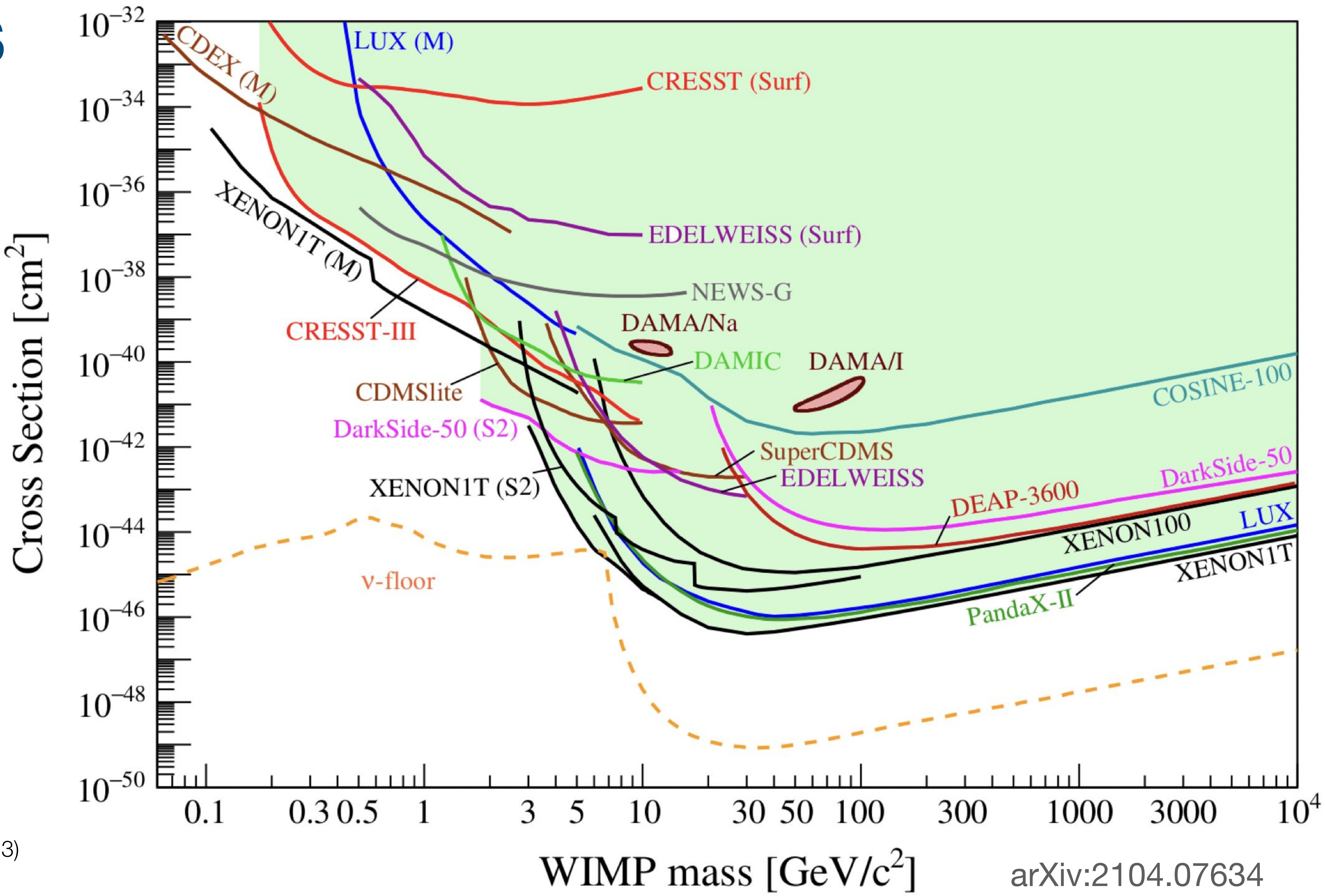
Search for light Dark Matter with a spherical proportional counter

Francisco Vazquez de Sola

ICHEP, Prague, July 2024

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



arXiv:2104.07634

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[3] K.M. Zurek, Phys. Rep., 537(3), 91 (2014)
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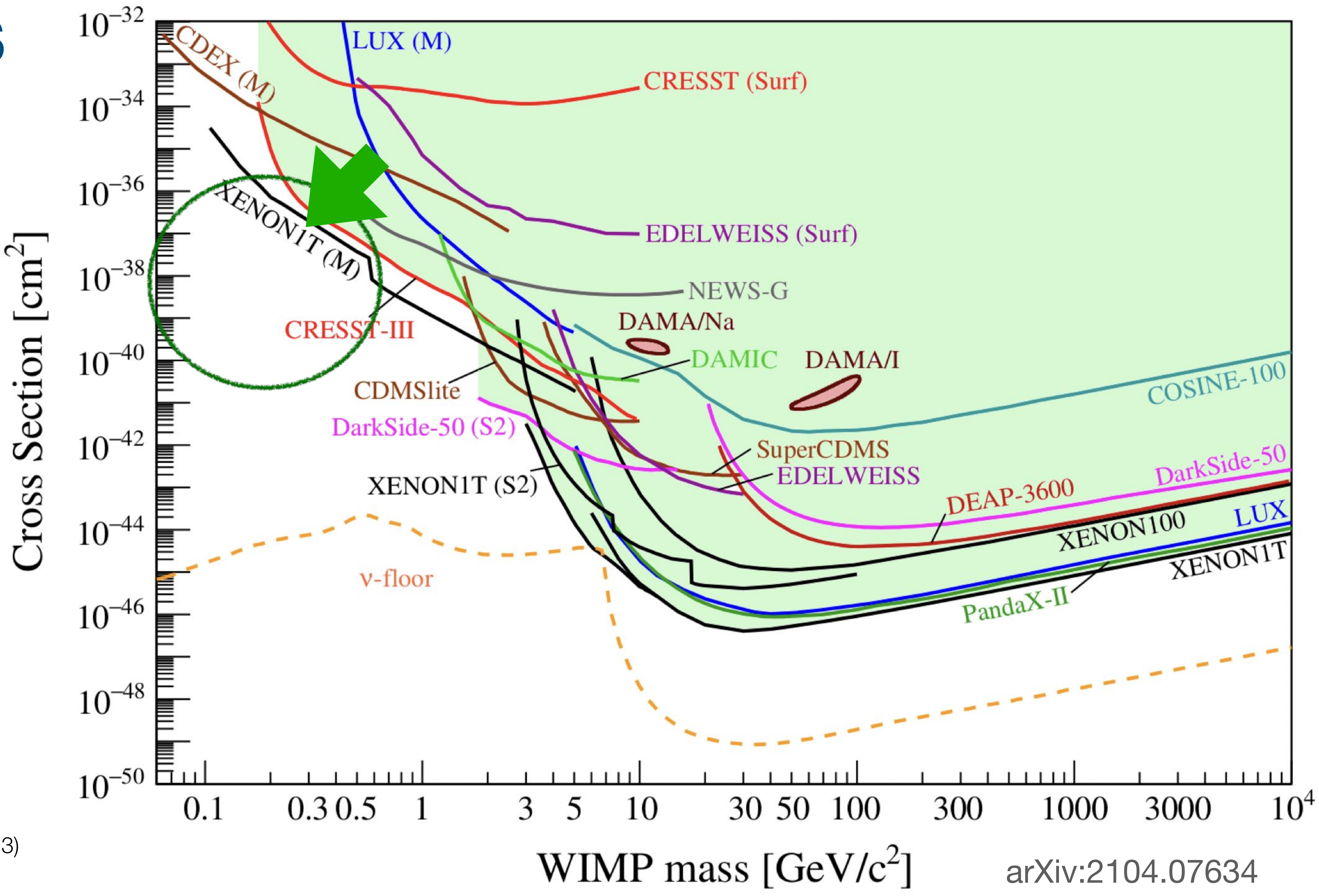

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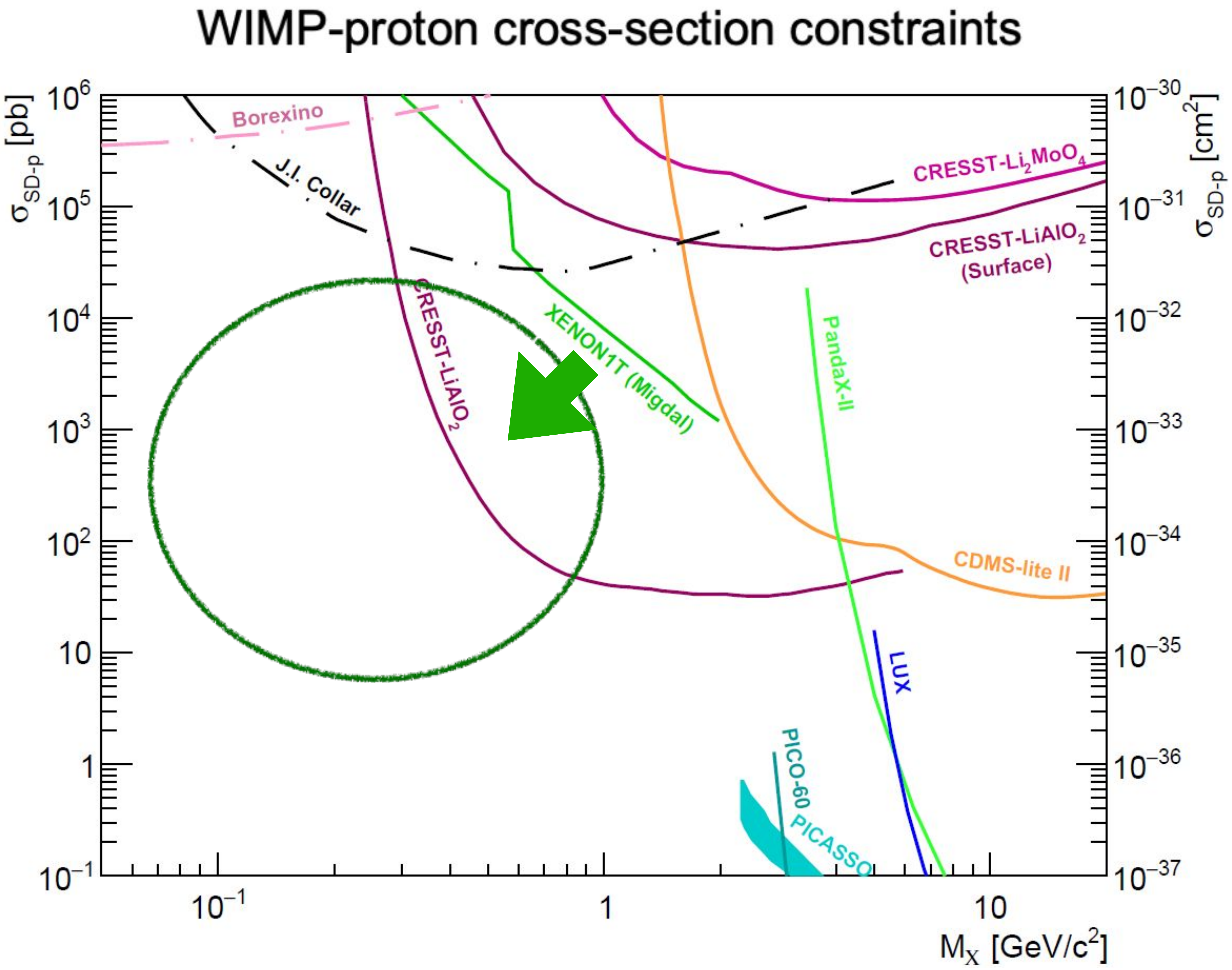

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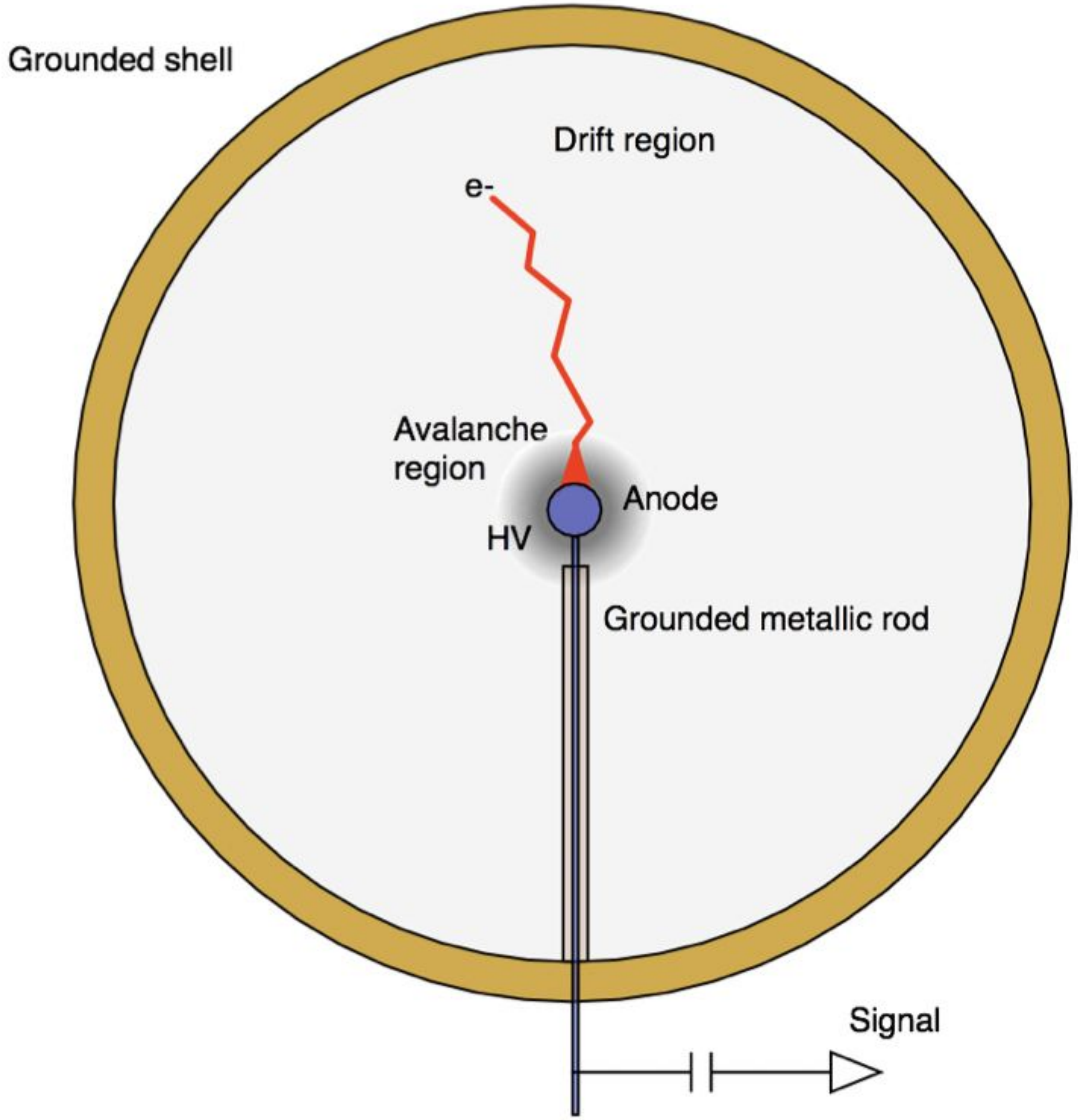
Spherical Proportional Counter

Working Principle

Ionisation detector

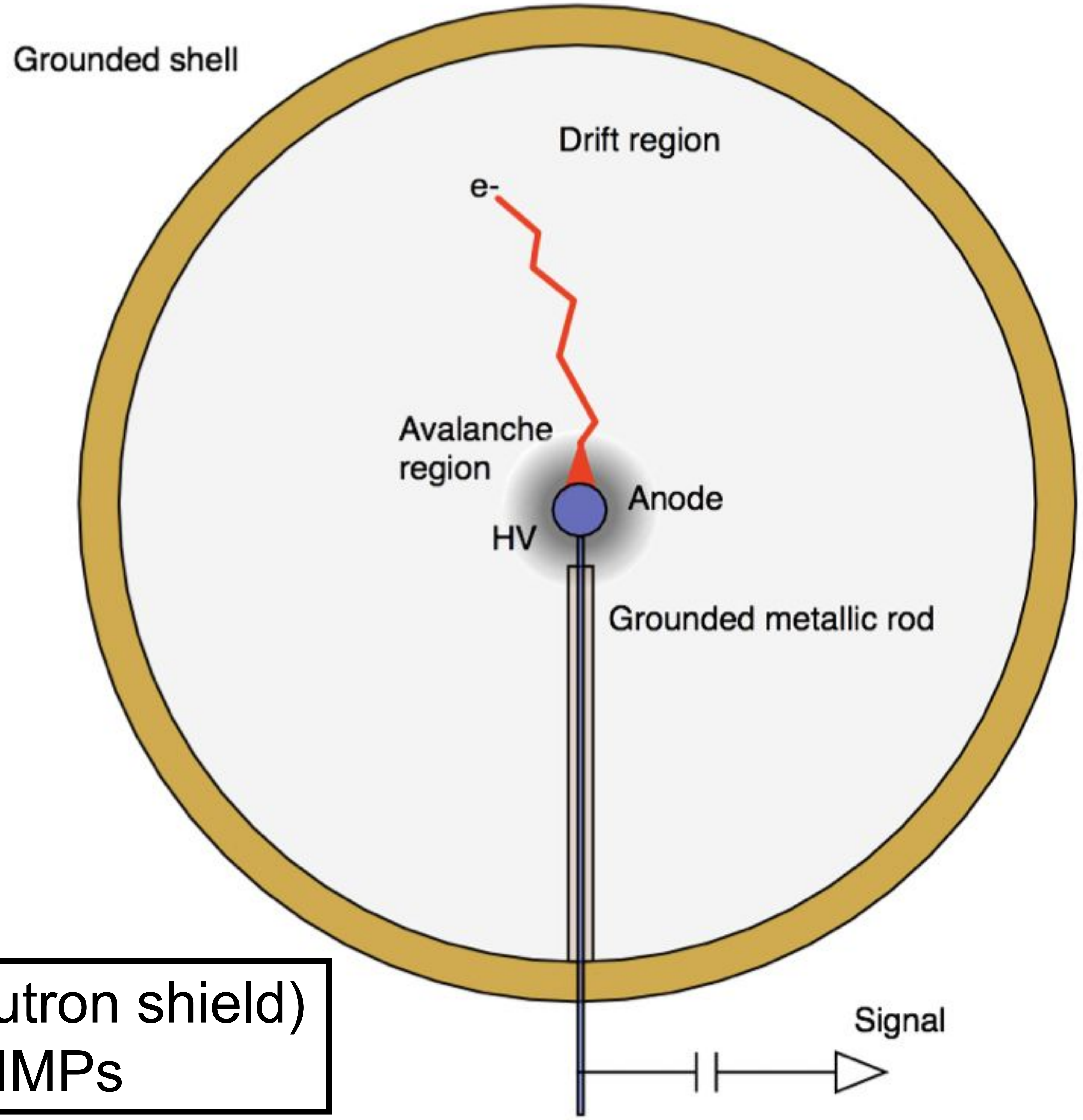
- Incident particle induces recoil, ionizing gas molecules
- Primary electrons drift and diffuse towards central anode
- High field in $1/r^2$ at anode produces $\sim 10^3$-10^4 avalanche multiplication
- Drifting ions induce current on anode



Spherical Proportional Counter

Advantages

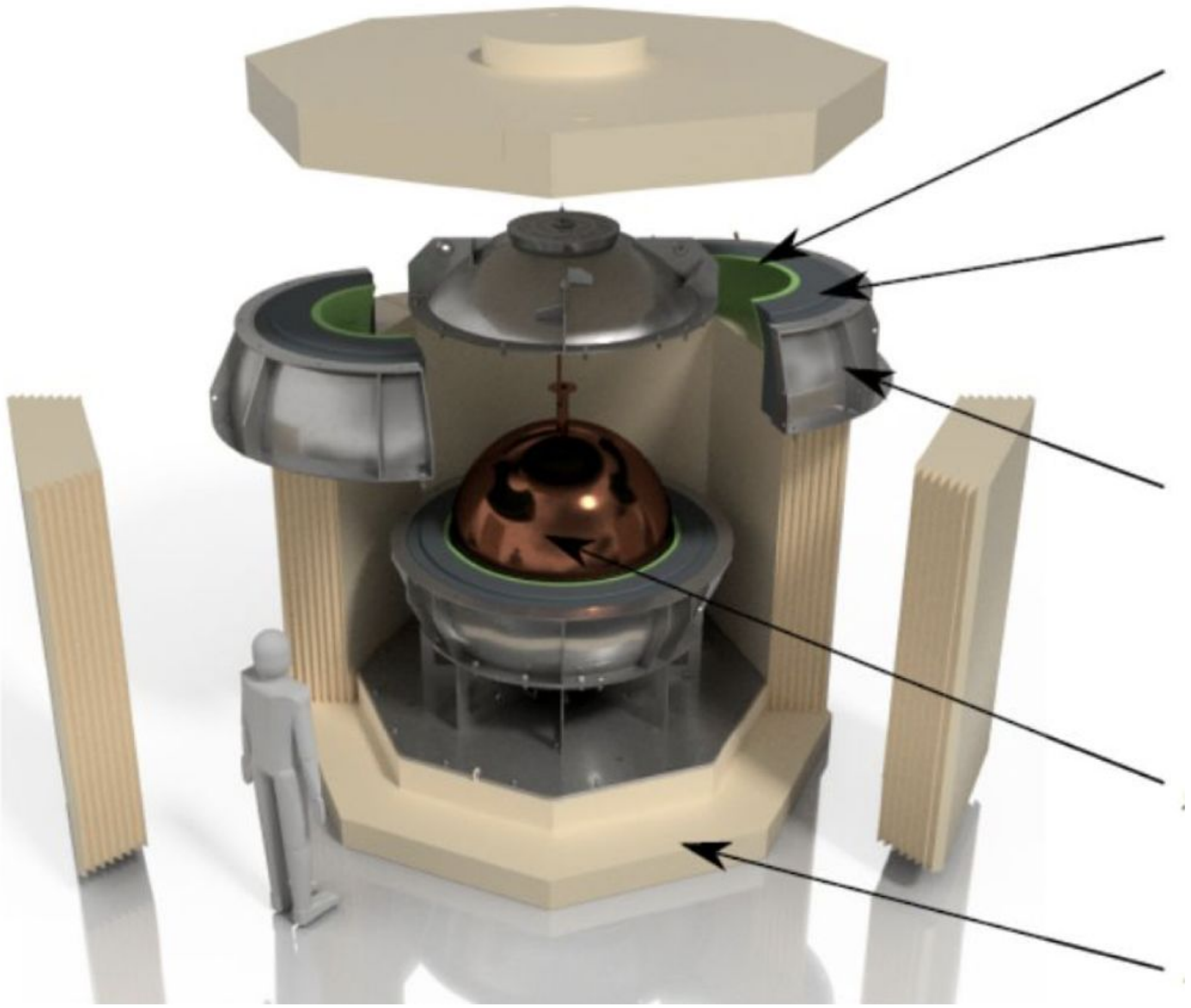
- Low capacitance + high gain -> single electron threshold
- Variable gas (H, He, Ne) & pressure choice for different physics goals
  - Light target : better kinematic match with light WIMPs
- Radiopurity of materials
- Pulse-Shape Discrimination to differentiate surface/volume backgrounds



