Direct Dark Matter Detection with XENON1T

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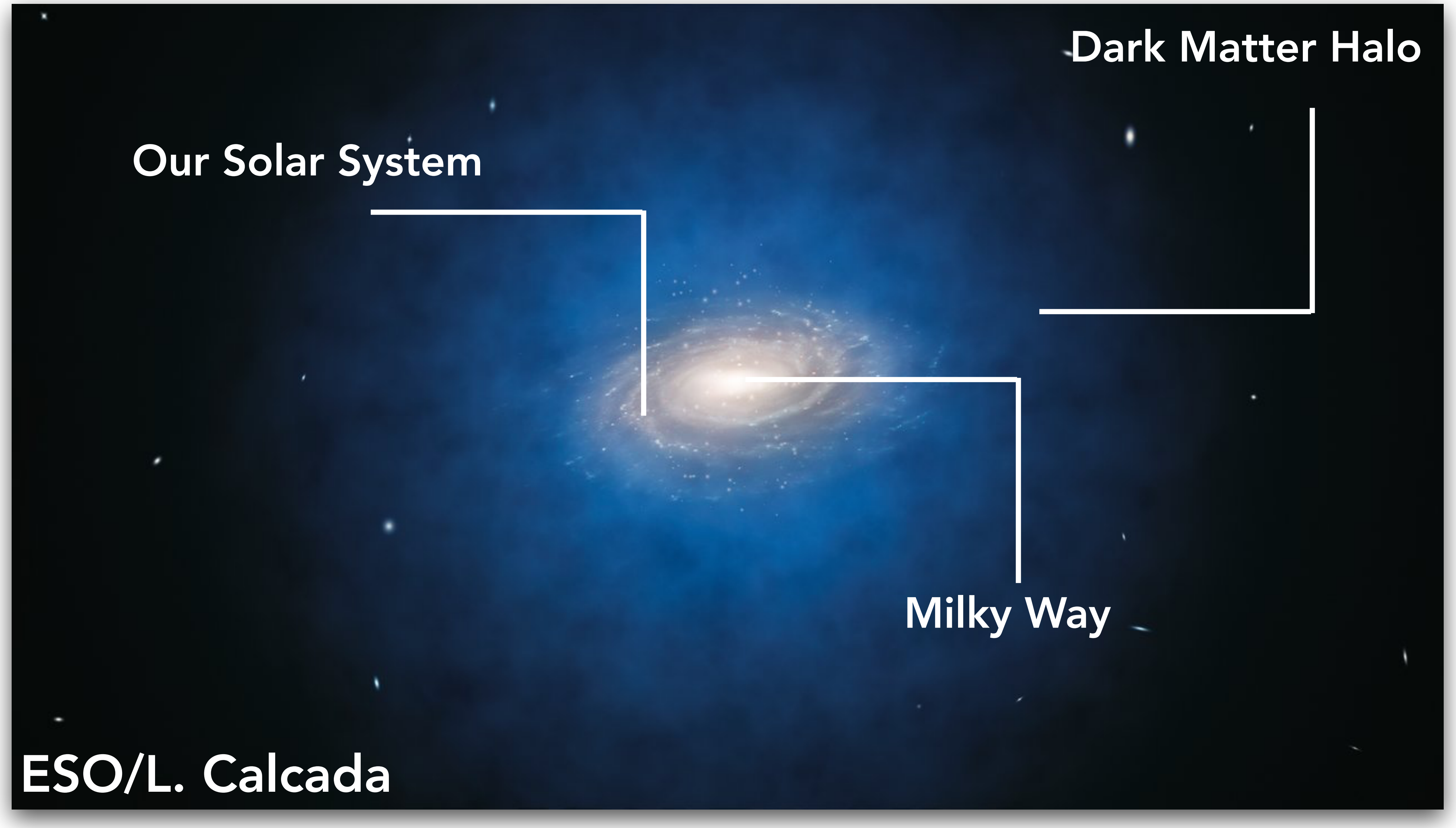
University of Zurich
On Behalf of the XENON Collaboration

TeVPA, 28 August, 2018

DIRECT DARK MATTER DETECTION



- Elastic scattering of WIMPs with atomic nuclei
- Measure energy of recoiling nucleus in an earth-bound detector (few keV - tens of keV)

$$E_{NR} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \sim \ 10\,\mathrm{keV}$$

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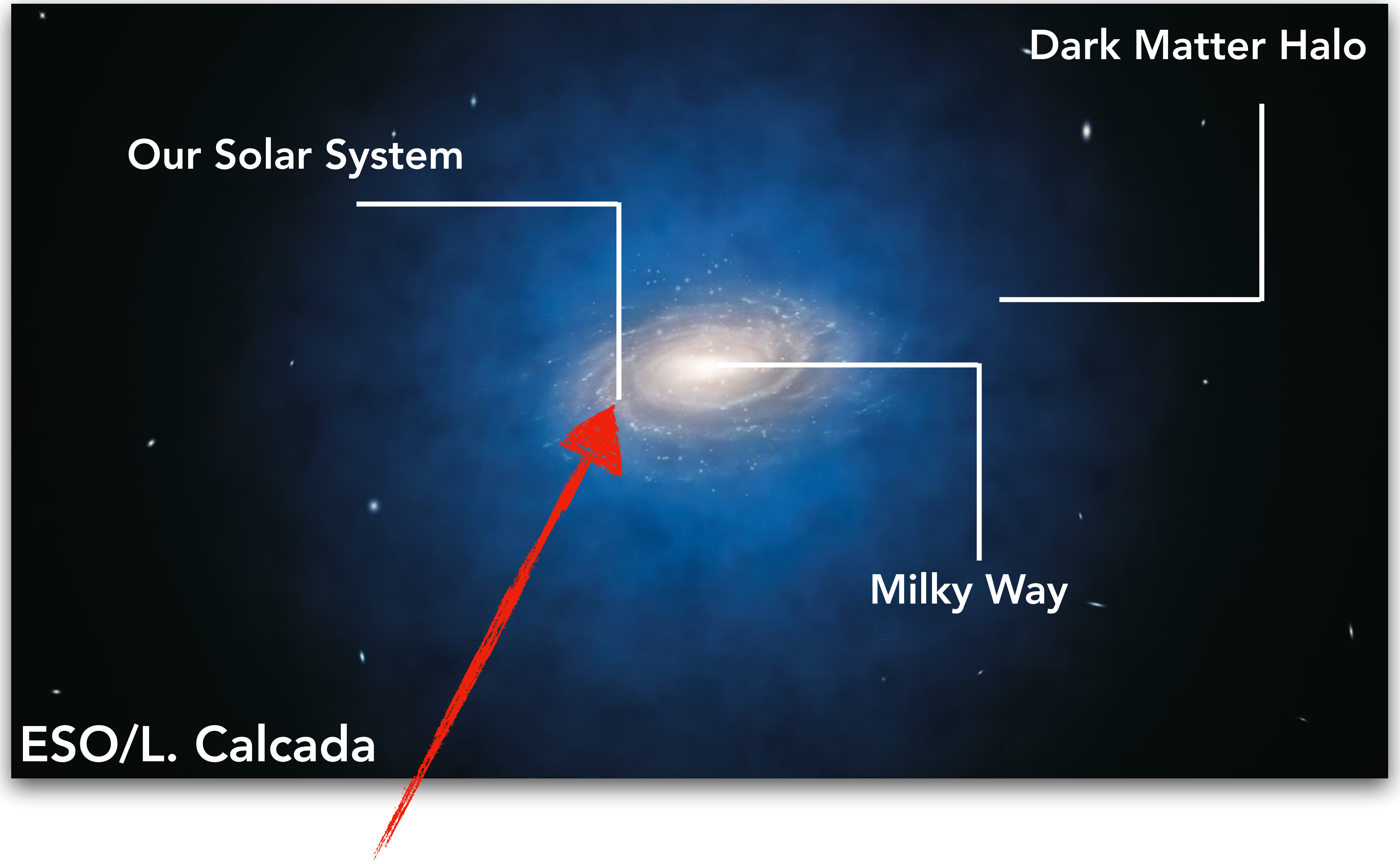

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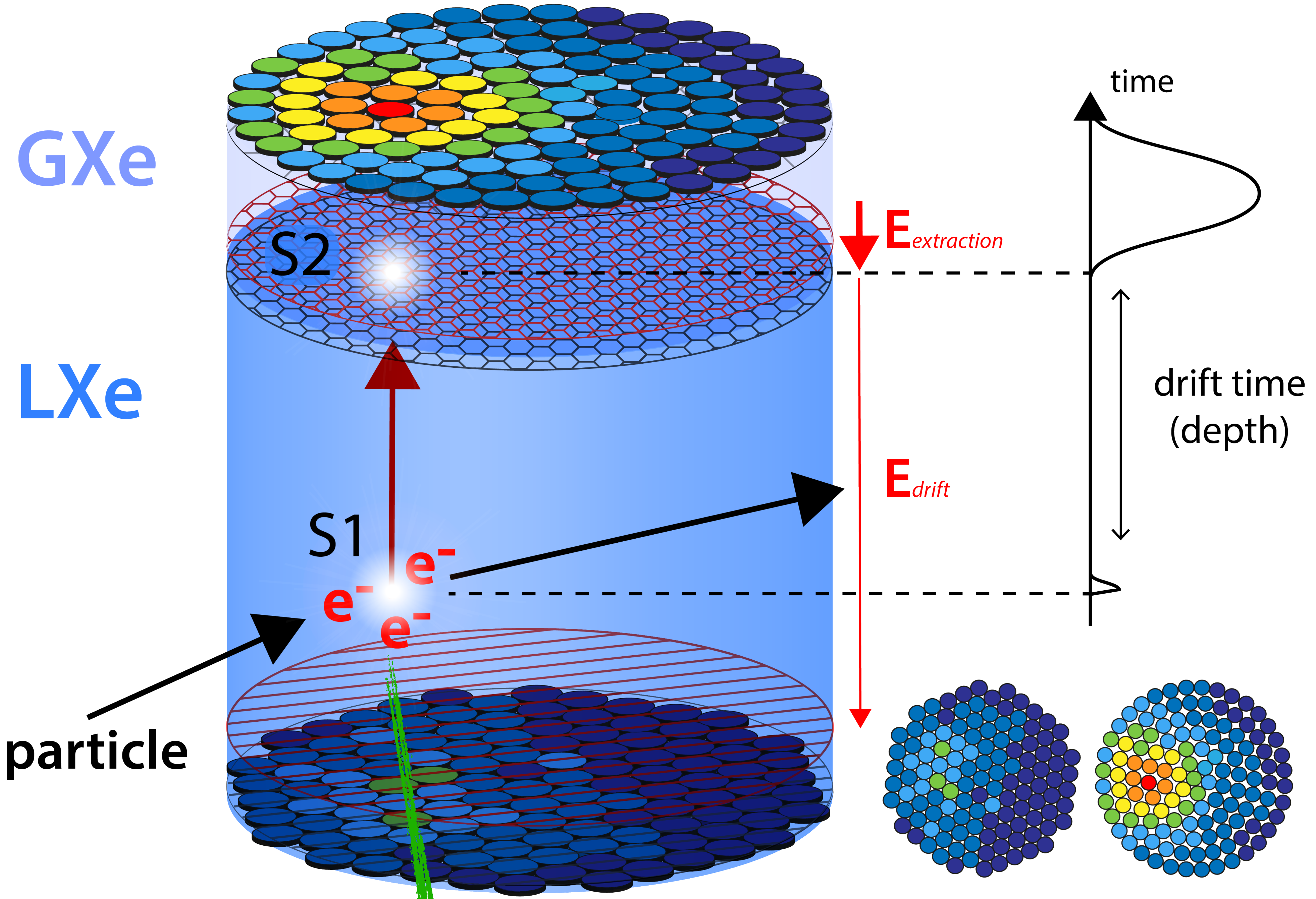
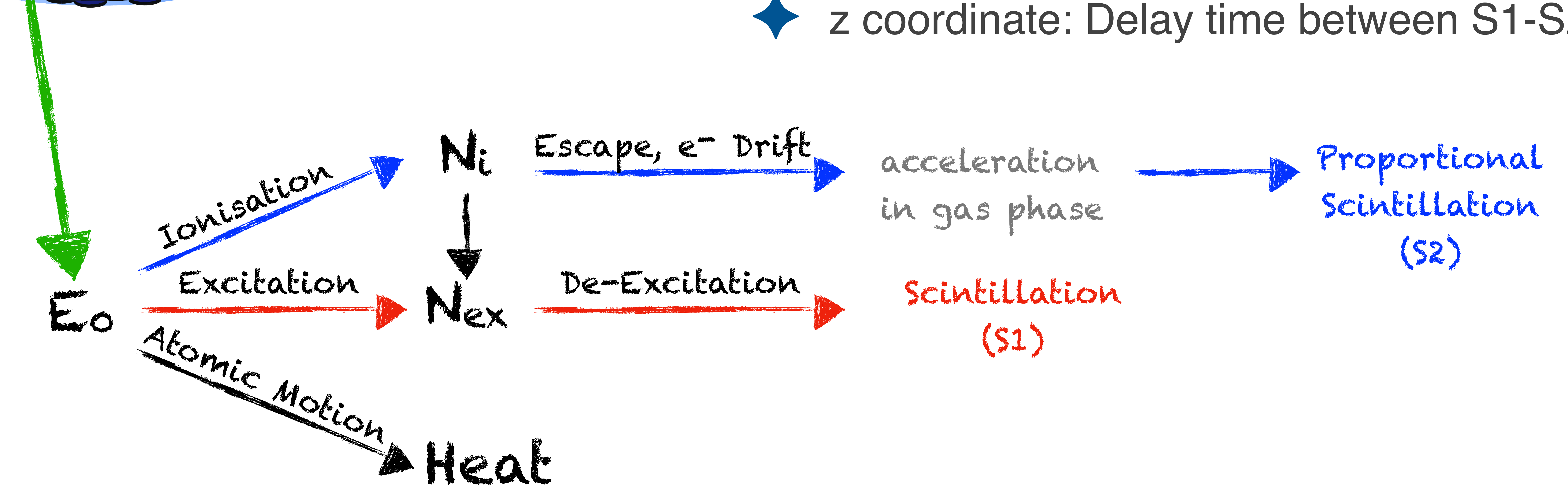
Detector physics	Particle/nuclear physics	Astrophysics
N_T	$m_w, \sigma_{\mathrm{SI/SD}}$	$\rho_0, f(v)$

$$R \sim N_T \times \frac{\rho_0}{m_w} \times \langle v \rangle \times \sigma$$

XENON-BASED DUAL-PHASE TPC



- Particle interaction in liquid xenon
  - S1: Prompt scintillation in liquid xenon
  - S2: Proportional scintillation in gaseous xenon caused by drifted electrons
- 3D vertex reconstruction
  - x-y coordinates: S2 hit pattern in top PMTs
  - z coordinate: Delay time between S1-S2



