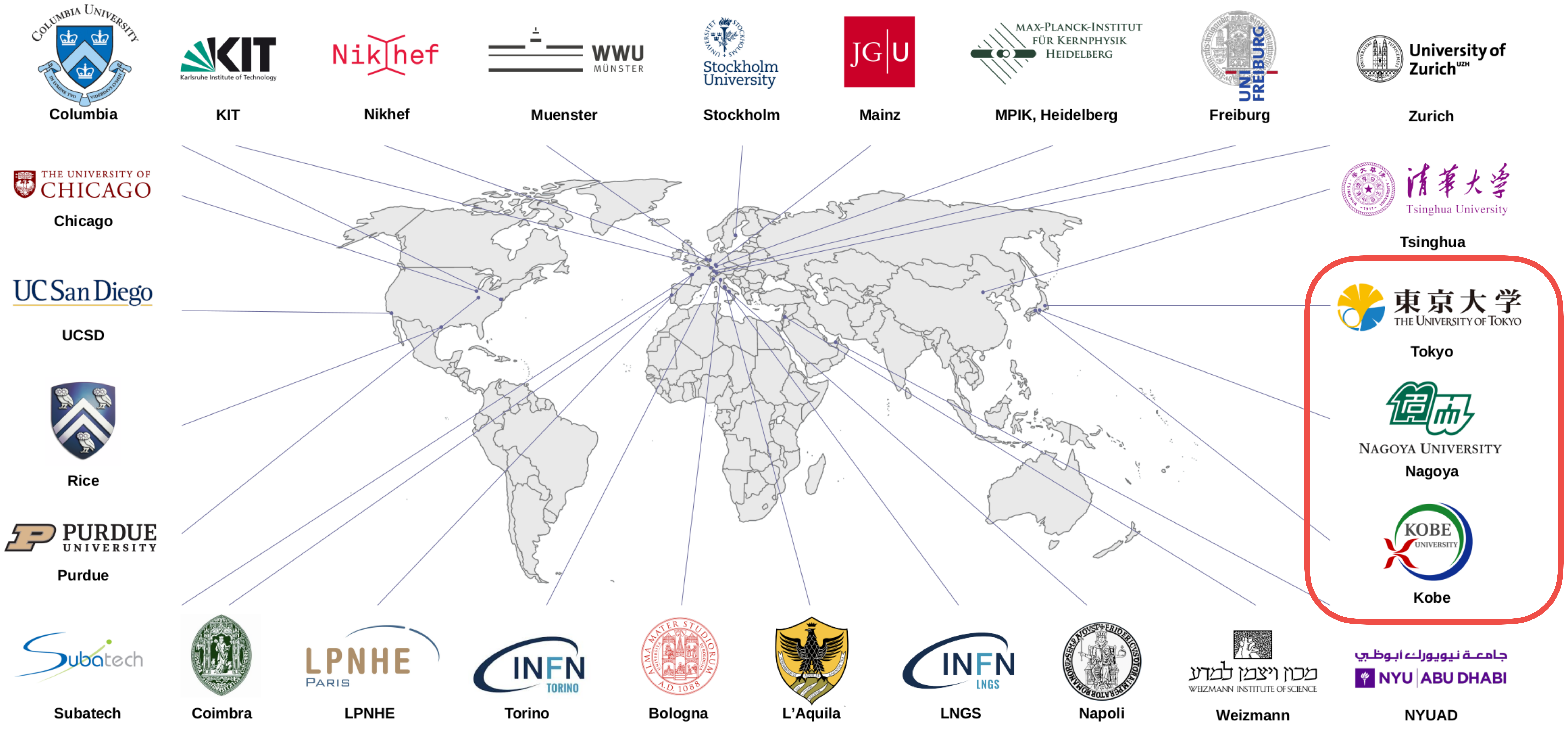
Credit: Henning Schulze Eißing

Direct Dark Matter Search with XENON

Shingo Kazama (Nagoya, KMI)

June 13th 2022, @UGAP2022

XENON Collaboration

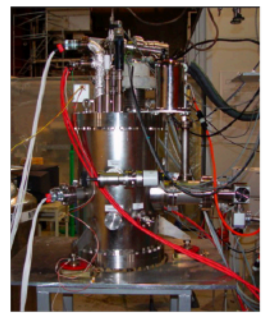


- 170 scientists, 27institutions, and 11 countries
- Nagoya, Kobe, and Tokyo groups from Japan
- Our contributions: LXe purification, NeutronVeto, and Analysis

XENON and DARWIM Program

XENON

DARWIN

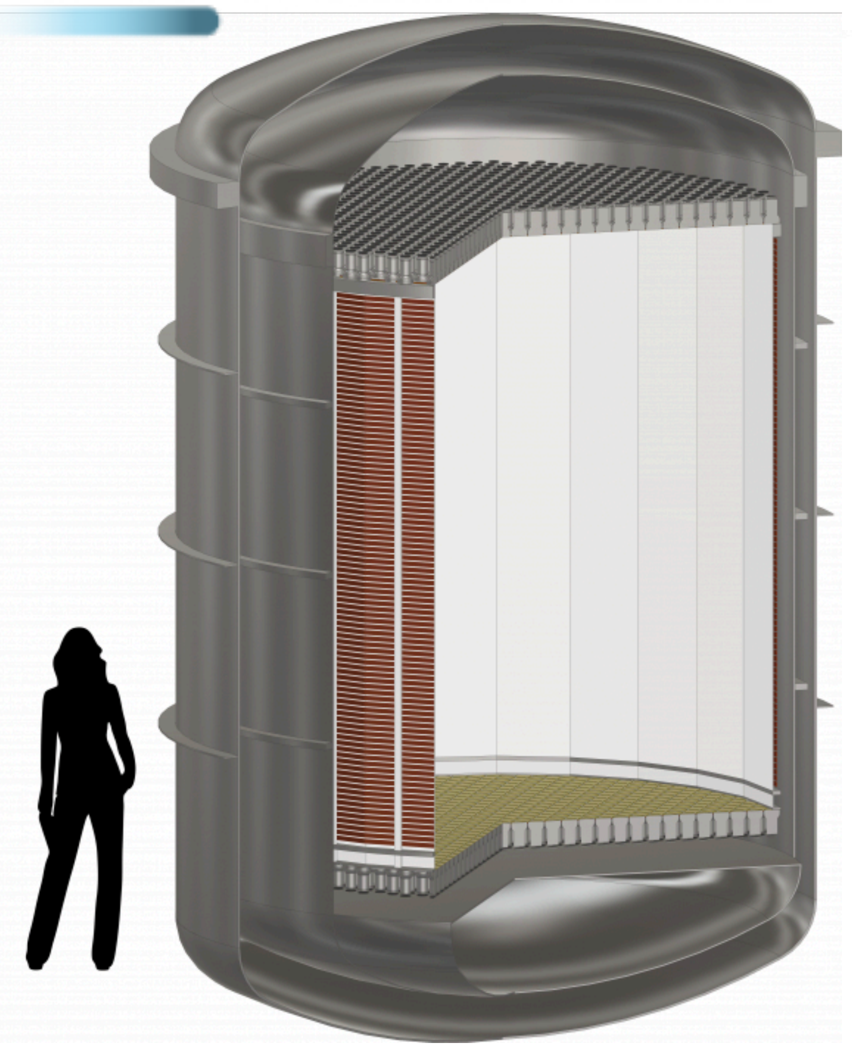


XENON10
Total Xe: 25 kg
Target: 14 kg
Fiducial: 5.4 kg

XENON100
Total Xe: 162 kg
Target: 62 kg
Fiducial: 48 kg

XENON1T
Total Xe: 3.2 ton
Target: 2.0 ton
Fiducial: 1.3 ton

XENONnT
Total Xe: ~ 8.6 ton
Target: ~5.9 ton
Fiducial: ~4 ton

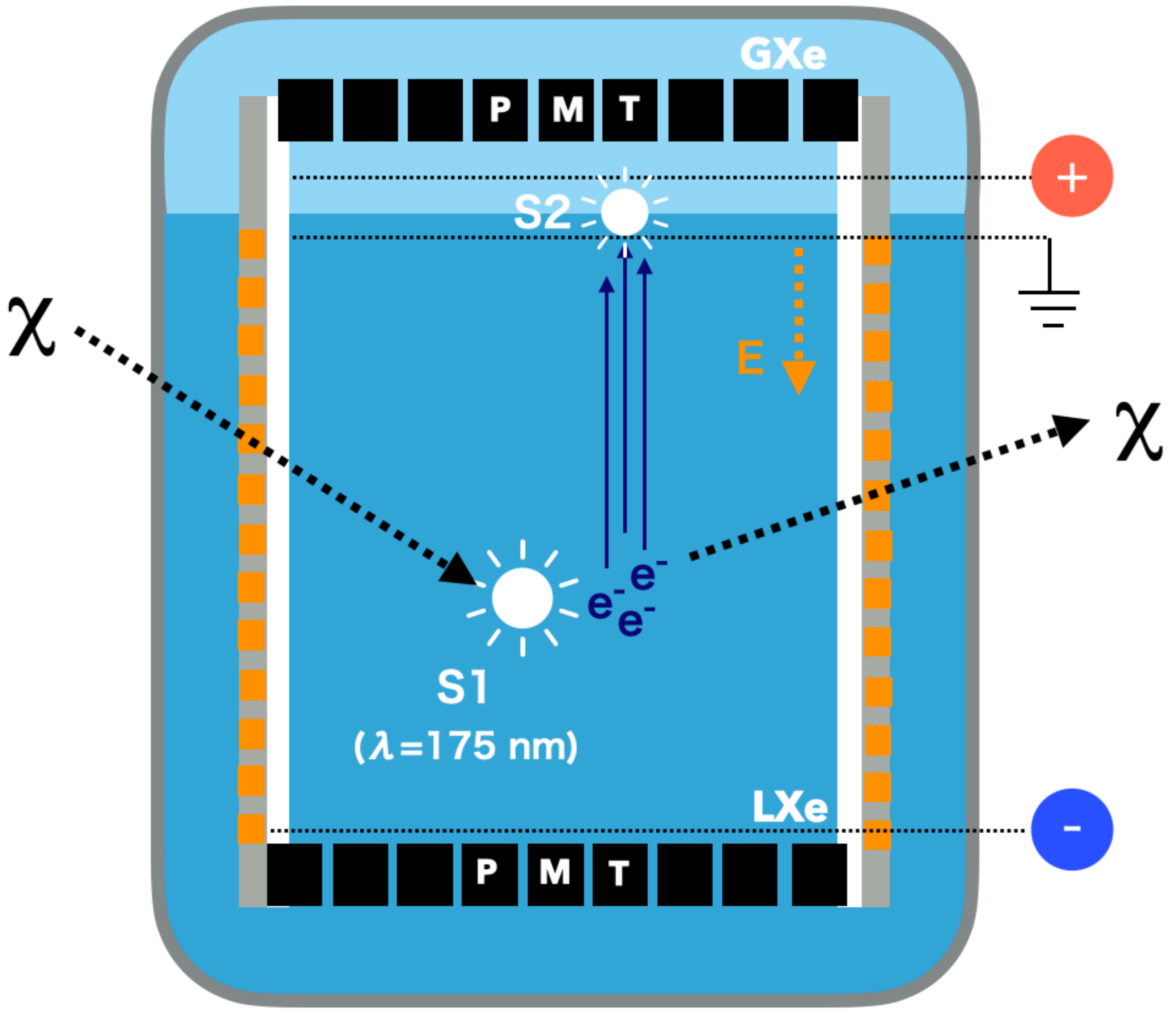


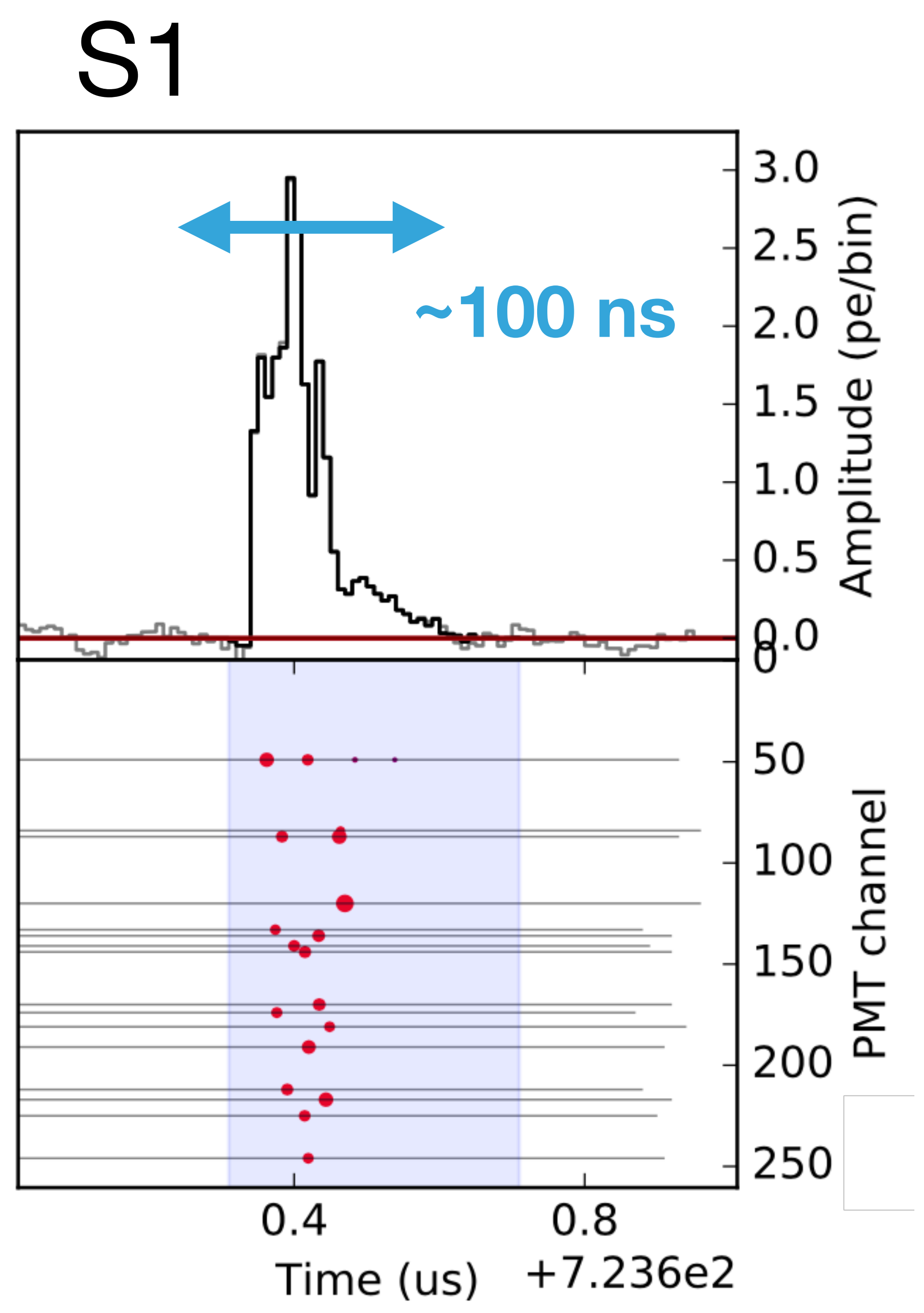
DARWIN
Total Xe: ~50 ton
Target: ~40 ton
Fiducial: >30 ton

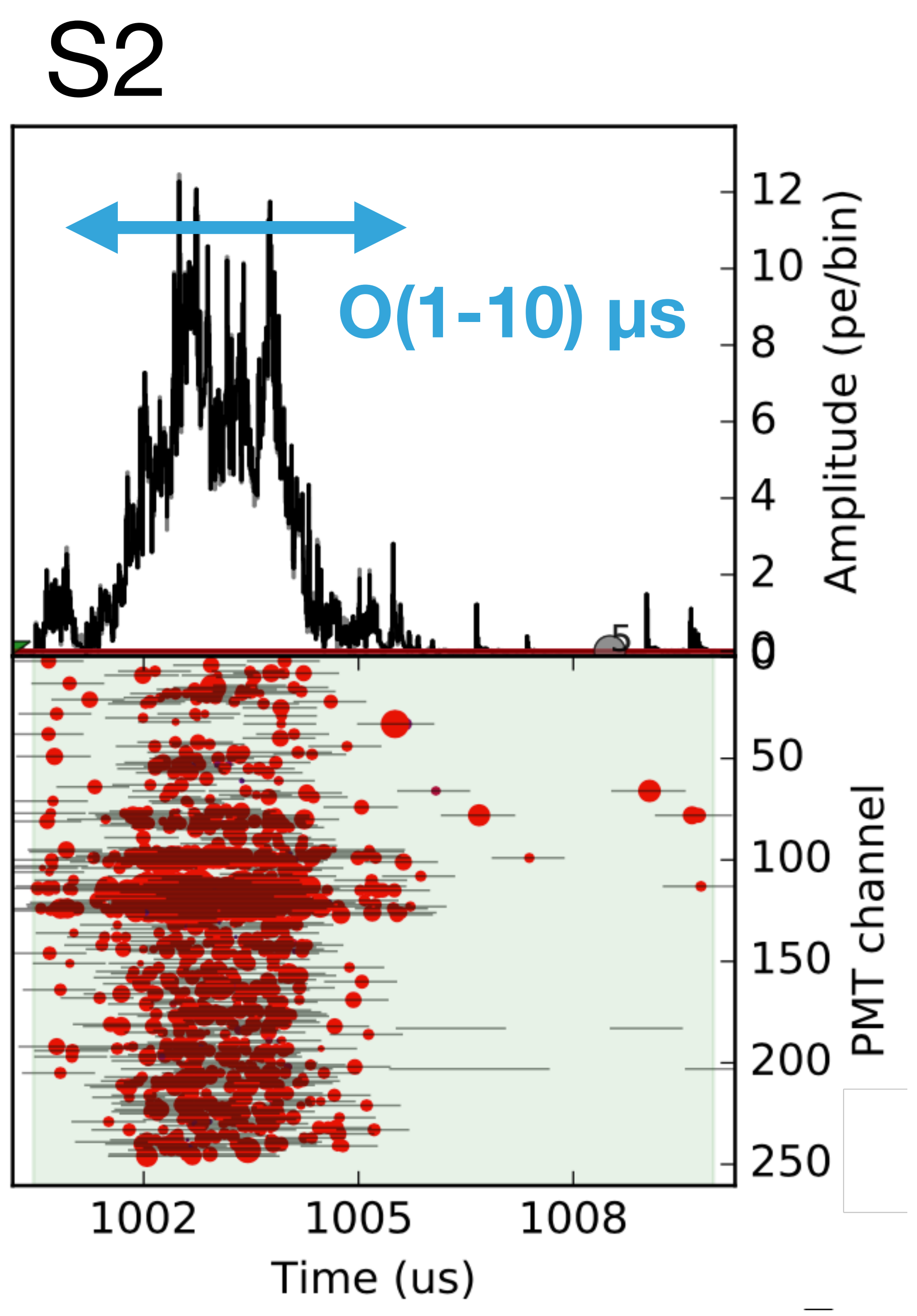
XENON1T
DARWIN
XENON10
XENON100
XENONnT

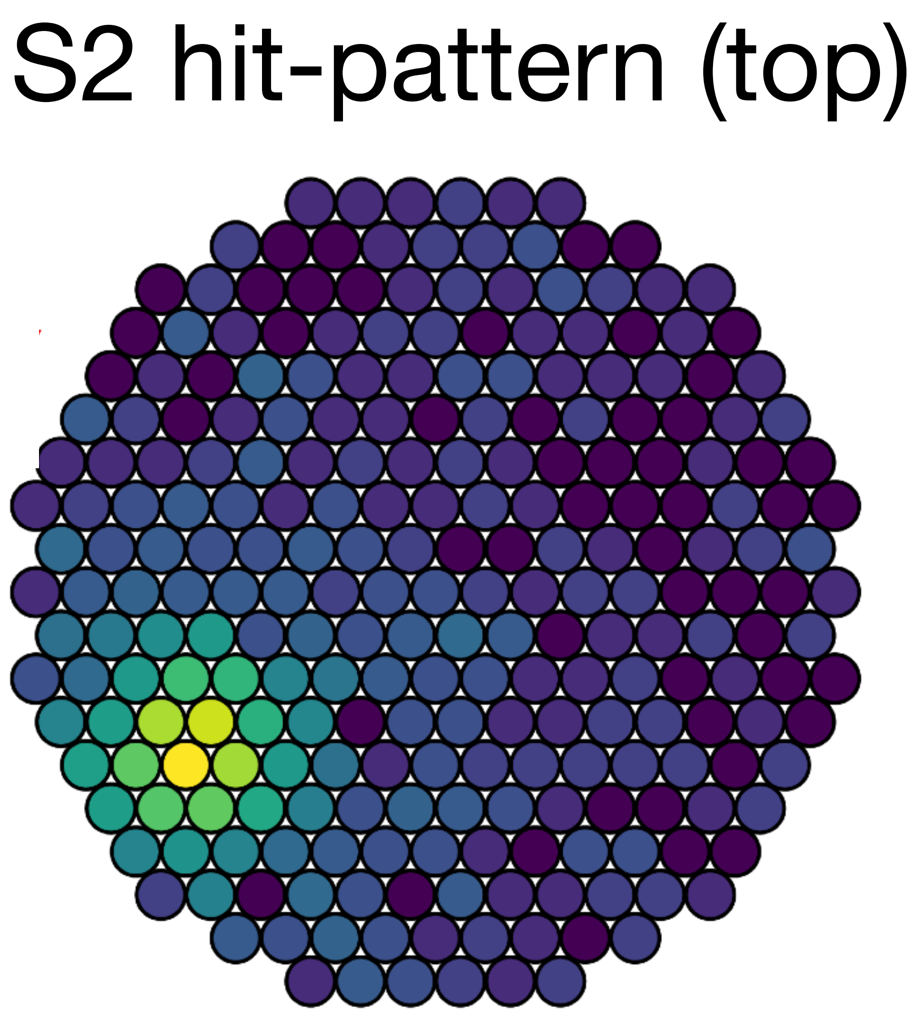
2005
2010
2015
2020
2027

Liquid Xenon Time Projection Chamber







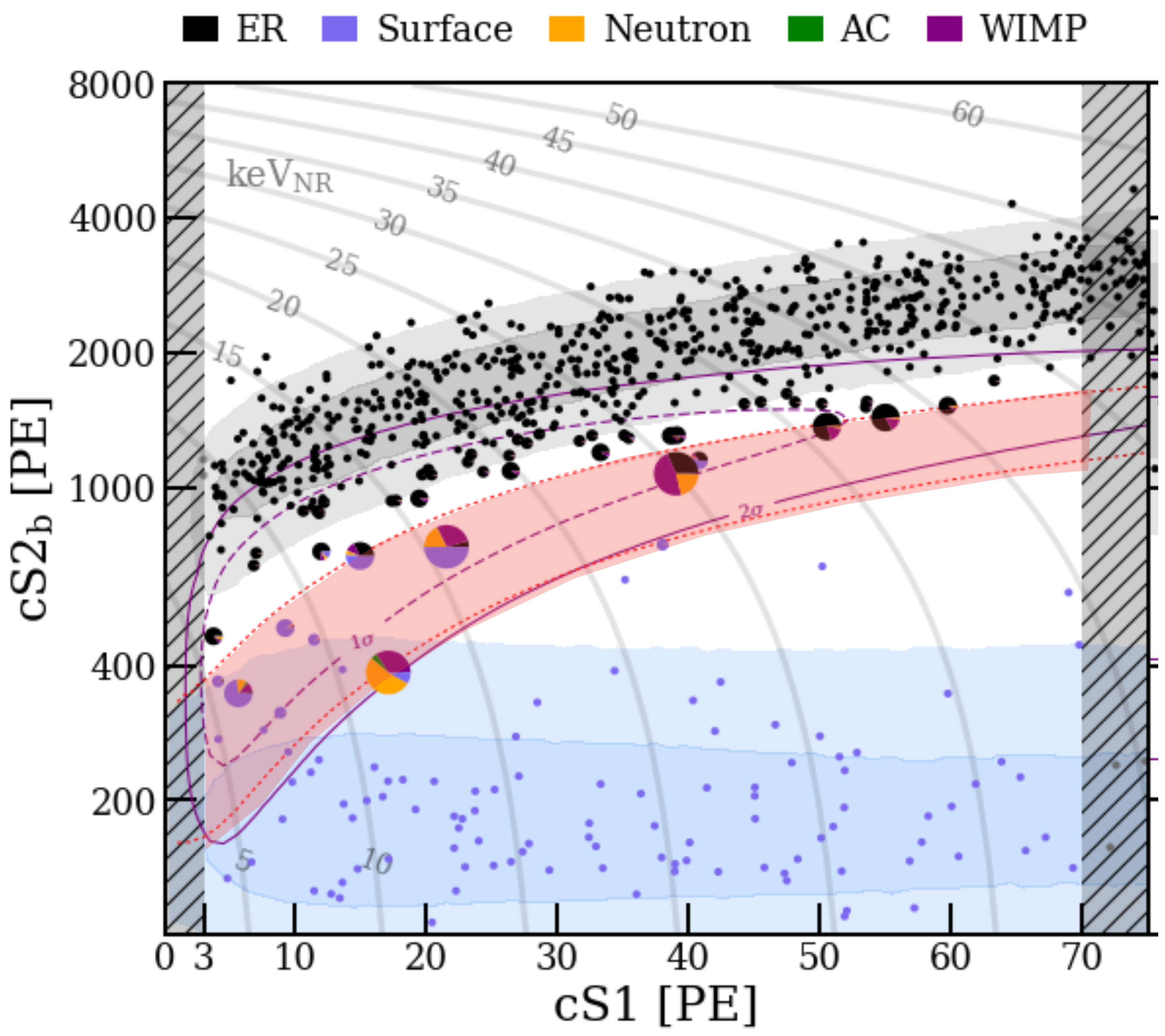


- LXe/GXe at -100 °C
- Z-position from electron drift time: Δt (s1, s2)
- X-Y position from S2 hit pattern in the top PMT array
- Particle ID based on S2/S1: **(S2/S1)γ,e (ER) > (S2/S1)WIMP, neutron (NR)**

