First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment

Xin Xiang, Ph.D.
On behalf of LZ Collaboration

Particle Physics Seminar @ BNL 09-01-2022

Sanford Underground Research Facility
South Dakota Science and Technology Authority

Brookhaven National Laboratory

BROWN

Outline

- LZ in the Landscape of Particle Dark Matter Search
- Overview of LZ-ZEPLIN Detector
- First Results of LUX-ZEPLIN
- Future LZ, XLZD and Beyond

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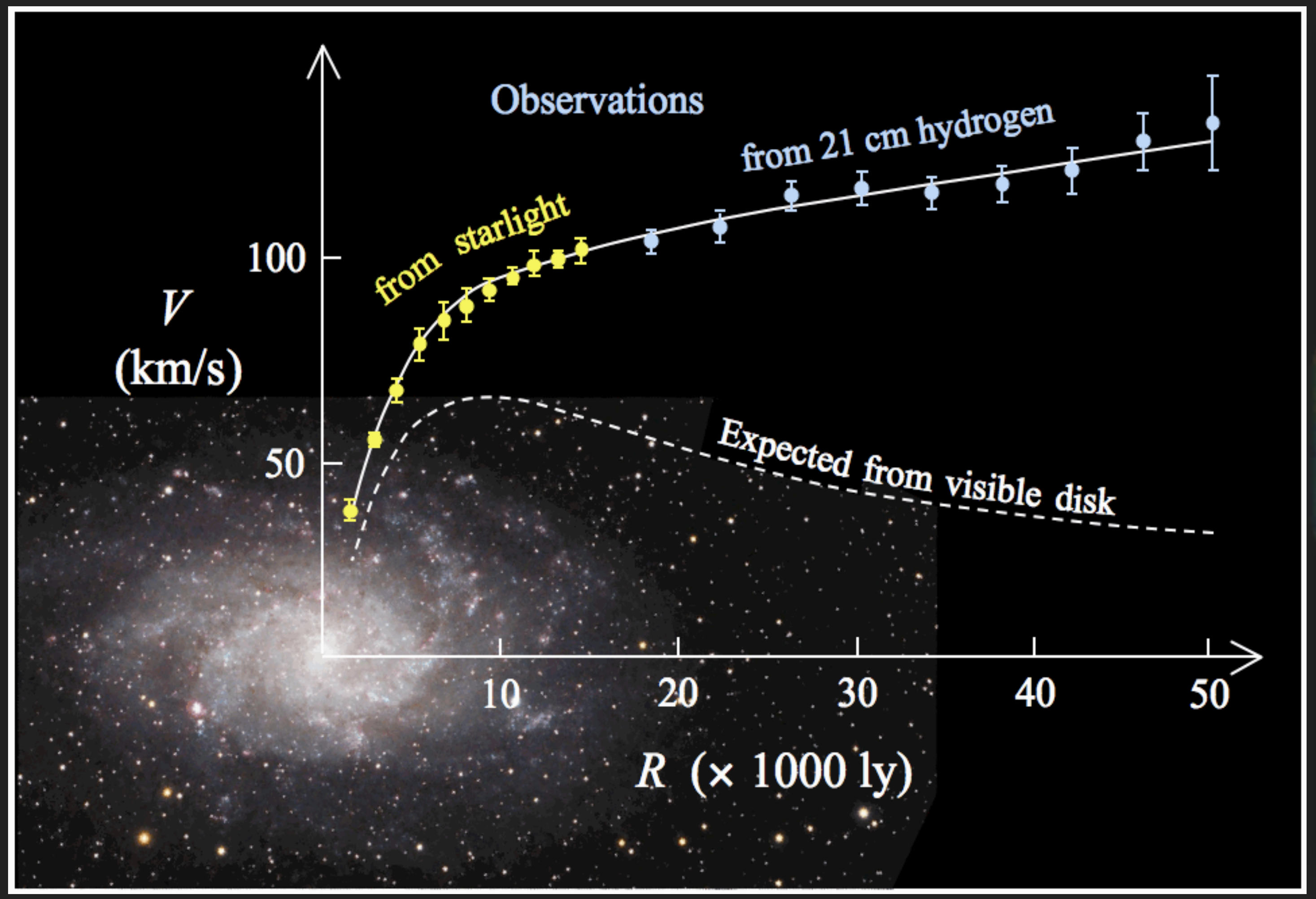
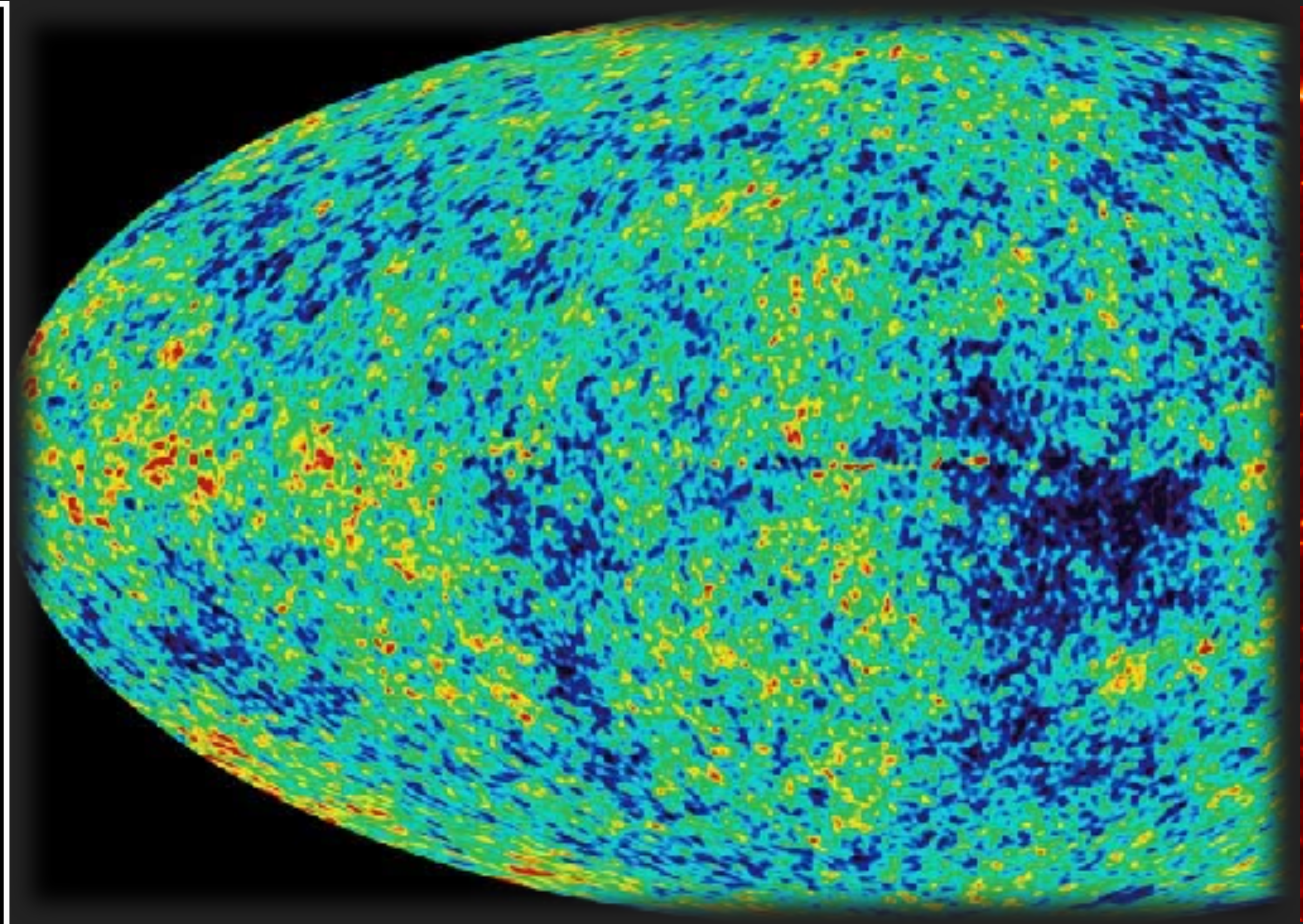
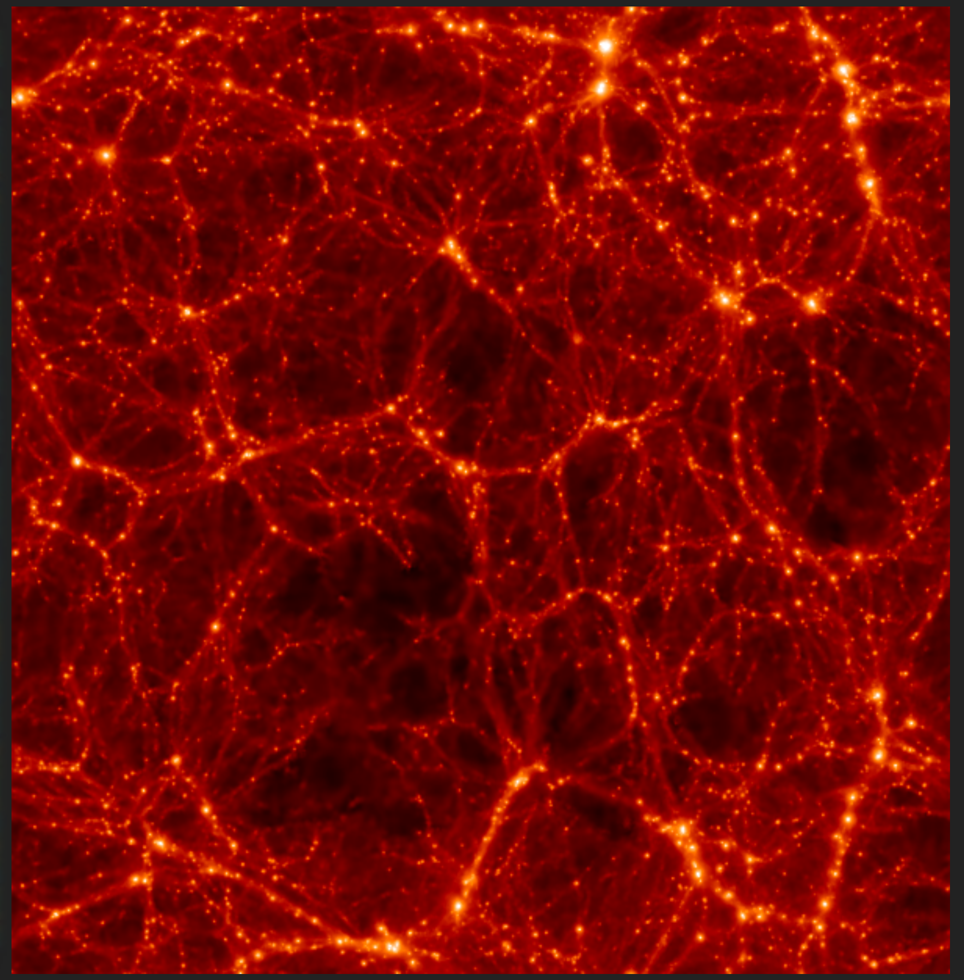
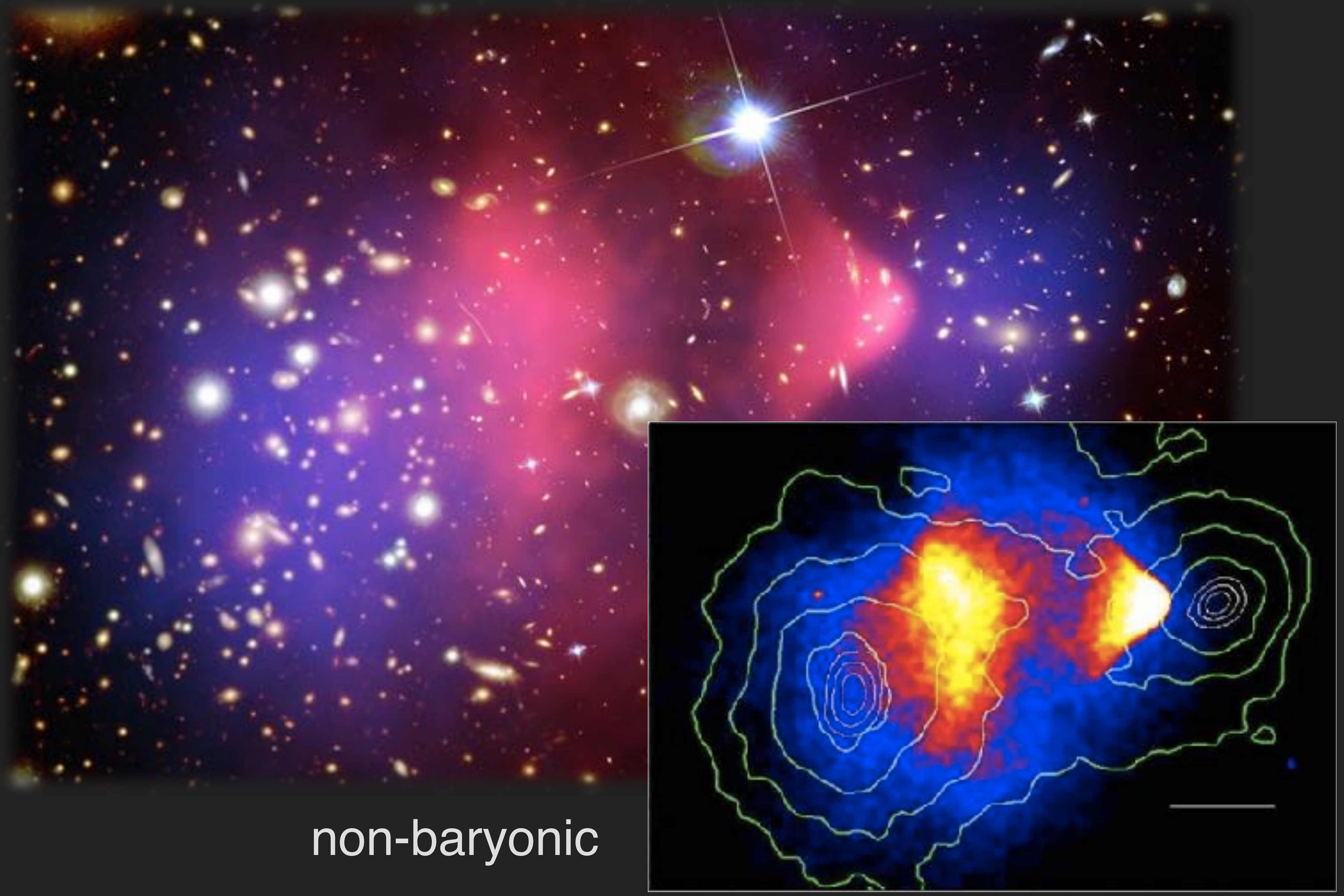
EVIDENCE FOR DARK MATTER

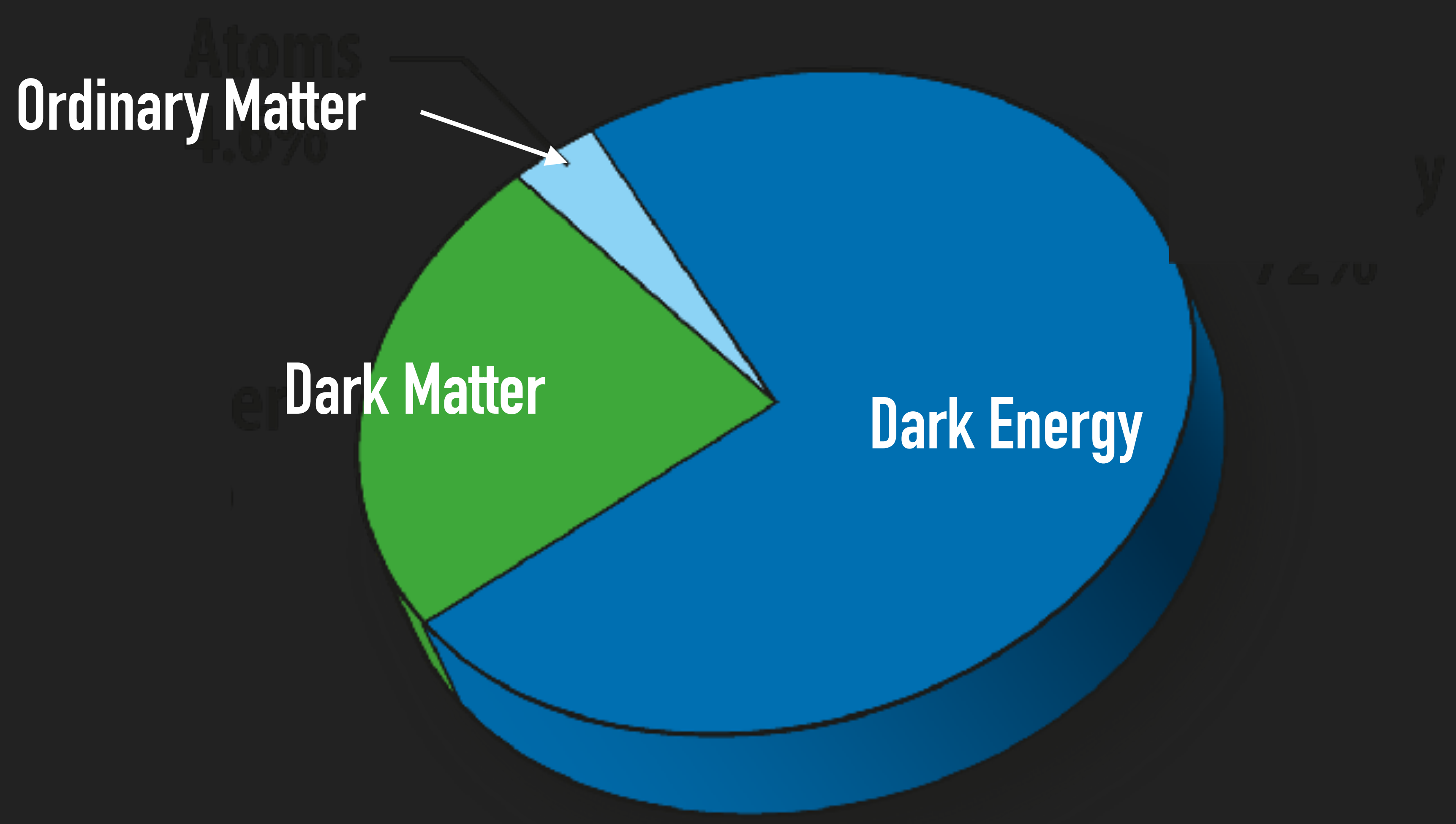




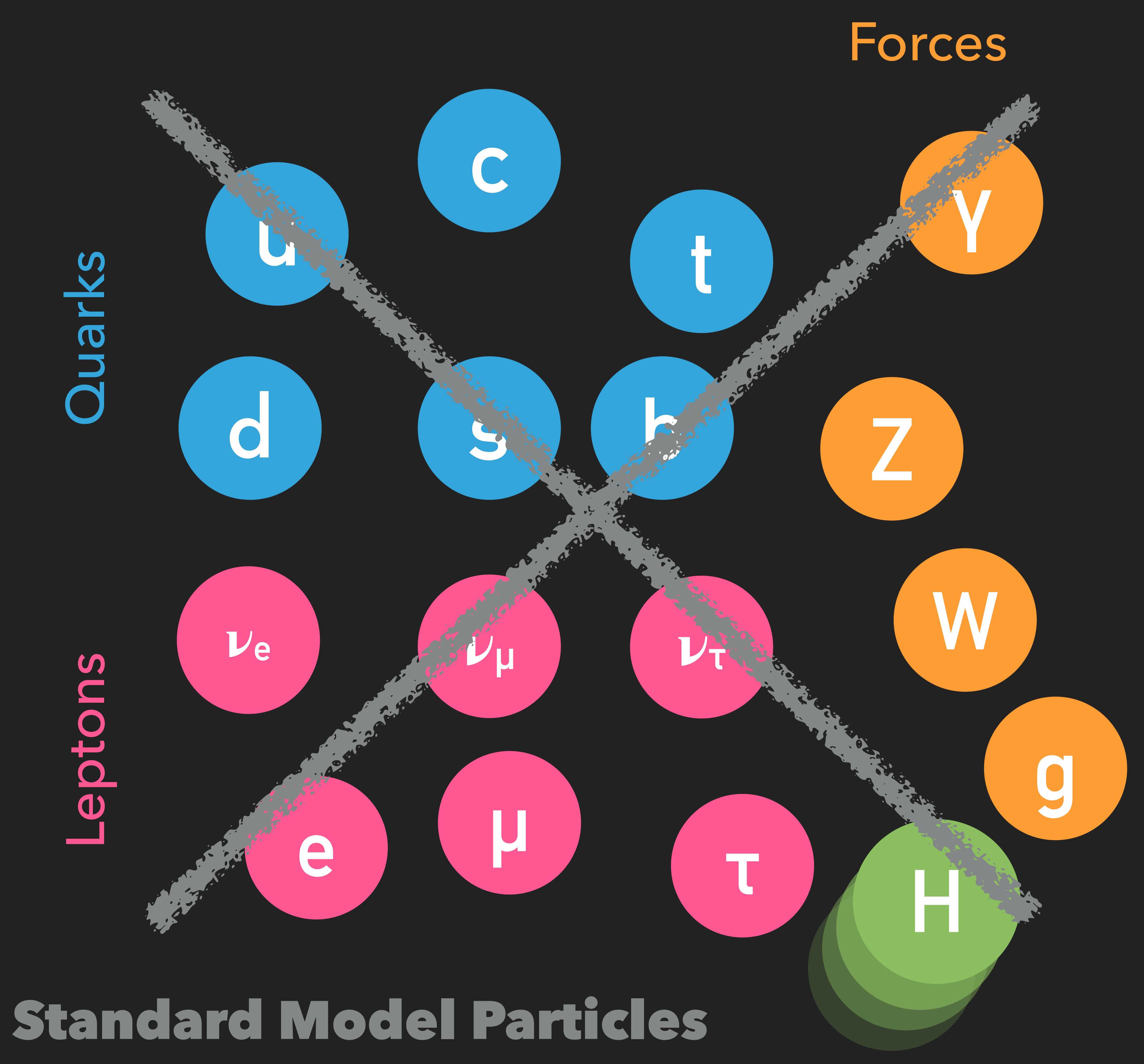




non-baryonic



DARK MATTER PROPERTIES

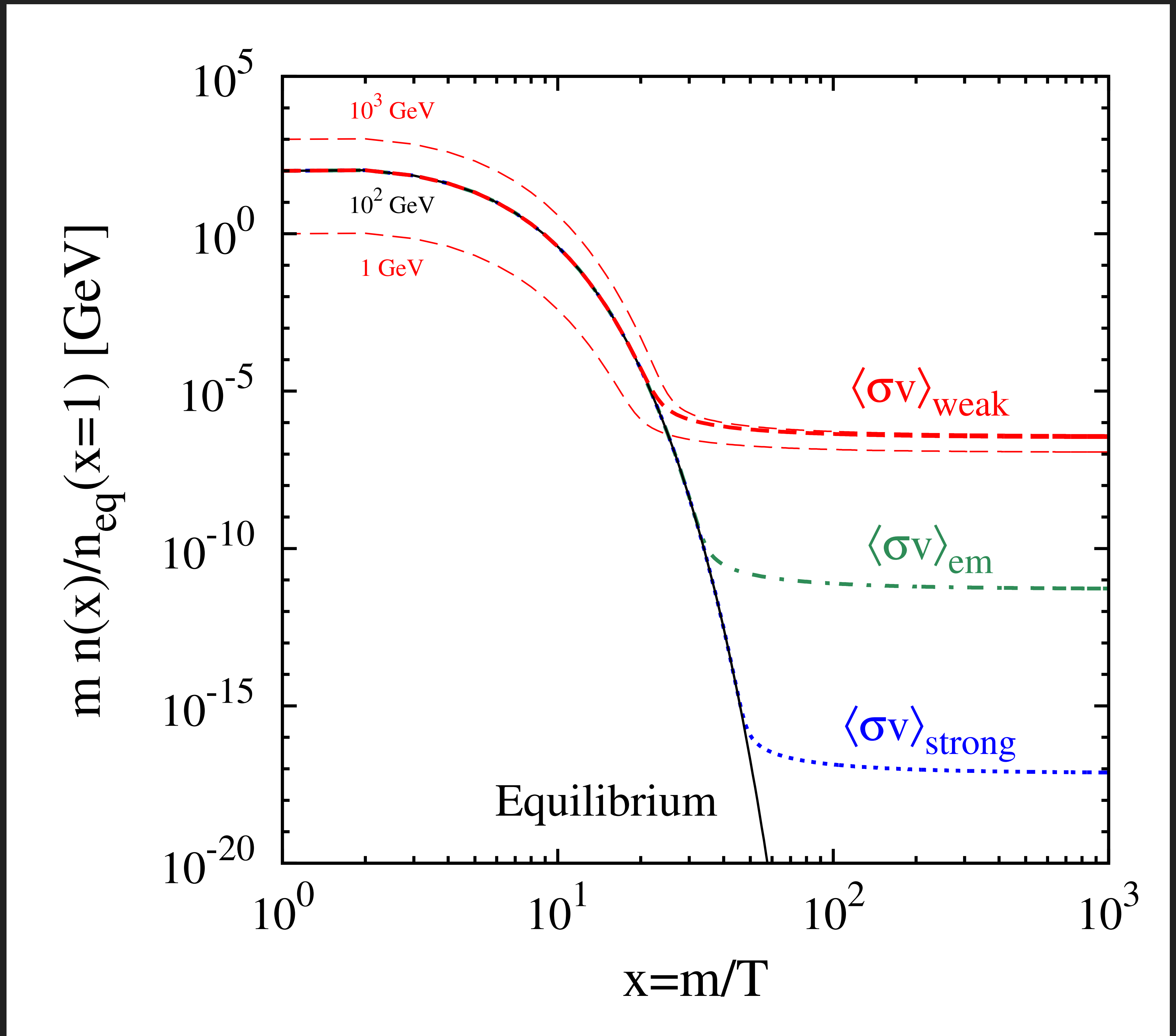


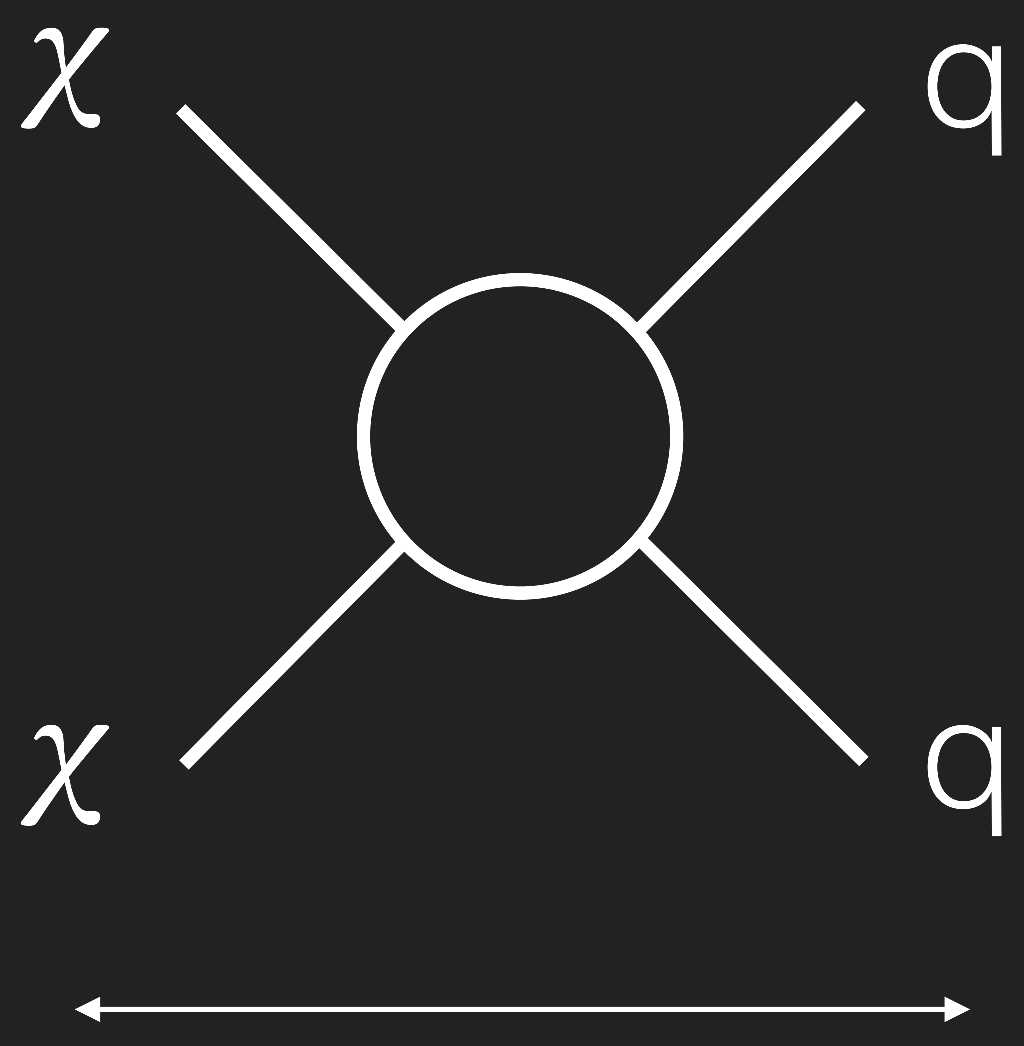
- Gravitationally interacting
- Stable particle
- Not hot
- Not Baryon

New Physics Beyond Standard Model!!

Weak Interacting Massive Particles (WIMPs) - lightest neutralino?

A WIMP MIRACLE





1. When $T \gg m$, equilibrium
2. When $T < m$, χ decay exponentially.
3. When $\Gamma = H$, χ can not find each other.

$\Gamma = n(x)\langle\sigma v\rangle \Rightarrow n_f(x) = H/\langle\sigma v\rangle$

Weak-scale cross section reproduces the expected relic abundance of DM (ΛCDM)

LOCAL DENSITY OF DM

- Local density of DM, $\rho_{DM} \sim 0.3$ GeV/cm^3

=

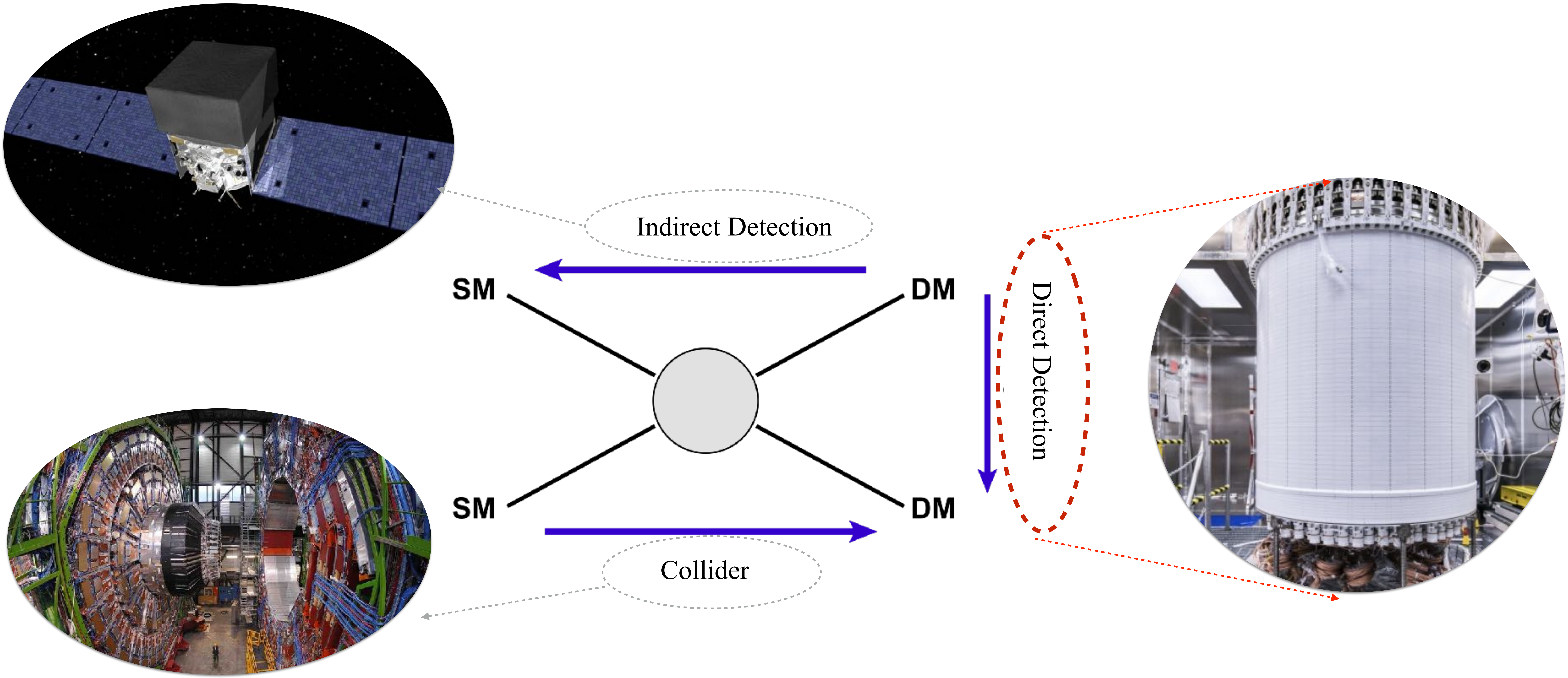
DARK MATTER
~ 500 g

Only mass (energy) density is known.

