WIMP Dark Matter searches with the XENONnT experiment

Henning Schulze Eißing (h.se@uni-muenster.de)
on behalf of the XENON collaboration

living.knowledge

GRK 2149

Bundesministerium für Bildung und Forschung

Contract number 05A20PM1

Universität Münster

XENON

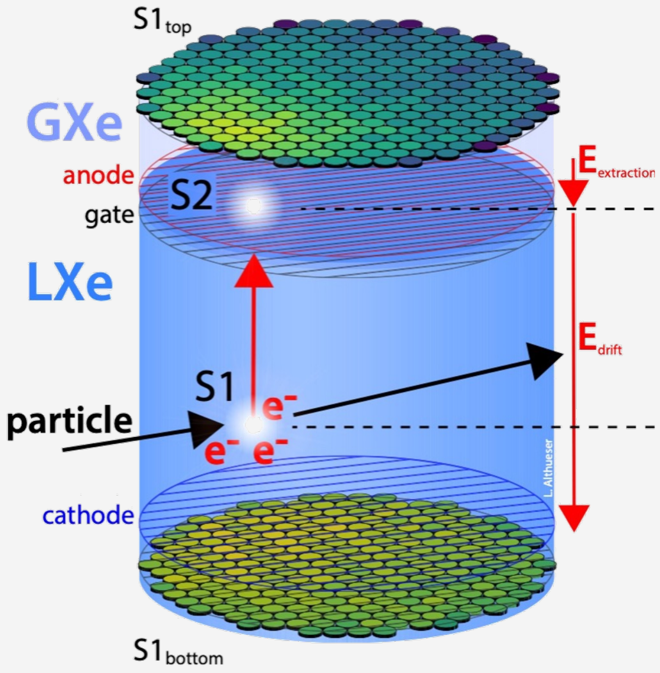
XENON Collaboration

~180 Scientists
29 Institutions

Universität Münster XENON

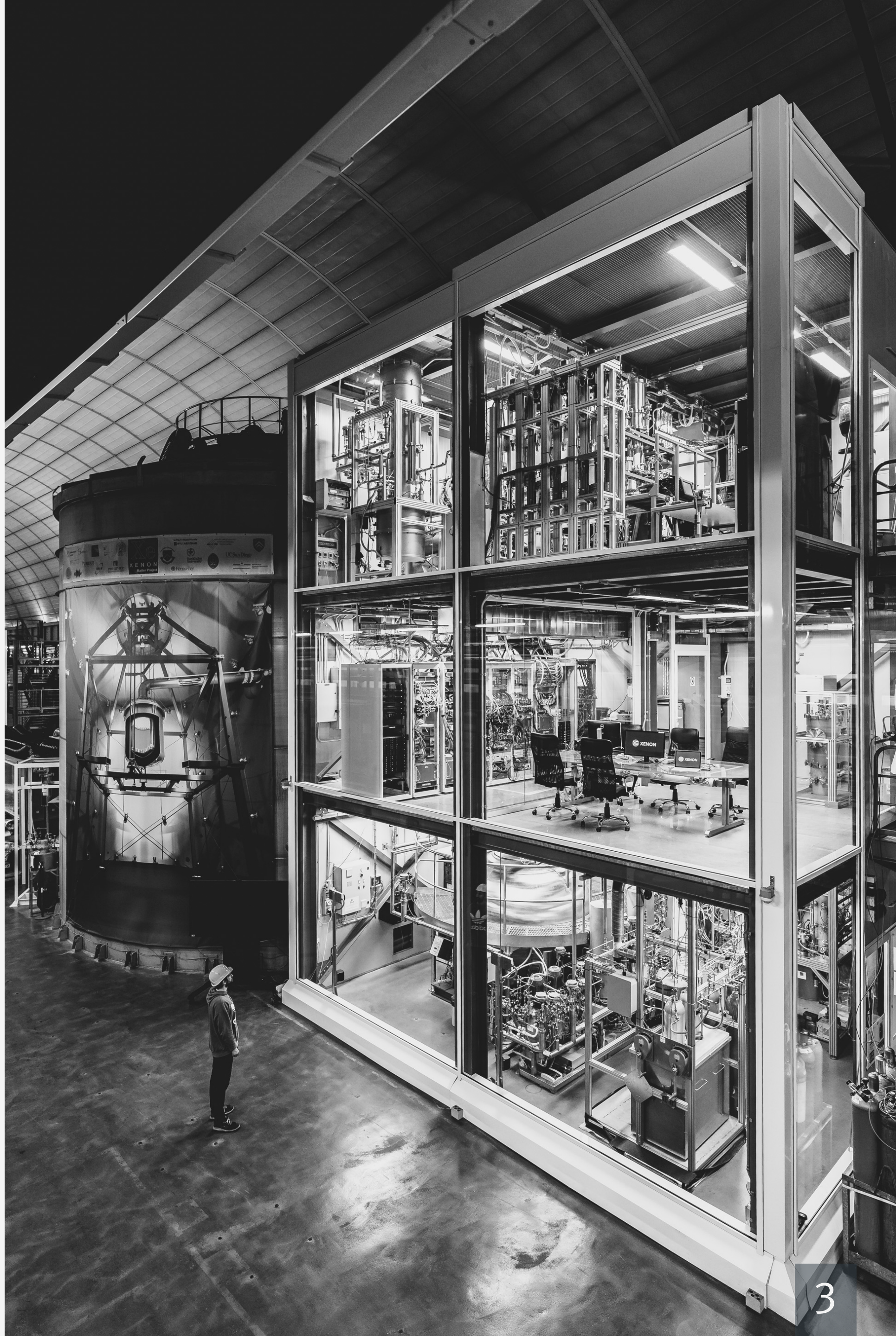
The XENONnT Experiment

- Dark matter direct detection experiment
- At the INFN Laboratori Nazionali del Gran Sasso (LNGS) in Italy
- Underground ultra-low background experiment



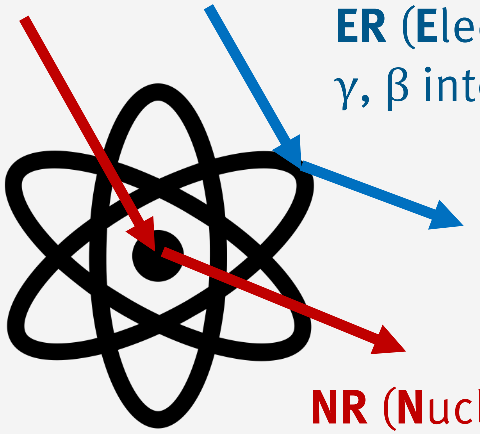
Dual Phase Time Projection Chamber

- Scintillation and ionization
- Photosensor arrays at top and bottom
- Detection of direct scintillation light by PMTs (**S1**)
- Drift and extraction of electrons into the gas phase
- Secondary proportional scintillation signal (**S2**)



 arXiv:2402.10446 accepted at Eur. Phys. J. C

Signals in Liquid Xenon

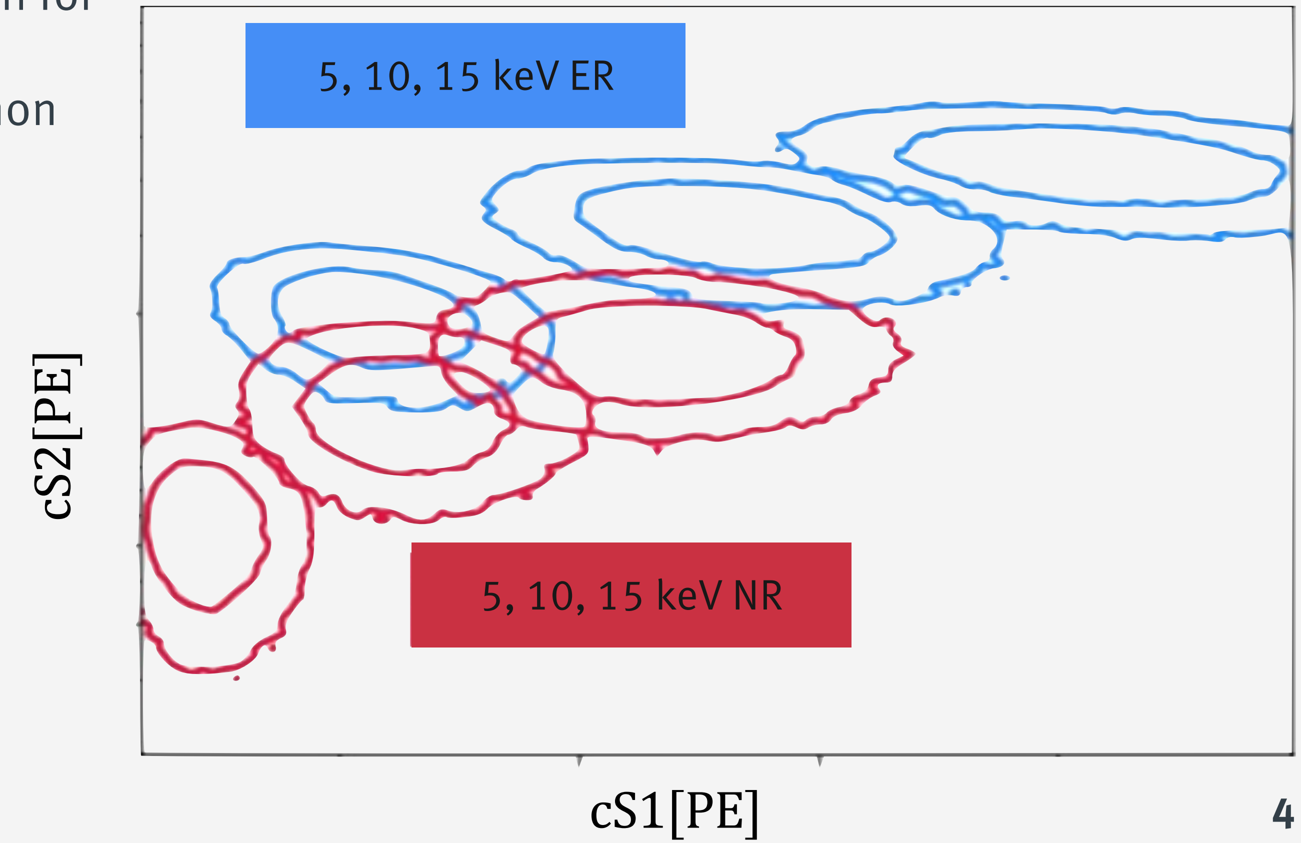


Signal Type Discrimination

- Separation of ER and NR interactions by ratio of light to charge signals
- XENON detectors conceived and designed to search for NR signals created by **WIMPs**
- ~ 1keV ER recoil energy deposited in the liquid xenon target is enough to produce a characteristic scintillation and charge signal

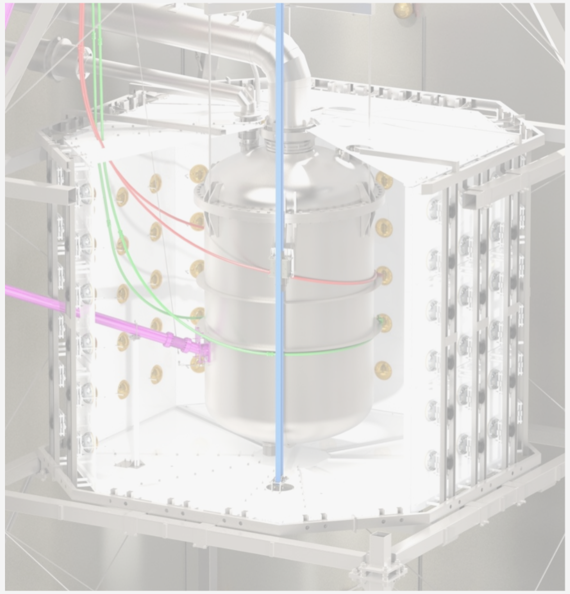
Additional physics cases

- Solar axions, axion-like particles
- Solar neutrinos, SN neutrinos, CEvNS
- (neutrinoless) Double β-Decay, double EC
- Other BSM processes

