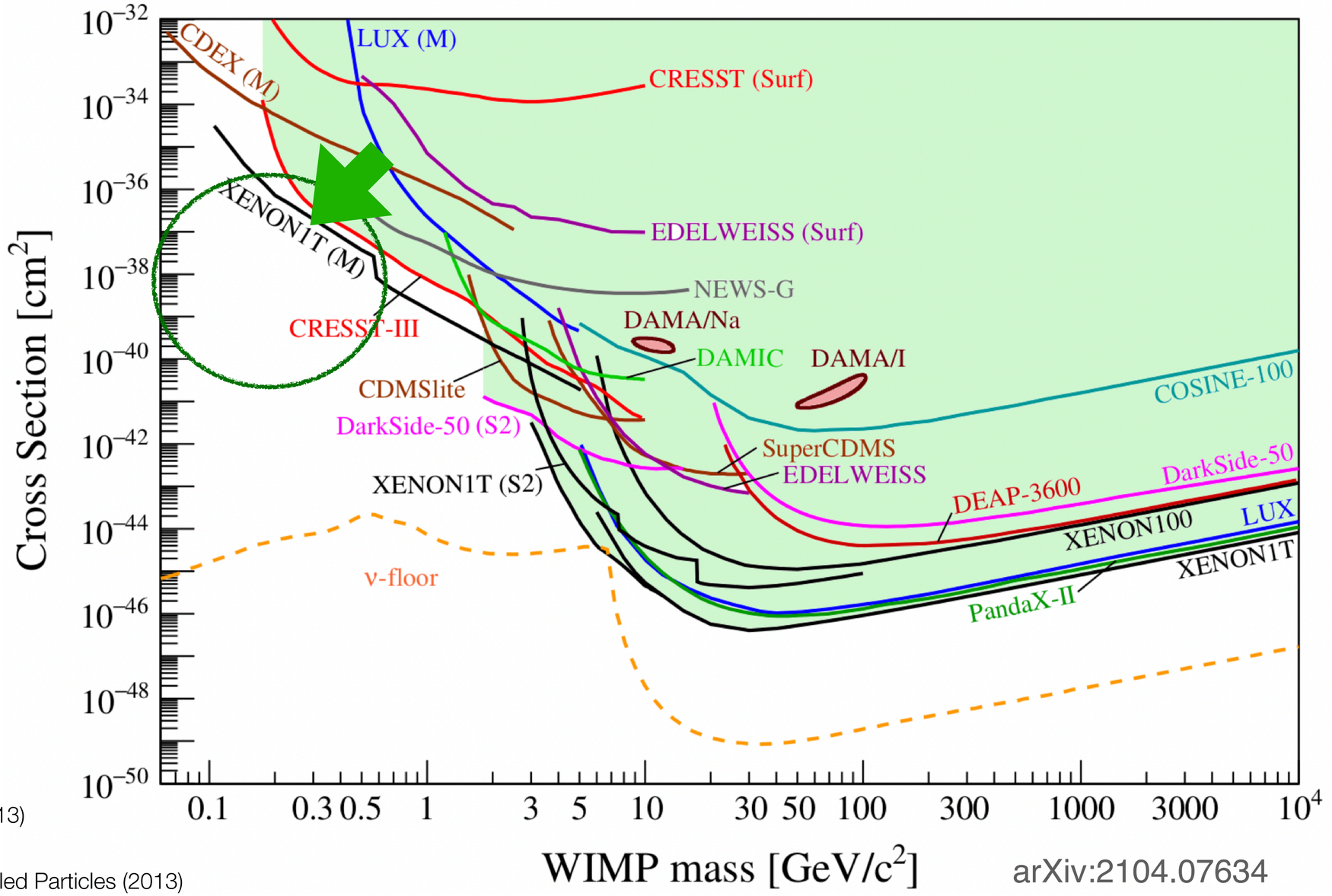
Search for light WIMP recoils on methane with NEWS-G

Francisco Vazquez de Sola, on behalf of the NEWS-G collaboration

Rencontres de Blois, May 2022

Light WIMPs

Absence of canonical WIMPs [1,2] motivates searches for low-mass WIMP-like Dark Matter candidates [3,4], in O(0.1 GeV)-O(1 GeV) range



[1] D. Bauer et al, Phys. Dark Univ., 7–8, 16–23 (2015)
[2] K. Petraki et al, Int. J. Mod. Phys. A, 28(19), 1330028 (2013)
[3] K.M. Zurek, Phys. Rep., 537(3), 91 (2014)
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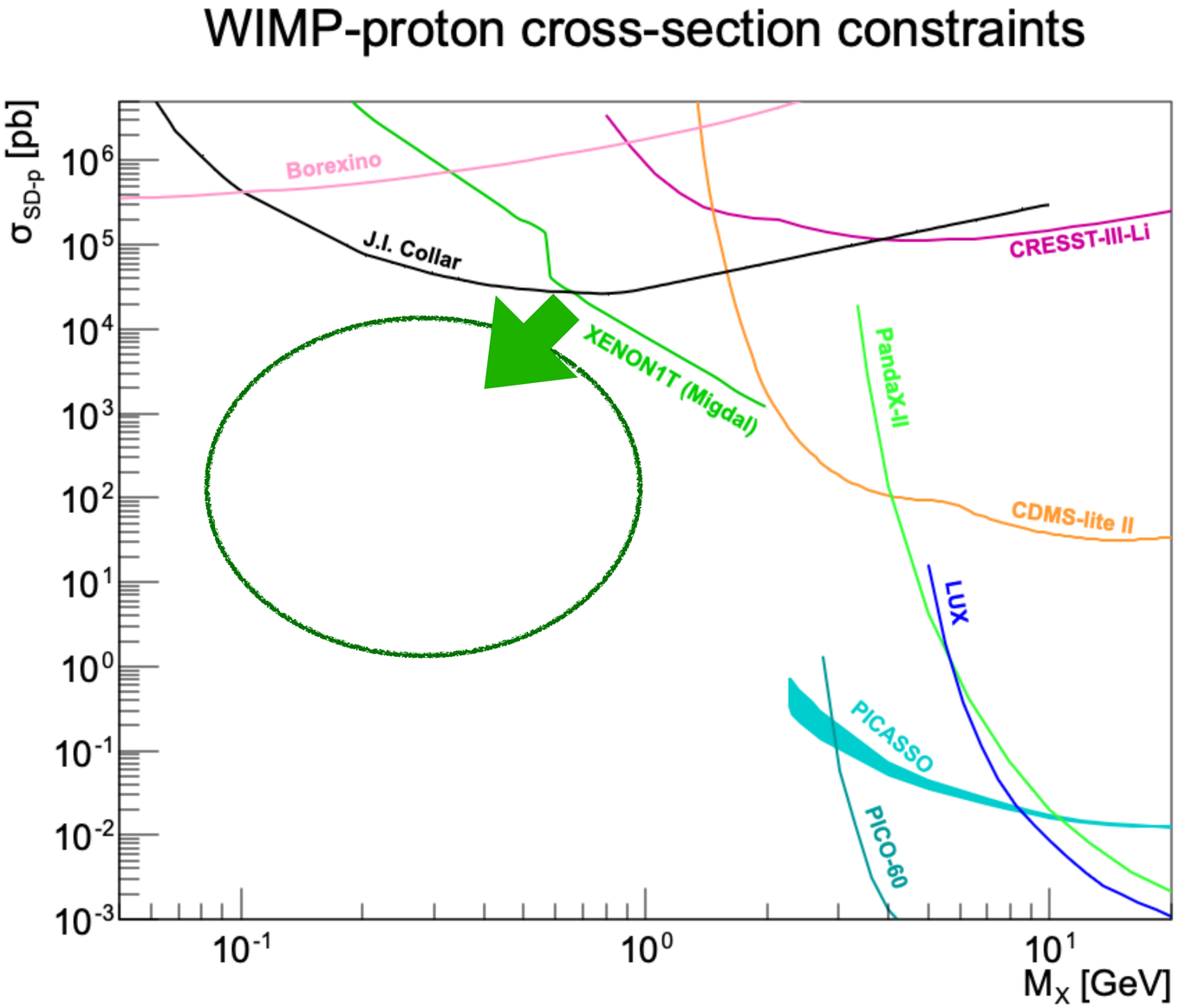

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New Experiments With Spheres - Gas

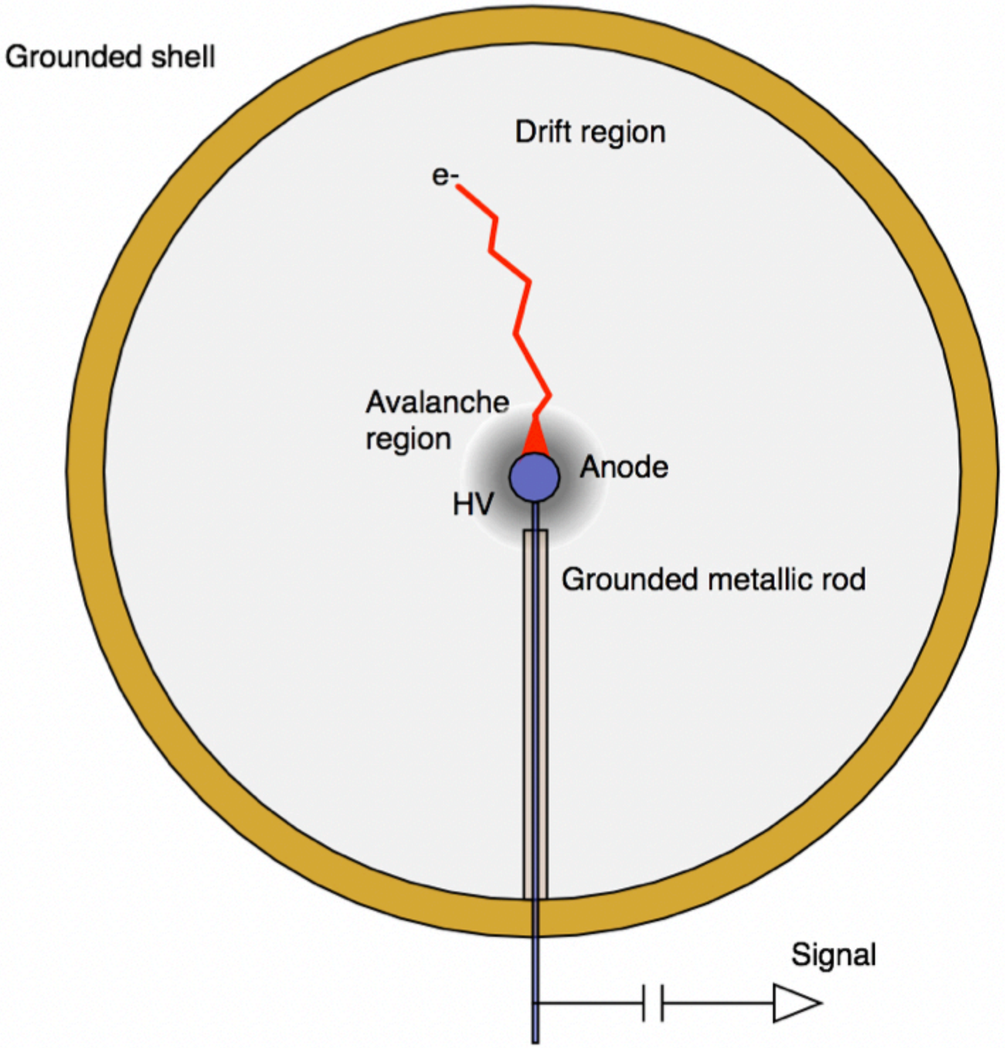
- Focus on **Dark Matter Direct Detection**
- NEWS-G collaboration:
  - 5 countries
  - 10 institutes
  - ~ 40 collaborators
- Three underground laboratories:
  - Laboratoire Souterrain de Modane
  - SNOLAB
  - Boulby Underground Laboratory

Spherical Proportional Counter

Working Principle

Ionisation detector

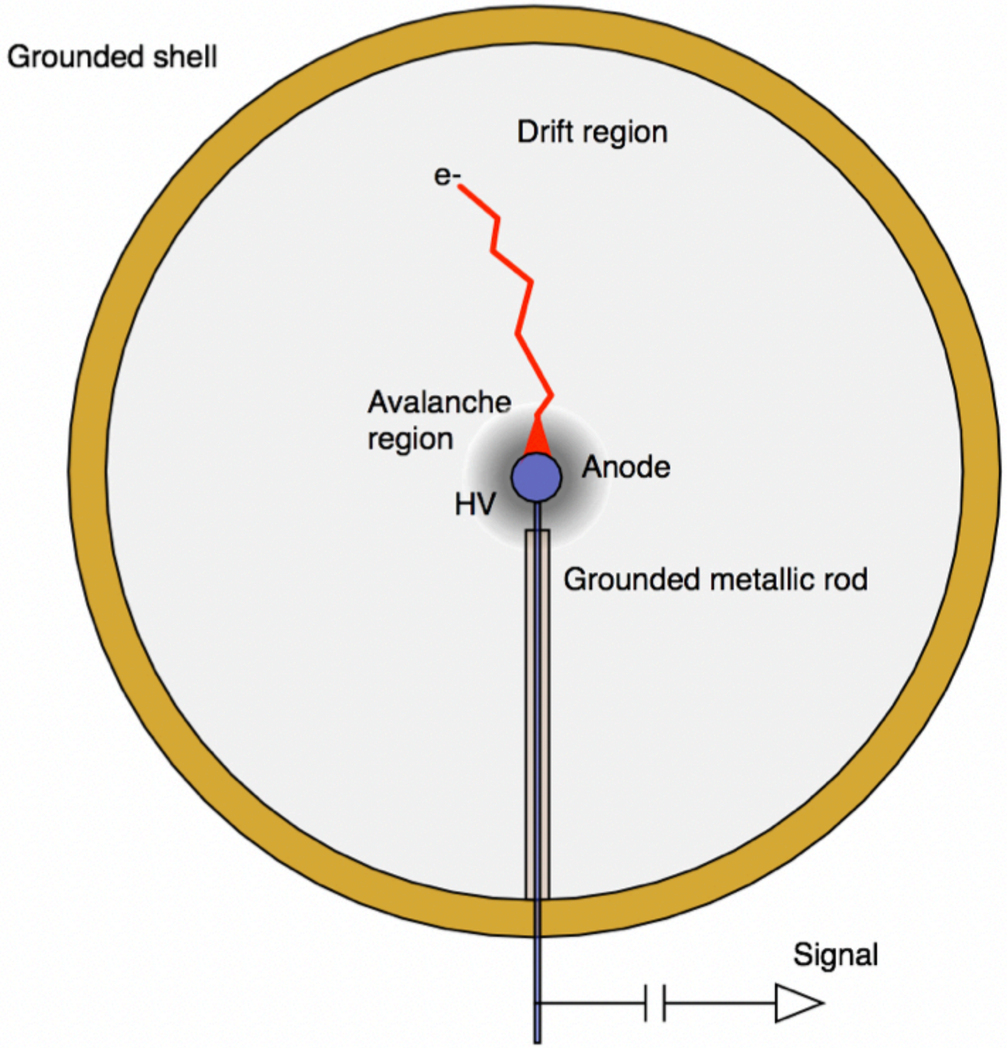
- Incident particle induces recoil, releasing ionisation energy
- Primary electrons drift and diffuse towards central anode
- High field in $1/r^2$ at anode produces ~10^3-10^4 avalanche multiplication
- Drifting ions induce current on anode