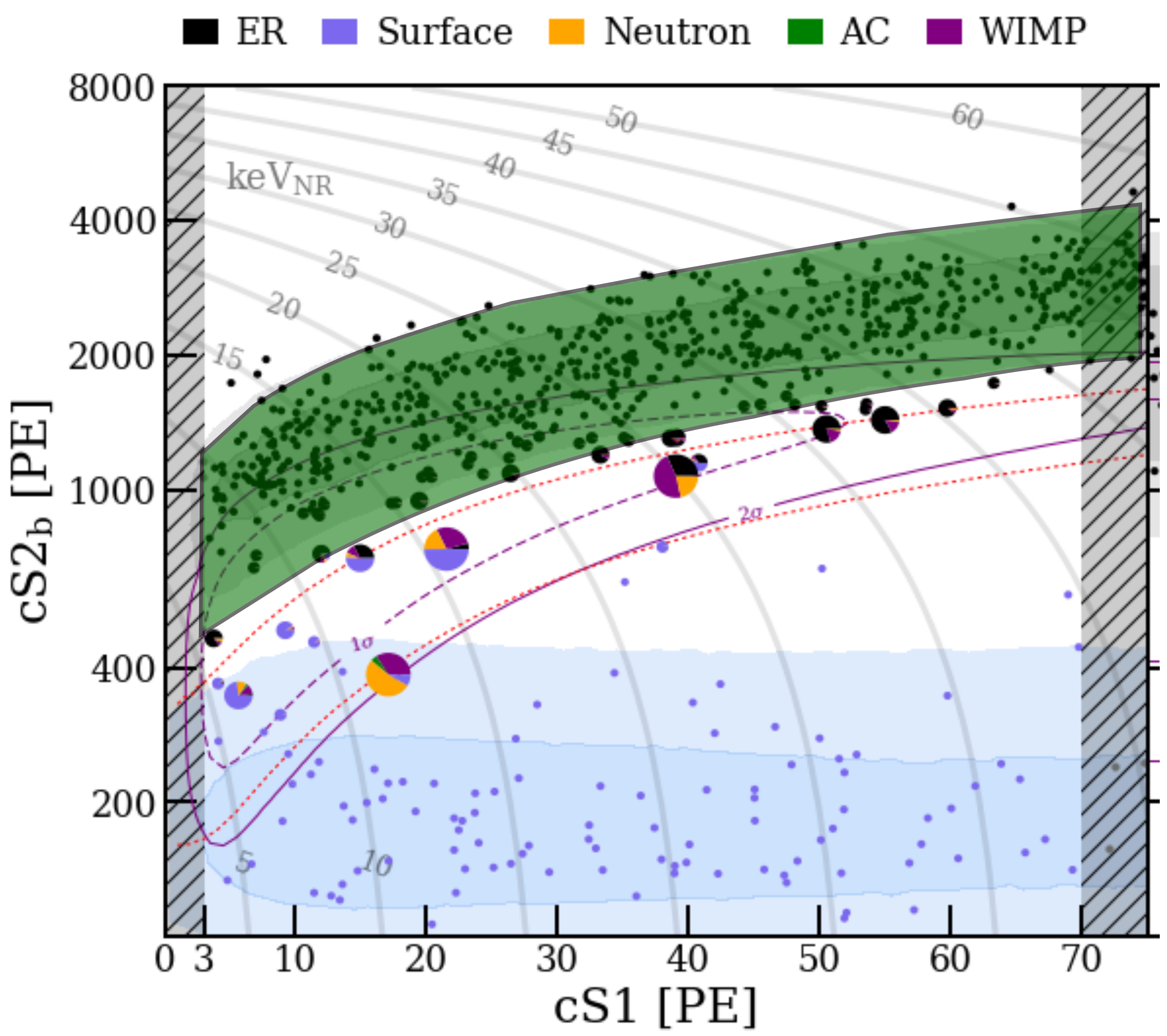
Particle Discrimination

Phys. Rev. Lett. 121, 111302

Nuclear Recoil (NR)



Electric Recoil (ER)



- Neutron
- WIMPs, coherent neutrino scattering

→ a few events / ton / year

PID helps to discriminate NRs from lots of ERs

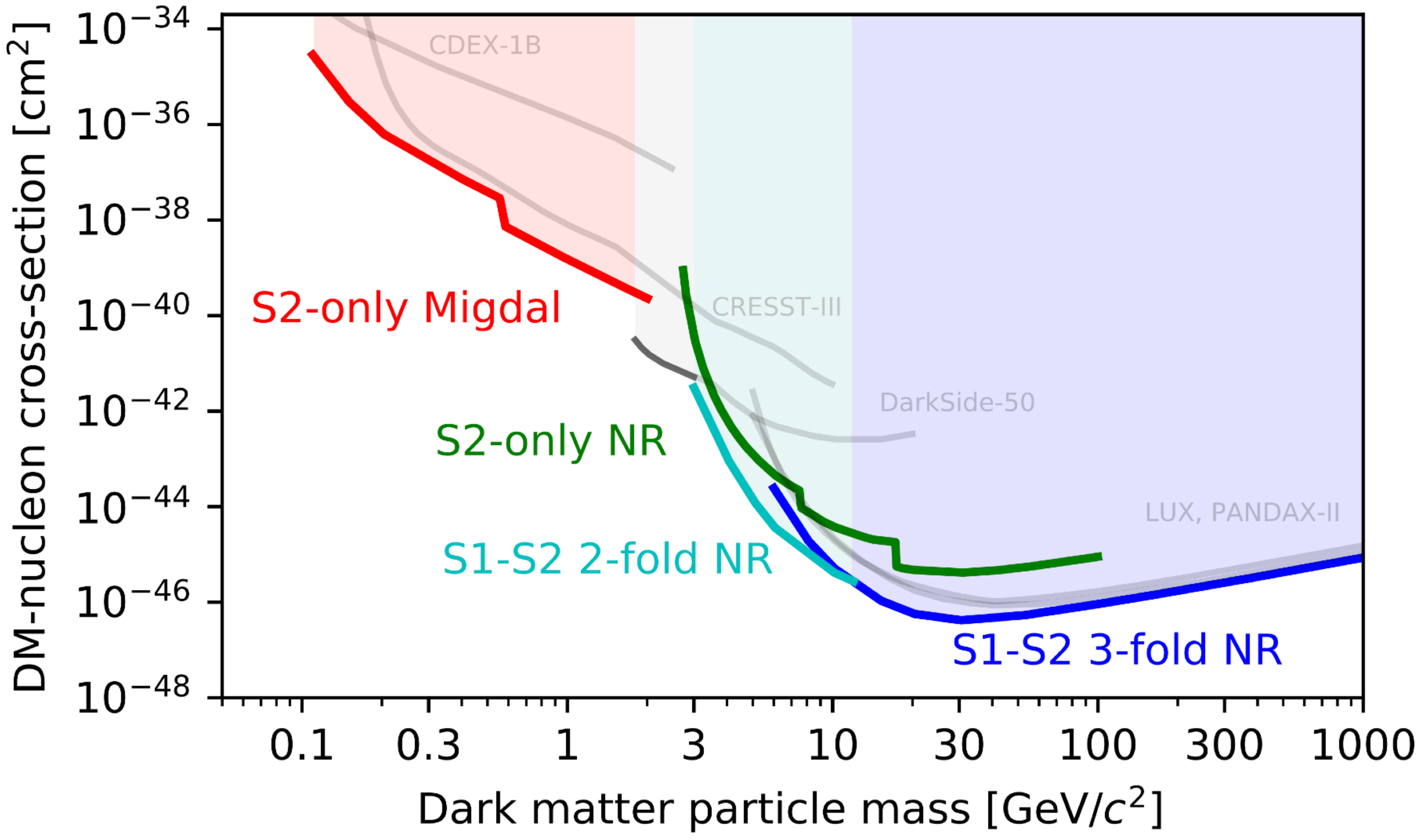
- Pb214, Kr85, solar pp-neutrino, etc
- Axion, ALPs, dark-photon

→ O(10-100) events/ton/year/keVee

search for excess above well-known ER BGs

XENON1T WIMP Results

Phys. Rev. Lett. 121, 111302, Phys. Rev. Lett. 123, 241803, Phys. Rev. Lett. 126, 091301



- The most promising DM candidate is thermal DM with weak charge
- XENON1T is currently leading the searches both in low & high mass regions, but no evidences
  →See Michelle's talk for Migdal search
- Other DM candidates? 10^{-55} g and 10^{40} g: 100 orders of magnitude in mass…
- Performed dedicated searches based on so called "S2-only" and "single-electron" analysis for low mass DM.

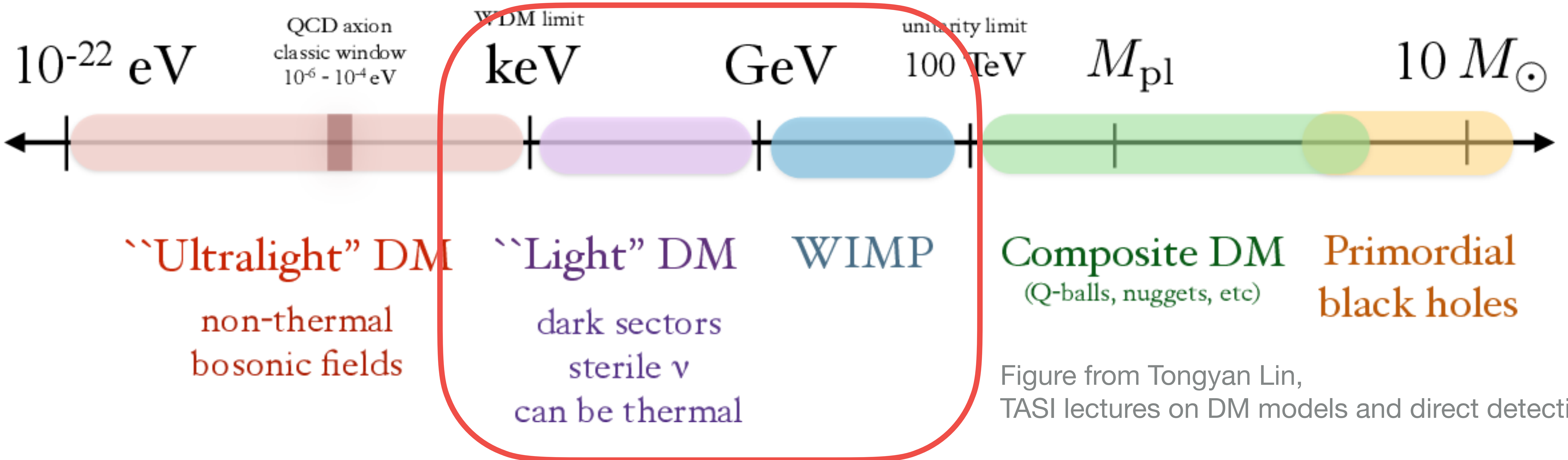
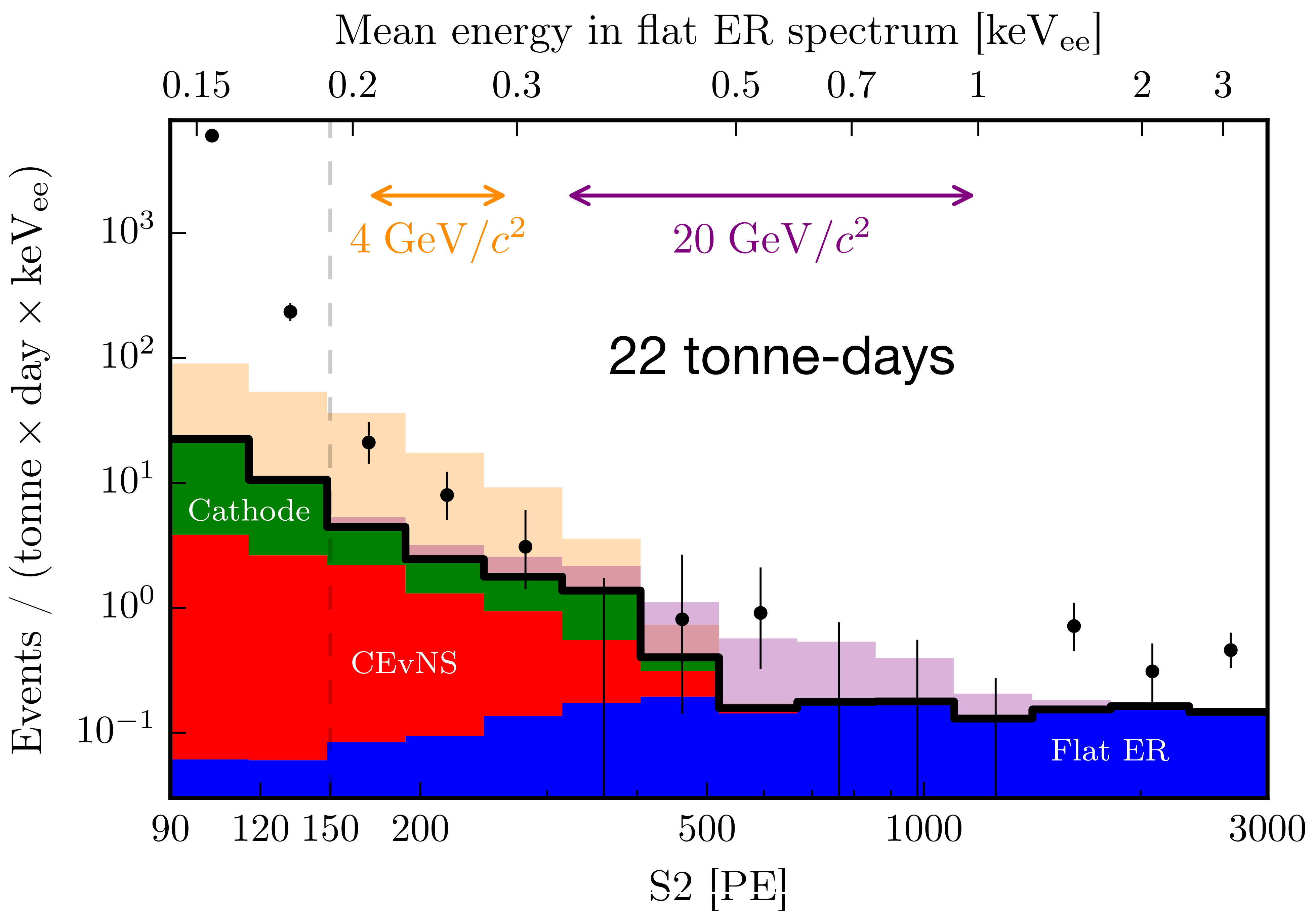


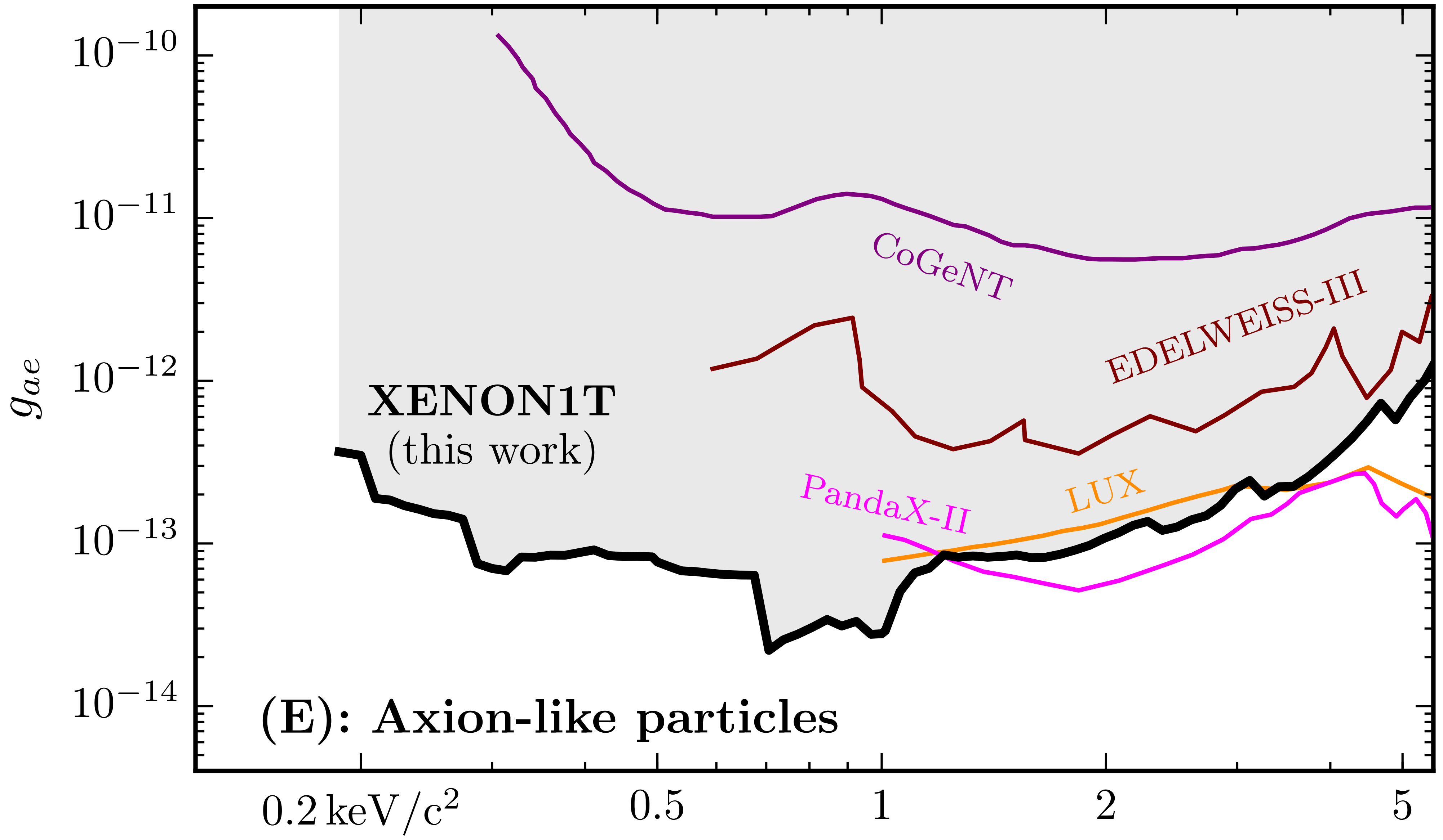
Figure from Tongyan Lin,
TASI lectures on DM models and direct detection, arXiv:1904.07915

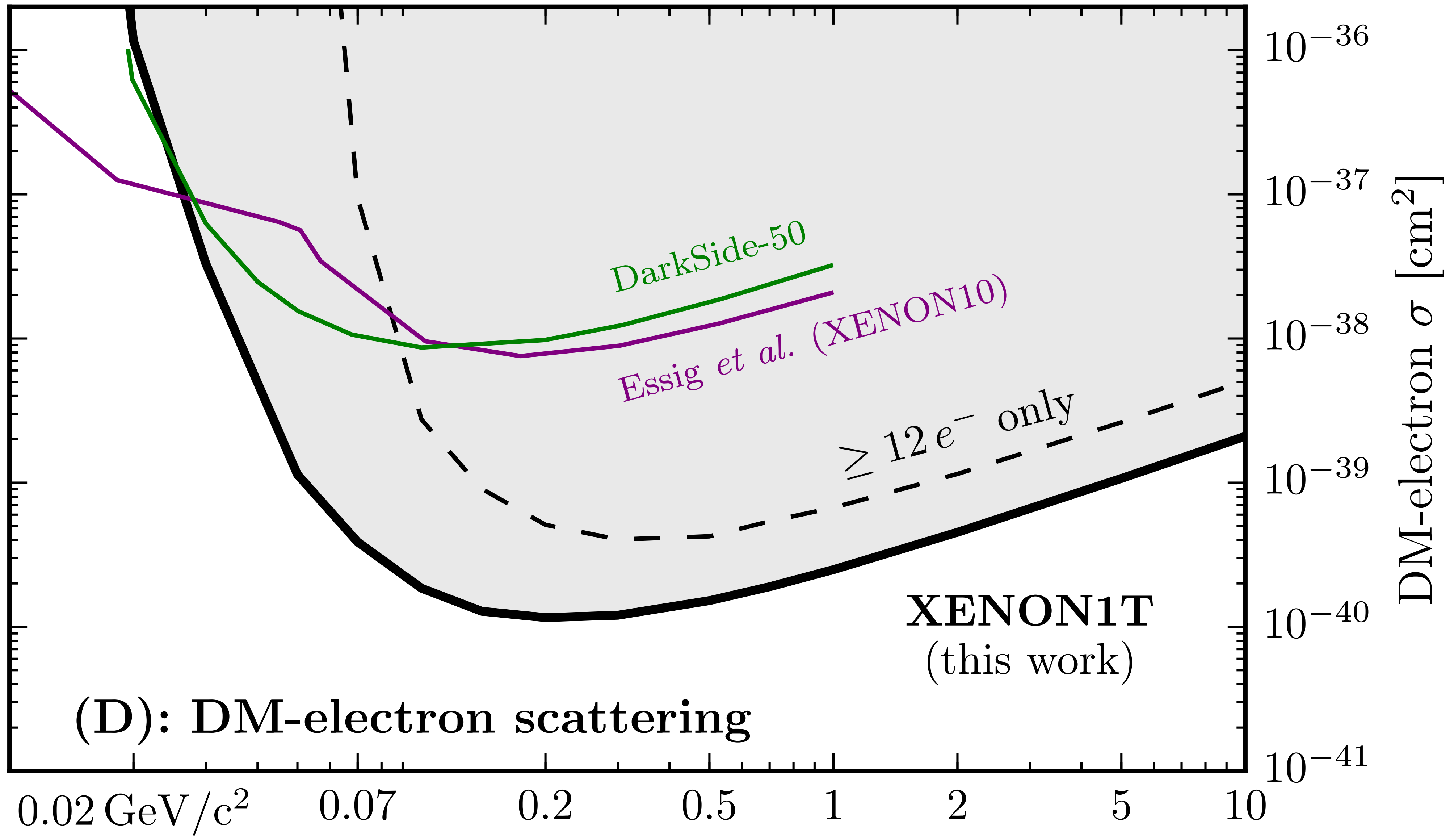
XENON1T: S2-only Analysis

Phys. Rev. Lett. 123, 251801



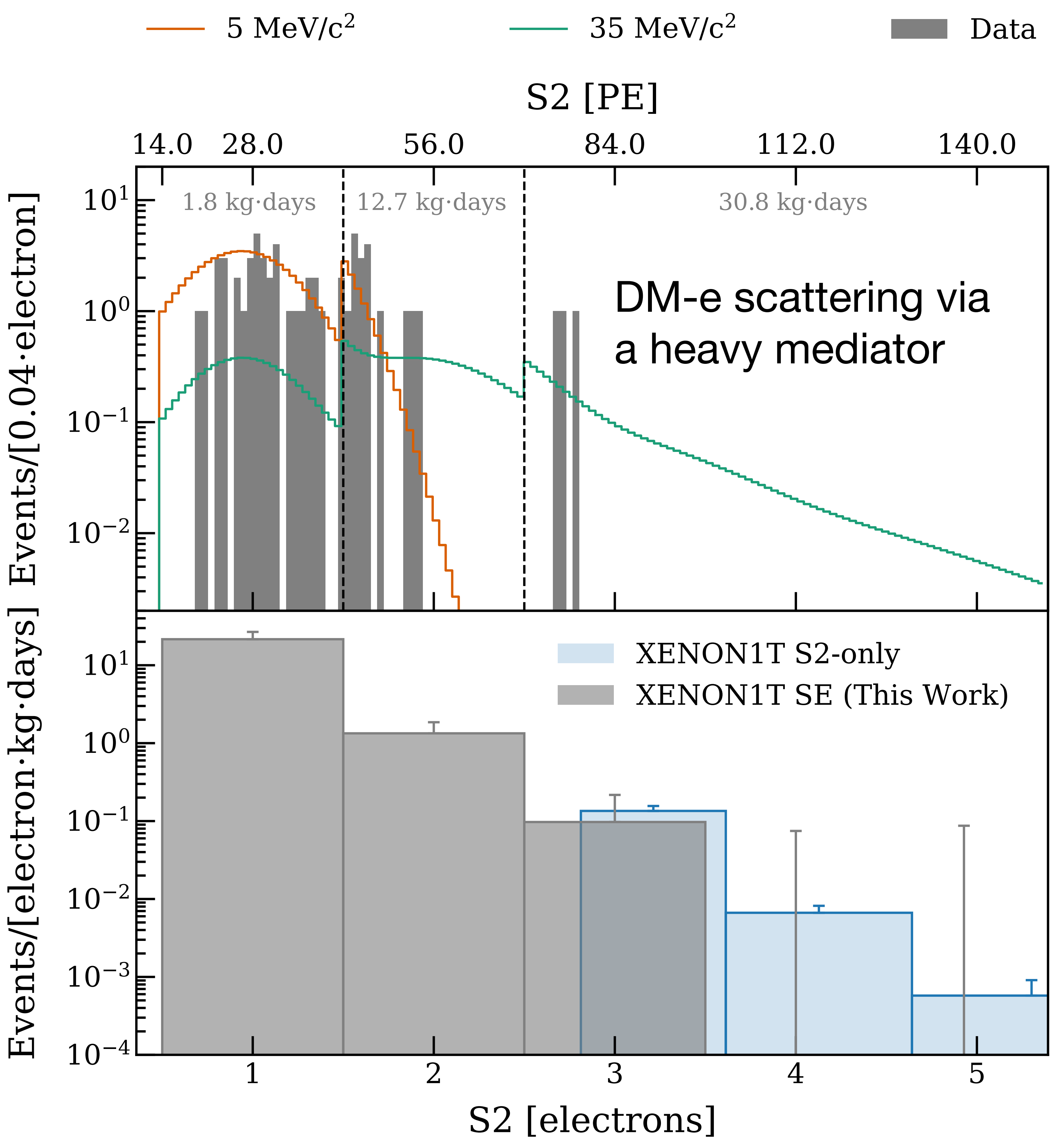
- single photon detection eff. ~ 10% <-> single electron: 90-100%
- Without S1 signals (= S2-only), we can improve reconstruction eff. for low mass DM.
- However, no complete BG models are available
- New limits on several BSM models: ALPs, dark-photon, DM-e scattering

