Search for solar ^{8}B neutrinos with XENONnT

TAUP 2023

Vienna | August 28 – September 1 2023

Christian Wittweg on behalf of the
XENON Collaboration

The XENON collaboration

Columbia | KIT | Nikhef | Muenster | Stockholm | Mainz | MPIK, Heidelberg | Freiburg | Zurich

Chicago

UCSD

Rice

Purdue

Tsinghua

Tokyo

Nagoya

Kobe

Subatech | Coimbra | LPNHE | Torino | Bologna | L'Aquila | LNGS | Napoli | Weizmann | NYUAD

The XENON collaboration

Columbia | KIT | Nikhef | Muenster | Stockholm | Mainz | MPIK, Heidelberg | Freiburg | Zurich

Chicago

UCSD

Rice

Purdue

XENON

170 scientists,
27 institutions,
12 countries.

Tsinghua

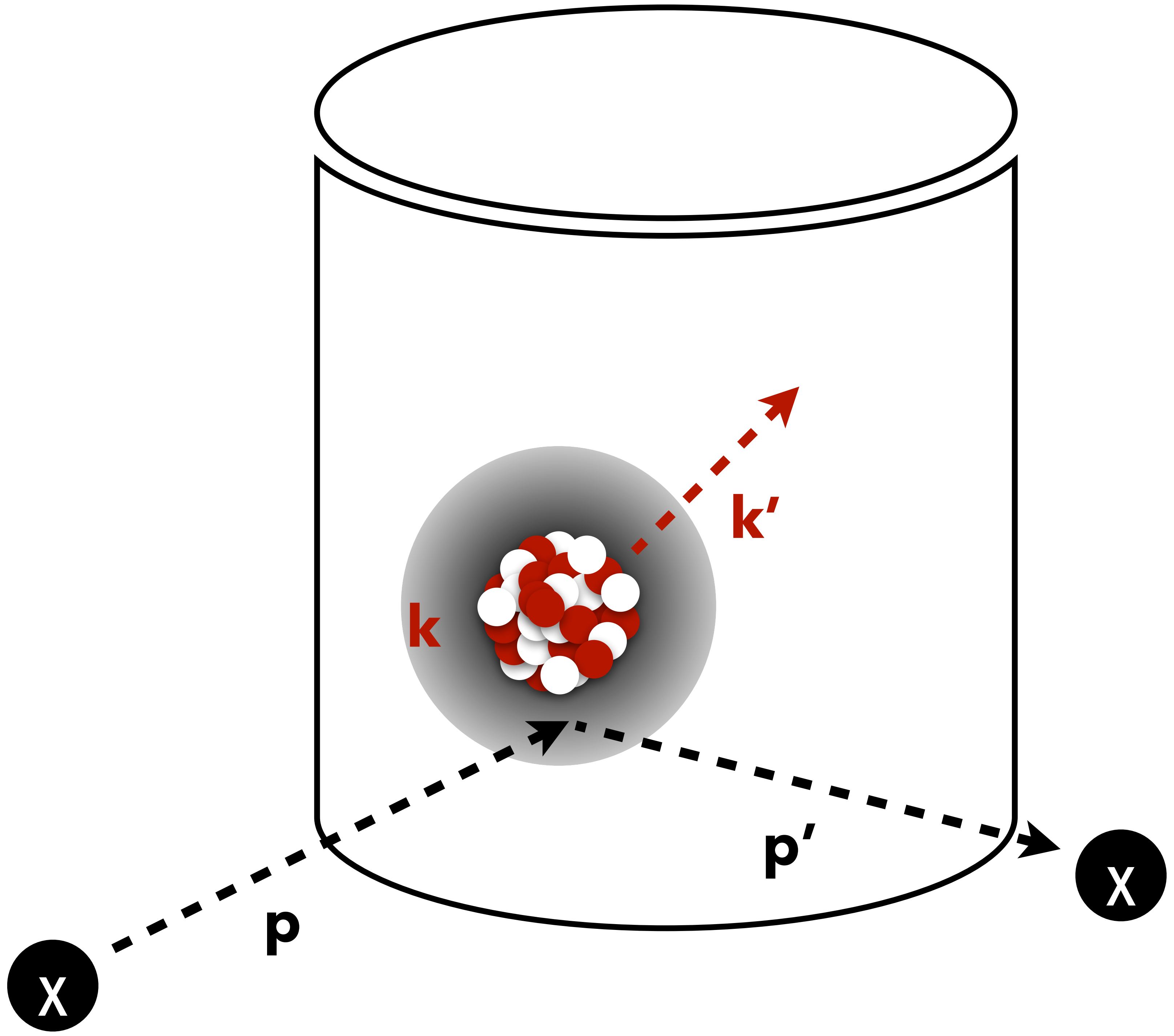
Tokyo

Nagoya

Kobe

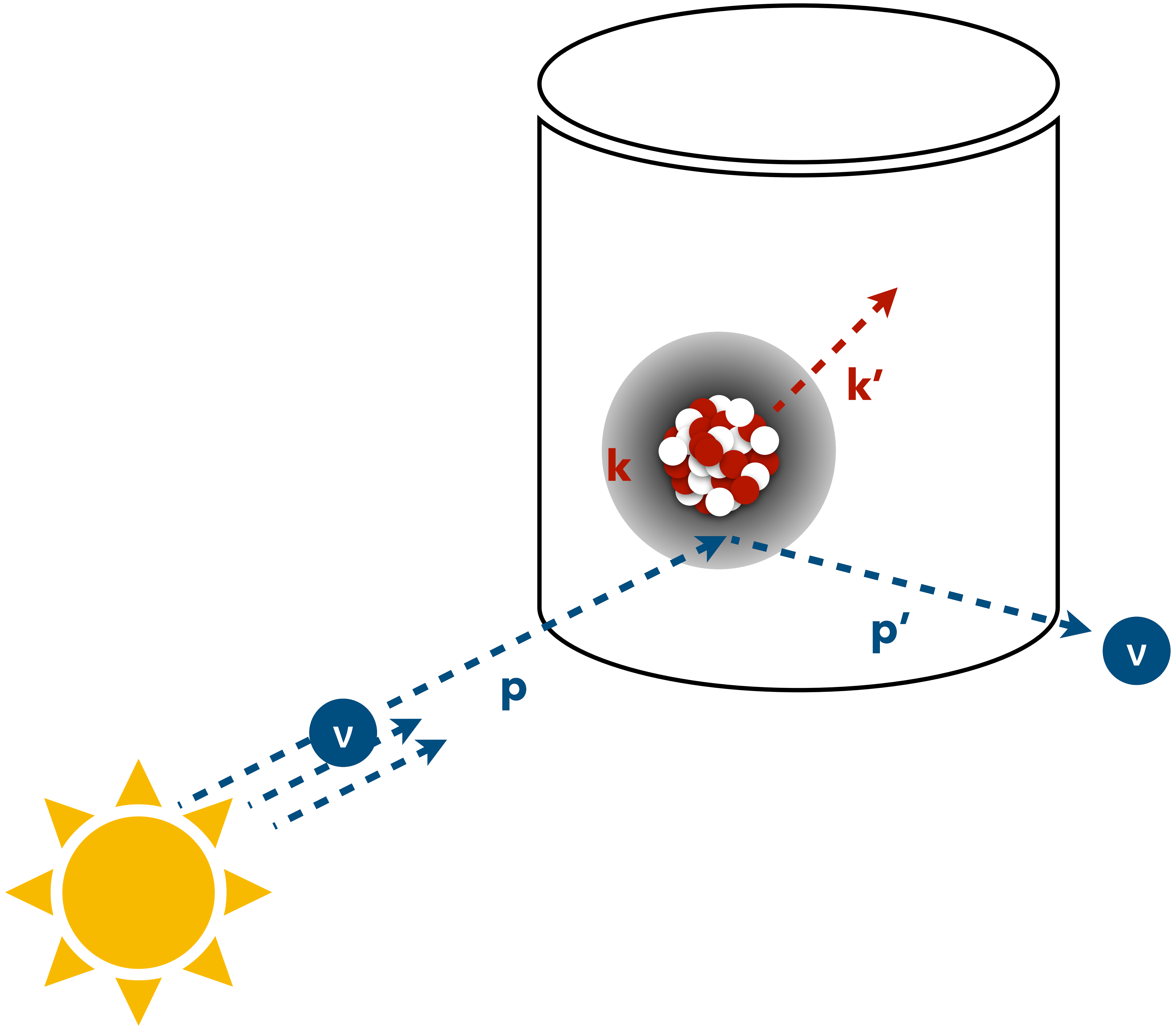
Subatech | Coimbra | LPNHE | Torino | Bologna | L'Aquila | LNGS | Napoli | Weizmann | NYUAD

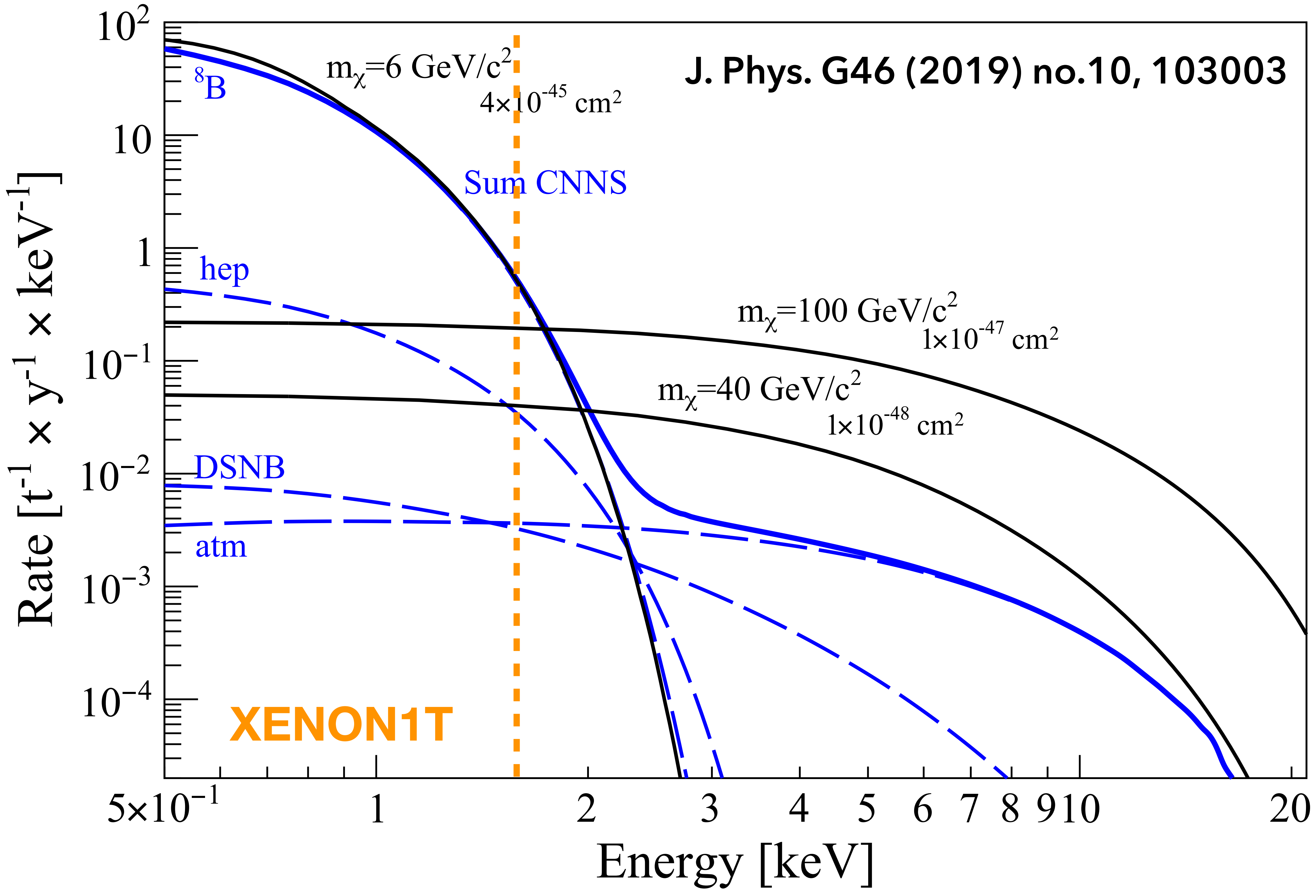
Direct dark matter detection and neutrinos



Detect WIMPs **directly** by measuring the **O(1) keV nuclear recoil** after scattering in a **large, low background, low threshold detector.**

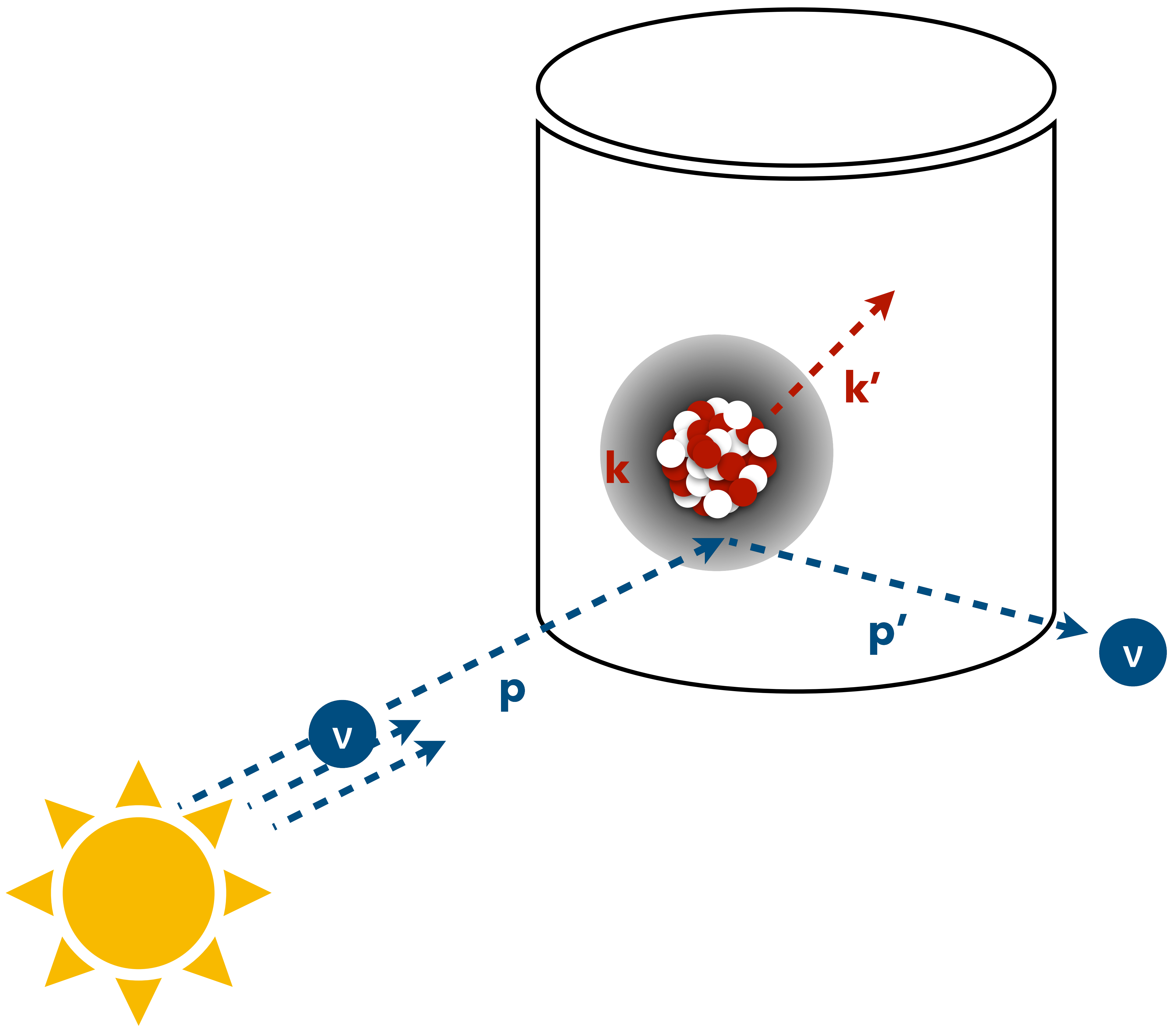
Direct dark matter detection and neutrinos



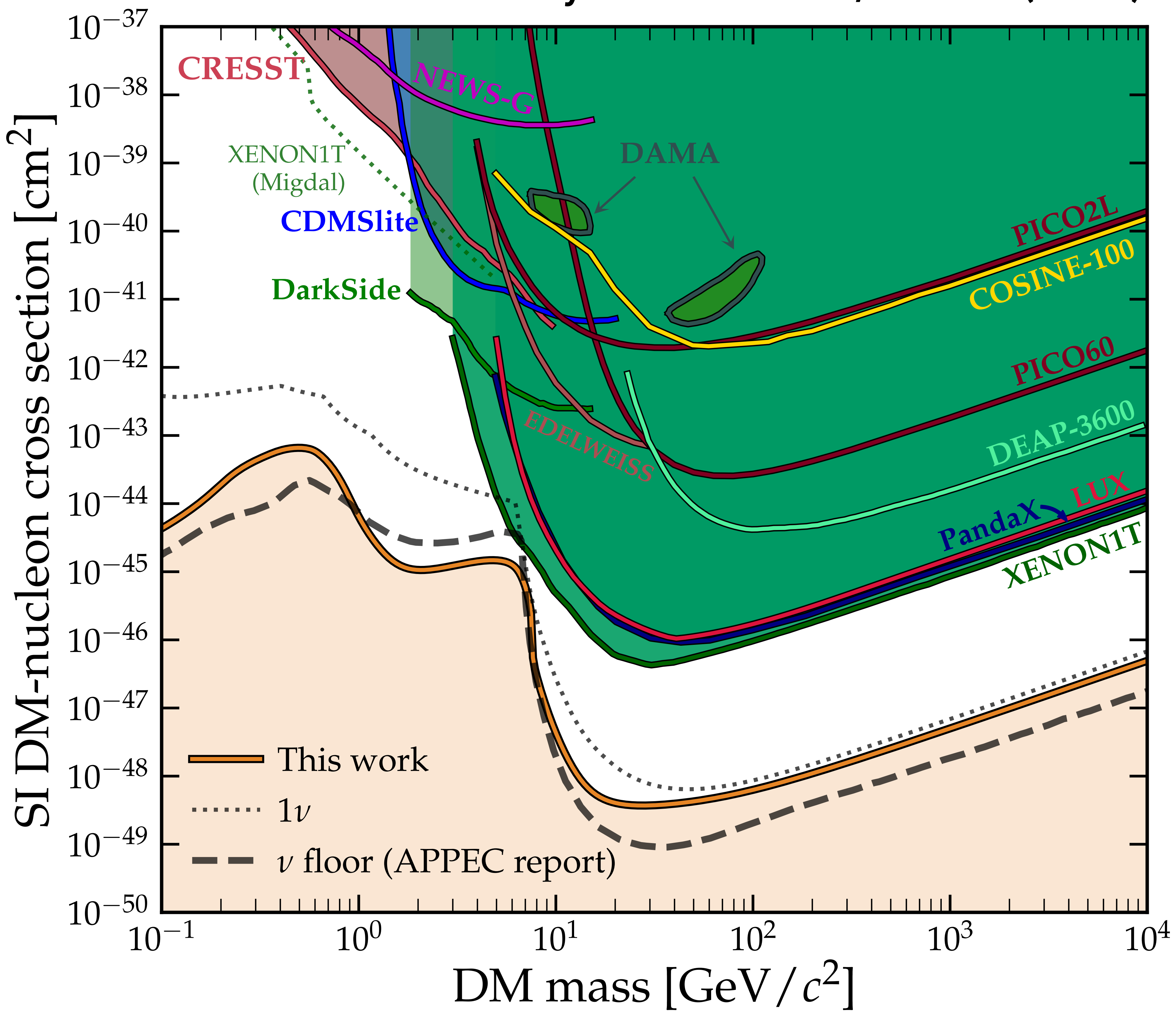


Coherent elastic neutrino nucleus scattering (CEvNS) of solar ^{8}B neutrinos mimics ~ 6 GeV/c^2 WIMPs!

Direct dark matter detection and neutrinos

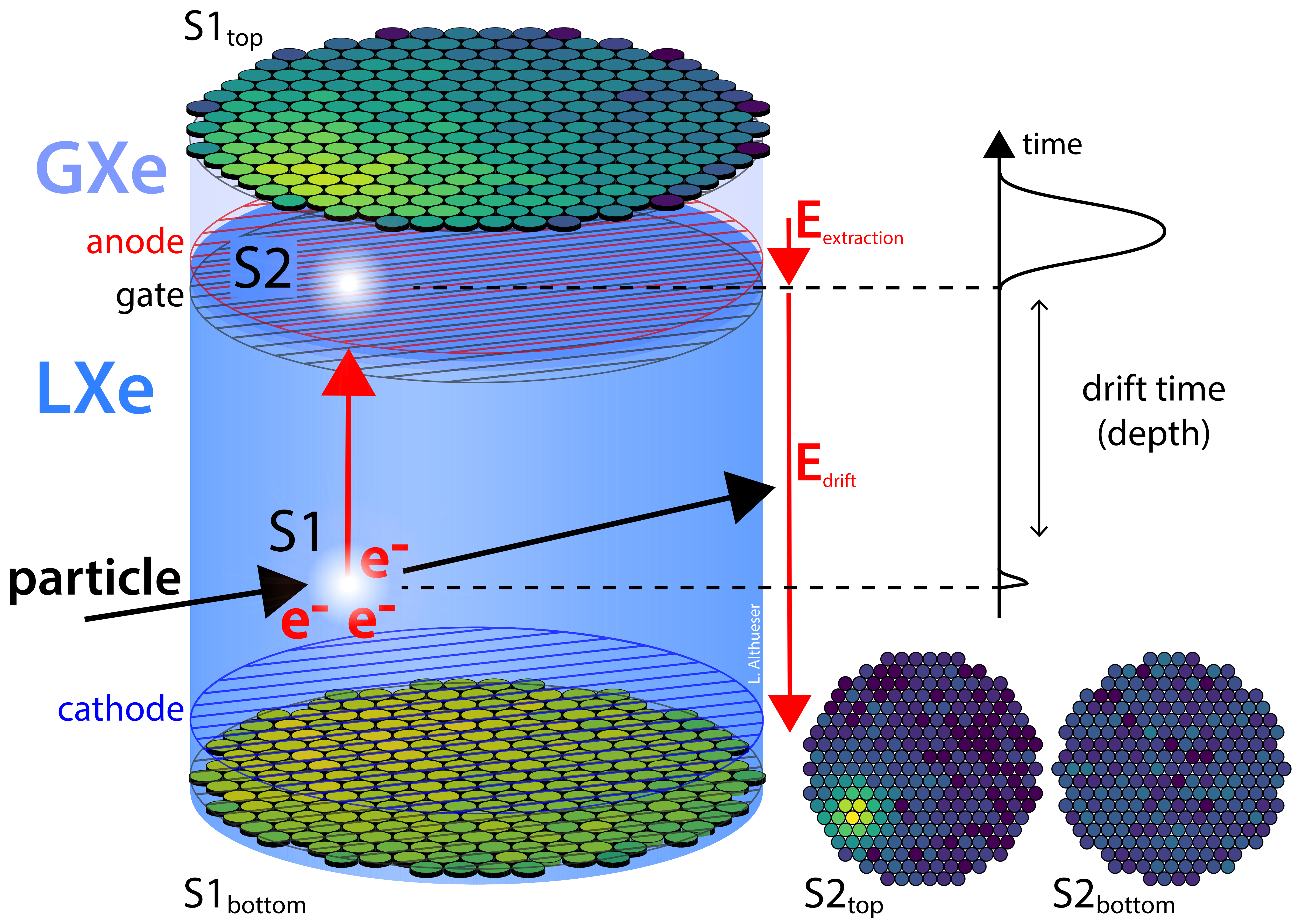


Phys. Rev. Lett. 127, 251802 (2021)



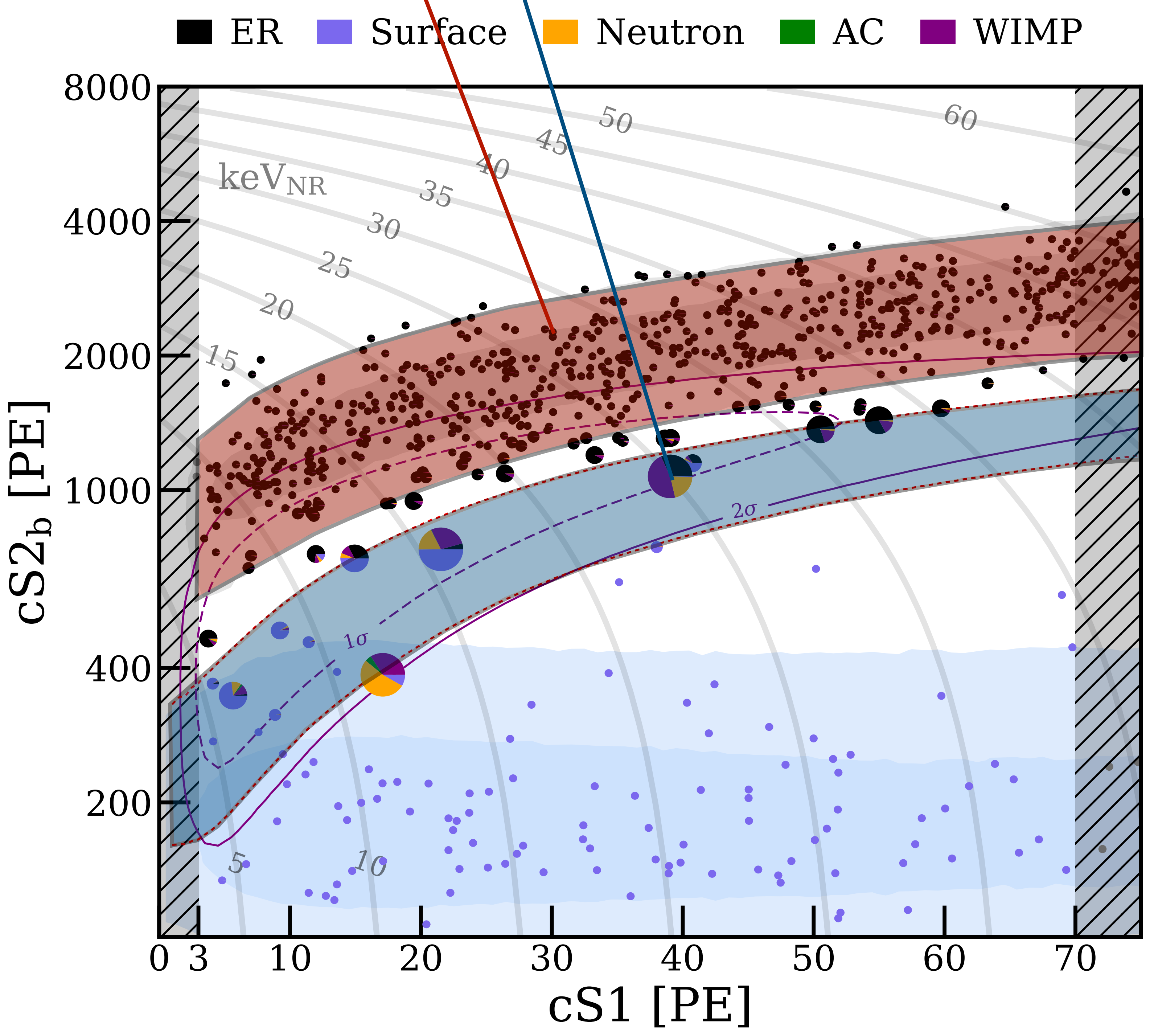
But these are not only a background! They are also a signal!

Dual-phase time projection chamber



Scintillation and **ionization**:

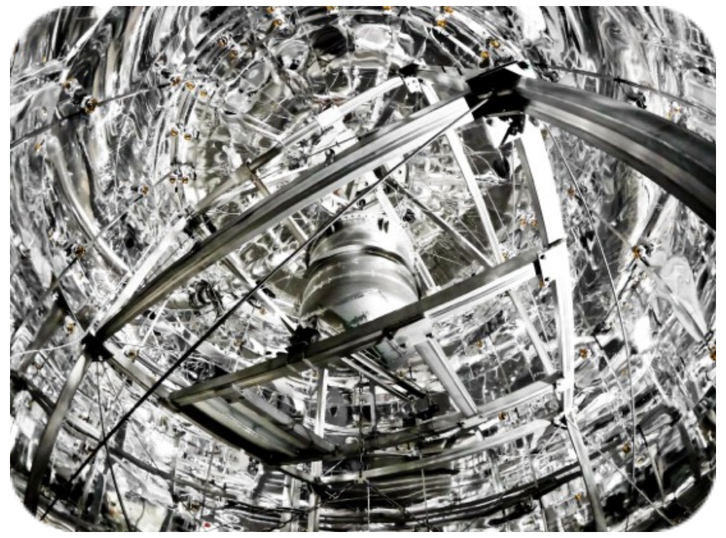
- Prompt light signal (**S1**)
- Secondary light in GXe from drifted charges (**S2**)
- Position reconstruction (**x, y, z**), calorimetry (**E**) and interaction type (**ER**/**NR**)



XENON1T at LNGS (2016 – 2018)

1500 m overburden
(3600 m.w.e.)