Spherical Proportional Counter

Advantages

- Low capacitance + high gain -> single electron threshold
- Variable gas (H, He, Ne) & pressure choice for different physics goals
  - Light target : better kinematic match with light WIMPs
- Radiopurity of materials
- Pulse-Shape Discrimination to differentiate surface/volume backgrounds



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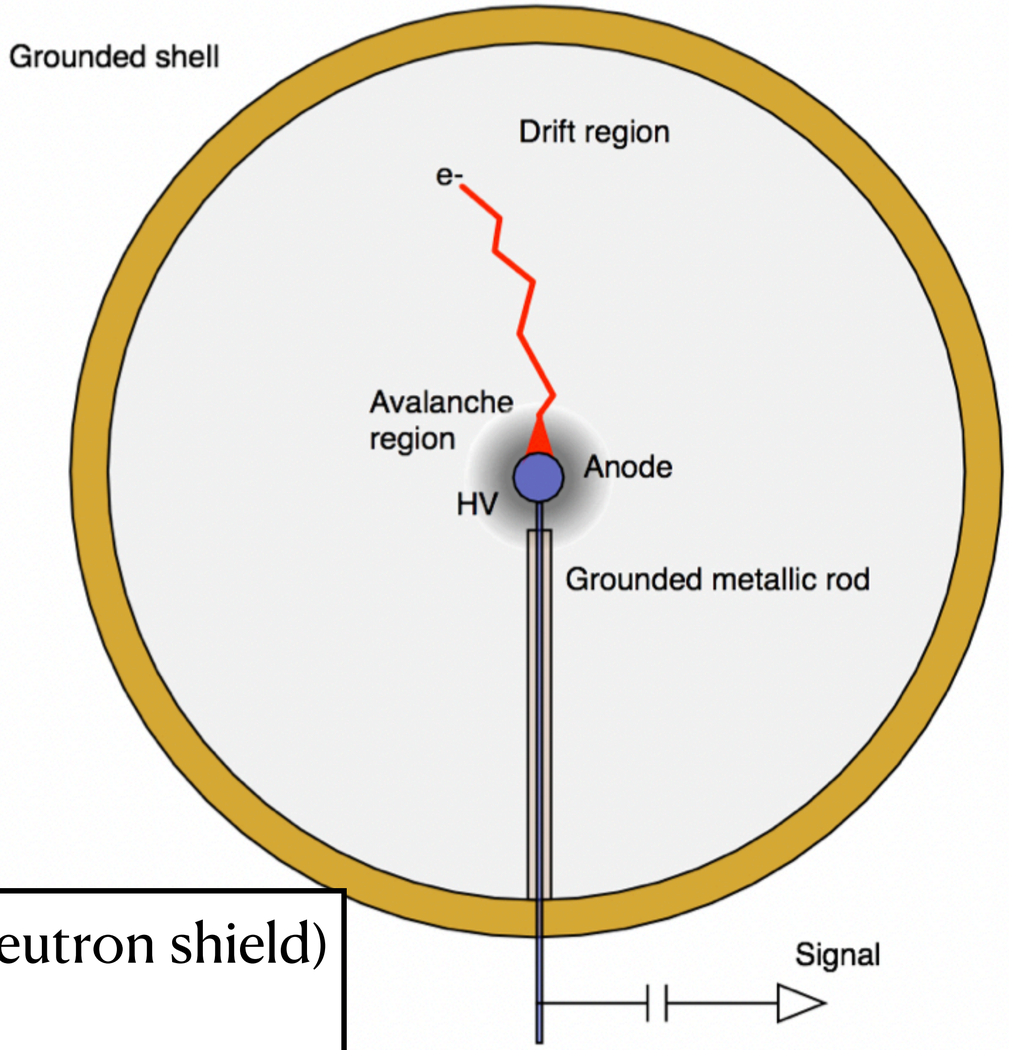
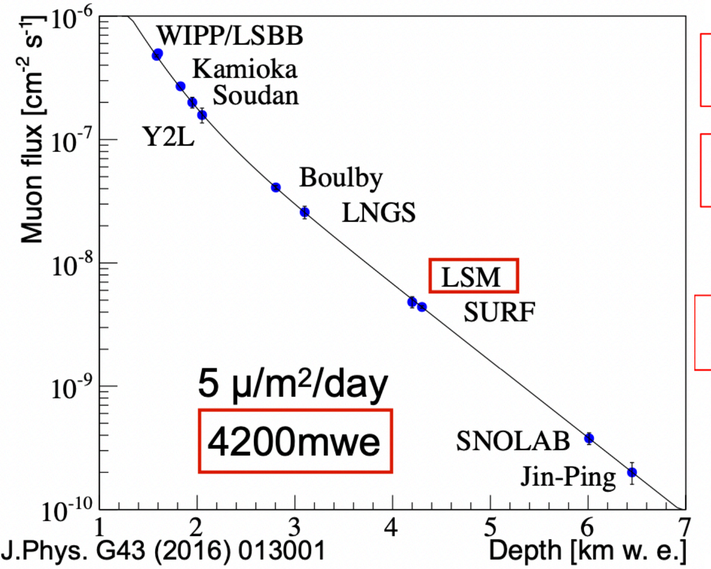
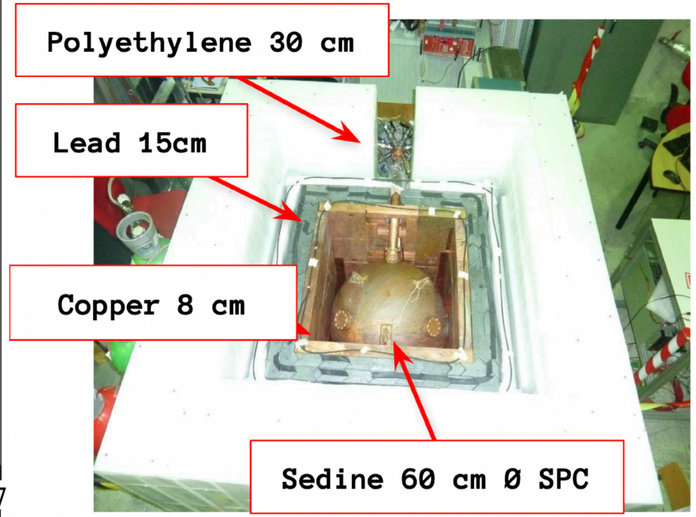
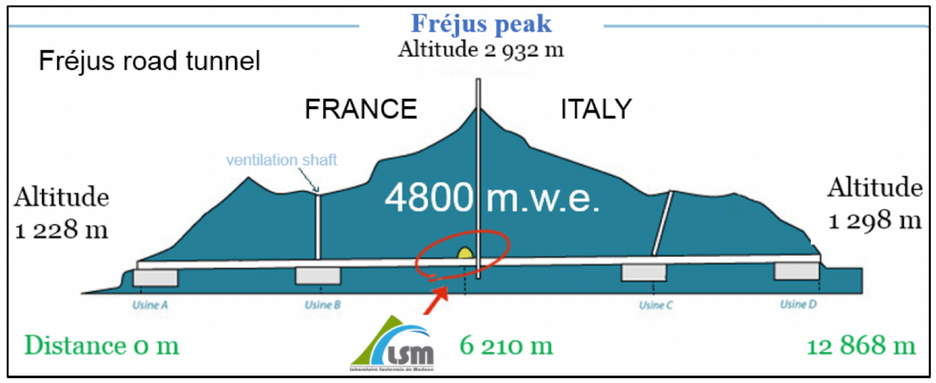


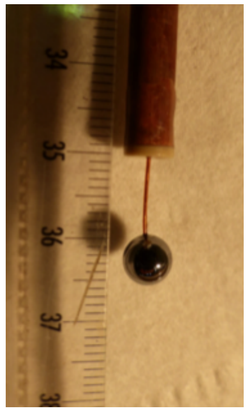
Low radioactivity set-up (high radiopurity and gamma/neutron shield) **and** underground environment needed to study WIMP

Results with SEDINE prototype at LSM

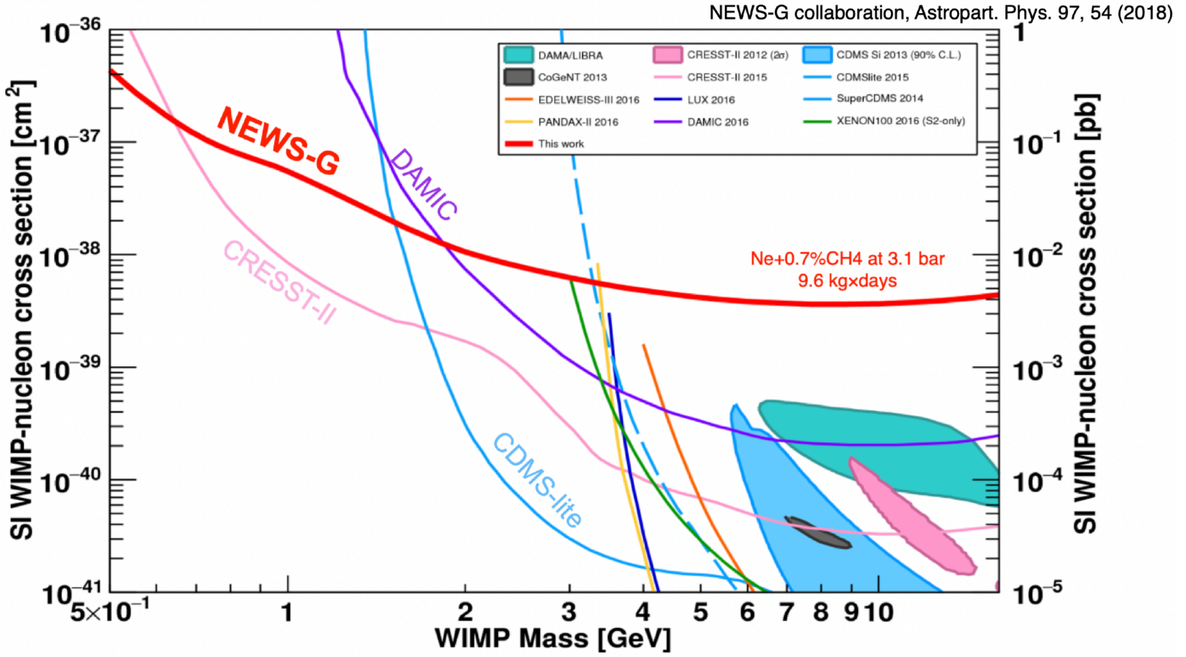




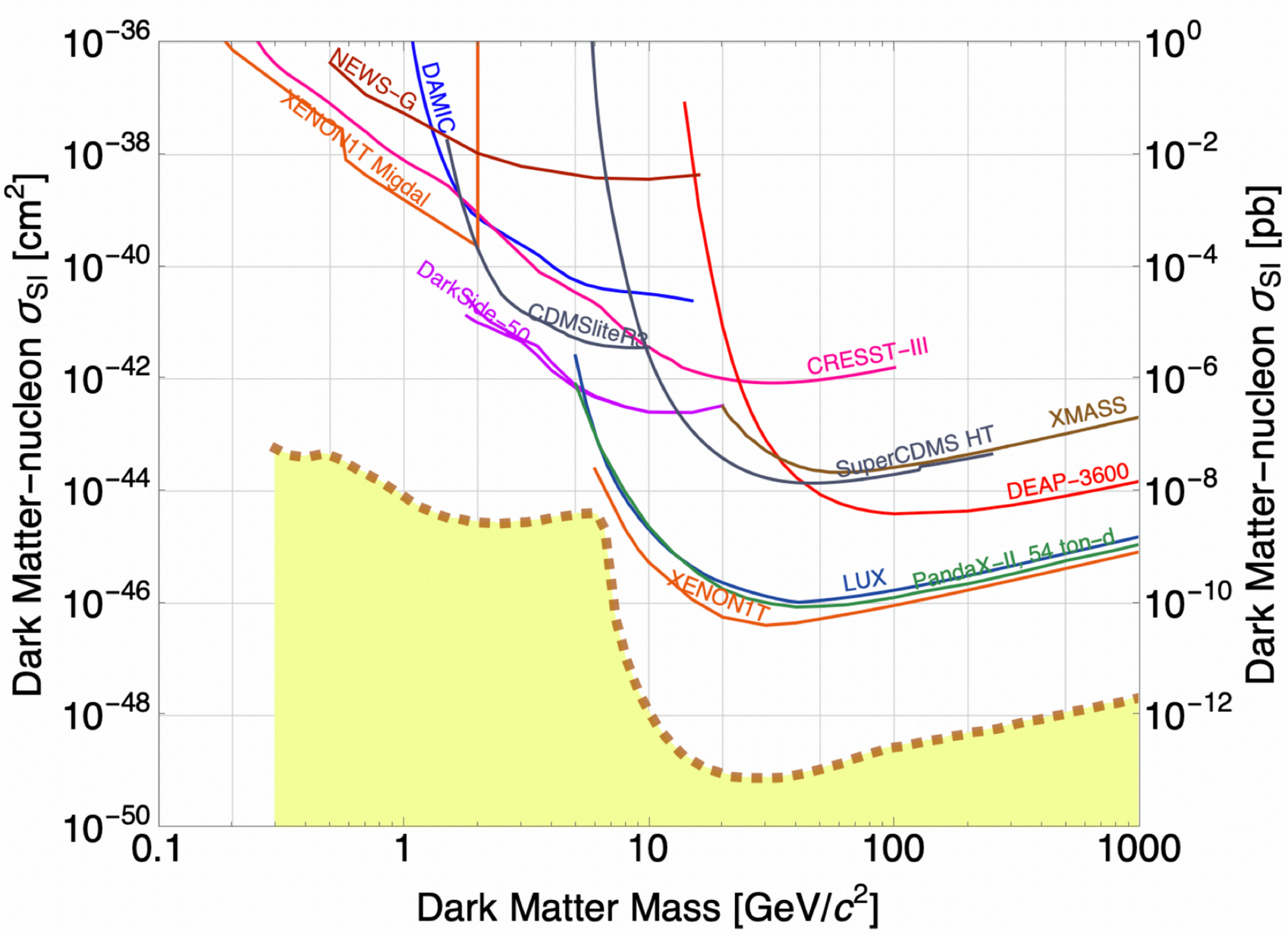




- ⌀60cm NOSV copper vessel, ⌀6.3 mm single-anode sensor
- Physics: 42-day run with 3.1bar of Neon + 0.7% CH_4 (280g, total 9.7 kg·day)
- Main backgrounds:
  - Radon daughters on inner surface of vessel
  - ^{210}Pb in copper bulk

