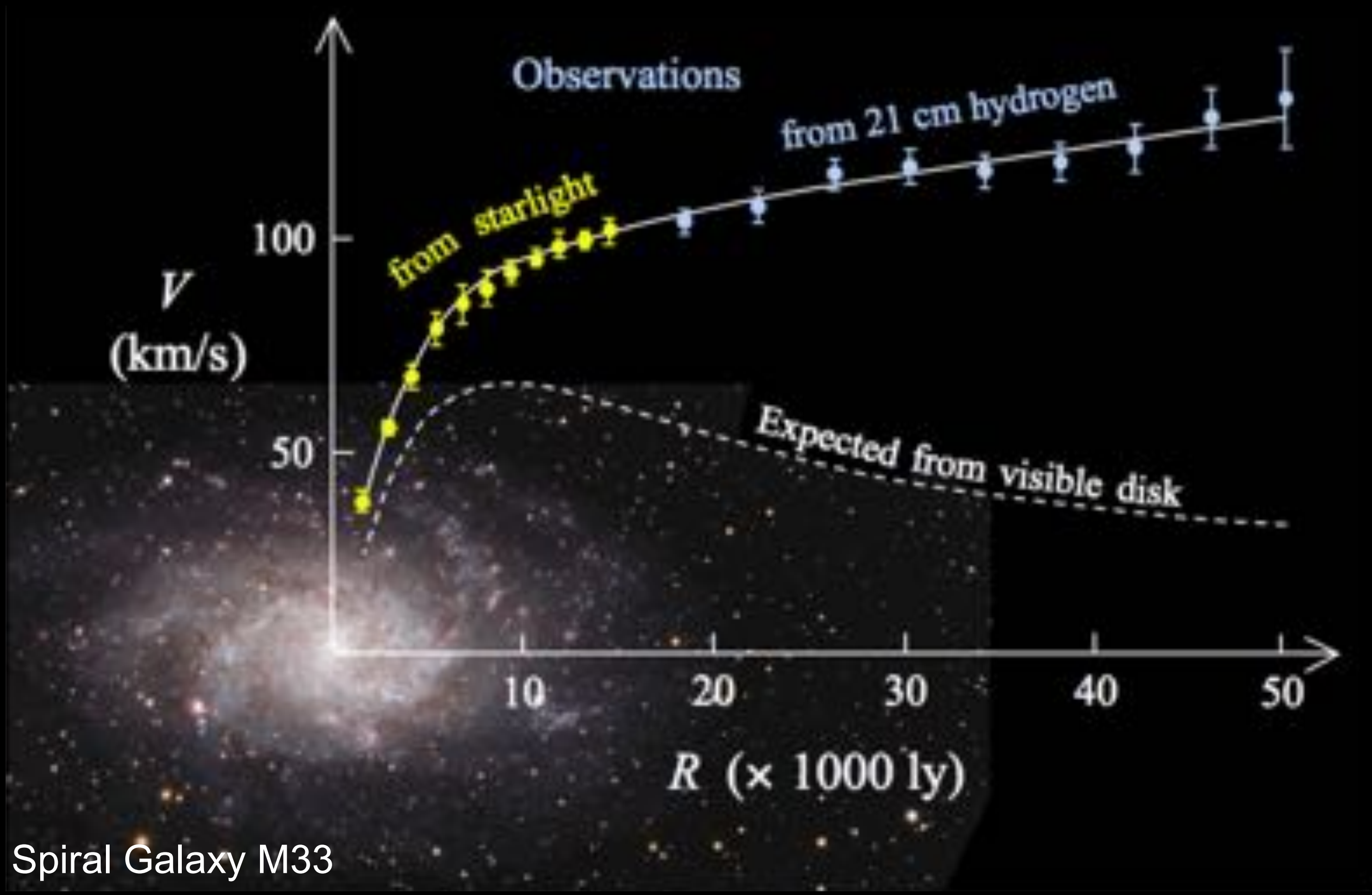

Standard Model
Atoms
5%
Dark Matter
27%
68%
Dark Energy

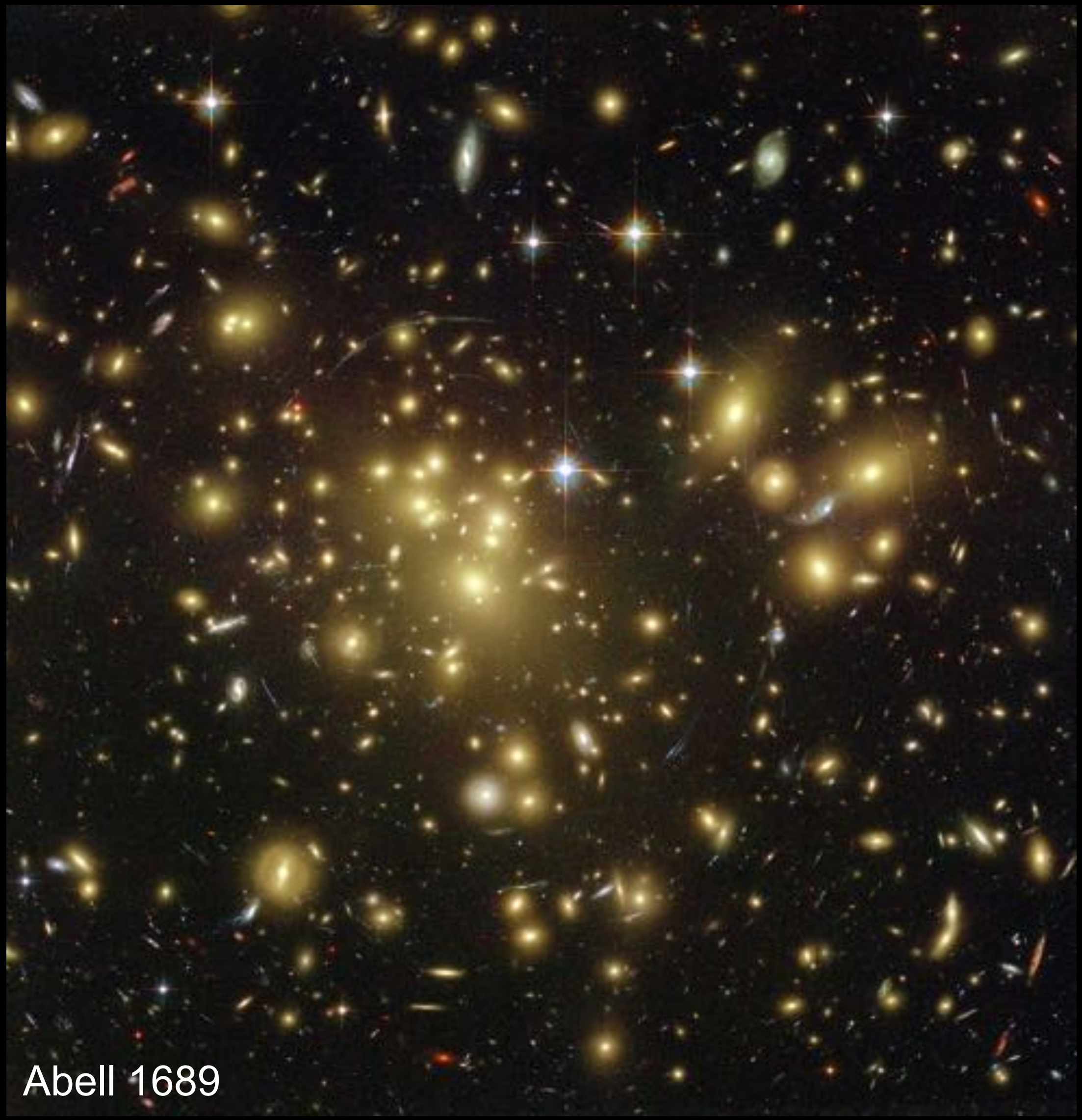


Spiral Galaxy M33


Abell 1689

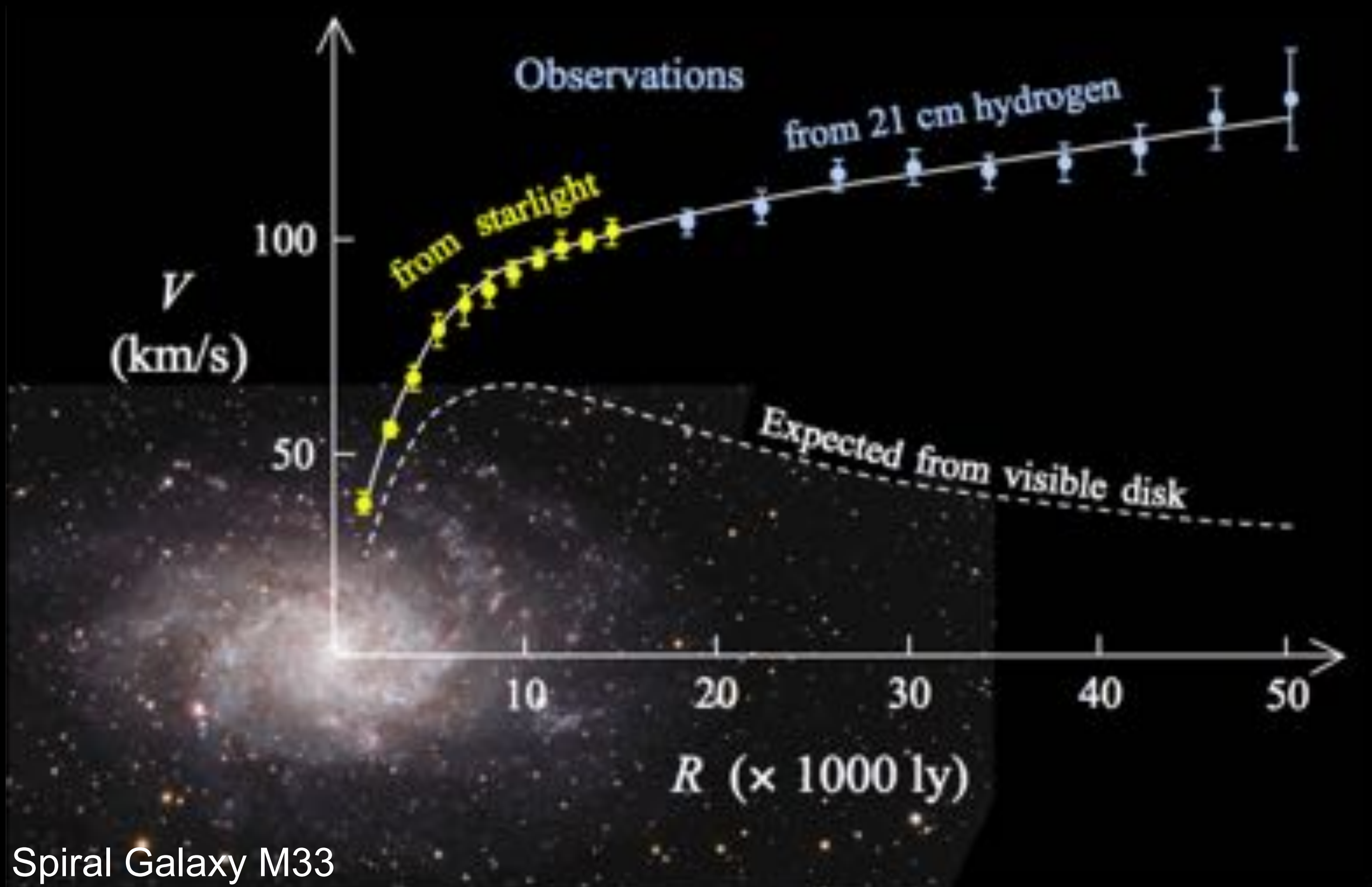
- **Evidence from gravitational interactions over many distance scales**
  - Rotational curves (galaxies and galaxy clusters)
  - Gravitational lensing
  - Cosmology
    - Cosmic microwave background
    - Large scale structure formation
  - Big Bang Nucleosynthesis

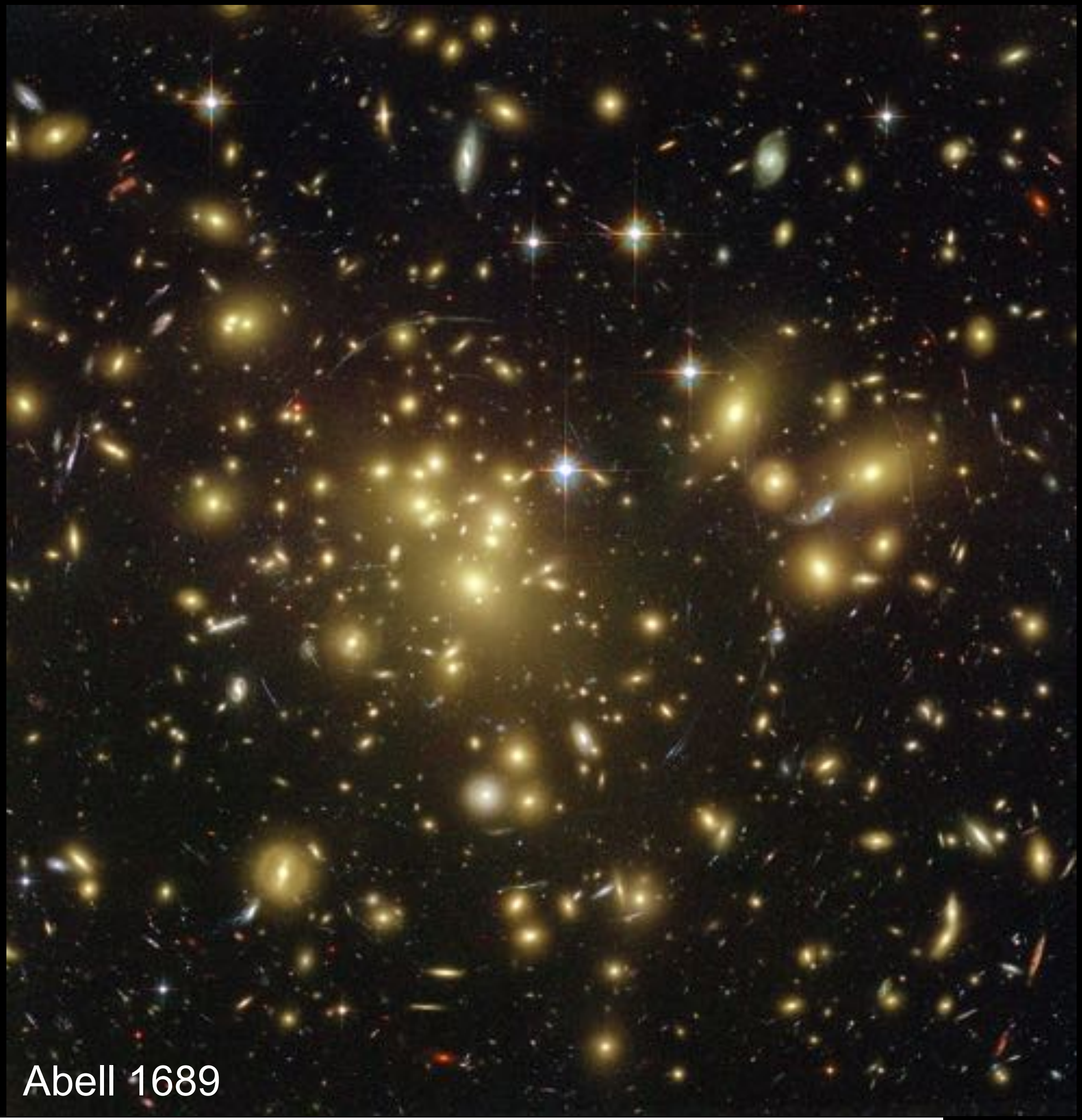




What we know about Dark Matter

- Non-Baryonic
- Mostly "cold"
- Electrically neutral (or milli-charged?)
- "Weakly" interacting
- $\Omega_{DM}h^2=0.120\pm0.001$
- Stable or $\tau_{DM} \gg \tau_u$





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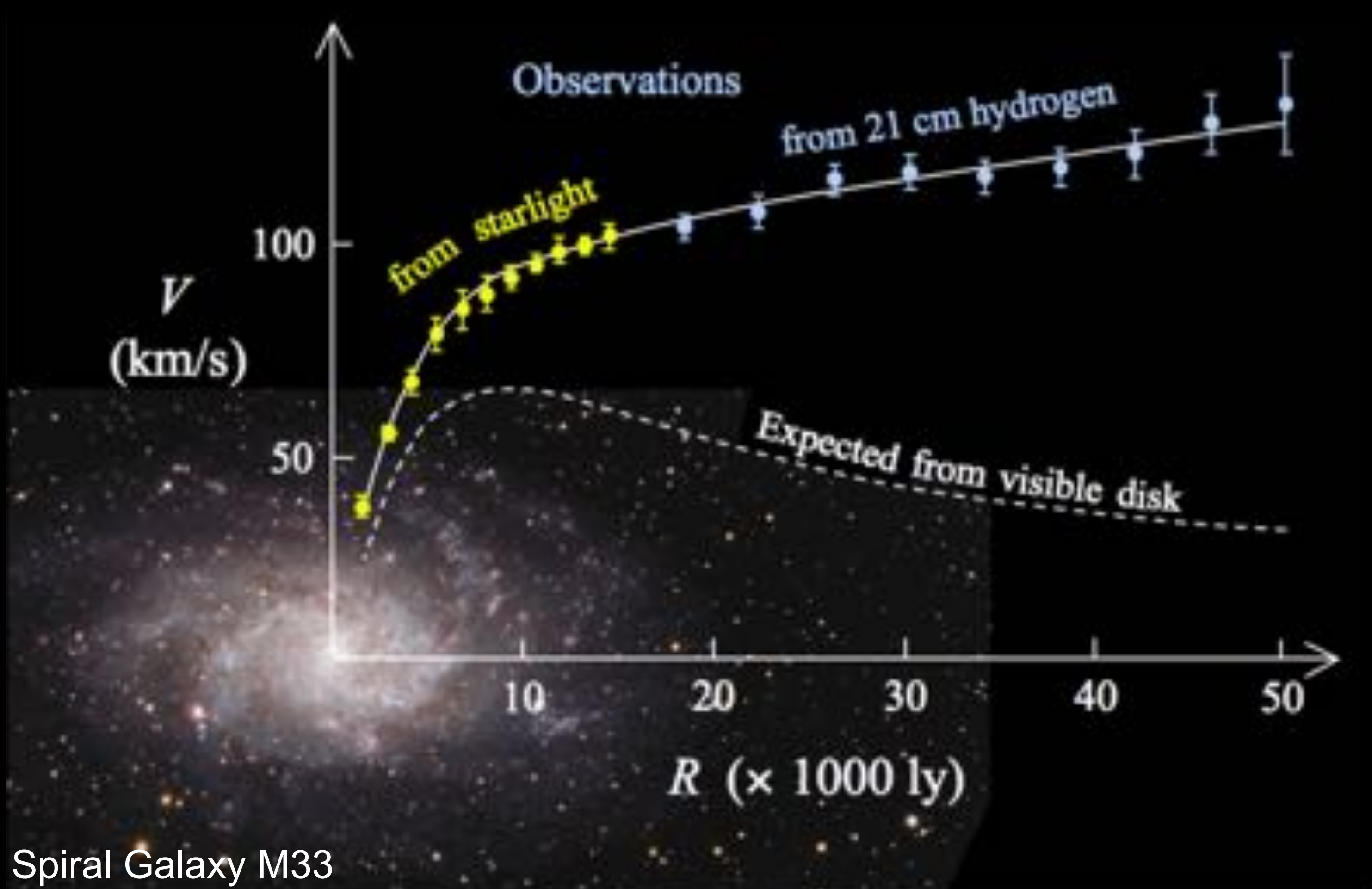
Dark Matter Particle (X^0)

X^0 mass: $m = ?$
X^0 spin: $J = ?$
X^0 parity: $P = ?$
X^0 lifetime: $\tau = ?$
X^0 scattering cross-section on nucleons: ?
X^0 production cross-section in hadron colliders: ?
X^0 self-annihilation cross-section: ?



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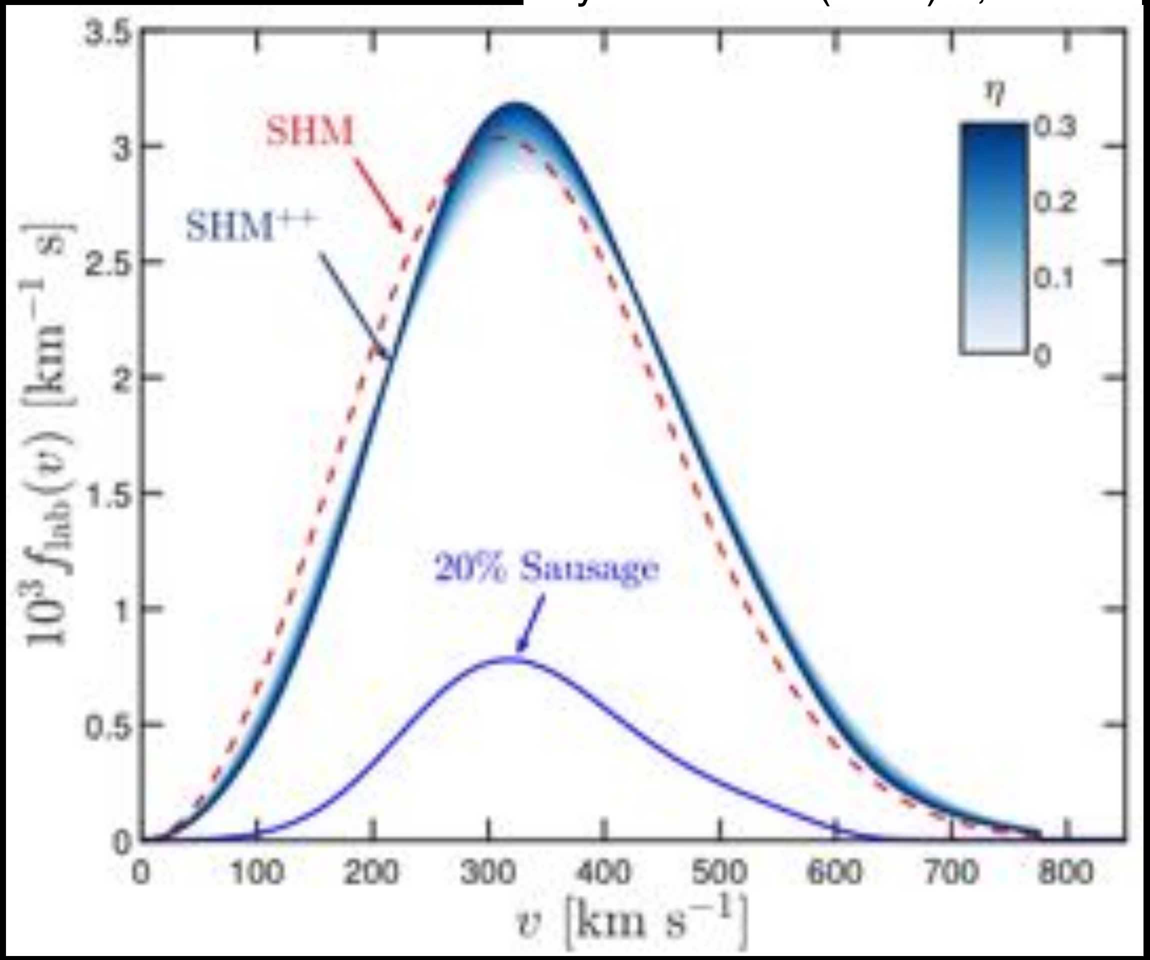
No known particle fits the bill!

- **Standard Halo Model**
  - Spherical and Isotropic
  - Maxwell velocity distribution
  - No substructure
- **Locally**
  - DM density is $\rho \sim 0.3\text{-}0.4$ GeV cm^{-3}
  - Solar system travelling through “DM Wind”
  - Flux: $107/m_\chi$ GeV $cm^{-2}s^{-1}$

Phys.Rev.D 99 (2019) 2, 023012



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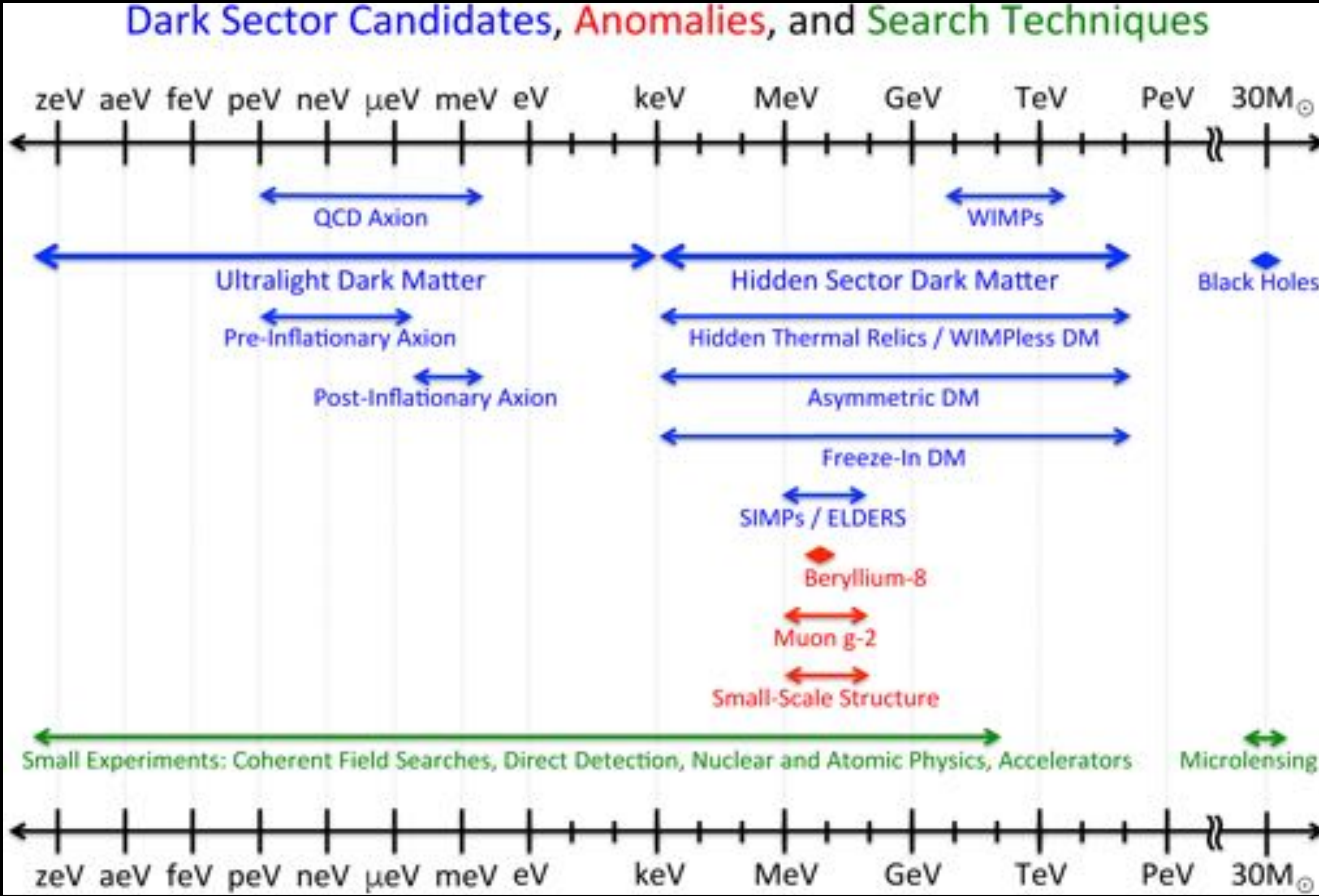
Wide field of possibilities!



Cosmic visions
arXiv:1707.04591

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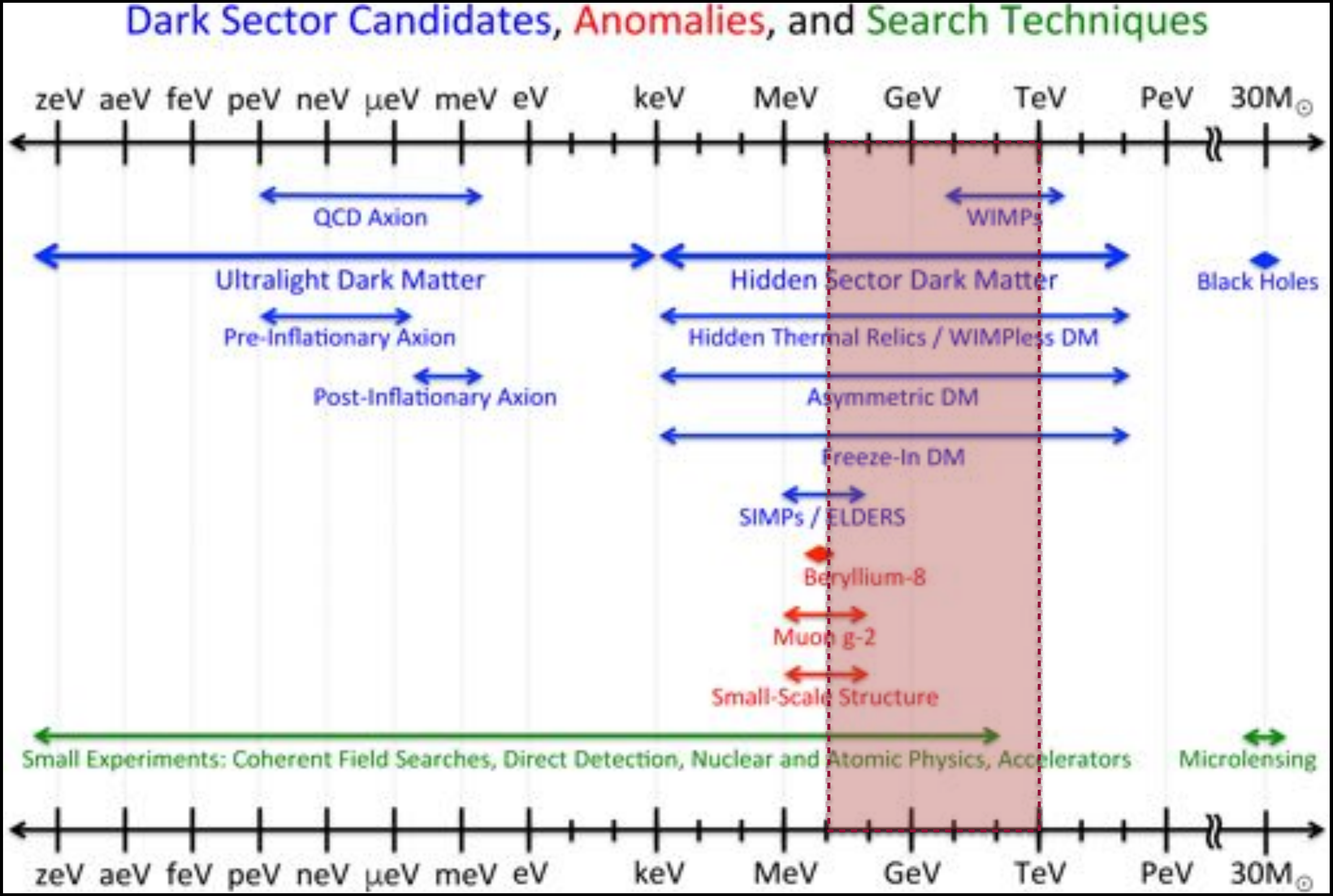

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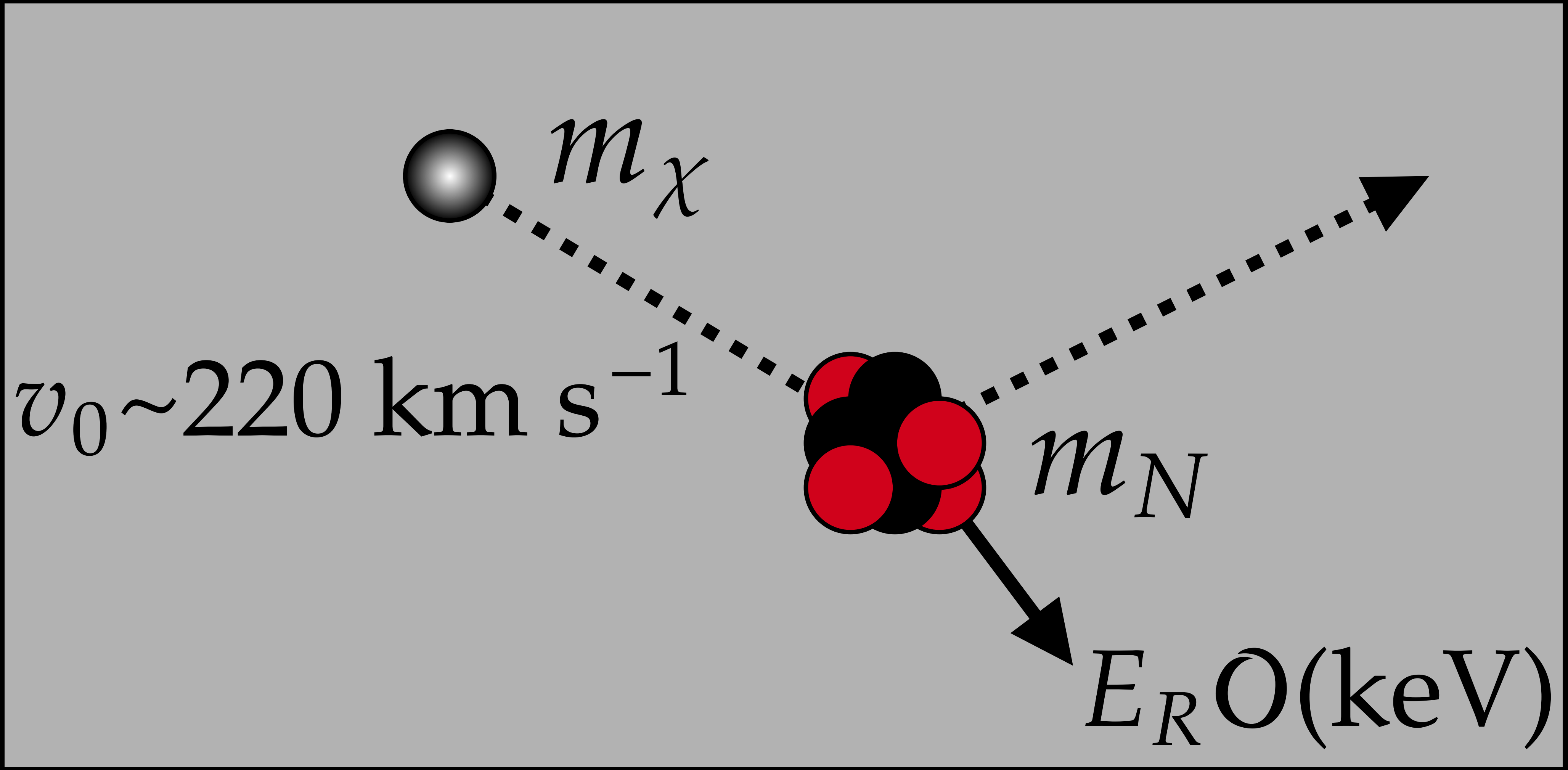
Direct Dark Matter detection



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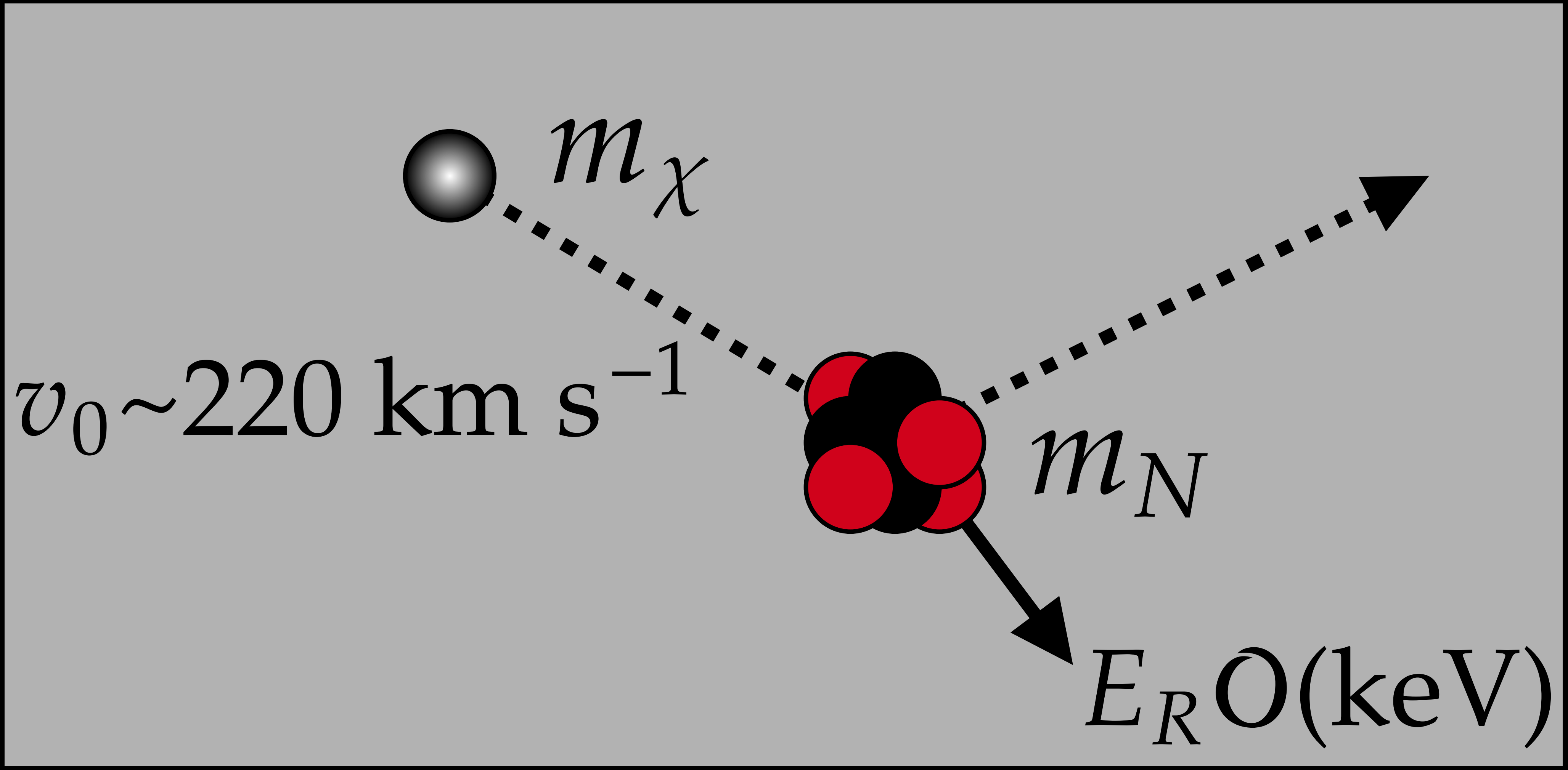
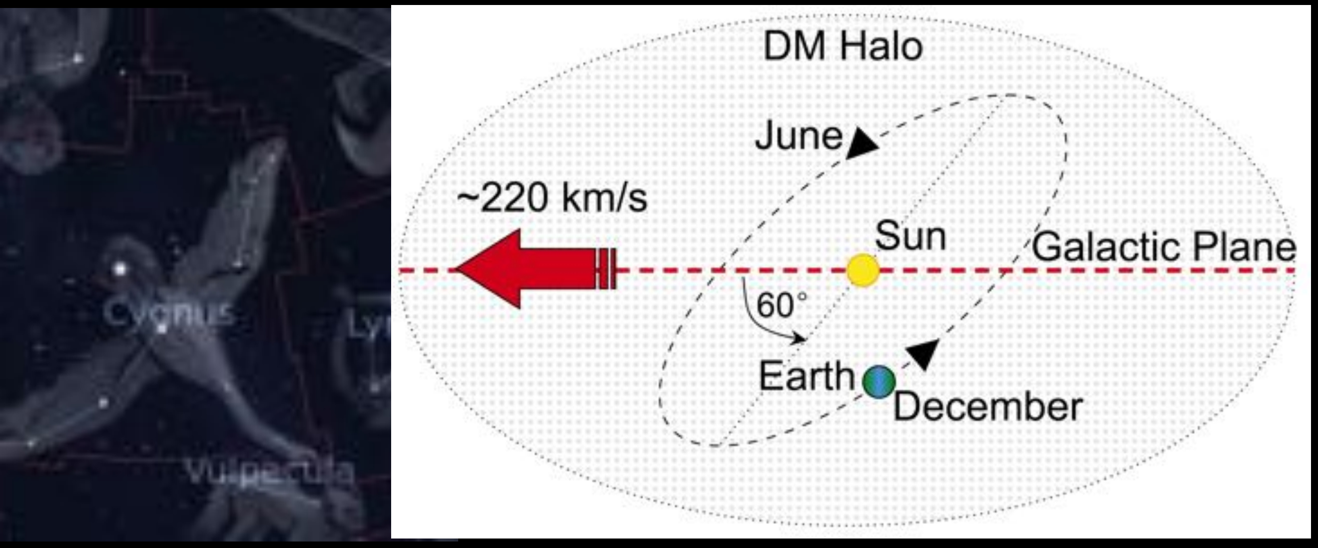
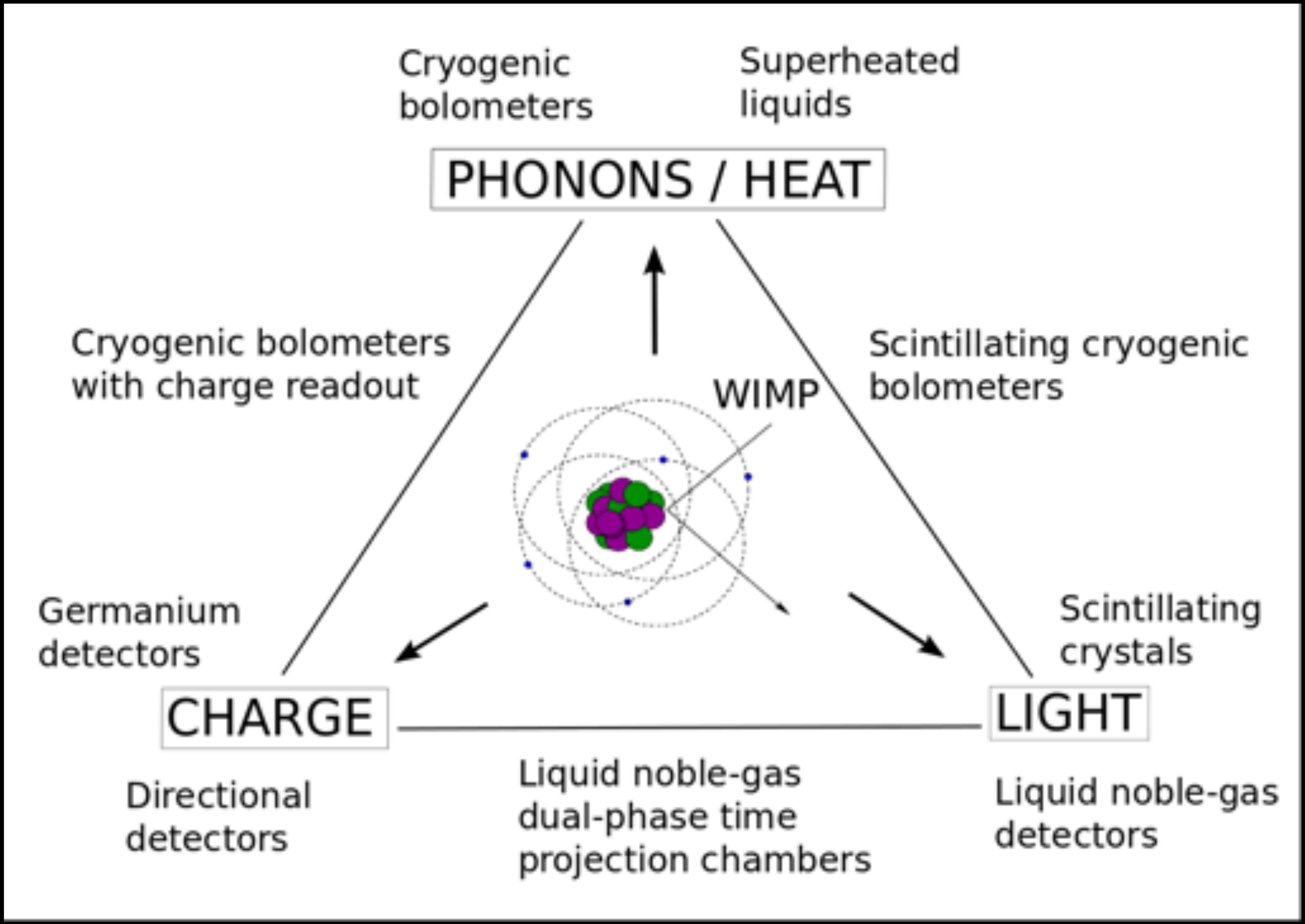




- Handles to confirm possible signal
  - Recoil energy distribution
  - Seasonal flux variation
    - DM velocity is season dependent
  - Directional detection
    - DM signal should point to Cygnus

Direct Detection Signals



J.Phys. G43 (2016) 013001

- Recoiling nucleus can deposit energy in several forms
- Experiments sensitive to one or more of these deposits
  - Multiple signals can be used for background suppression

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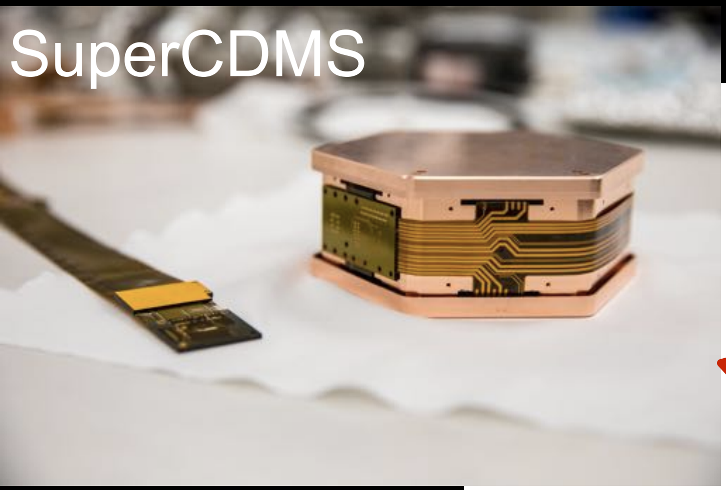

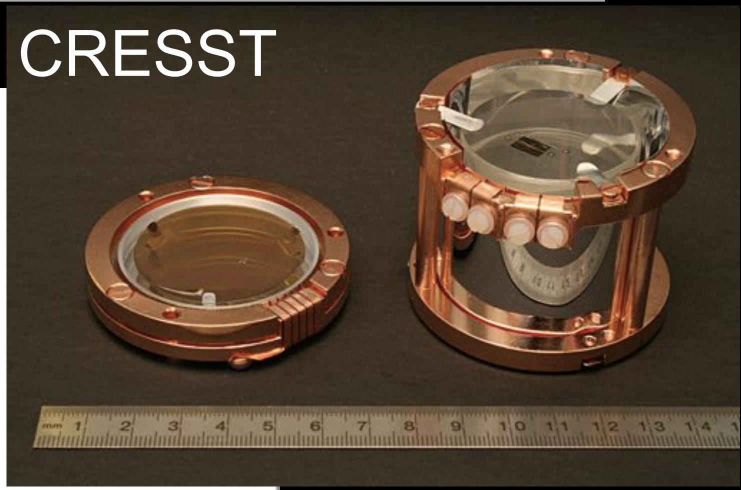

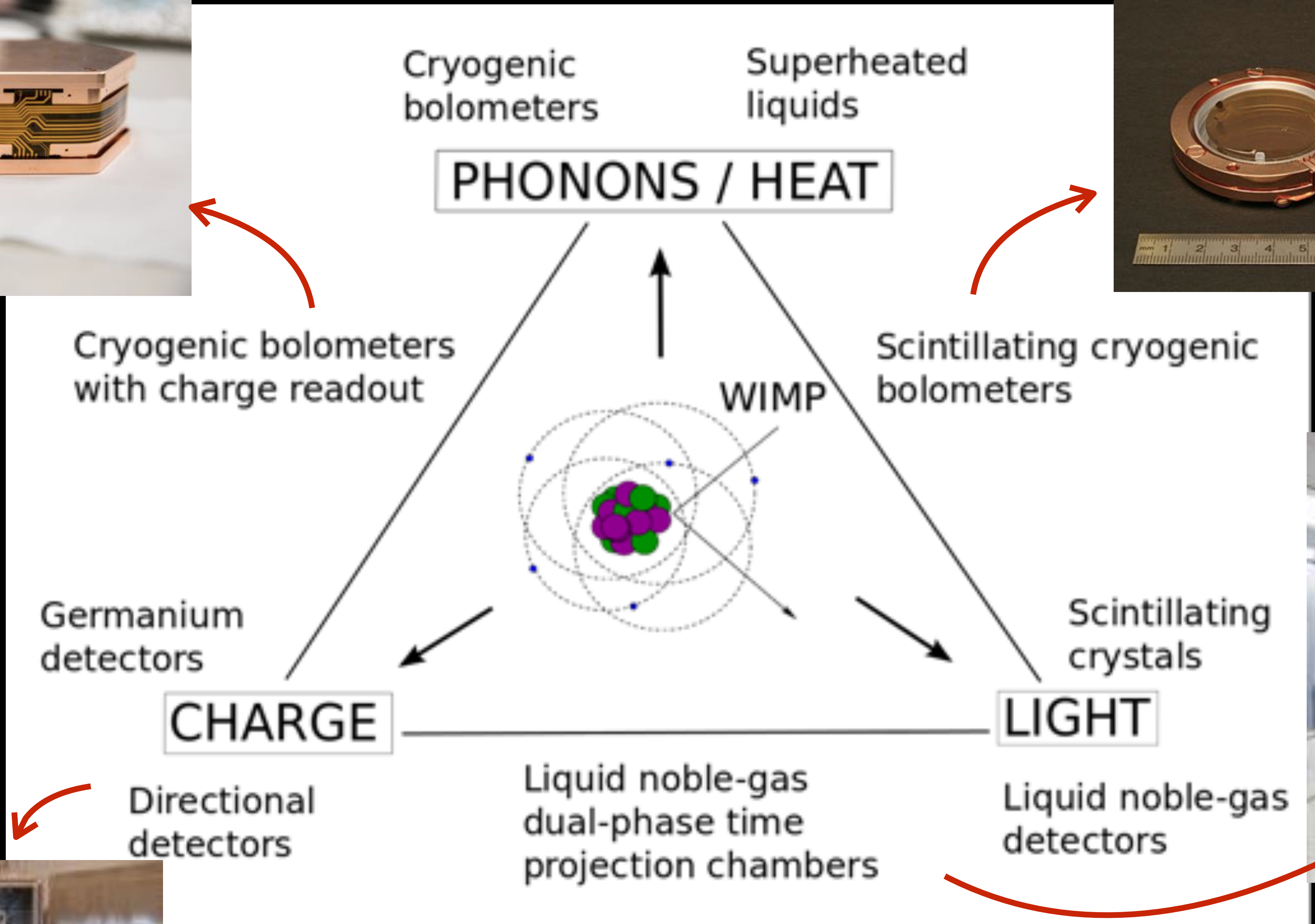

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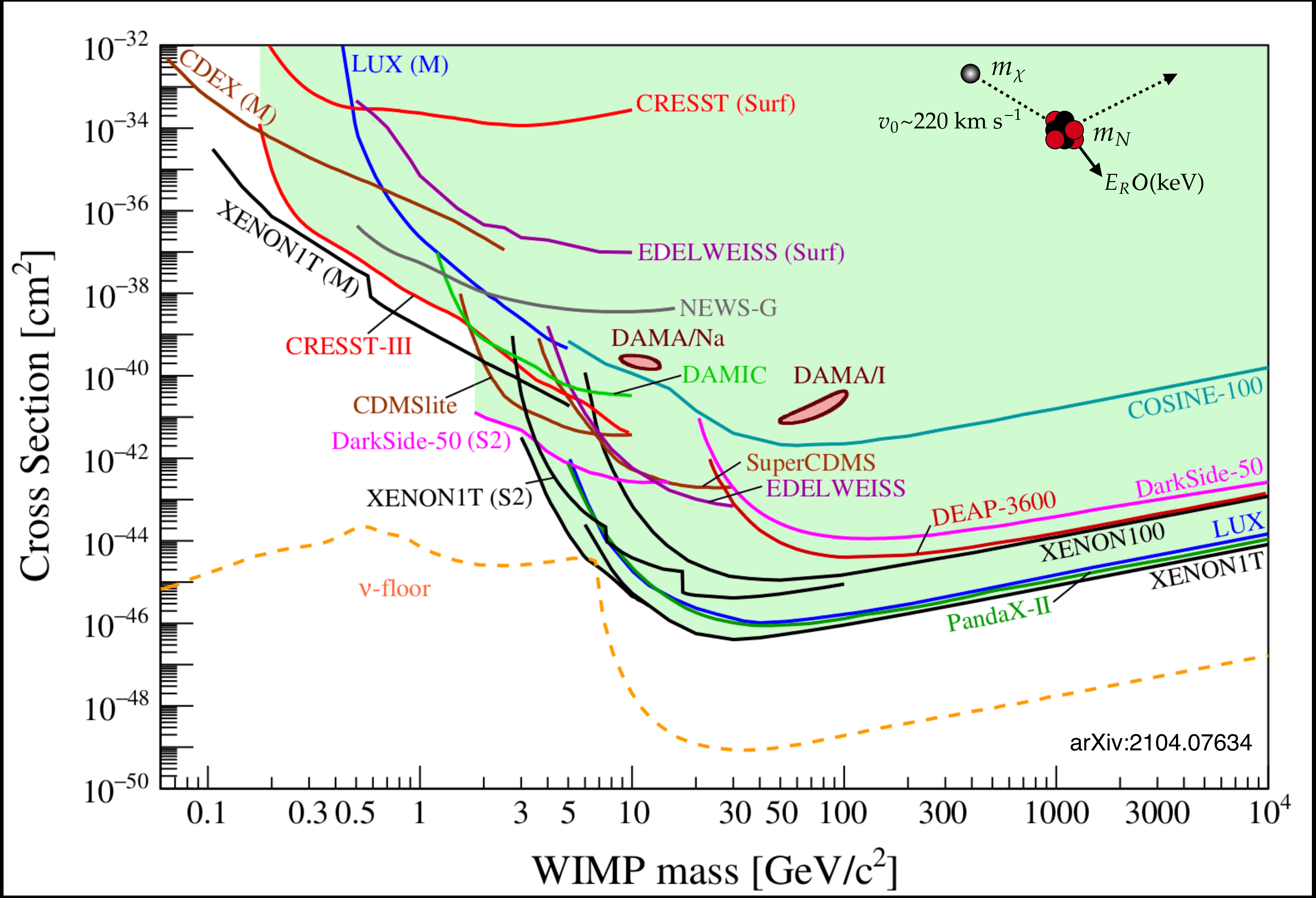
Landscape of Direct Detection searches



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

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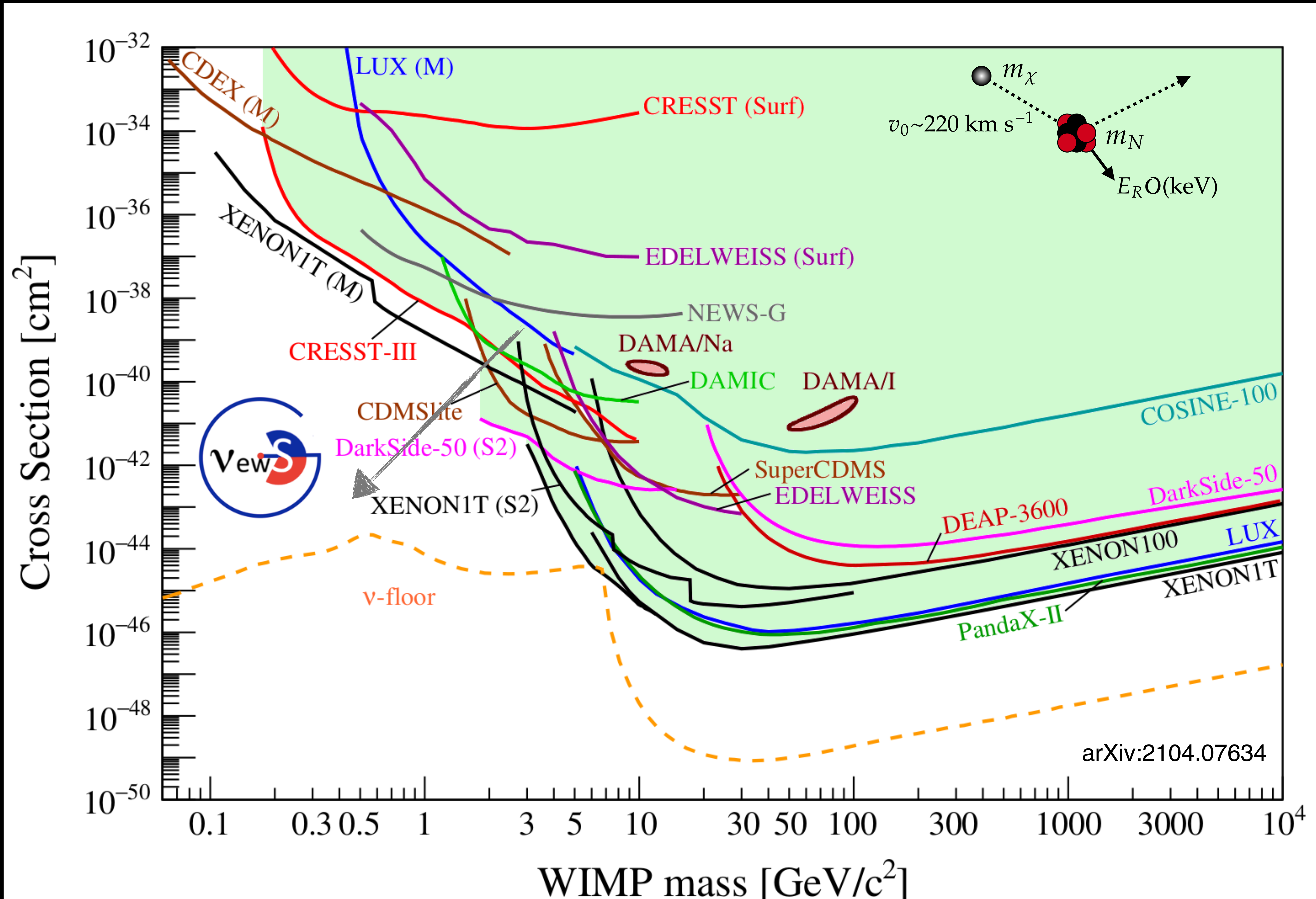