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

S140

« SNOGLOBE »



3 cm of archeological Lead

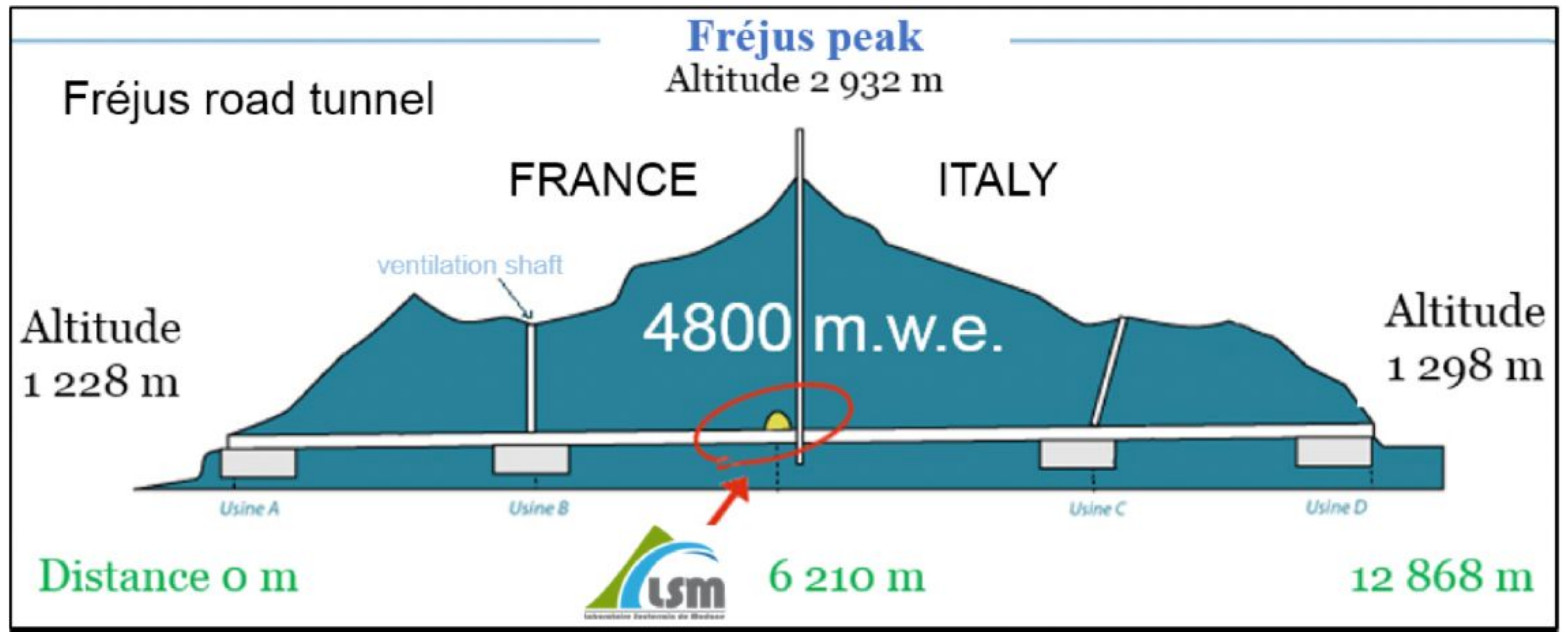
22 cm of low-activity Lead

Stainless steel skin

C10100 copper S140, with 0.5mm inner layer of electroformed copper

40 cm High-Density Polyethylene

L. Balogh et al 2020 JINST 18 T02005



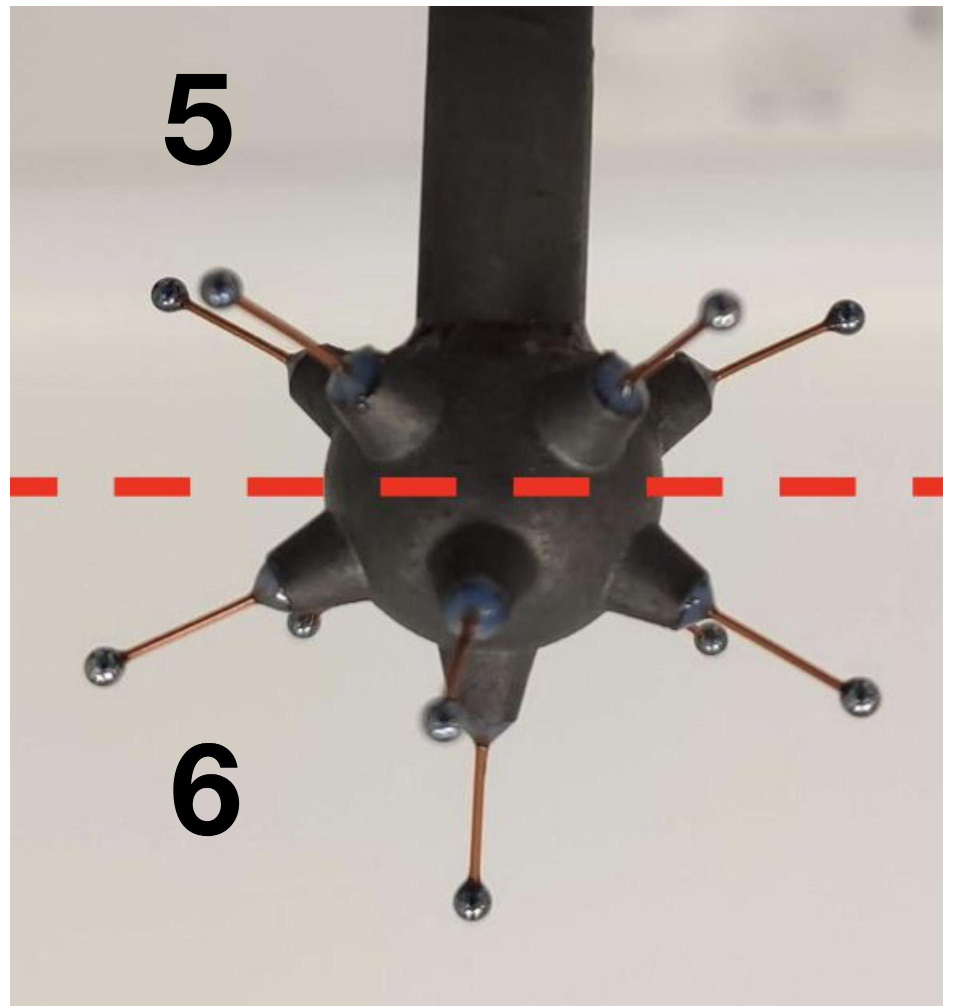
Commissioning in LSM from July to October 2019 **(including ~ten days of physics data with 135 mbar of CH_4)**
Currently installed in SNOLAB

Detector simulation

ACHINOS : 5-6 configuration

- Multi-anode sensor
  - same avalanche E-field as single anode
  - enhanced drift E-field
- 2-channel readout: 5 “near” and 6 “far” anodes

Near/North



Far/South

R. Ward et al 2020 JINST 15 C06013

I. Giomataris et al 2020 JINST 15 P11023

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  - Confirmed with Ar37 calibrations

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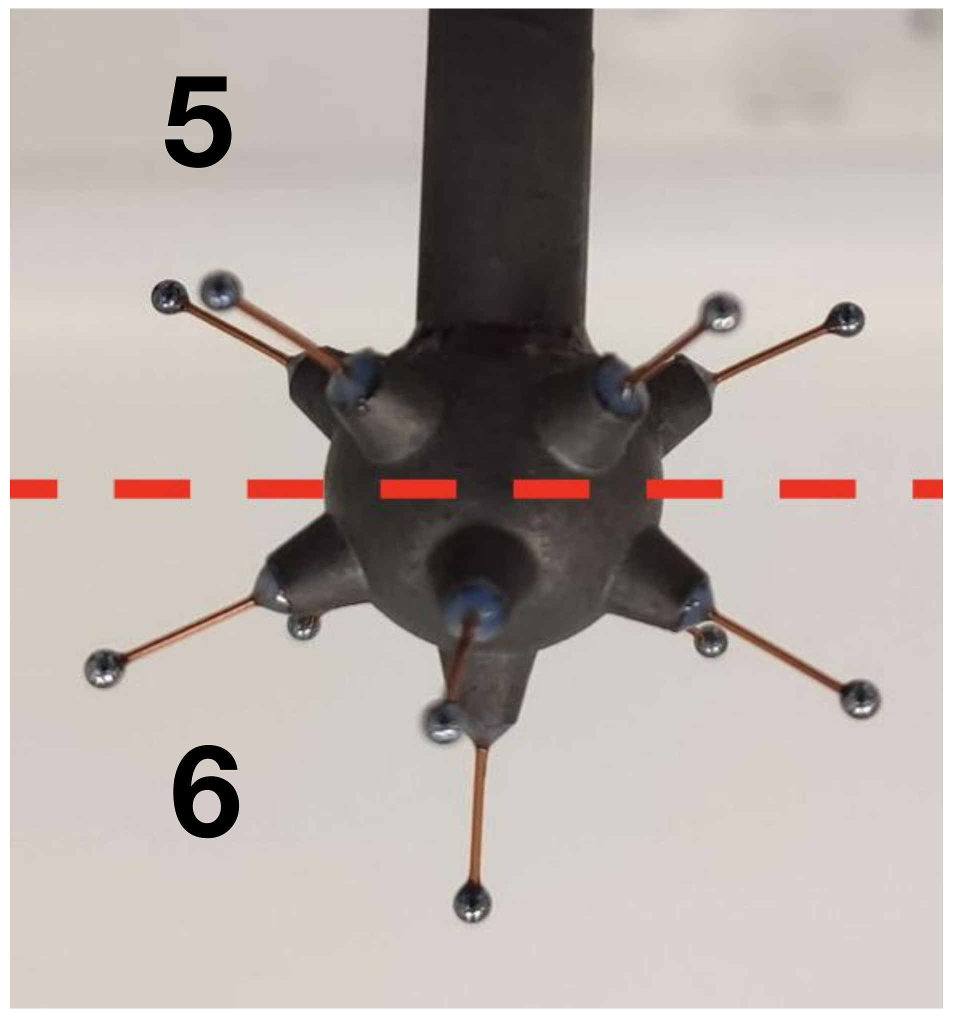
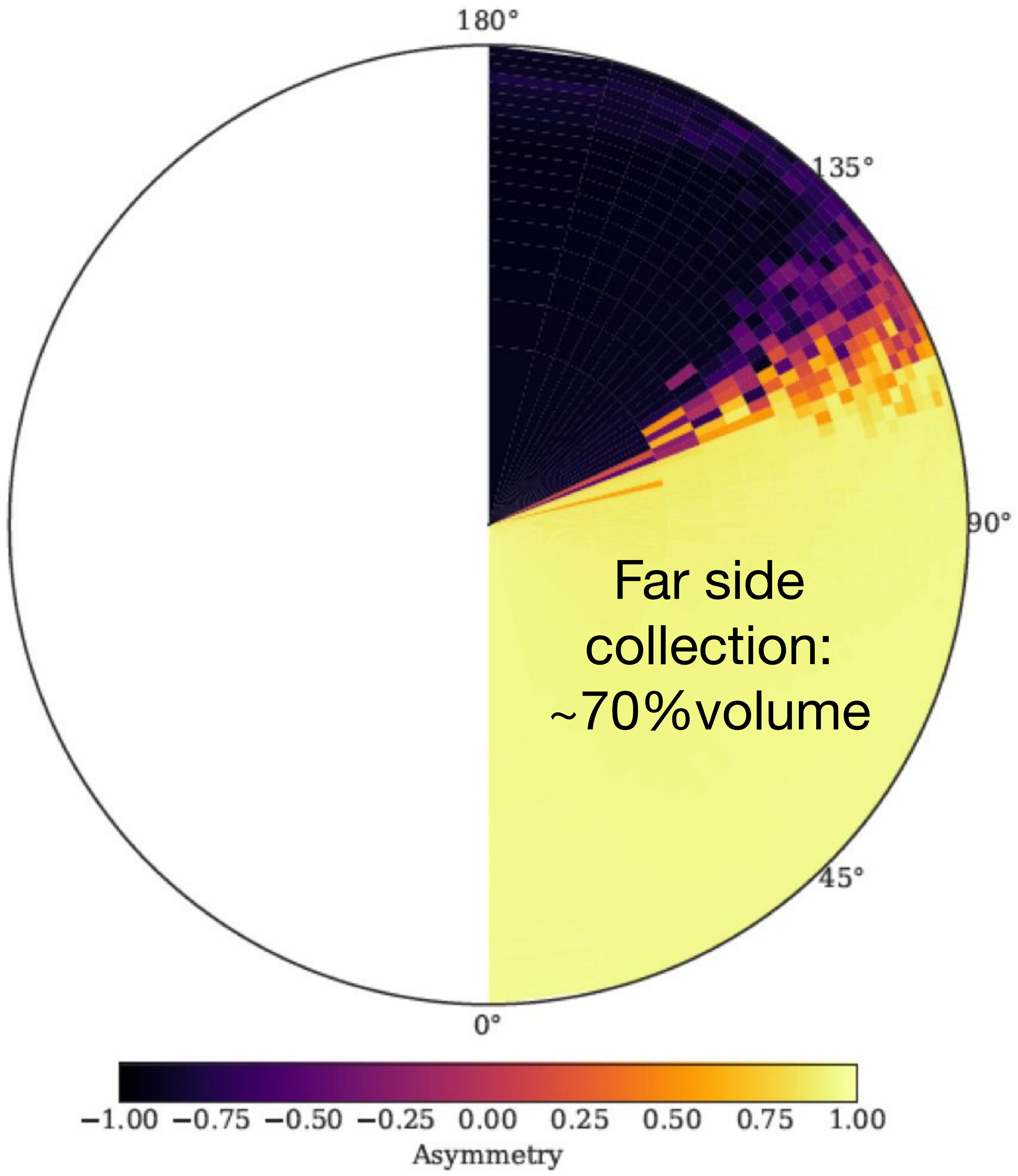


Far/South



R. Ward et al 2020 JINST 15 C06013

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Detector simulation

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- Multi-anode sensor
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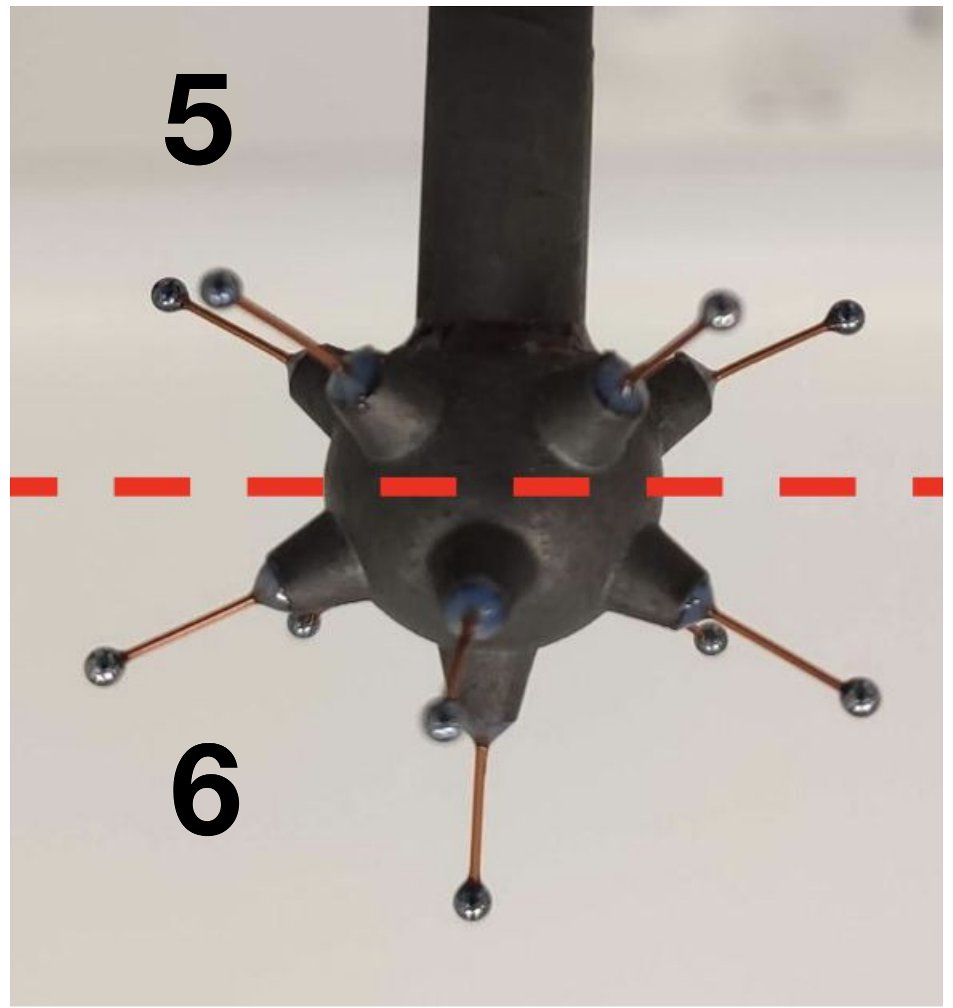
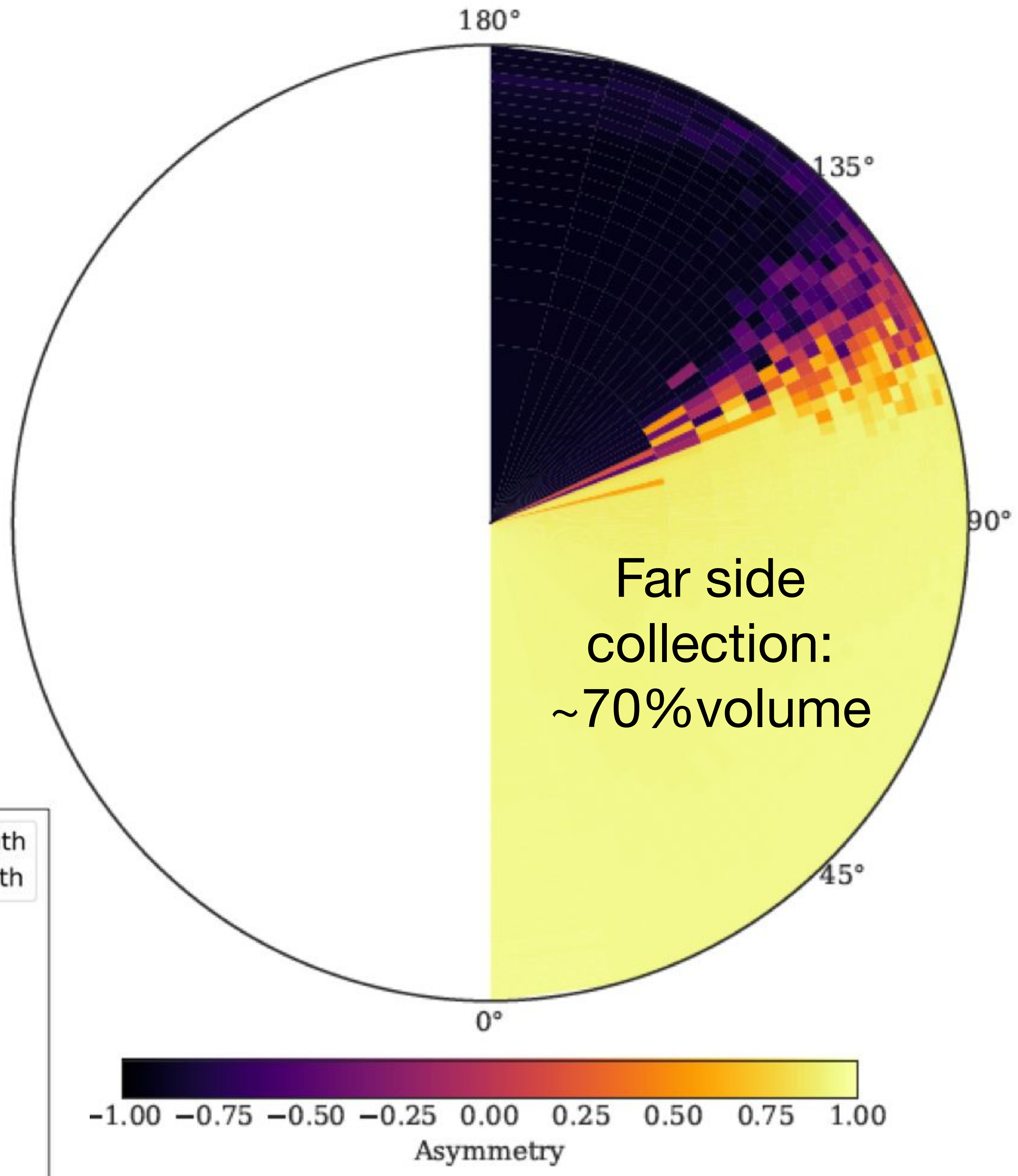
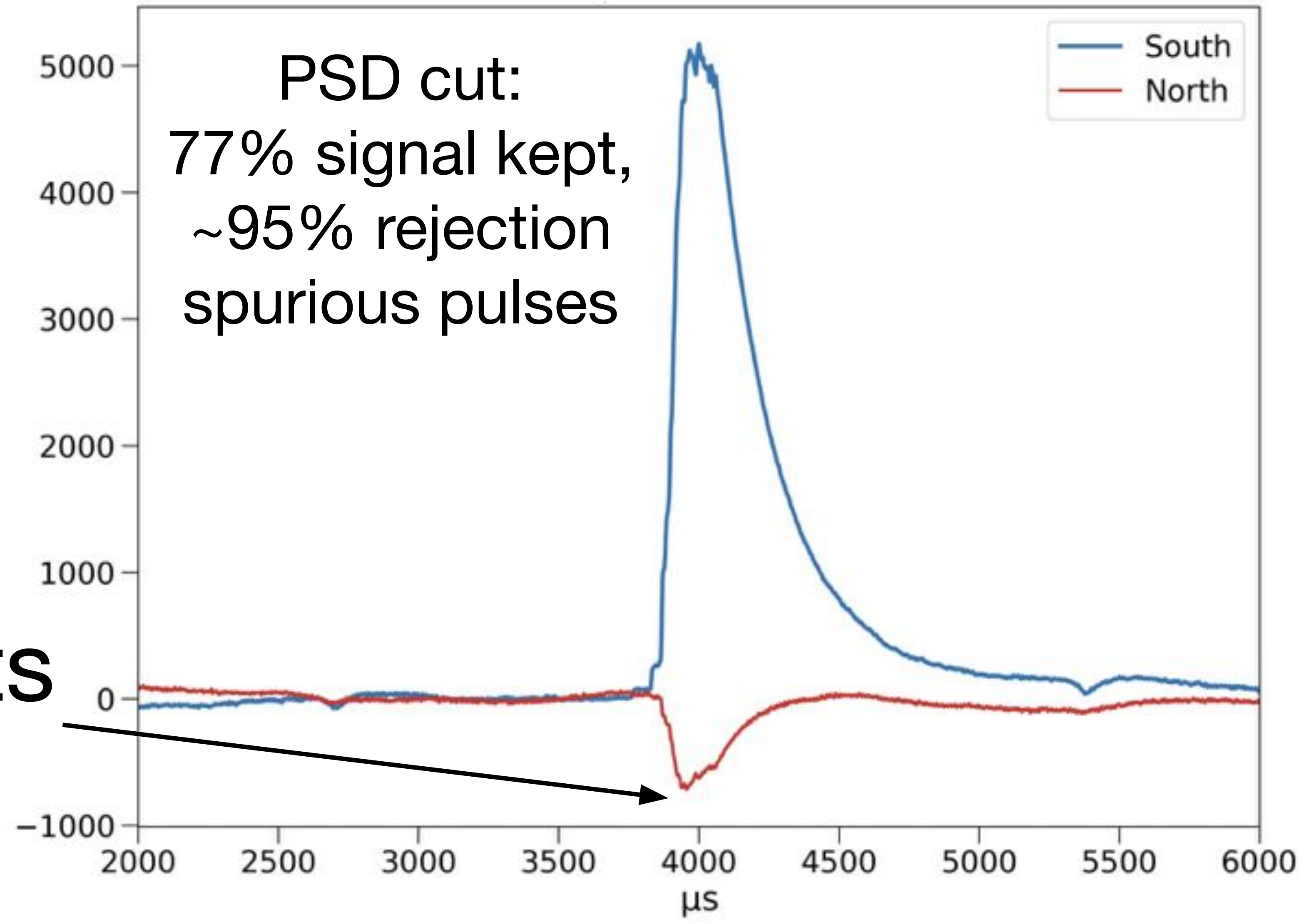
  - enhanced drift E-field
- 2-channel readout: 5 “near” and 6 “far” anodes
- Volume associated with each channel simulated with Geant4, Garfield++, ANSYS/COMSOL
  - Confirmed with Ar37 calibrations
- Simulations predict negative cross-channel induction for physical events
  - Confirmed with Laser calibrations

