

Dark Matter Experiments - II

Maxime Pierre

Lecture 1 - Dark Matter Direct Detection part 1

Direct Detection Principle

Low-background Experiments

Experimental Landscape

Lecture 2 - Dark Matter Direct Detection part 2

Case Example: XENONnT

New indication for DM?

Axions

Lecture 3 - Dark Matter Production

Dark Matter Indirect Detection

1

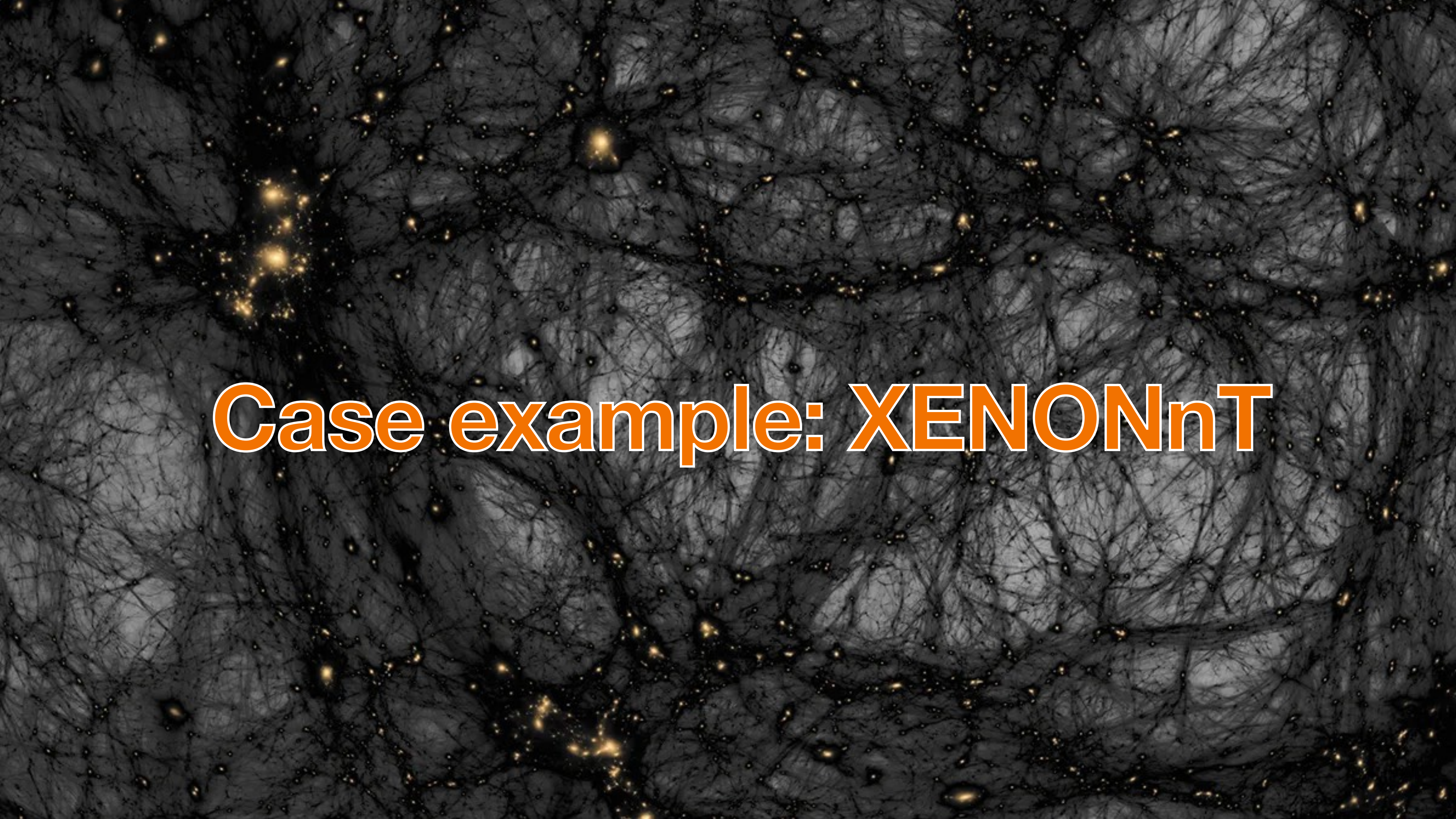
Case example: XENONnT

Let's study a specific case example: XENONnT

2

Application to Neutrino Physics

More than just Dark Matter Direct Detection

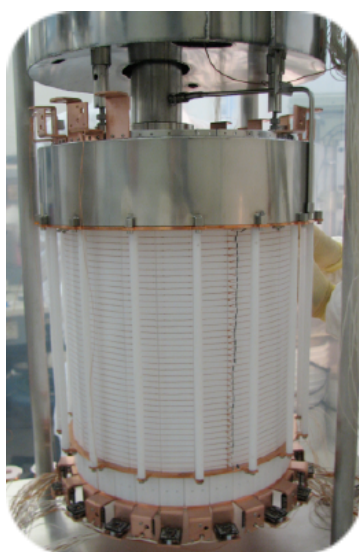
The background of the slide is a detailed visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. Numerous bright yellow and orange points of light, representing galaxies, are scattered throughout the dark, textured space. The text "Case example: XENONnT" is centered in the middle of the image.

Case example: XENONnT

- Fourth generation of XENON experiment
 - ➔ Based on the same detection technology: **dual-phase Time Projection Chamber**
 - ➔ Already **demonstrated the scalability** of this technology



Xe XENON10

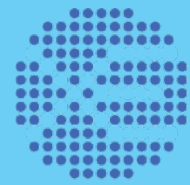


Xe XENON100



Xe XENON1T



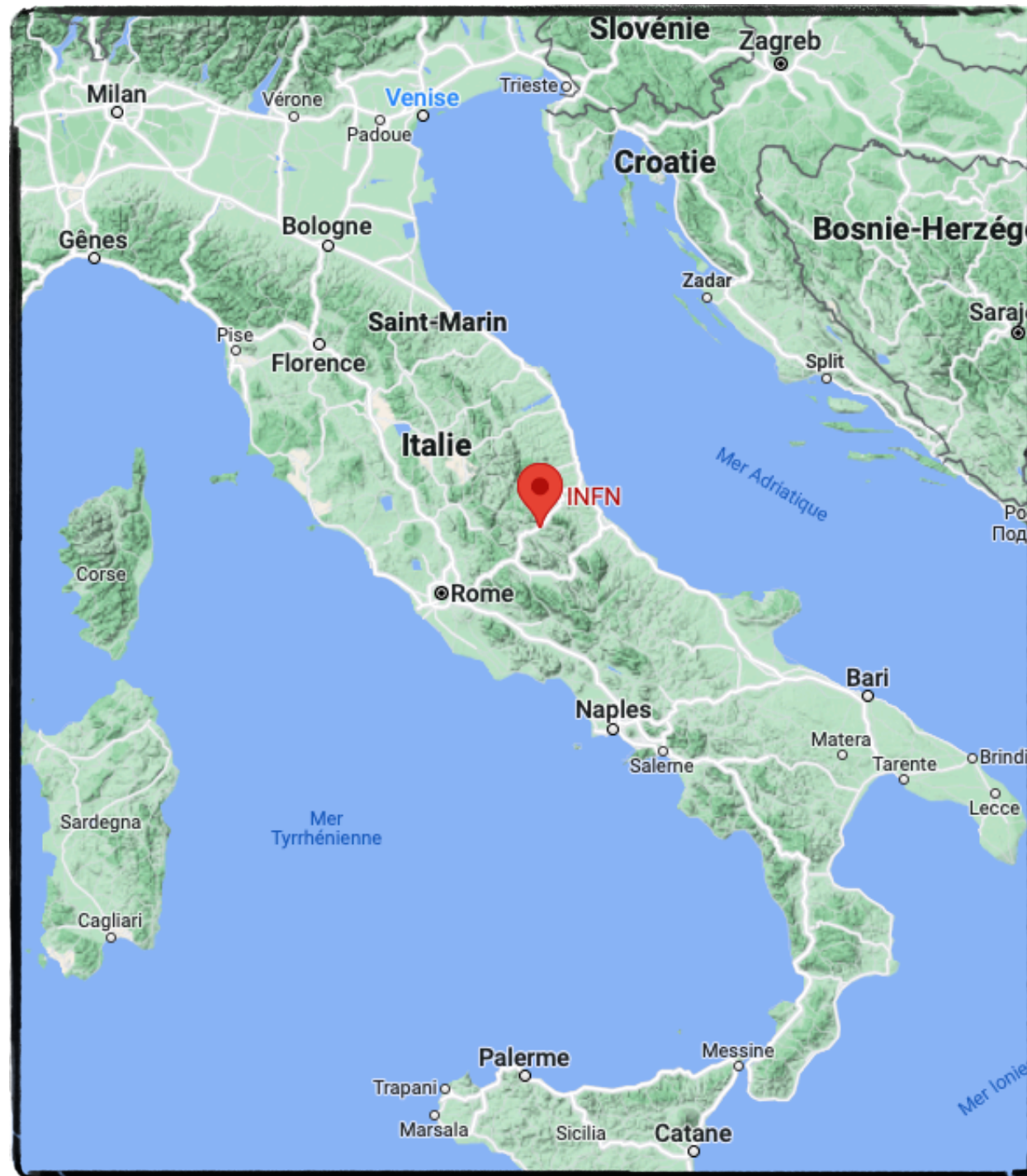
 XENONnT

Time		2005	2008	2016	2021	Projections * ↑
Active mass		15 kg	62 kg	2000 kg	5900 kg	
[t.day.keV] ⁻¹ Background		~1000	5.3	0.2	*0.04	
[cm ²] DM Sensitivity		~10 ⁻⁴⁴	~10 ⁻⁴⁵	~10 ⁻⁴⁷	*~10 ⁻⁴⁸	

Laboratori Nazionali del Gran Sasso (LNGS) 6

Aboveground Laboratory

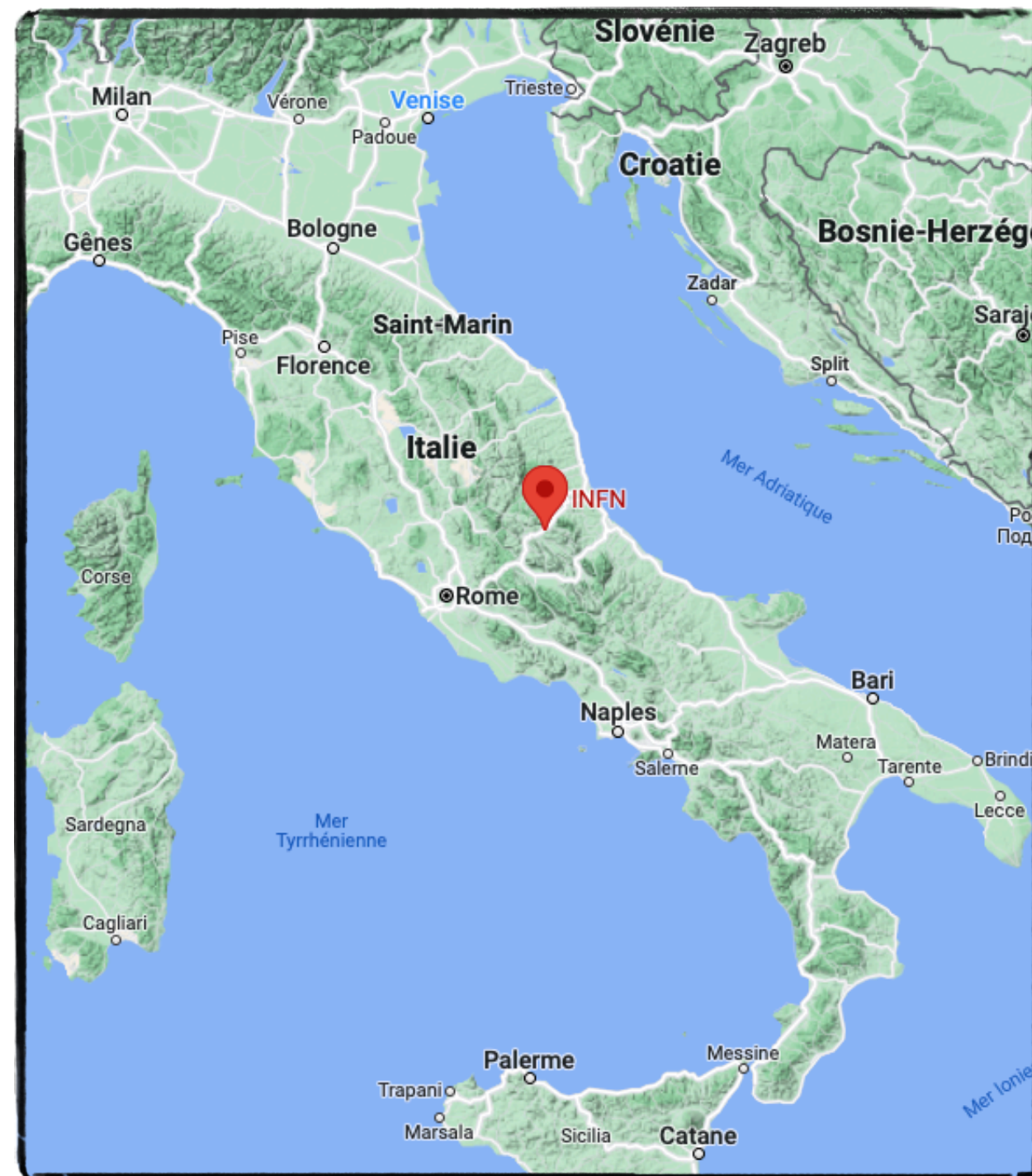
- Operating at the **INFN - Laboratori Nazionali del Gran Sasso (LNGS)**
 - ➔ Underground laboratory with 1300 m overburden (3600 m.w.e)



Laboratori Nazionali del Gran Sasso (LNGS) 6

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Laboratori Nazionali del Gran Sasso (LNGS) 7

Underground Laboratory



Xenon Properties

- Most radiopure Noble Gases.

Isotope	Abundance [%]	Decay mode	Half-life [years]
^{124}Xe	0.09	$2\nu\text{ECEC}$	$(1.1 \pm 0.2_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}$
^{126}Xe	0.09	stable	-
^{128}Xe	1.92	stable	-
^{129}Xe	26.4	stable	-
^{130}Xe	4.08	stable	-
^{131}Xe	21.2	stable	-
^{132}Xe	26.9	stable	-
^{134}Xe	10.4	stable	-
^{136}Xe	8.87	$2\nu\beta\beta$	$(2.165 \pm 0.016_{\text{stat}} \pm 0.059_{\text{sys}}) \times 10^{21}$

Xenon Properties

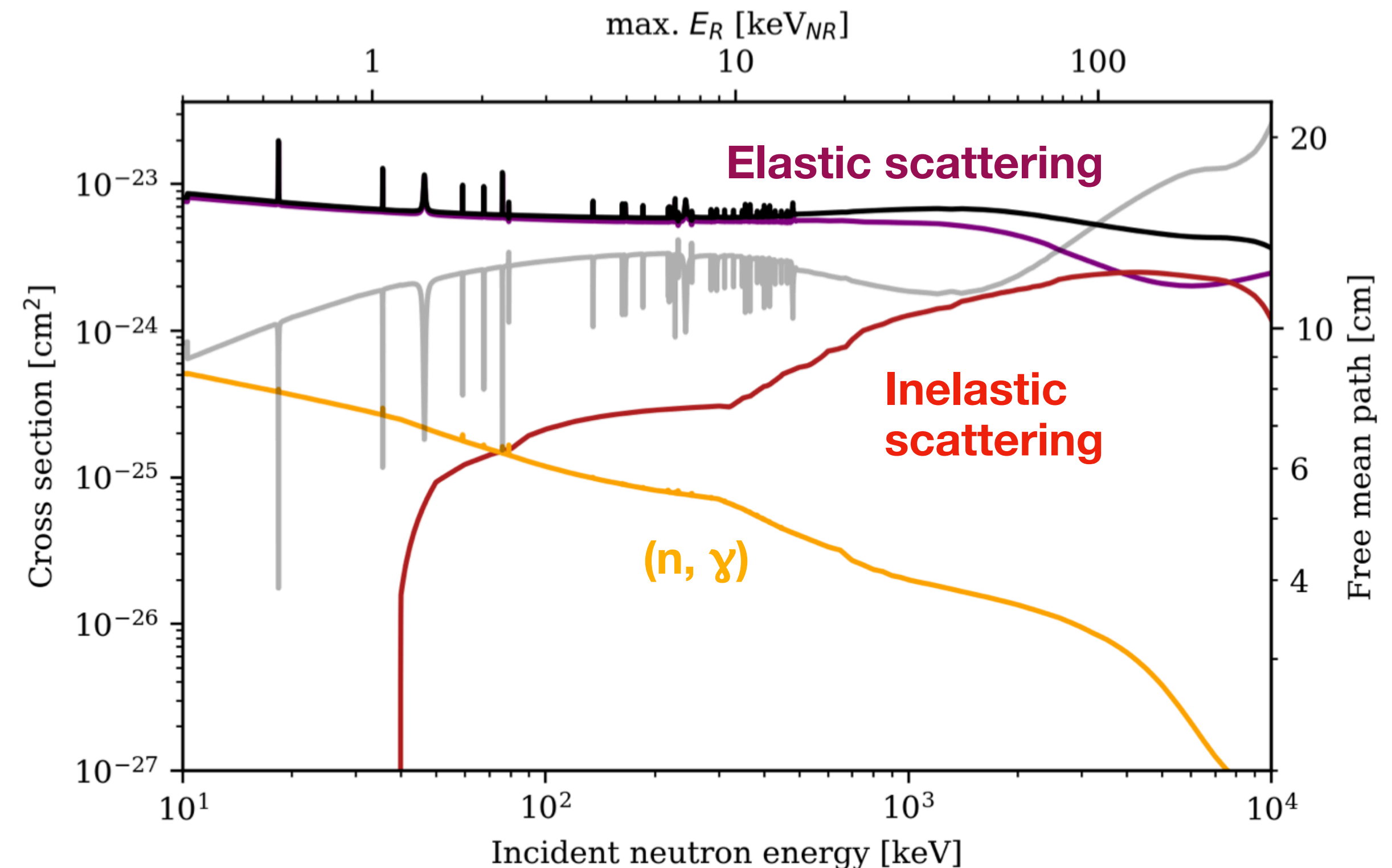
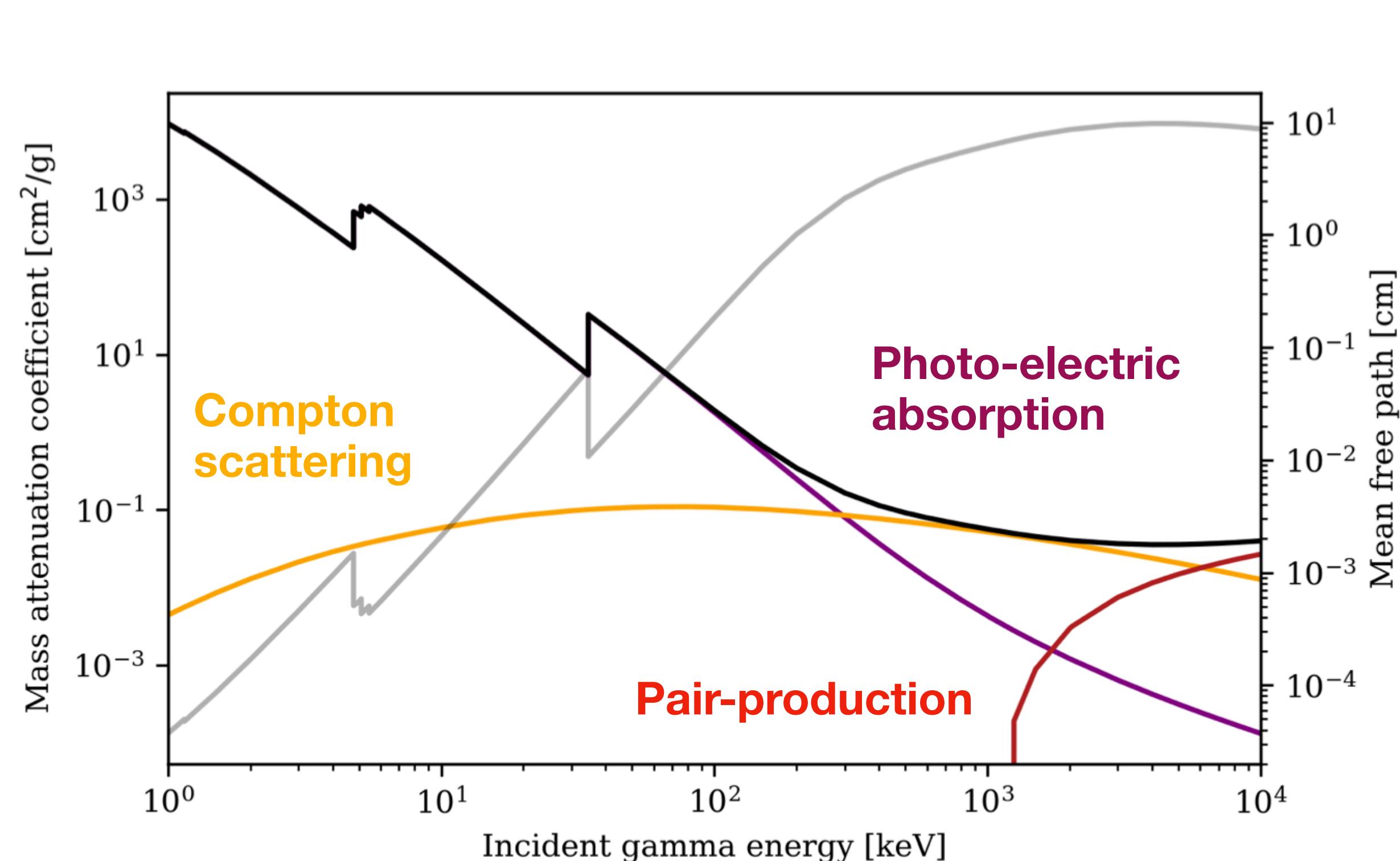
- Most radiopure Noble Gases.
- Efficient (Self-)shielding material ($Z=94$, $\rho_{\text{LXe}} \sim 2.9 \text{ g/cm}^3$).

→ Electron $< \mathcal{O}(1\text{-}10) \text{ mm}$

→ Gamma $< \mathcal{O}(10) \text{ cm}$

→ Neutron $< \mathcal{O}(10) \text{ cm}$

Tend to do
Multiple-Scatter



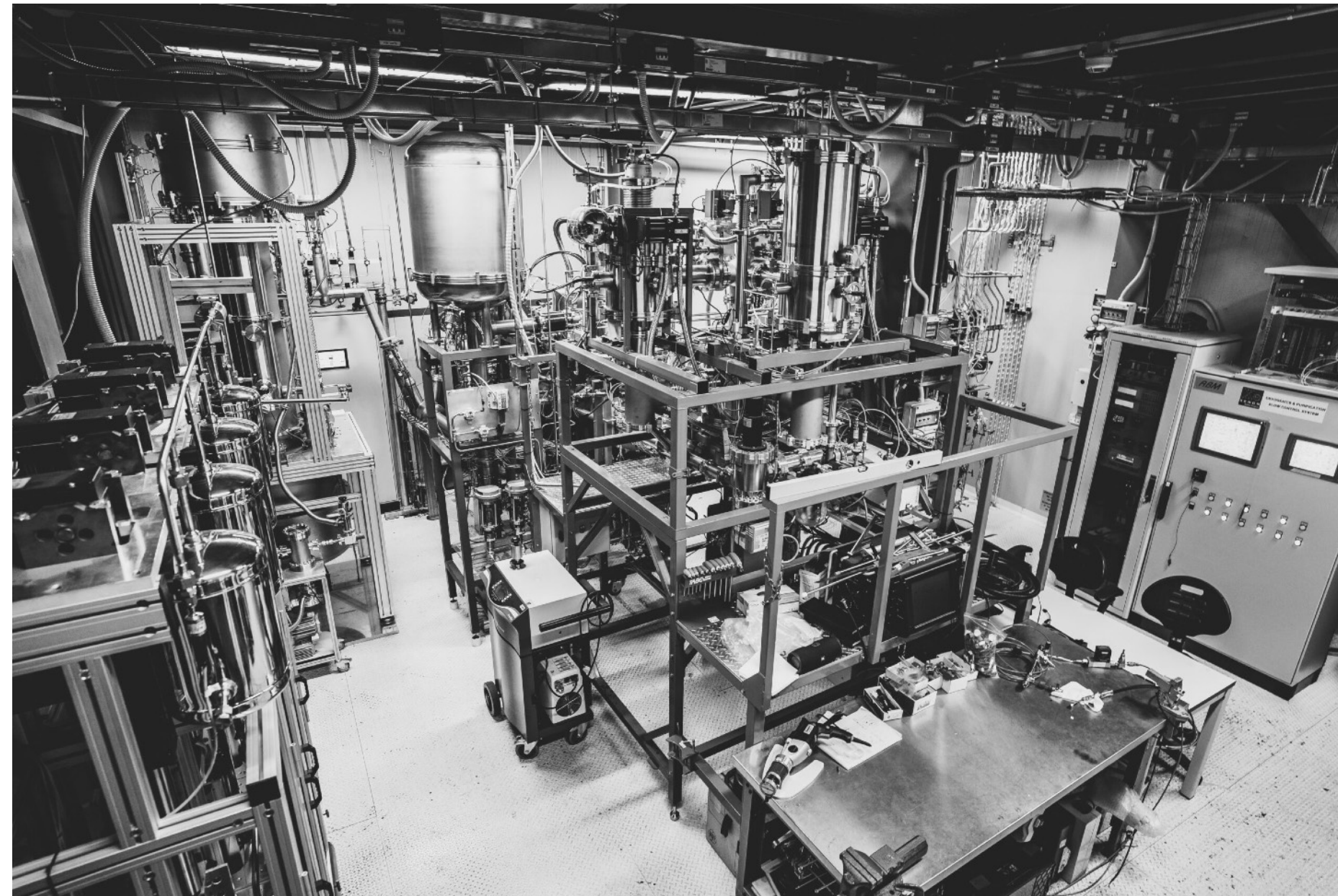
Xenon Properties

- Most radiopure Noble Gases.
- Efficient **(Self-)shielding** material ($Z = 94$, $\rho_{\text{LXe}} \sim 2.9 \text{ g/cm}^3$).
- Relatively easy to operate in liquid phase:
 - Can build compact detector and can be **scaled to largest mass**
 - high boiling point temperature ($\sim 178 \text{ K}$ at $P \sim 2 \text{ bar}$) $\rightarrow$

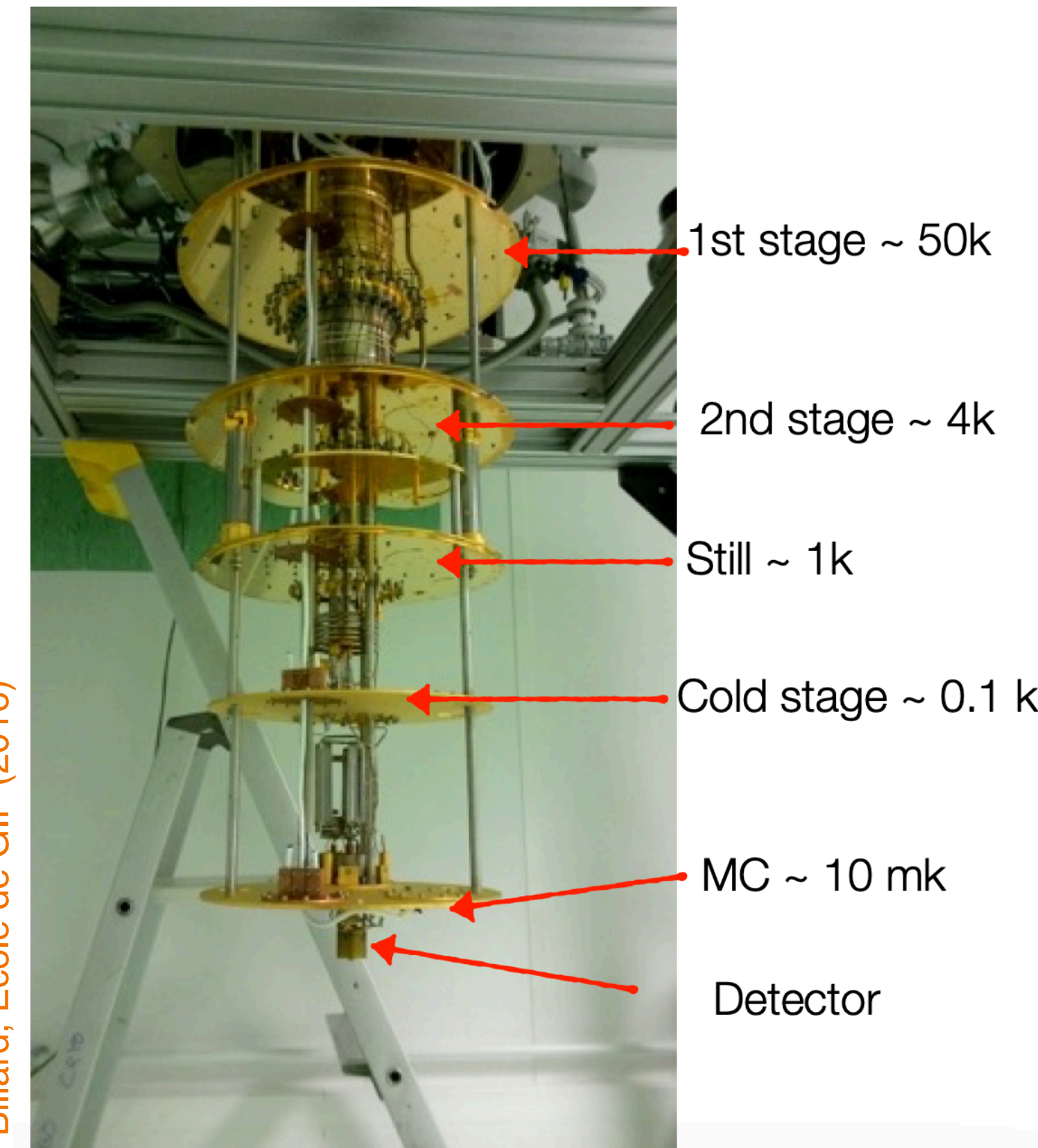
“Modest” cryogenic

XENONnT Cryogenic system

<https://xenonexperiment.org/photos/>



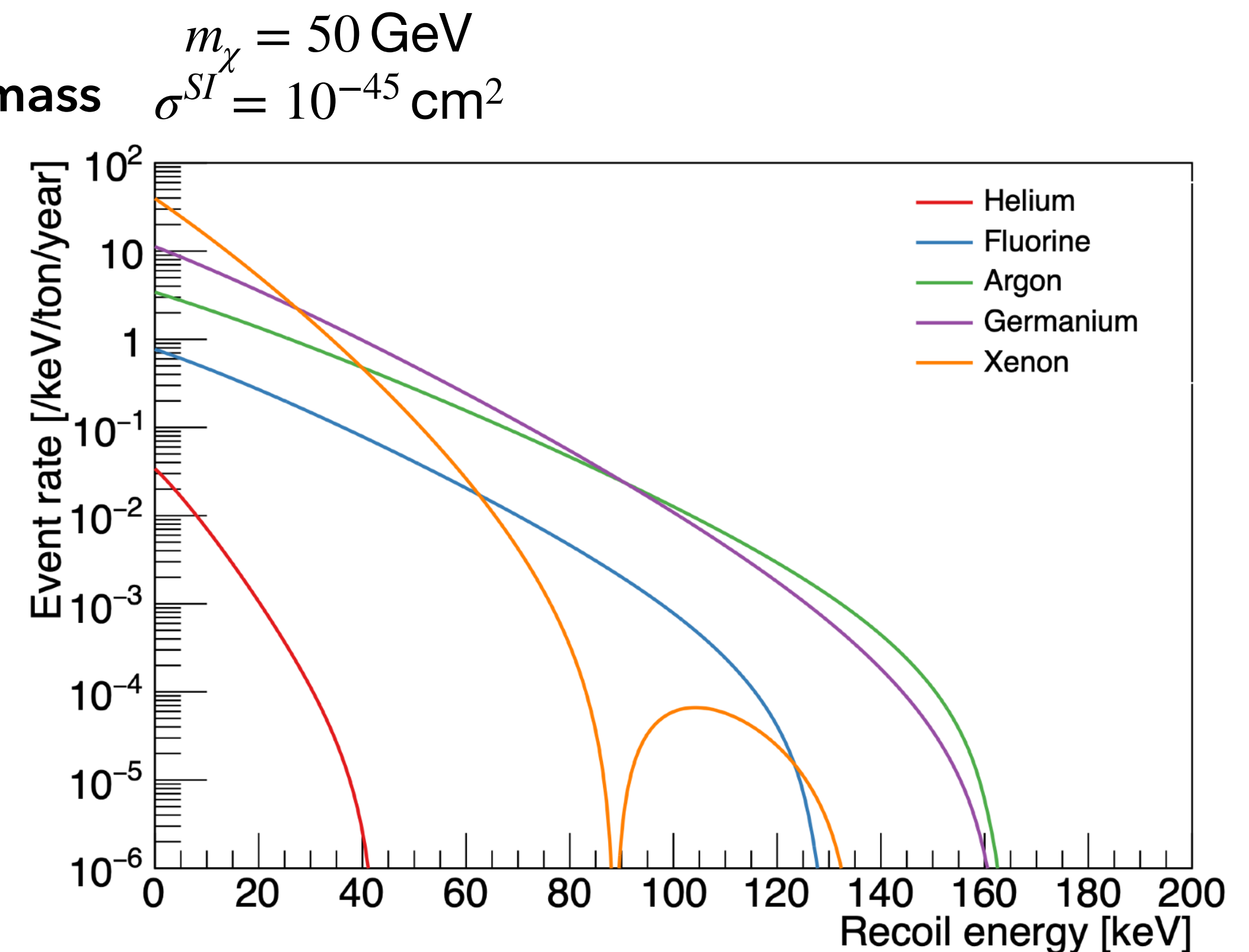
Multi-stage cooling for cryogenic bolometers



J. Billard, Ecole de GIF (2016)

Xenon Properties

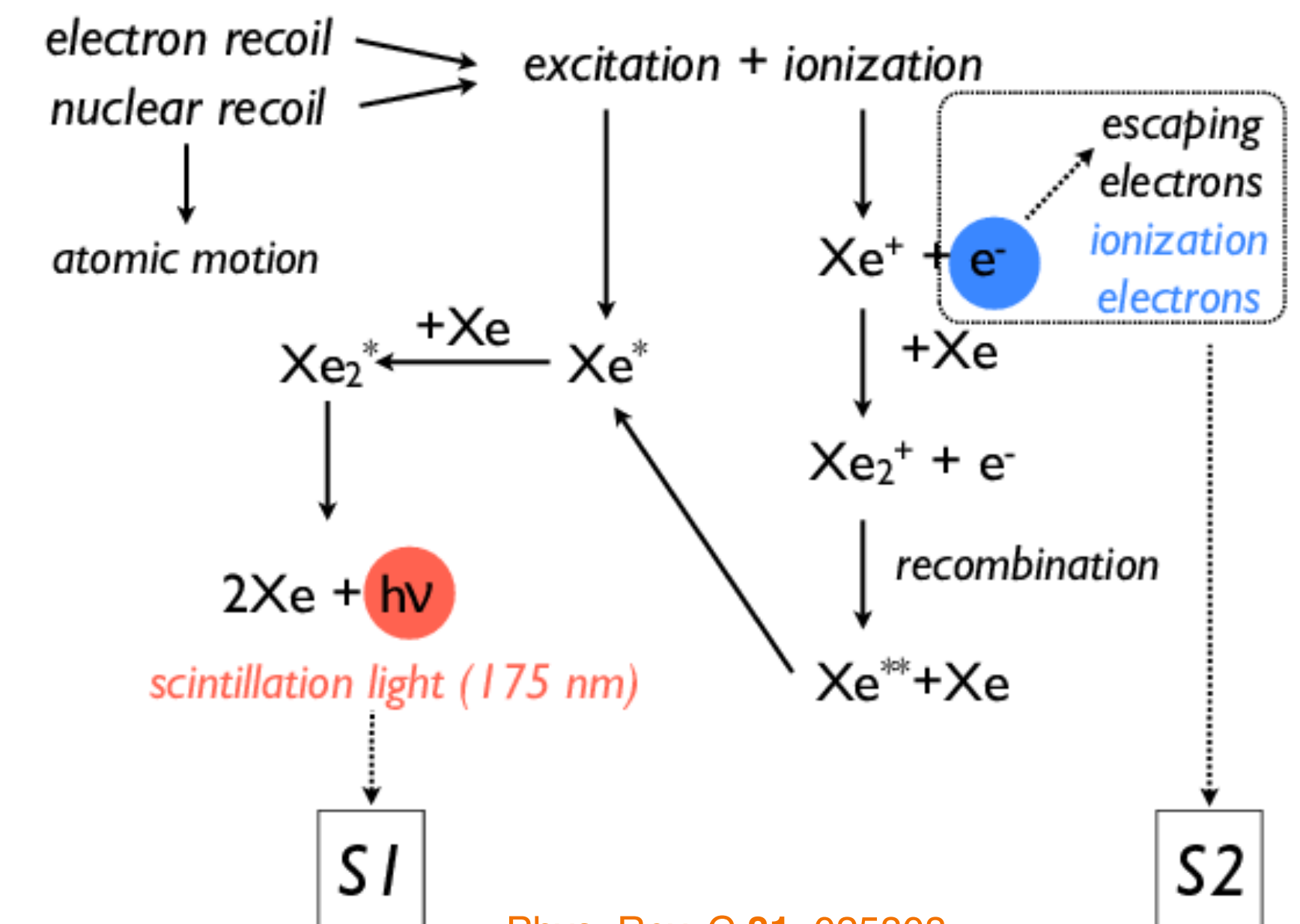
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“Modest” cryogenic
- Act as both a target and detection medium!



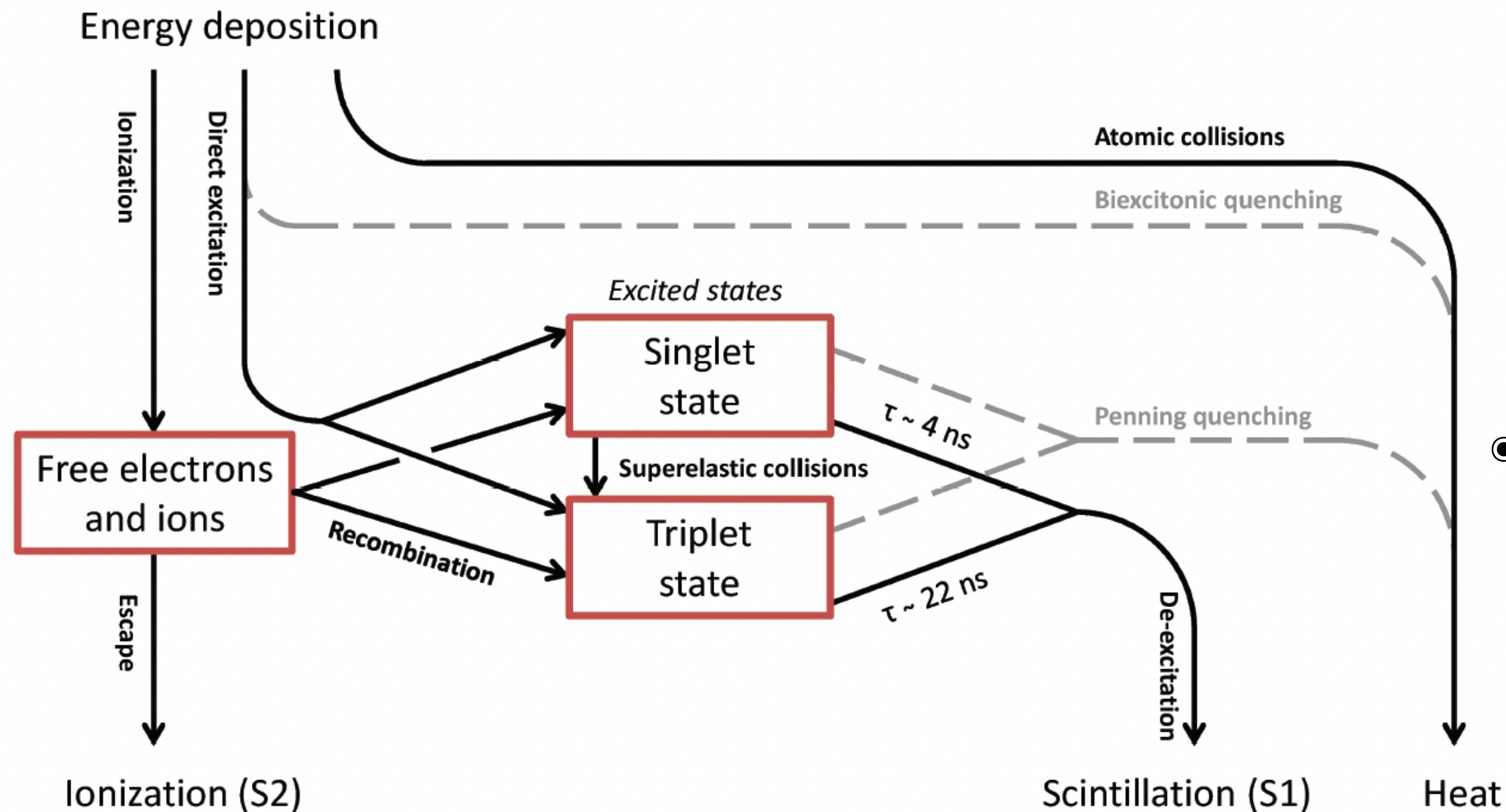
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Xenon is transparent to its own scintillation light (VUV photon)!



