# Low mass WIMP searches with NEWS-G: First results with methane target

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

GDR DUPHY, October 2022

Subatech

CNRS IN2P3 Les deux infinis

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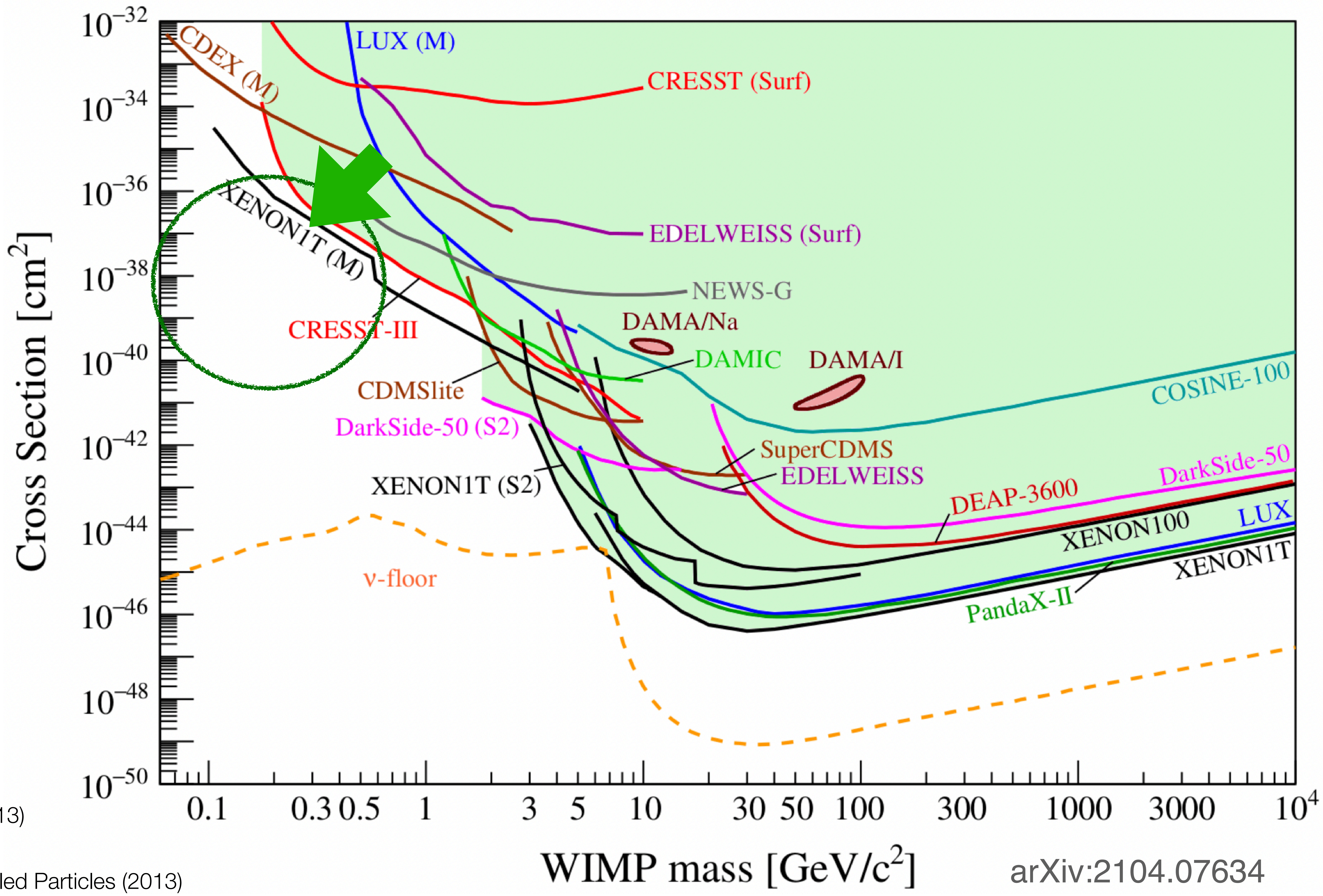
Nantes Université

# Outline

- NEWS-G introduction
- The S140 detector
- Calibrations
- Data quality cuts & First results
- Outlook & Other projects

# 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


[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)
[4] R. Essig et al, Dark Sectors and New, Light, Weakly-Coupled Particles (2013)

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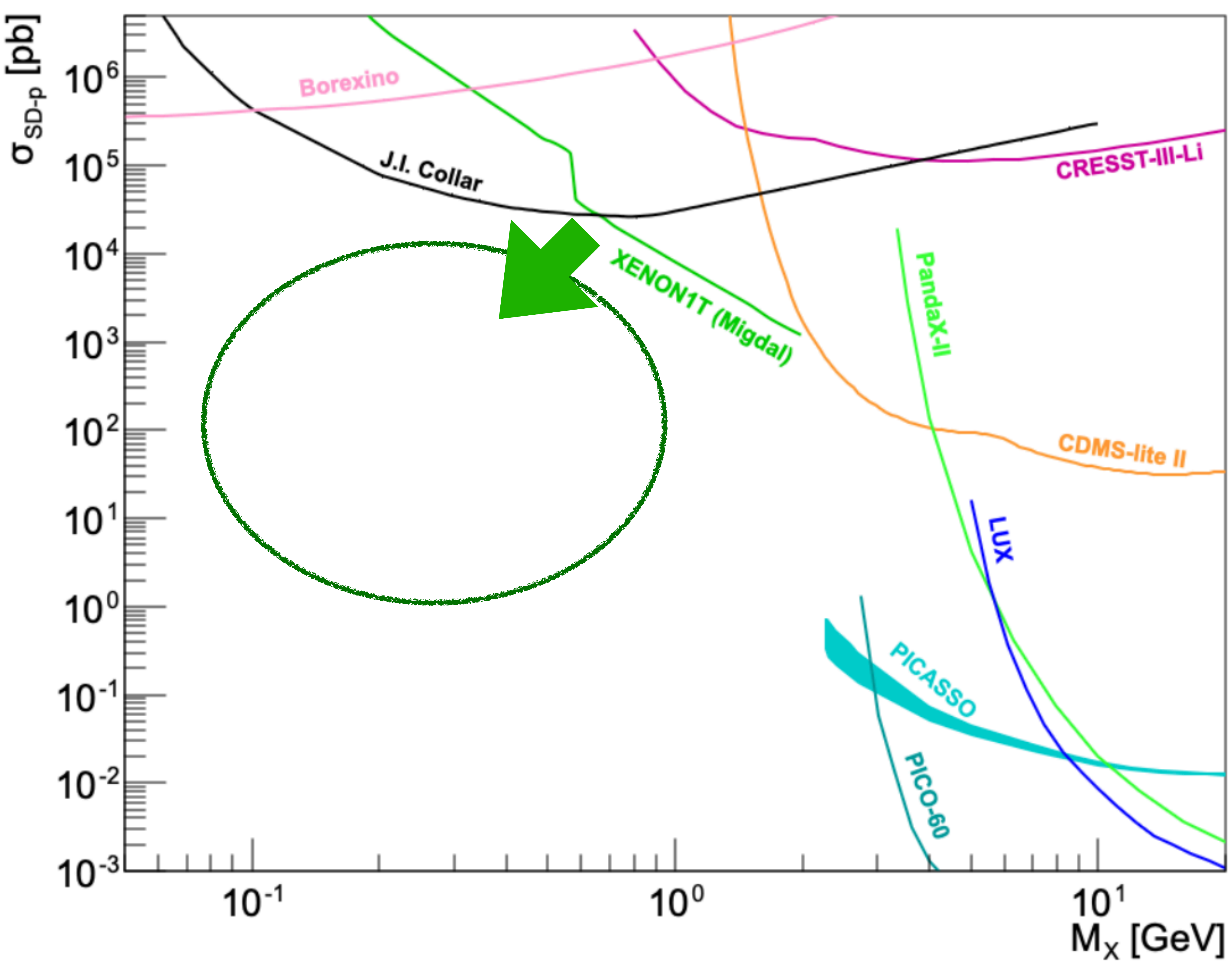
WIMP-proton cross-section constraints





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# New Experiments With Spheres - Gas

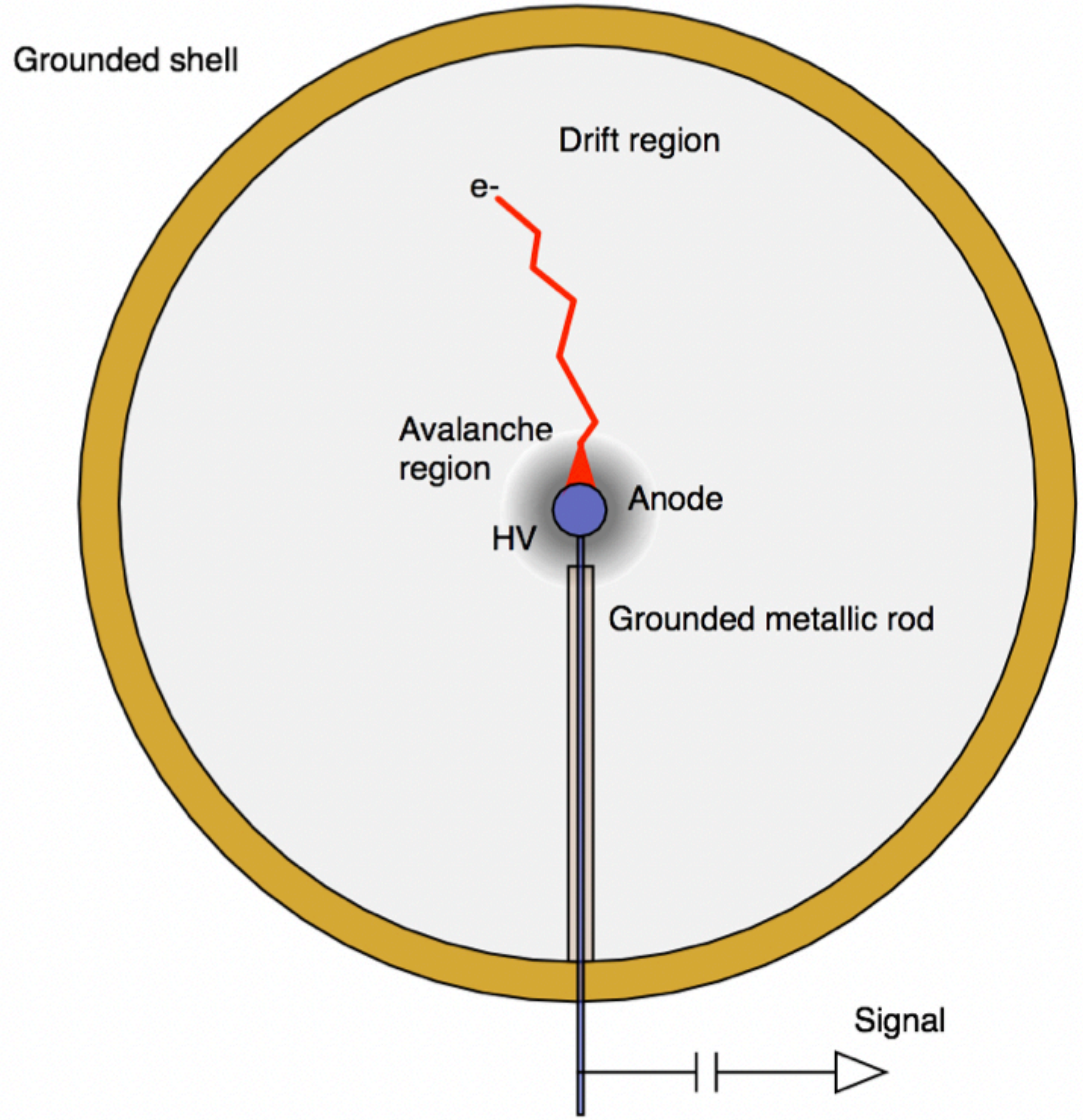
- Focus on **Dark Matter Direct Detection**
- NEWS-G collaboration:
  - 5 countries
  - 10 institutes
  - ~ 40 collaborators
- Three underground laboratories:
  - Laboratoire Souterrain de Modane
  - SNOLAB
  - Boulby Underground Laboratory

# Spherical Proportional Counter

## Working Principle

Ionisation detector

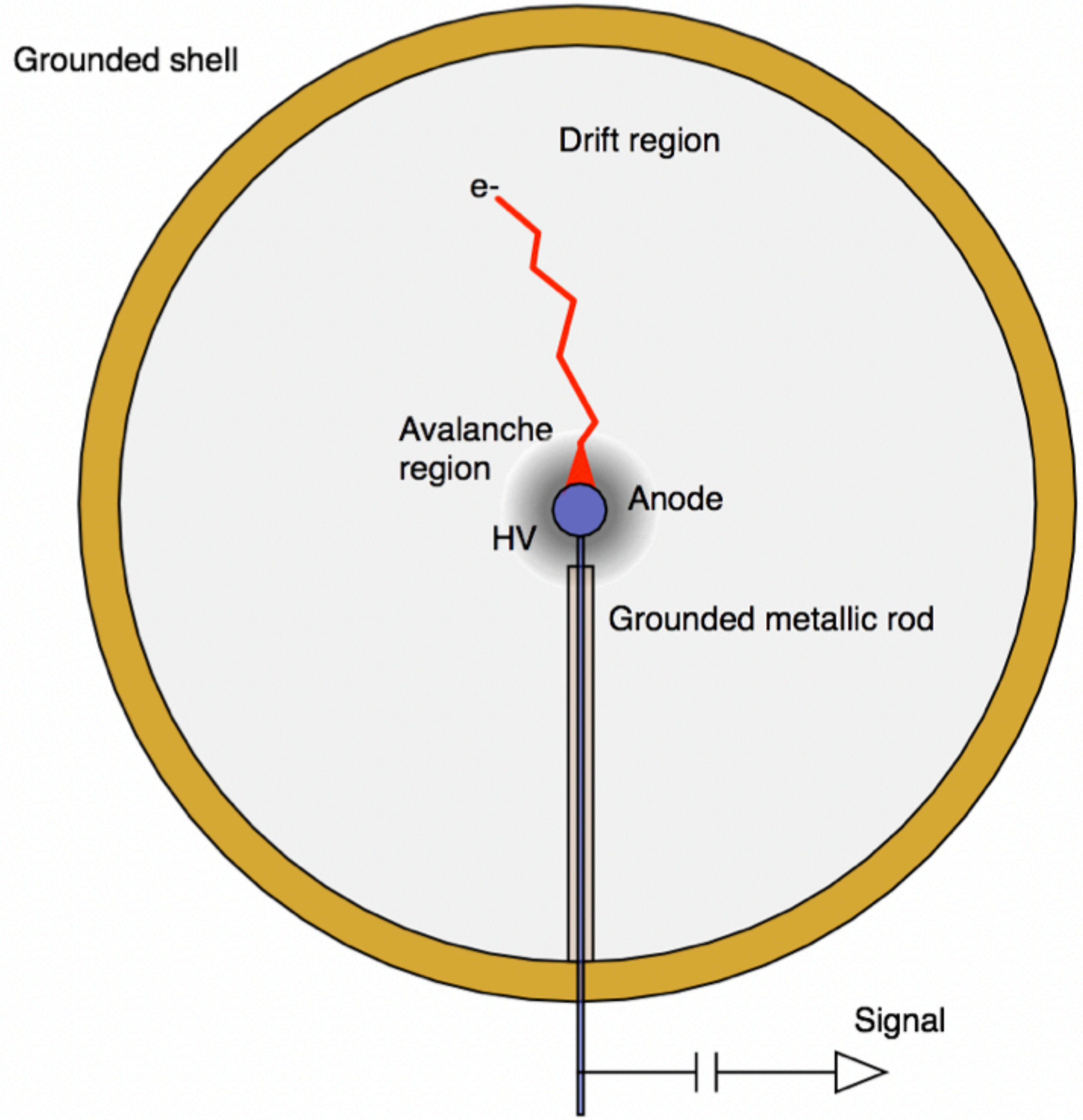
- Incident particle induces recoil, releasing ionisation energy
- Primary electrons drift and diffuse towards central anode
- High field in $1/r^2$ at anode produces ~$10^3$-$10^4$ avalanche multiplication
- Drifting ions induce current on anode



# 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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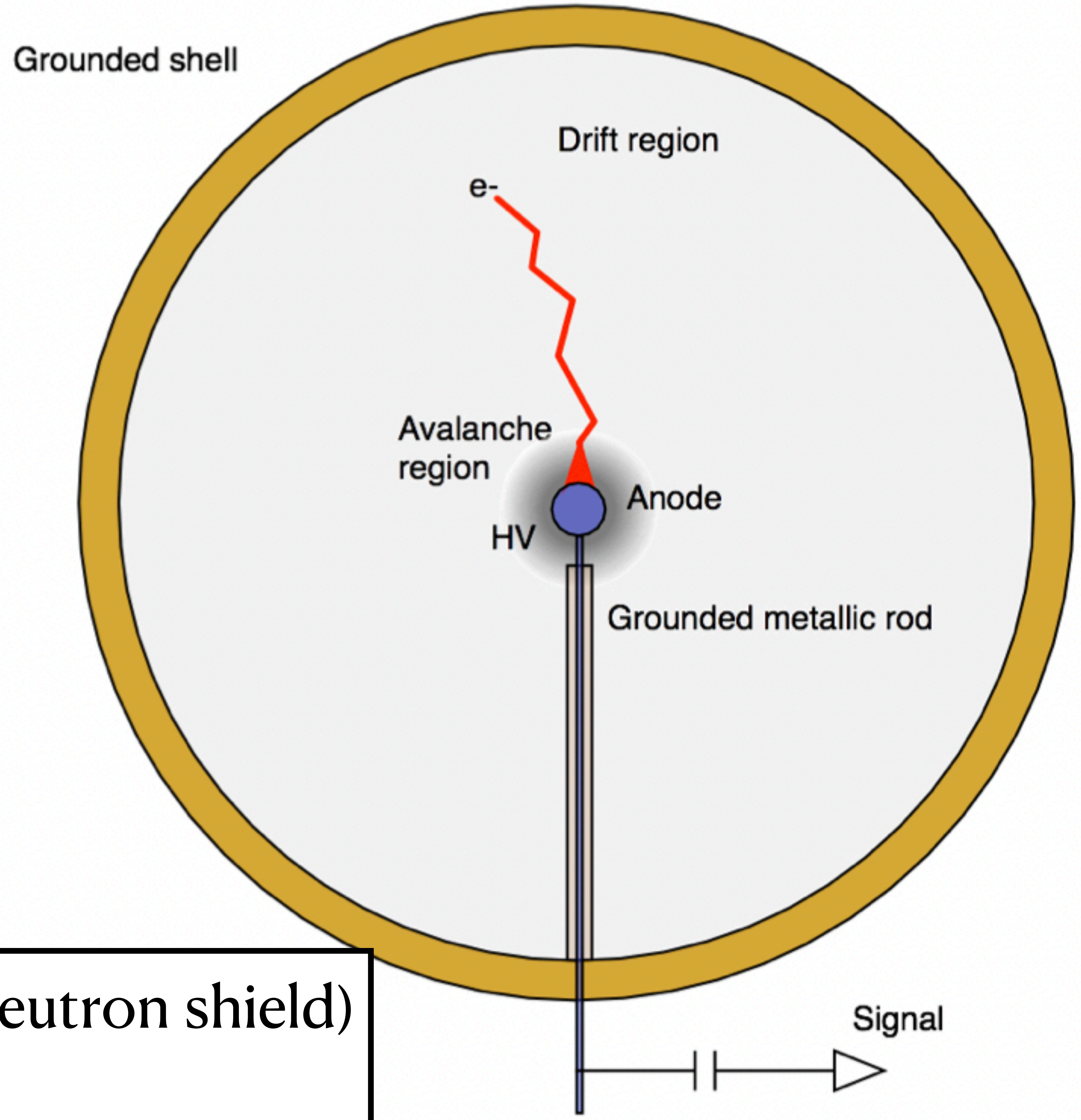
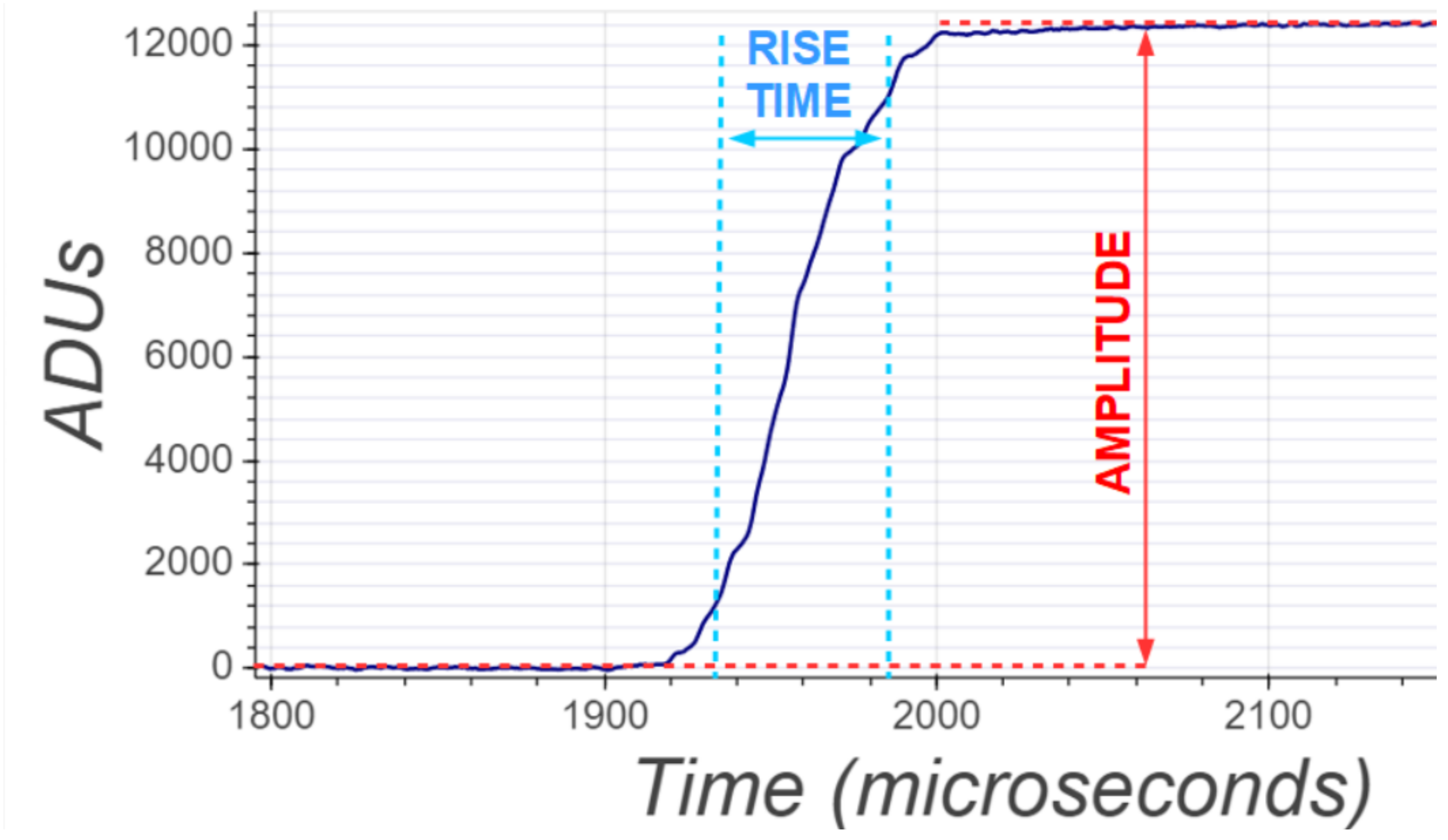
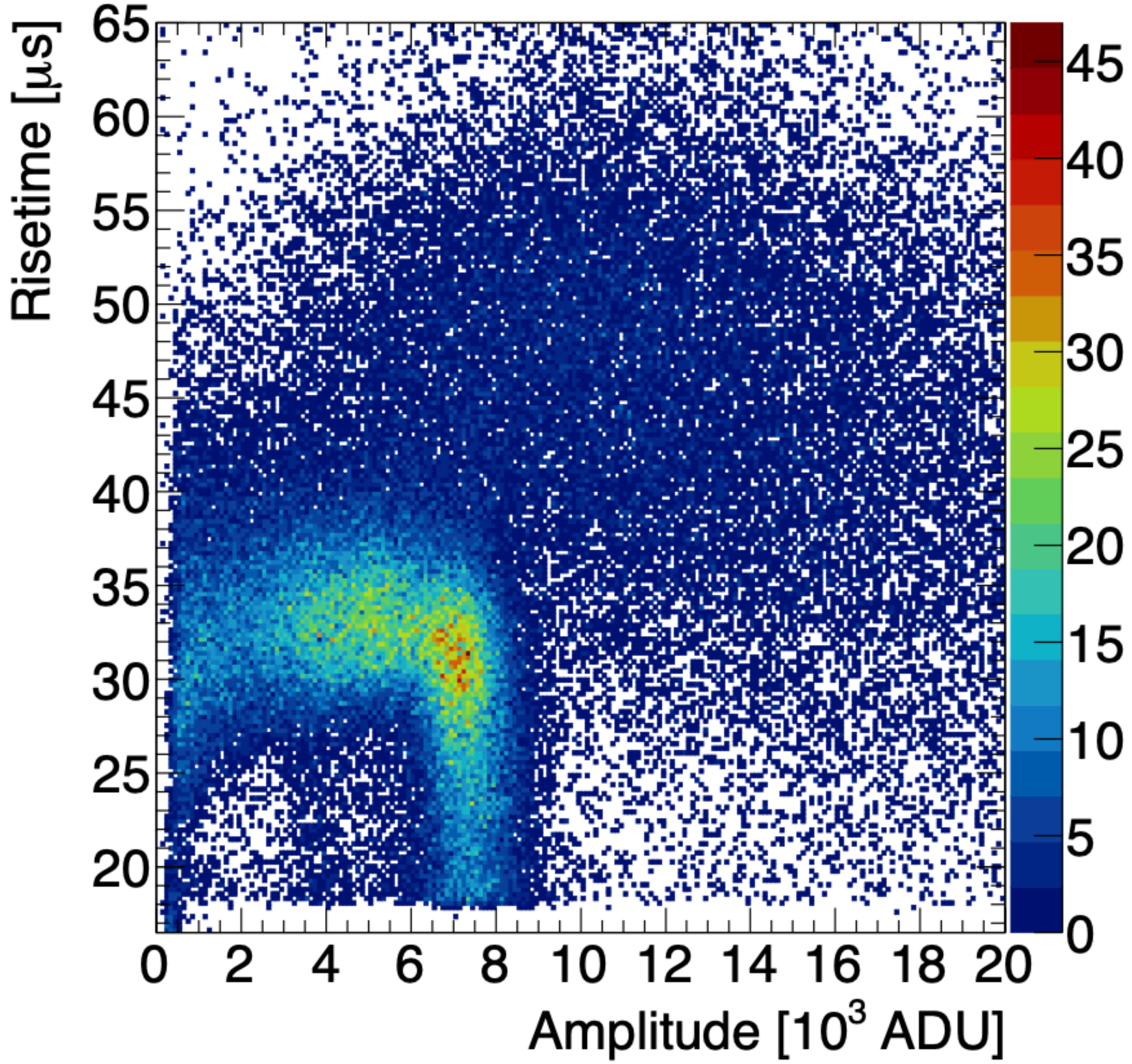



Low radioactivity set-up (high radiopurity and gamma/neutron shield) **and** underground environment needed to study WIMP

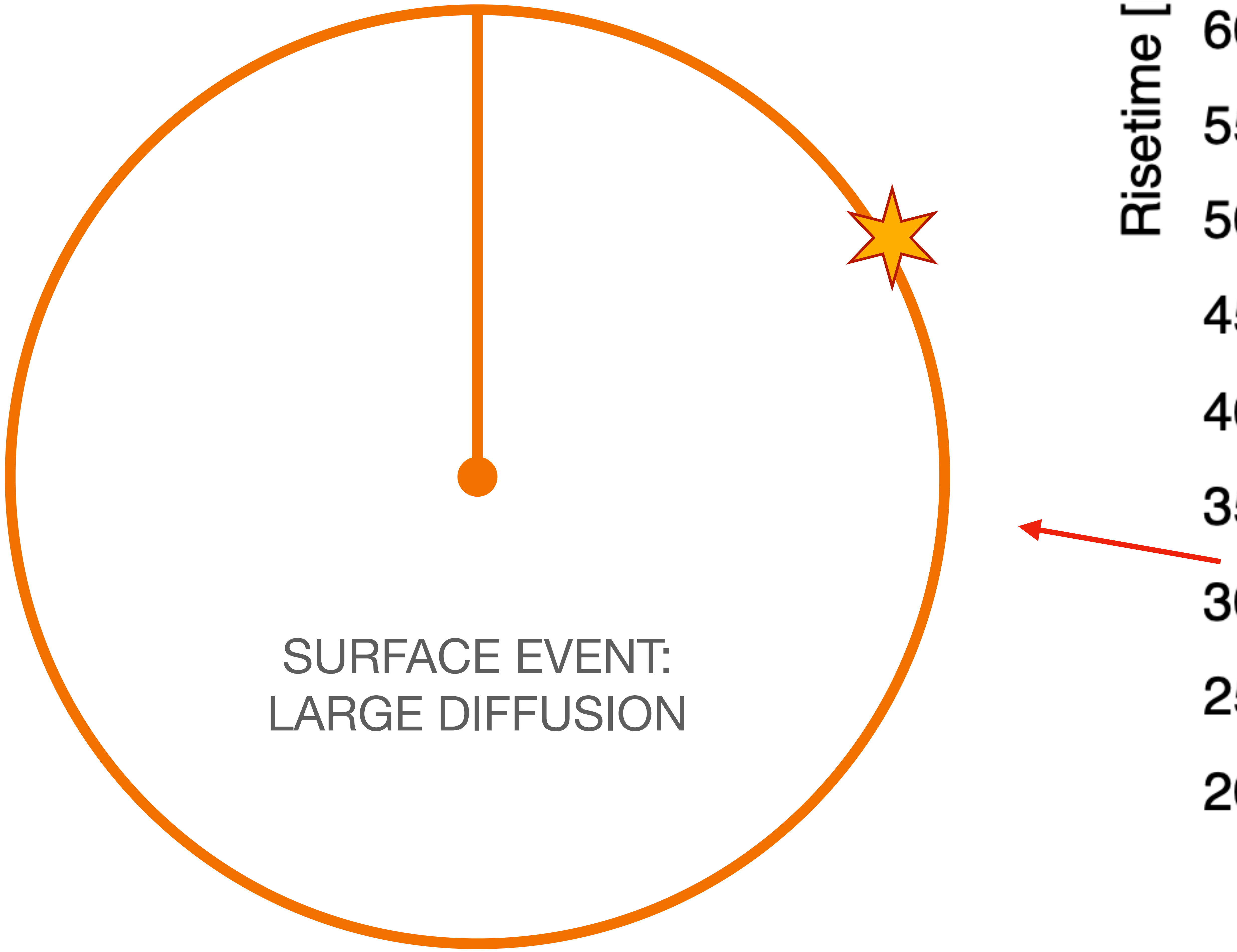
# Pulse Shape Discrimination

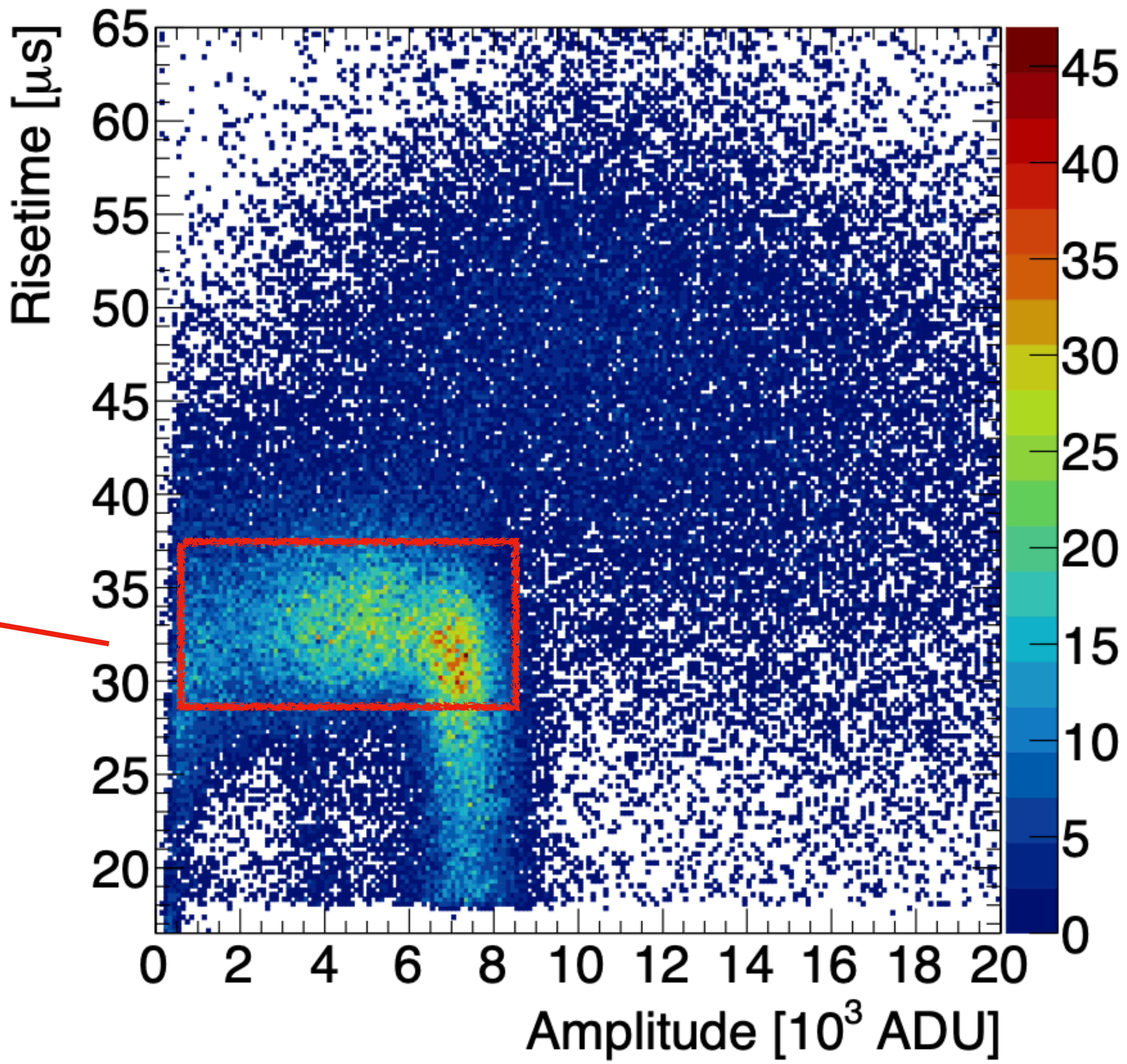



Amplitude: Energy of event
Risetime: Determine type of interaction



# Pulse Shape Discrimination



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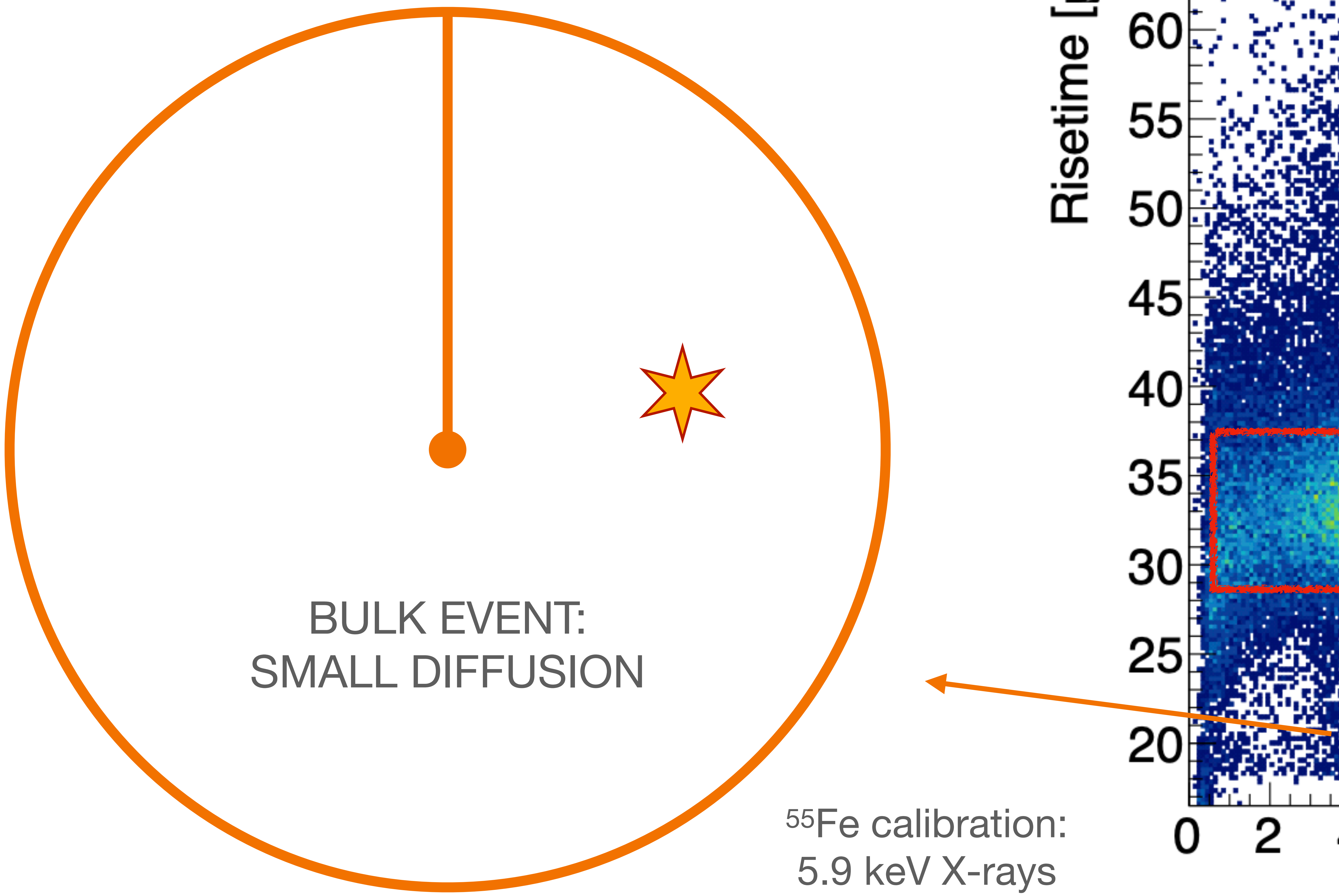
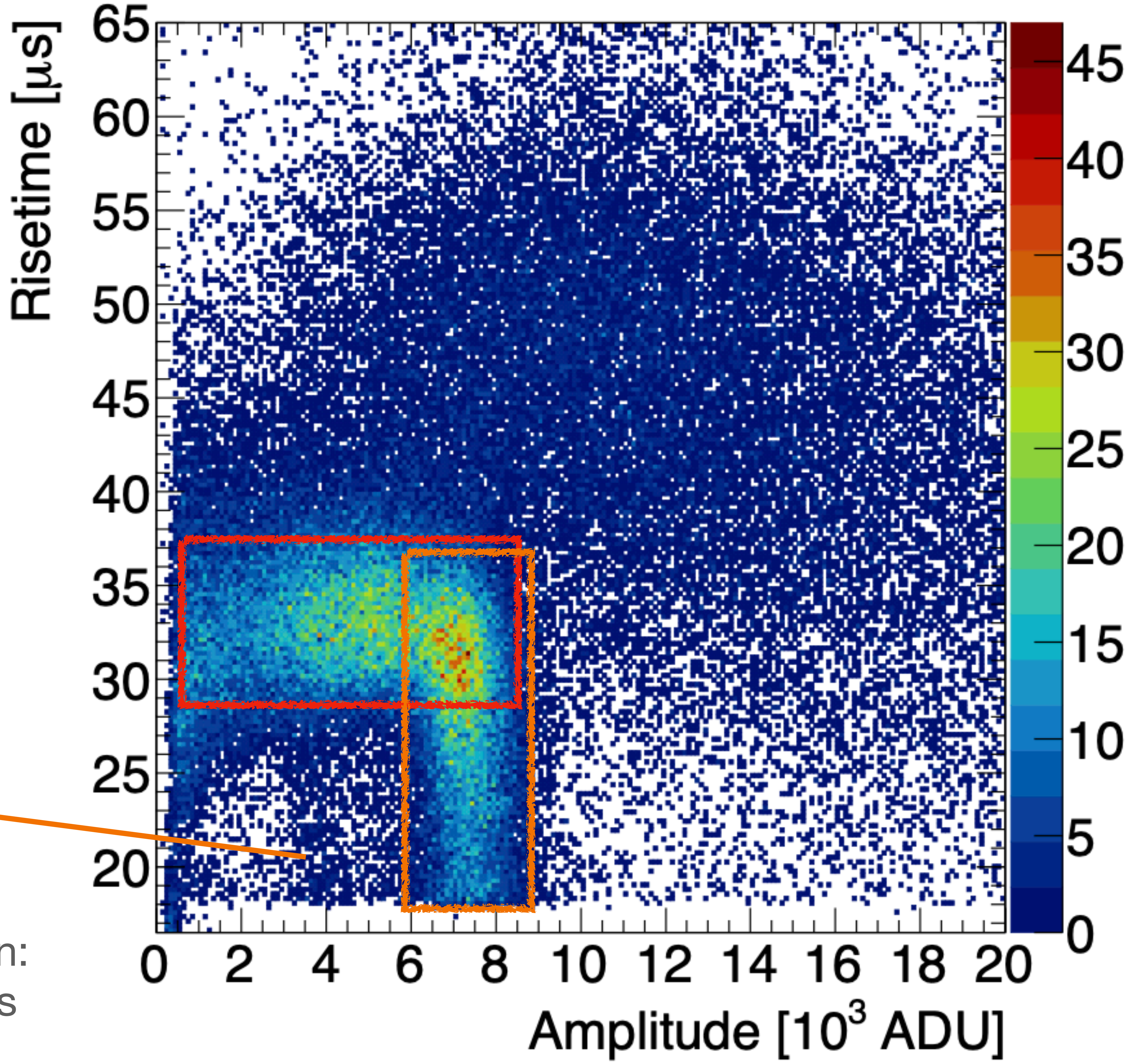



