# The DarkSide Experimental Program: Dark Matter detection with Argon targets

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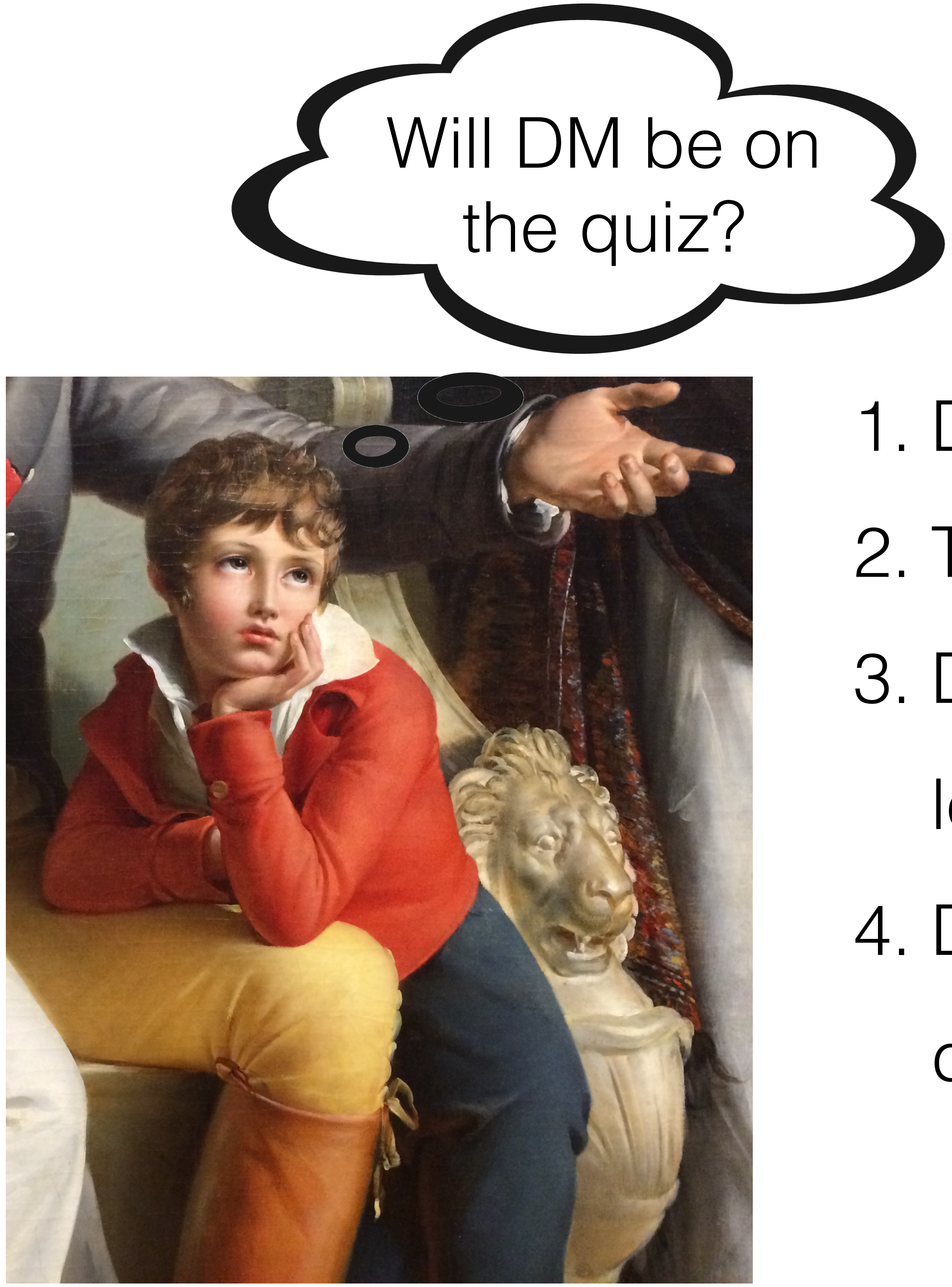
*on behalf of the Global Argon Dark Matter Collaboration*

Princeton University

*PASCOS2023*
*UC Irvine, June 28th 2023*

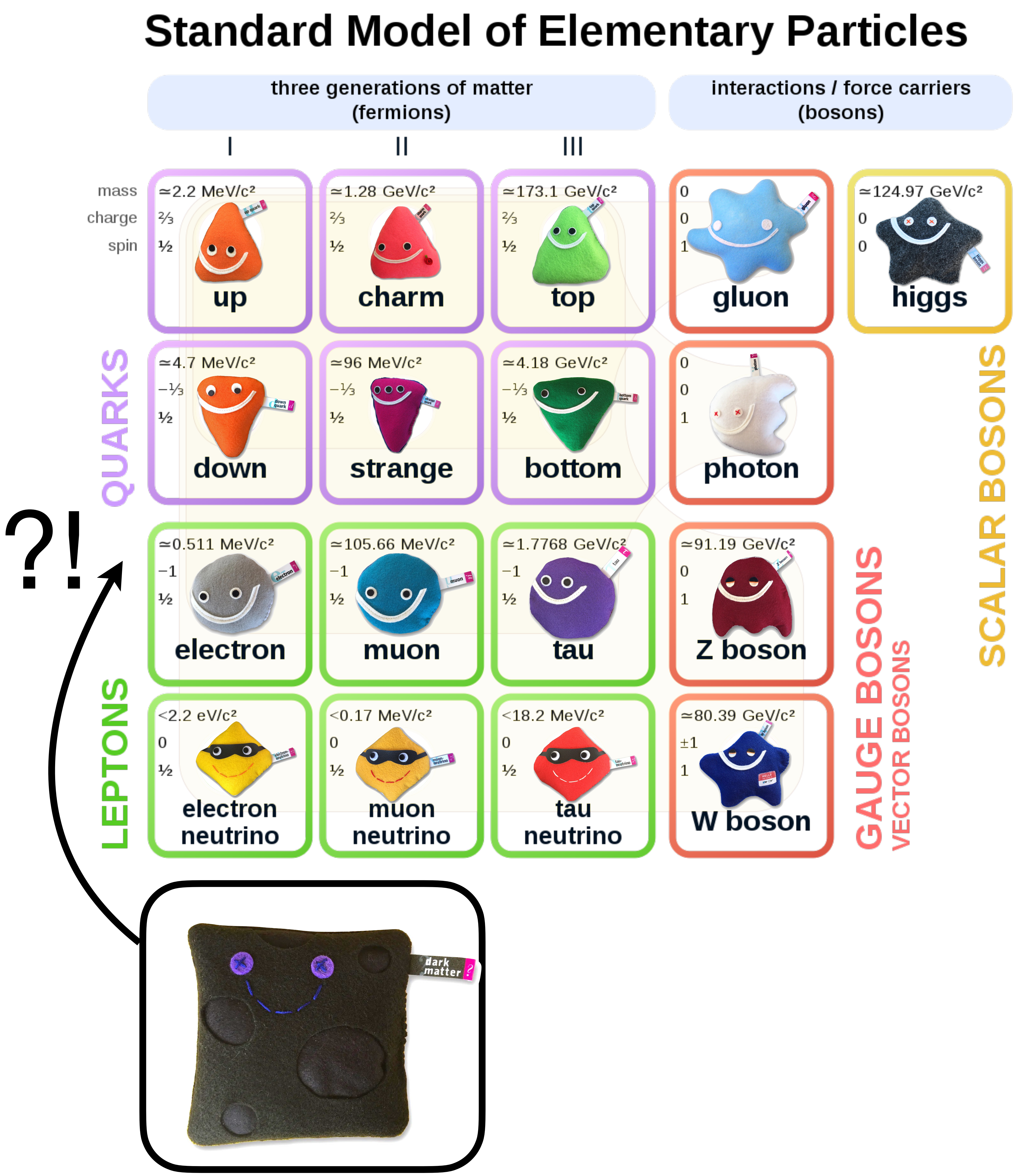
# Overview



1. Dark Matter detection 101
2. The DarkSide Program
3. DarkSide-50:

   low-mass searches
4. DarkSide-20k:

   design and physics reach



# Is something missing?

CMB

Galactic clusters

Galaxies

Multipole expansion

CMB thermal anisotropies

Galaxy velocities

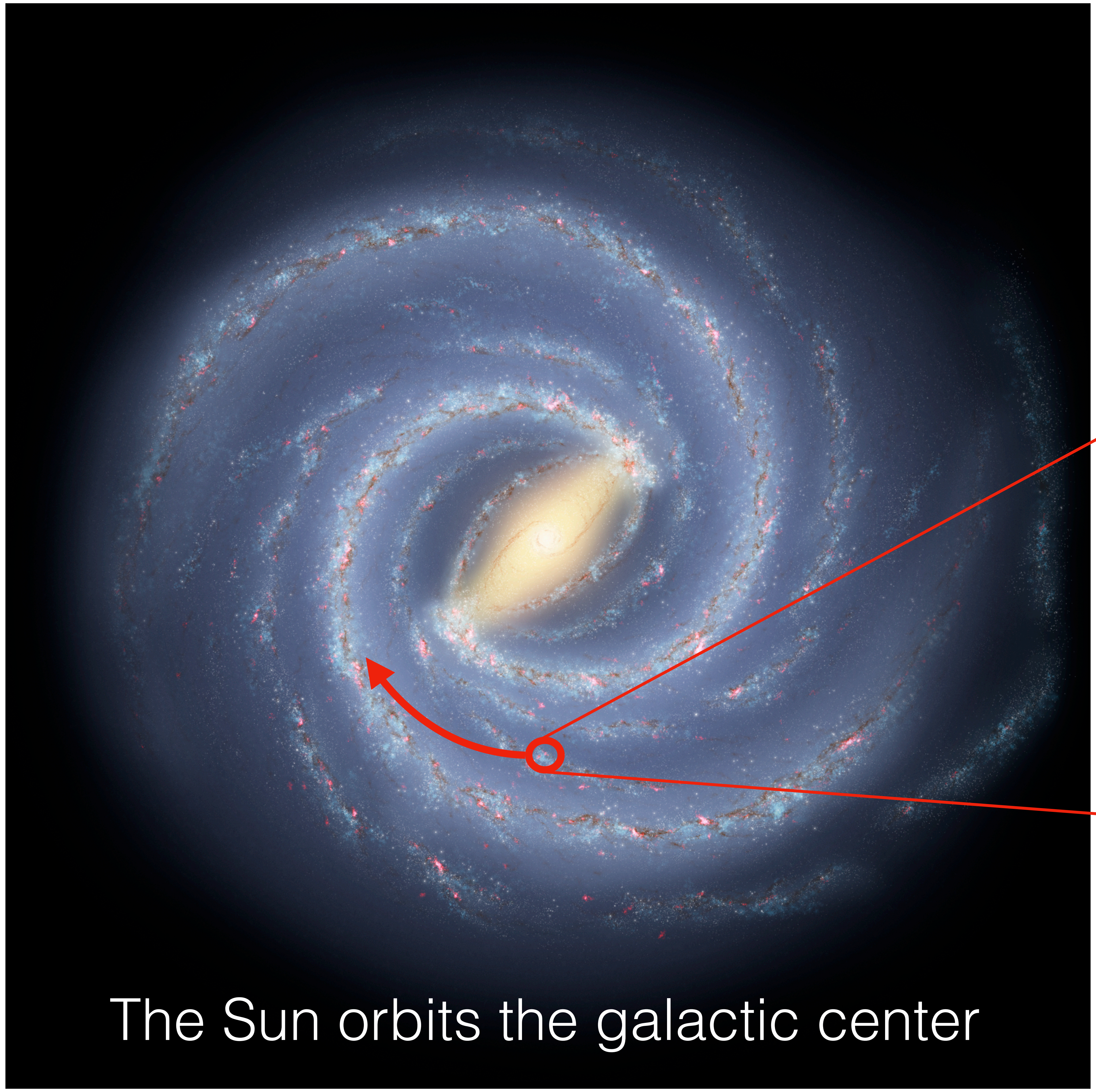
Gravitational lensing (Bullet)

Rotation curves

Gravitational lensing

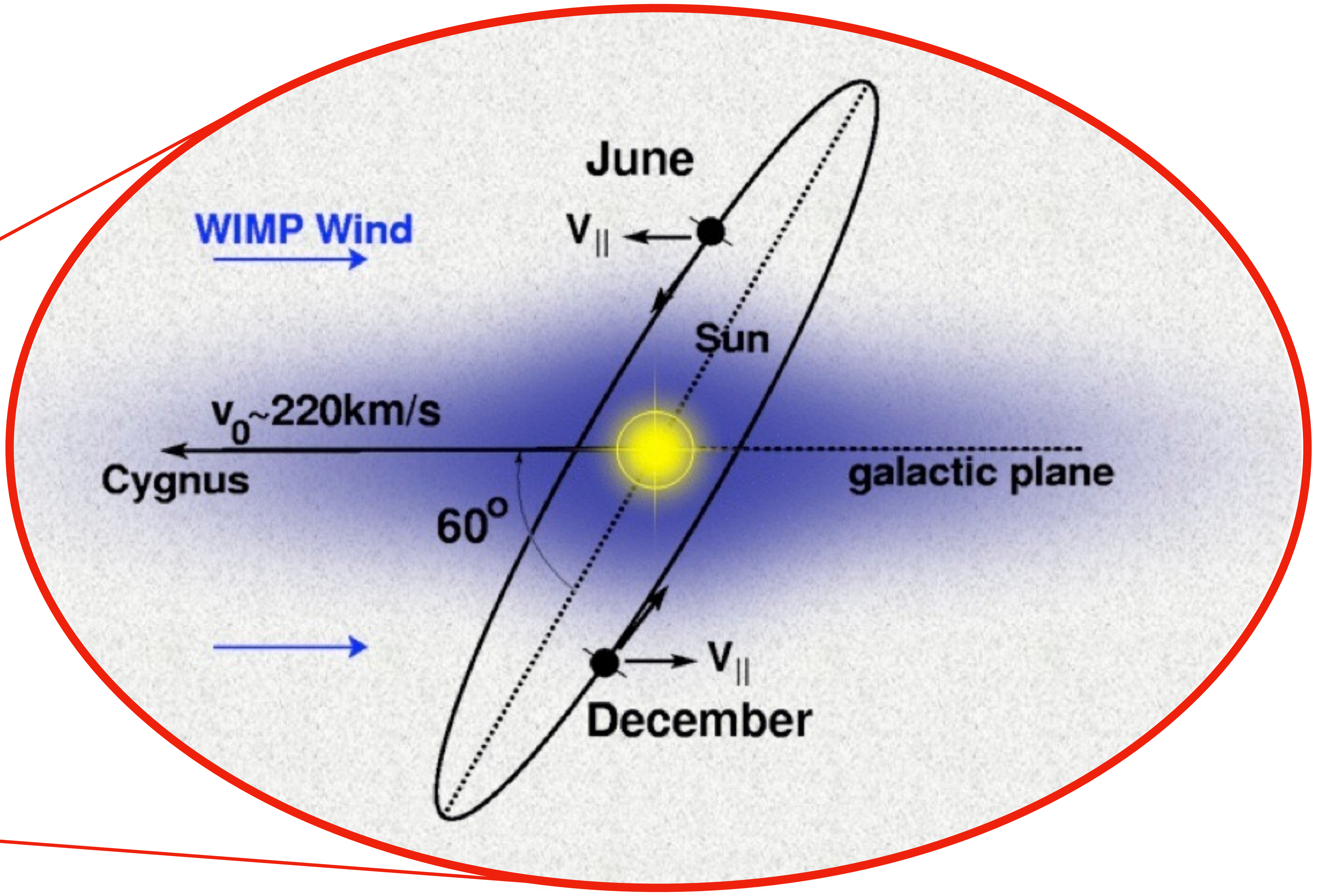
**Compelling evidence at all scales**

# WIMP Wind



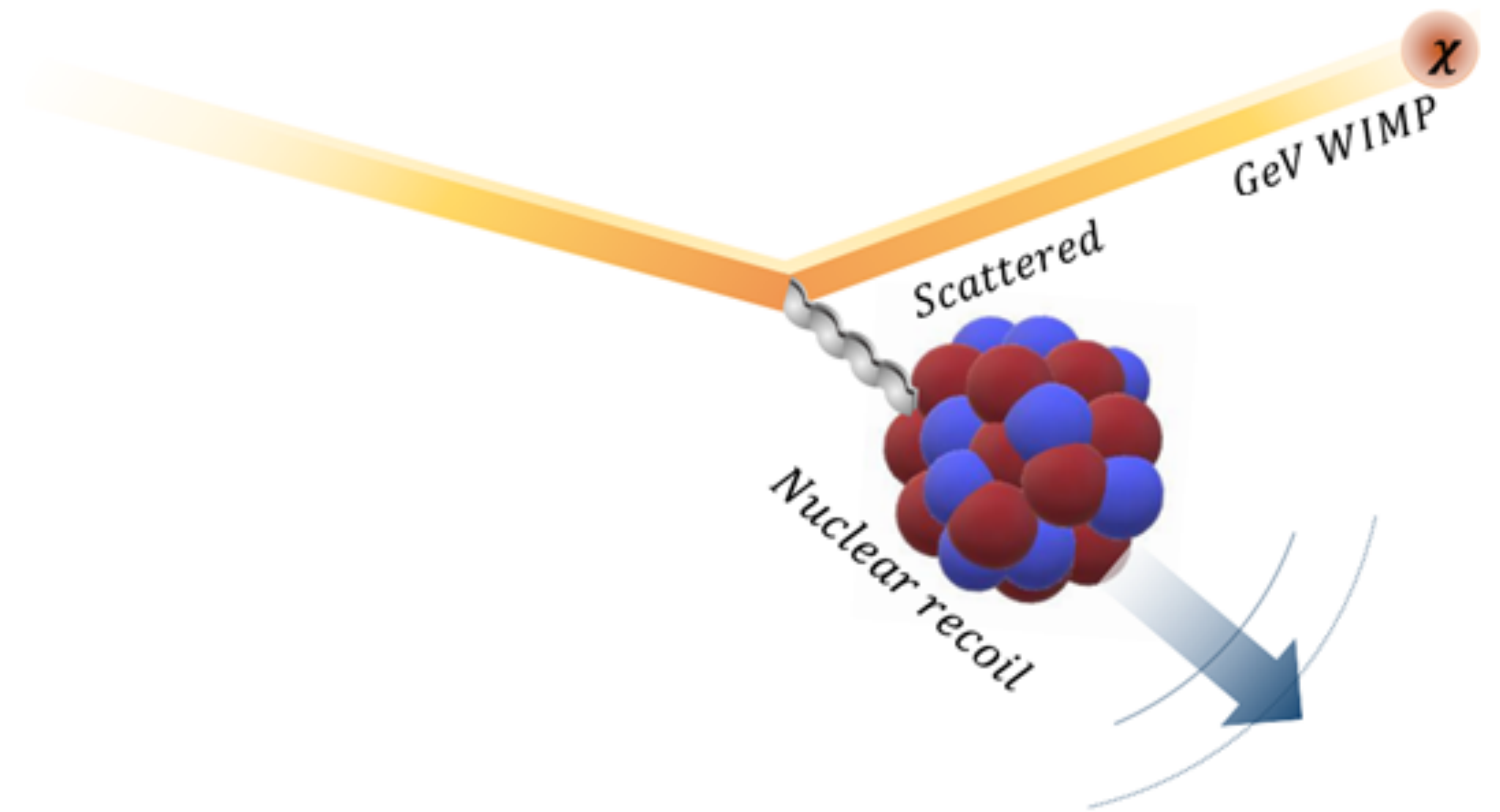
The Sun orbits the galactic center

“Gas” of WIMPs



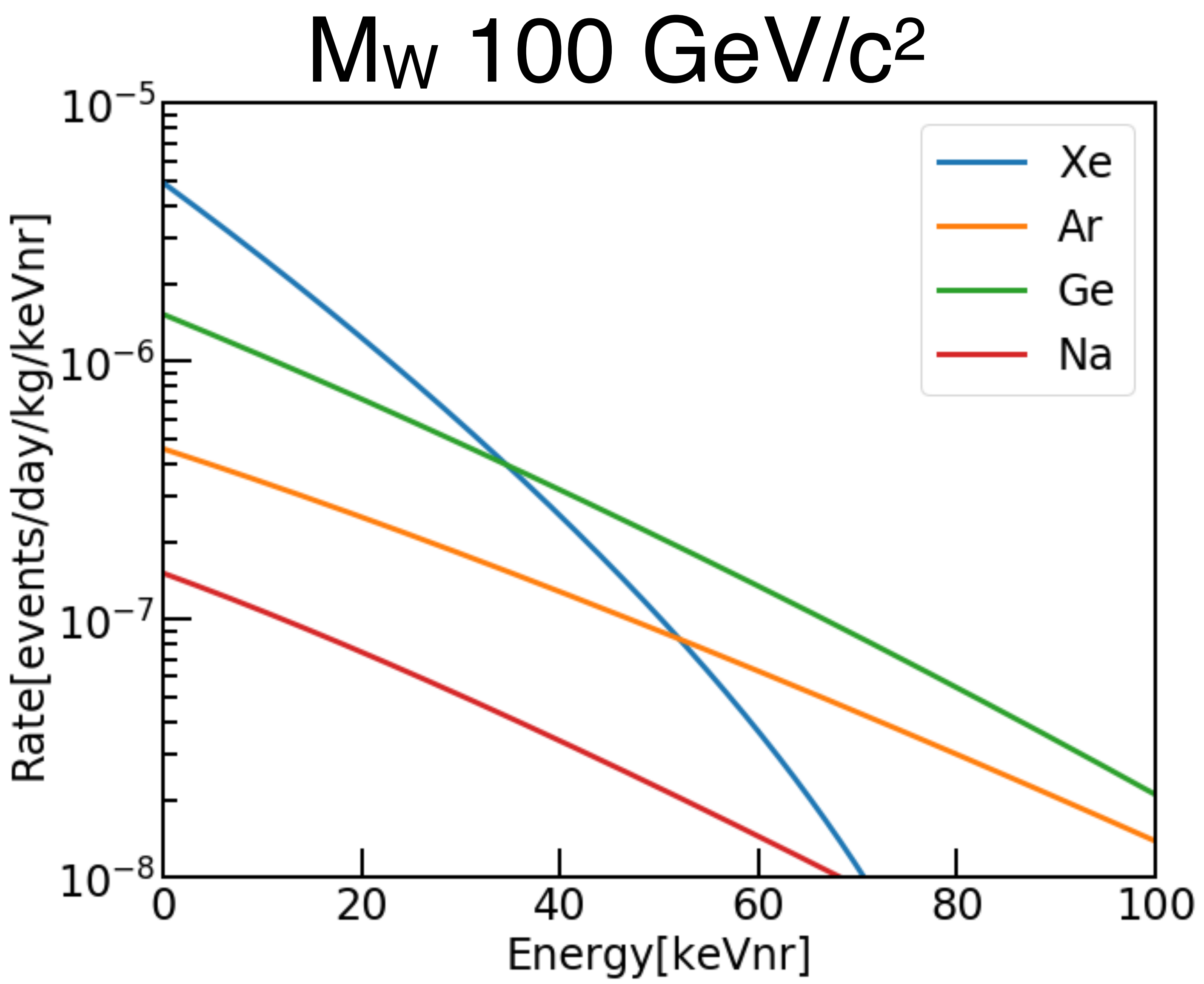
The Sun moves through a WIMP “gas”
“WIMP wind” on Earth

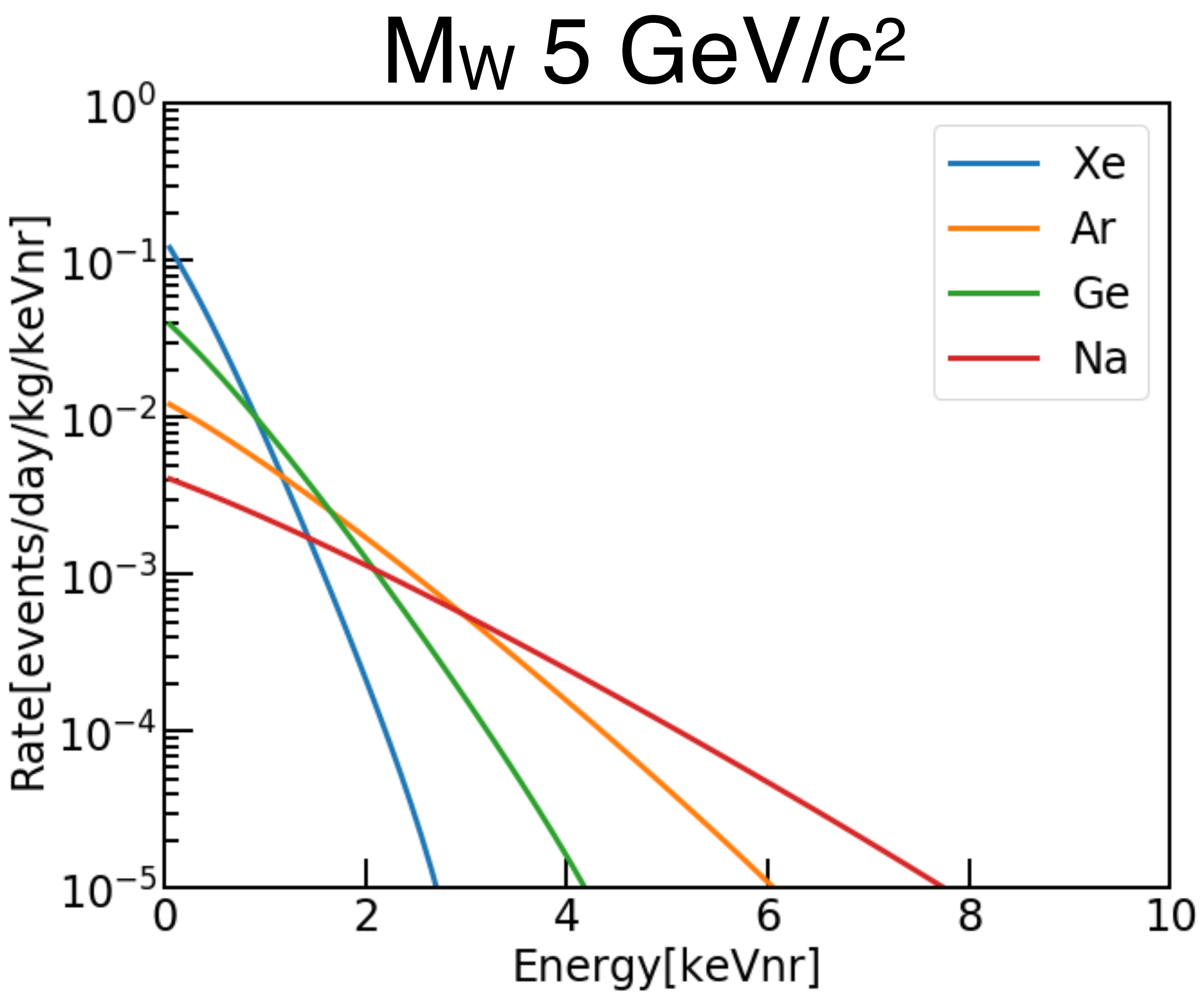
# WIMP Signal



- Non relativistic regime (v << c)
- Coherent scattering enhancement ($A^2$)
- **Signal: nuclear recoils (NR)**
- Rate exponential in obs. energy

$$\frac{dR}{dE_r} = \frac{MT}{2m_W\mu_N^2} \times \underbrace{\boxed{\sigma_{Wn}}}_{\text{Particle physics}} \times \frac{\mu_N^2}{\mu_p} A^2 \times \underbrace{\boxed{F^2(E_r)}}_{\text{Nuclear physics}} \times \underbrace{\boxed{\rho_0 \times \int_{v_{min}}^{v_{max}} \frac{f(\vec{v})}{v} d^3v}}_{\text{Astrophysics}}$$