Zoom in energy transfer in Xenon:

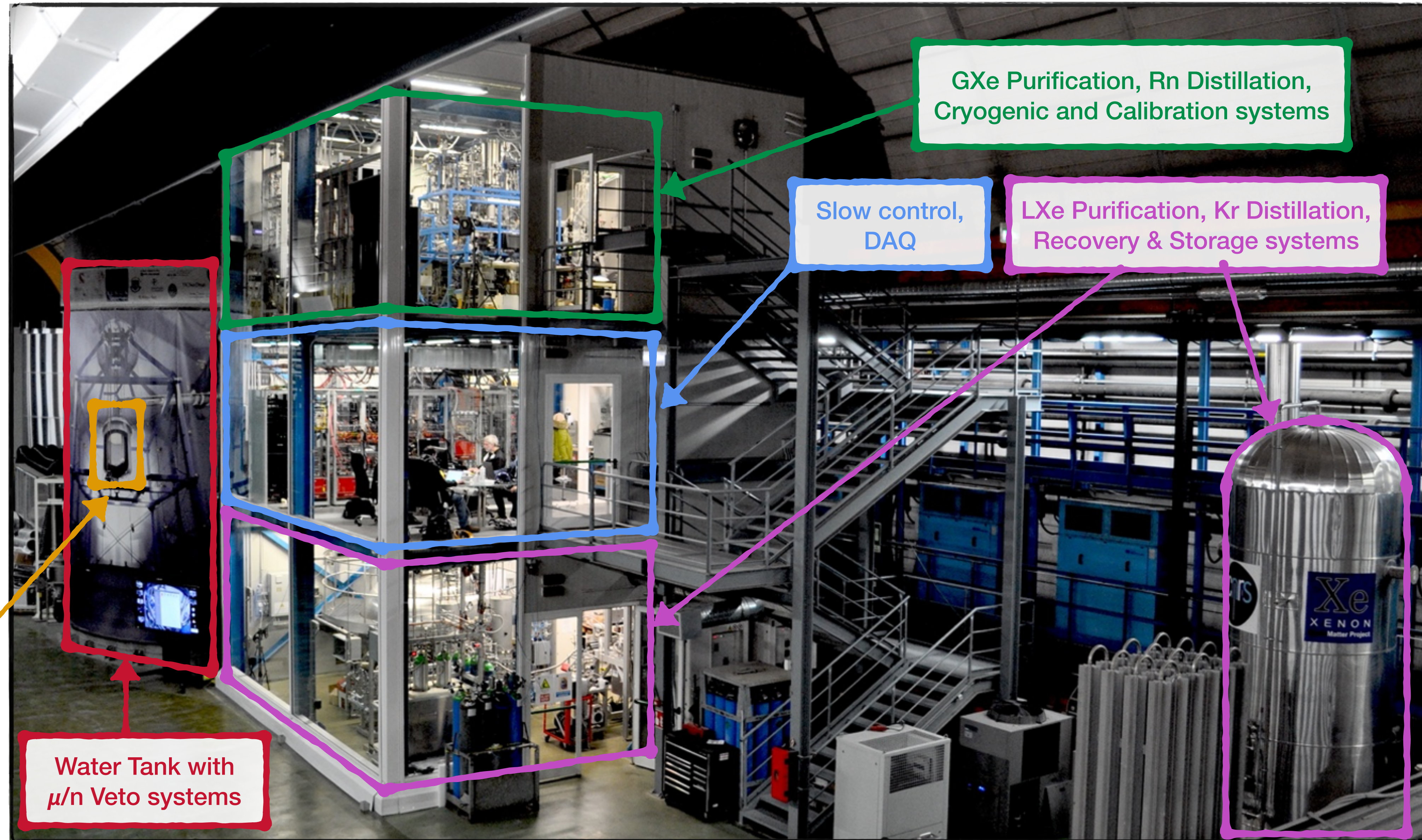


- Singlet/Triplet lifetime are very different between Argon (~ 6 ns, $\sim 1.5\mu\text{s}$) and Xenon (~ 4 ns, ~ 22 ns)
 - ➔ Scintillation Pulse-Shape
 - ➔ Ratio between two states depends on the energy deposited density distribution (particle dependent) $\rightarrow$ PSD
- Use Electric field to extract free electrons and infer the light and charge quanta produced.
 - ➔ Light and charge quanta ratio depends on Linear Energy Transfer (LET), which vary for different particle $\rightarrow$ ER/NR discrimination

XENONnT Experiment Overview

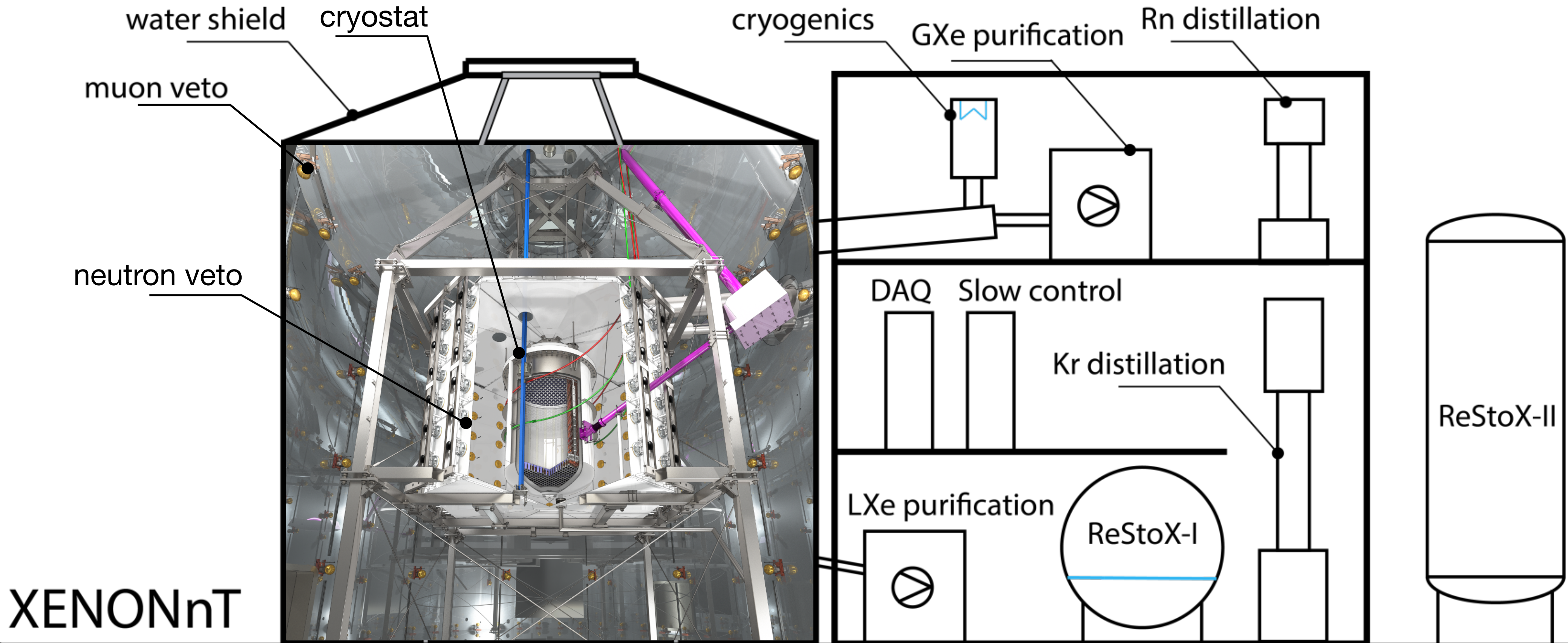
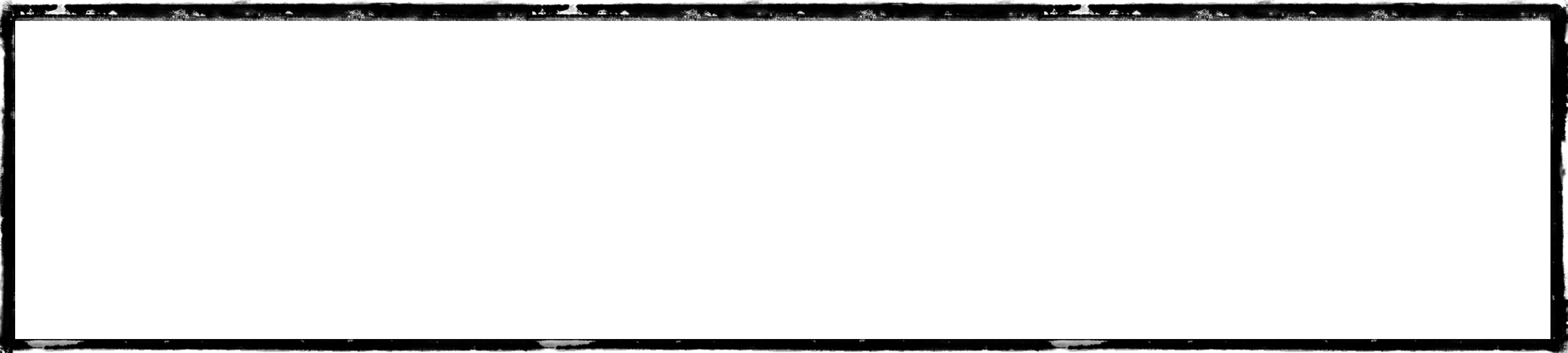
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Not just one
detector



XENONnT Experiment Overview

XENON1T
UPGRADE



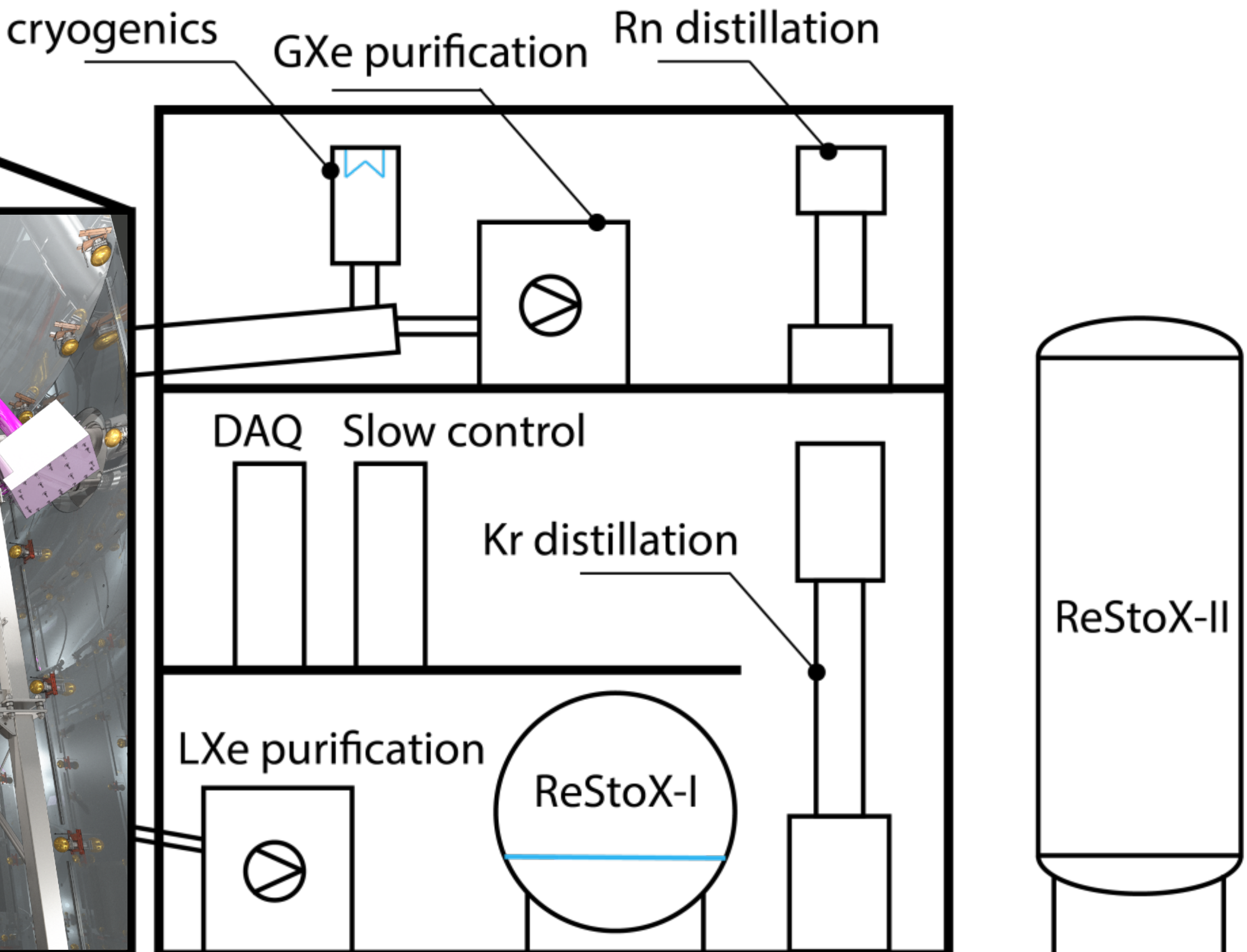
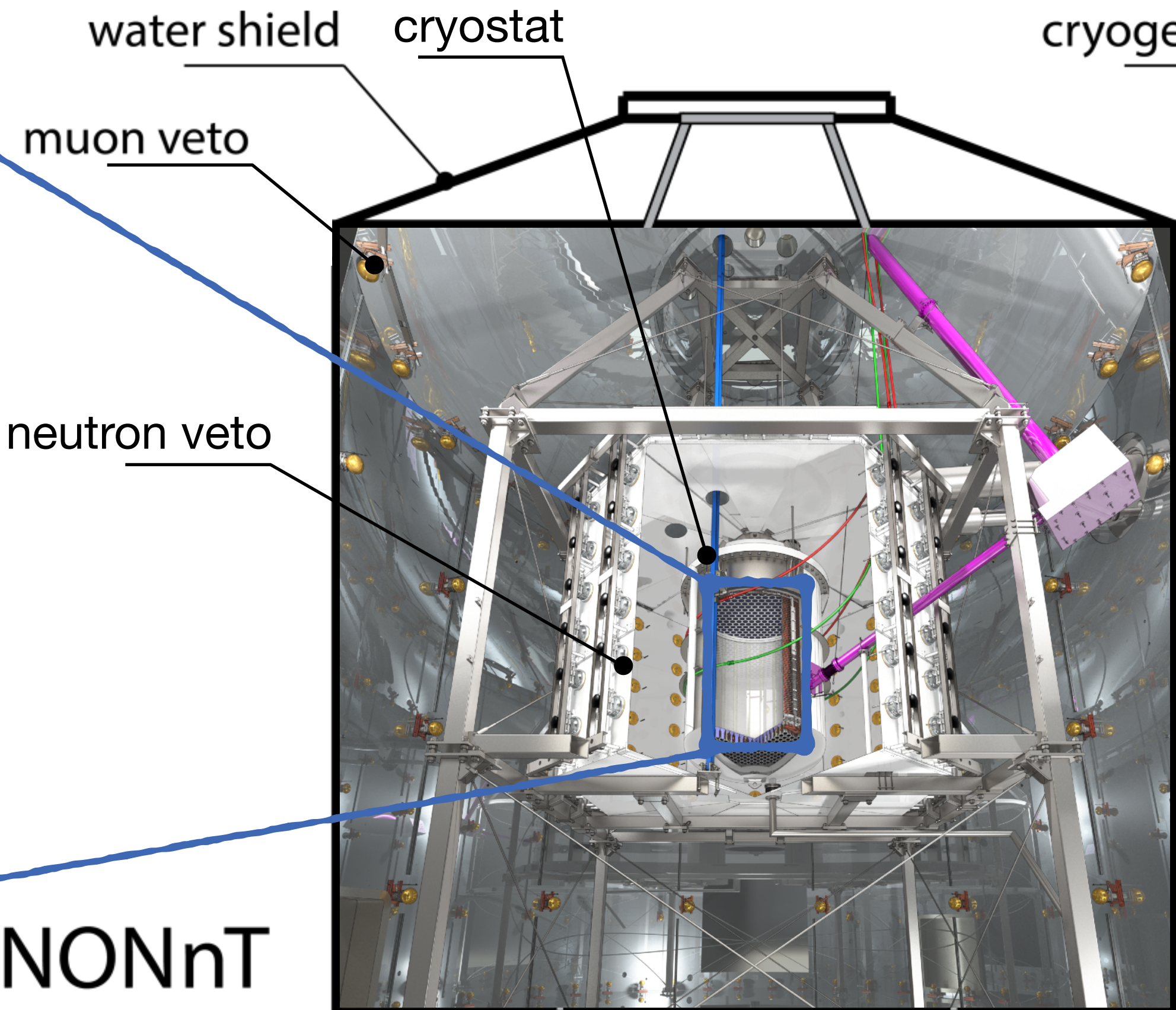
XENONnT Experiment Overview

XENON1T
UPGRADE

x3 larger TPC
8.5 t LXe
494 PMTs



XENONnT

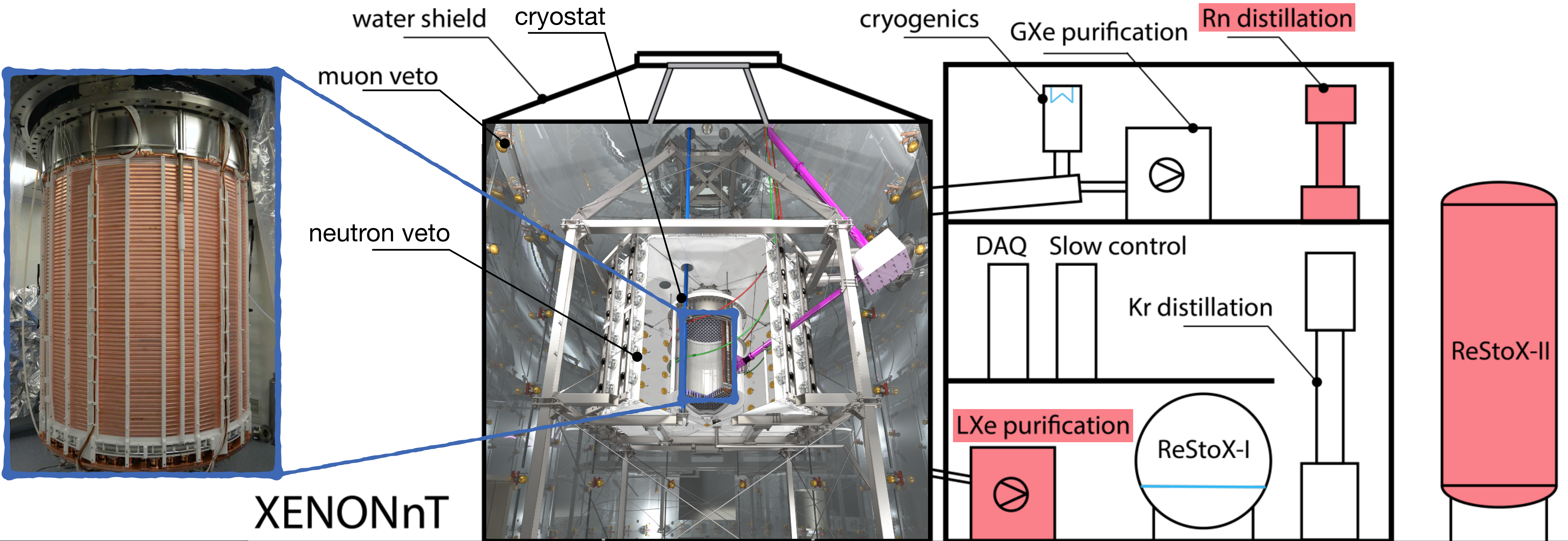


XENONnT Experiment Overview

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UPGRADE

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Xenon handling
New purification
& ER bkg. reduction
New recovery/storage



XENONnT

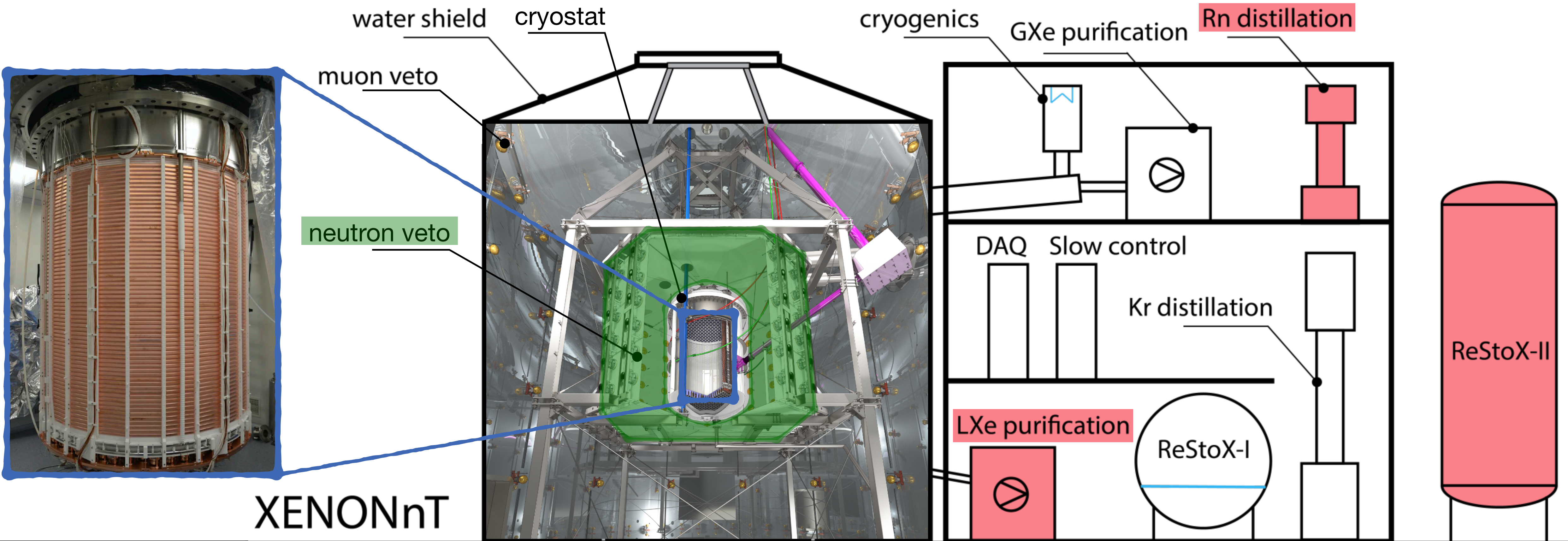
XENONnT Experiment Overview

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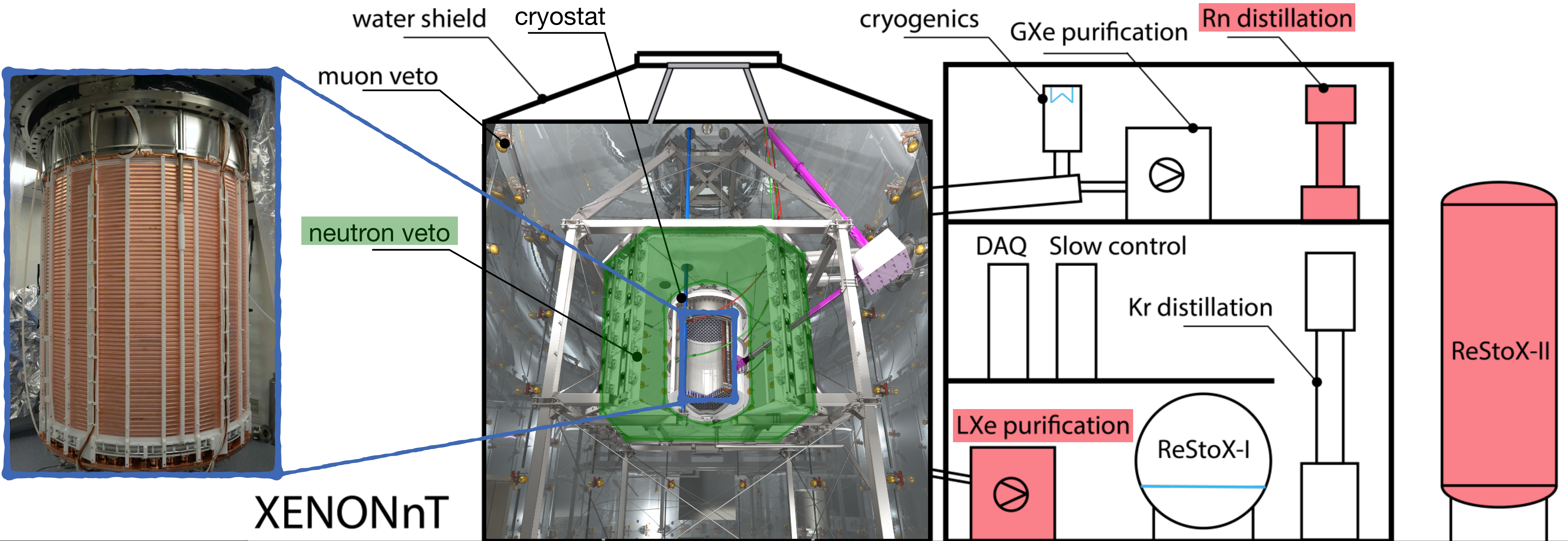
Xenon handling
New purification
& ER bkg. reduction
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Water Cherenkov
Neutron Veto
Gd-doping in
preparation



XENONnT Experiment Overview

XENON1T
UPGRADE



XENONnT Experiment Overview

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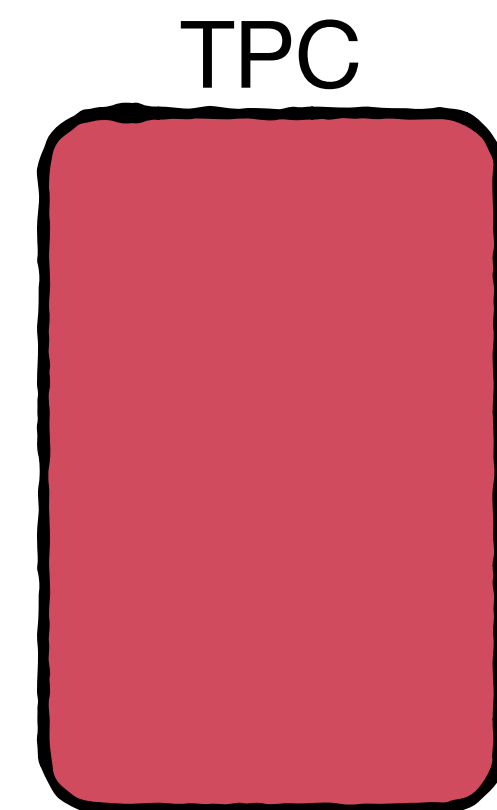
How to achieve an ultra-low background experiments:

XENONnT Experiment Overview

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How to achieve an ultra-low background experiments:

- Material selection/cleaning
 - Screening campaign
 - Cleaning pre-construction



XENONnT Experiment Overview

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How to achieve an ultra-low background experiments:



- Material selection/cleaning
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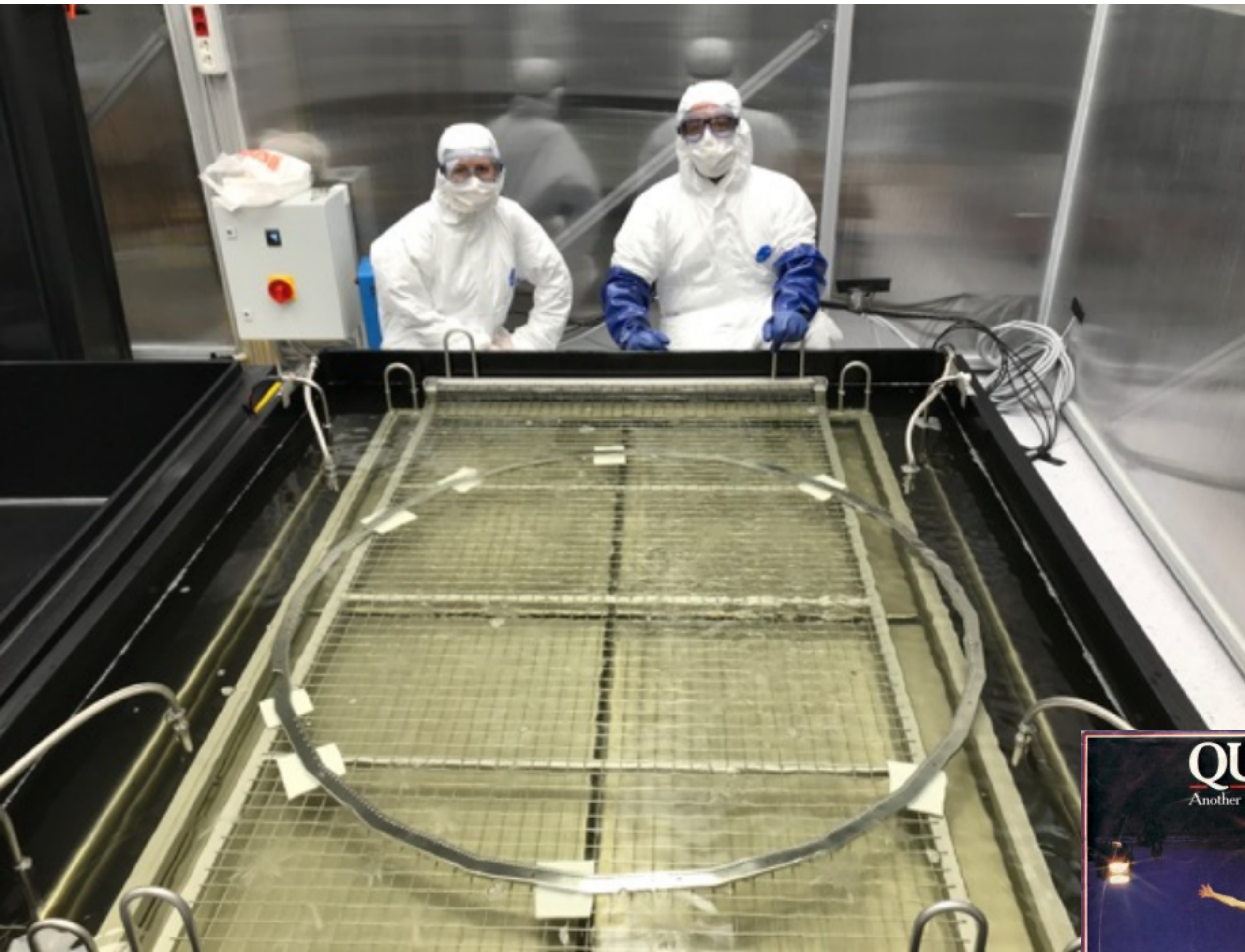
XENON Collaboration, Eur. Phys. J. C (2022) 82:599

Sample	Component	Manufacturer	Facility	Mass [kg]	Livetime [d]	Units	²³⁸ U	²³⁵ U	²²⁶ Ra	²²⁸ Ra (²³² Th)	²²⁸ Th	⁴⁰ K	⁶⁰ Co	¹³⁷ Cs
Stainless Steel (304)														
0	Bell/Vessel	Nironit	GeMPI	7.8	11.7	mBq/kg	13(7)	0.7(3)	0.3(1)	0.6(2)	0.5(1)	1.6(6)	2.4(2)	< 0.2
0	Bell/Vessel	Nironit	ICP-MS	—	—	mBq/kg	3.7(6)	—	—	0.10(8)	—	—	—	—
1	Bell/Vessel	Nironit	GeMPI	7.8	57.1	mBq/kg	4(2)	0.2(1)*	1.3(1)	0.9(1)	0.57(6)	1.4(2)	0.61(5)	0.03(2)
1	Bell/Vessel	Nironit	ICP-MS	—	—	mBq/kg	8.6(4)	—	—	< 8.1	—	—	—	—
2	Bell/Vessel/Electrodes	Nironit	GeMPI	8.4	27.5	mBq/kg	< 11	< 0.6	0.6(1)	0.4(1)	0.4(1)	< 2.4	0.4(1)	< 0.2
2	Bell/Vessel/Electrodes	Nironit	ICP-MS	—	—	mBq/kg	2.5(3)	—	—	0.4(2)	—	—	—	—
3	Welding Rods (Vessel)	Nironit	GeMPI	2.6	30.6	mBq/kg	< 5.7	< 0.3*	3.1(3)	2.9(4)	11.4(7)	7(1)	1.6(2)	< 0.3
Oxygen-Free High-Conductivity Copper														
4	Field Shaping Rings	Luvata	Gator	71.7	32.5	mBq/kg	< 0.33	< 0.02	< 0.18	< 0.22	0.18(5)	0.45(14)	0.03(1)	< 0.05
4	Field Shaping Rings	Luvata	ICP-MS	—	—	mBq/kg	0.03(1)	—	—	0.010(4)	—	—	—	—
5	Guard Rings	Niemet	GeMPI	56.5	42.1	mBq/kg	< 1.6	< 0.14	0.13(3)	< 0.06	< 0.04	0.6(2)	0.05(1)	< 0.03
6	Wires	-	GeMSE	12	-	mBq/kg	< 2.3	—	< 0.1	< 0.06	< 0.04	0.55(2)	0.43(3)	< 0.04
7	Array Support Plate	Niemet	GeMSE	93.4	35.6	mBq/kg	< 1.06	—	< 0.21	< 0.08	< 0.01	< 0.42	0.08(1)	< 0.011
7	Array Support Plate	Niemet	ICP-MS	—	—	mBq/kg	0.0014(4)	—	—	0.004(1)	—	—	—	—
8	Array Support Pillar	Luvata	GeMPI	57.3	26.2	mBq/kg	< 2.7	< 0.23	< 0.06	< 0.08	< 0.04	< 0.27	0.10(2)	< 0.05

XENONnT Experiment Overview

XENON Collaboration pictures

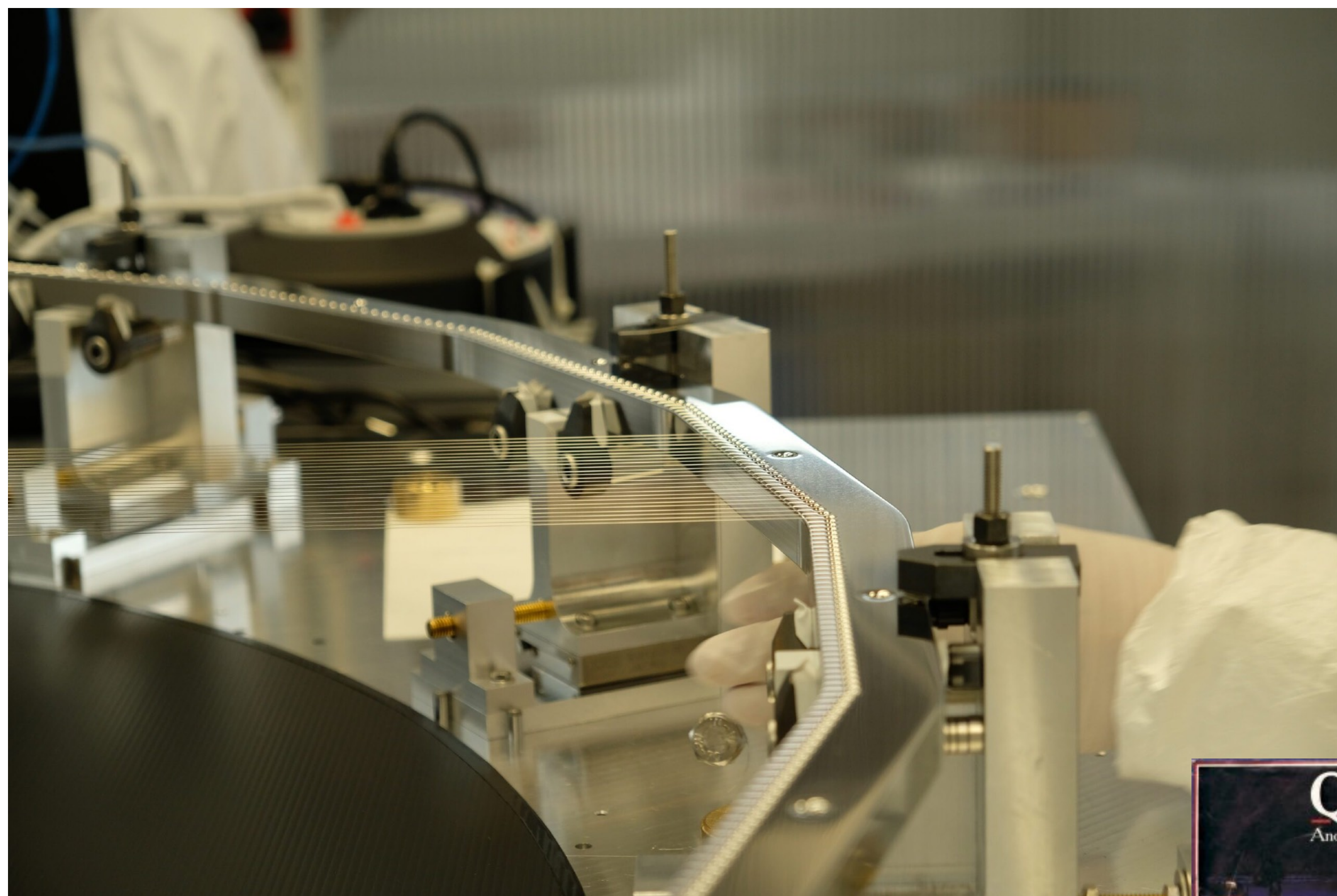
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XENONnT Experiment Overview

XENON Collaboration pictures

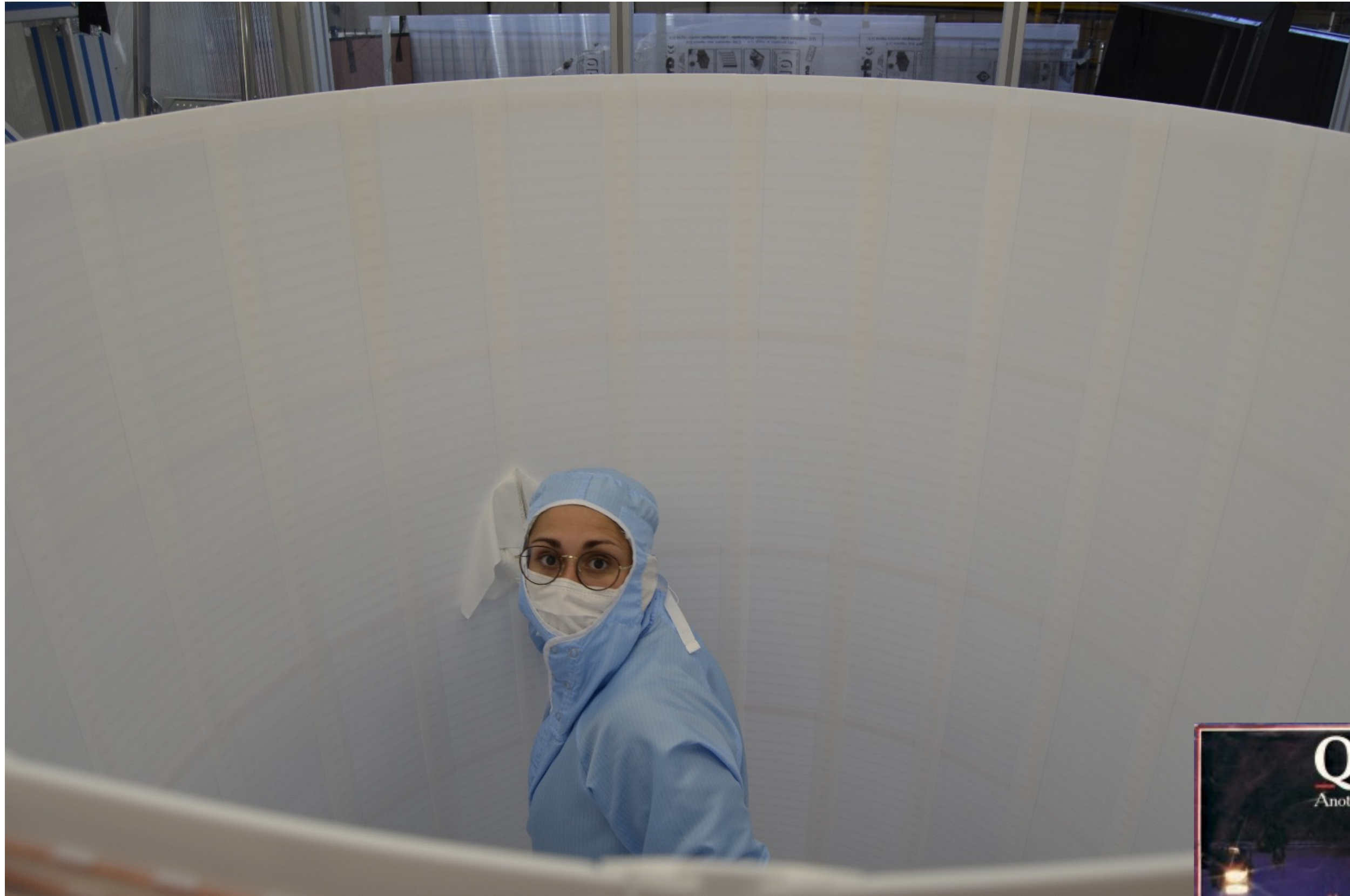
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XENONnT Experiment Overview

XENON Collaboration pictures

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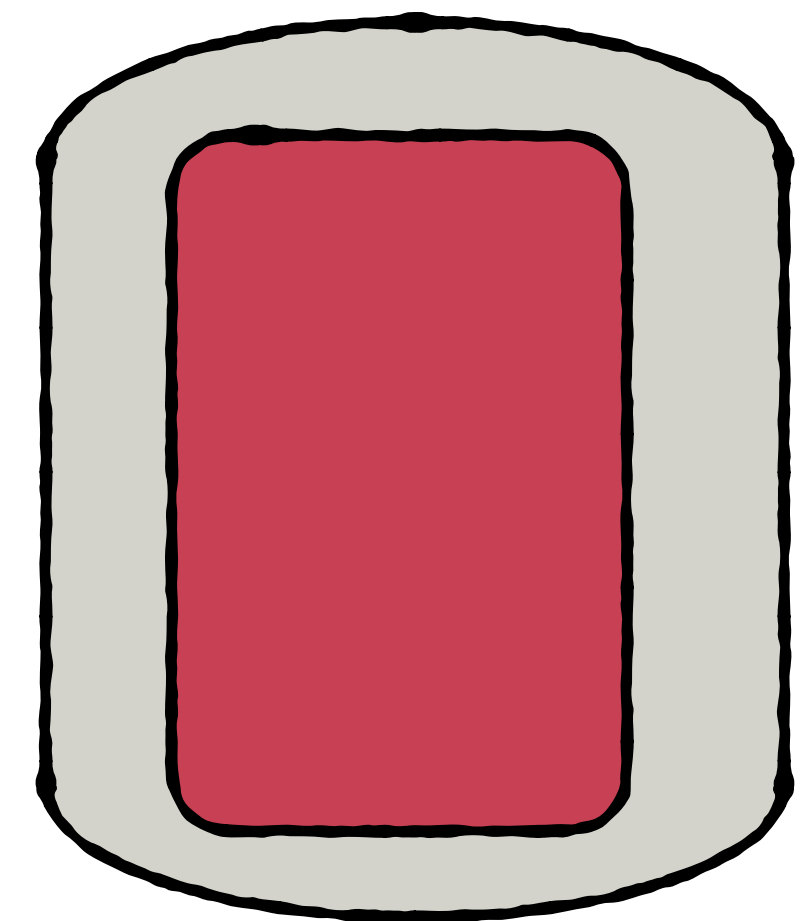
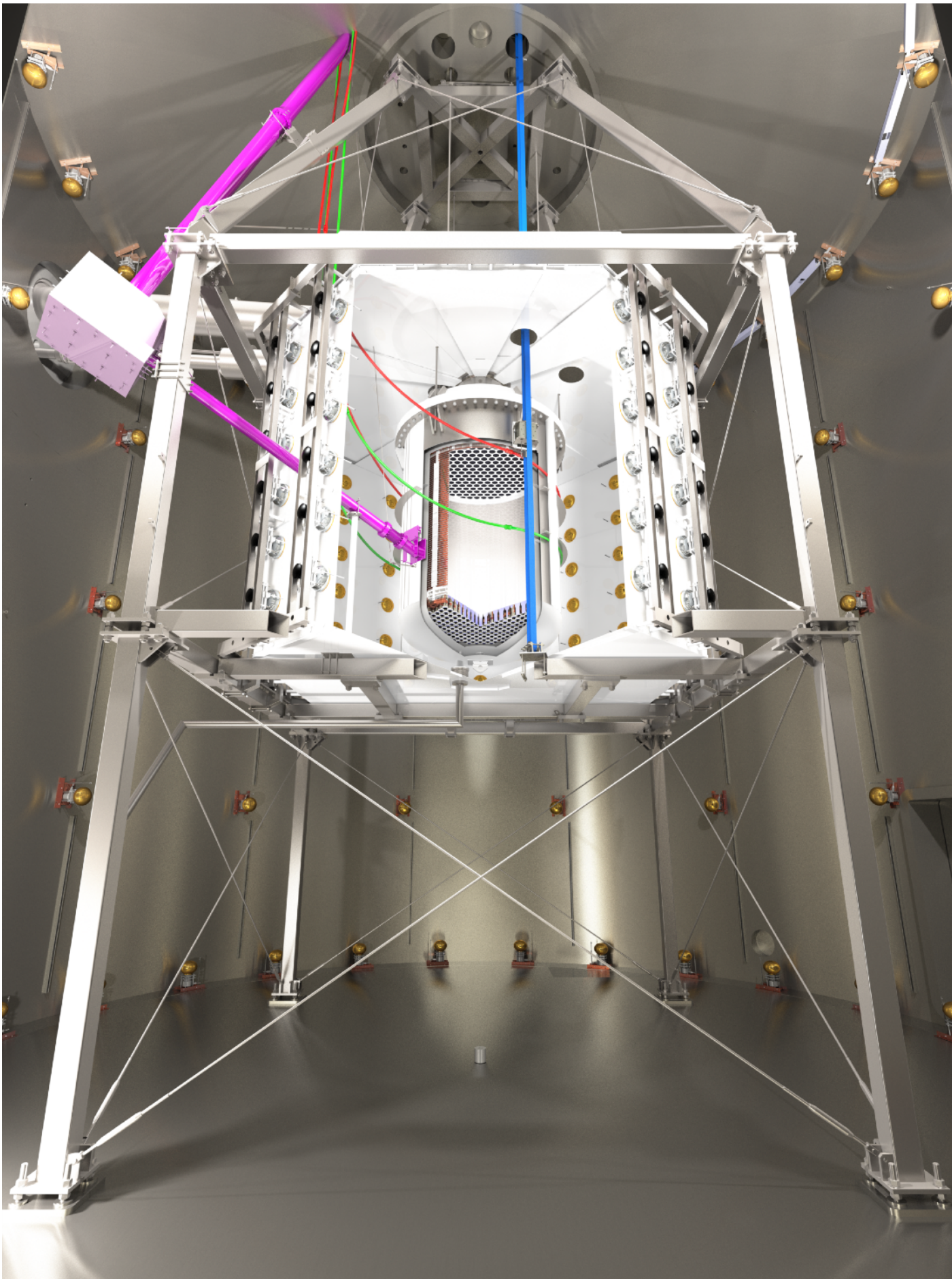


