Dark Matter Experiments - II

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BND Graduate School — Blankenberge 2024

Overview

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
- Application to Neutrino Physics

Lecture 3 - Dark Matter Production

Dark Matter Indirect Detection

1 Case example: XENONnT

Let's study a specific case example: XENONnT

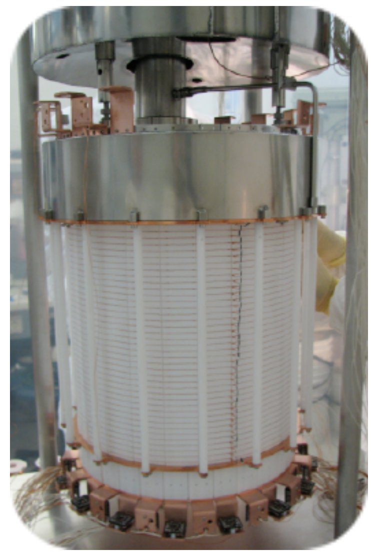
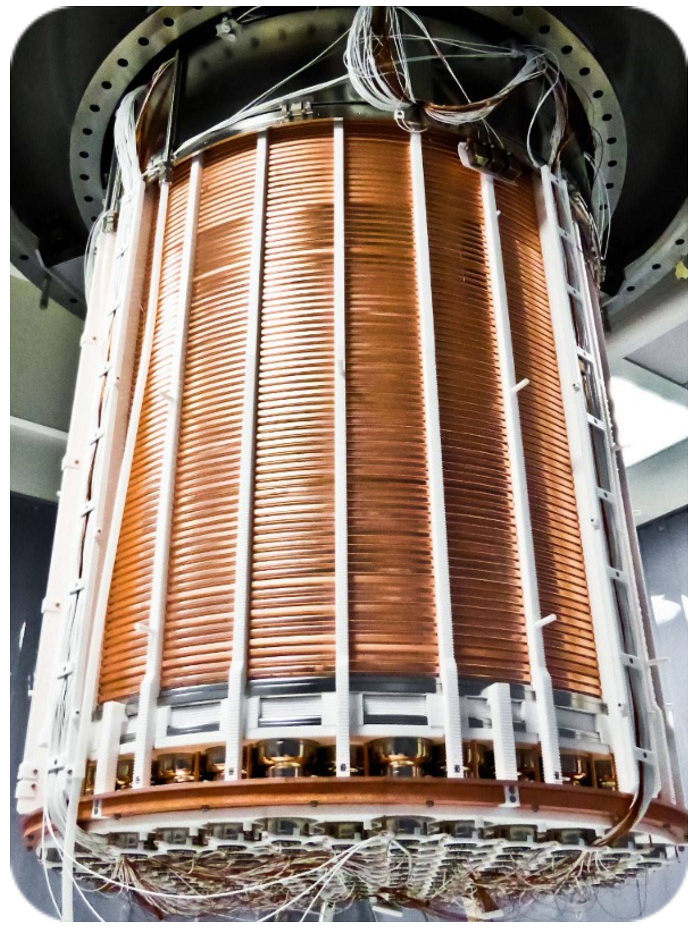
2 Application to Neutrino Physics

More than just Dark Matter Direct Detection

Case example: XENONnT

XENON program

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


	XENON10	XENON100	XENON1T	XENONnT
Time	2005	2008	2016	**2021**
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}**

* → Projections

Laboratori Nazionali del Gran Sasso (LNGS)

Aboveground Laboratory

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

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Laboratori Nazionali del Gran Sasso (LNGS)

Underground Laboratory

Xenon Properties

- Most radiopure Noble Gases.