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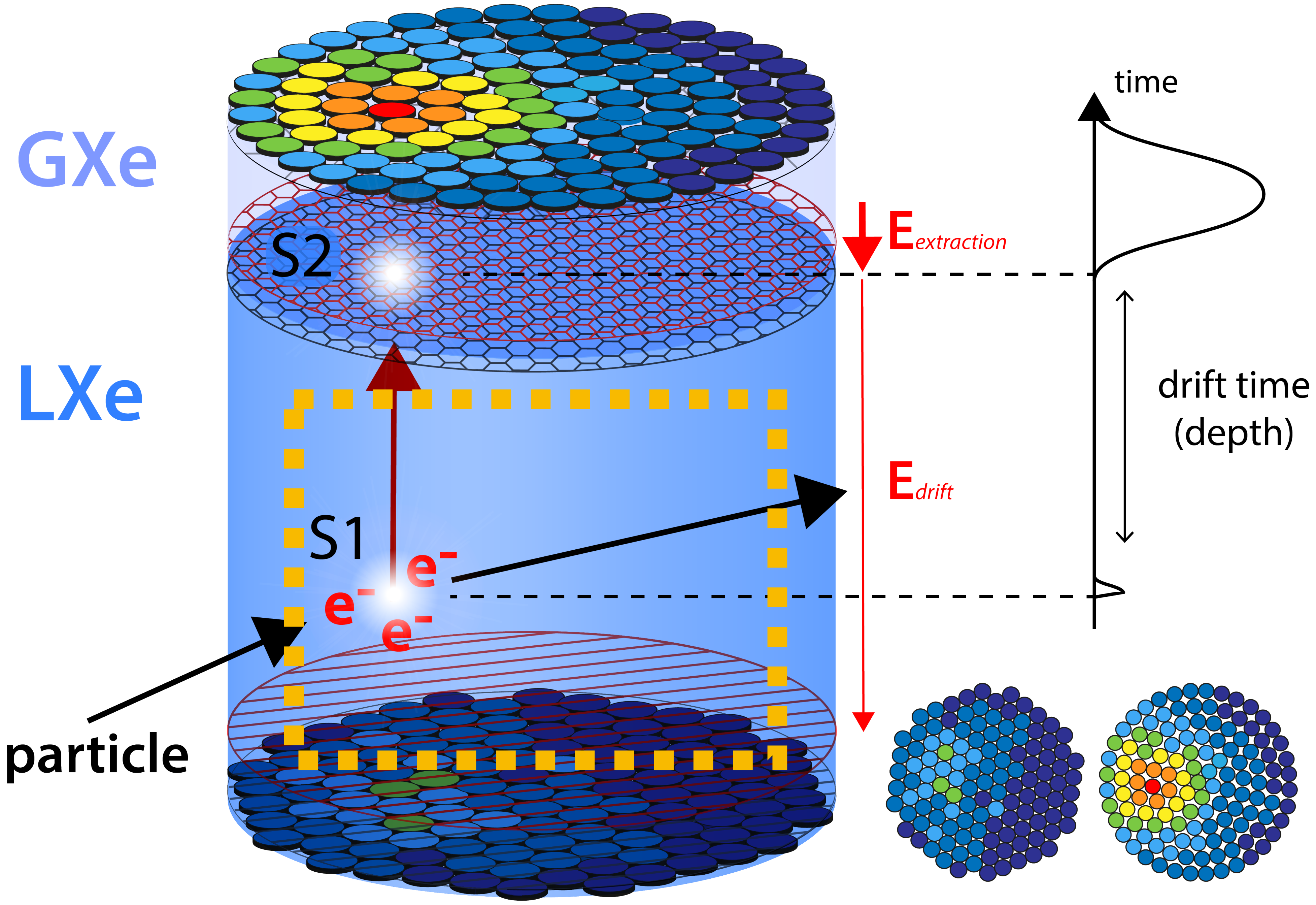
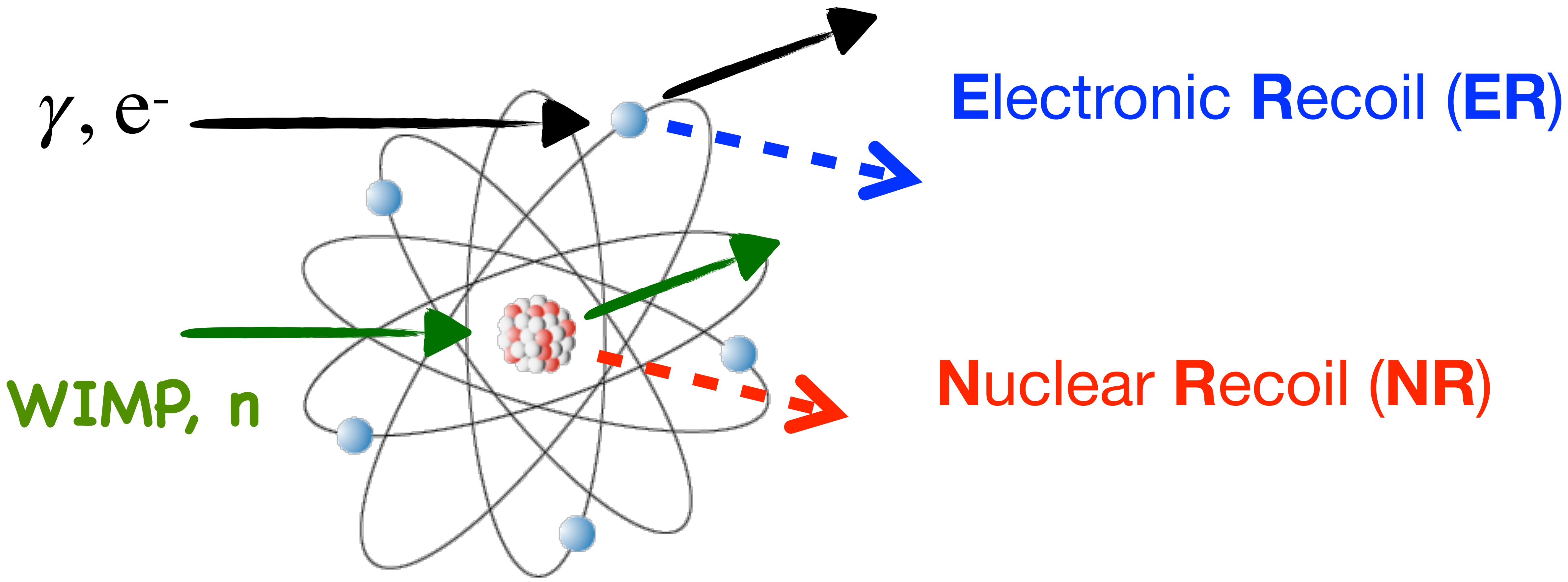
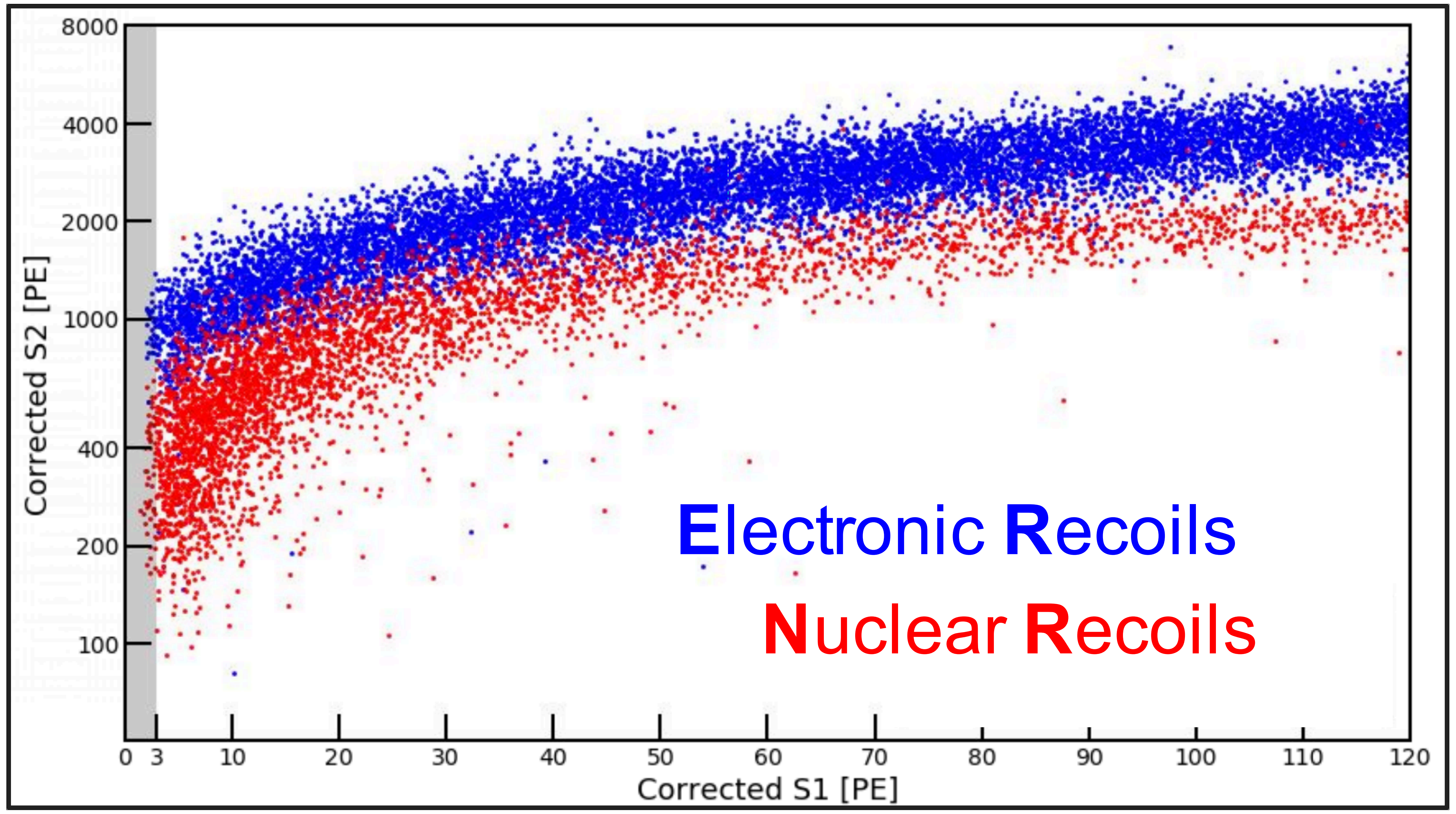


- Background reduction
  - (S2/S1) ratio for NR/ER discrimination
  - Self-shielding of the liquid xenon
  - Single versus multiple scatter
  - Fiducialisation of the liquid xenon target

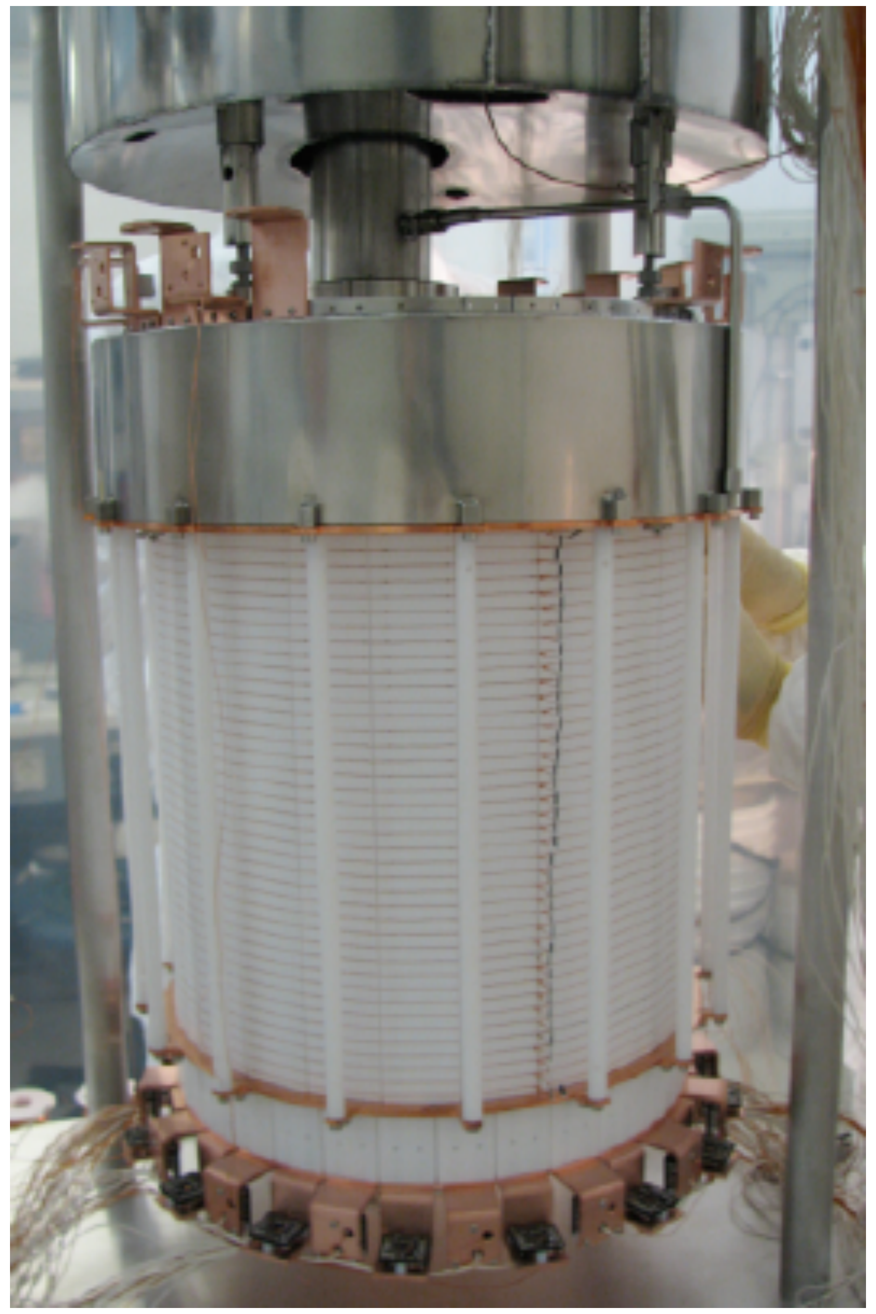


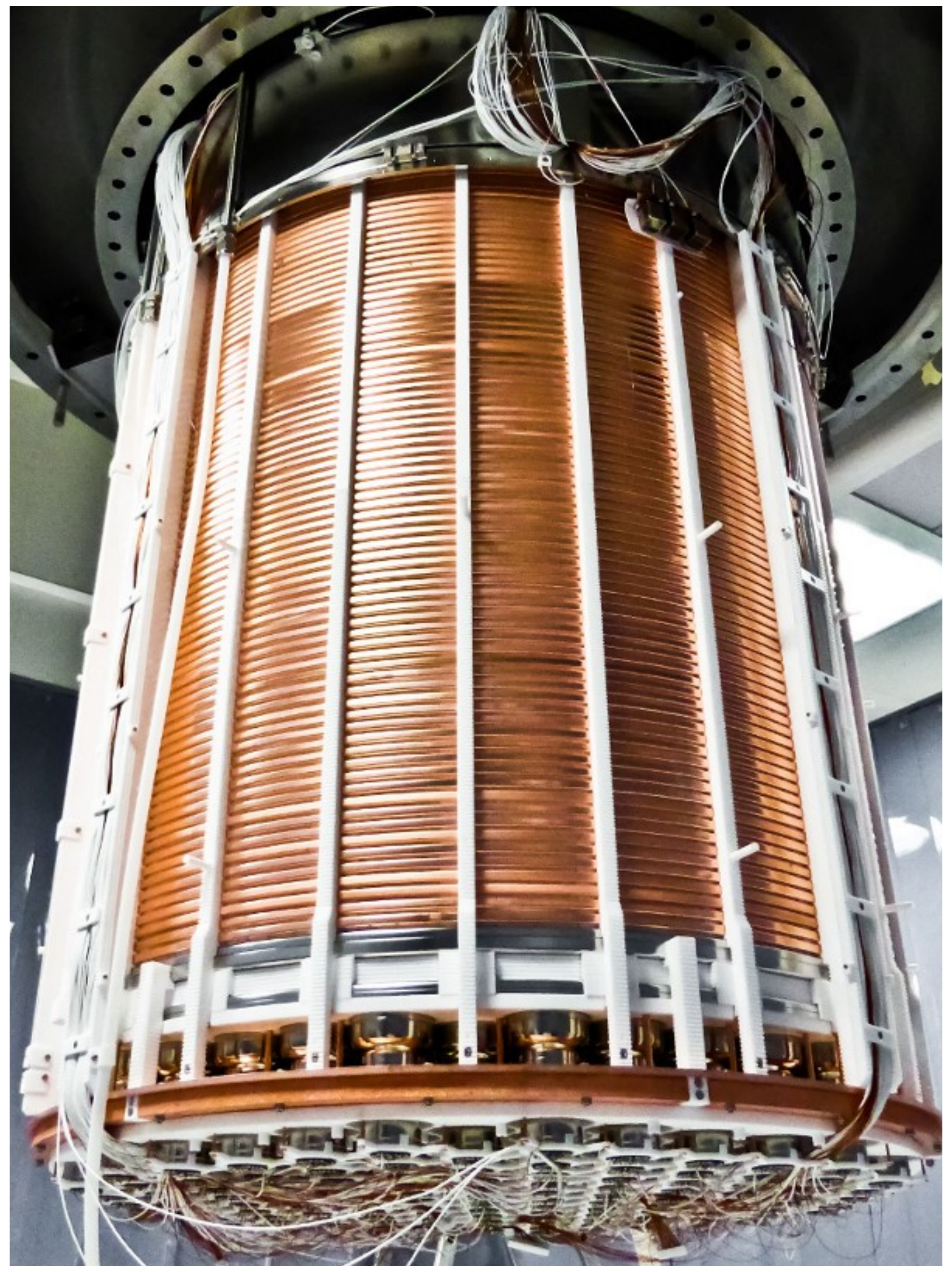


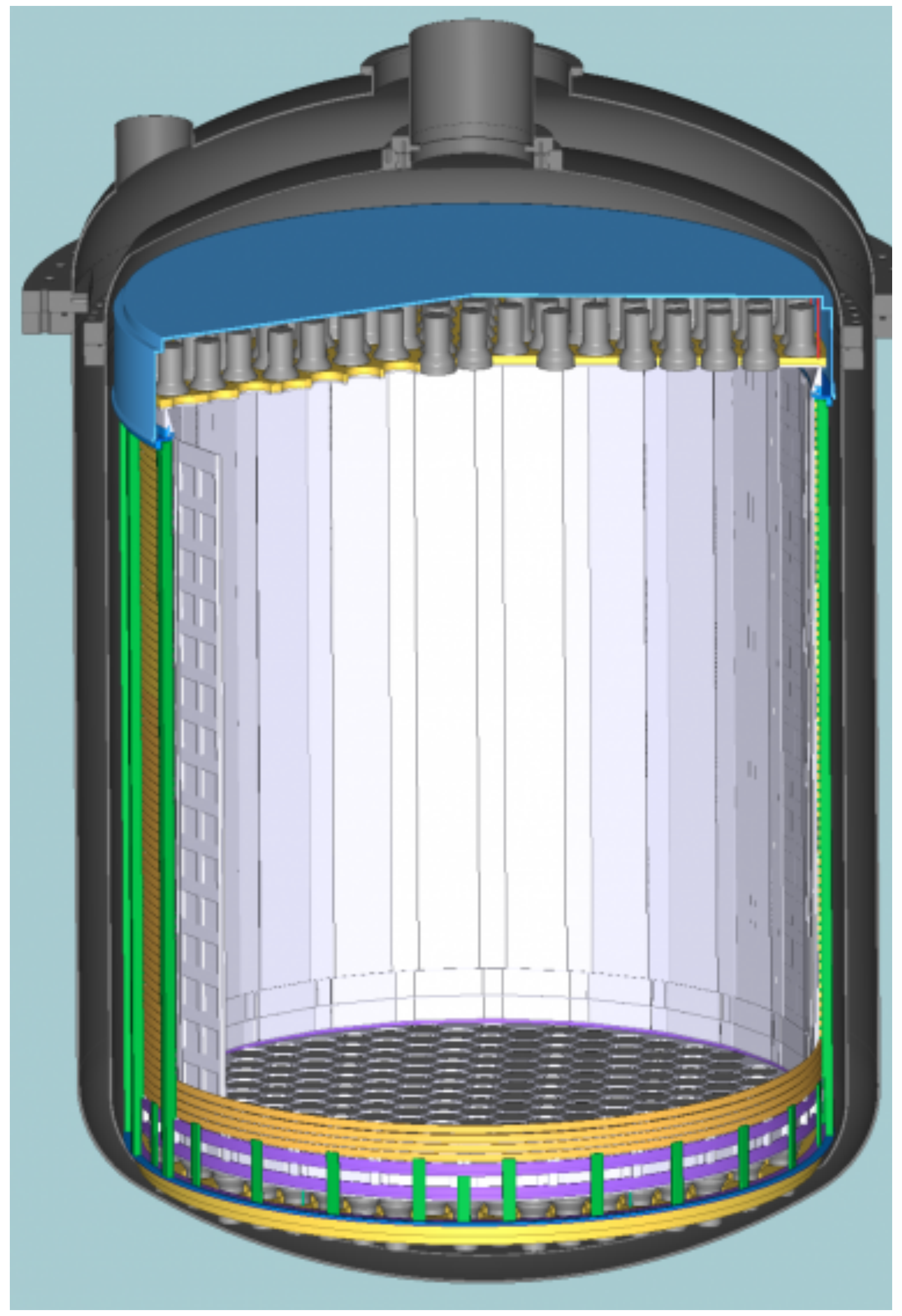
e^-, γ backgrounds scattering off shell electrons → **ER**