XENONnT Experiment Overview

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How to achieve an ultra-low background experiments:

- ⦿ Material selection/cleaning
- ⦿ Self-shielding with LXe:
 - ⦿ LXe Shell
 - ⦿ Fiducialization



Cryostat with LXe Shell

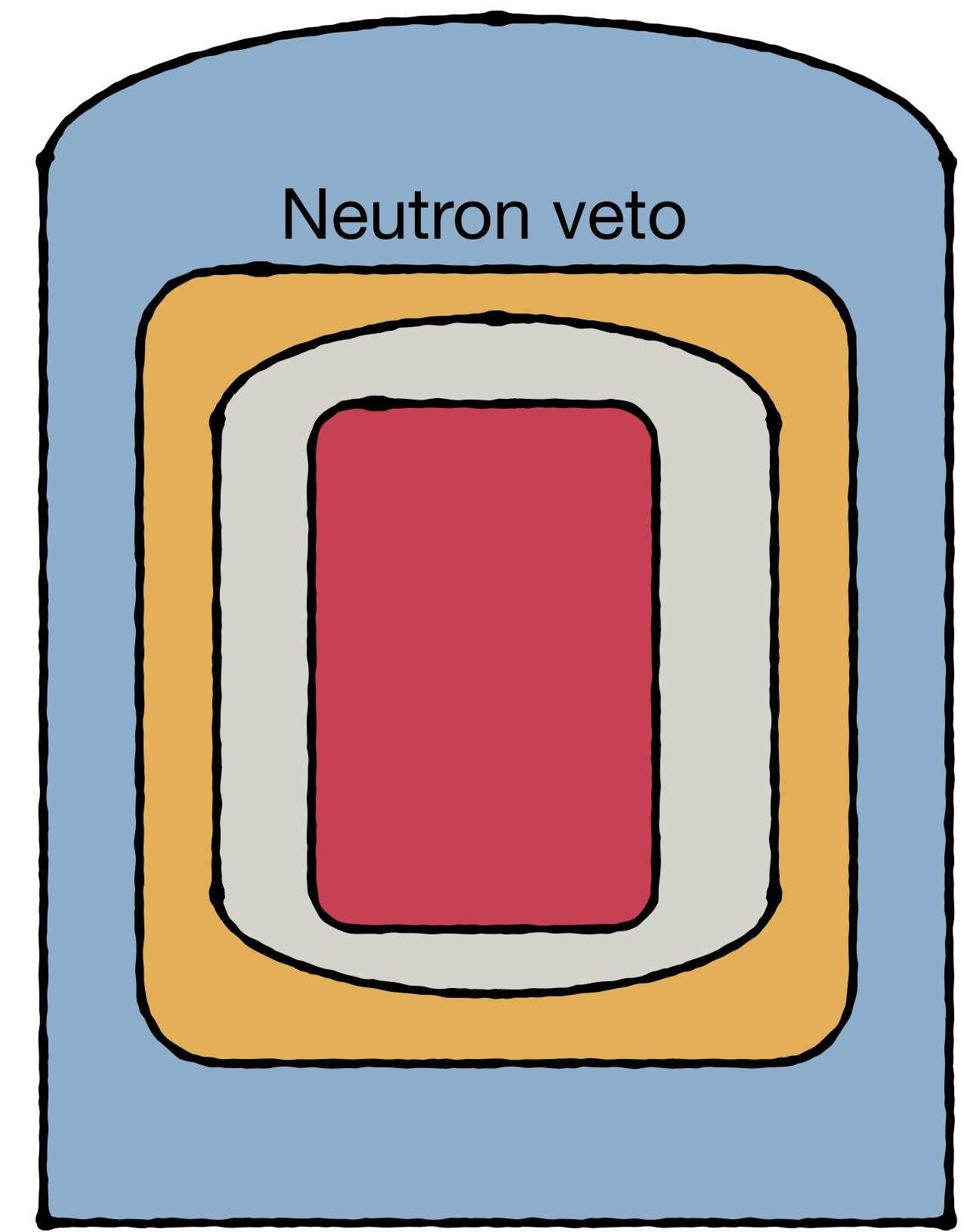
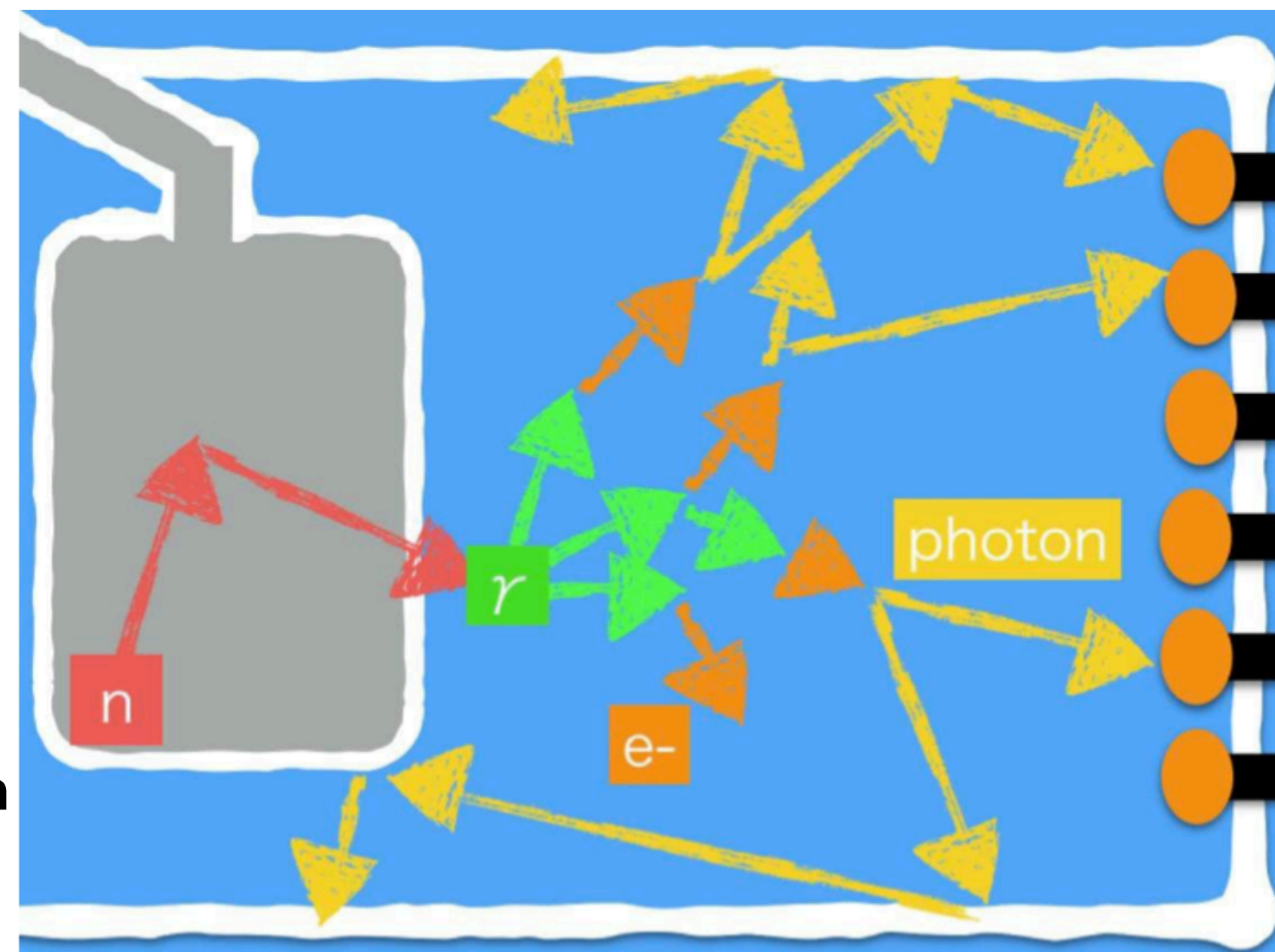
XENONnT Experiment Overview

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How to achieve an ultra-low background experiments:

- Material selection/cleaning
- Self-shielding with LXe:
- Active Shielding
 - n-veto | (n, γ) capture
 - μ -veto | Cherenkov light

Water Čerenkov Muon veto



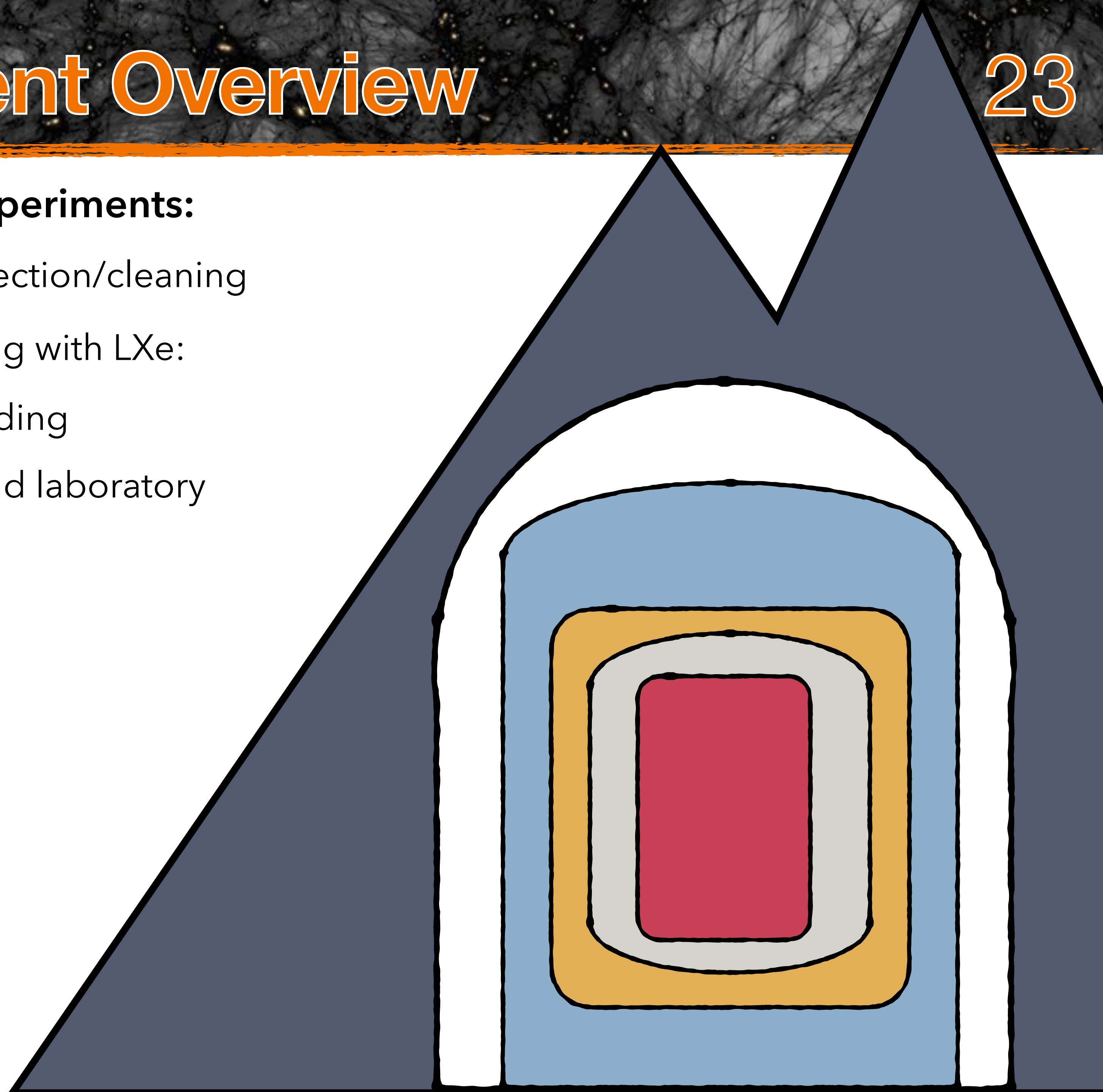
Tag neutrons through the neutron capture on hydrogen which releases a 2.2 MeV gamma

XENONnT Experiment Overview

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How to achieve an ultra-low background experiments:

- Material selection/cleaning
- Self-shielding with LXe:
- Active Shielding
- Underground laboratory

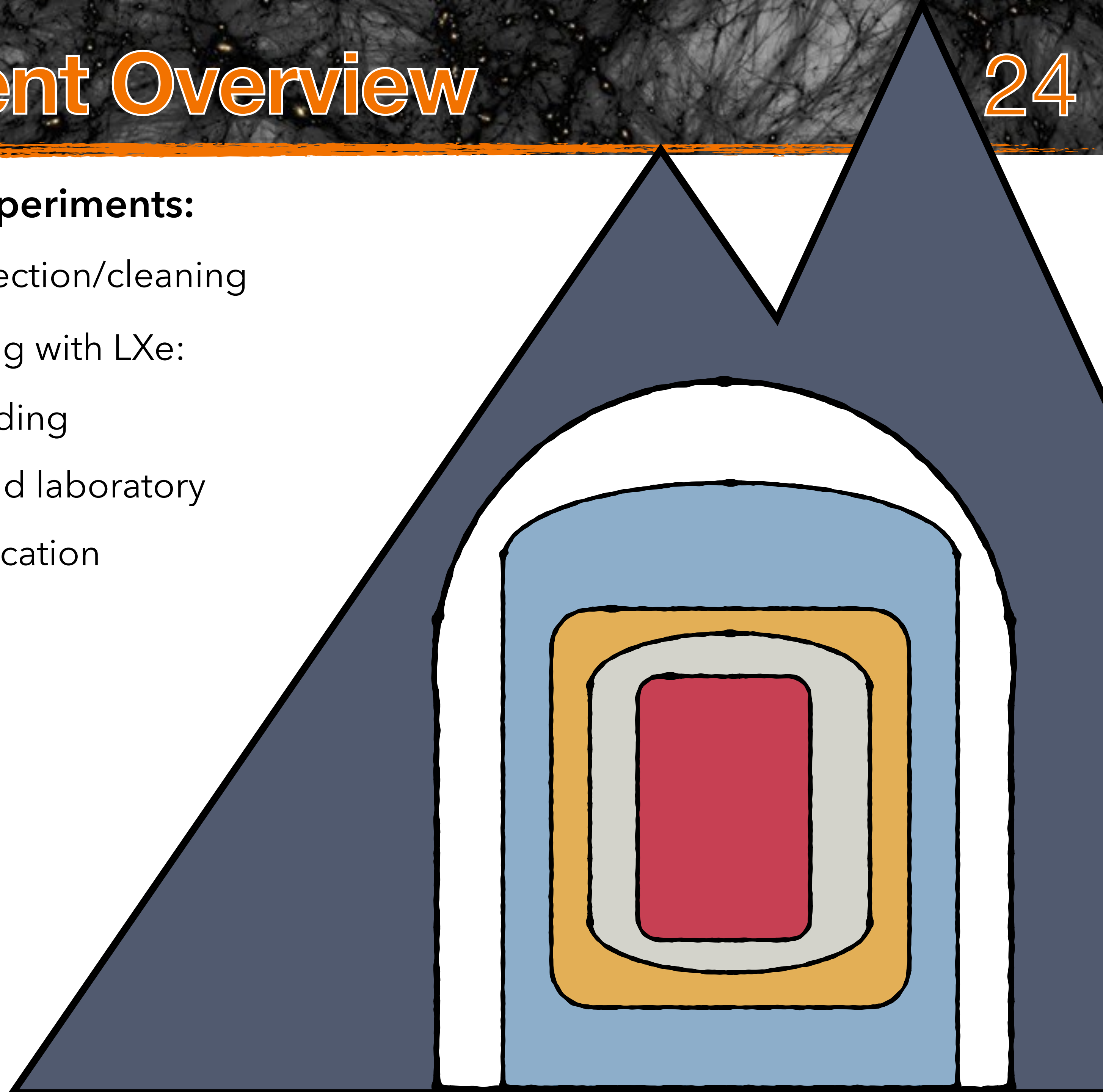


XENONnT Experiment Overview

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How to achieve an ultra-low background experiments:

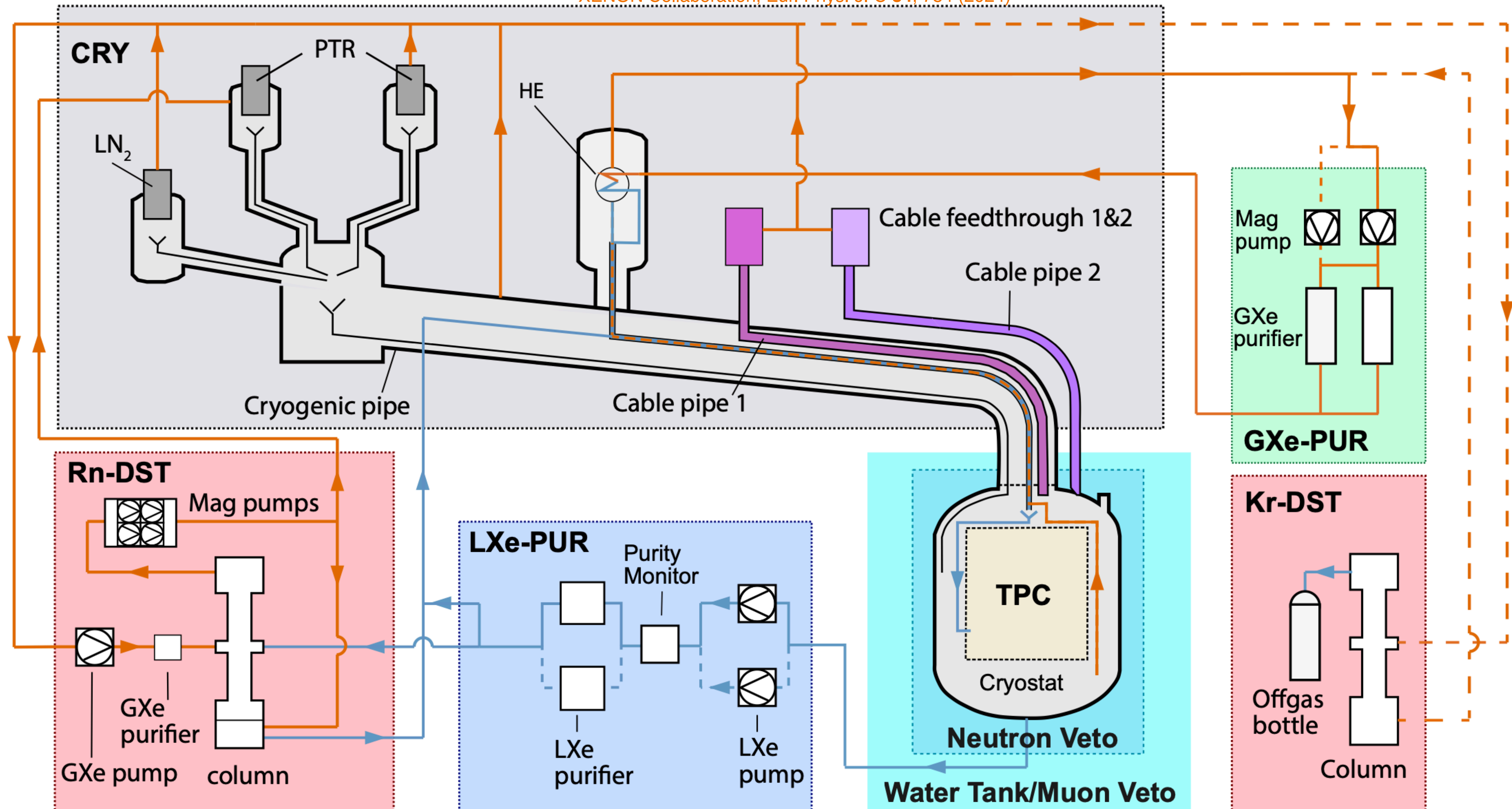
- Material selection/cleaning
- Self-shielding with LXe:
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- Target purification



Purification systems

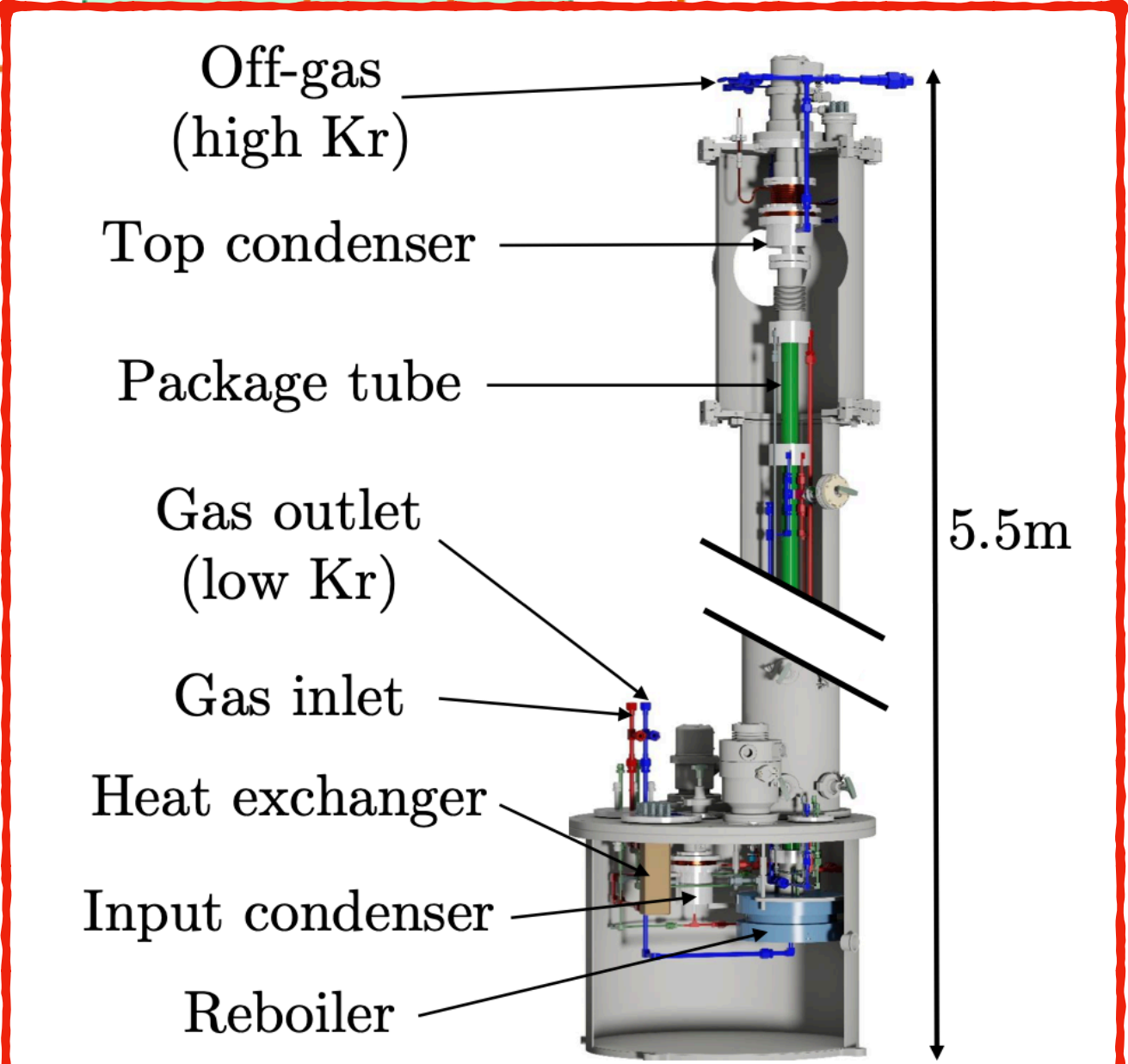
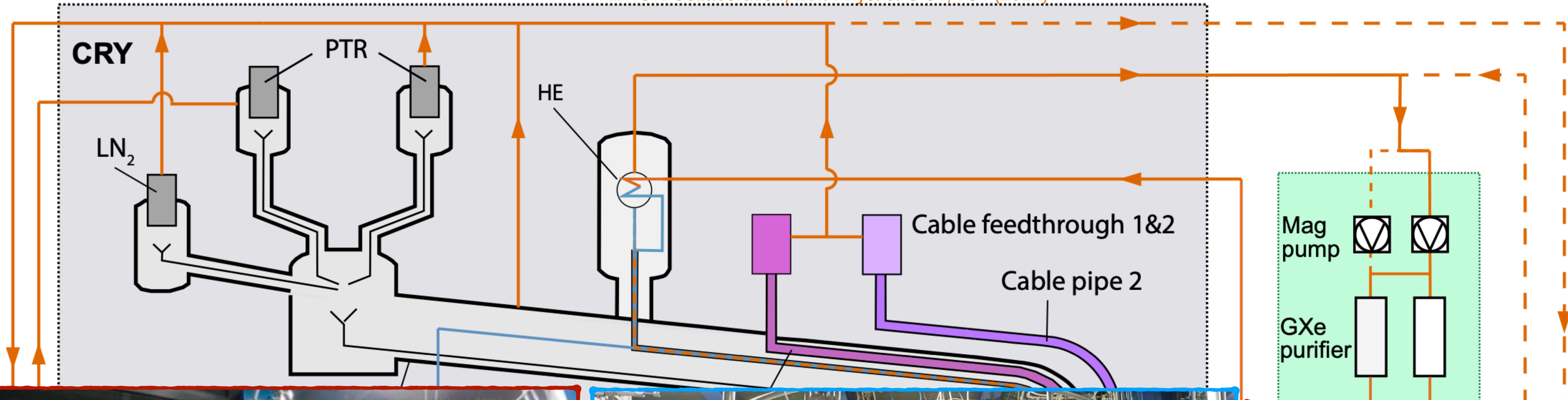
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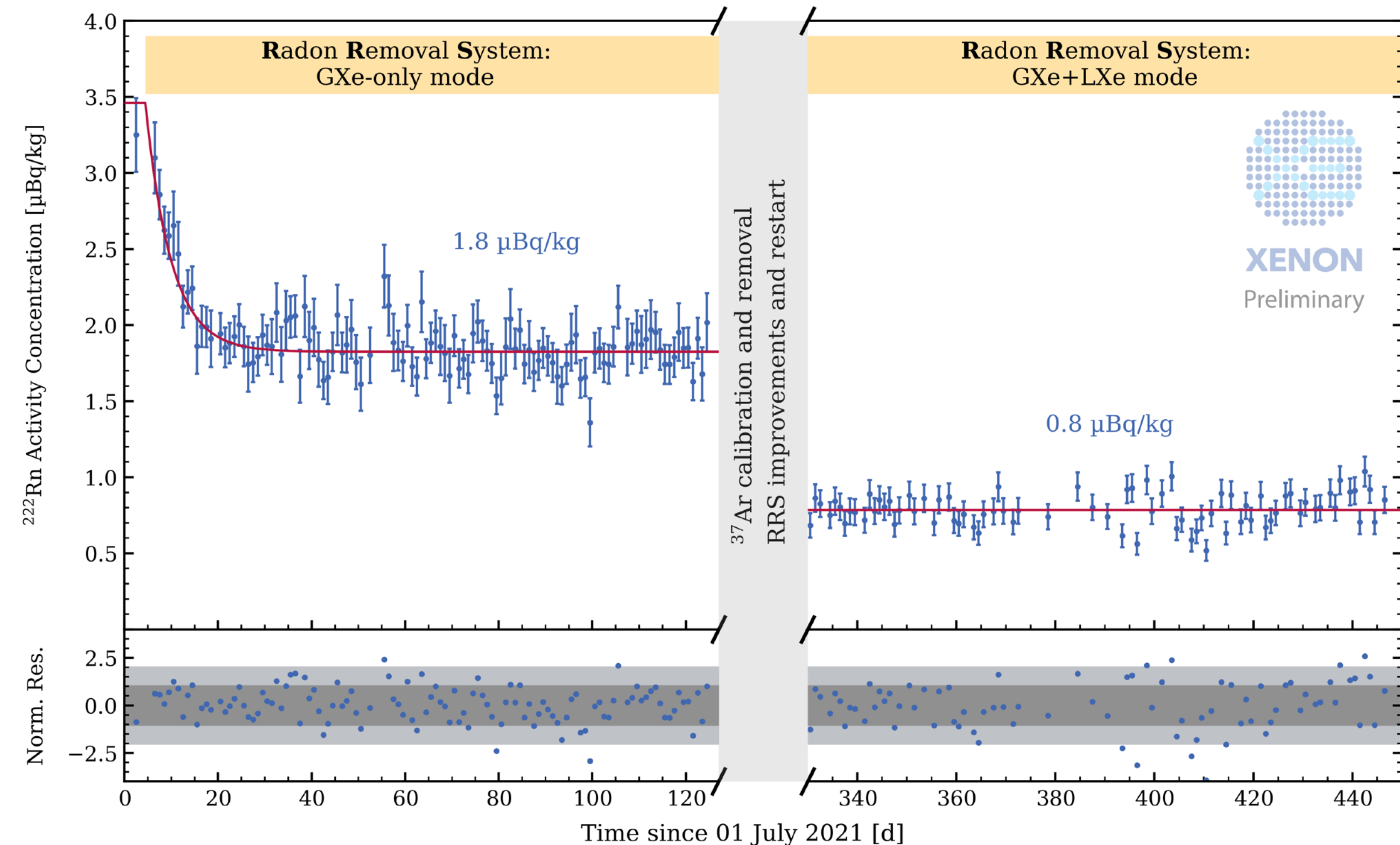
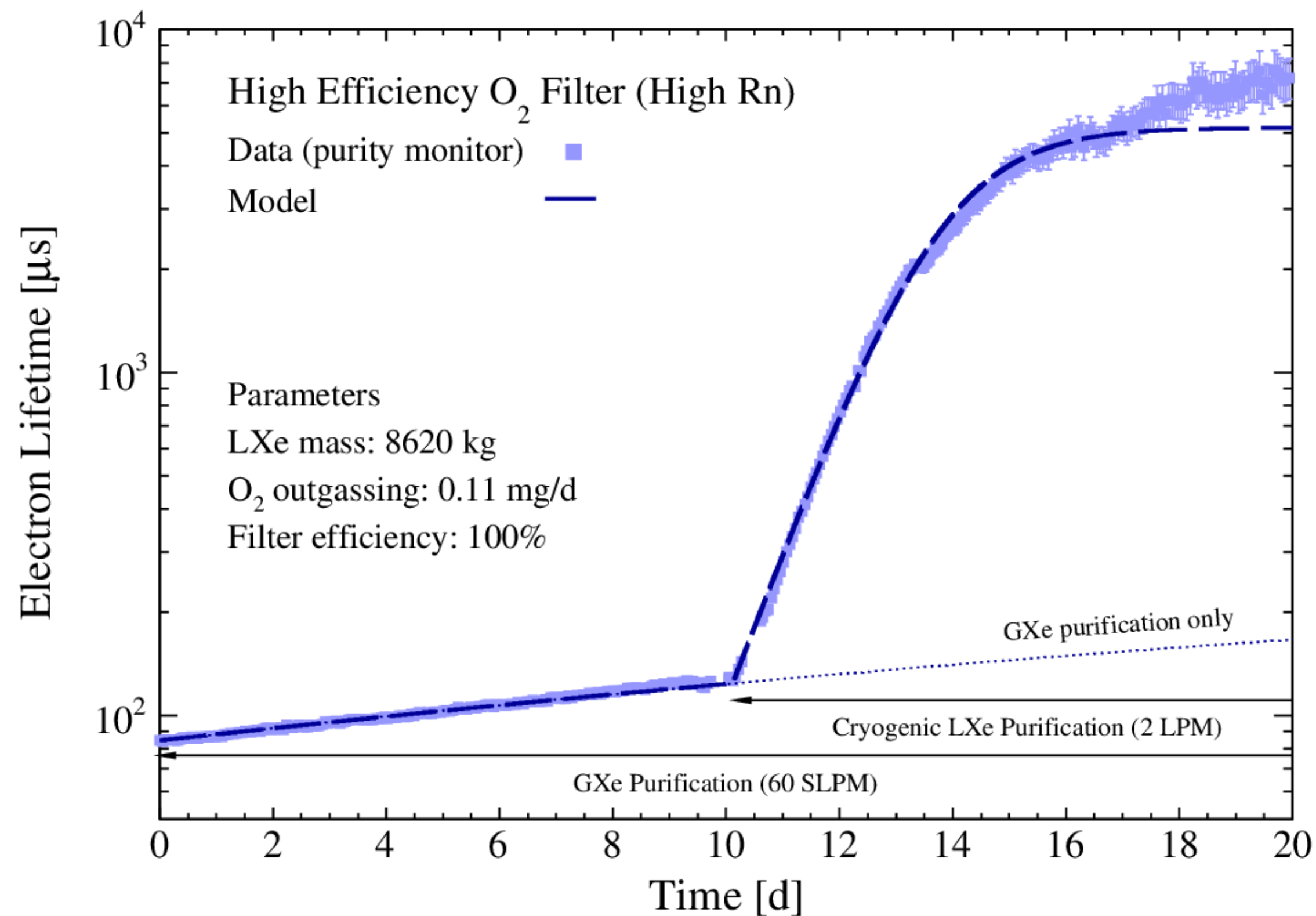
XENON Collaboration, Eur. Phys. J. C **84**, 784 (2024)



Purification systems

XENON Collaboration, Eur. Phys. J. C 84, 784 (2024)





- Electron lifetime (impacted by electronegative impurities in the LXe) > 10 ms, wrt a 2.2 ms drift time
- Radon intrinsic contamination $< 1 \mu\text{Bq/kg}_{\text{Xe}}$
- Reached natKr/Xe = (56 ± 36) ppq (world leading)

XENONnT Experiment Overview

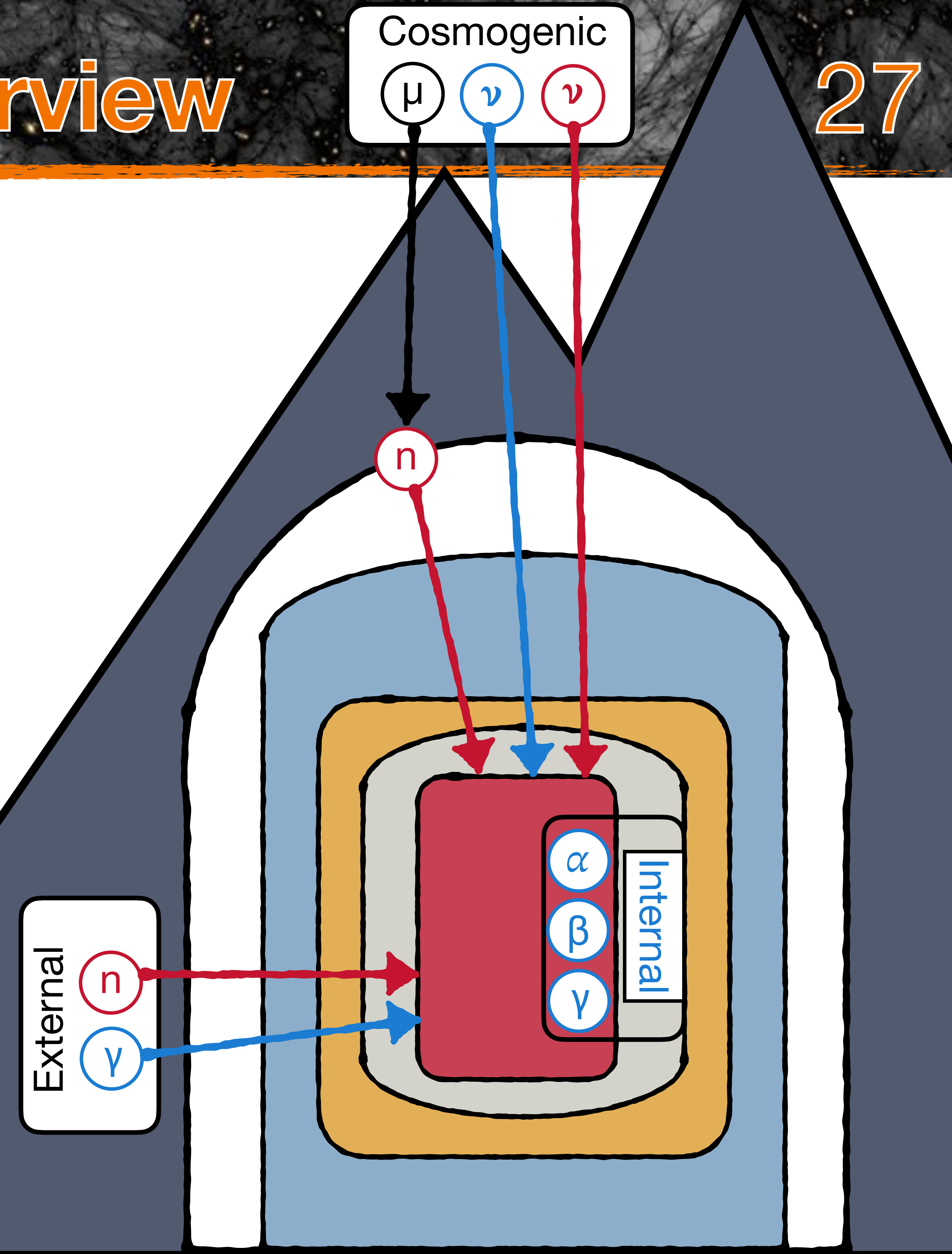
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- Material selection/cleaning
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- Underground laboratory
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Remaining backgrounds reaching the TPC:

- External
- Internals
- Cosmogenic





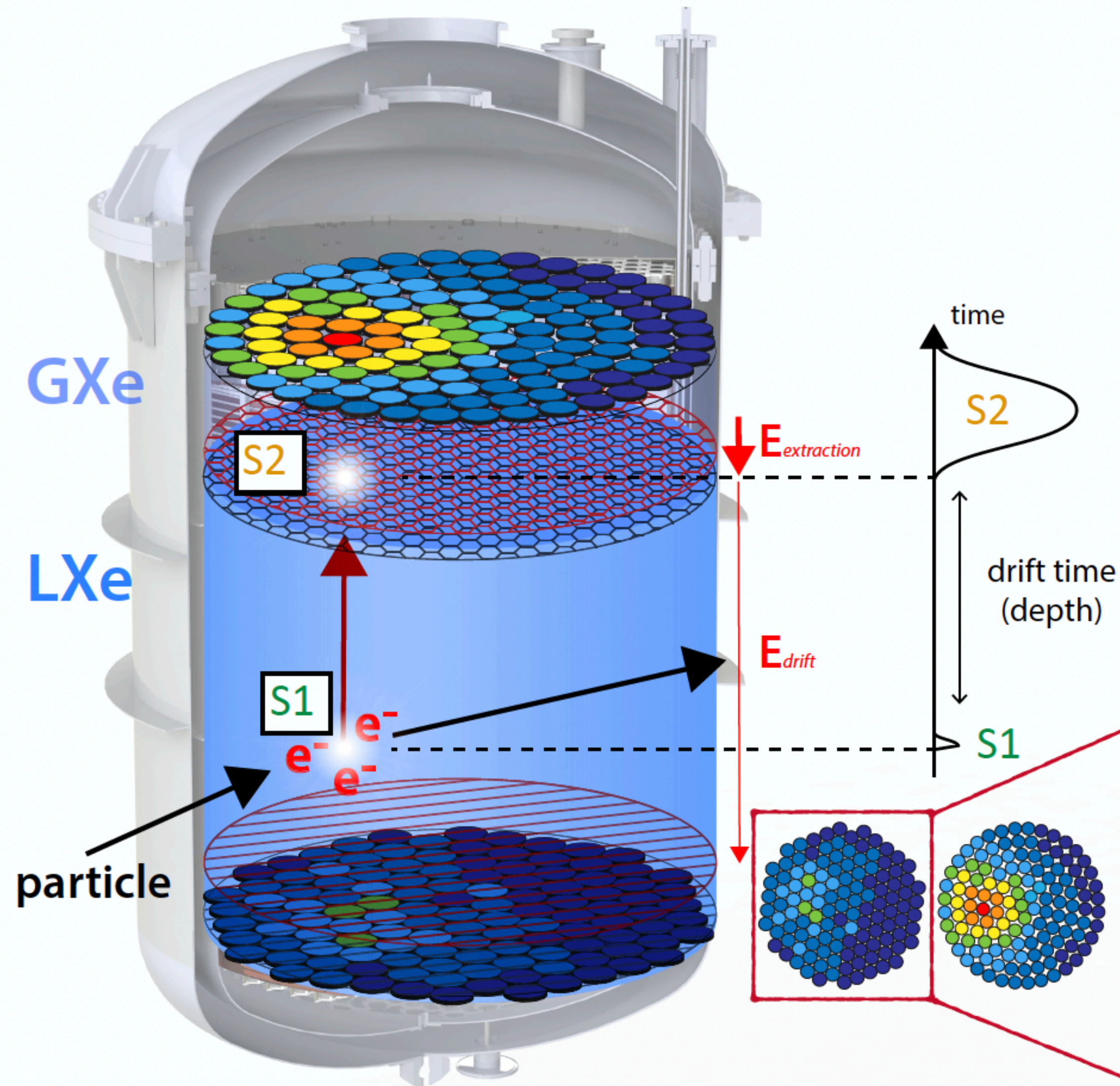
New Larger TPC

- ◎ x3 larger volume w.r.t. XENON1T
- ★ 2.0 t $\rightarrow$ 5.9 t LXe active mass
- ★ ~ 1 m $\rightarrow$ ~ 1.5 m drift length
- ★ ~ 1 m $\rightarrow$ ~ 1.3 m diameter
- ★ 248 $\rightarrow$ 494 3" PMTs