Isotope	Abundance [%]	Decay mode	Half-life [years]
^{124}Xe	0.09	2νECEC	$(1.1 \pm 0.2_{stat} \pm 0.1_{sys}) \times 10^{22}$
^{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	$2\nu\beta\beta$	$(2.165 \pm 0.016_{stat} \pm 0.059_{sys}) \times 10^{21}$

Xenon Properties

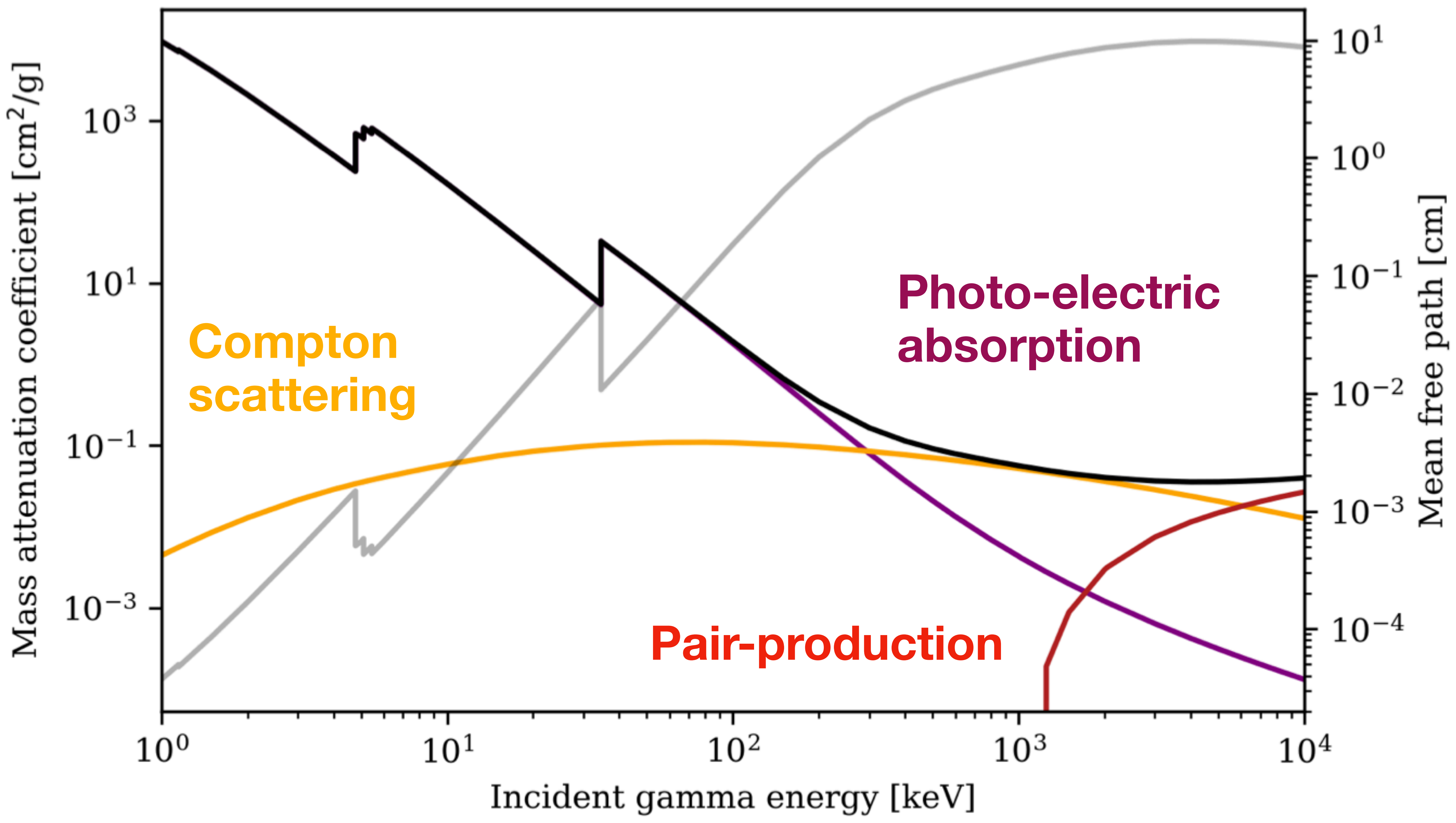
- **Most radiopure Noble Gases.**
- Efficient **(Self-)shielding** material (Z= 94, ρ_{LXe} ~ 2.9 g/cm³).

