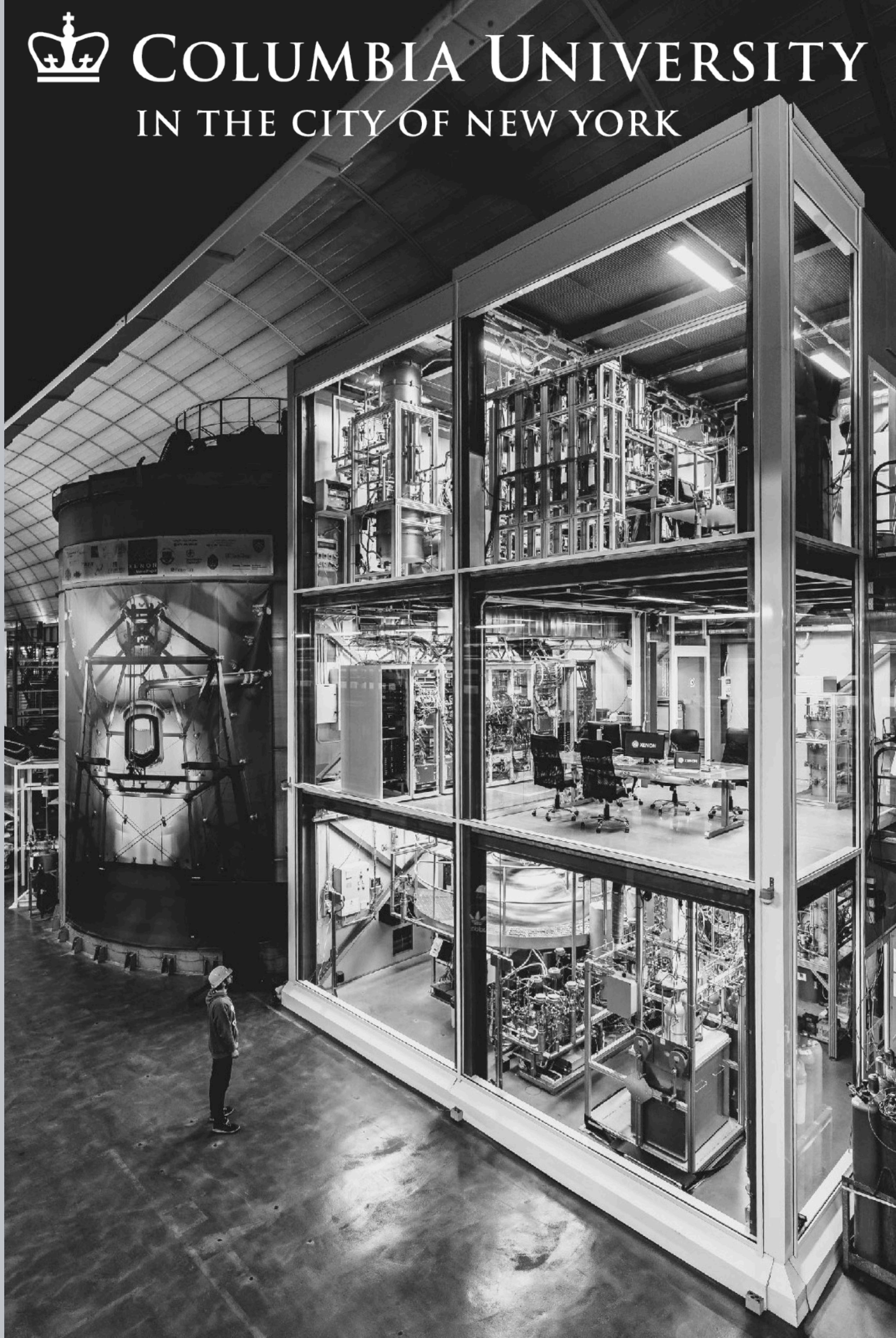
XENONnT first results on Electronic Recoil events

XENON

IDM2022 Knut Dundas Morå
(knut.dundas.moraa@columbia.edu)



Progress of XENONnT

New techniques for removal of impurities and intrinsic background

Blinded analysis of the first science data

A probe of the XENON1T excess

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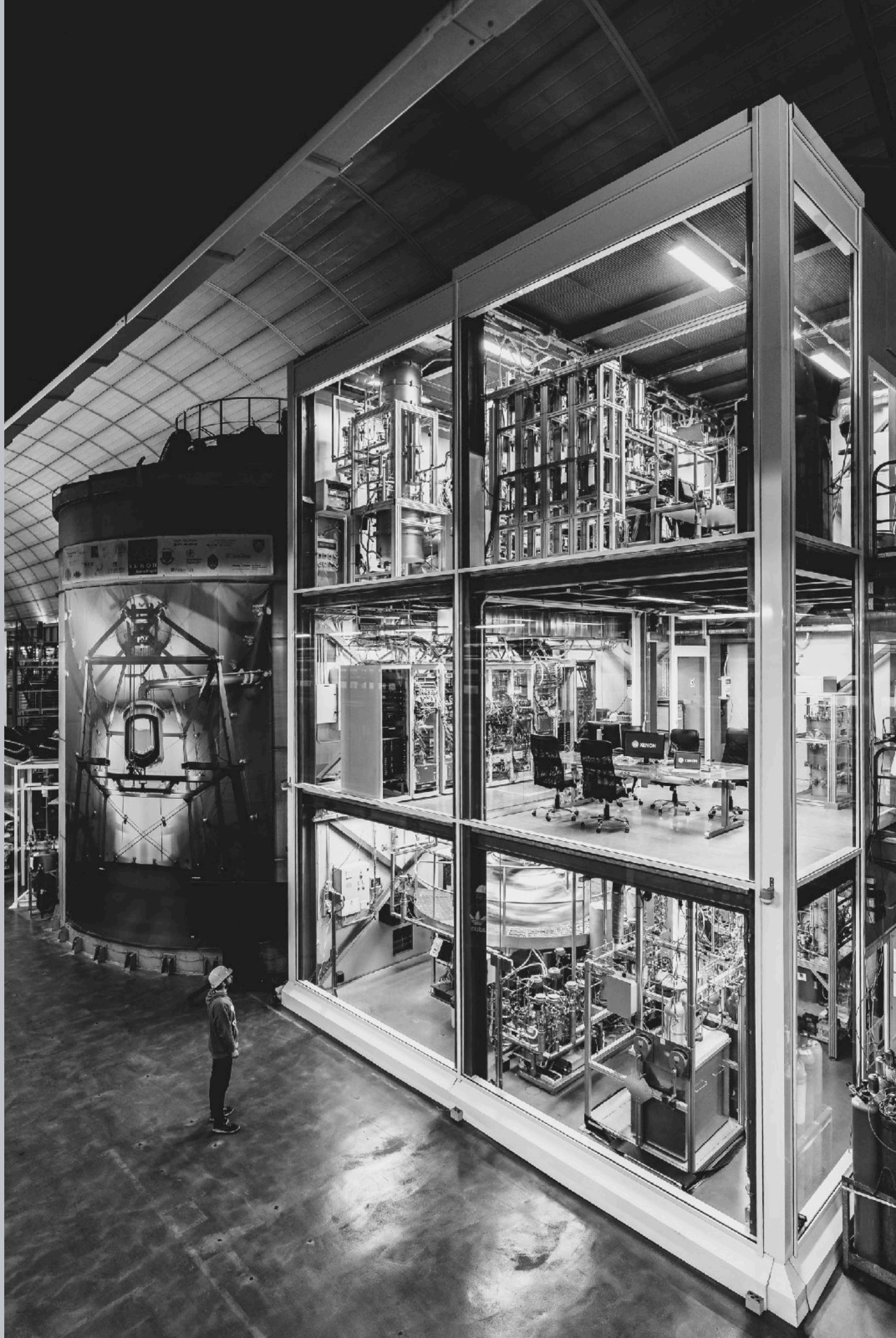

XENON

27 institutes:

Columbia

KIT

Nikhef

Muenster

Stockholm

Mainz

MPIK, Heidelberg

Freiburg

Zurich

Chicago

Tsinghua

UCSD

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Kobe

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Coimbra

LPNHE

Torino

Bologna

L’Aquila

LNGS

Napoli

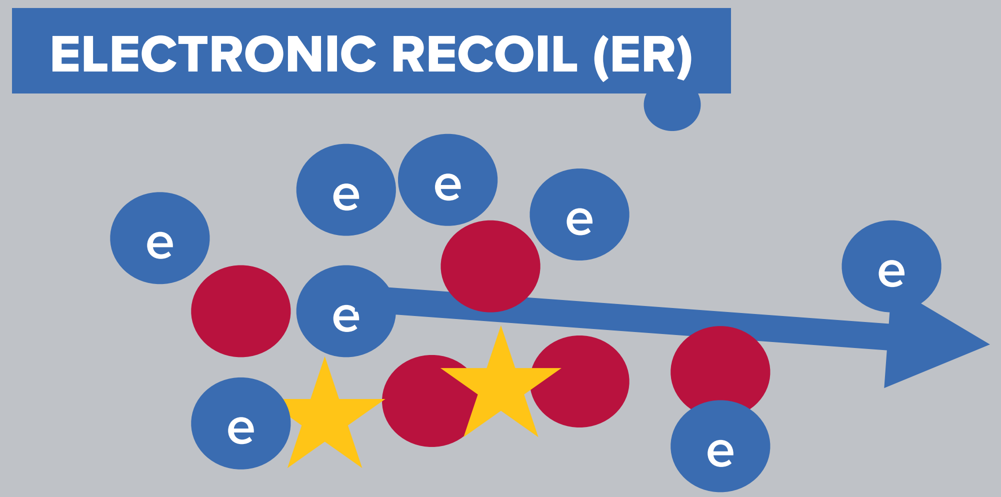
Weizmann

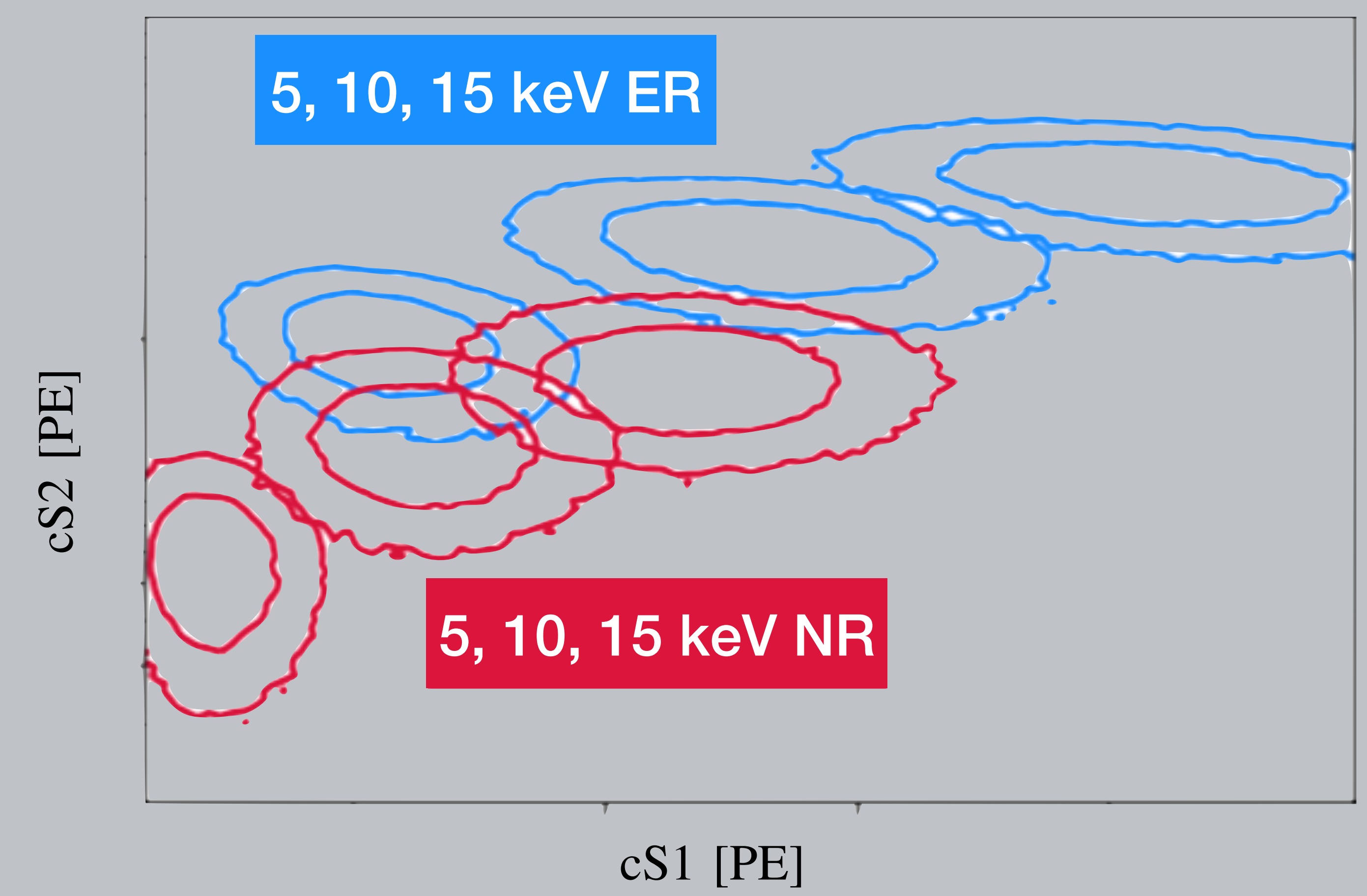
NYUAD

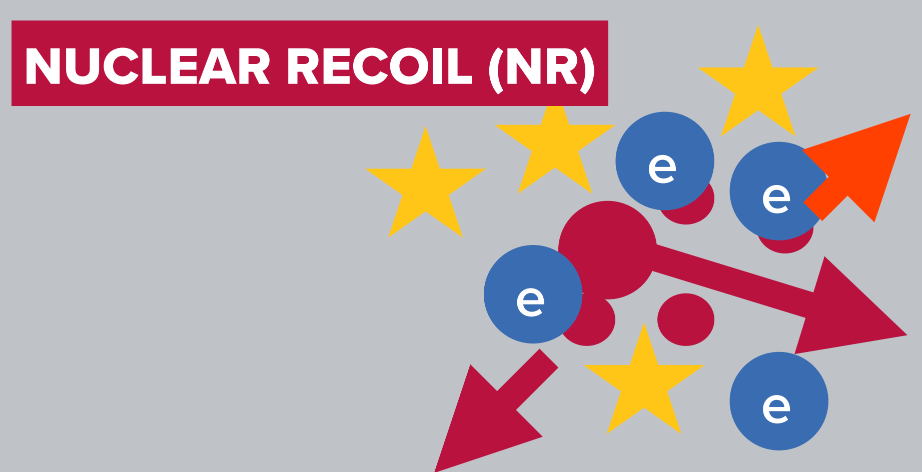

XENON
167 members!

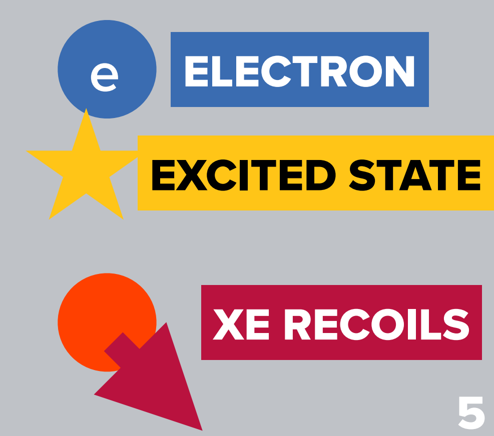
OBSERVABLE SIGNALS IN LIQUID XENON

- The XENON detectors were conceived and designed to search for nuclear recoil signals from WIMP
- $\sim 1\ \mathrm{keV}$ ER recoil energy deposited in the liquid xenon target is enough to yield a characteristic scintillation + charge signal
- In addition to WIMP dark matter and backgrounds, several other dark matter or new physics candidates can give a signal:
  - Axions or axion-like particles,
  - Dark Photons
  - Neutrinos