$M_W$ 100 GeV/c²


$M_W$ 5 GeV/c²

High $M_W$
- Low number density ✘
- High recoil energies ✔
- High A target ✔

Low $M_W$
- High number density ✔
- Low recoil energies ✘
- Low A target ✘

# Liquefied Noble Elements

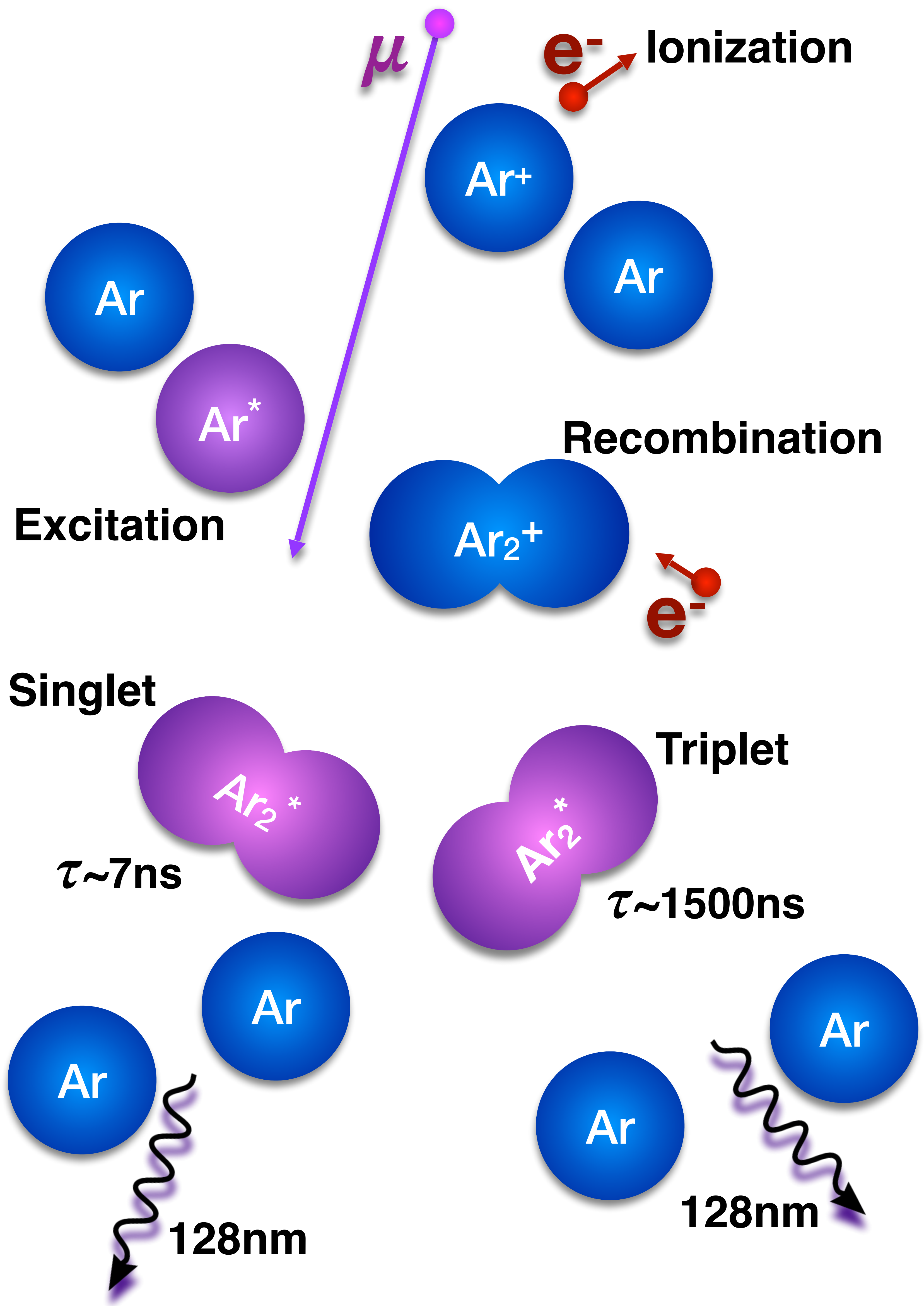
- WIMP DM signal: nuclear recoils (NR)
- Electron Recoils (ER) are background

- High density ✔
  - Self screening
  - Good scalability
- Easy(-ish) purification, also online ✔
- Target Excitation:
  - Scintillation ✔
  - Ionization ✔
- ER (background) rejection ✔
- NR quenching at low energies ✘

| | | *LAr* | *LKr* | *LXe* |
|---|---|---|---|---|
| Physical properties | Atomic number | 18 | 36 | 54 |
| | Boiling point at 1 bar, $T_b$ (K) | 87.3 | 119.8 | 165.0 |
| | Density at $T_b$ ($g/cm^3$) | 1.40 | 2.41 | 2.94 |
| Ionisation | W (eV)[1] | 23.6 | 20.5 | 15.6 |
| | Fano factor | 0.11 | ~0.06 | 0.041 |
| | Drift velocity (cm/$\mu$s) at 3 kV/cm | 0.30 | 0.33 | 0.26 |
| | Transversal diffusion coefficient at 1 kV/cm ($cm^2/s$) | ~20 | | ~80 |
| Scintillation | Decay time[2], fast (ns) | 5 | 2.1 | 2.2 |
| | slow (ns) | 1000 | 80 | 27/45 |
| | Emission peak (nm) | 127 | 150 | 175 |
| | Light yield[2] (phot./Mev) | 40000 | 25000 | 42000 |
| | Radiation length (cm) | 14 | 4.7 | 2.8 |
| | Moliere radius (cm) | 10.0 | 6.6 | 5.7 |

Excellent discrimination power!

# ER rejection in liquid argon



$\mu$

$e^-$ Ionization

$Ar^+$

Ar

Ar

$Ar^*$

Excitation

Recombination

$Ar_2^+$

$e^-$

Singlet

$Ar_2^*$

$\tau$~7ns

Triplet

$Ar_2^*$

$\tau$~1500ns

Ar

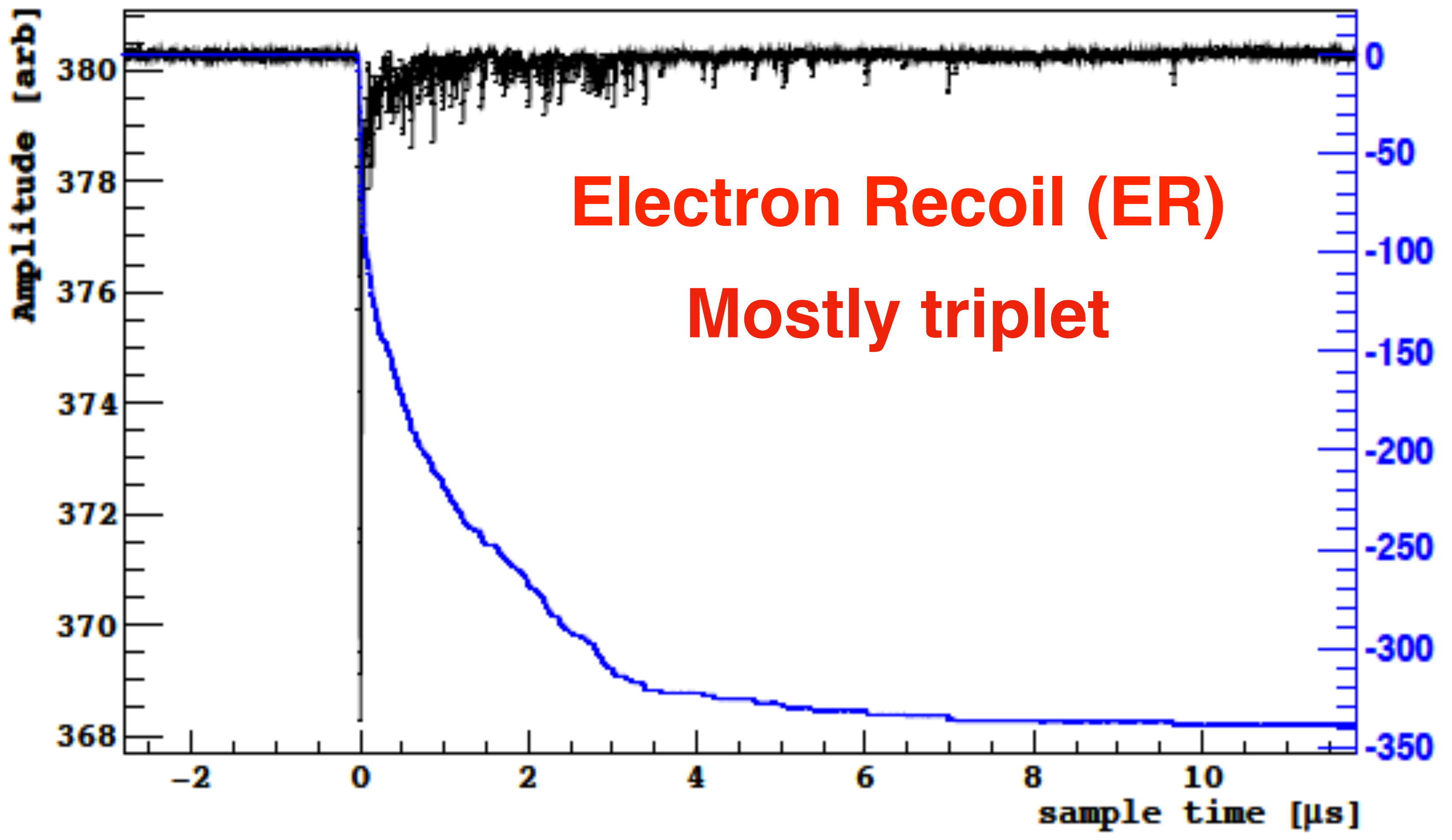
Ar

Ar

Ar

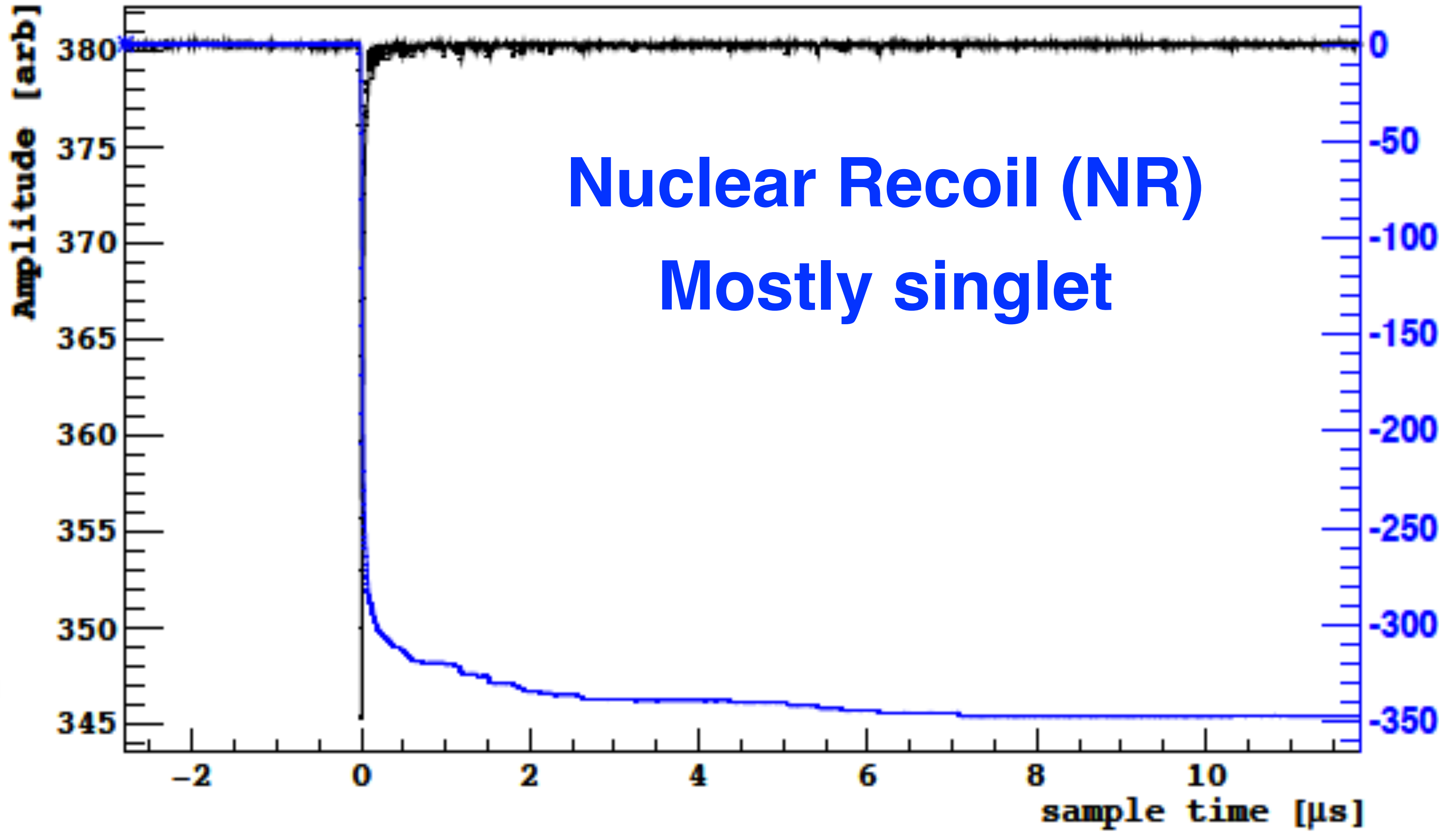
128nm

128nm



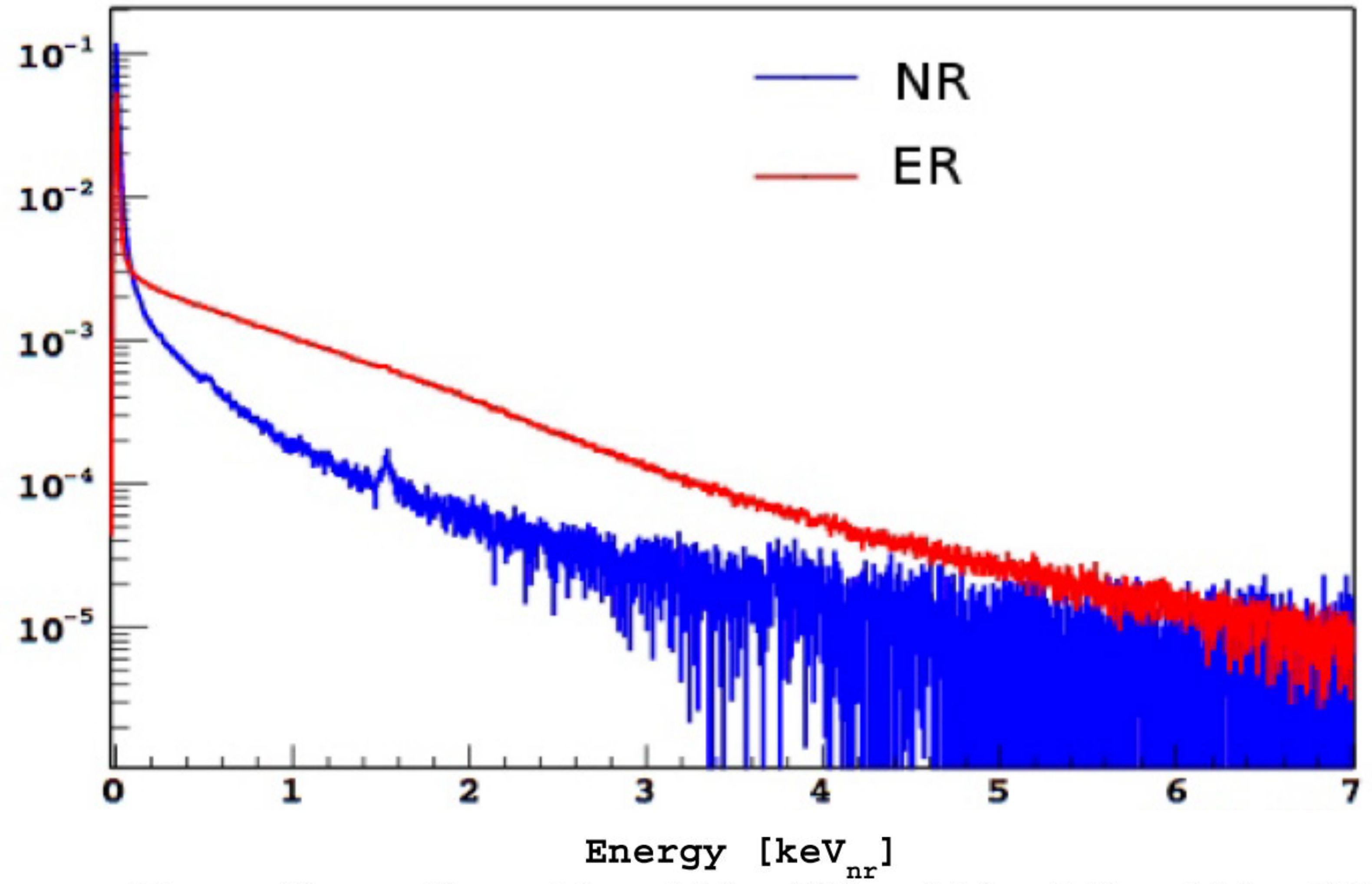
Electron Recoil (ER)

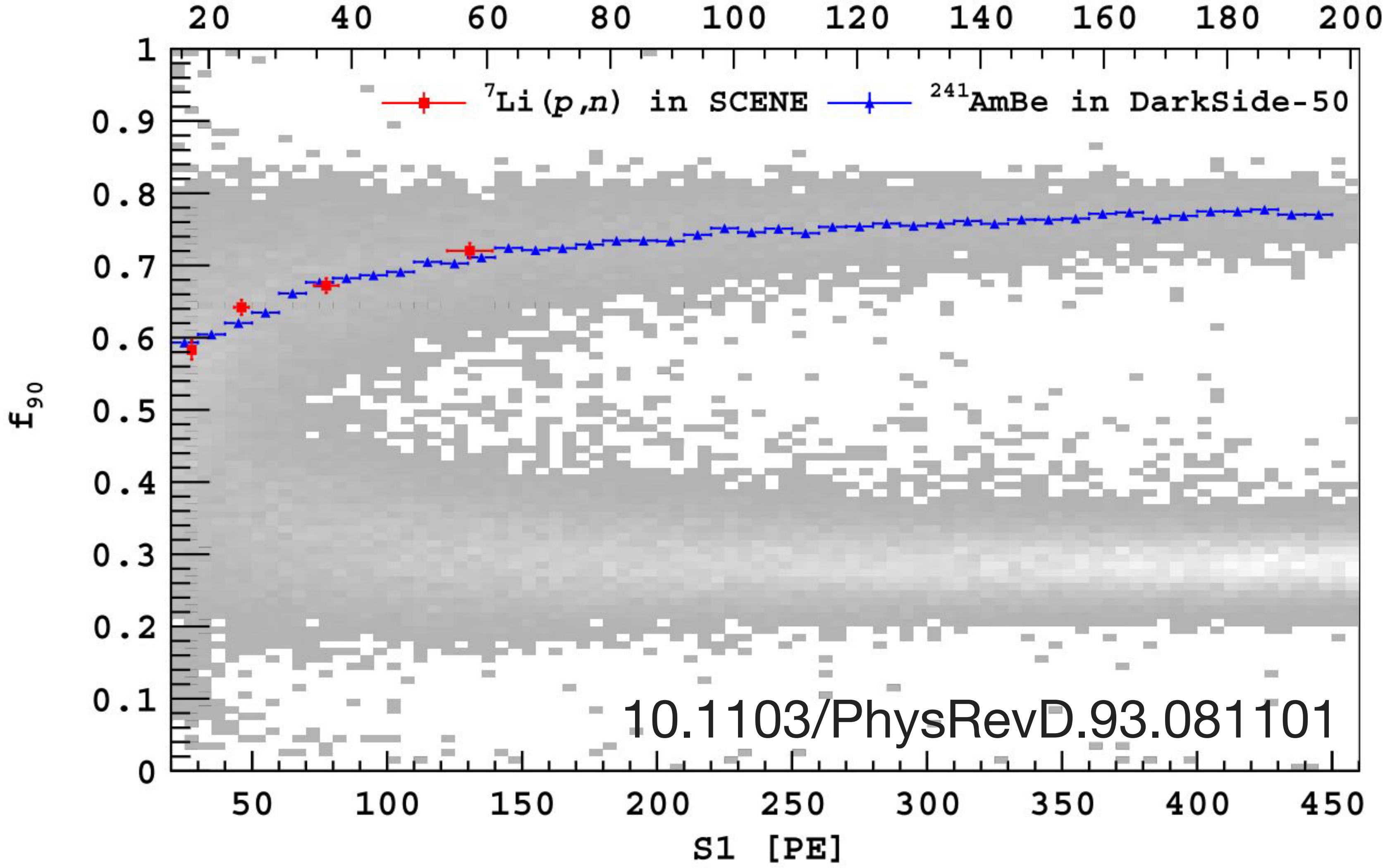
Mostly triplet



Nuclear Recoil (NR)

Mostly singlet





10.1103/PhysRevD.93.081101

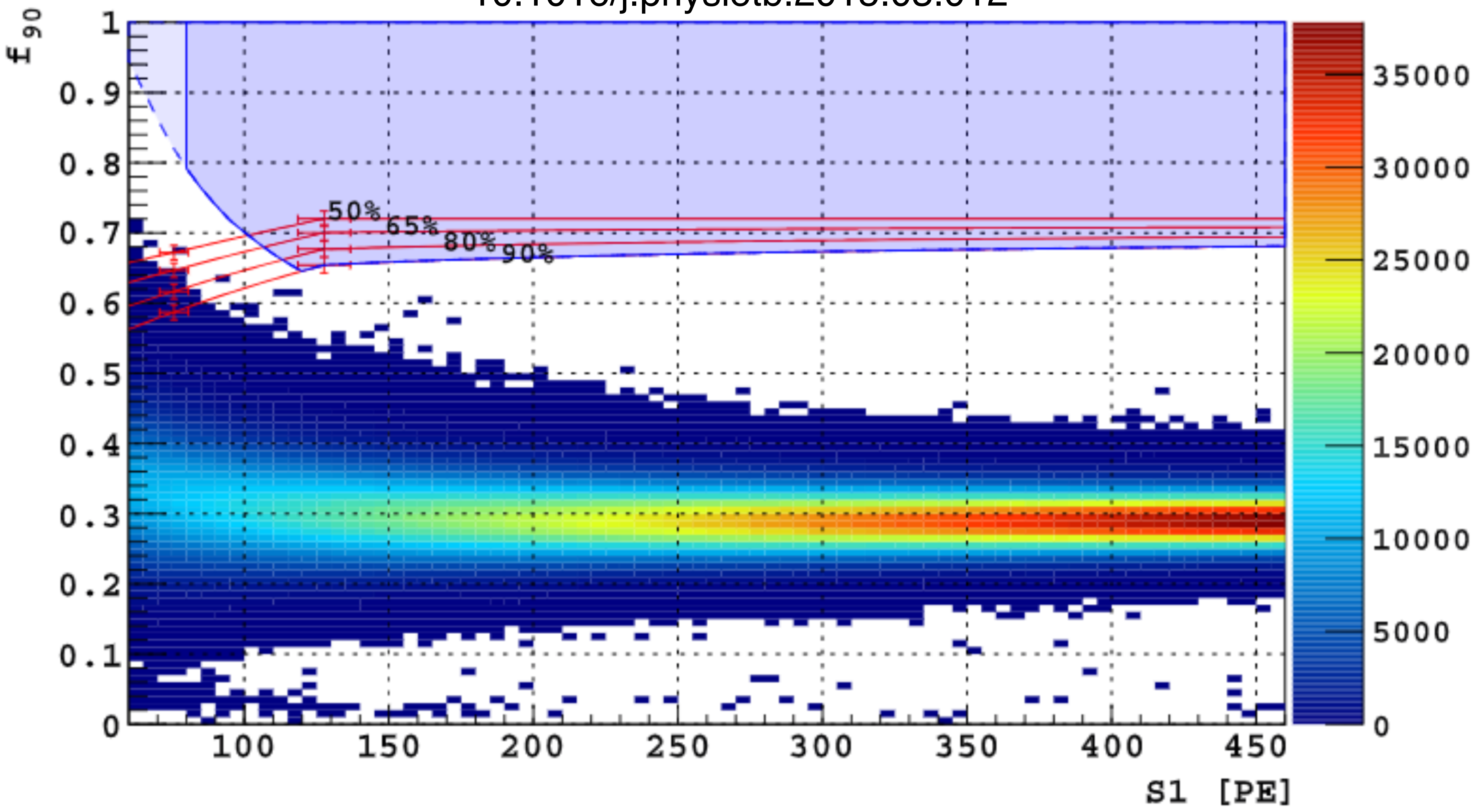
$\boldsymbol{\beta},\boldsymbol{\gamma}$ → ER  $\boldsymbol{\nu}$, n, WIMPs → NR