TPC

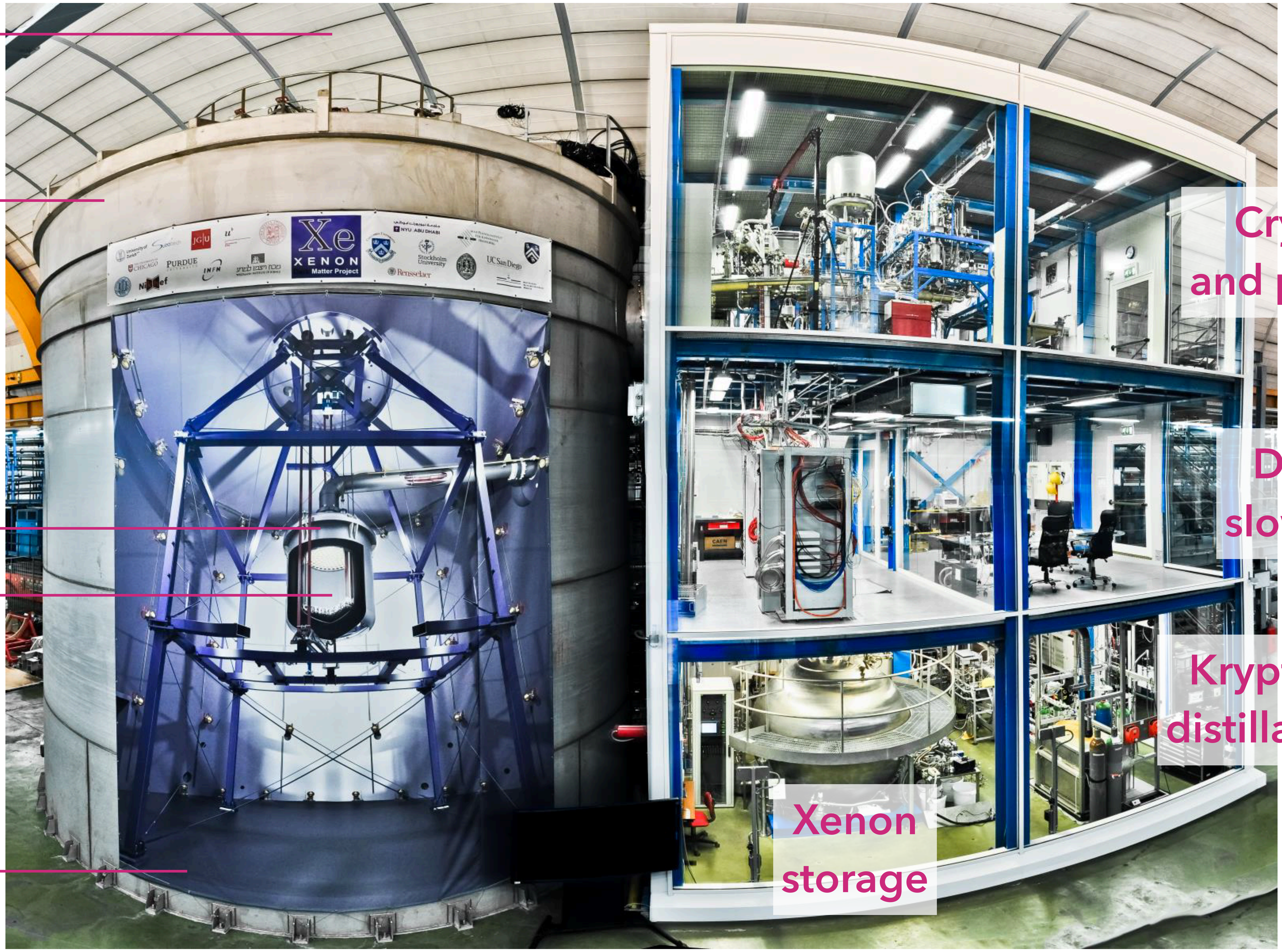


84
8″ PMTs as water
Cherenkov muon
veto

LNGS hall B

700 t
demi-water

Cryostat

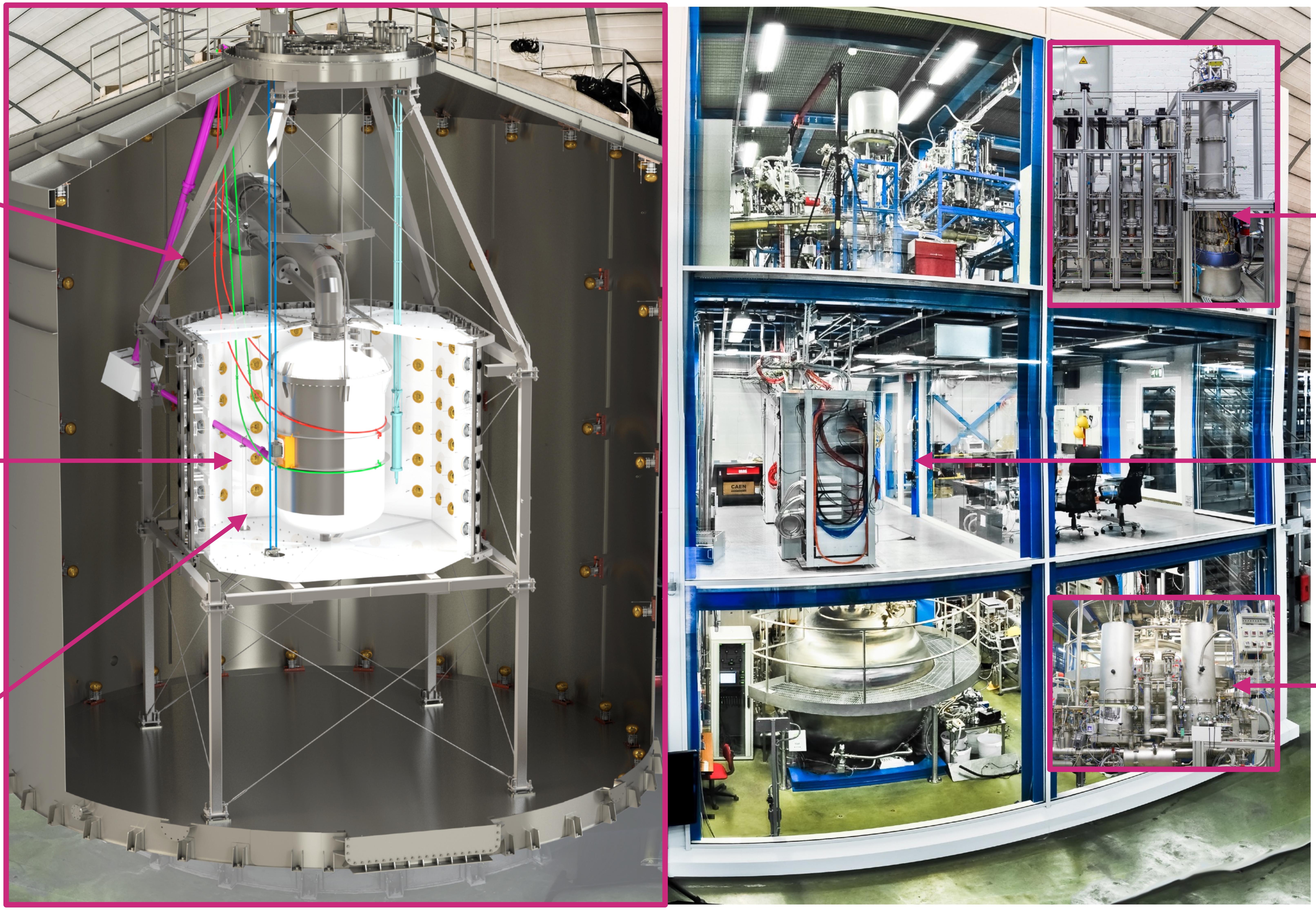


XENONnT at LNGS (now)

New ER and NR calibration systems

Larger TPC with 3x active volume

Gd-loaded (planned) water Cherenkov neutron veto



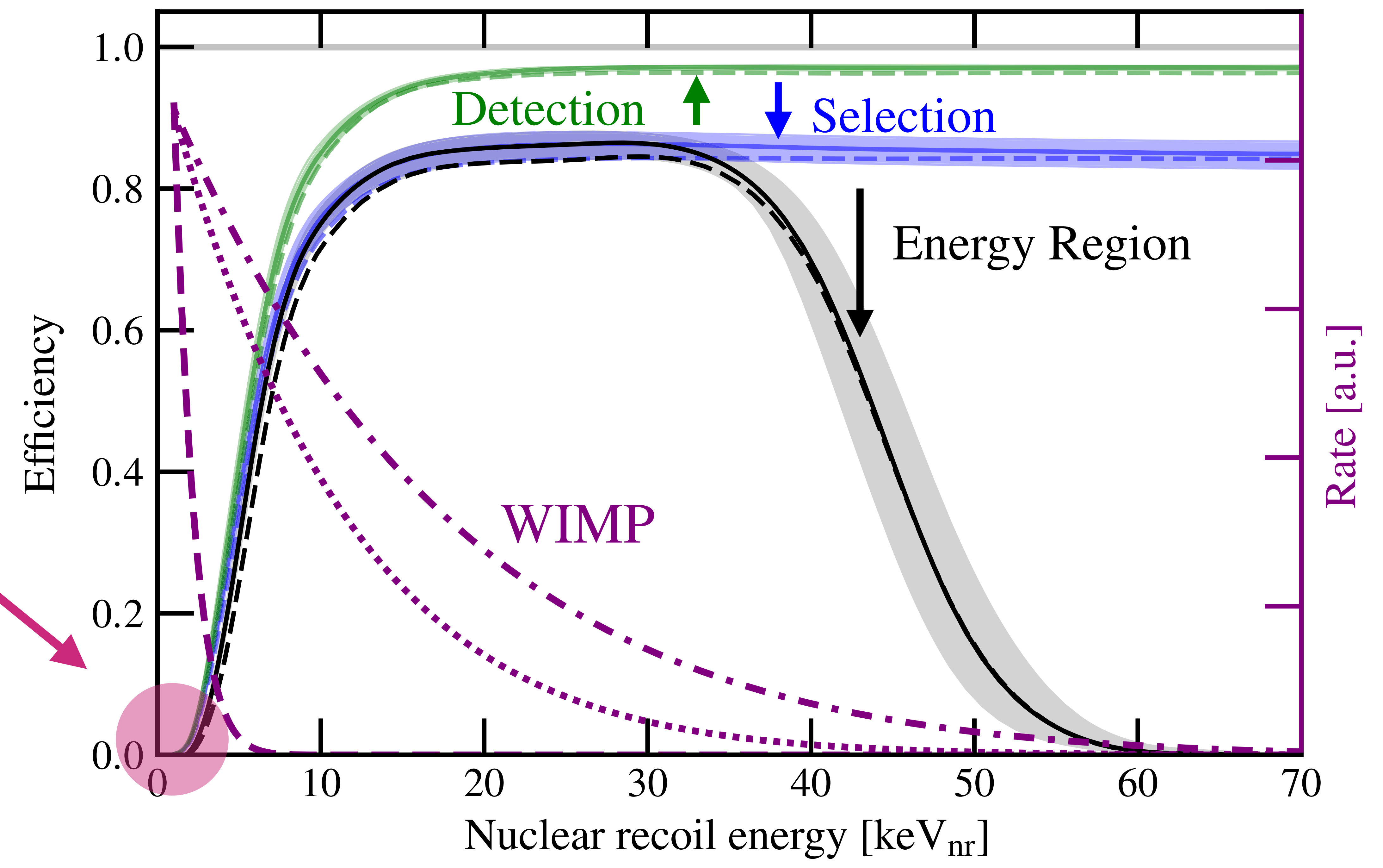
Radon distillation column

Upgraded DAQ with high-energy readout

Liquid xenon purification

Solar neutrinos in XENON1T WIMP results

Mass (ton)	1.3
ER	627 ± 18
Neutron	1.43 ± 0.66
CEνNS	0.05 ± 0.01
AC	$0.47^{+0.27}_{-0.00}$
Surface	106 ± 8
Total BG	735 ± 20
WIMP$_{\text{best-fit}}$	3.56
Data	739



Phys. Rev. Lett. 131 (2023) 041003

- We expect hundreds of events from $$R = \phi_\nu \cdot \sigma_\nu \cdot N_{\text{Xe}} \cdot \text{exposure}$$
- We do not see them because the WIMP analysis only has 0.01 % detection efficiency.

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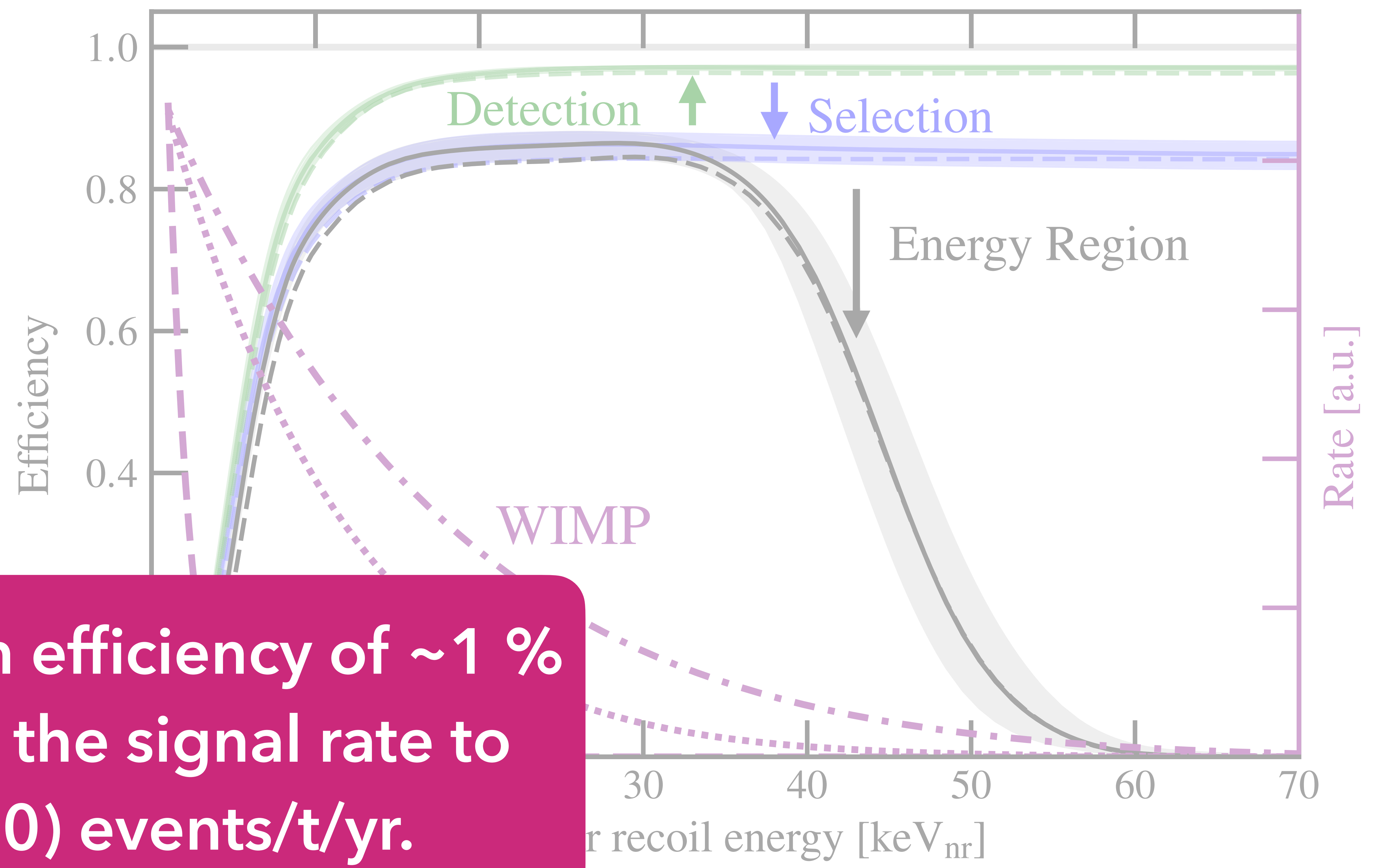

A detection efficiency of ~1 % increases the signal rate to O(1–10) events/t/yr.

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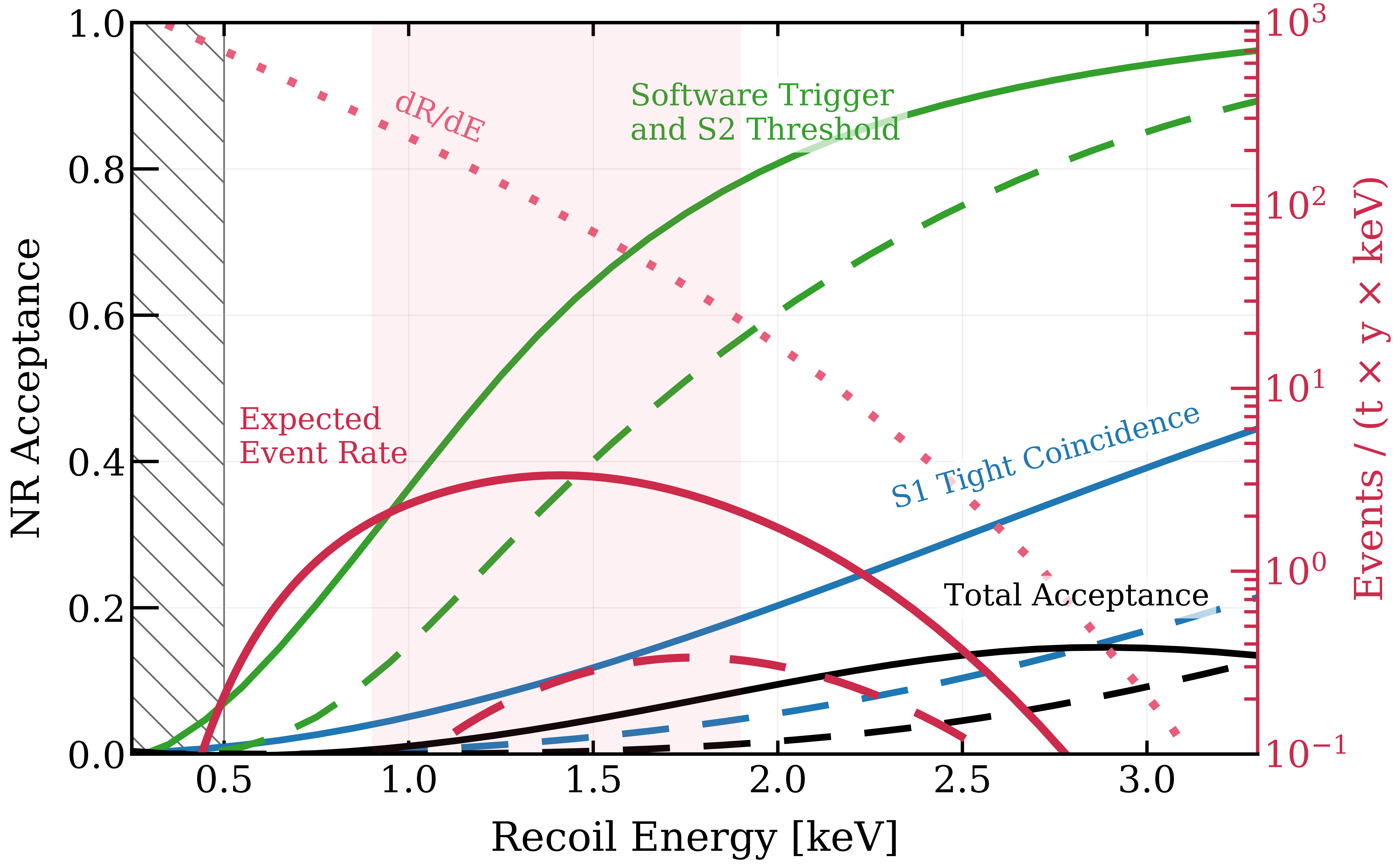
Lowering the energy threshold

- Lower threshold increases **expected event rate to 2.11 events in 0.6 t × yr**
- Detection efficiencies driven by
  - **S2 software trigger threshold**: 200 → 120 PE
  - **S1 tight coincidence**: 3 → 2 PMTs

Phys. Rev. Lett. 126 (2021) 091301



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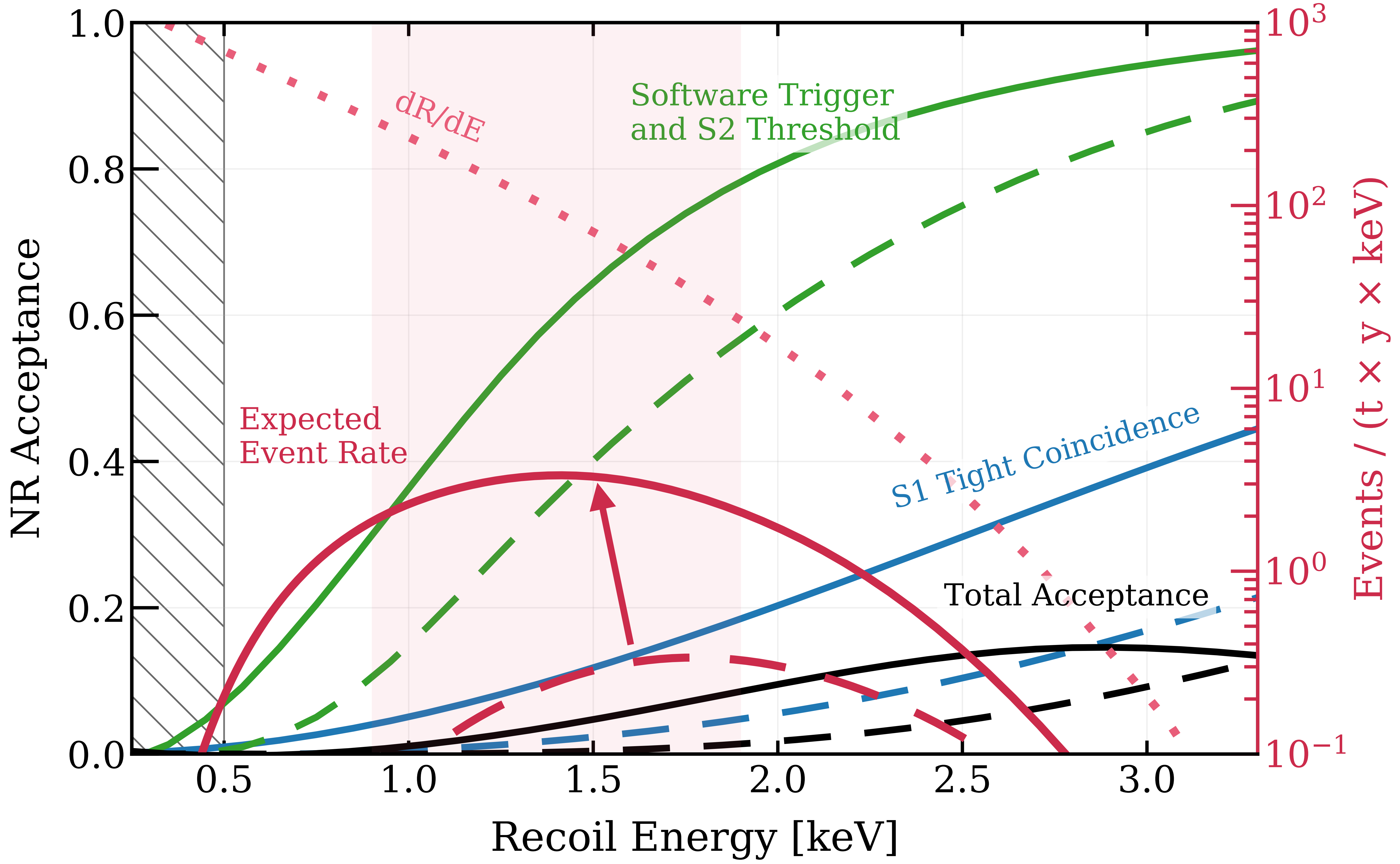

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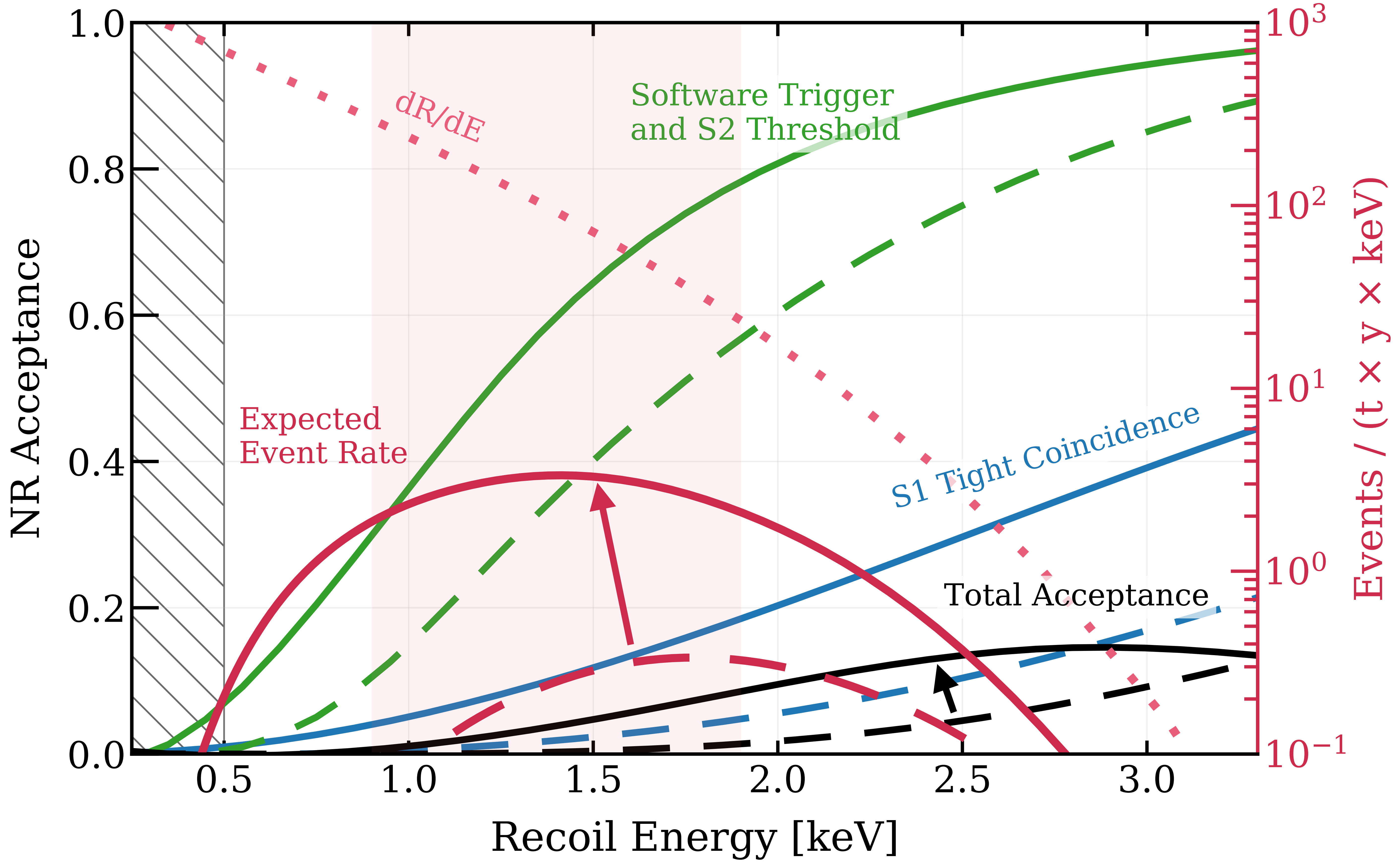

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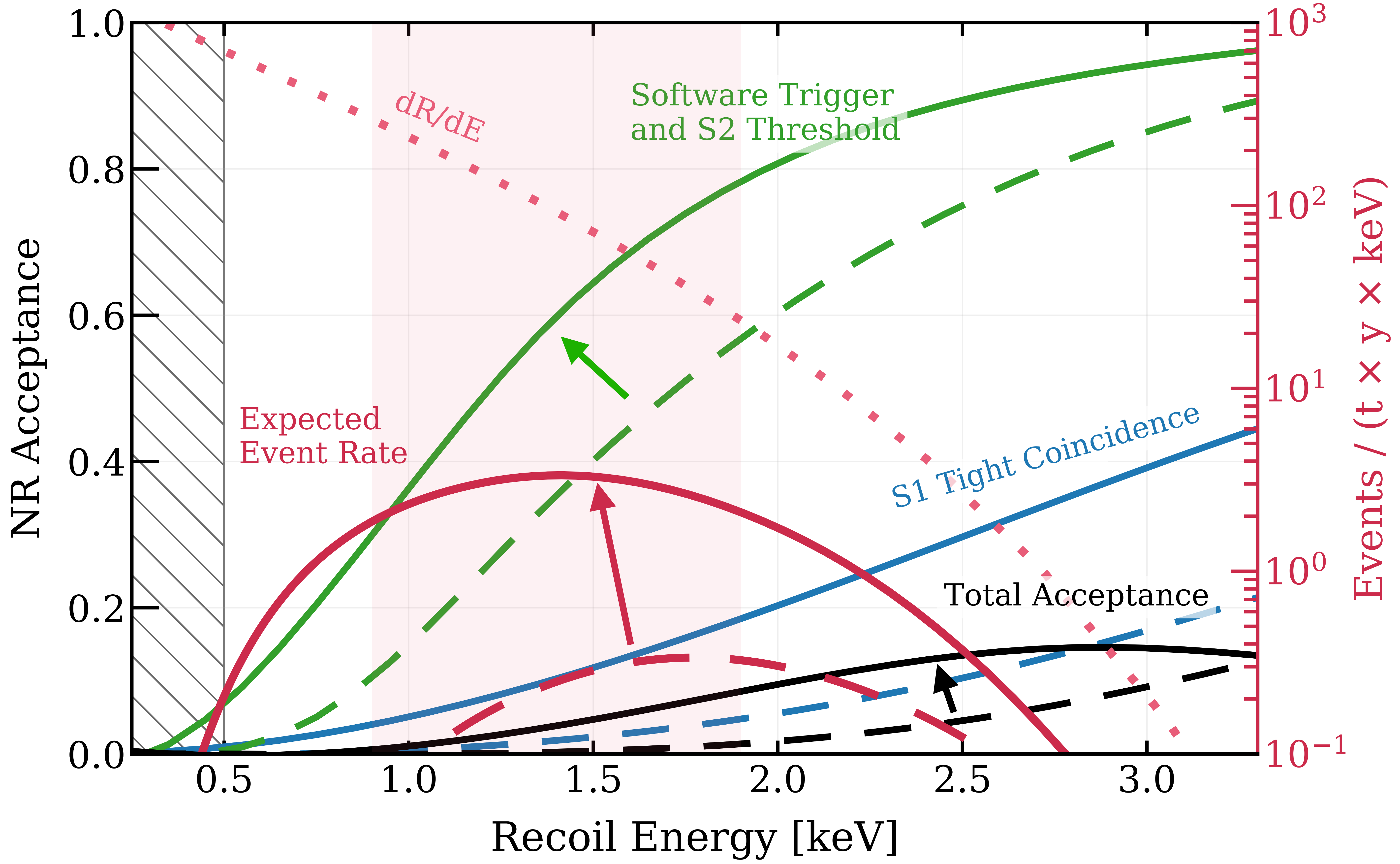

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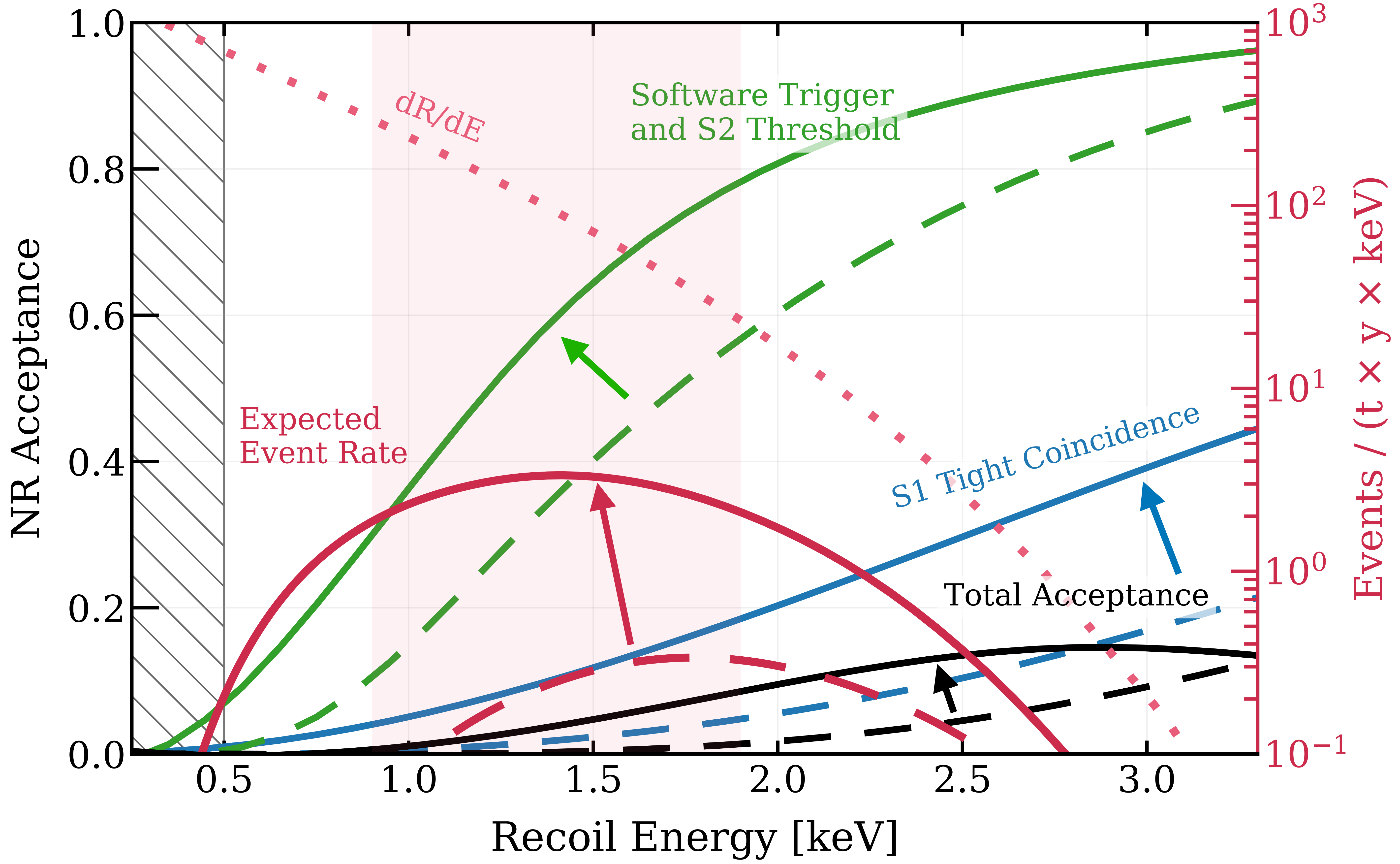

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The lower threshold comes at the expense of a background rate increase by two orders of magnitude!