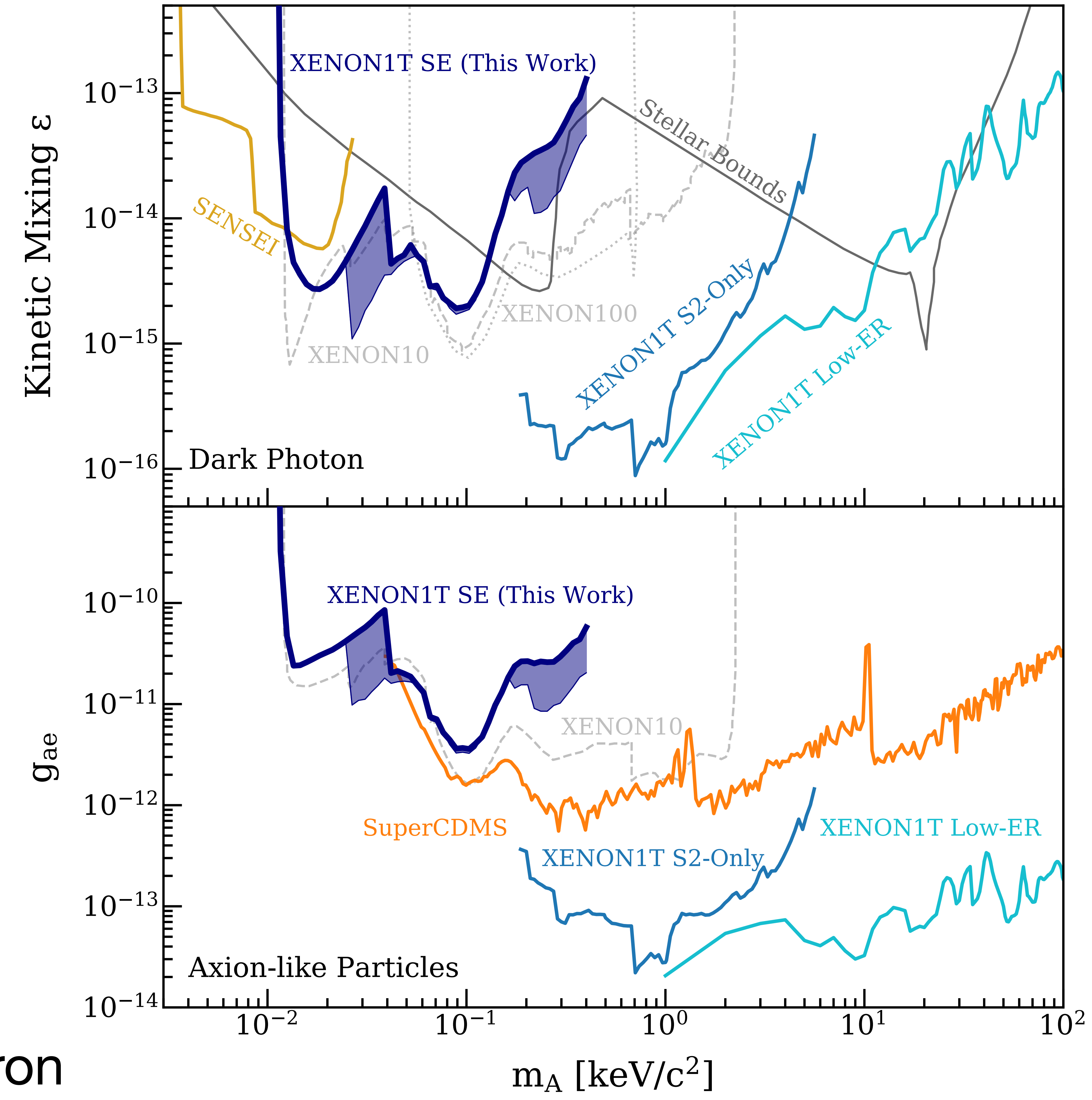




XENON1T: Single-Electron Analysis

arxiv: 2112.12116





- Extended S2-only analysis down to a single electron
- BG = delayed electrons correlated in time and position with high-energy events
- No complete BG models → Set upper limits by considering all the observed data are DM candidates
- New limits on several BSM models: ALPs, dark-photon, DM-e scattering

XENON1T: Electronic Recoil Excess

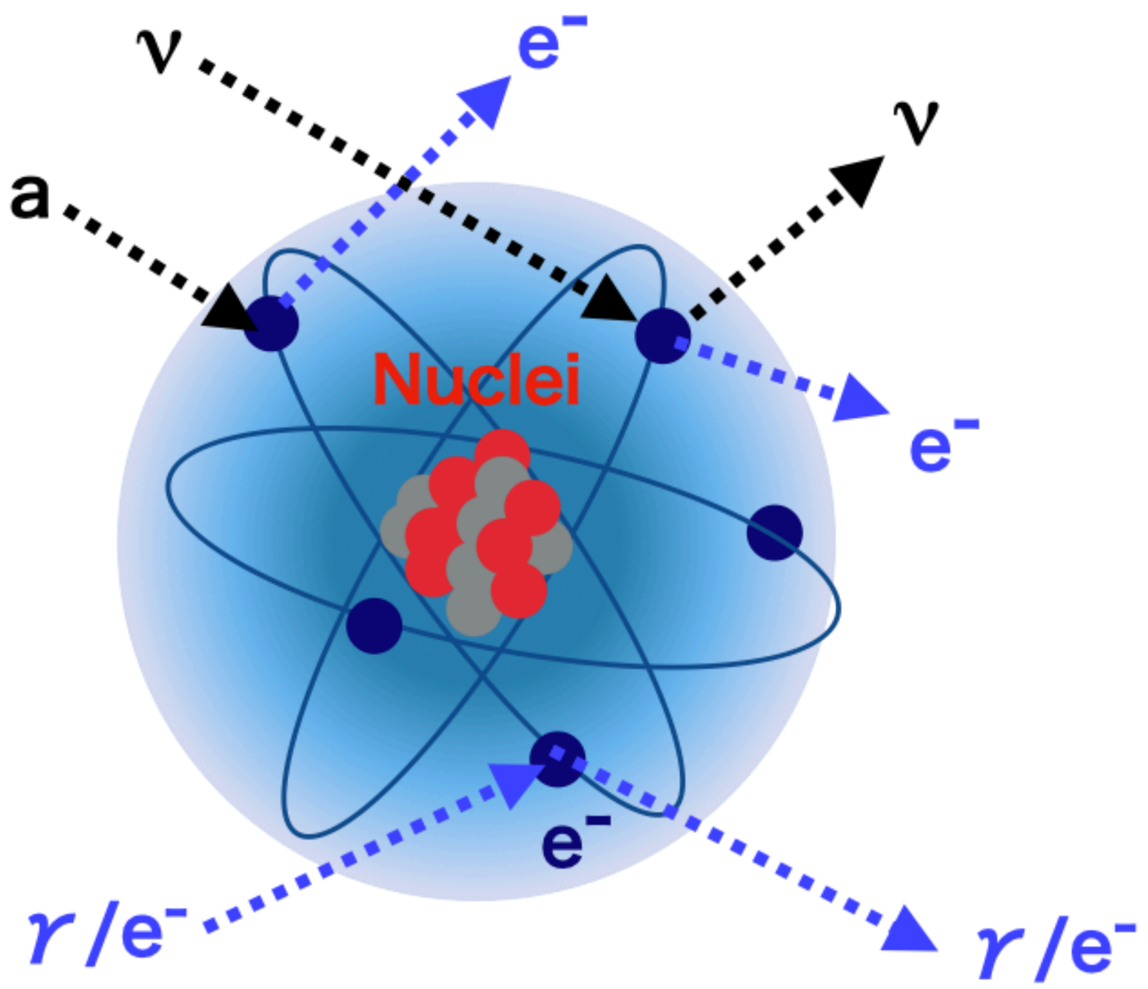
Phys. Rev. D 102, 072004

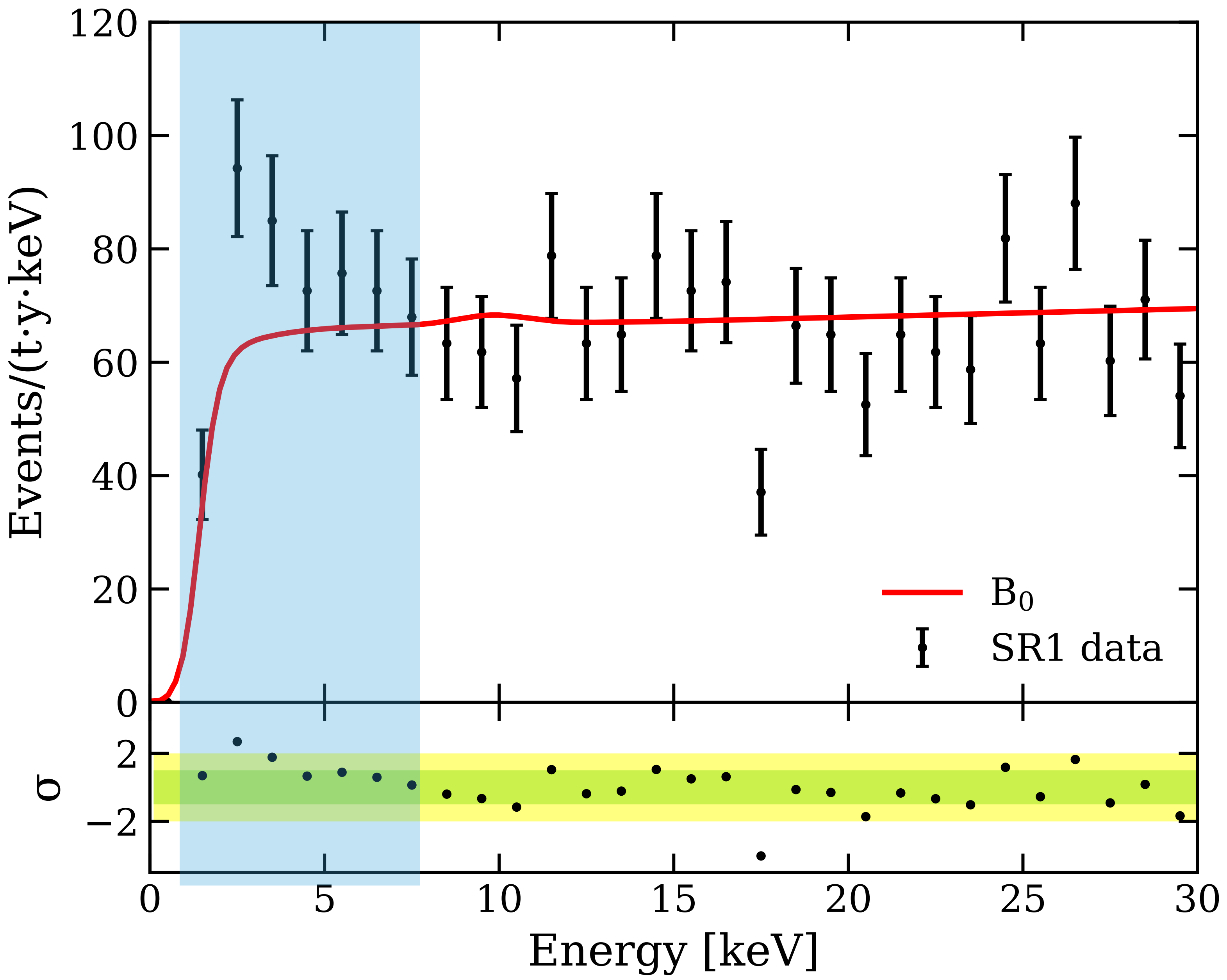
Excess in (1,7) keV;
- 285 events expected
- (232±15) events expected

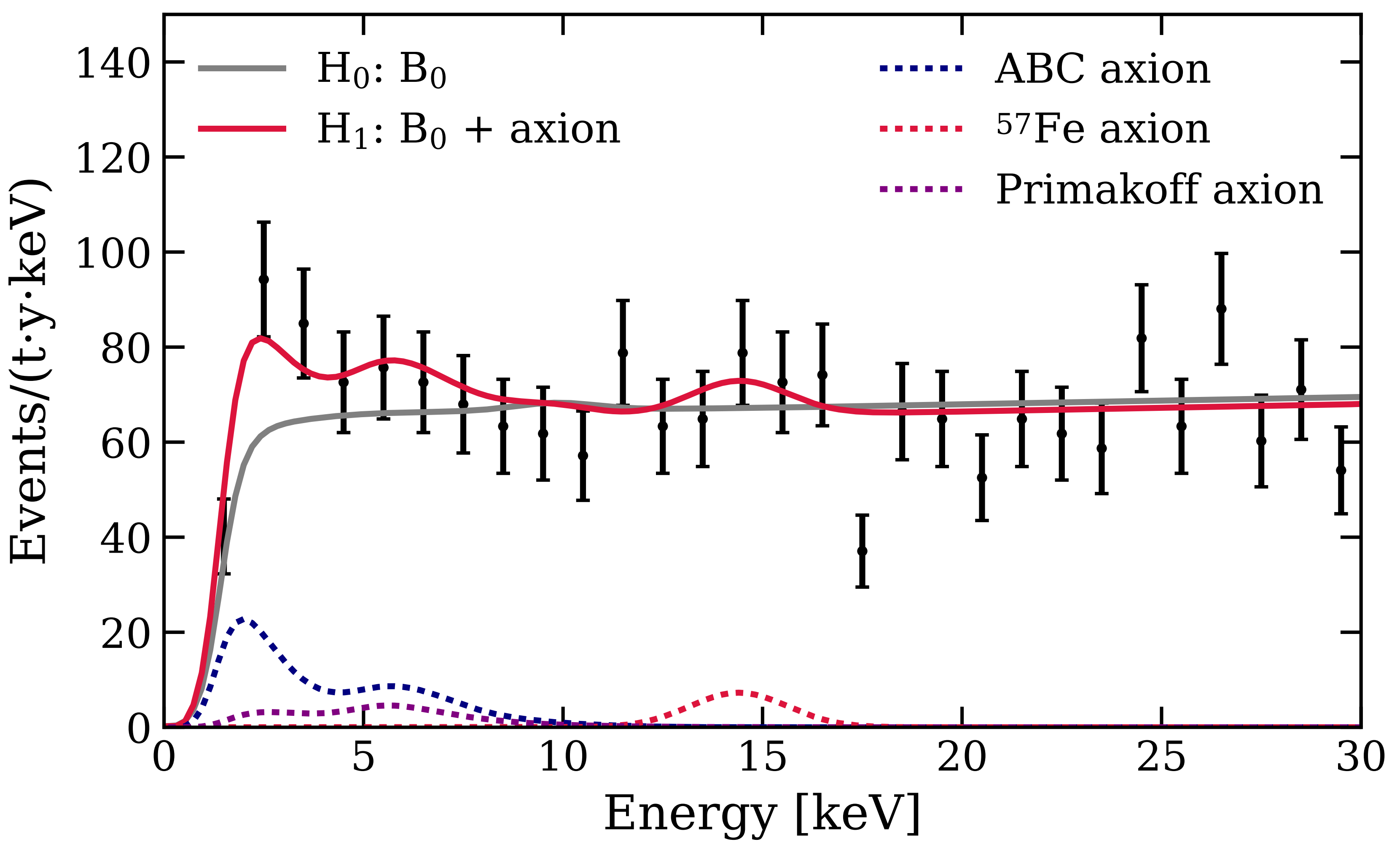
⇒ 3.3σ fluctuation

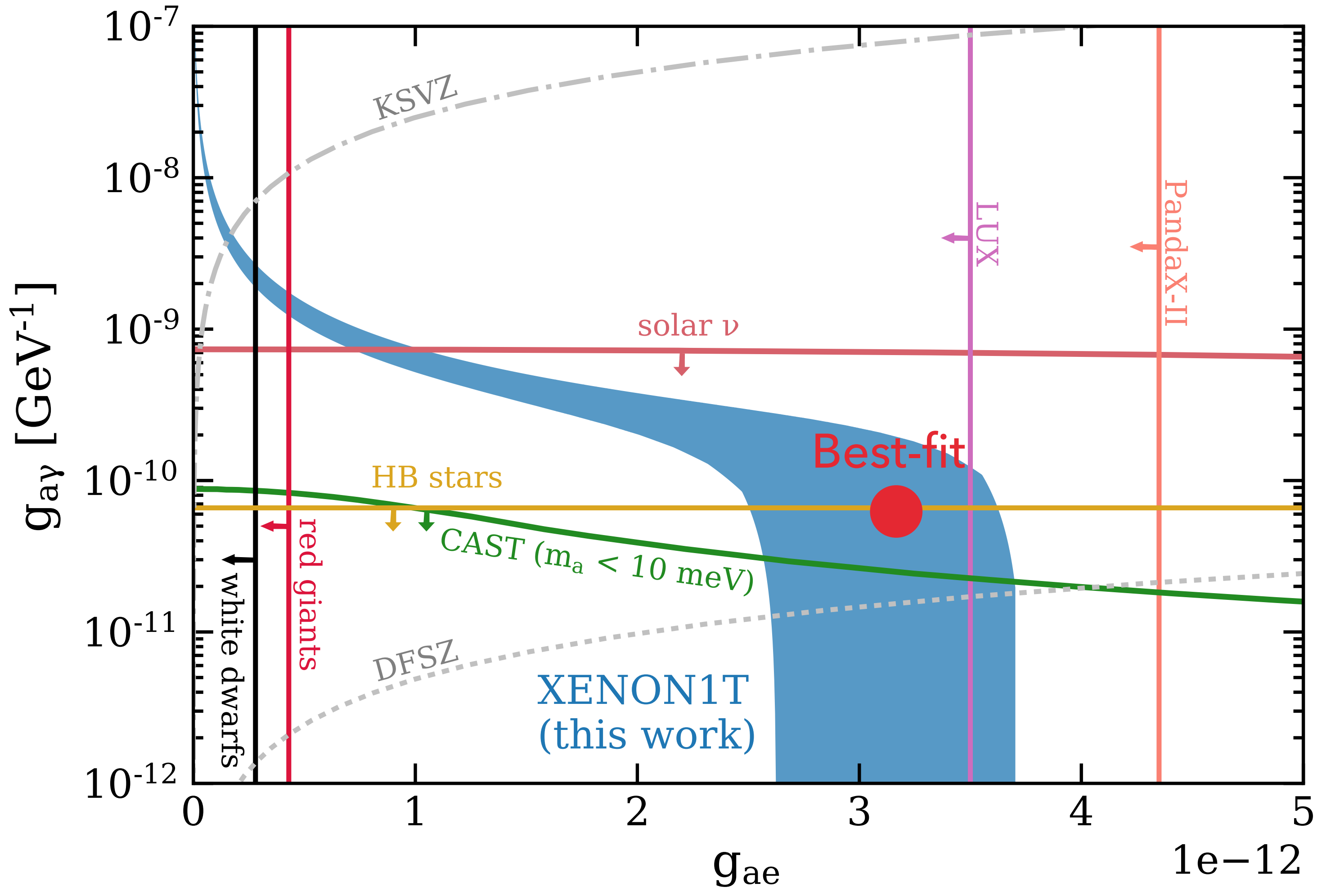
Unknown origin: tritium, solar axions, ALPs, dark photons, something else?

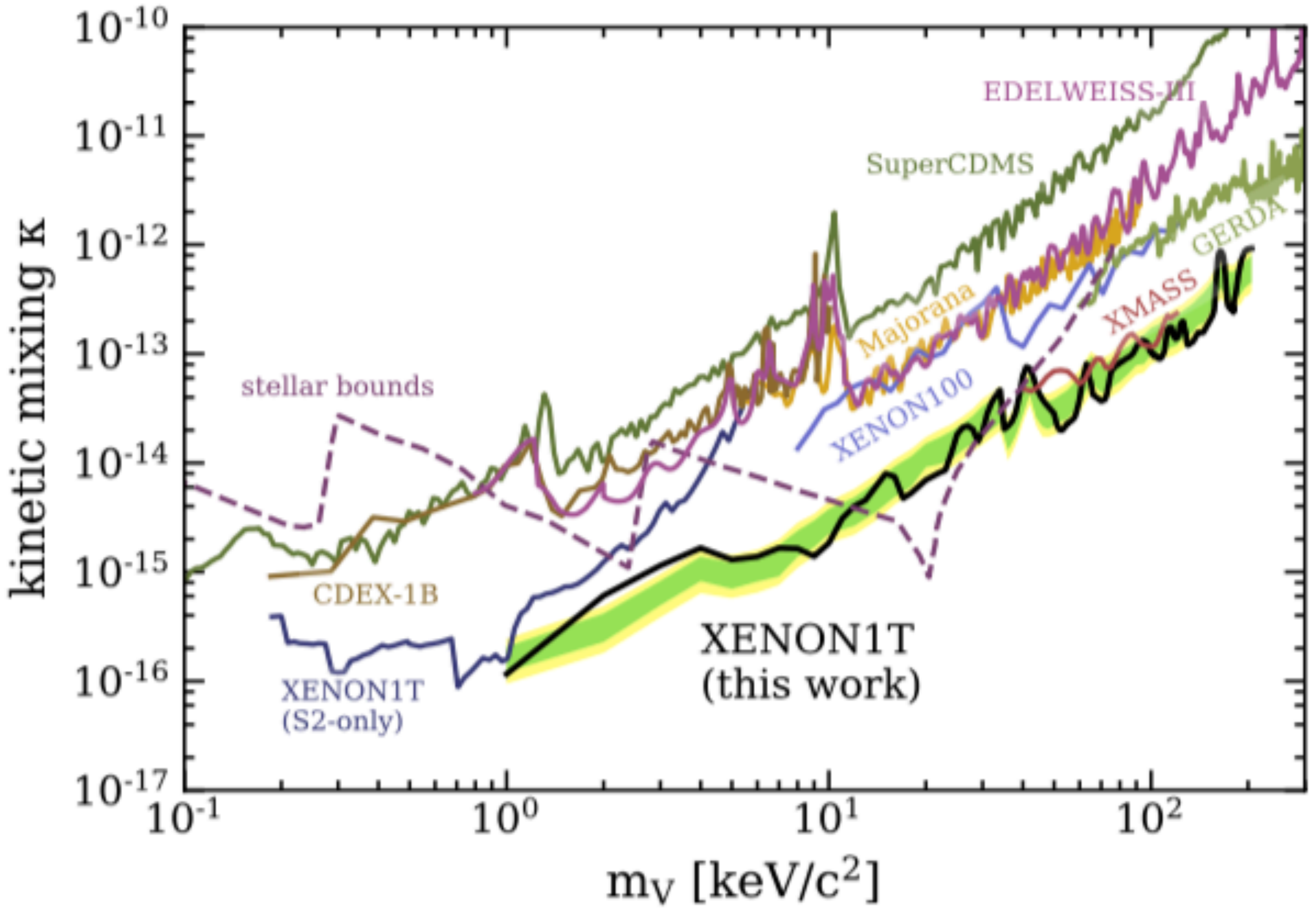
⇒ XENONnT can probe the excess with better LXe purity and lower BG level (~10%)





