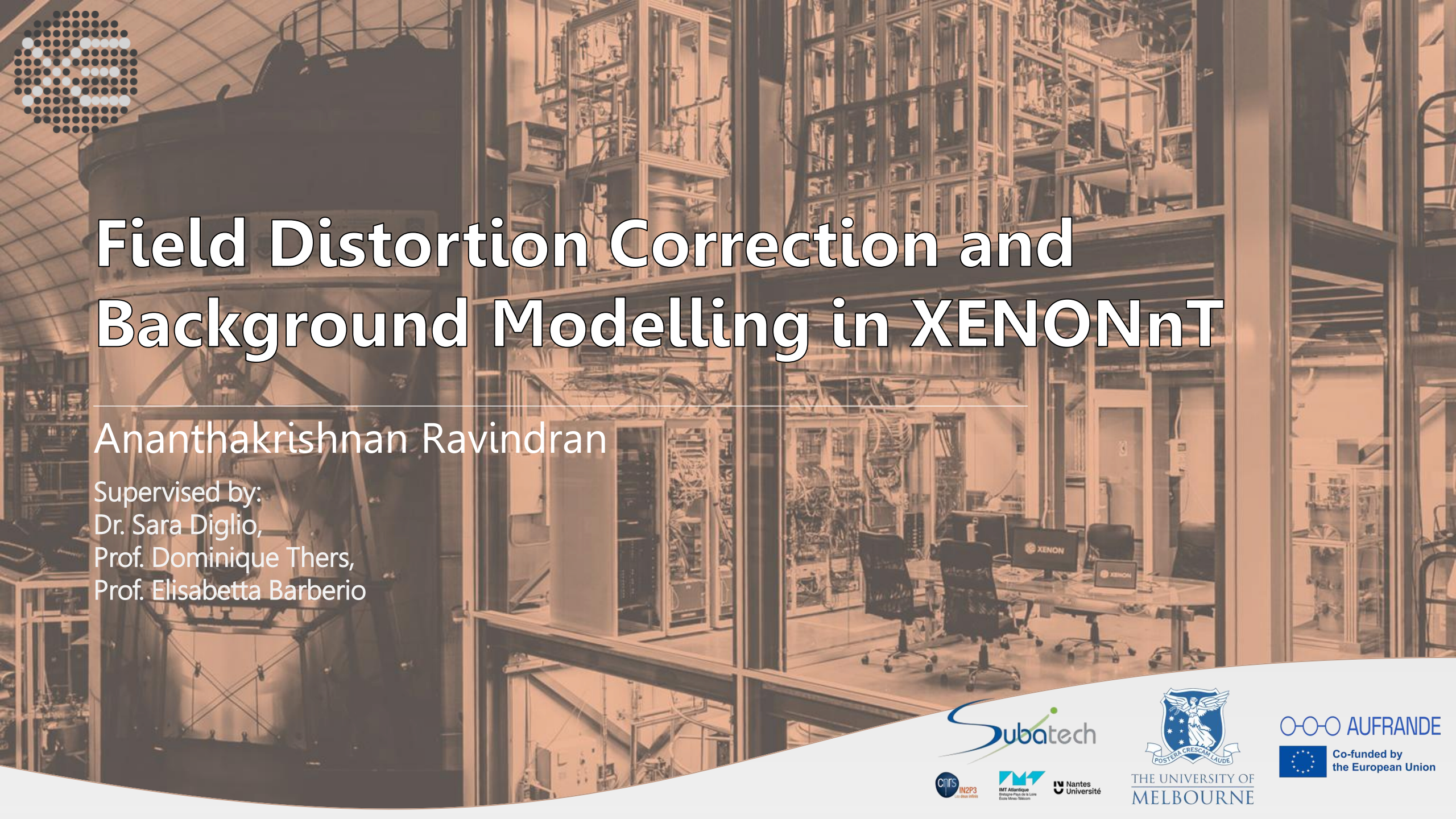


Field Distortion Correction and Background Modelling in XENONnT

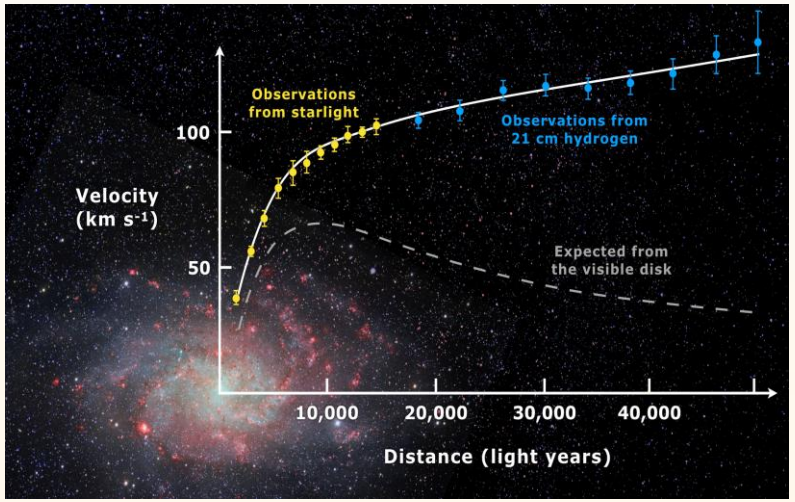
Ananthakrishnan Ravindran

Supervised by:
Dr. Sara Diglio,
Prof. Dominique Thers,
Prof. Elisabetta Barberio

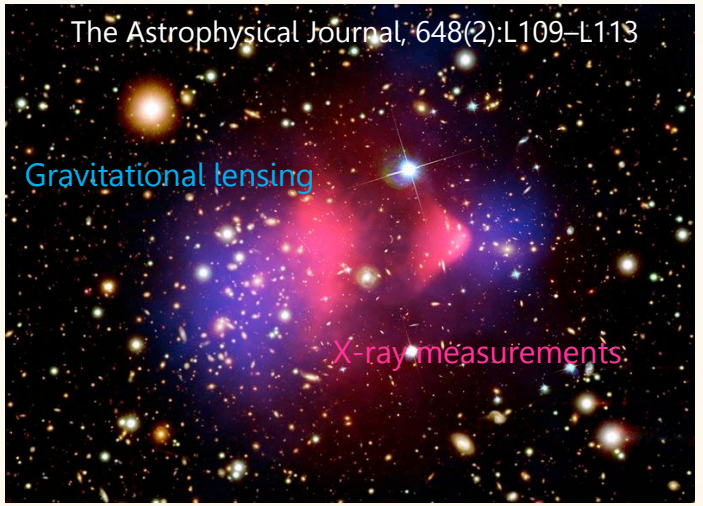
Co-funded by the European Union

Section 1:
Evidence for Dark Matter

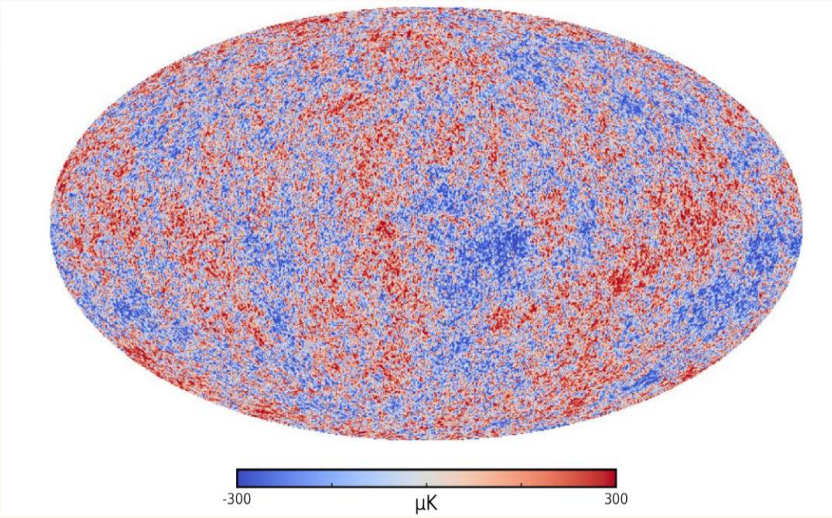
Evidence for Dark Matter



Rotation curves of spiral galaxies

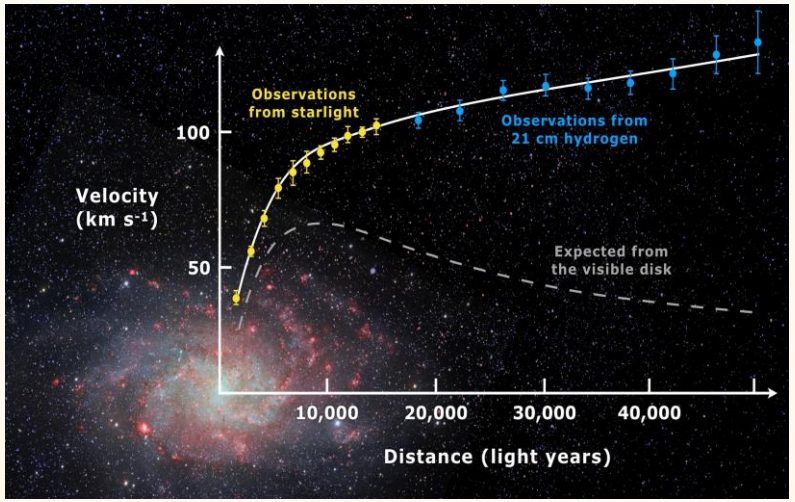


Mass distribution in galaxy collisions



Anisotropies in CMB

Evidence for Dark Matter



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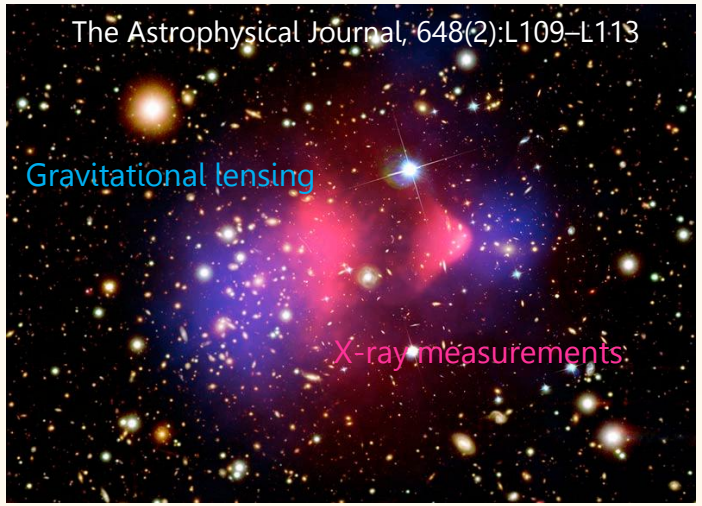

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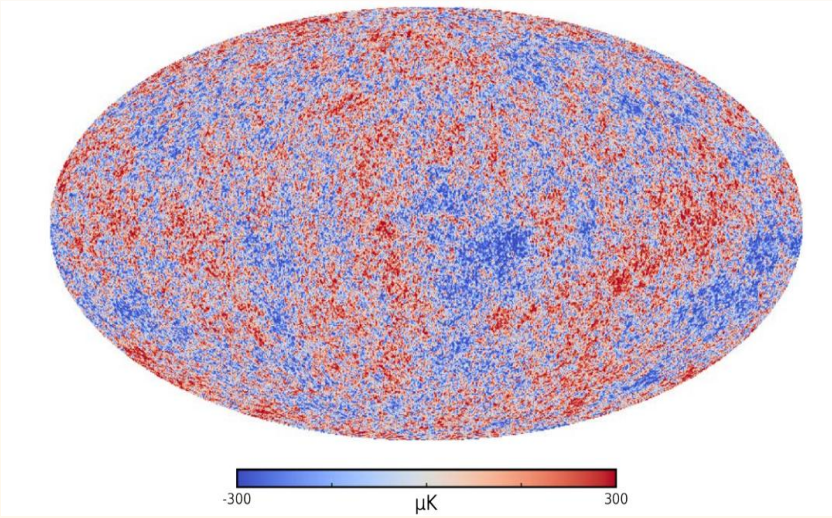
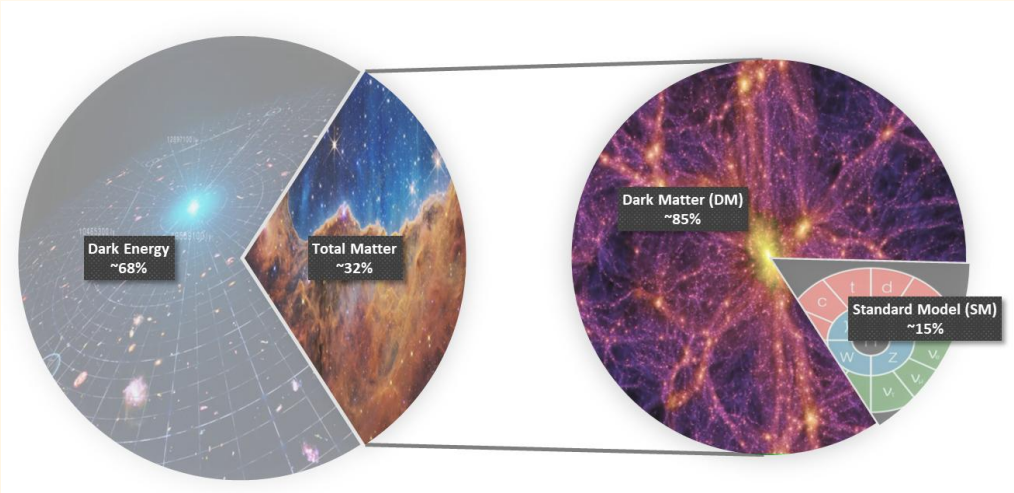
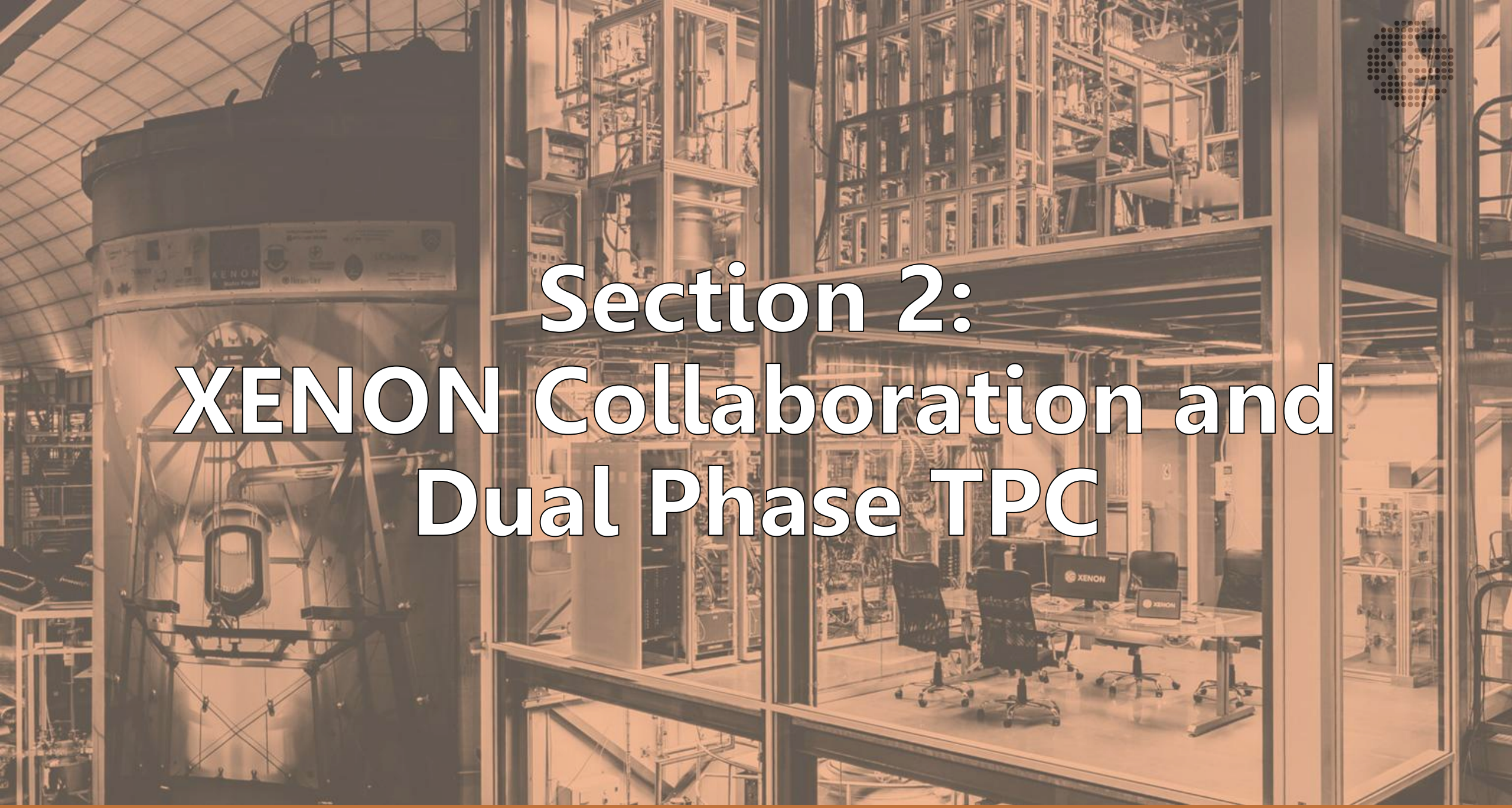