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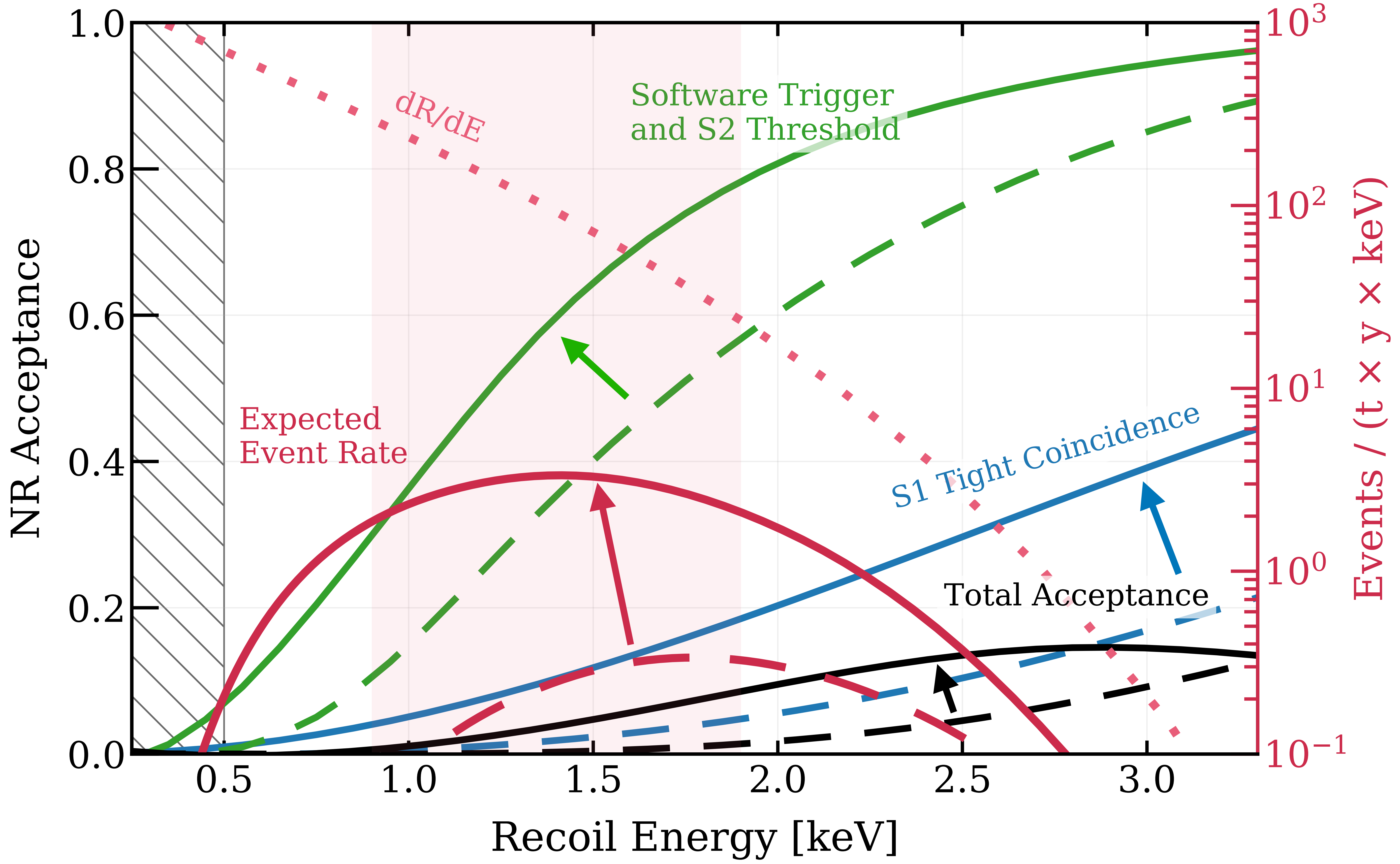
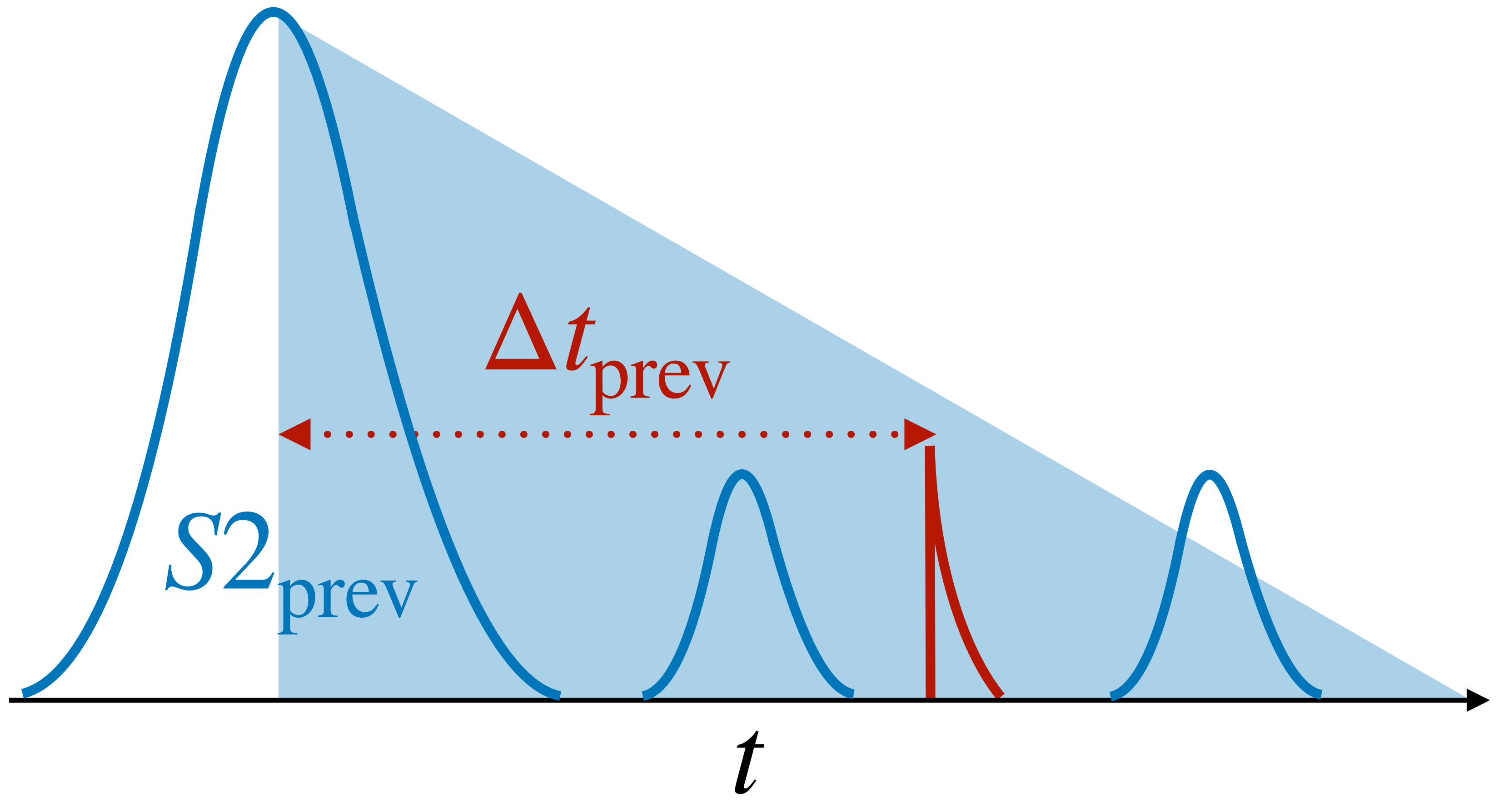


Accidental coincidence background

Isolated S1s…

…get paired with **isolated S2s**



- Pileup of PMT dark counts
- Misidentified single electrons
- Below-cathode and surface events
- …

- Single electrons:
  - delayed extraction
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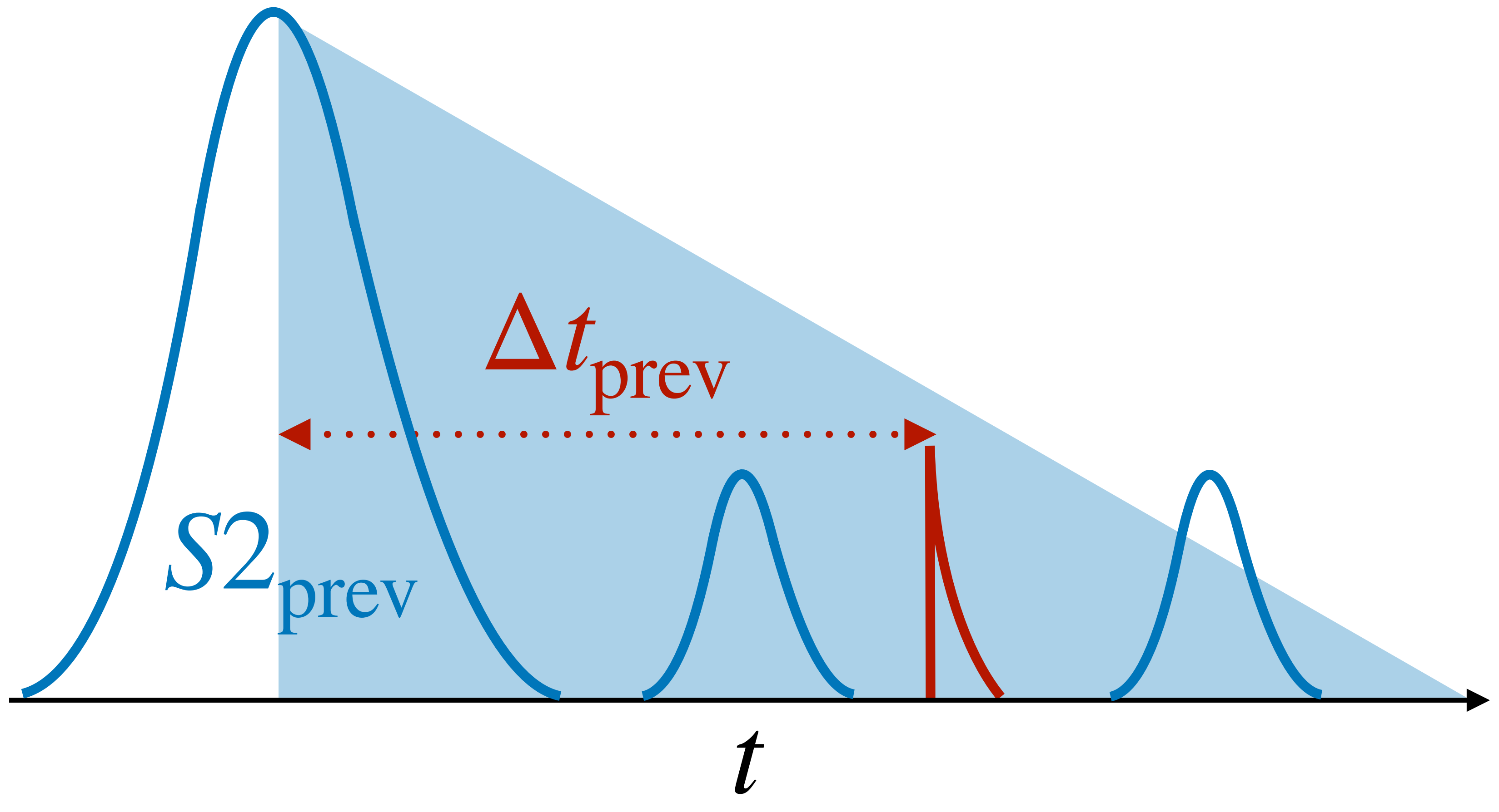

Mitigation strategies:

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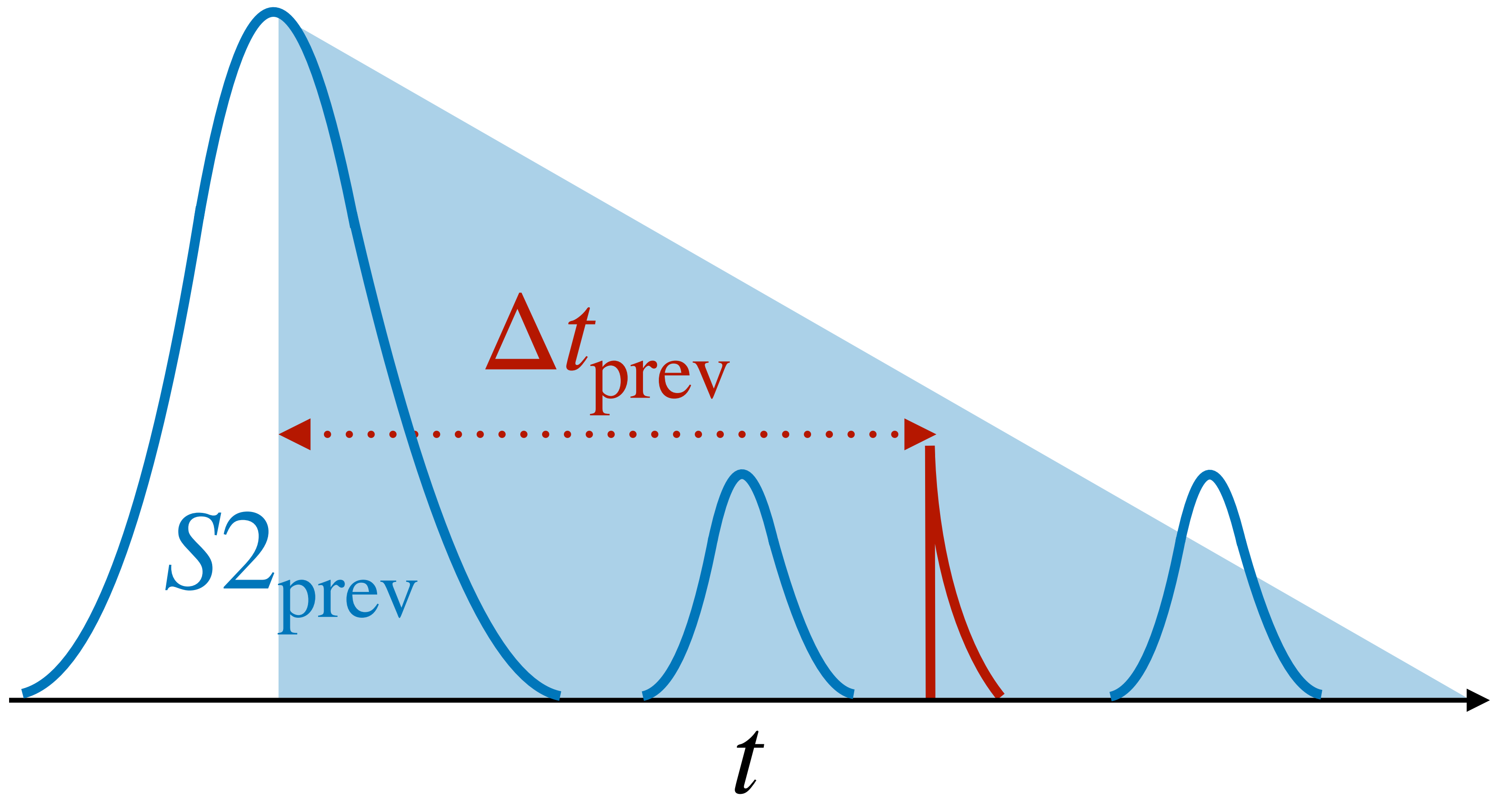

Mitigation strategies:

- Remove “shadow” and “ambience” of large peaks

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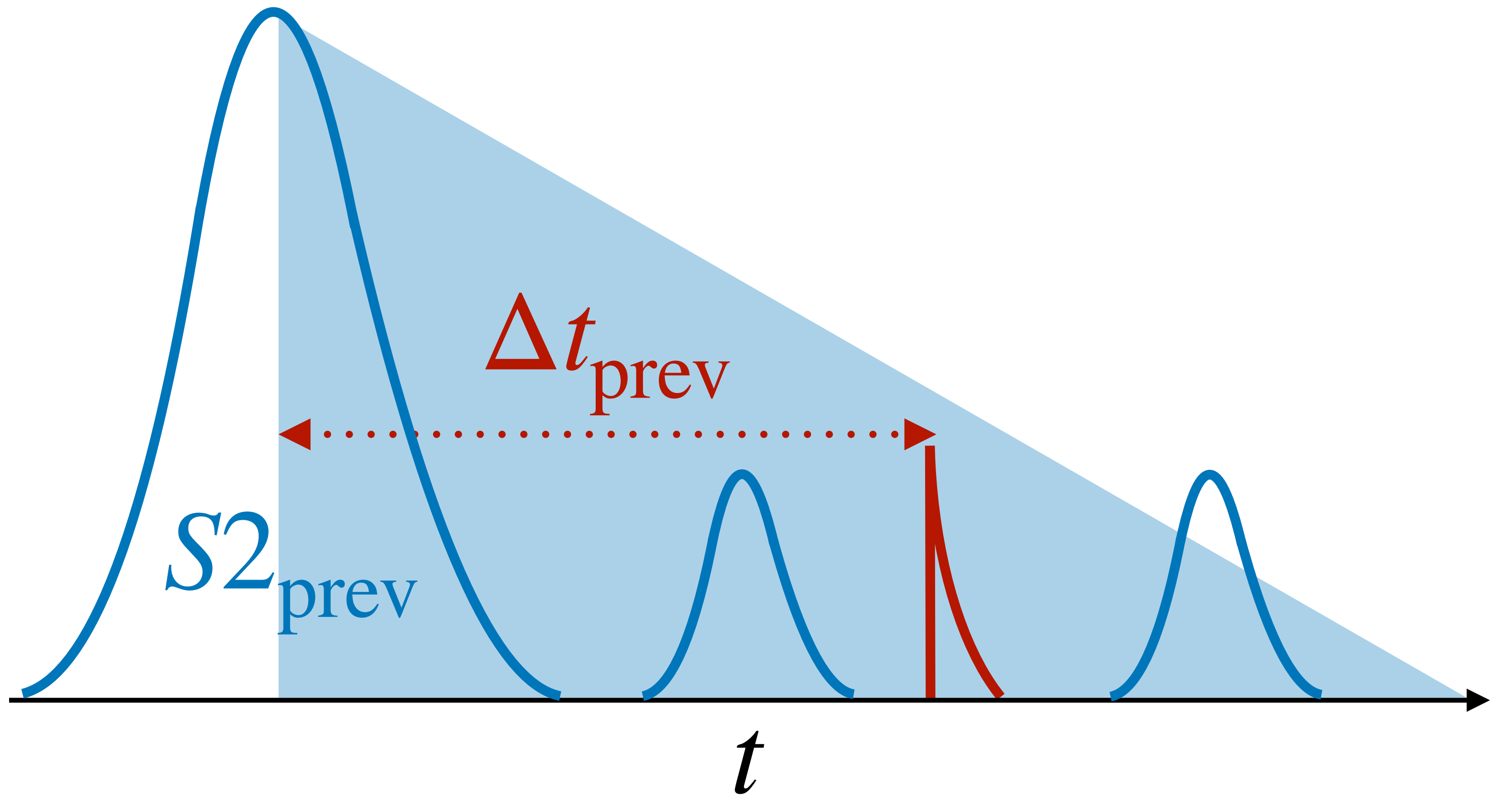

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- Use S1 and S2 correlations unique to AC events…

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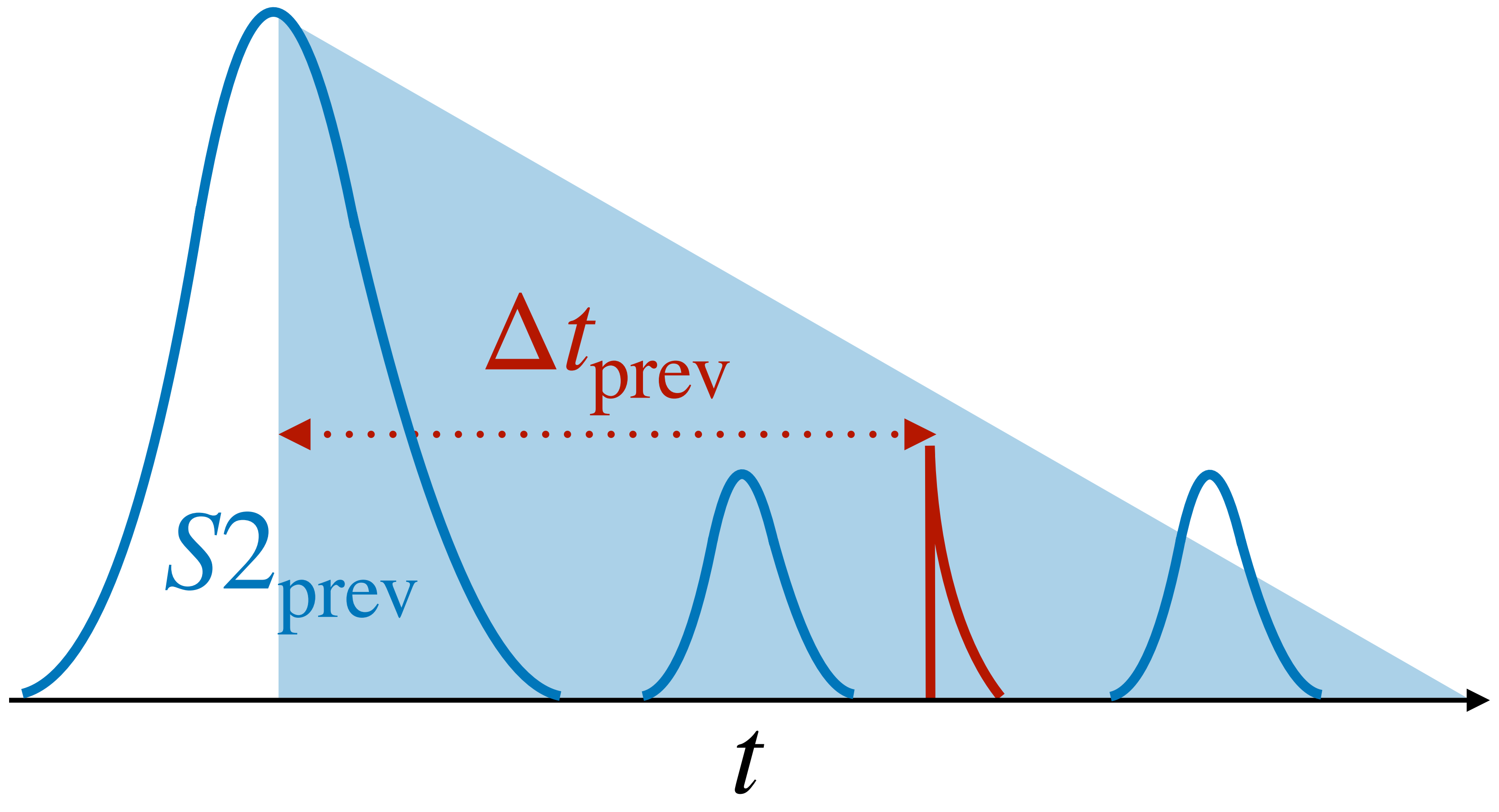

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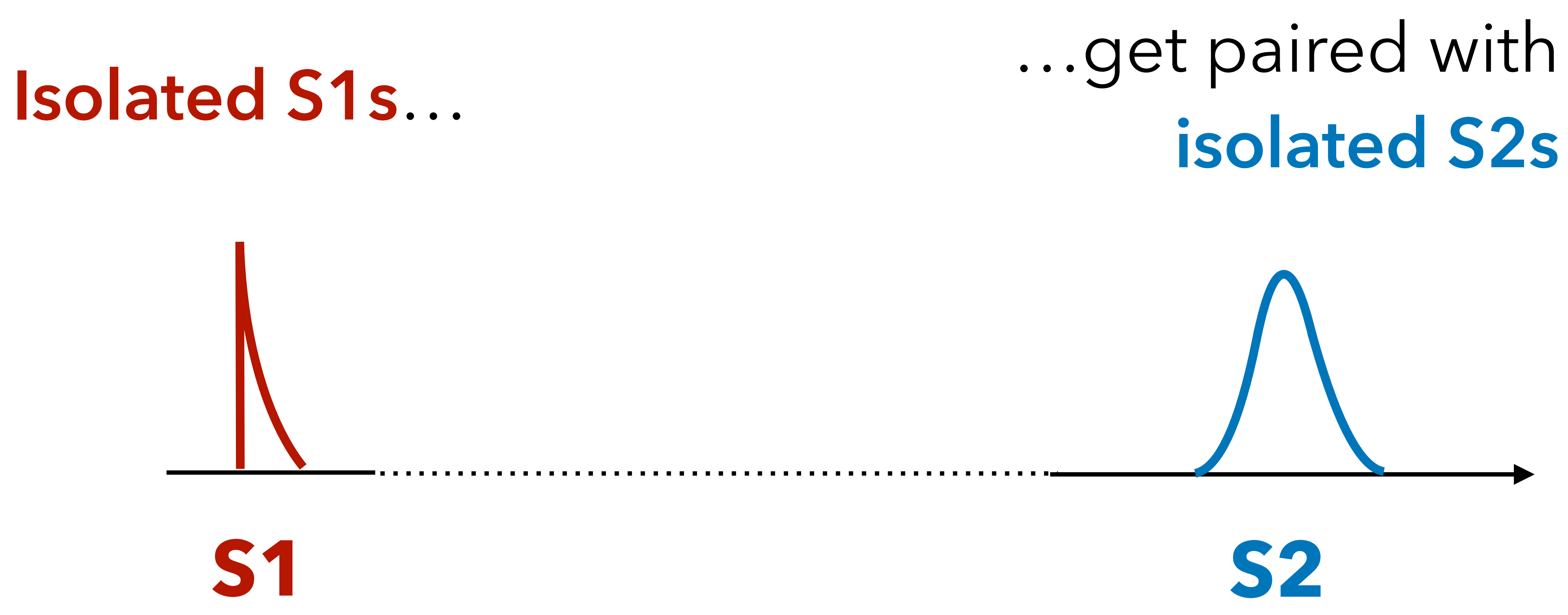

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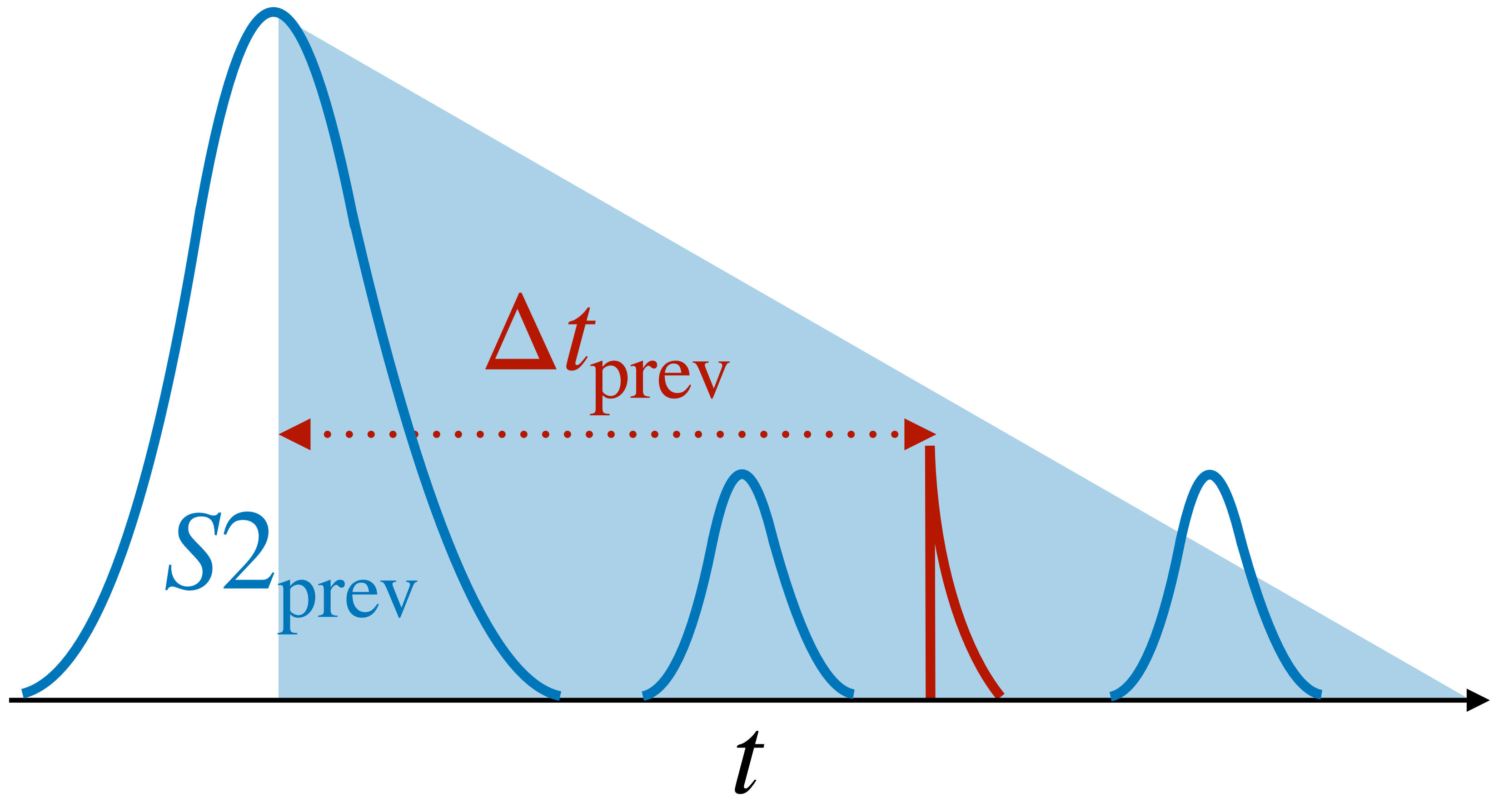

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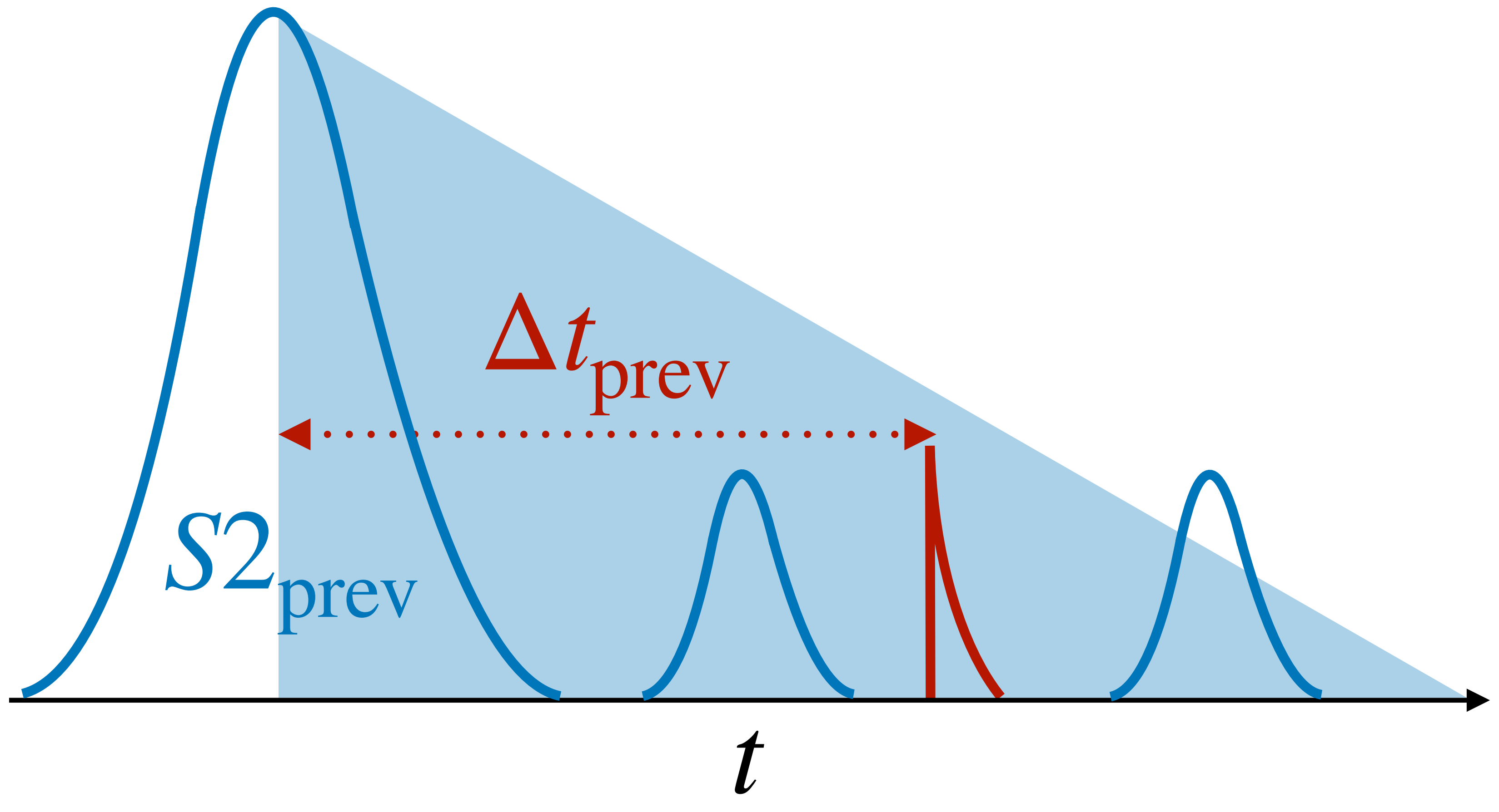

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  - … high-dimensional parameter spaces (machine-learning techniques)
- Model remaining AC background.