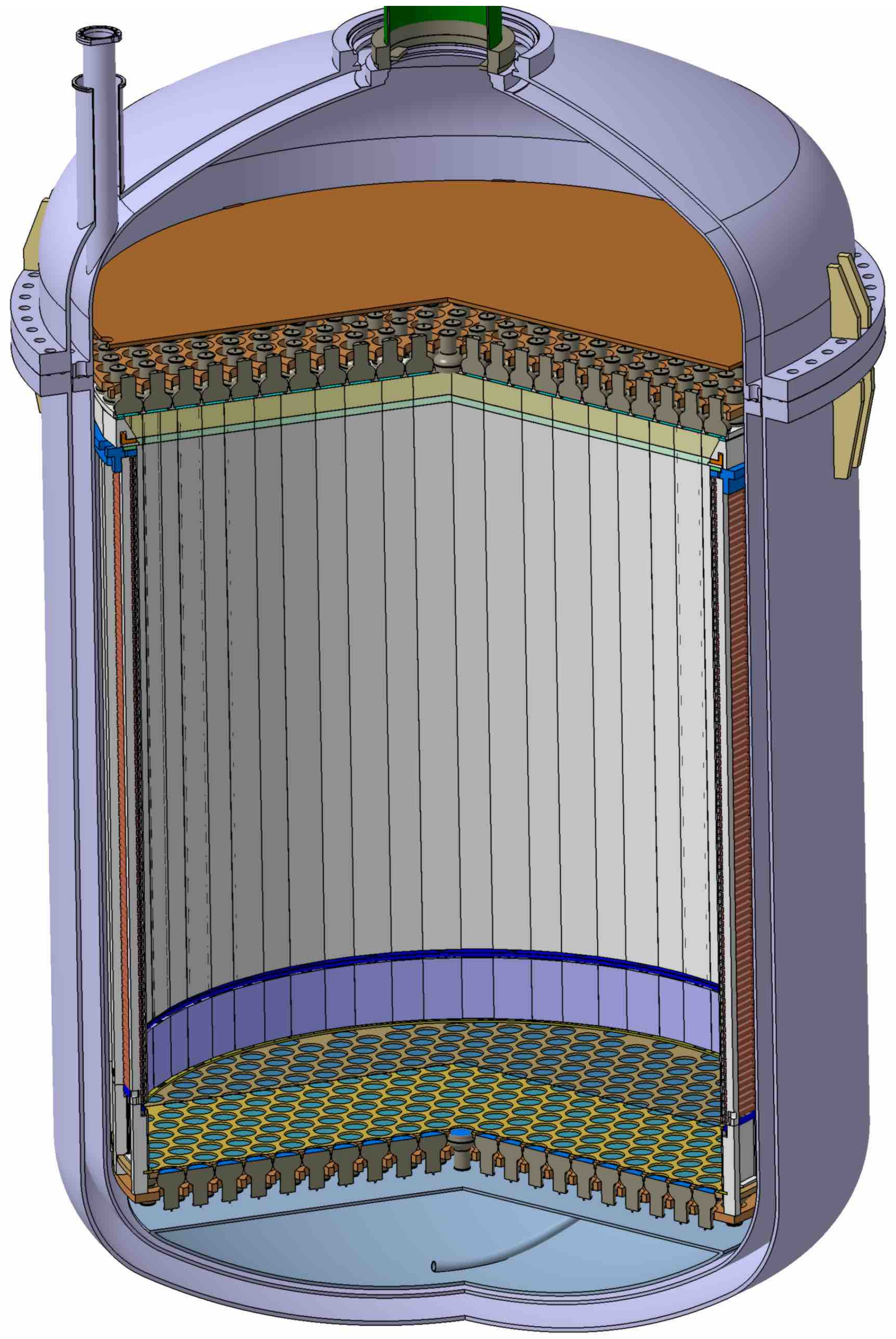
WIMPs (or n) scattering off xenon nucleus → **NR**

ENLIGHTENING THE DARK









XENON10	XENON100	XENON1T	XENONnT	DARWIN
2005-2007	2008-2016	2012-2018	2019-2023	2020+
15 kg - 15cm drift	161 kg - 30cm drift	3200 kg - 1 m drift	8200 kg - 1.5m drift	50 tonnes - 2.6m drift
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

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	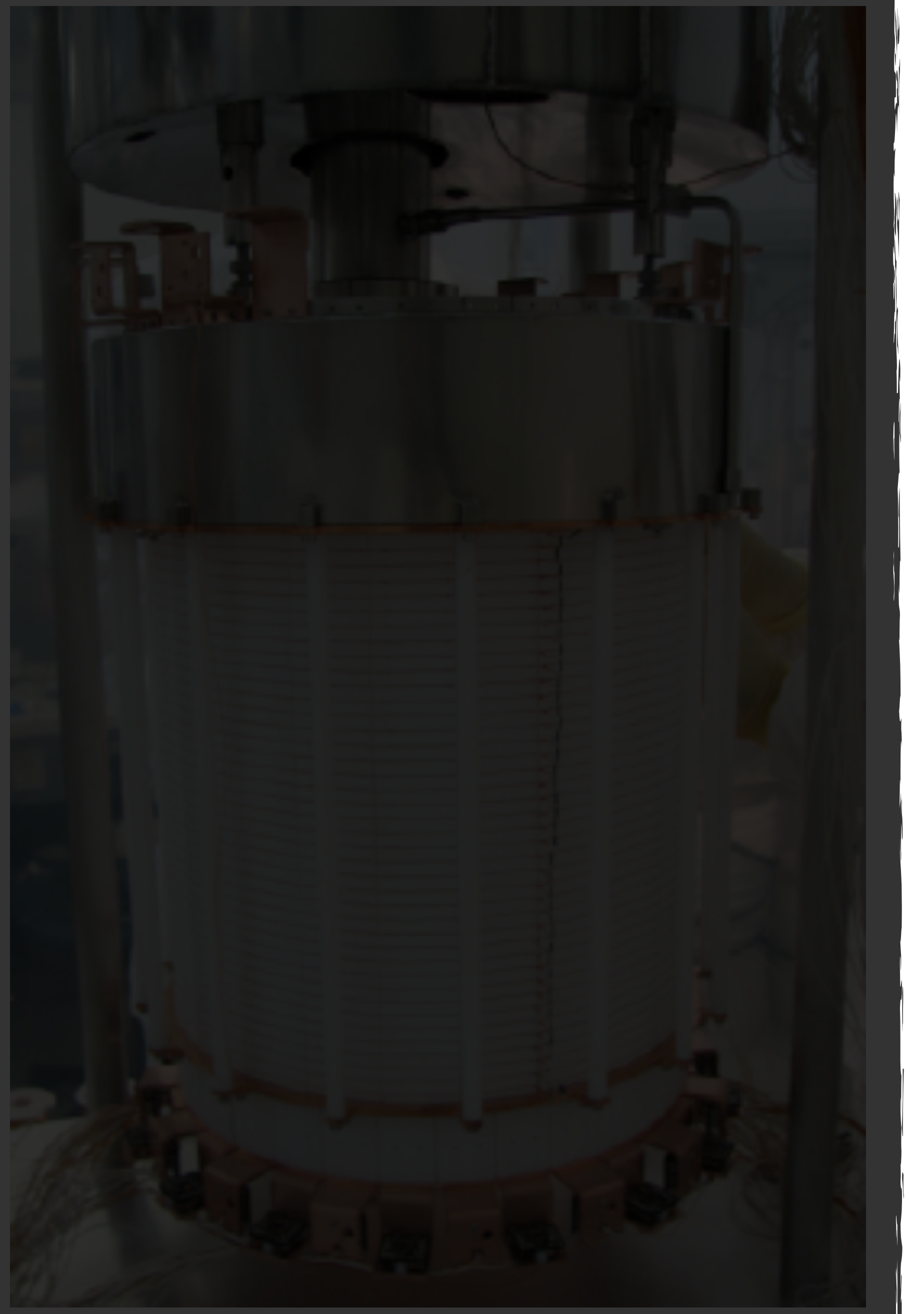	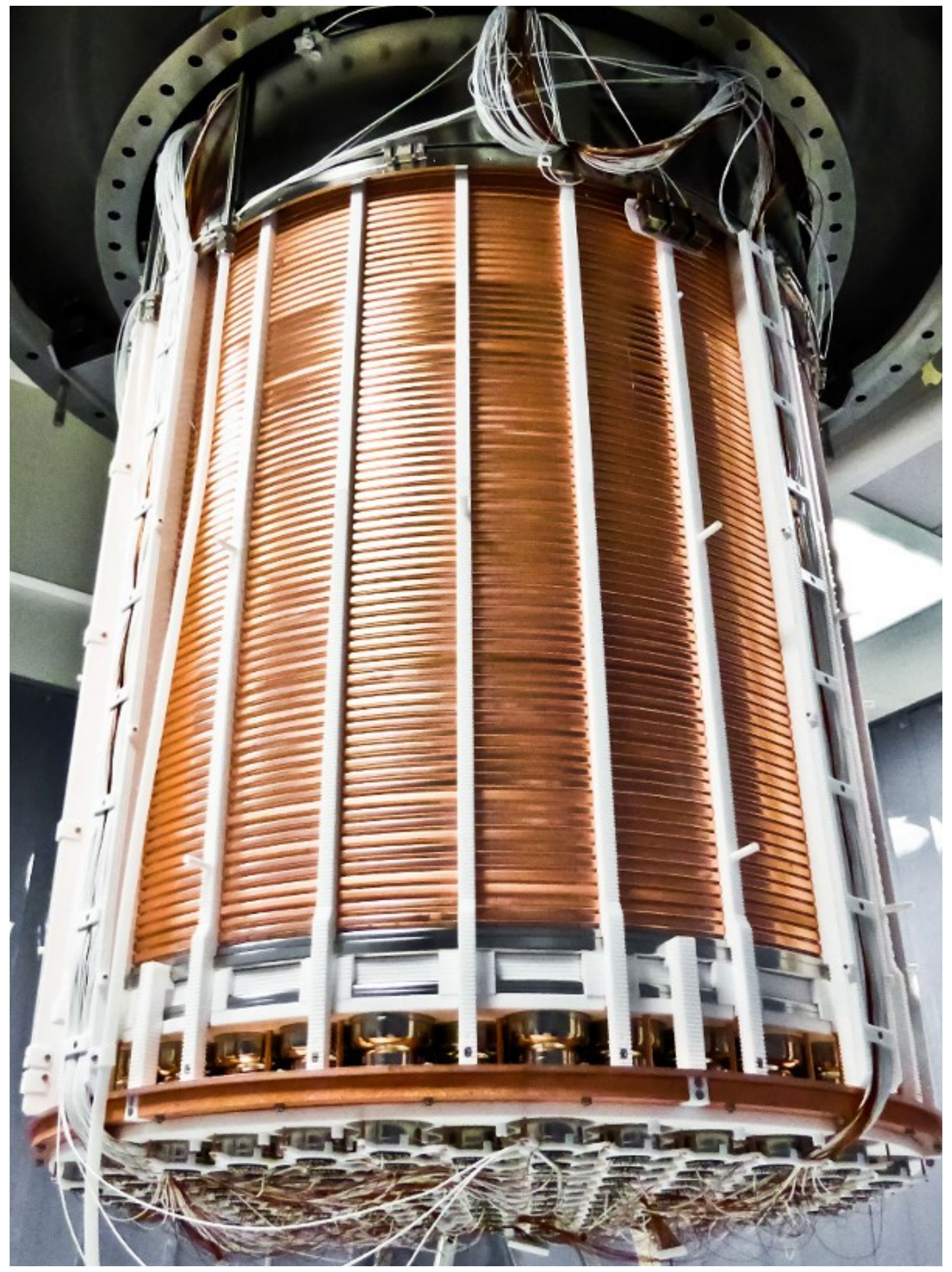	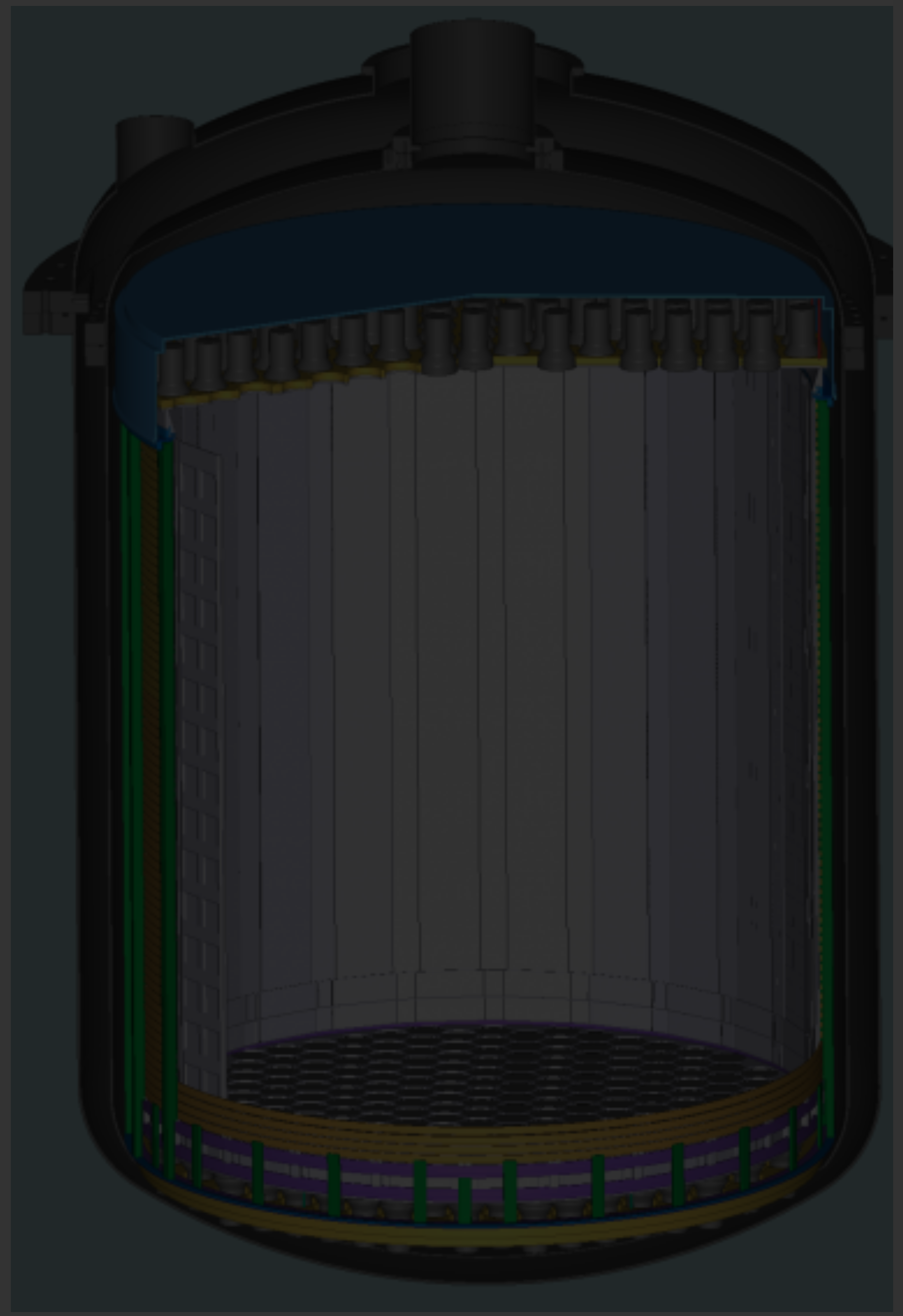	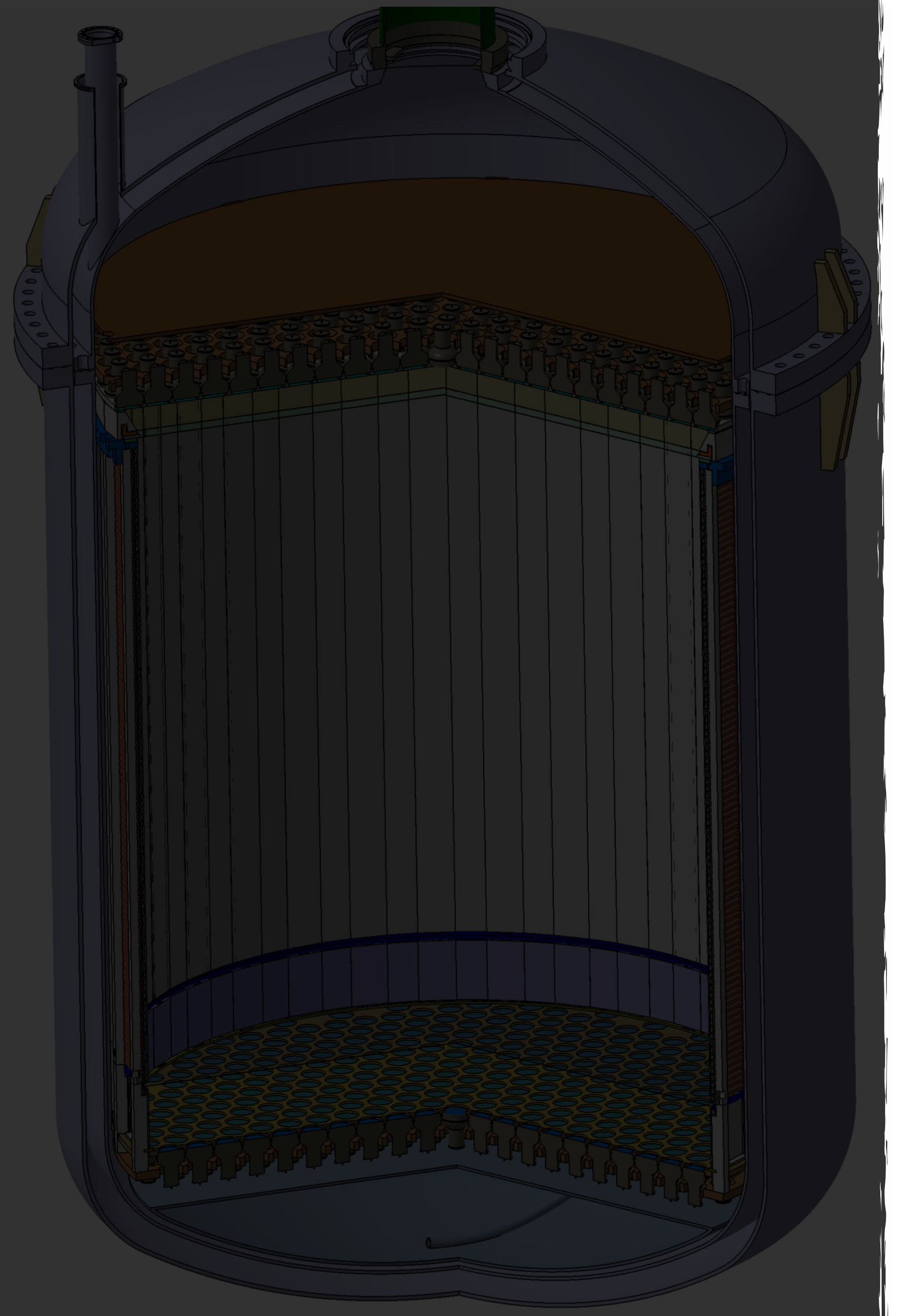
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THE XENON1T COLLABORATION