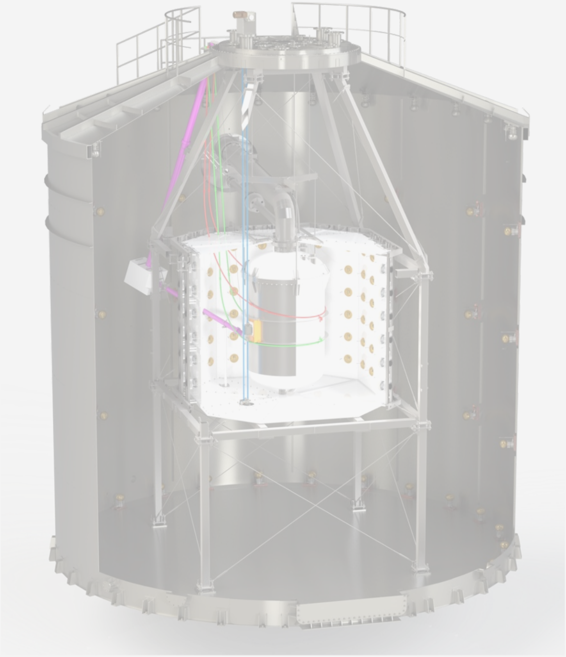


Three Nested Detectors

Time Projection Chamber (TPC)
- 8.5 t ultra pure xenon target
- 5.9 t Xe observed by 494 PMTs
- Active target diameter/height: 1.3m/1.5m



Neutron Veto (NV)
- (Gd-salted) Water Cherenkov detector
- 120 8” PMTs inside enclosure of reflective panels
- Neutron tagging efficiency of 53% in pure water



Muon Veto (MV)
- 700 t Water Cherenkov detector
- 84 8” PMTs
- Active veto against muons
- Passive shielding

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Three Nested Detectors

The XENONnT Neutron Veto: performances without and with Gd-doping
Marco Selvi – Today 17:10

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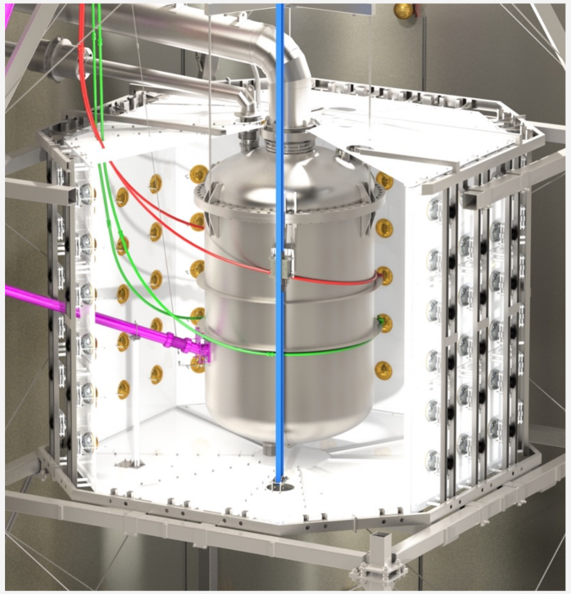

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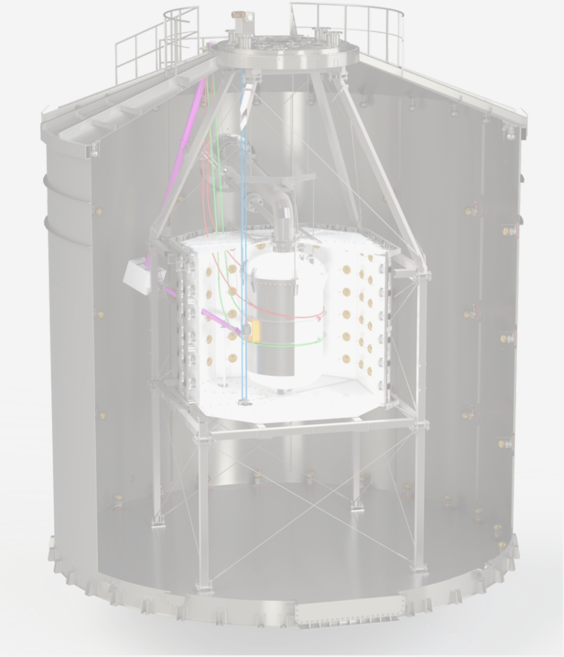

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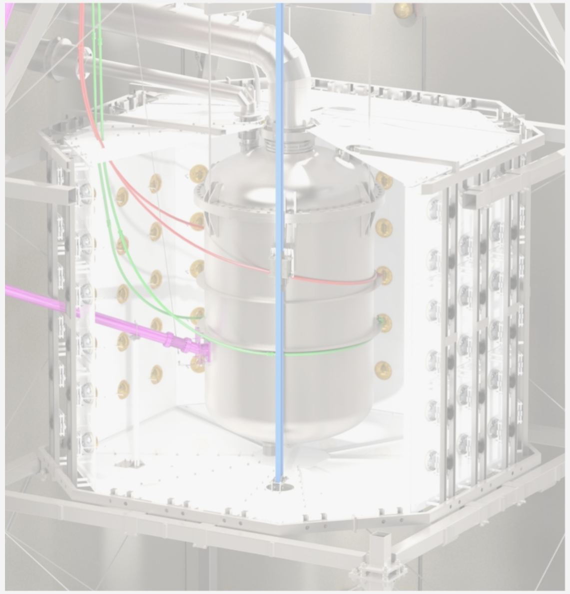

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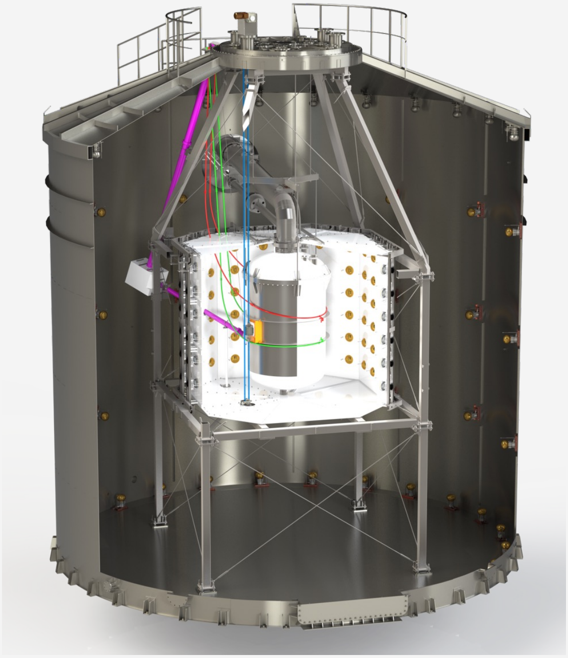

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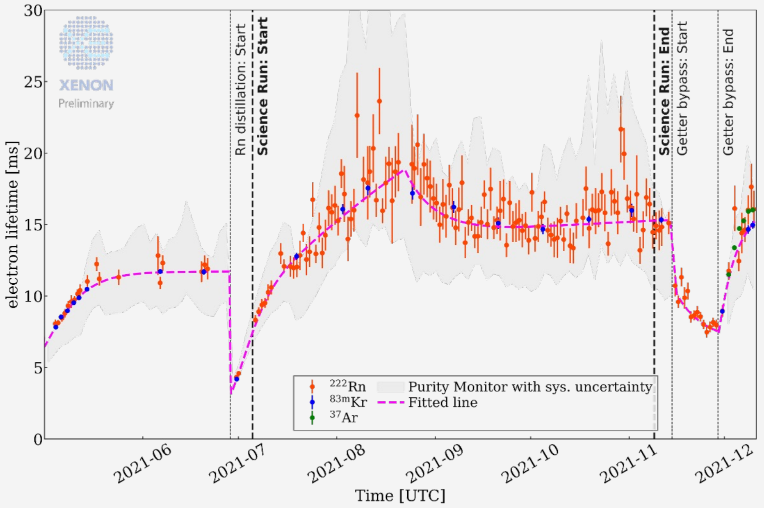
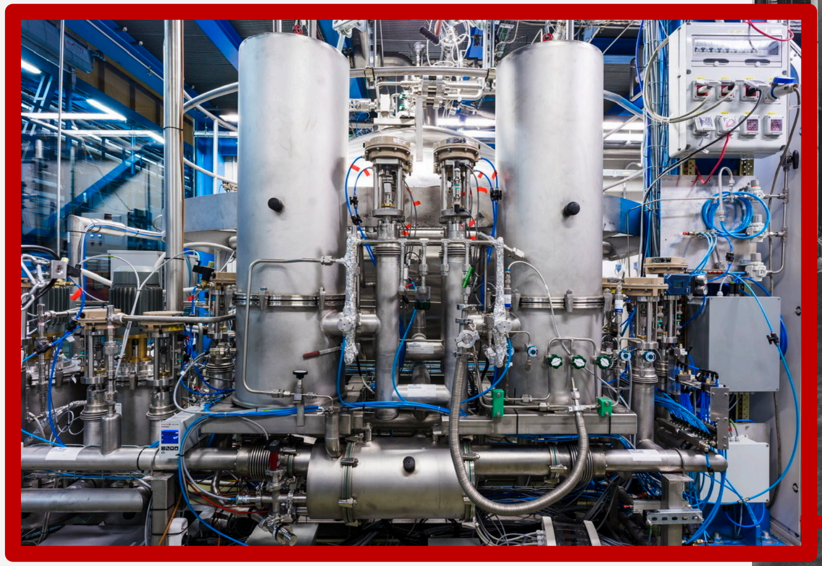
Selected Upgrades

	Max TPC drift time	Electron Lifetime	e^- survival @ max. drift length
XENON1T	0.67 ms	0.65 ms	30%
XENONnT	2.2 ms	› 15 ms	› 90%

Liquid xenon purification

- LXe purity is crucial to drift electrons along the entire detector length
- Novel liquid-phase purification system with replaceable filters and extremely low radon emanation
- High flow of 2 liters LXe per minute, recirculate entire inventory in 18h





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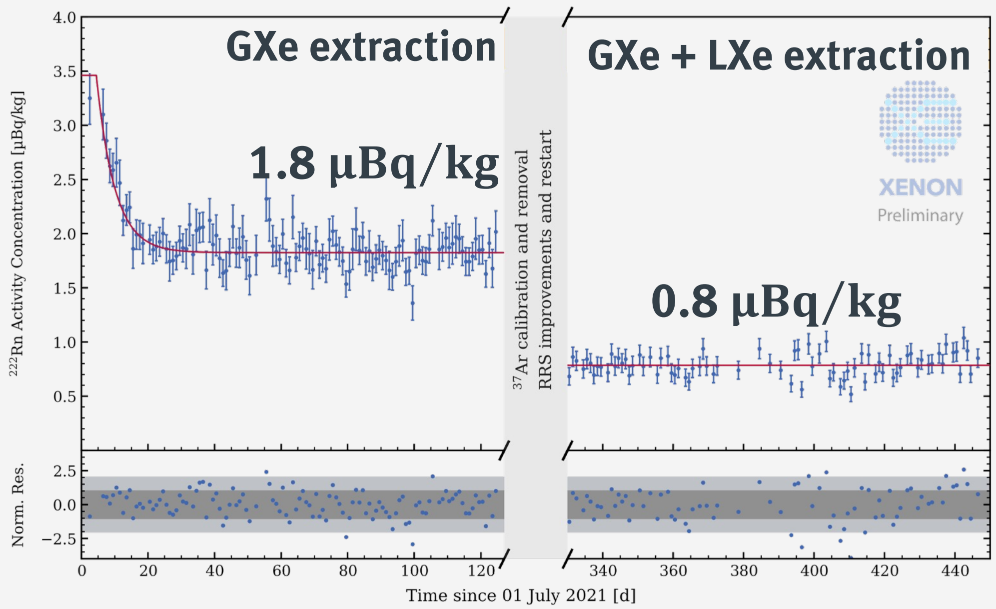
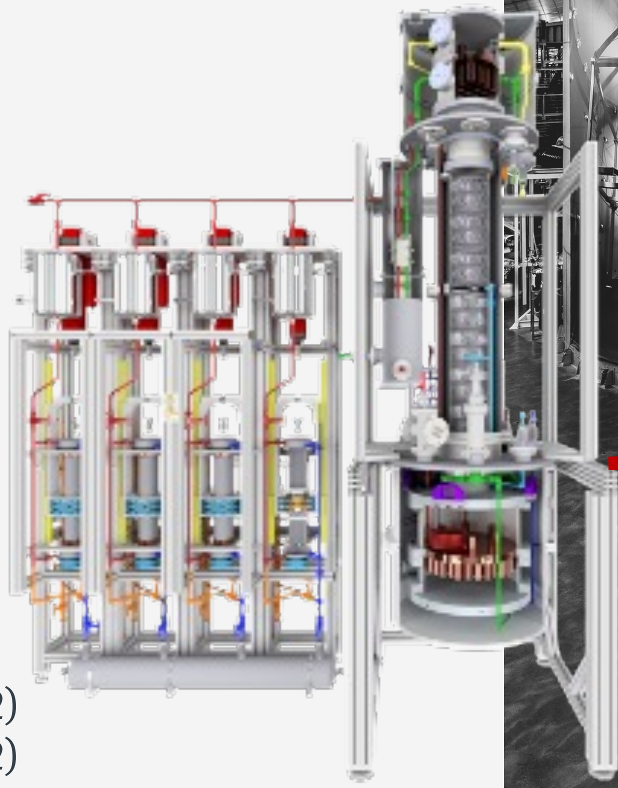
Eur. Phys. J. C 82, 860 (2022)