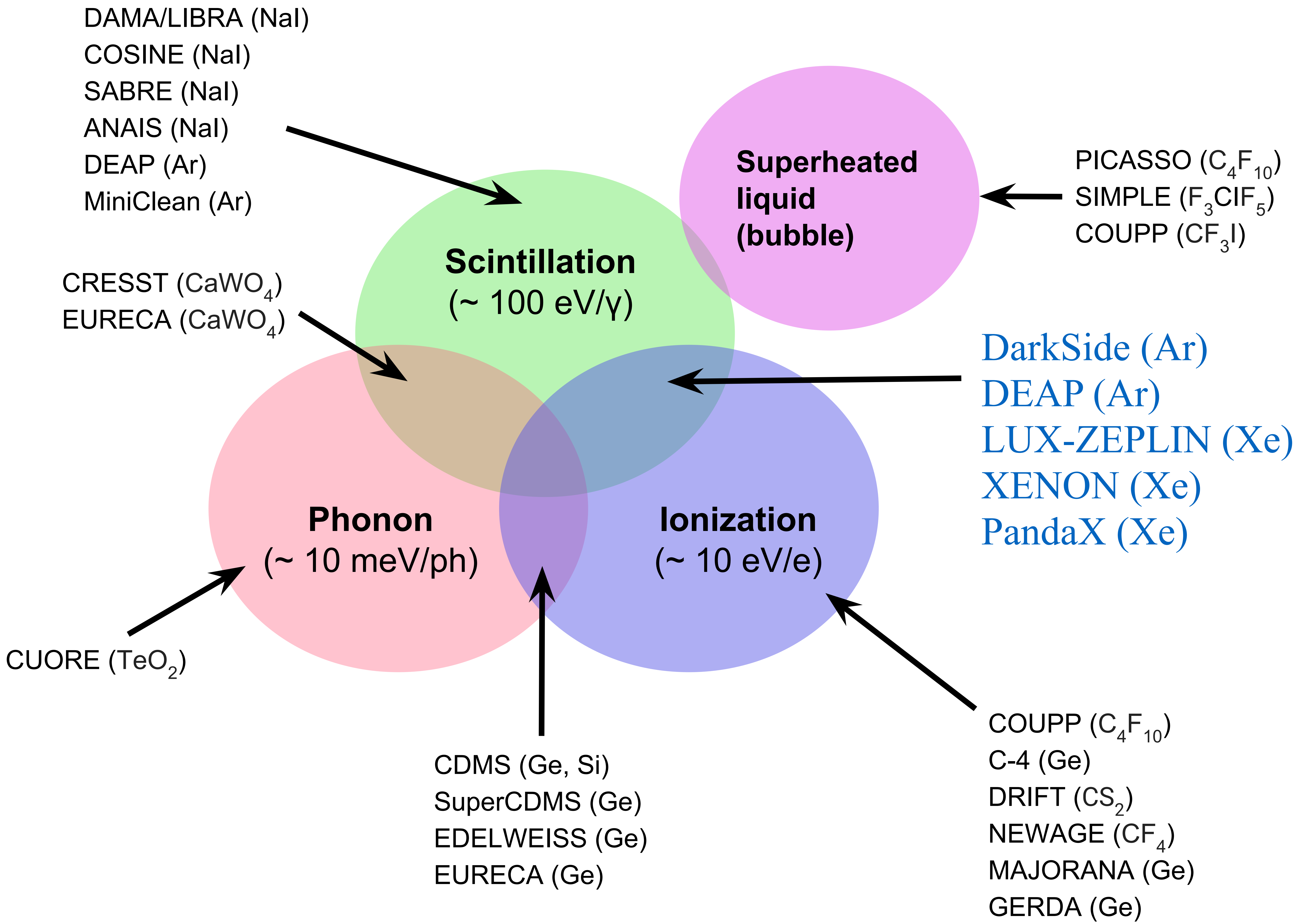
The heavier DM mass, the lower the number density is.

The direct WIMP search is a rare event search.

Direct Detection

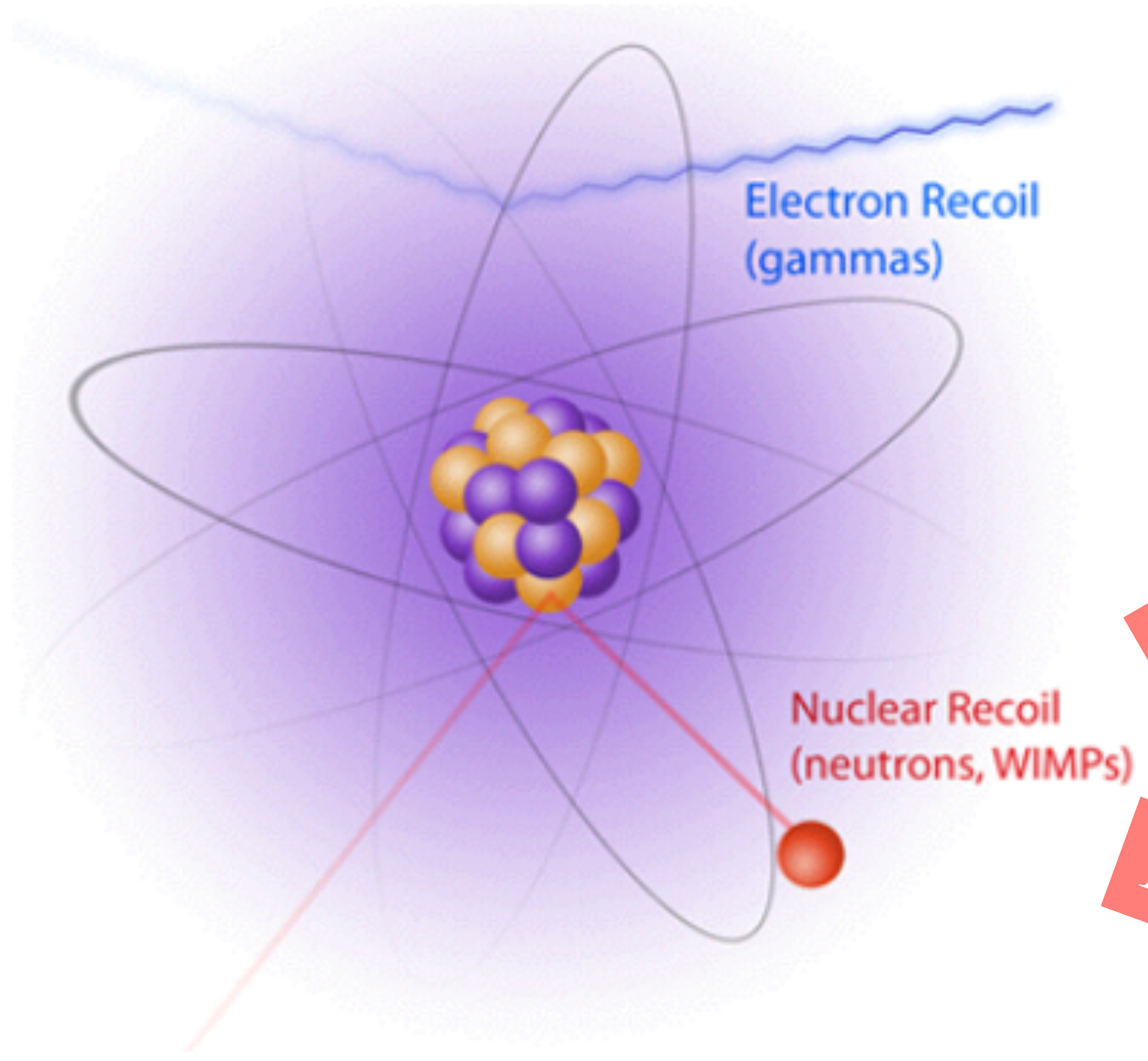


Techniques of Direct Detection



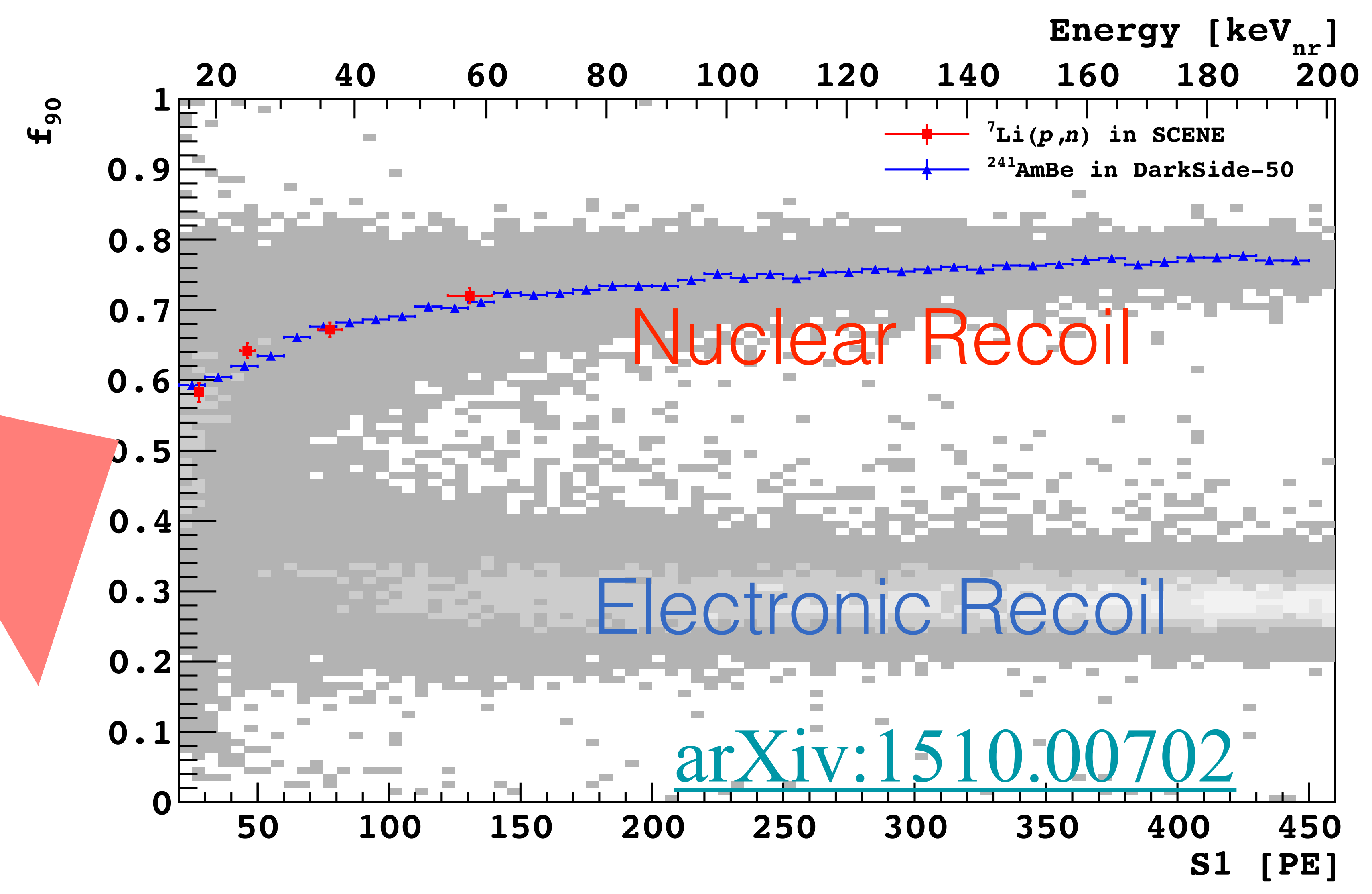
Why Noble Liquid?

Electron Recoil: background-like

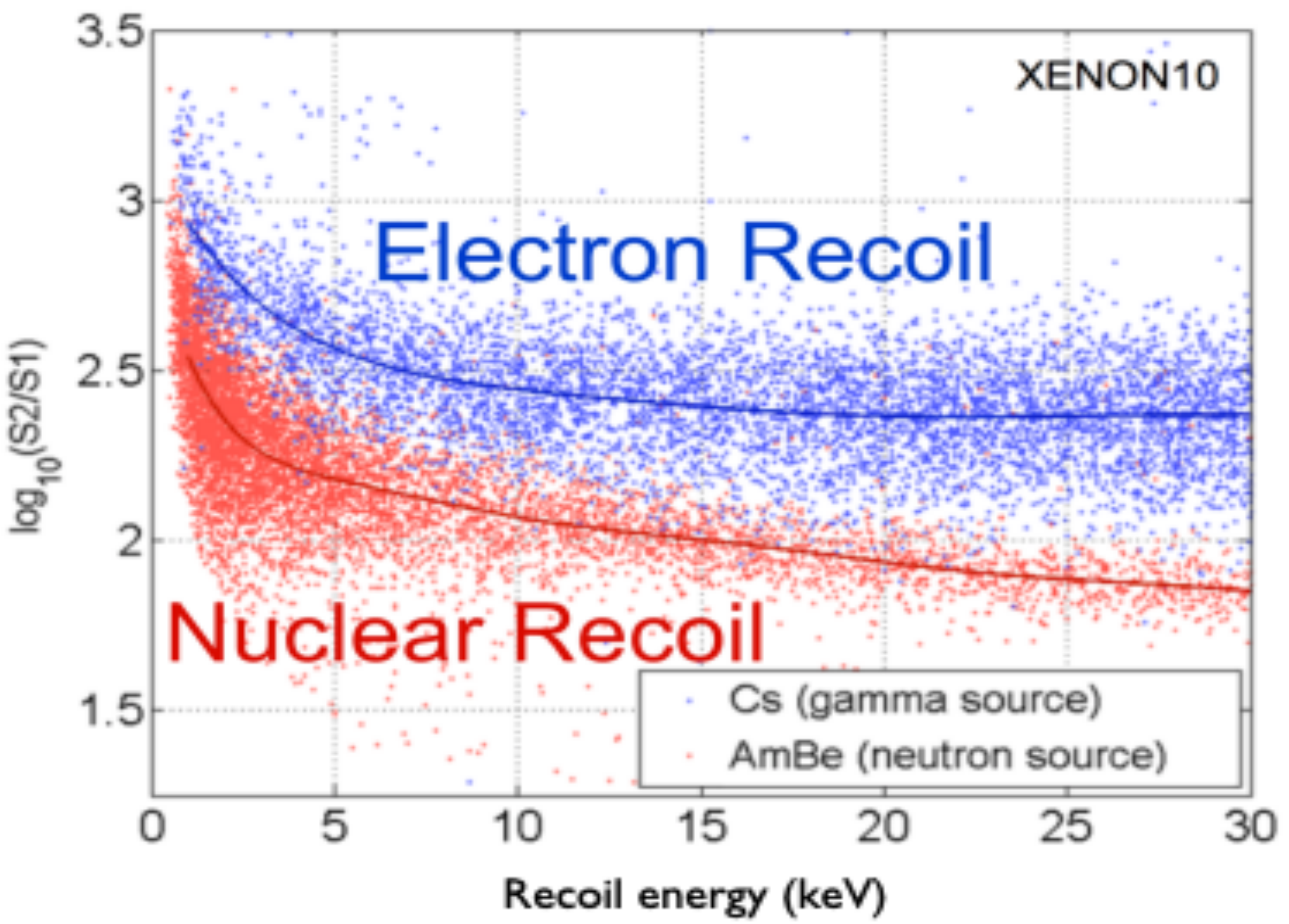


Nuclear Recoil: signal-like

Recoiling Ar Nucleus



Recoiling Xe Nucleus



Low-background and good discrimination!
LXe ER Leakage suppression >99.9%

Outline

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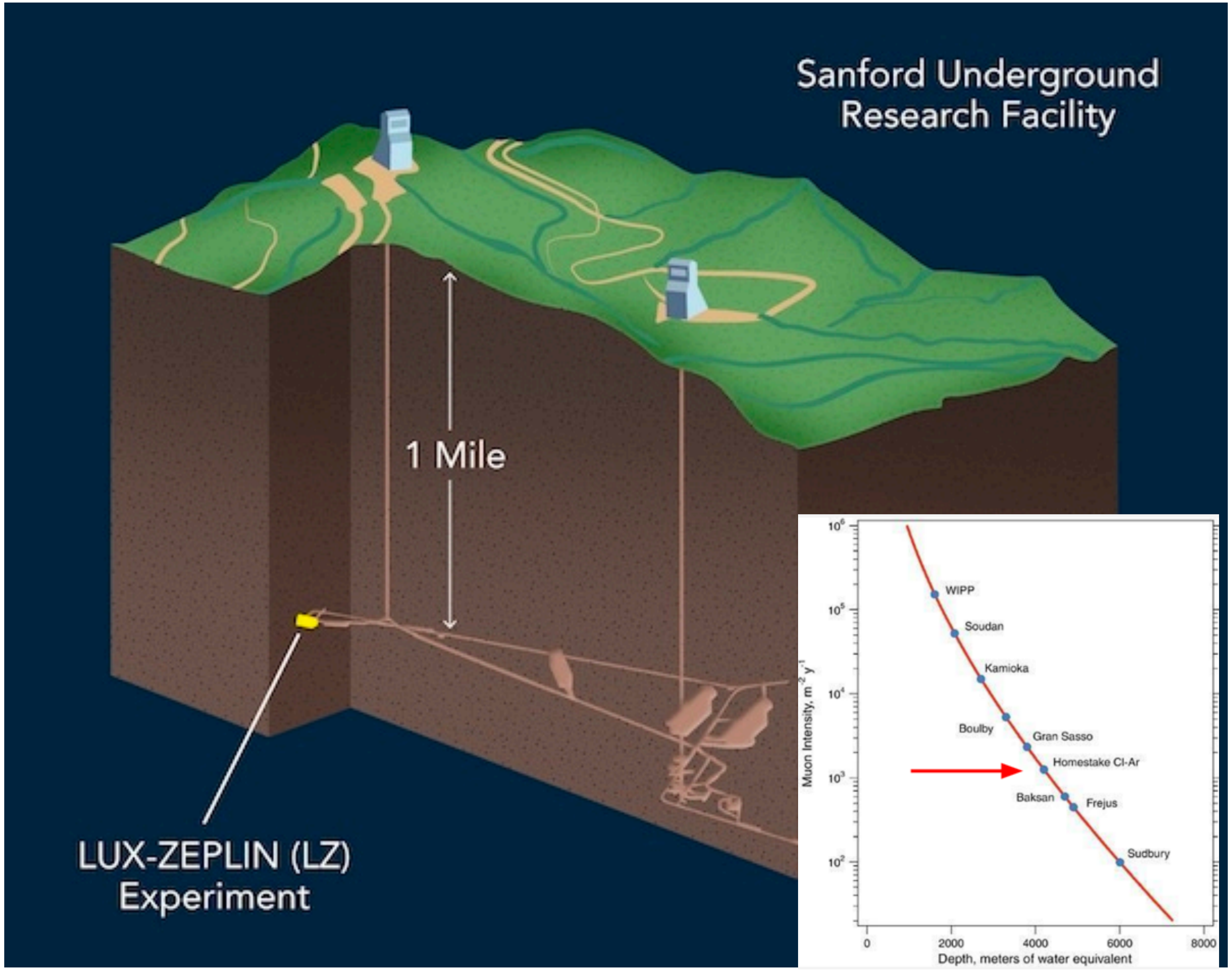
Where is LZ Detector?

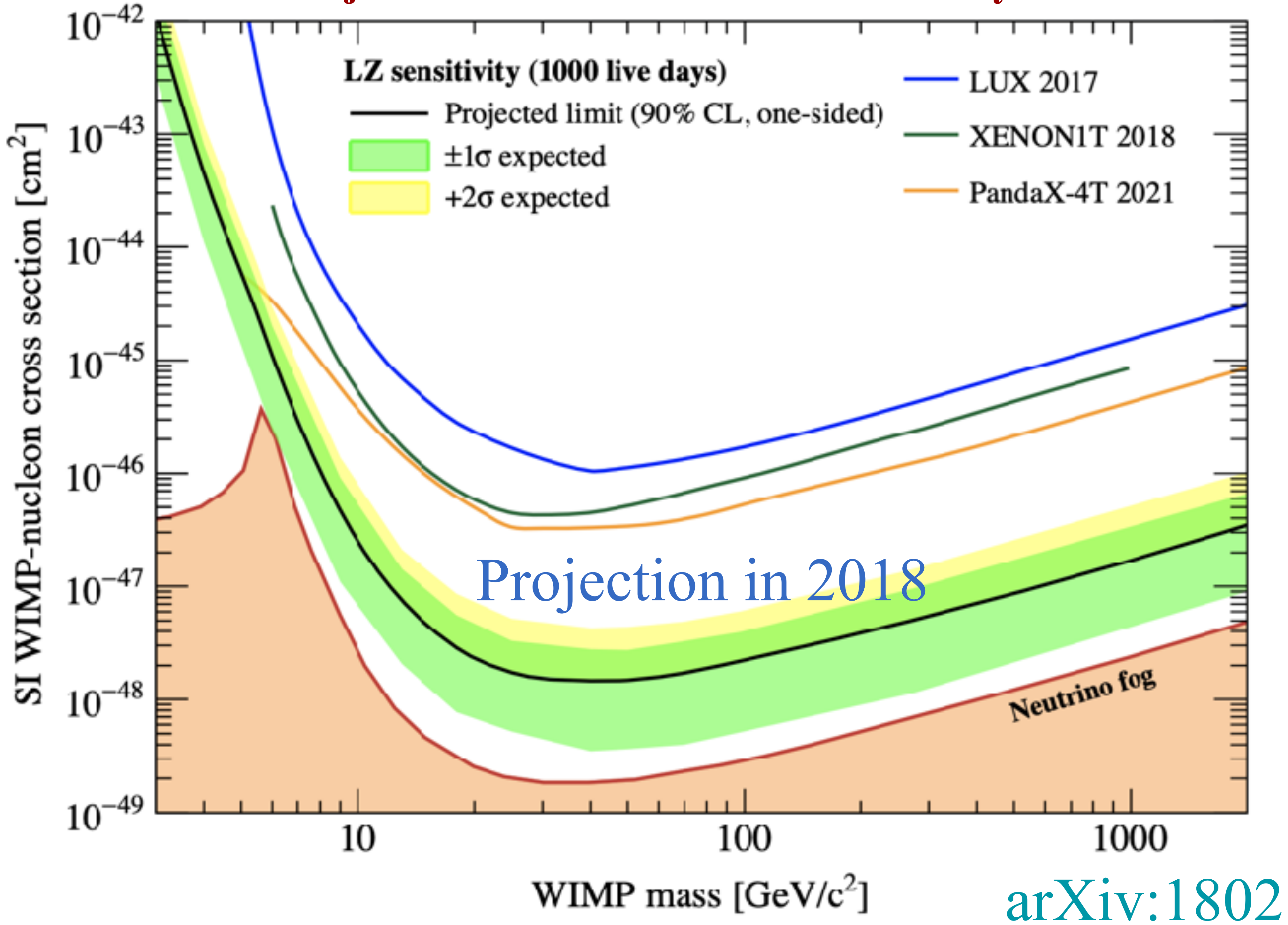
- Located 4850 ft under Sanford Underground Research Facility (SURF) in South Dakota
- Former gold mine, now the underground lab
- 4300 m.w.e, 10^6 muon reduction



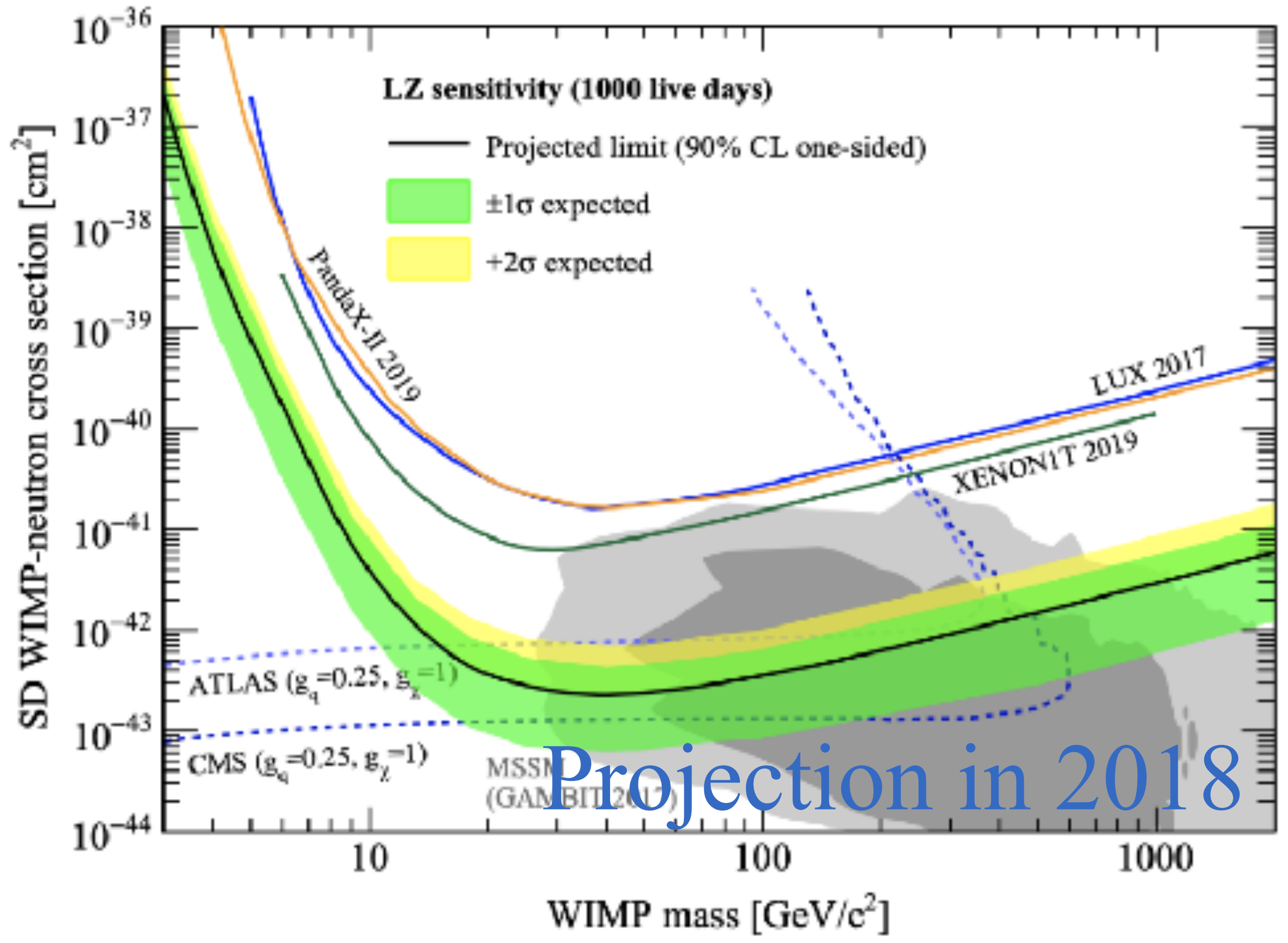
What is LZ trying to do?

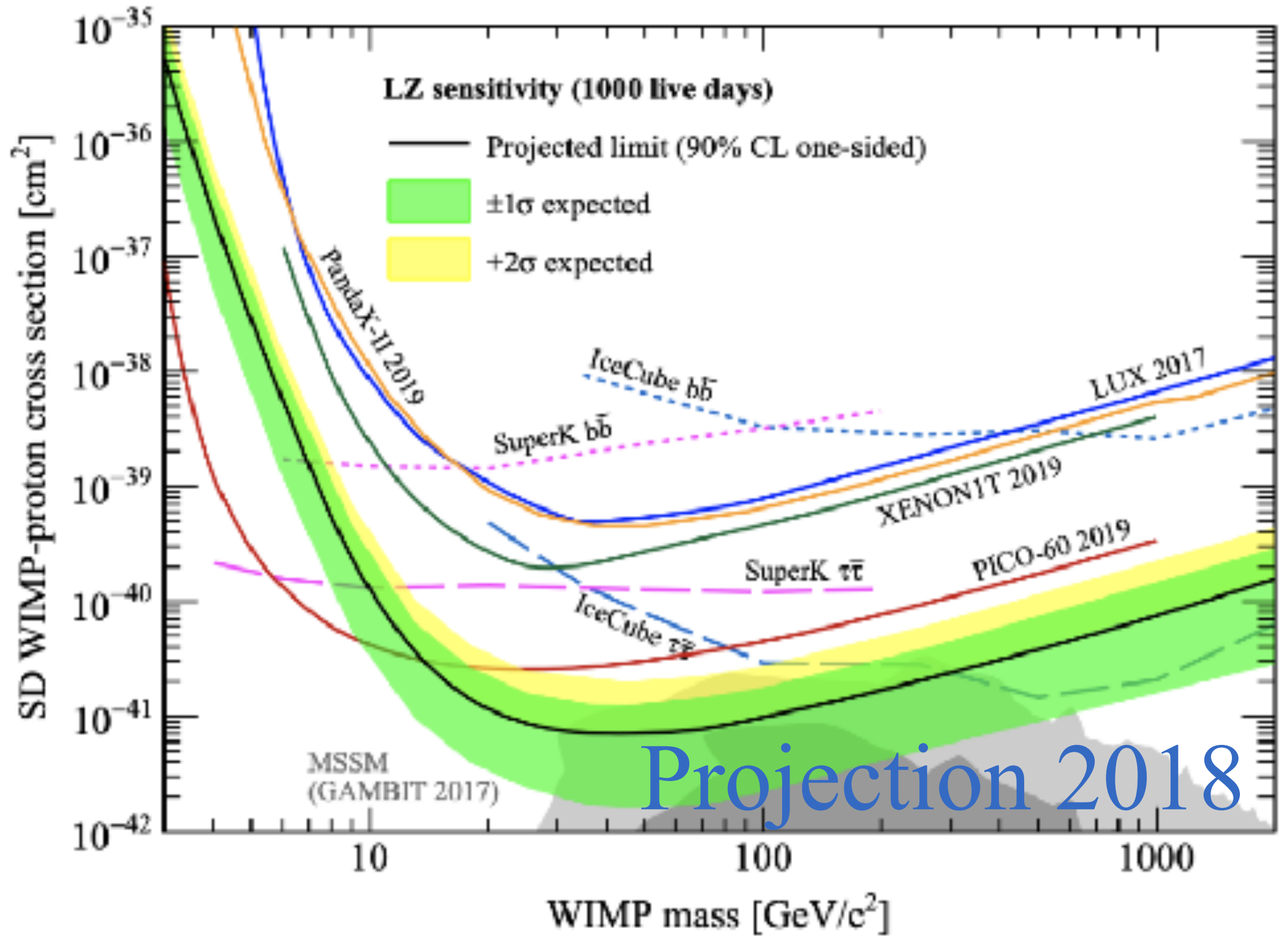
- LZ detector is multi-purpose (Swiss-Army-Knife)
- Projected (2018) to have world-leading DM Sensitivity
  - Full exposure: 15.3 tonne-year
  - SI WIMP-nucleon sensitivity: 1.4×10^{-48} cm^2 @ 40 GeV
  - SD WIMP-neutron (proton) sensitivity: 2.7×10^{-43} (7.1×10^{-42}) cm^2 @ 40 GeV
  - Sub-GeV masses accessible via Migdal effect, S2-only search
- Search of Other DM Candidates:
  - ALPs, hidden photon, mirror DM, etc
- Non-DM Physics
  - Solar axions, supernova neutrinos
  - Neutrino magnetic moment
  - Search of $0\nu\beta\beta$
  - 2νECEC on ^{124}Xe

Projected SI WIMP-nucleon sensitivity



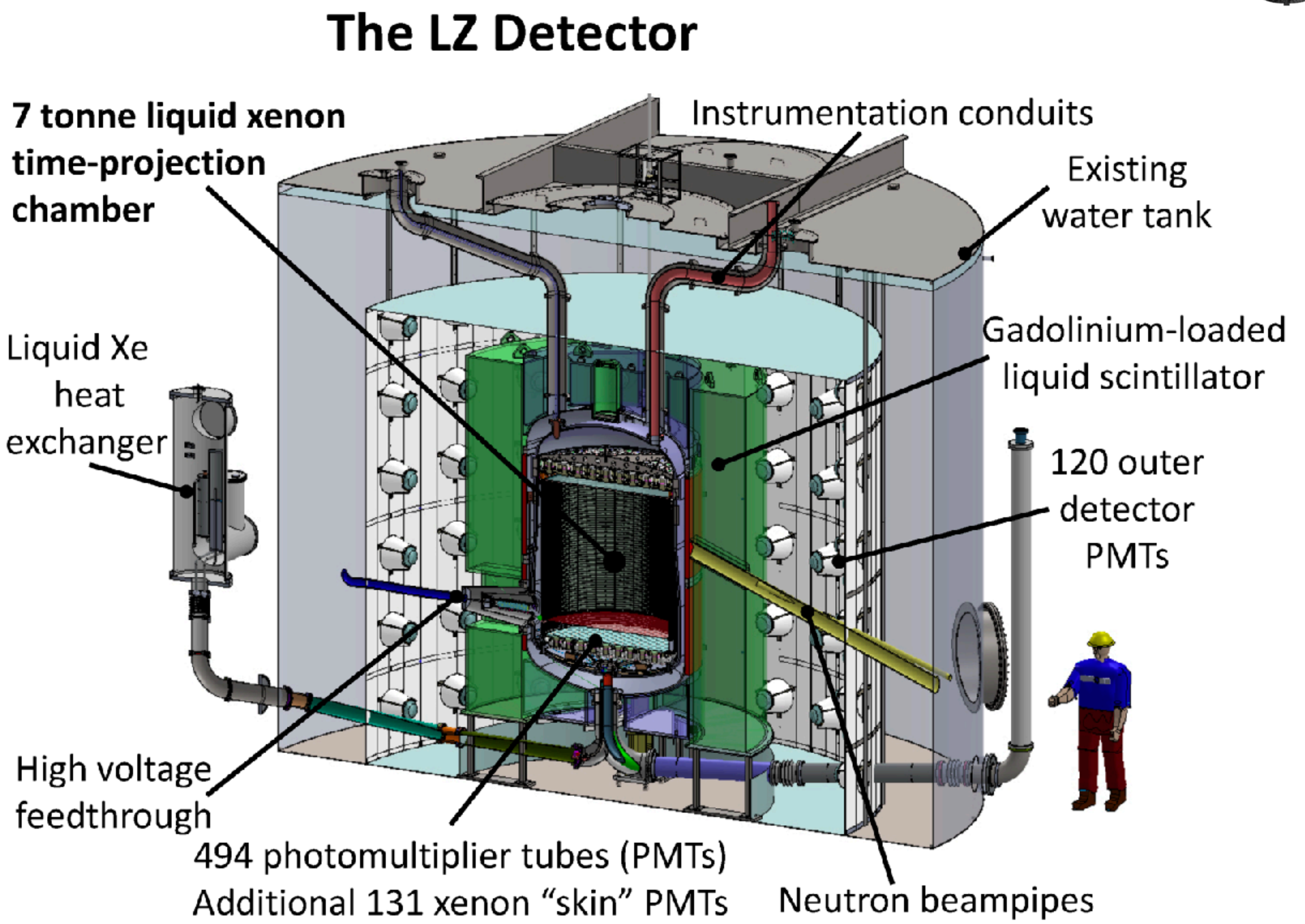
arXiv:1802.06039



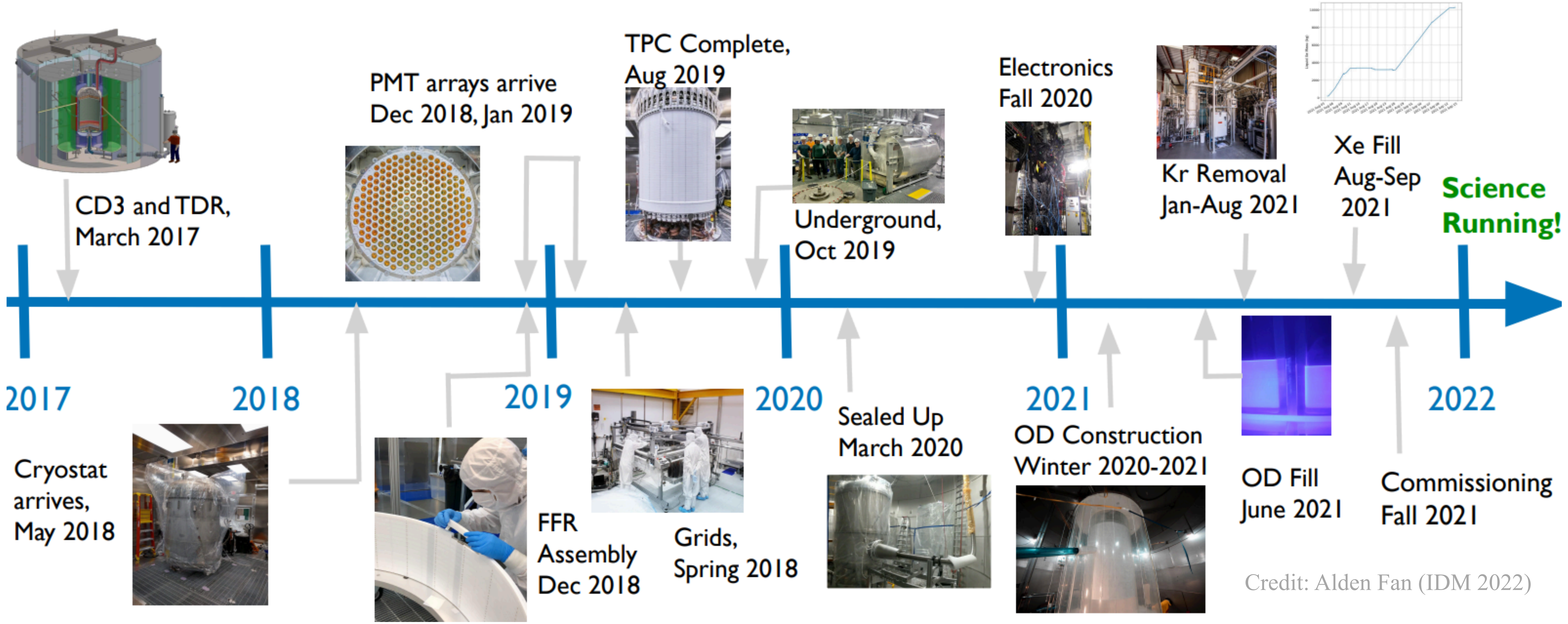


How is LZ detectors structured?