$^{55}$Fe calibration:
5.9 keV X-rays



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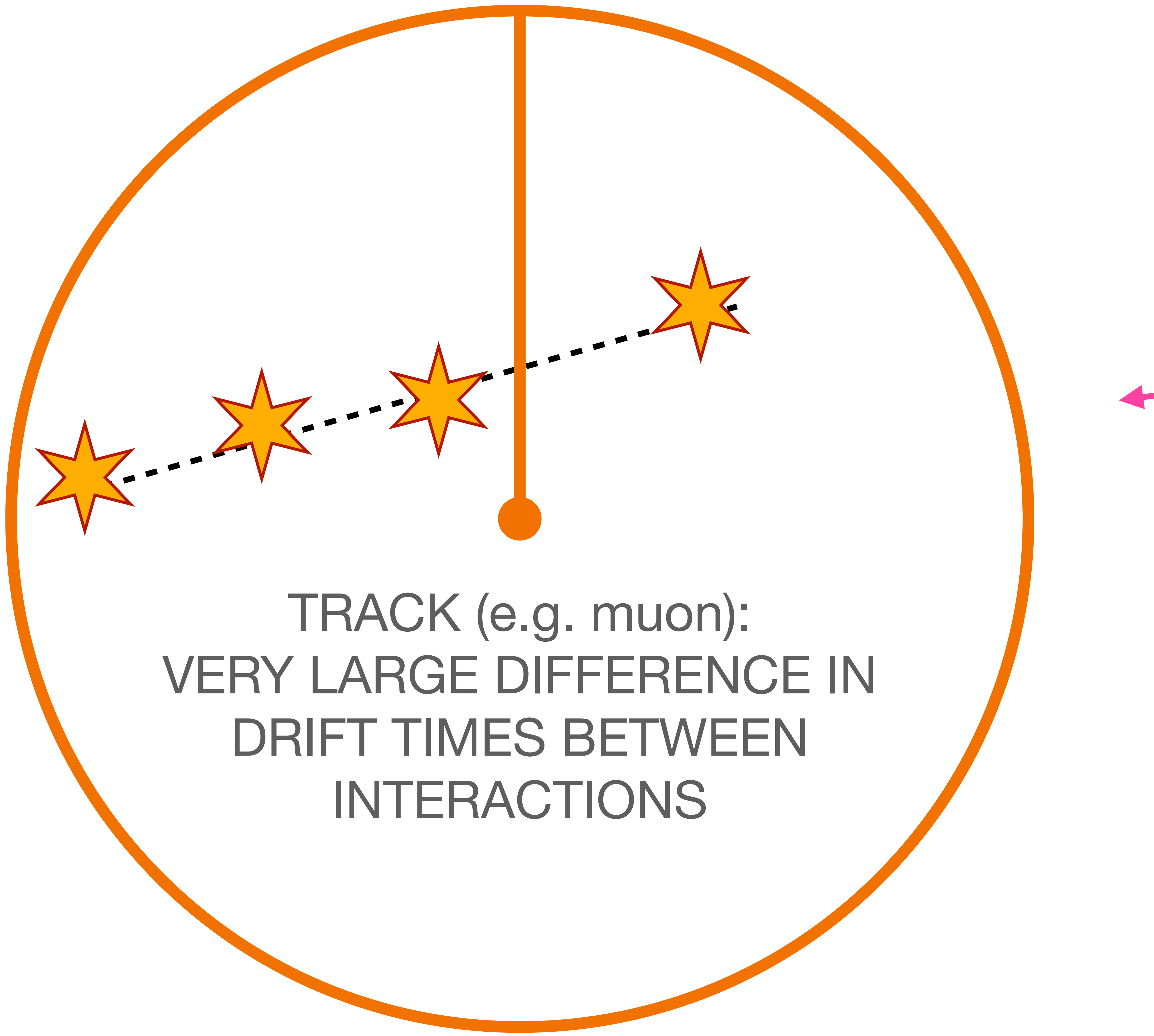
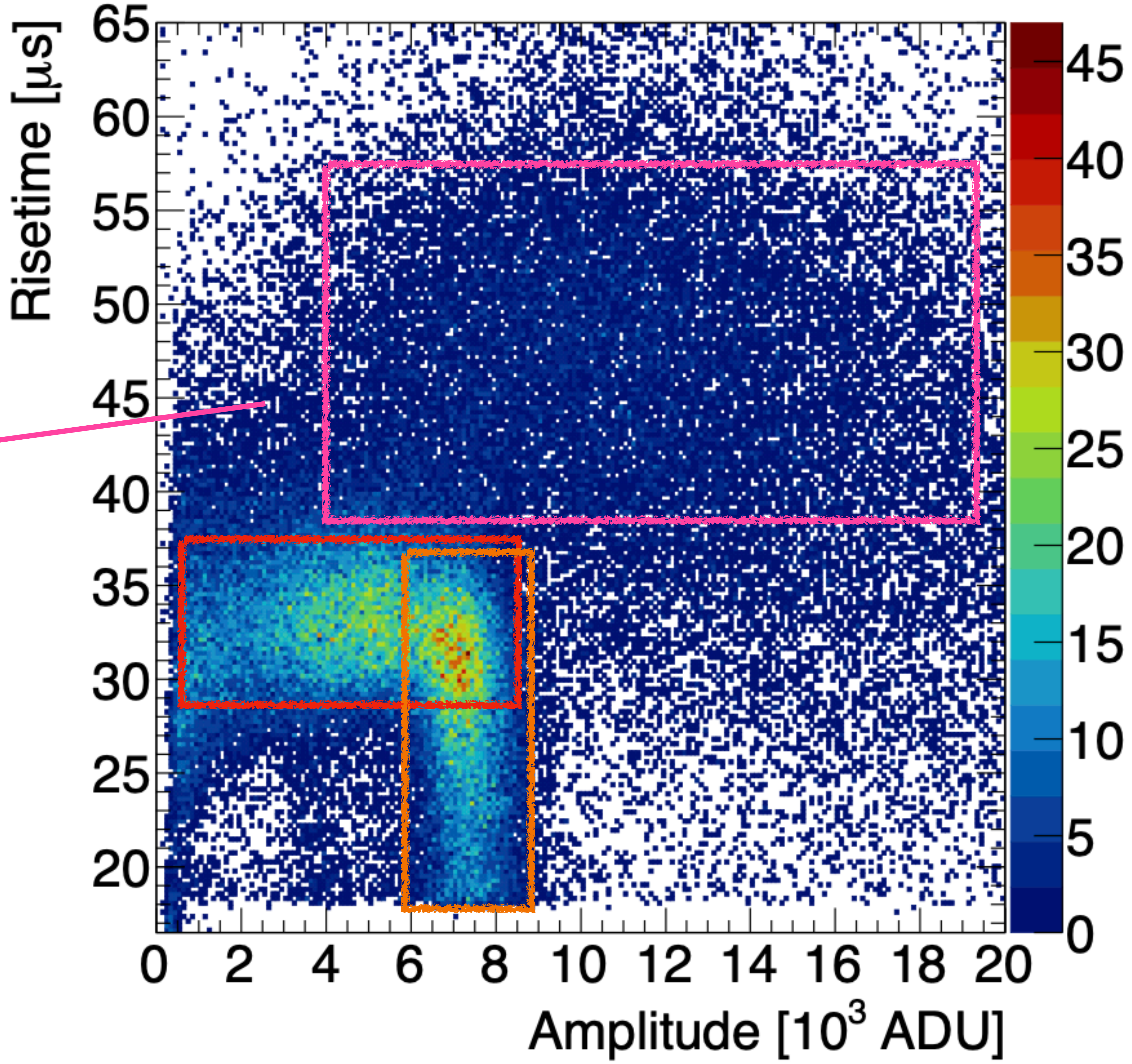
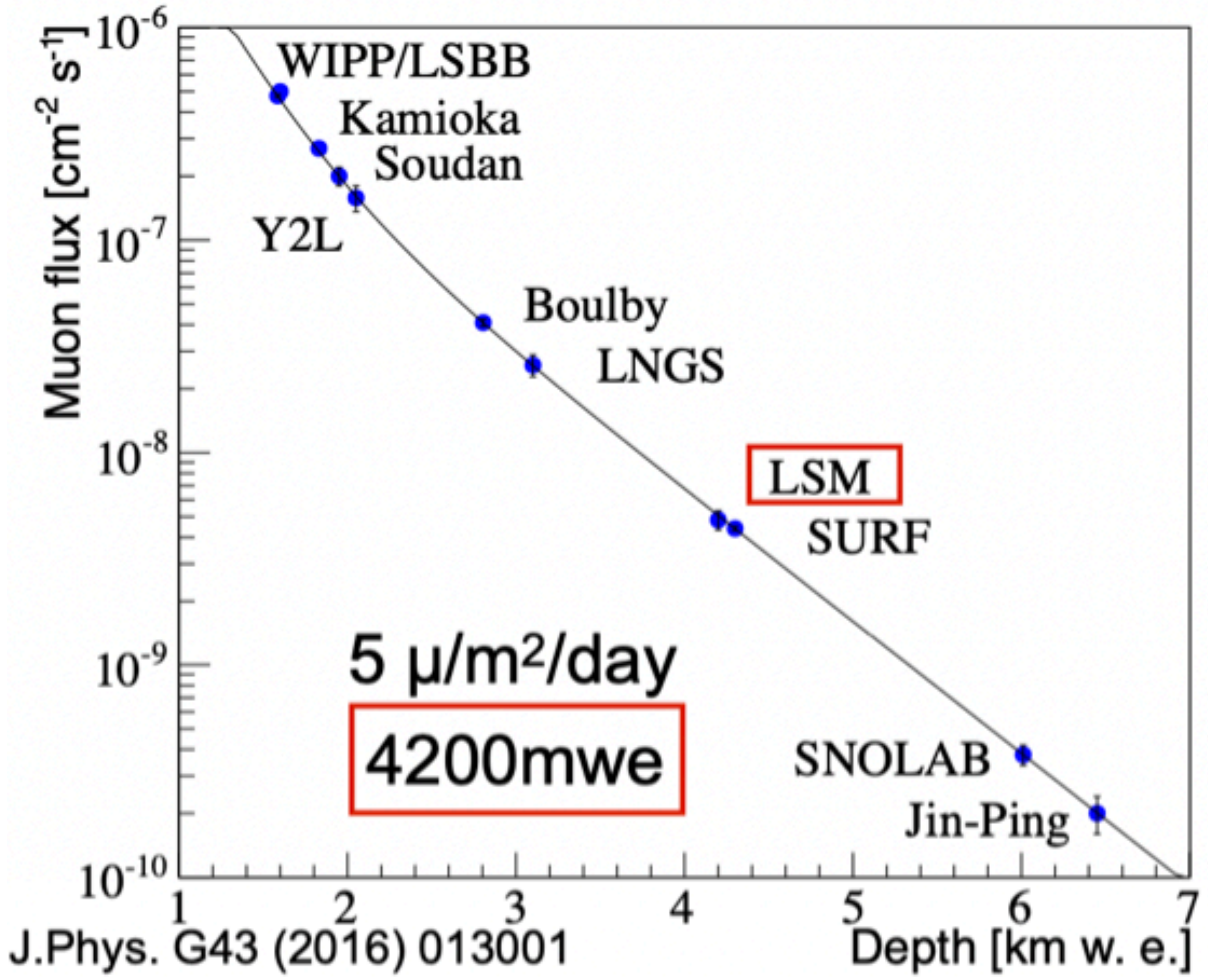
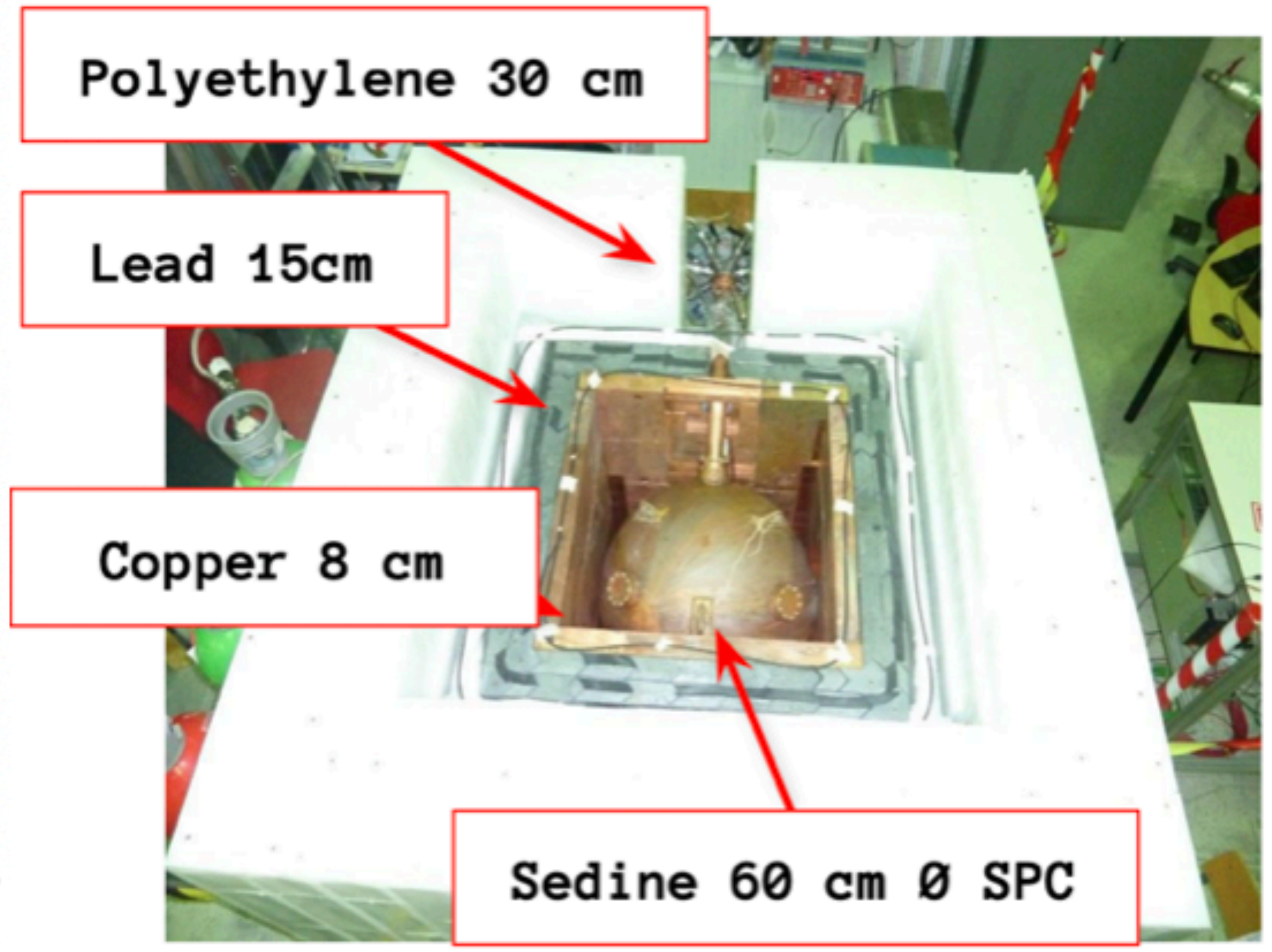


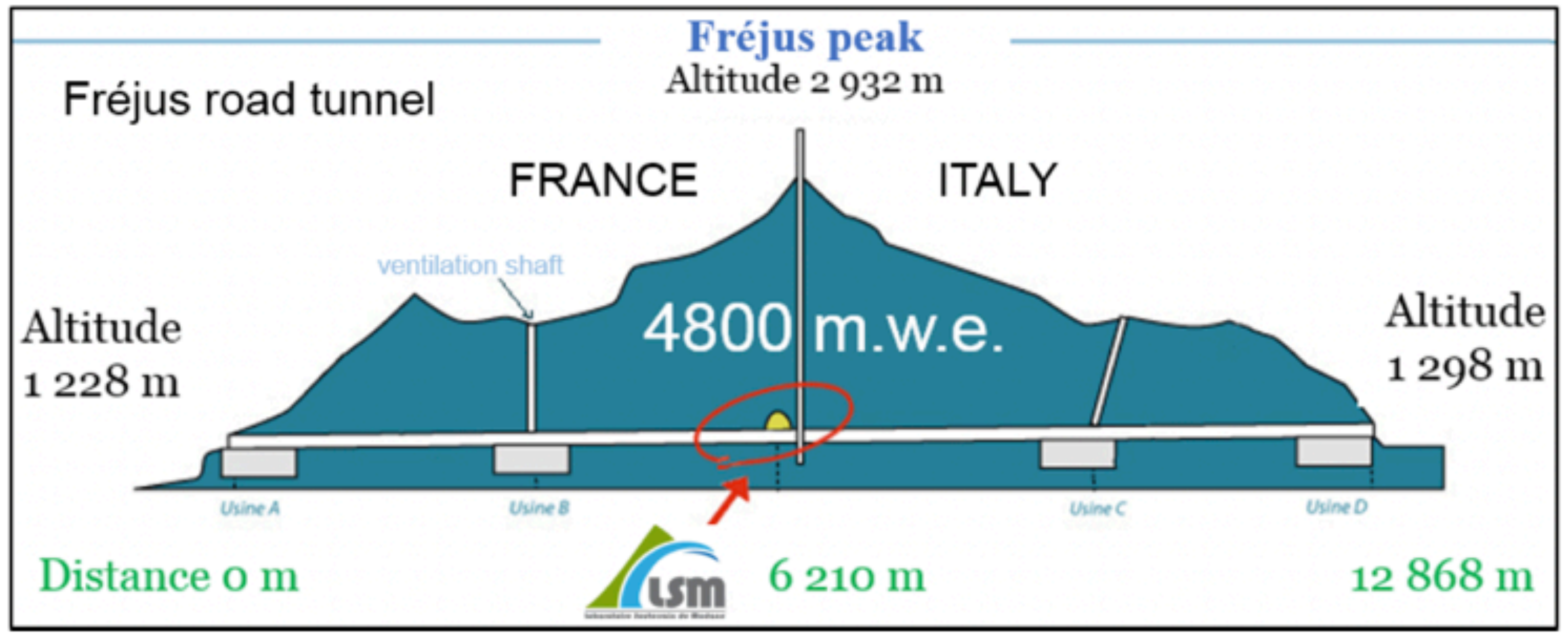



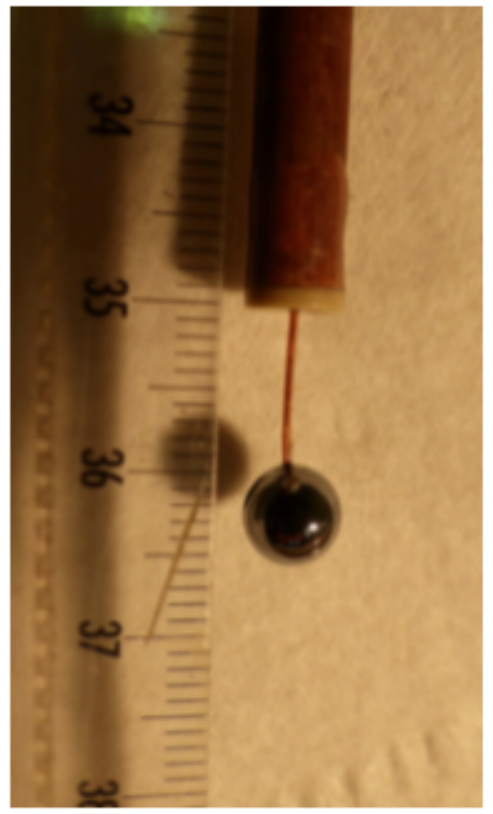
# Results with SEDINE prototype at LSM



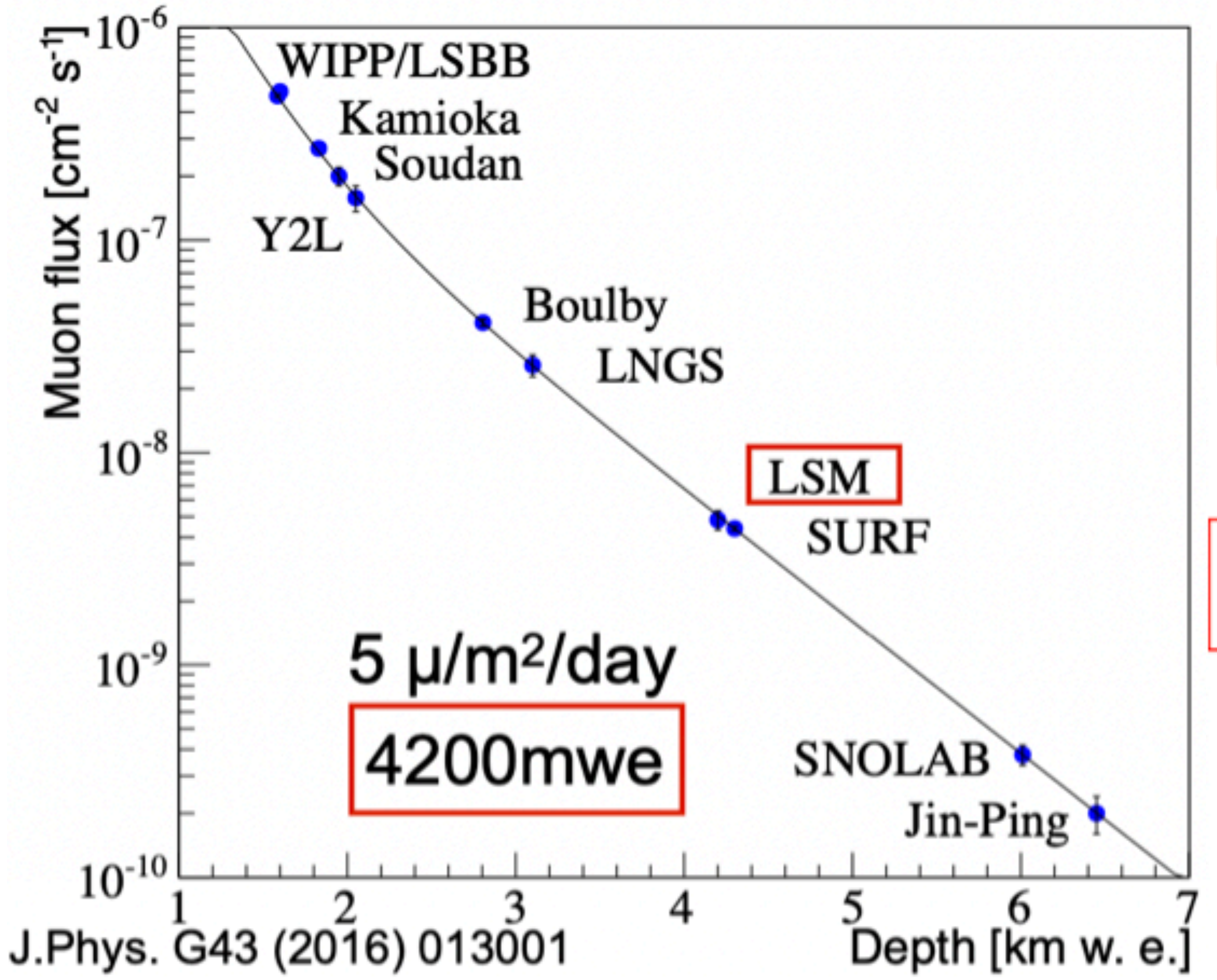

- ⌀60cm NOSV copper vessel, ⌀6.3 mm single-anode sensor

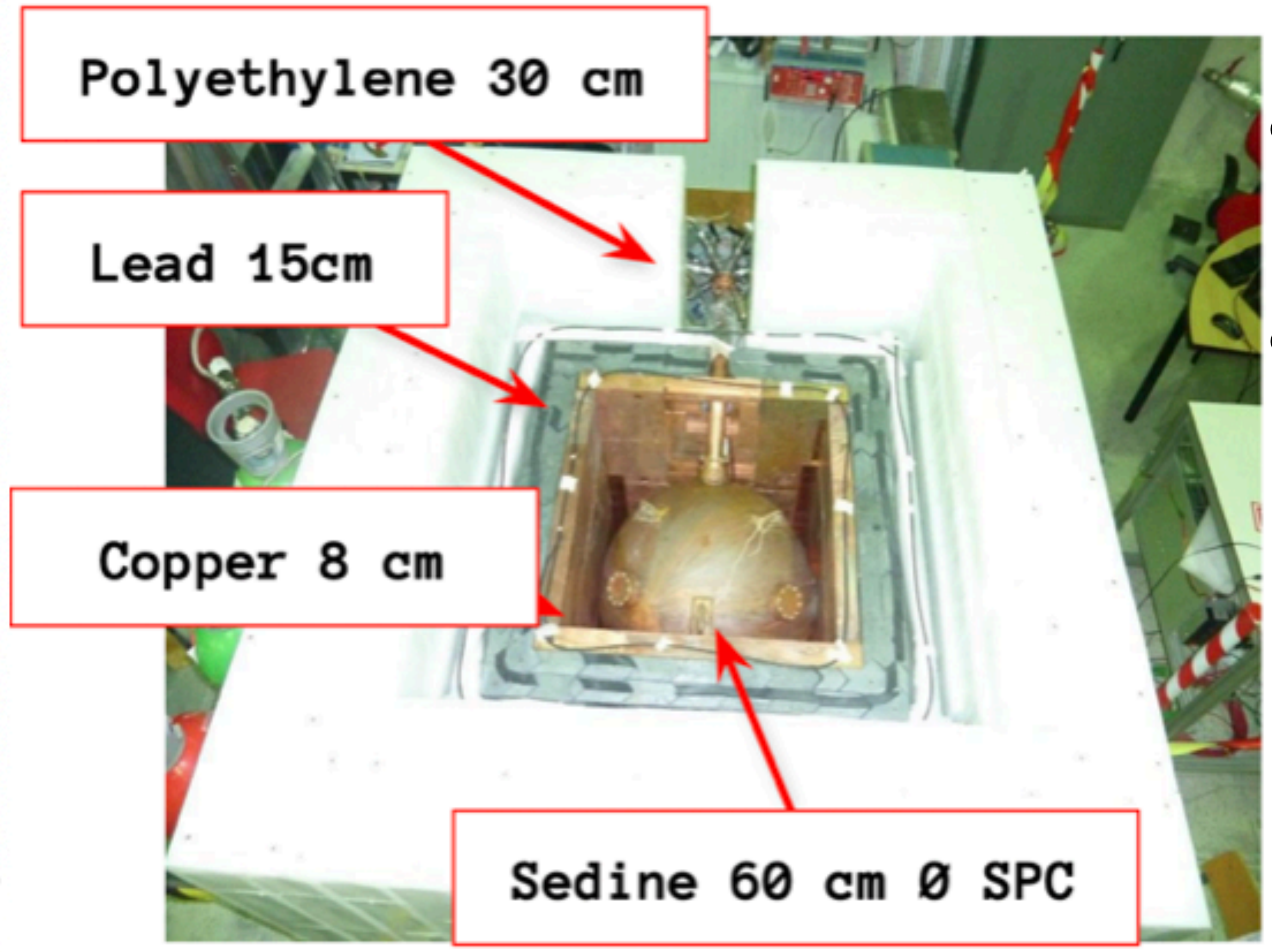


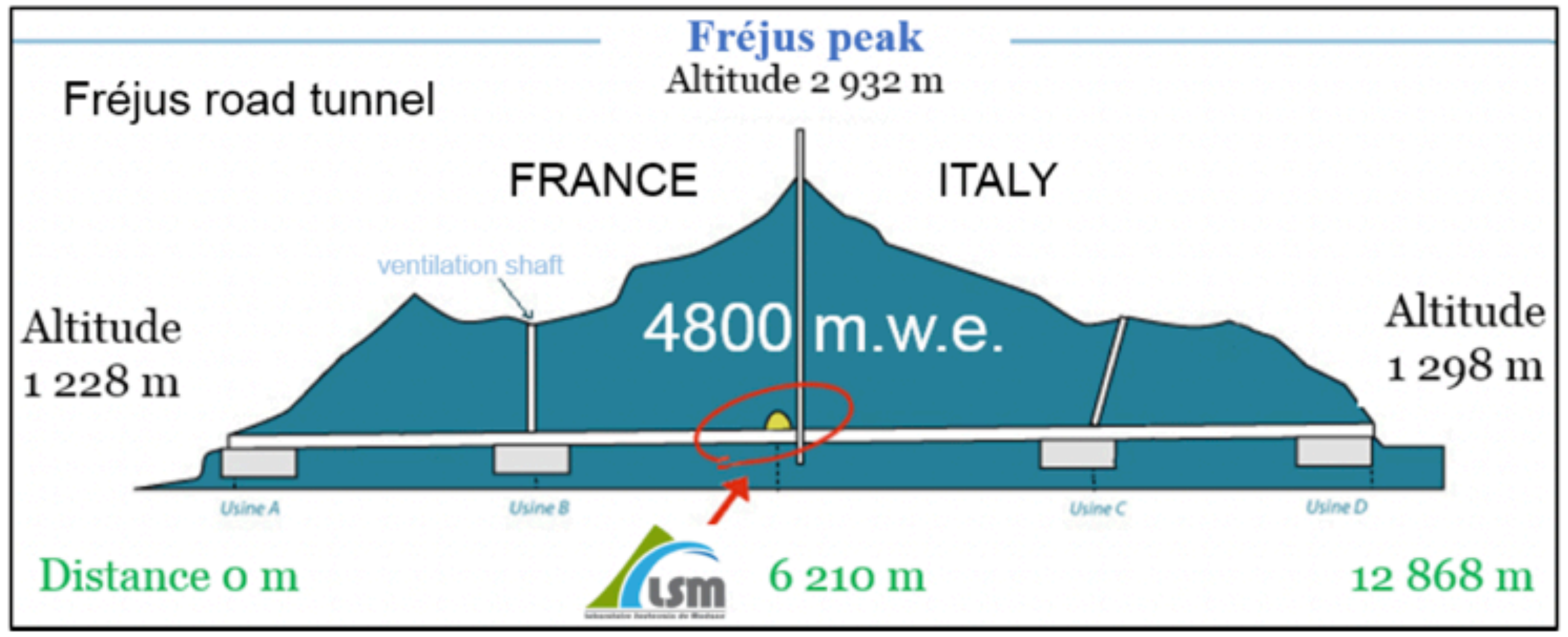



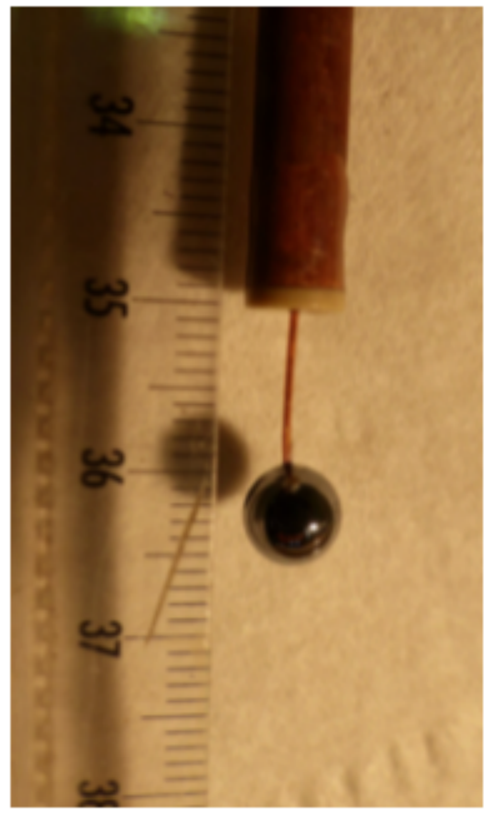
# Results with SEDINE prototype at LSM

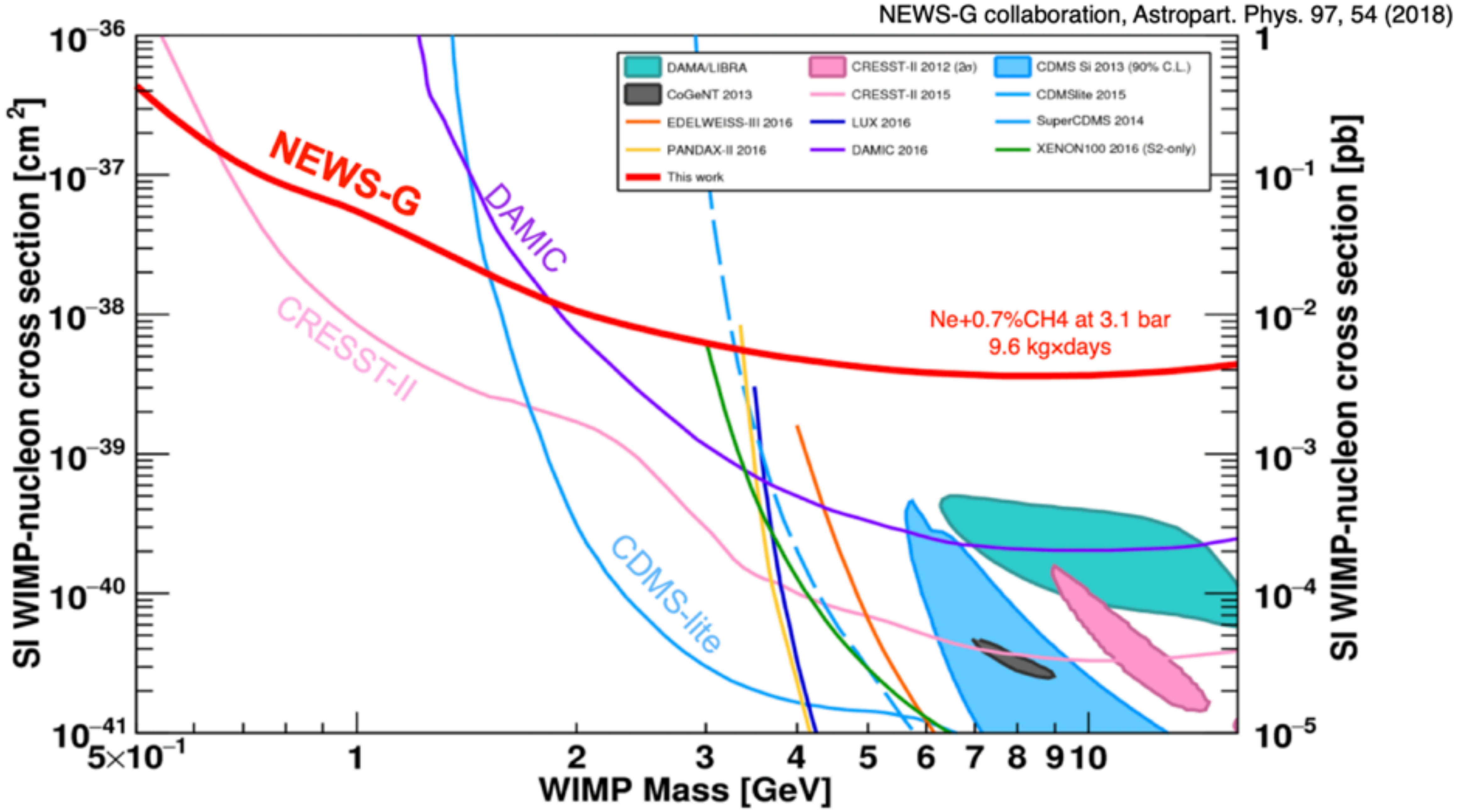
- ⌀60cm NOSV copper vessel, ⌀6.3 mm single-anode sensor
- Physics: 42-day run with 3.1bar of Neon + 0.7% $CH_4$ (280g, total 9.7 kg·day)
- Main backgrounds:
  - Radon daughters on inner surface of vessel
  - $^{210}Pb$ in copper bulk