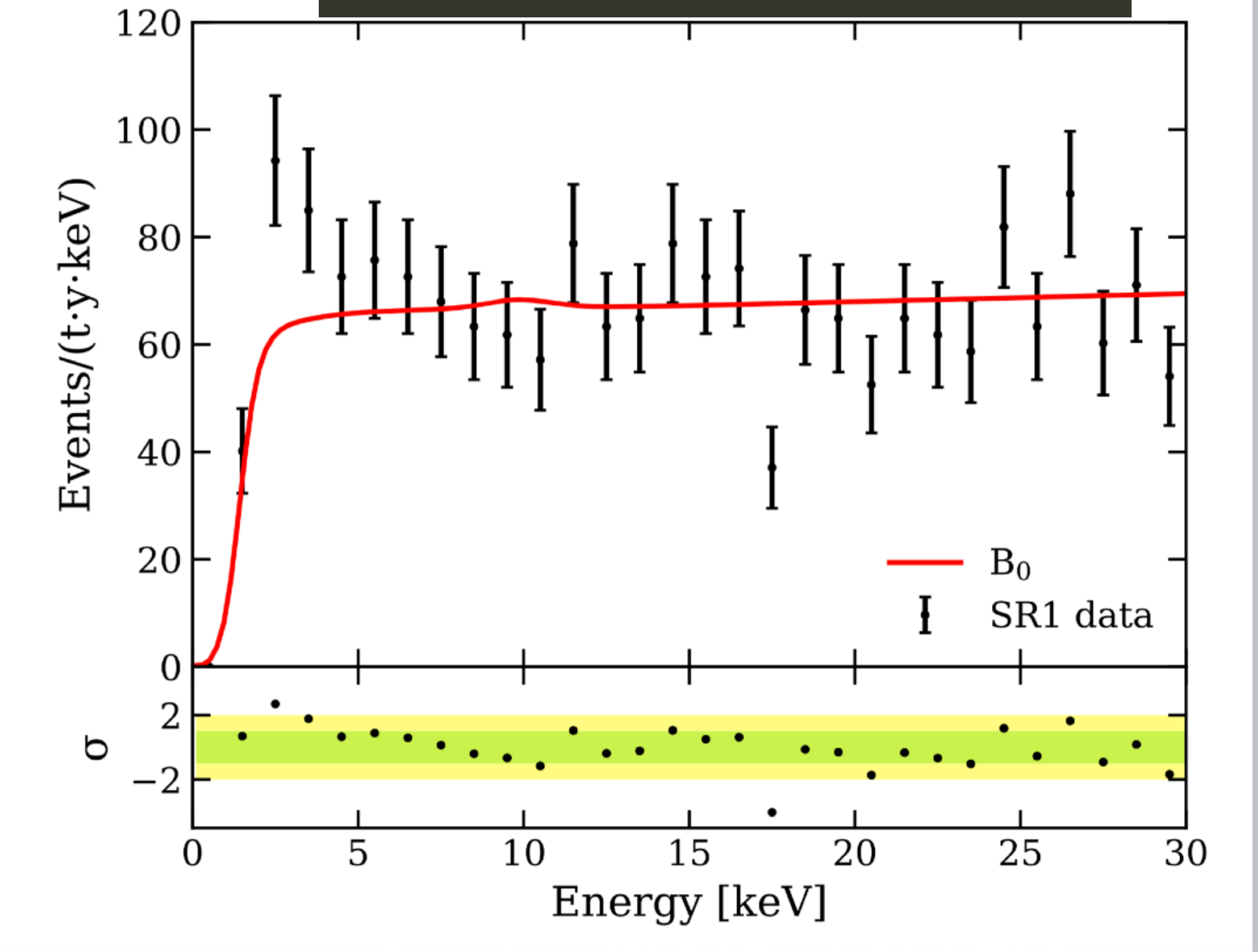


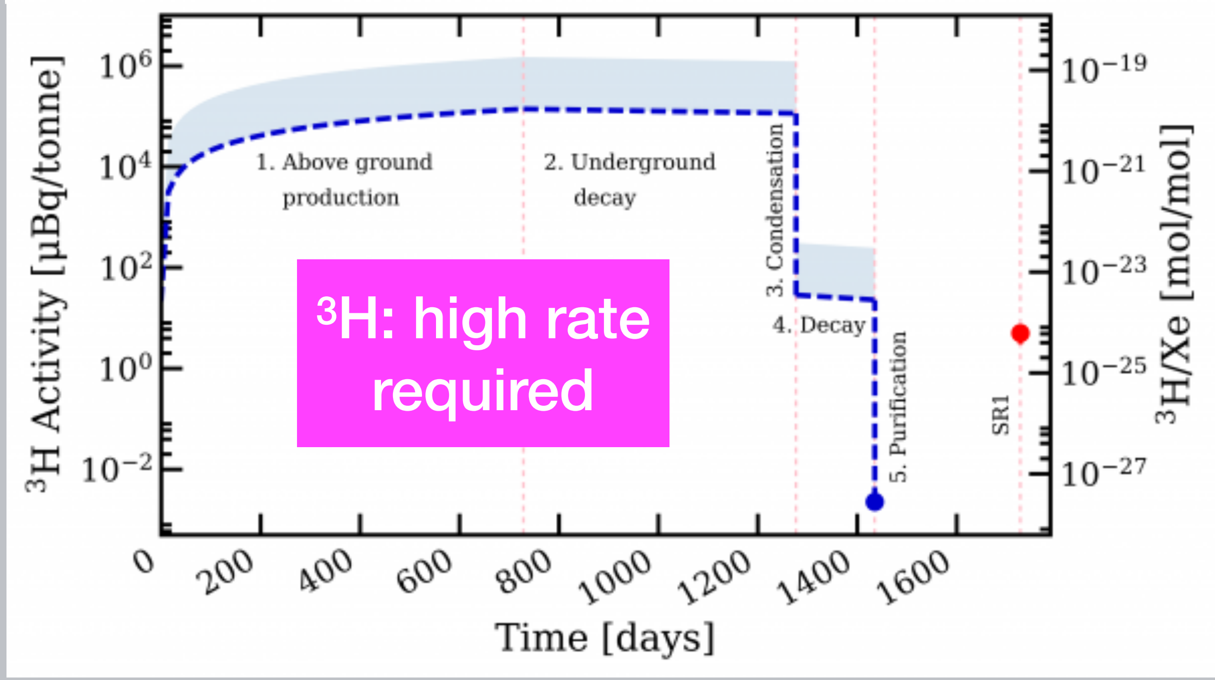


XENON1T ER SEARCH

- XENON1T observed a peak in its ER spectrum below ~7 keV
- Excess fit to 2.3 keV peak, $\sim 3\sigma$.
- ^{37}Ar would be removed by the online Kr distillation. The necessary air leak to explain the excess is > 13 l/y, upper limit is 0.9 l/year
- ^{3}H is possible— not as water but as tritiated hydrogen. Required rate much greater than expected from purification.
- A range of new physics could be compatible with the peak: solar axions, dark photons, a neutrino magnetic moment and many more

Excess electronic recoil events in XENON1T
Phys.Rev.D 102 (2020) 7, 072004



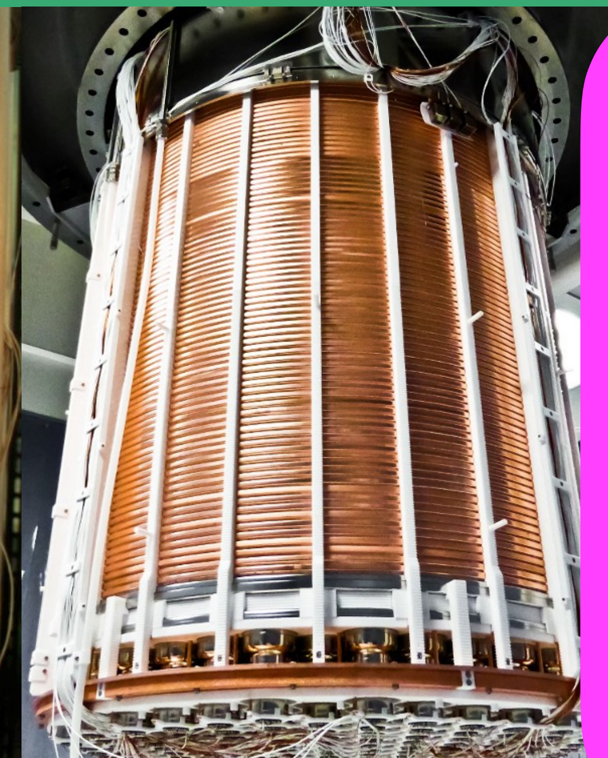
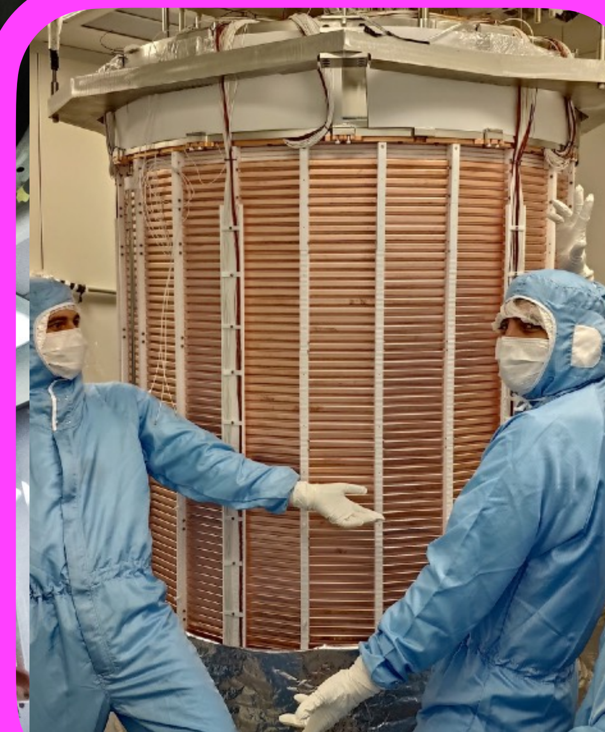


Review of signals in Snowmass2021 Cosmic Frontier White Paper: on dark matter excesses

THE XENON DETECTORS

XENON

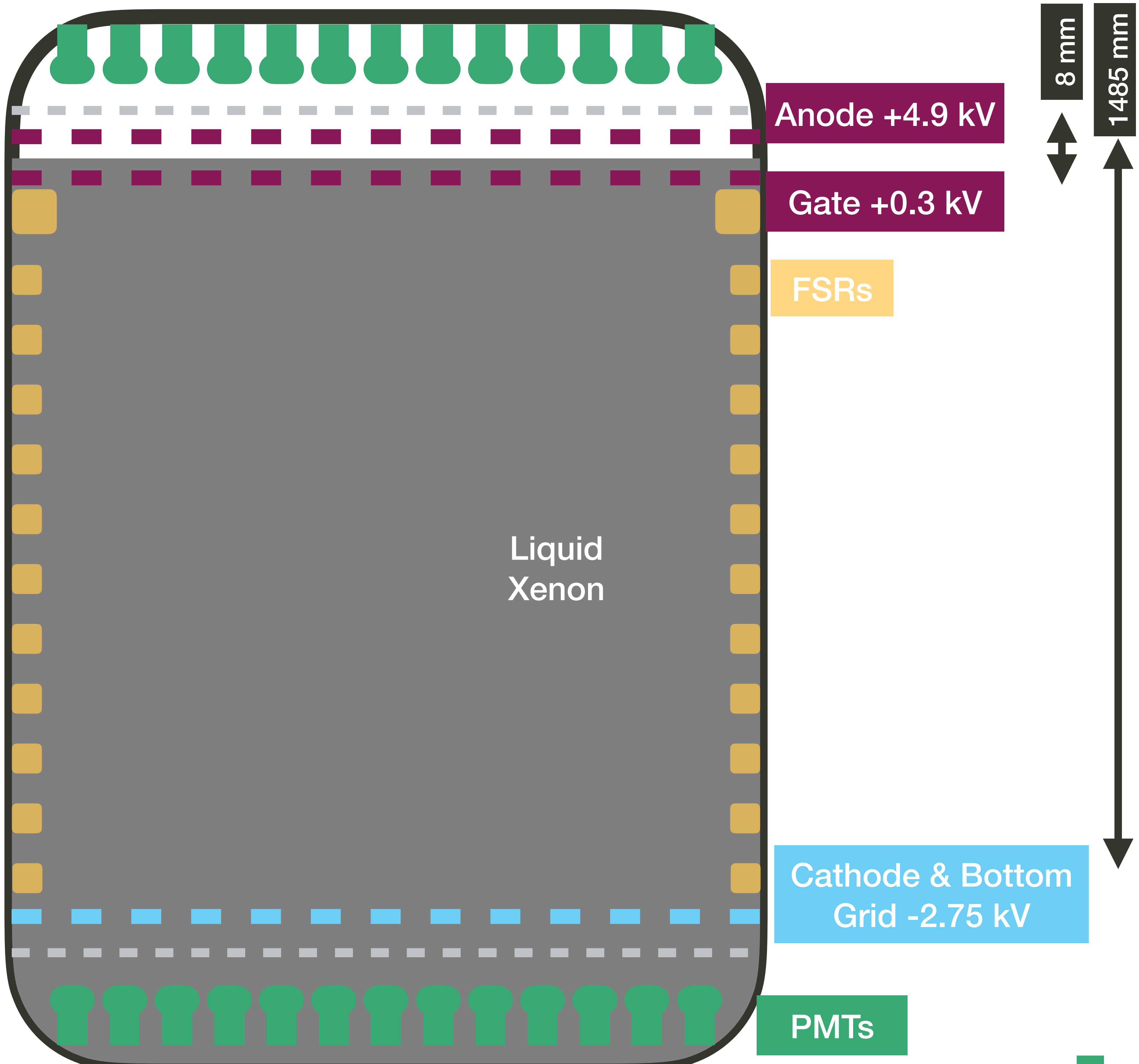


XENON10	XENON100	XENON1T	XENONnT
2005-2007	2008-2016	2012-2019	2020-2026 (taking science data)
14 kg Xe target	62 kg Xe target	2 t Xe target	~6 t Xe target, 8.6t total
~10^{-43} cm^2	~10^{-45} cm^2	4 ×10^{-47} cm^2	Projection: 1.4×10^{-48} cm^2 for 20 tonne-year
~2000000 background ER events/(keV t y)	1800 background ER events/(keV t y)	82 background ER events/(keV t y)	16.1 background ER events/(keV t y)

TWO-PHASE TPC

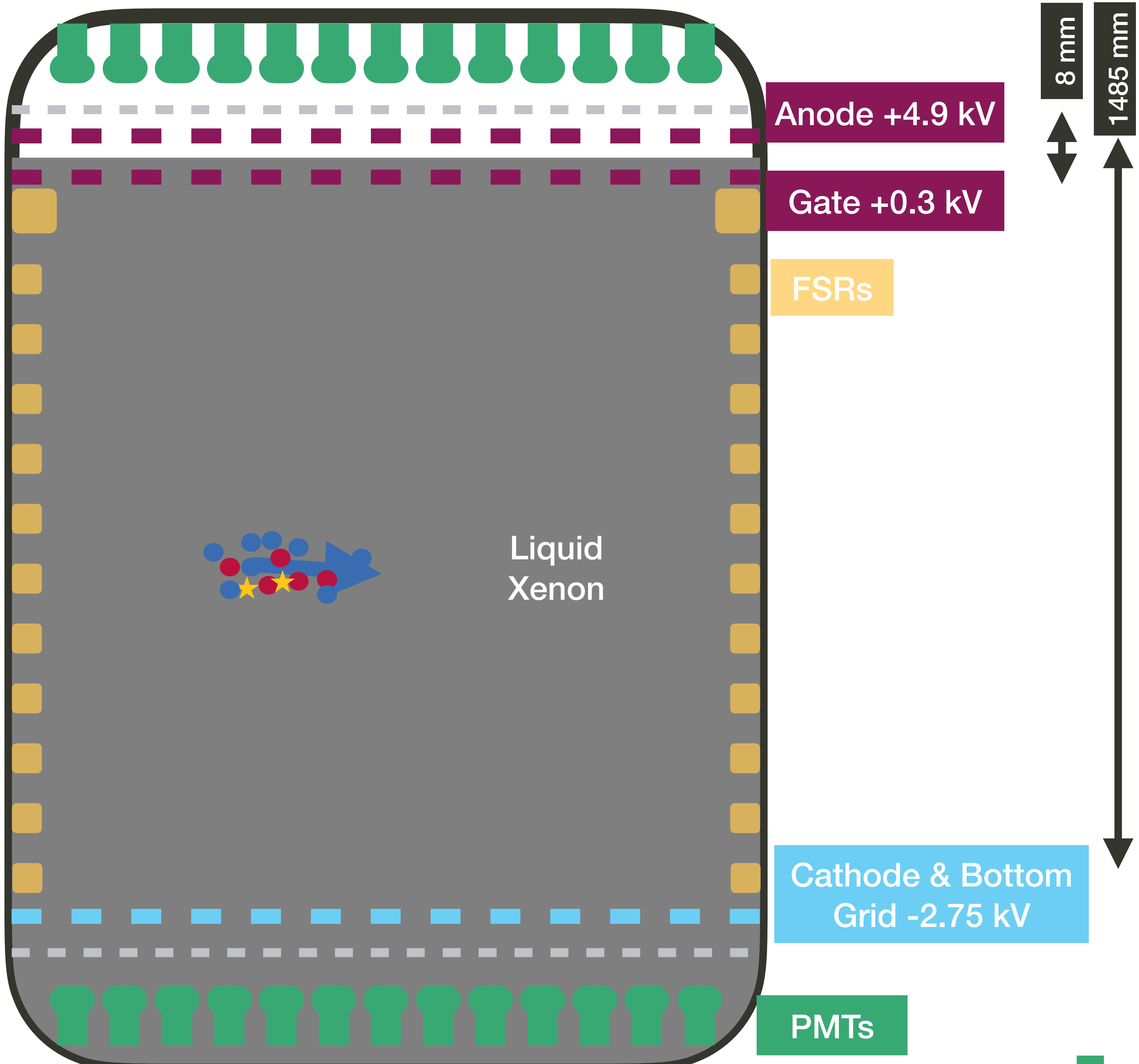
With XENONnT SR0 numbers



TWO-PHASE TPC

With XENONnT SR0 numbers

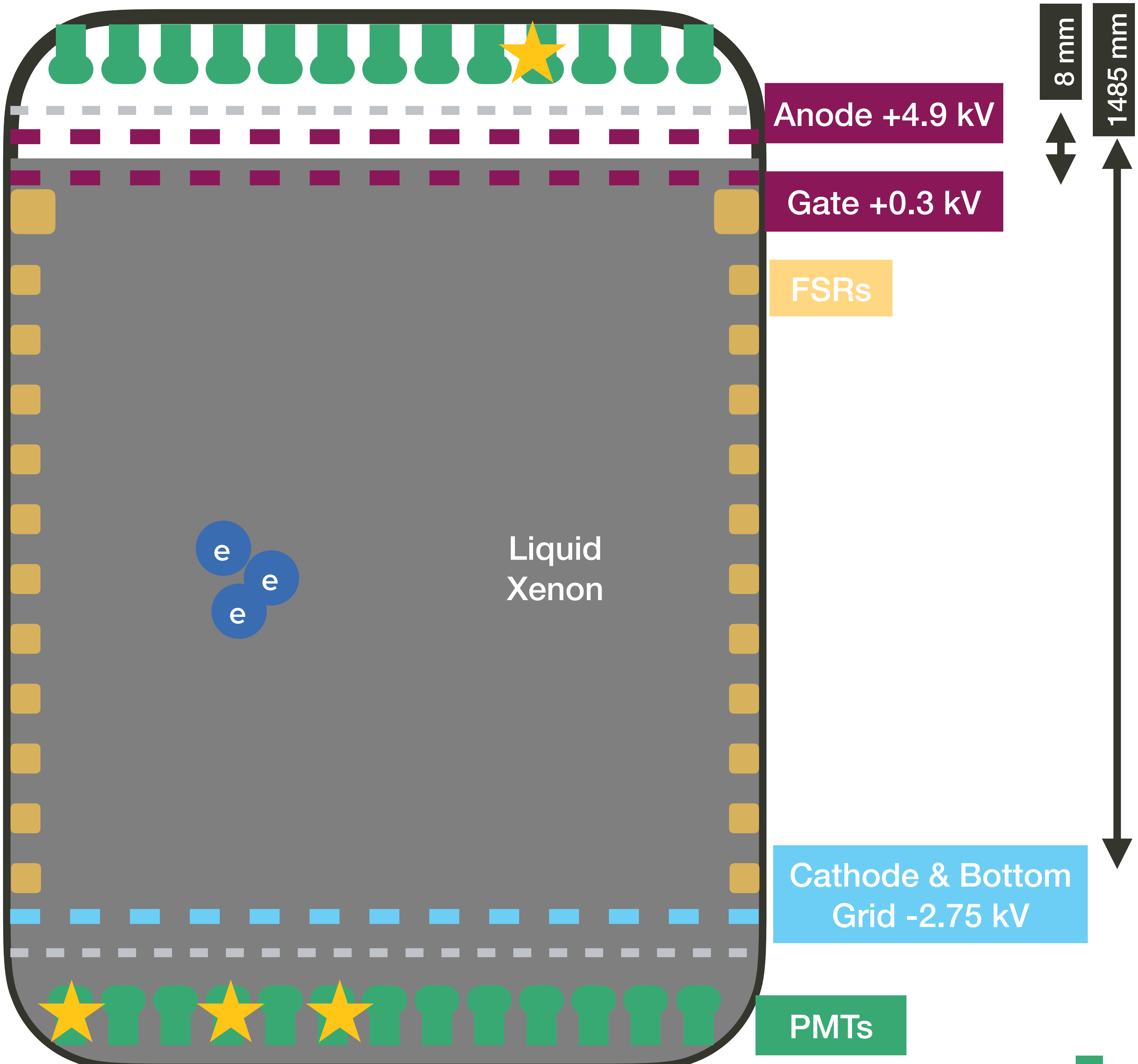
- An Interaction deposits energy, scintillation light and charge is liberated