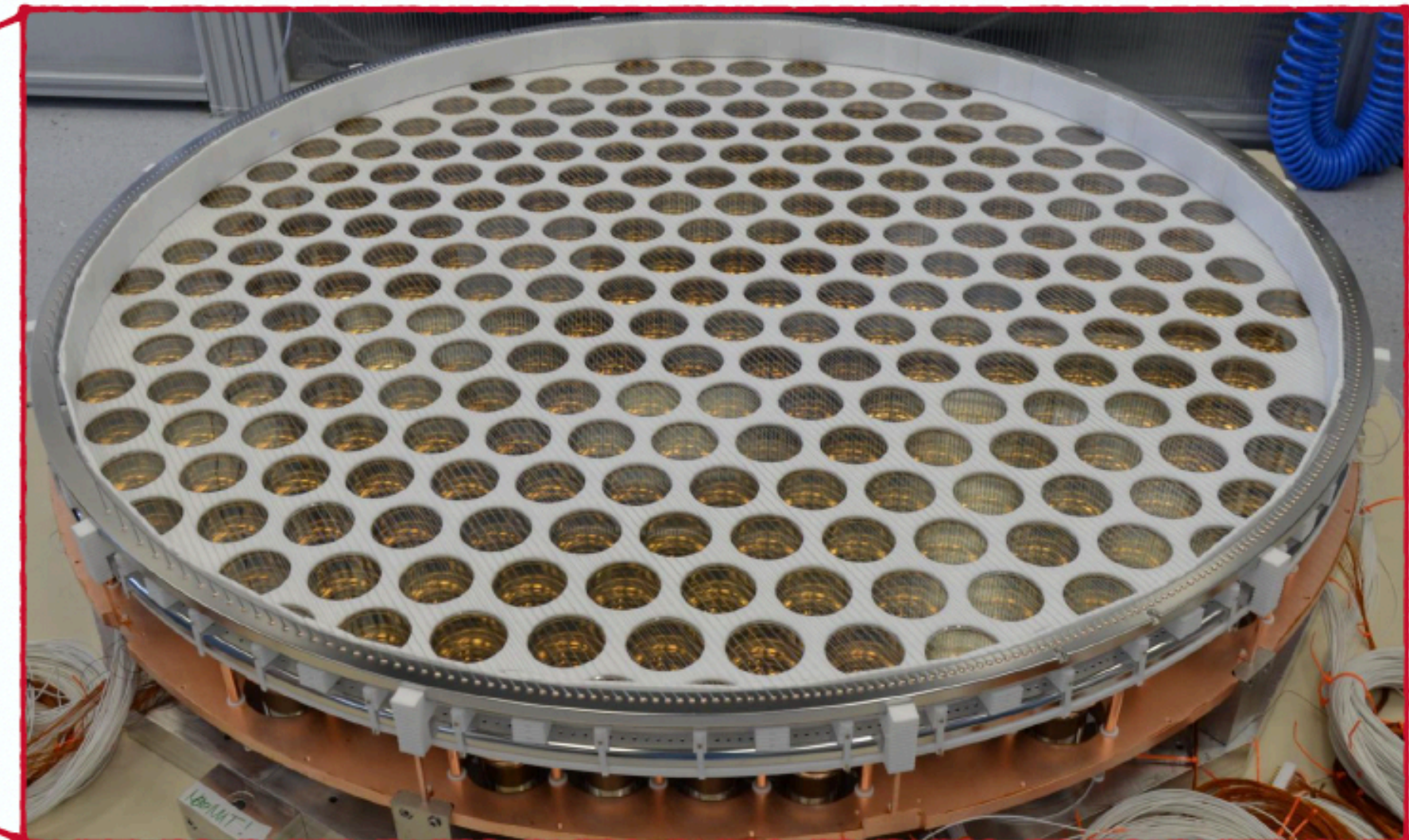
TPC Working Principle

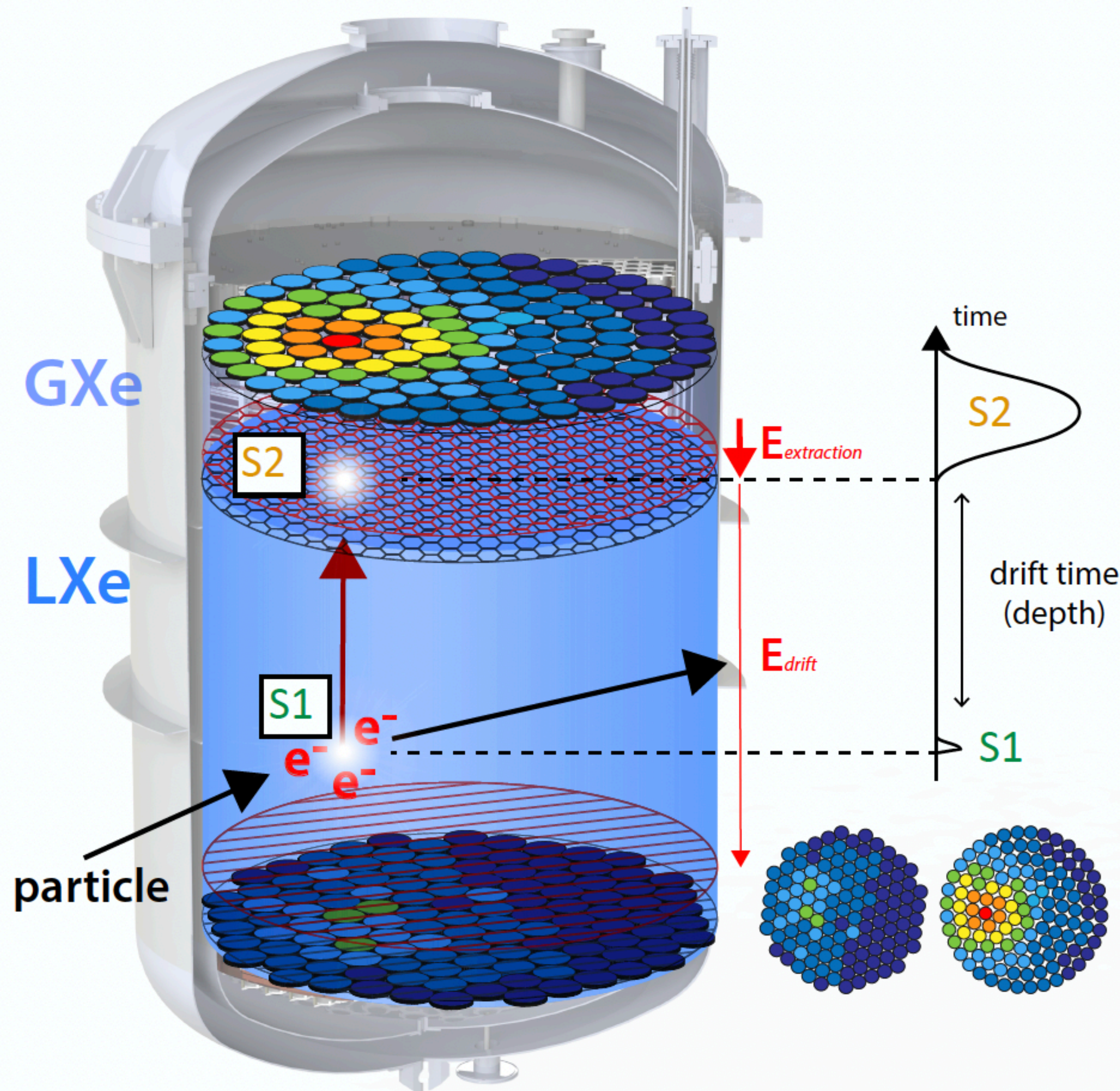
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Light and Charge readout

- Prompt scintillation signal (**S1**)
- Secondary proportional scintillation signal in GXe from drifted electrons (**S2**)



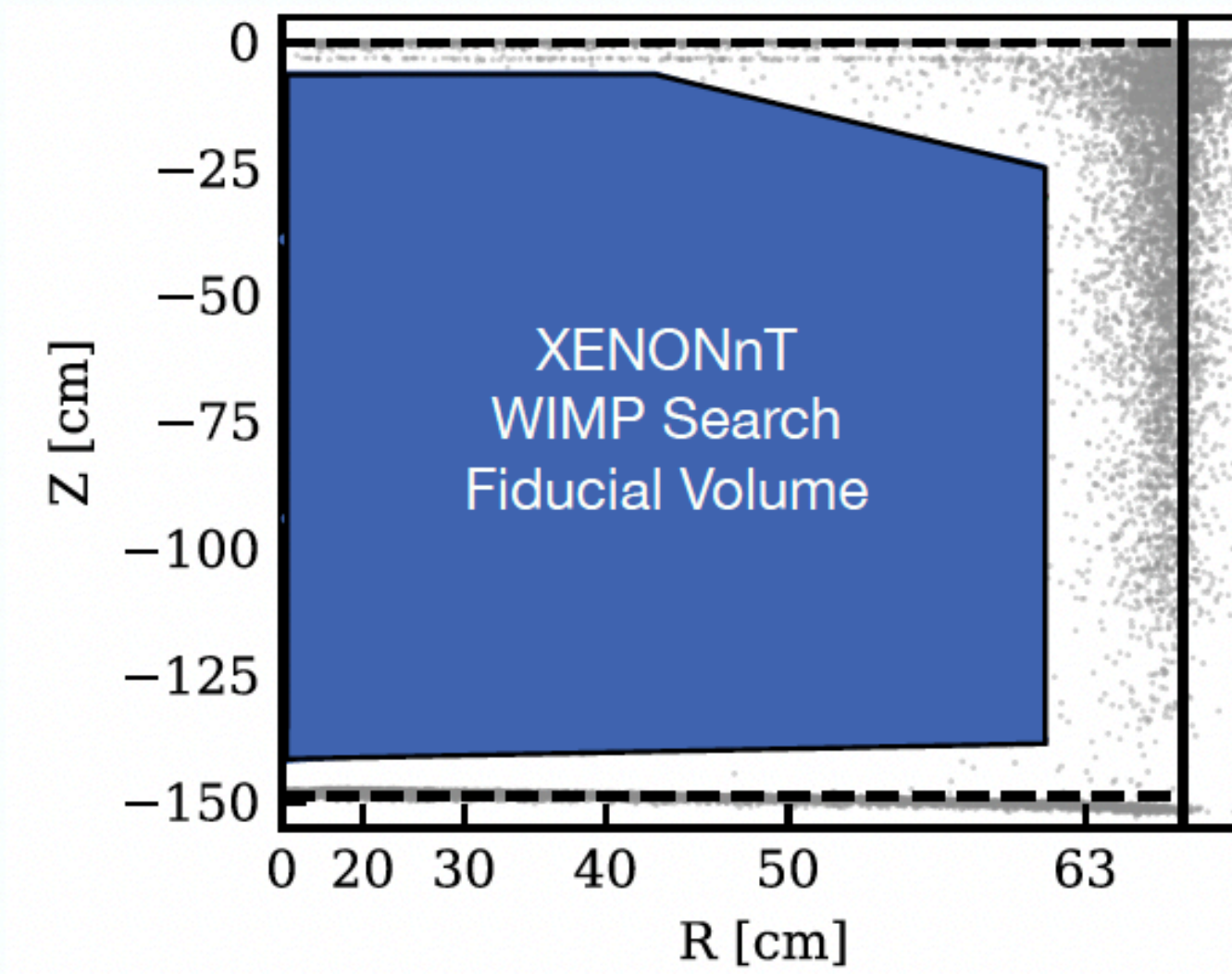


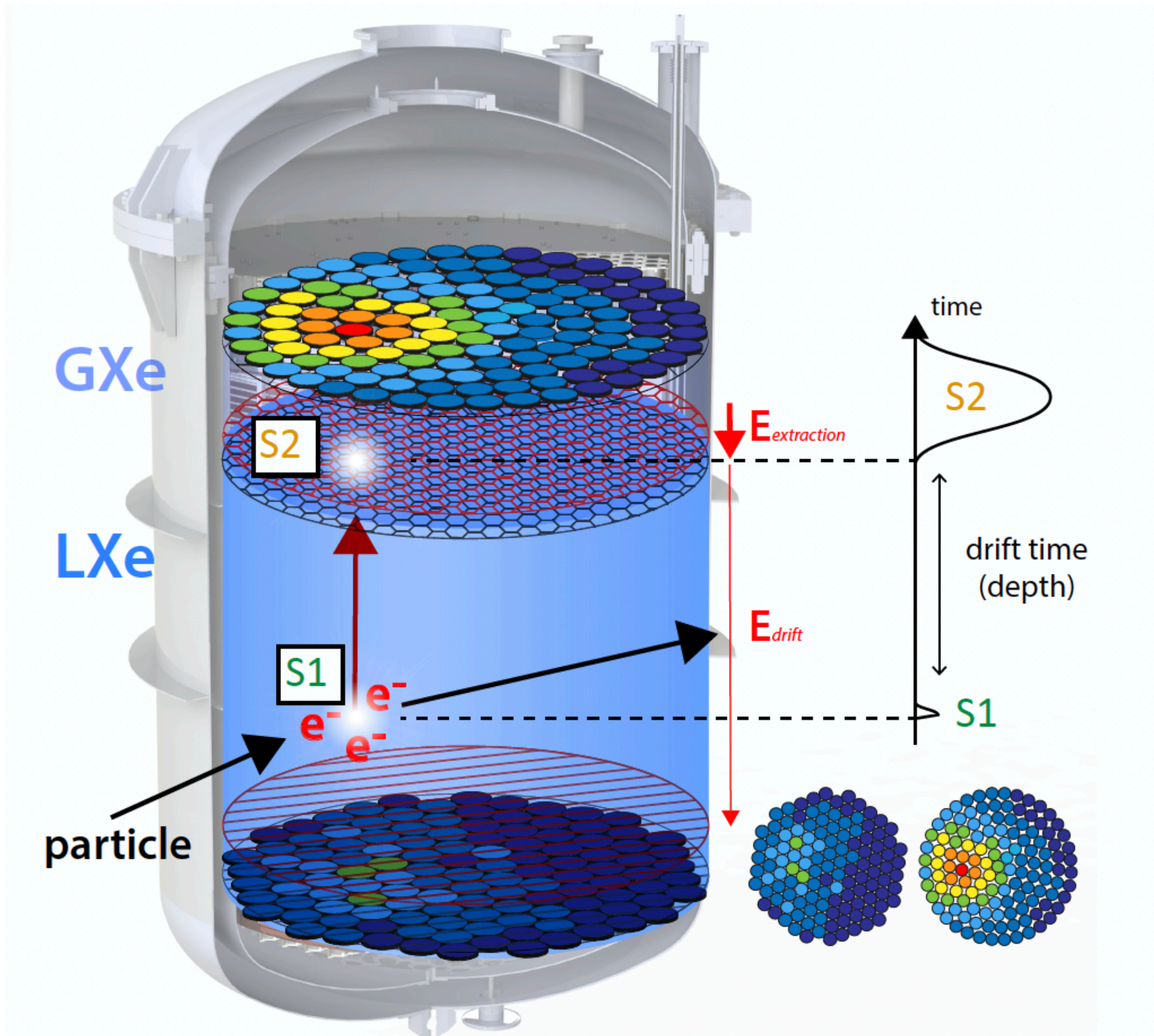
Light and Charge readout

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Event reconstruction

- **3D Position:**
 - **Z** from drift time
 - (X, Y) from PMTs hit pattern
- **Energy** $\rightarrow E = W \cdot (n_{ph} + n_e)$





Light and Charge readout

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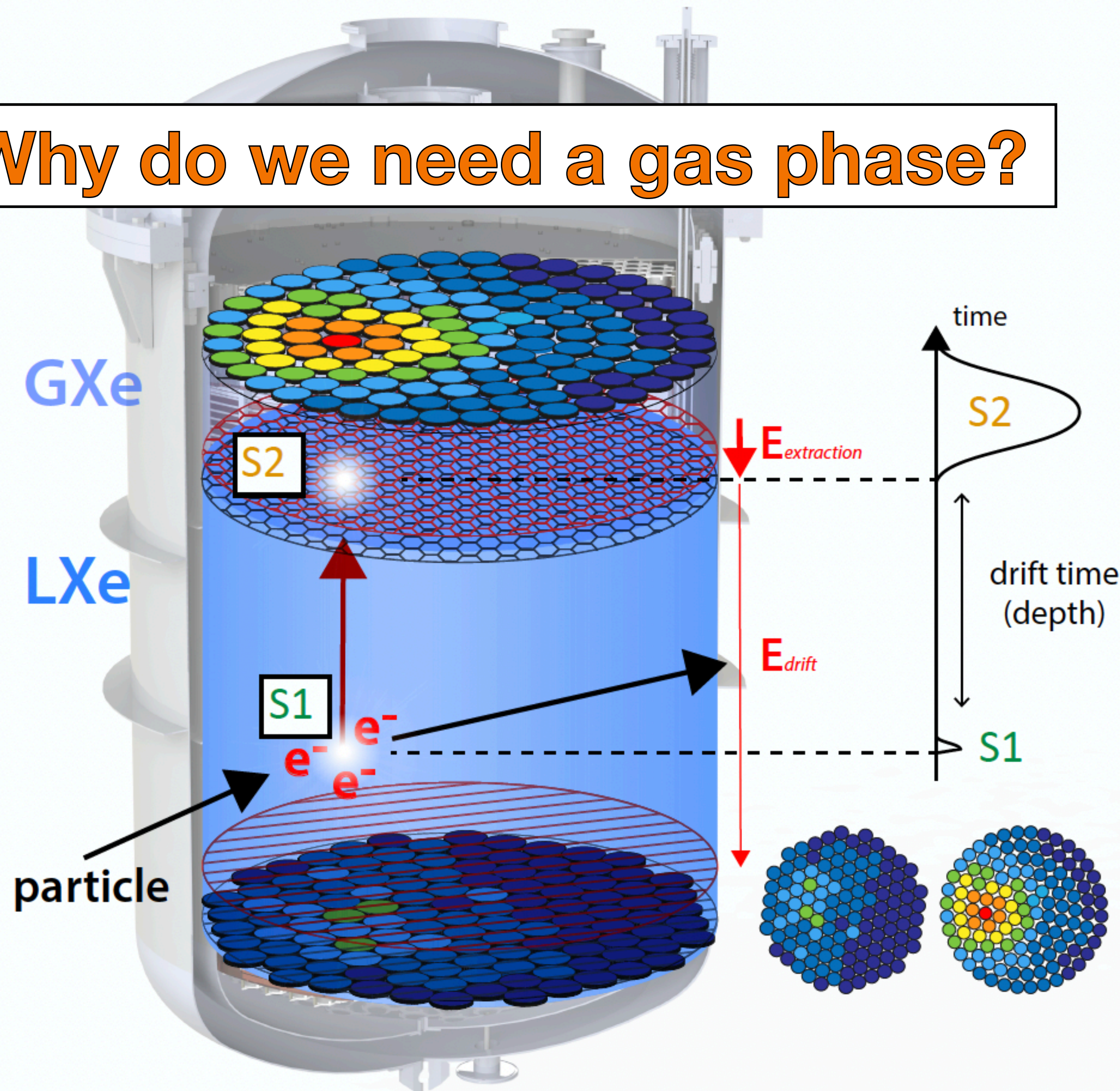
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Particle discrimination

- Interaction type **Nuclear Recoil (NR)/Electronic Recoil (ER)** through **S1/S2** ratio

$$\left(\frac{S2}{S1} \right)_{NR} < \left(\frac{S2}{S1} \right)_{ER}$$

Why do we need a gas phase?



Light and Charge readout

- Prompt scintillation signal (**S1**)
- Secondary proportional scintillation signal in GXe from drifted electrons (**S2**)

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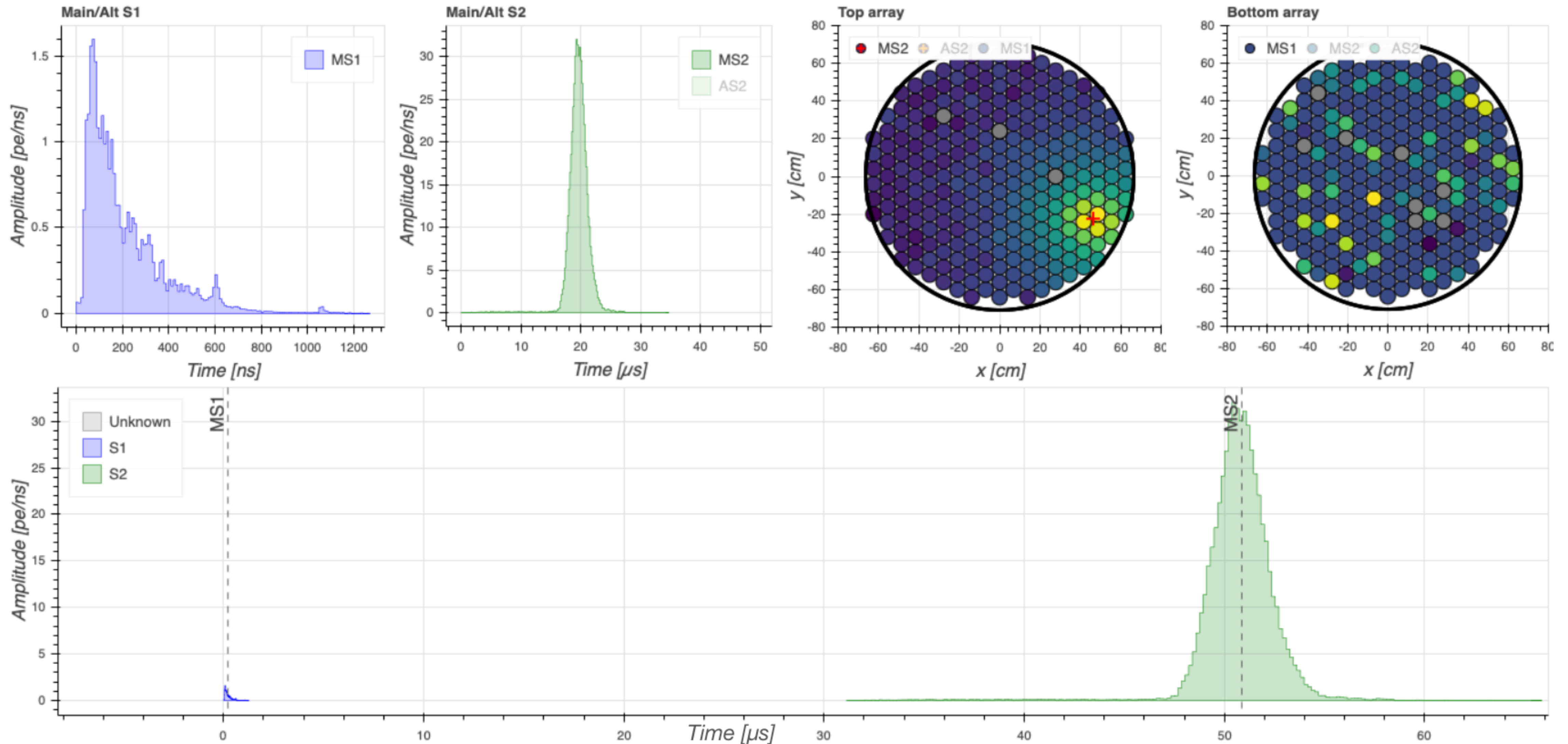
$$\left(\frac{S2}{S1} \right)_{NR} < \left(\frac{S2}{S1} \right)_{ER}$$

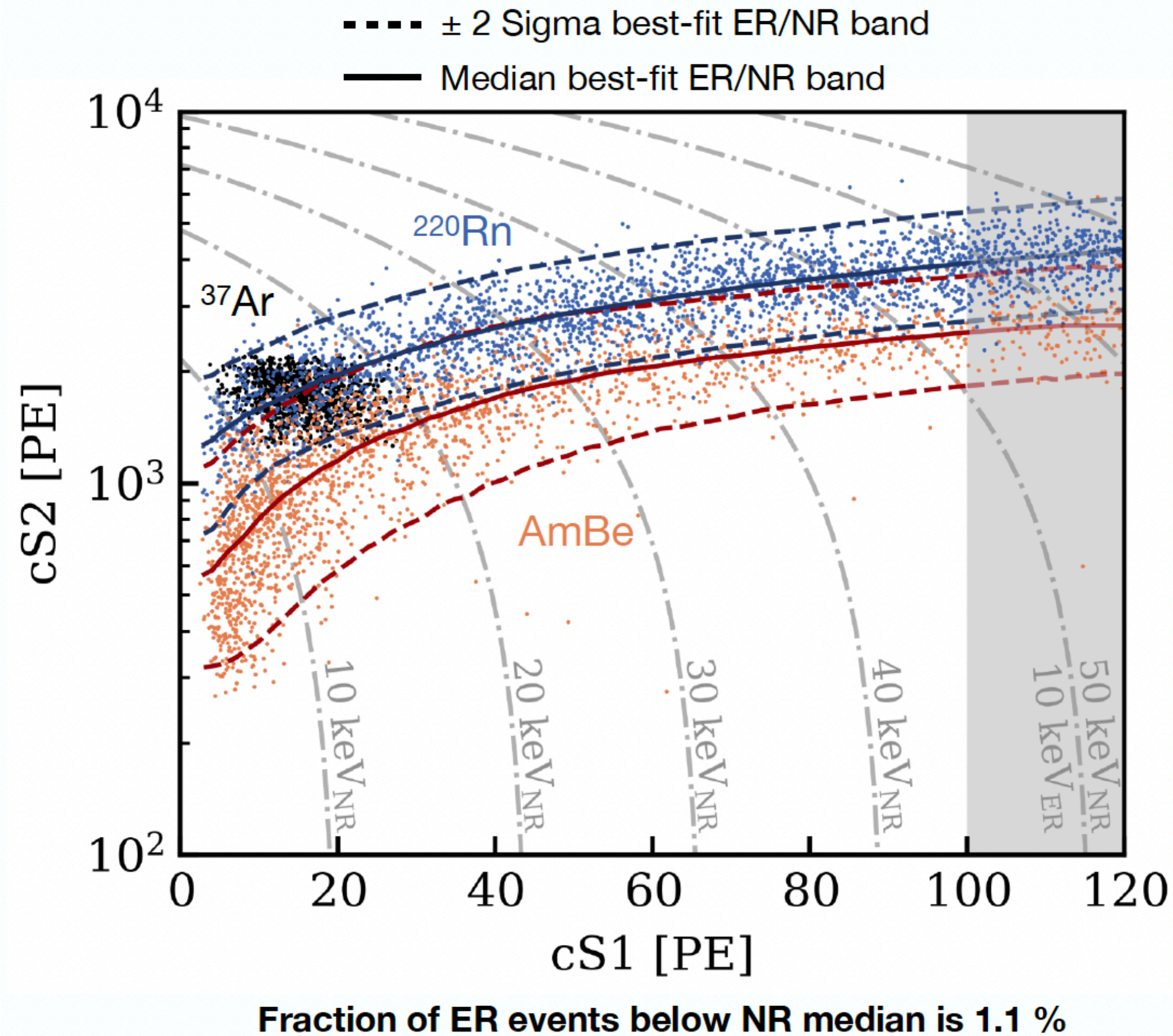
Waveform example

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Event 164 from run 023537

Recorded at 2021-06-20 T18:13:31 UTC, 289971792 ns - 292733570 ns





Signal Characterisation and Correction

- $^{83\text{m}}\text{Kr}$ internal calibration source:
 - ➔ 2 successive IC @ 32.2 keV & 9.4 keV
 - ➔ Building block of the signal correction

Electronic Recoil Calibration

- ^{220}Rn internal source
 - ➔ ^{212}Pb β -decay offer $\sim$ flat energy spectrum in ROI
- ^{37}Ar internal source
 - ➔ ER line from K-Shell @ 2.8 keV
 - ➔ Validate detector performances & study threshold

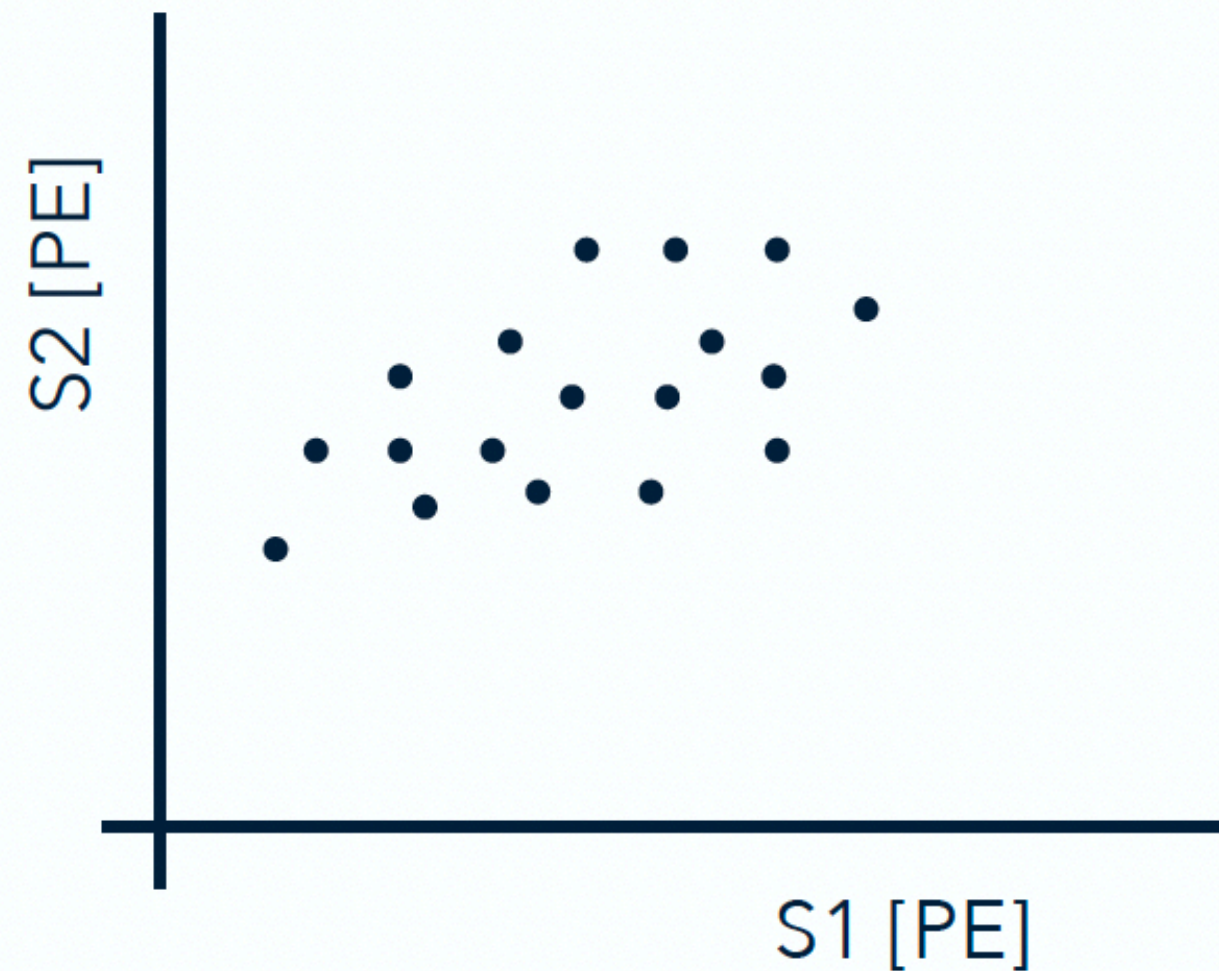
Nuclear Recoil Calibration

- External AmBe neutron source
 - ➔ Clear NR selection via coincident 4.4 MeV γ in nVeto

We can search for DM and other new physics in both ER and NR band!

Combined energy reconstruction from S1 and S2:

2D analysis

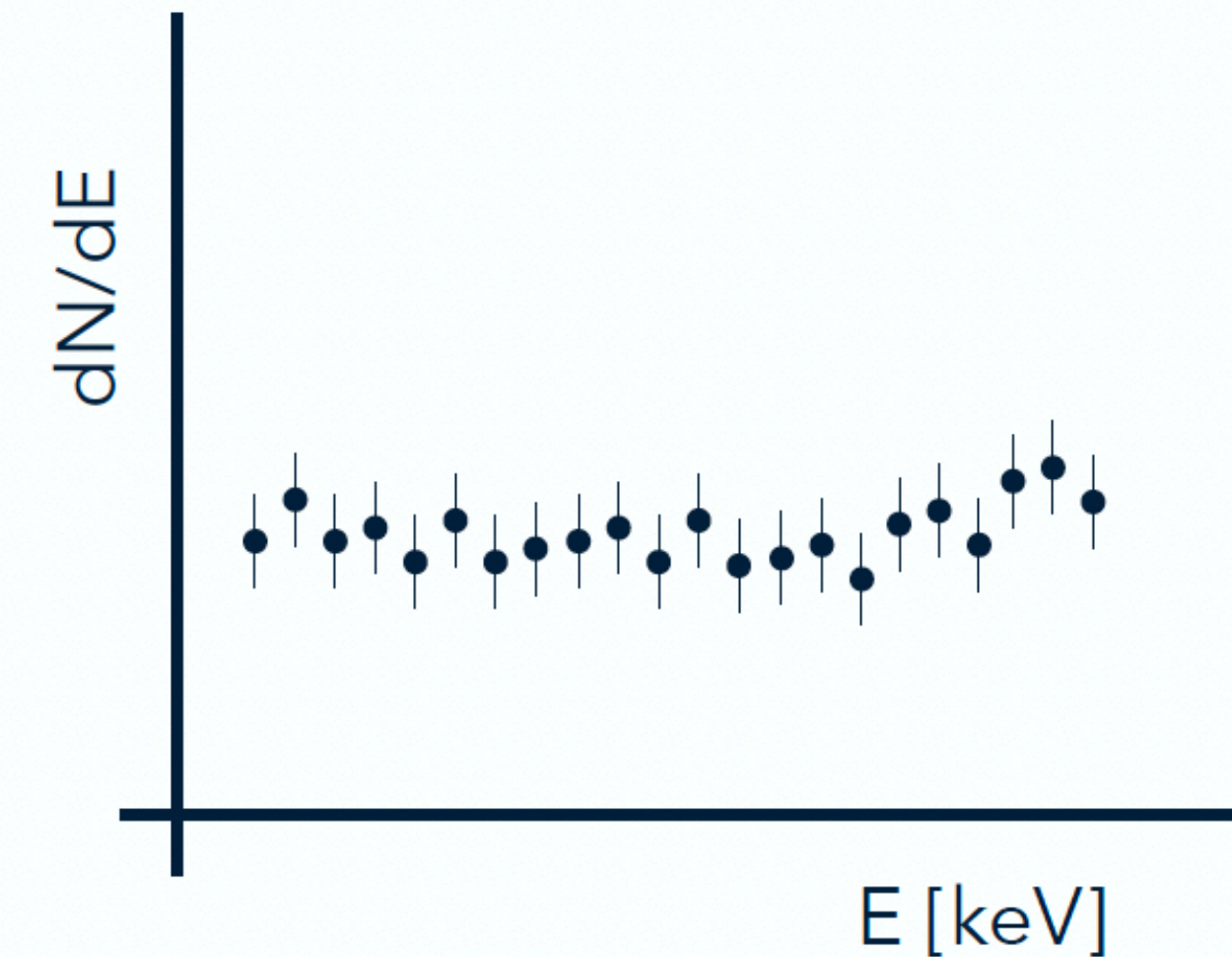


$$W = 13.7 \text{ eV/quantum}$$

$$E = W(n_{ph} + n_e)$$

$$E = W \left(\frac{S1}{g1} + \frac{S2}{g2} \right)$$

1D analysis



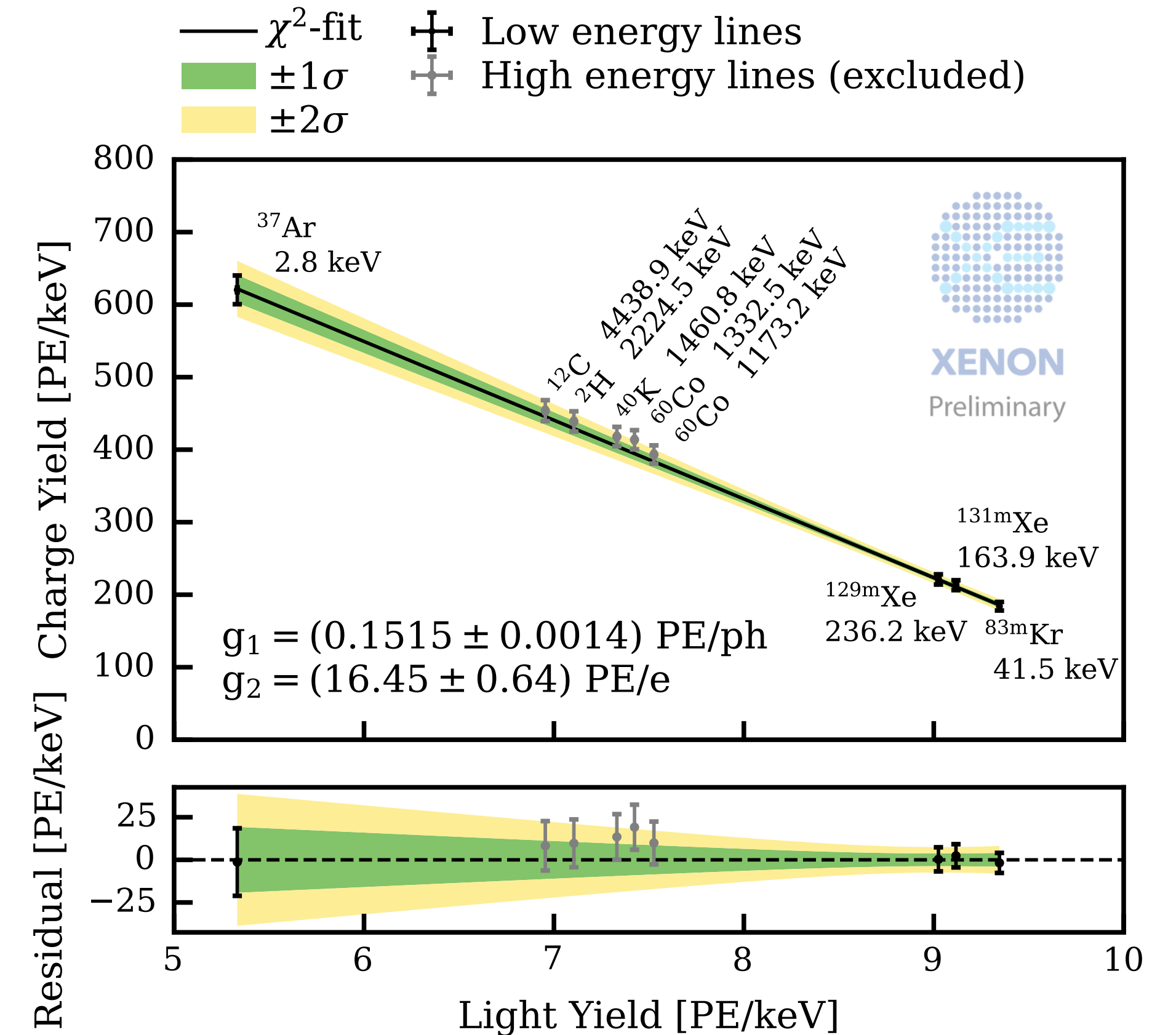
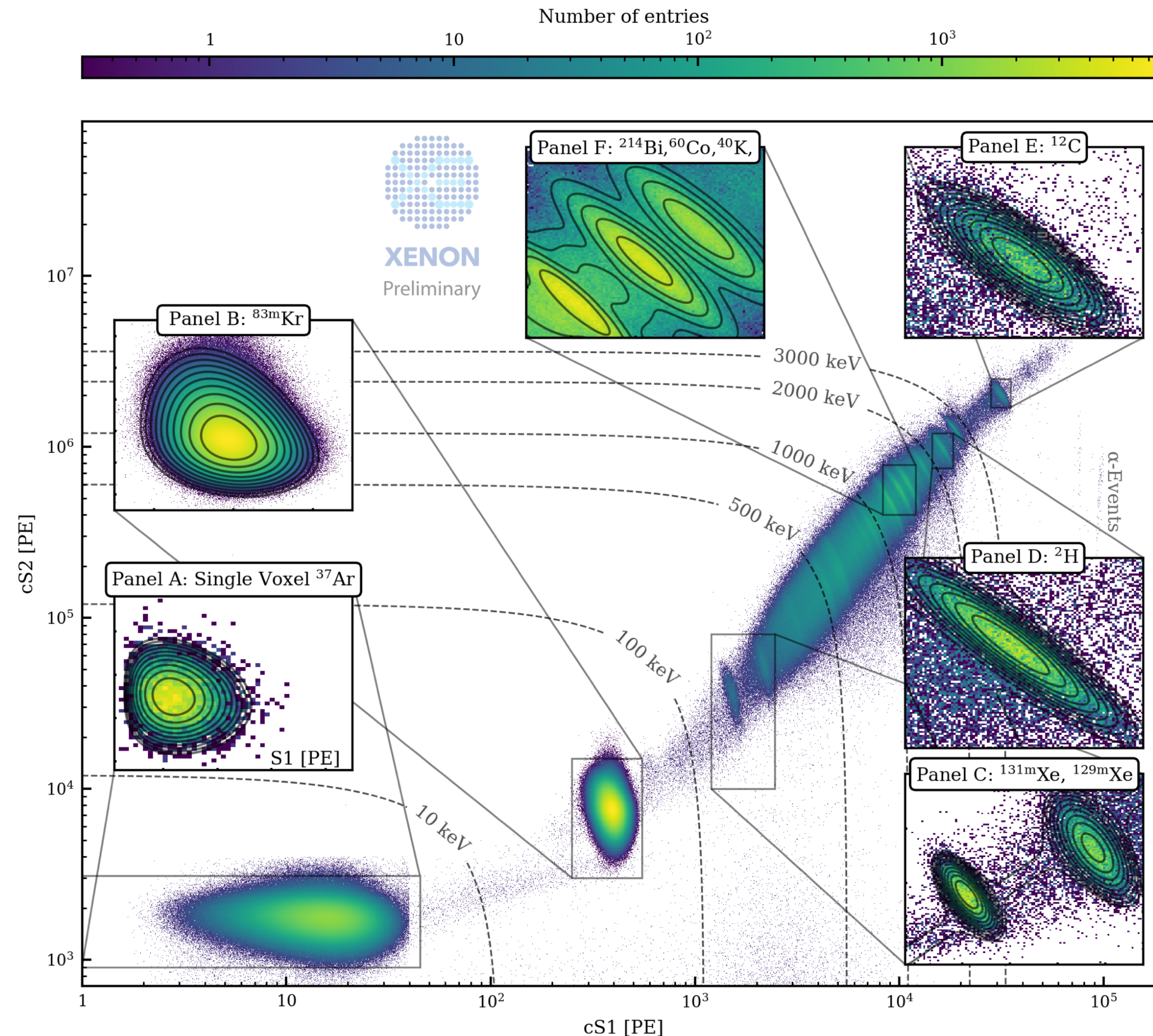
- Energy reconstruction based on detector-dependent parameters:

- g1: photon detection efficiency.
- g2: charge amplification factor.