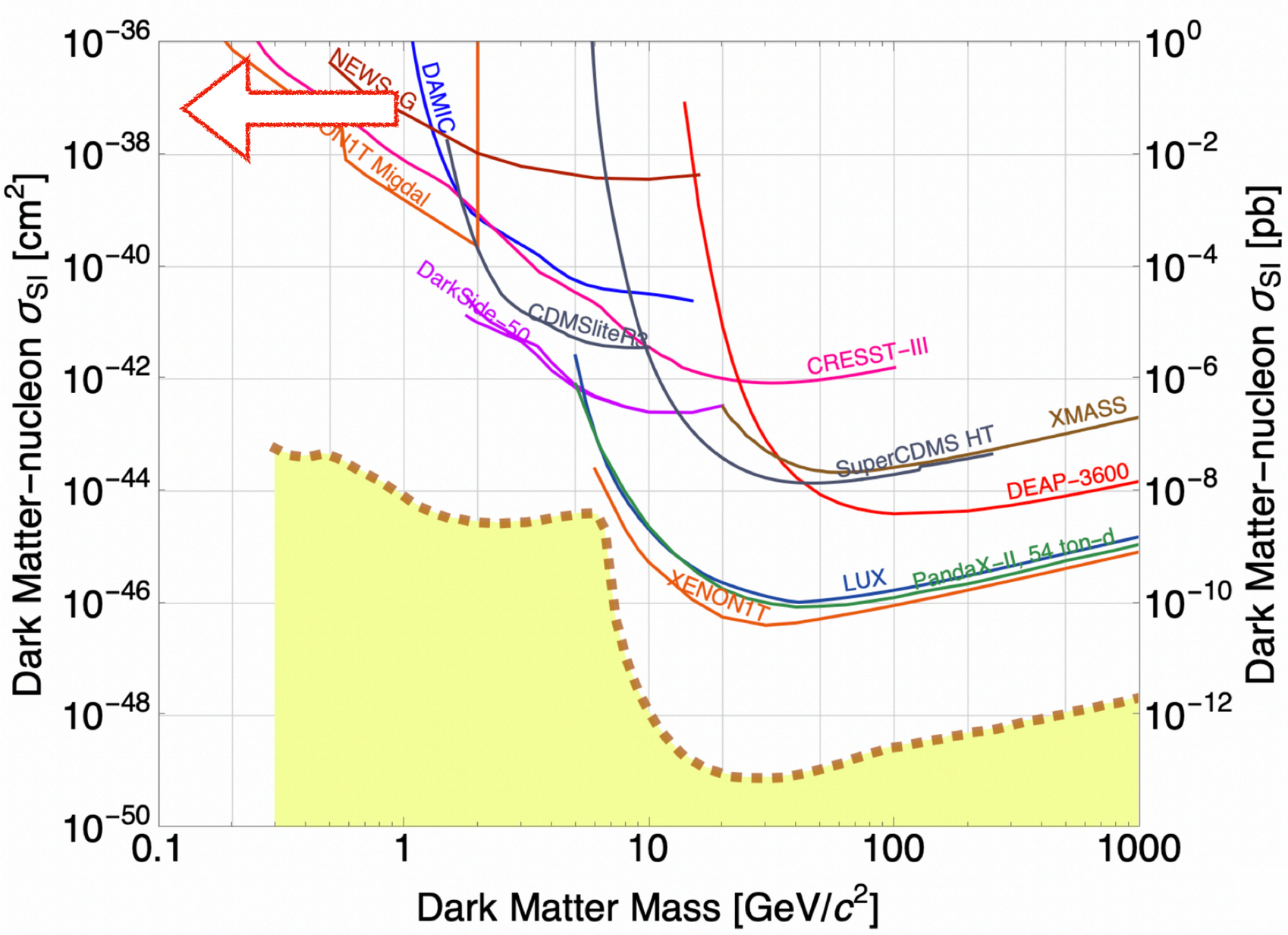


Improve?


NEWS-G
DAMIC
XENON1T Migdal
DarkSide-50
CDMSliteP3
CRESST-III
SuperCDMS HT
XMASS
DEAP-3600
LUX
PandaX-II, 54 ton-d
XENON1T
Dark Matter–nucleon σ_{SI} [cm^2]
Dark Matter–nucleon σ_{SI} [pb]
Dark Matter Mass [GeV/c^2]
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
0.1
1
10
100
1000

Improve?

- Use low mass targets, improve energy threshold



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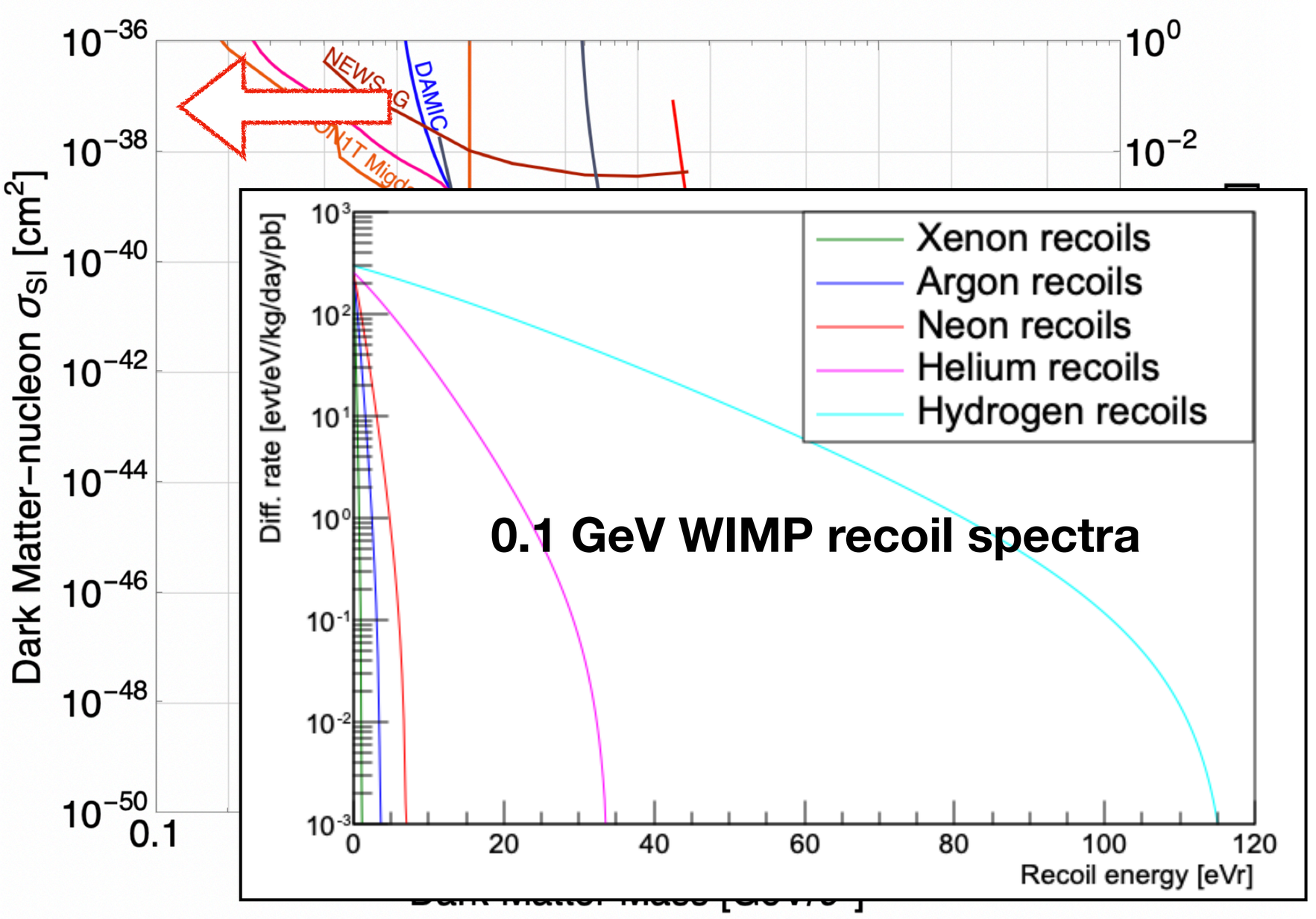
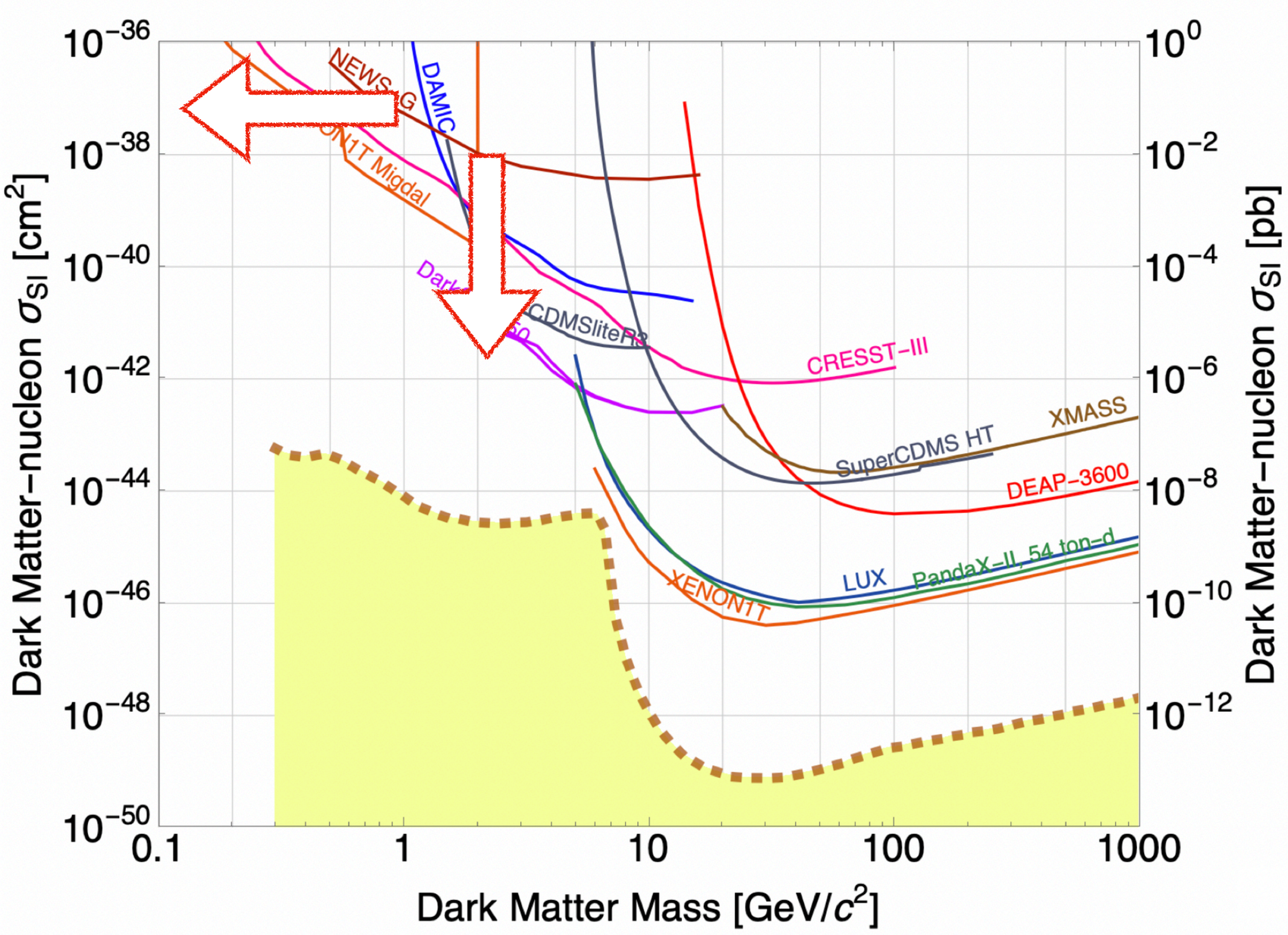


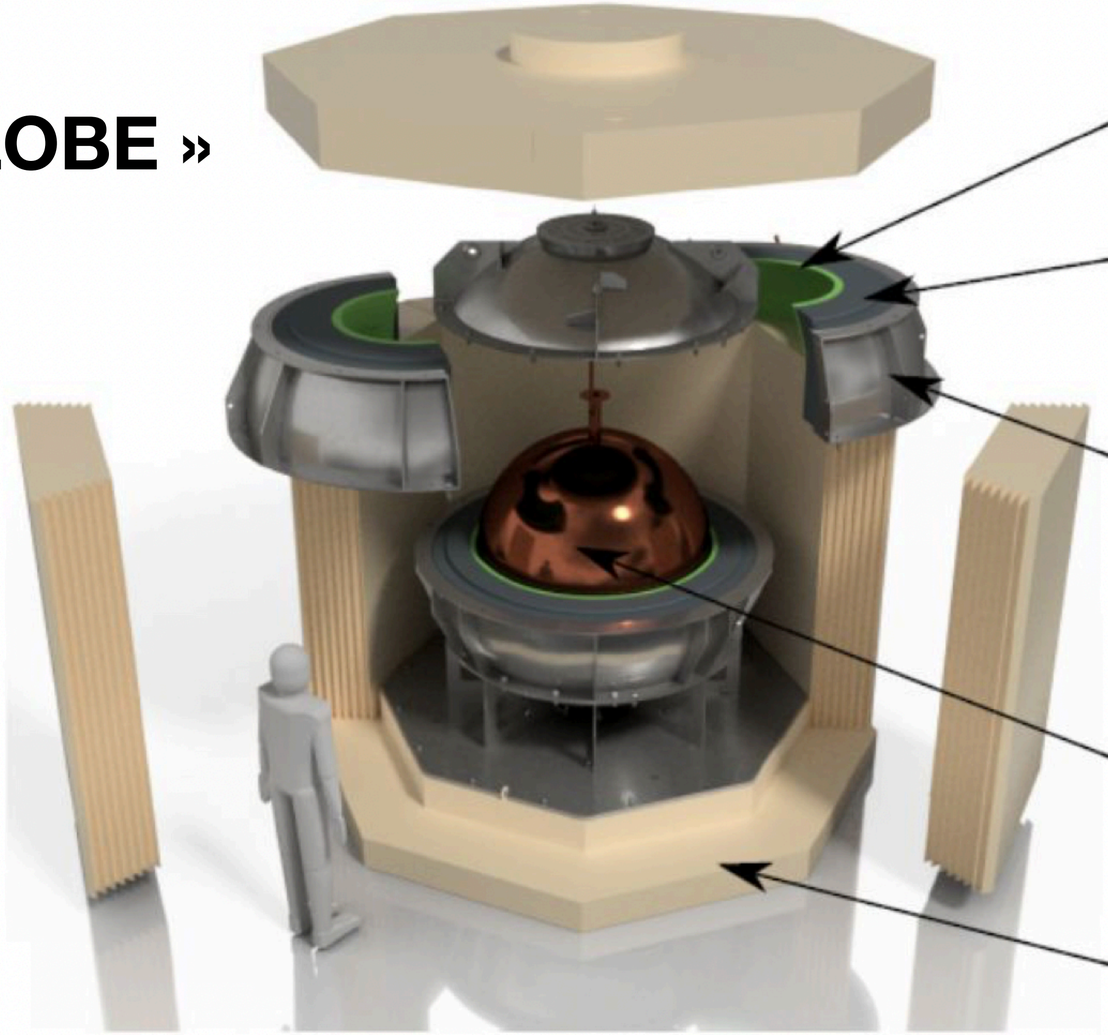
Improve?

