Electronic Recoil

First Results from XENONnT

Khai Bui, on behalf of XENON

Theory meeting experiments (TMEX-2023)

Particle astrophysics and Cosmology

January 5 – 11, 2023

THE UNIVERSITY OF TOKYO 東京大学

KAVLI IPMU 東京大学 国際高等研究所 カブリ数物連携宇宙研究機構 KAVLI INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

DMNet ERAN

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Unraveling the History of Universe and Matter Evolution with Underground Physics

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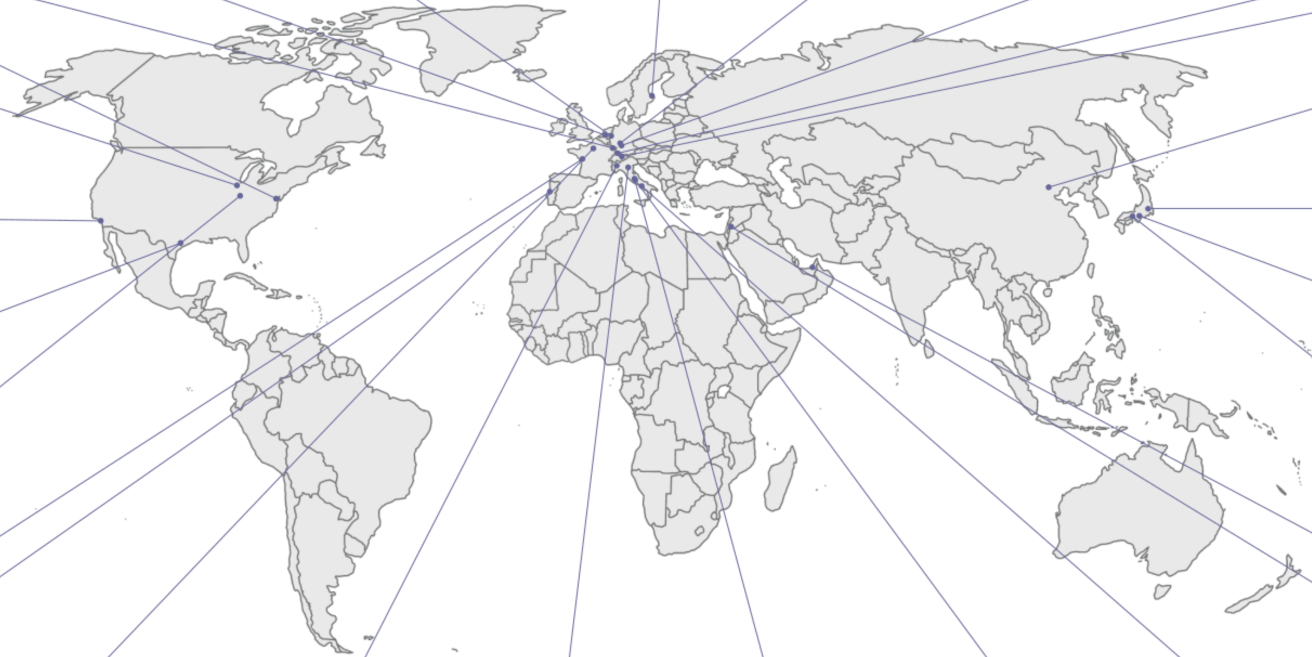

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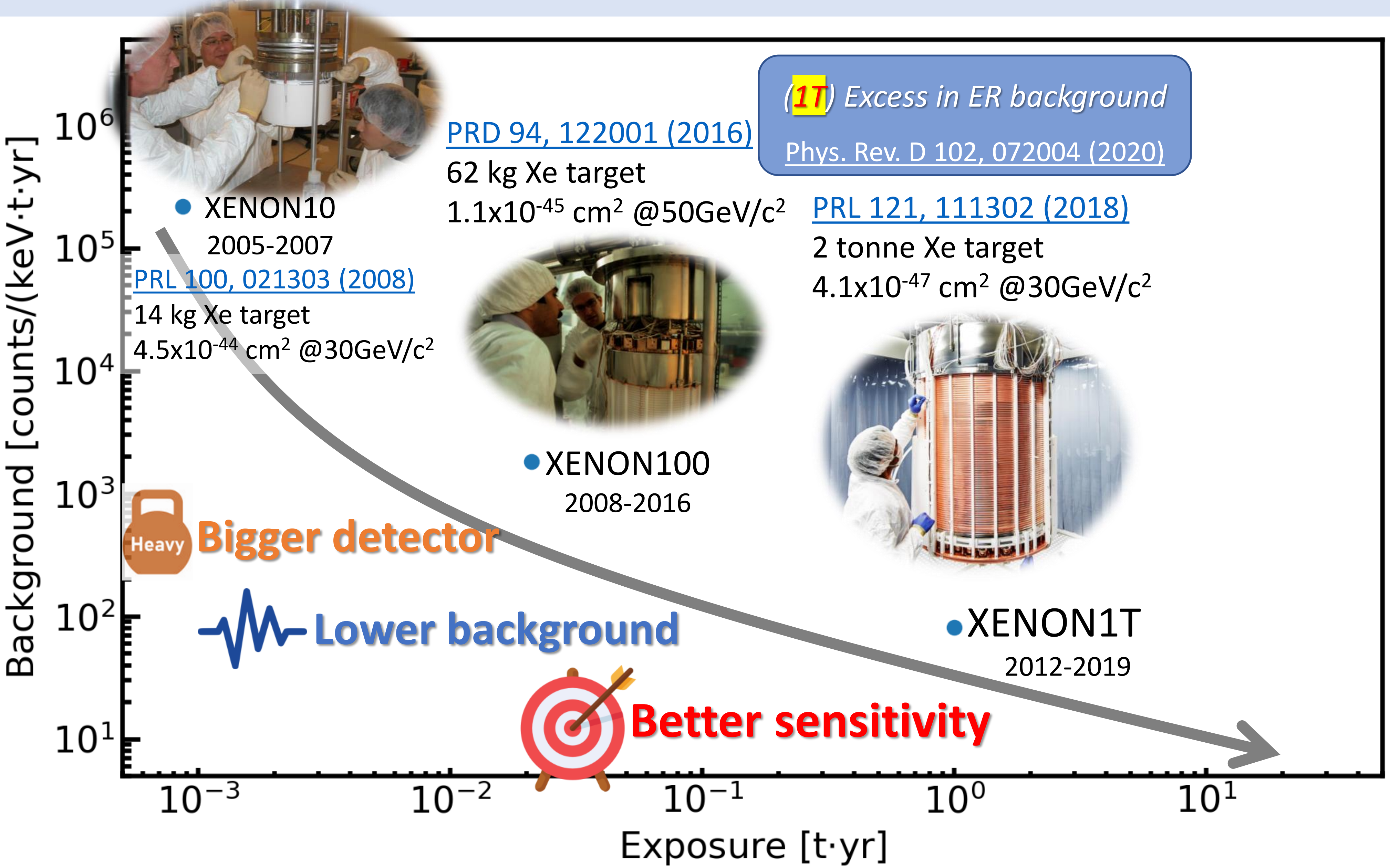
The XENON projects: **Direct Detect DM**



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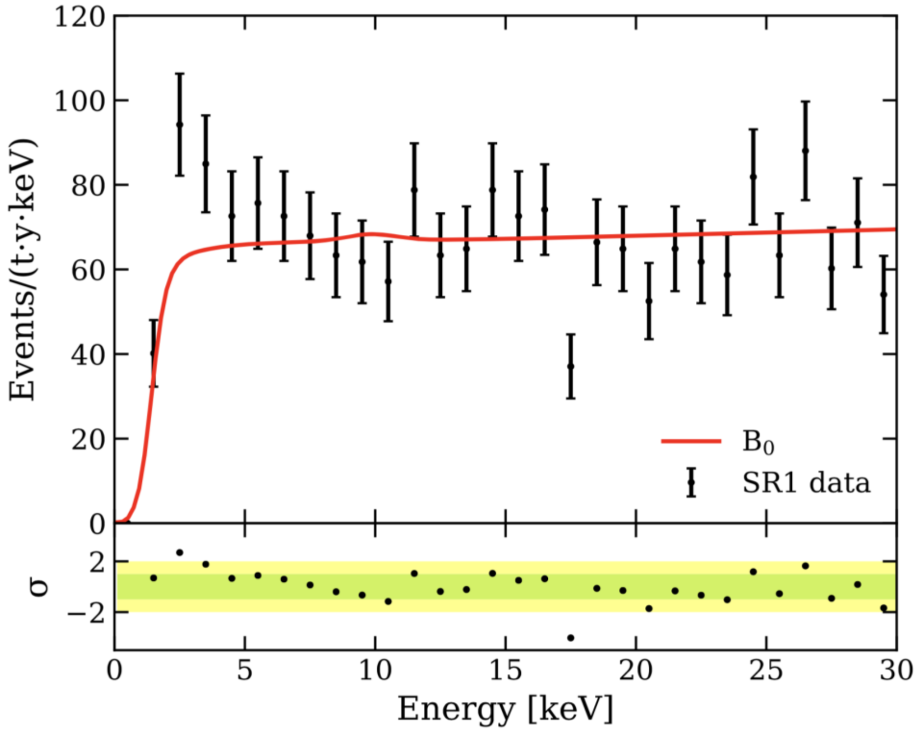
Excess in ER background in XENON1T

PRD 102, 072004 (2020)

- In <30 keV region, expect background events 232±15, while we observed 285 events (~3σ)
- Excess fit to 2.3 keV peak.



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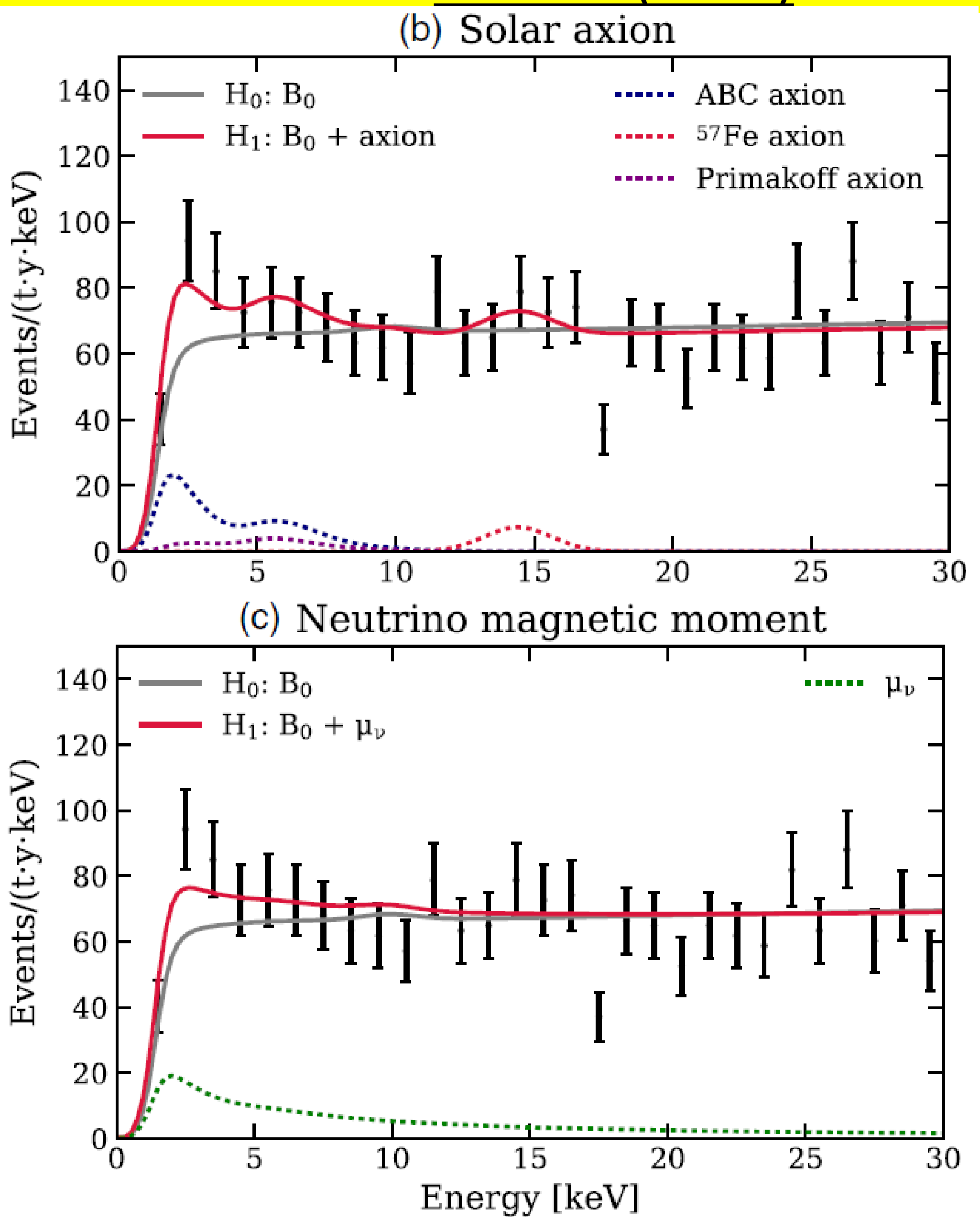
Solar axions, Neutrino magnetic moment, ALPs, dark photons

$\Rightarrow$ would be exciting! but need to confirm other BKG



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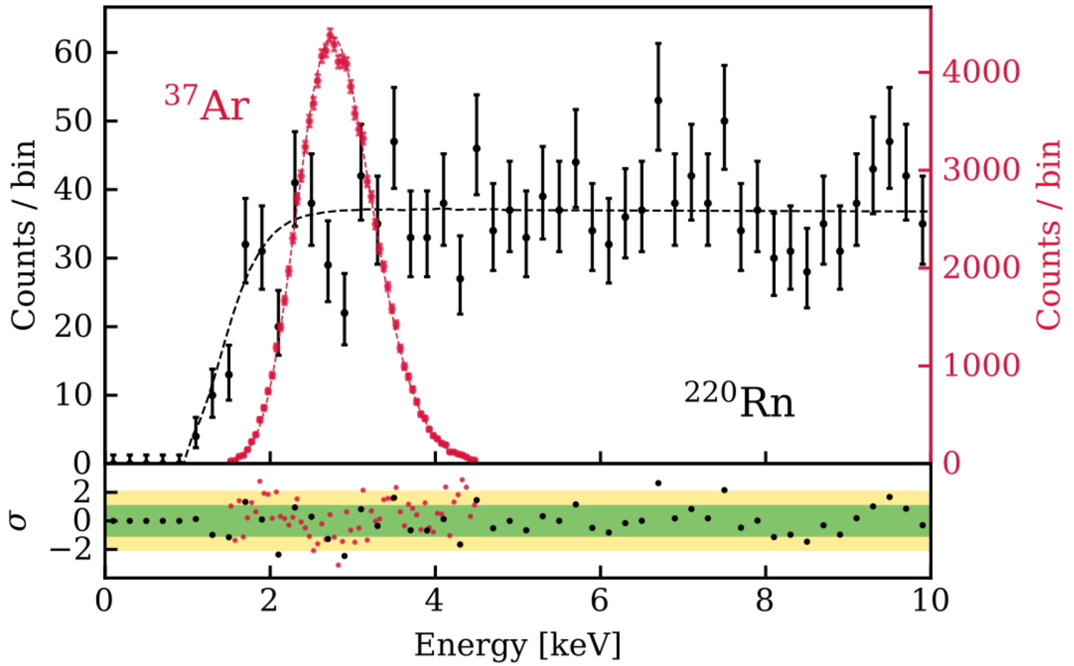
^{37}Ar (peak at 2.8 keV) as a background?