Determined through several calibrations

Energy reconstruction

35



- Derive Light and Charge Yield from multiple mono-energetic lines and infer g_1/g_2 to build our energy scale

Energy reconstruction

36

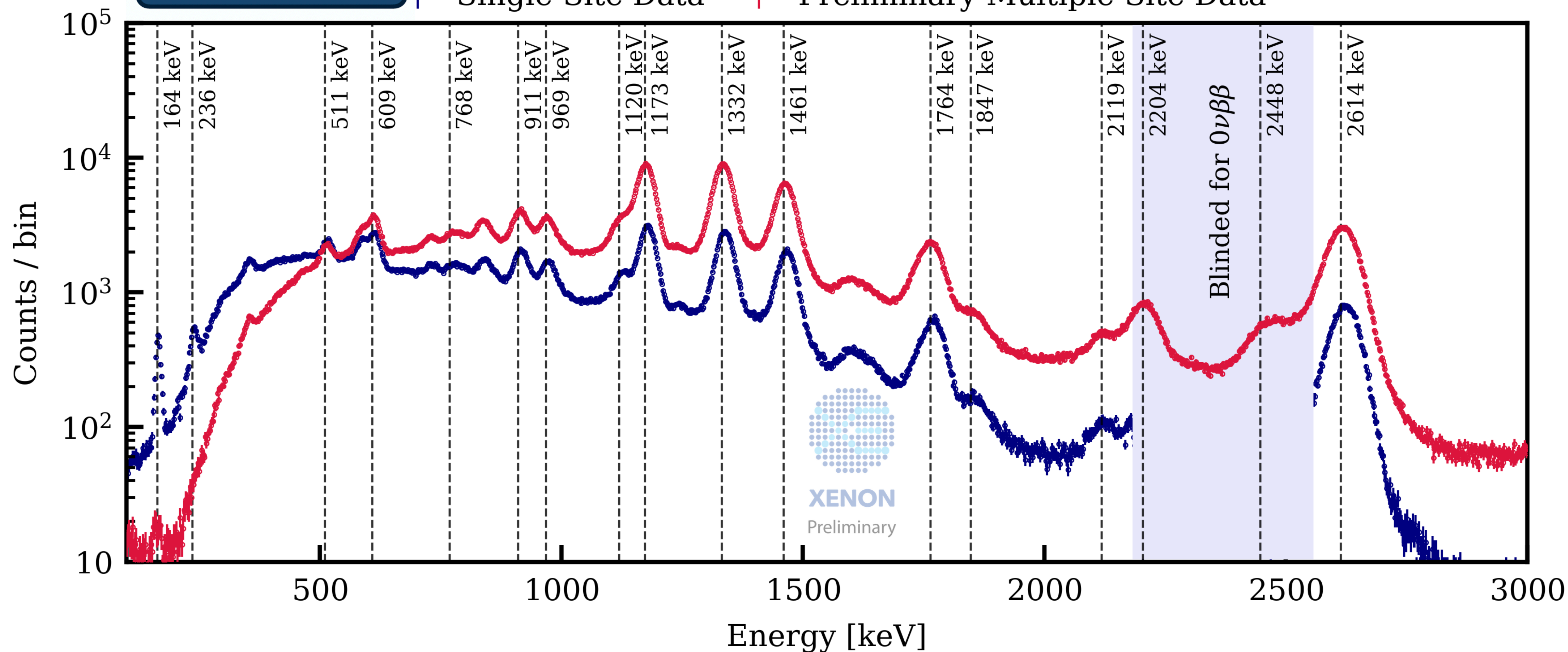
$$E = W \left(\frac{S1}{g1} + \frac{S2}{g2} \right)$$

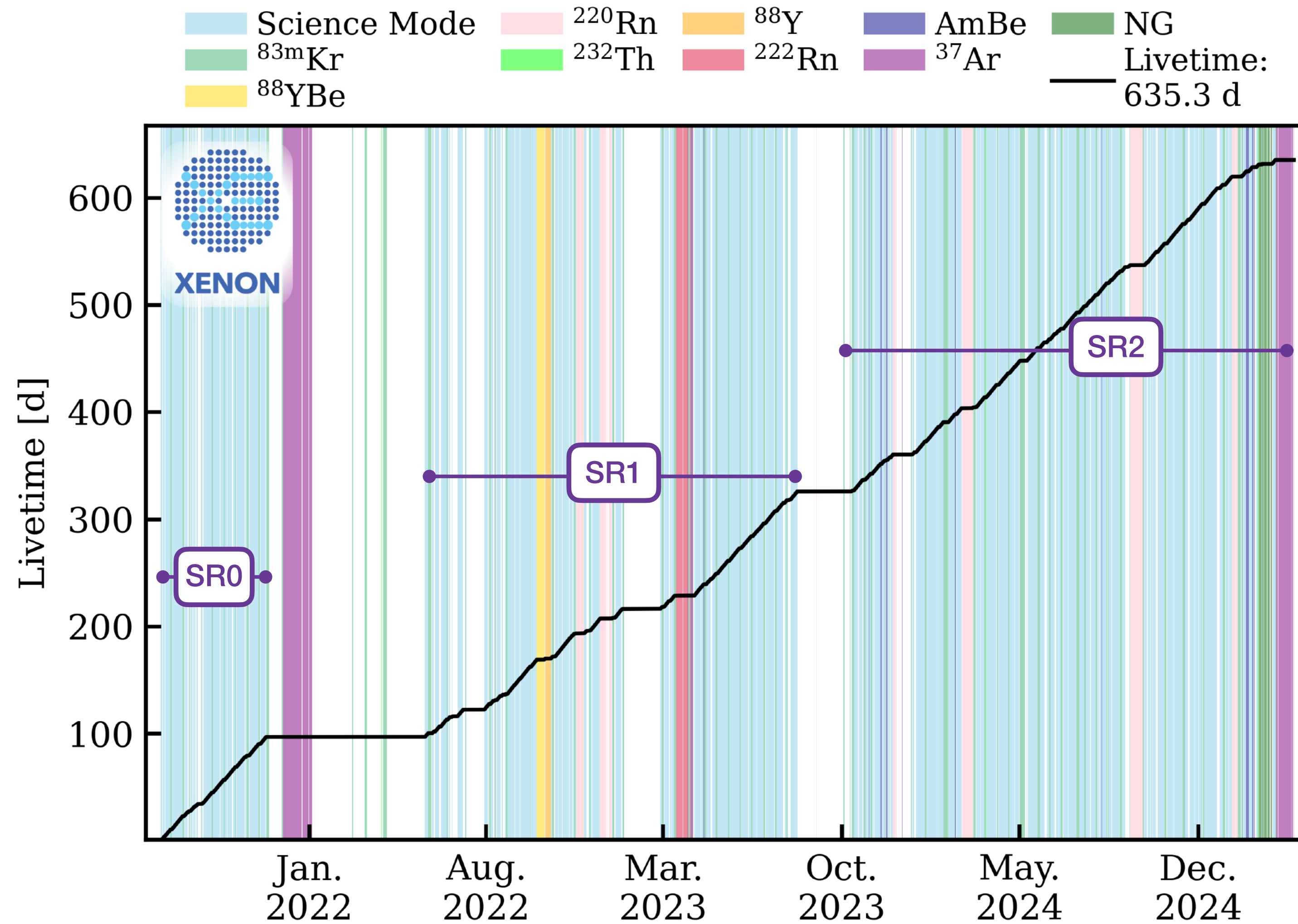


Single-Site Data



Preliminary Multiple-Site Data

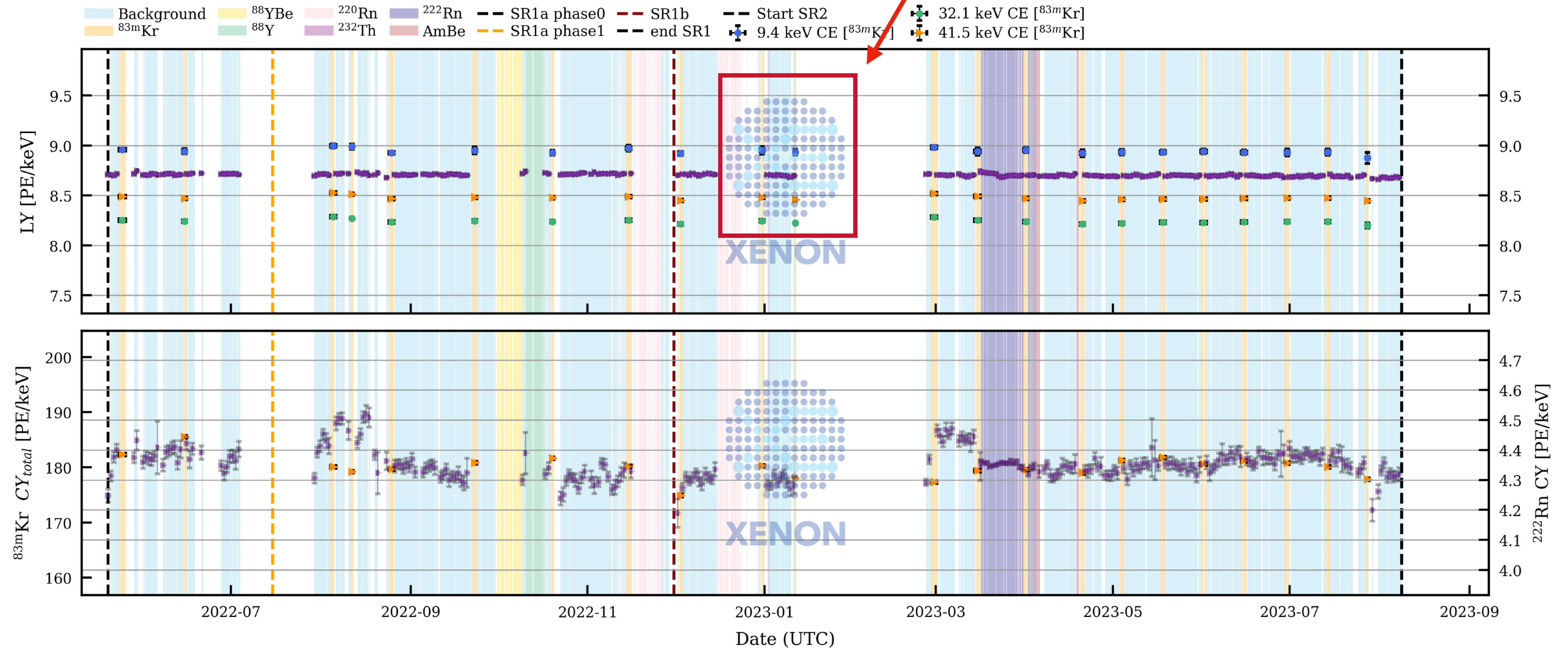




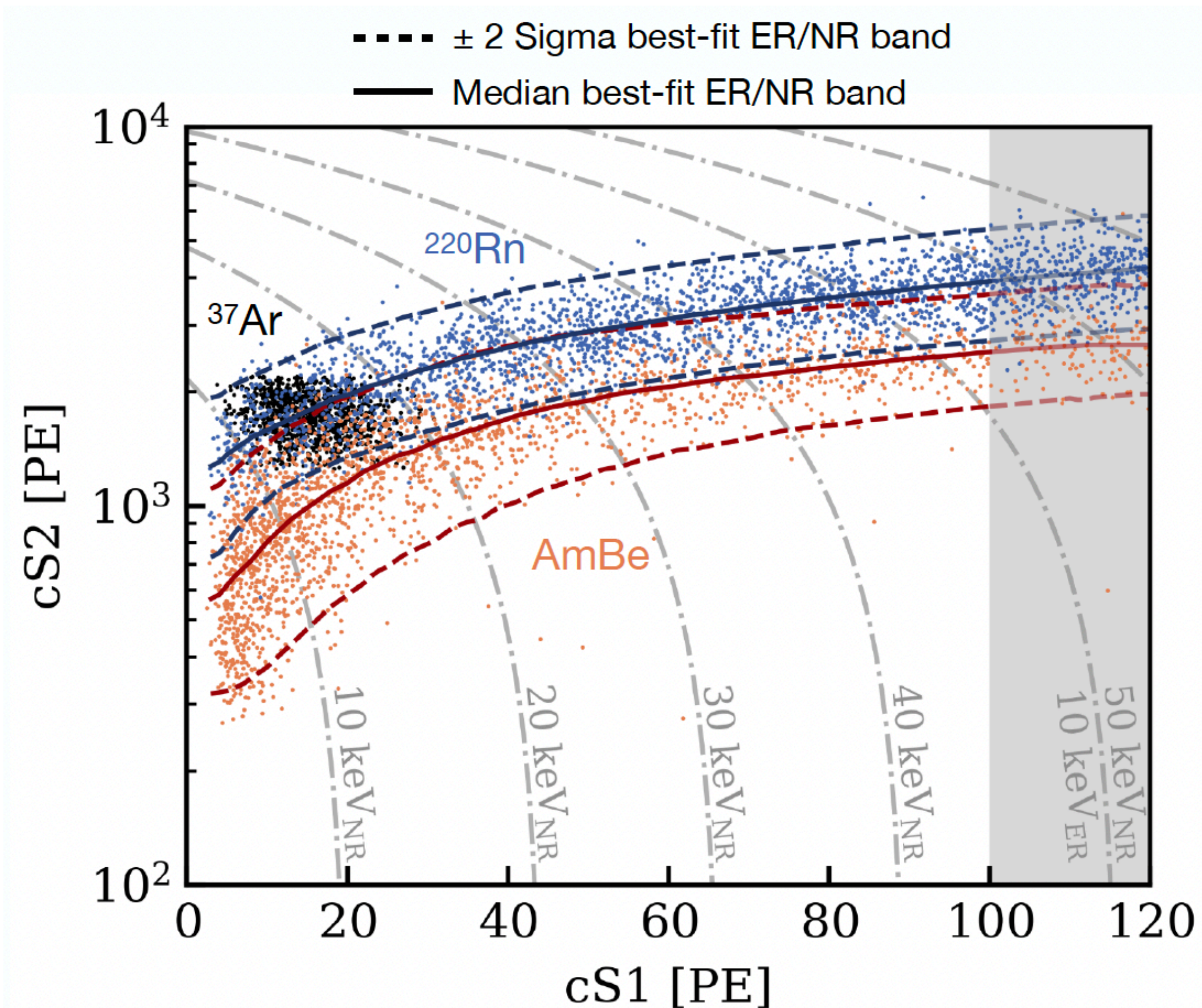
Stability of the detector

38

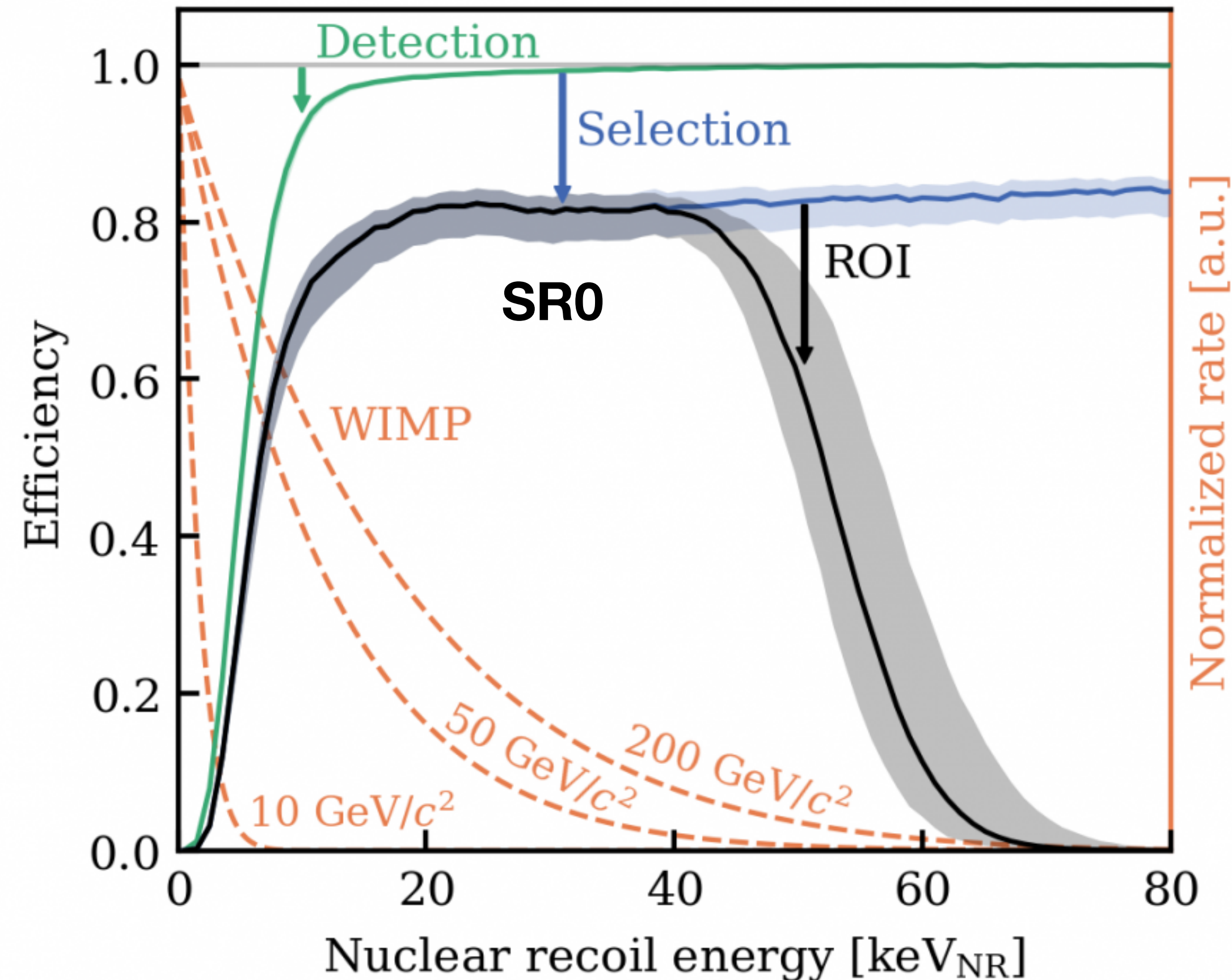
Might look sad, but the stability is actually good :)



Standard WIMP analysis



- Use our Calibration data to characterise the yield response of the detector to energy deposition, using NEST
- It allow us to simulate the expected light and charge quanta produced by a given energy deposition from ER/NR
- We can thus determine where our signals, and potential background would fall in our ROI
- We will then define a set of selection criteria to maximise the acceptance of this signal, while rejecting potential backgrounds



- **Detection:** dominated by 3-fold requirement (3 PMTs to be in coincidence)
- **Event building:** whether an event is successfully reconstructed
- **Selection:** efficiency due to cut acceptance

Region of Interest (ROI)

$$cS1 < 100 \text{ PE}$$

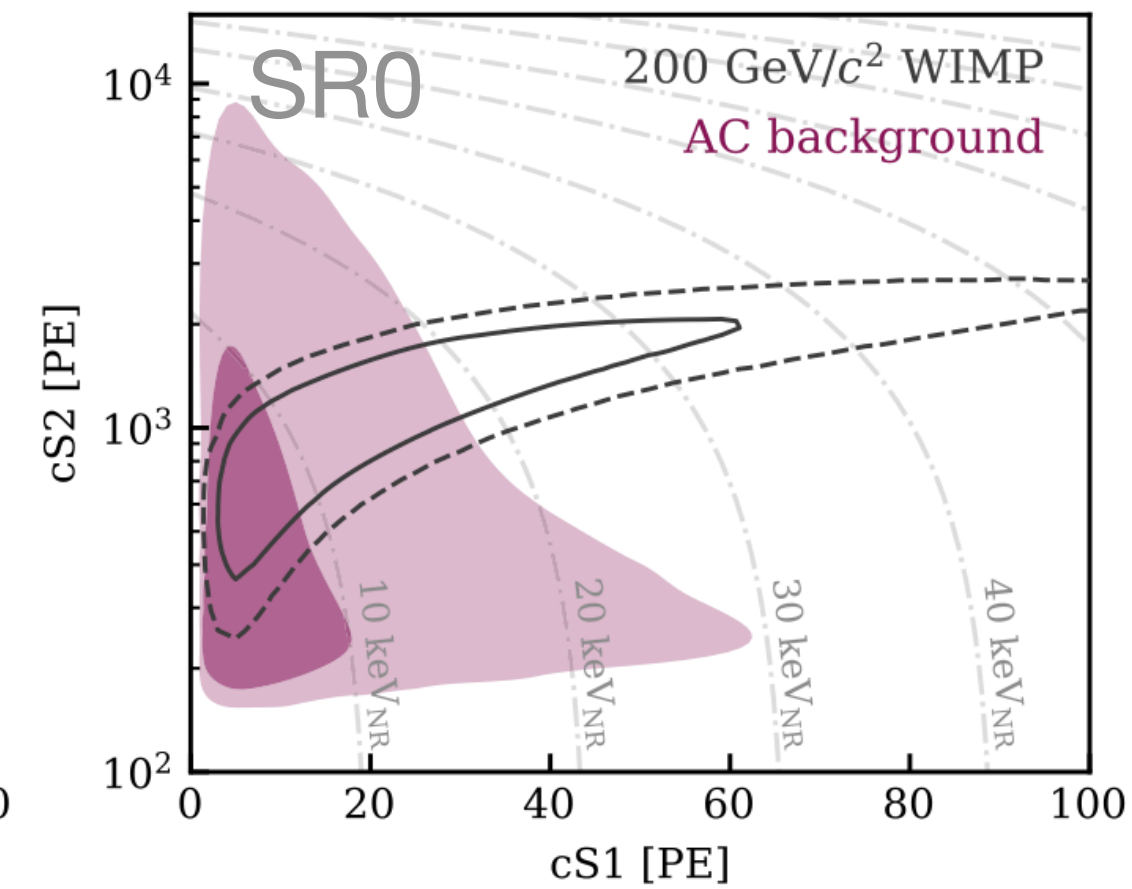
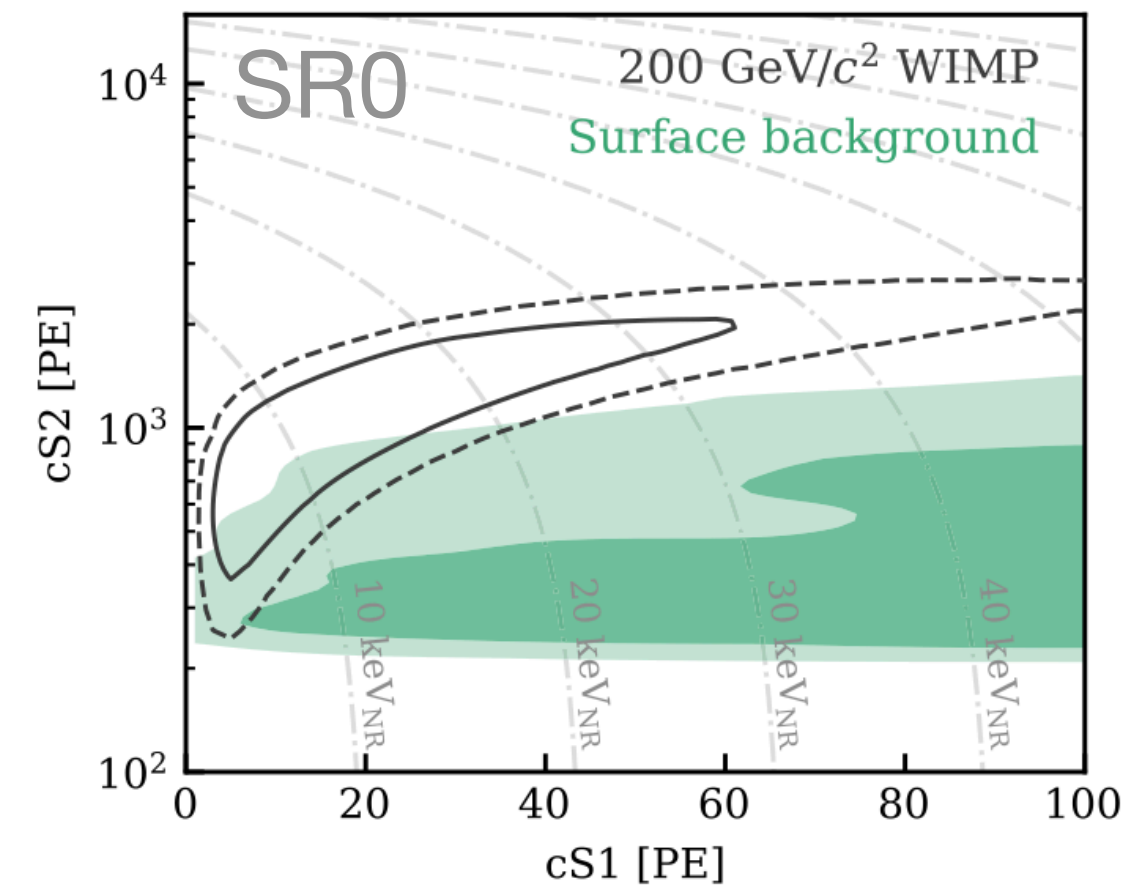
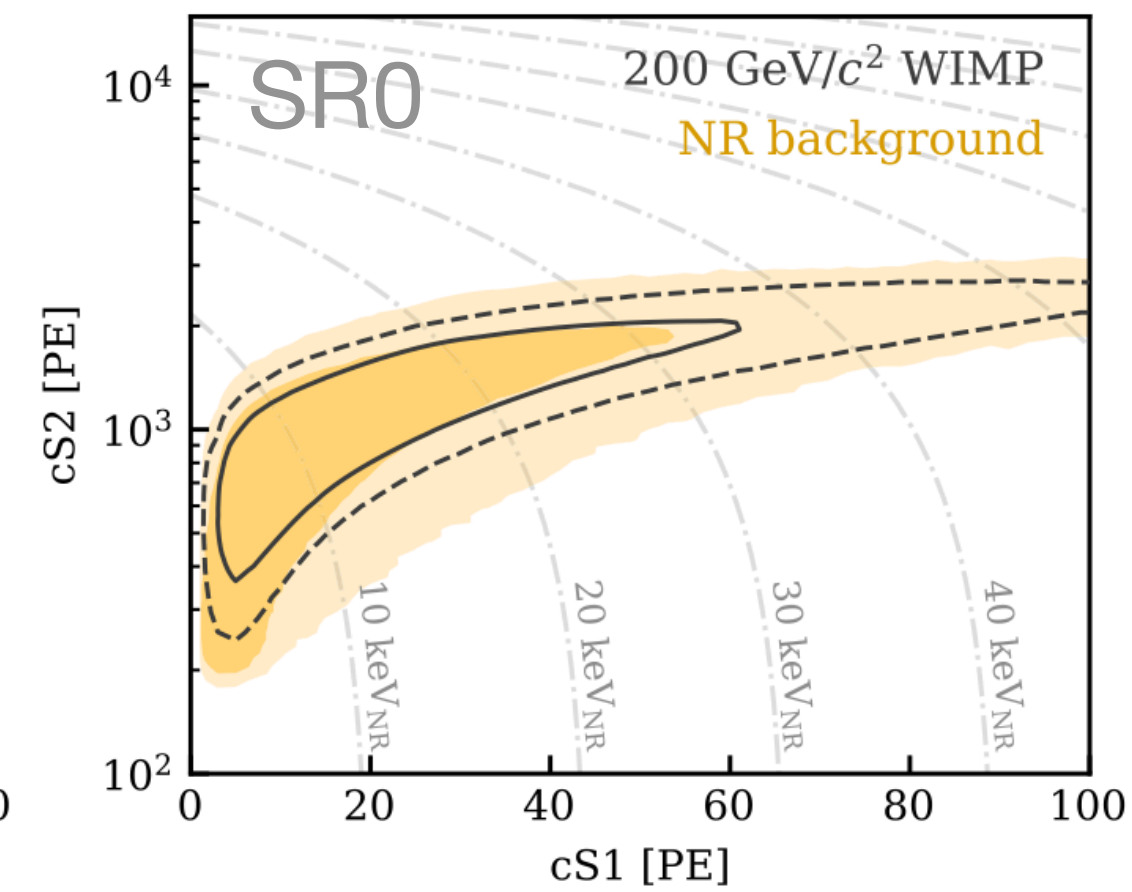
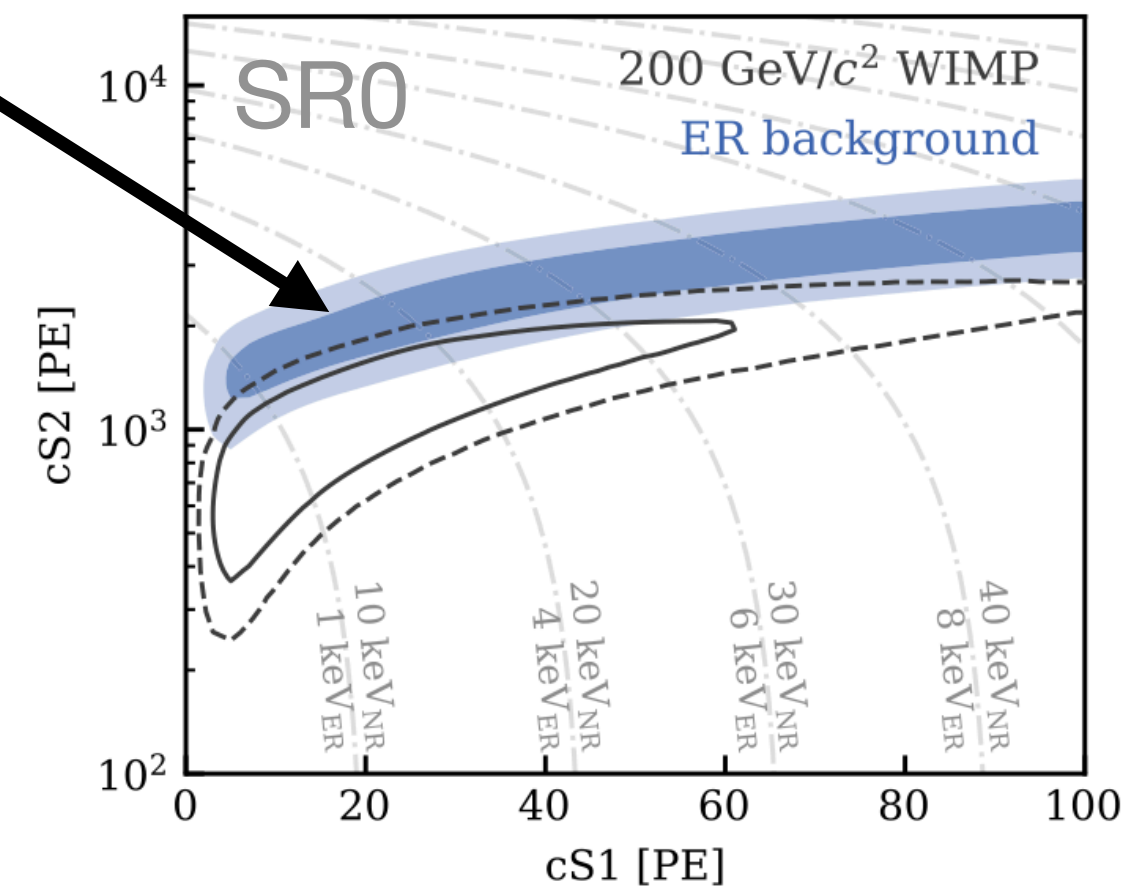
$$cS2 \in [10^{2.1}, 10^{4.1}] \text{ PE}$$

Signal & Background Modeling

42

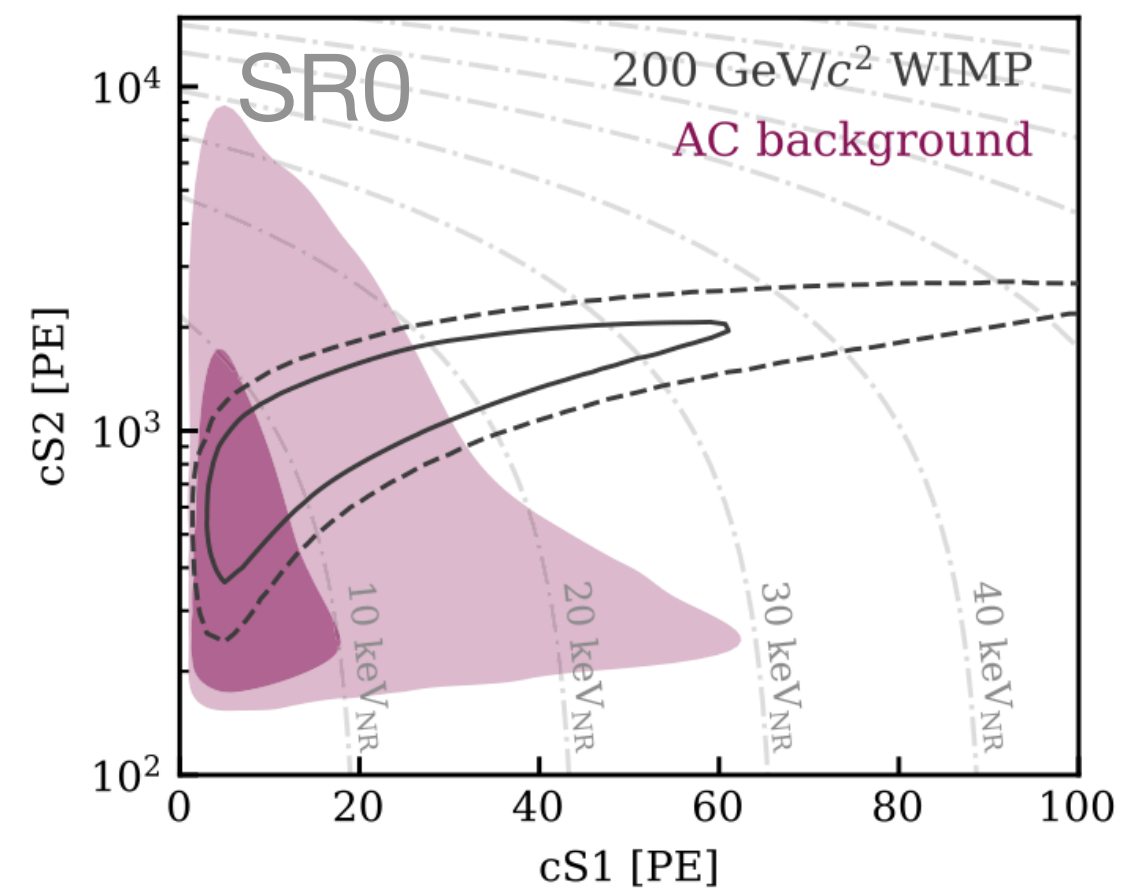
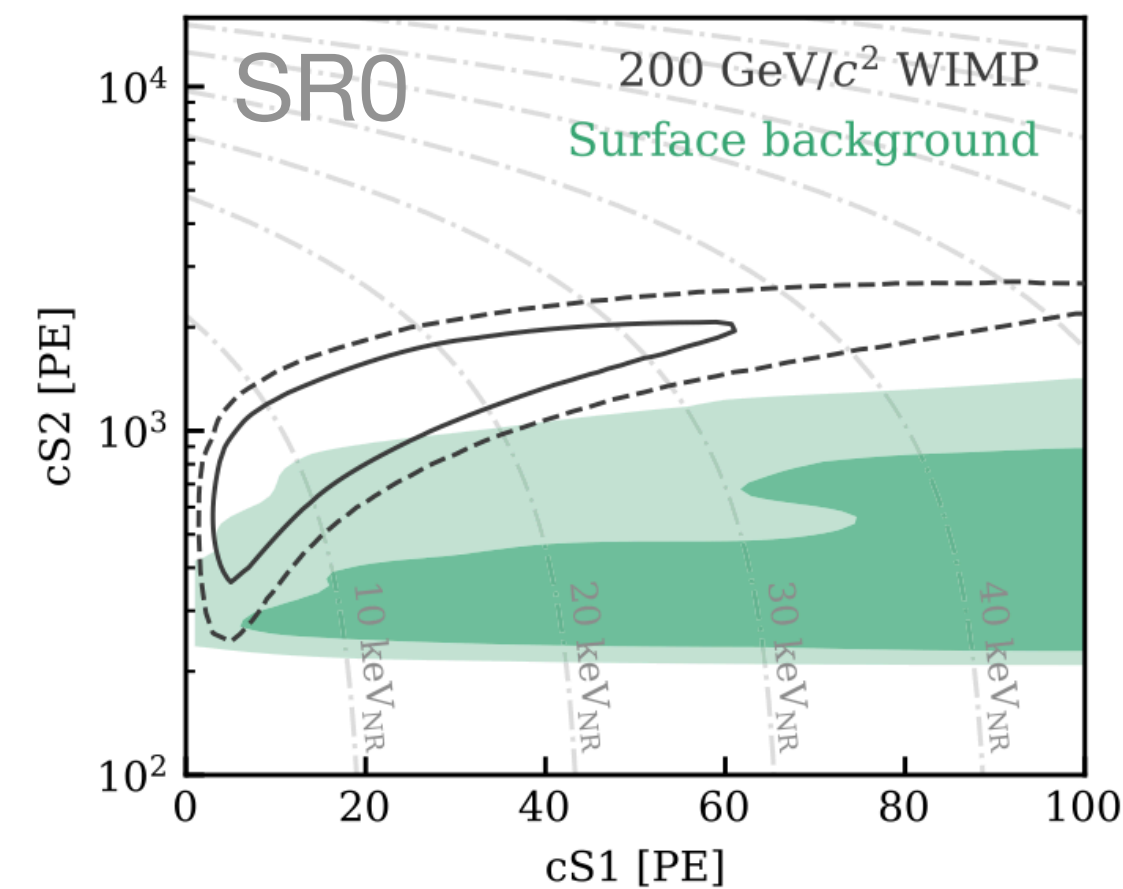
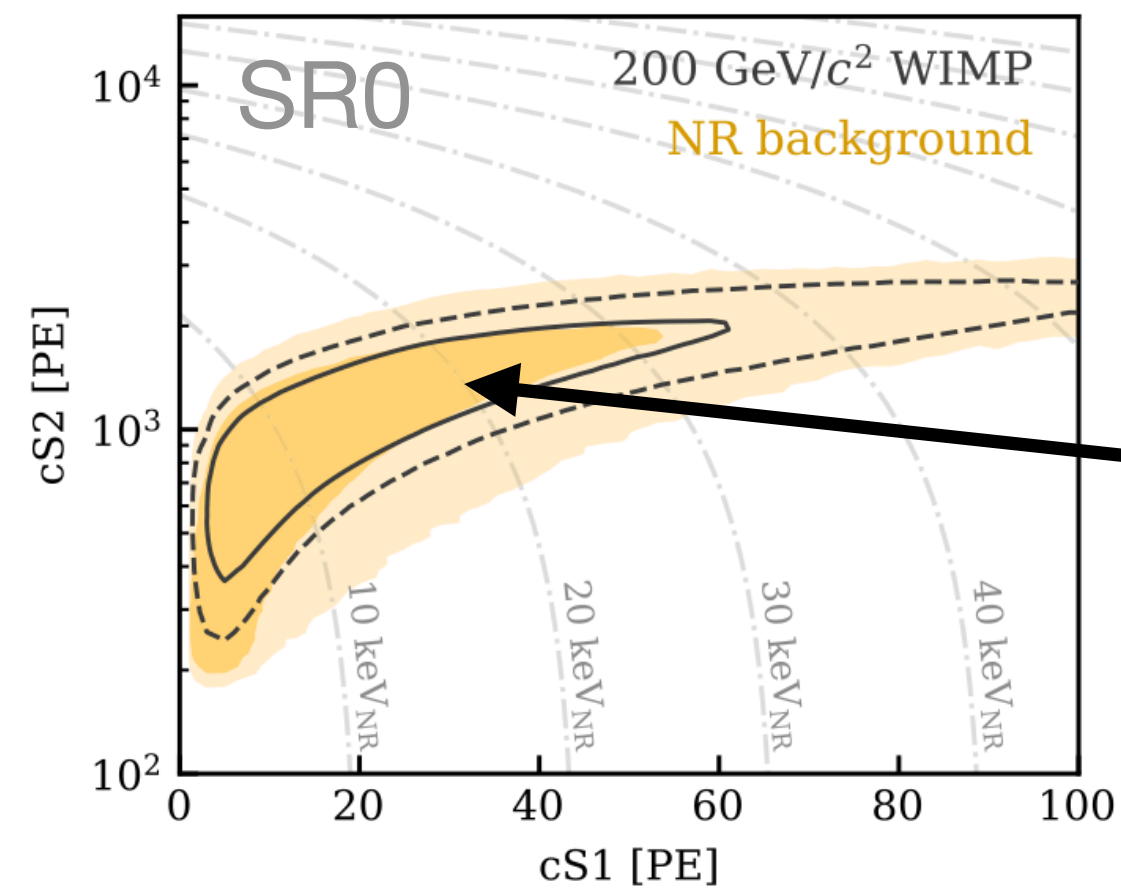
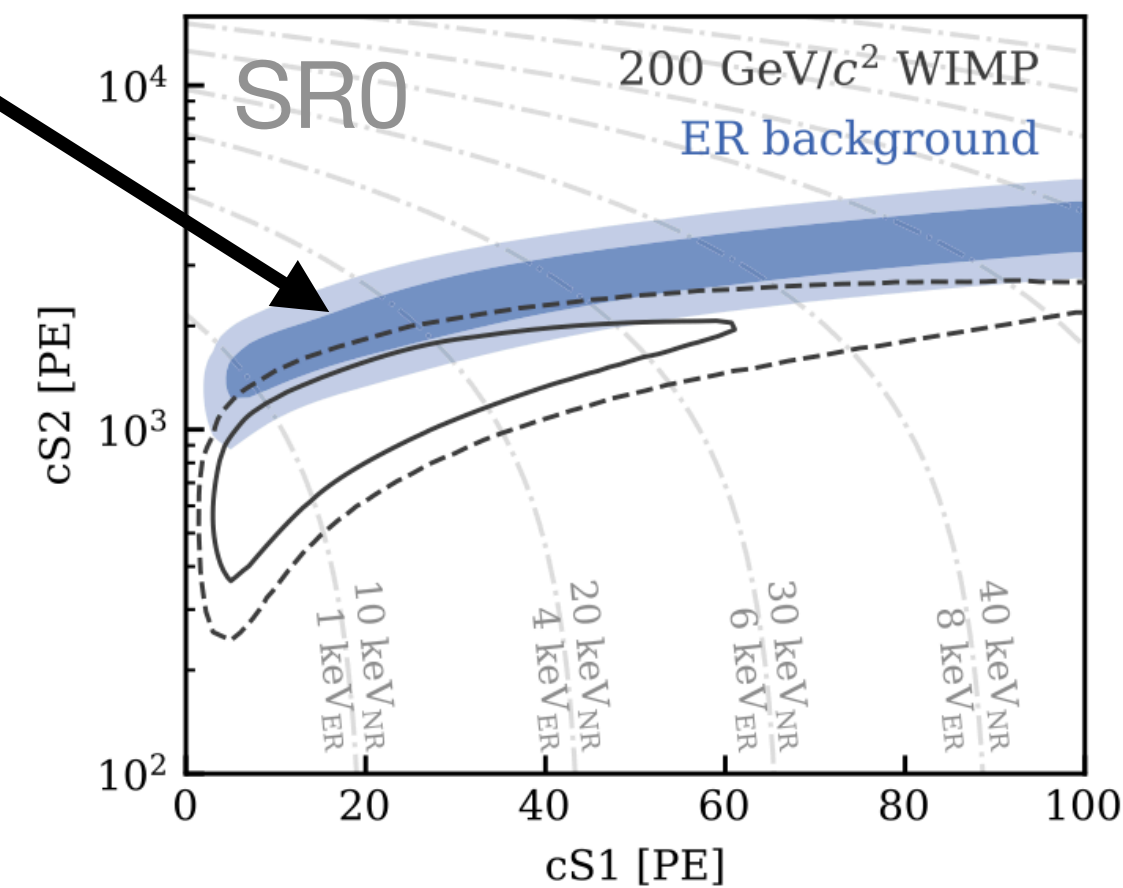
Electronic Recoils:

- ^{214}Pb , ^{85}Kr β -decays, ^{124}Xe $2\nu\text{ECEC}$, solar $\nu\text{-e}^-$ scatter
- Shape constrained with ^{220}Rn calibration
- Rate constrained by fit to reconstructed spectrum in $[20, 140] \text{ keV}_{\text{ER}}$



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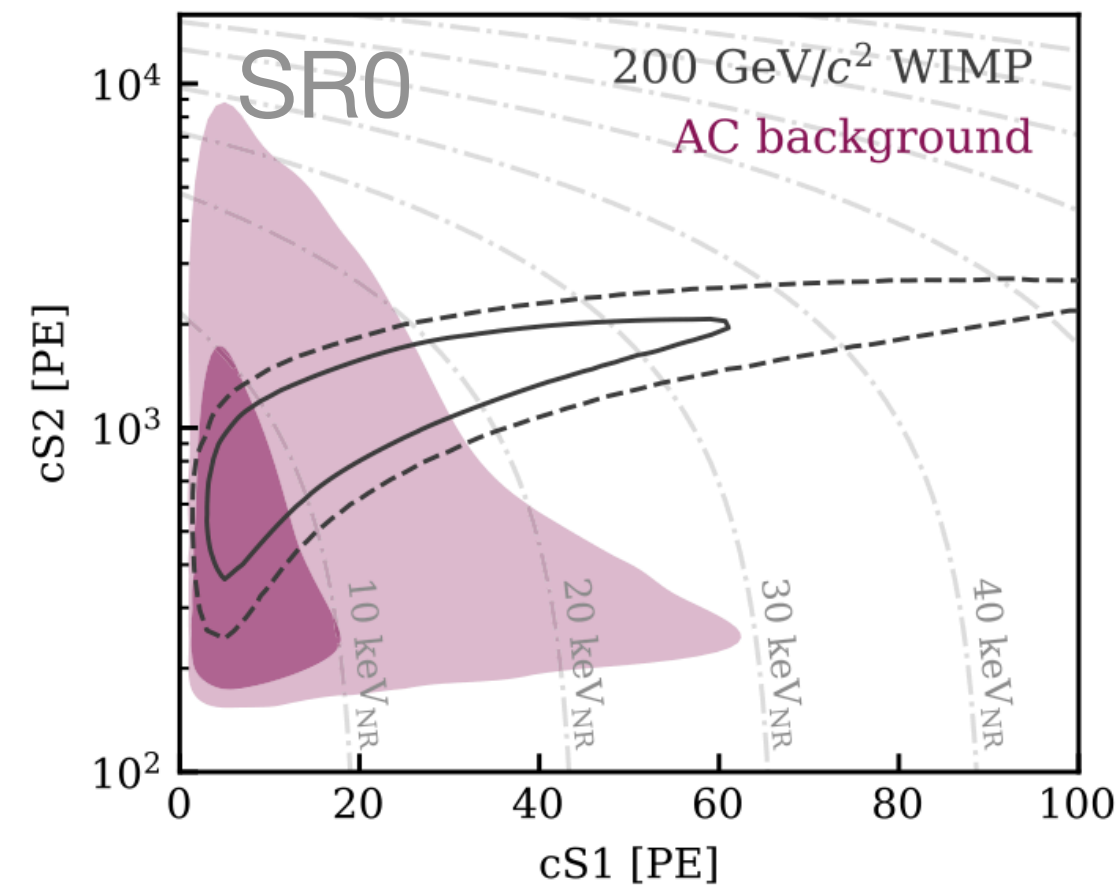
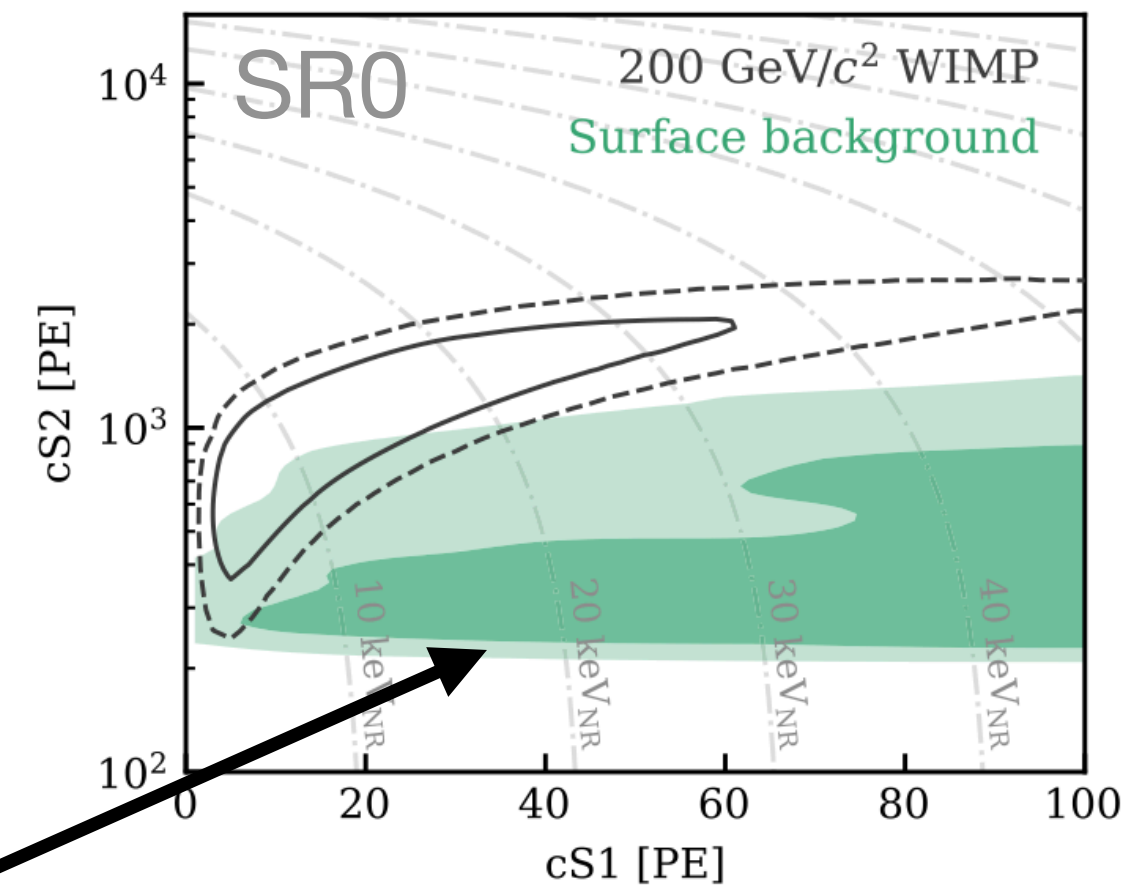
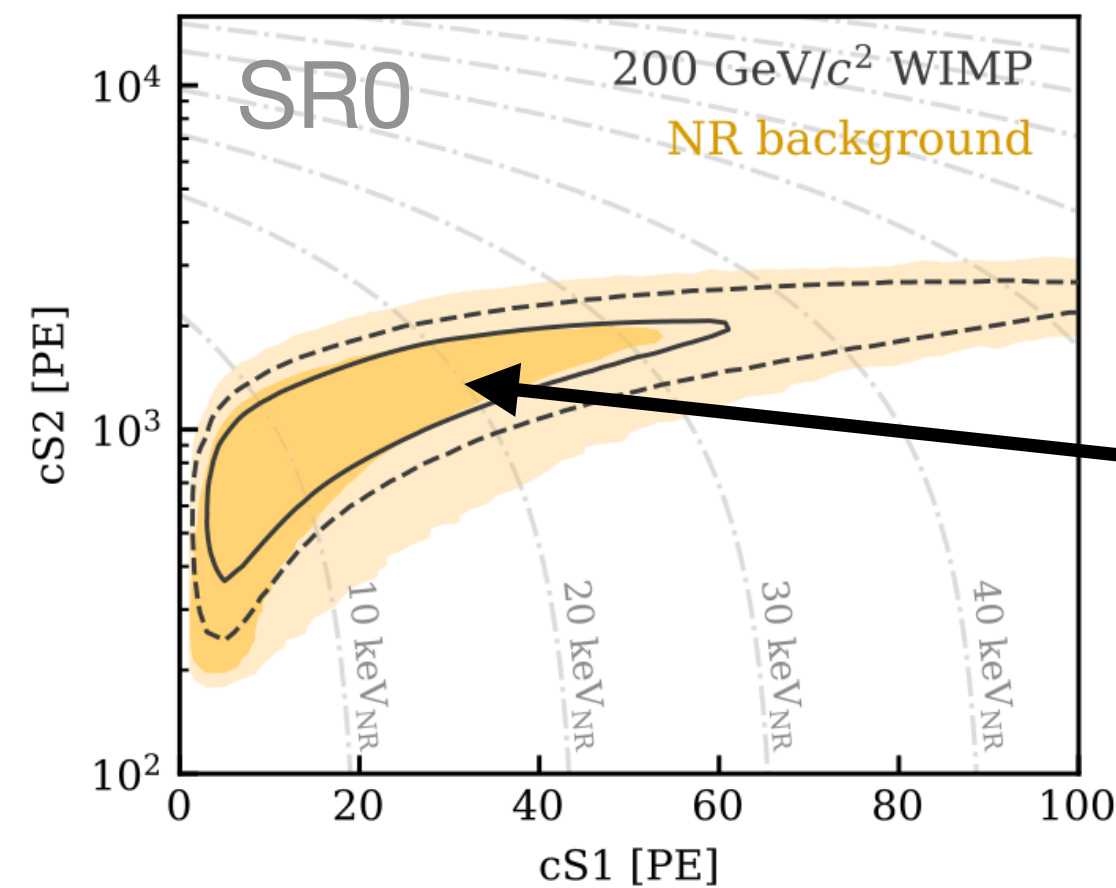
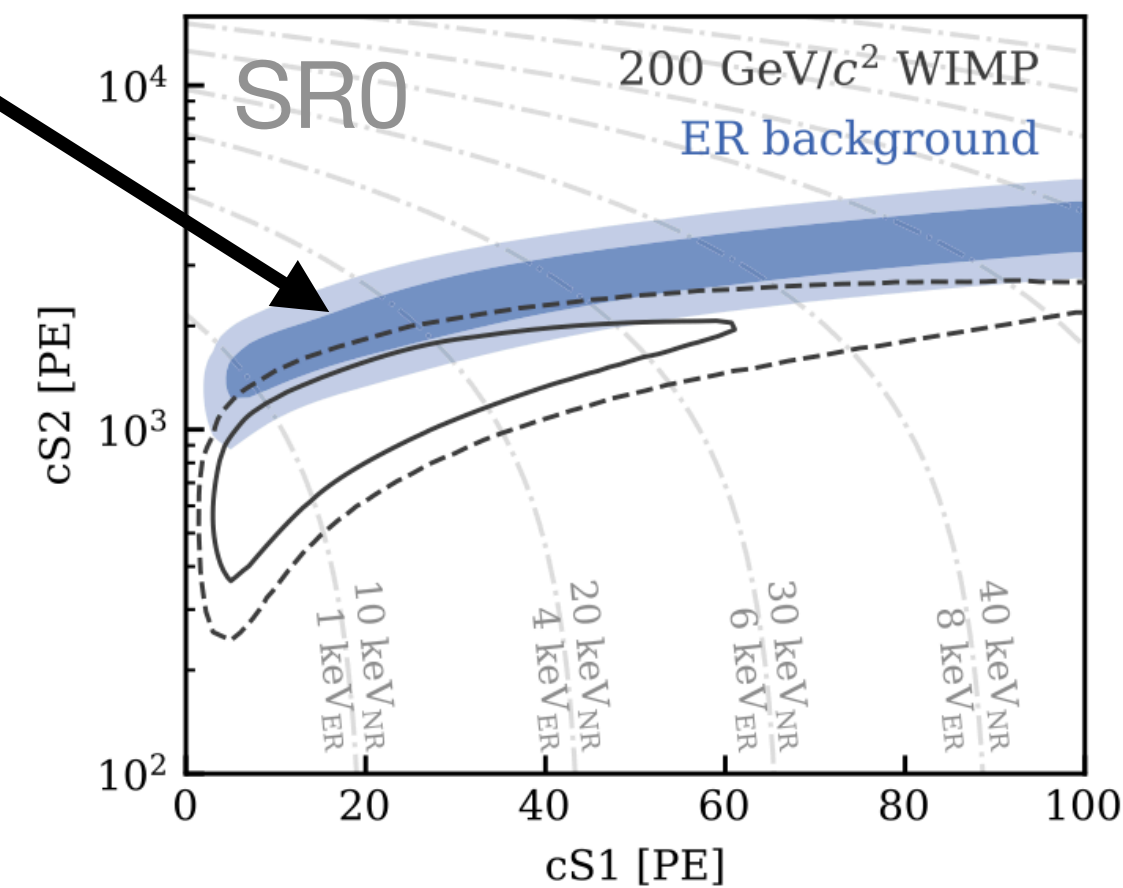


Nuclear Recoils:

- Radiogenic neutrons from materials, suppressed by **NV tagging** and **multi-scatter (MS) rejection** and constrained by **sideband** of MS and single-scatter events tagged by NV
- **CEvNS**, constrained by **neutrino flux** and **uncertainties on NR emission model**

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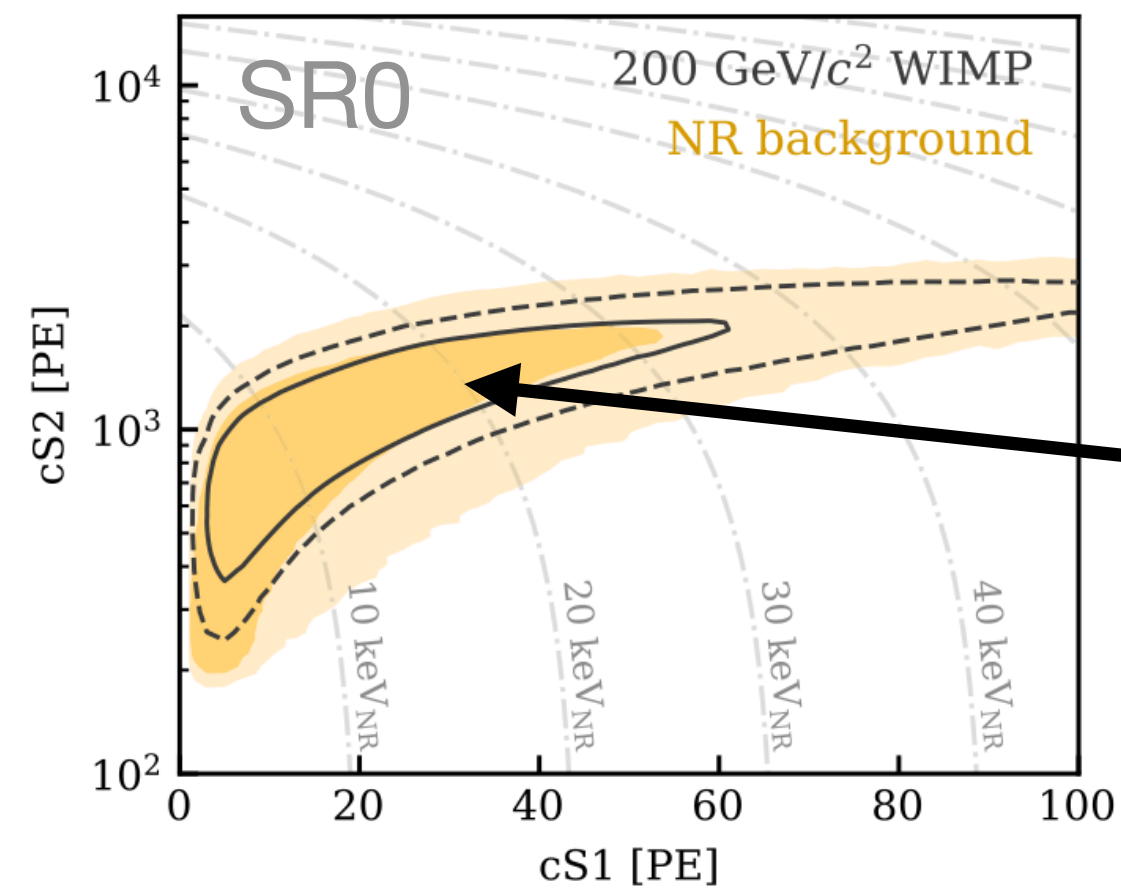
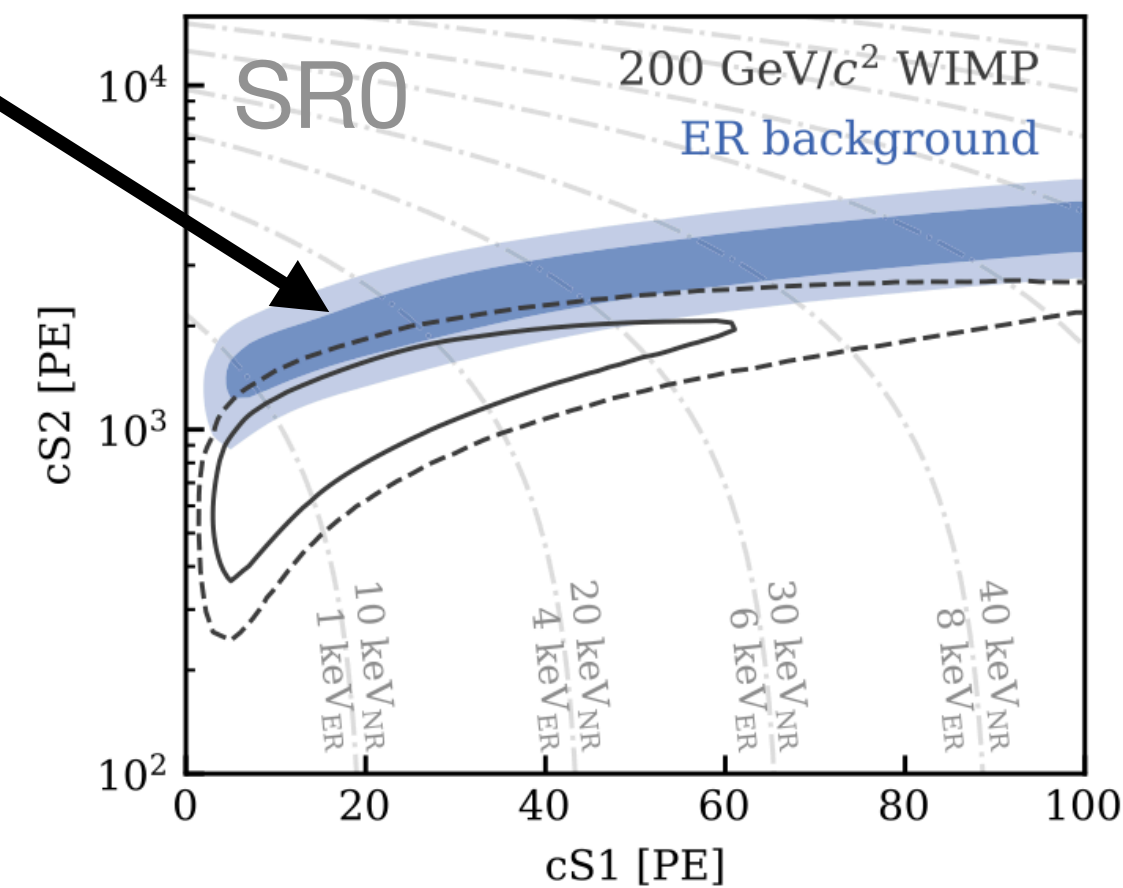
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Surface:

- ^{210}Pb β -decay from PTFE walls due to **plate-out effect**
- Suppressed by **fiducial volume (FV) selection**
- **Data-driven** constrain validated **outside FV**

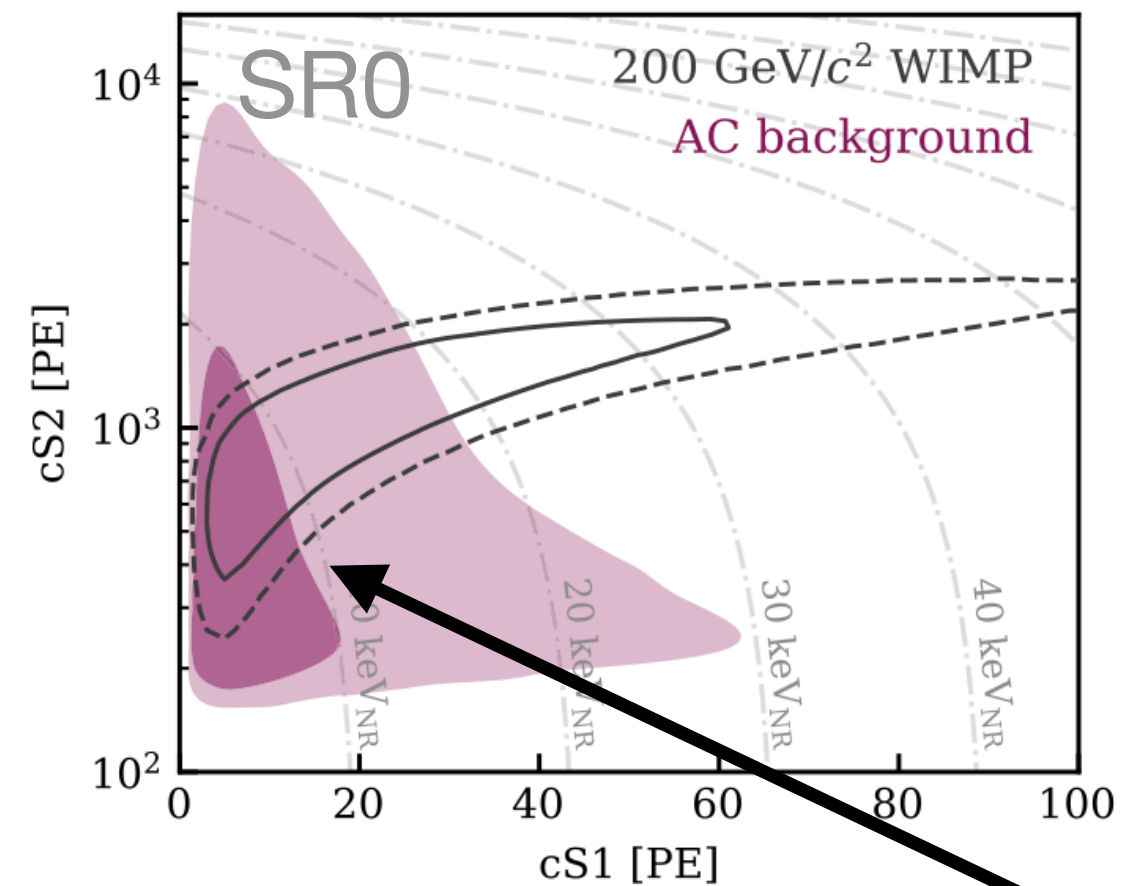
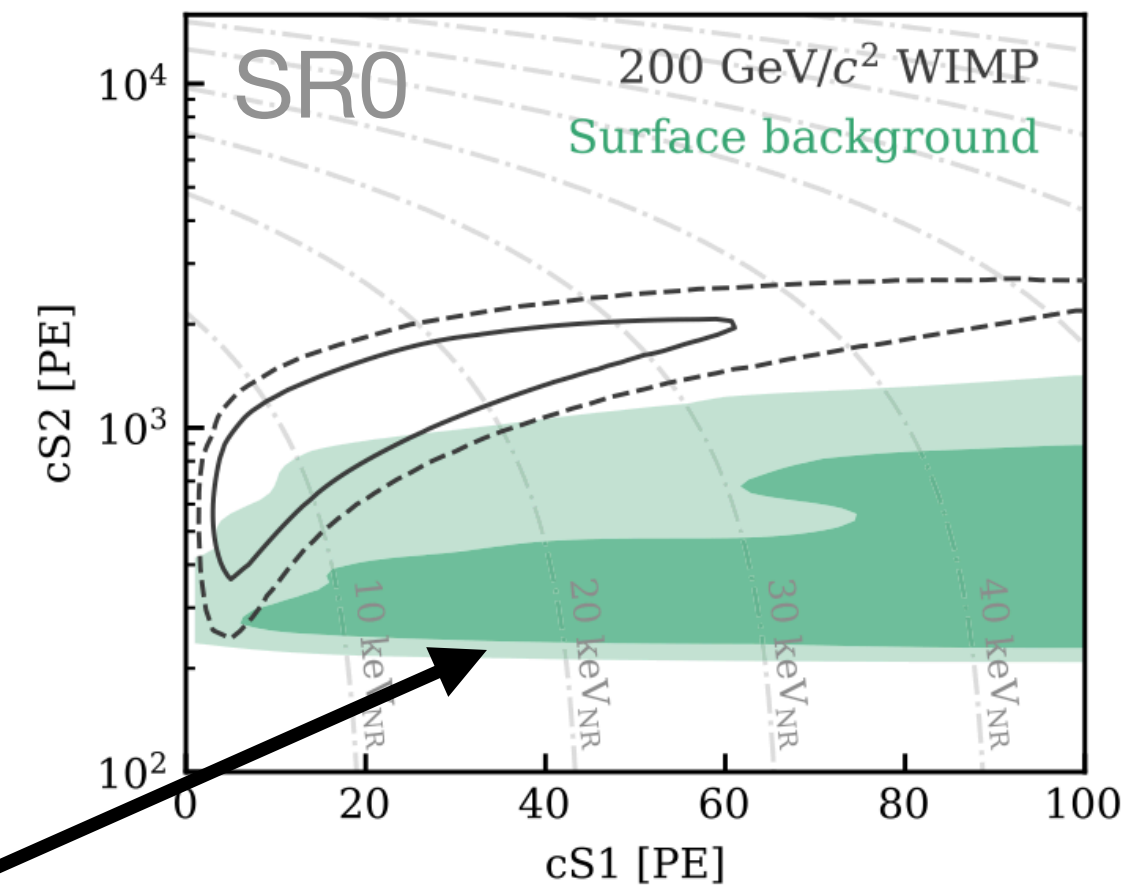
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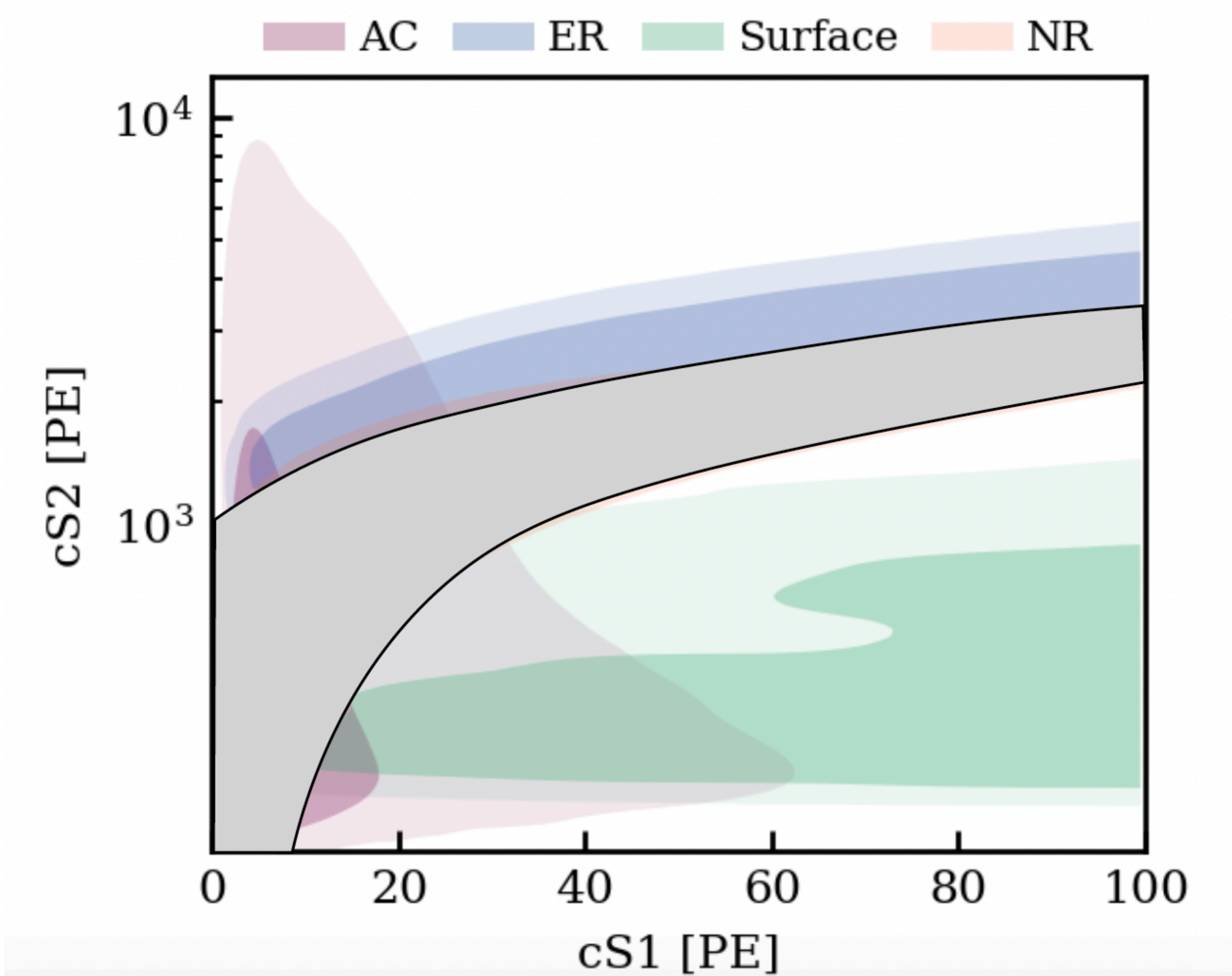
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Accidental Coincidence:

- Accidental pairing of isolated S1-S2, removed by **dedicated machine learning based cuts**
- **Data-driven** modeling, validated with **sideband unblinding**

Blinded data analysis

	Expectation
ER	134
Neutrons	$1.1^{+0.6}_{-0.5}$
CEvNS	0.23 ± 0.06
AC	4.3 ± 0.2
Surface	14 ± 3
Total	154
²⁰⁰ GeV/c ² WIMP	-
Observed	-



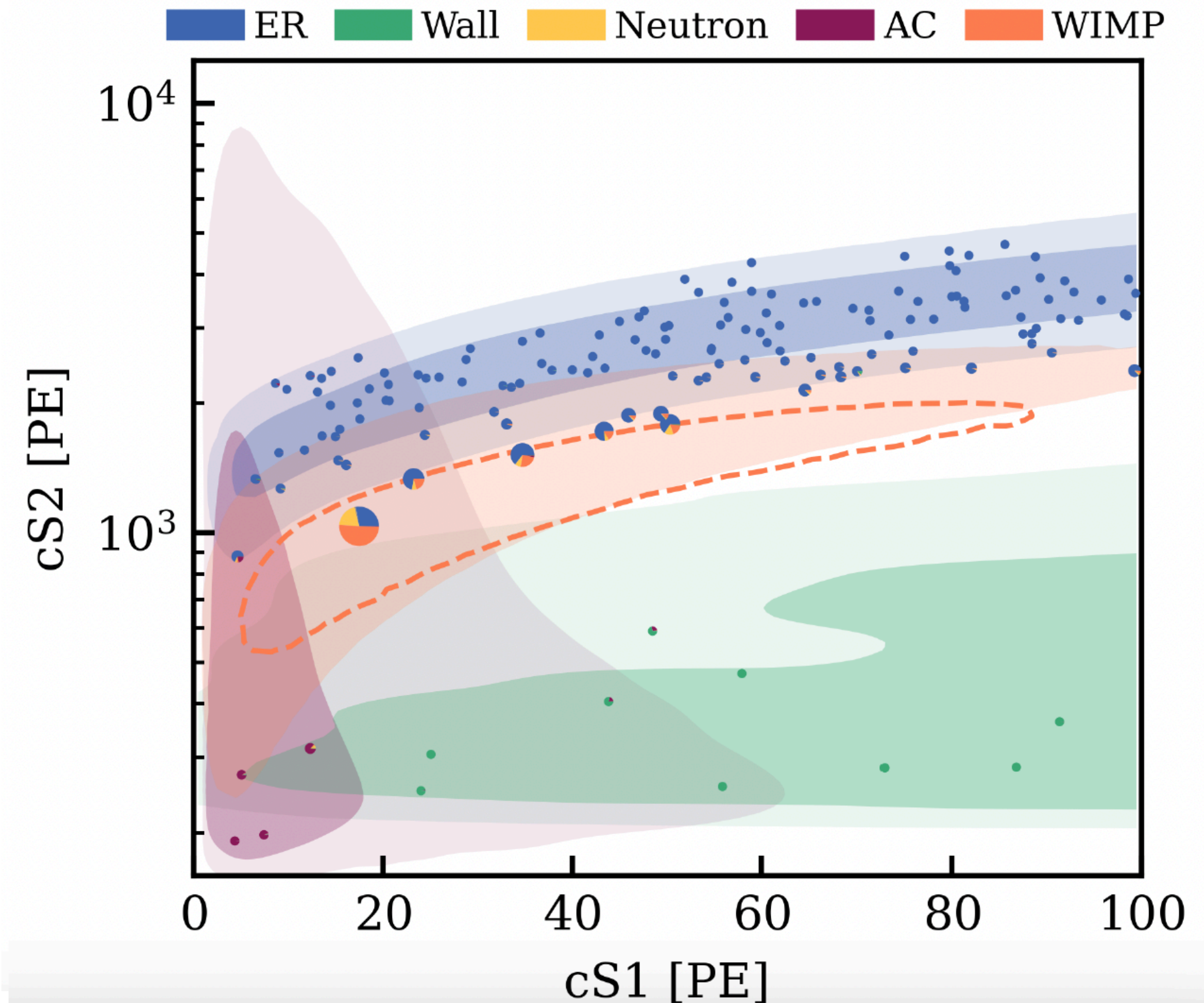
Blinded data analysis

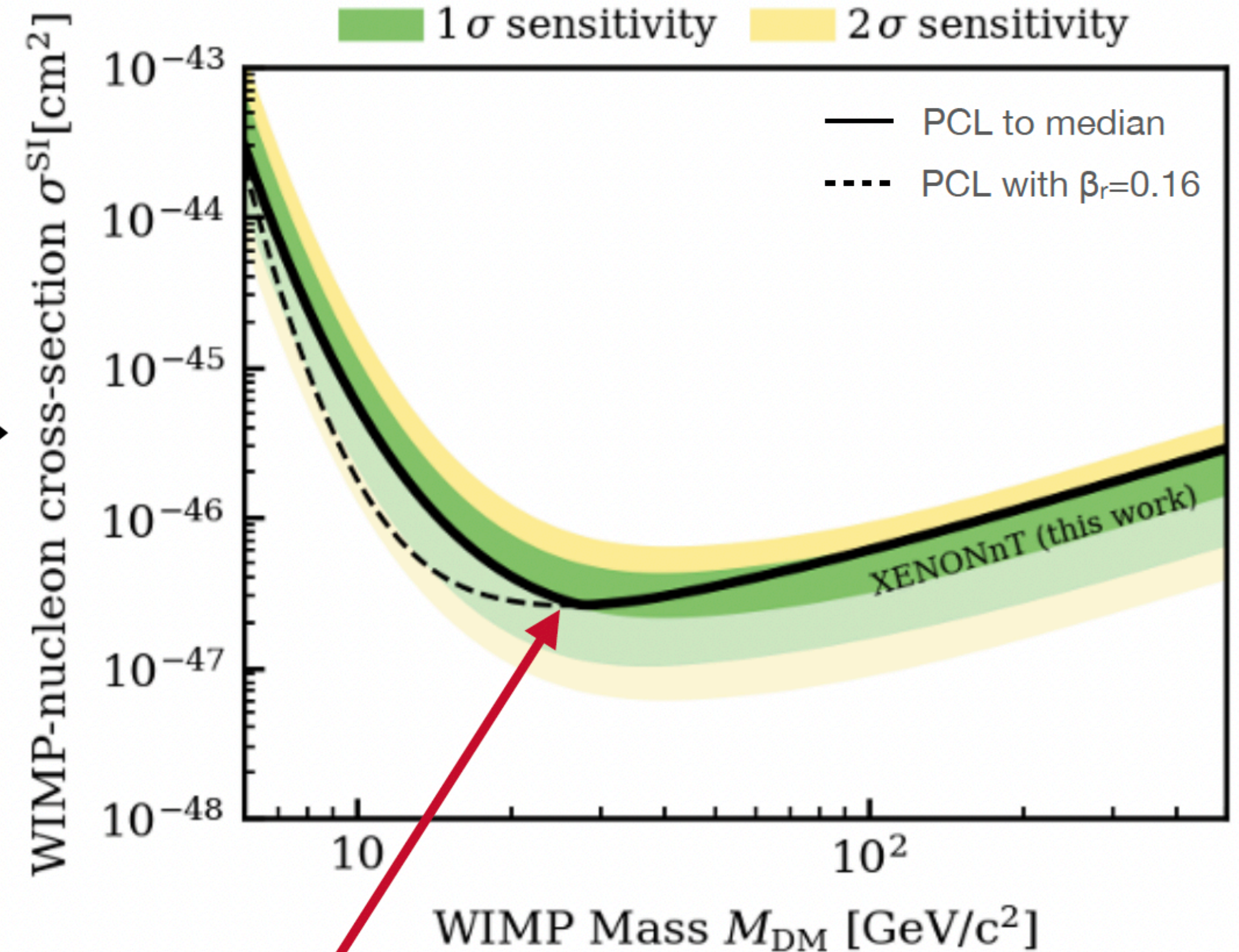
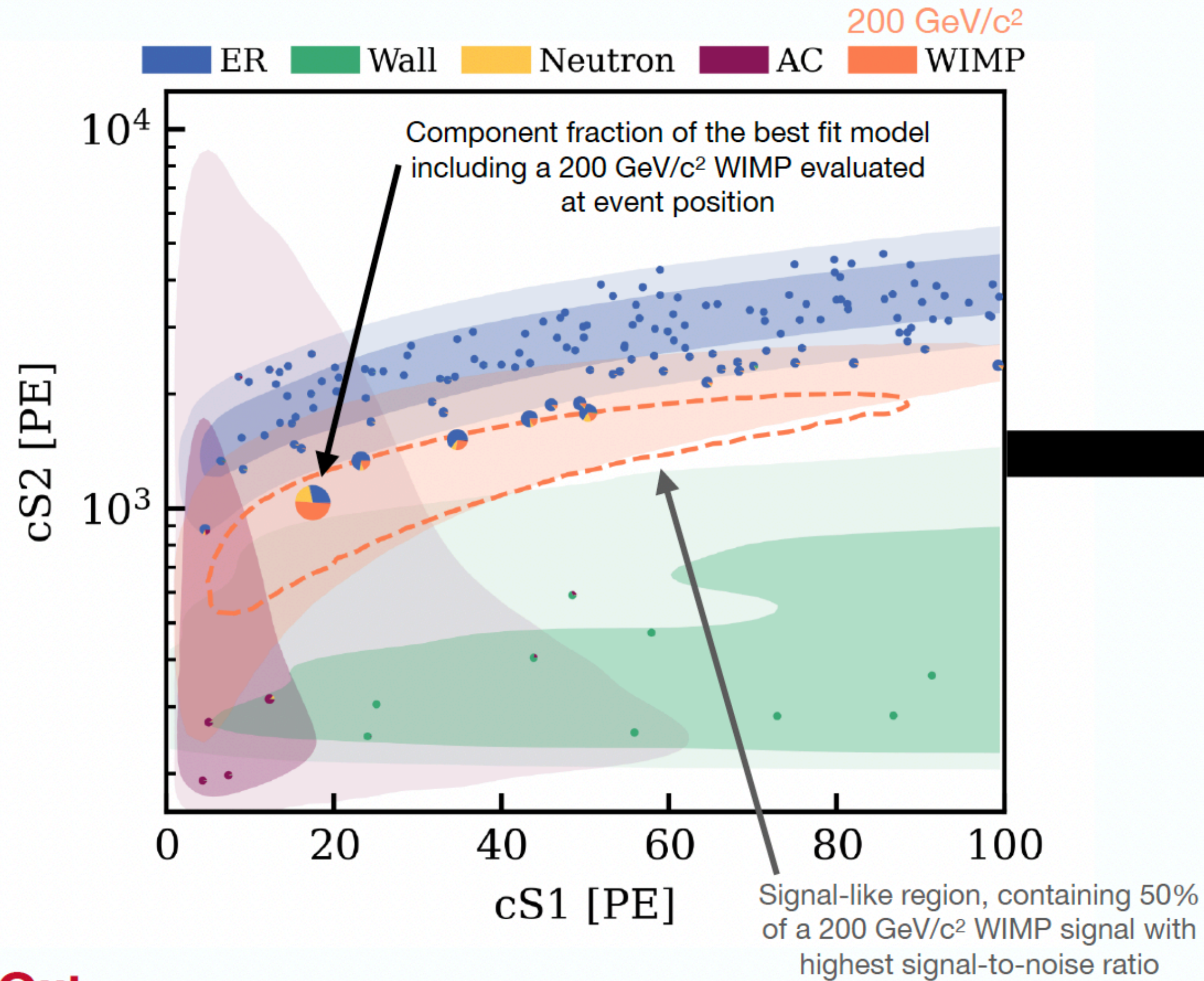
	Expectation	Best Fit
ER	134	135^{+12}_{-11}
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.4
CEvNS	0.23 ± 0.06	0.23 ± 0.06
AC	4.3 ± 0.2	4.32 ± 0.15
Surface	14 ± 3	12^{+0}_{-4}
Total	154	152 ± 12
²⁰⁰ GeV/c ² WIMP	-	2.4
Observed	-	152

Unblinding

⊙ Profile log-likelihood-ratio test statistic

➔ **No significant excess observed**





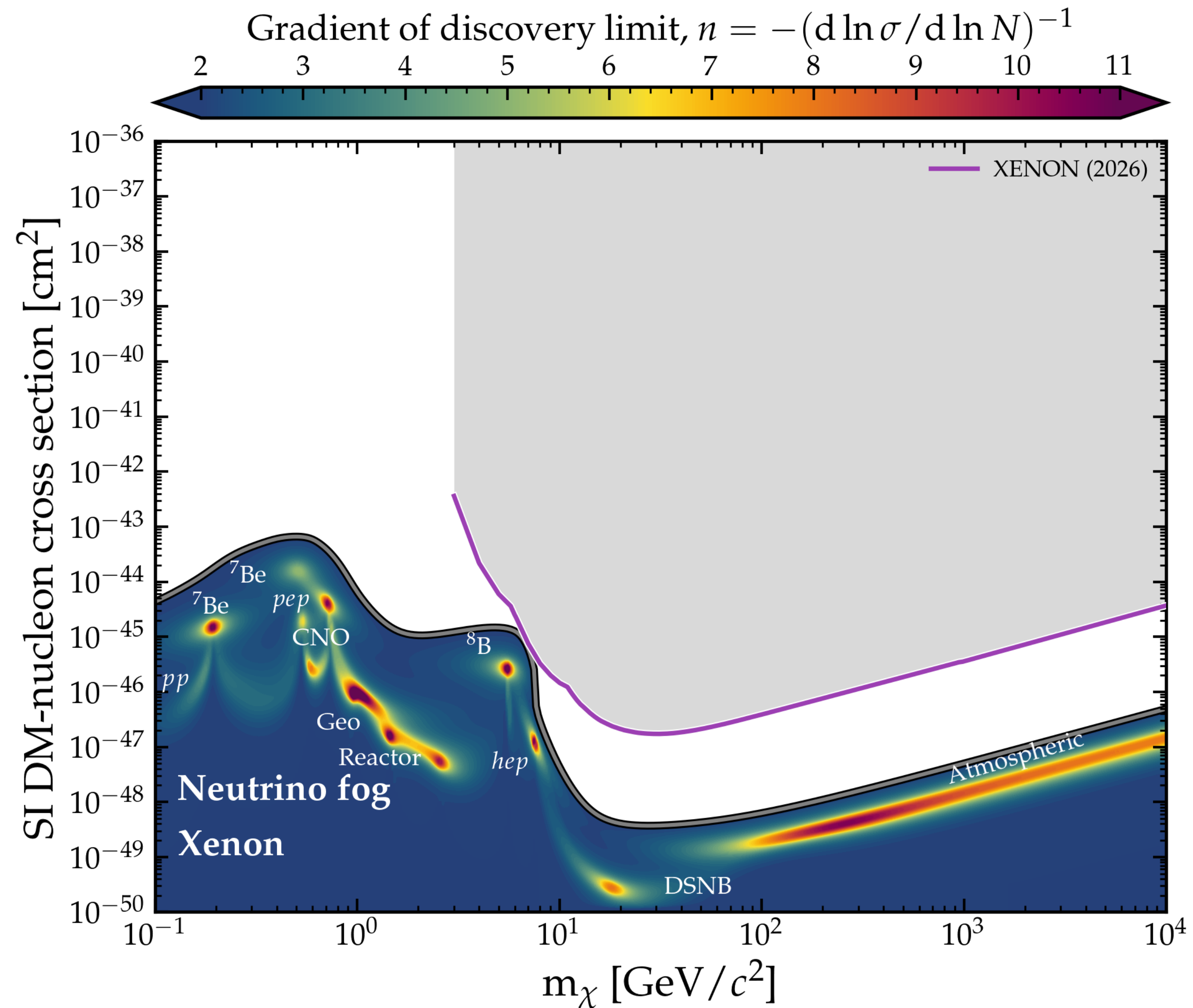
Outcome:

- 152 events in ROI, 16 in blinded region
 - Profile log-likelihood-ratio test statistic
- ➔ **No significant excess observed**

Strongest limit: $2.6 \times 10^{-47} \text{ cm}^2$ (90% C.L.) @ $28 \text{ GeV}/c^2$ PRL 131, 041003 (2023)

Current Best Limit

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How to go to lower DM masses?