165 scientists, 25 institutions, 11 countries

Columbia RPI Nikhef Muenster Stockholm Mainz MPIK, Heidelberg Freiburg Zurich

Chicago

Tokyo

UCLA

Nagoya

UCSD

Rice

Kobe

Purdue Coimbra Subatech LPNHE LAL Bologna LNGS Torino Napoli Weizmann NYUAD

THE XENON1T EXPERIMENT AT LNGS

Water tank
- 700 t ultra-pure water

+

Muon veto
- 84 8-inch PMTs

External calibrations
- AmBe
- Neutron generator

Cryostat

TPC
- 248 3-inch PMTs
- 3.2 t liquid xenon

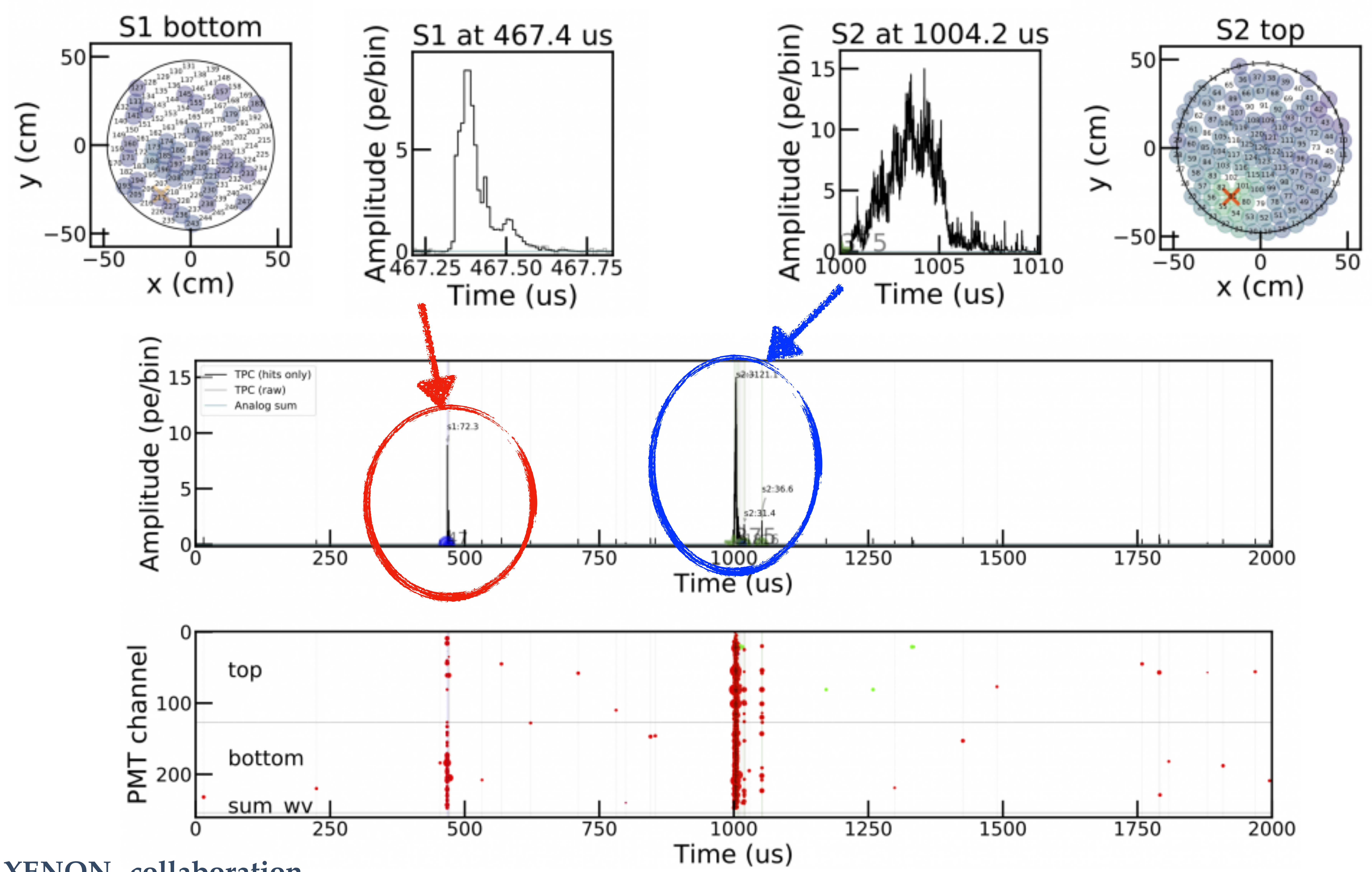
Cryogenic, purification
+
Internal calibrations
- ^{83m}Kr, ^{220}Rn

DAQ
+
Slow control

Xenon storage
+
Krypton distillation

Eur. Phys. J. C. (2017) 77:881

EXAMPLE OF AN EVENT IN THE TPC

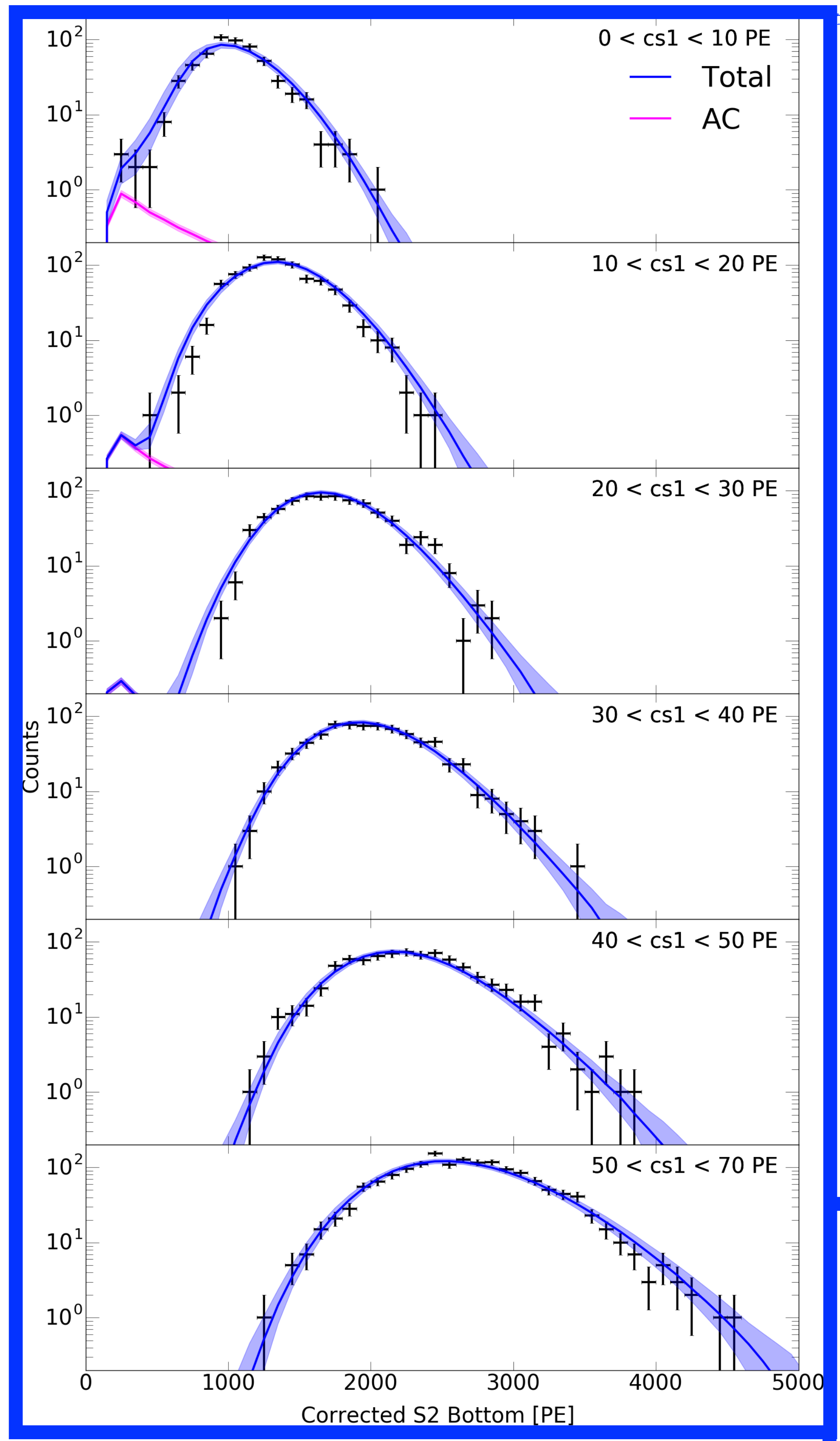


Developed by the XENON collaboration
Publicly available to the community
https://github.com/XENON1T/pax

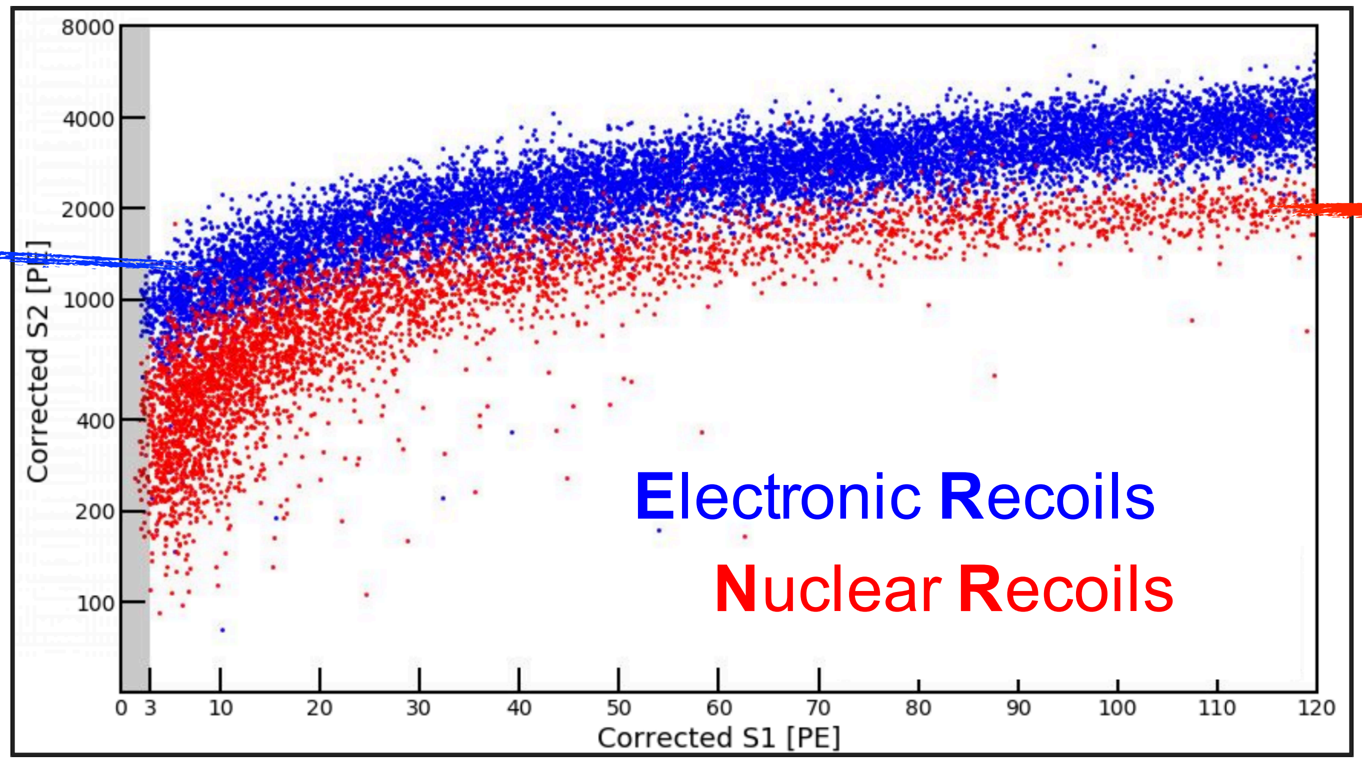
PAX
Processor for Analyzing XENON

ER AND NR CALIBRATIONS

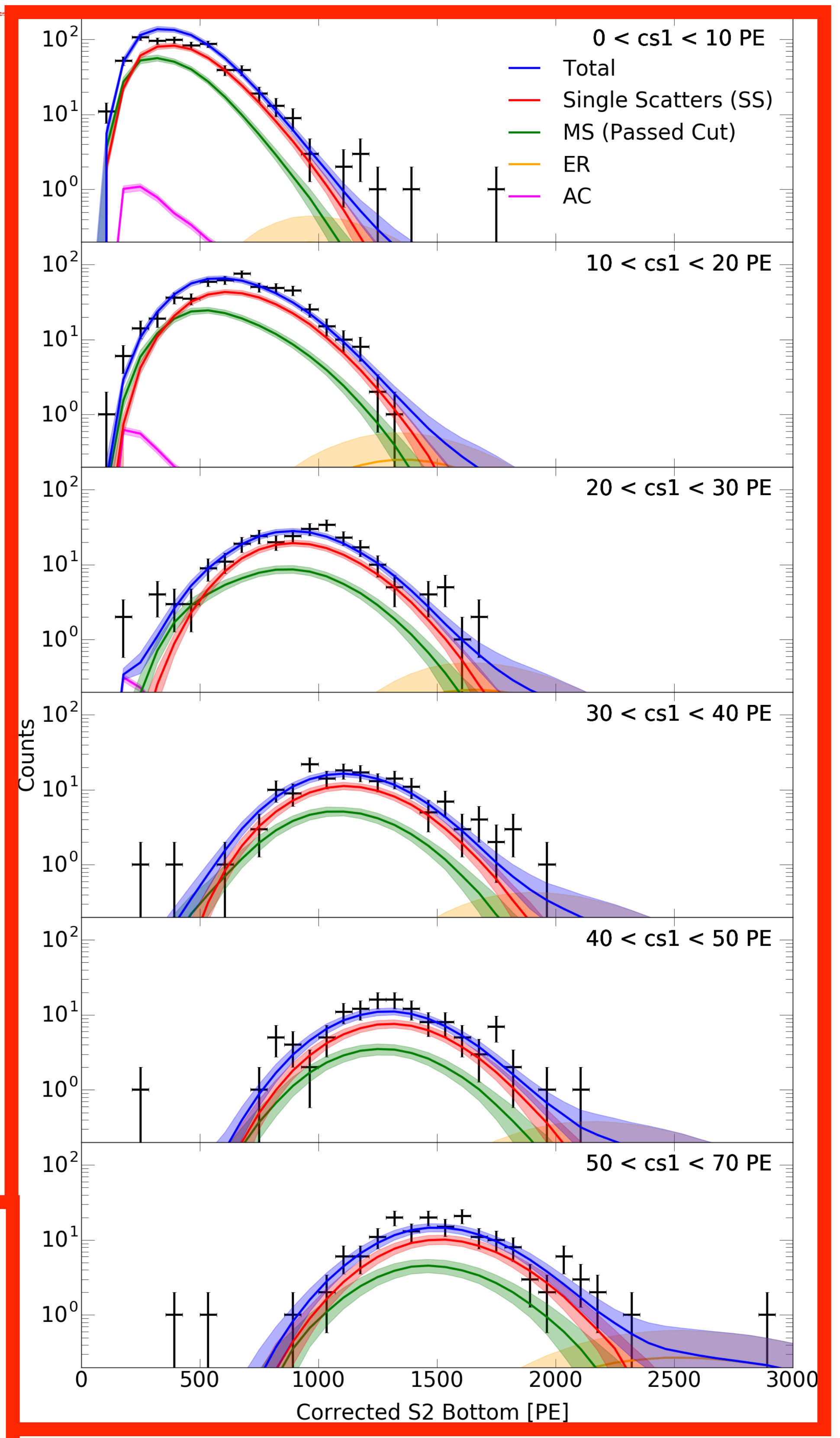
ER - ^{220}Rn



S2 projection in S1 slices



NR - neutron generator

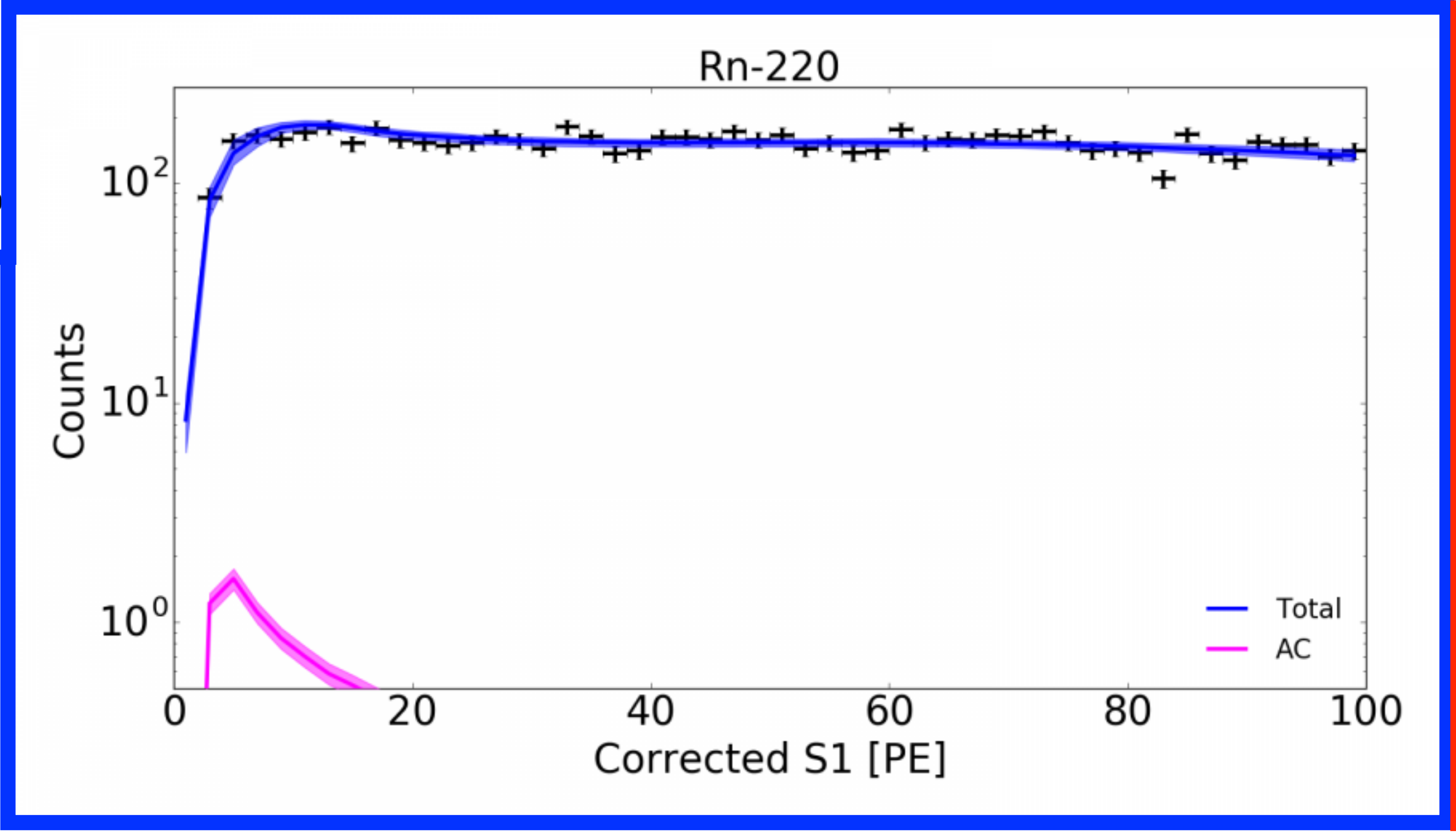


S2 projection in S1 slices

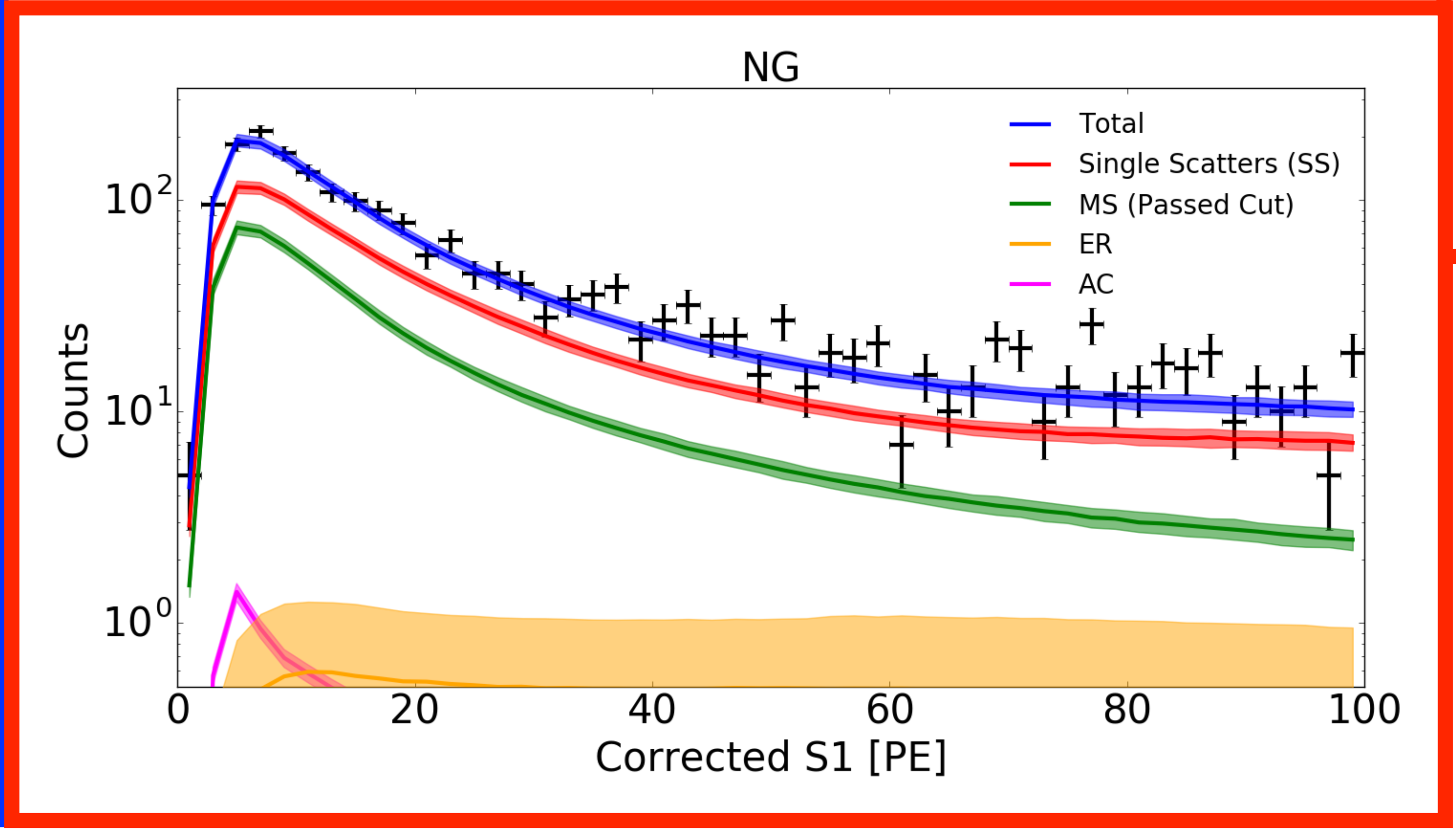
Detailed MC simulations of liquid xenon **microphysics** and **detector processes**