Anisotropies in CMB

Characteristics of Dark Matter

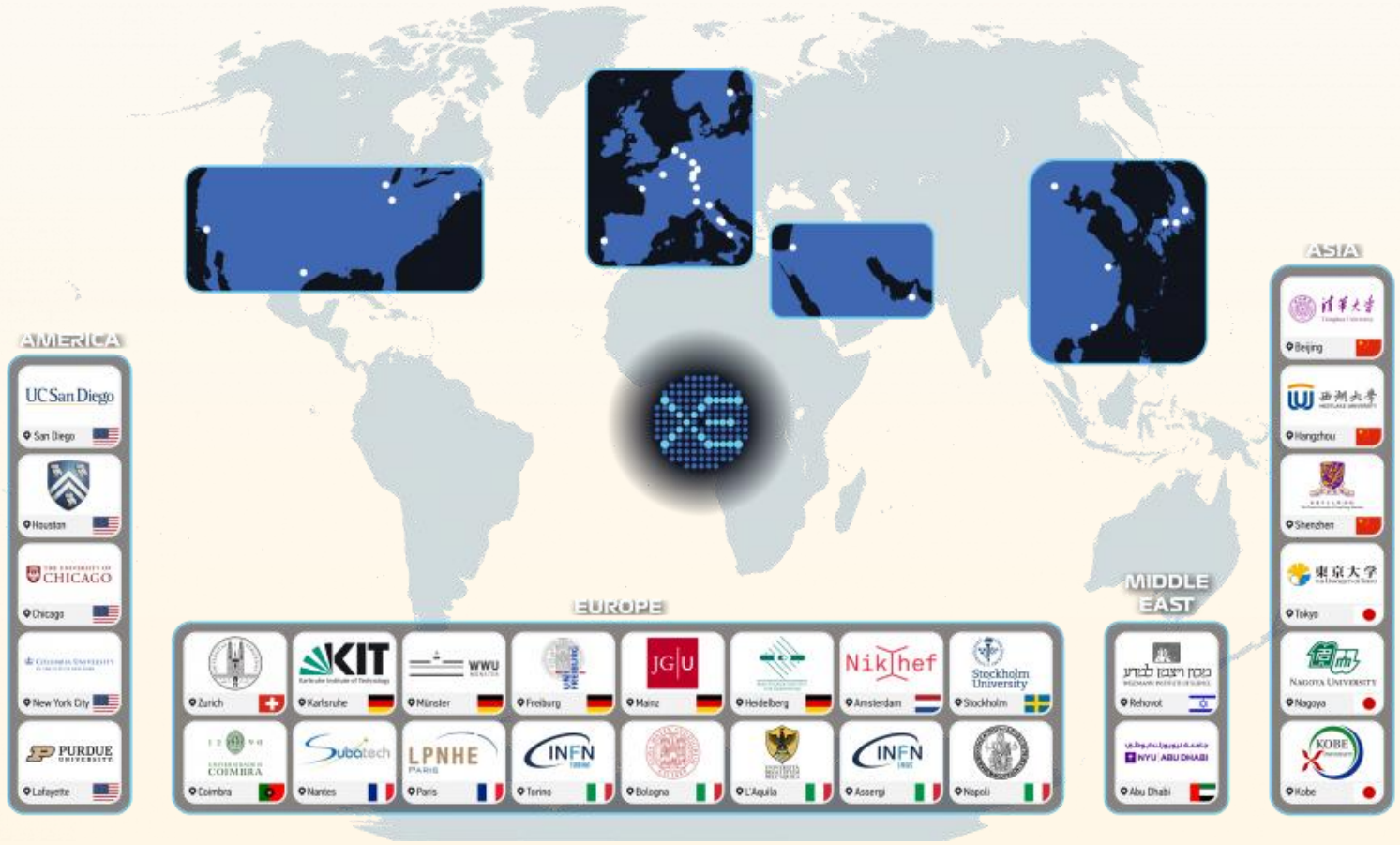
- Constitutes **85% of the mass** in the observable universe.
- Non baryonic and neutral.
- Cold (non relativistic) and stable on the scale of the lifetime of the universe.
- Could be weakly interacting and massive.





Section 2: XENON Collaboration and Dual Phase TPC

The XENON Collaboration



200+ Scientists

29 Institutions

12 Countries

Main Motivation

Discover **Weakly Interacting Massive Particles (WIMPs)**.

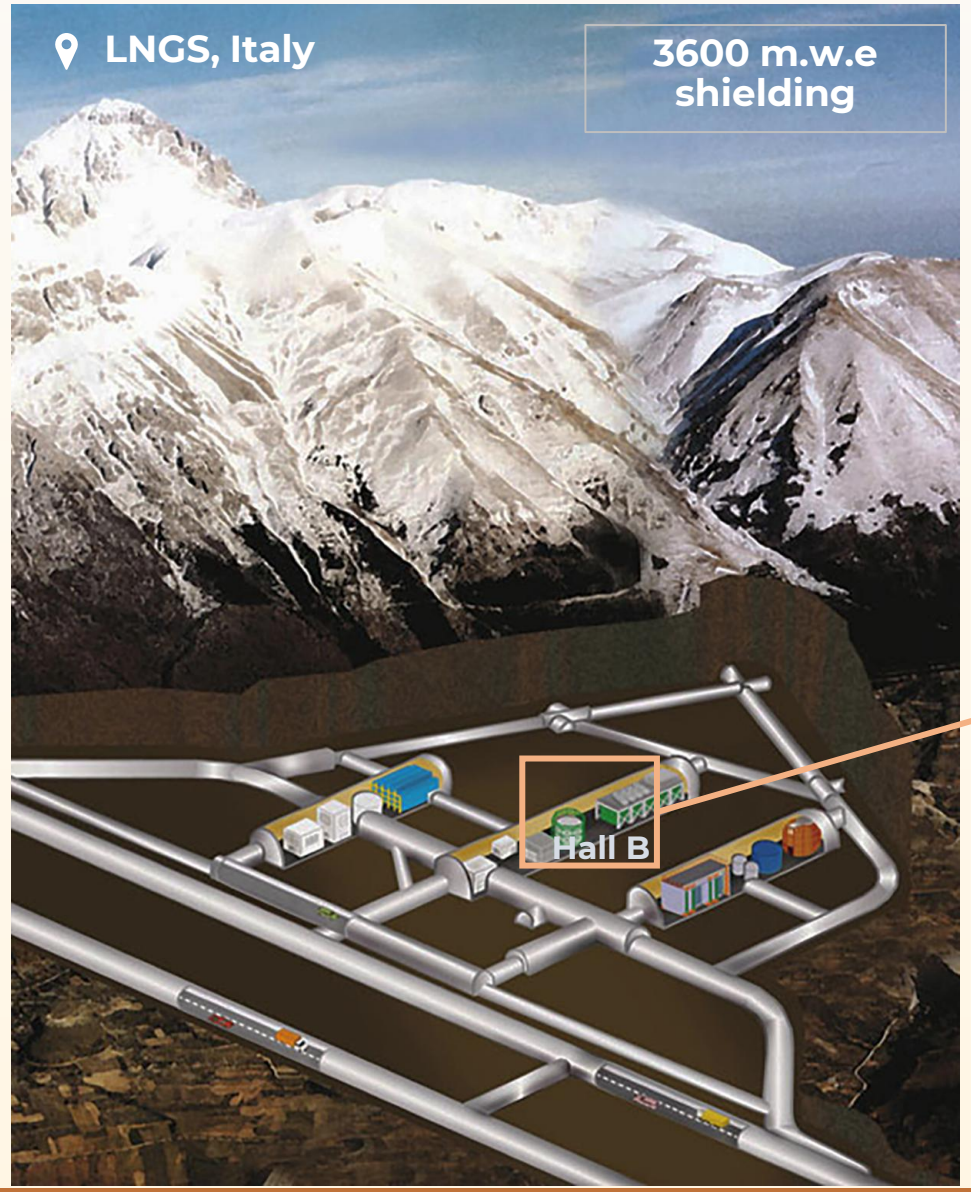
Other studies

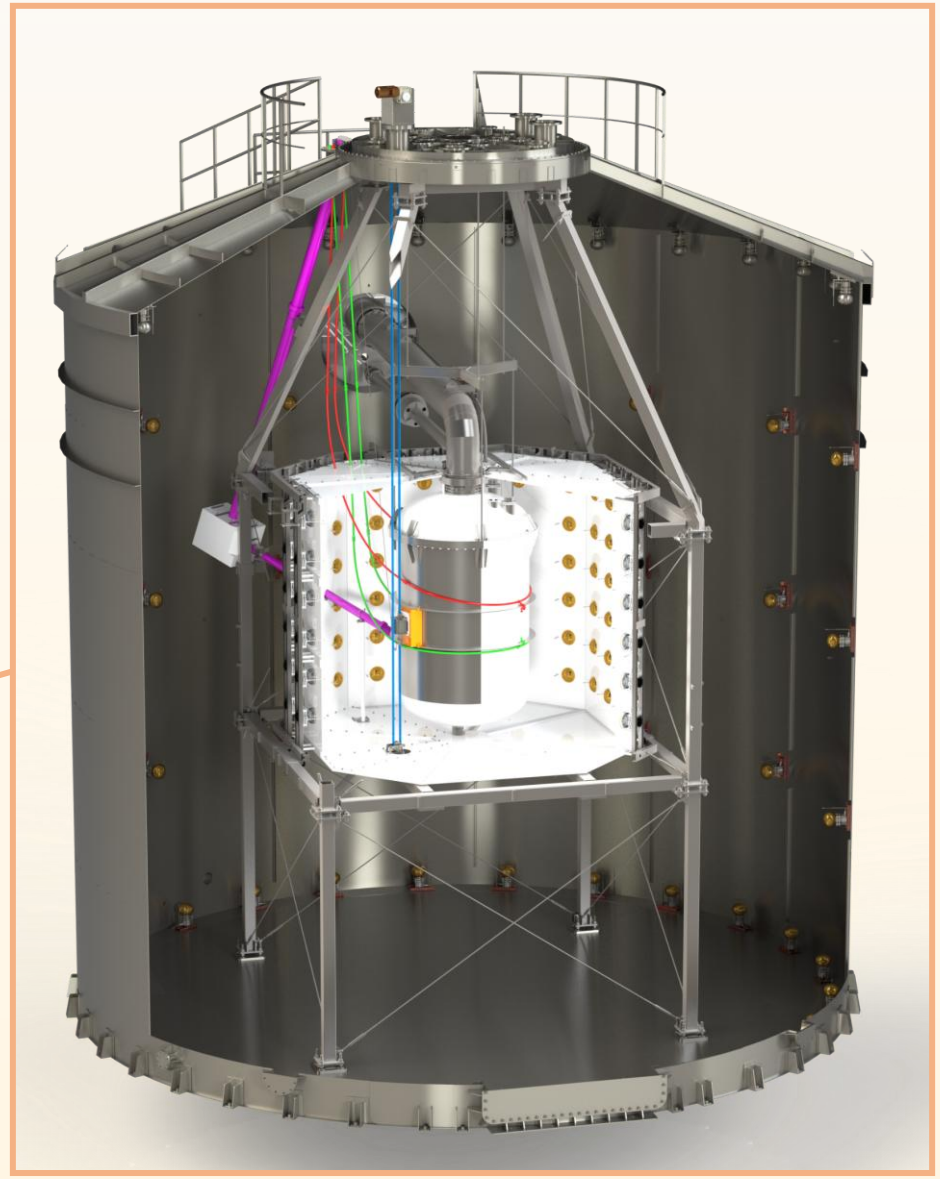
Coherent Elastic Neutrino-Nucleus Scattering **(CEvNS)**, $0\nu\beta\beta$, Solar Axions and ALPs, Supernovae, etc.

How we do it:

- **Very low backgrounds:** active and passive shielding, fiducialization, etc.
- Robust tools to correct detector effects and look for very small signals.
- Perform a "blind analysis".

XENONnT Experiment



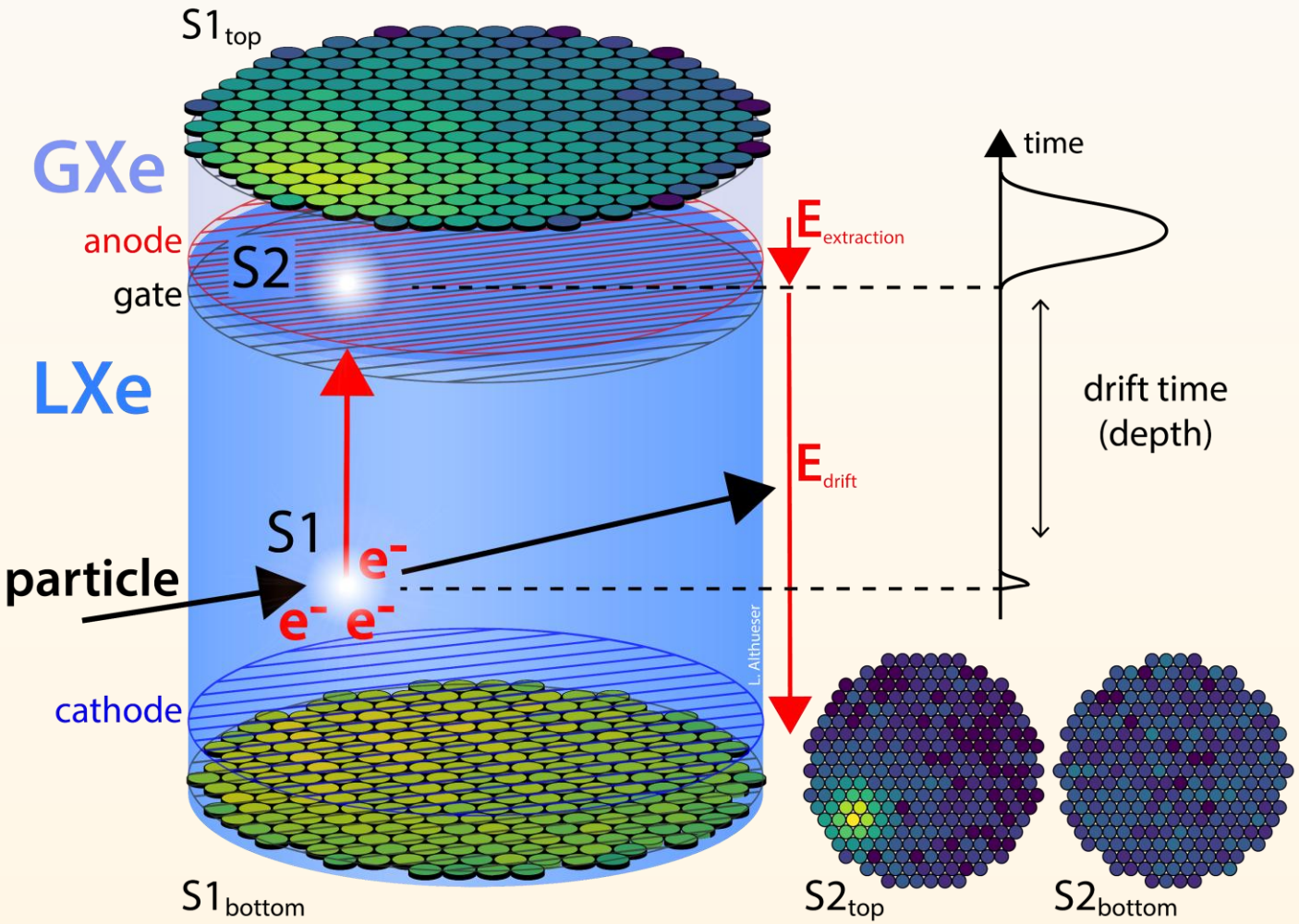


3 Nested Detectors

Sharing the same DAQ

- LXe Dual Phase **Time Projection Chamber (TPC)** with 5.9t active volume. (Eur. Phys. J. C 84, 784 (2024), JCAP11(2020)031)
- Gd-doped Water Cherenkov **Neutron Veto (NV)**.
- Gd-doped Water Cherenkov **Muon Veto (MV)** (2014 JINST 9 P11006)

Dual Phase Time Projection Chamber

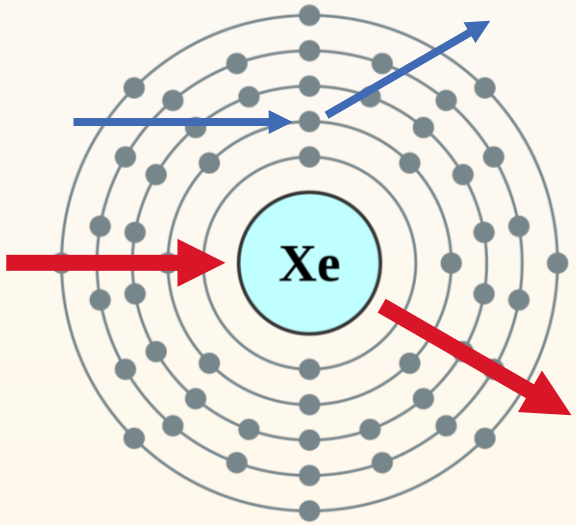


- Particle interaction in LXe create both **prompt scintillation(S1)** and **delayed ionization** signals.
- Ionization electrons drifted upwards by **drift field** ($E_{drift\_XnT} = 23V/cm$) and extracted into gas phase by **extraction field** ($E_{extraction\_XnT} = 2.9kV/cm$); leads to **electroluminescent light(S2).**
- Signals collected by a total of 494 PMTs in the top and bottom arrays.

3D Position Reconstruction	**Energy Reconstruction**
x, y : S2 hit pattern z: Drift time of e-	Combined S1 and S2 area; calibrated with known sources.

Recoil Type Discrimination: ER or NR?