Near/North



Far/South





R. Ward et al 2020 JINST 15 C06013

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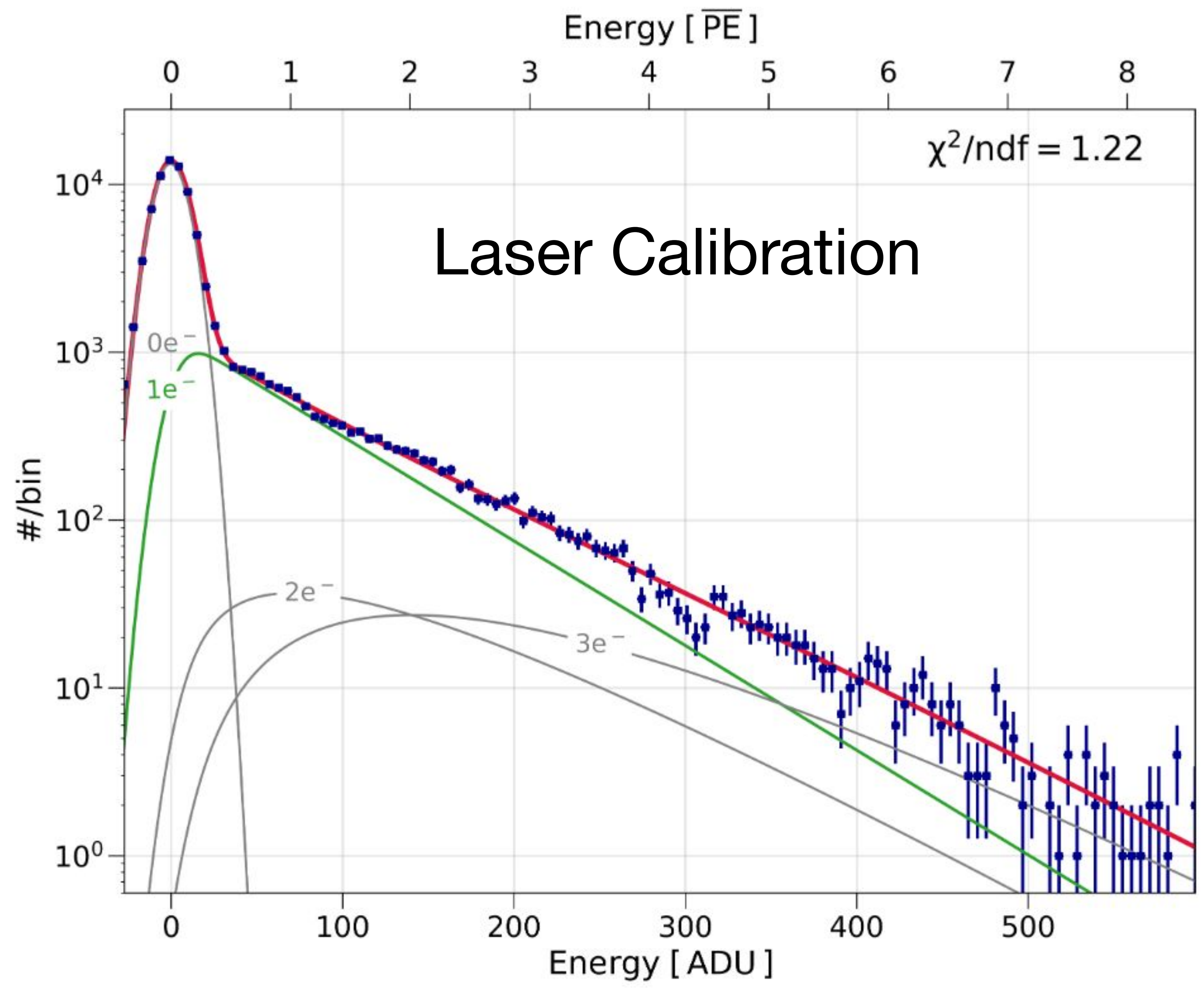
Calibrations of Ionization Statistics

Mean Ionization energy

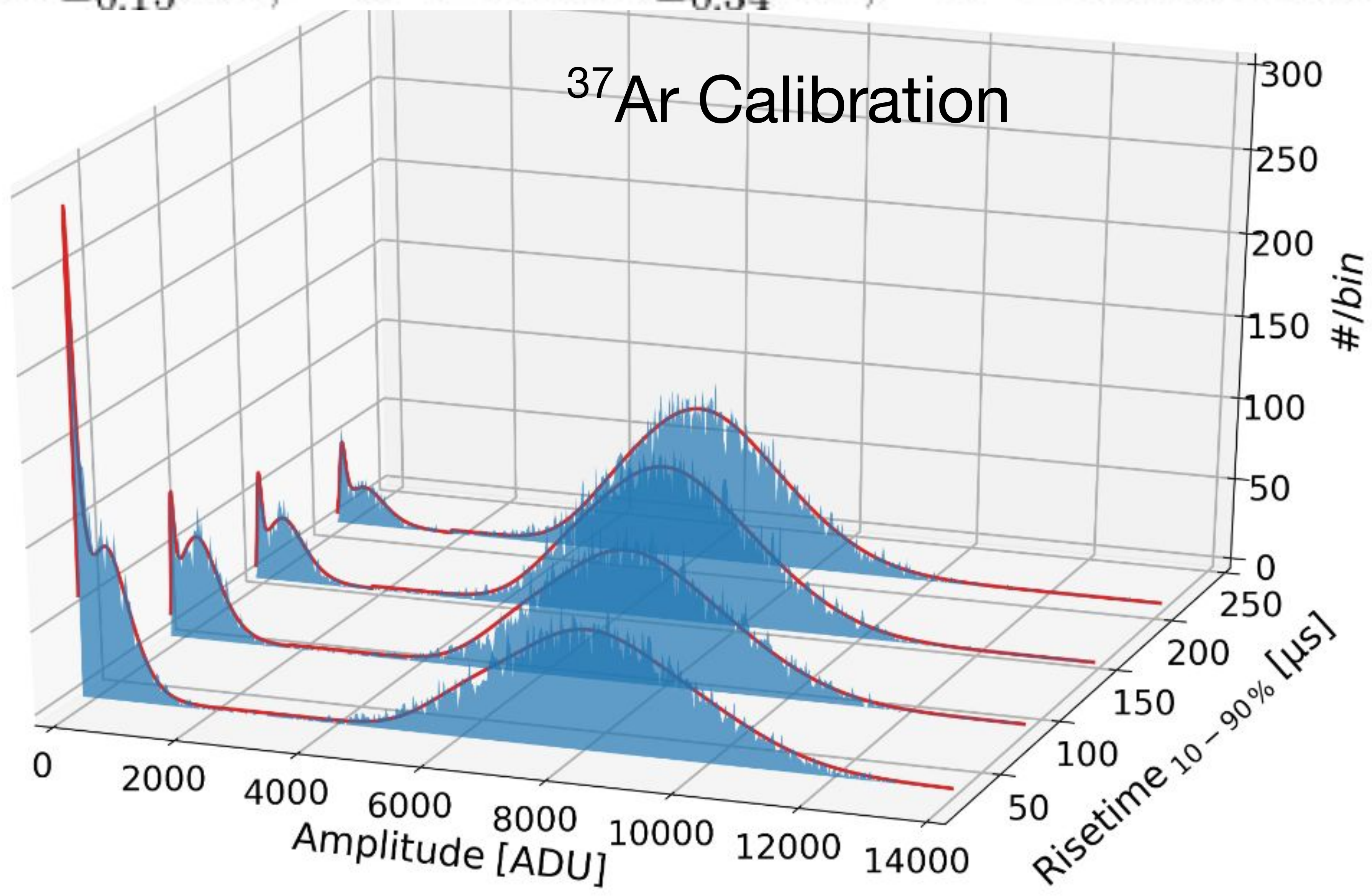
Pulsed 213 nm LASER calibration used to obtain single-electron response of detector

Combined with 2.8 keV, 270 and 200 eV lines from ^{37}Ar (gas, probing whole volume):

- Confirmation of linearity
- Measurement of gain of Far-channel anodes
- Parametrization of electron attachment
- In-situ measurement of W and Fano factor



$$W_0 = 30.0^{+0.14}_{-0.15}\,\mathrm{eV}, \quad U = 15.70^{+0.52}_{-0.34}\,\mathrm{eV}, \quad F = 0.43 \pm 0.05$$



Improving on techniques described in **Phys. Rev. D 99, 102003 (May 2019)**
New paper in preparation describing considerable improvements

doi:10.1088/1742-6596/2156/1/012059

Calibrations of Ionization Statistics

Quenching Factor

More about current & future NEWS-G QF measurements in N. Panchal's talk!

Quenching factor values from existing W-value measurements for ions and measurements from COMIMAC

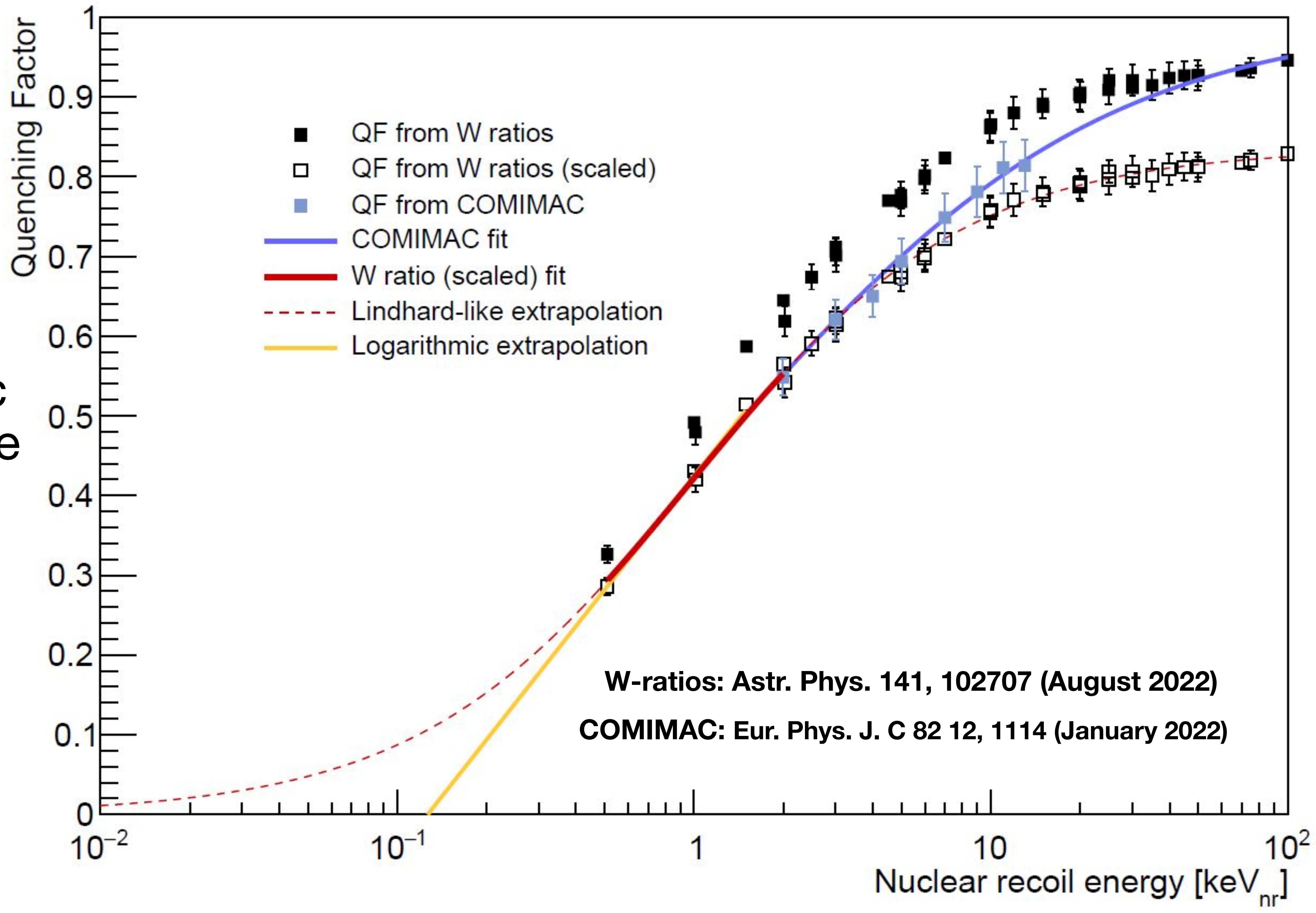
The (more conservative) logarithmic extrapolation was used to derive the expected WIMP signal

