NEWS-G searches for light dark matter
Results with a hydrogen-rich target

Konstantinos Nikolopoulos
University of Birmingham

on behalf of the NEWS-G Collaboration

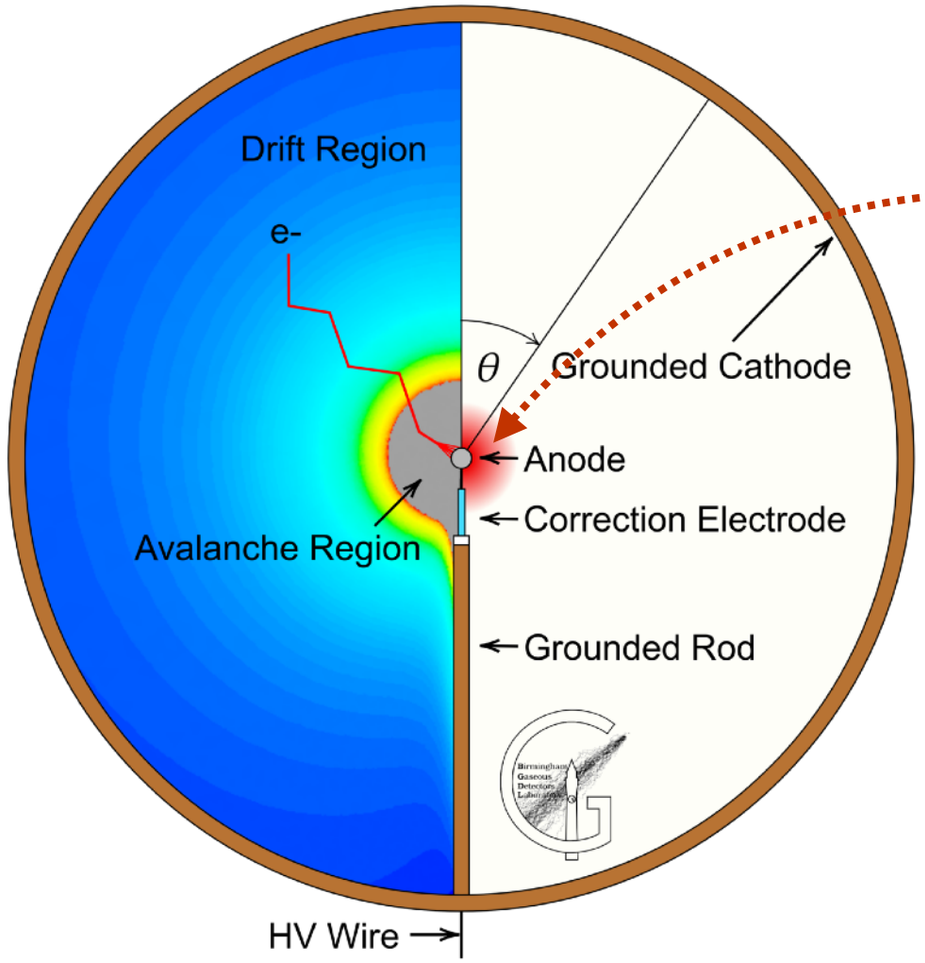
XLI International Conference on High Energy Physics (ICHEP)
July 9th, 2022, Bologna, Italry

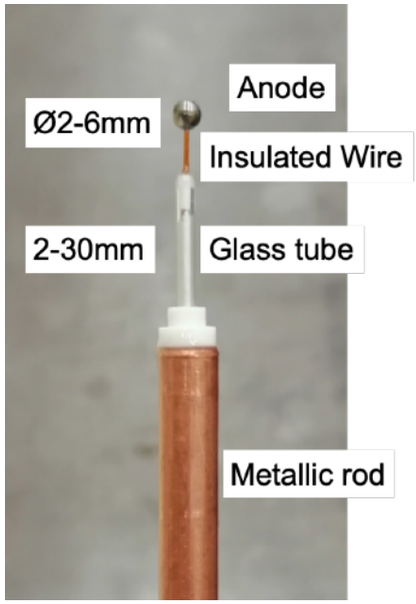
This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement 714893-ExclusiveHiggs and under Marie Skłodowska-Curie agreement 841261-DarkSphere, 895168-neutronSPHERE

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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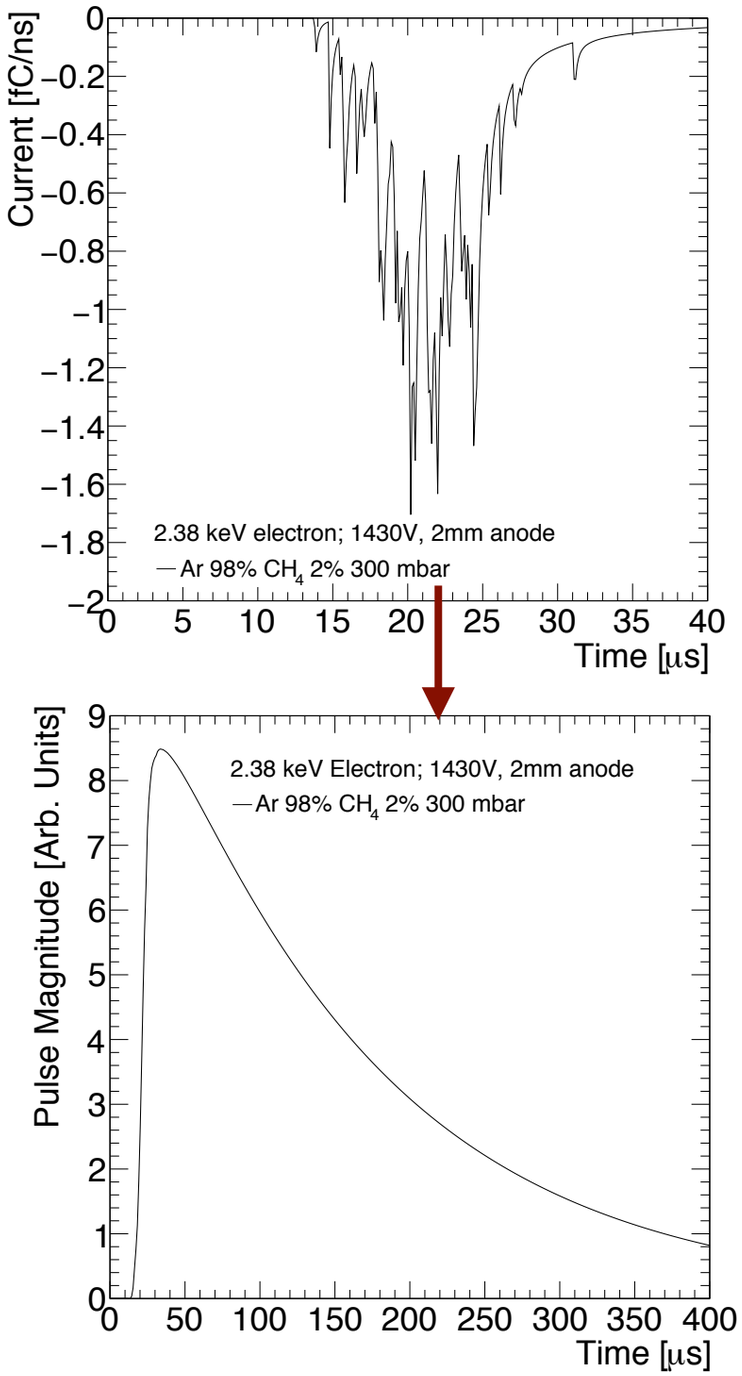

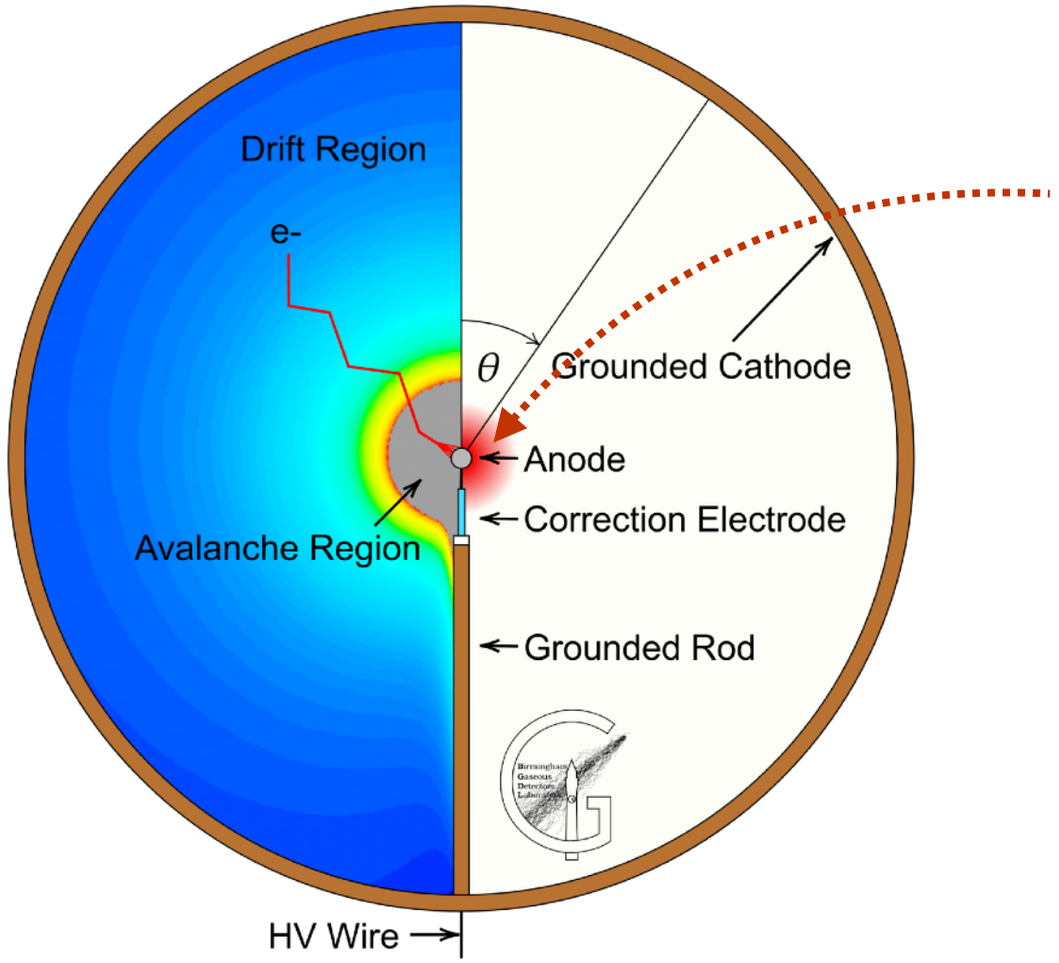

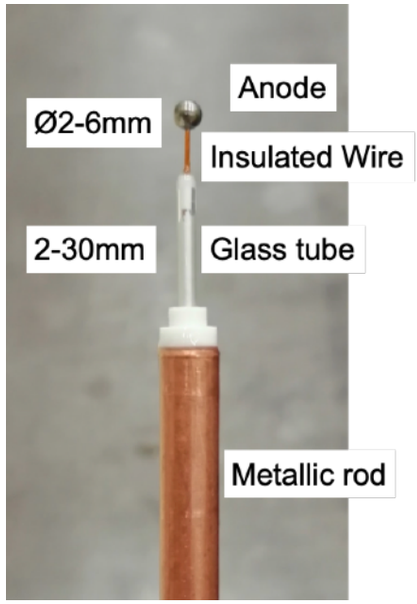

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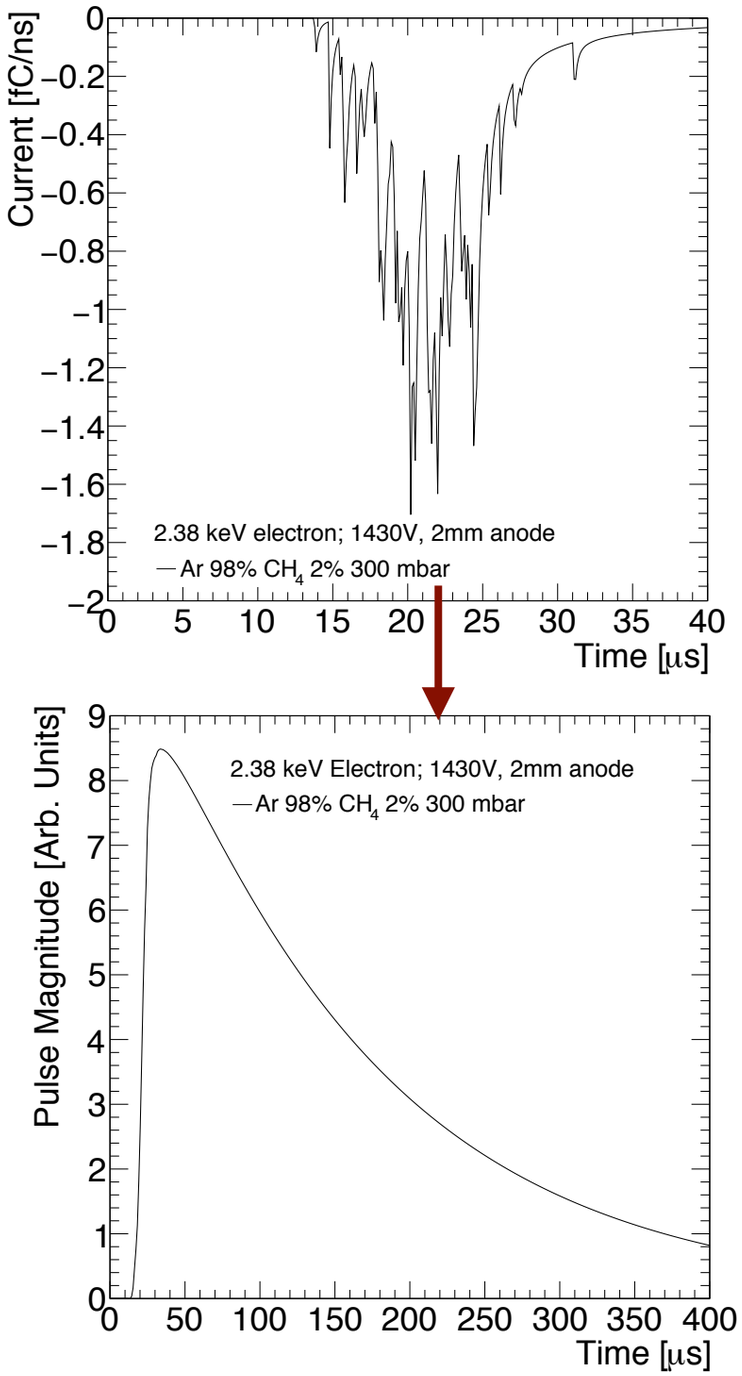
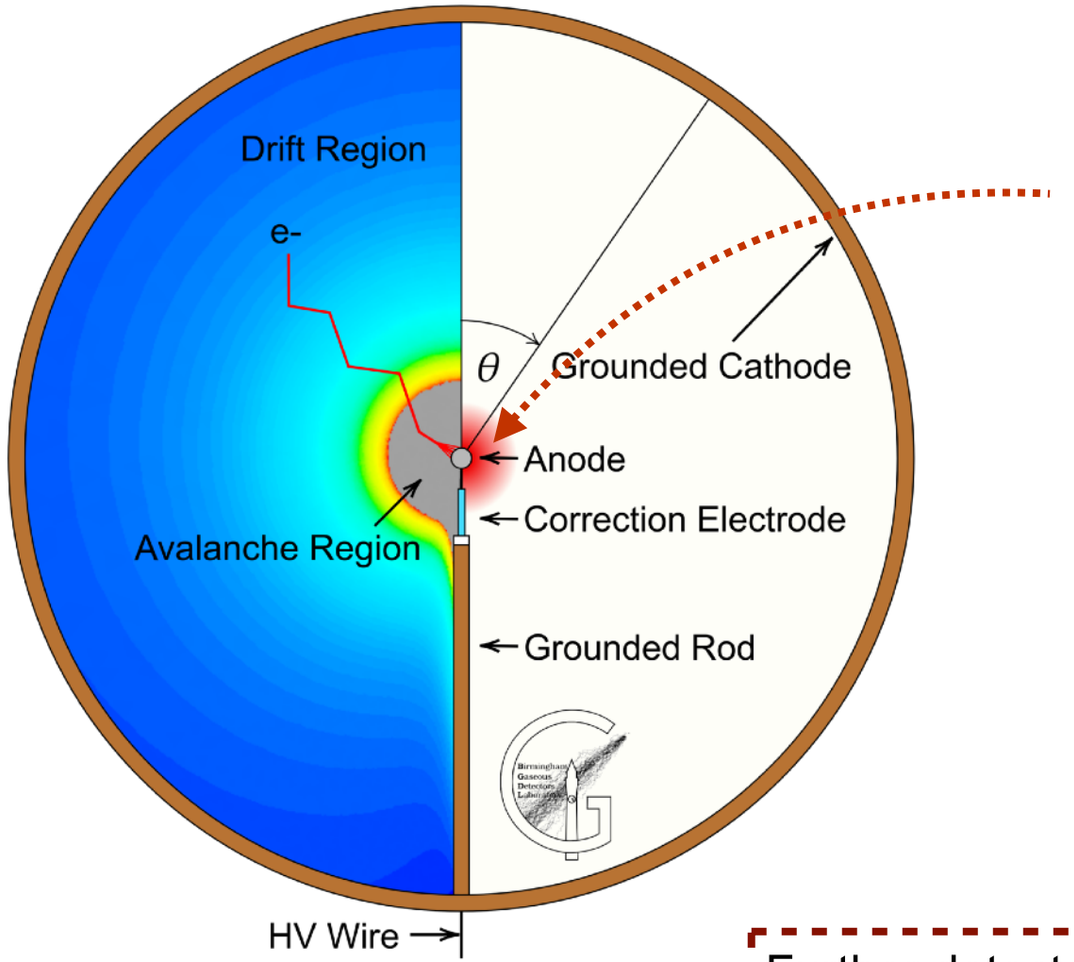
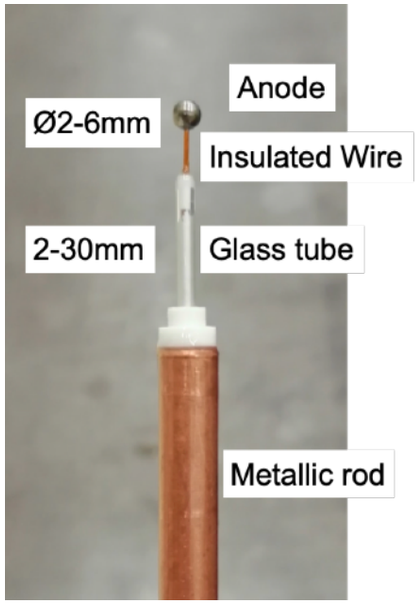


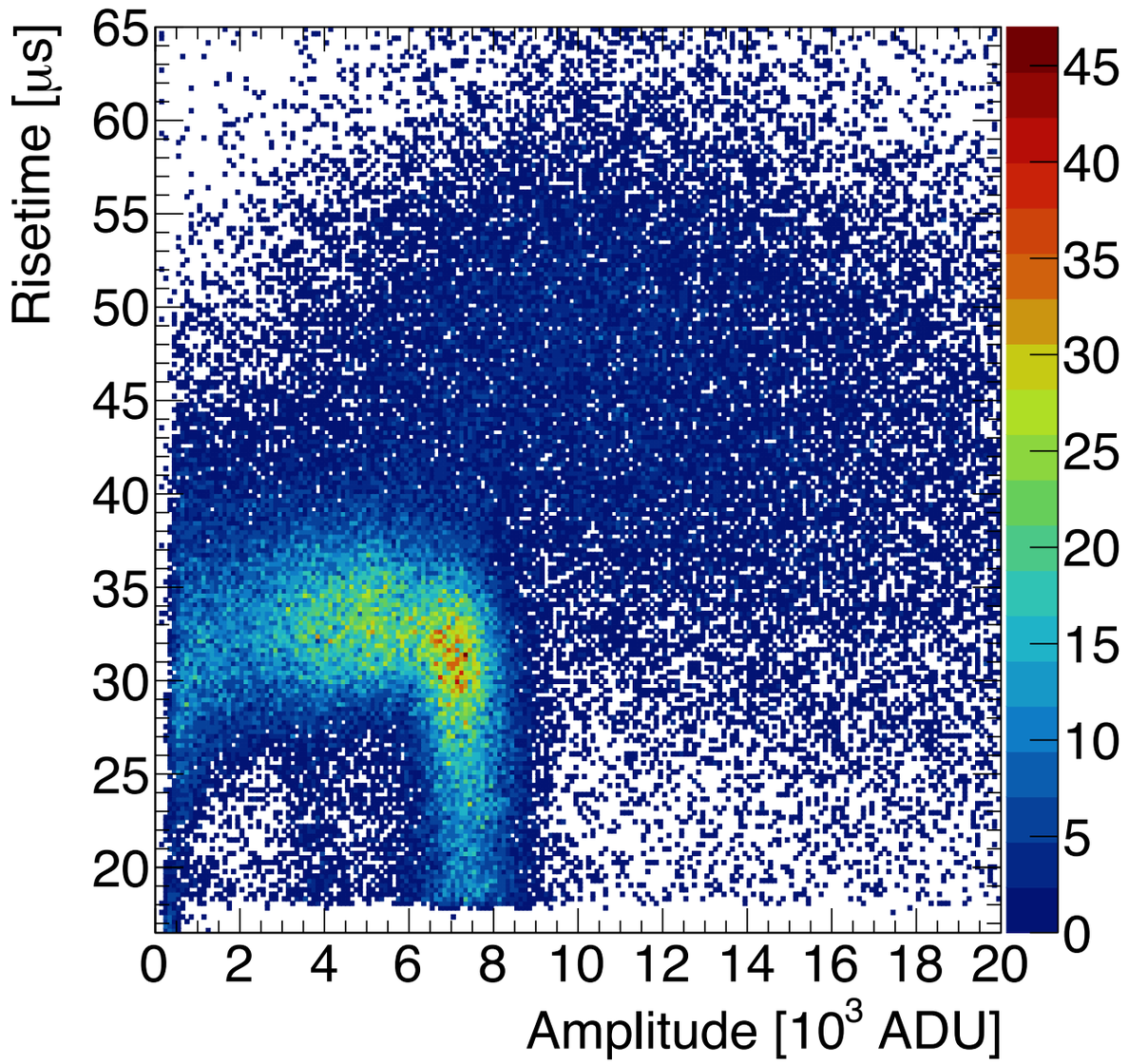




Further detector applications:

- Ioannis Manthos
  - Tech. and Ind. App. session
  - 17:15 on Thursday
- Robert Ward
  - Neutrino Phys. session
  - 16:15 on Saturday

Pulse Shape Discrimination



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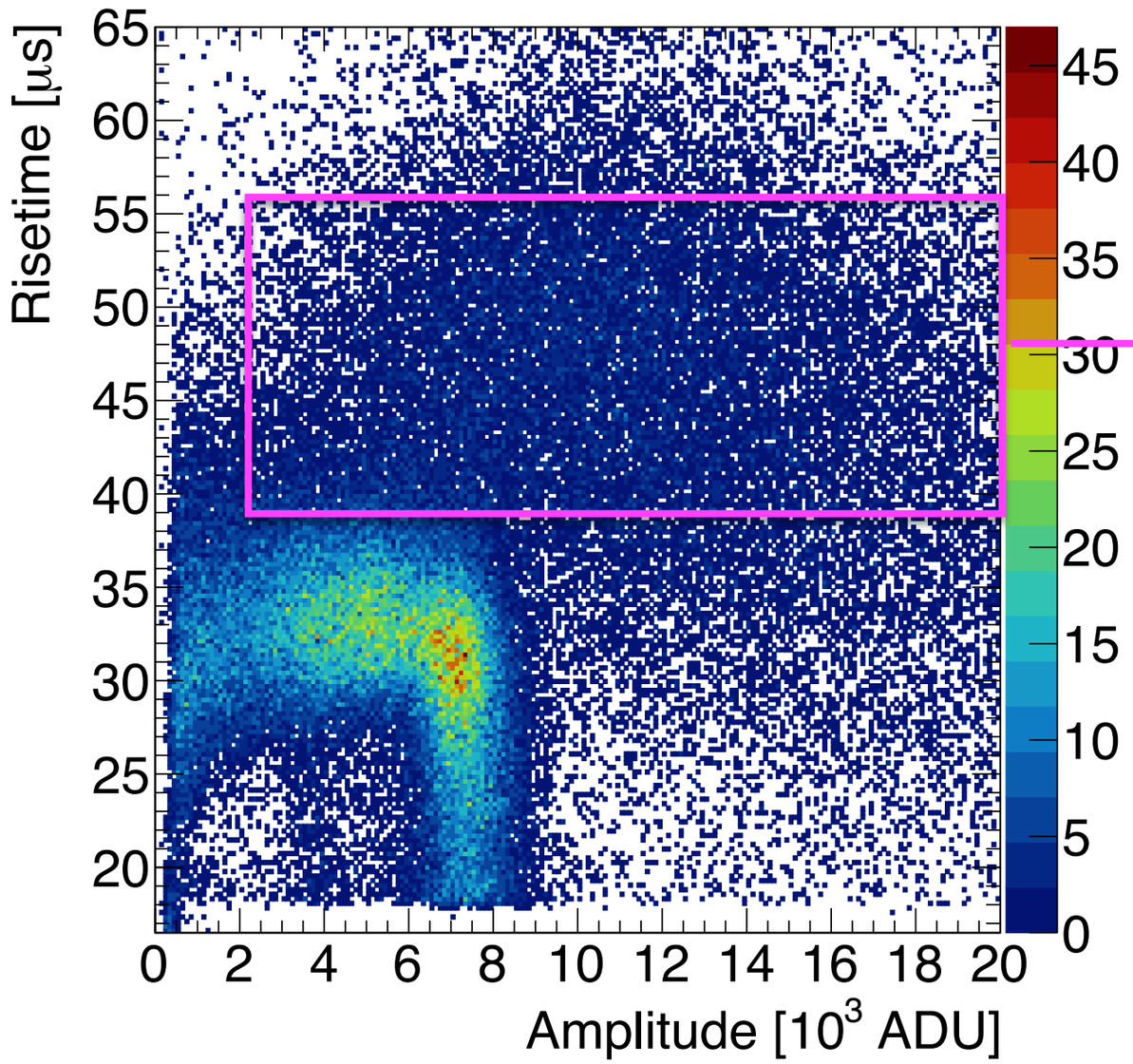
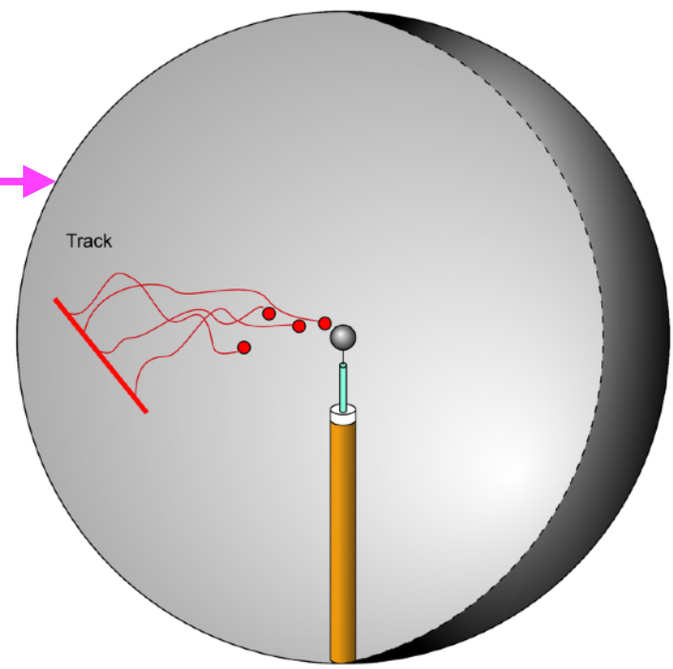
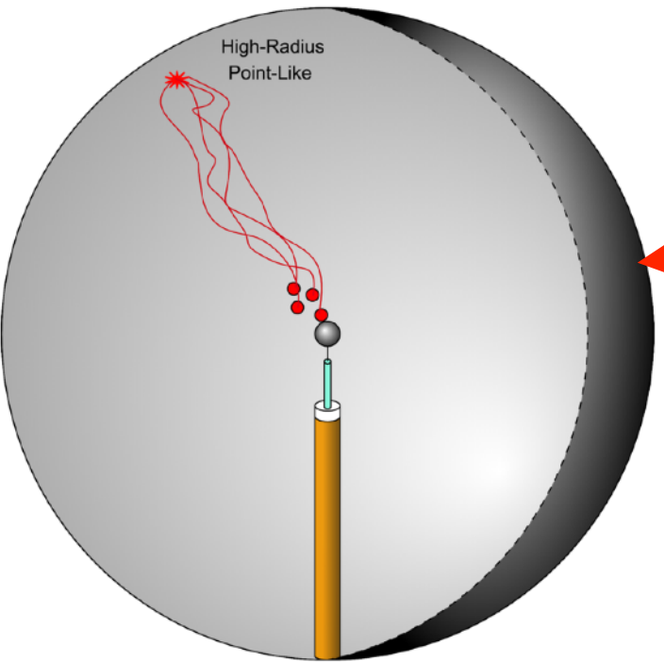


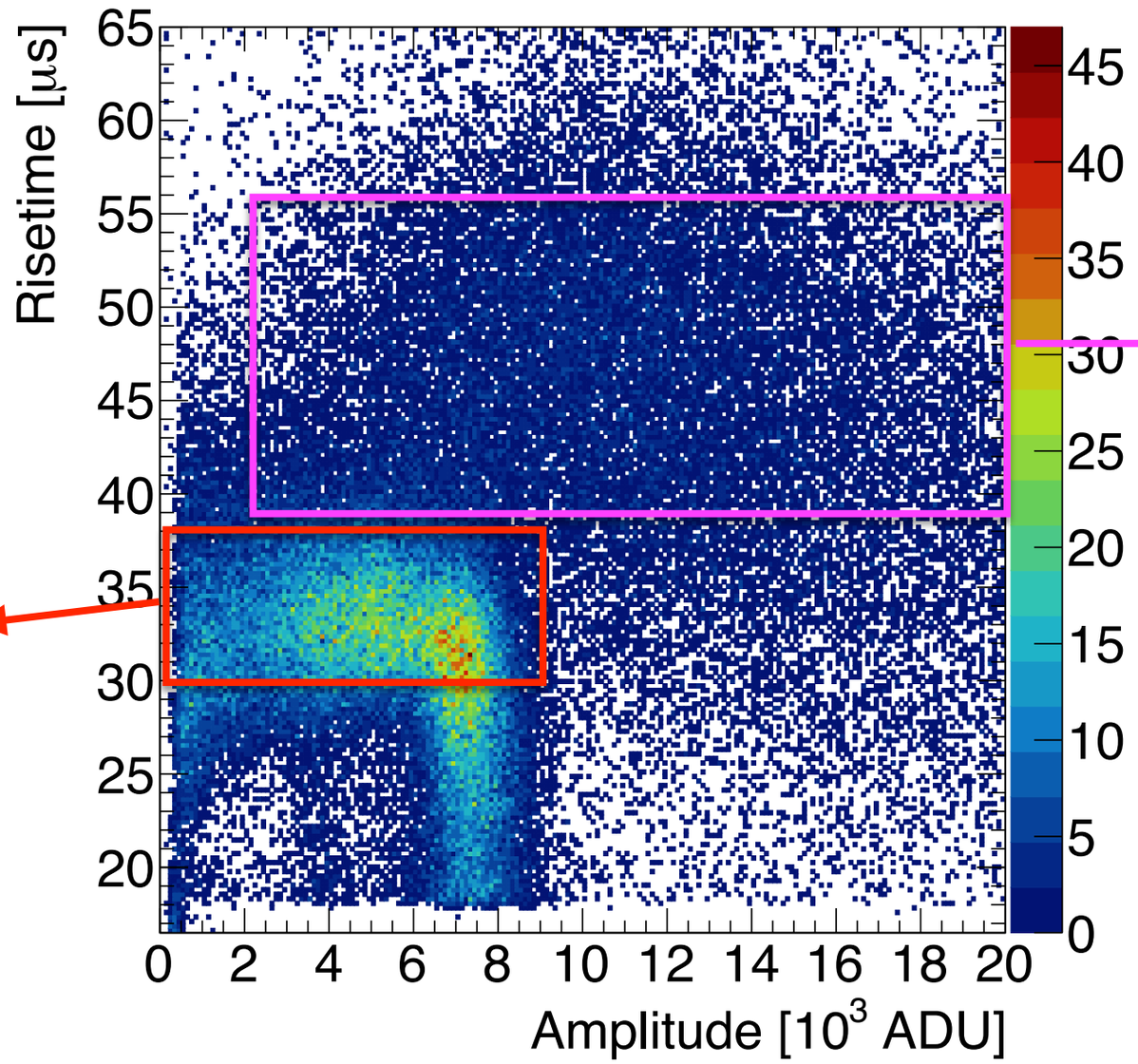


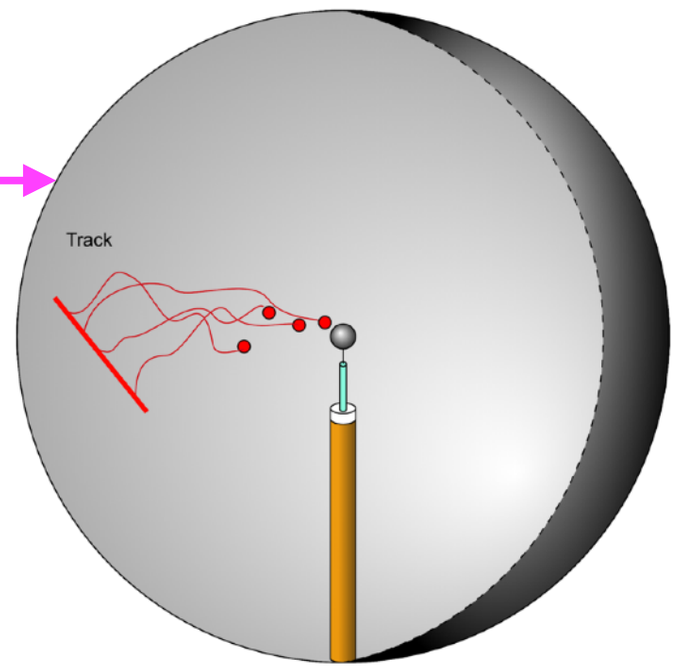
"Muon"-like events

Pulse Shape Discrimination



“Surface”-like events





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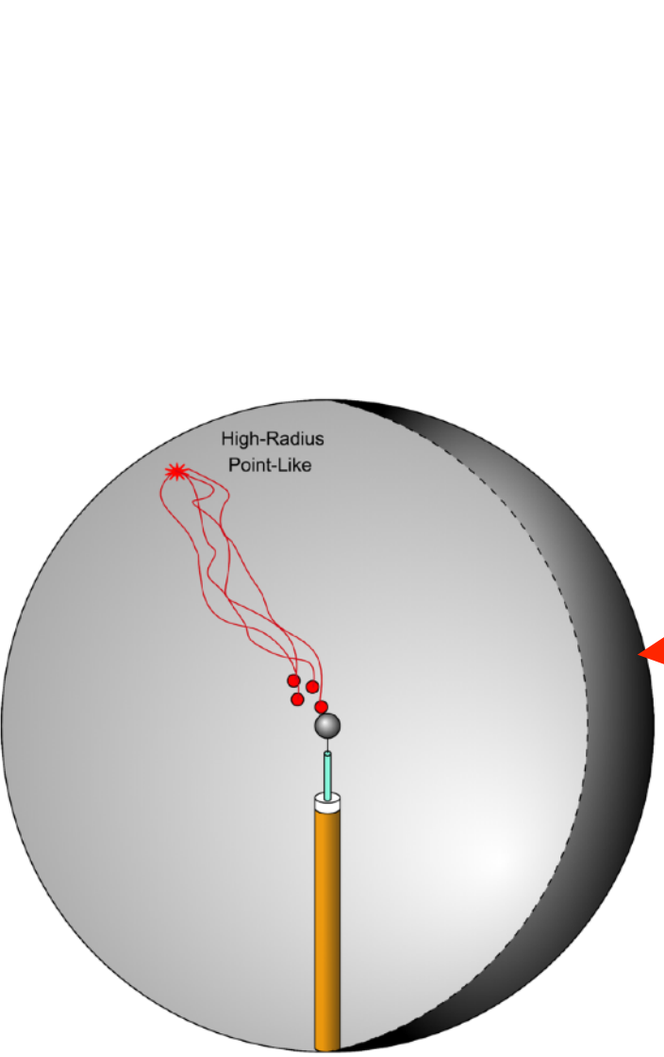

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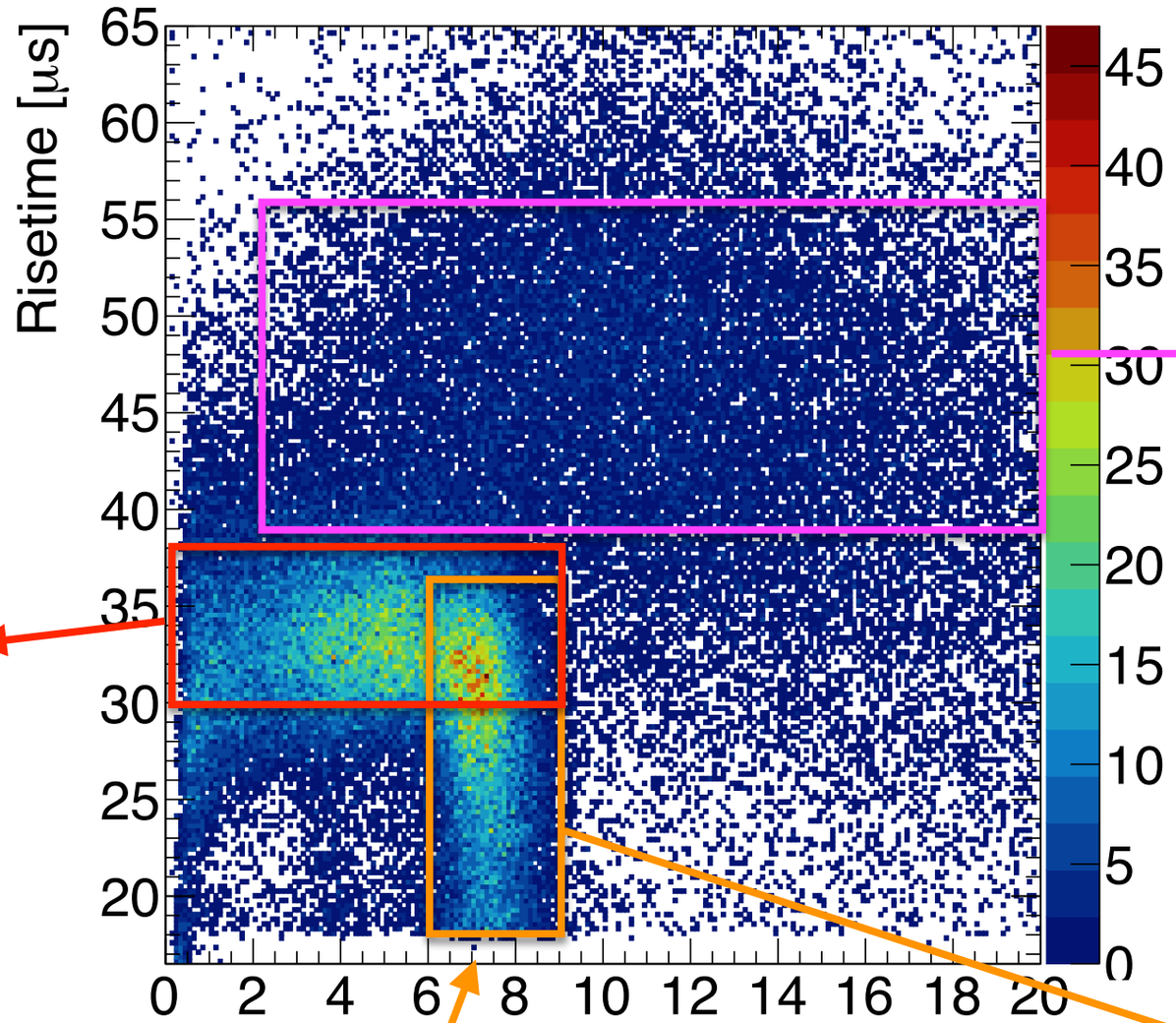
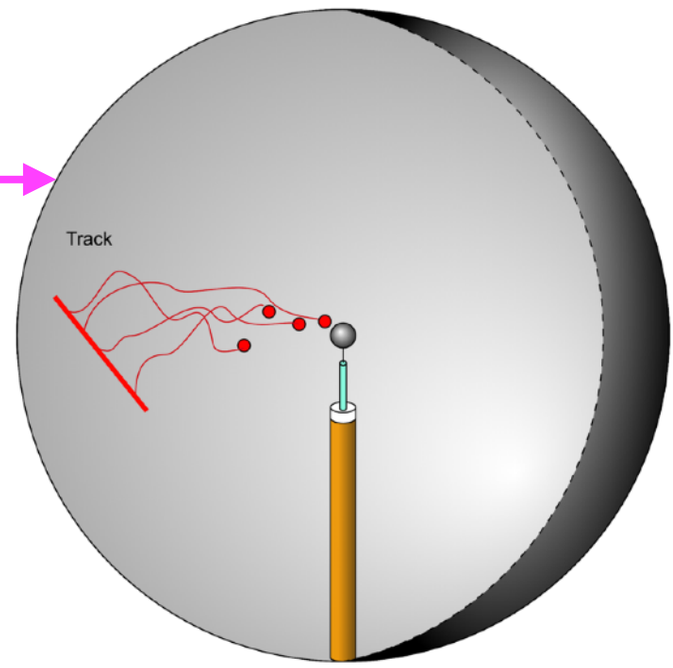


5.9 keV X-rays
from ^{55}Fe decays



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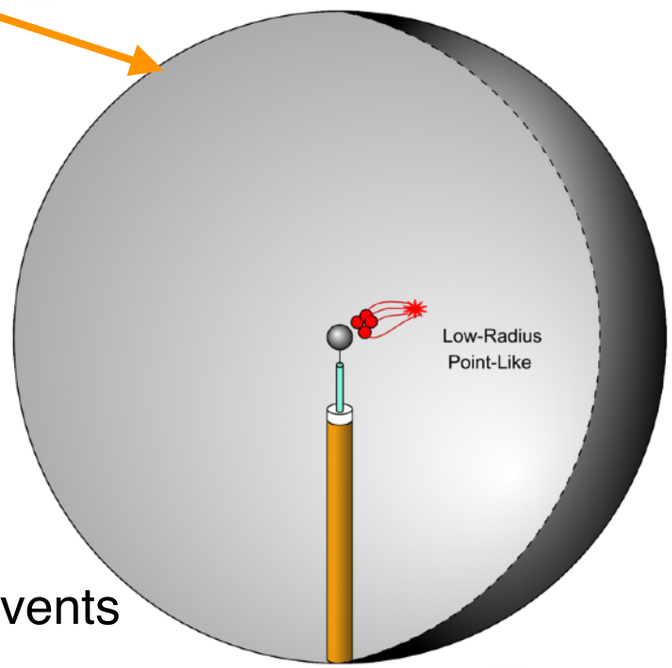
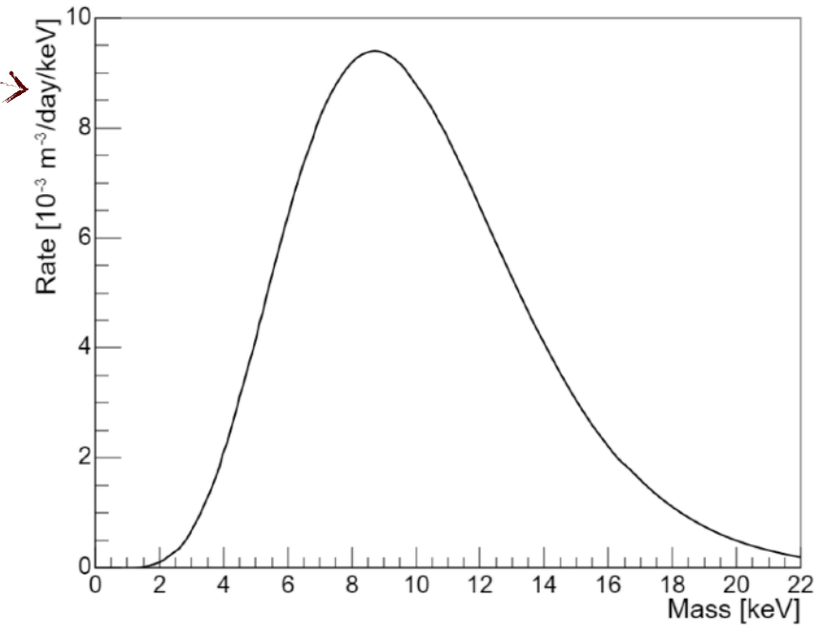


“Signal”-like events

Search for Kaluza-Klein axions

- Search for solar Kaluza-Klein axions
  - Gravitationally bound to the solar system
  - Potential explanation of the corona heating problem
- Decays to two photons
  - Two coincident point-like events with similar energy
- Data collected at LSM Astropart.Phys. 97 (2018) 54-62
  - Exposure: $4.3\ \mathrm{day} \cdot \mathrm{m}^3$
  - Ne:CH_4(0.7%) at 3.1 bar