Electronic Recoils (ER)



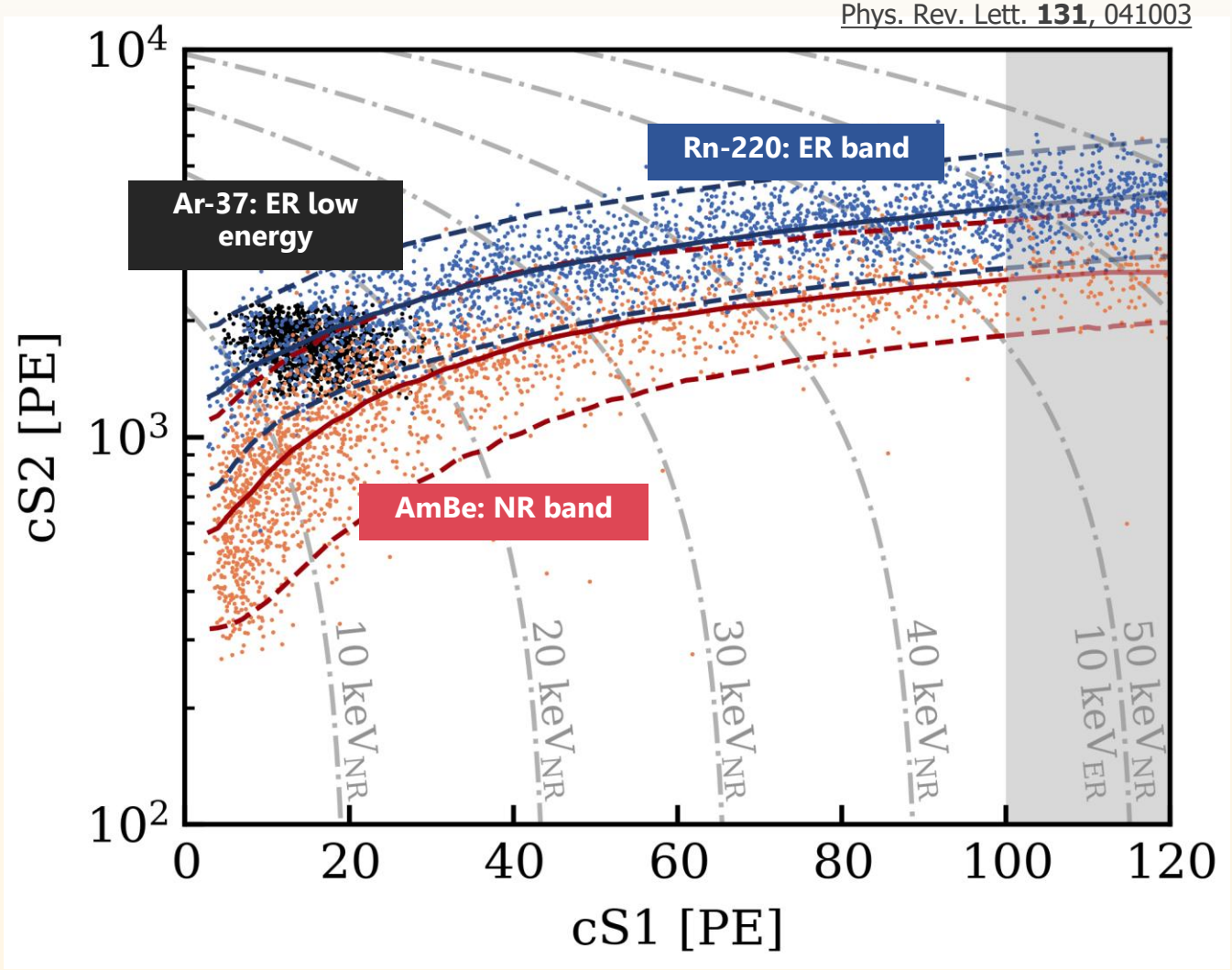
Nuclear Recoils (NR)

NR
- ✗ | Neutrons
- ✓/✗ | Neutrinos (CEvNS)
- ✓ | WIMPs

ER
- ✗ | Gamma & Beta
- ✓/✗ | ^{136}Xe $0\nu\beta\beta$, $2\nu\beta\beta$.
- ✓/✗ | Neutrino elastic scattering.
- ✓ | Solar axions, ALPs.

✓ Signal ✗ Background

Phys. Rev. Lett. **131**, 041003



Discriminated via different S2/S1 ratio.

Other Calibrations

Kr83m

TPC characterization and signal correction.

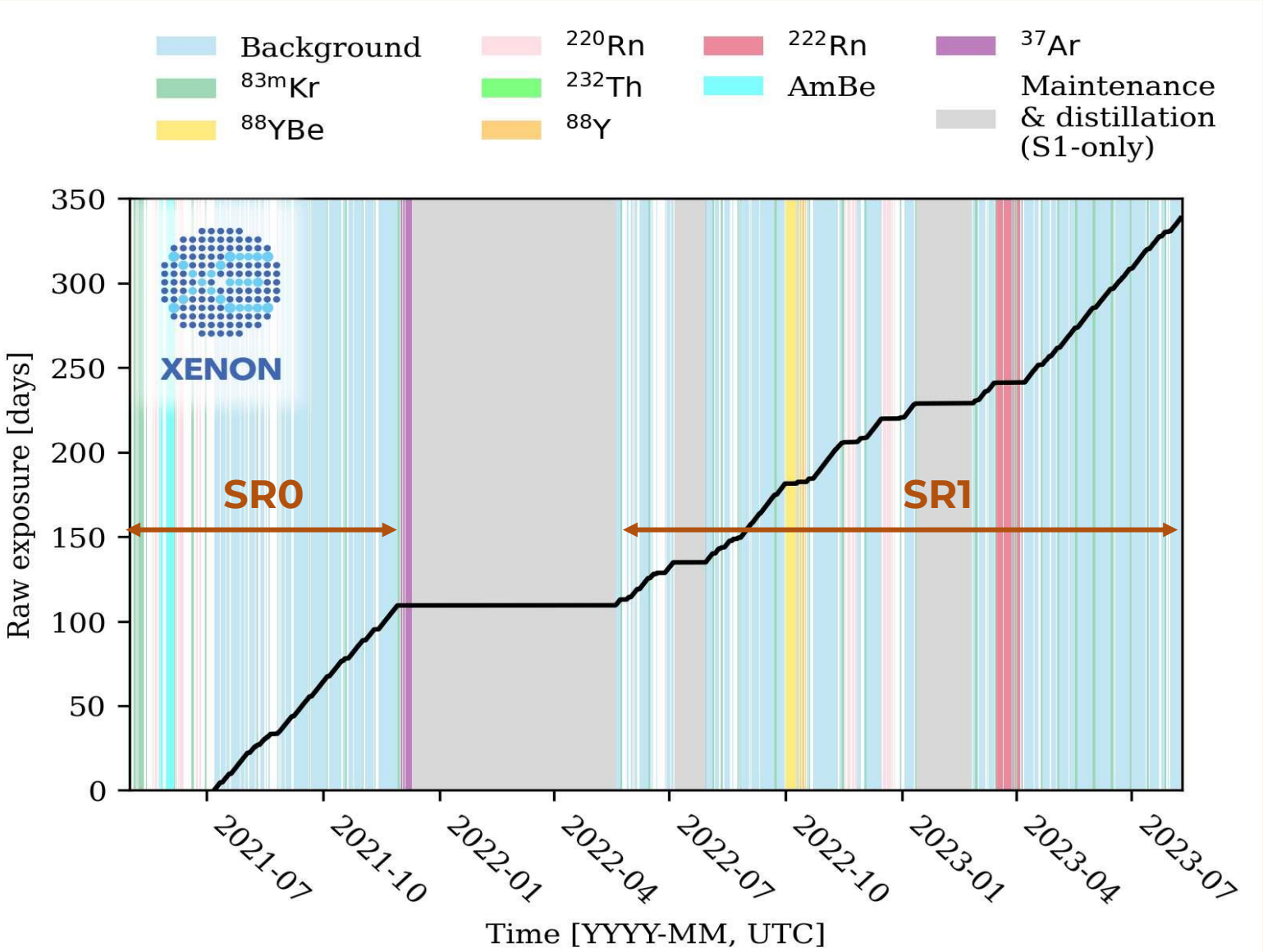
Th232

High energy response (~MeV).

YBe

Low energy NR response (~keV$_{NR}$).

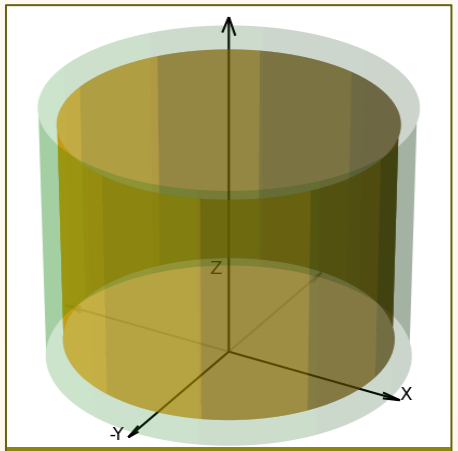
XENONnT Science Data



- Science data divided into various Science Runs (SR). Total exposure ~340 days.
- Regular (~biweekly) Kr83m calibrations.
- Very stable detector conditions maintained.

Section 3: Field Distortion Correction in XENONnT

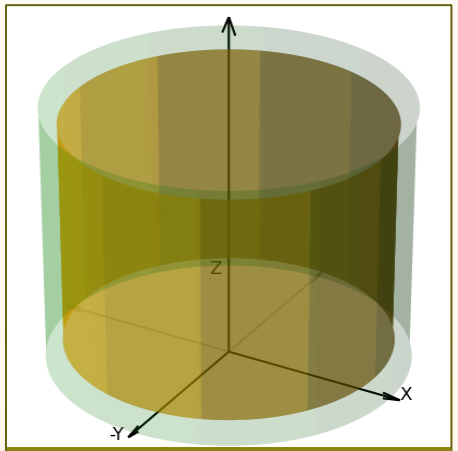
Field Distortion Correction



Only inner volume used for science searches

- (x,y) position of event reconstructed from **hit-pattern of S2** on top PMT array.
- Good radial reconstruction required for **Fiducialization** of inner volume; lower background in the inner volume.

Field Distortion Correction



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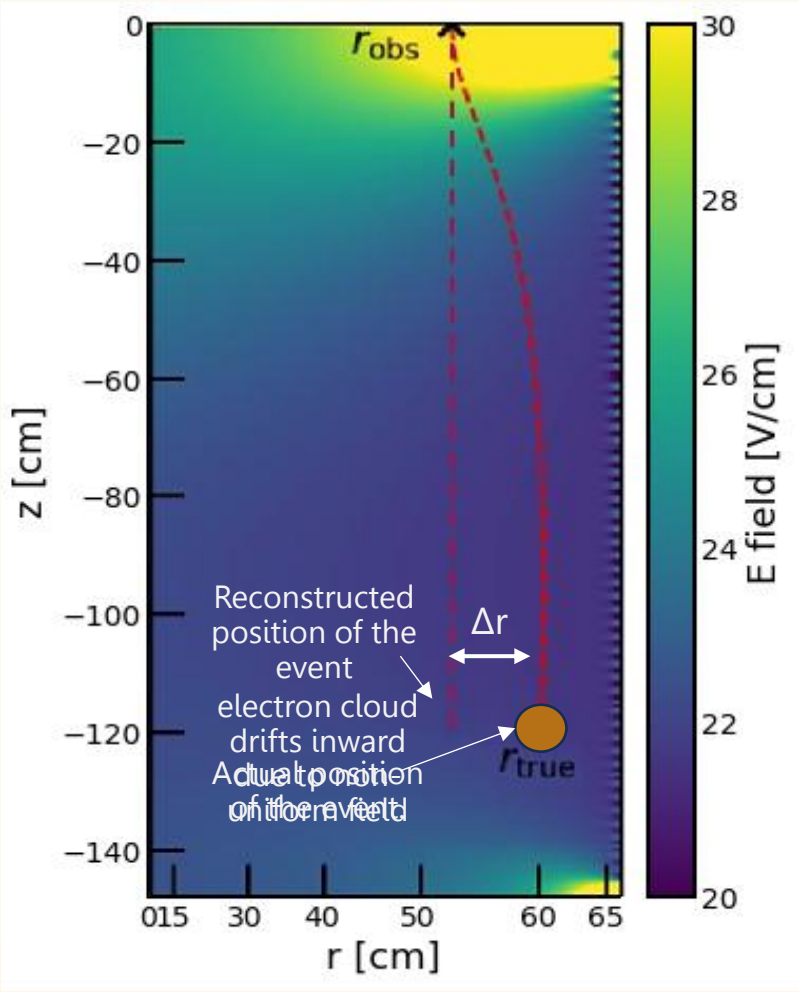
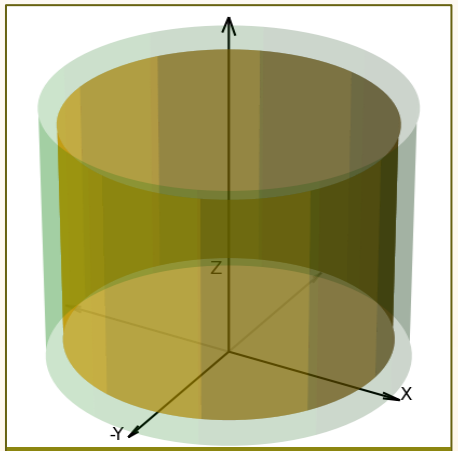
XENONnT operates at a **low non-uniform drift field** of 23V/cm; leads to a bias in reconstructed position.



Field Distortion Correction



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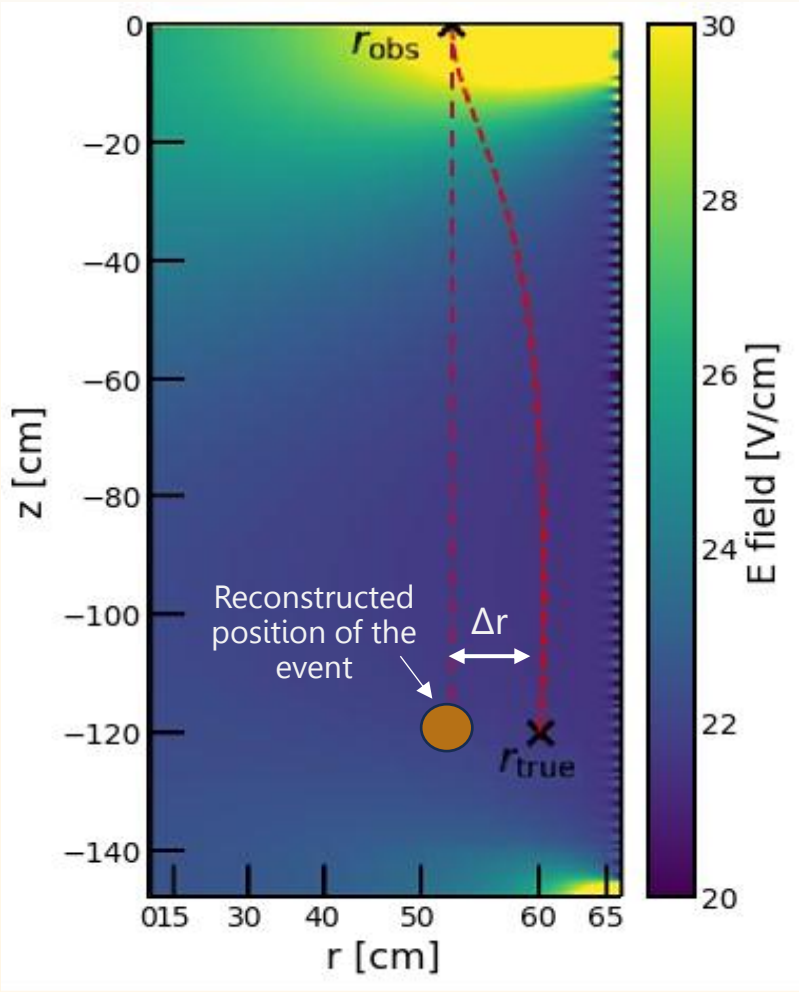
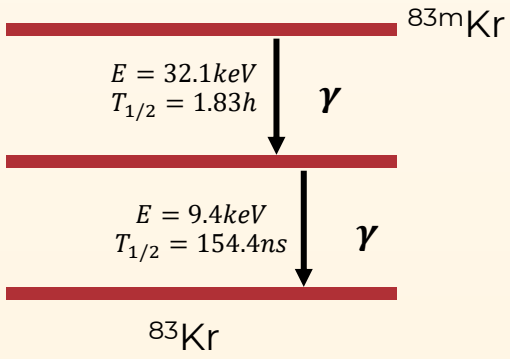
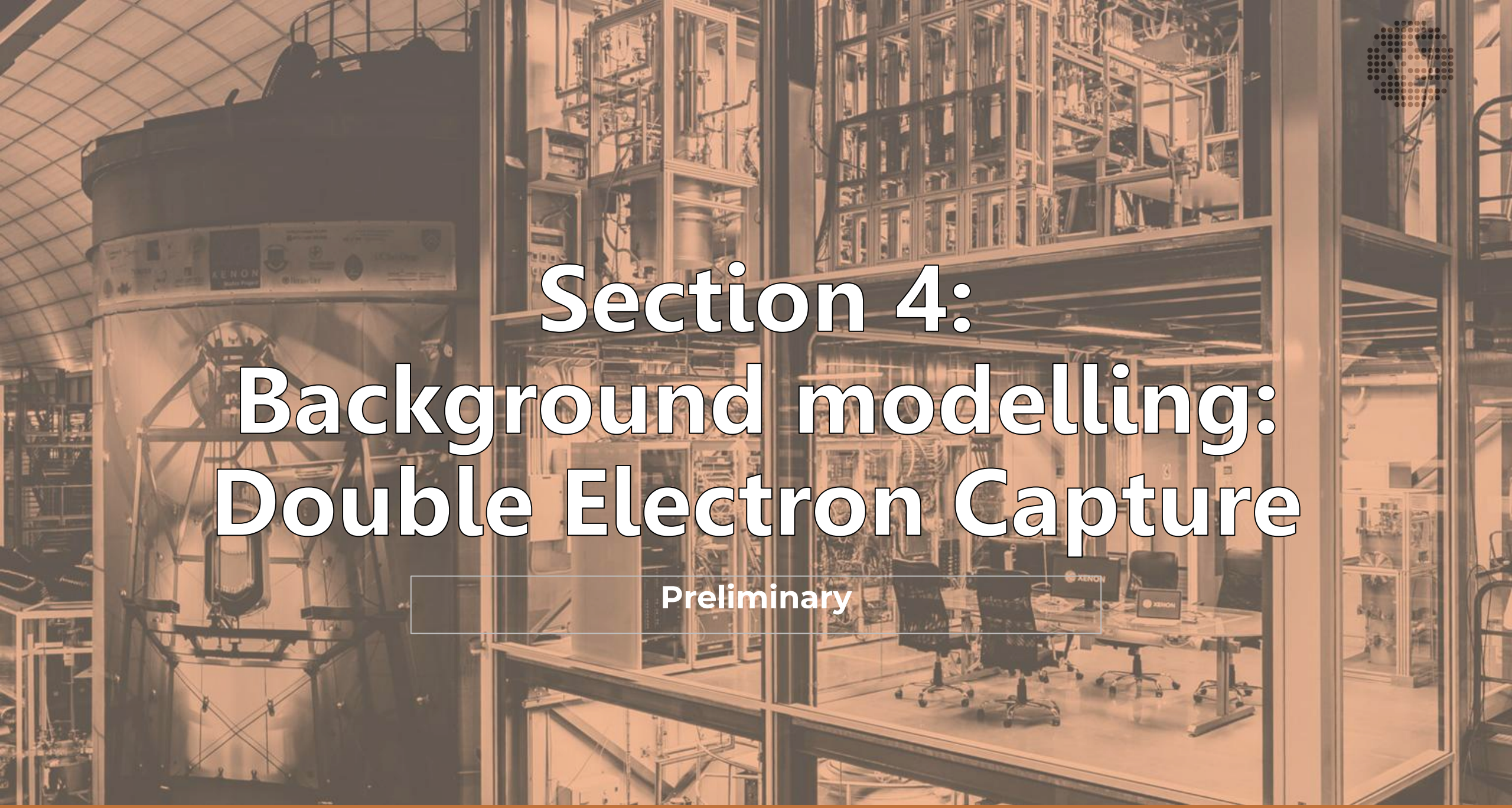


Calculated the **"real" mass** contained in the fiducial volume.