- Use low mass targets, improve energy threshold
- Increase exposure, reduce backgrounds



S140

« SNOGLOBE »



3 cm of archeological Lead

22 cm of low-activity Lead

Stainless steel skin

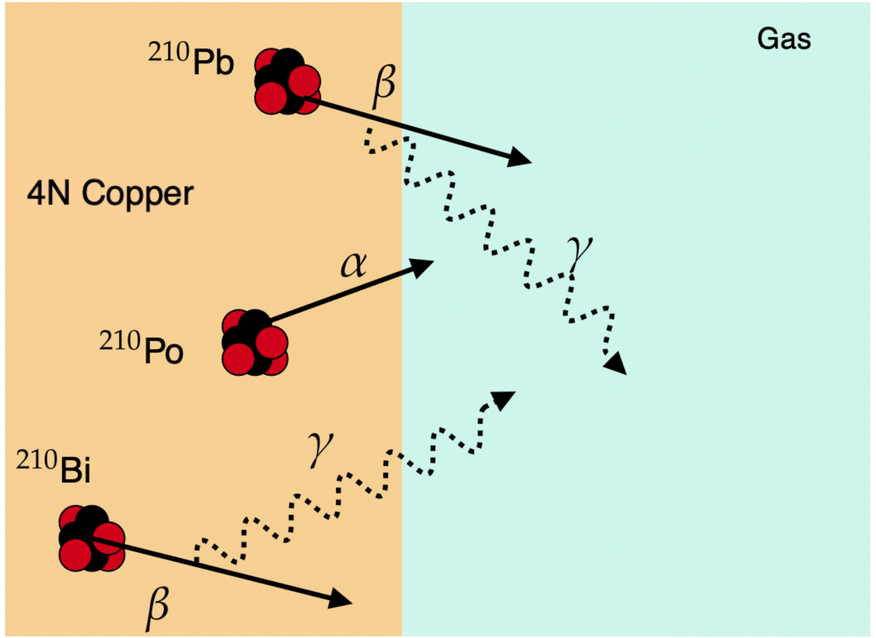
C10100 copper S140

40 cm high-density Polyethylene

Electroplating

Background reduction

- Background: Bremsstrahlung X-rays from ^{210}Pb and ^{210}Bi β-decays in (and on) the copper
  - ^{210}Pb main background under 10 keV



L. Balogh et al, Nucl.Instrum.Meth.A 988 (2021)

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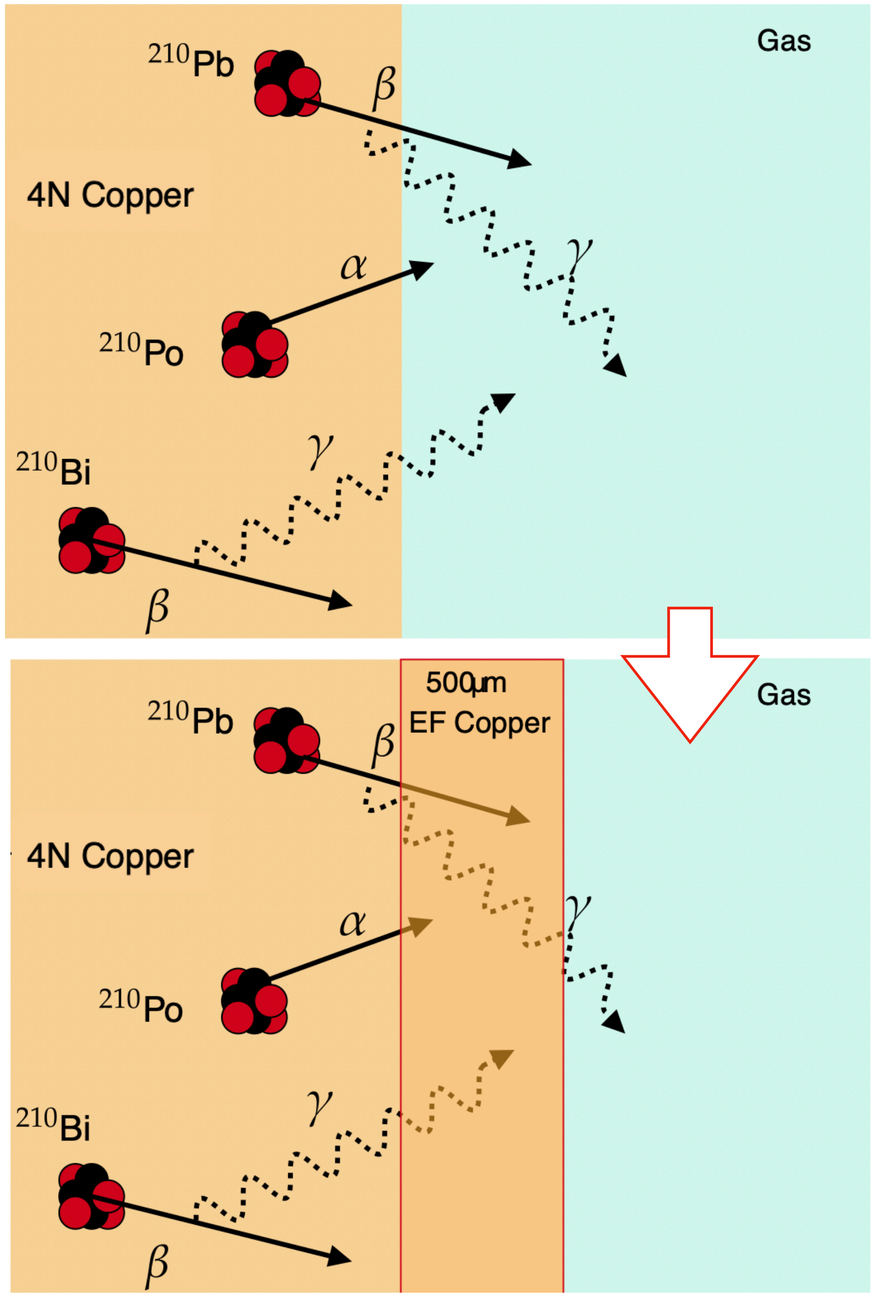
- Plating 0.5mm of ultra-pure copper expected to reduce background under 1 keV by factor 2.6, and total rate by factor 50



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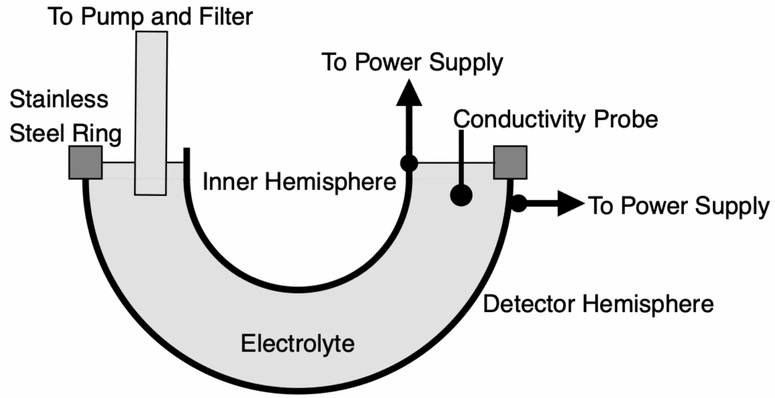
- Intervention successfully carried out at LSM (underground) in collaboration with PNNL

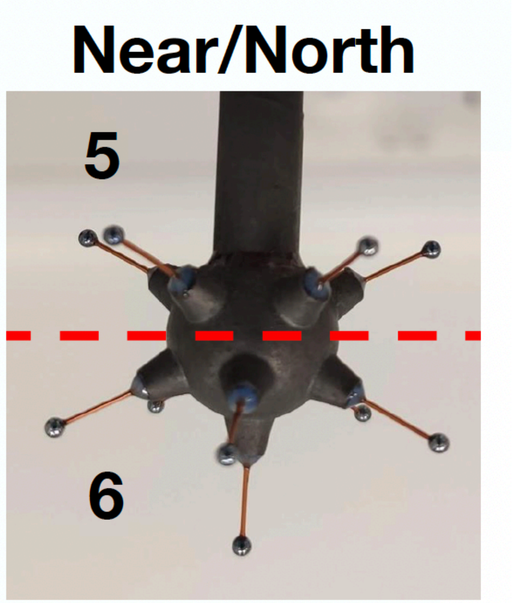


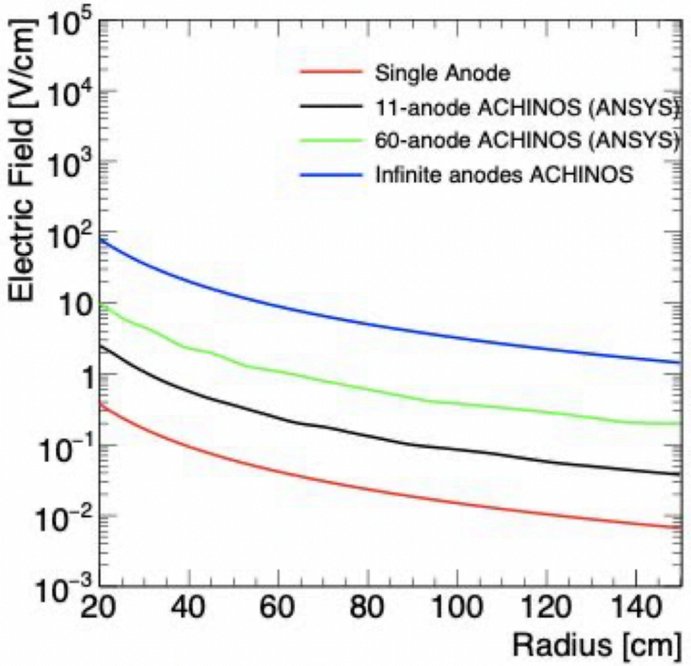
L. Balogh et al, Nucl.Instrum.Meth.A 988 (2021)

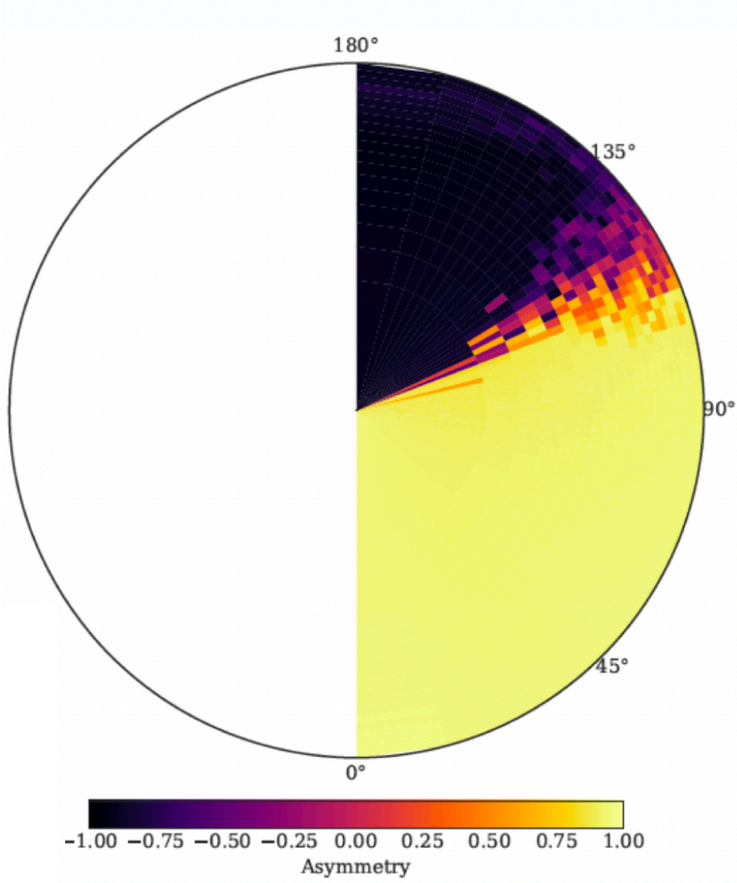
Sensor development

ACHINOS

- Multi-anode sensor
  - same avalanche E-field as single-anode
  - enhanced drift E-field
- 2-channel readout: 5 north and 6 south anodes
- Volume associated with each channel simulated with Geant4, Garfield++, ANSYS/COMSOL
  - Confirmed with Ar37 calibrations





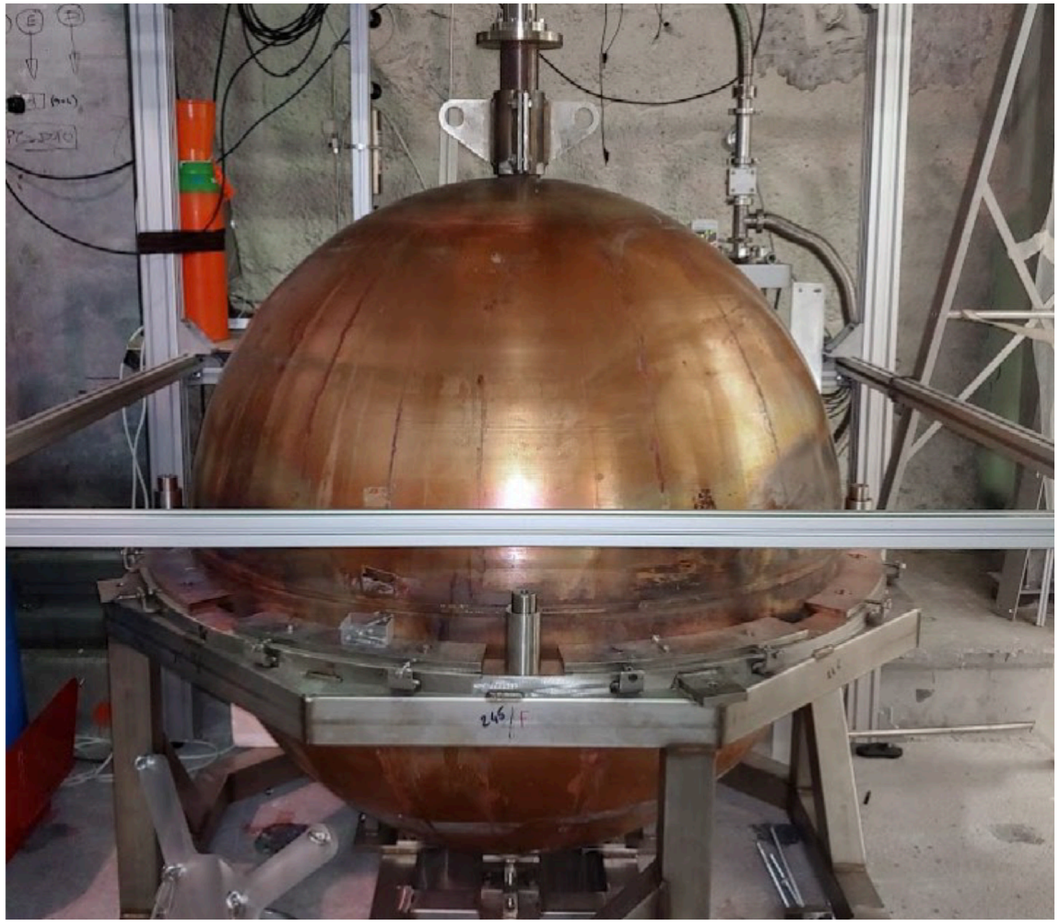


R. Ward et al 2020 JINST 15 C06013

I. Giomataris et al 2020 JINST 15 P11023

S140: Commissioning at LSM

2019: S140 e-beam welded in France, 3T archeological lead provided by LSM. S140 arrives at LSM in April 2019, starting first commissioning