Phys.Rev.D 105 (2022) 1, 012002

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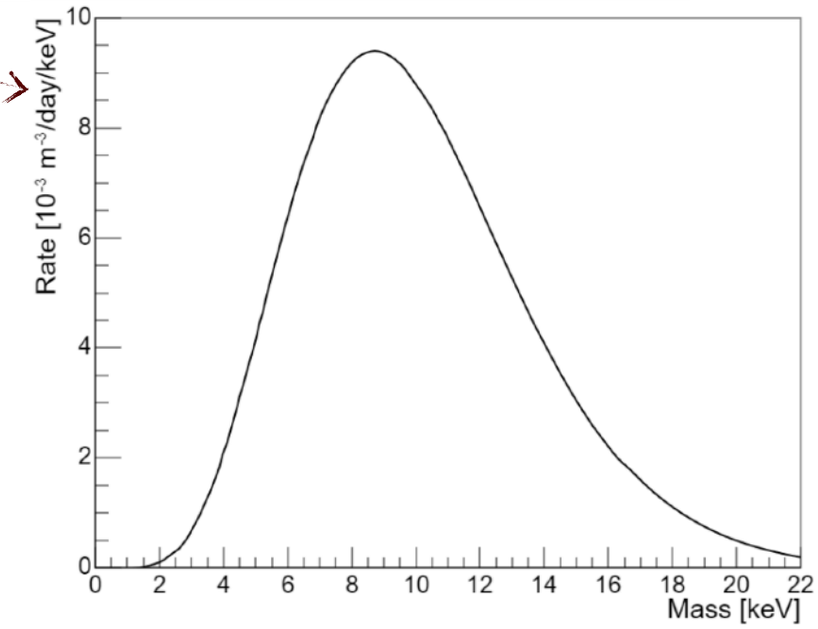

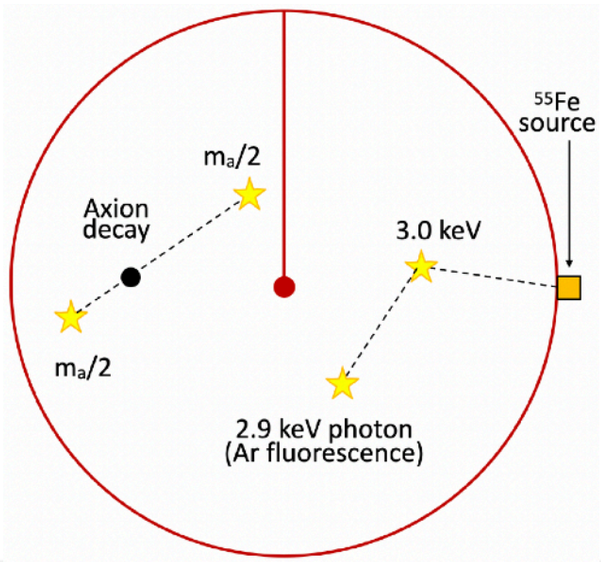

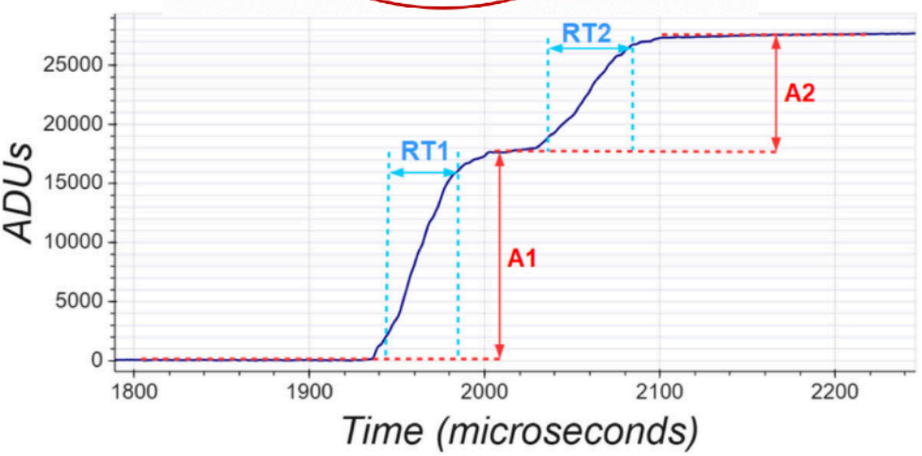

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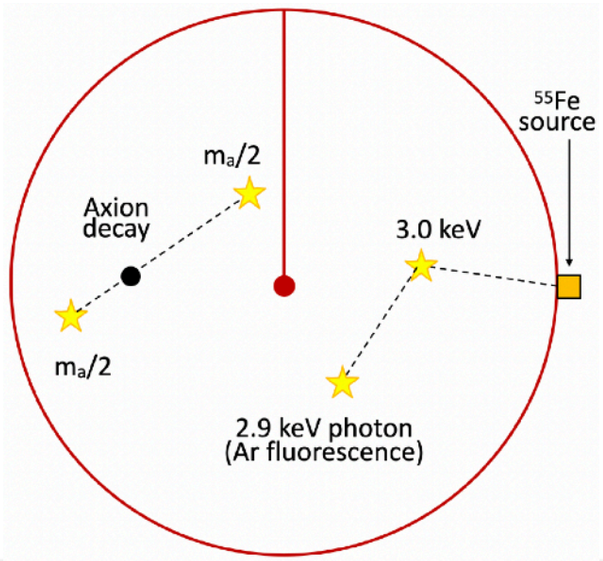
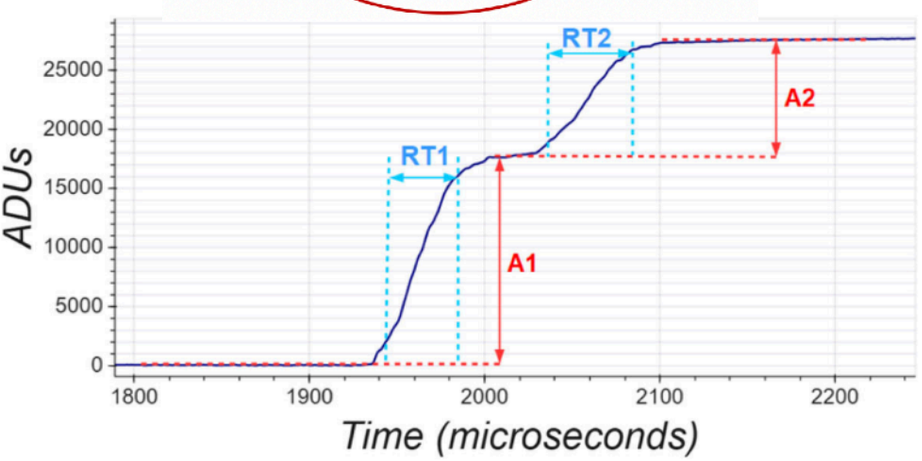
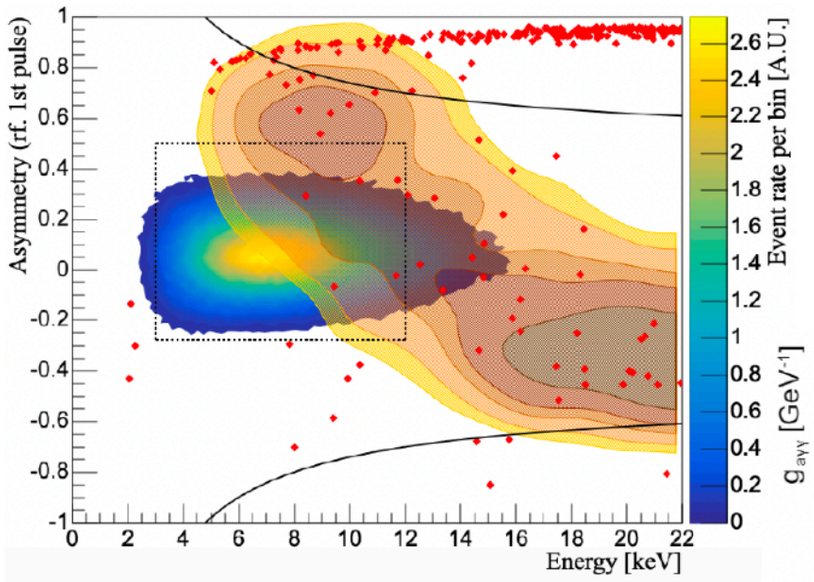
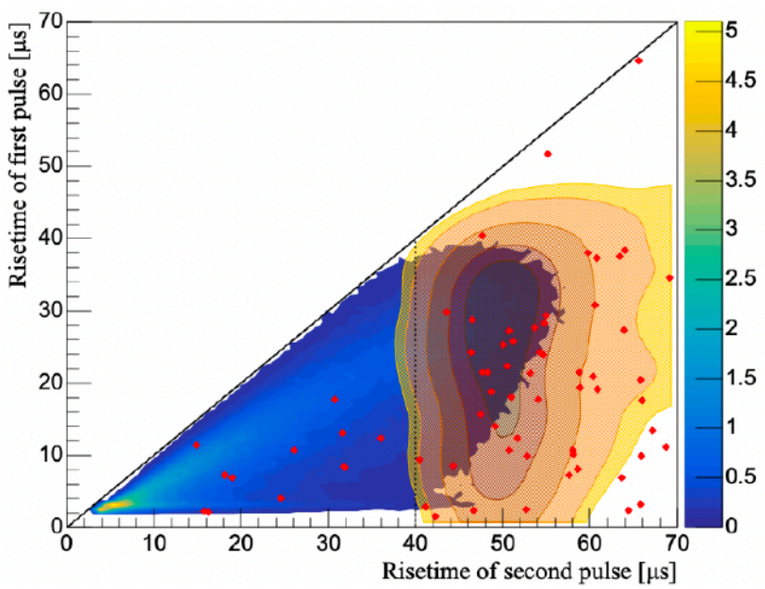
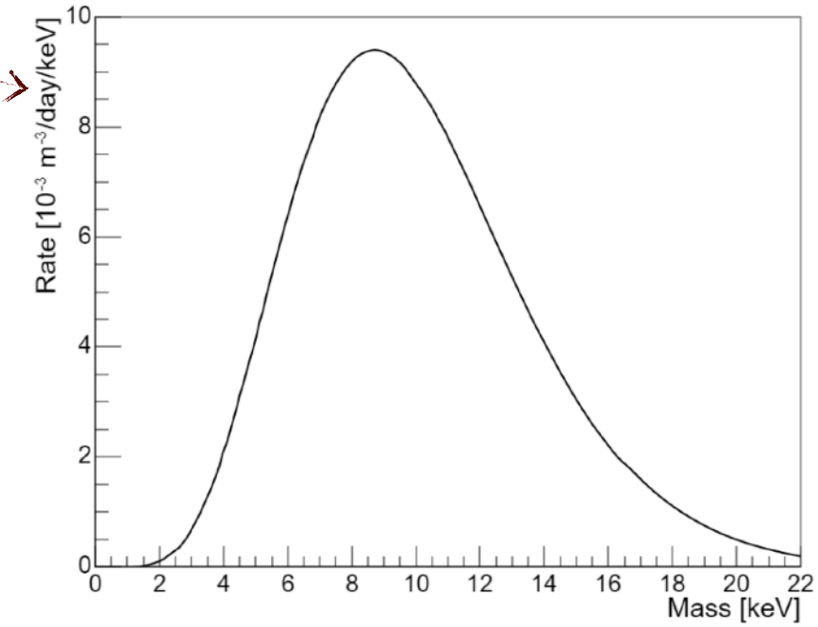
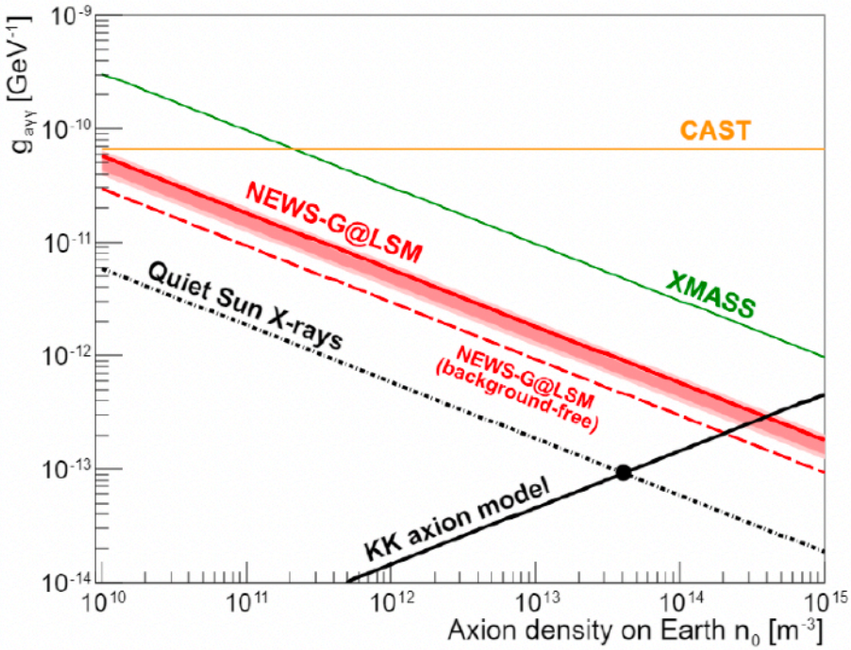












Phys.Rev.D 105 (2022) 1, 012002

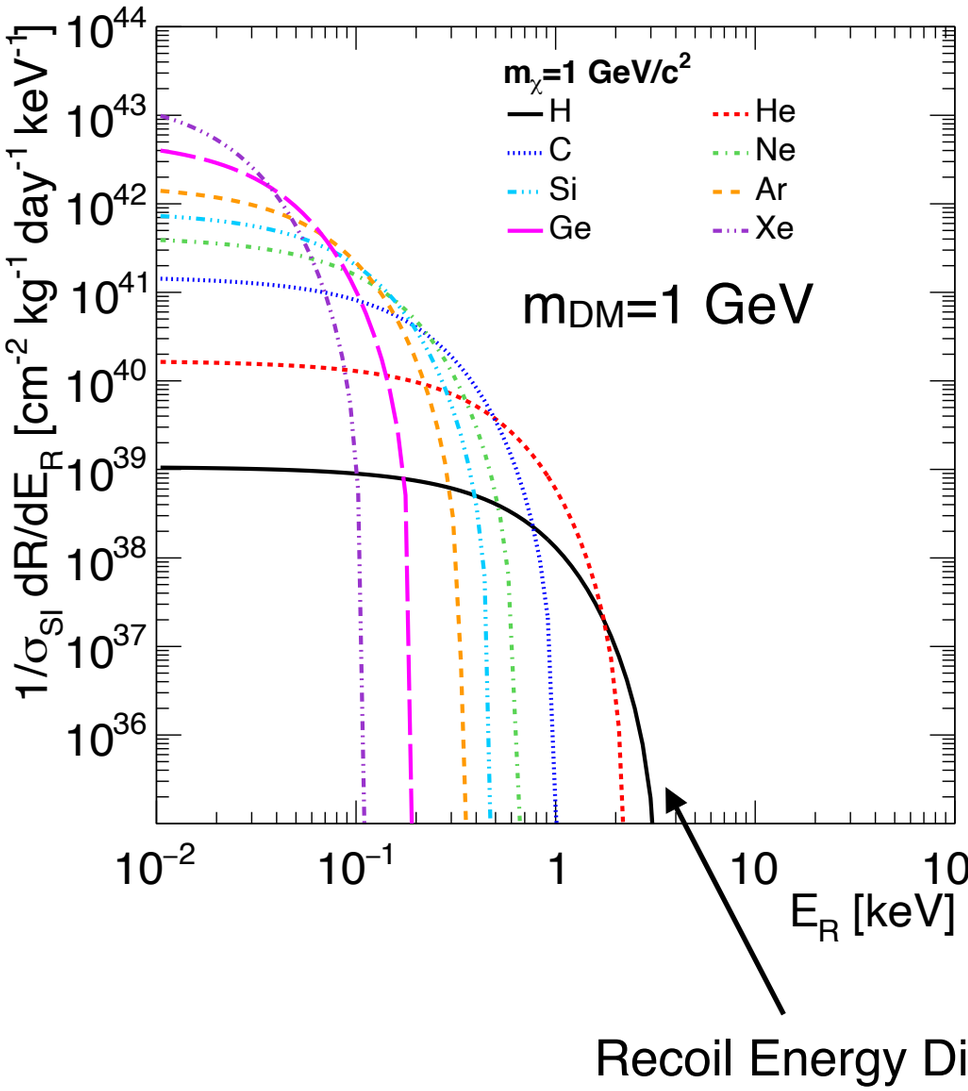
New Experiments With Spheres - Gas

https://news-g.org/

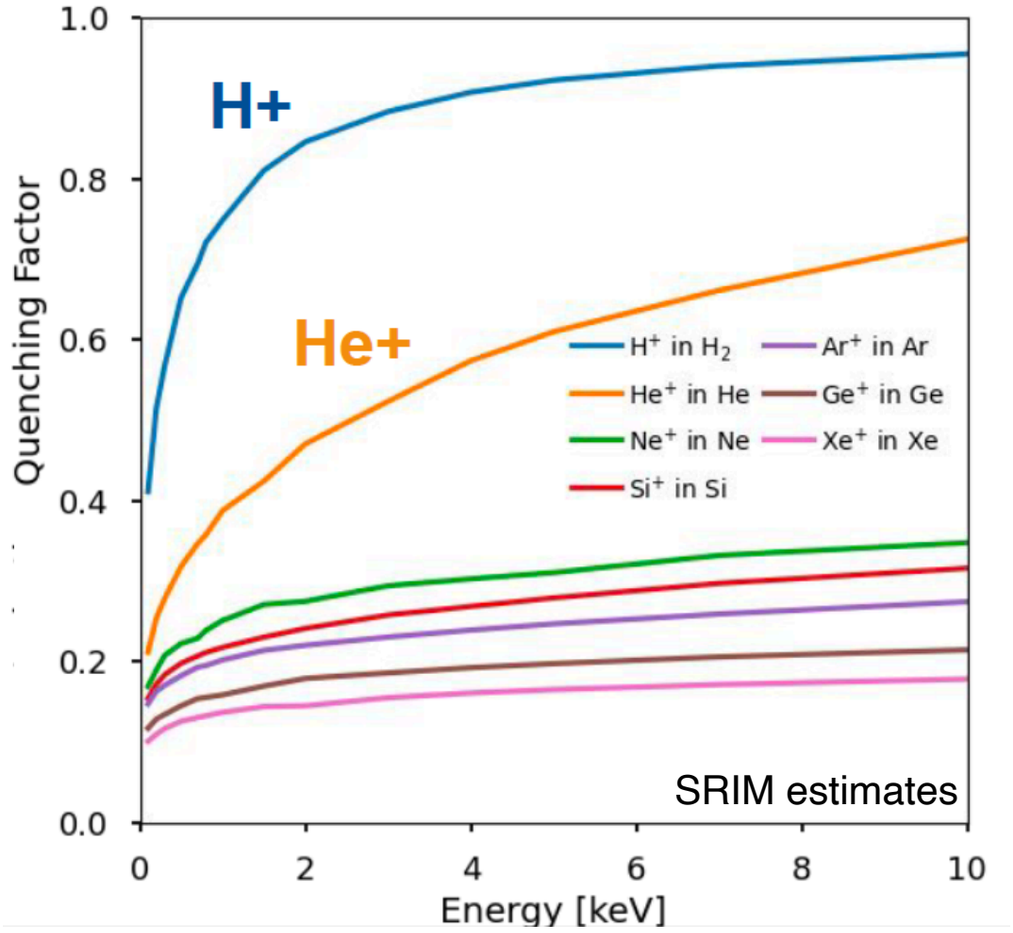
- NEWS-G Collaboration
  - 5 countries
  - 10 institutes
  - ~40 collaborators
- Direct light DM search
  - Light gaseous tagets (H, He, Ne)
  - Low energy threshold
  - Favourable quenching factor
- Three underground laboratories
  - SNOLAB
  - Laboratoire Souterrain de Modane
  - Boulby Underground Laboratory

Direct Detection: Light Dark Matter

Favourable recoil energy distribution for lighter targets

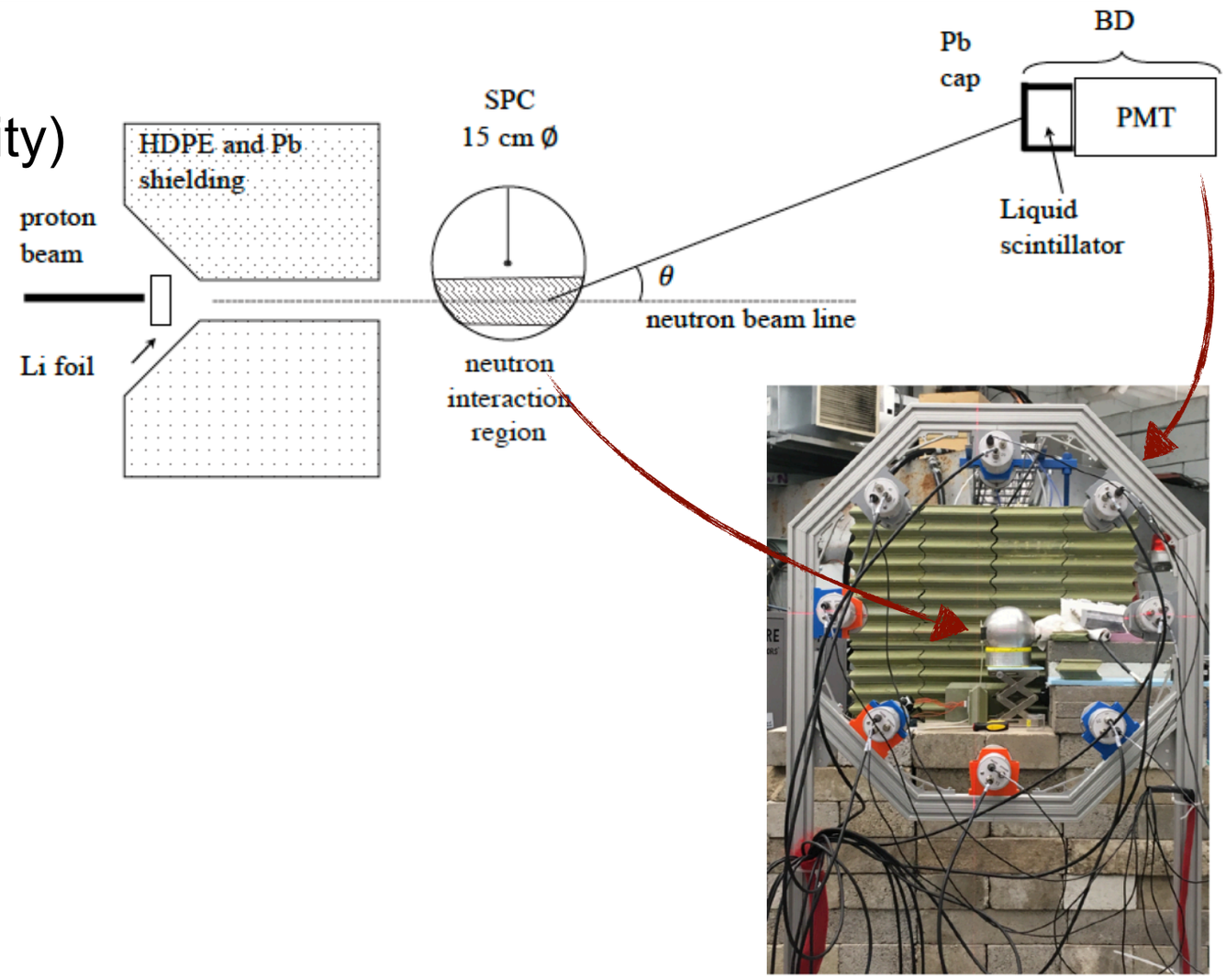


For lighter elements more of the recoil energy turns into detectable signal



Quenching factor measurements: TUNL

- Neutron scattering-induced nuclear recoils
  - Van de Graaff accelerator (Duke University)
  - 20 MeV protons (pulsed) on ^{7}Li
    - (Quasi-)mono-energetic neutrons
    - Calibration using an ^{55}Fe source



PRD 105 (2022) 5, 052004

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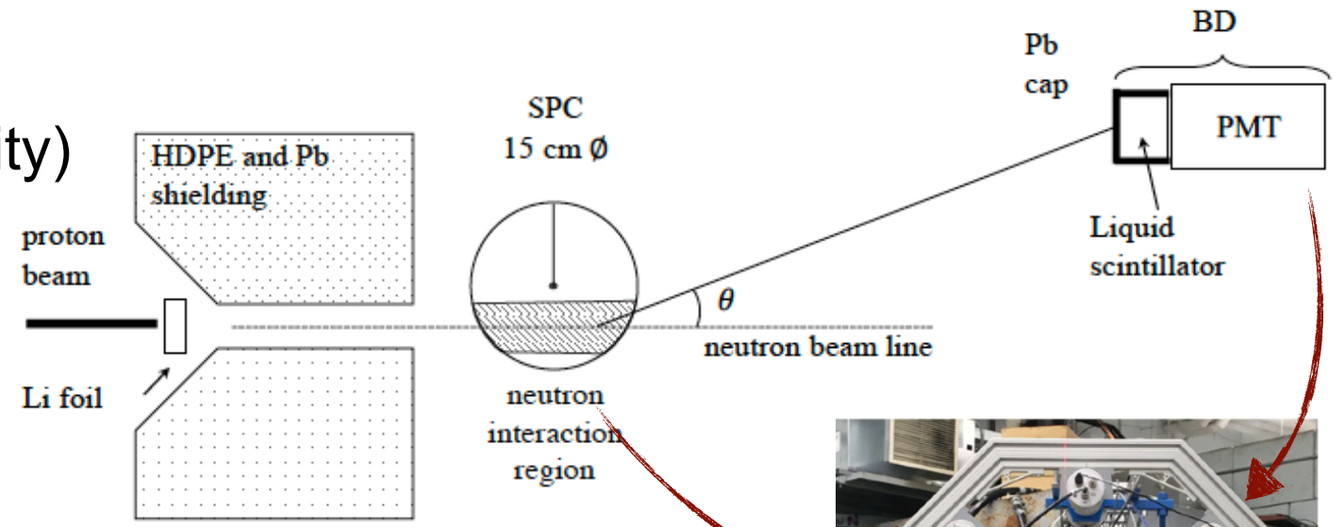

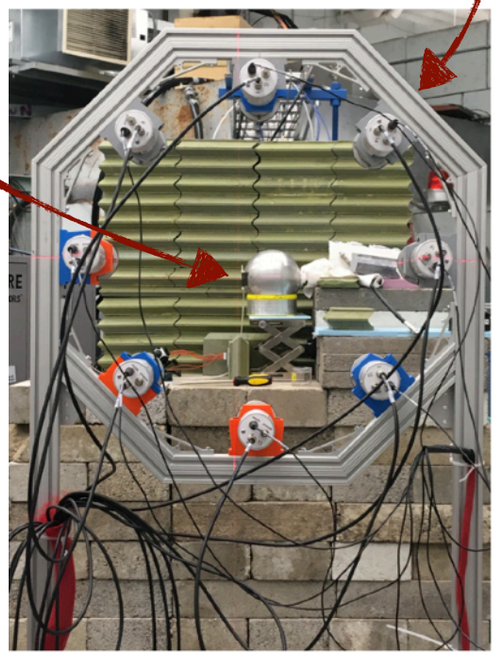

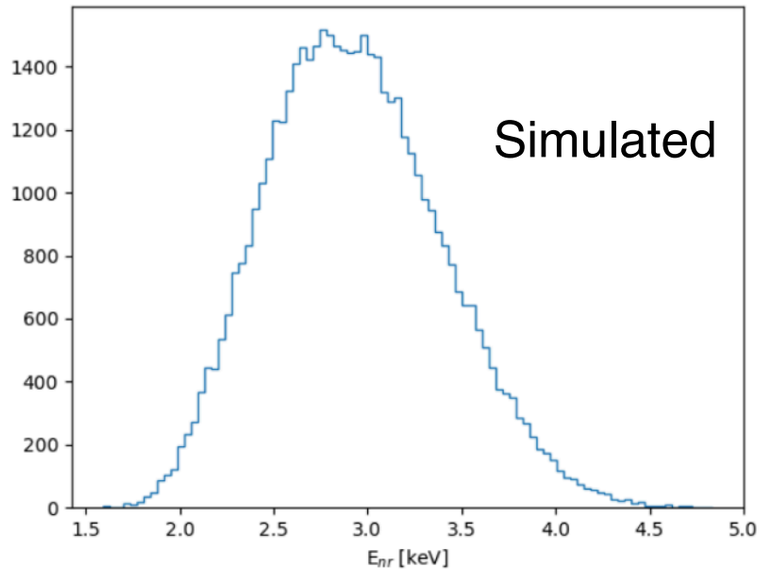

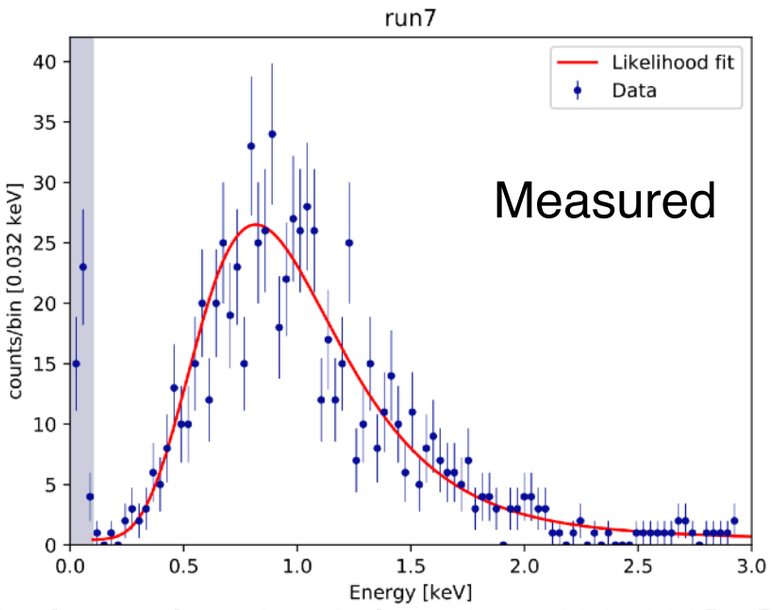

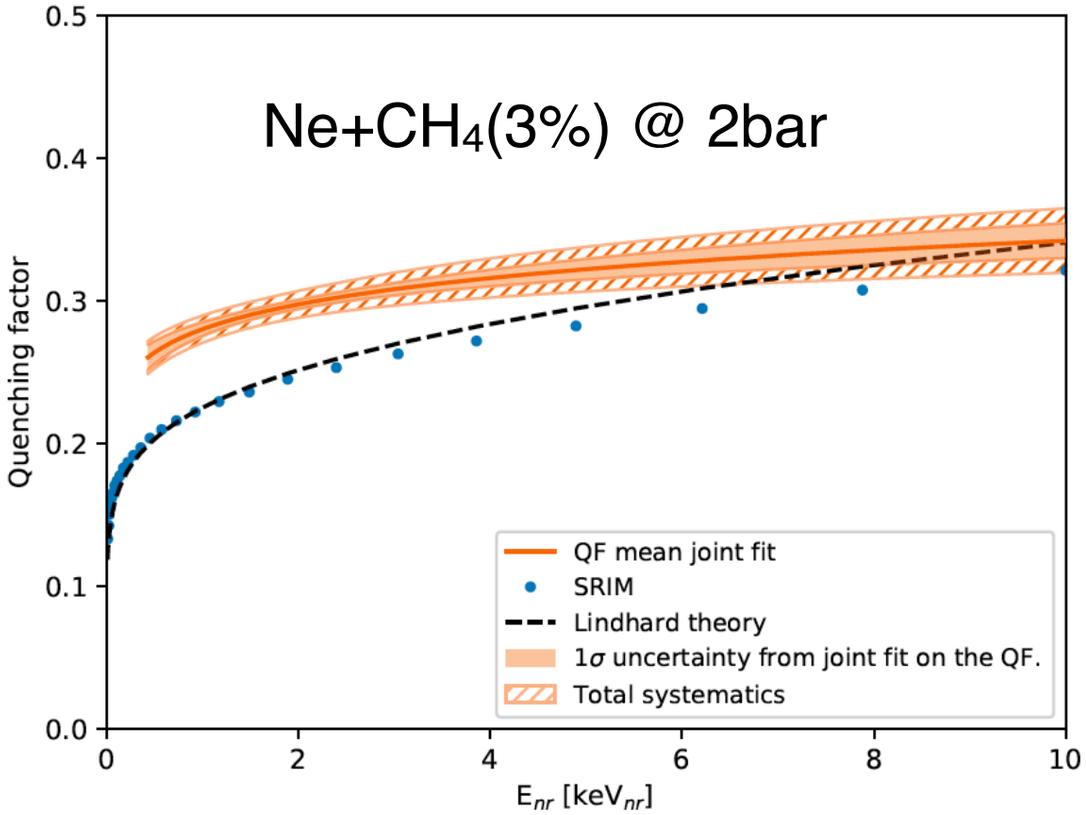

PRD 105 (2022) 5, 052004

Quenching factor measurements: COMIMAC

- Electrons and ions of known kinetic energy
  - Compare detector response
  - Ion energy 2 - 13 keV
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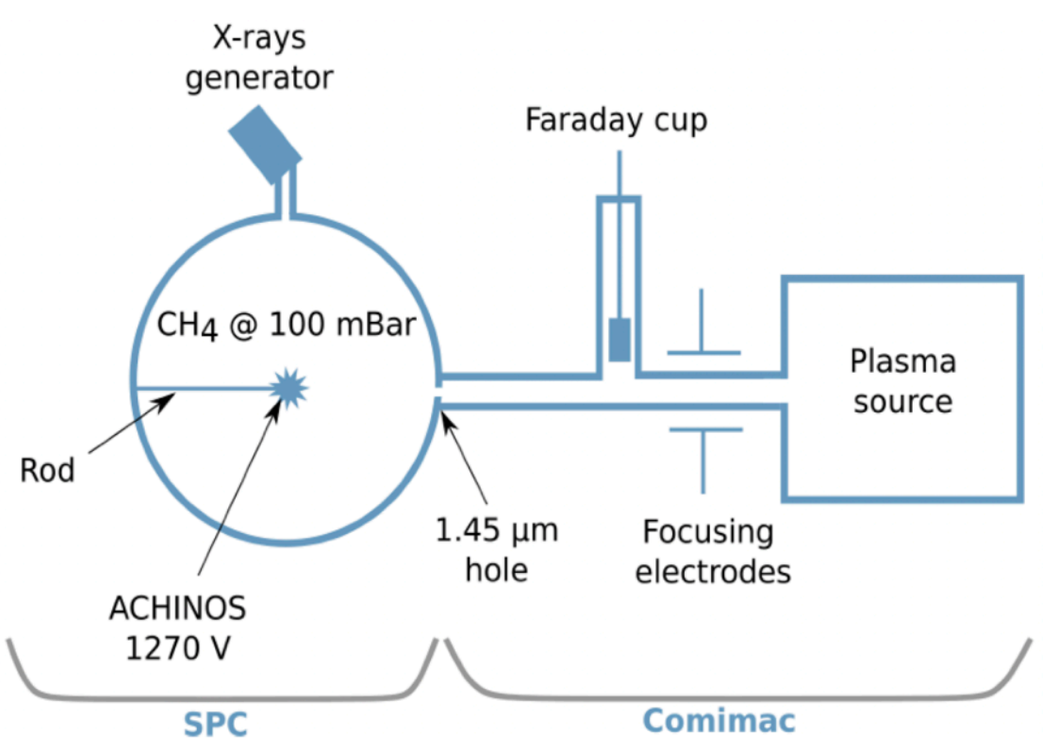

arXiv:2201.09566

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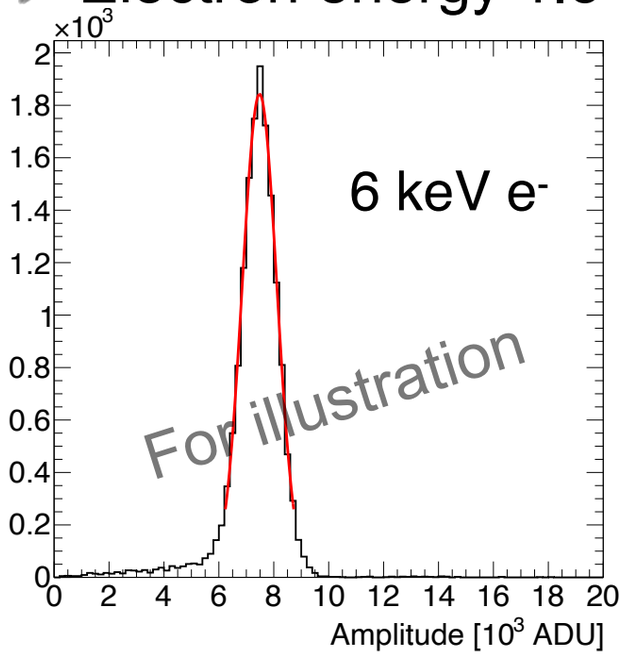

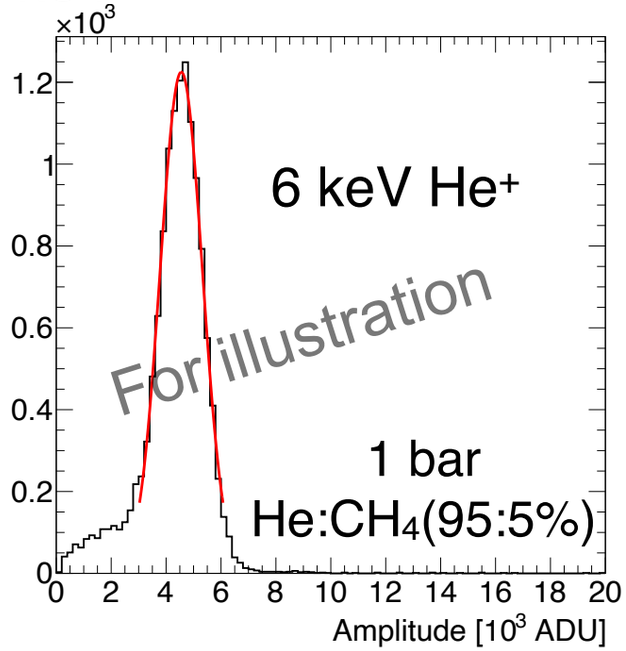

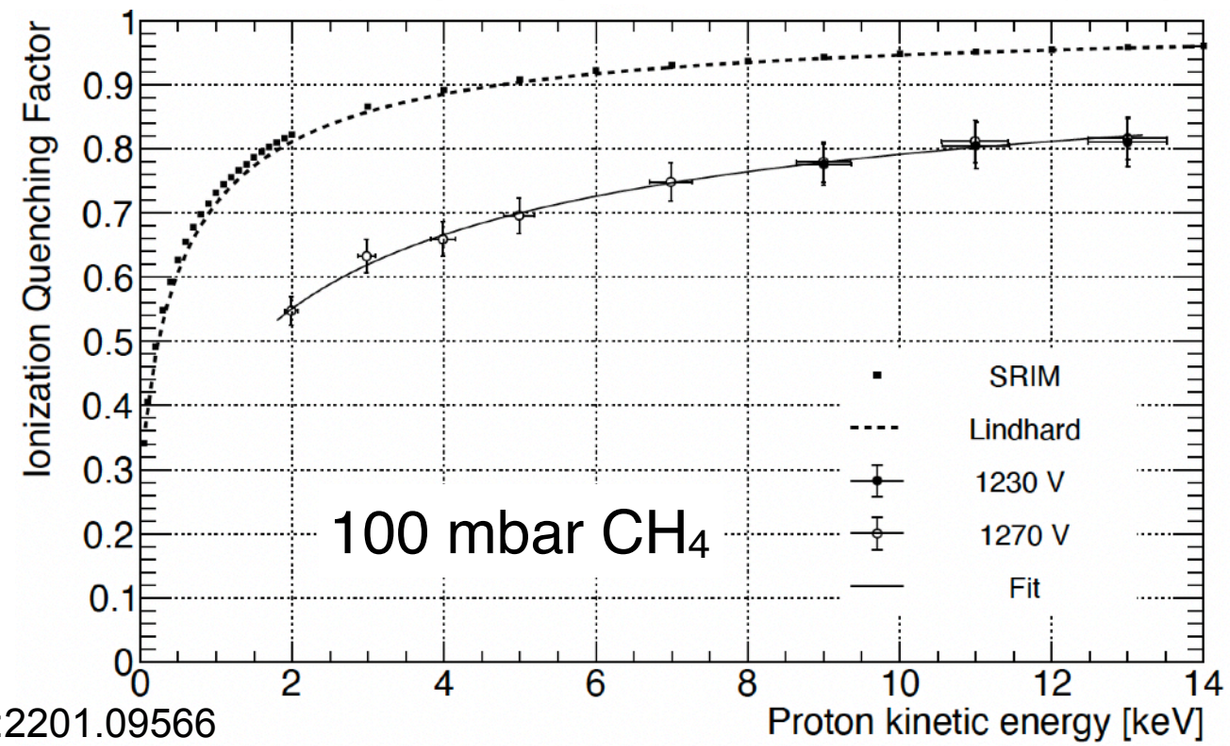

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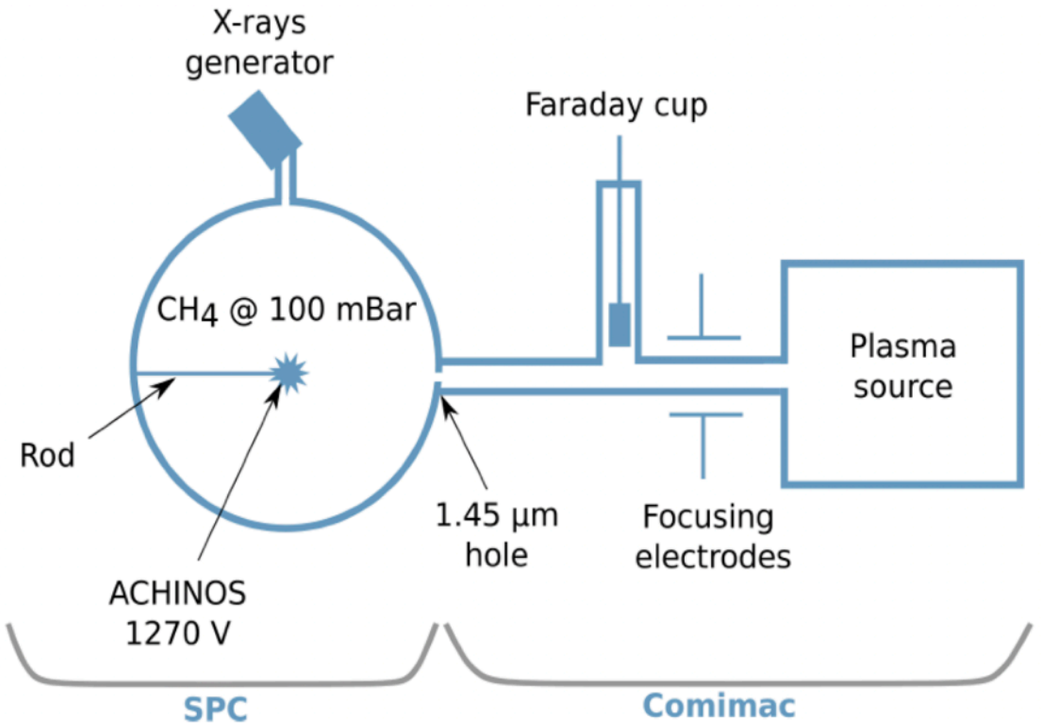

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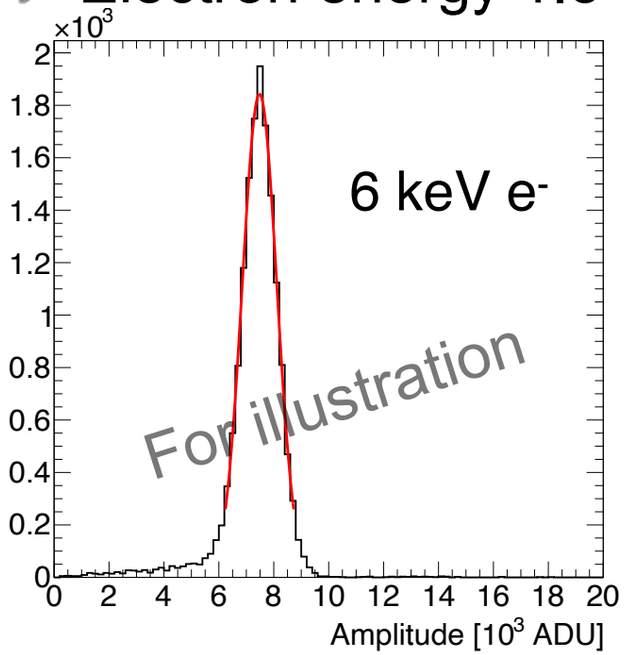