FDC corrects for this effect:

- Uses Kr83m calibration data.
- Produce a map with the correction for each point inside the TPC.
- Implemented in both **data** and **simulation pipelines.**

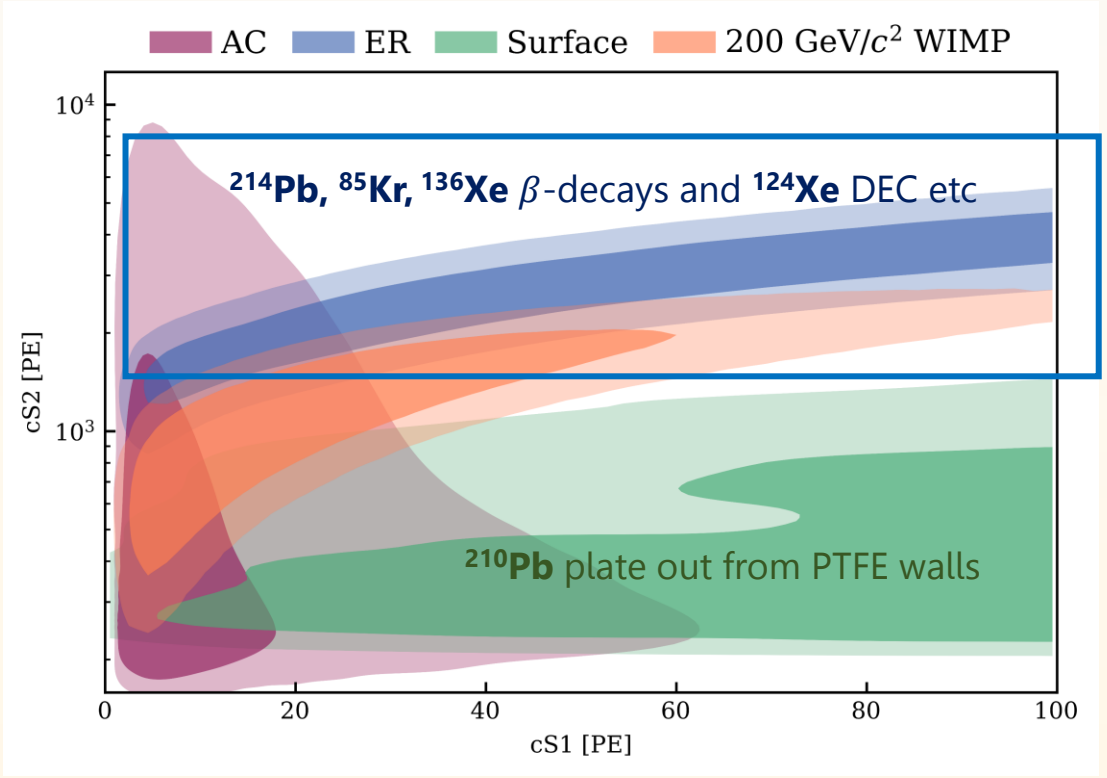




Section 4: Background modelling: Double Electron Capture

Preliminary

Backgrounds for WIMP searches

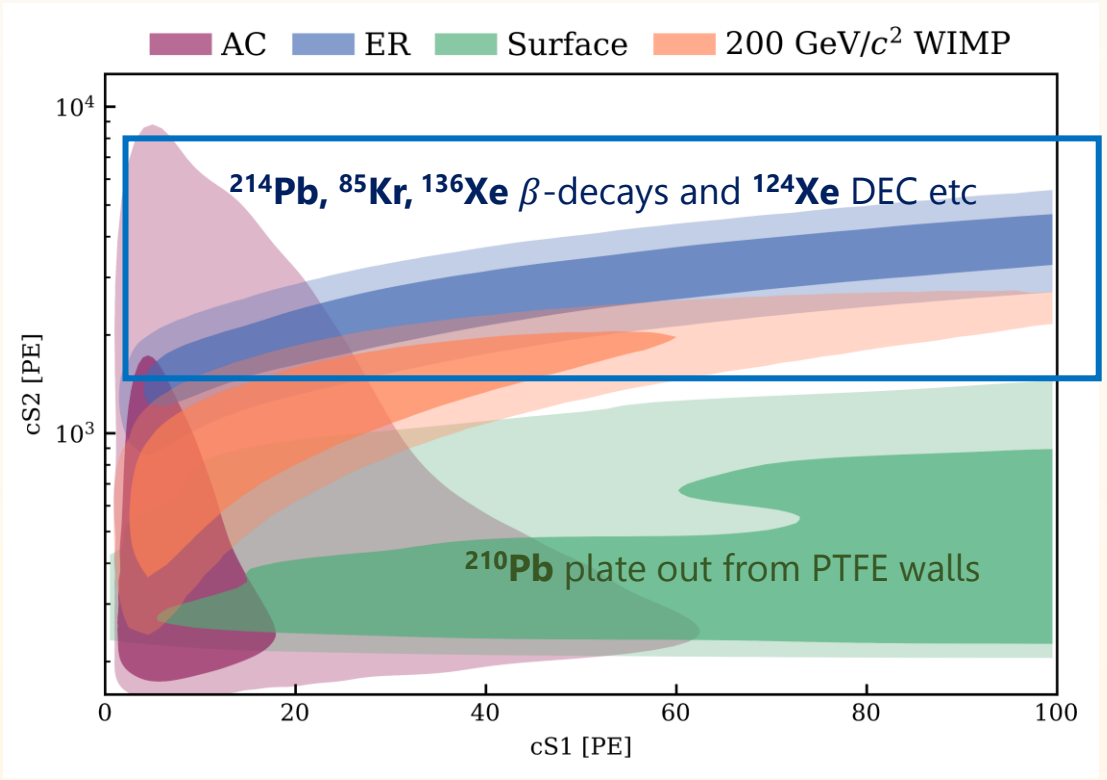


Accidental coincidences: Random pairing of S1s and S2s.

NR background: Radiogenic neutrons and CEvNS events in RoI.

- In terms of number of events, **ERs** are the largest backgrounds; but they are mostly **separated from signal region** due to the NR/ER discrimination.

Backgrounds for WIMP searches



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- In terms of number of events, **ERs** are the largest backgrounds; but they are mostly **separated from signal region** due to the NR/ER discrimination.

But some ERs may not be in the ER band?

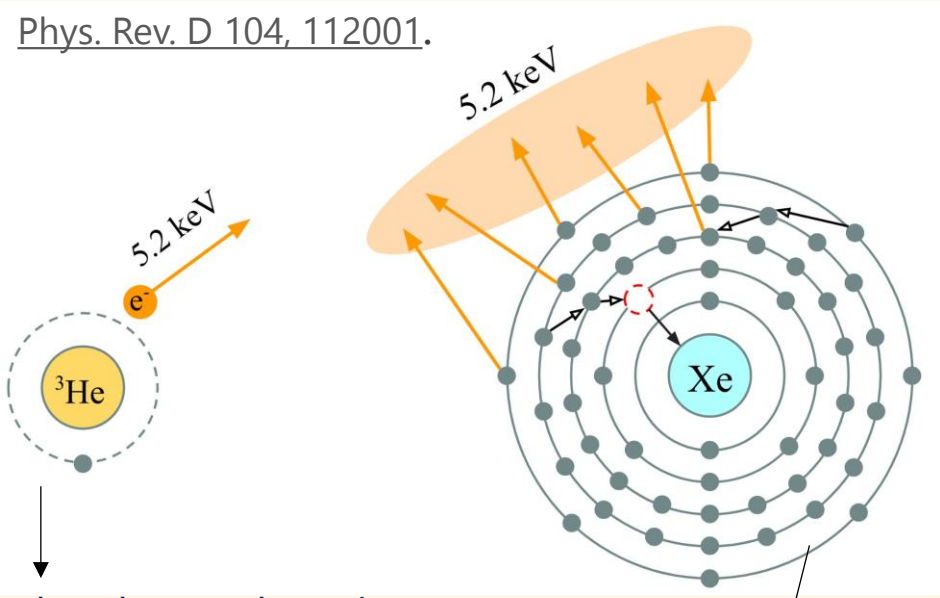
- **XELDA*** and **LZ#** recently reported a suppression in charge yield (CY) for **^{127}Xe L-shell electron captures**. (Phys. Rev. D 104, 112001, arXiv:2410.17036 [hep-ex]).
- No measurements available at nT drift field (23 V/cm).

* 177 g LXe TPC @ Uni. Michigan
\# 7 tonne LXe TPC @ SURF

CY suppression in Electron Captures

Preliminary explanation (by XELDA):

Phys. Rev. D 104, 112001.



Normal β-decays deposit energy in **single interaction**

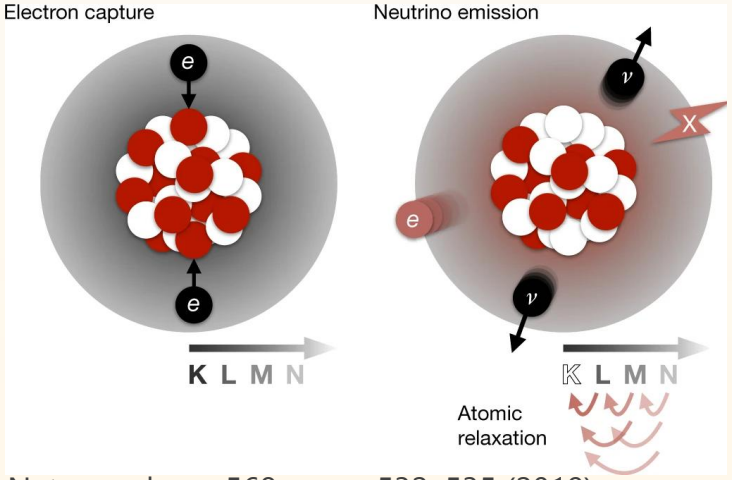
For EC, total energy deposited by **multiple cascade particles**; higher charge density; leads to **larger recombination**?

Phys. Rev. D 104, 112001.

	Source	$\mathcal{Q}_y$ (e/keV$_{ee}$)
XELDA	^{127}Xe – L, 363 V/cm	33.63 ± 0.03 (stat) ±0.33 (sys)
NEST	β, $r = 0.4789$	36.42 ± 0.14
NEST-mod	β, $r = 0.5196$	32.98 ± 0.02
XELDA	^{127}Xe – L, 258 V/cm	32.87 ± 0.07 (stat) ±0.37 (sys)
NEST	β, $r = 0.4984$	35.10 ± 0.23
NEST-mod	β, $r = 0.5319$	32.16 ± 0.03

The observed charge yields by XELDA are a better match for a higher recombination factor than in NEST (Noble Element Simulation Technique) beta-model.

^{124}Xe Double Electron Capture



Nature volume 568, pages532–535 (2019)

- First measured in **XENON1T**
- Abundance of isotope <0.1%, Very rare decay ($t_{1/2} = \sim 10^{22} years$):
- **LL** (~10keV) and **LM** (~6keV) capture peaks [~15 events] are inside the WIMP RoI.
- Similar process as ^{127}Xe L-shell capture.

Nature volume 568, pages532–535 (2019)

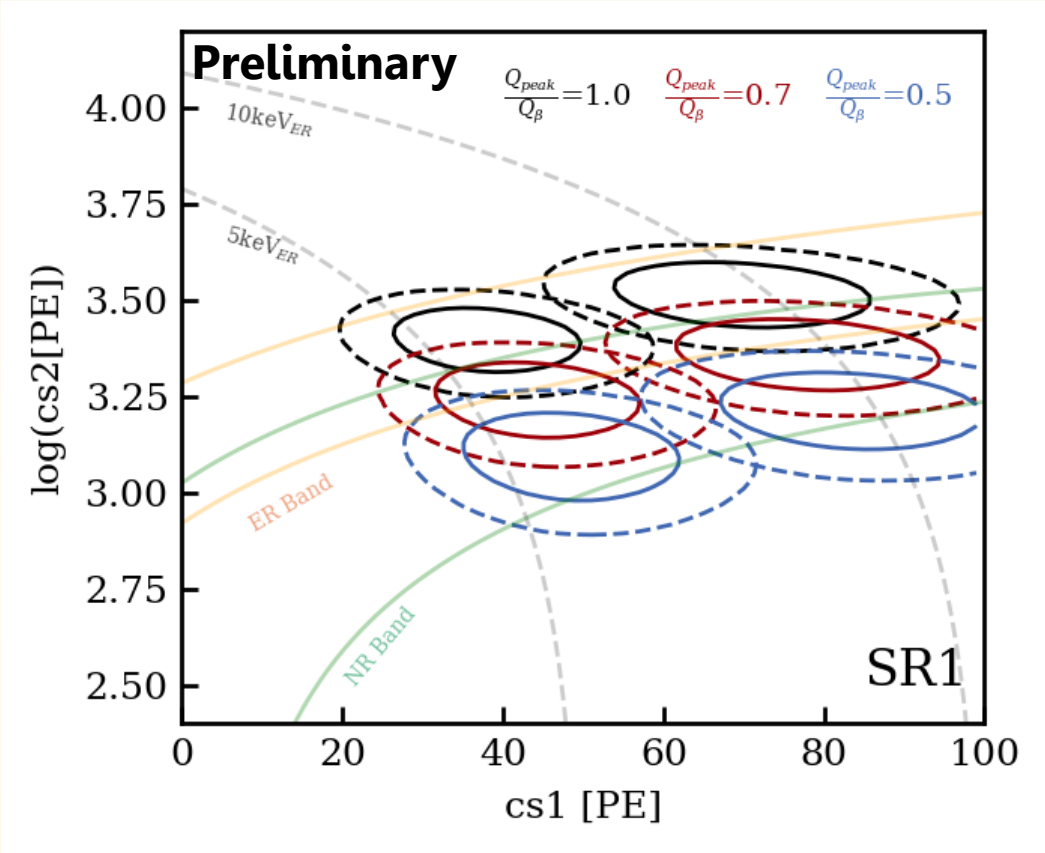
? Is the ^{124}Xe DEC signal **'charge-yield' suppressed** in XENONnT?

? Can it explain the **excess of events at high cs1** reported in the SR0 WIMP results? (Phys. Rev. Lett. 131, 041003)

Preliminary: Publication in preparation.

^{124}Xe DEC Model

- We adopt a statistical approach**: create a model with free charge yields** for the peaks and **fit on science data**.