TWO-PHASE TPC

With XENONnT SR0 numbers

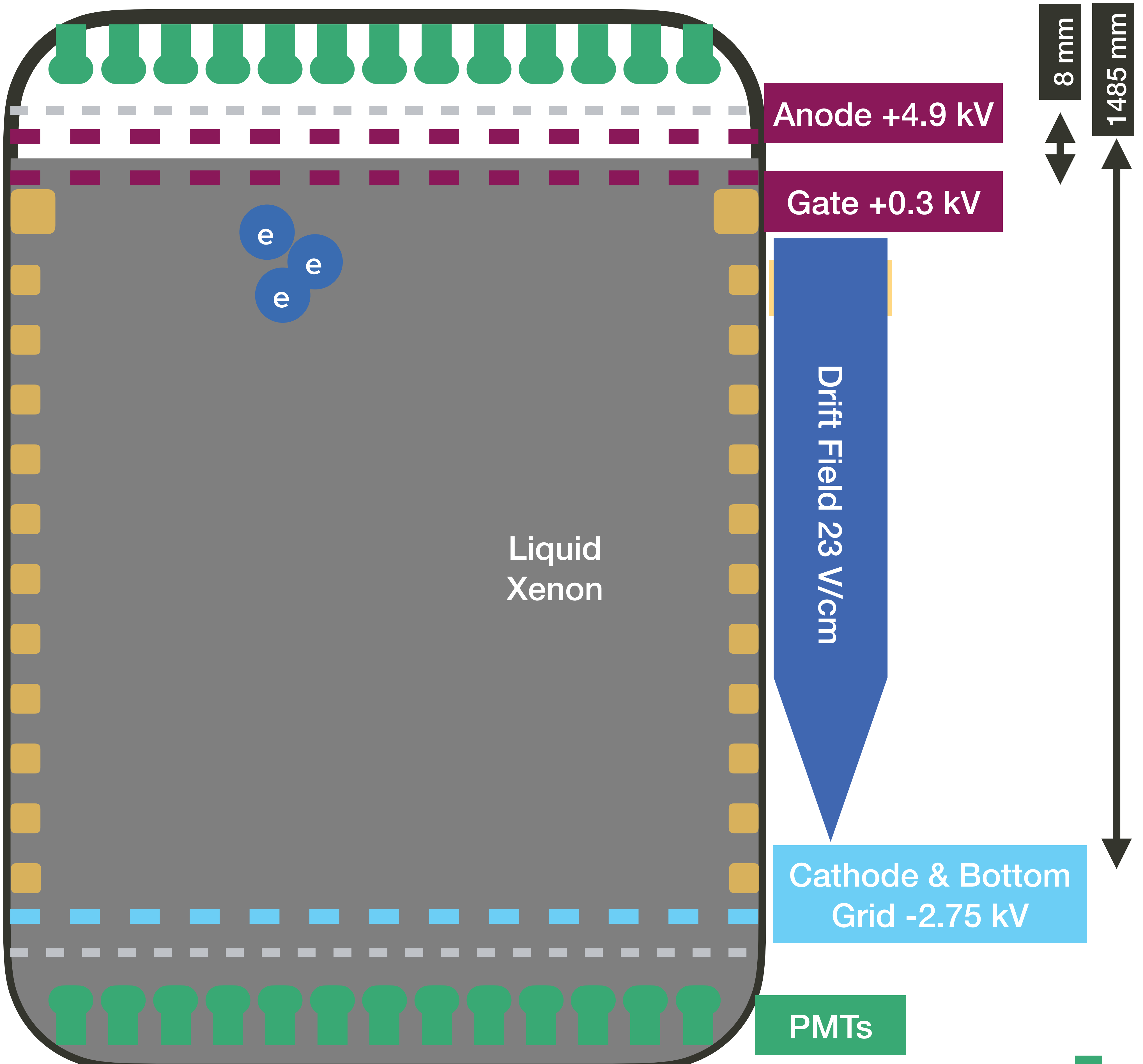
- An Interaction deposits energy, scintillation light and charge is liberated
- S1 signal reaches photomultipliers



TWO-PHASE TPC

With XENONnT SR0 numbers

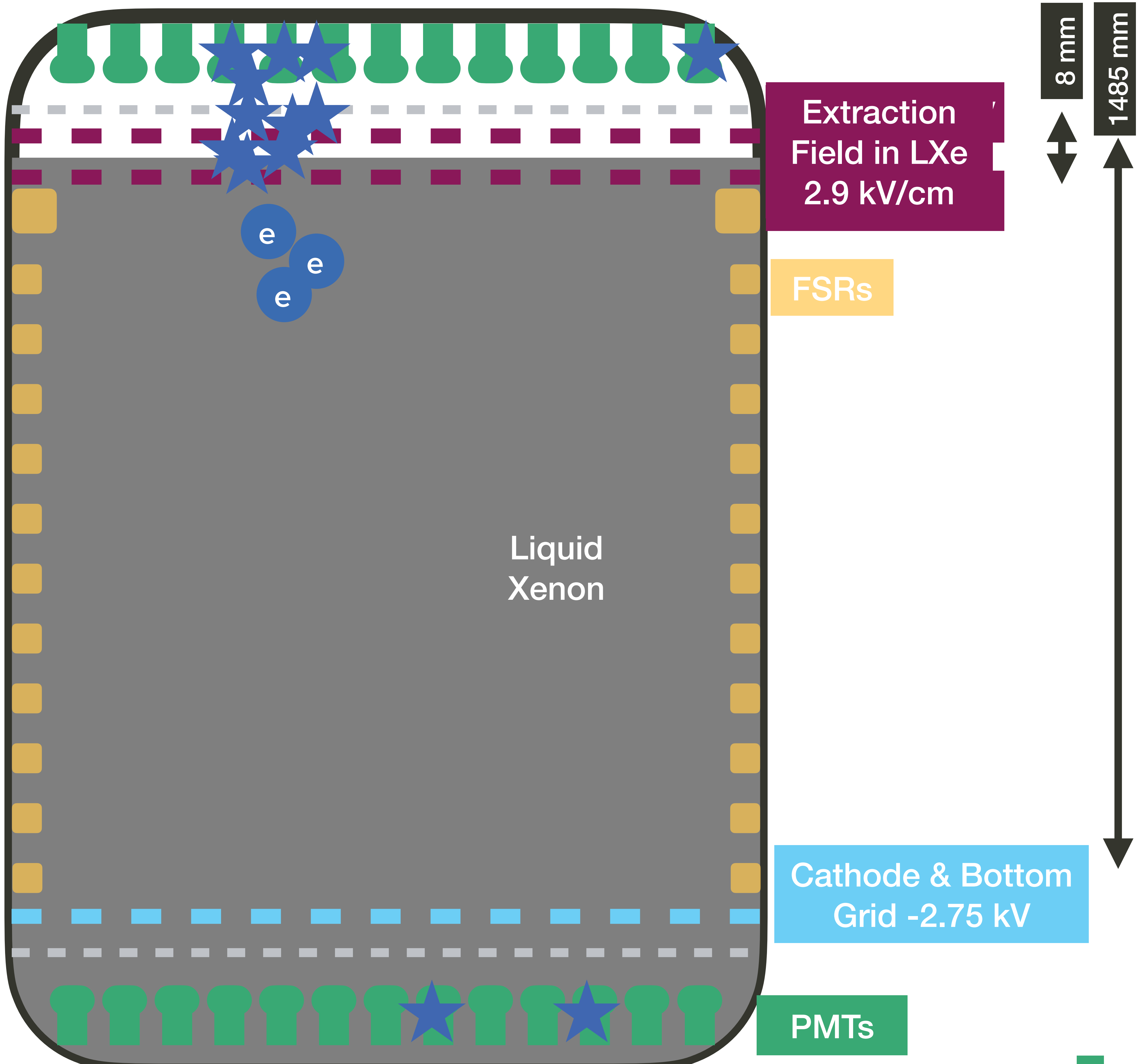
- An Interaction deposits energy, scintillation light and charge is liberated
- S1 signal reaches photomultipliers
- Electrons drift to the surface



TWO-PHASE TPC

With XENONnT SR0 numbers

- An Interaction deposits energy, scintillation light and charge is liberated
- S1 signal reaches photomultipliers
- Electrons drift to the surface
- The extraction field pulls the electrons to the gas phase where they make more scintillation light



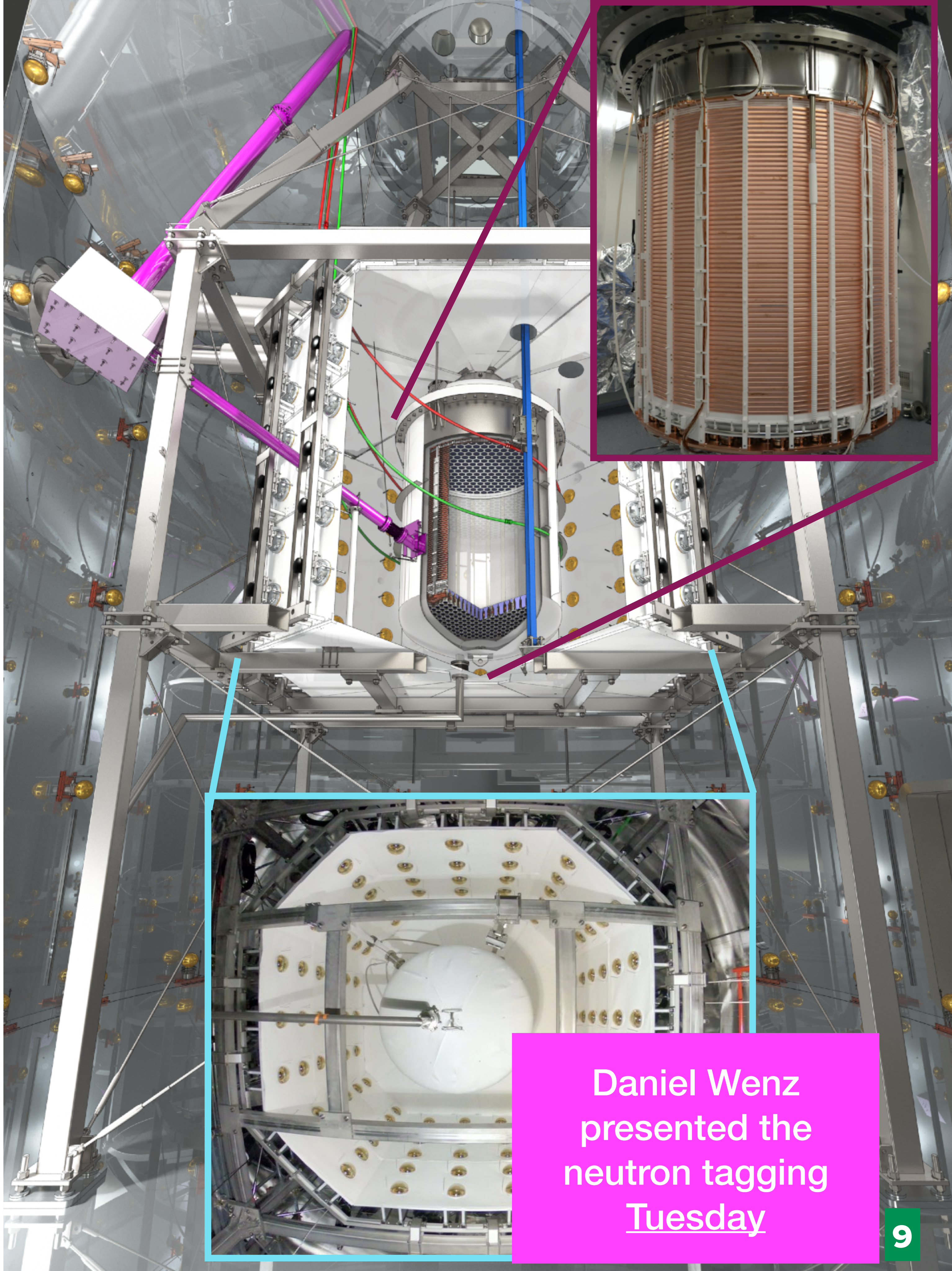
UPGRADES TO THE DETECTORS

The new TPC:

- increases the drift length to 1.5 m (from 1m)
- contains a 5.9 t active mass (from 2 t)
- Doubles the number of PMTs to 494, and has a larger light detection efficiency (34->36%)
- Field shaping ring, tuneable potential for the top one

A 4m x 3m neutron veto is now enclosing the TPC, with 120 PMTs placed inside an enclosure of reflective panels

- neutron tagging efficiency projected to 0.87 with (planned) Gd-doping, 0.68 with current pure water



Daniel Wenz presented the neutron tagging Tuesday

LIQUID XENON PURIFICATION

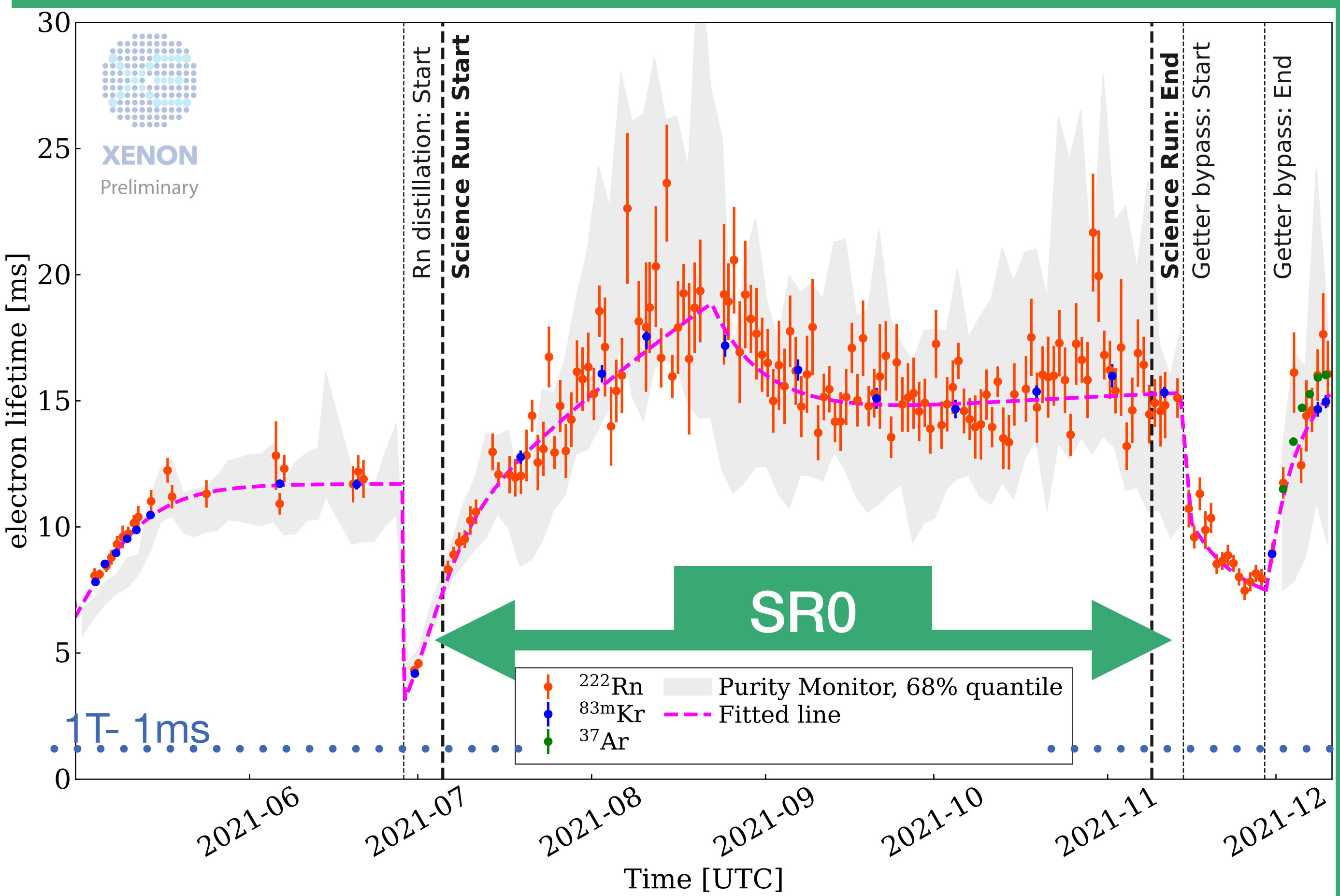
G. Plante E. Aprile, J. Howlett, Y. Zhang

e-Print: 2205.07336 [physics.ins-det]

XENON

- The 1.5 times longer drift length demands improvements in removing electronegative impurities that dampen the S2 signal
- XENONnT uses a new liquid purification technique with replaceable filter units with extremely low radon emanation (in the science run mode).
- High flow of 2 liters liquid xenon / minute— 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	86 % @ 15 ms

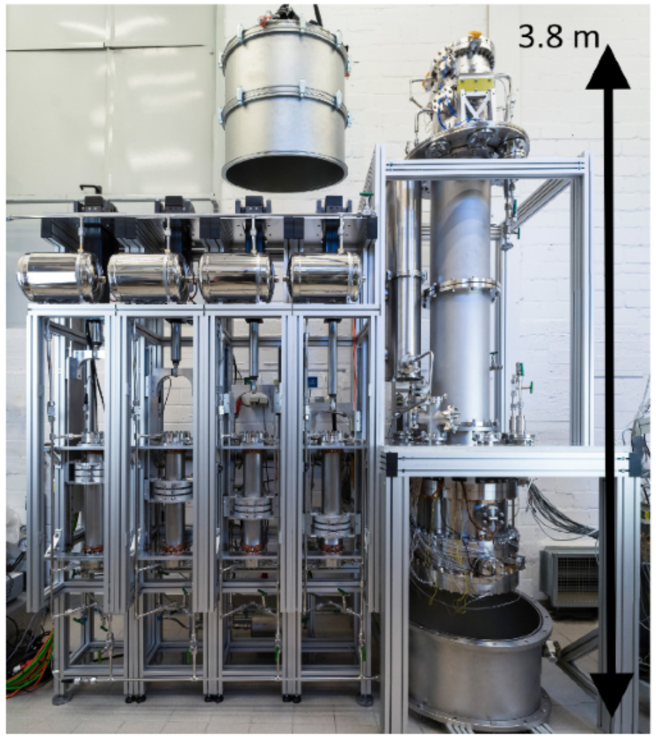


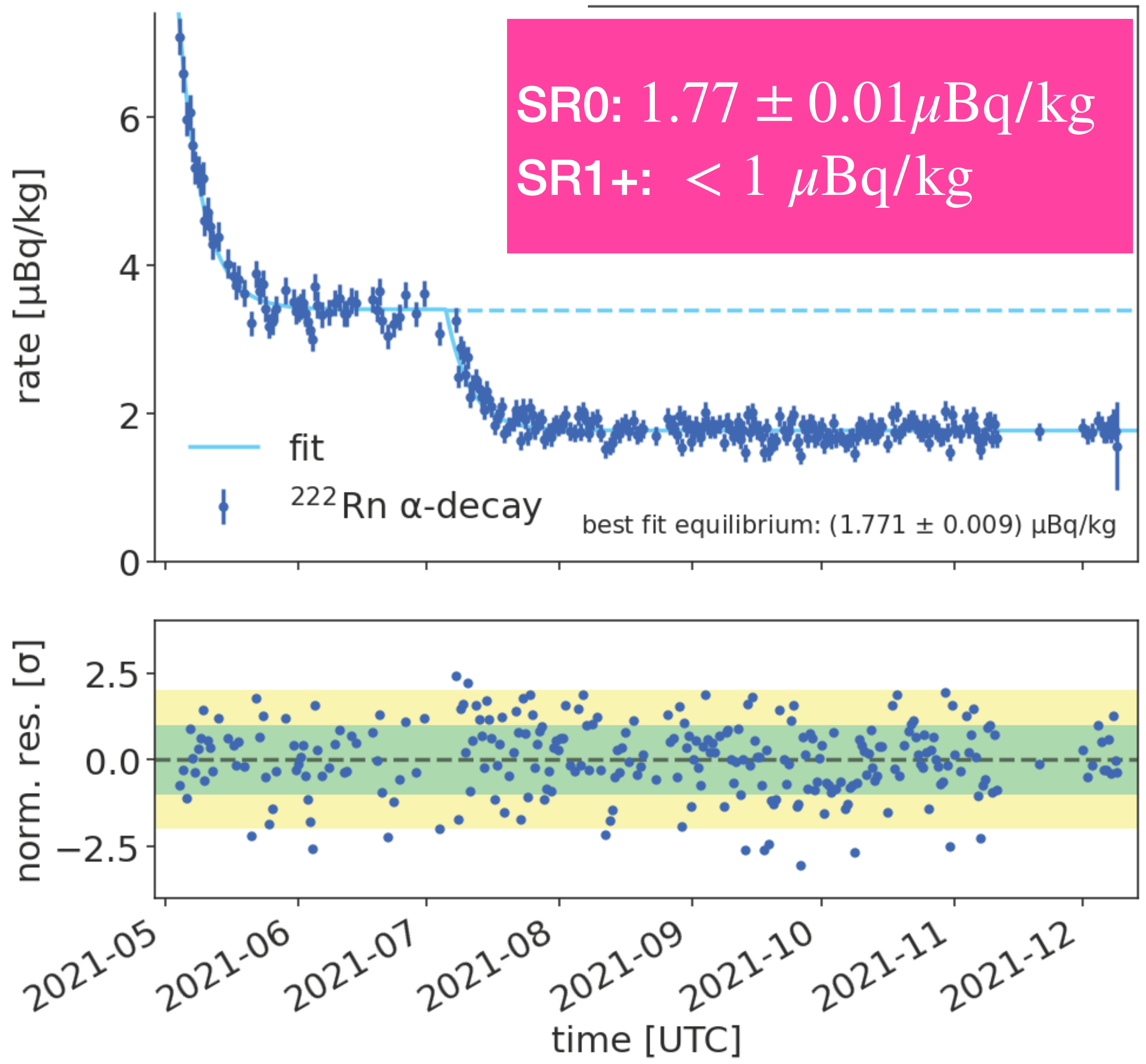
RADON DISTILLATION

- $^{222}\mathrm{Rn}$ is the primary source of background events in both XENON1T and XENONnT.
- The newly developed Rn column can handle large xenon flows using radon-free compressors and heat exchangers
- For the first science run, the column operated in gas-only mode
- **currently we have been able to reach $< 1\ \mu\mathrm{Bq/kg}$ in science running mode**