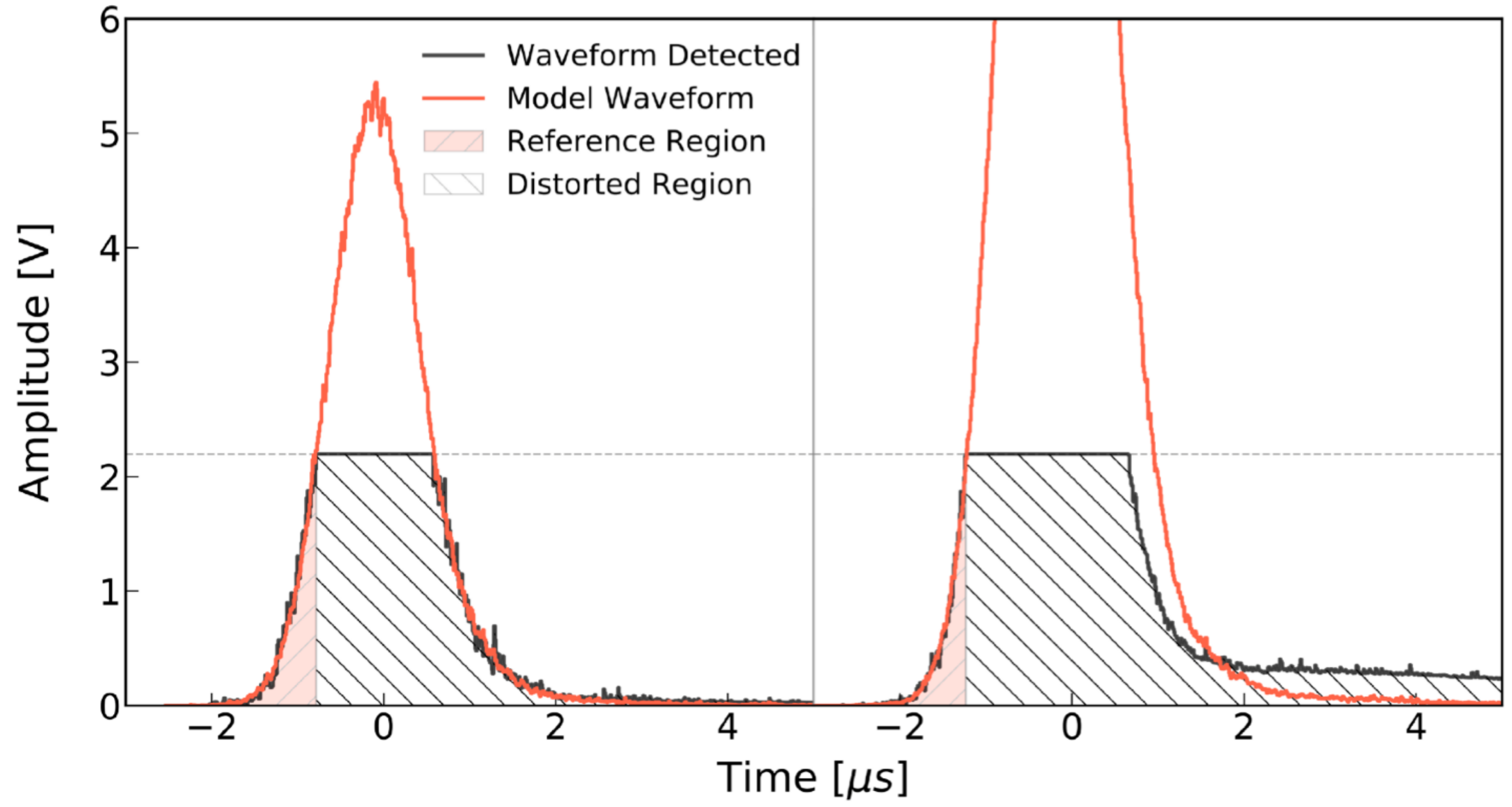


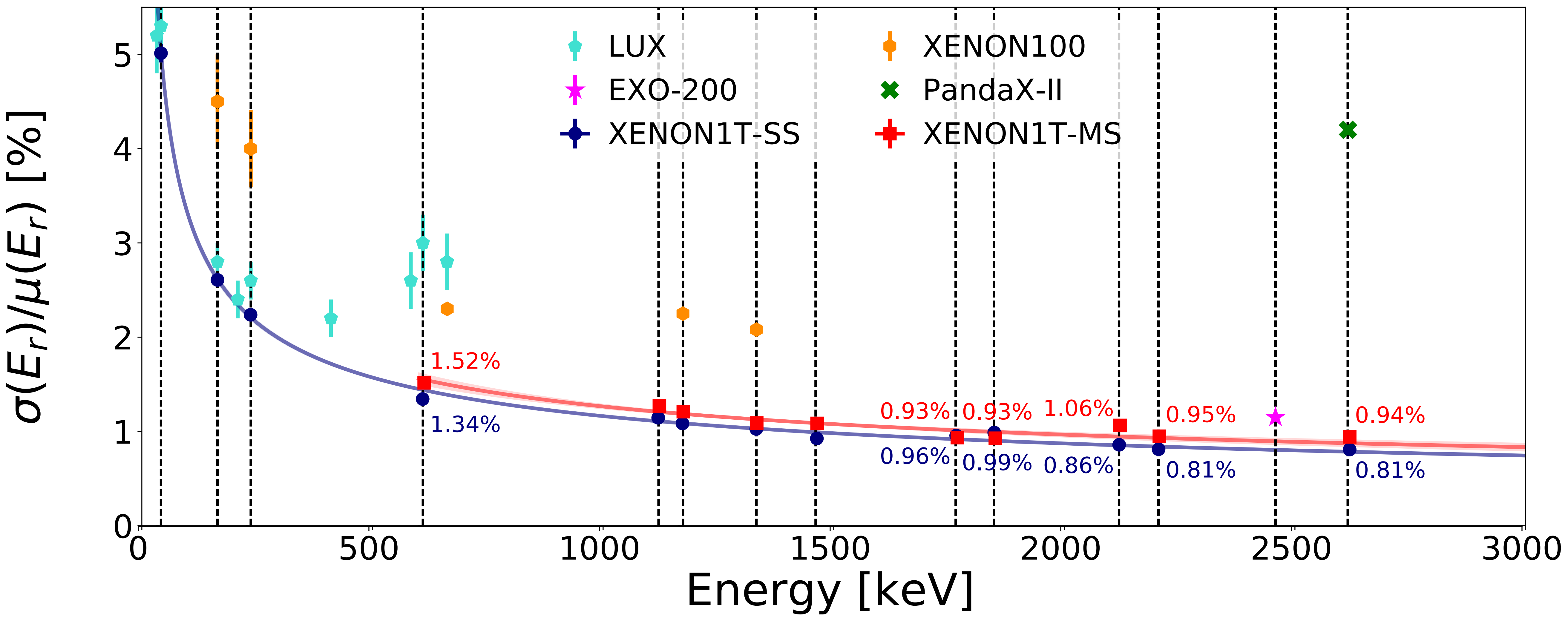


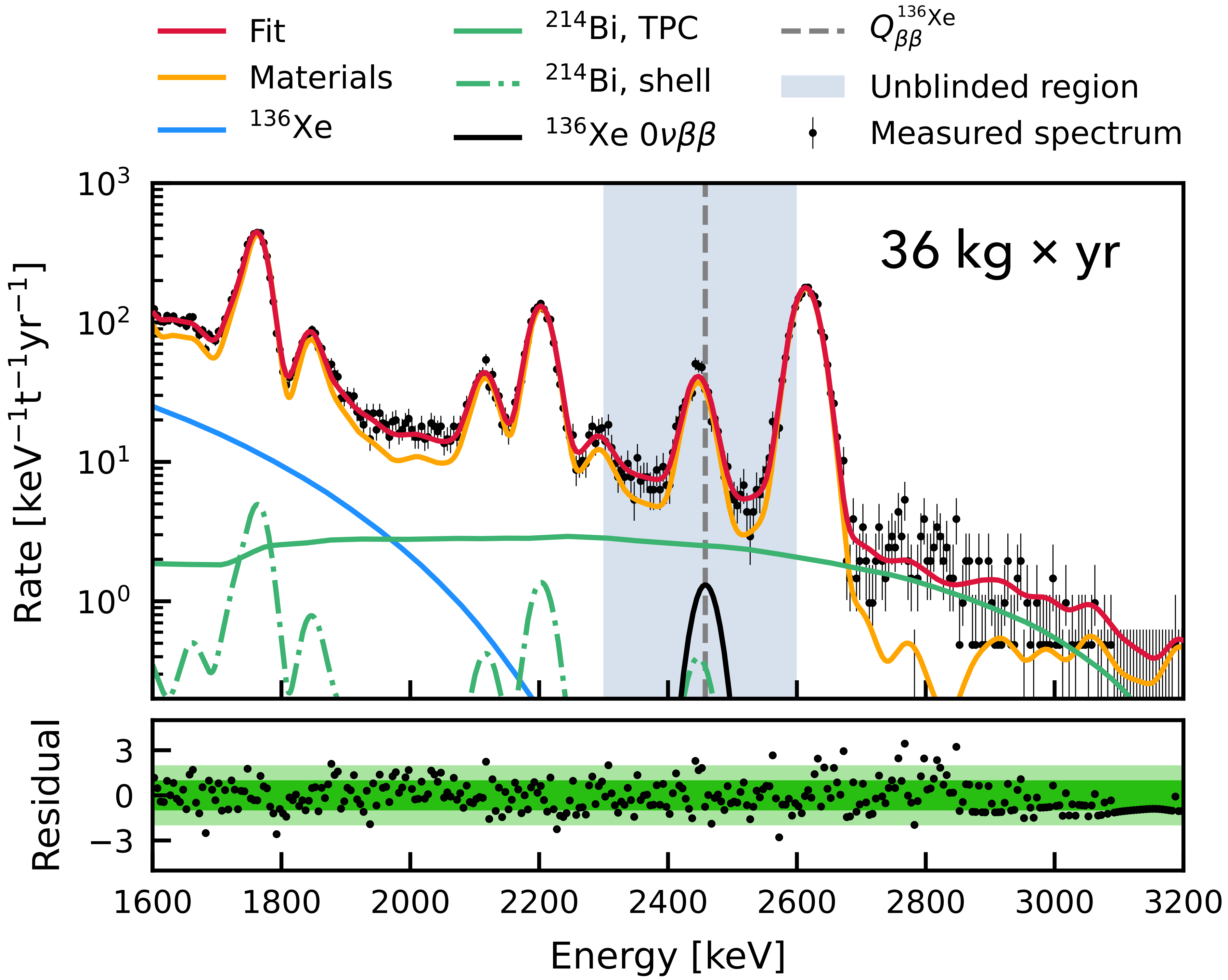


XENON1T: Neutrinoless Double Beta Decay

arxiv: 2205.04158
Eur. Phys. J. C (2020) 80:785







- DM: S2 = 100 - 1000 PE <-> Qββ = 2457.83 keV (S2 ~1e6 PE)
- Saturation correction using non-saturated nearby PMT channels.
- High-energy reconstruction resolution (σ/E): ~0.8% at Qββ
- Best result from a DM detector without an enriched target

(XENON1T: 36 kg × yr <-> KamLAND-Zen: 970kg yr)

$$T_{1/2}^{0\nu\beta\beta} > 1.2 \times 10^{24}\ \mathrm{yr}$$

XENONnT Experiment

New ER and NR calibration systems

Larger TPC with 3x active volume

Gd-loaded water Cherenkov neutron veto (our contribution) See poster by Tuan Khai Bui!

Rn distillation column

~8 times less Rn level already achieved

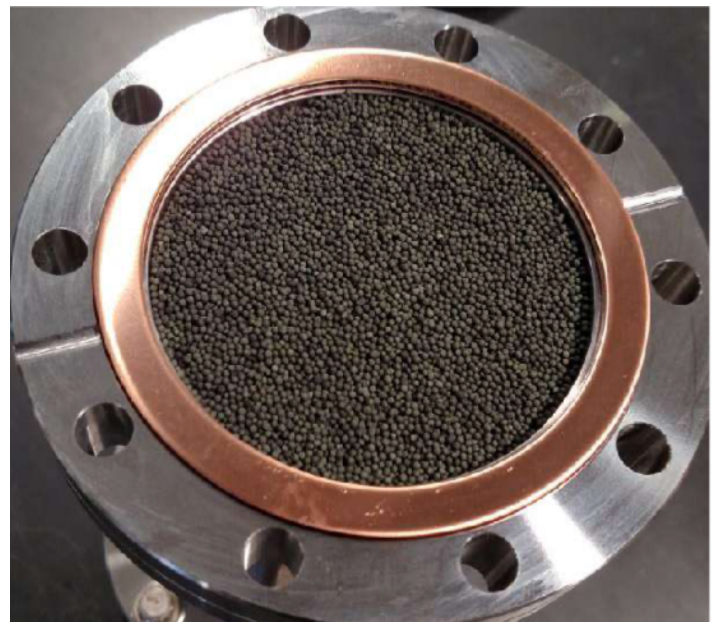
Upgraded DAQ with dedicated high-energy readout

LXe purification (our contribution)

Much better purity level achieved (less Tritium)

LXe Purification

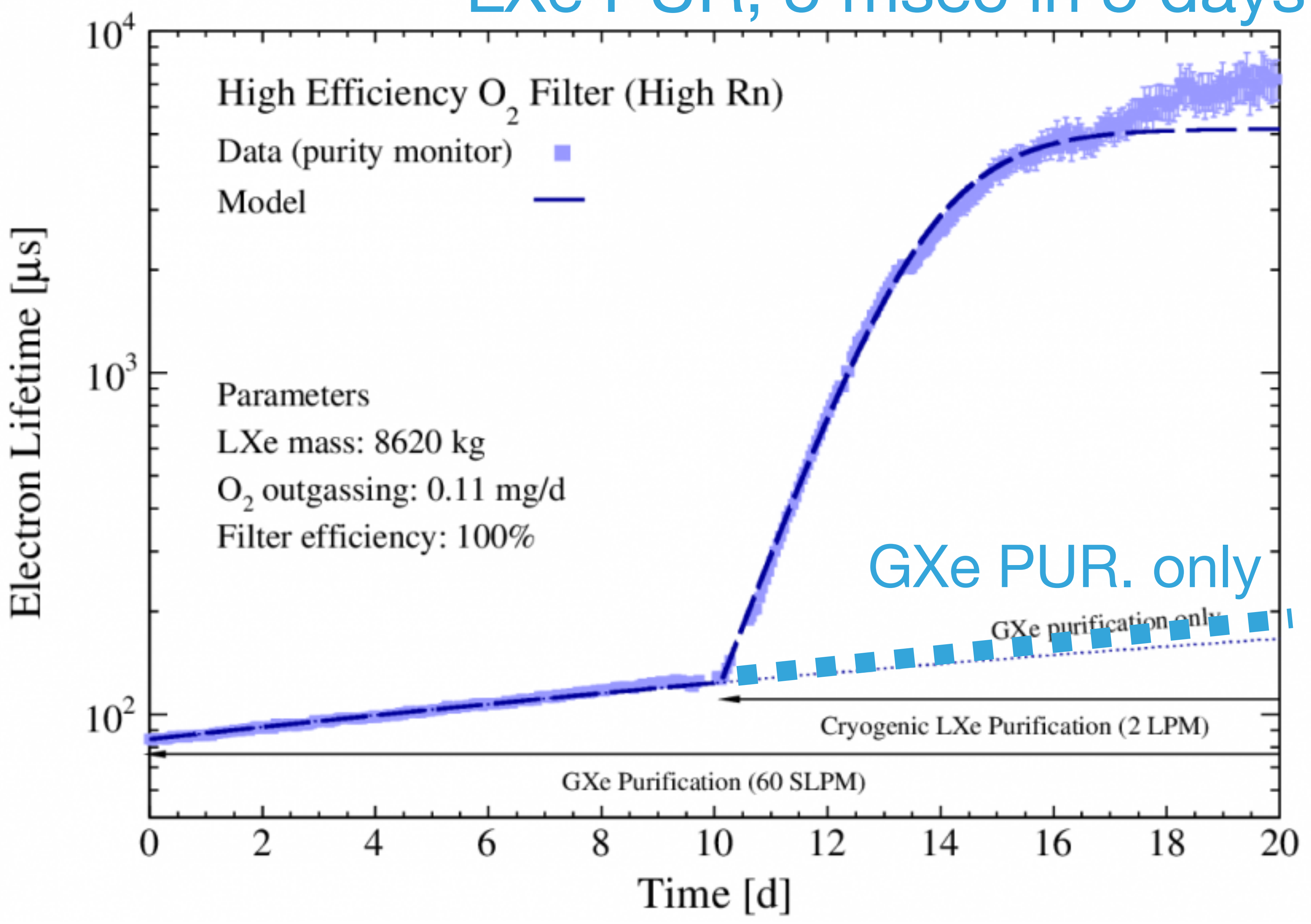
Cu powder on ceramic ball



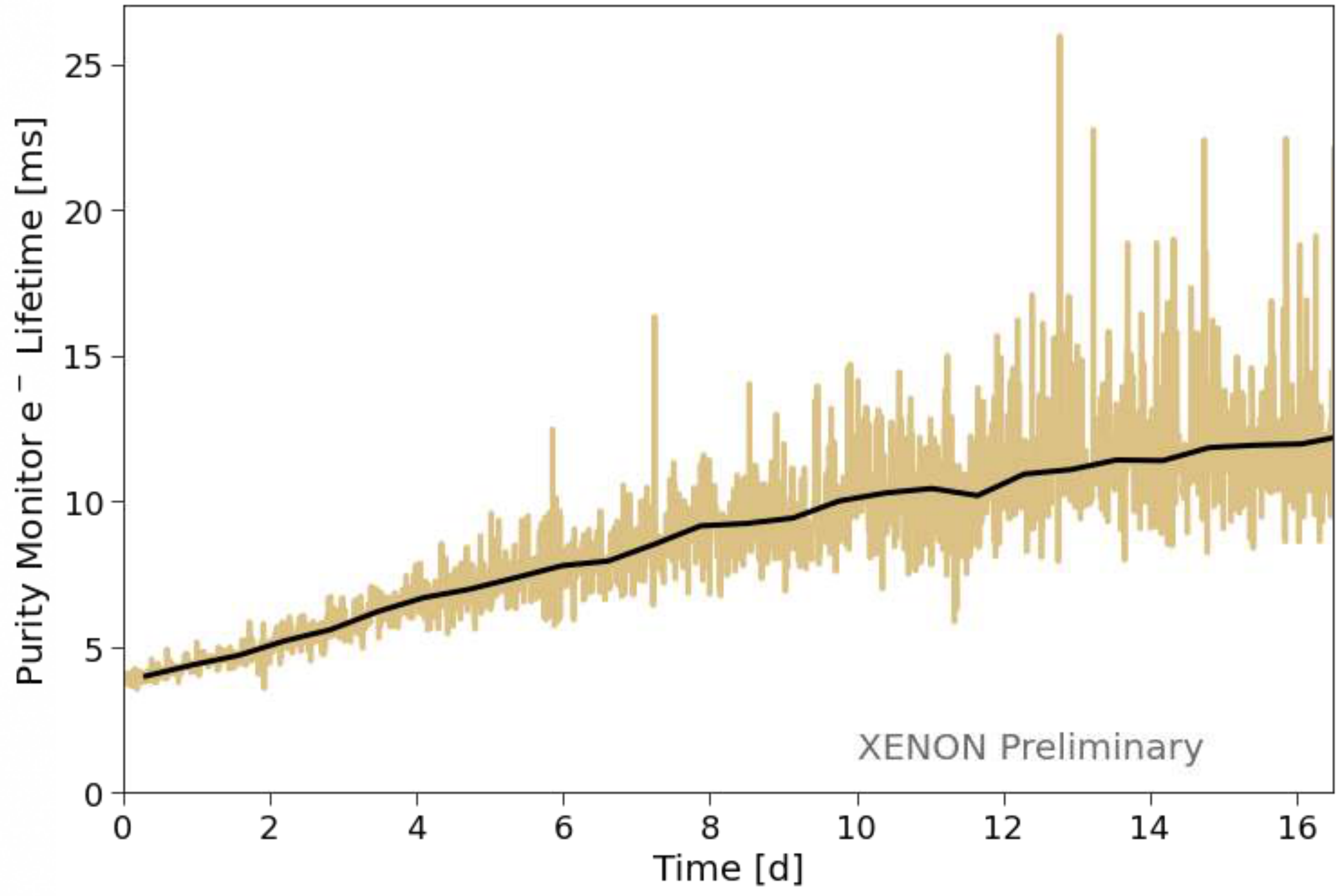
Non evaporable getter

Figure from SAES

LXe PUR, 5 msec in 5 days

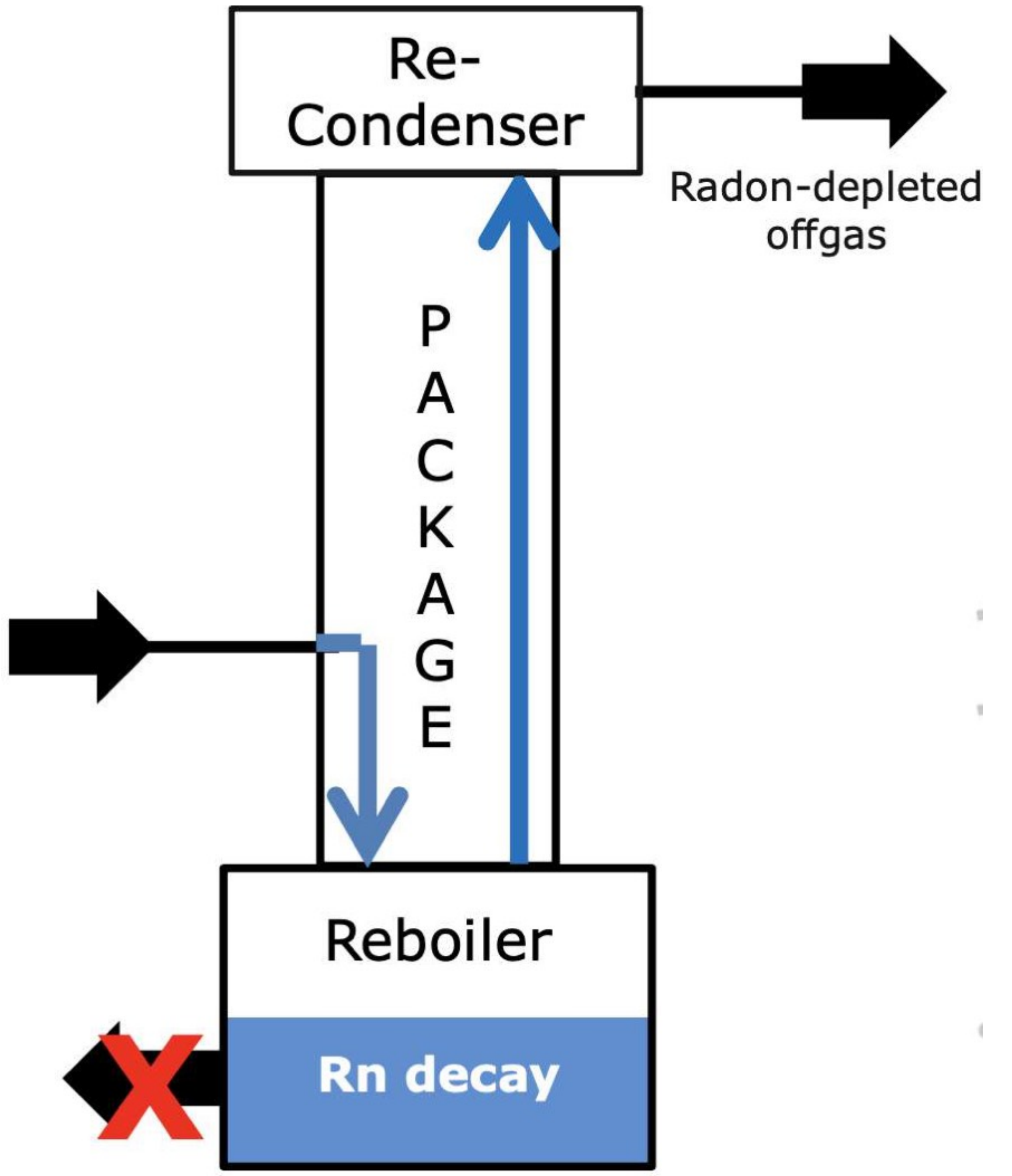


> 10 msec with low Rn filter

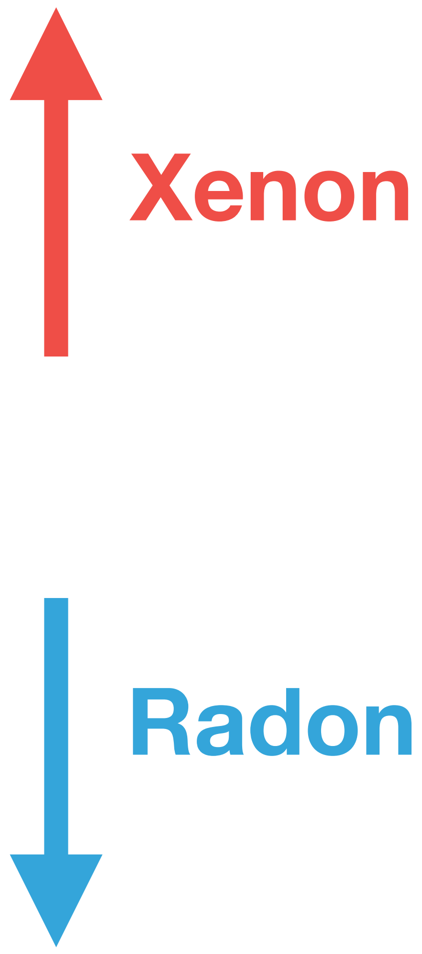


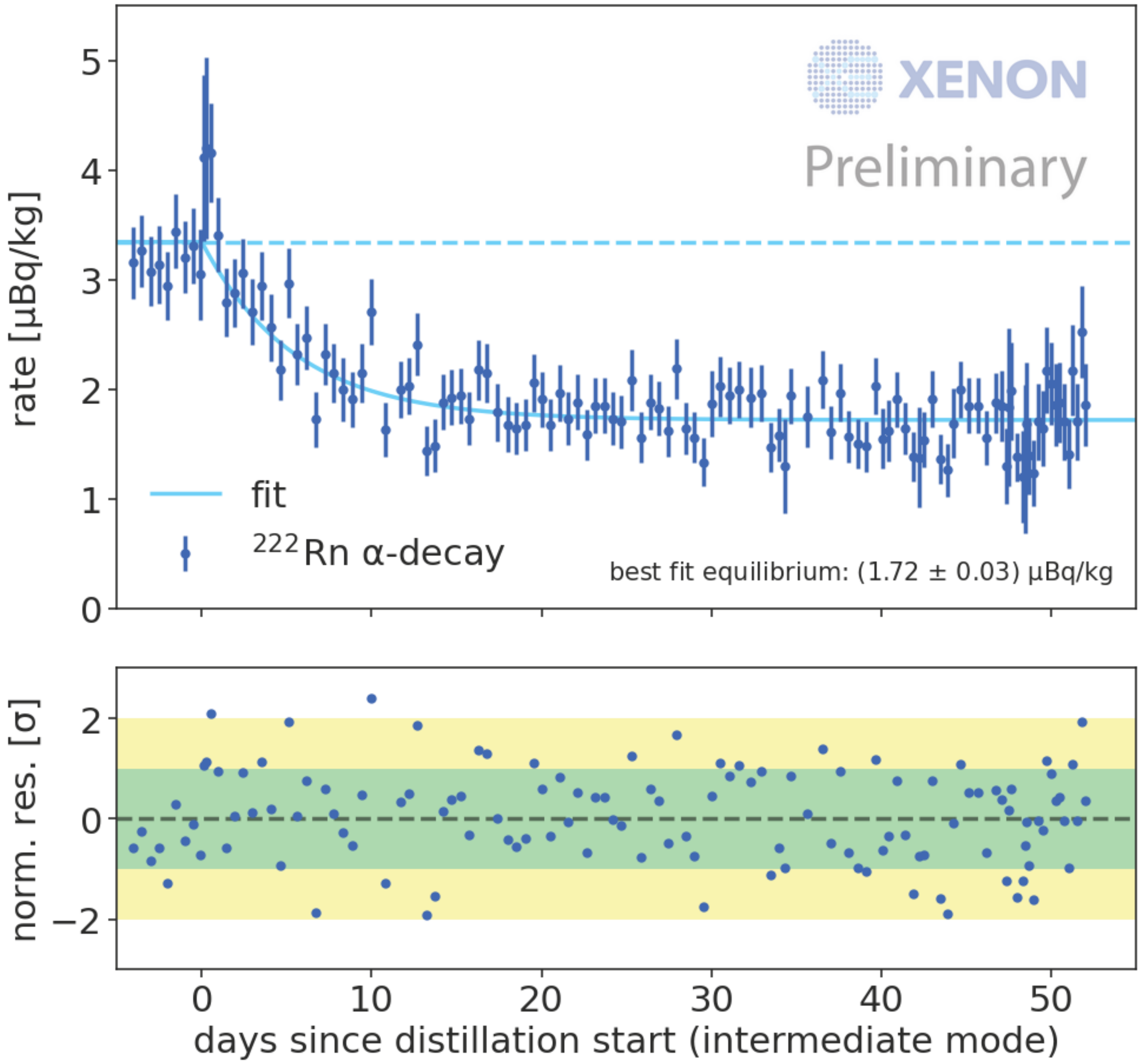
- Direct liquid circulation with cryogenic pump
- Multiple filters
  - High eff / high Rn (for fast purification)
  - Mid eff / low Rn (for DM data taking)
- Achieved x10 better purity than XENON1T (>10 msec)