- ^{37}Ar: removed by the online Kr distillation.
- The necessary air leak to explain the excess is > 13 L/y, while upper limit is 0.9 L/y

⇒ Exclude this hypothesis



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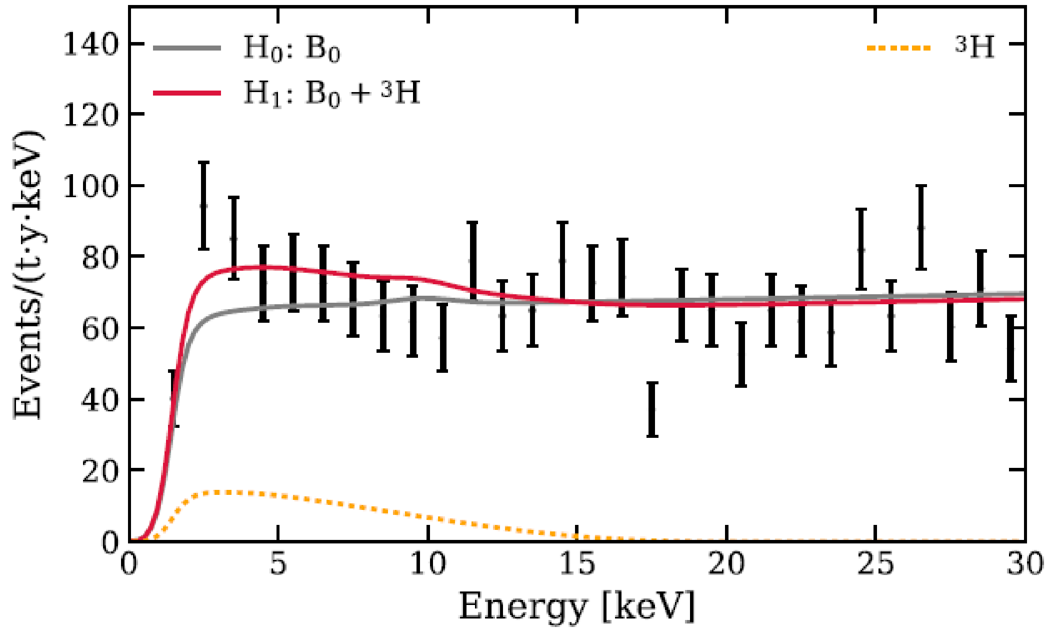
(a) Tritium

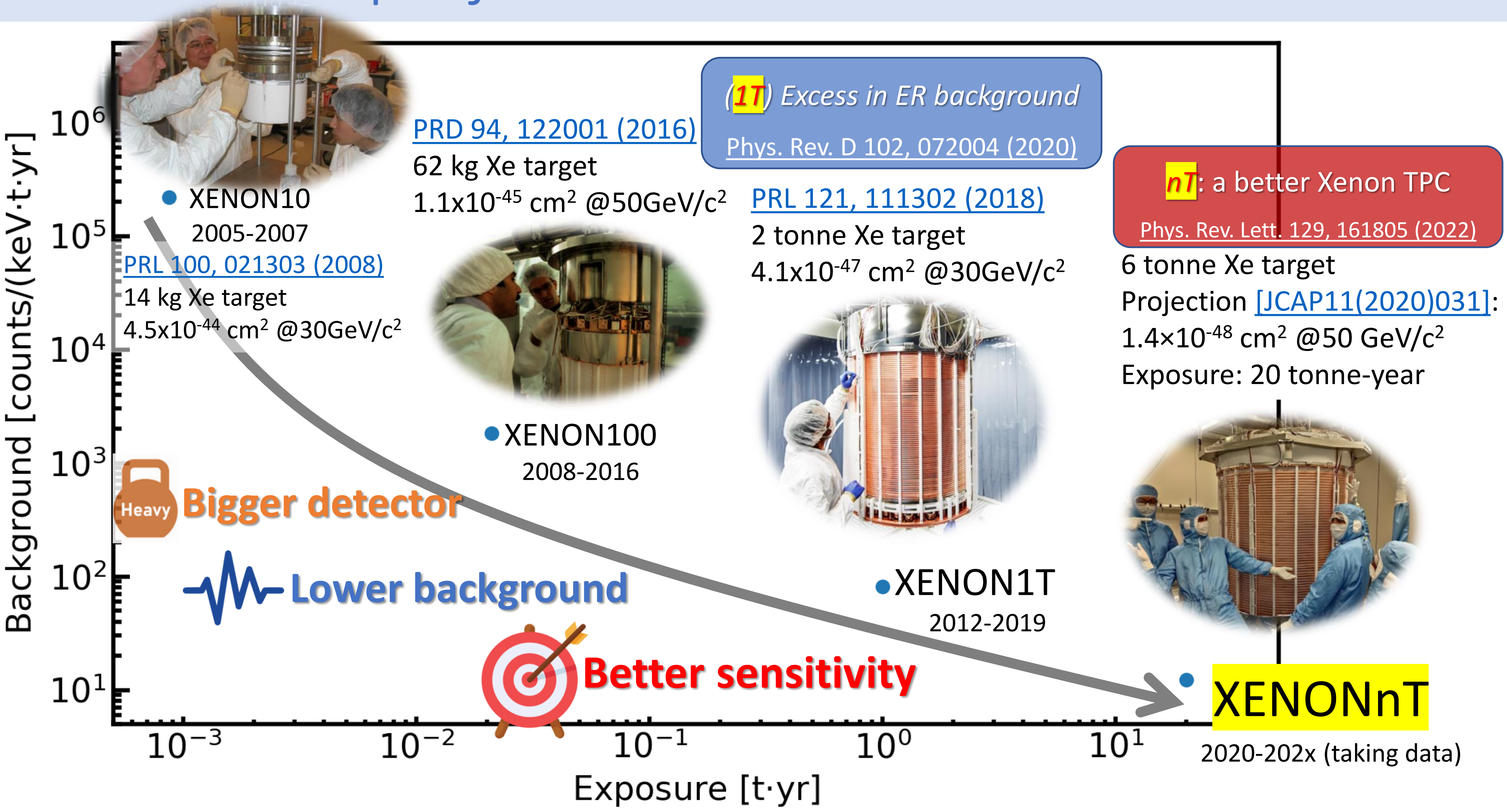


^3H as background?

- Contamination in tritiated forms (HT and HTO)
- Q-value = 18.6 keV, $T_{1/2}$ = 12.3 yr
- ^3H:Xe concentration $6.2 \pm 2.0 \times 10^{-25}$ mol/mol

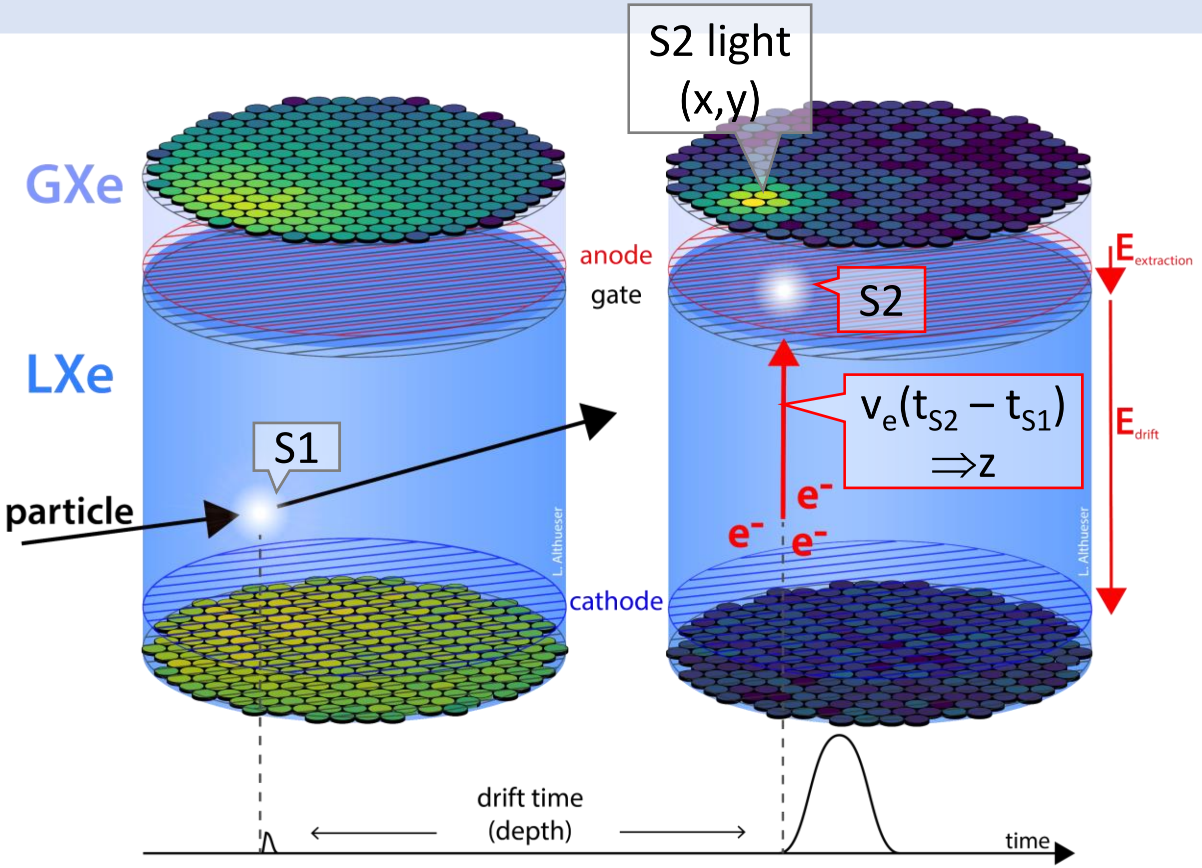
$\Rightarrow$ Could not confirm or exclude this hypothesis

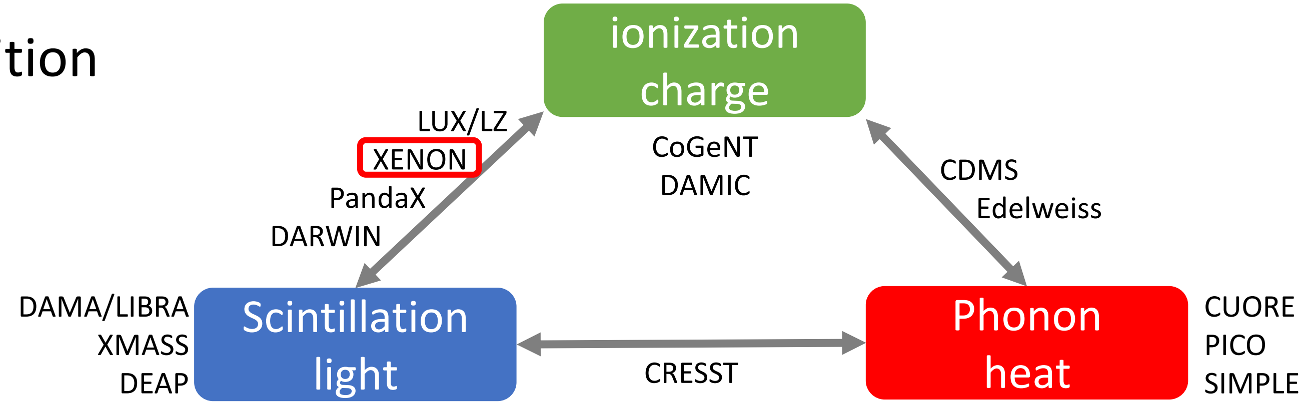
The XENON projects: **Direct Detect DM**



XENONnT: a Xe-based TPC

- TPC consists of: dual-phase Xenon (liquid + gas), PMTs at top & bottom, electrodes
- An interaction deposits energy in Xe, liberates both scintillation light and electrons
- Scintillation Light: reach PMTs (S1)
- Electrons: drift upward by electrical field, extracted at the gas phase, produce more scintillation light (S2)
- Based on S1 & S2, reconstruct energy, x-y position (S2 patern) and z position (drift time S1→S2)





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XENONnT: ER/NR discrimination

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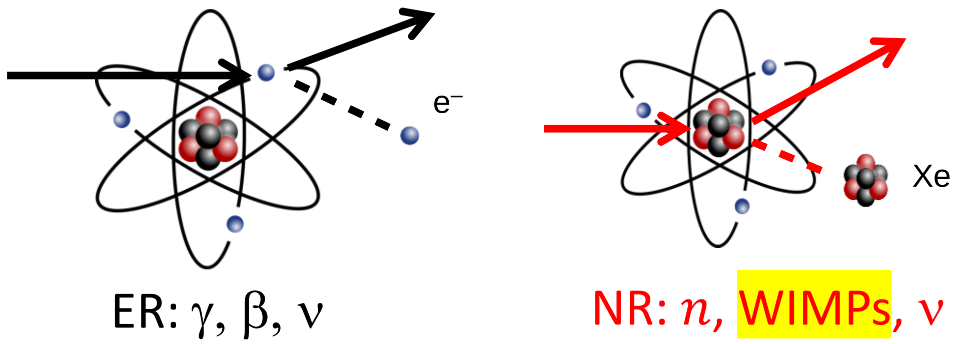
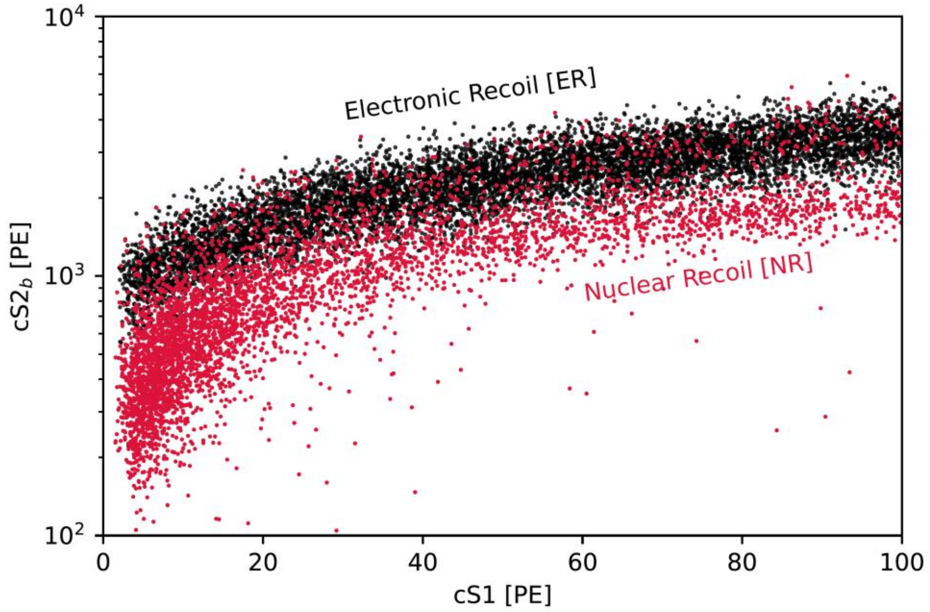
- Based on S1 & S2, reconstruct energy, x-y position (S2 patern) and z position (drift time S1→S2)
- Electronic Recoil (ER): from γ, β, ν; high S2:S1 ratio
- Nuclear Recoil (NR): from n, **WIMPs**, ν; low S2:S1

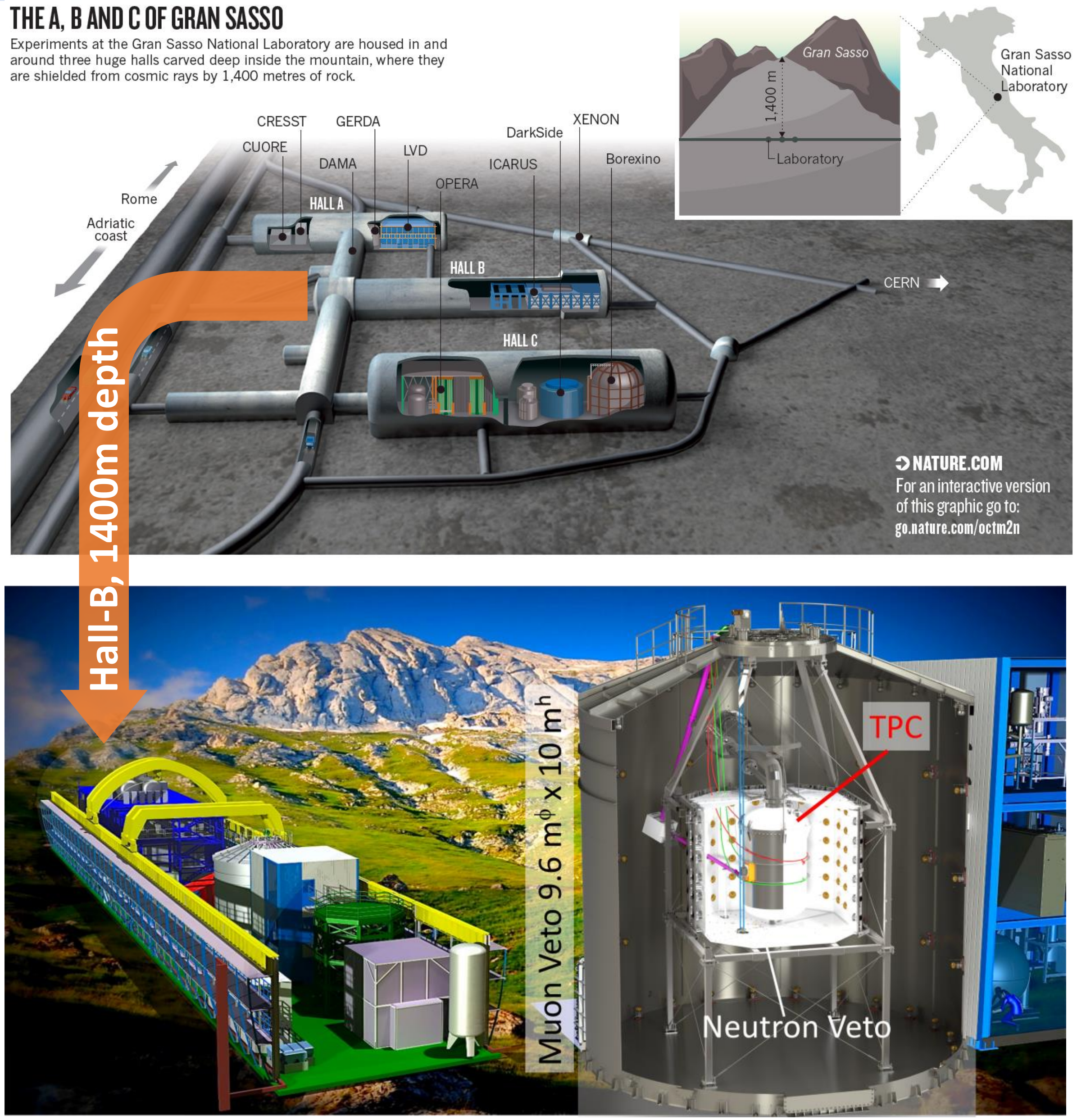


Particle identification by S2:S1 ratio



Low background techniques in XENON

- The experiment is set up at 1400 m depth LNGS with μ-flux ≈1 $m^{-2}\cdot h^{-1}$ *JCAP05(2012)015*
- Active water cherenkov muon veto: $9.6m^{\phi}$ x $10m^{h}$ water tank *JINST 9, P11006*
- Neutron veto: Gd-loaded water Cherenkov and Gd water purification
- Strict material screening *EPJ C 82, 599 (2022)*
- LXe properties: Radiopure & Self-shielding
- Distillation of krypton *PTEP 2022, 053H01* and radon *arxiv:2205.11492*