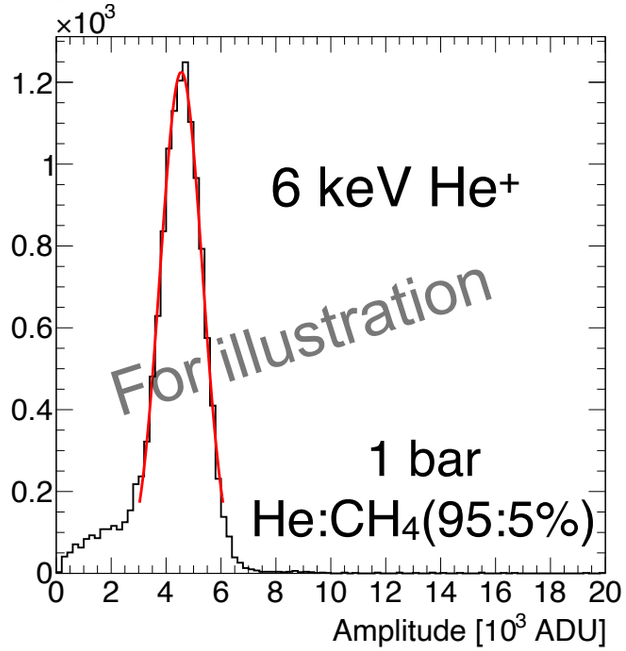

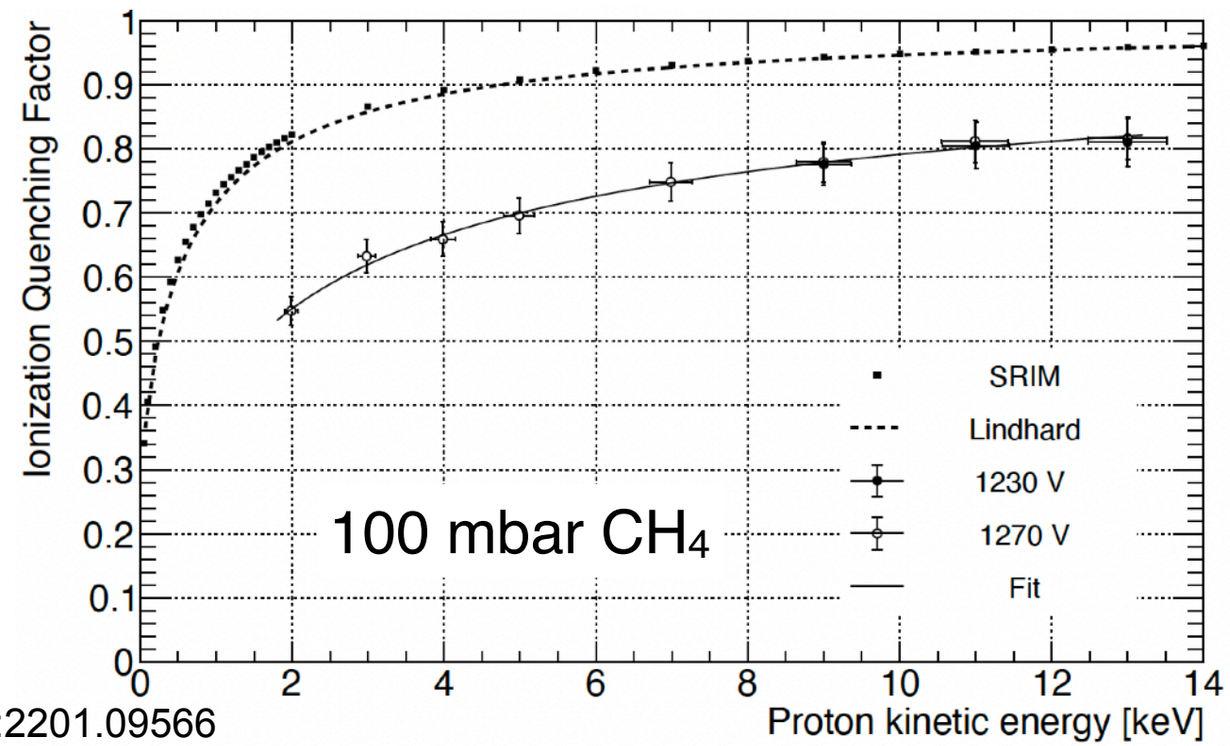

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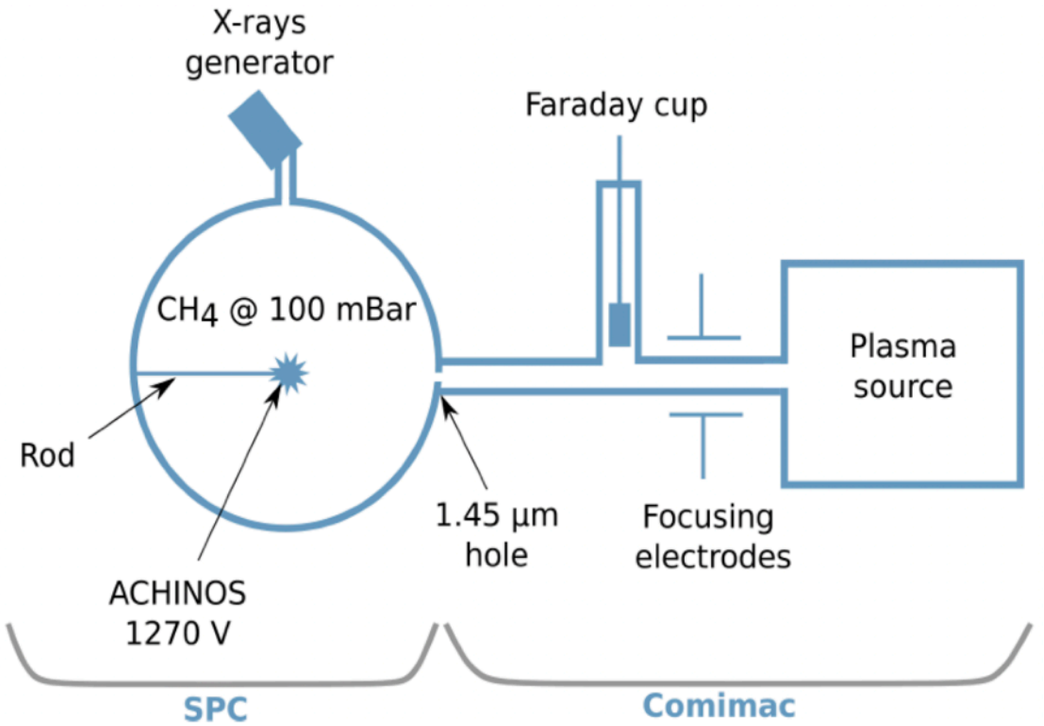
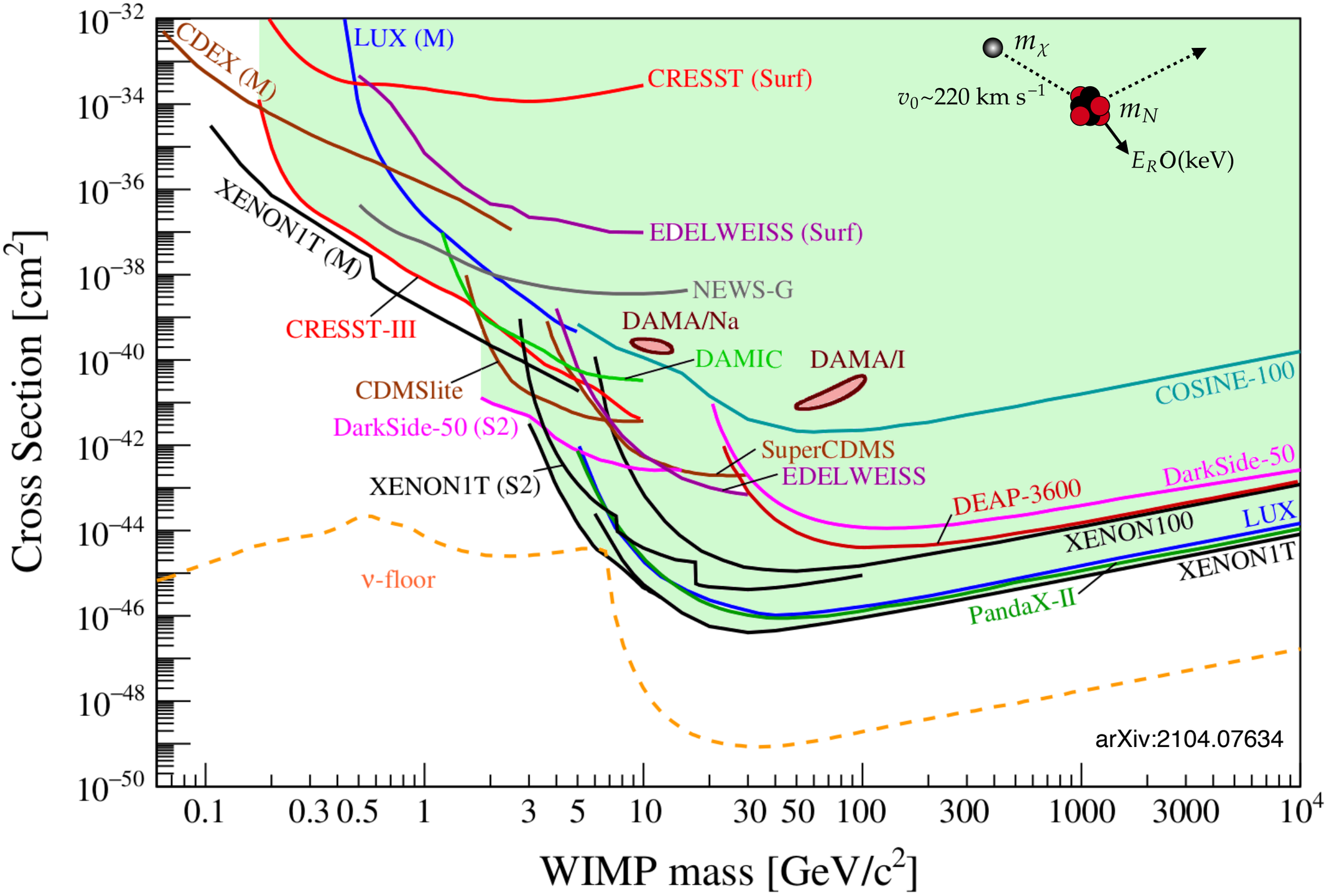


Complementary approach: Quenching factor estimates through W-value measurements

Astropart.Phys. 141 (2022) 102707

Landscape of Direct Detection searches



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

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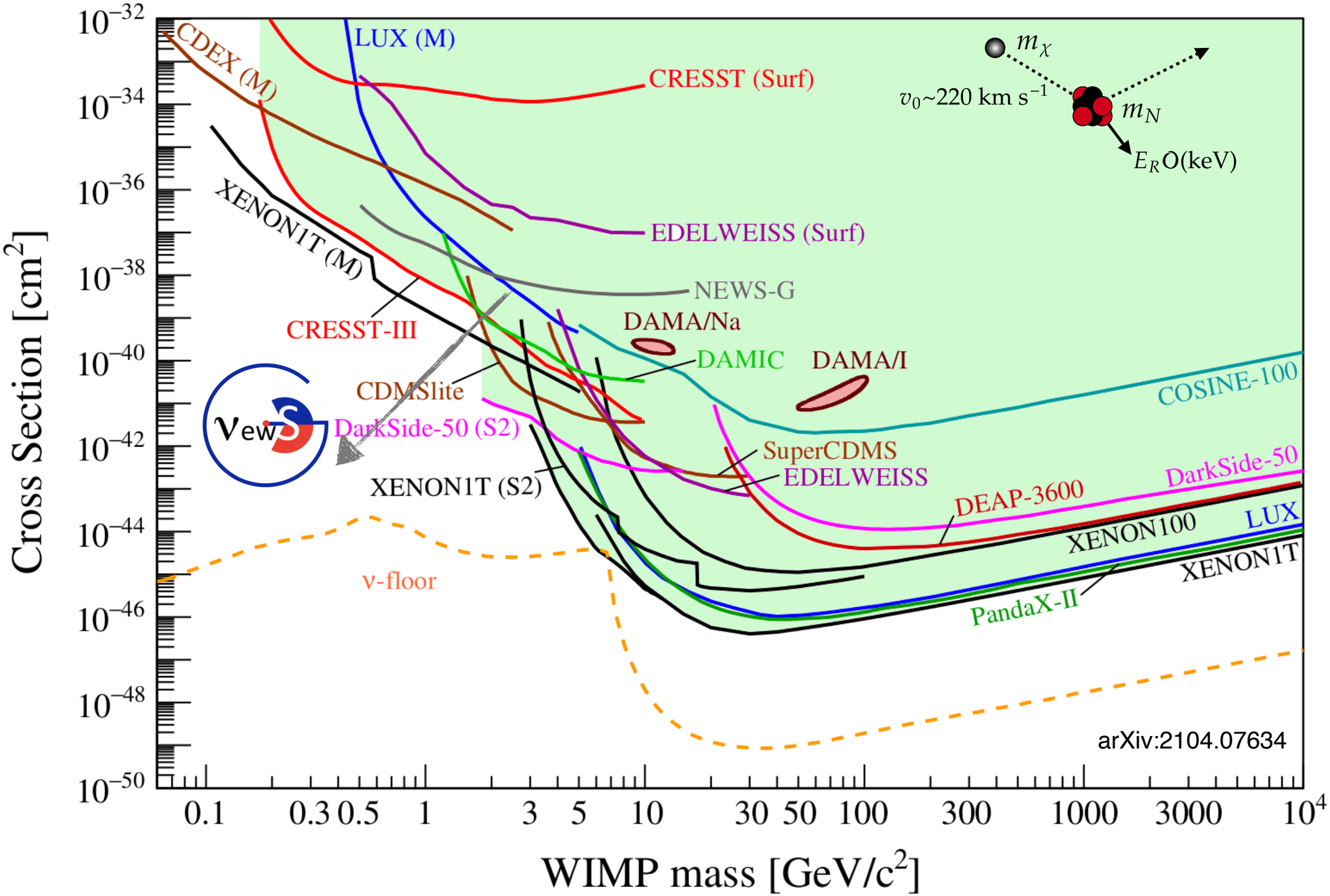

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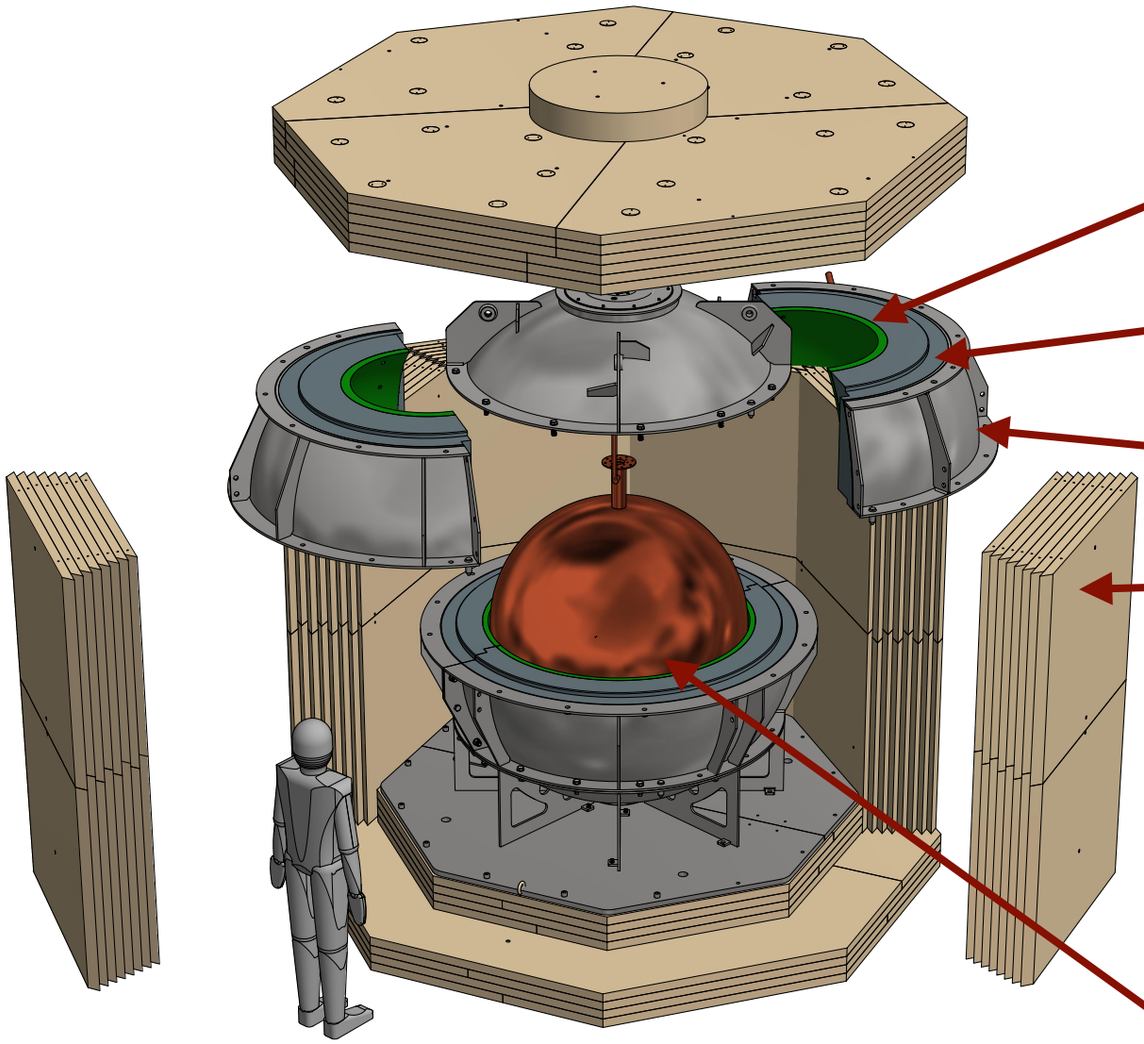
SNOGLOBE: ø140 cm detector



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)
Ultra-pure electroplated inner layer

Sensor read-out

Single anode: Drift and Amplification fields connected

$$E = \frac{V_a}{r^2}\frac{r_a r_c}{r_c - r_a} \approx \frac{V_a r_a}{r^2}$$

Simulation:JINST 15 (2020) 06, C06013

Sensor read-out

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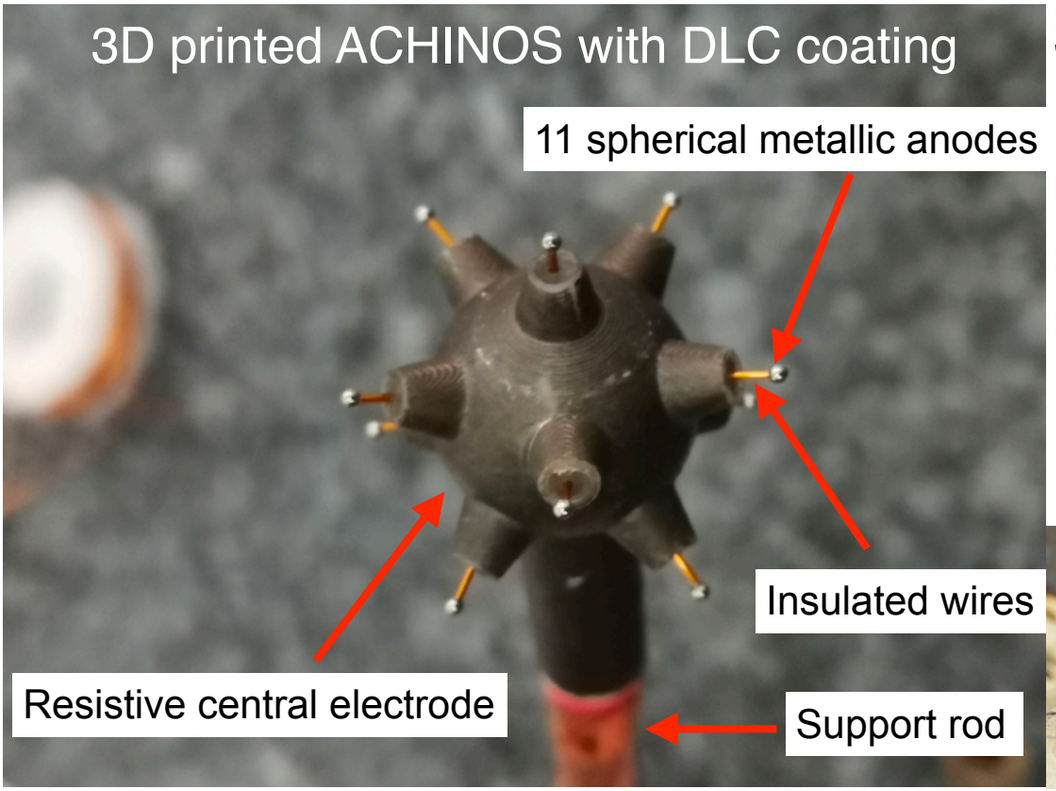
- ACHINOS: Multi-anode sensor JINST 12 (2017) 12, P12031
  - Multiple anodes placed at equal radii
  - Decoupling drift and amplification fields
  - Opportunity: individual anode read-out

Simulation:JINST 15 (2020) 06, C06013

Sensor read-out



JINST 15 (2020) 11, 11

Single anode: Drift and Amplification fields connected

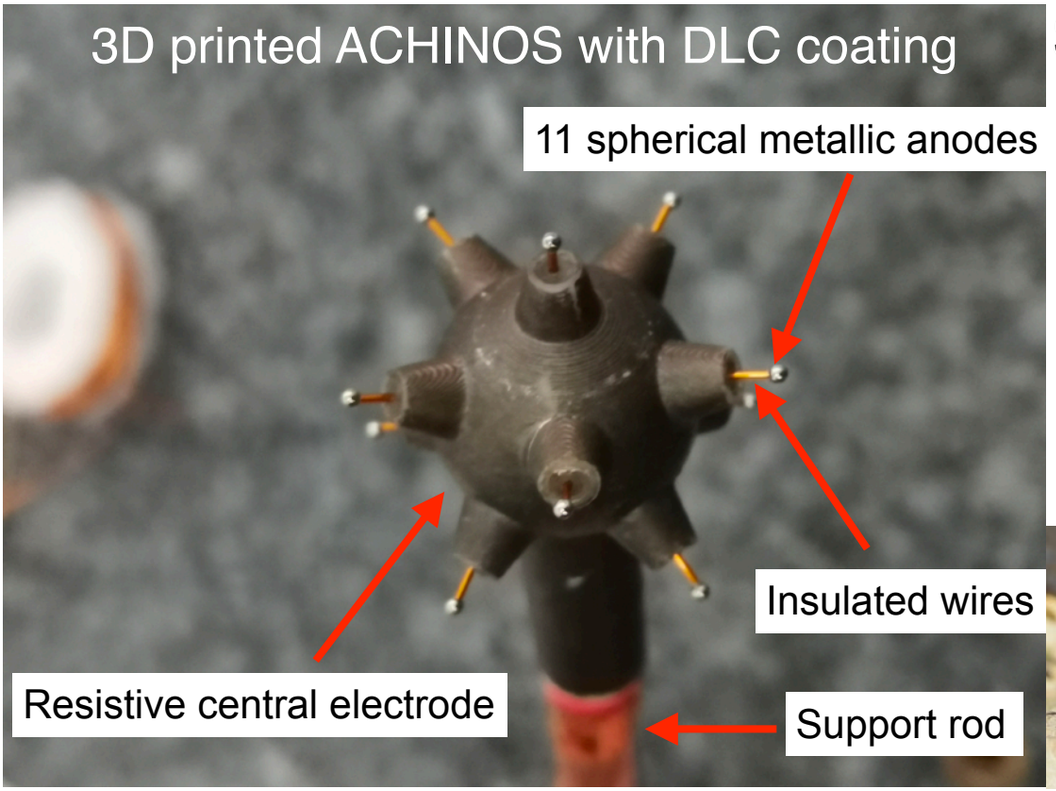
$$E = \frac{V_a}{r^2}\frac{r_a r_c}{r_c - r_a} \approx \frac{V_a r_a}{r^2}$$

- ACHINOS: Multi-anode sensor JINST 12 (2017) 12, P12031
  - Multiple anodes placed at equal radii
  - Decoupling drift and amplification fields
  - Opportunity: individual anode read-out

Αχινός (EL: sea urchin)

Simulation:JINST 15 (2020) 06, C06013

Sensor read-out



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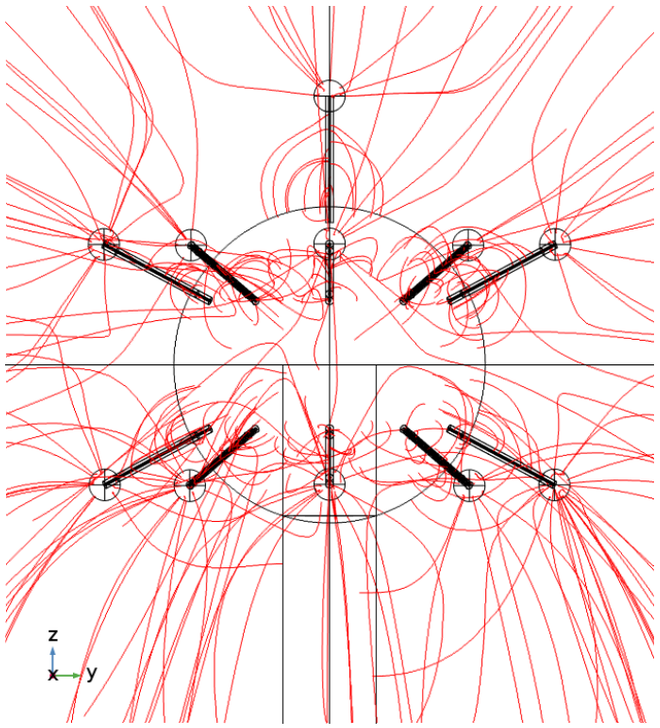
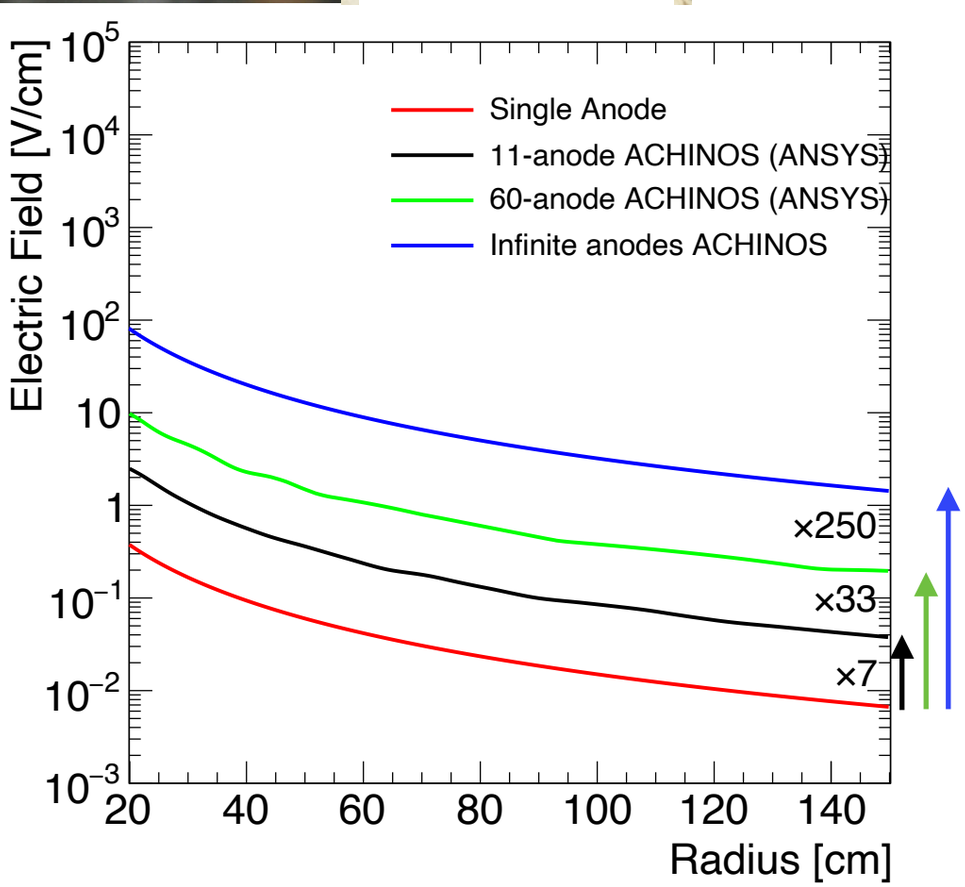
JINST 15 (2020) 11, 11





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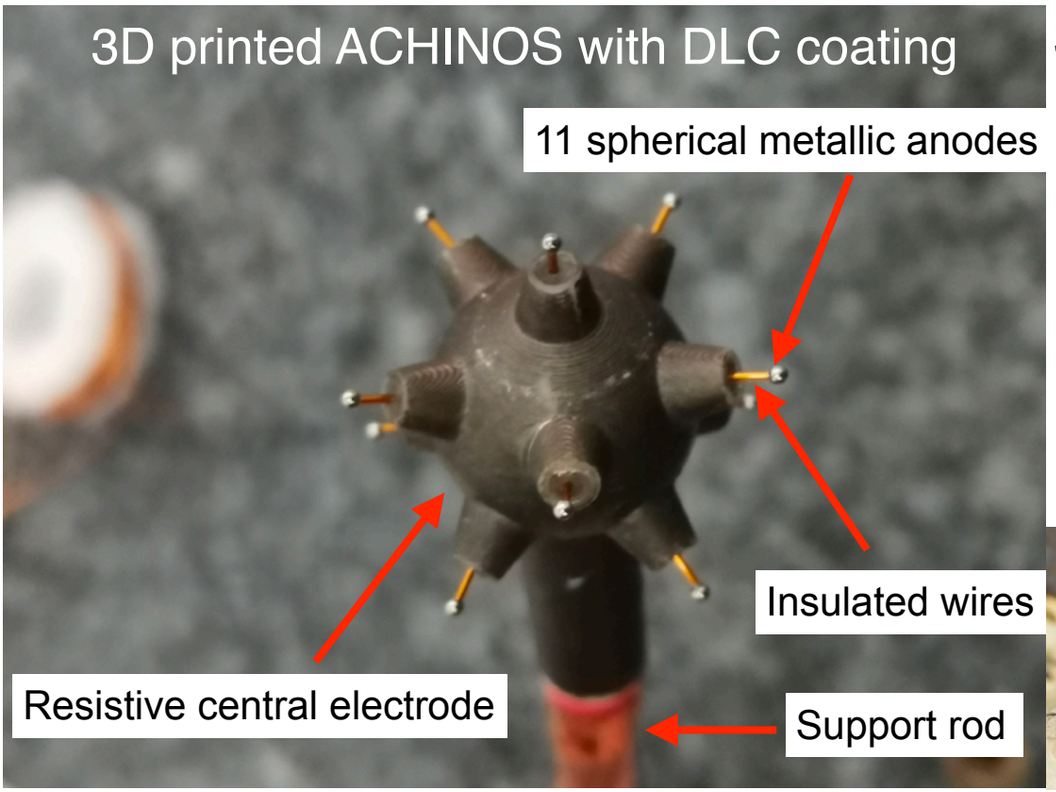

JINST 15 (2020) 11, 11

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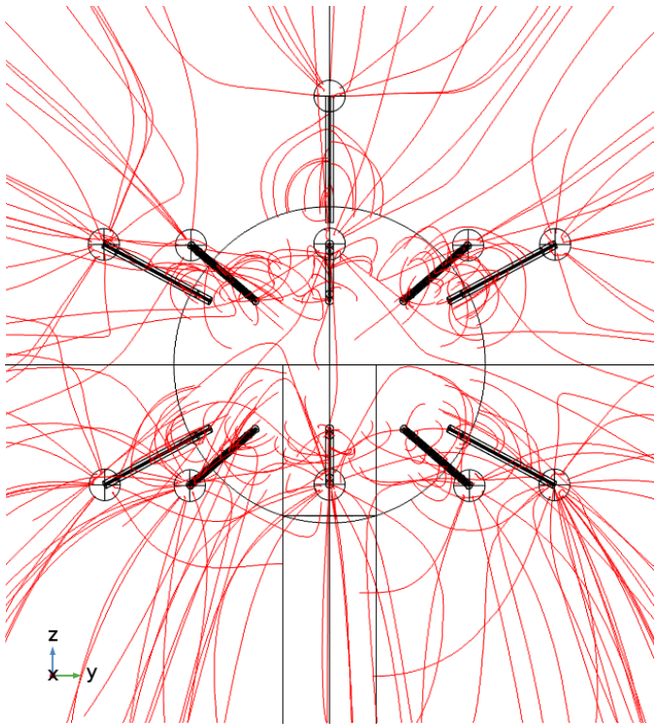
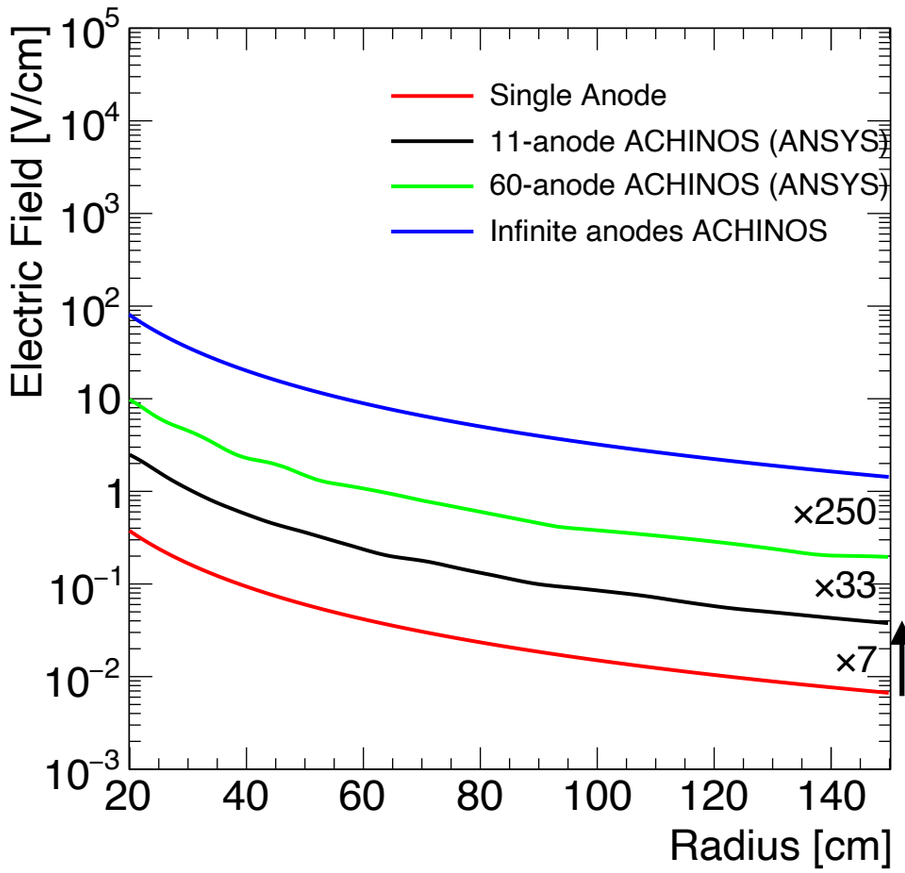
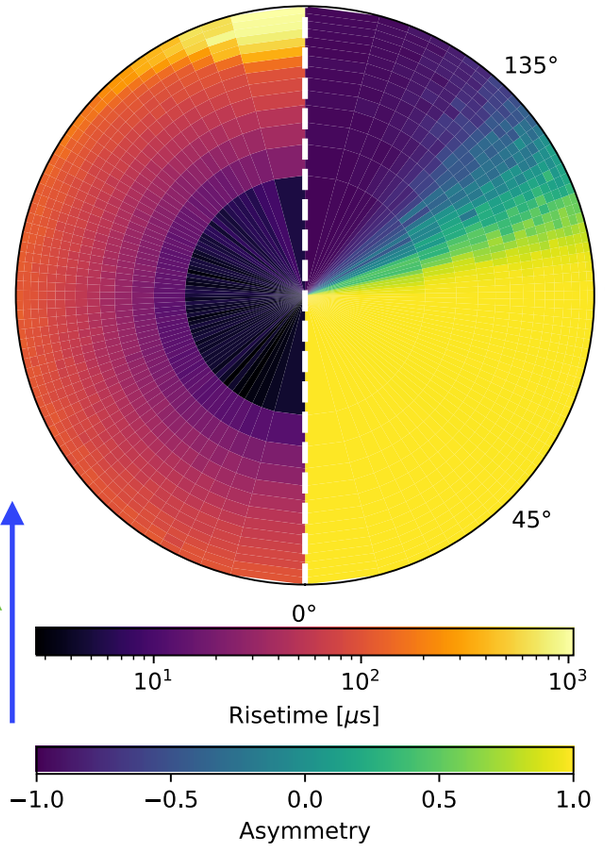
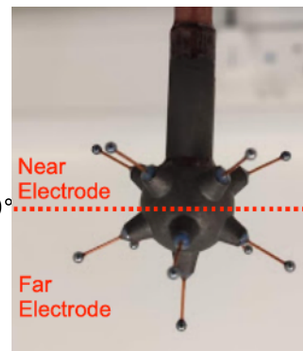






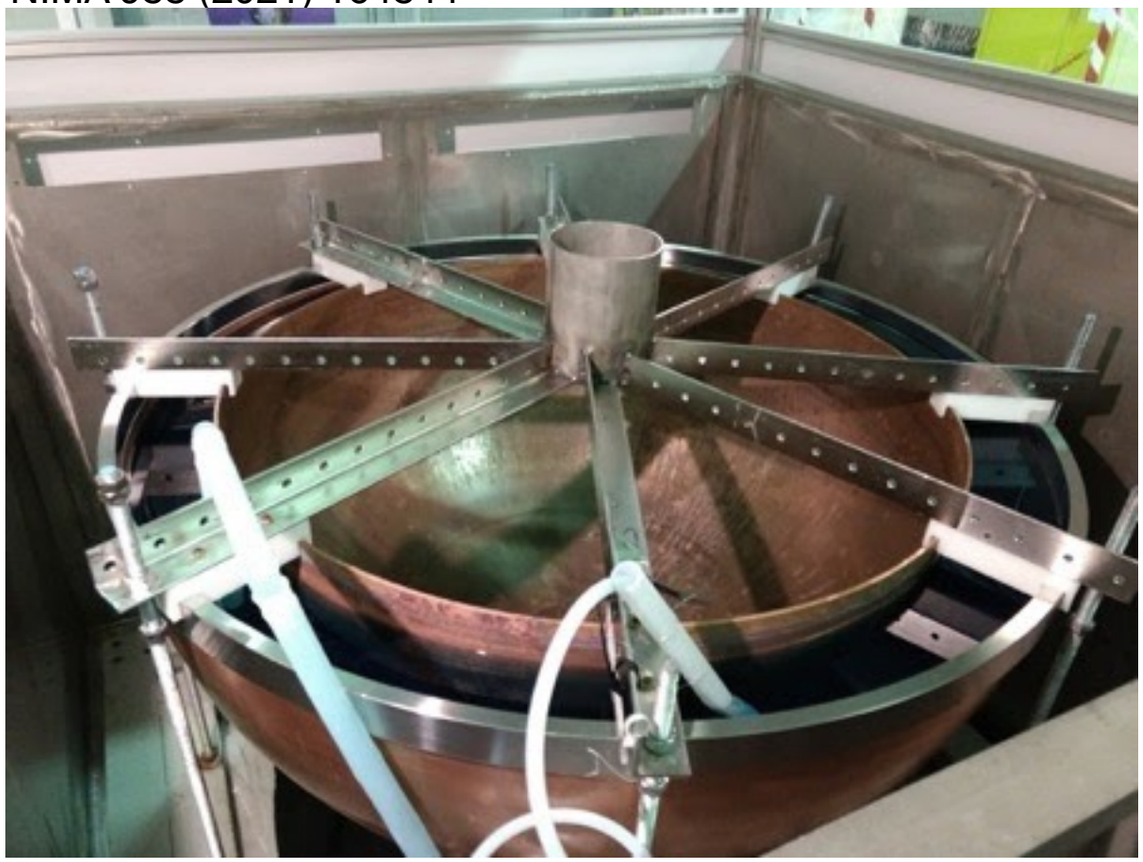


Simulation:JINST 15 (2020) 06, C06013

SNOGLOBE at LSM

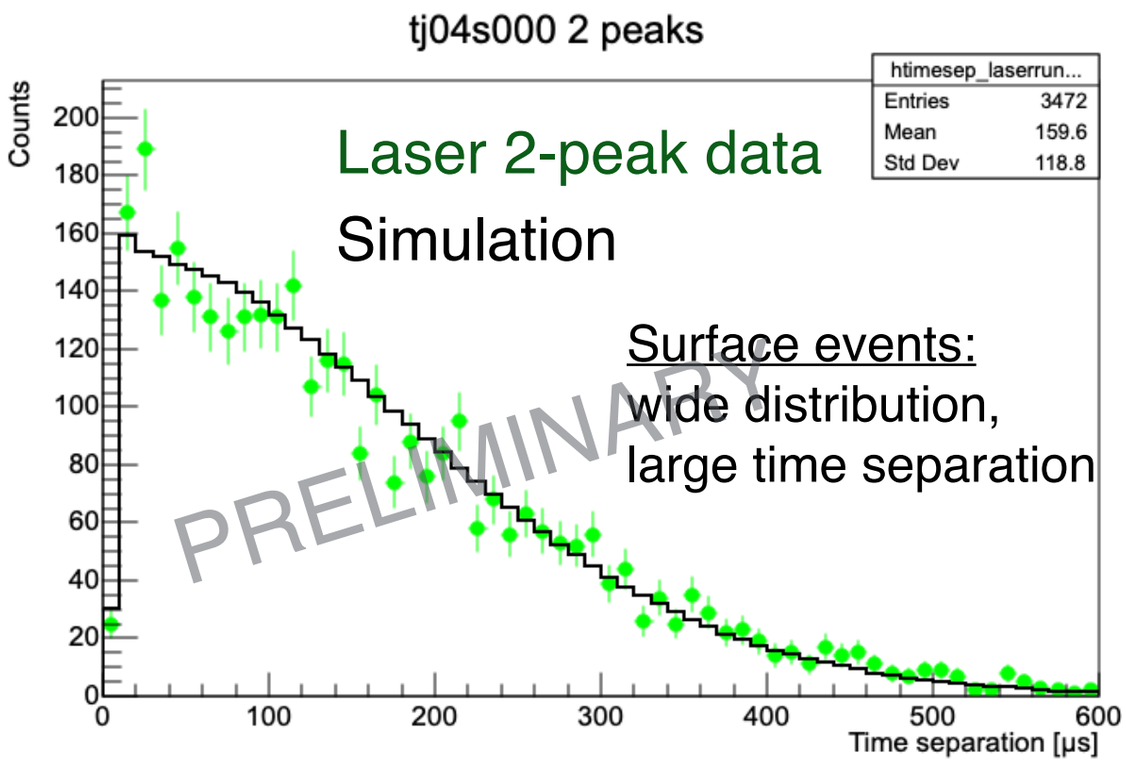
- 2019: detector assembly in France
  - Hemispheres e-beam welded
  - 500 µm electroformed inner layer
- April 2019: initial commissioning at LSM
  - UV laser and ^{37}Ar calibration
  - Multi-anode sensor
- July 2019: Pb and H_2O shield installed
  - ~10 days of physics data
  - 135 mbar of CH_4 (~100g)