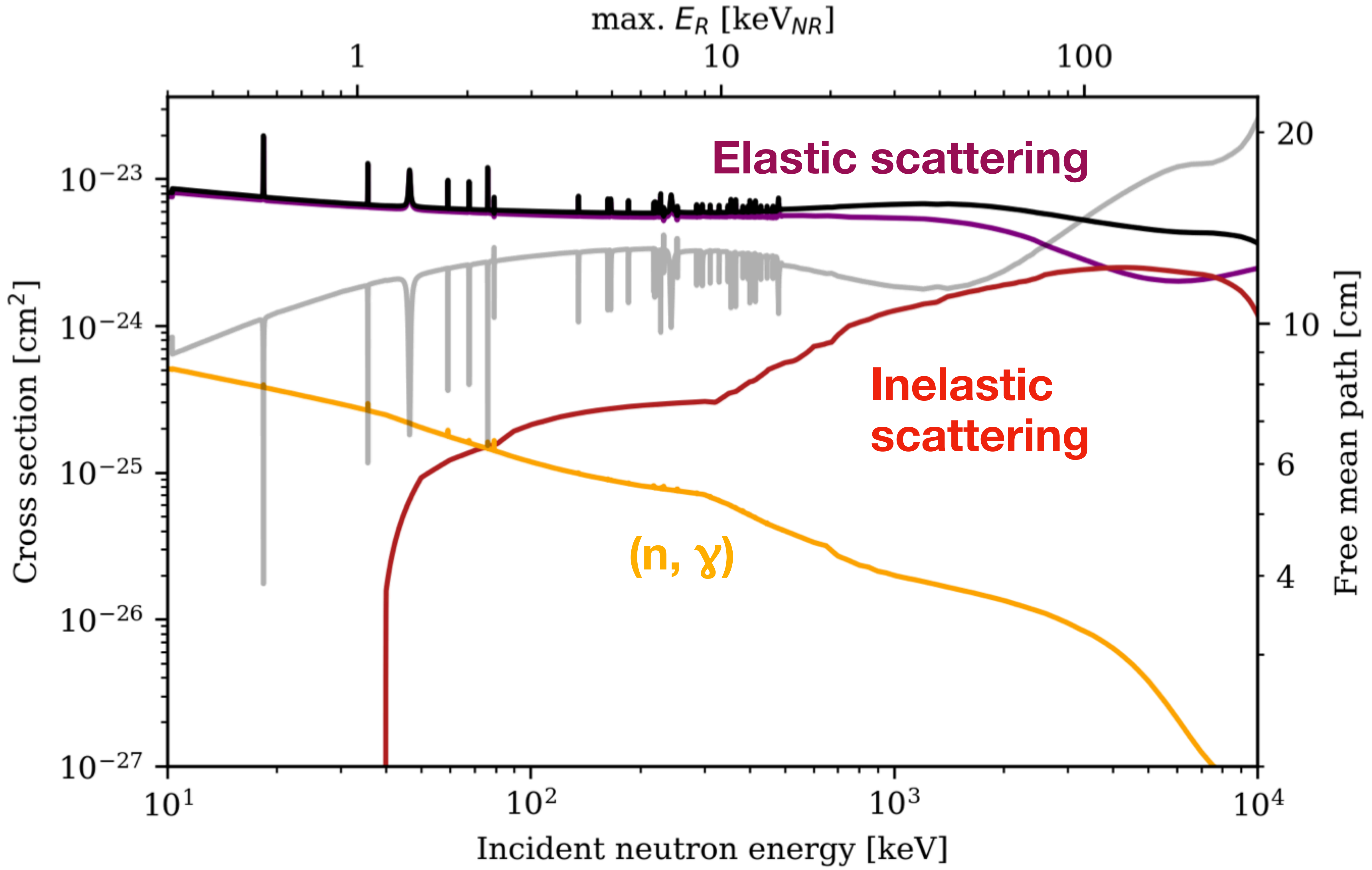
➡ Electron < $\mathcal{O}$(1-10) mm

➡ Gamma < $\mathcal{O}$(10) cm

➡ Neutron < $\mathcal{O}$(10) cm

Tend to do Multiple-Scatter