- Lindhard-like

$$QF(Er) = m*(\alpha E_r^{\beta})/(1+\alpha E_r^{\beta})$$

- Logarithmic

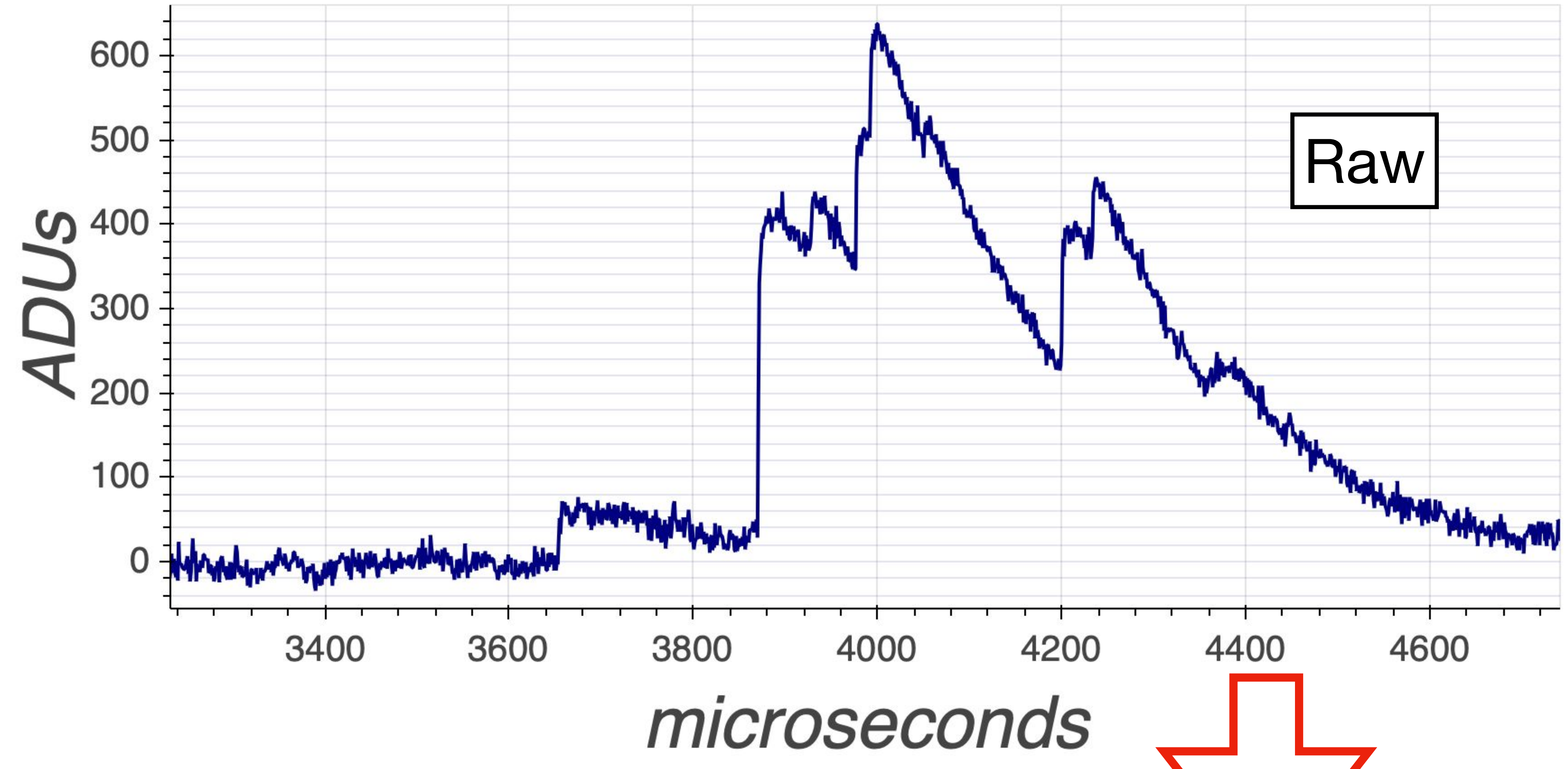
$$QF(Er) = a + b*\log(E_r)$$

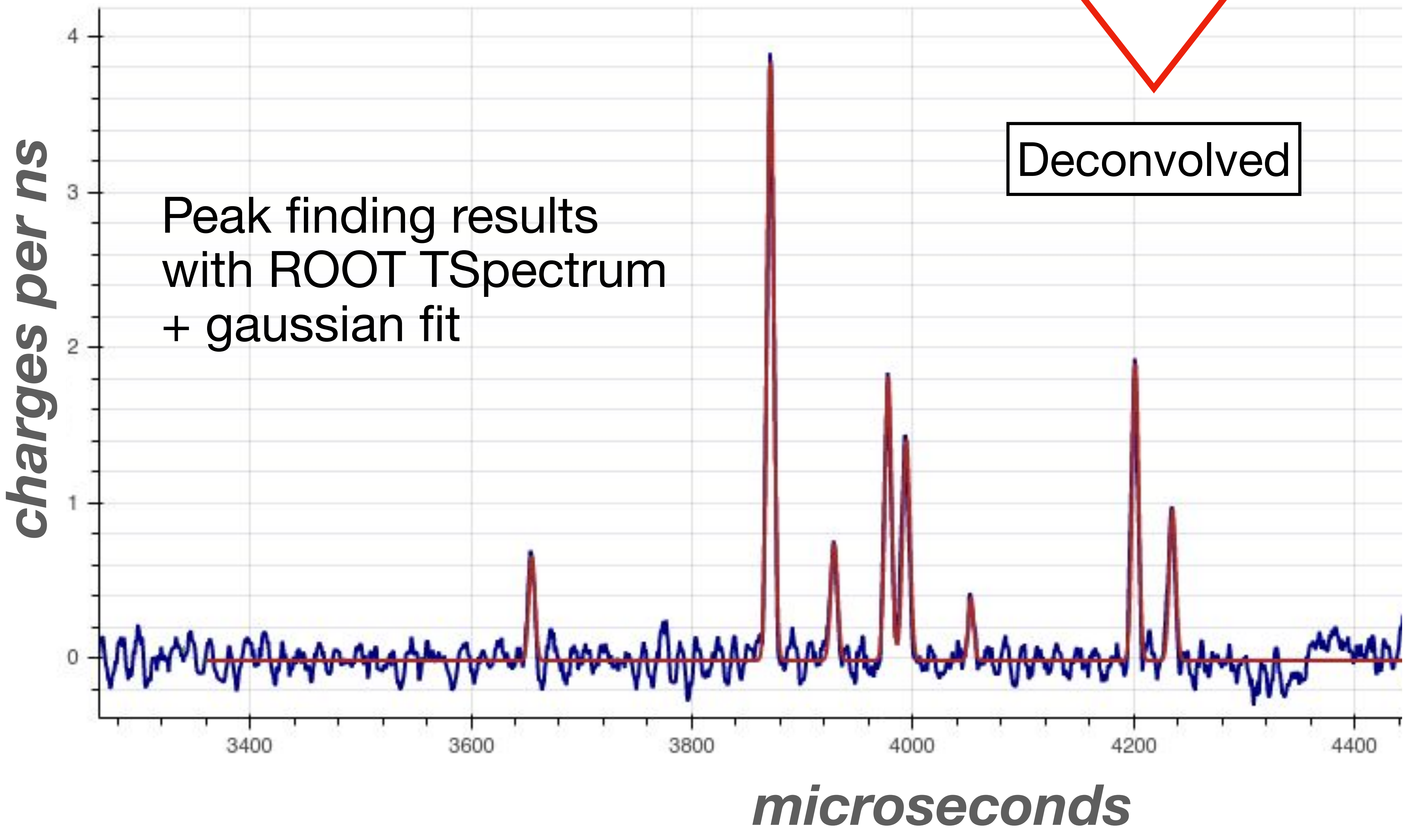


Electron counting

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

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



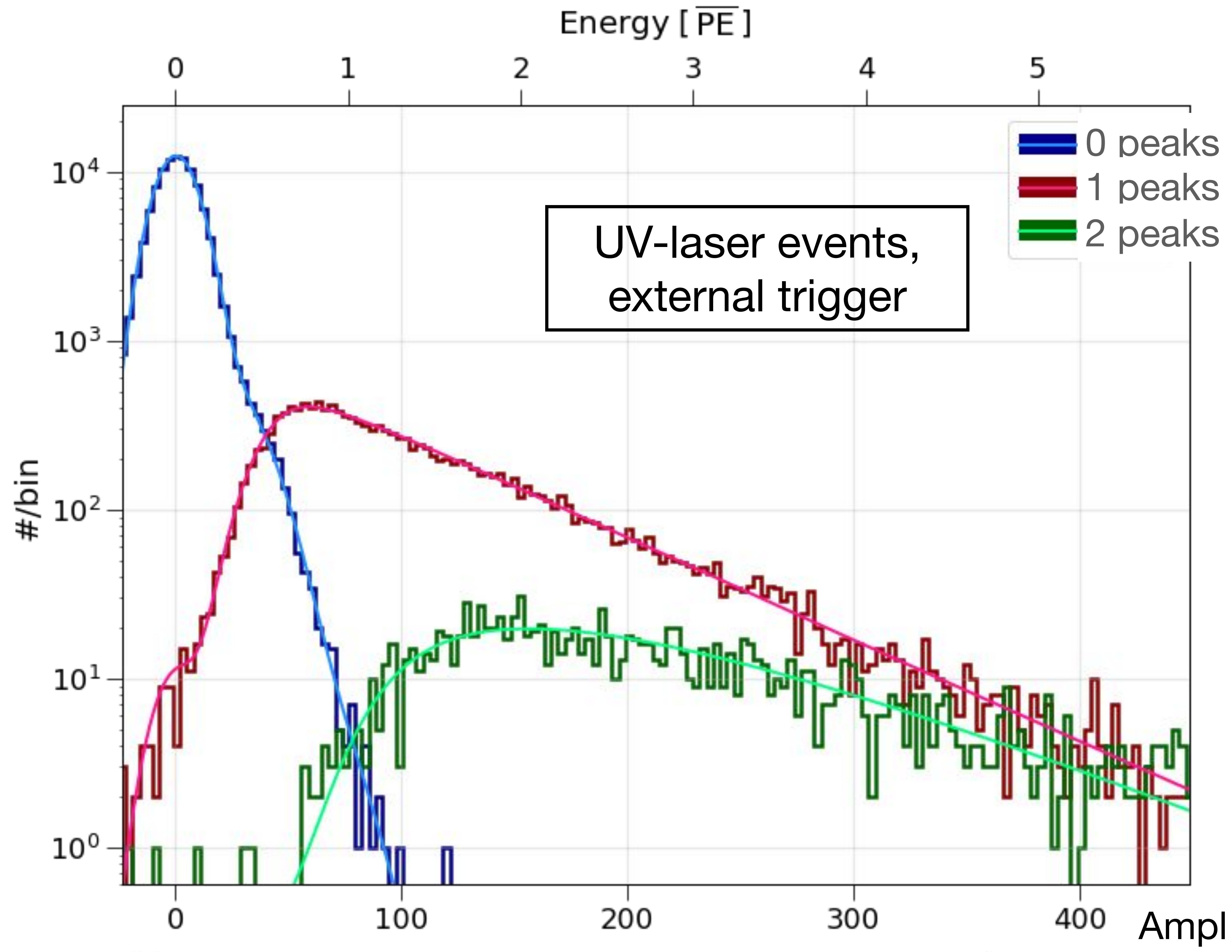


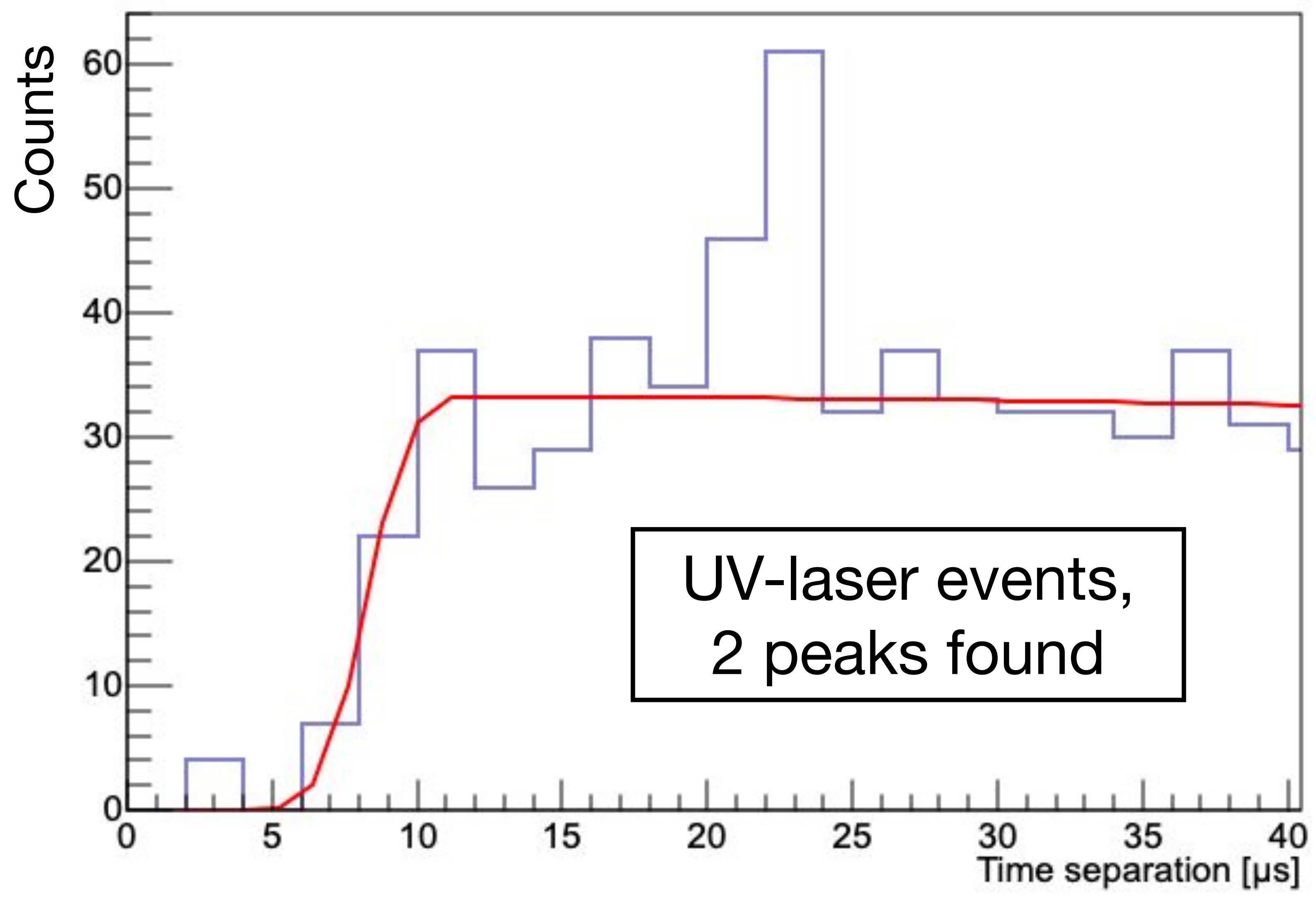
Electron counting

Characterisation

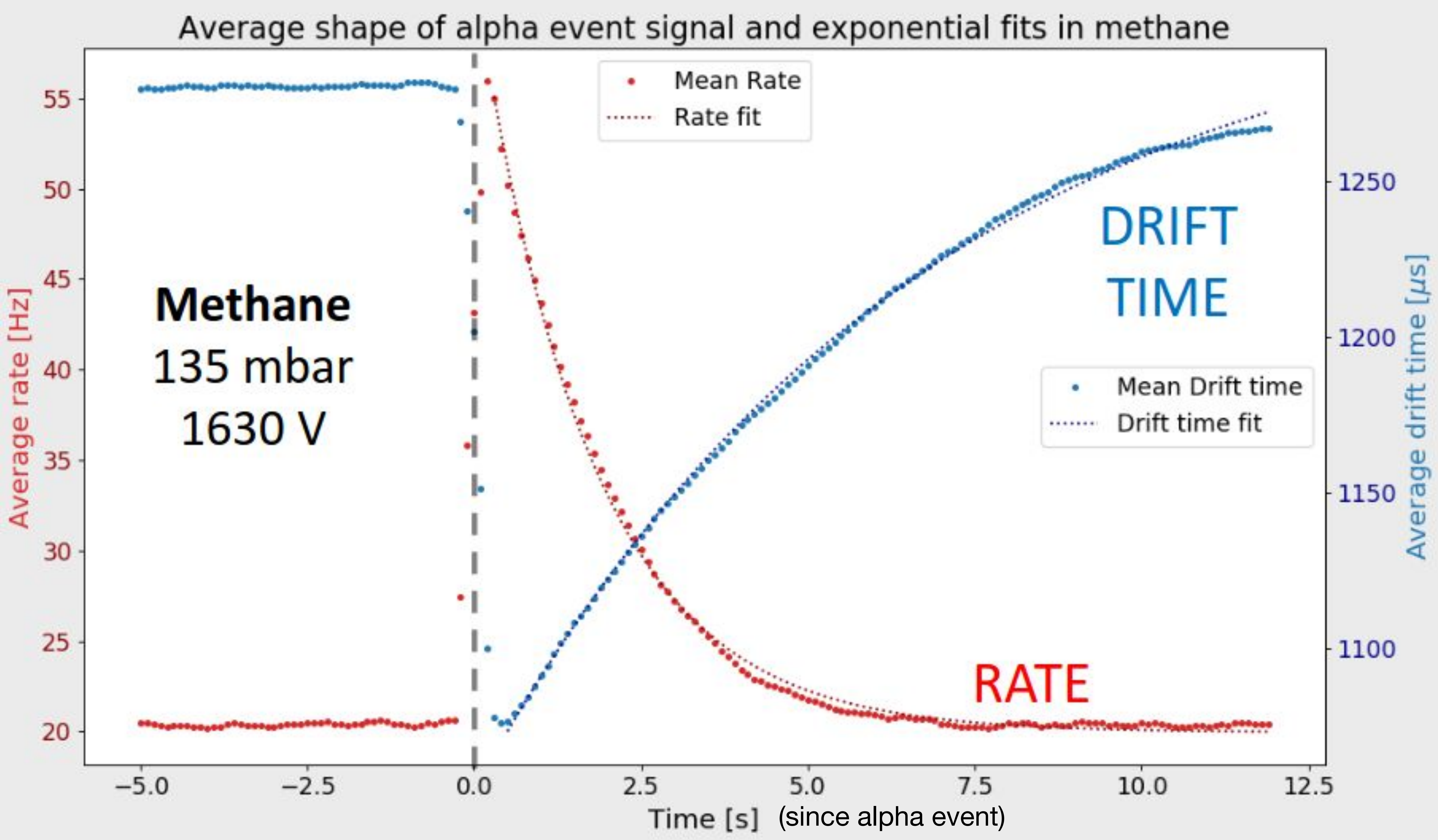
UV-laser extracts electrons from copper surface. At low intensity to extract ~1e-, can be used to characterise peak-counting performance:

- Electron detection efficiency : 64%
- Separation of electron peaks above 8 μs





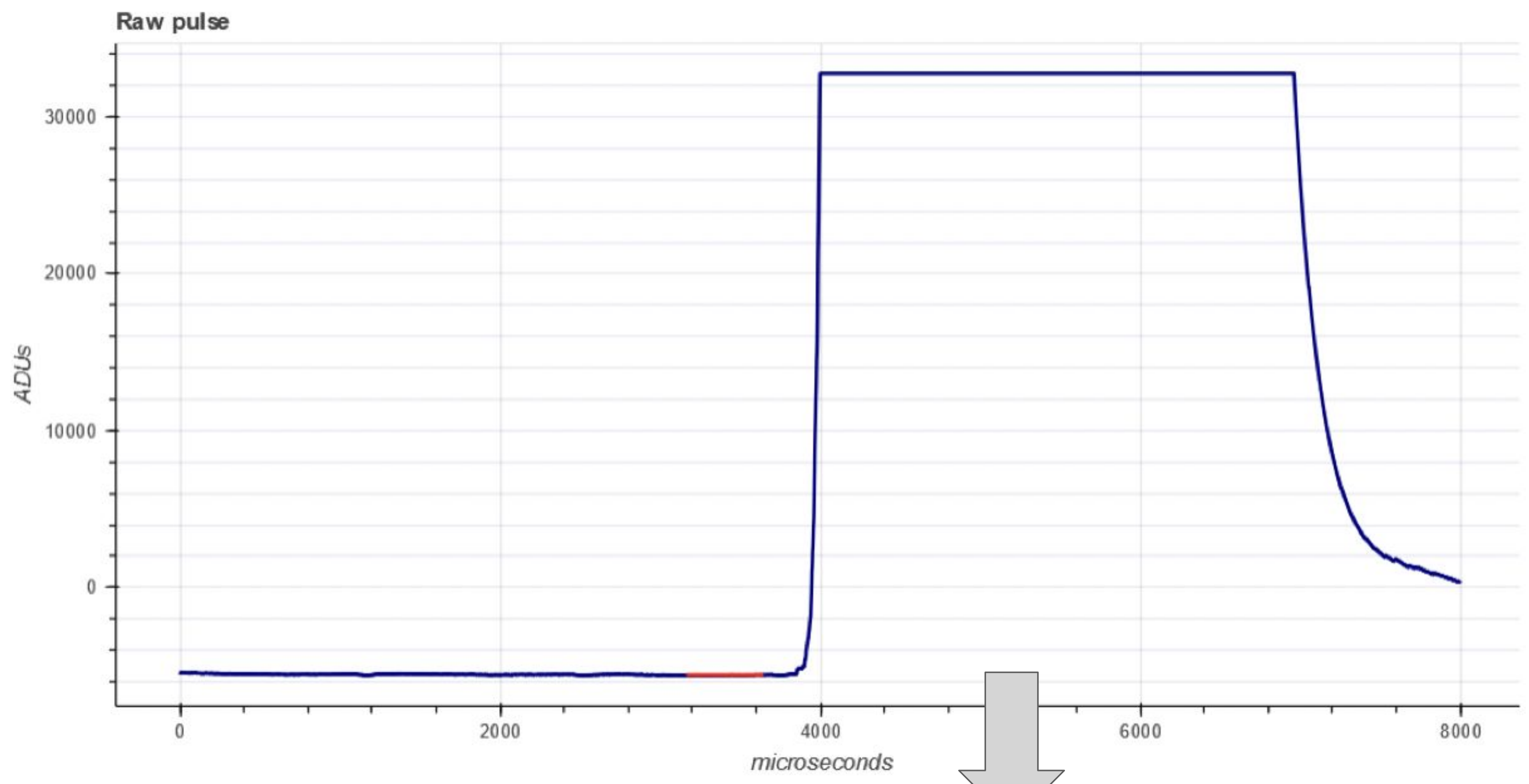
Alpha-correlated electrons



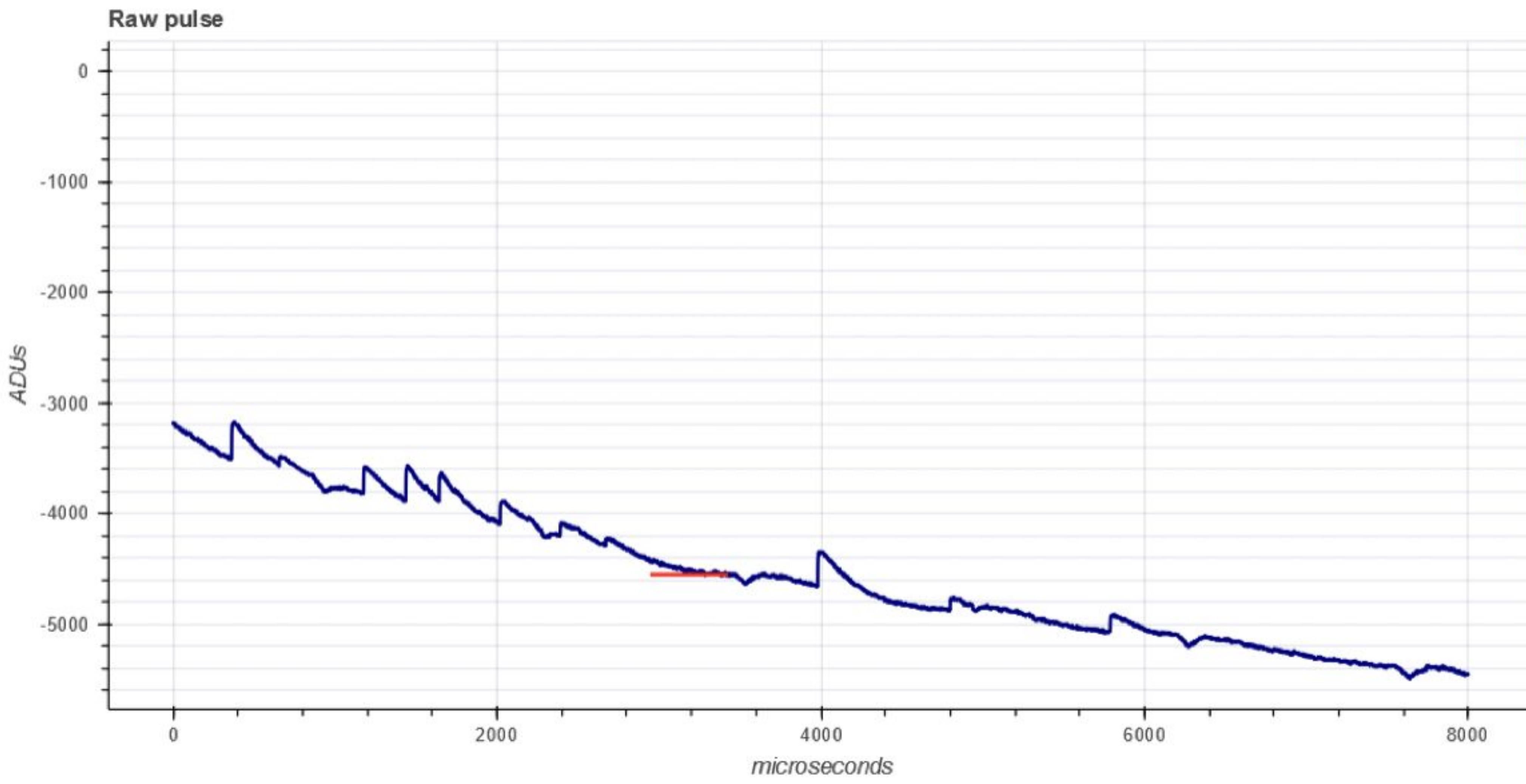
For CH4 data, removing 5s after each alpha reduces exposure by 14%, but reduces background rate by ~70%