$$f_{prompt} = \frac{\text{prompt light}}{\text{total light}}$$

# ER rejection in LAr

**DarkSide-50**

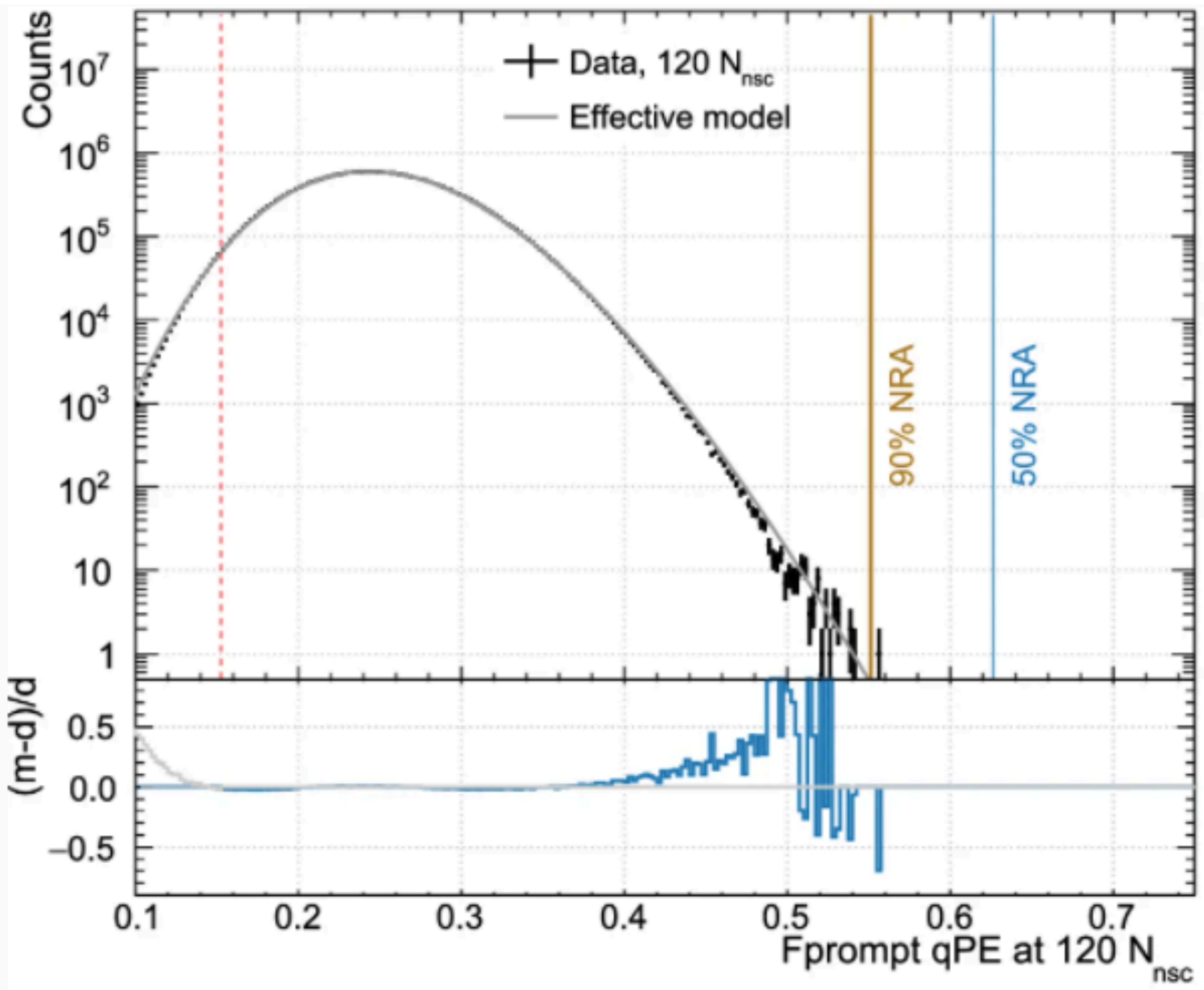
10.1016/j.physletb.2015.03.012



$\beta,\gamma$ rejection better than 1.5x$10^7$

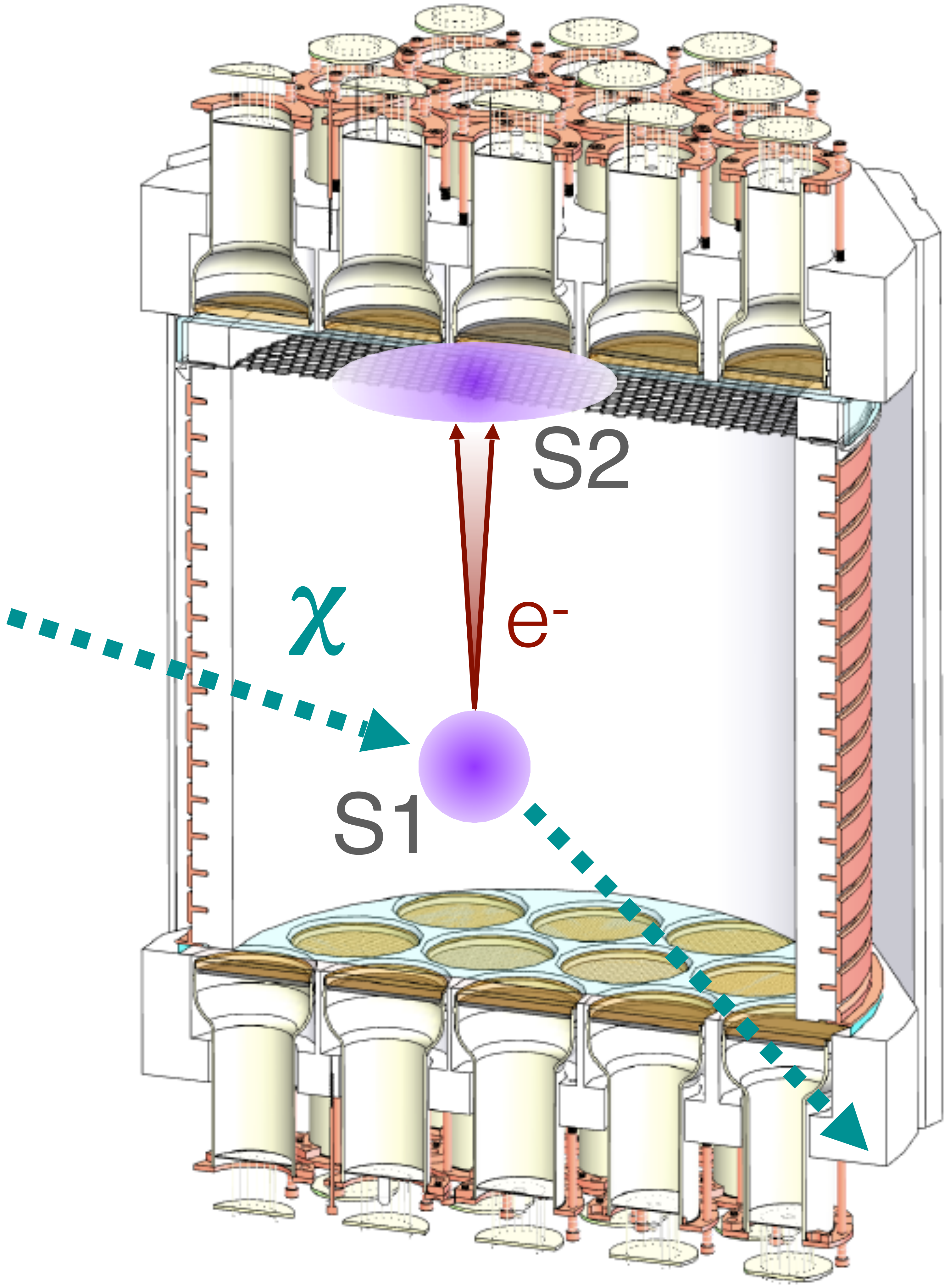
**DEAP-3600**

Eur. Phys. J. C 81,823 (2021)



$\beta,\gamma$ rejection better than $10^8$

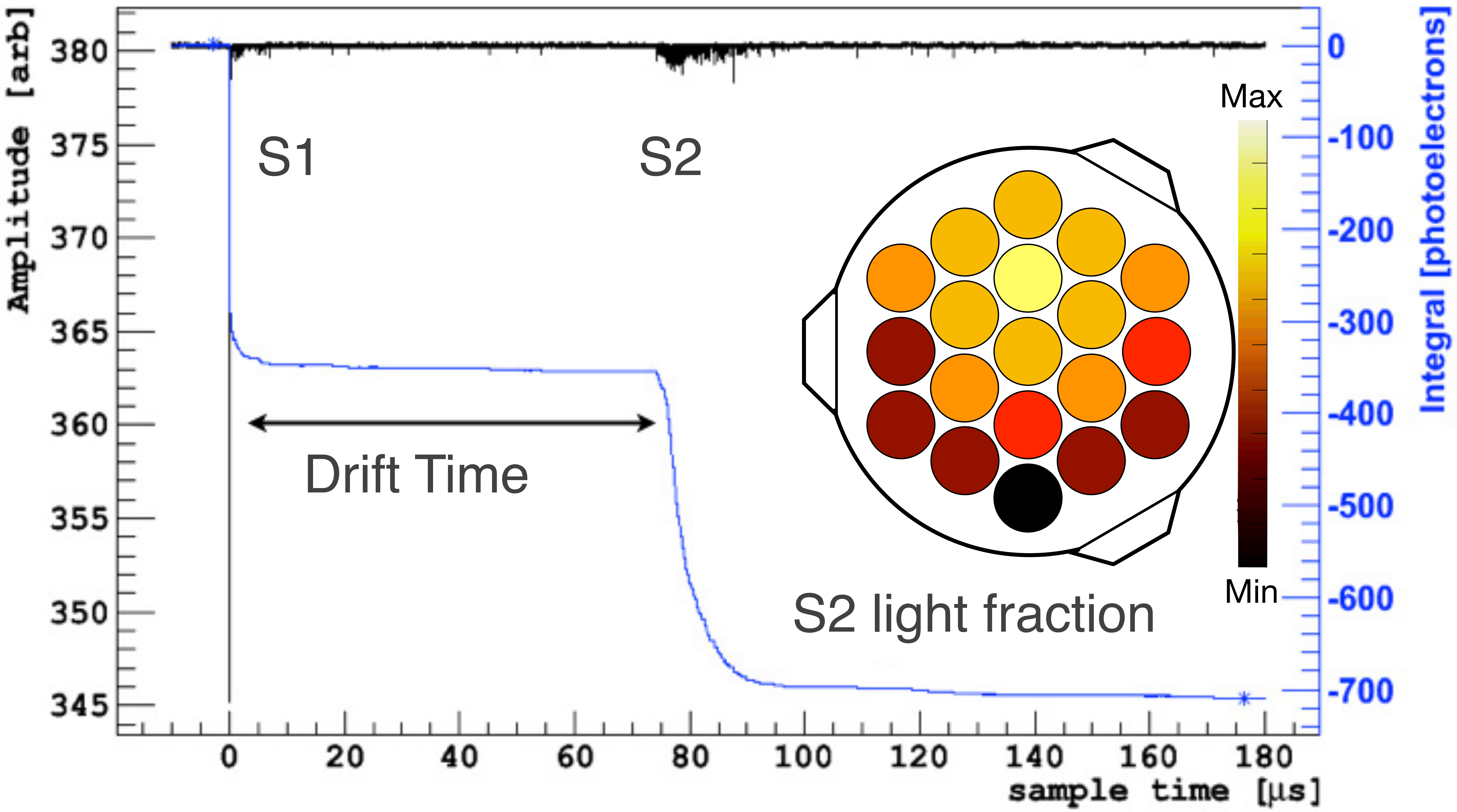
# Dual-phase TPCs



S1 = Scintillation Light

S2 = Light from ionization e$^-$

## 3D position reconstruction



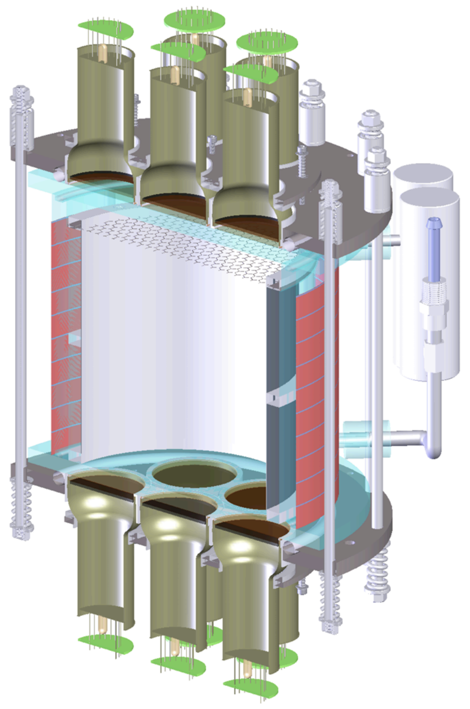
- Z from S1-S2 time difference
- XY from S2 light distribution

- Definition of a Fiducial Volume
- Rejection of multiple scattering

# The DarkSide Program

# A multi-stage approach

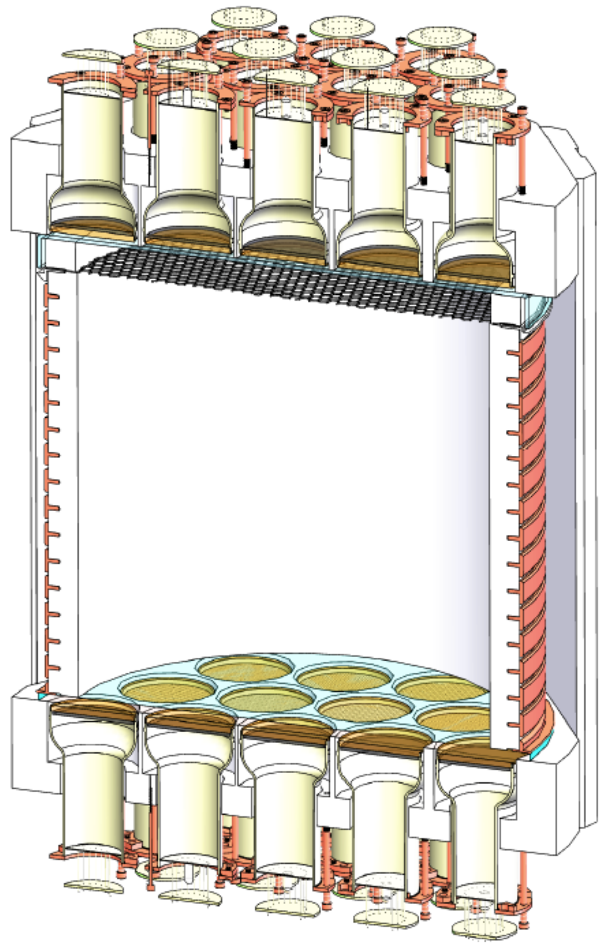
**2012**



**DarkSide-10**

- First prototype
- Helped to refine TPC design
- Demonstrated a light yield >9PE/$\text{keV}_{ee}$

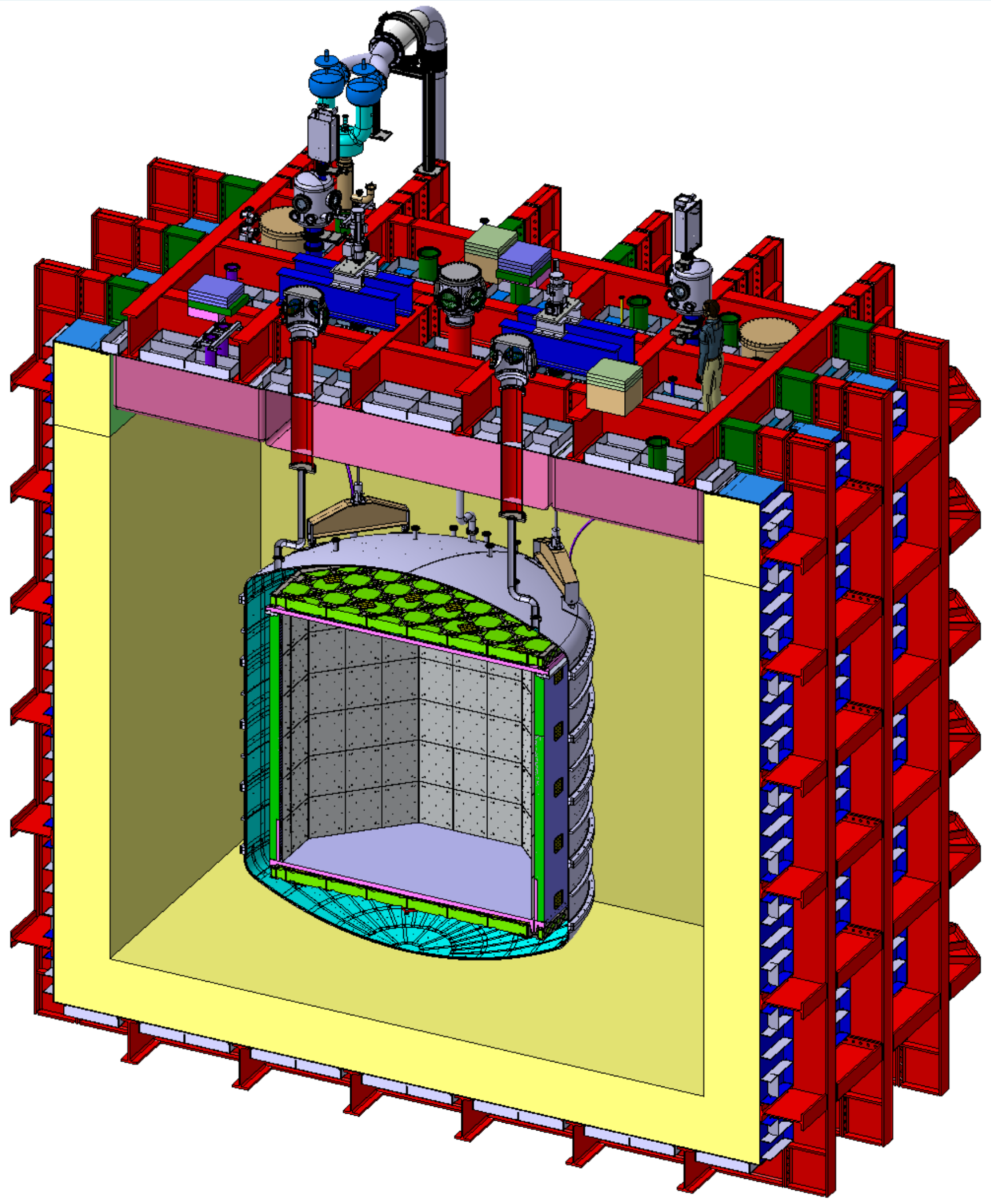
**2013 - 2018**



**DarkSide-50**

- Science detector
- Demonstrated the use of UAr
- First background-free results
- Best limits for low mass WIMP searches

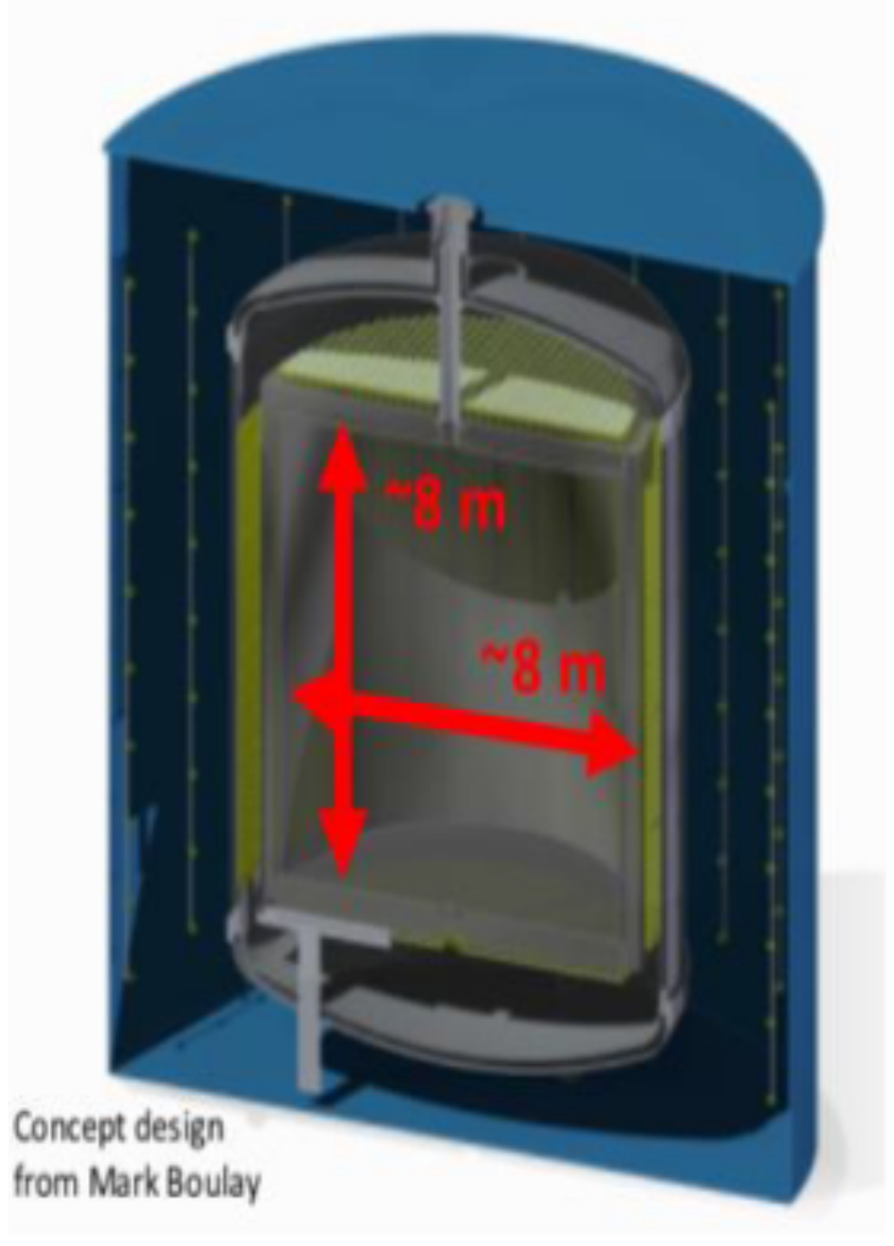
**2025 - 2035**



**DarkSide-20k @ LNGS**

- Novel technologies
- First peek into the neutrino fog
- Nominal exposure: 200 t y

**2030s - ...**



Concept design
from Mark Boulay

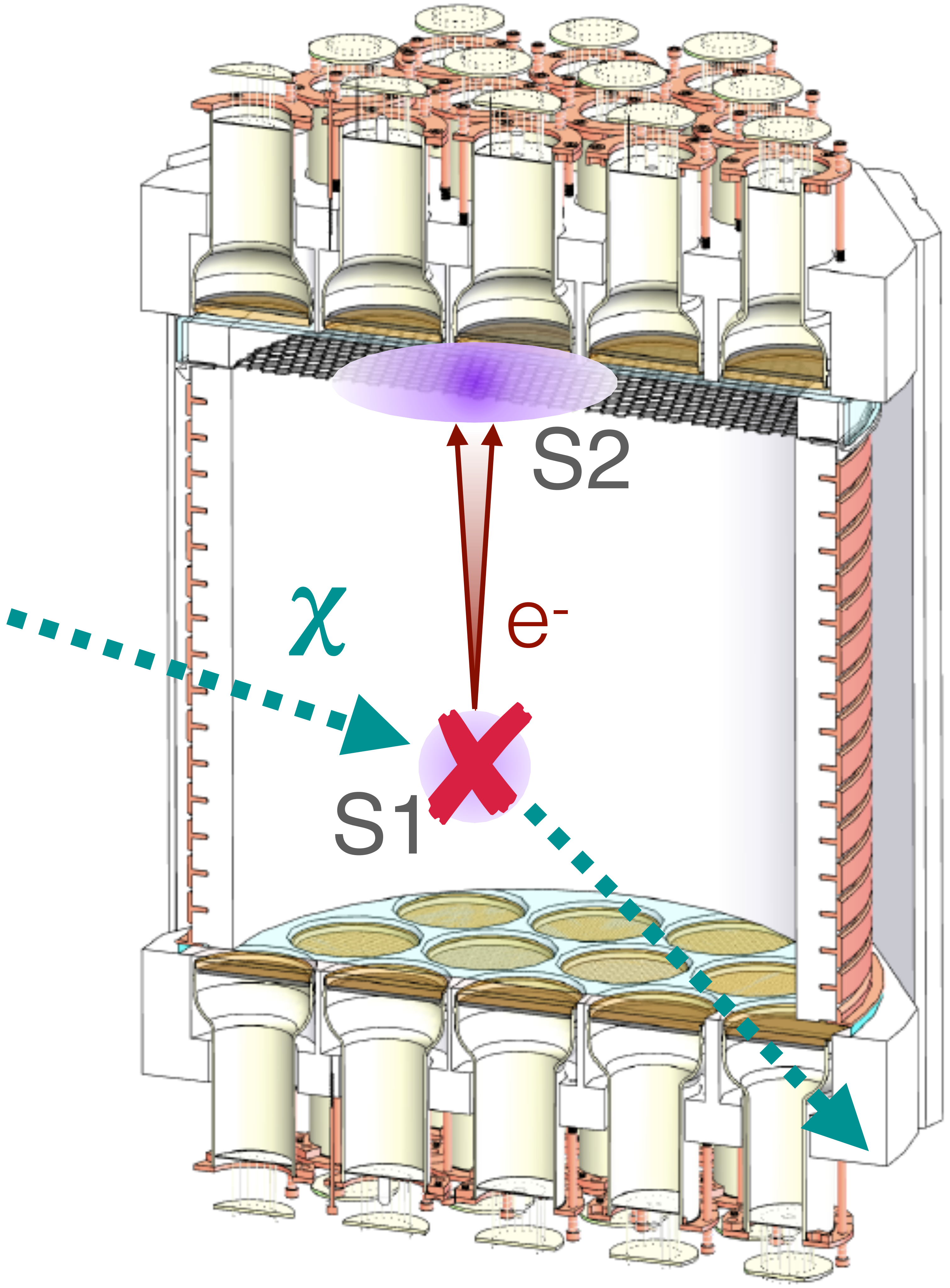
**Argo @ SNOLAB**

- Ultimate LAr DM detector
- Push well into the neutrino fog
- Nominal exposure: 3000 t y

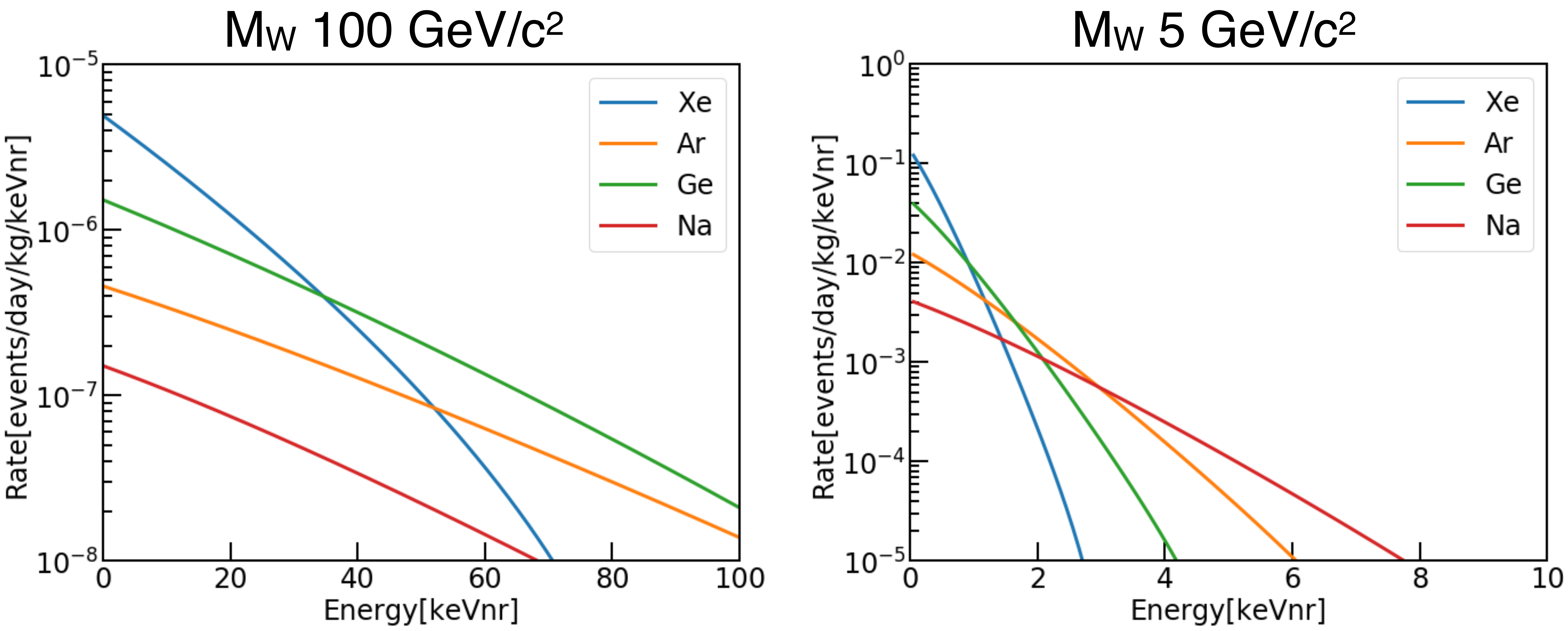
# DarkSide-50
# 2023 Results

*Phys.Rev.Lett.* 130 (2023) 10, 101002
*Phys.Rev.Lett.* 130 (2023) 10, 101001
*Phys.Rev.D* 107 (2023) 6, 063001