~99.7% **ER** rejection in **NR** reference region **[NR median,-2σ]**

S1 projection

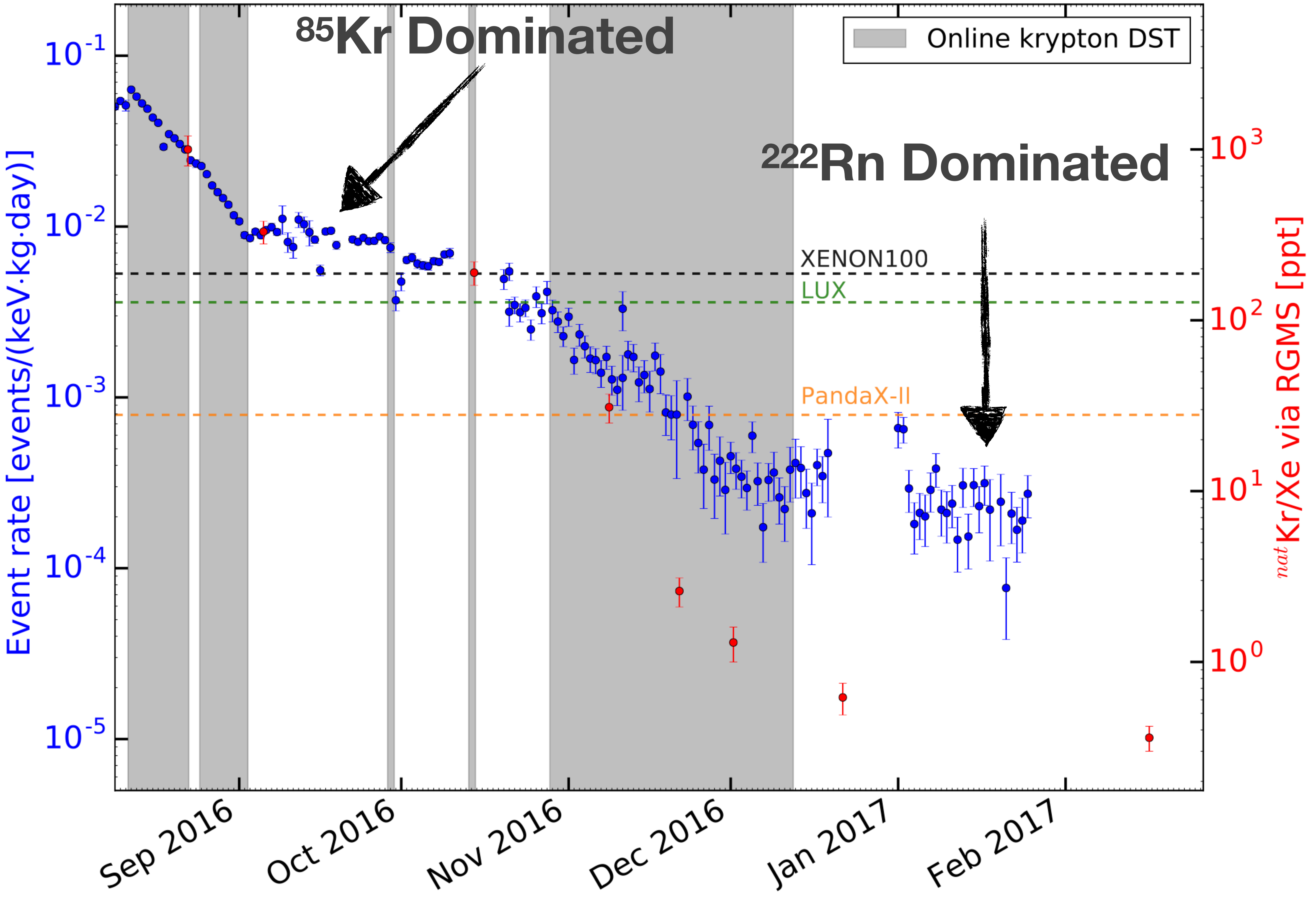


S1 projection



ELECTRONIC RECOIL BACKGROUNDS

Low energy β-spectrum from Kr-85 and Rn-222 (Pb-214)



Predicted: (75 ± 6) events/(ton·year·keV)

Measured: 82^{+5}_{-3}(sys) ± 3(stat) events/(ton·year·keV)

(In 1300 kg fiducial volume and below 25 keV_{ee})

Lowest ER background ever achieved in a DM detector !

- **^{222}Rn: ~10 μBq/kg**
  Careful surface emanation control and further reduction by online cryogenic distillation
- **^{nat}Kr/Xe: (0.66 ± 0.11) ppt**
  Achieved with online cryogenic distillation
  → ^{85}Kr not dominant
- **Material background**
  Suppressed by fiducialization

JCAP 04, 027 (2016)

Type	Fraction [%]
^{222}Rn	85.4
^{85}Kr	4.3
solar ν	4.9
Materials	4.1
^{136}Xe	1.4

Expectations in 1 t FV, in [1,12] keV_{ee}, single scatters, **before ER/NR discrimination**

NUCLEAR RECOIL BACKGROUNDS

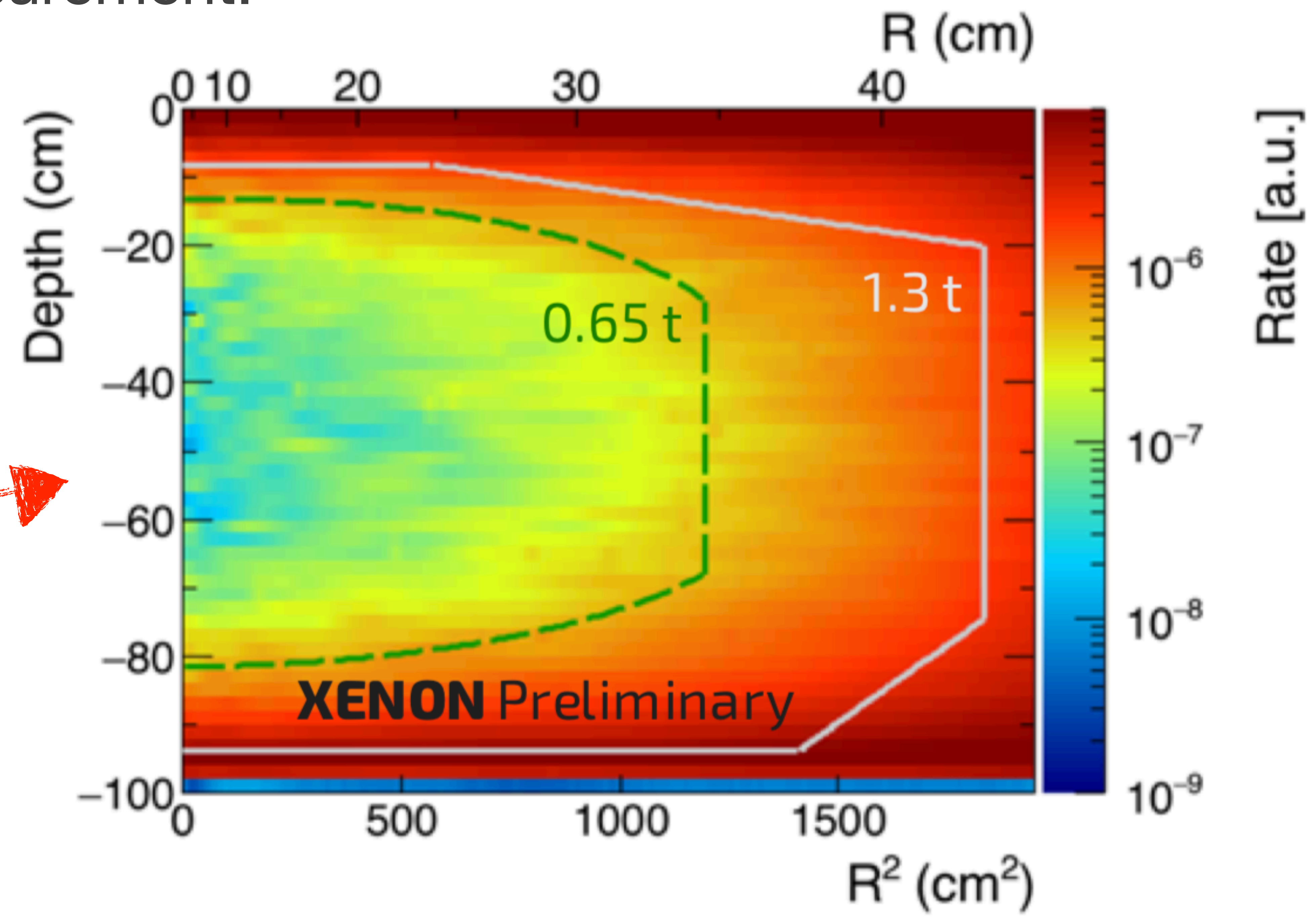
- **Cosmogenic neutrons**
  Induced by cosmic muons. Reduced to negligible contribution by rock overburden, water passive shield and active Cherenkov Muon Veto. **JINST 9, P11006 (2014)**

- **Radiogenic neutrons**
  From (α,n) and spontaneous fission in detector's materials.
  Reduced via radiopure material selection, scatter multiplicity and fiducialization. **Eur. Phys. J. C. (2017) 77:890**

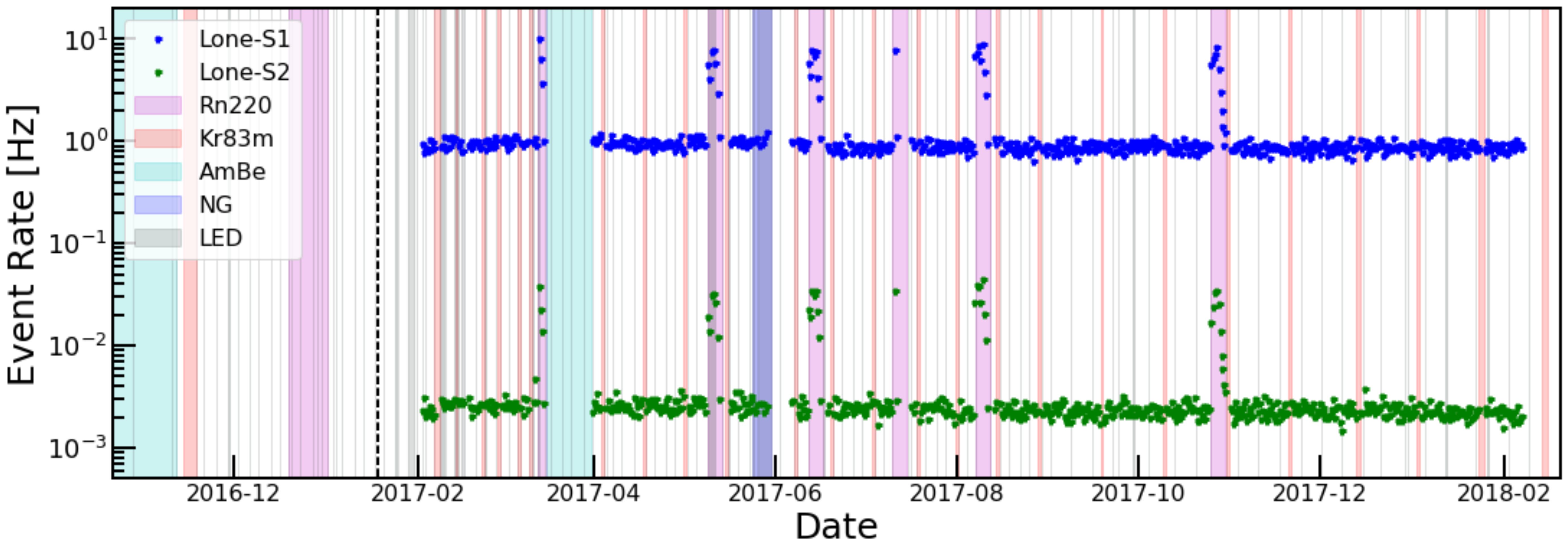
- **Coherent elastic neutrino-nucleus scattering**
  Mainly from ^{8}B solar ν. Constrained by flux and cross section measurement.
  Irreducible background at very low energy (< 1 keV).

JCAP 04, 027 (2016)

Type	Fraction [%]
Cosmogenic Neutrons	<2
Radiogenic neutrons	96.5
CEνNS	2

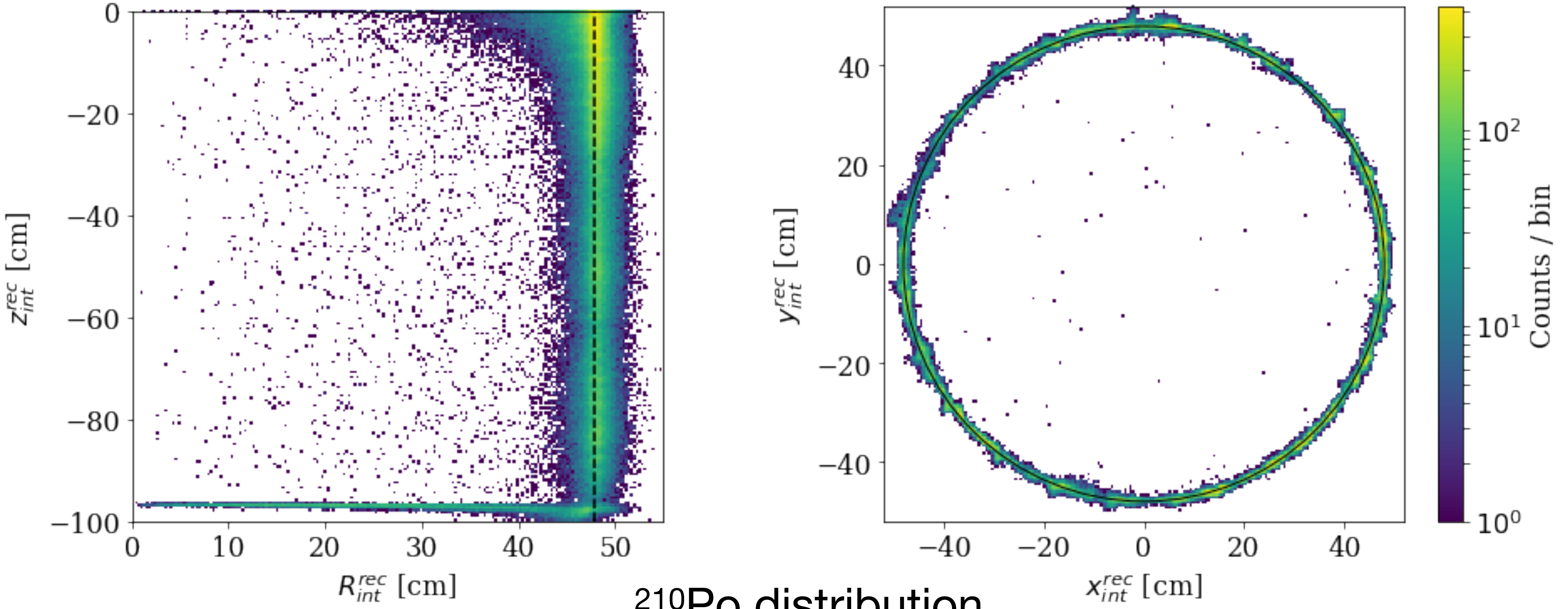


ADDITIONAL BACKGROUNDS



- **Accidental coincidence (AC)**
  - Lone-S1 signals may accidentally coincide with lone-S2 signals → fake interactions
  - Empirical model verified with ^{220}Rn calibration data and background sidebands

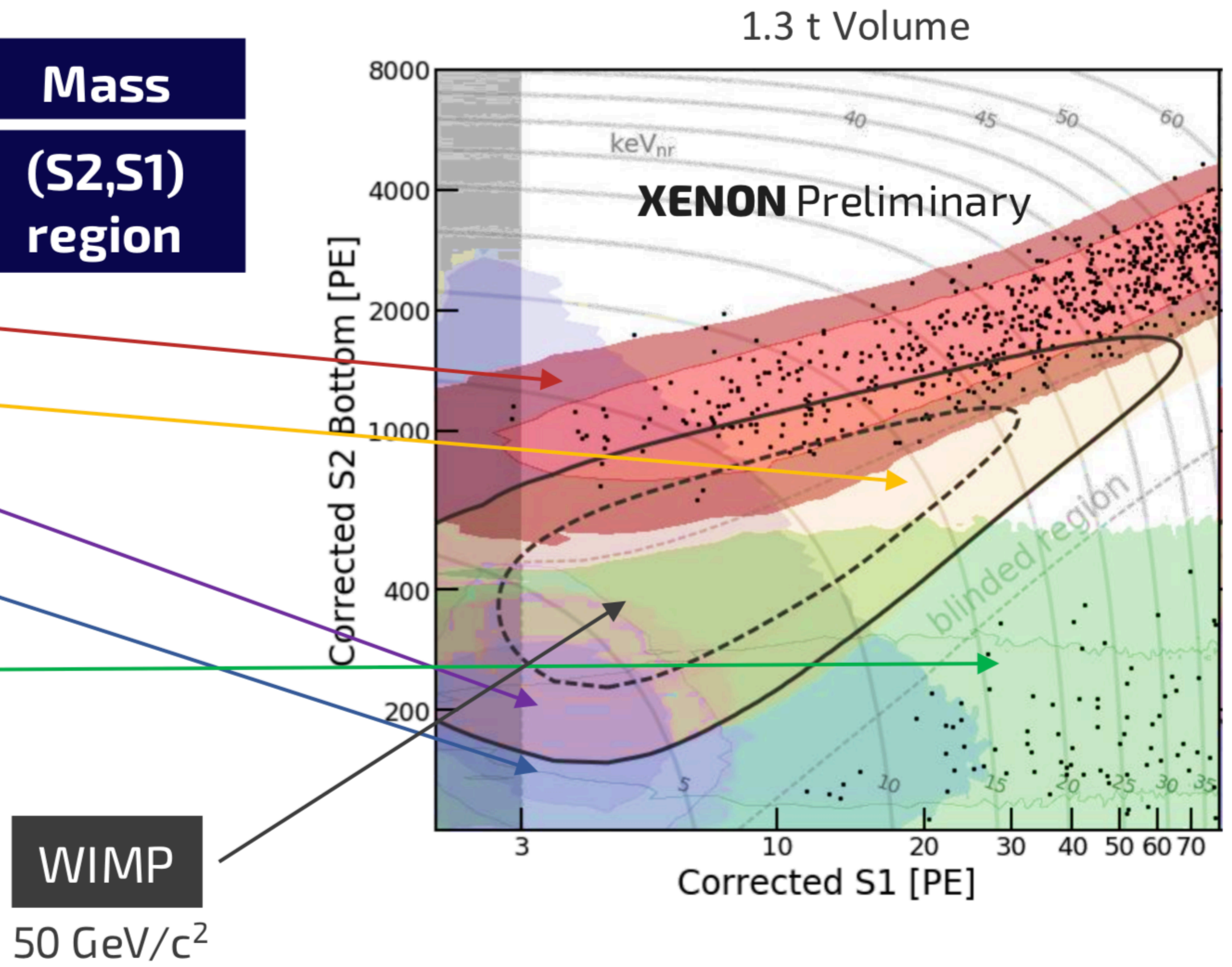
- **Surface events**
  - ^{210}Pb from ^{222}Rn chain plates out on PTFE surfaces
  - S2 signal loses charge when ^{210}Pb β-decay happens on surface → leakage into signal region
  - Data driven model based on ^{210}Po surface control samples.