M. Murra, D. Schulte, C. Huhmann, C. Weinheimer
e-print: arXiv:2205.11492 [physics.ins-det]

XENON



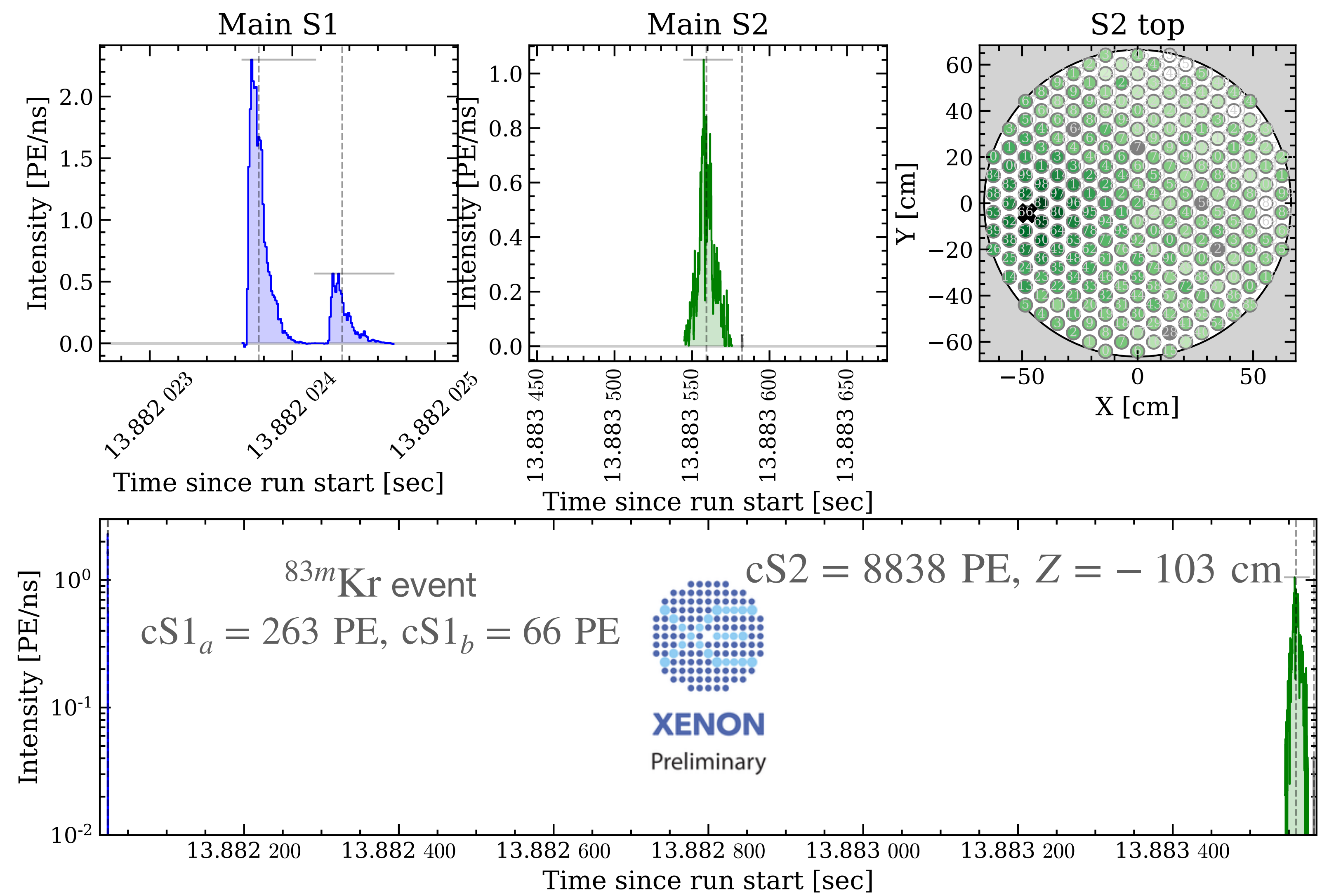


COMPUTING AND DAQ

- XENON data is acquired at 100 MHz in "triggerless" mode— individual channels are read out any time they cross the threshold
- The data is reconstructed and processed with the open-source Strax+Straxen framework
- 2+ orders of magnitude faster than its XENON1T predecessors

The XENON1T Data Acquisition System
JINST 14 (2019) 07, P07016

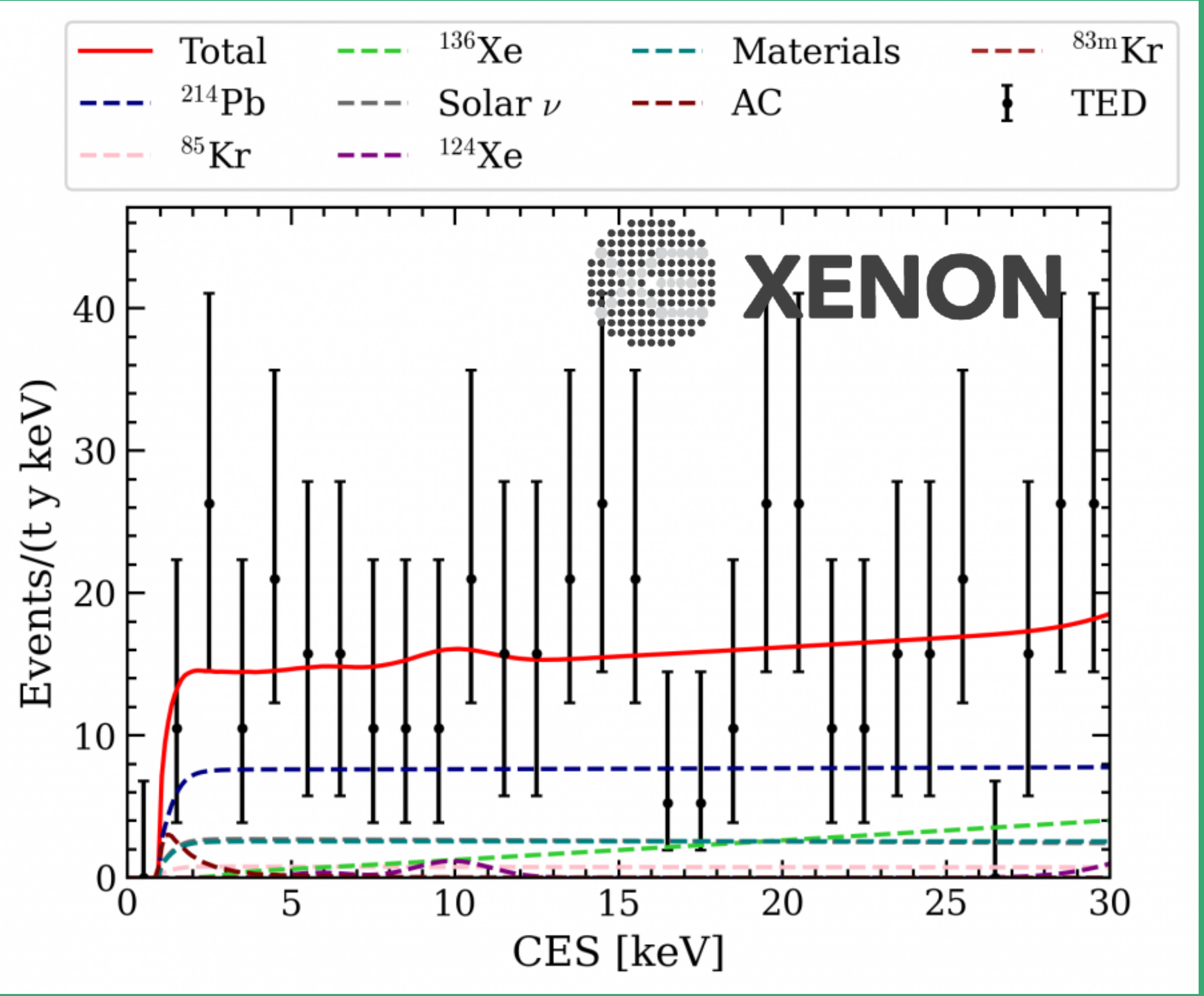
Example Waveform Display:



Check out Straxen at github.com/XENONnT/straxen

CONTROLLING ^3H

- XENONnT went through significant efforts to reduce possible sources of a low-energy excess
- Two months of outgassing, and purification of gaseous xenon with Zr getters and 3 weeks of gaseous xenon cleaning reduces possible hydrogen contamination
- Bypassing getters in the purification loop would increase the equilibrium hydrogen concentration in the detector
- large uncertainty but a best-estimate of several orders of magnitude, and a very conservative estimate of x10
- 14.3 days was taken after the main science run to give an extra handle on a possible excess



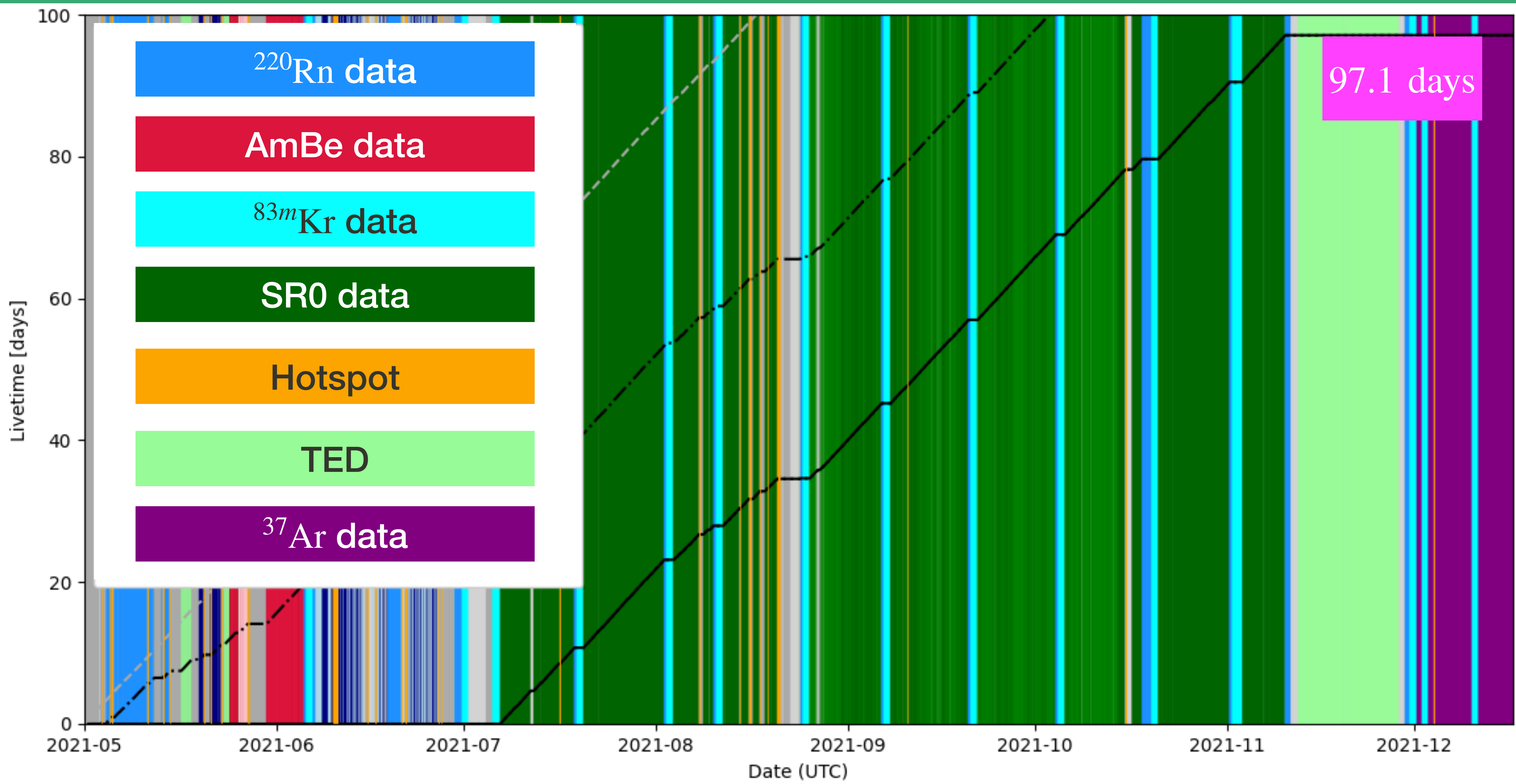
Tritium-enhanced data (TED) sideband data used to look for ^3H bypassing getters

No ^3H excess

FIRST SCIENCE RUN– XENONnT SR0

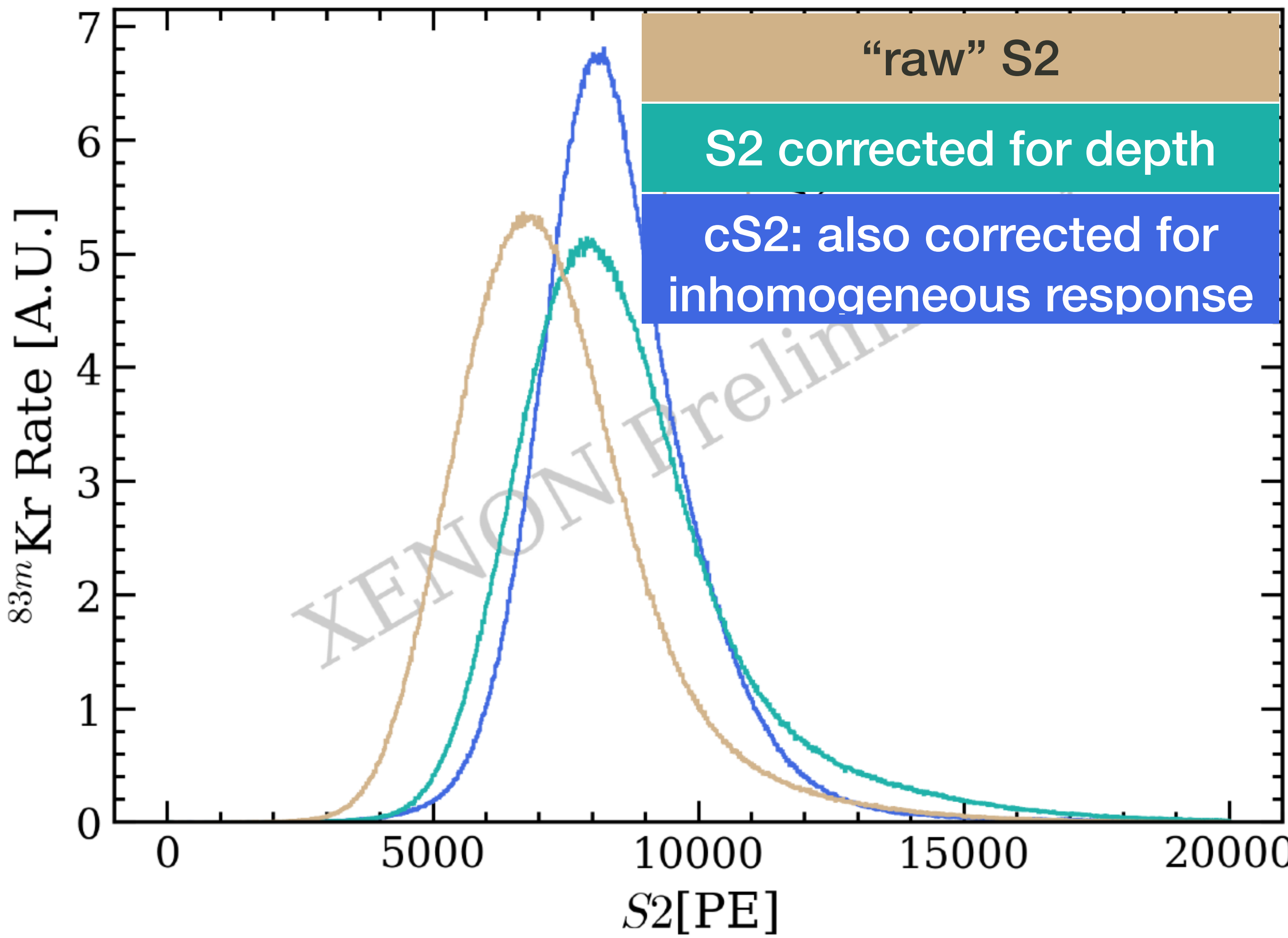
XENON

- 97.1 days exposure from July 6th-Nov 11th 2021
- Rn column in gas-only mode
- All but 17 PMTs working, gain stable at 3%
- 23 V/cm drift field, Extraction Field in LXe 2.9 kV/cm
- Localised high single-electron emission occurring seemingly at random, anode ramped down



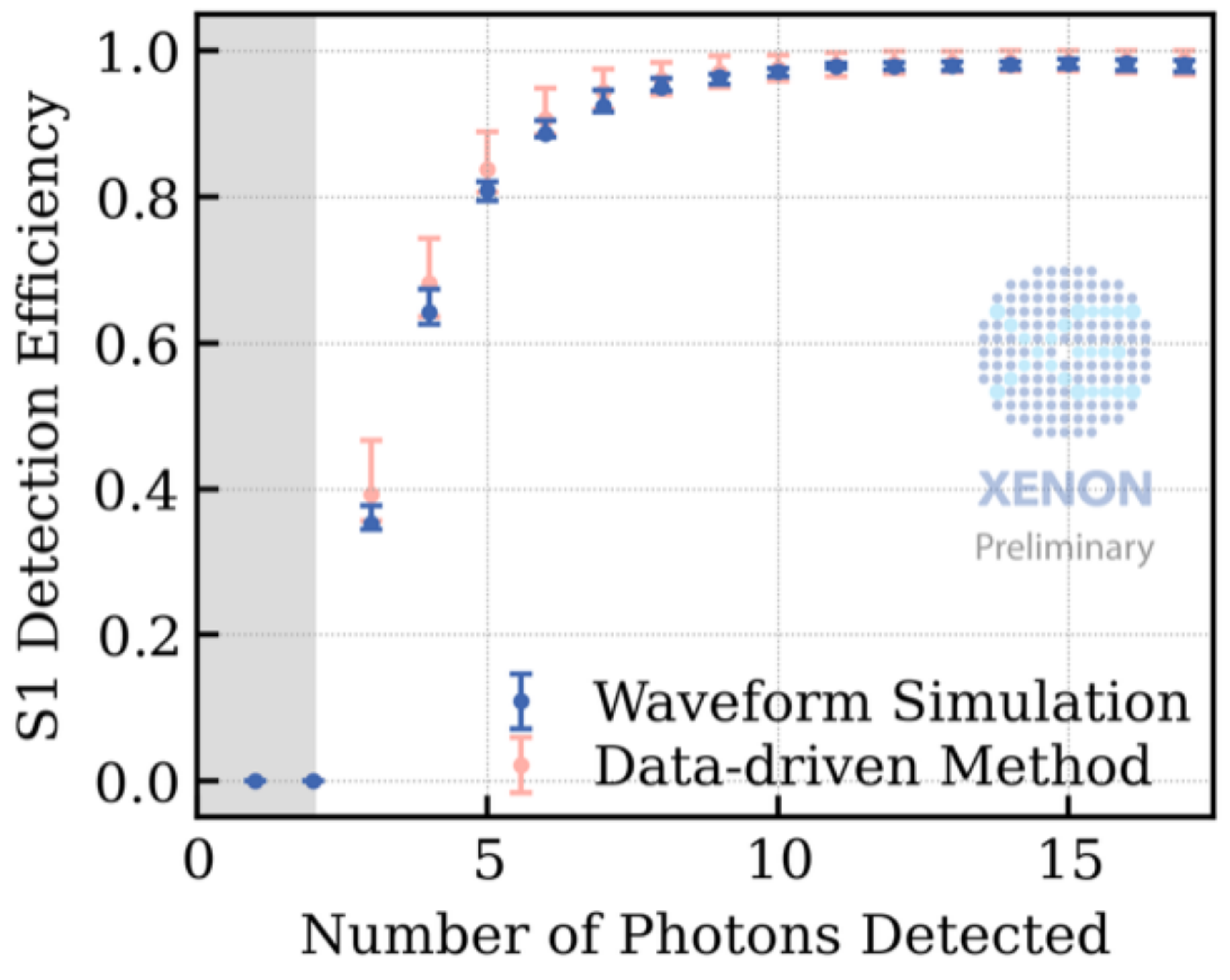
CALIBRATION AND ANALYSIS

- The SR0 analysis effort covers
  - Peak and event reconstruction,
  - “corrections”—compensating for detector responses to give good estimators
  - Data quality validation, cuts against backgrounds
  - Backgrounds models
  - Detector response modelling
  - Inference