# Lower the energy threshold

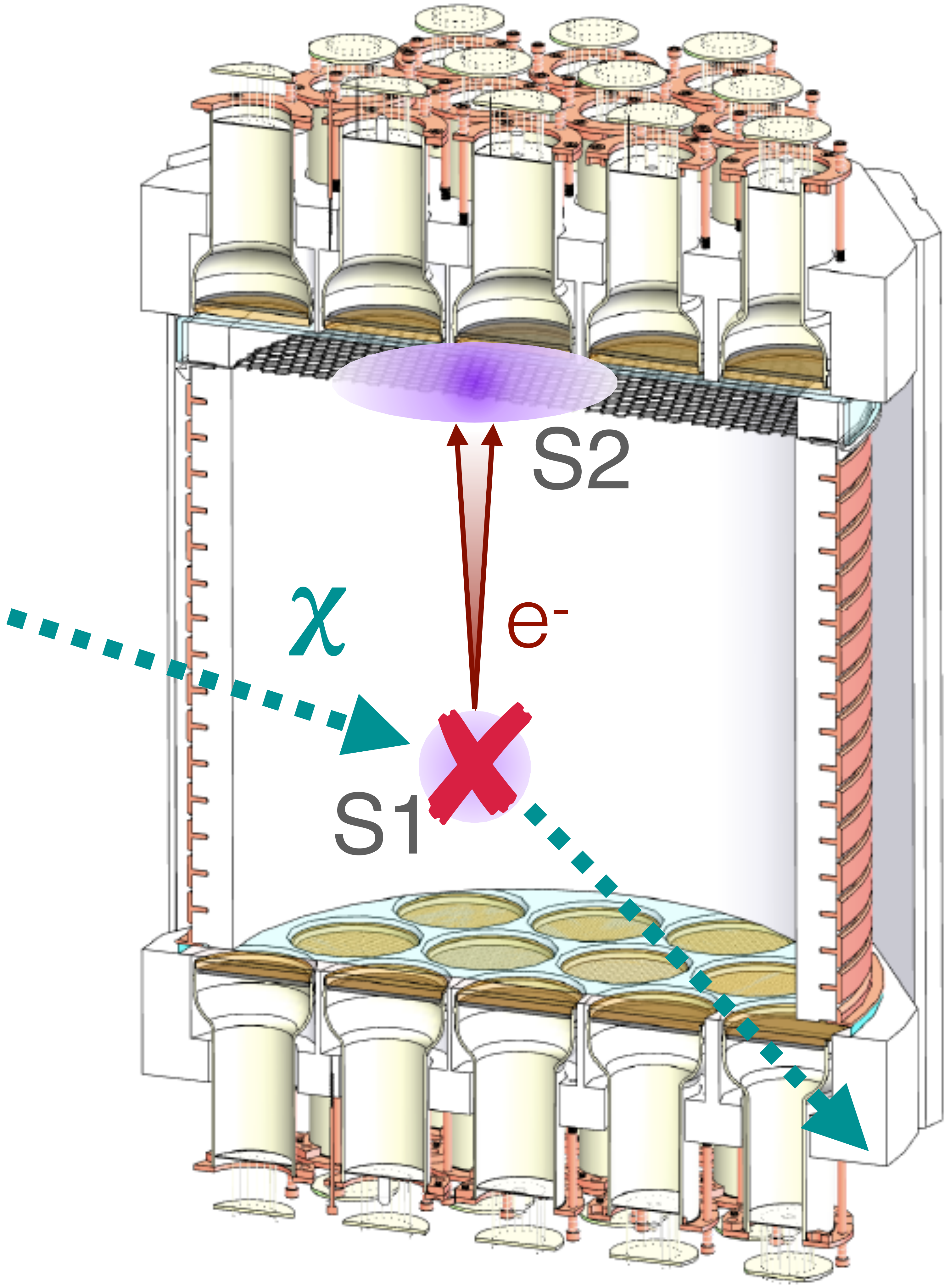


Lower the energy threshold ⇒ Look at the S2 only events



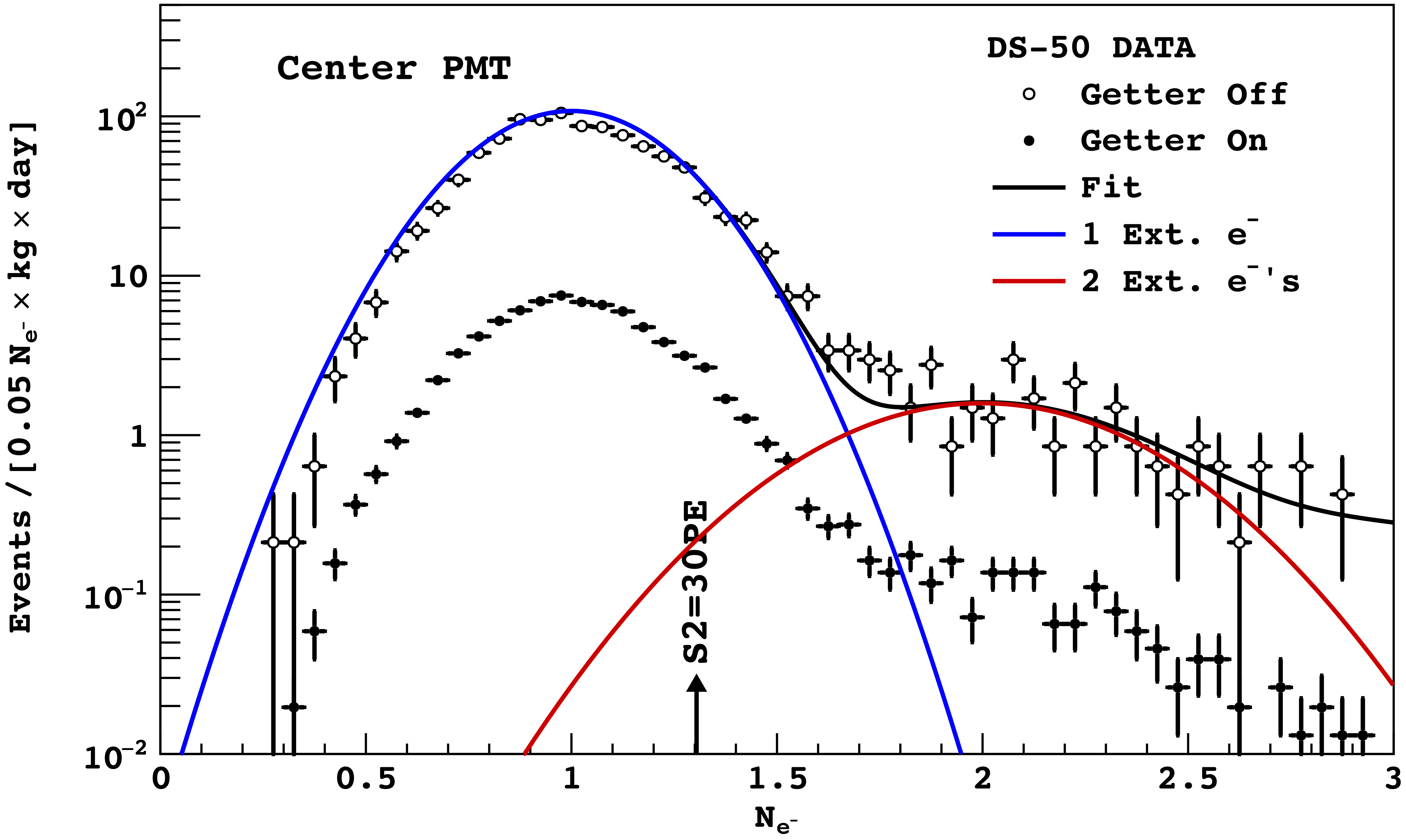
- S2 >> S1 (23ph/e- in DS50)
- 100% Trigger eff. > ~40PE
- 100% S2 identif. eff. > ~30PE
- Thresholds: <0.1keV$_{ee}$, 0.4keV$_{nr}$

# Lower the energy threshold



Lower the energy threshold ⇒ Look at the S2 only events

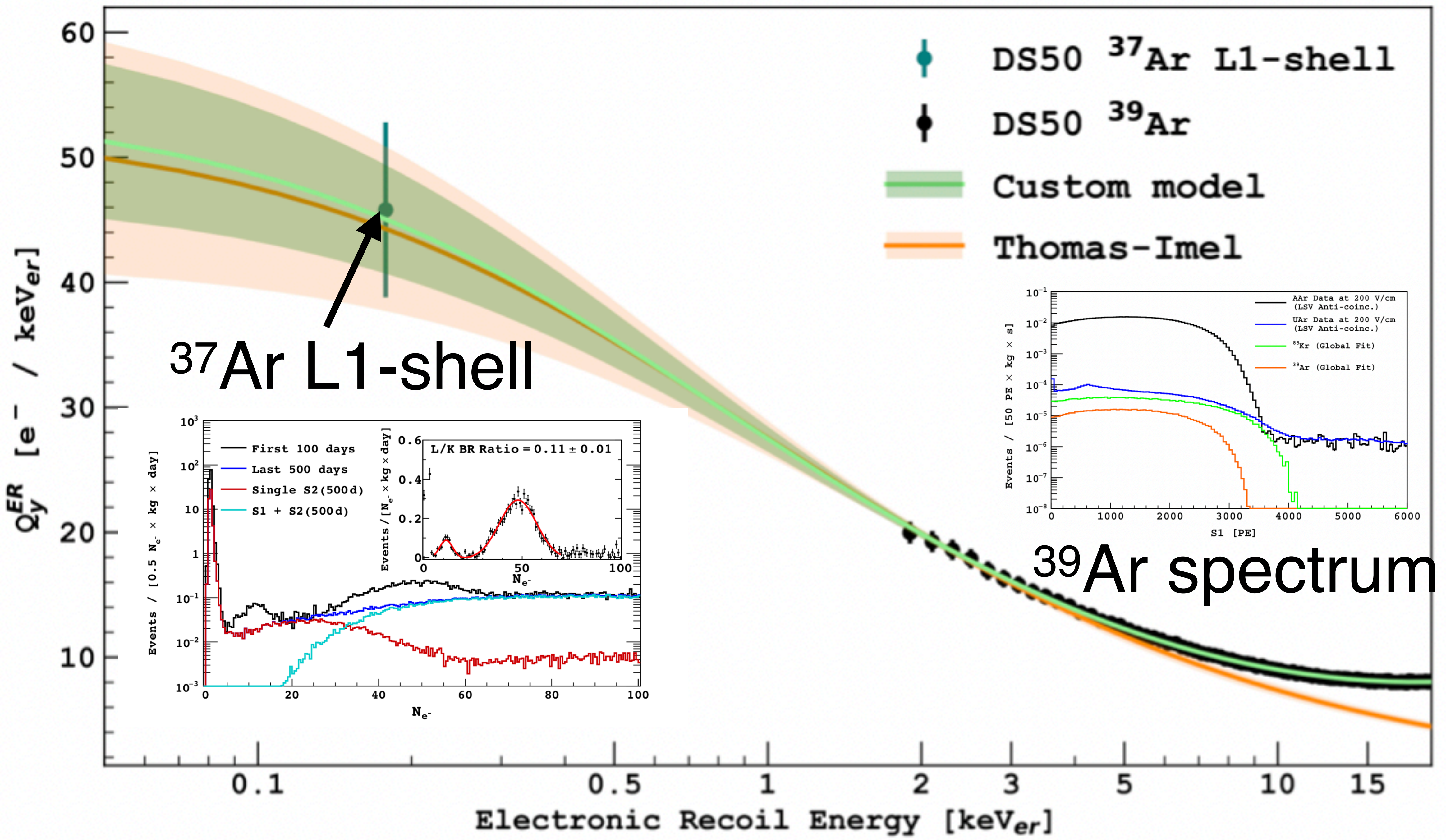
Phys. Rev. Lett. **121**, 081307



- S2 >> S1 (23ph/e$^-$ in DS50)
- 100% Trigger eff. > ~40PE
- 100% S2 identif. eff. > ~30PE
- Thresholds: <0.1keV$_{ee}$, 0.6keV$_{nr}$

# ER and NR energy scales

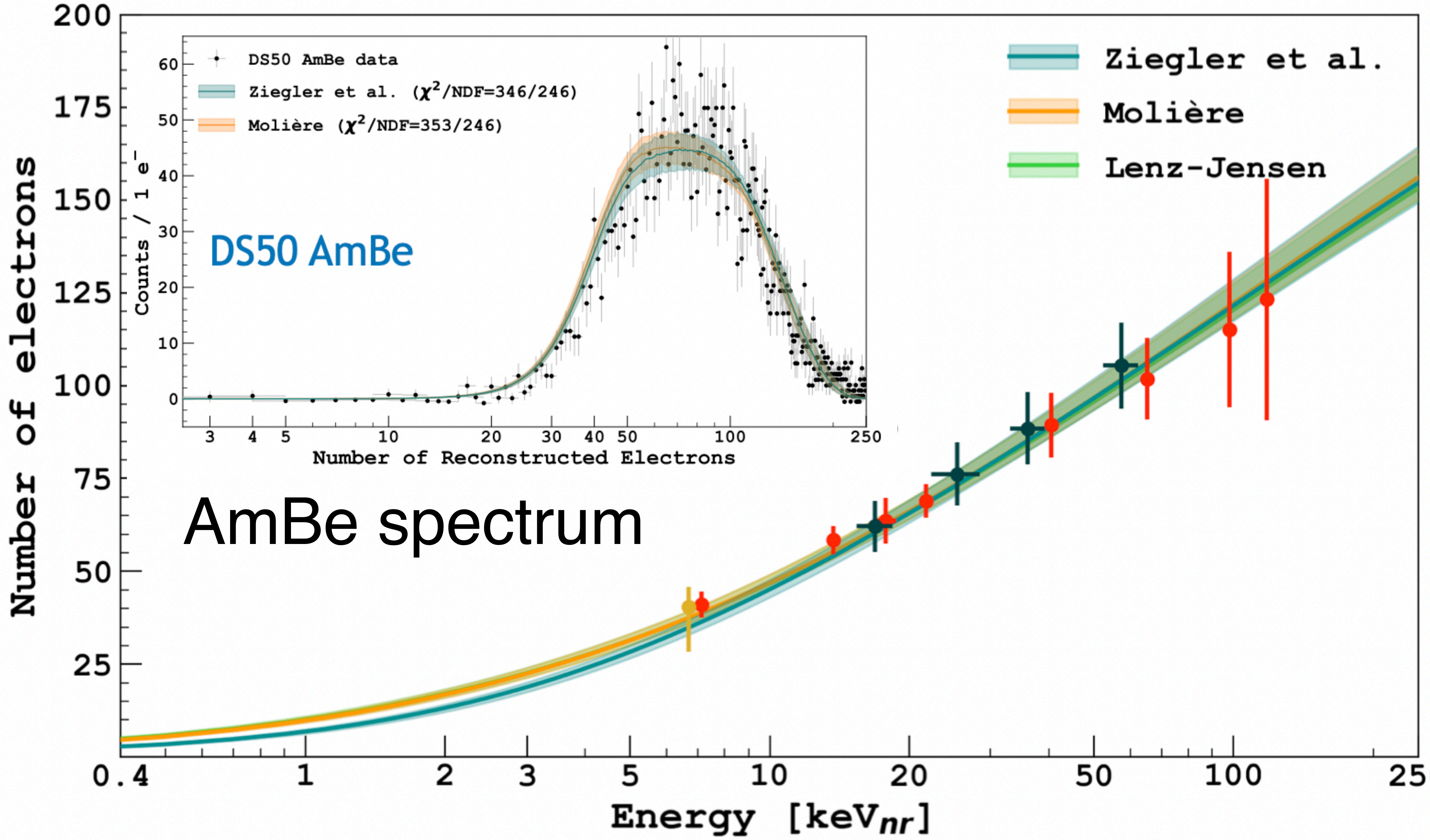
Phys. Rev. D **104**, 082005



$^{37}$Ar L1-shell

$^{39}$Ar spectrum

Phys. Rev. D **104**, 082005

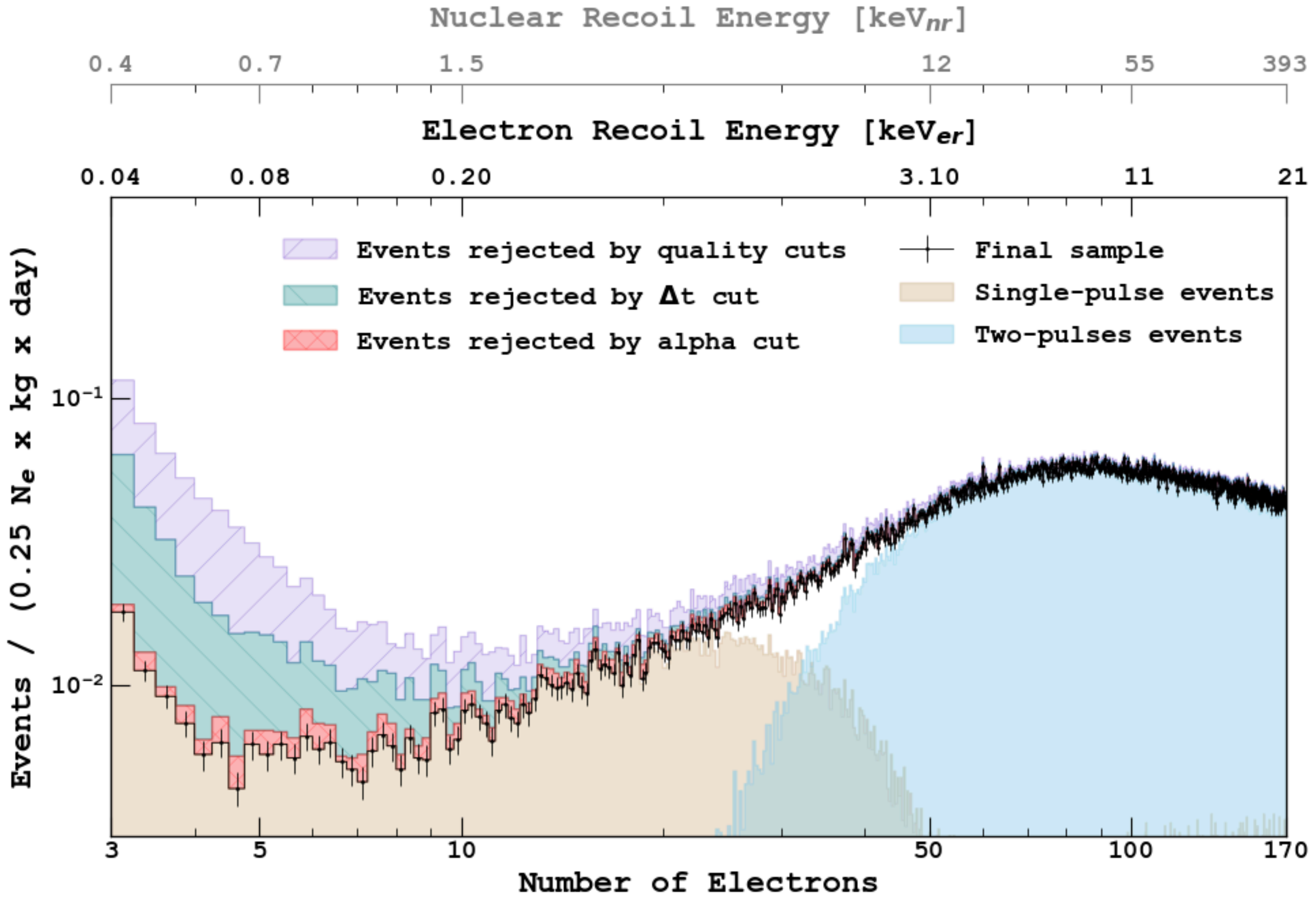


AmBe spectrum

- First 100 days UAr dataset
- ER calibration from $^{37}$Ar EC ($t_{1/2}$ = 35d)
- $^{37}$Ar lines:
  E = 0.27 keV → Ne = 11
  E = 2.82 keV → Ne = 48

- MC template fit to DS50 AmBe and Am$^{13}$C neutron spectra data
- Red and black data points from external neutron calibrations (ARIS, SCENE)

# Dataset



- Exposure: 653.1 live-days
- Average **trigger rate**: 1.54 Hz

**Quality cuts**

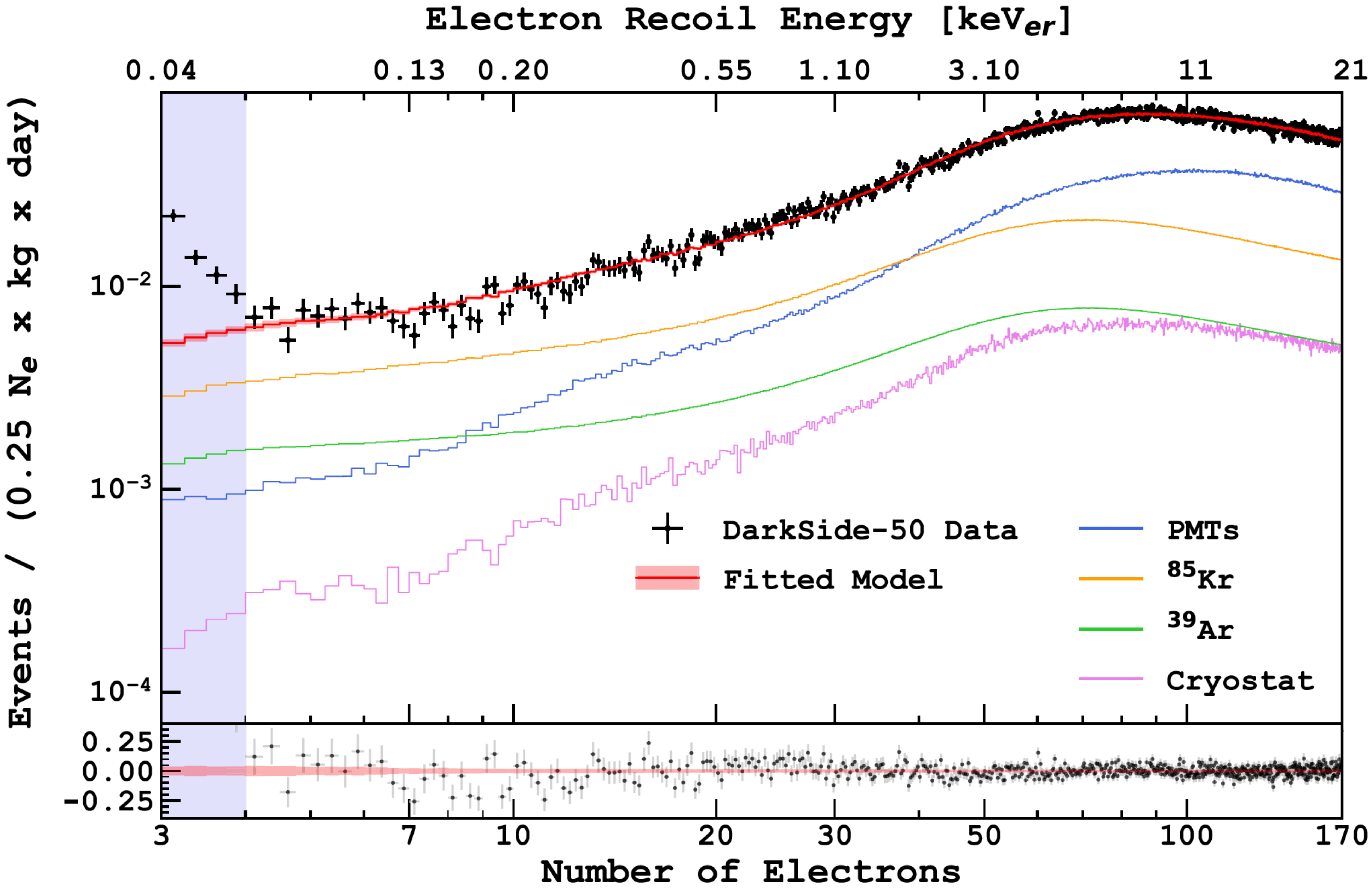
- Pulse-shape: remove anomalous pulses due to the pile-up
- Acceptance: 95% at 4 Ne and 99% at >15 Ne

**Selection Cuts**

- Fiducialization
- S2/S1 against S2's from alphas
- Time veto agains spurious electrons