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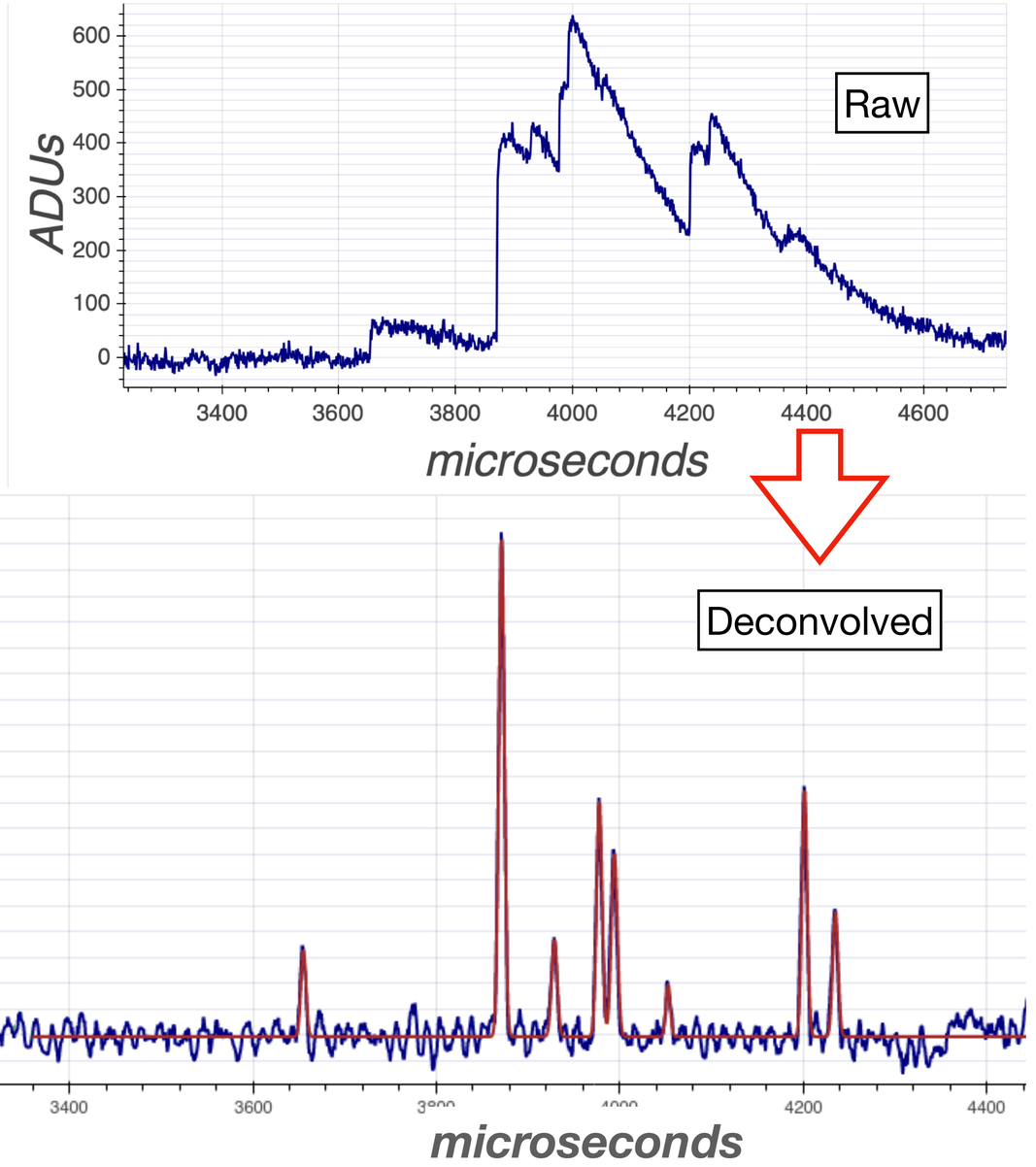
Packed in November 2019 to go to SNOLAB! First signal in summer 2021, currently finishing installation/ commissioning, physics data-taking to restart in coming weeks

Electron counting

In physics run at LSM with 135 mbar CH_4, >100 μs diffusion of primary charges

- After pulse processing, individual electron (~30 eV) signal become apparent
- Capacity to distinguish 1e- from 2e- (etc.) events, despite avalanche process with standard deviation comparable to mean!
- Processing adapted to identify peaks

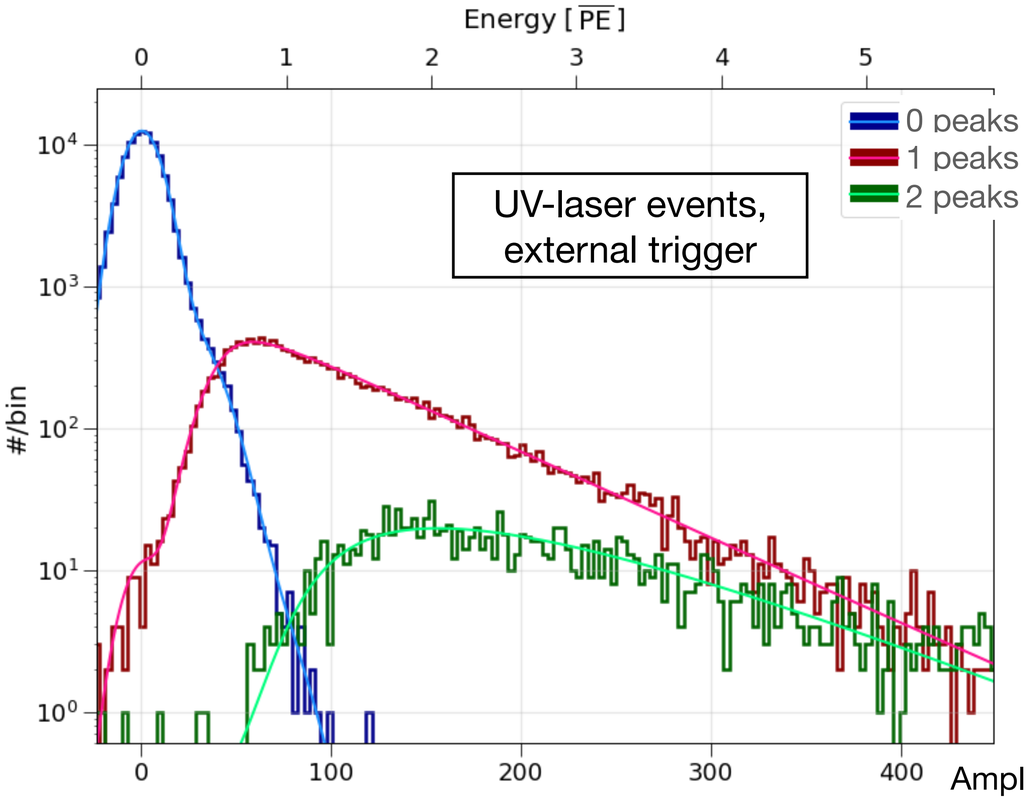


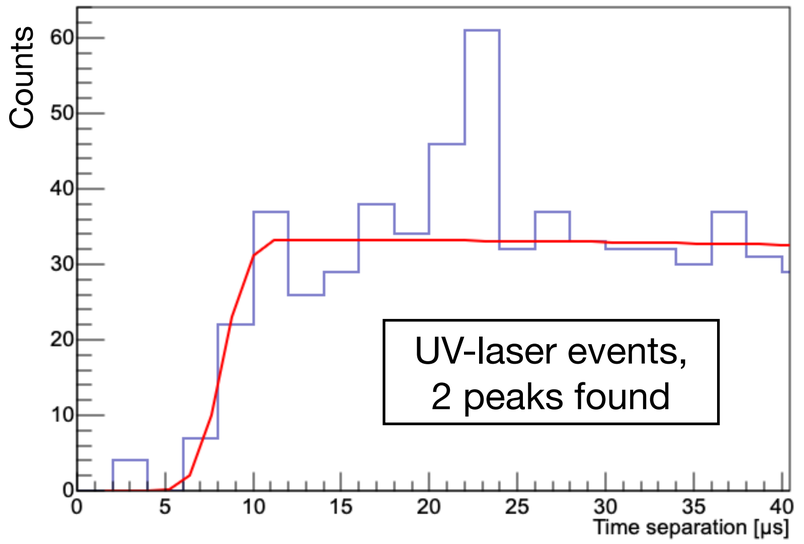
Electron counting

Characterisation

Low-intensity, 213nm UV-laser extracts electrons from copper surface. Used to characterise avalanche gain, peak-counting

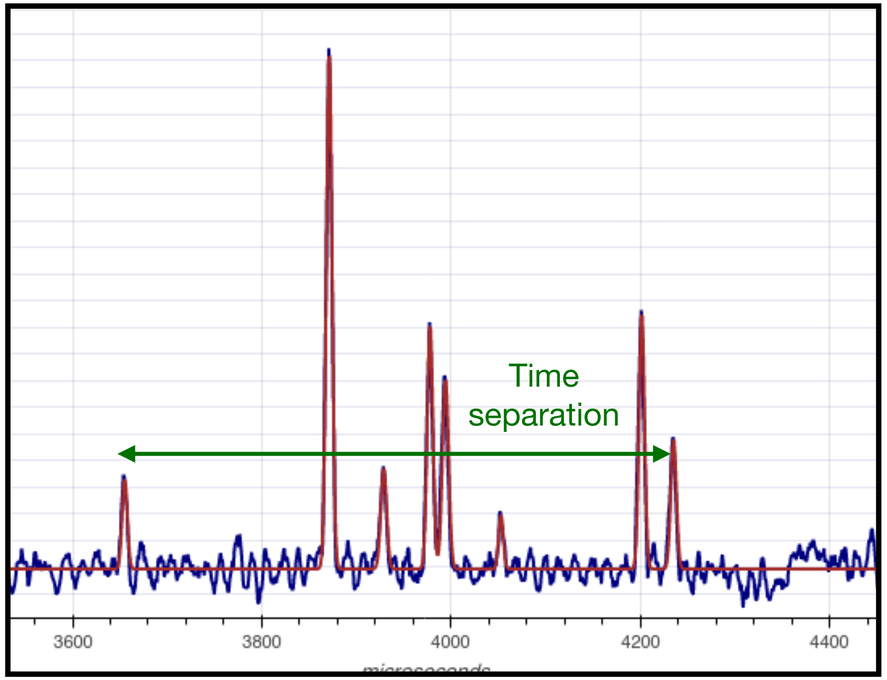
- Electron detection efficiency : 60%
- Separation of electron peaks above 8 μs

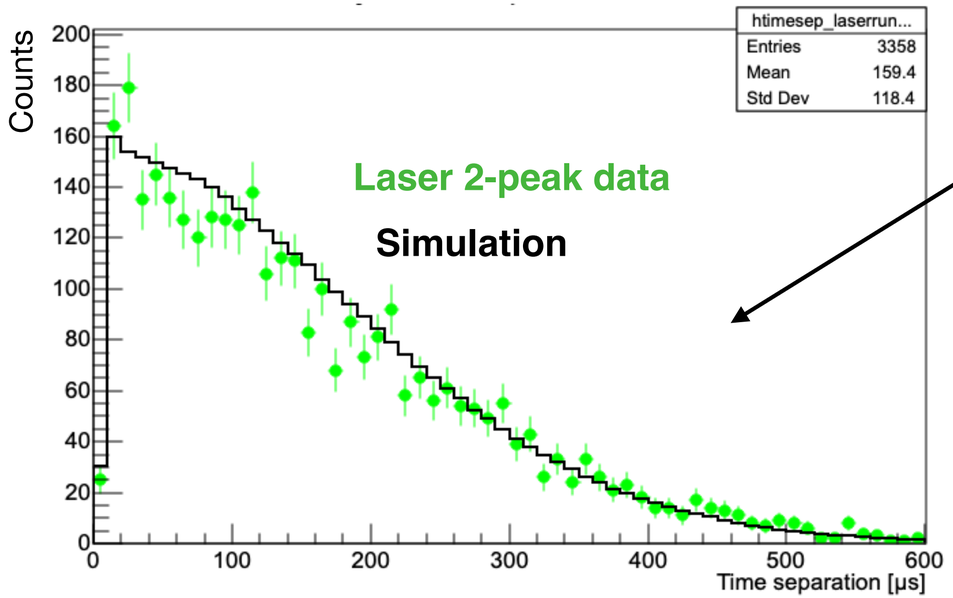




Electron diffusion

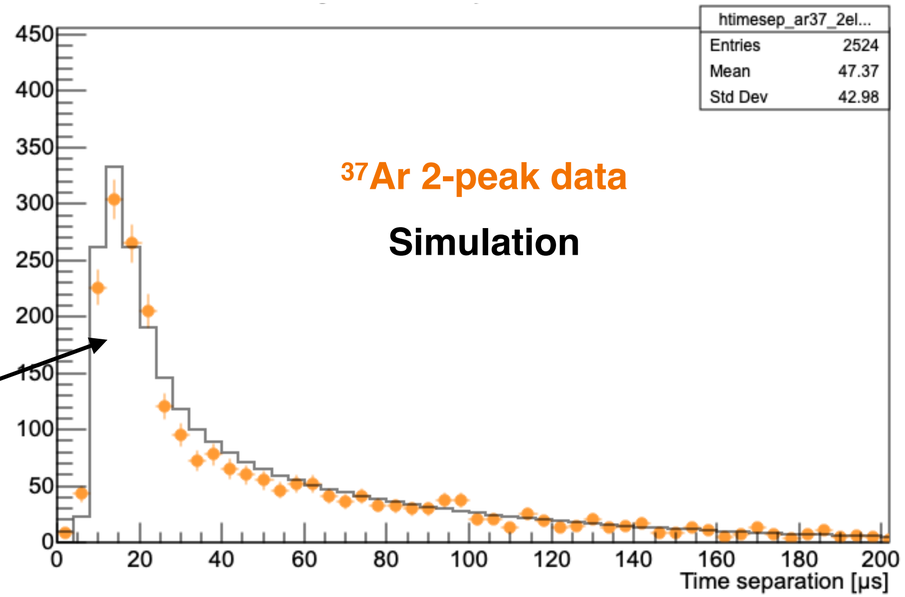
- Time separation between first and last peak inform on radial position of interaction
- Simulations of surface and volume events in agreement with Laser and ^{37}Ar data respectively
- Need >1e- to use





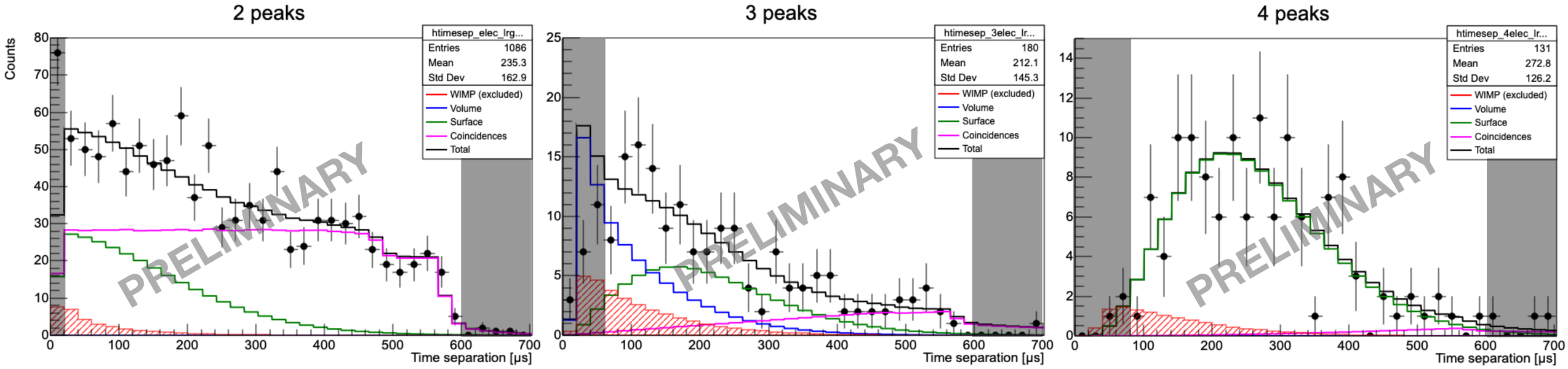
Surface events:
wide distribution,
large time separations