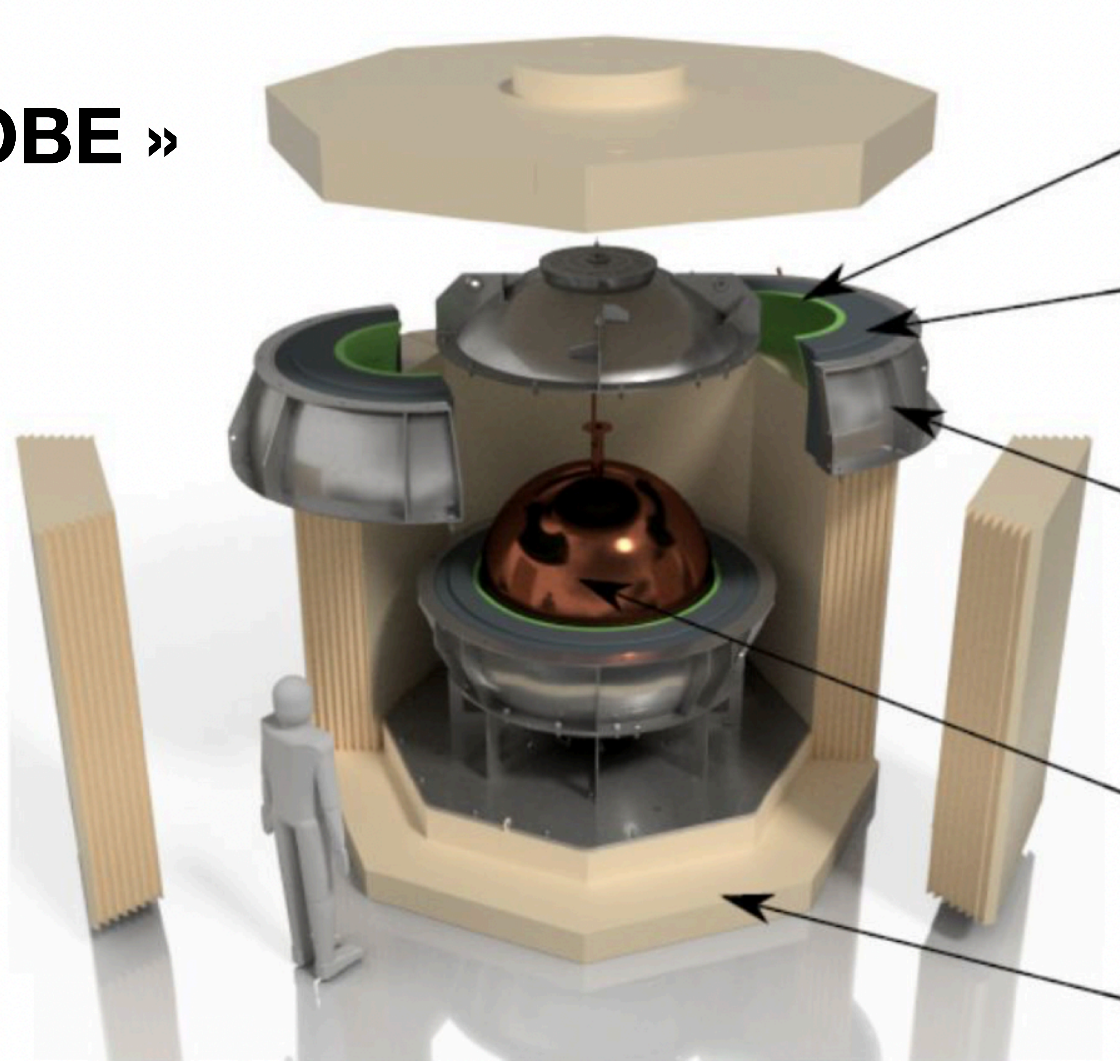





# S140

## « SNOGLOBE »



**3 cm of archeological Lead**

**22 cm of low-activity Lead**

**Stainless steel skin**

**C10100 copper S140**

**40 cm borated Polyethylene**

**Detector paper: https://arxiv.org/abs/2205.15433, pending publication in JINST**

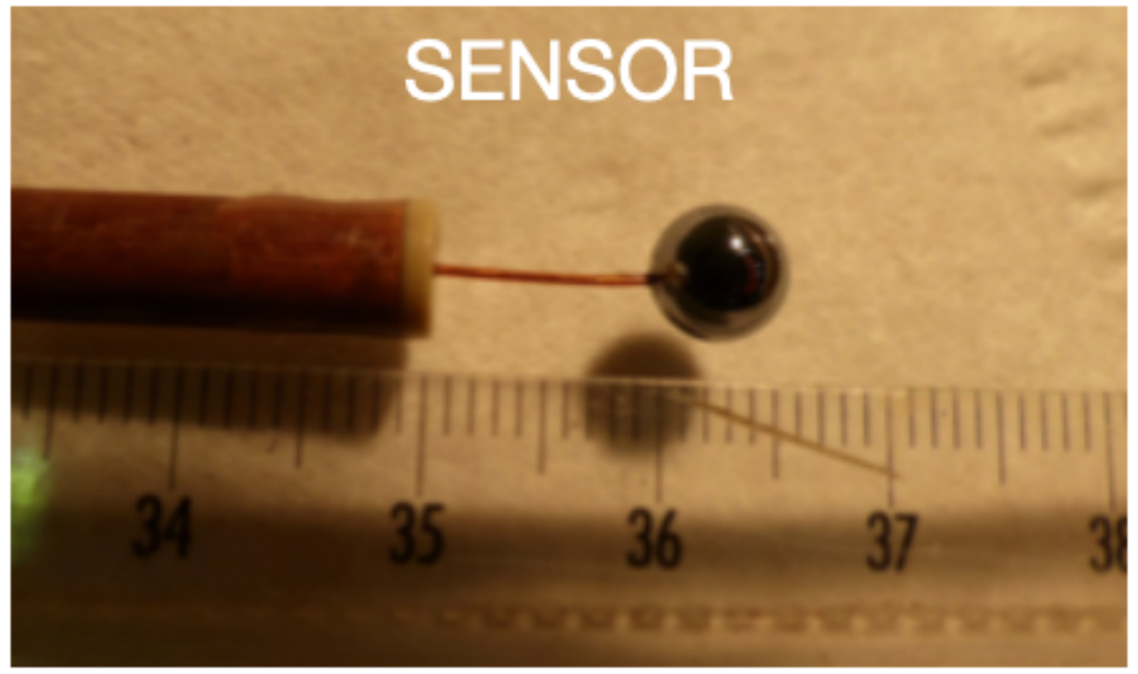
# Sensor development

## 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



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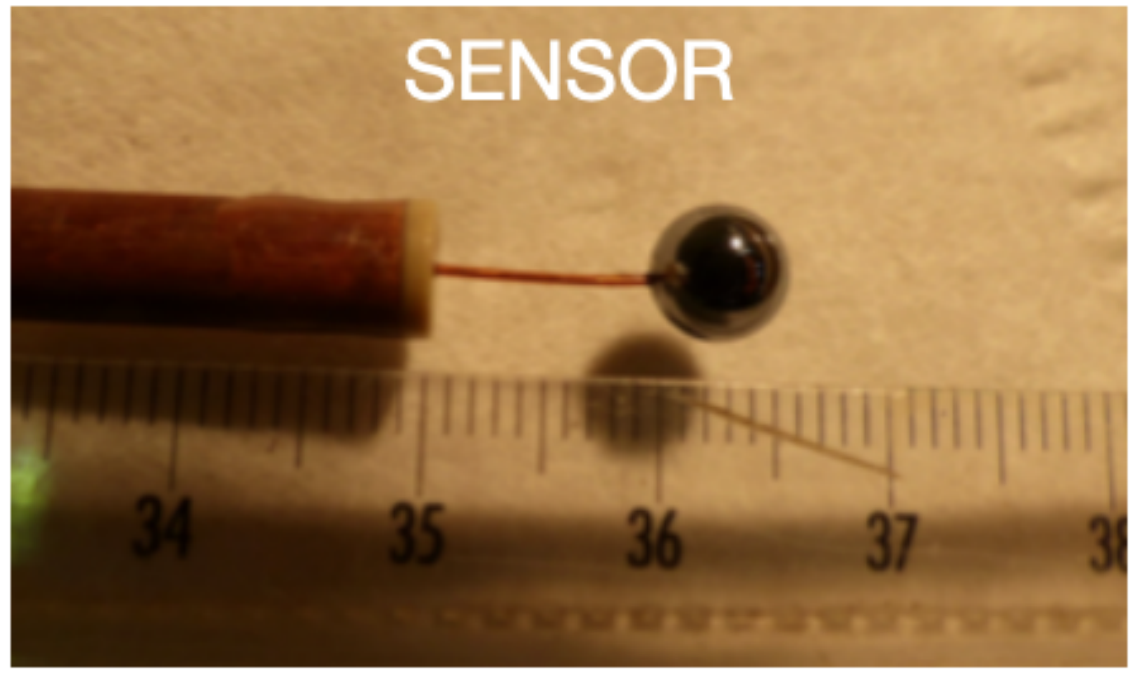
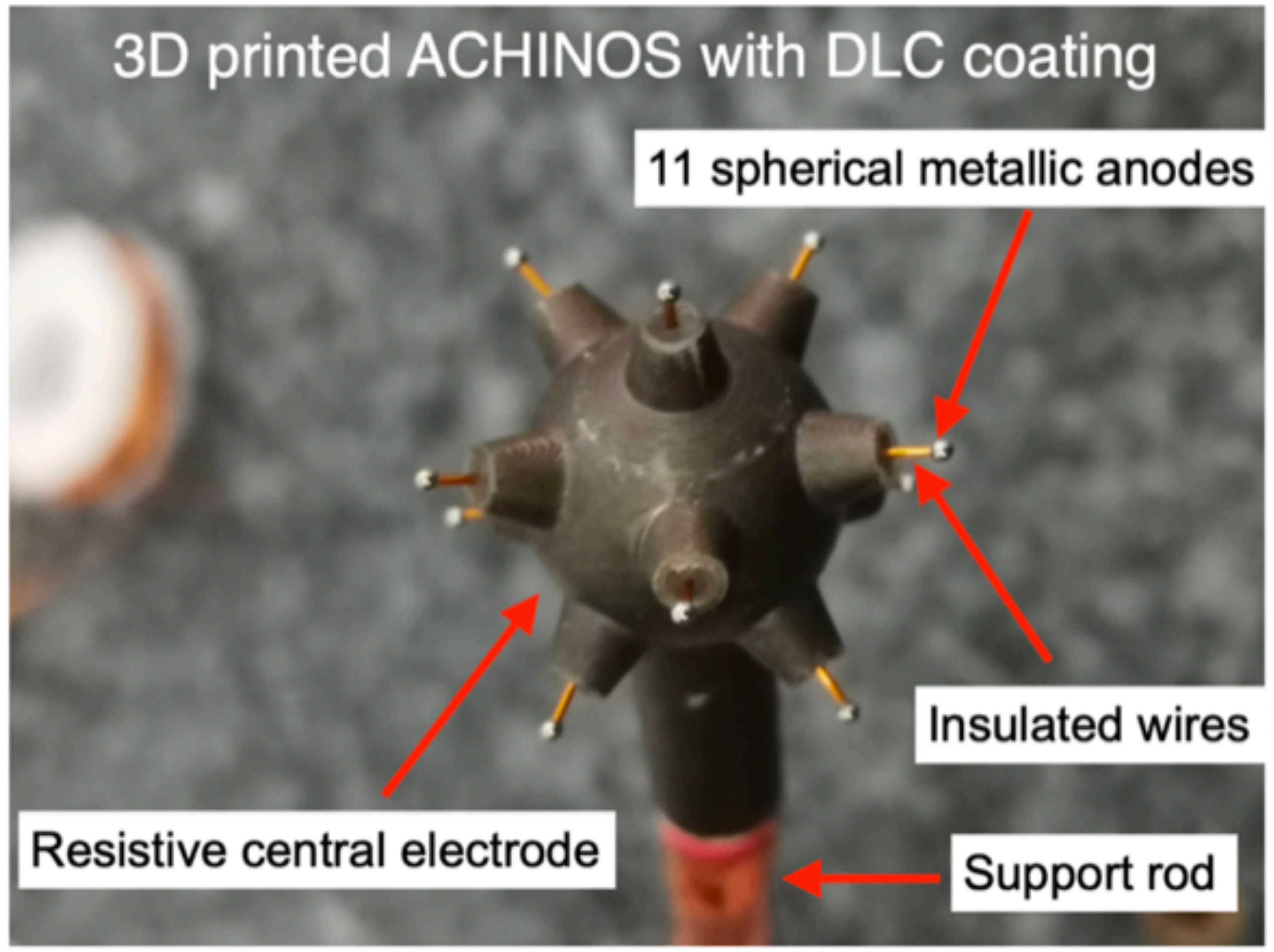
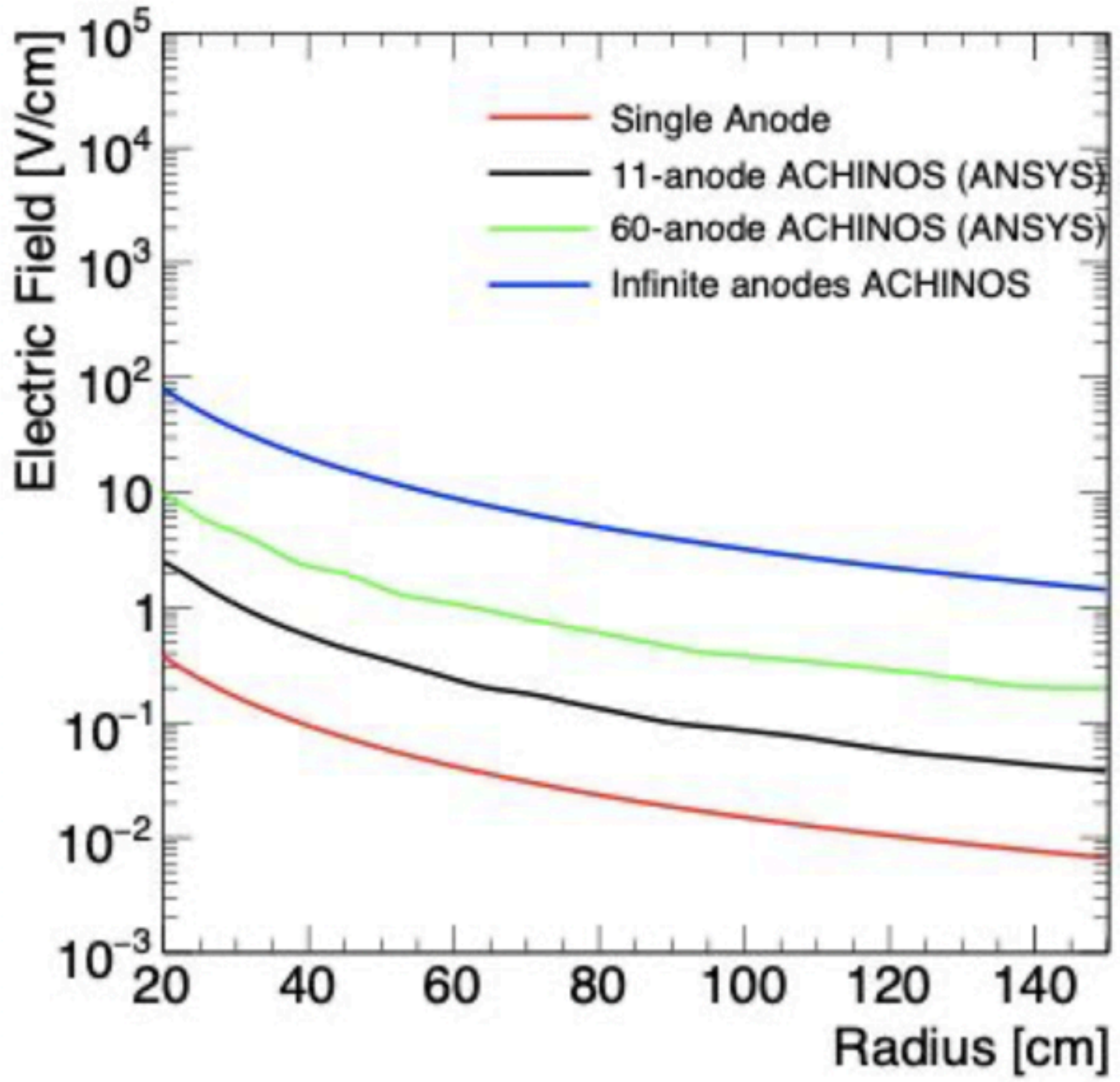



Αχινός (greek. sea urchin)




Enter ACHINOS

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

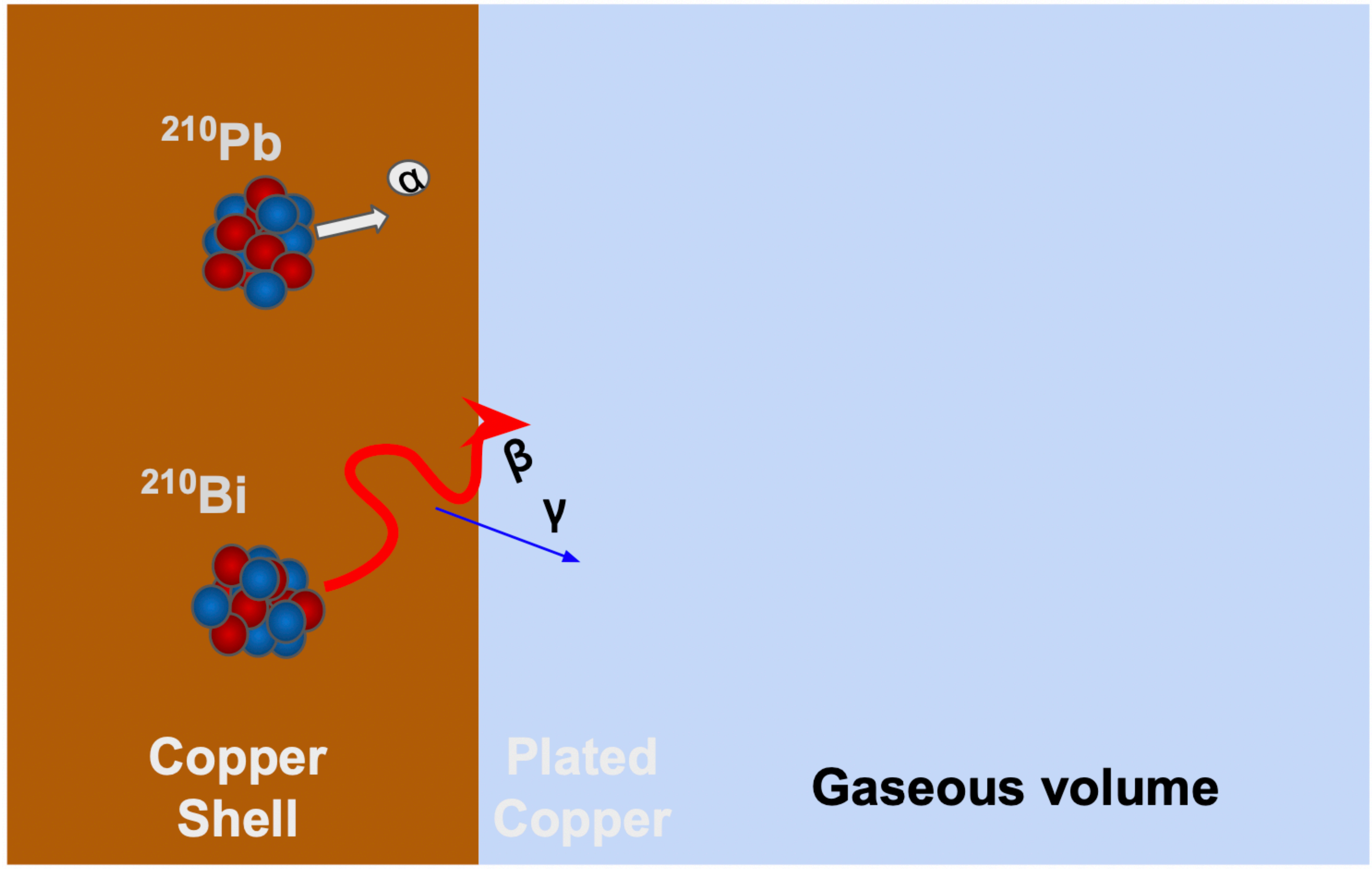



JINST 12 (2017) 12, P12031

# S140: Improvements

## Background reduction

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




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

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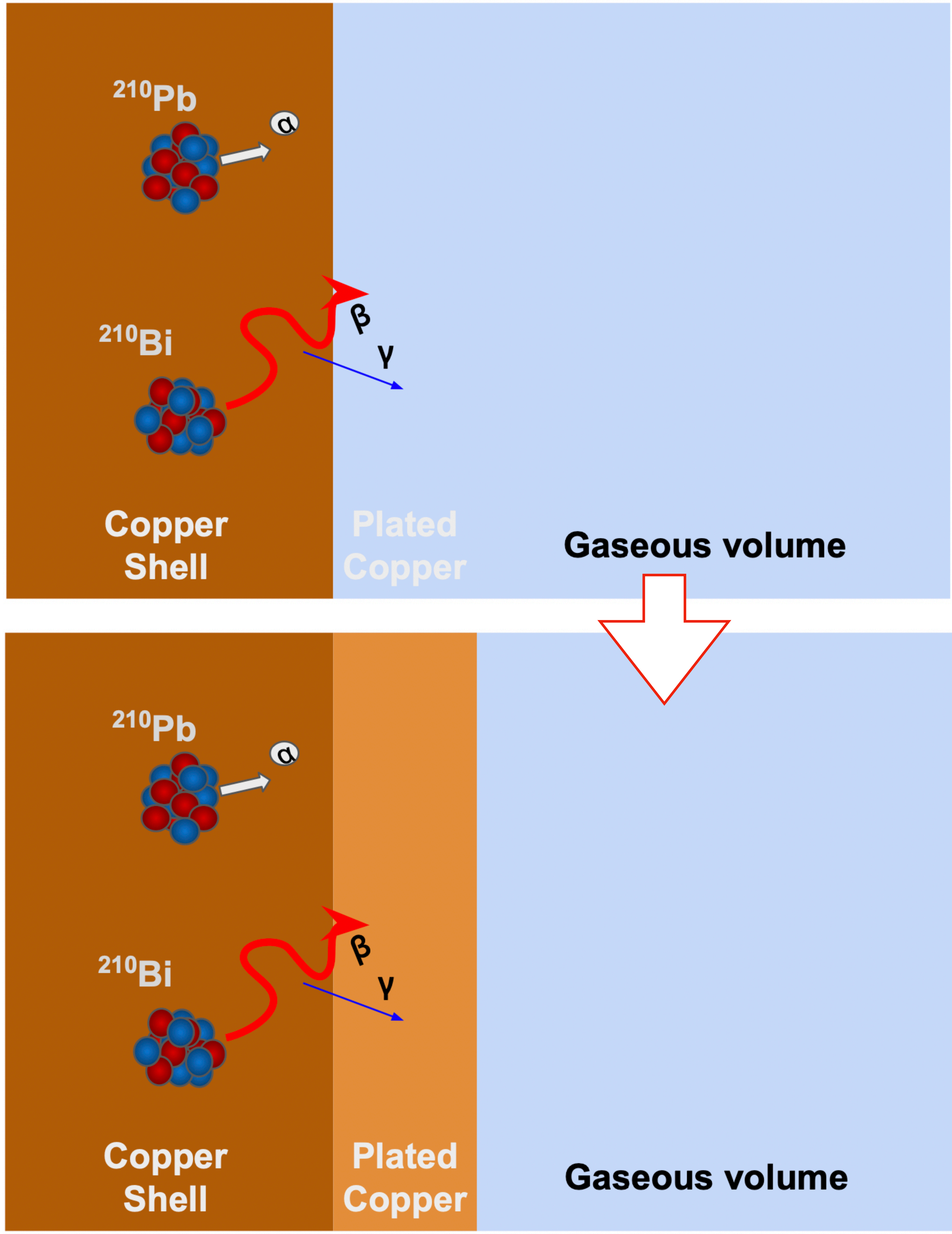
- Plating 0.5mm of ultra-pure copper on inner surface of detector expected to reduce background under 1 keV by factor 2.6, and total rate by factor 50

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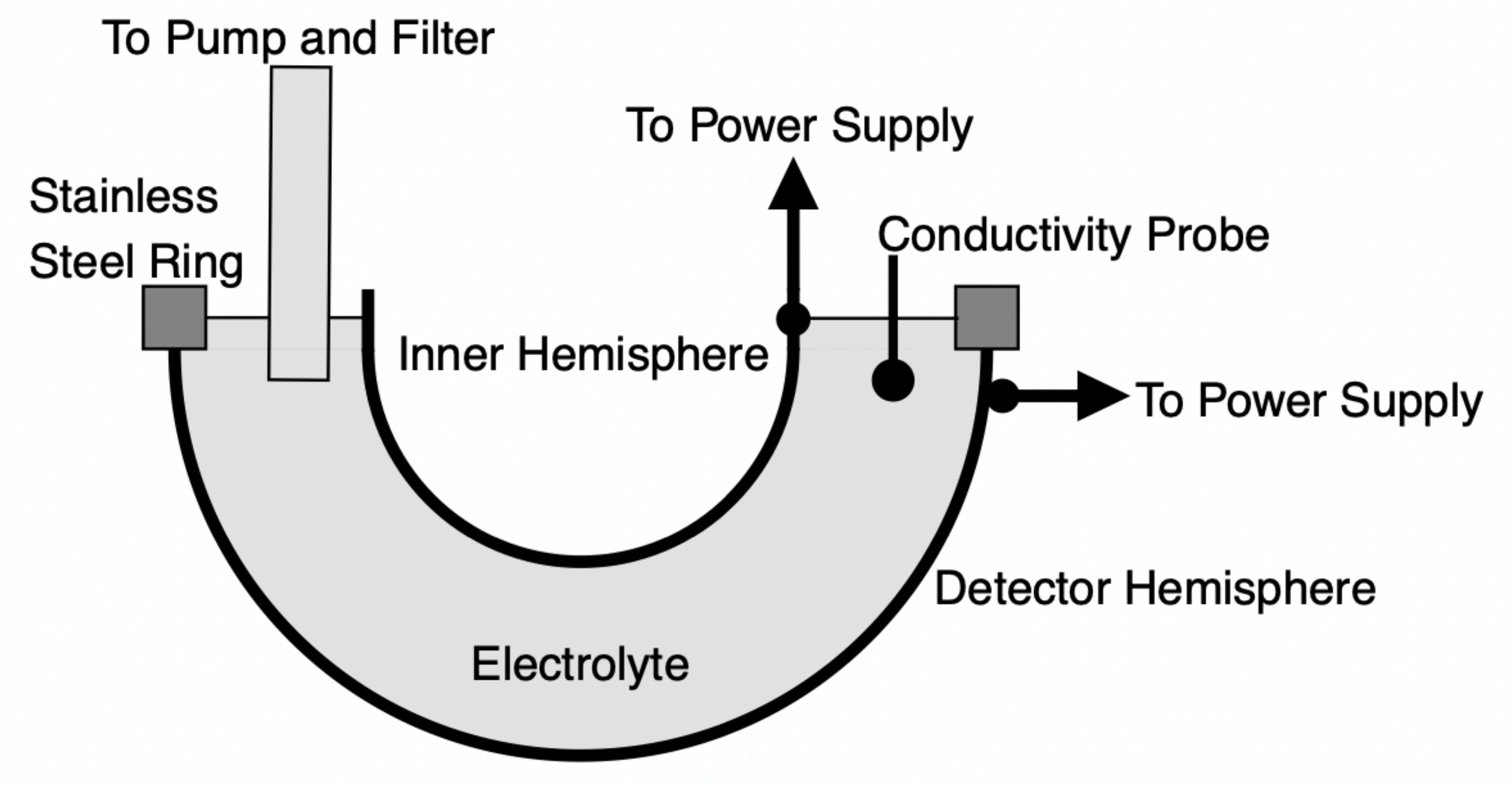
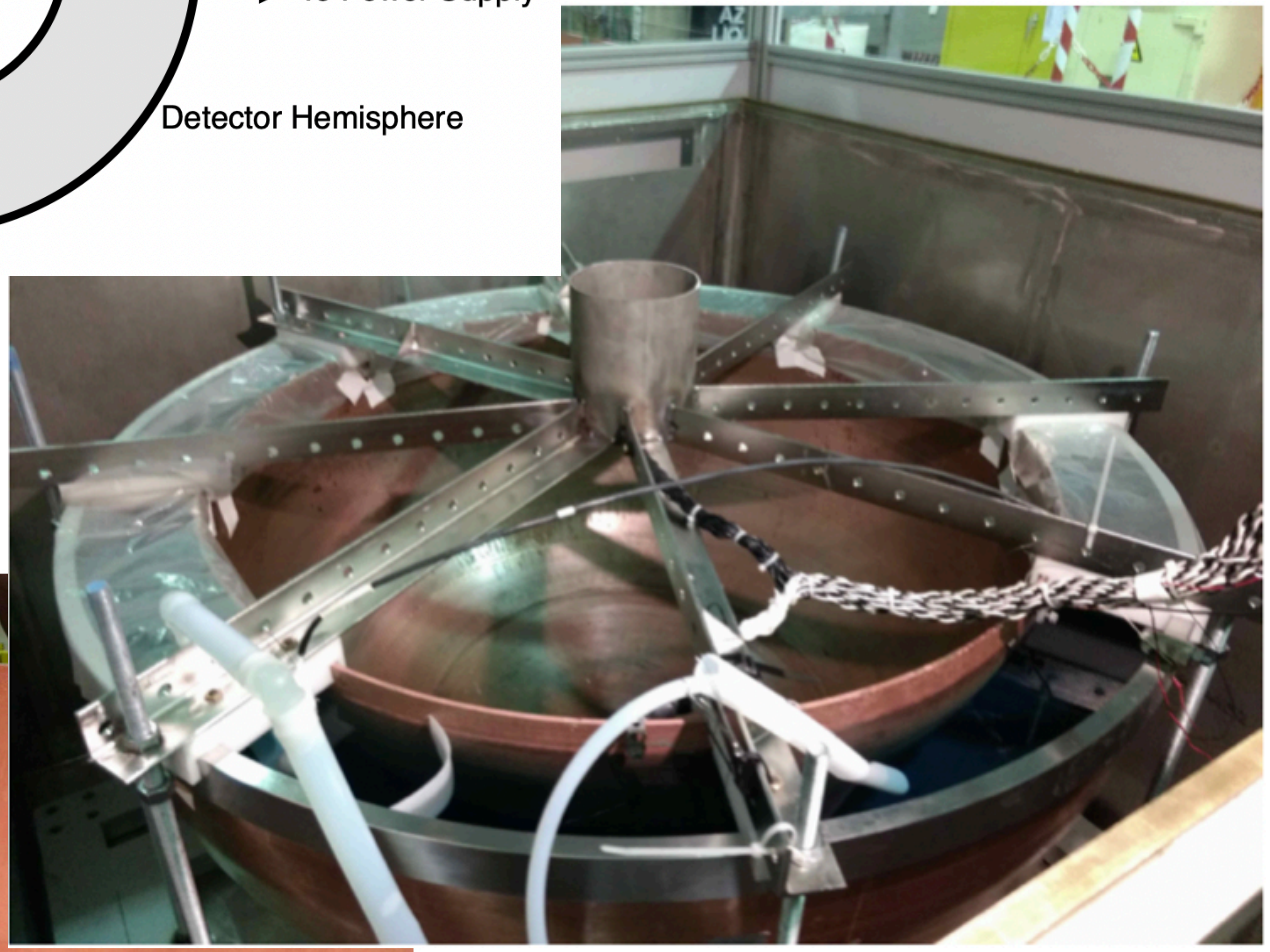
- Intervention successfully carried out at LSM in collaboration with PNNL



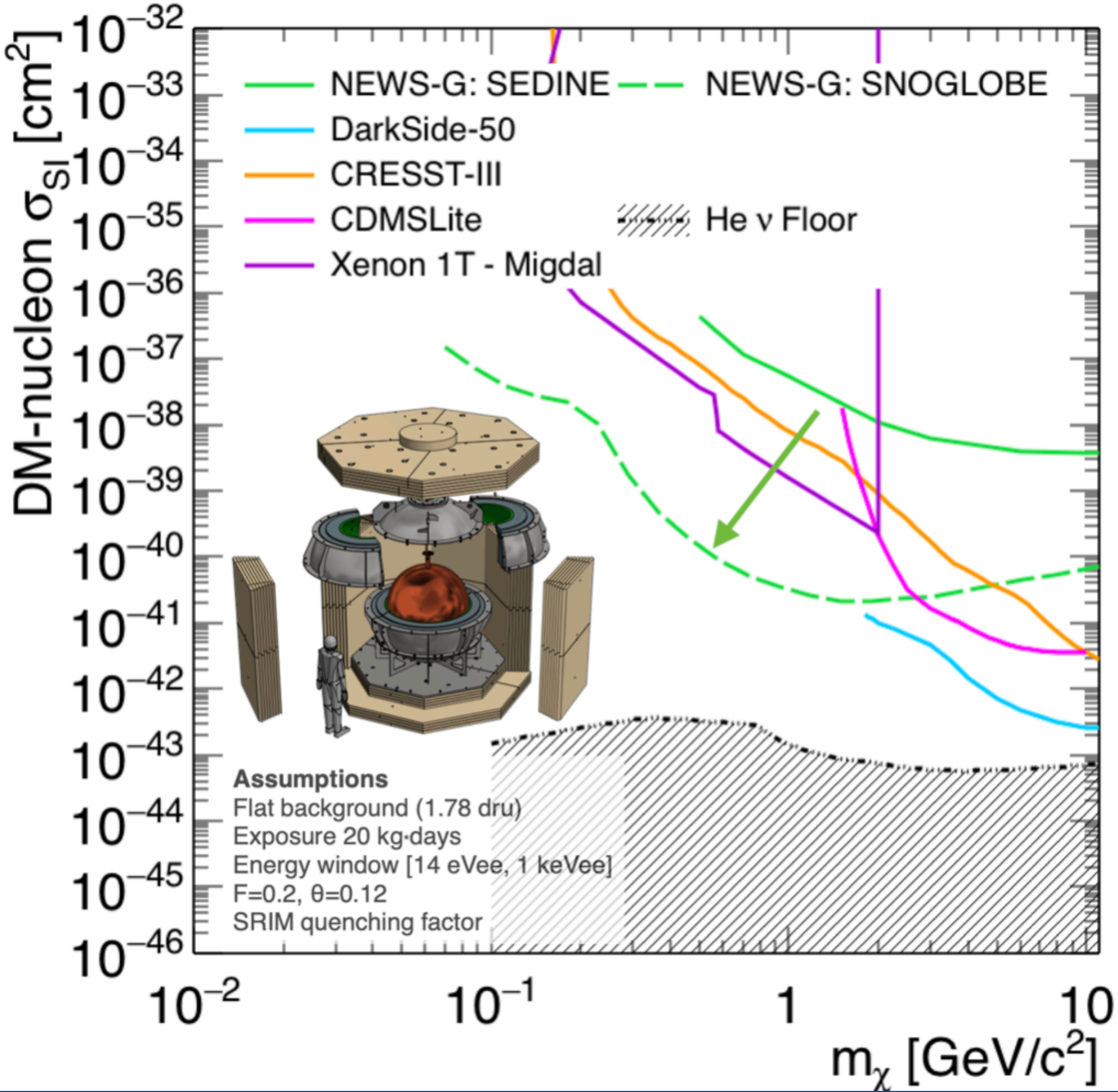
**L. Balogh et al, Nucl.Instrum.Meth.A 988 (2021)**

# S140

## Projections

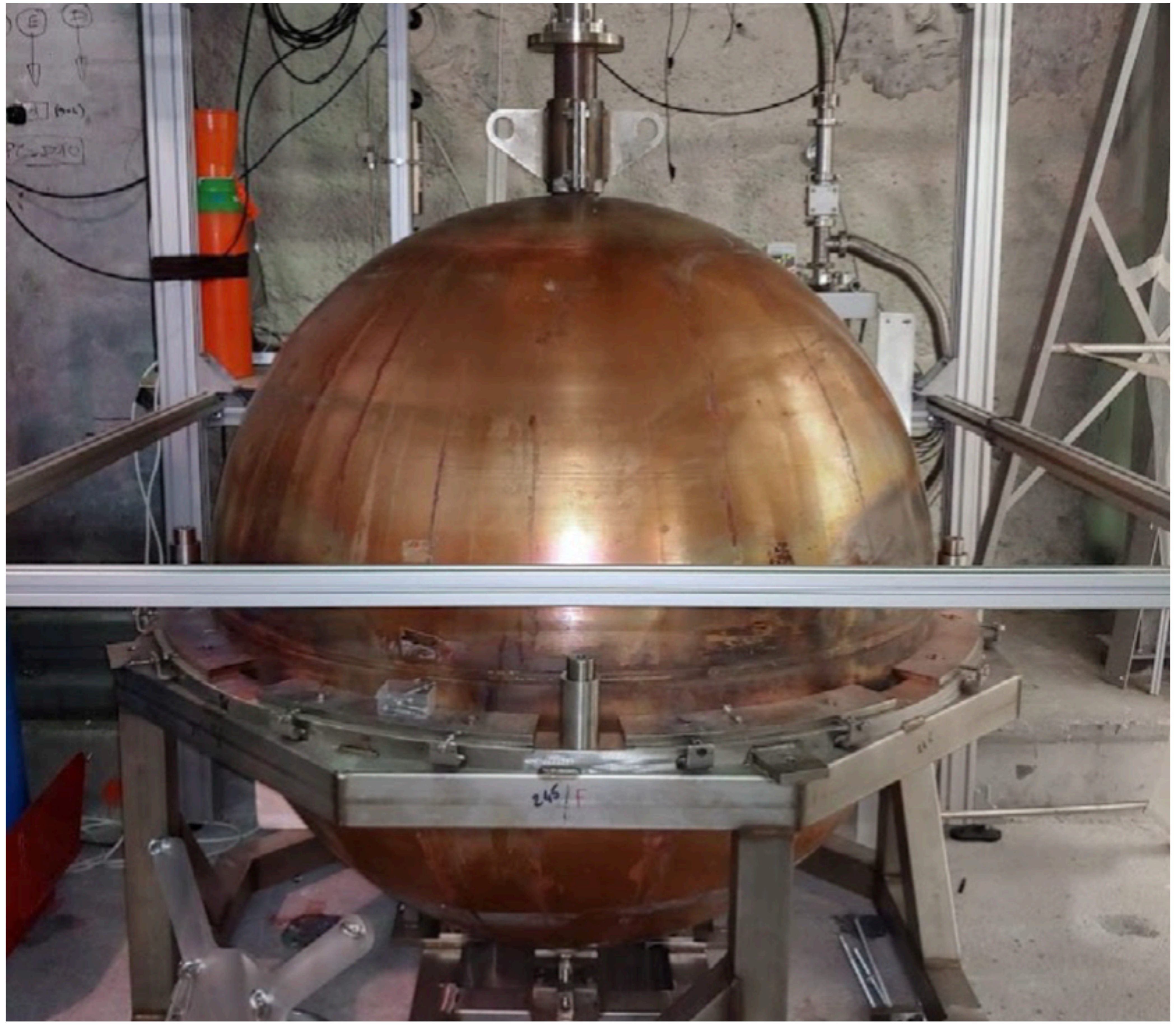
S140 improvements:

- Larger volume
- Increased radiopurity of materials
- ~0.5 mm of electroplated copper on inner surface of copper shell
- Radon and oxygen filtering
- Laser calibrations (gain, drift…)
- Multi-anode sensor



# 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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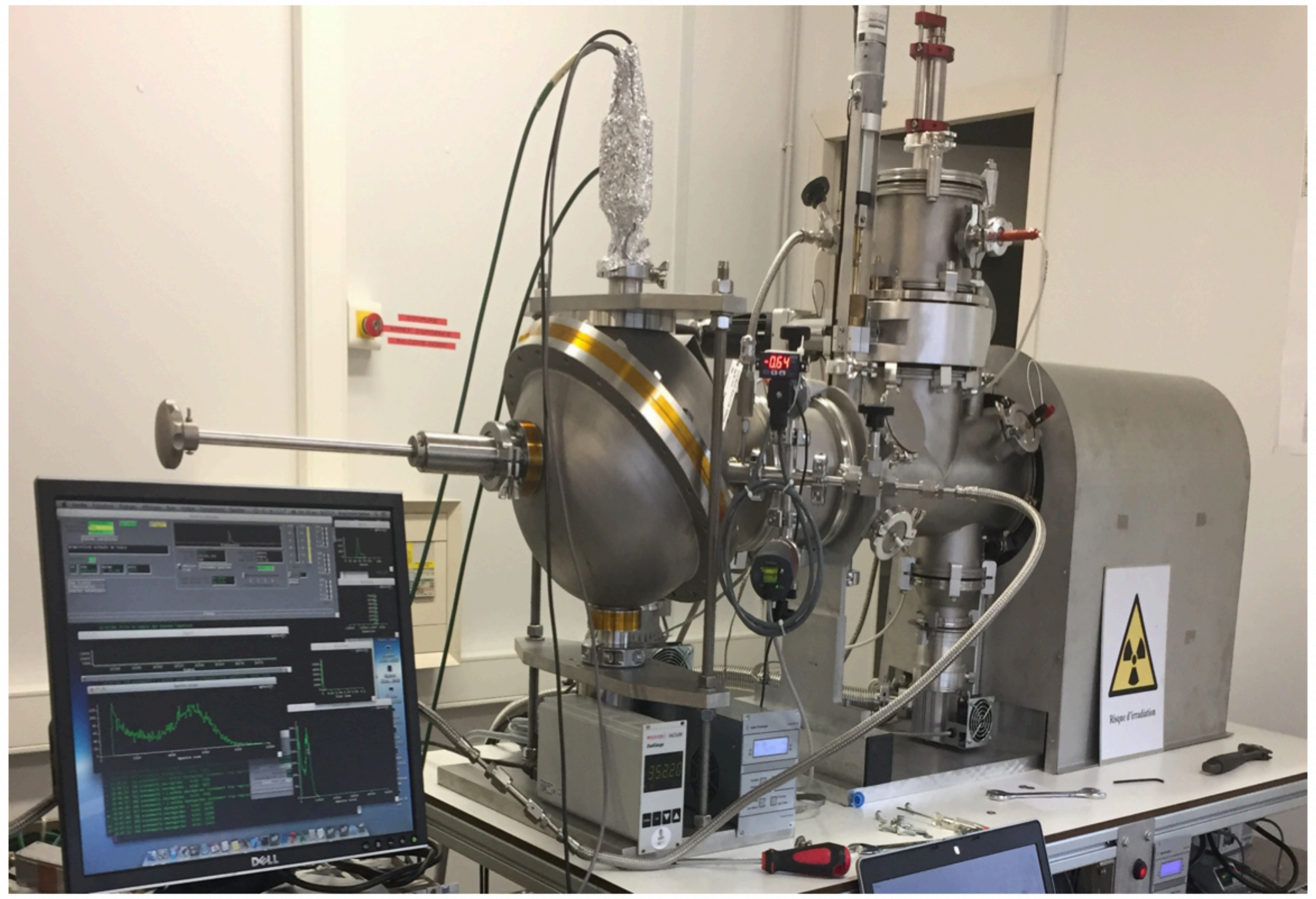
Packed in November 2019 to go to SNOLAB! First signal in summer 2021, finished installation/commissioning, physics data-taking to restart in coming days!