- Nested doll structure (from center out):
  - Ultra-low background dual-phase TPC
  - 2-tonne of LXe skin as gamma veto
  - 17.3 t Gd-loaded LS as neutron+gamma veto
  - Water tank as muon veto



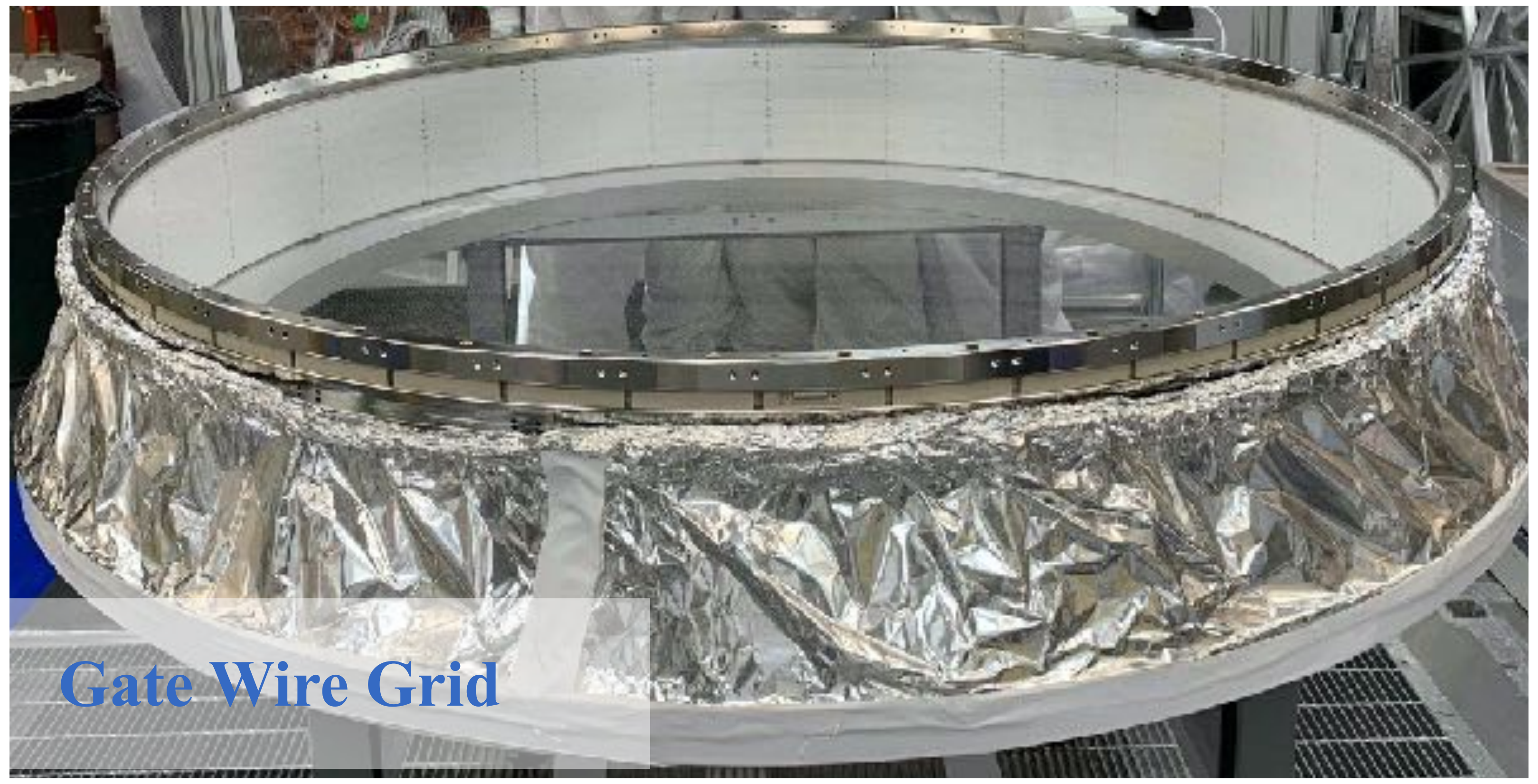
Construction Timeline



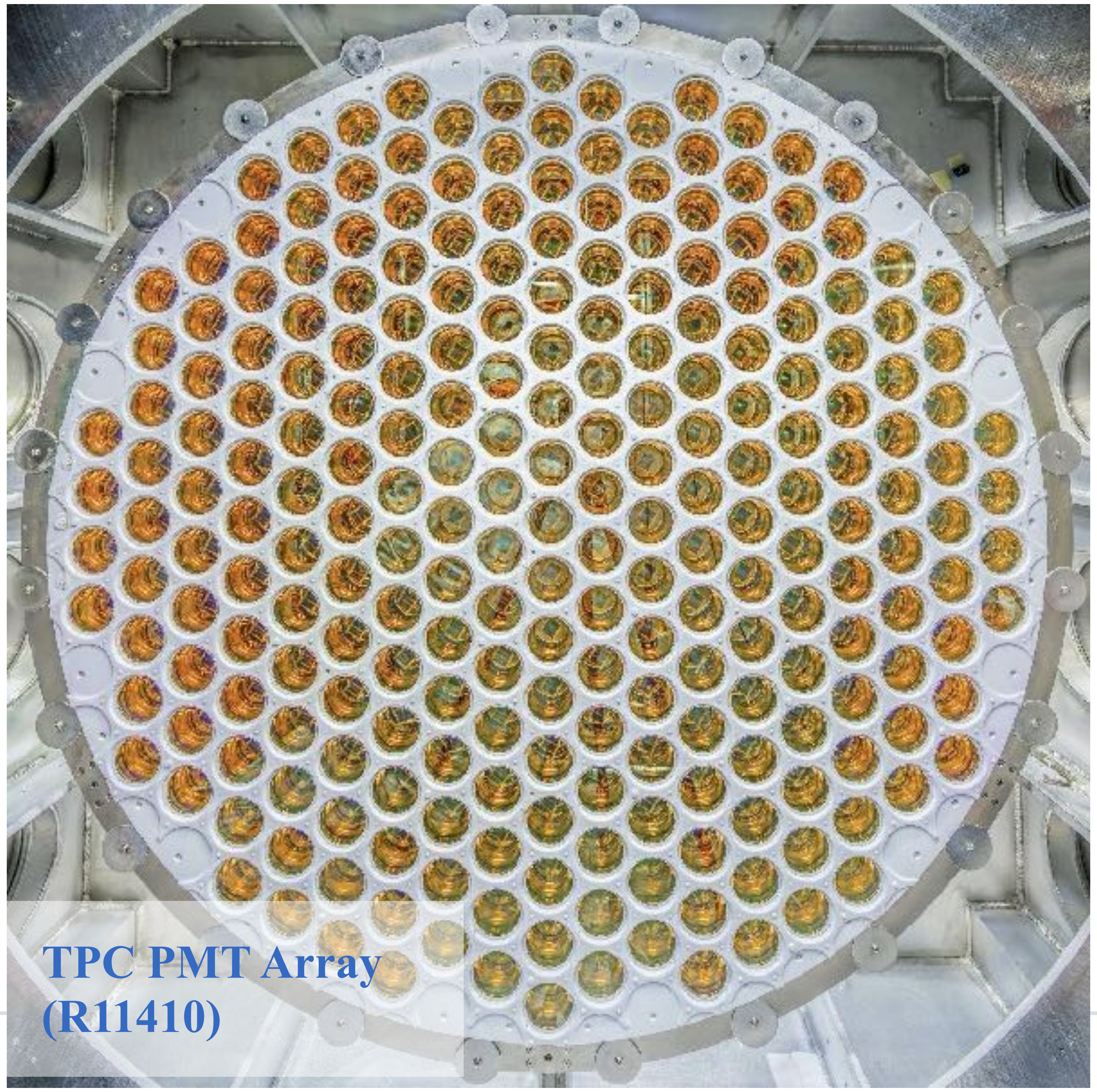
Credit: Alden Fan (IDM 2022)

Photo of the LZ TPC

TPC Assembled



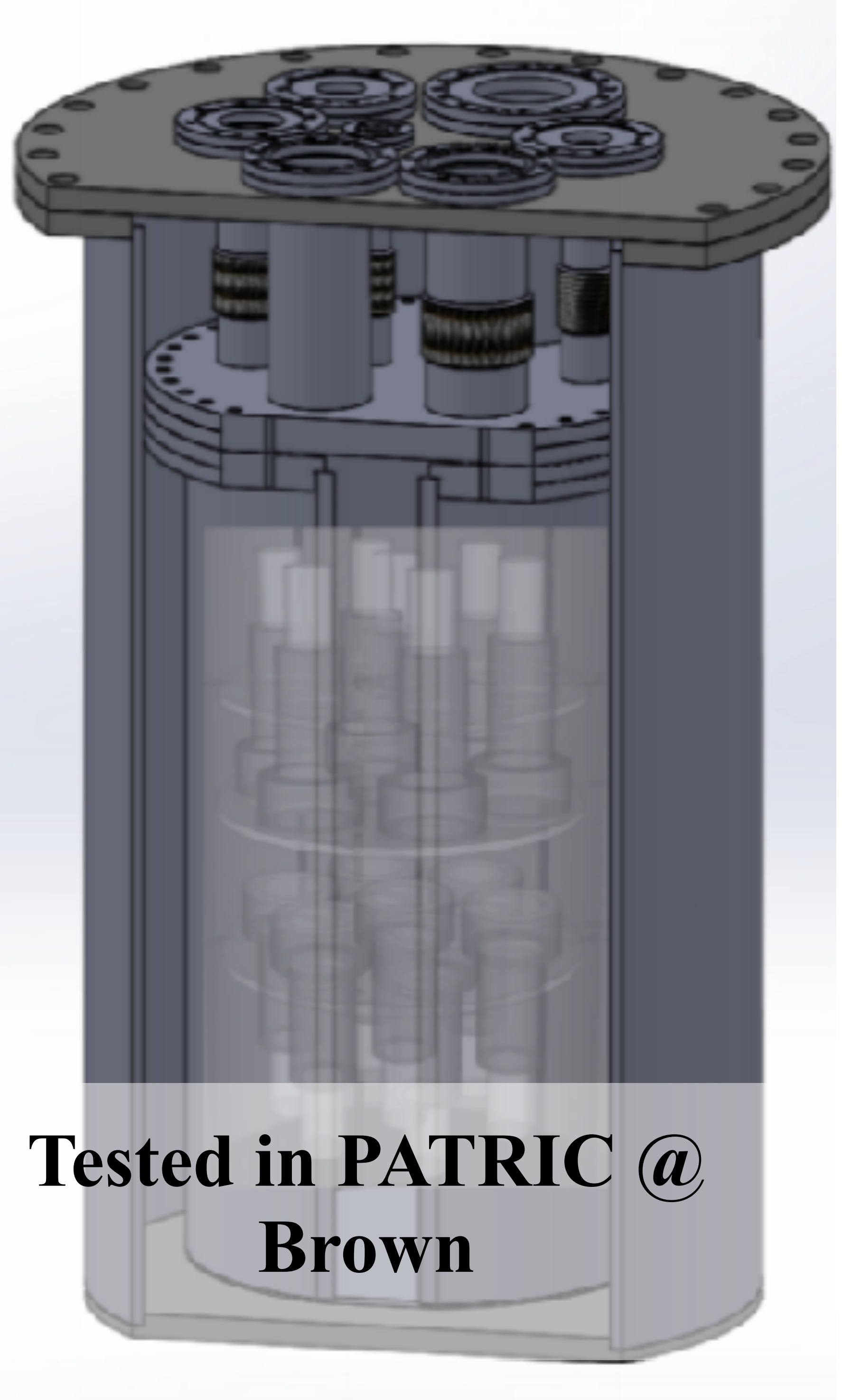
Gate Wire Grid



TPC PMT Array (R11410)

TPC as it descends into Ti cryostat

PMTs in LZ TPC



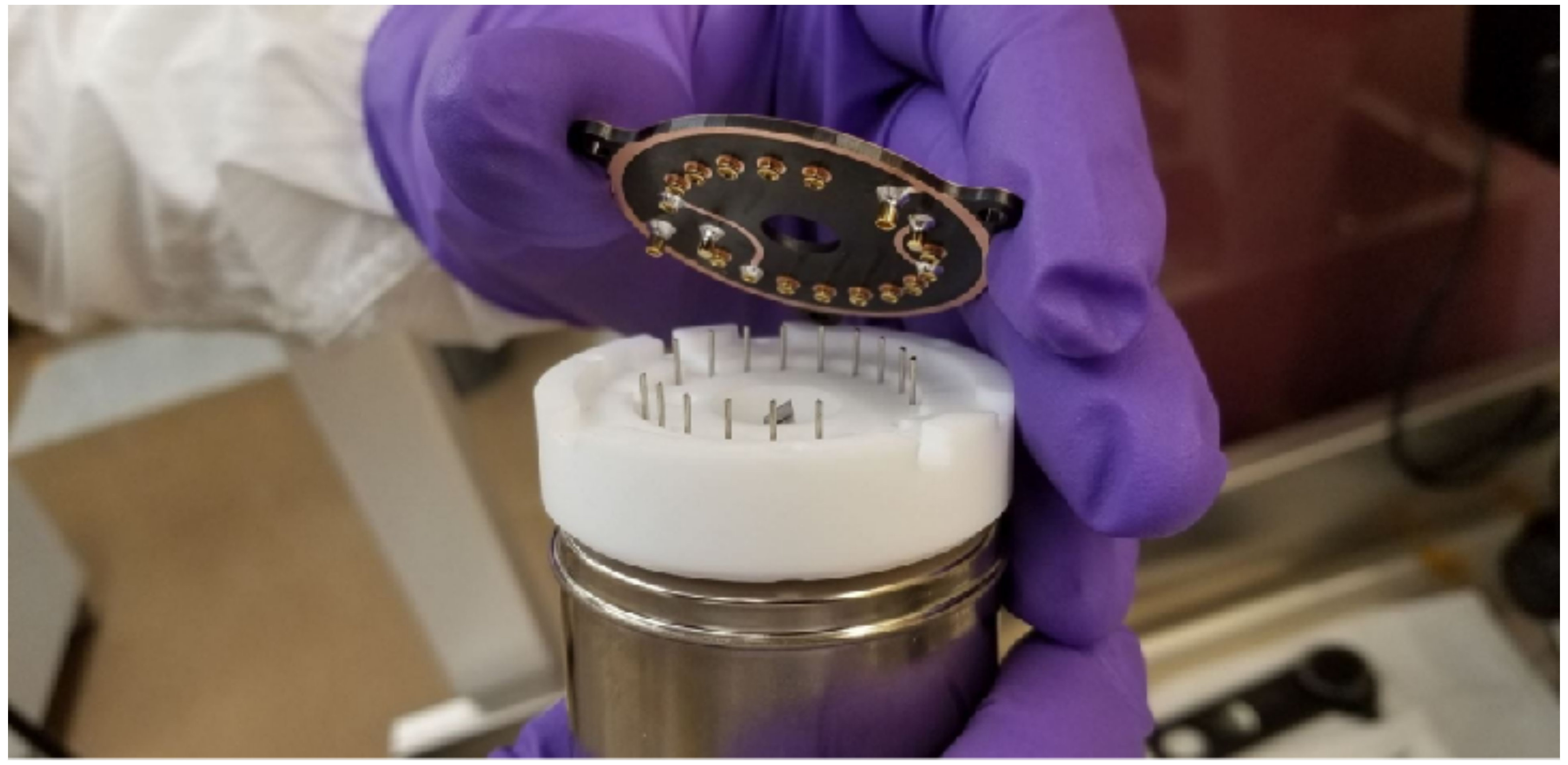
Tested in PATRIC @ Brown

494 Hamamatsu R11410- 22 in LZ

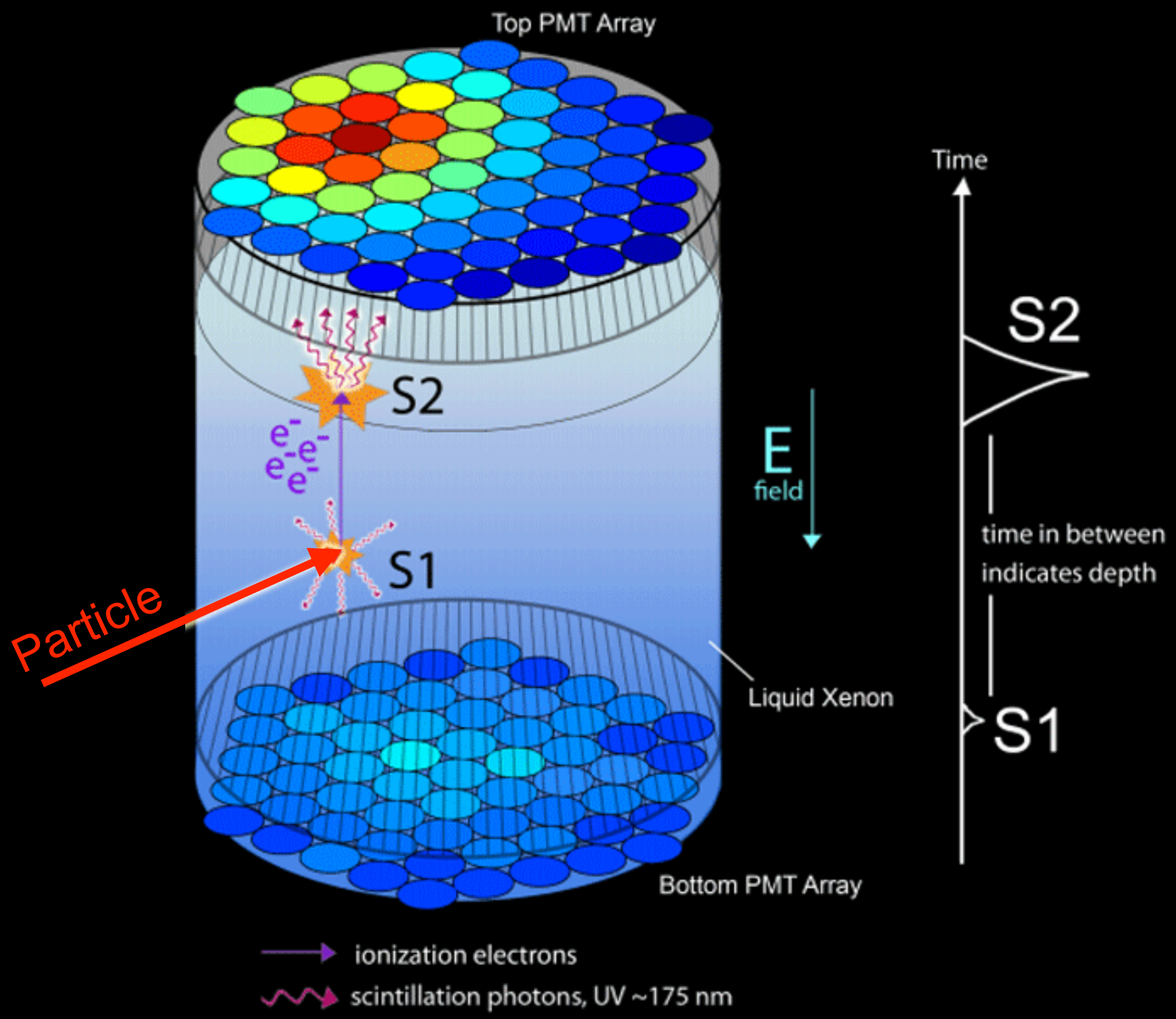
Me Looking Tired

Transported to SURF in a customized enclosure system

Assembled in Brown's clean room



How does liquid xenon TPC work?



Principle of a TPC

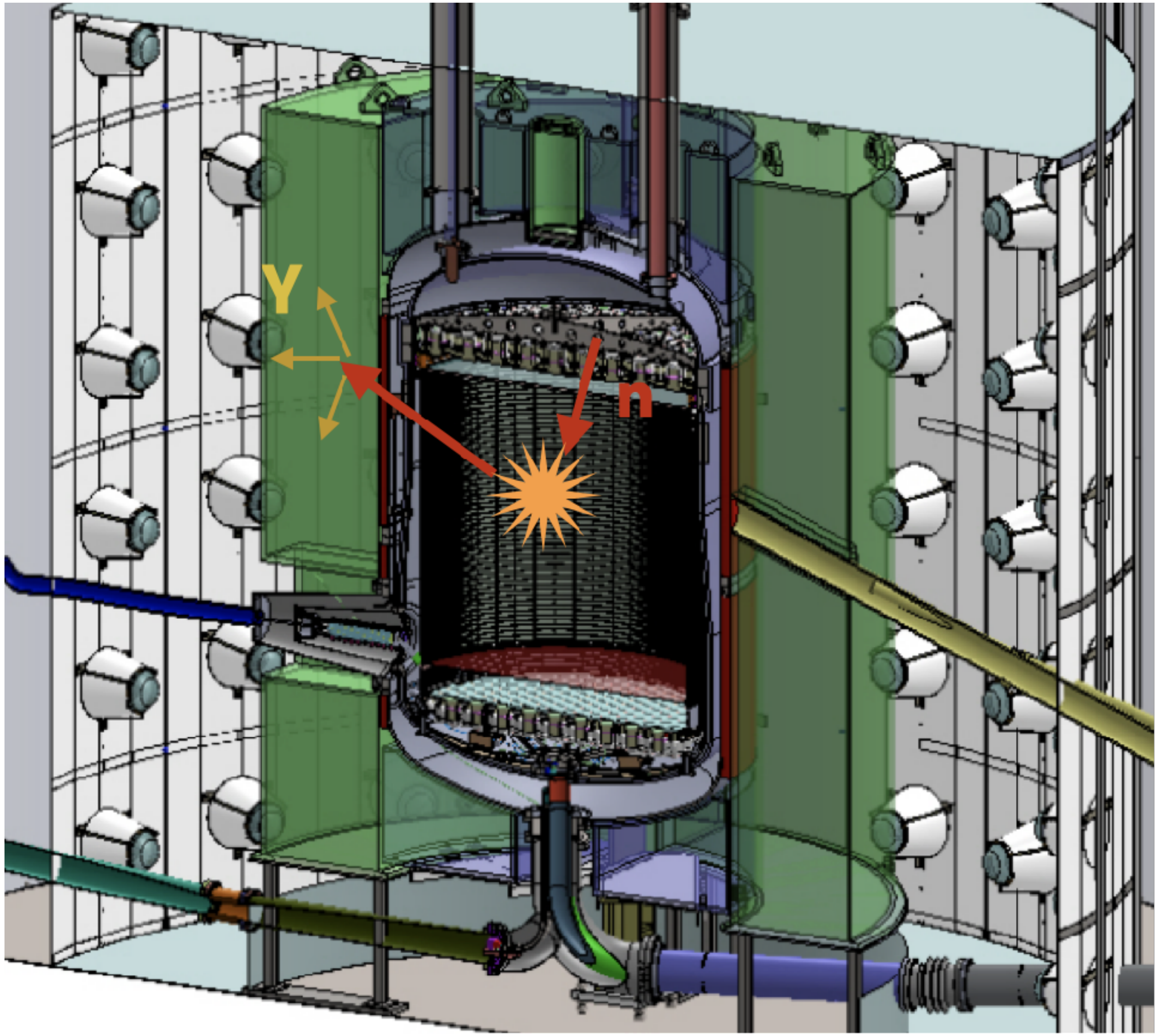
- Prompt primary scintillation light at interaction site → **S1**
- Ionization electrons are drifted to gas pocket where it produces light via electroluminescence → **S2**
- Drift time → z position at O(mm) precision.
- S2 channel pattern → (x,y) positions at O(cm) precision
- S2/S1 ratio → Background discrimination:
  - S2/S1 ratio depends on dE/dx
  - ER produces relatively more charge than NR

Non-relativistic elastic scattering at the keV scale => a single-scatter is point-like

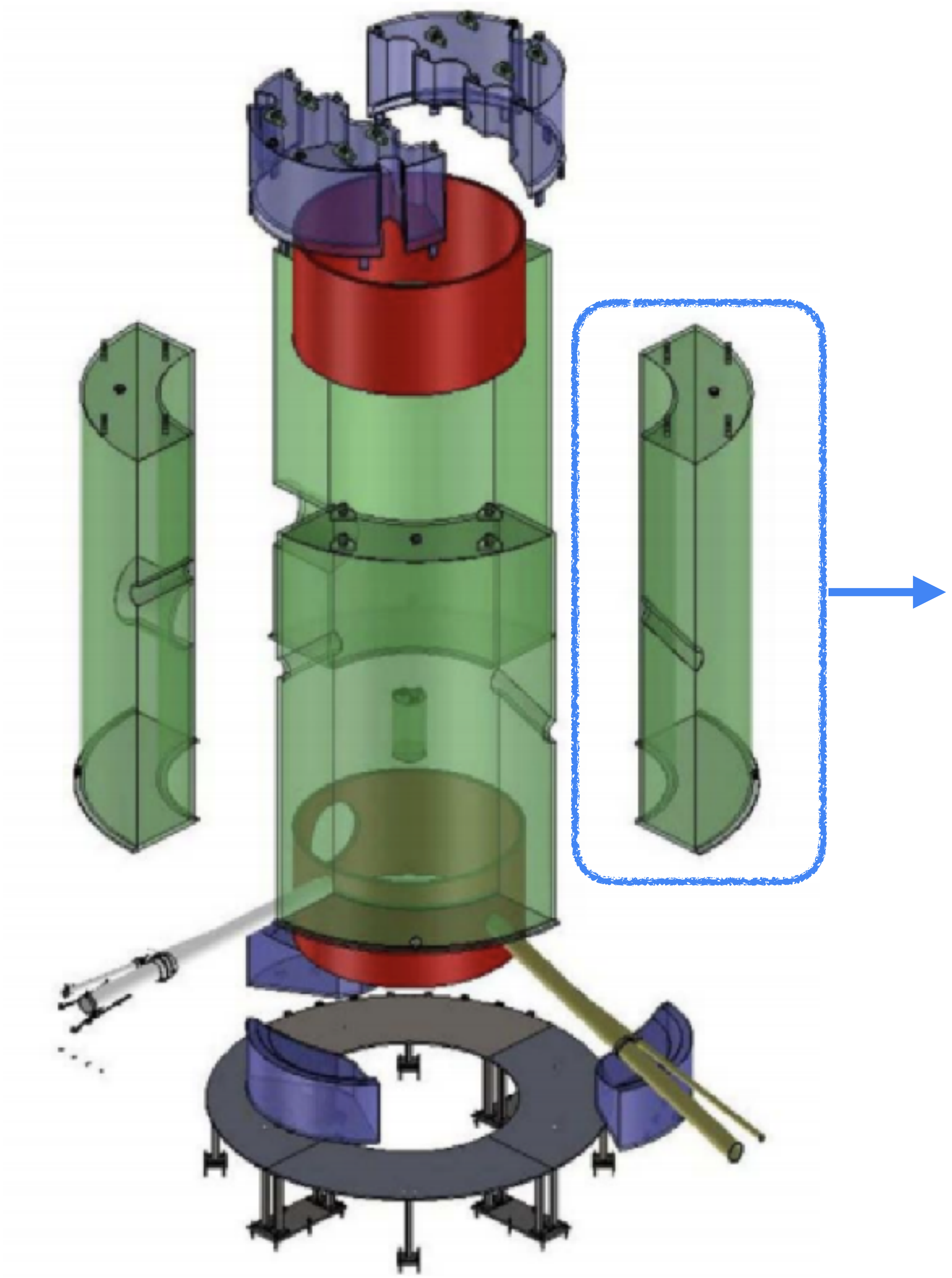
How does the Veto system work?

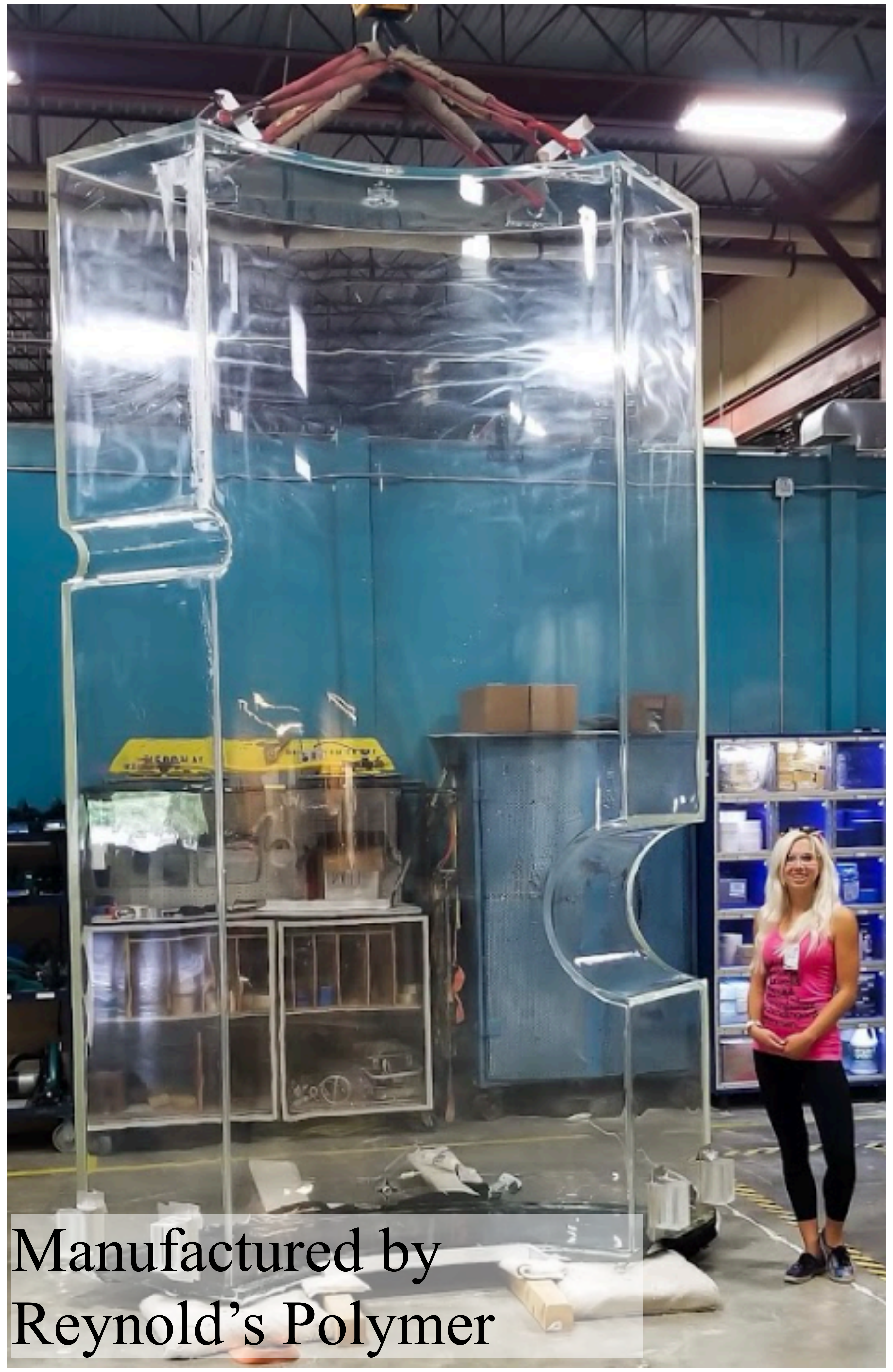
Three Layers System:

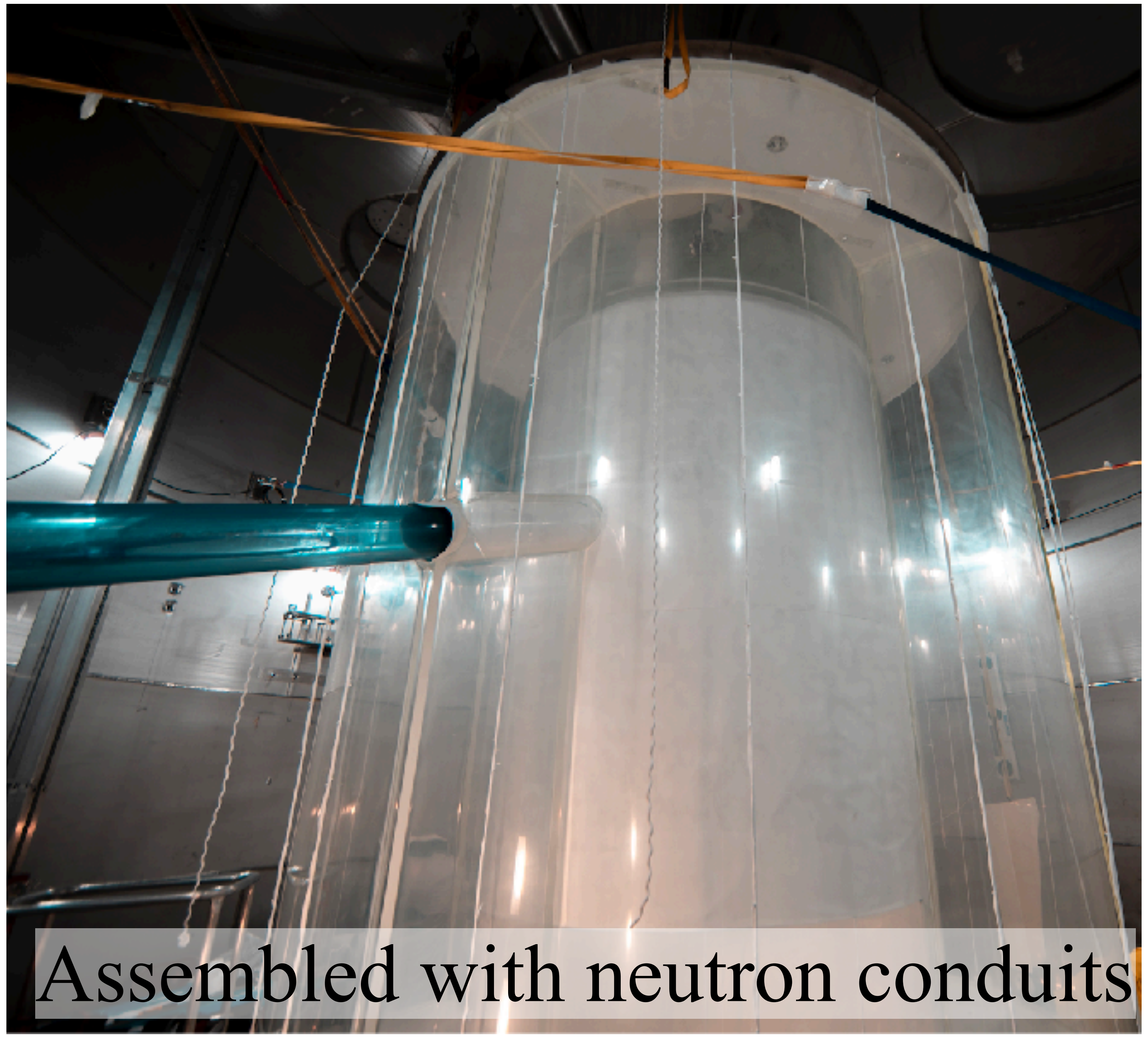
1. A layer of **LXe skin** in the TPC inner cryostat, monitor by separated PMTs
   a. Projected tagging γ-rays: **>70%**
2. Acyclic vessels surrounding TPC cryostat
   a. Gd (0.1% doped) loaded LS (Linear Alkyl Benzene) [**manufactured at BNL (M. Yeh)**]
   b. Neutron captured on H: 2.2 MeV
   c. Neutron captured on Gd (4-5 γ-rays):
      i. $n + {}^{155}Gd \rightarrow {}^{156}Gd + 8.5$ MeV (18%)
      ii. $n + {}^{157}Gd \rightarrow {}^{158}Gd + 7.9$ MeV (82%)
   d. Neutron veto: **(88.5±0.7)% efficiency with 5% acceptance loss**
3. Water Tank as a passive shielding



Acyclic Vessels Inside the Water Tank







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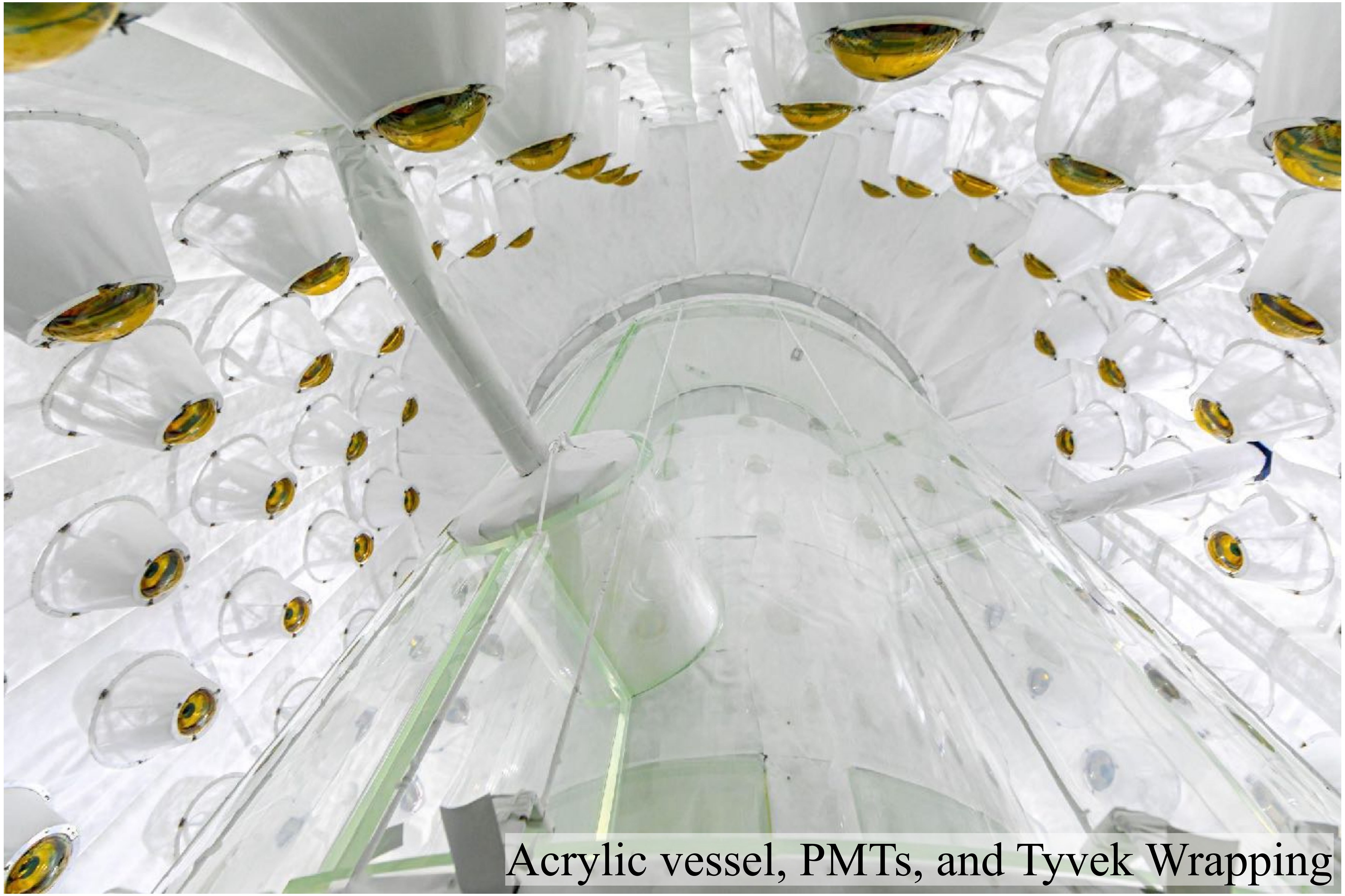

Acrylic vessel, PMTs, and Tyvek Wrapping

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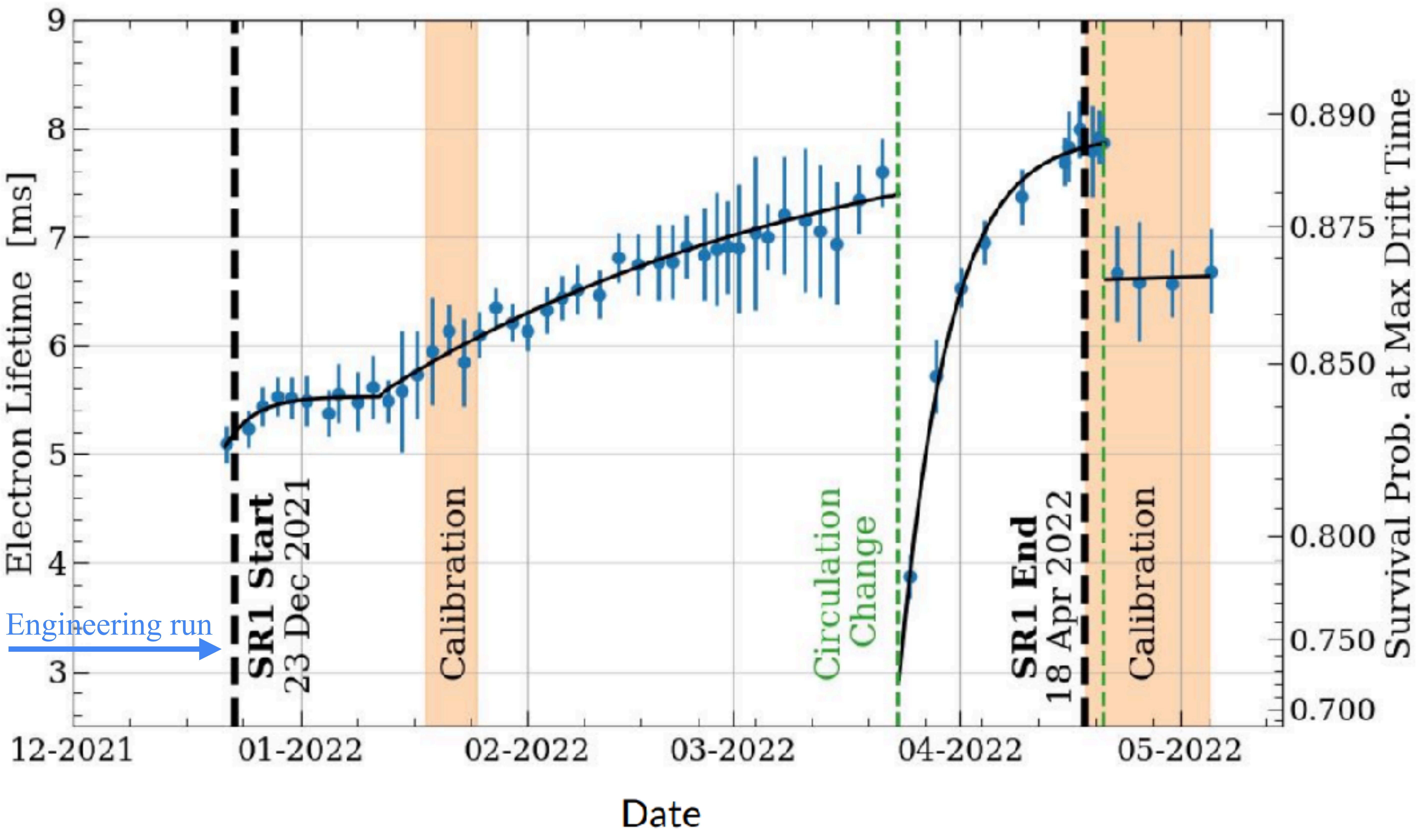
SR1 Timeline

- Begin on Dec 23, 21 end on May 12, 22
- 60 live days of for WIMP search
- Stable operation throughout the run:
  - Drift field: **193 V/cm**
  - Extraction field: **7.3 kV/cm**
  - Electron drift lifetime is steadily improved
  - **>97%** PMTs operational throughout the run
- Two main Goals of SR1:
  - Demonstrate the capability of the detector
  - Competitive SI-WIMP sensitivity



Calibration (but first let's review the notation)

Reminders:

S1: Prompt primary scintillation light at interaction site.

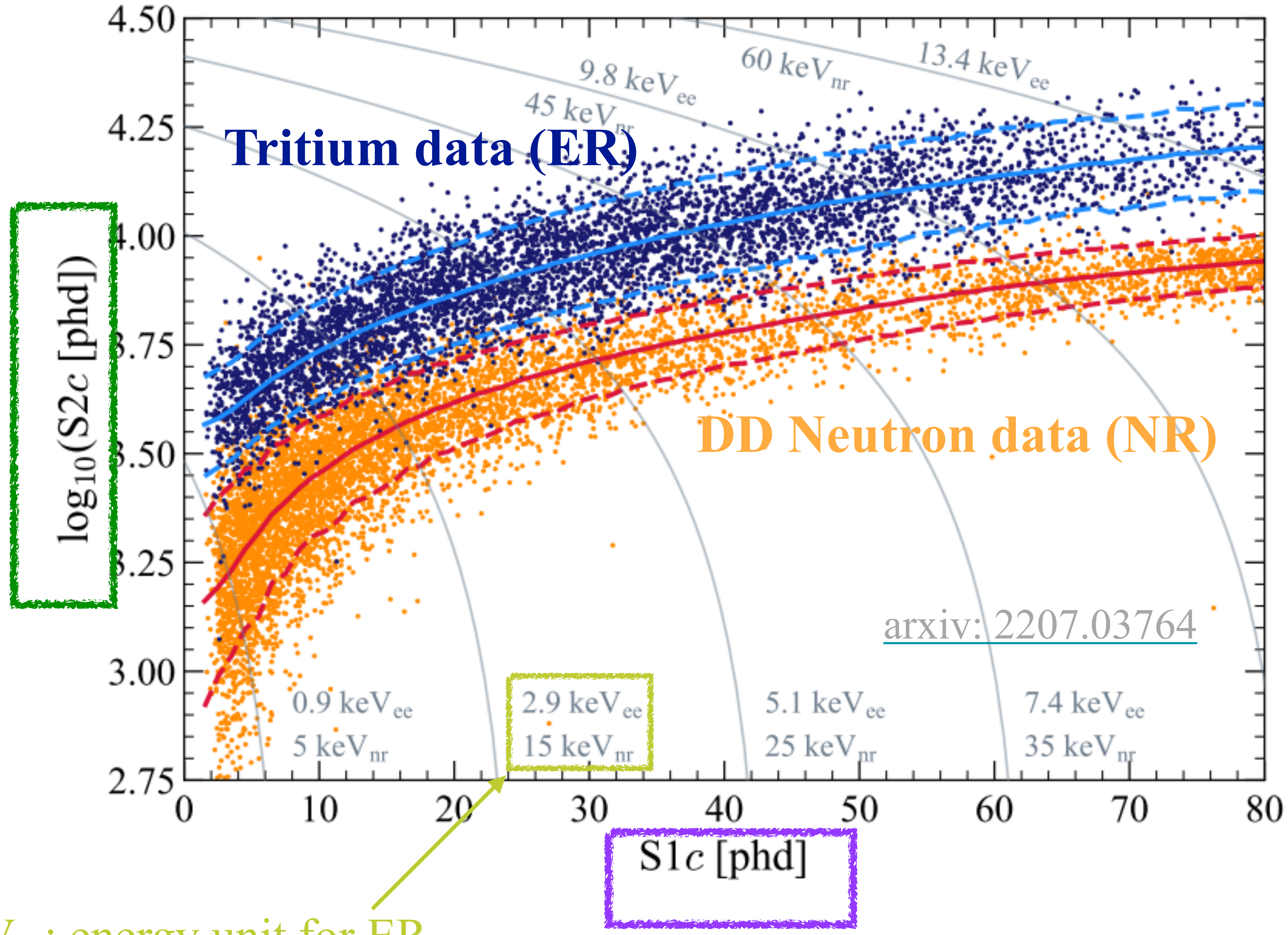
S2: Electroluminescence produced in the gas pocket; S2 is proportional to the ionization electrons.

Nuclear Recoil (**NR**): signal-like

Electronic Recoil (**ER**): background-like

Subscript "c" means S1, S2 are corrected to the TPC's geometric center

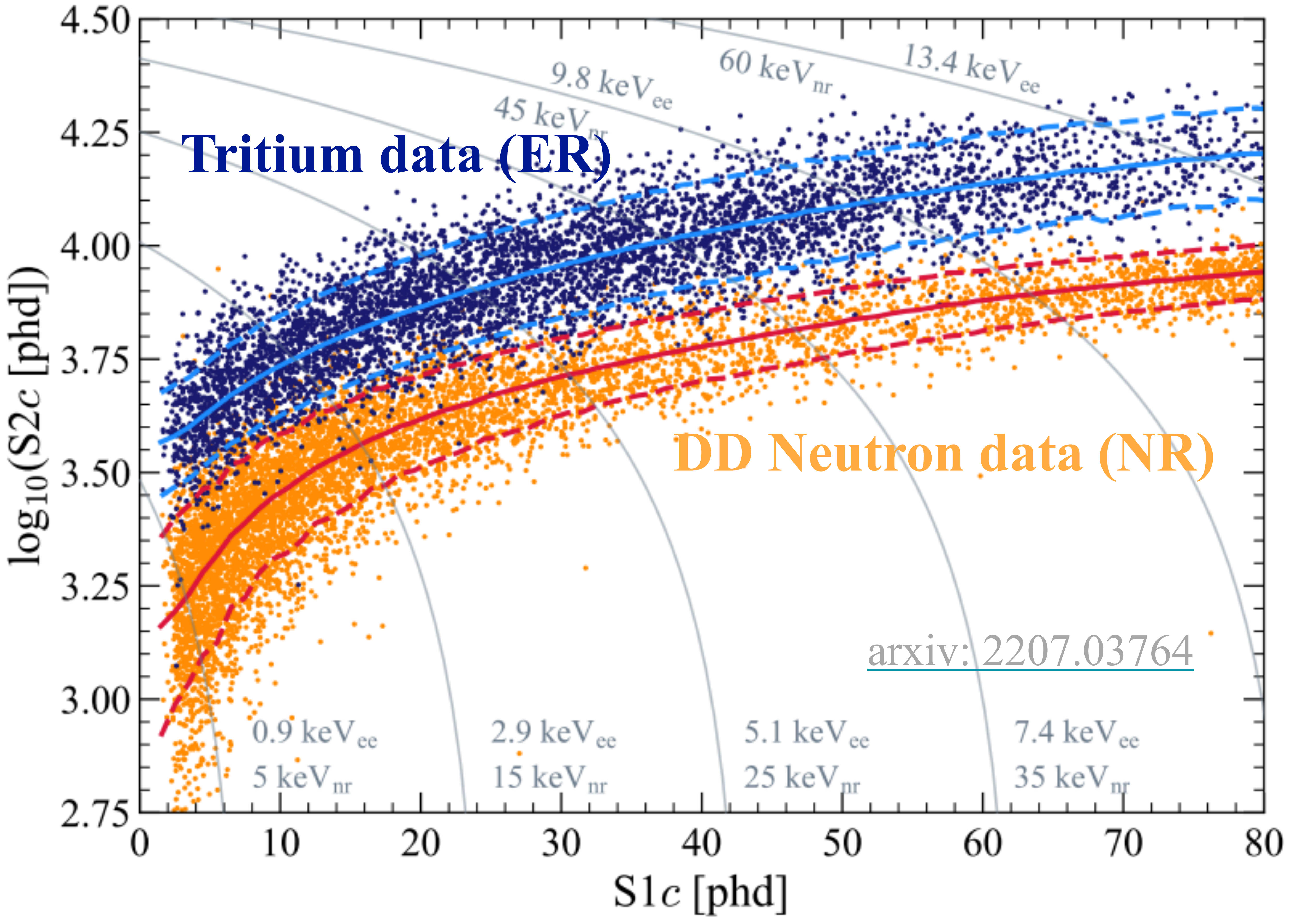
Unit "phd" stands for photon detected



keV_{ee}: energy unit for ER
keV_{nr}: energy unit for NR

Calibration

- ER Sources:
  - **Tritium: continuum beta (end-point: 18.6 keV)**
  - Monoenergtic ^{83m}Kr (32.1keV, 9.4 keV)
  - Monoenergtic ^{131m}Xe (164 keV)
  - Various Xe activation lines
- NR Sources:
  - **Deuterium-deuterium (DD) triggered 2.45 MeV neutron**
  - AmLi: continuous, isotropic
  - Alphas peaks
- Calibrated detector parameters:
  - Light collection efficiency (g1): **0.114 ± 0.002 phd/photon**
  - Charge gain (g2): **47.1 ± 1.1 phd/electron**
  - **>99.9%** rejection of ERs below the NR median
  - Single electron size: 58.5
  - Max drift time: 951 μs



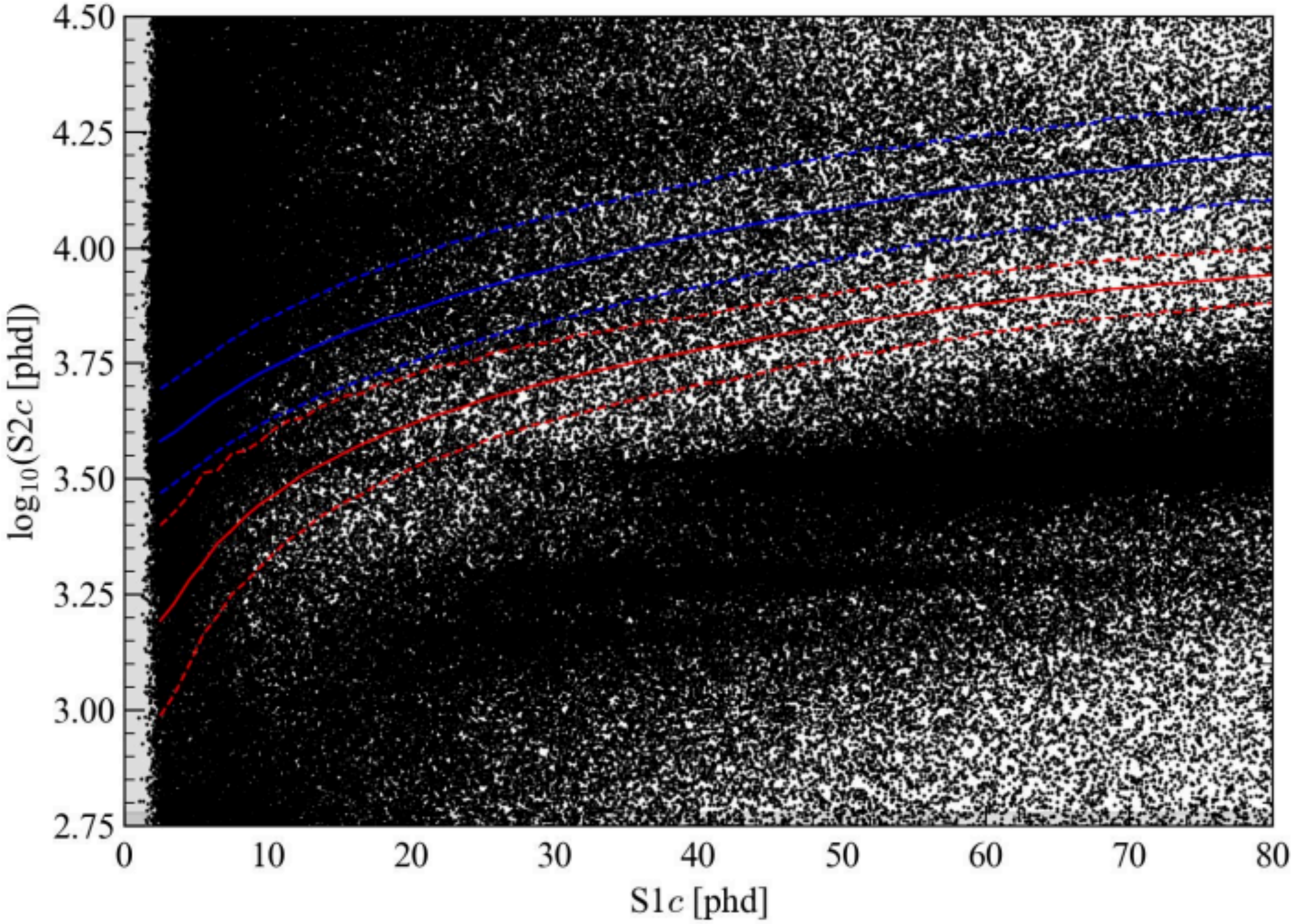
The response of TPC, skin, and OD are comprehensively calibrated!

WIMP Analysis Strategy

Direct WIMP search at its heart is a **process by elimination**

1. Data Selection (final live-time: 60±1 d):
2. Event Selection
   A. WIMP signature cut
   B. Background rejection cut
3. Profile Likelihood Ratio (PLR)

All single scatters before ANY other cuts

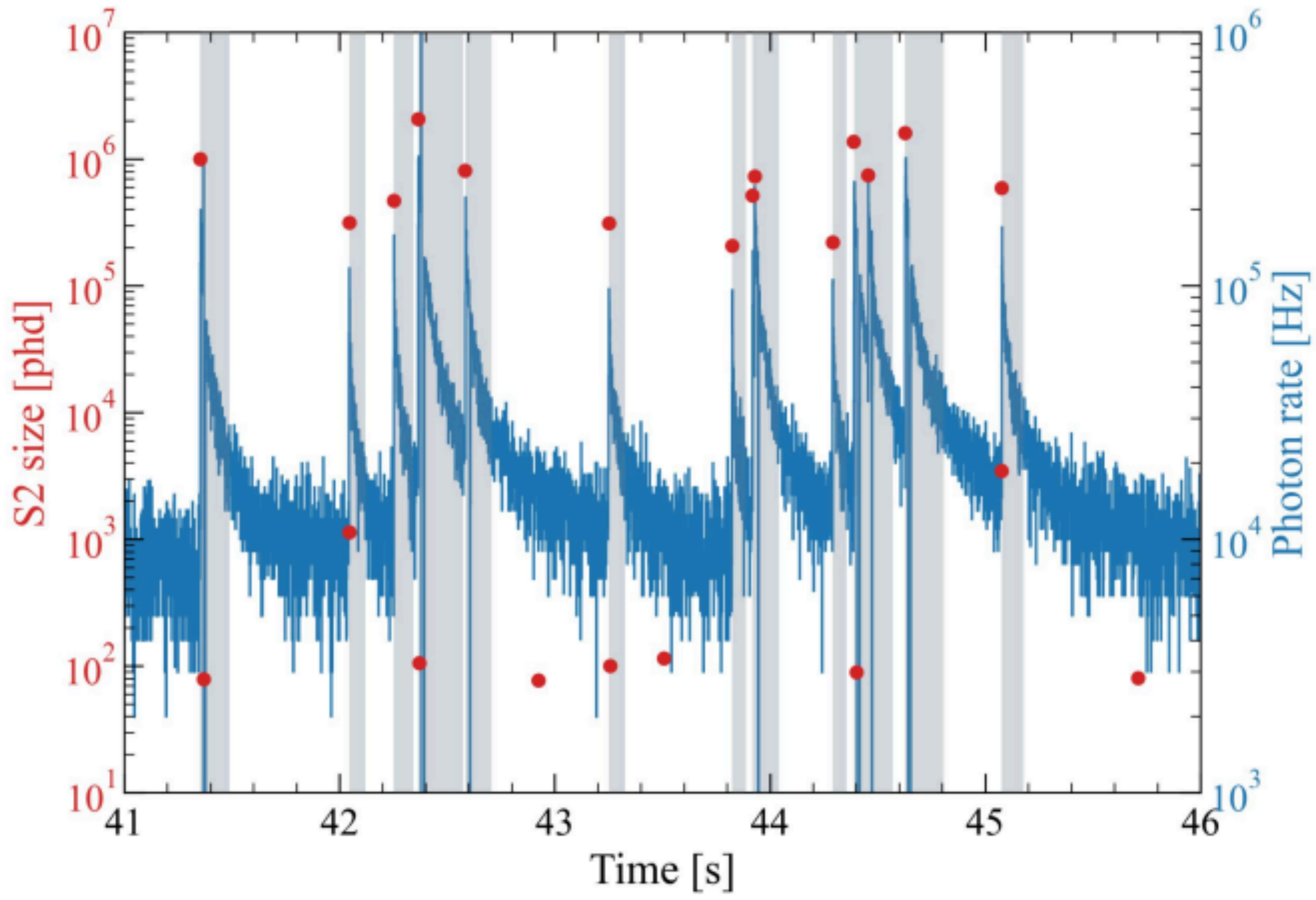


- No blinding in signal region or salting
- All analysis cuts were developed and optimized using calibration and sideband selection

1. Data Selection

Elevated activities due to spurious instrumental effects

1. Data Selection (final live-time: 60±1 d):
   - Exclude time period of elevated activities (7% loss).
   - Exclude DAQ deadtime (3% loss)
   - **Hold-off after large S2s (30% loss)**
   - Hold-off after cosmic muon



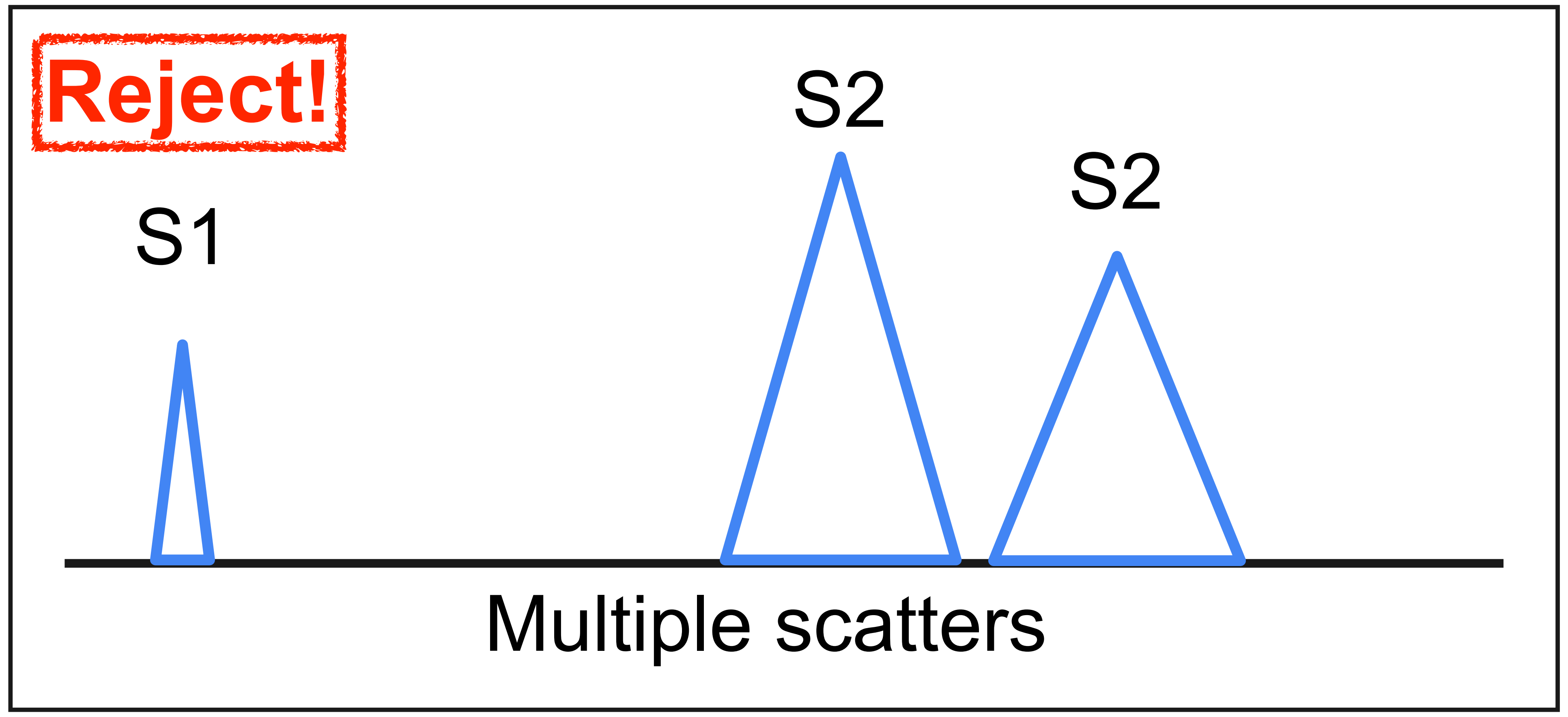
The grey regions are the hold-off time after large S2s

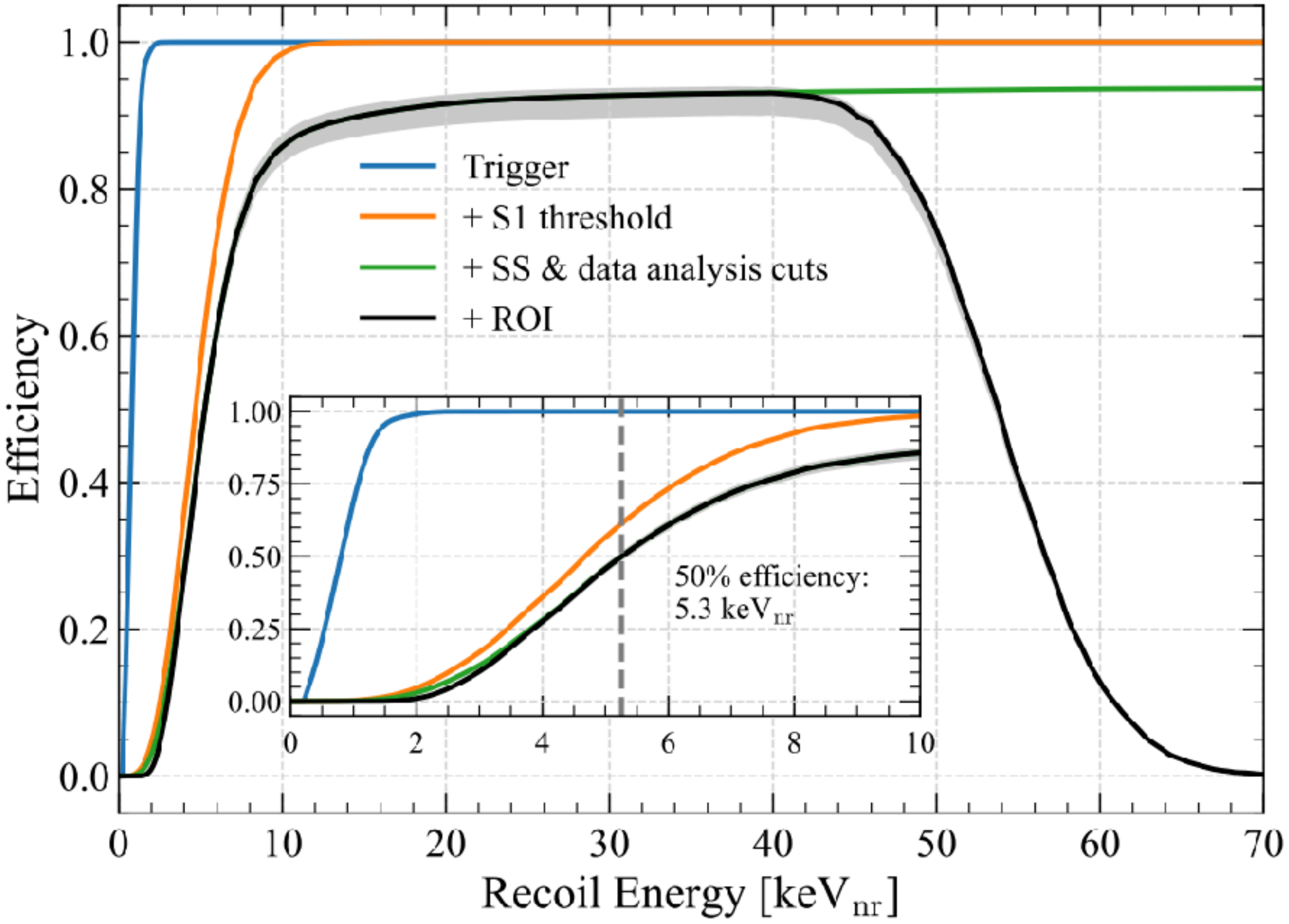
2. Event Selection

A. WIMP Selection

- Single-scatter without any OD coincidence
- Within the Region of Interest (ROI)