**New high statistics Background Model**

# Background Model



- High statistics MC samples

**Internals**

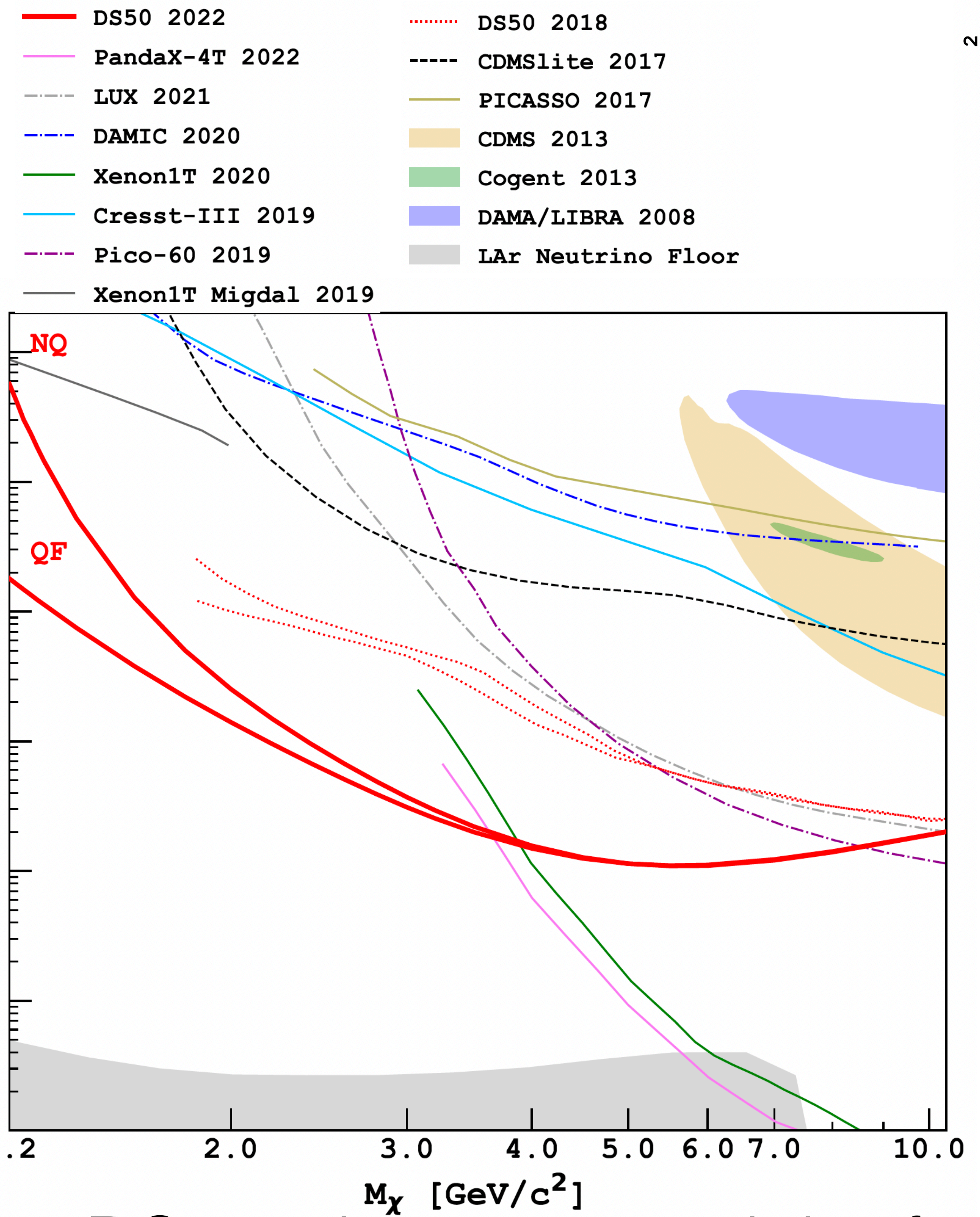
- Argon-39
- Kripton-85

**Externals**

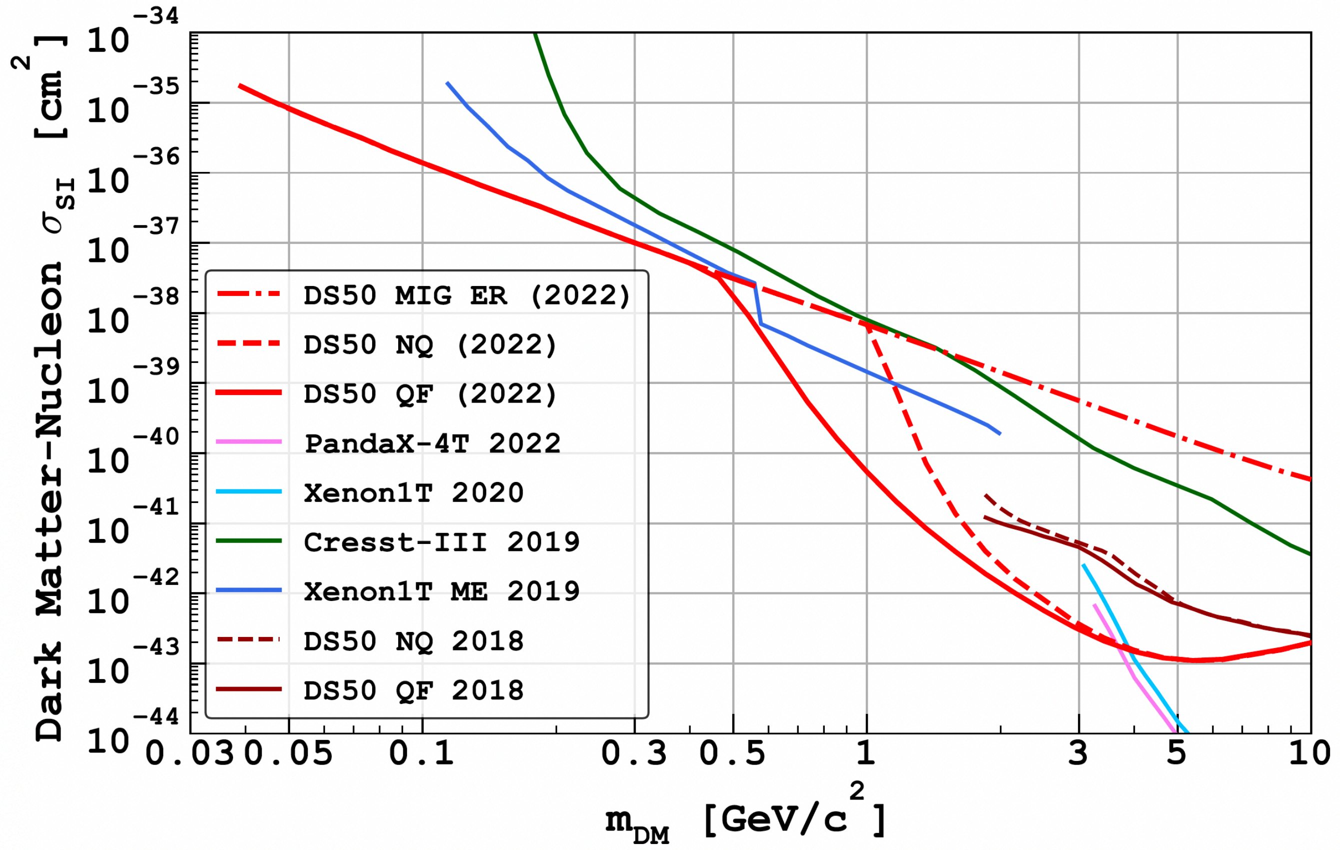
- PMTs
- Cryostat

# A treasure trove of new limits

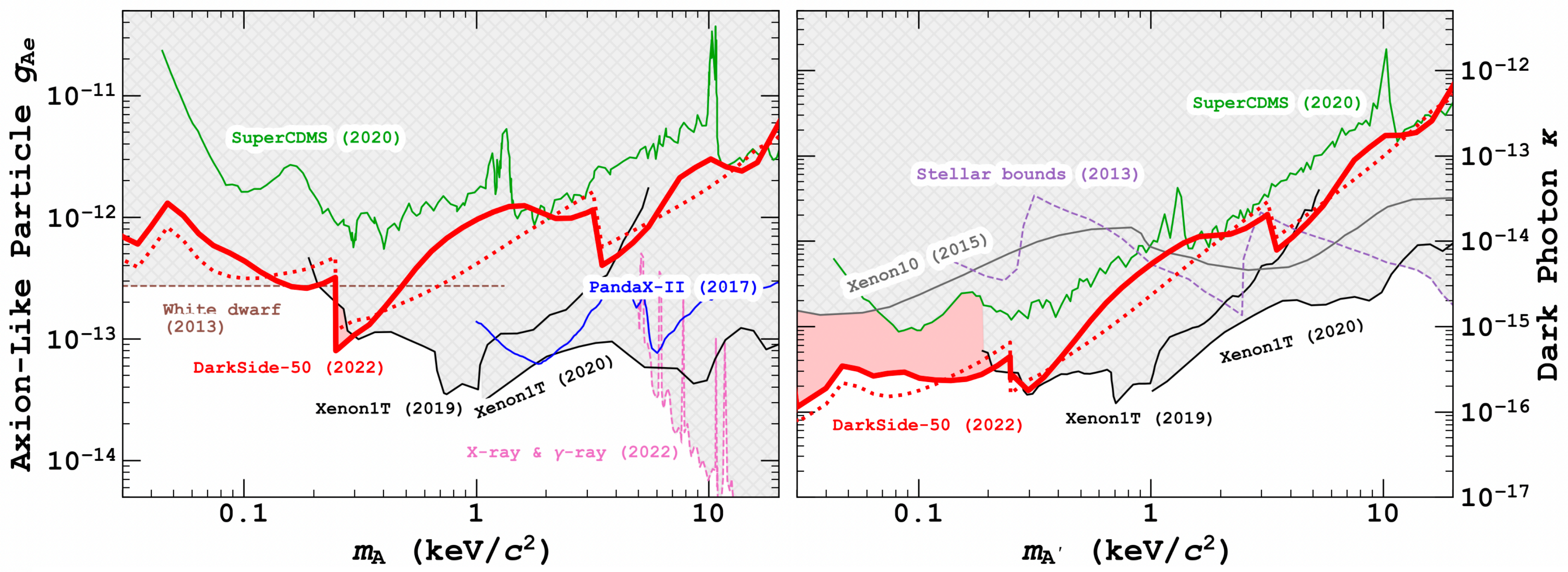
*Phys.Rev.D* 107 (2023) 6, 063001

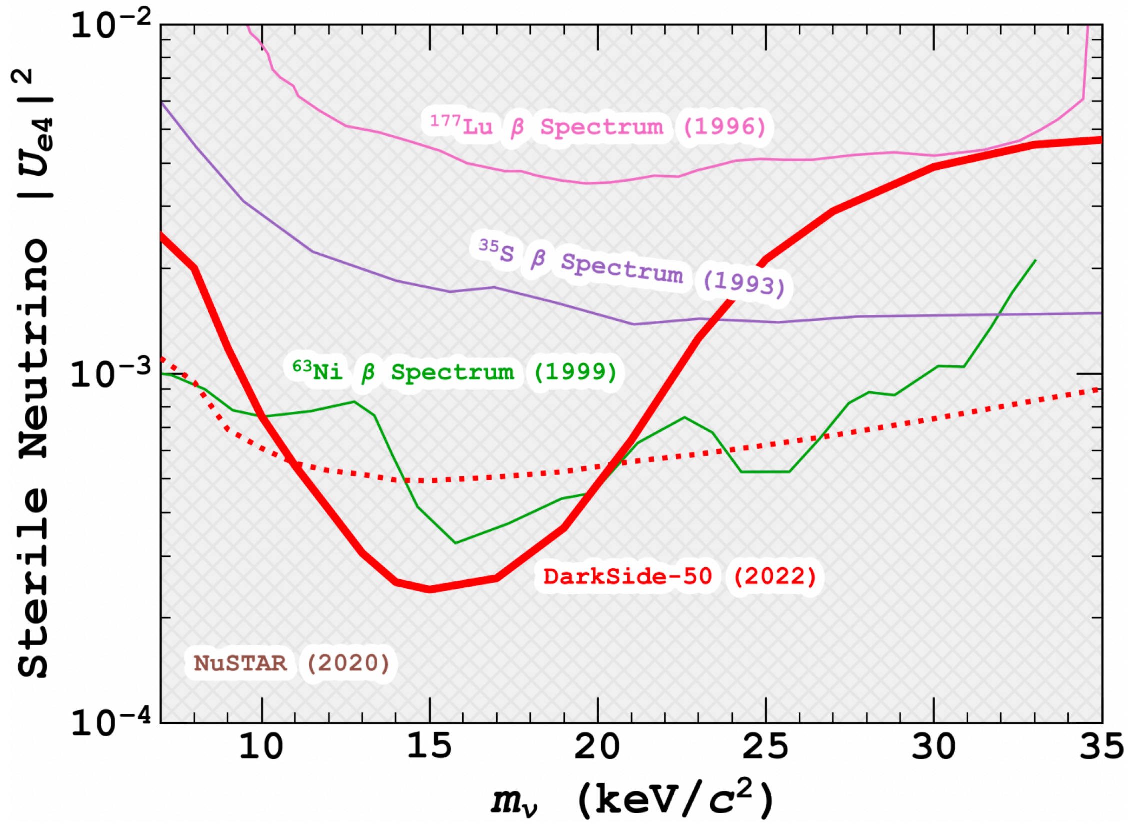


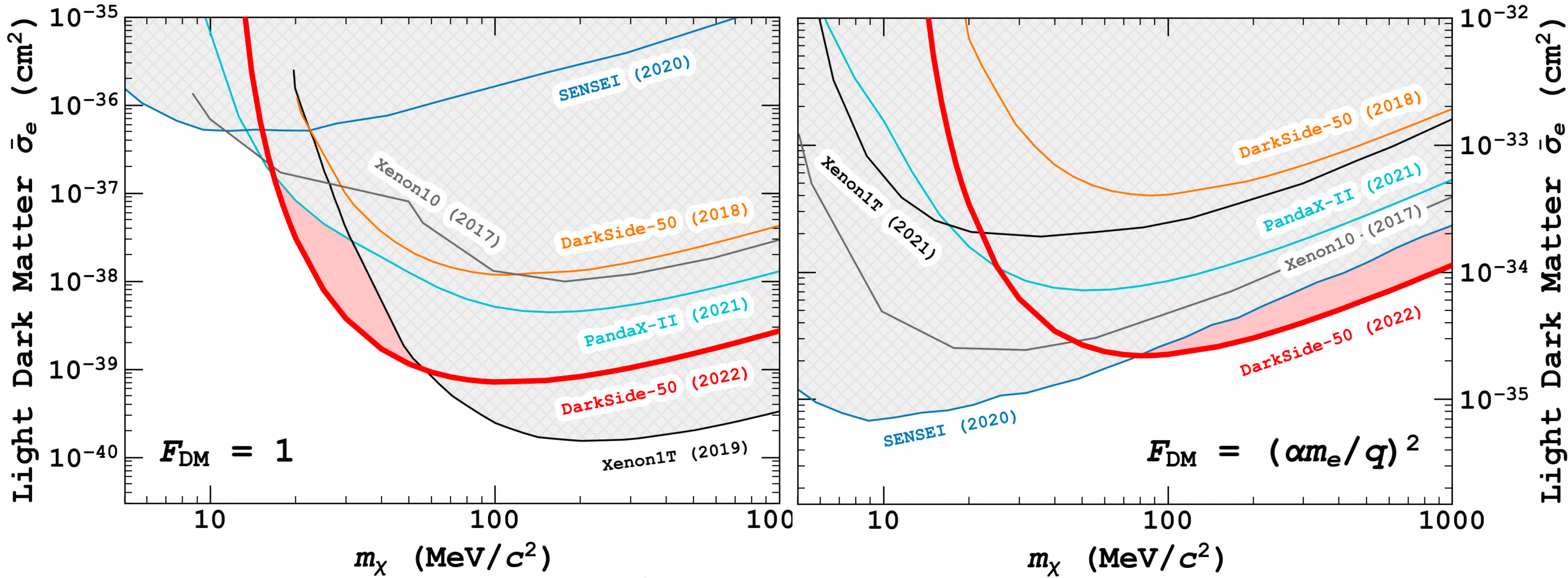
*Phys.Rev.Lett.* 130 (2023) 10, 101001



*Phys.Rev.Lett.* 130 (2023) 10, 101002



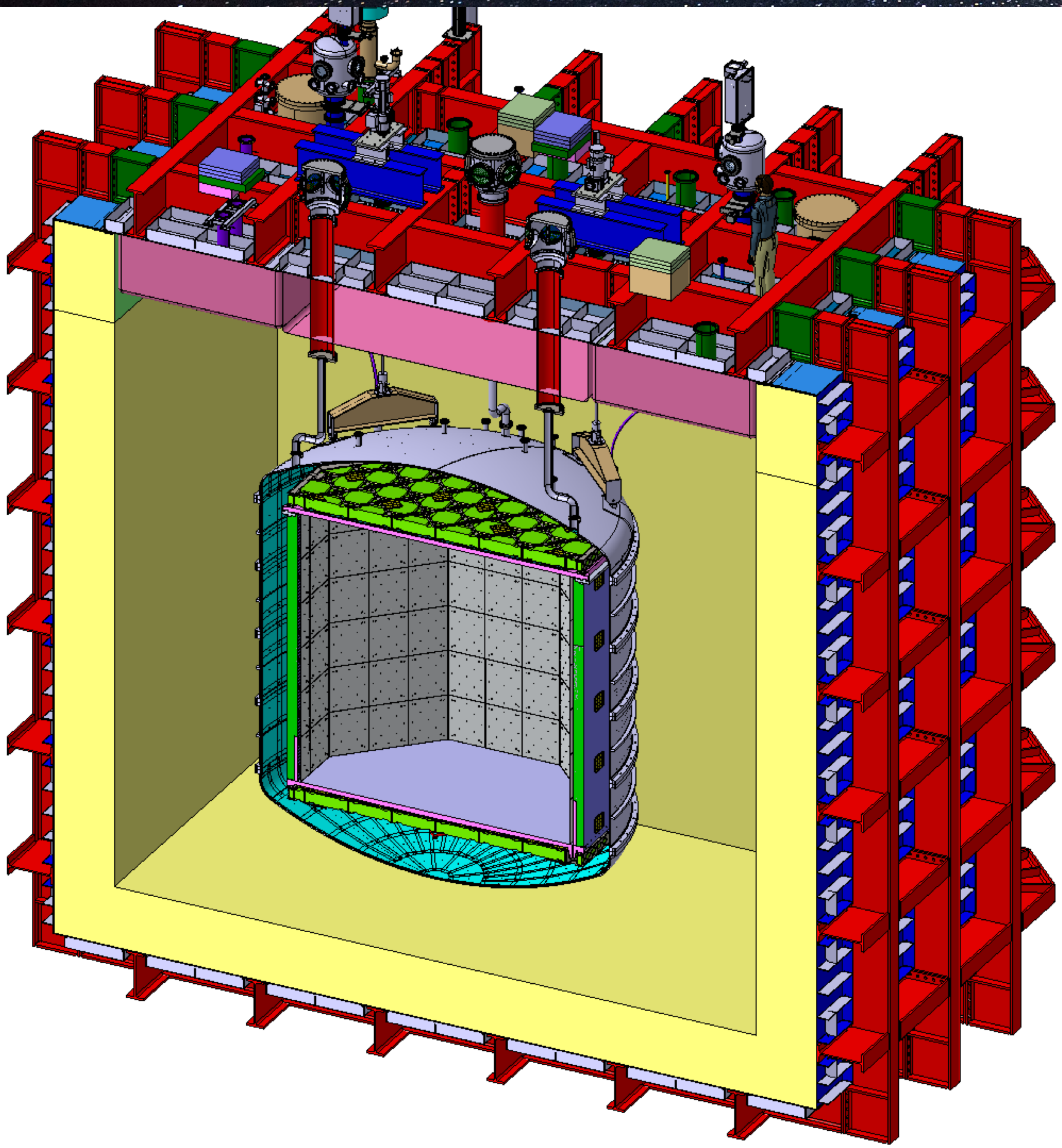




- DS-50 demonstrated the feasibility of LDM searches with dual-phase LAr TPCs.
- Use of ionization signals only: down to $E_{th} = 0.05\,\mathrm{keV}_{ee}$ with 100% trigger efficiency.
- Many LDM models probed and world-leading limits. 4 papers published in Q2 of 2023 in PRD + 2 PRL

# The DarkSide-20k Detector

# Detector overview



**Nested detectors structure:**

ProtoDUNE-like cryostat ($8x8x8m^3$) - Muon veto

SS vessel separating AAr from underground UAr.

Neutrons and γ veto

WIMP detector: dual-phase TPC hosting 50t of LAr

Fiducial mass: 20 tonnes

**Multiple detection channels for bkg supression:**

Neutron after cuts: < 0.1 in 100 t yr

β and γ after cuts: < 0.1 in 100 t yr

**Position reconstruction resolution:**

~ 1 cm in XY

~ 1 mm in Z

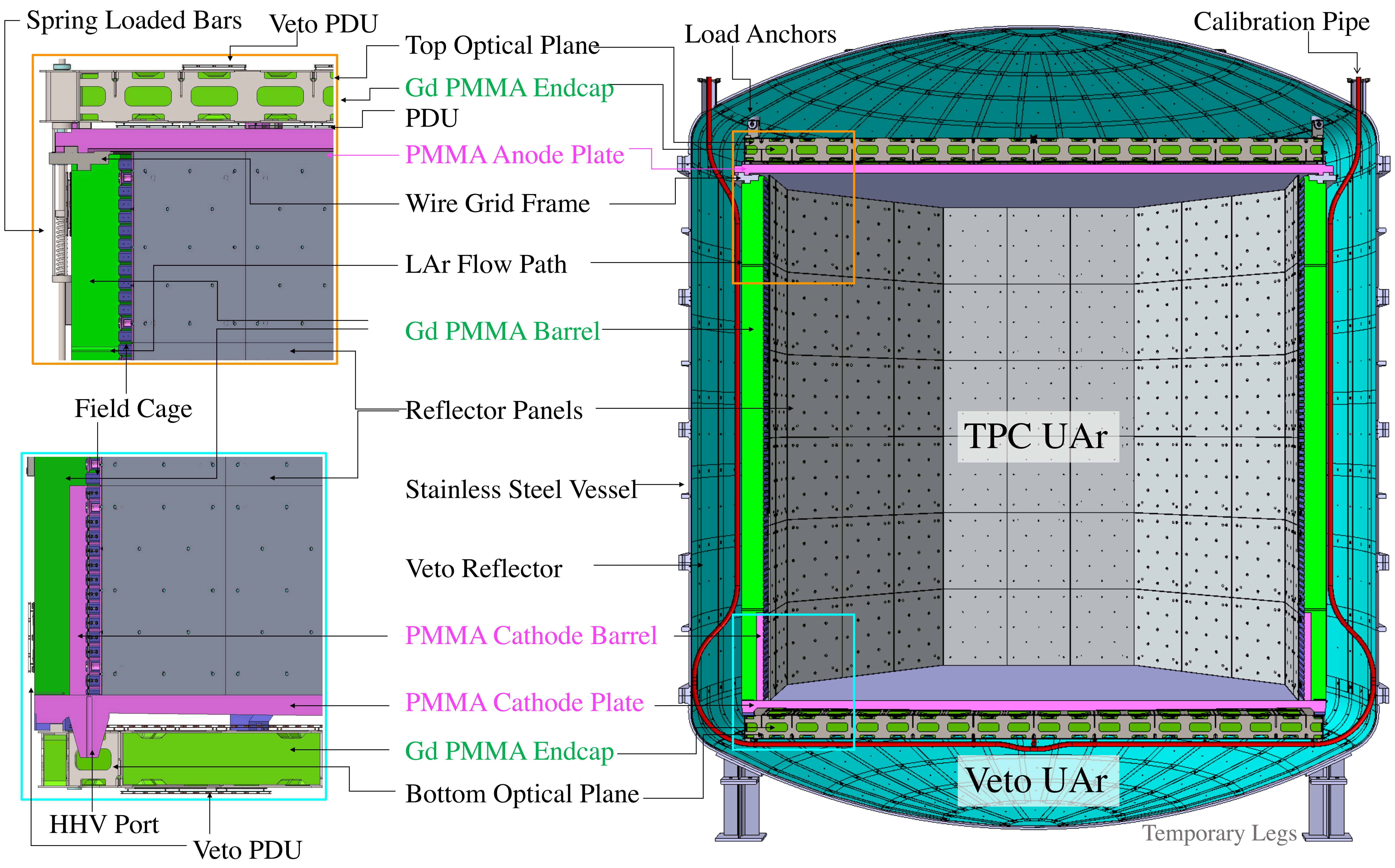
# Inner Detector

- **ID: TPC** and **VETO** integrated

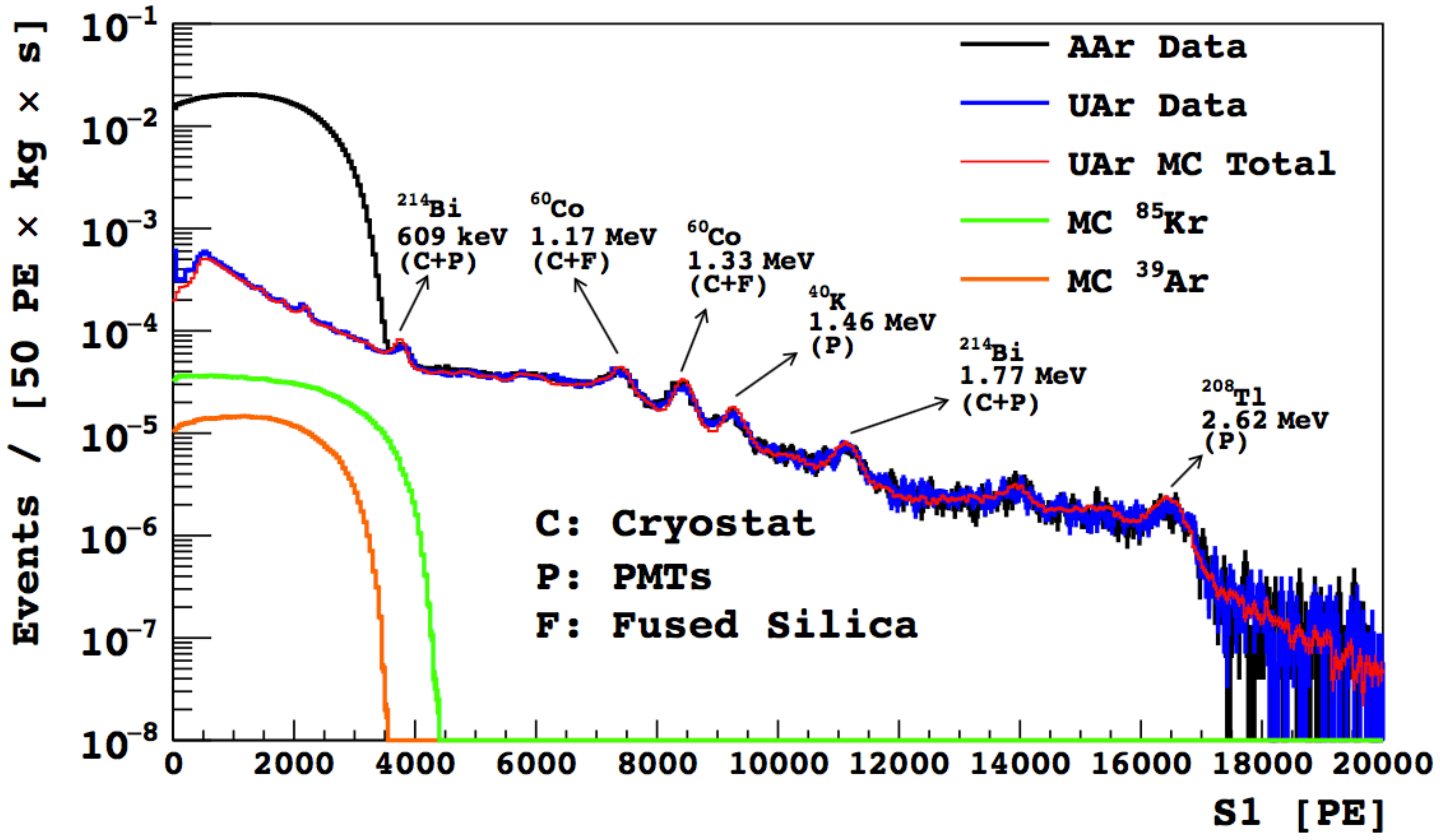
- **TPC:**
  - top + bottom: PMMA + TPB
  - lateral walls: Gd-PMMA + ESR + TPB
  - anode + cathode + field cage: Clevios
- **TPC Readout:** 21m$^2$ of cryogenic SiPMs