RECONSTRUCTION EFFICIENCY

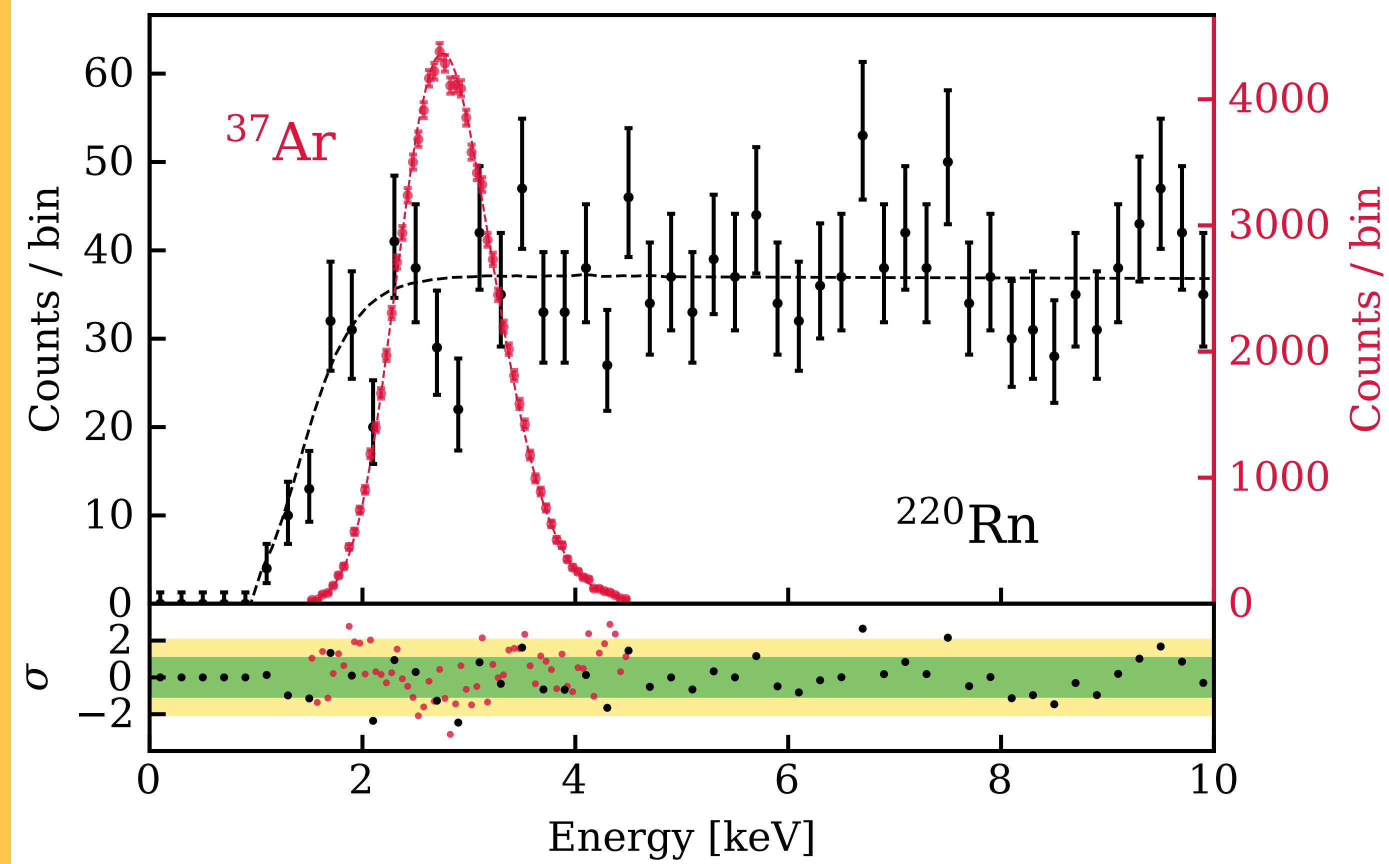
- At threshold, S1s may consist of only a handful of photons, while we require 3 coincident hits.
- Estimated with detailed "waveform simulation" and a data-driven approach drawing subsamples of photon hits to make up a pulse
- In both cases, given to the reconstruction chain to characterise efficiency: probability to reconstruct a peak
- Waveform simulation used for this analysis, data-driven for validation— include an uncertainty band that covers the difference between these methods.

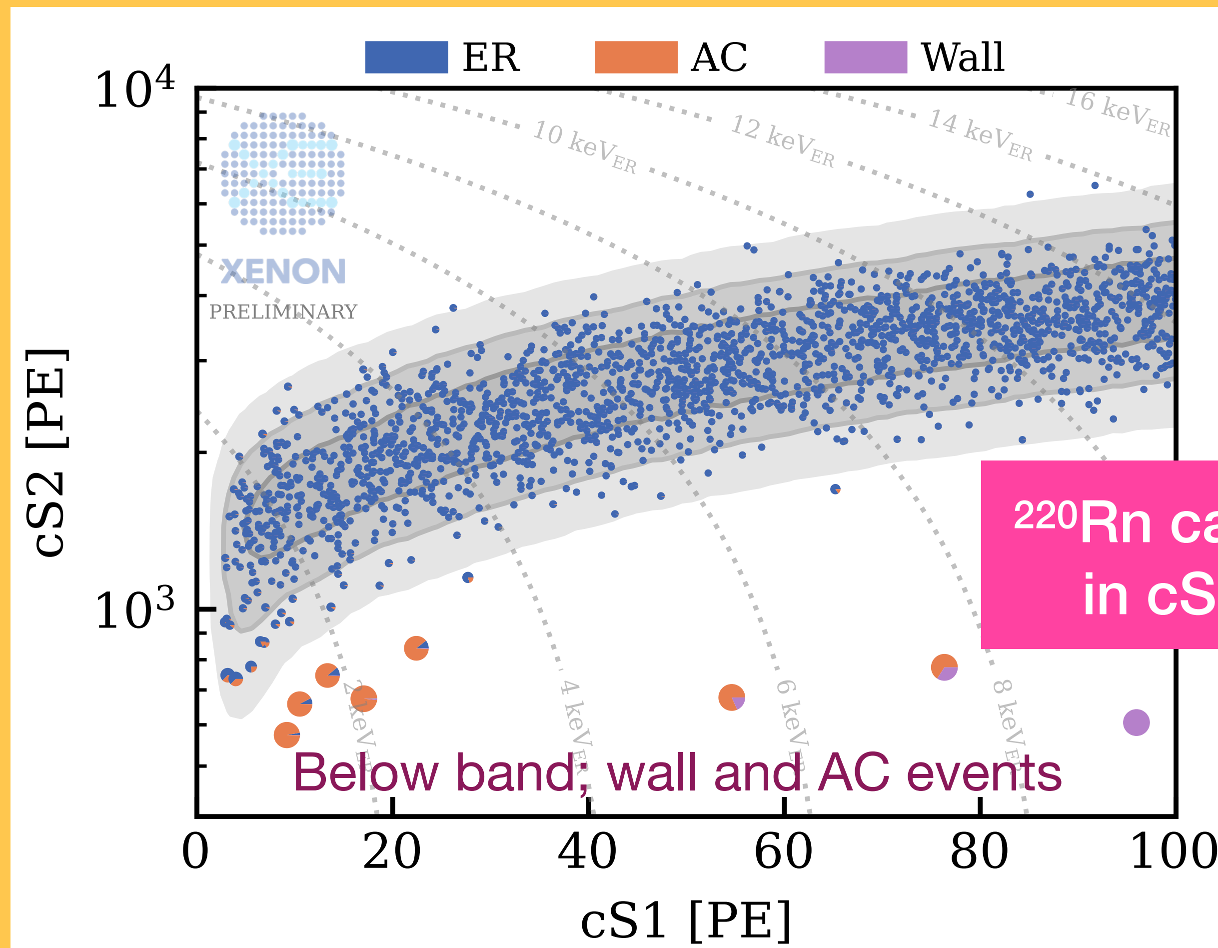


CALIBRATION SOURCES

- At low energy, we have two ER calibration sources:
  - $^{37}\mathrm{Ar}$, which gives mono-energetic $2.82\ \mathrm{keV}$ peak used to anchor the low-energy response and resolution models with high statistics
  - $^{212}\mathrm{Pb}$ from $^{220}\mathrm{Rn}$ gives a roughly flat β-spectrum to estimate cut acceptances and also validates our threshold.
    - Also used to define our blinding region

Rn and Ar calibration in reconstructed energy



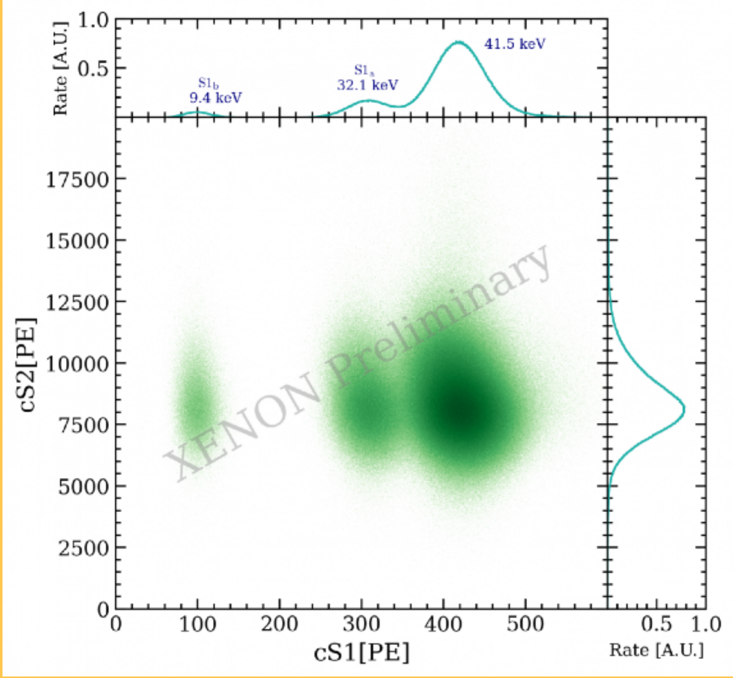


^{220}Rn calibration in cS1, cS2

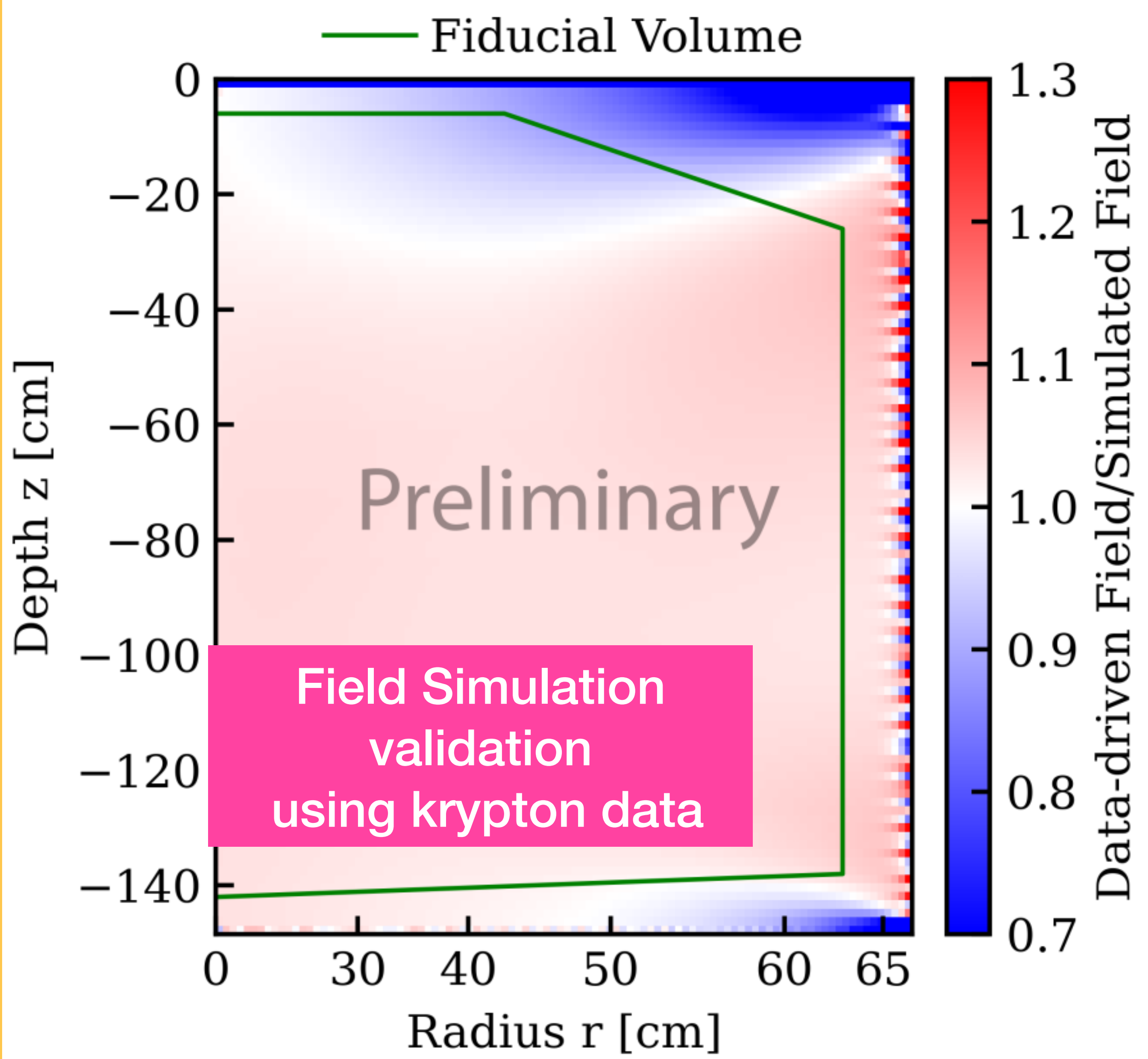
CALIBRATION AND ELECTRIC FIELD SIMULATION VALIDATION

- ^{83m}Kr is injected every 14 days
- Decays slowly enough ($T_{1/2} = 1.83$ h) to distribute uniformly in the detector, used to compute:
  - the S1 light collection efficiency as function of position
  - The S2 light collection efficiency as function of horizontal position
  - The position reconstruction distortion induced by our field
- Validated COMSOL field simulation using observed ^{83m}Kr signal ratio $S(32.1\ \mathrm{keV})/S(9.4\ \mathrm{keV})$

XENON



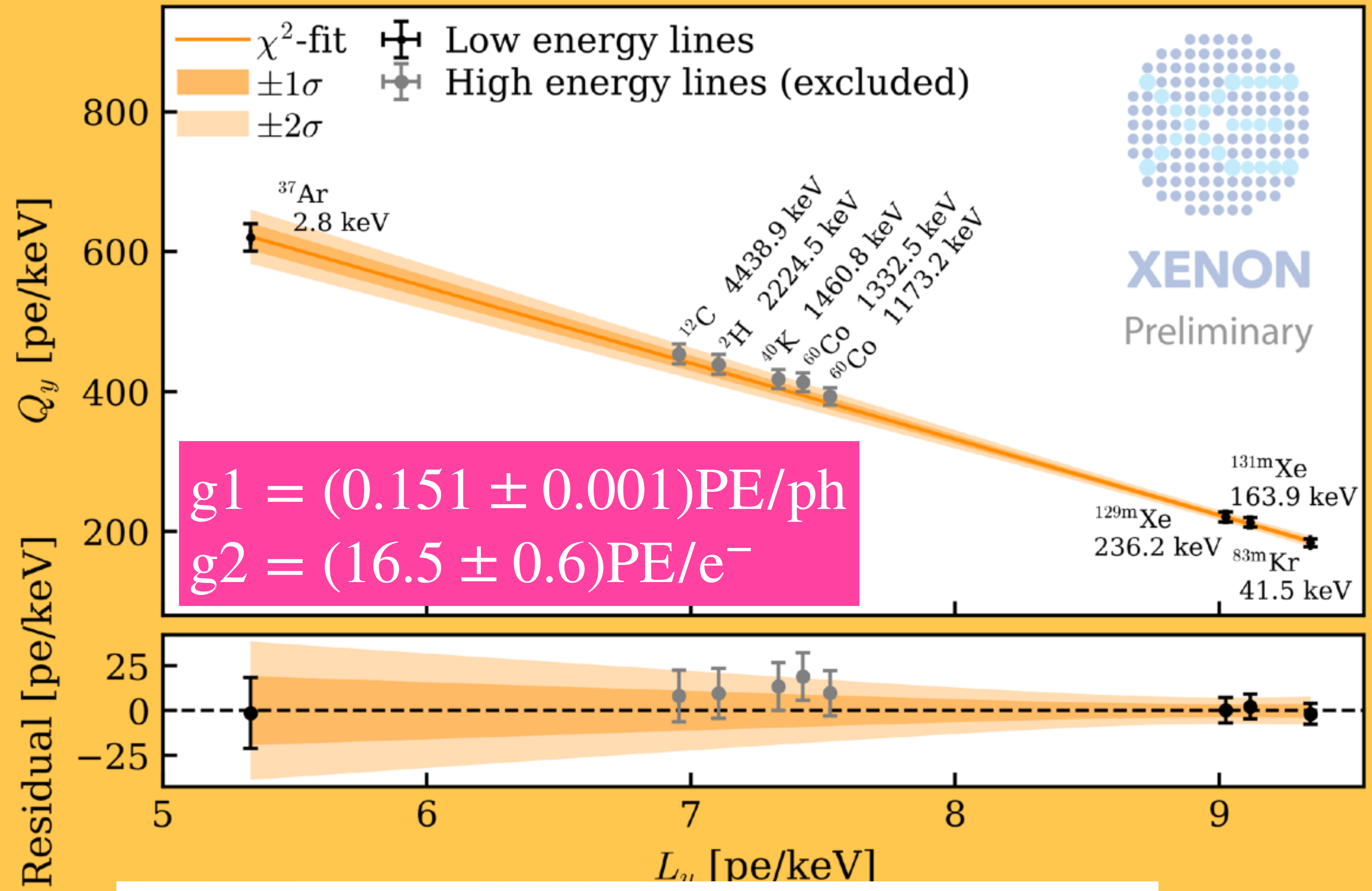
LUX describing the field method: Phys. Rev. D 96, 112009 (2017)