B. Background rejection cuts



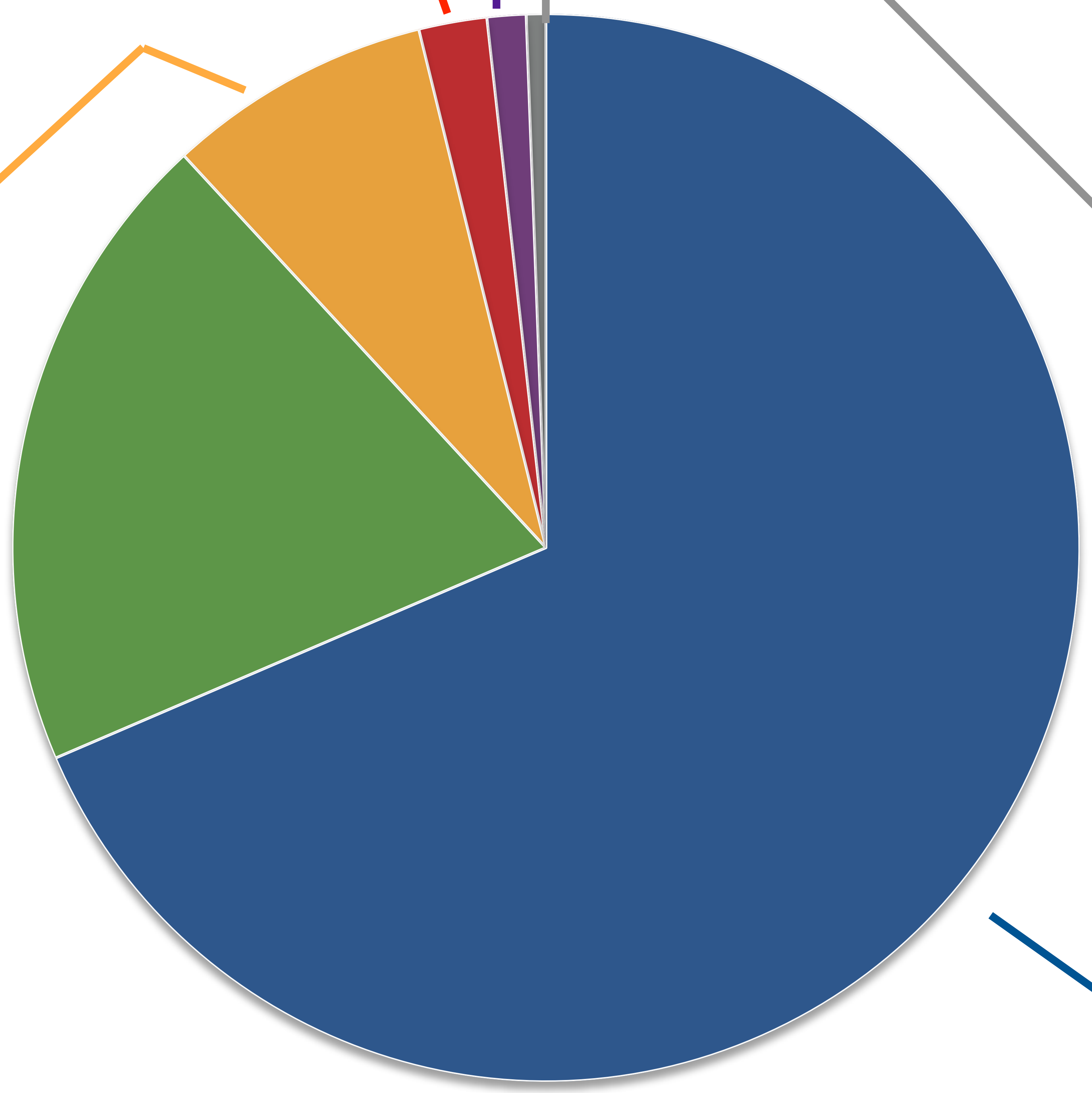


Background Model

Accidental Coincidence (instrumental)
- An Isolated S1 piled-up with an isolated S2

Solar ν e-scattering:
- *pp* + 7Be + 13N

Dissolved e-captures:
- 37Ar
- 127Xe
- 124Xe (double e-capture)



Detector γ-emitters:
- 238U chain
- 232Th Chain
- 40K
- 60Co

Nuclear Recoil
- Solar 8B CEvNS
- Radiogenic (α, n) neutron
- Spontaneous fission

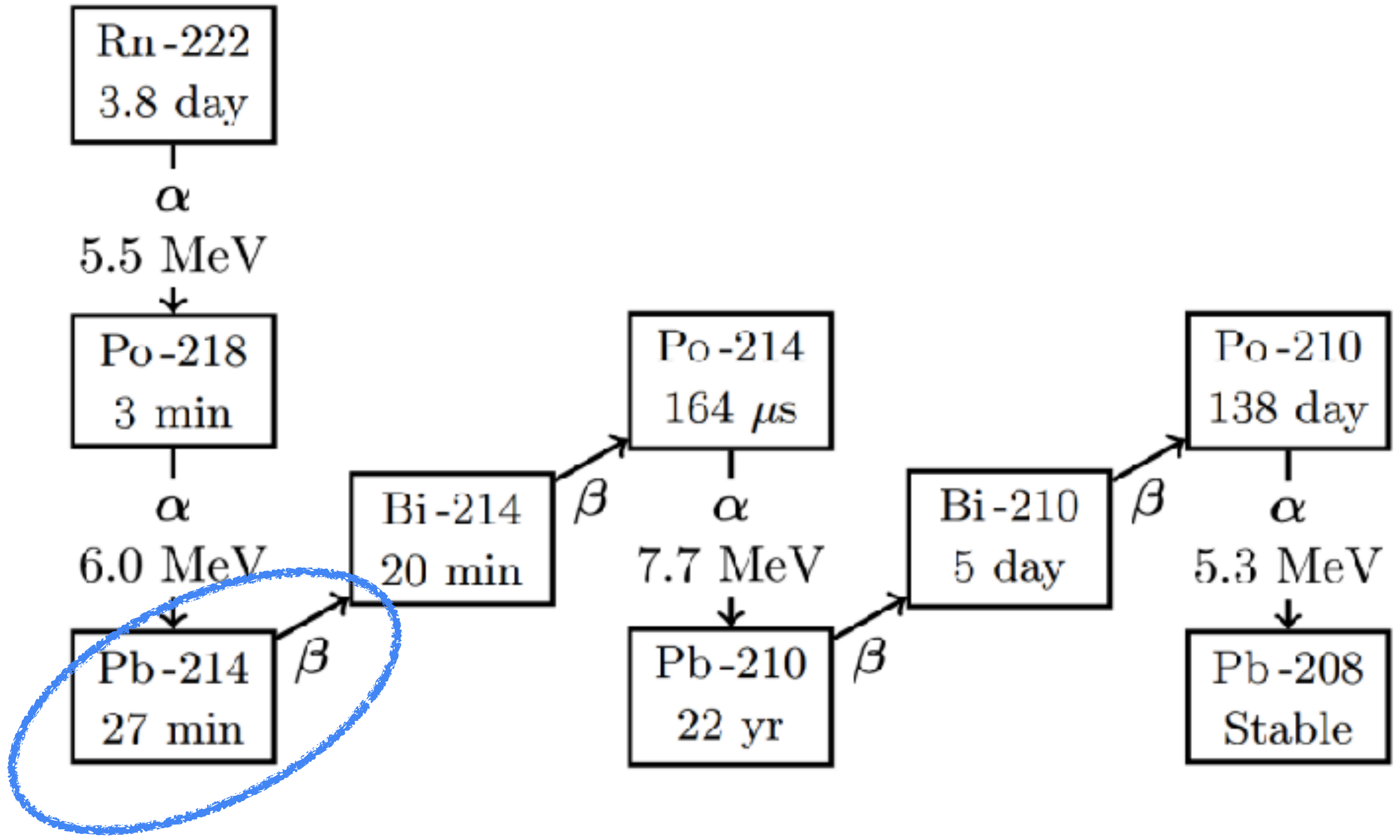
Dissolved β-emitters:
- 214Pb (222Rn daughter)
- 212Pb (220Rn daughter)
- 85Kr
- 136Xe ($2\nu\beta\beta$)

Radon as the main beta sources

Naked 214Pb β-decays are the main source of background in the WIMP search

Constraint Rn-chain via α tagging

- MeV-scaled α are hard to miss
- 222Rn activity within assay expectations



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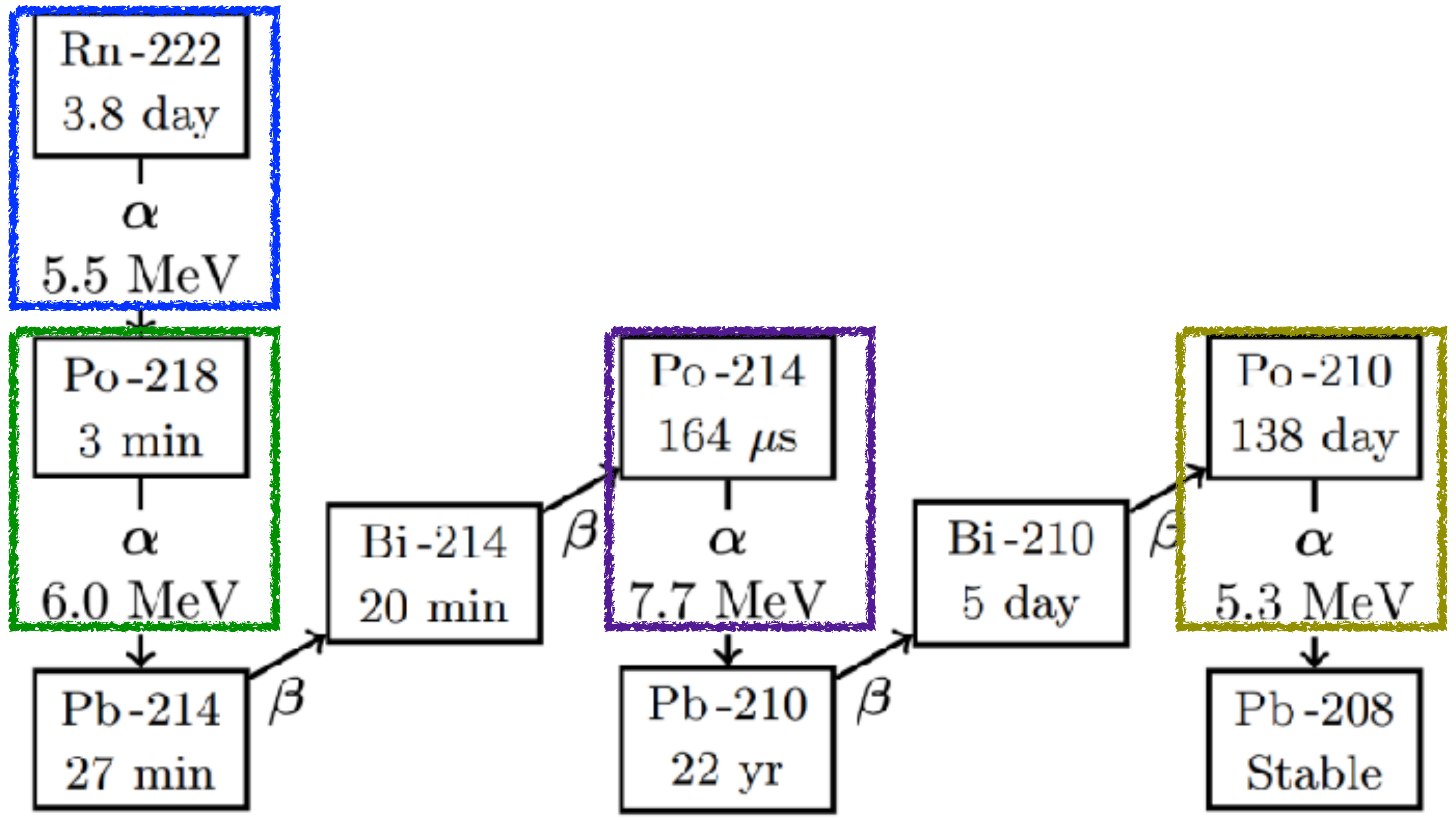
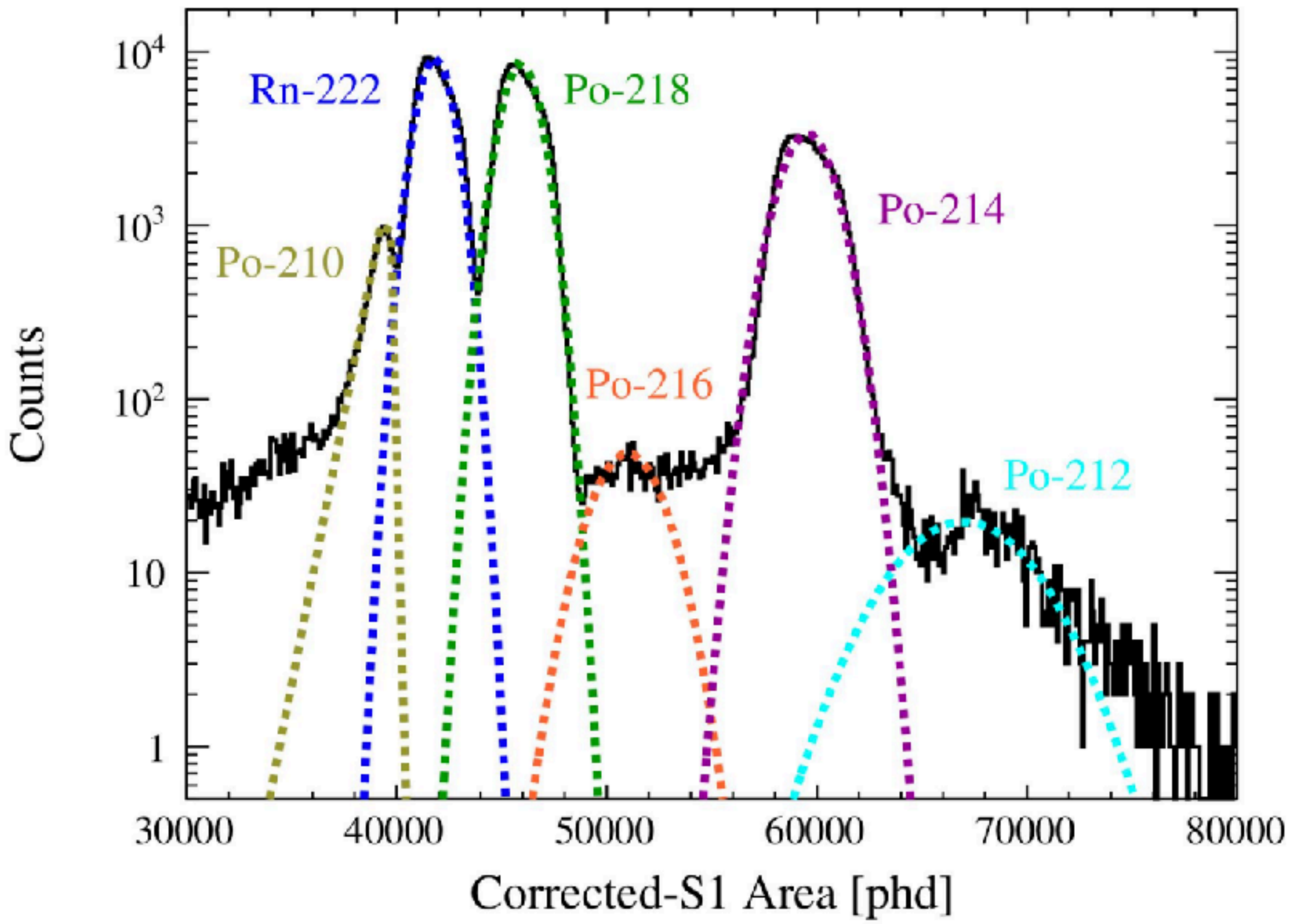


Rn220-chain:
- Po-212
- Po-216

Credit: A. Al Musalhi (IDM 2022)



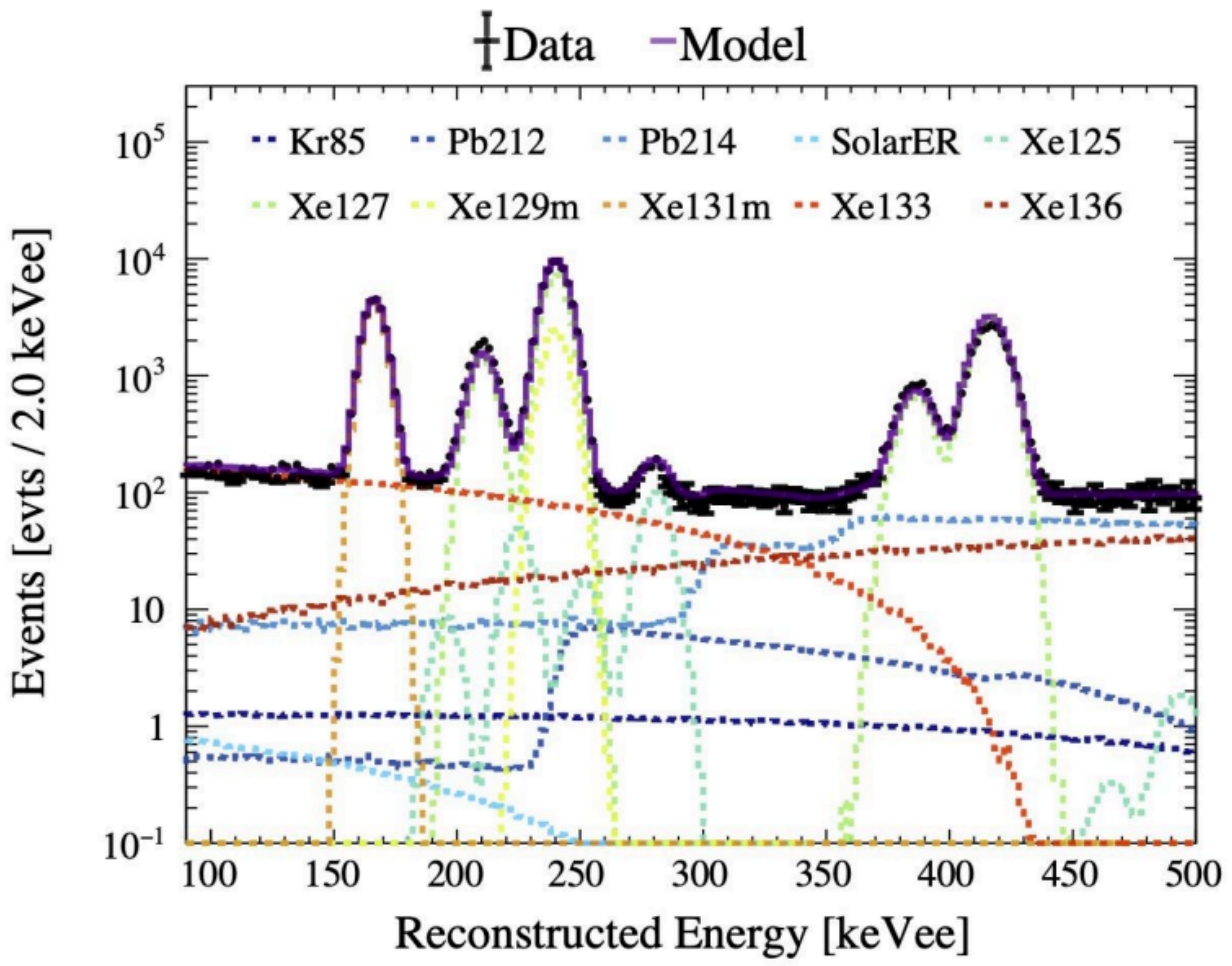
Isotope (decay)	Activity [μBq/kg]
^{222}Rn (alpha)	4.37 ± 0.31 (stat)
^{218}Po (alpha)	4.51 ± 0.32 (stat)
^{214}Pb (beta)	**3.26** ± 0.13(stat) ± 0.57(sys)
^{214}Po (alpha)	2.56 ± 0.21 (stat)

Radon as the main beta sources

Naked 214Pb β-decays are the main source of background in the WIMP search

Constraint via spectrum fit above WIMP energy ROI

- Various featured Xe activation peaks outside energy ROI
- 214Pb constrained by baseline



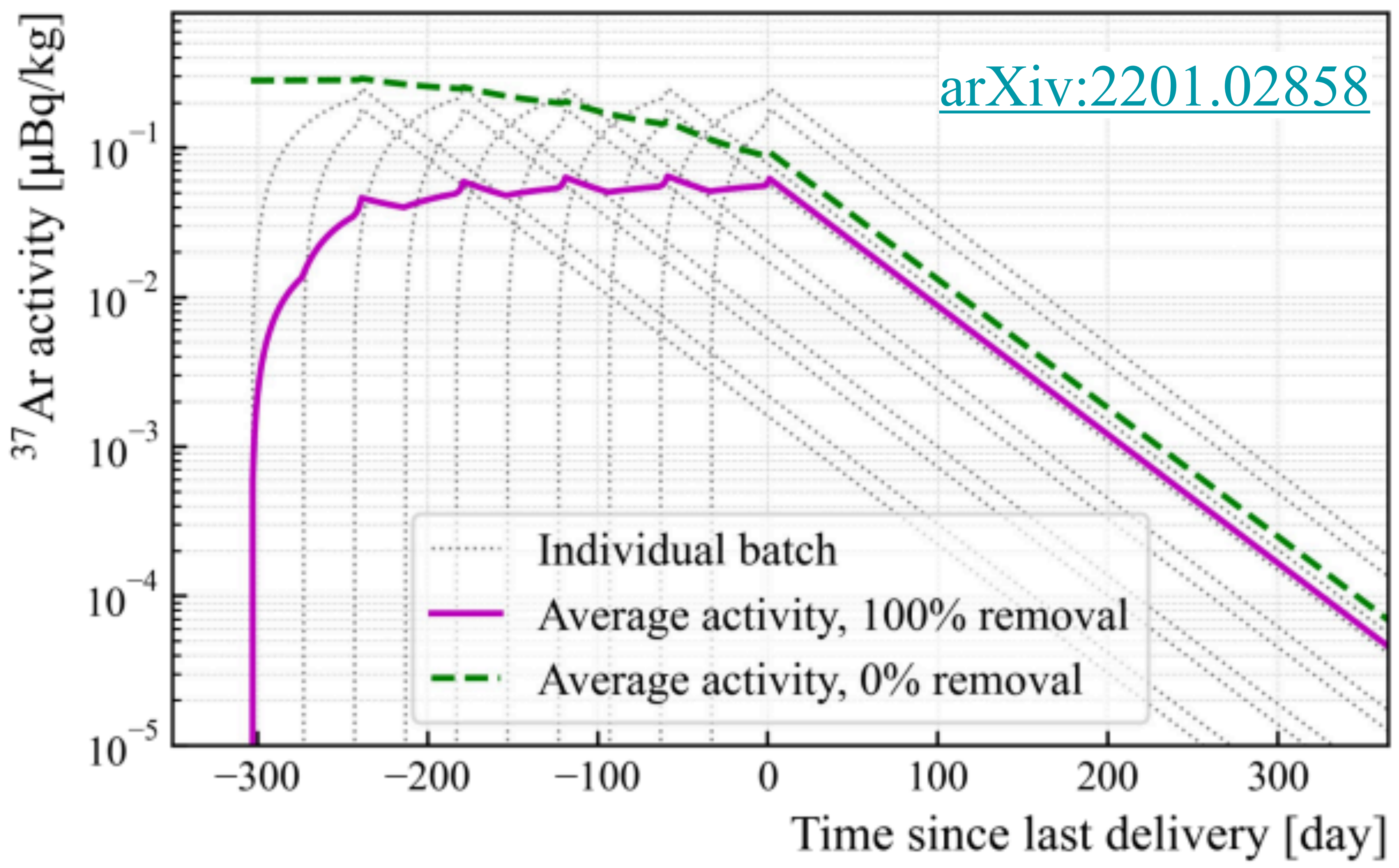
Credit:
A. Al Musalhi (IDM 2022)

Electron-captured

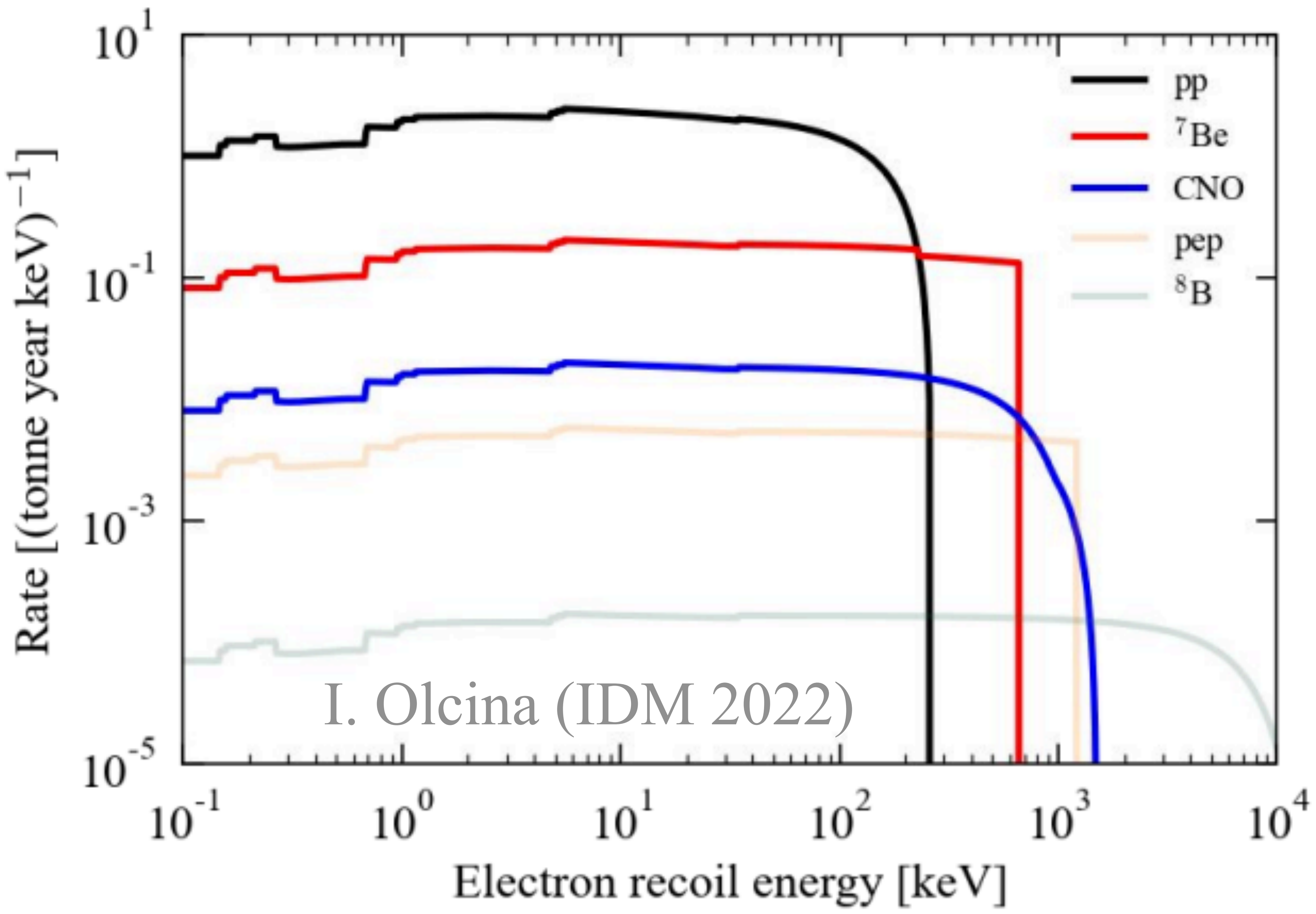
37Ar (2.8 keV, $t_{1/2}$=35d) dominates at low energy

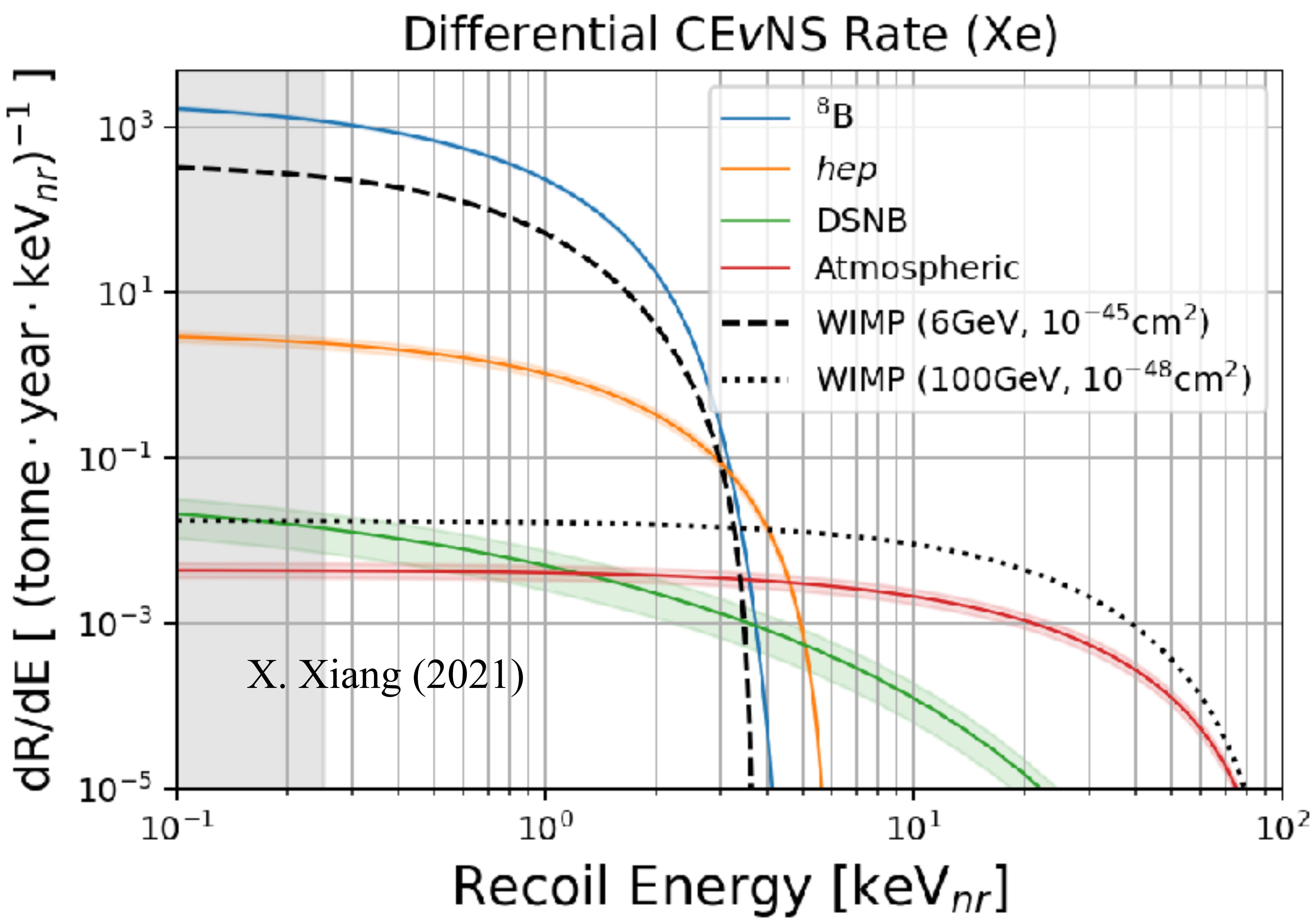
Produced by cosmic spallation of natural xenon during the transport

- Activity calculated using delivery schedule
- Expected **~100 decays** of 37 Ar in SR1 with large uncertainty



Solar Neutrinos (small overall)

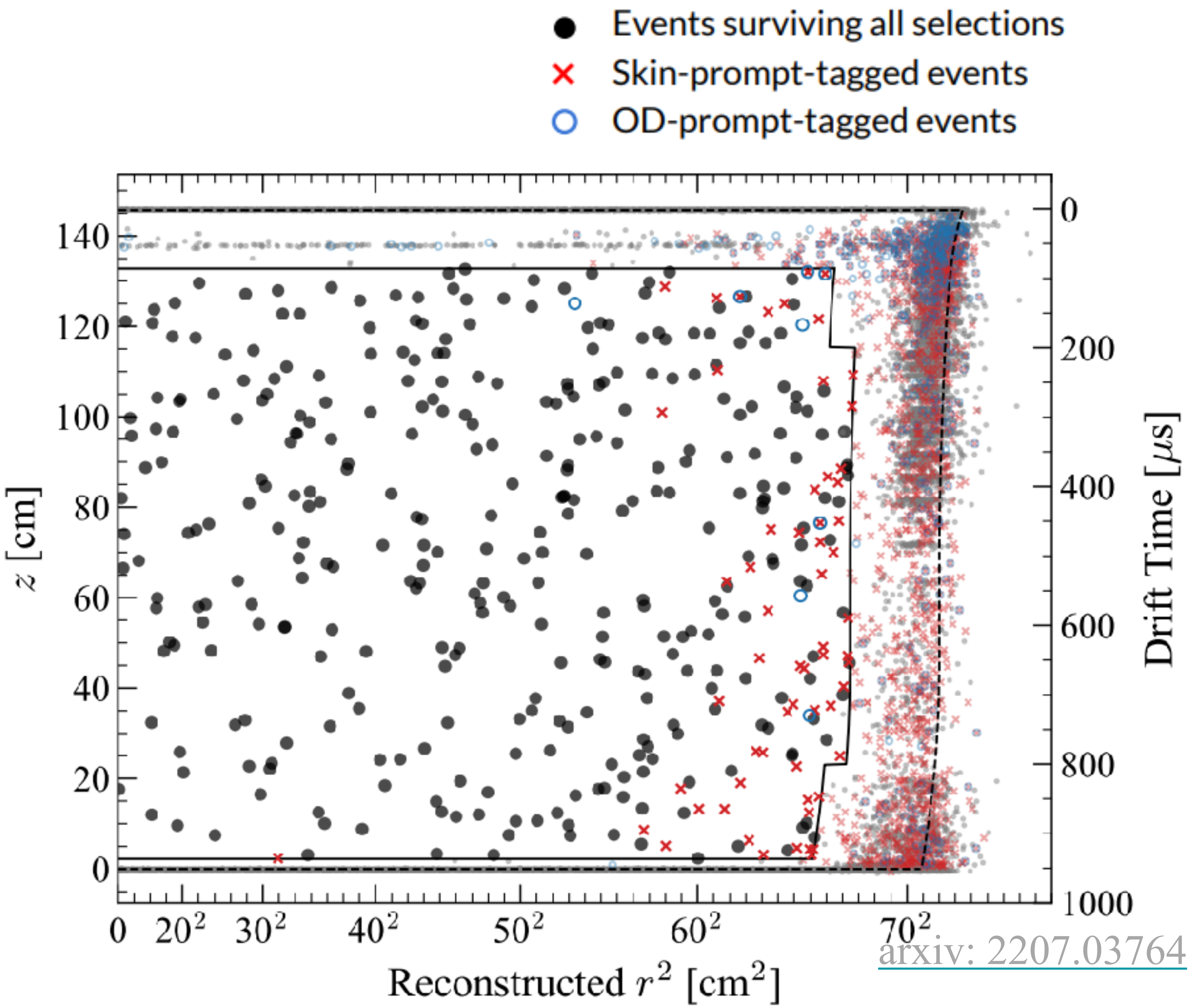




- Neutrino induced ER are mostly: pp, 7Be, CNO neutrinos (27.3 events)
- NR are mostly 8B CEvNS, suppressed by relatively high threshold (0.15 events)
  - S1c> 3phd & S1 coincidence >=3-fold
  - S2>600 phd (electron > 10)