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NEWS-G

Light Dark Matter searches with Spherical Proportional Counters

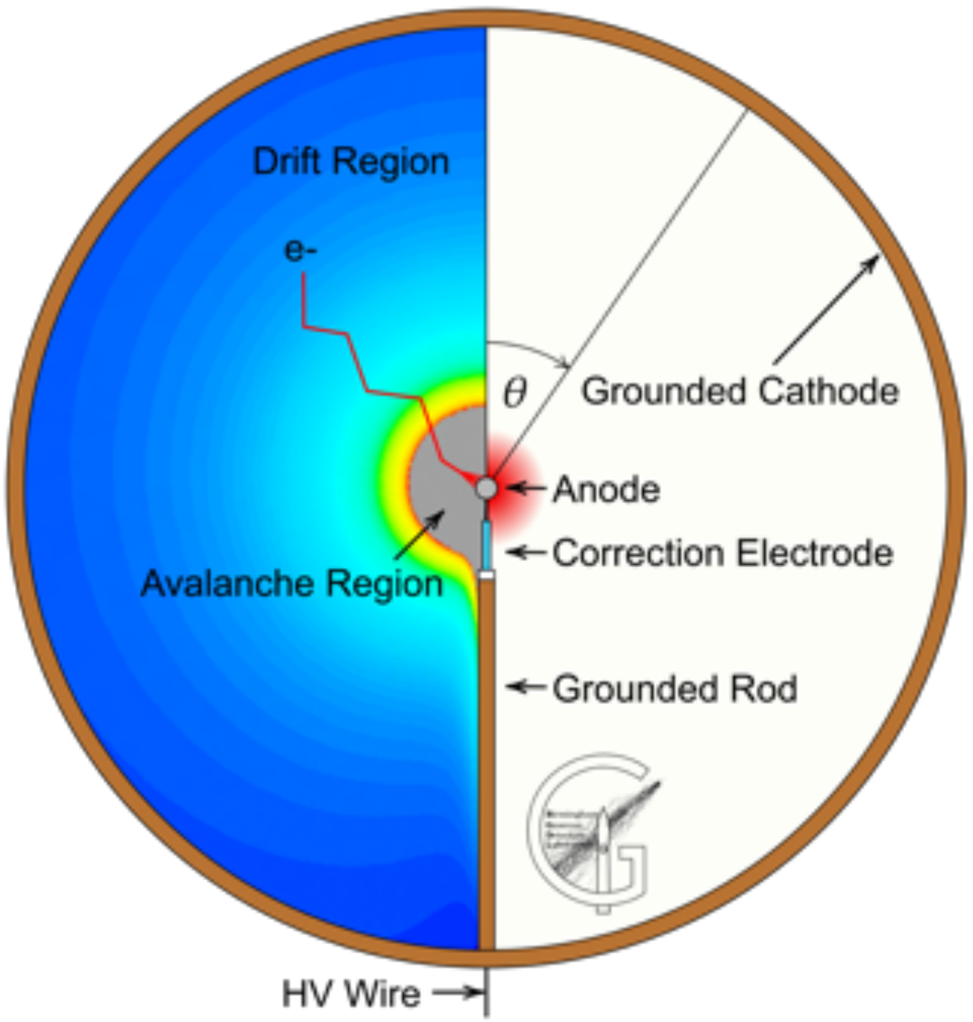
New Experiment With Spheres - Gas

11th collaboration meeting, August 2022

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

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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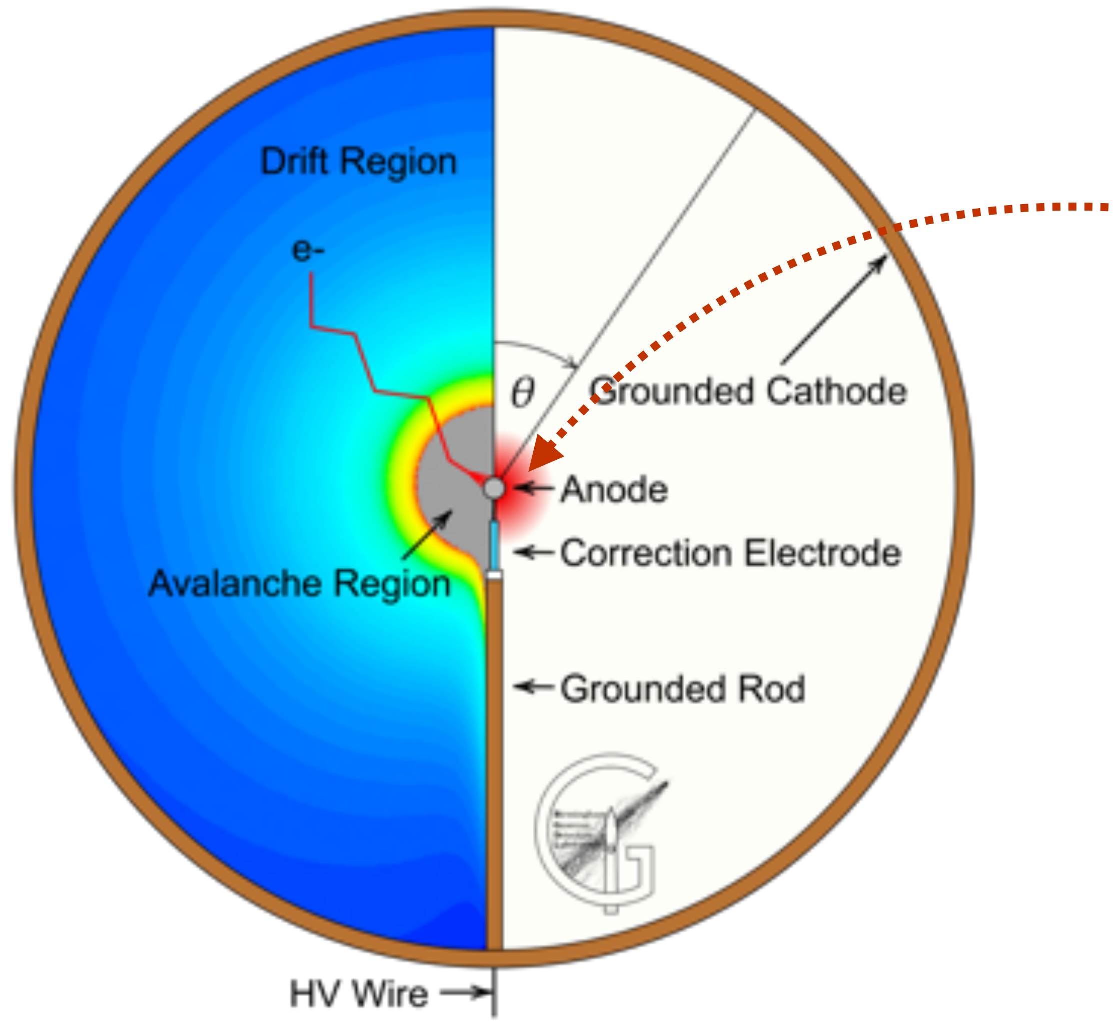

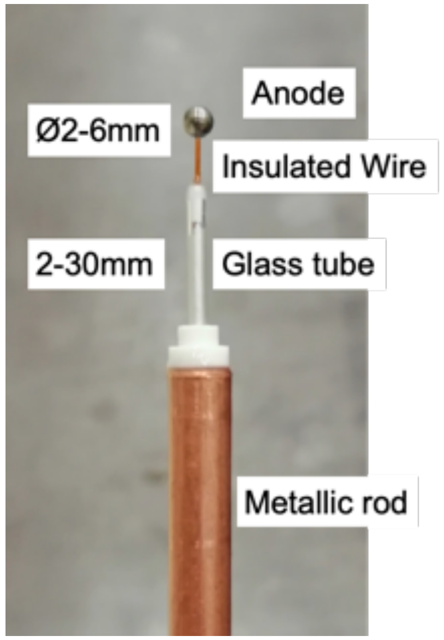

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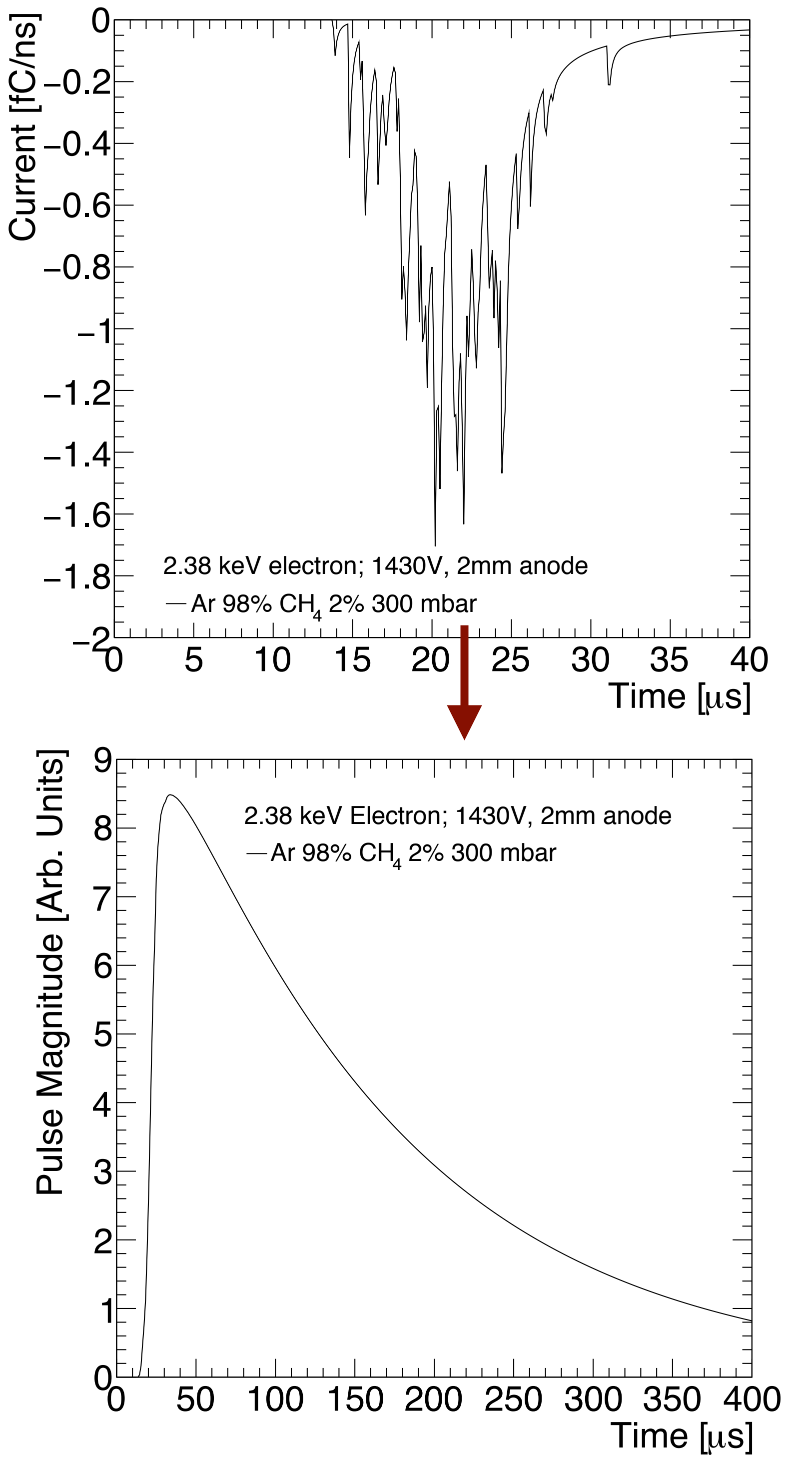

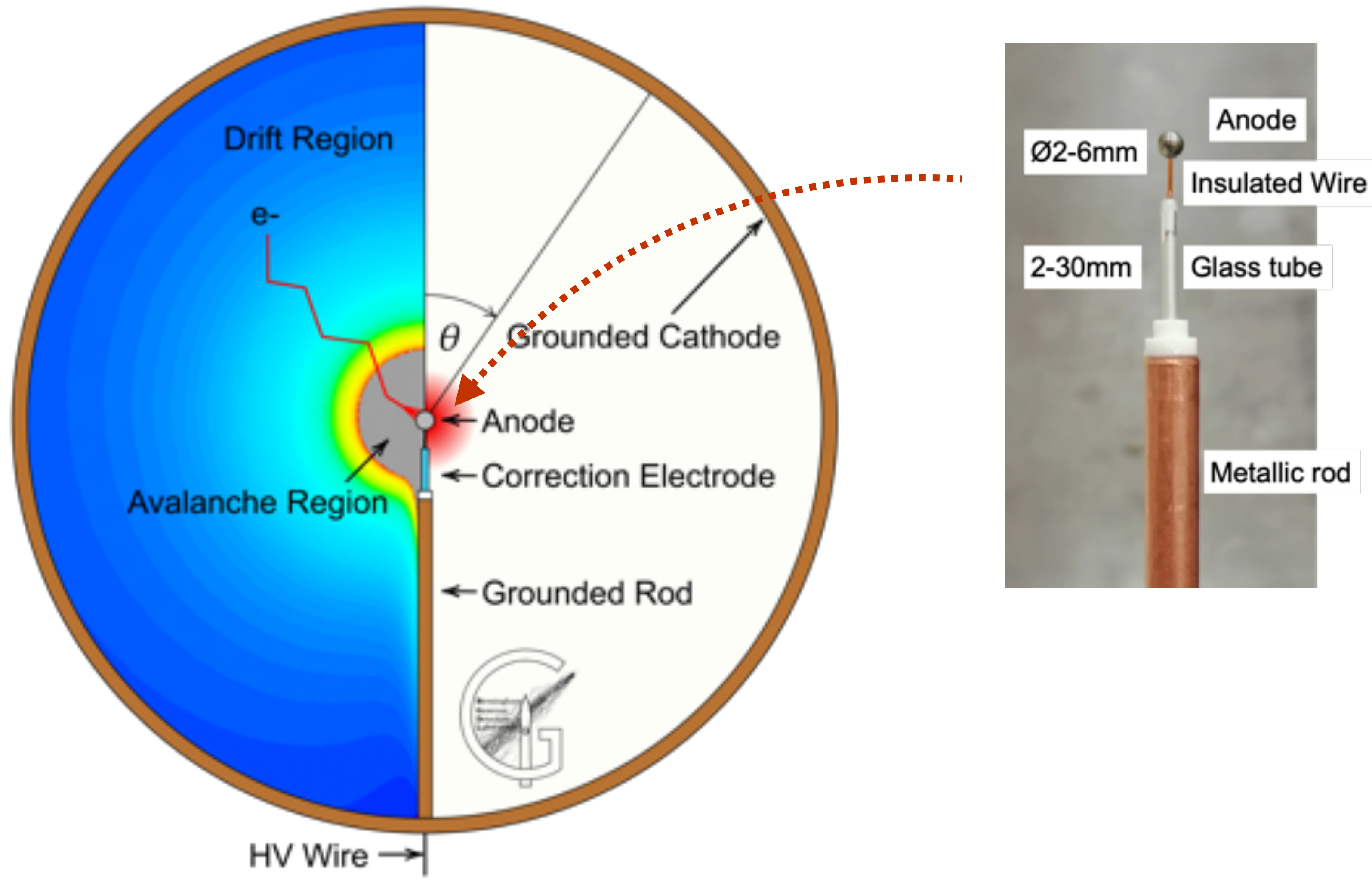

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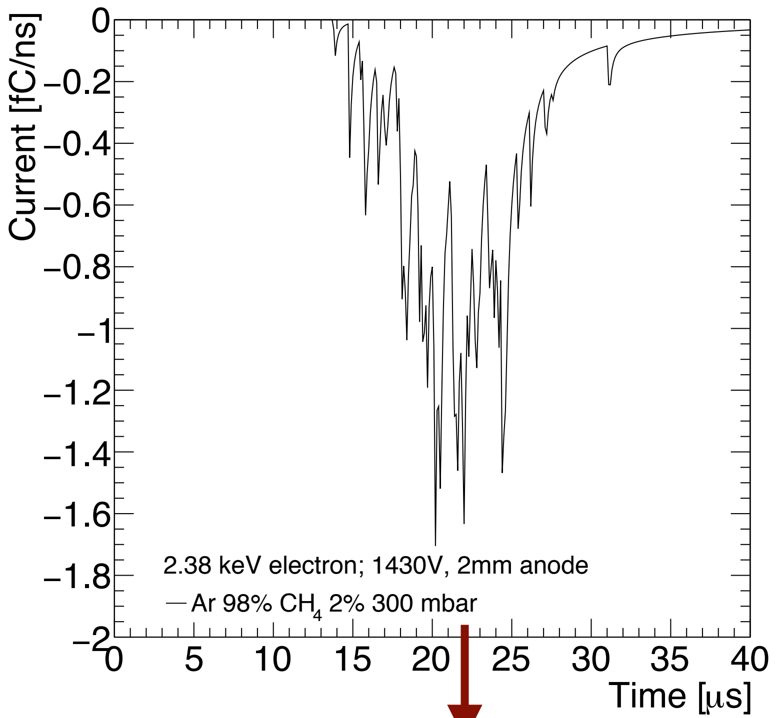
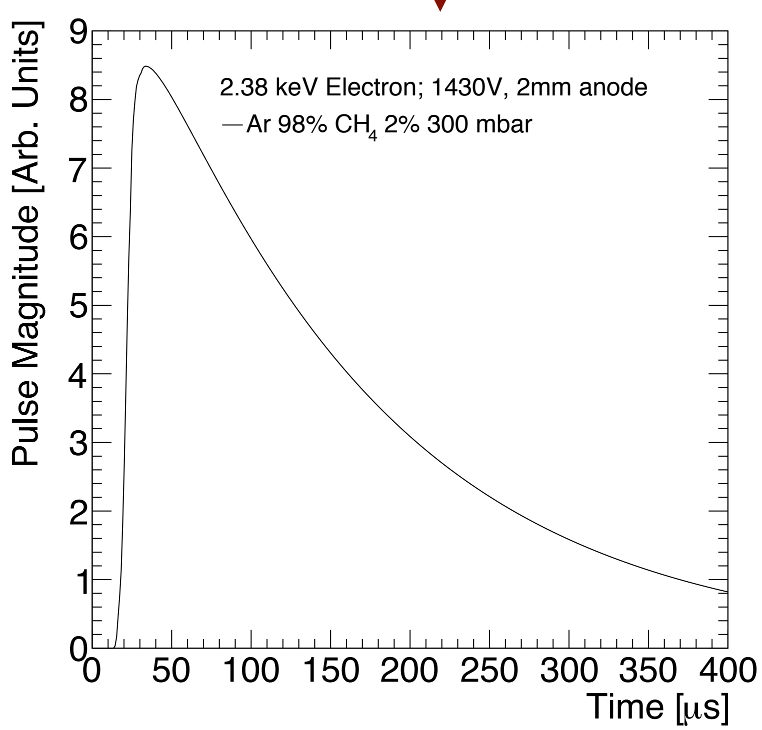
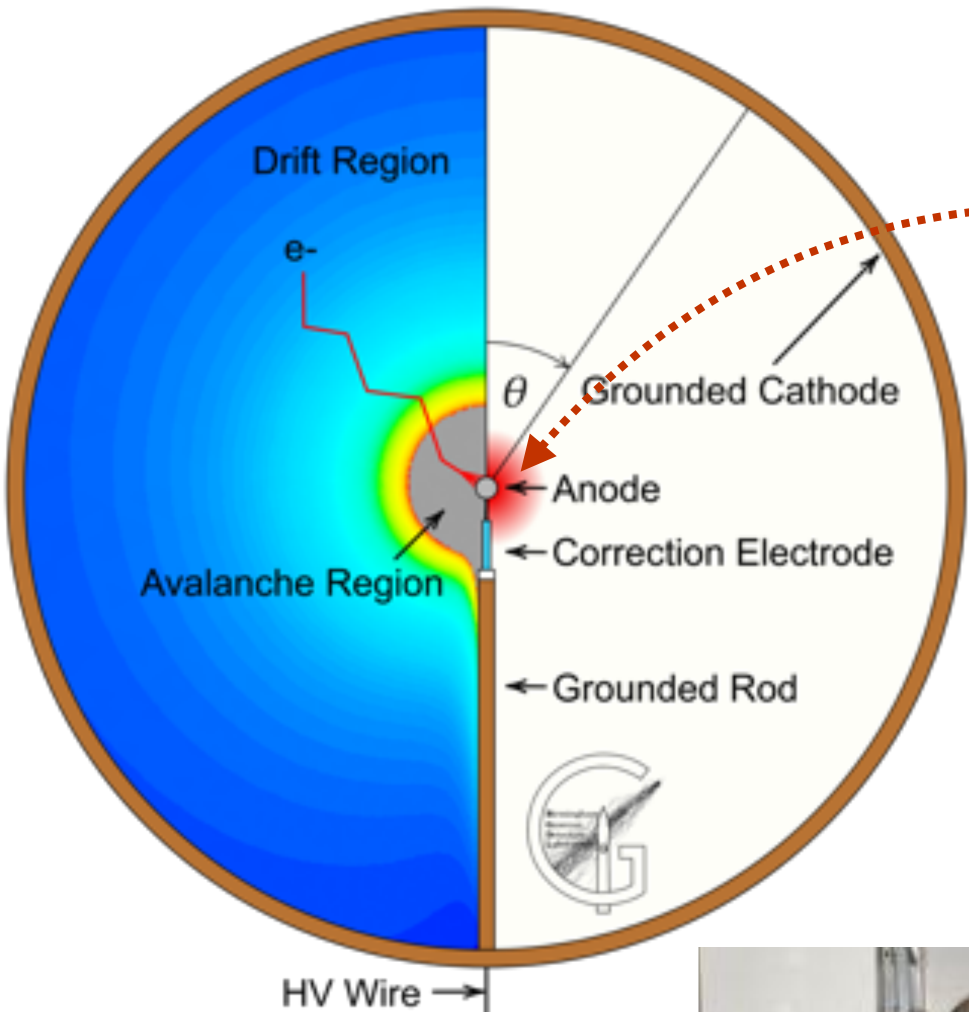
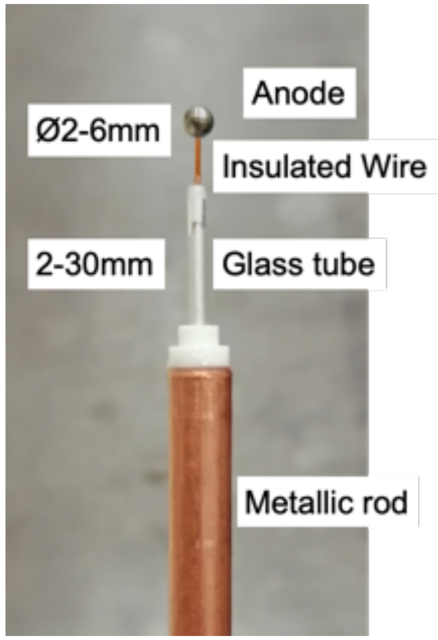
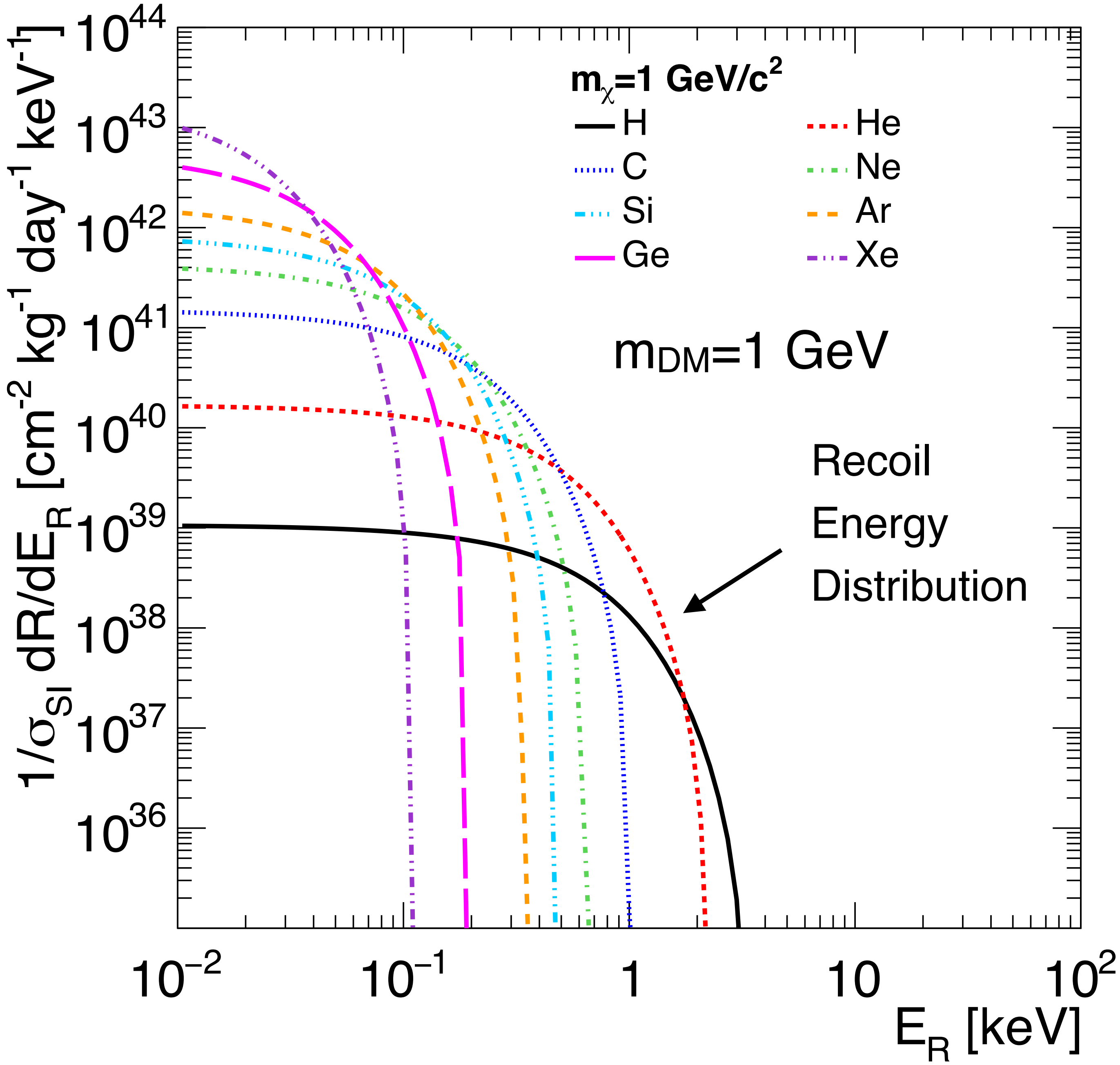






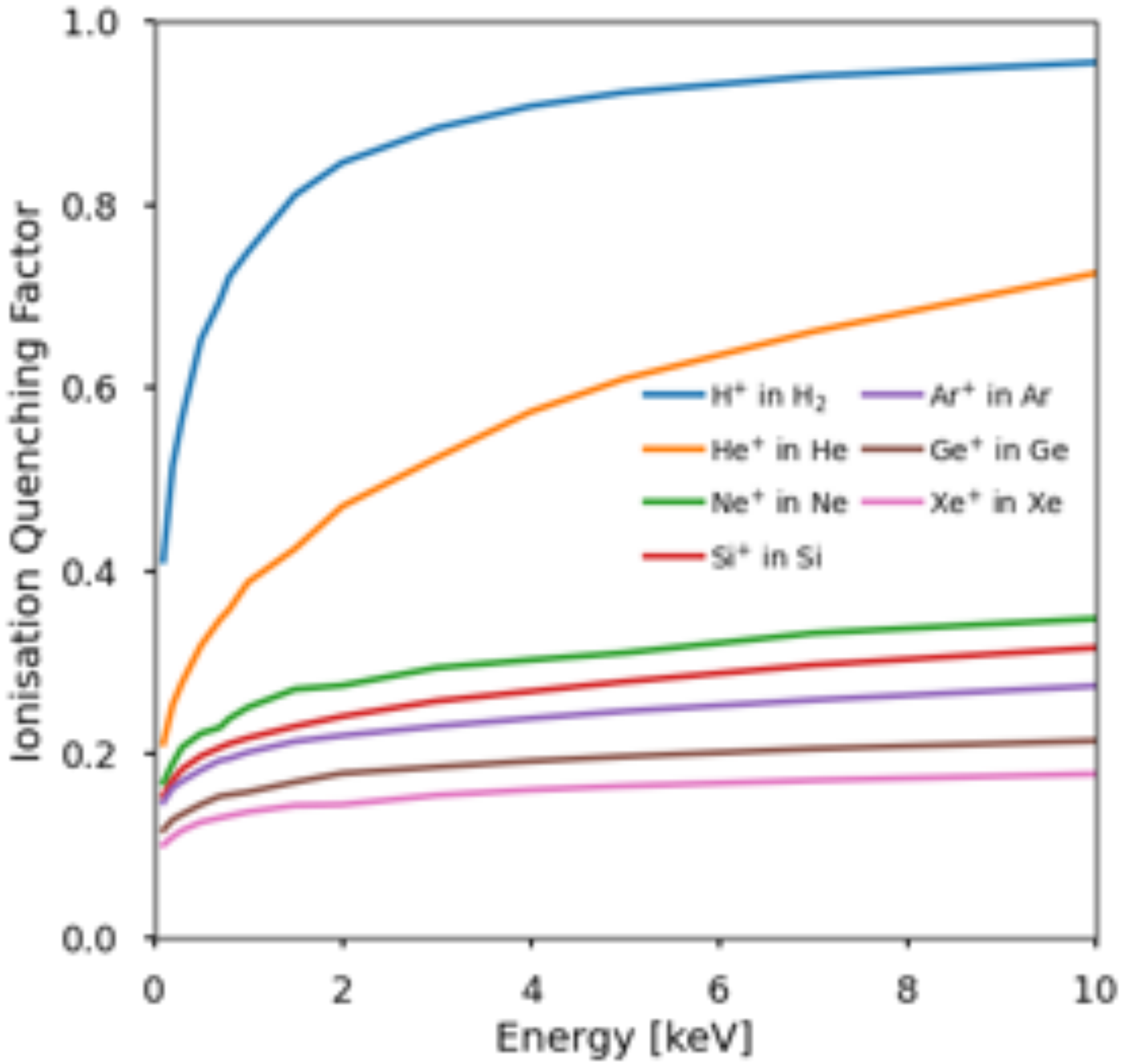


Direct Detection: Light Dark Matter



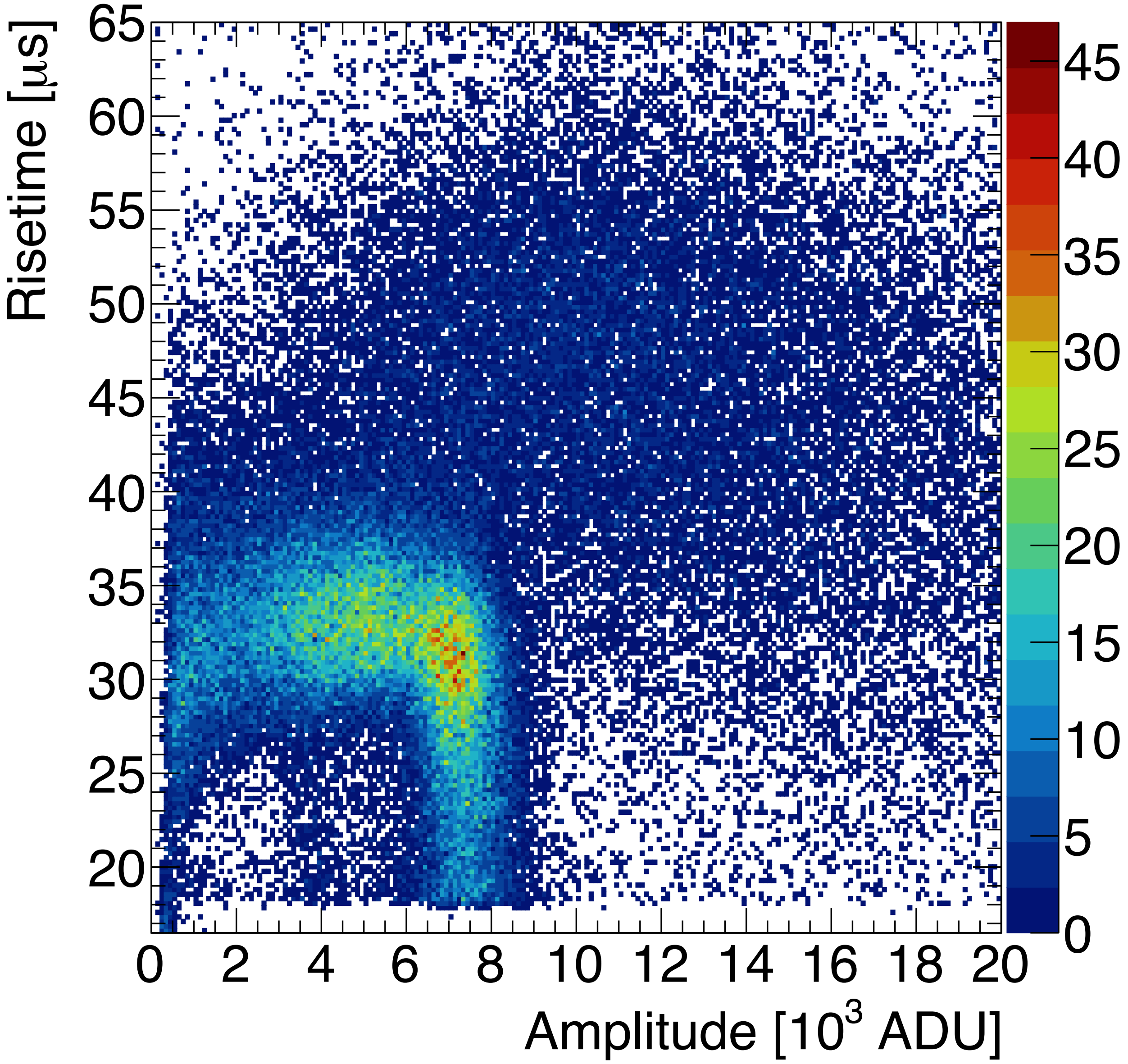
Favourable recoil energy distribution for lighter targets

Direct Detection: Light Dark Matter



- Fraction of energy dissipated as ionisation quantified by quenching factor
  - Several definitions of quenching factor in the literature
- For lighter elements more of the recoil energy turns into detectable signal
  - Larger fraction of energy deposited by recoil nucleus is visible to detector

Pulse Shape Discrimination



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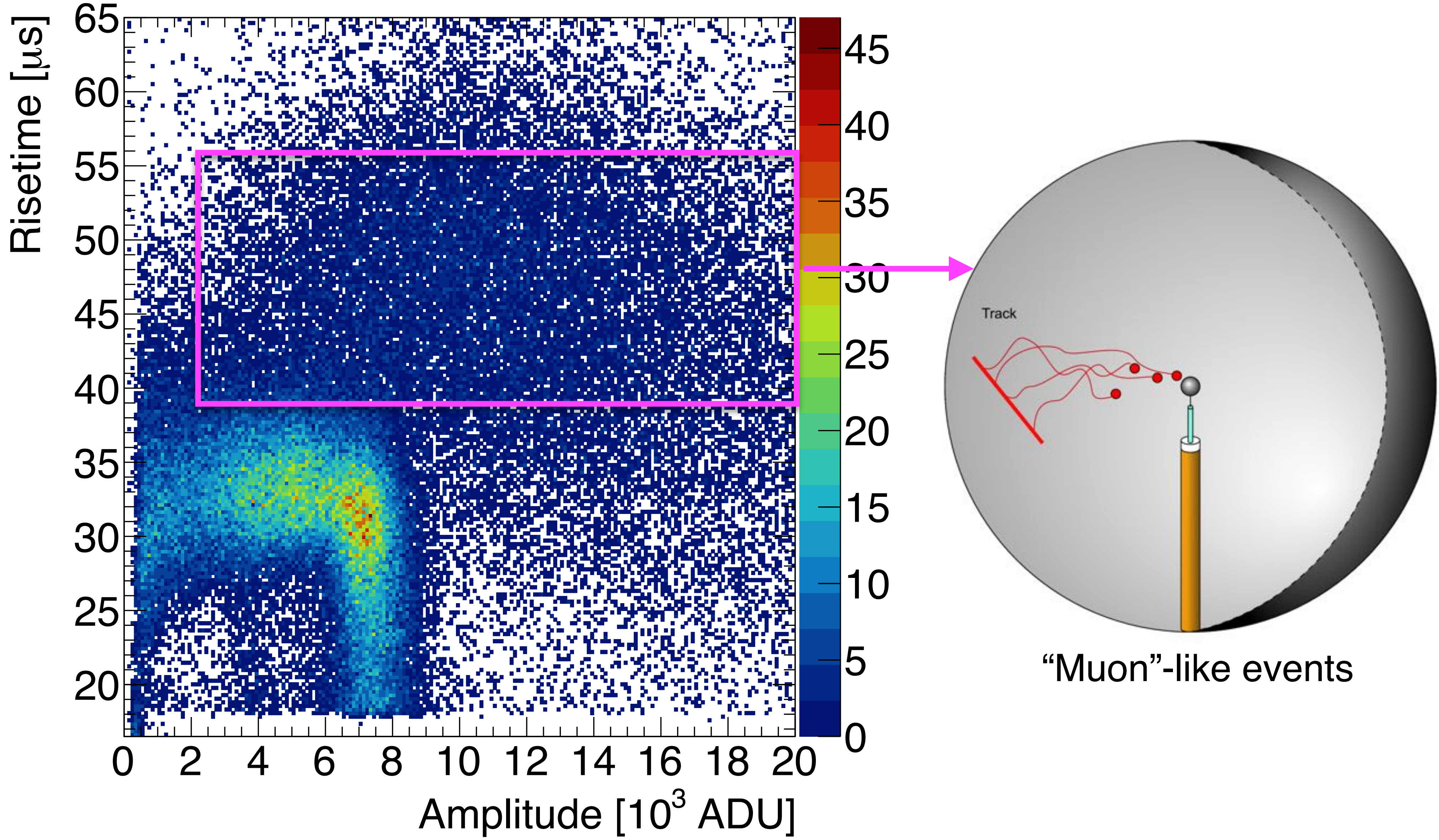
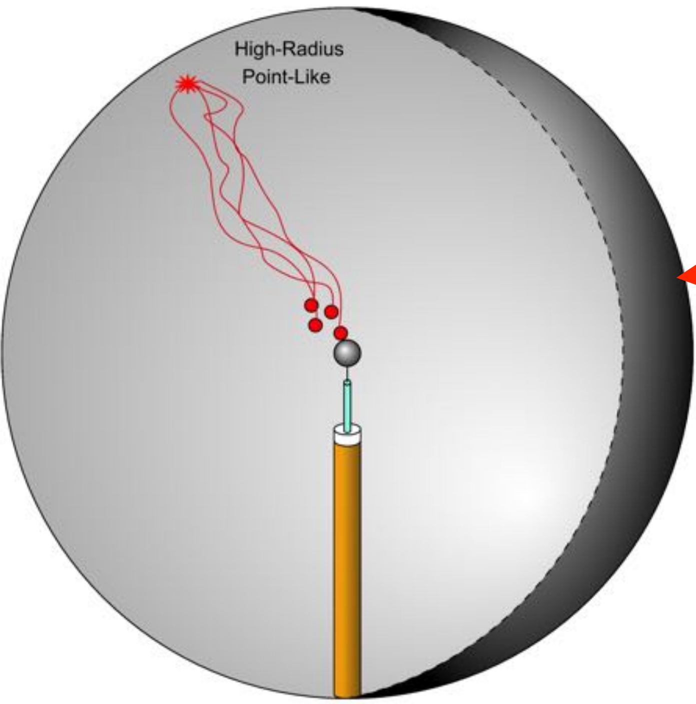
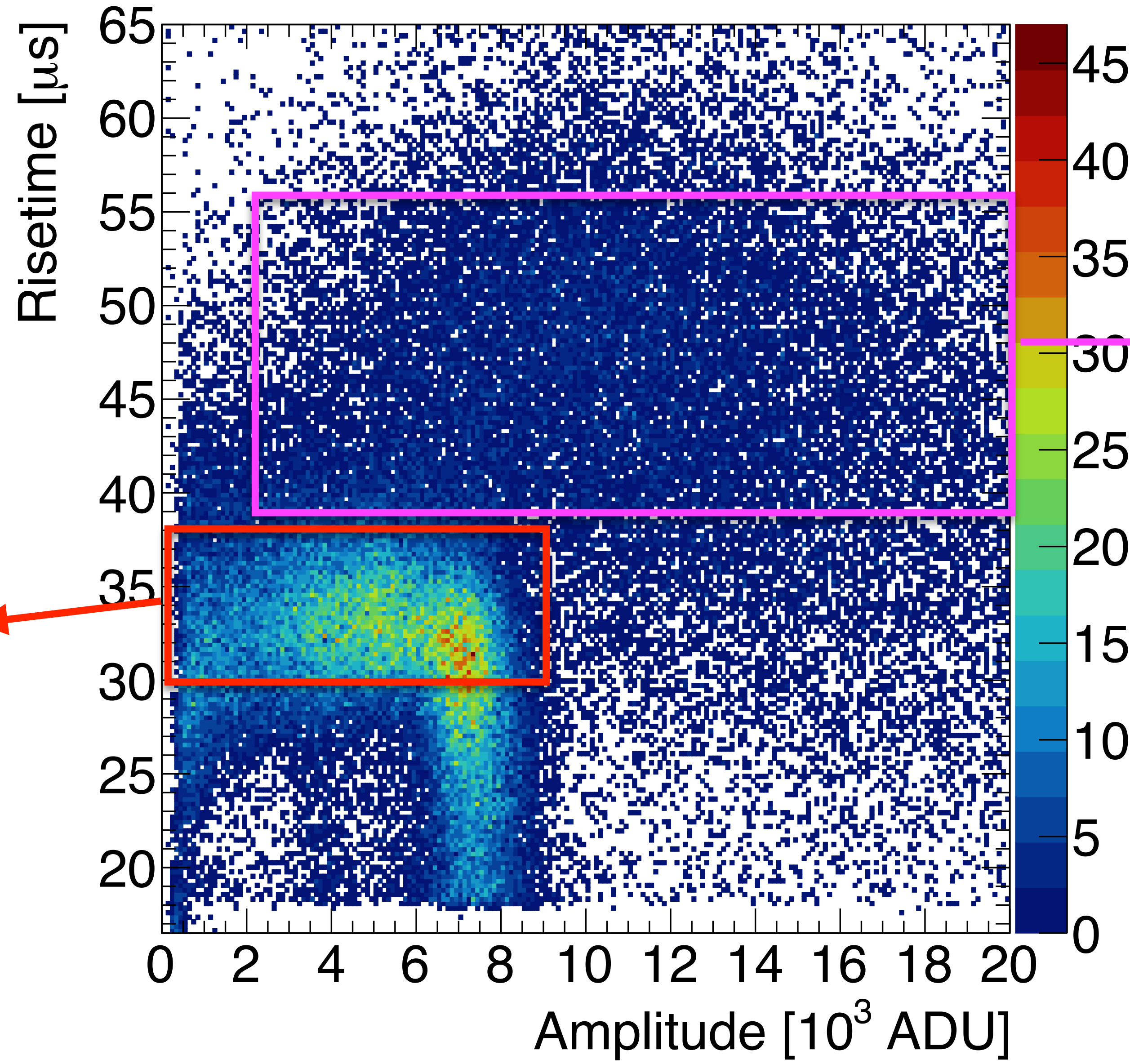


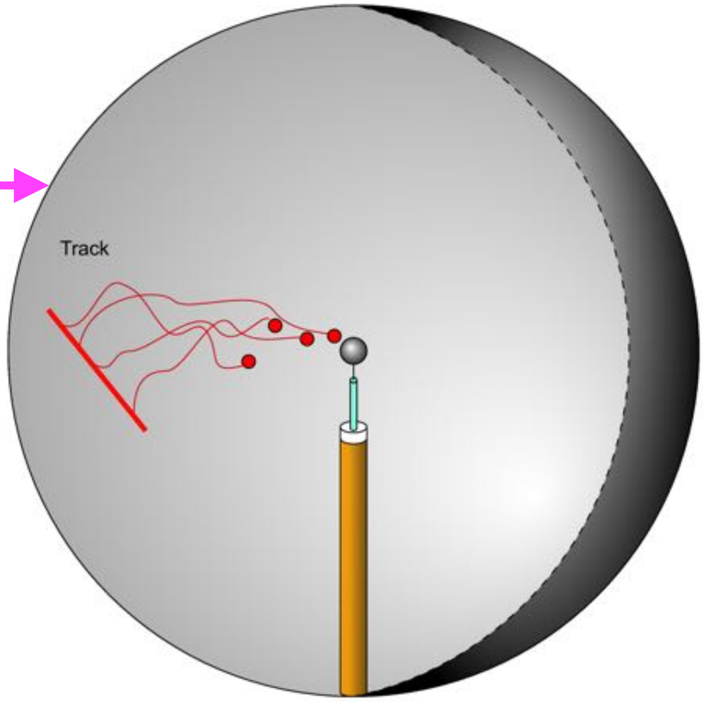
"Muon"-like events

Pulse Shape Discrimination



“Surface”-like events





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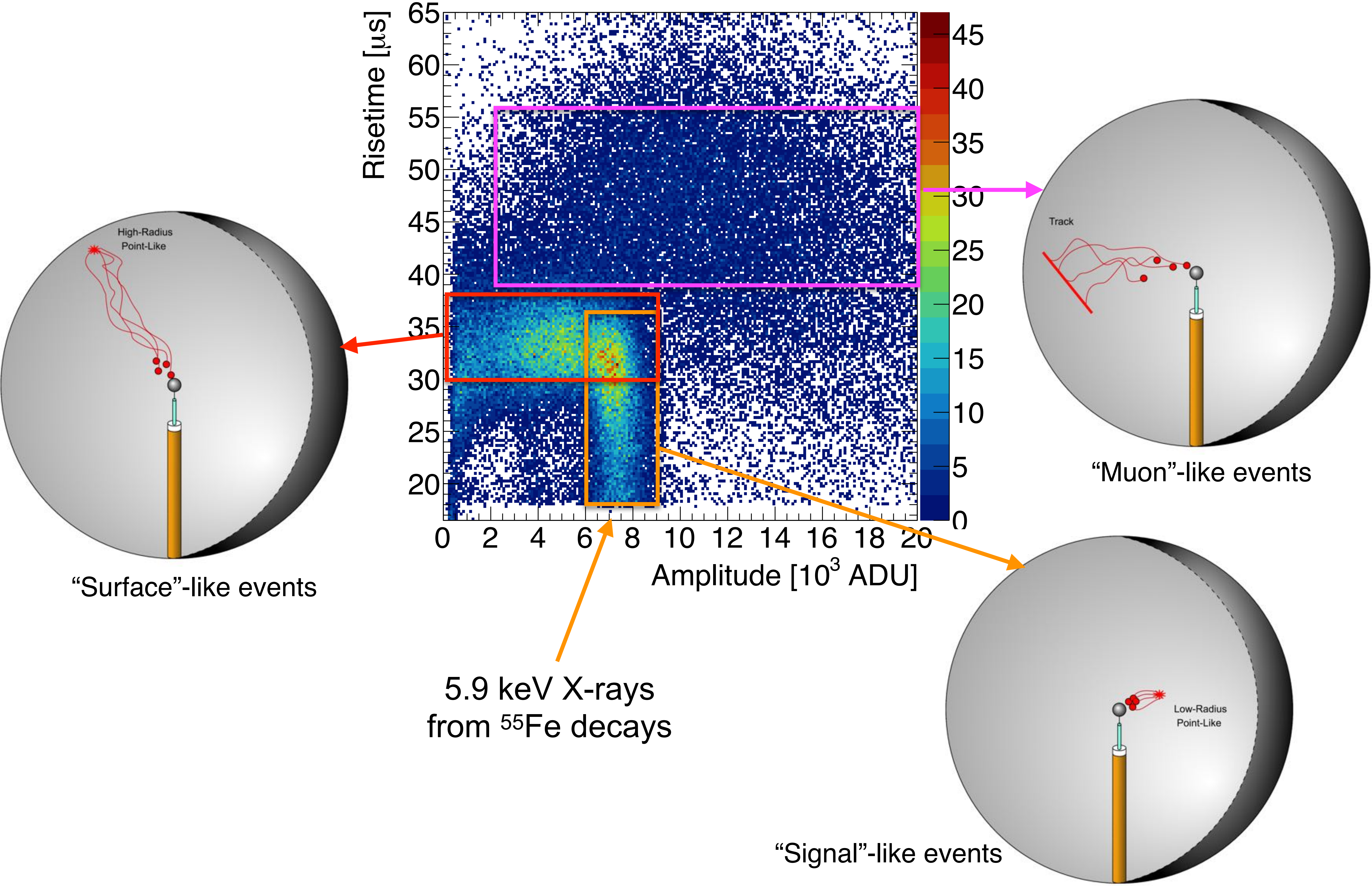
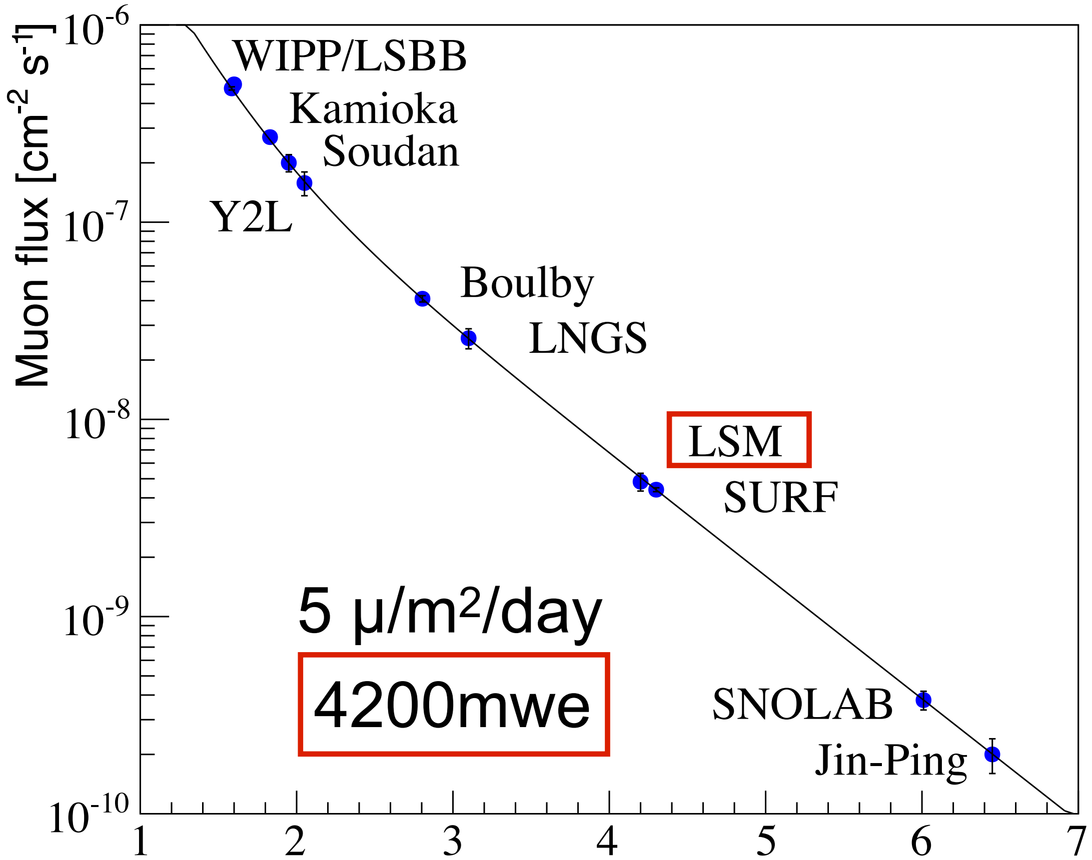
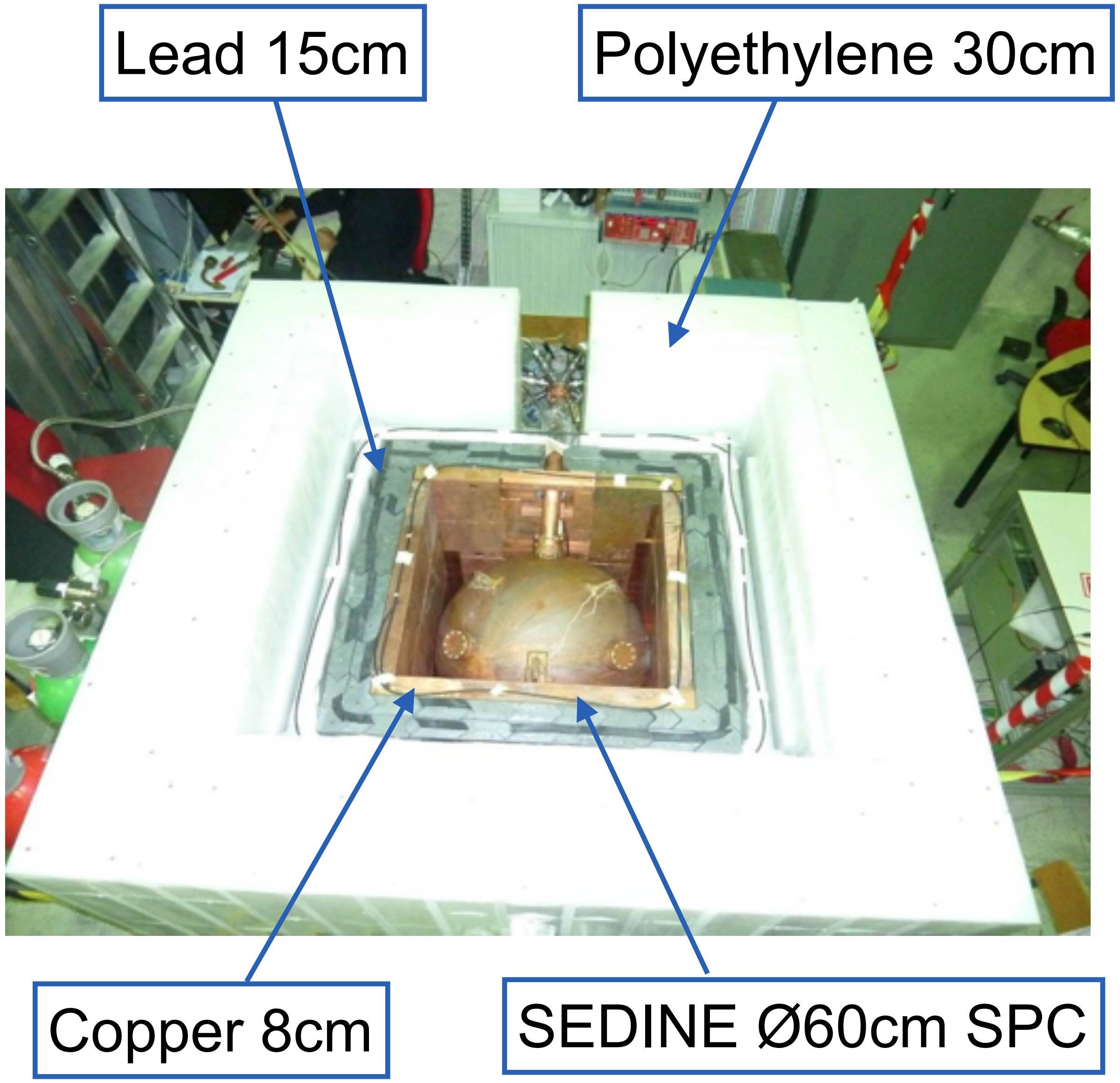
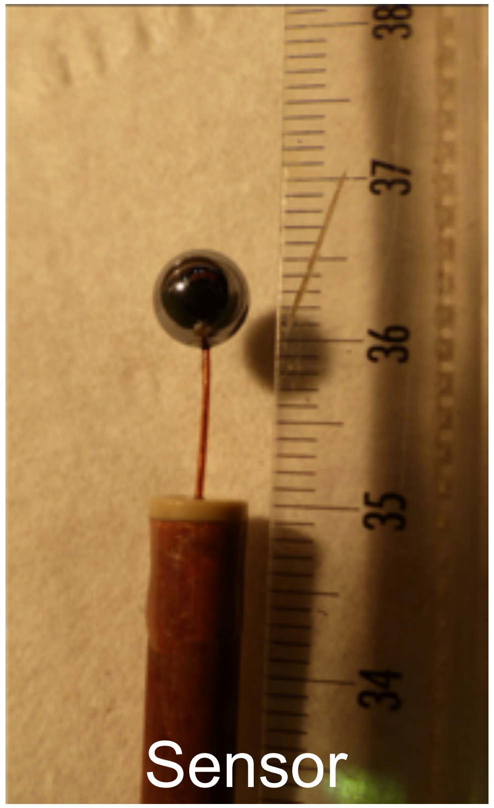


NEWS-G: Prototype at Modane



J.Phys. G43 (2016) 013001

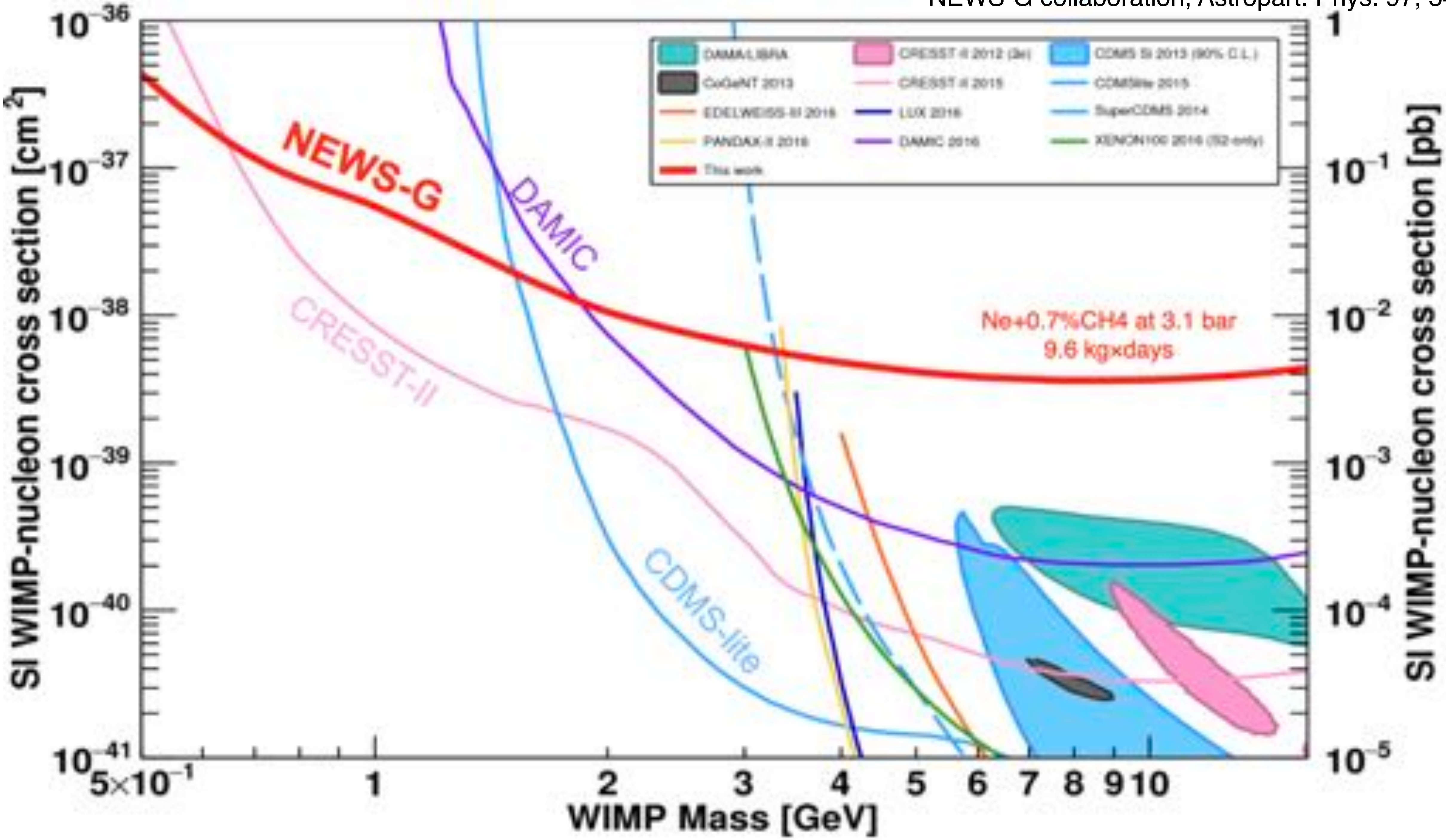




- NOSV Copper vessel (Ø60 cm)
- Equipped with a Ø6.3 mm sensor
- Chemically cleaned several times for Rn deposit removal

NEWS-G: First results

NEWS-G collaboration, Astropart. Phys. 97, 54 (2018)