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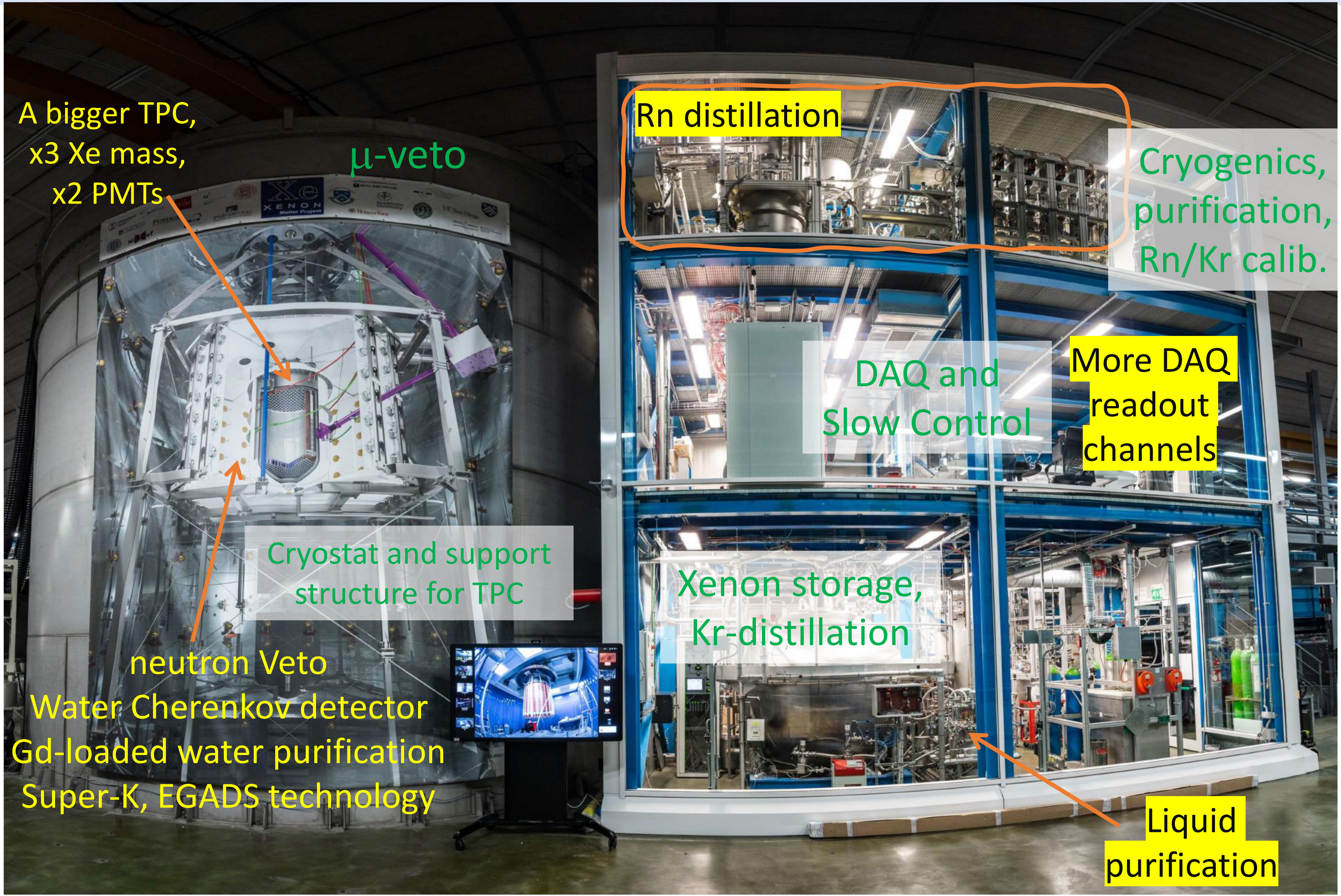
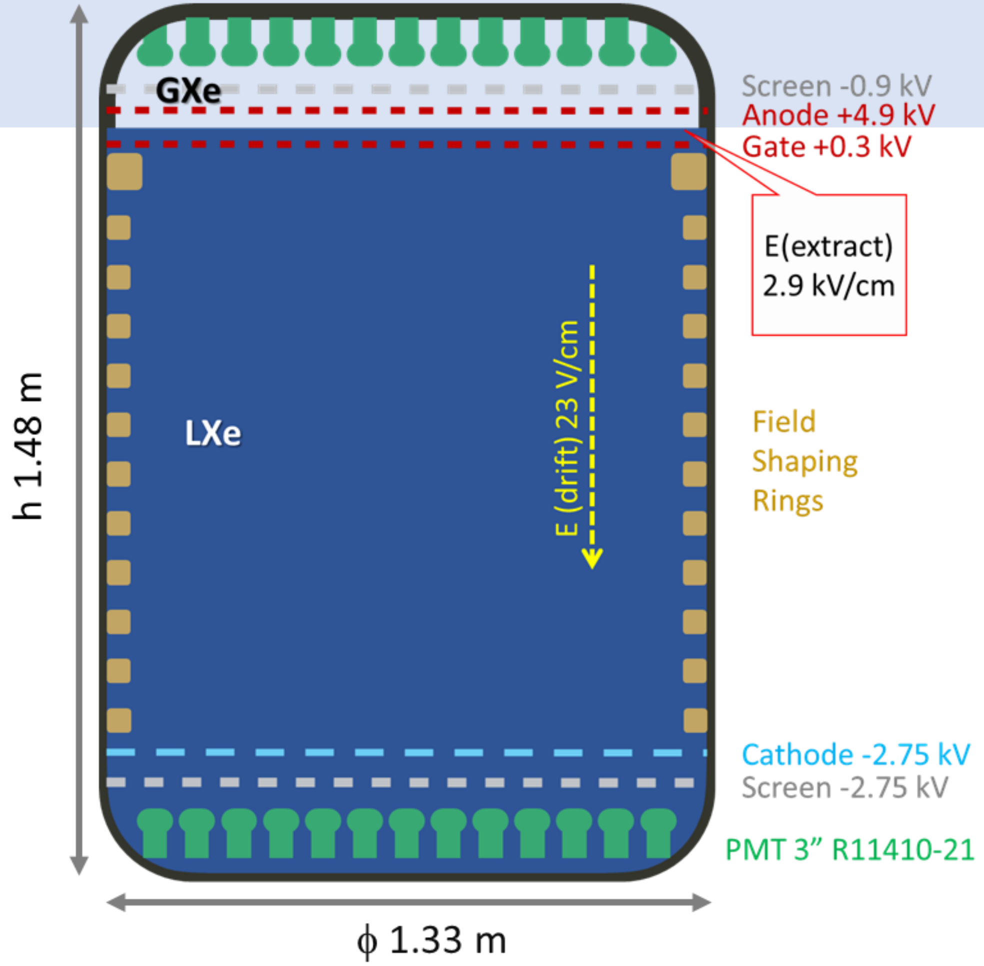
From XENON1T to XENONnT: Reuse + Upgrade



More storage
for Xenon

Newly added: **bigger TPC**

- Size: 1^{ϕ}x1^{h}m (1T) → 1.3^{ϕ}x1.5^{h}m (nT)
- Active/Total Xe: 2t/3.2t (1T) $\xrightarrow{\times 3}$ 5.9t/8.6t (nT)
- Number of PMTs: 248 (1T) $\xrightarrow{\times 2}$ 494 (nT)
- PTFE reflectors maximize light detection efficiency: 34% (1T) → 36% (nT)
- Field shaping rings with tuneable potential
- E(drift): 23 V/cm, E(extract): 2.9 kV/cm
- short-circuit between the cathode and bottom screen limited the cathode voltage to -2.75 kV



Newly added: **Liquid purification**

EPJC 82, 860 (2022)
arXiv:2205.07336

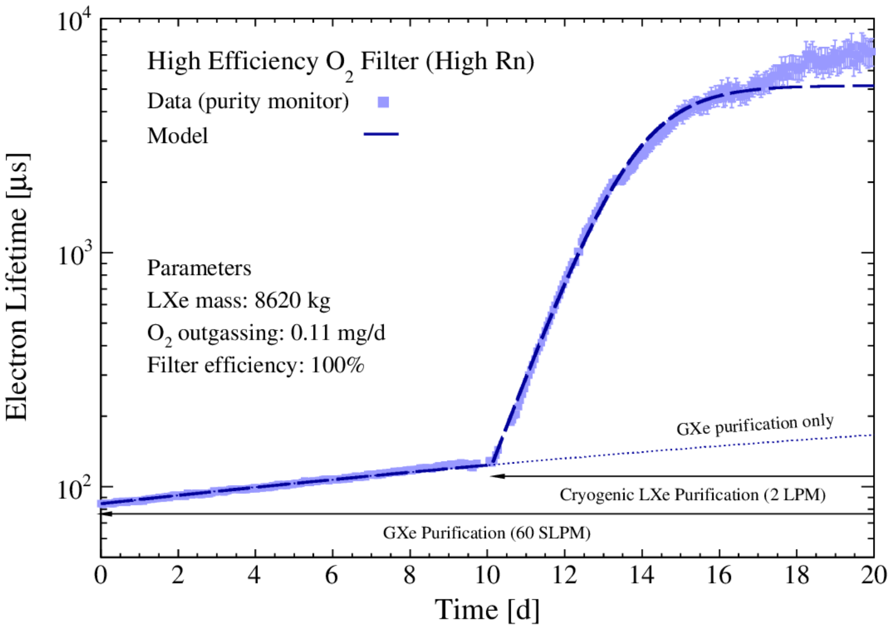
- Electronegative impurities in Xe cause loss of drift e^- and worsen S2 signals
- New TPC: x1.5 drift length, x3 total Xe mass

⇒new liquid purification technique with:

  - high flow of 2 L/min (or 1000 SLPM)
  - replaceable low-radon filter units
  - online purity monitor

⇒reach very high purity in less than a week, 18 h to exchange the entire volume

	Full TPC drift time	electron lifetime	electrons surviving a full drift length
XENON1T	0.67 ms	0.65 ms	30 %
XENONnT	2.2 ms	10+ ms	>90%



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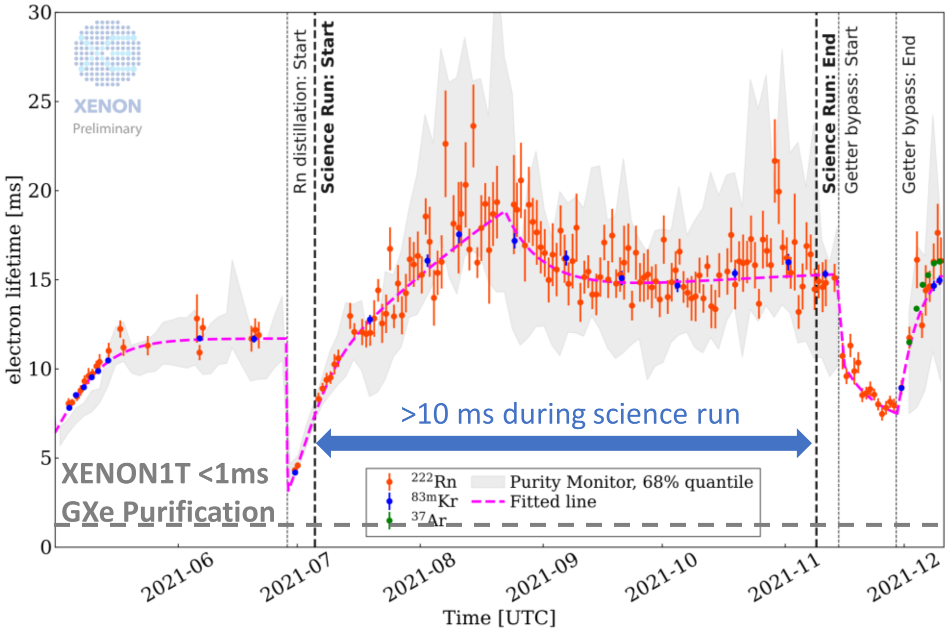
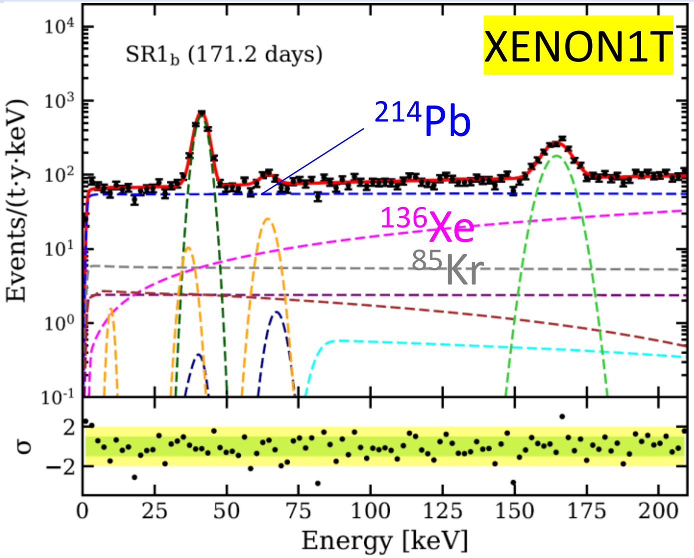


Newly added: **Radon distillation**

EPJC 82, 1104 (2022)
arxiv:2205.11492



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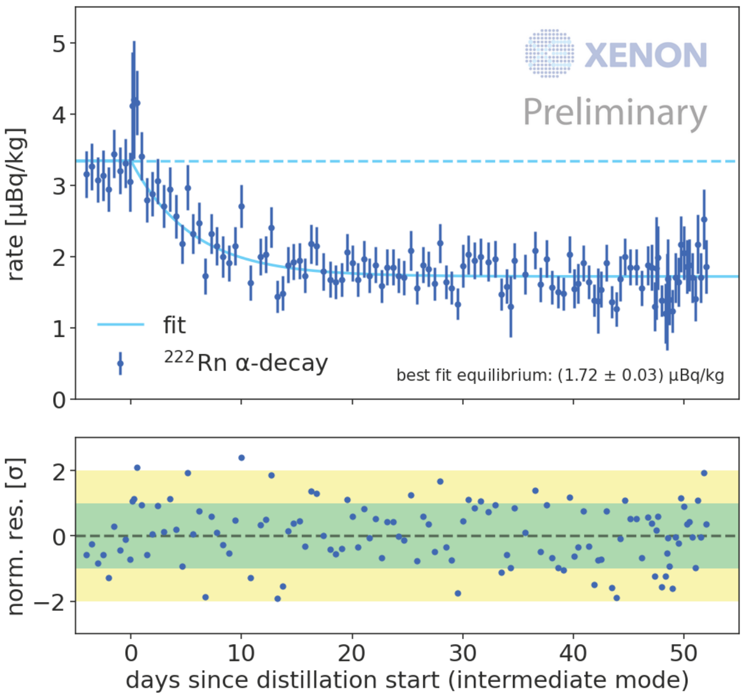


- ^{214}Pb is dominant in low energy

⇒originated from ^{222}Rn in LXe/GXe

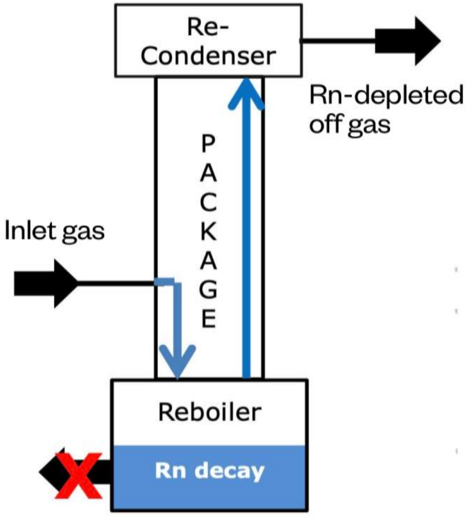
- Rn column is operated in during science run

⇒**1.7 µBq/kg** (GXe-only mode)

⇒Next Run (LXe+GXe): **<1 µBq/kg**

Rn column with 2 operation modes:

- GXe: Remove Rn from signal cables, cryogenic pipes…
- LXe: Remove Rn from TPC body, PMT, …



Newly added: **neutron Veto – nVeto**

- Inside muon Veto water tank, surround TPC
- Octagonal structure 3x4 m
- 120 PMTs 8’’ Hamamatsu R5912-100 HQE (~40%)