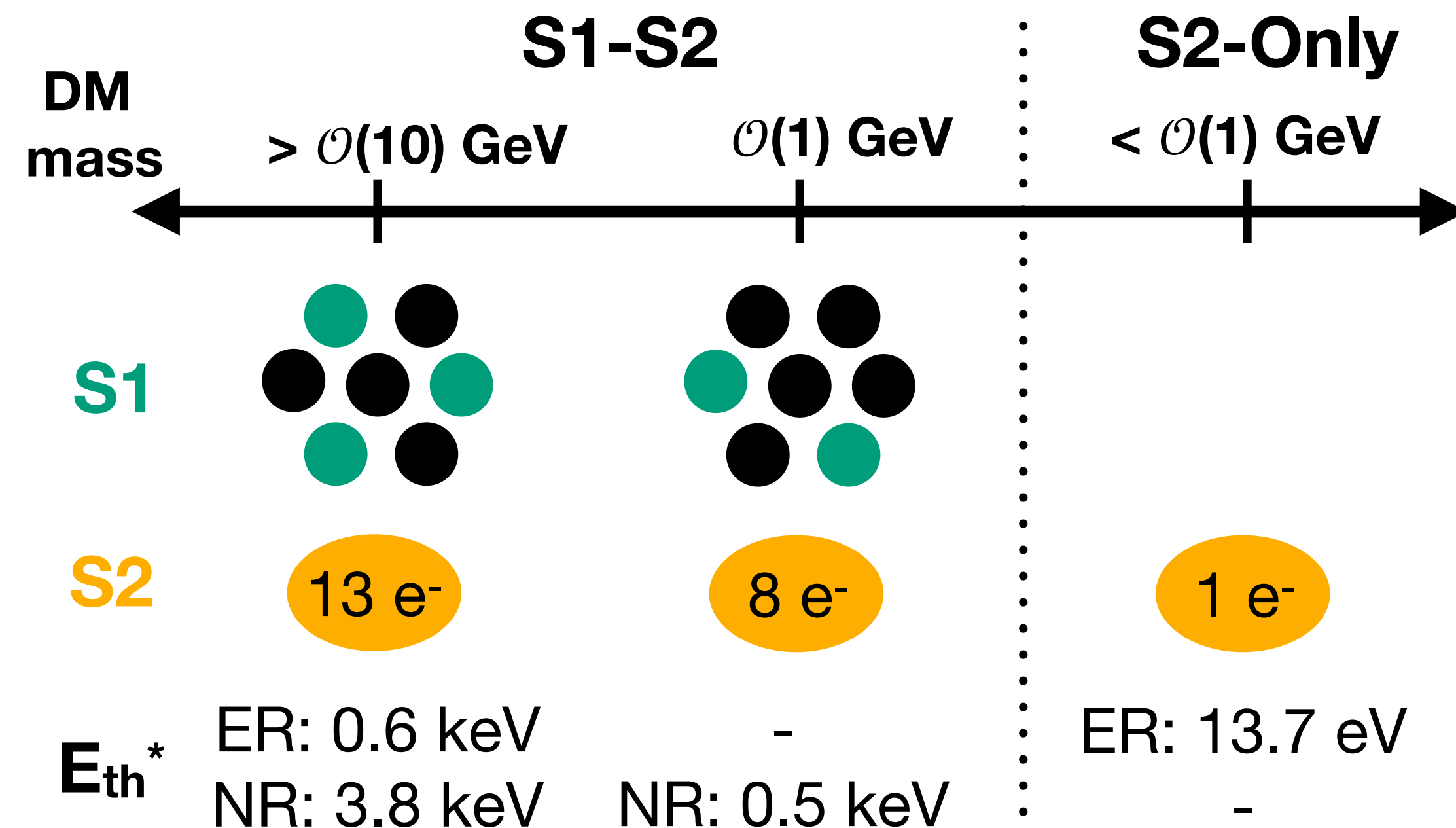
47

Energy Scale:

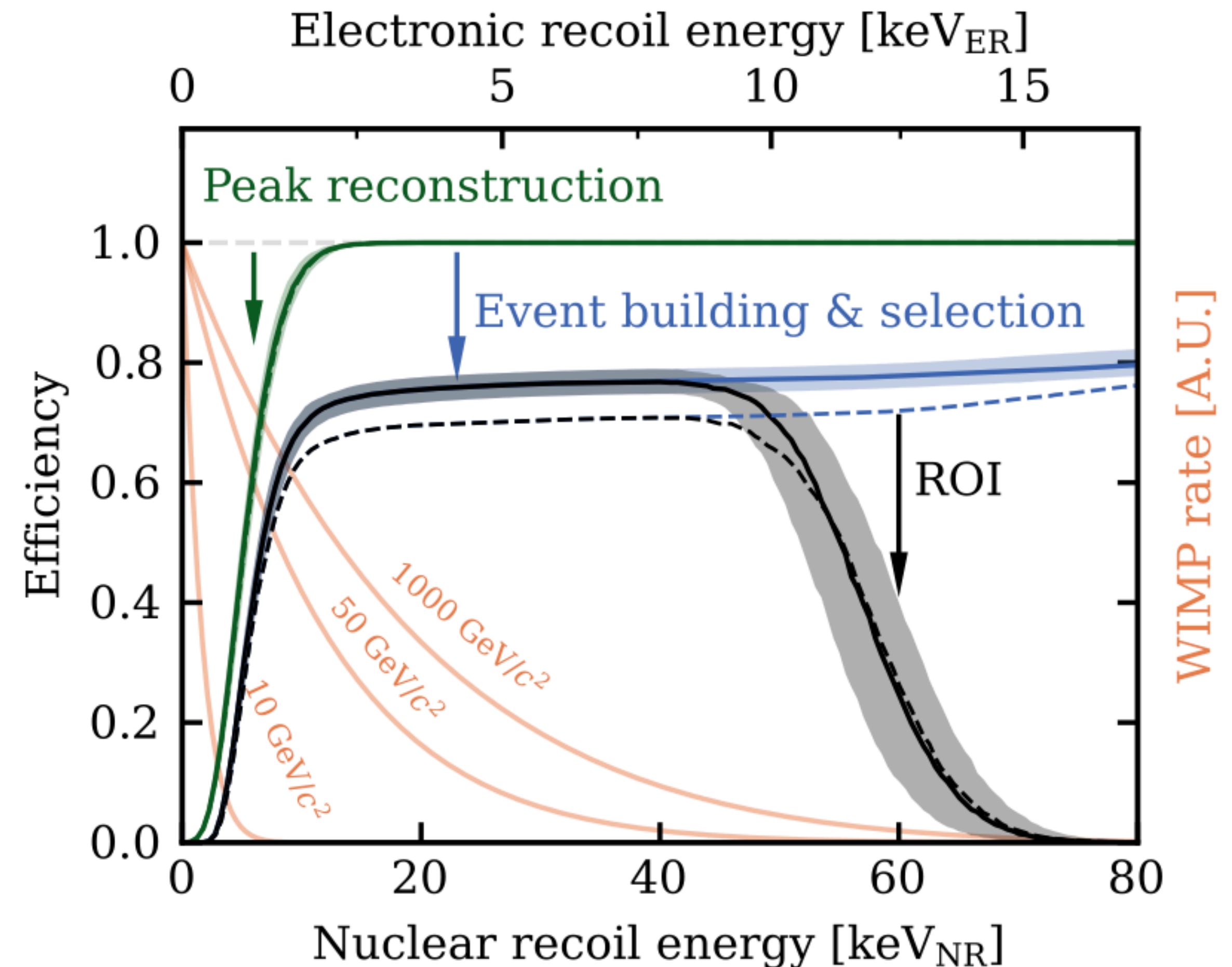
- g1: photon detection efficiency.
- g2: charge amplification factor.

$$E = W \times (n_{ph} + n_e) = W \times \left(\frac{S1}{g1} + \frac{S2}{g2} \right)$$

Energy threshold:



*>10% efficiency



How to go to lower DM masses?

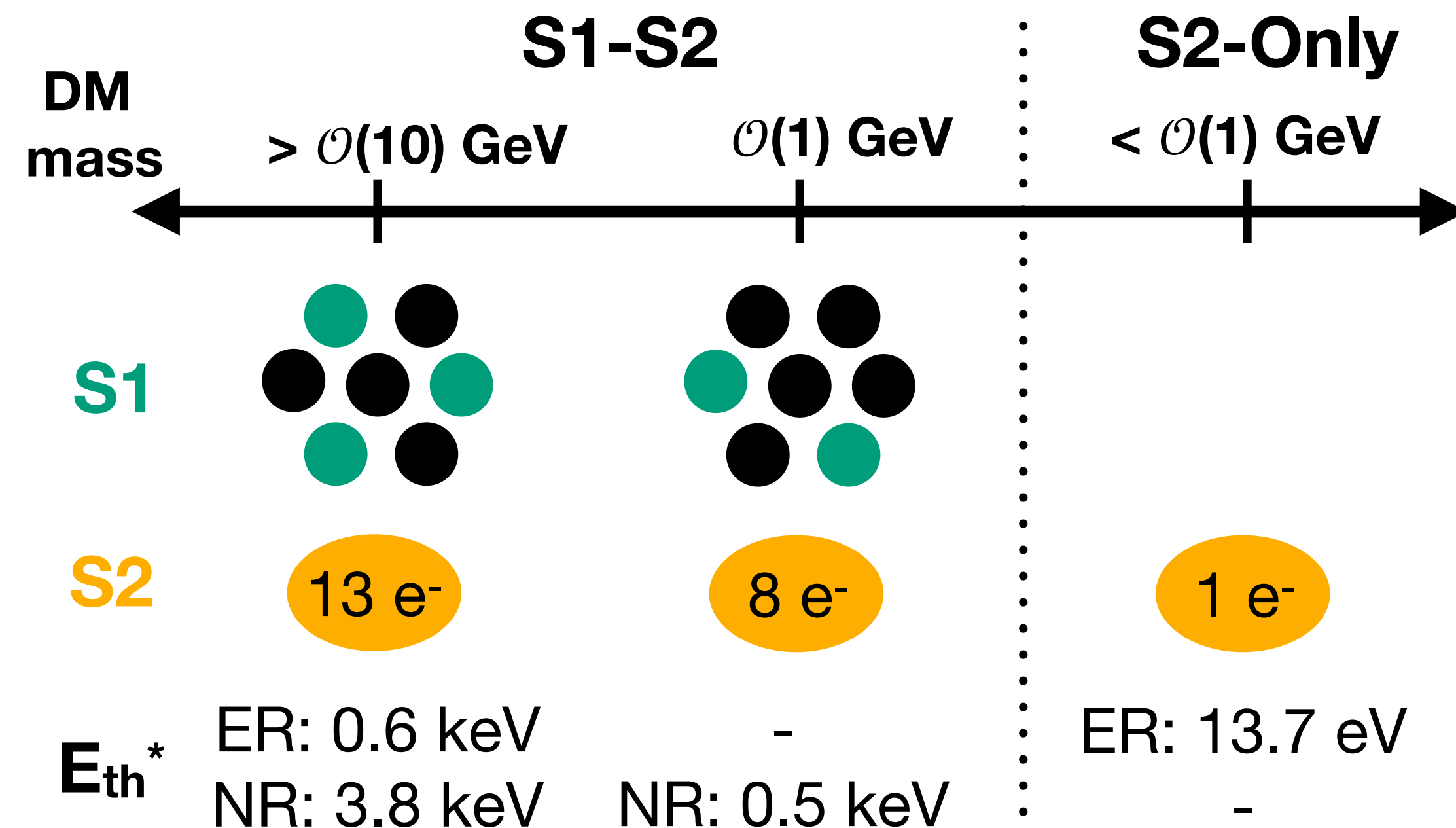
47

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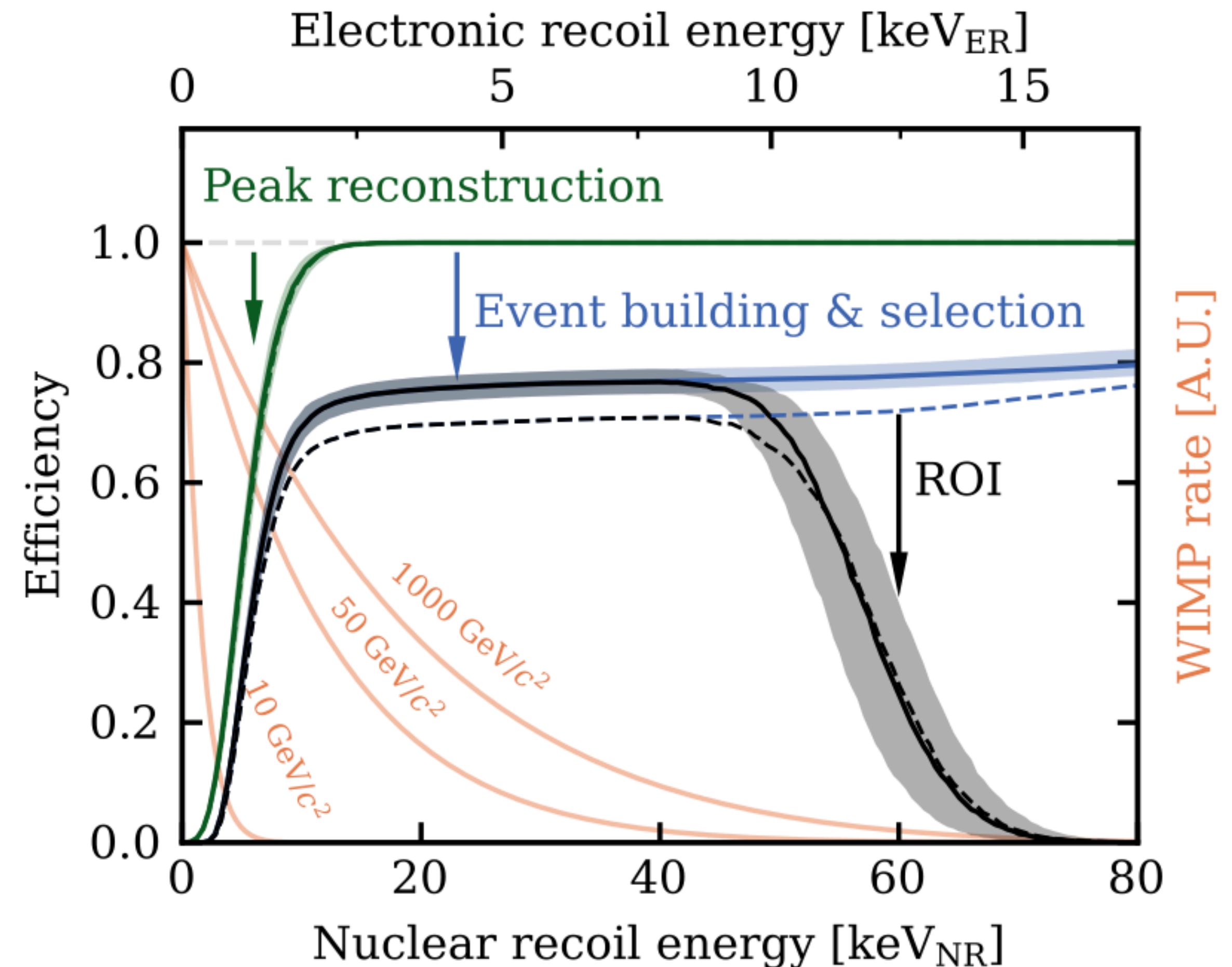
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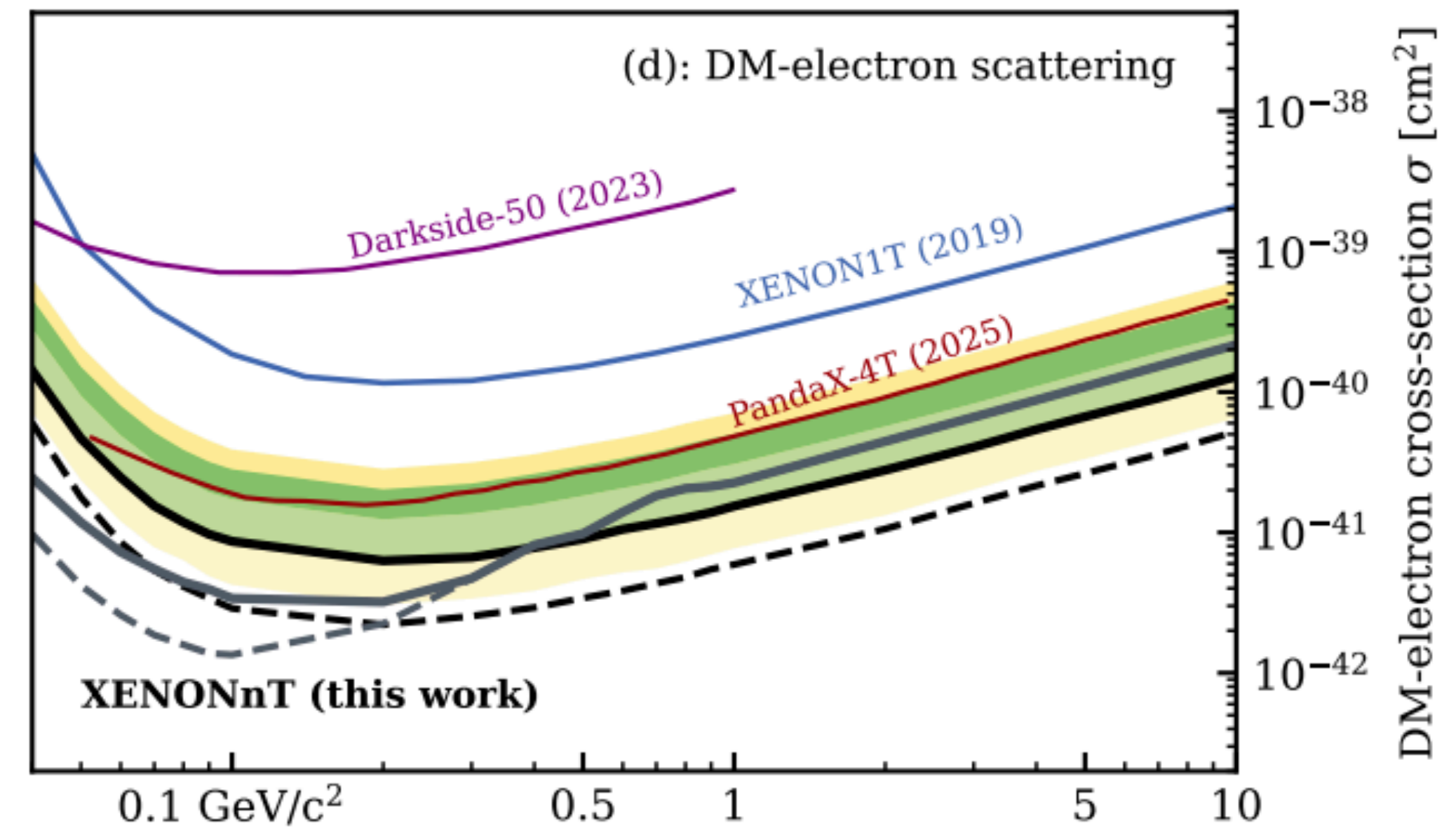
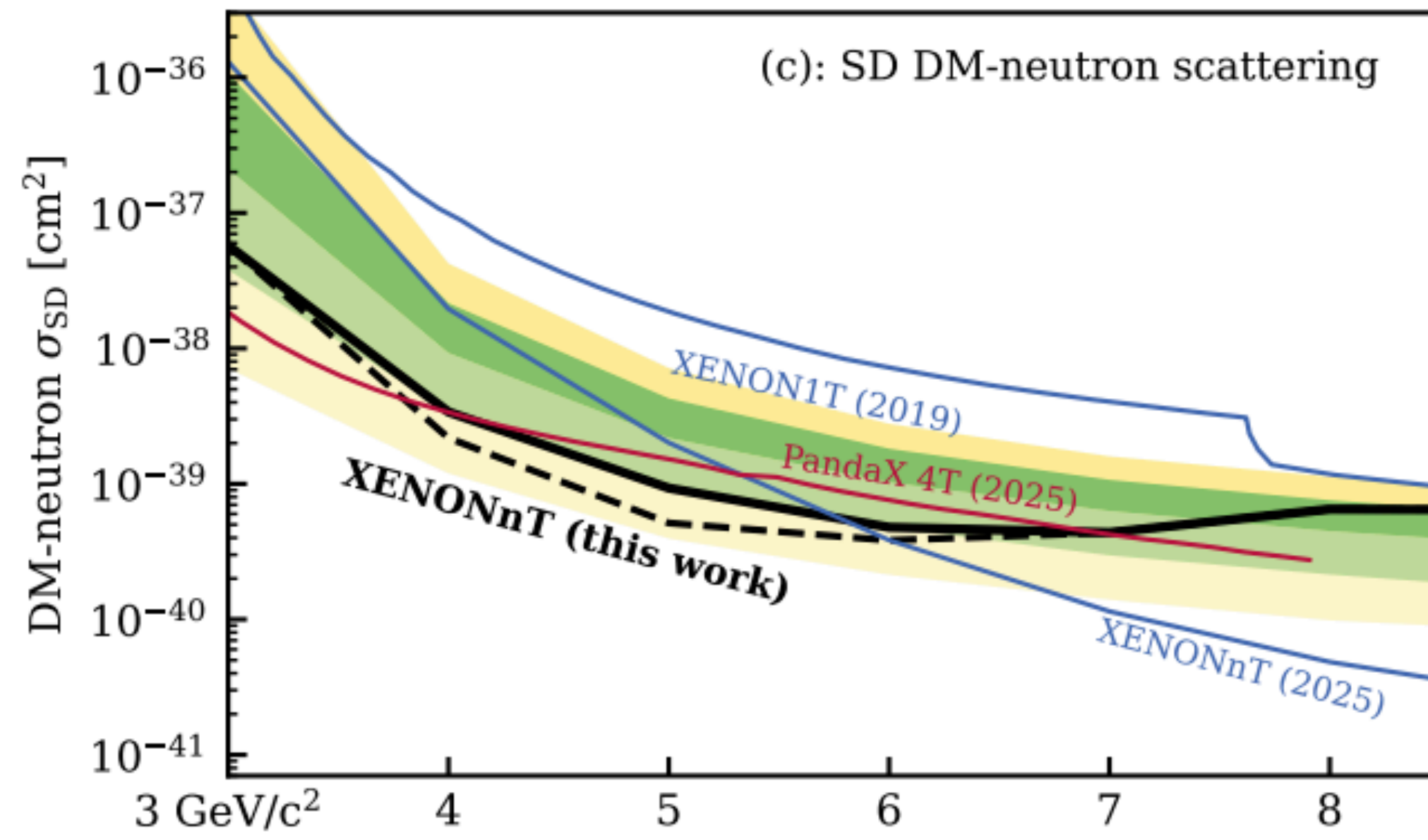
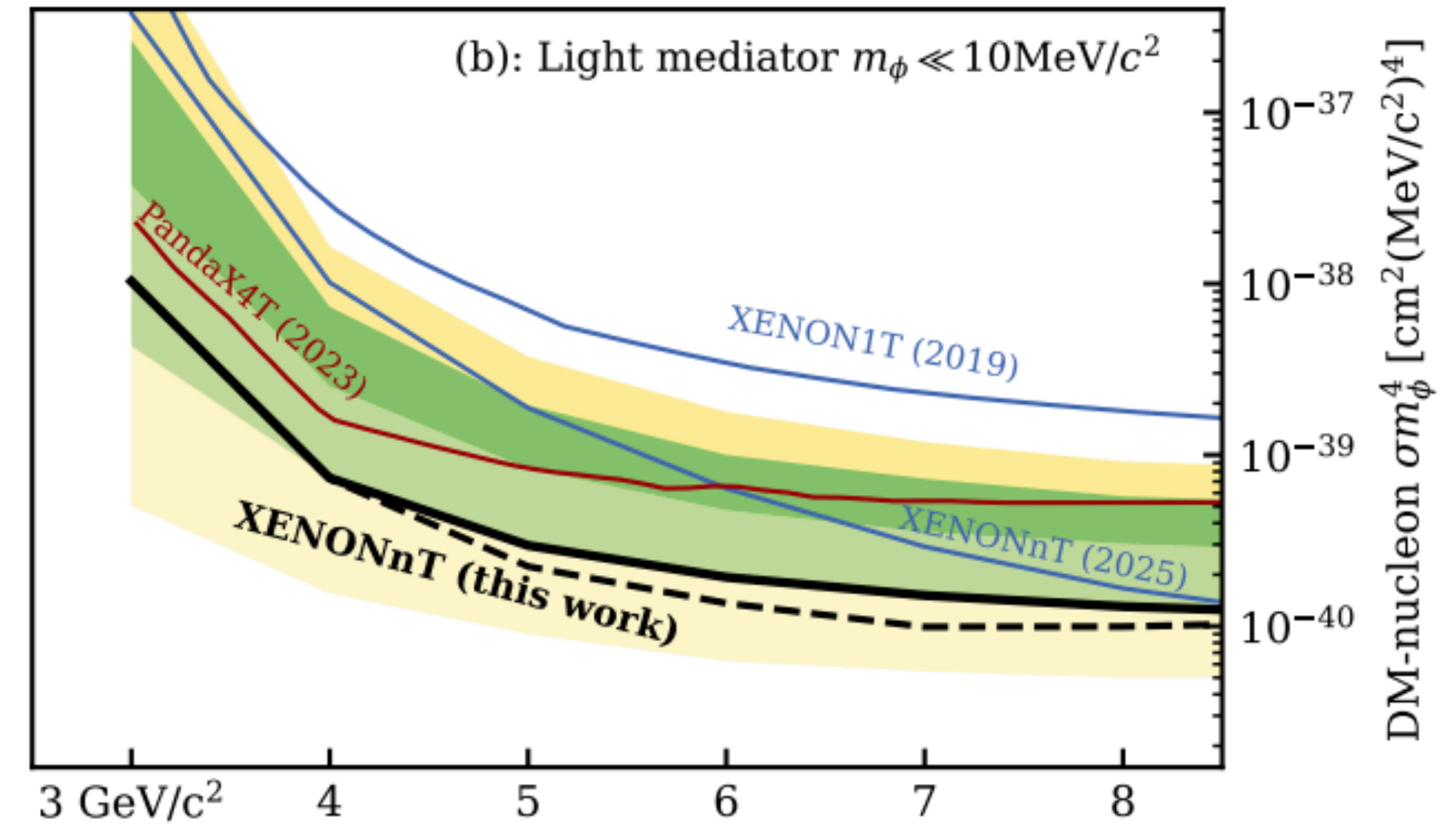
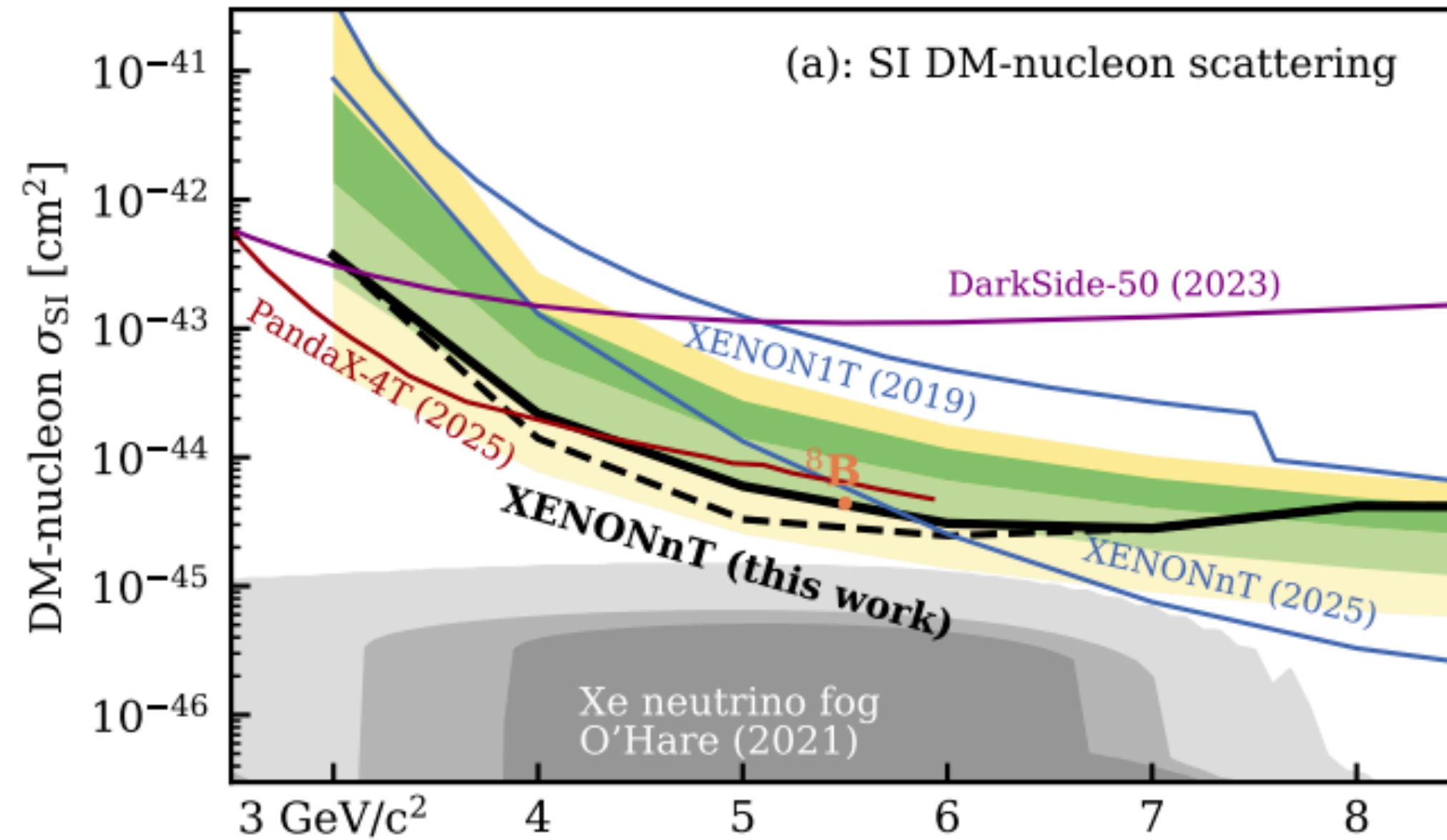
*>10% efficiency



Cost: Potential Larger Background!

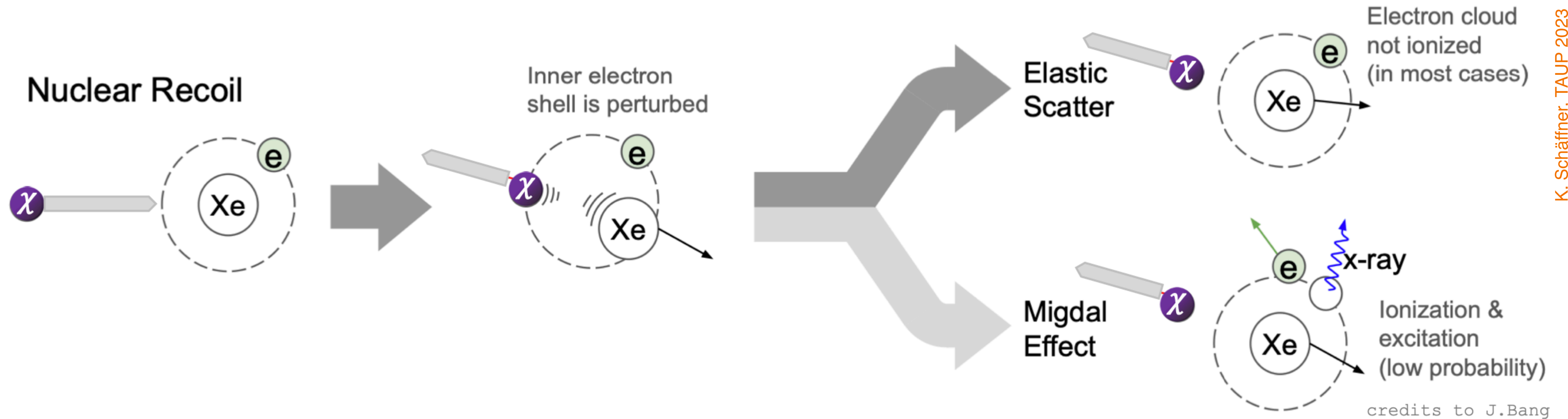
Ionisation signal only | XENONnT results

48



Or to use Migdal effect

49

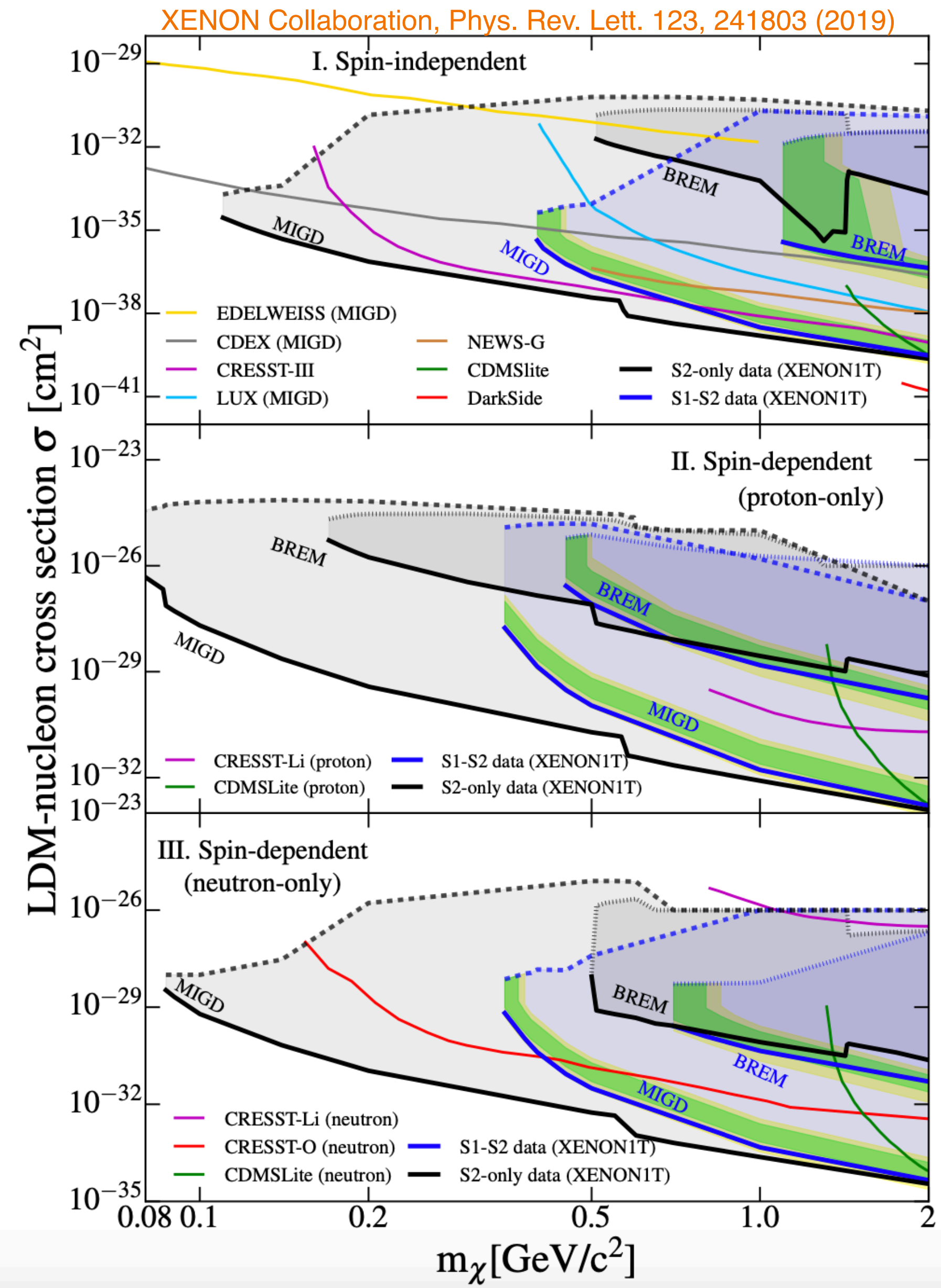


K. Schaffner, TAUP 2023

- ◎ Particular topology of events (ER+NR component from the same vertex)
 - ➡ Readjustment of the electron cloud → emission of a $\sim \mathcal{O}(100)$ eV electron = **ionisation signal (can be detected)**
 - ➡ But it have a cost: **signal rate is suppressed...**

Migdal effect | XENON1T results

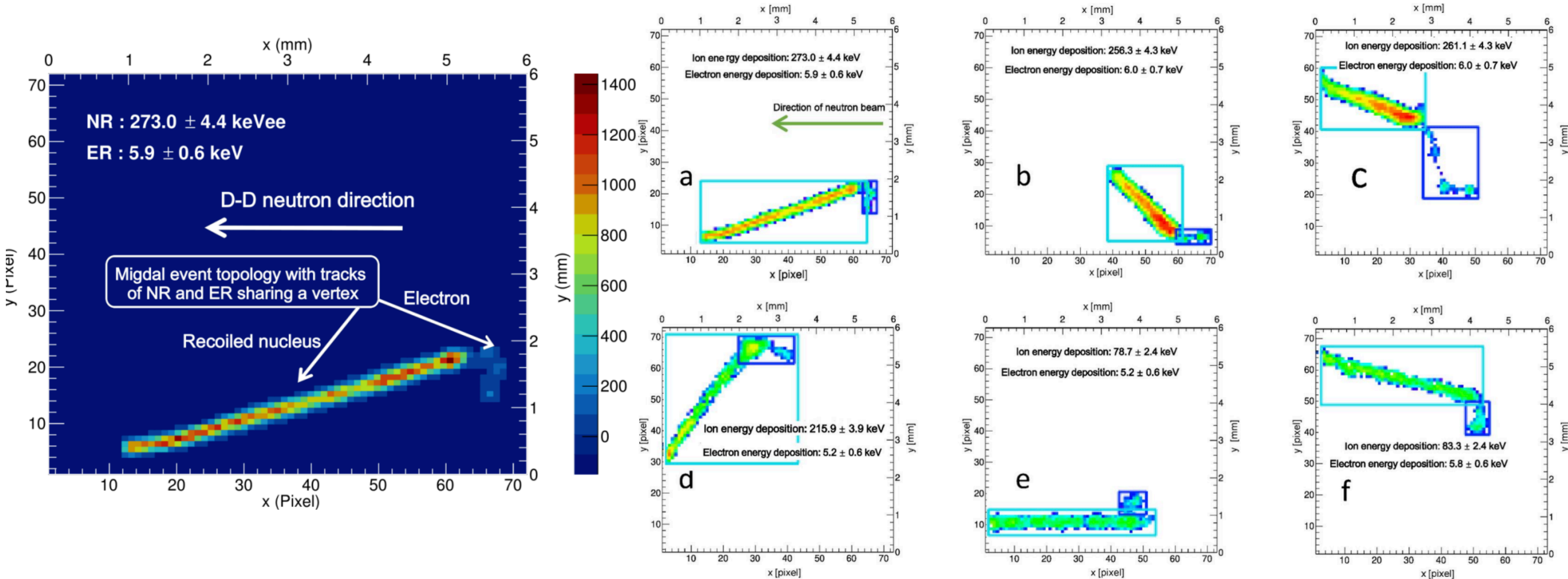
50



First Observation of Migdal

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Q. Liu, on behalf of the MARVEL group, at IDM 2026



Not in Xe, and to be confirmed.