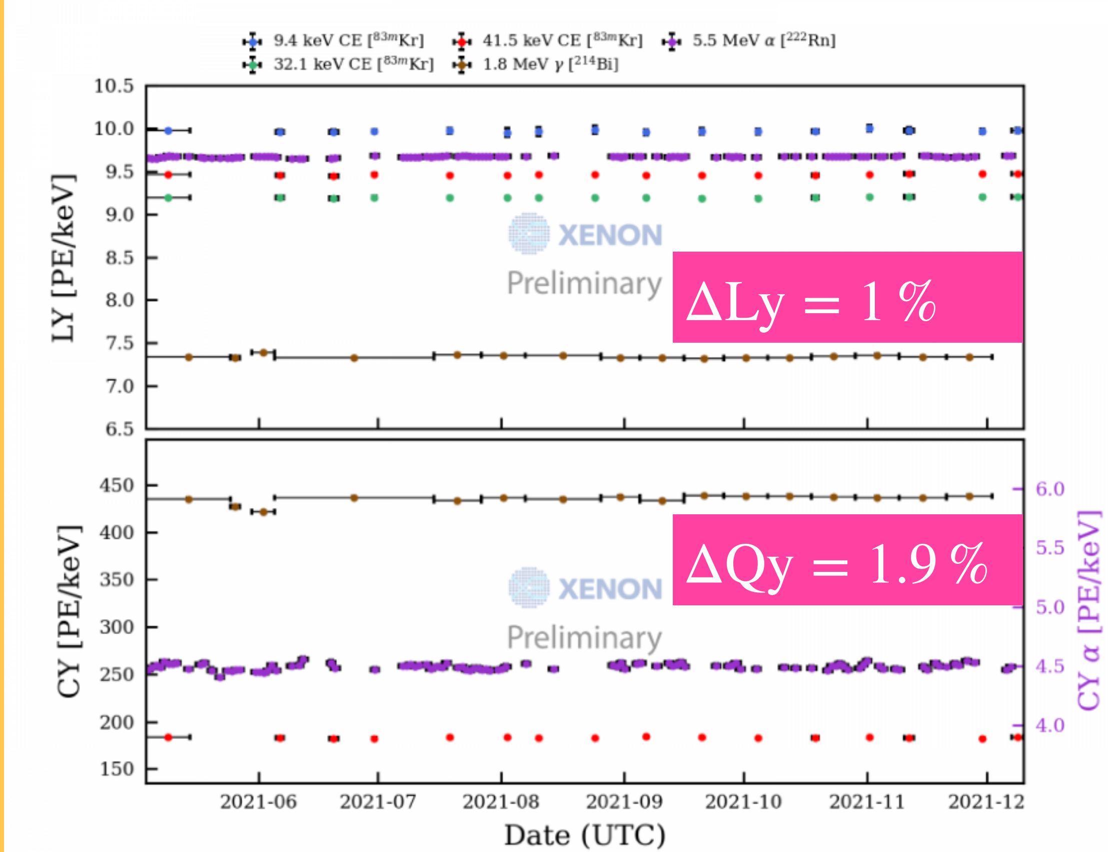


ENERGY SCALE CALIBRATION, YIELD STABILITY

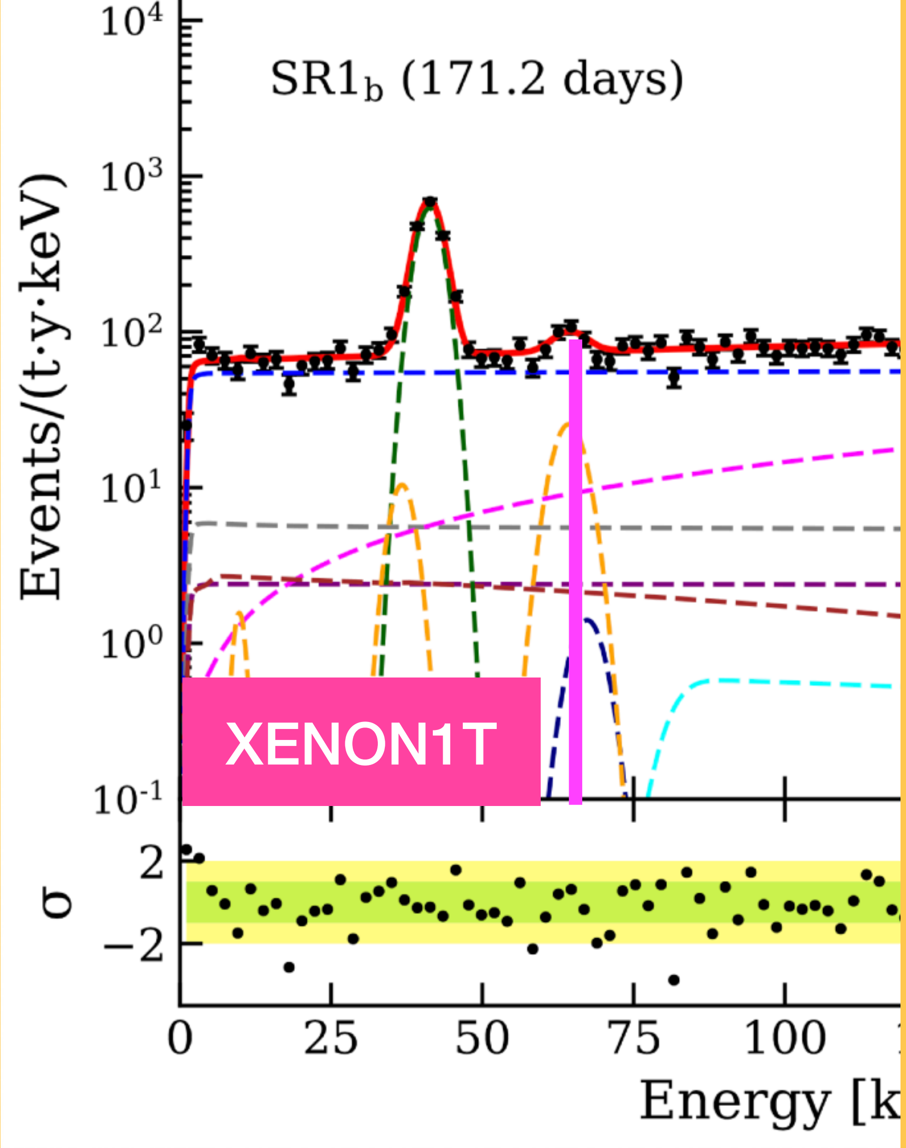
- For ER sources, the entire deposited energy goes to observable light and charge quanta:
  $E = 13.7\text{eV} \times (\text{cS1/g1} + \text{cS2/g2})$
- Mono-energetic peaks with energies relevant to our ER search ($1 - 140$ keV).
  - ^{37}Ar
  - ^{83m}Kr
  - ^{129m}Xe
  - ^{131m}Xe
- The observed bias in energies from our reconstruction, between 1-2% is included in the modelling.
- We monitor the stability of the light and charge yield over SR0 using the calibration sources, ^{222}Rn αs and material γs

See Henning Schulze Eißings poster (216)!



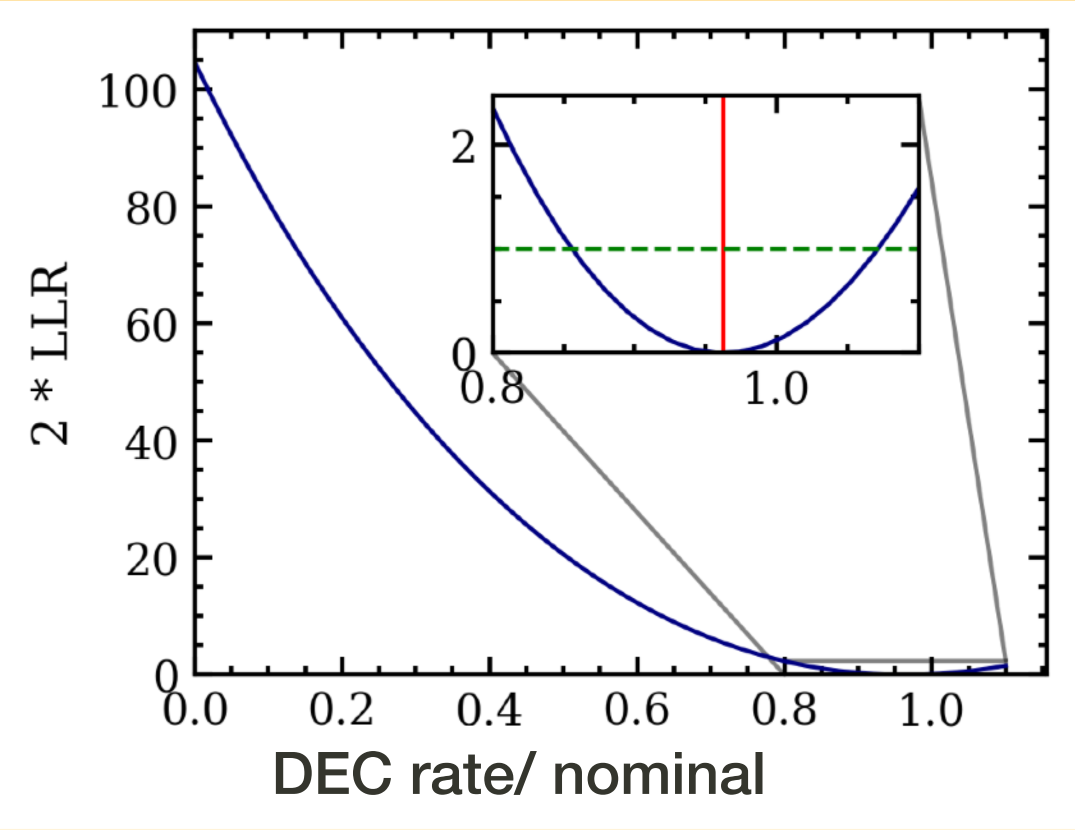


RARE SIGNAL BECOMES A VALIDATION TOOL



- XENON1T first observed the double-electron capture signature from ^{124}Xe— longest half-life directly detected
- In XENONnT, appears as a very clear peak over the lower background, with a rate compatible with previous measurements, left free in background.
- DEC used to cross-check g1/ g2 fit

$$T_{1/2}^{2\nu\mathrm{ECEC}} = (1.15 \pm 0.13_{\mathrm{stat}} \pm 0.14_{\mathrm{sys}}) \times 10^{22}\mathrm{yr}$$



XENON1T observation of Double-Weak Decays of ^{124}Xe and ^{136}Xe, arXiv:2205.04158

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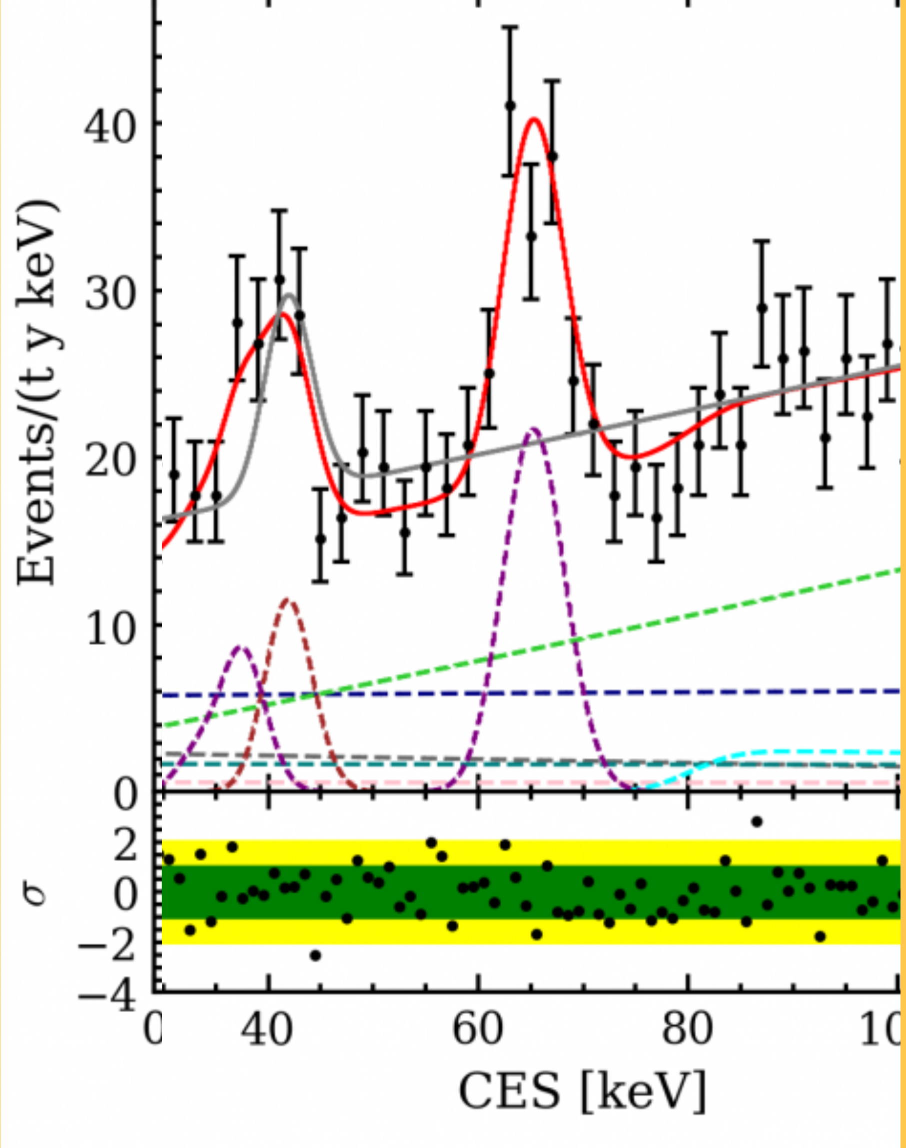
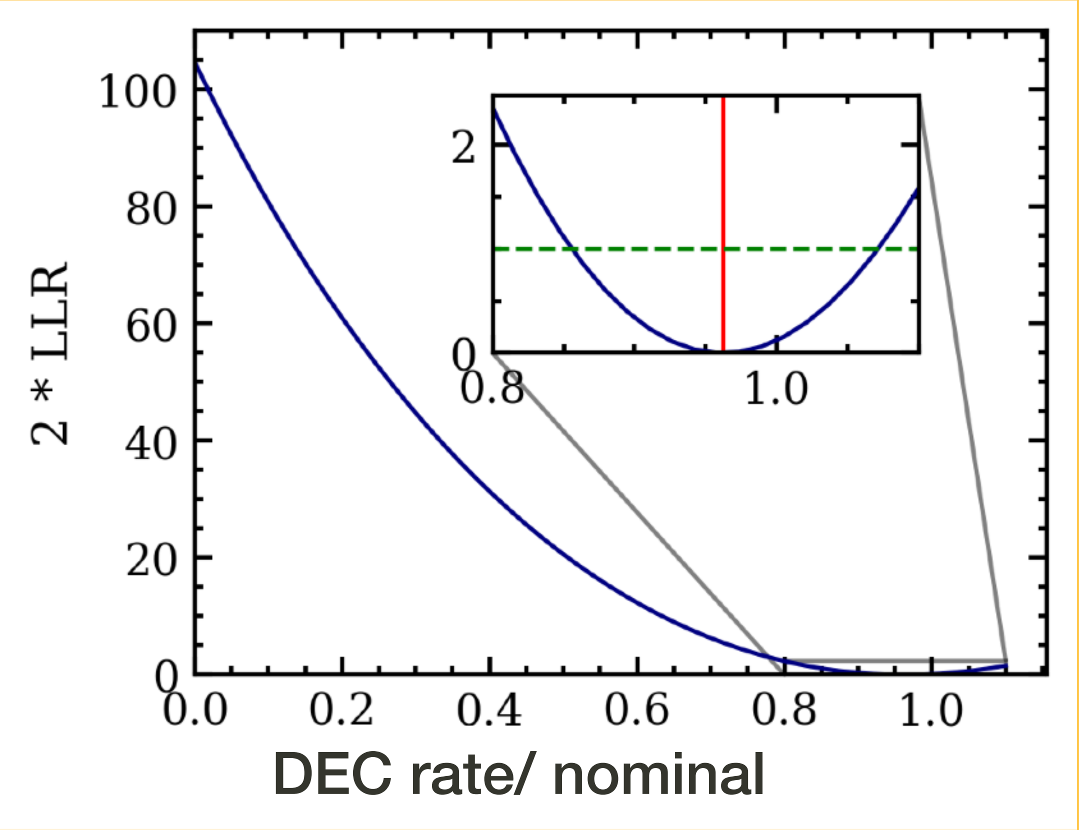
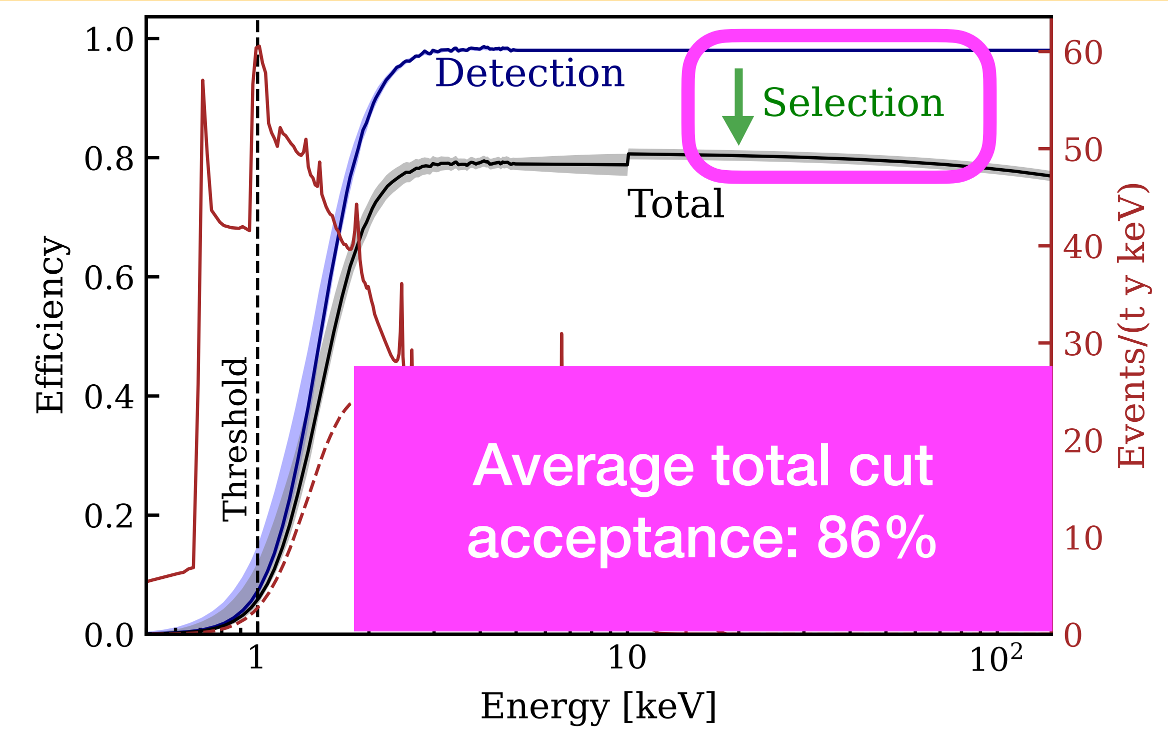