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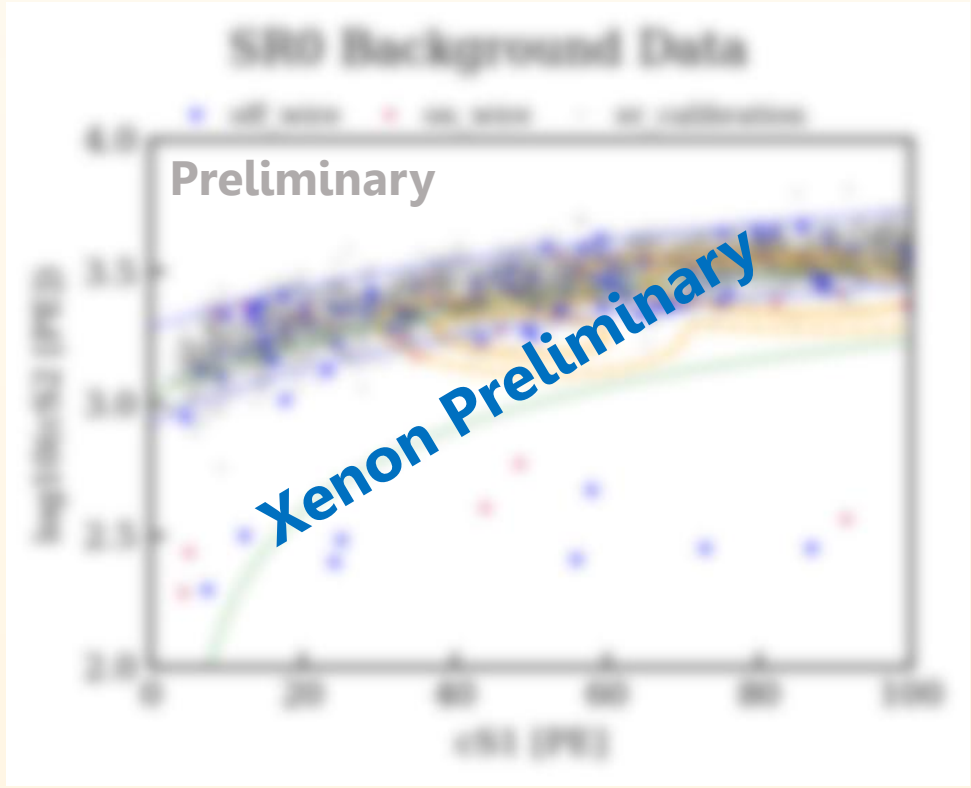
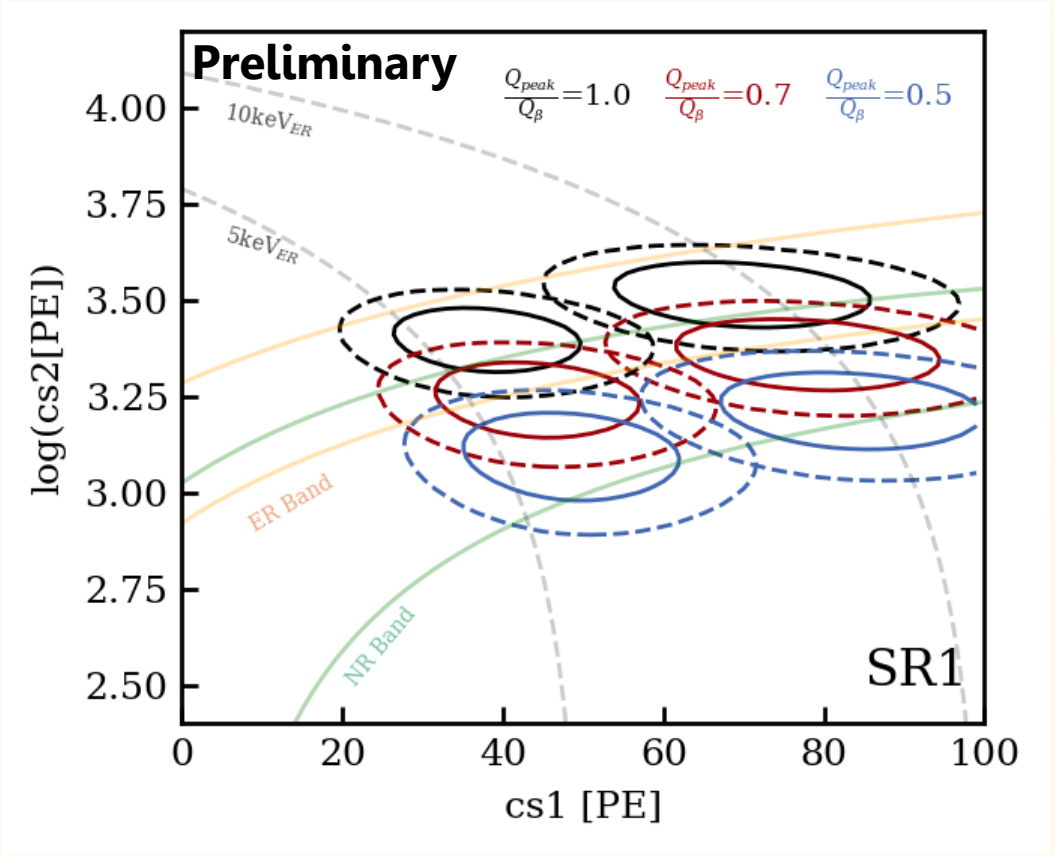
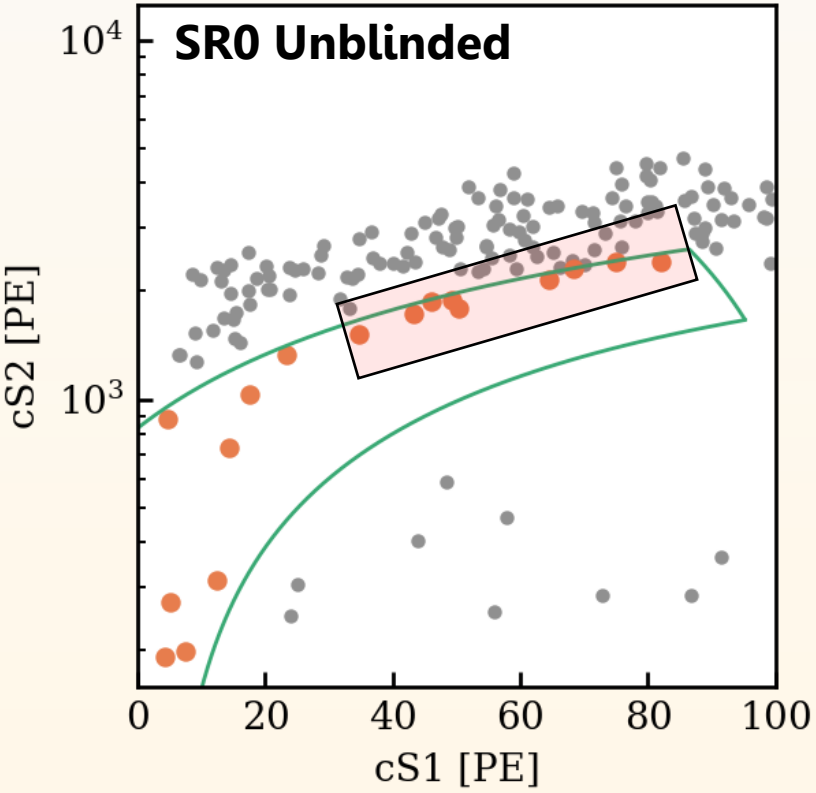


B-only fit on already unblinded SR0 data.

Best fit of both peaks **are suppressed** from beta-model, but **with large confidence intervals.**

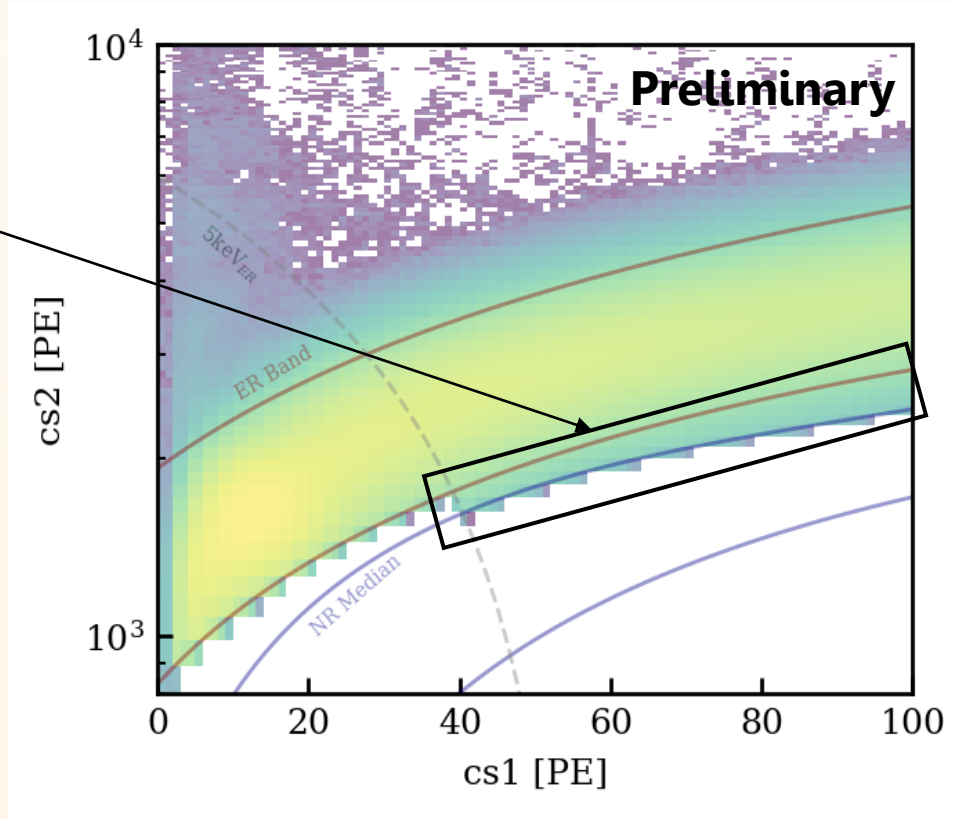


ER leakage sideband



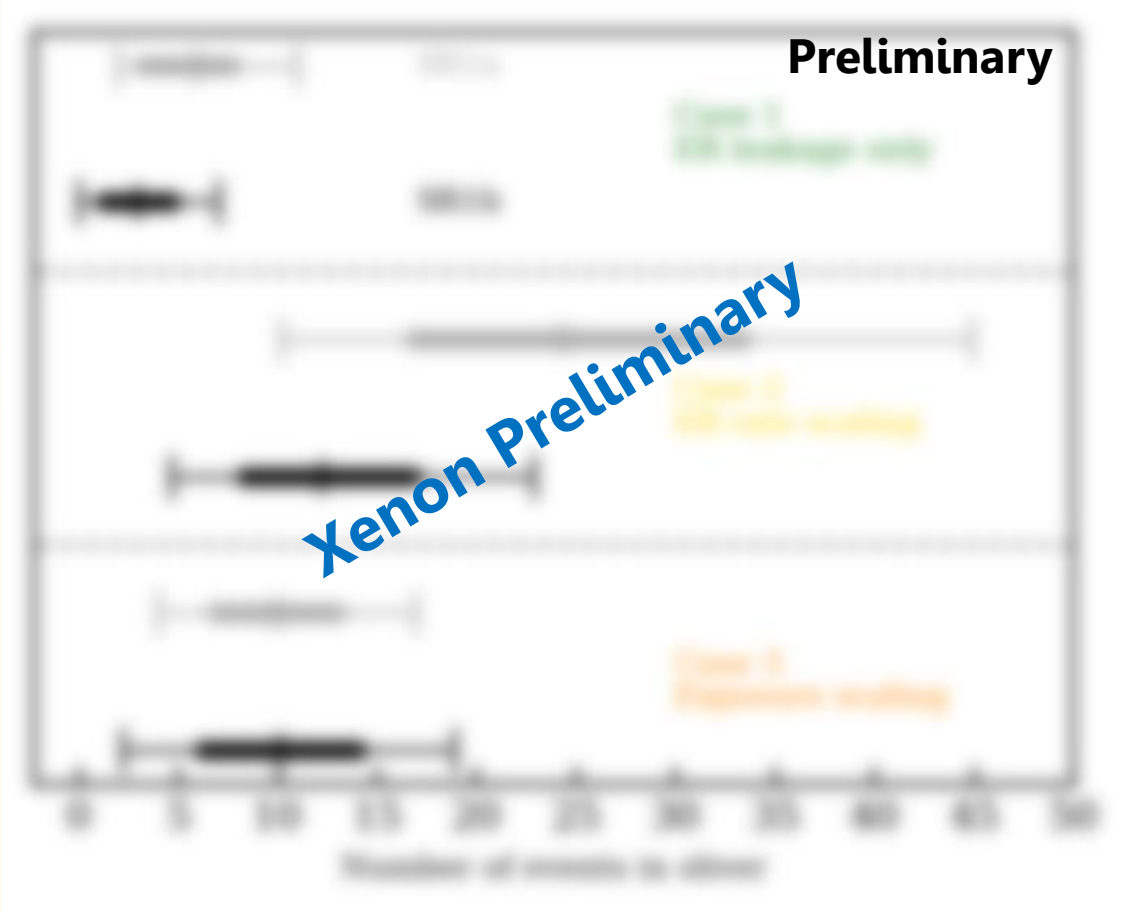
- In SR0, a small excess of events at high cs1 was observed.
- Events looked like ER events; mismodelling of bands?

- Before full unblinding, an **ER "leakage" sideband** was unblinded to identify any **mismodelling**.
- Statistical tests defined before unblinding with predefined **decision tree** depending on results.



Tests can identify "general" mismodelling only; **not powerful** enough to discriminate CY suppressed DEC from beta-model.

ER leakage sideband



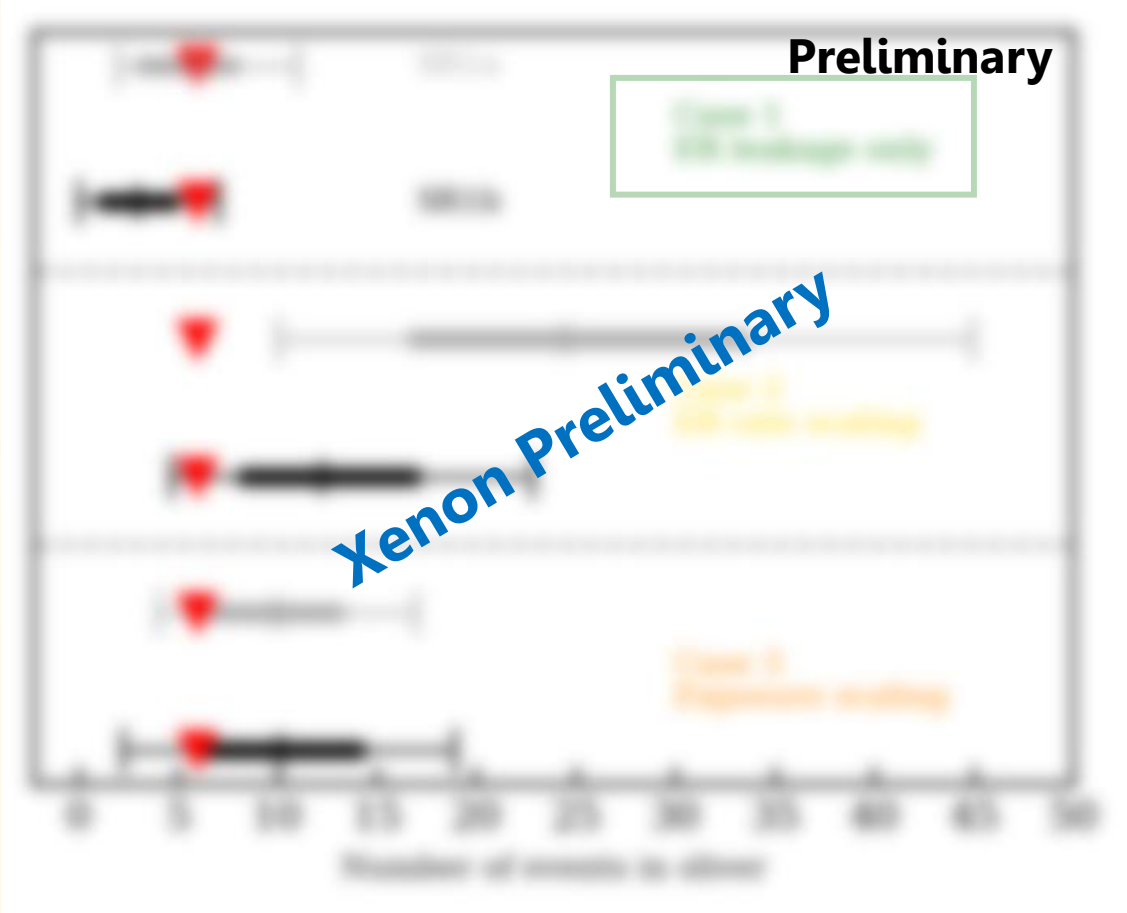
Tests for **ER band mismodelling**

SR1 is **divided into two**: SR1a and SR1b, periods of higher and lower ER rate.

Science data only unblinded in the leakage sideband; rest remains blinded.

Acceptance regions are modelled by probability distributions calculated from the **expected rate of events and their uncertainties;** obtained from other sidebands.

ER leakage sideband



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After Unblinding:

No general mismodelling of the ER band!

Tests for **spatial homogeneity** also showed **no evidence against** the nominal model.

DEC in final SR0+1 inference

What was known before the full unblinding:

- **Deviation from beta-model observed in SR0 data**, but not enough statistics in SR0 for a good fit.
- **No general mismodeling** in the shape of the ER band.

For full unblinding; Use both models on full dataset.

Nominal model: DEC CY fixed to beta-model

v/s

Alternate model: DEC CY allowed to vary

Perform a **profiled likelihood ratio (PLR) test** to reject the nominal model on SR1 data.

- If fail to reject: Nominal model is the main model.
- If rejected: Alternate model is the main model.