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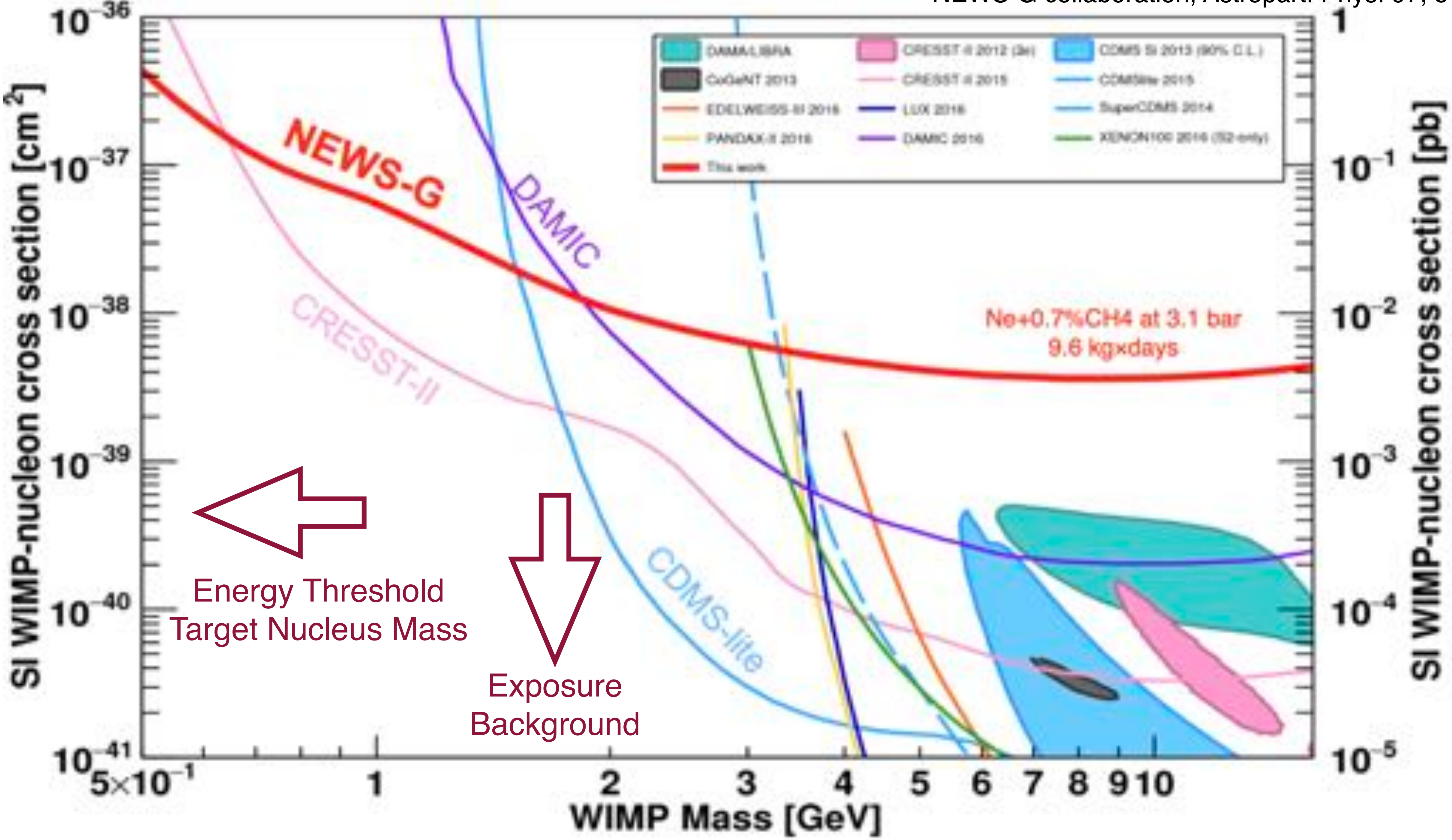
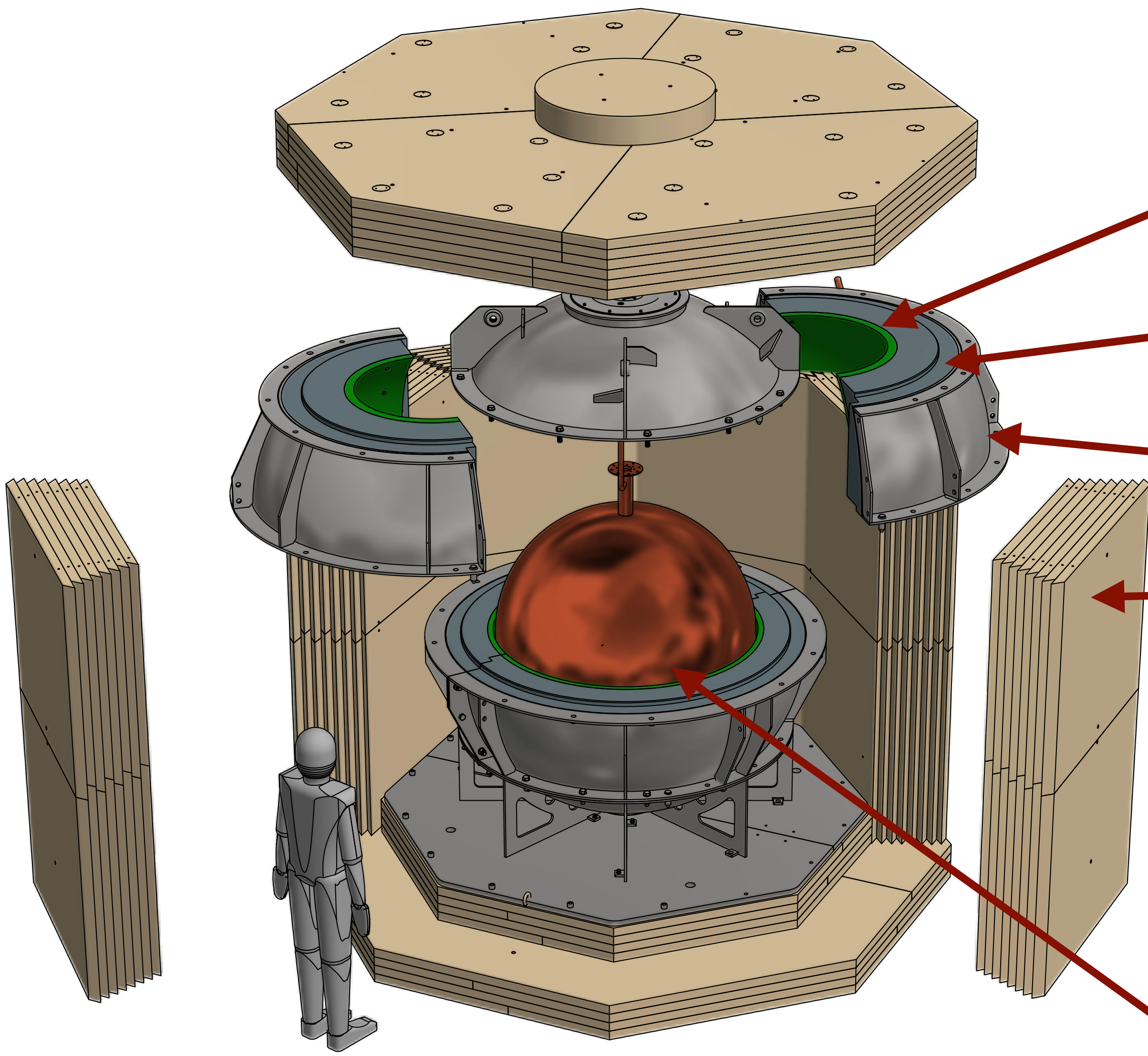


Exposure: Larger volume and higher operating pressure

Backgrounds: Higher purity materials

NEWS-G at SNOLAB

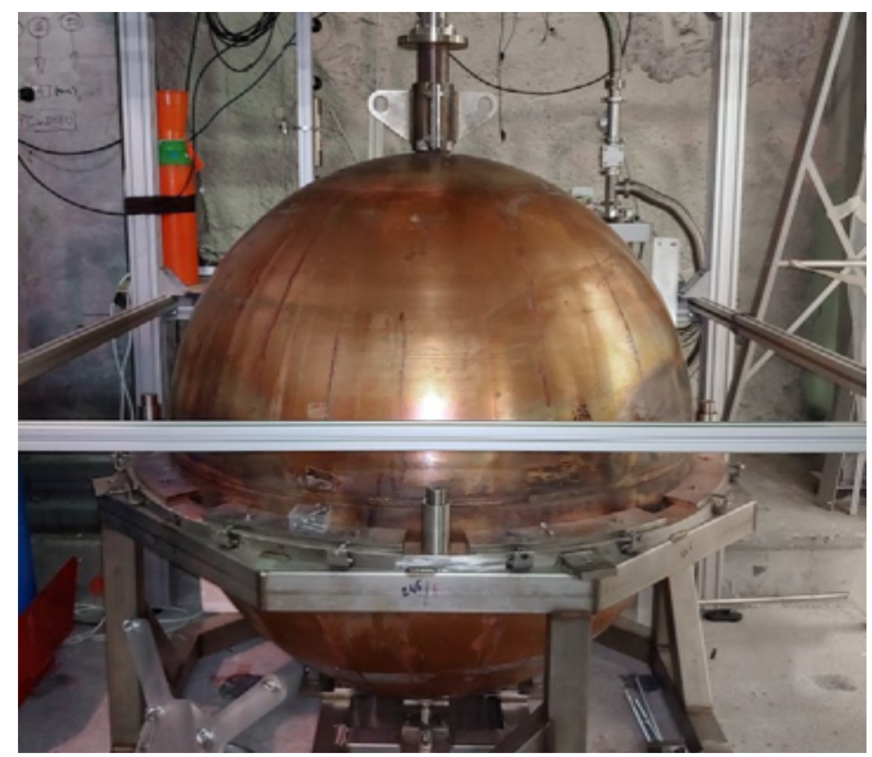


3 cm archaeological lead

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

Increasing Target Mass

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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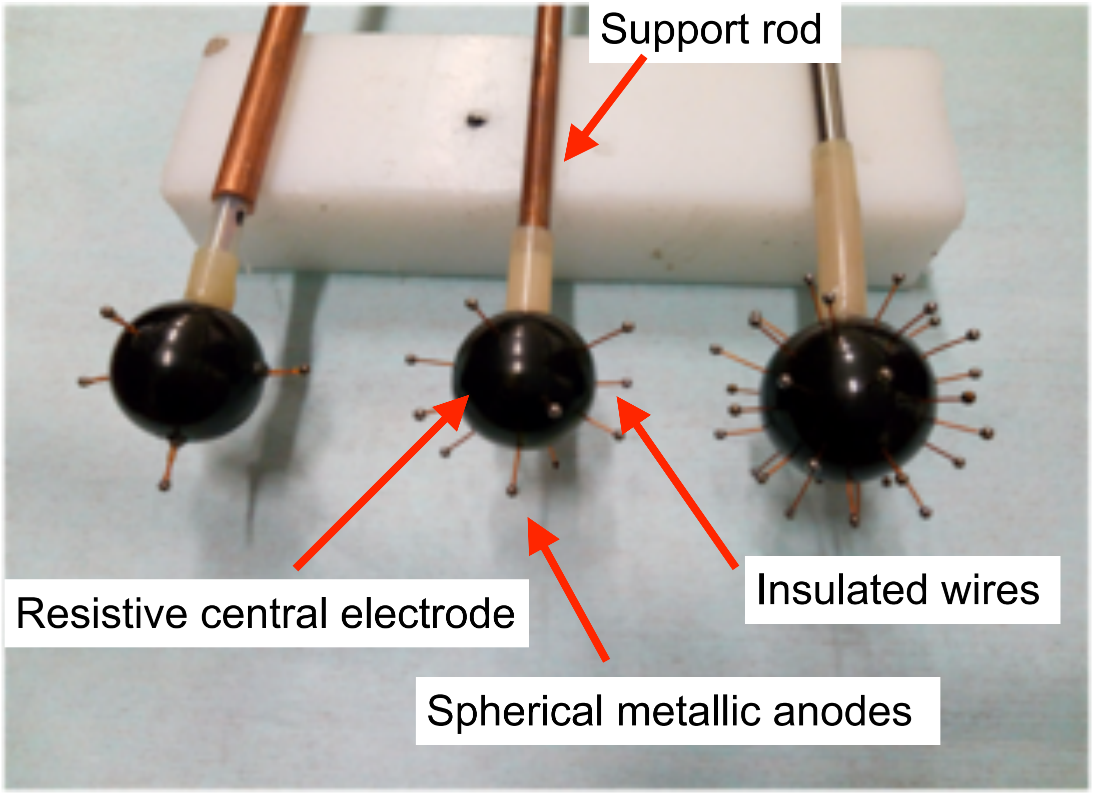

- ACHINOS: Multi-anode sensor JINST 12 (2017) 12, P12031
  - Multiple anodes placed at equal radii
    - Sensors with 5, 11, 33 anodes operated
  - Decoupling drift and amplification fields
  - Opportunity: individual anode read-out
    - TPC-like capabilities

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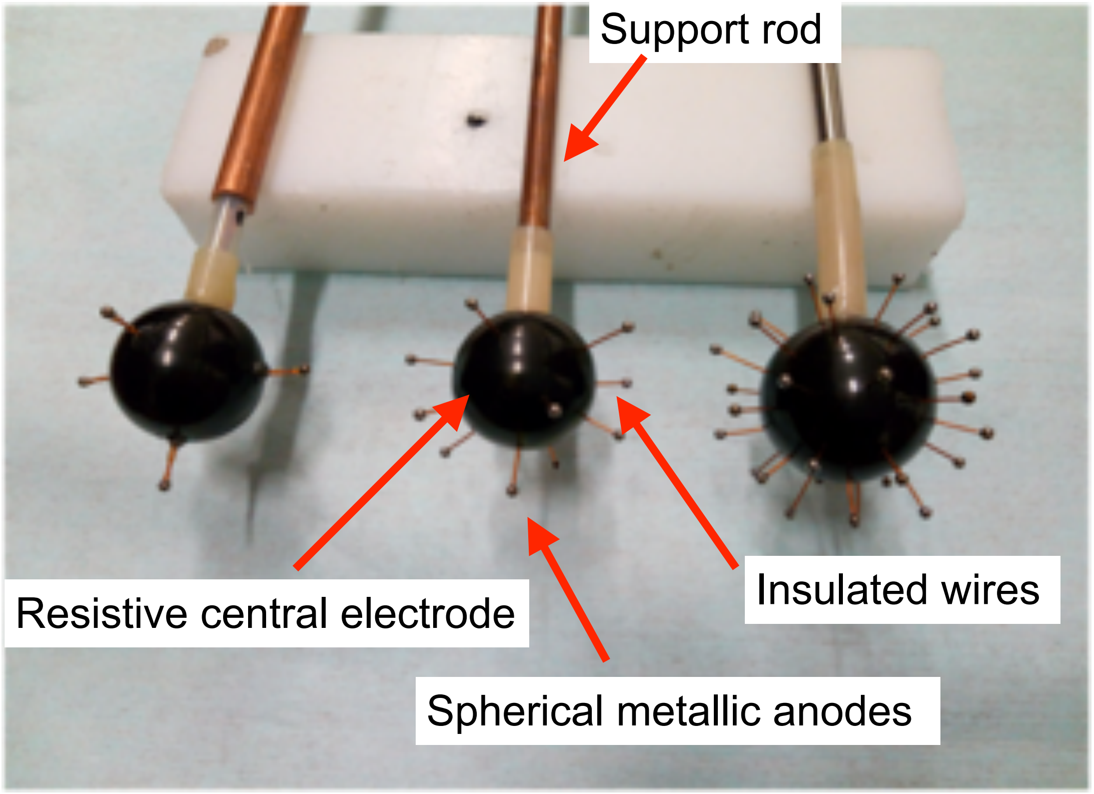

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Αχινός (greek. sea urchin)

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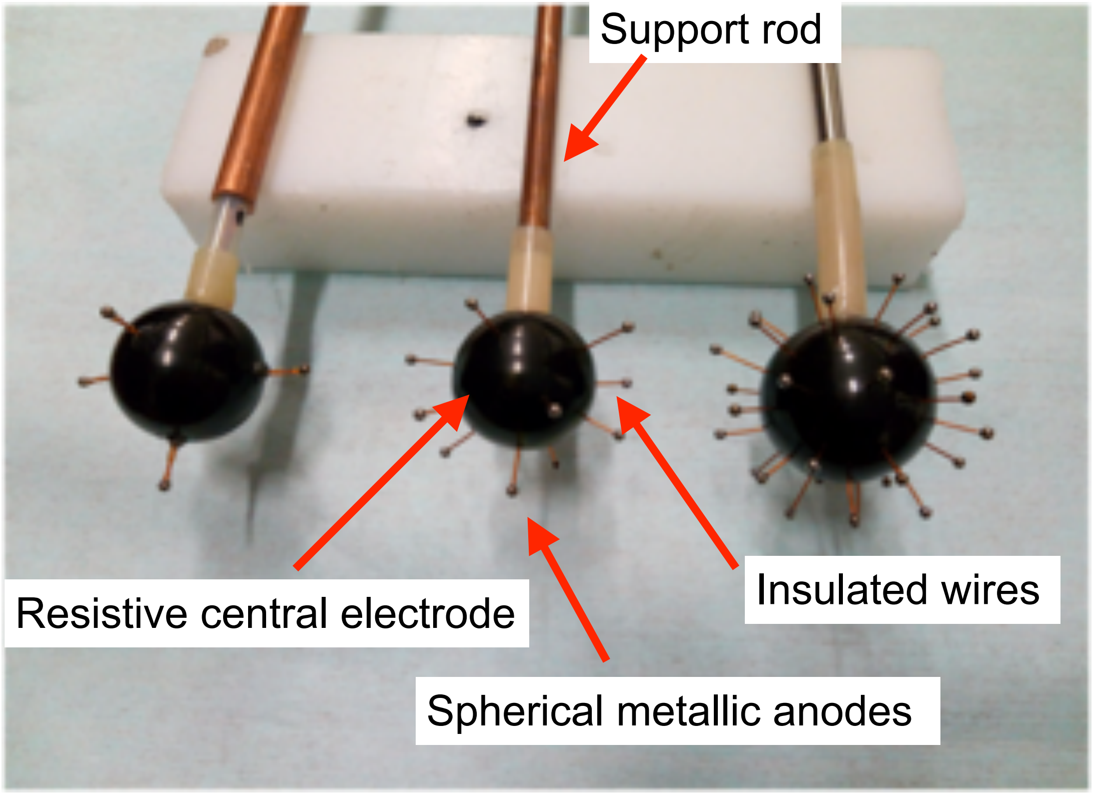

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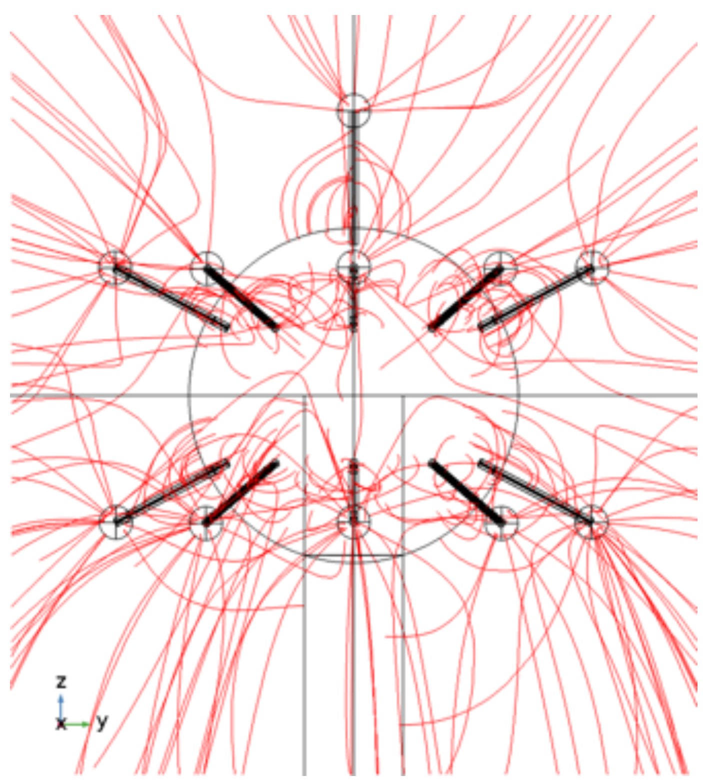
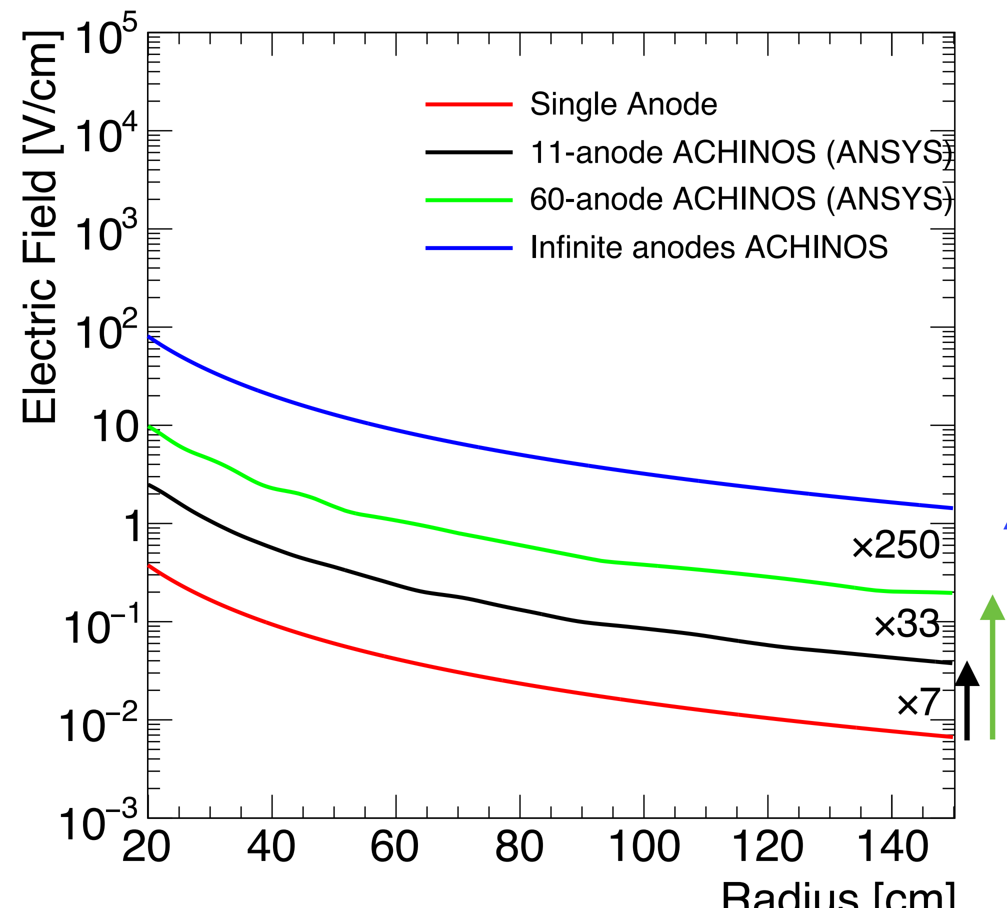
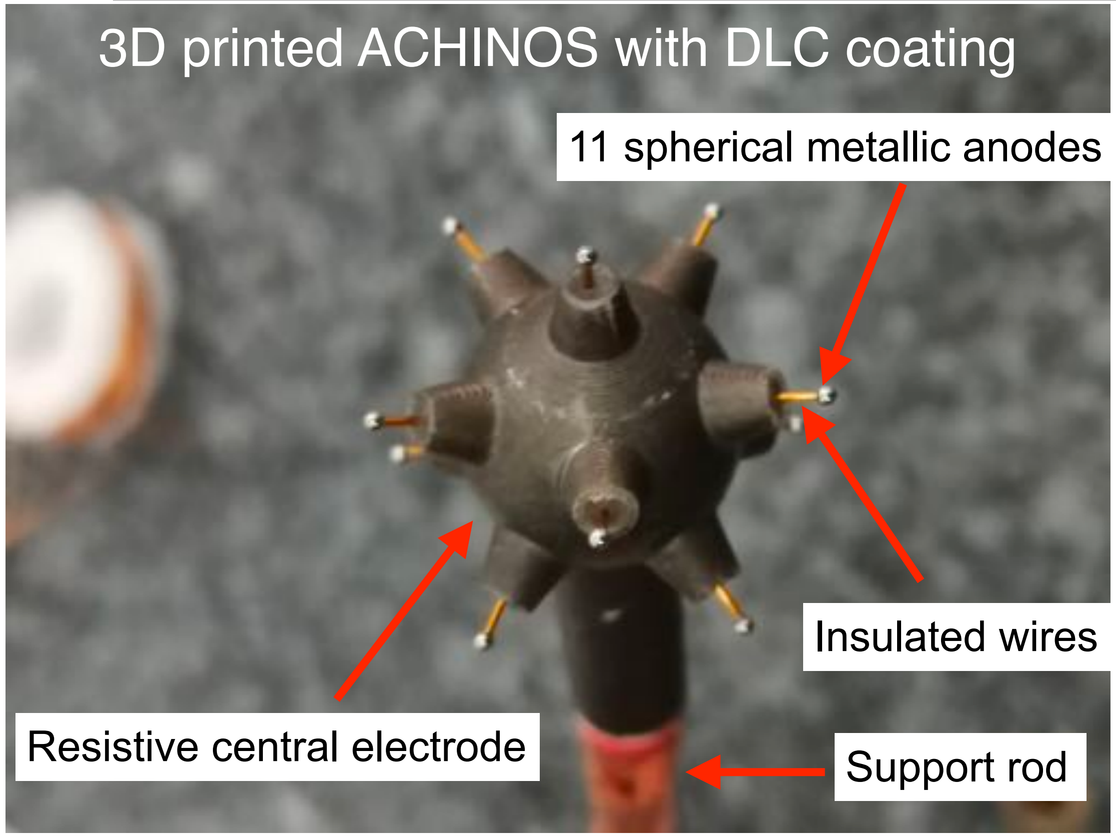




ACHINOS performance with DLC coating



JINST 15 (2020) 11, 11

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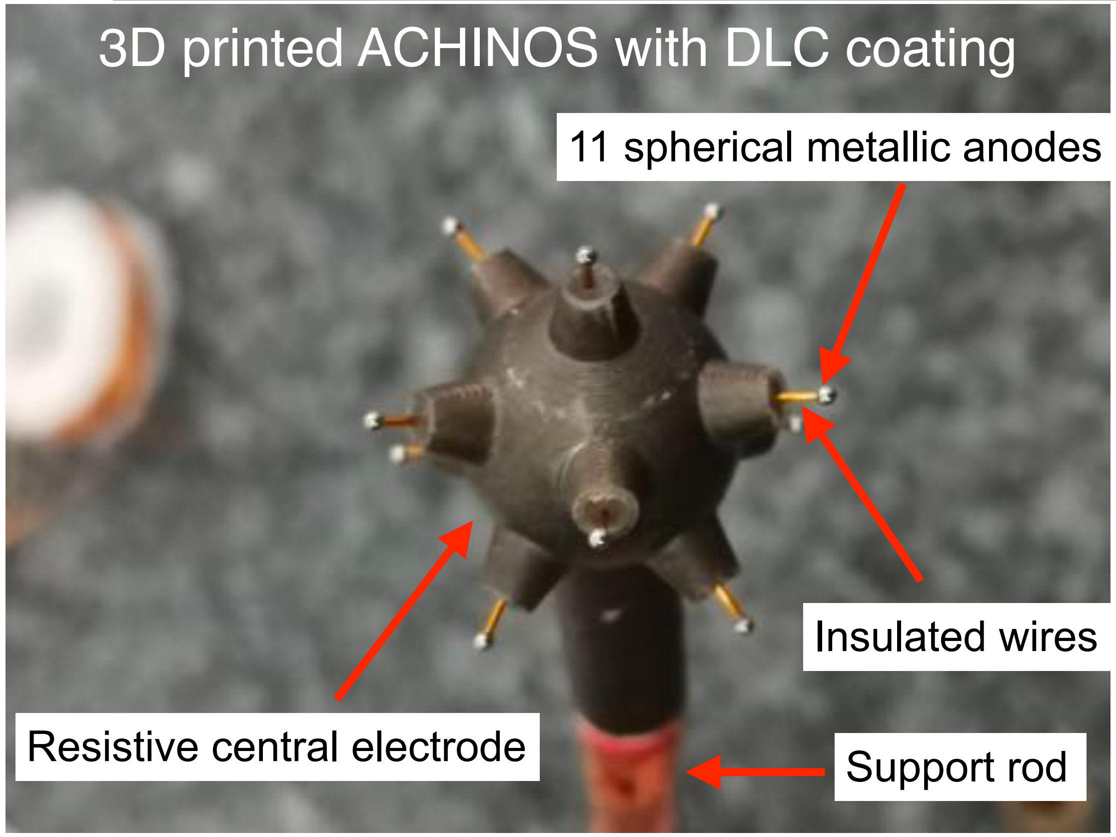
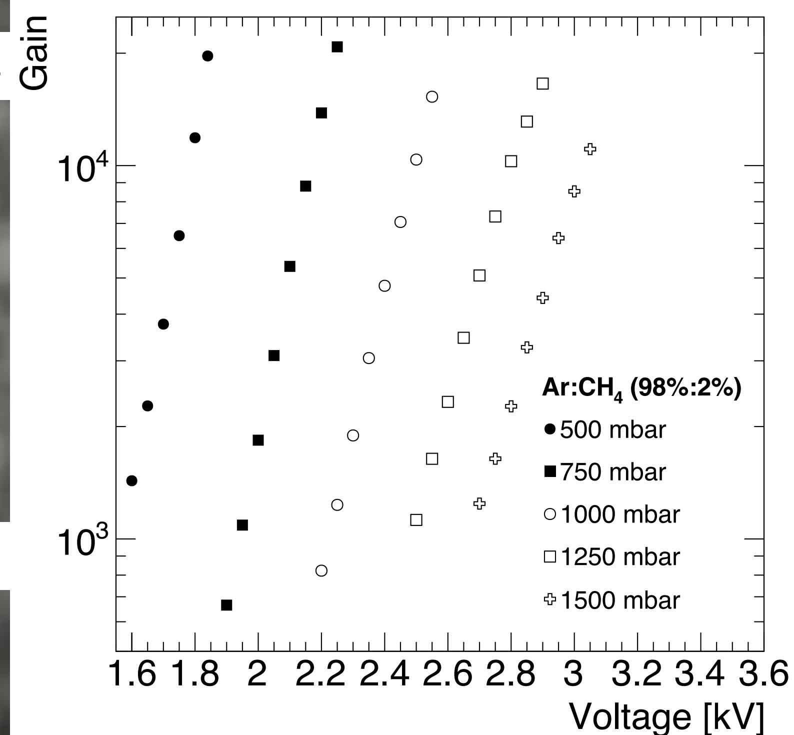
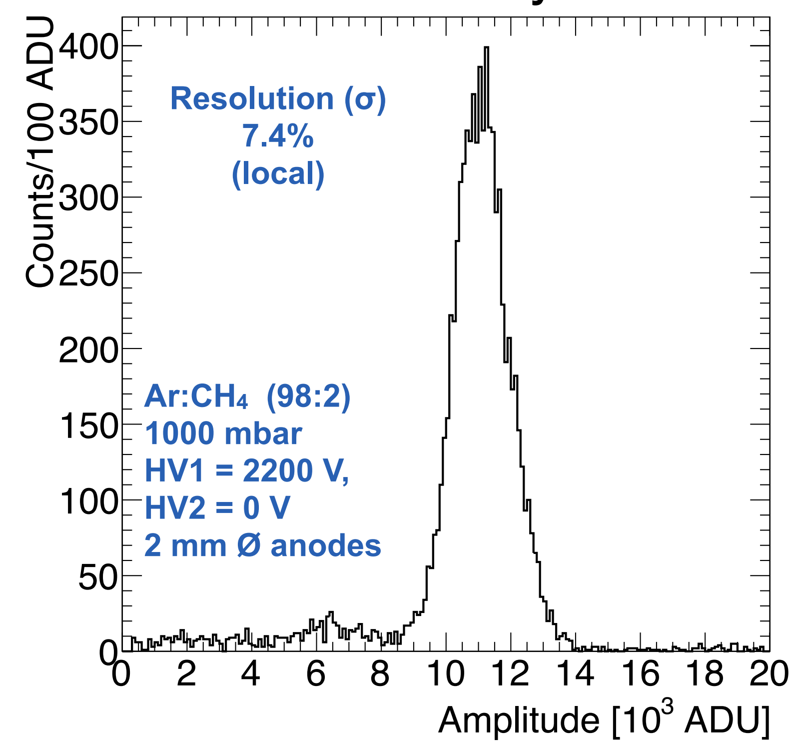


Measurement of the 5.9 keV ^{55}Fe X-ray line





- Performance
  - Good energy resolution
  - High gain/pressure operation
  - Stable operation

JINST 15 (2020) 11, 11

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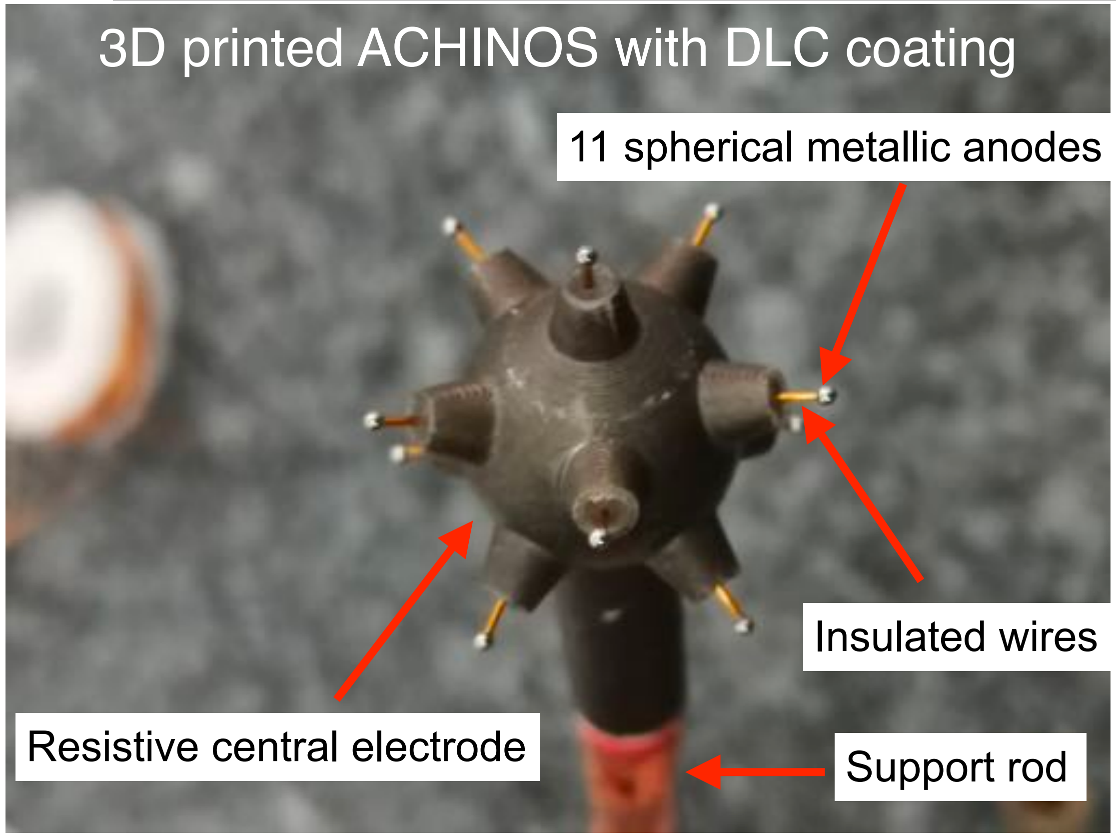

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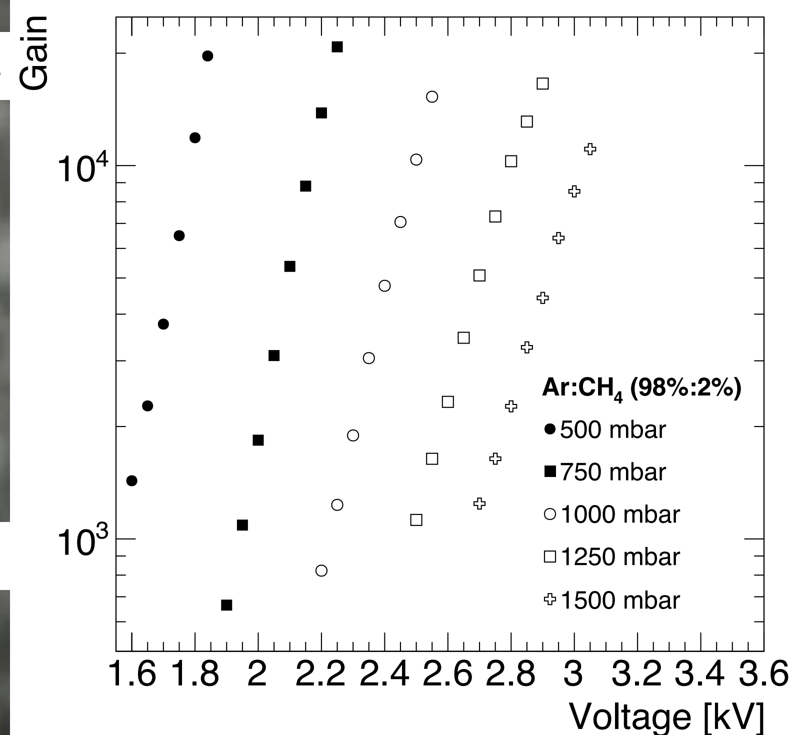
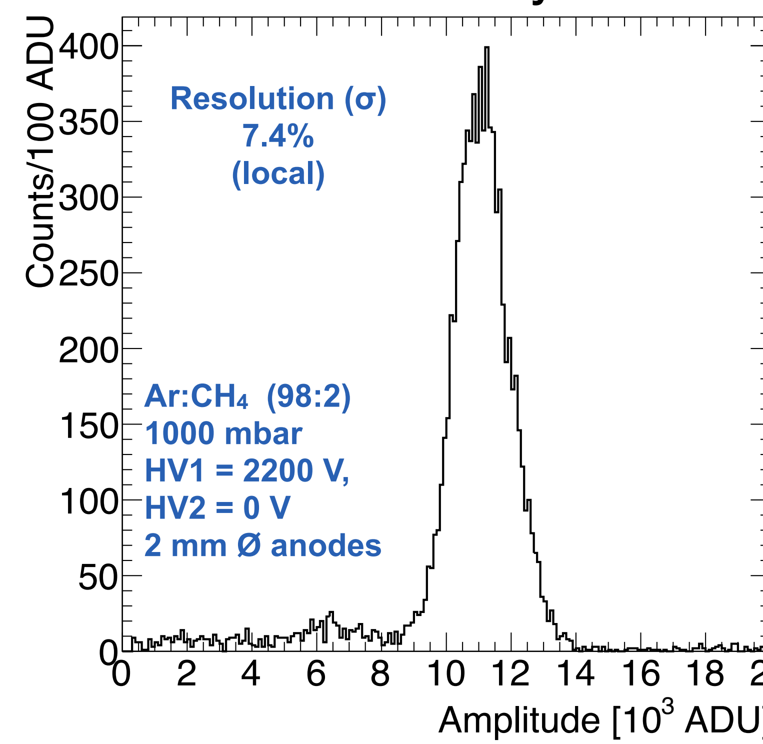
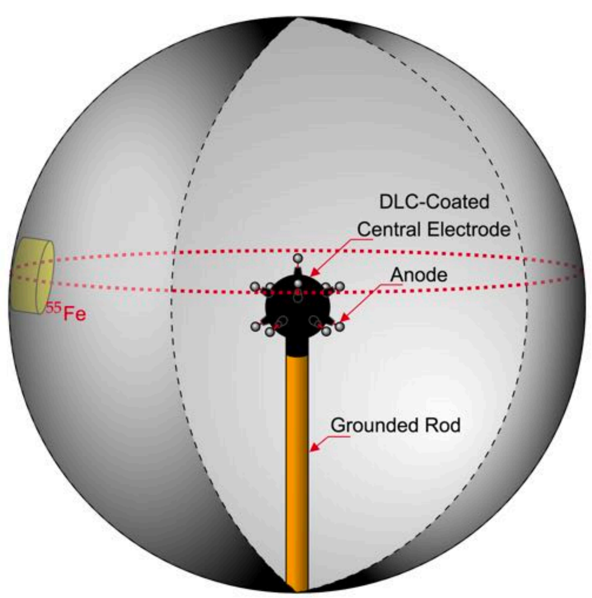


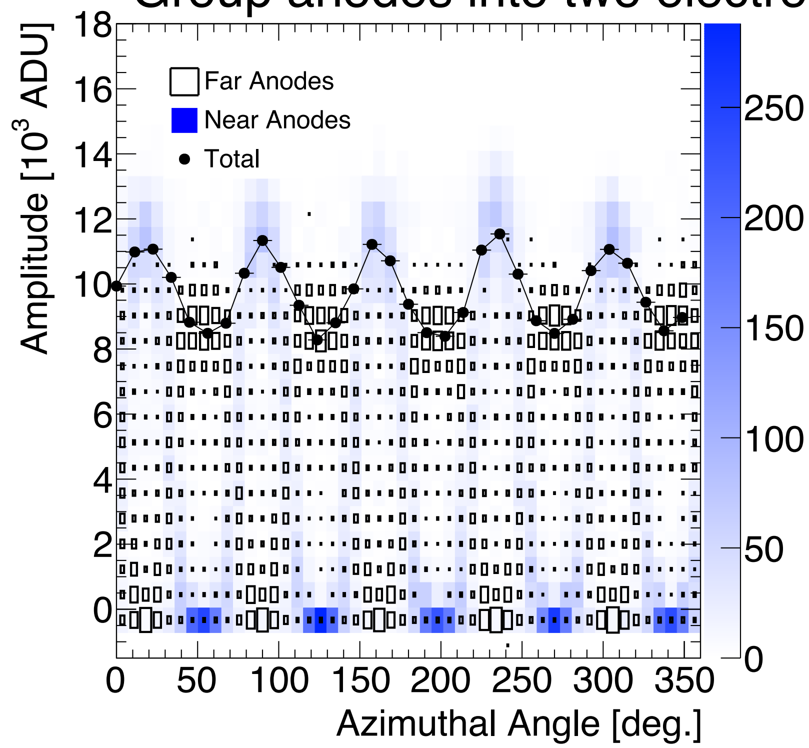


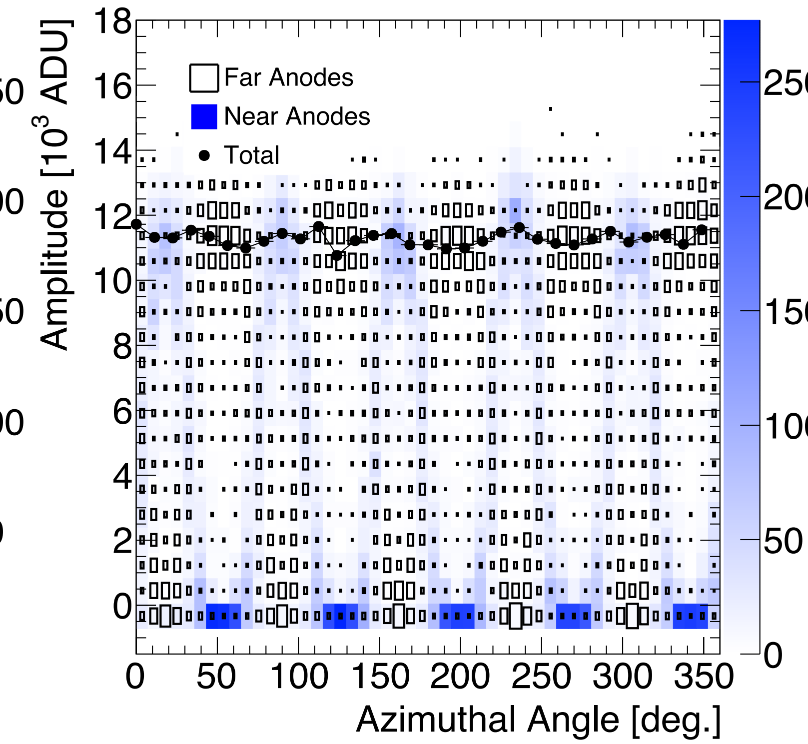
- Performance
  - Good energy resolution
  - High gain/pressure operation
  - Stable operation



Simulations

Group anodes into two electrodes: Near and Far from the rod



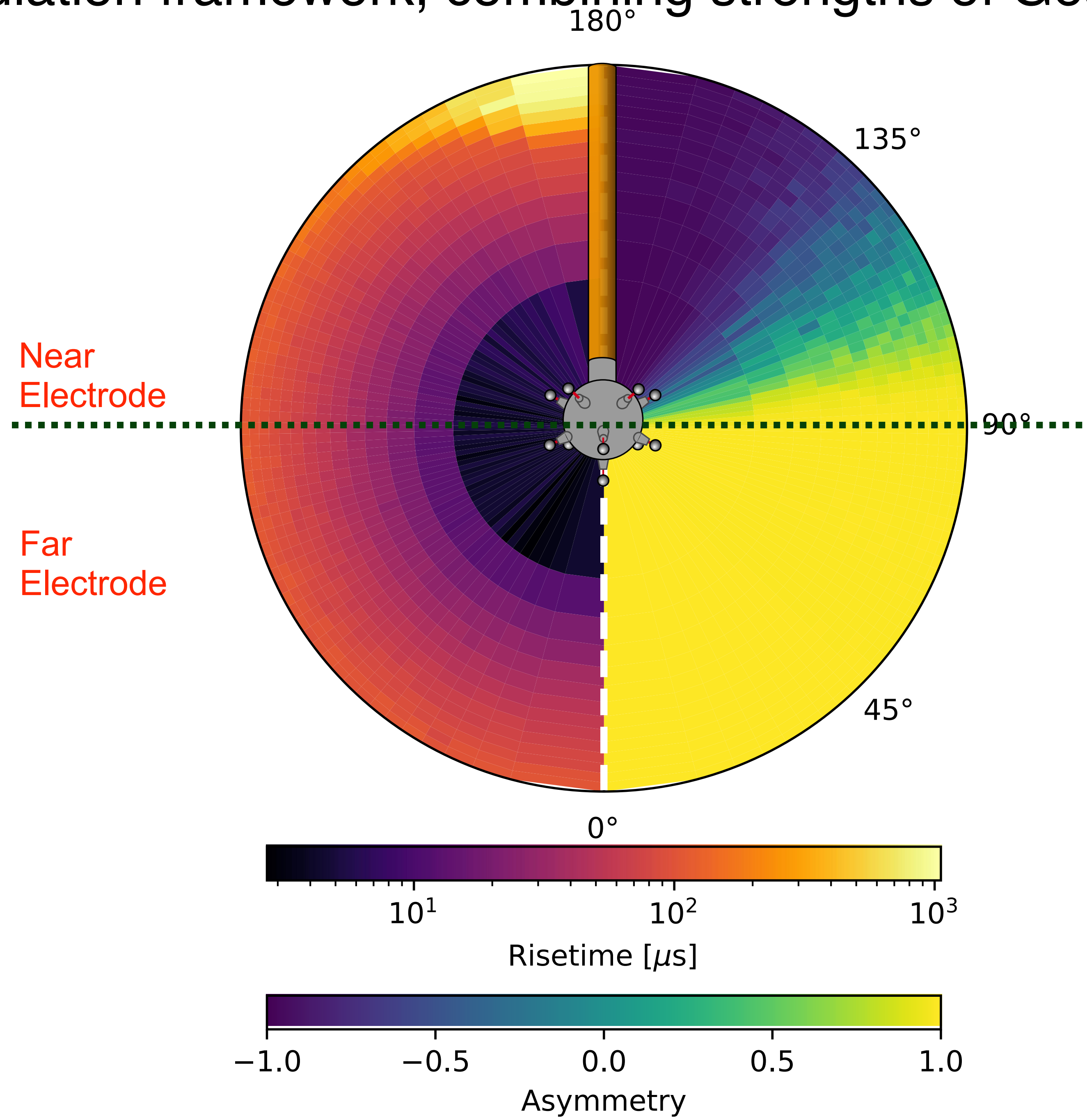


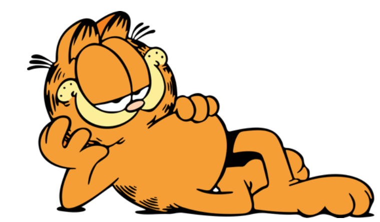
JINST 15 (2020) 11, 11

Fiducialisation

Birmingham simulation framework, combining strengths of Geant4 and Garfield++

JINST 15 (2020) 06, C06013





- Reading out individual ACHINOS anodes: position of interaction can be reconstructed
- First tests: Separate the anodes in two electrodes “Near” and “Far” (from the rod)
  - Asymmetry of pulse amplitudes: zenith angle
  - Pulse rise-time: radius

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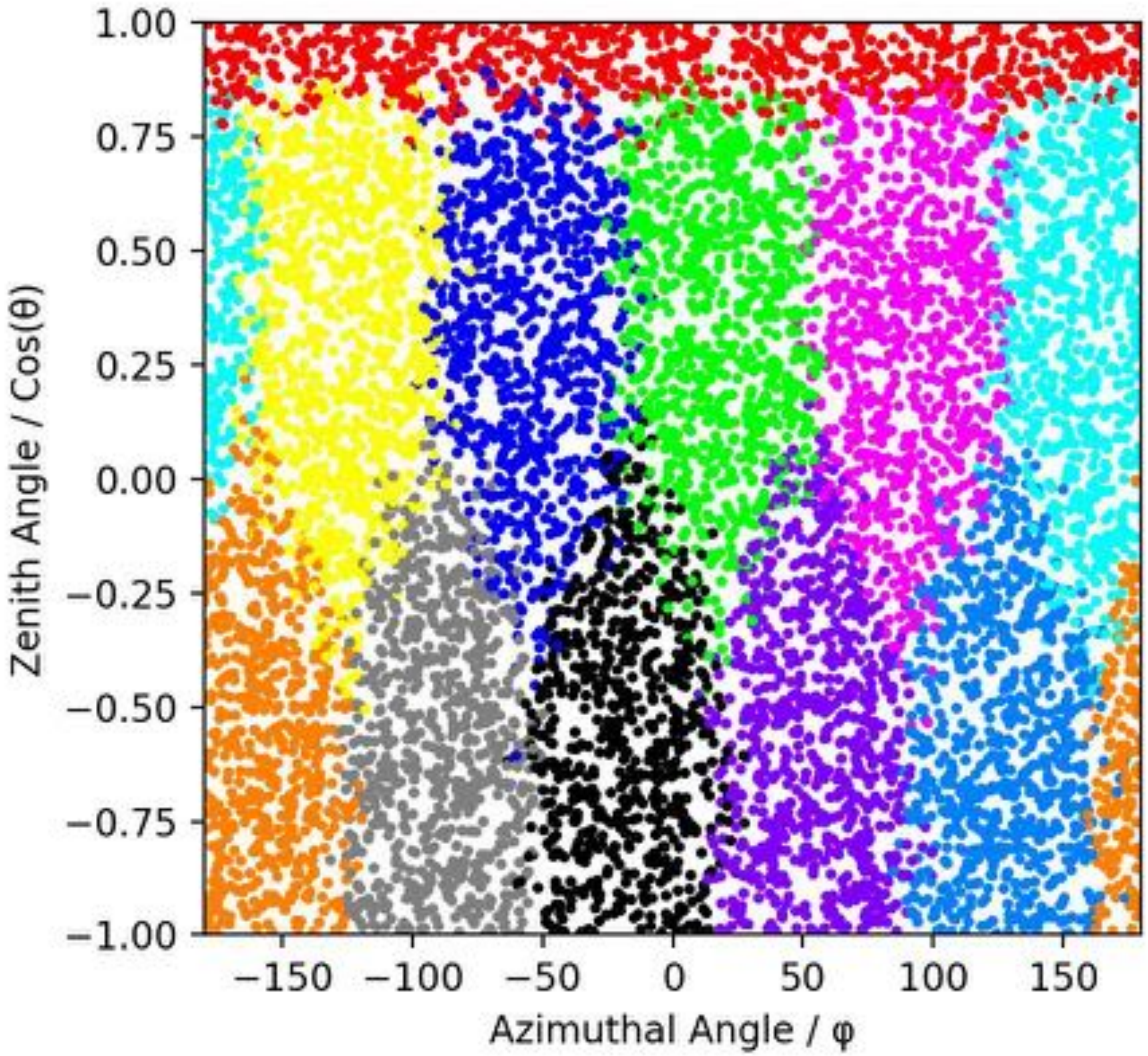

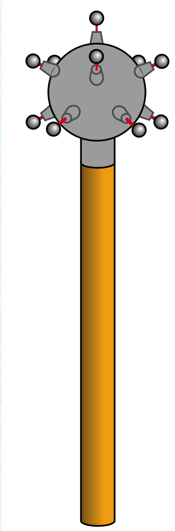

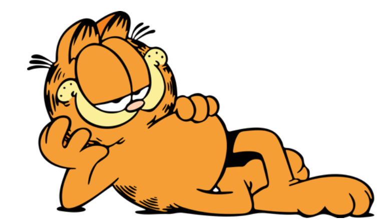

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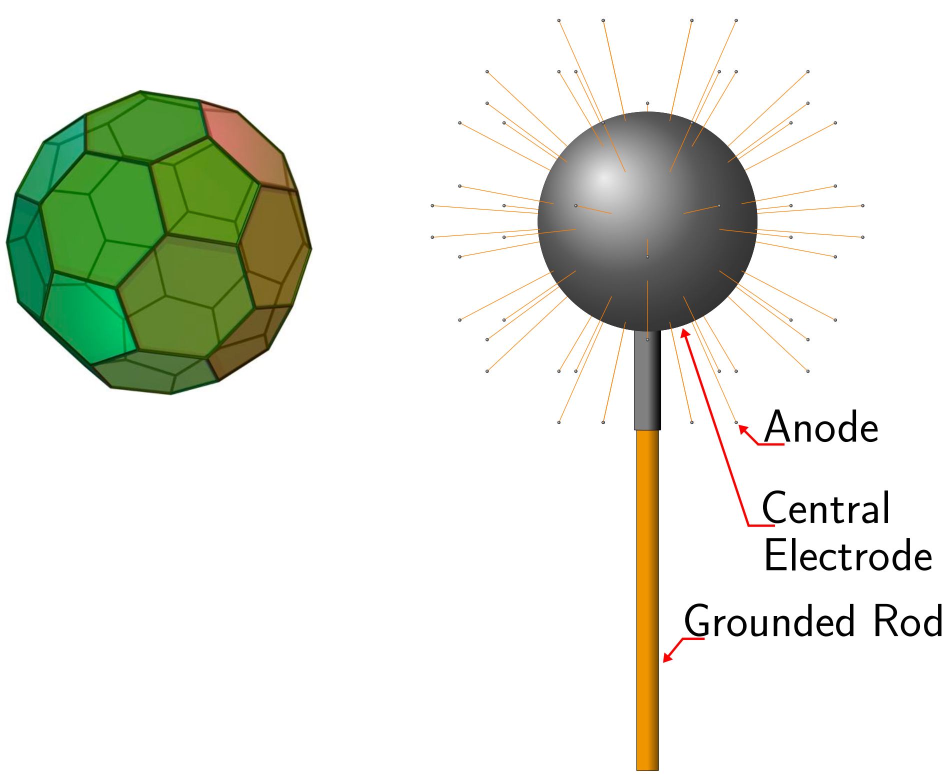
Birmingham simulation framework, combining strengths of Geant4 and Garfield++

JINST 15 (2020) 06, C06013

Many anodes with individual read-out: track reconstruction



60-anodes (truncated icosahedron)

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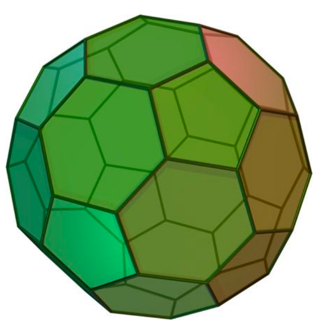

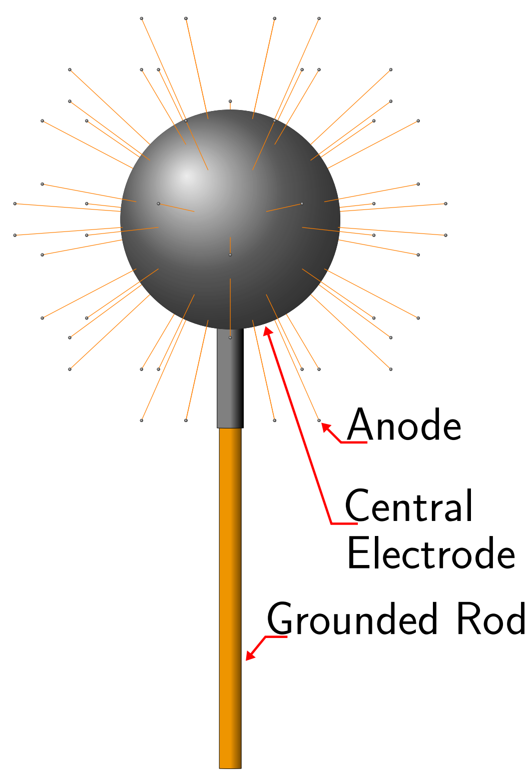

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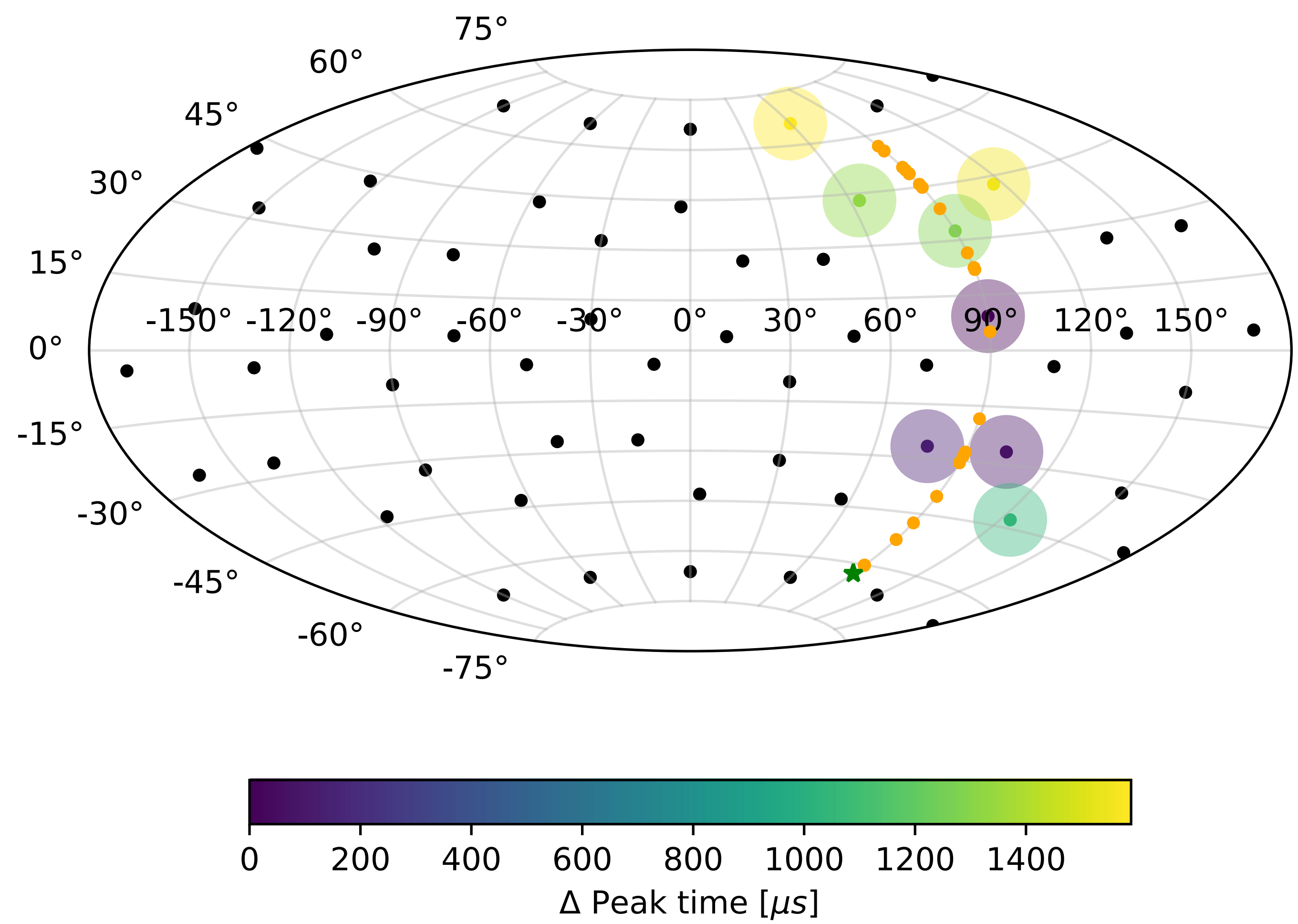