# Quenching Factor measurements

## QF: ratio of ionisation energy to total energy

### COMIMAC, LPSC Grenoble



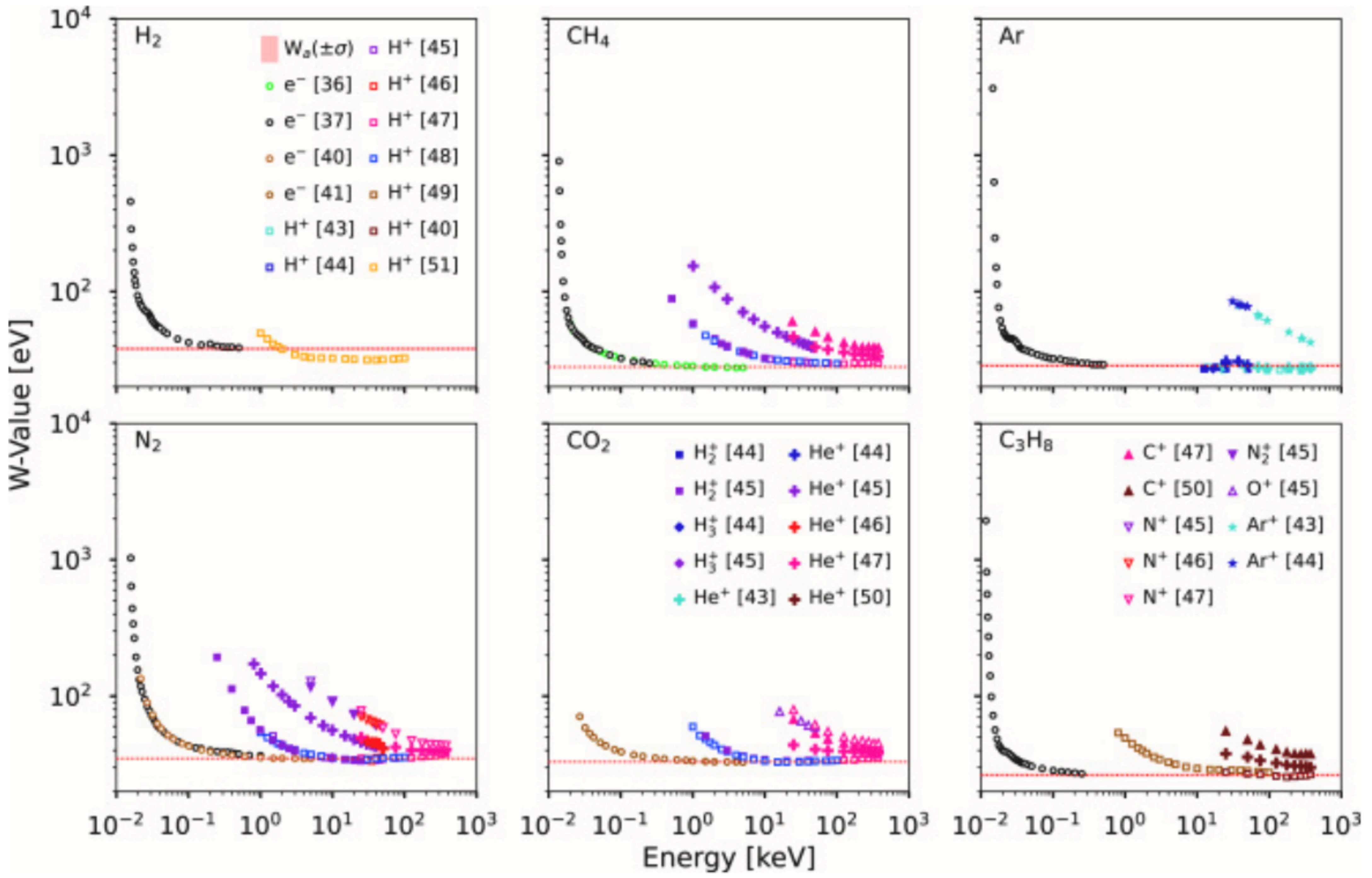
Generates electrons/ions of known energy, accelerated in electric field

https://arxiv.org/abs/2201.09566, undergoing journal review

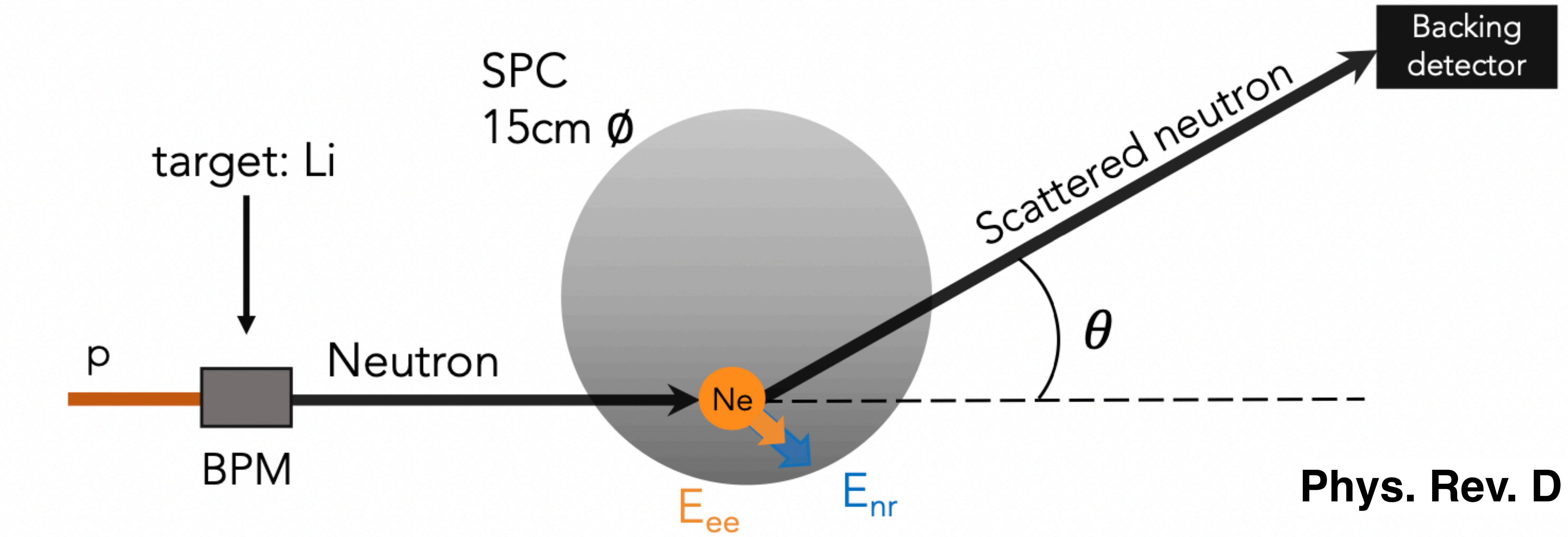
### Ratio of literature values for W, Birmingham U.

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)**

# Calibrations of Ionization Statistics

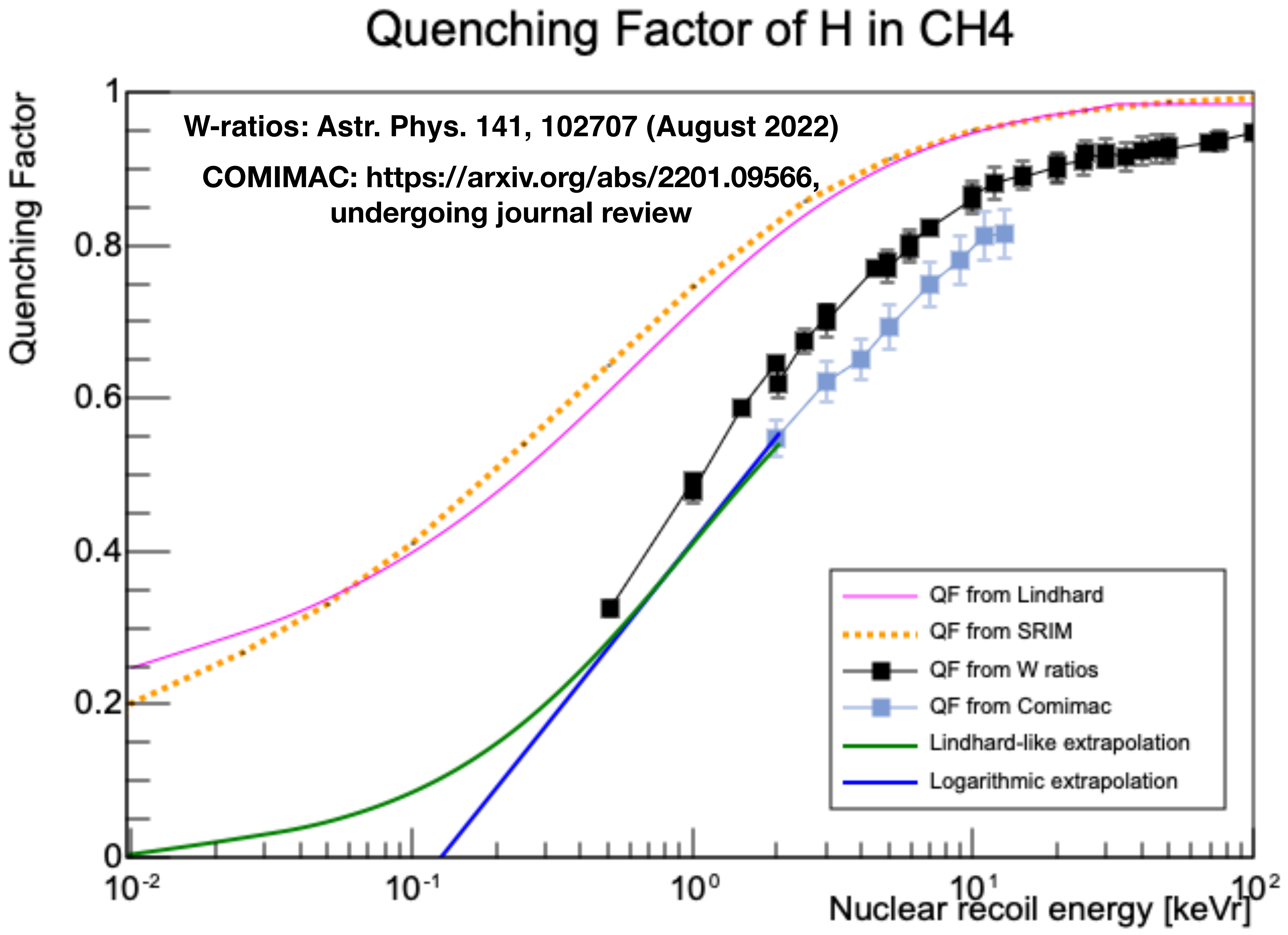
## Quenching Factor

- 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

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

  - Logarithmic

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

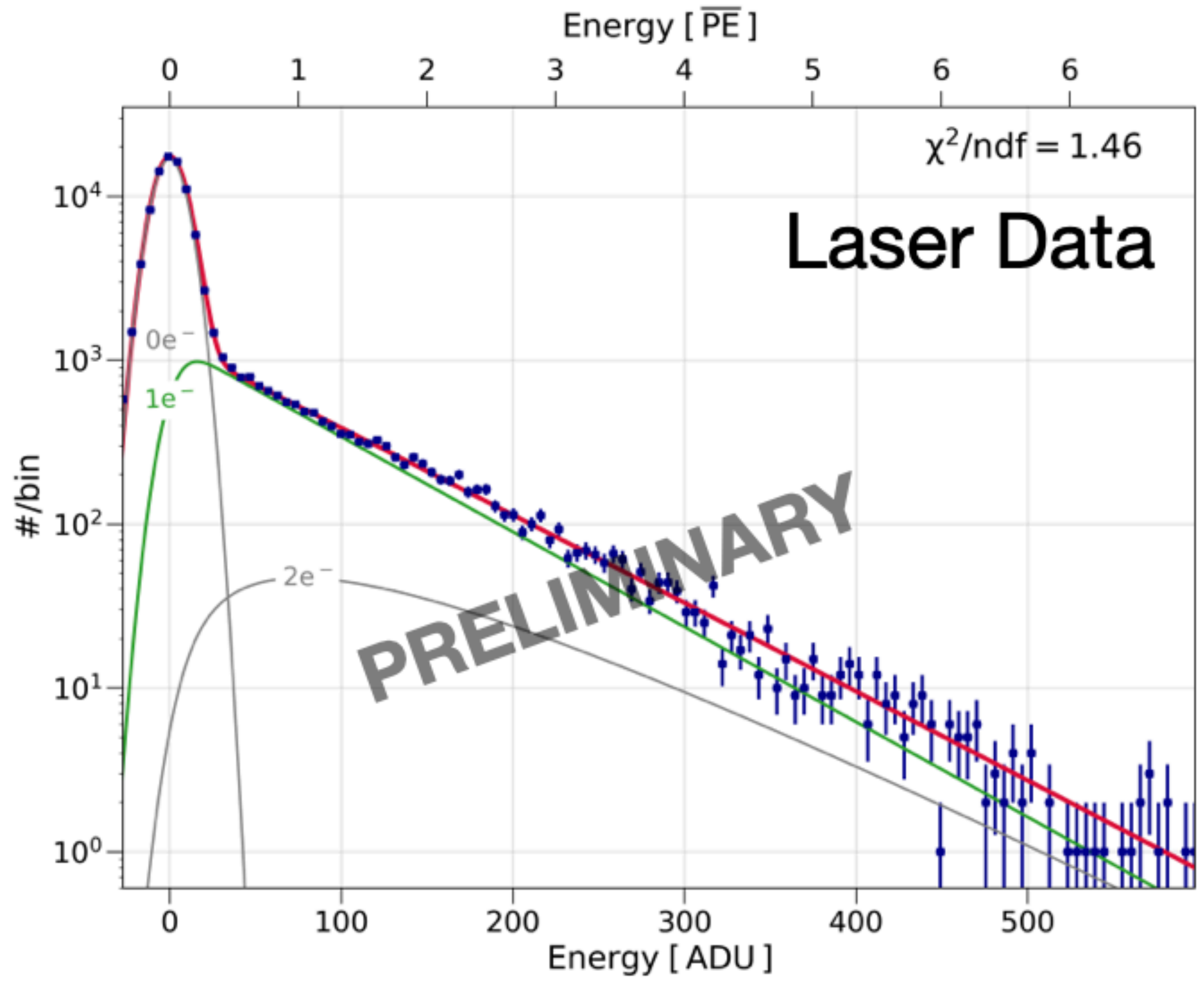


# Calibrations of Ionization Statistics

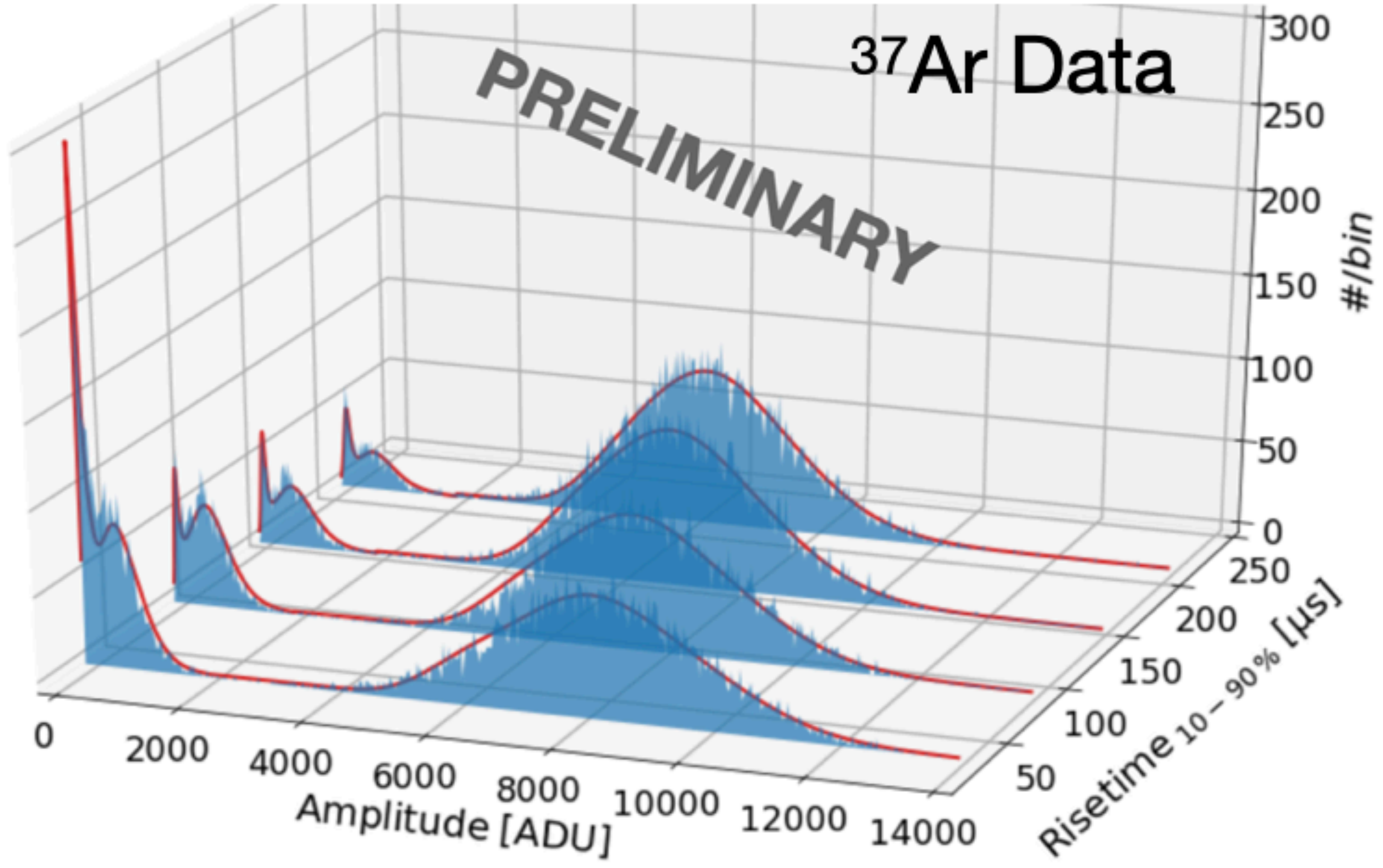
## Mean Ionization energy

- Pulsed 213 nm UV-Laser calibration shining on SPC internal surface extracts single-electron events, calibrates response of detector
- Combine with 2.8 keV, 270 and 200 eV lines from $^{37}Ar$ (gas, probing whole volume):
  - Confirmation of linearity
  - Measurement of gain of south-channel anodes
  - Parametrization of electron attachment
  - In-situ measurement of W and Fano factor

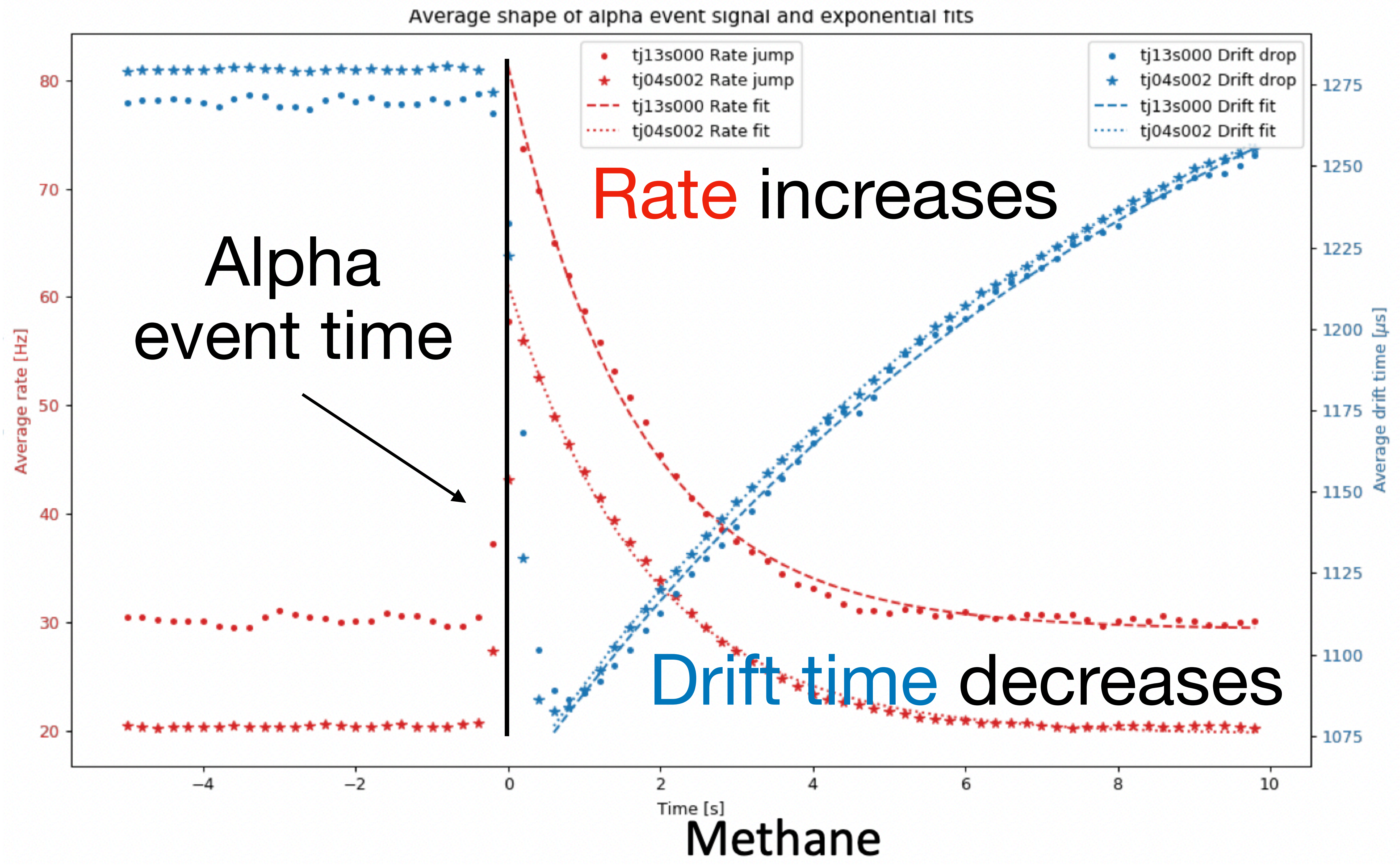
Technique applied to test detector data described in
**Phys. Rev. D 99, 102003 (May 2019)**




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

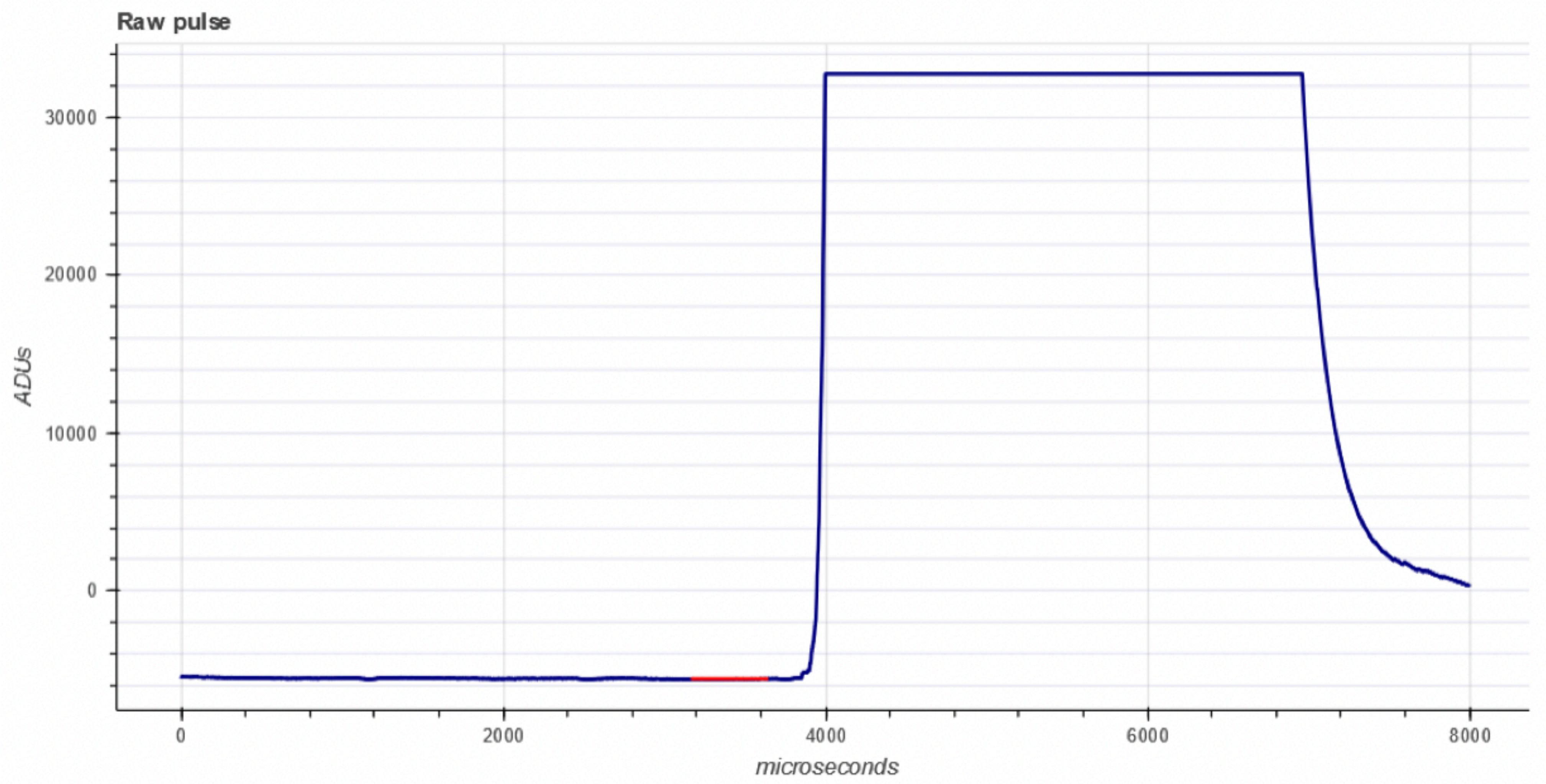


# Alpha-correlated electrons

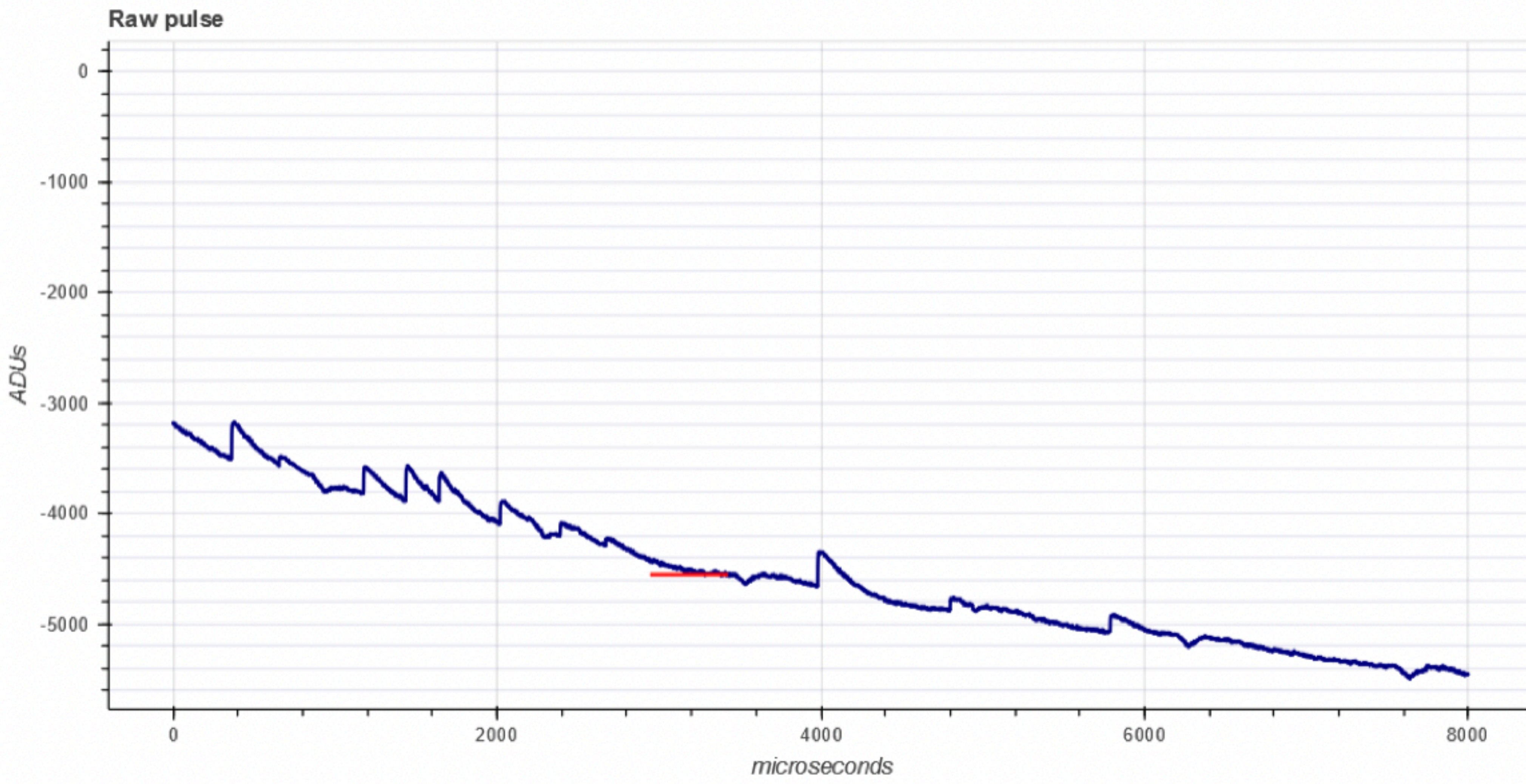



For CH4 data, removing 5s after each alpha reduces exposure by 12%, but reduces background rate by ~70%

Alpha event



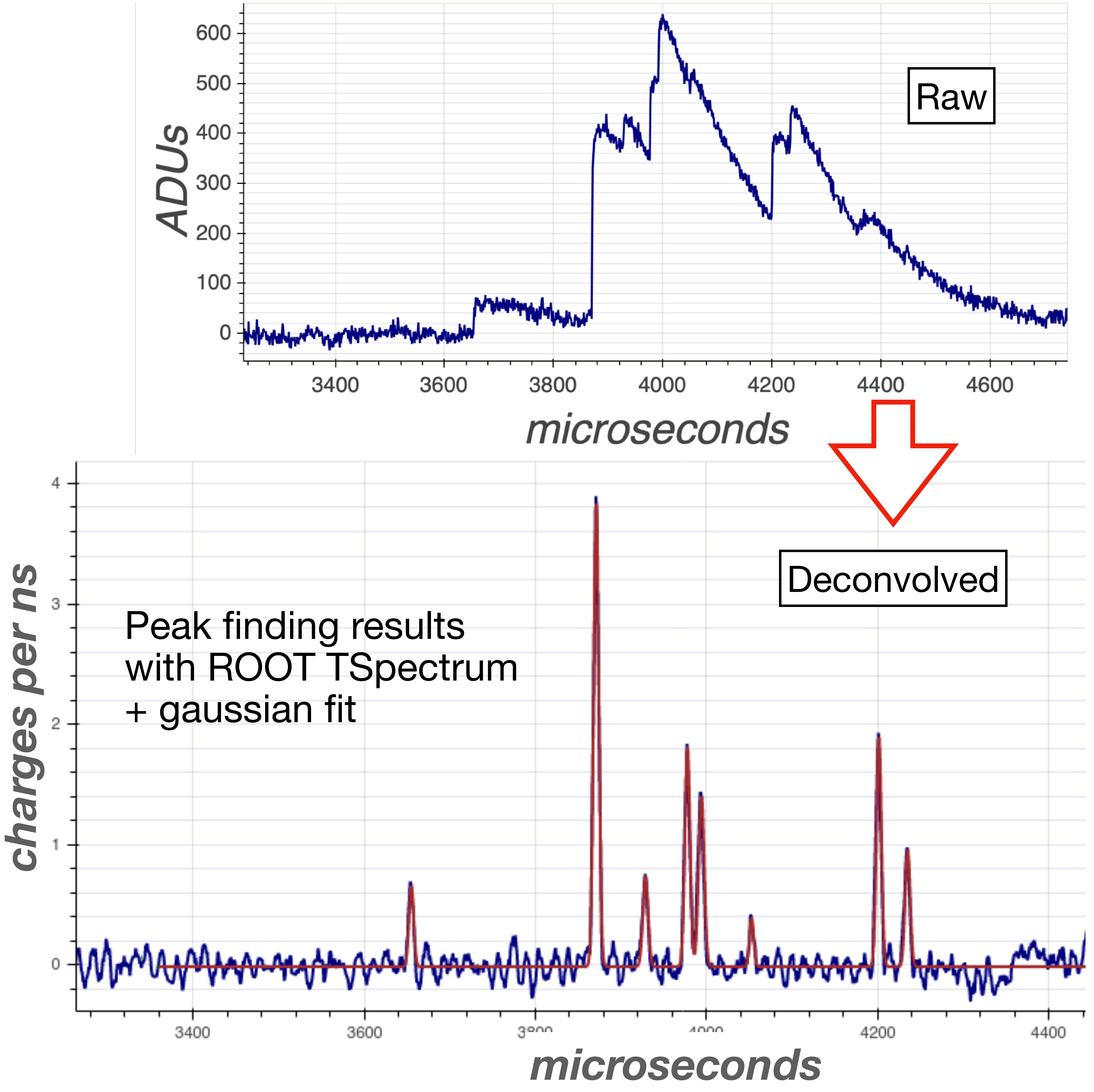

Long tail on following detected event



# Electron counting

In physics run at LSM with 135 mbar $CH_4$, >100 $\mu$s 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