Fiducial Volume

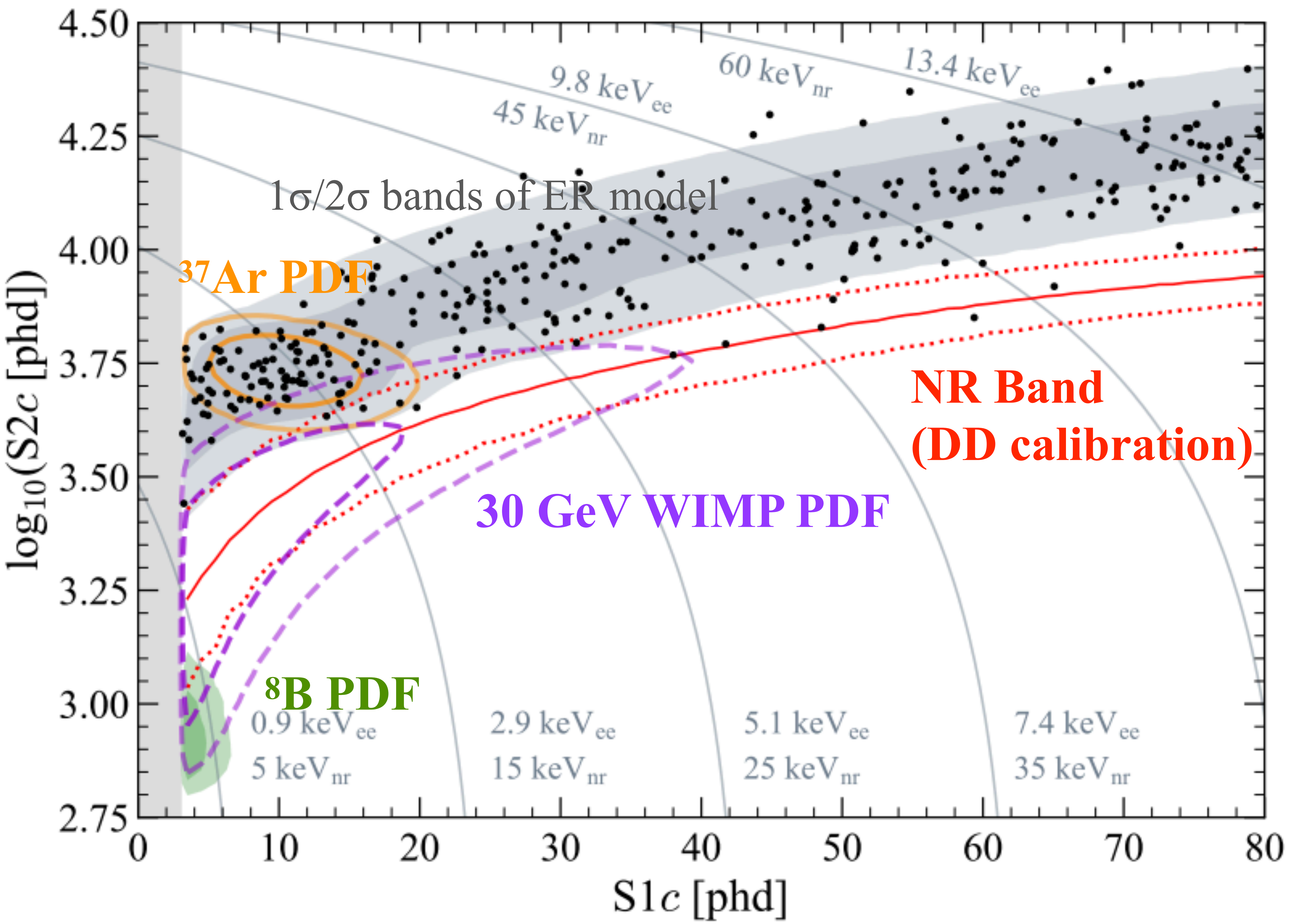
- **Events surviving all cuts** in the 5.5 tonne fiducial volume (FV) are distributed uniformly
  - Radial cut (4 - 5.2cm) driven by “wall-BG” (degraded S2 due to charge loss near the PTFE wall)
  - Vertical z cut (86μs<drift times< 936.5μs) is driven by gas events
- **Skin and OD prompt tag:**
  - Removes gammas
  - Skin reduces bare L,M-shell 127Xe background 5x
- **OD (and skin) delayed tag:**
  - 1200 μs capture window, ~200 keV threshold
  - Provides in situ counting on neutron BG:
  - 0 +0.2 neutron events in SR1



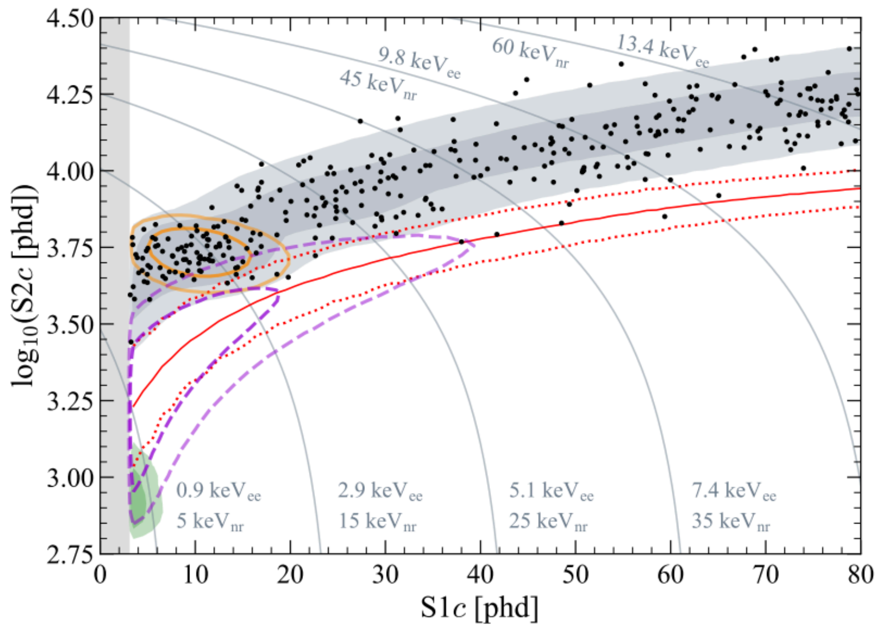
arxiv: 2207.03764

Events after all cuts

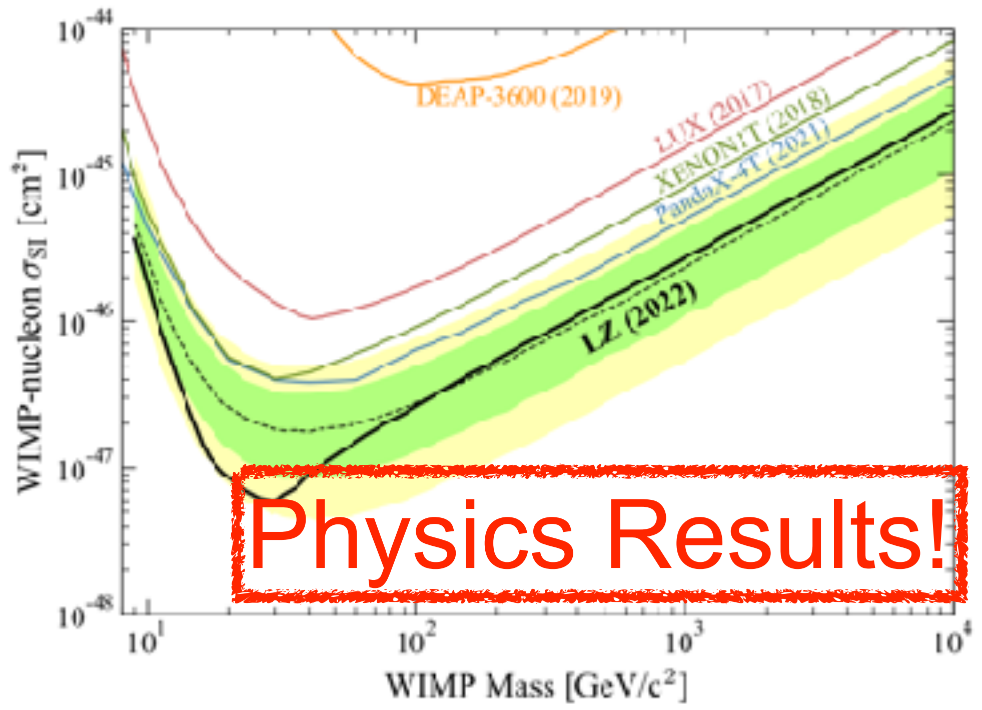
- A total of 335 events after all cuts in the ROI
- 60 ± 1 live days
- 5.5 ± 0.2 tonne FV
- This is the input to PLR



Profile Likelihood Ratio



PLR



Parameters of interest: signal mean (μ_s)

Observables: (S1, S2)

Nuisance parameters: background means

$$\mathcal{L}(\boldsymbol{\theta}) = \left[\mathrm{Pois}(n_0|\mu(\boldsymbol{\theta}))\prod_{e=1}^{n_0}\frac{1}{\mu(\boldsymbol{\theta})}\left(\mu_s f_s(\boldsymbol{x}_e|\boldsymbol{\theta}) + \sum_{b=1}^{N_c}\mu_b f_b(\boldsymbol{x}_e)\right)\right]\prod_{p=1}^{N_c} f_p(\boldsymbol{g}_p|\mu_p)$$

Extended term

Constraint functions

Global observables: expected events

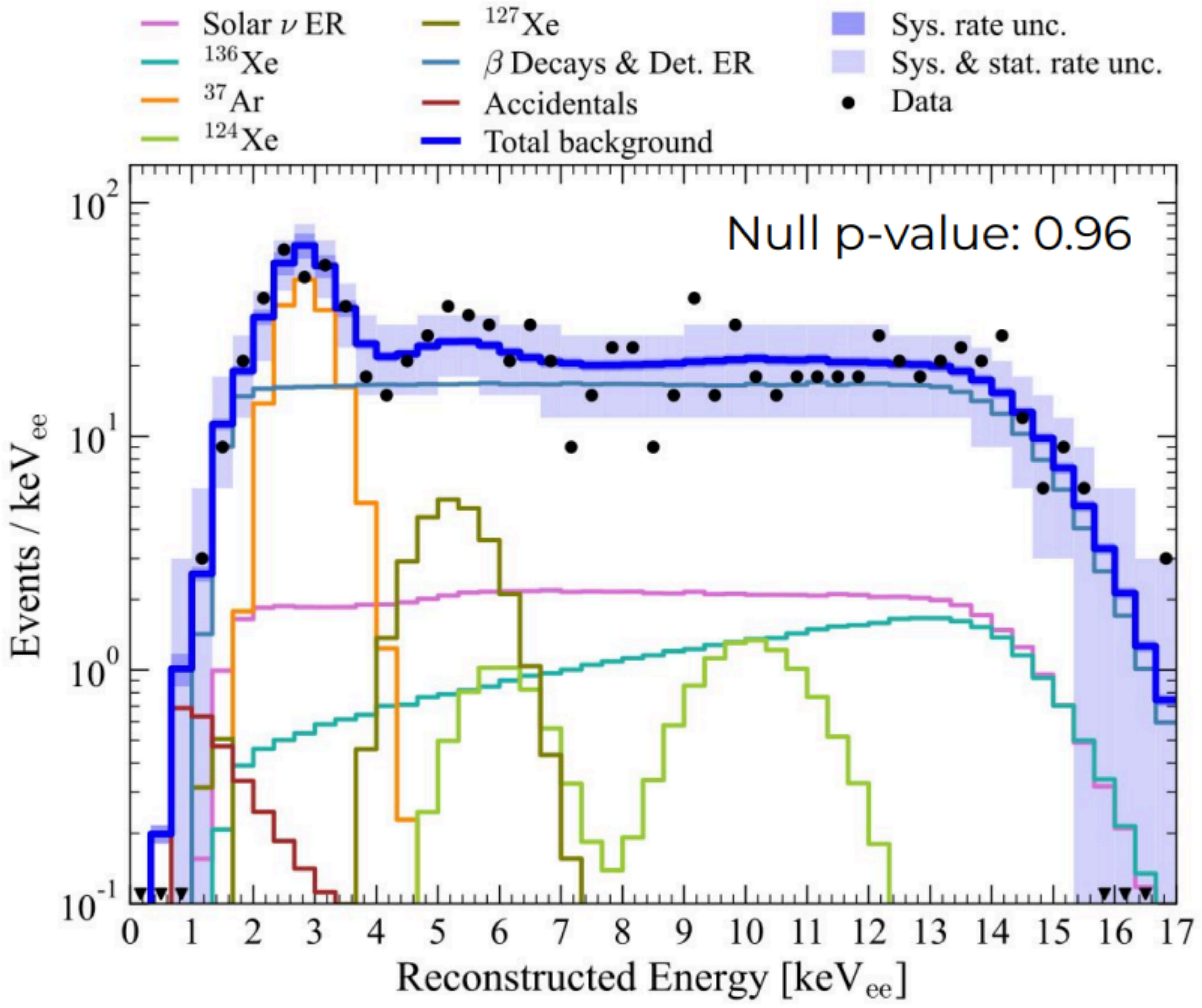
- Follow agreed statistics convention to report dark matter search (Eur Phys J C (2021) 81:907)
  - Frequentist, two-sided, signal-strength is strictly positive, asymptotic limit is not used

PLR Fitting Results

Best fit is consistent with zero WIMP hypothesis at all masses

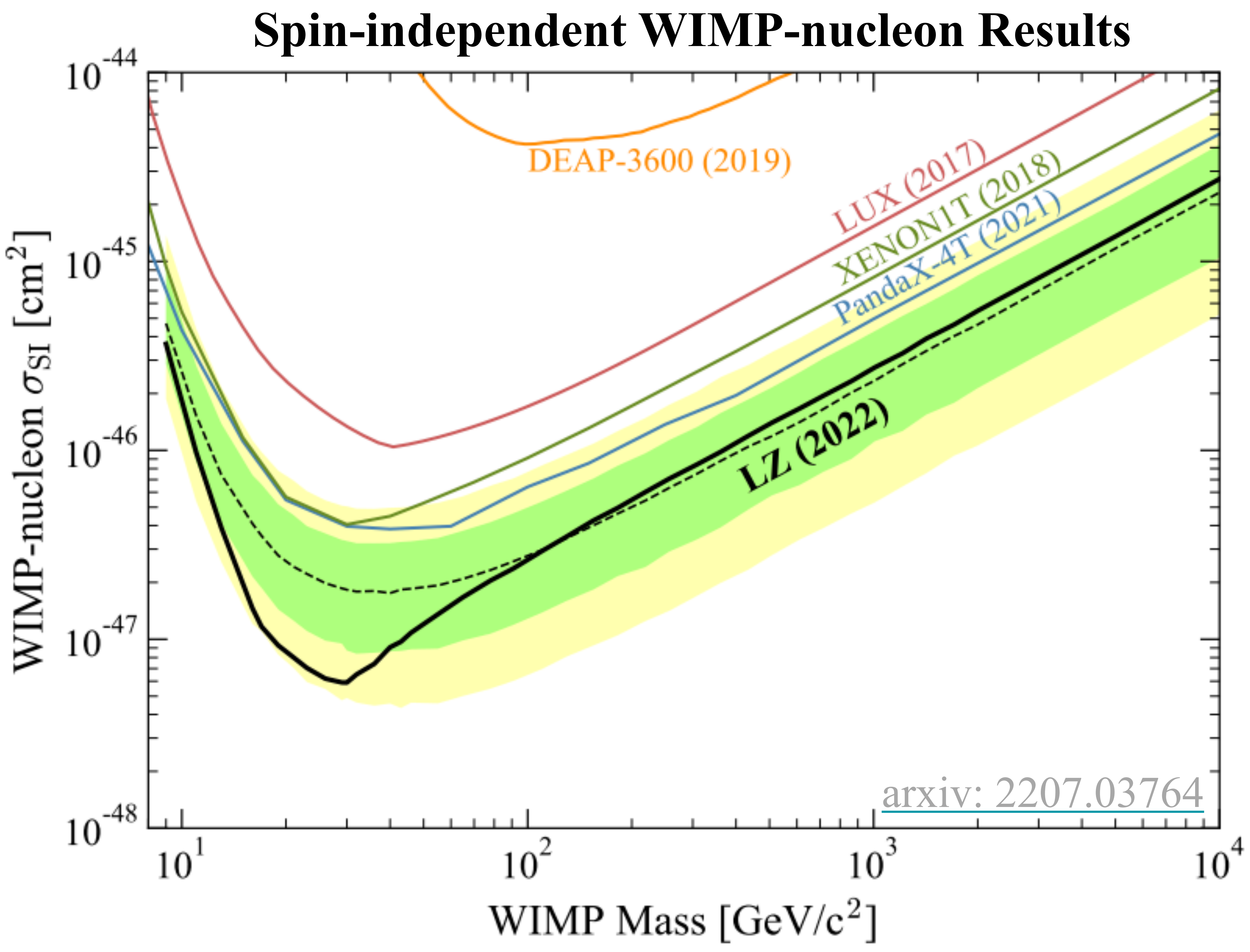
Source	Expected Events	Fit Result
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

arxiv: 2207.03764

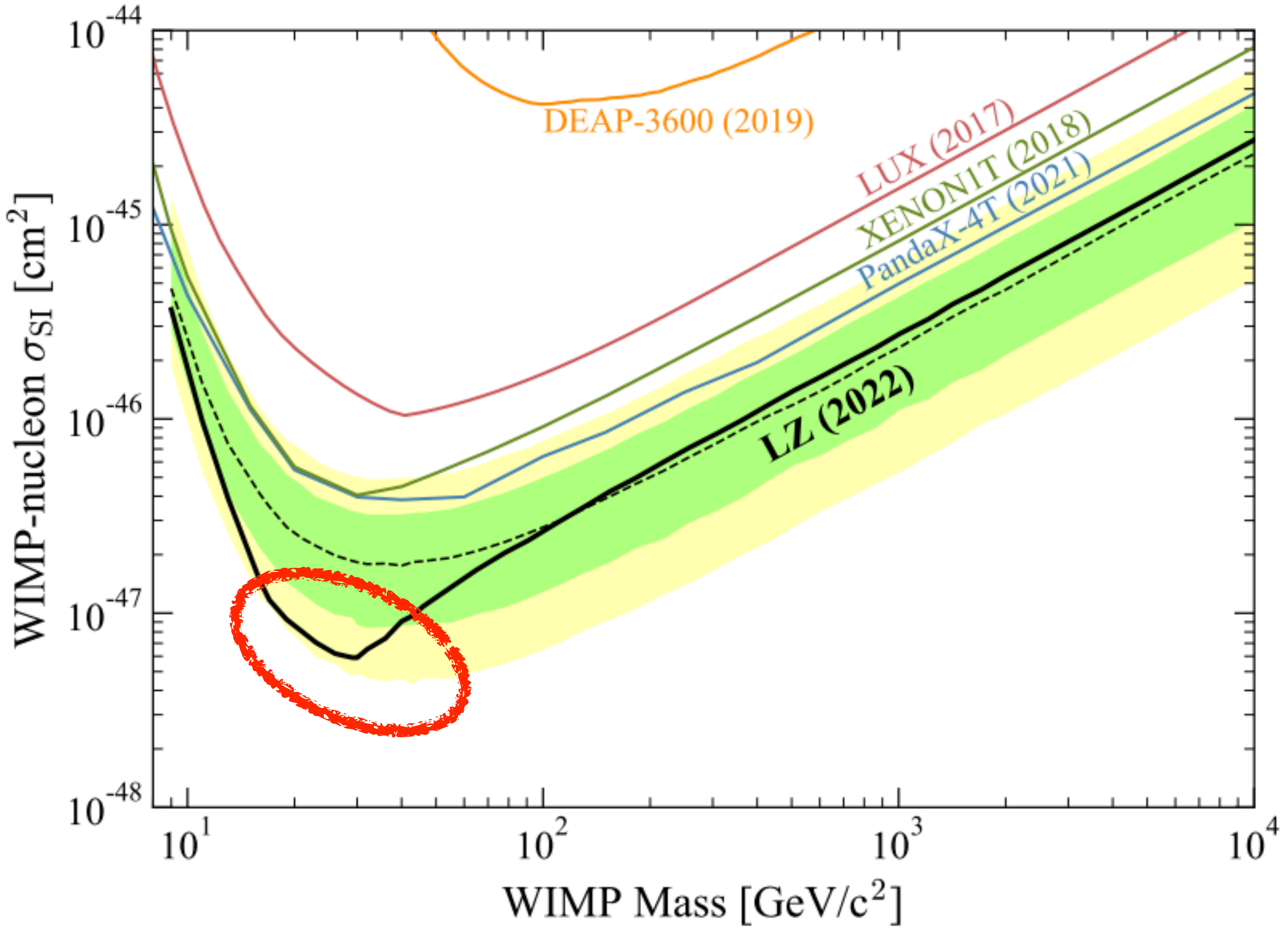


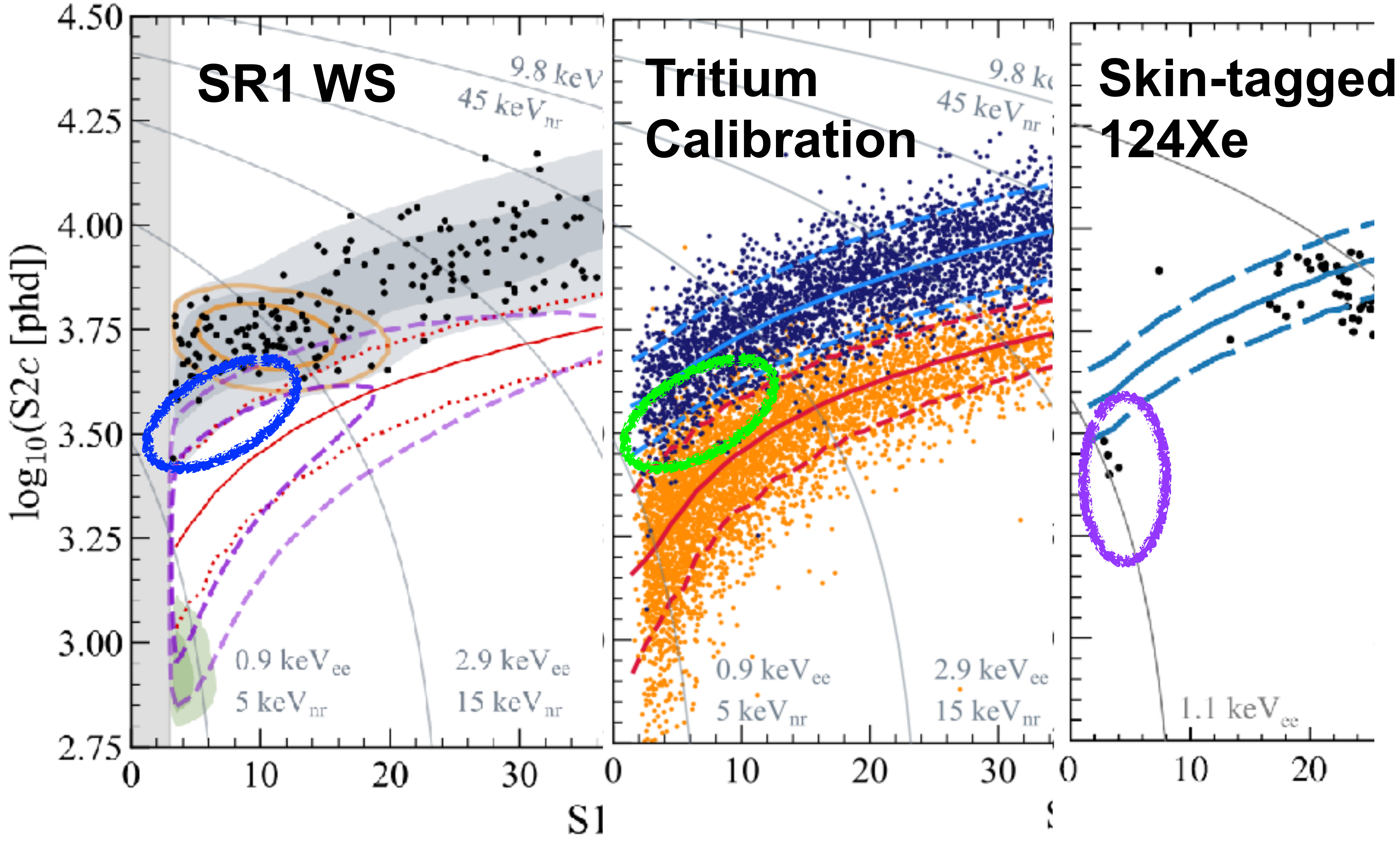
The Exclusion Limit

- Best limit (90% CL) on SI WIMP-nucleon cross section
  - Minimum 5.9×10^{-48} cm^2 at 30 GeV
  - High mass matches expectation while low-mass benefits from the under-fluctuation of data
- A power constraint of $\Pi_{crit}= 0.32$ was applied (recommendation by Eur Phys J C (2021) 81:907)



Downward fluctuation=> Power constrained limit





Downward fluctuation in the observed upper limit near 30 GeV

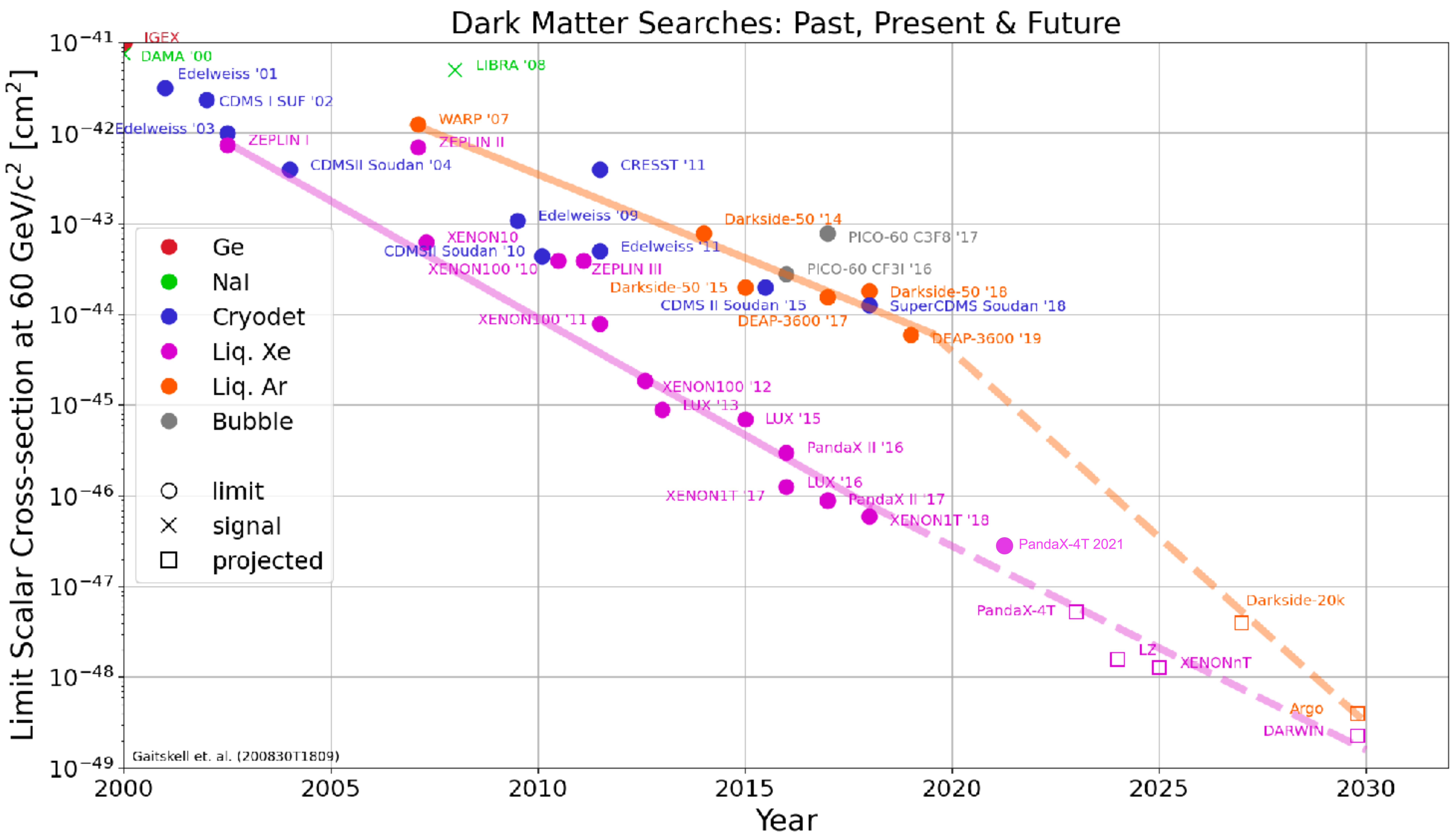
Deficit of events under 37Ar population is observed

However Tritium &DD data are well-covered in the same region (no deficit)

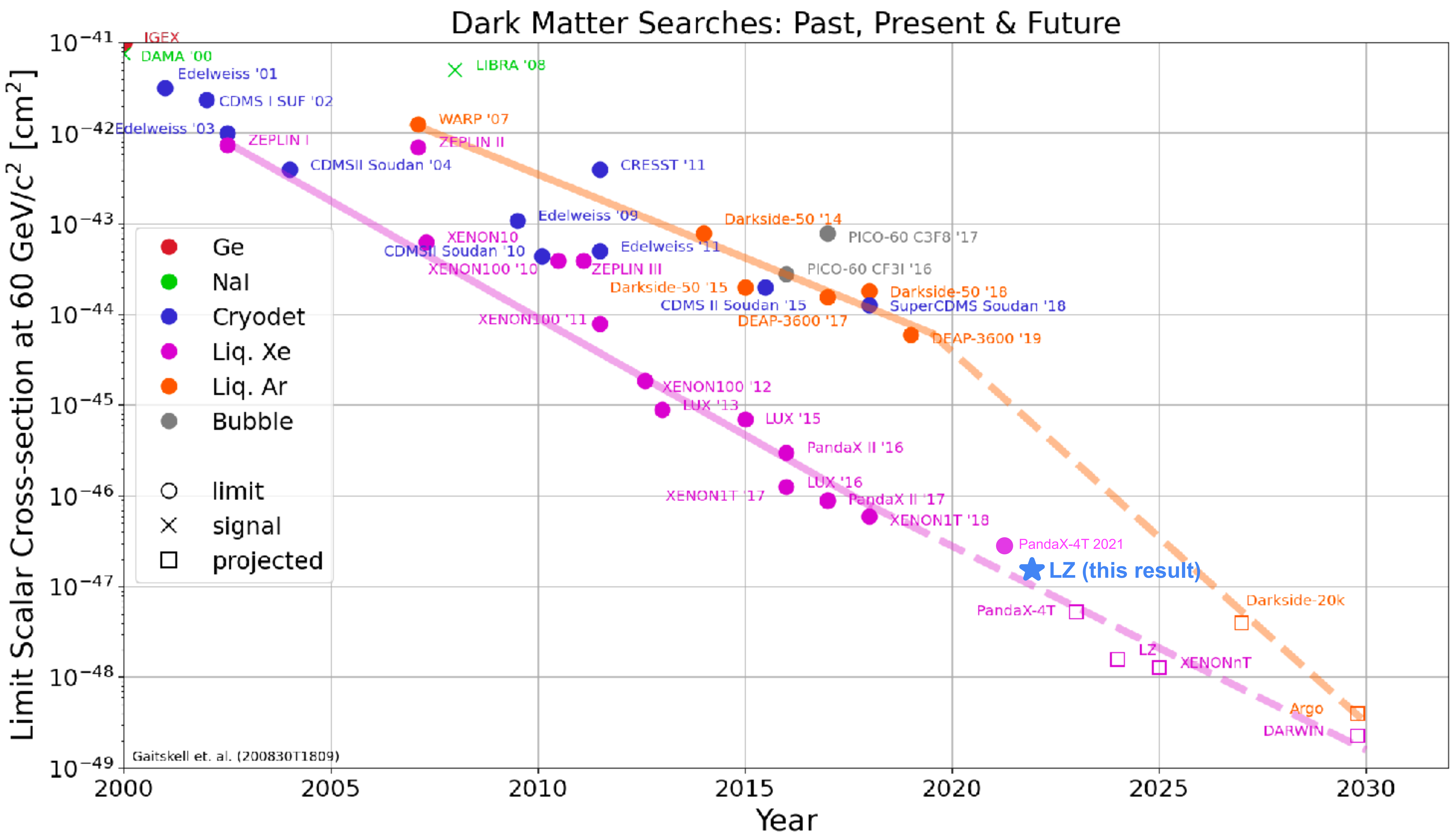
Skin-tagged M-shell 124Xe is consistent with expected count.

Conclusion: a statistical fluctuation; use power constrained limit

Where are we in the “Moore’s Law”?