$\Rightarrow$ Detect Cherenkov radiations

- Covered by ePTFE reflecting foils:

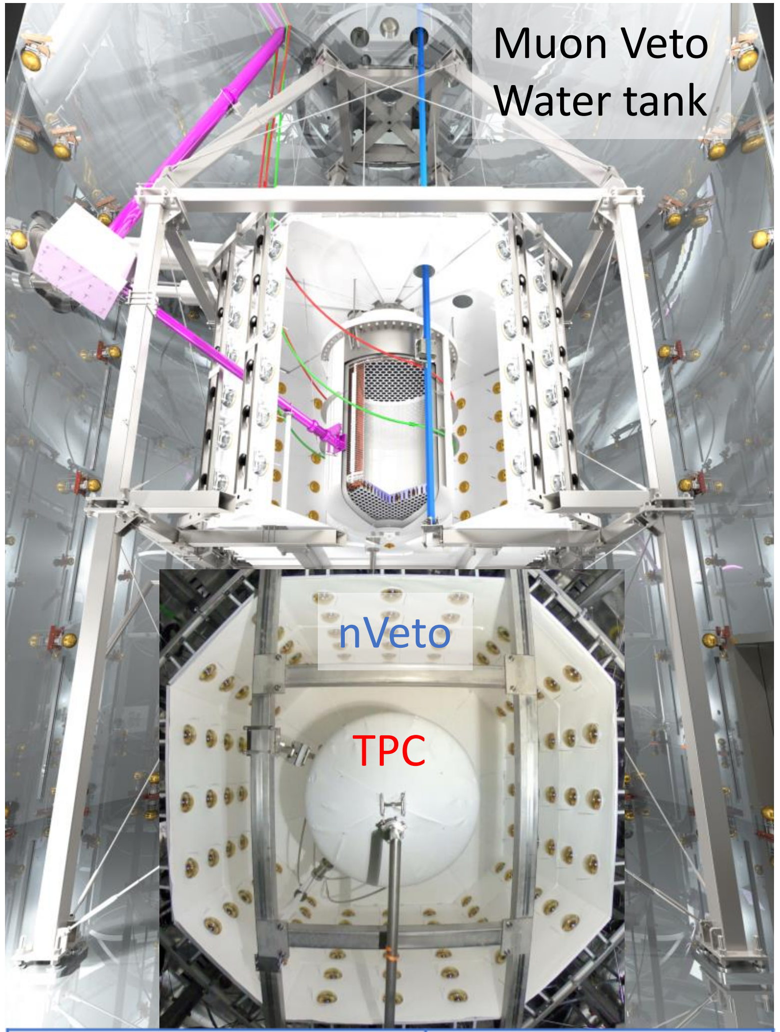
$\Rightarrow$ high coverage & light collection efficiency

- Pure water: n-capture on ^{1}H ***current***

$\Rightarrow$ $H(n,\gamma)$ 2.2 MeV peak; $\tau_{capture}$ ~200 μs, $\varepsilon_{n\text{-}tag}$ ~68%

- Gd-loaded water: n-capture on ^{155}Gd, ^{157}Gd ***Next step***

$\Rightarrow$ γ-cascade, $\Sigma E_{\gamma} \approx 8 MeV$, $\tau_{capture}$ ~30 μs , $\varepsilon_{n\text{-}tag}$ ~87%



n-capture cross-section

^{1}H (99.98%)	0.3326 barn
^{155}Gd (14.80%)	60900 barn
^{157}Gd (15.65%)	254000 barn

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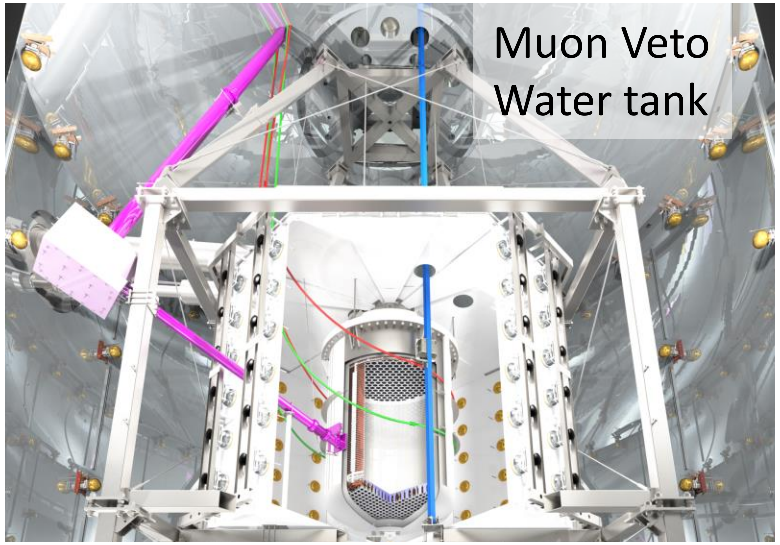

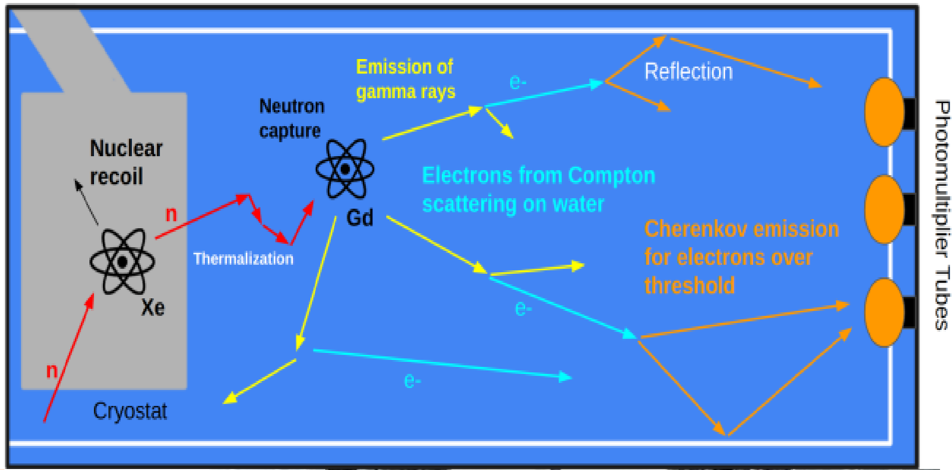

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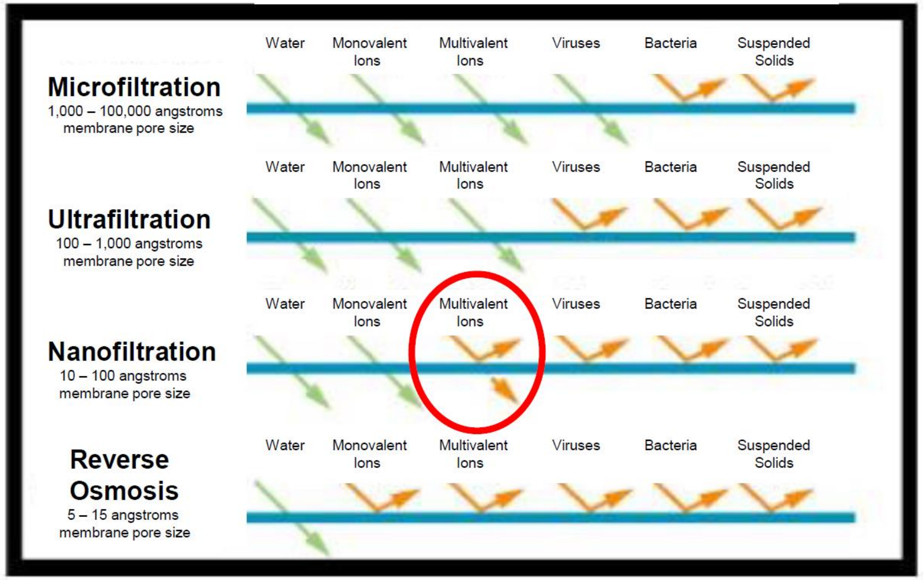
$Gd_2(SO_4)_3 \rightarrow 2\ Gd^{3+} + 3\ (SO_4)^{2-}$



Gd Water Purification System (GdWPS):
For 3.4 t $Gd_2(SO_4)_3 \cdot 8H_2O$ (0.2% Gd)

DAQ & Computing for TPC, MV and NV

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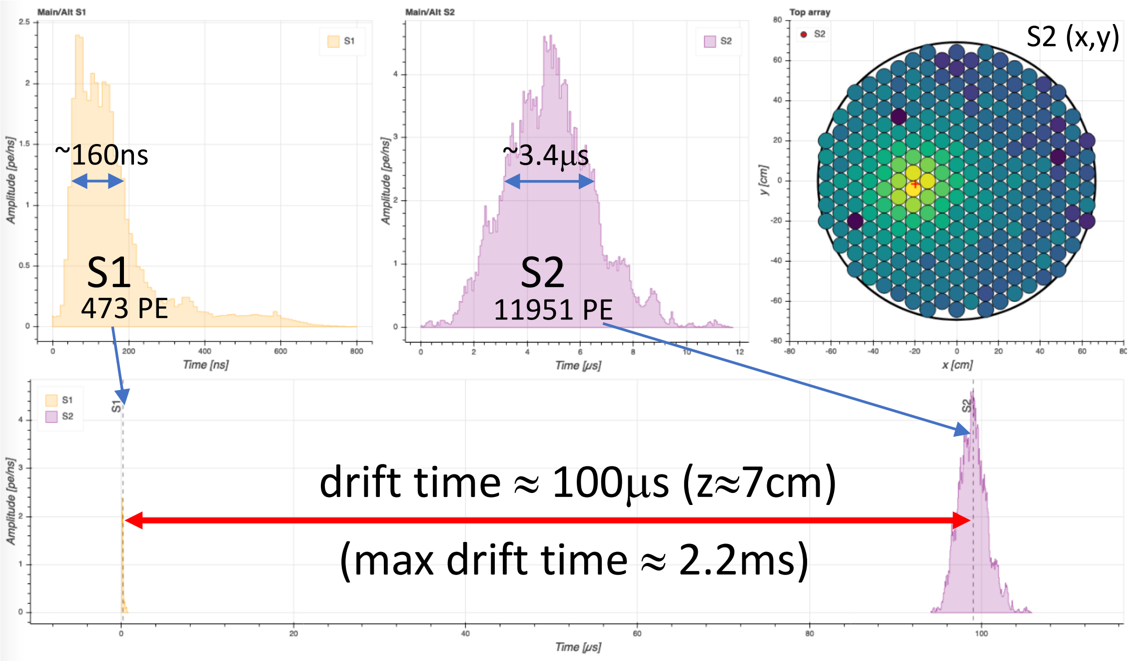
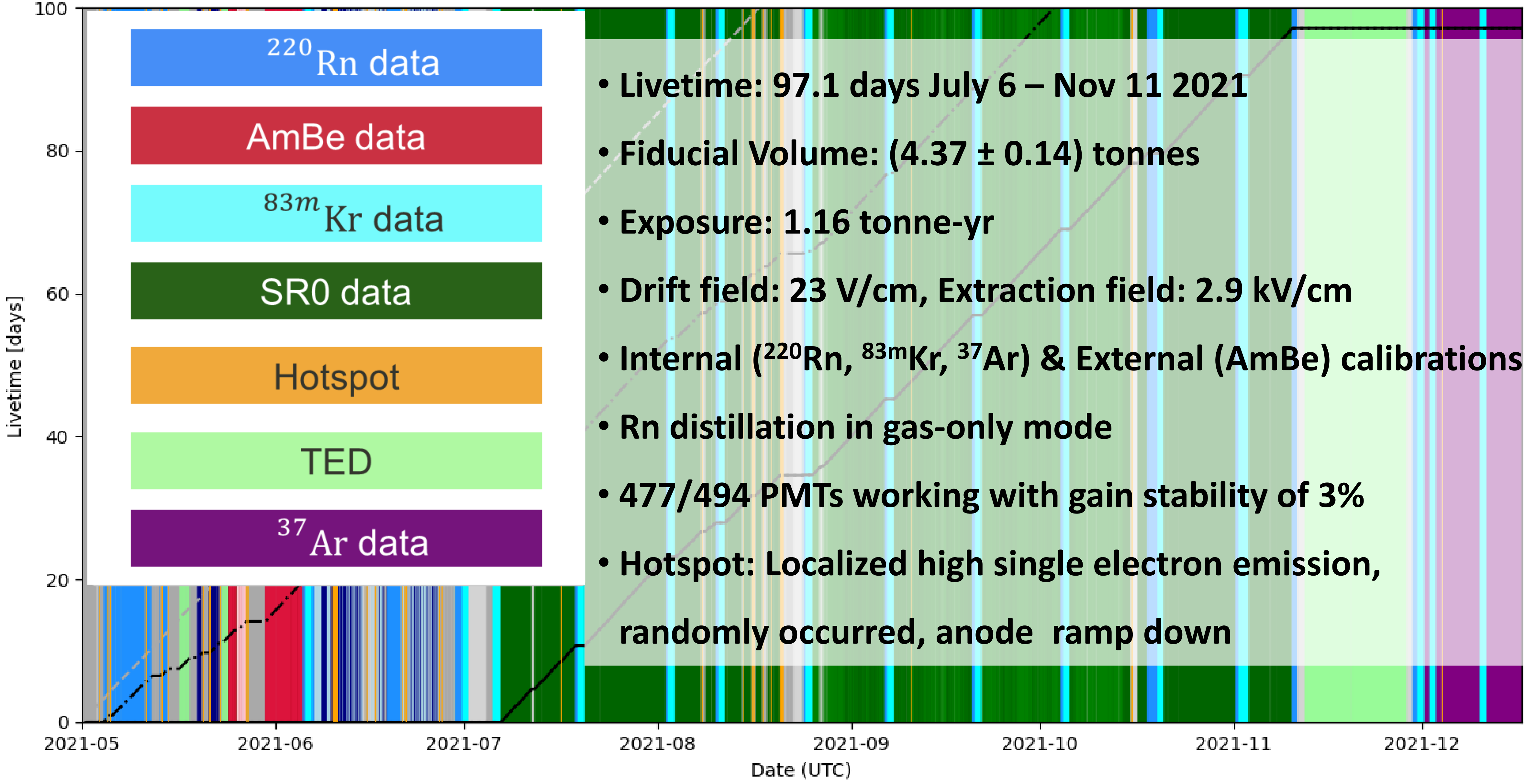


- GPS synchronization for all 3 detectors
- Fully live processing
- Open-source software: strax+straxen

Check out github.com/XENONnT/straxen
arxiv:2212.11032 on DAQ of XENONnT

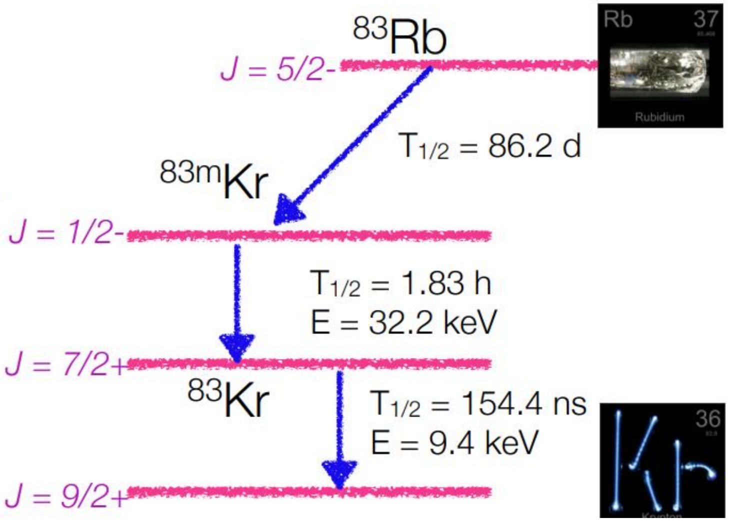
- Readout for TPC: 494 PMTs + top-array PMTs with lower gain for high-energy study
- Readout for muon Veto, and neutron Veto
- "Triggerless" mode: individual channels are read out any time they cross the threshold