Selected Upgrades

Radon Distillation Column

- ^{222}Rn daughters are the main background
- Continuous emanation from detector components
- Continuous cryogenic distillation removing Rn from LXe
- High flow: 71 kg/h (200 slpm)
- $< \mathbf{1\ \mu Bq/kg}$ ^{222}Rn activity





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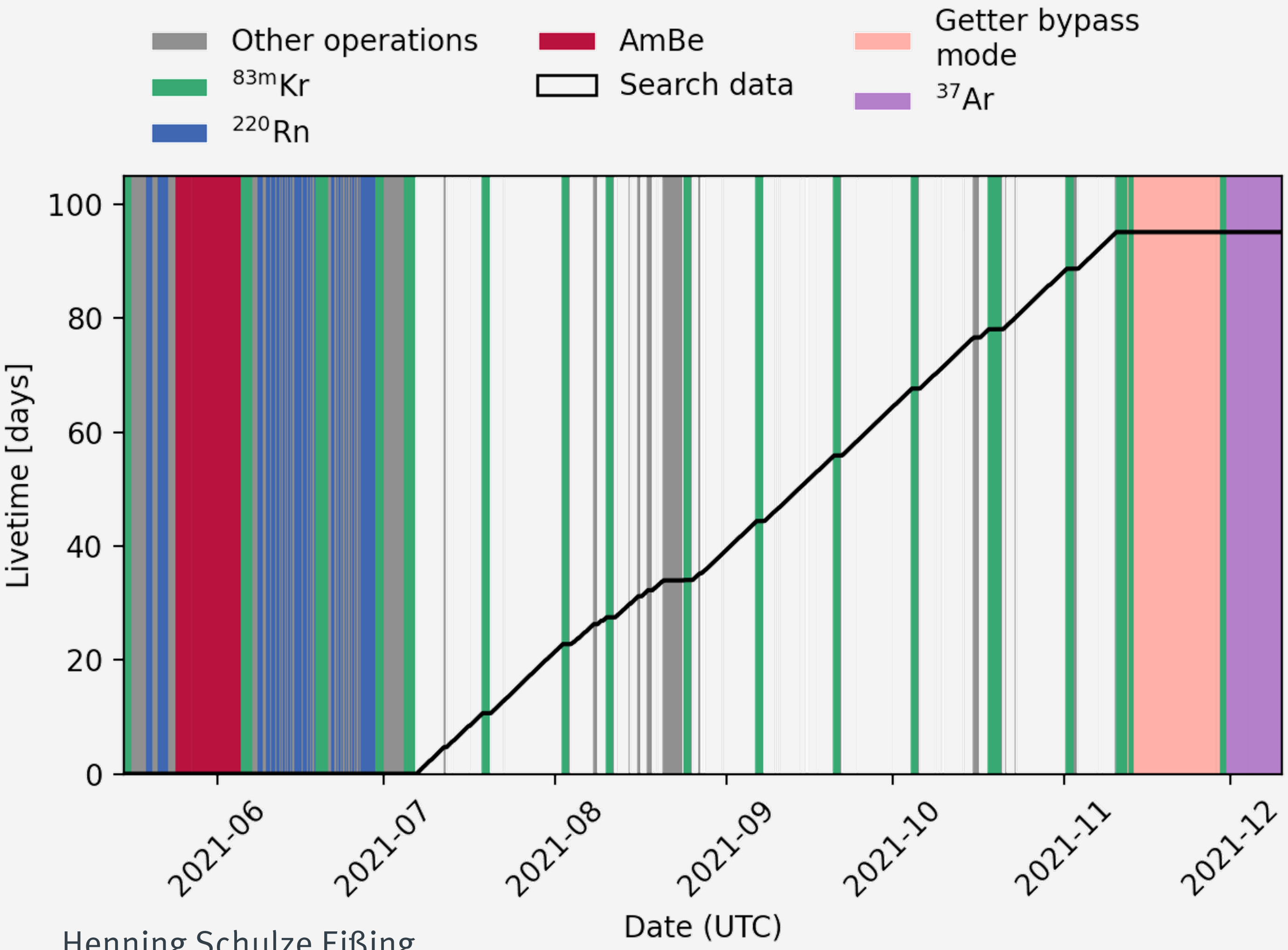
Eur. Phys. J. C 82, 1104 (2022)
J. Inst. 17, P05037 (2022)

XENONnT SR0



Data Taking

- 97.1 days exposure from July 6th to November 11th 2021
- 95.1 days lifetime corrected
- Rn column in gas-only mode

Detector Conditions

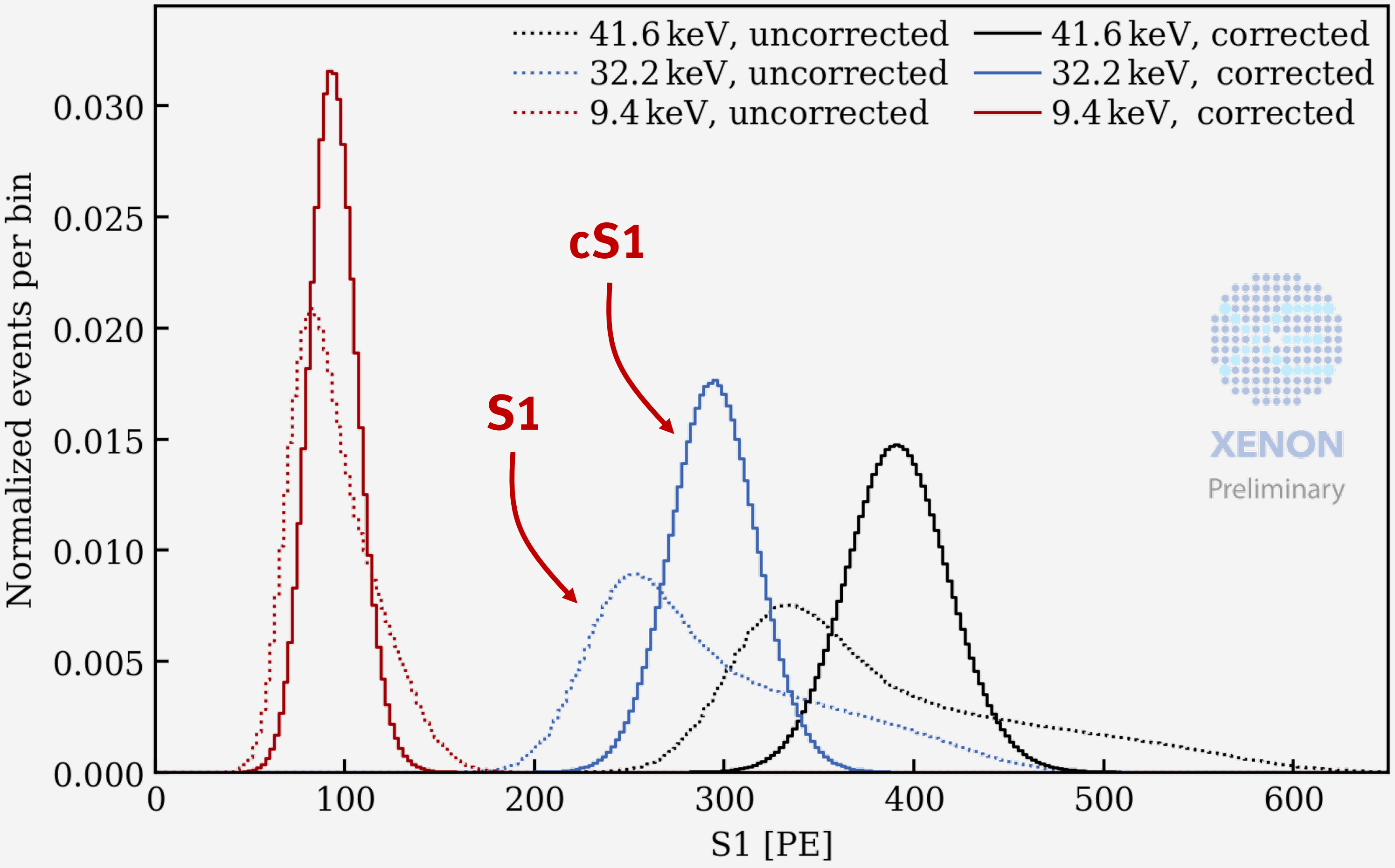
- ›96% PMTs working, gain stable at 3%
- 23 V/cm drift field, extraction field in LXe 2.9 kV/cm
- Localized high single-electron emission, occurring seemingly at random: cured with short anode ramp-down

Phys. Rev. Lett. 129, 161805 (2022)
Phys. Rev. Lett. 131, 041003 (2023)

Calibration and Analysis

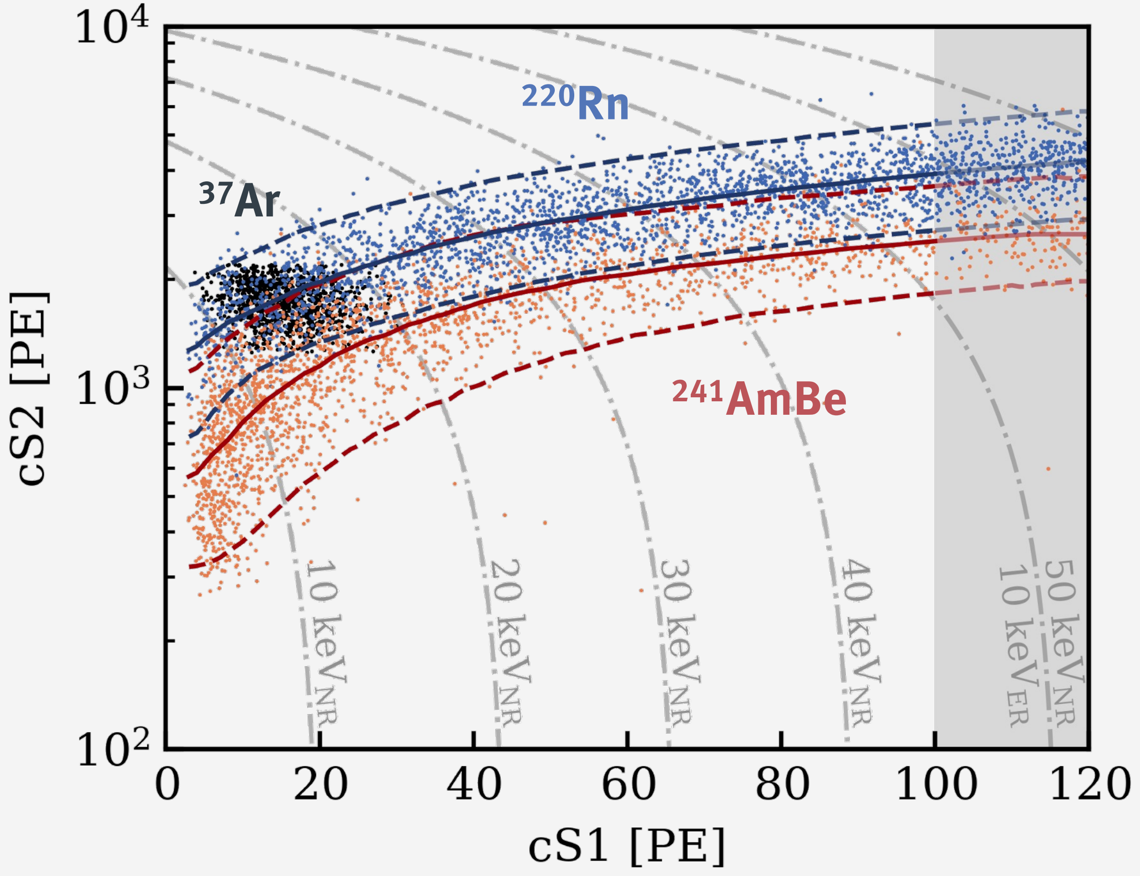
Multi-step analysis effort

- Peak and event reconstruction
- Signal Corrections – Compensate inhomogeneous (spatial, temporal) detector response
- Data quality validation
- Cuts against backgrounds
- Background modeling
- Detector response modeling
- Inference