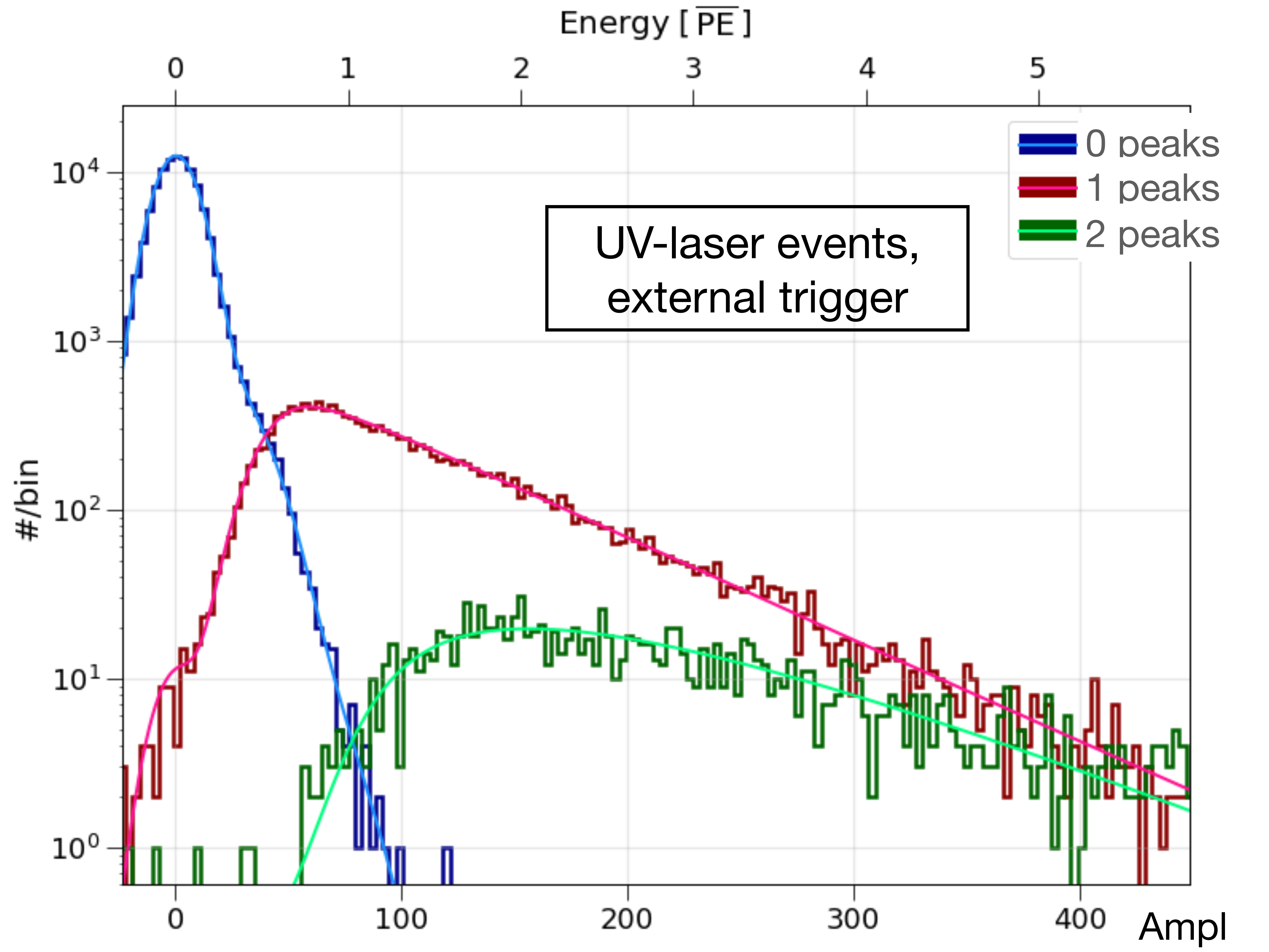


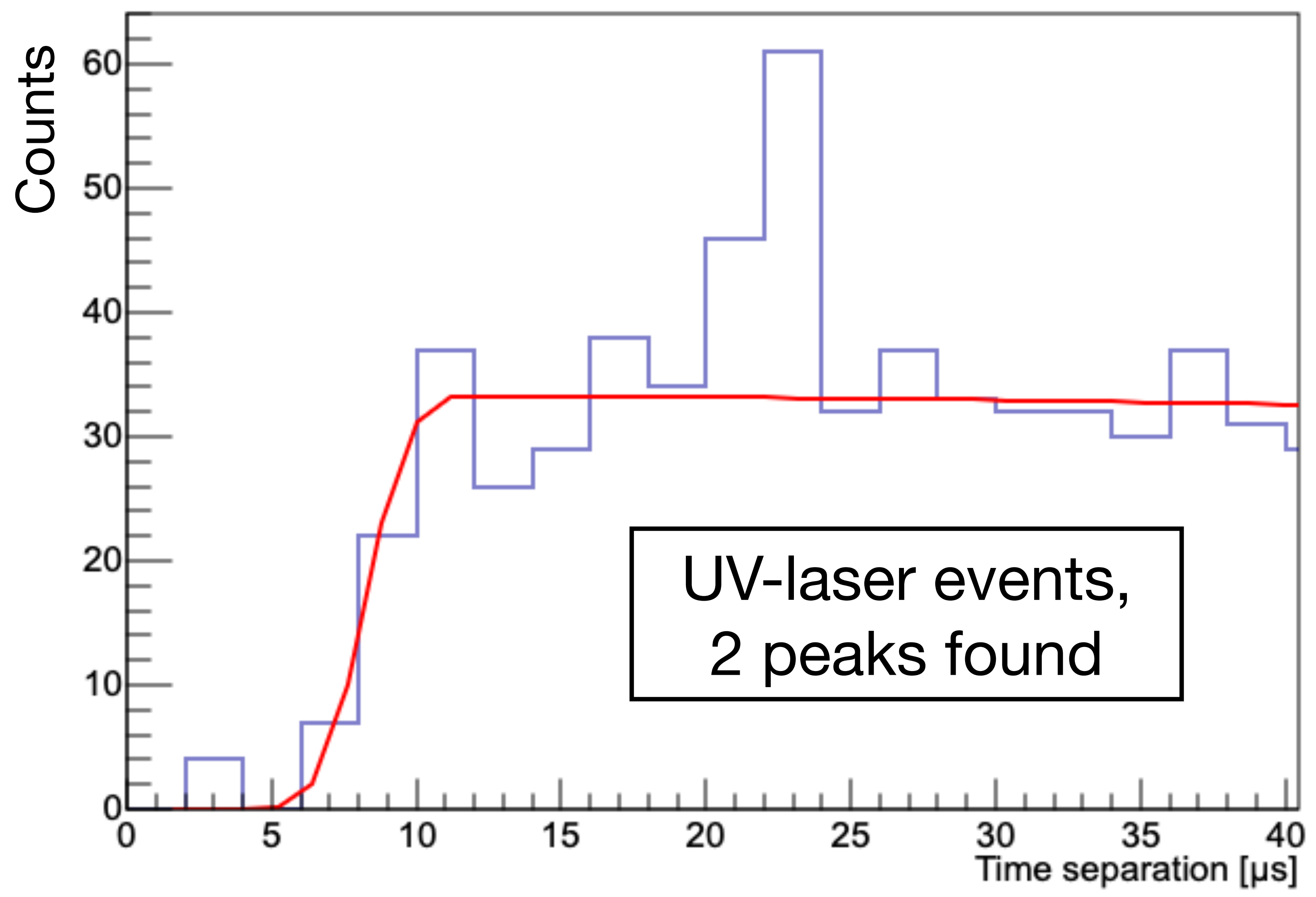
# Electron counting

## Characterisation

Pulsed 213nm UV-laser used to extract few-electron events from SPC internal surface. Characterises performance of peak-finding algorithm :

- Electron detection efficiency : 60%
- Separation of electron peaks above 8 $\mu s$



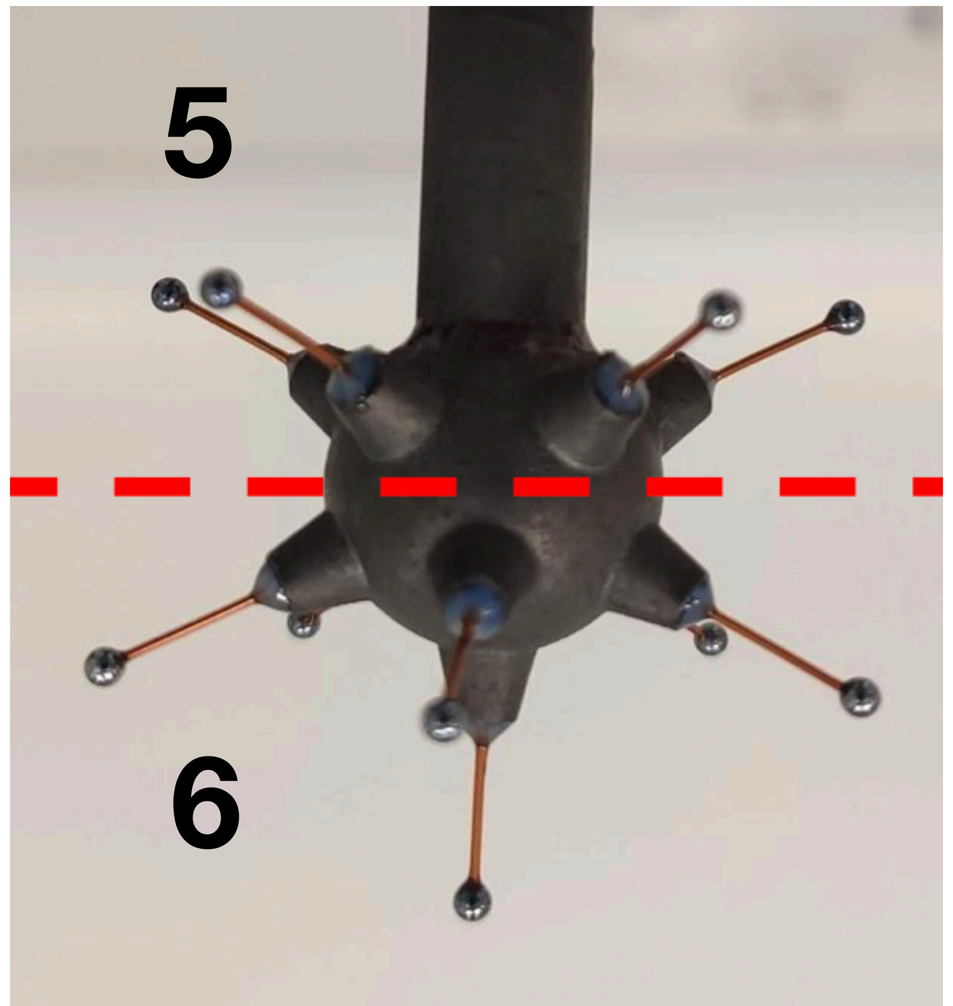



# Detector simulation

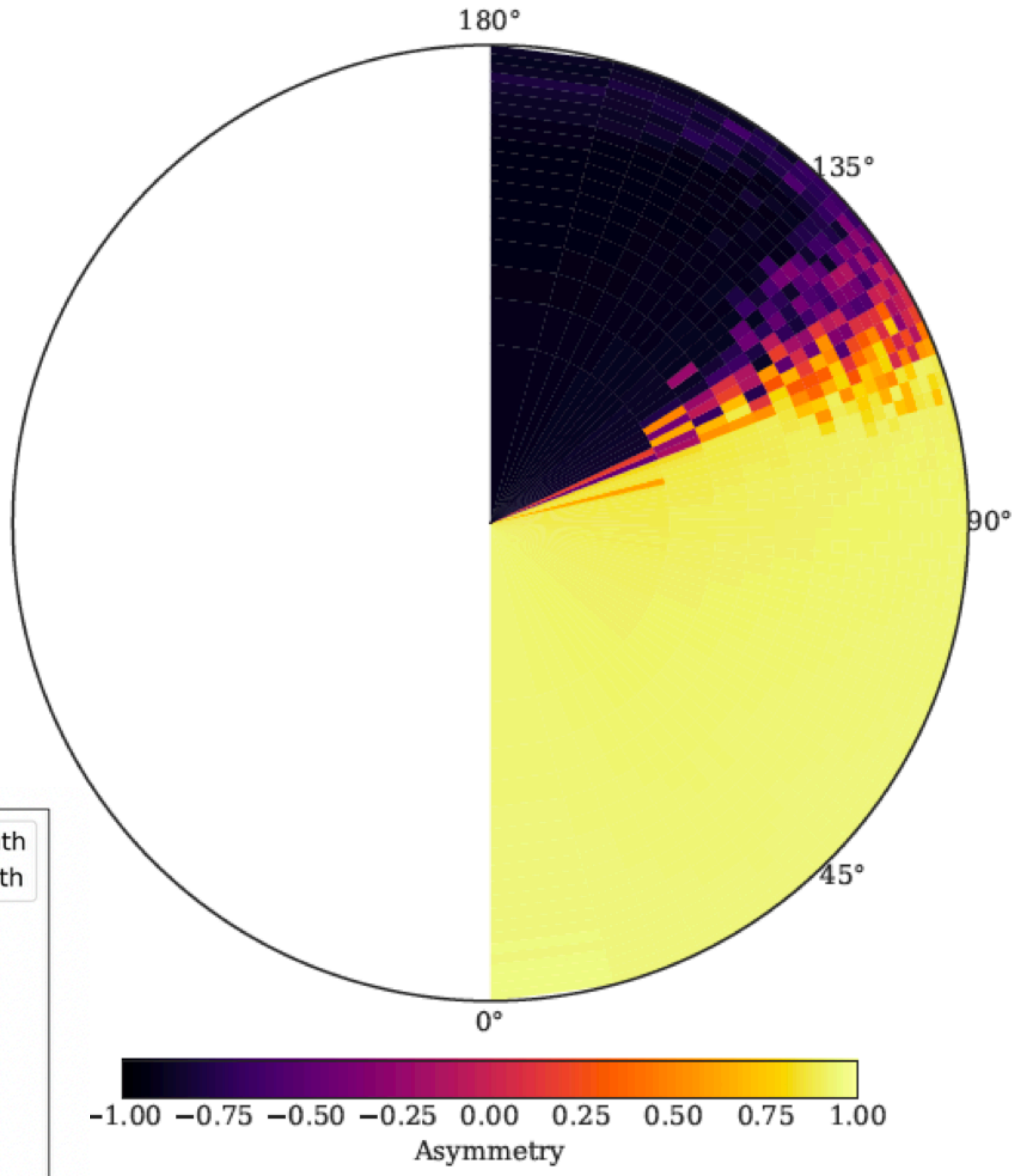
## ACHINOS : 5-6 configuration

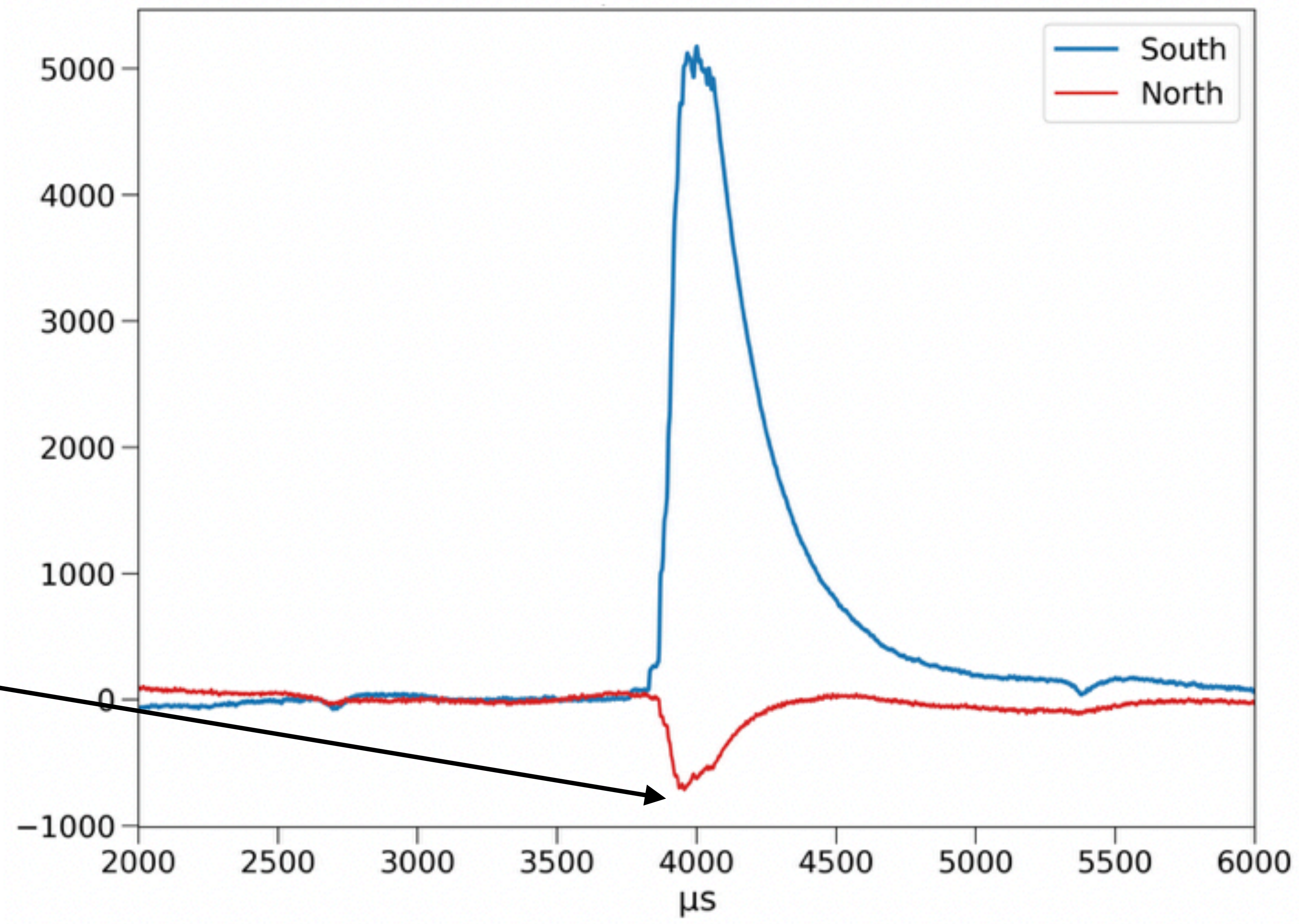
- For S140@LSM runs, achinos split into two channels
- Detector simulation performed with Geant4, Garfield++, ANSYS
- Used to estimate fiducial volume of each channel, effect of the support structure, gas choice, etc., verified with $^{37}Ar$ calibrations
- ***Predicted negative cross-channel induction for «physical» events due to ion movement***

Near/North




Far/South



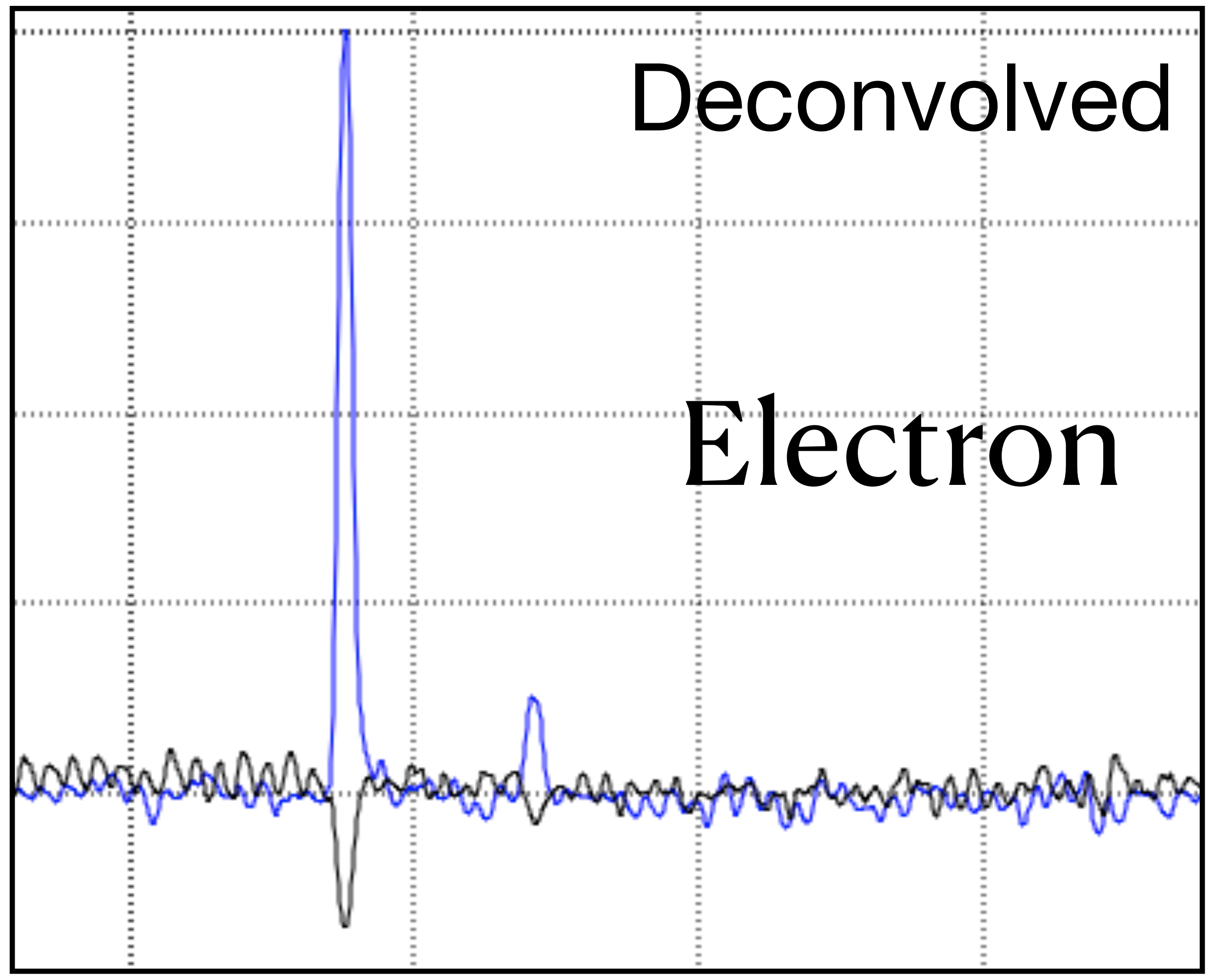



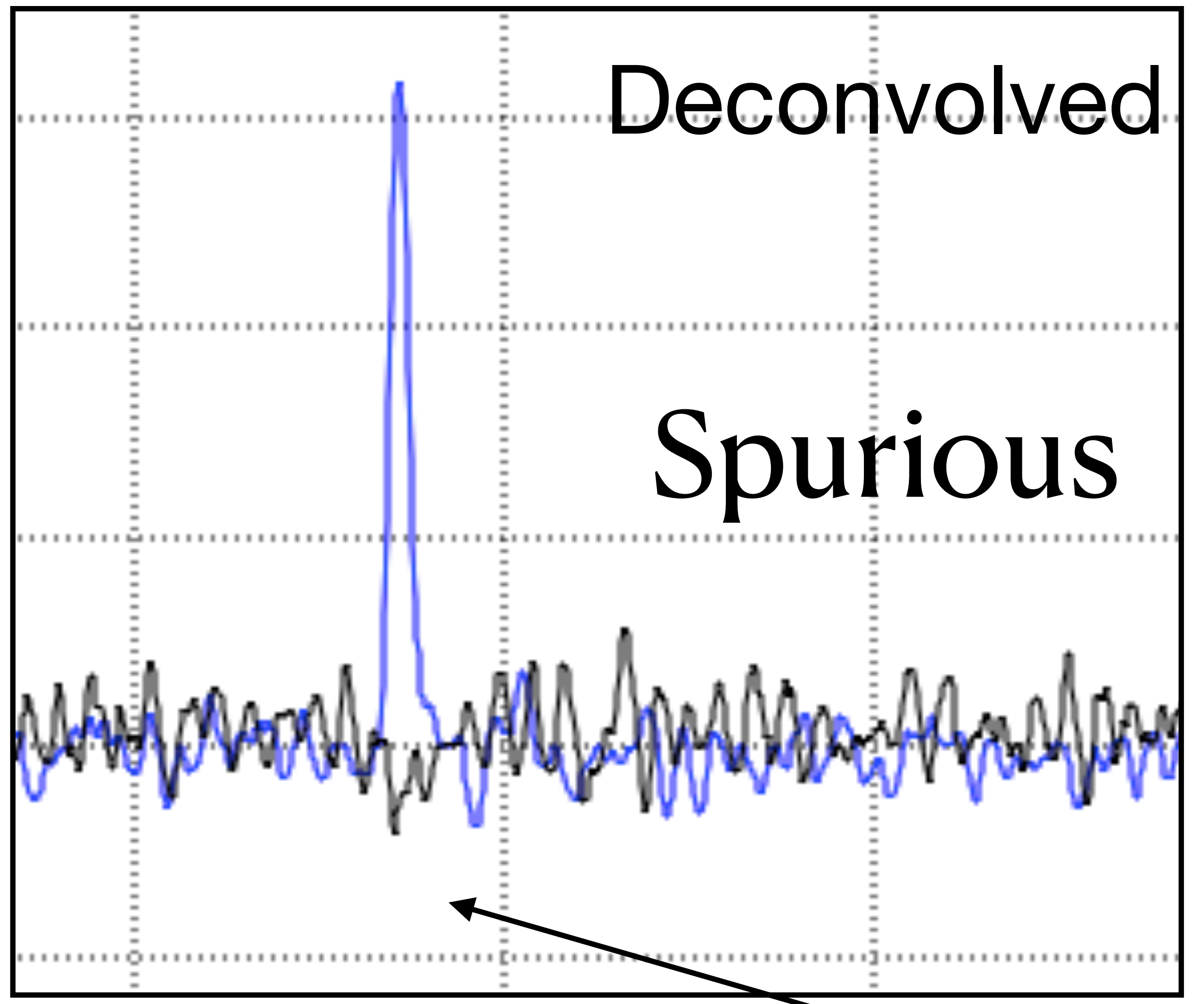

R. Ward et al 2020 JINST 15 C06013

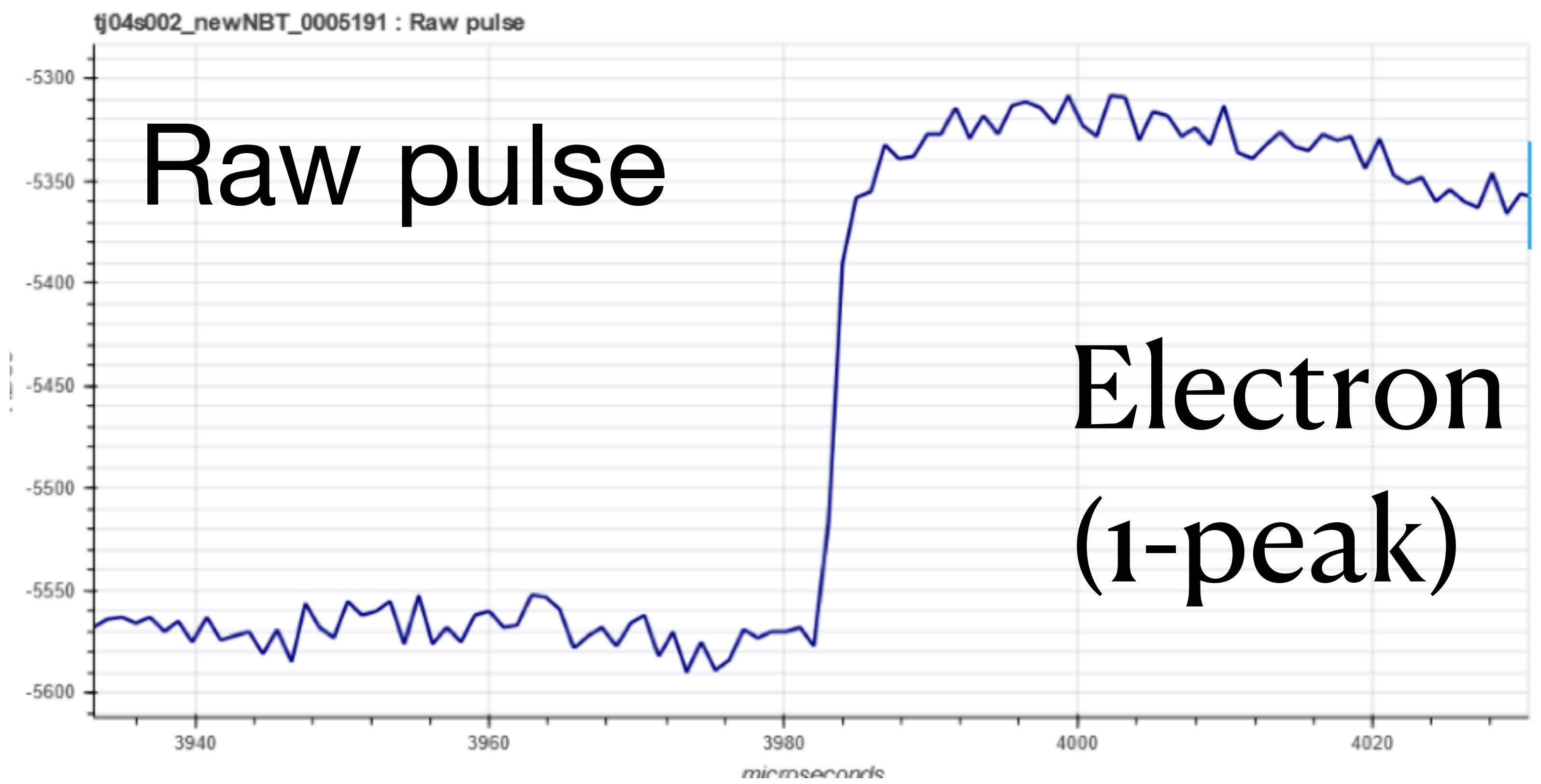
I. Giomataris et al 2020 JINST 15 P11023

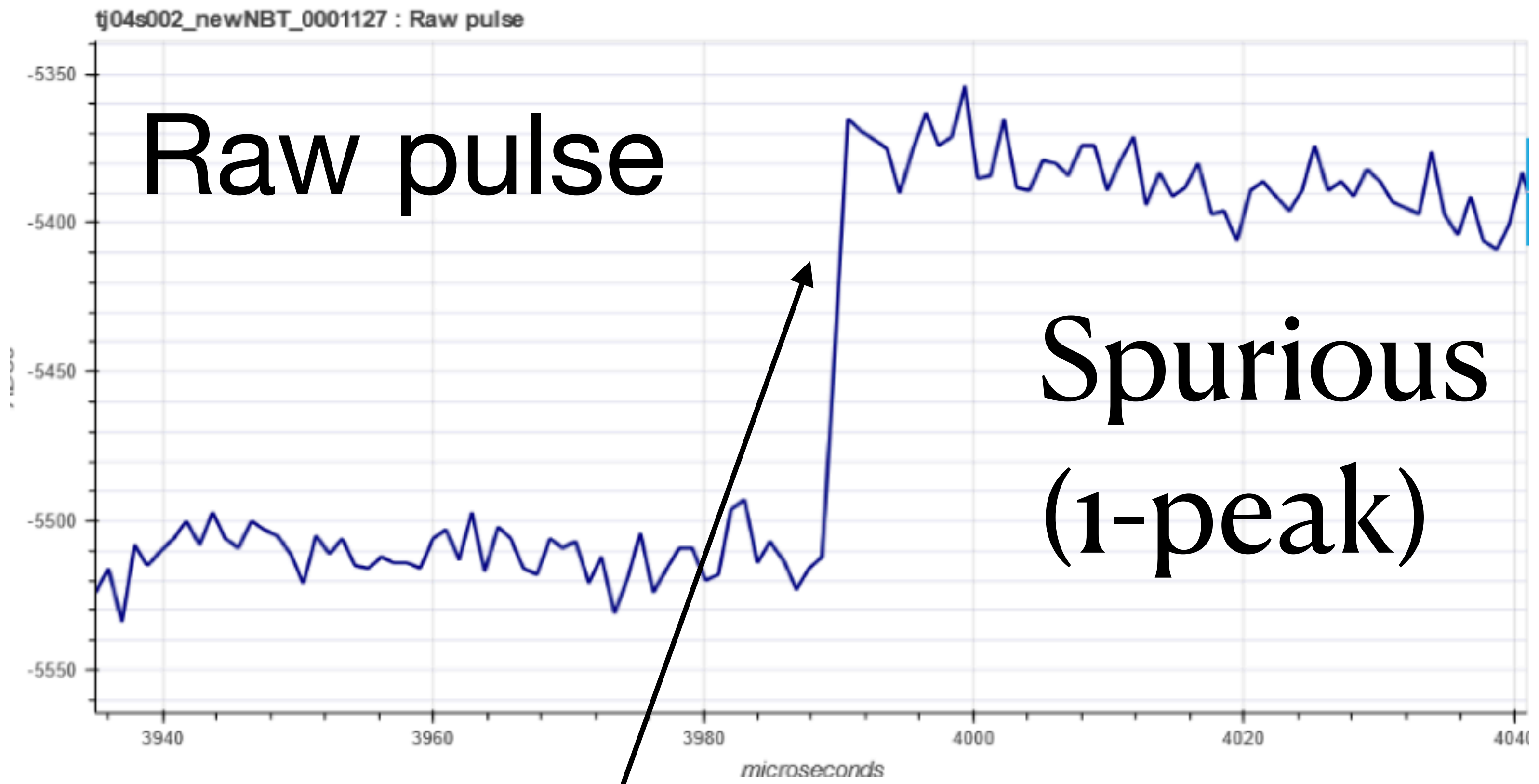
# Pulse Shape Discrimination

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



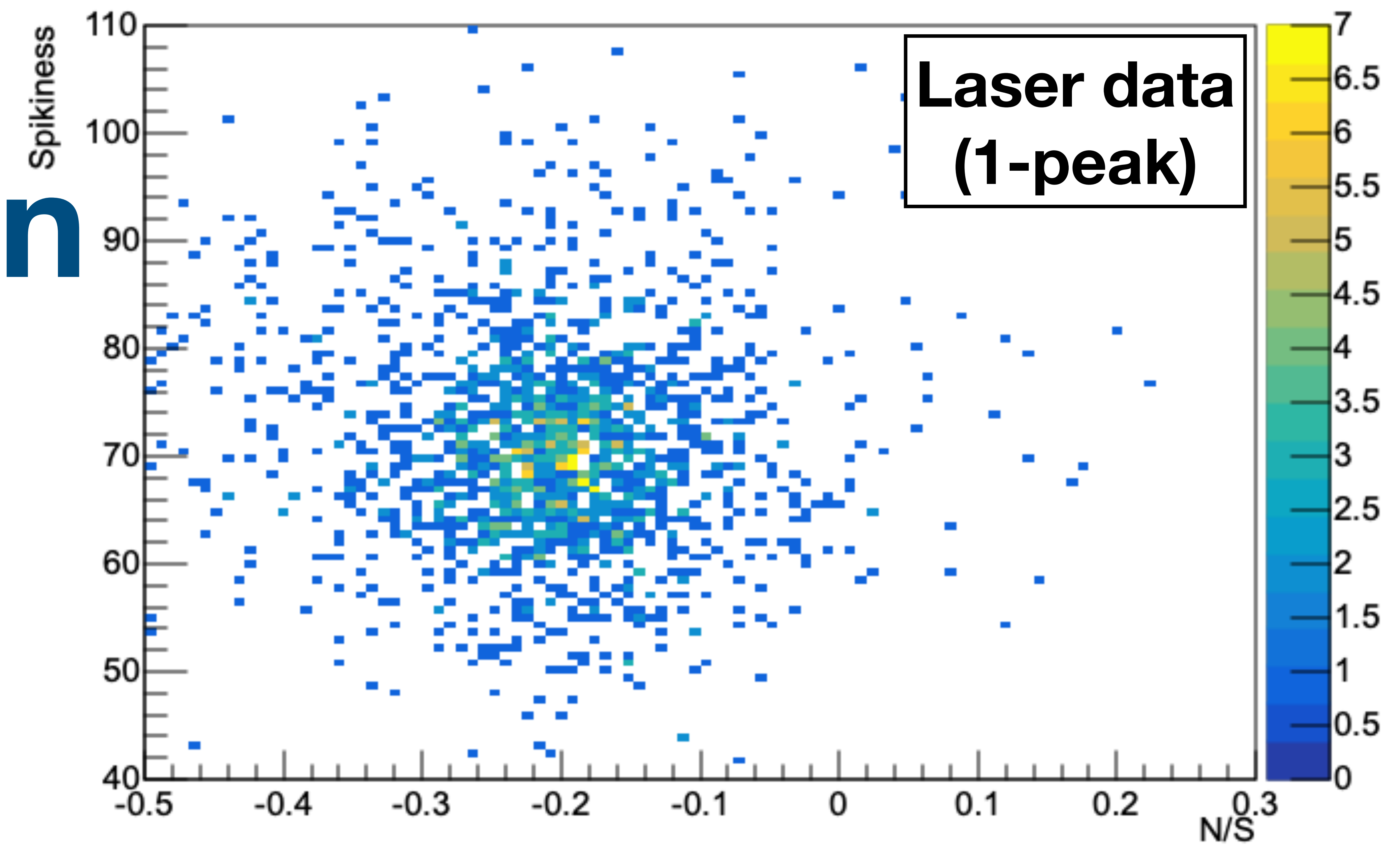



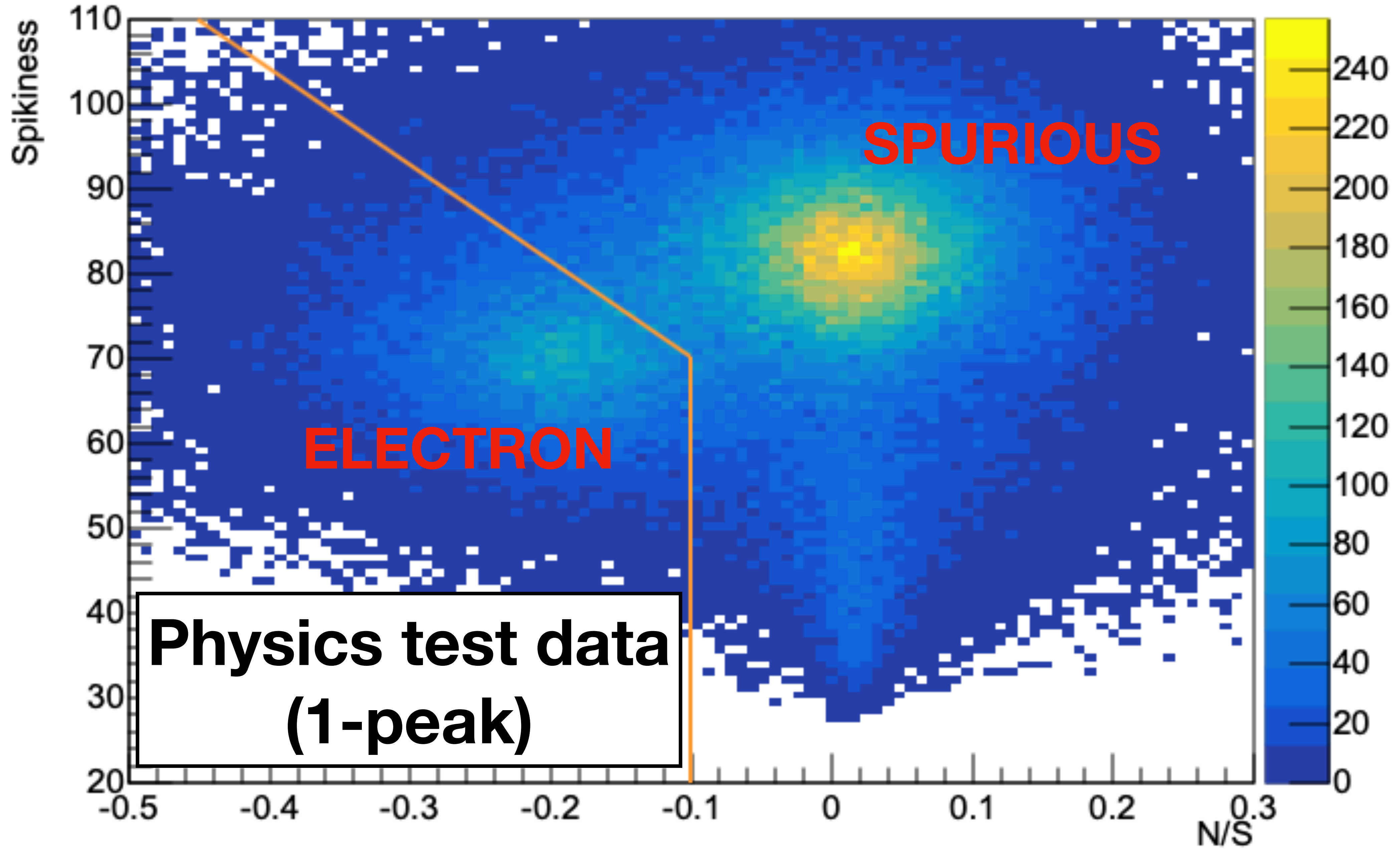




- sharp rise of raw signal
- lack of negative signal on opposite channel (observed for « electron-like » events)

# 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

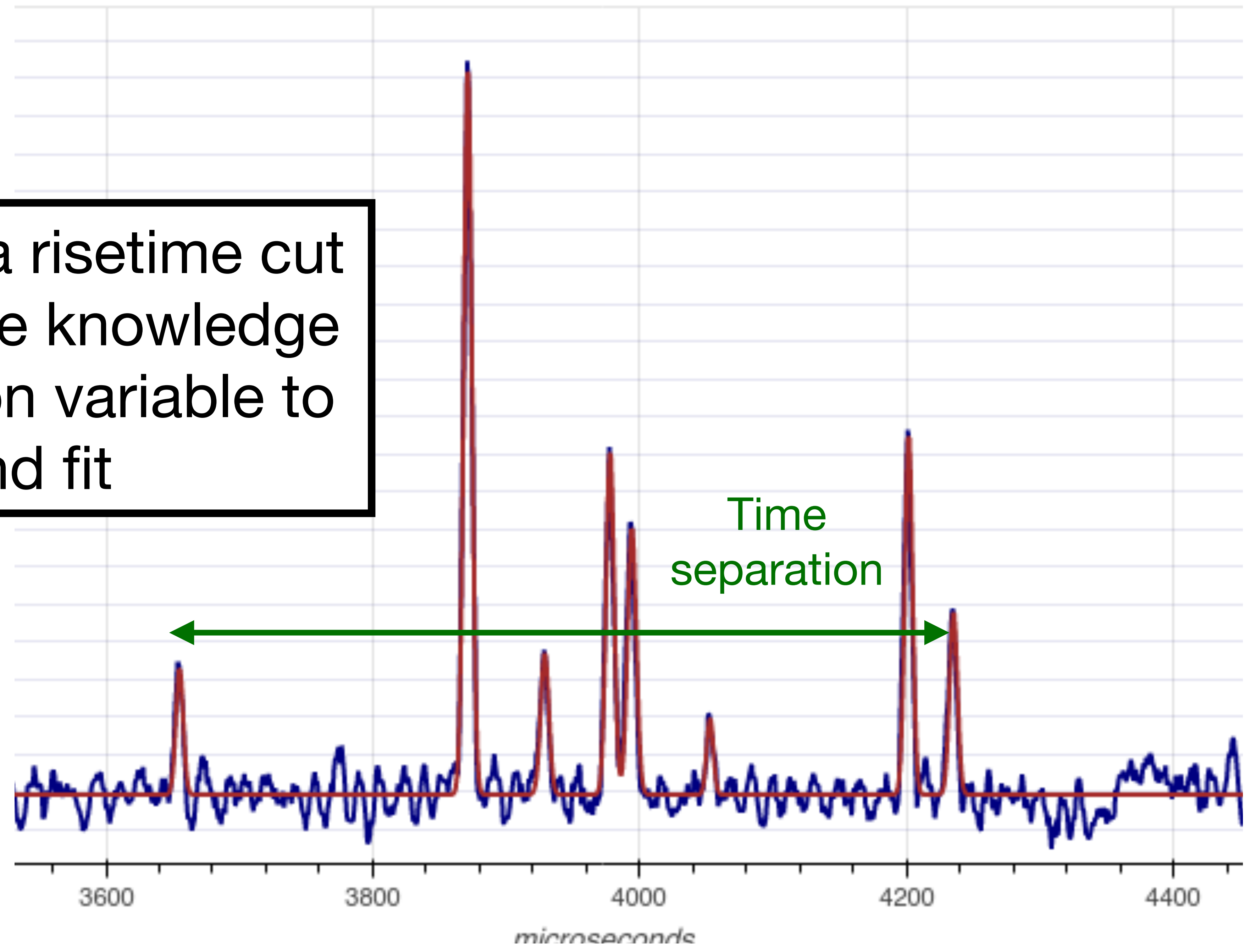


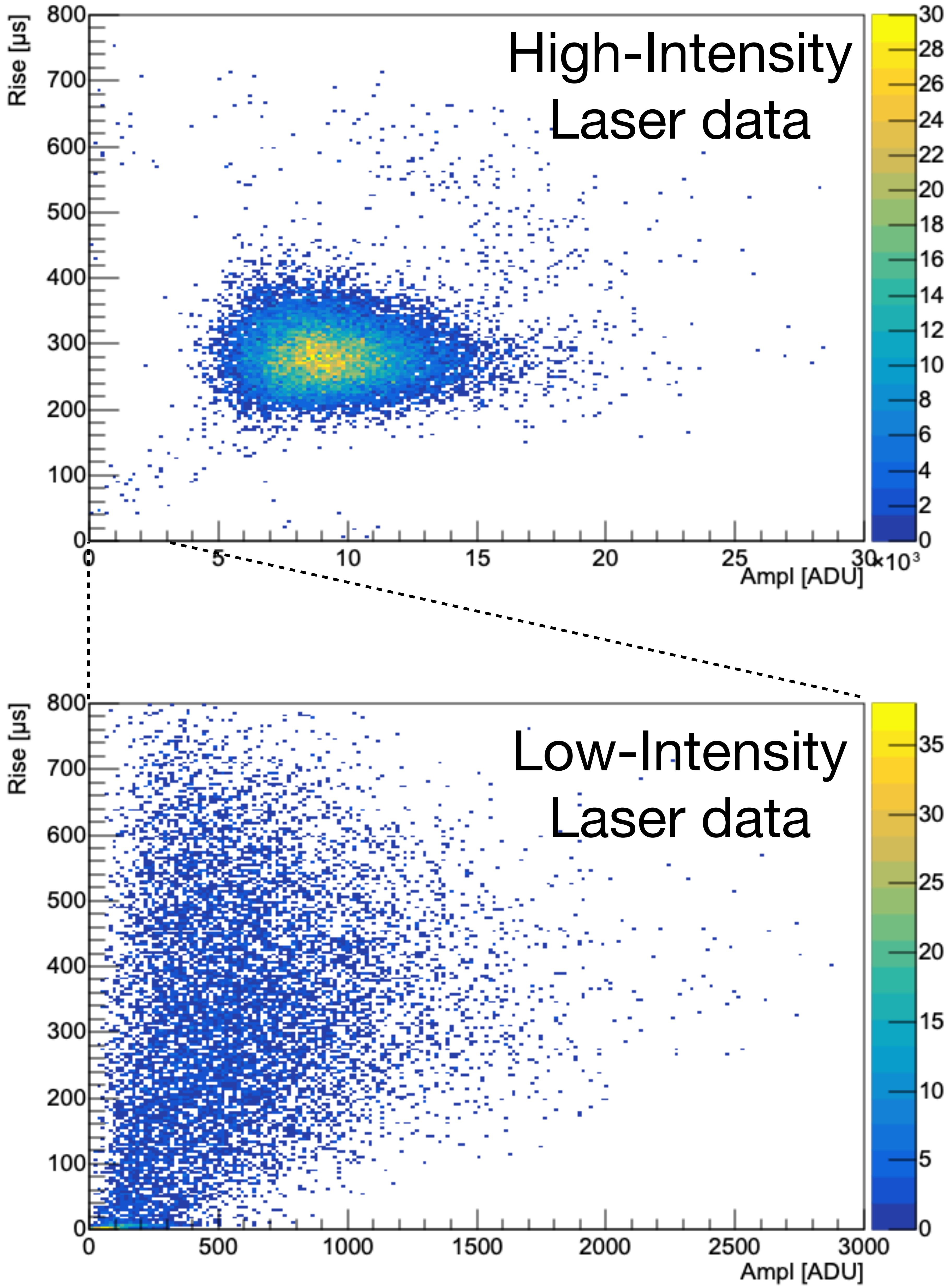



# New diffusion variable

- As we go to lower amplitudes / fewer primary electrons, risetime becomes poorly defined, cannot separate surface and volume events
- New variable tested: time separation between first and last peak found (need >1e- to use!)