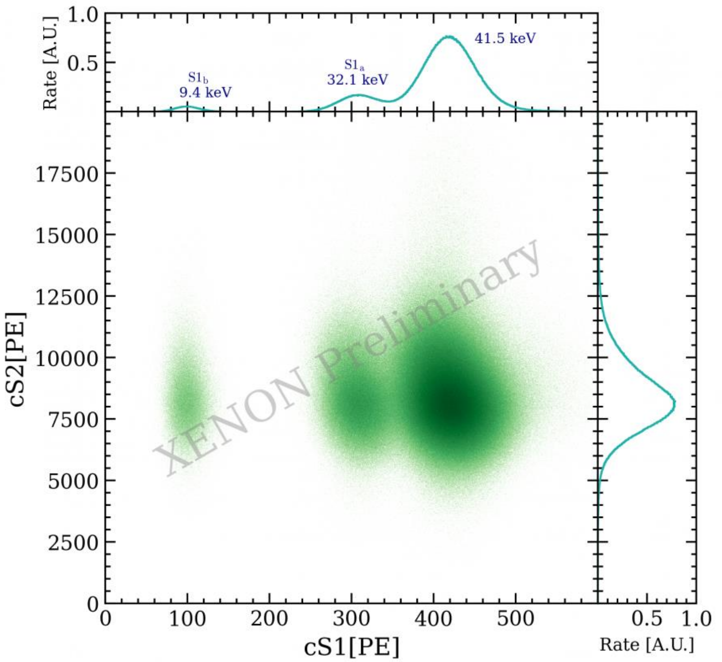
First Science Run of XENONnT

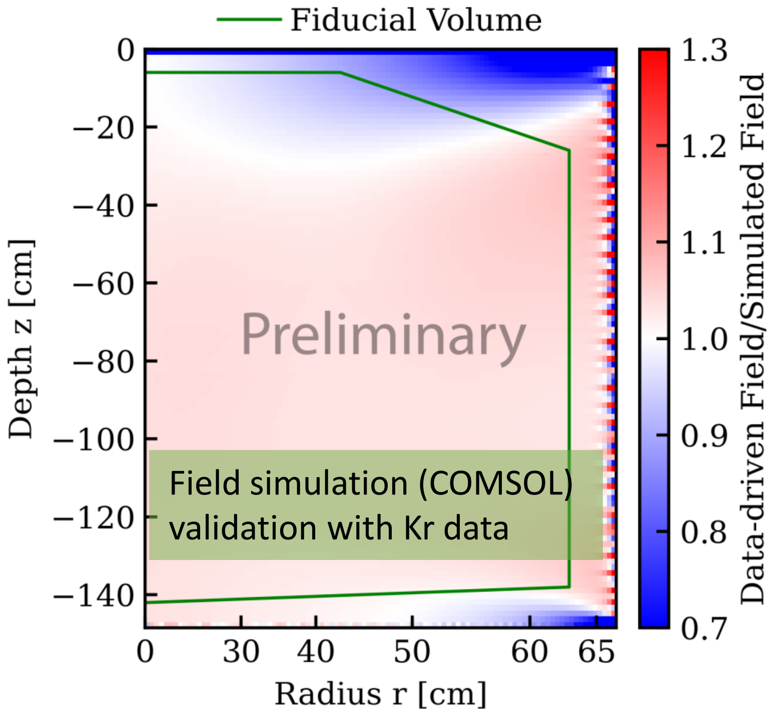


- Livetime: 97.1 days July 6 – Nov 11 2021
- Fiducial Volume: (4.37 ± 0.14) tonnes
- Exposure: 1.16 tonne-yr
- Drift field: 23 V/cm, Extraction field: 2.9 kV/cm
- Internal (^{220}Rn, ^{83m}Kr, ^{37}Ar) & External (AmBe) calibrations
- Rn distillation in gas-only mode
- 477/494 PMTs working with gain stability of 3%
- Hotspot: Localized high single electron emission, randomly occurred, anode ramp down

Calibration (ER): ^{83m}Kr







- ^{83m}Kr bi-weekly calibration: inject to LXe
- 32.2 keV and 9.4 keV gamma emissions
- $T_{1/2}$ =1.83 h $\Rightarrow$ Expect to distribute uniformly in our detector

- Used to study position dependence of: S1 light collection efficiency, S2 light collection efficiency, distortion in position reconstruction

Calibration (ER): ^{220}Rn and ^{37}Ar

^{220}Rn ($T_{1/2}$=55.8s) $\xrightarrow{\alpha}$ ^{216}Po ($T_{1/2}$=150ms) $\xrightarrow{\alpha}$ ^{212}Pb ($T_{1/2}$=10.6h) $\xrightarrow{\beta}$

- ^{212}Pb from **^{220}Rn** decay chain (injected to Lxe) gives a roughly flat β-spectrum

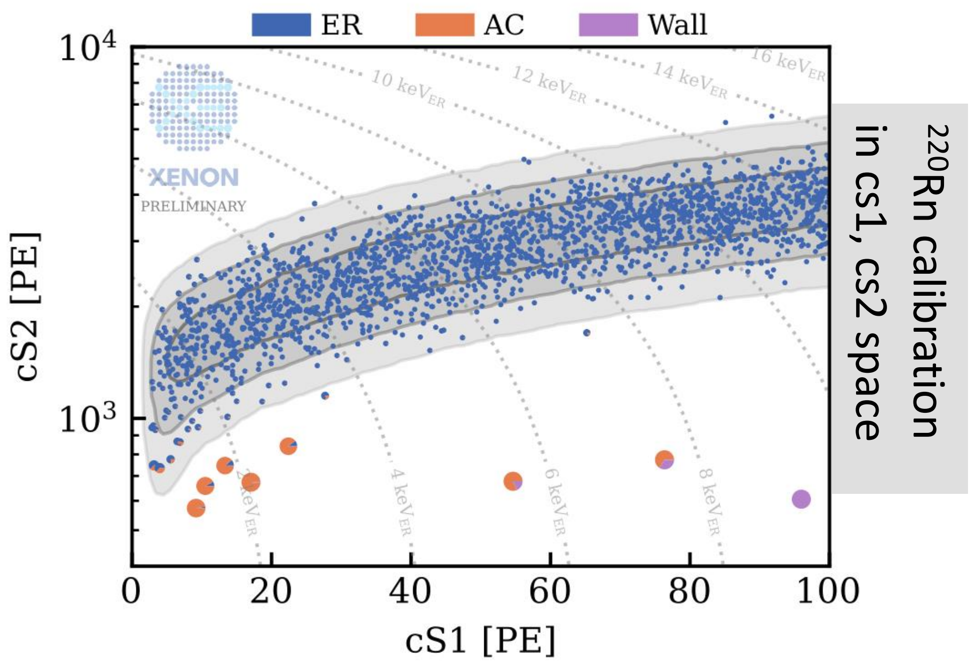
⇒ estimate cut acceptance, validate threshold, ER band calibration

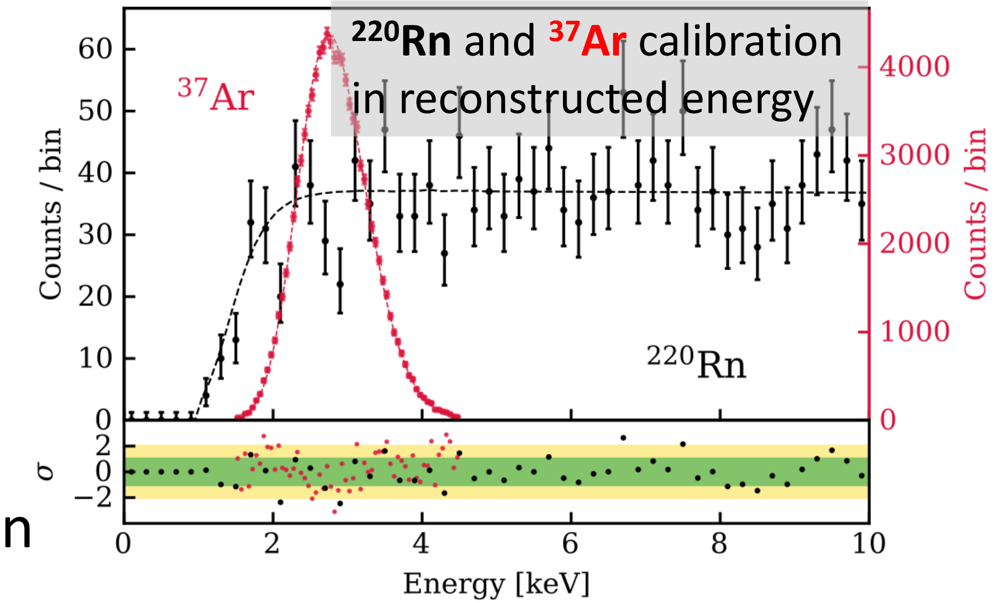
- **^{37}Ar** emits a mono-energetic 2.82 keV peak

⇒ Validate energy reconstruction and resolution at low-energy with high statistics

arxiv:2211.14191 on ^{37}Ar calibration

⇒ Long $T_{1/2}$ (35 days), inject ^{37}Ar at the end of science run





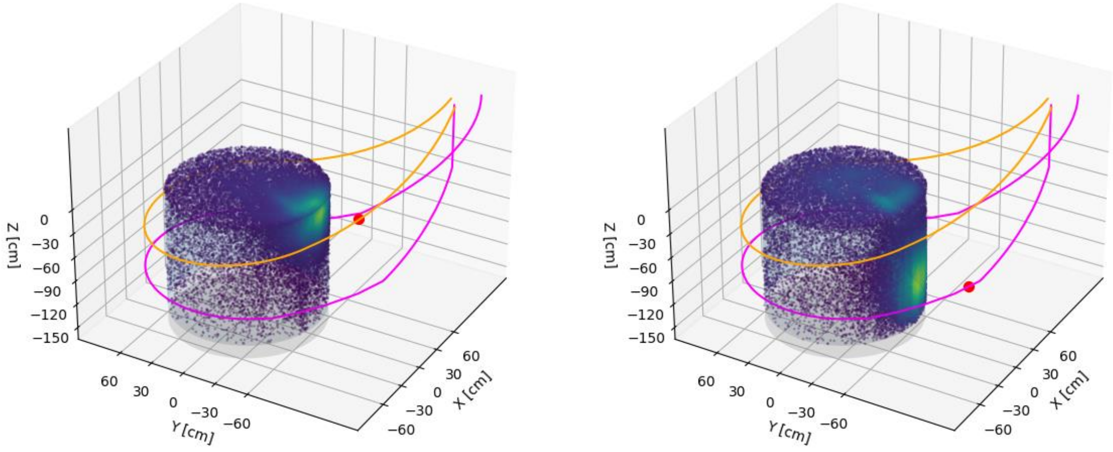
Calibration (NR): ^{241}Am(α,n)Be

- AmBe emits 4.4 MeV γ-ray and neutron

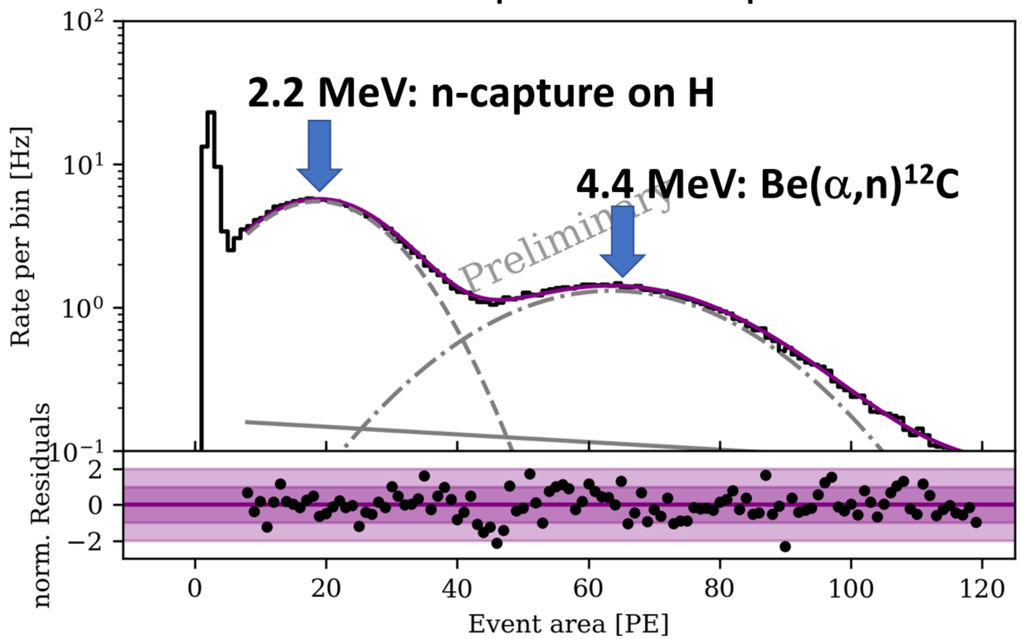
- For NR calibration:
  - select 4.4 MeV γ-ray in nVeto
  - Tight coincidence between S1 and NV signals

  ⇒ Strong suppression of accidental coincidence (AC) and Electronic Recoil (ER) events.

- Used for: NR band calibration in TPC, estimate neutron tagging and detection efficiency in nVeto



AmBe source response with pure water



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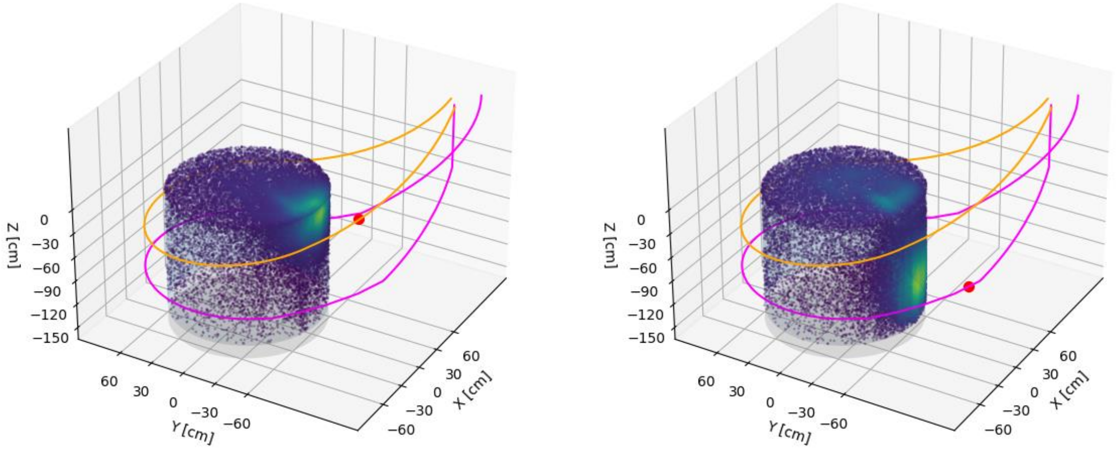