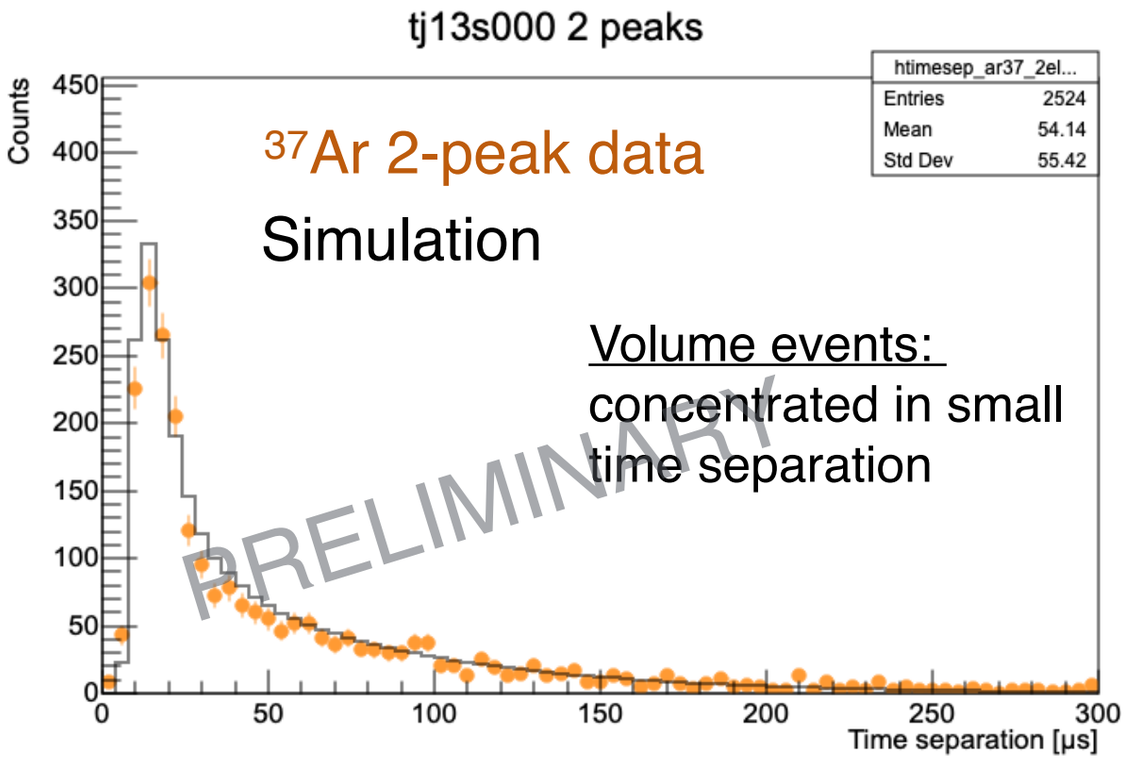
NIMA 988 (2021) 164844



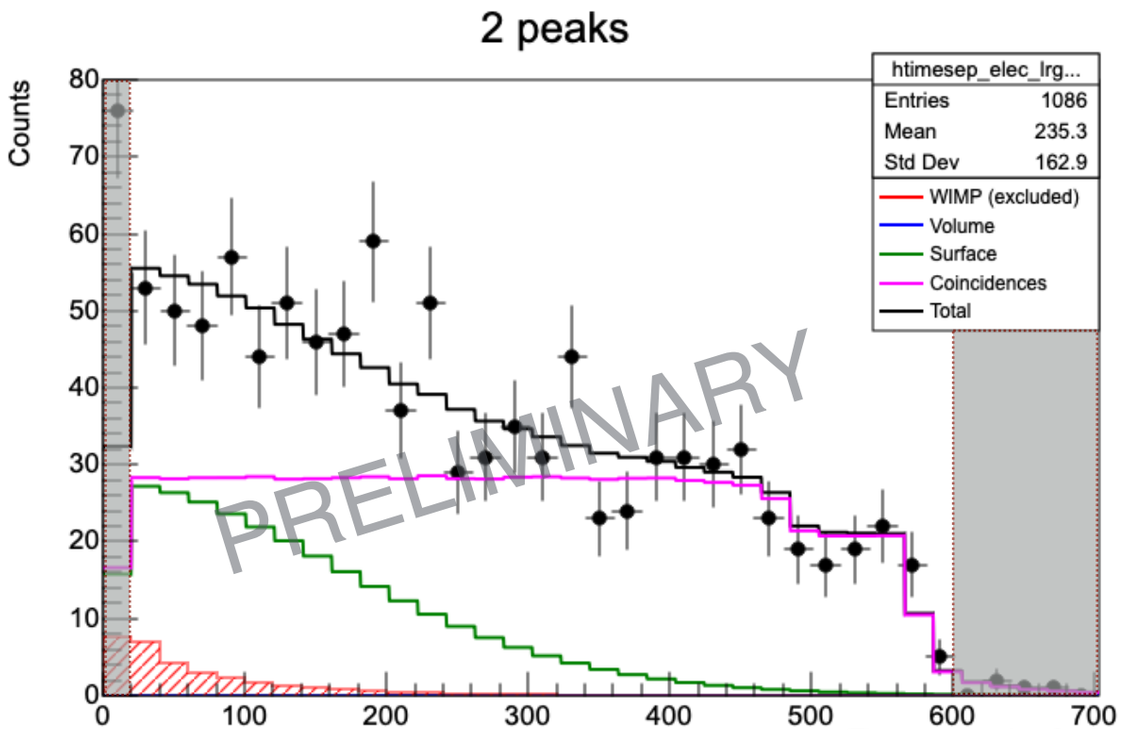
Electron Counting

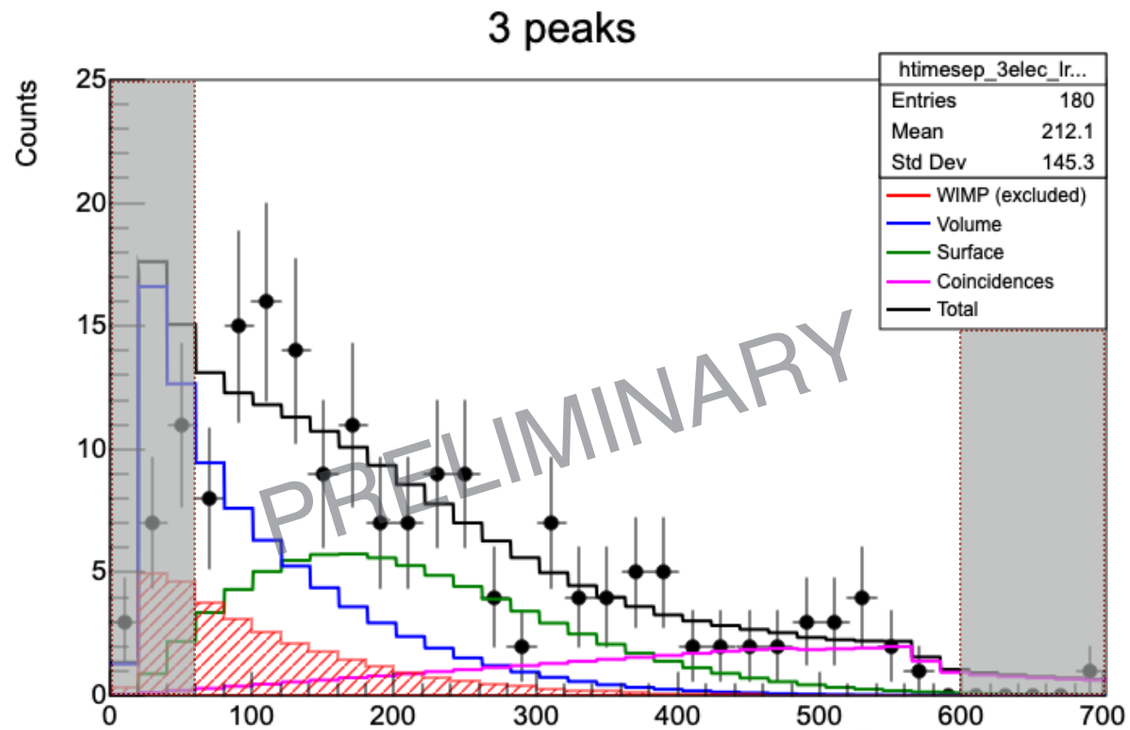
- Pulse treatment (deconvolution)
  - Resolve individual electrons
- Diffusion O(100µs)
  - Obtain time separation of peaks
  - Surface vs volume discrimination
- Signal and background model
  - Derived from simulations
  - Validated with calibration data



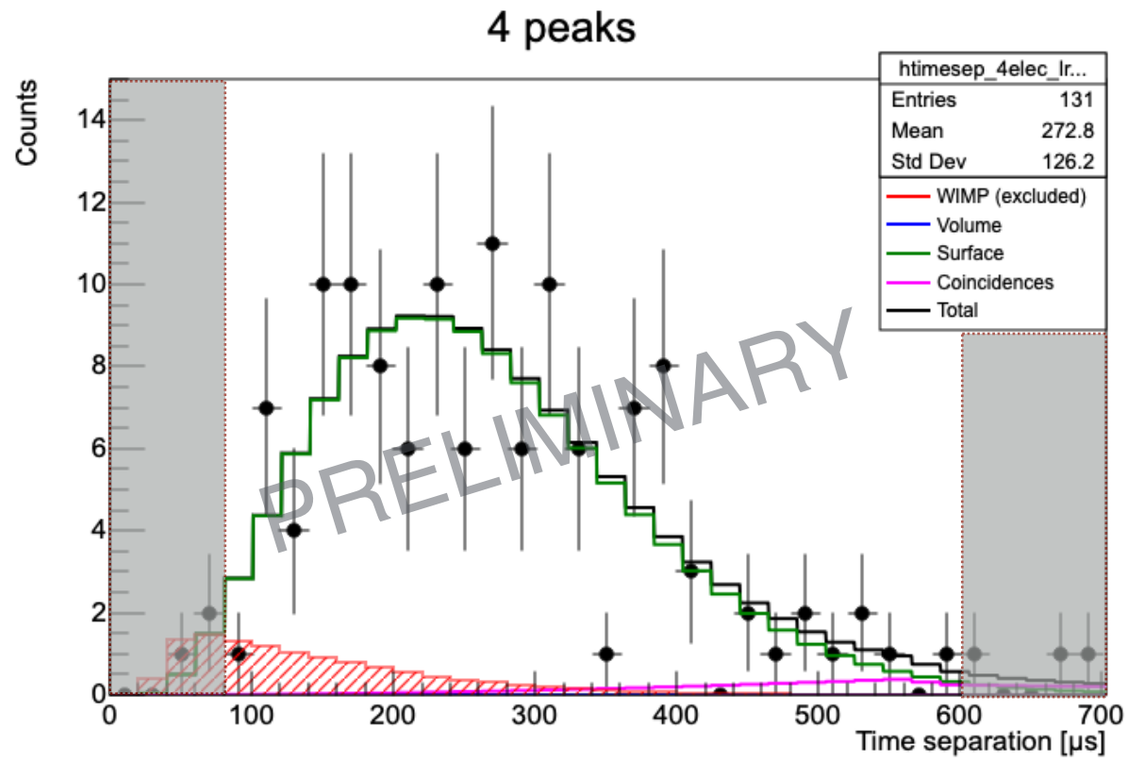


Results with LSM data

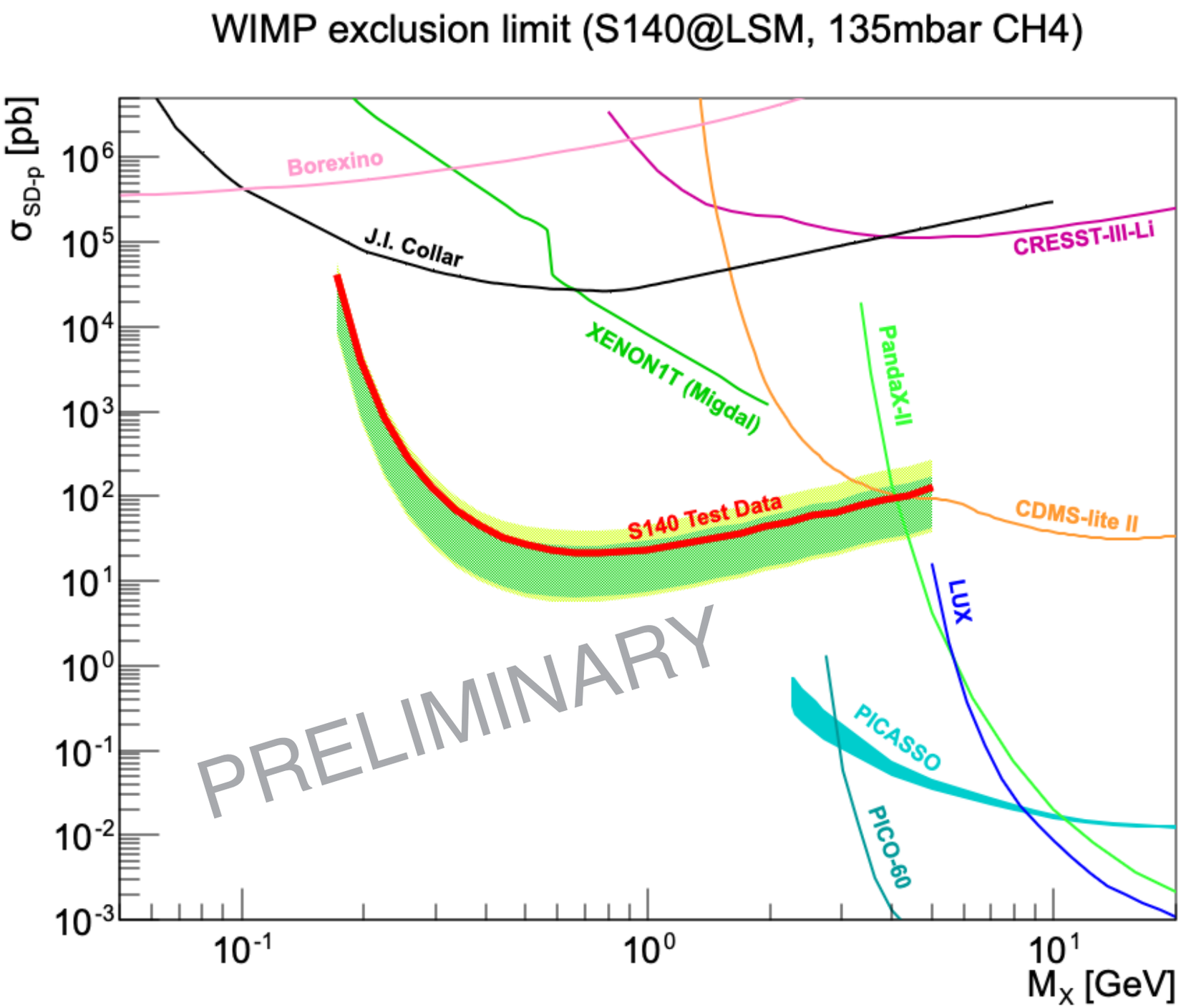




- Data divided into 2/3/4 peak
- Maximum likelihood fit to time separation
- Only test data analysed so far: ~30% data
  - Remaining data is blinded



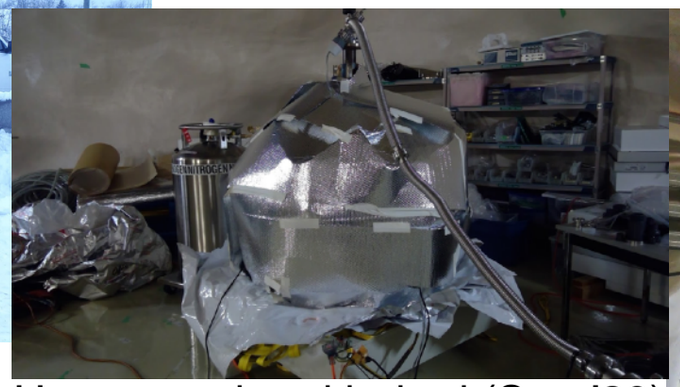
LSM Physics Result



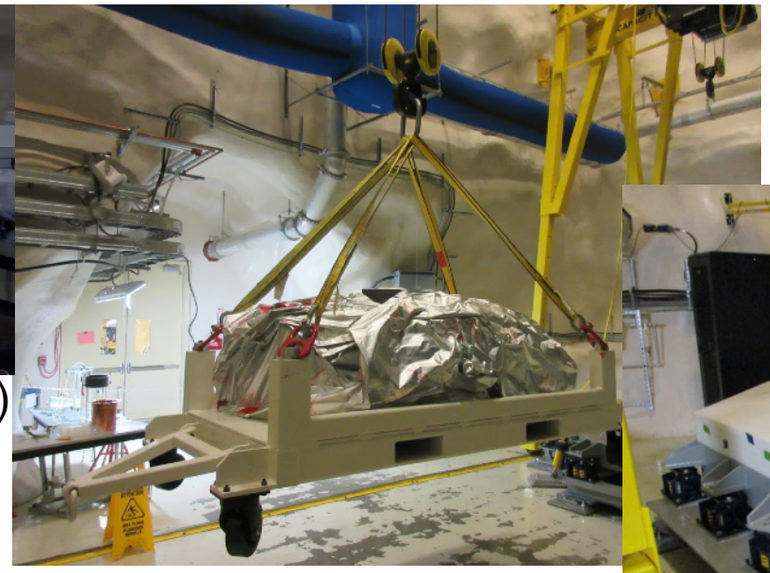
- 90% upper limits set with profile likelihood ratio
- Exposure 0.12 kg·days

Installation at SNOLAB

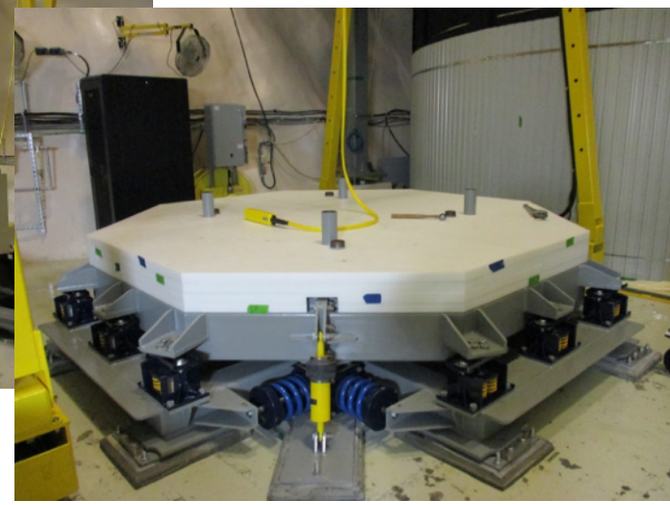
Arrival at SNOLab (Dec ’19)



Unwrapped and baked (Sep ’20)

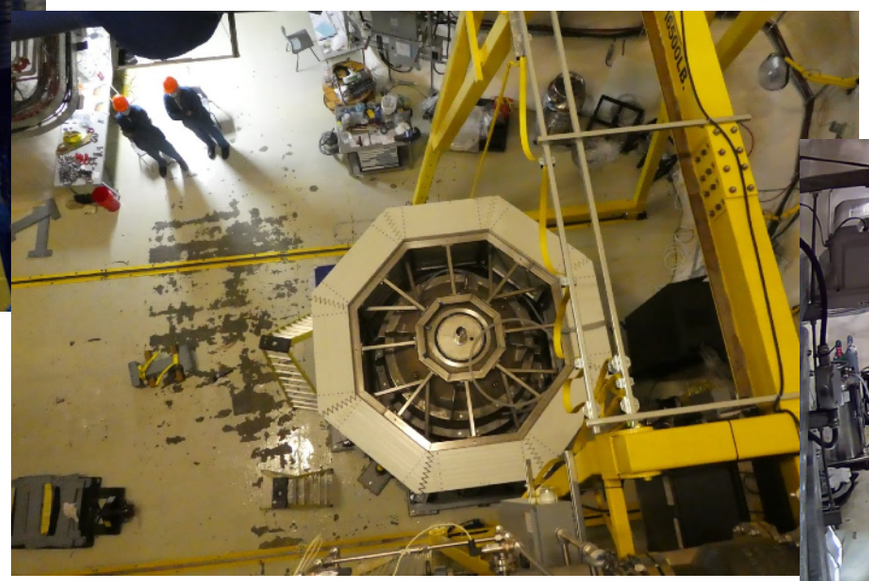


Pb shielding arrival



Seismic platform installation

Detector Installation

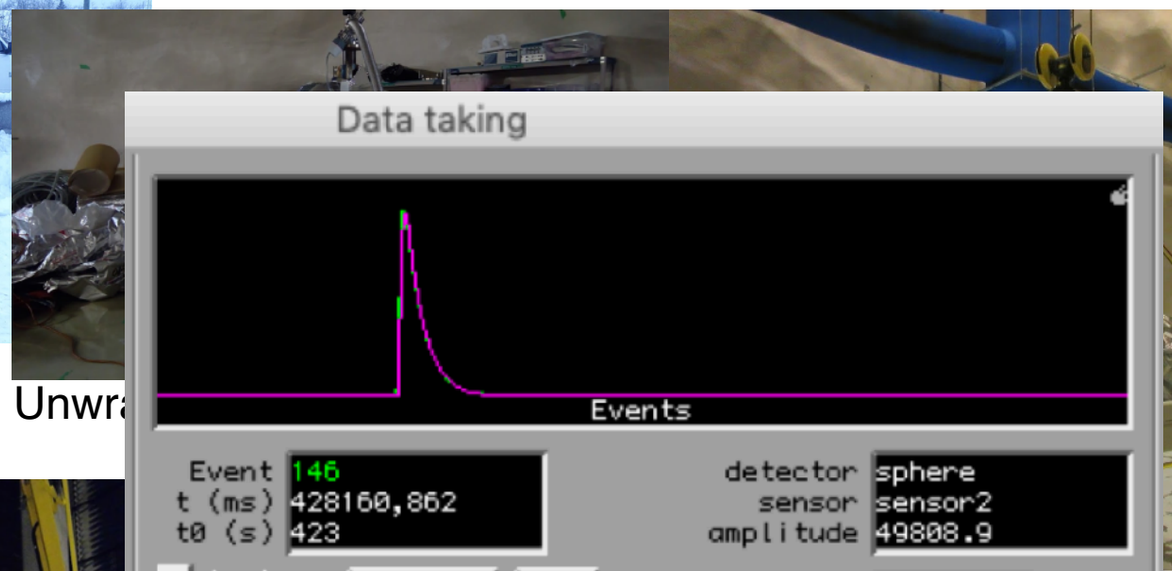


PE shielding installation

SNOGLOBE complete (Dec ’20)

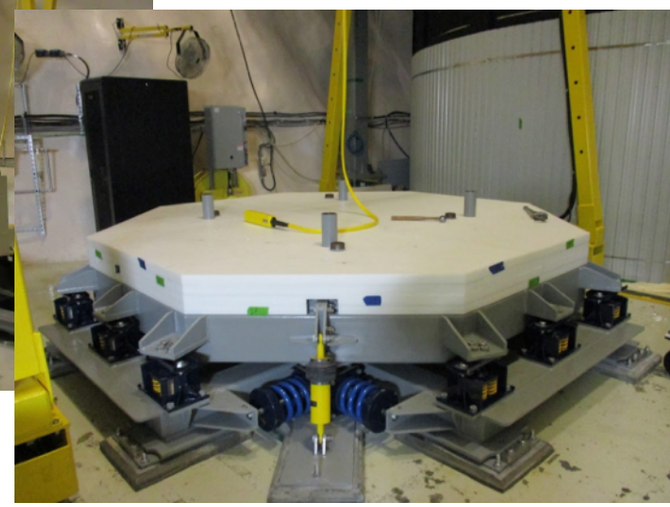
Installation at SNOLAB

Arrival at SNOLab (Dec ’19)

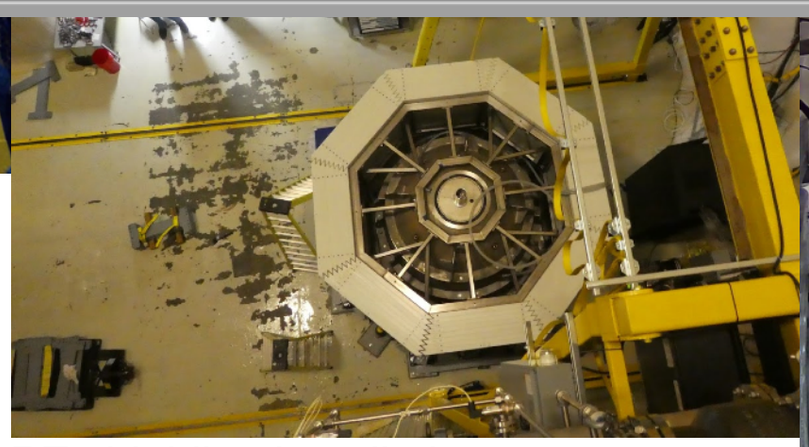


Unwra

Detector Installation



Seismic platform installation



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Arrival at SNOLab (Dec ’19)

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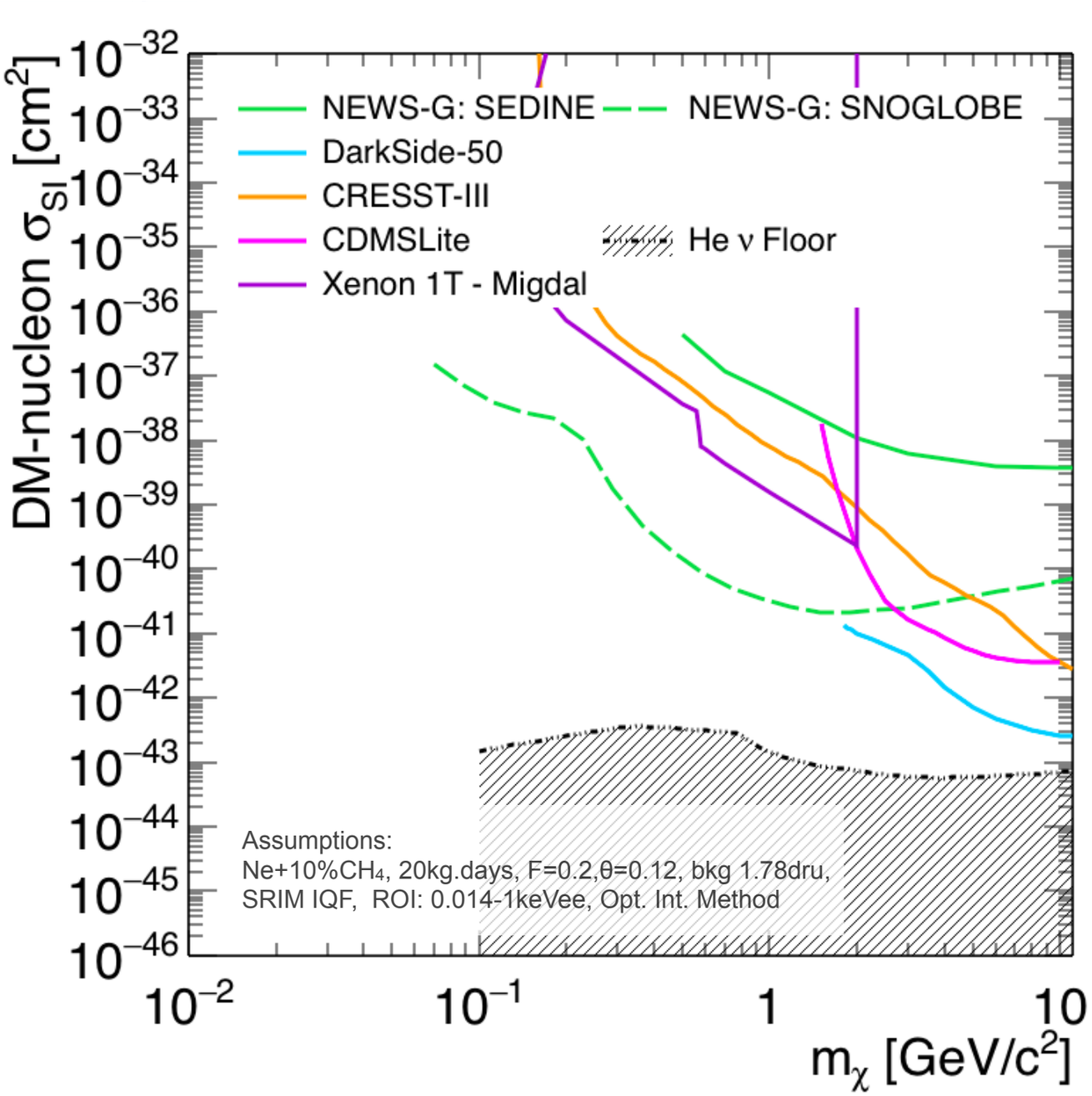

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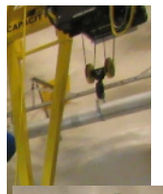
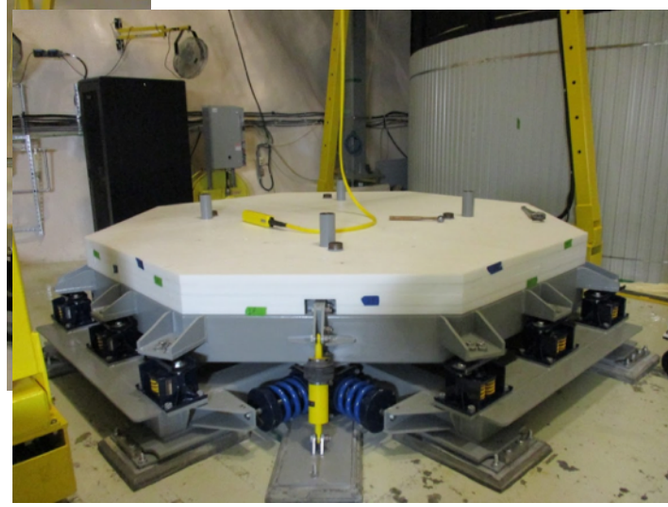
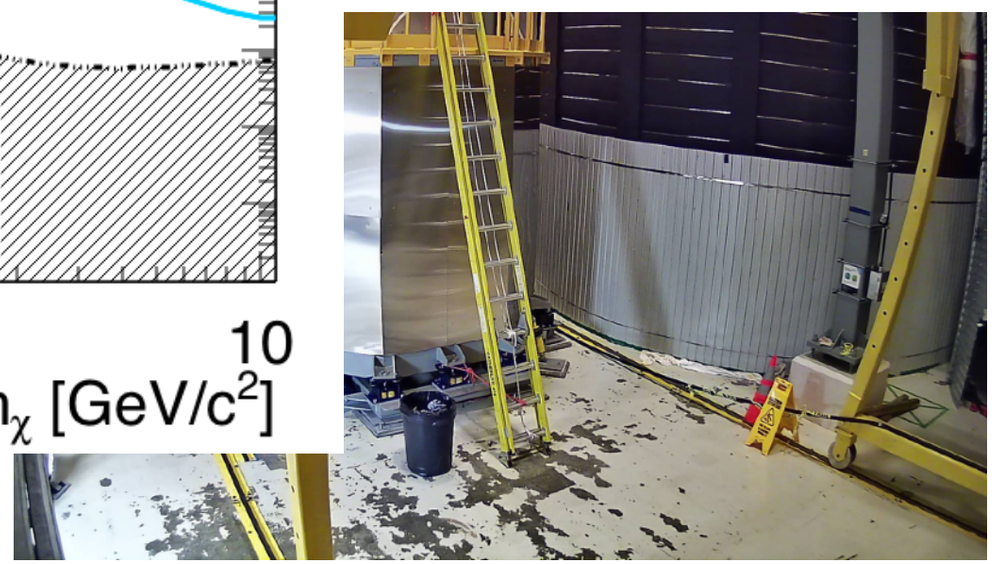


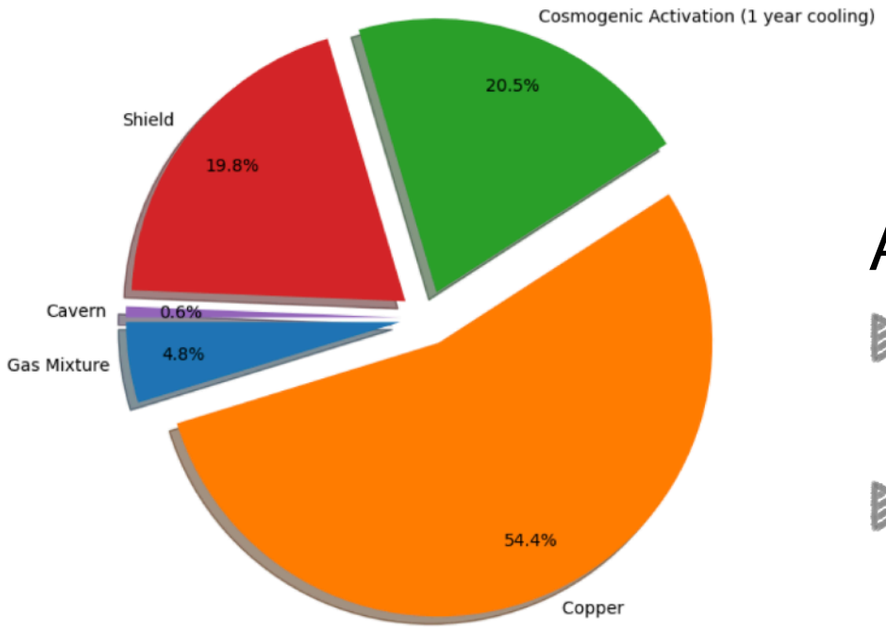


Seismic platform installation



SNOGLOBE complete (Dec ’20)

Electroformed Cuprum Manufacturing Experiment

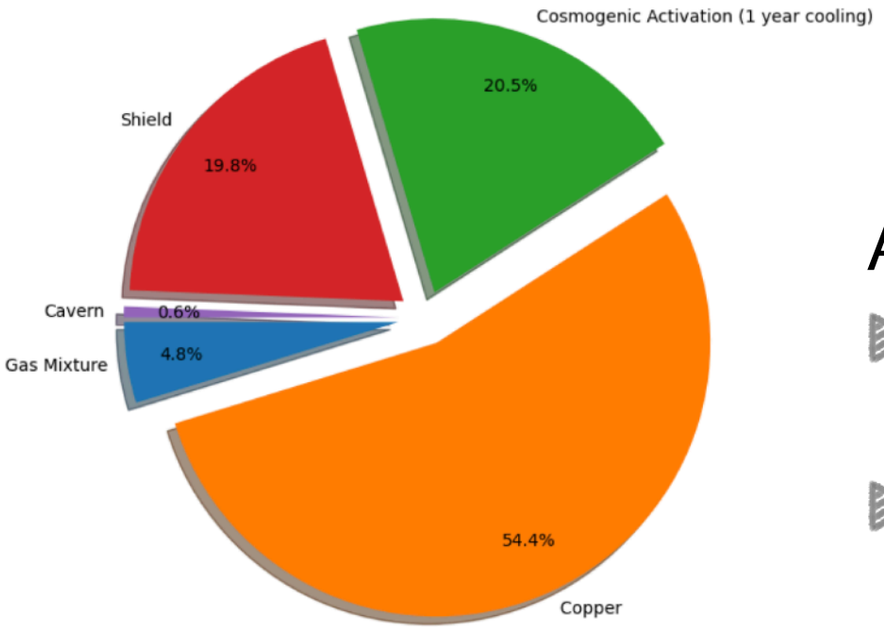


ECuME

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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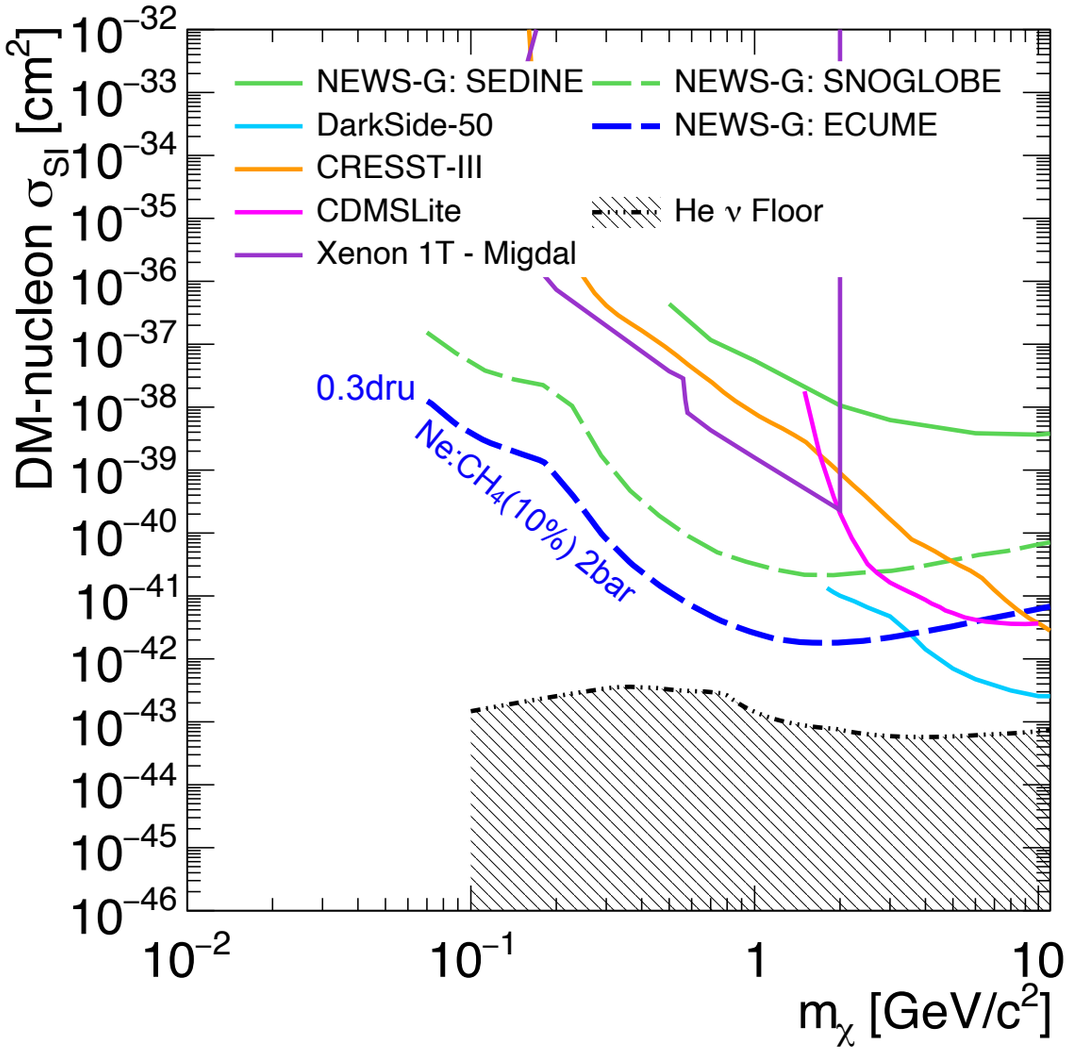
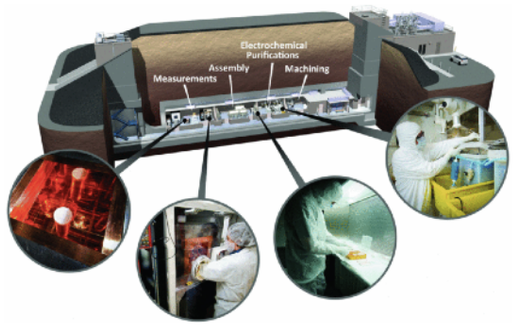


Current Status

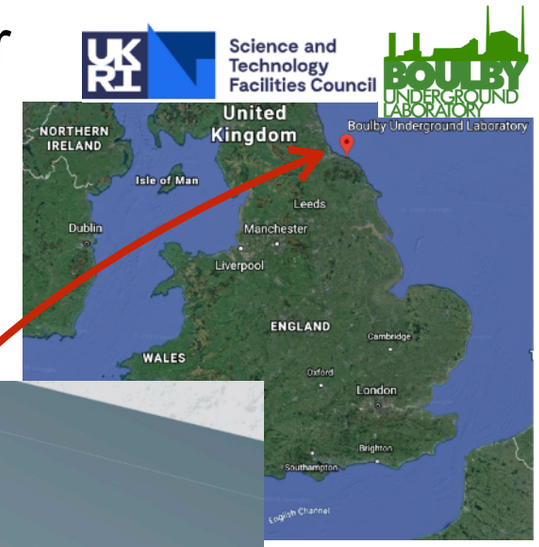
- ⌀30 cm scale prototype to be produced at PNNL
  - Bath designed and assembled
  - Initial electroformation tests undertaken
- ⌀140 cm detector to follow shortly after
  - Use existing shielding for physics exploitation

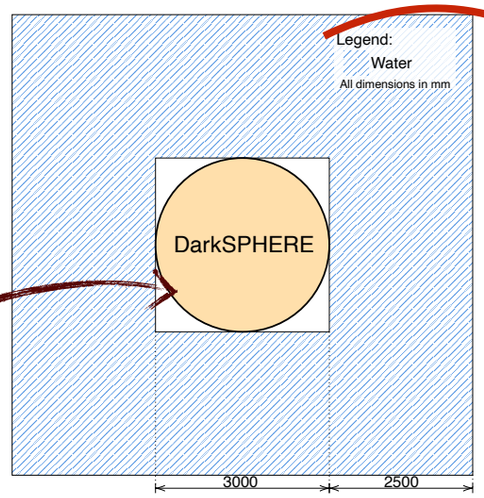


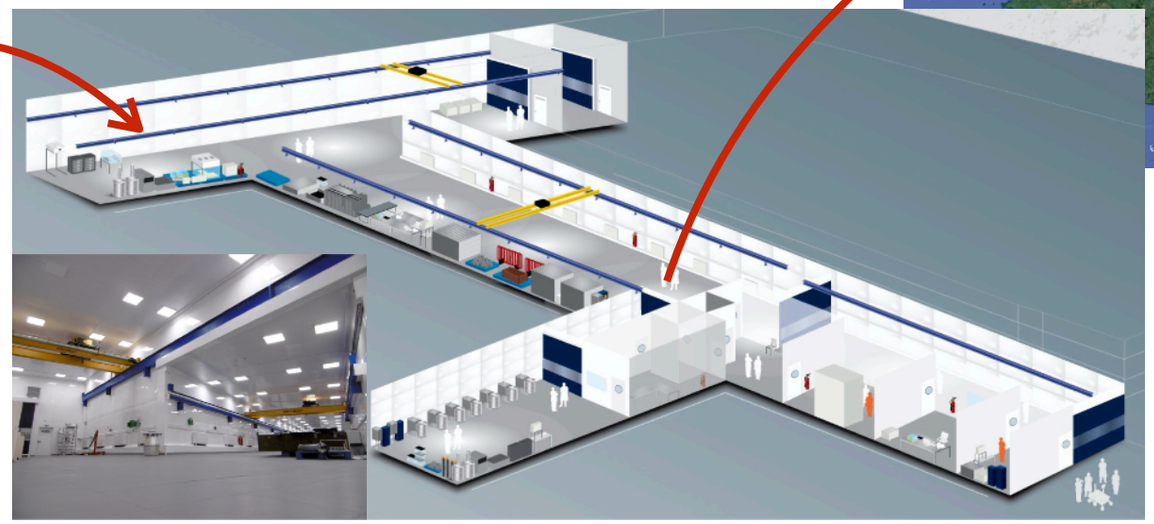
PNNL Shallow Underground Laboratory

DarkSPHERE

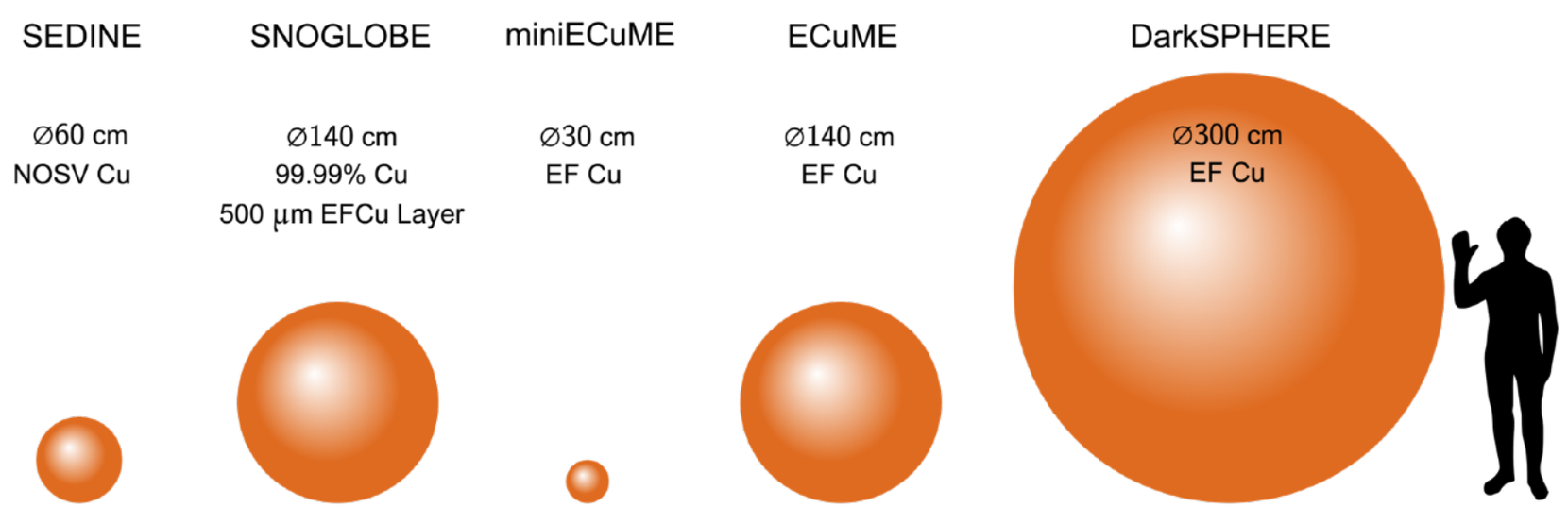
- ⌀300cm intact underground electroformed spherical proportional counter
  - Low background water-based shield
  - 2.5 m thickness sufficient for <0.01 dru
  - Dominant background photos in the cavern
  - R&D on-going for ACHINOS