Volume events:
Concentrated at low
time separations



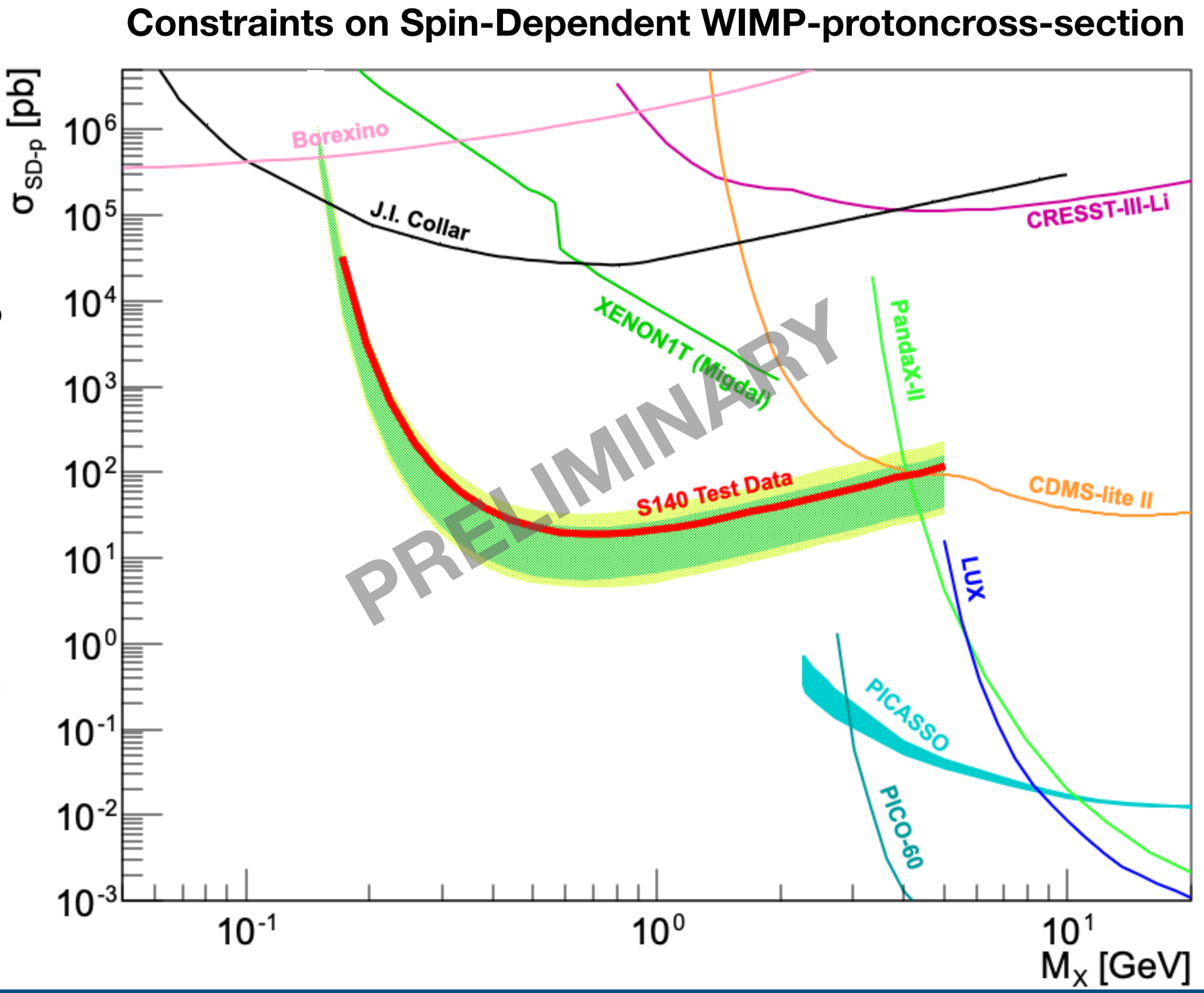
Physics data fit

- Use ~30% of physics data as test data (effective 37h)
- Profile likelihood fit to the 2,3,4-peak data including contributions from WIMP signal, surface, volume and random coincidence backgrounds
- Use modeling derived from simulations and validated with calibration data
- No significant signal observed



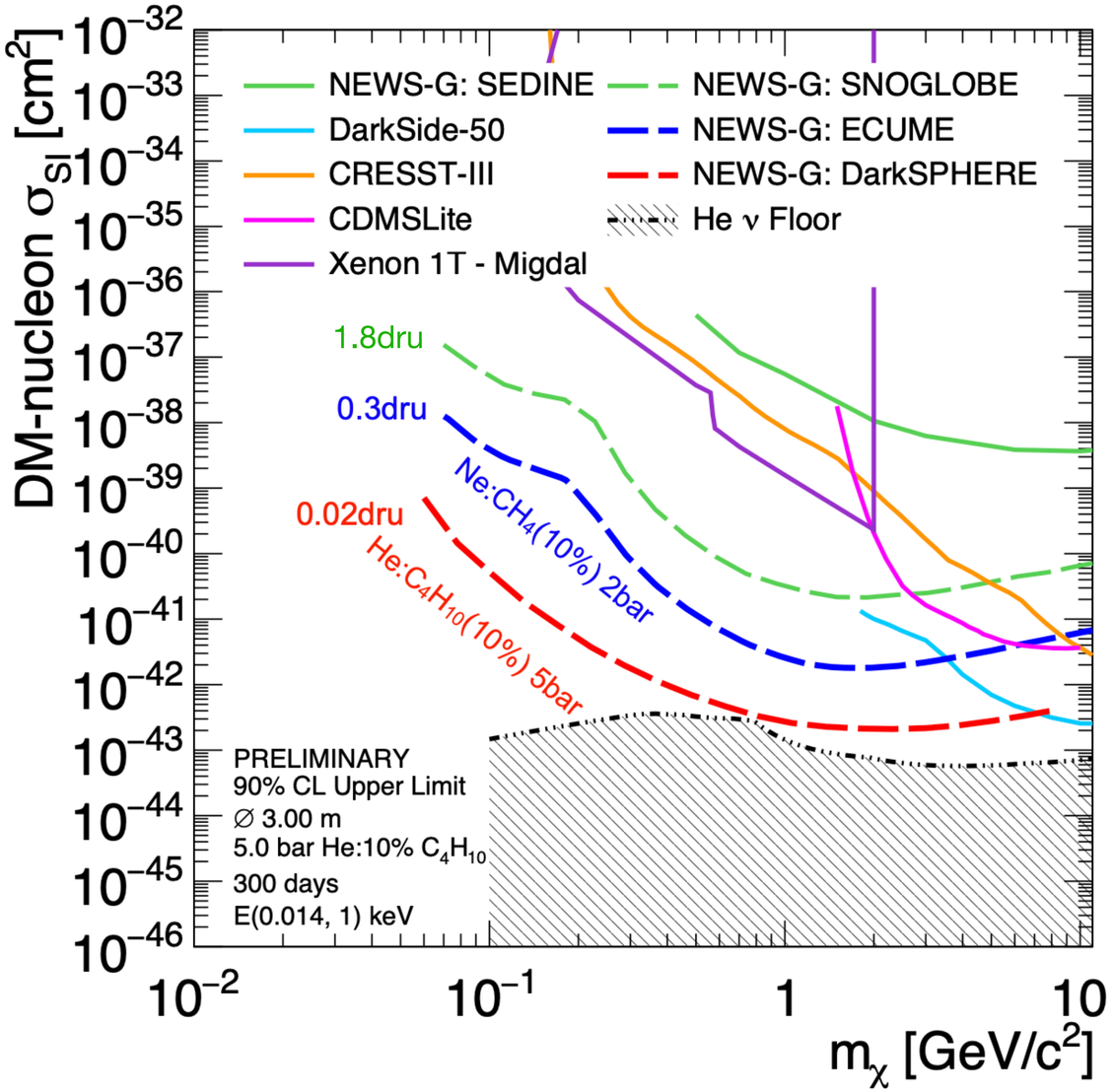
New WIMP constraints

- Profile Likelihood used to generate constraints on WIMP cross-section
- Results on test data (effective 0.12 kg·day) : strongest constraint on spin-dependent WIMP-proton cross-section in 0.2-2 GeV range!
  - Final results on blind data in coming weeks



Future prospects

- S140 : more data at SNOLAB
  - Internal surface etching, more CH_4 data for improved SD-p constraints
  - Ne+CH_4 mixture for improved SI constraints
  - Possible low-pressure run for NR/ER discrimination
- ECUME : fully electro-formed vessel directly in underground lab, completely remove background from vessel
  - Demonstrations ongoing at PNNL
- DarkSPHERE : fully electro-formed vessel, and full water shield; ultimate project, under consideration



Summary

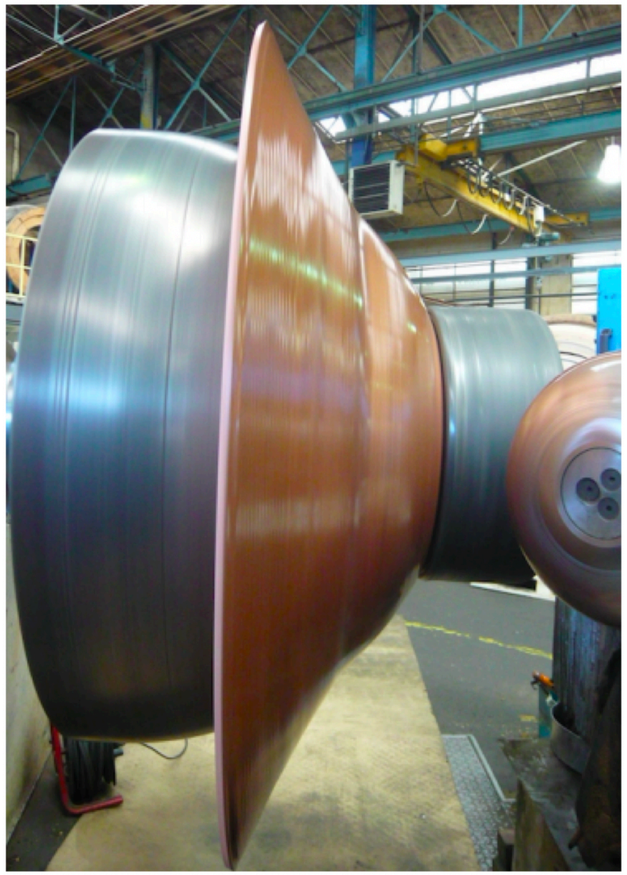
- New S140, larger and more radio-pure than SEDINE prototype, tested with new ACHINOS sensor in dual-channel configuration
- Pilot run at LSM :
  - Electron counting for improved low-energy background discrimination and threshold
  - Detailed understanding of detector with Laser, ^{37}Ar calibrations
  - First WIMP constraints with proton target in underground lab : 3-4 order of magnitude improvement on constraint on *O*(1) GeV WIMP SD-p cross-section
- Physics run at SNOLAB with improved shielding about to start
  - Surface etching already redone
- Beyond S140 : Future projects ECUME & DarkSPHERE

Thank you for your attention!

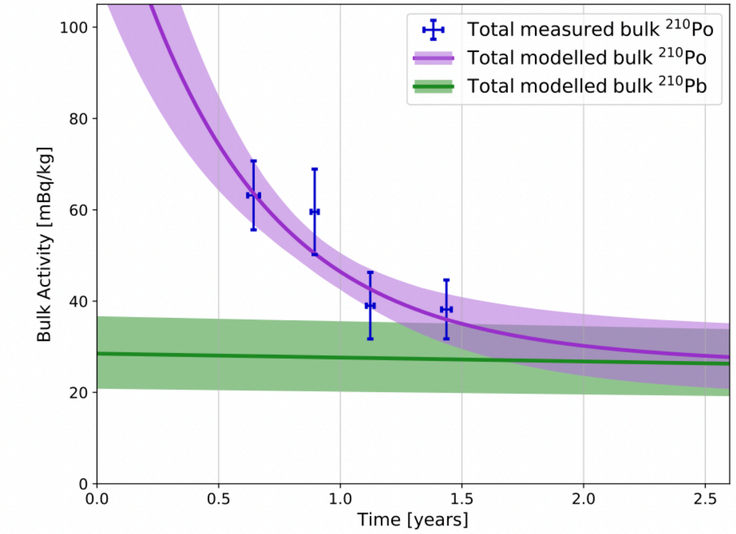
Extra slides

S140: Improvements

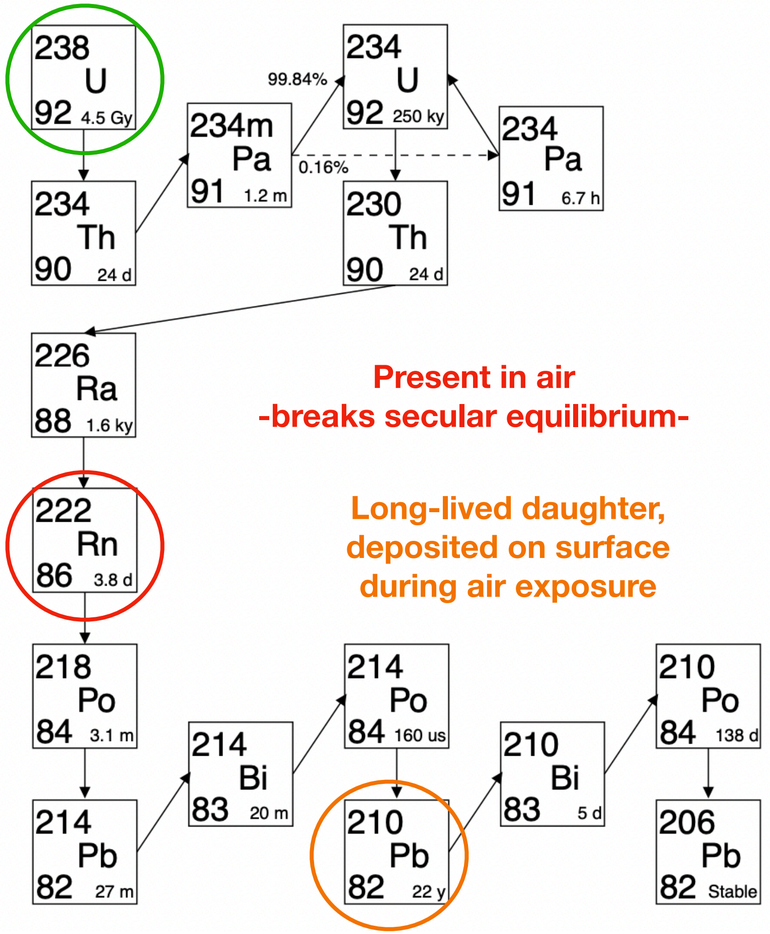
Background reduction



- 2 hemispheres of C10100 (4.5N) copper, electron-beam welded together
- XIA alpha counter estimated ~30 mBq/kg ^{210}Pb in copper bulk (collaboration with XMASS)