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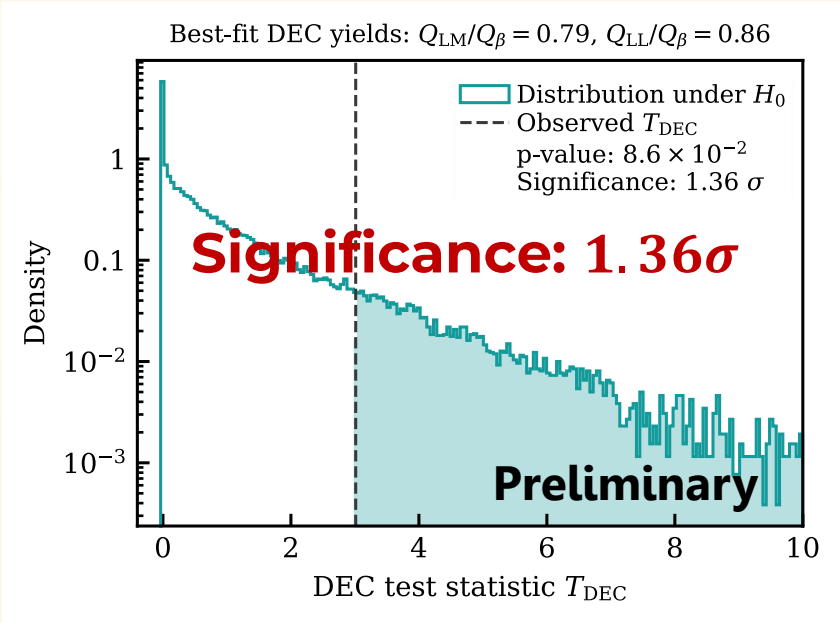

Use **Nominal model** as the main model.

Summary and Prospects

Field Distortion Correction (FDC)

- Correcting for bias in position reconstruction due to low non-uniform drift field.
- Map produced and implemented in **both data and simulation pipelines** and **used in all analyses**.
- Used for calculation of various correction factors; eg. **real fiducial mass in the geometric fiducial volume**

Summary and Prospects

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Background modelling: ^{124}Xe DEC Model

- Is the ^{124}Xe DEC signal 'charge-yield' suppressed in XENONnT?
- Can it explain the excess of events at high cs1 reported in the SR0 WIMP results? (Phys. Rev. Lett. 131, 041003)
- **Charge yield (CY) suppressed** background model implemented.
- Statistical tests to identify shape mismodeling before the full unblinding; **No evidence of mismodeling.**

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- **Charge yield (CY) suppressed** background model implemented.
- Statistical tests to identify shape mismodeling before the full unblinding; **No evidence of mismodeling.**

Prospects

- Full SR0+1 WIMP publication in preparation.
- XENONnT continues to collect more blinded science data**; I will be in charge of the sensitivity studies and final inference for the next science run.**
- In preparation for the inference in next science run(s), **upgrades to the inference software "alea"** for efficient handling of many parameters.

Exciting work to be done as part of the proposed **next-gen detector**

Thank you for your attention!

Subatech

cnrs IN2P3

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

Nantes Université

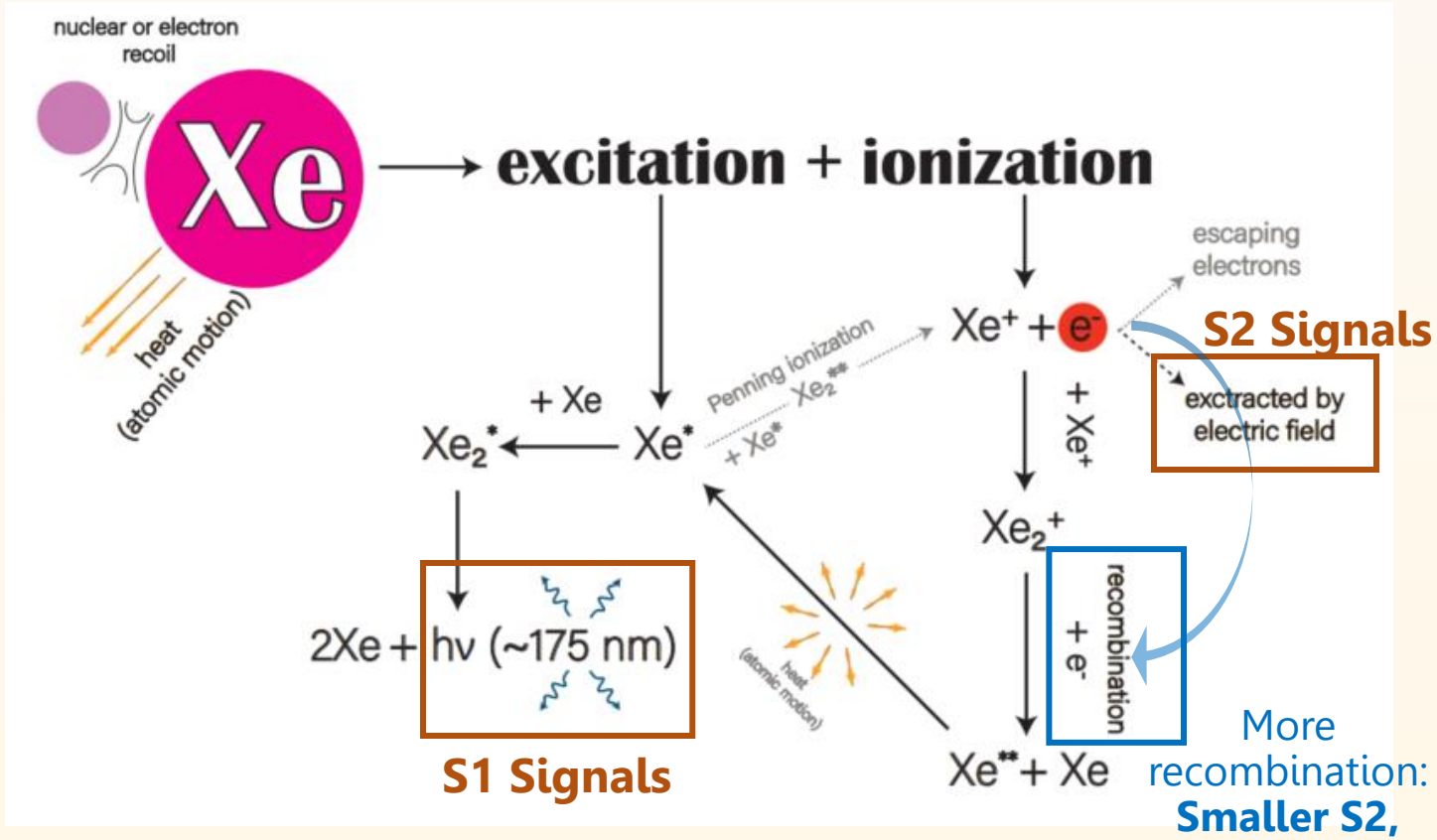
THE UNIVERSITY OF MELBOURNE

AUFRANDE

Co-funded by the European Union

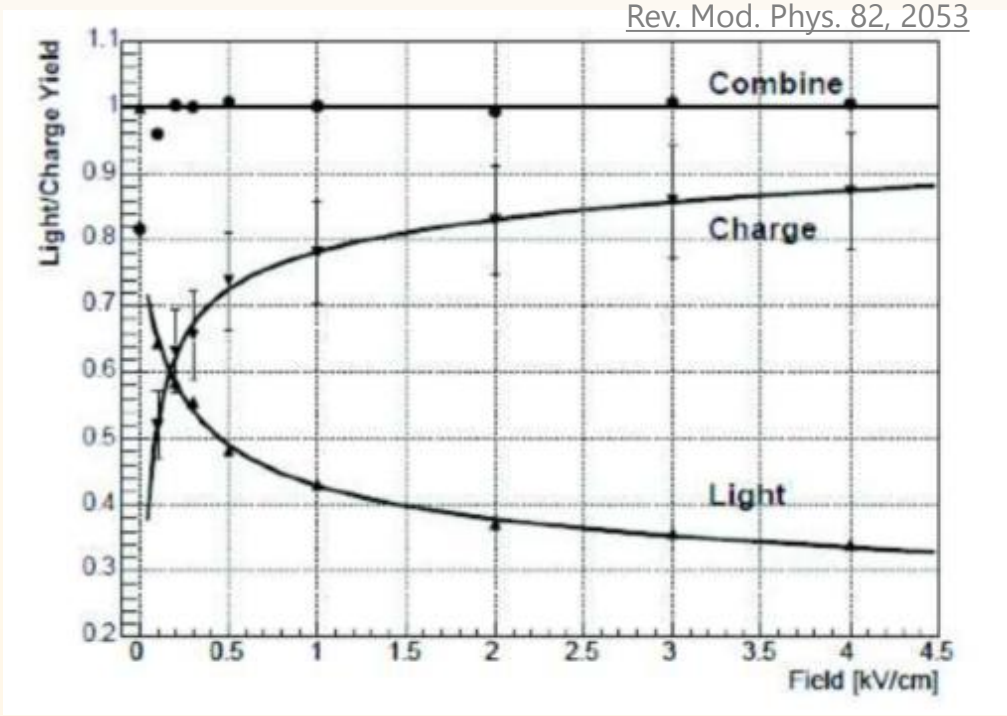
Backup Slides

Signal Production in LXe



More recombination: **Smaller S2, Larger S1**

Rev. Mod. Phys. 82, 2053

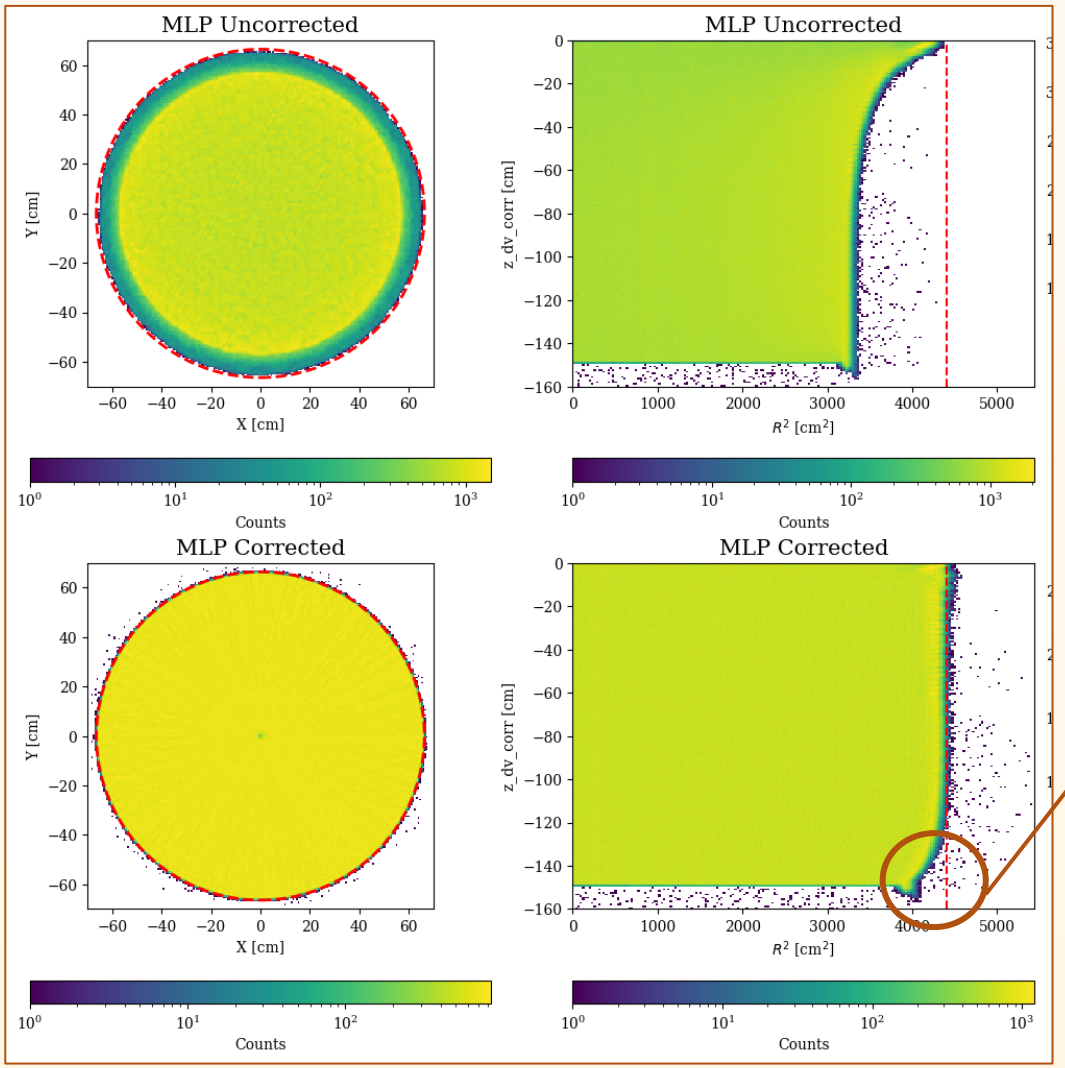


S2 and S1 signal sizes are **anticorrelated**

Field Distortion Correction in fuse

xenon-fuse 1.4.4

```
pip install xenon-fuse
```



- Also implemented in fuse; the simulation software for XENONnT.
- Uses simulated Kr83m events.

Impact of "Charge Insensitive Volume" (CIV): e- are lost to the wall here.

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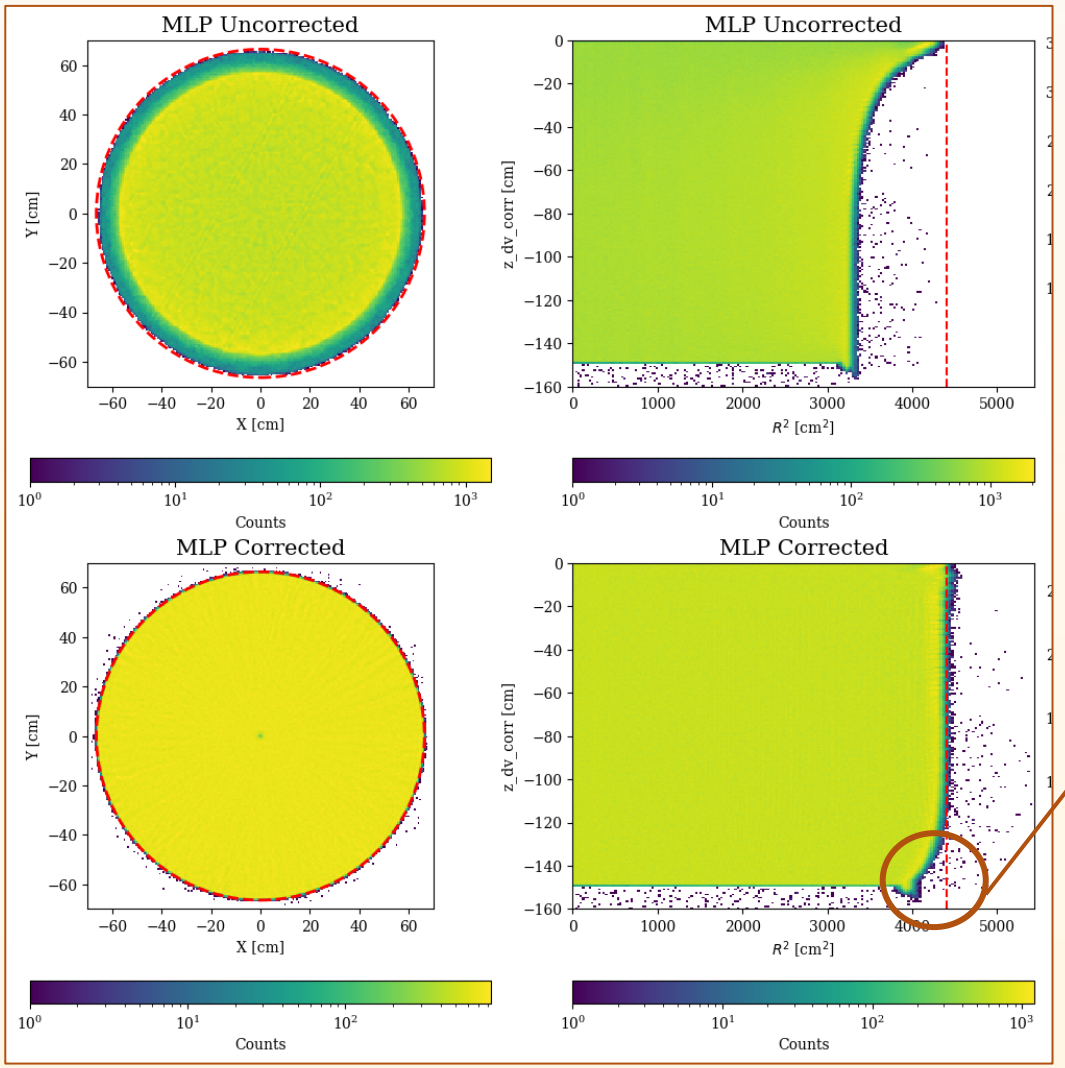