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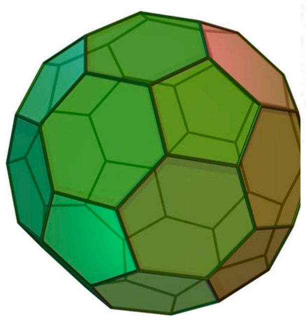

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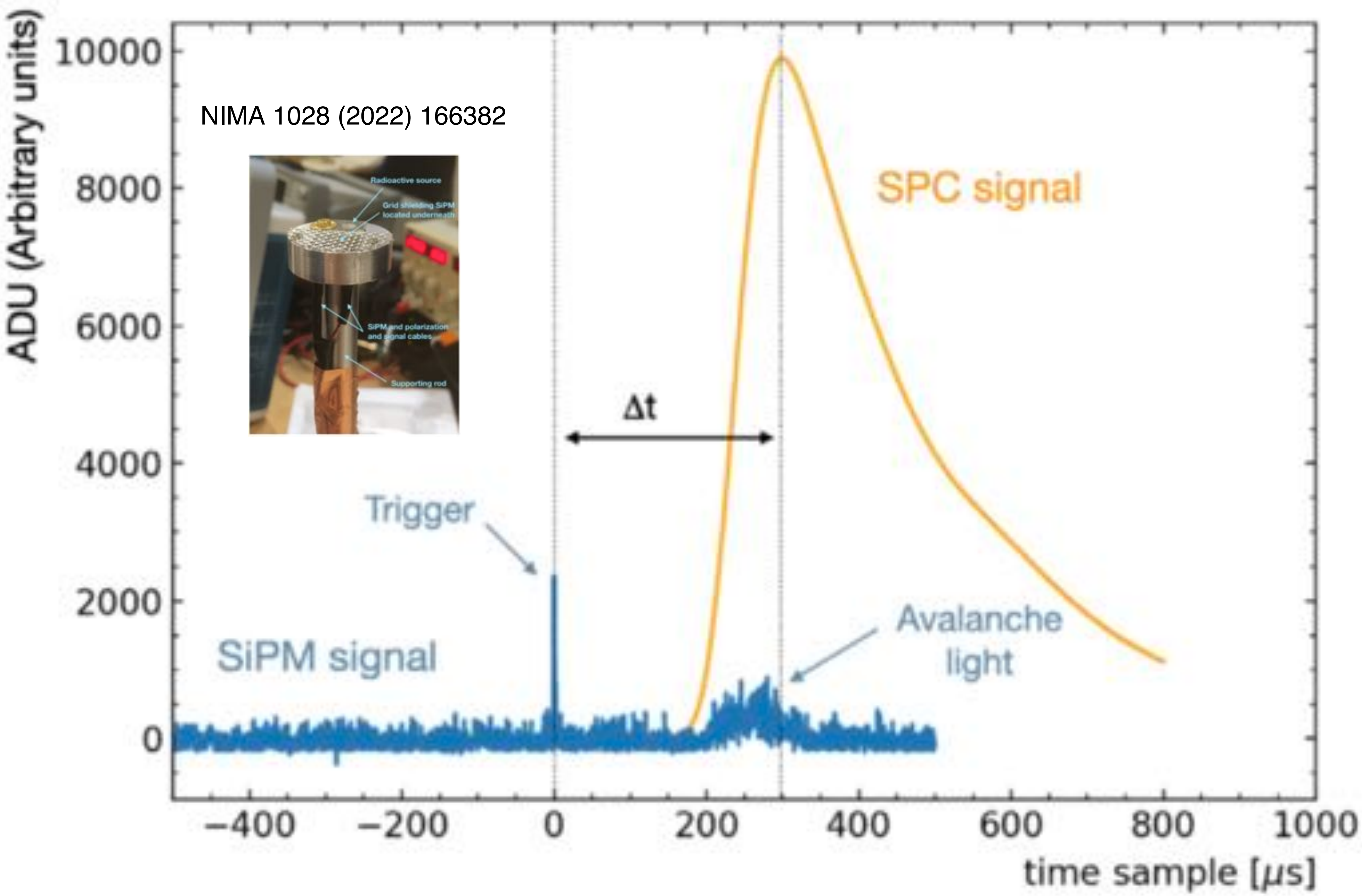
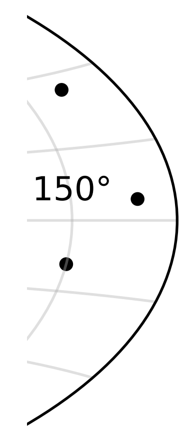
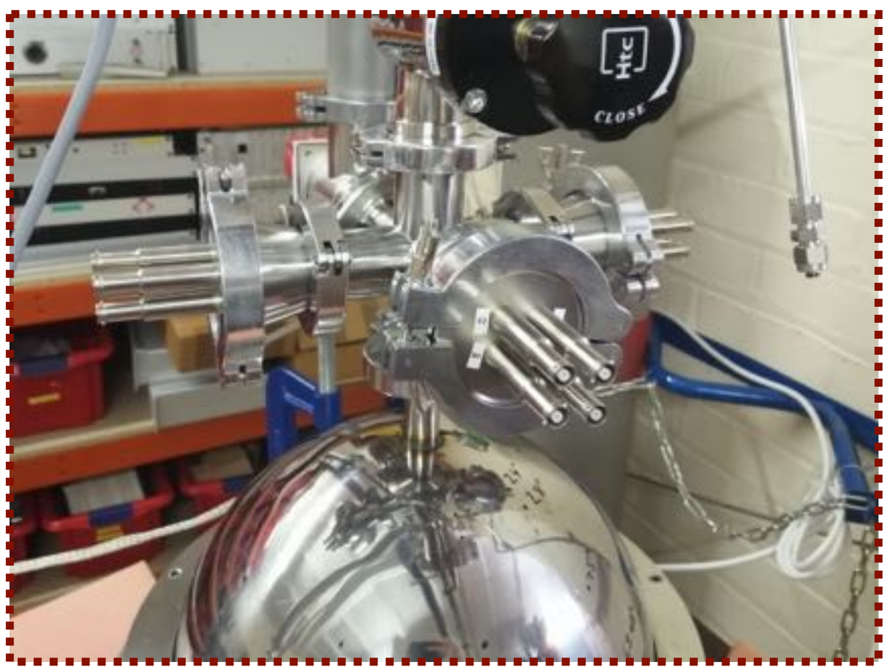
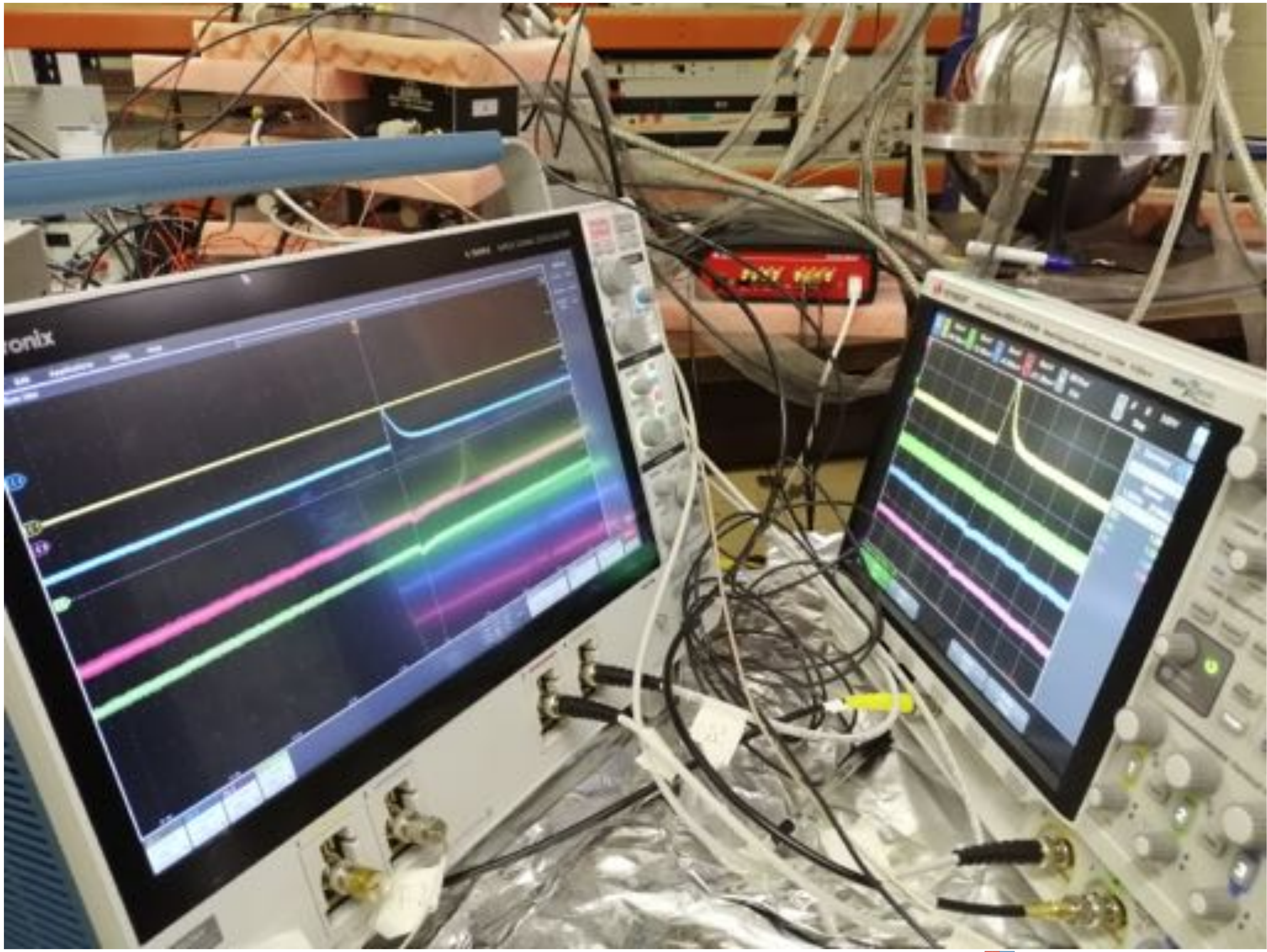




Event reconstruction

- Work underway to individually readout 11 anodes with custom-built preamplifier boxes
- Data with 200 mbar Ar:CH4 (2%) and ^{210}Po α-particles
  - Range ~15 cm
  - See 'tracks' where multiple anodes collect electrons
  - See induced signal on other anodes (negative)





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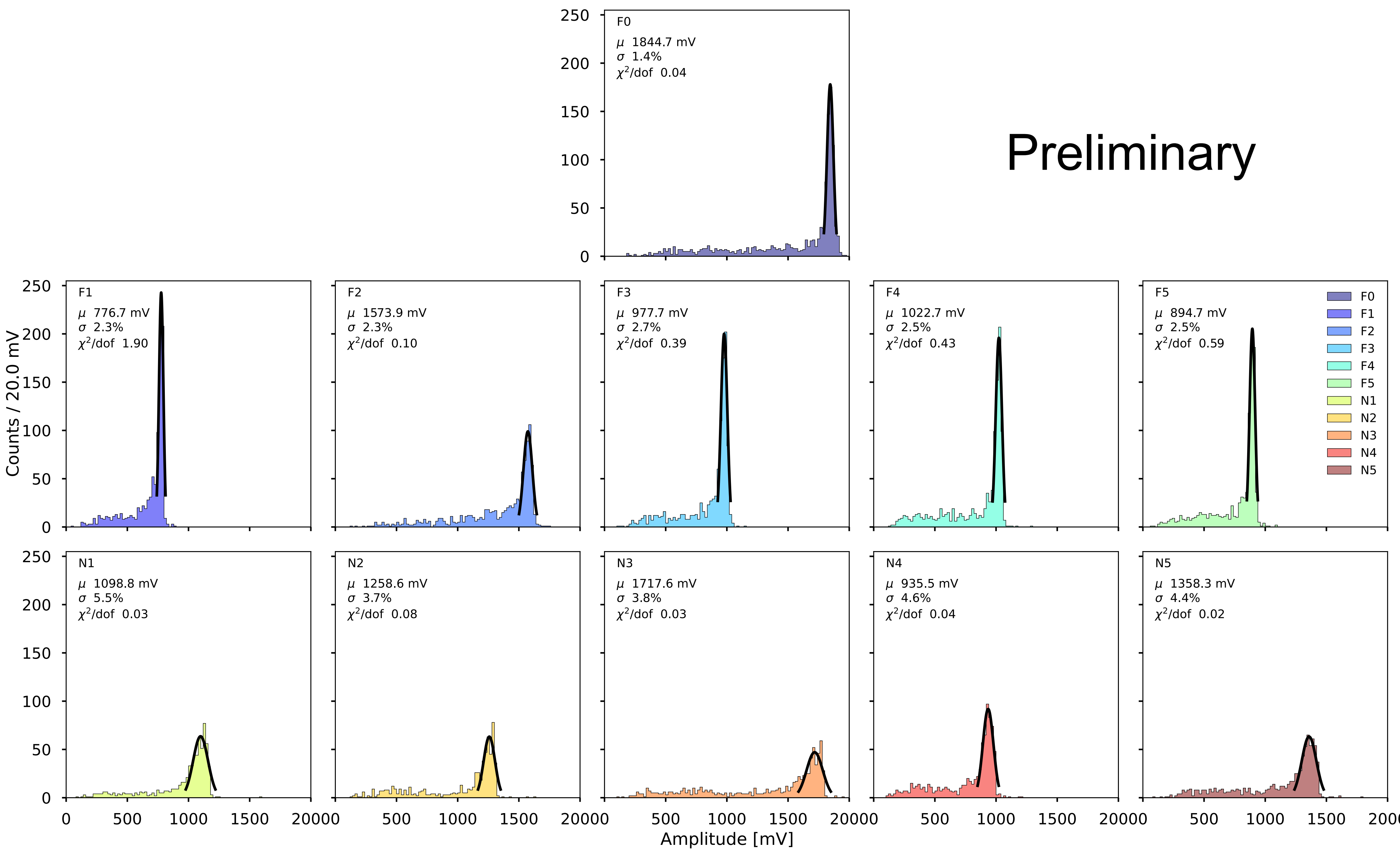
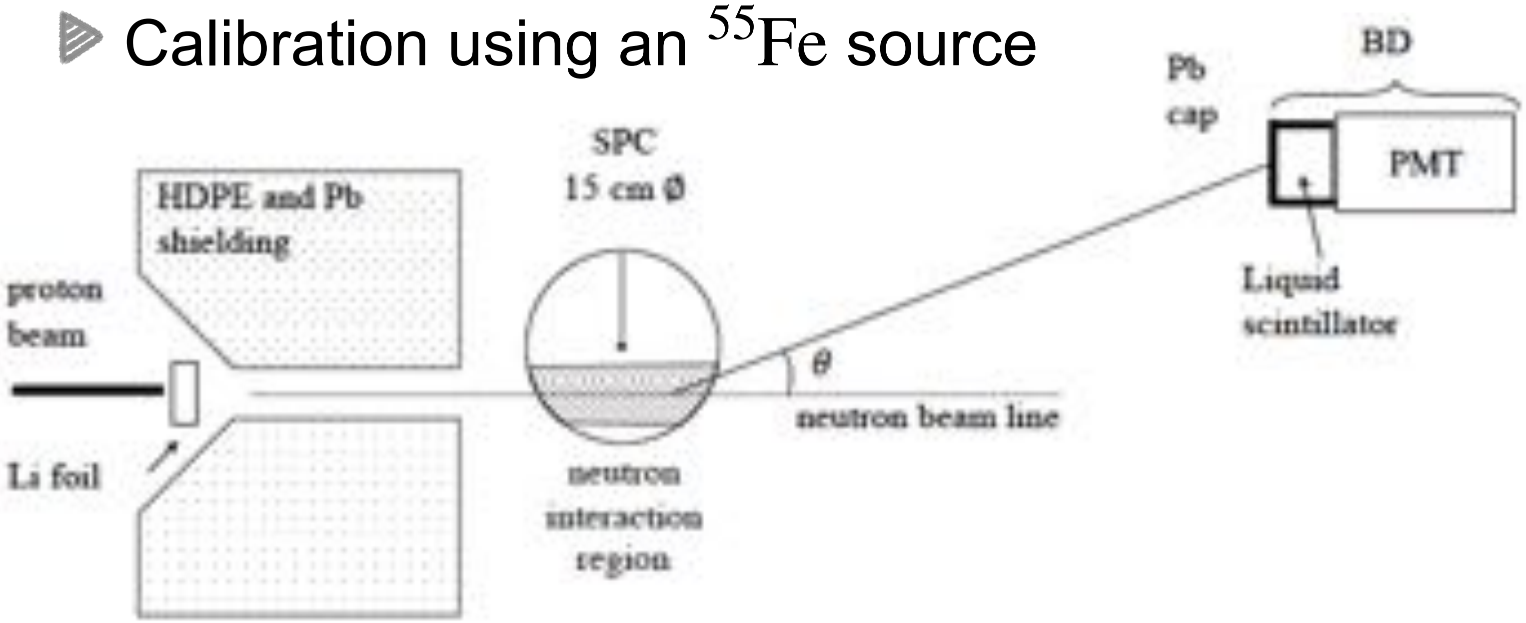


Estimating the expected response

Quenching factor measurements: TUNL

- TANDEM Van de Graaff accelerator at TUNL (USA)
- Pulsed 20 MeV proton beam on $^{7}\mathrm{Li}$
  - (Quasi-)Mono-energetic neutrons at a given angle
  - Neutron energy at $0°$: $545 \pm 20\ \mathrm{keV}$
- Detector: ∅15 cm stainless-steel SPC
  - Calibration using an $^{55}\mathrm{Fe}$ source



Phys.Rev.D 105 (2022) 5, 052004

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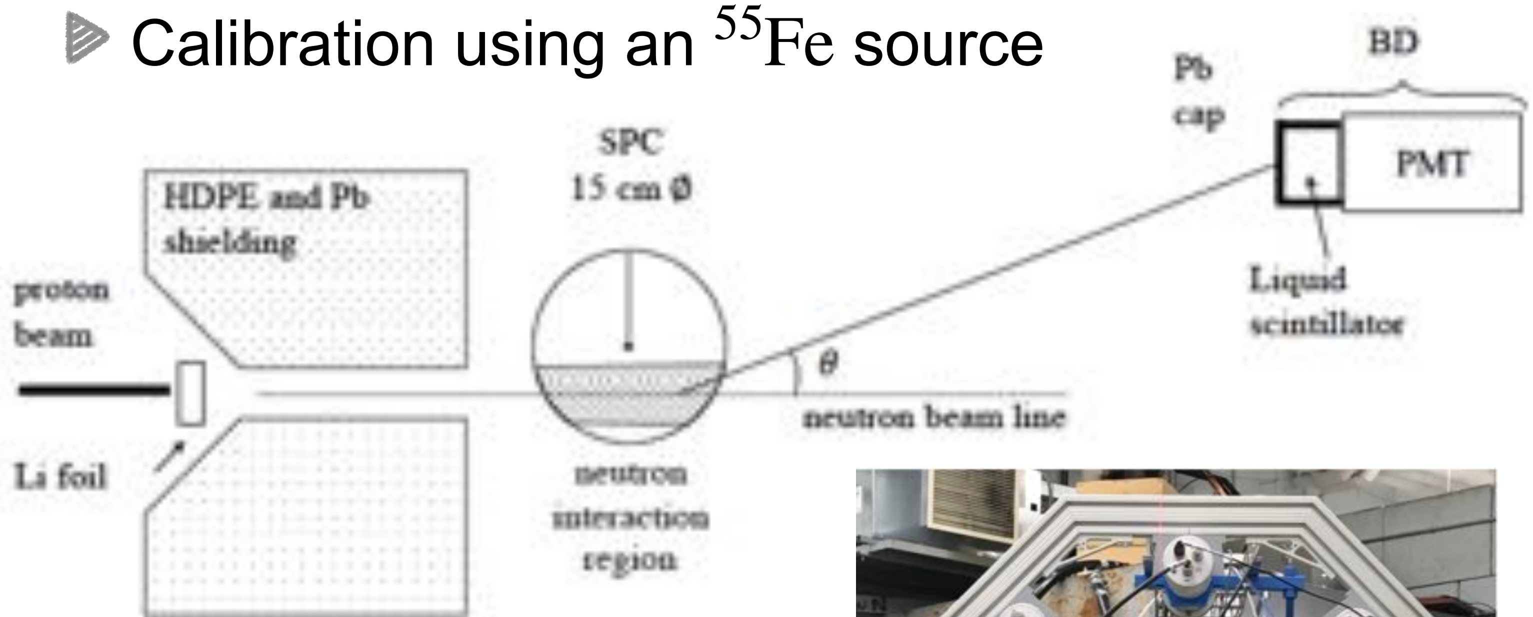
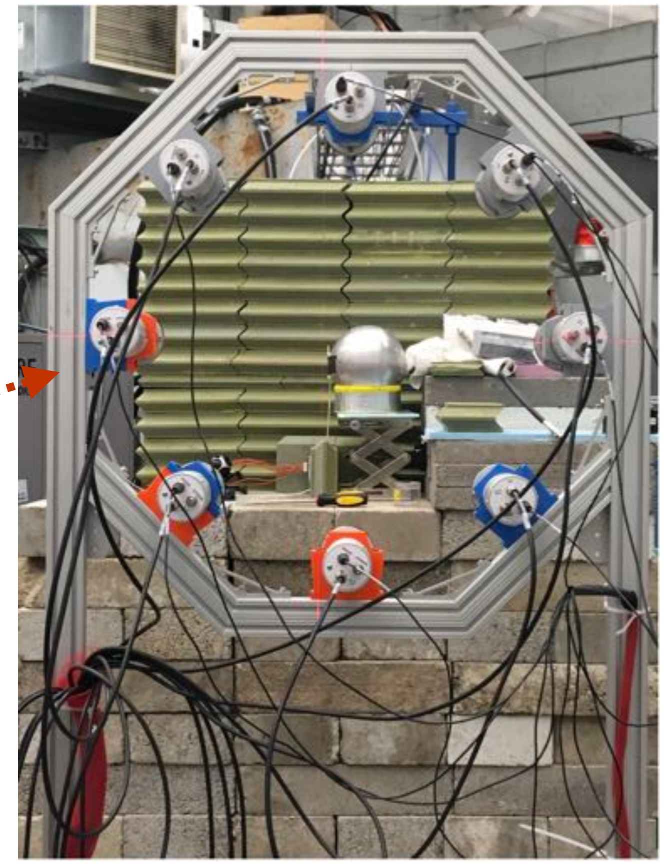


liquid-scintillator/PMT backing detectors



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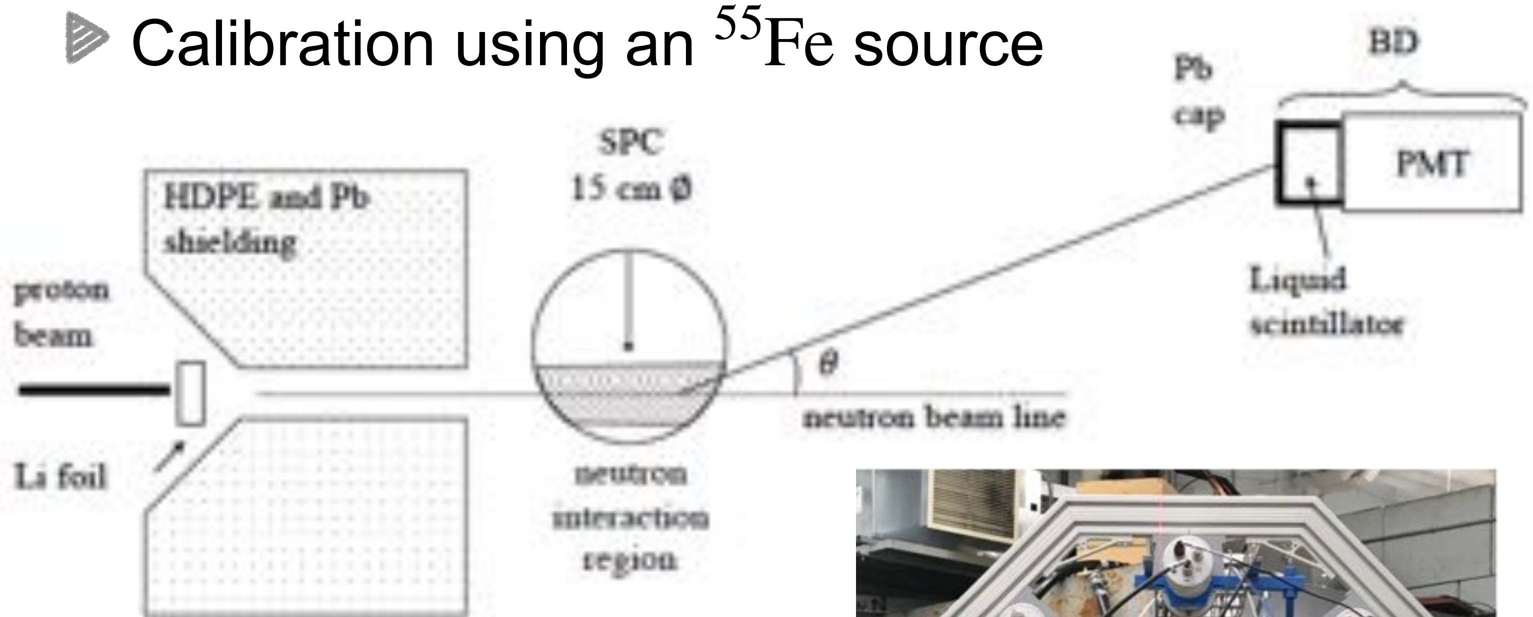
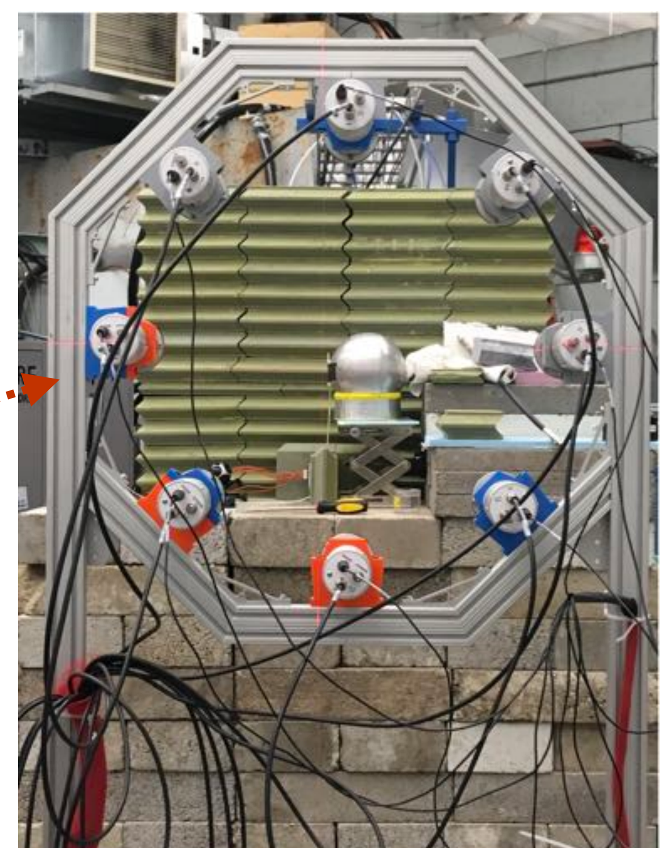
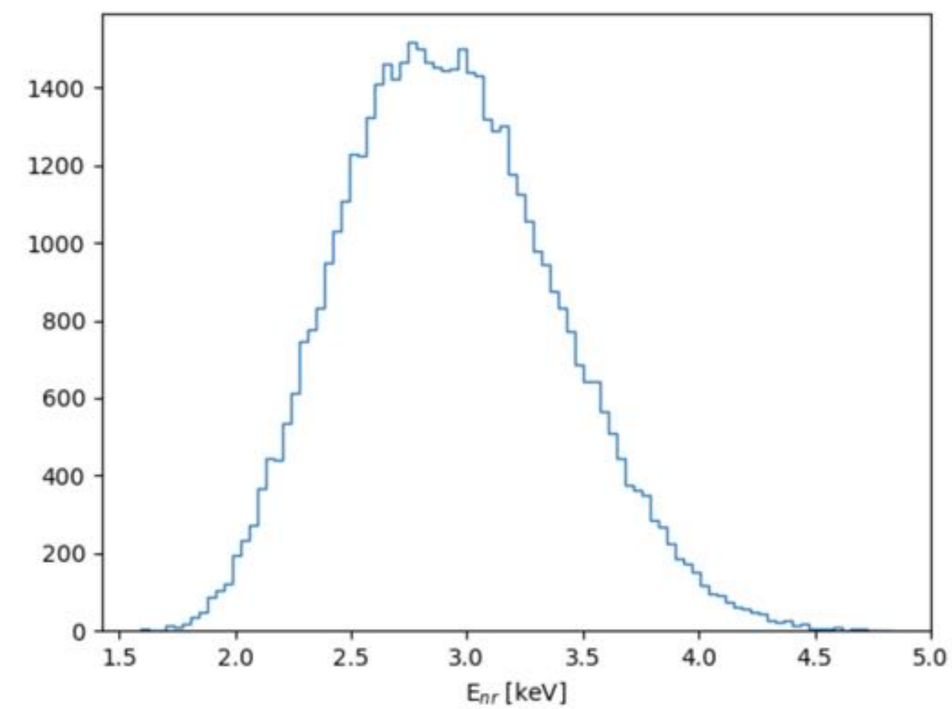


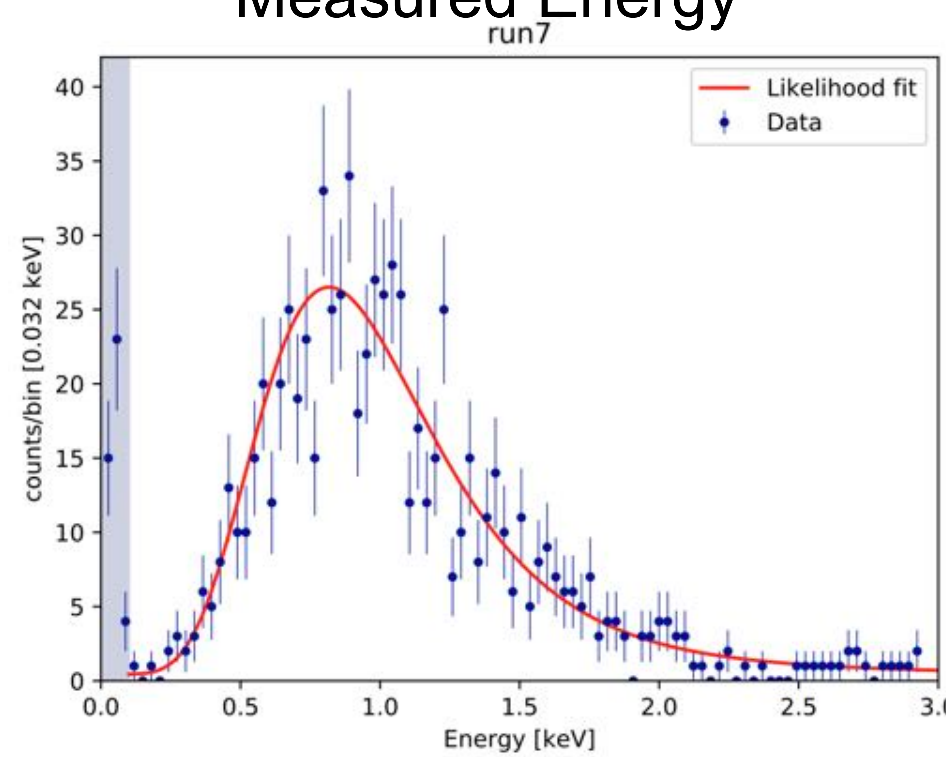


liquid-scintillator/PMT backing detectors

Estimated Recoil Energy



Measured Energy



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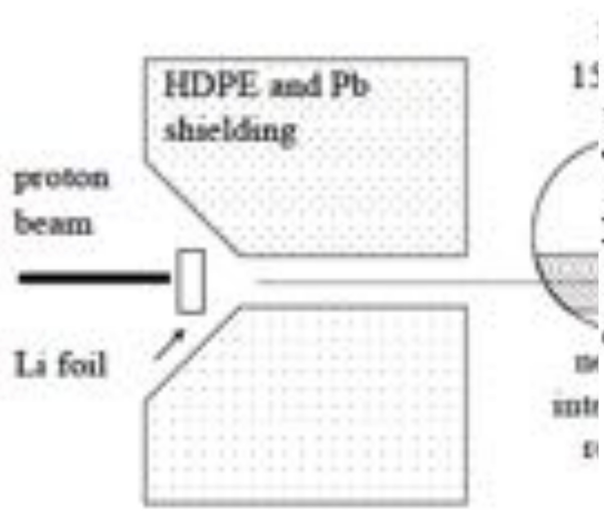

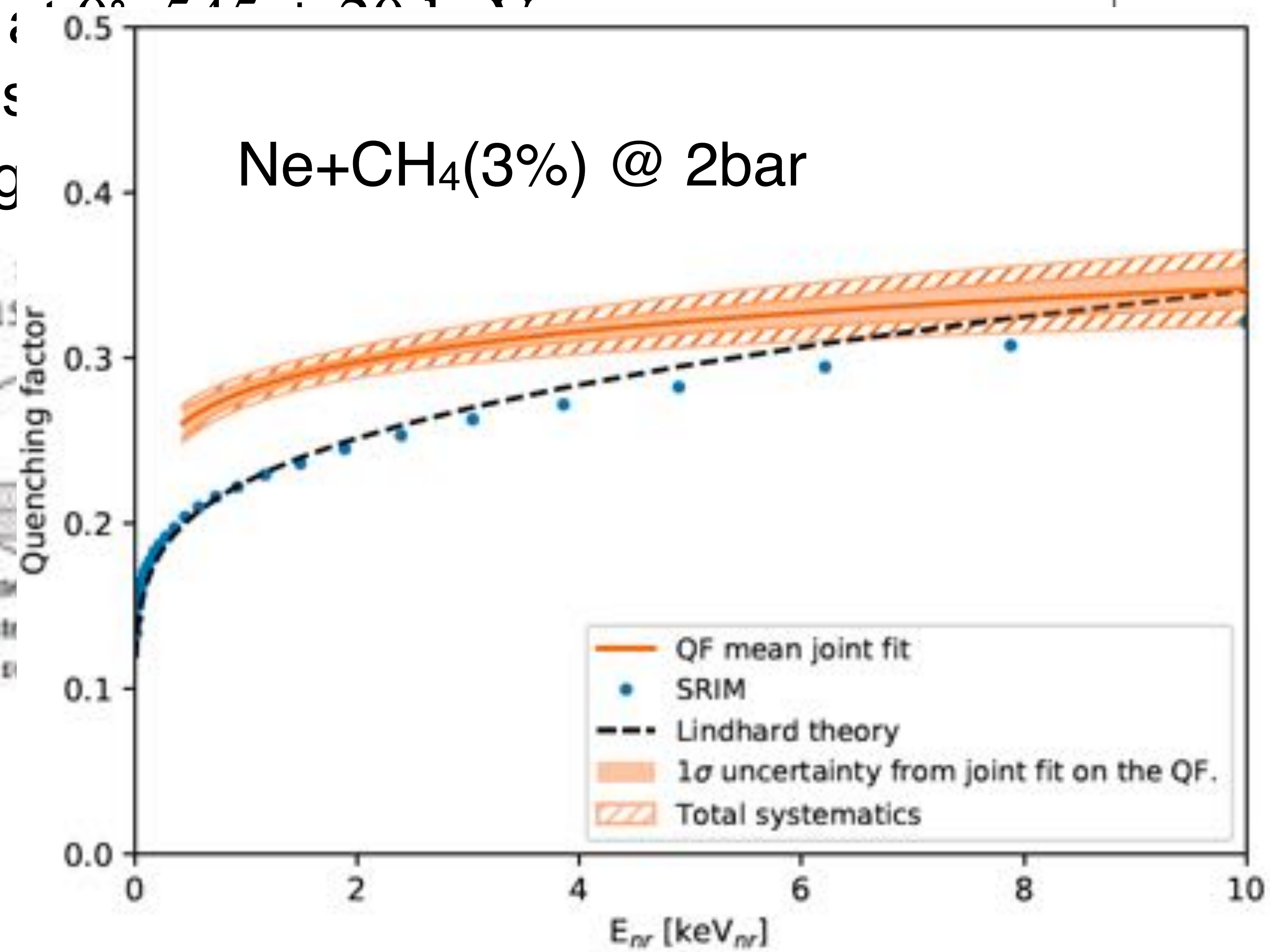

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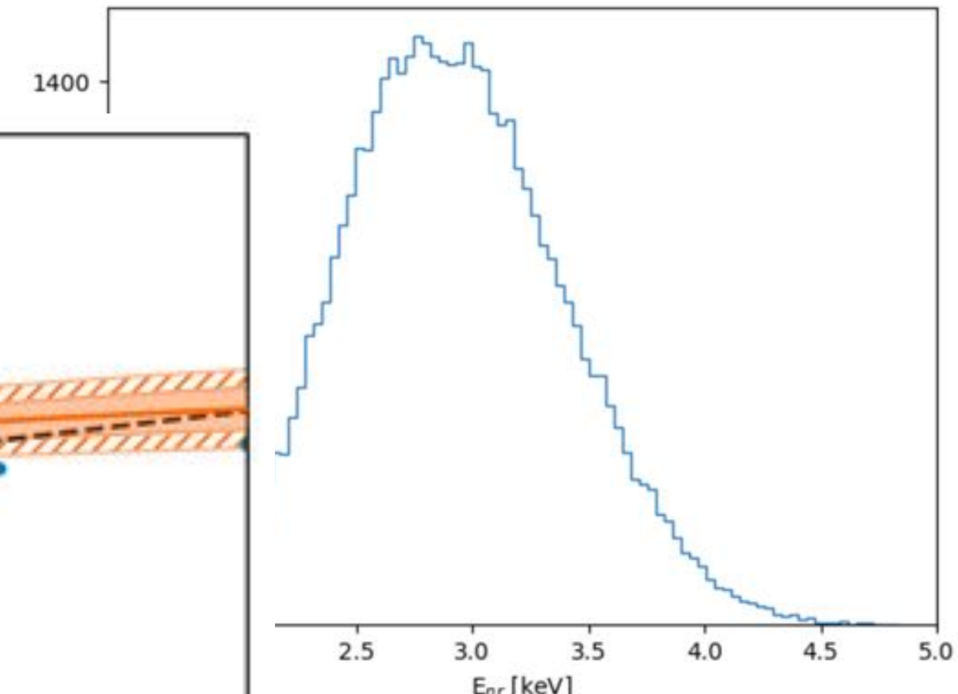

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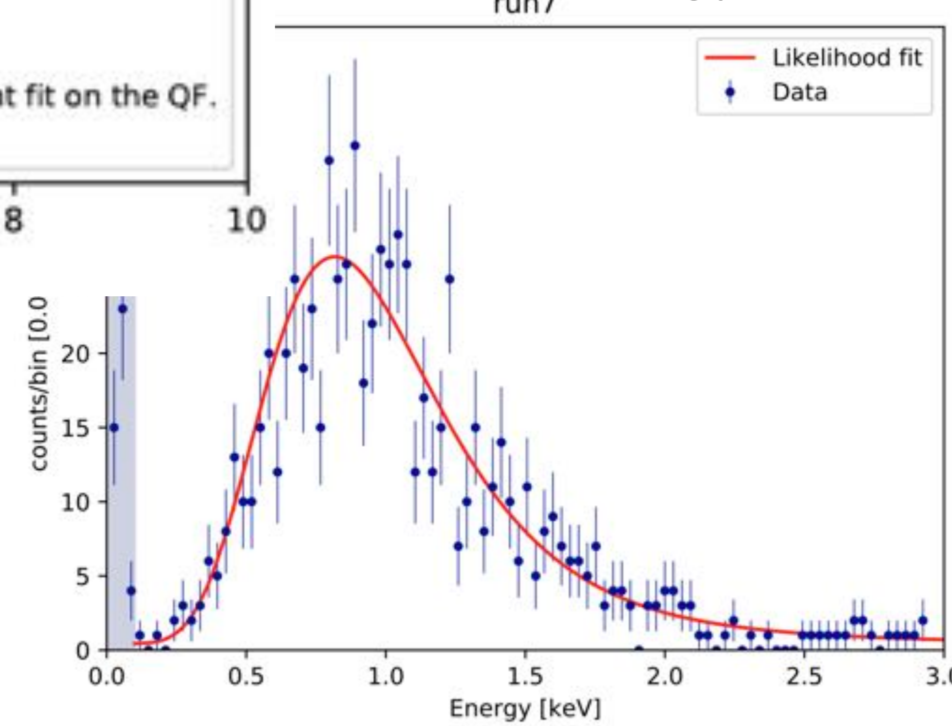

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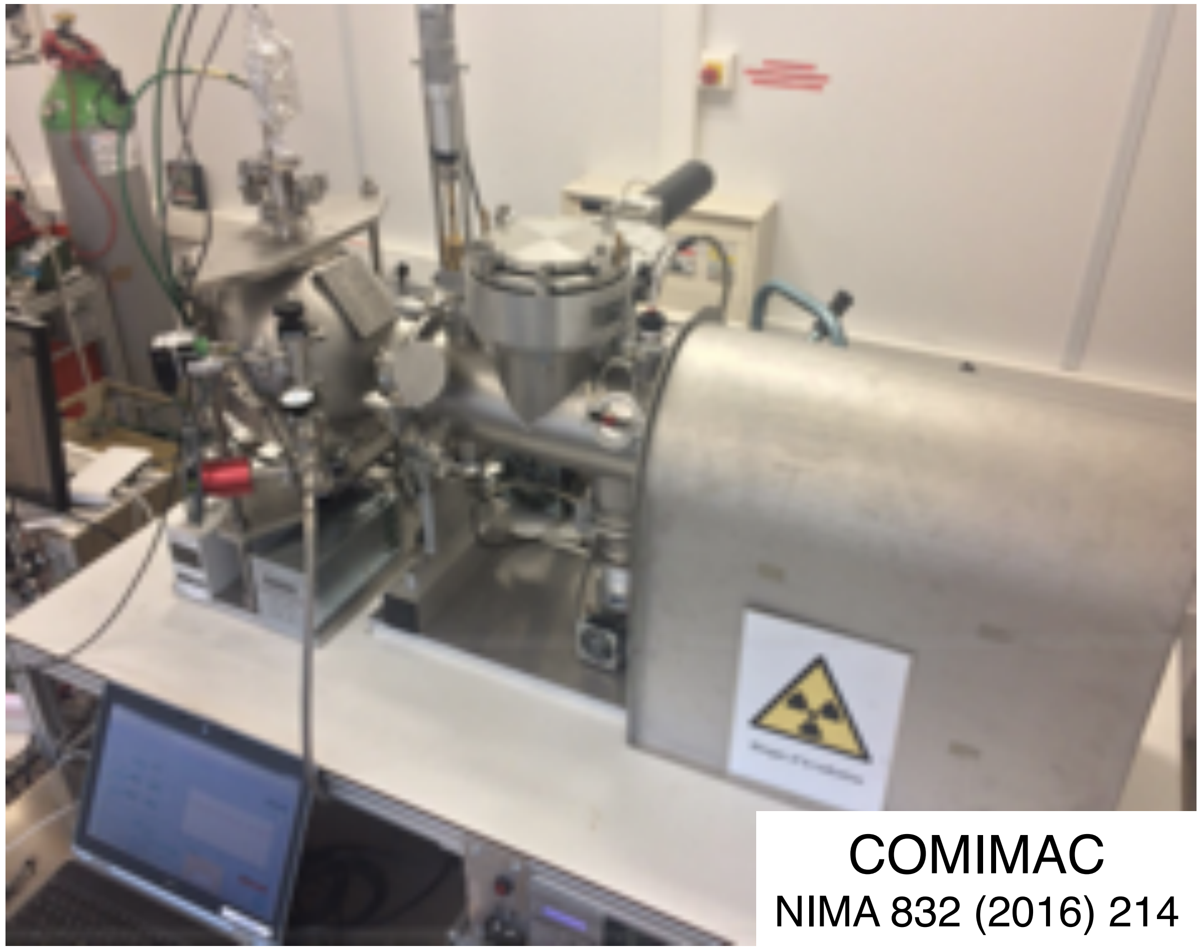
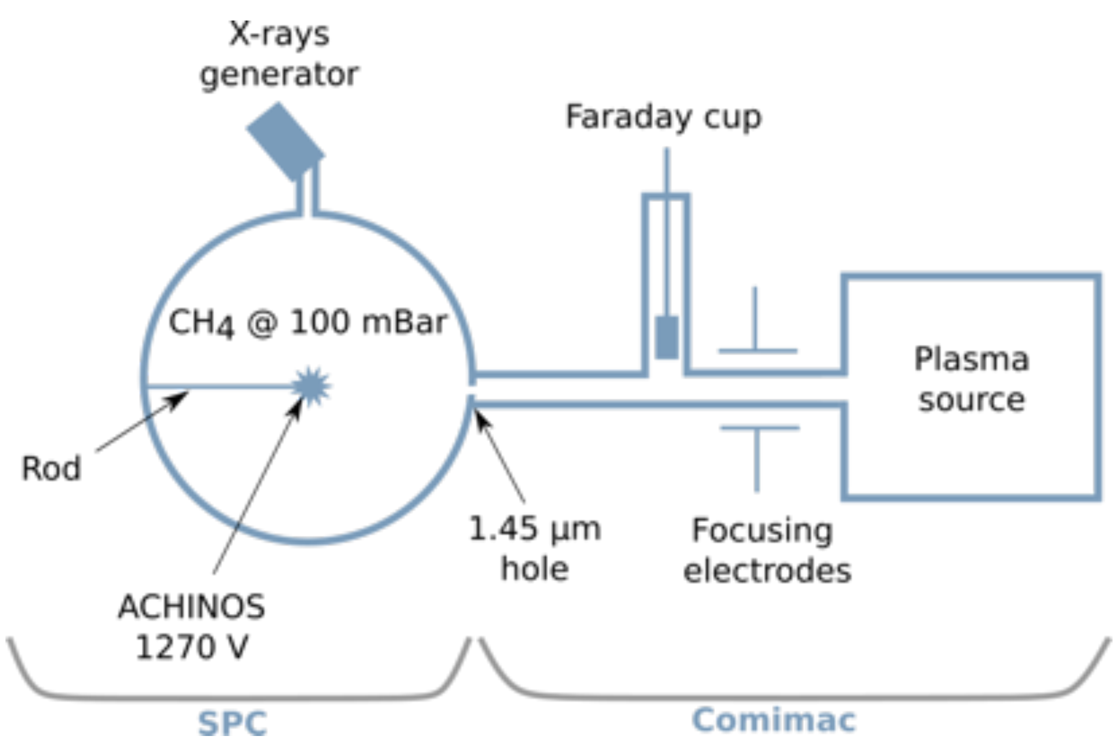


COMIMAC
NIMA 832 (2016) 214



Eur.Phys.J.C 82 (2022) 12, 1114

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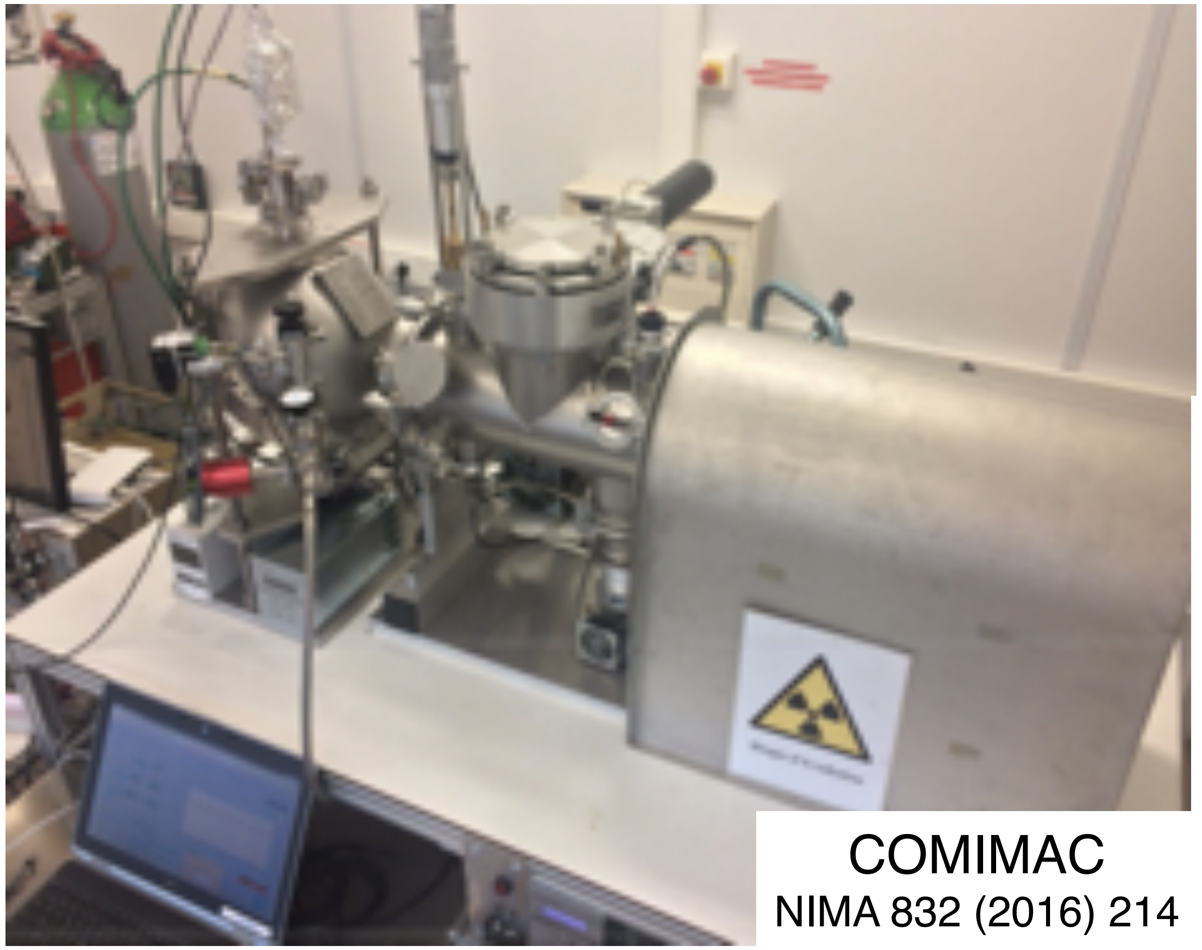

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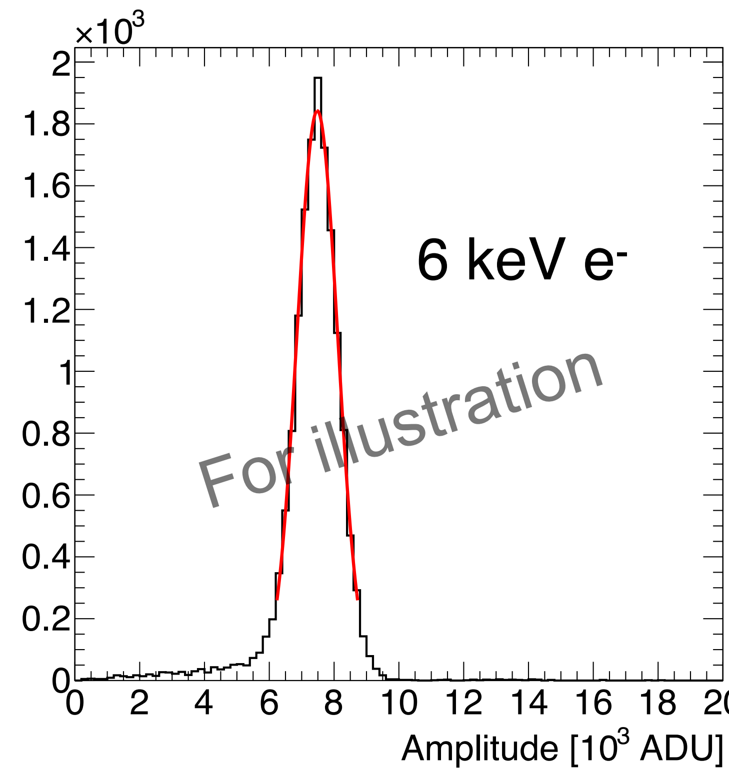

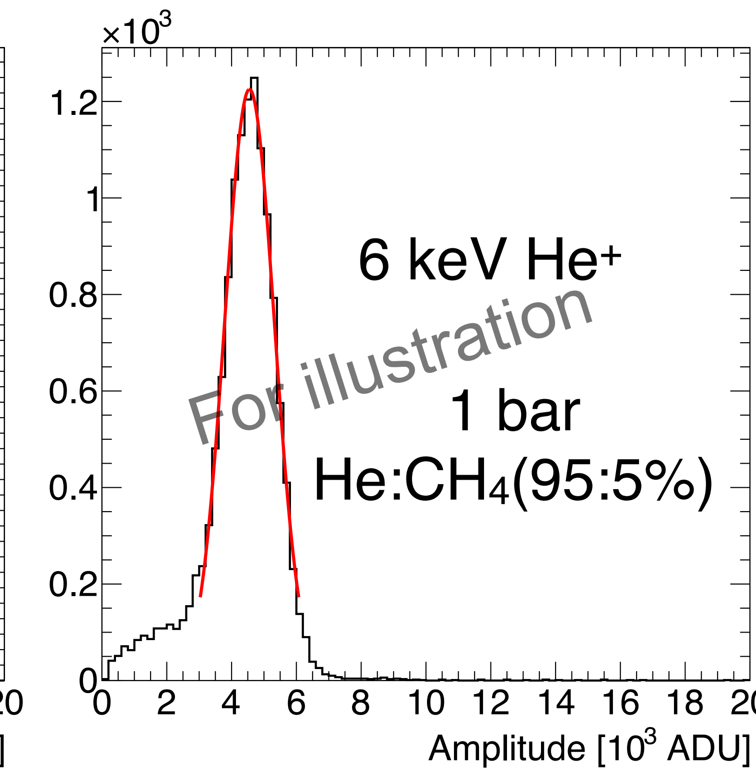

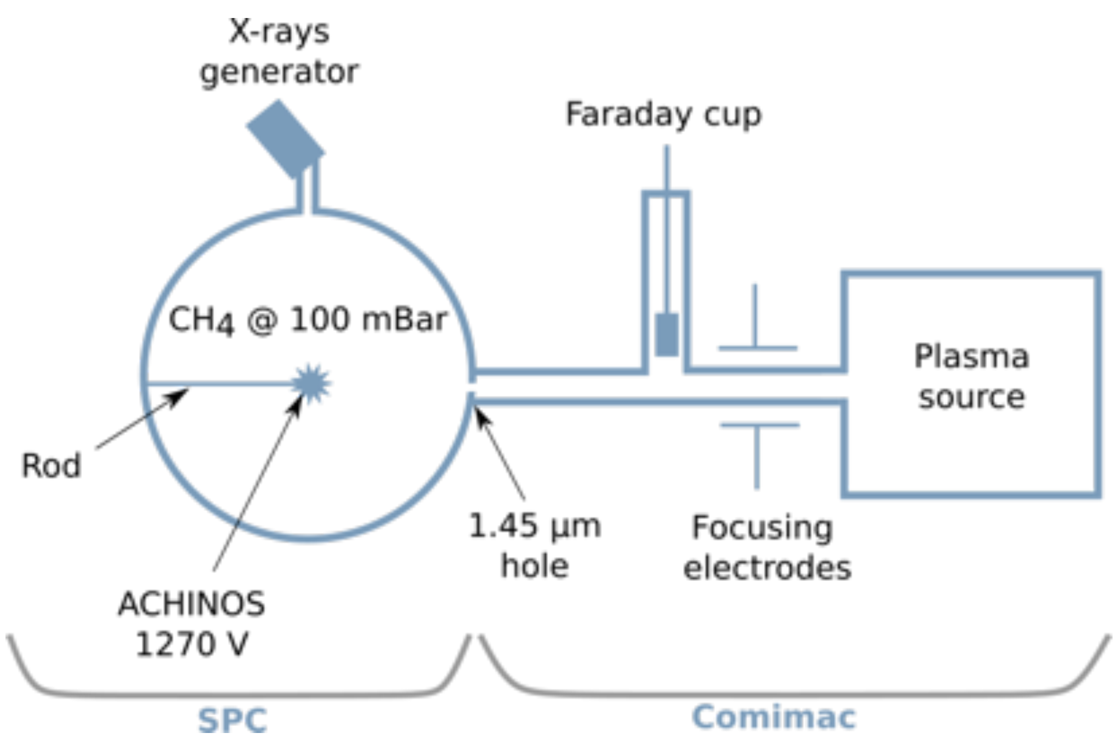

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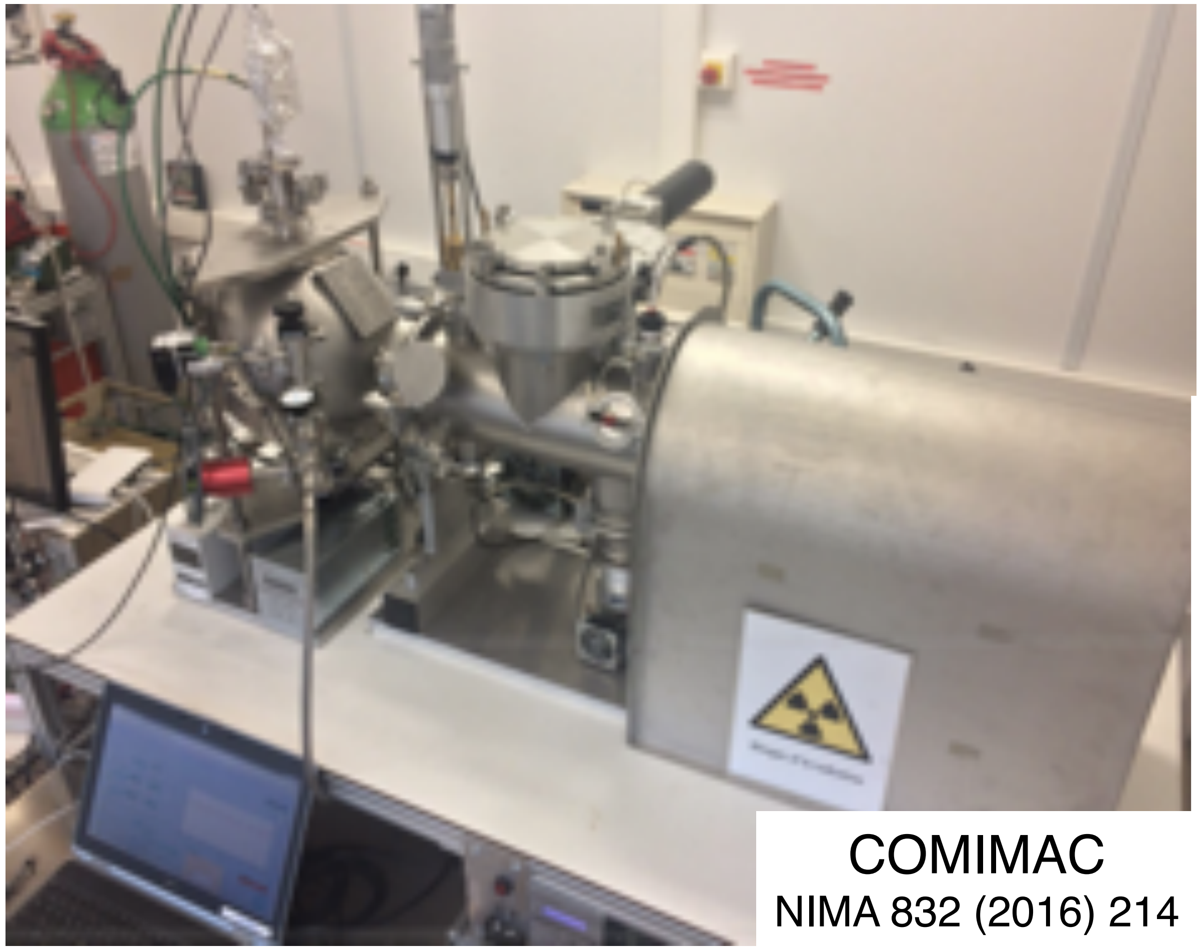