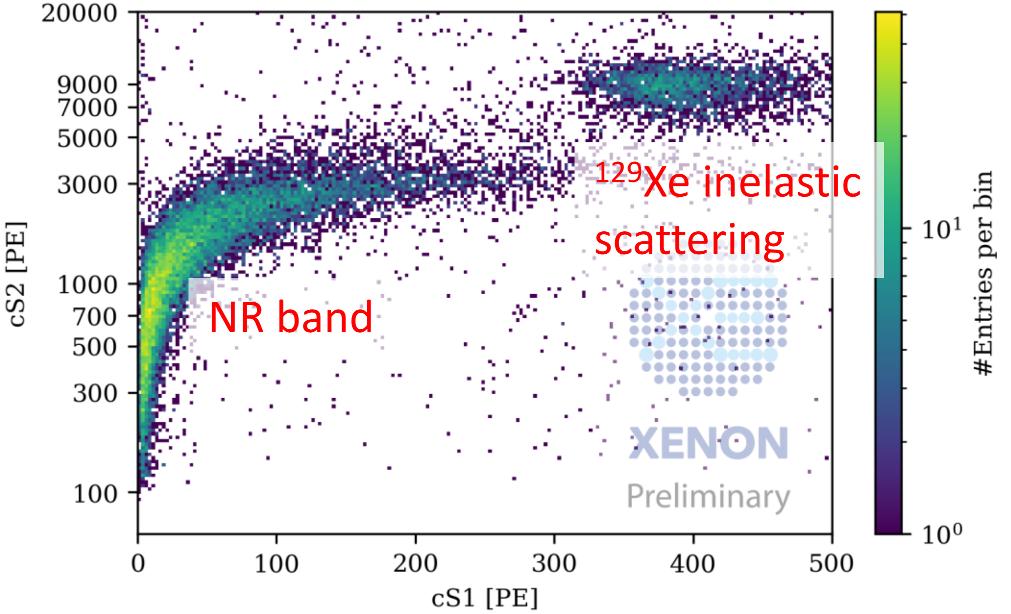

Energy reconstruction

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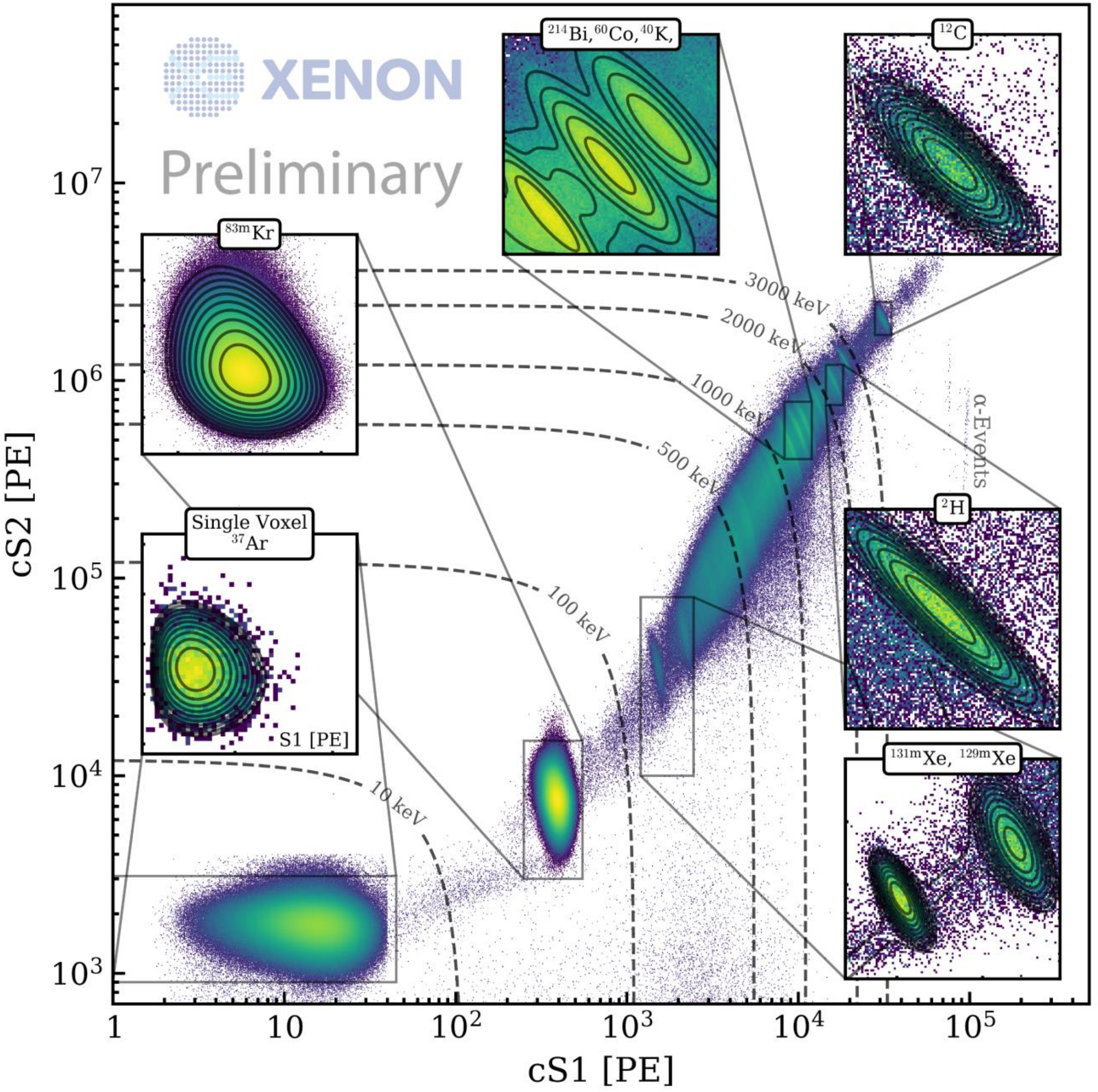
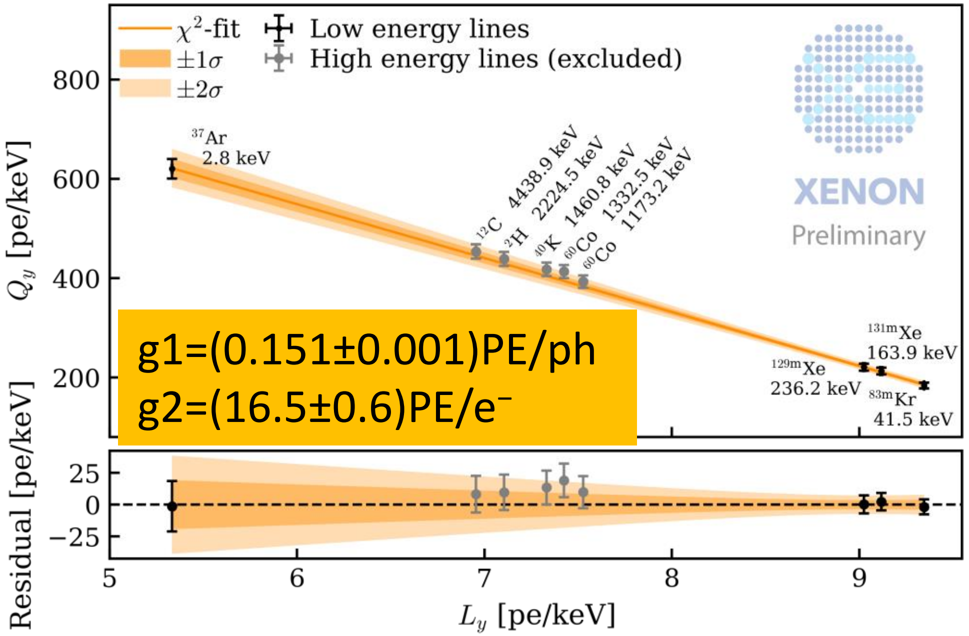




g1=(0.151±0.001)PE/ph
g2=(16.5±0.6)PE/e⁻

- The energy is a combination of cS1 and cS2:

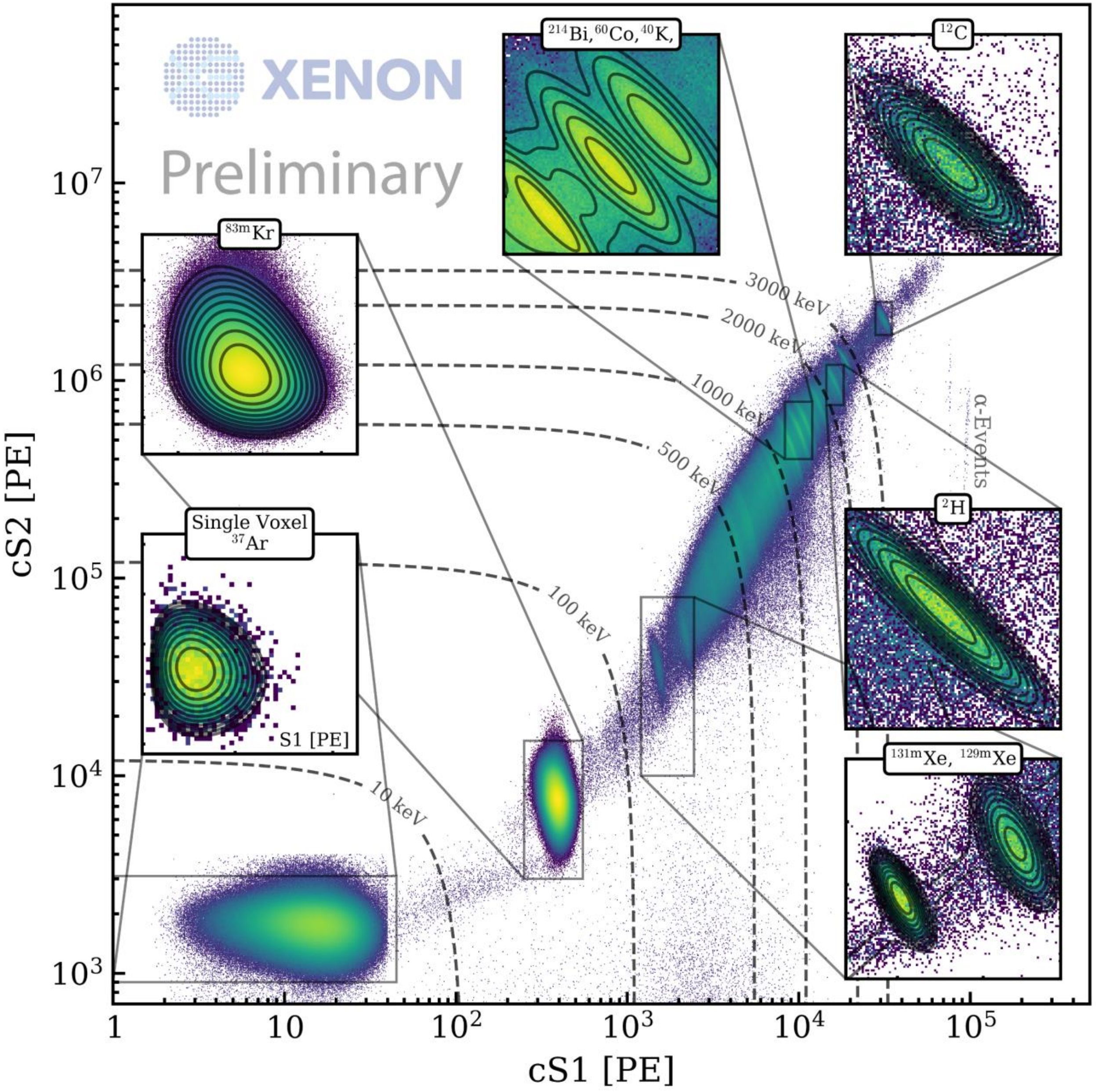
$$E = 13.7\text{eV} \times \left({}^{cS1}/_{g1} + {}^{cS2}/_{g2} \right)$$

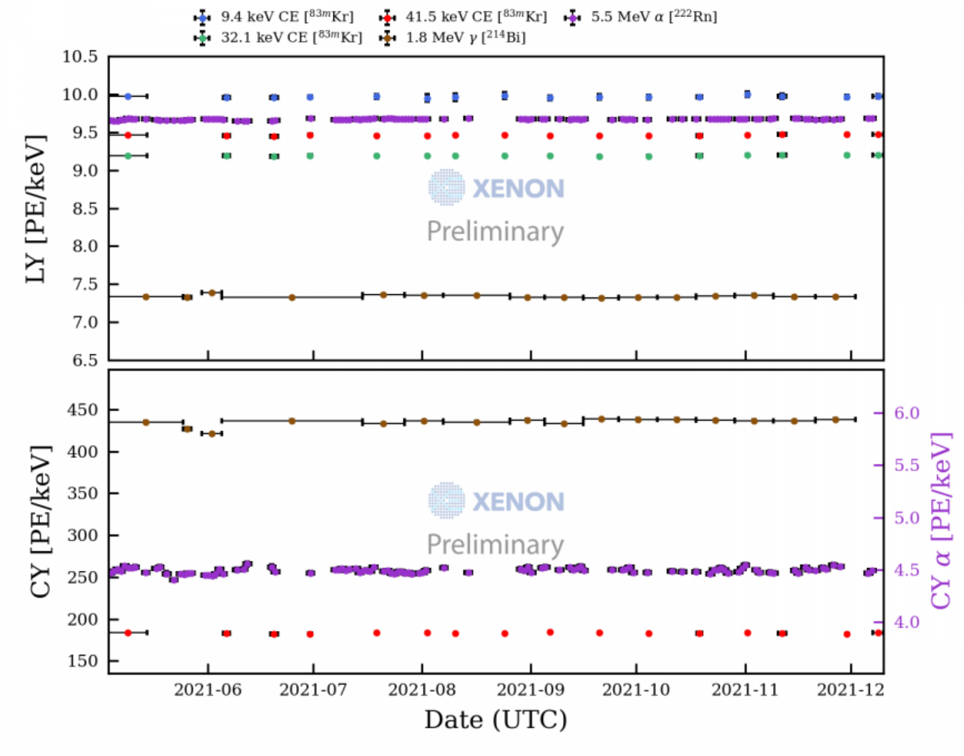
- Doke plot ⇒ determine g1 and g2

⇒ Use mono-energy peaks to calibrate for low-E (1-140 keV): ^{37}Ar, ^{83m}Kr, ^{129m}Xe, ^{131m}Xe

- LY and CY overtime: small variations (1%-2%)

Energy reconstruction





- The energy is a combination of cS1 and cS2:

$$E = 13.7\text{eV} \times \left({}^{cS1}/_{g1} + {}^{cS2}/_{g2} \right)$$

- Doke plot ⇒ determine g1 and g2

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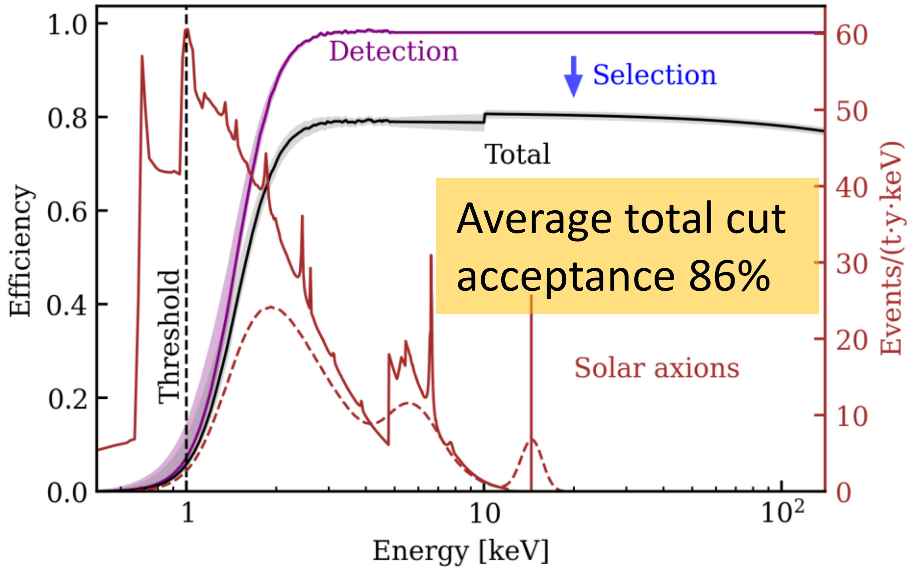
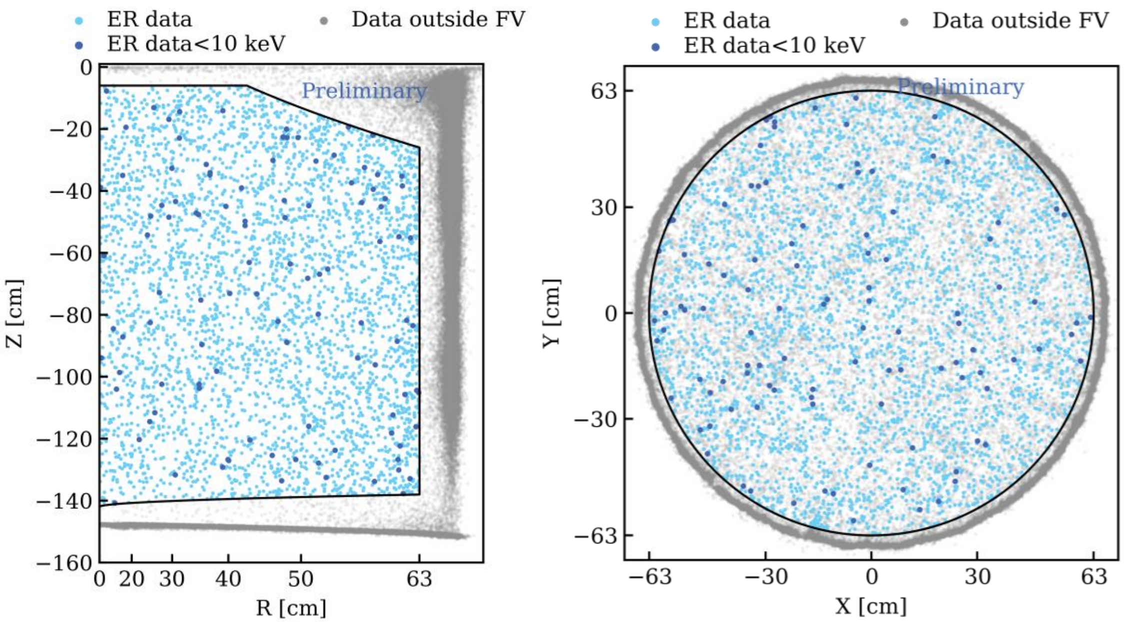
- LY and CY overtime: small variations (1%-2%)

Data Quality Cuts

Events are required to pass a range of quality cuts:

- S1 and S2 peak should each have patterns, top/bottom ratios etc. consistent with real events
- S2 width consistent with the expected diffusion
- An S2 over 500 PE
- Not within ±300ns of a neutron veto event
- Events must be within ER band
- Fiducial volume cut selects a mass of (4.37±0.14)tonnes with low backgrounds



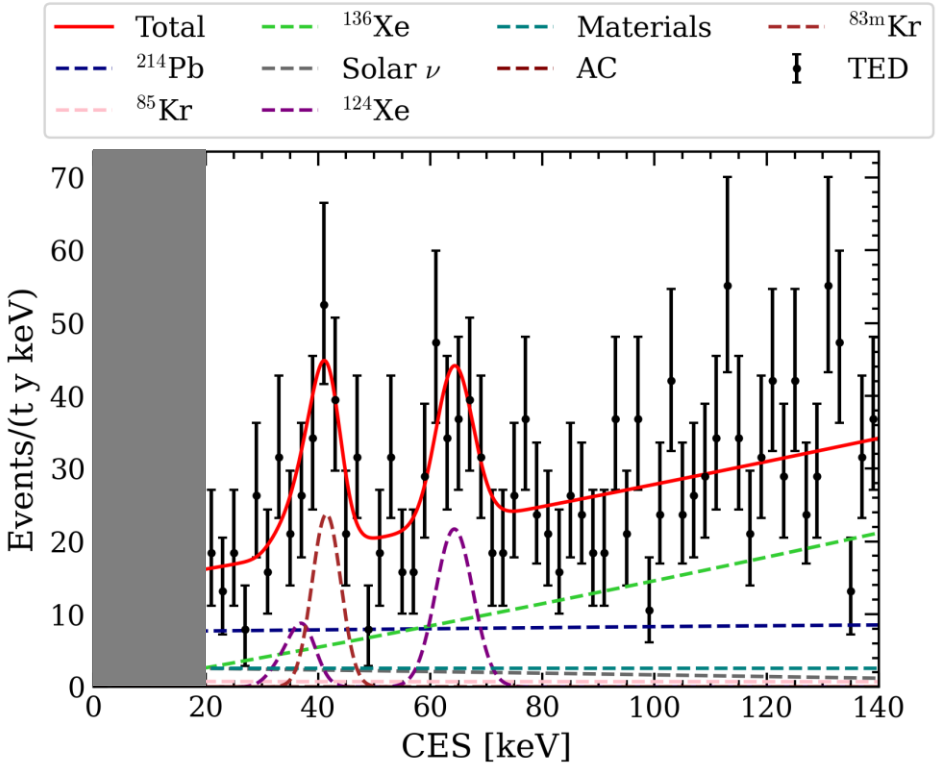


Control ^3H in XENONnT

- Aim to reduce possible HT or HTO in XENONnT

⇒ 2 months-outgassed + GXe purification with Zr getters; 3 weeks of GXe cleaning

- To clarify Tritium hypothesis:
  - Carry out a Tritium Enhanced Data (TED) run for 14.3 days after the first science run
  - TED: Bypass GXe purification, which enhance the HT and HTO in LXe by a factor 10-100
  - Data collected in this TED mode were blinded