AC cuts and validation in XENON1T

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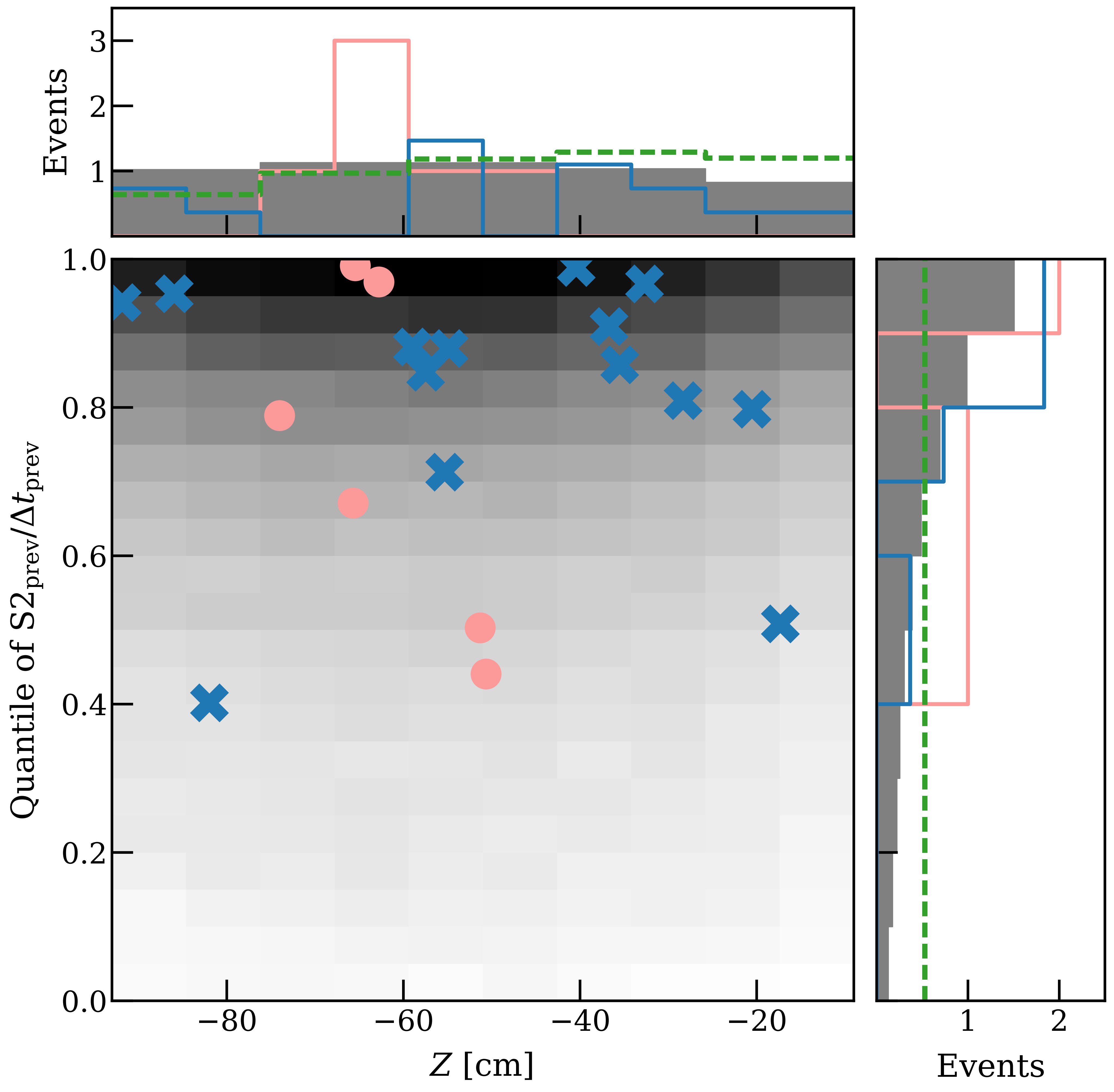

- S2 shadow selection
- Gradient boosted decision tree (GBDT) cut
  - AC features data-driven
  - S2 area, S2 rise time, S2 top PMT area fraction, reconstructed depth *z*
- Define AC-enriched sideband region with 50 % of AC contained in S2 < 120 PE

	AC Rejection	Signal Acceptance
S2 shadow selection	65 %	87 %
Gradient boosted decision tree (GBDT) cut	70 %	≥ 85 %

Measured: 23 events

Expected: 27.7 ± 1.4 events

AC cuts and validation in XENON1T

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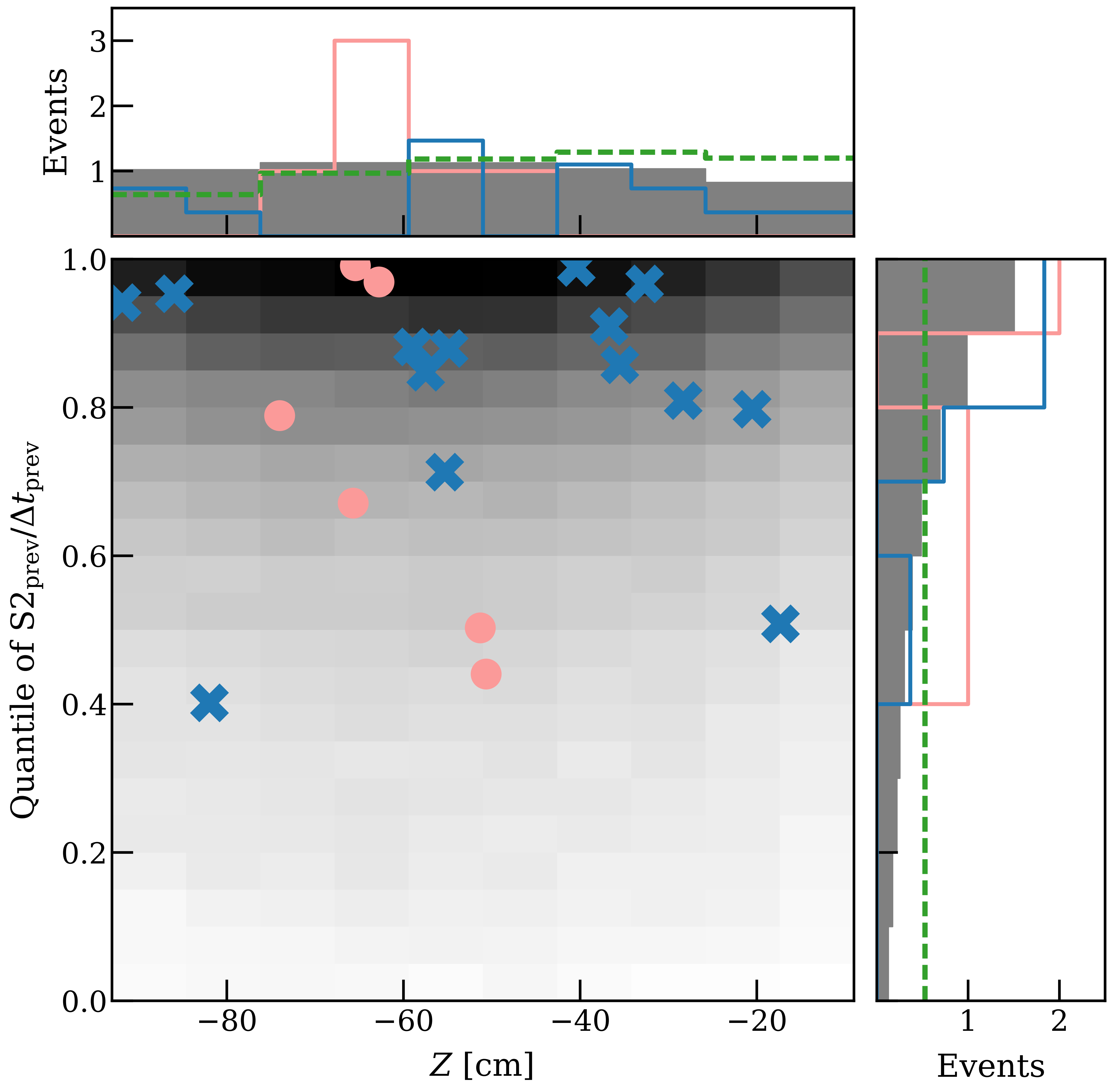
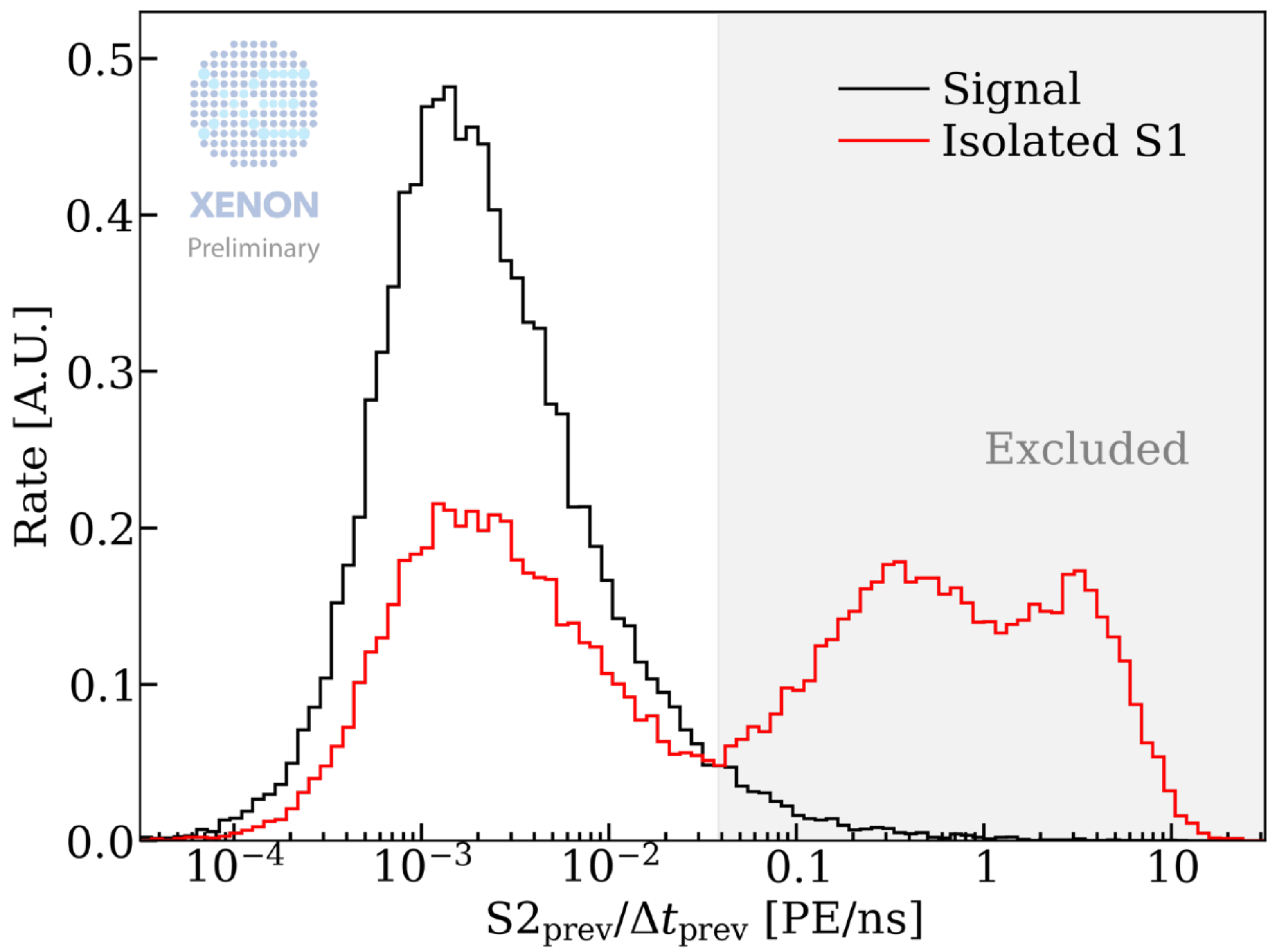


Source	Expected
CEvNS	2.11
AC	5.14
ER	0.21
Radiogenic neutrons	0.04
Total	**7.50**
Observed	**6**

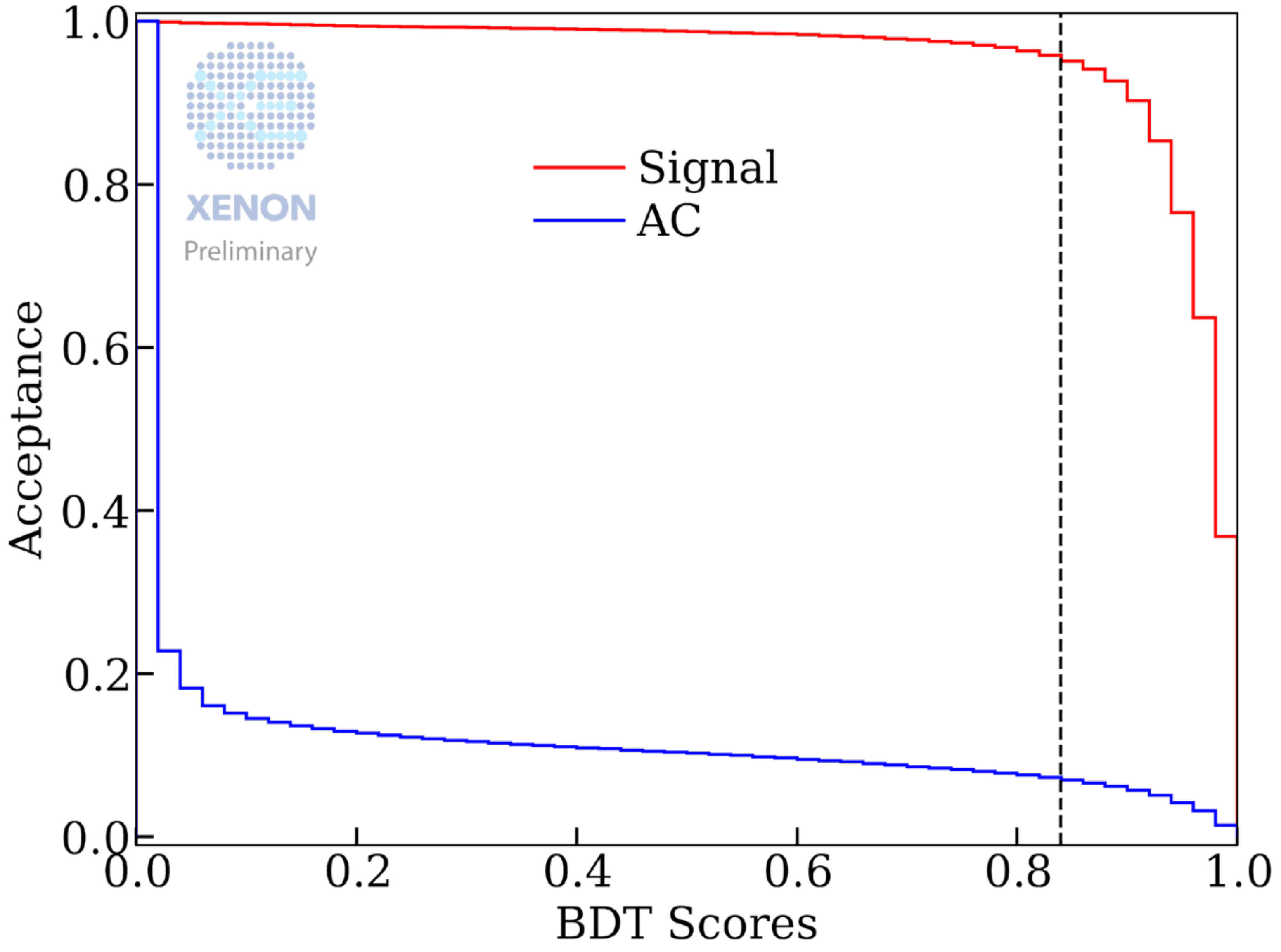
Consistent with background-only hypothesis.
p ~ 0.5

AC in XENONnT WIMP analysis

Remove "shadow" of large S2s

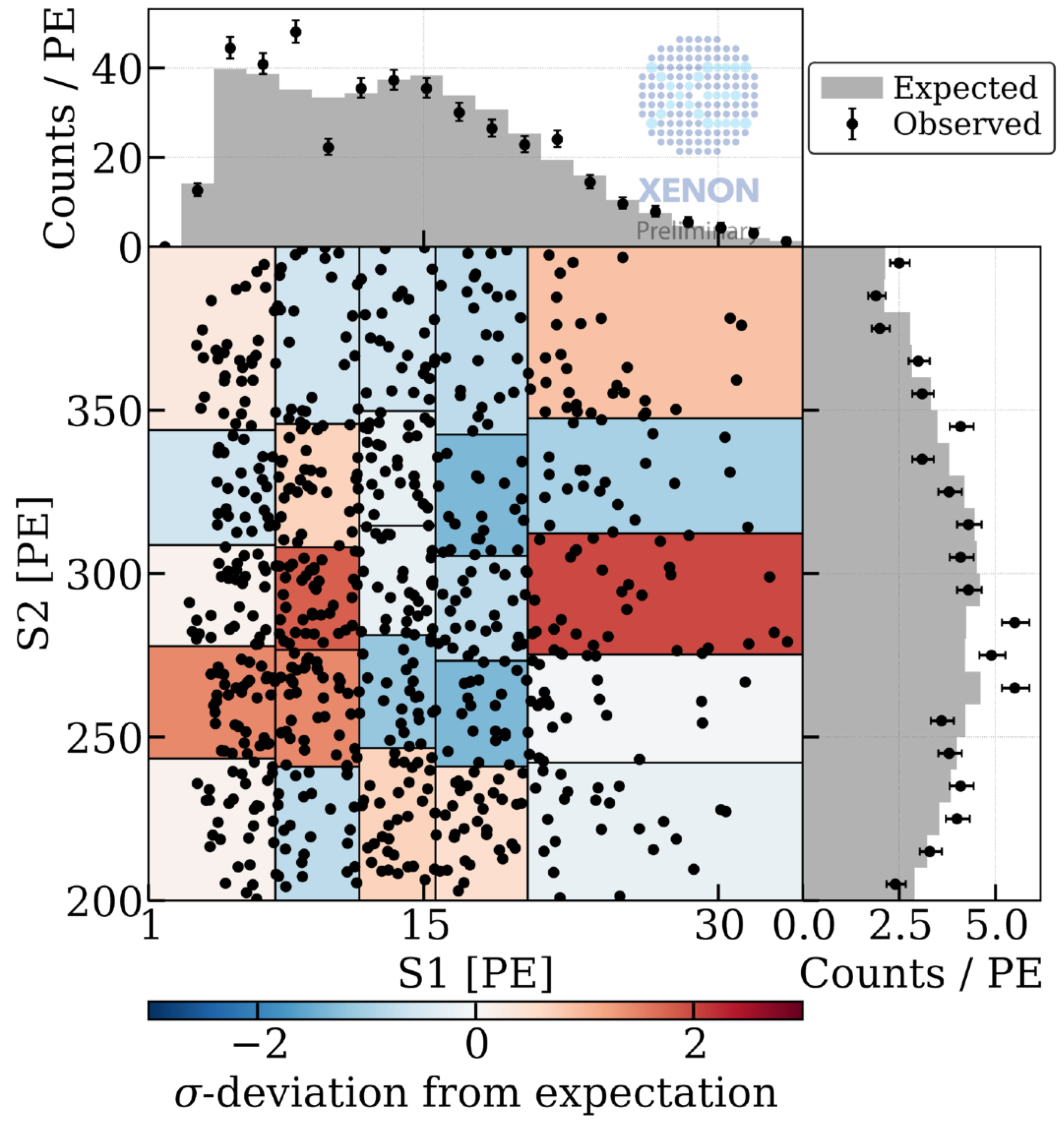


Use features of S1 and S2 signals in AC vs. physical events.



See talk by Chris Tunnell on ML in XENONnT at 17:15 h.

Model remaining AC background



AC model validated to 5 % precision.

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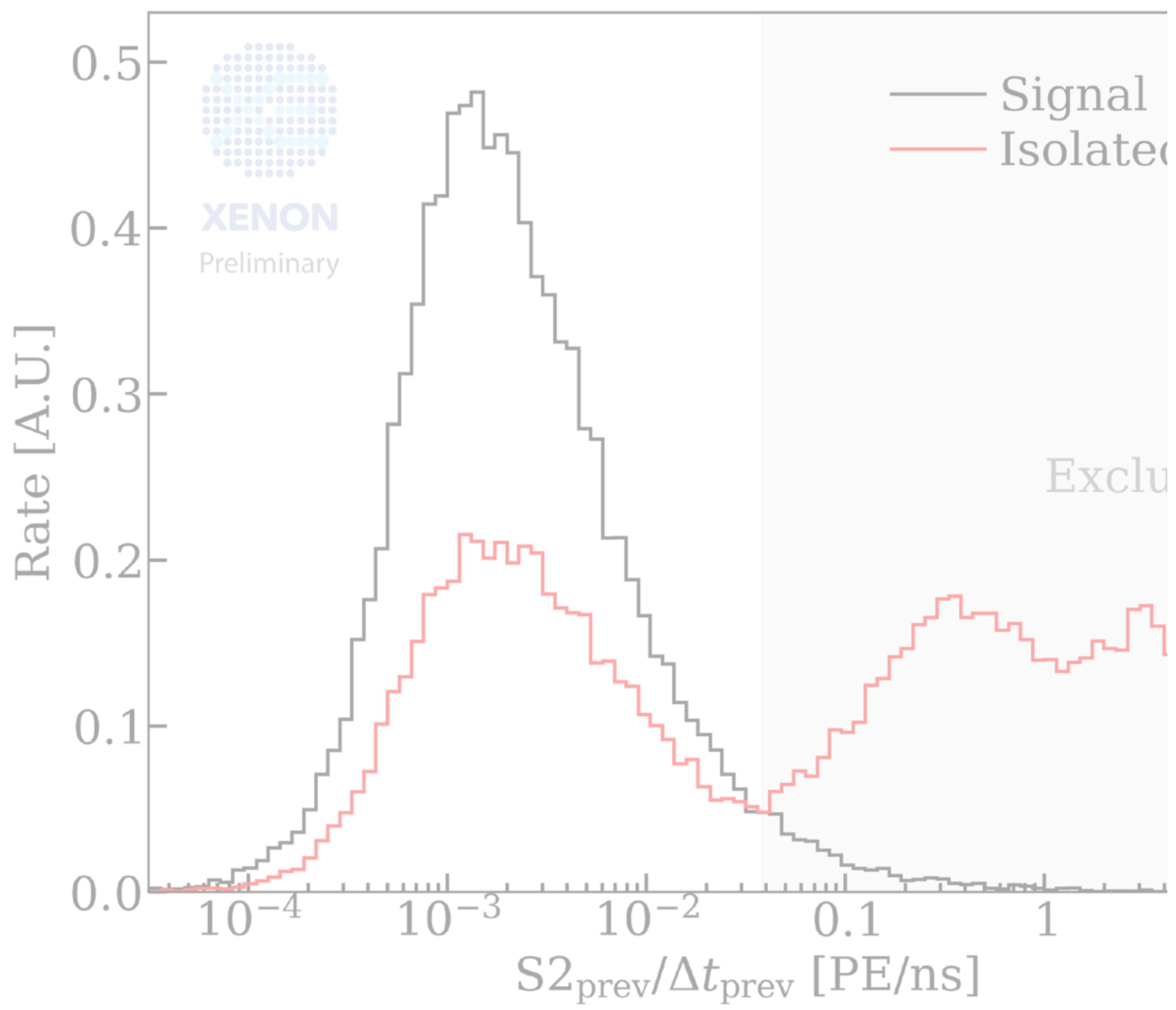

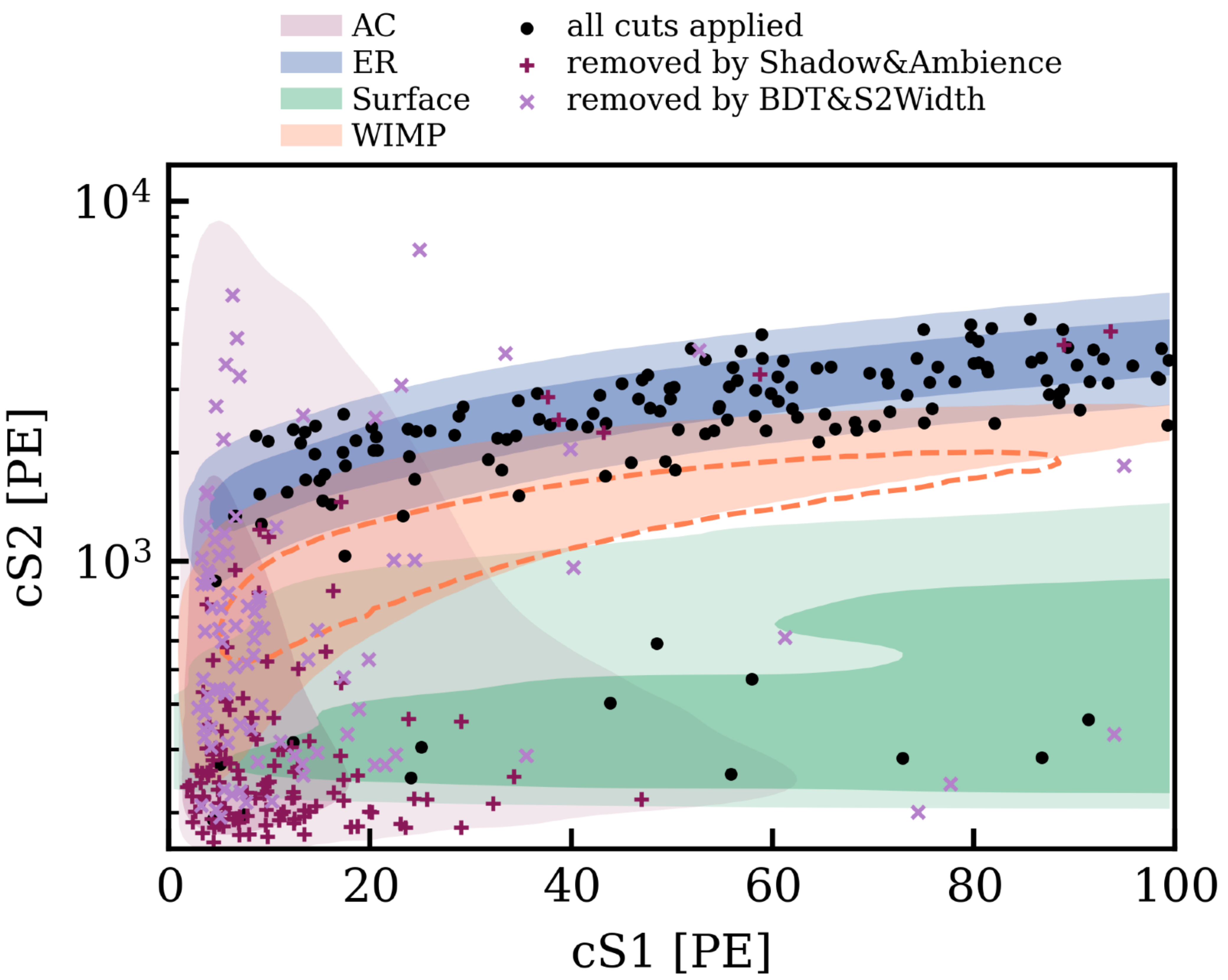

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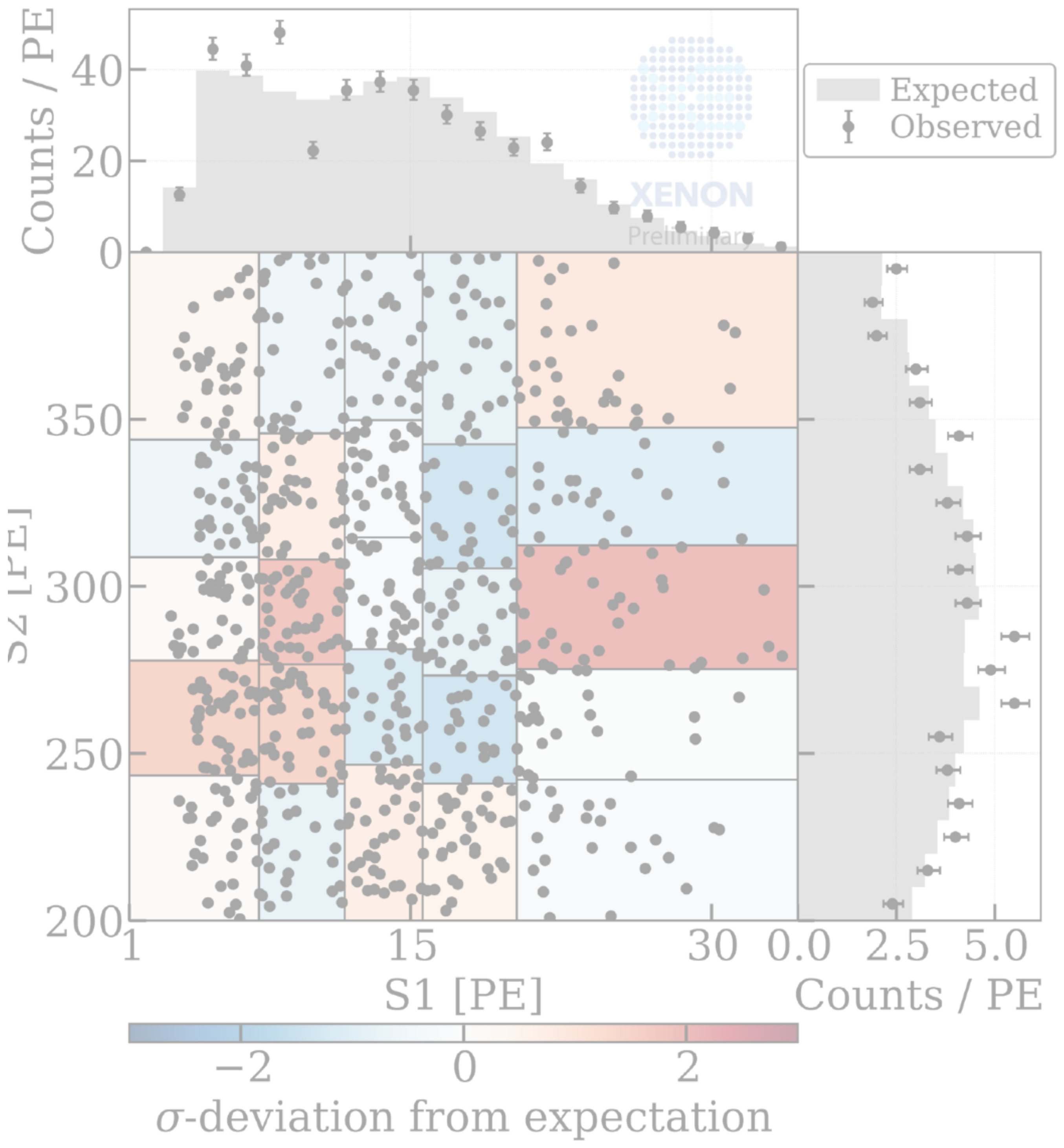