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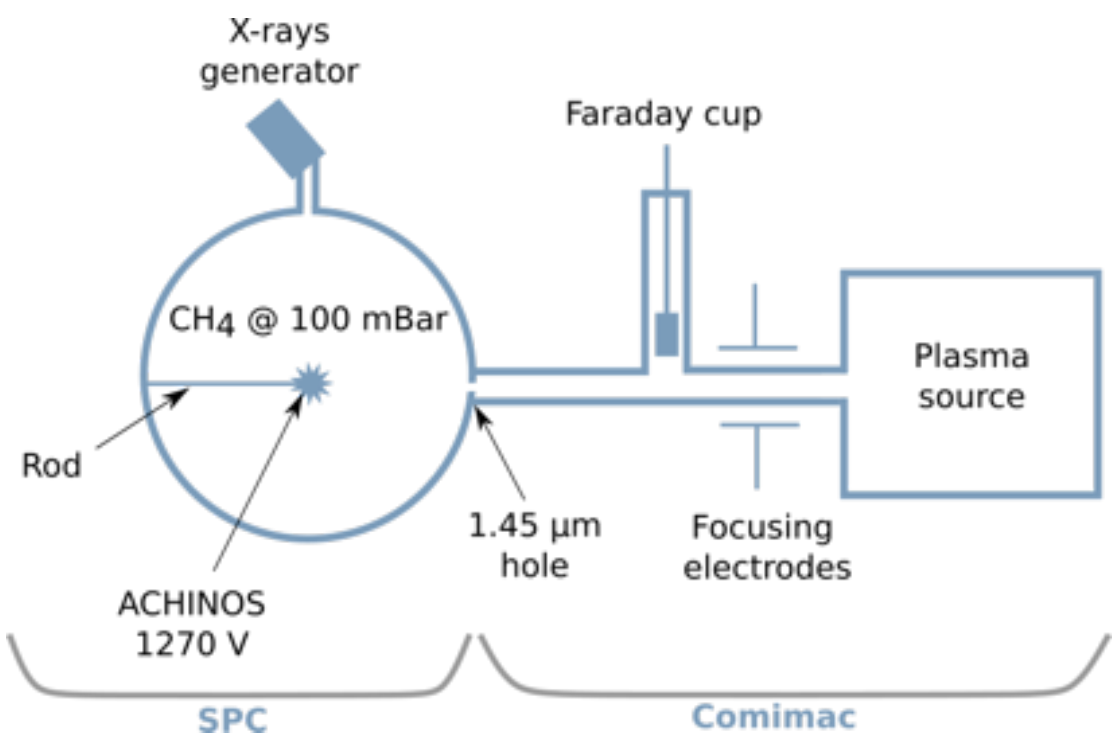

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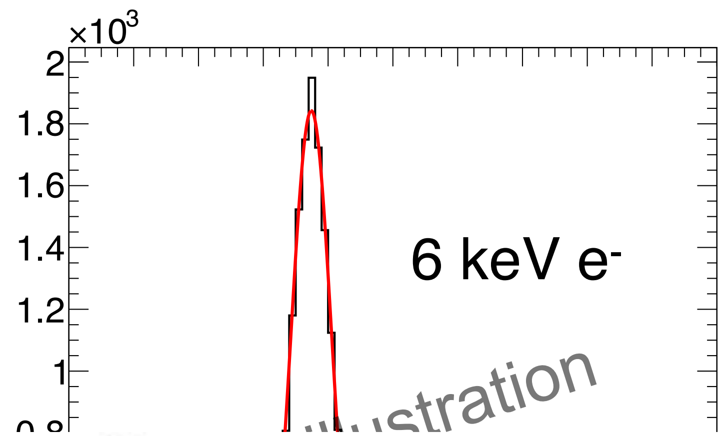
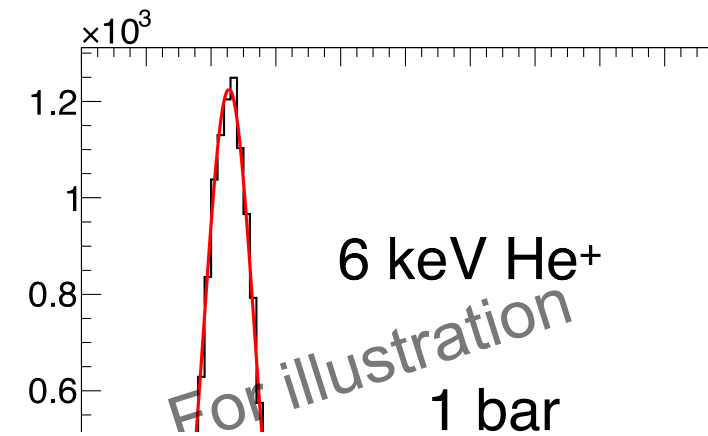
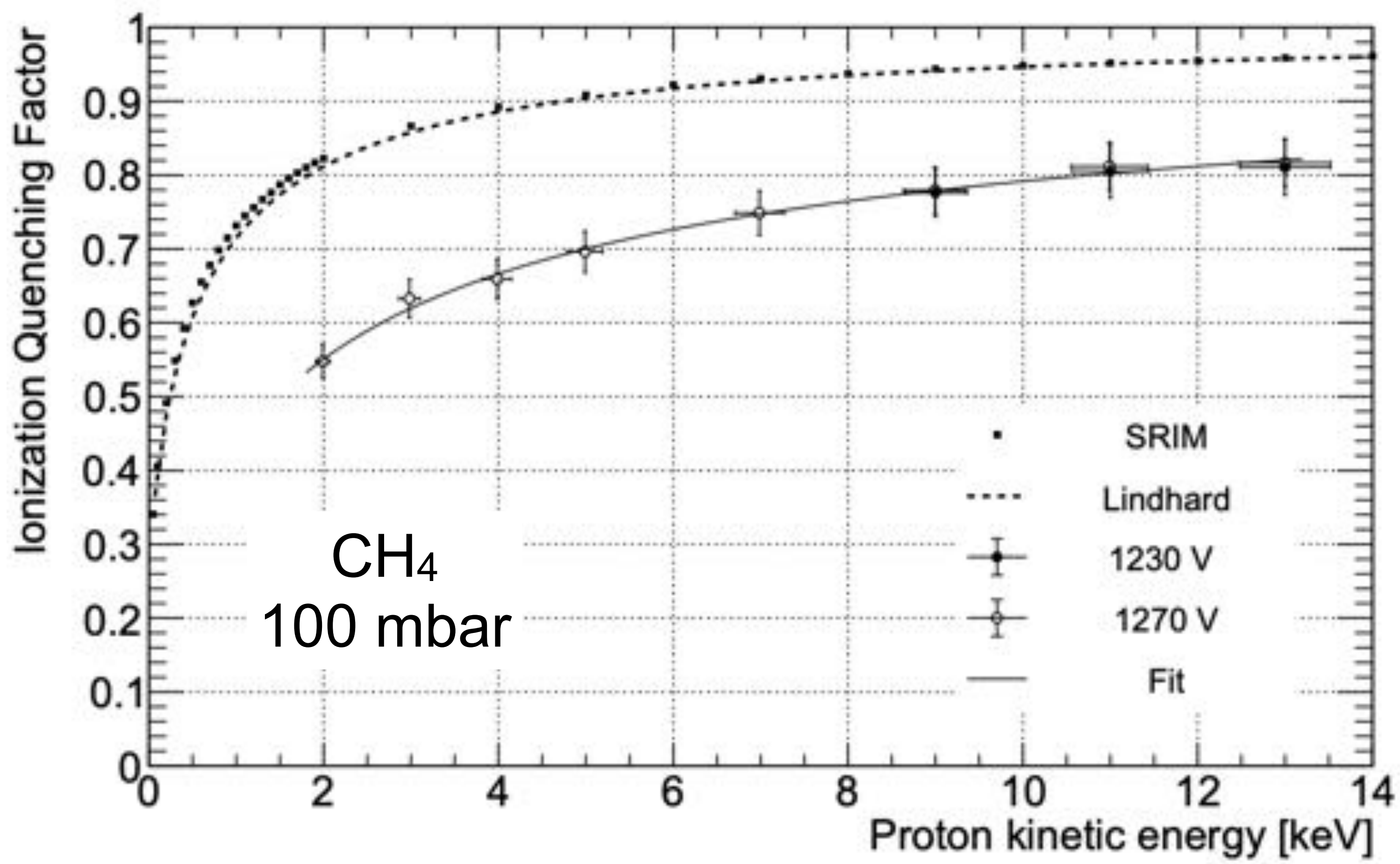


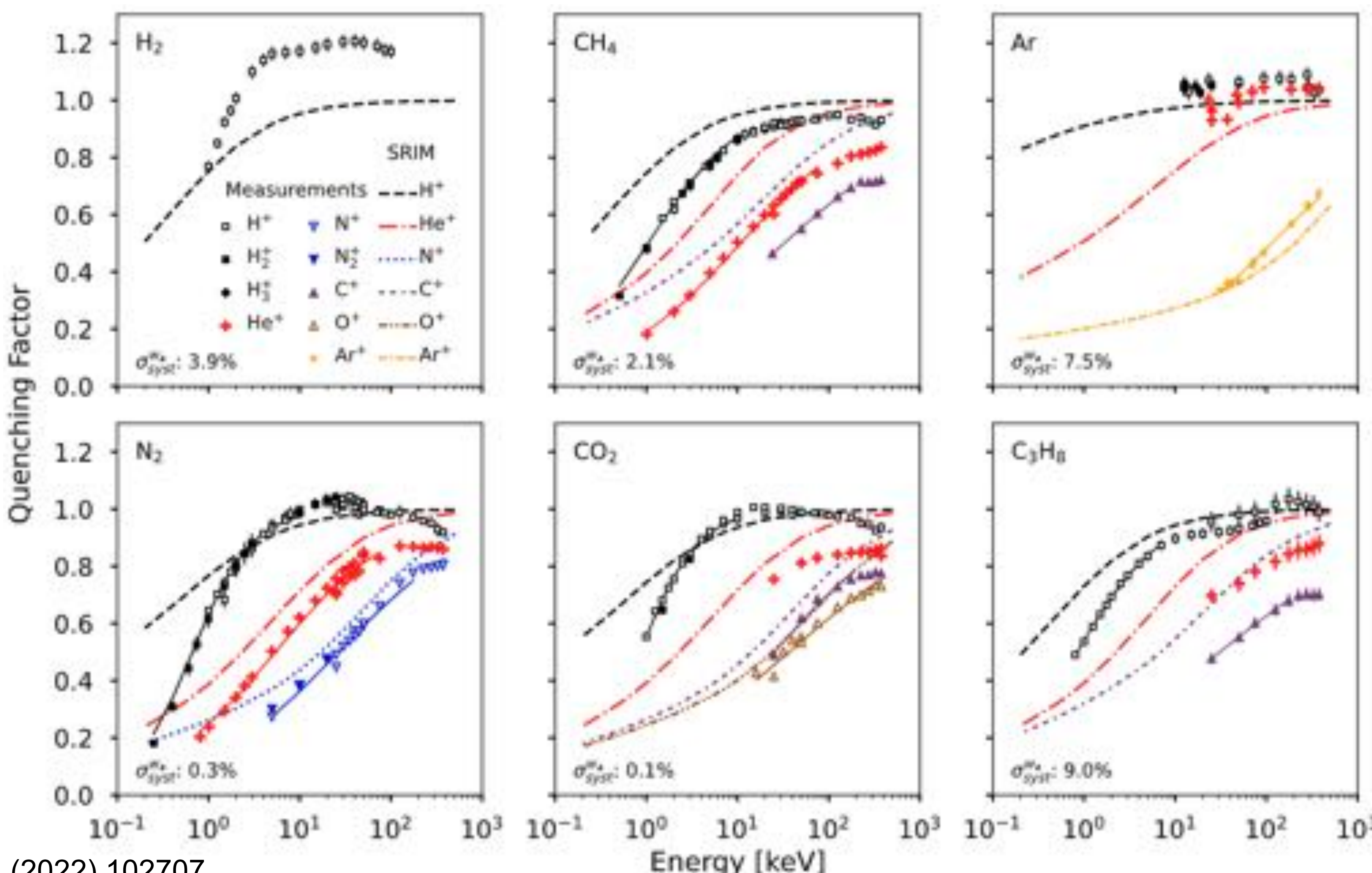




Quenching factor: W-value measurements

- Quenching factor intimately connected to W-value
  - W-value is the average energy required to liberate an e-ion pair
  - Typically, detector response calibrated with electrons of known energy

$$q_f(E) = \frac{E_{ee}}{E} = \frac{N_i^i \cdot W_e(E)}{E} = \frac{W_e(E)}{W_i(E)}$$



Astropart.Phys. 141 (2022) 102707

In-situ background measurements

Background measurements: neutrons

- **Neutrons: background in DM searches**
  - Identical signature to signal events
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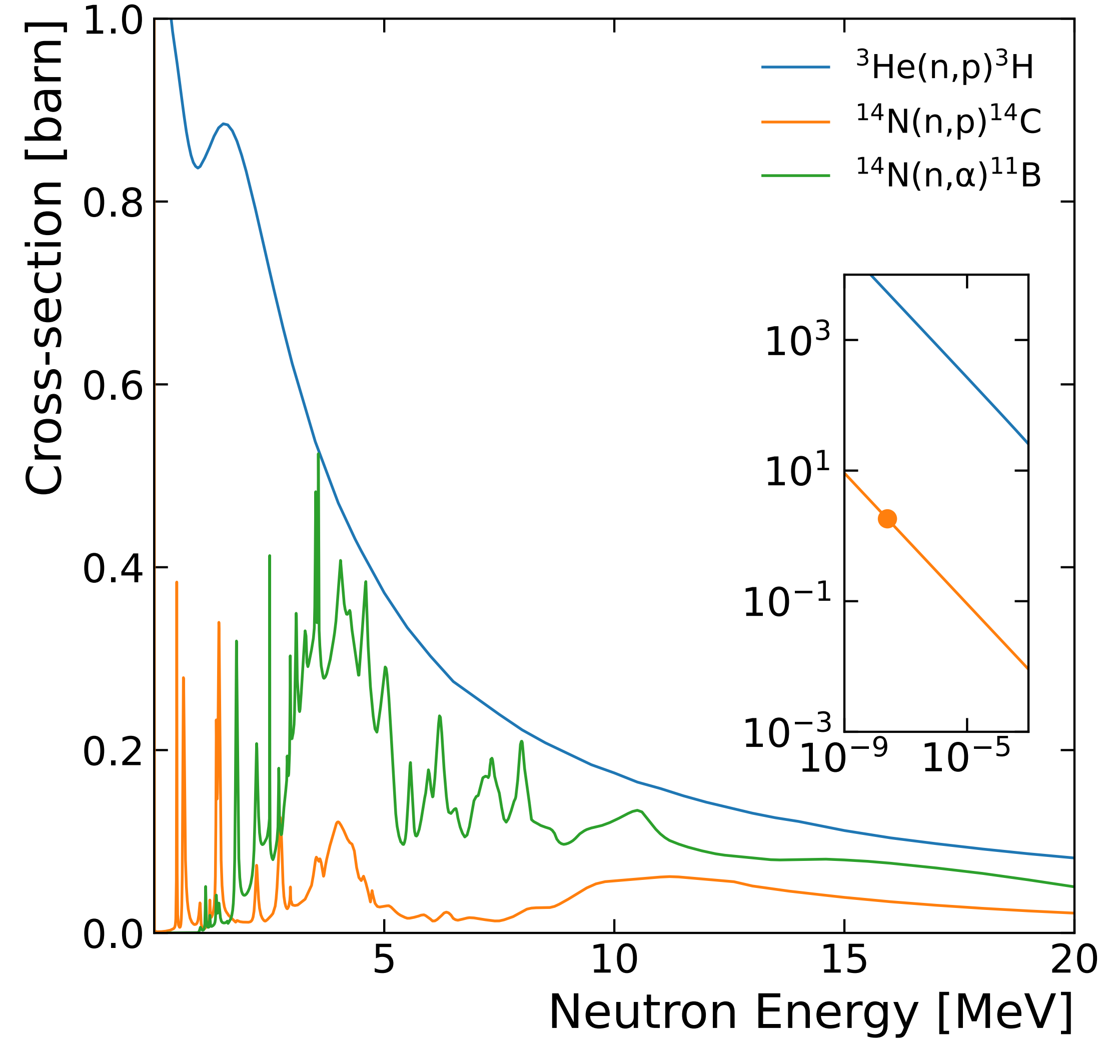

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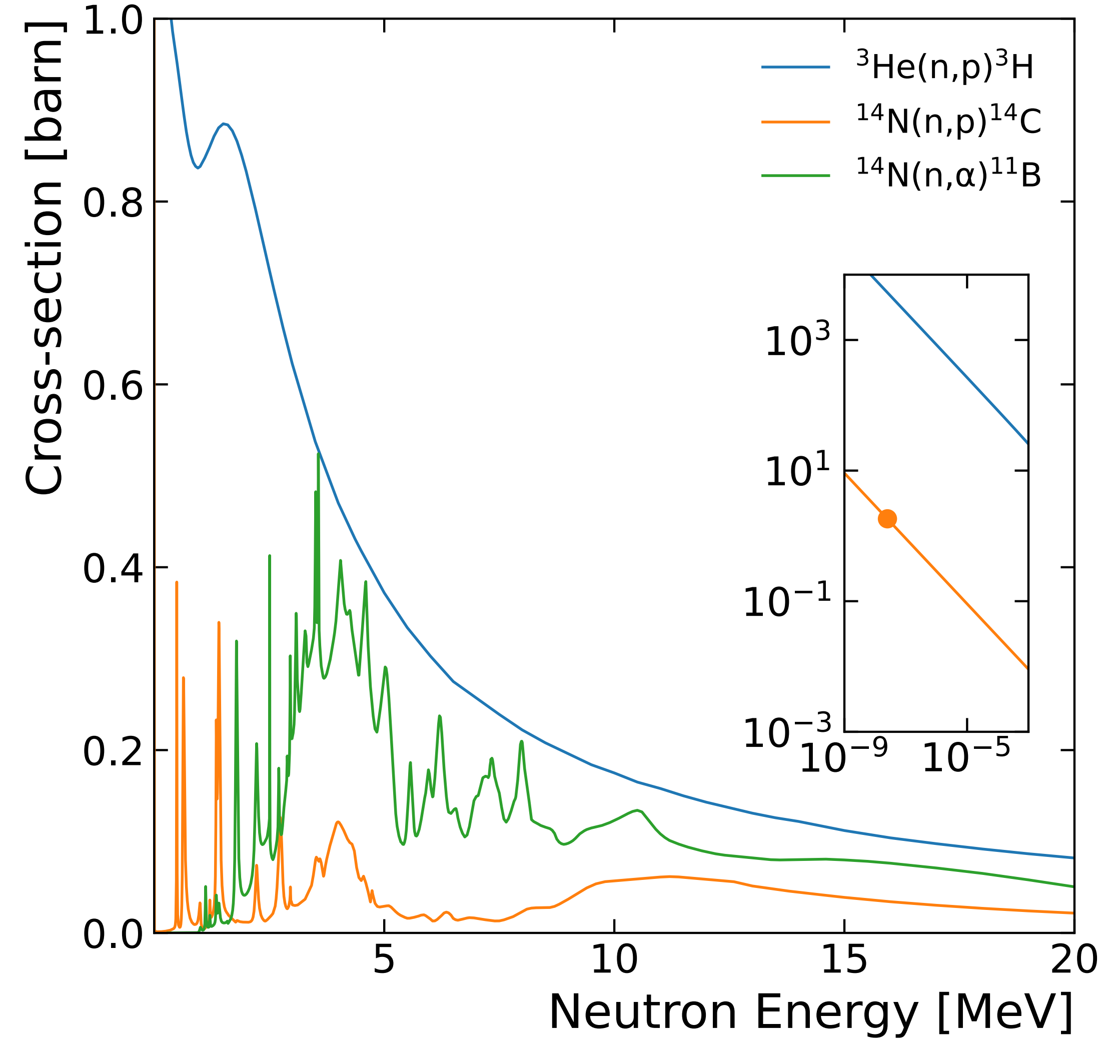
  - Thermal neutrons
  - Operation at 0.2-0.5 bar → HV at 6 kV



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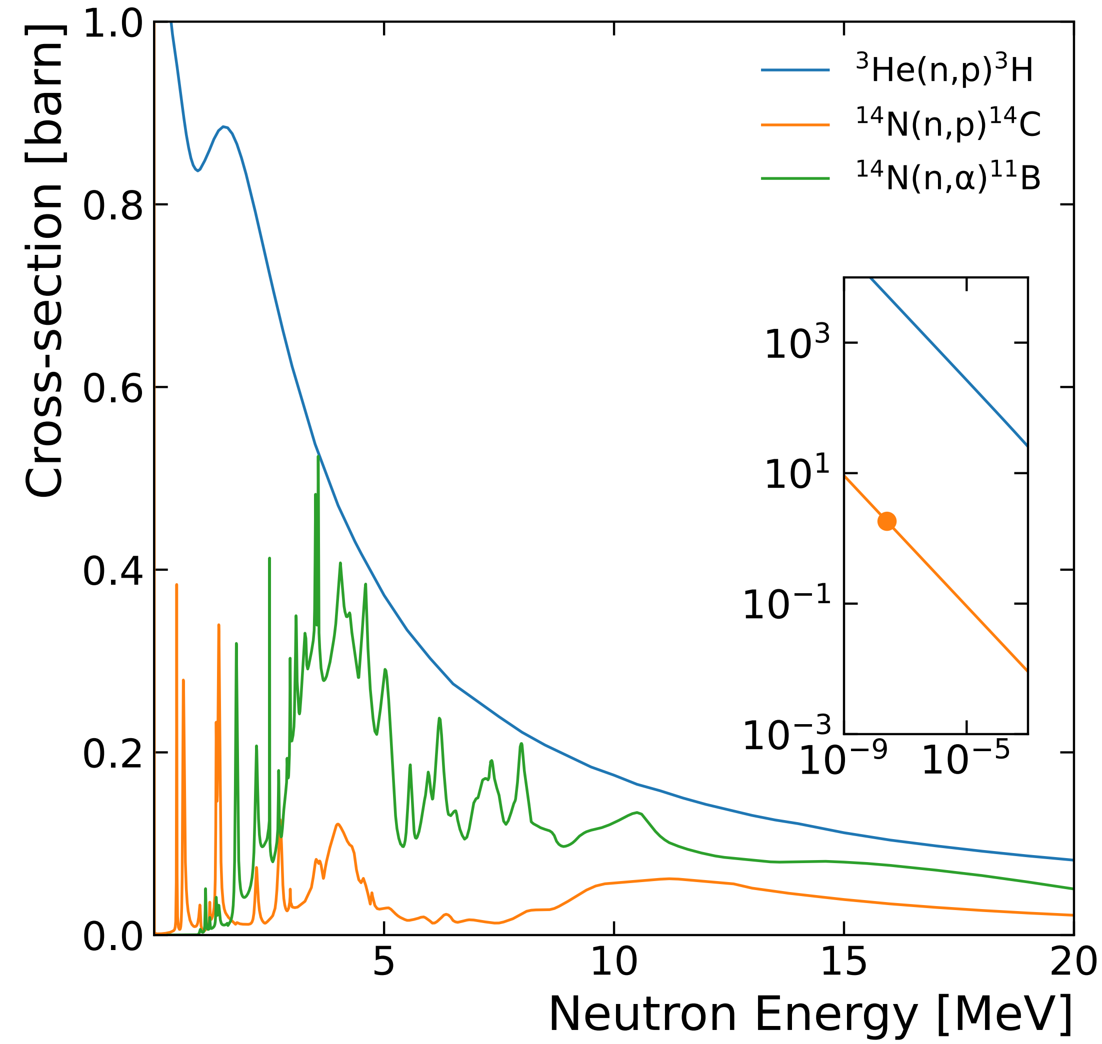

- **Limiting Factors:**
  - Low pressure operation ⟶ Wall effect
  - Sparking/Stability ⟶ Gas gain
  - Impurities
  - Charge collection efficiency

Progress in all fronts!

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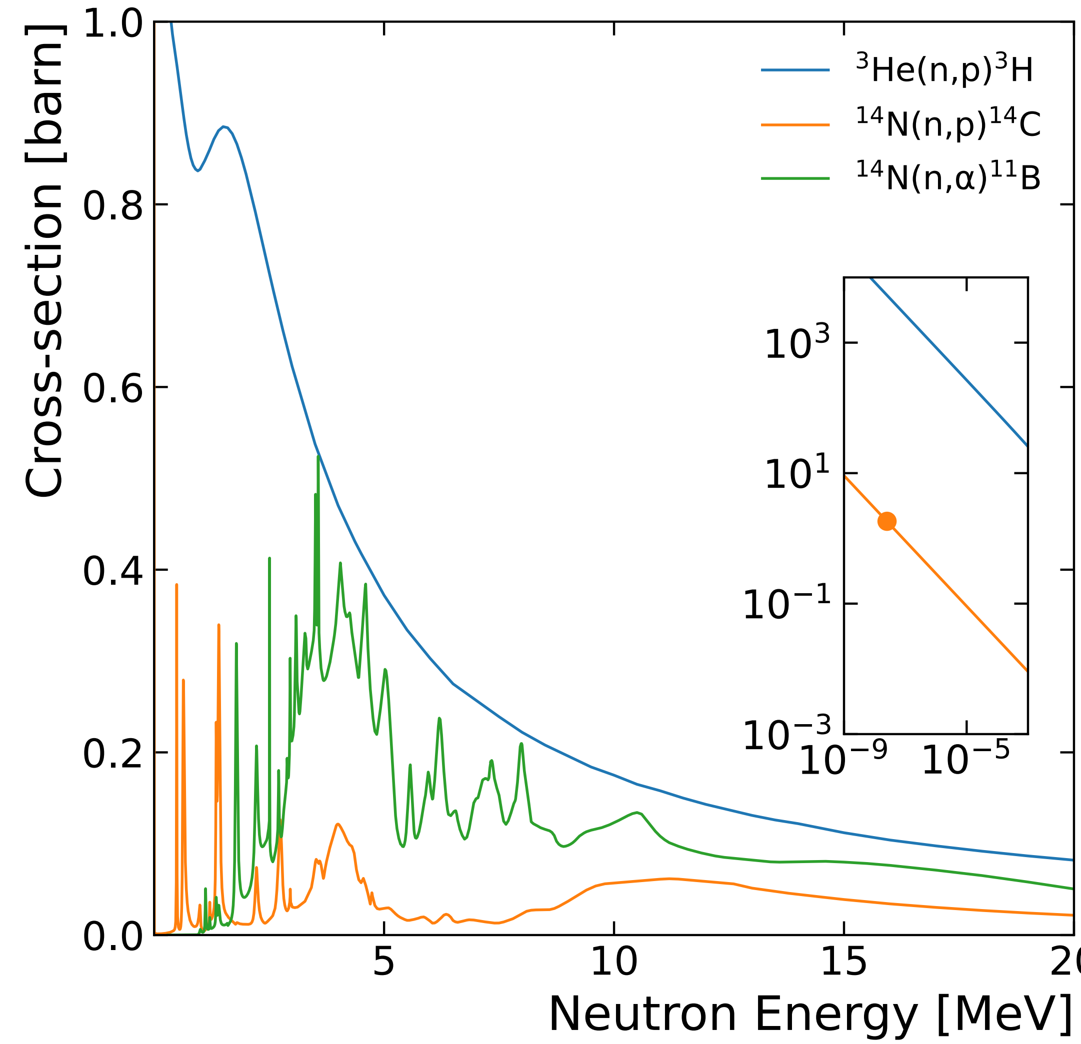

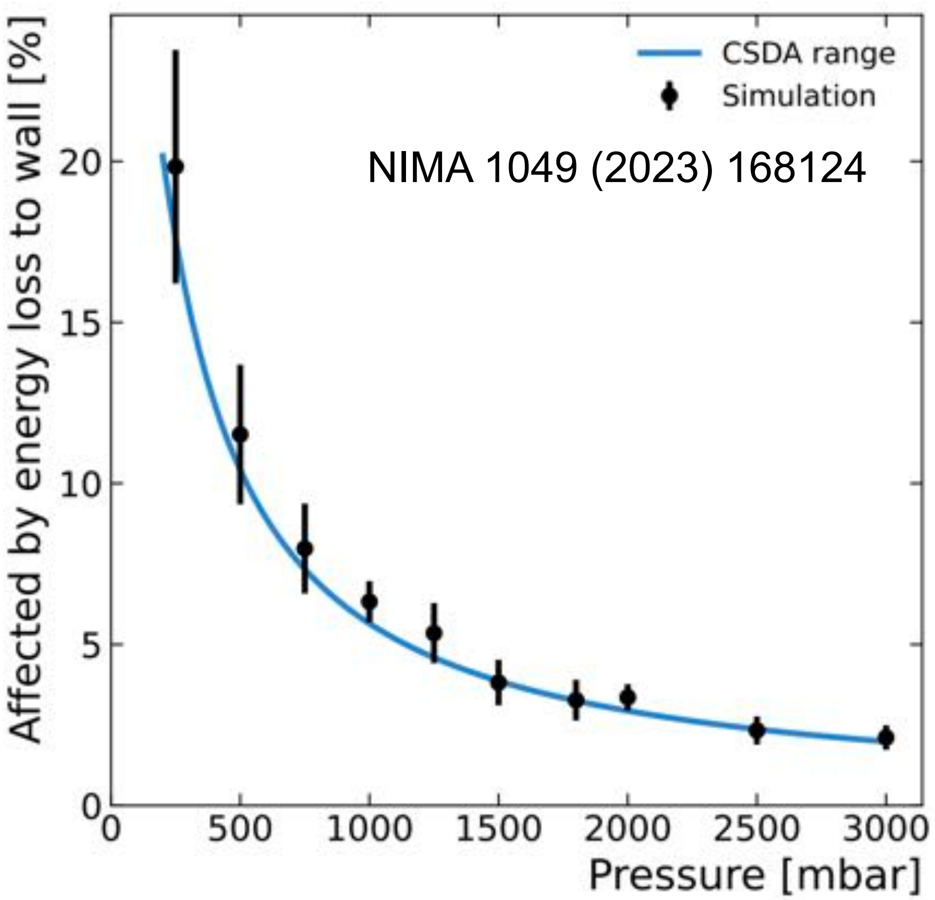

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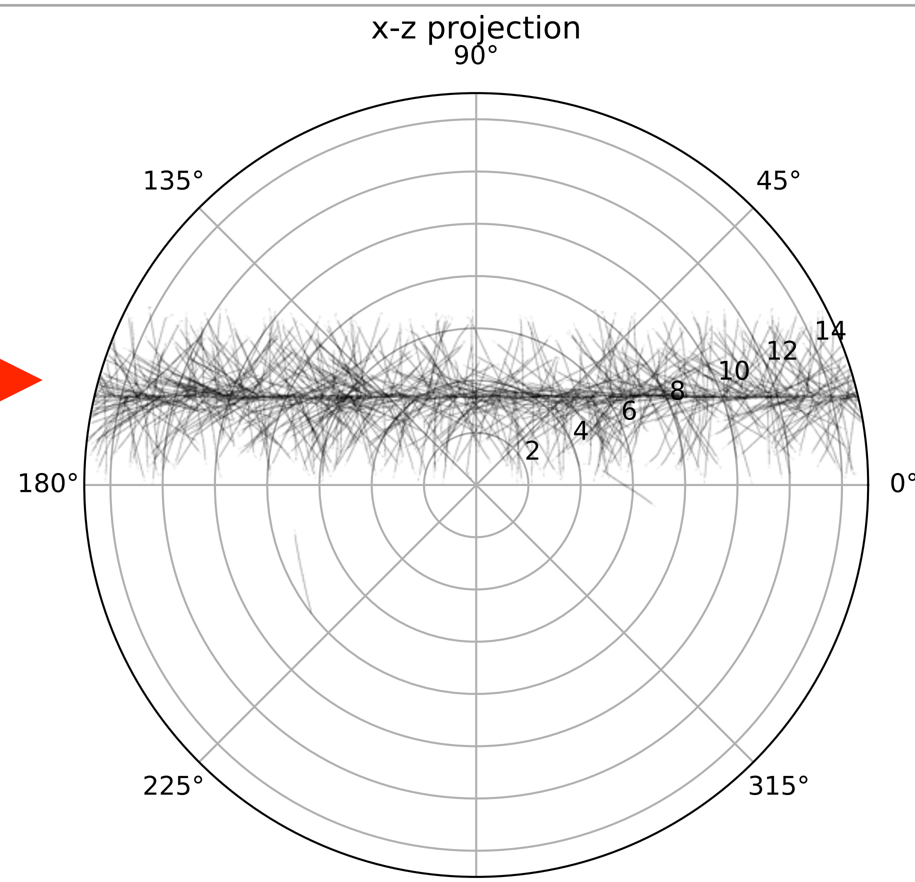
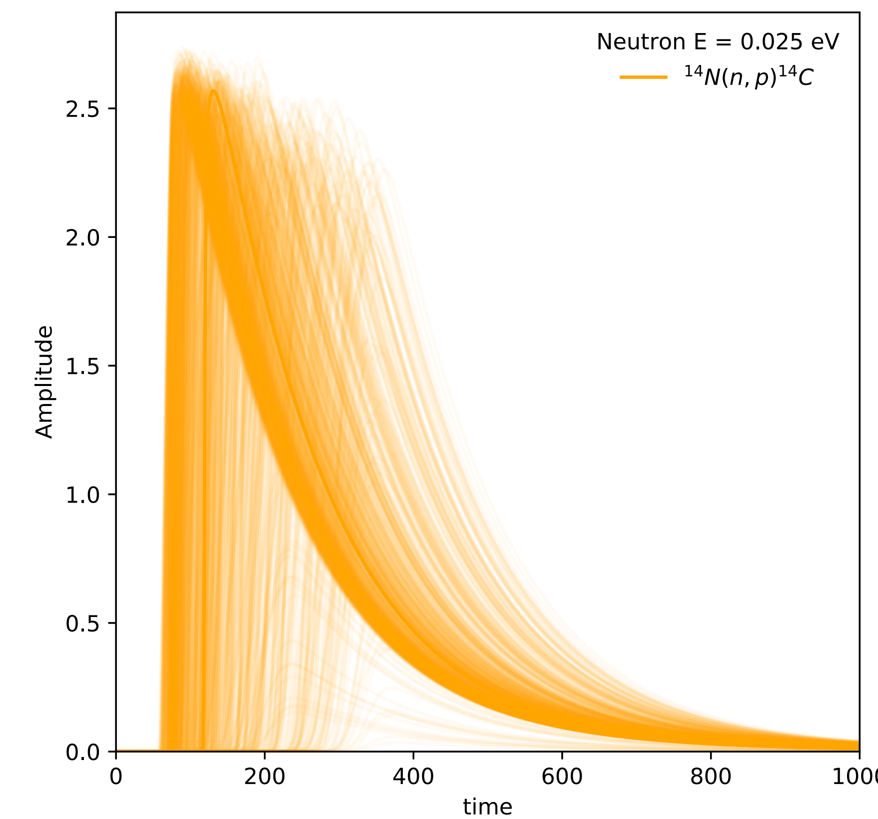
Progress in all fronts!

Simulation of neutron transport

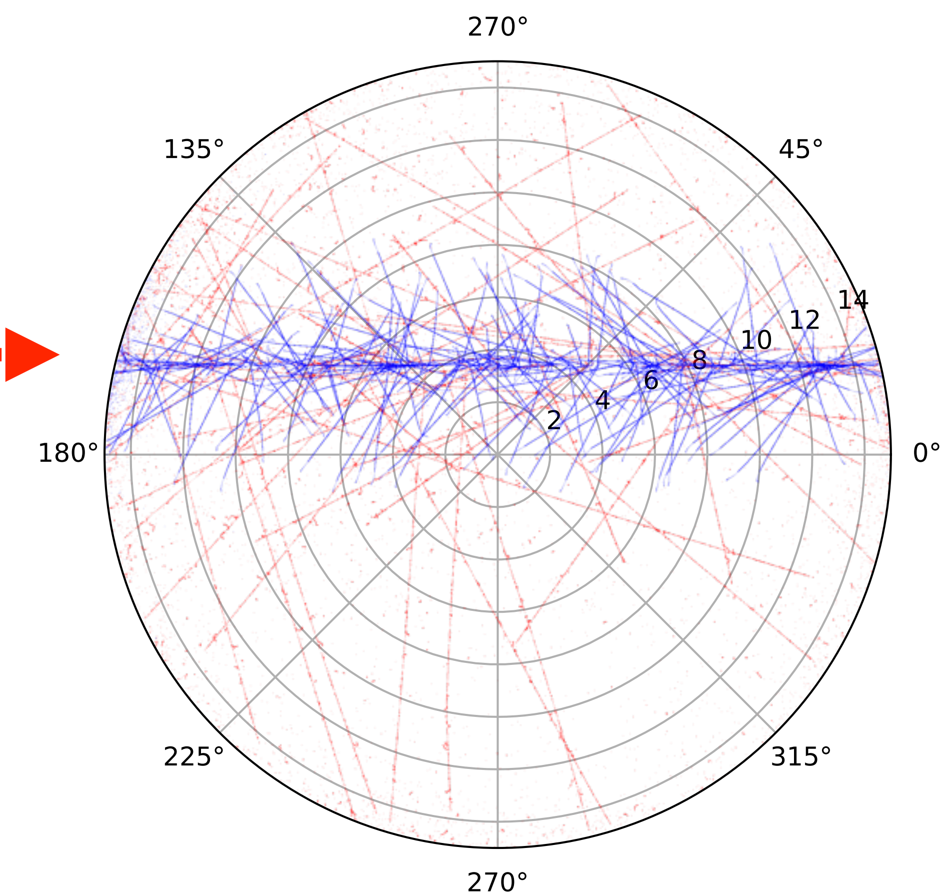
Neutron Beam
0.025 eV

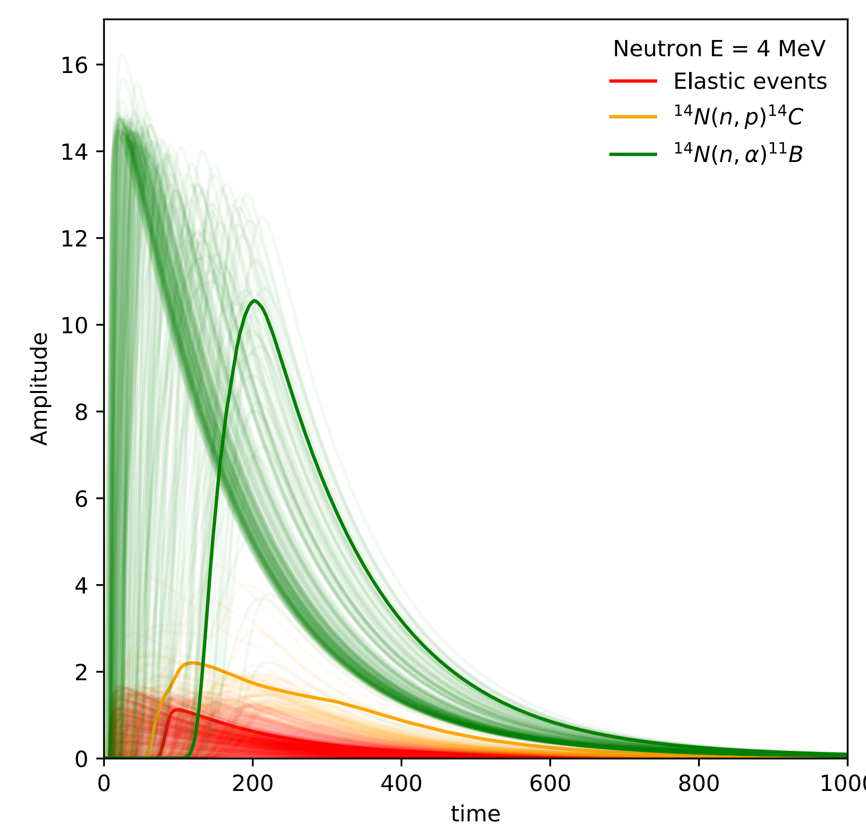




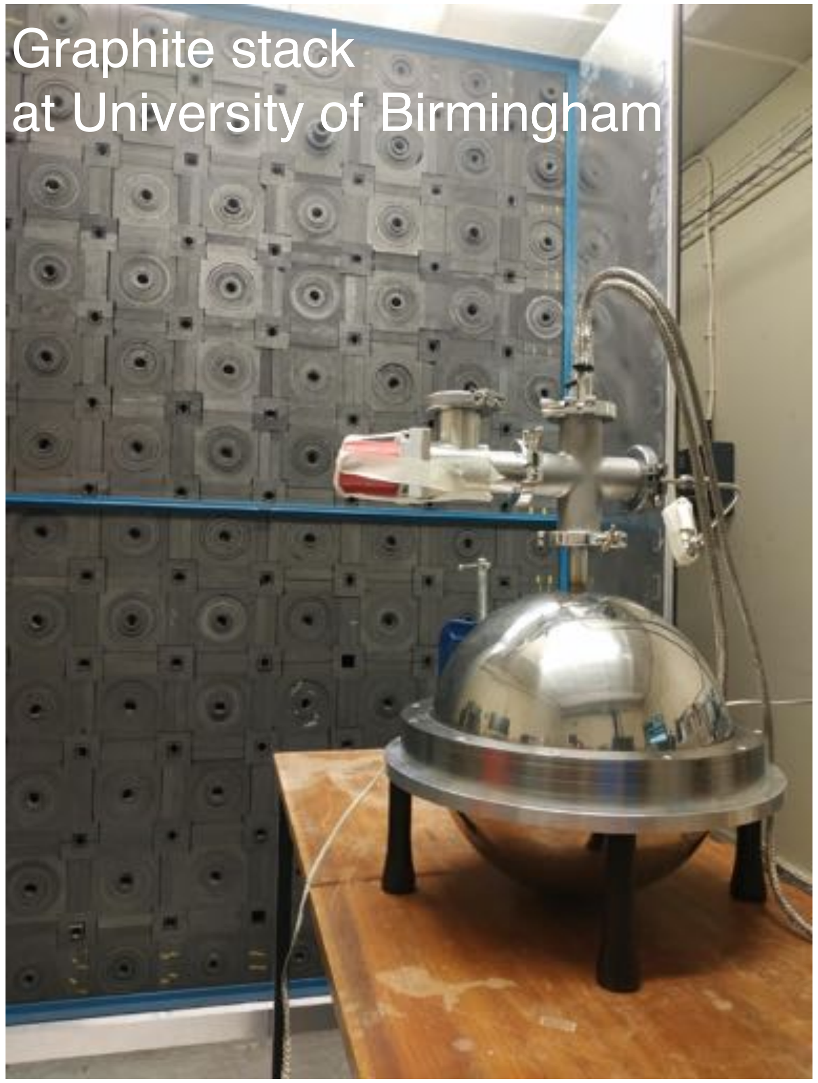
<u>Parameters</u>
Ø30cm vessel
N_2 at 300mbar
Ø2mm anode

Neutron Beam
4 MeV





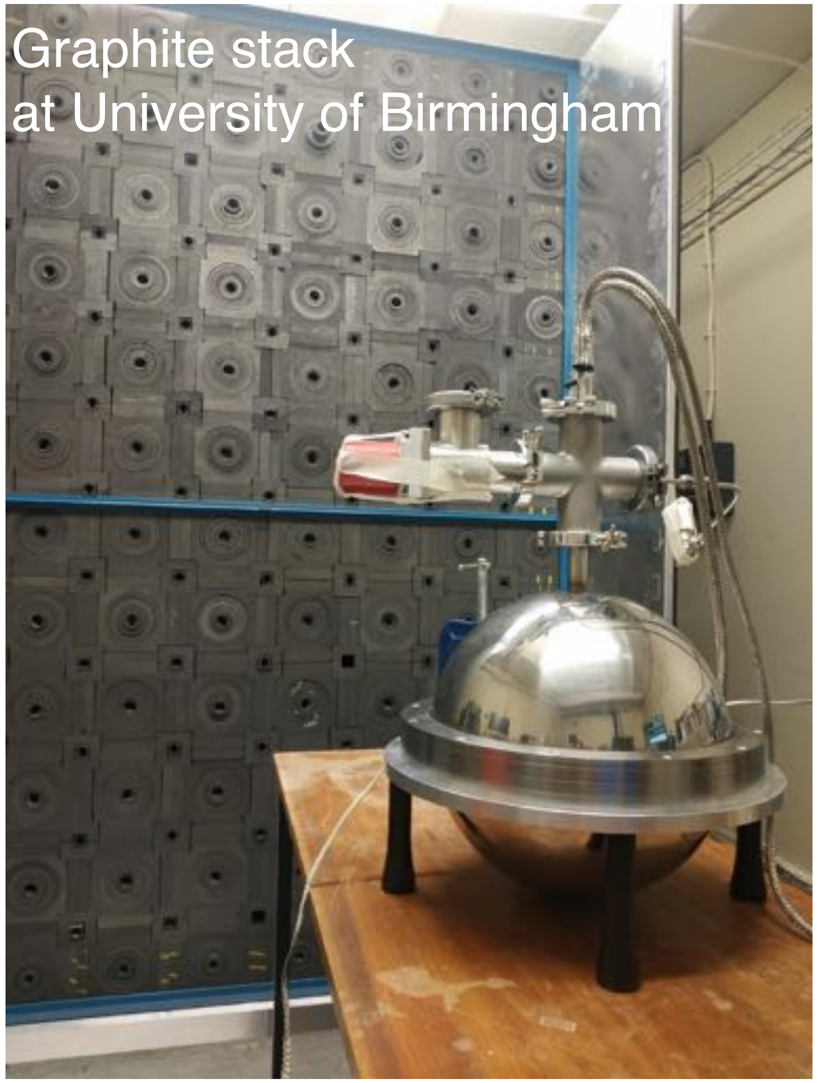
In-situ neutron measurements

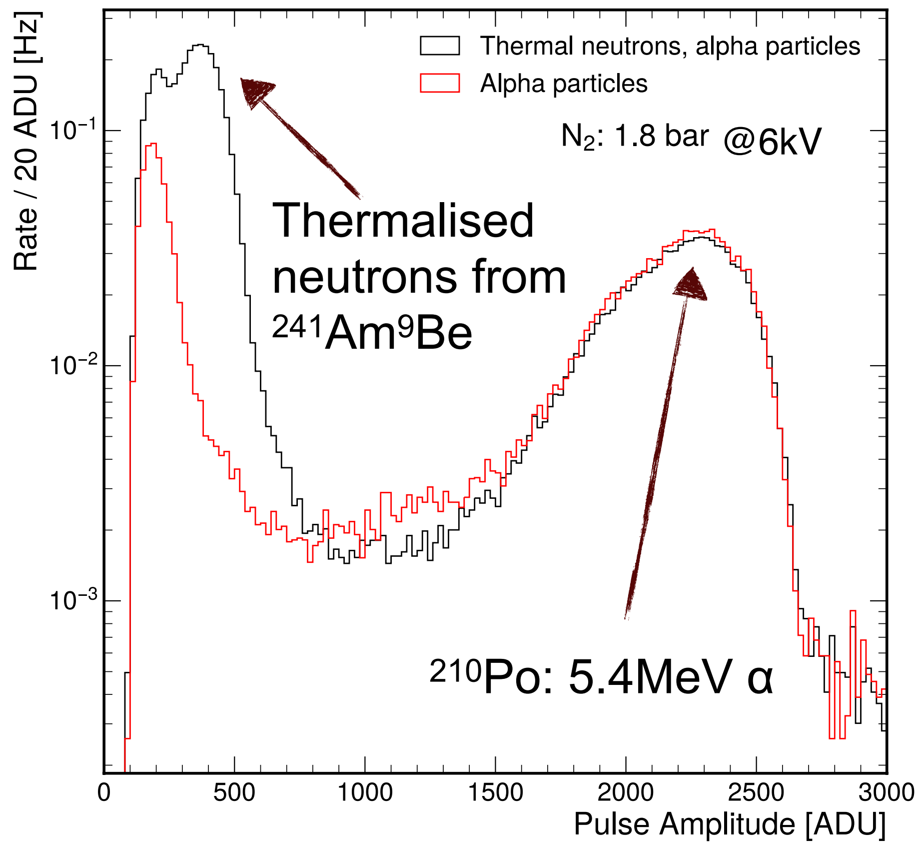


- Nitrogen-filled SPC
  - ∅ 30 cm
- Multi-anode sensor
  - 11 anodes, ∅ 1mm
  - “Near” - “Far” read-out

NIMA 1049 (2023) 168124

In-situ neutron measurements





- Nitrogen-filled SPC
  - ∅ 30 cm
- Multi-anode sensor
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NIMA 1049 (2023) 168124

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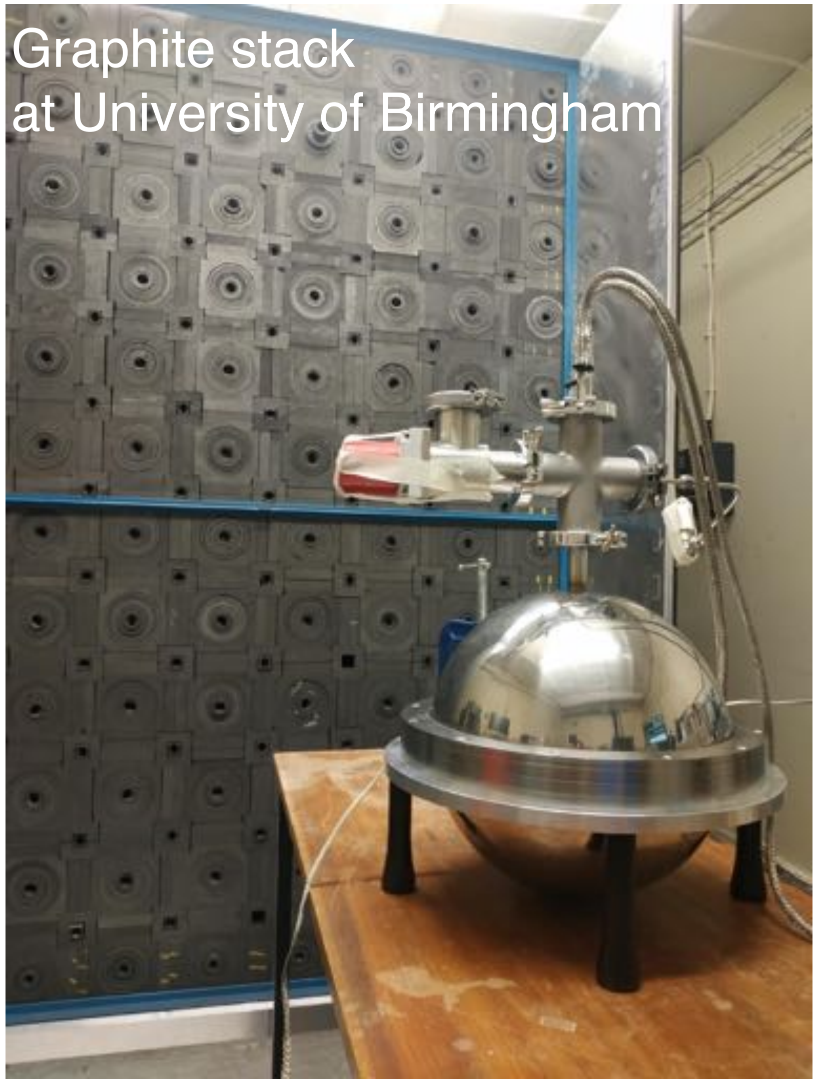

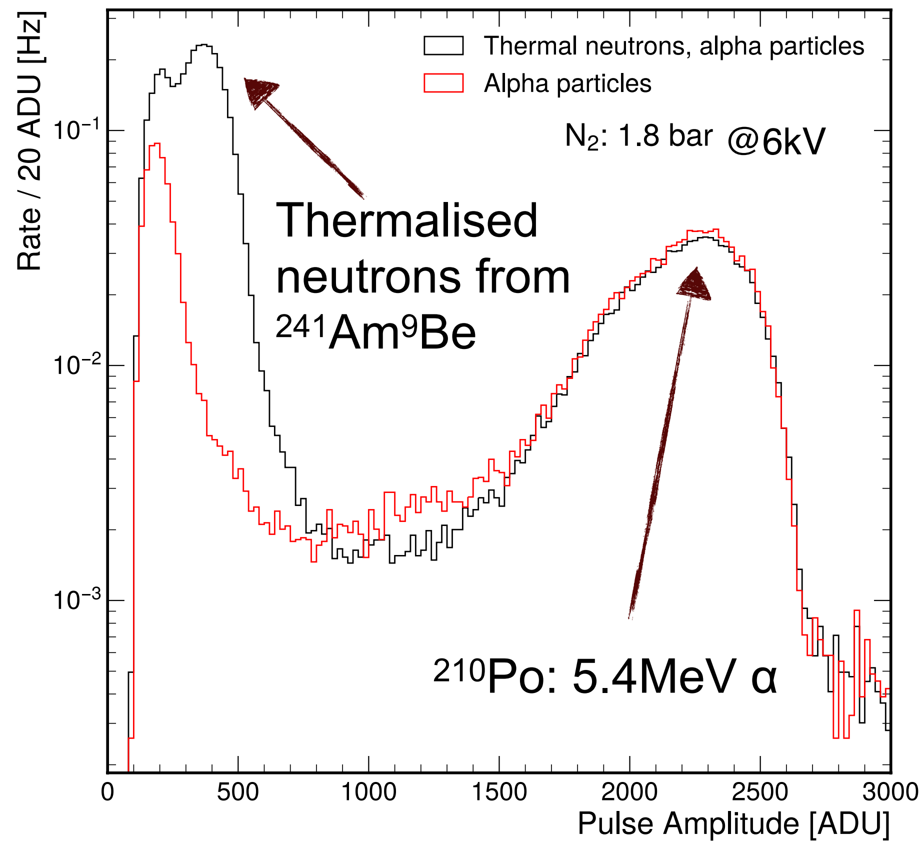

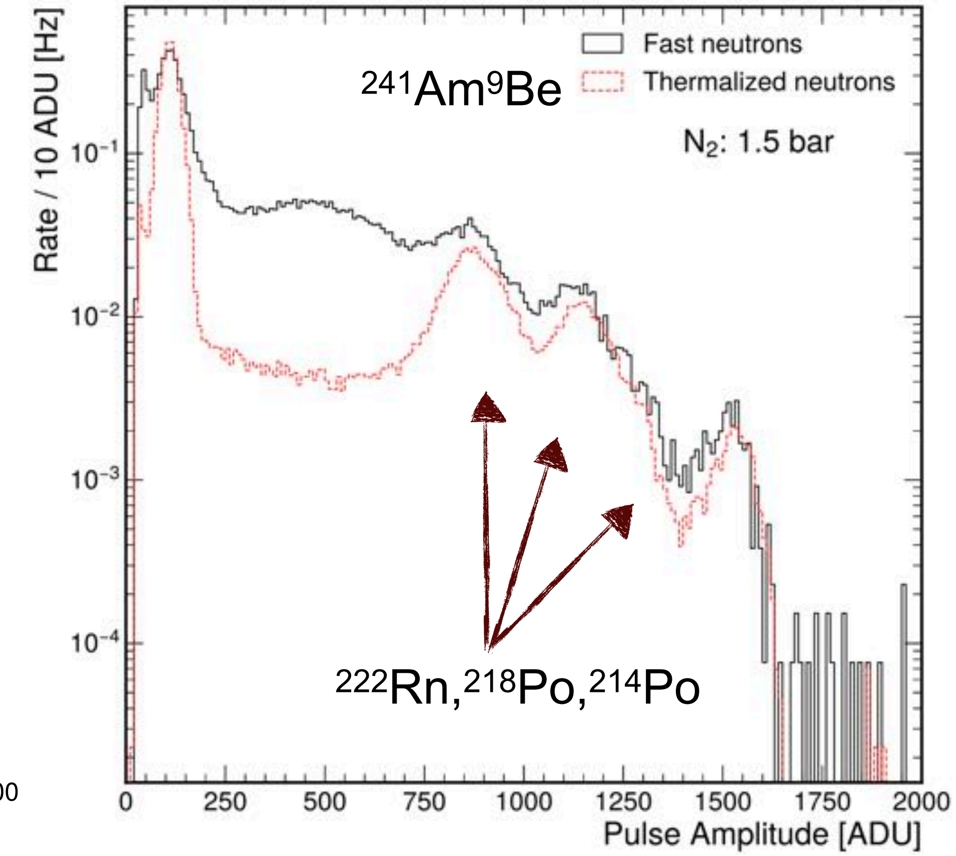

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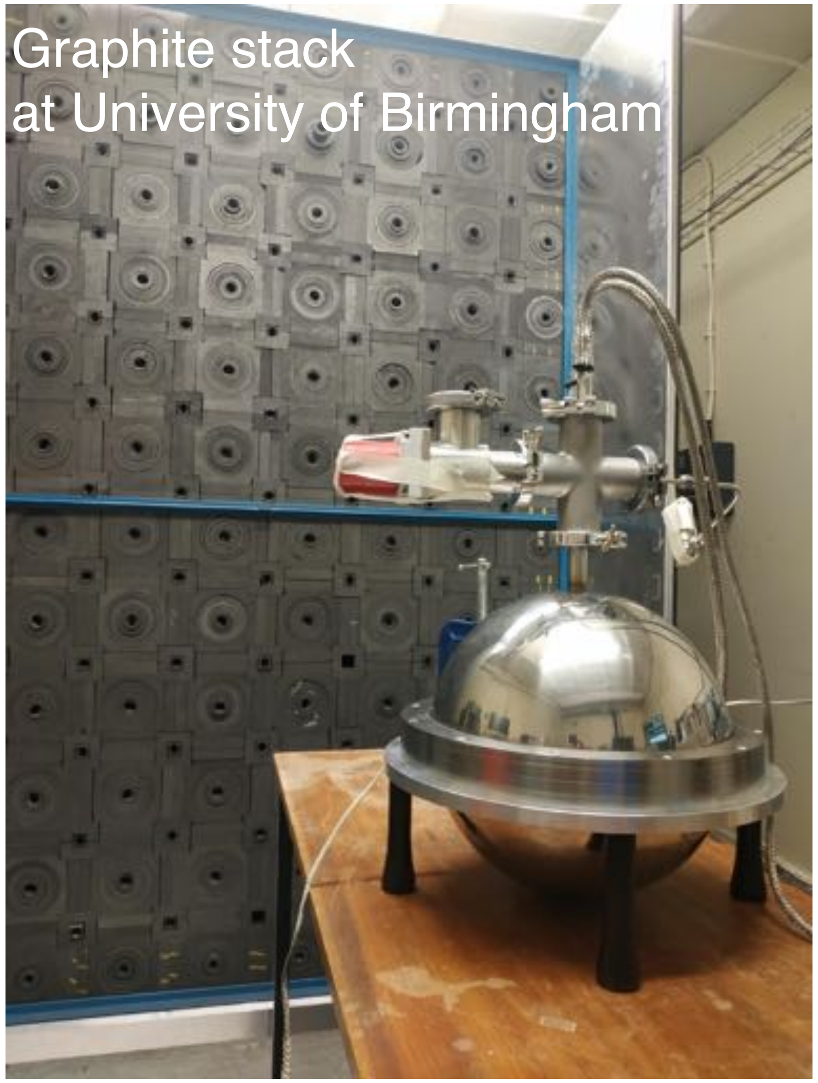