Alpha event

J.M. Coquillat

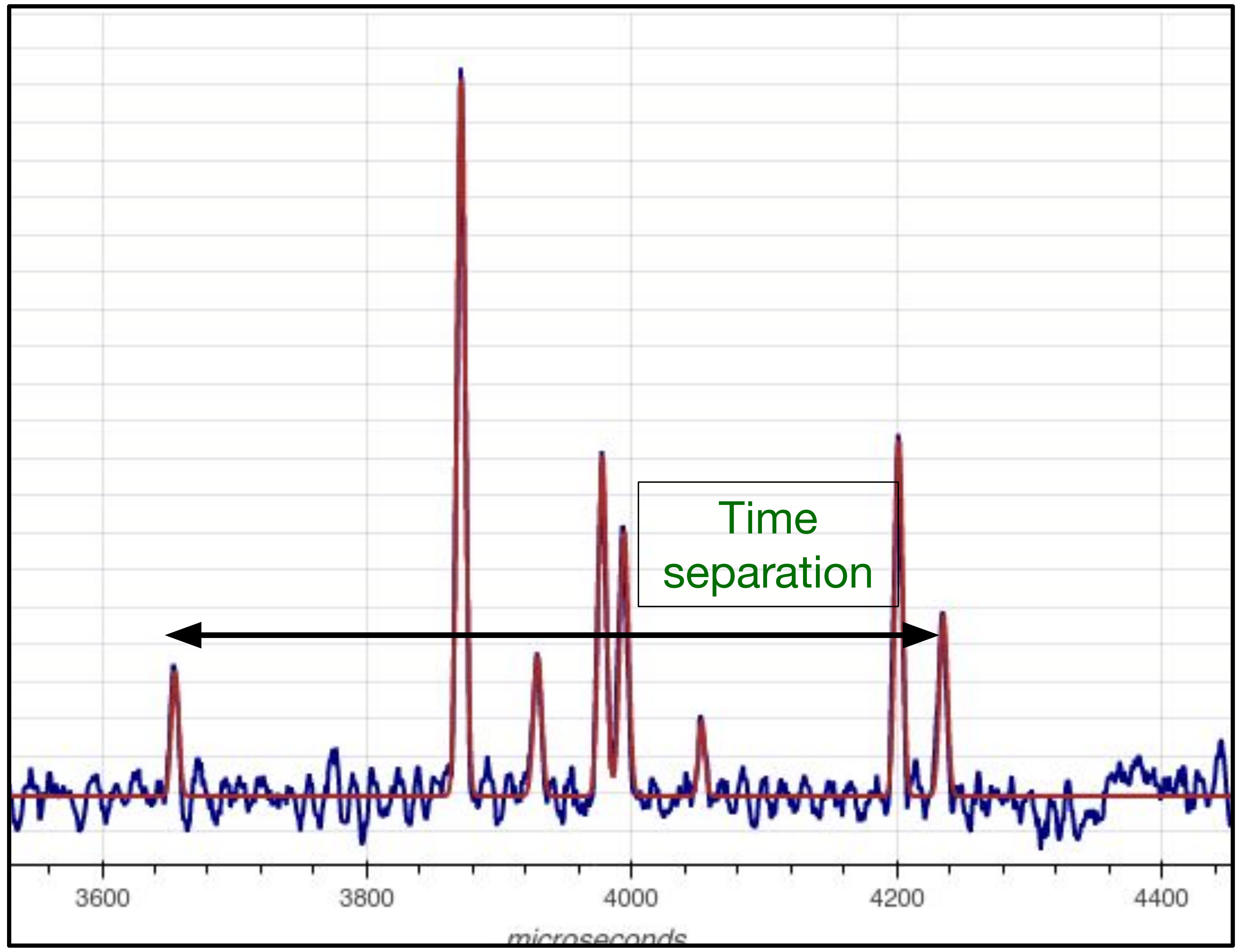


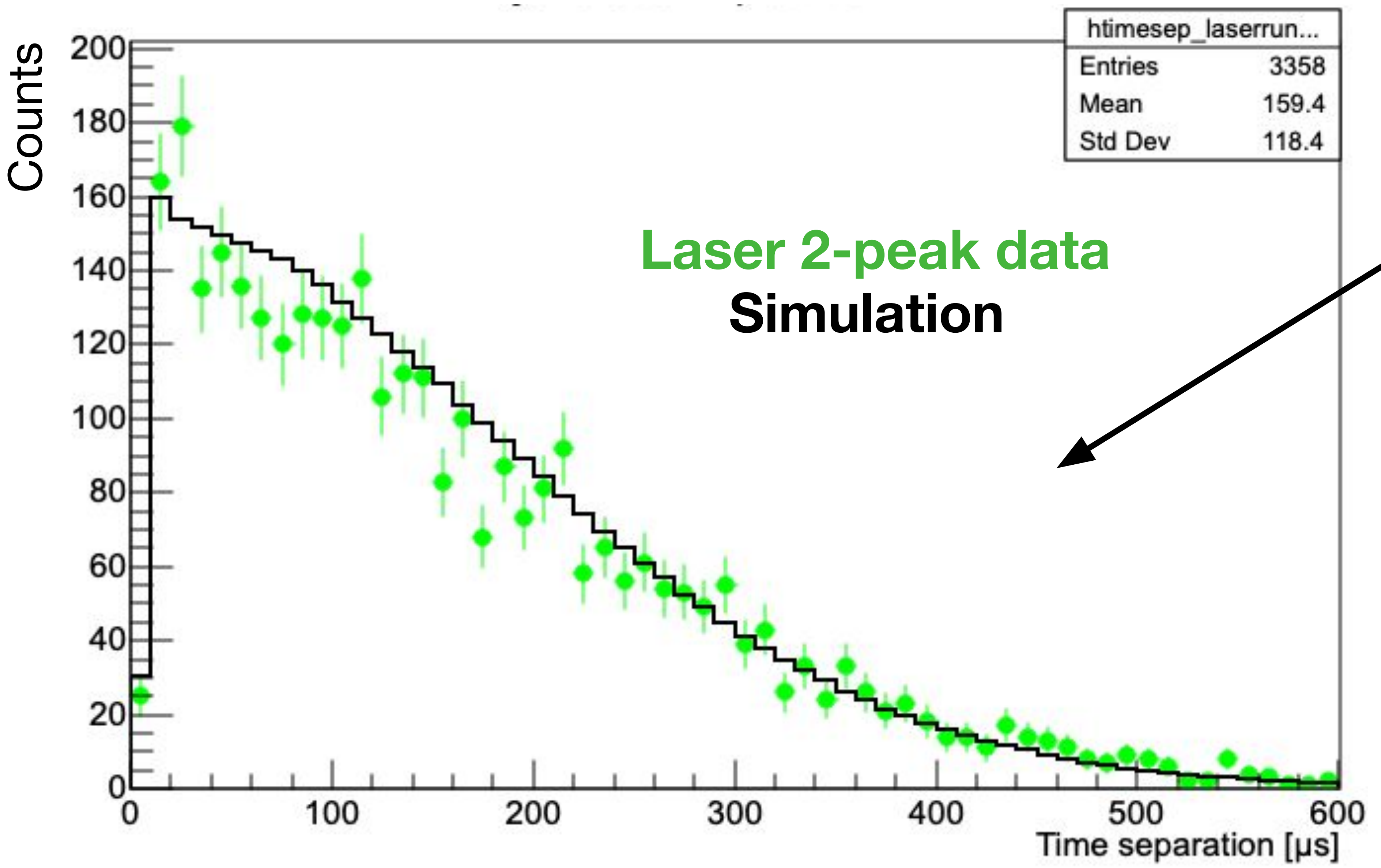
Long tail on following detected event



New diffusion variable

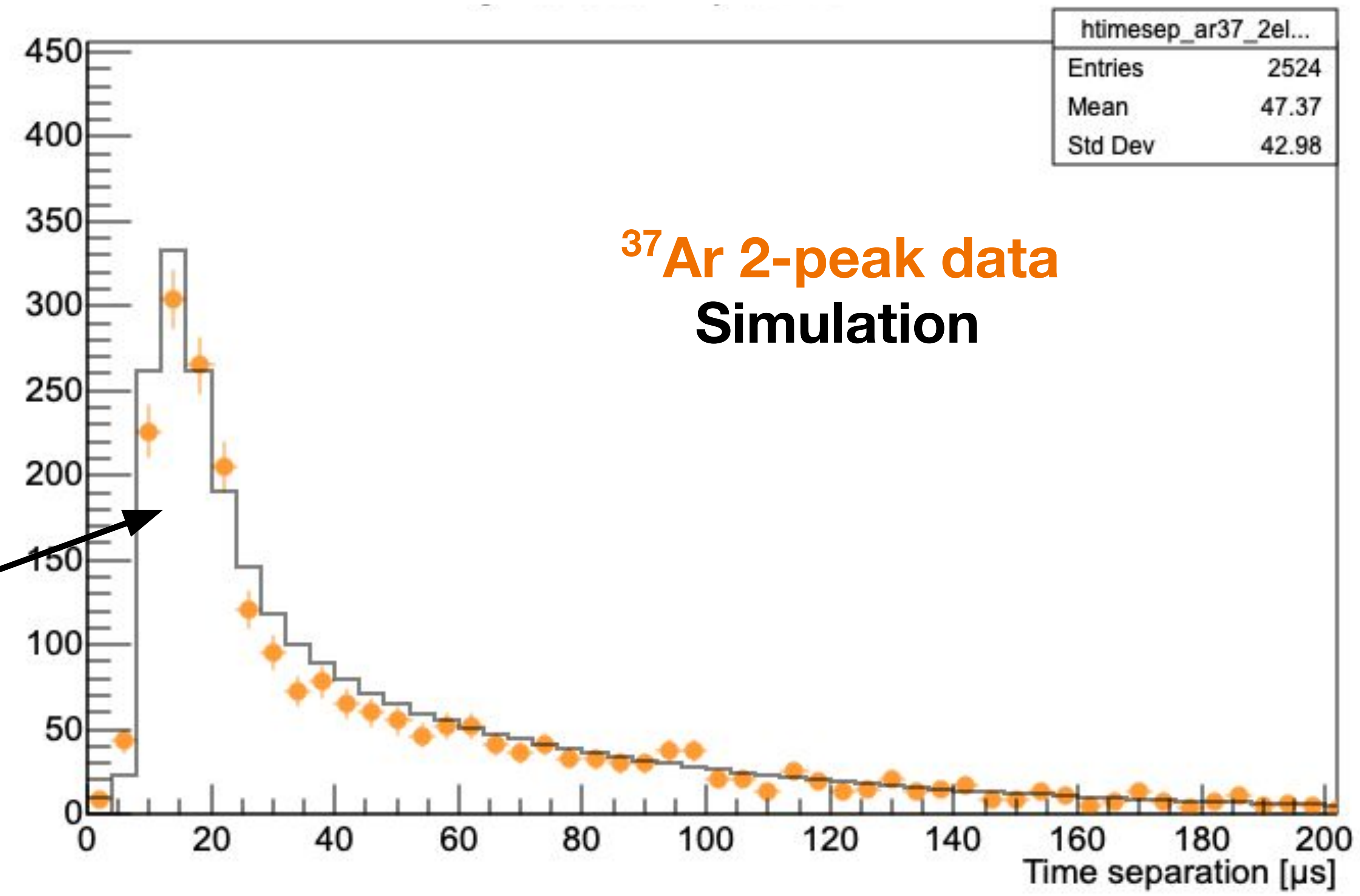
- Time separation between first and last peak informs on radial position of interaction
- Simulations of surface and volume events in agreement with Laser and 37Ar data respectively
- Need >1e- to use





Surface events:
wide distribution,
large time separations

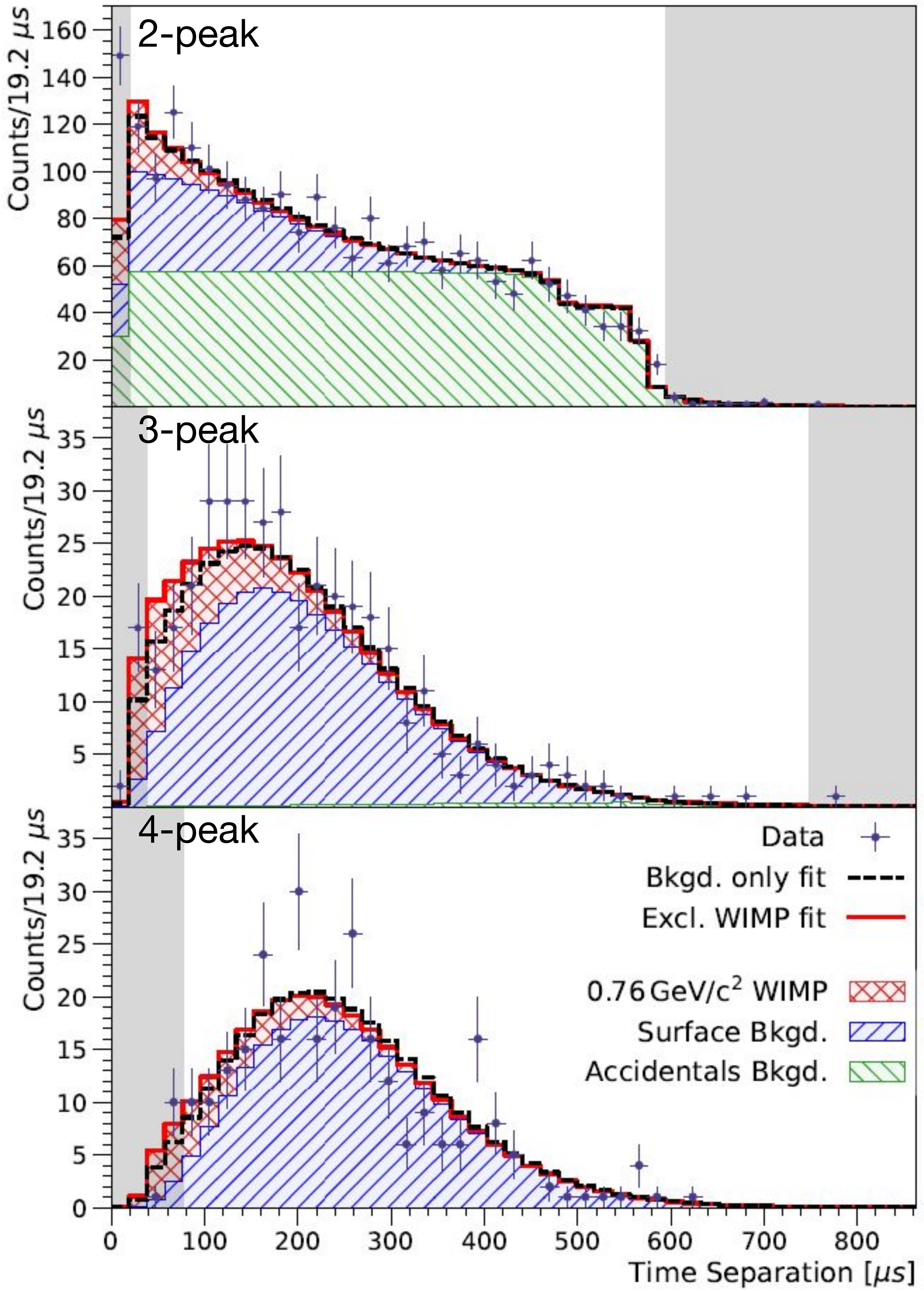
Volume events:
Concentrated at low
time separations



Physics data fit

- Use 77% of data for DM searches (effectively 5.3 days, excluding dead time)
- Profile likelihood fit to the 2,3,4-peak data including contributions from **WIMP signal**, **surface**, **volume** and **accidental coincidence** backgrounds
- Use modelling derived from simulations and validated with calibration data

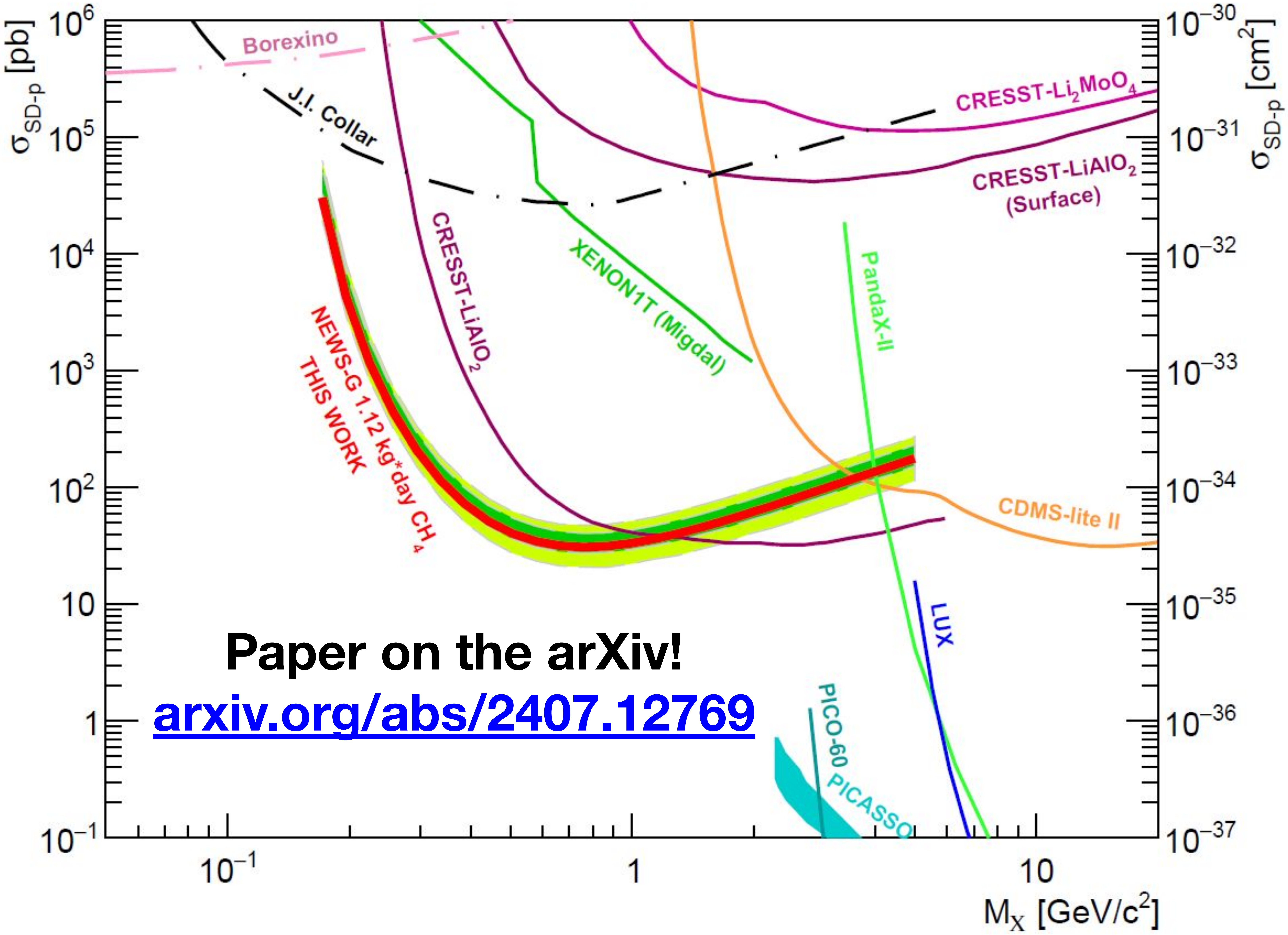
- No significant signal observed



New WIMP constraints

Profile Likelihood Ratio used to generate constraints on WIMP cross-section

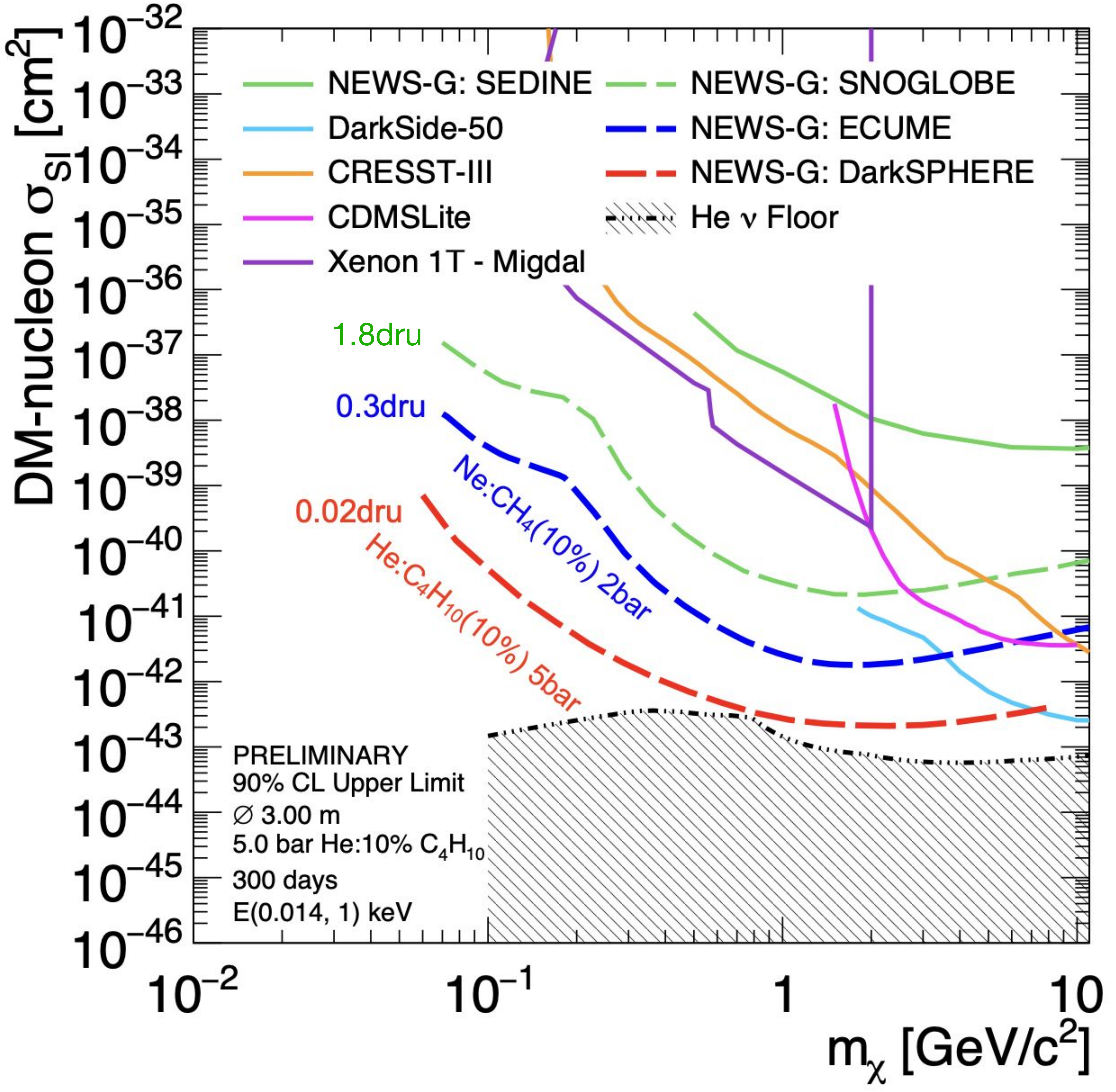
Final results on blind data : strongest constraint on spin-dependent WIMP-proton cross-section in 0.17-1.2 GeV range!



Paper on the arXiv!
arxiv.org/abs/2407.12769

Future prospects

- S140 : more data at SNOLAB
  - Installation of gas purifier and radon trap
  - 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 previous SPC prototype(s), 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 : world-leading for WIMP SD-p cross-section in 0.17-1.2 GeV mass range
- NEWS-G prospects:
  - Physics run with Ne+CH4 at SNOLAB complete and undergoing analysis, with new gas mixtures on the way
  - Beyond S140 : Future projects ECUME & DarkSPHERE

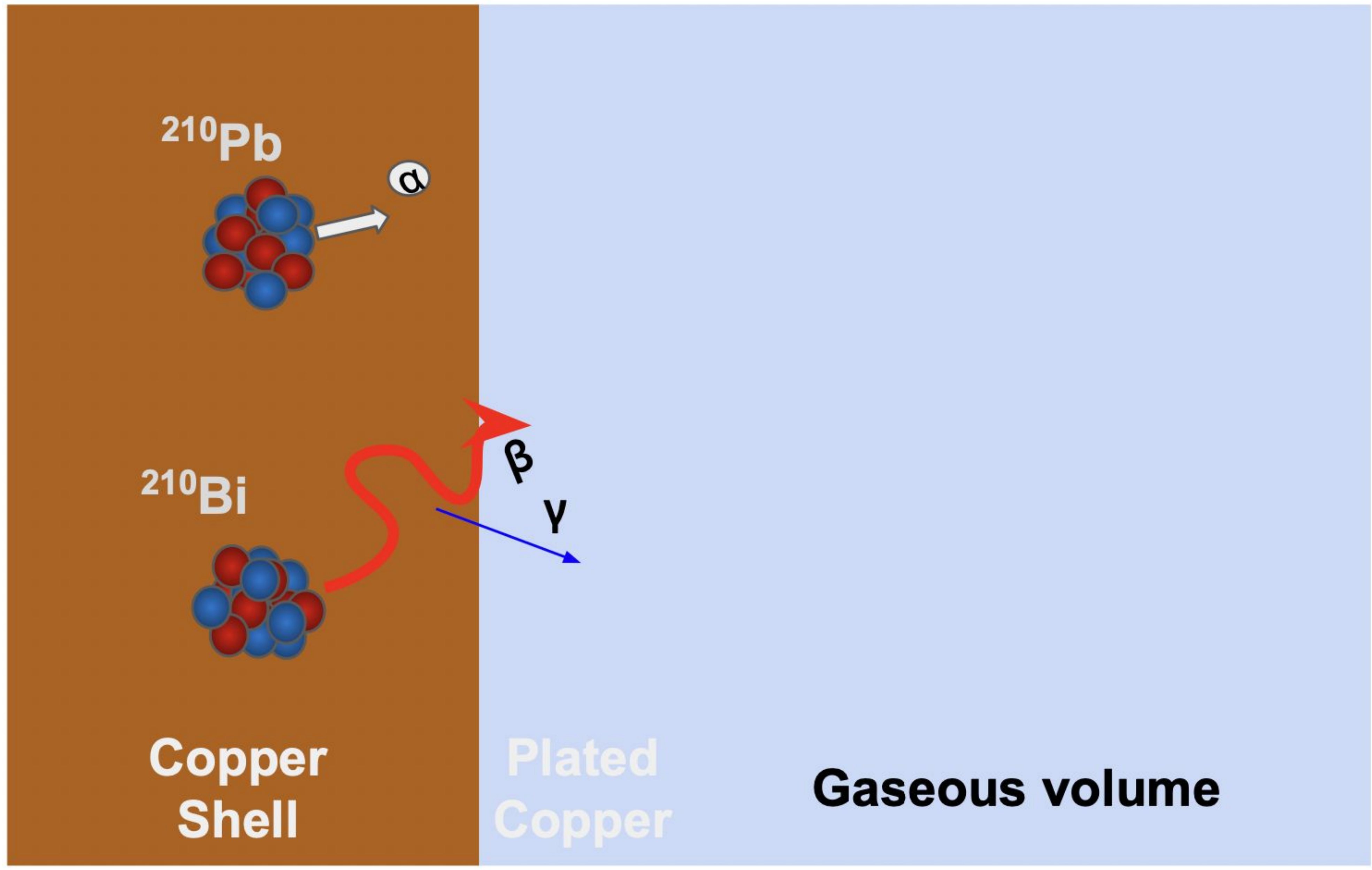
Thank you for your attention!