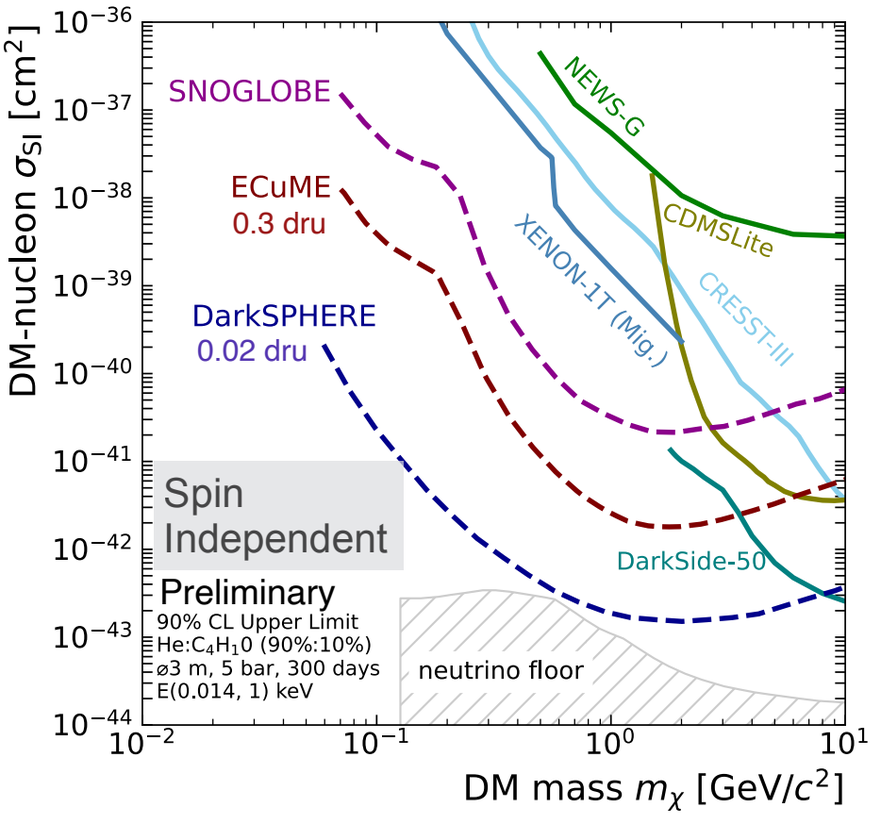


5 bar He:C_4H_{10} (90%:10%)
(27 kg target mass)



DarkSPHERE: Physics Potential

Nuclear Recoils



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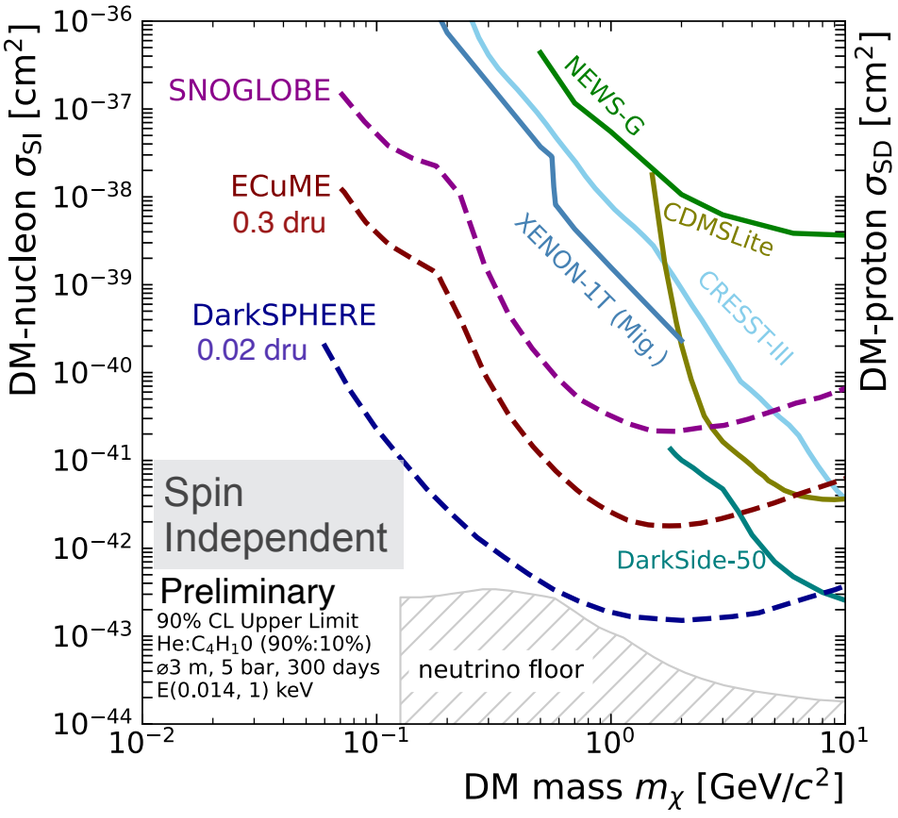

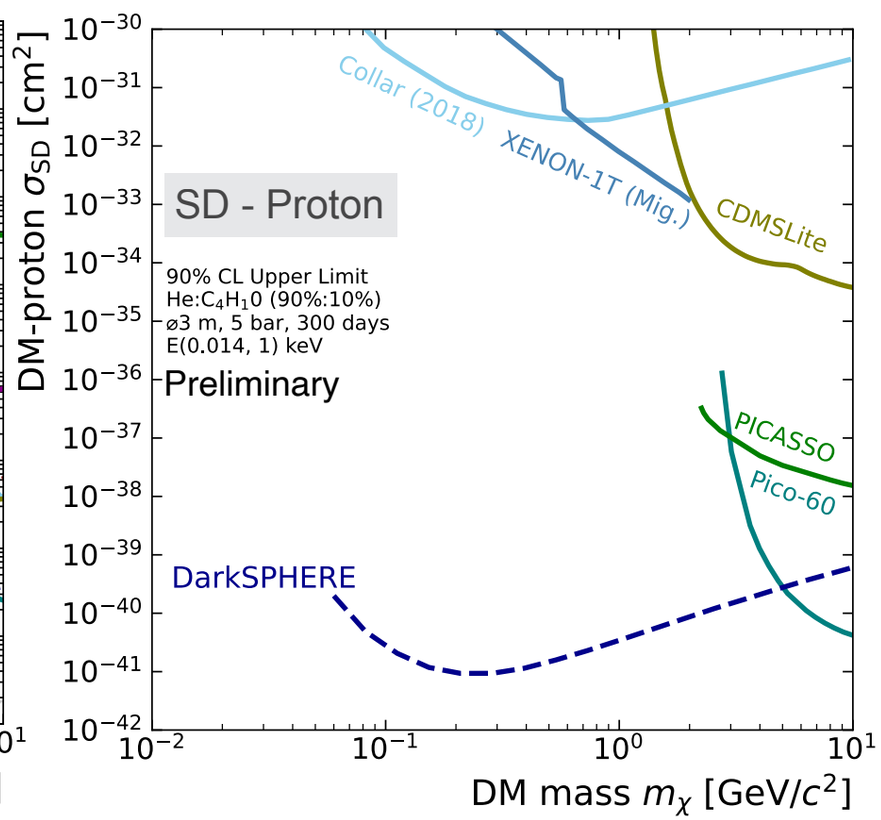

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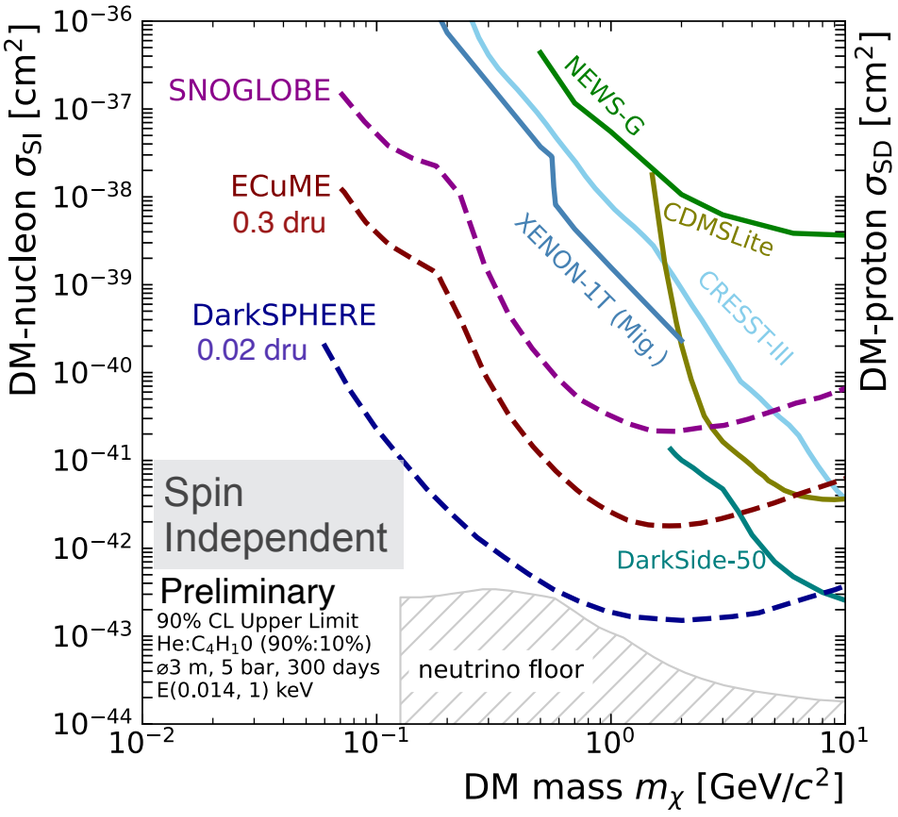

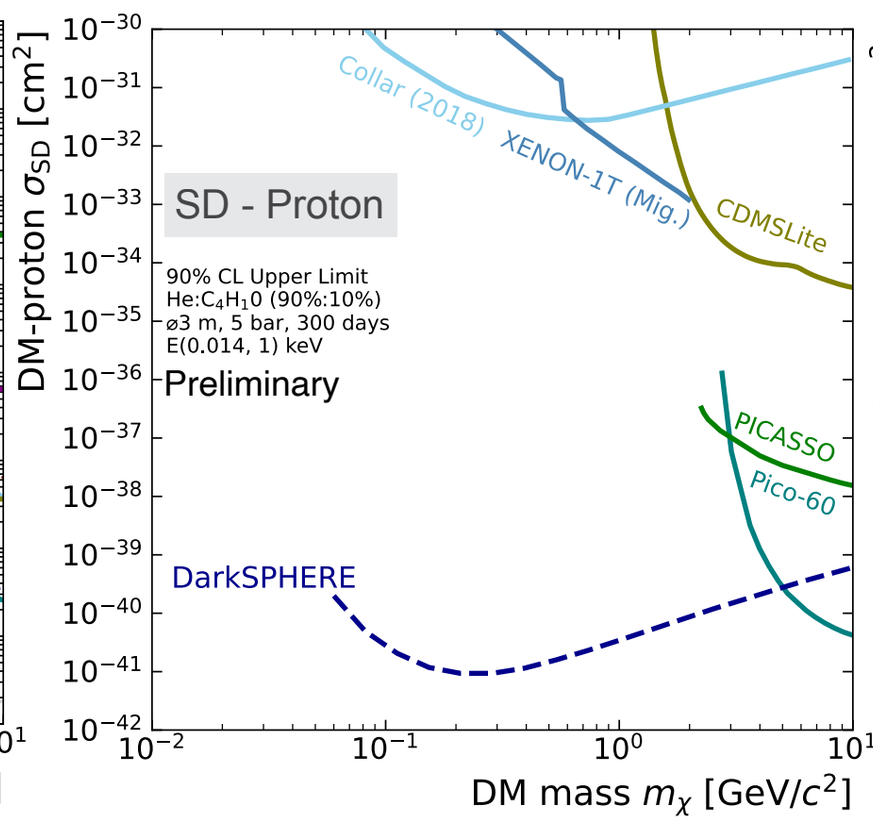

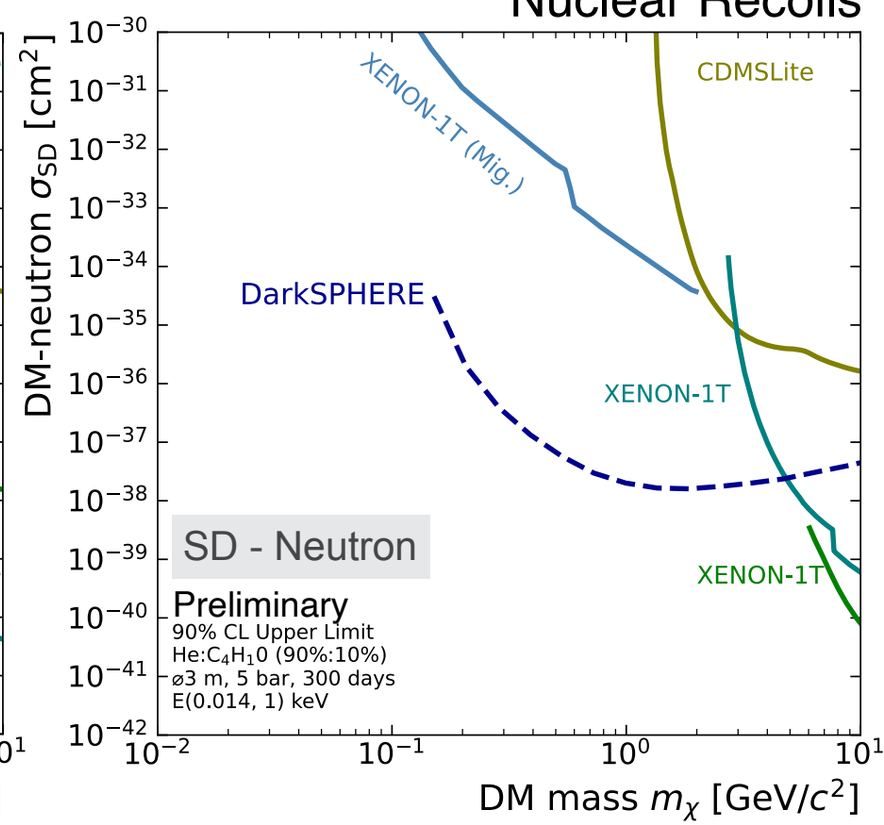

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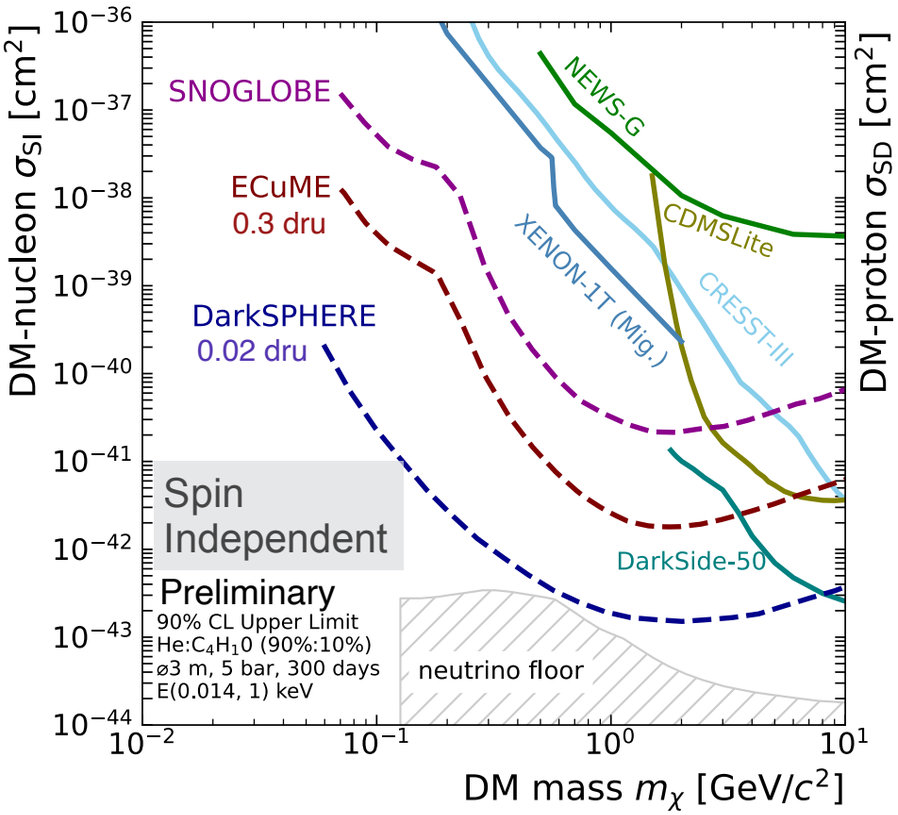

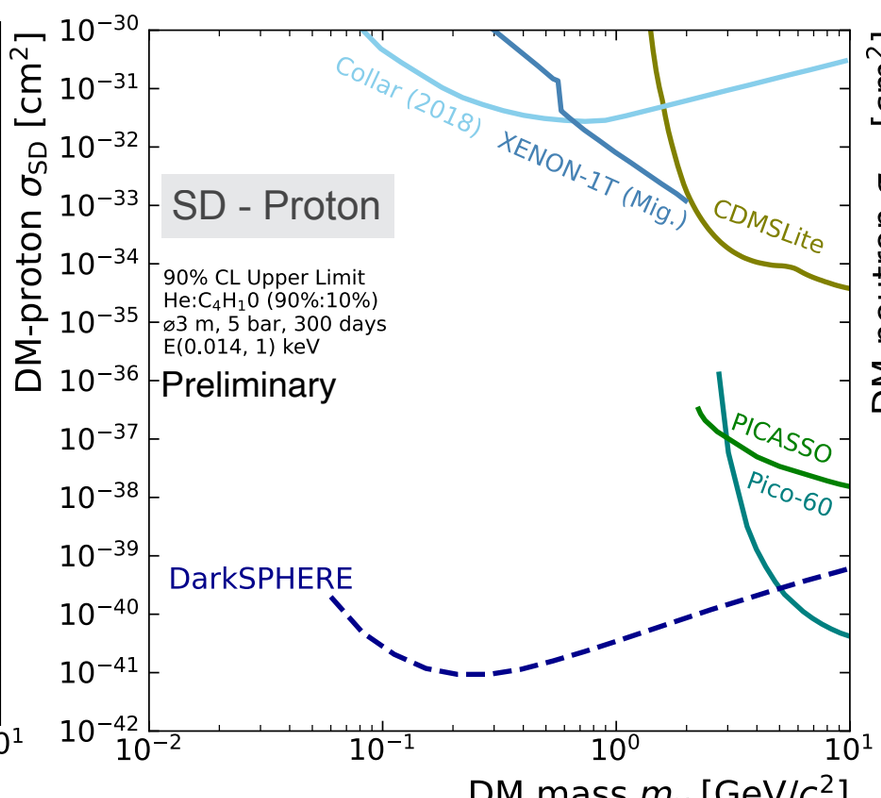

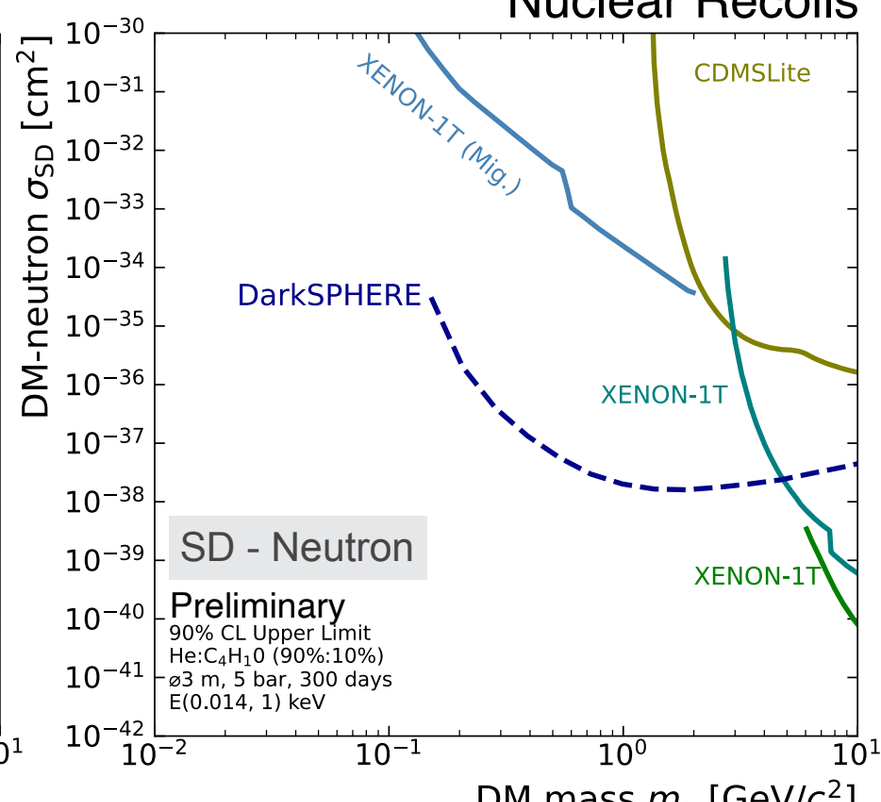

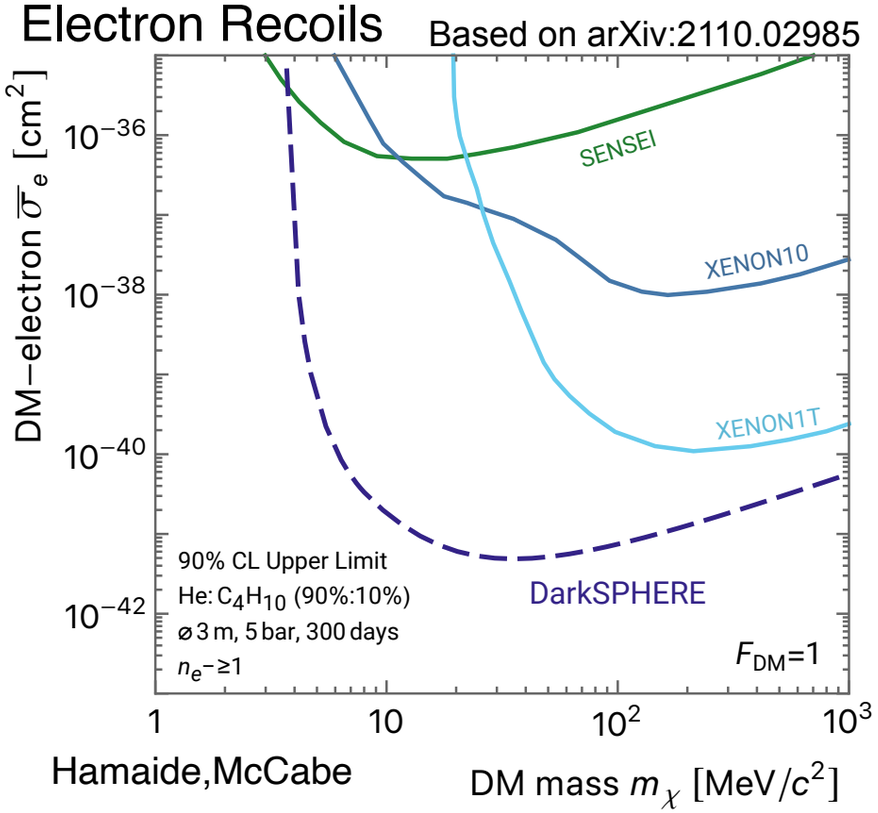

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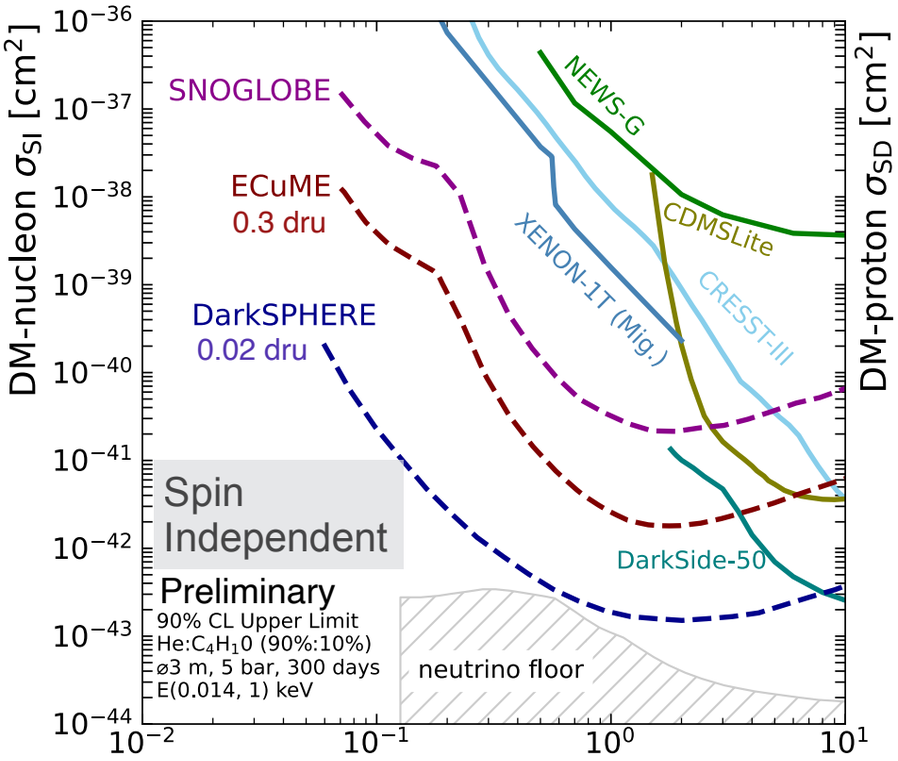
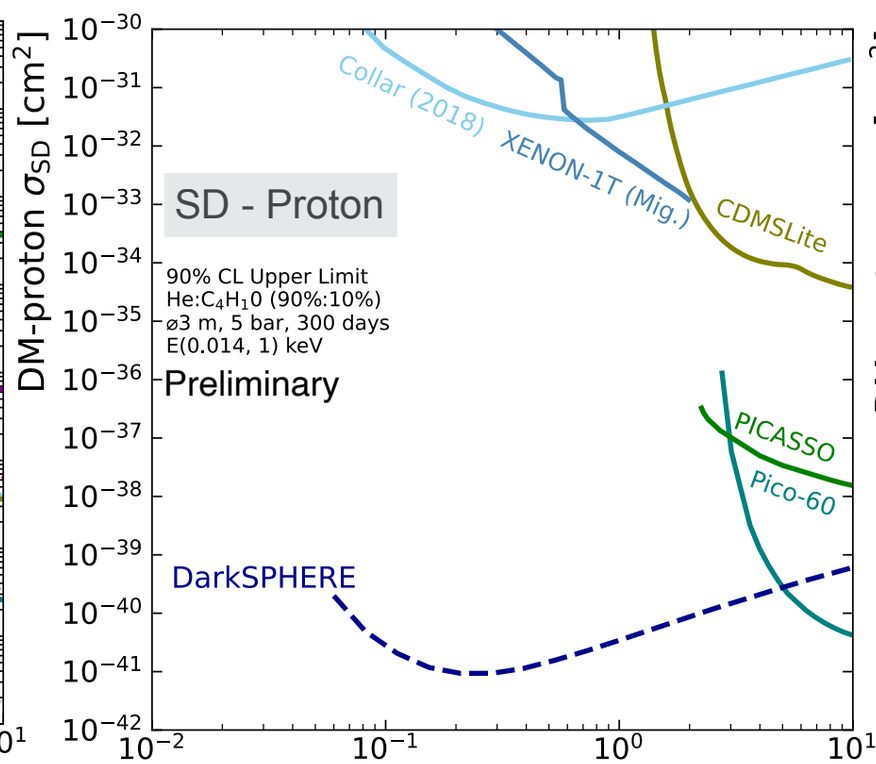
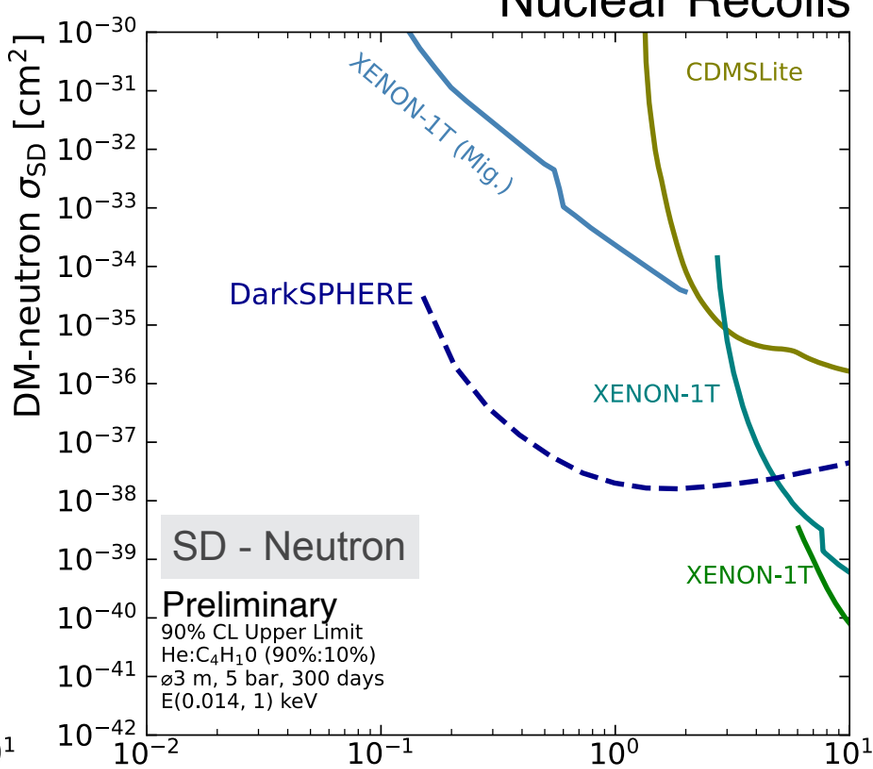
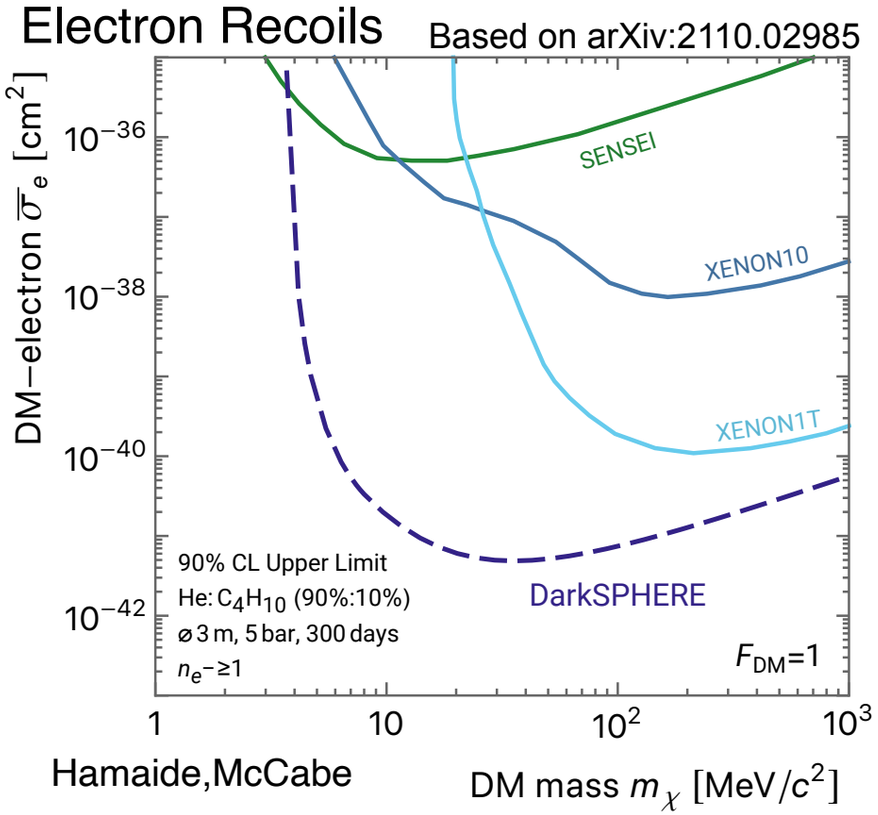
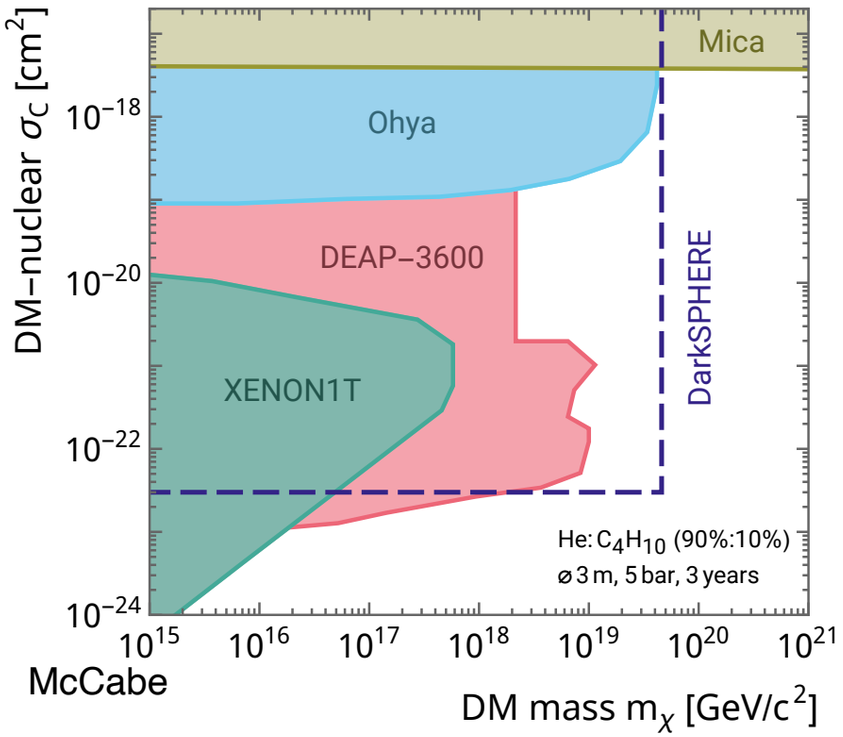








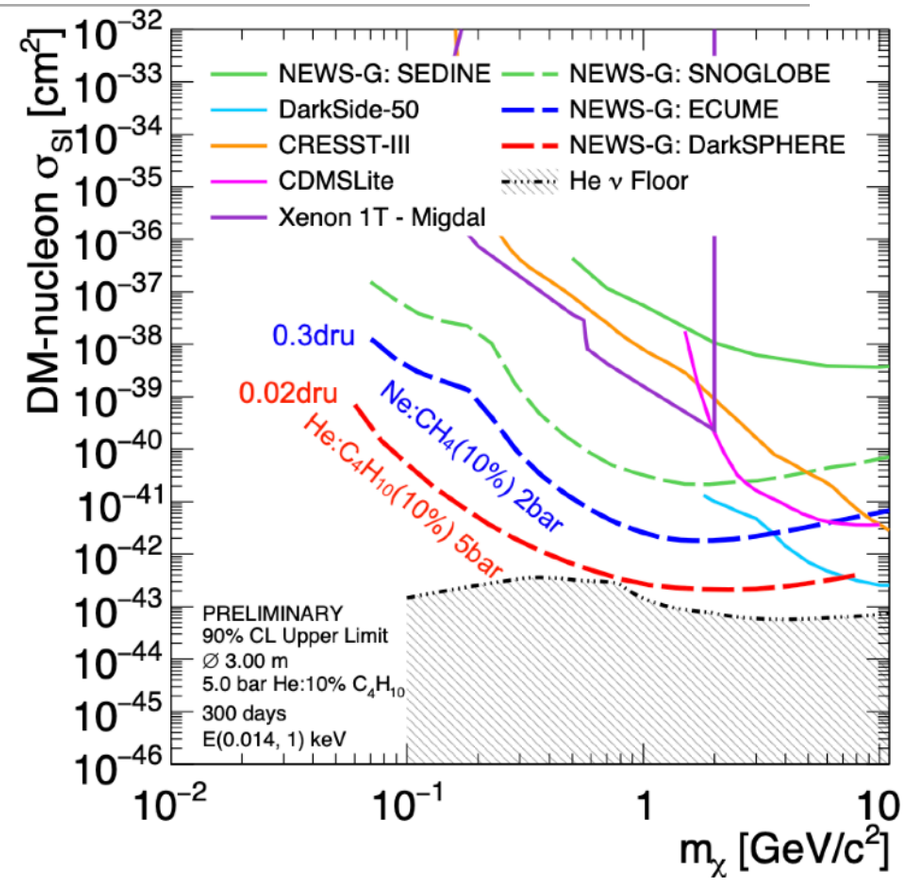


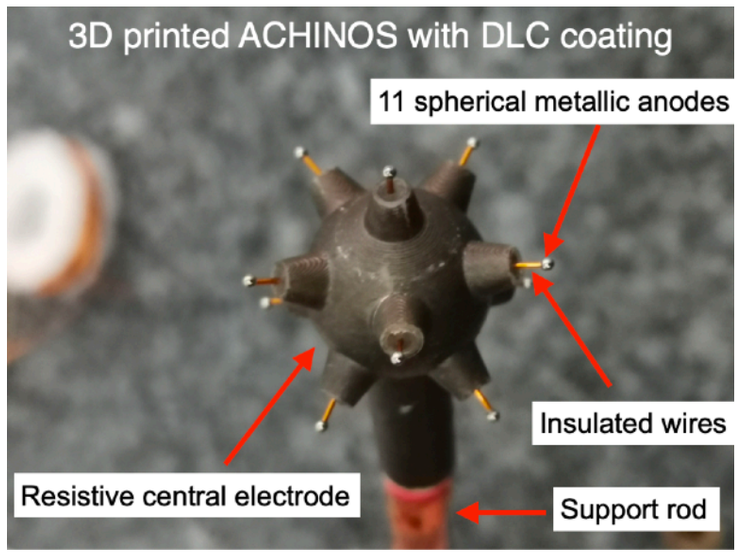
Summary

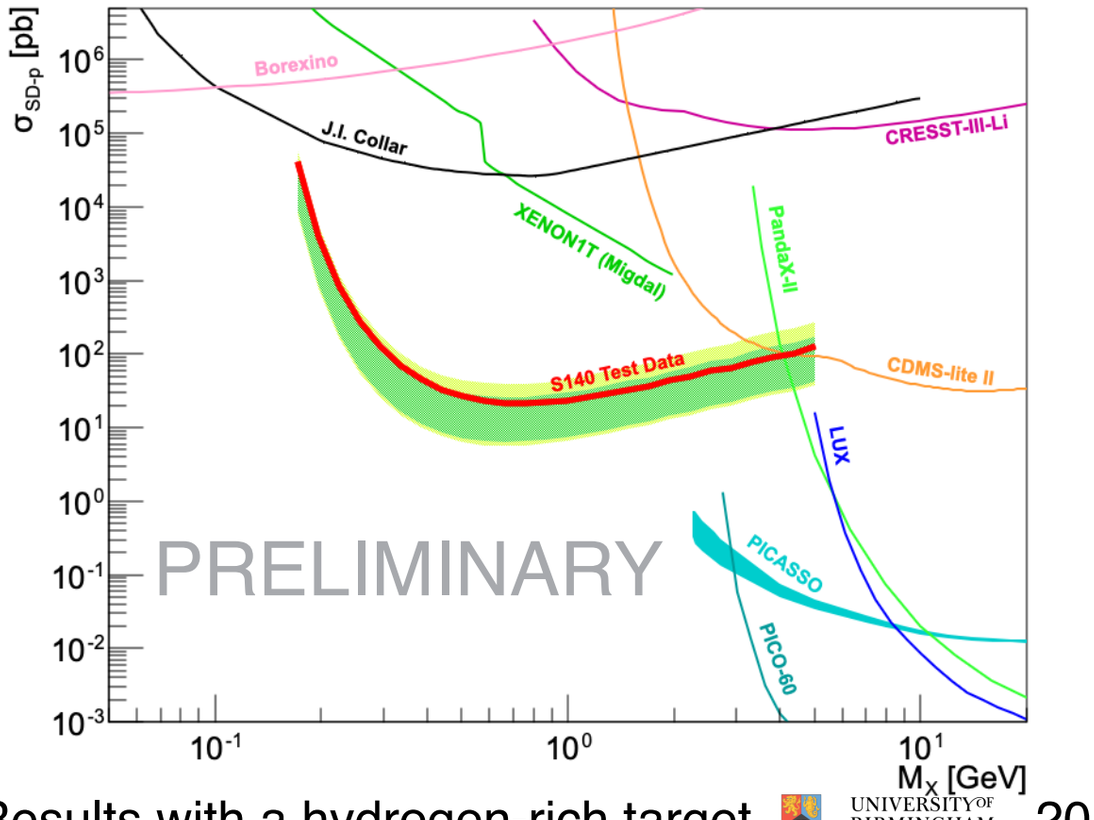
NEWS-G: rich physics and R&D programme, exploring new territory with Spherical Proportional Counters

- Significant advances on instrumentation and techniques
  - Electroformation, ACHINOS, …
  - Quenching factor measurements
  - Electron counting
- New world-leading constraints
- Data taking in SNOLAB to start imminently
- Several detectors scheduled/planned for the coming years

Many physics opportunities to look forward to!