^{210}Po distribution

BACKGROUND PREDICTIONS

278.8 days live-time	1.3 t Full ROI	0.65 t NR Reference	Mass (S2,S1) region
ER	627 ± 18	0.60 ± 0.13	
neutron	1.43 ± 0.66	0.14 ± 0.07	
CEνNS	0.05 ± 0.01	0.01	
AC	$0.47^{+0.27}$	$0.04^{+0.02}$	
Surface	106 ± 8	0.01	
TOTAL BKG	**735 ± 20**	**0.80 ± 0.14**	

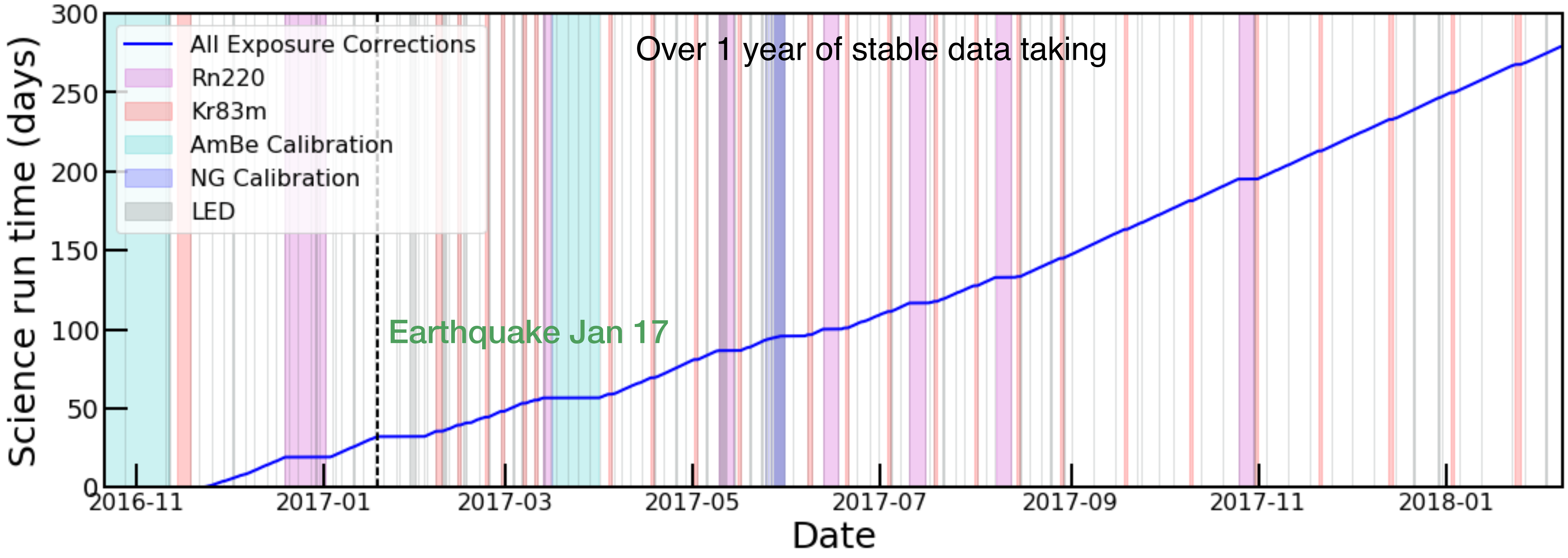


- **Background models**
  In 4-dimensional space: S1, S2, R, Z
- **Statistical inference**
  Done with PLR analysis in 1.3 t fiducial volume and full (S1,S2) space, corresponding to [4.9, 40.9] keV$_{nr}$ and [1.4, 10.6] keV$_{ee}$
- **NR reference region**
  Between NR median and -2σ quantile.
  Numbers in table are for illustration; final results from complete PLR statistical inference

EXPOSURE

- 279 days high quality data (livetime-corrected) spanning more than 1 year of stable detector's operation. The LXe TPC has been "cold" since Spring 2016

- 1 tonne x year exposure given 1.3 tonne fiducial volume: the largest reported to-date with this type of detector



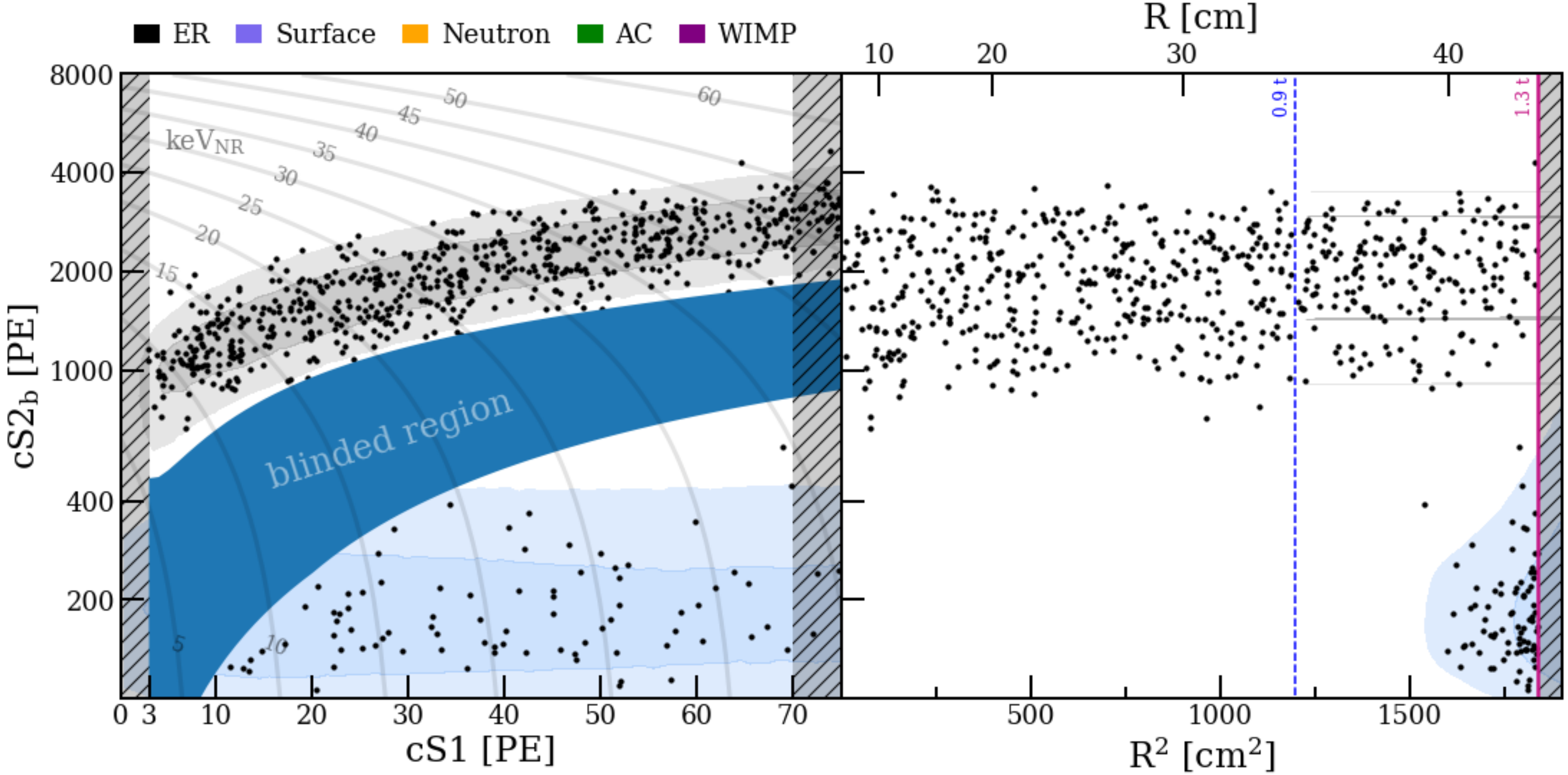
BLINDED DATA

- **Exposure**

  1 tonne x year exposure given 1.3 tonne fiducial volume. (278.8 days of science data)

- **Blinding and salting**

  Data were blinded **[NR median,-2σ]** and salted with unknown number of fake events

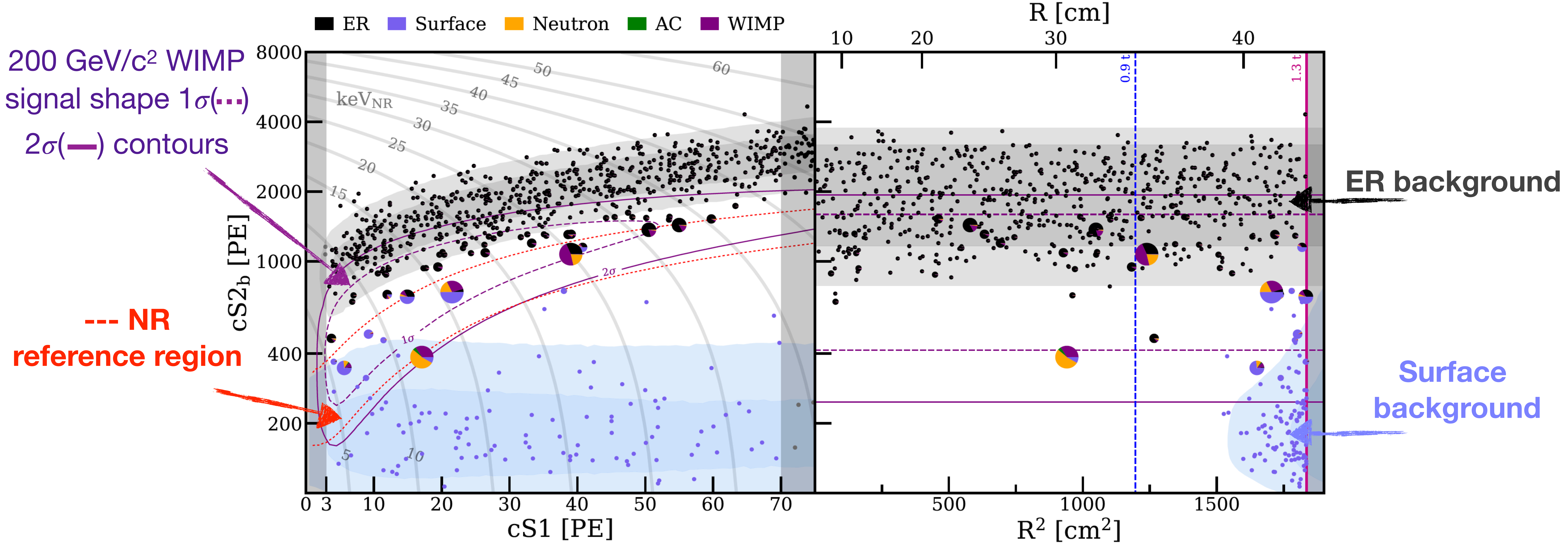


UNBLINDING - ENERGY DISTRIBUTION

Results interpreted with un-binned profile likelihood analysis in cS1, cS2, R, Z space (here: cS2b vs cS1, R2)

- **Pie charts**

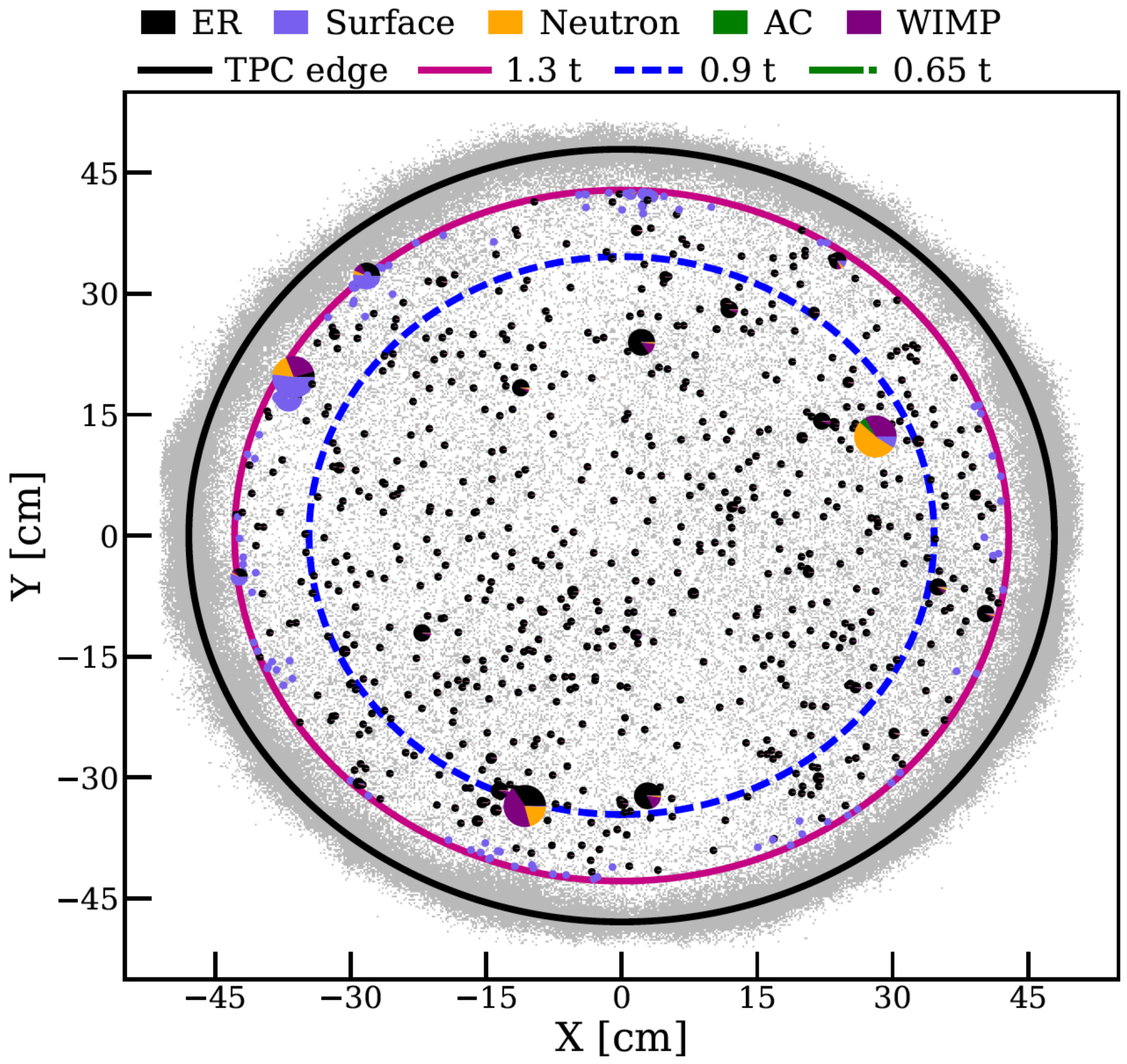
  Events passing all selection criteria are shown as pie charts representing the relative PDF from each component for the best-fit model for 200 GeV/c² WIMP (σ_{SI} = 4.7 x 10^{-47}cm²). Larger charts represent events with larger WIMP probability.