Radon Distillation



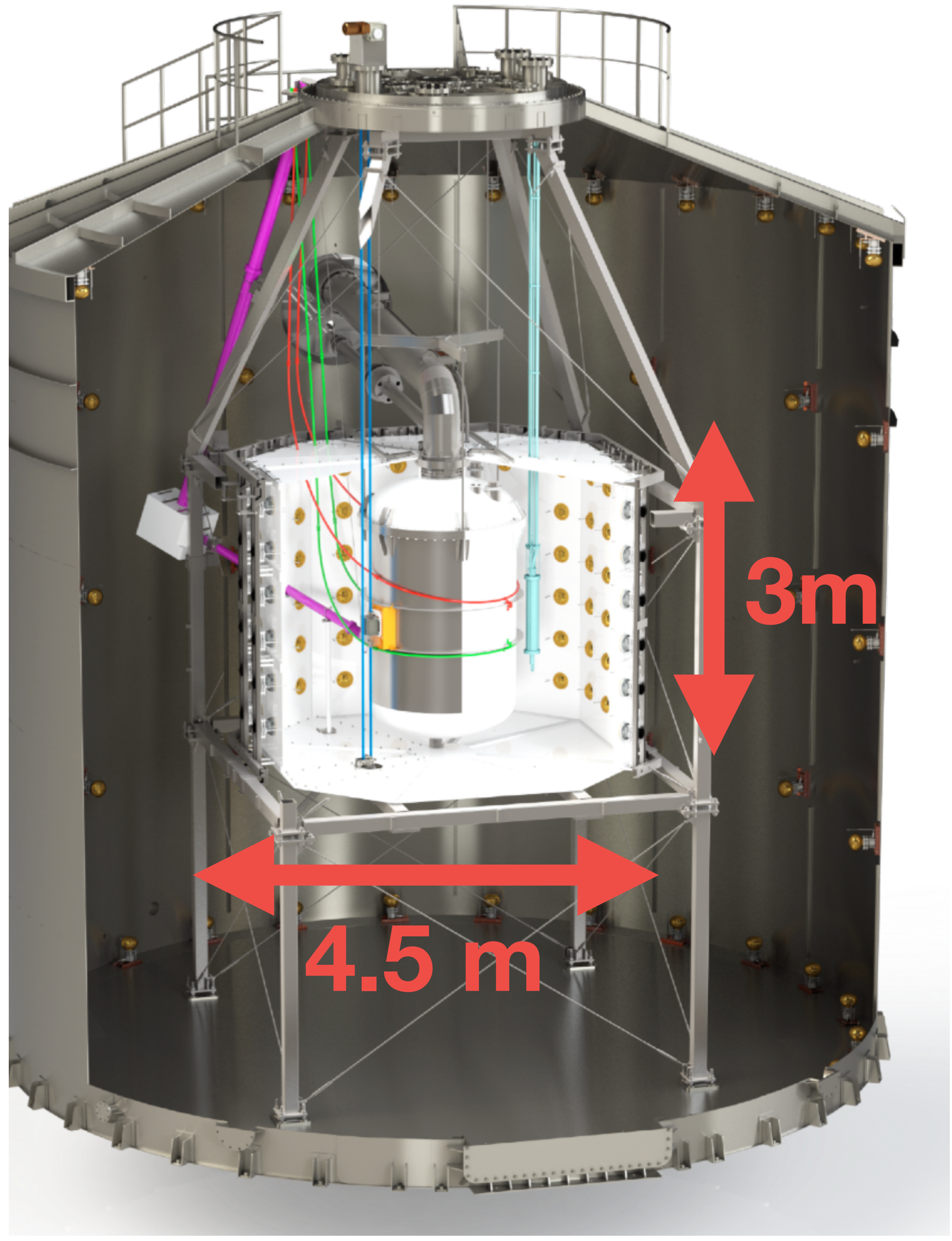
arxiv: 2205.11492

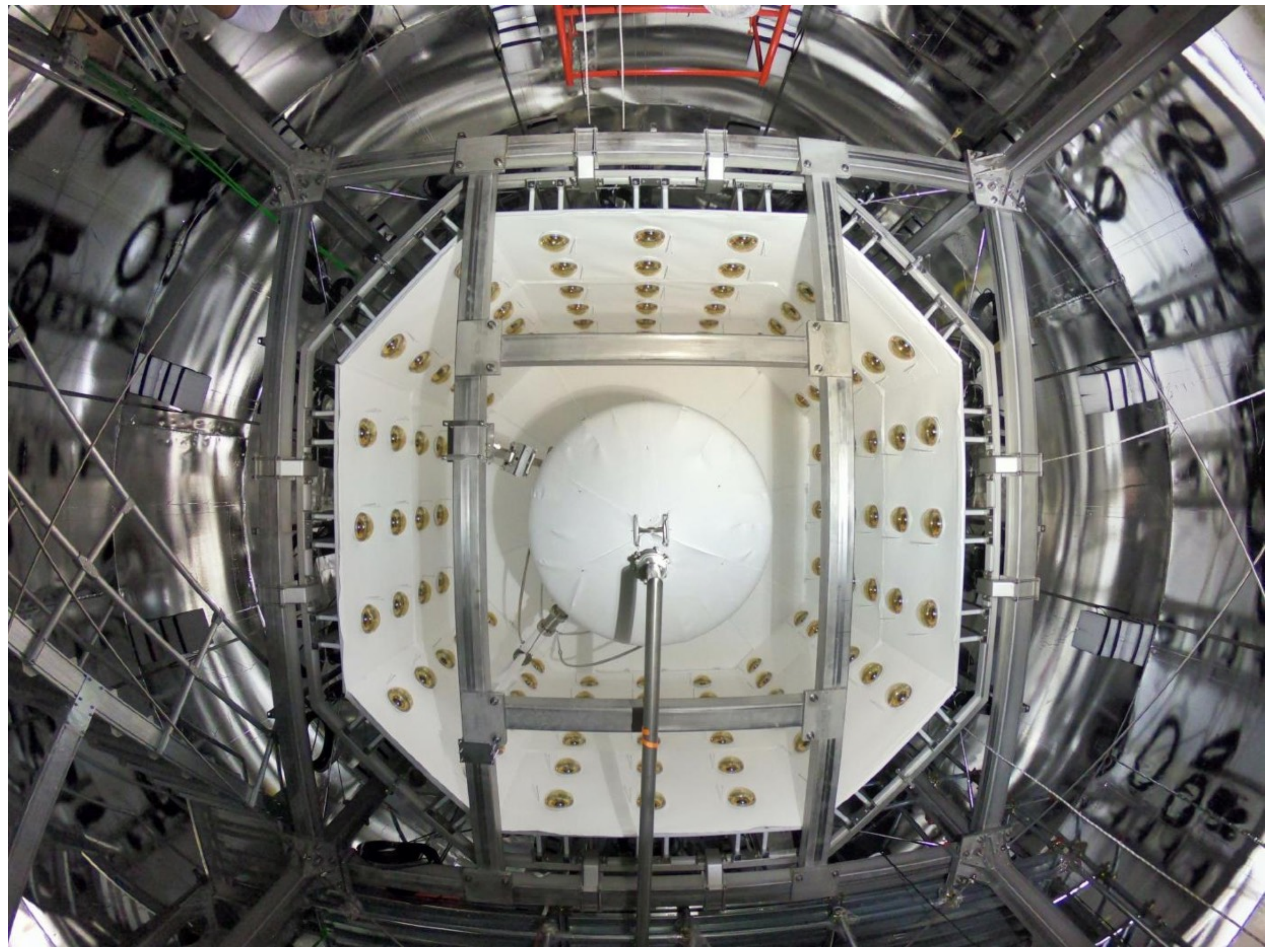


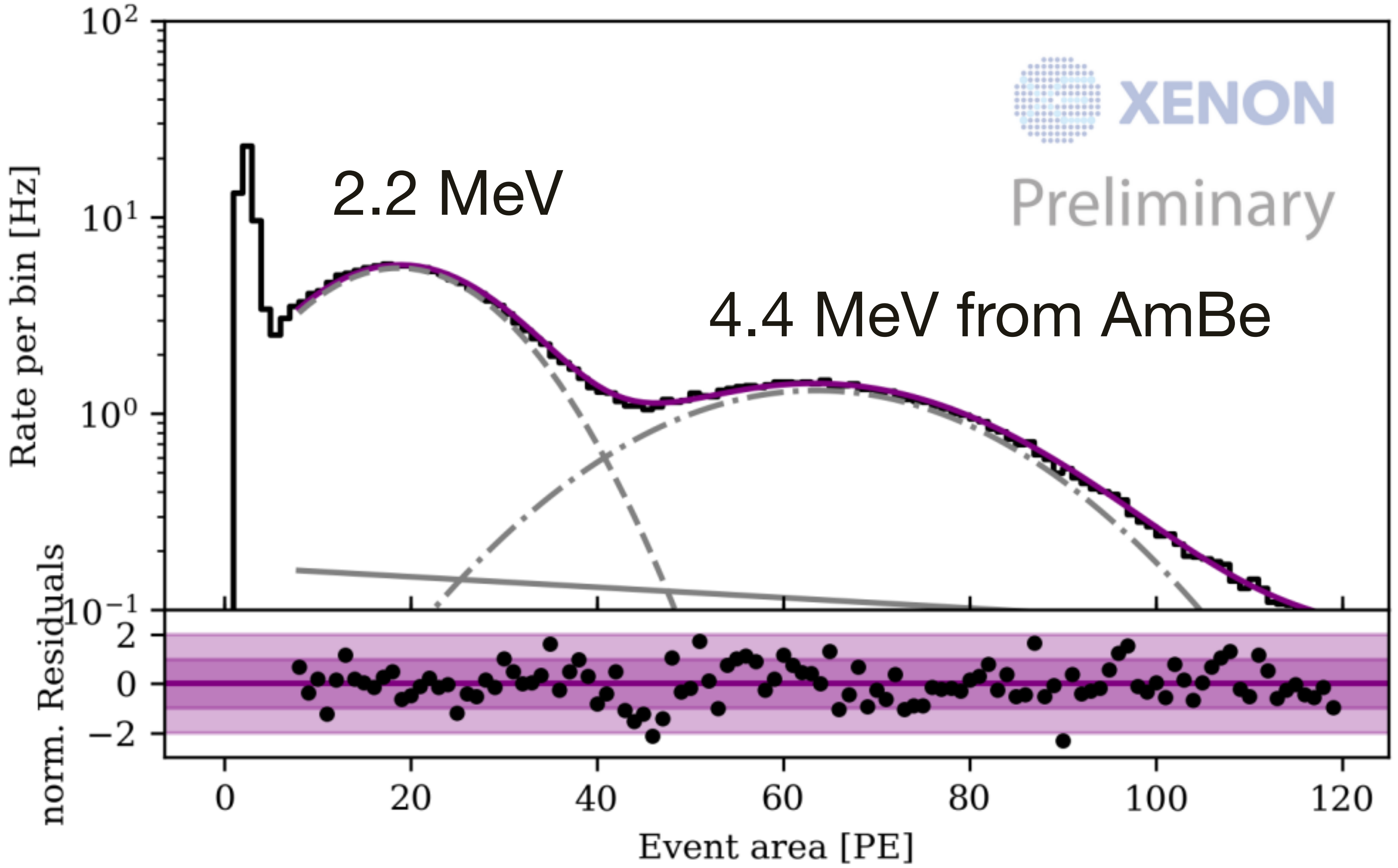


- Design: 1μBq/kg ^{222}Rn level (XENON1T: 13μBq/kg)
- Constant removal of emanating Rn using difference in vapor pressure (Rn atom accumulates into LXe more than GXe)
- Reached equilibrium concentration of 1.7 μBq/kg by gas extraction only (~8 times less BG w.r.t. 1T)
- Additional factor 2 reduction is possible via liquid extraction

Neutron Veto



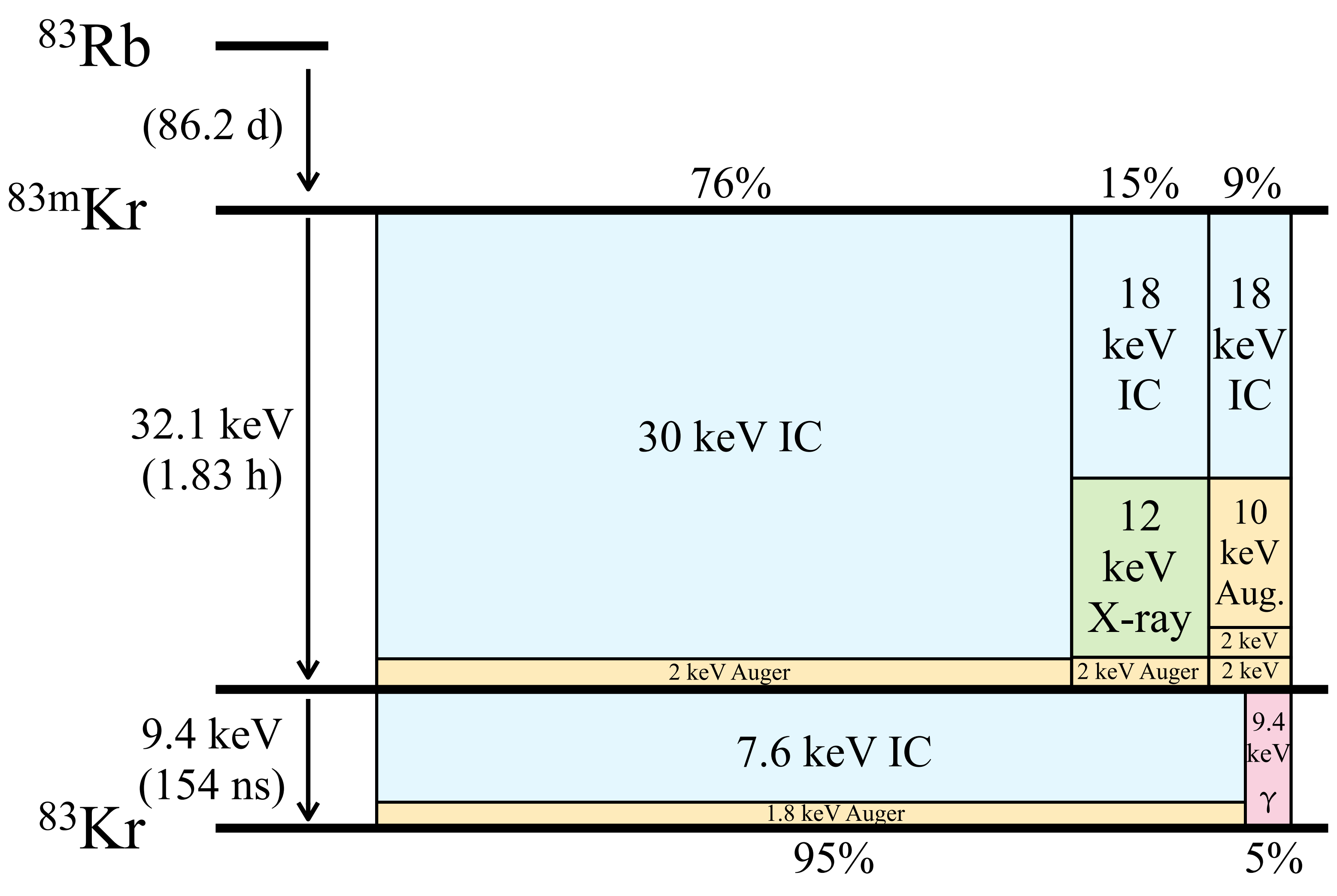




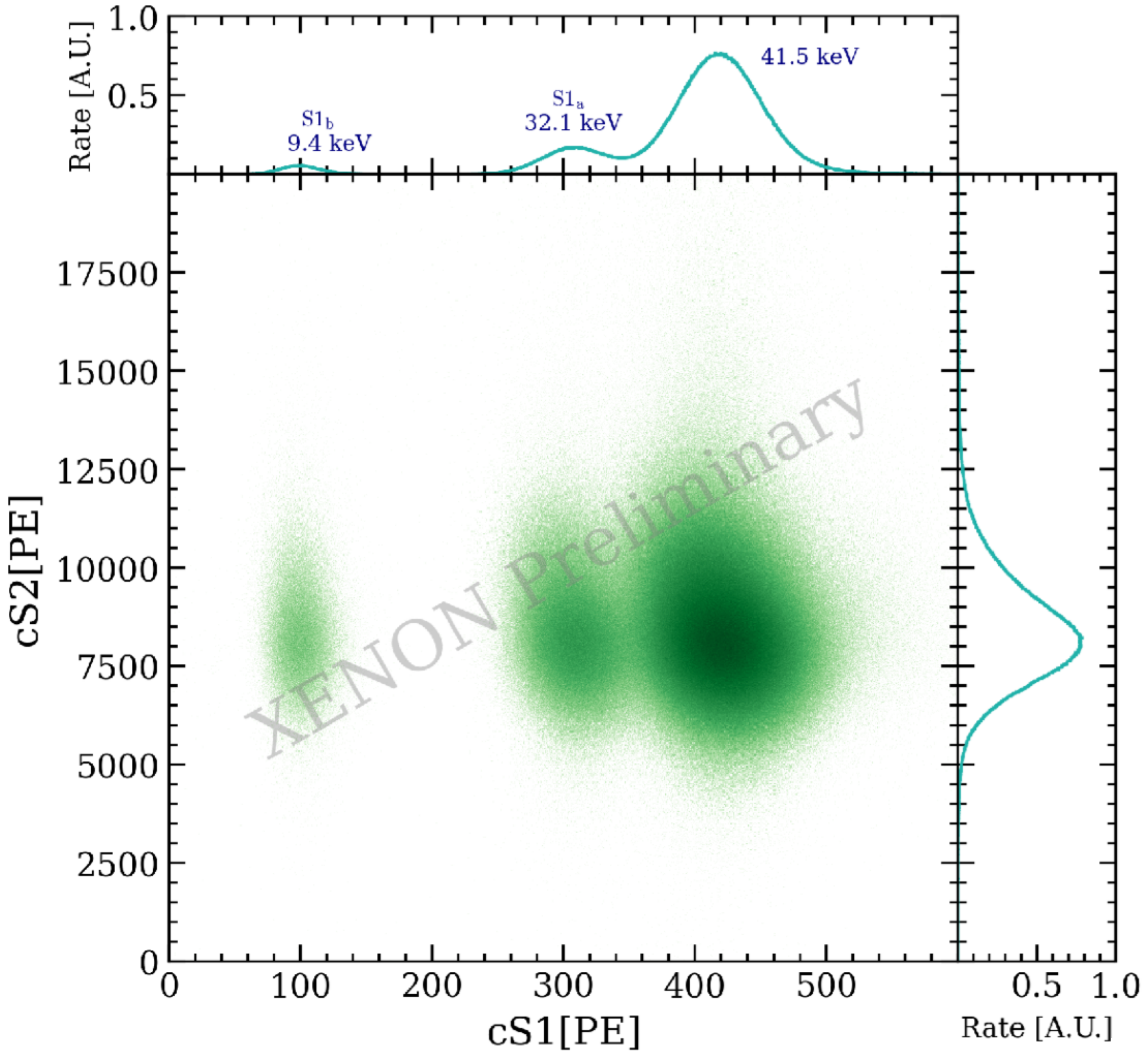
- Gd-Water Cherenkov detector (SuperK/EGADS technology)
- Neutrons are captured by Gd, then produce gammas with total energy of 8MeV
- Covering the entire detector wall with ePTFE with ~99% reflectivity
- Can reconstruct 2.2 MeV gamma
- Tagging efficiency: 80-90% (simulation) with 0.5% Gd2(S04)3・8H20

See poster by Tuan Khai Bui!

XENONnT Experiment: ^{83m}Kr Calibration



Phys. Rev. D 96, 112009 (2017)



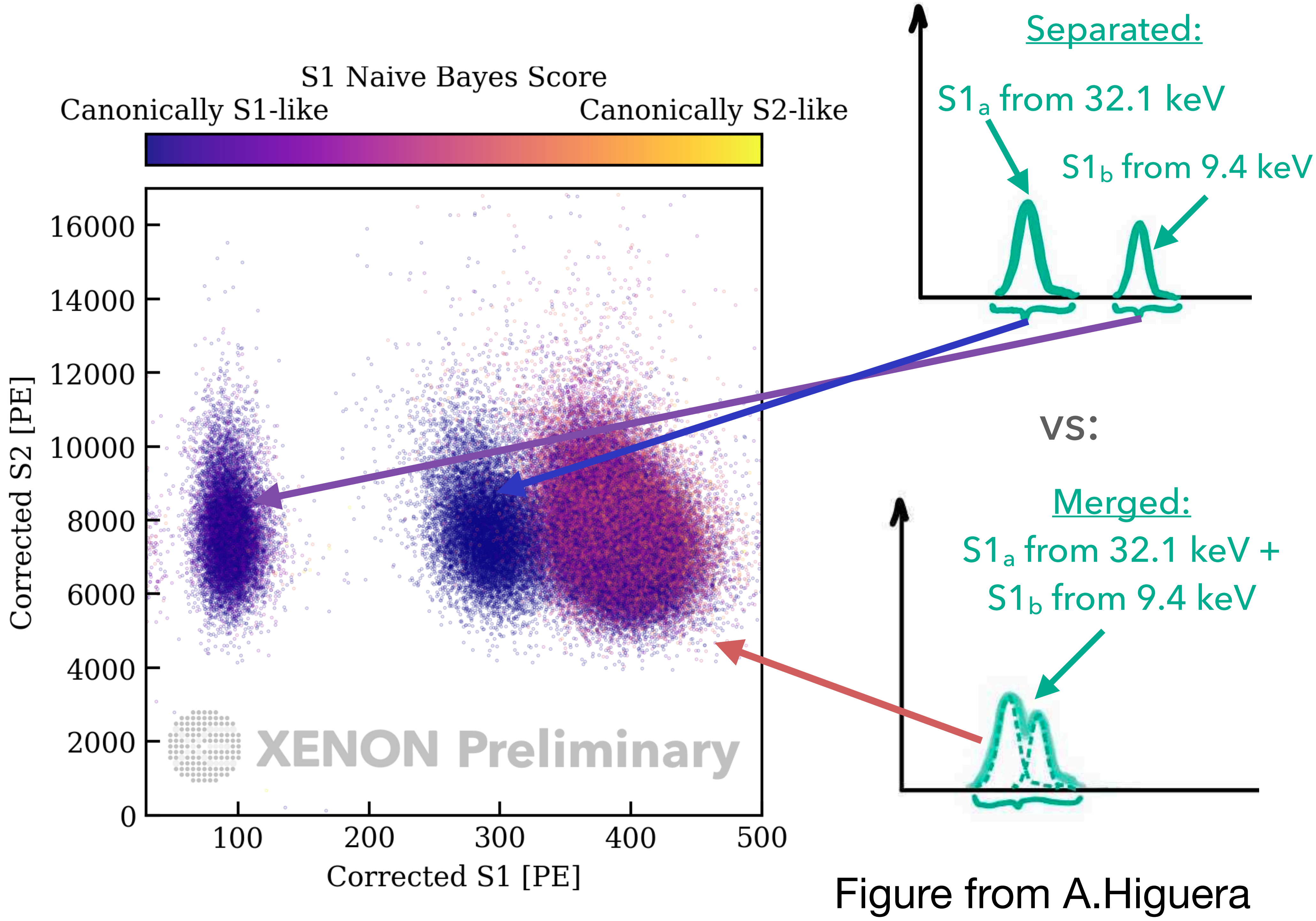
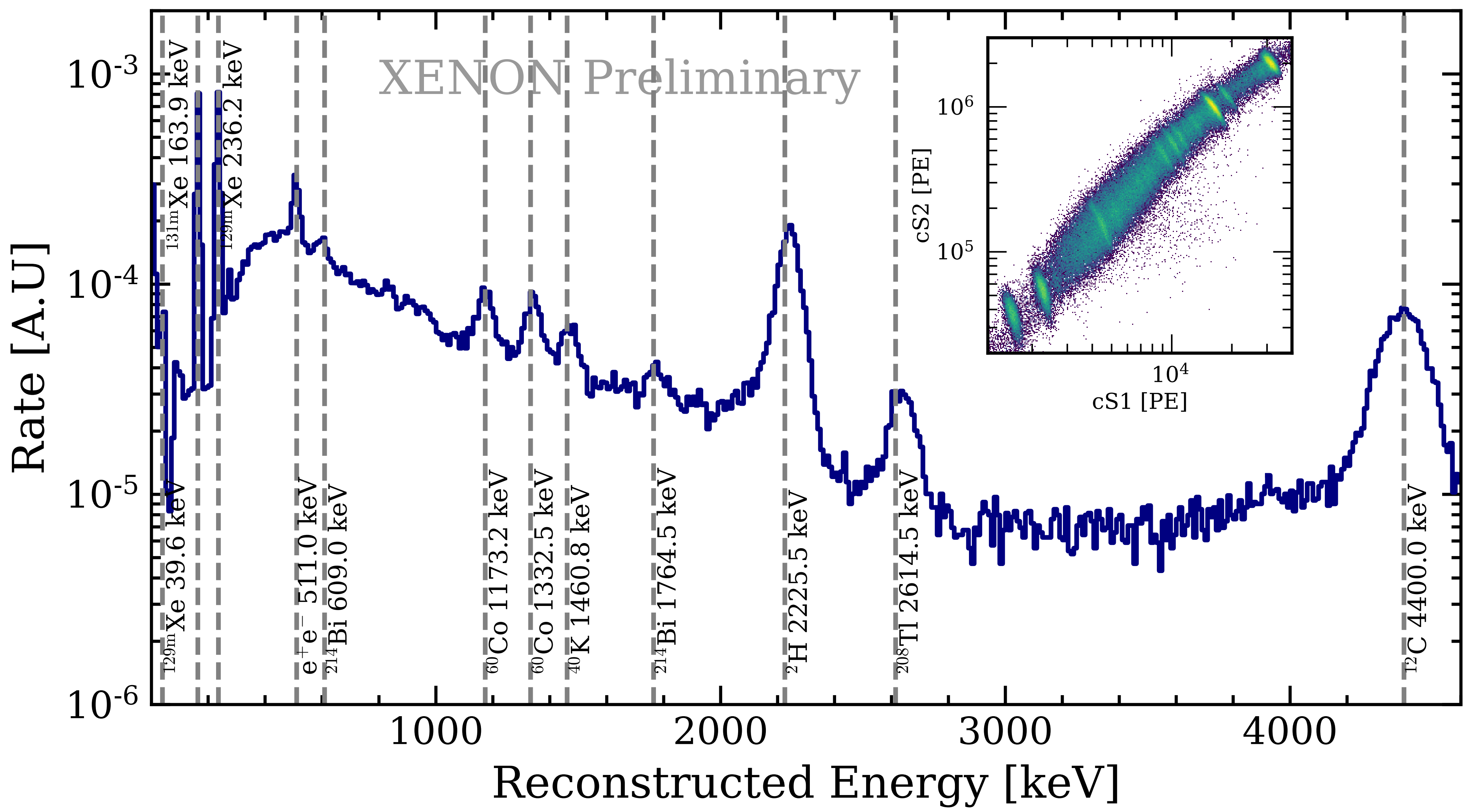


Figure from A.Higuera

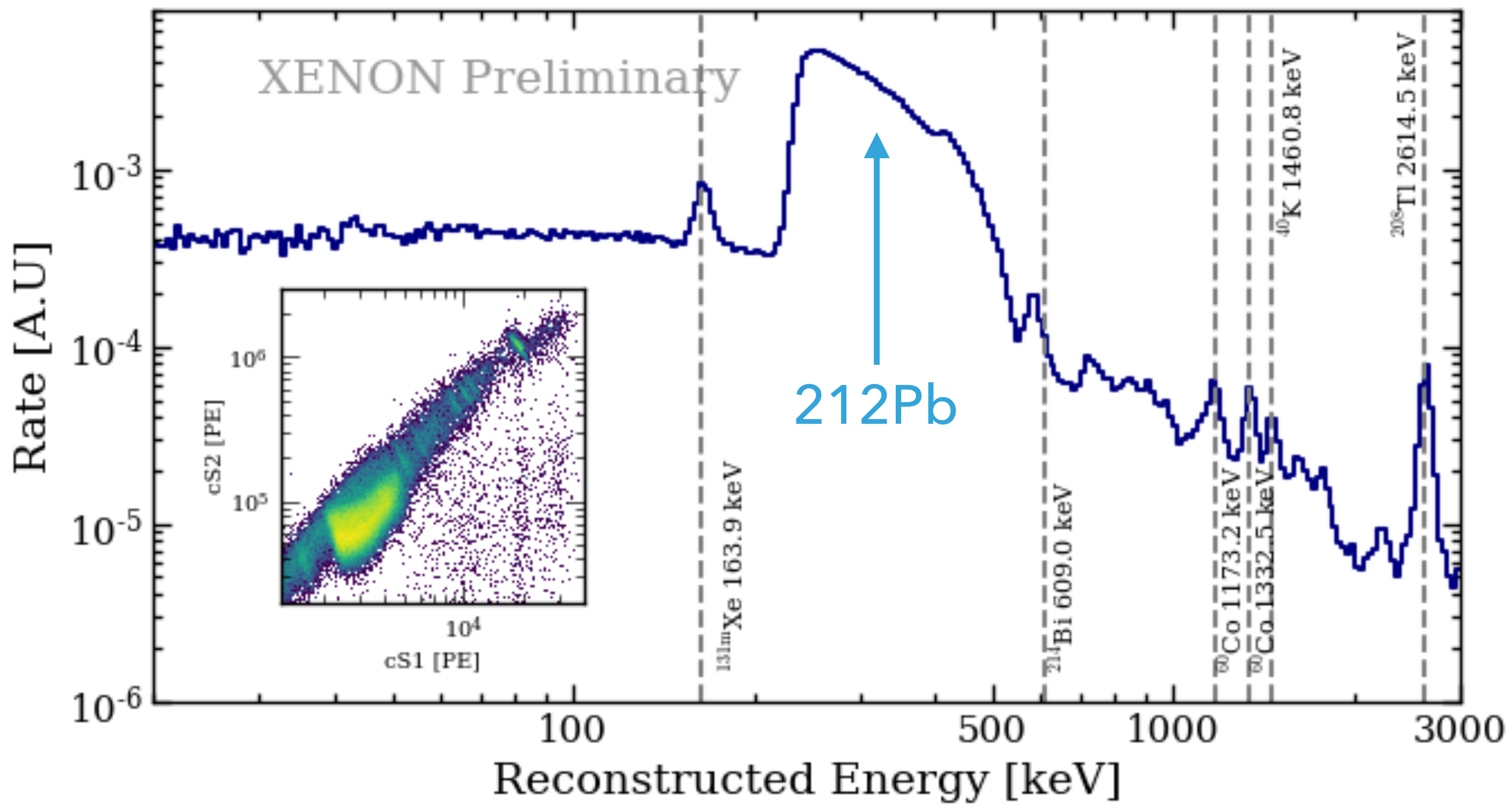
- Resolved peaks in S1-S2 space
- Photon detection efficiency ~ 0.17 PE/photon (1T: ~0.14 PE/ph)
- Energy resolution at 41.5 keV ~ 7.6 % (1T: 8 %)
- Machine-learning based classification of S1/S2 signals established