Extra slides

S140: Improvements

Background reduction

- Background: Bremsstrahlung X-rays from ^{210}Pb and ^{210}Bi -decays in (and on) the copper

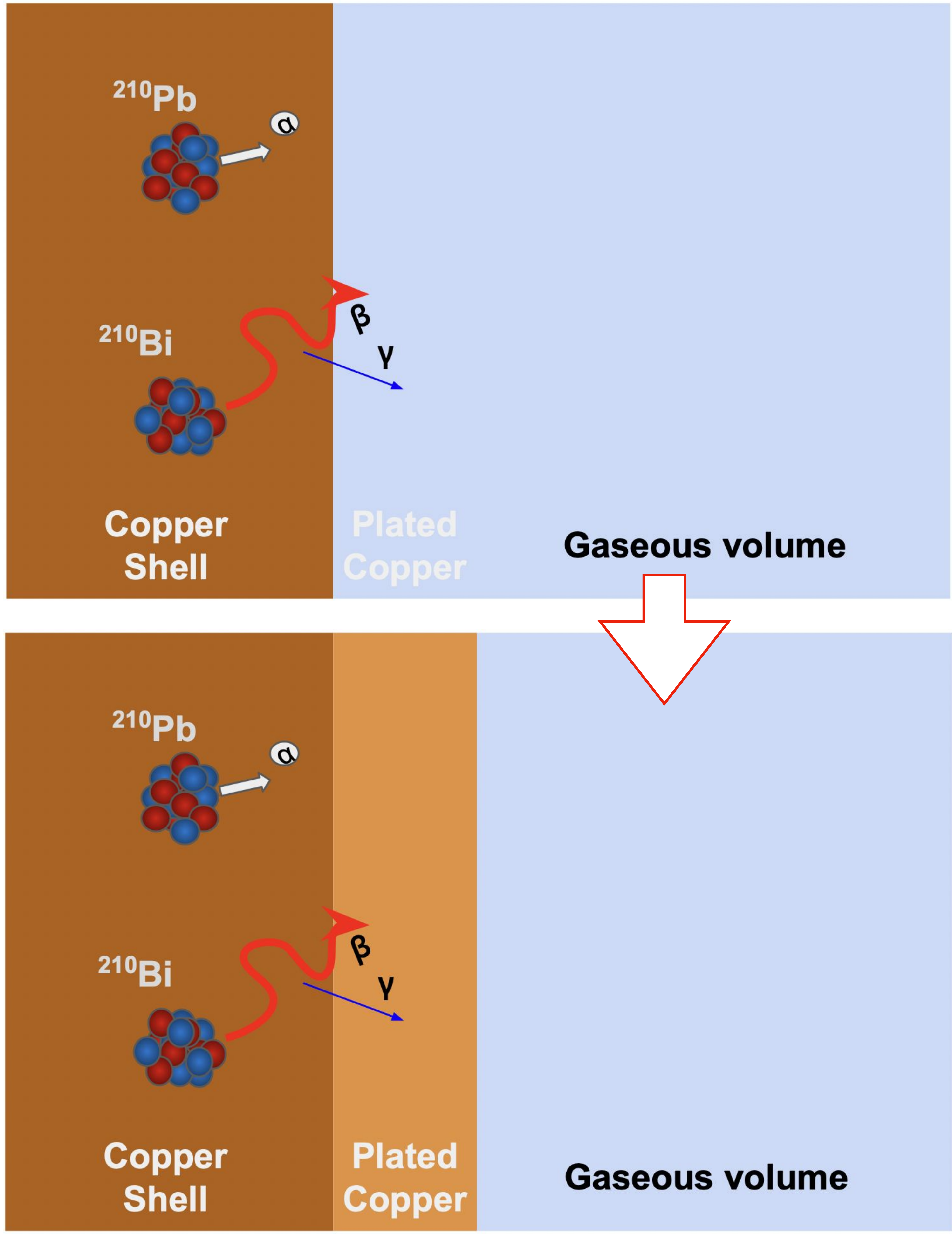


L. Balogh et al, Nucl.Instrum.Meth.A 988 (2021)

S140: Improvements

Background reduction

- Background: Bremsstrahlung X-rays from ^{210}Pb and ^{210}Bi -decays in (and on) the copper
- Plating 0.5mm of ultra-pure copper on inner surface of detector expected to reduce background under 1 keV by factor 2.6, and total rate by factor 50



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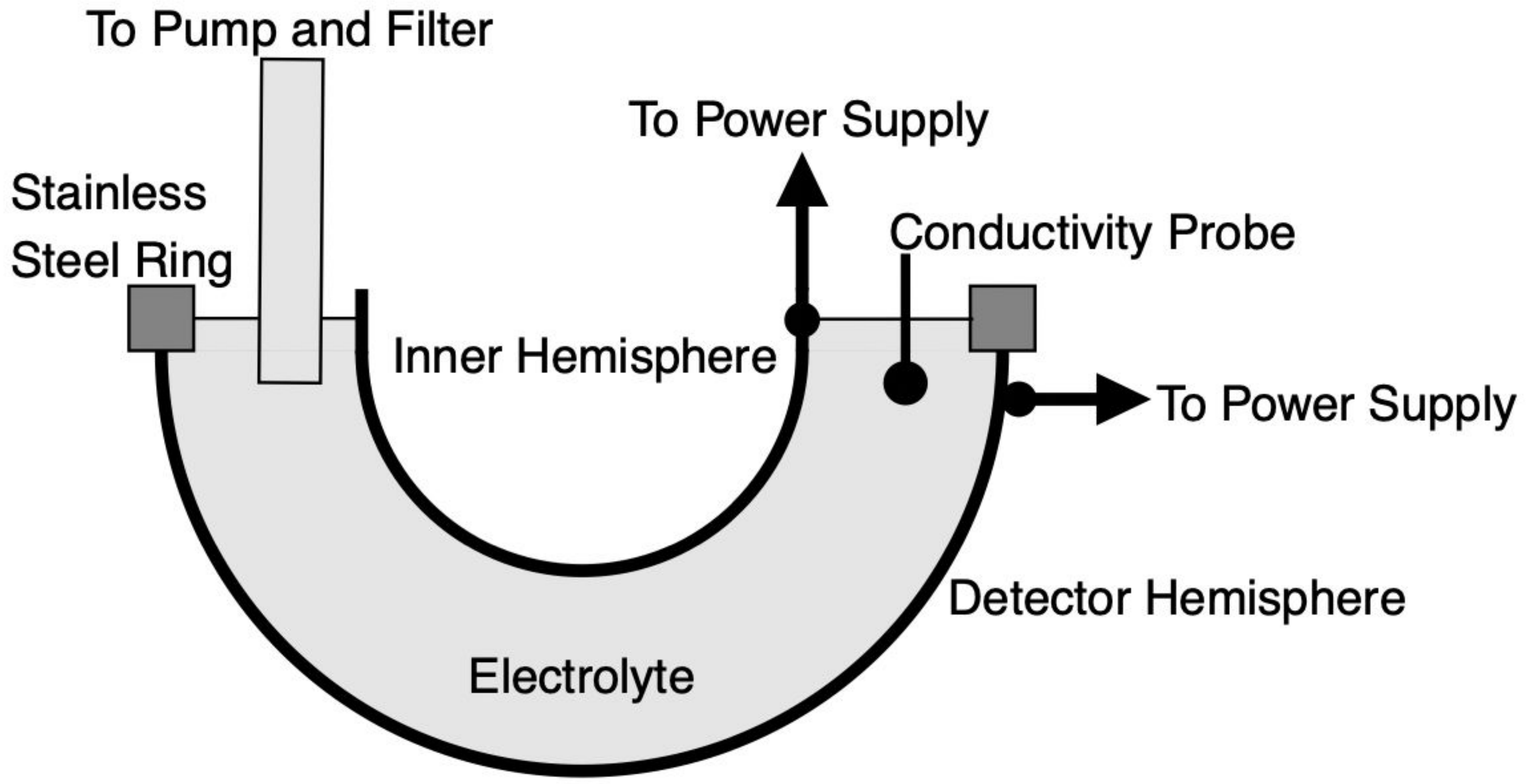

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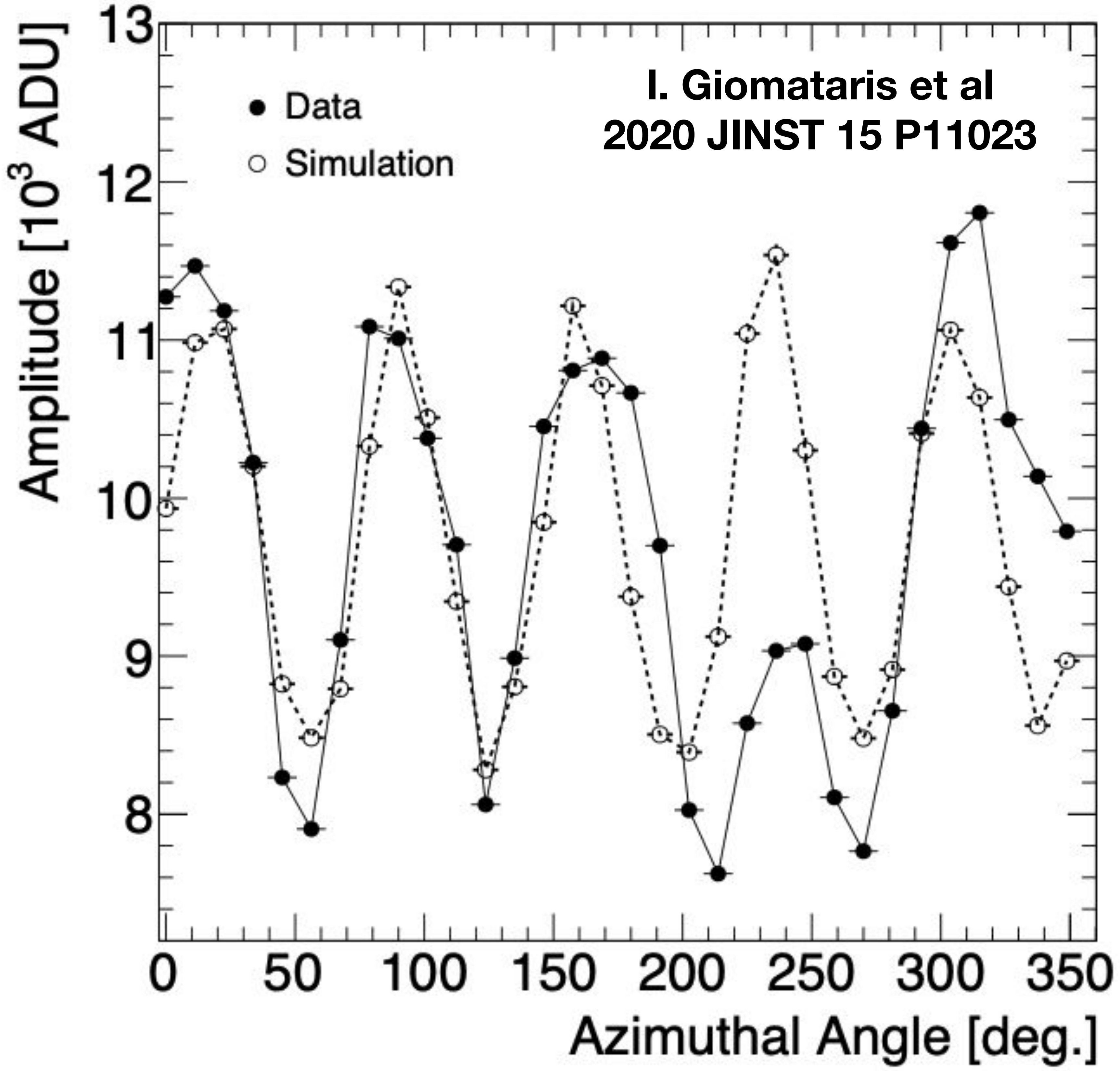
- Plating 0.5mm of ultra-pure copper on inner surface of detector expected to reduce background under 1 keV by factor 2.6, and total rate by factor 50

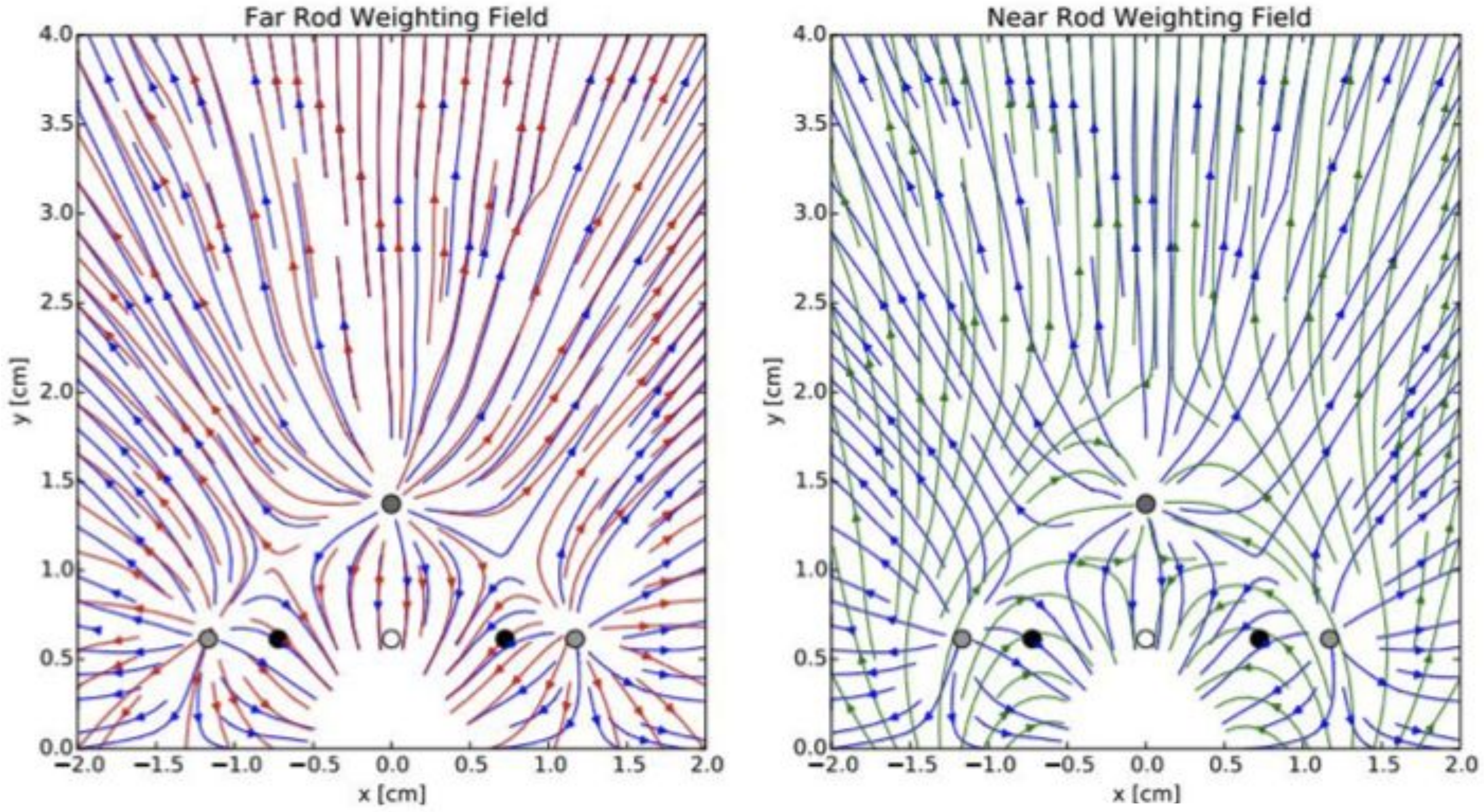
- Intervention successfully carried out at LSM in collaboration with PNNL

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

Some simulation plots



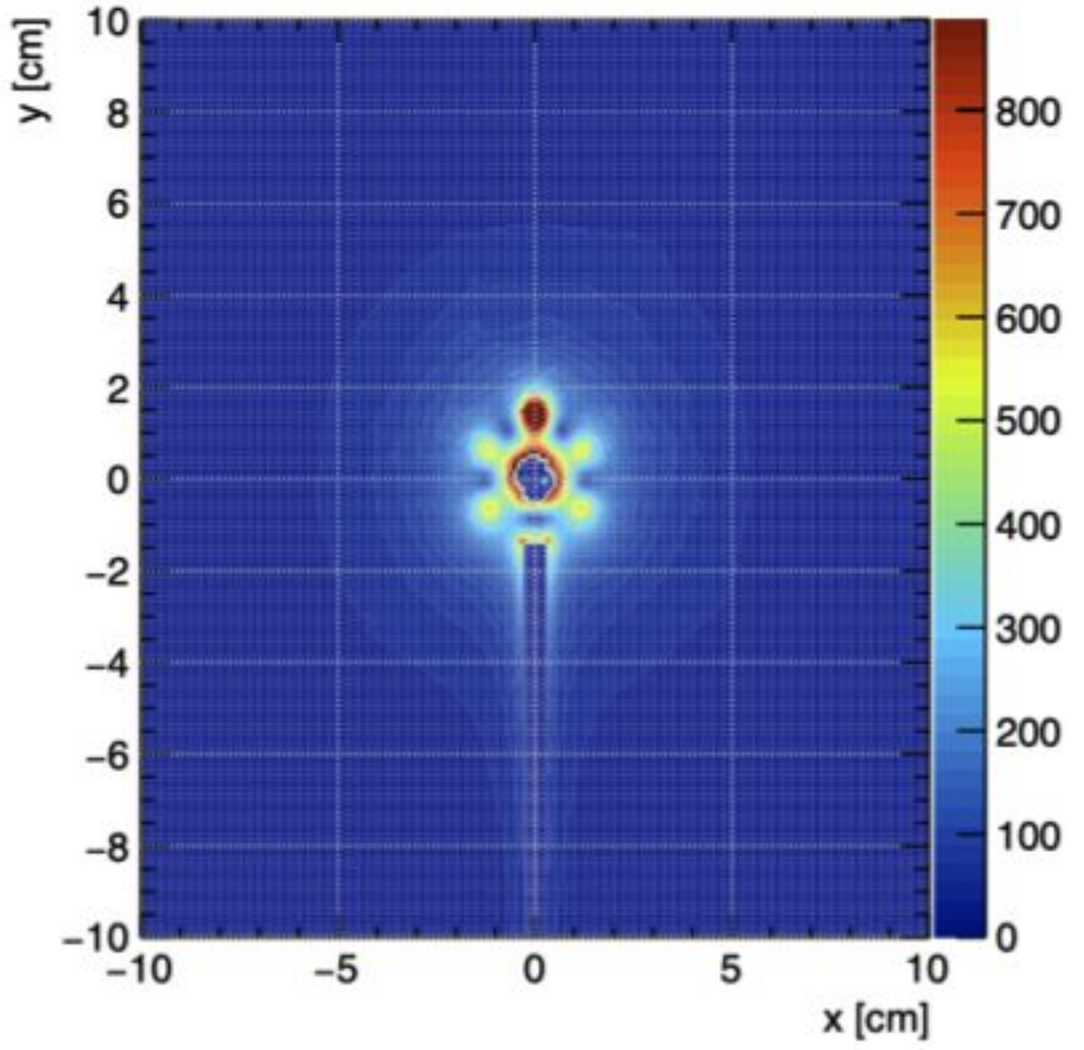
- Reproduction of angular variation of gain observed with Fe55 calibration



From work described, but not shown, in:

R. Ward et al 2020 JINST 15 C06013

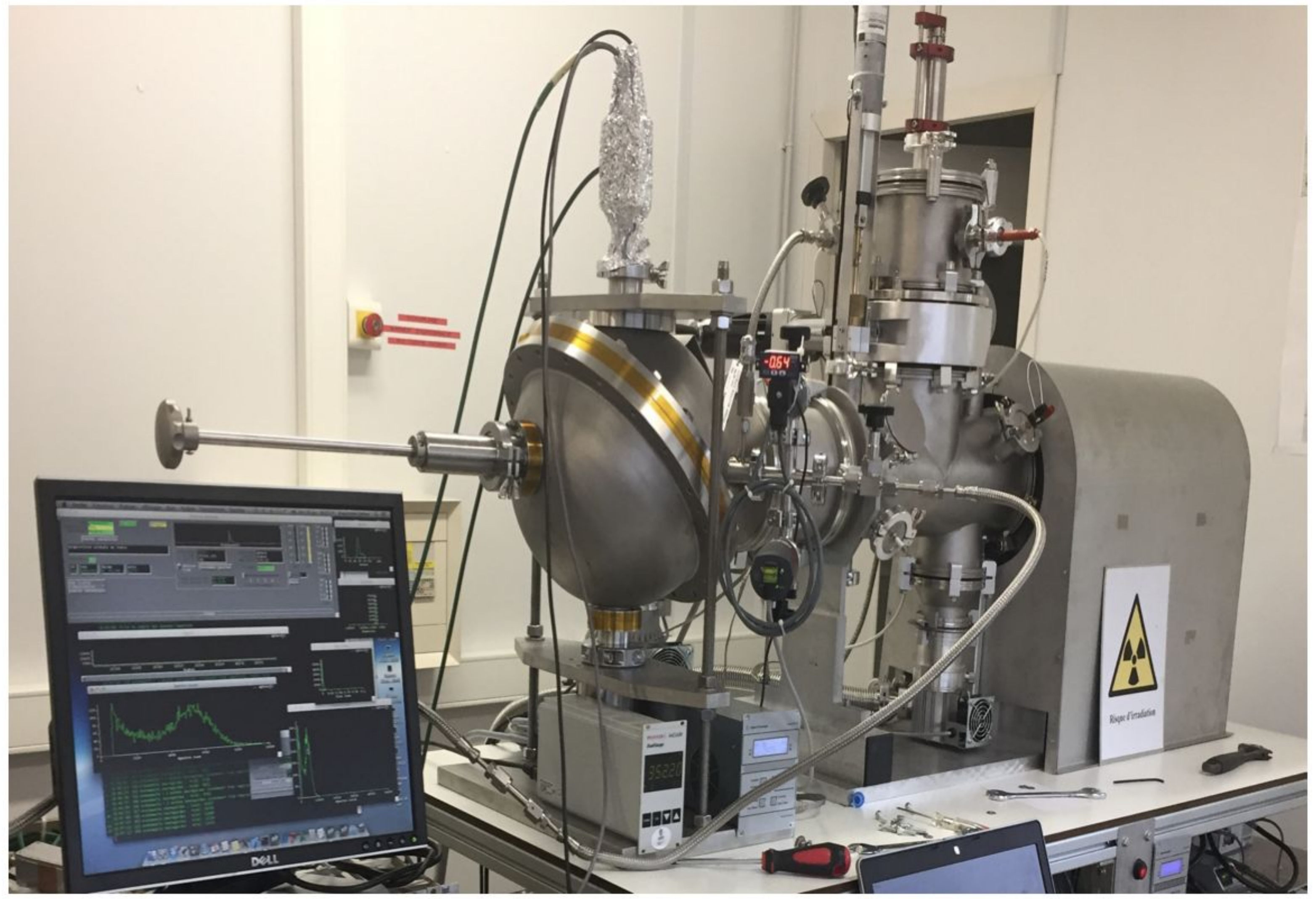
- Weighting fields used to compute induced current on anode / channels