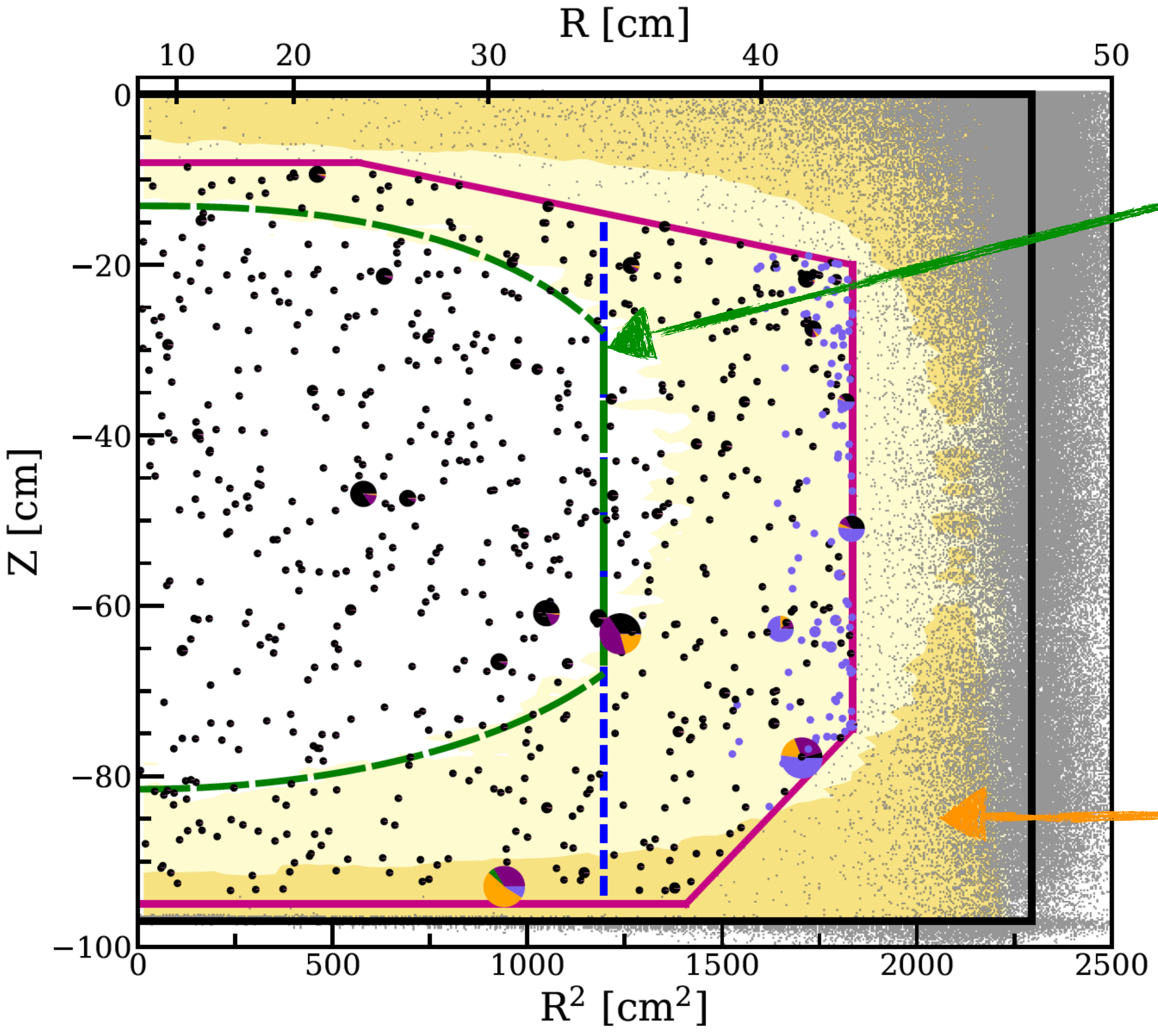


UNBLINDING - SPATIAL DISTRIBUTION

Results interpreted with un-binned profile likelihood analysis in cS1, cS2, R, Z space (here: Y vs X, Z vs R2)

- **Core volume (0.65 t)**
  Modelled in order to have a negligible amount of surface and neutron background. The two bins, in/out core volume, allow to increase the fiducial volume.





SENSITIVITY AND LIMIT

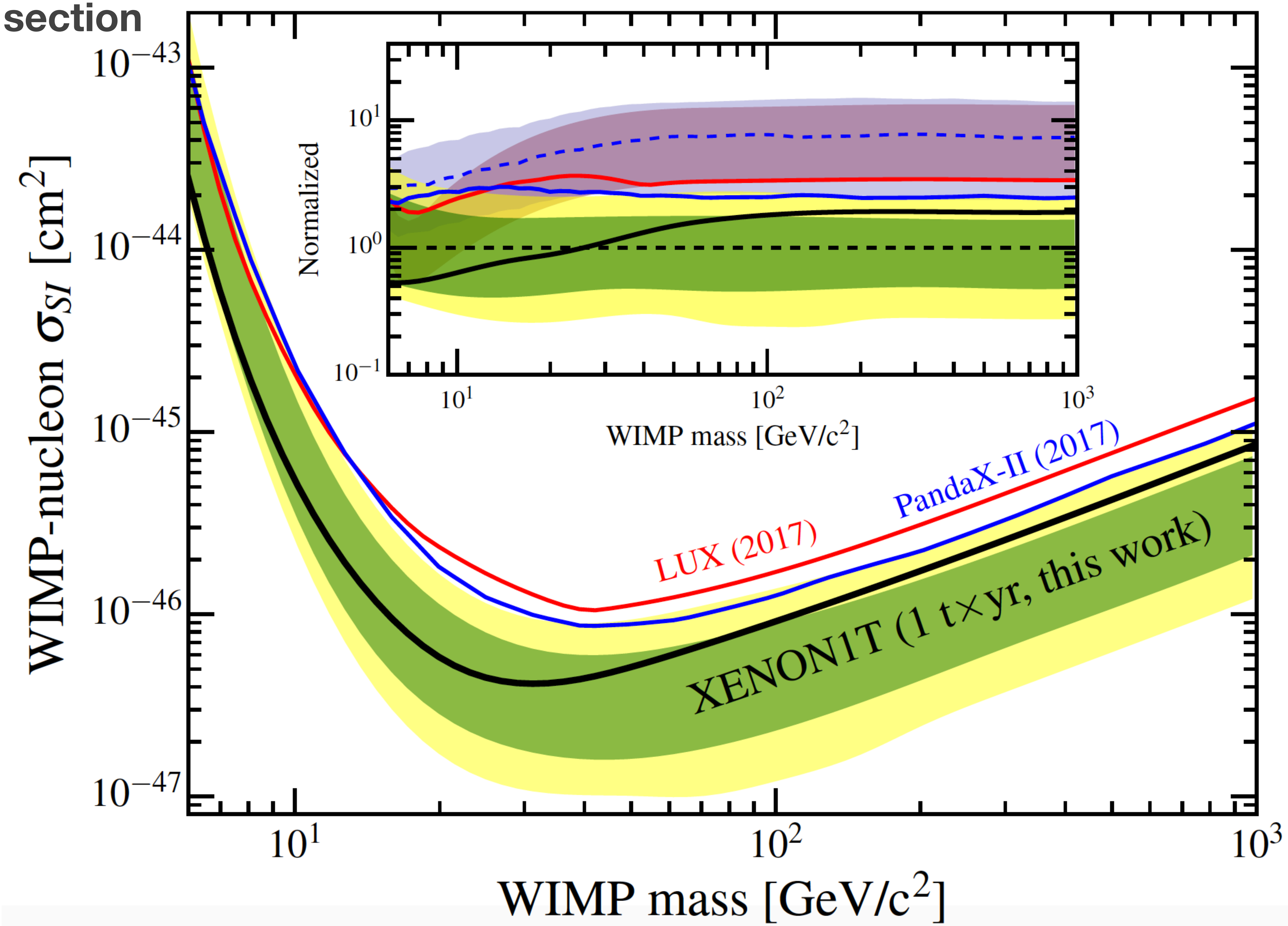
No significant excess at any scanned WIMP mass

- **Spin-independent WIMP-nucleon cross section**
  Strongest exclusion limits (at 90% C.L.) on WIMP mass > 6 GeV/c^2

- **Sensitivity**
  7 times better than previous generation experiments (LUX, PANDAX-II)

- **Limit**
  Under-fluctuation for masses ≲ 8 GeV/c^2, while over-fluctuation at higher masses

- **Minimum**
  $\sigma_{SI} < 4.1 \times 10^{-47}$ cm^2 at 30 GeV/c^2

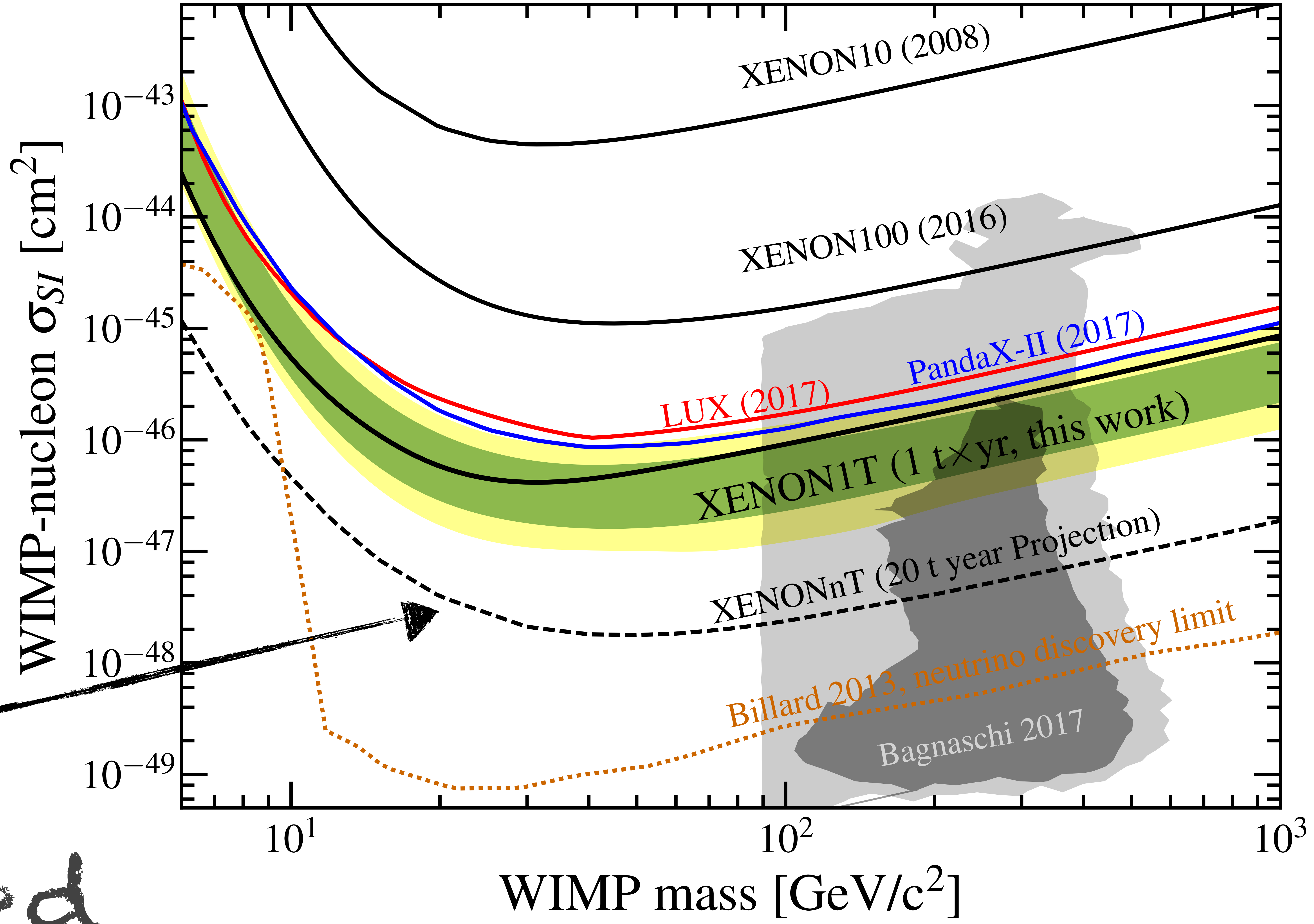


Accepted by PRL ArXiv: https://arxiv.org/abs/1805.12562

SUMMARY AND OUTLOOK

- Successfully operated the first multi-ton scale LXe TPC for > 1 year
- Achieved lowest background in any DM detector: 0.2 events/(t·keV·d)
- Strongest exclusion limits (at 90% C.L.) on WIMP mass > 6 GeV/c^2

- **XENONnT**
  - ✦ Larger fiducial mass
  - ✦ Use existing systems of XENON1T
  - ✦ Reduce background by factor 10
  - ✦ Reach 10^{-48} cm^2 with 20 t x year
  - ✦ Commissioning in 2019



→ Stay Tuned

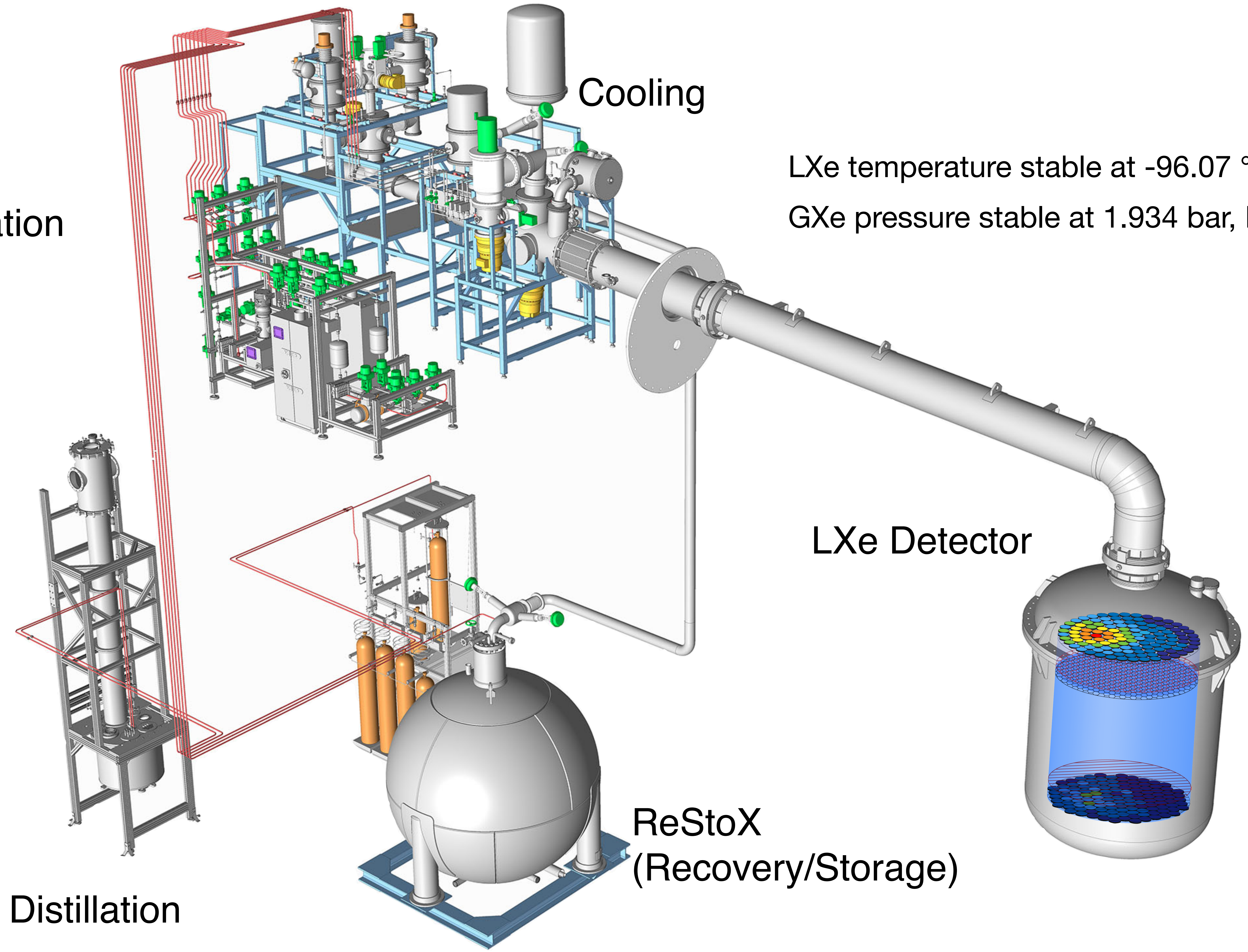
THANK YOU
FOR YOUR ATTENTION

BACKUP SLIDES

THE XENON1T CRYOGENIC PLANTS

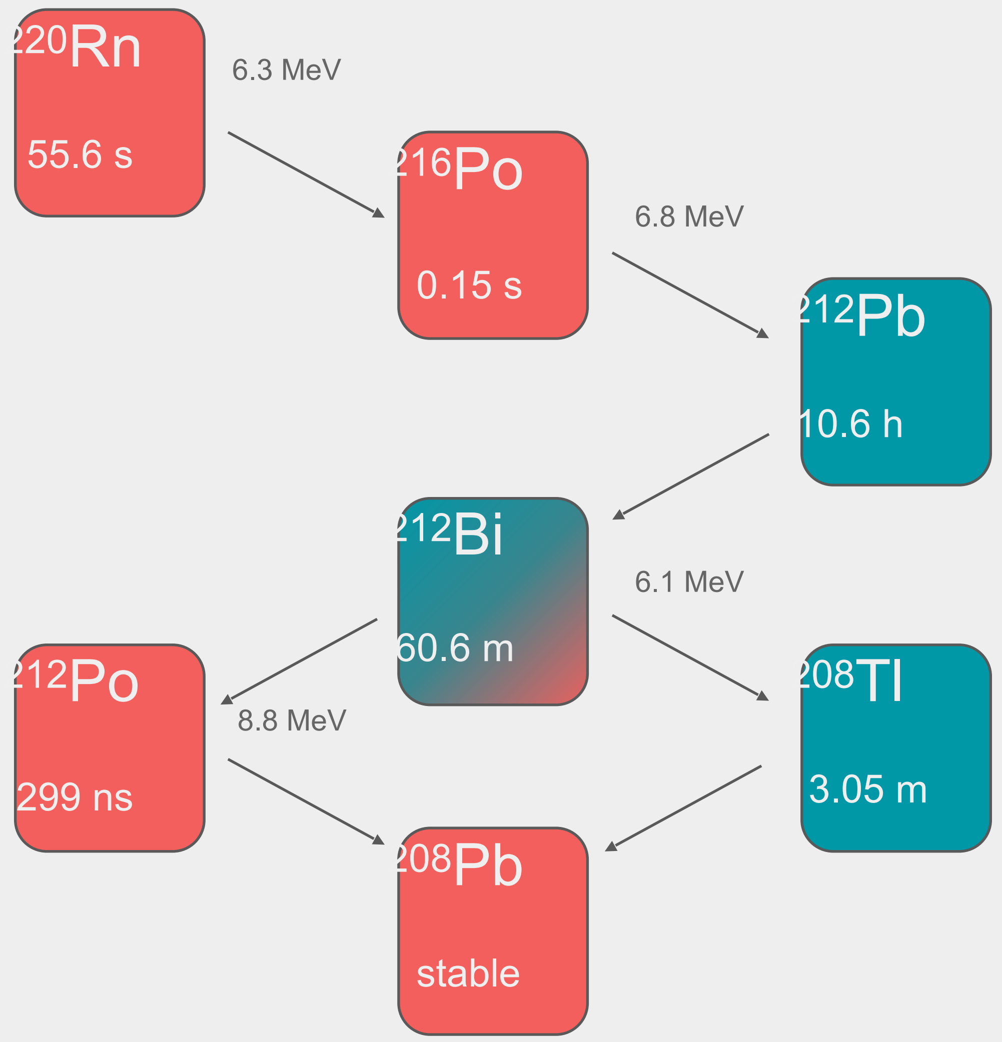
LXe temperature stable at -96.07 °C, RMS 0.04 °C