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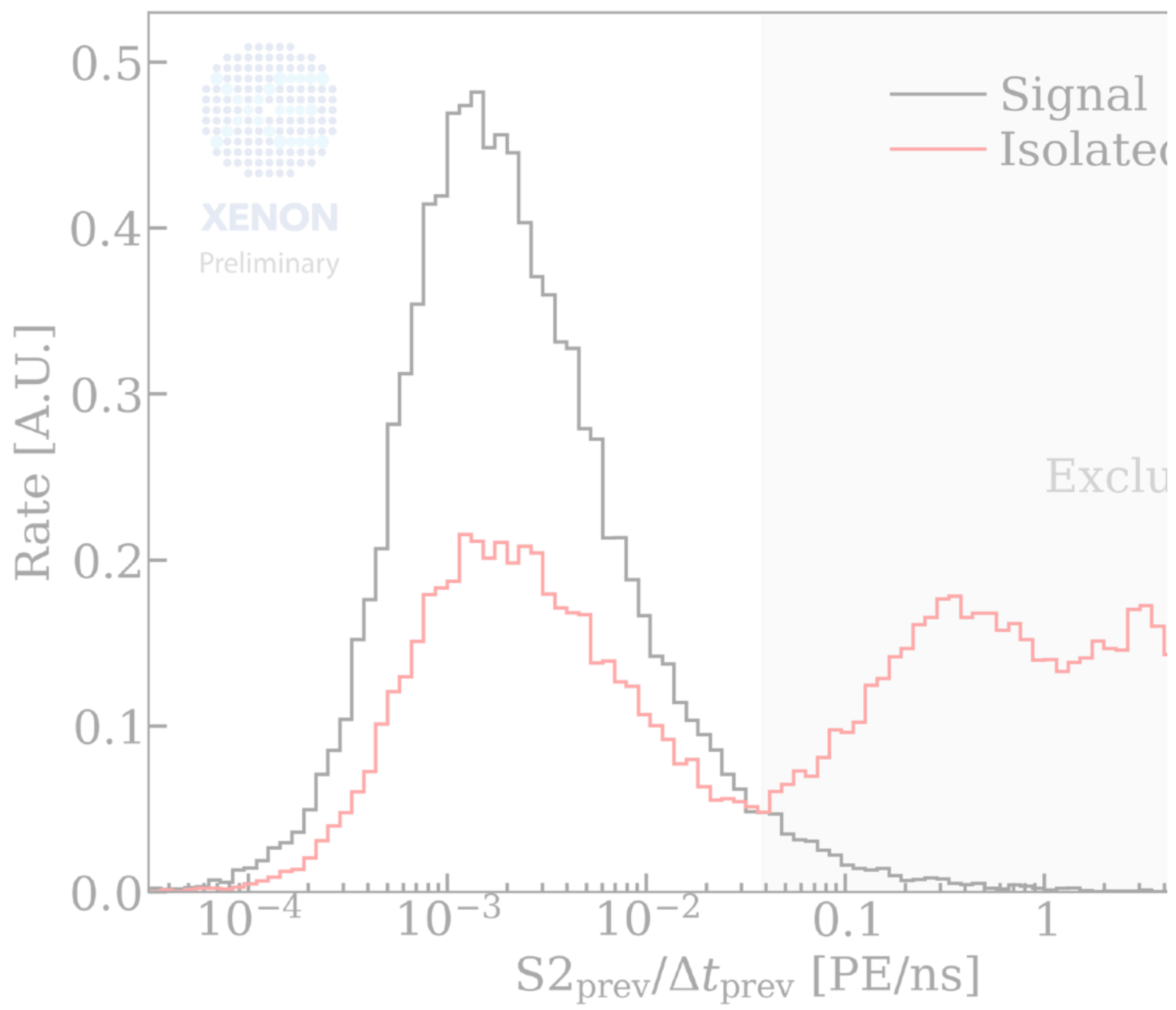

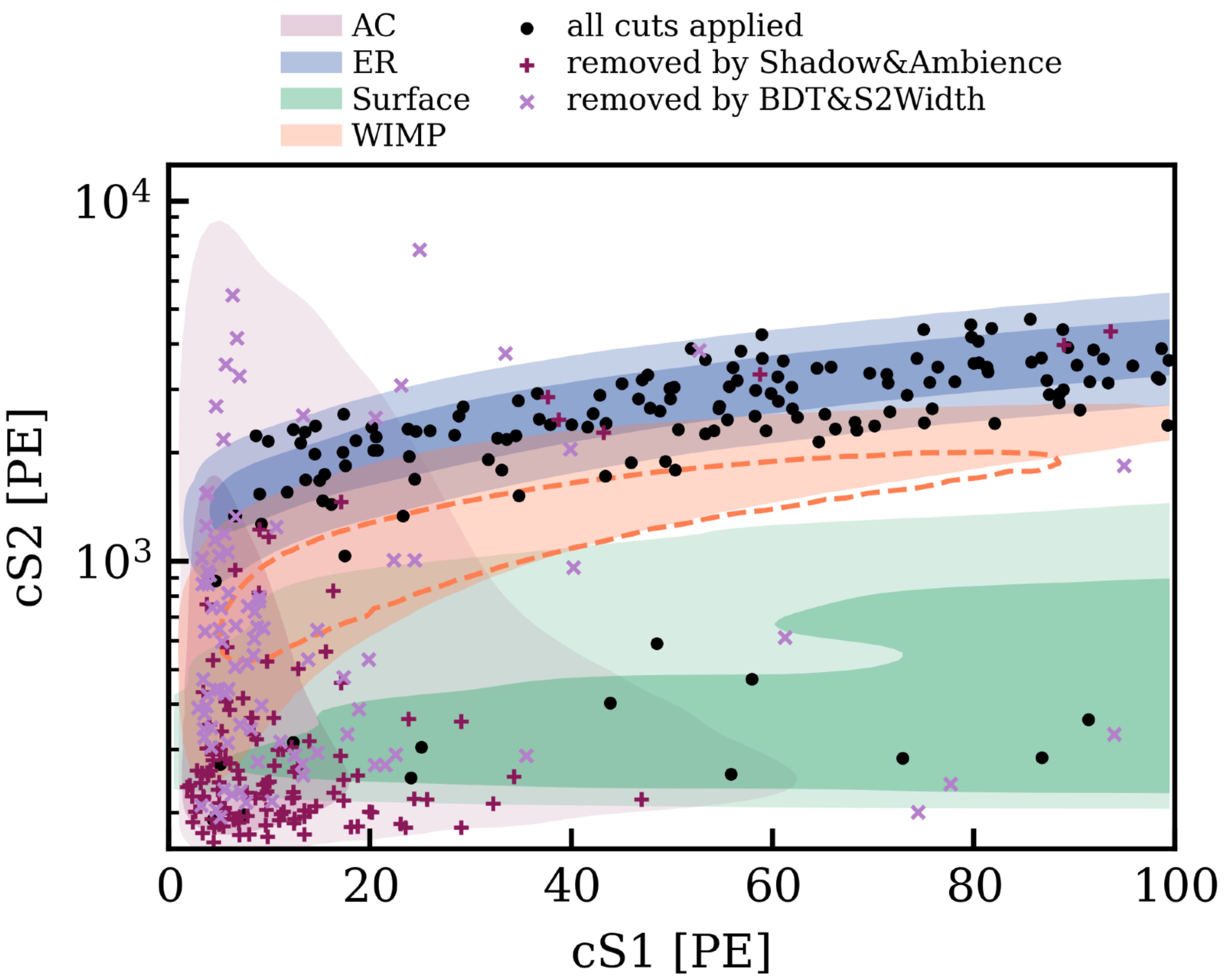

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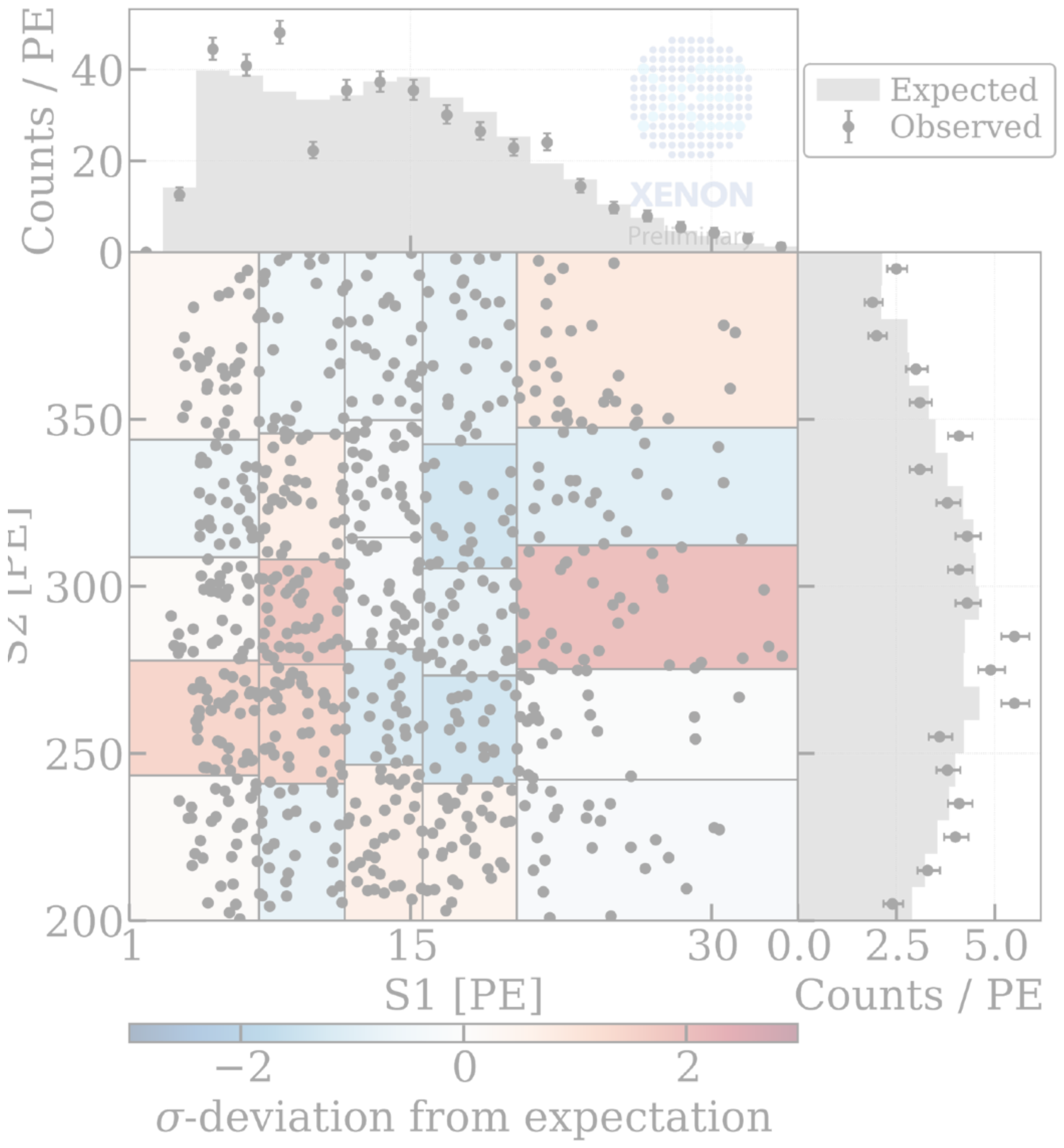

AC background mitigated and validated well in the XENONnT WIMP analysis.

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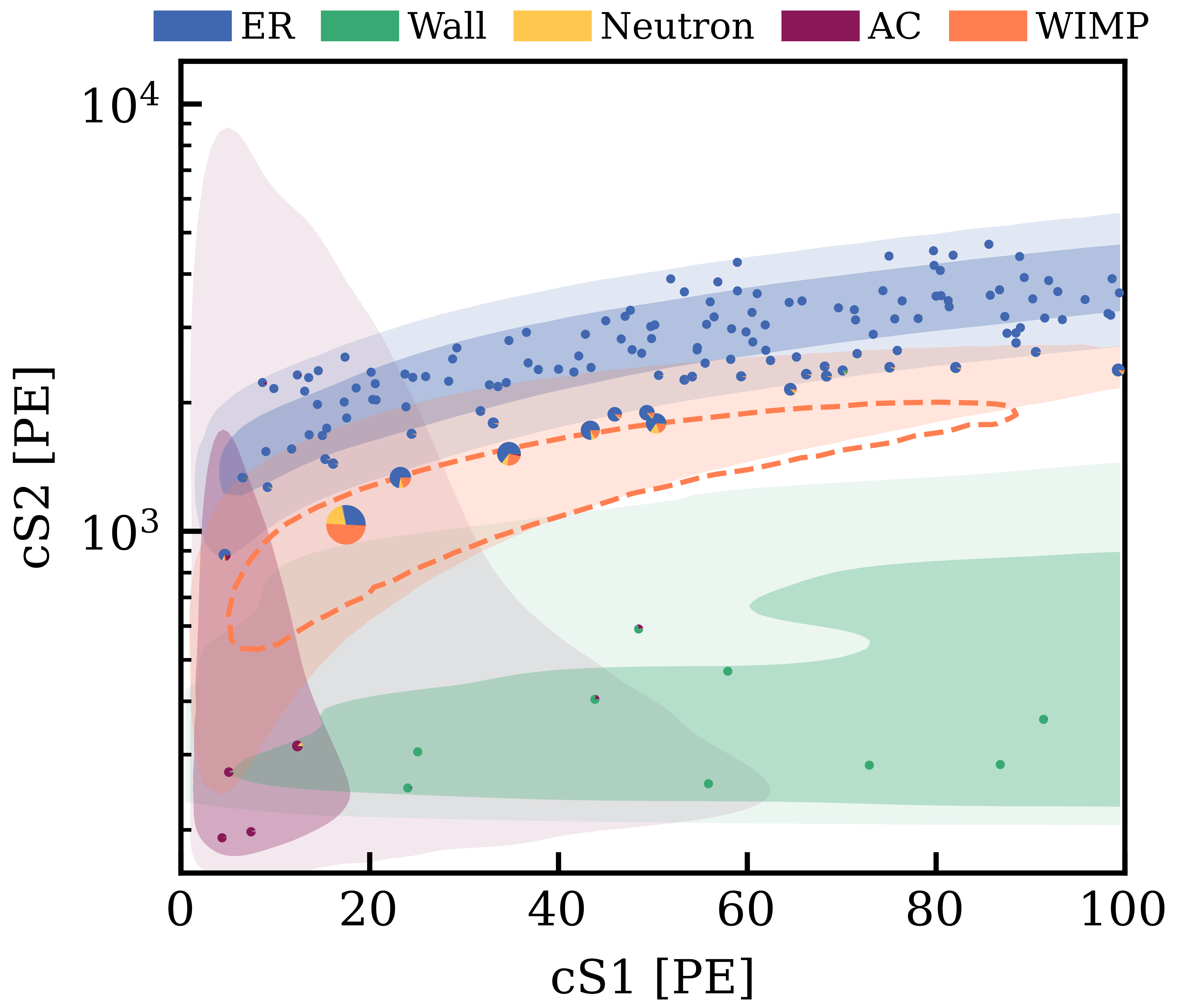
Solar neutrinos in XENONnT WIMP results

	Nominal	Best fit	
	ROI		Signal-like
ER	134	135^{+12}_{-11}	0.92 ± 0.08
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.4	0.42 ± 0.16
CEνNS	0.23 ± 0.06	0.23 ± 0.06	0.022 ± 0.006
AC	4.3 ± 0.9	$4.4^{+0.9}_{-0.8}$	0.32 ± 0.06
Surface	14 ± 3	12 ± 2	0.35 ± 0.07
Total background	154	152 ± 12	$2.03^{+0.17}_{-0.15}$
WIMP	…	2.6	1.3
Observed	…	152	3

See talk by Zihao Xu from August 28.



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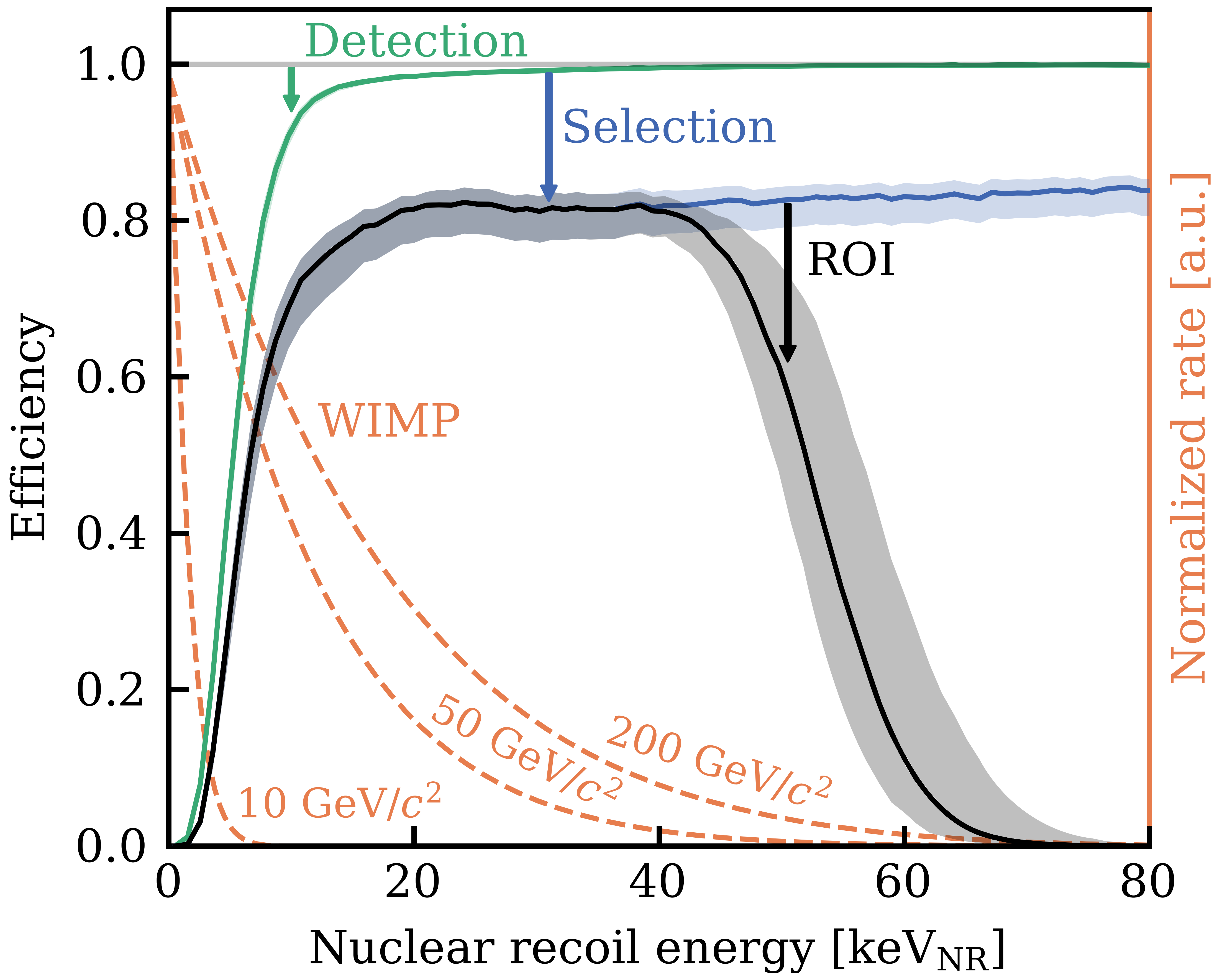

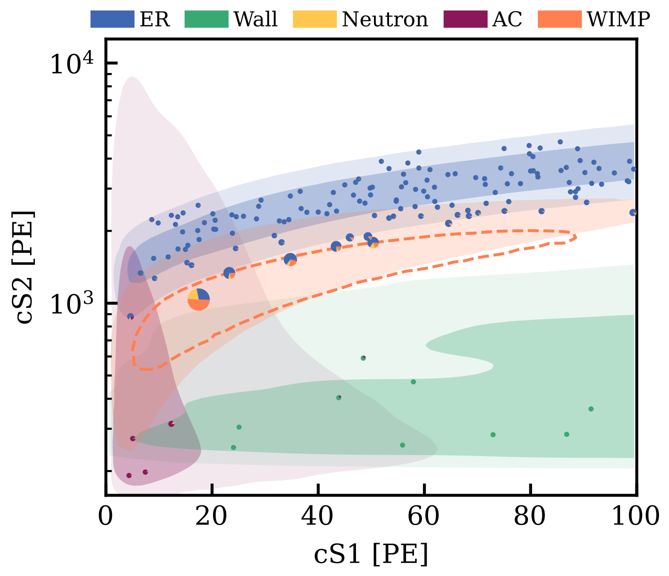

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Next step: Transition to low-threshold 2-fold coincidence analysis.

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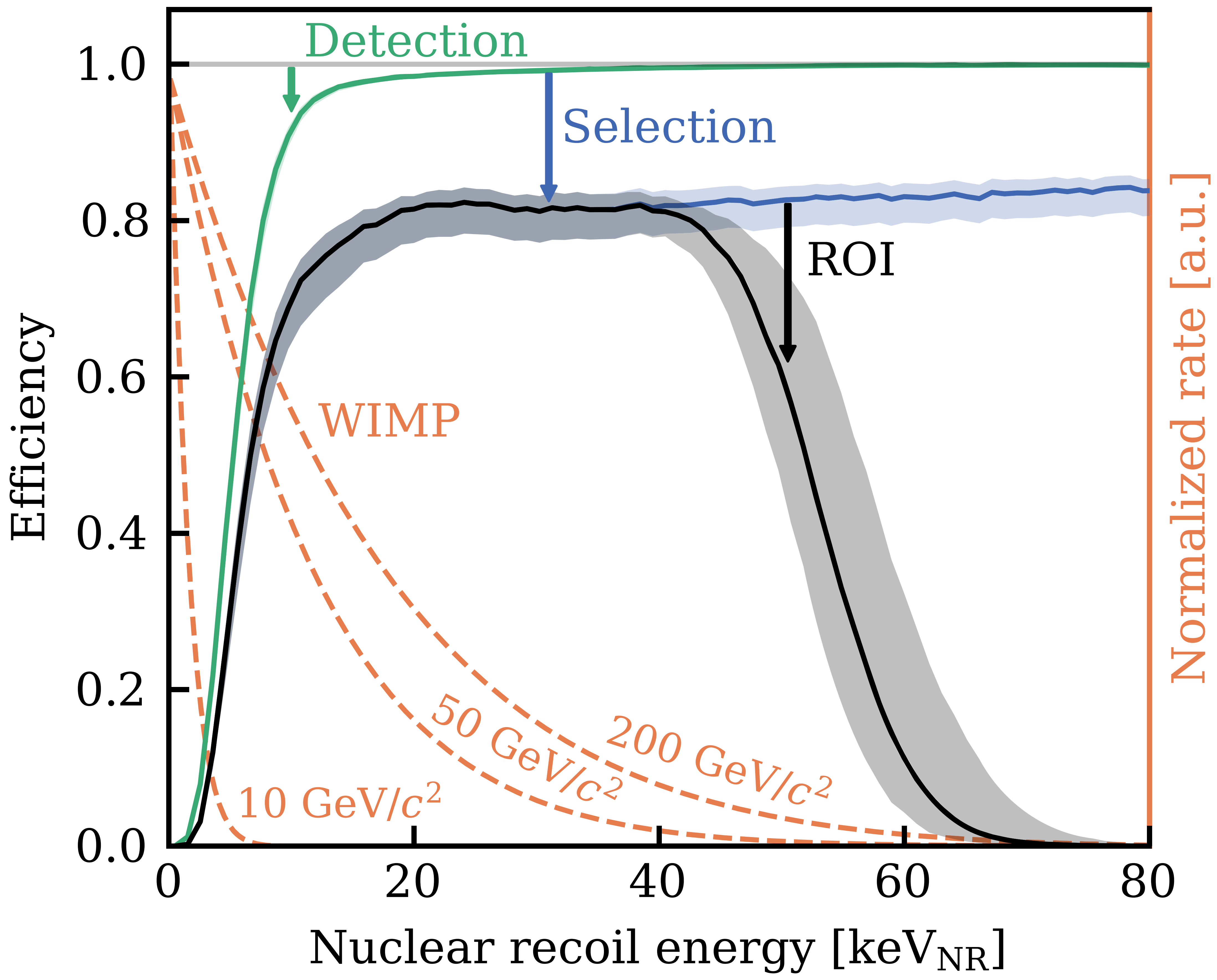

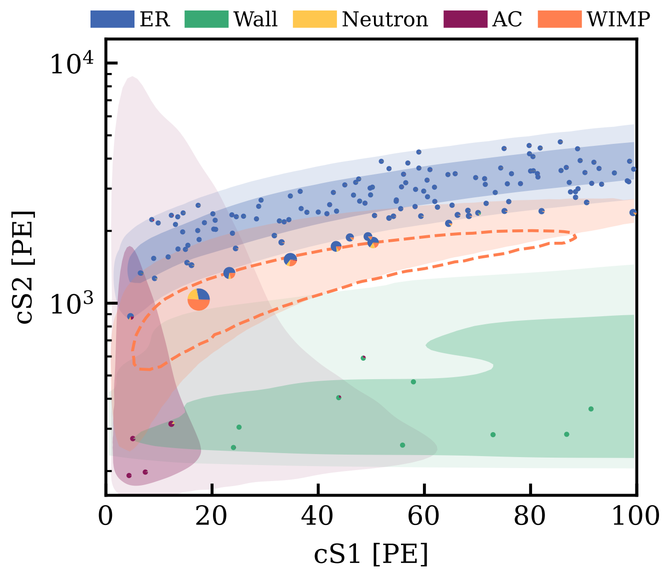

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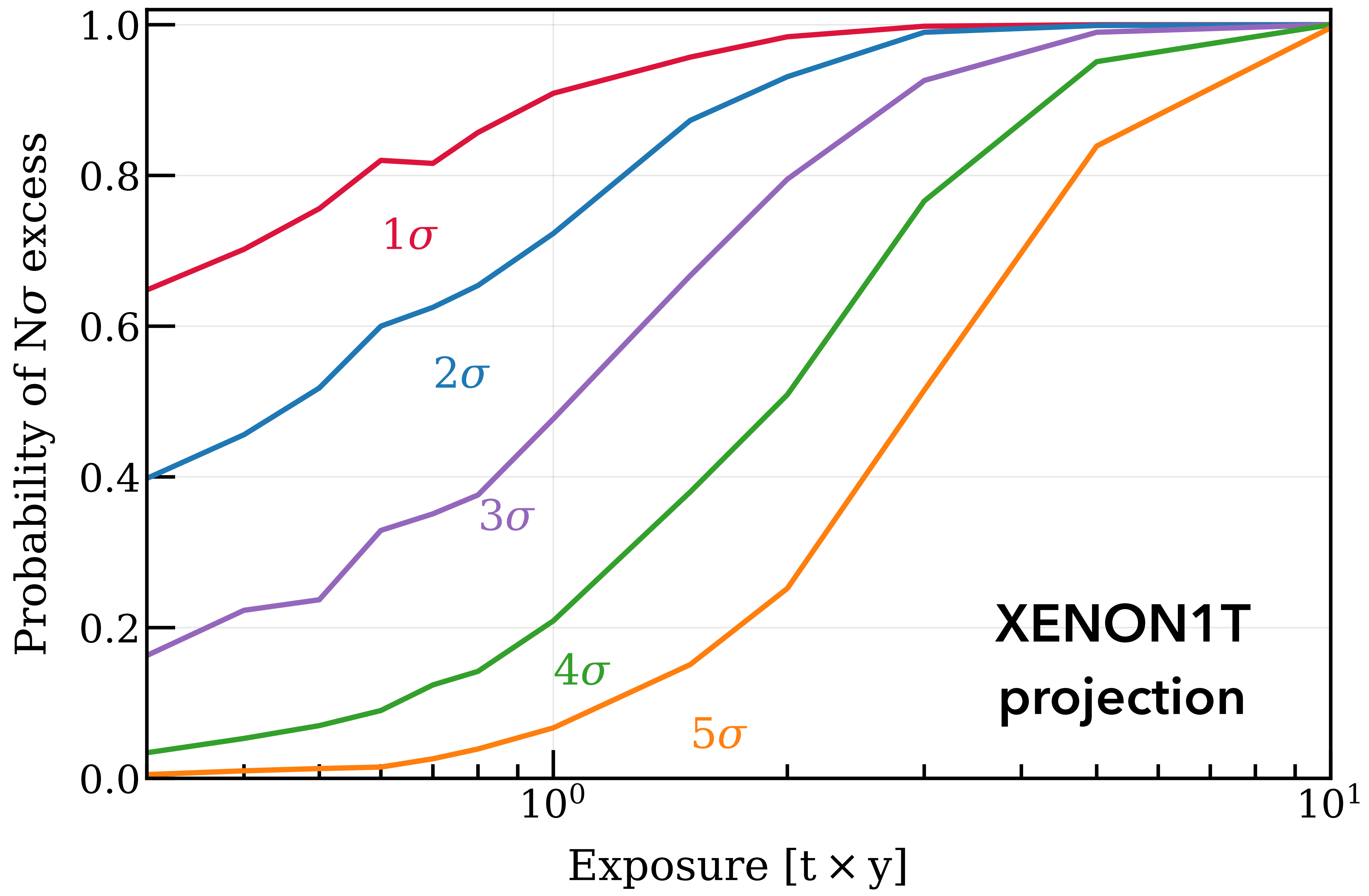
^{8}B discovery potential in XENONnT

Experiment	Isolated S1	Isolated S2	Max drift	Relative AC	Exposure
XENON1T	11.2 Hz	1.1 mHz	730 μs	1	0.6 t × yr
XENONnT	2.5 Hz	18.5 mHz	2200 μs	~ 11	> 0.6 t × yr



- Lower field:
  - Larger isolated S2 rate
  - Longer drift
  - Affects discrimination, but ER background still negligible for CEvNS
- Increased exposure compared to XENON1T
- Reducing AC rate to the XENON1T level would bring a ^{8}B observation within reach.