Towards a multi-ton scale xenon observatory

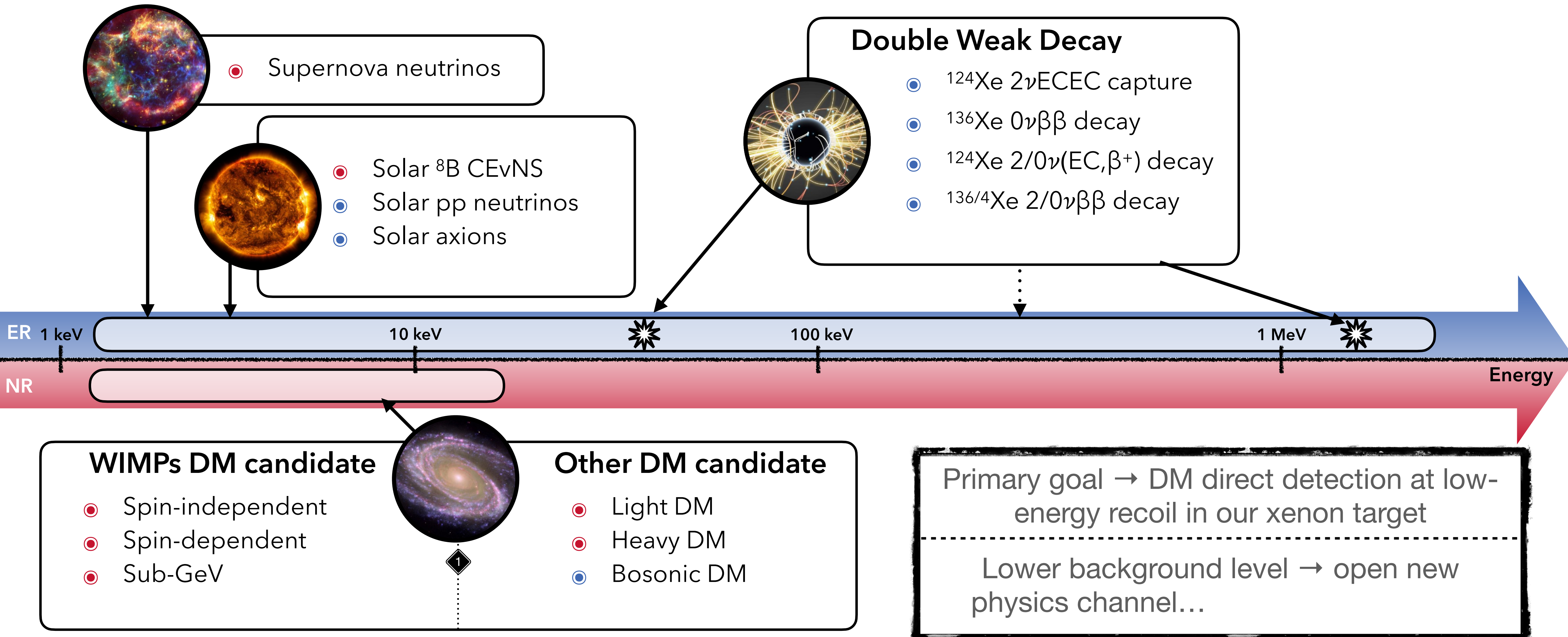
XLZD consortium: Merger of leading collaborations for a
future multi-ton scale Xenon-based experiment

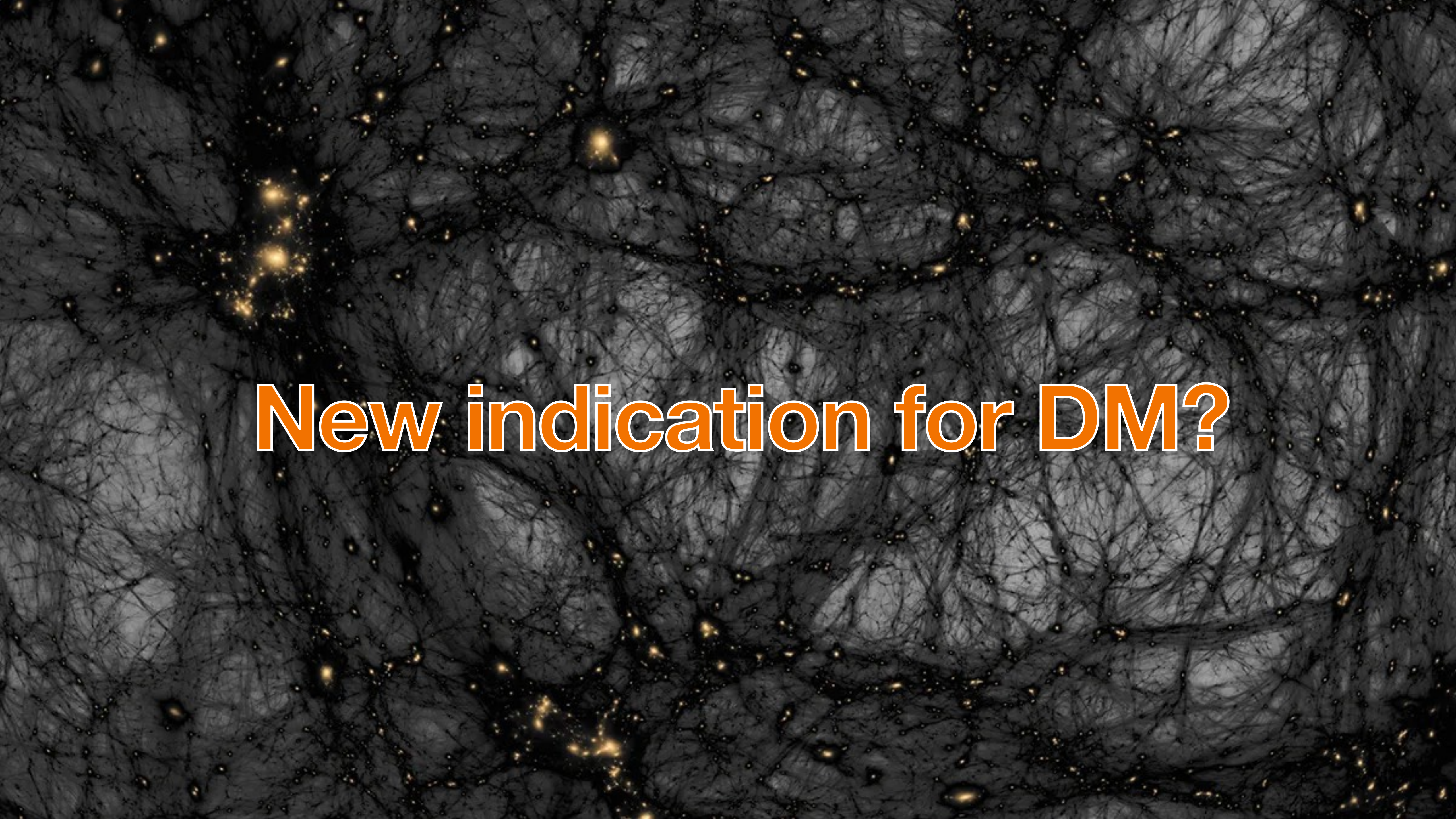


Community Whitepaper
J. Phys. G: Nucl. Part. Phys. 50, 013001

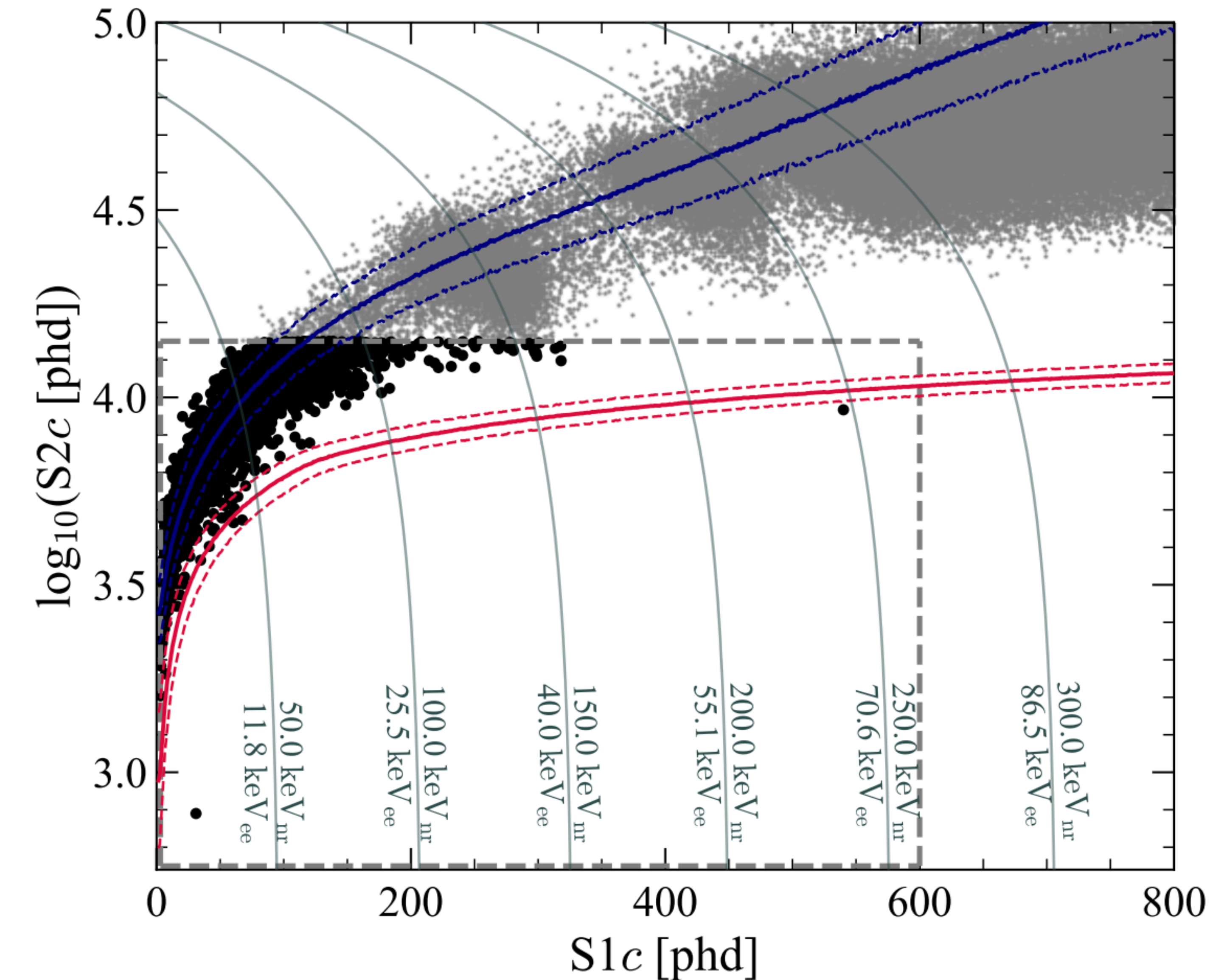


60-80 T of Liquid Xenon
To find WIMP interaction down to
the neutrino fog, and much more

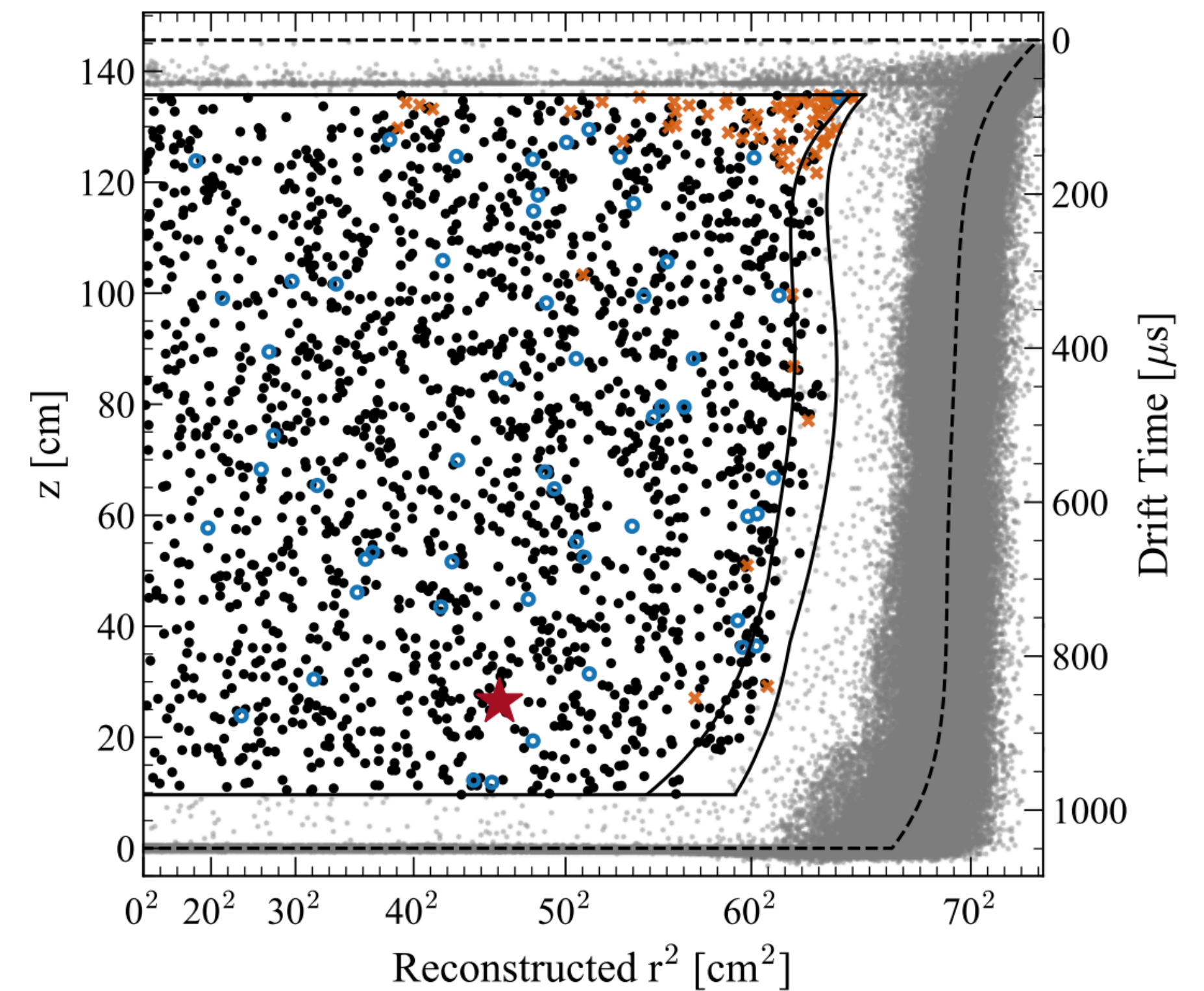


A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The background is a dense, dark, and textured field of grey and black lines representing the web. Numerous bright, yellowish-orange points of light are scattered throughout, representing galaxies and galaxy clusters. The text "New indication for DM?" is overlaid in the center in a bold, orange font with a white outline.

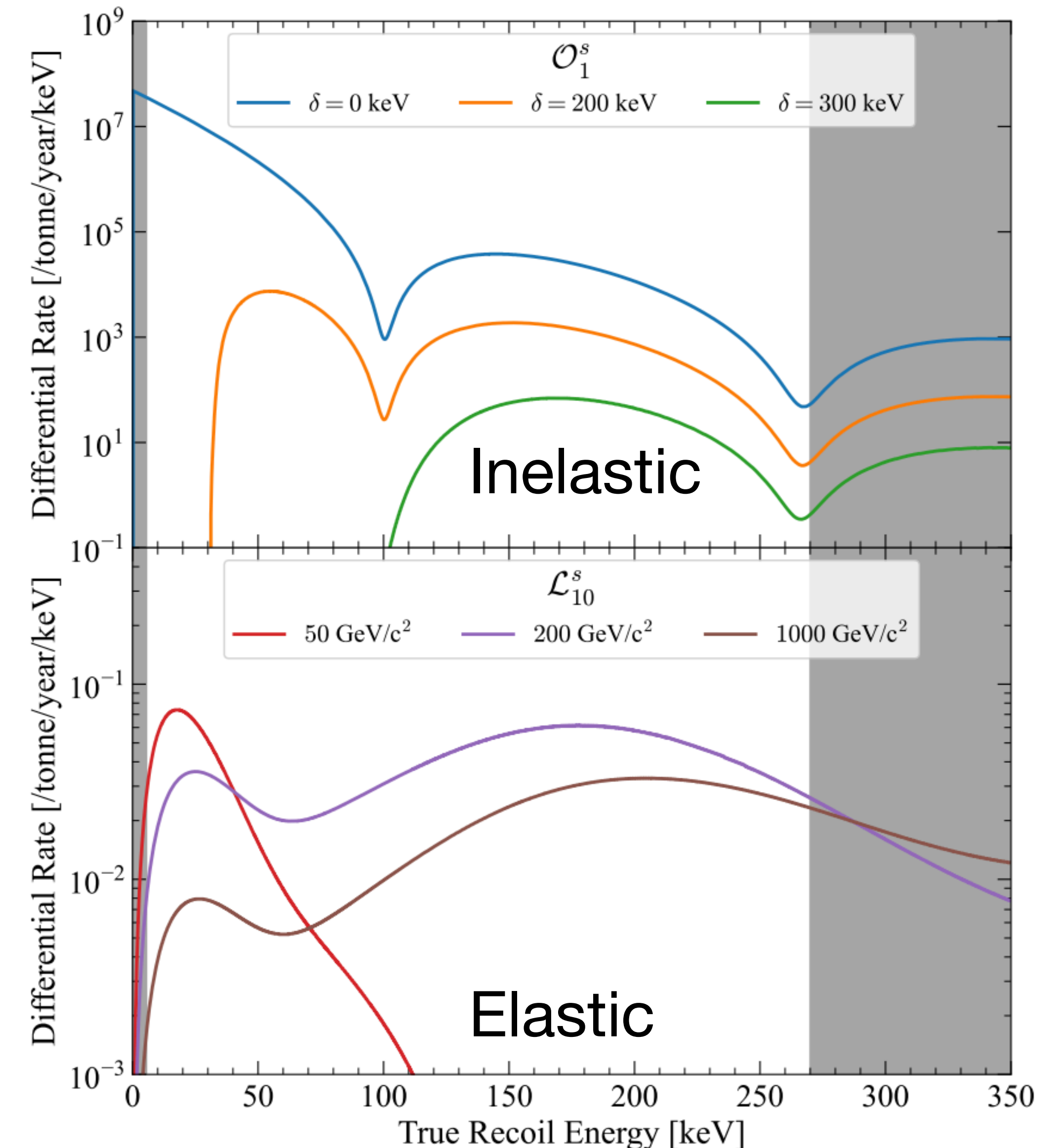
New indication for DM?



- Observe one event at ~ 250 keV NR recoil energy
- expect no Background in that ROI (far from ER Band)



- Search performed at much higher recoil energy than the standard WIMP analysis, which usually induce $E_r < 100$ keV
- Effective Field Theories (EFT), provide a more general framework for DM scattering than the usual SD & SI treatment, and can also cover inelastic interactions
 - In that we can expect a suppression of the expected rate at low-energy recoil.



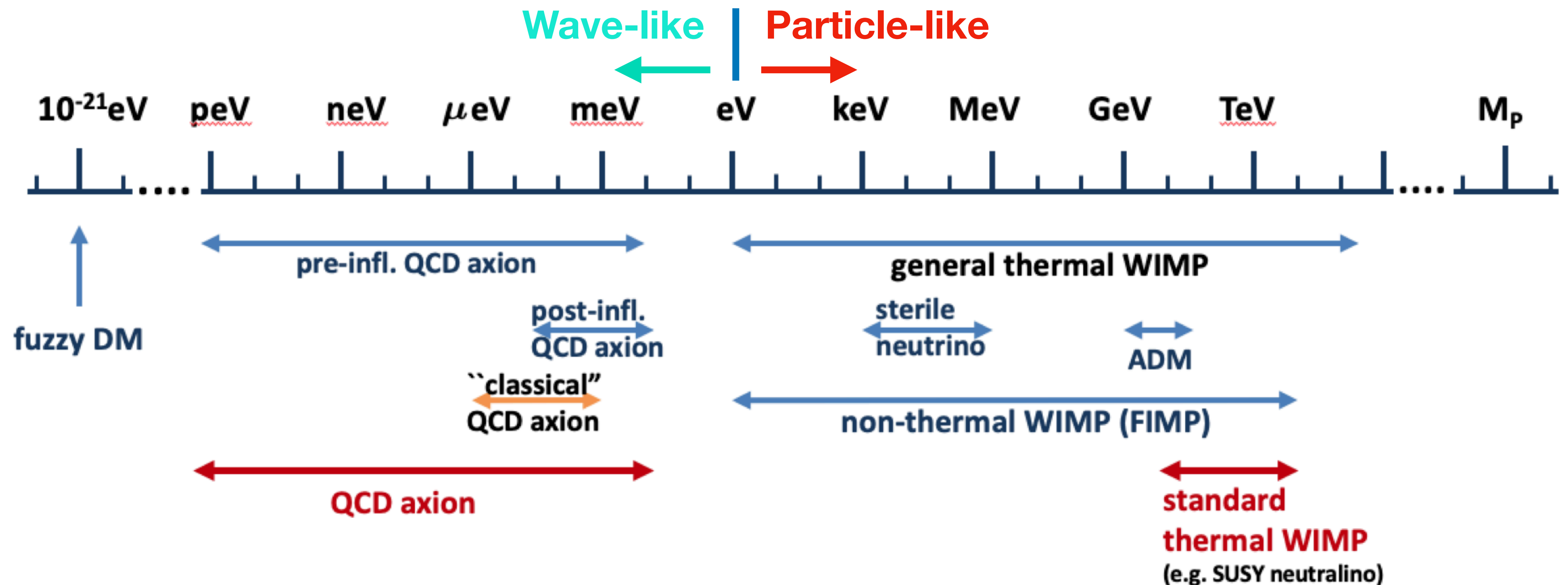
What are the implications?

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- Did we find DM? We don't know yet, **it is only a 2.6σ global significance.**
- Careful attention of the Background modeling, did they miss any potential source?
- Next steps?
 - LZ still have more data available, they didn't use everything yet
 - **Other experiments, like XENONnT, can perform the same search and confirm or reject the observation**

Really interesting, but too soon to conclude anything, and claim the discovery of DM.

Search for axions



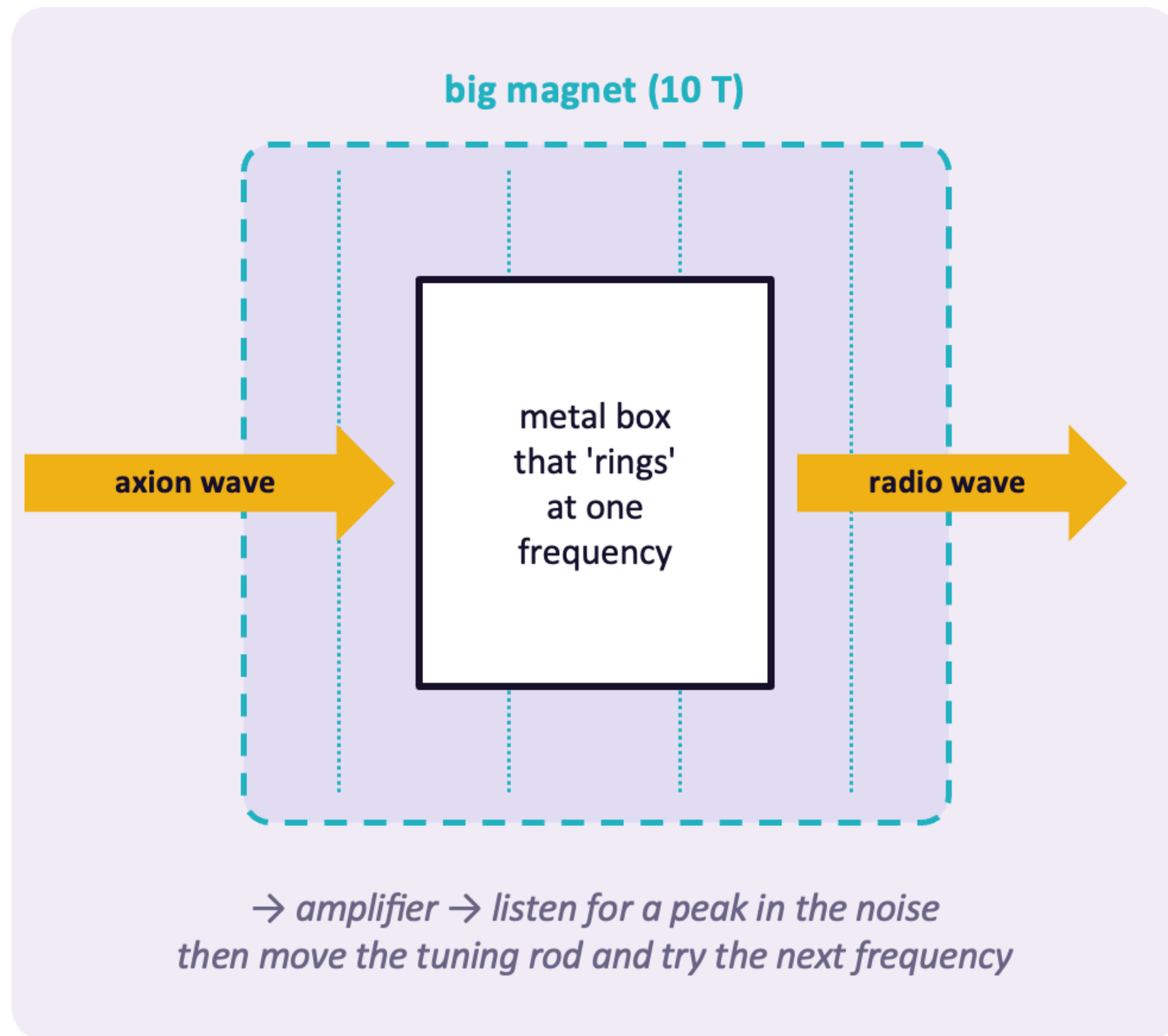
Two problems, one particle

- QCD allows a CP-violating term, the angle θ . It would give the neutron an electric dipole moment; experiments say $\theta < 10^{-10}$. Why so small? The strong CP problem
- Peccei & Quinn (1977): add a new field that relaxes this away. The leftover ripple of that field is a particle: the (QCD) axion.
- Bonus: the early Universe naturally makes a huge number of them, cold and slow: exactly what DM needs.

WIMP vs axion

	WIMP	Axion
Mass	$\sim 100\times$ a proton	$\sim 10^{-11} \times$ an electron
Number in 1 cm ³	about 0.003	about 10^{14}
Behaves like	a billiard ball	a wave
Wavelength	smaller than a nucleus	metres
Detector sees	one nucleus being kicked	a faint, steady radio hum

The Haloscope: a radio that turns the dial 60



1 A magnet turns the axion wave into light

Axions barely talk to anything, but in a strong magnetic field they slowly turn into radio waves of exactly the same frequency (about 1 GHz for the masses we expect).

2 A resonant box makes it louder

Like a wine glass ringing at one note, a metal cavity stores waves of one frequency. If the axion's frequency matches, the signal builds up thousands of times.

3 Then you listen, very quietly

The signal is $\sim 10^{-22}$ W: a few hundred photons per second. So the whole thing is cooled to 0.1 K and read out with the quietest amplifiers in existence.

4 ...and turn the dial

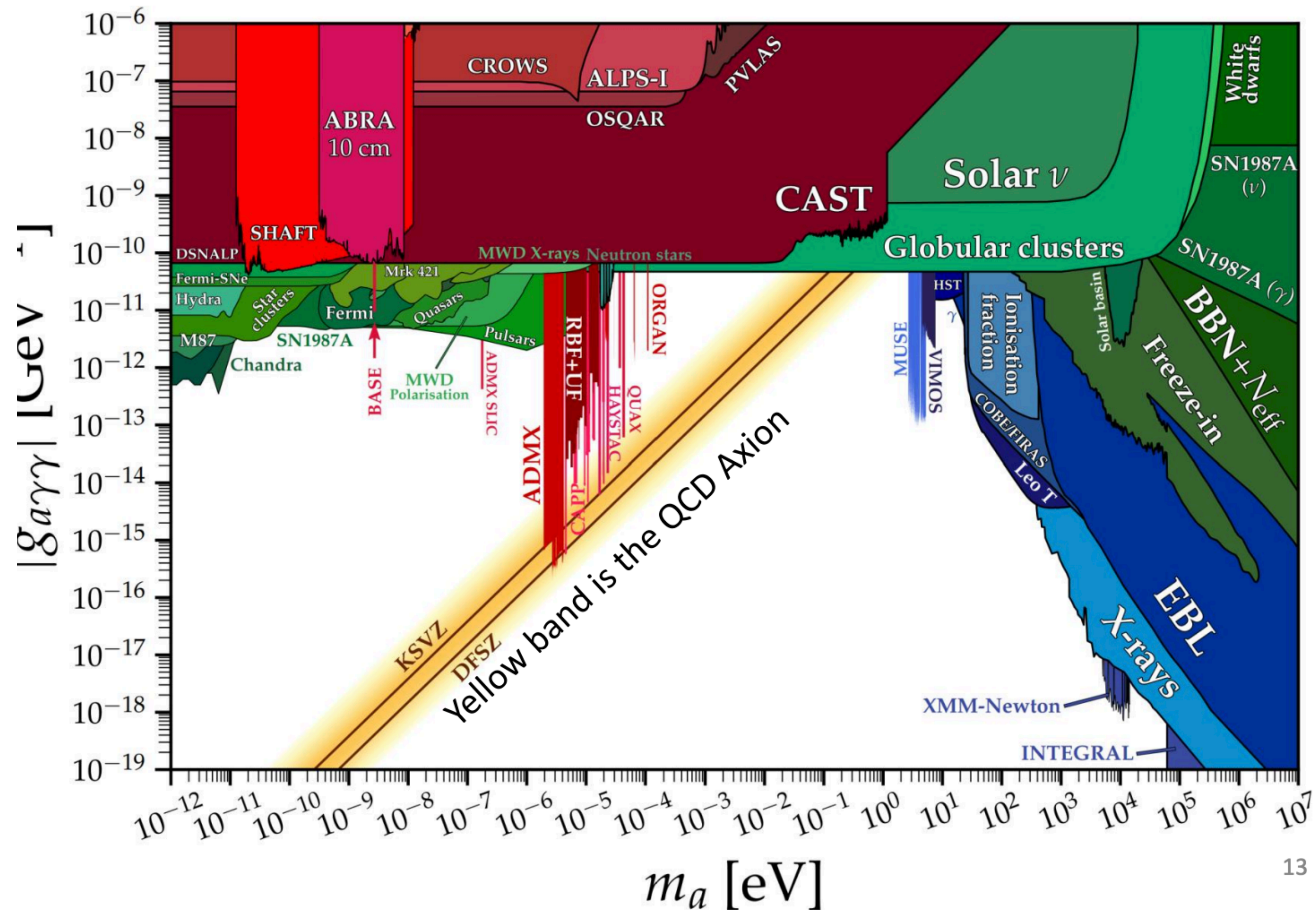
We don't know the axion's mass, so we don't know the station. Move the rod, change the note, listen again. Thousands of times.

QCD Axion search landscape

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How to read it

- Across: axion mass (log scale). Up: coupling to light. Shaded regions are ruled out
- Yellow diagonal band: where a QCD axion must sit (KSVZ, DFSZ). The target
- Red: lab experiments. Haloscopes (ADMX, HAYSTAC, CAPP, QUAX) tuned in and heard no peak: the only ones reaching the band. CAST looked for solar axions turning into X-rays in a magnet. ALPS, OSQAR: laser through a wall
- Green: stars and astrophysics. Axions would carry heat out of stars or appear as extra photons from supernovae and pulsars. Not seen
- Blue: telescopes. Heavy axion dark matter would decay into visible or X-ray photons. The sky is too dark for that



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What matters about the box

- Size: more volume, more signal. But size sets the note (a 1 GHz box is ~25 cm wide), so heavier axions force smaller boxes
- Shape: only the part of the wave lined up with the magnetic field counts. A plain cylinder keeps ~70%; rods and odd shapes lose some
- Quality: how long it rings. Copper $\sim 10^5$ oscillations; superconductors or sapphire reach 10^6 but must survive 10 T
- Plus the magnet (signal $\propto B^2$) and cold, quiet electronics

The catch: heavier axion = higher frequency

- Shorter wavelength $\rightarrow$ smaller box $\rightarrow$ less signal
- Copper boxes ring less well at high frequency
- Even a perfect amplifier gets noisier (quantum limit)
- So at high mass a single box stops working

Three shapes of 'radio' for three mass ranges

● Light axions (below $\sim 1 \mu\text{eV}$, kHz–MHz)

Wavelength of kilometres, so no box can hold it. Use the magnet to drive a current and pick it up with a coil and a SQUID, like a giant, very cold inductor.

ABRACADABRA, DMRadio

● Middle range ($1\text{--}50 \mu\text{eV}$, $\sim\text{GHz}$)

The sweet spot: microwave cavities of litres to tens of litres. This is where the most sensitive searches are today.

ADMX, HAYSTAC, CAPP, QUAX

● Heavy axions (above $\sim 50 \mu\text{eV}$, 10–100 GHz)

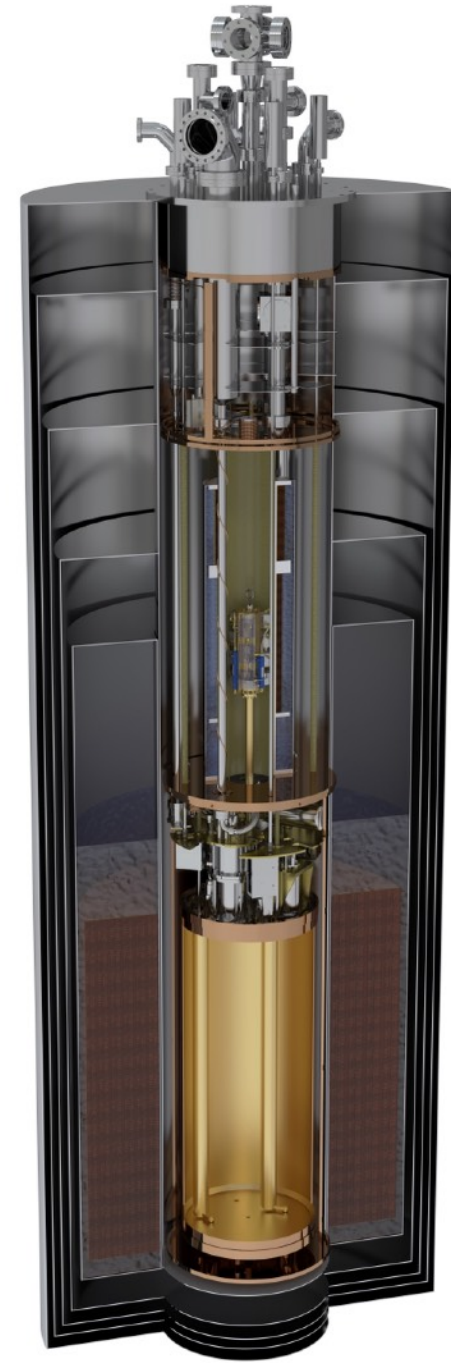
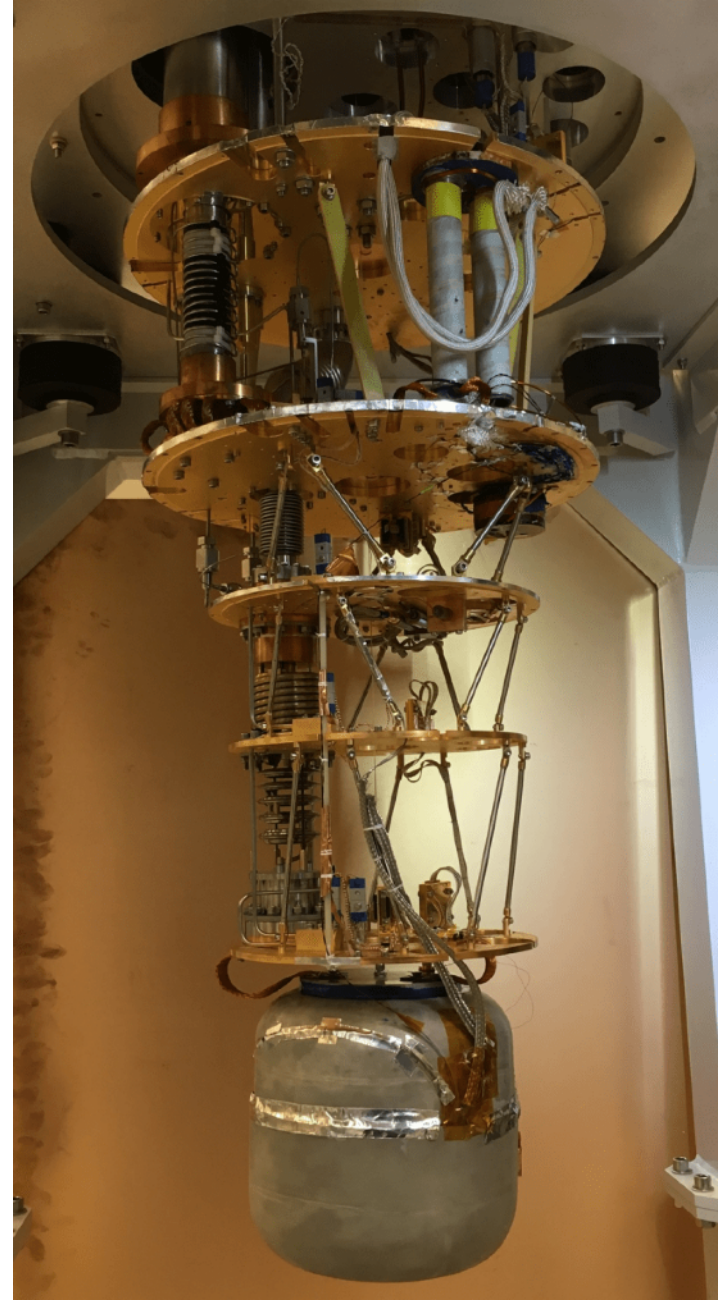
Replace the single box by a stack of dielectric discs, an artificial 'plasma' of wires, or a broadband dish plus a single-photon counter.

MADMAX, ALPHA, BREAD

Different frequency, different challenges

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<https://abracadabra.mit.edu/>



<https://www.fnal.gov/pub/science/particle-physics/experiments/admx.html>

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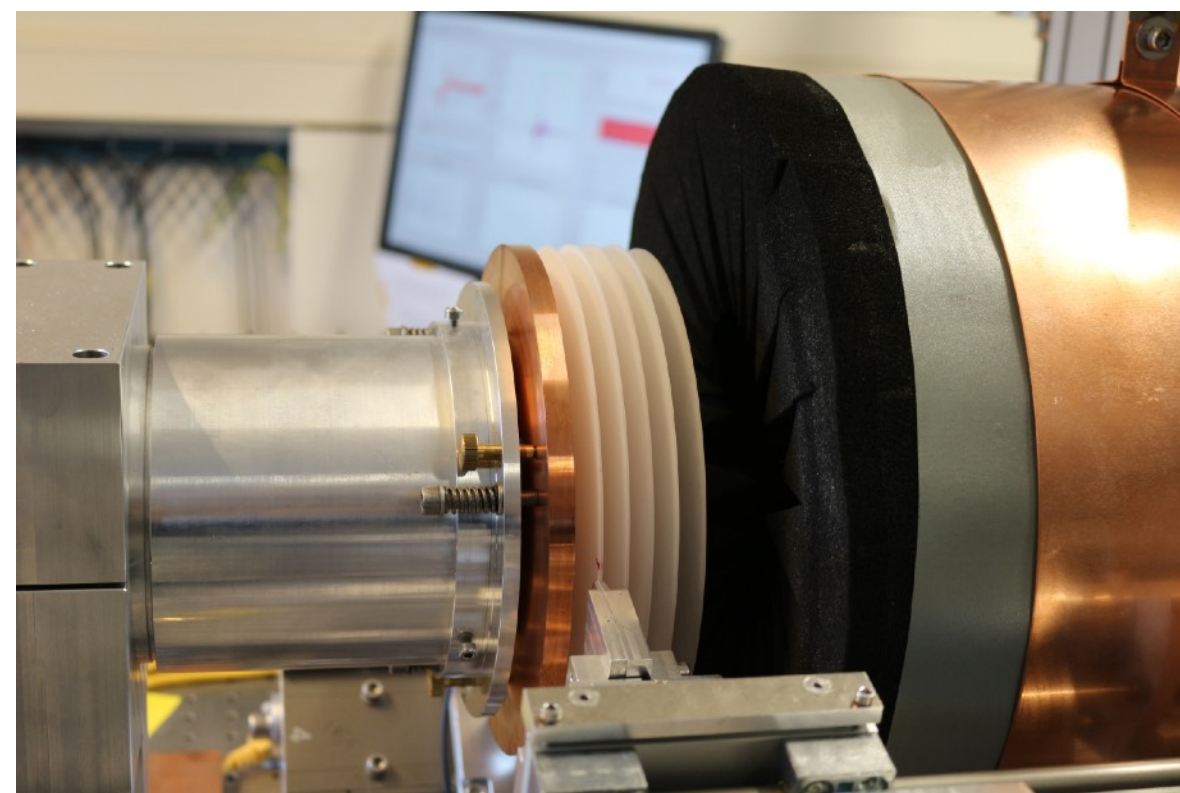
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MADMAX, ALPHA, BREAD



<https://madmax.mpp.mpg.de/>



Particle-like vs Wave-like DM

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Particle-like DM (WIMPs, sub-GeV DM)

Wave-like DM (axions, dark photons, ALPs)

Mass range

Above ~ 1 eV: few particles per cm^3 , each carries energy

Below ~ 1 eV: so many per cm^3 that they add up to a classical field

What you look for

Rare, single events: one nucleus or electron kicked, a few times a year

A continuous, very narrow oscillation, present all the time

The enemy

Radioactivity: radon, cosmic rays, neutrons, and eventually neutrinos

Noise: thermal and quantum noise of the resonator and amplifier

Where

Deep underground, under a mountain

A surface lab is fine, no need for rock overhead

Key hardware

Radiopure materials, shielding, muon veto, event discrimination

Strong magnet, tunable resonator, 0.1 K fridge, quantum-limited readout

Sensitivity grows with

Target mass $\times$ time (exposure) and lower background

Field strength, volume, Q, lower noise, time per frequency

What you scan

Nothing: one detector covers a wide mass range at once

Frequency: you must step through masses one by one

Examples

LZ, XENONnT, PandaX, DarkSide, SuperCDMS

ADMX, HAYSTAC, MADMAX, DMRadio, CASPEr

The background of the image is a complex, dark, and textured pattern resembling a cosmic web or a dense network of fibers. It is composed of numerous small, bright, golden-yellow points of light, which are scattered across the dark, almost black, background. These points of light are connected by a network of thin, dark, and slightly irregular lines, creating a sense of depth and complexity. The overall effect is that of a vast, intricate, and somewhat chaotic structure, possibly representing a network of galaxies or a complex system of data.

Thank You!