GXe pressure stable at 1.934 bar, RMS 0.001 bar



CALIBRATION SOURCES

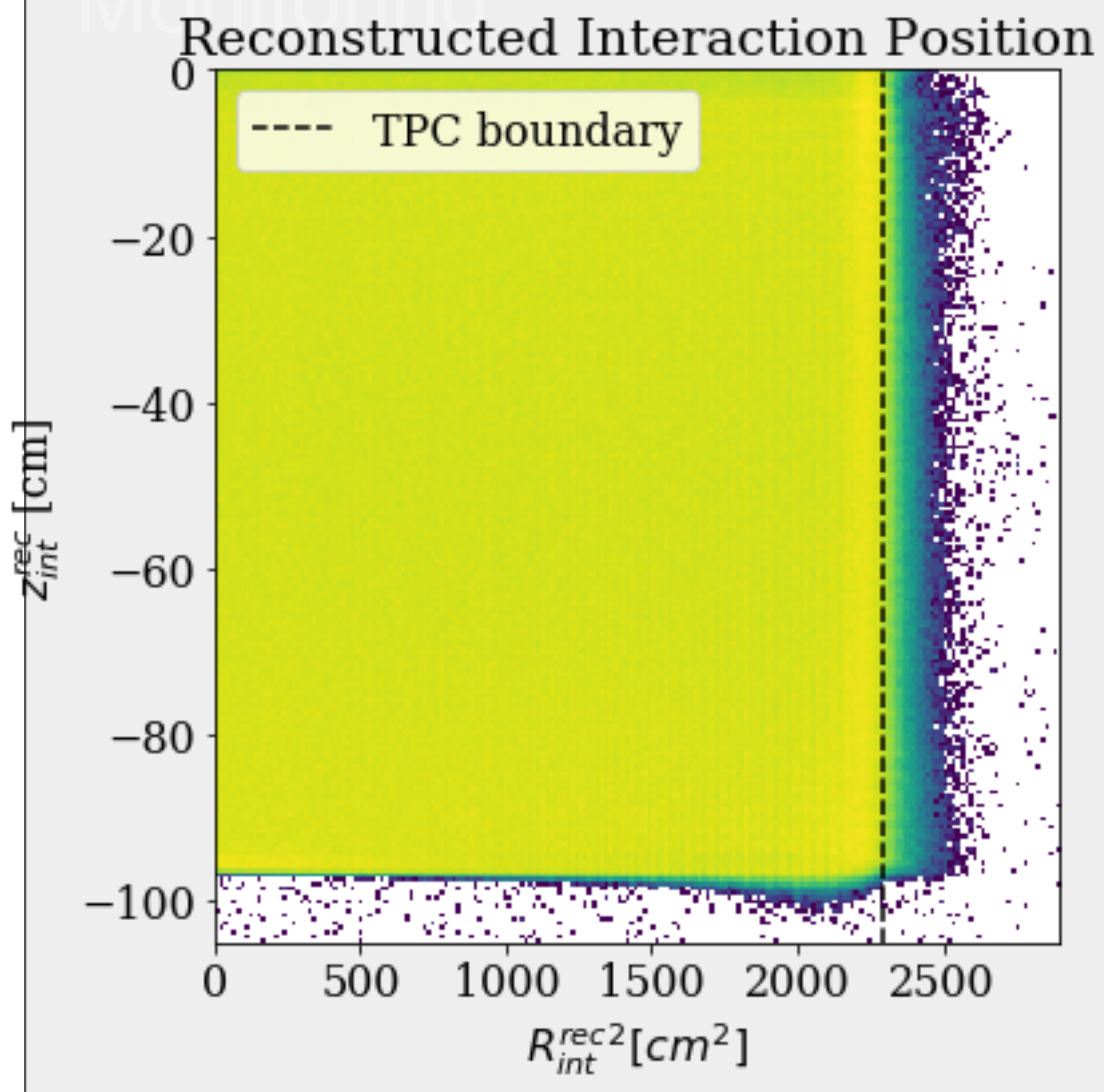
^{220}**Rn:** Low Energy ER



Type: Internal
Freq: 1-2 Months
Length: Few days

Stable background conditions after a couple days (10.6h longest $T_{1/2}$)

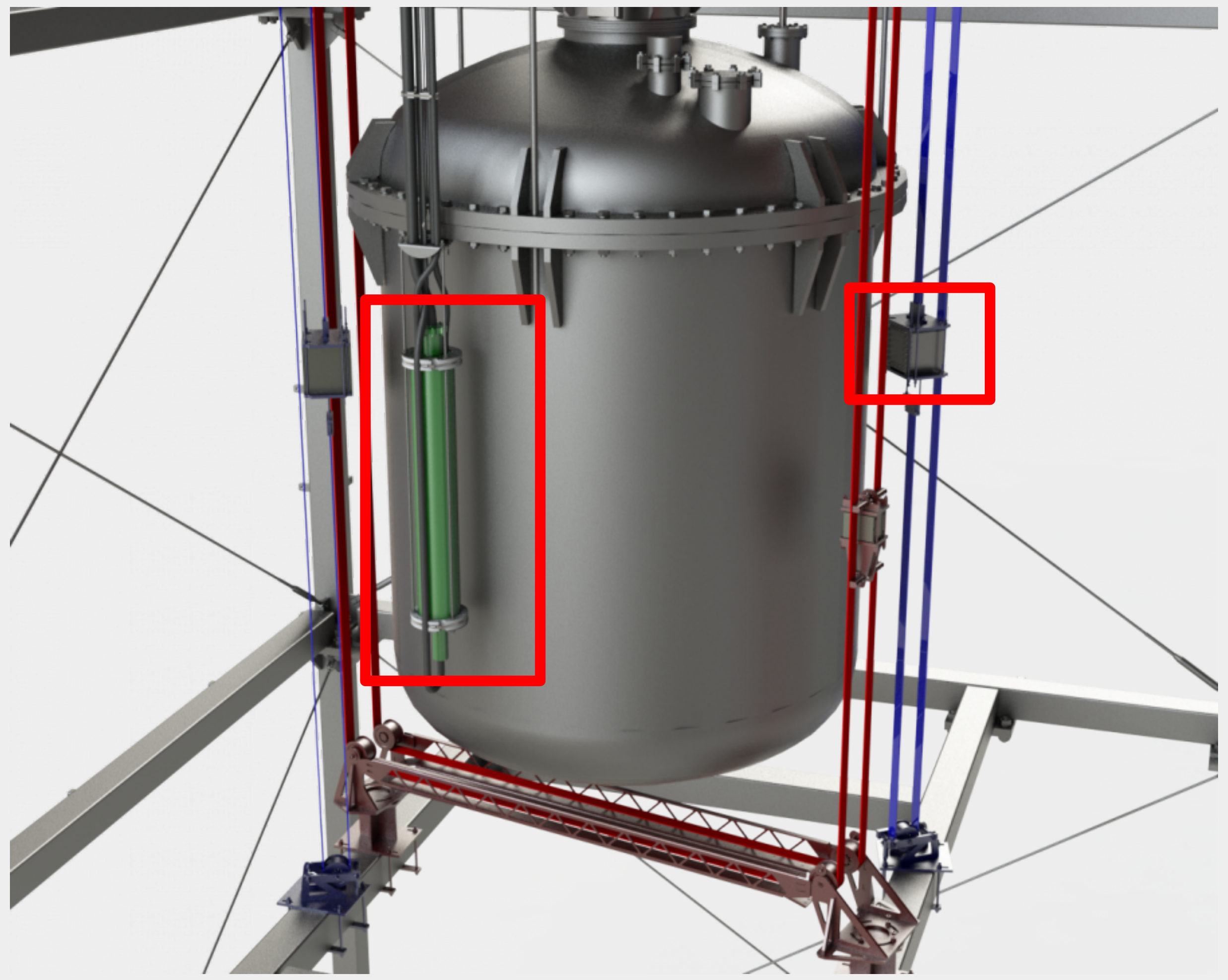
^{83m}**Kr:** Stability and Monitoring



Type: Internal
Freq: 2-3 weeks
Length: 1 day
Half life: 1.83h

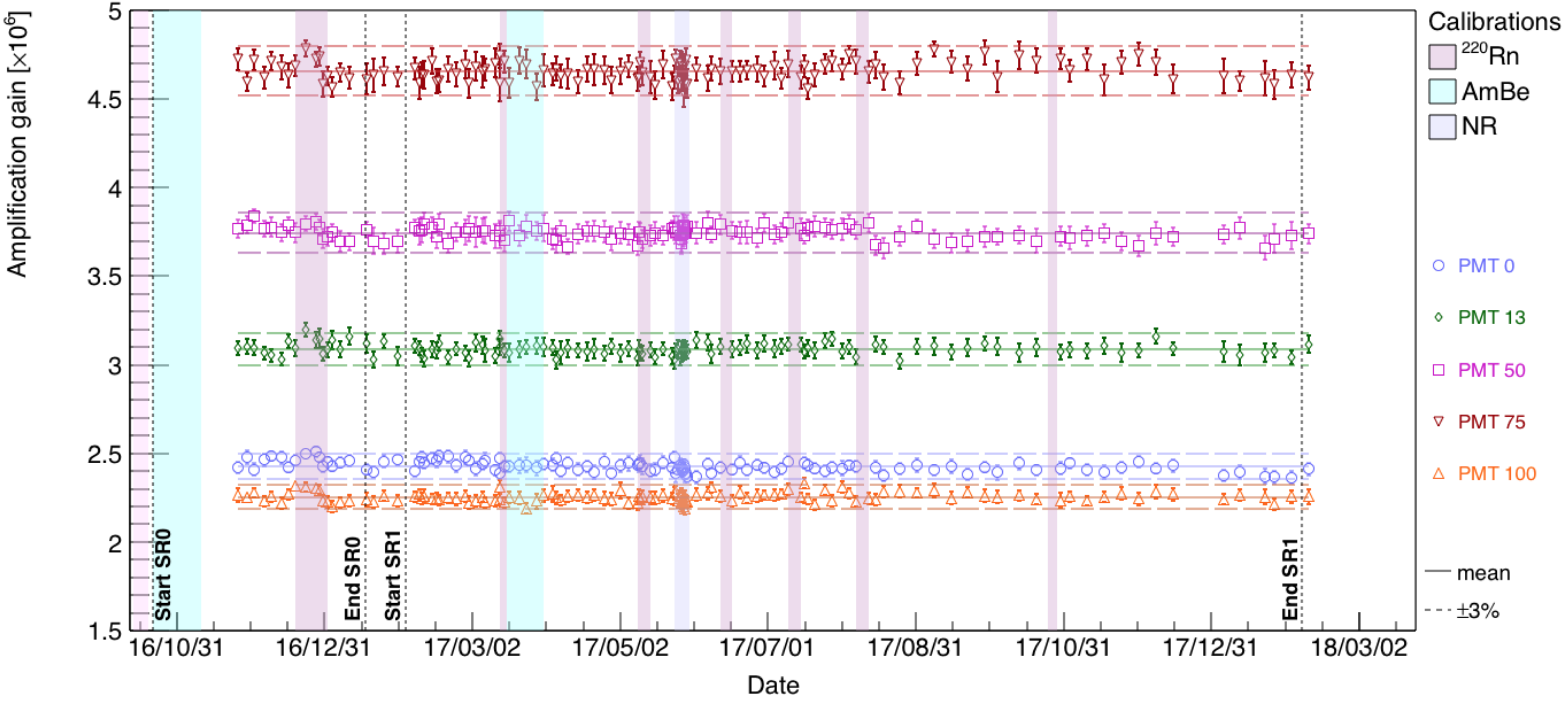
9.4 keV and 32.1 keV lines (~150 ns delay) homogeneous in volume

Neutrons: Signal Response

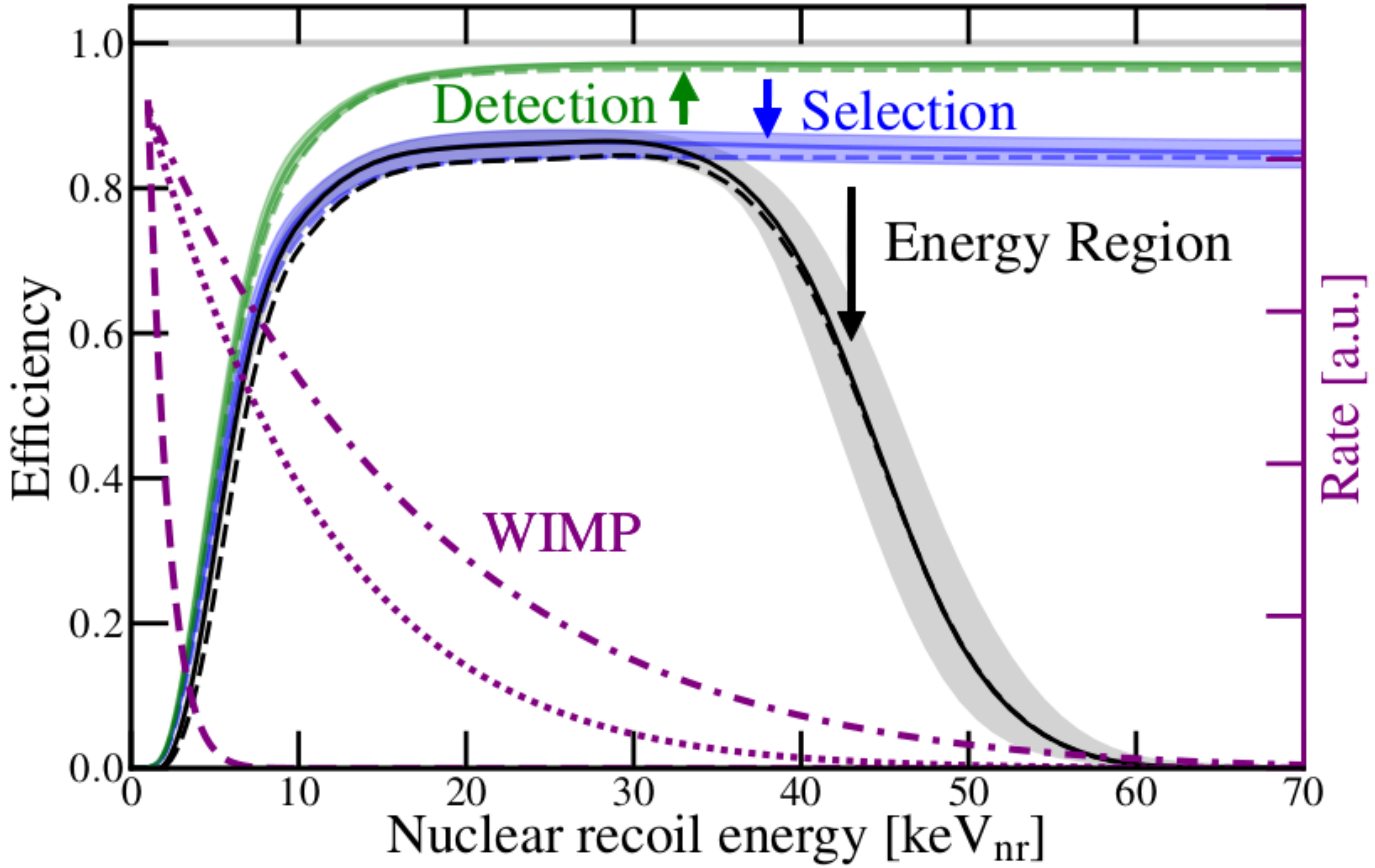


Type: External
Freq: As needed
Length: 6 weeks (AmBe)
2 days (generator)

PMT STABILITY

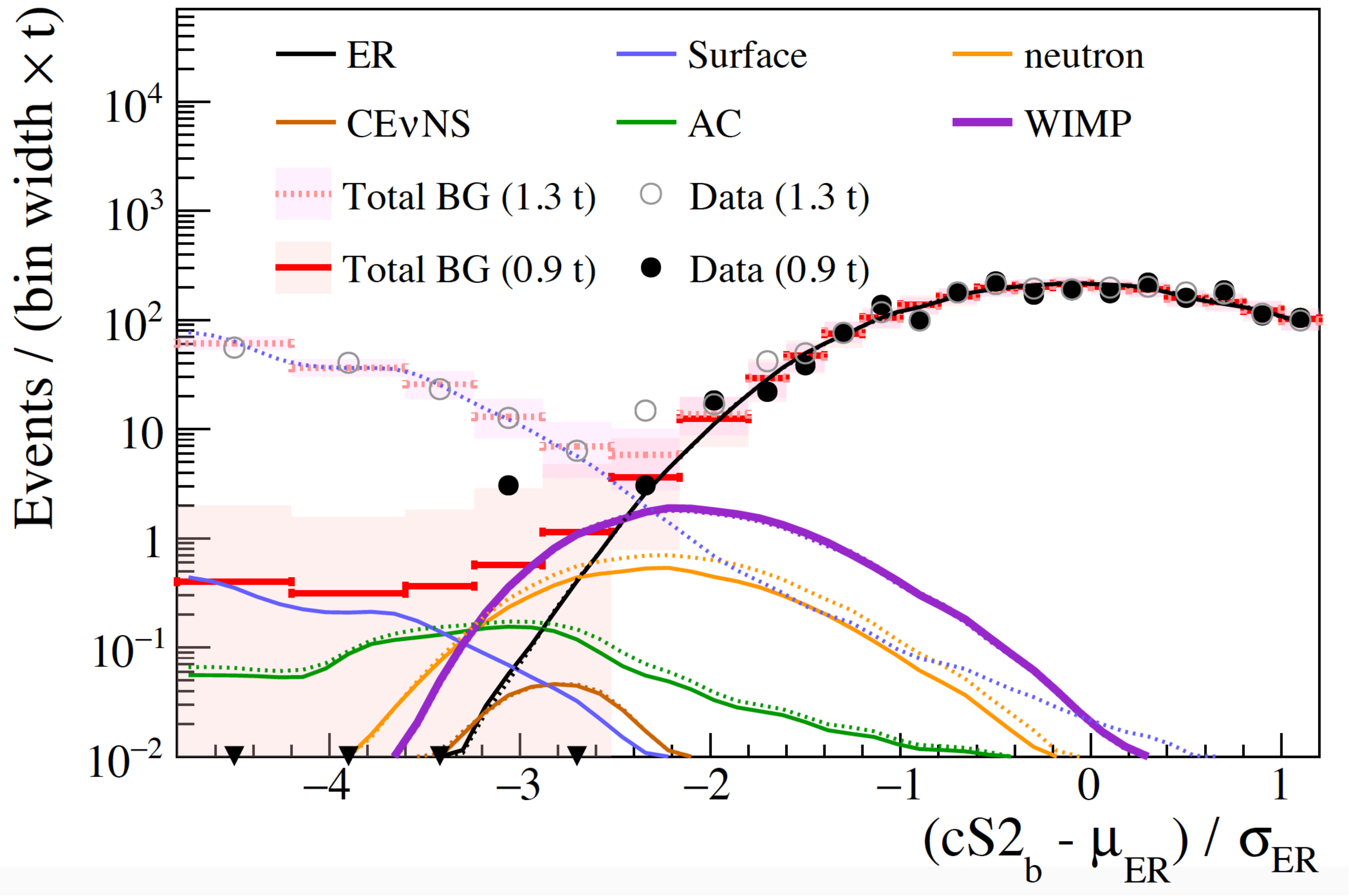


EVENT SELECTION & DETECTION EFFICIENCY



- Detection efficiency dominated by 3-fold coincidence requirement
  - Estimated via novel waveform simulation including systematic uncertainties
- Selection efficiencies estimated from control or MC data samples
- Search region defined within 3-70 PE in cS1
- 10 GeV (dashed), 50 GeV (dotted) and 200 GeV (dashed-dotted) WIMP spectra shown

STATISTICAL INTERPRETATION



- No significant (>3 sigma) excess at any scanned WIMP mass
- Background only hypothesis is accepted although the p-value of ~0.2 at high mass (200 GeV and above) does not disfavor a signal hypothesis either

- Extended unbinned profile likelihood analysis
- Example left: Background and 200 GeV WIMP signal best-fit predictions, assuming 4.7 x 10^{-47} cm^2, compared to data in 1.3 t and 0.9 t
- Most significant ER & Surface backgrounds shape parameters included
- Safeguard to protect against spurious mis-modeling of background