Summary

University of Zurich[UZH]

- Liquid xenon detectors of the current generation sensitive to ^{8}B solar neutrinos
- Search demonstrated in XENON1T, but did not find a signal
- Accidental coincidence background dominant in low-threshold analysis and mitigated with S1+S2 correlations and strict data selections
- XENONnT will be more sensitive with a larger exposure and improved AC rejection techniques

www.xenonexperiment.org

instagram.com/xenon_experiment

twitter.com/xenonexperiment

XENON

XENON at TAUP 2023:

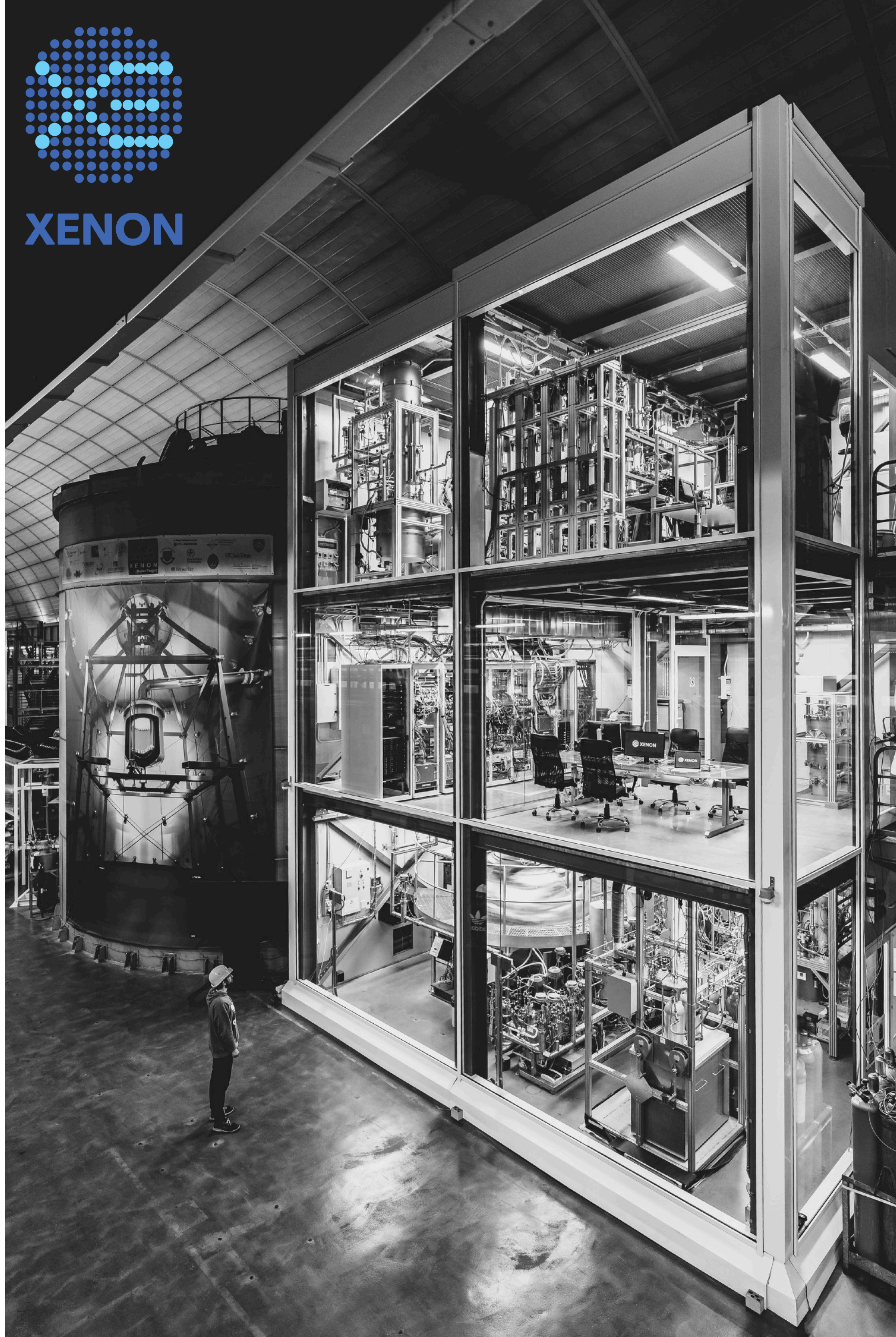
- **Monday, 16:45:** *XENONnT WIMP results* by Zihao Xu
- **Tuesday, 14:15:** *MeV signals and new physics* by Maxime Pierre
- **Tuesday, 17:15:** *ML in XENONnT* by Chris Tunnell

- **Poster:** *Planck mass dark matter* by Shengchao Li
- **Poster:** *Surface background modeling* by Cecilia Ferrari
- **Poster:** *Radon removal in XENONnT* by David Koke
- **Poster:** *Krypton distillation in XENONnT* by Johanna Jakob
- **Poster:** *Ultra-clean pumps for noble gas experiments* by Andria Michael.

University of Zurich[UZH]

XENON

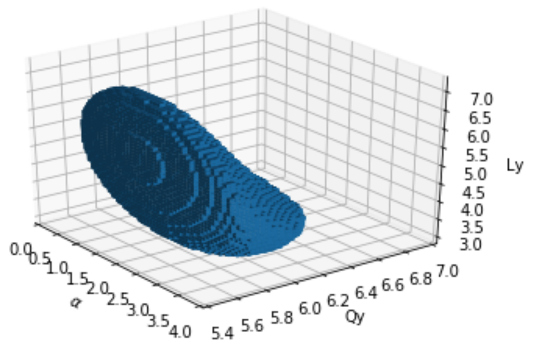
Backup



Inference with Different Sets of Constraints

Light yield: Ly **Charge yield: q**

Neutrino flux: ϕ



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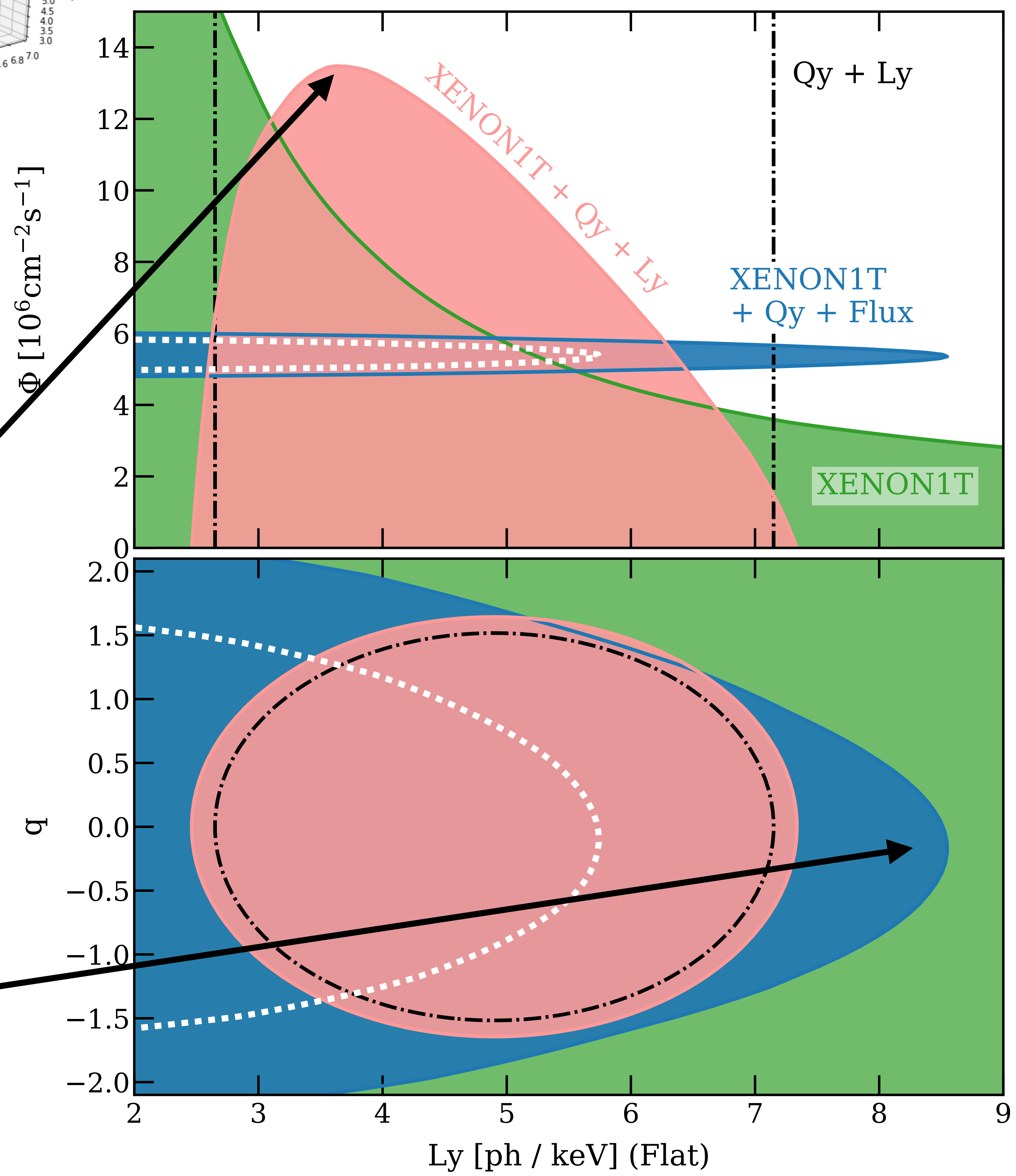
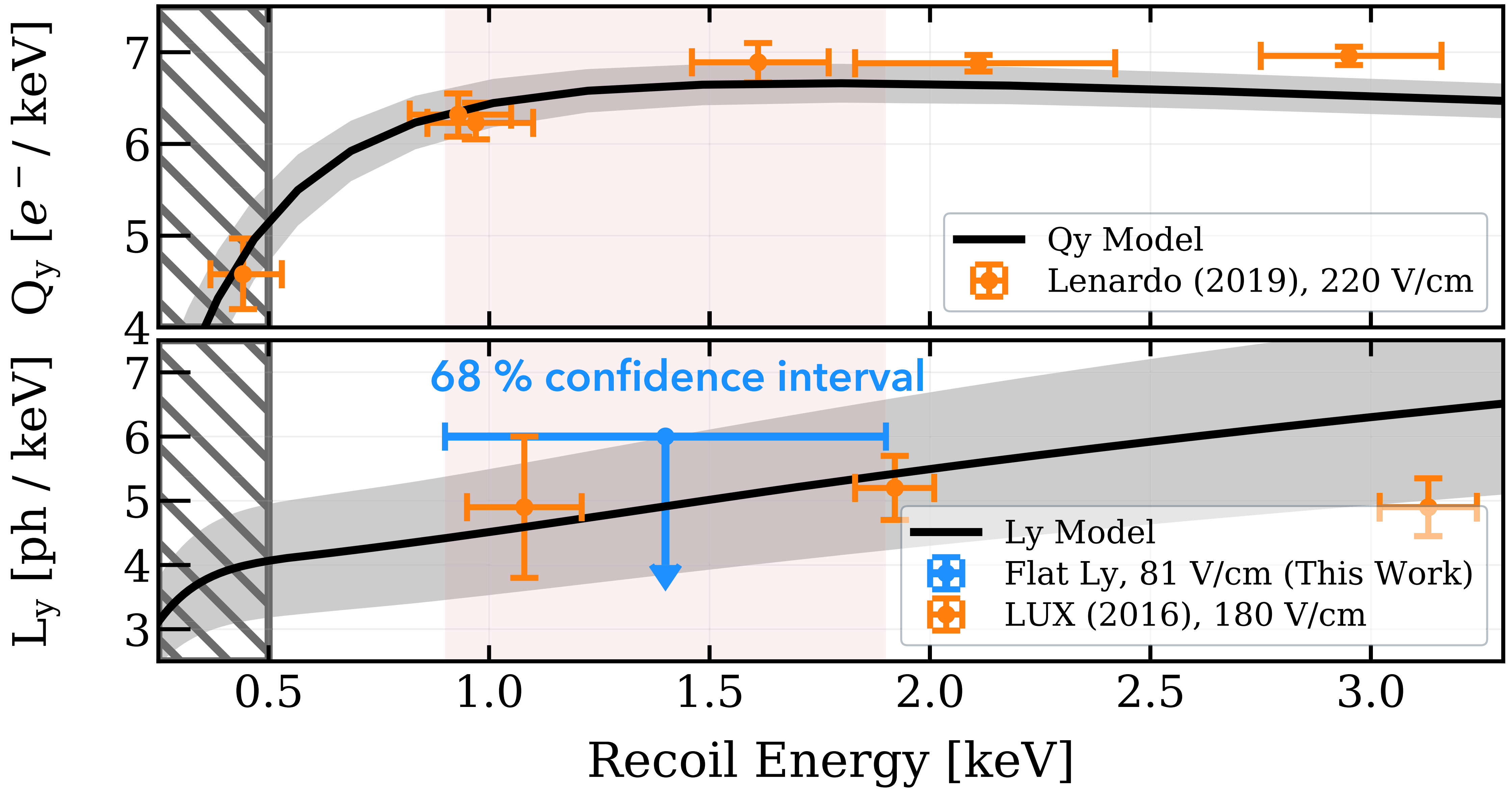


- Light yield and signal rate highly correlated, so **XENON1T-only result** becomes an upper limit on the combination of both
- Combination of XENON1T, LLNL charge yield and LUX light yield enables to set **upper limit on neutrino flux** $\Phi < 1.4 \cdot 10^{7}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (90 % C.L.)
- Measured neutrino flux from SNO enables to set **upper limit on the light yield**

Light and charge yields at low energy

- No response assumed below 0.5 keV_{NR} in absence of measurements and with detection efficiency below 10^{-3}
- Charge yield measurements by Lenardo et al. set strong Q_Y constraints. Use their NEST v2.1.0 best fit and uncertainty to obtain shape and scale with single parameter *q*.
- Large light yield uncertainties of ≈ 20 % near 1 keV
- Fit L_y measurements using a free parameter that scales the NEST v2.1.0 best-fit curve for measurements between 0.9 – 1.9 keV

Phys. Rev. Lett. 126 (2021) 091301



XENON1T upper limit on NR light yield from constraining charge yield and neutrino flux.

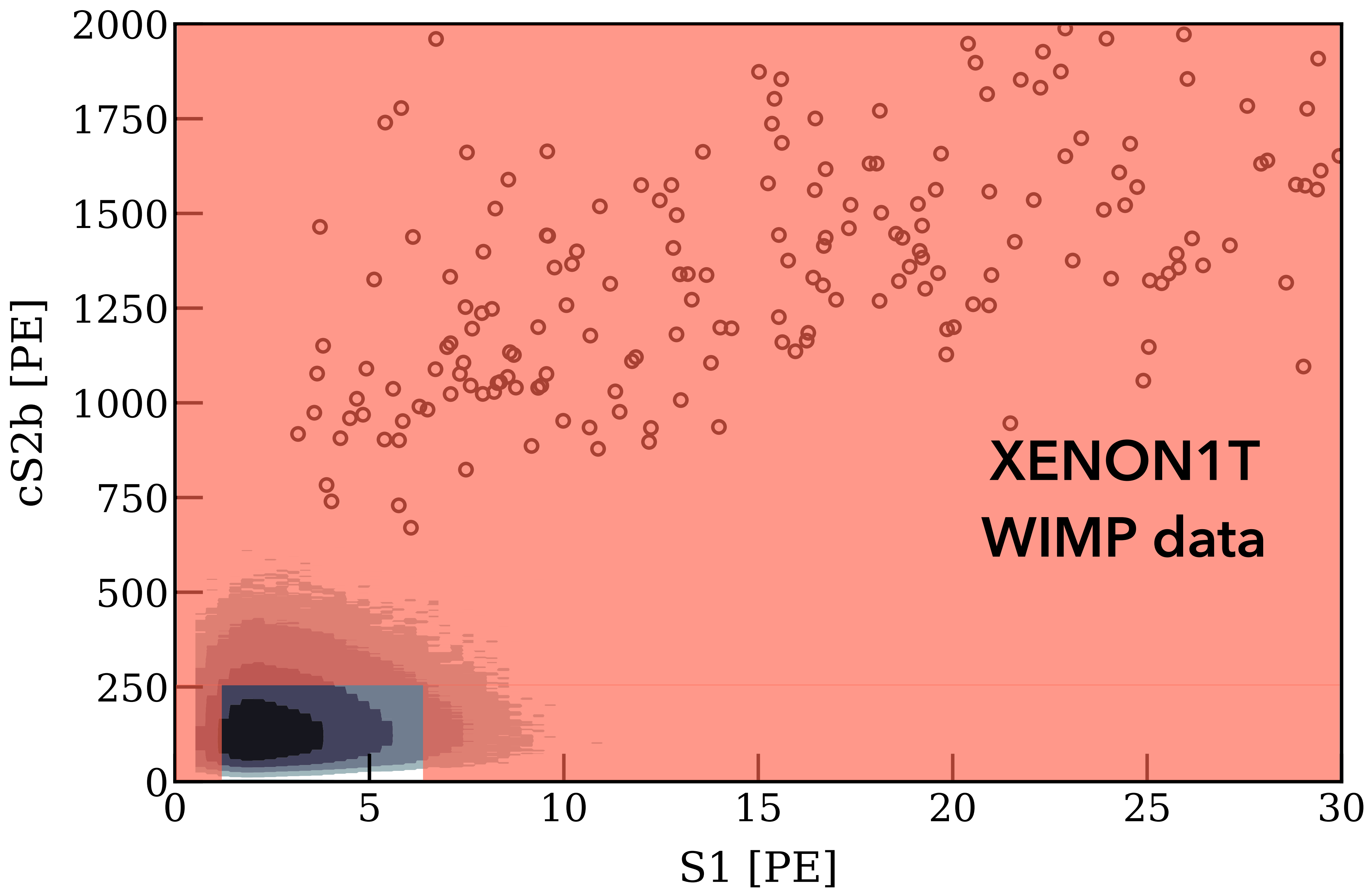
ROI and backgrounds

Source	Expected
CEvNS	2.11
AC	5.14
ER	0.21
Radiogenic neutrons	0.04
Surface	Negligible
Total	**7.50**
Observed	**6**

$cS2_b$ < 250 pe

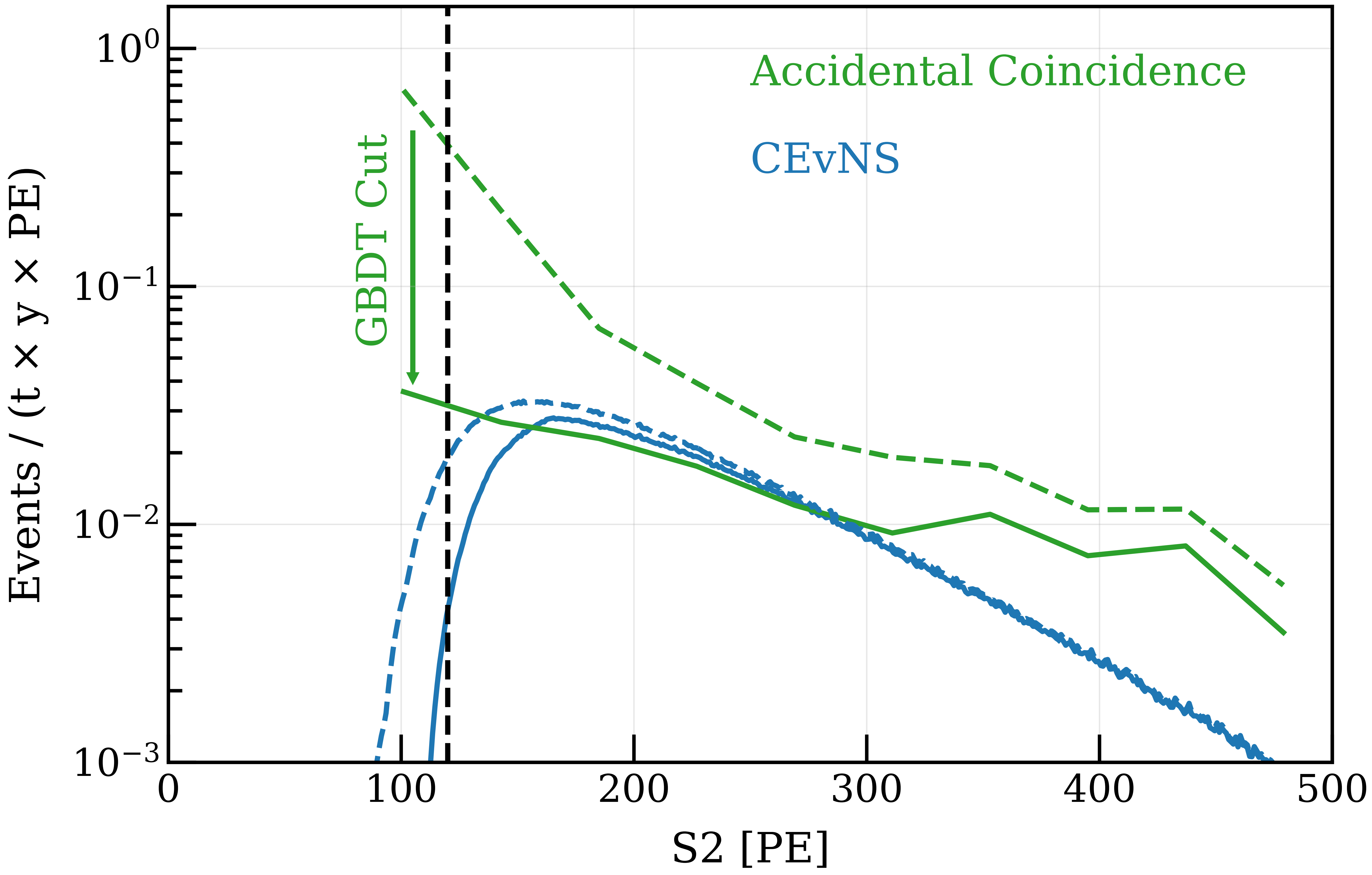
Tight ROI

1.04 t fiducial volume



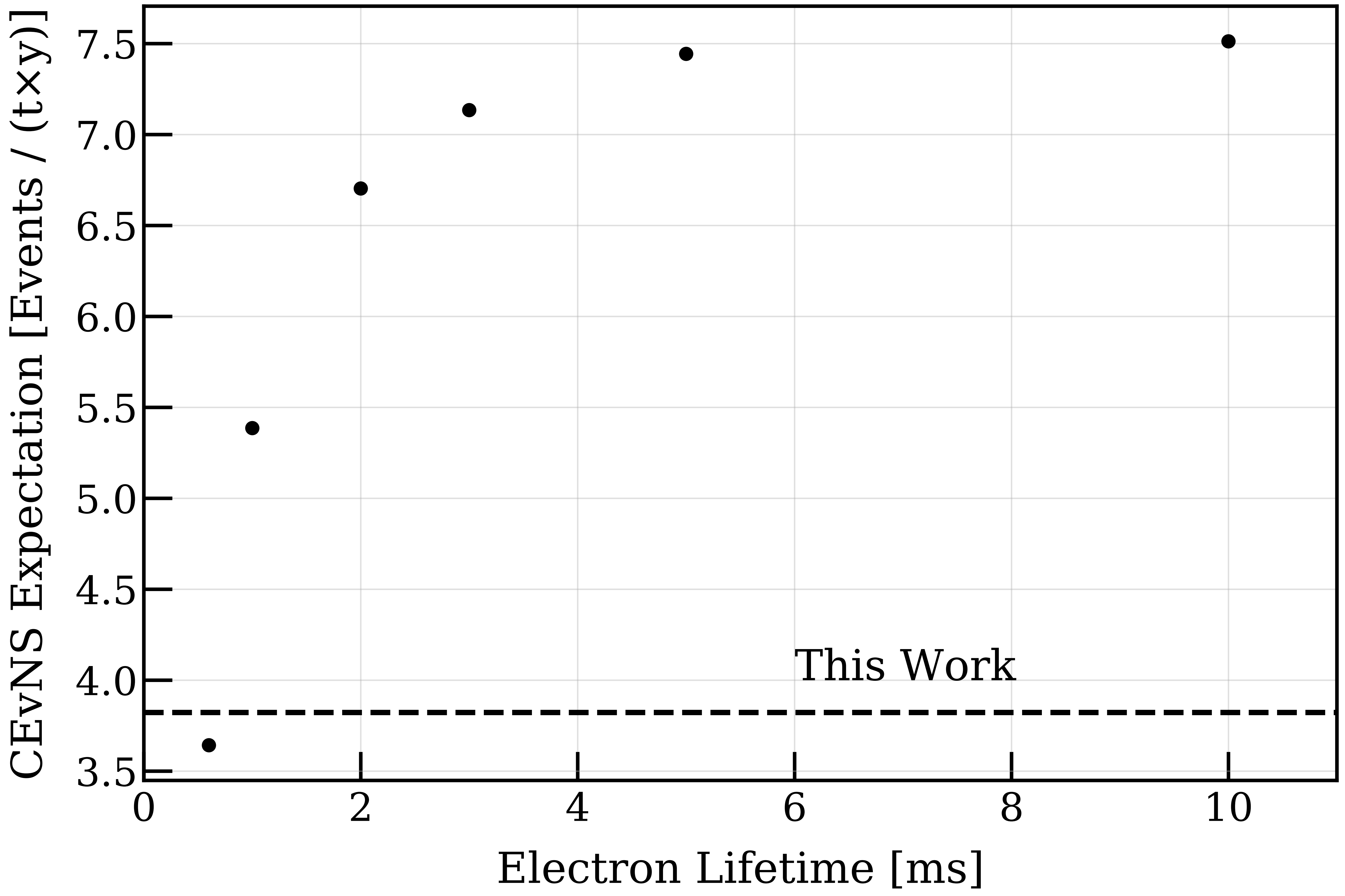
- 0.6 t × yr after livetime reducing cuts:
  - S2 shadow, PMT signal sum < 40 pe within first 40 ms of an event.
- 2 or 3 PMT hits with 1 PE ≤ S1 ≤ 6 PE
- 120 PE ≤ S2 ≤ 500 PE

GBDT cut in XENON1T



Electron lifetime dependence of CEvNS rate

Assume everything is the same as in XENON1T analysis except for electron drift lifetime.



Non-Standard Neutrino Interactions

4.6 x 10[27] nuclei/ tonne Xe

ν_e survival probability

Neutrino flux

CEvNS cross-section

$\tilde{Q}_W = Z \cdot (g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}) + N \cdot (g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})$

$$\frac{dR_e}{dT} = \mathcal{N} \cdot \int_{E_{\nu,\min}} P_e(E_\nu) \cdot \frac{dN}{dE_\nu} \cdot \frac{d\sigma(E_\nu, T)}{dT} dE_\nu \propto \tilde{Q}_W^2(\epsilon_{ee}^{uV}, \epsilon_{ee}^{dV})$$

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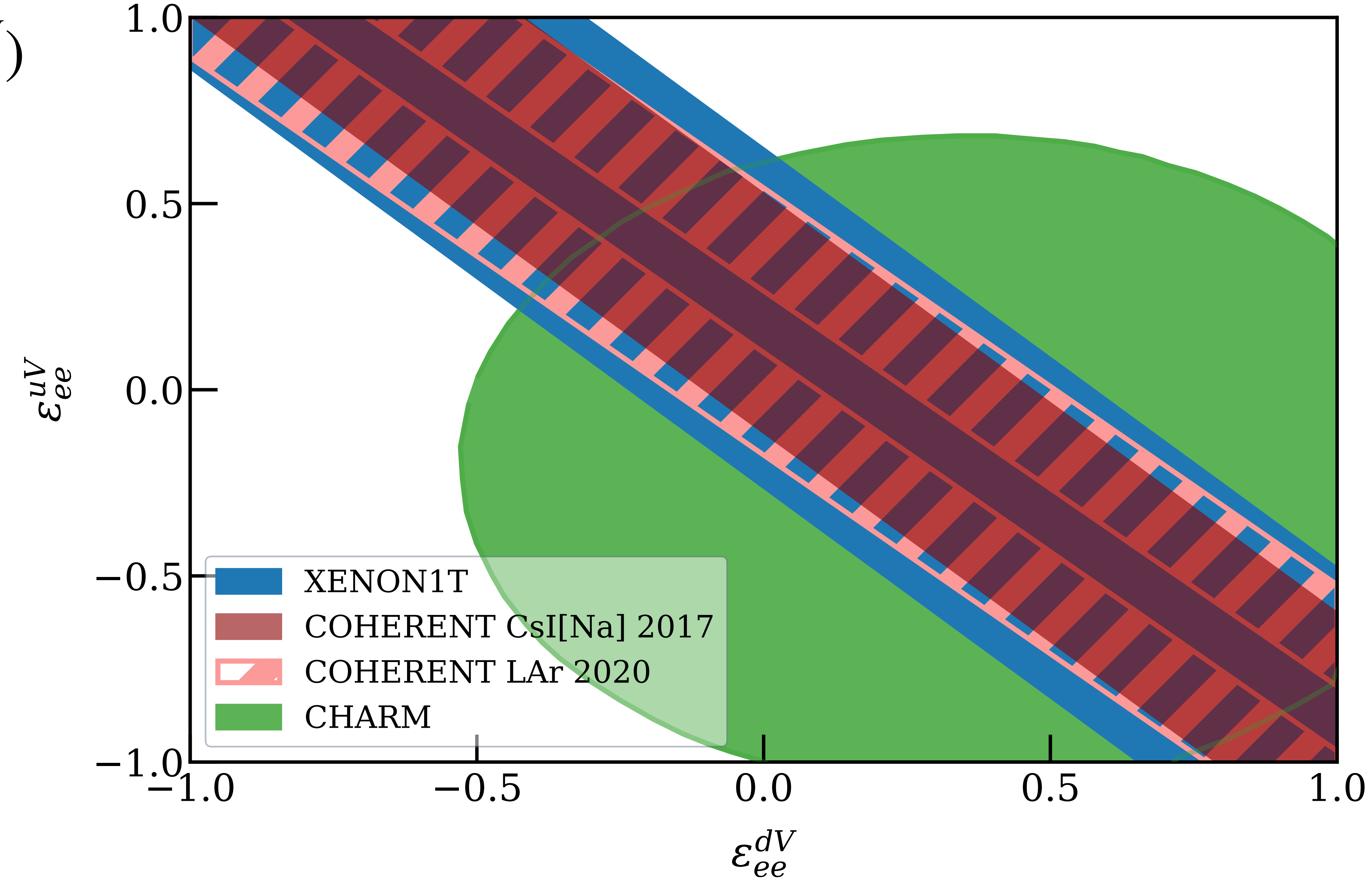
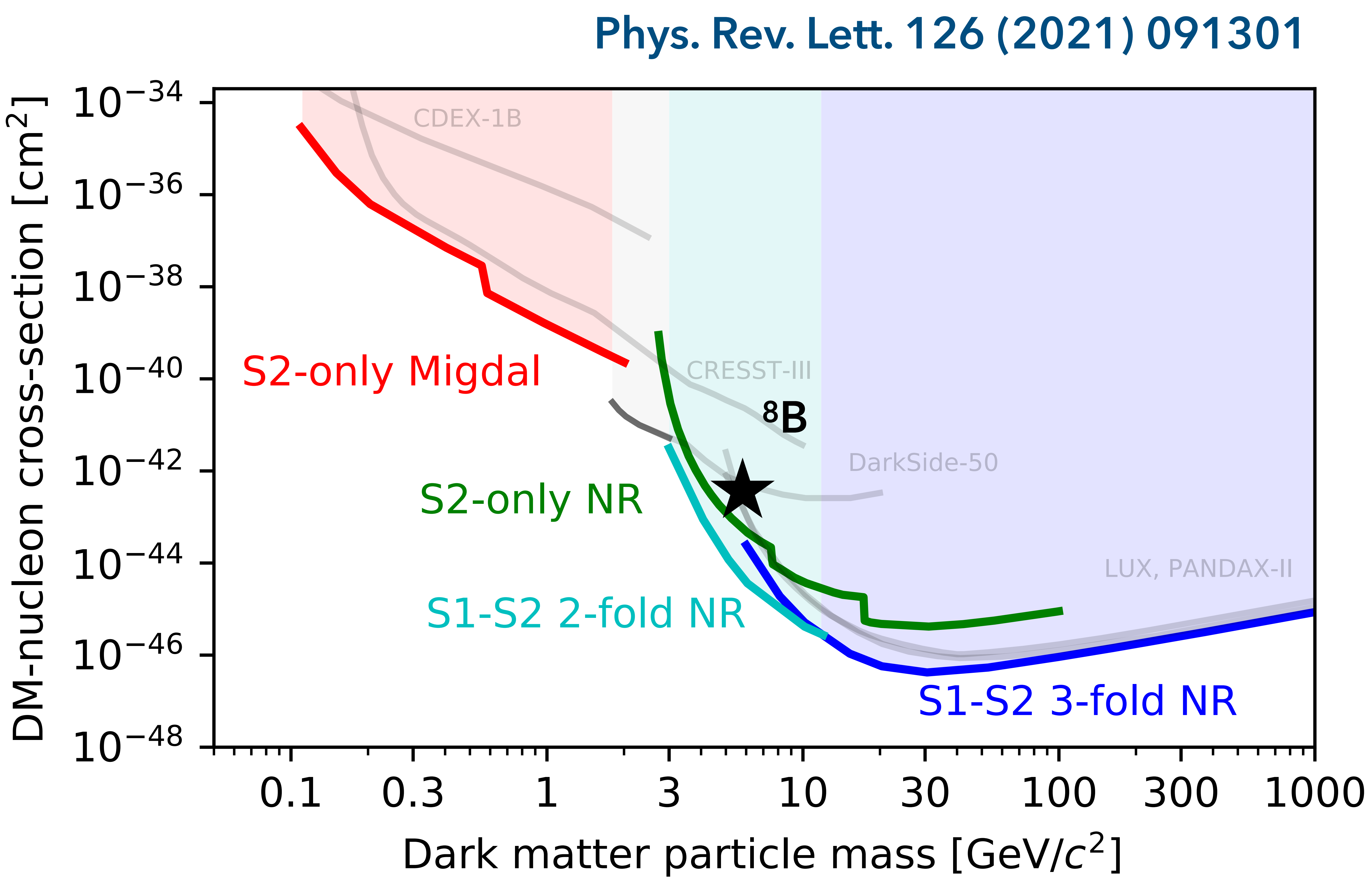


Compare integrated rate to SM prediction.