arXiv:2406.13638

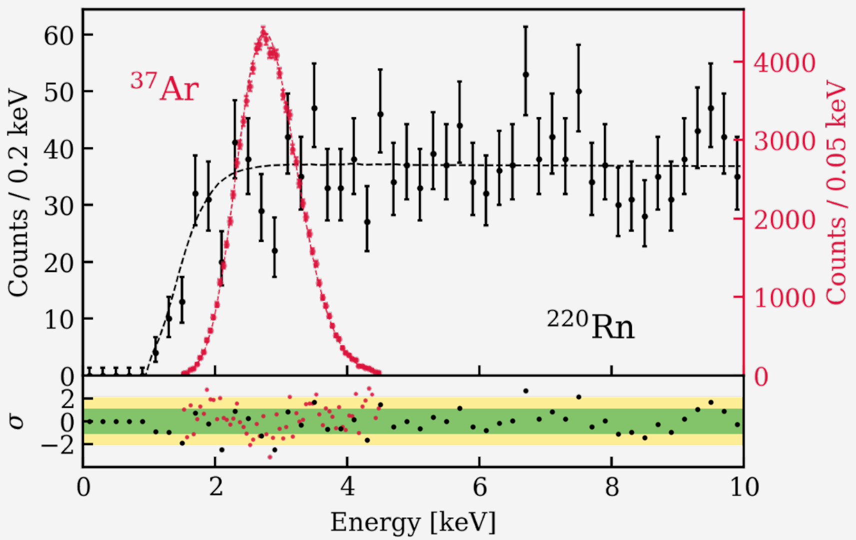
ER and NR Response



Phys. Rev. Lett. 131, 041003 (2023)

Electronic Recoil Calibration

- **^{212}Pb** from ^{220}Rn gives a roughly flat β-spectrum to estimate cut acceptances and energy threshold
- **^{37}Ar** gives a mono-energetic 2.82 keV peak to model the low energy response and resolution near the detector energy threshold



Nuclear Recoil Calibration

- External **^{241}AmBe** neutron source with clean NR selection via coincident 4.4 MeV γ-ray observed in the neutron veto

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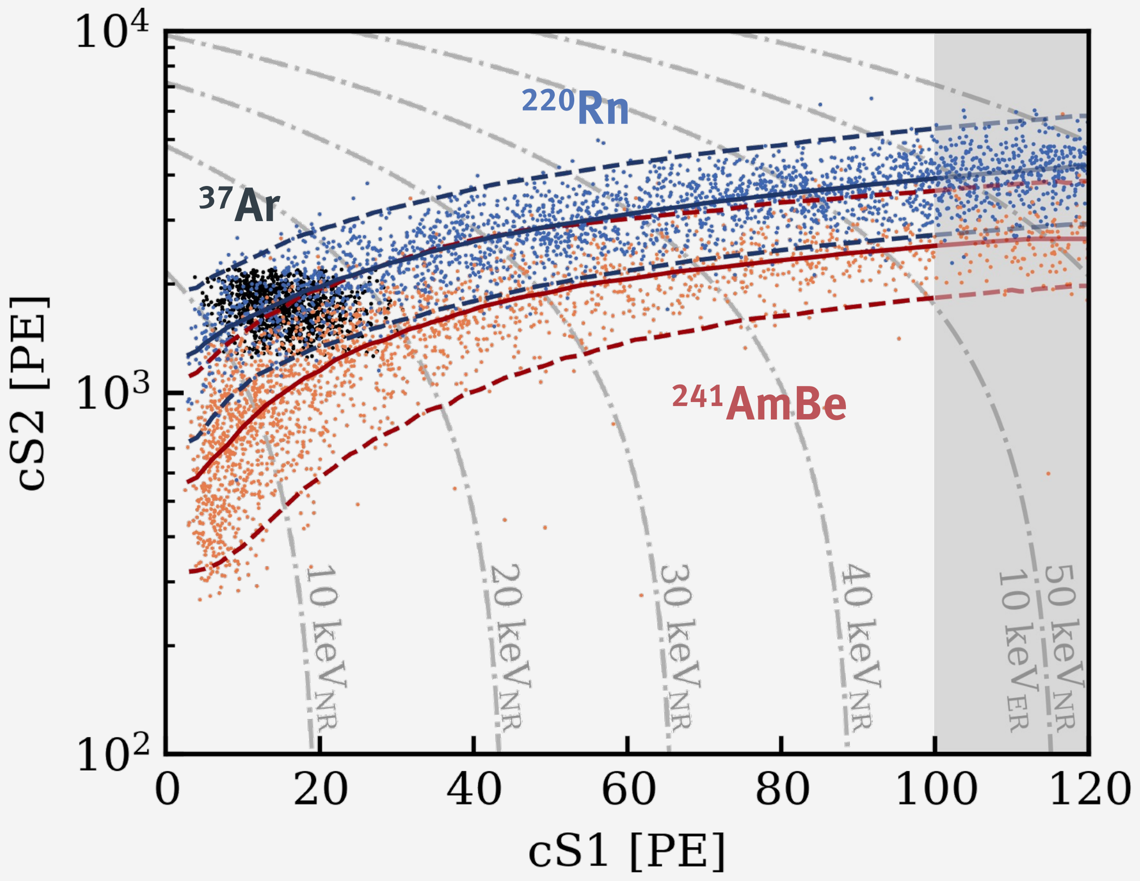
Physics Searches

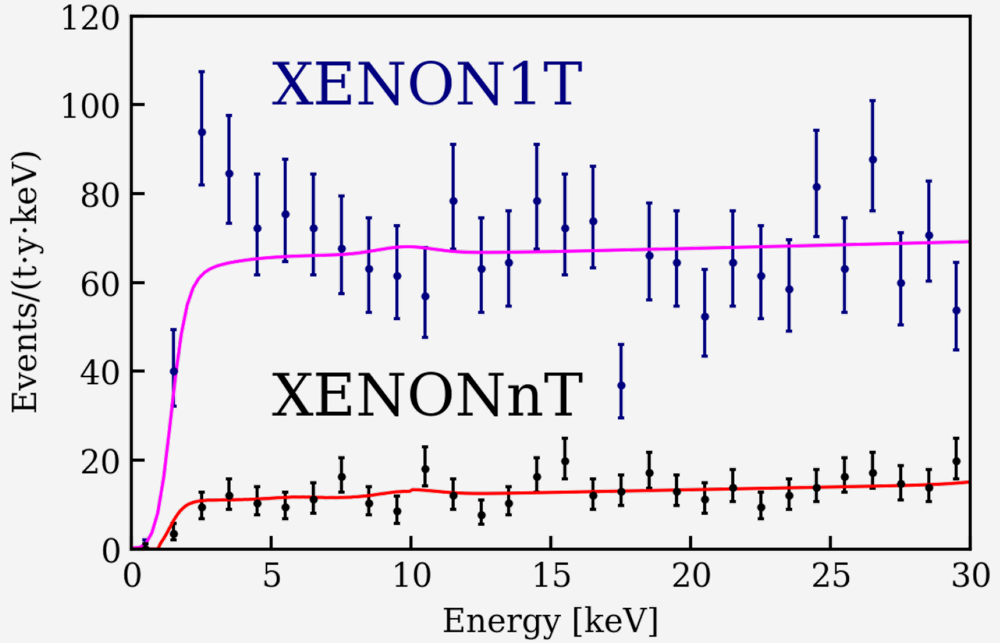


Phys. Rev. Lett. 131, 041003 (2023)

Electronic Recoils

- Search in energy reconstructed from S1 and S2
- Unprecedented low background: 15.8 ± 1.3 events / $(t \cdot y \cdot keV)$
- No low-energy ER excess found excluding BSM explanation of XENON1T excess

Phys. Rev. Lett. 129, 161805 (2022)



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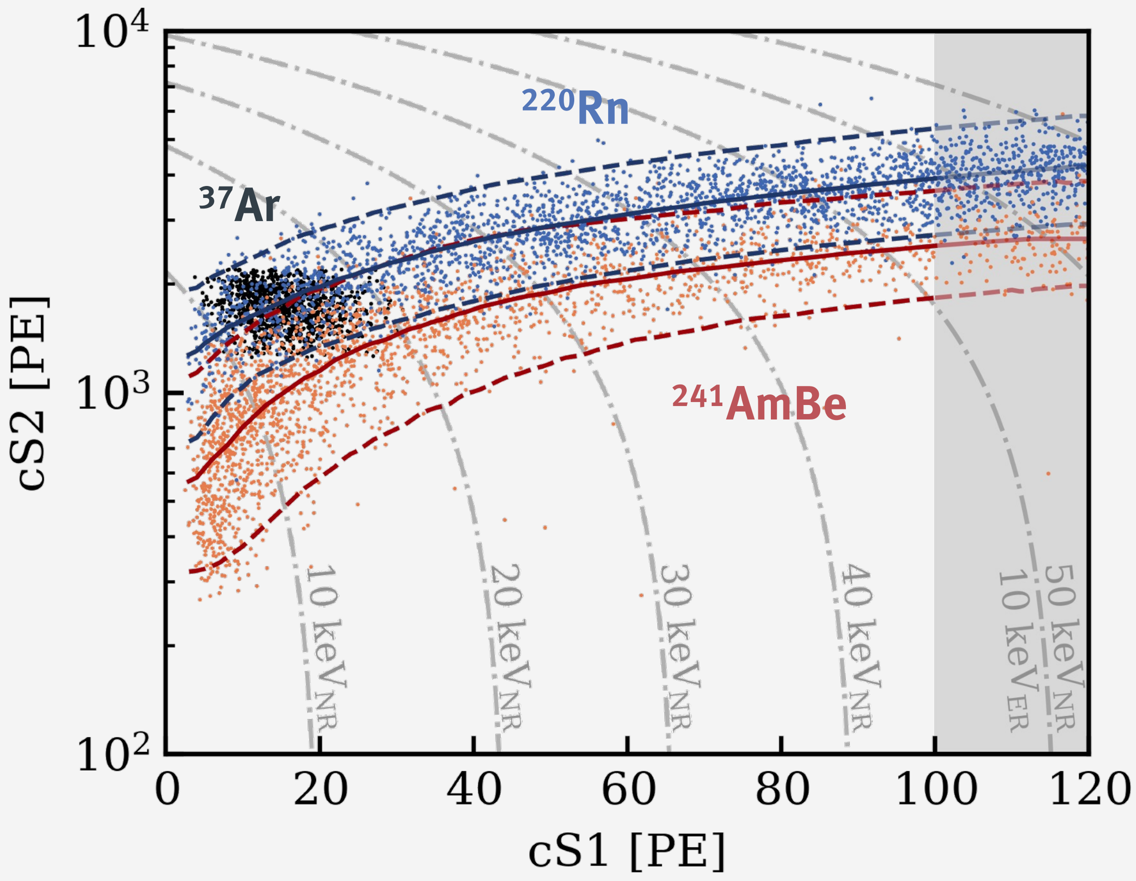

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Phys. Rev. Lett. 129, 161805 (2022)

Nuclear Recoils

- Search in cS1, cS2 and r (radius) for WIMP dark matter
- Even lower NR background boosted by ER/NR discrimination
- Blind analysis leading to stringent limits on WIMP interactions

Phys. Rev. Lett. 131, 041003 (2023)

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Accidental Coincidence Background Modeling for Low Energy Nuclear Recoil Search in XENONnT
Kexin Liu – Today 15:00