Quenching Factor measurements

QF: ratio of ionisation energy to total energy

COMIMAC, LPSC Grenoble



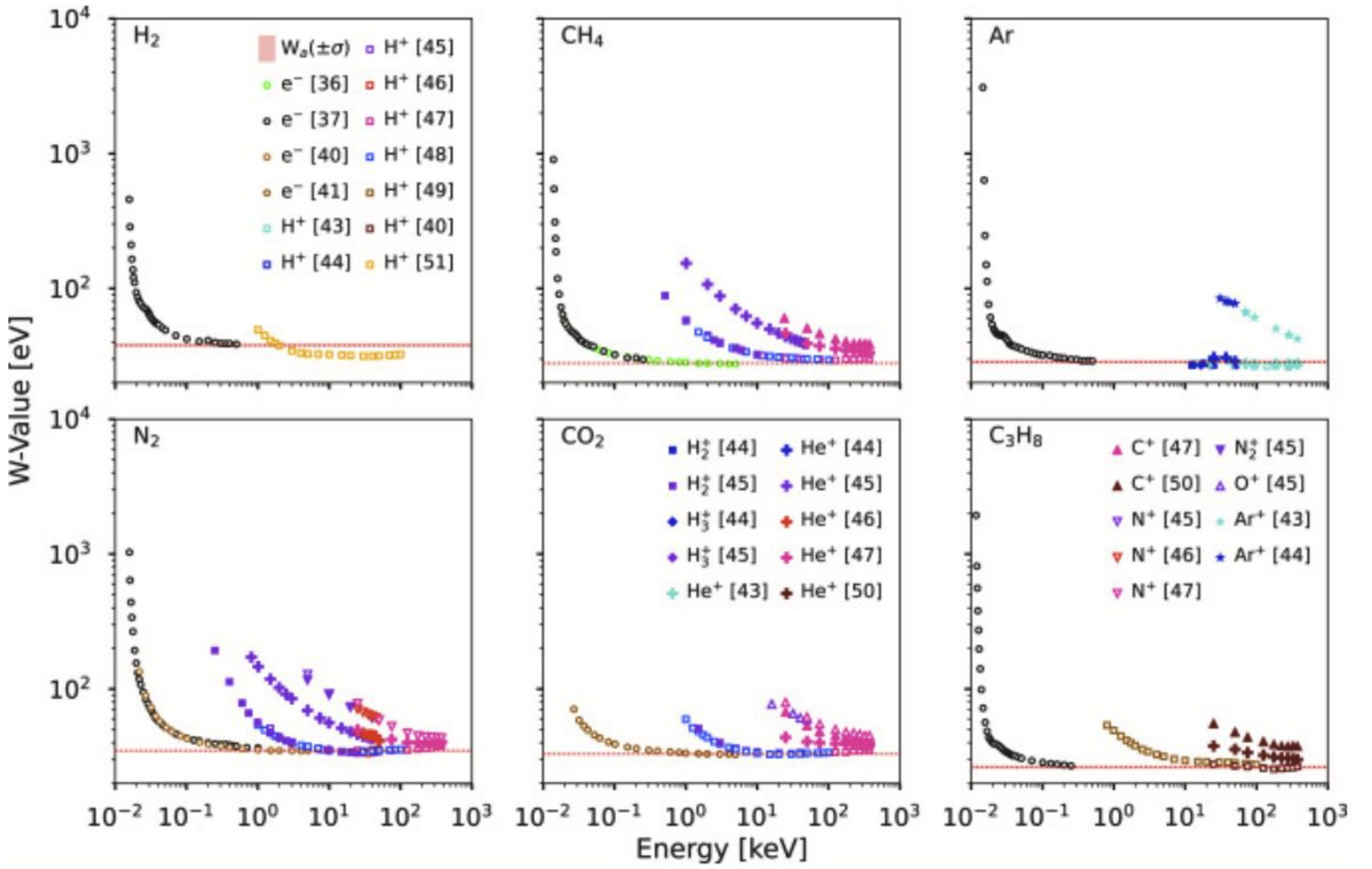
Generates electrons/ions of known energy, accelerated in electric field

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

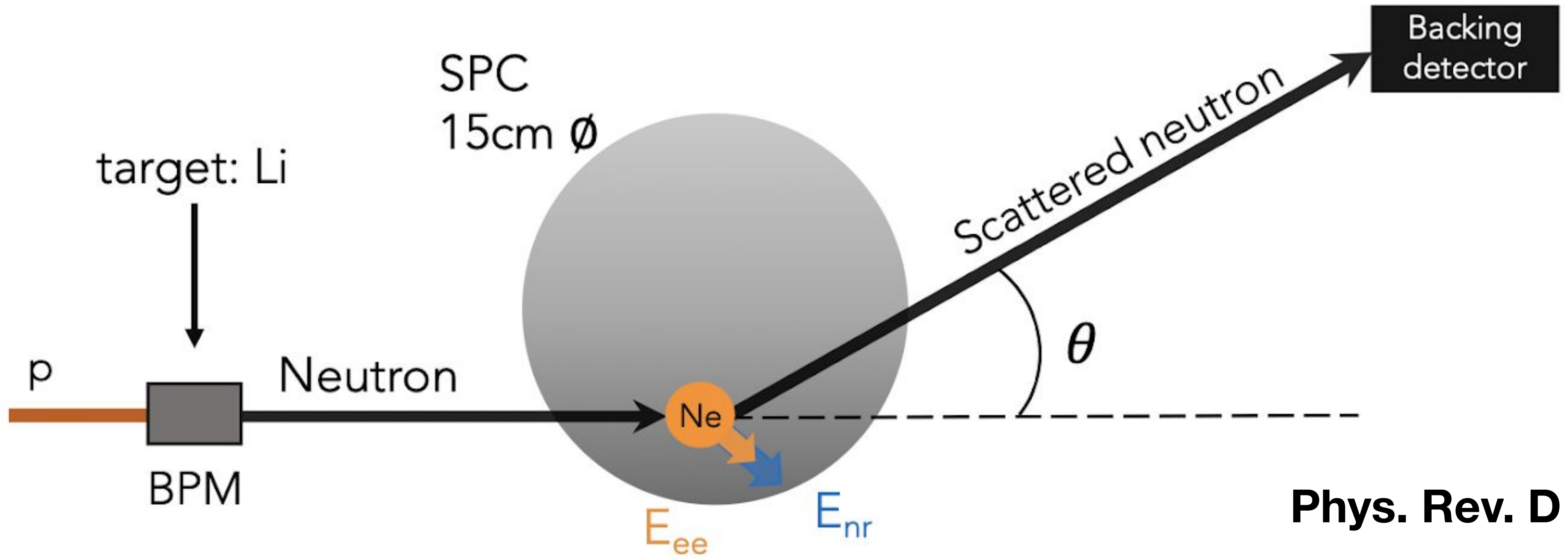
Ratio of literature values for W, Birmingham U.

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

Astr. Phys. 141, 102707 (August 2022)



545keV neutron beam, TUNL

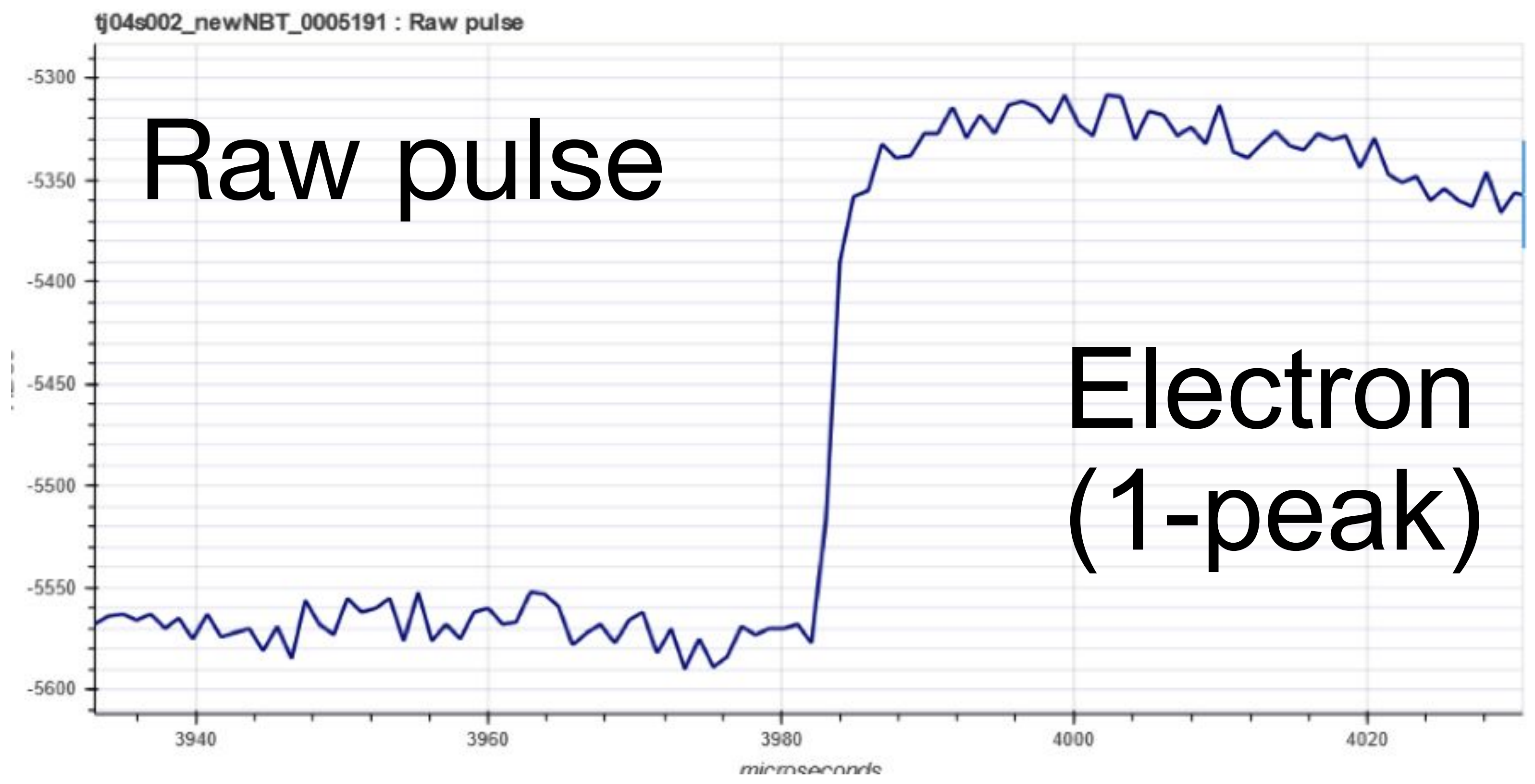


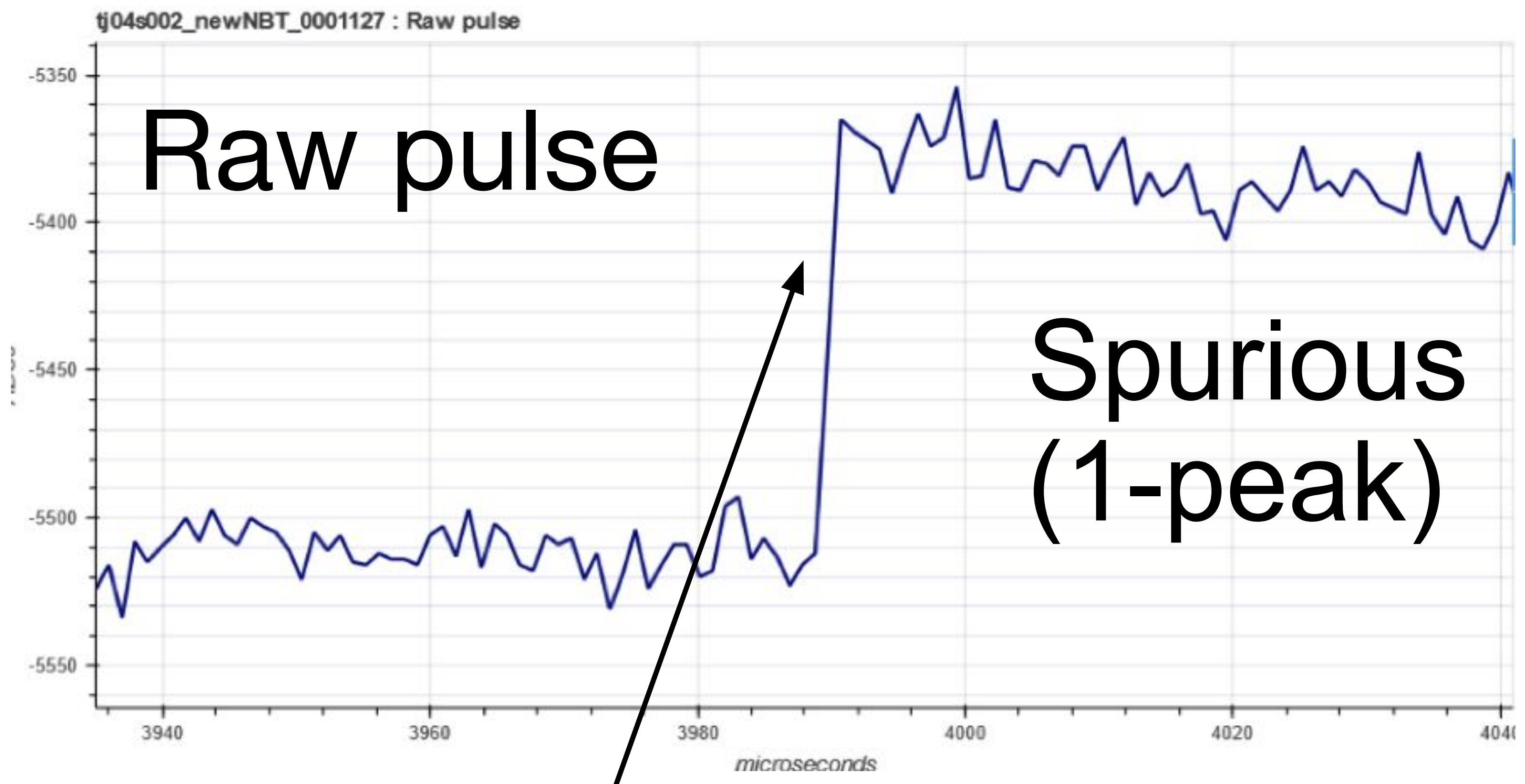
Neutron beam generates recoils on target, energy derived from angle of recoil with Backing Detector

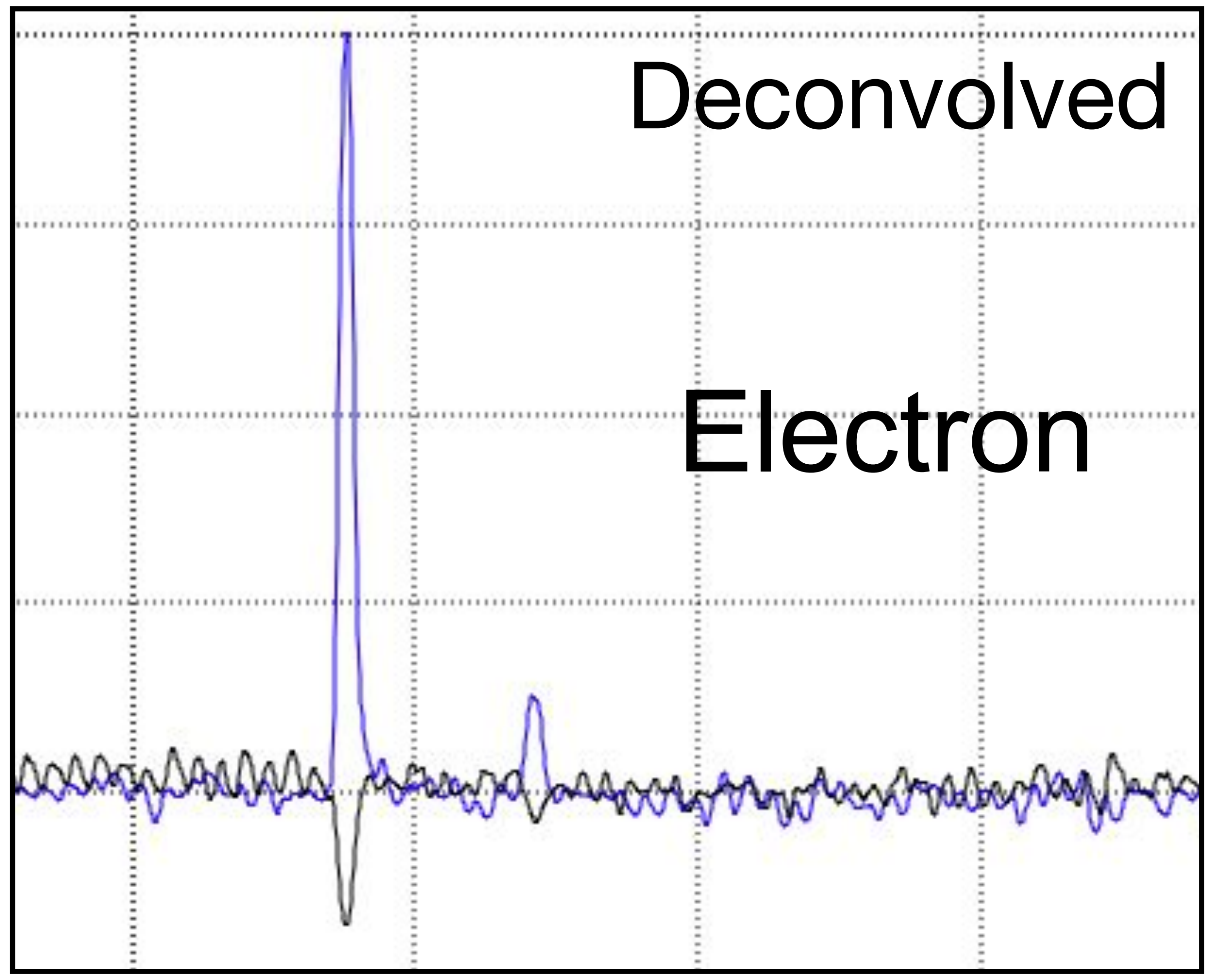
Phys. Rev. D 105, 052004 (March 2022)

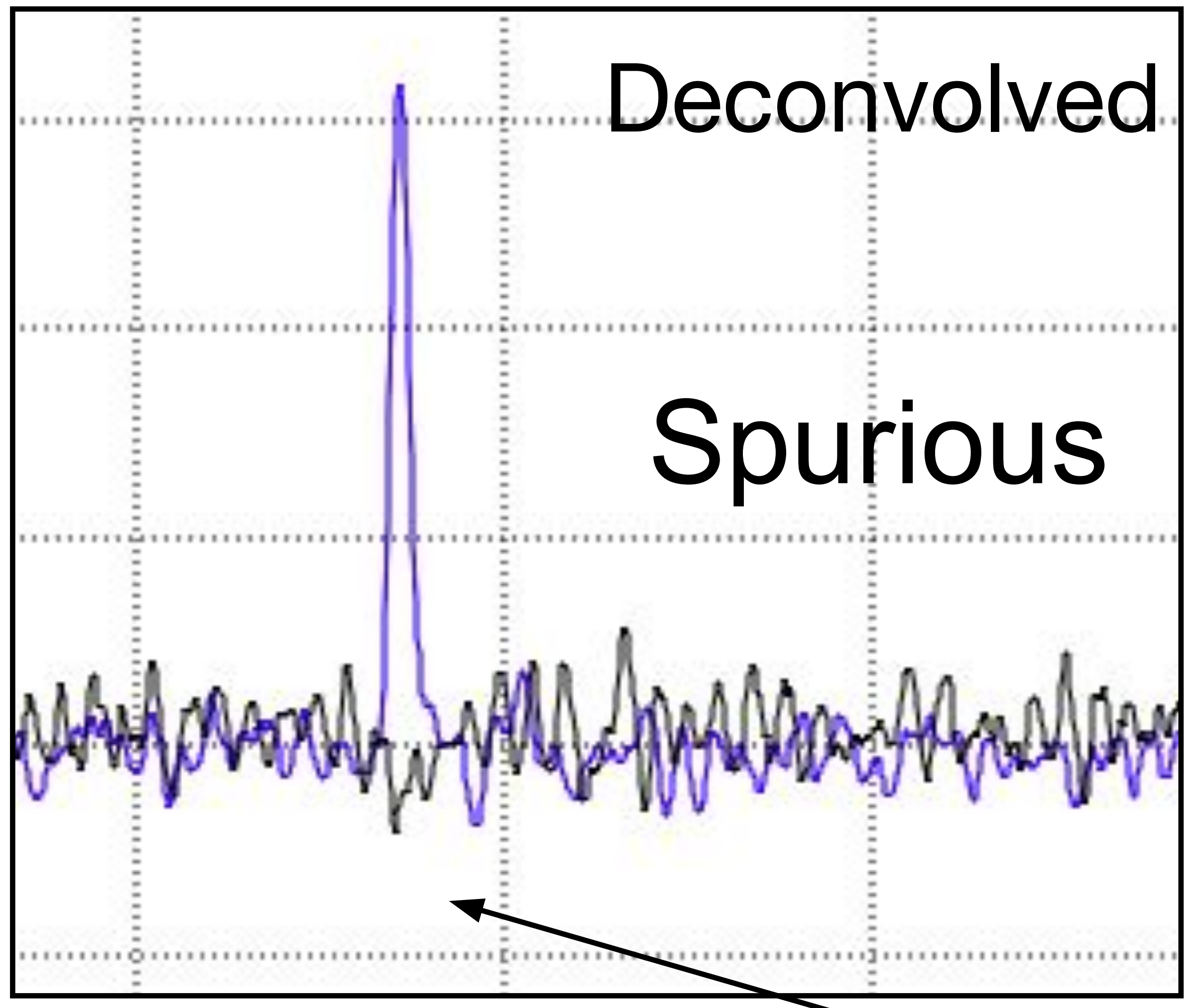
Pulse Shape Discrimination

Spurious pulses generated in the electronics do not have characteristic shape of physical pulses









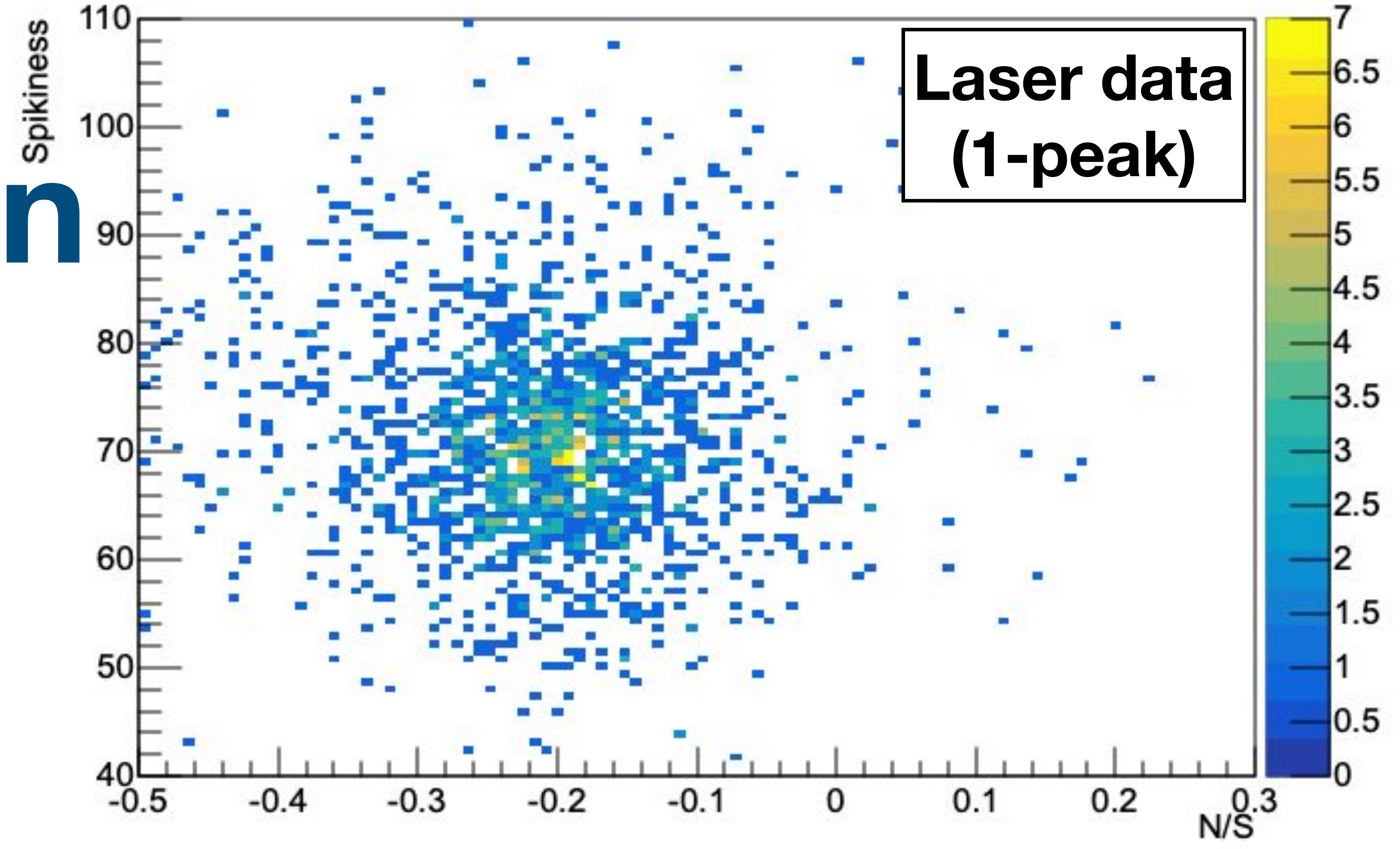
- sharp rise of raw signal
- lack of negative signal on opposite channel (observed for « electron-like » events)