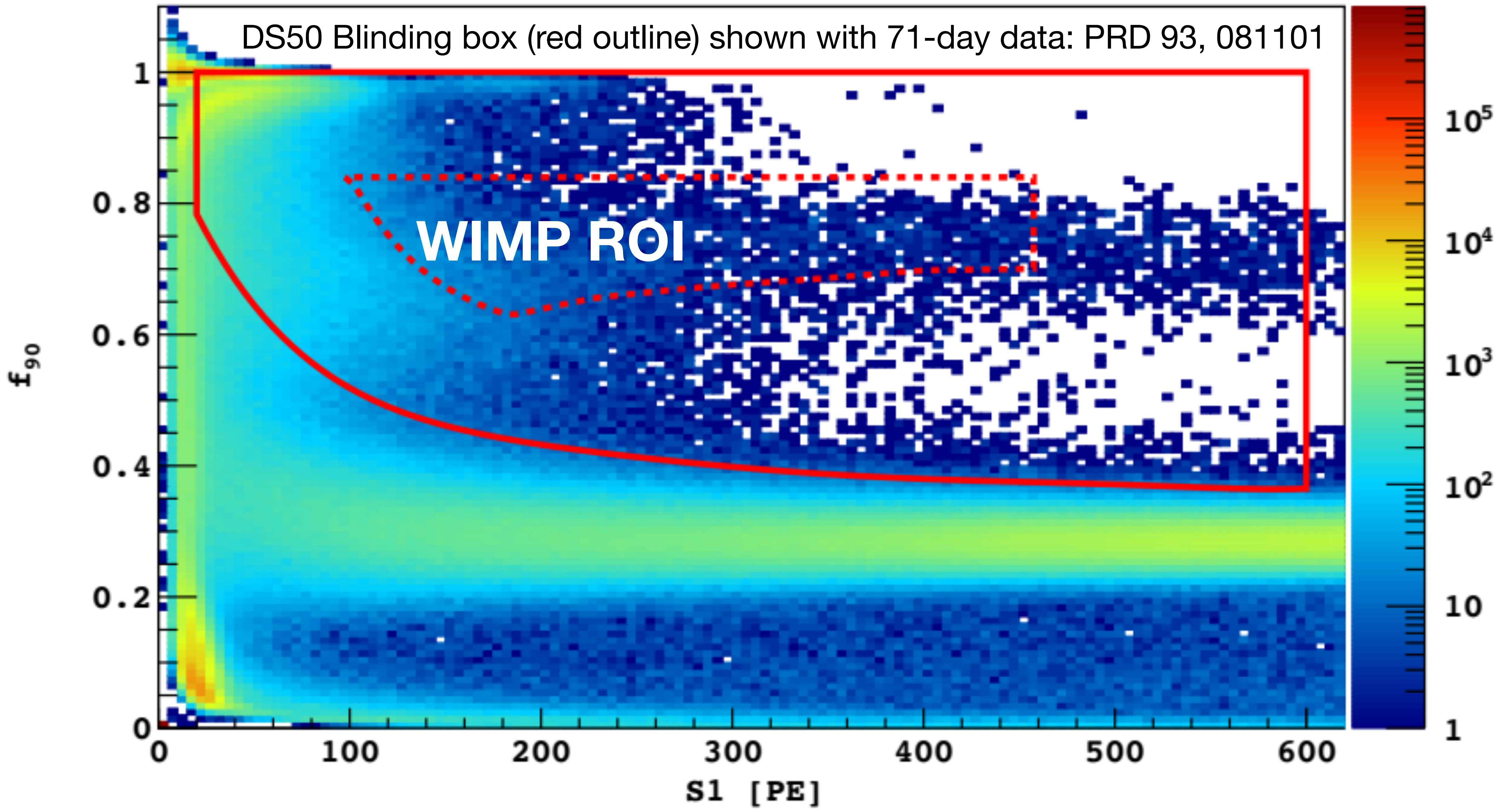
- **Veto:**
- Single phase detector in UAr
- TPC lateral walls + additional top&bottom planes in Gd-PMMA. Mechanism:
  - ○ Neutron thermalization
  - ○ Capture moderated n on Gd
  - ○ Emission of 8 MeV shower of γ
- **Veto Readout:** 5 m$^2$ cryogenic SiPMs

**99 tonnes of UAr held in SS vessel**



# Background Mitigation Strategies





## Electron Recoils (ER)

$^{39}$Ar β decays → Use of UAr, PSD

γ decays from U,Th chains + non actinides
($^{40}$K, $^{60}$Co, $^{137}$Cs) → Material selection, PSD

## Surface events

Position reconstruction

Radon progeny → Surface cleaning
Rn abatement

## Nuclear Recoils (NR)

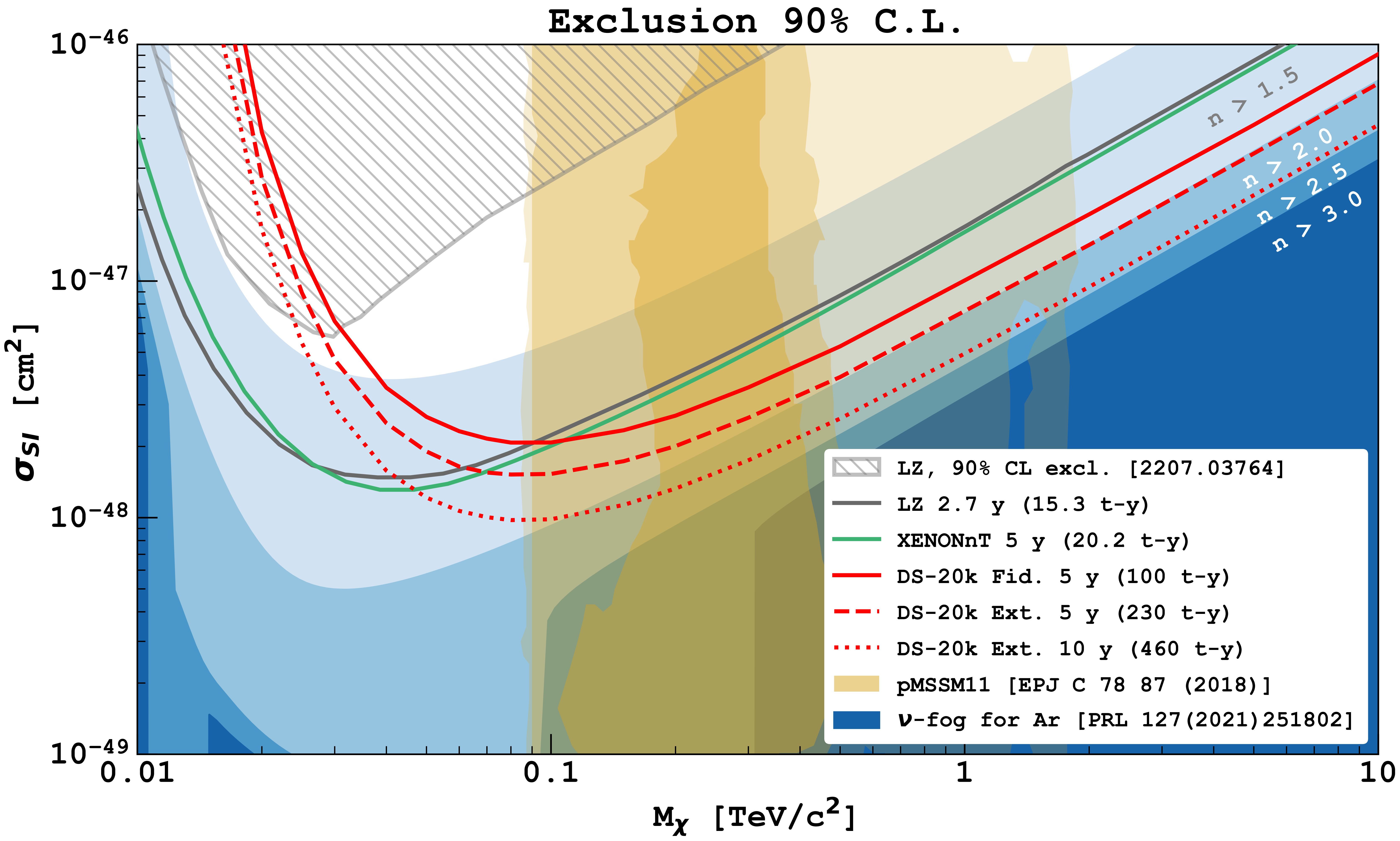
Radiogenic neutrons, mainly from ($\alpha$,n) reactions.
→ Material selection, Neutron Veto

Cosmogenic neutrons, from materials activation
due to residual muon flux → Muon Veto

Atmospheric neutrinos → Irreducible

# Sensitivity to WIMPs

- Upper limits for a 1 TeV/c$^2$ WIMP (90% C.L. exclusion)
    - 200 t-y: $7.4 \times 10^{-48}$ cm$^2$
- First probe of the argon **neutrino fog** at gradients n>1.5



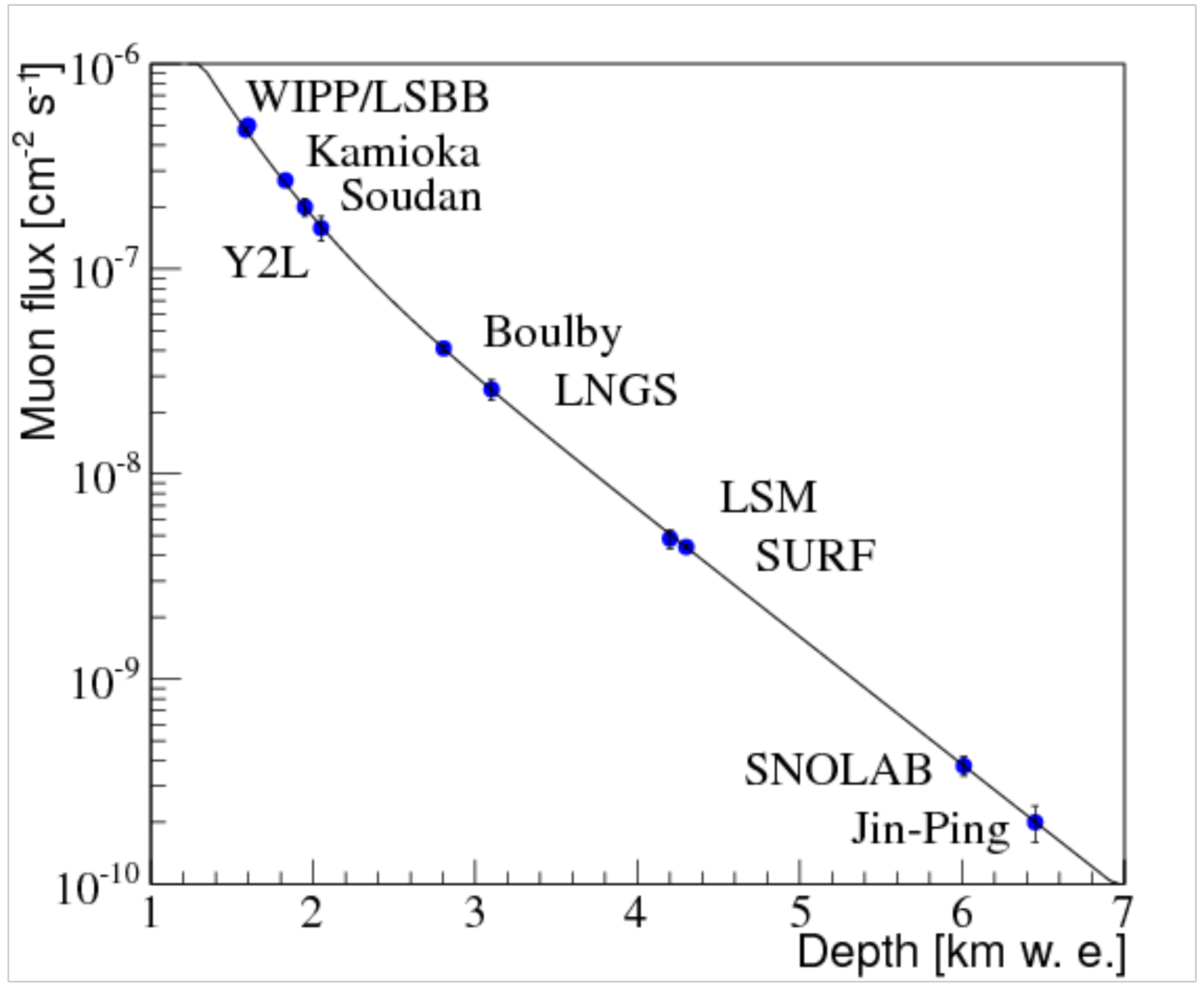
# Thanks!

**Contacts:**
claudios@princeton.edu
373 Jadwin Hall, Physics Department, Princeton University
(609) 258-4372

# Extras for Q&A

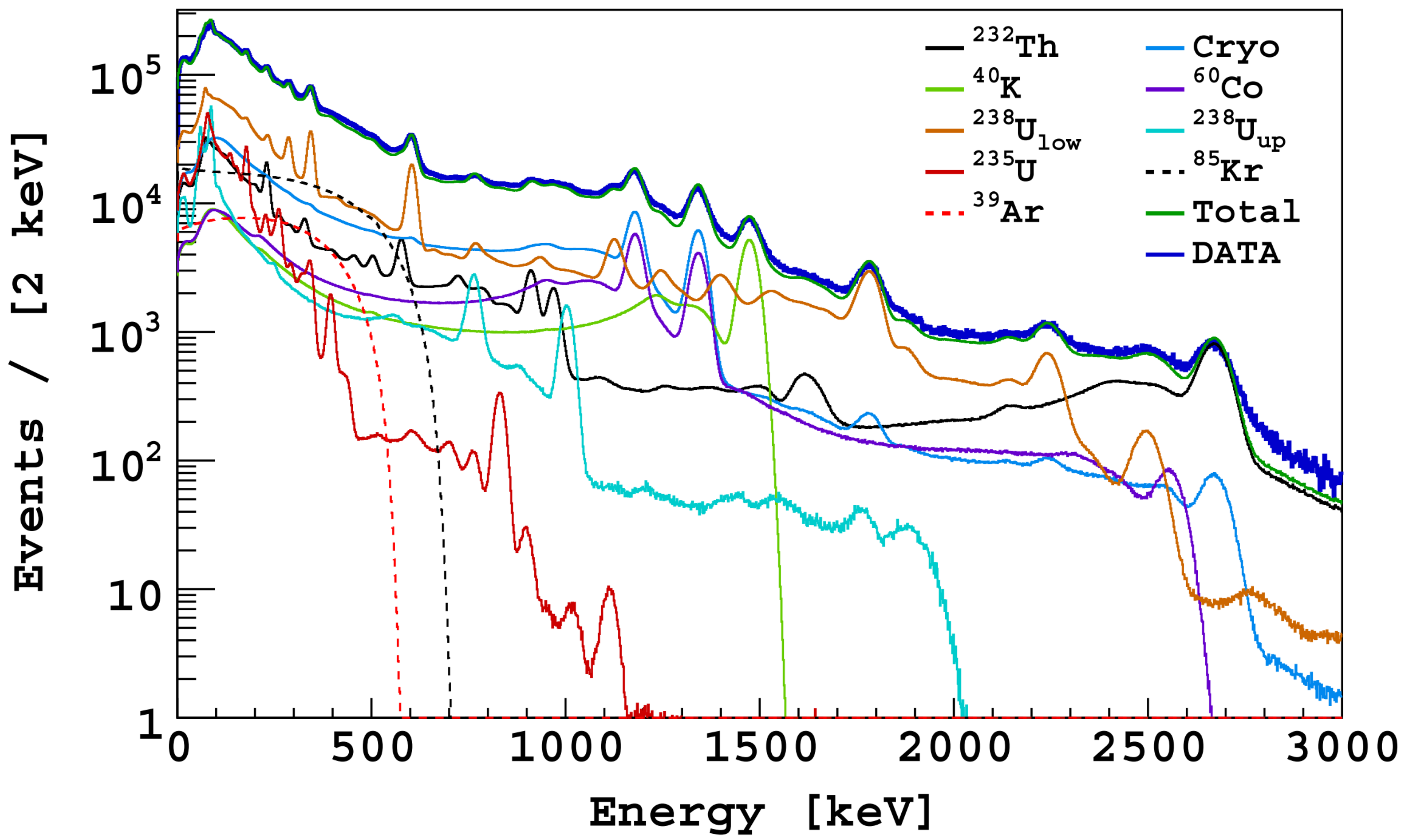
# Backgrounds

## From above



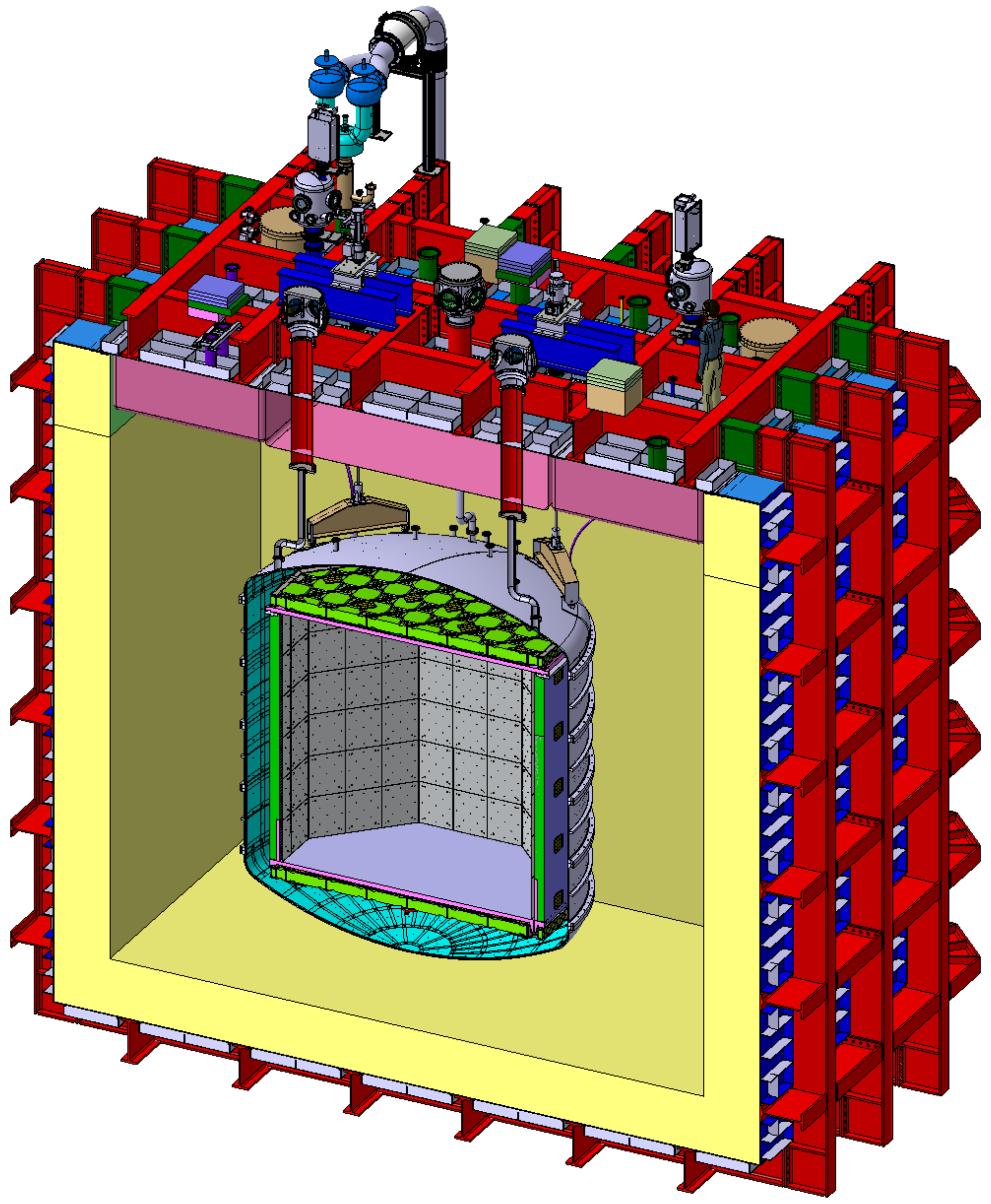
- Excessive muon rate at surface
- Radioactive isotopes activated
- Neutron generation
- Go underground!

## From below



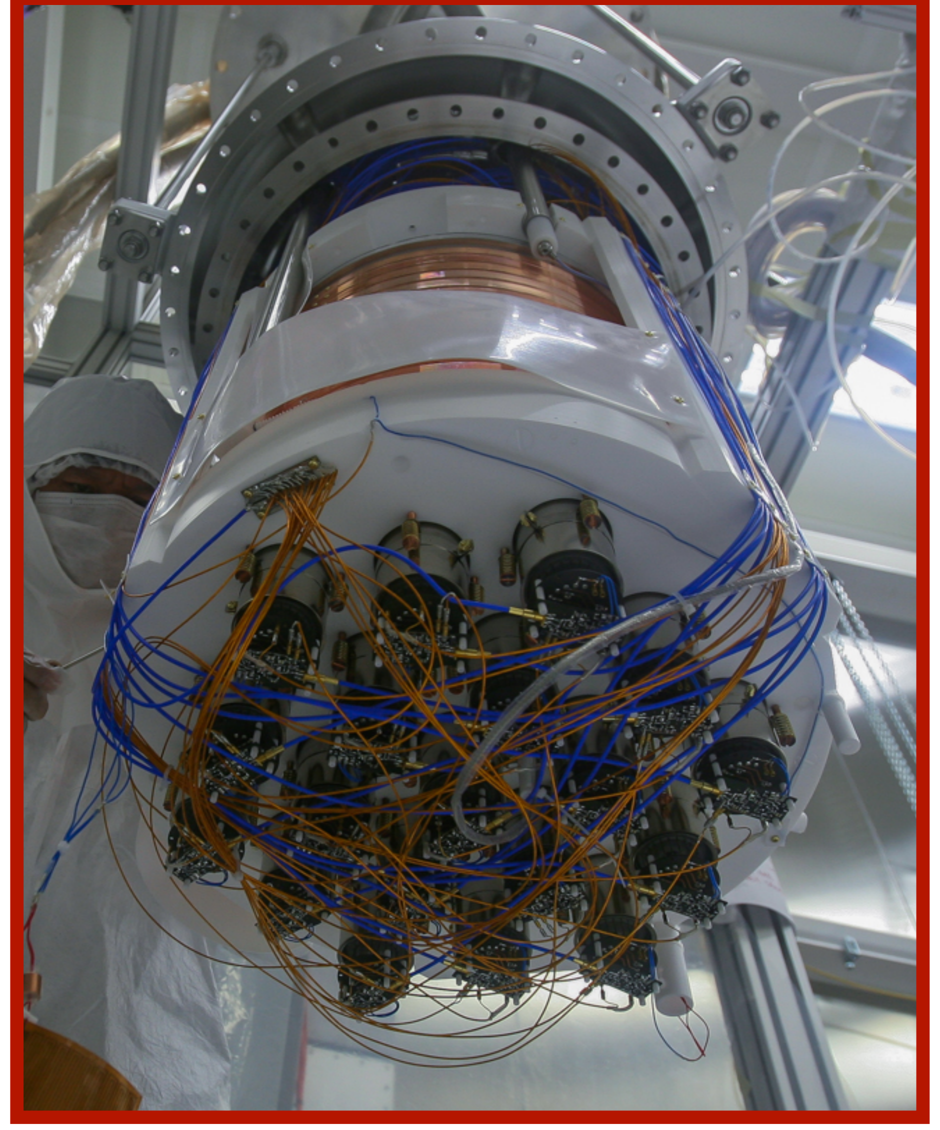
- Natural radioactive isotopes: U and Th chains, non-actinides
- Material assay and selection
- Particle identification: ER/NR
- Fiducialization: surface events

## Solution



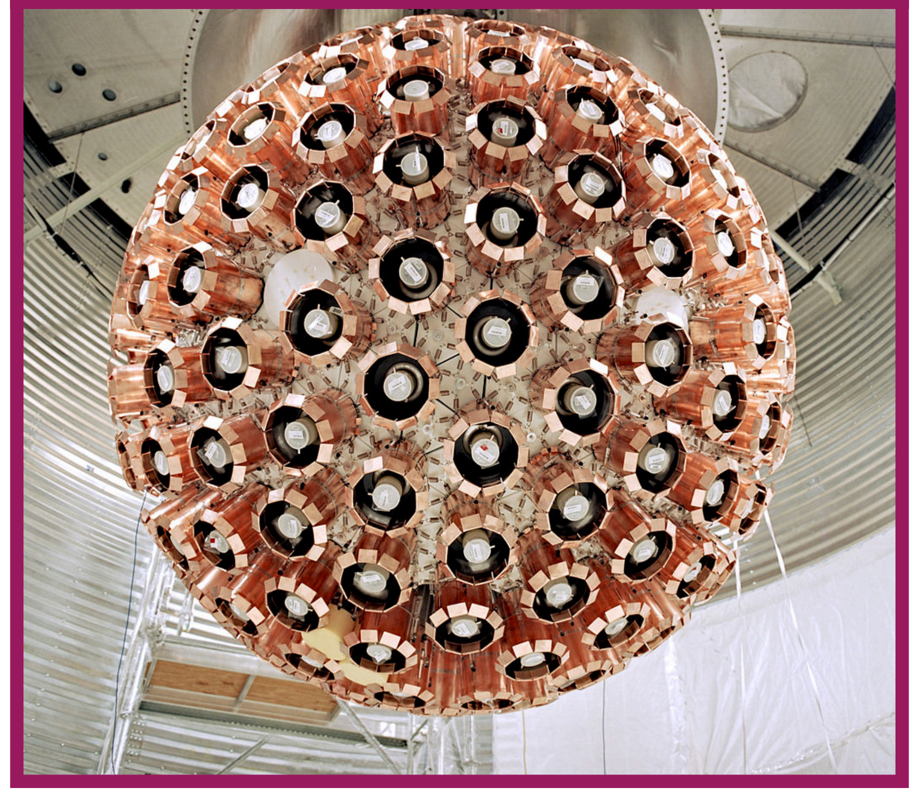
- Onion-like structure:
  1. Muon veto
  2. Neutron veto
  3. WIMP detector