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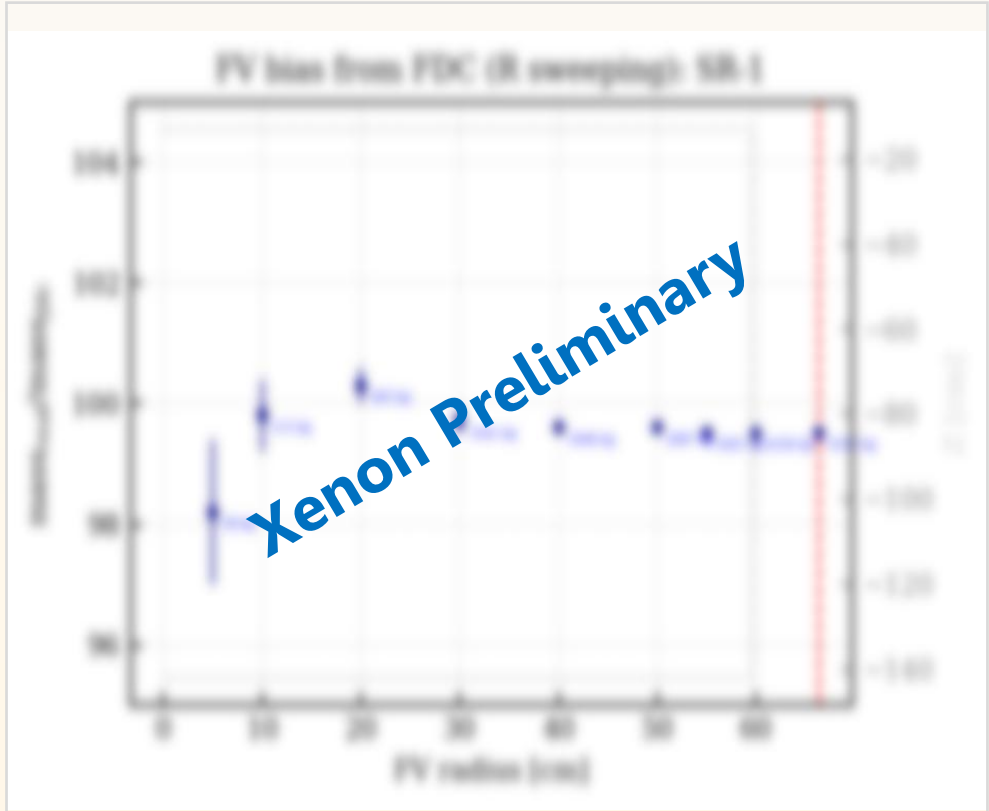


Correction factor for **"real" mass** in fiducial volume

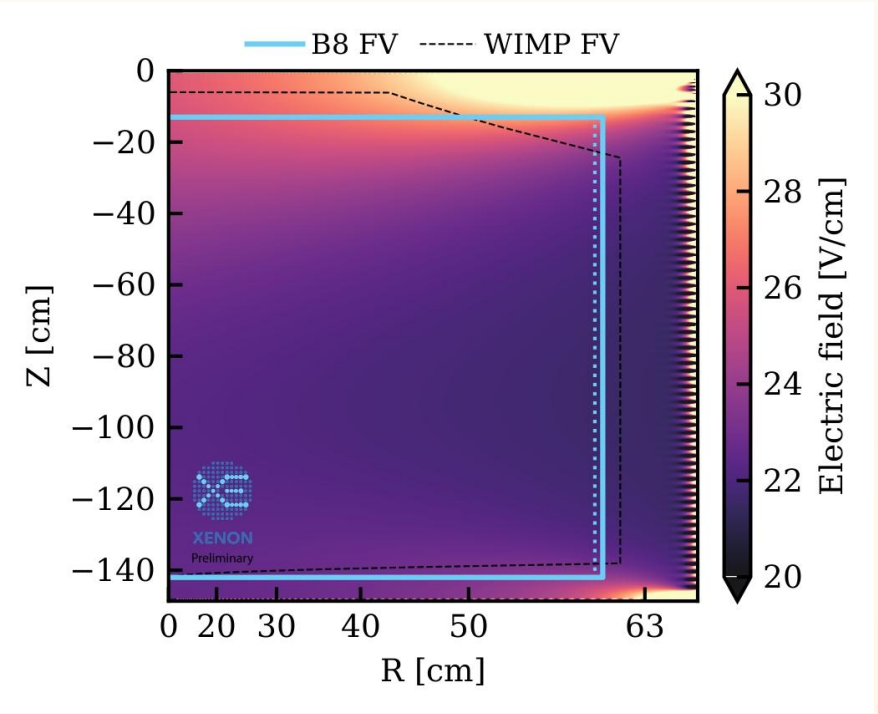
$$\frac{mass_{real}}{mass_{geometric}}$$

SR1: **99.5%**

$$\frac{mass_{real}}{mass_{geometric}}$$

SR0: **94.6%**

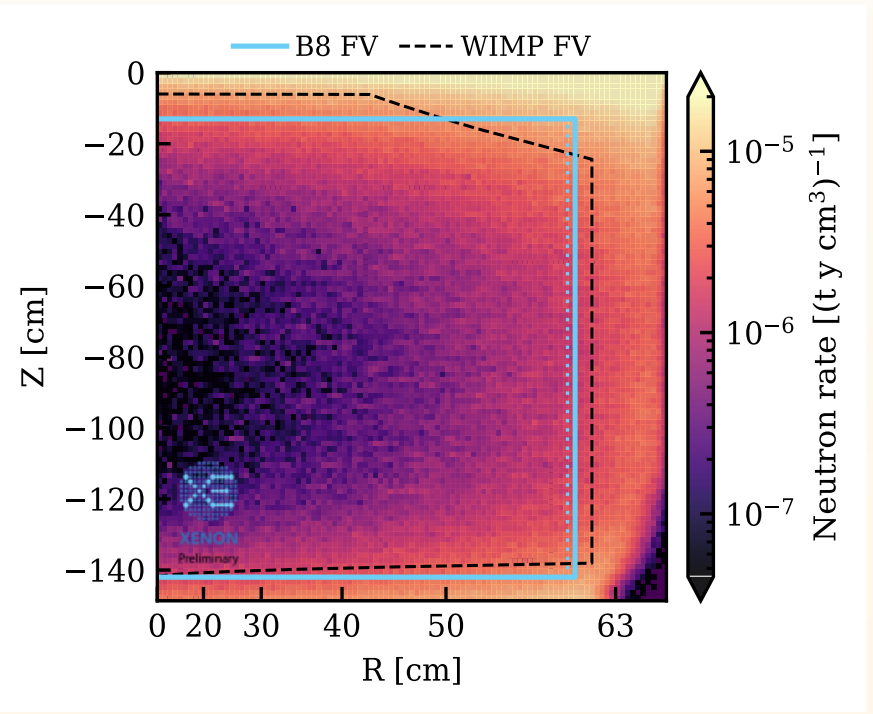
FDC and Fiducial Mass



Choice of Fiducial Volume

WIMP analysis; FV chosen to give the best signal-background discrimination ratio.

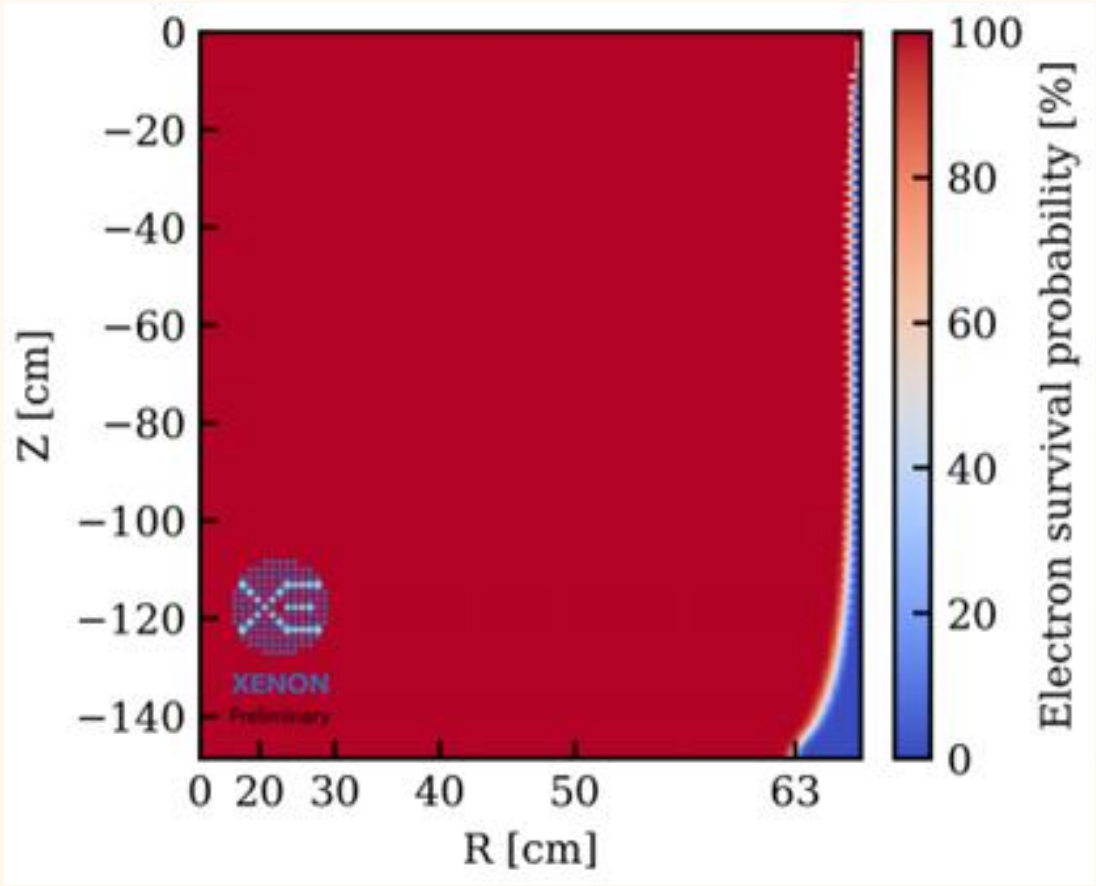
CEvNS analysis; FV chosen to exclude regions with limited detector modelling and higher background rates.



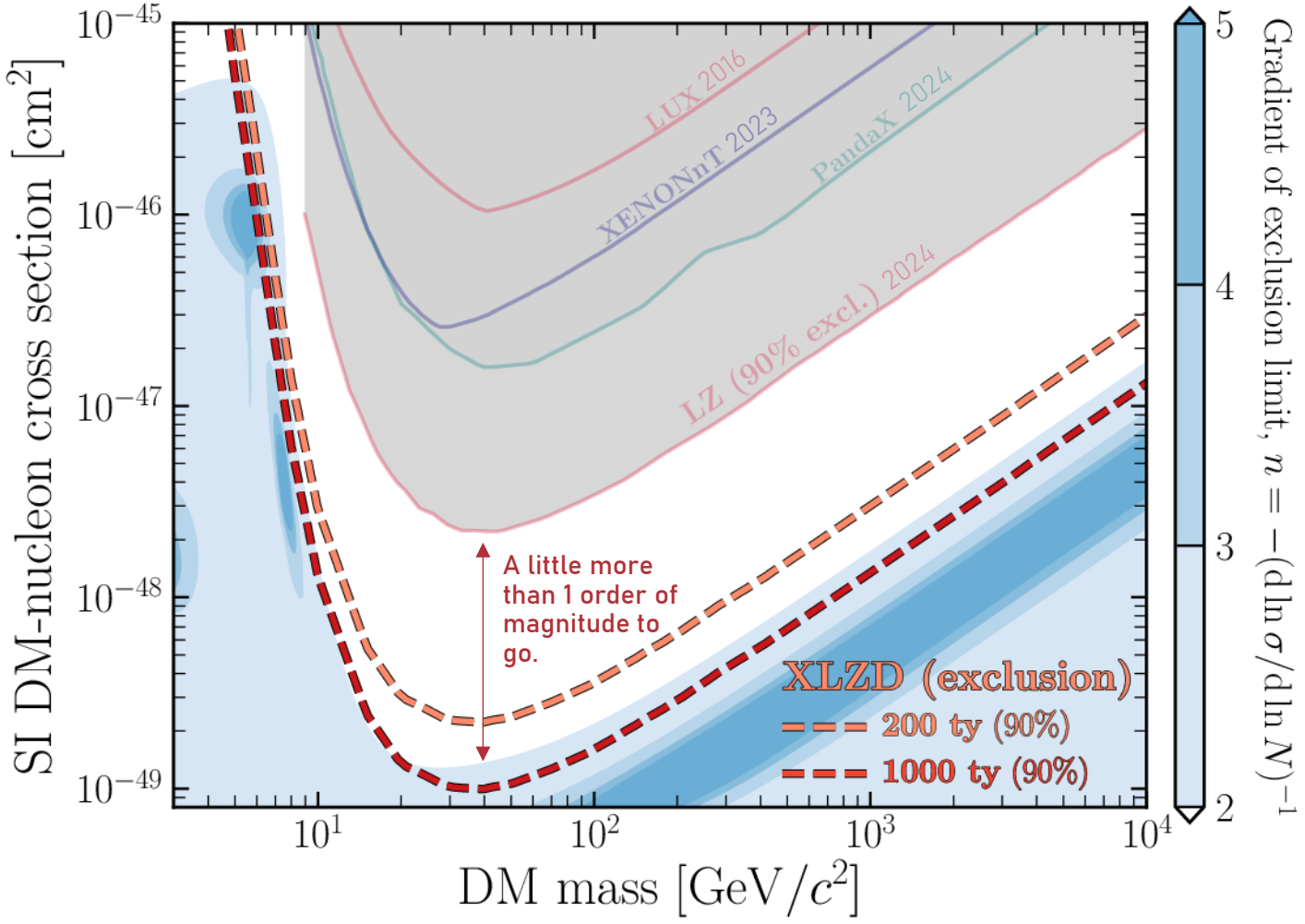
- But **"real" mass** within these volumes maybe **different** from what is calculated from **geometric volumes due to FDC.**
- Implementing the 'same' FDC procedure in both data and simulation pipelines allow to estimate the correction.

Charge Insensitive Volume (CIV)

- Electrons near the edge in the bottom part of the TPC may not reach the liquid-gas interface.
- These electrons **end up on the walls** of the TPC.
- The “farthest” event at this depth, that is reconstructed happened inward from the physical wall of the TPC.
- Pushing events till the physical wall (SR0 FDC) is **overcorrecting the position**.



Status of WIMP searches with LXe



XLZD is a collaboration between researchers in XENON, LZ and DARWIN to build the ultimate LXe based TPC with active target mass up to **80t**.

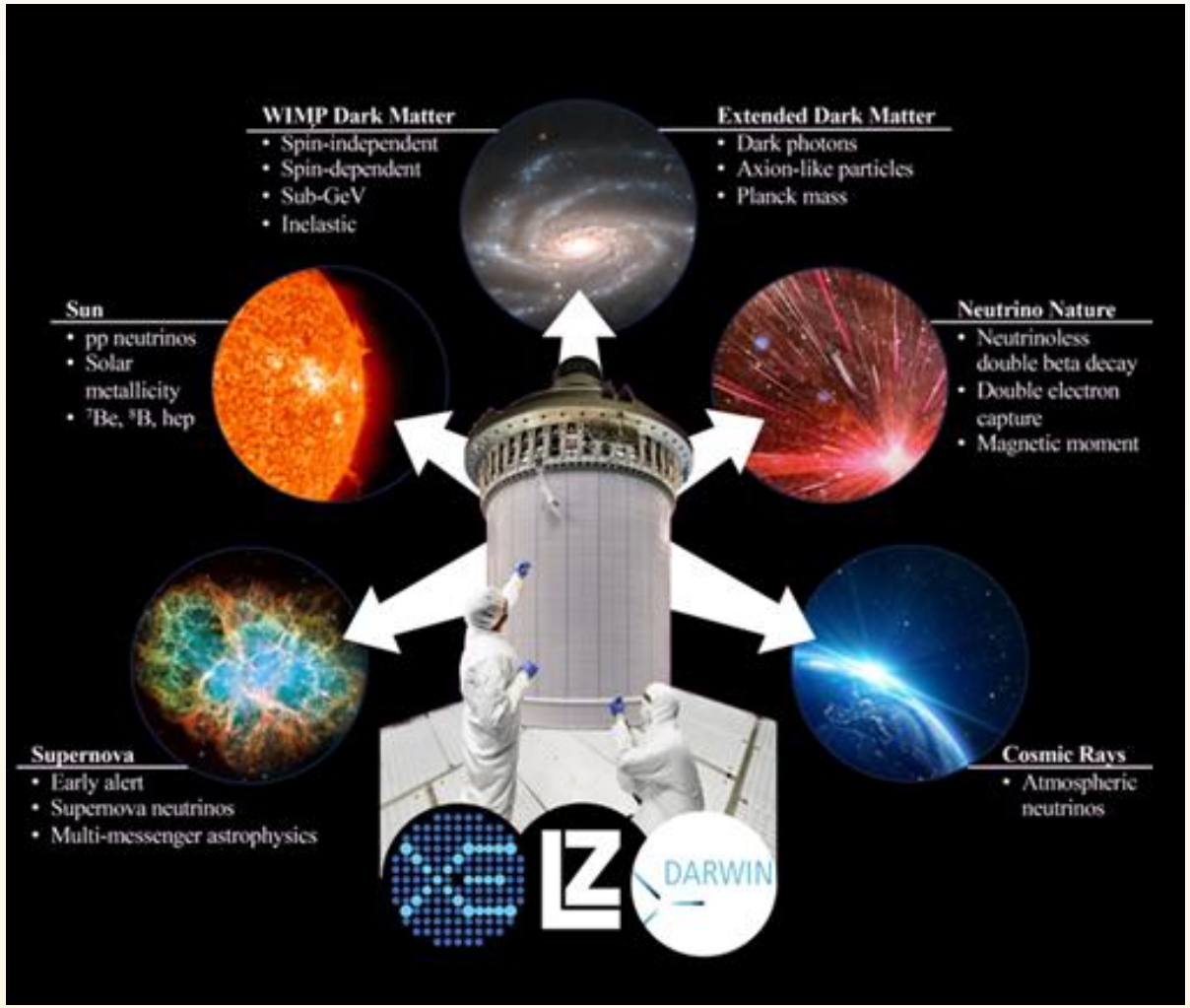
Design sensitivity all the way to the neutrino fog in the WIMP RoI.

arXiv:2410.17137 [hep-ex]