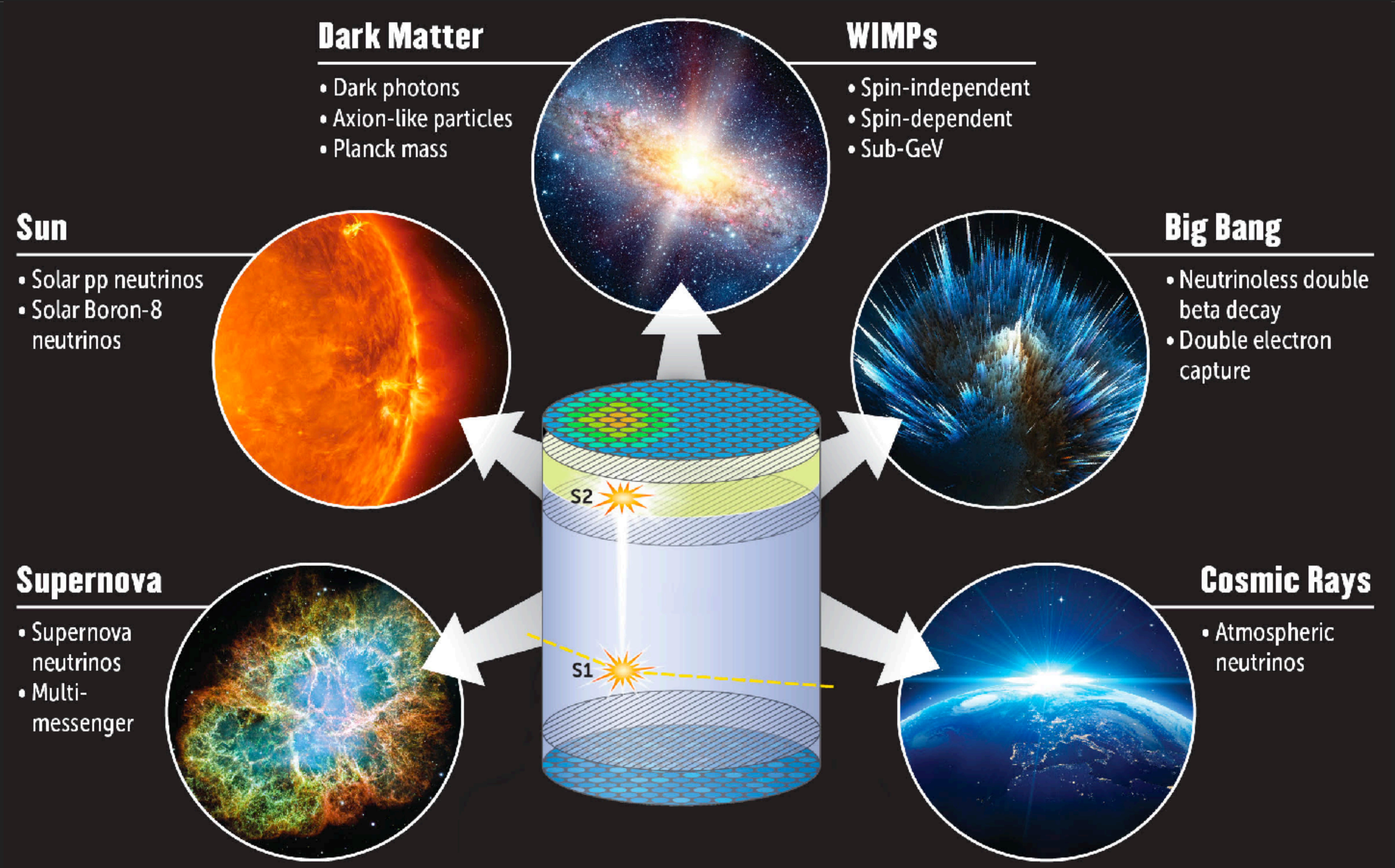
Best and on-track



Outline

- Landscape of Particle Dark Matter Search
- Overview of LZ-ZEPLIN Detector
- First Results of LUX-ZEPLIN
- Future LZ, XLZD and Beyond

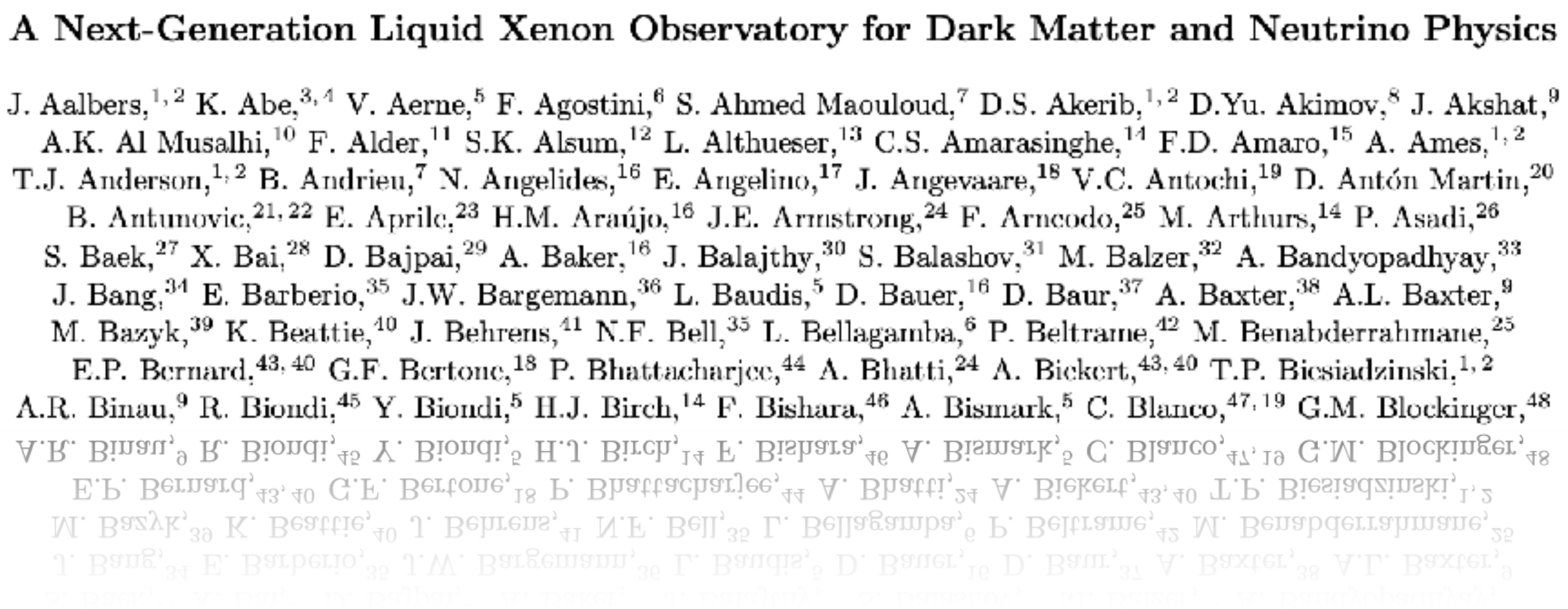
Physics of future LZ and beyond



Credit: Next Generation Liquid Xenon Observatory

XLZD Consortium

- XLZD = **X**enon + **LZ** + **D**ARWIN
- Website: https://xlzd.org/
- White paper: “A Next-generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics” (2203.02309)
  - Signed by over 600 scientists from 150 institutions in 28 countries
  - 40-100 tonnes of Xenon



A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

J. Aalbers,[1,2] K. Abe,[3,4] V. Aerne,[5] F. Agostini,[6] S. Ahmed Maouloud,[7] D.S. Akerib,[1,2] D.Yu. Akimov,[8] J. Akshat,[9] A.K. Al Musalhi,[10] F. Alder,[11] S.K. Alsum,[12] L. Althueser,[13] C.S. Amarasinghe,[14] F.D. Amaro,[15] A. Ames,[1,2] T.J. Anderson,[1,2] B. Andrieu,[7] N. Angelides,[16] E. Angelino,[17] J. Angevaare,[18] V.C. Antochi,[19] D. Antón Martin,[20] B. Antunovic,[21,22] E. Aprile,[23] H.M. Araújo,[16] J.E. Armstrong,[24] F. Arneodo,[25] M. Arthurs,[14] P. Asadi,[26] S. Baek,[27] X. Bai,[28] D. Bajpai,[29] A. Baker,[16] J. Balajthy,[30] S. Balashov,[31] M. Balzer,[32] A. Bandyopadhyay,[33] J. Bang,[34] E. Barberio,[35] J.W. Bargemann,[36] L. Baudis,[5] D. Bauer,[16] D. Baur,[37] A. Baxter,[38] A.L. Baxter,[9] M. Bazyk,[39] K. Beattie,[10] J. Behrens,[41] N.F. Bell,[35] L. Bellagamba,[6] P. Beltrame,[42] M. Benabderrahmane,[25] E.P. Bernard,[43,40] G.F. Bertone,[18] P. Bhattacharjee,[44] A. Bhatti,[24] A. Bickert,[43,40] T.P. Biesiadzinski,[1,2] A.R. Binau,[9] R. Biondi,[45] Y. Biondi,[5] H.J. Birch,[14] F. Bishara,[46] A. Bismark,[5] C. Blanco,[47,19] G.M. Blockinger,[48]

Photo Credit: Joachim Wolf/ KIT (APPEC July 2022)

Summary

- LZ is on commissioning and taking high quality physics data
- The SR1 found no evidence of dark matter, but its results demonstrates the potential to reach new physics
- Xenon community is united as XLZD

Acknowledgements - Thank You!

@lzdarkmatter

https://lz.lbl.gov/

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- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
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FCT Fundação para a Ciência e a Tecnologia

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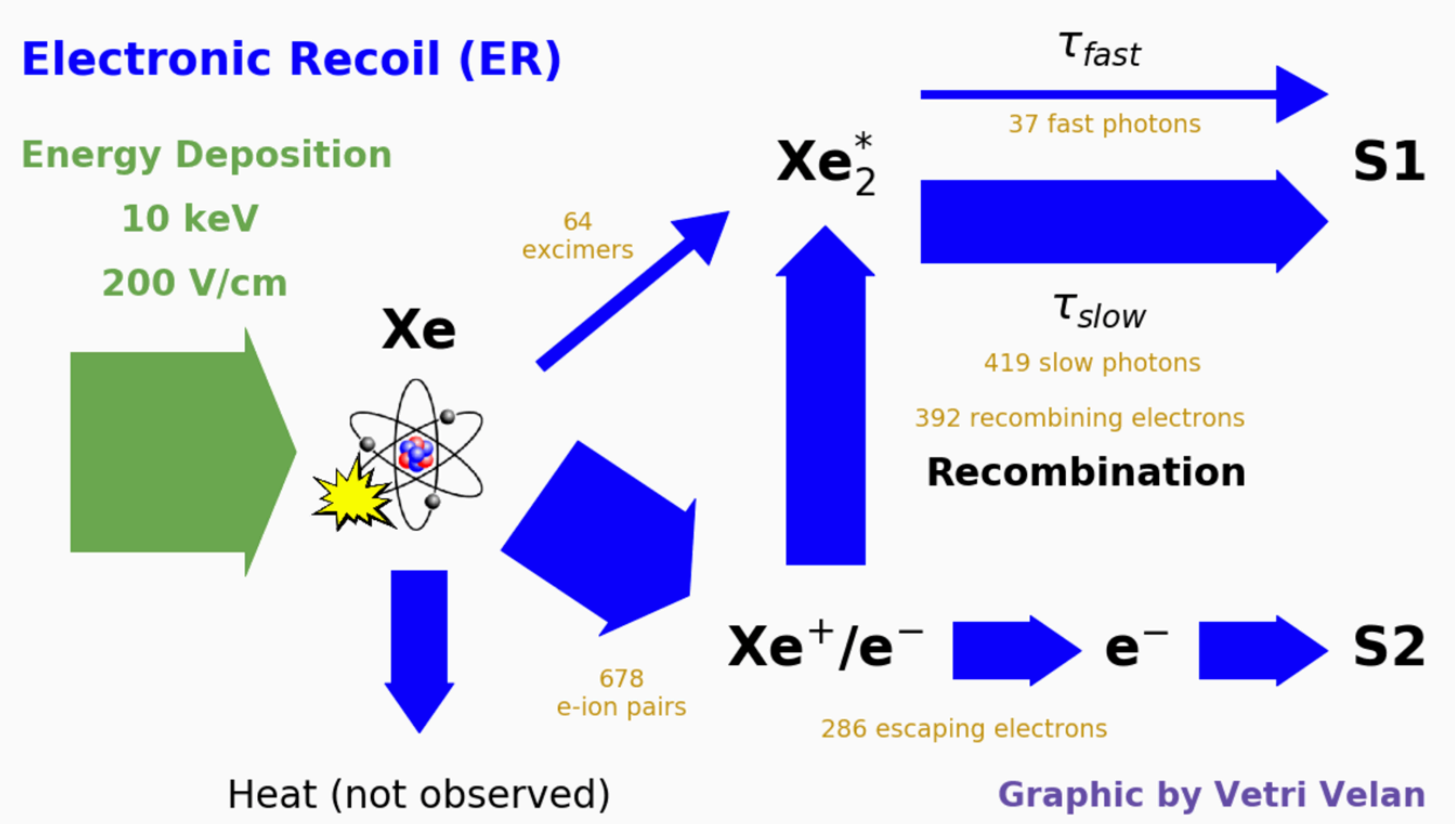
Back up

Microphysics of Xenon



Xe127

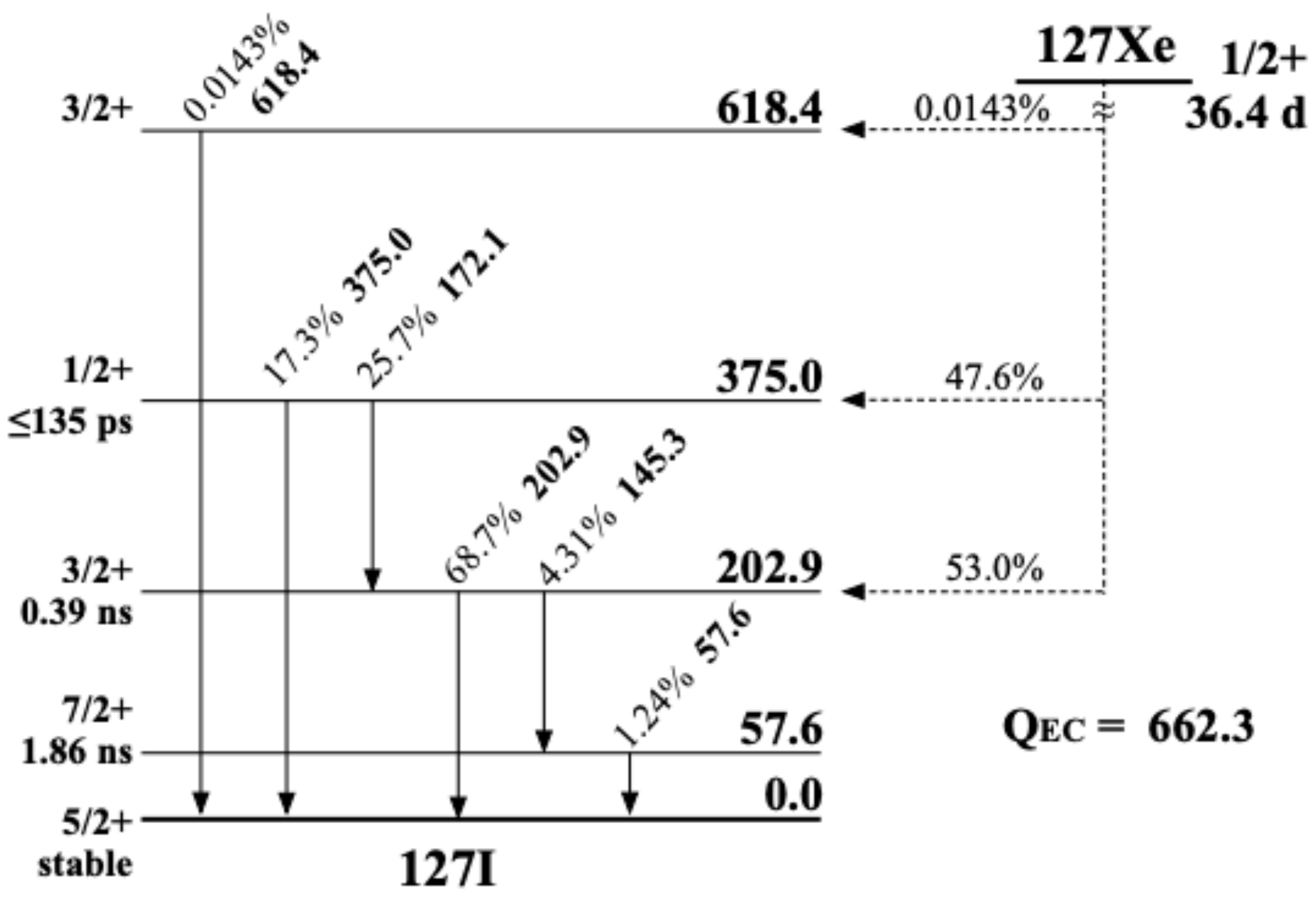
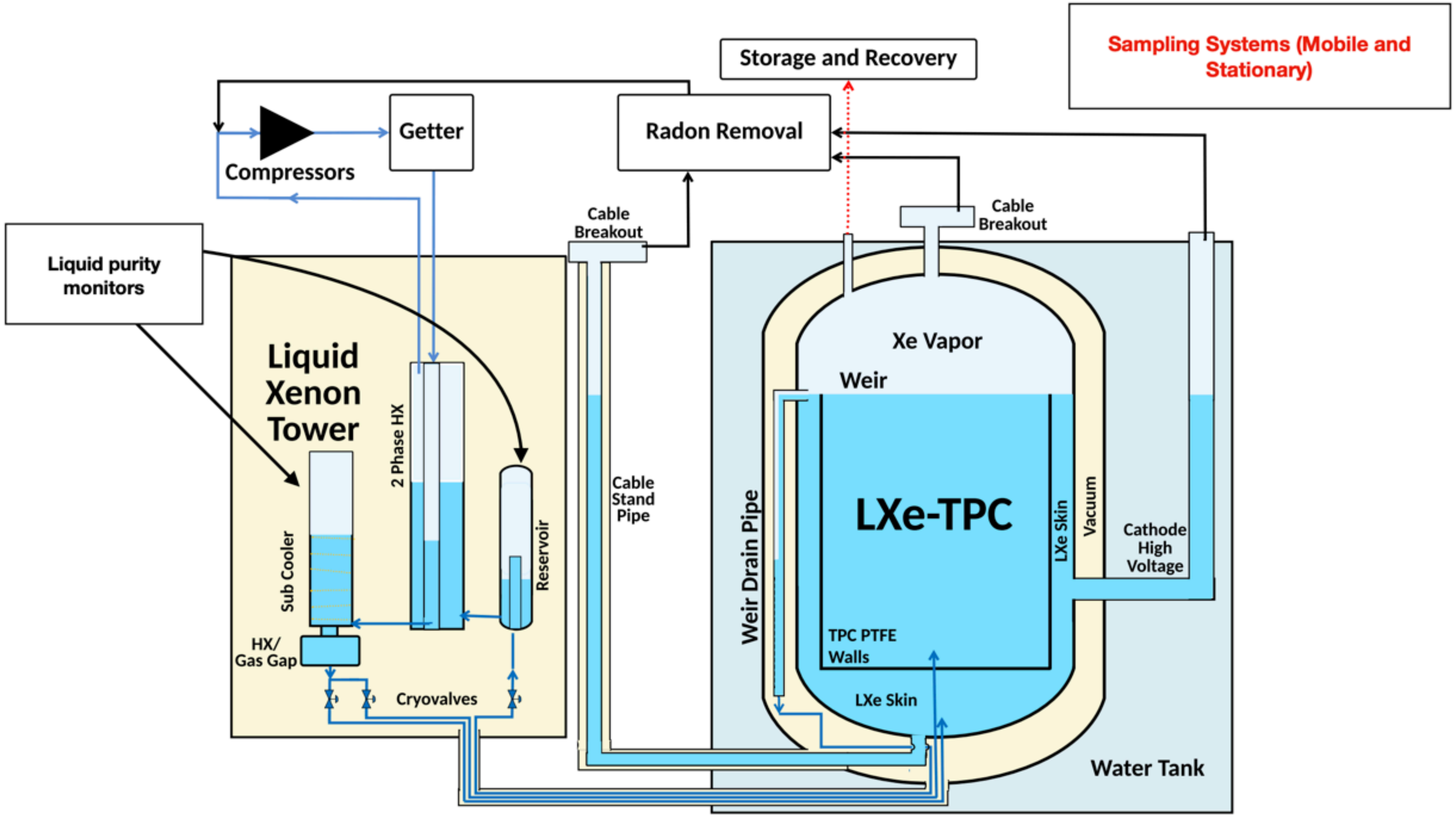


FIG. 1. Decay scheme of ^{127}Xe [25] with units of keV. The ^{127}Xe decays via electron capture to ^{127}I. The percentage above the transition arrow is the gamma-ray intensity as fraction of parent (^{127}Xe) decay.

Circulation System



Credit: David Woodward

Fit Uncertainty from PLR

- Except for betas and 37Ar, backgrounds have tight constraints from sideband analysis or external measurements
- Fit in statistical dominant region, and the impact from constraint is relatively small,
- The fit uncertainties do shrink a little bit, but below the statistical fluctuation.
- Final result has good agreement between data and fit output model

Source	Expected Events	Best Fit
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
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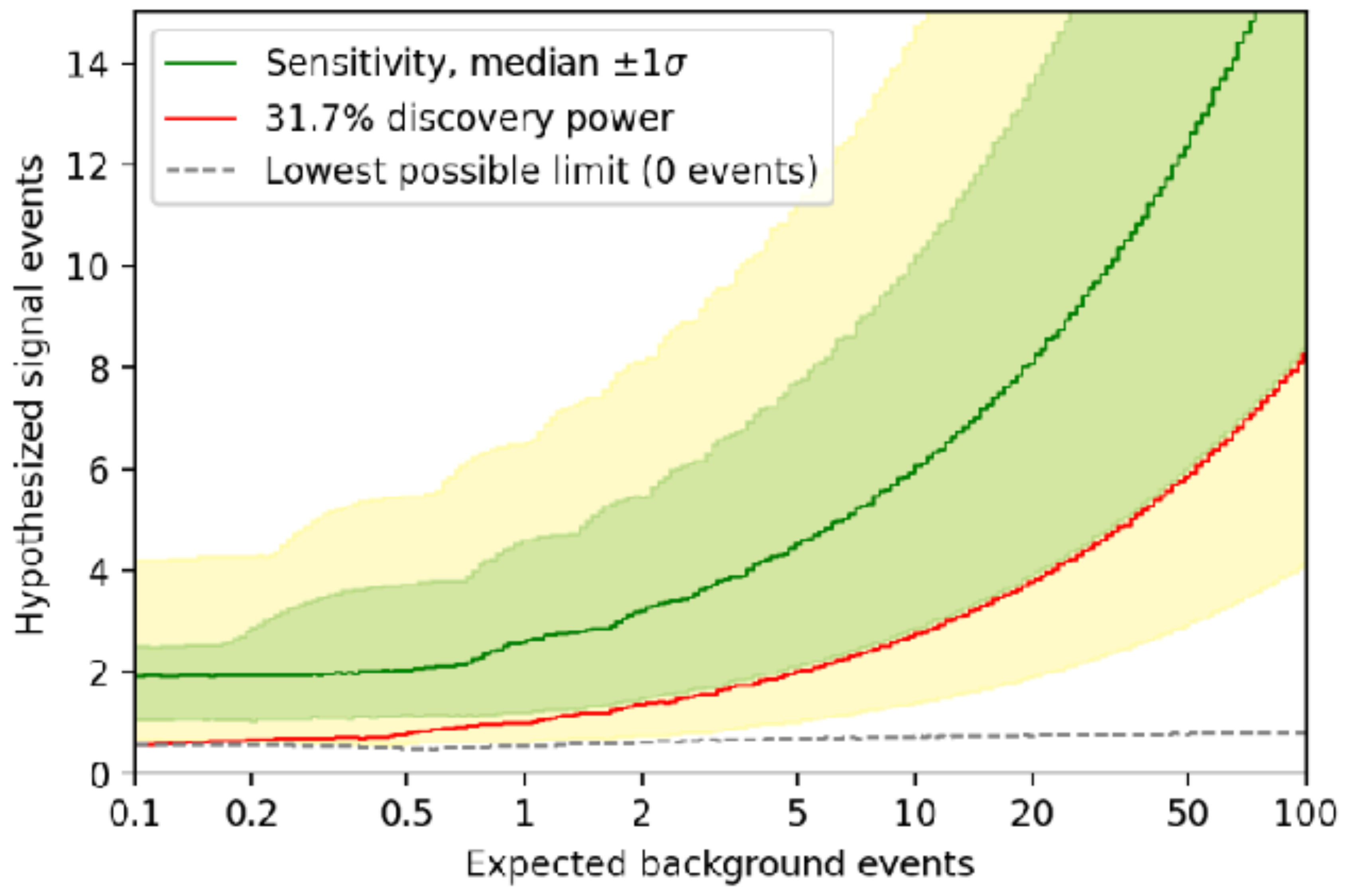
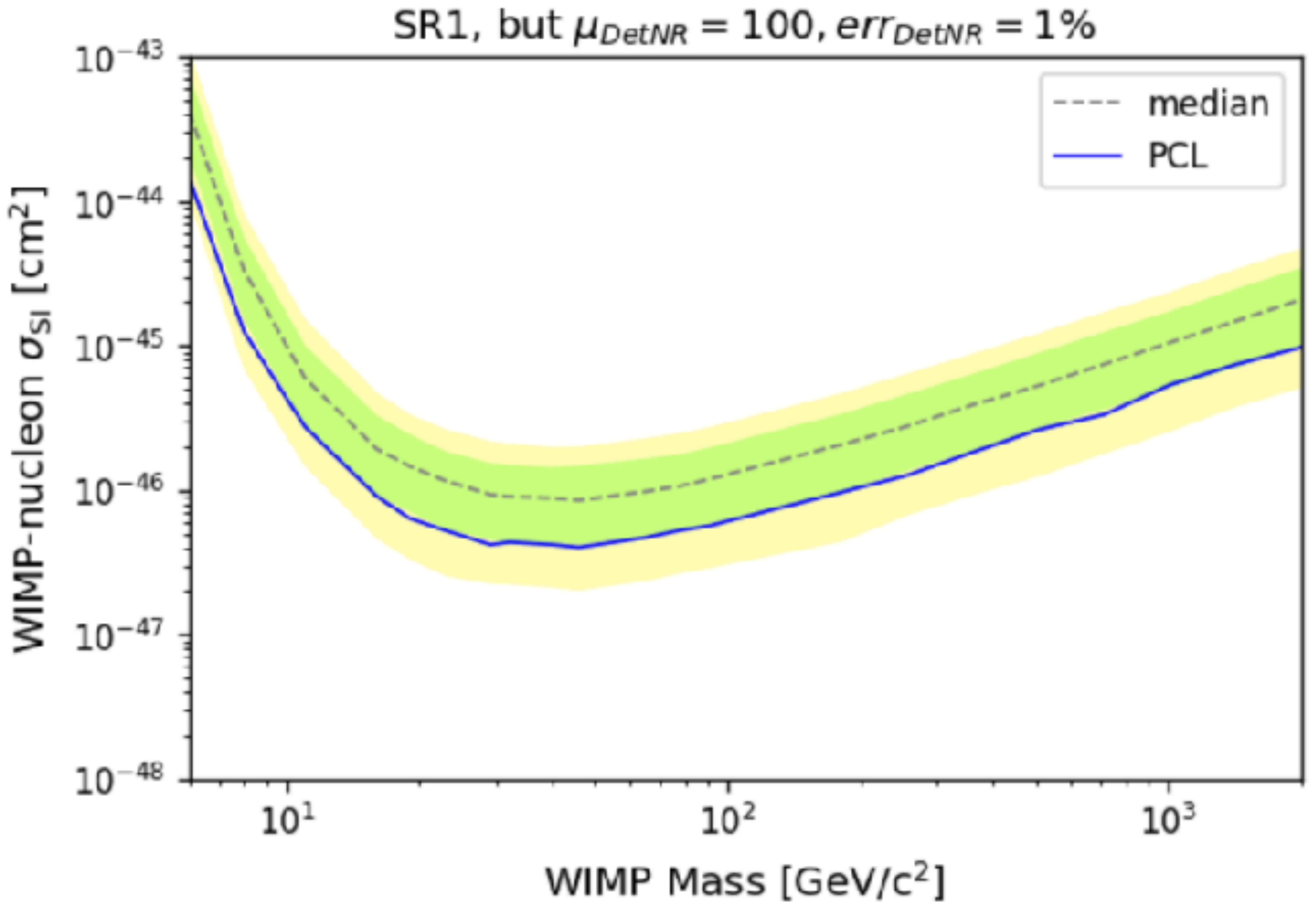
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

Why Power Constraint not following -1σ?

- LZ follows the convention from community-wide, statistical white paper to power constrain its limits
- The discovery power threshold was chosen to be 0.32, corresponds to -1 sigma for a Gaussian case
- Due to low event count, the discovery power is highly enhanced — even a very small value of the will satisfy the discovery power requirement.
- Top plot: departure from the 1 sigma contour at low number of expected background events in a Gaussian toy simulation
- Bottom: confirmation that we "hug" the -1 sigma contour when the expected number of detector NR events is increased from 0 to 100



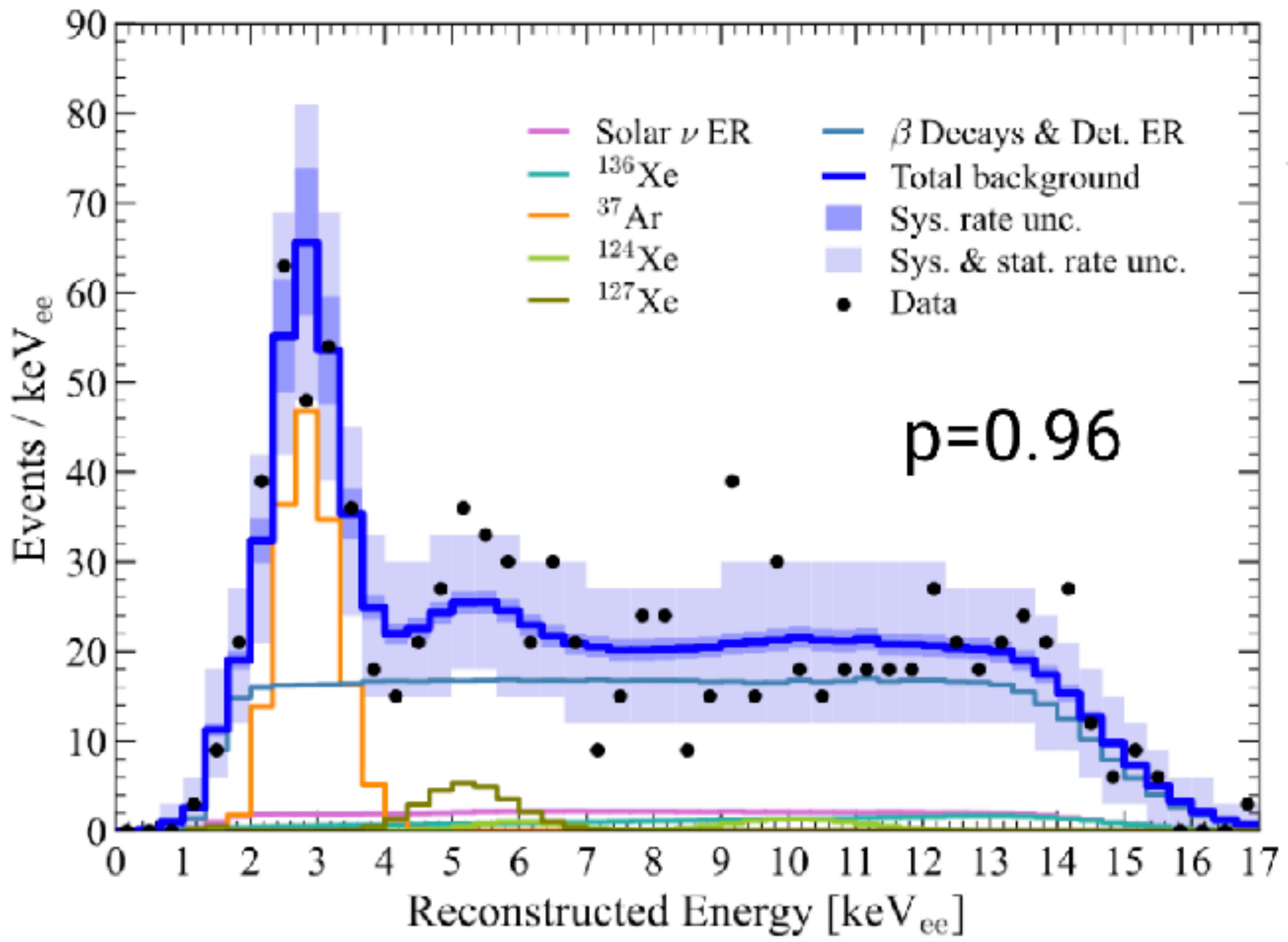
Credit: Jelle A

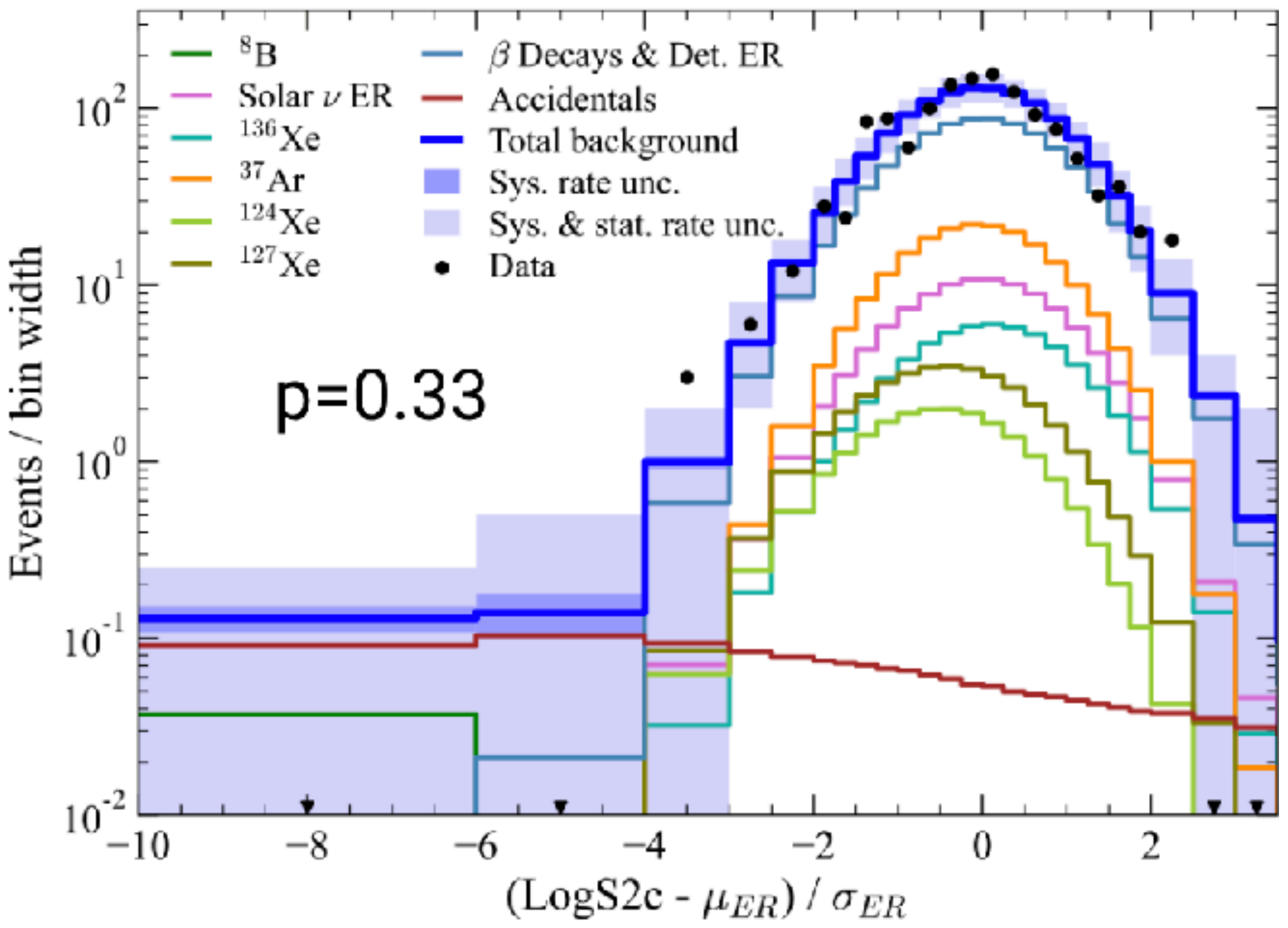


Credit: Xin X.