$\frac{dR}{dT} \propto \tilde{Q}_W^2$ gives constraint along a line in $\epsilon_{ee}^{uV} - \epsilon_{ee}^{dV}$

Improving XENON1T WIMP Limits



- No positive detection of CEvNS signal
- Use lowered threshold to set improved low-mass WIMP limits down to 3 GeV/c^2
- External constraints on neutrino flux and detector response
- Improvement over previous S2-only analysis range

Isolated peaks

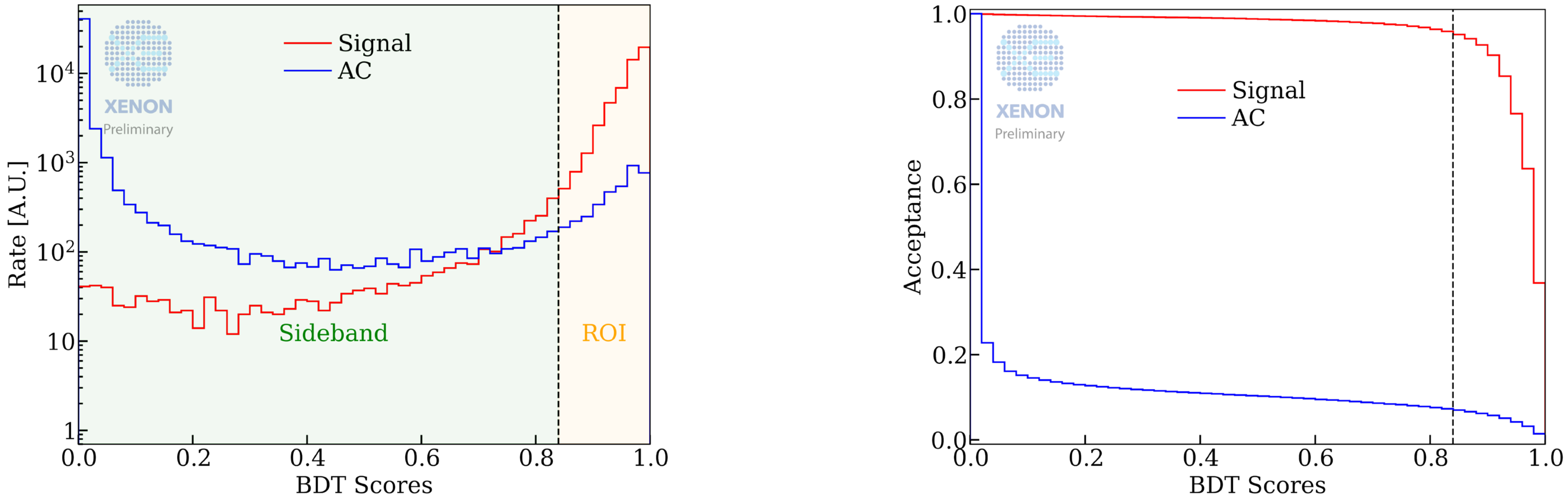
Isolated S1:

- Identified as S1, 3-PMT coincidence, < 150 PE
- No S2 in maximum drift time window…
- … or no correlation with S1 and S2 as defined by BDT or S1 top area fraction cuts

Isolated S2:

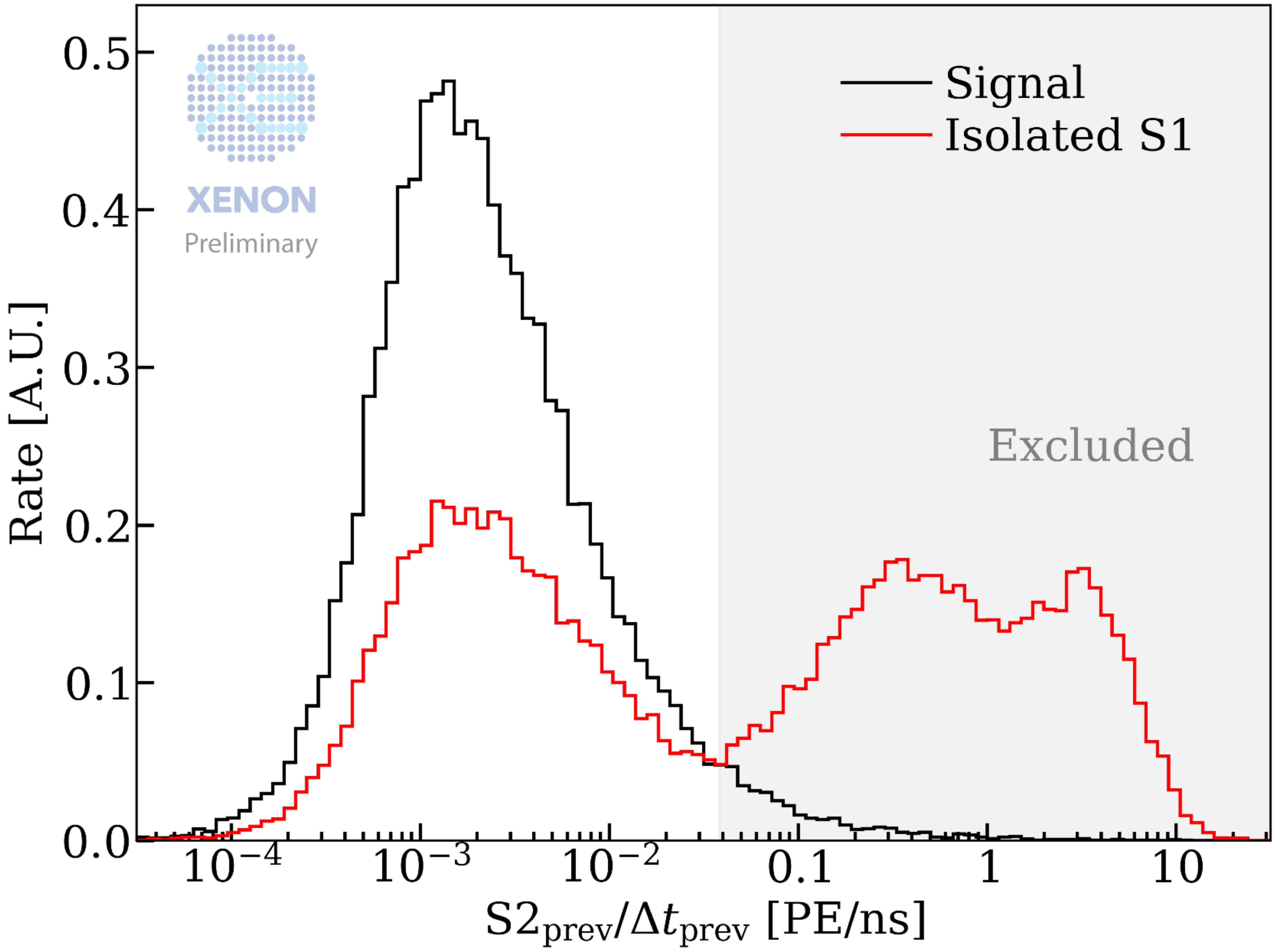
- Select at the event level and also analyze "ambience" (e.g. lone hits before S1 + S2) around them in order to suppress correlated S1 + S2 events.
- In order to not lose isolated S2s at the modeling stage
- Either S1 < 150 PE or no S1 within the same event window.

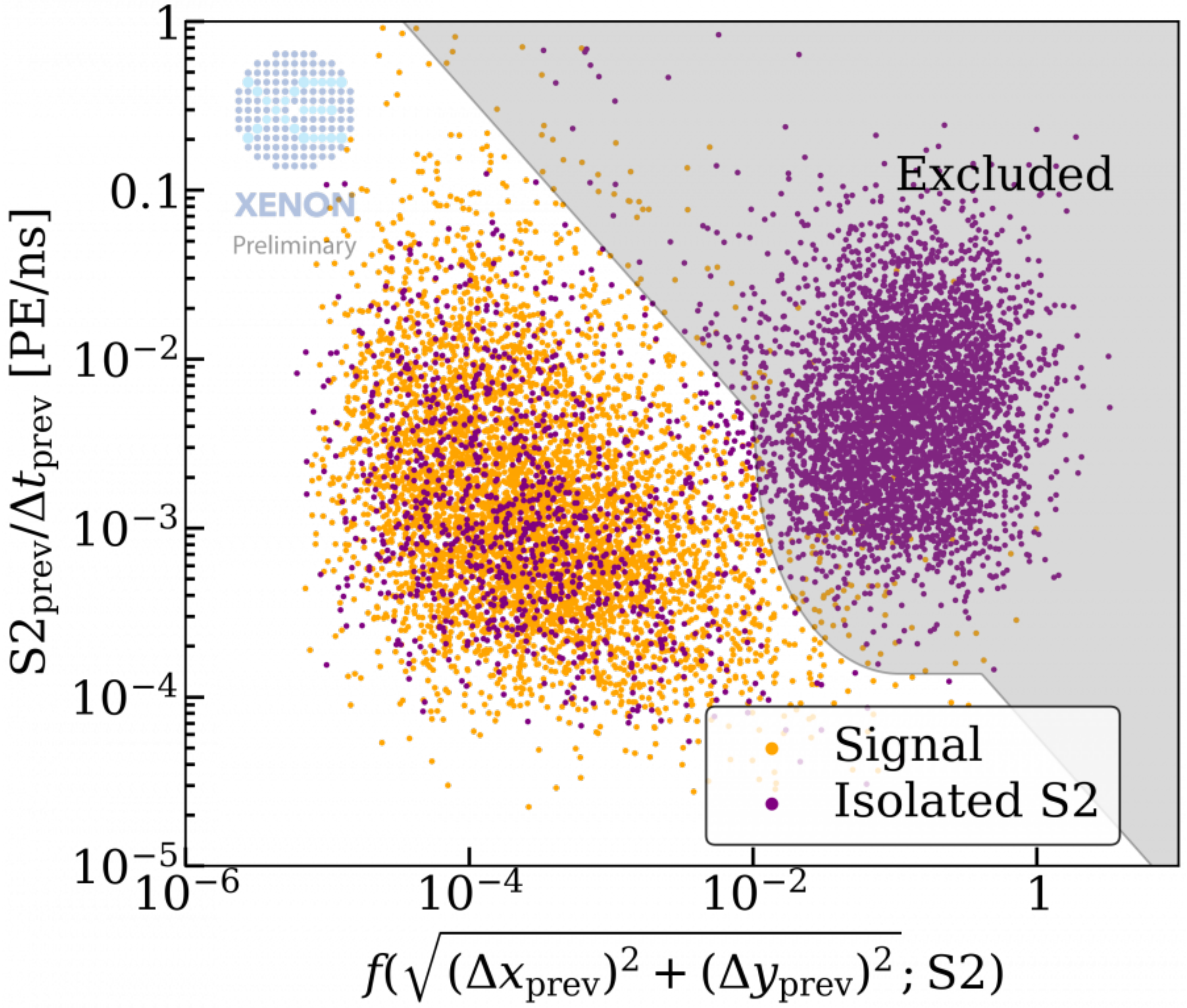
Boosted decision tree cut



- Random pairing of isolated S1 and S2 will lead to random drift times and unphysical values for peak features depending on the event position
- In essence multi-parameter space extension of an S2 width cut using gradient boosted decision trees
- Train on data-driven AC templates, pick signal acceptance and associated AC rejection based on full waveform simulation of signals

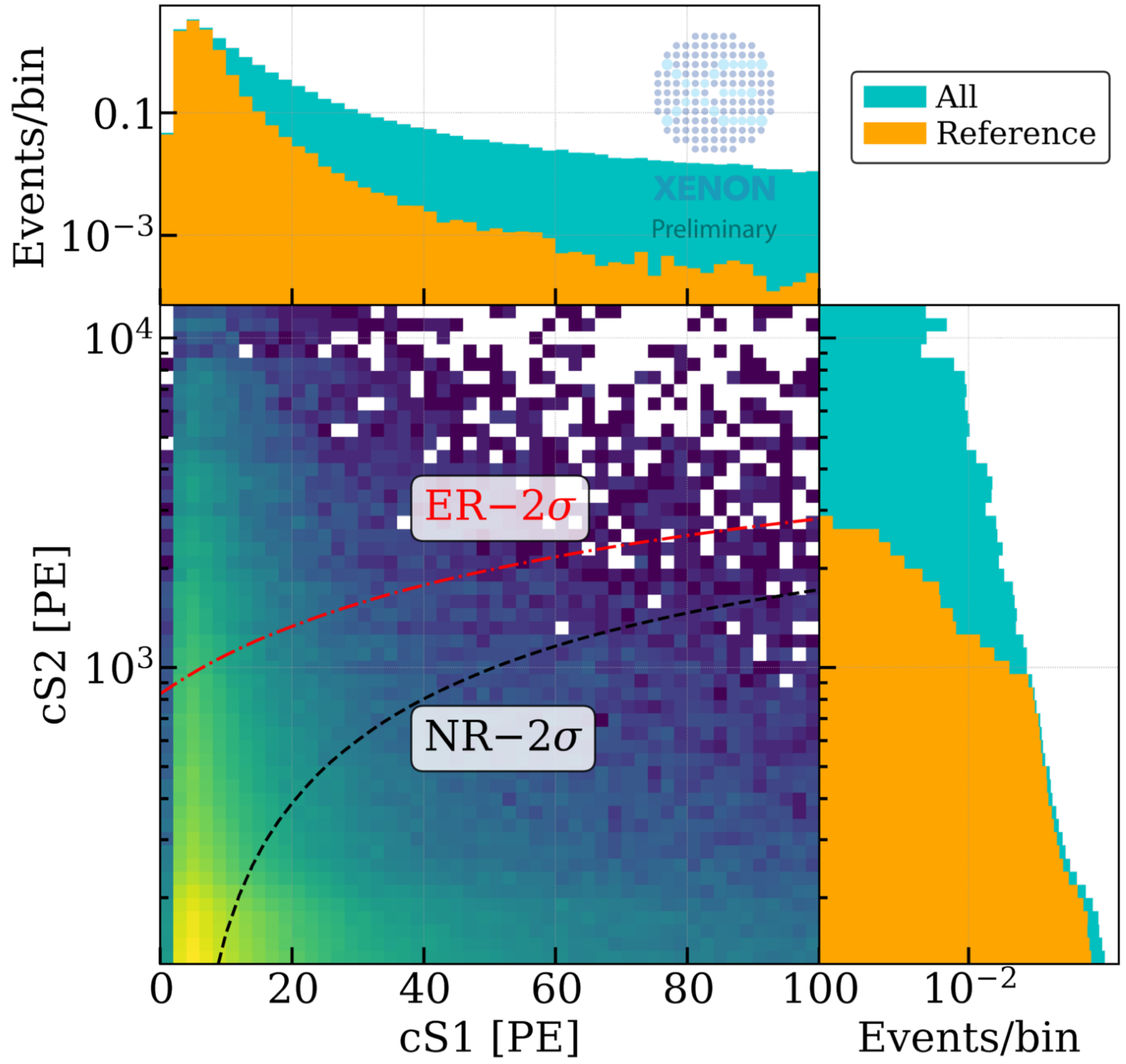
Shadow cut





- Time veto that rejects everything within certain periods of large S1s or S2s
- Shadow veto rejection based on $S2_{prev}/\Delta t_{prev}$
- Position correlation veto based on S2 spatial correlation with preceding S2

AC model in XENONnT WIMP analysis

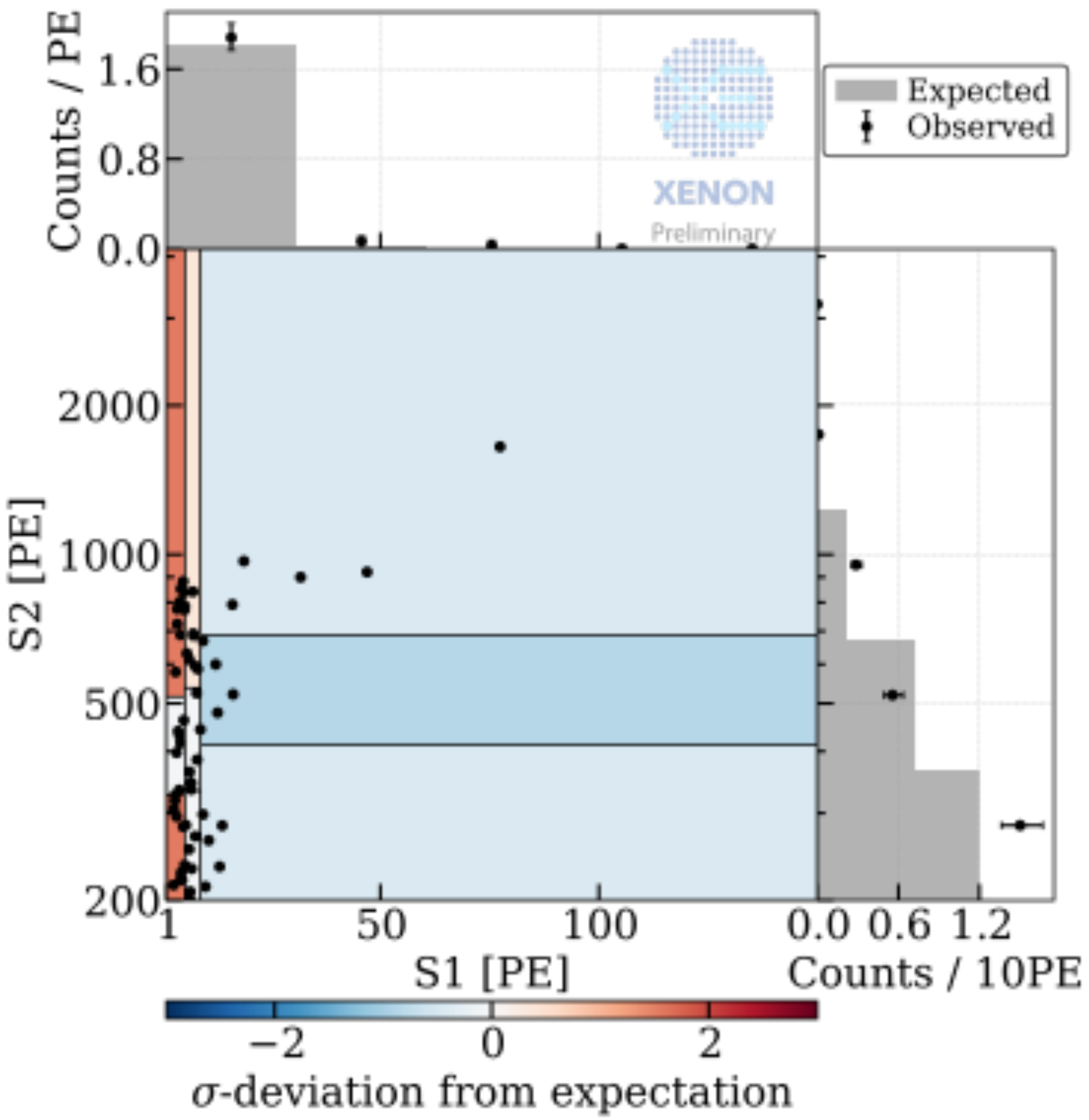


- Model is purely data-driven, large isolated S1 and S2 samples achieved due to triggerless DAQ
- Isolated S1 rate similar to XENON1T, isolated S2 rate 100 times higher (lower extraction efficiency)
- Make AC template by random pairing of isolated S1 and S2
- AC rate prediction from isolated peak rates after preparing cuts: 3.2 events in SR0 WIMP data
- Suppression at peak (shadow and S2 spatial correlation with preceding large S2) and event level (S2 width, BDT)

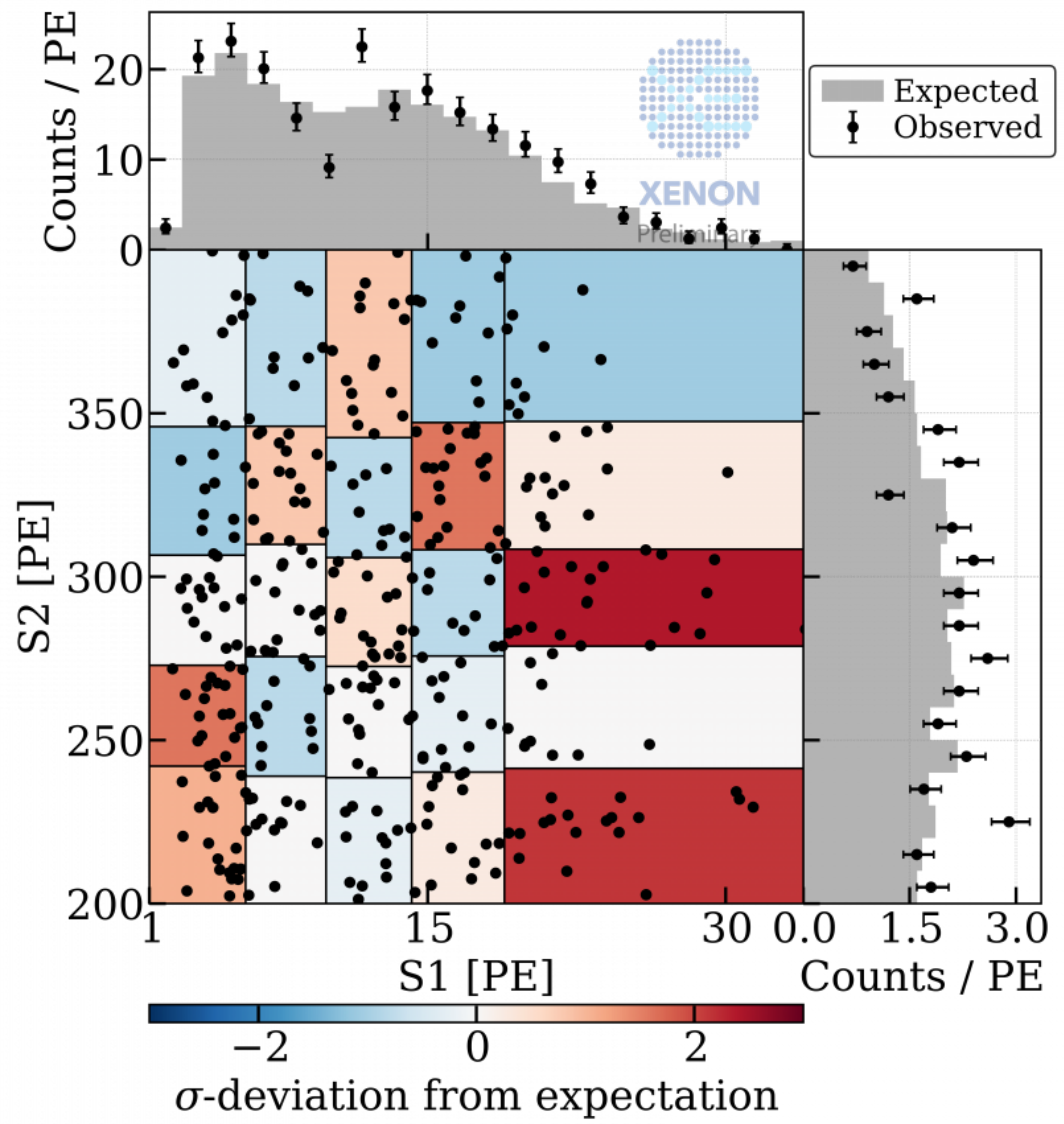
AC validation in XENONnT WIMP analysis

- Model validation in AC-domiated samples of science data, ^{220}Rn and ^{37}Ar:
  - WIMP ROI passing all cuts
  - AC sideband not passing S2 width or BDT