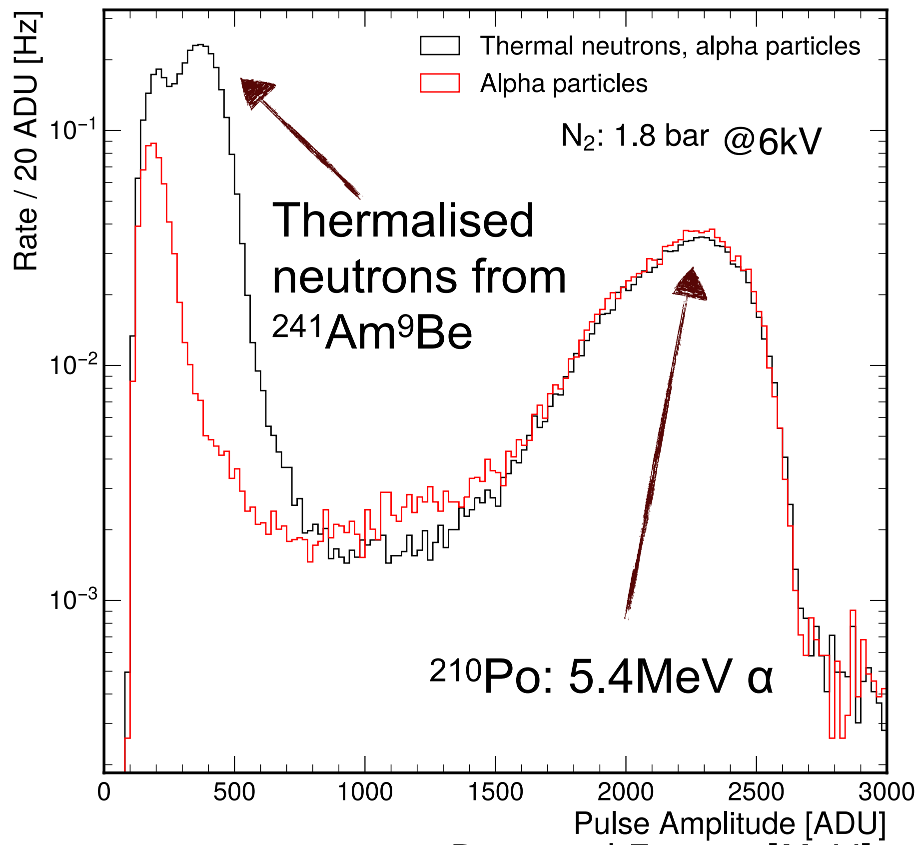

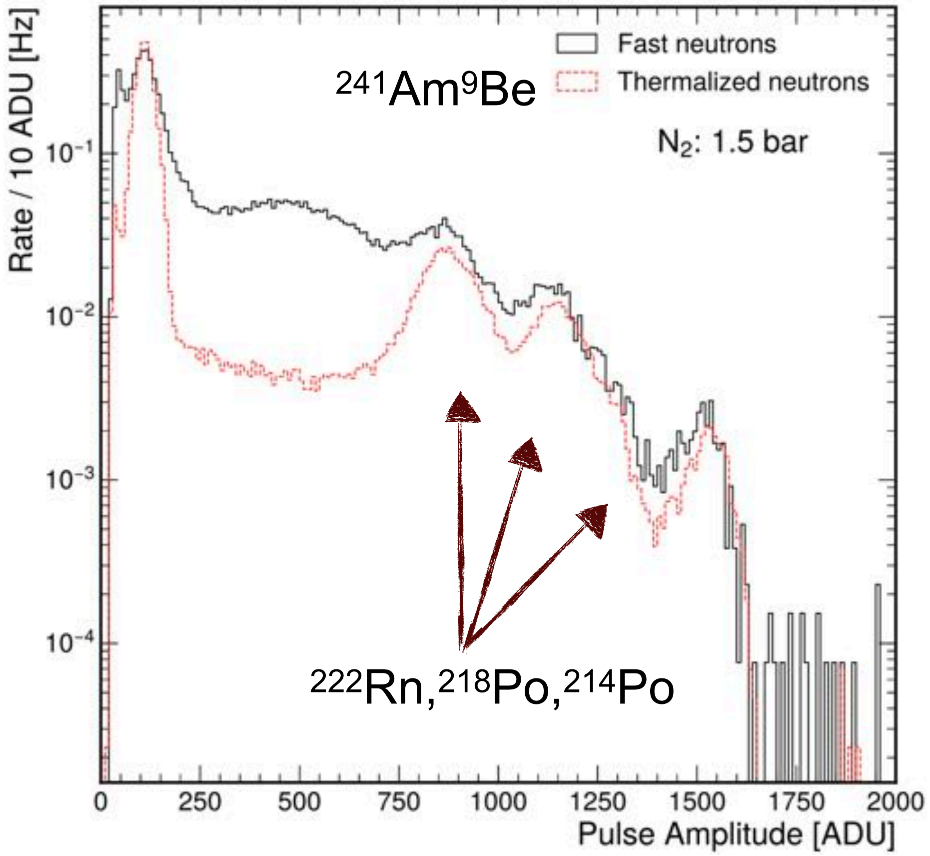

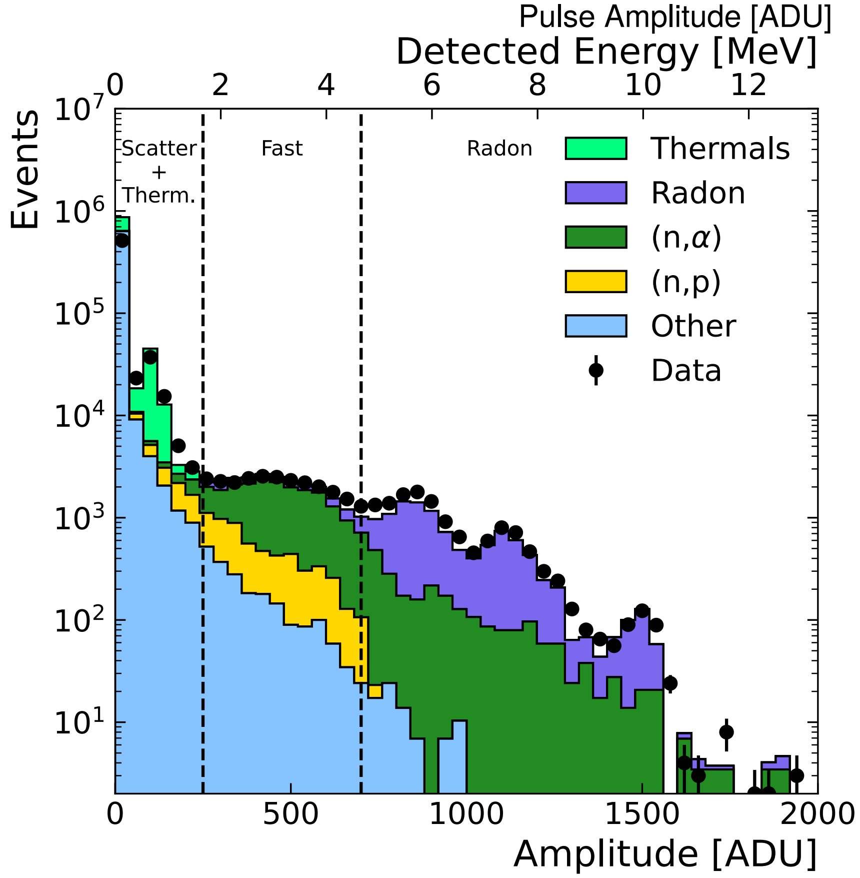

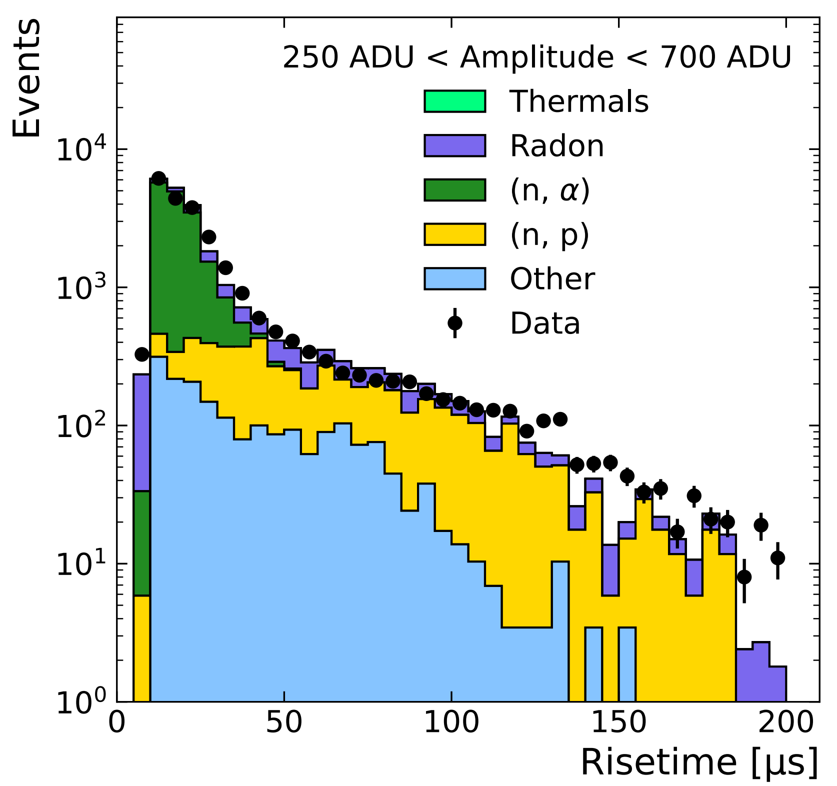

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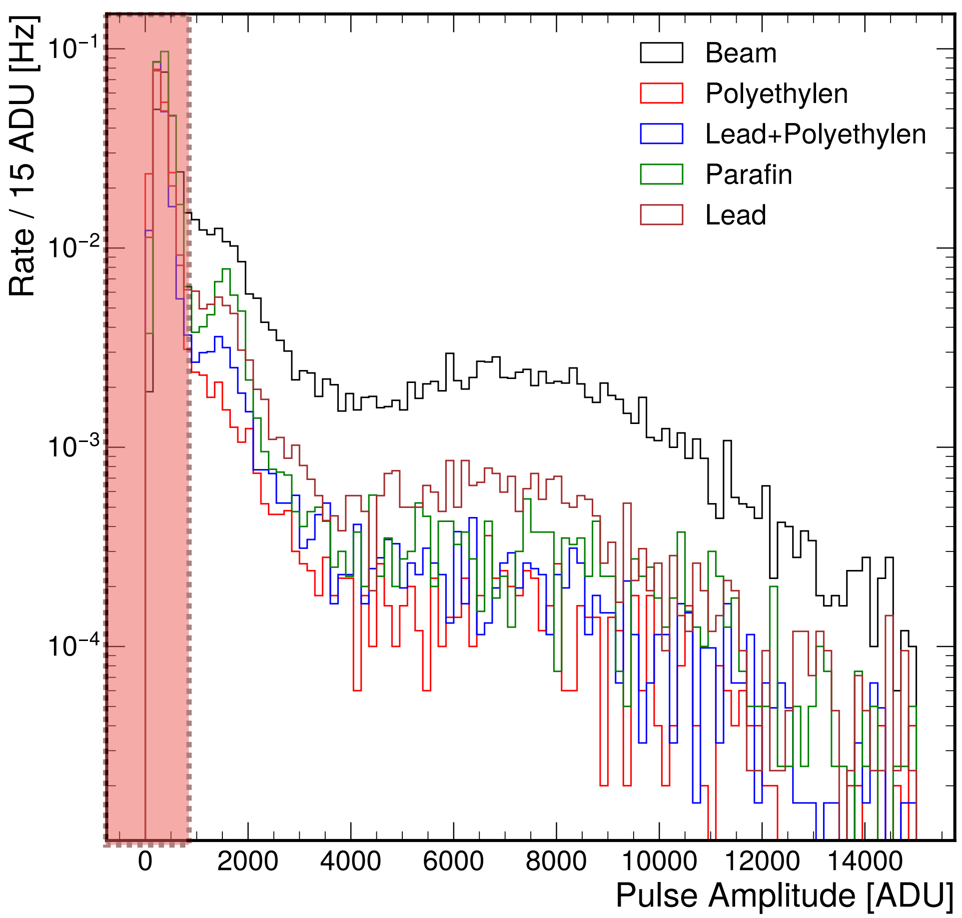
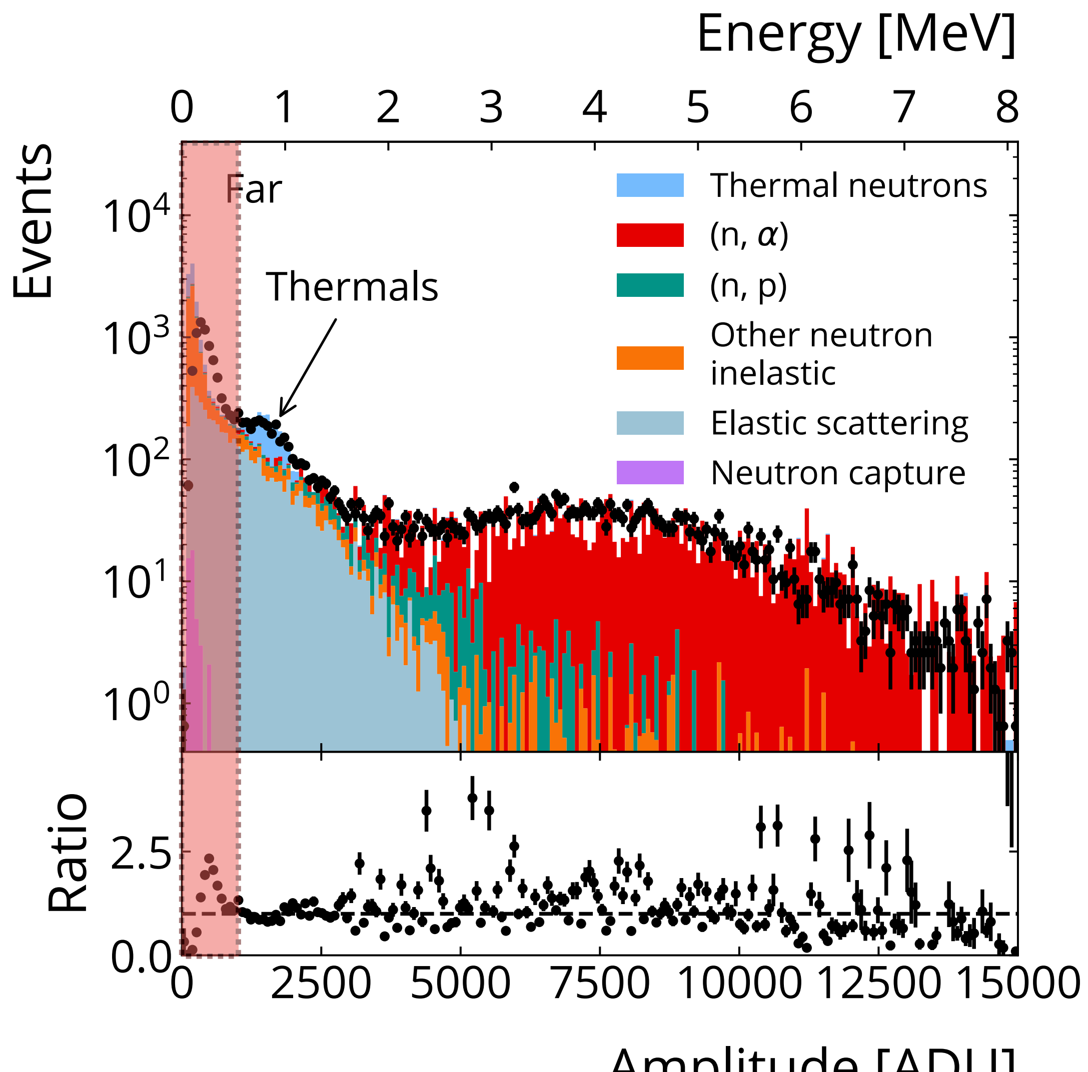
NIMA 1049 (2023) 168124

In-situ neutron measurements

UNIVERSITY OF BIRMINGHAM | CYCLOTRON FACILITY

- Deuterium beam on ^{9}Be
  - 5.90±0.08 MeV deuterons
  - $^{9}Be(d,n)^{10}B$ reaction
  - Moderators used to study neutron detection





Reducing Backgrounds

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
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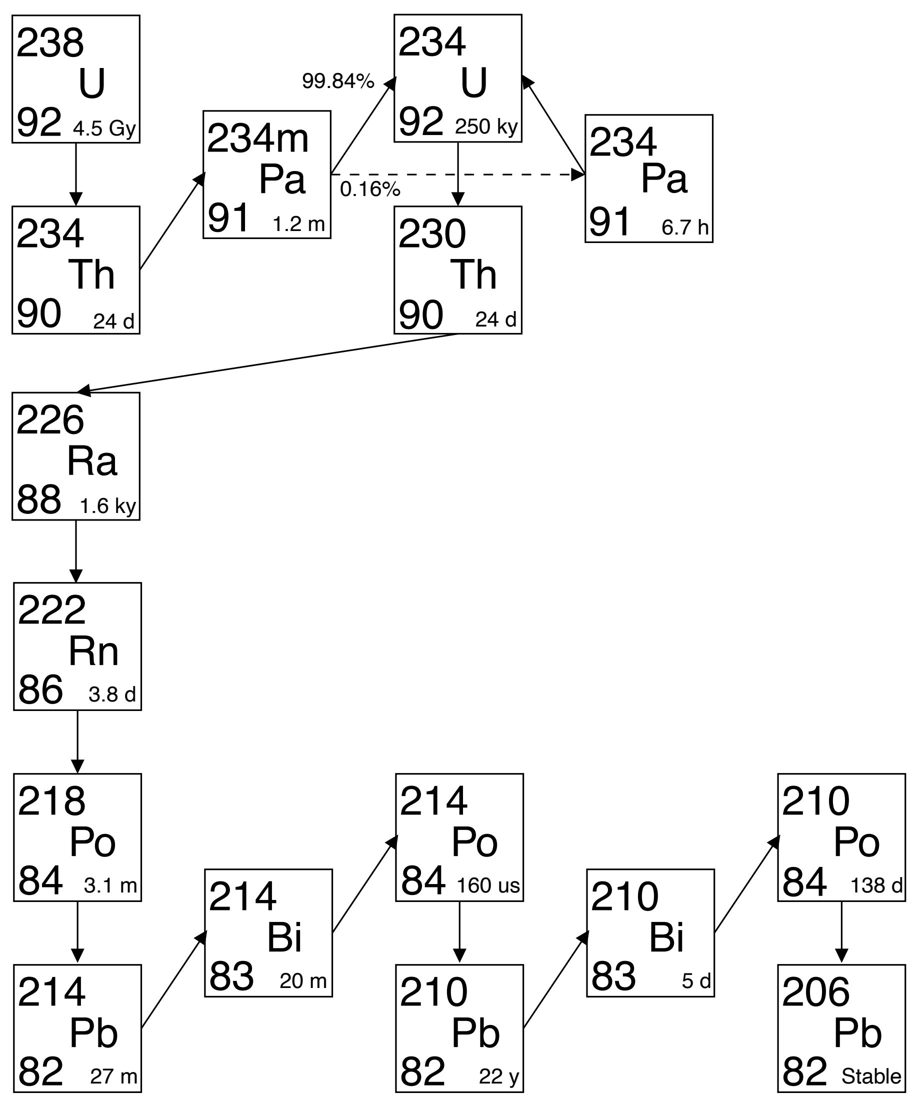

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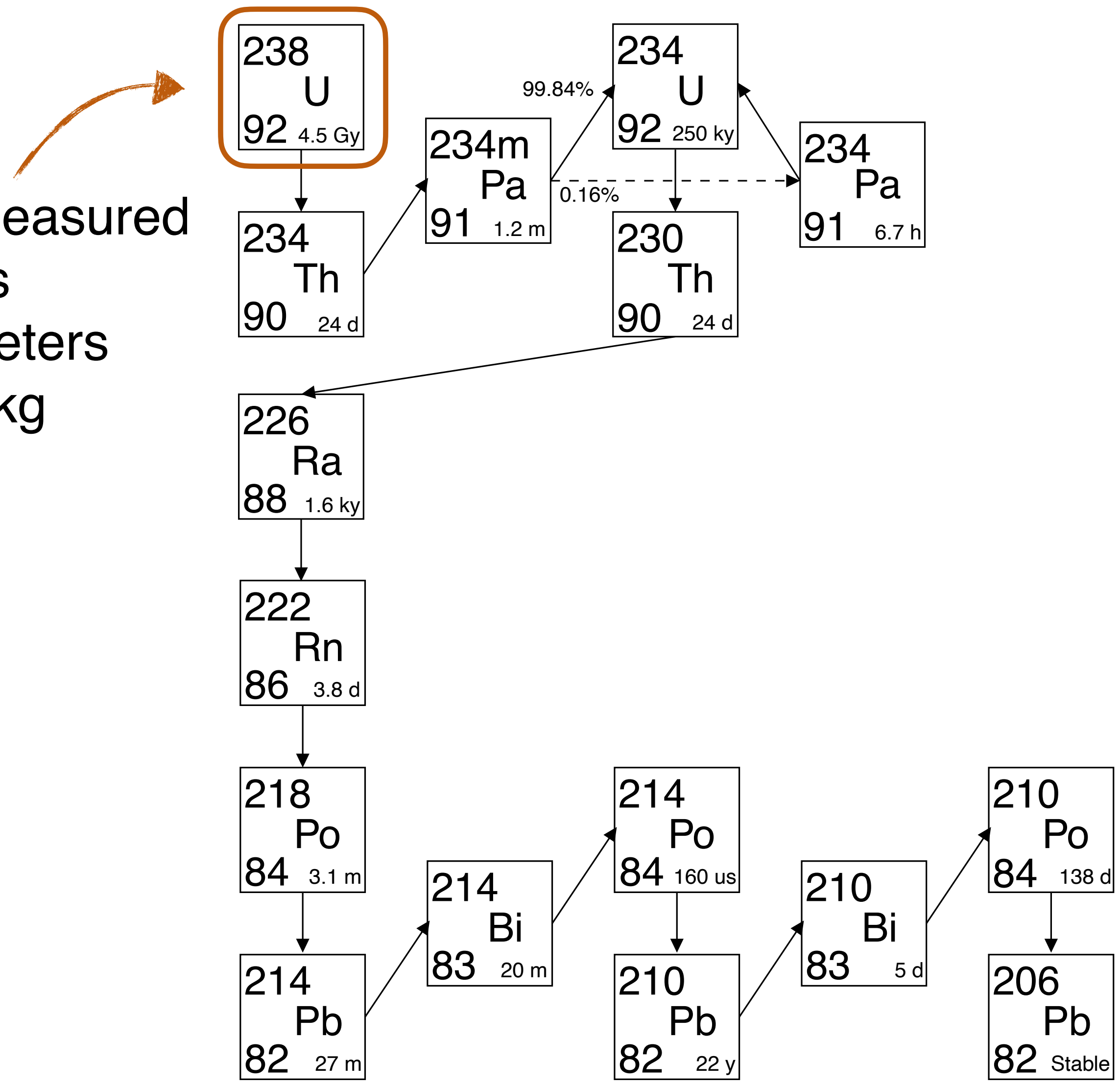
directly measured with mass spectrometers ~10 µBq/kg



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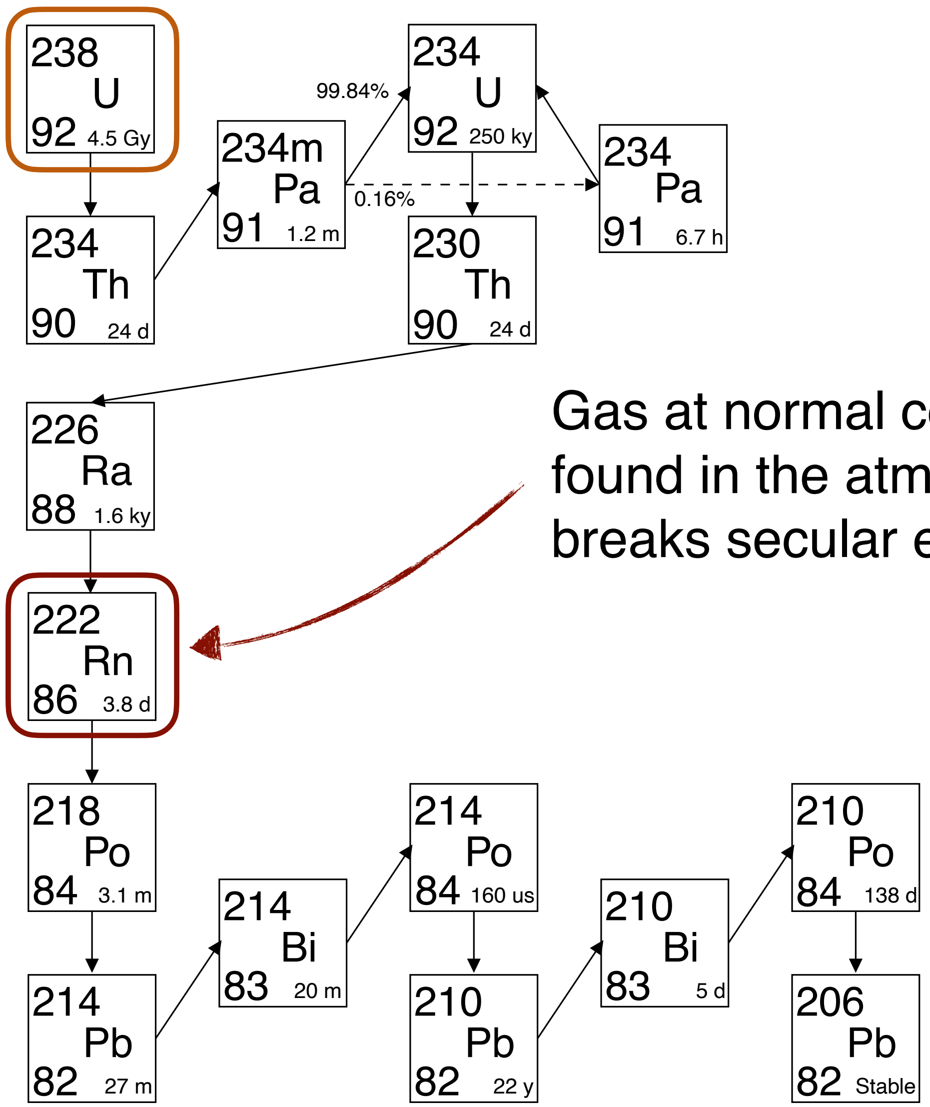

Gas at normal conditions: found in the atmosphere breaks secular equilibrium

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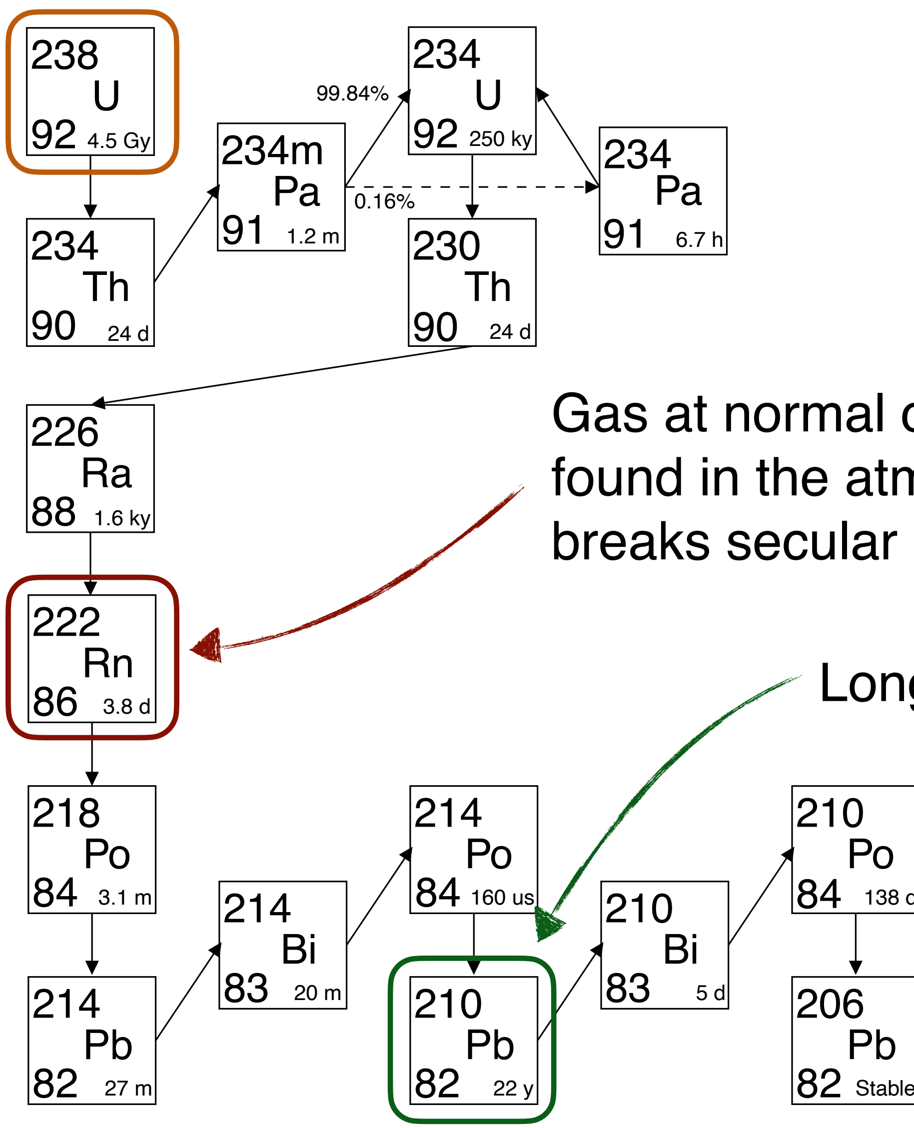

Gas at normal conditions: found in the atmosphere breaks secular equilibrium

Long-lived!

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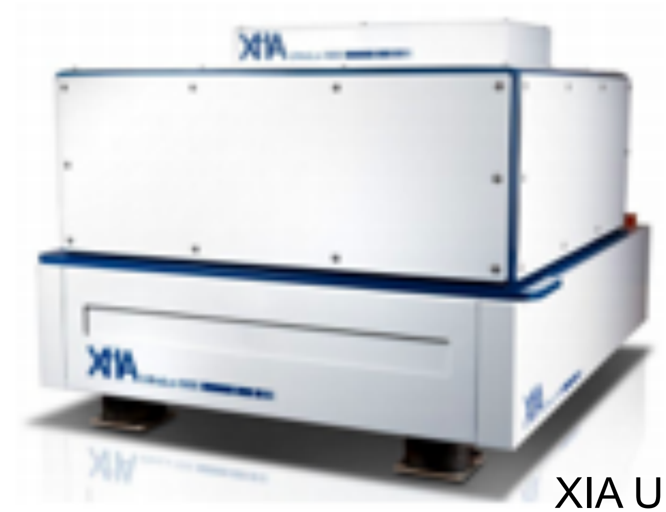
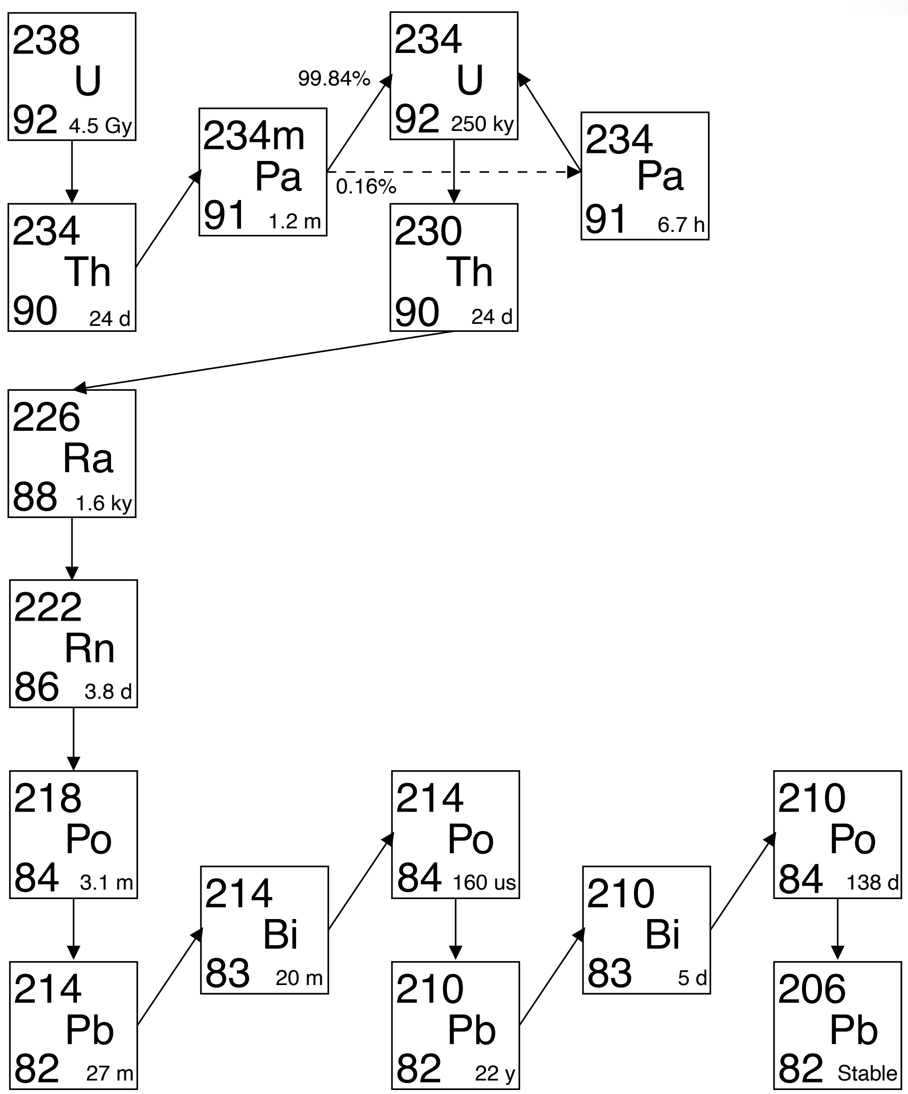
^{210}Pb contamination

Recent development: low background α-particle counting



XIA UltraLo-1800
https://www.xia.com/ultralo-theory.html



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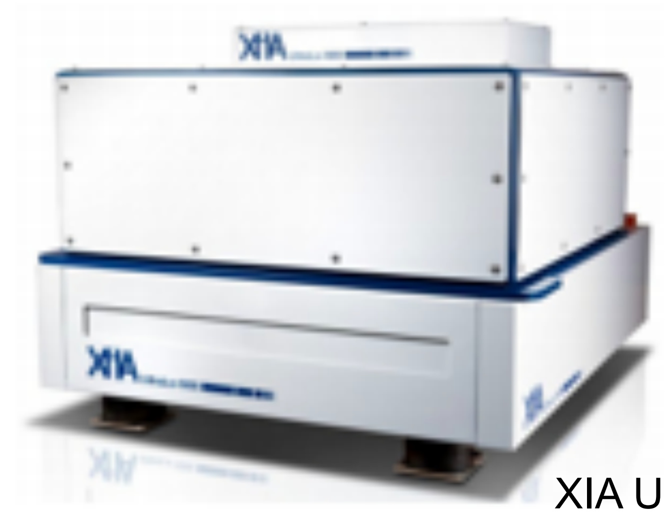

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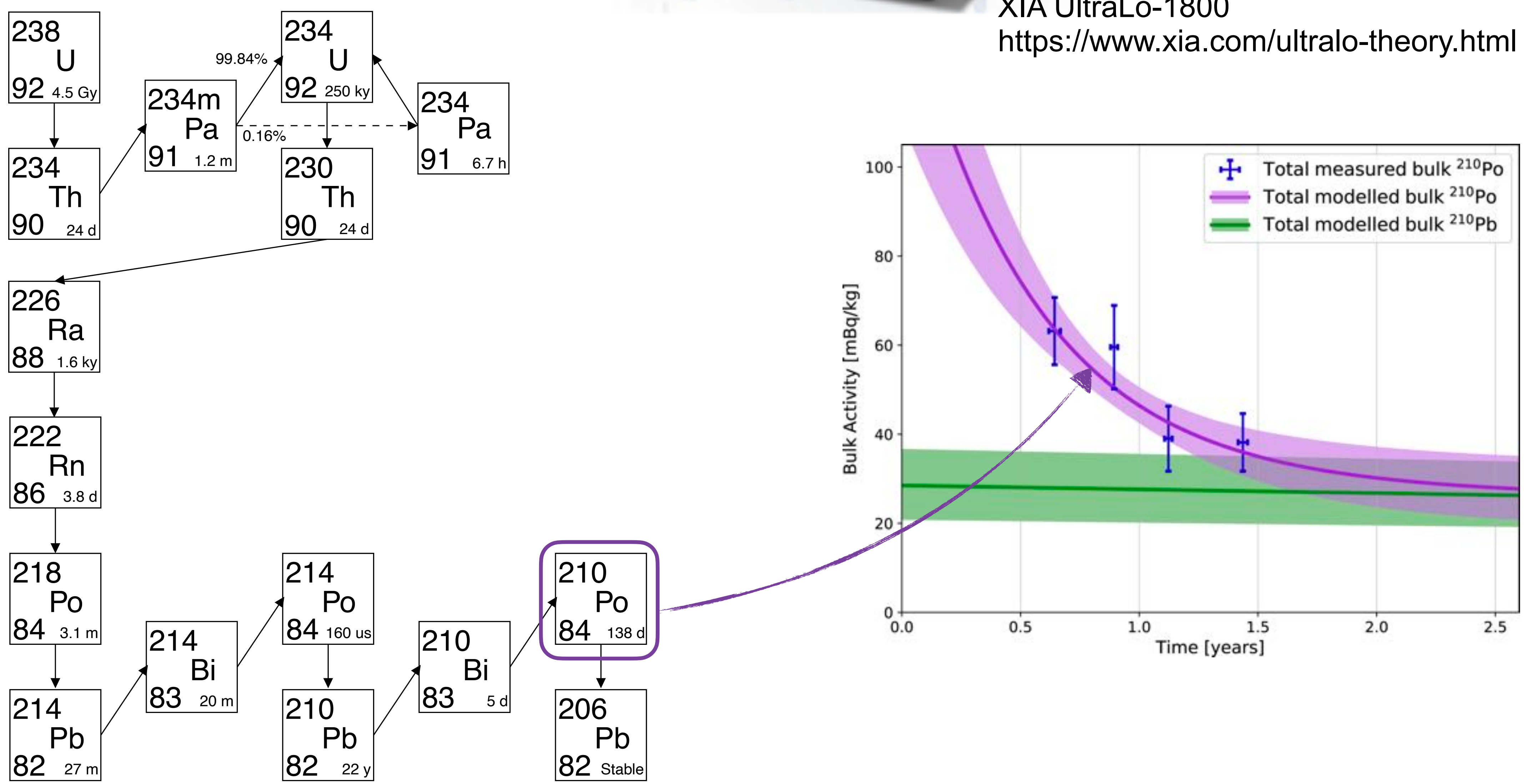

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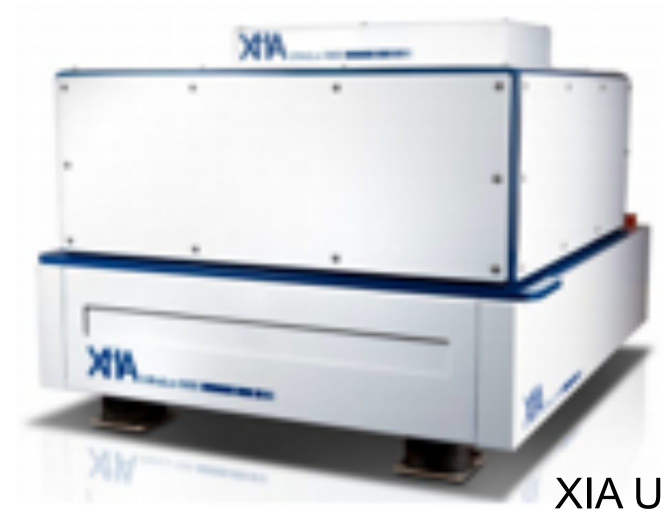

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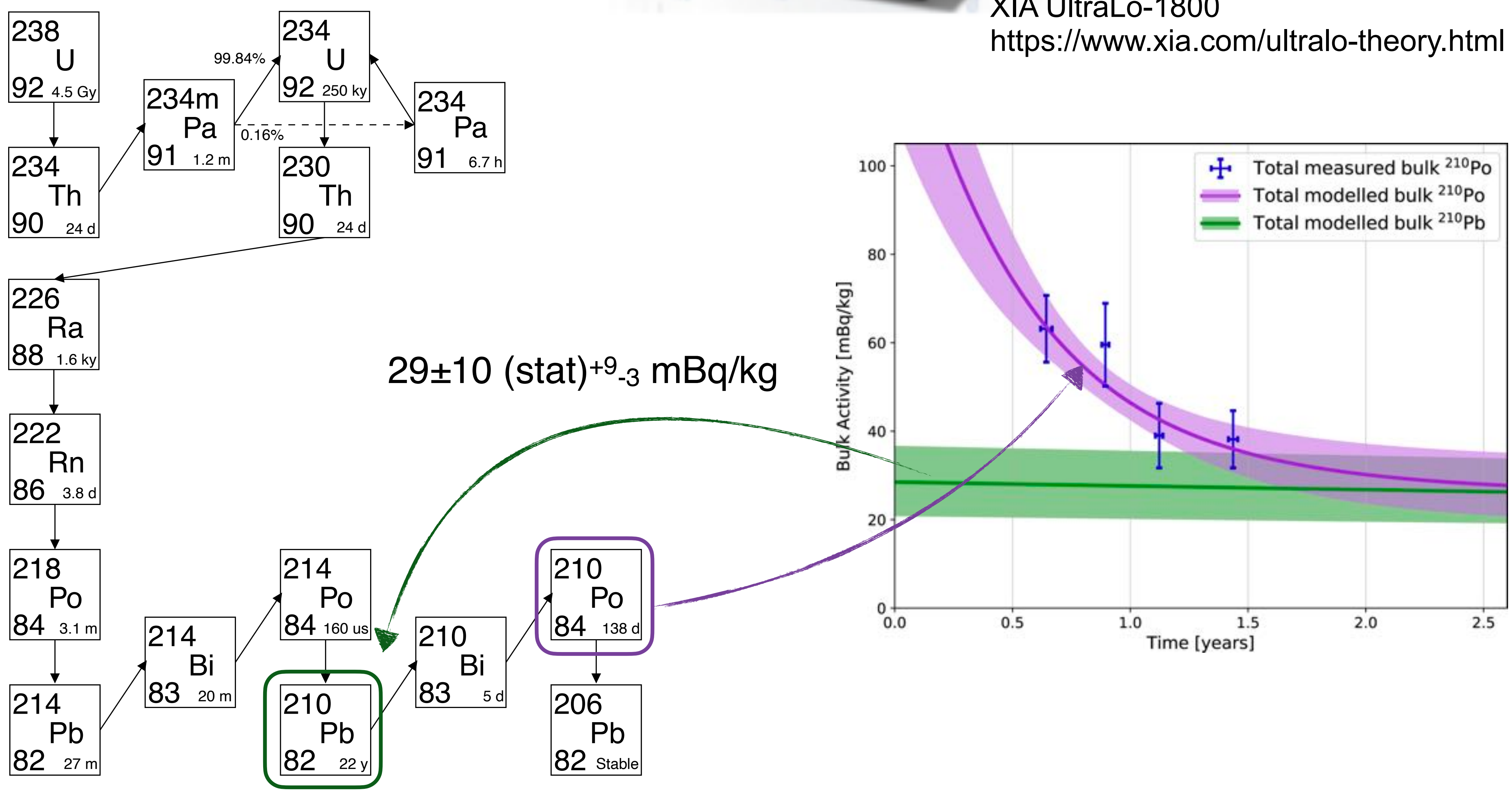

Copper Electroplating

SNOLAB detector: 4N Aurubis AG Oxygen Free Cu (99.99% pure)

- Out-of-equilibrium ^{210}Pb contamination: $29 \pm 10\ (stat)^{+9}_{-3}$ mBq/kg

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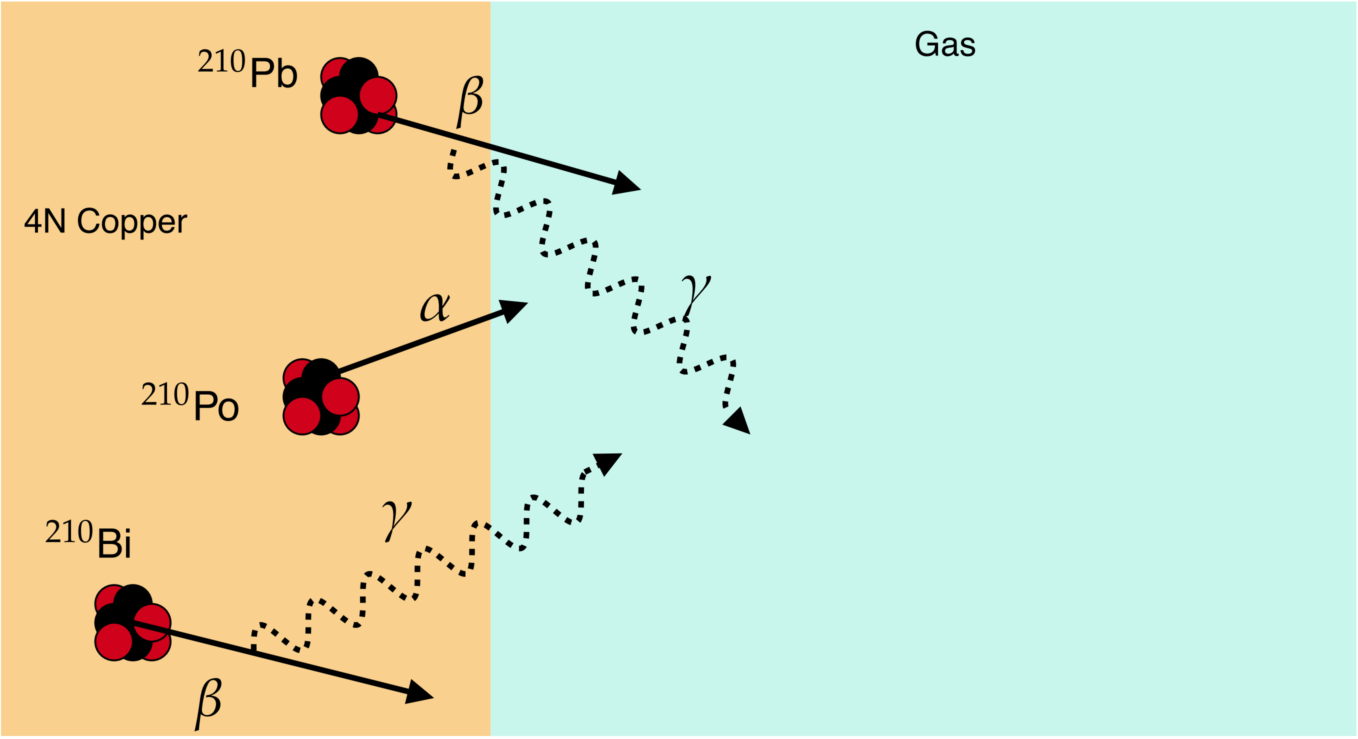
- Bremsstrahlung X-rays from ^{210}Pb and ^{210}Bi β-decays in Cu



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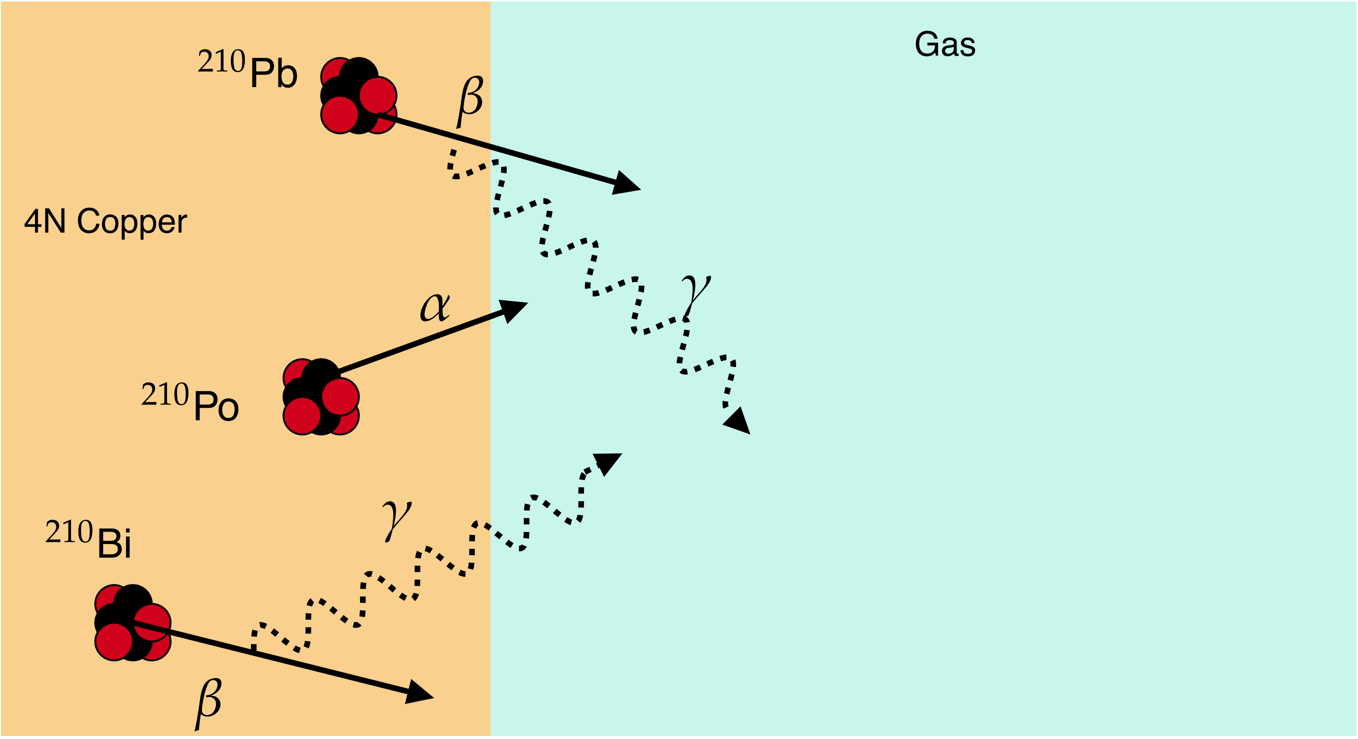
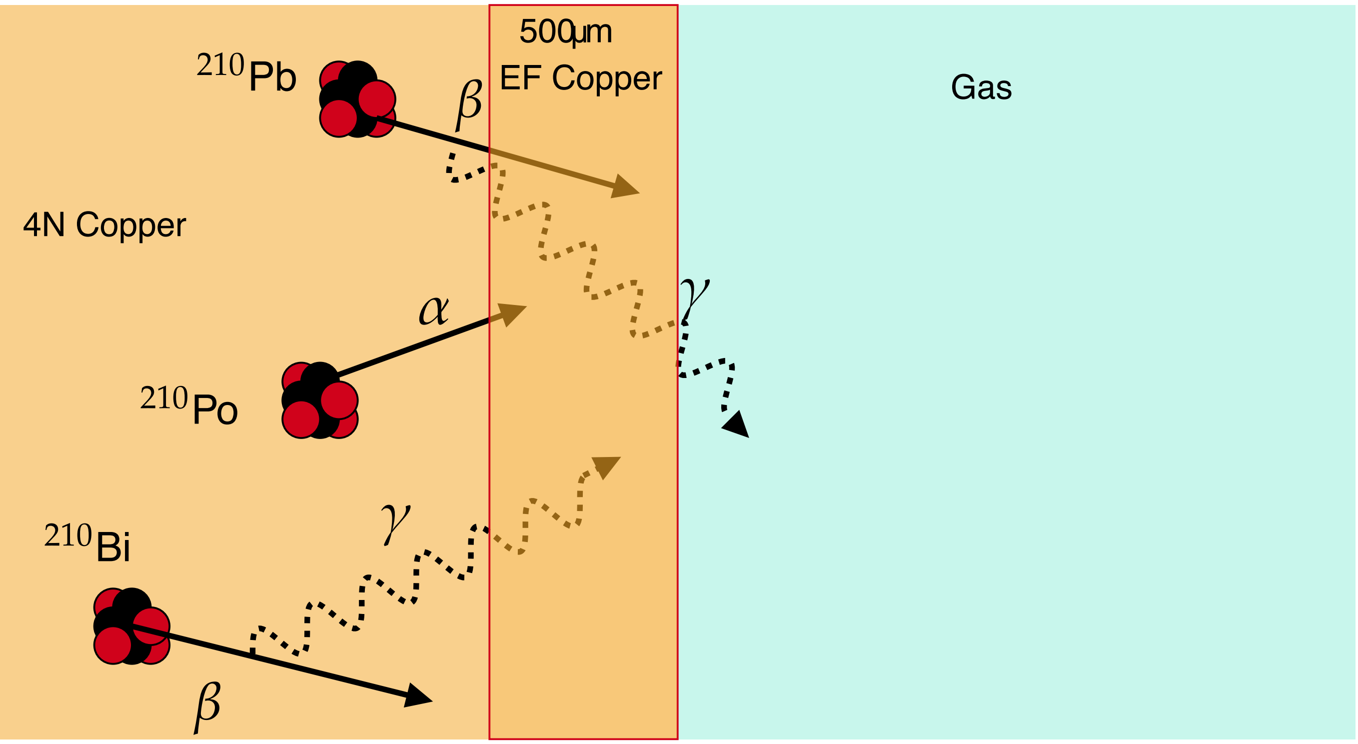
- Bremsstrahlung X-rays from ^{210}Pb and ^{210}Bi β-decays in Cu

Internal shield

- Ultra-pure Cu layer on detector inner surface
- Suppresses ^{210}Pb and ^{210}Bi backgrounds by factor 2.6 under 1 keV





Copper Electroplating

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

NIM A 988 (2021) 164844

Copper Electroplating

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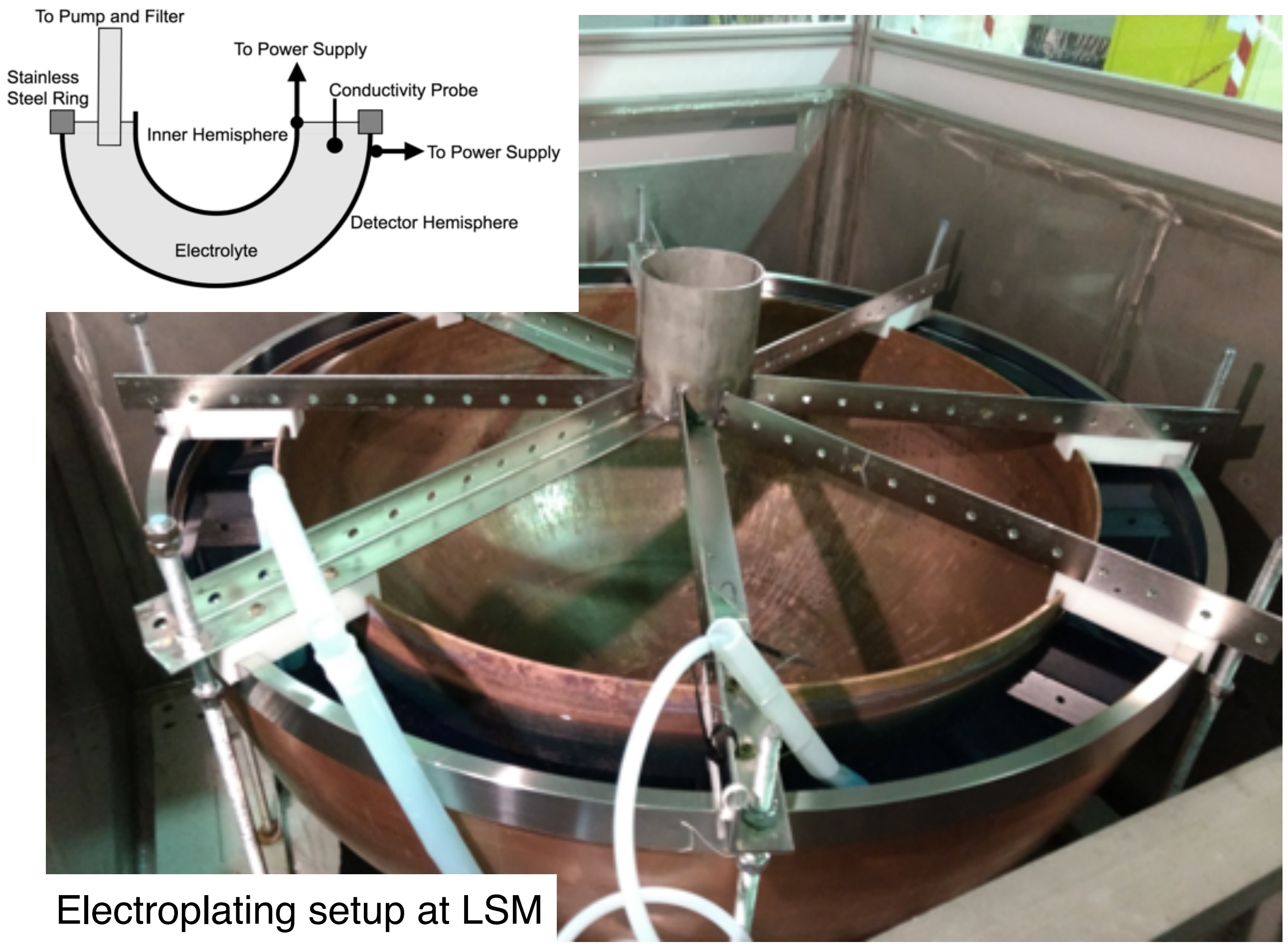

Electroplating setup at LSM

NIM A 988 (2021) 164844

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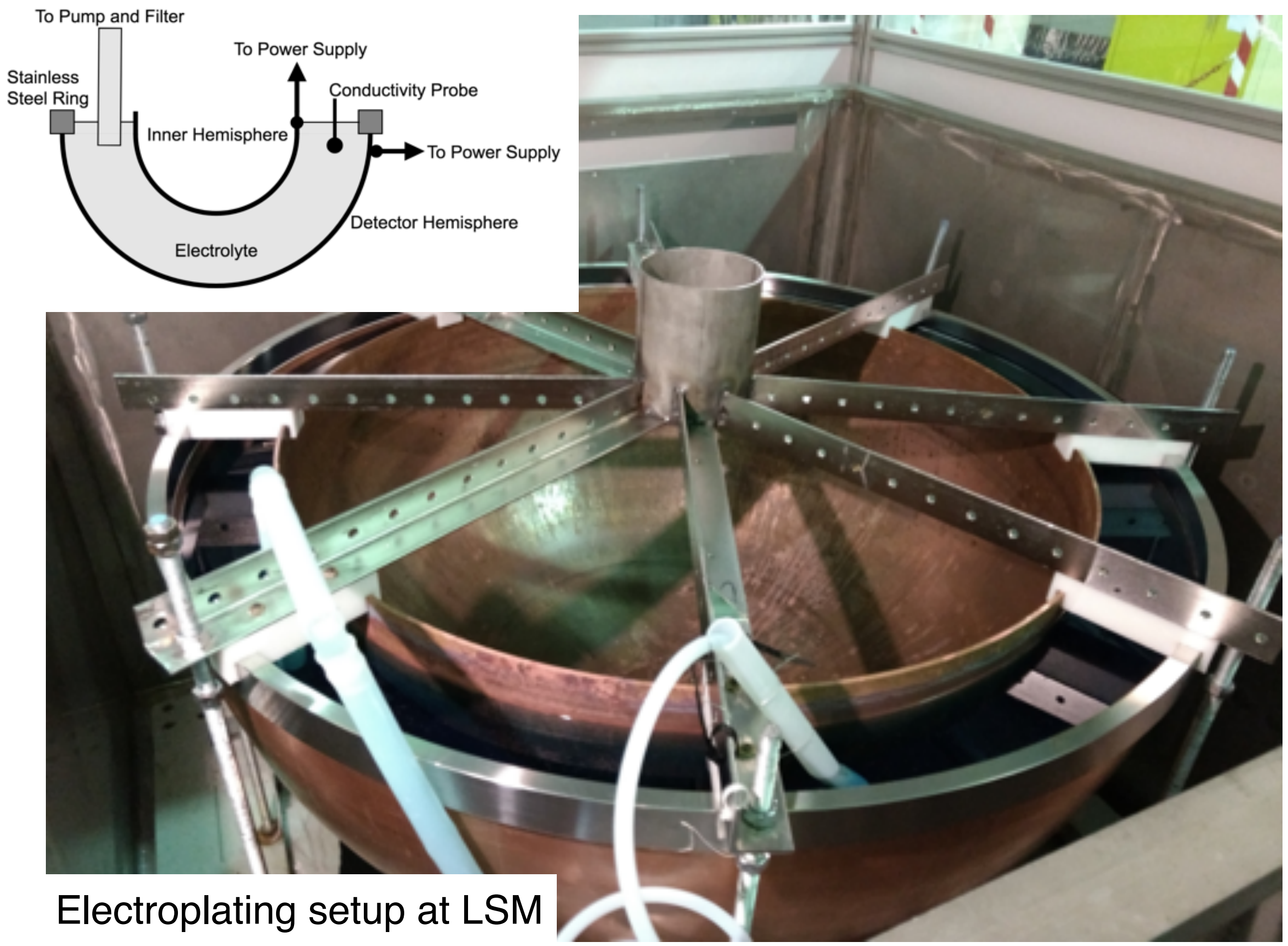