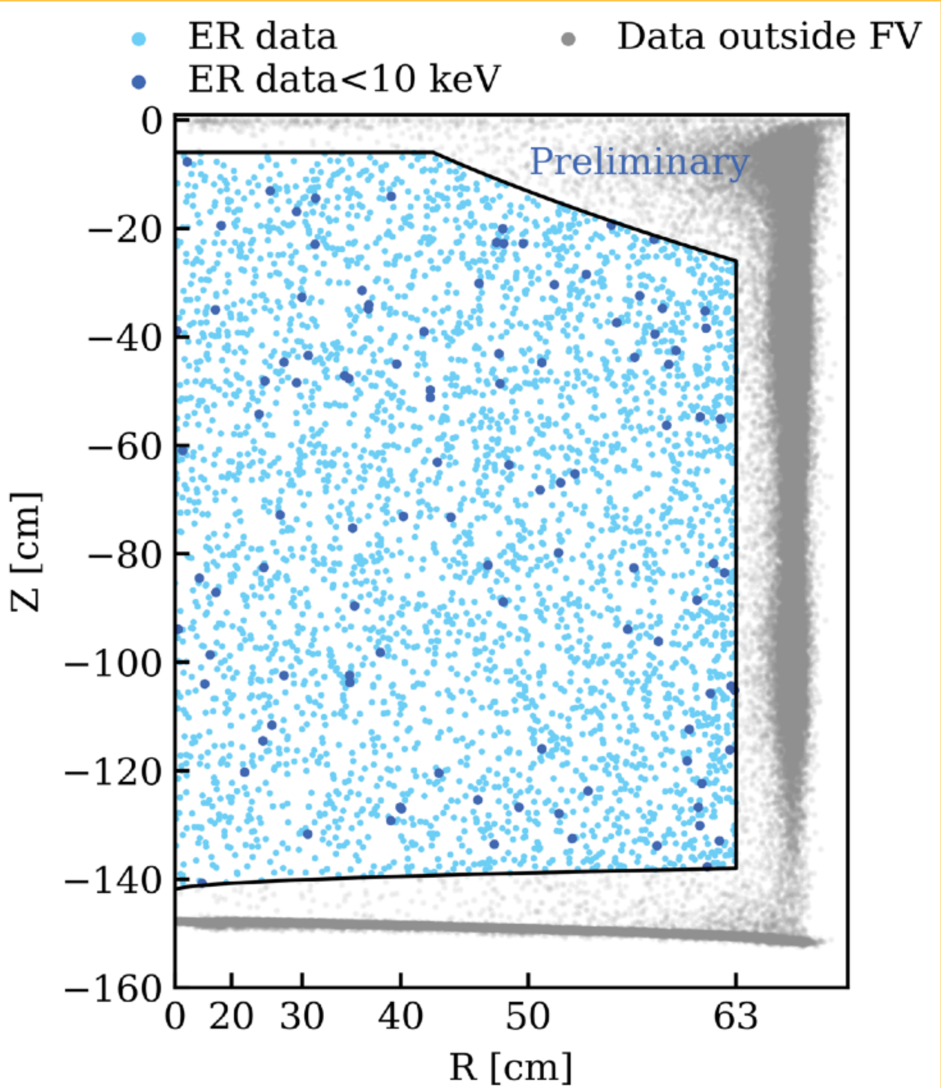


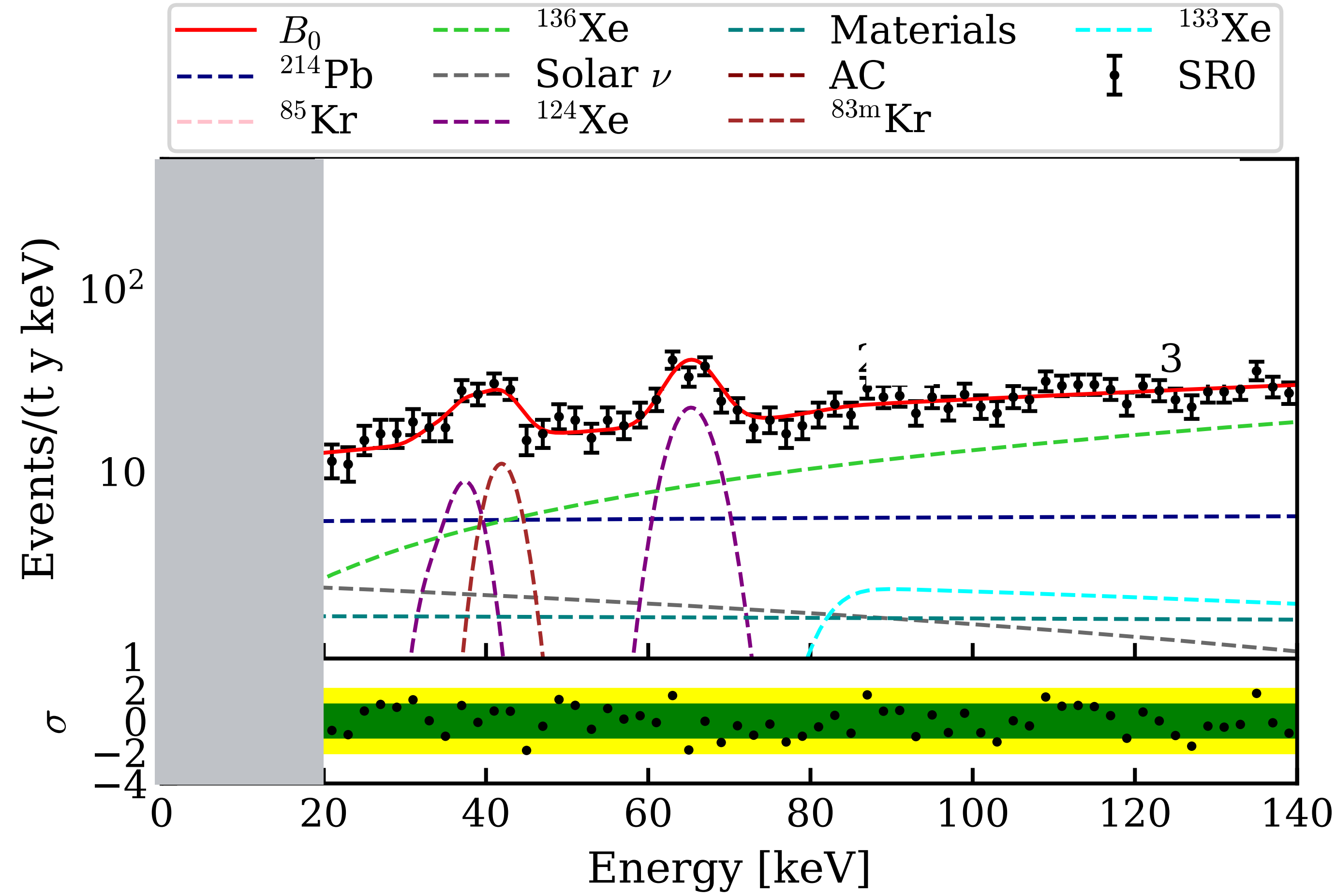
DATA QUALITY CUTS

- Events are required to pass a range of quality cuts:
  - The S1 and S2 peak should each have patterns, top/bottom ratios etc. consistent with real events
  - An S2 width consistent with the expected diffusion
  - An S2 over 500 PE
  - Not within $< 300\ ns$ 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

XENON







XENON

BACKGROUNDS

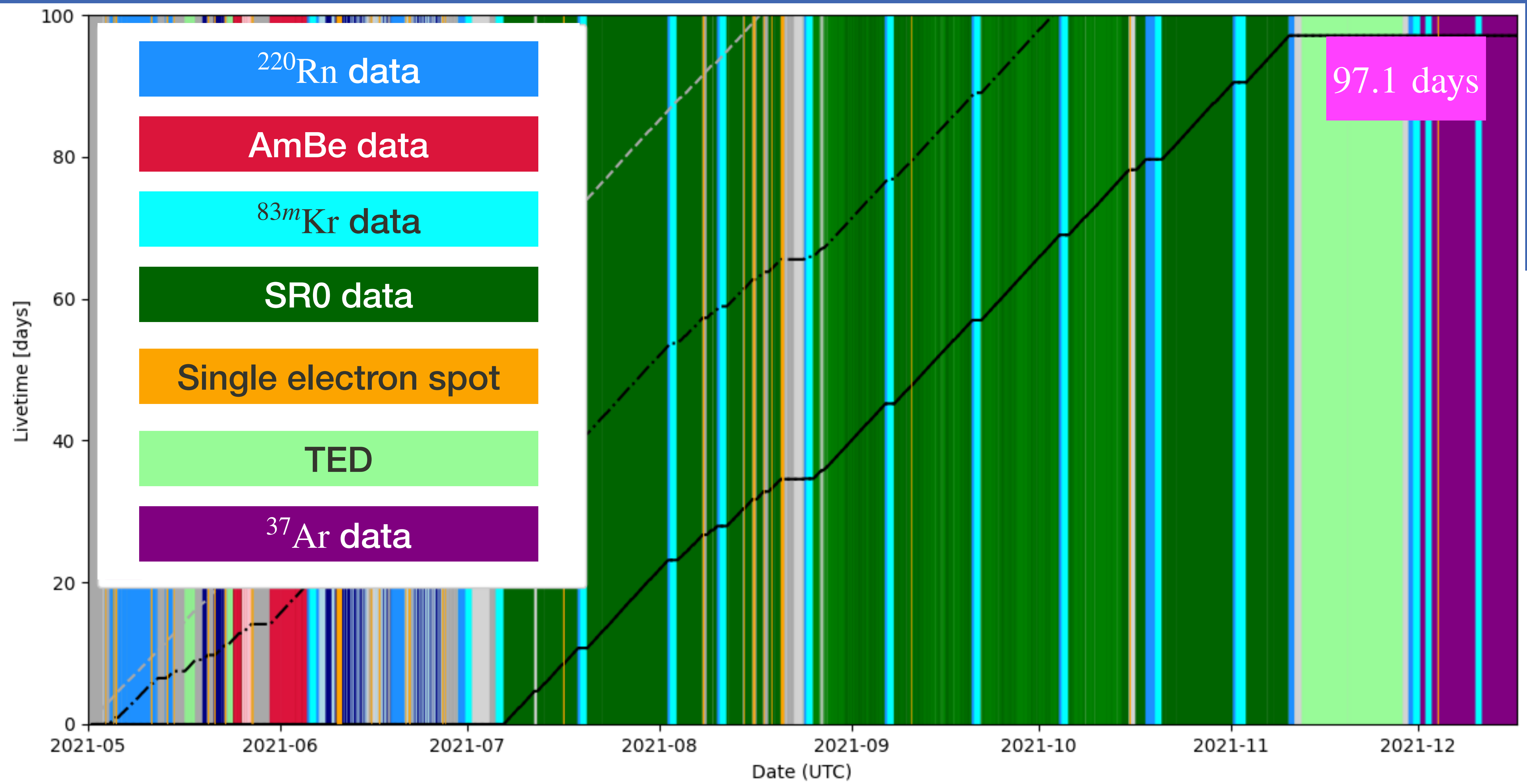
	Number of events in ER band	Expected < 10 keV
^{214}Pb	980 ± 120	56 ± 7
^{85}Kr	91 ± 58	5.8 ± 3.7
Materials	267 ± 51	16.2 ± 3.1
^{136}Xe	1523 ± 54	8.7 ± 0.3
Solar neutrino	298 ± 29	24.5 ± 2.4
^{124}Xe	256 ± 28	2.6 ± 0.3
Accidental coincidence	0.71 ± 0.03	0.71 ± 0.03
^{133}Xe	163 ± 63	0
^{83m}Kr	80 ± 16	0

- **The low-energy ER spectrum is dominated by ^{214}Pb at the very lowest energy, plus contributions for materials, ^{136}Xe and solar neutrinos.**
- **External constraints are included for**
  - **^{85}Kr, 2×10^{-11} of (56 ± 36) ppq using RGMS**
  - **material γs, (2.1 ± 0.4) events/(t × yr × keV) from GEANT4 and screening measurements**
  - **^{136}Xe from RGA and $T_{1/2}$ measurements, with a shape uncertainty**
  - **solar neutrinos have a 10% rate uncertainty given the Borexino measurements of the flux.**
  - **AC is constrained from its data-driven model**

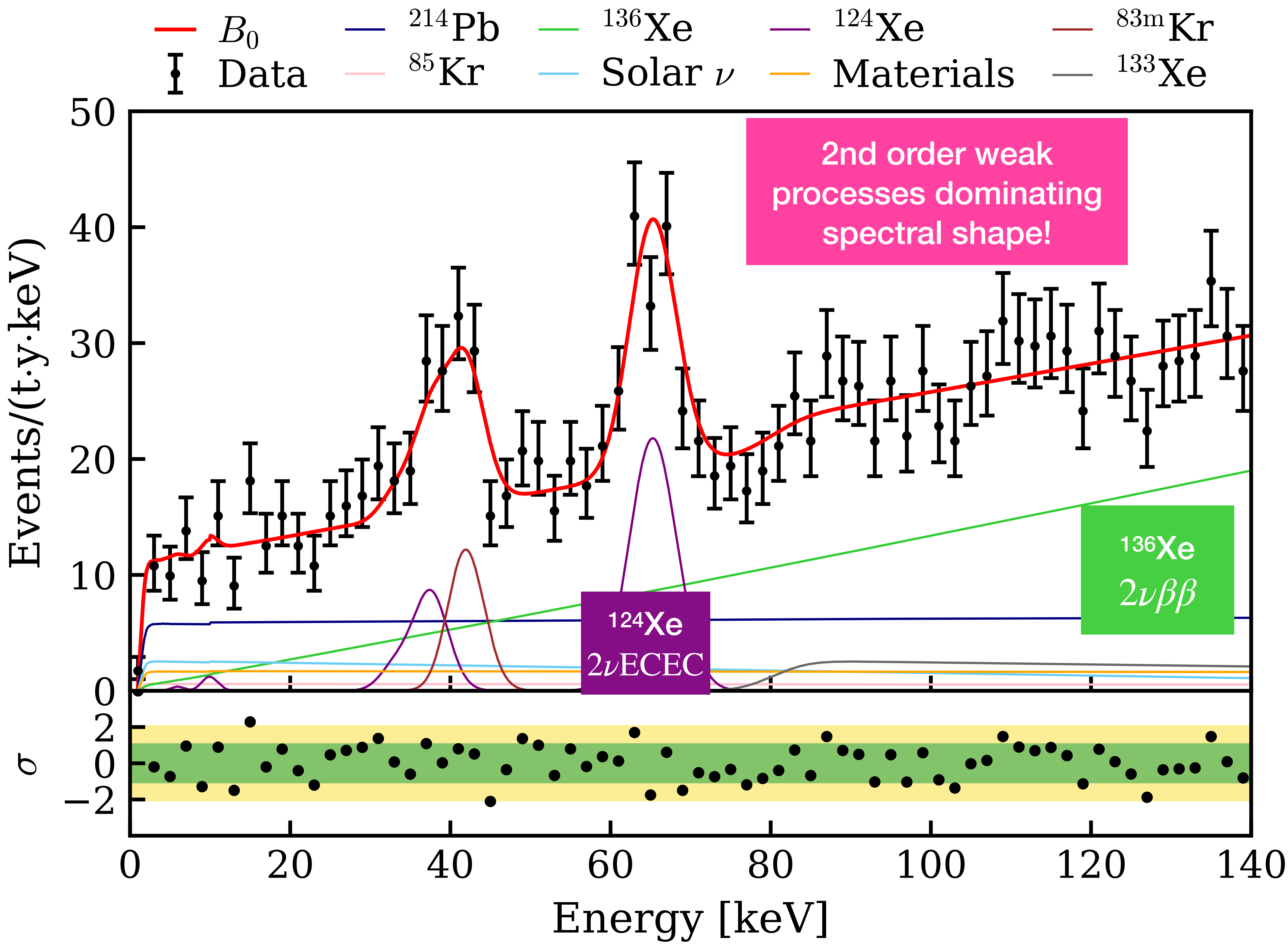
COLLECTED DATA

XENON

- 97.1 days exposure from July 6th-Nov 11th 2021
- Rn column in gas-only mode
- All but 17 PMTs working, gain stable at 3%
- 23 V/cm drift field, Extraction Field in LXe 2.9 kV/cm
- Localised high single-electron emission occurring seemingly at random, anode ramped down



THE XENONnT ELECTRONIC RECOIL SPECTRUM



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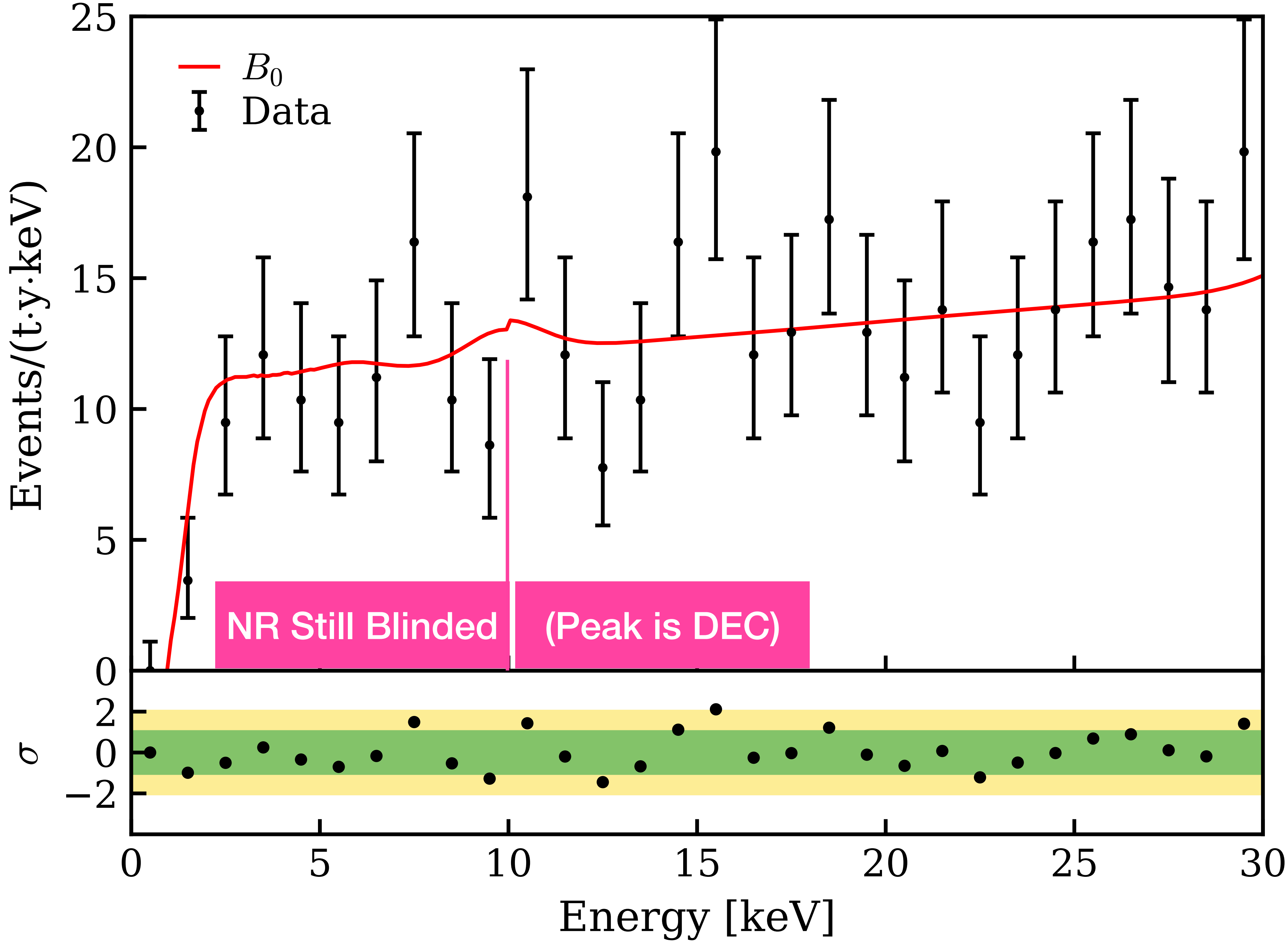
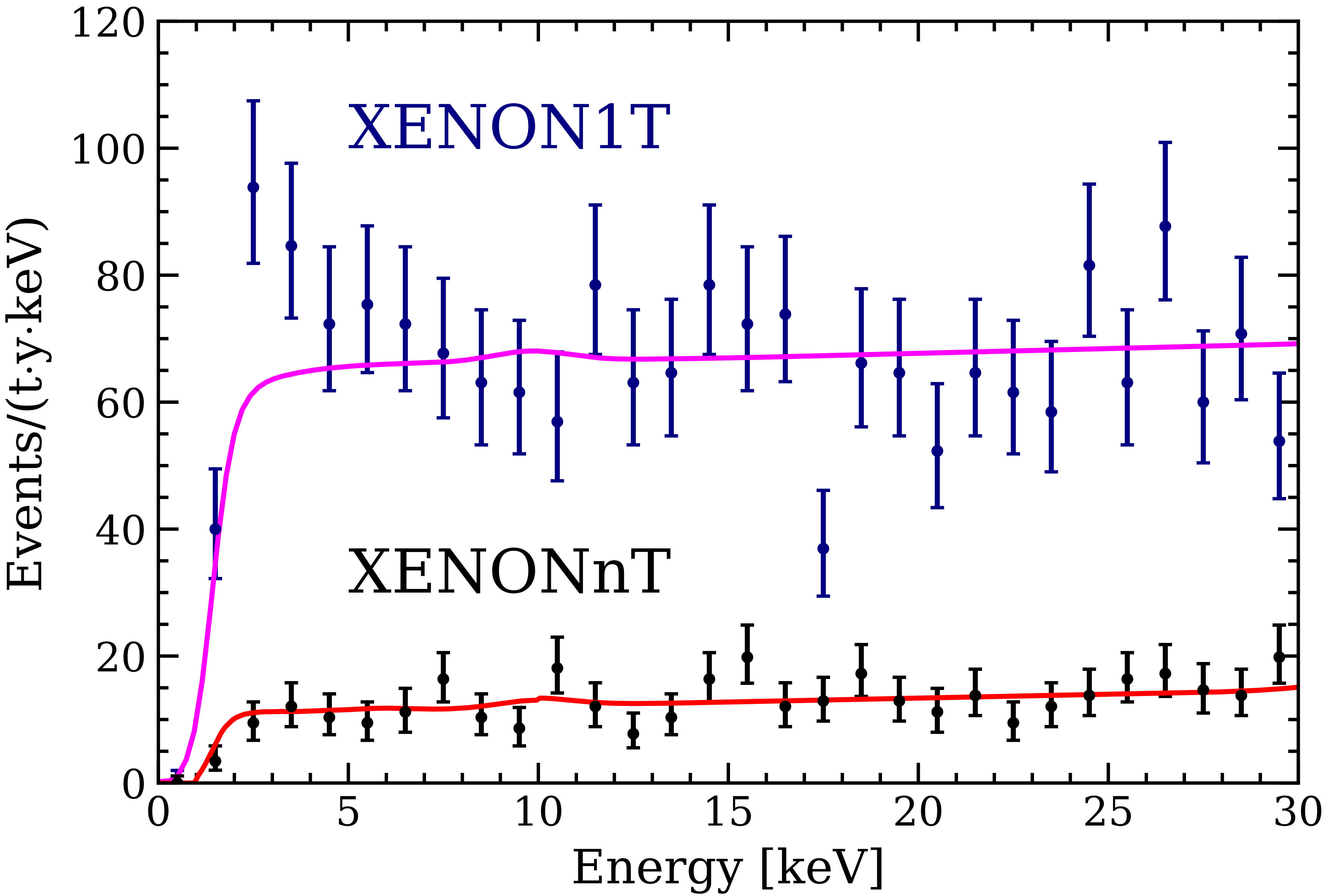
XENON