XENONnT Experiment: Calibration

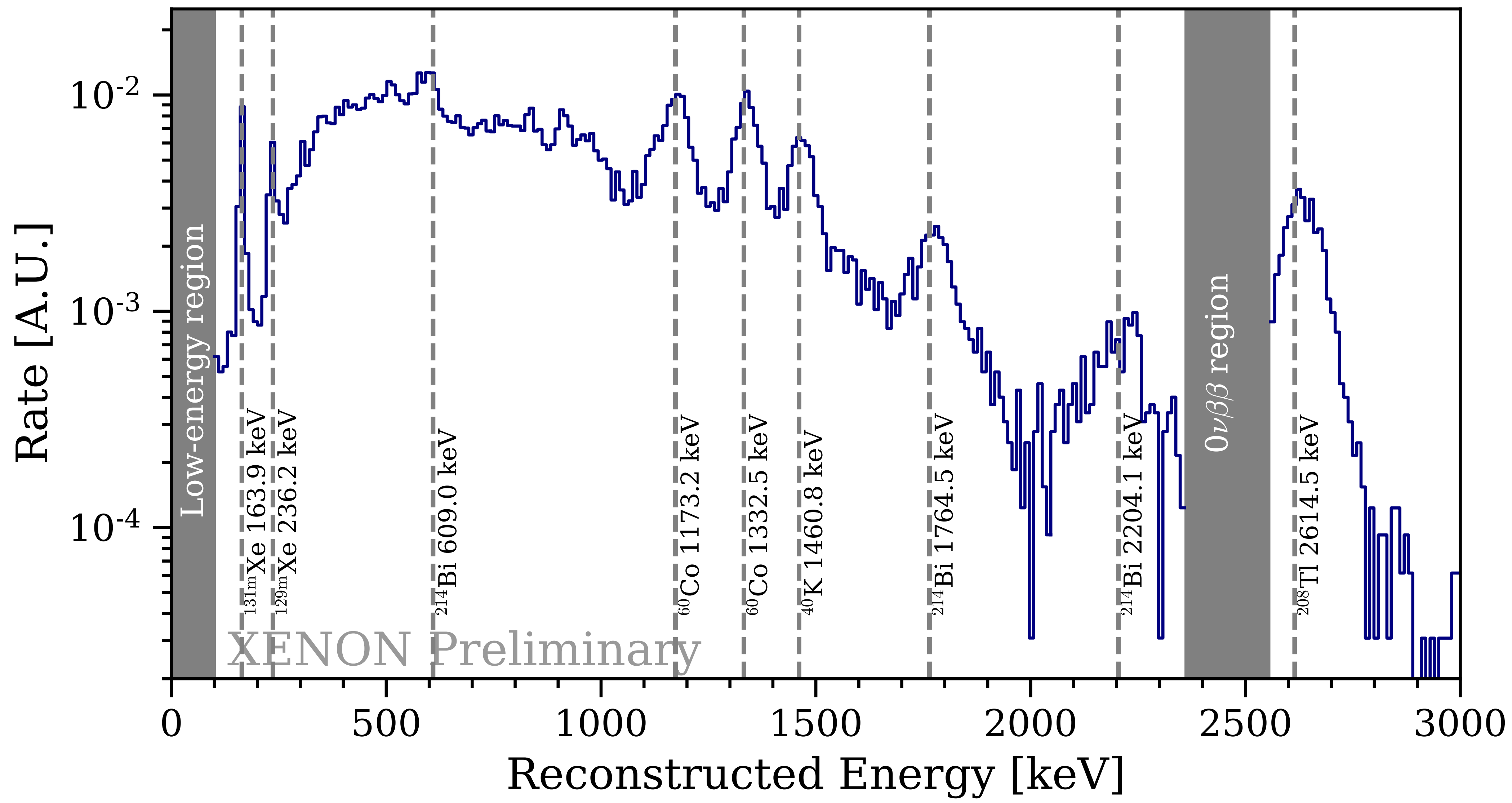
^{241}AmBe (neutron + gammas)



^{220}Rn calibration



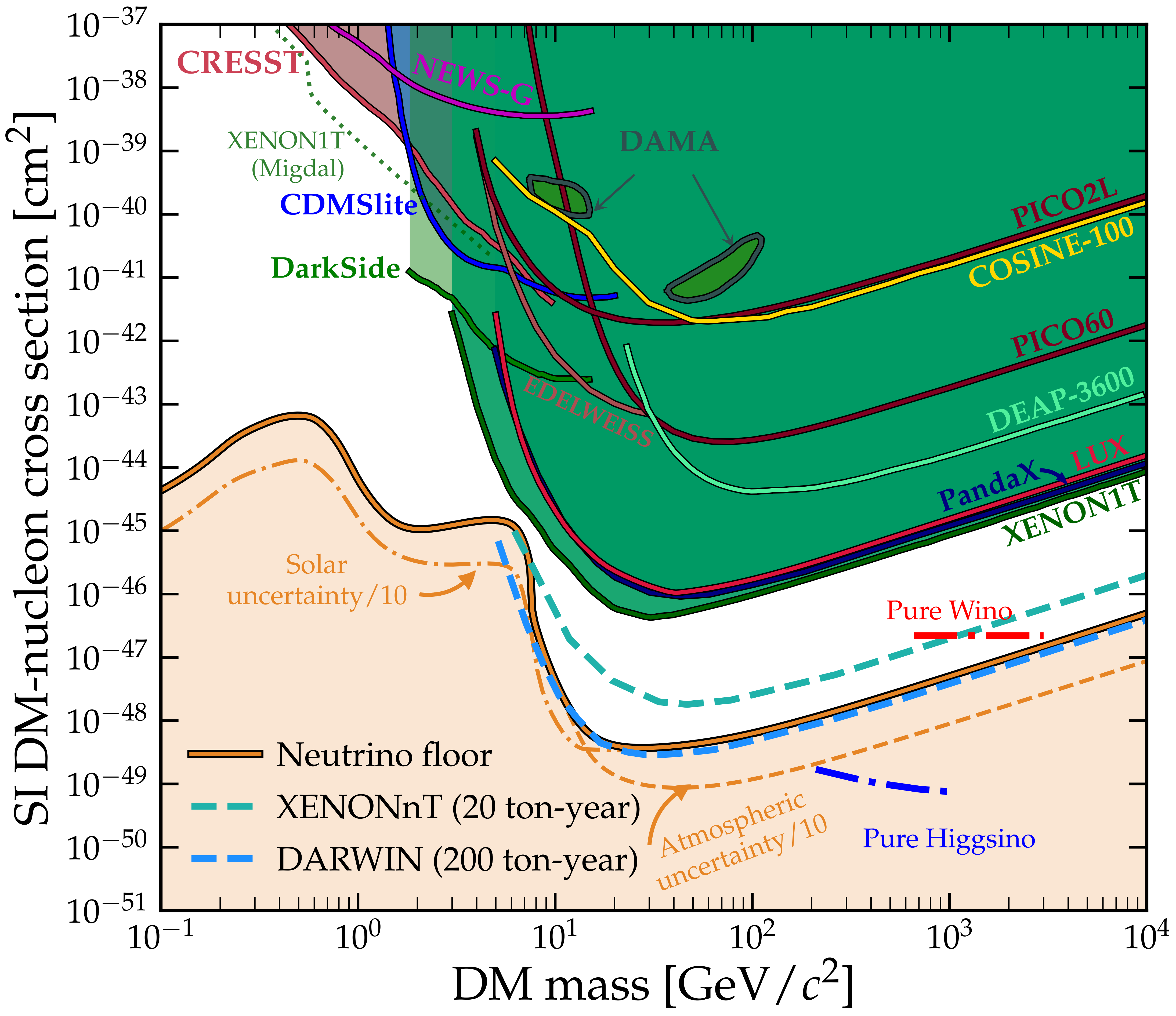
Science Data

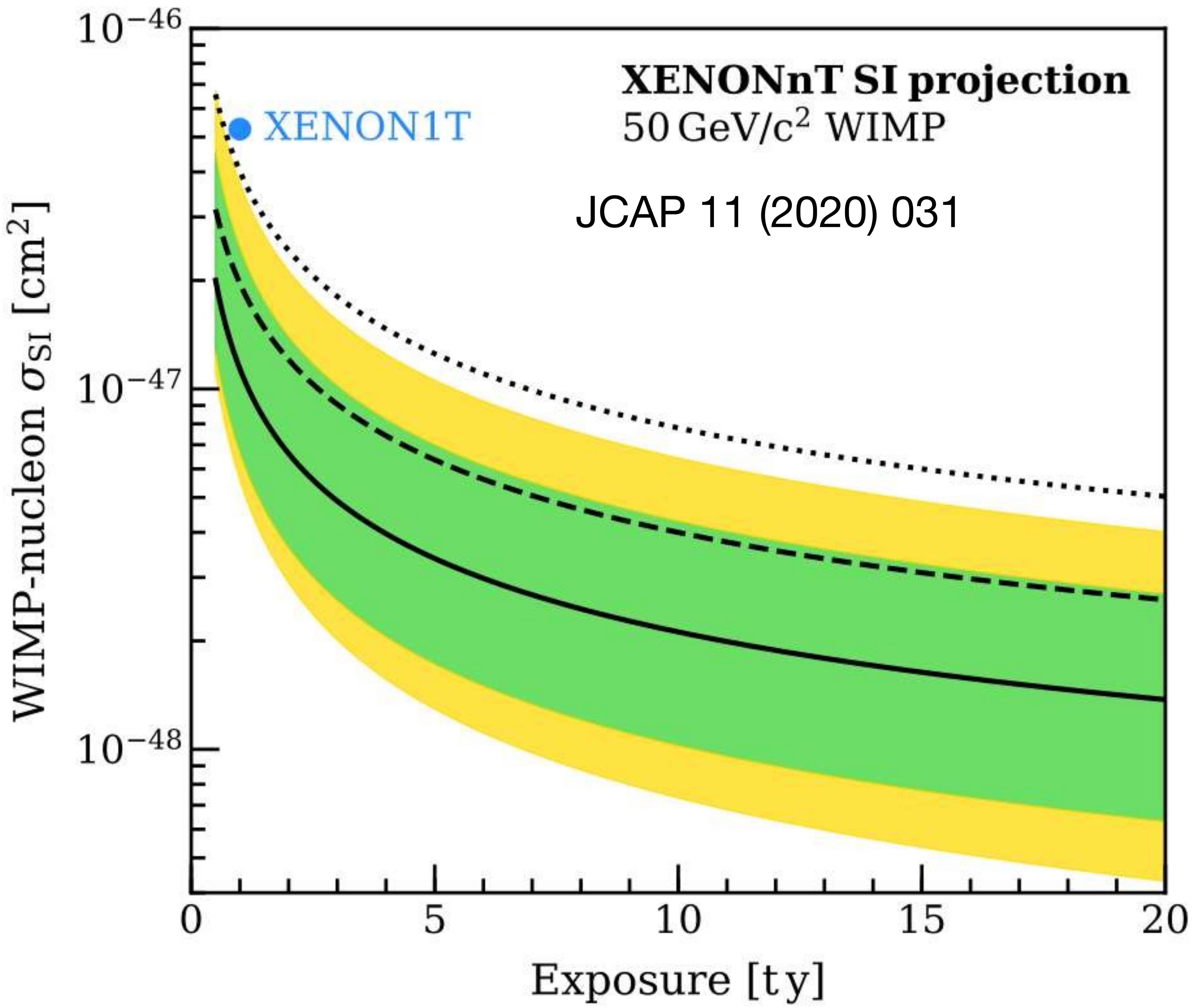


XENONnT is taking science data!

WIMP

Based on Phys. Rev. Lett. 127 (2021) 25180

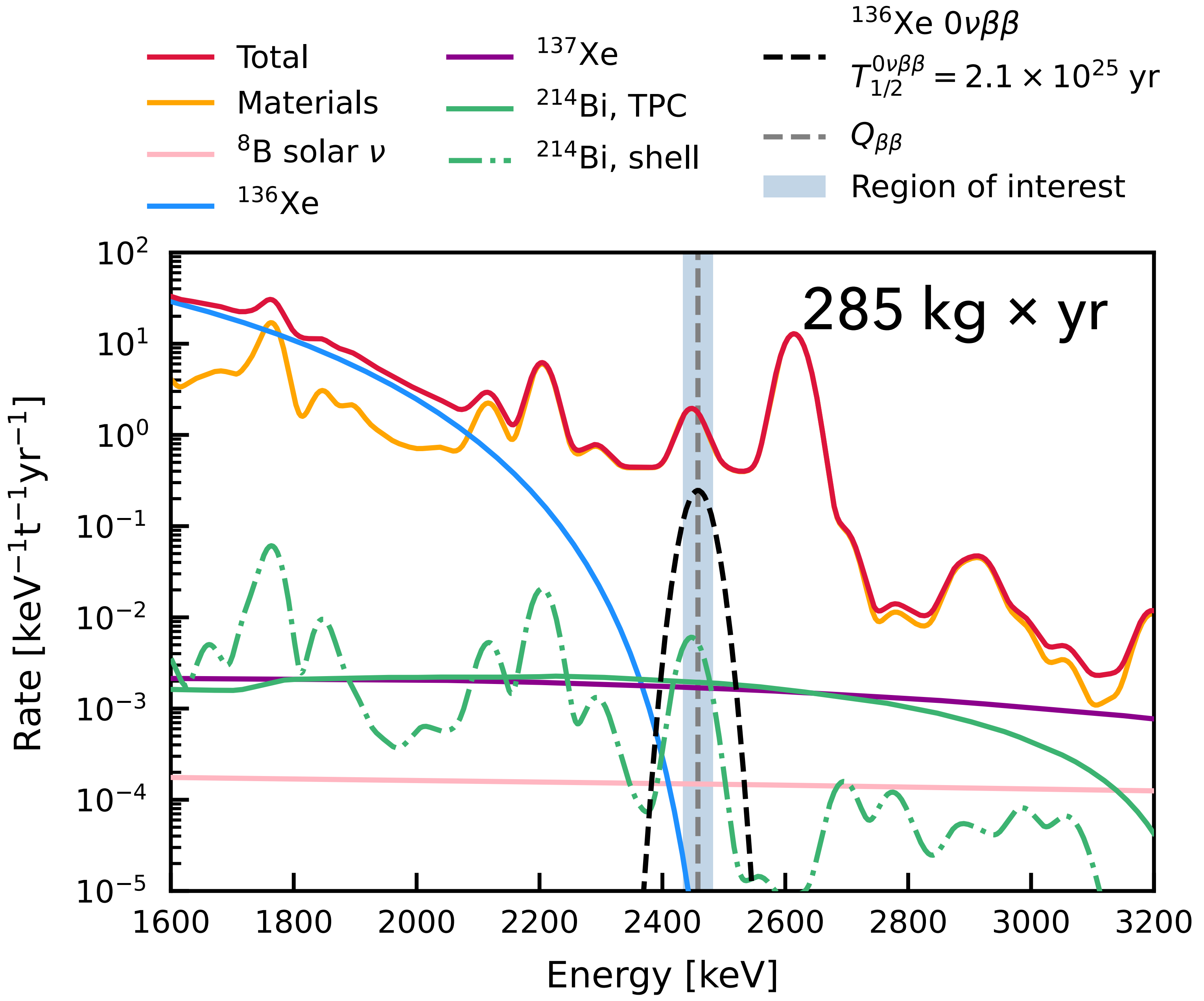


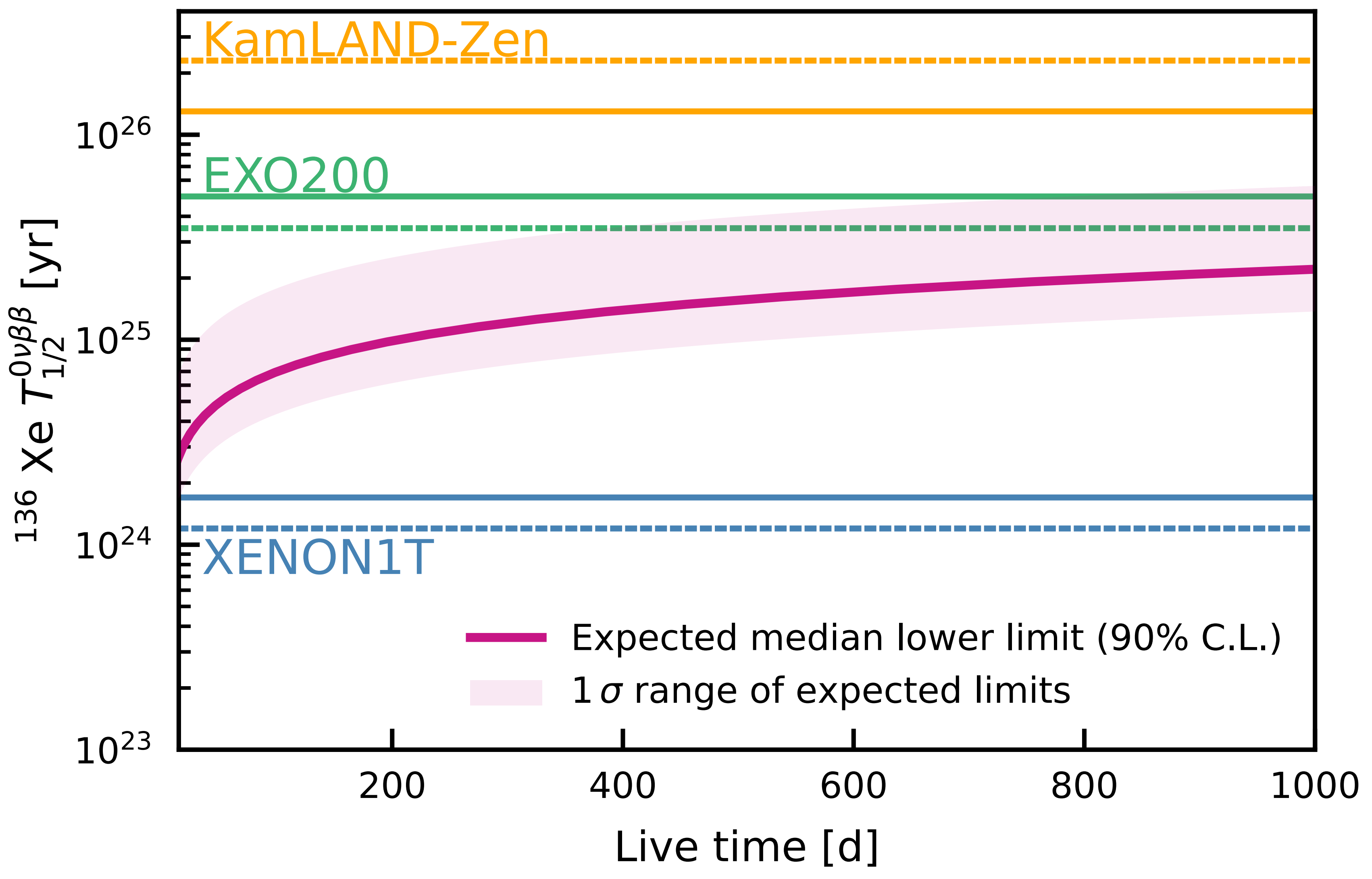


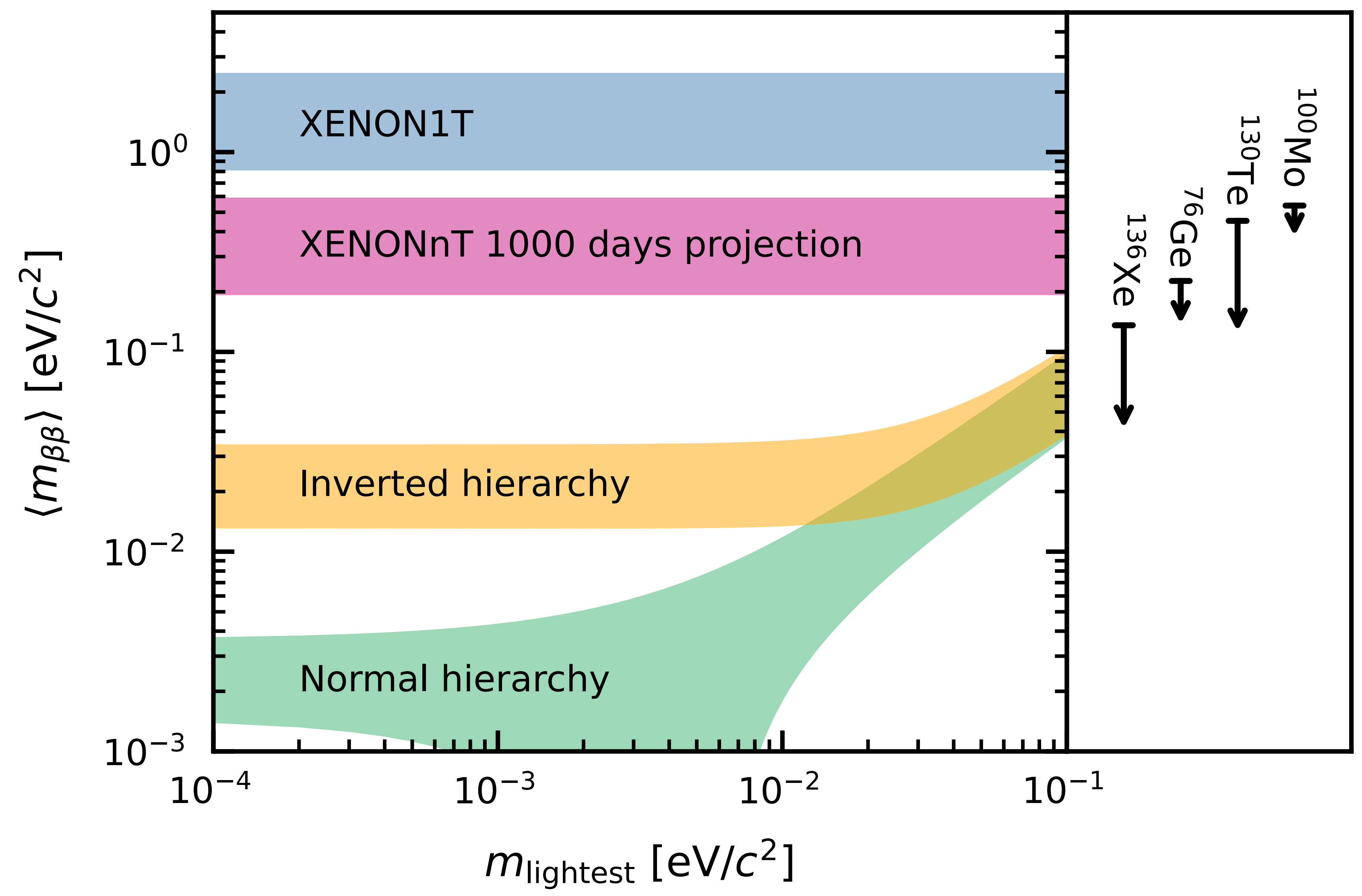
- Improve existing WIMP limits by more than one order of magnitude with 20 tonne-year exposure
- Can reach some interesting SUSY parameter spaces (ex: pure-Wino LSP scenario)