XENONnT physics-driven 6D Surface Background Model
Cecilia Ferrari – Poster

Backgrounds in WIMP search

ER Background

- Dominated by radon background (^{214}Pb beta decay, GXe extraction only)
- Sub-dominant ^{85}Kr background (cryo. Distillation)

Surface Background

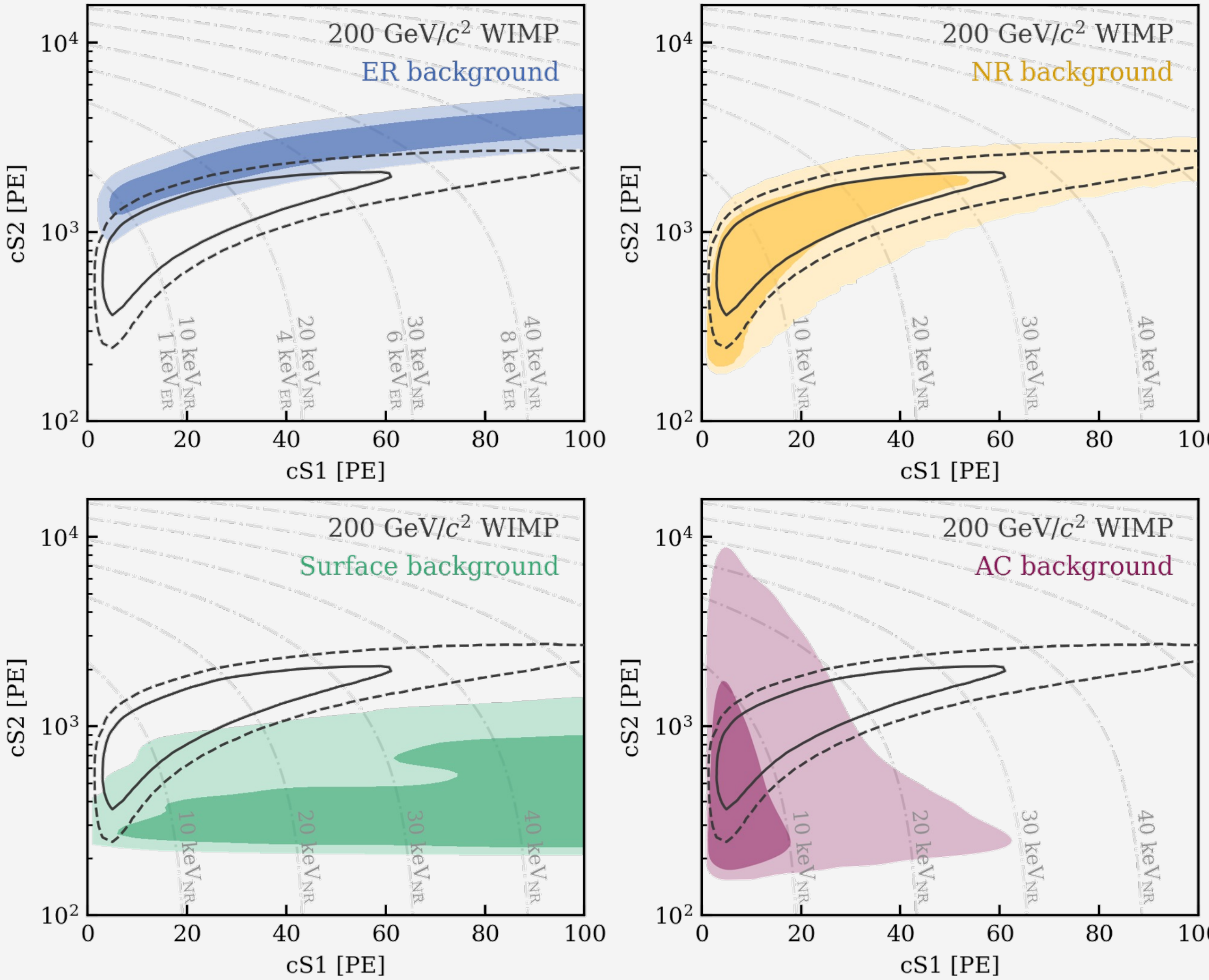
- ^{210}Pb plate-out at the PTFE walls leading to ^{210}Po α-decays with electron loss
- Suppressed by fiducial volume cut

Accidental Coincidences

- Random pairing of isolated S1 and S2 signals
- Suppression using a gradient BDT cut based on S2 shape, R and Z information

NR Background

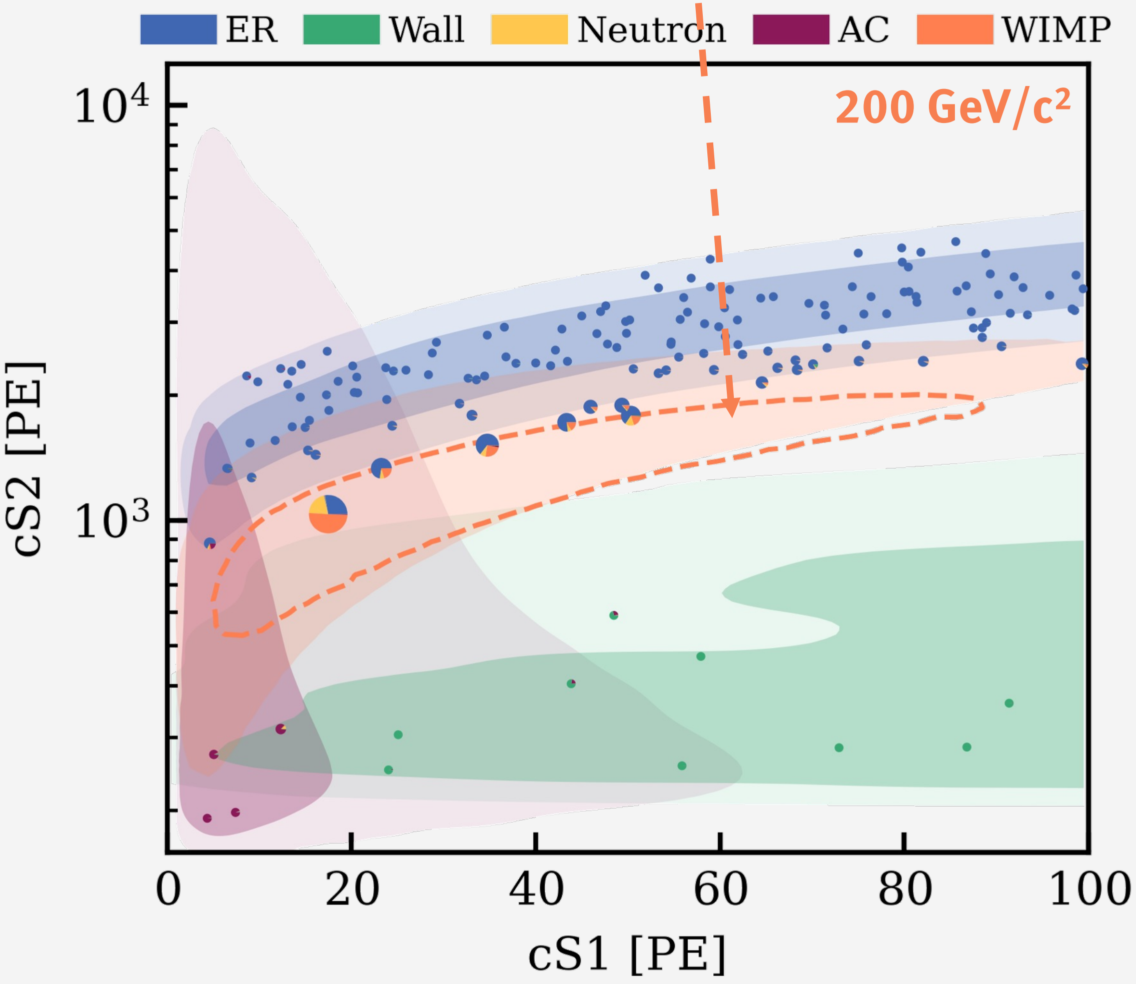
- Radiogenic neutron rate constrained by NV tagging
- CEvNS constrained from solar ^{8}B neutrino flux



WIMP search results

	Nominal	Best Fit (200 GeV/c^2)
ER	134	135(+12)(-11)
Neutrons	1.1(+0.6)(-0.5)	1.1 ± 0.4
CEvNS	0.23 ± 0.06	0.23 ± 0.06
AC	4.3 ± 0.2	4.32 ± 0.16
Surface	14 ± 3	12(+0)(-4)
Total Background	154	152 ± 12
WIMP	-	2.6
Observed	-	152

Signal like region, containing 50% of WIMP signal with highest signal-to-noise



No significant excess found!

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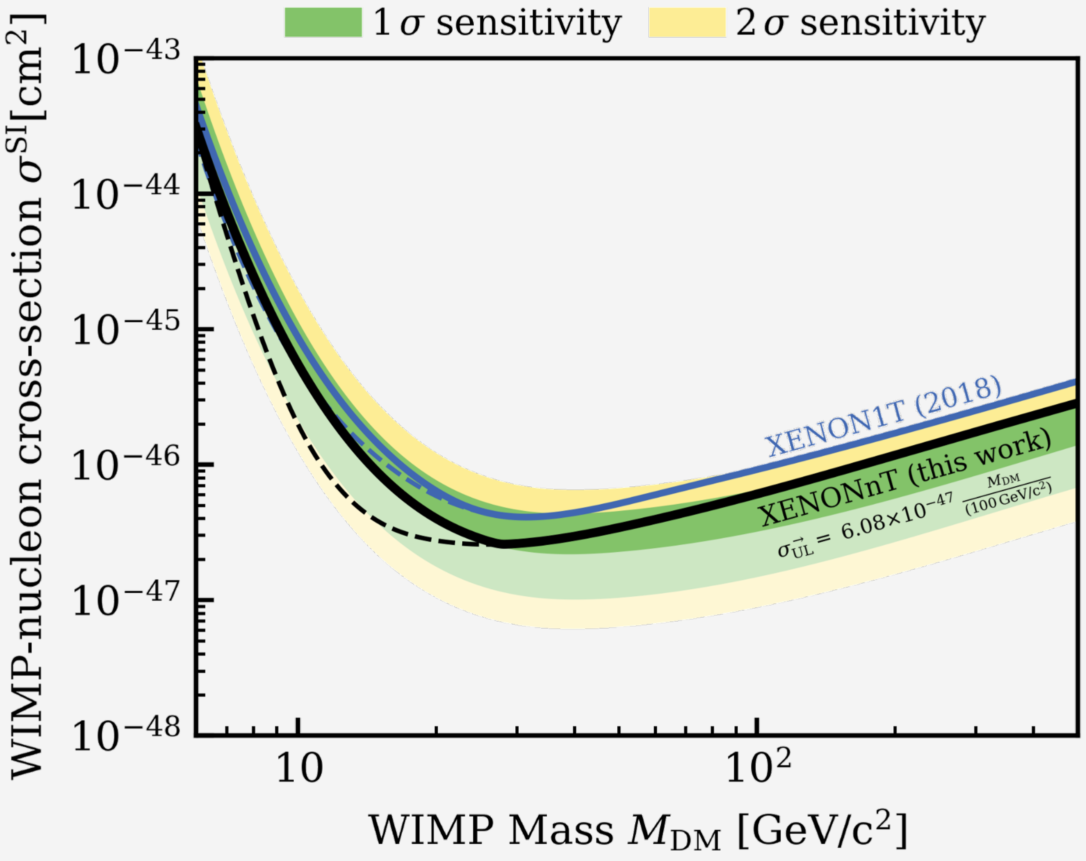
Limit on SI WIMP-nucleon Cross Section

Limit Setting
- Unbinned maximum likelihood
- Power constraint limits (PCL) to avoid spurious exclusion limits
- Only exclude the parameter space that the detector is sensitive to.
- Conservative choice at median of sensitivity band
- This needs to be discussed within the community

Results
- Strongest limit: $\mathbf{2.6 \cdot 10^{-47} cm^2}$ at WIMP mass of $\mathbf{28\ GeV/c^2}$
- Factor 1.6 improvement w.r.t. XENON1T (with considerably shorter lifetime)
- Similar improvements in spin-dependent limits