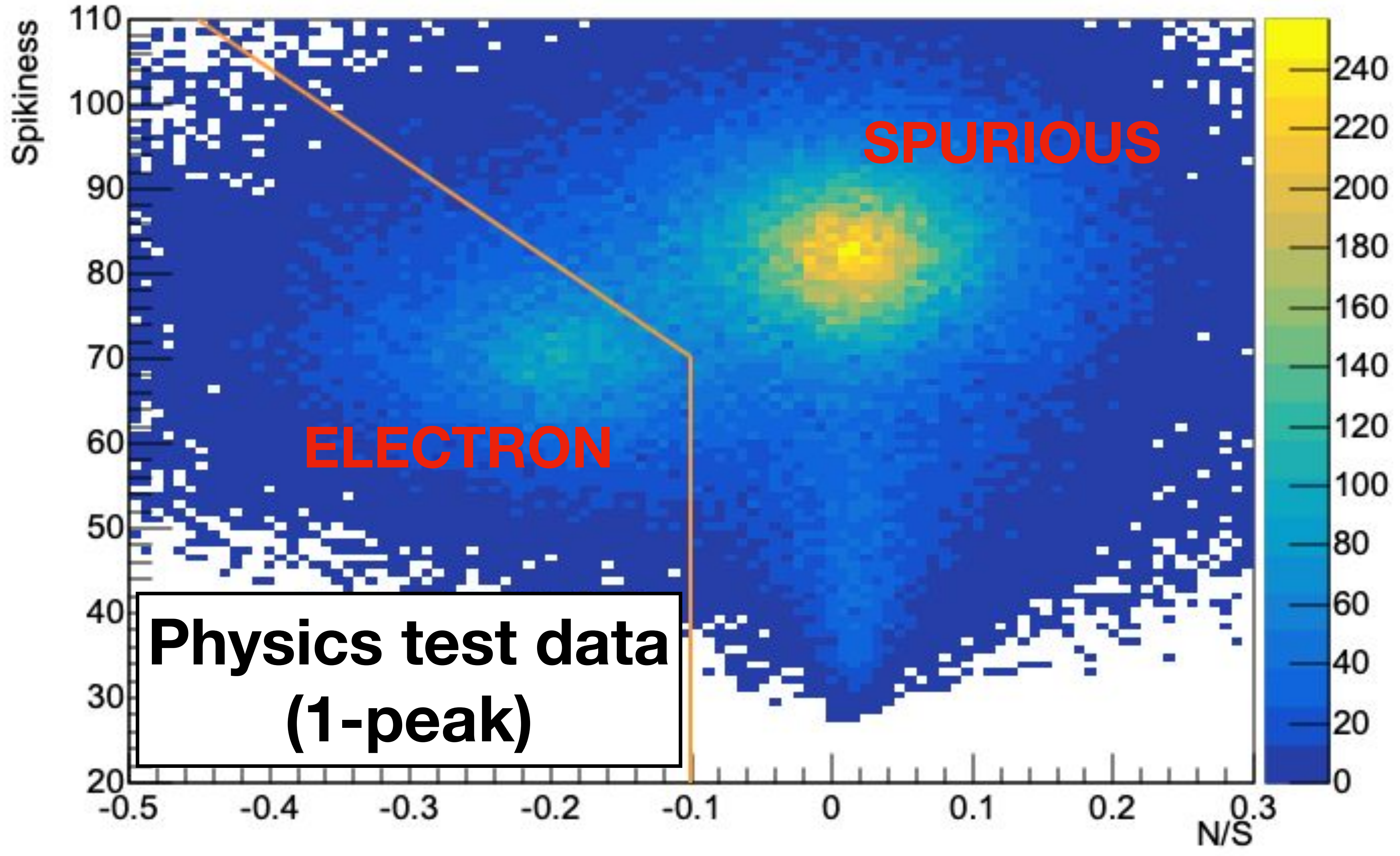
Pulse Shape Discrimination

Spurious pulses generated in the electronics do not have characteristic shape of physical pulses

Cuts on «Crosstalk» (Ampl_North/Ampl_South) and «Spikiness» (MaxDerivative/Ampl) chosen by comparing single-peak events from laser calibrations with those from test physics data.

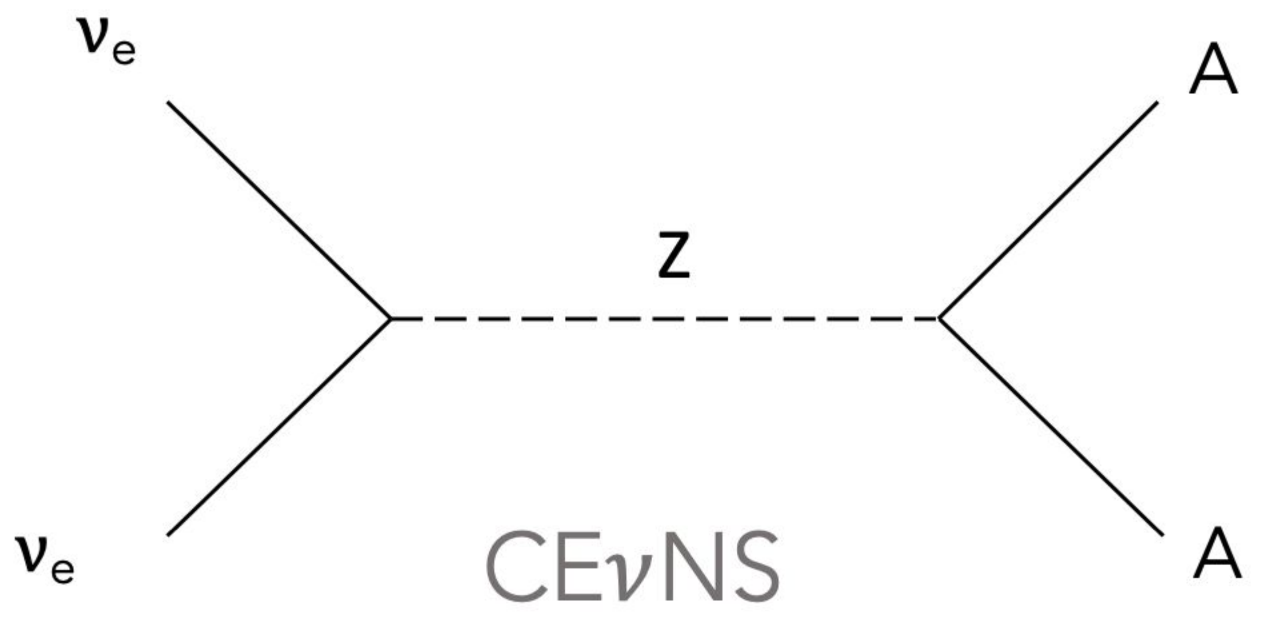
Keep 77% of «physical» events, and rejects ~95% of spurious pulses





Other projects

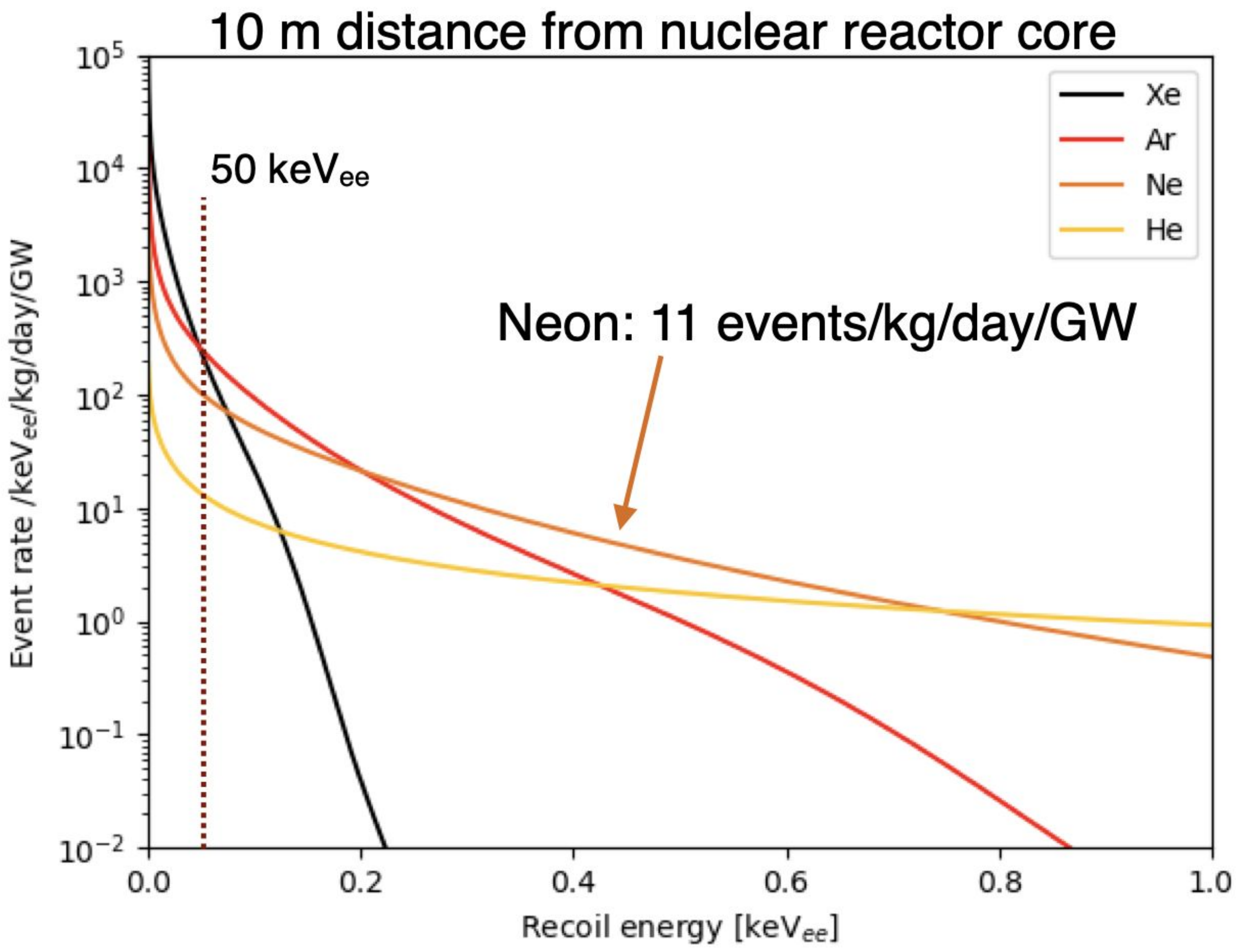
Coherent Elastic Neutrino-Nucleus Scattering



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. Shielding constructed at Queen's University, prepared for commissioning.



M. Vidal thesis
http://hdl.handle.net/1974/29507

Other projects

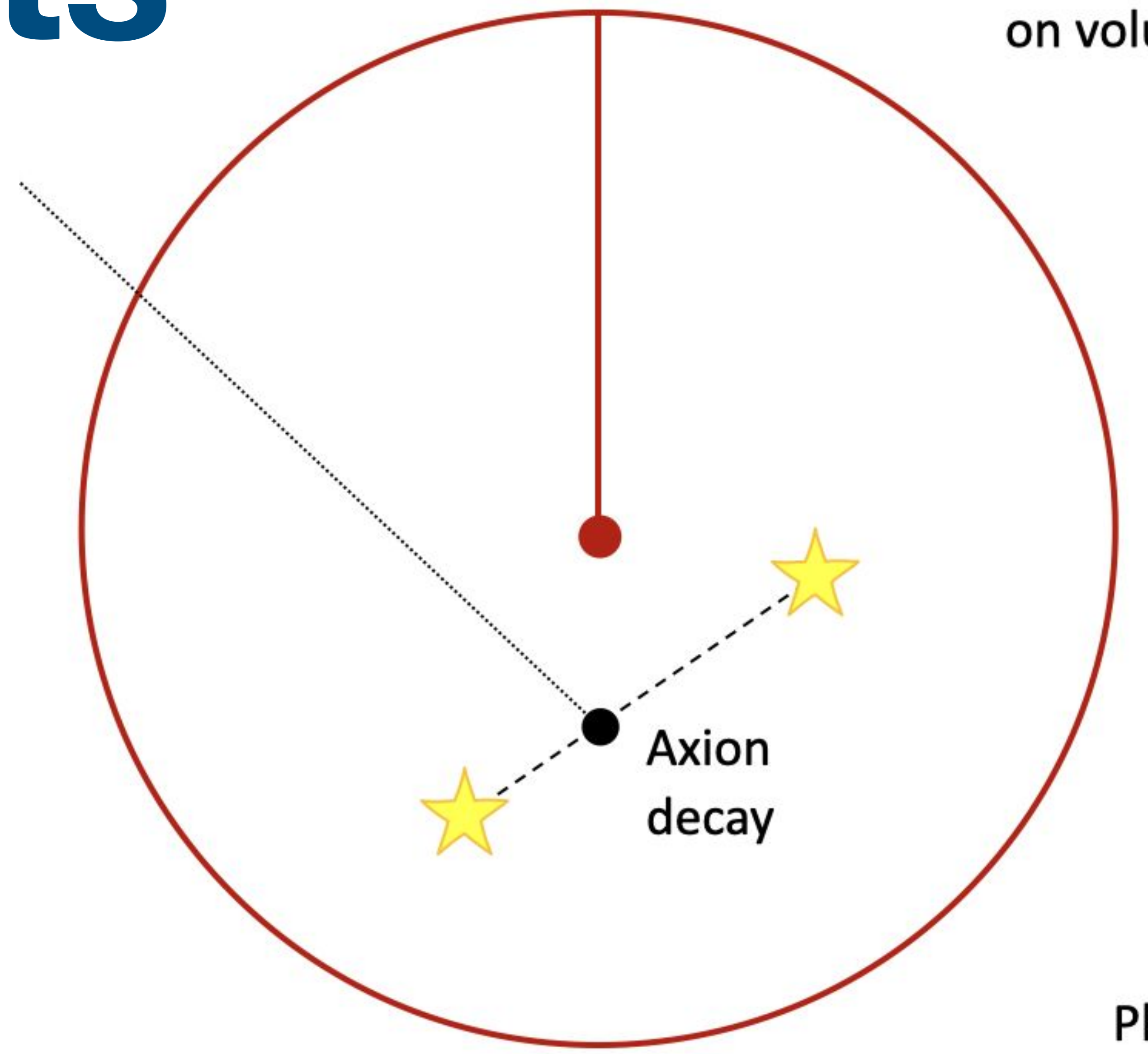
Solar KK axions

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.

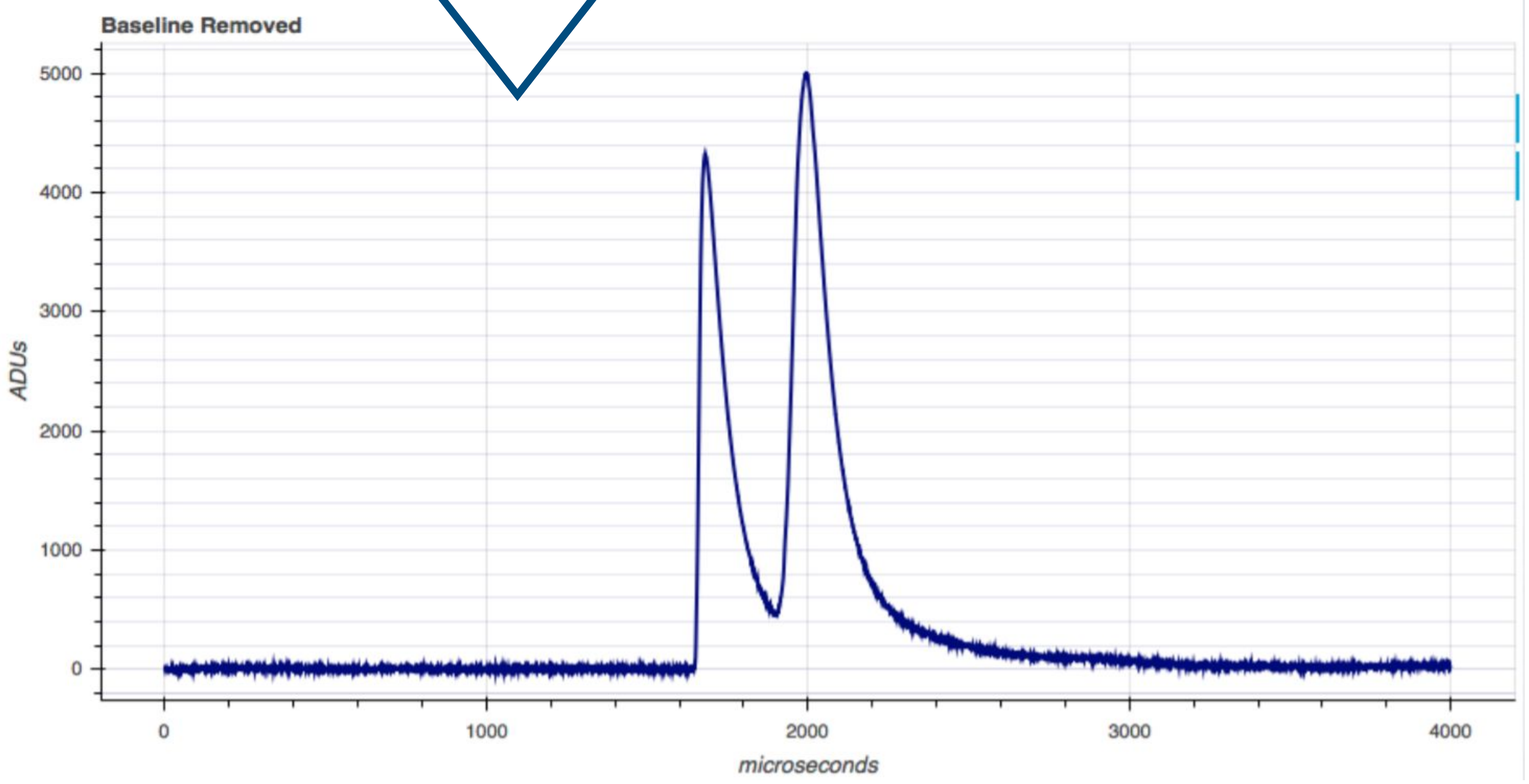
Can reject background at 99.99% in 2-22 keV range by keeping only events with two pulses of similar amplitude arriving shortly after each other.

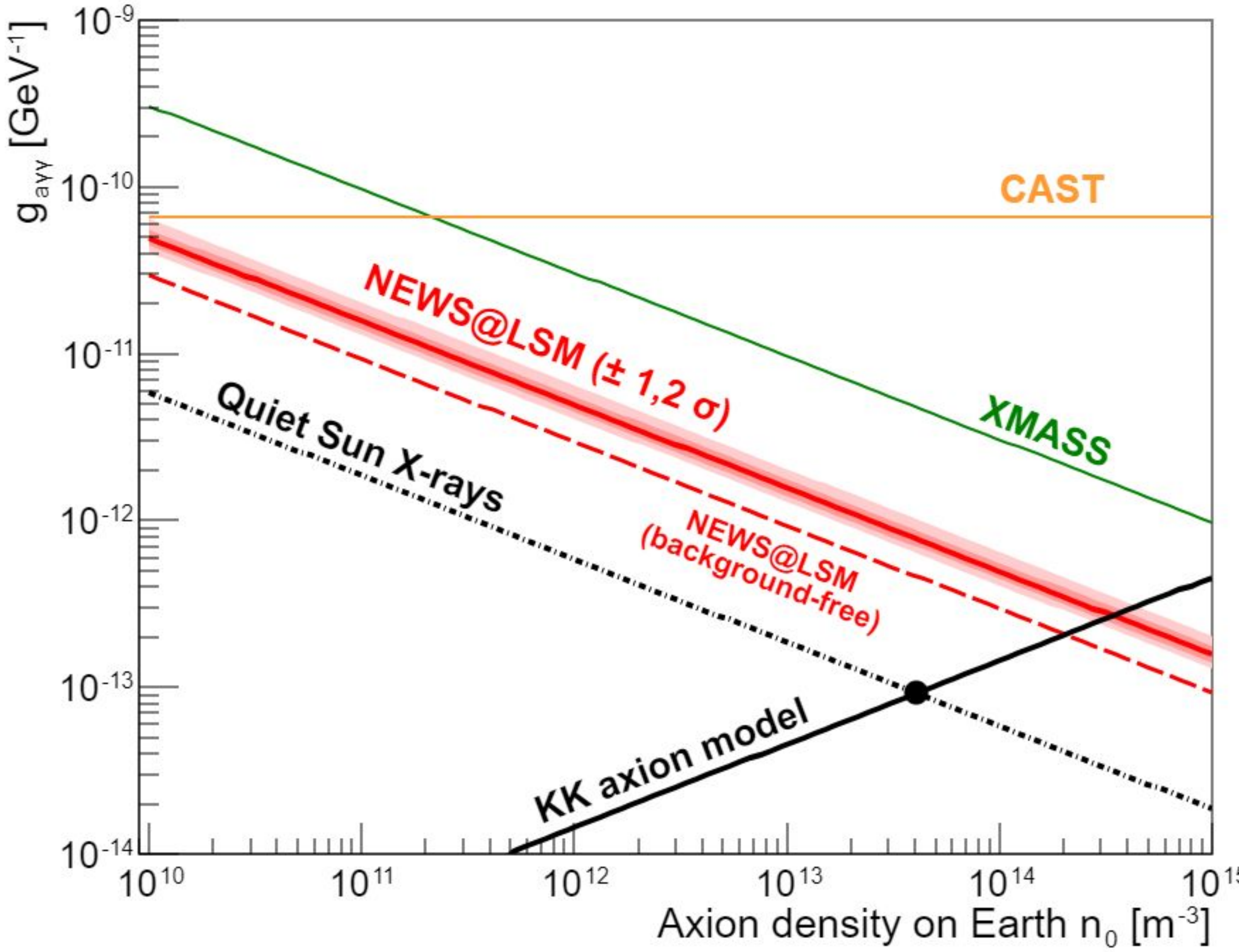
With 42 day exposure of SEDINE detector, and an integrated sensitivity to solar KK axion decays of 16%, still improve over previous XMASS limit by factor ~6.

Axion decay rate depends only on volume of detector, not its mass!



Photons < 10 keV:
Single photoelectric interaction





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

(though note more restrictive constraint from quiet Sun X-rays published shortly beforehand: M. Bastero-Gil et al., JCAP 10 (2021) 048)