COMPARISON WITH THE 1T EXCESS



Key conclusions

XENON

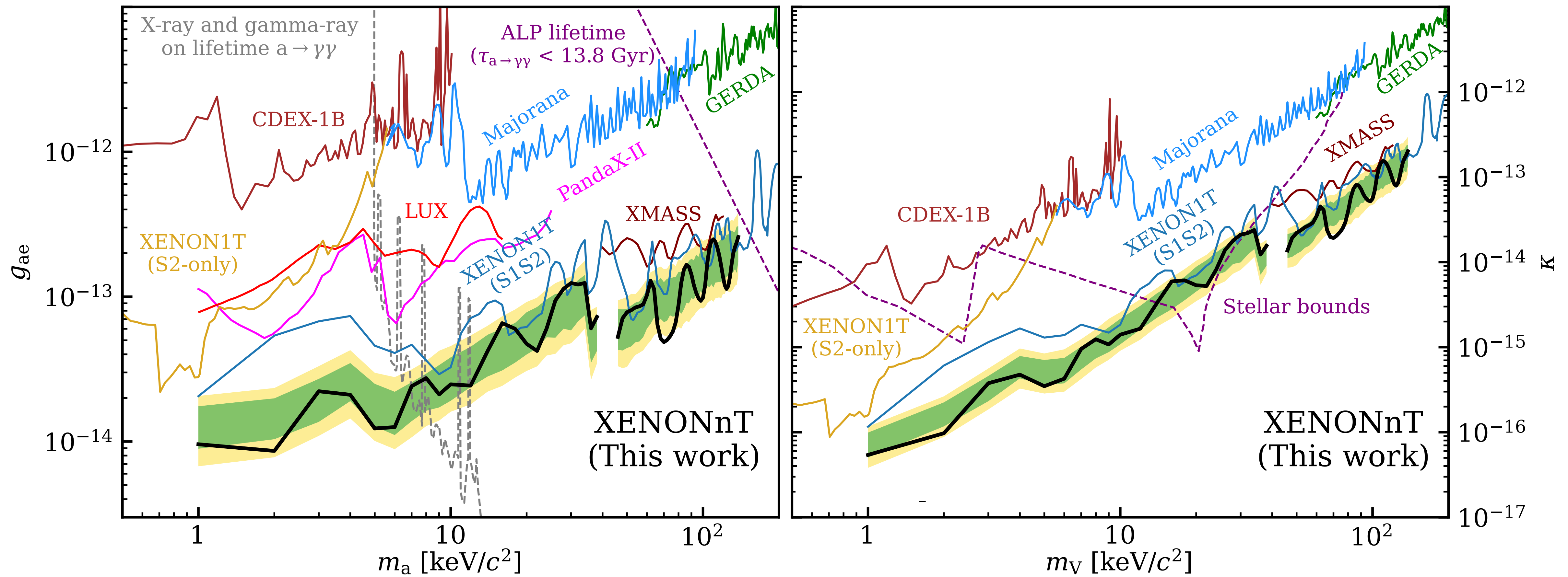
Exposure: $1.16\ \text{tonne} - \text{years}$	$\sim \times 2$ XENON1T ER search (0.65 tonne-years)
Background rate: $(16.1 \pm 0.3)\ \text{events}/(\text{t} \times \text{yr} \times \text{keV})$ in 1-30 keV range	$\sim \times 0.2$ XENON1T
Best-fit signal strength: 0	XENONnT rejects a XENON1T-size peak at 8.6σ
Exclusion of XENON1T excess $(2.3\ \text{keV})$ peak.	Measurements incompatible at ~4σ

Most likely explanation of XENON1T excess is a small ^{3}H contamination. XENONnT, taking steps to reduce tritium outgassing sees no excess

LIMITS ON ALPS AND DARK PHOTONS

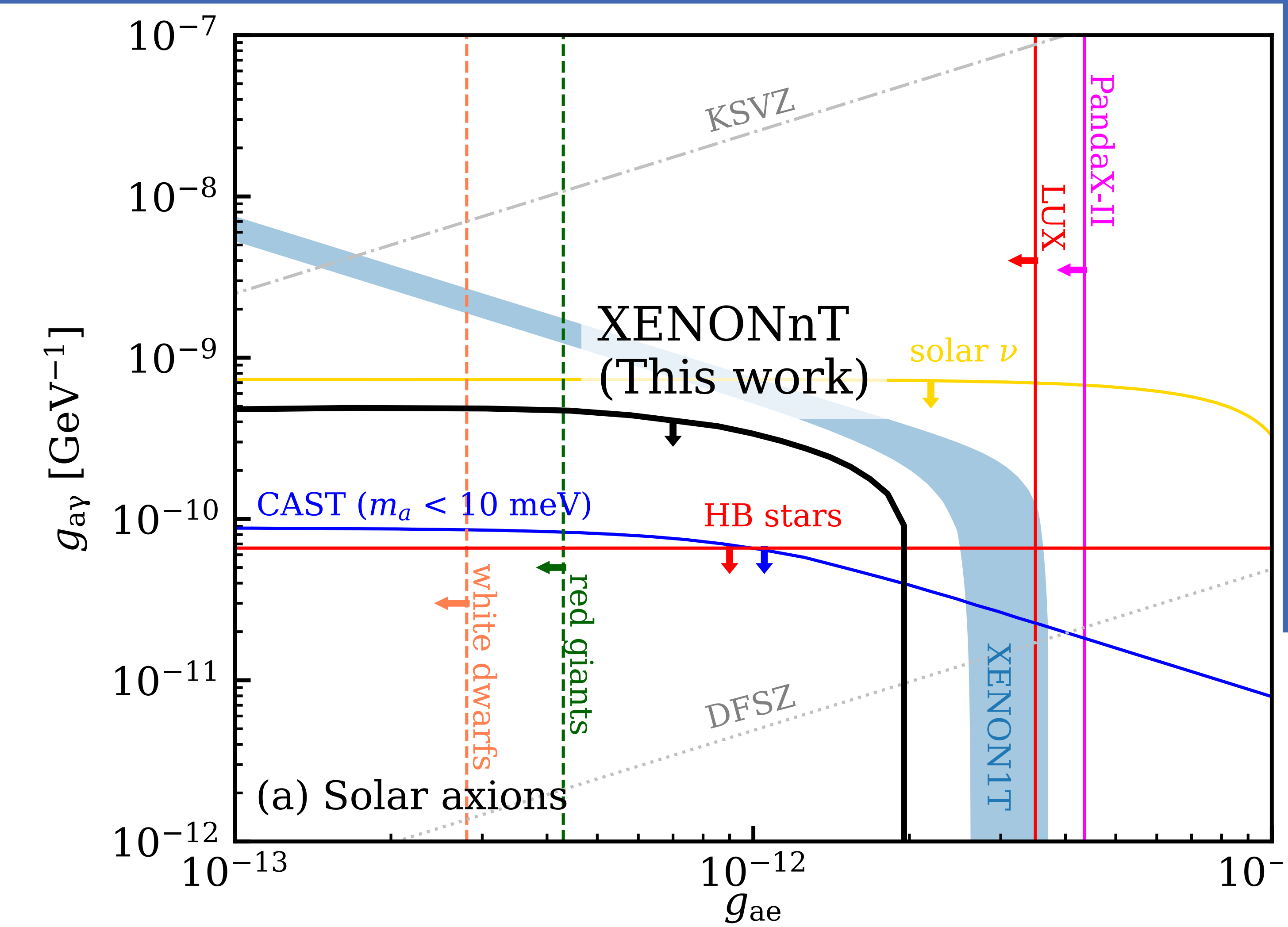
XENON

ALPs | Dark γ



- A search for a peak from axion-like particles or dark photons sees no significant excess, but places new stringent limits between 1-140 keV
- Since the ^{83m}Kr rate is left unconstrained, we do not place limits at 41.5 keV

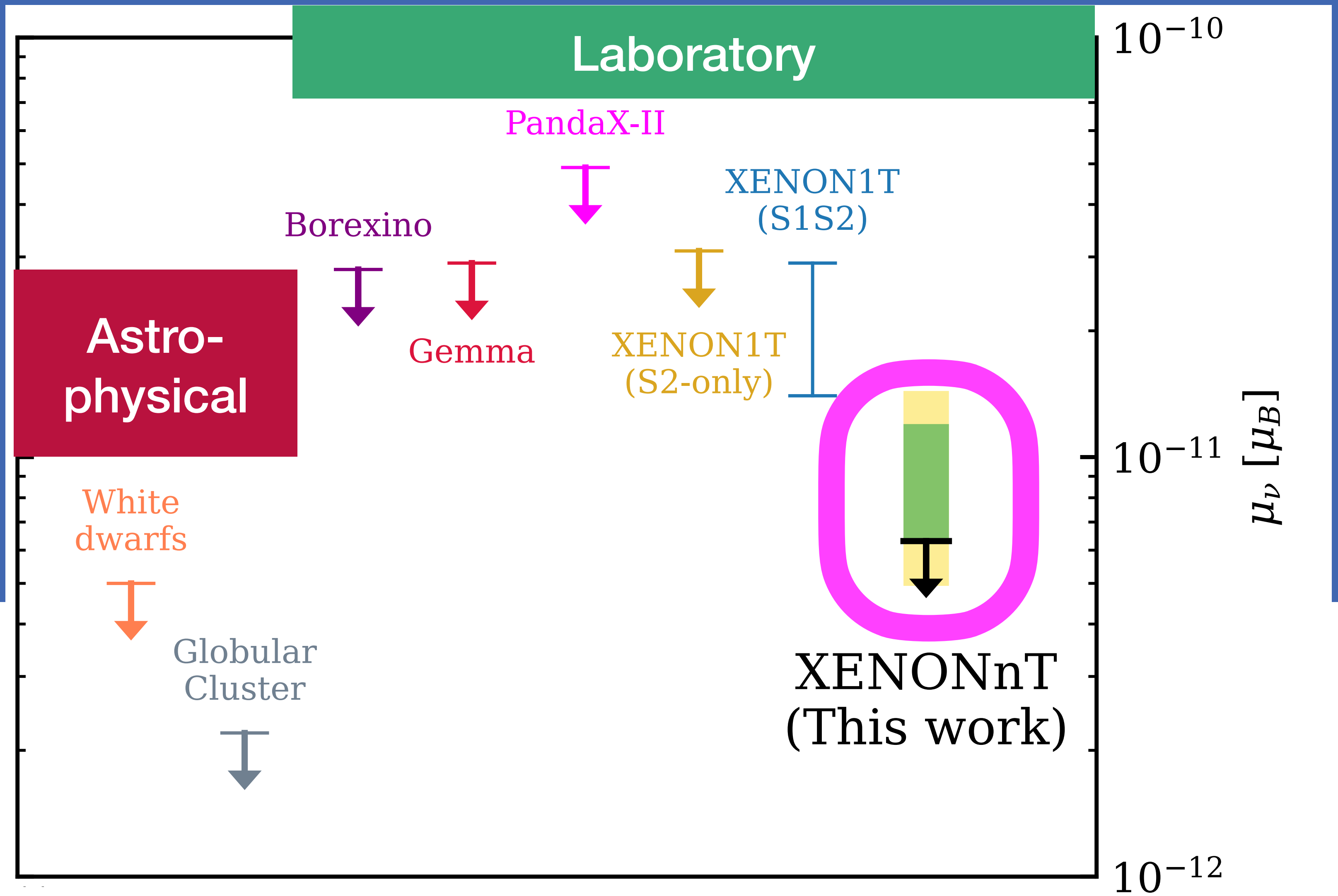
LIMITS ON SOLAR AXIONS



- XENONnT is compatible with background-only and places new limits on the axion-electron, γ and nucleon couplings.
- Axion signal assumes axio-electric effect and reverse Primakoff effect; described by g_{ae}, $g_{a\gamma}$, g_{an}
- 90% upper limit on ^{57}Fe solar axion component is 20.4 events/(t $\times$ yr)

LIMITS ON NEUTRINO MAGNETIC MOMENT

XENON



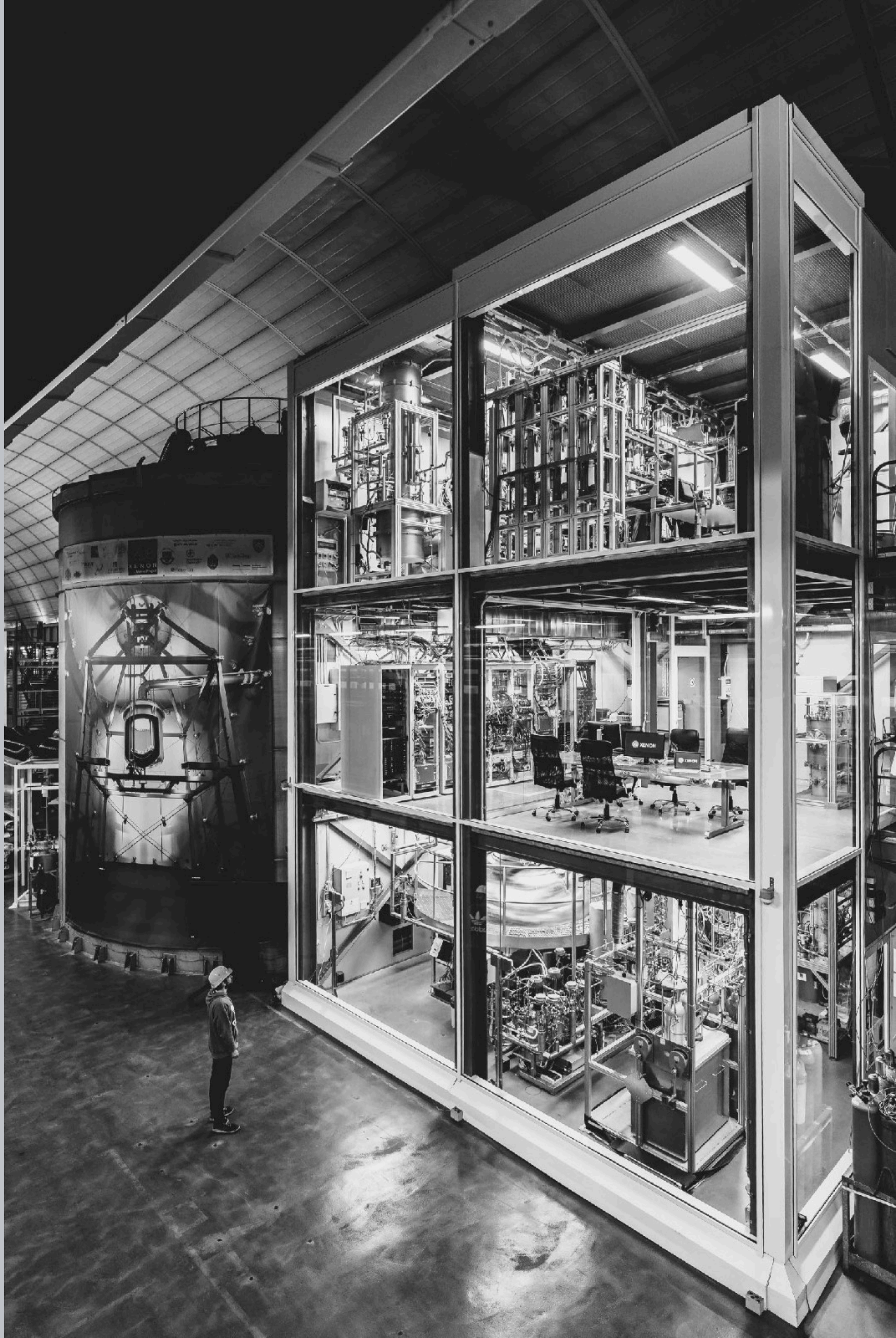
- A magnetic moment is implied by neutrinos being massive— if new physics raises this magnetic moment, it may cause an enhanced neutrino scattering rate
- Upper limit at $\mu_\nu < 6.3 \times 10^{-12} \mu_B$

Summary

> 10 ms **electron lifetime,** $1.77 \pm 0.01\ \mu$Bq/kg **radon concentration**

Blinded analysis of ER data (double-blinded?)

Excellent agreement with our background model



XENONnT lowER paper online

arXiv imminent

Until then:
xenonexperiment.org/
later today

IDM2022 Knut Dundas Morå
(knut.dundas.moraa@columbia.edu)

More to Come!

The combined liquid+gas Rn removal will further reduce the background level

Further analysis channels and deeper detector knowledge

Nuclear recoil search results soon

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And farther in the future:
xlzd.org

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