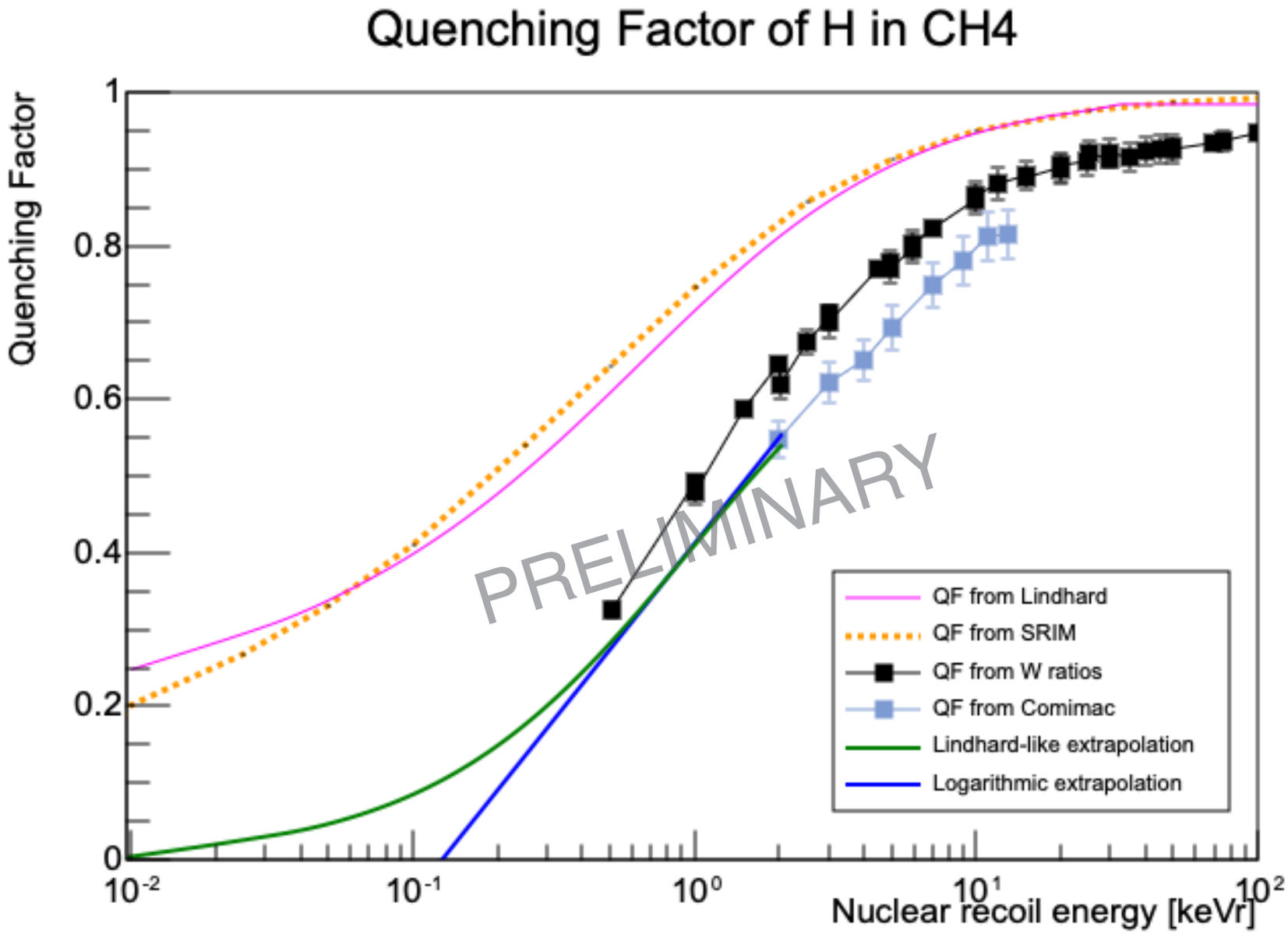




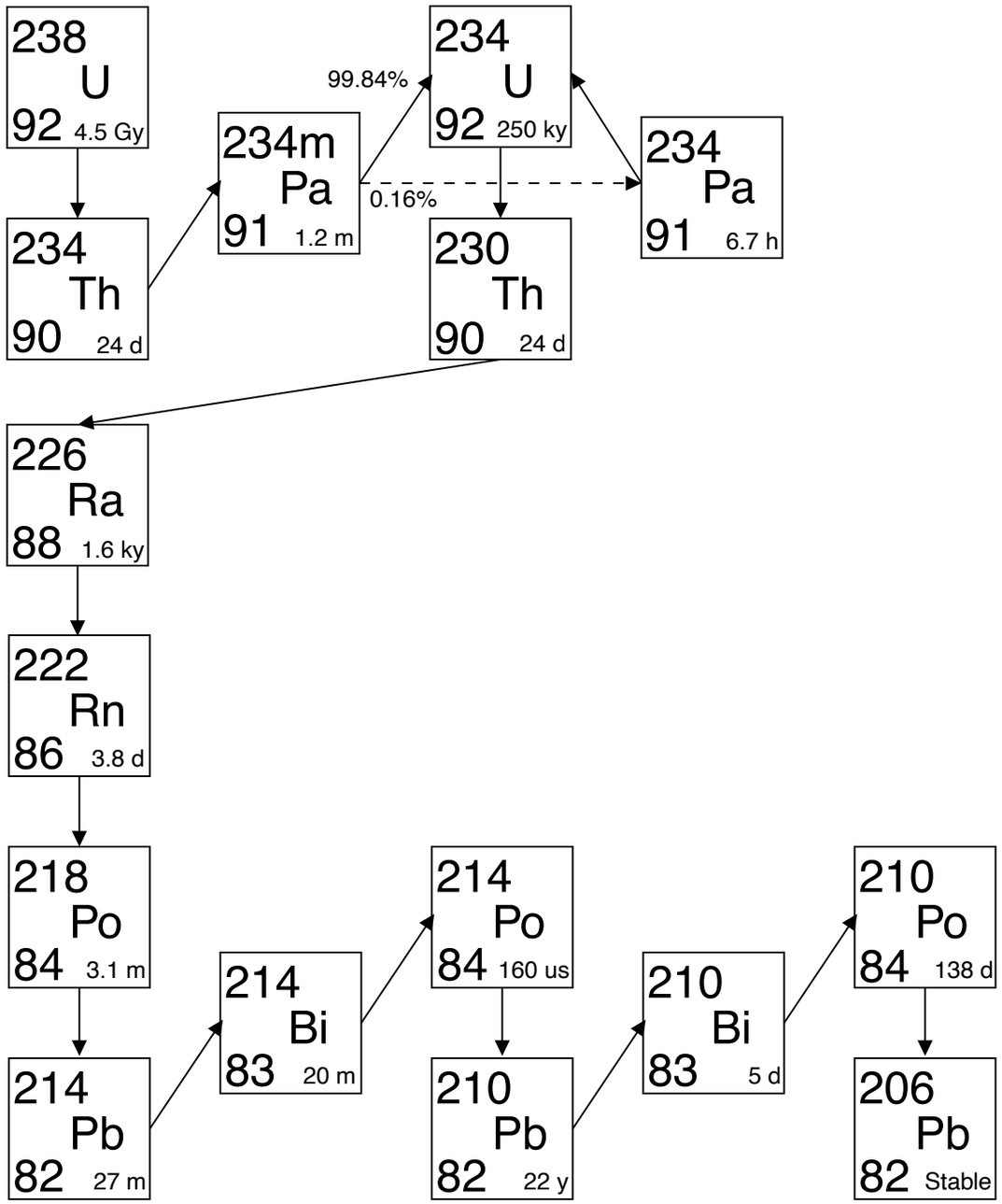


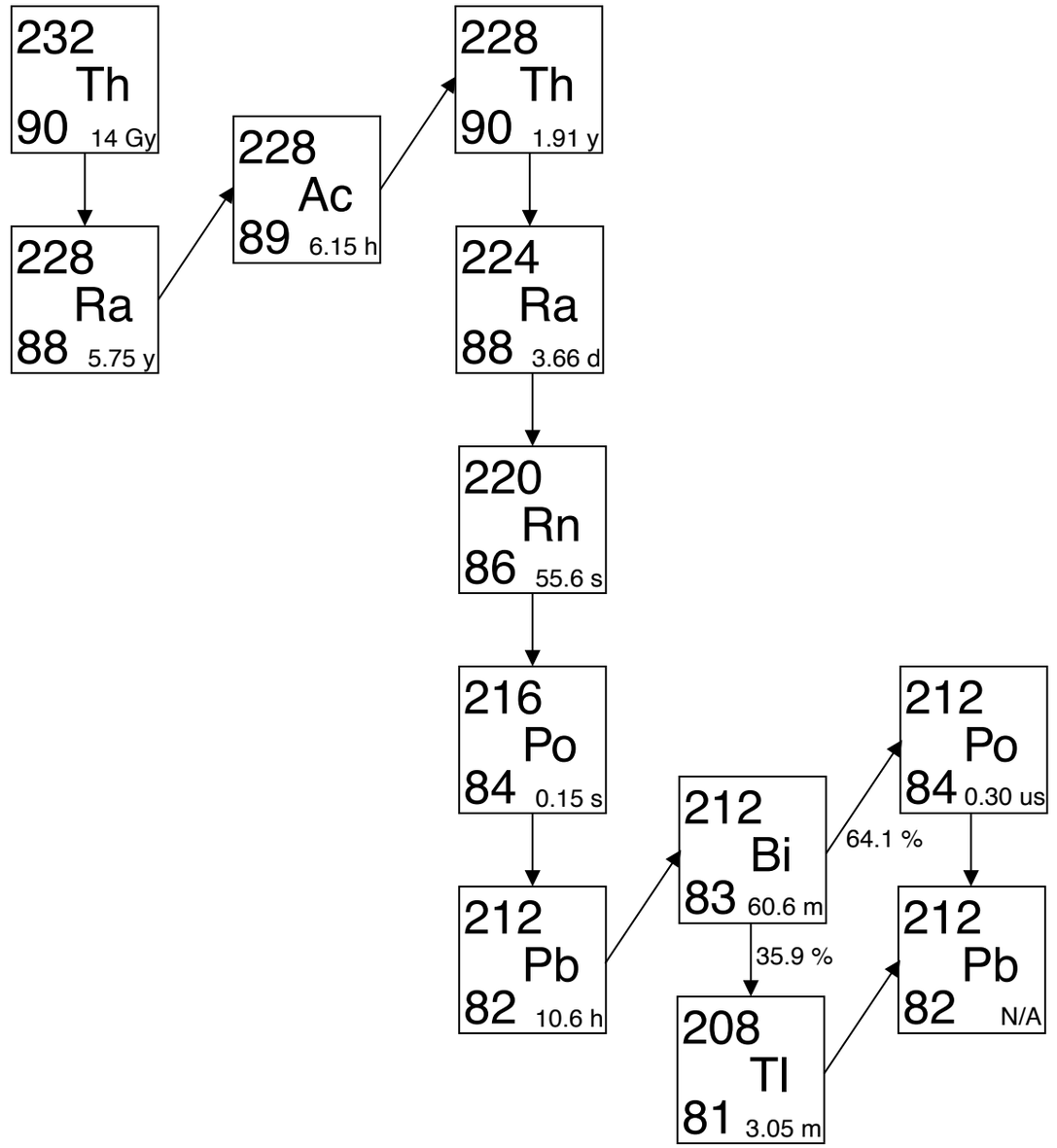
Additional Slides

Ionisation quenching factor



^{238}U and ^{232}Th decay chains





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
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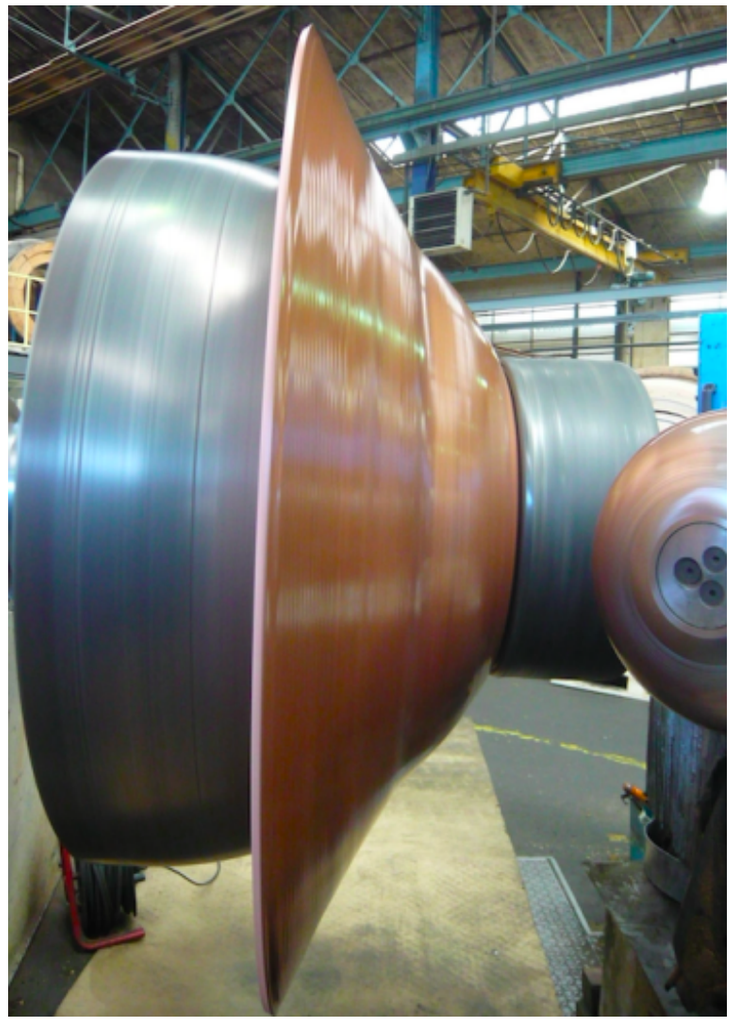

4N Aurubis AG Oxygen Free Copper (99.99% pure)

- Spun into two hemispheres
- Electron-beam welded together

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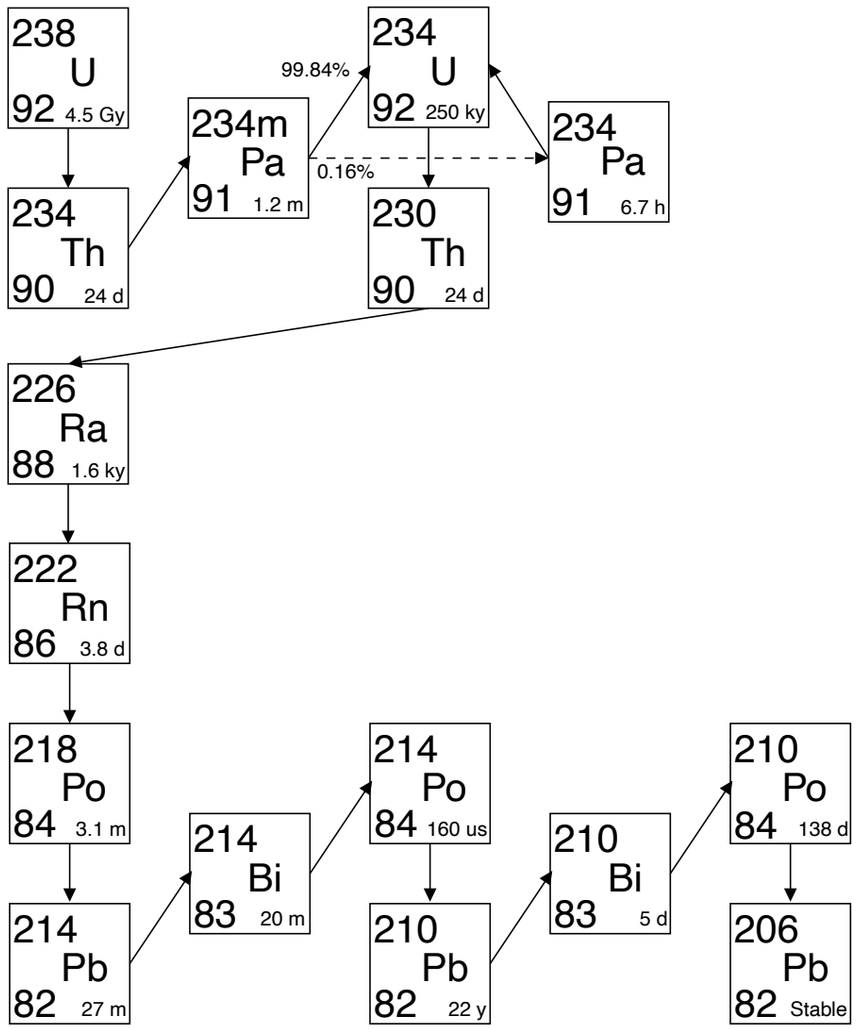

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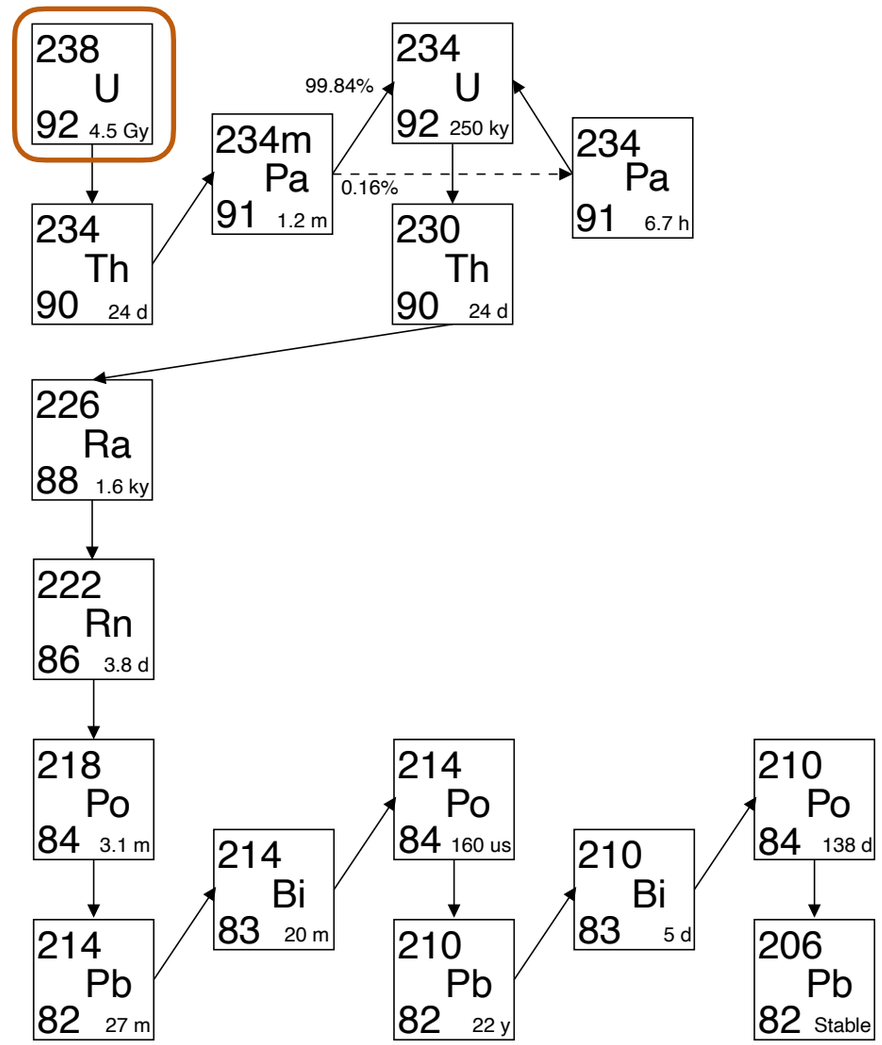
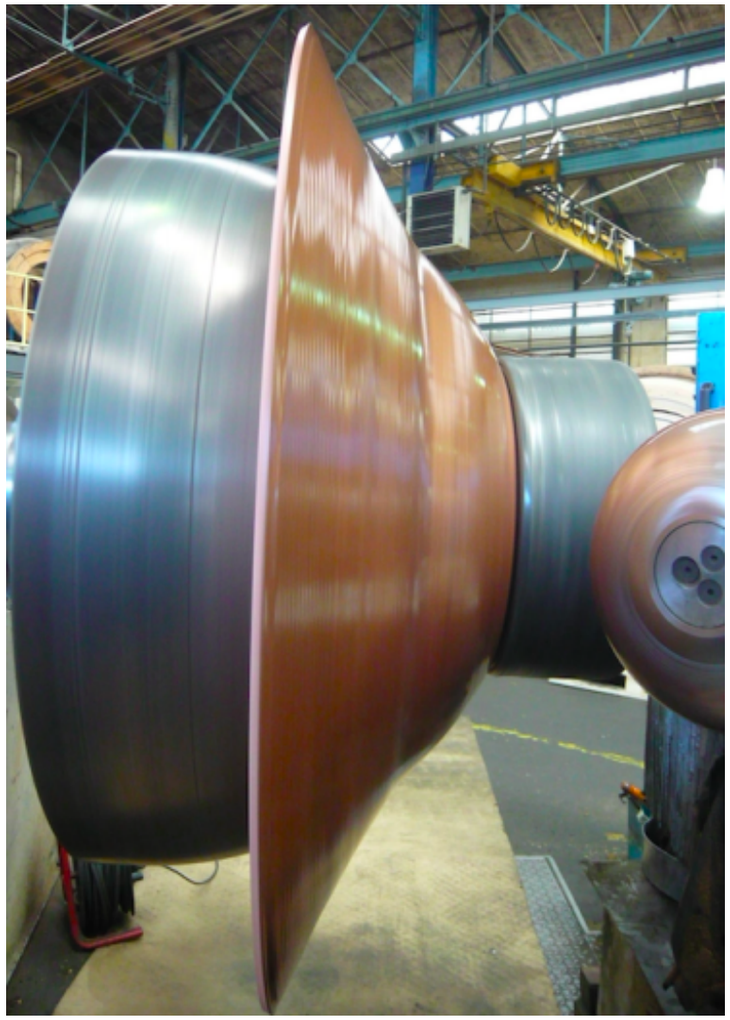
directly measured with mass spectrometers ~10 µBq/kg





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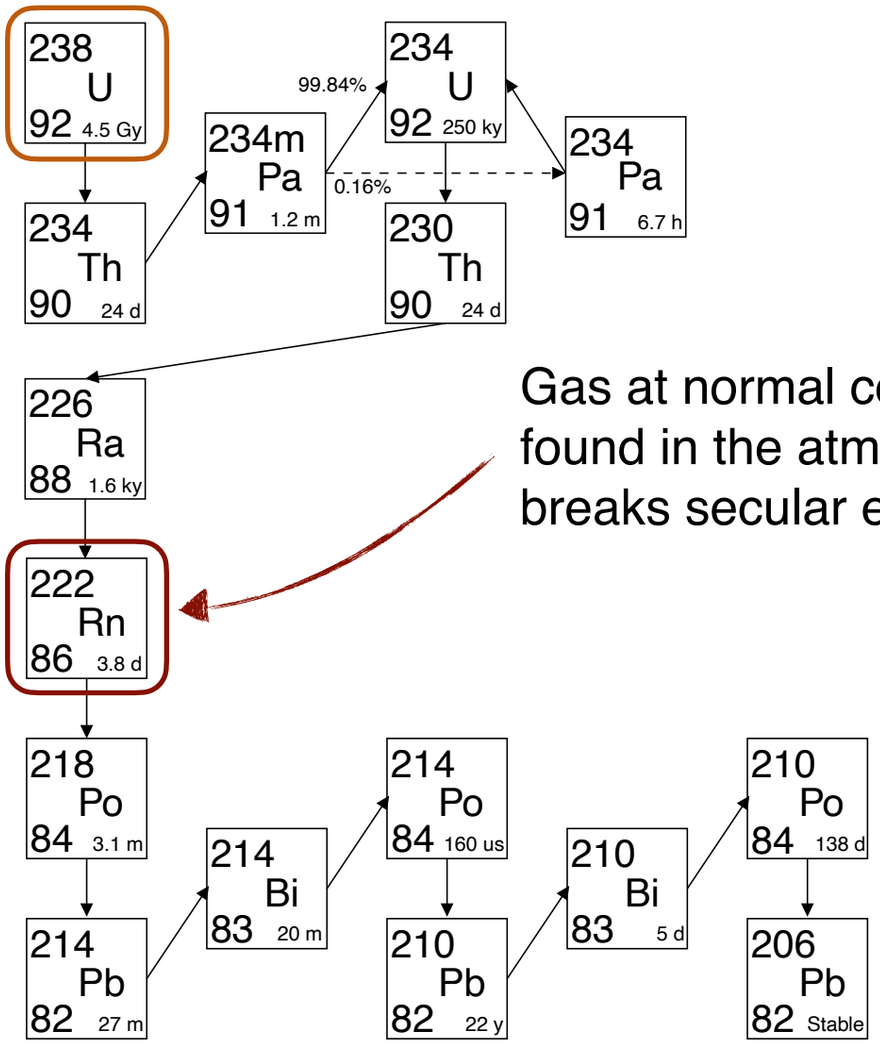
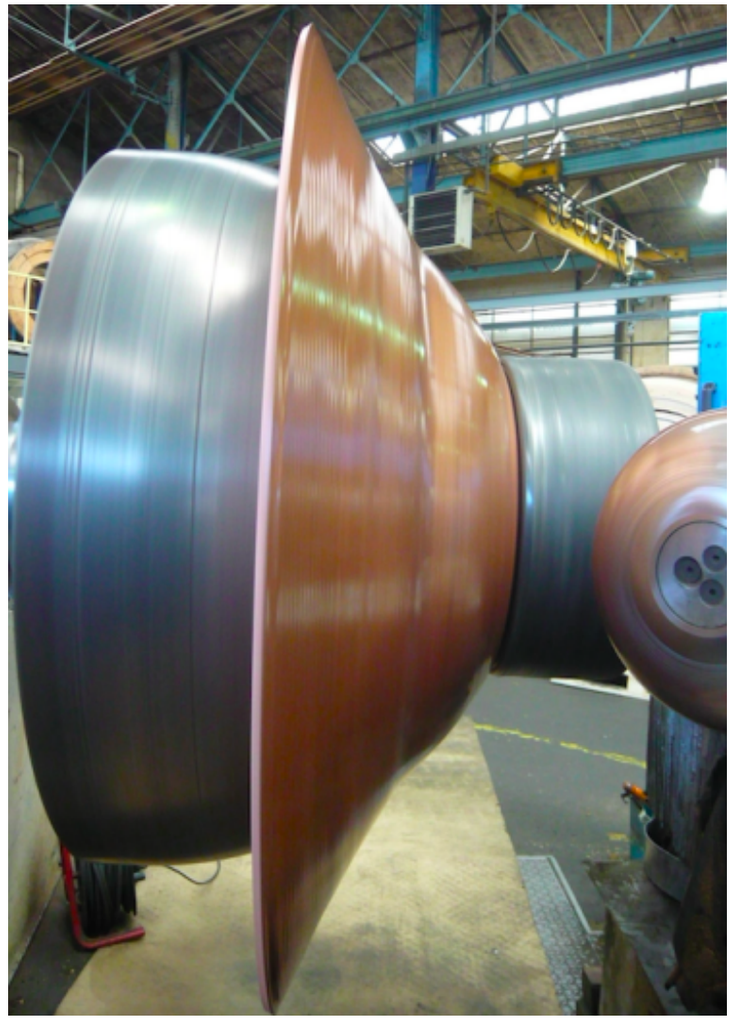


Gas at normal conditions: found in the atmosphere breaks secular equilibrium



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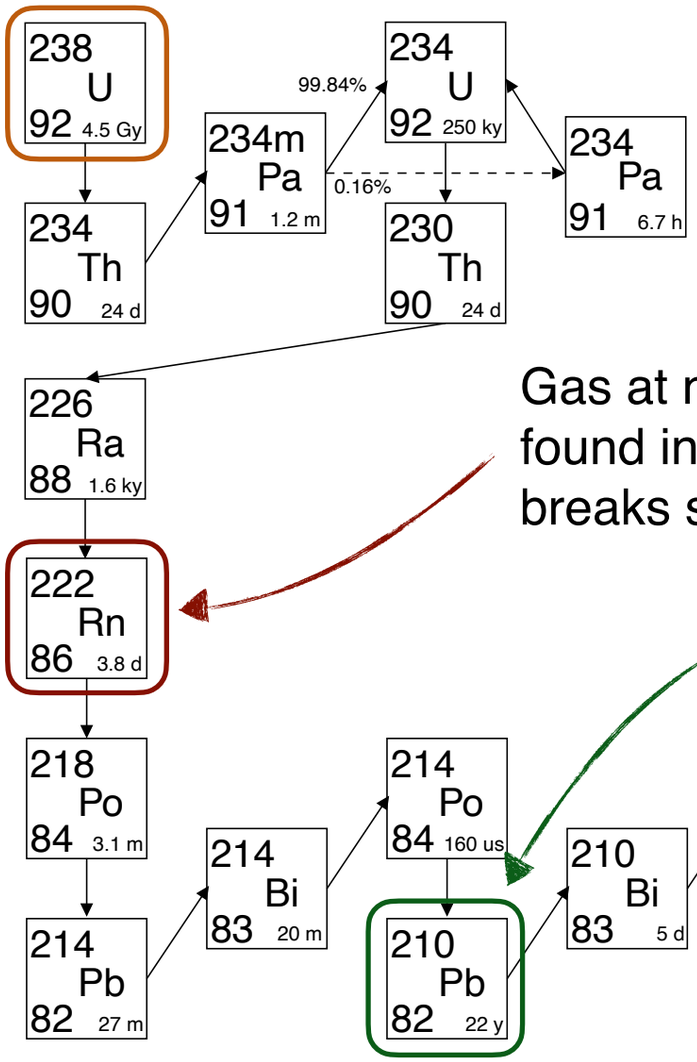

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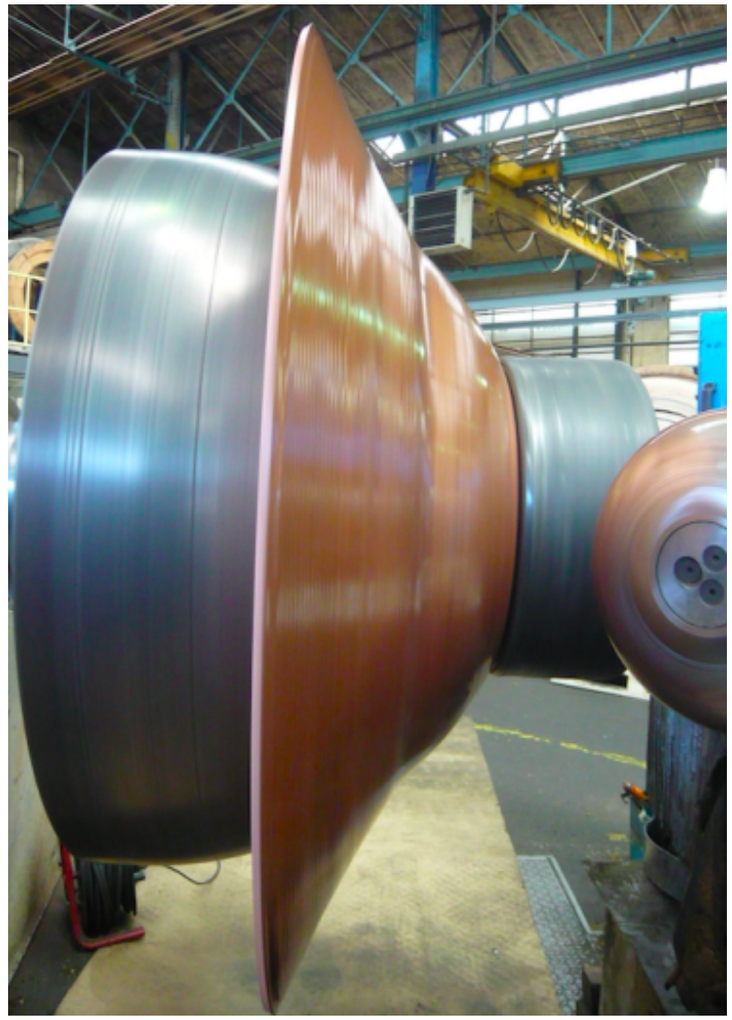
Long-lived!



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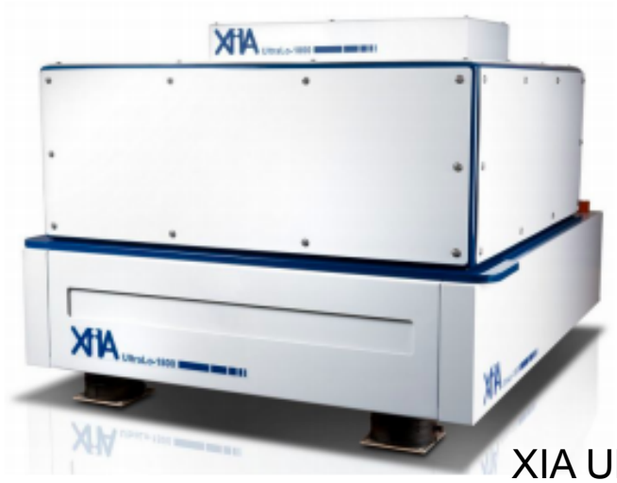
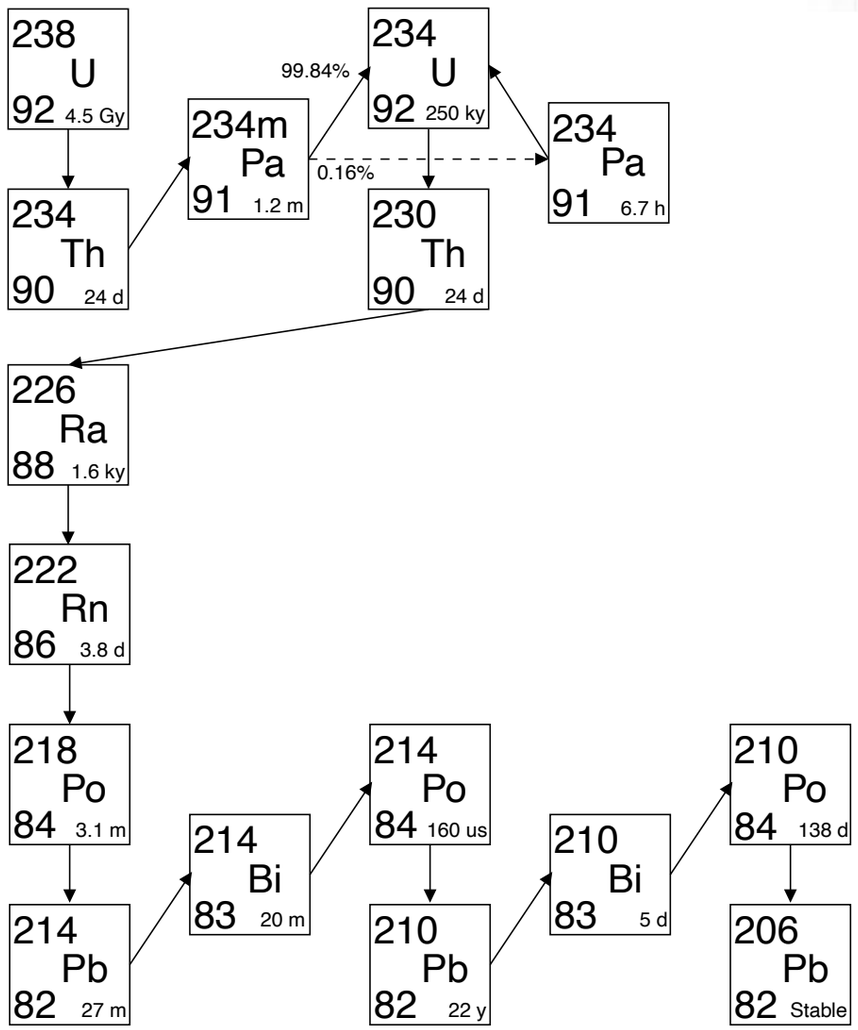
^{210}Pb contamination

Estimation of out-of-equilibrium ^{210}Pb contamination through low background α-particle counting



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



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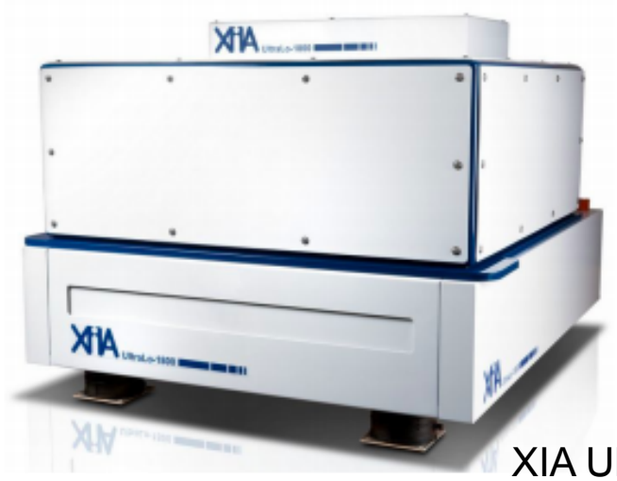

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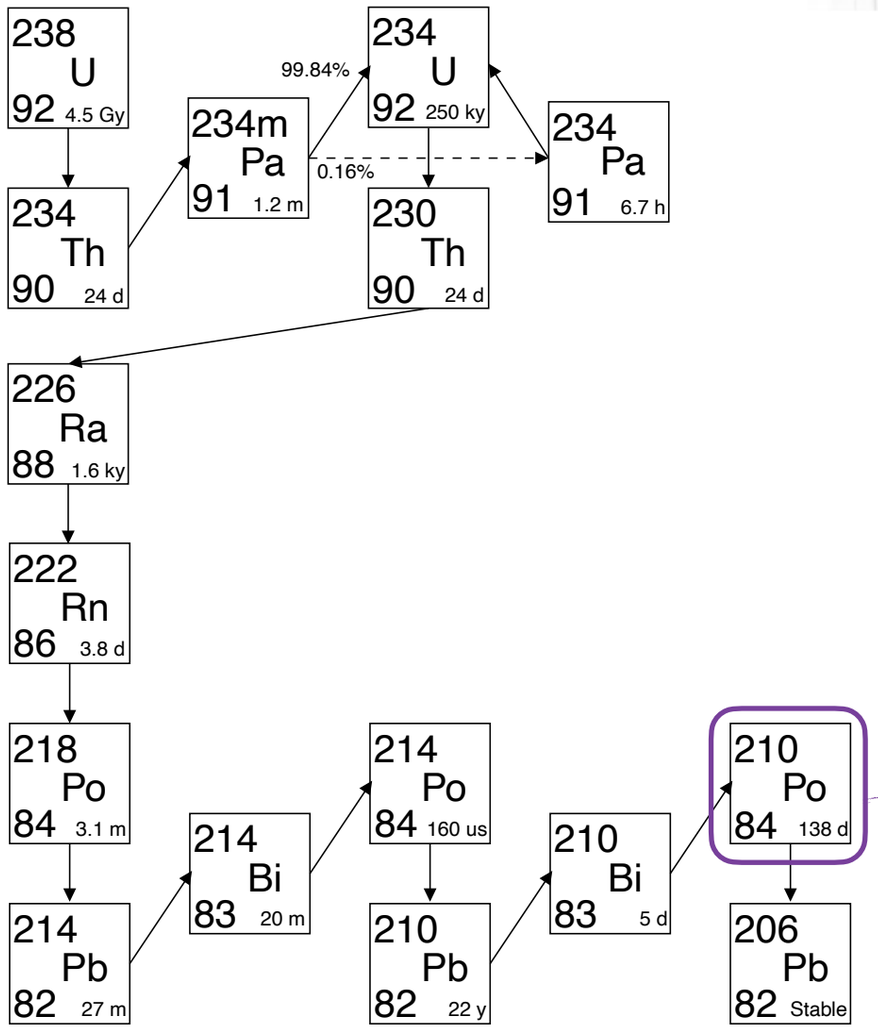

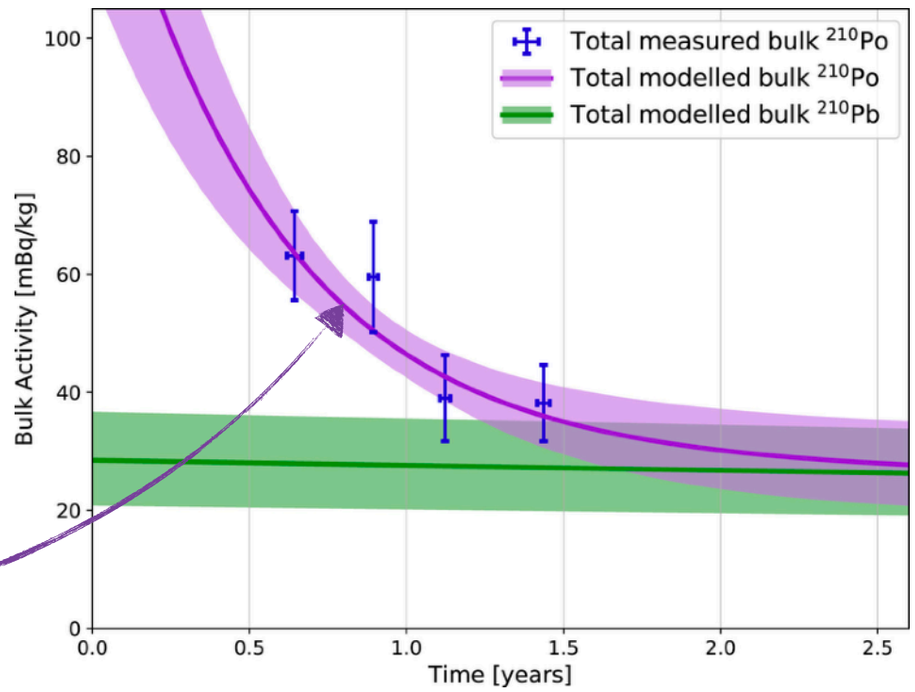

NIM A 988 (2021) 164844

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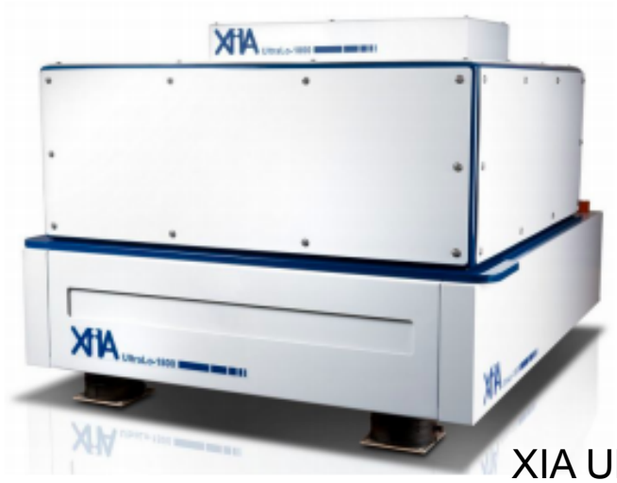

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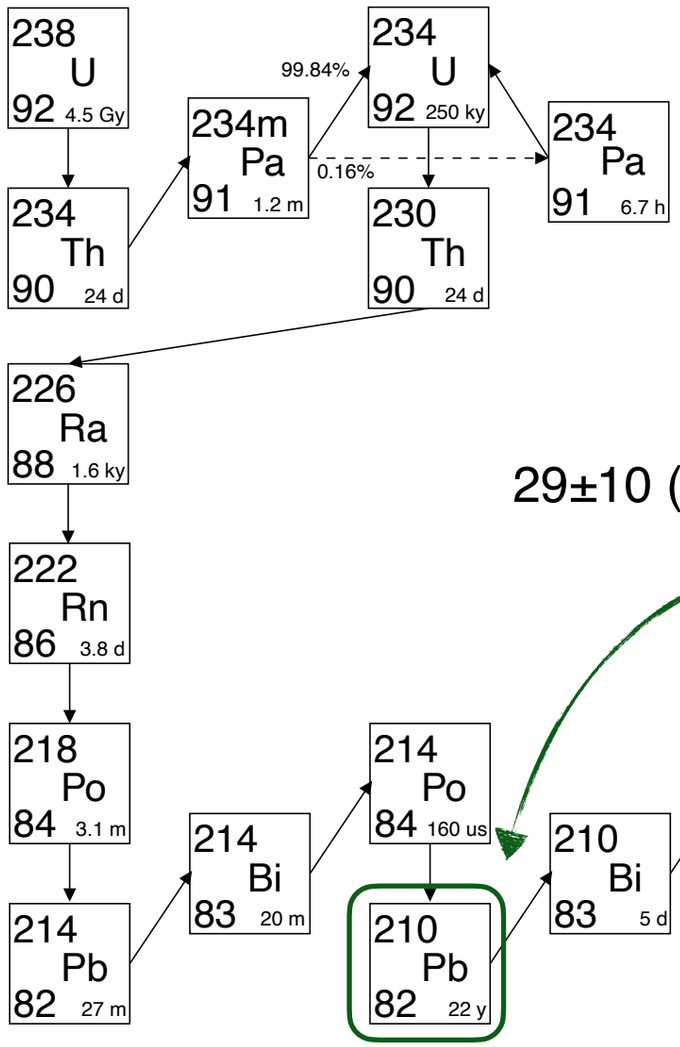
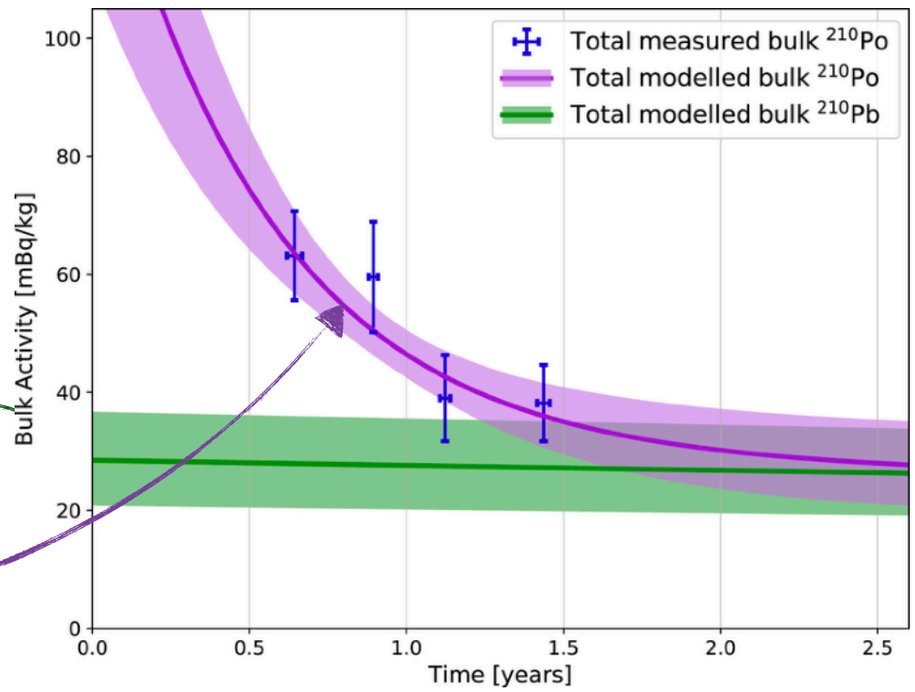


29±10 (stat)$^{+9}_{-3}$ mBq/kg



NIM A 988 (2021) 164844

Copper Electroplating

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

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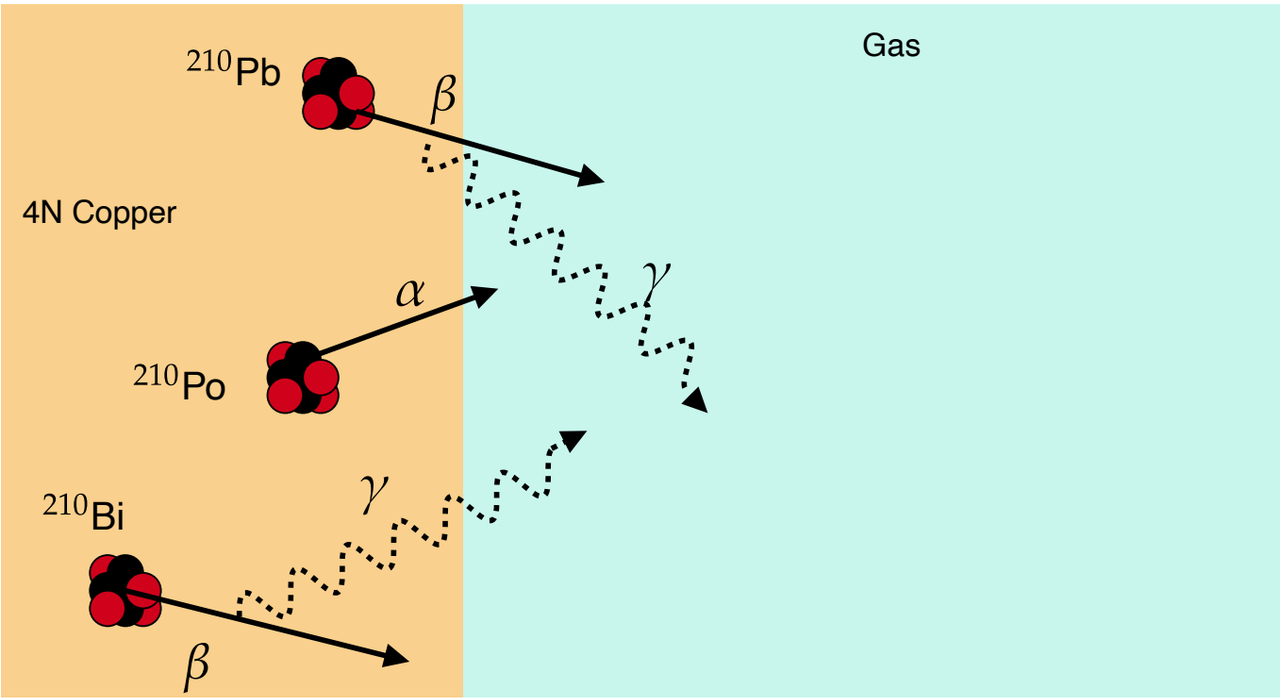