Present in copper



Present in air
-breaks secular equilibrium-

Long-lived daughter, deposited on surface during air exposure

L. Balogh et al, Nucl.Instrum.Meth.A 988 (2021)

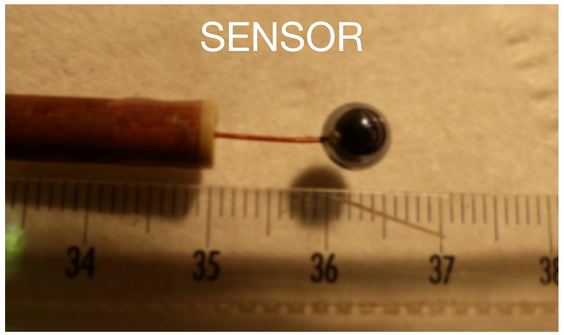
Sensor development

From single to multi-anode

- Single anode sensor field:

$$E \approx r_A \frac{V}{r^2}$$

- Contradictory constraints:
  - High gain requires small radius anode
  - Field far from anode requires large radius anode

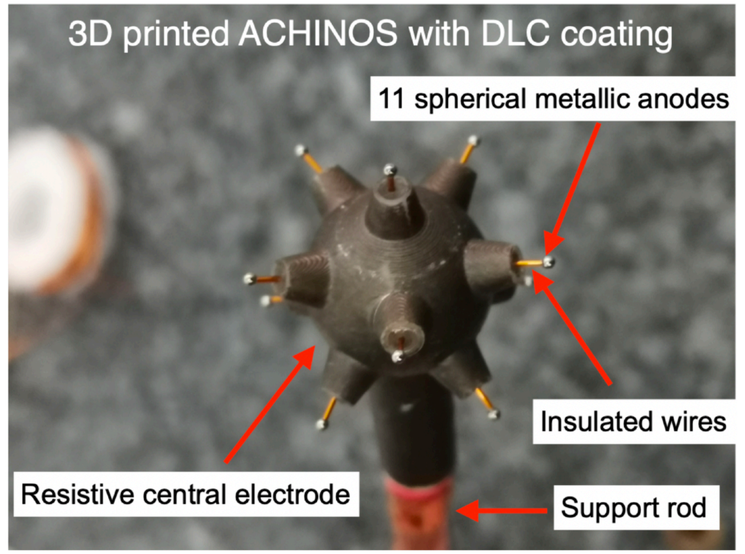


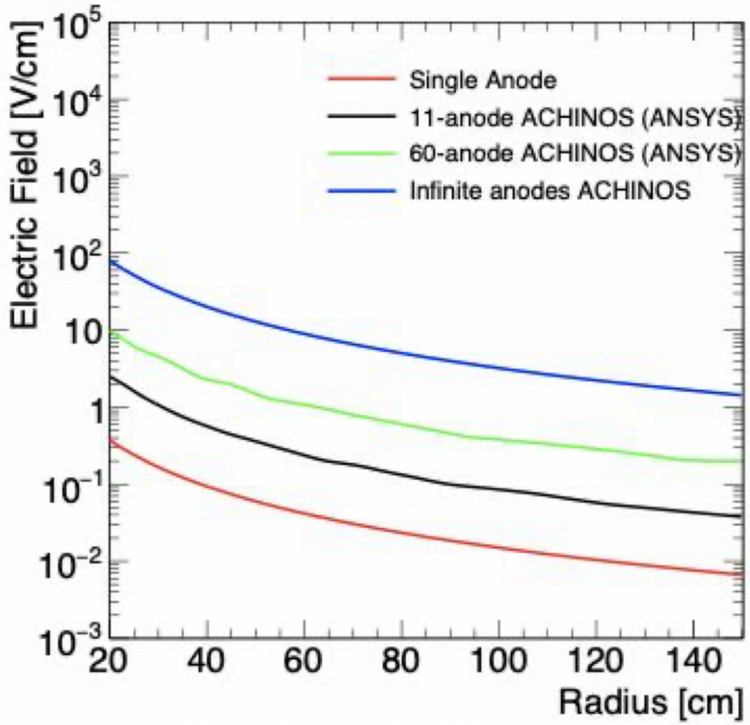
Αχινός (greek. sea urchin)

Enter ACHINOS

- Multiple anodes placed at equal radii
- Boosted field far from anodes, without changing avalanche field: can scale detector up!

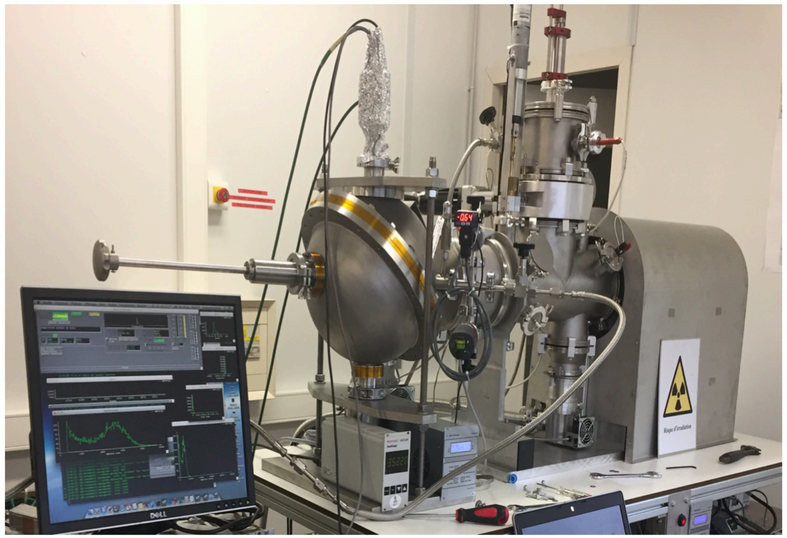
JINST 12 (2017) 12, P12031





Quenching Factor measurements

COMIMAC, LPSC Grenoble

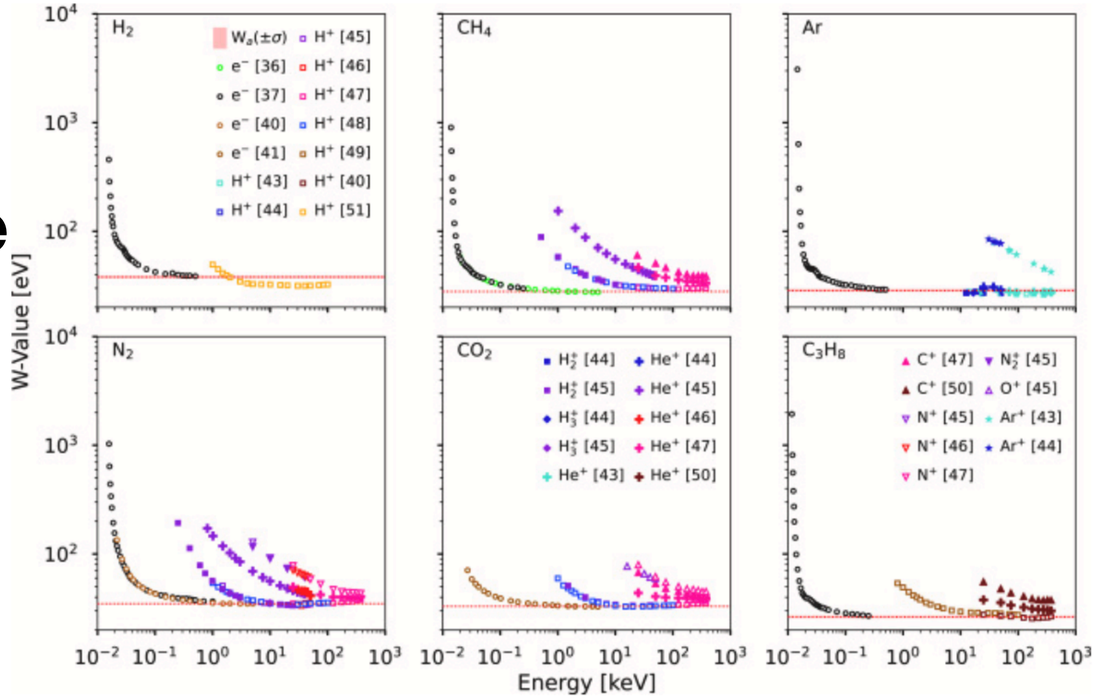


Generates electrons/ions of known energy, accelerated in electric field

https://arxiv.org/abs/2201.09566, pending publication in EPJC

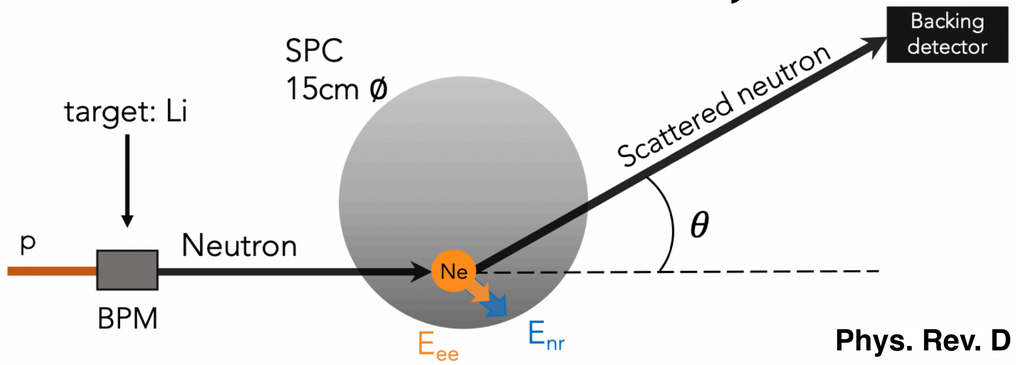
Ratio of literature values for W, Birmingham U.

Exploit literature on mean ionization energy for electrons and ions to produce QF values



Astr. Phys. 141, 102707 (August 2022)

545keV neutron beam, TUNL

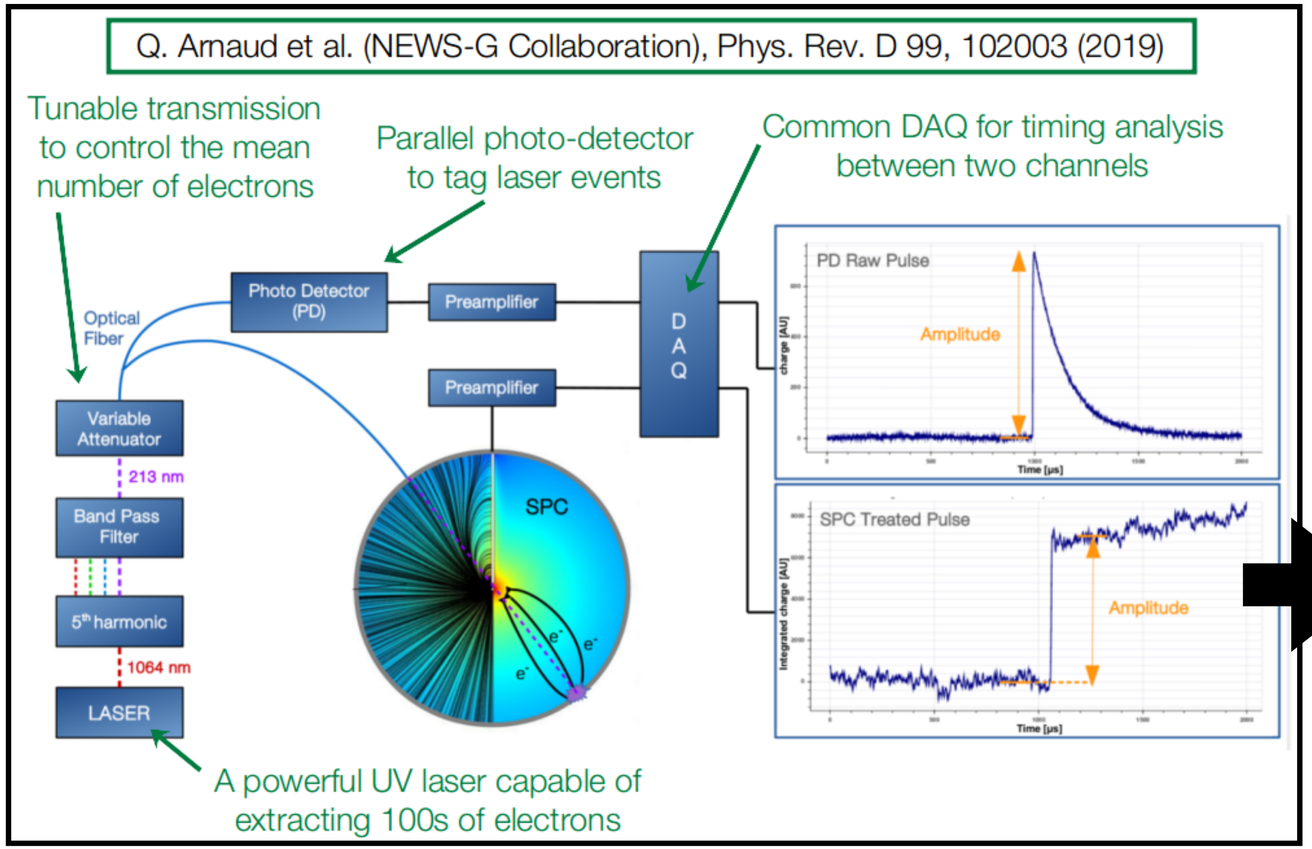


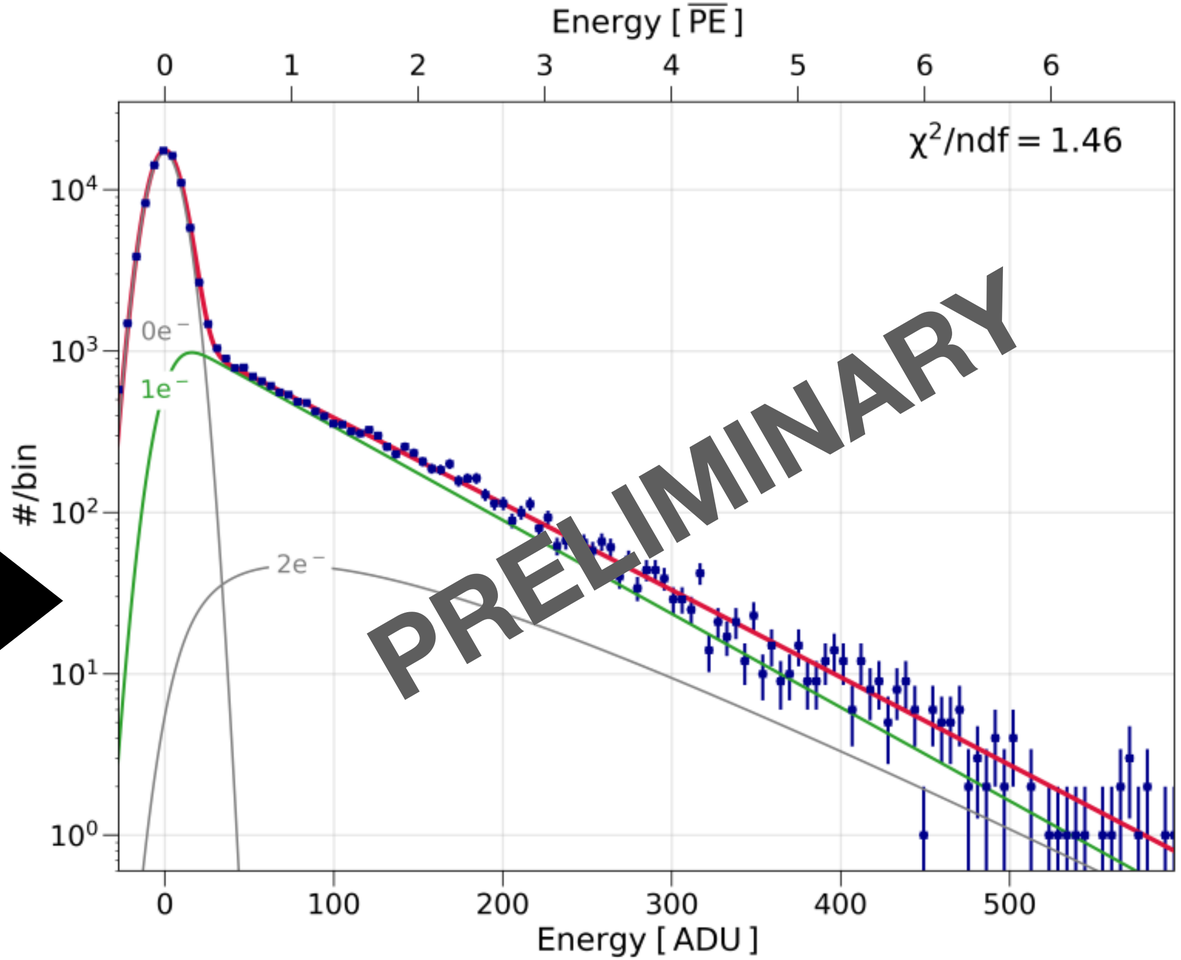
Neutron beam generates recoils on target, energy derived from angle of recoil with Backing Detector