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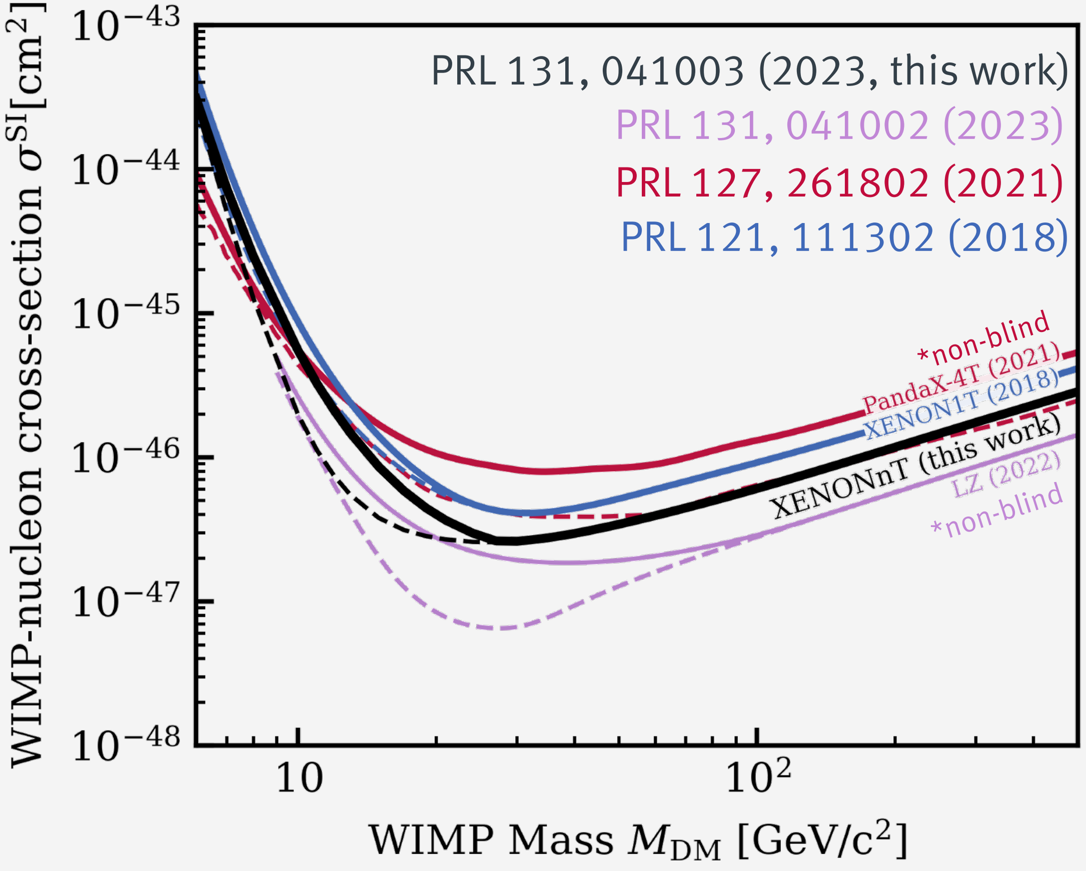

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Summary and Outlook

XENONnT SR0

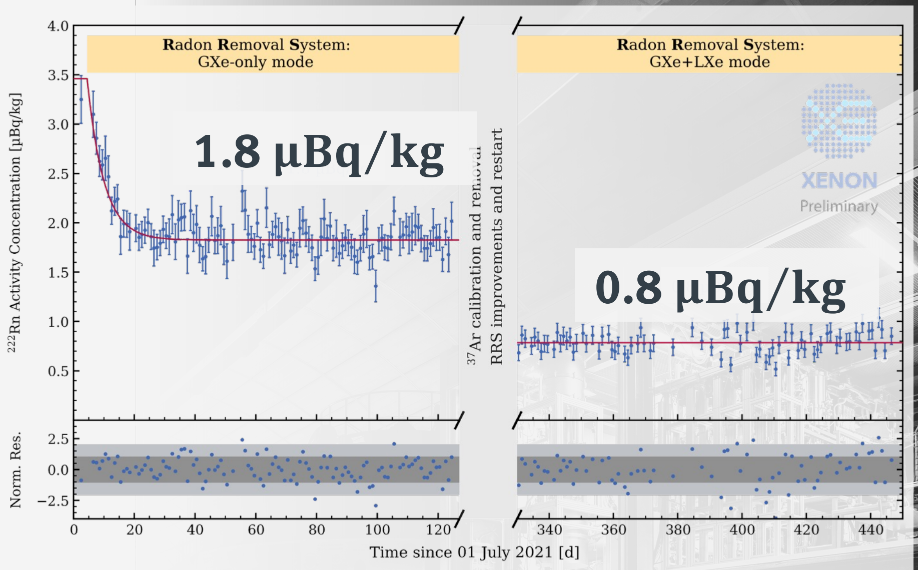
- Ultrapure target with an electron lifetime above 15 ms
- Lowest ER background in the field: $(15 \pm 1.3)(\mathrm{t\ yr\ keV})^{-1}$ ~5x background reduction w.r.t. XENON1T

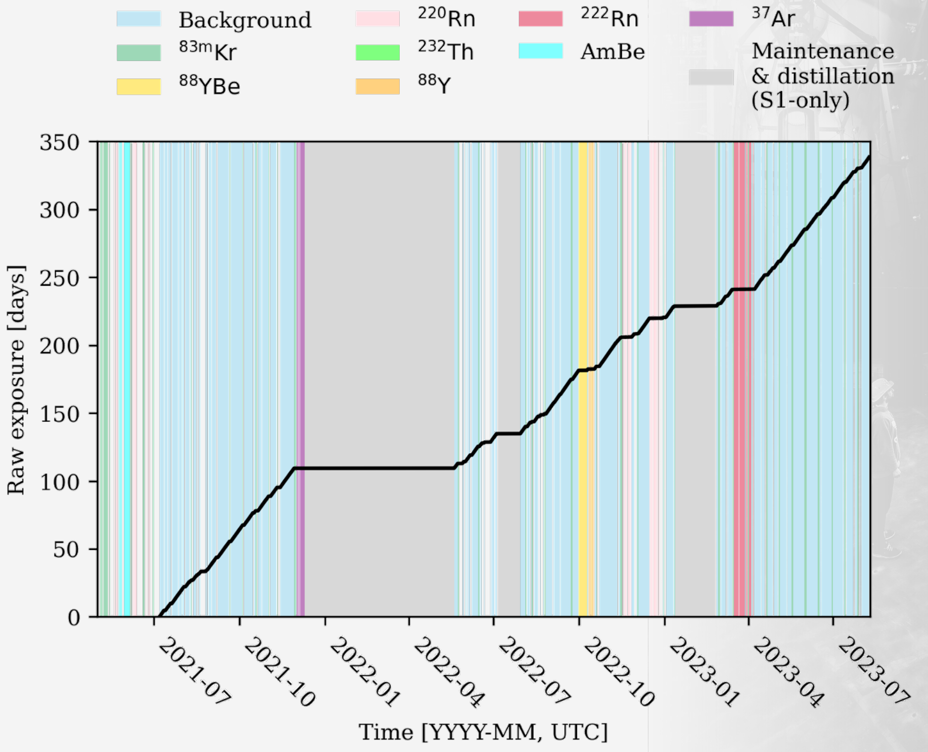
First Results

- Blinded electronic recoil (ER) and nuclear recoil (NR) searches
- No significant excess over background found

Prospects

- ~2x improved ^{222}Rn level
- Improved neutron tagging by Gd-loaded neutron veto
- WIMP search with increased exposure in preparation
- Continue to accumulate low BG data





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Backup Slides

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XENON Dark Matter Project

XENON10	XENON100	XENON1T	XENONnT
2005	2009	2016	2020

Target Mass

XENON10	XENON100	XENON1T	XENONnT
15 kg	161 kg	3.2 t	8.6 t

Relative Background

XENON10	XENON100	XENON1T	XENONnT
1	$5 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$3 \cdot 10^{-5}$

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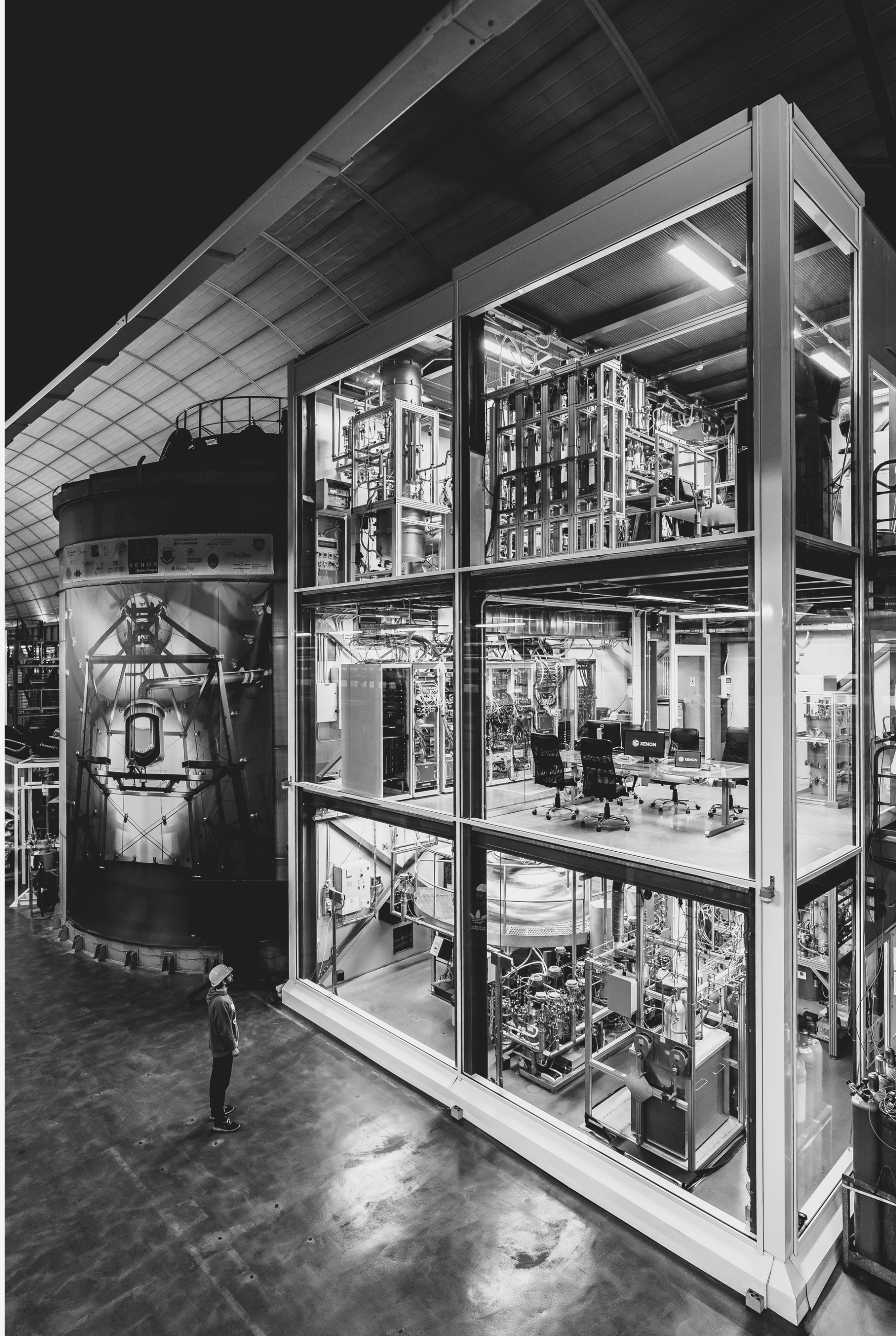

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J. Inst. 18, P07054 (2023)