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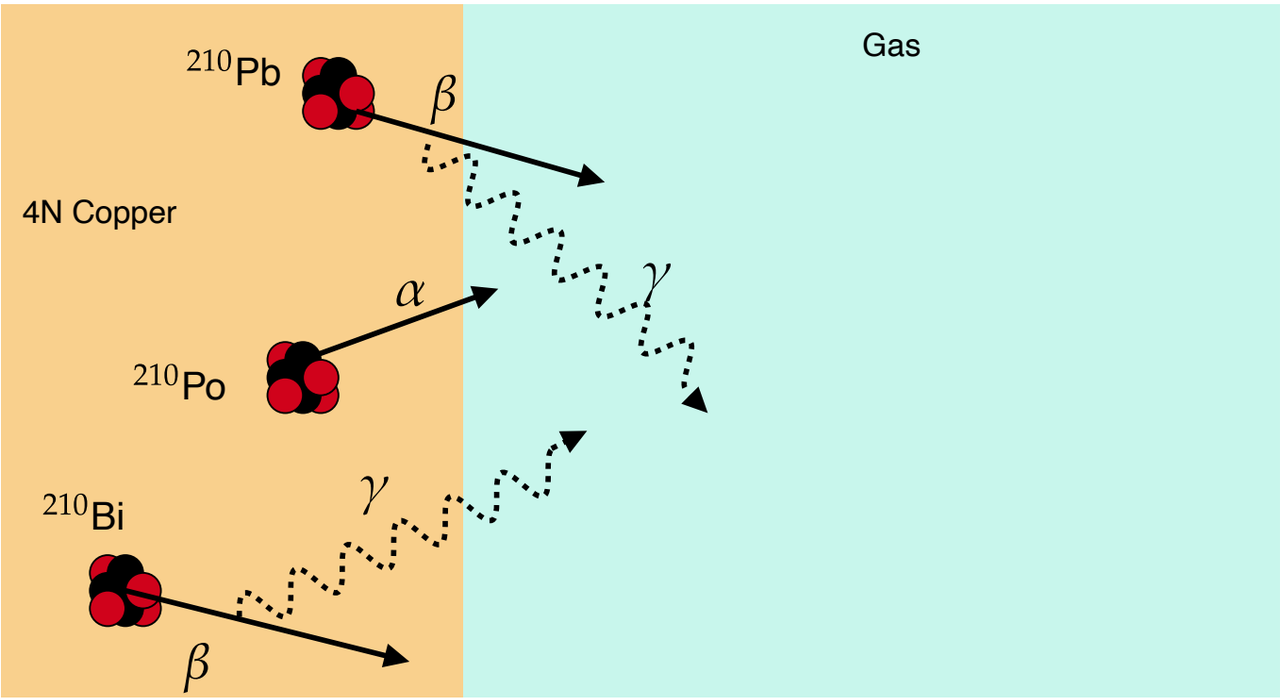
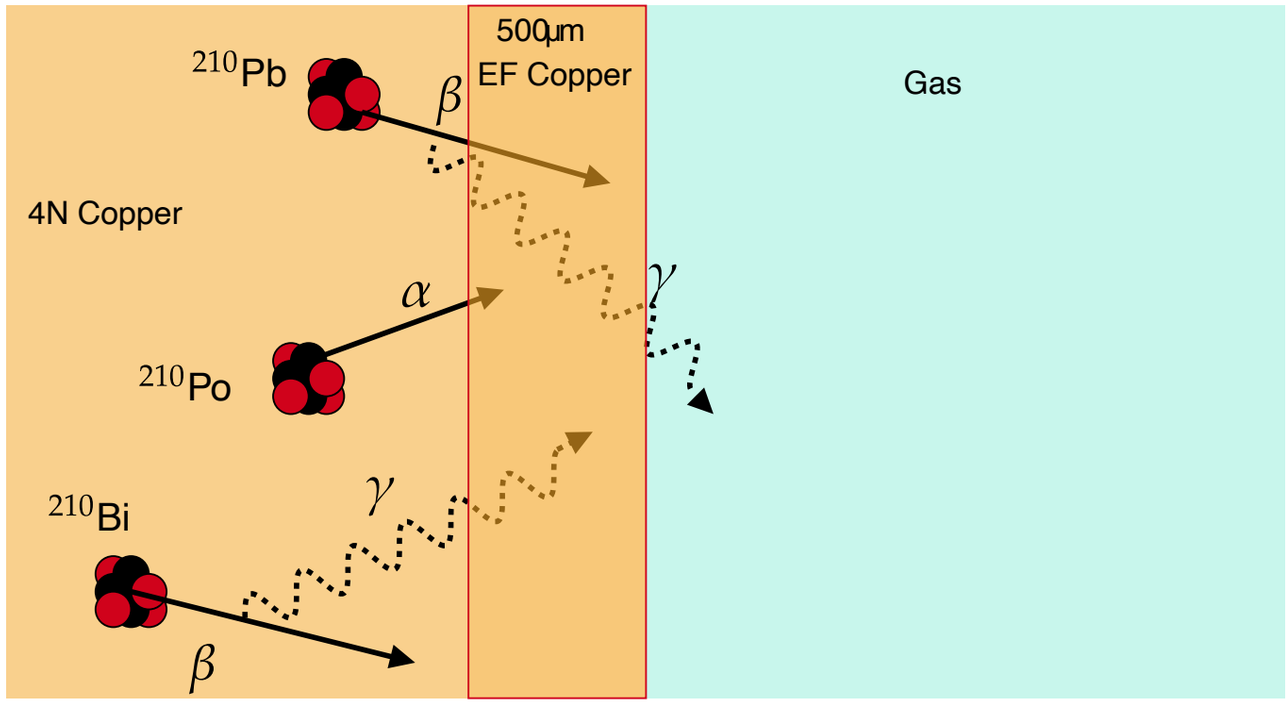
Internal shield

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





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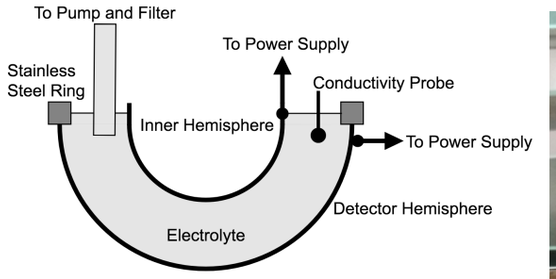
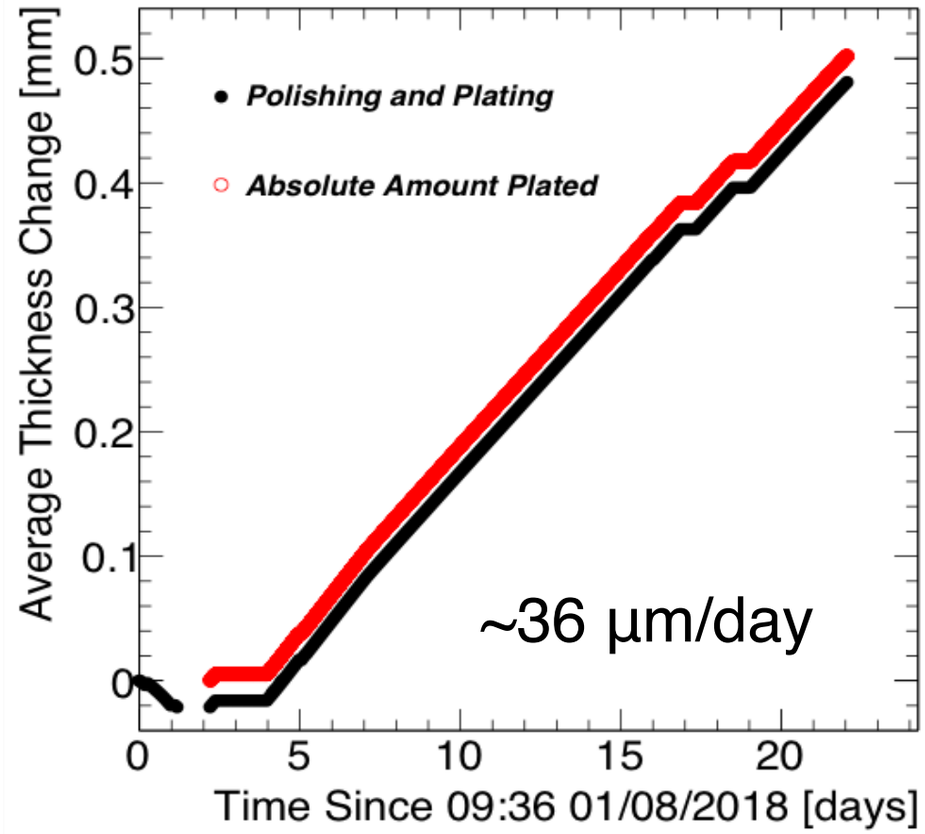


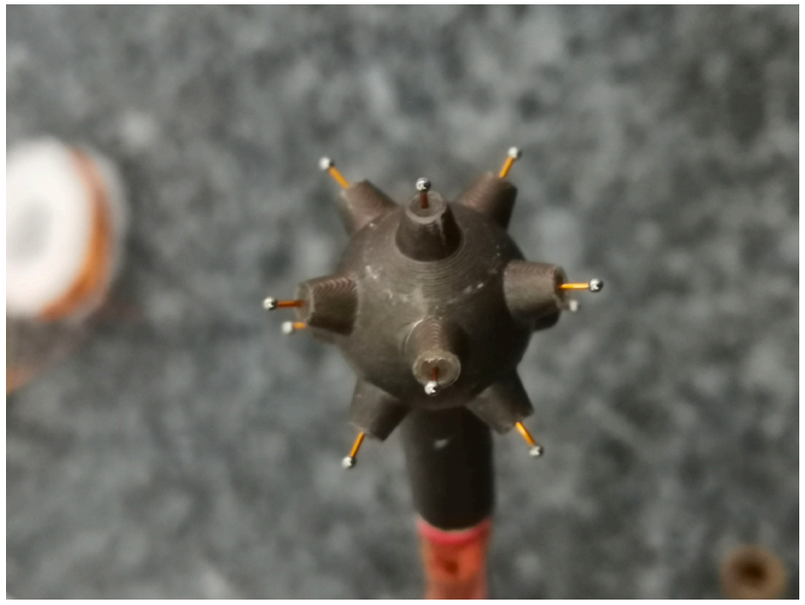
Electroplating setup at LSM



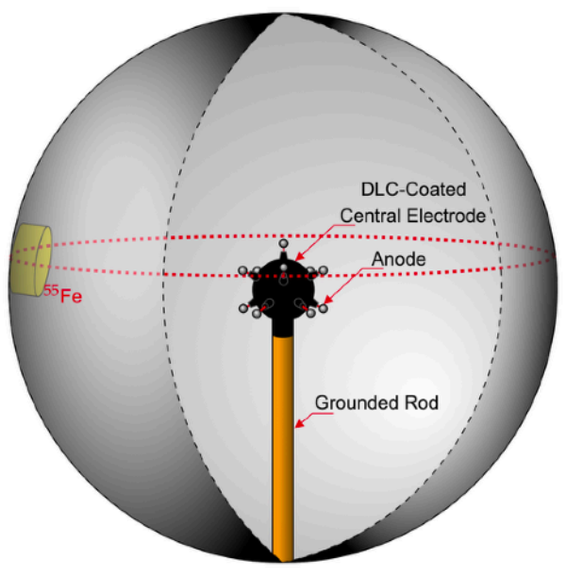
Sample	Weight [g]	^{232}Th [µBq/kg]	^{238}U [µBq/kg]
C10100 Cu (Machined)	-	8.7 ± 1.6	27.9 ± 1.9
Cu Electroformed	-	< 0.119	< 0.099
Hemisphere 1	0.256	< 0.58	< 0.26
Hemisphere 2	0.614	< 0.24	< 0.11

NIM A 988 (2021) 164844

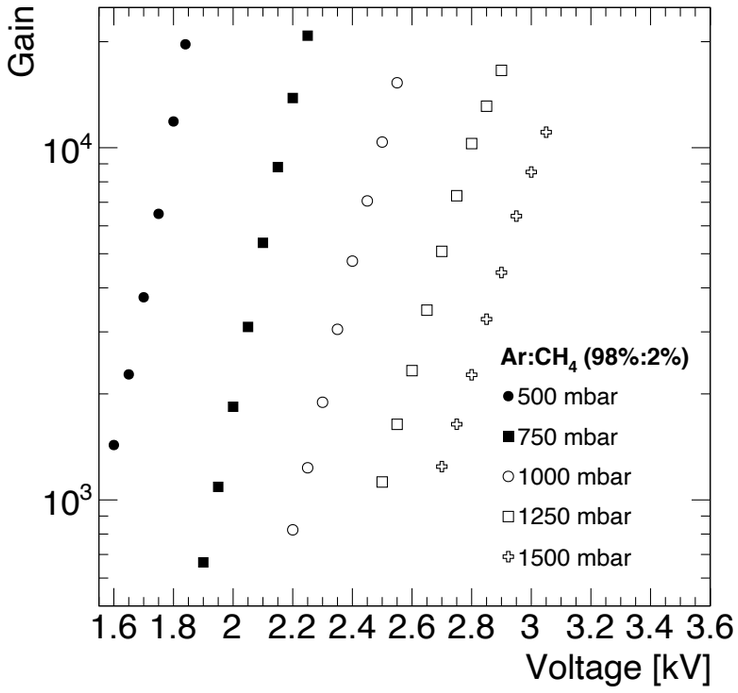
ACHINOS performance with DLC coating

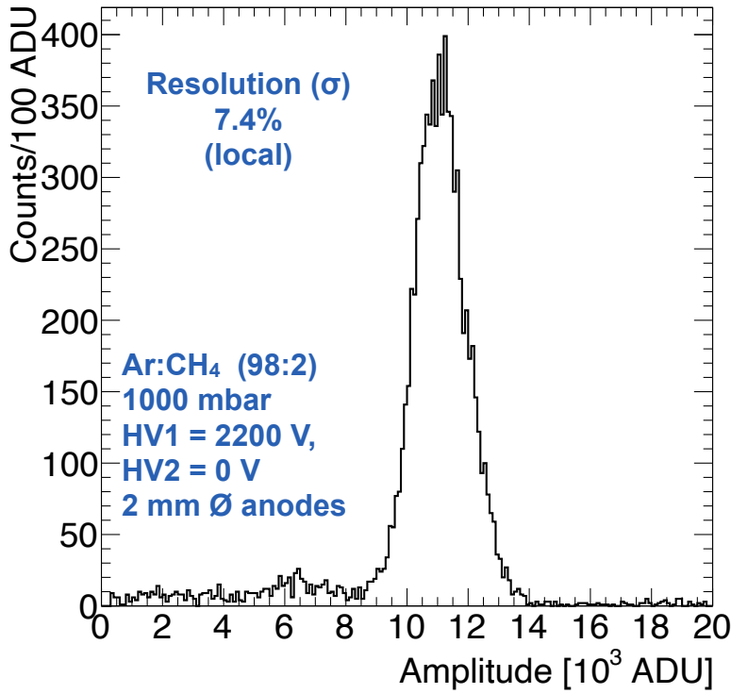


- Good energy resolution
- High pressure operation
- High gain
- Stability
- 2 channel read-out



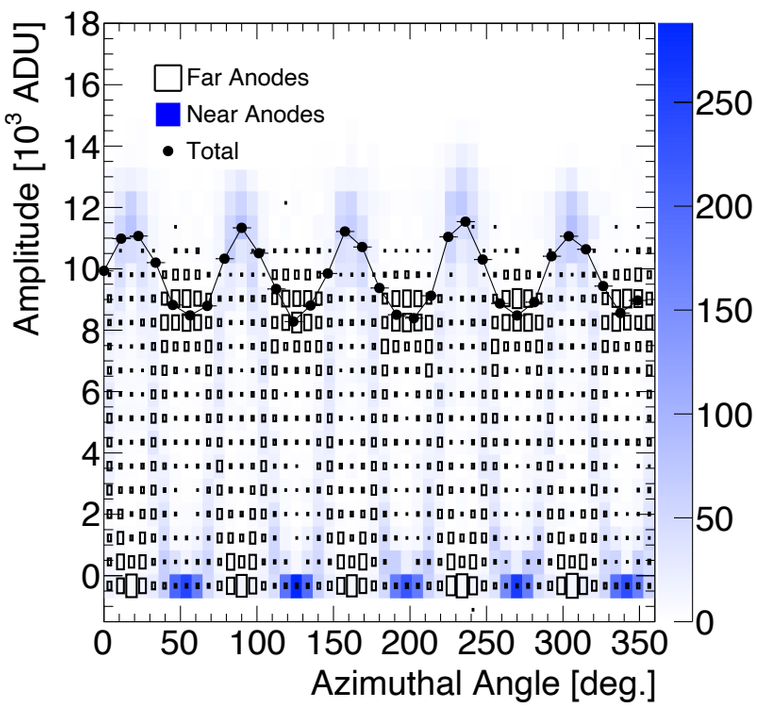
Measurement of the 5.9 keV ^{55}Fe X-ray line

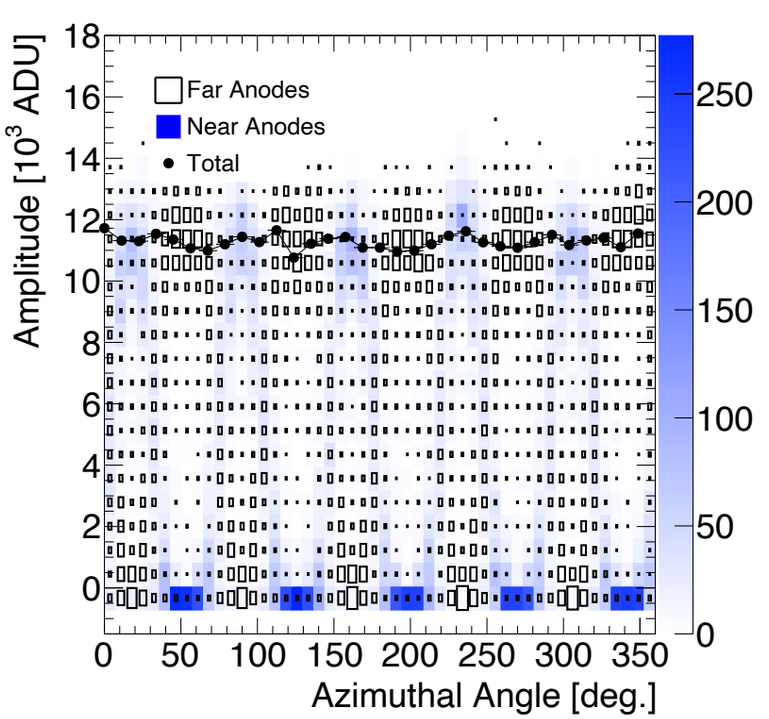




Simulations

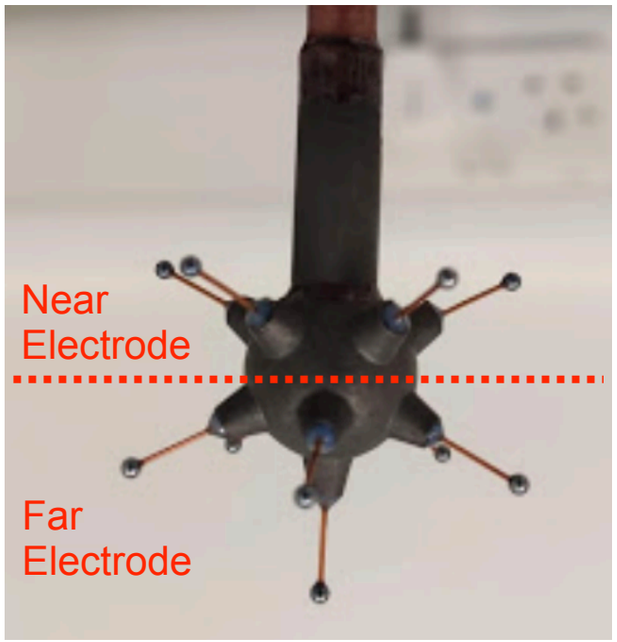
JINST 15 (2020) 11, 11



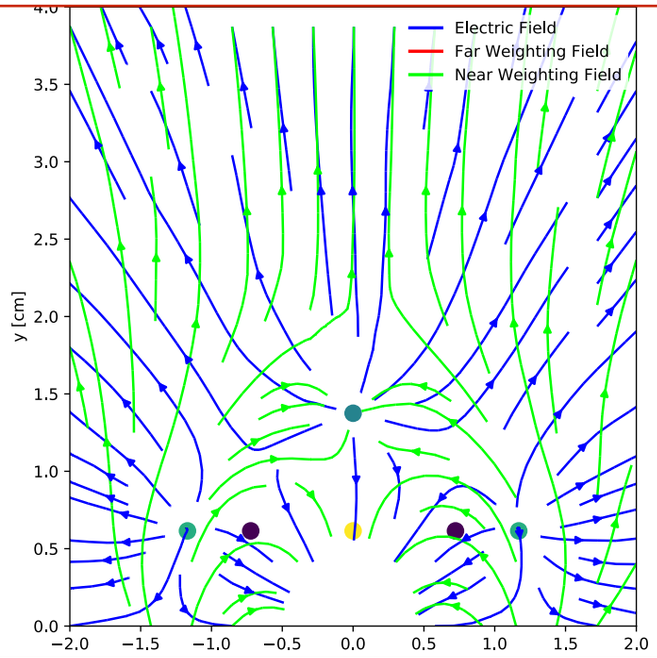


Towards individual anode readout

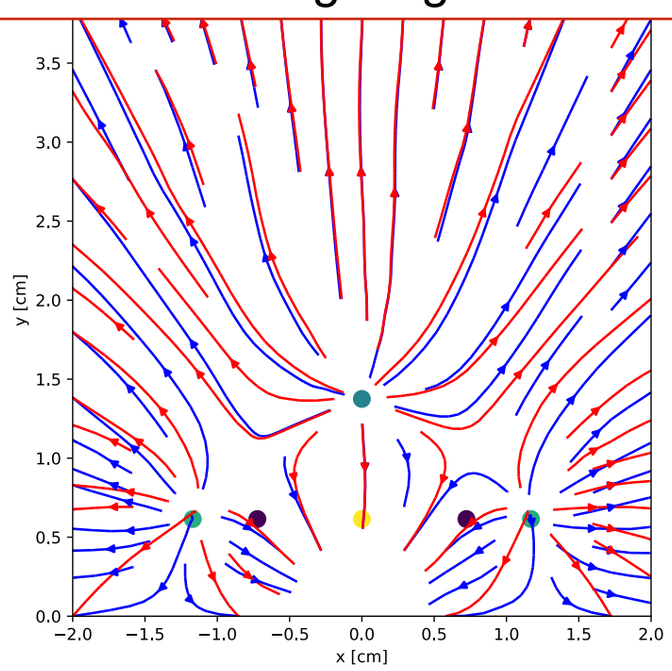
- Reading out individual ACHINOS anodes: position of interaction can be reconstructed
- First tests: Separate the anodes in two electrodes “Near” and “Far” (from the rod)

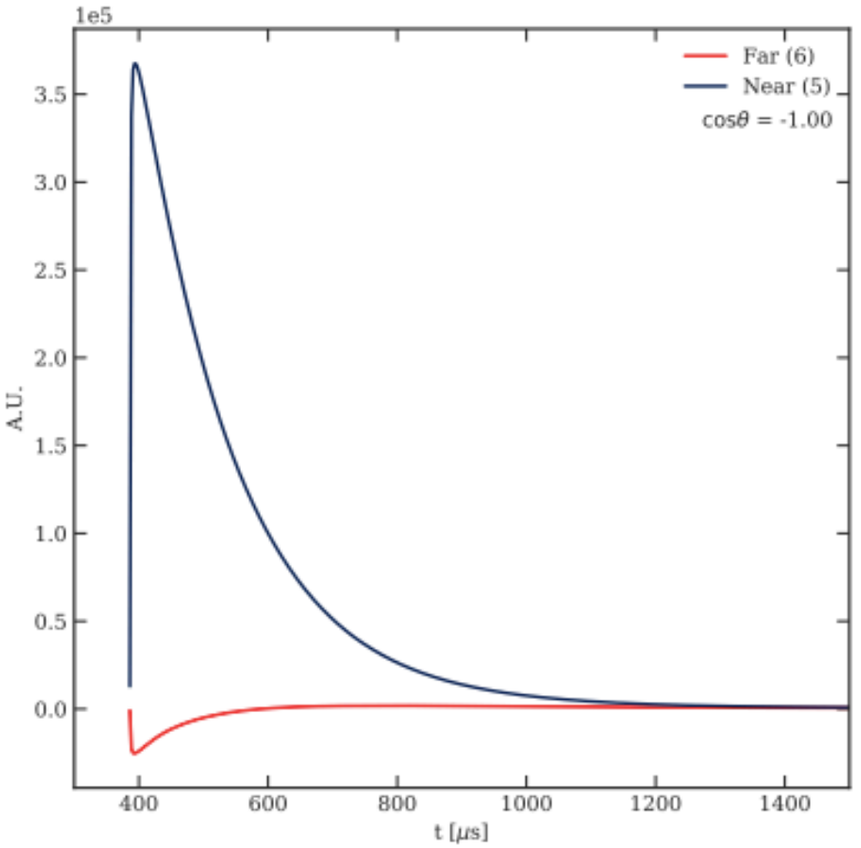


Near electrode weighting field on Far Side



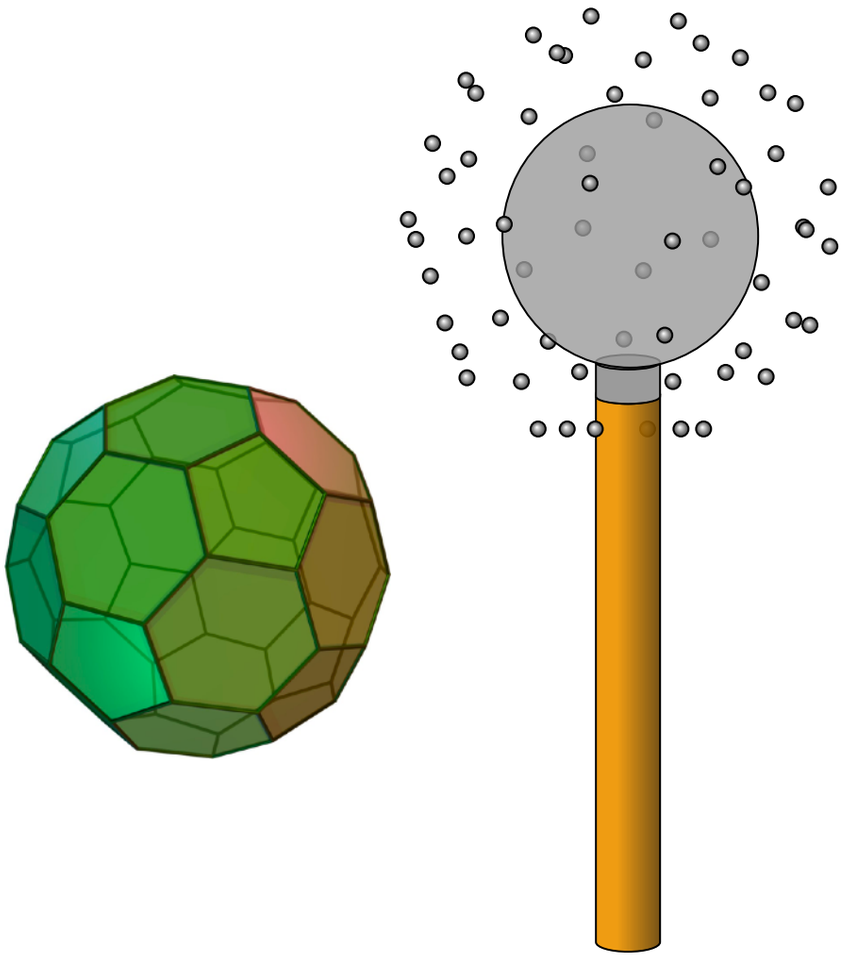
Far electrode weighting field on Far Side



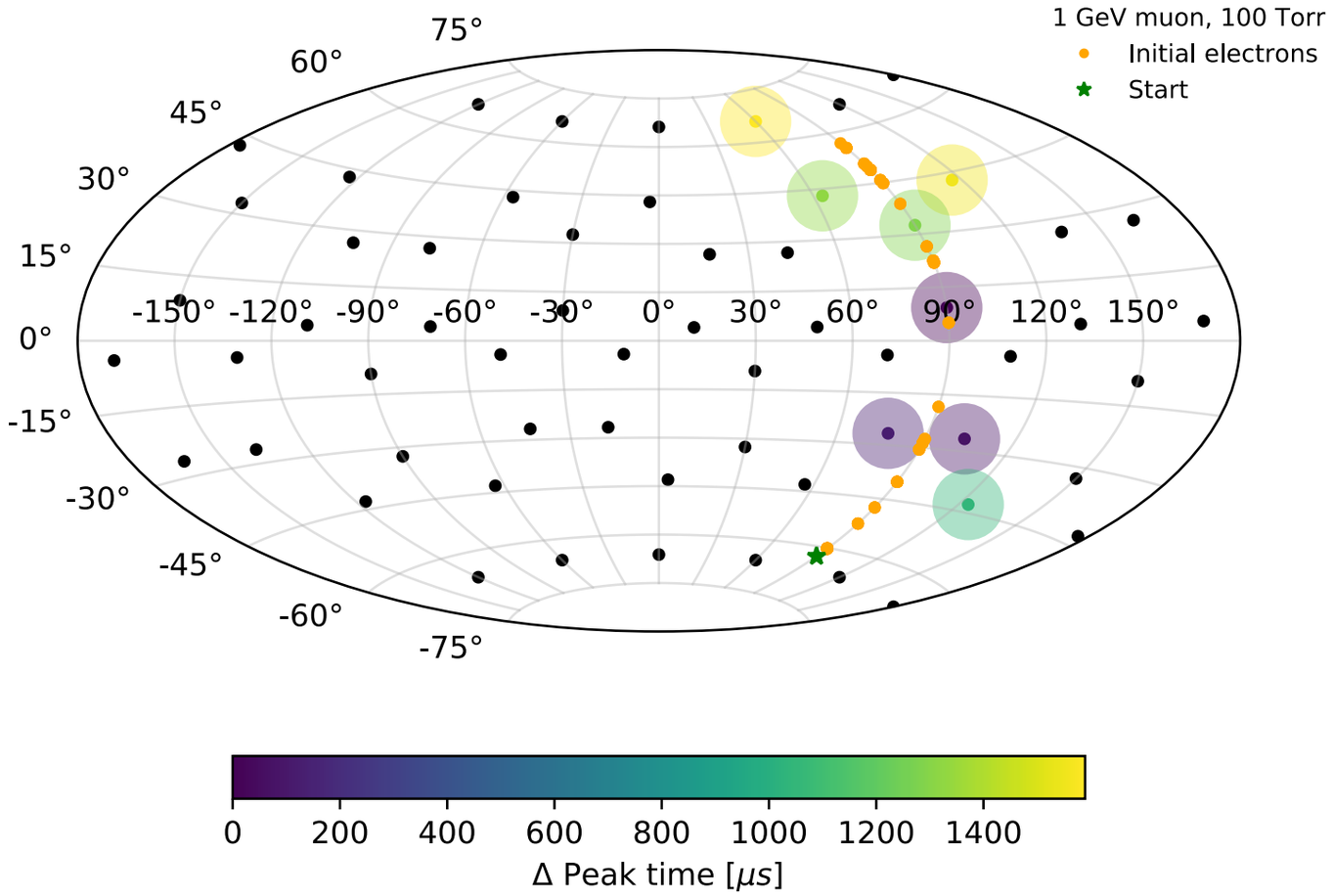


Event reconstruction

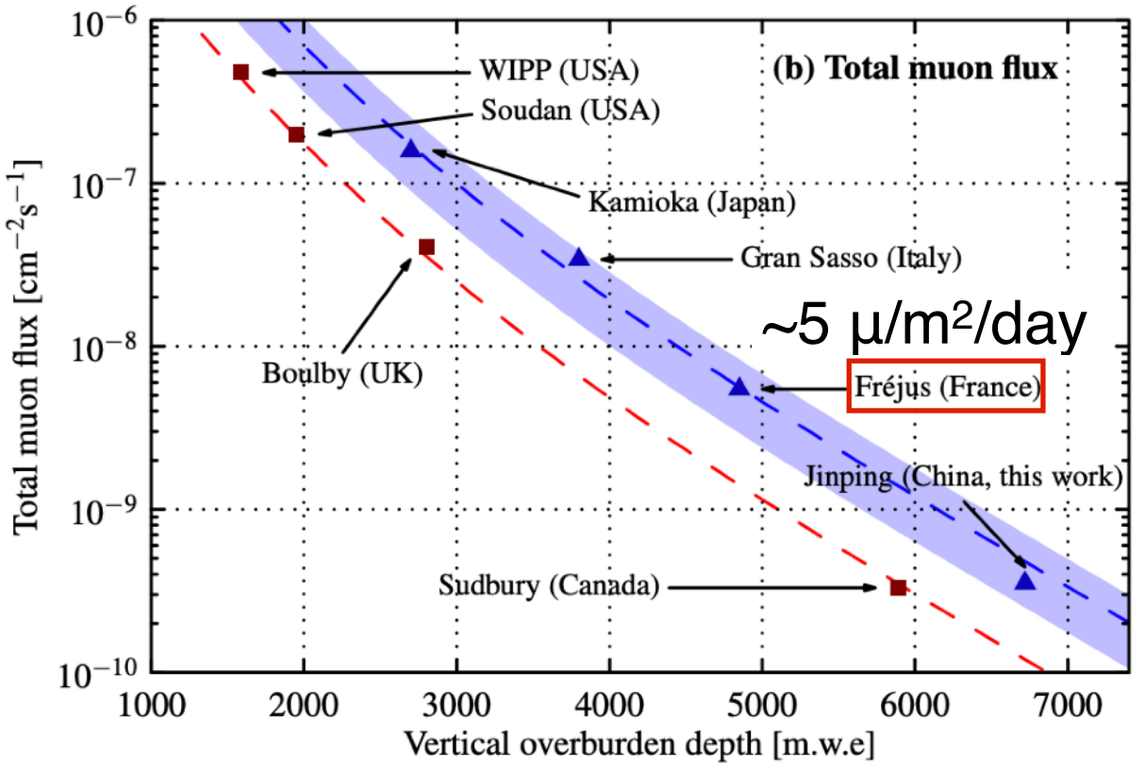
<u>In the future:</u> Individual anode read-out → track reconstruction



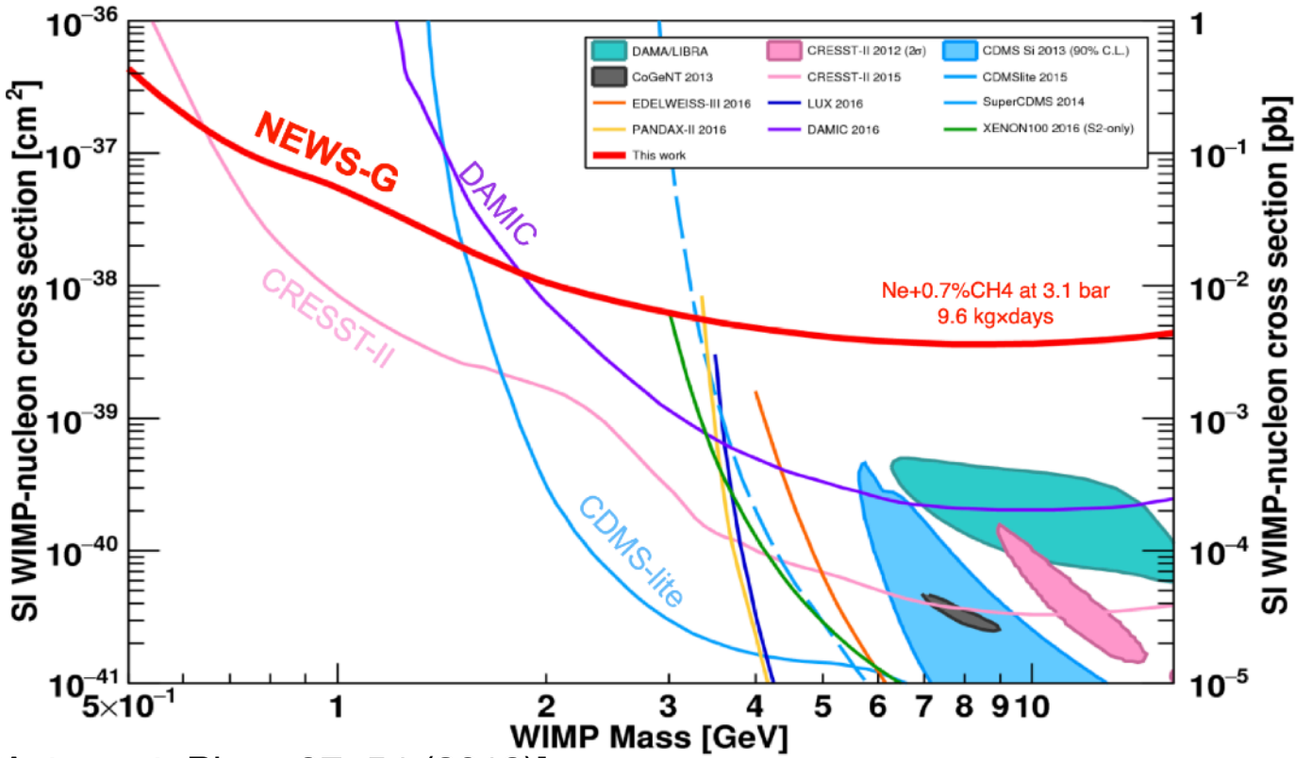
60-anodes (truncated icosahedron)



NEWS-G: Prototype at LSM

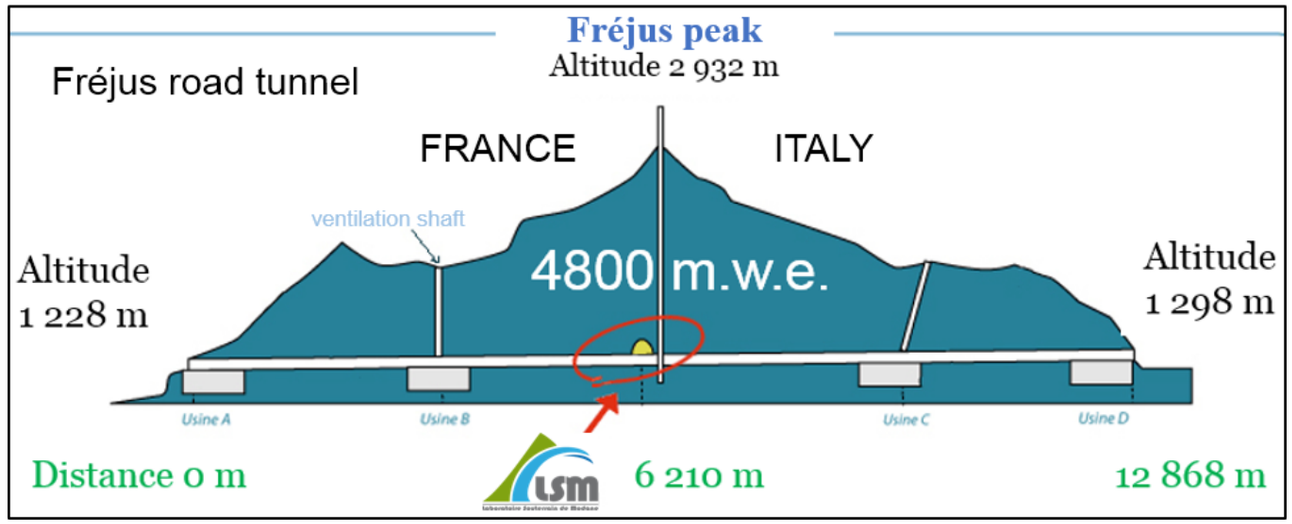


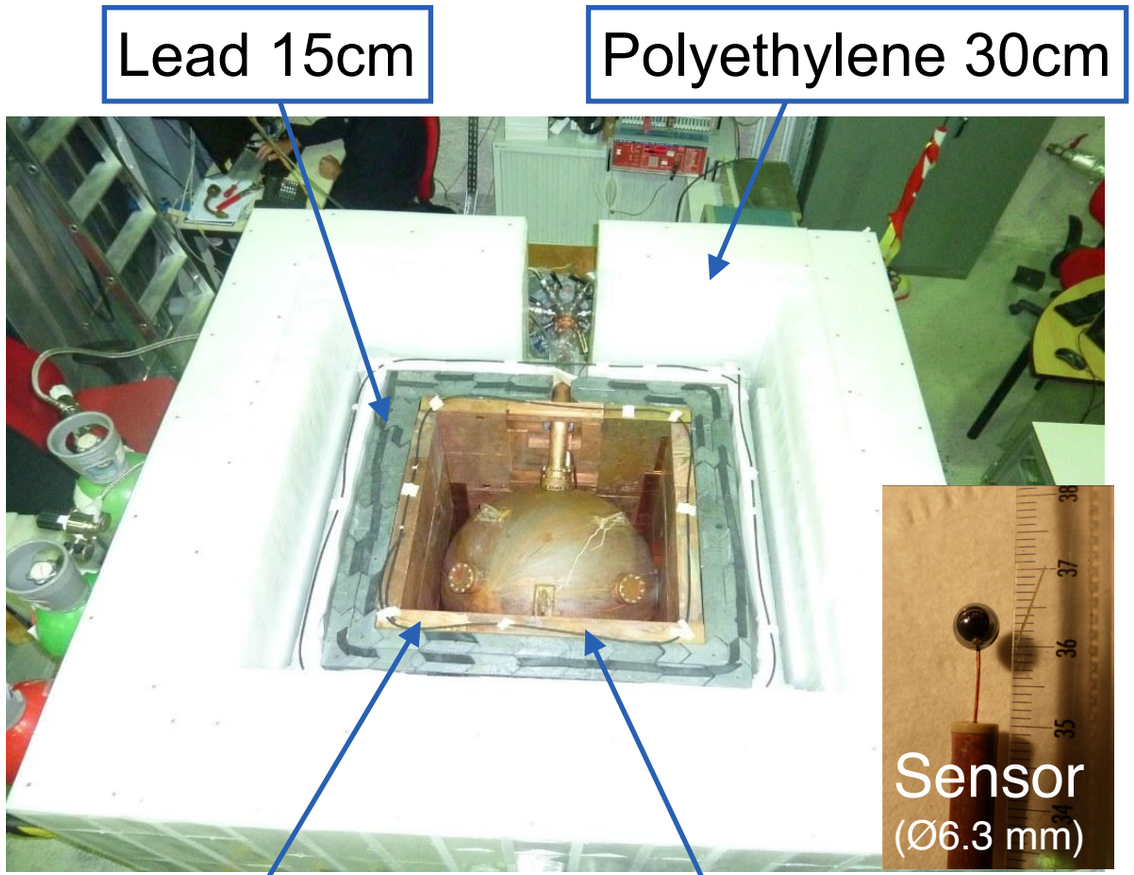
Chin.Phys.C 45 (2021) 2, 025001



[Astropart. Phys. 97, 54 (2018)]

Laboratoire Souterrain de Modane





Quenching factor: W-value measurements

- Various quenching factor definitions in the literature
  - fraction of ion kinetic energy dissipated as ionisation electrons and excitation of atomic and quasi-molecular states
  - ratio of the “visible” energy in an ionisation detector to the recoil kinetic energy
  - conversion factor between kinetic energy of an electron and ion that result to the same “visible” energy in the ionisation detector

Astropart.Phys. 141 (2022) 102707

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  - Typically, detector response calibrated with electrons of known energy

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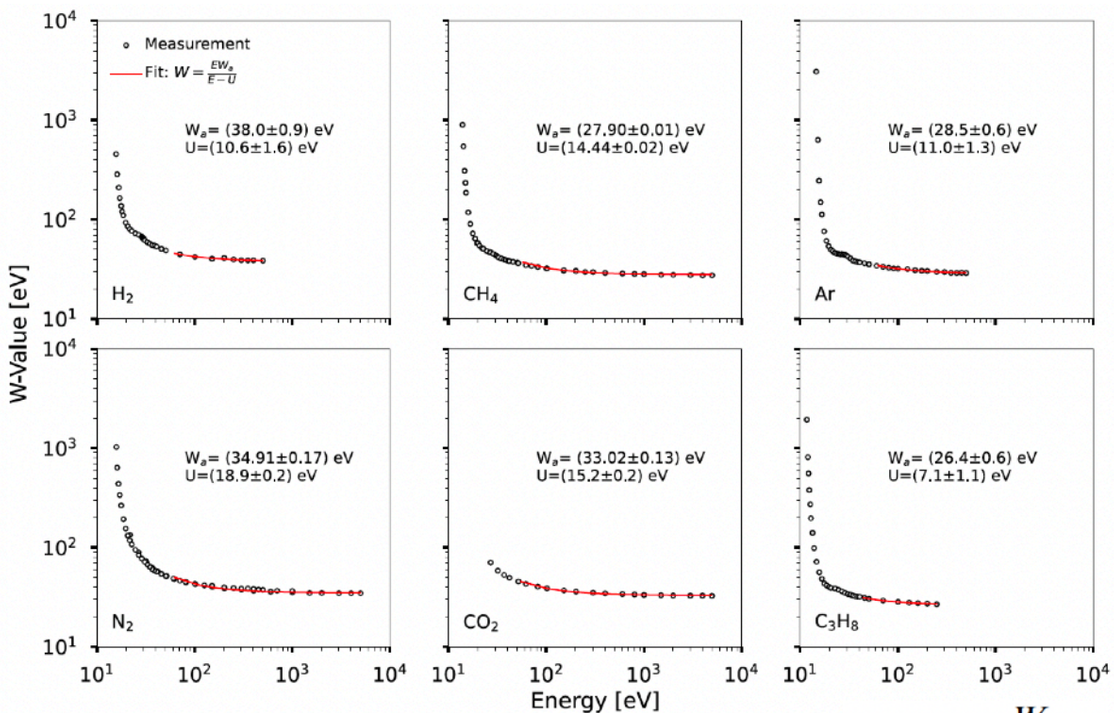