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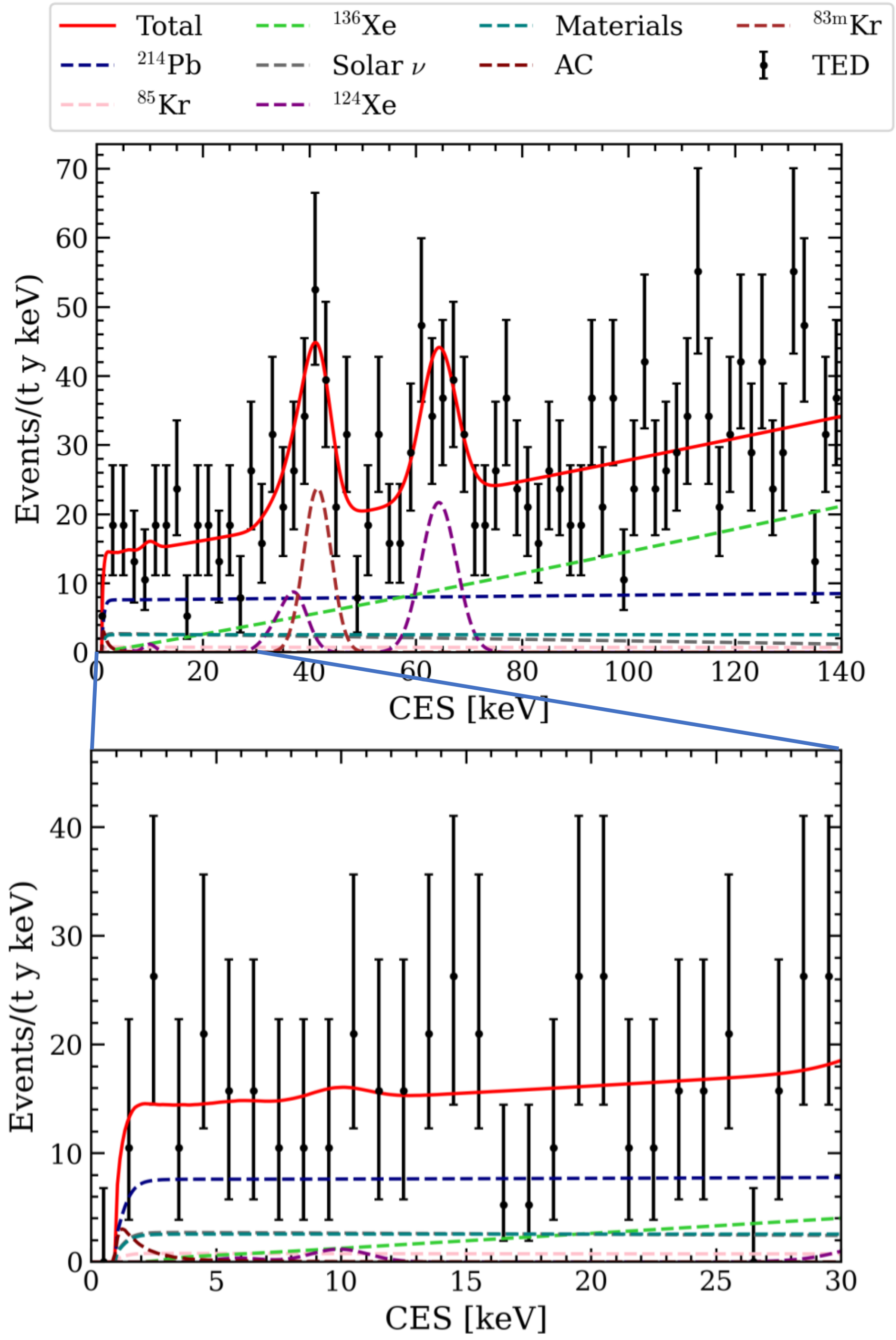
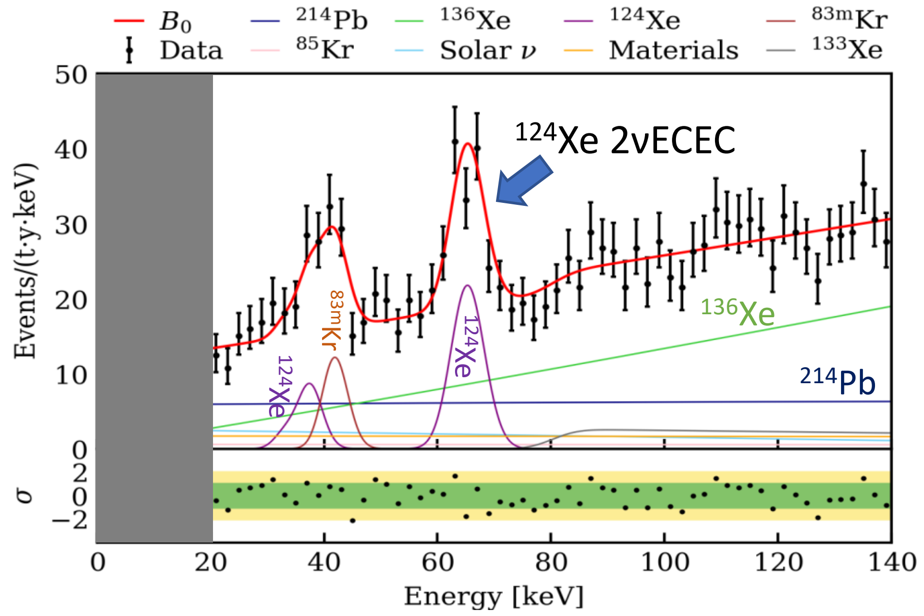
  - TED: Bypass GXe purification, which enhance the HT and HTO in LXe by a factor 10-100
  - Data collected in this TED mode were blinded
- After the unblinding, no evidence was found for a tritium-like excess.

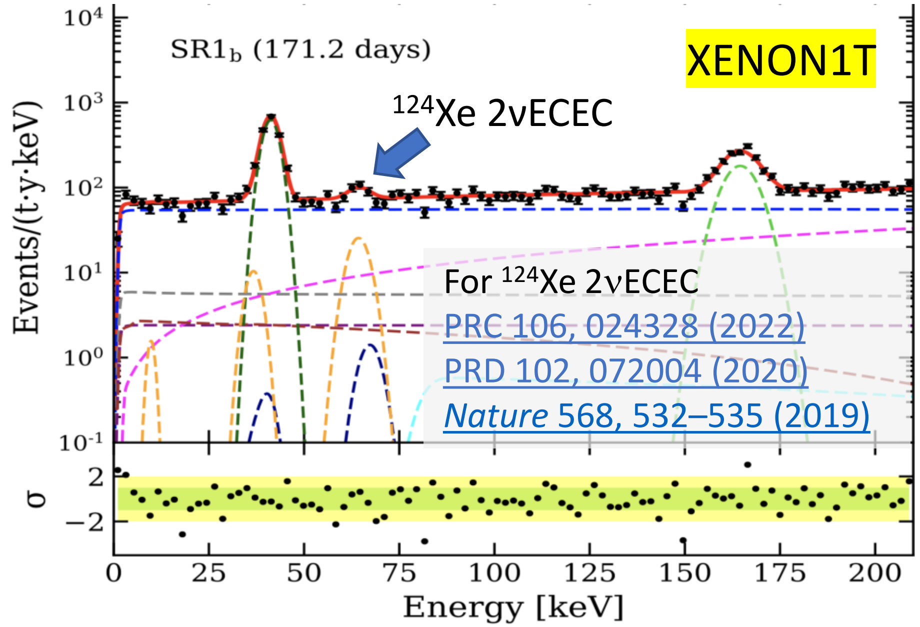
⇒ ^3H is therefore not included in the BKG model.



Science Run: Blinded analysis & BKG model

- 9 components in the Background Model
- Full blind analysis with various stages of unblinding
- Energy range: (1-140) keV
- Fiducial mass: (4.37±0.14) t, Exposure: 1.16 t·yr
- ^{124}Xe 2νECEC: clearly observed in nT





For ^{124}Xe 2νECEC
PRC 106, 024328 (2022)
PRD 102, 072004 (2020)
Nature 568, 532–535 (2019)

Science Run: Blinded analysis & BKG model

TMEX2023 1/8/2023, Quy Nhơn, Việt Nam, Khai Bui <tuankhai.bui@ipmu.jp>

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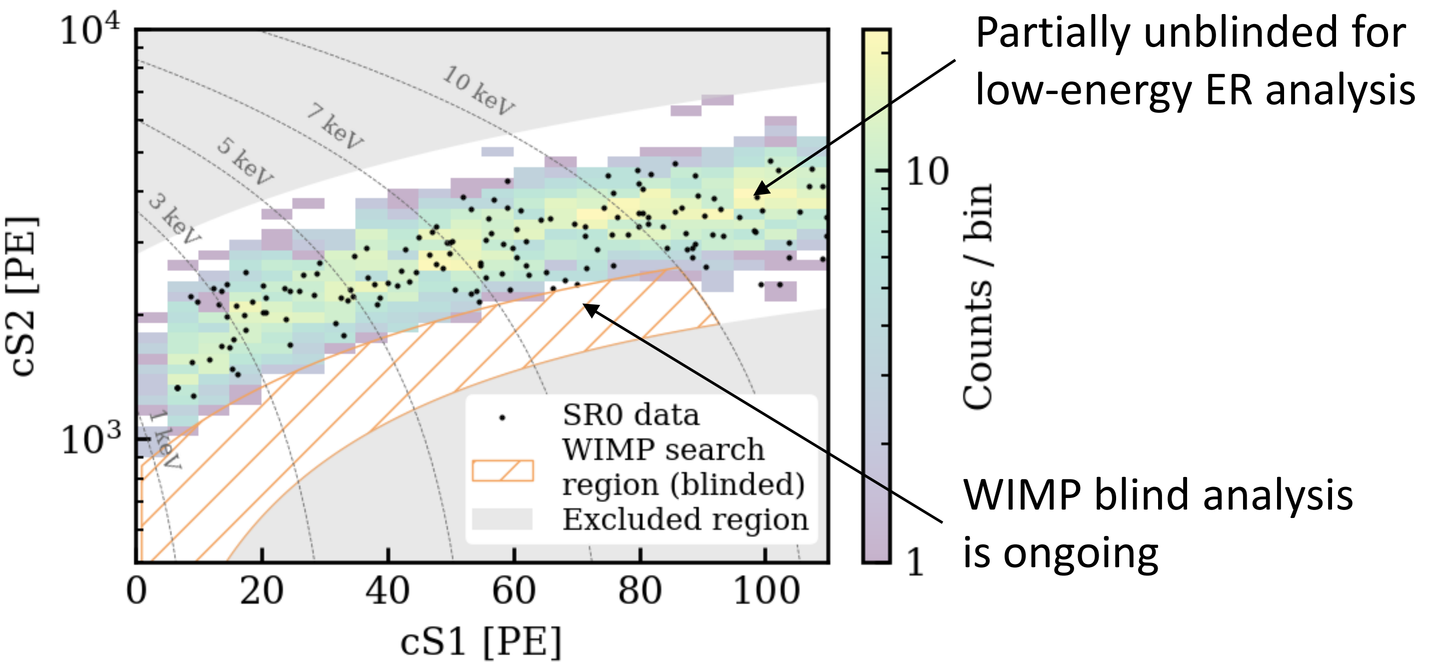
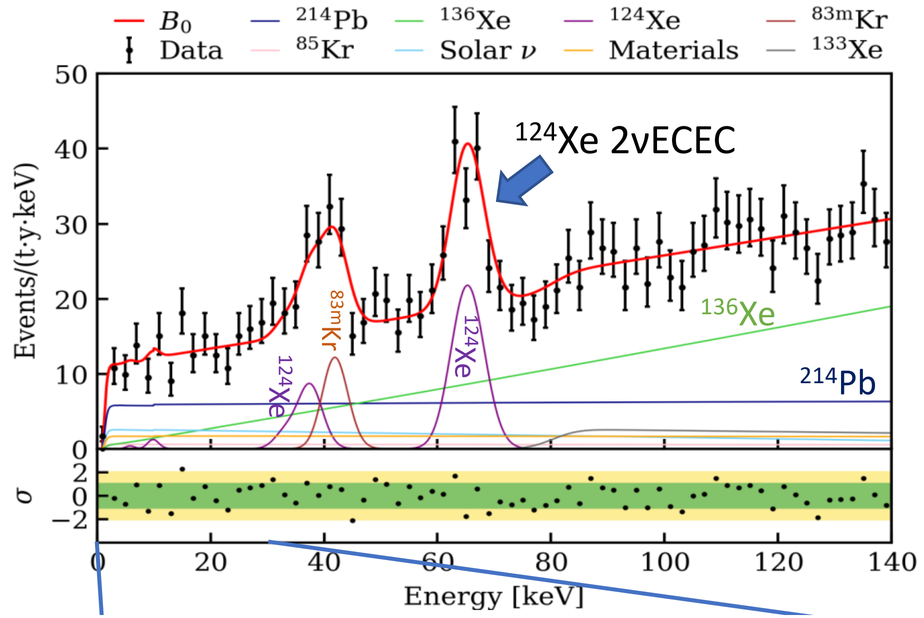
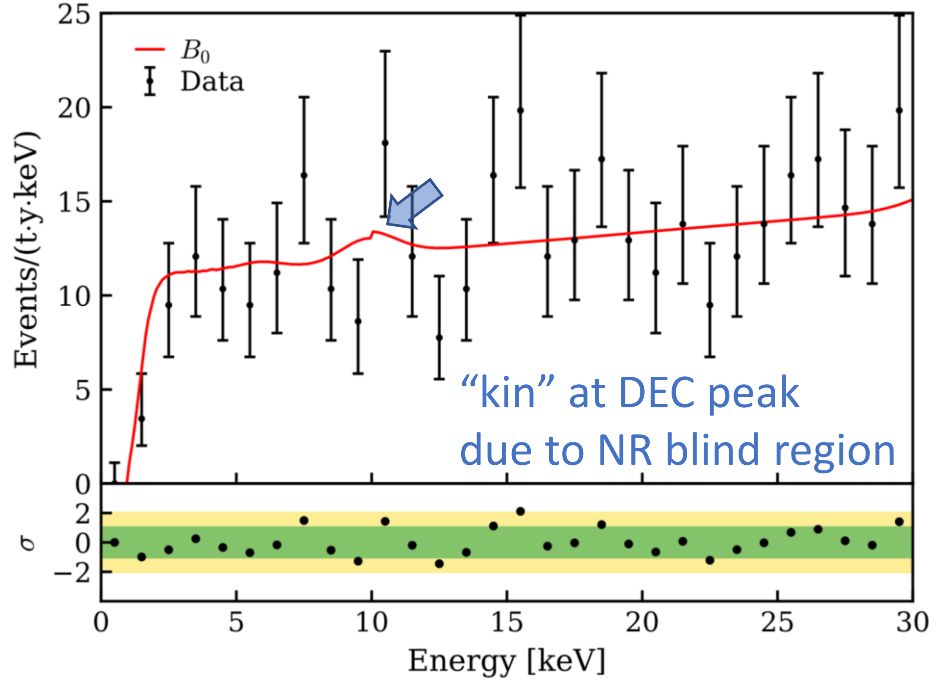
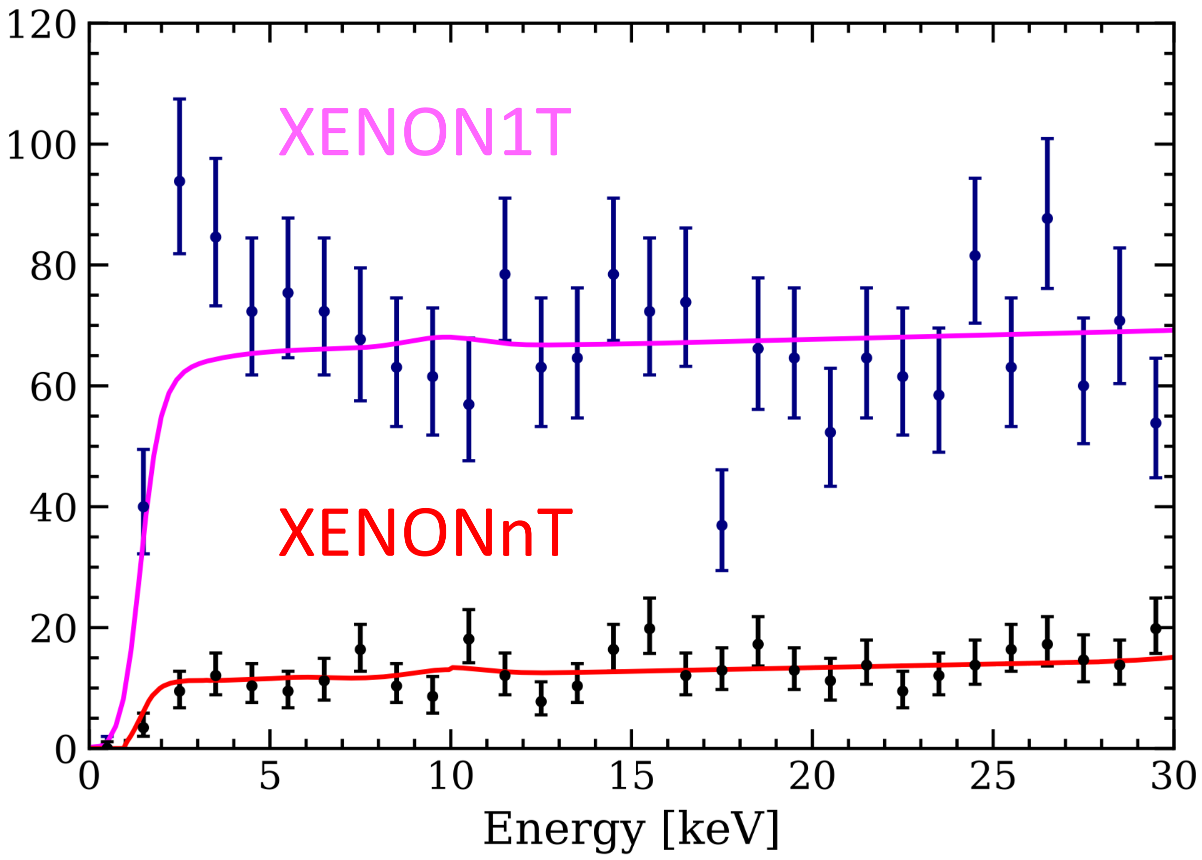