Neutrinoless Double Beta Decay

arxiv: 2205.04158





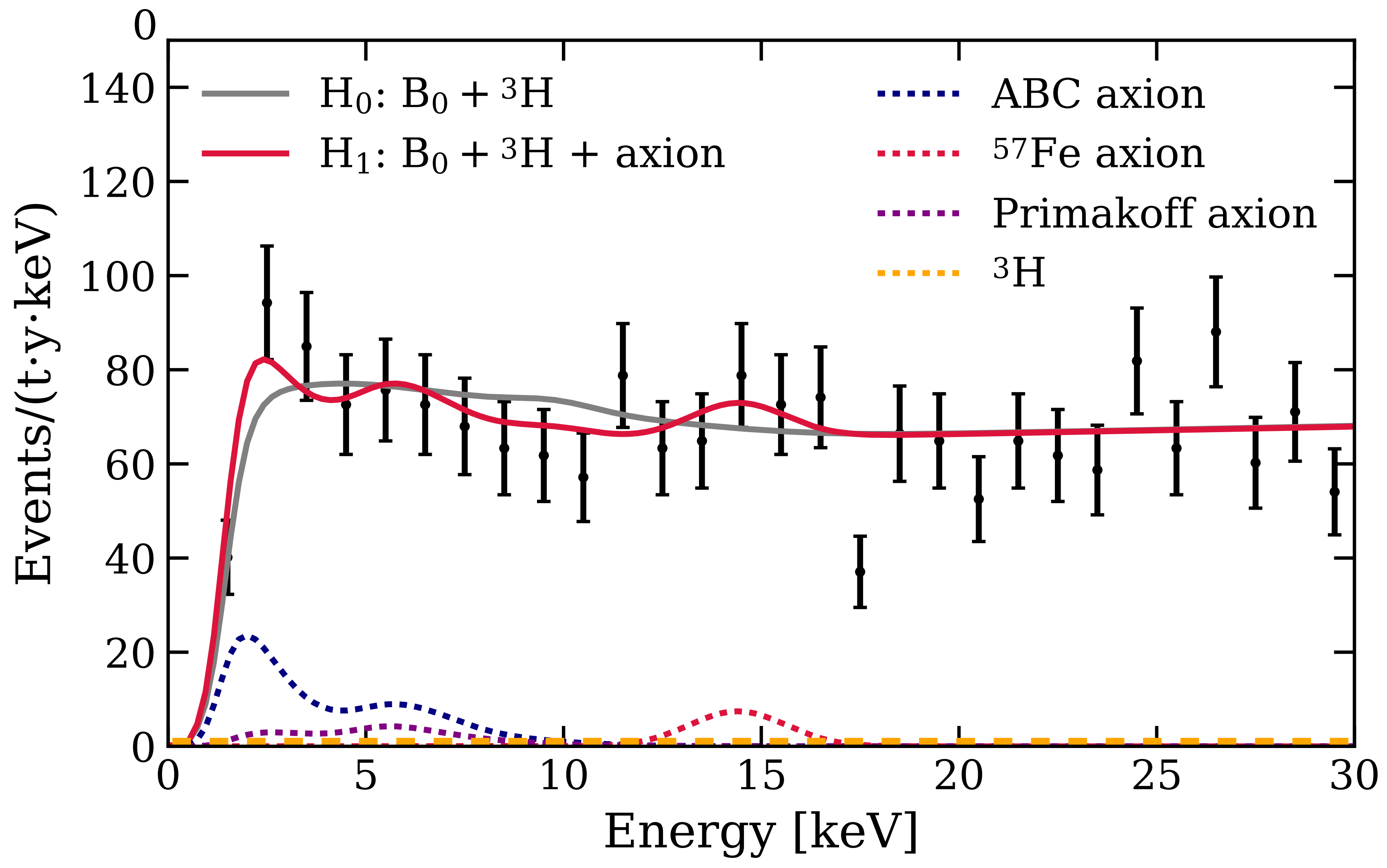


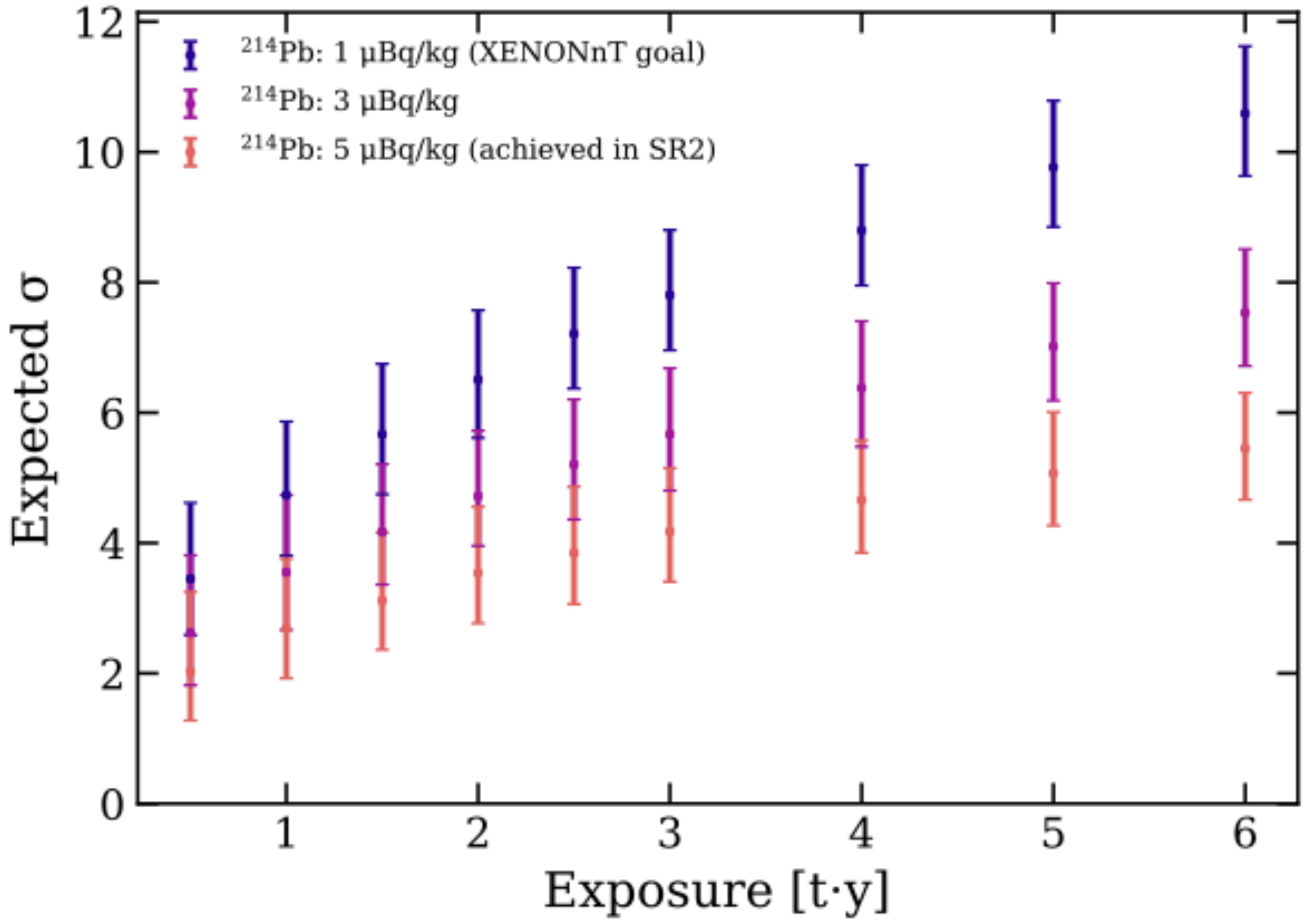
(XENON1T) $T_{1/2}^{0\nu\beta\beta} > 1.2 \times 10^{24}$ yr → (XENONnT) $T_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{25}$ yr

- Not competitive with dedicated experiments due to non-enriched target and BG optimization for keV energies.

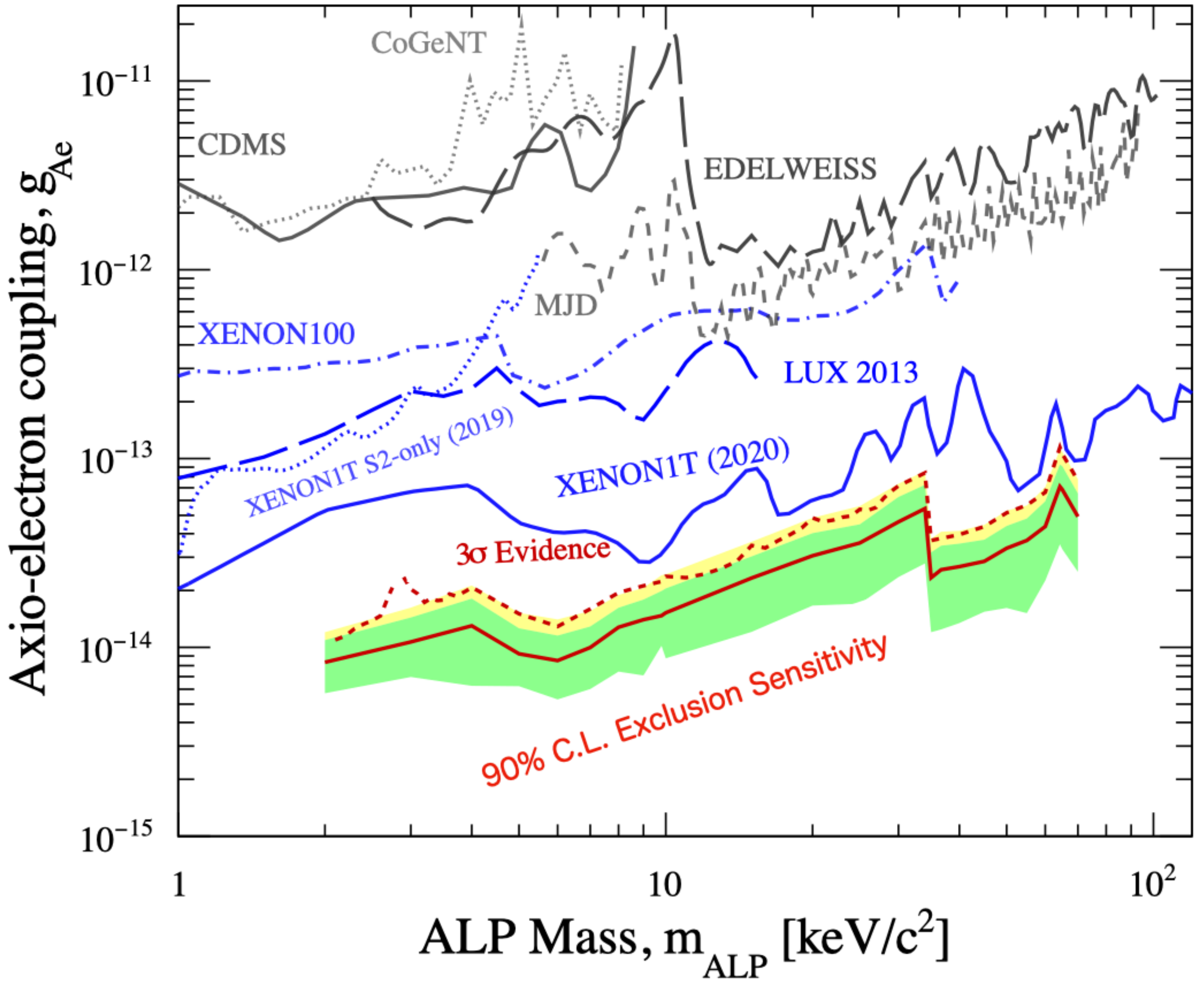
- Results demonstrate feasibility in future xenon DM experiments such as DARWIN

Low-Energy ER Excess





From LZ, Phys.Rev.D 104 092009



- ~ 8 times less Rn BG already achieved using Rn-distillation (13μBg/kg@1T → 1.7μBg/kg@nT)
- Shape differences between tritium and solar axion enables to distinguish both models with a few months of data.
- If no signals, XENONnT can improve the limits for solar-axion, ALPS, dark-photon, etc

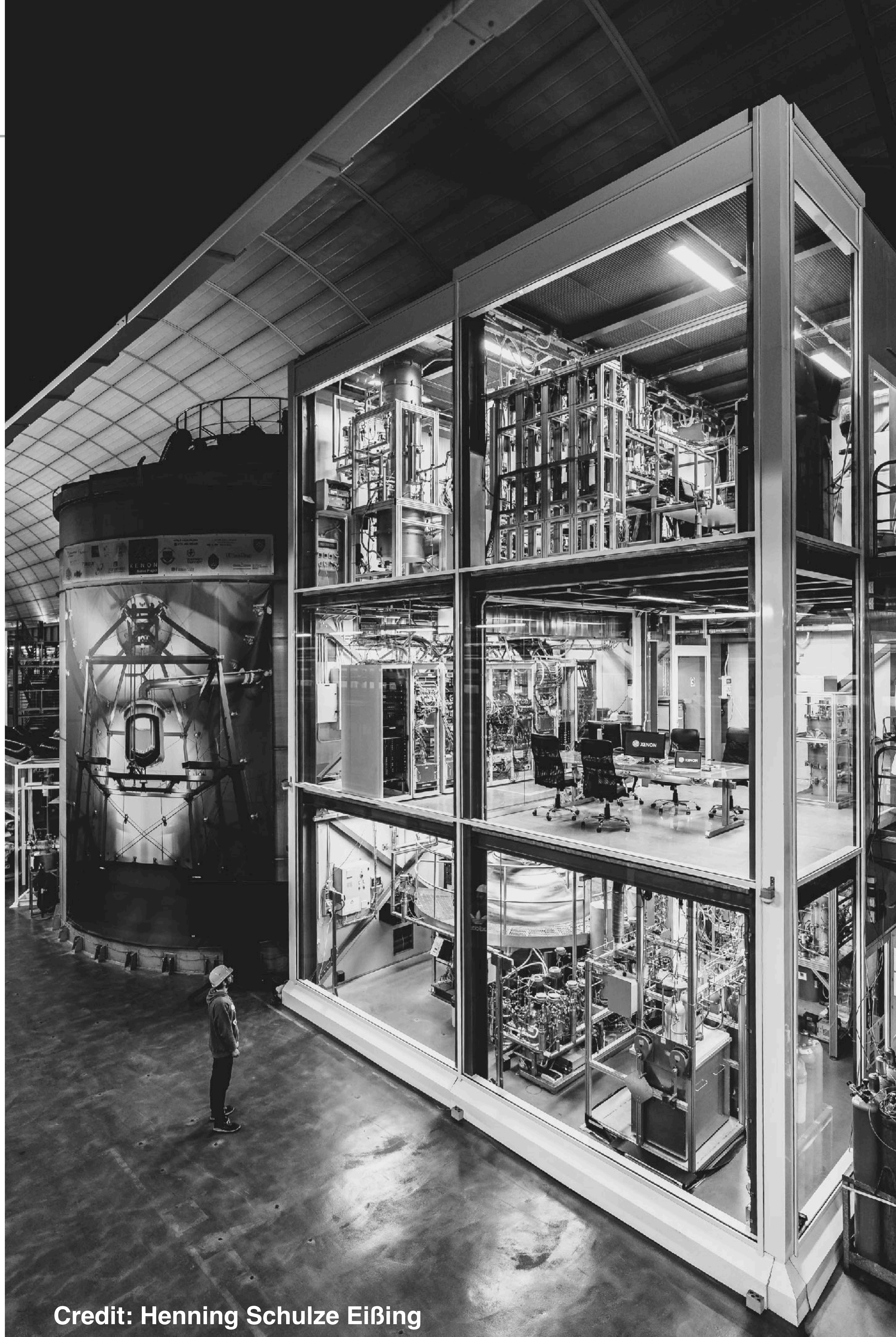
Summary

- XENON1T has set the strongest upper limit for WIMPs between 0.1 - 1000 GeV
- Dedicated S2-only/Single-electron analysis has been performed for low mass DM searches
- XENON1T observed an unexpected excess of low-energy ERs of unknown origin, which will be confirmed or excluded with the XENONnT
- XENONnT will improve on XENON1T with ~10% BG and 20 times more exposure.
- XENONnT is now taking science data. Please stay tuned!

www.xenonexperiment.org

instagram.com/xenon_experiment

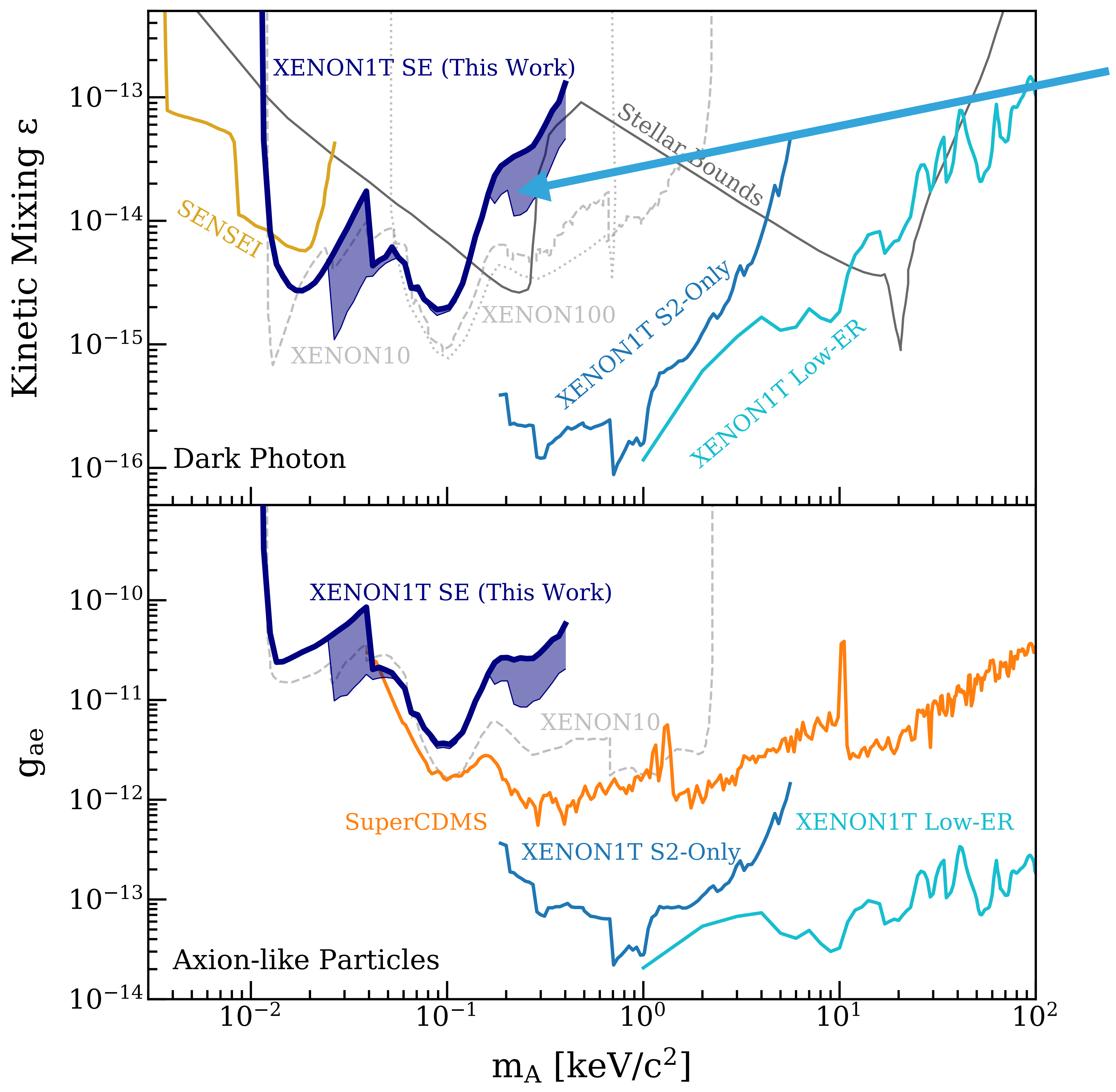
twitter.com/xenonexperiment



Credit: Henning Schulze Eißing

Back Up

XENON1T: Single-Electron Analysis

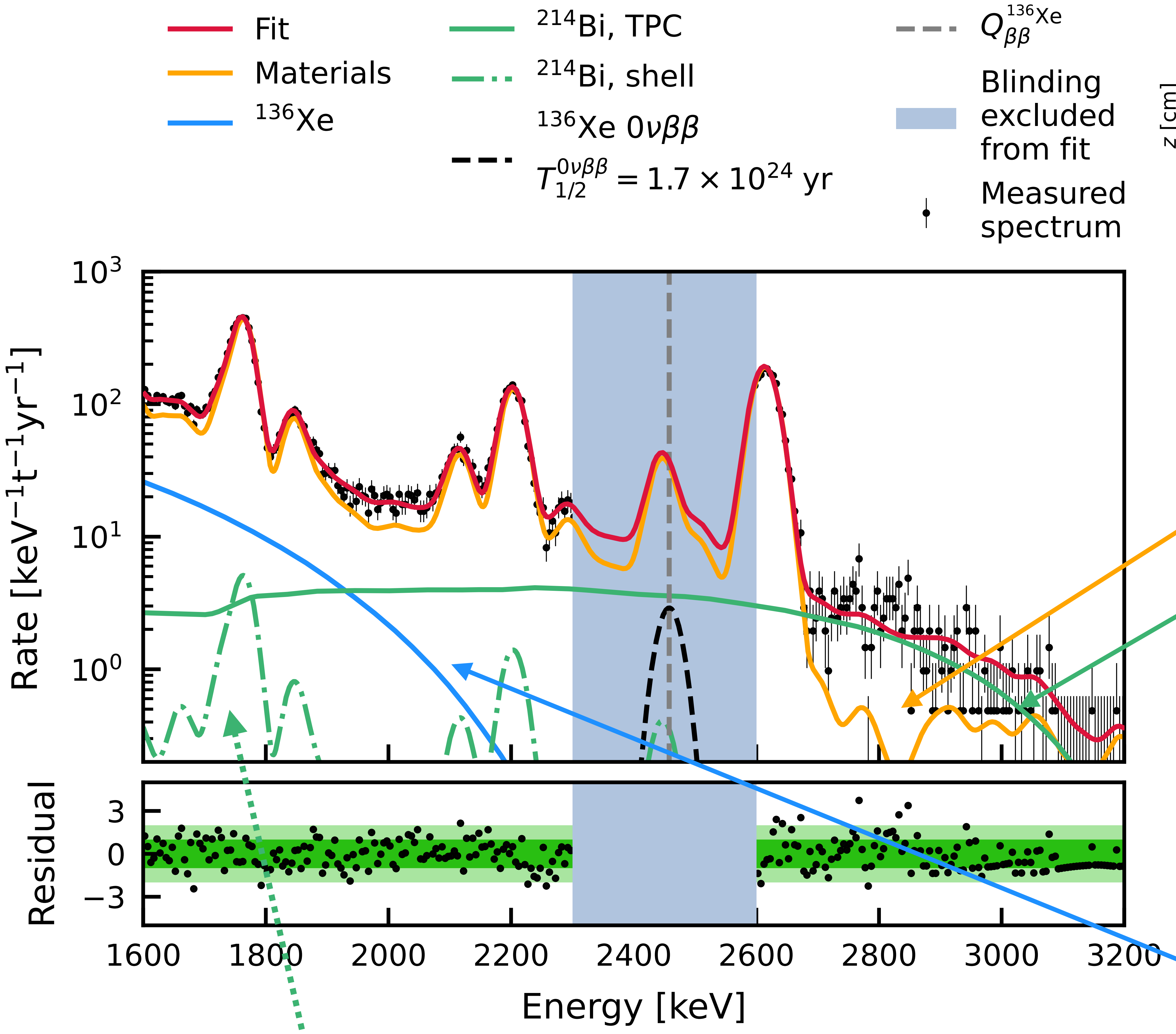


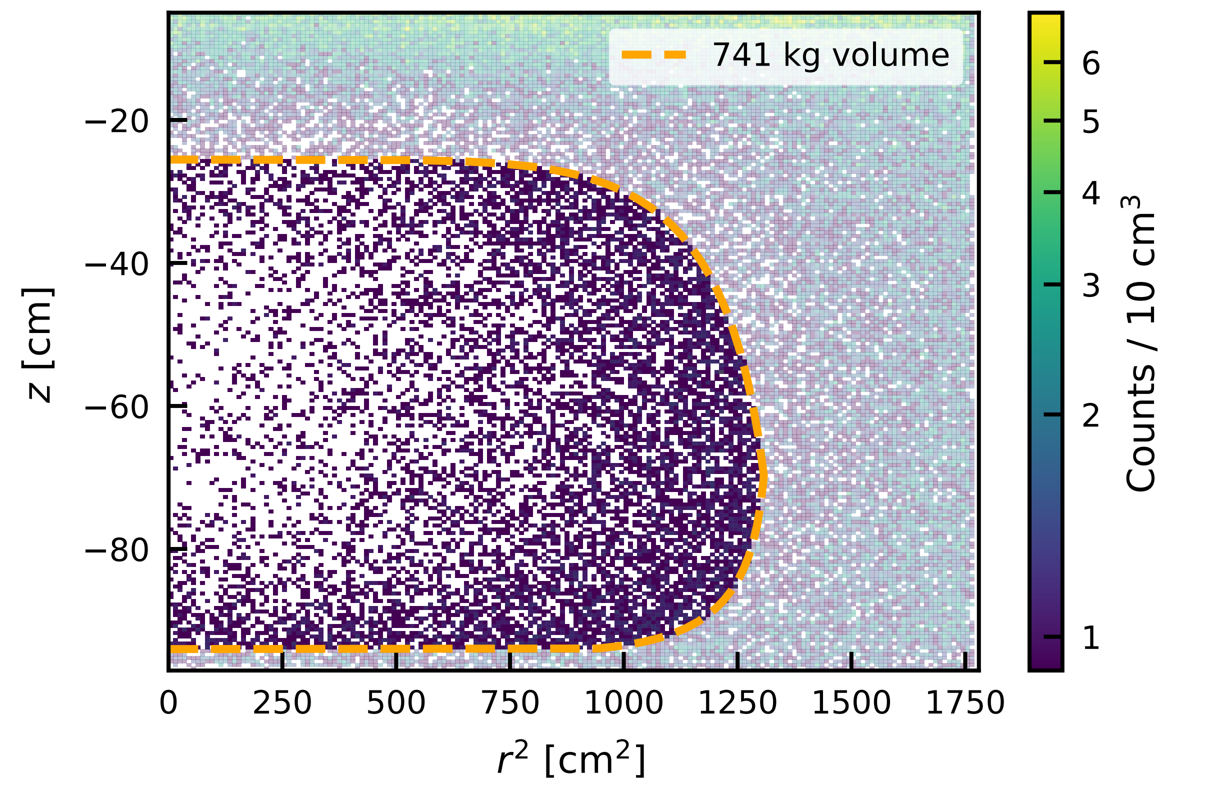
- Assuming ionized electrons are always produced from the lowest electron shell for which the mass of the DM particle exceeds the binding energy of that specific shell.
- unknown differential ionization rate of the various electron shells in xenon.
- the uncertainty between the two assumptions is covered as a blue shaded region

BG in Neutrinoless Double Beta Decay

- Science data blinded between 2300 and 2600 keV.
- 90.3 % of hypothetical 0νββ signals recorded as single-site events.
- Events with a single S1 + S2 pair in a 741 kg fiducial volume with optimal signal to background ratio.
- Sensitivity at 90 % CL:

$$T^{0\nu\beta\beta}_{1/2,\text{ expected}} > 1.7 \times 10^{24}\text{ yr}$$





Detector material γ-rays.

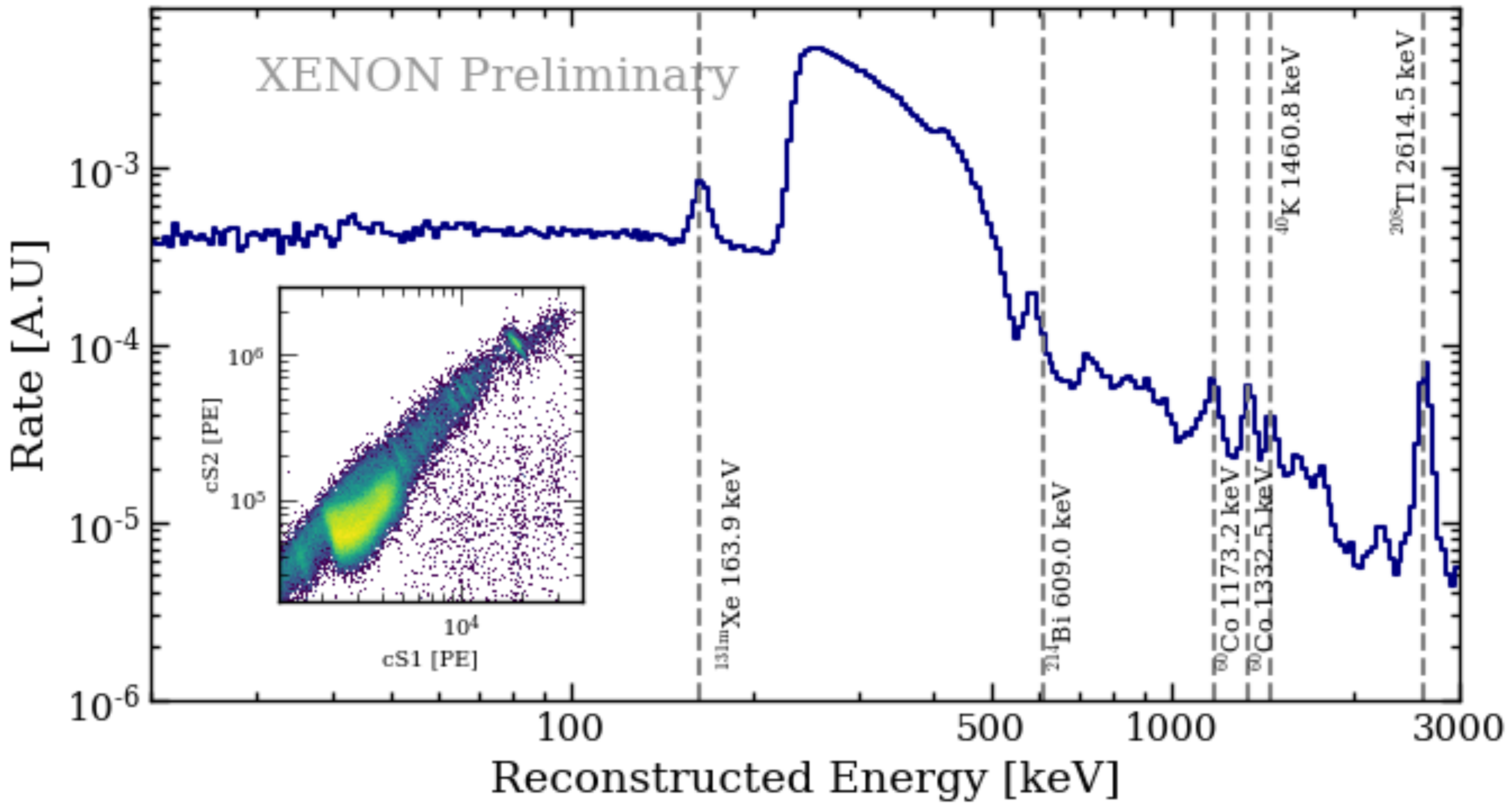
Merged γ + β signal from ^{214}Bi decay inside the active volume suppressed by ^{214}BiPo coincidence.