# The GADMC


**DarkSide-50 @ LNGS**

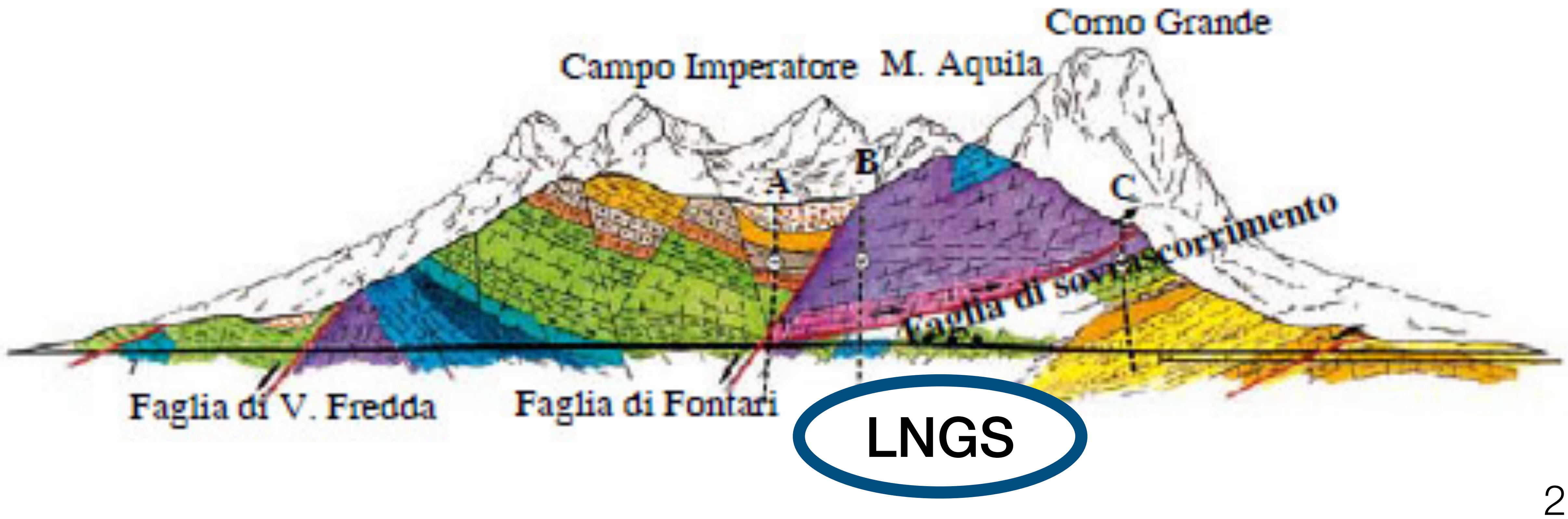

**ArDM @ Canfranc**


**MiniClean @ Snolab**


**DEAP @ Snolab**

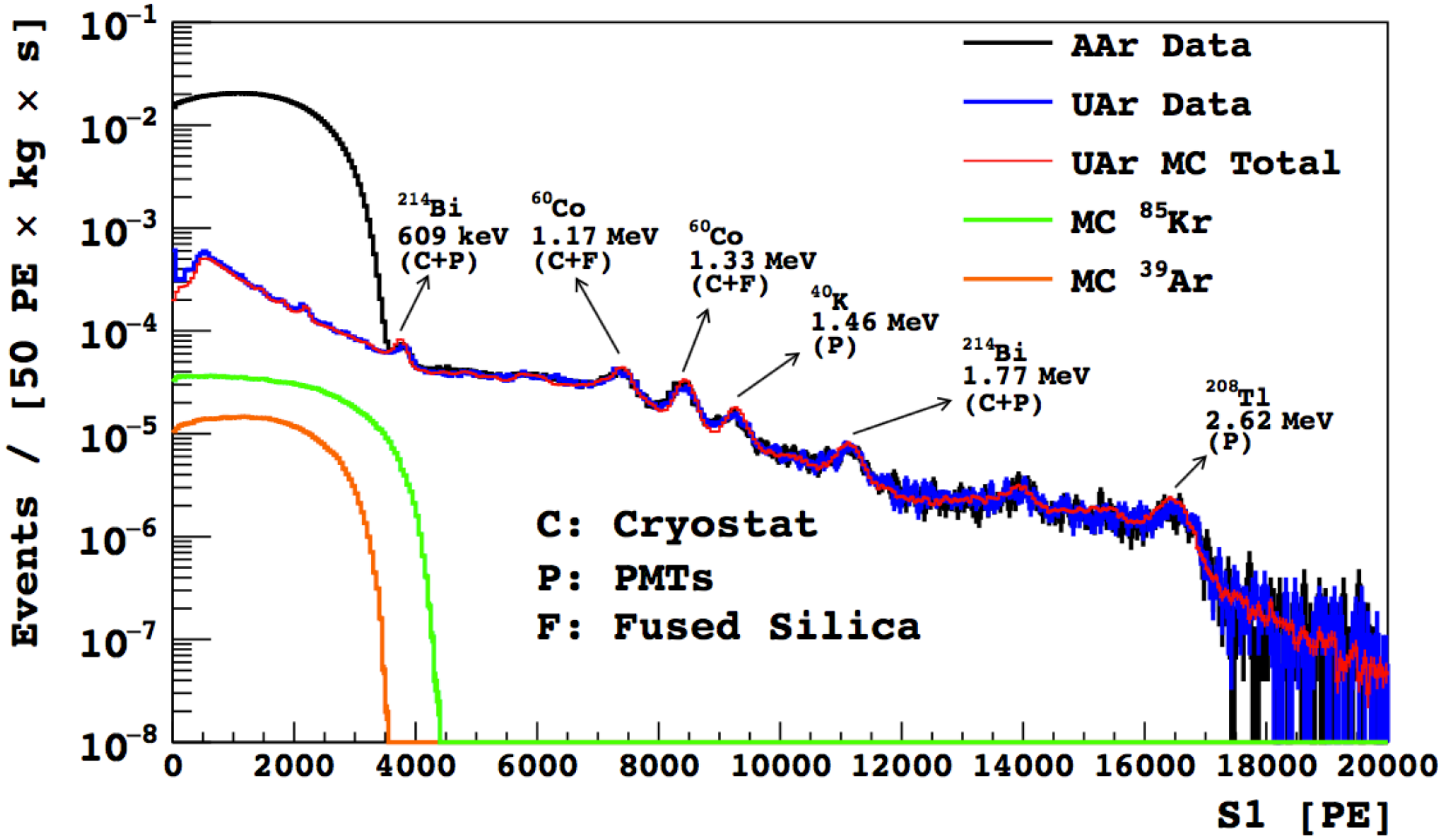
>400 scientists, >100 institutions distributed across 13 countries

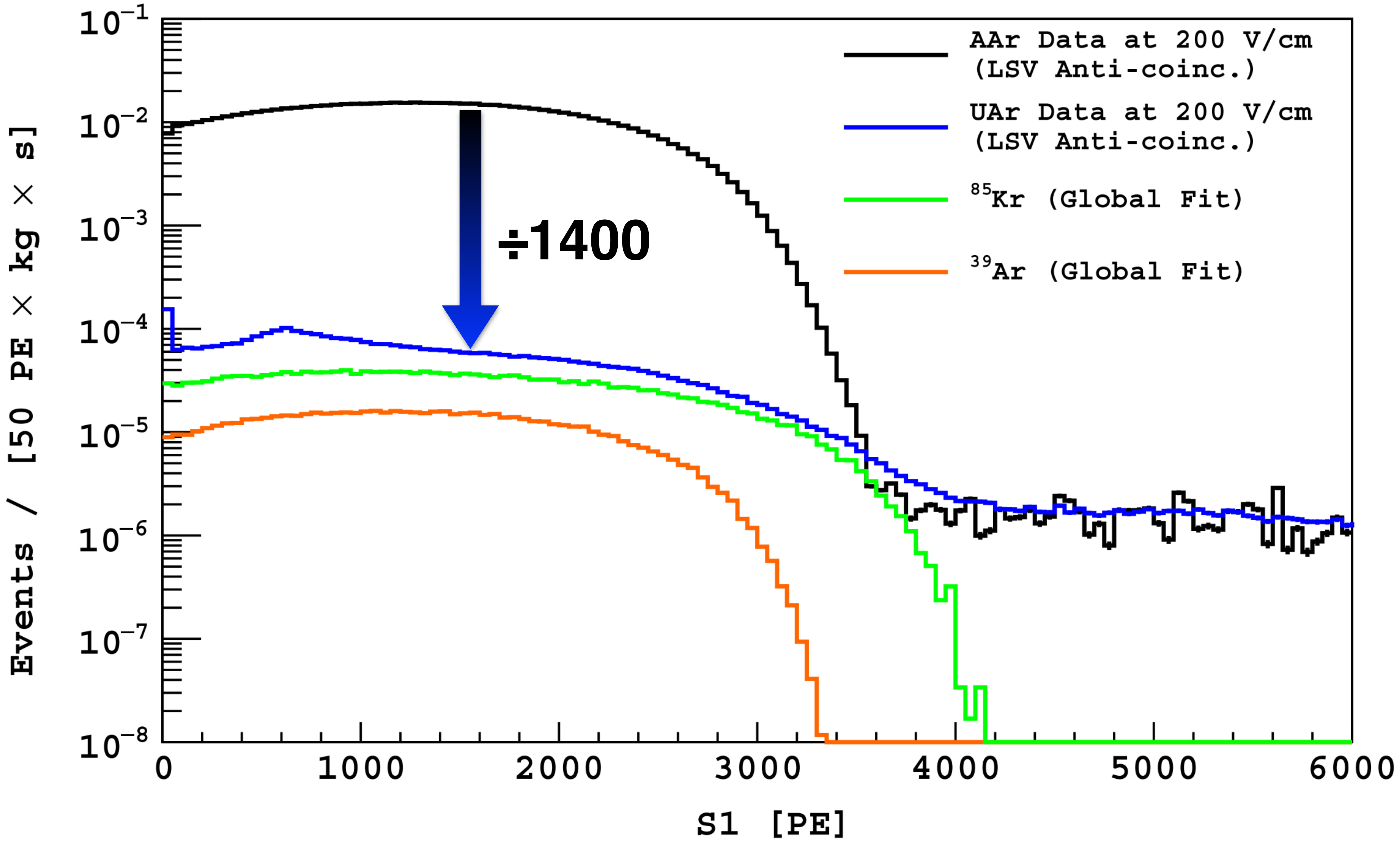
# Host laboratory: LNGS



- Below ~1400m of rock (3400 m.w.e)
- Muon flux reduction factor ~$10^6$
- 3 main experimental halls ($20 \times 100 \times 18$ $m^3$)

# Argon from underground (UAr)

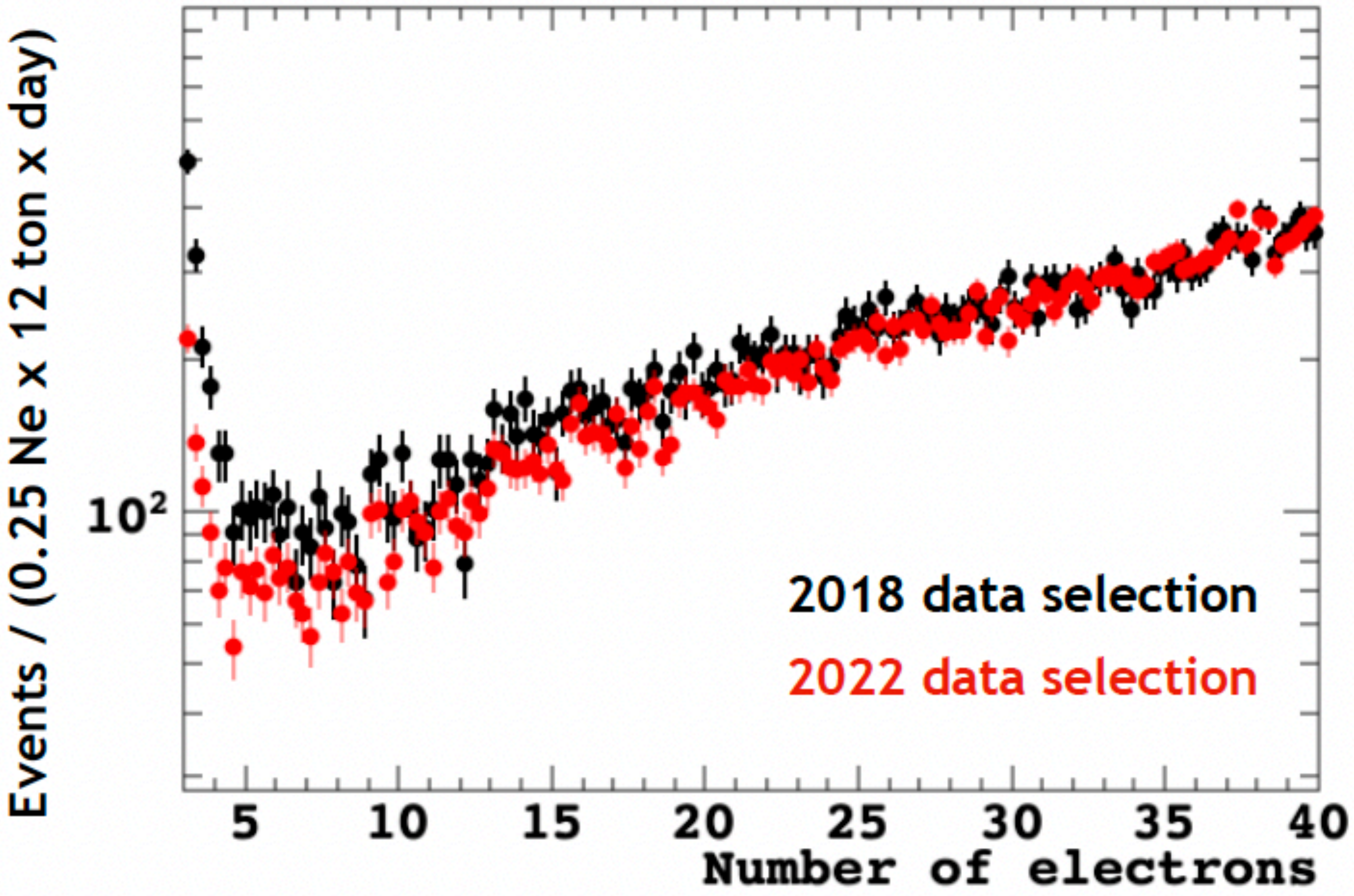




- $^{39}$Ar is a cosmogenic isotope
- β-decay with 565 keV endpoint and ~269y of half life
- ~1Bq/kg in atmospheric Ar
- Rejection possible with PSD, but there’s pile-up!

- No activation in Ar from deep gas reservoirs (UAr)
- Suppression factor ~1400 demonstrated in DS-50
- Possibly higher depletion factor

# Dataset



- Exposure: 653.1 live-days
- Average **trigger rate**: 1.54 Hz

**Quality cuts**

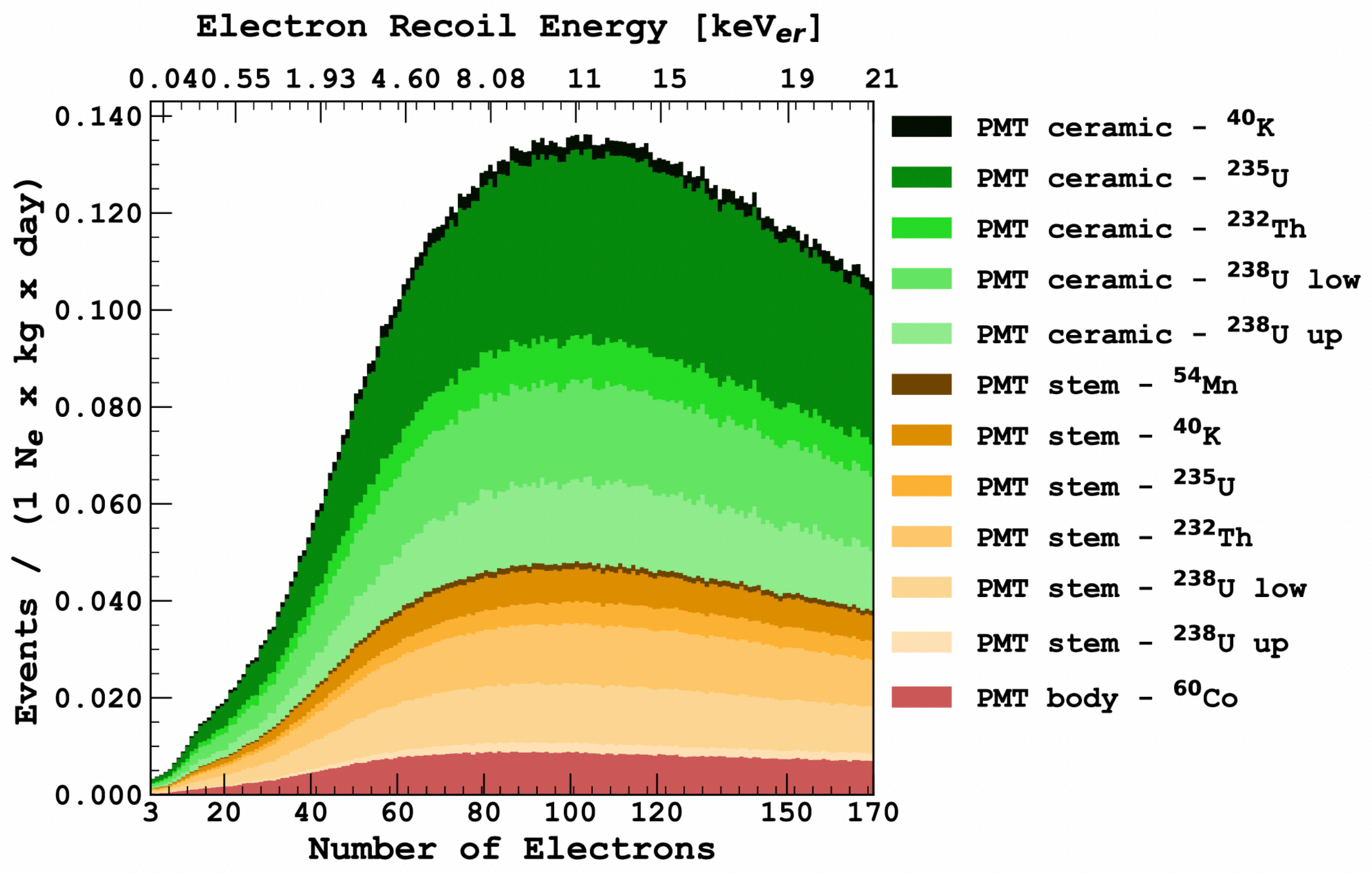
- Pulse-shape: remove anomalous pulses due to the pile-up of multiple S2's or S1+S2
- Acceptance: 95% at 4 Ne and 99% at >15 Ne

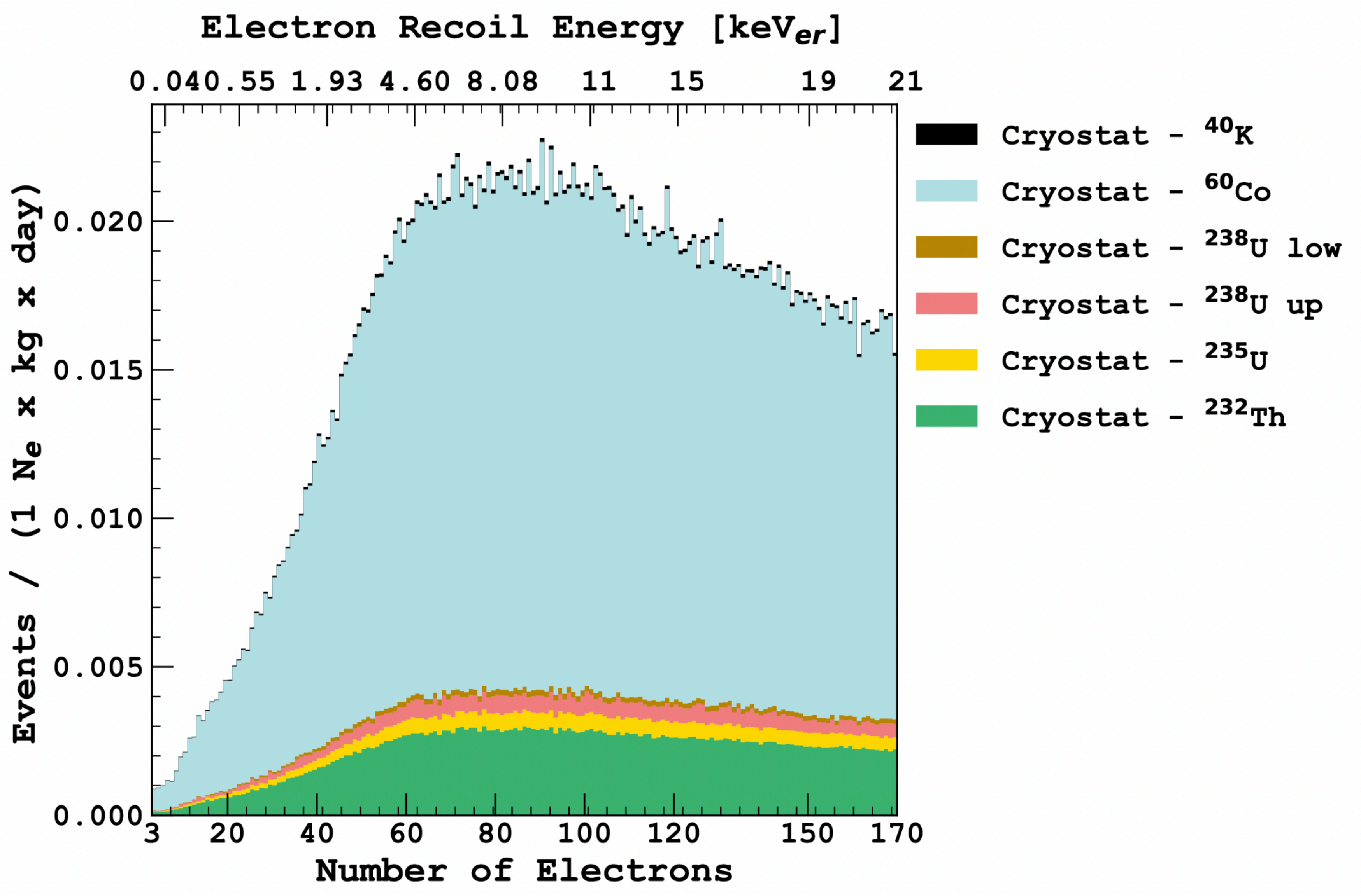
**Selection Cuts**

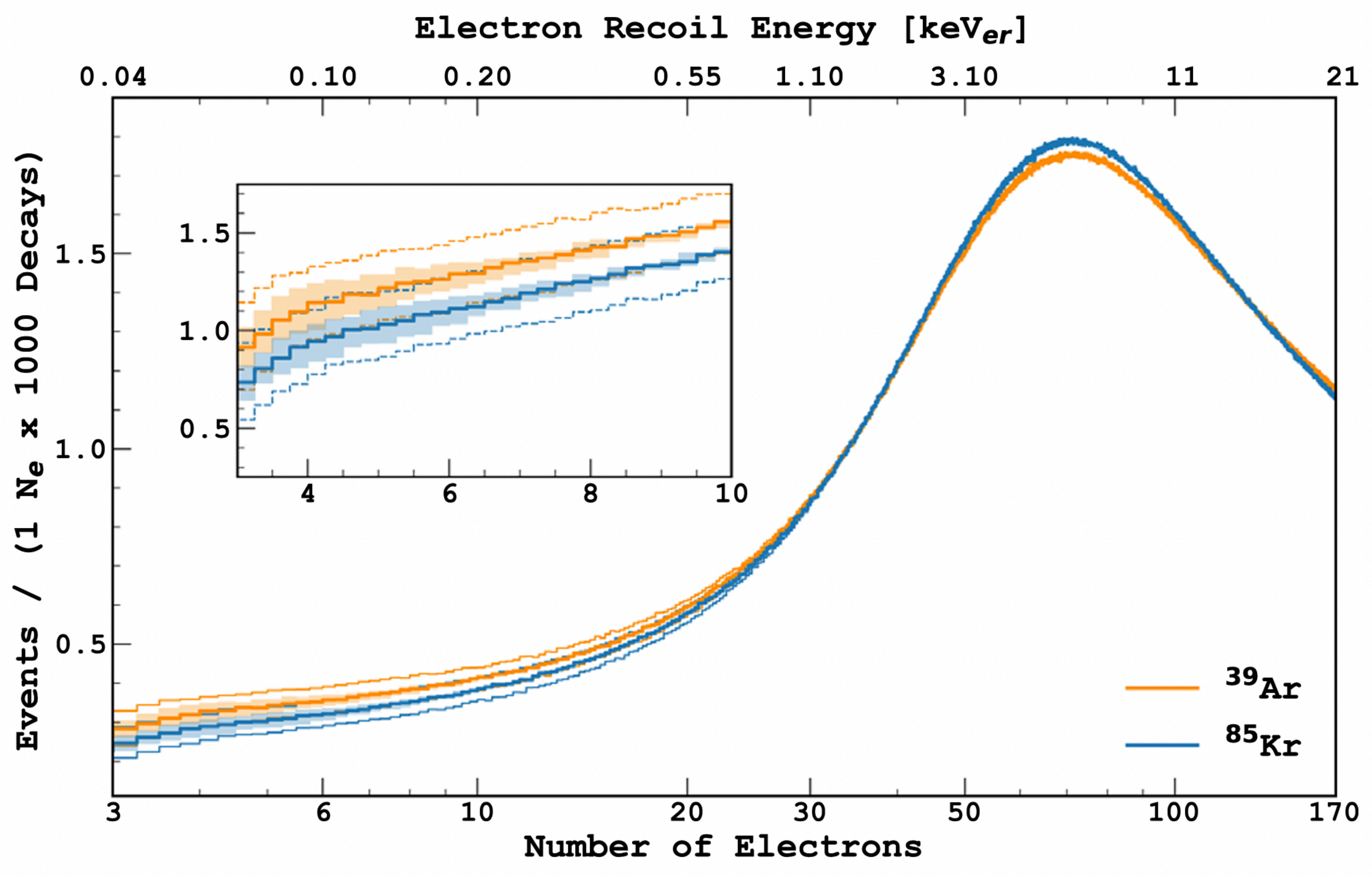
- Fiducialization
- S2/S1 against S2's from alphas
- Time veto agains spurious electrons

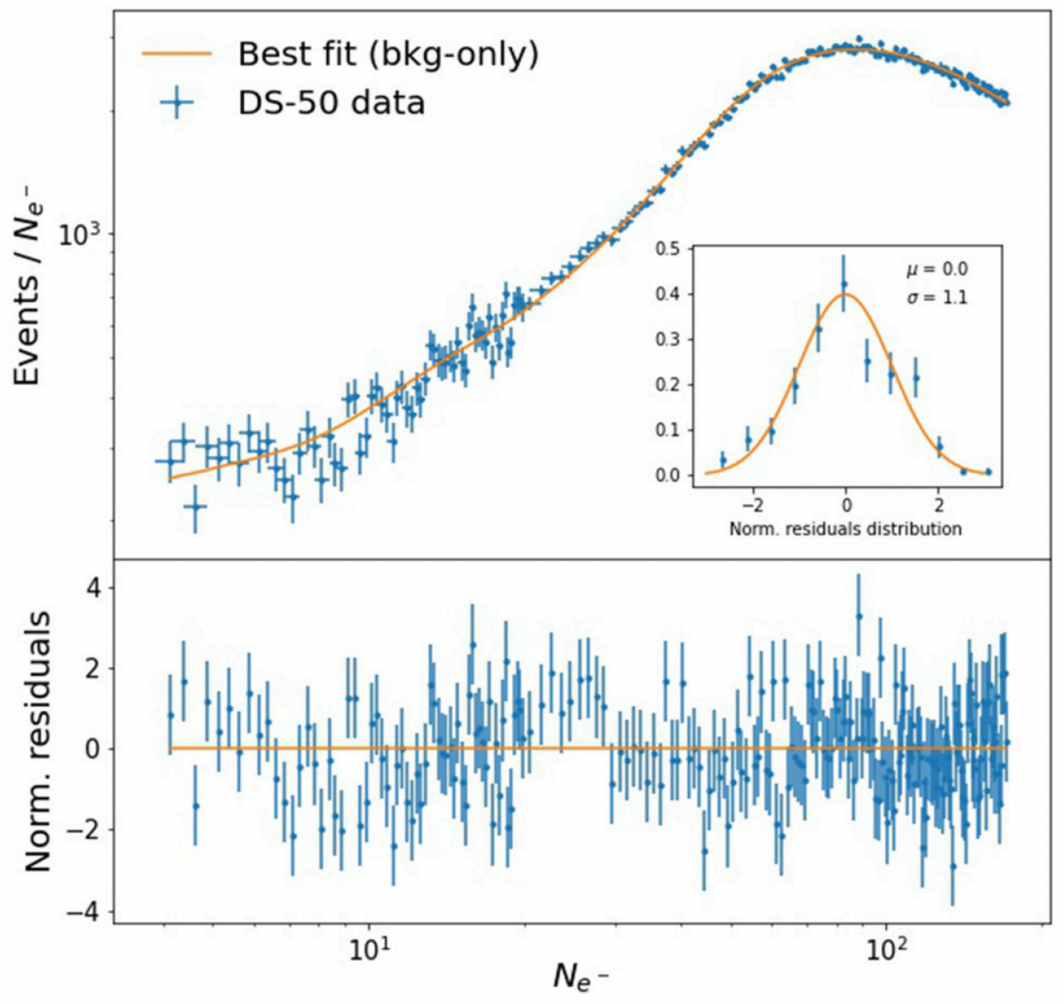
**New high statistics Background Model**