Why p-value is so good?

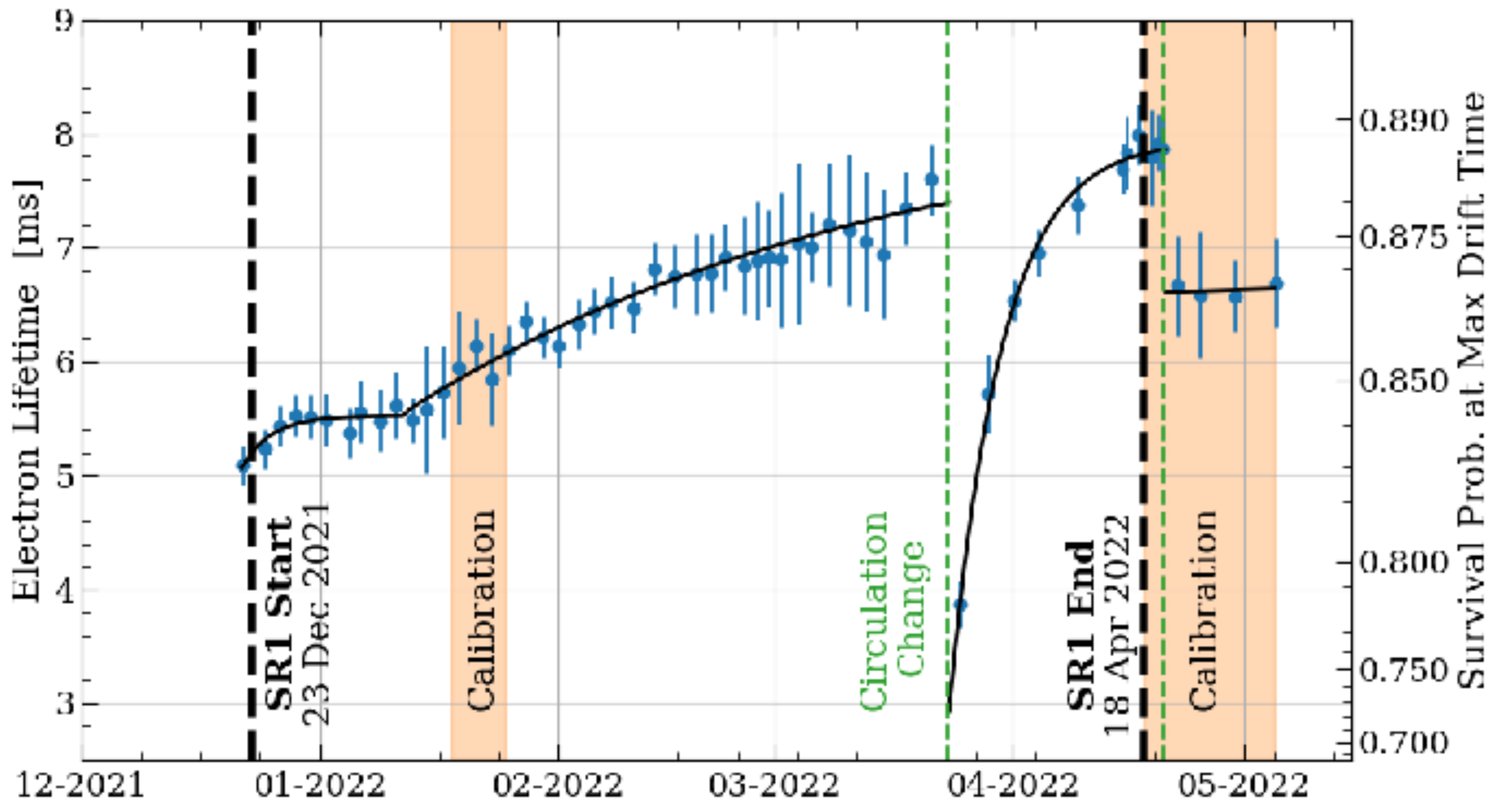
- We chose the binning for the reconstructed energy spectrum to best show the resolution of the 37Ar peak
- If we look at other observables (e.g. reduced ER band) or rebinning in Erec, the p-value returns other values, which show that the data is not inconsistent with the background-only model
- This appears to be a random fluctuation





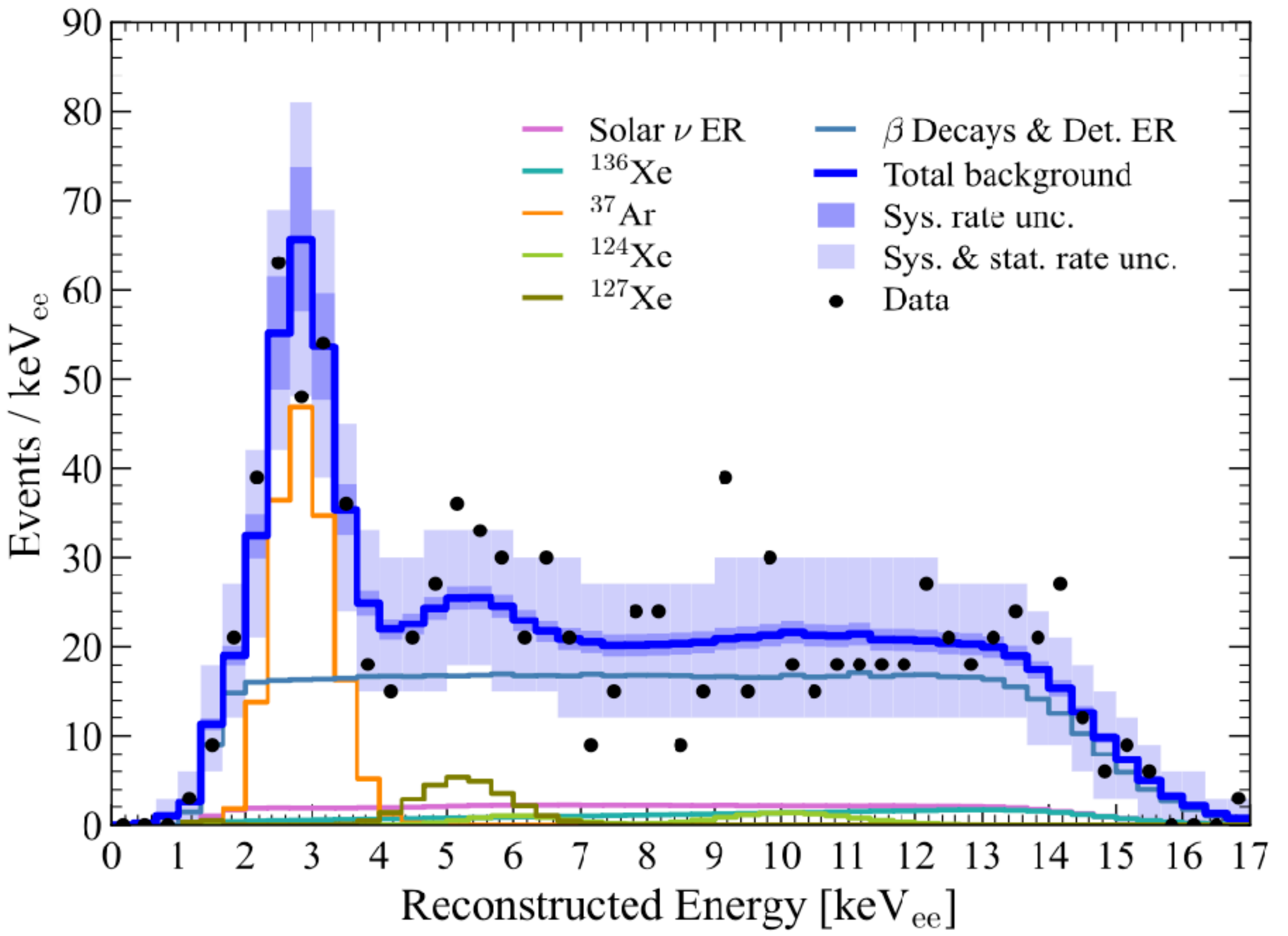
Why purity dropped?

- A problem in operational activity caused the reservoir that the detector drains into to rapidly empty of liquid xenon
- This caused displacement of xenon and electronegative impurities, contaminating the main system
- Overall, the duration of the event was ~10 minutes
- The impurities were removed by the getter as expected, and the purity recovered quickly
- The second circulation change was to perform source injection calibrations with increased liquid mixing in the TPC

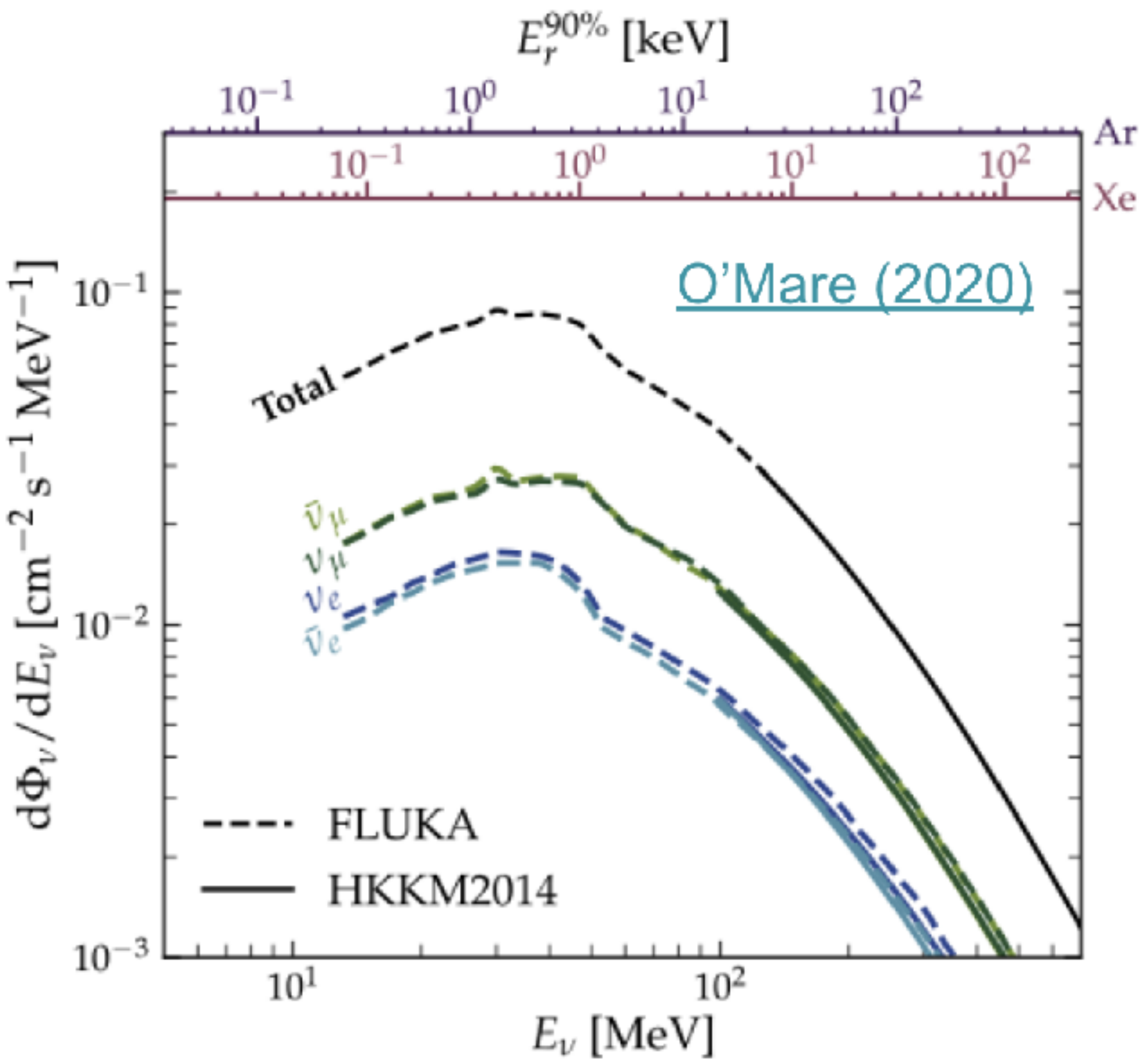


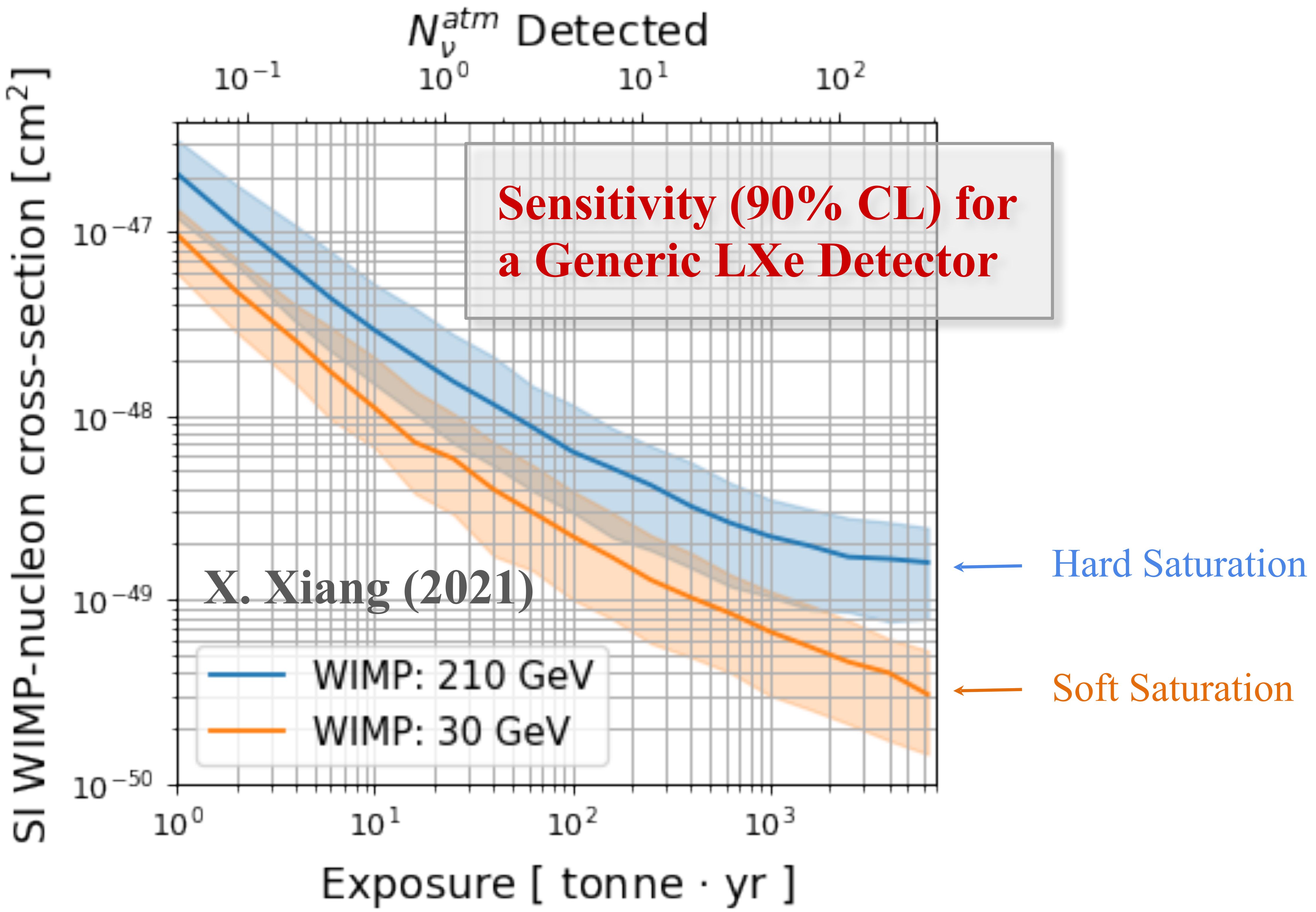
Status of Ar37 in LZ?

- For the SR1 WIMP search, we include 37Ar as a background, but do not include any time dependence in the analysis
- We do see a decrease of rate in 37Ar energy region over the run period
- This does not preclude some other signal sitting underneath the 37Ar peak
- Work in progress to include time-dependence in a search for low energy ER signals



Atmospheric Neutrino and the Neutrino Floor (Fog)





Atm. Neutrino Flux Uncertainty:

- Current **20% (E_ν<100 MeV)**, 15% (E_ν<1 GeV) u/c from calculation [Honda 2011]. No direct experimental measurement for sub-GeV.
- Future experimental constraint (not necessarily a completed list):
  - *DUNE [K. J. Kelly 2019]: 0.1 - 1* GeV range
  - *Hyper- Kamiokande* [Z. Li 2017], 100 MeV - 10 TeV
  - *JUNO [G. Settanta 2019], 0.1 GeV - 10 GeV range, projected u/c: 10% to 25%*

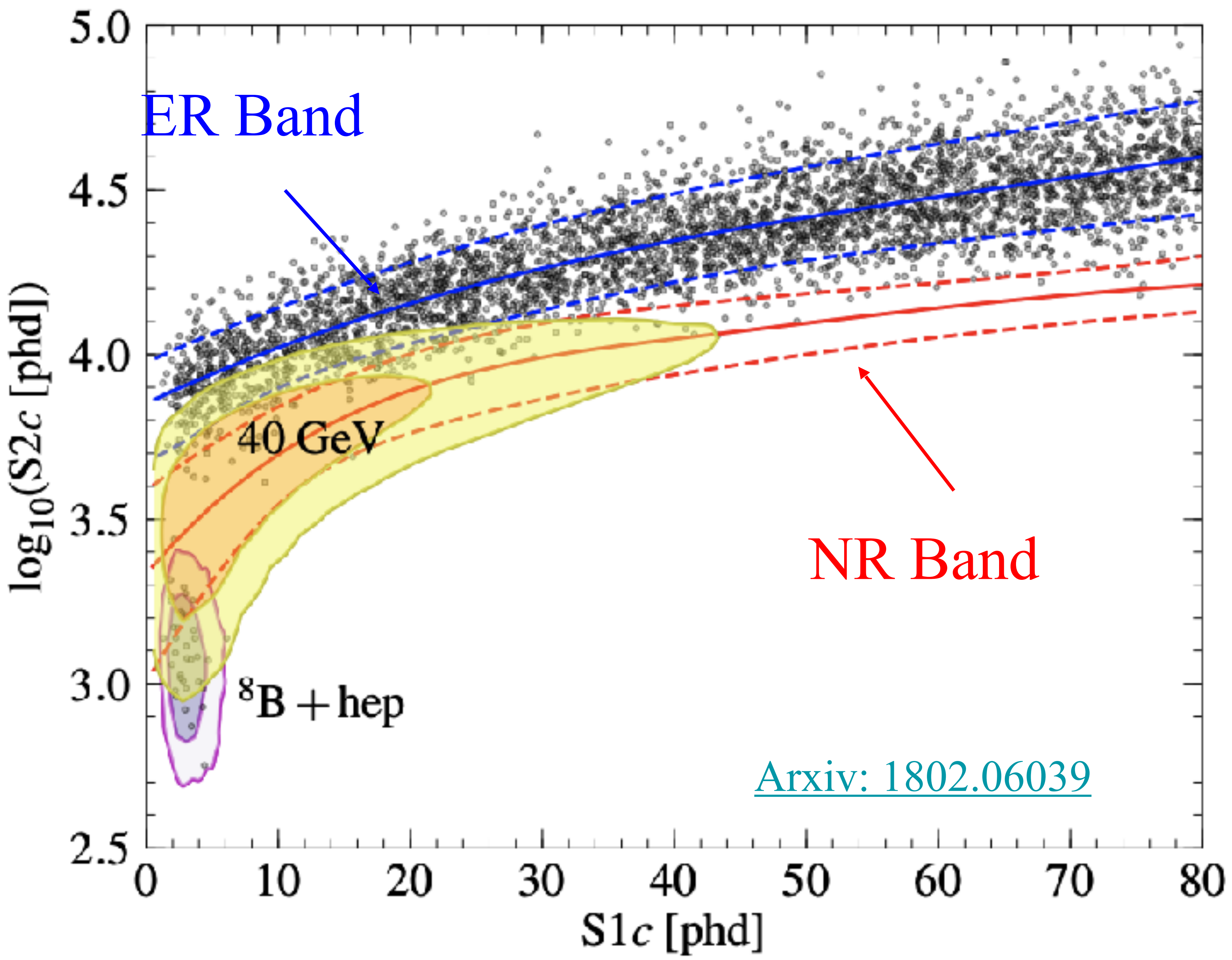
Effect on WIMP Sensitivity (neutrino floor/fog)

- An generic LXe detector simulated by NEST
  - NR efficiency curve is similar to LZ (slide 10, black curve)
  - Total ER leakage: 10^{-4} below NR median
- Backgrounds considered (Rn is ignored):
  - Atmospheric neutrino (20% u/c)
  - *pp* neutrinos
  - ^{136}Xe $2\nu\beta\beta$ (N.A., $T_{1/2} = 2.11 \times 10^{21}$ yr [EXO-200])
- PLR Setting:
  - Two-sided, Frequentist, μ_s>0, ... [arxiv: 2105.00599]

X. Xiang (2021)

Opportunity: the First ^{8}B Observation via CEνNS

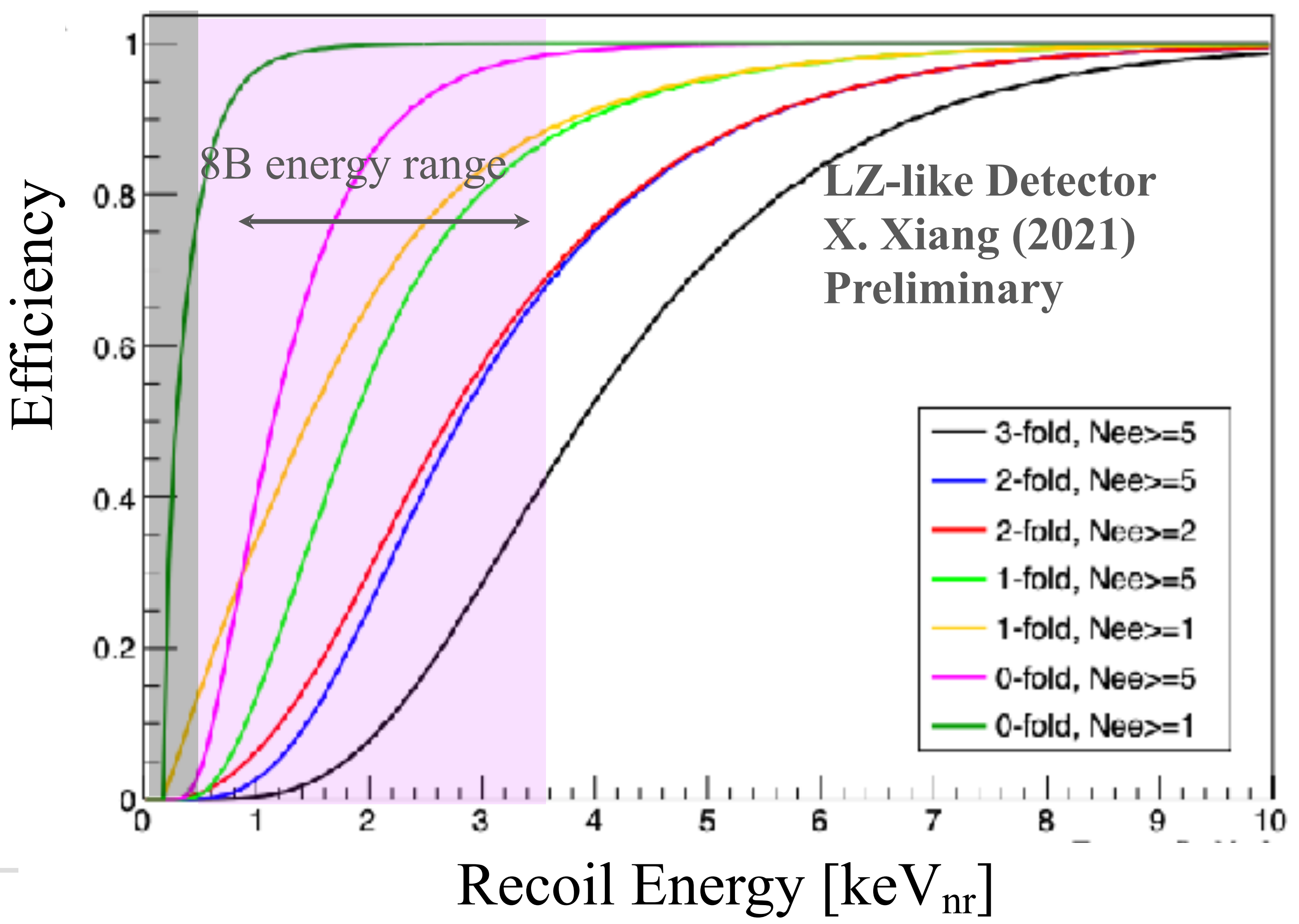
- ^{8}B has never been observed in CEνNS channel. This is exciting!
- Events populate near threshold (purple).
- The expected event rate (FV=5.6e3 kgd) is sensitive to the thresholds (preliminary):
  - LZ threshold (3-fold, $N_{ee}\geq5$): **(2.7 ± 0.69^{yield}) evt/100 day**
  - Lower threshold (2-fold, $N_{ee}\geq5$): **(12 ± 2.3^{yield}) evt/100 day**
- A significant claim is not a matter of if, but a matter of when



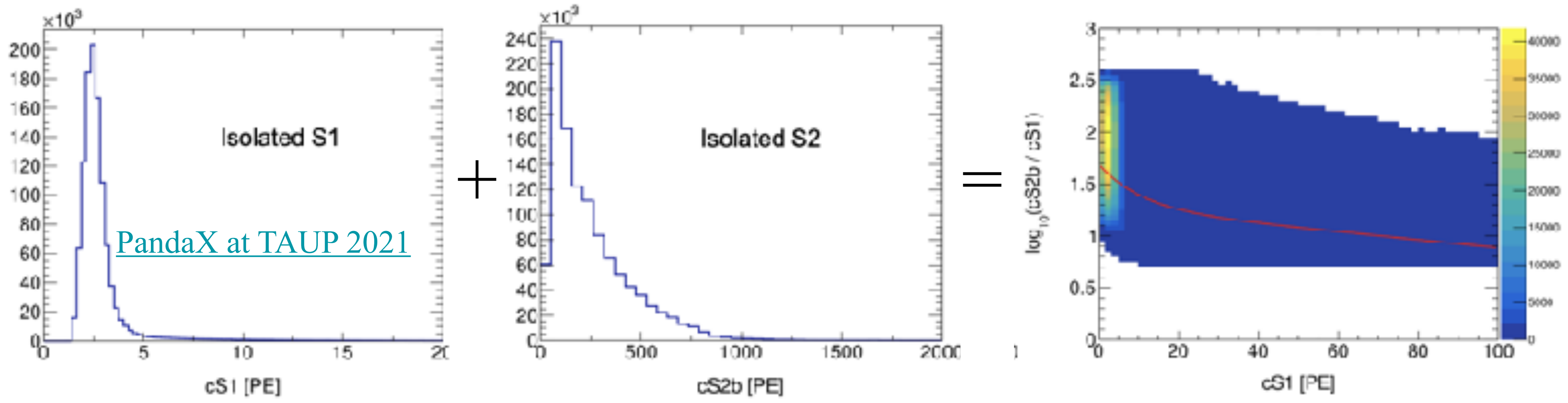
NEST Simulation of ^{8}B Rate in 100 day (preliminary)
(Assuming efficiency from the right plot)

	3-fold (S1 ≥ 3 phd)	2-fold (S1 ≥ 2 phd)	S2-only (0 or 1 phd)
Nee ≥ 8 e-	1.39	5.32	23.6
Nee ≥ 7 e-	1.78	7.1	37.8
Nee ≥ 6 e-	2.23	9.42	58.4
Nee ≥ 5 e-	**2.73**	**12.1**	91.7
Nee ≥ 4 e-	3.25	15.4	142
Nee ≥ 3 e-	3.73	18.8	217

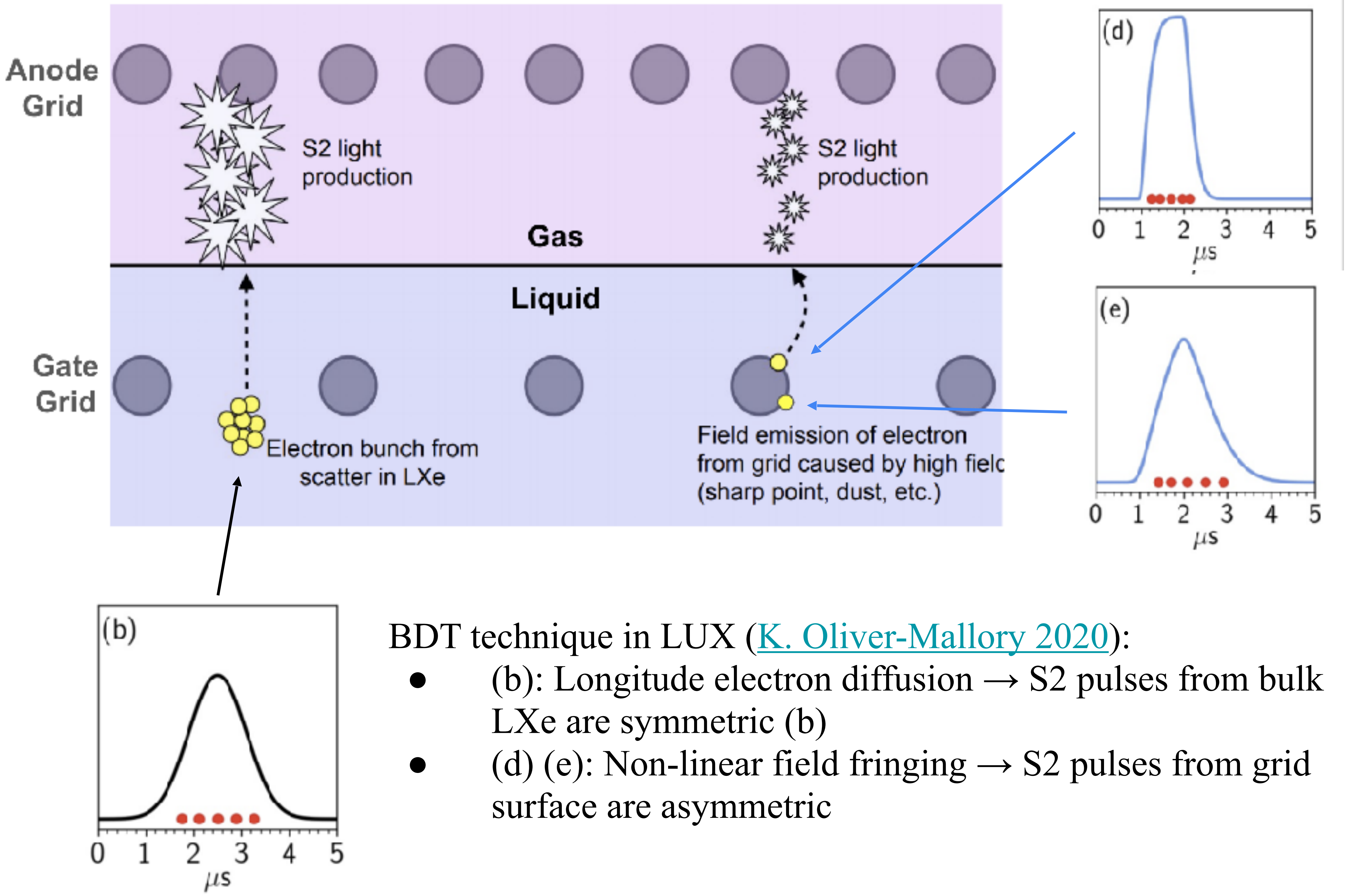
NR Efficiency for Various Thresholds



Challenge: Accidental Coincidence



- An accidental coincidence event occurs when an isolated S1 randomly pile-up with an isolated S2
- Possible sources of isolated S1:
  - Dark count pile up
  - Cherenkov in PMT windows / PTFE wall
  - Energy deposition occurs in non-drifting region
- Possible sources of isolated S2:
  - field electron emission from gate and cathode grids
  - delayed electron emission following S2s (ex. electron trapped at liquid surface or captured by impurity)
  - radiogenic grid emission
- Data-driven Modeling
  - Find isolated S1 events and isolated S2 pulse, and randomly pair them up (top plots)



BDT technique in LUX (K. Oliver-Mallory 2020):

- (b): Longitude electron diffusion → S2 pulses from bulk LXe are symmetric (b)
- (d) (e): Non-linear field fringing → S2 pulses from grid surface are asymmetric

- Features & Rejection:
  - Asymmetric S2 pulse shape (Machine Learning)
  - Drift time is uncorrelated to electron diffusion (Drift time vs S2 width)
  - Correlate with PMT that has abnormally high DC rate (PMT tagging)

Summary

- Ton-scale LXe detector is sensitivie MeV-scale natural neutrinos via CEvNS
- Opportunity for LZ to make the first detection of 8B in CEvNS channel
- CEvNS presents challenges for WIMP searches
    - Above 100 GeV: hard neutrino floor (fog) due to atm. uncertainty
    - 4-10 GeV: neutrino floor (fog) due to ^{8}B uncertainties (light yield)
        - Short-term impact is subdominat to Poisson fluntation .
        - Long-term impact on sensitivity → **improvement in light yield measurement is crucial**
    - 10 GeV - 100 GeV: soft neutrino floor (fog) due to different spectrum shape between WIMP and atm neutrinos
- Next Generation Liquid Xenon experiment may (aside from WIMP search) measure:
    - solar *pp (Weinberg's angle* $sin^2\theta_W$*)* via electron scattering
    - ^{8}B (NC NSI) via CEvNS
    - *CNO* (Solar metallicity) via Charge Current