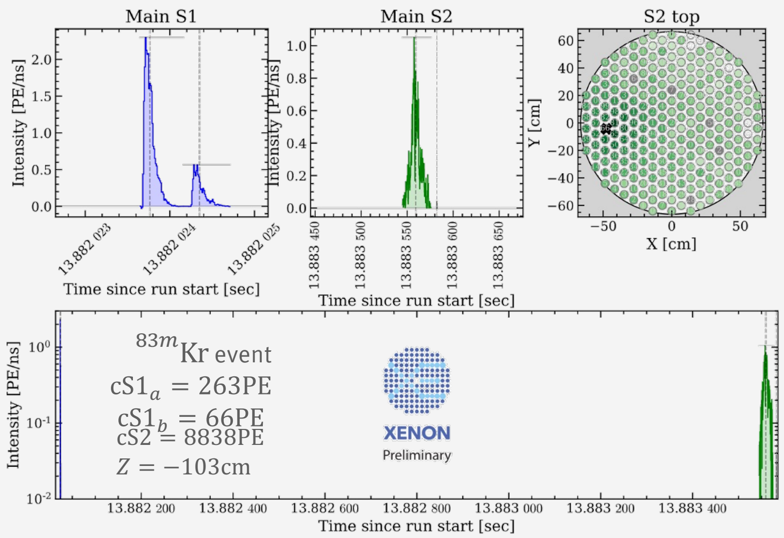
Selected Upgrades

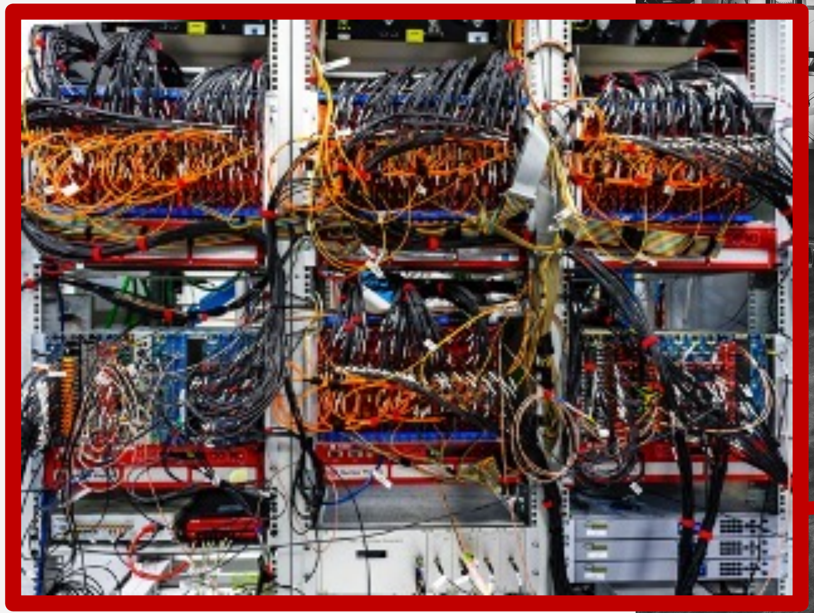
Triggerless Data Acquisition

- All data above per-channel threshold stored long-term
- Fully live processing

Open Source Software

- Available on GitHub
- Processing: strax, straxen
- Simulation: fuse, appletree, WFSim, epix
- Inference: alea





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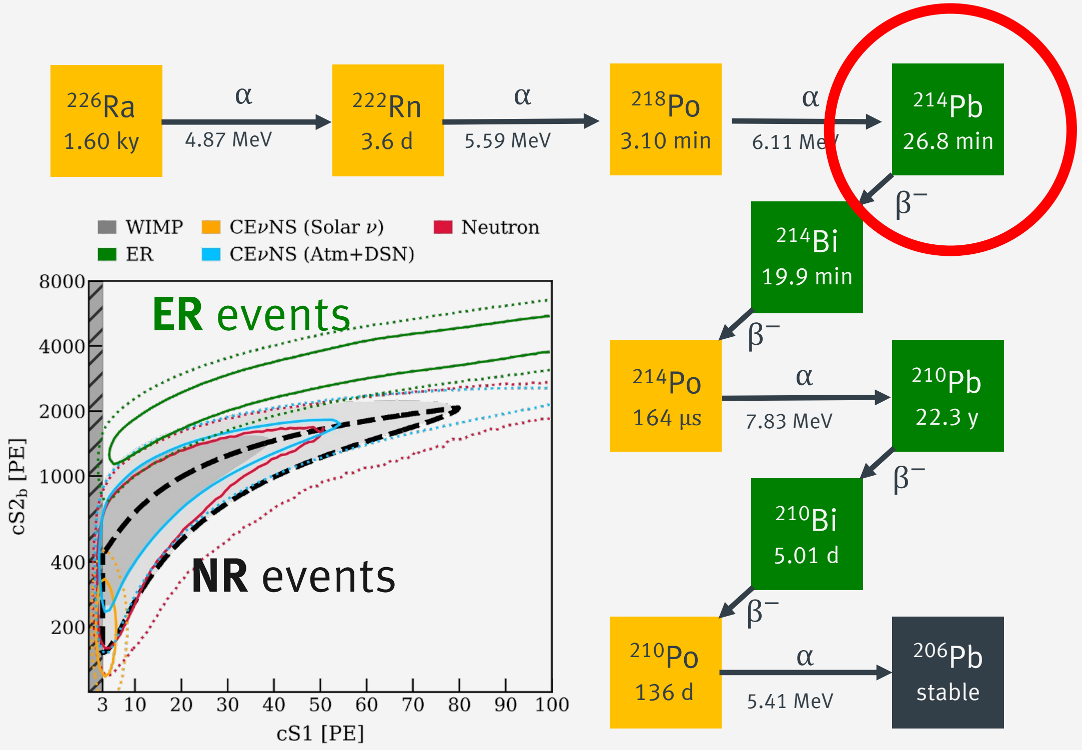
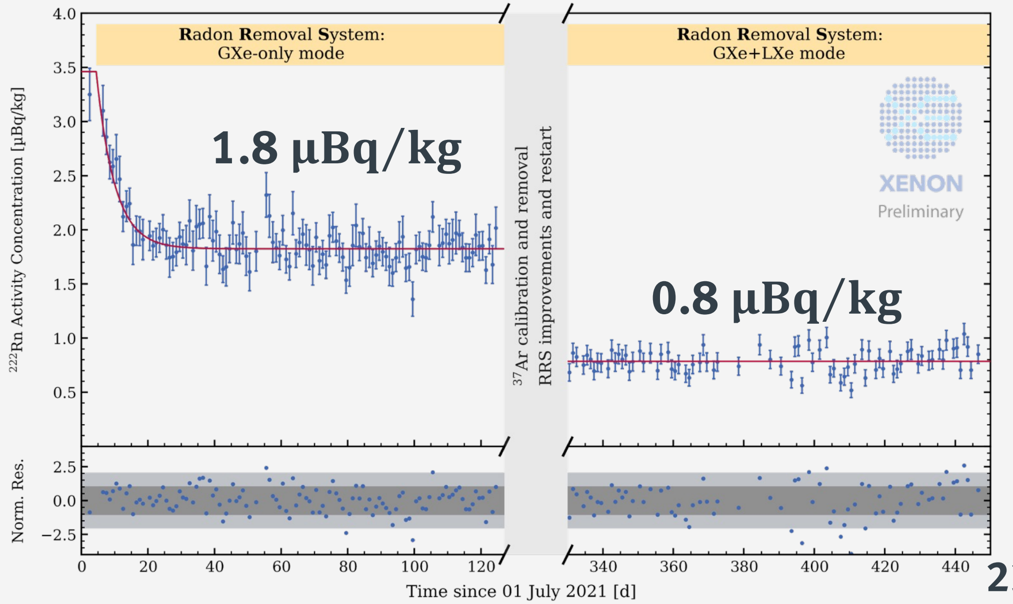
^{222}Rn Background Reduction

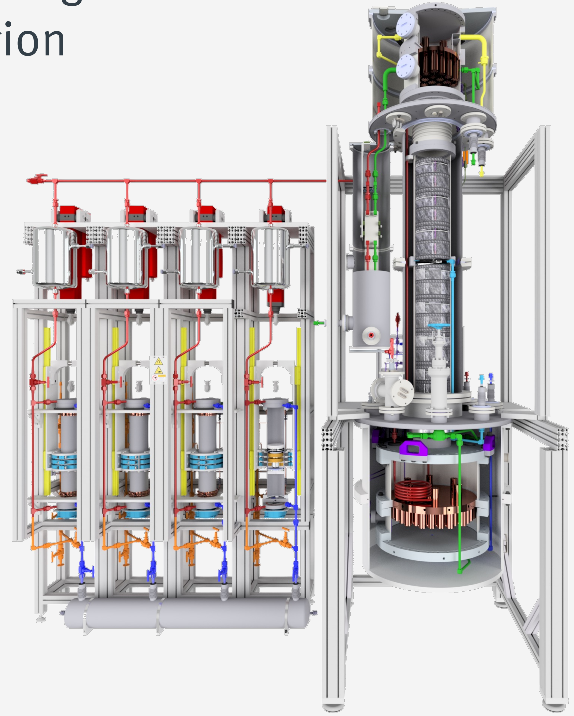
Radon in XENONnT
- ^{222}Rn daughters are the main background
- Continuous emanation from detector components
- Homogeneous distribution in detector

^{214}Pb
- Beta decay with high probability to ground state of ^{214}Bi
- Leakage of ER events into NR region

Radon reduction
- Cryogenic distillation removing Rn from LXe
- Newly developed Distillation column
- High flow: 71 kg/h (200 slpm)
- **< 1 μBq/kg** ^{222}Rn activity