XENON1T vs XENONnT



- Exposure: 1.16 t·yr

⇒ x2 exposure of XENON1T 0.65 t·yr

- Background in [1-30] keV: 16.1±0.3 events/(t·yr·keV)

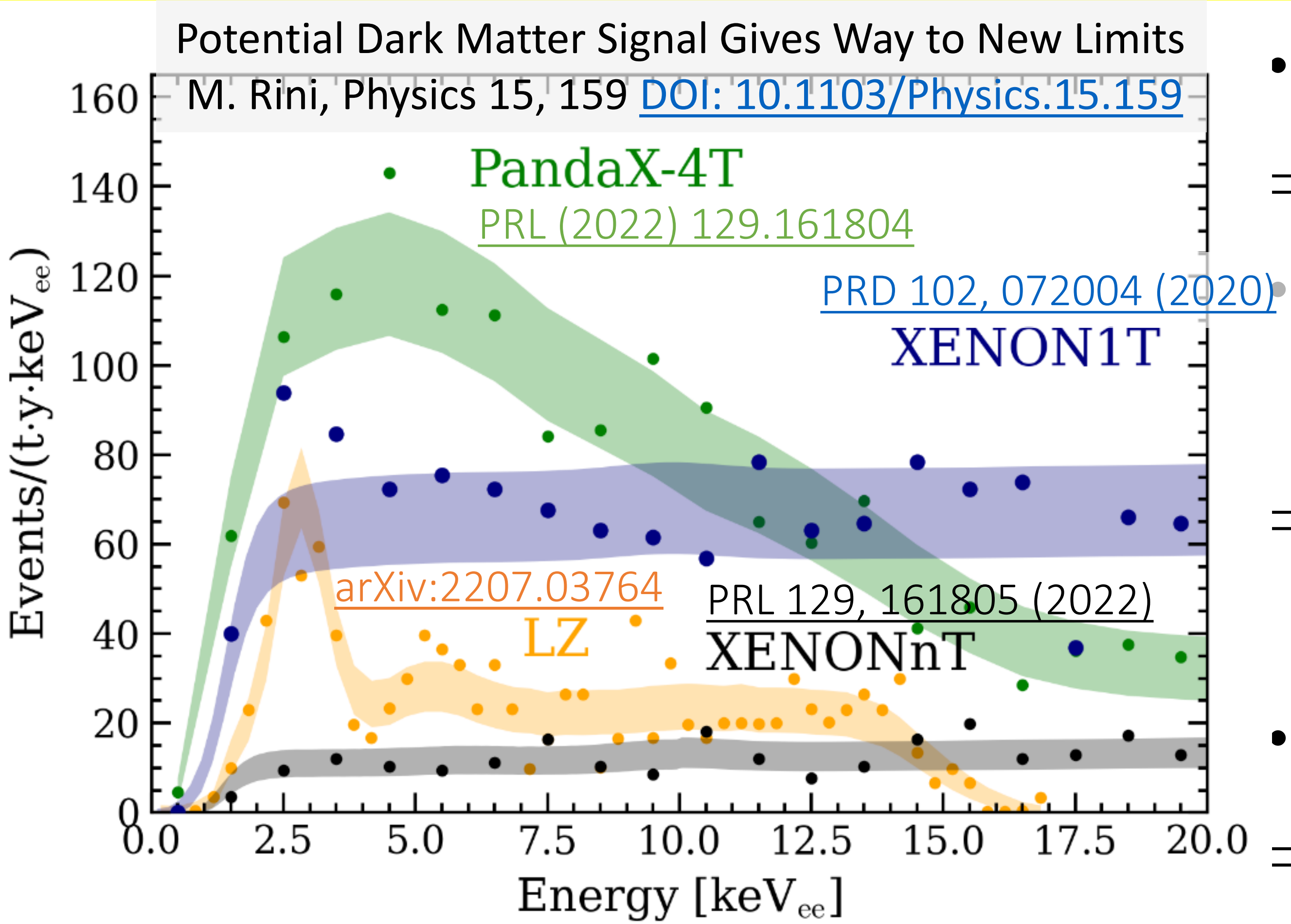
⇒ × $^1/_5$ background rate in XENON1T 82±3 events/(t·yr·keV)

- Exclude XENON1T excess in [1-30] keV

⇒ Most likely explanation of XENON1T excess is a small ^3H contamination.

⇒ In XENONnT, taking steps to reduce tritium outgassing sees no excess

XENON1T vs XENONnT



XENONnT: achieved **the lowest background level ever** in ER search

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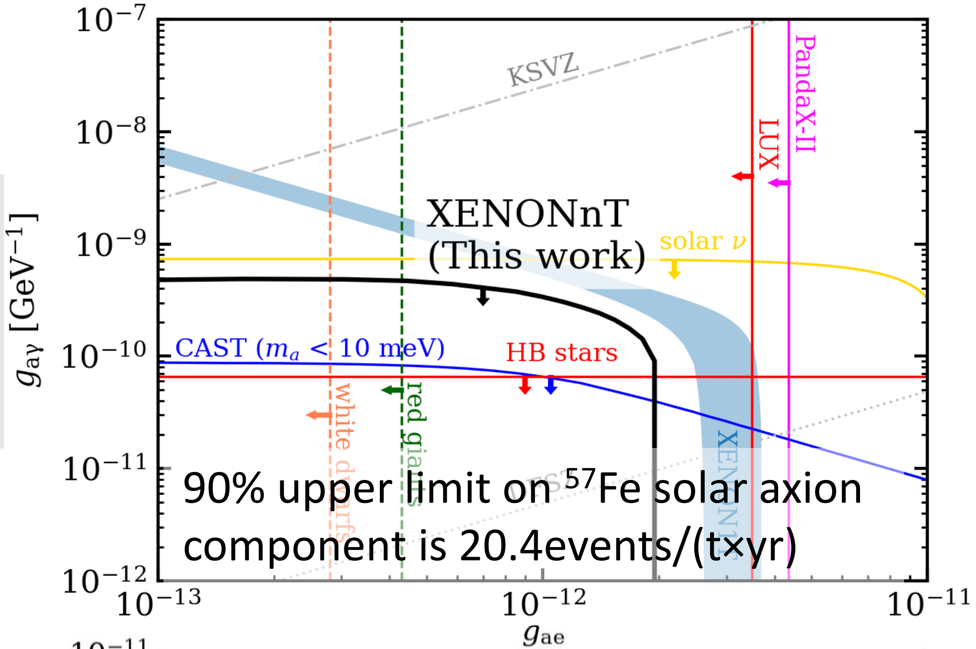
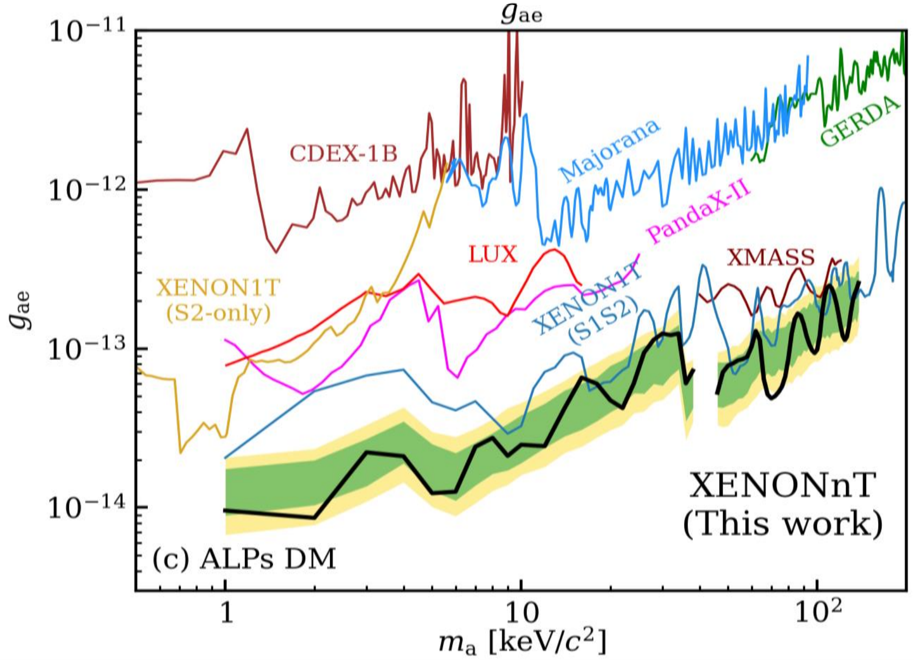
Limit on New Physics

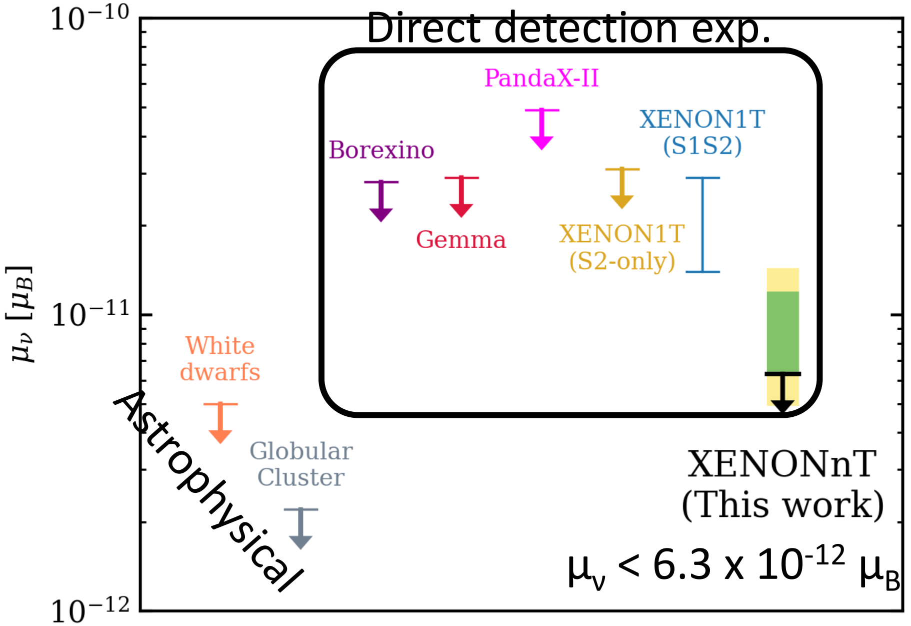
Solar axions



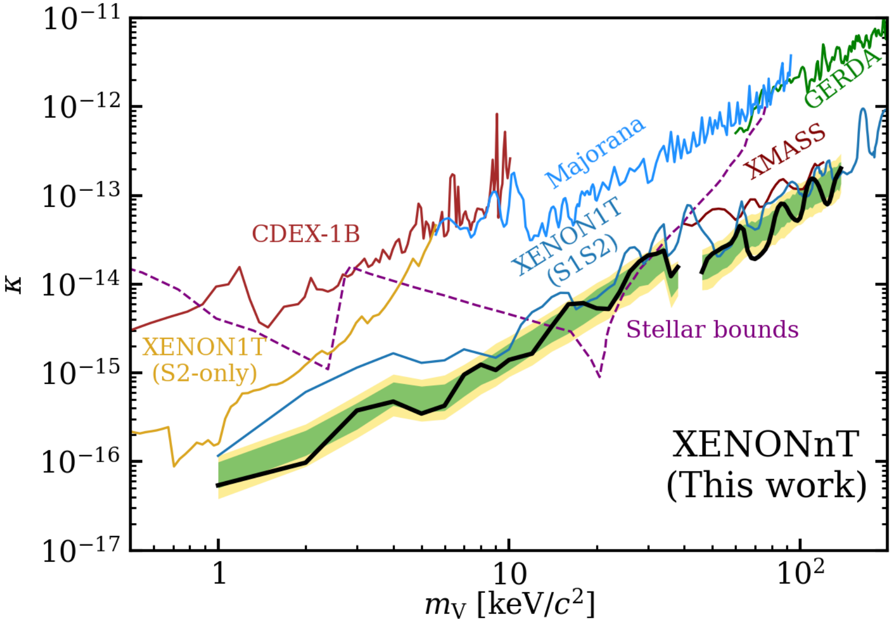
Axion-like Particle



ν magnetic moment



Dark photon



Summary and Outlook

- Successful construction and commissioning of XENONnT

$\Rightarrow$ Current exposure 1.16 t·yr

$\Rightarrow$ Lowest BG ever achieved: 16.1±0.3 events/(t·yr·keV)

- Fully blinded analysis of ER data: No excess [1-140] keV

$\Rightarrow$ BSM models that explain the XENON1T excess are excluded

$\Rightarrow$ New world-leading limits on solar-axions, ALP, DP, and neutrino magnetic moment

- XENON1T excess is most likely due to the small ^3H contamination
- More info: **PRL 129, 161805 (2022)**, **arXiv:2207.11330**
- **NR WIMP unblinding is in progress (STAY TUNED!)**

What's next:

- Unblinding NR
- WIMP search analysis
- Ongoing science run (SR1) with factor 2 lower radon level

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XLZD: Next-generation Dark Matter Detector

- **Leading Xenon Researchers unite to build next-generation Dark Matter Detector**
- **The XENON/DARWIN and LUX-ZEPLIN collaborations (XLZD) have now joined forces to work together on the design, construction, and operation of a new, single, multi-tonne scale xenon observatory to explore dark matter.**
- White paper: A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics [arxiv:2203.02309]

2021/4/26, 27 XENON/DARWIN, LUX-ZEPLIN meeting

https://www.ipmu.jp/20210721-NextGenerationLiquidXenonDetector

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Leading xenon researchers unite to build next-generation Dark Matter Detector

July 21, 2021
Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU)

Researchers in the XENON/DARWIN and LUX-ZEPLIN collaborations have signed an MOU to work together to design, construct, and operate a new, single, multi-tonne scale xenon observatory to explore dark matter, it was announced on July 20.

Dark matter makes up 85 per cent of matter in the Universe, but its nature remains a mystery. The direct identification of the dark matter particle is amongst the highest priorities in science and also one of the most challenging.

The LUX-ZEPLIN experiment operates at the Sanford Underground Research Facility in the US, and the XENONnT experiment is located at the INFN (National Institute for Nuclear Physics) Gran Sasso Laboratory in Italy. Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) Principal Investigator Kai Martens and Project Associate Professor Masaki Yamashita are two of the 104 researcher group leaders from 16 countries who signed the MOU on July 6. Nagoya University and Kobe University are the other Japanese universities who have researchers involved in the new project.

A summary of what the Next Generation Liquid Xenon Detector experiment will attempt to uncover. It includes the direct detection of dark matter, neutrinoless double-beta decay, hypothetical axion particles, and measurement of neutrinos created in the Sun and Earth's atmosphere, and potentially galactic supernovae. (Credit: Next Generation Liquid Xenon Observatory)

XENON DARWIN