WIMP data sideband

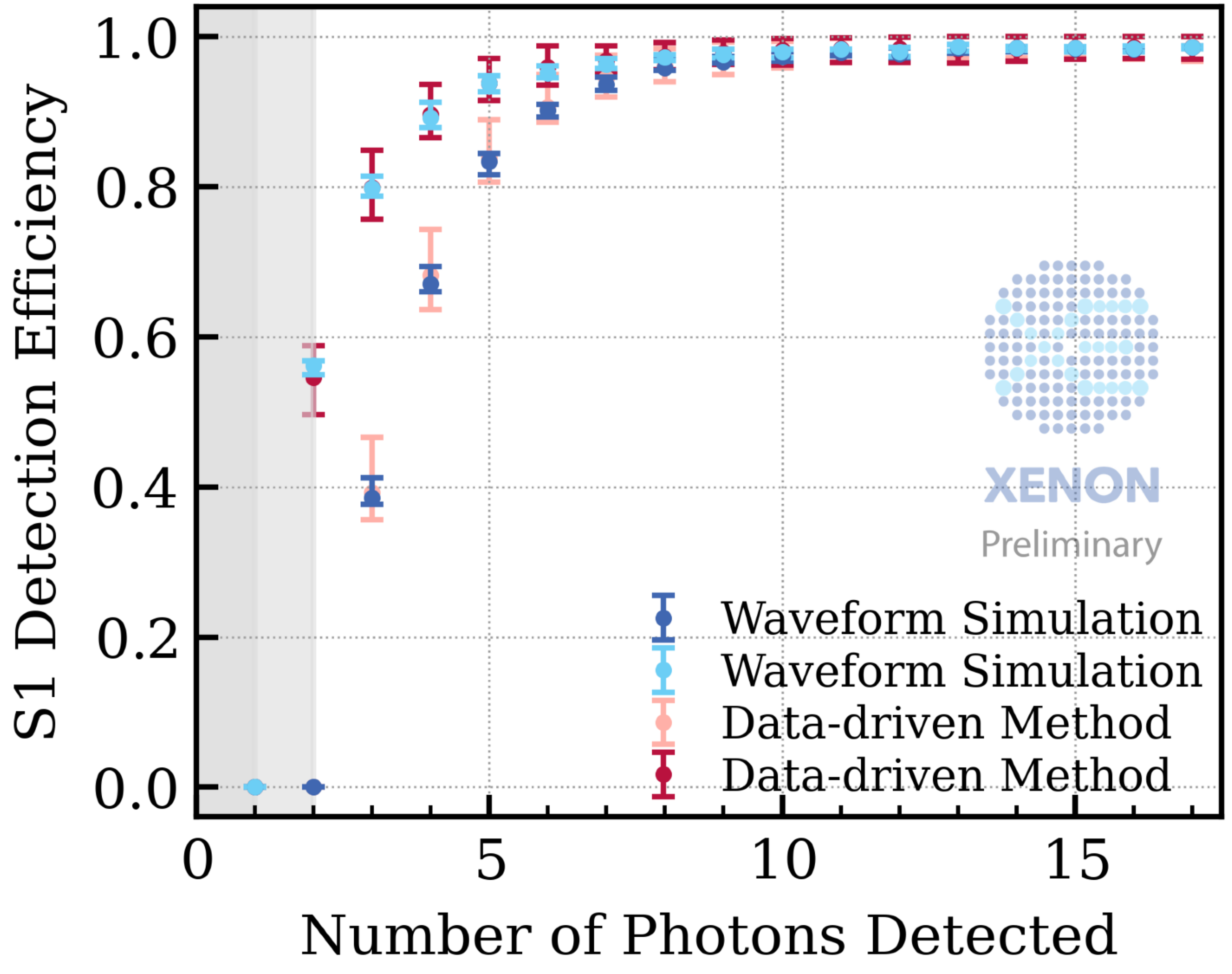


Ar-37 sideband

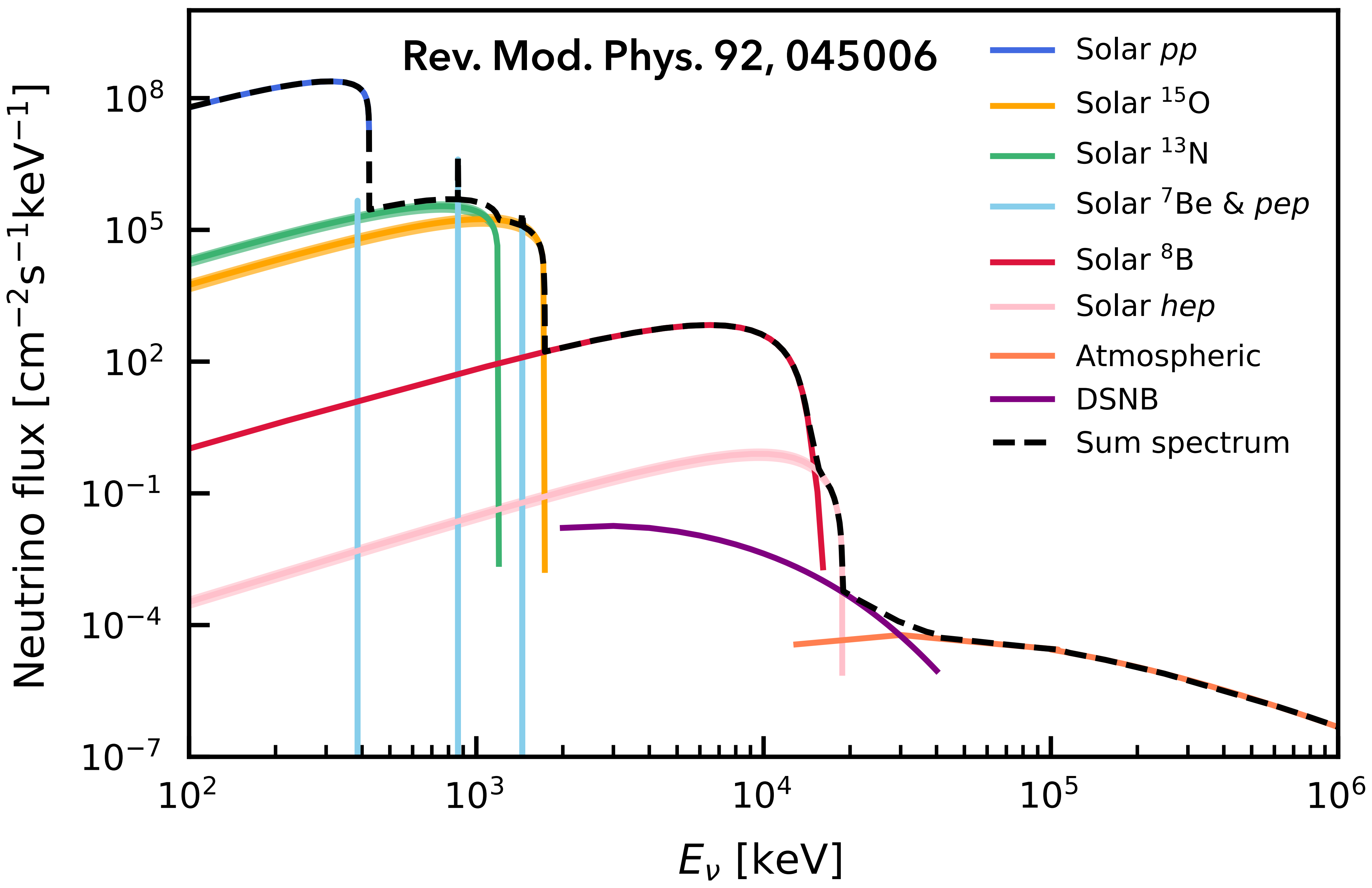


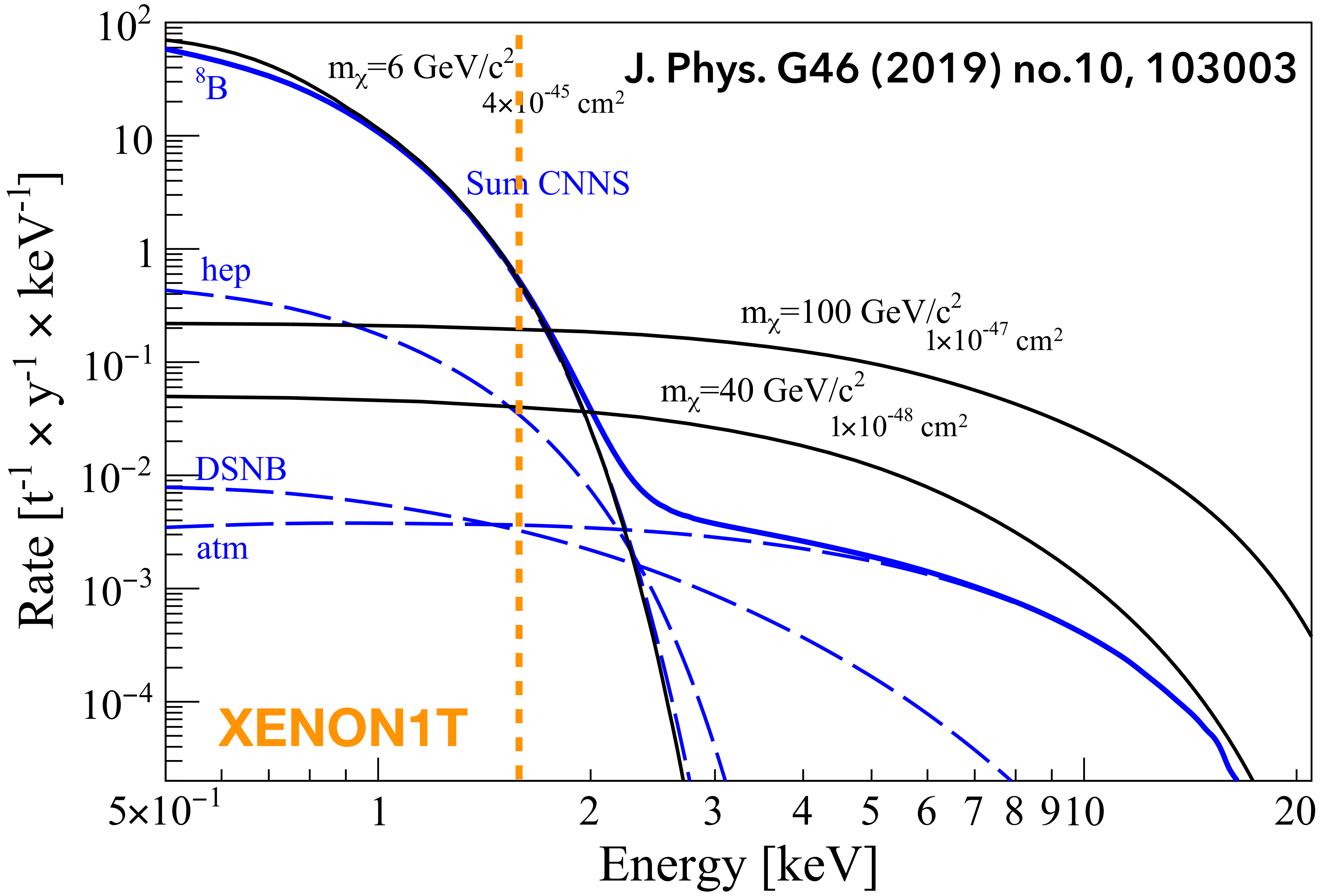
S1 detection efficiency

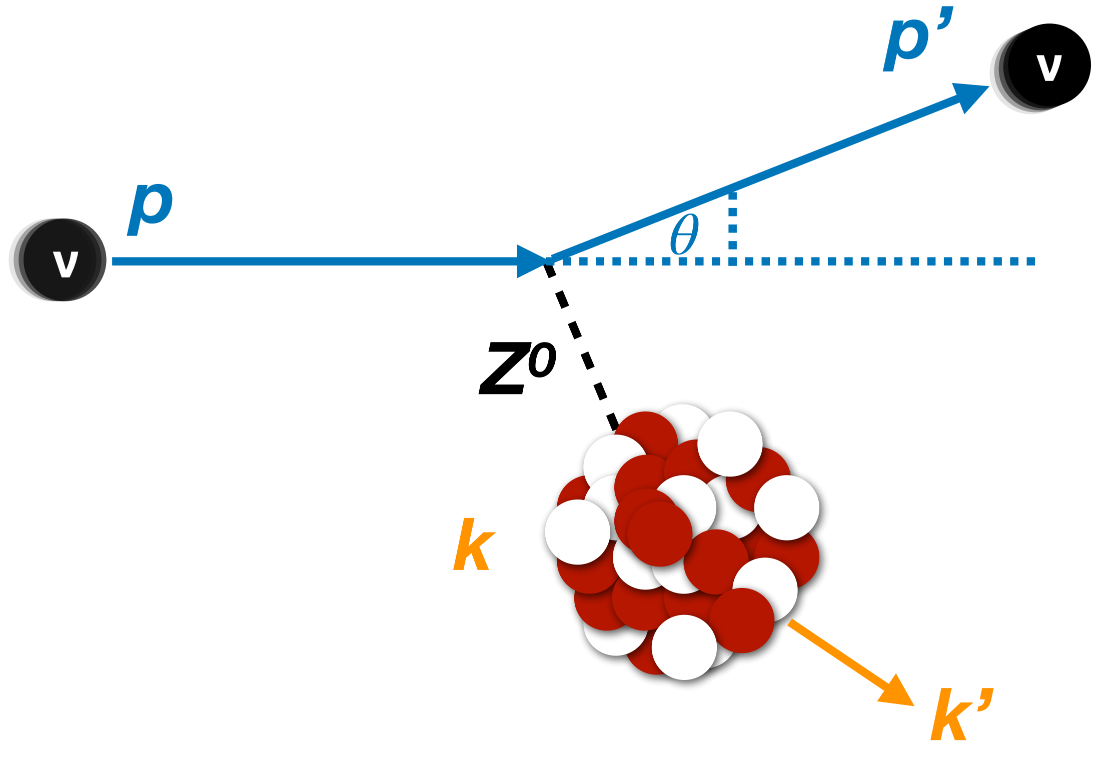
- S1 detection efficiency modeled either by:
  - waveform simulation (final model)
  - bootstrapping of S1 hits from ^{37}Ar and ^{83m}Kr S1s at 2.8 keV, 9.4 keV and 32.1 keV (cross-check)
- Grey regions denote invalid areas from requiring 2- or 3-PMT tight coincidence within 50 ns
- Data-driven uncertainties from data selection bias, energy- and position dependence of S1 pulse shape, and statistical uncertainty
- Simulation uncertainties dominated by position-dependence of S1 pulse shape



Neutrino fluxes and recoil spectra







$$T_{\max} = \frac{2E_\nu^2}{2E_\nu + m_A c^2} \approx \mathcal{O}(1)\ \mathrm{keV}$$

CEvNS of solar ^8B neutrinos mimics ~ 6 GeV/c² WIMPs (neutrino fog)

XENON1T Time Projection Chamber

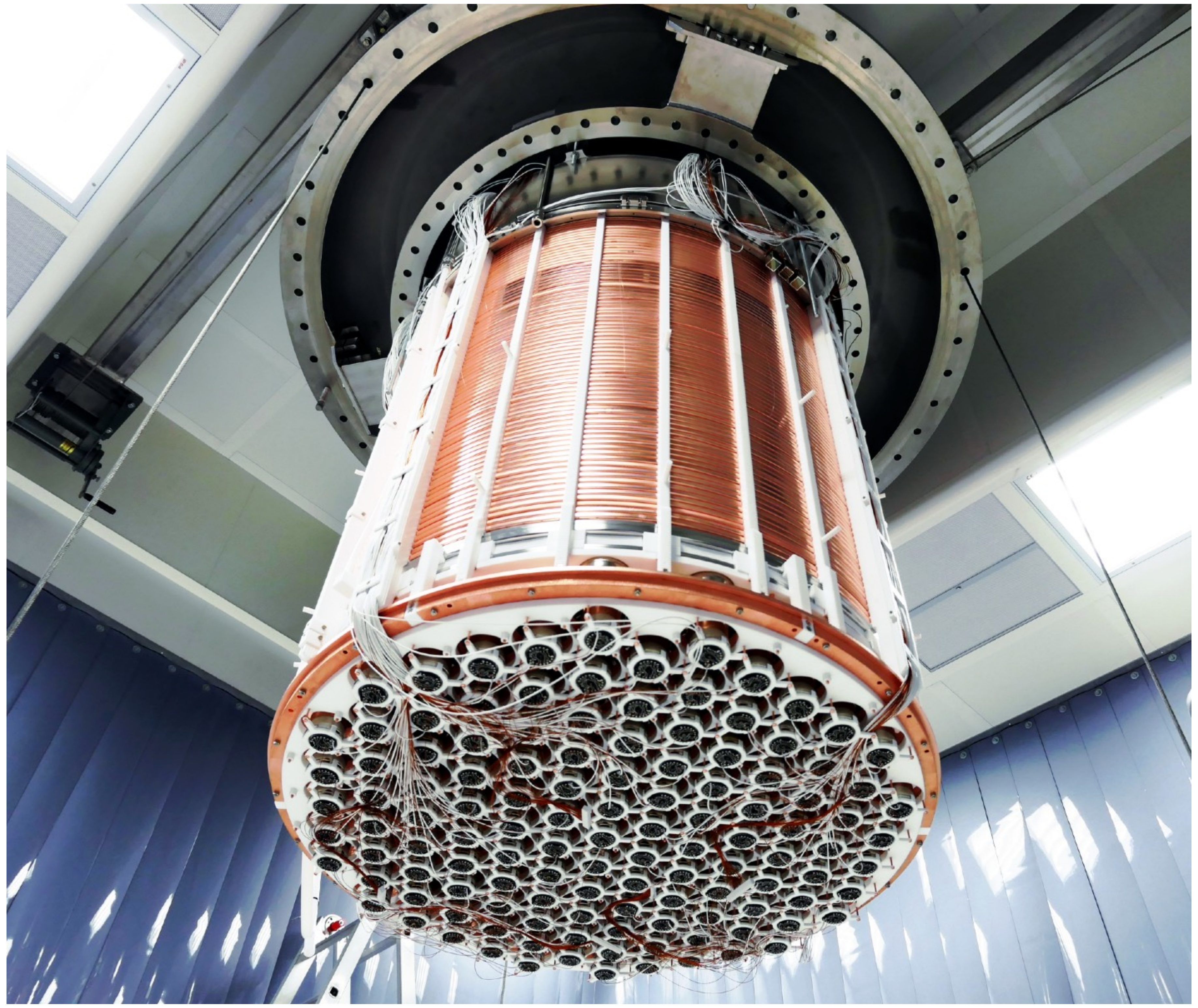
2 t LXe in active volume

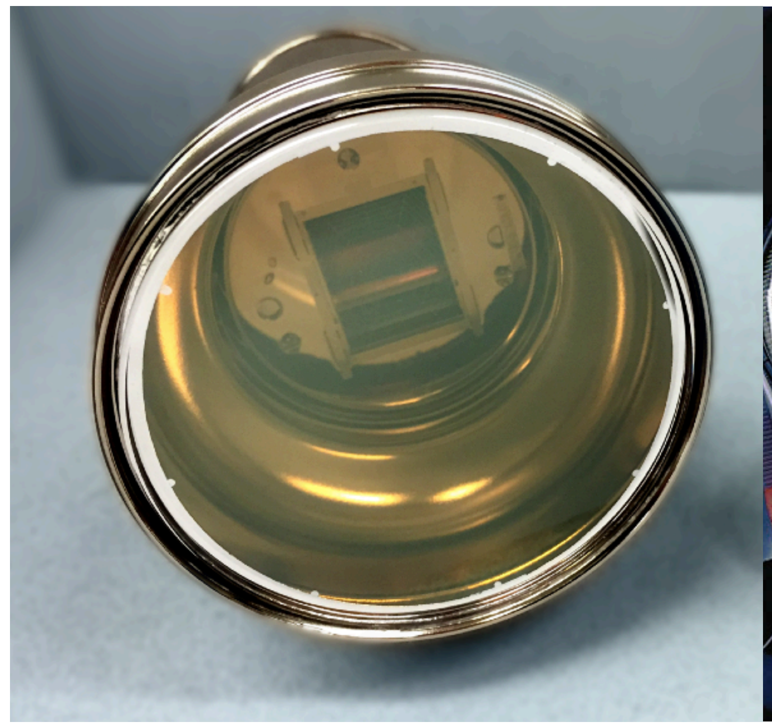
~ 1 m diameter
~ 1 m length

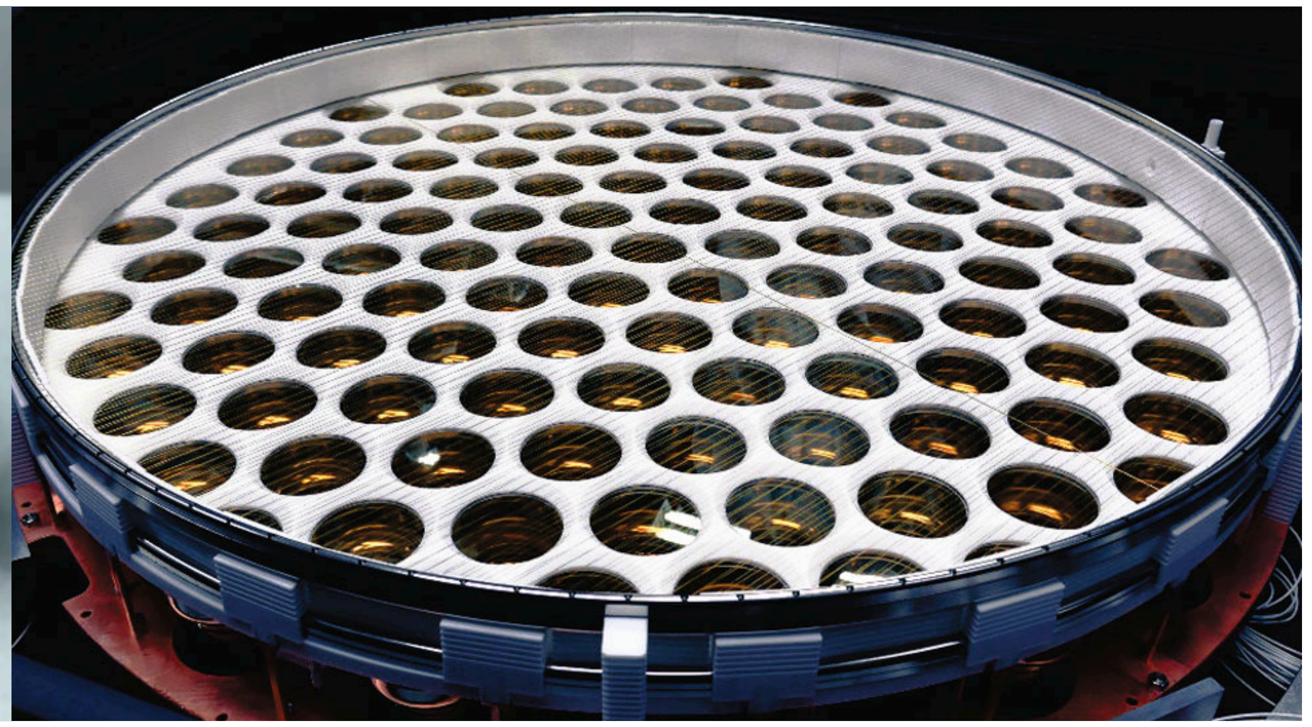
Highly reflective
PTFE walls

74 copper field shaping
rings

Five high-transparency
electrodes





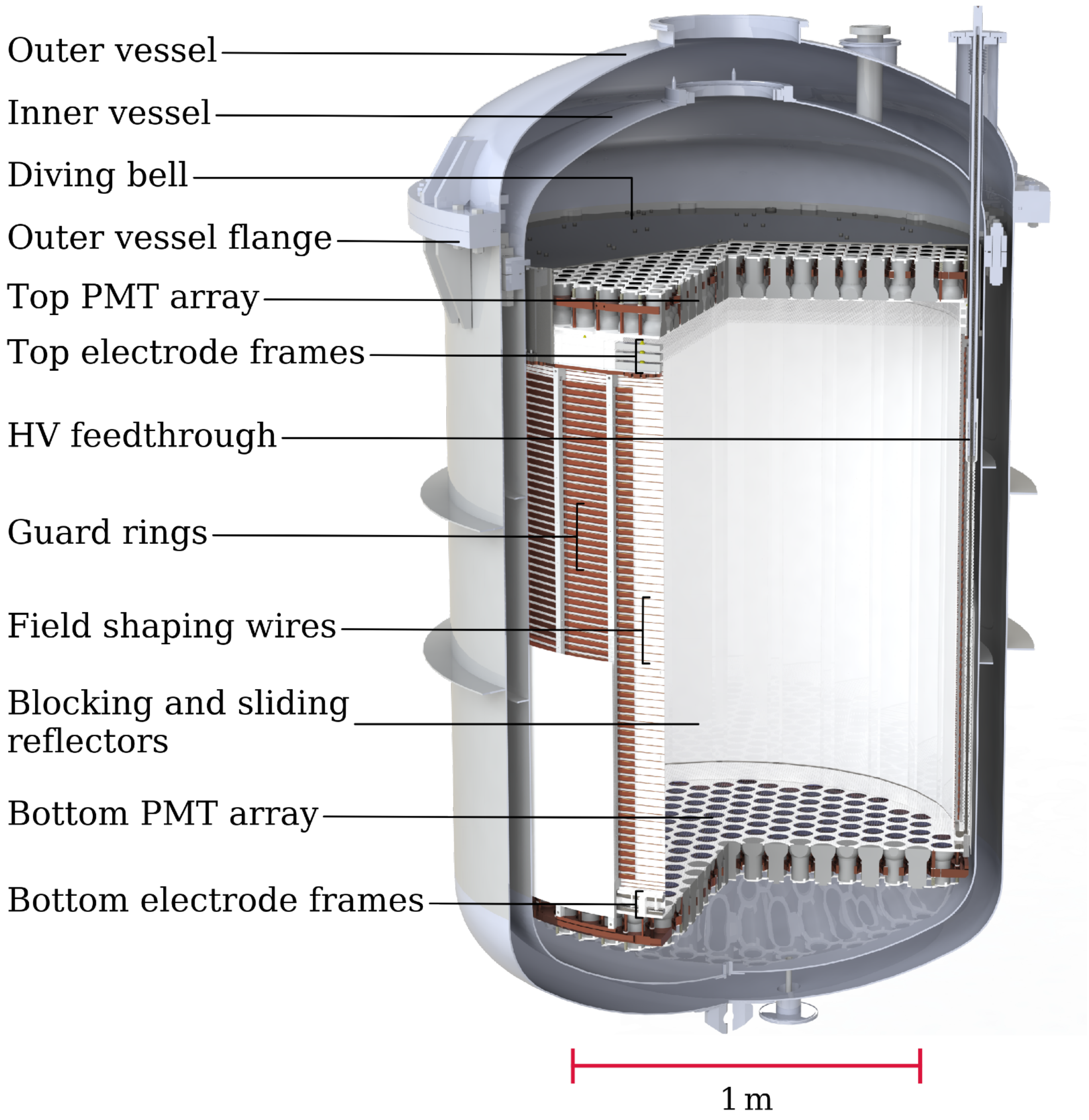


EPJ C 11:546 (2015)

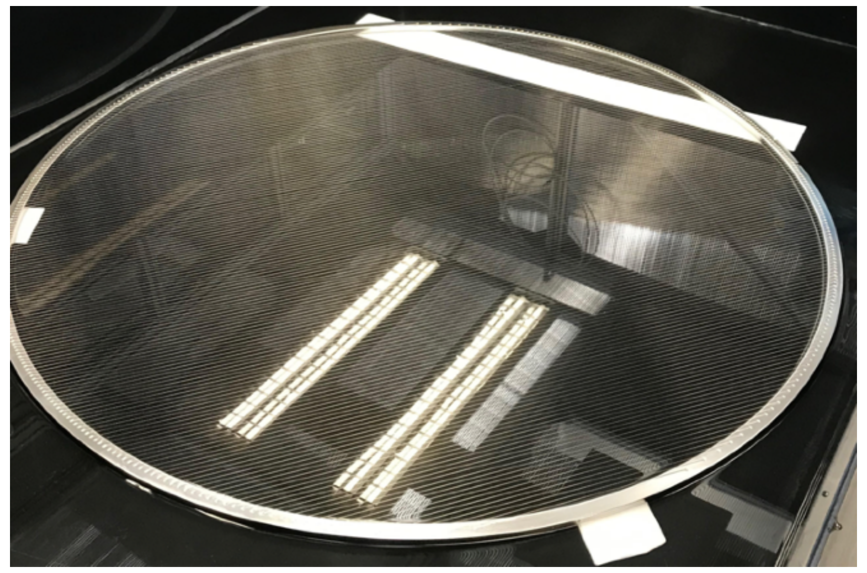
238 Hamamatsu R11410-21 PMTs

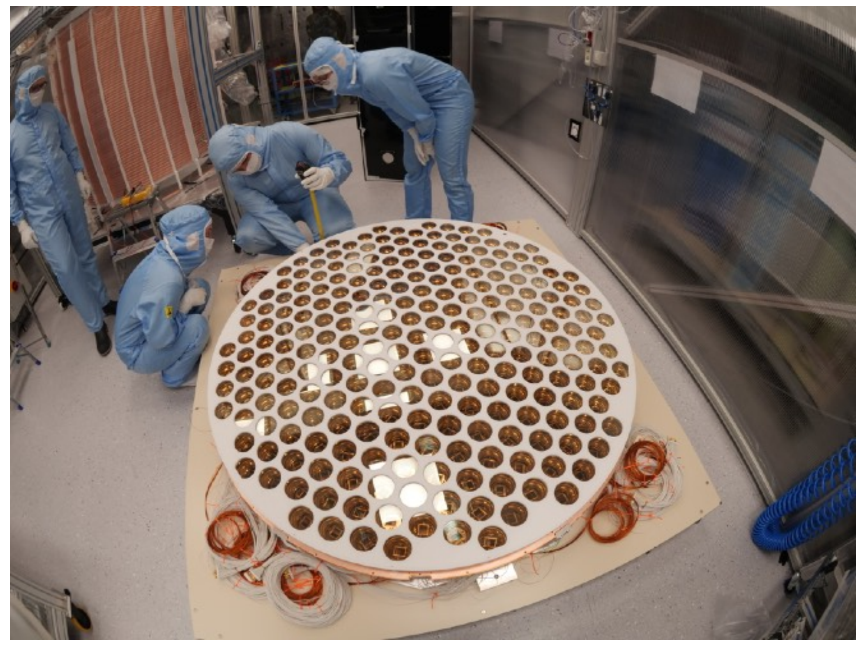
3″ PMTs, low radioactivity, QE ~ 35 % at 175 nm

XENONnT Time Projection Chamber

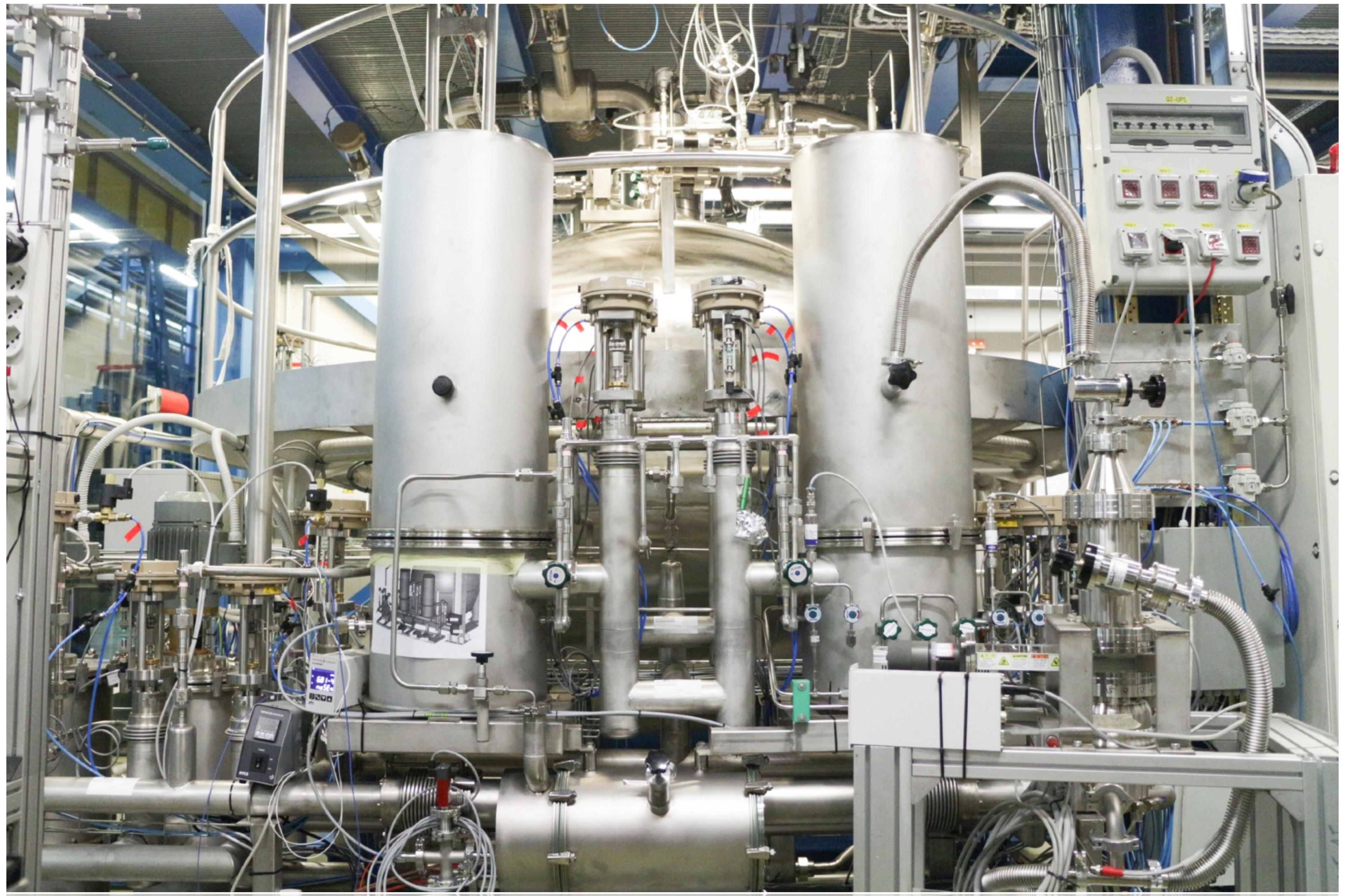


- 5.9 t active mass (planned 4.0 t fiducial)
- 1.5 m drift, 1.3 m diameter
- 494 PMTs (3”), Hamamatsu R11410-21
- Two sets of concentric field-shaping rings



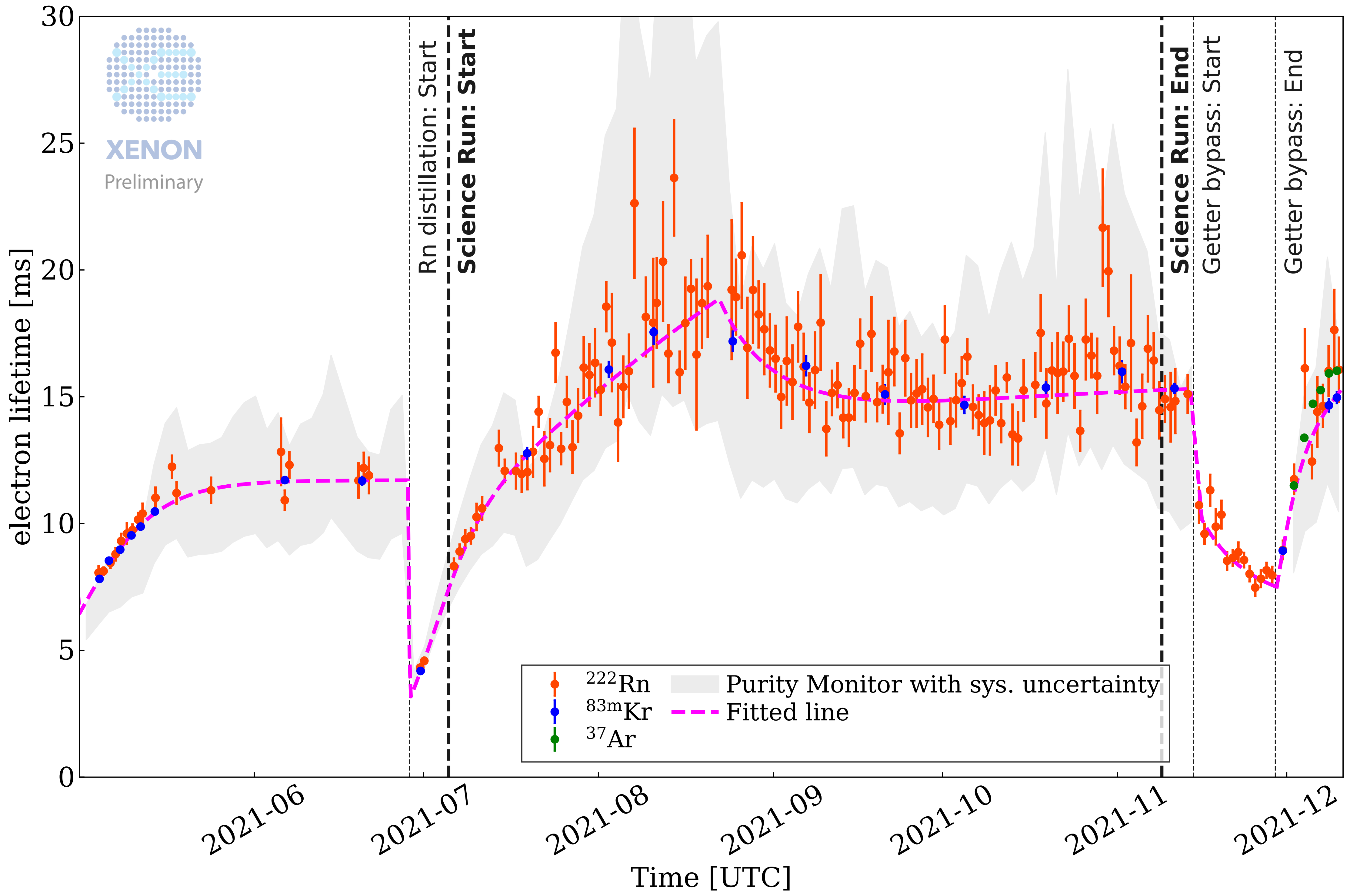


XENONnT Liquid Purification



XENON1T: 0.65 ms ≈ 0.9 x maximum drift-time (30 % cathode survival)

XENONnT: 2.2 ms maximum drift (> 90 % cathode survival)



- High purification flux for removing electronegative impurities: 2 l /min LXe ≈ 350 kg/h
- Low-Rn filters for science data taking
- Achieved electron-lifetime of > 20 ms

XENONnT Radon Distillation Column

- Constantly remove emanating radon from xenon using difference in vapor pressure
- Remove radon faster than it decays ($T_{1/2}$ = 3.8 d)
- Liquid xenon inlet and outlet with 0.4 l/min ≈ 70 kg/h LXe

XENONnT Radon Distillation Column

- Reached equilibrium concentration of 1.72 µBq/kg by gas extraction only
- Background goal 1 µBq/kg
- Additional factor 2 in Rn removal possible in the future using originally planned liquid extraction