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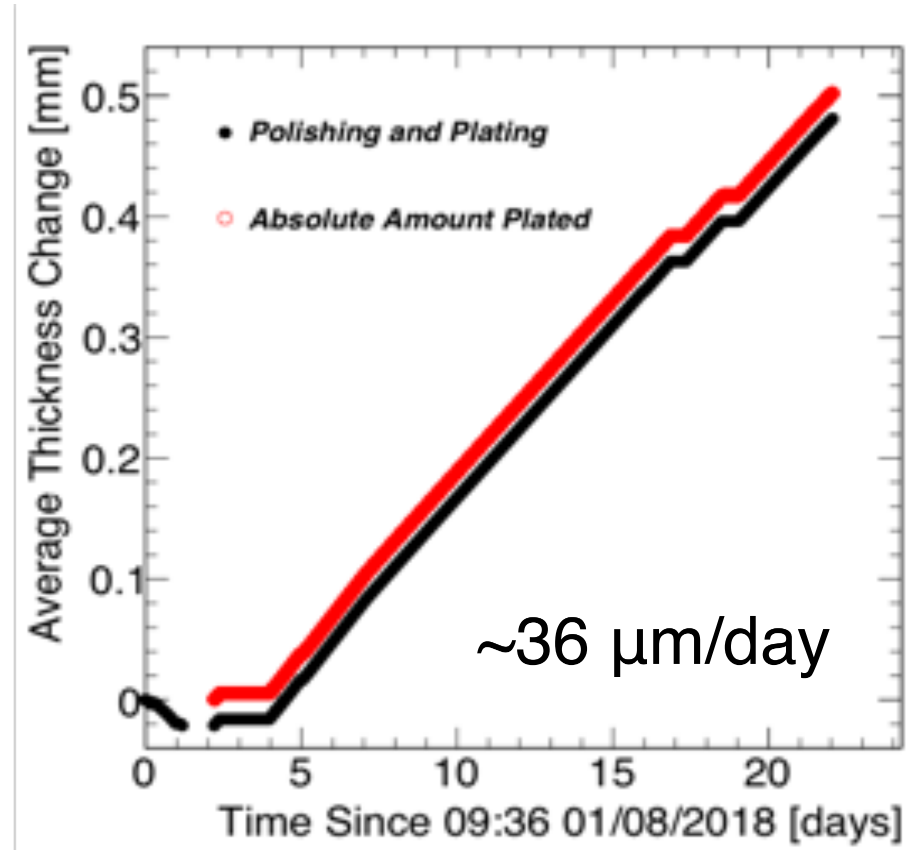

NIM A 988 (2021) 164844

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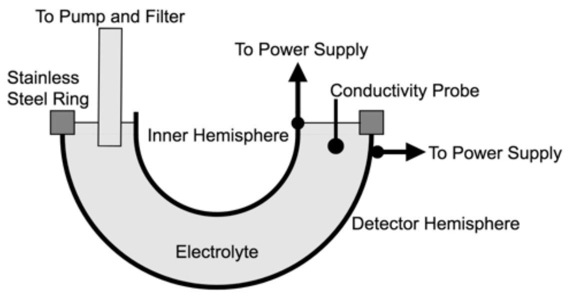

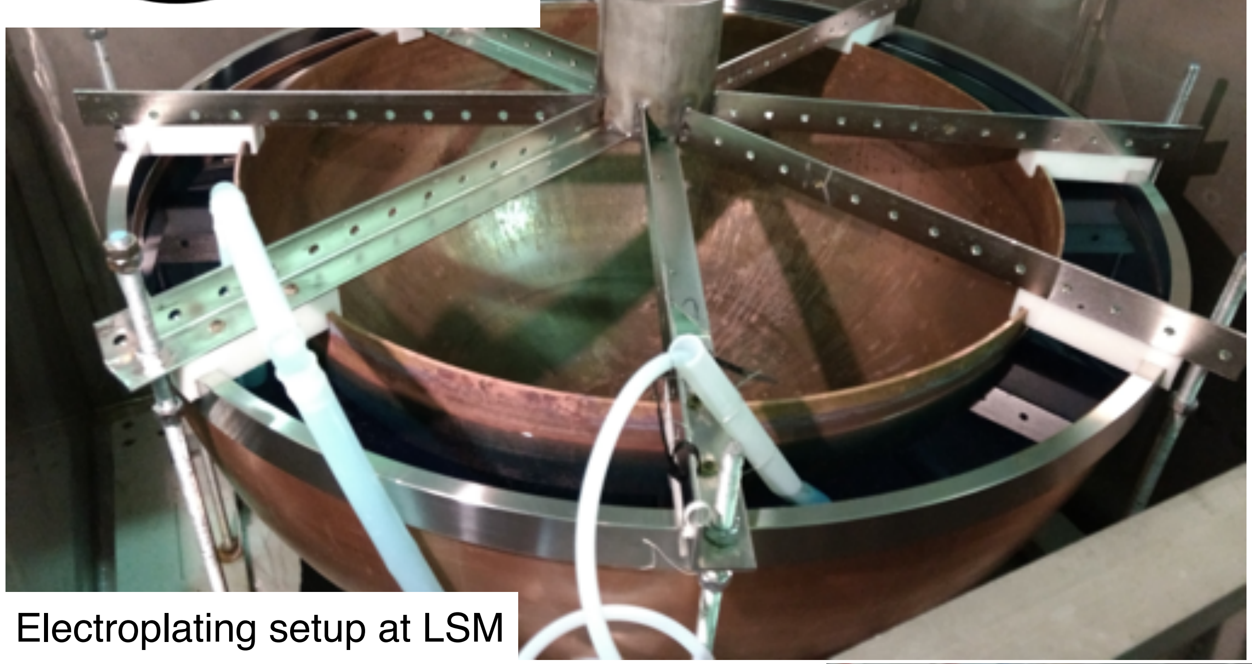

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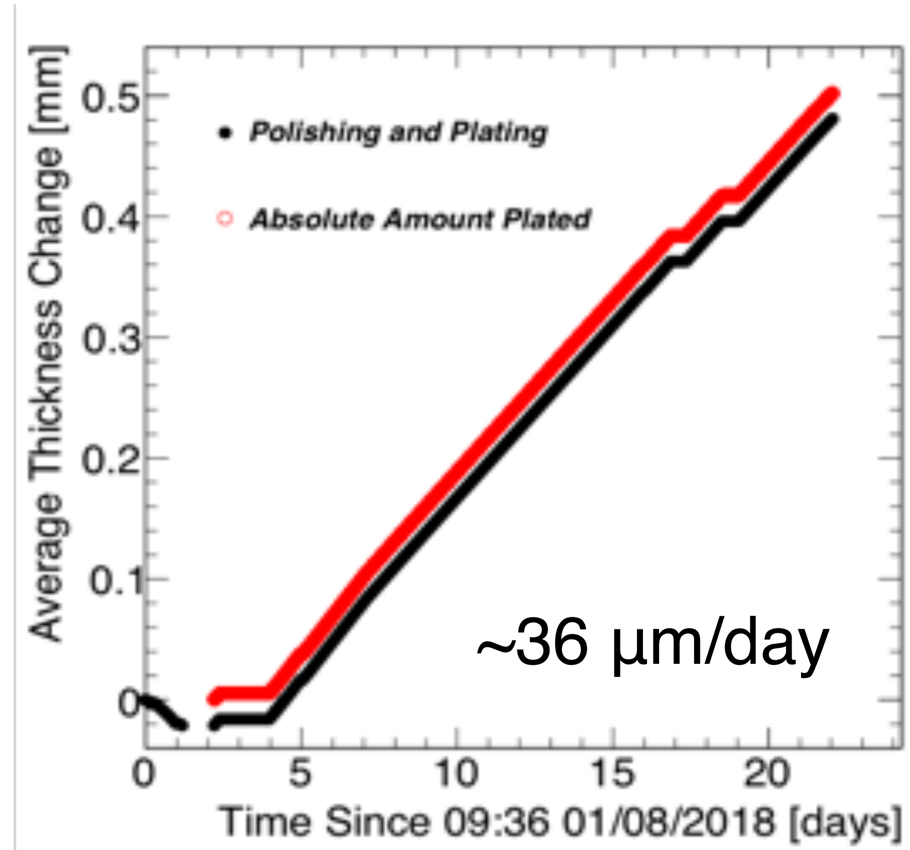


Sample	Weight [g]	^{232}Th [µBq/kg]	^{238}U [µBq/kg]
C10100 Cu (Machined)	-	8.7 ± 1.6	27.9 ± 1.9
Cu Electroformed	-	< 0.119	< 0.099
Hemisphere 1	0.256	< 0.58	< 0.26
Hemisphere 2	0.614	< 0.24	< 0.11

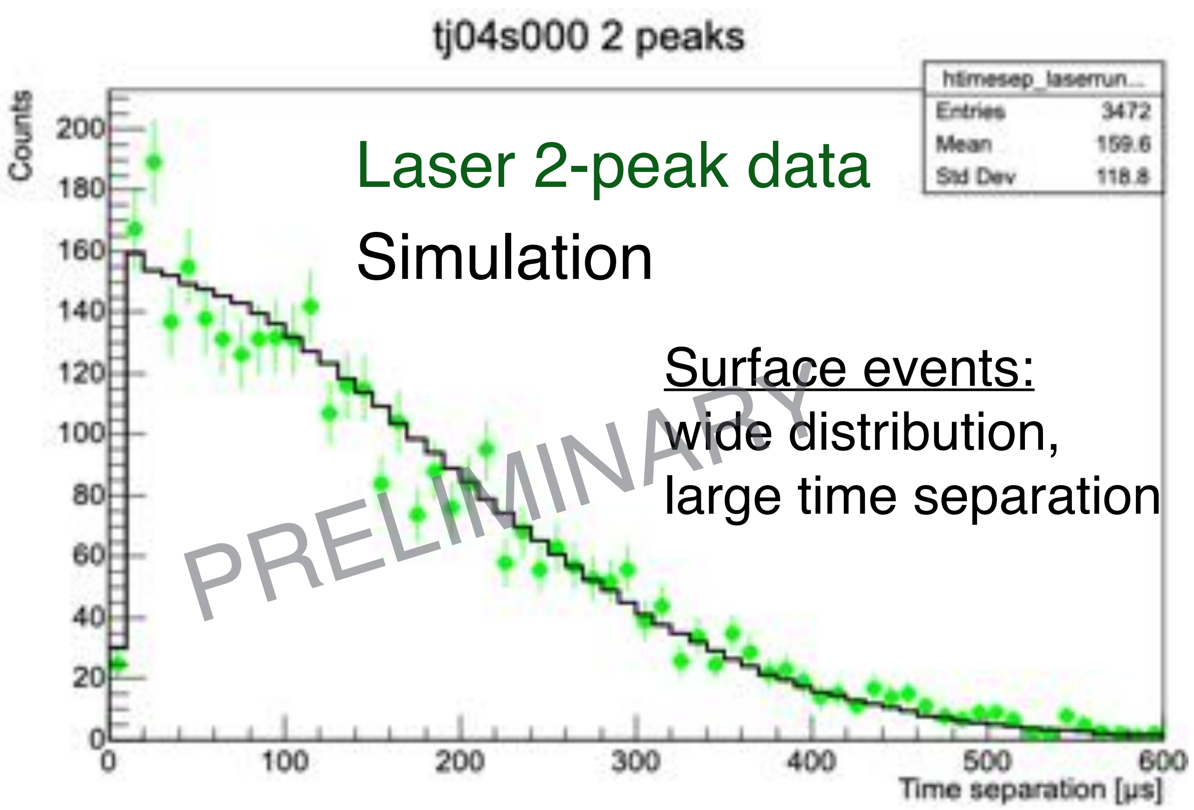
NIM A 988 (2021) 164844

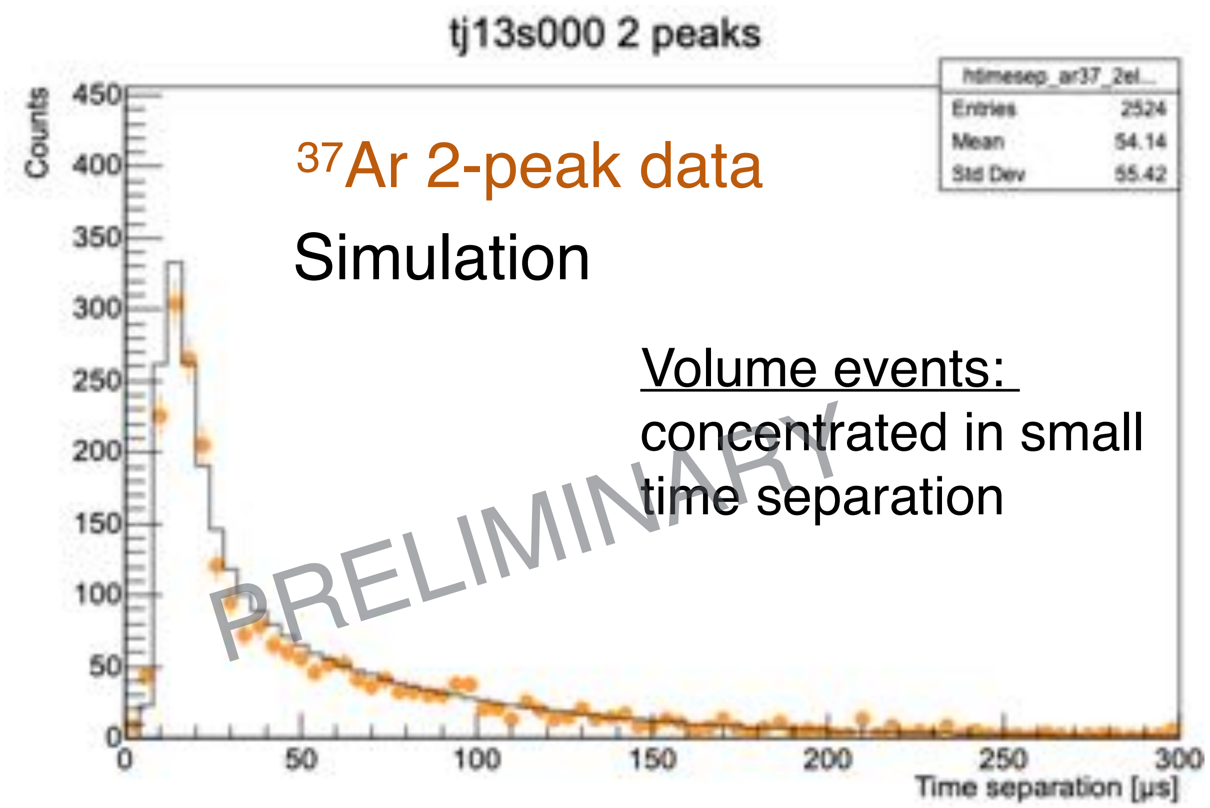
SNOGLOBE at LSM

- 2019: detector assembly in France
  - Hemispheres e-beam welded
  - 500 μm electroformed inner layer
- April 2019: initial commissioning at LSM
  - UV laser and ^{37}Ar calibration
  - Multi-anode sensor
- July 2019: Pb and H_2O shield installed
  - ~10 days of physics data
  - 135 mbar of CH_4 (~100g)

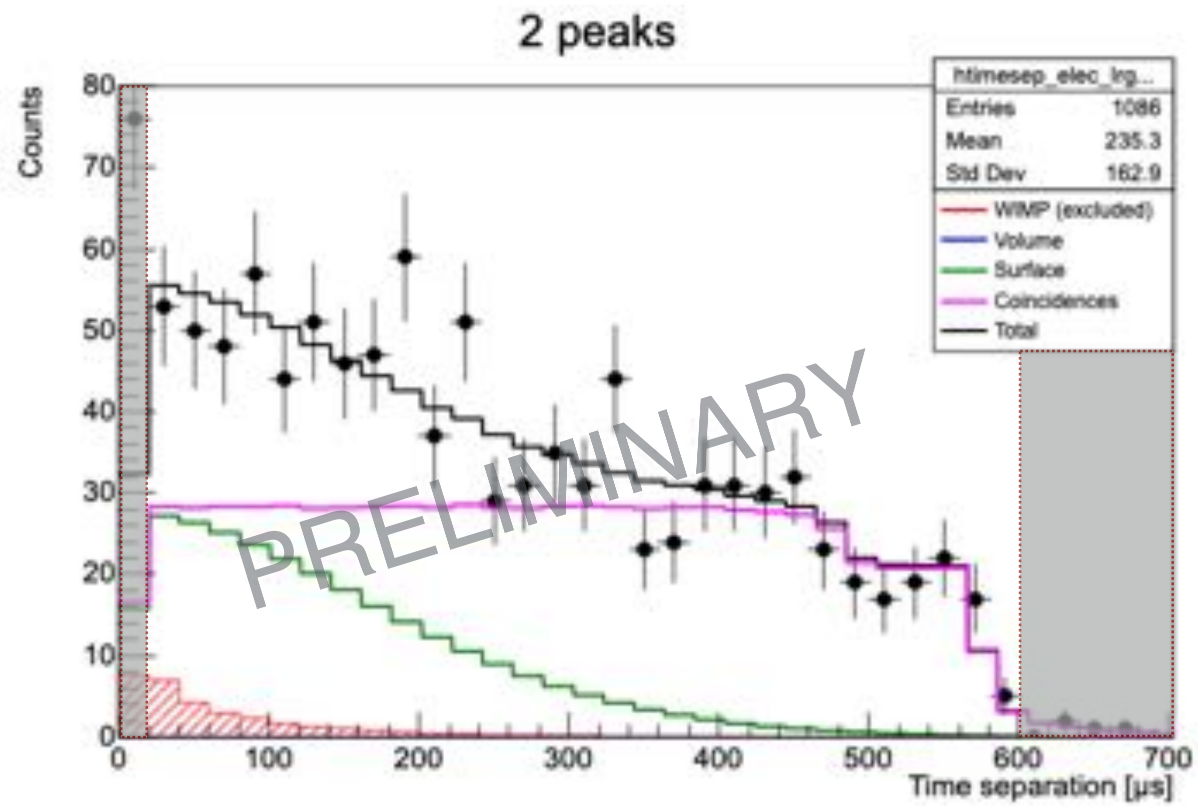
Electron Counting

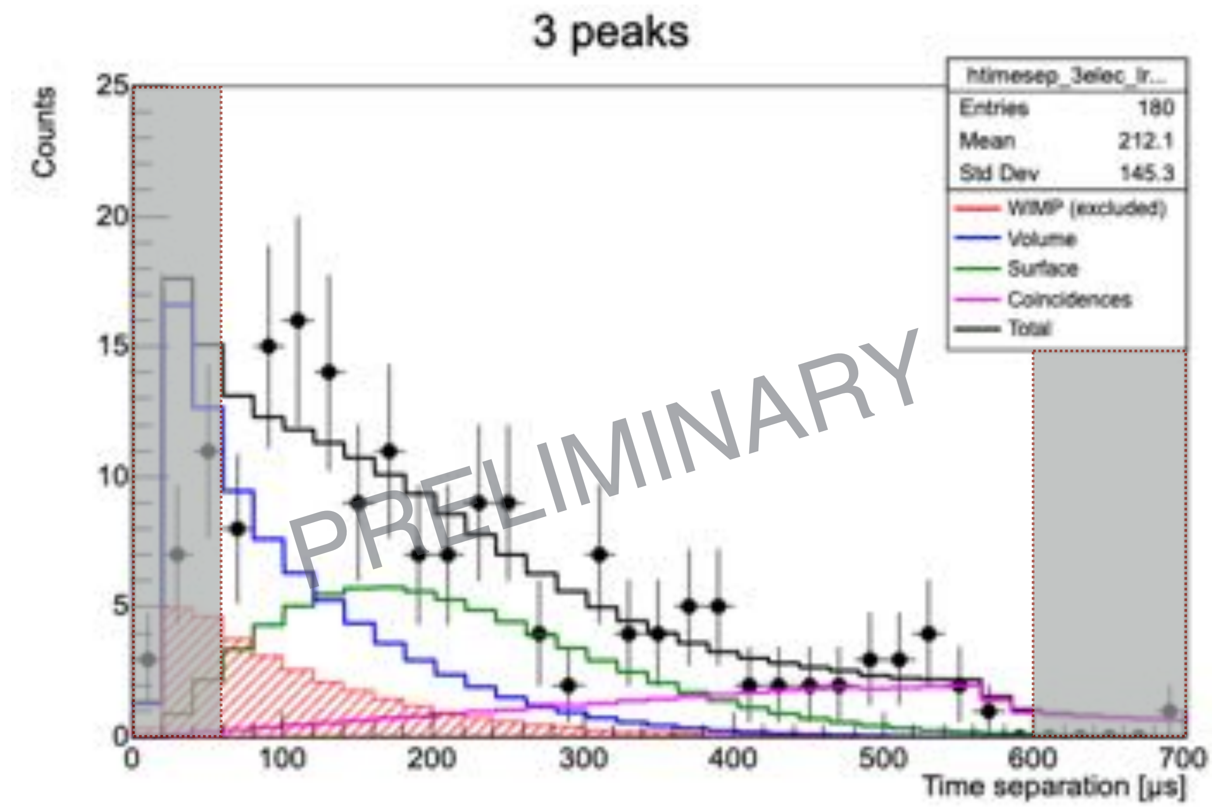
- Pulse treatment (deconvolution)
  - Resolve individual electrons
- Diffusion O(100µs)
  - Obtain time separation of peaks
  - Surface vs volume discrimination
- Signal and background model
  - Derived from simulations
  - Validated with calibration data

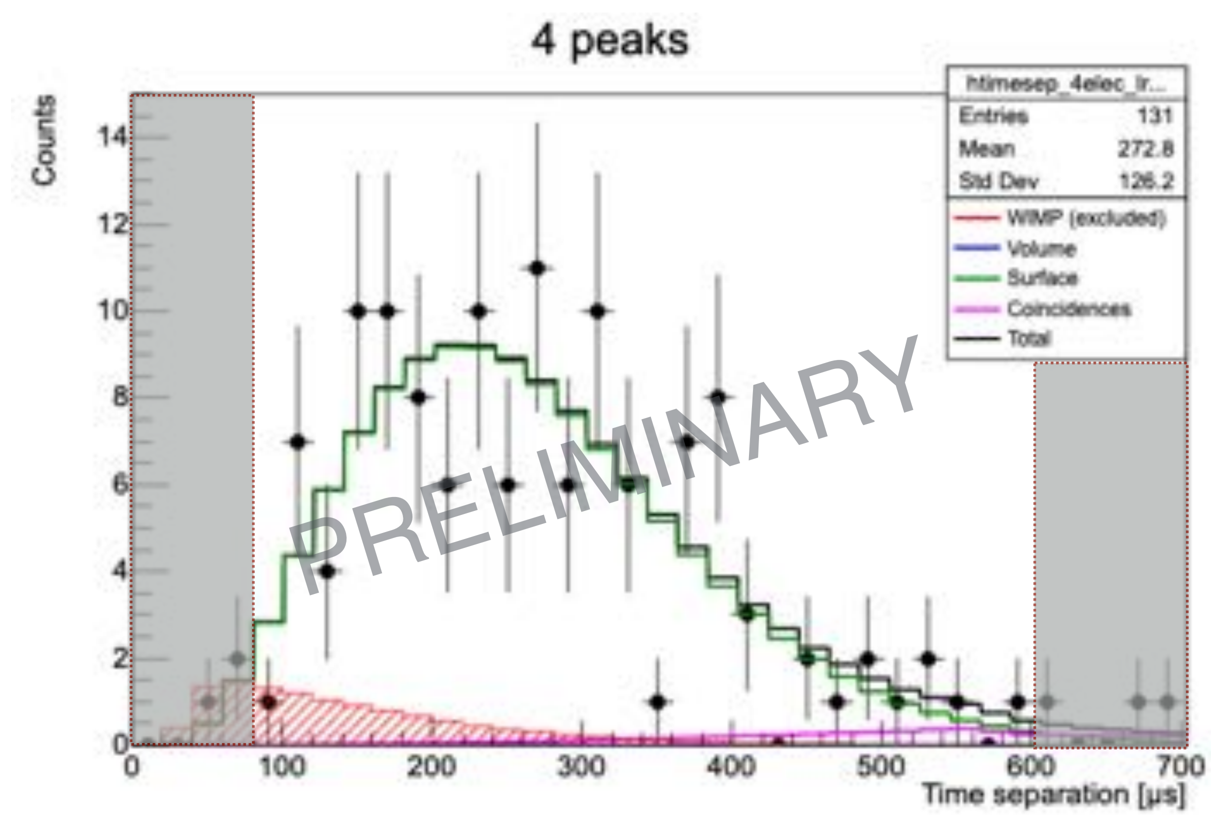




Results with LSM data

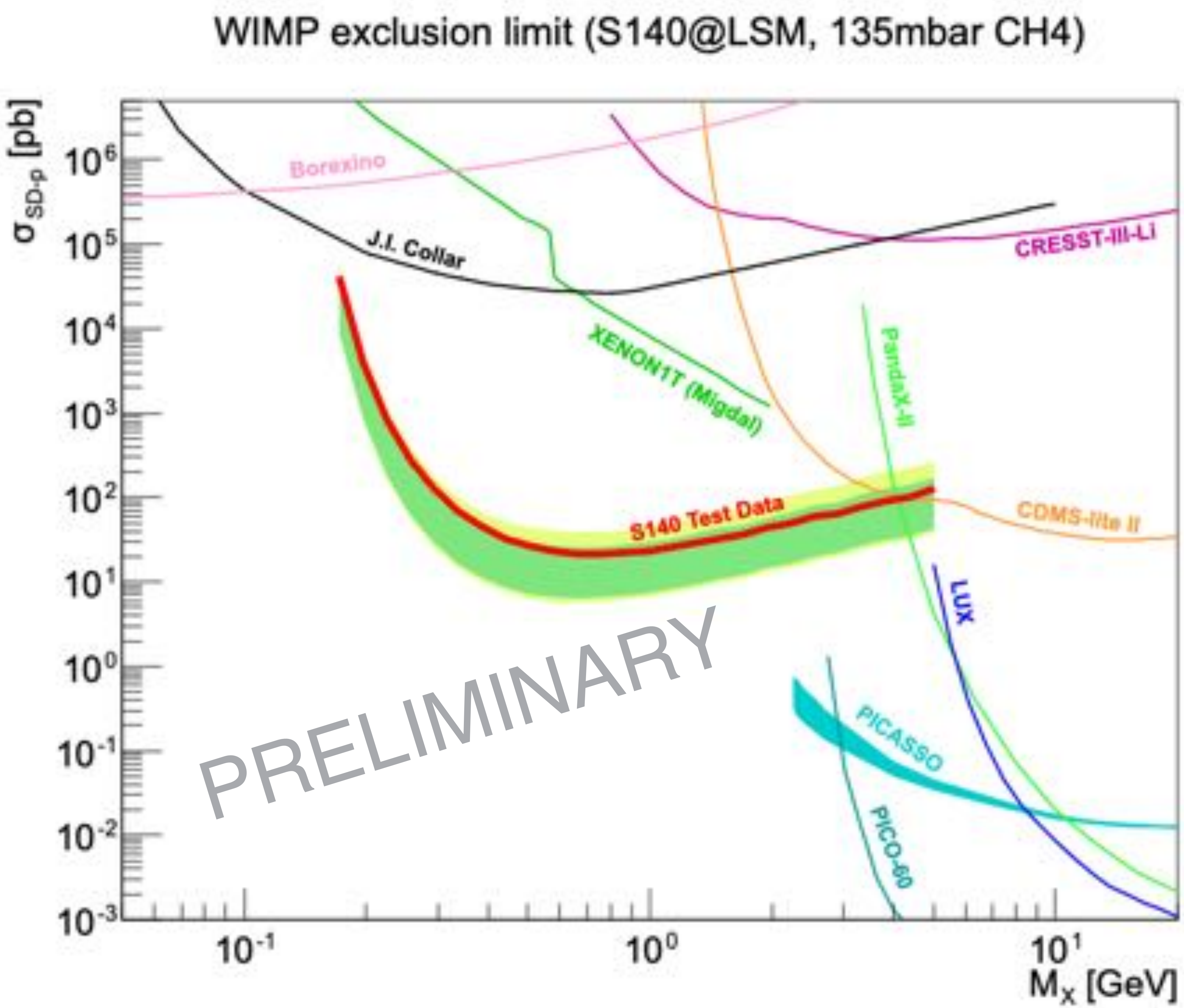






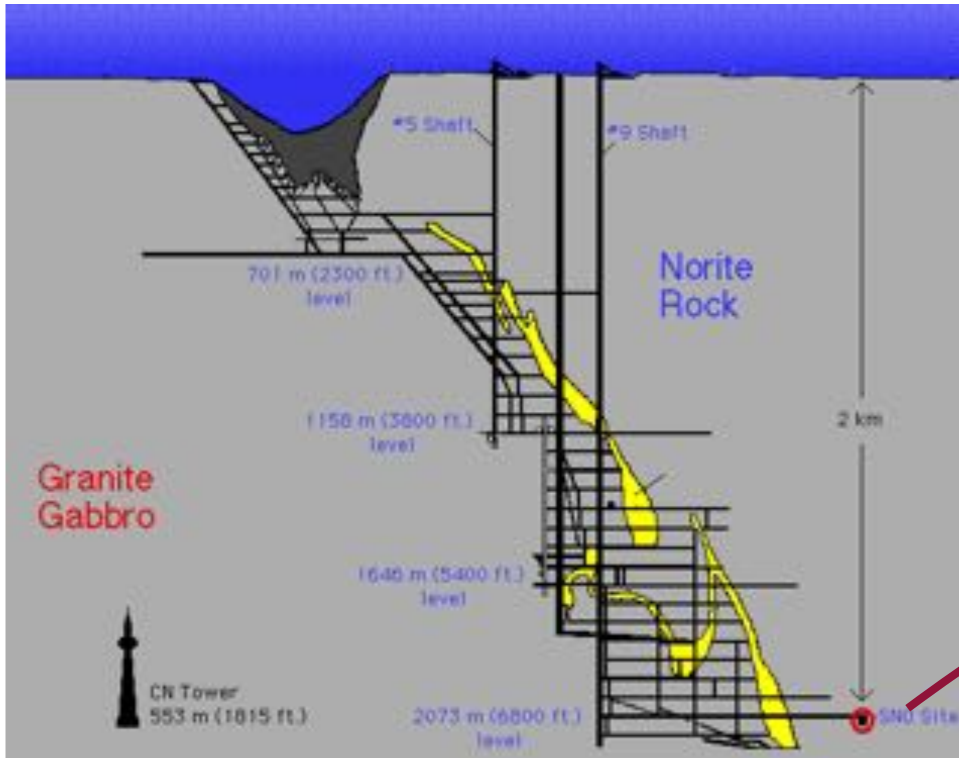
- Data divided into 2/3/4 peak
- Maximum likelihood fit to time separation
- Only test data analysed so far: ~30% data
  - Remaining data is blinded

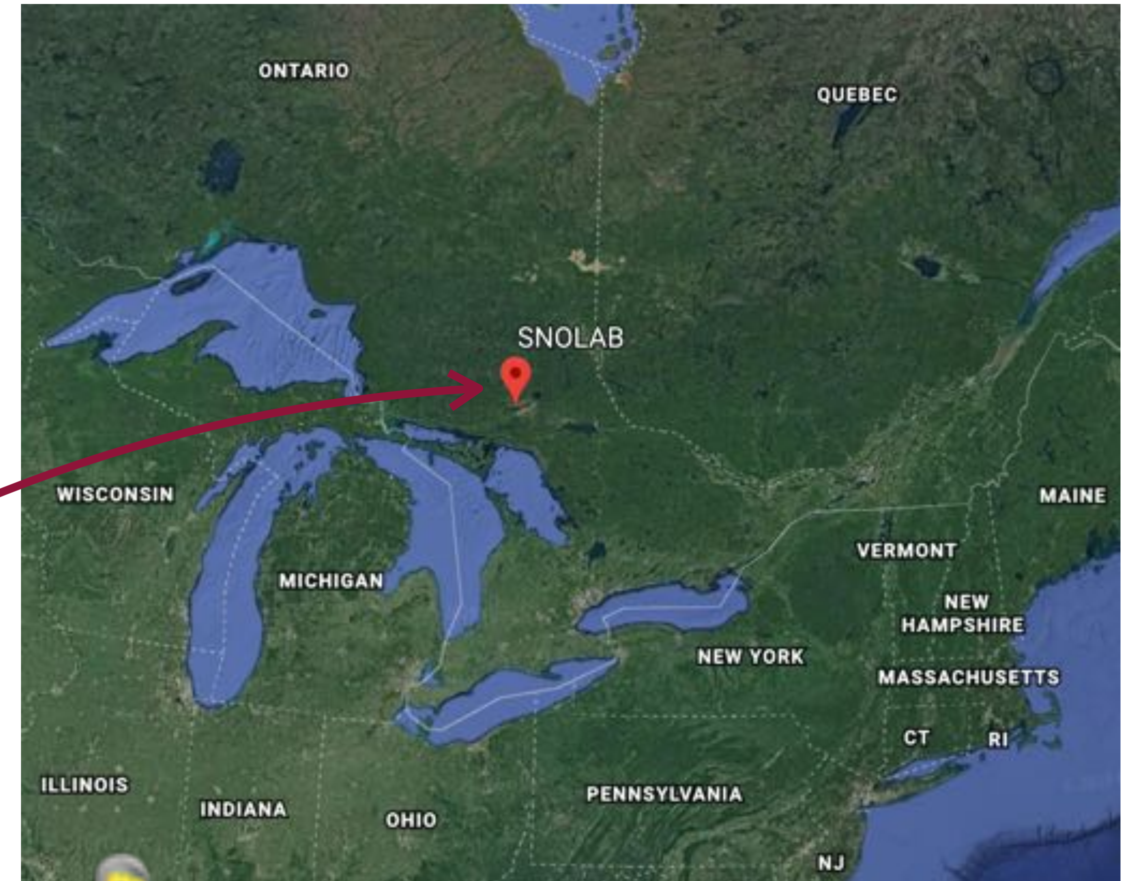
LSM Physics Result

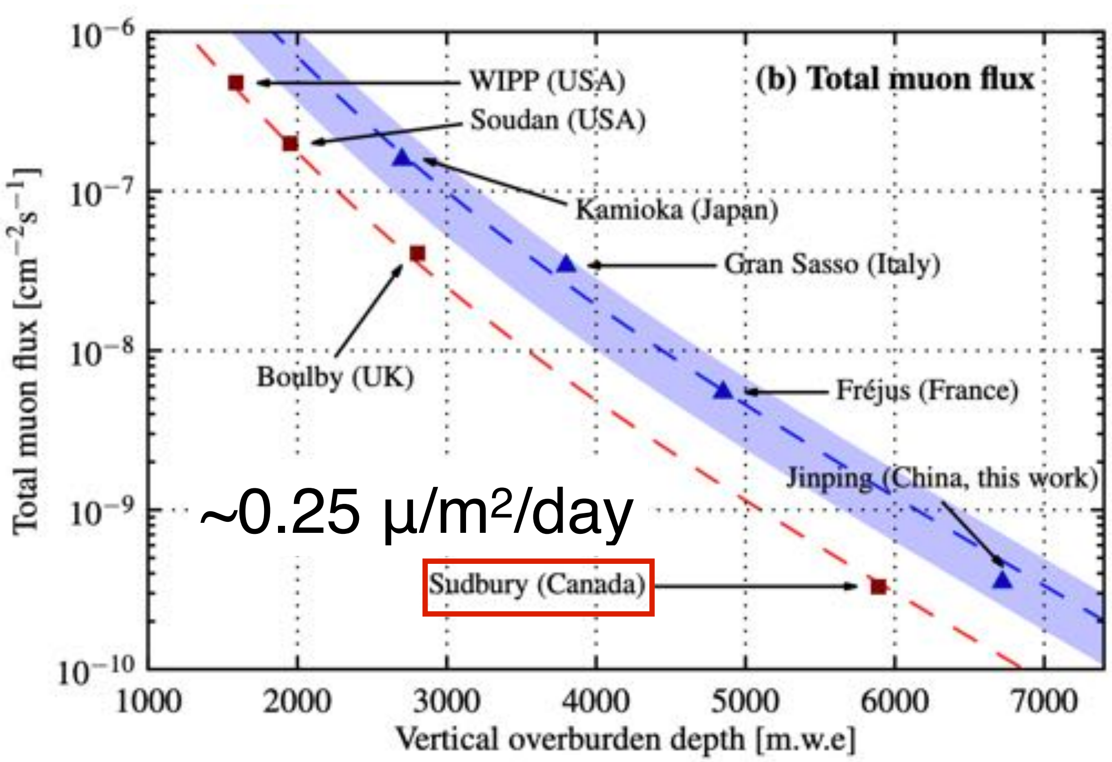


- 90% upper limits set with profile likelihood ratio
- Exposure 0.12 kg·days

NEWS-G at SNOLAB





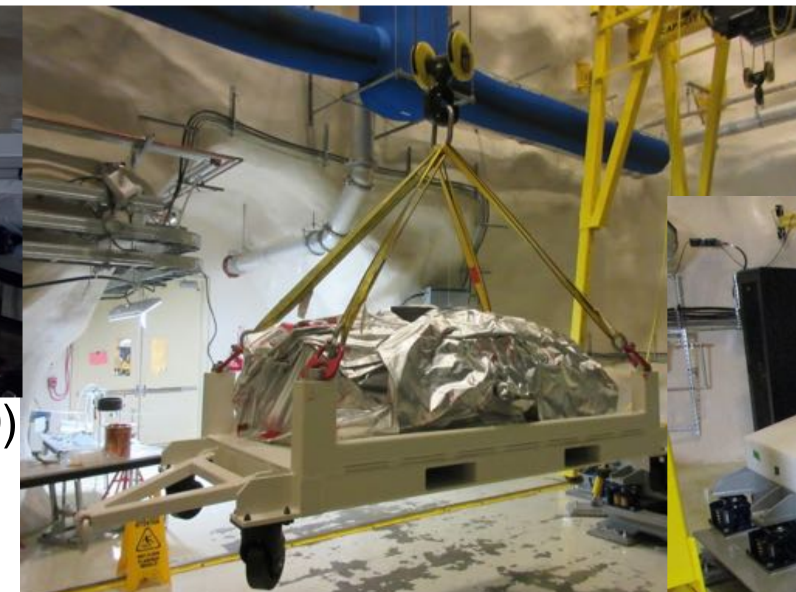


Chin.Phys.C 45 (2021) 2, 025001

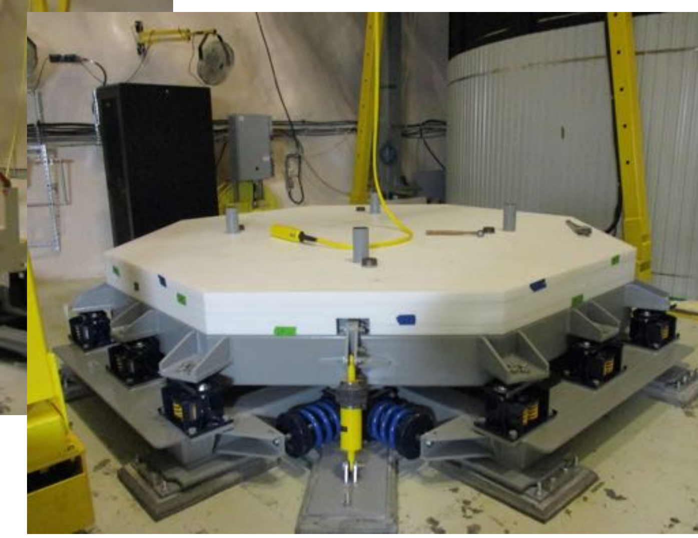
Installation at SNOLAB

Arrival at SNOLab (Dec ’19)

Unwrapped and baked (Sep ’20)

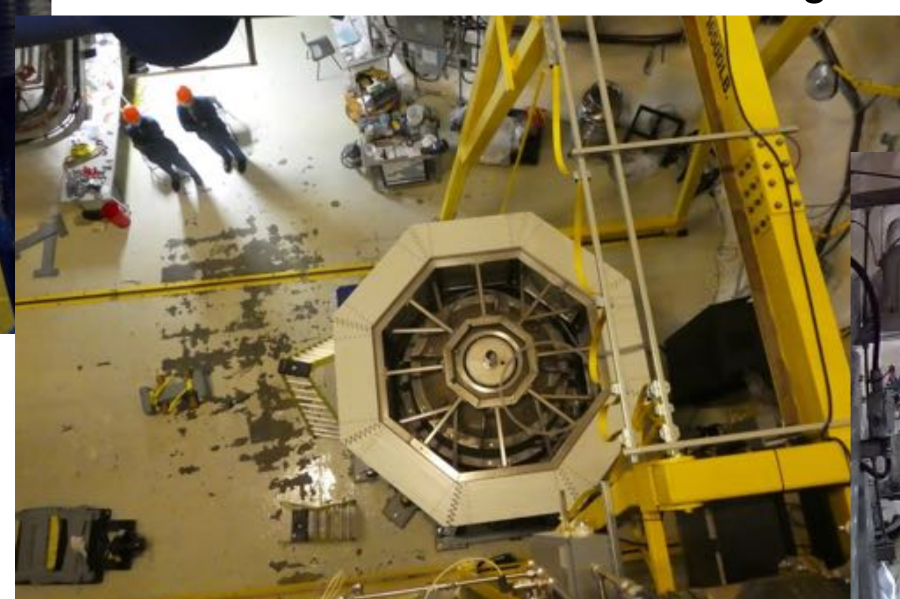


Pb shielding arrival



Seismic platform installation

Detector Installation



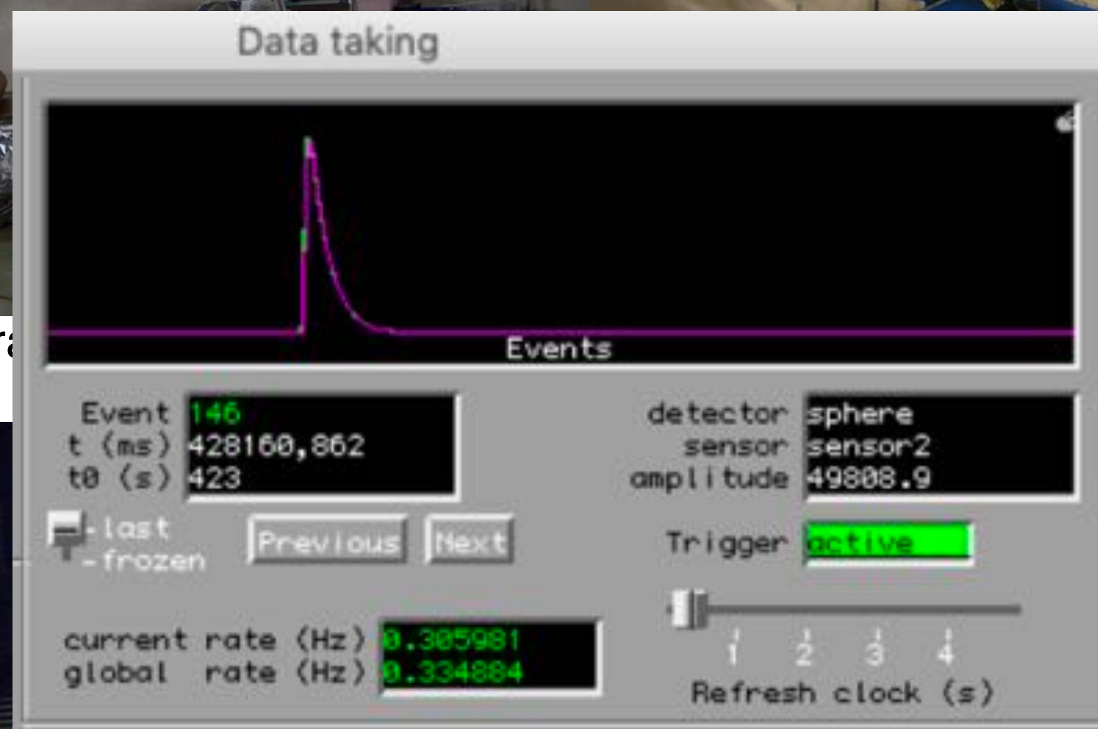
PE shielding installation

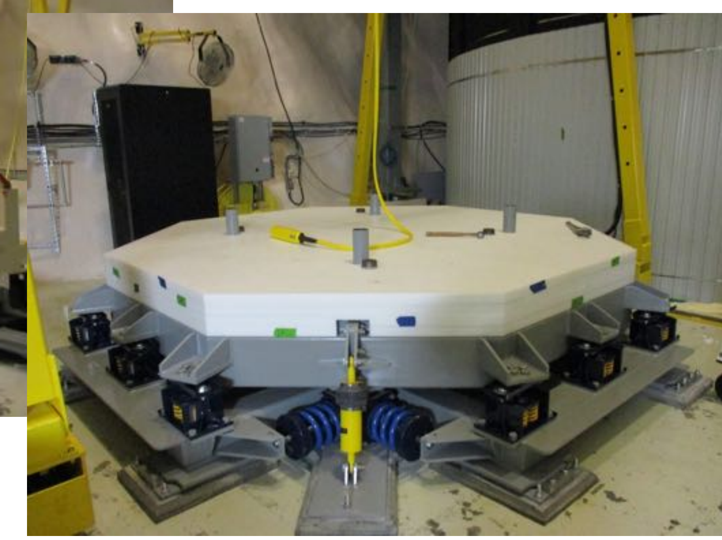
SNOGLOBE complete (Dec ’20)

Installation at SNOLAB

Arrival at SNOLab (Dec ’19)

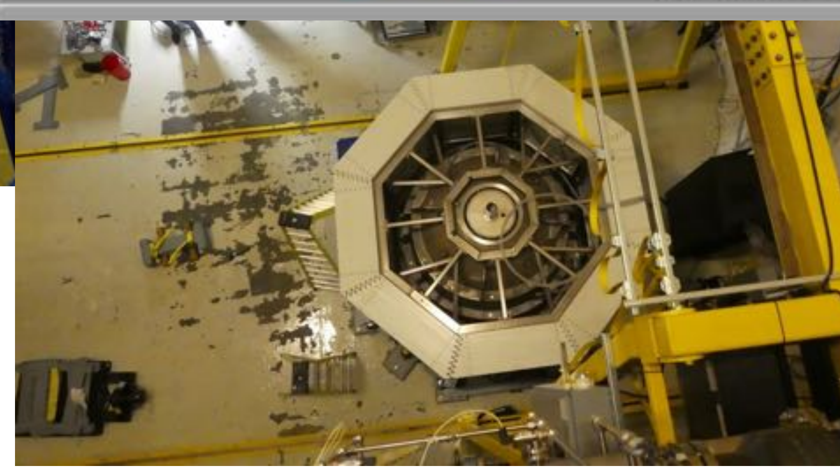
Unwra





Seismic platform installation

Detector Installation



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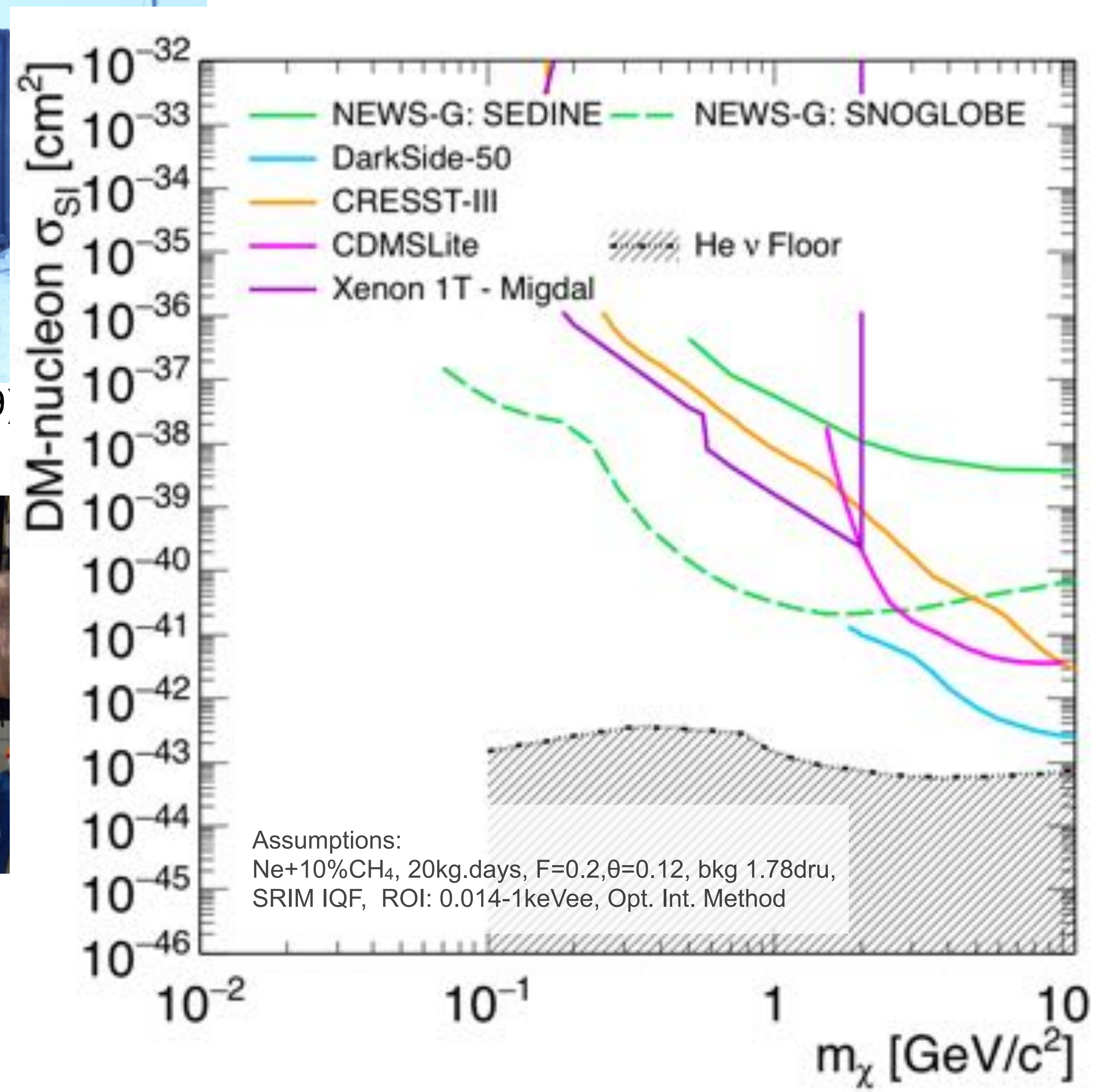
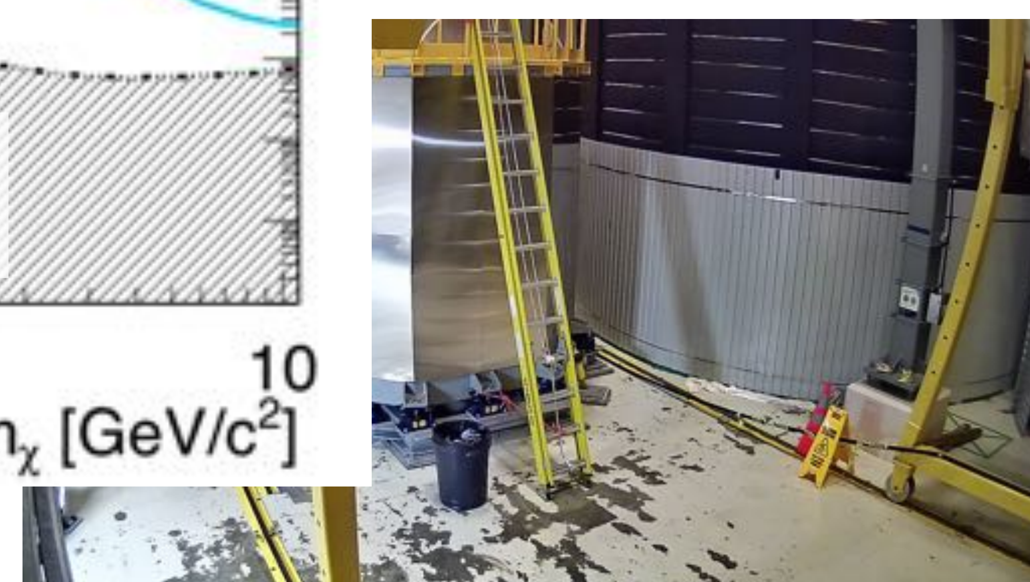


Detector Installation

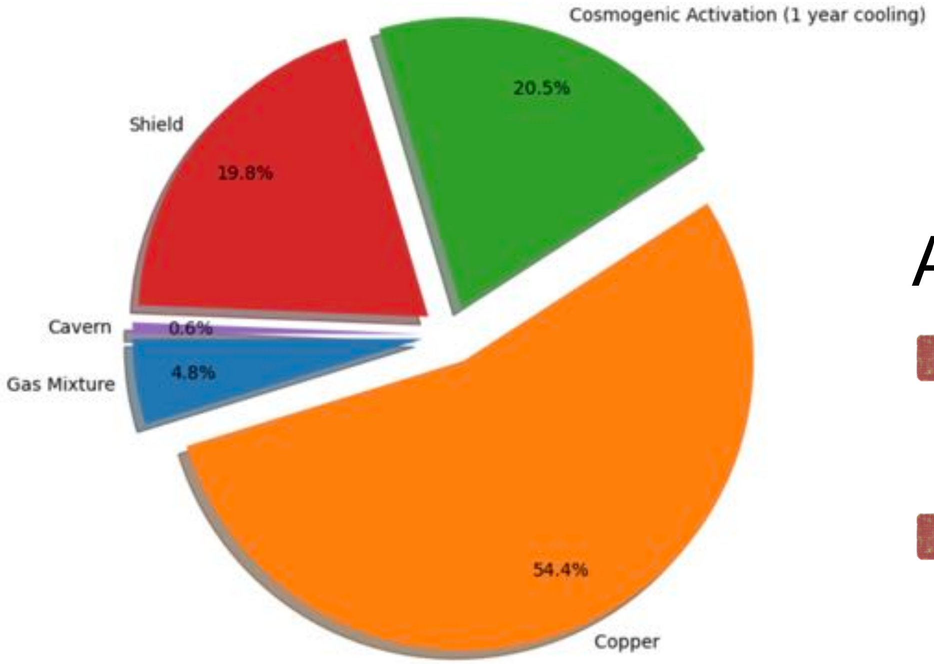
PE shielding installation

Seismic platform installation



SNOGLOBE complete (Dec ’20)

Electroformed Cuprum Manufacturing Experiment

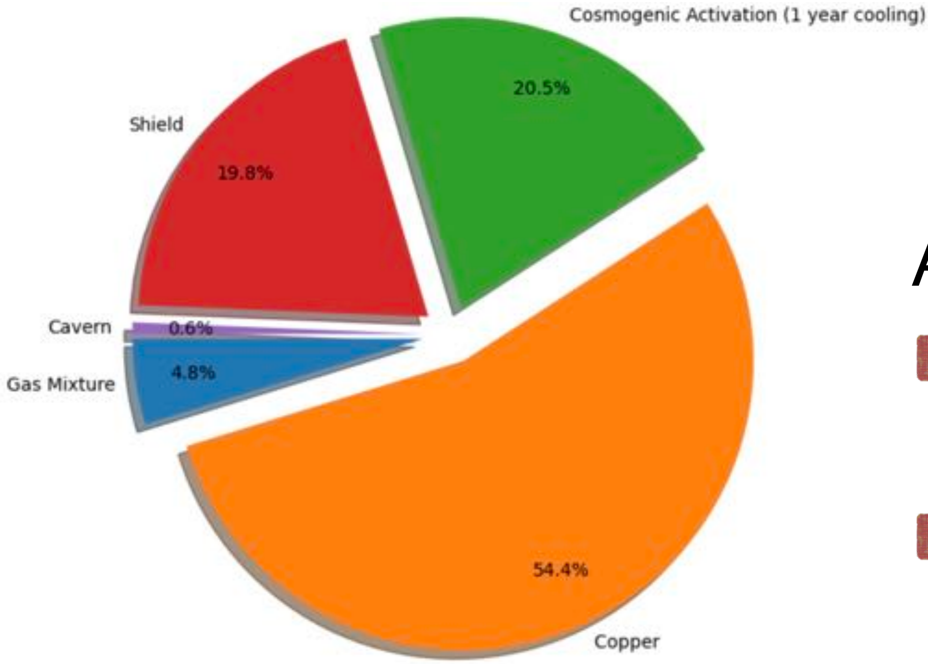


ECuME

A ⌀140 cm sphere electroformed underground in SNOLAB

- Builds on achievements of NEWS-G electroplating
  - 36 μm/day → ~1 mm/month
- No machining or welding - grow sphere directly