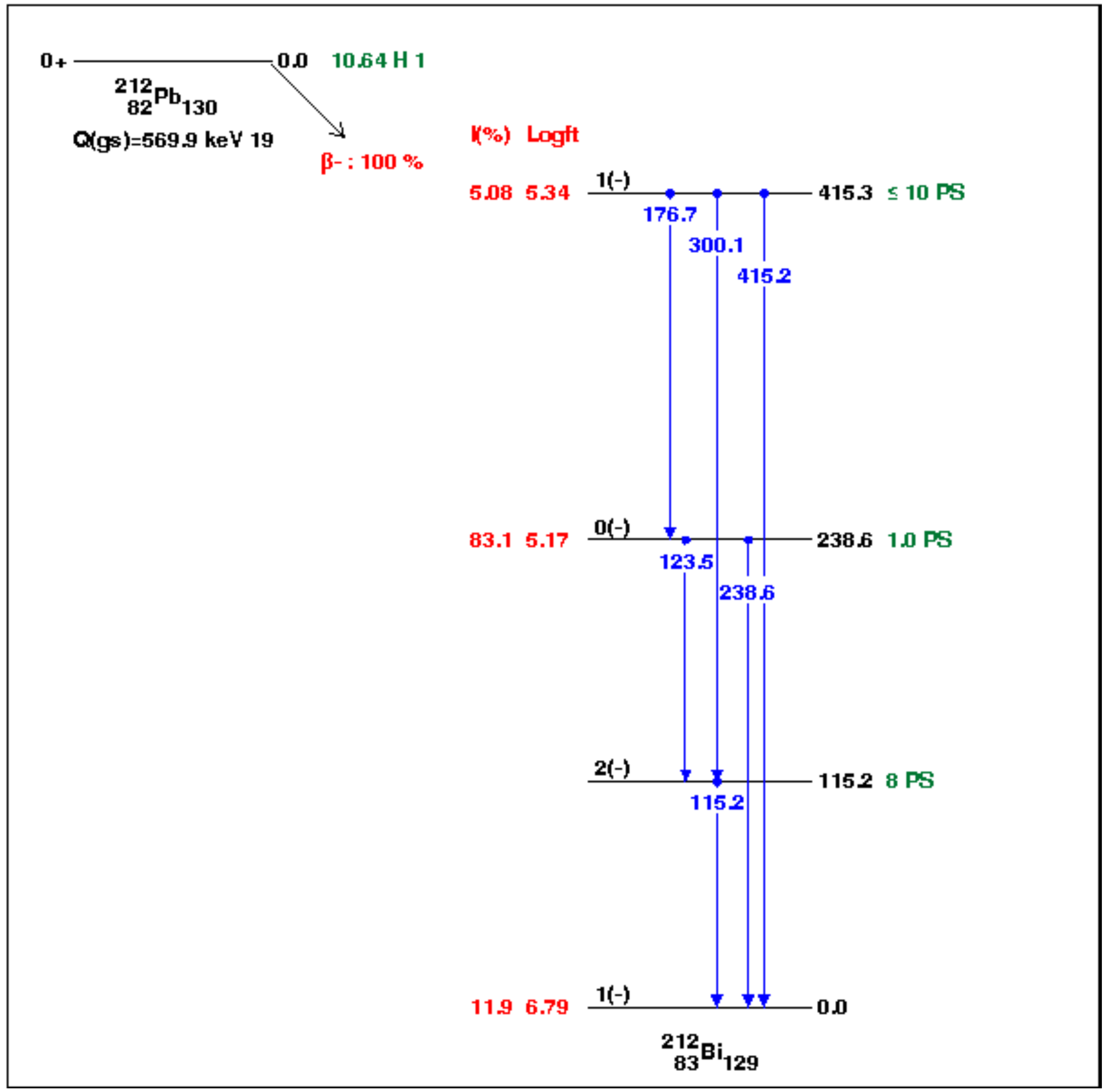
2νββ of ^{136}Xe subdominant.

Decay of ^{214}Bi outside the active volume leads to additional γ-ray background.

XENONnT Experiment: Calibration

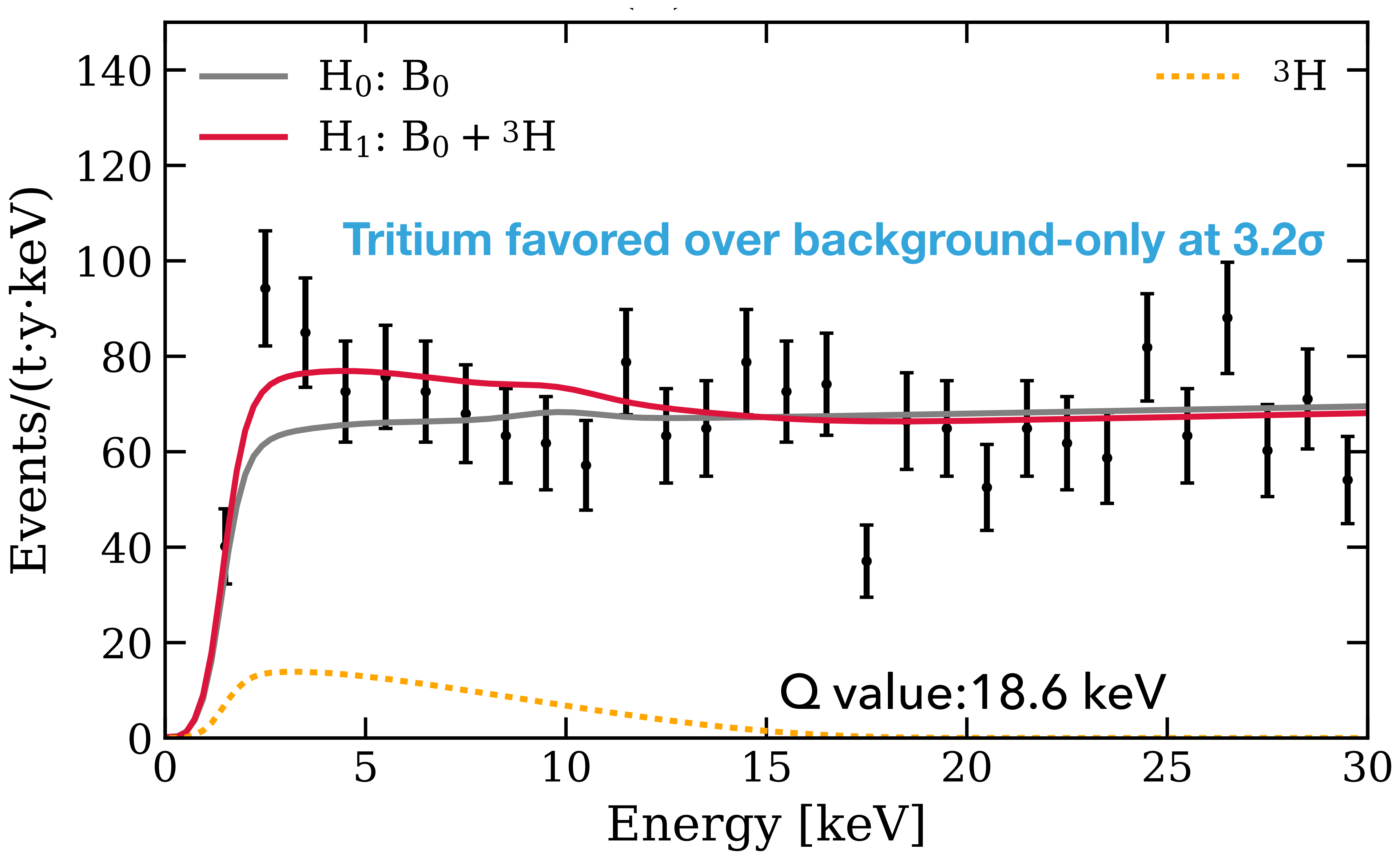
^{220}Rn calibration

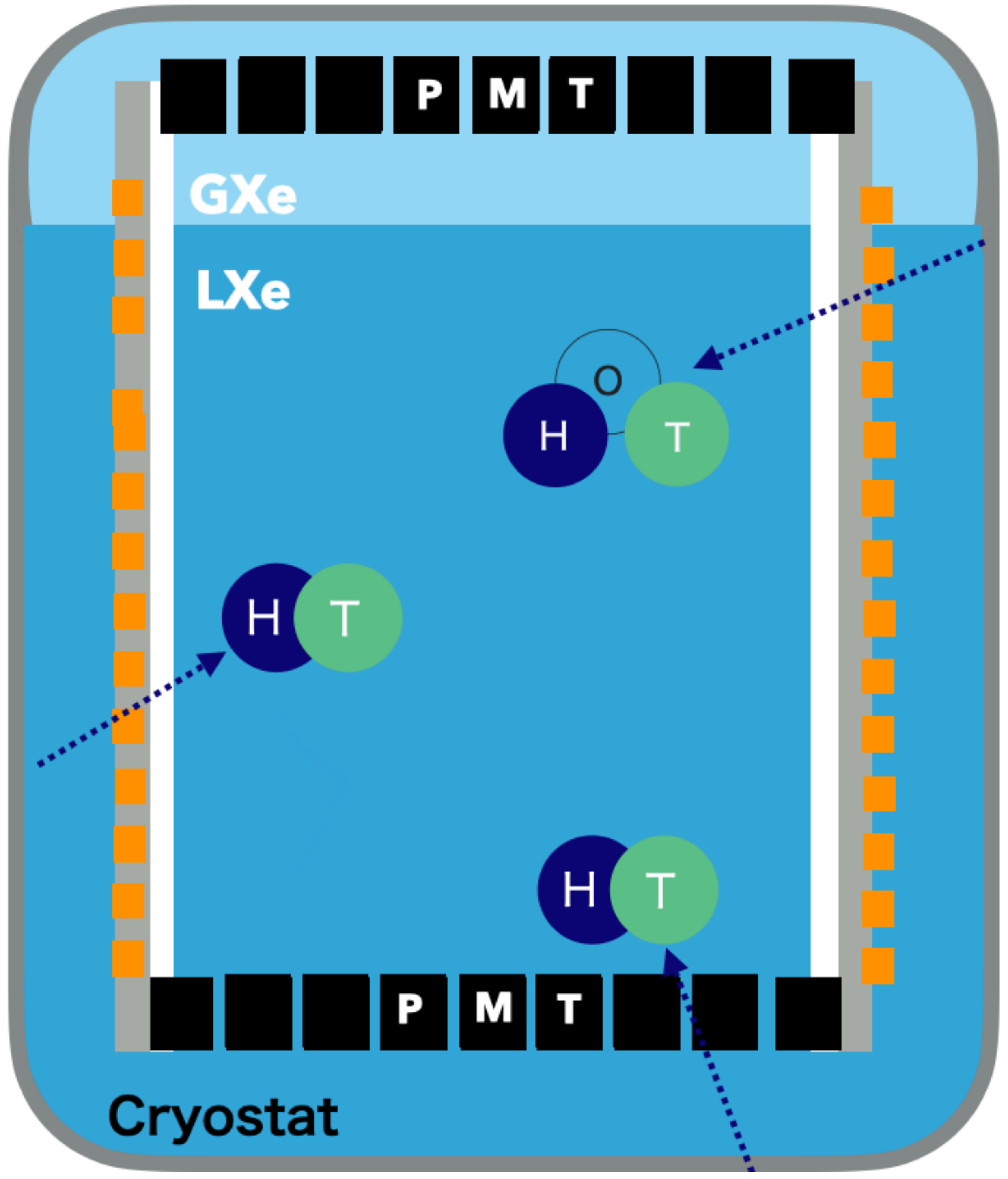




Along the beta decay of 212Pb, gamma ray with energy of 238 keV are likely to be accompanied with a branching ratio of 83%.

Unexpected Background? Tritium?

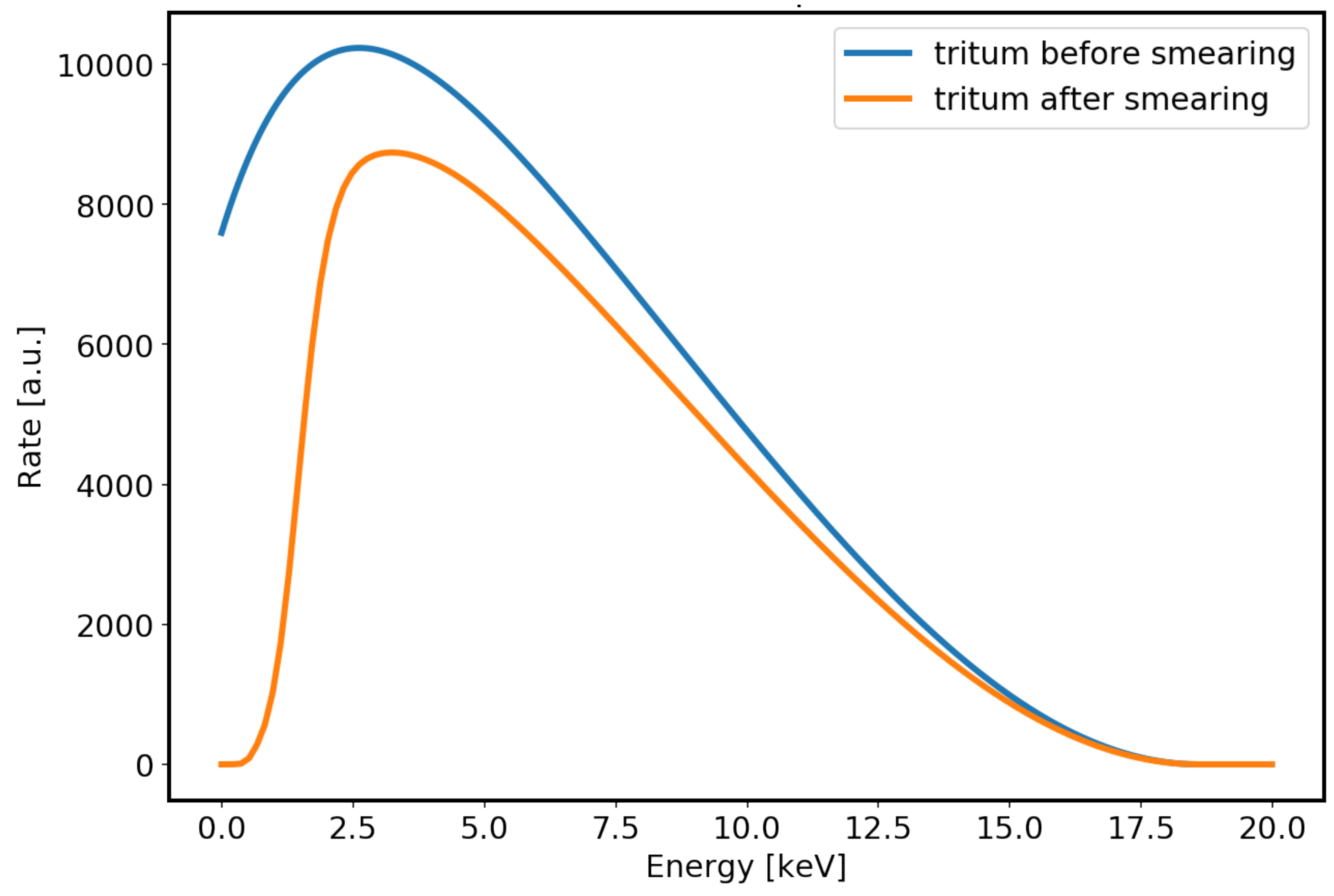


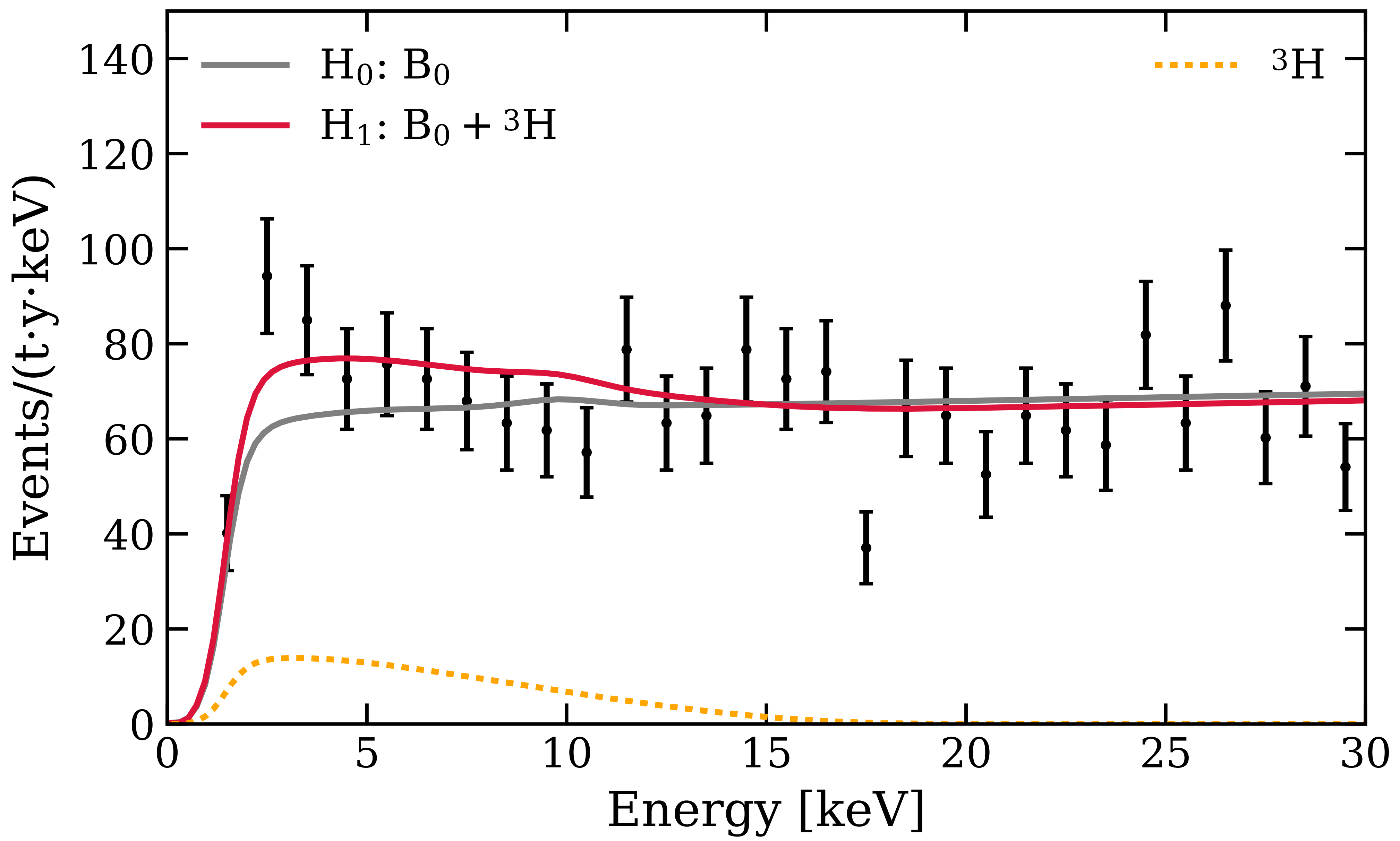


- Production by cosmogenic activation of Xenon: not-likely
- Atmospheric abundance in Materials: cannot exclude because no direct constraint on H2 outgassing
- half-life = 12.3 y, ~constant in our dataset
- from fit: less than 3 tritium atoms per kg of Xe (3H: Xe concentration = $6.2 \pm 2.0 \times 10^{-25}$ mol/mol)

we can neither confirm nor exclude the Tritium hypothesis at this point: need XENONnT!

Testing Tritium Hypothesis





Tritium favored over background-only at 3.2σ

Best-fit tritium rate:

$$159 \pm 51 \text{ events}/(\text{t} \cdot \text{y} \cdot \text{keV})$$

^{3}H half-life 12.3 years (too long to observe in SR1)

^{3}H:Xe concentration:

$$6.2 \pm 2.0 \times 10^{-25} \text{ mol/mol}$$

fewer than 3 tritium atoms per kg of xenon!

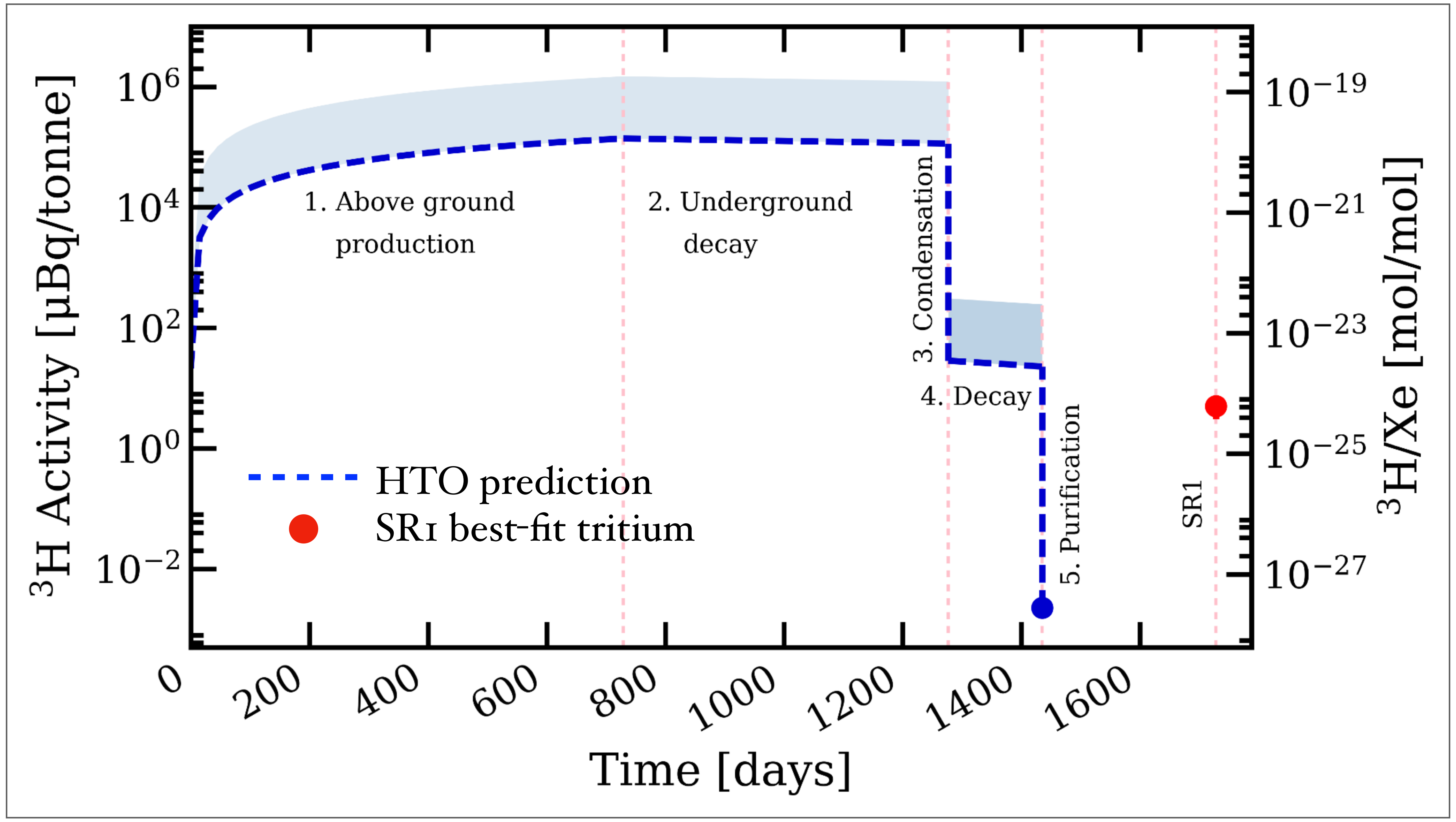
1. Cosmic Activation of Xenon

Cosmogenic activation of xenon: ~32 tritium atoms/kg/day (Zhang, 2016)

1 ppm water in bottles implies tritium forms predominately HTO.

Efficient removal (99.99%) in purification system (SAES getter with hydrogen removal unit)

Tritiated water (HTO)



(note: tritium from activation While underground is negligible.)

Expected concentration more than 100x smaller than measured → From purification and handling, this component seems unlikely.

2. Atmospheric Abundance in Materials

What about T emanating from materials in equilibrium with removal?

*Hydrology measurements from IAEA nuclear database

HTO:H_2O concentration*	$5\text{–}10 \times 10^{-18}$ mol/mol
HT:H_2 concentration →	**Assuming same concentration as for H20**

Required (H_2O + H_2):Xe concentration to explain	**60–120 ppb**

Tritiated molecules can emanate into LXe target from water and hydrogen in detector materials in the form of **HTO** and tritiated hydrogen (**HT**). emanation in equilibrium with removal.

But…

H20

H2O in XENON1T: O(1) ppb, otherwise can not detect light

H2

O2 in XENON1T: <1ppb, otherwise can not drift electrons

H2 ~100 ppb? -> ~100x higher than O2 possible?

Summary of Tritium Hypothesis

Many unknowns about tritium in a cryogenic LXe environment

- Radiochemistry, particularly isotopic exchange (formation of other molecules?)
- Diffusion properties of tritiated molecules
- Desorption and emanation
- For HT, no direct measure of either abundance or H2 concentration.

We can neither confirm nor exclude the presence of tritium.

- We consider it a hypothesis, but don't include it in the background model.
- Report additional results (but not constraints on signal parameters) with tritium included as a background component.