**CONTEXT:** instead of doing a risetime cut to remove surface events, use knowledge of distribution of new diffusion variable to perform a background fit



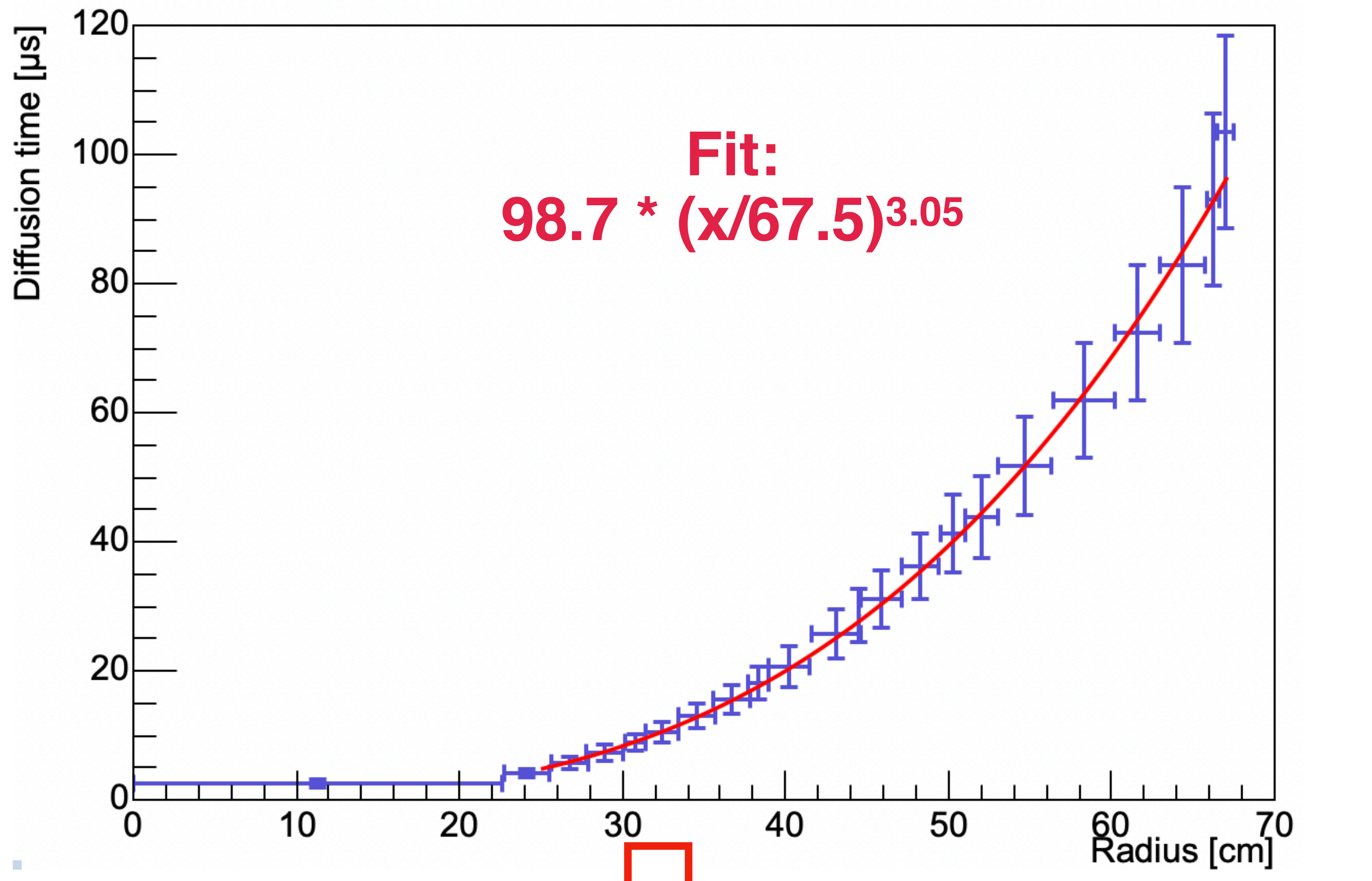



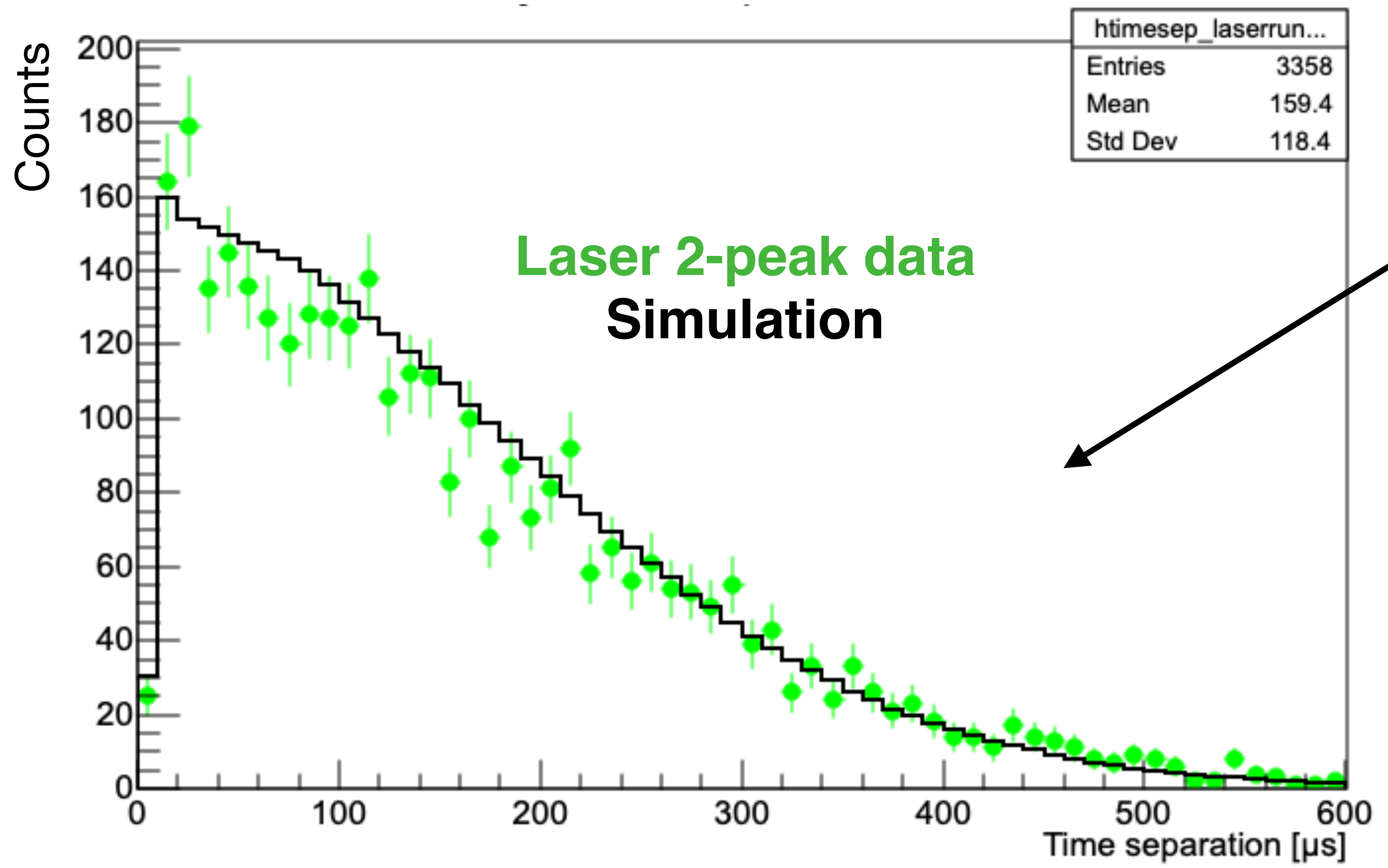
# Time separation

## Surface / Volume events

- $^{37}$Ar data calibrates electron diffusion vs radius, used to simulate volume events in S140
- Simulations of surface and volume event reconstruction in agreement with Laser and $^{37}$Ar data respectively, up to 4-peak event data

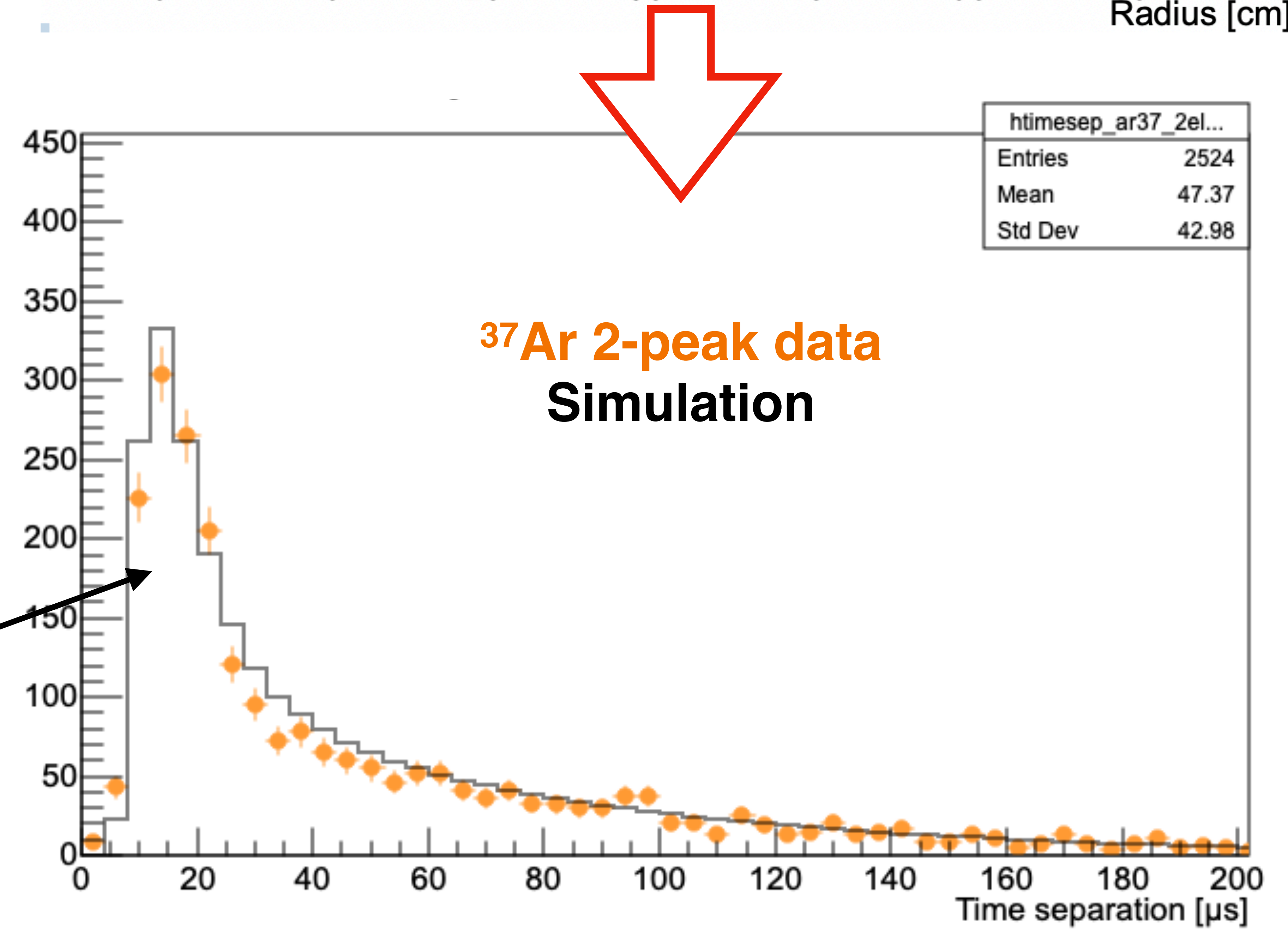
**Reconstructed diffusion vs radius from $^{37}$Ar calibrations**




Surface events:
wide distribution,
large time separations

Volume events:
Concentrated at low
time separations

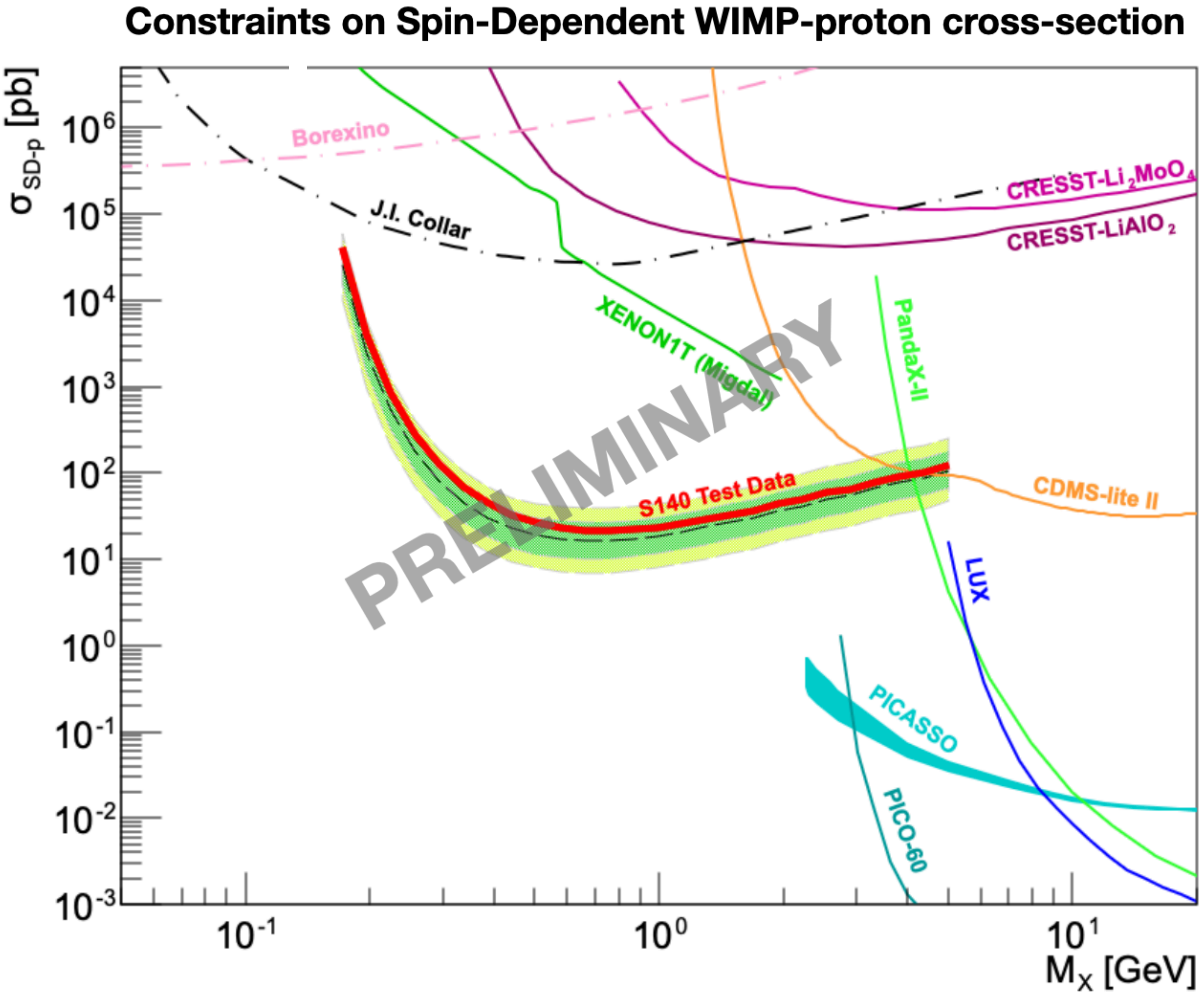


# Physics data fit

- 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 modelling derived from simulations and validated with calibration data
- No significant signal observed

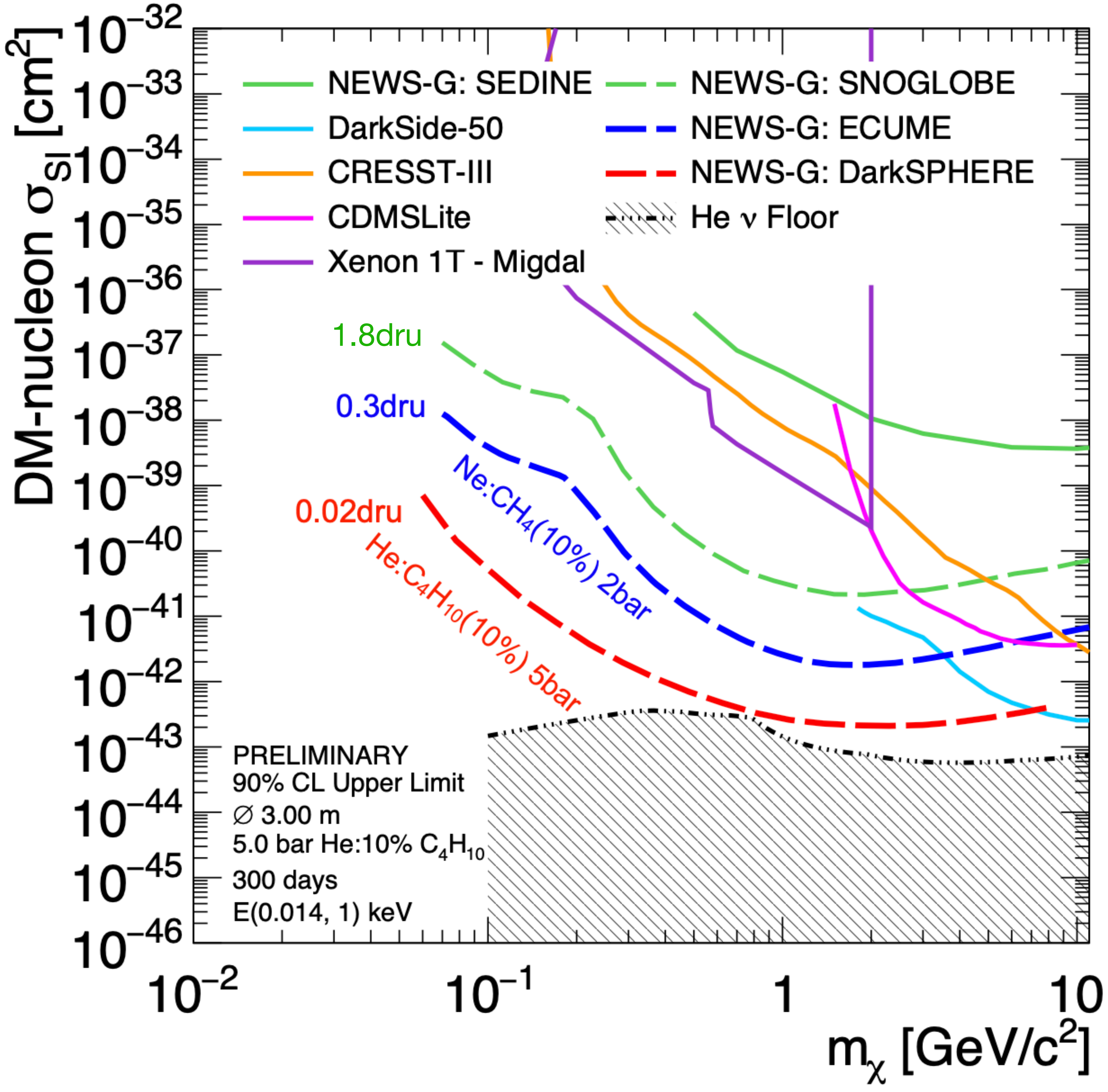
# New WIMP constraints

- 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

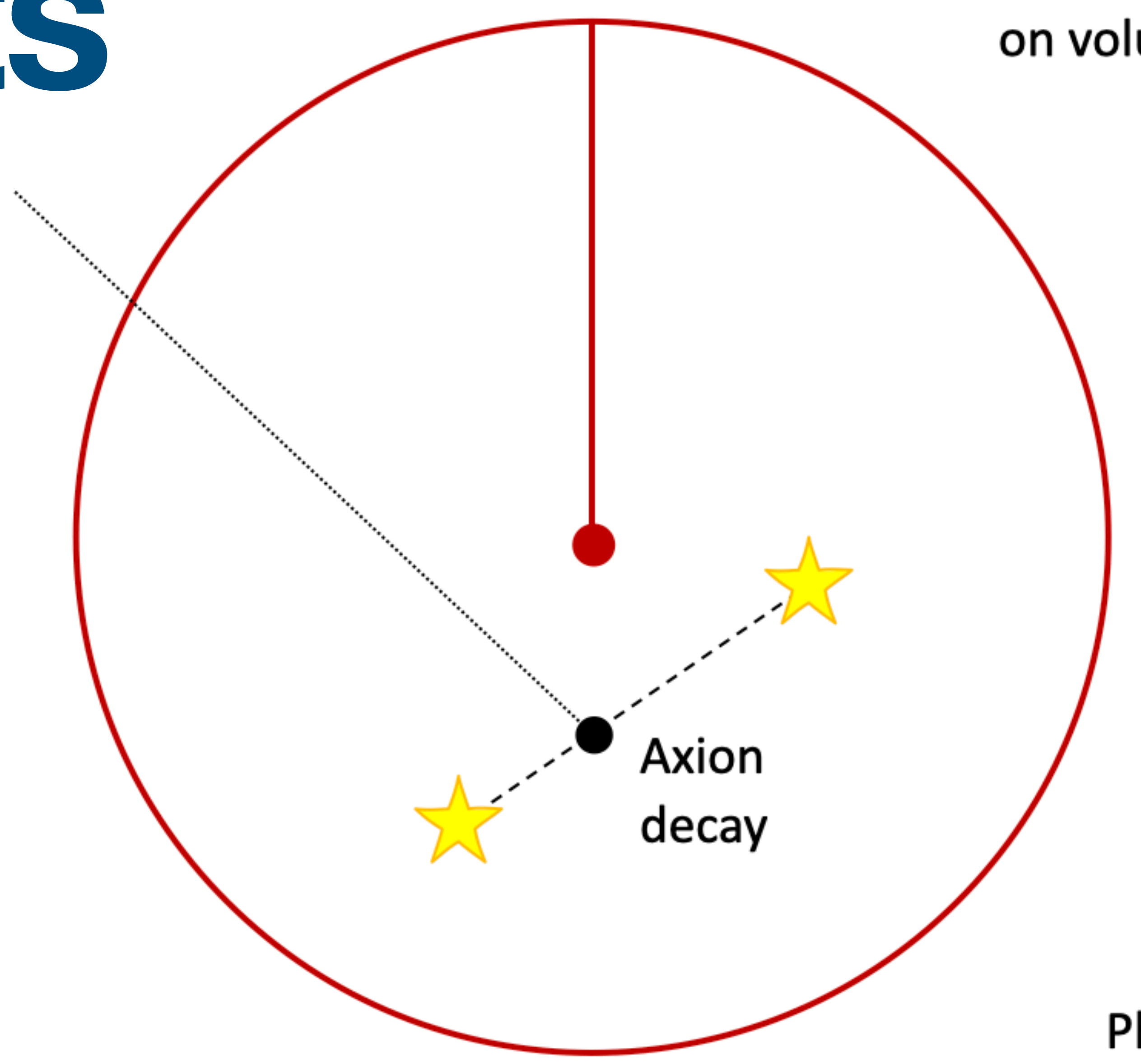
- S140 : more data at SNOLAB
  - Internal surface etching, more $CH_4$ data for improved SD-p constraints
  - Ne+$CH_4$ mixture for improved SI constraints
  - Possible low-pressure run for NR/ER discrimination
- ECUME : fully electro-formed vessel directly in underground lab, completely remove background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



# 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.



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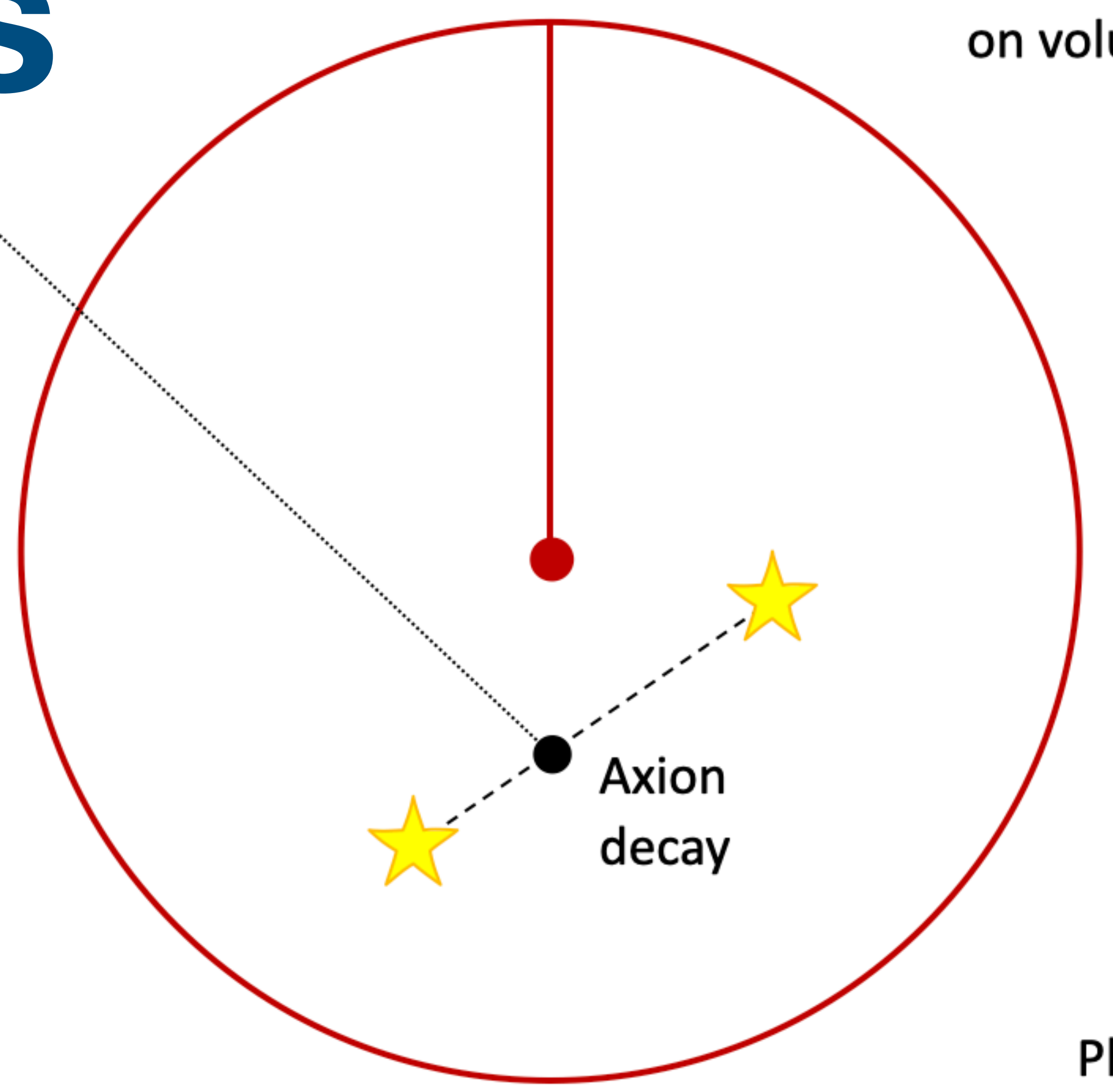
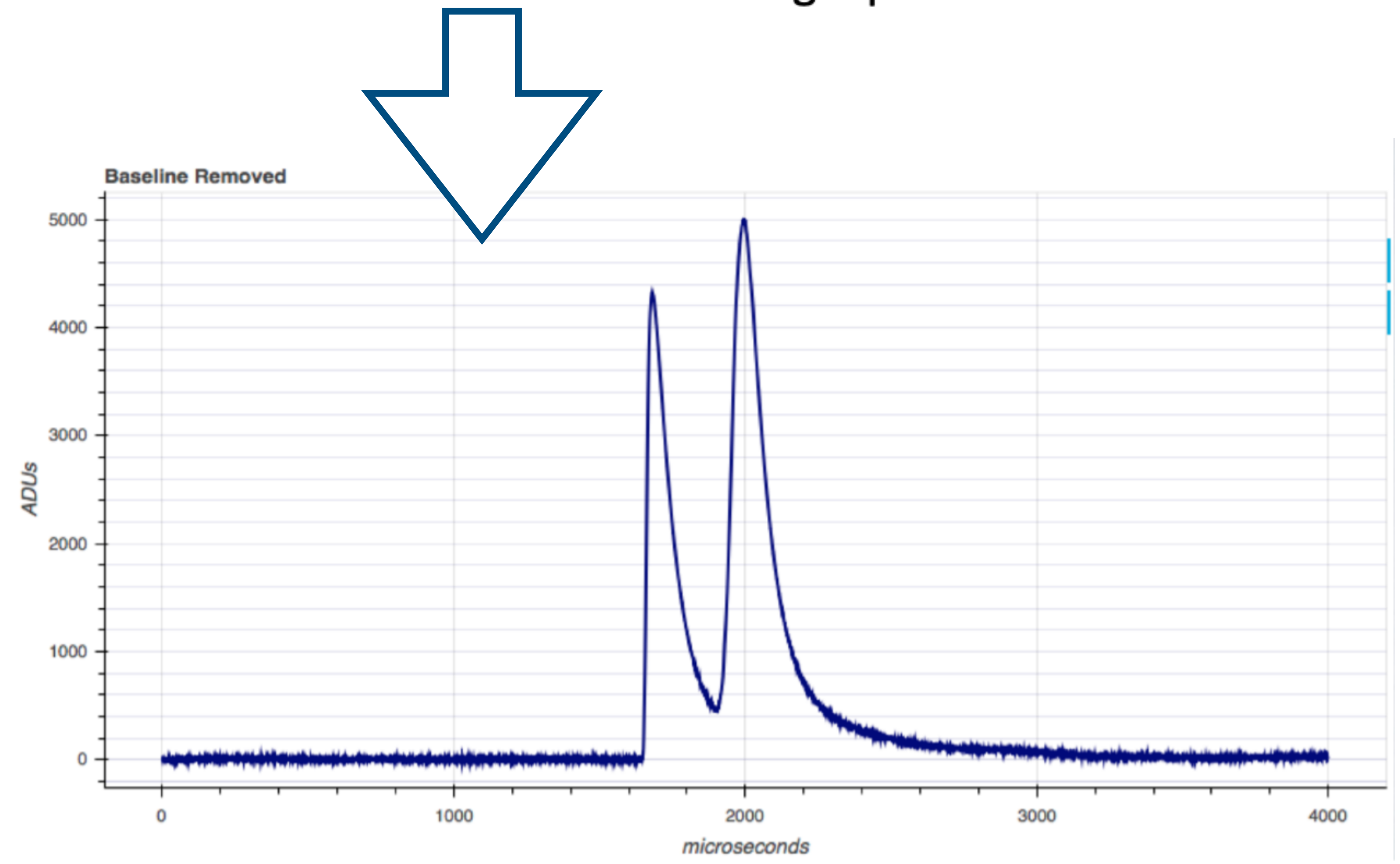
Can reject background at 99.99% in 2-22 keV range by keeping only events with two pulses of similar amplitude arriving shortly after each other.

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




Photons < 10 keV:
Single photoelectric interaction



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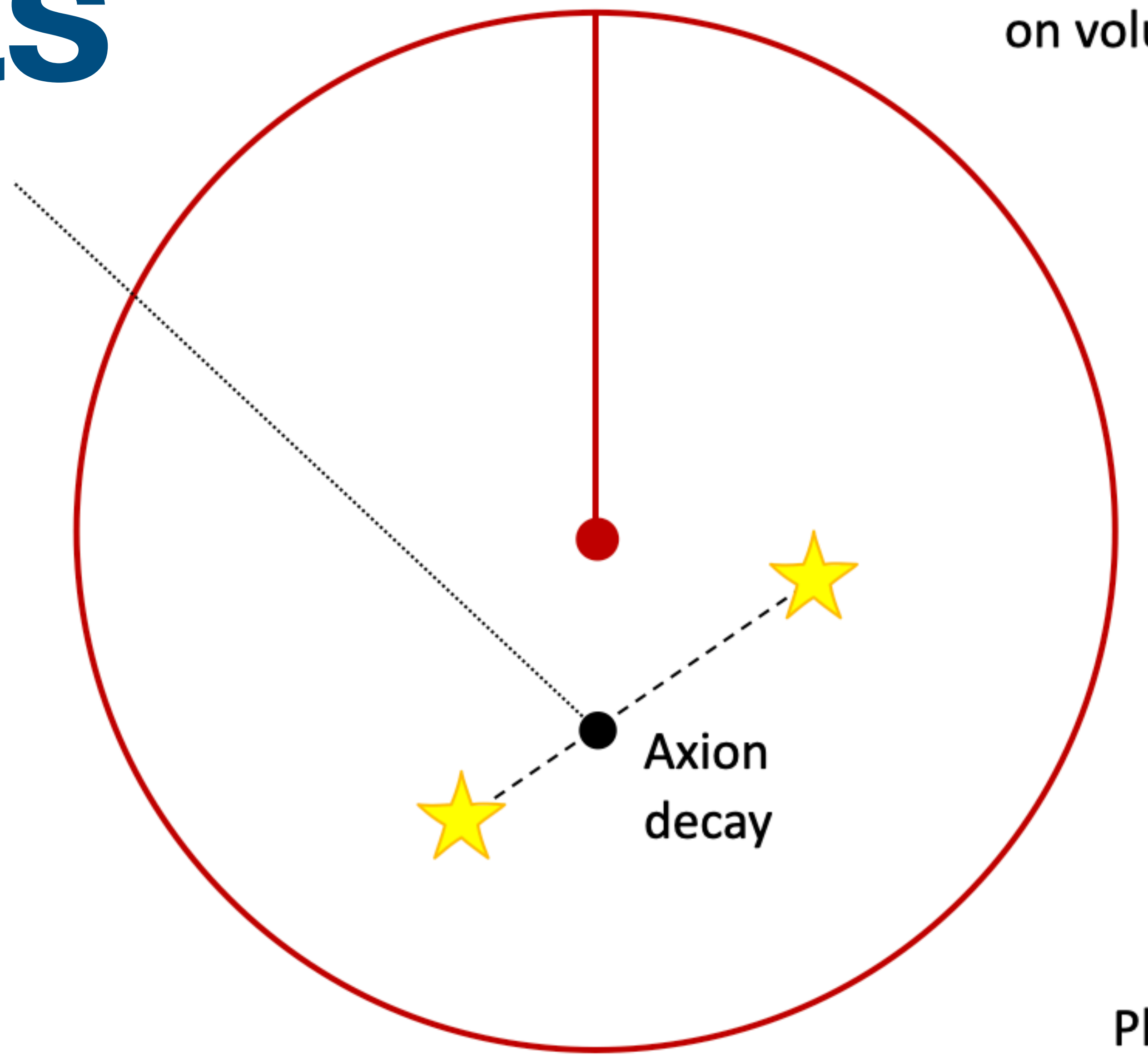
With 42 day exposure of SEDINE detector, and an integrated sensitivity to solar KK axion decays of 16%, still improve over previous XMASS limit by factor ~6.