Electroformed Cuprum Manufacturing Experiment



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- Builds on achievements of NEWS-G electroplating
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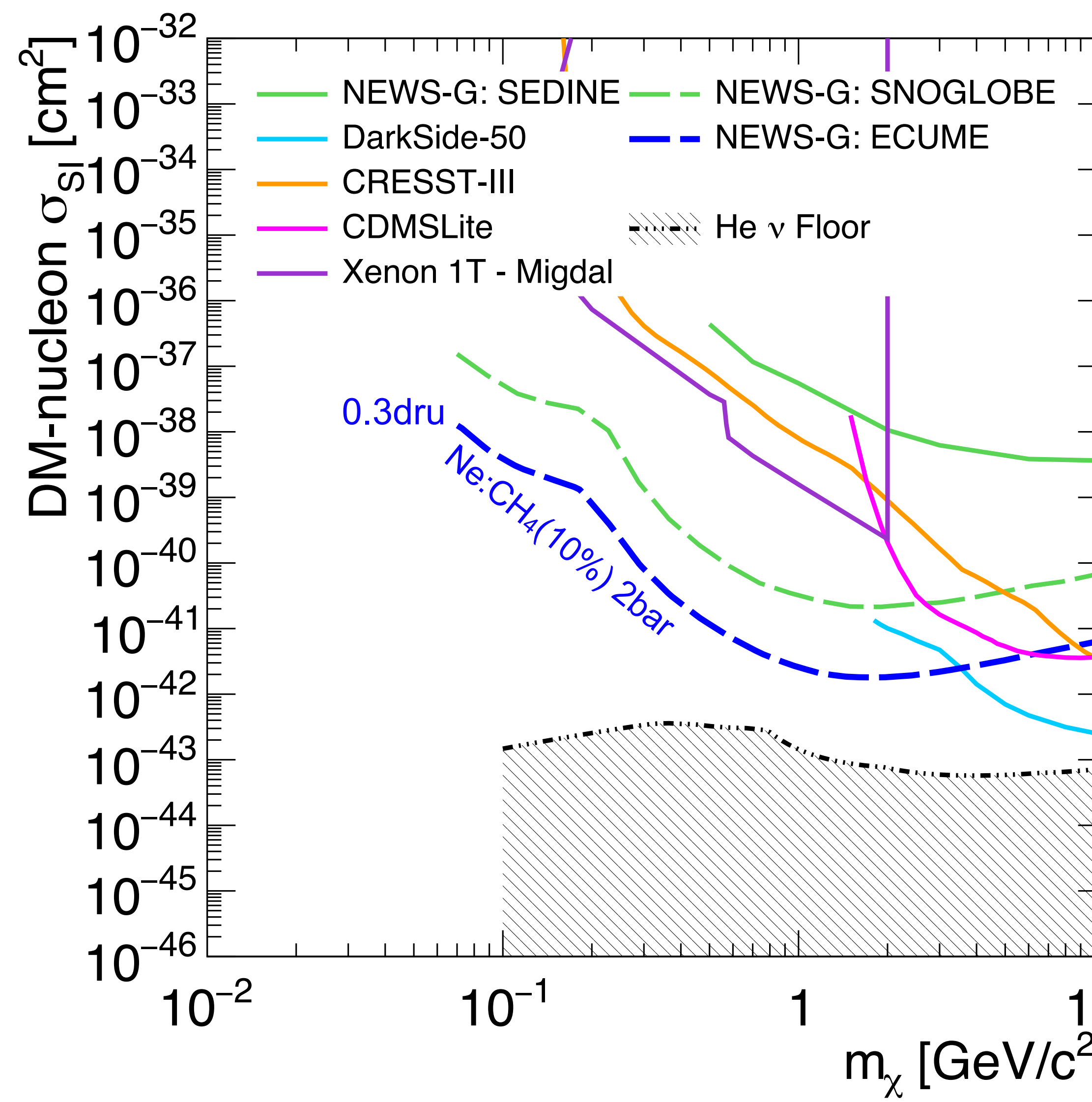
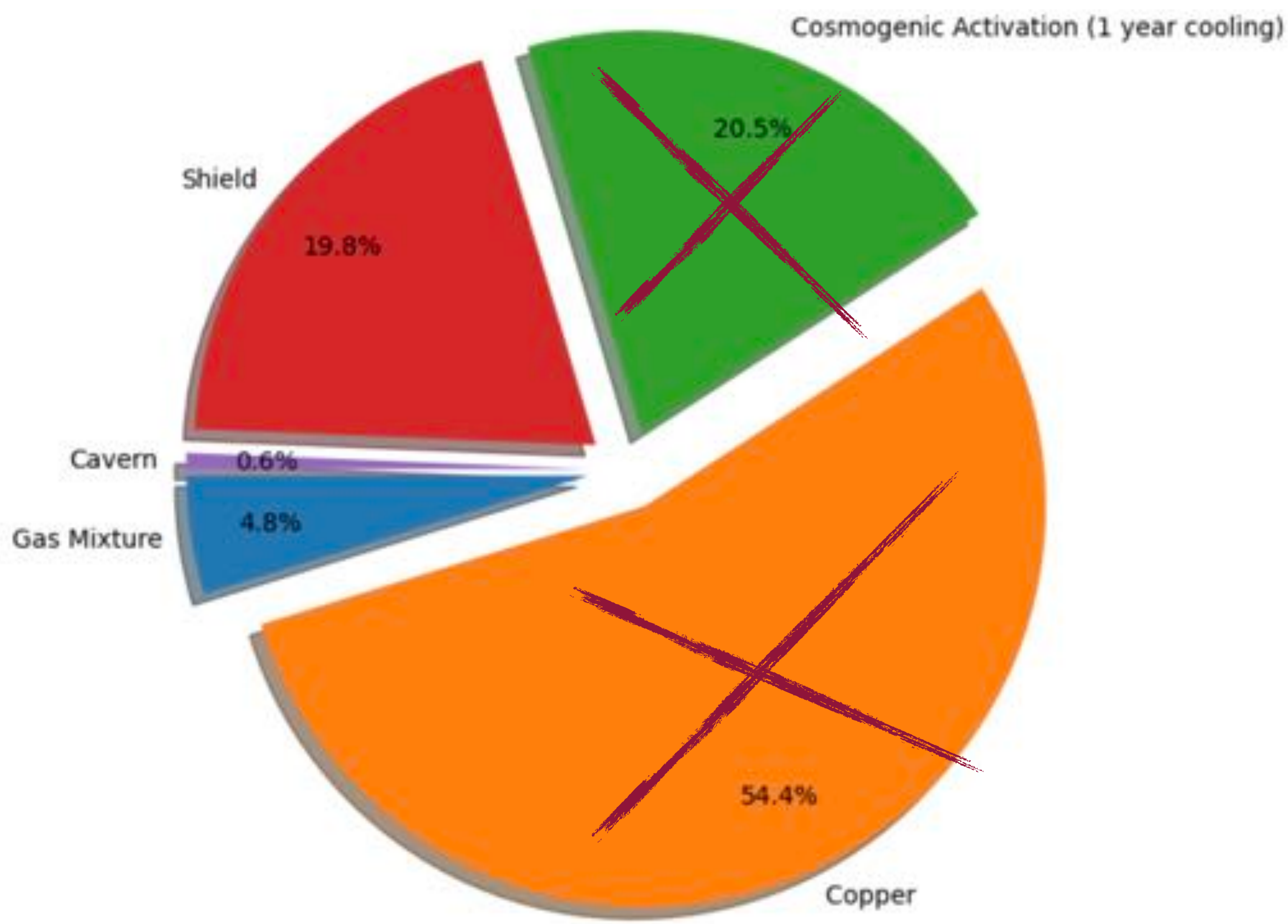
Current Status

- ⌀30 cm scale prototype to be produced at PNNL
  - Bath designed and assembled
  - Initial tests on electrolyte quality successful
  - Potential to undertake similar efforts at Boulby
- ⌀140 cm detector to follow shortly after
  - Use existing shielding for physics exploitation
- R&D on EF CuCr alloys through PureAlloys project

PNNL Shallow Underground Laboratory

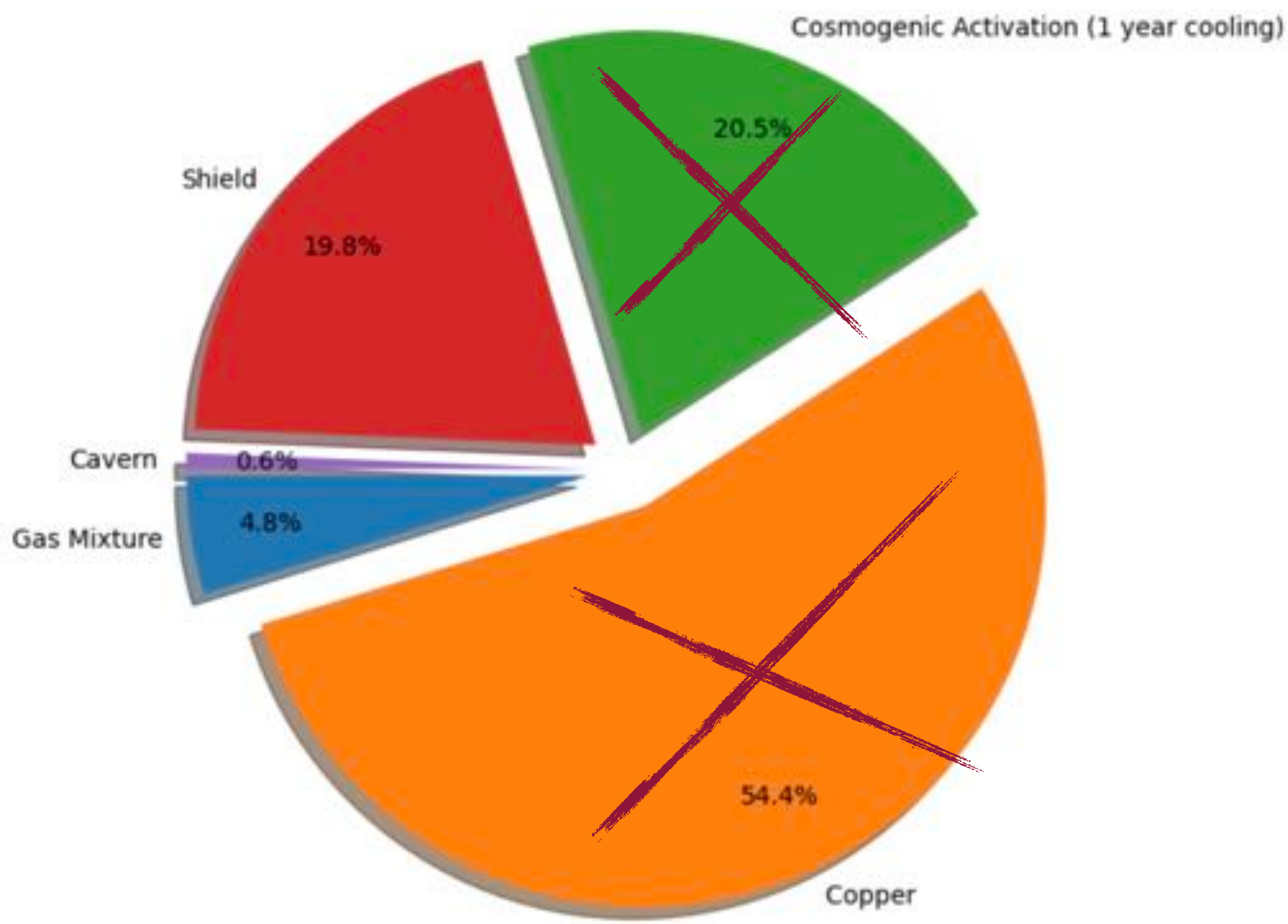


Reaching the neutrino floor



Reaching the neutrino floor

Scale volume and improve shielding



DarkSPHERE

Volume ×10: ⌀300cm intact underground electroformed spherical proportional counter with water-based shield

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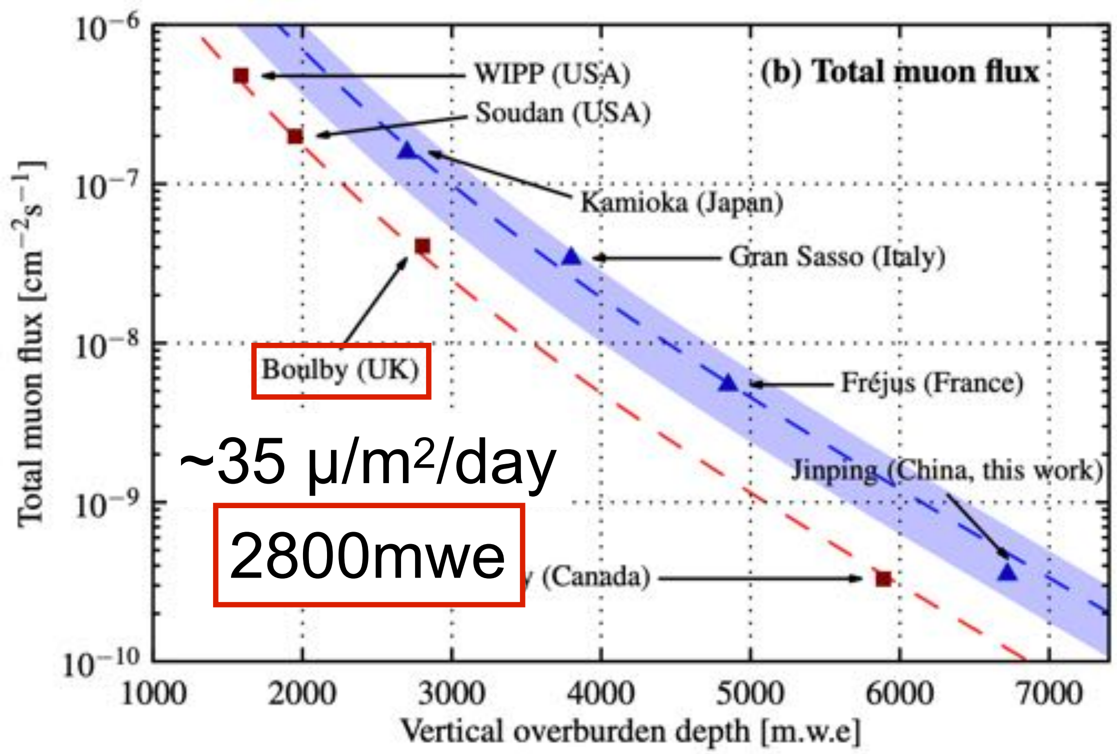

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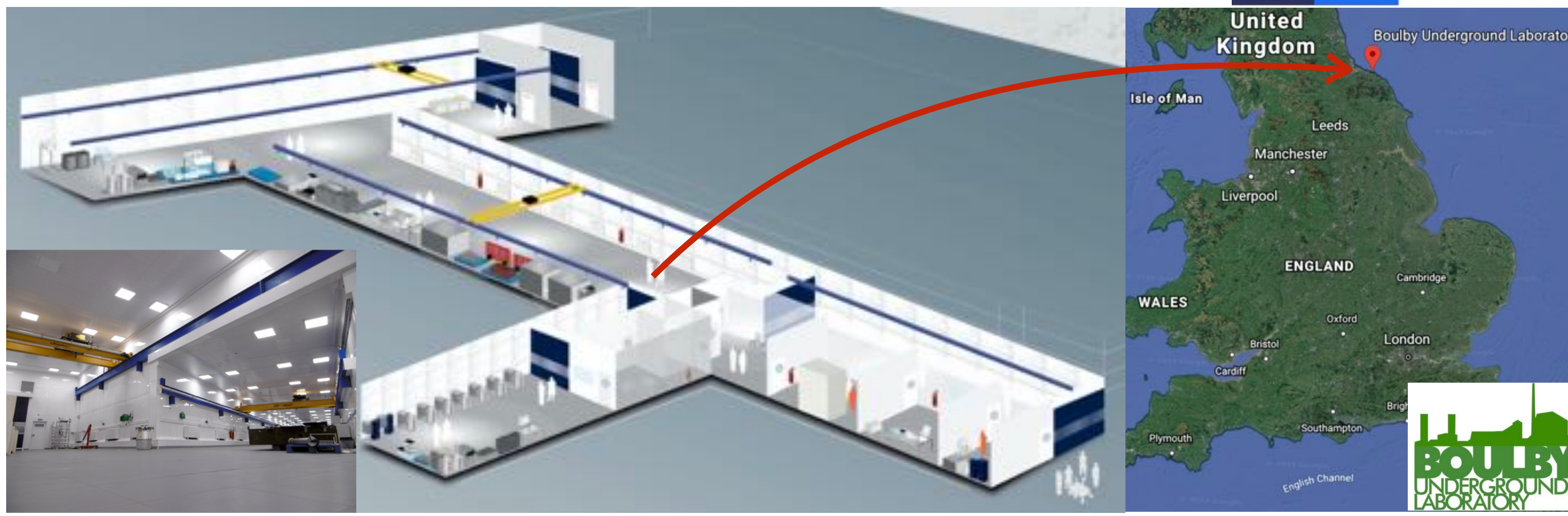
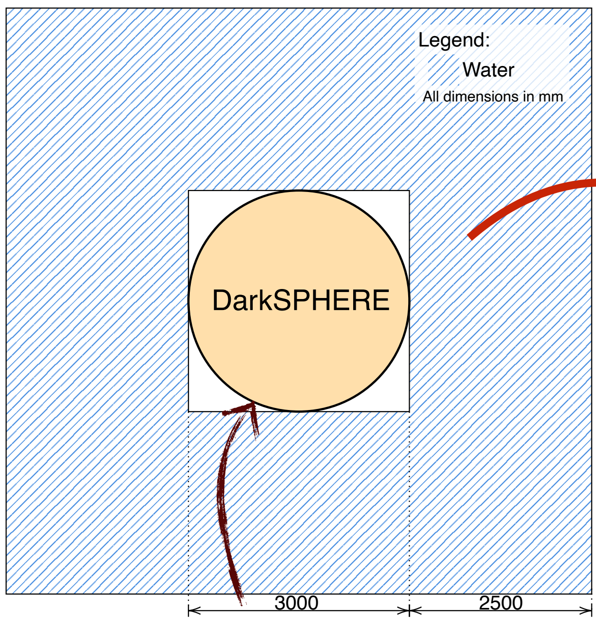


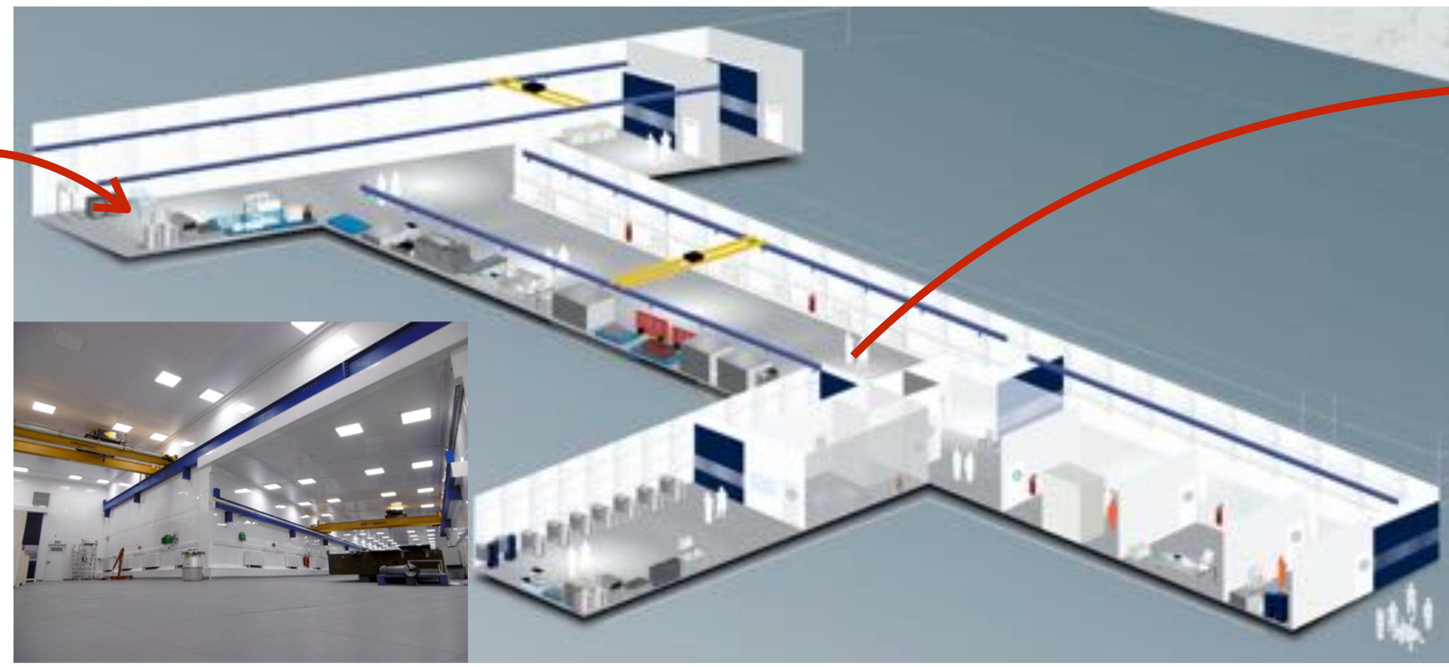
DarkSPHERE

Volume ×10: ⌀300cm intact underground electroformed spherical proportional counter with water-based shield

Science and Technology Facilities Counc



5 bar He:C_4H_{10} (90%:10%)
(27 kg target mass)



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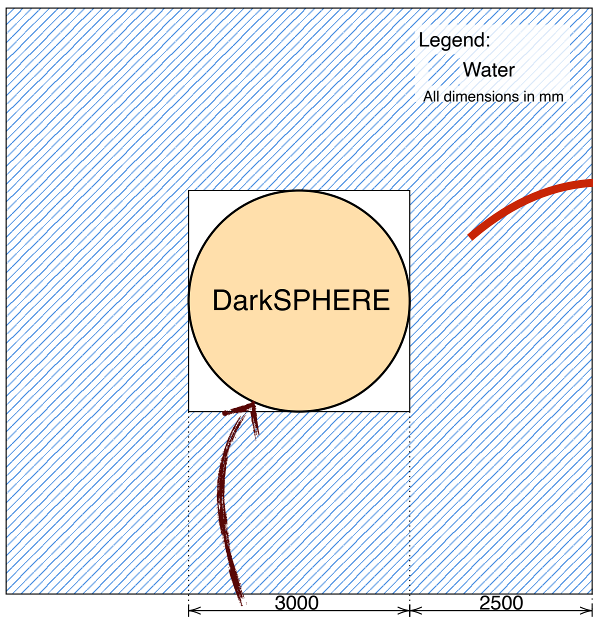

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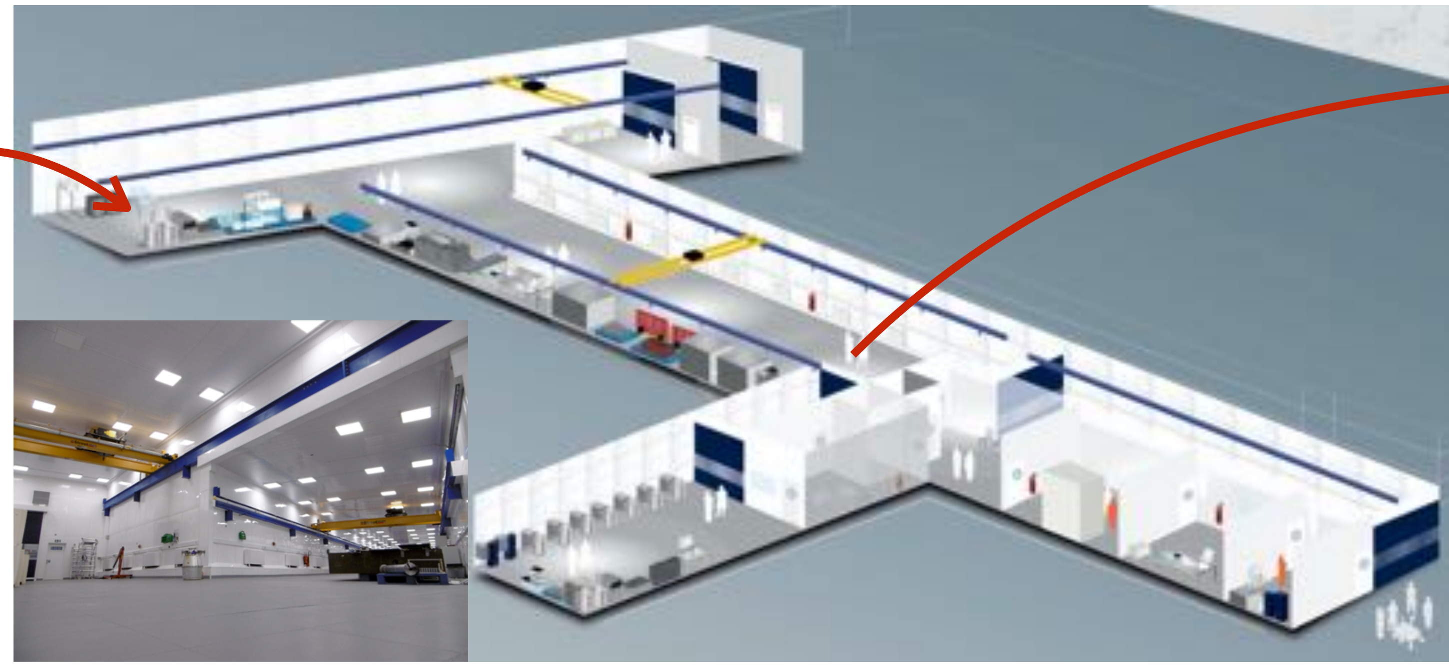
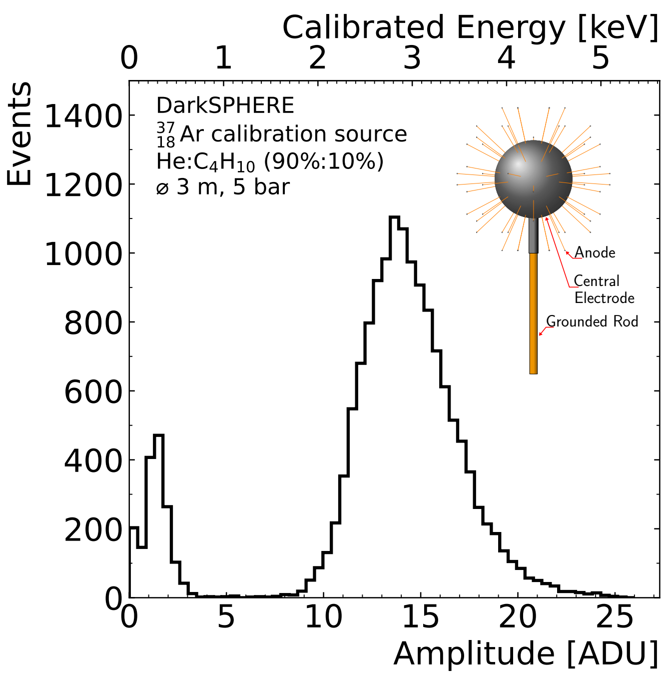


Possibility to host DarkSPHERE at Boulby's Large Experimental Cavern

- Possibility for a 8×8×8m³ detector without further excavations
- Funding obtained for setting-up electroformation facility



Simulation with 60-anode ACHINOS in DarkSPHERE

DarkSPHERE: Physics Potential

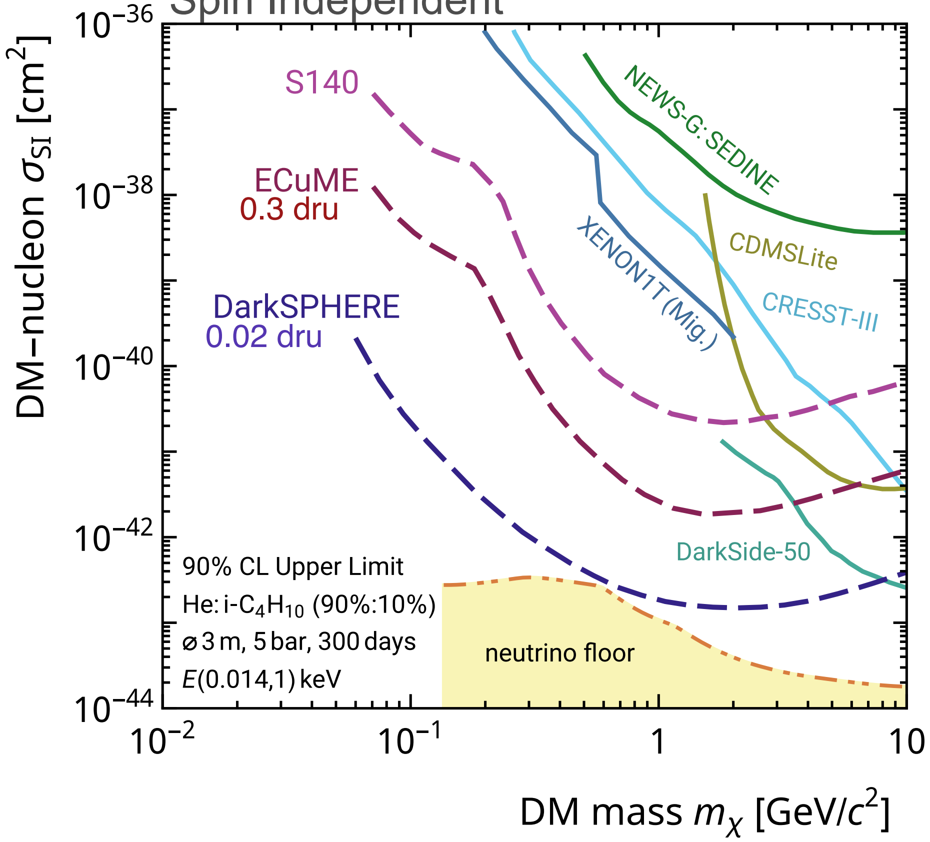
arXiv:2301.05183

DarkSPHERE: Physics Potential

Nuclear Recoils

arXiv:2301.05183

Spin Independent



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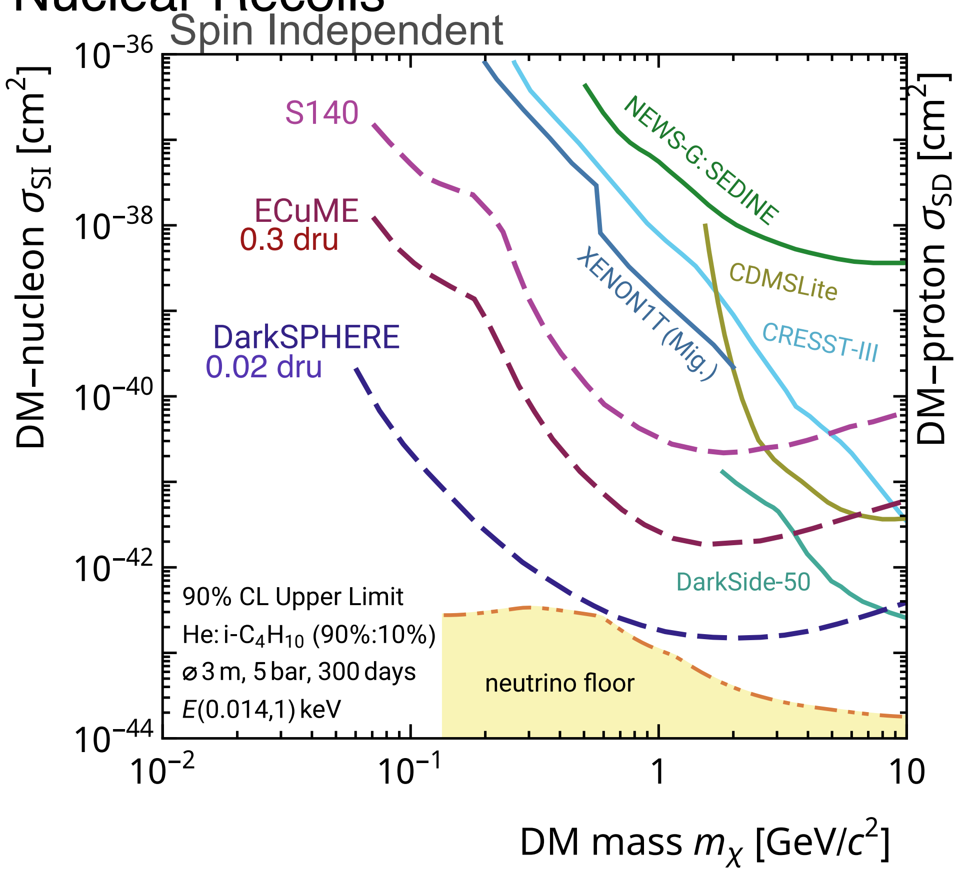

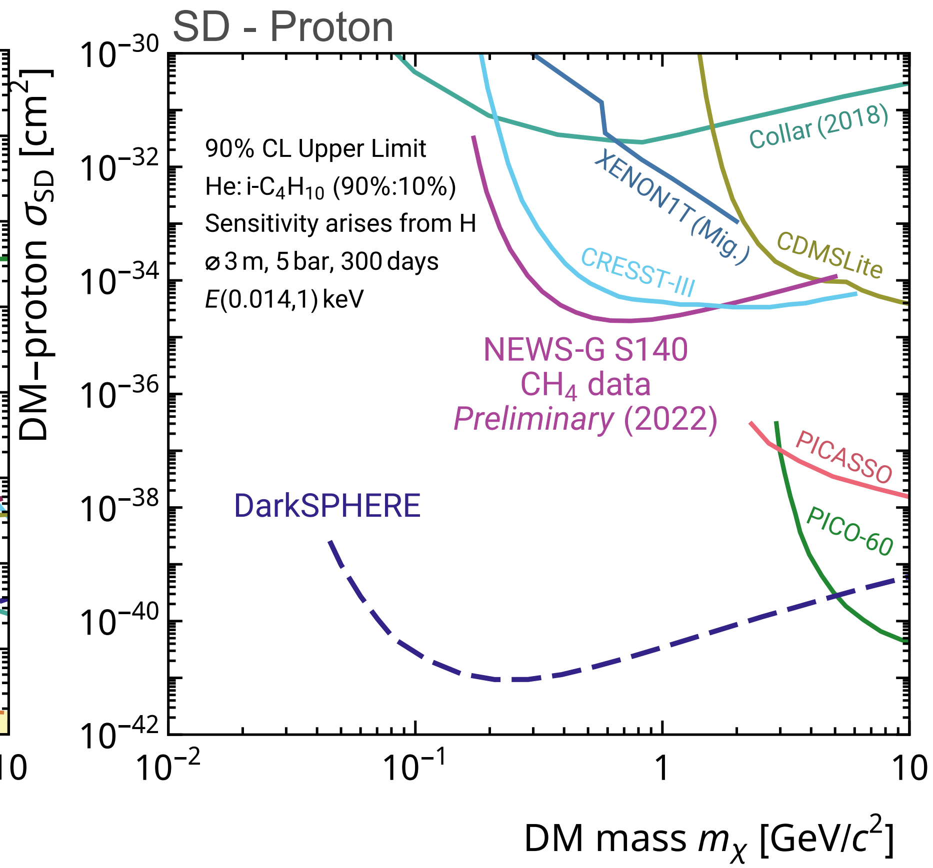

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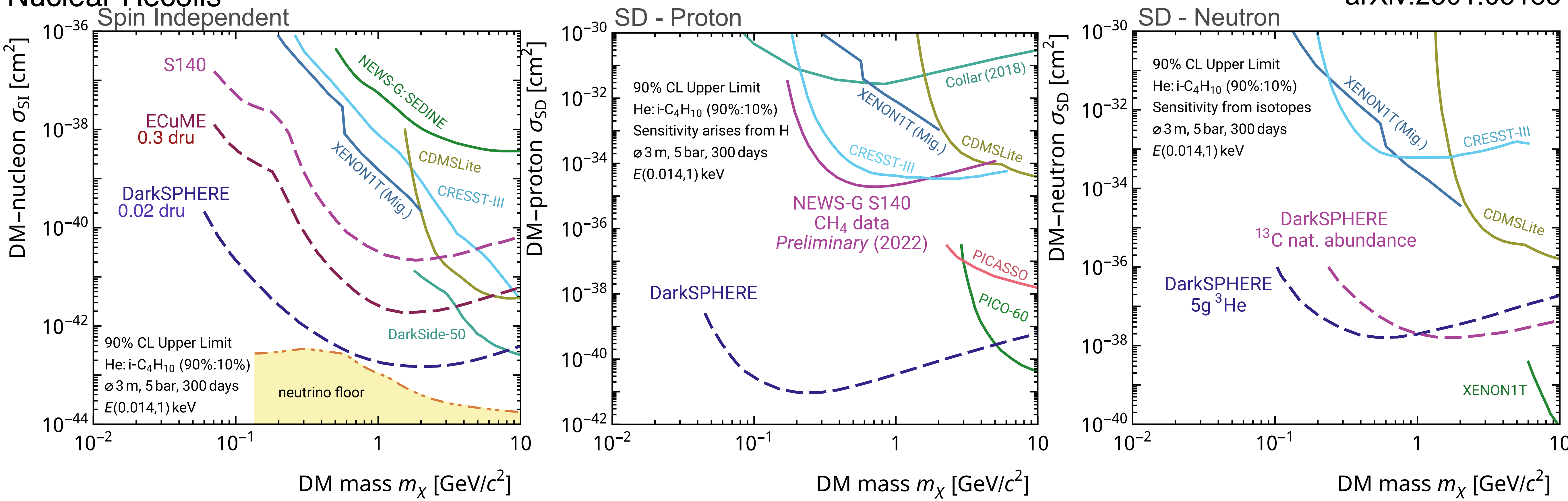

DarkSPHERE: Physics Potential

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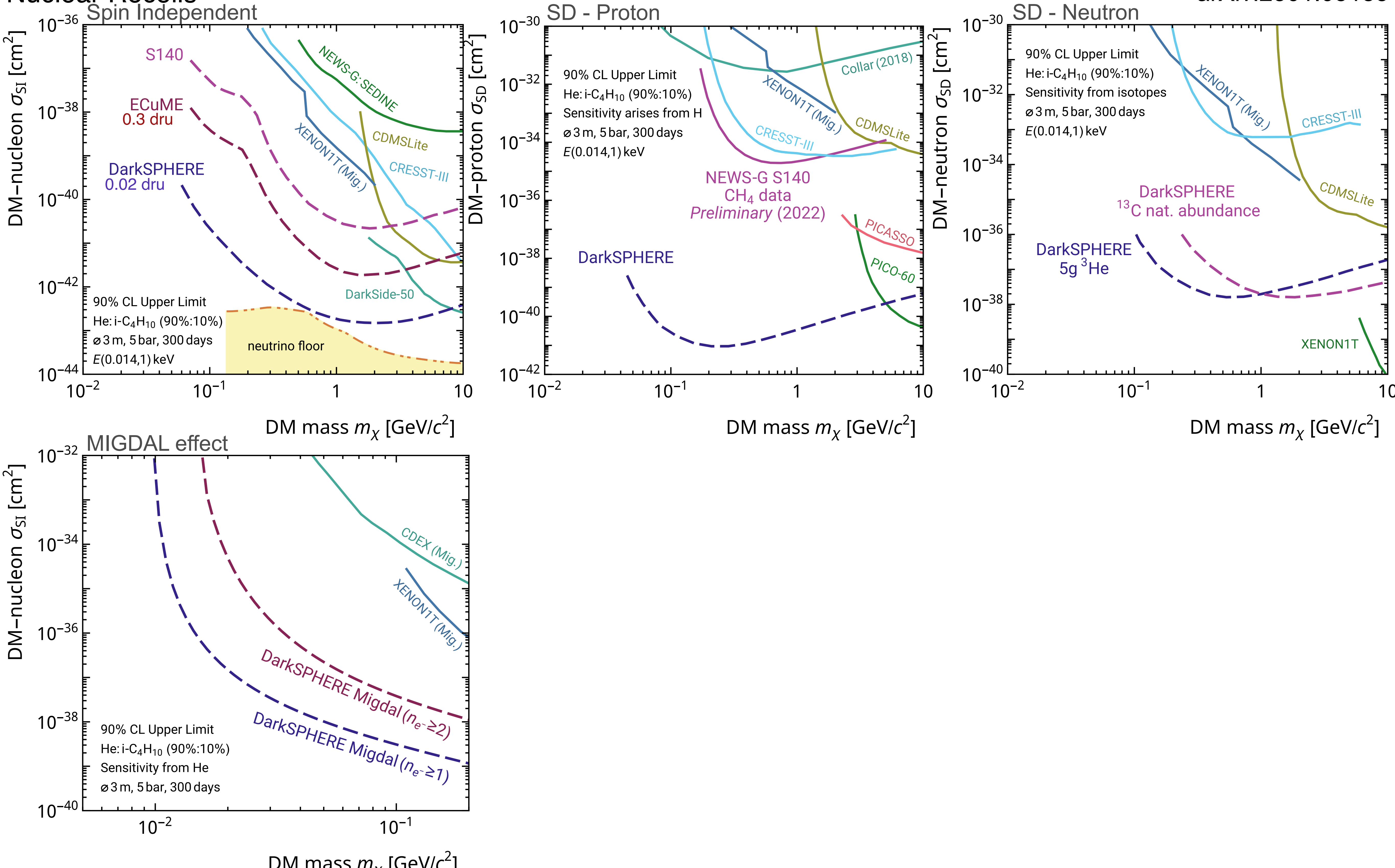
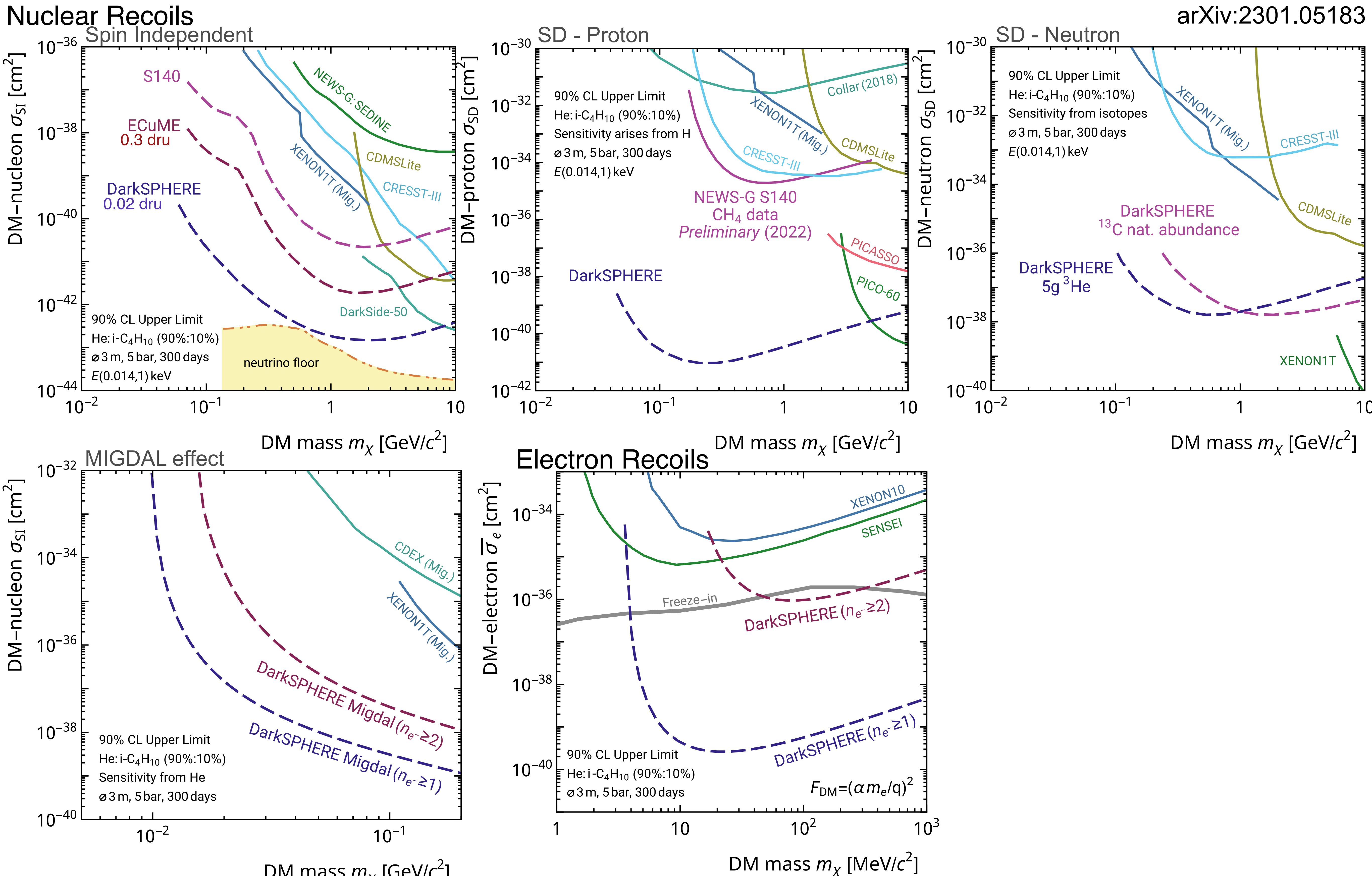


DarkSPHERE: Physics Potential



DarkSPHERE: Physics Potential

Nuclear Recoils

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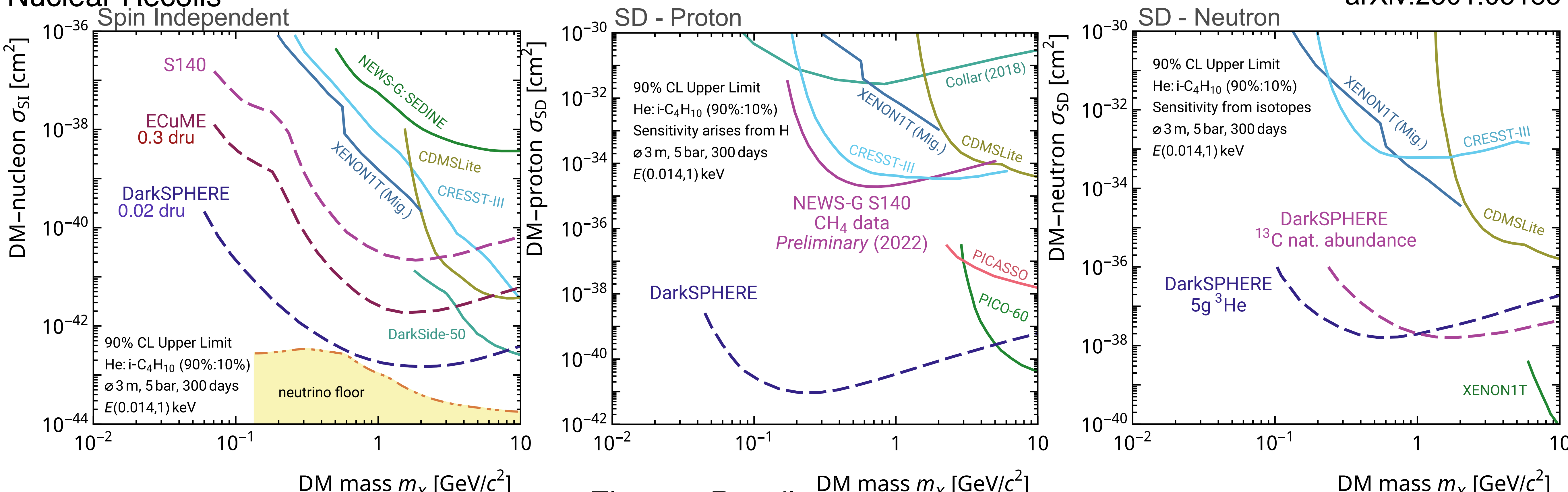
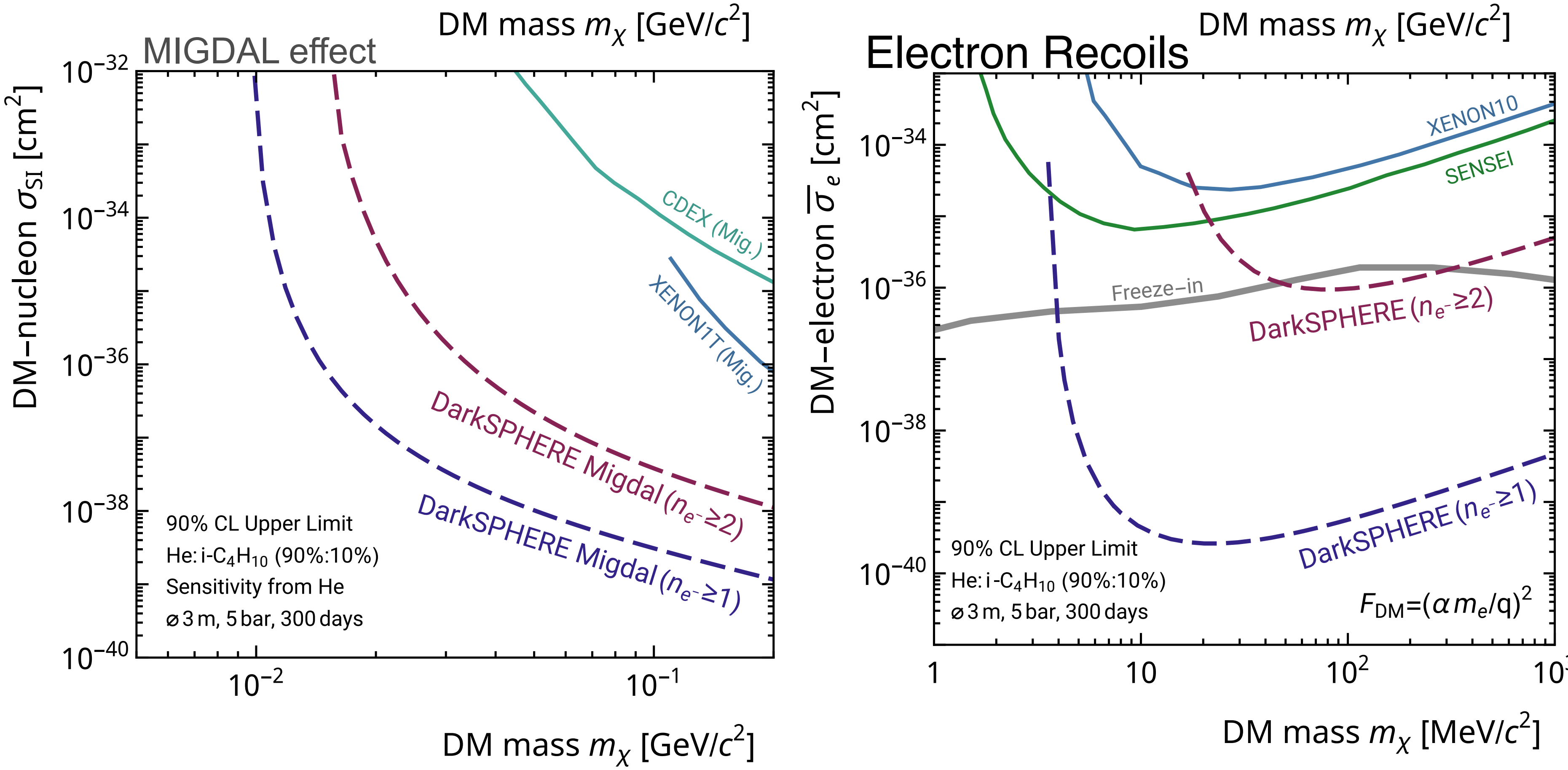




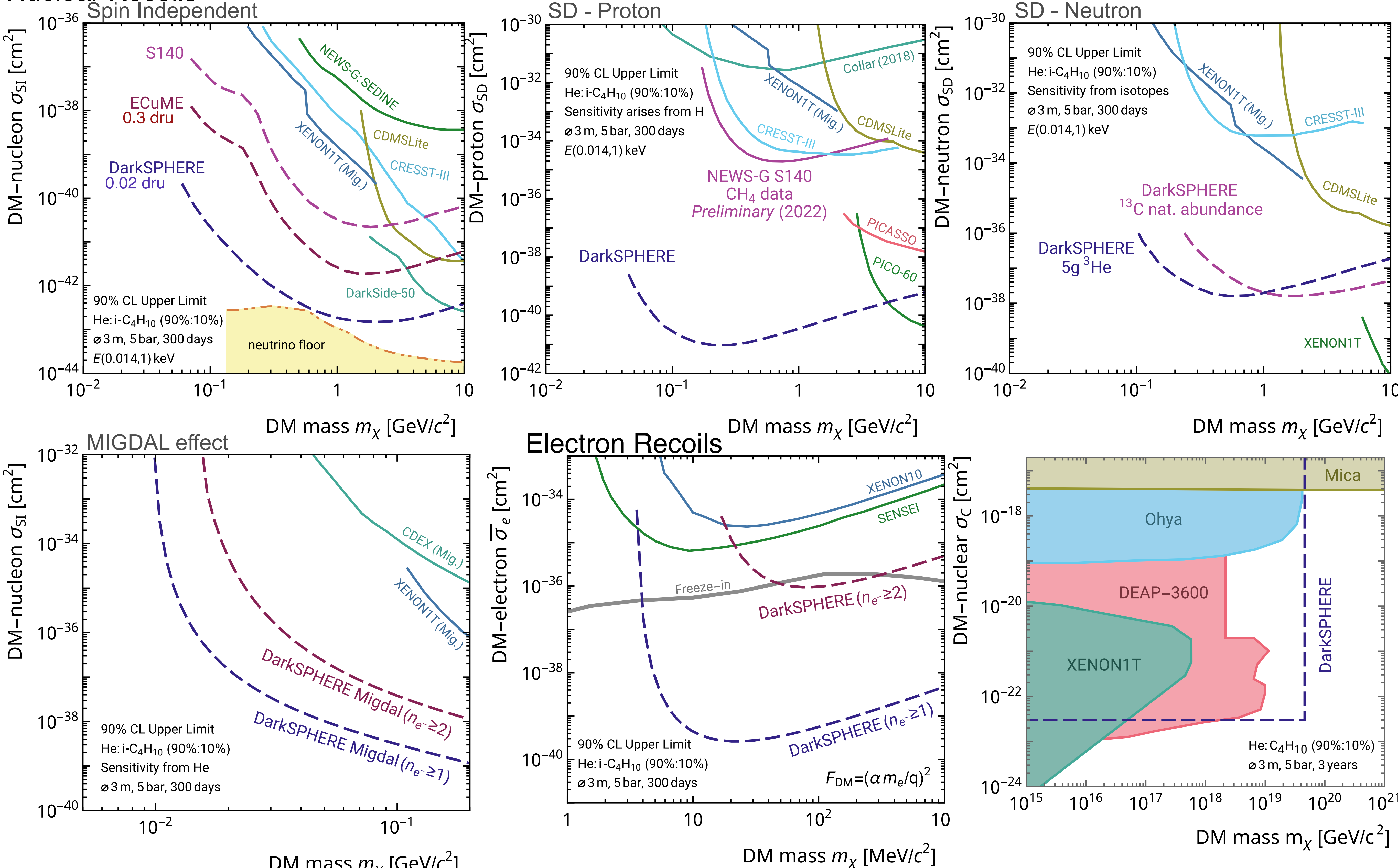
DarkSPHERE has the potential to probe uncharted territory in light Dark Matter searches

- Nuclear recoils: Spin-independent and spin-dependent
- Electron recoils

DarkSPHERE: Physics Potential

Nuclear Recoils

arXiv:2301.05183



Summary

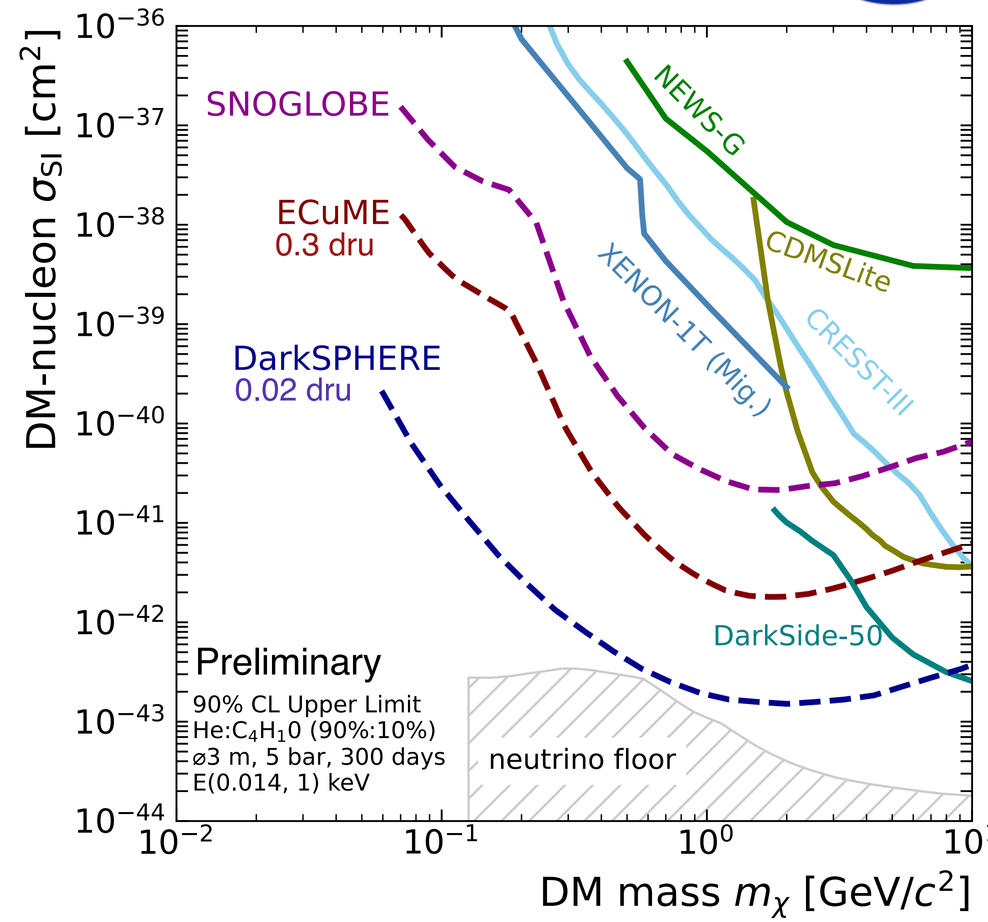
Particle nature of Dark Matter is unknown!

- Sub-GeV mass range is uncharted territory

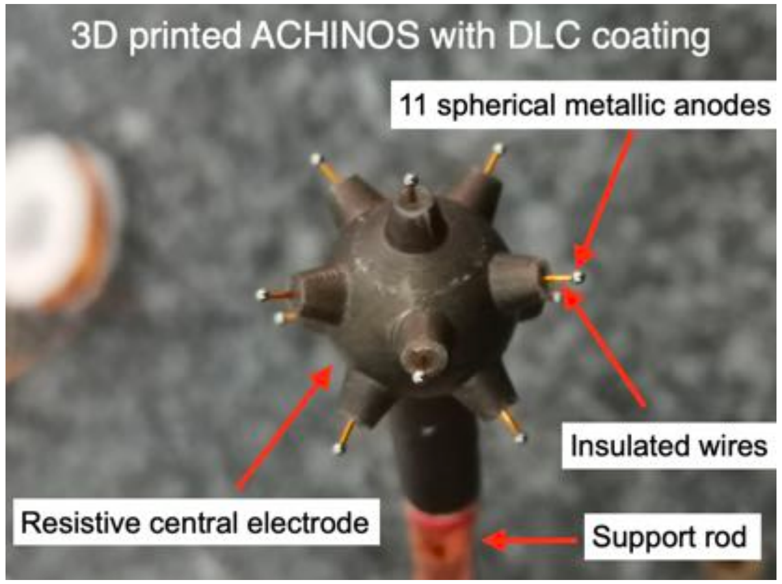
NEWS-G probes this key mass range

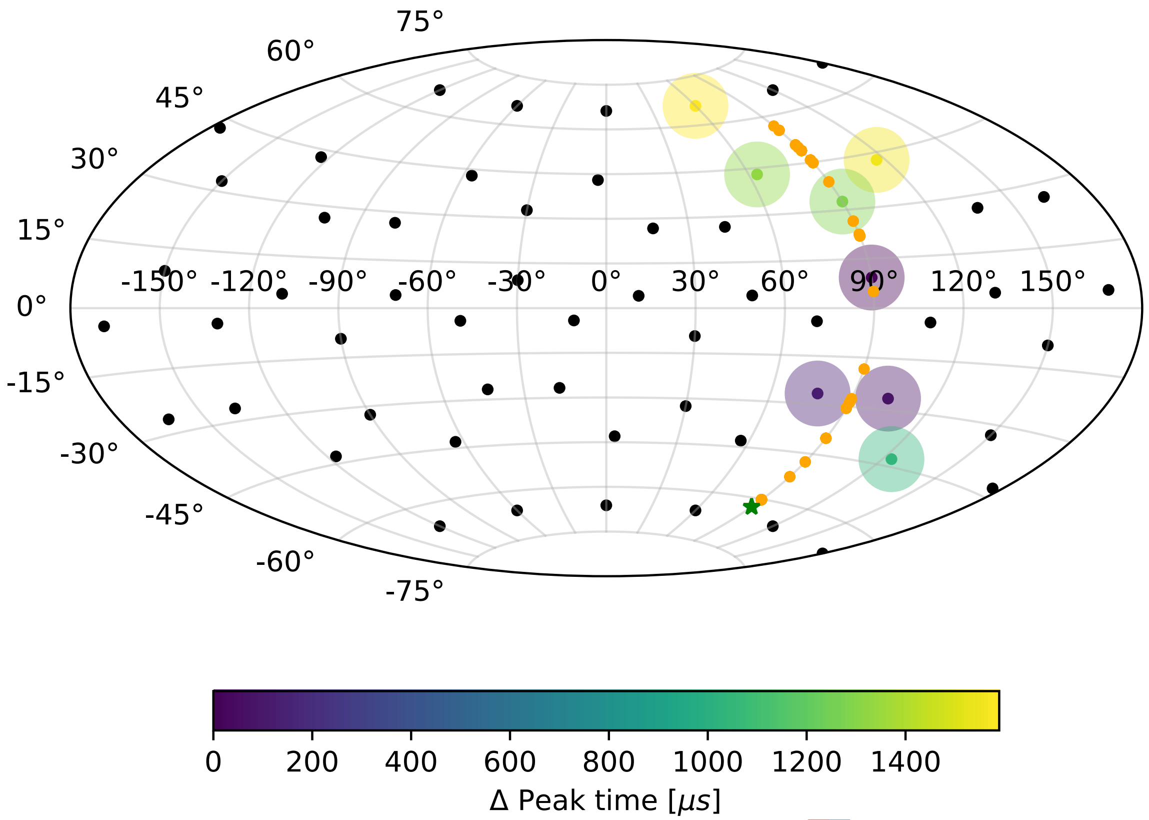
- Enabled by instrumentation advances
- New detectors planned for the coming years
- Many physics opportunities
- Eventually sensitivity could reach neutrino floor

Exciting physics programme ahead!



ECuME



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