# Background Model









- High statistics MC samples

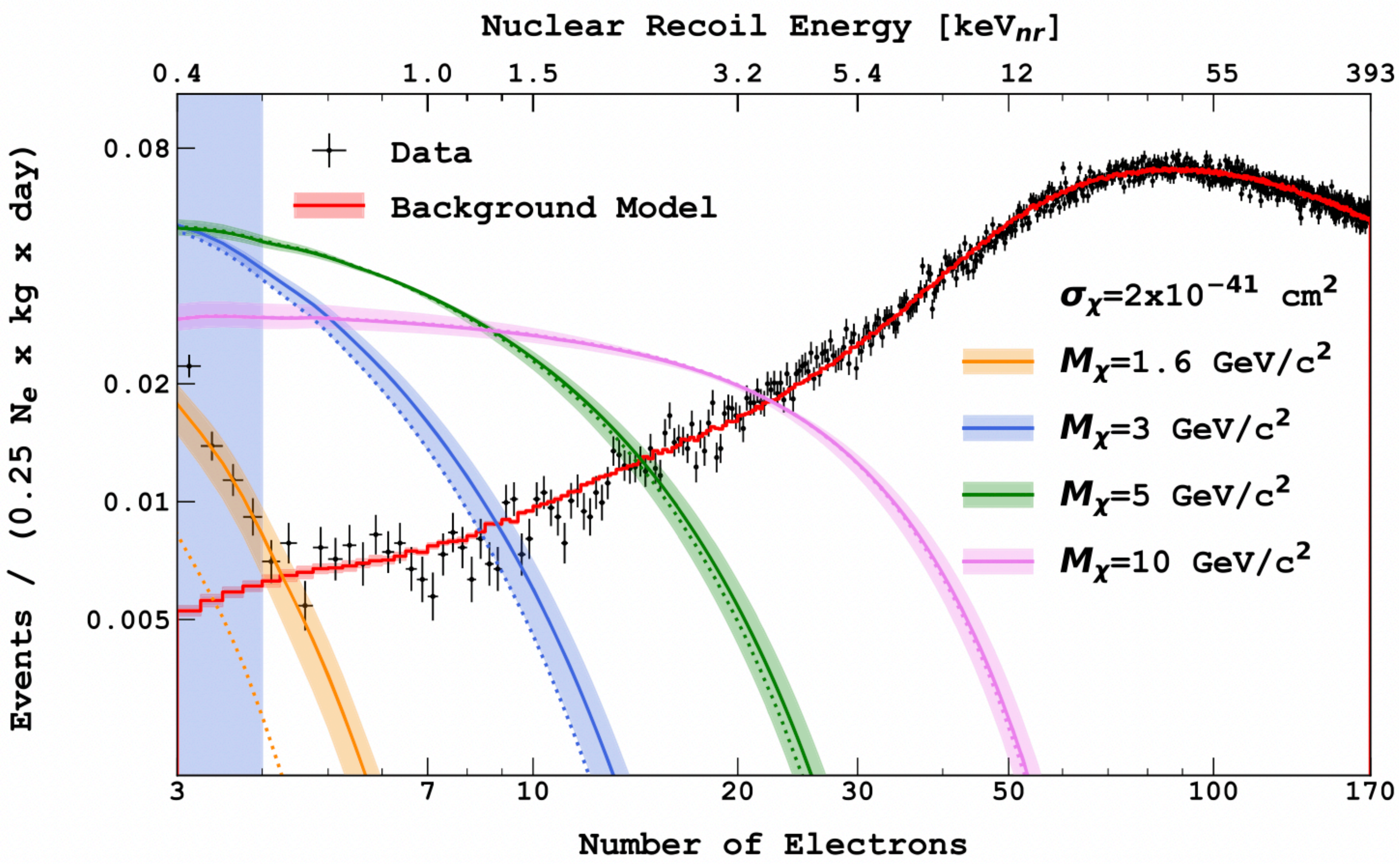
**Internals**

- Argon-39
- Kripton-85

**Externals**

- PMTs
- Cryostat

# Dataset



- Exposure: 653.1 live-days
- Average **trigger rate**: 1.54 Hz

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- Pulse-shape: remove anomalous pulses due to the pile-up of multiple S2's or S1+S2
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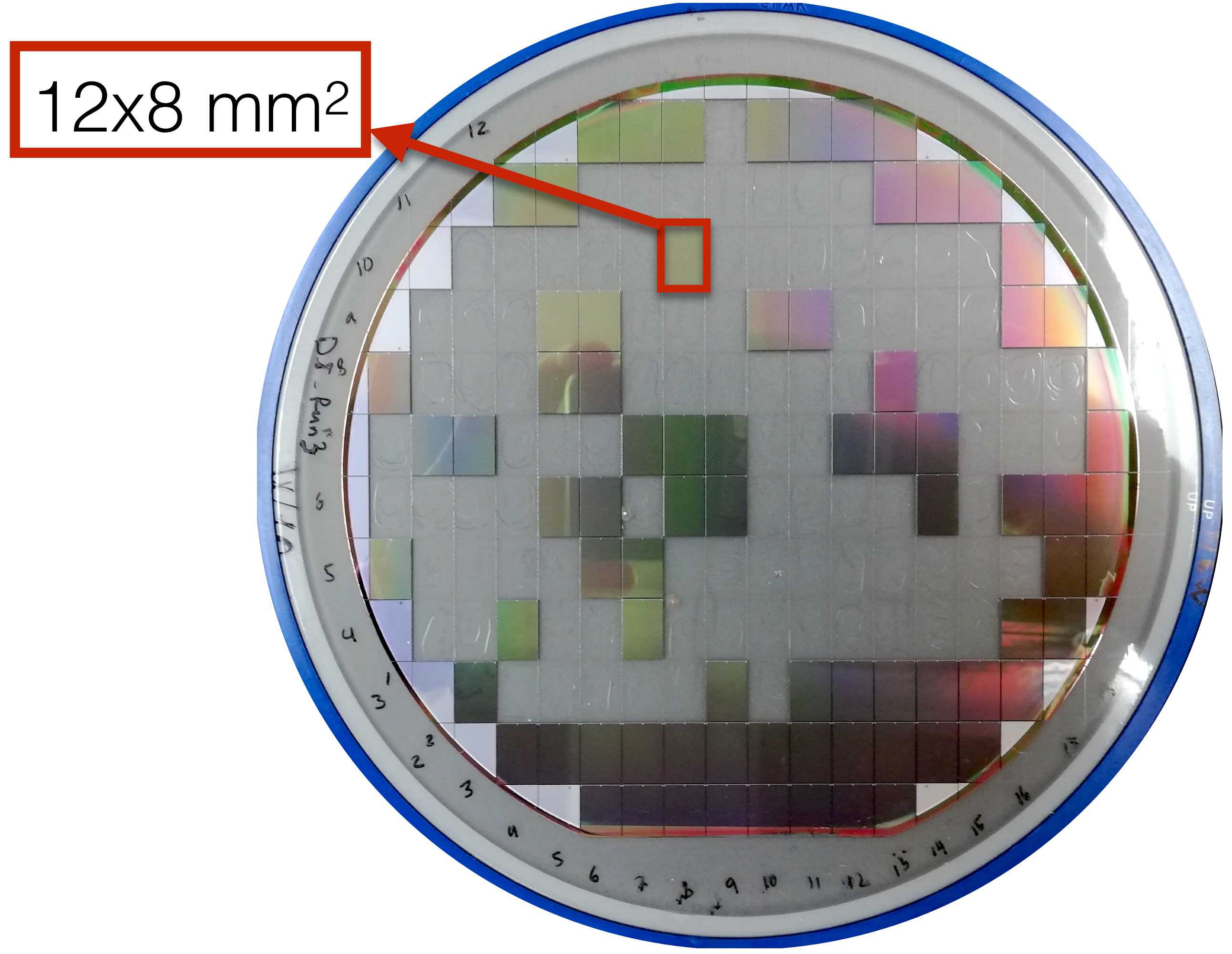
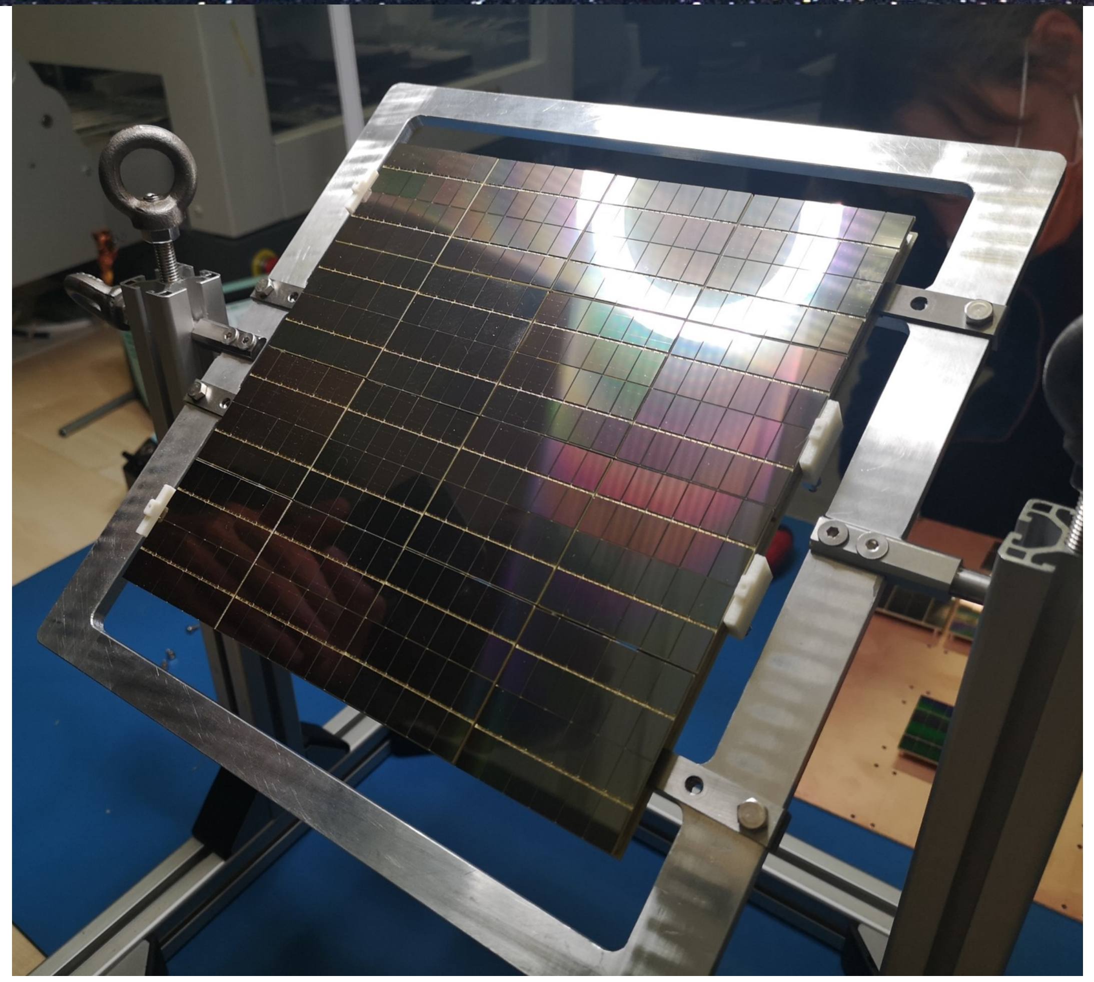
**Selection Cuts**

- Fiducialization
- S2/S1 against S2's from alphas
- Time veto agains spurious electrons

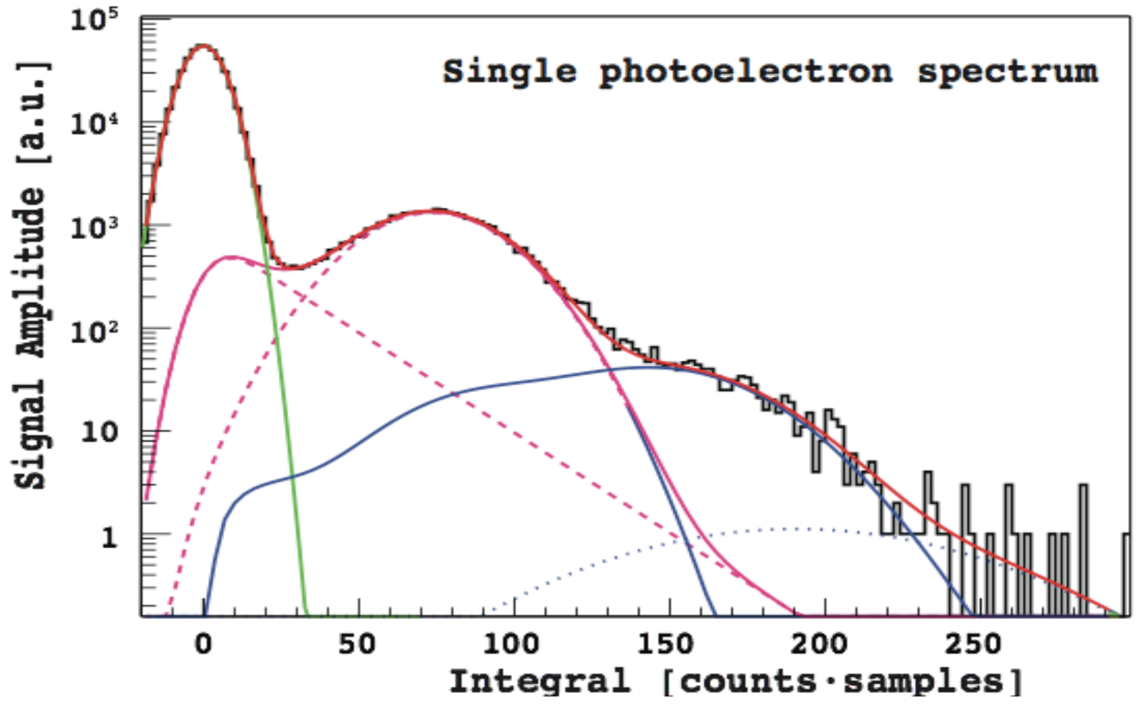
**New high statistics Background Model**

# SiPMs: an enabling technology

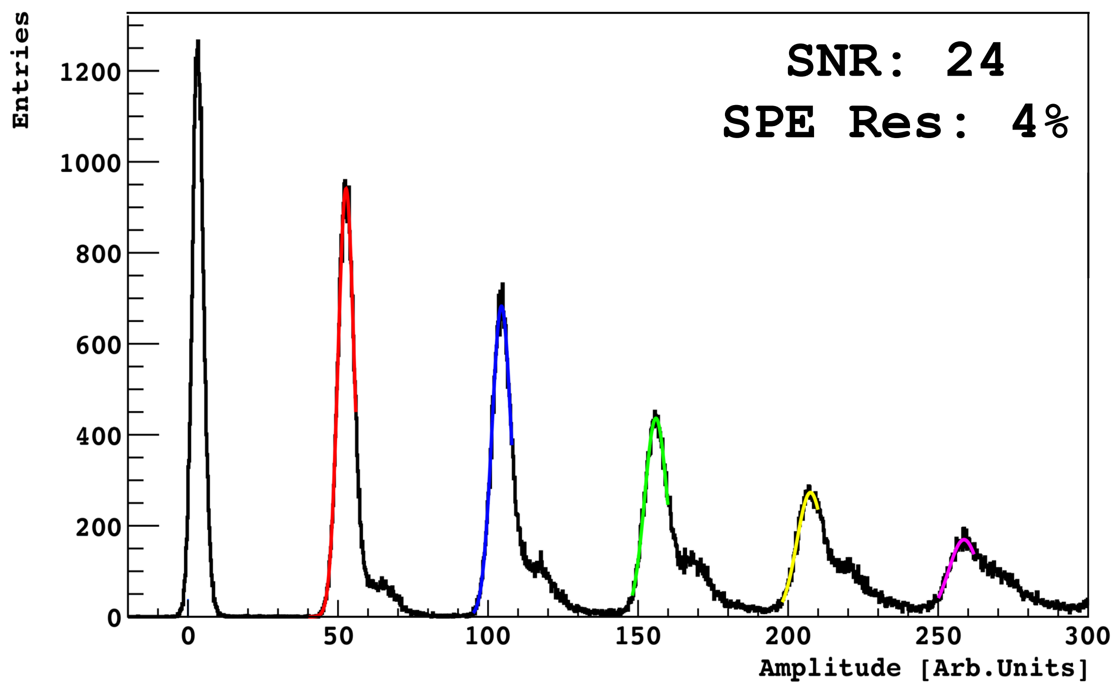




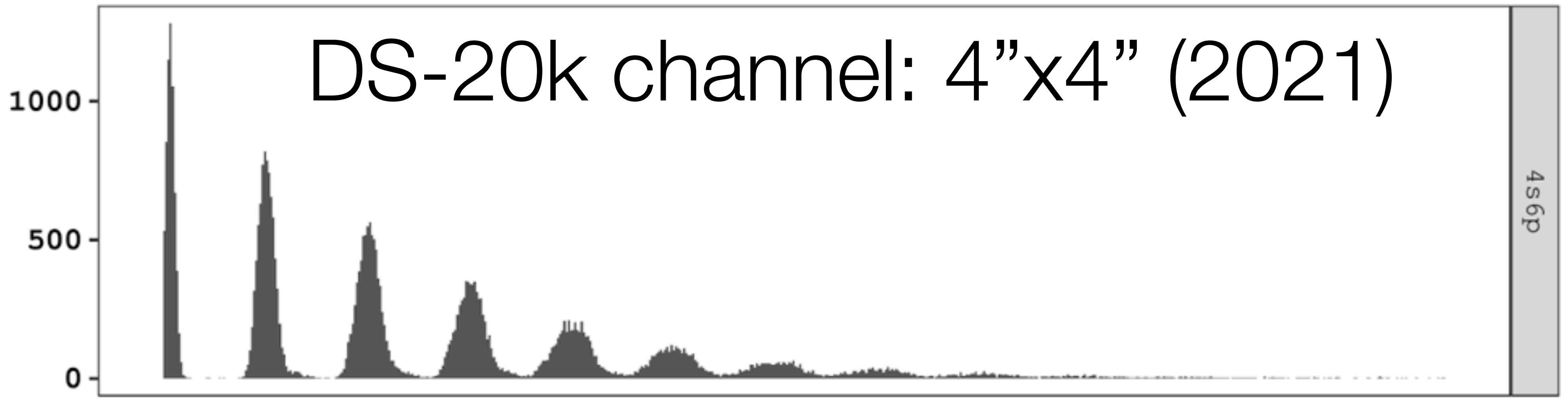
PMT ⌀3” (2012)



SiPM array 2” (2017)

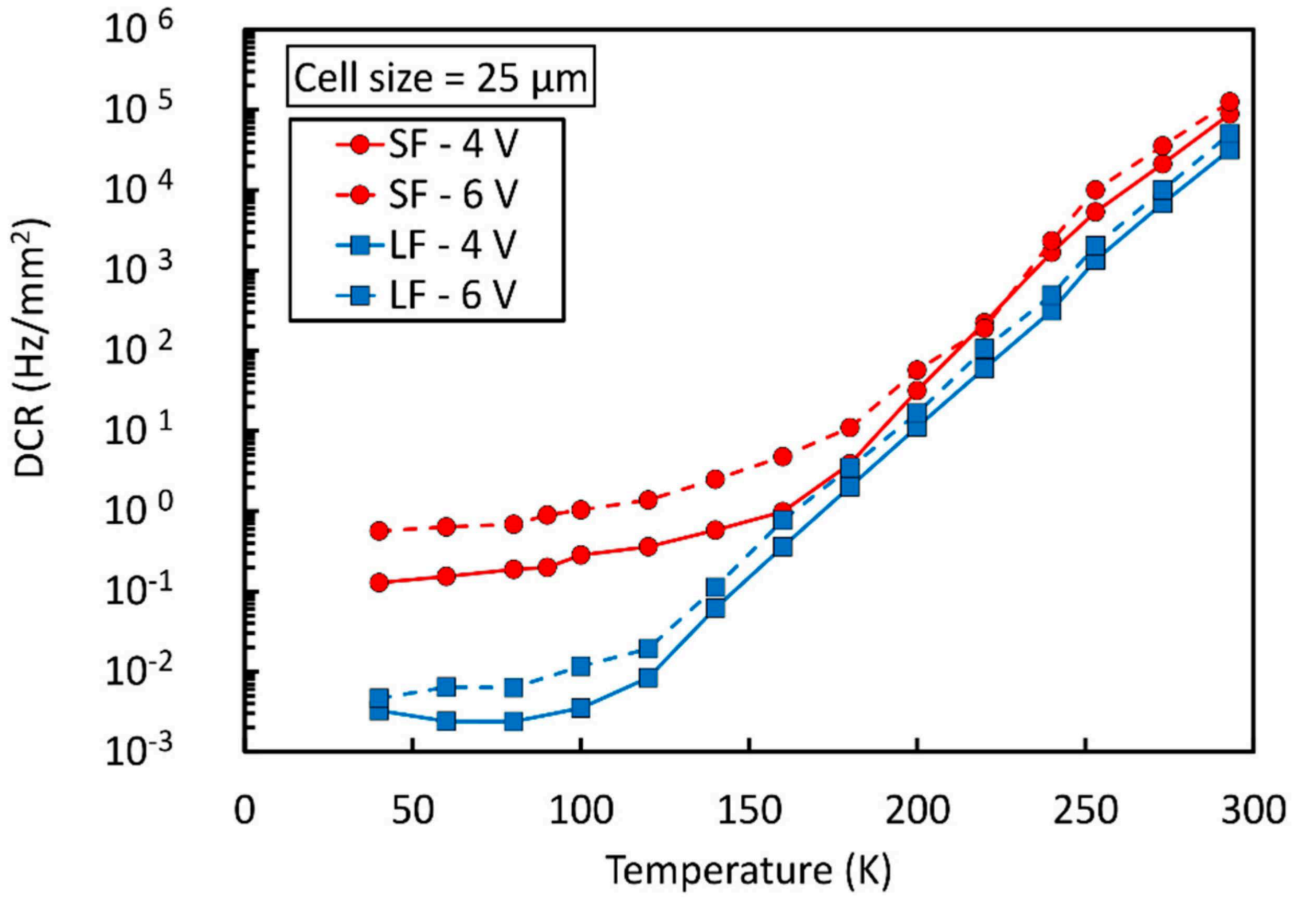


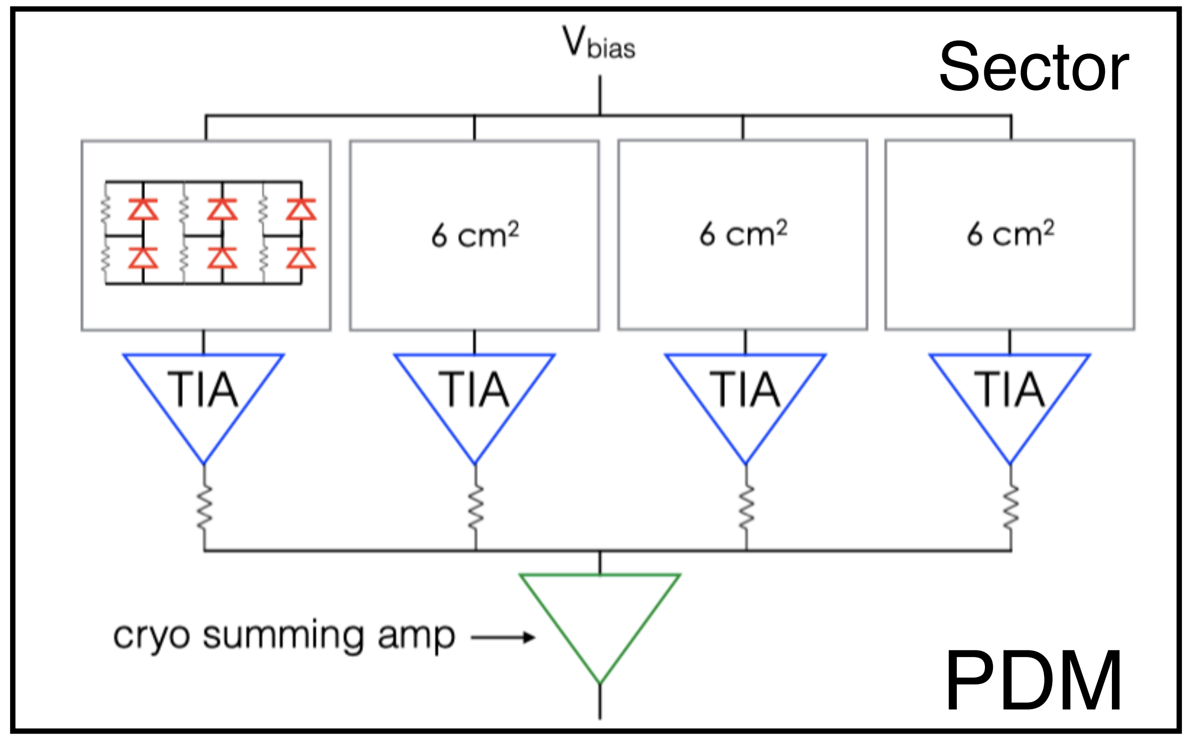
DS-20k channel: 4”x4” (2021)



PMT: sub-optimal operation in LAr, PDE~35%

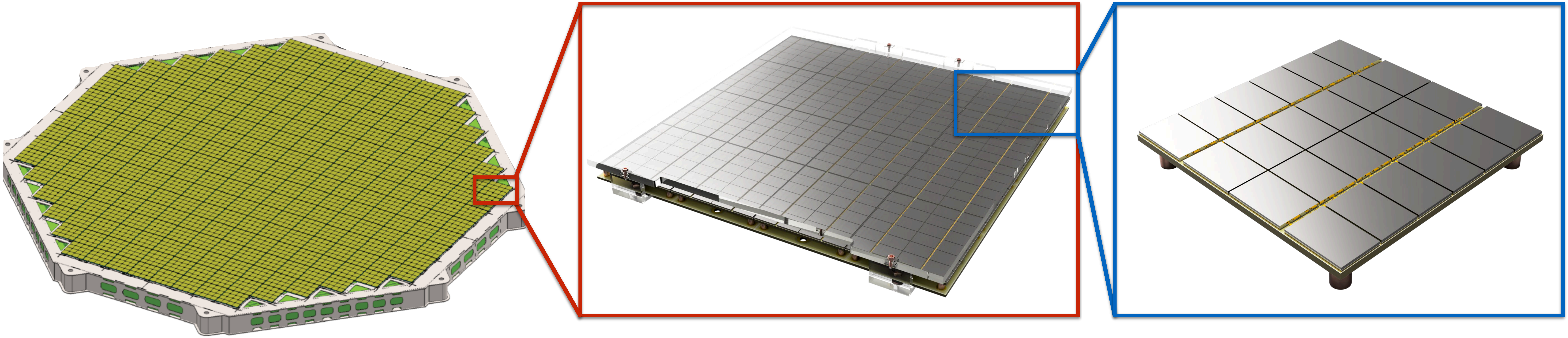
SiPMs: good PDE, but noise and readout challenges





- Requirements: 10.1140/epjp/i2018-11973-4
- Noise suppression: 10.1109/TED.2016.2641586, etc.
- Cryogenic amplifiers: 10.1109/TNS.2018.2799325
- Ganging: 10.1109/TNS.2017.2774779
- Final design: 10.1088/1748-0221/17/05/P05038

# Photo-detection system



## TPC optical plane

TPC planes area: 21m$^2$

2100 readout channels

100% coverage of TPC top and bottom

## Photo-Detection Unit

16 tiles arranged in 4 readout channels

Bias distribution

Signal transmission

## Tile

Photosensor

Array of 24 SiPMs

Signal pre-amplification

R&D and design phases completed. SiPM production completed.

Assembly of photo-sensors in NOA (LNGS clean-room facility) to start this summer.