Phys. Rev. D 105, 052004 – Published 8 March 2022

Laser gain calibration

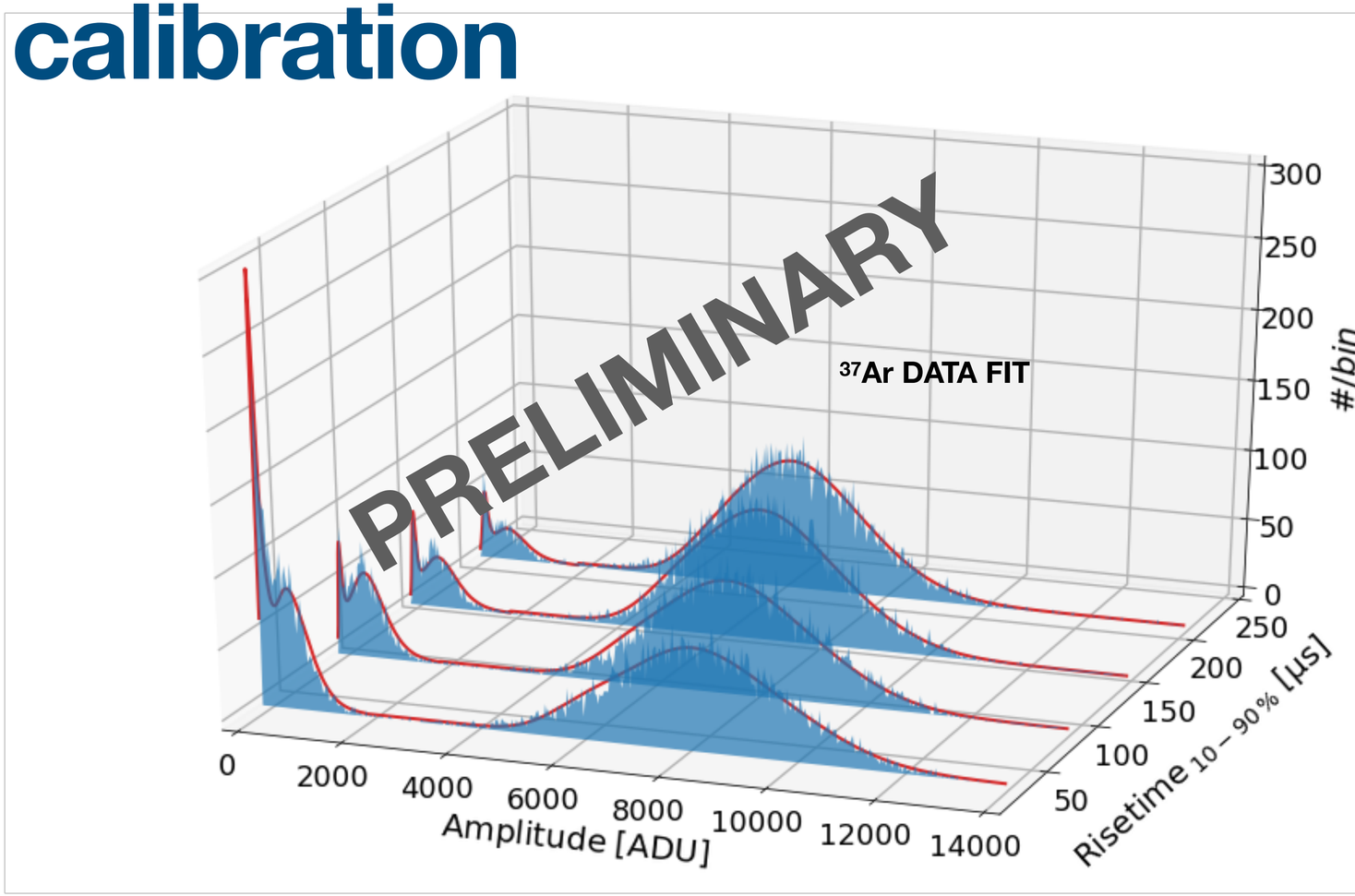
- Fit of laser data provides mean gain, theta of Polya distribution
- Triggering on Photodetector (instead of SPC trigger) also allows trigger efficiency calibration





Ionization process calibration

- Low-intensity laser data fit provides avalanche statistics
- ^{37}Ar (2.8 keV, 270eV, 200 eV) cascade and ionization simulation, convolved with avalanche process, provides ionization process calibration



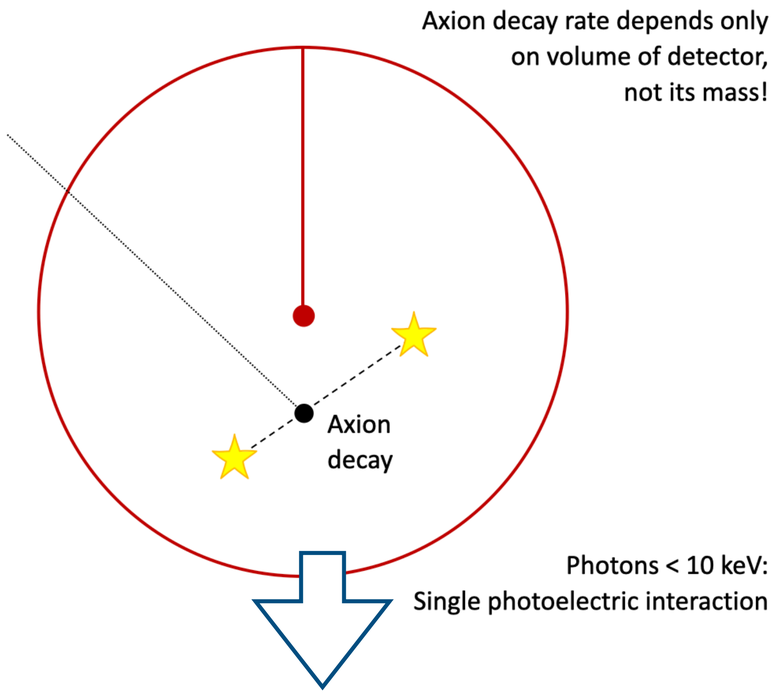
Other projects

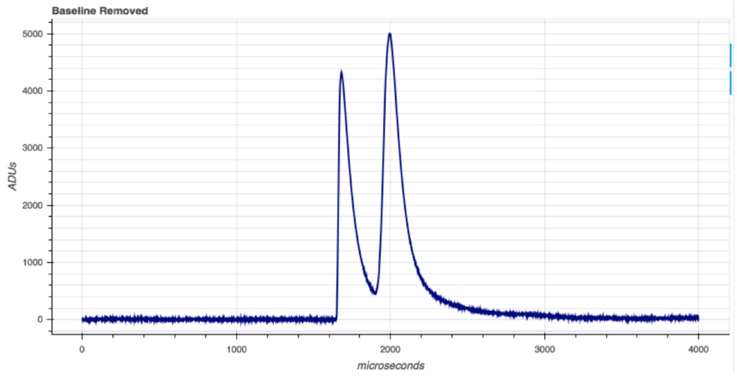
Solar KK axions

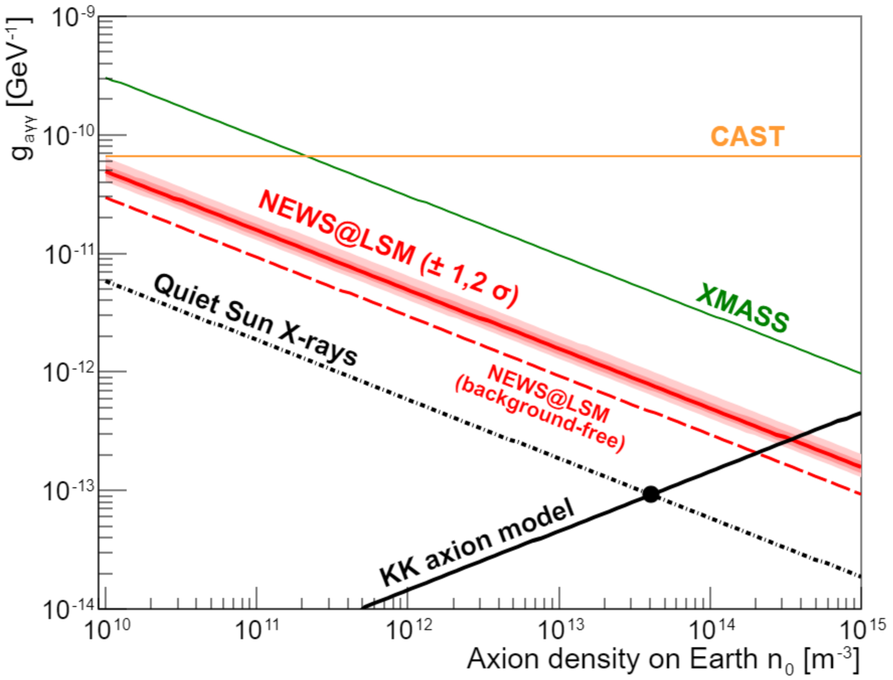
Solar KK axion model predicts accumulation of heavy (~10 keV) axions in the Solar System. These axions decay into two photons of equal energy, absorbed at different locations in an SPC.

Can reject background at 99.99% in 2-22 keV range by keeping only events with two pulses of similar amplitude arriving shortly after each other.

With 42 day exposure of SEDINE detector, and an integrated sensitivity to solar KK axion decays of 16%, still improve over previous XMASS limit by factor ~6.



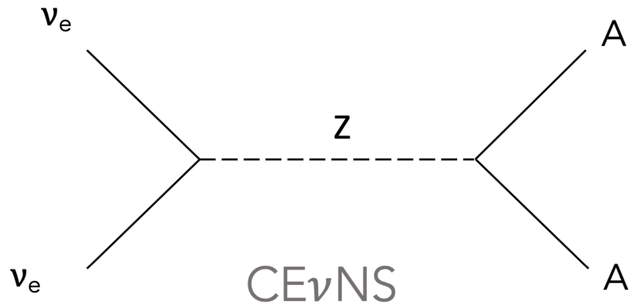




NEWS-G collab., PHYSICAL REVIEW D 105, 012002 (2022)

Other projects

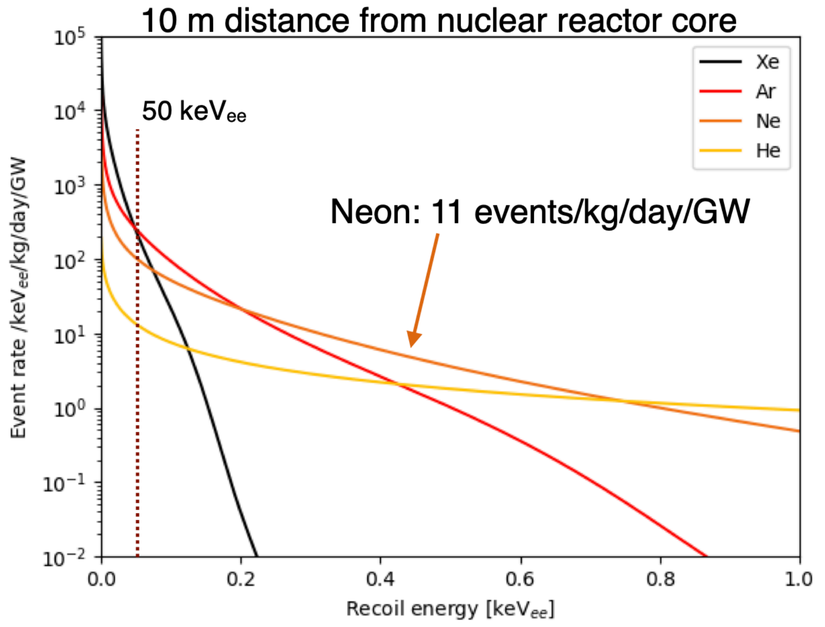
Coherent Elastic Neutrino-Nucleus Scattering

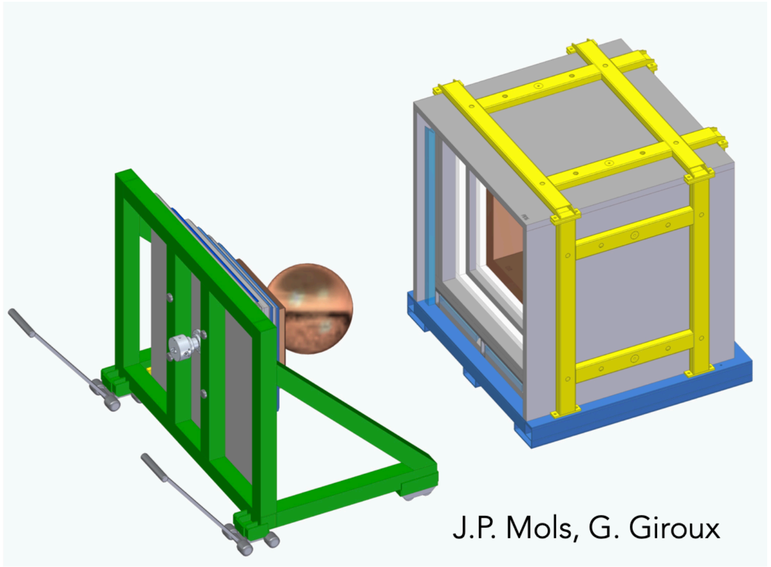


First observed by COHERENT in NaI (2017) and Ar (2020). Complementary with DM searches as detectors reach neutrino floor. Can also be used for nuclear reactor monitoring.

NEWS-G interested in detecting CEvNS at nuclear reactor. Feasibilty study requires understanding of both CEvNS signal and backgrounds (environmental, cosmogenic) for surface detectors.

Need for new compact shielding/ SPC facility. Design includes active muon veto, shielding alternating PE/ Pb layers, and innermost Cu shield. Commissioning planned for 2021.





NEWS-G3 shield