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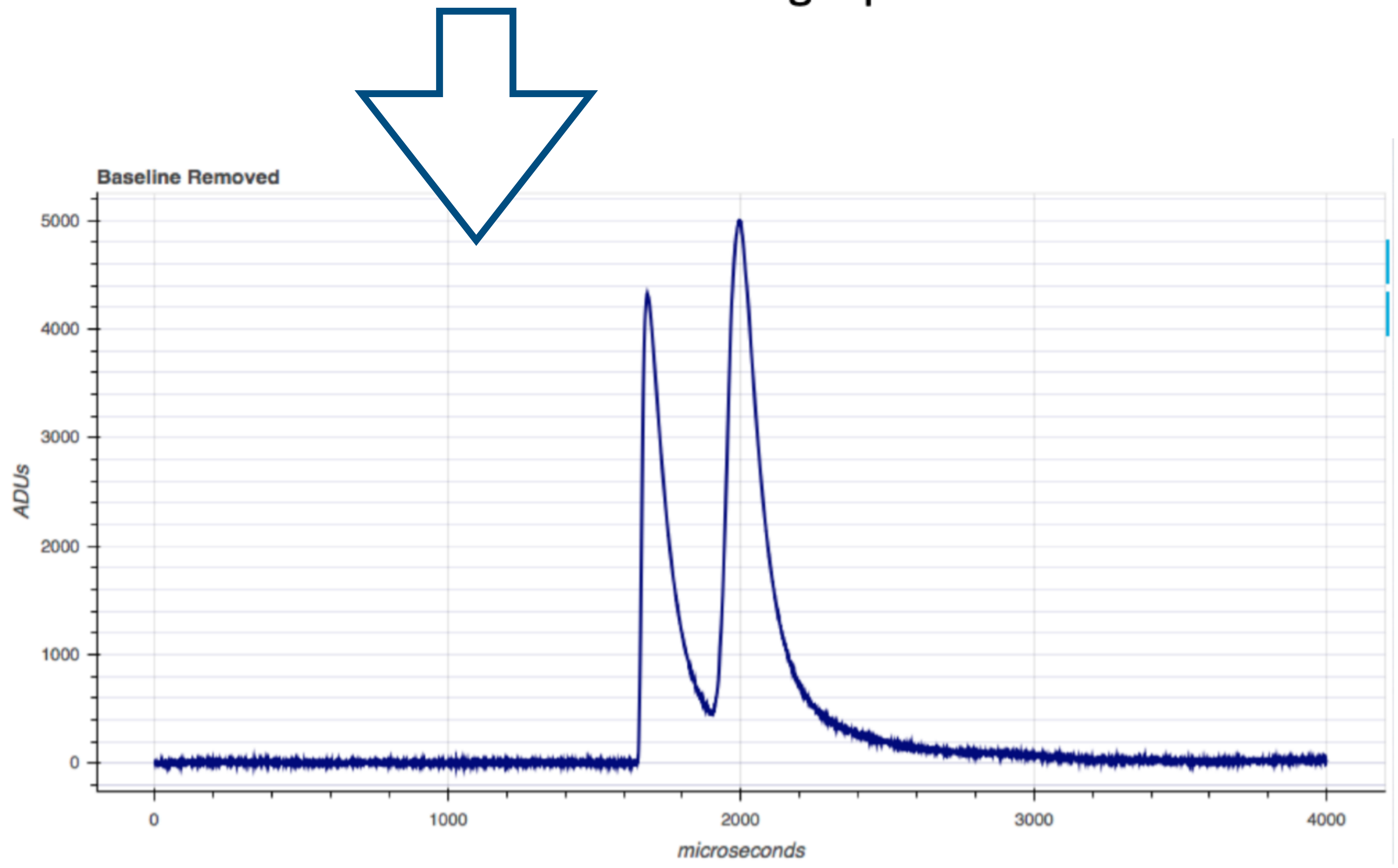
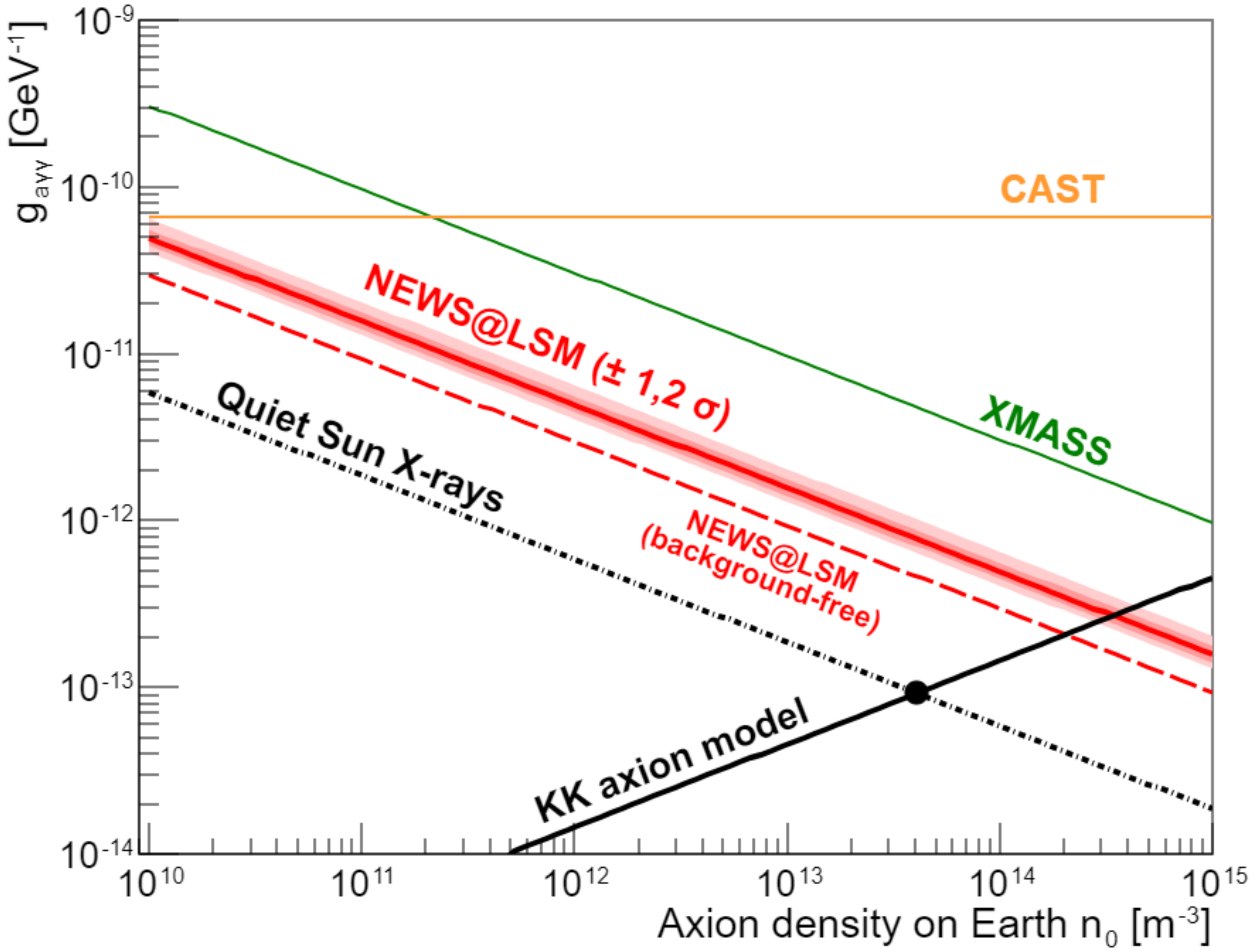


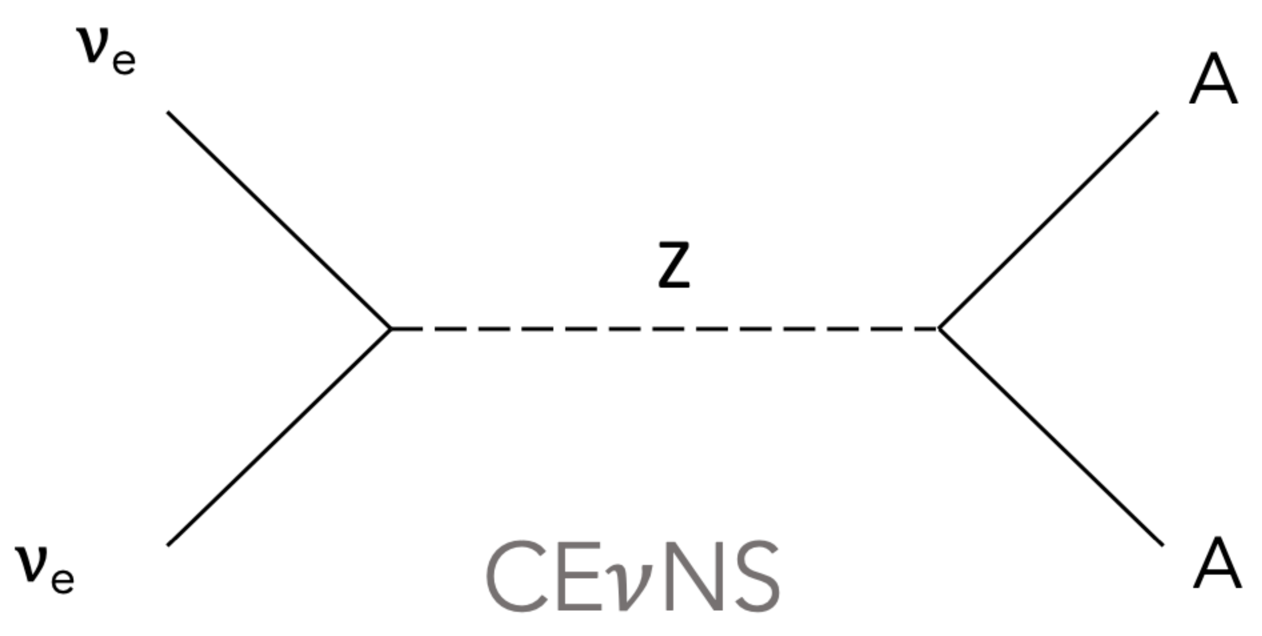




**NEWS-G collab., PHYSICAL REVIEW D 105, 012002 (2022)**

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

# 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.

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

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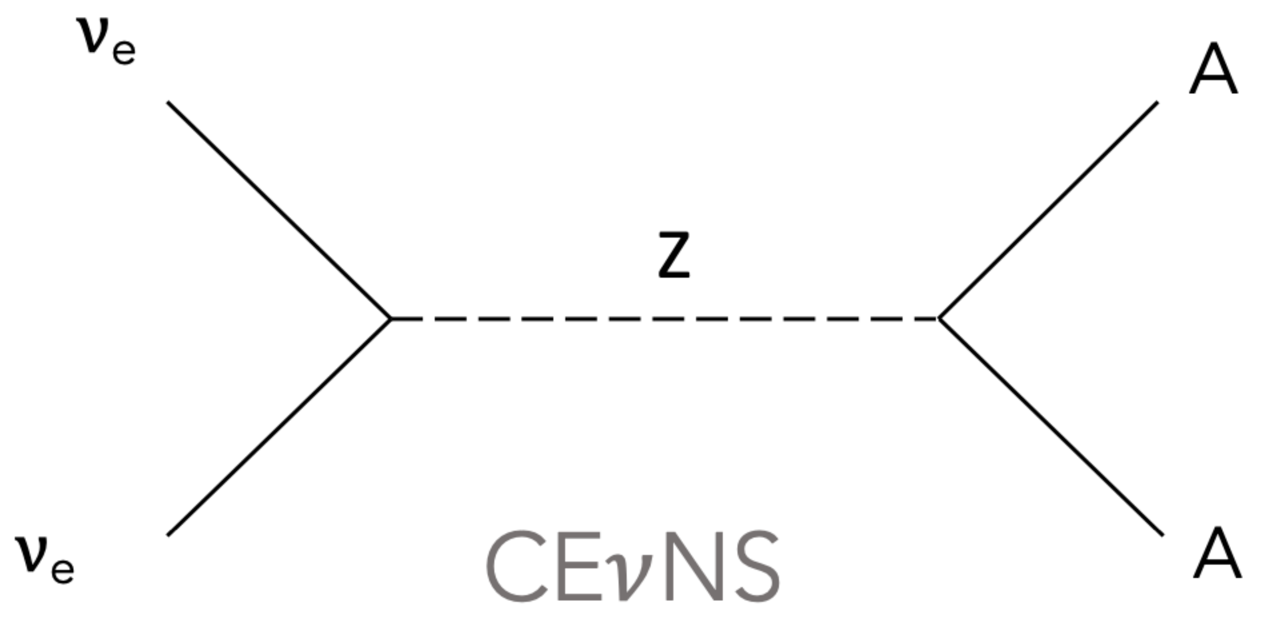


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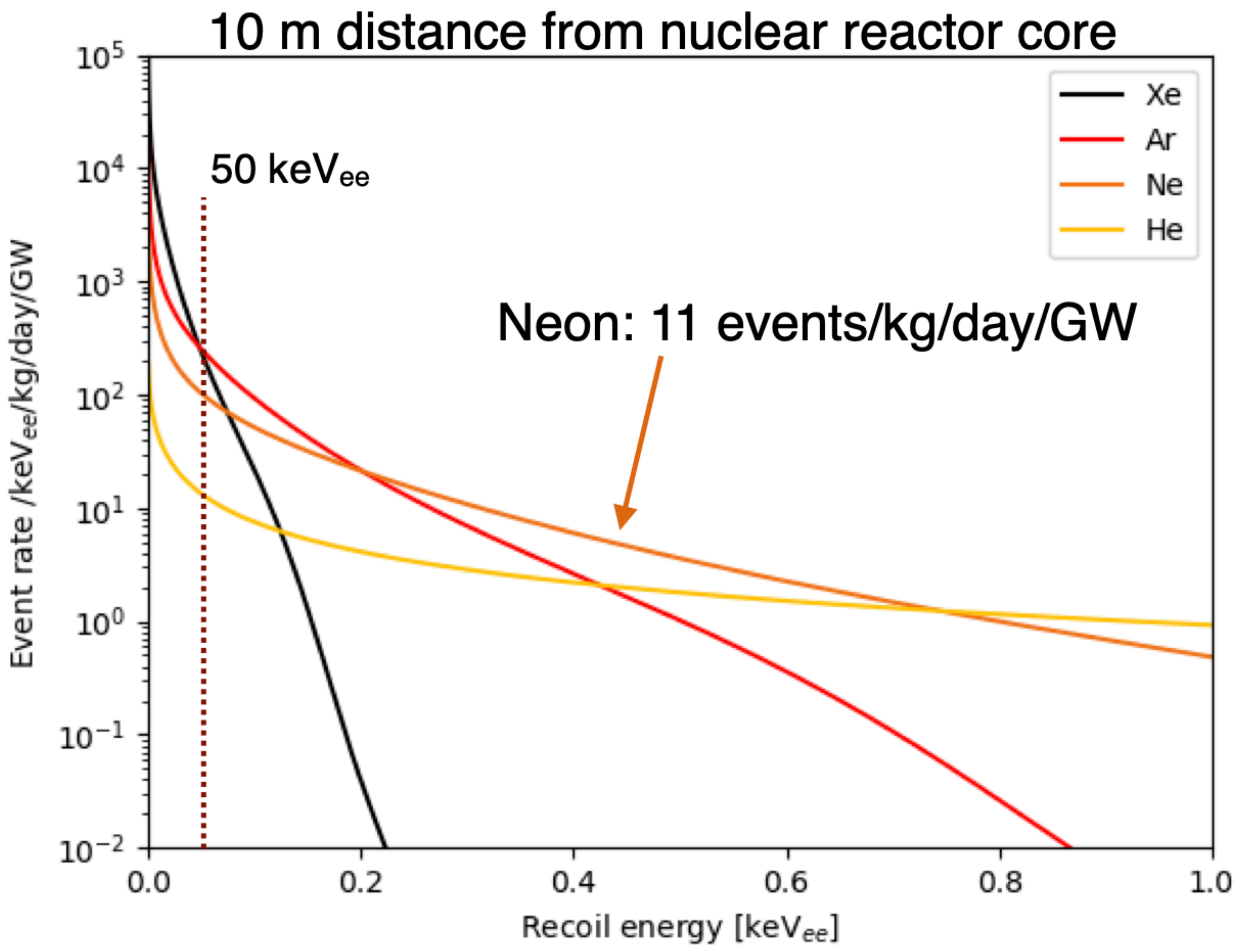
NEWS-G interested in detecting CEvNS at nuclear reactor. Feasibilty study requires understanding of both CEvNS signal and backgrounds (environmental, cosmogenic) for surface detectors.

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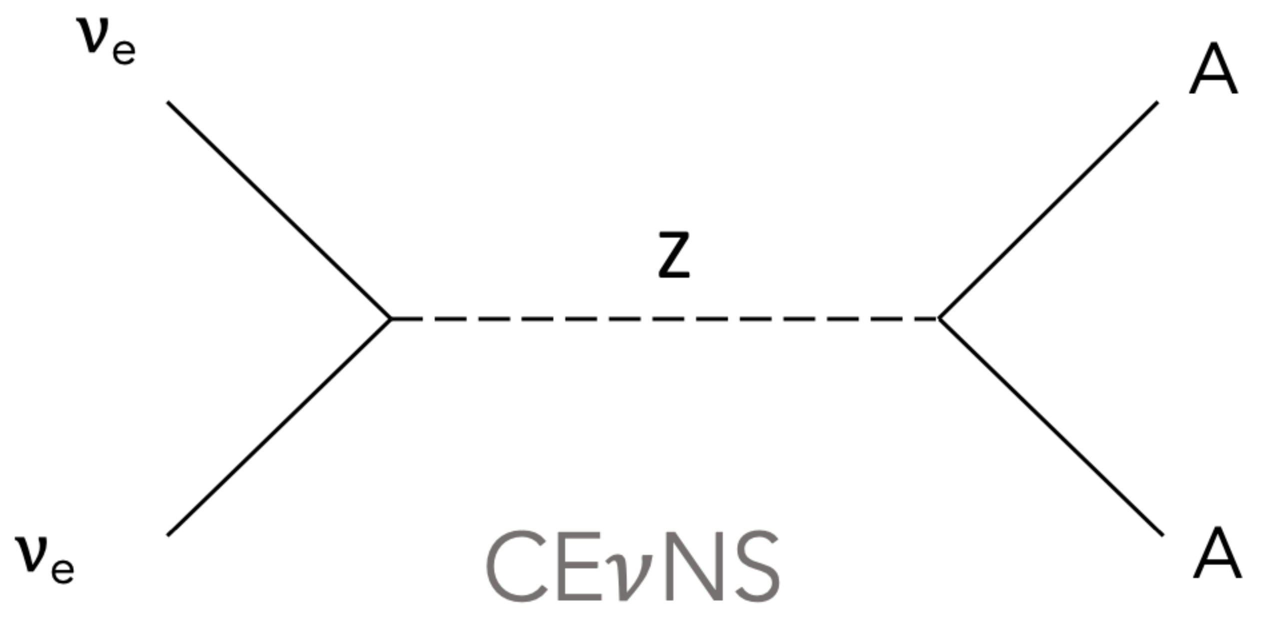


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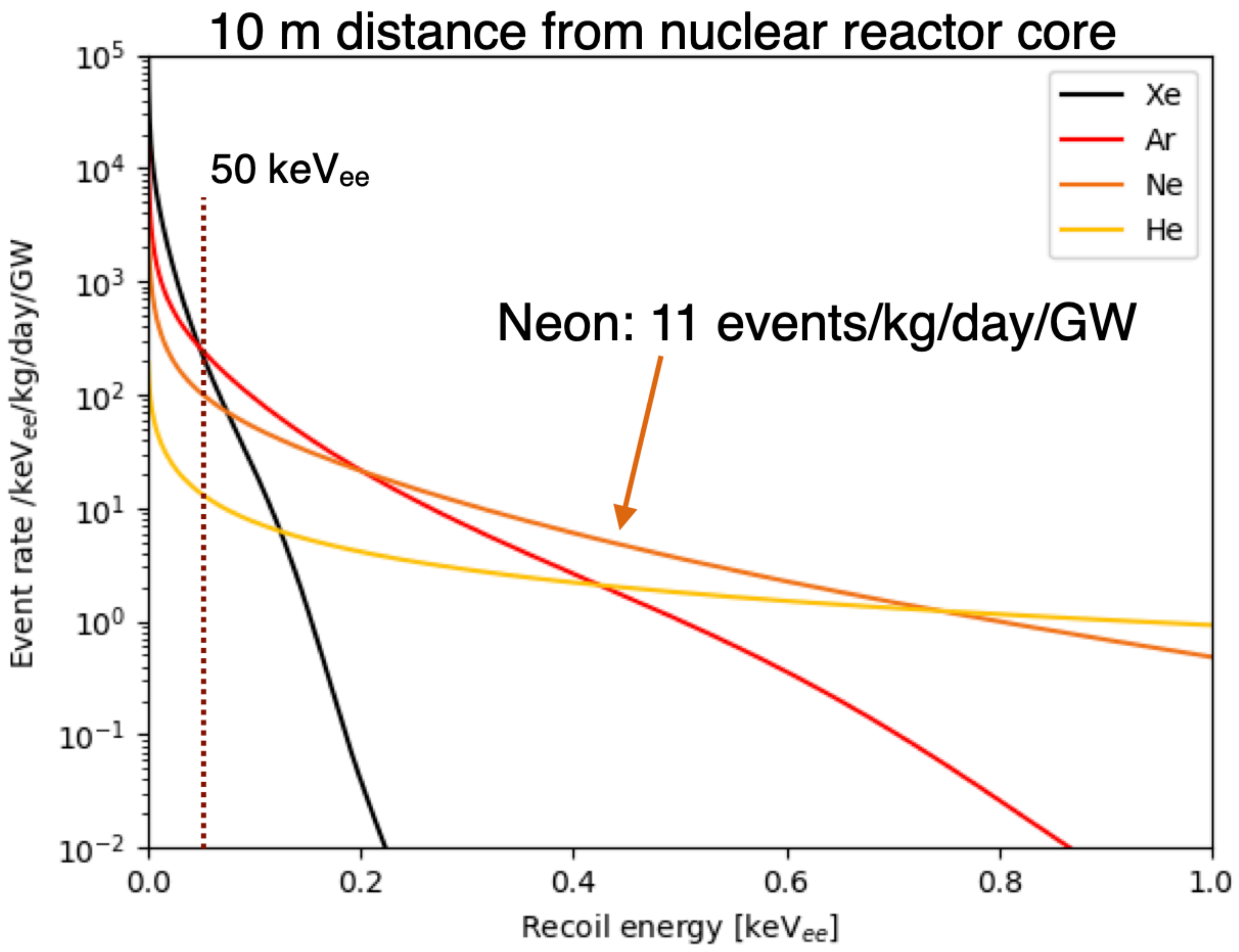
Need for new compact shielding/SPC facility. Design includes active muon veto, shielding alternating PE/Pb layers, and innermost Cu shield. Shielding constructed at Queen's University, prepared for commissioning.




M. Vidal thesis
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# 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

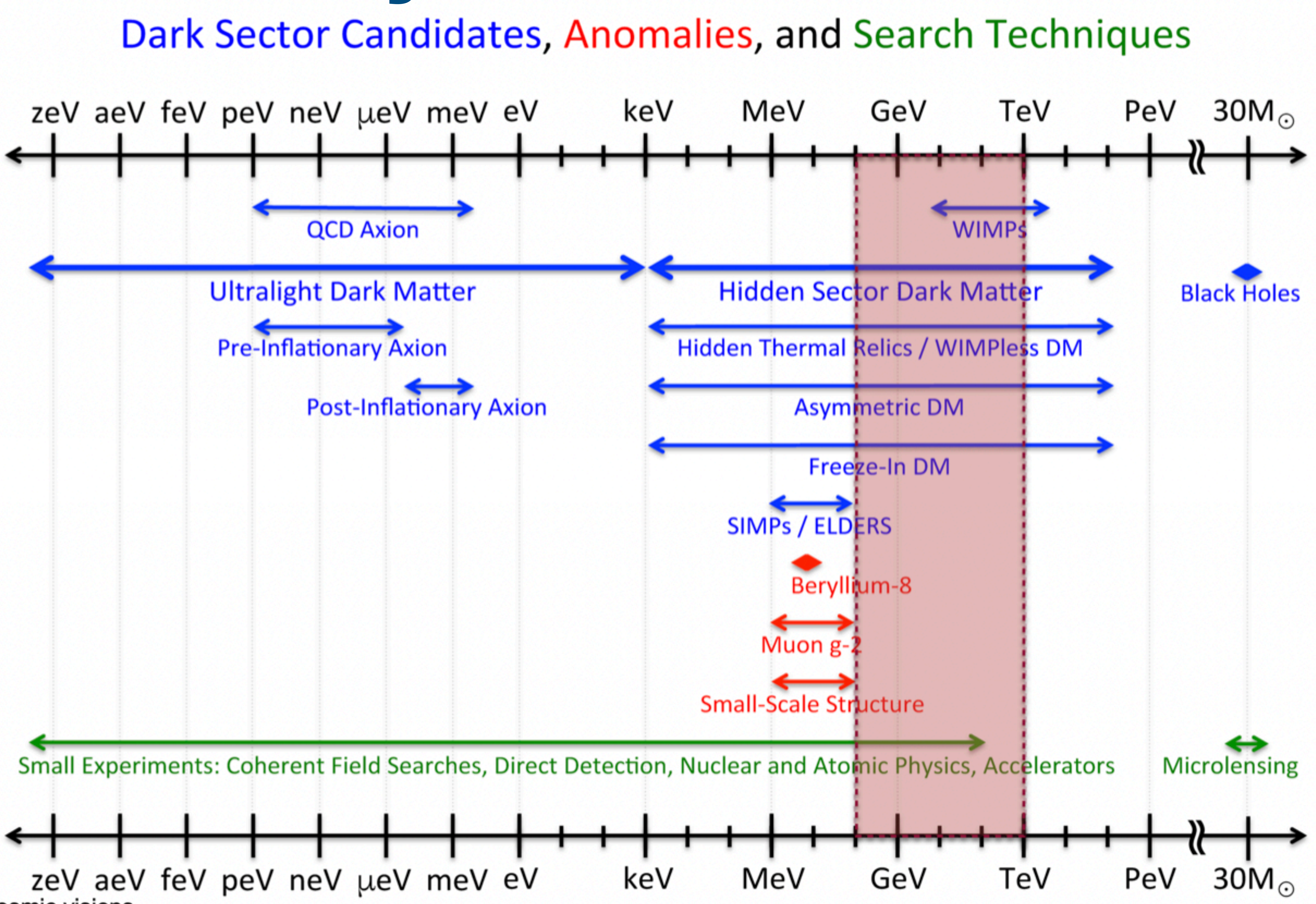
- Physics run at SNOLAB with improved shielding about to start
  - Surface etching already redone

- Beyond S140 : Future projects ECUME & DarkSPHERE

Thank you for your attention!

# Extra slides

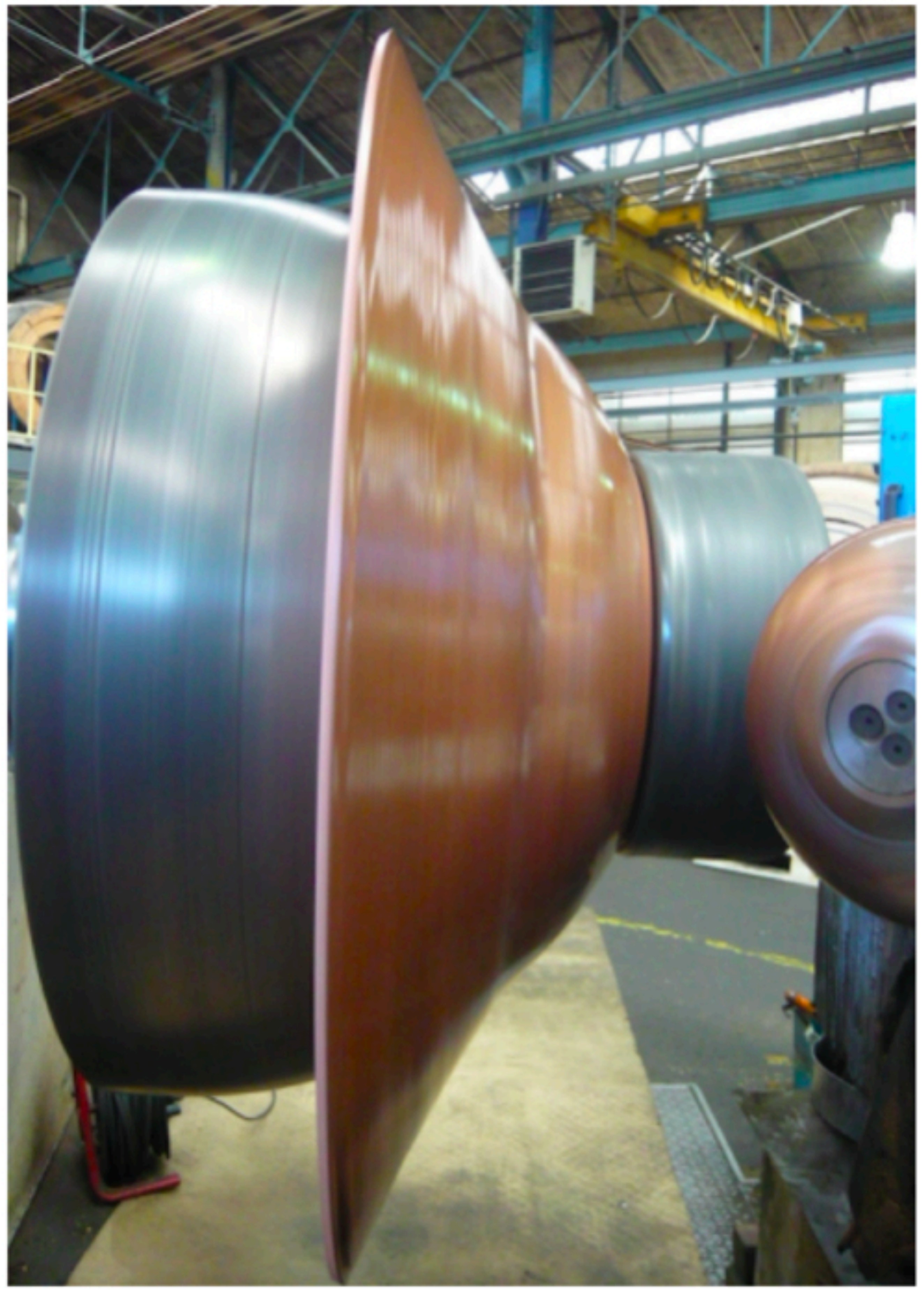
# Dark Matter: beyond WIMPS?