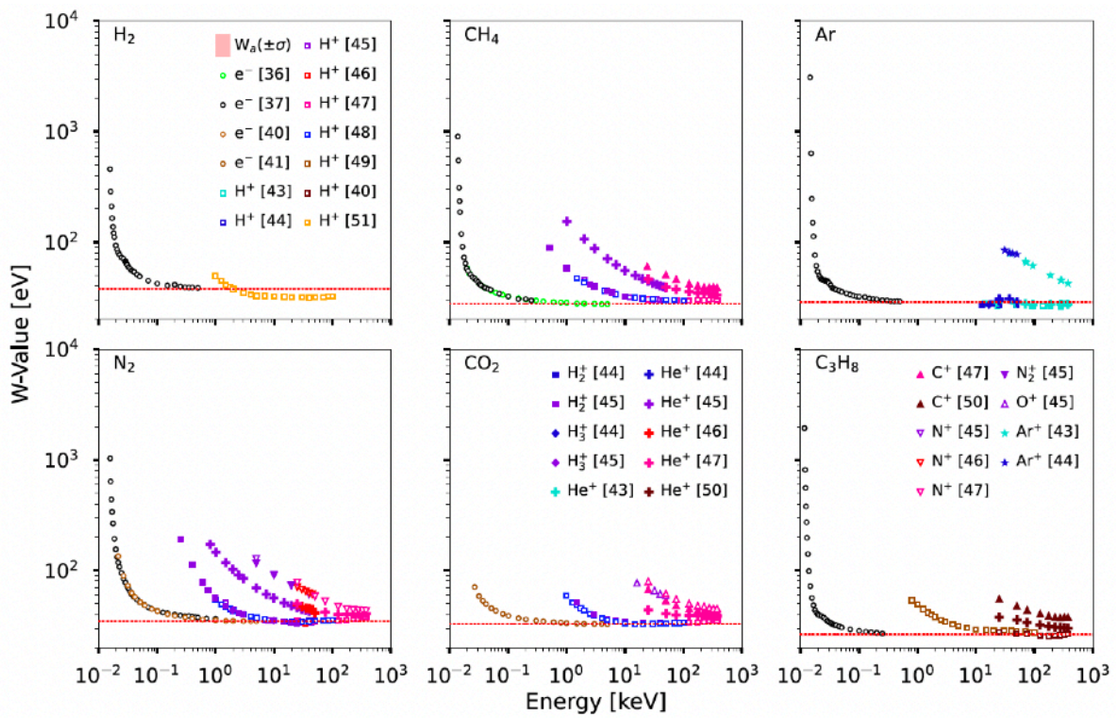

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$$W(E) = \frac{W_a}{1 - U/E}$$

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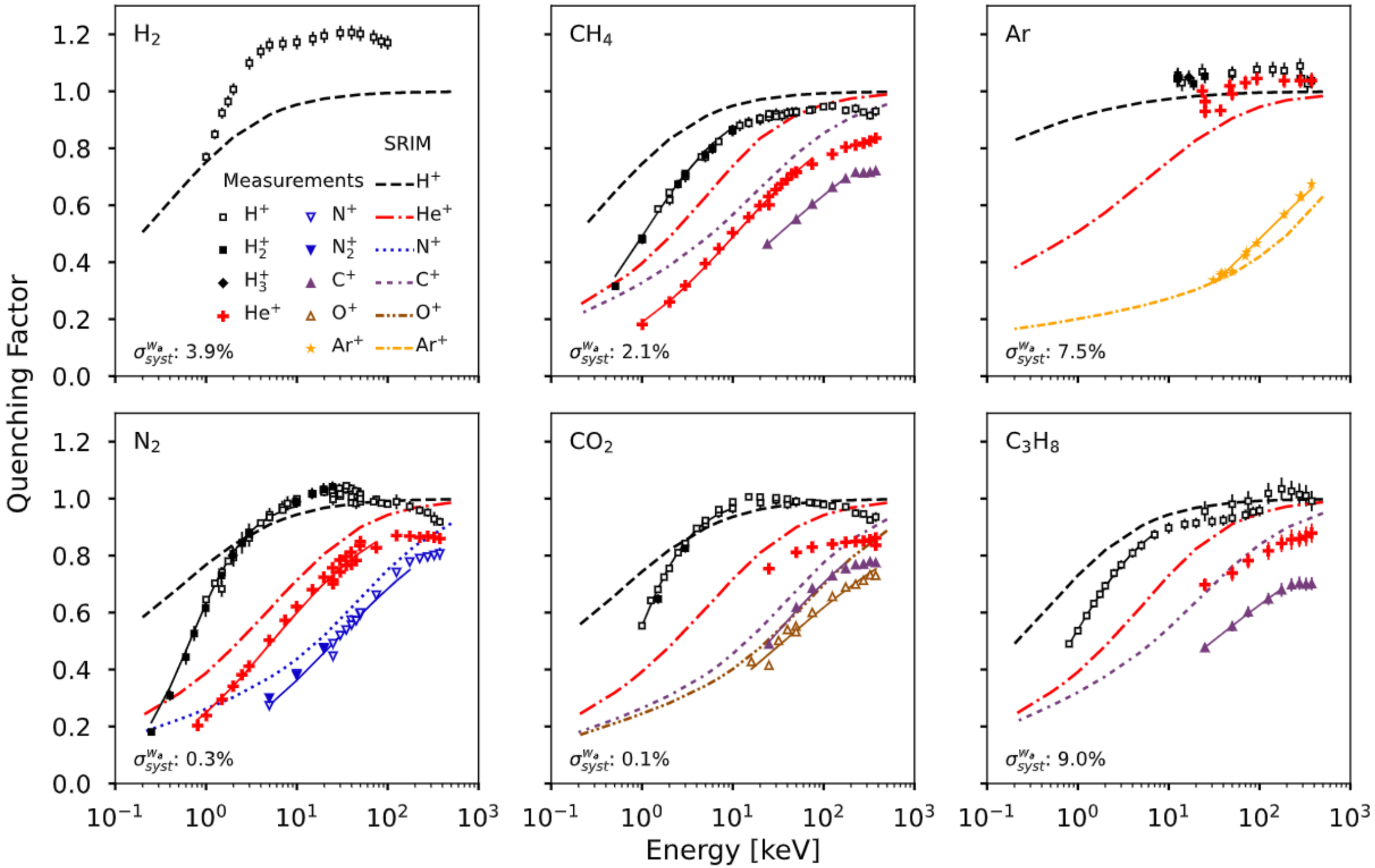

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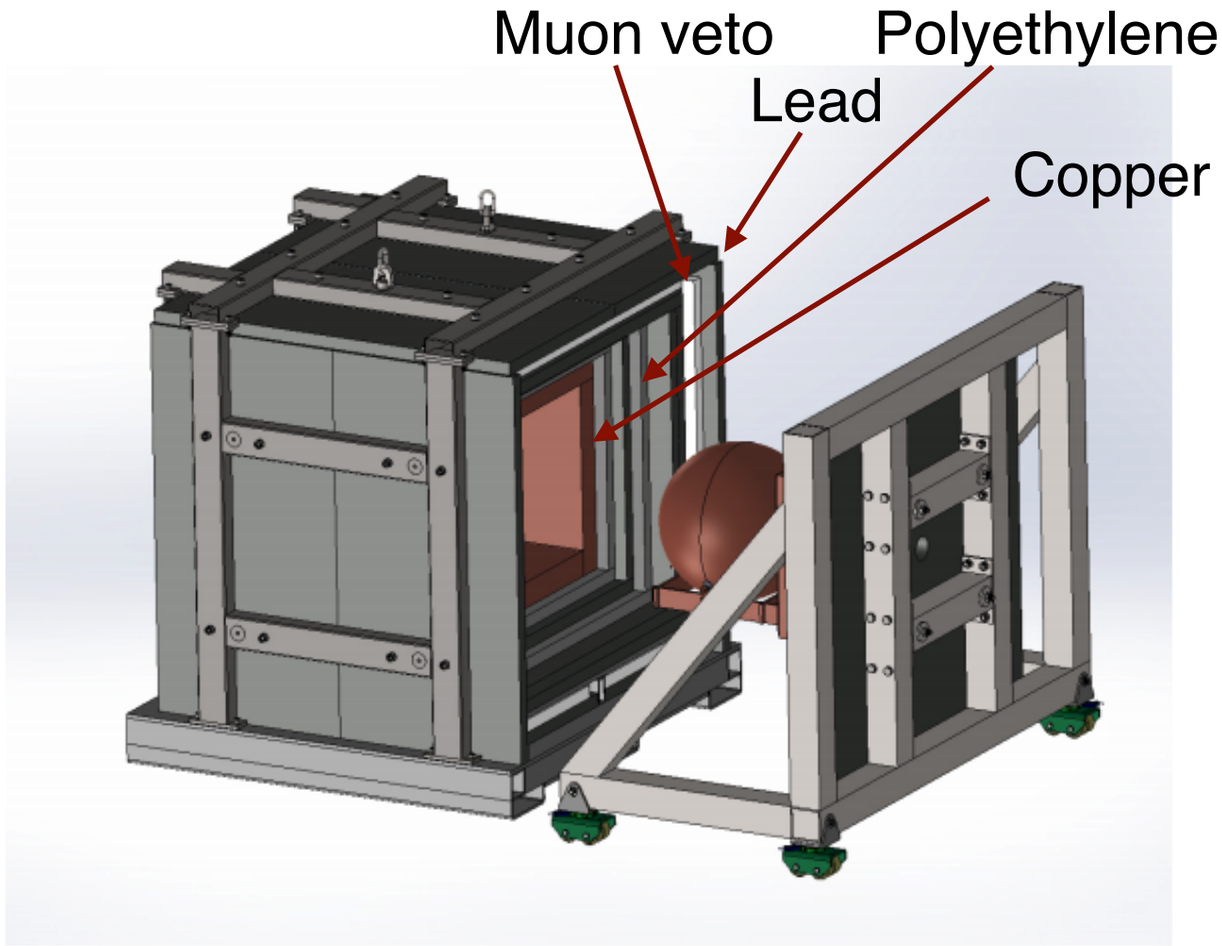
Coherent Elastic ν-Nucleus Scattering

- **CEvNS opens a window to investigation non-standard neutrino interactions**
  - First observations by COHERENT in NaI (2017) and Ar (2020)
  - Unique complementarity with DM searches as sensitivity reaches the neutrino floor
- **NEWS-G3: A low-threshold low-background sea-level facility**
  - Environmental and cosmogenic background studies towards reactor CEvNS studies
  - Shielding: Layers of pure copper, polyethylene, and lead, with active muon veto
  - Assembly has started



Detector Calibration

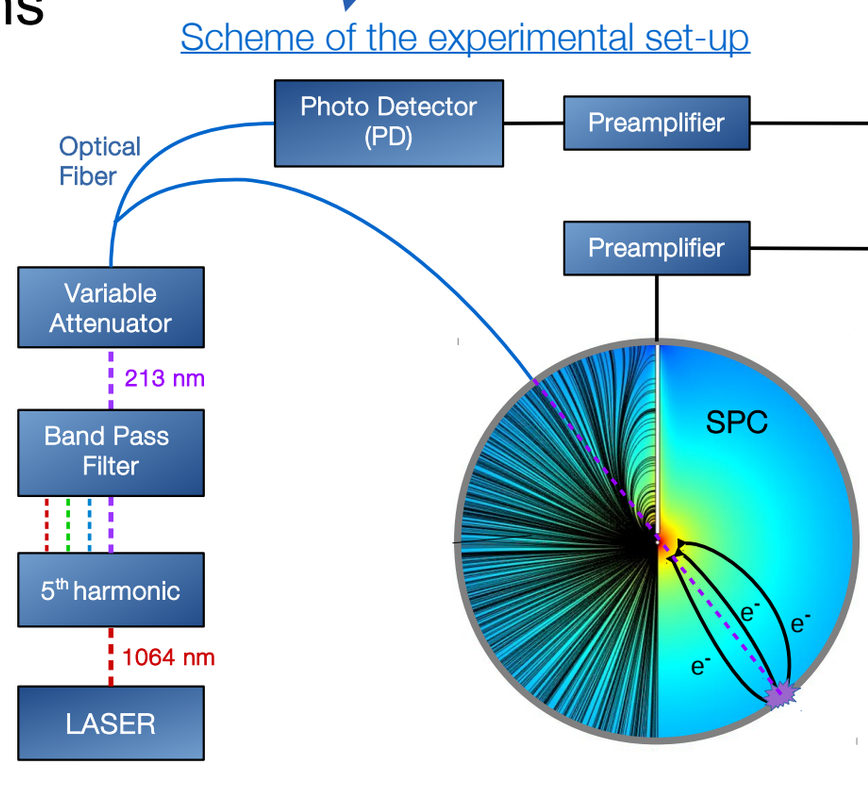
Phys. Rev. D 99, 102003 (2019)

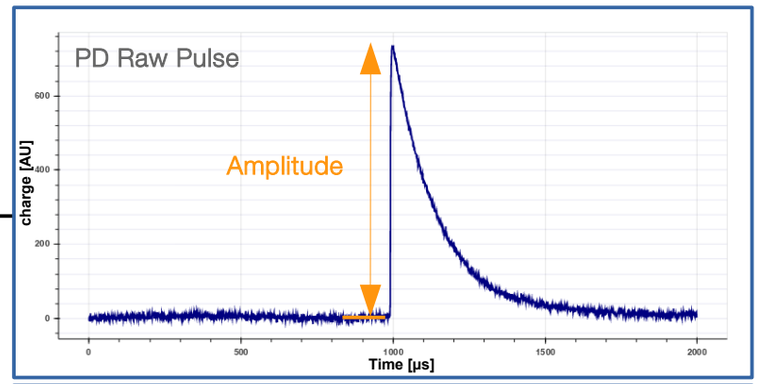
Parallel photo-detector to tag laser events

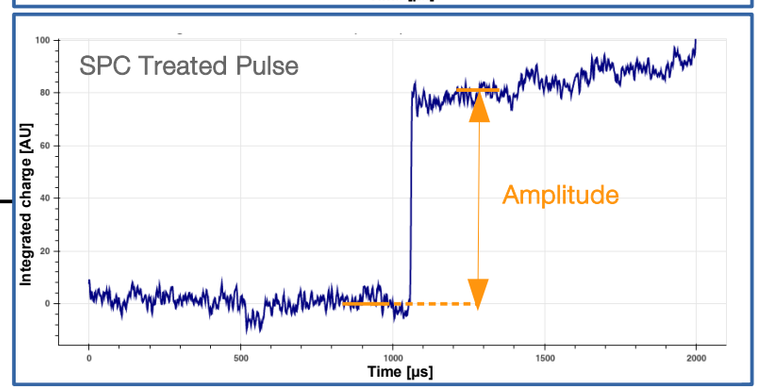
Tunable transmission to control the mean number of electrons

Common DAQ for timing analysis between two channel

Scheme of the experimental set-up







A powerful UV laser capable of extracting 100s of electrons

- 213 nm laser used to extract primary electrons from detector wall
- Photo-detector in parallel tags events and monitors laser power
- Laser intensity can be tuned to extract 1 to 100 photo-electrons

Modelling Single Electron Response

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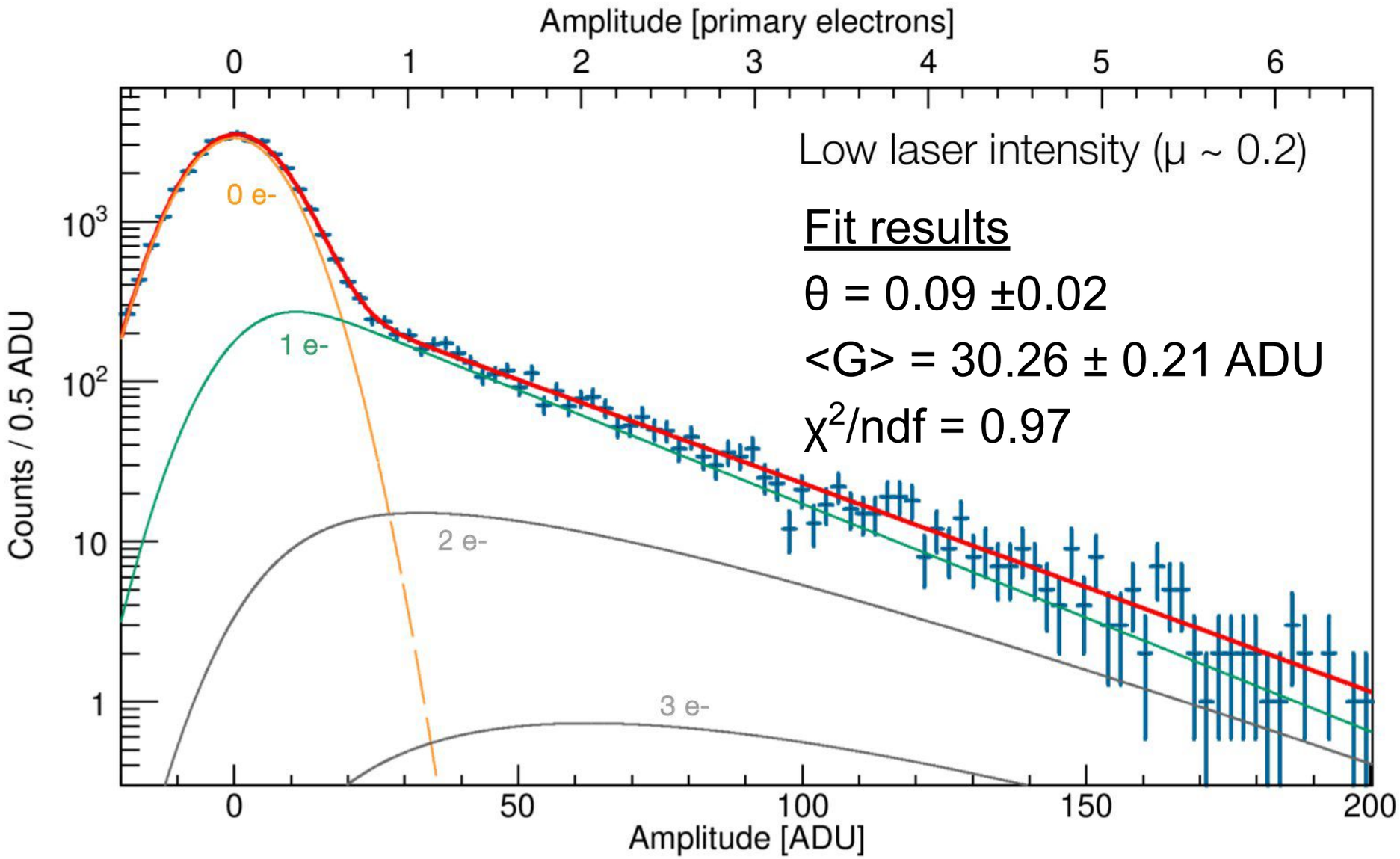
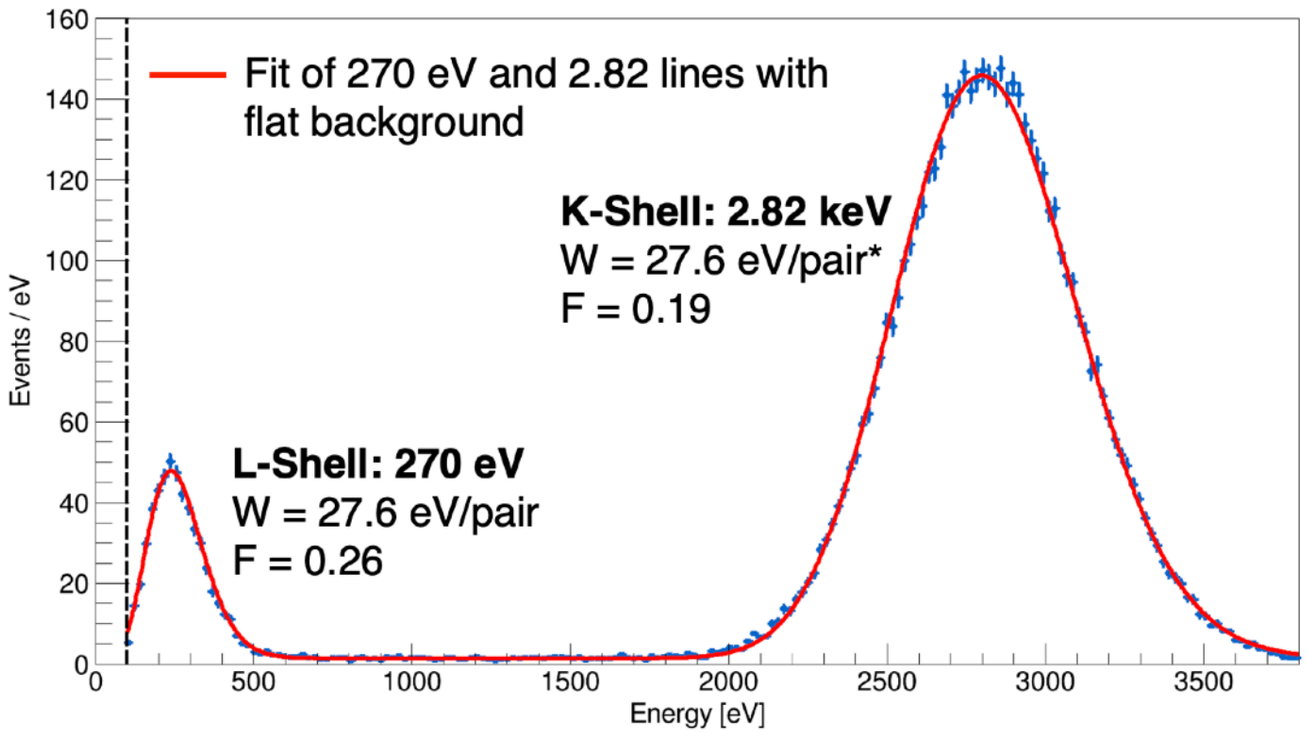


- N photo-electrons are extracted from the surface of the sphere: Poisson
- Each photo-electron creates S avalanche electrons
- Sum the contributions of all N photo-electrons: N^{th} convolution of Polya
- The overall response is convolved with a Gaussian to model baseline noise

Detector Monitoring

- Long runs, response fluctuations induced by:
  - temperature/pressure changes
  - O_2 contamination
  - sensor damage
  - …
- ^{37}Ar calibrations
  - crucial information
  - can only be used at the end of a run
- Laser system
  - detector response monitoring in physics runs



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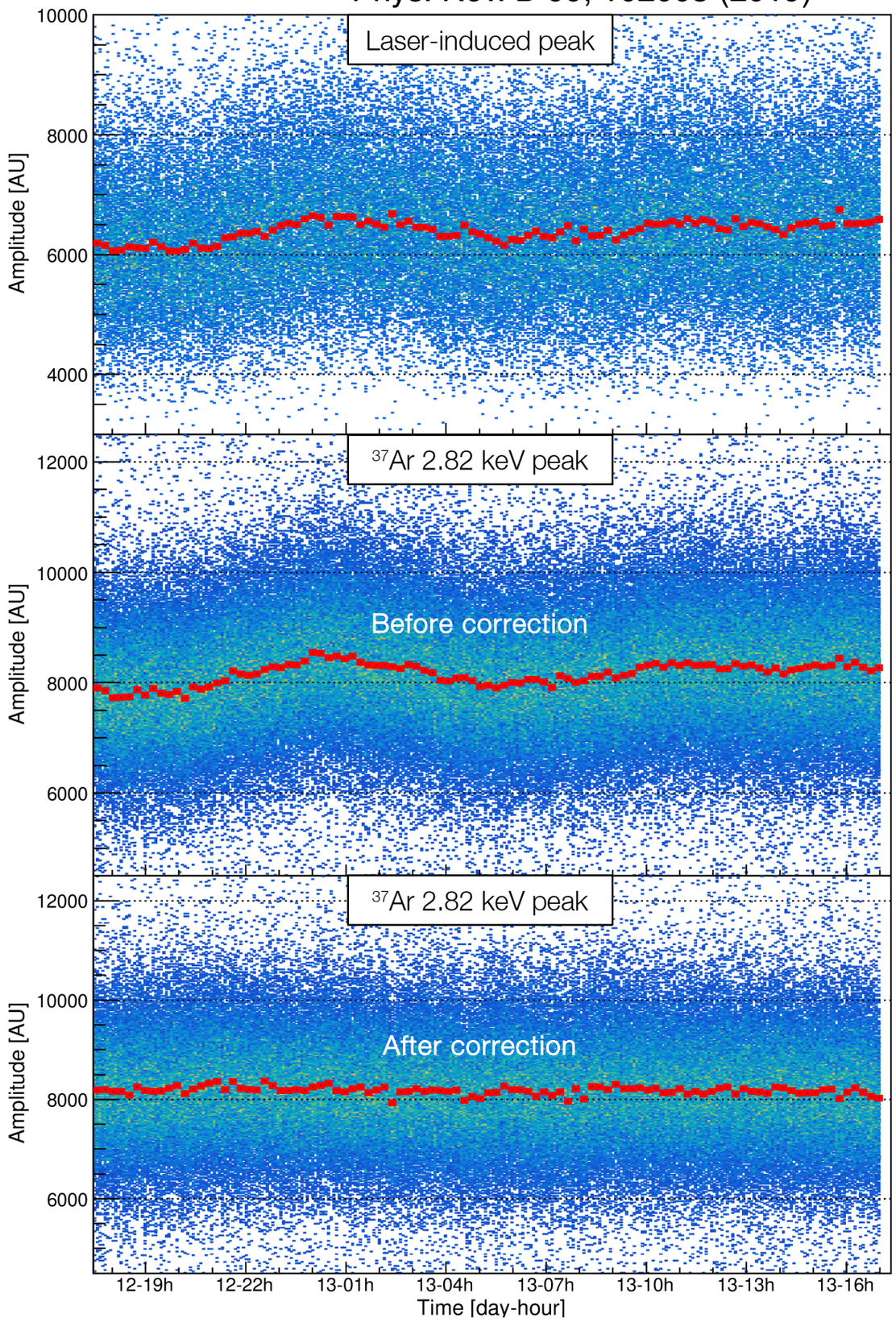
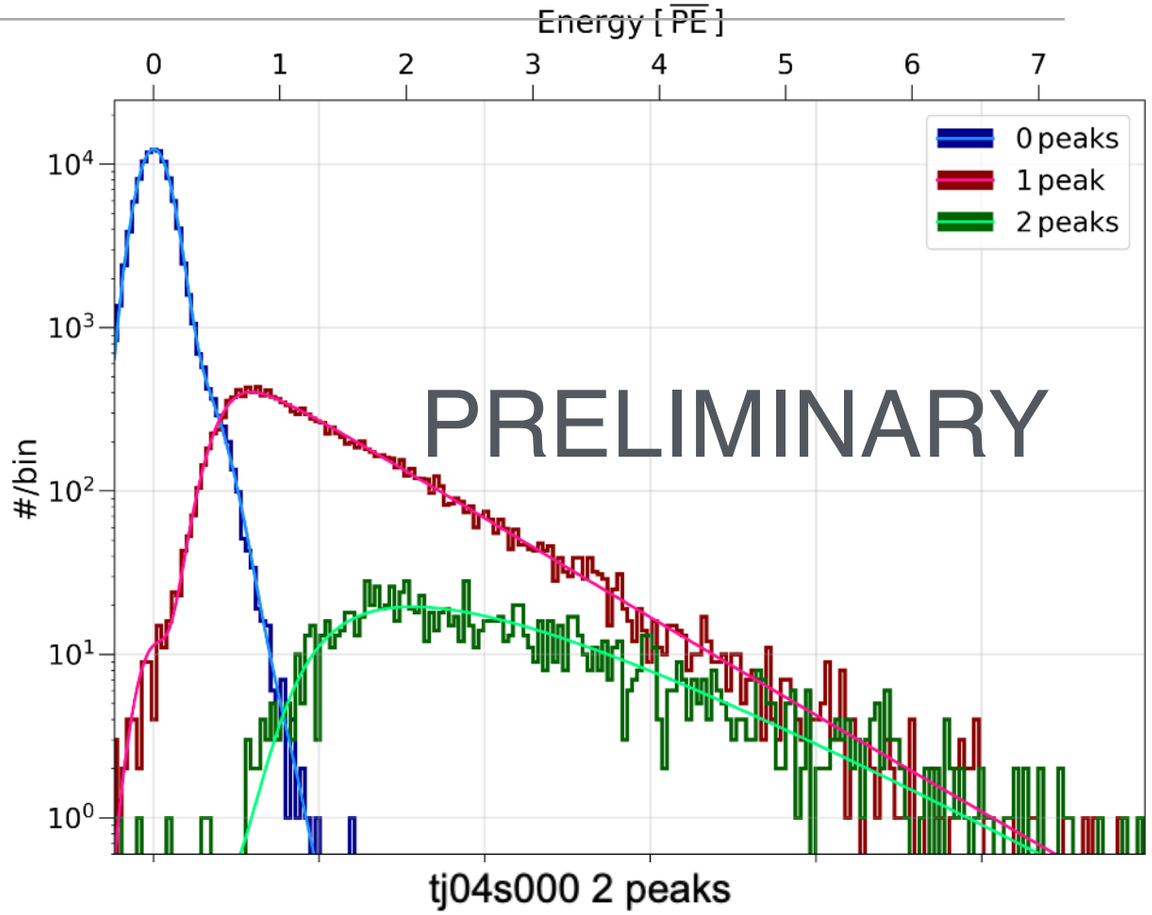
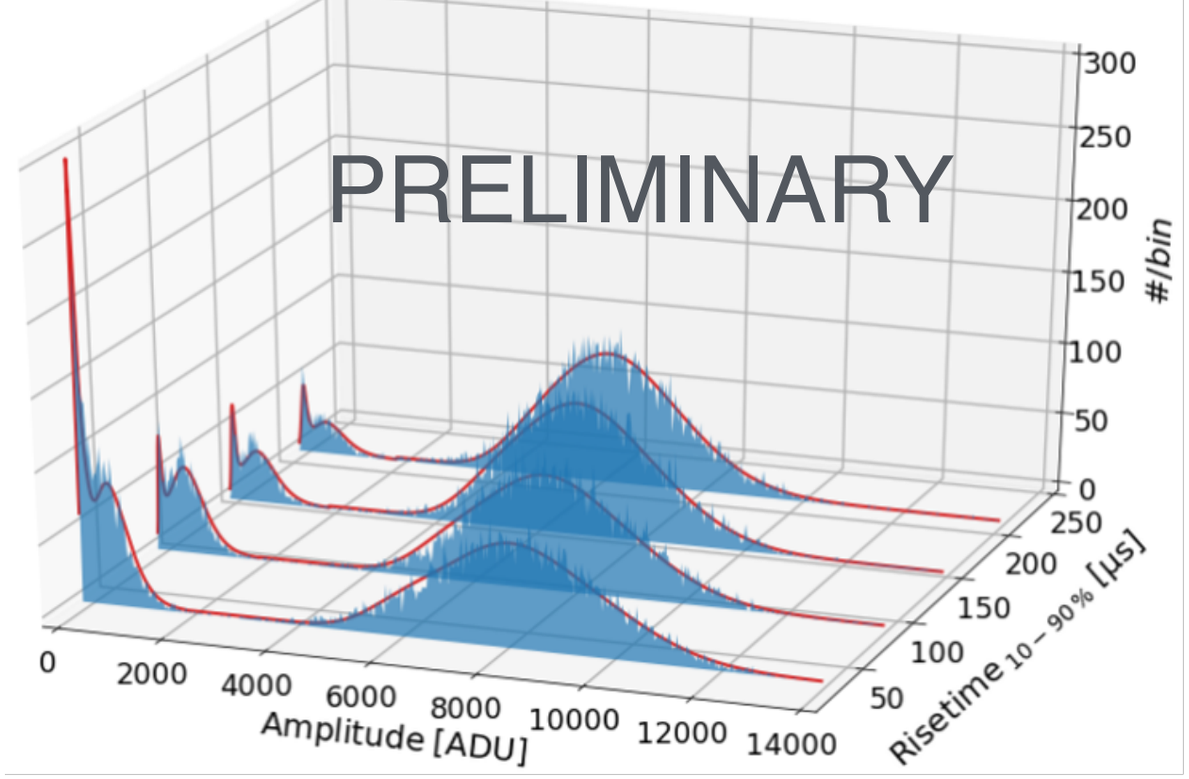
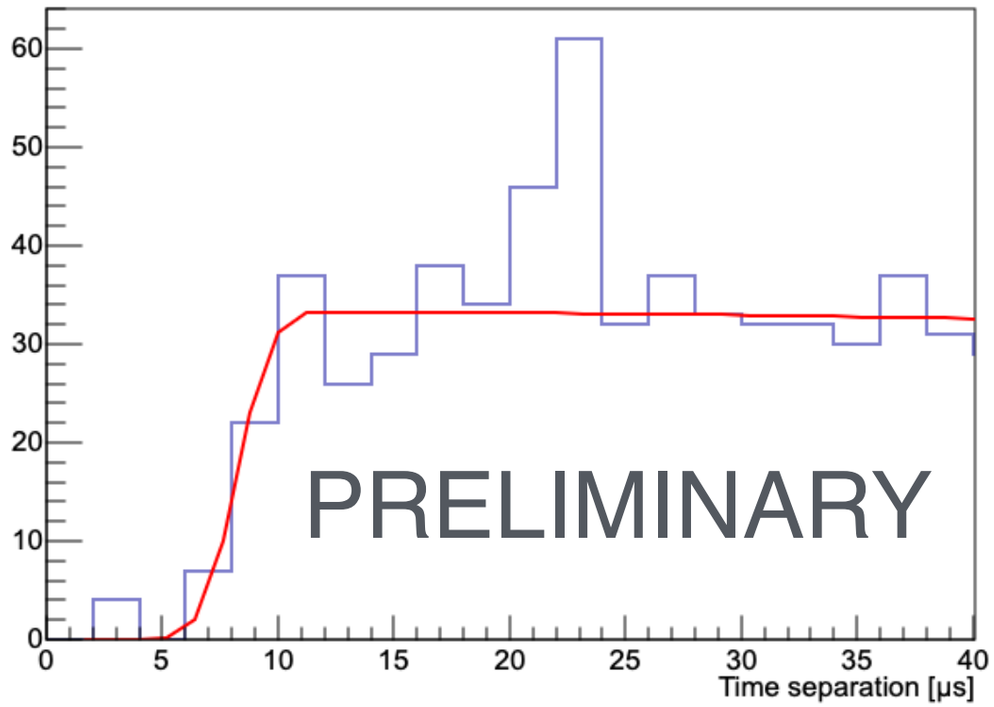


Electron counting characterisation

- Low-intensity, 213nm UV-laser extracts electrons from copper surface
  - Characterise avalanche gain and peak-counting
  - Electron detection efficiency: 60%
  - Separation of electron peaks above 8 µs
- ^{37}Ar injected at the end of physics campaign
  - (almost) mono-energetic lines at 200 eV, 270 eV, and 2.8 keV
  - detector response monitoring in physics runs

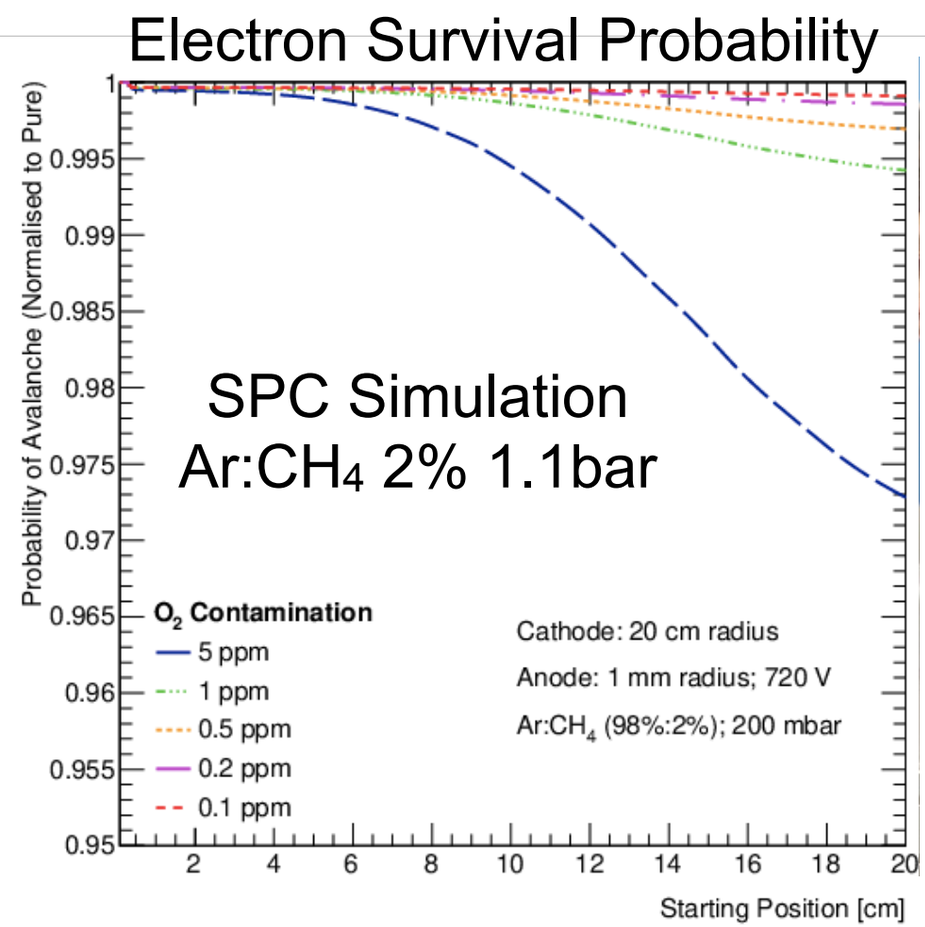






Gas Purification

- Gas purification required to avoid contaminants: O_2, H_2O, electronegative gases
  - Maintain high electron collection efficiency for large volumes
- Challenge: Radon emanation from purifiers
- Custom-made filter prepared in collaboration will Univ. Liverpool
  - Small number of controlled components
  - Assay emanation of individual components
  - *Tests at Univ. Birmingham and Univ. Zaragoza → interesting beyond NEWS-G*



Filter activation

UOB-F1

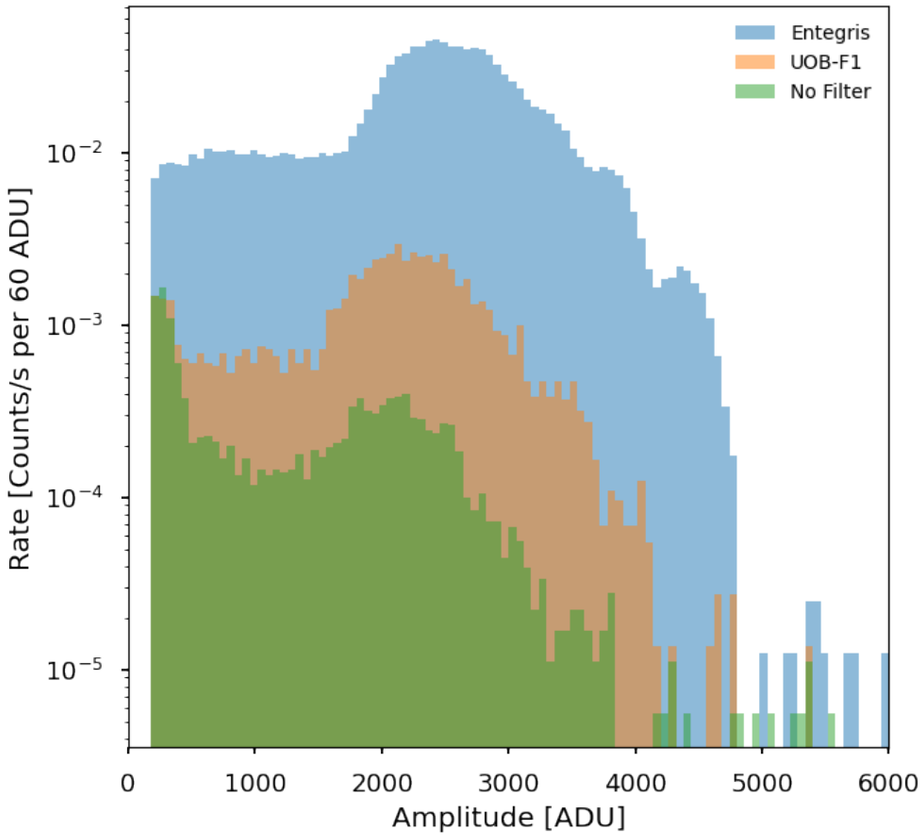
Copper Oxide
O_2 Removal

Molecular Sieves
H_2O Removal

UOB-F2 → Only H_2O component

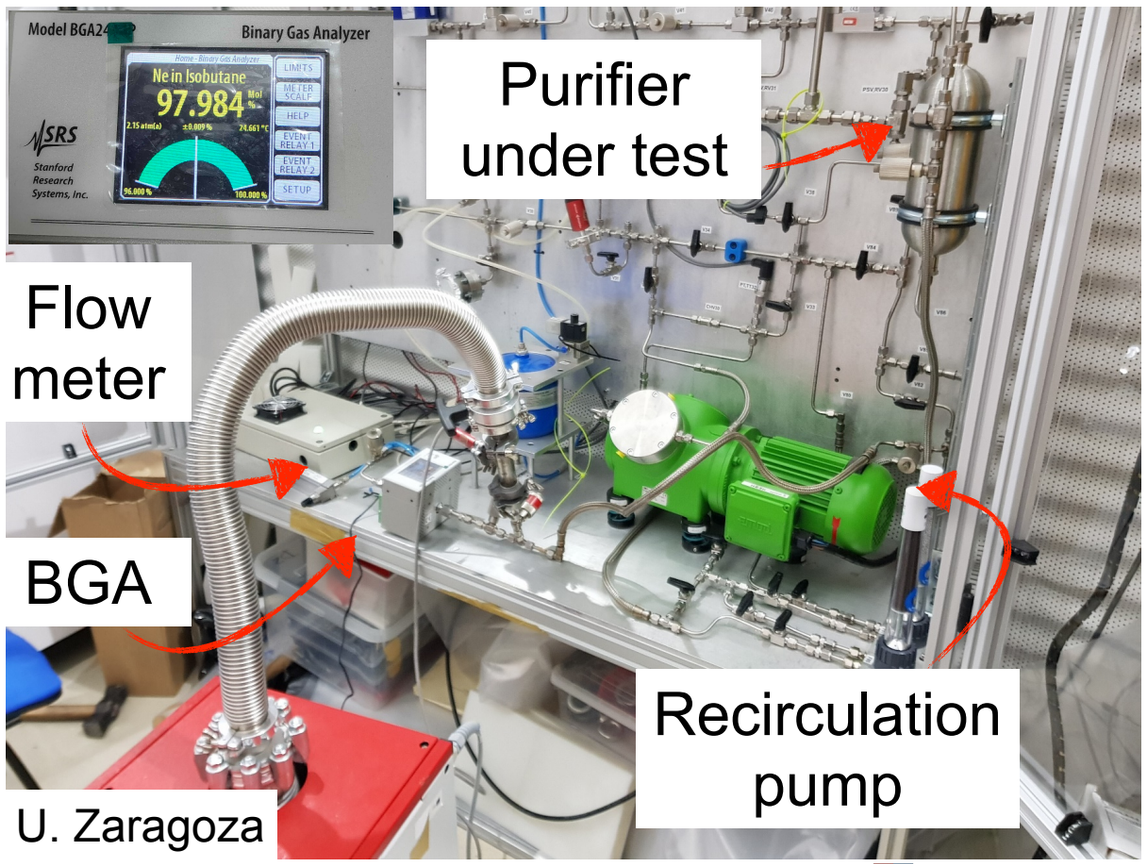
UOB-F3 → Only O_2 component

Gas Purification



- ^{222}Rn emanation tested with Single-Fill mode
  - Controlled injection through purifier at 3mbar/s
- No filter: 0.014Hz
- Entegris: 1.2 Hz
- UOB-F1: 0.06 Hz

- Purifiers may affect gas composition
  - e.g. remove larger molecules: CH_4, iC_4H_{10}
- UOB-F1 tested at Zaragoza
  - Ne:iC_4H_{10}(2%) with 2% relative uncertainty
- No change in gas composition observed



K. Altenmüller et al. N-33-03 IEEE NSS 2021