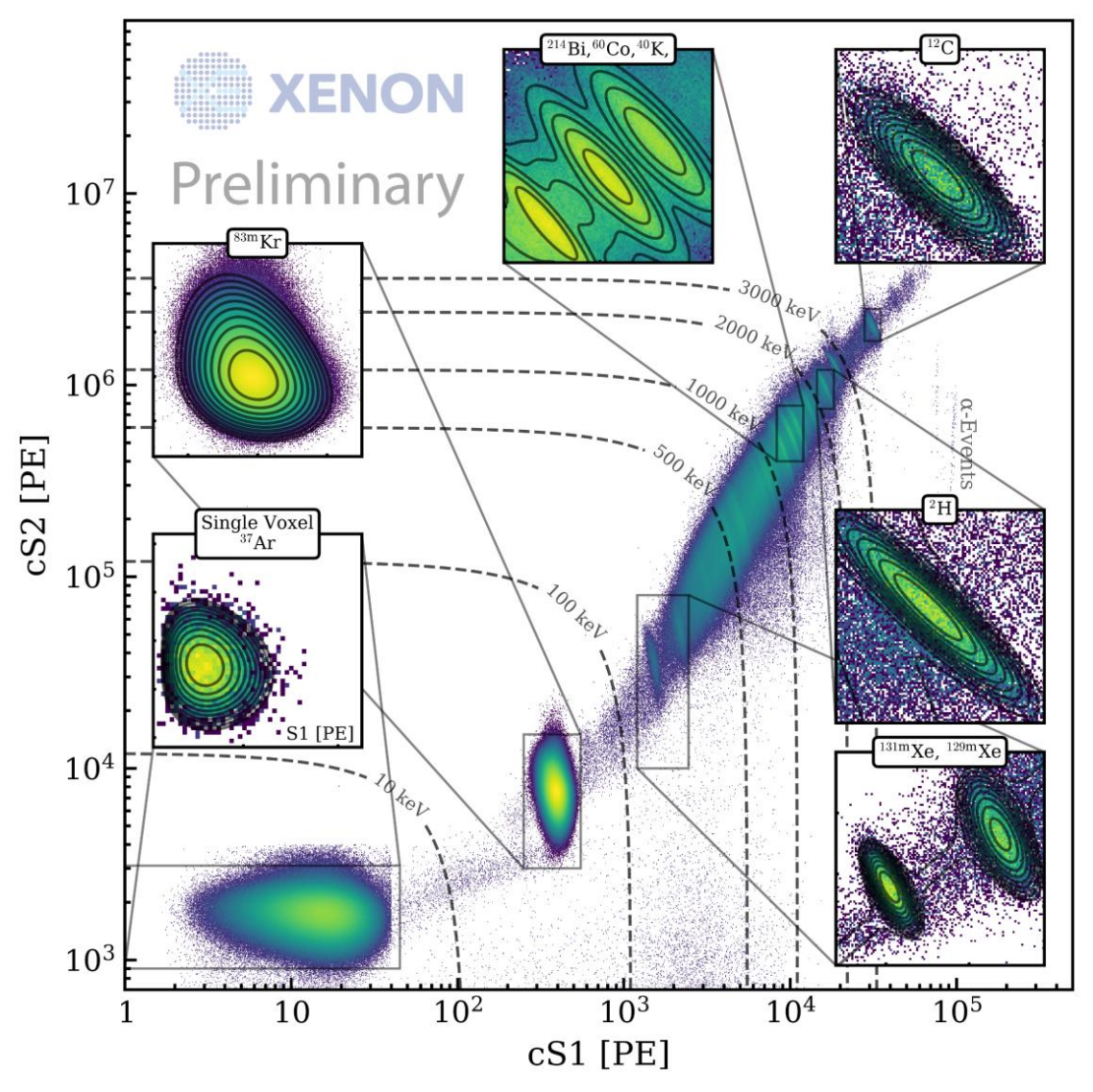
Next gen LXe TPC: XLZD

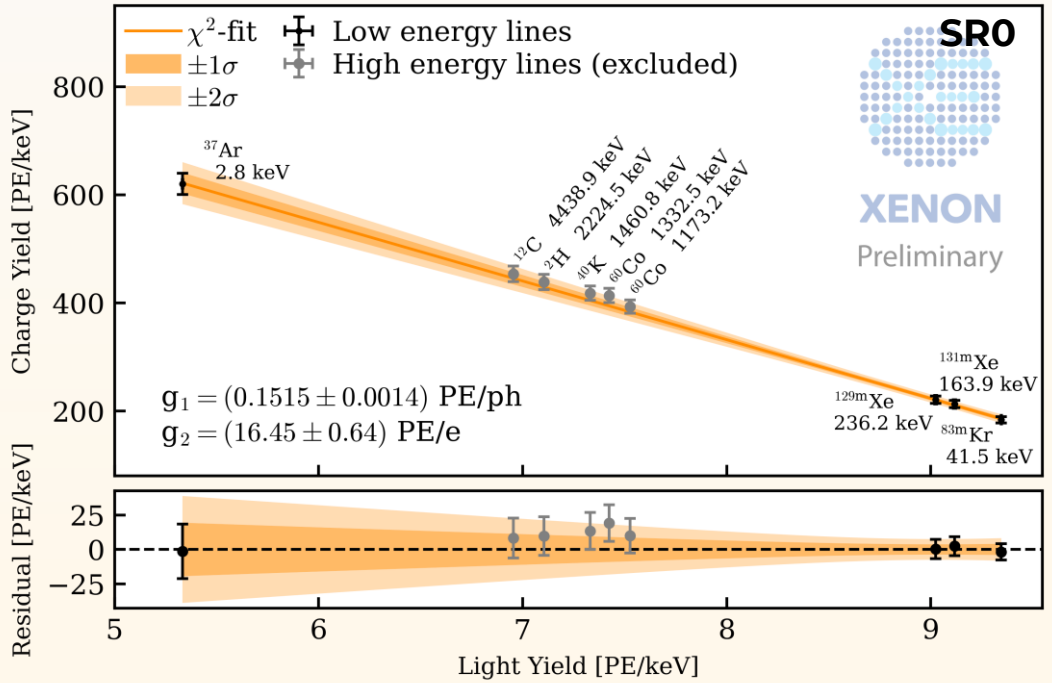
Baseline configuration: **60t LXe**

Expansion to **80t LXe** also proposed.



Energy Calibration: g1,g2

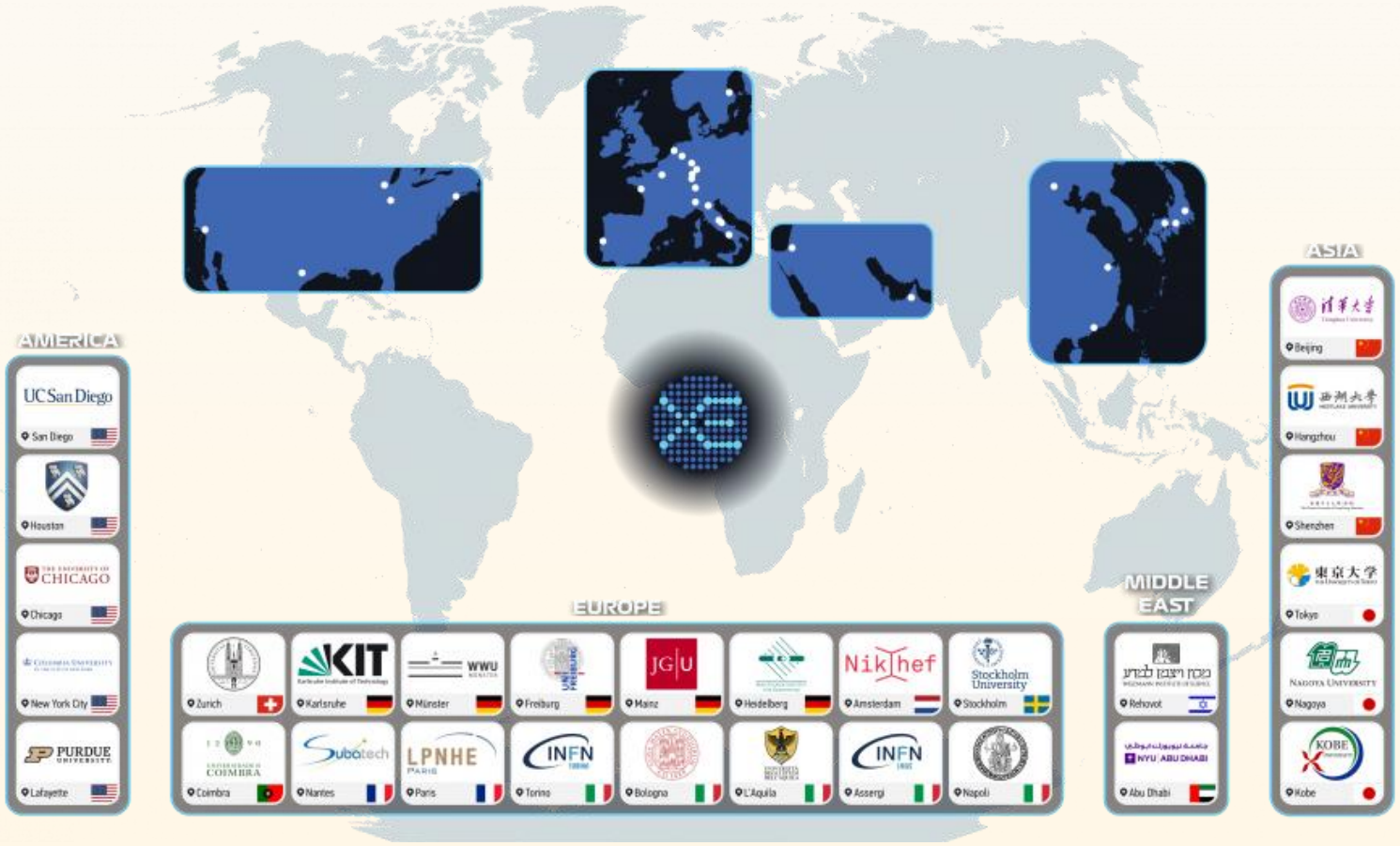




- g1,g2 calculated using monoenergetic peaks in cs1-cs2 space and the 'doke' plot.
- Combined energy scale: $E_{ces} = 13.7eV \times (cs1/g1 + cs2/g2)$

SR0	SR1
g1: $(0.151 \pm 0.001)PE/ph$ g2: $(16.45 \pm 0.64)PE/e$	g1: $(0.136 \pm 0.001)PE/ph$ g2: $(16.85 \pm 0.46)PE/e$

The XENON Collaboration



200+ Scientists	29 Institutions	12 Countries

XENON program timeline

XENON10
25 kg LXe

2006
58.6 livedays
BG: 600 / (t.d.keV)

XENON100
160 kg LXe

2008
477 livedays
BG: 5.3 / (t.d.keV)

XENON1T
3200 kg LXe

2015
279 livedays
BG: 0.2 / (t.d.keV)

XENONnT
8600 kg LXe

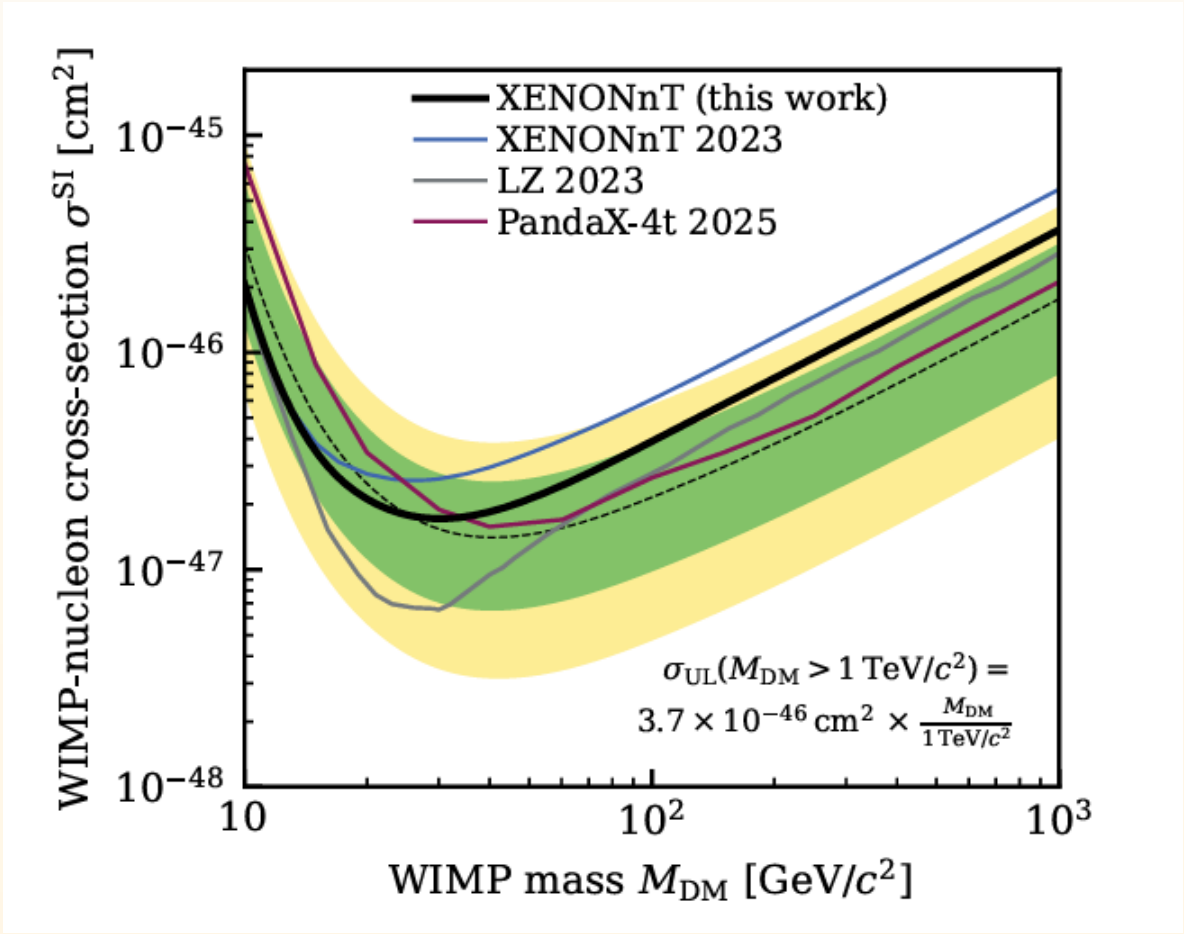
2020
300+ livedays
(ongoing)

BG: 0.04 / (t.d.keV)

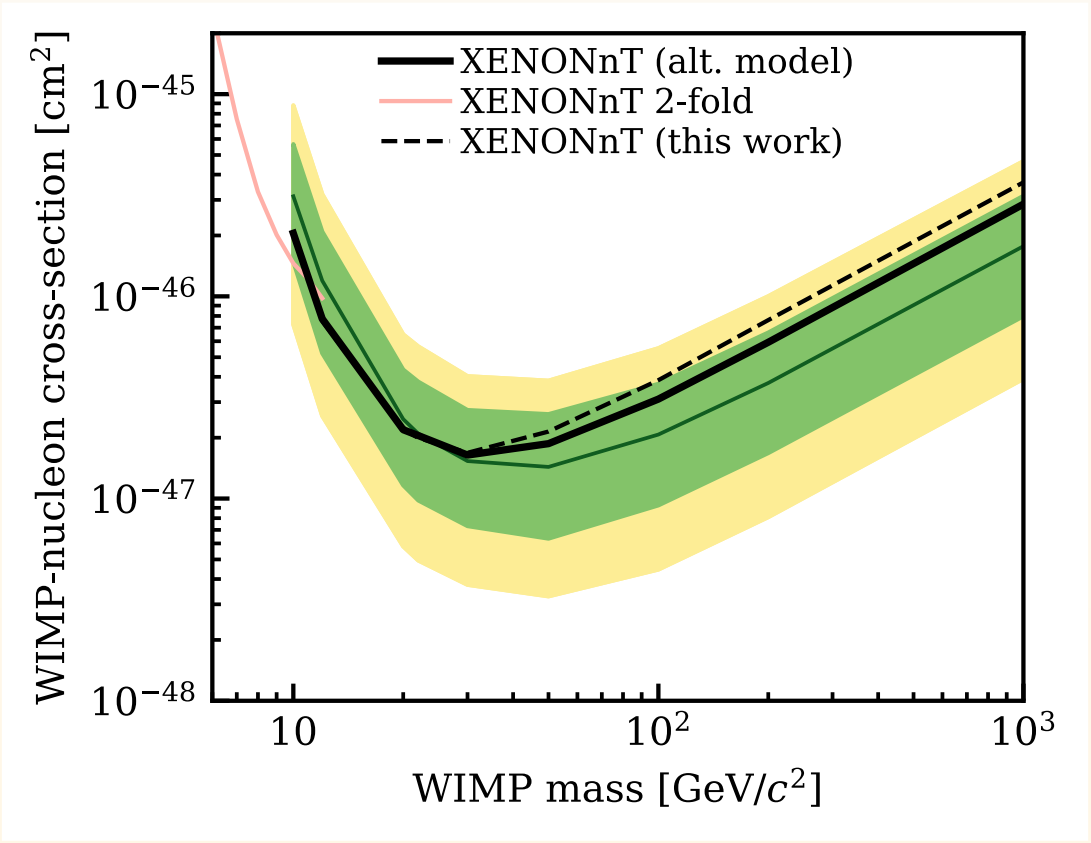
Lowest ER background level ever achieved in a LXe based experiment!!

WIMP Results: SR0+1

Preliminary: Publication in preparation.



Main result: with nominal model.



Comparison: with result using alternate model.