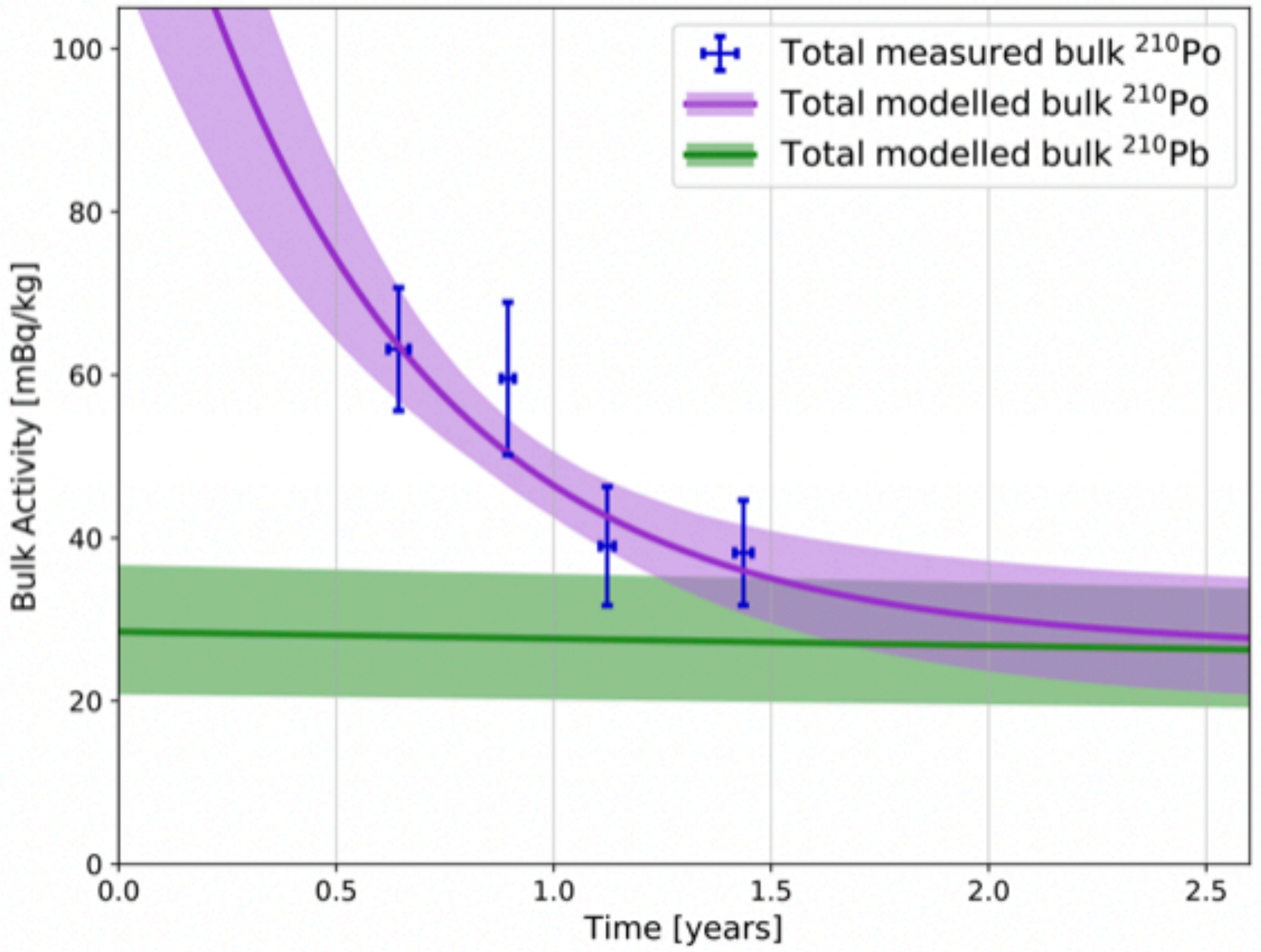

Cosmic visions
arXiv:1707.04591

# S140: Improvements

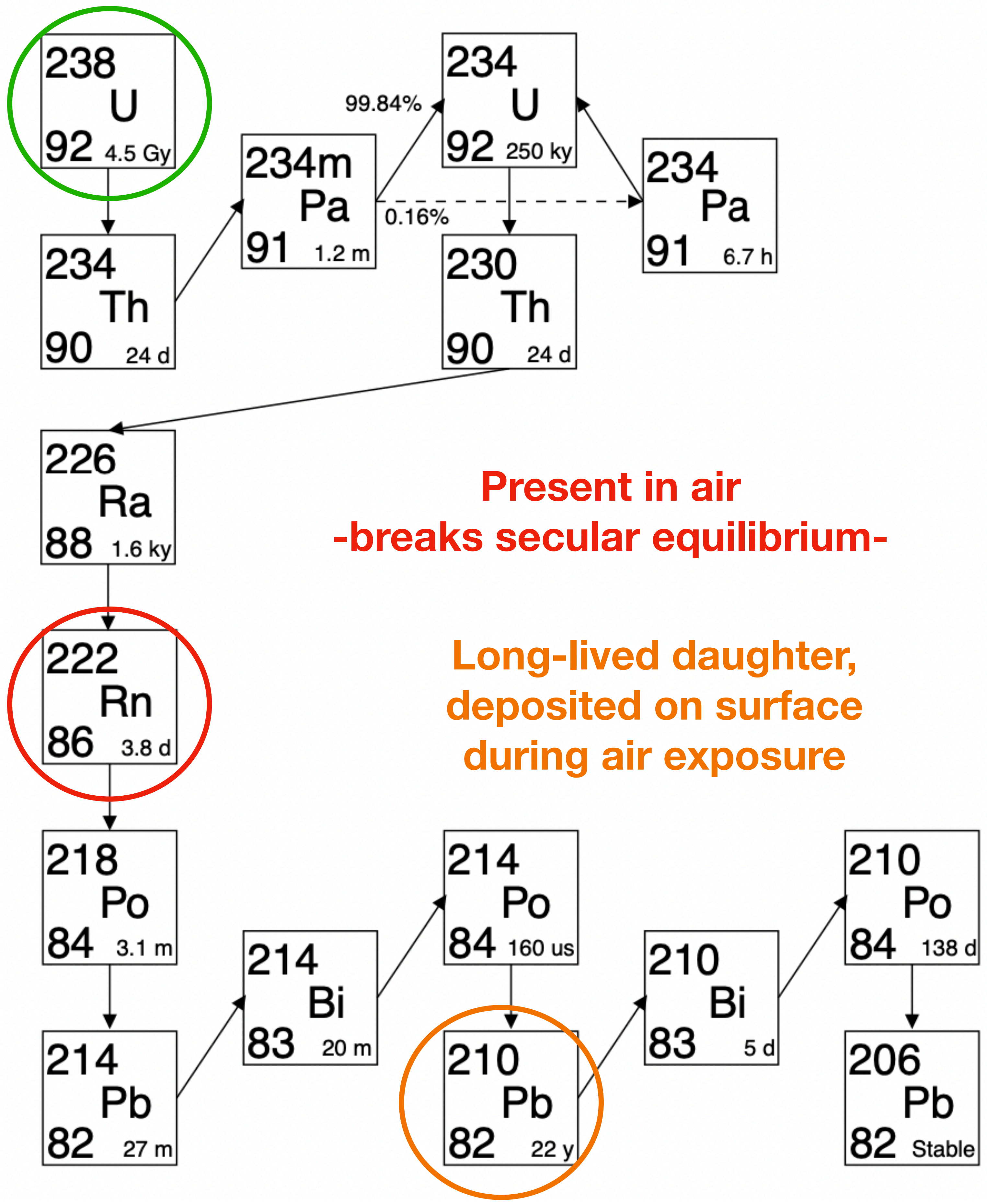
## Background reduction



- 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

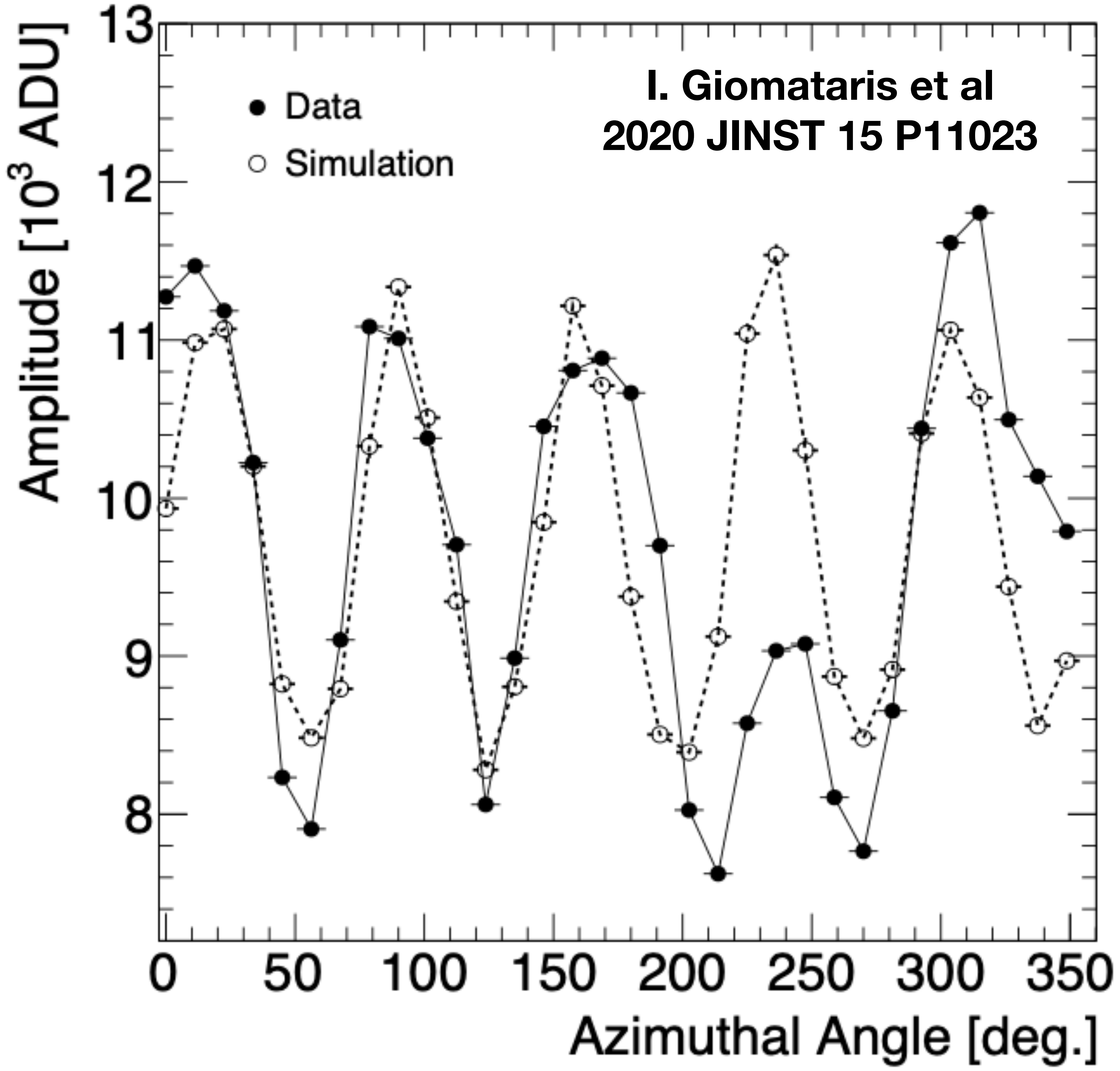



Present in air
-breaks secular equilibrium-

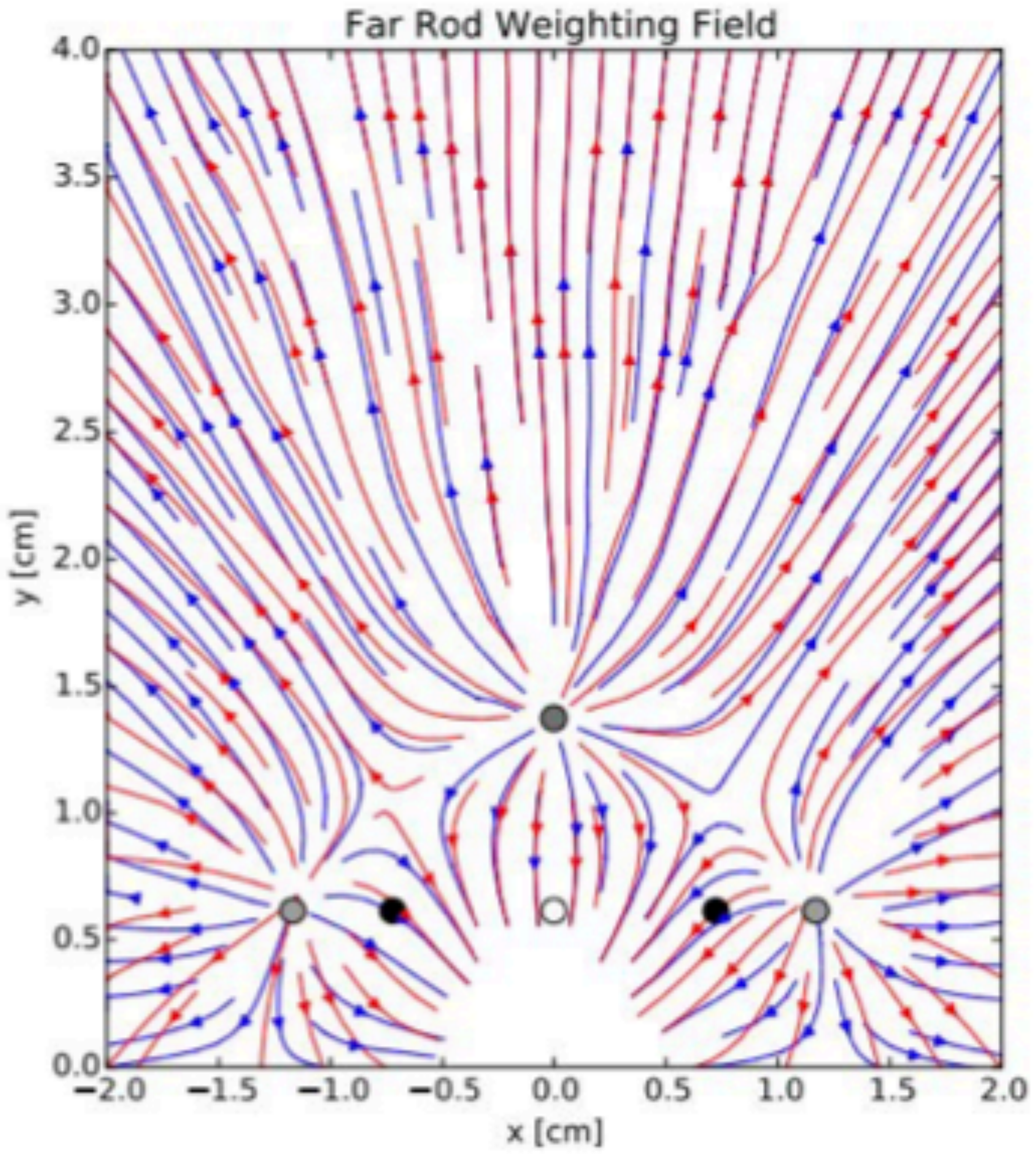
Long-lived daughter, deposited on surface during air exposure

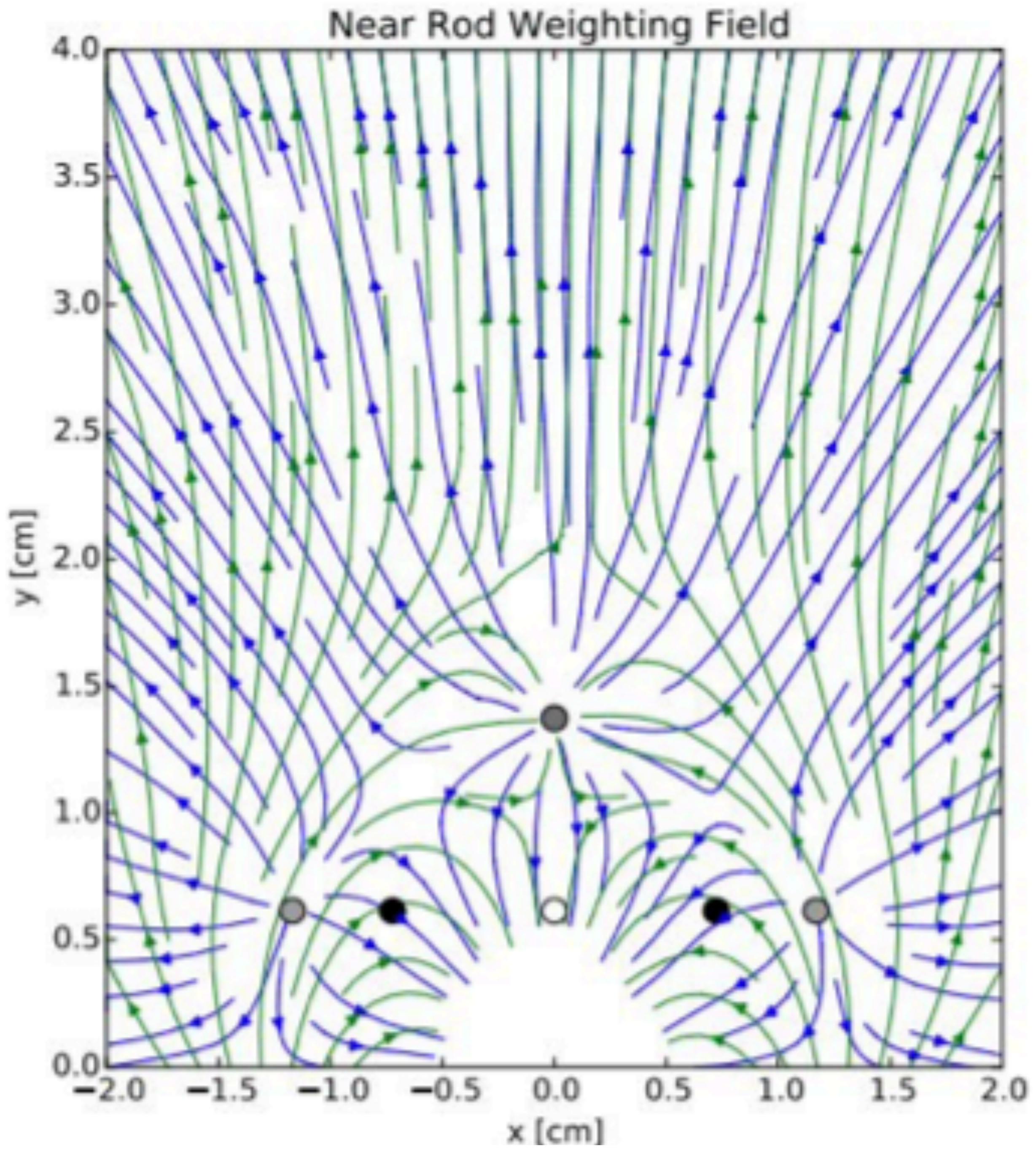
L. Balogh et al, Nucl.Instrum.Meth.A 988 (2021)

# Some simulation plots




- Reproduction of angular variation of gain observed with Fe55 calibration

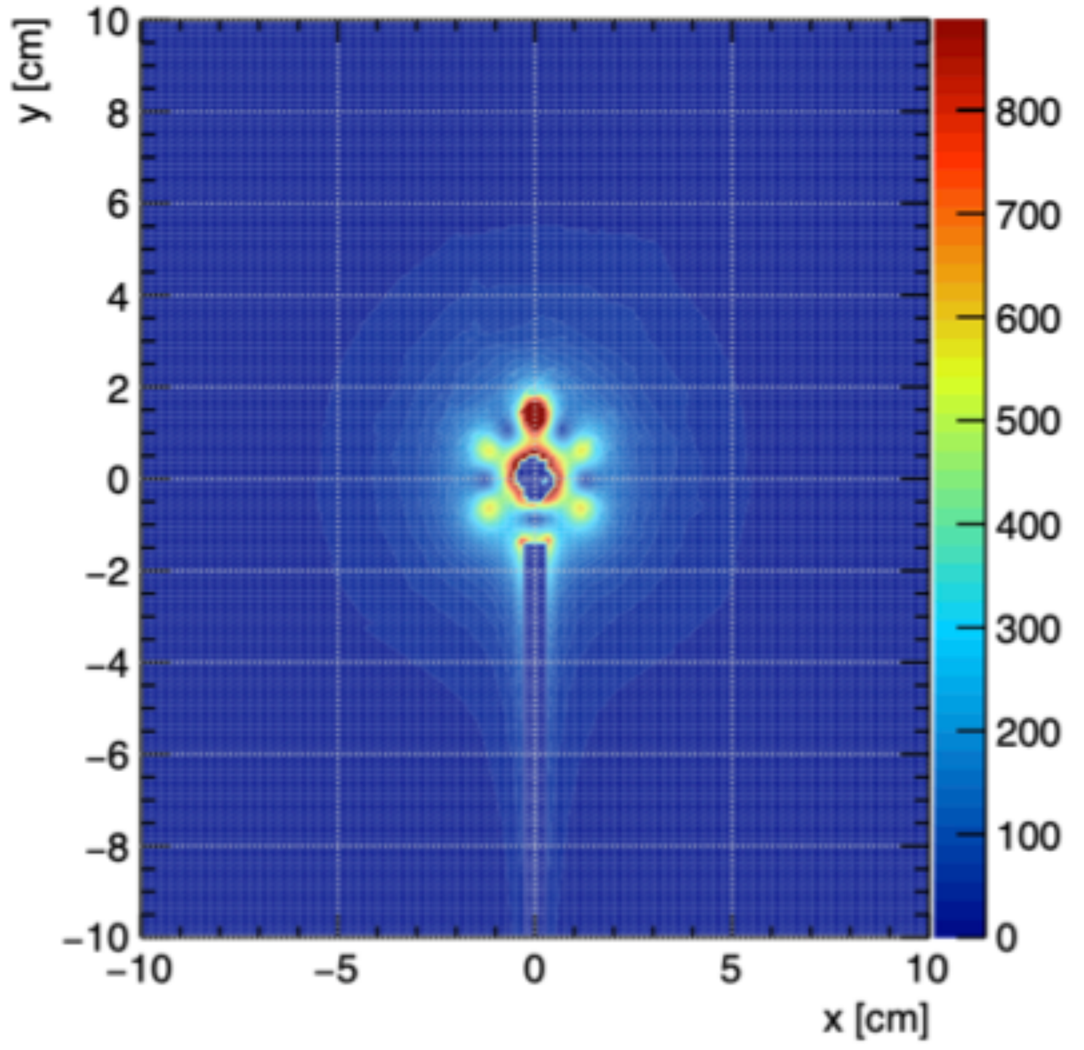



From work described,
but not shown, in:

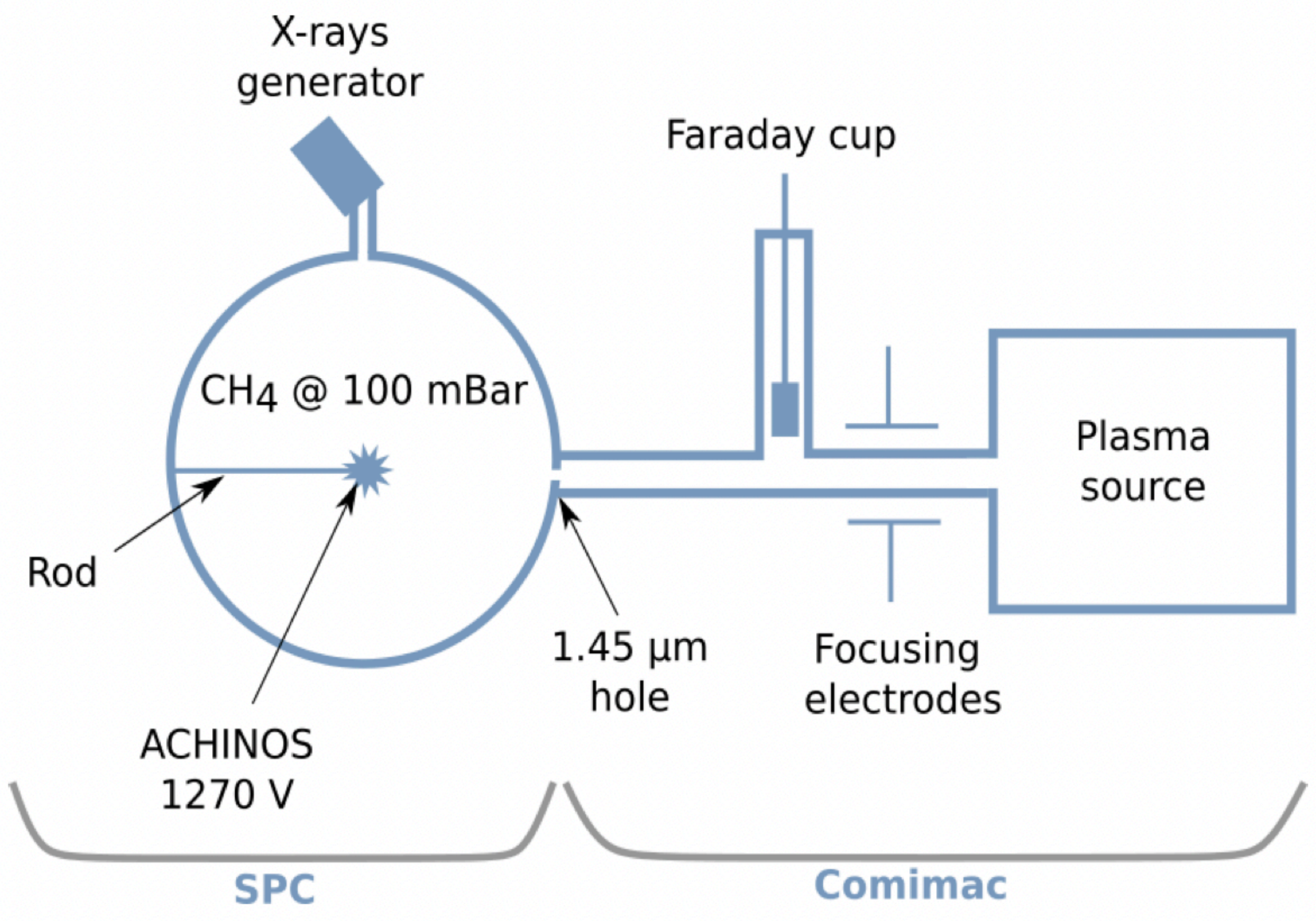
**R. Ward et al 2020 JINST 15 C06013**

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



# QF measurement #1

## COMIMAC, LPSC Grenoble




- **<u>QF: ratio of ionisation energy to total energy deposited by incident particle. Must be known down to ~100 eV to set WIMP limits at 0.1 GeV/c² with NEWS-G</u>**

- COMIMAC generates electrons or ions of known energy by accelerating them in electric field
- Ratio between observed signals for electrons and ions used to determine QF in 0.7-50 keV range

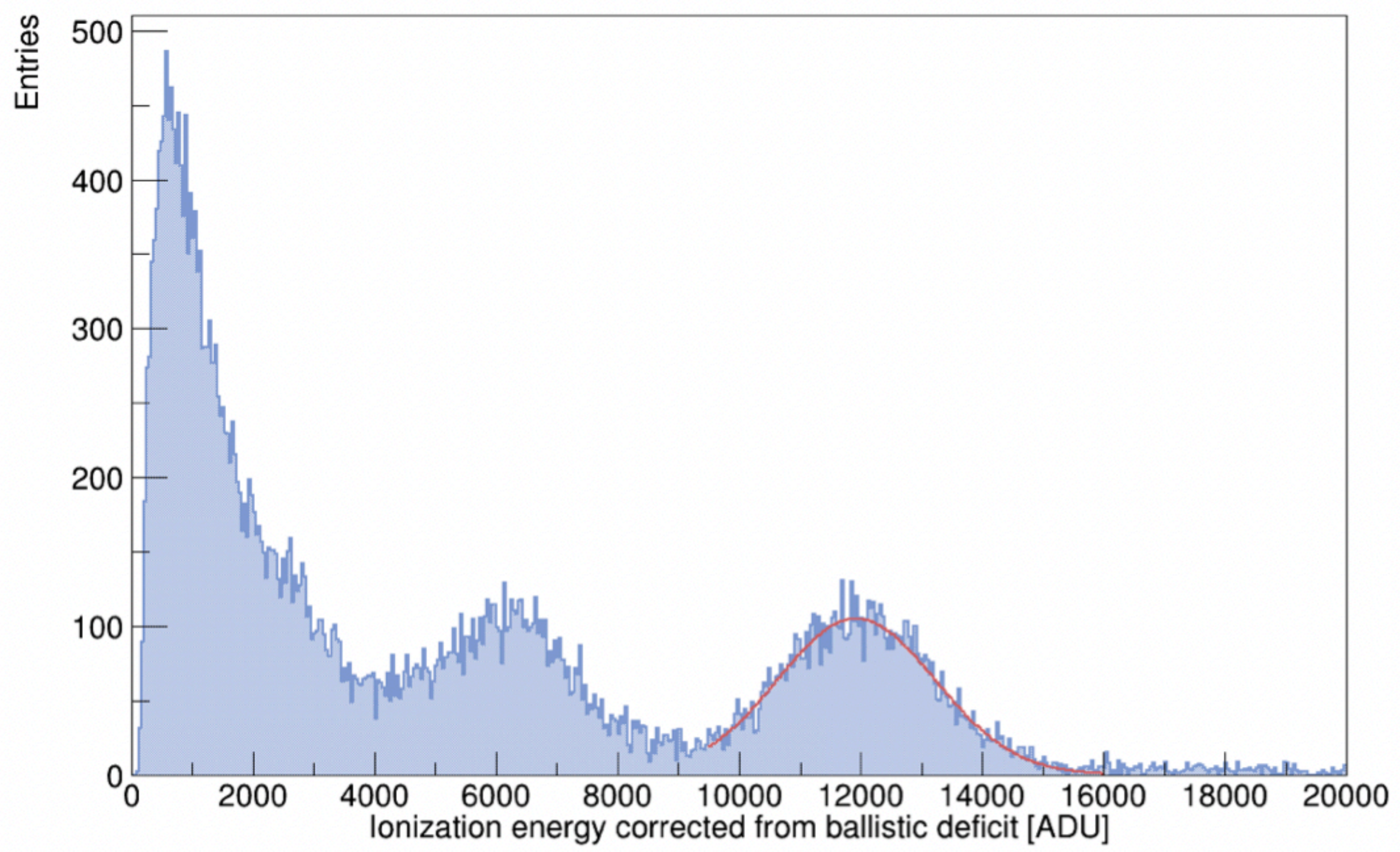
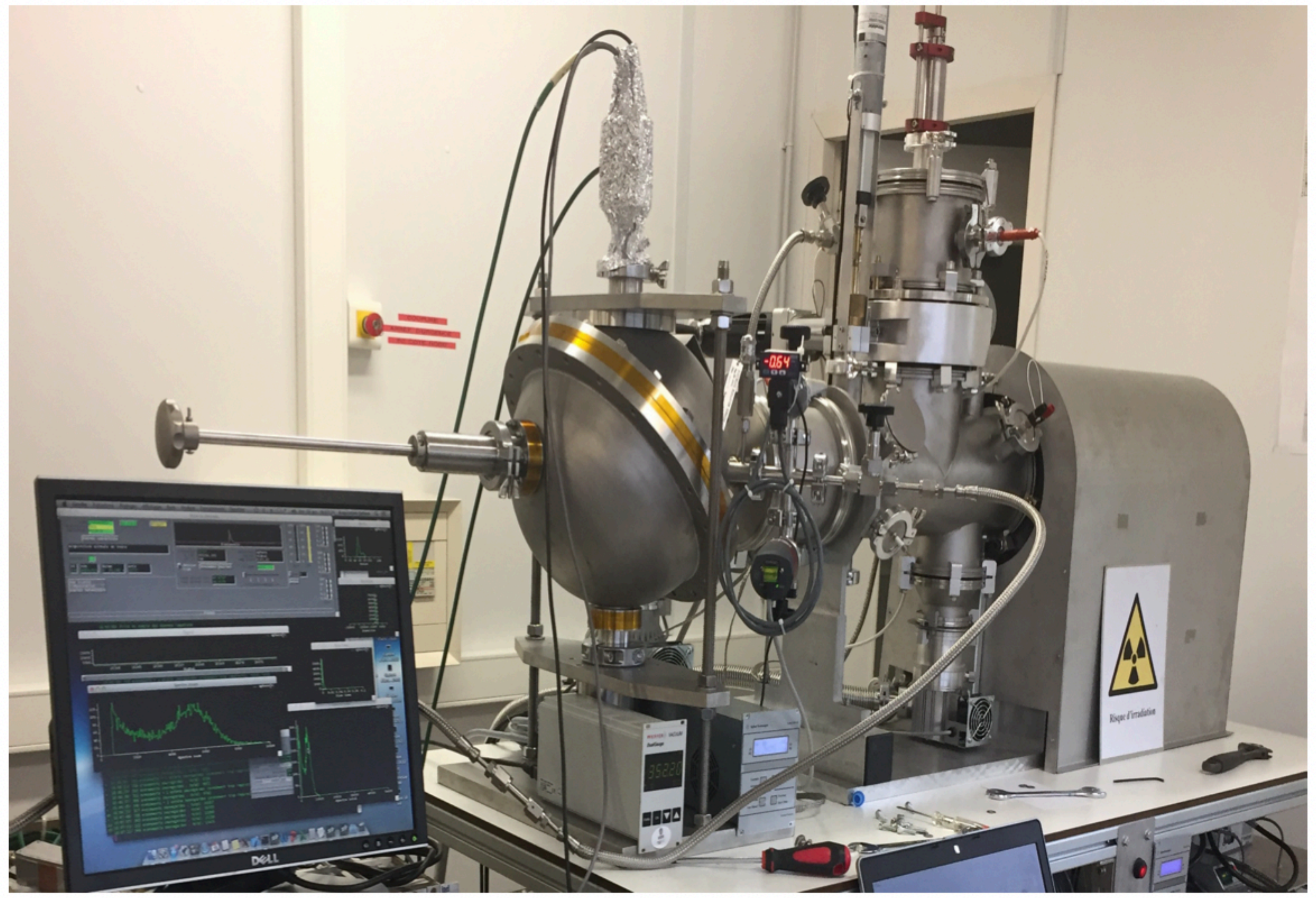



Figure 8: Example of a 5 keV proton spectrum at 1270 V. A Gaussian fit of the proton peak is shown in red.

**QF of H in CH4 in 2-13 keV range: https://arxiv.org/abs/2201.09566, submitted to EPJC**



# QF measurement #2

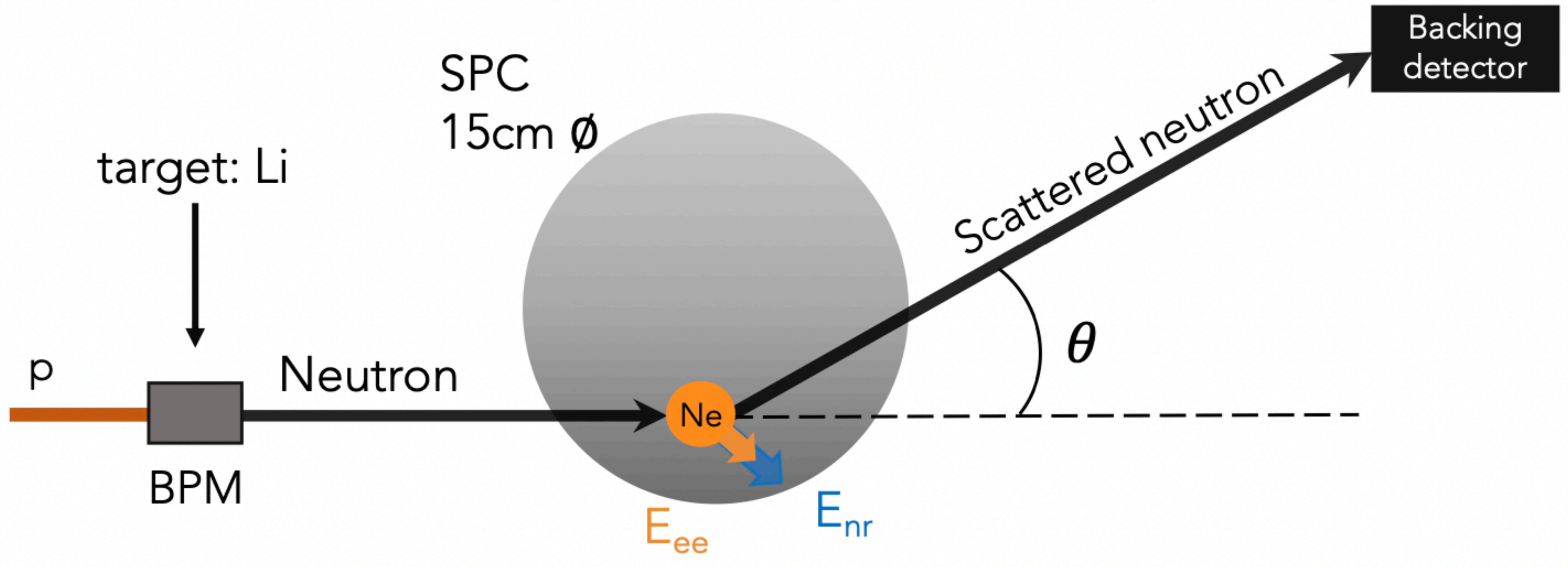
## 545keV neutron beam, TUNL

- Neutron beam of known energy generates recoils on target, emulating WIMP recoil.

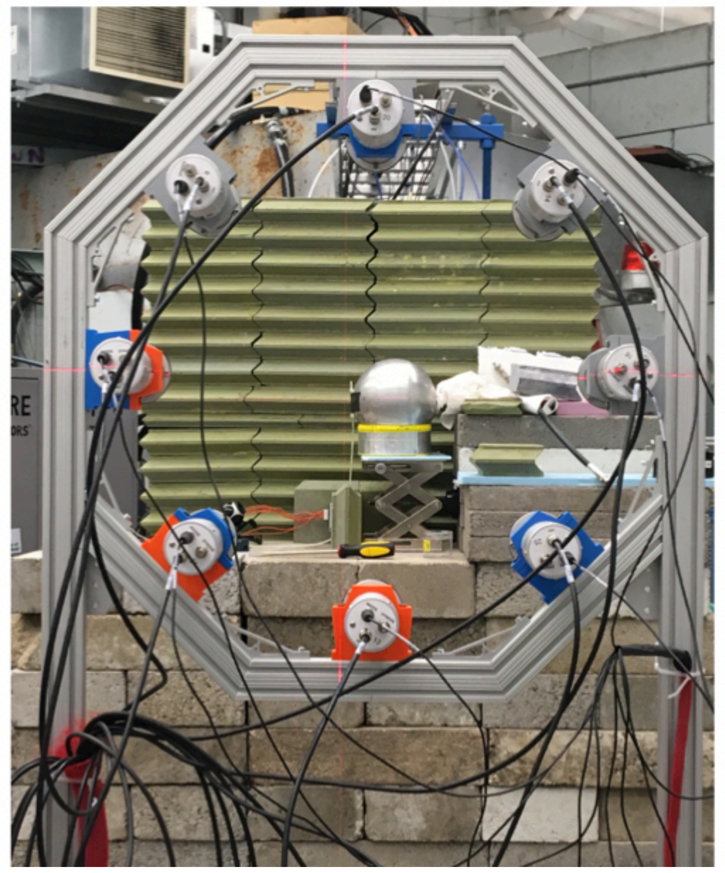
- Backing Detector off neutron beam detects scattered neutron. Angle of BD gives energy deposited in recoil through simple kinematics. Different angles are chosen for different energies.

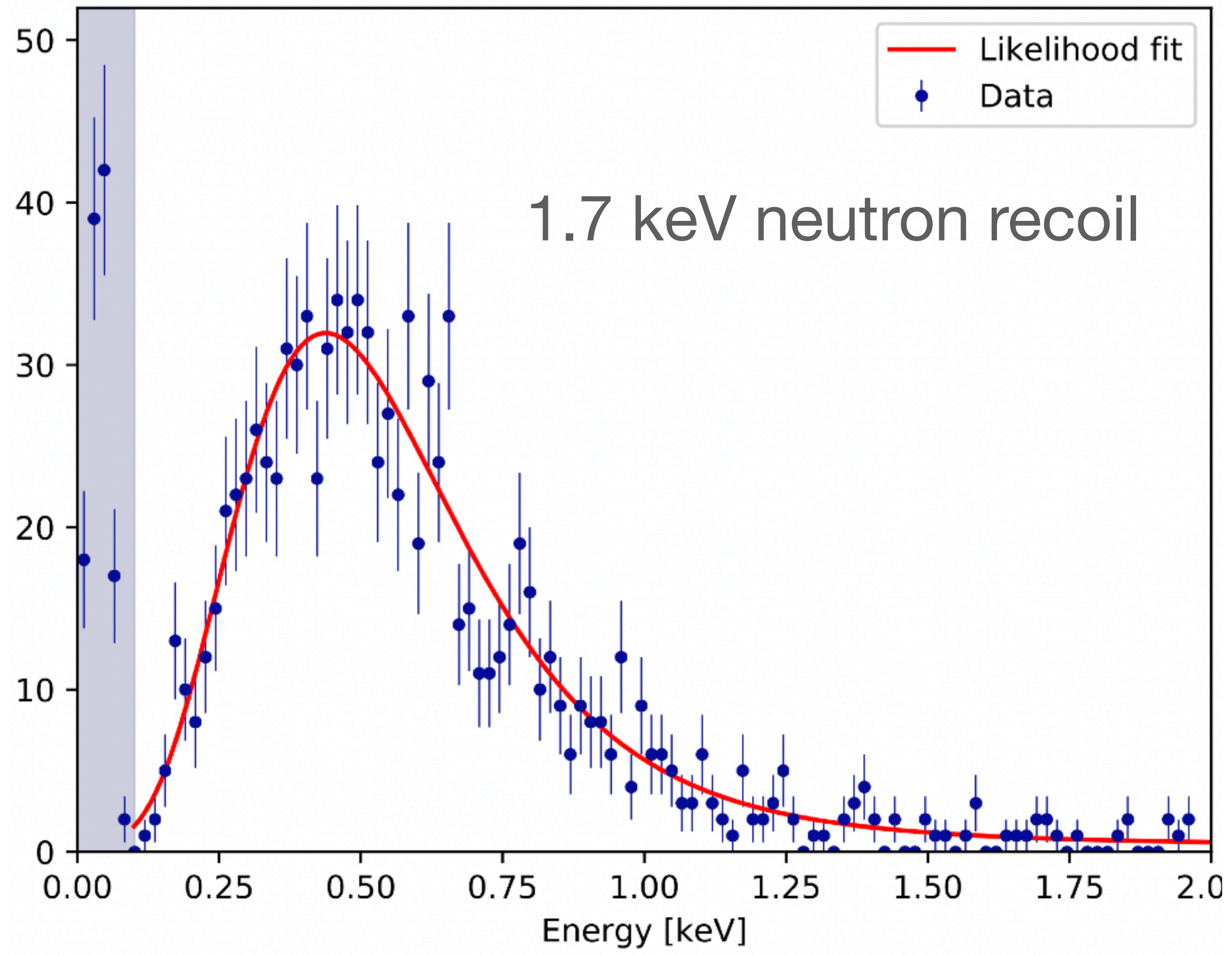
- Comparison with calibration of electronic interactions from $^{55}$Fe used to determine QF.

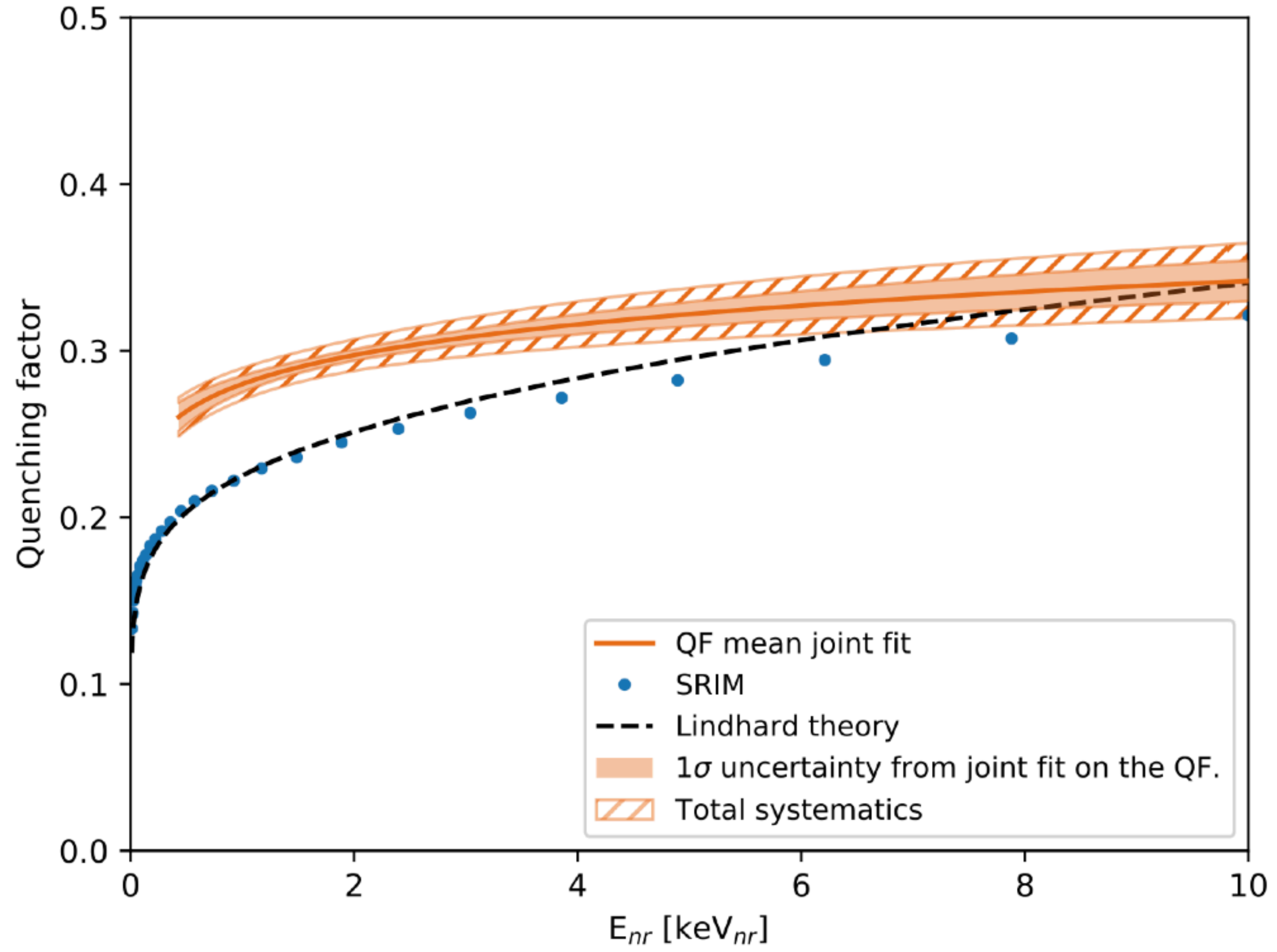
**QF of Ne in Ne+CH4 in 0.43-11 keV range: Phys. Rev. D 105, 052004 (March 2022)**




| Run | $E_{nr}$ [$keV_{nr}$] | $\theta$ [°] |
|---|---|---|
| 8 | 6.8 | 29.02 |
| 7 | 2.93 | 18.84 |
| 14 | 2.02 | 15.63 |
| 9 | 1.7 | 14.33 |
| 10 | 1.3 | 12.48 |
| 14 | 1.03 | 11.13 |
| 11 | 0.74 | 9.4 |
| 14 | 0.34 | 6.33 |





# Time separation

## Random coincidences

- Calibrate with post-alpha-event periods, when total even rate is much higher
- Match well behaviour of toy model assuming random coincidences, after accounting for peak-search window size and centering effects