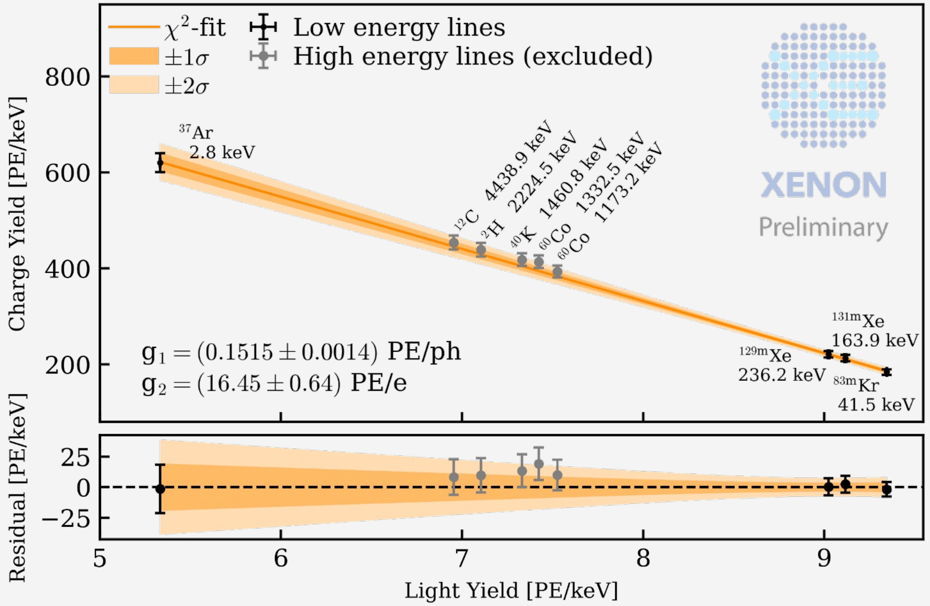


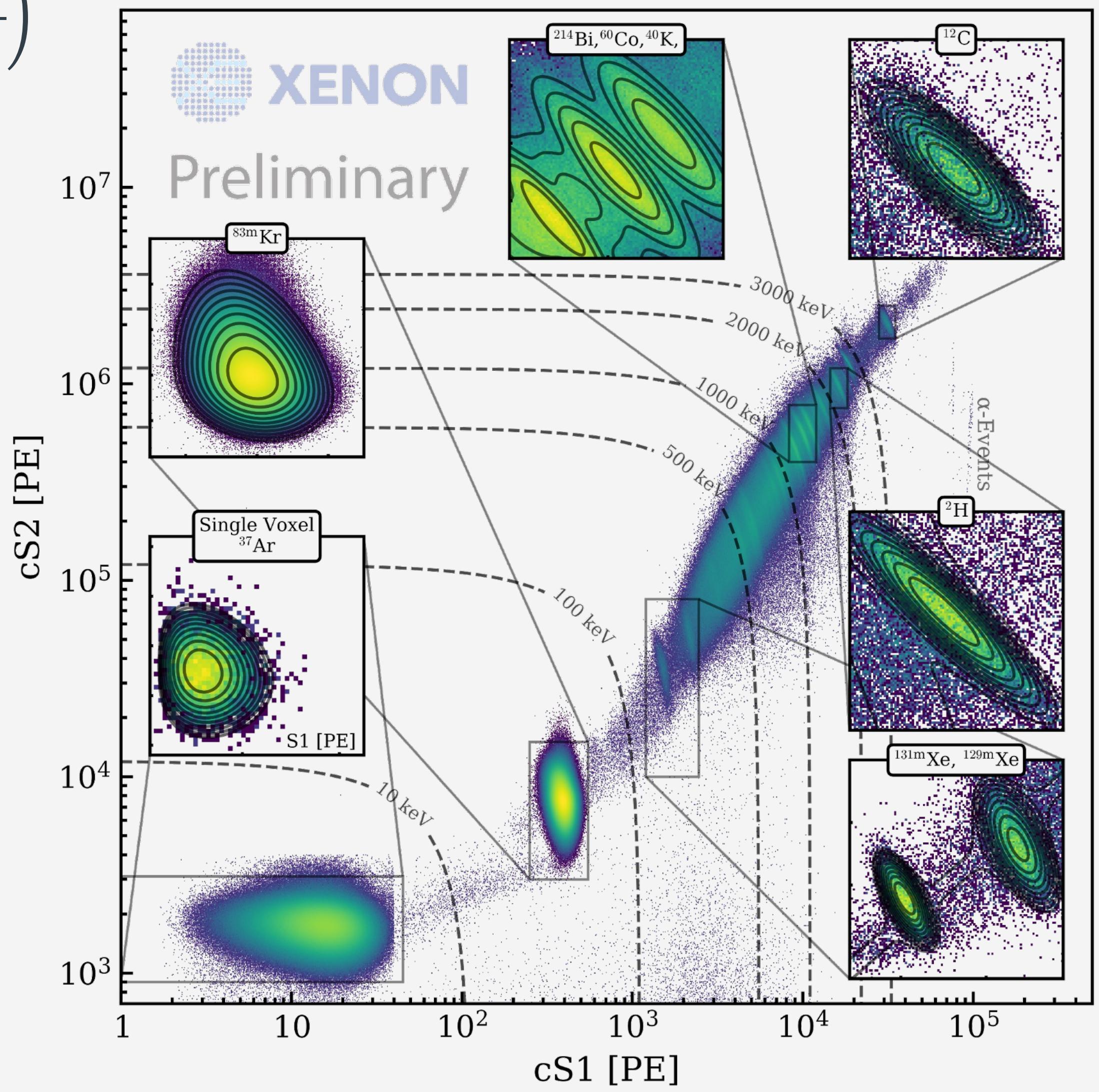




$$E = W \cdot \left(\frac{cS1}{g_1} + \frac{cS2}{g_2}\right)$$

Energy Reconstruction





Combined Energy Scale

- Use anti-correlation of charge and light signals
- Photon detection efficiency $\mathbf{g_1}$ and charge amplification $\mathbf{g_2}$
- Low energy calibration sources
  ^{37}Ar, ^{83m}Kr, ^{129m}Xe and ^{131m}Xe
- Reconstruction bias correction of O(1-2)%
- Calibration from 2.8 keV up to MeV region

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Detection and Selection Efficiencies

Detection efficiency

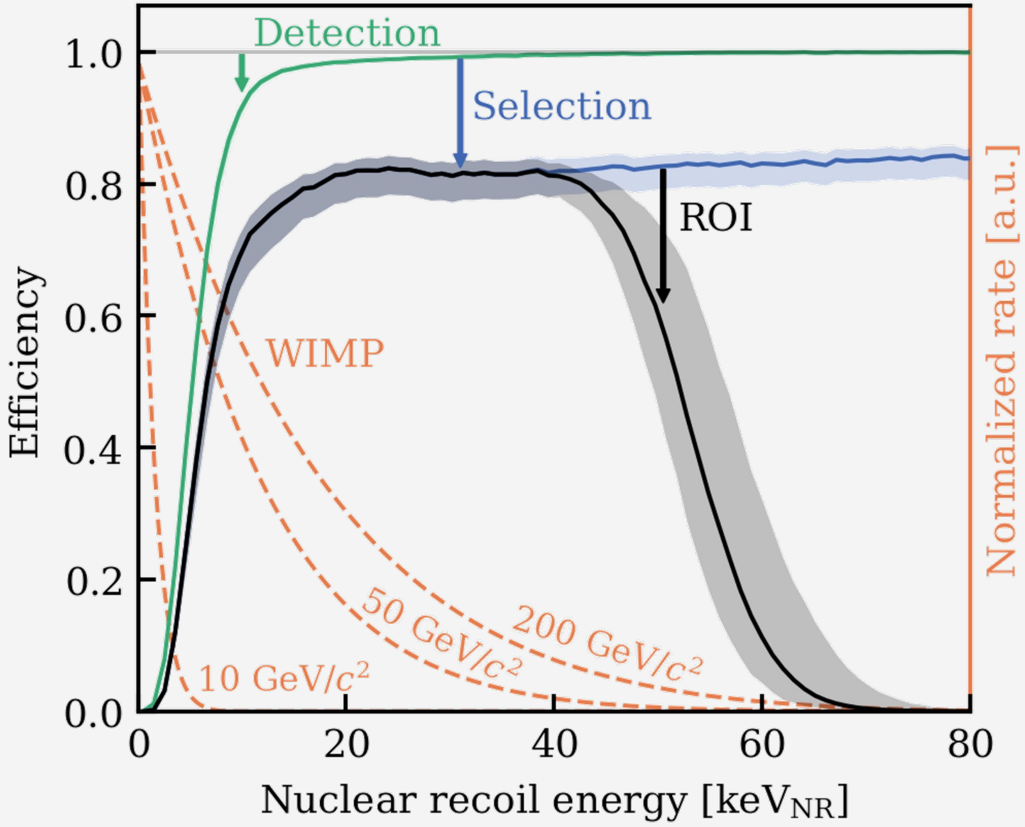
- Driven by 3-fold PMT coincidence requirement to identify peaks as S1
- Data- and simulations driven with good agreement

Selection efficiency (~80% acceptance)

- Data quality selections to remove unphysical events
- S1 and S2 peaks must have PMT hit patterns, top/bottom area ratios, etc. consistent with real events
- S2 width consistent with the expected diffusion along the drift path
- Single-site events

Region of interest (ROI)

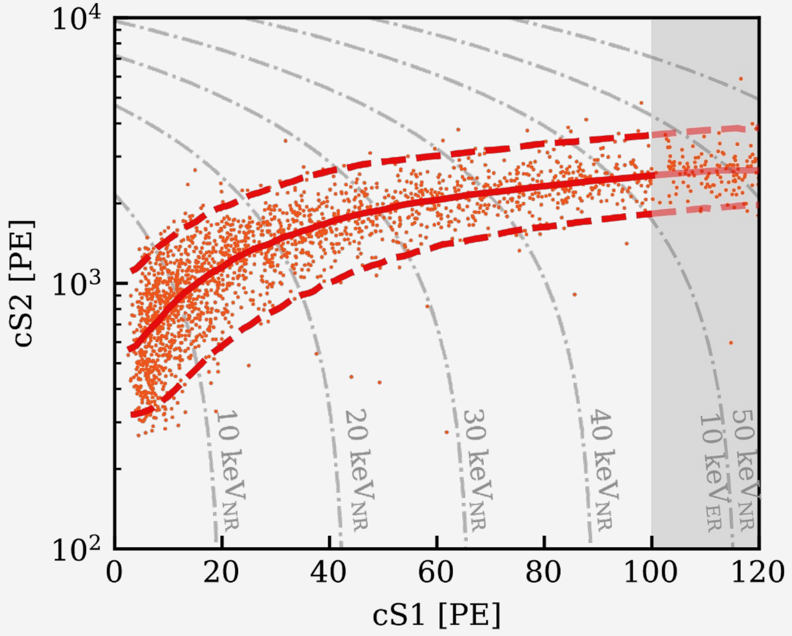
- Constructed to fully contain the WIMP recoil spectra
- cS1: 0-100 PE | cS2: $10^{2.1} - 10^{4.1}$ PE

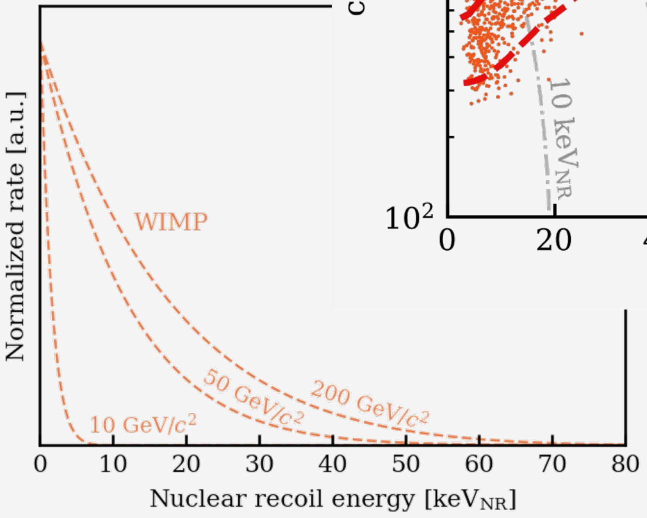


Phys. Rev. Lett. 131, 041003 (2023)

WIMP Signal Model

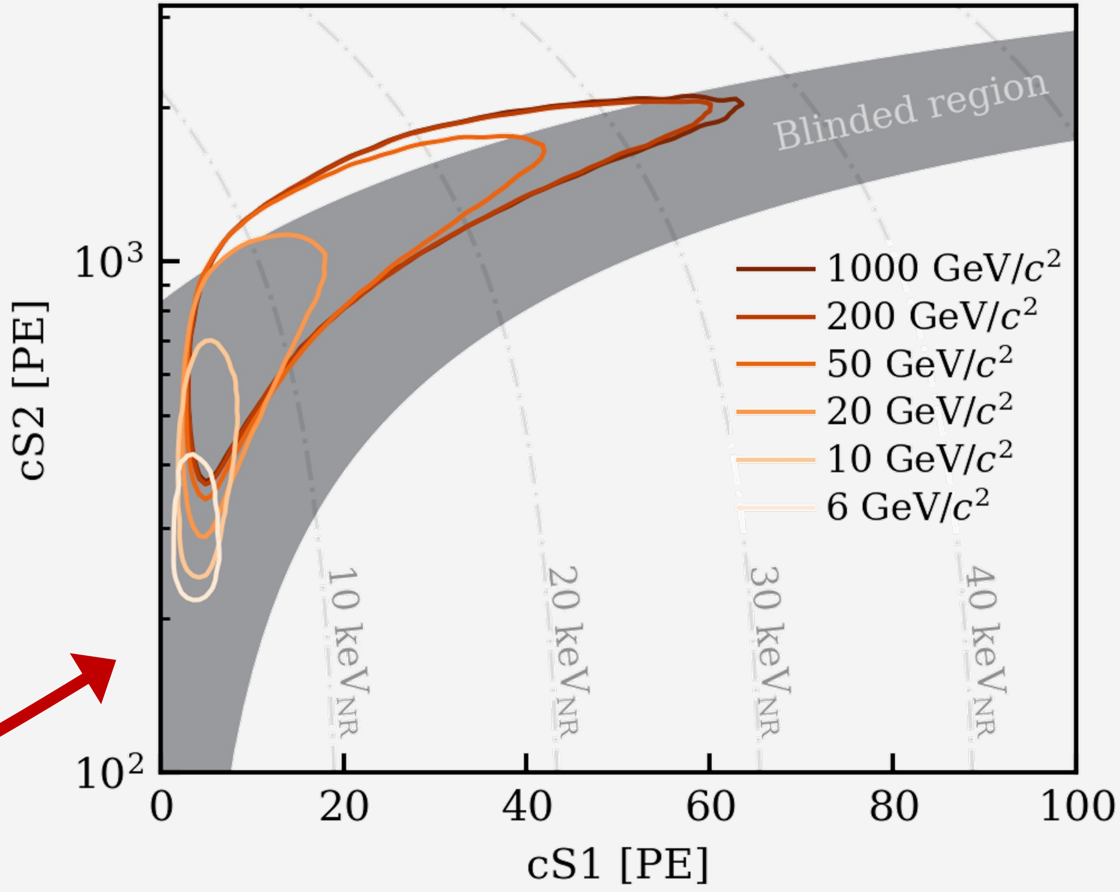
LXe NR response from calibrations





Theoretical WIMP NR energy spectra

Toy MCs



arXiv:2406.13638

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