D. Wenz, http://doi.org/10.25358/openscience-9654

Xenon Properties

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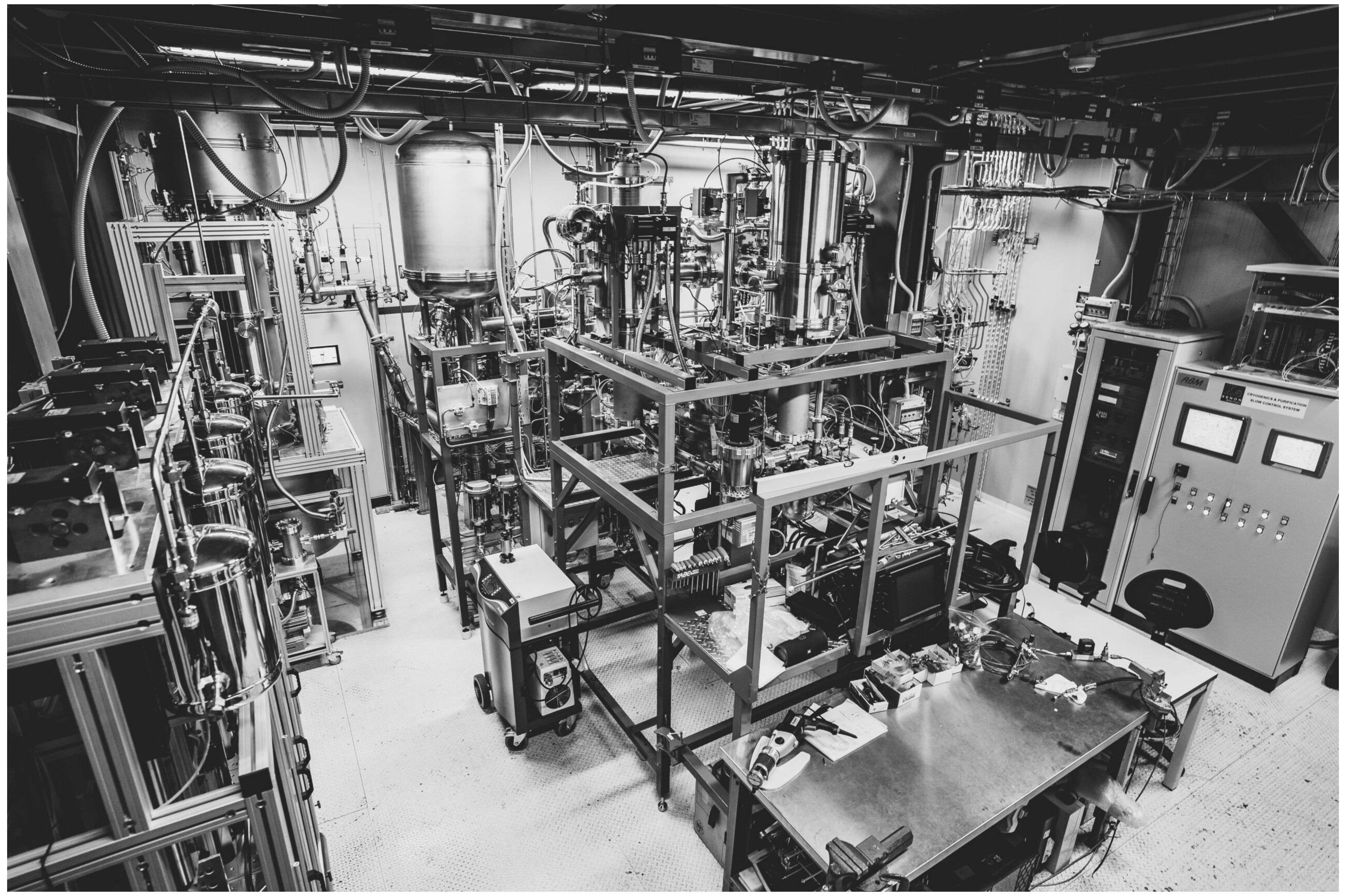
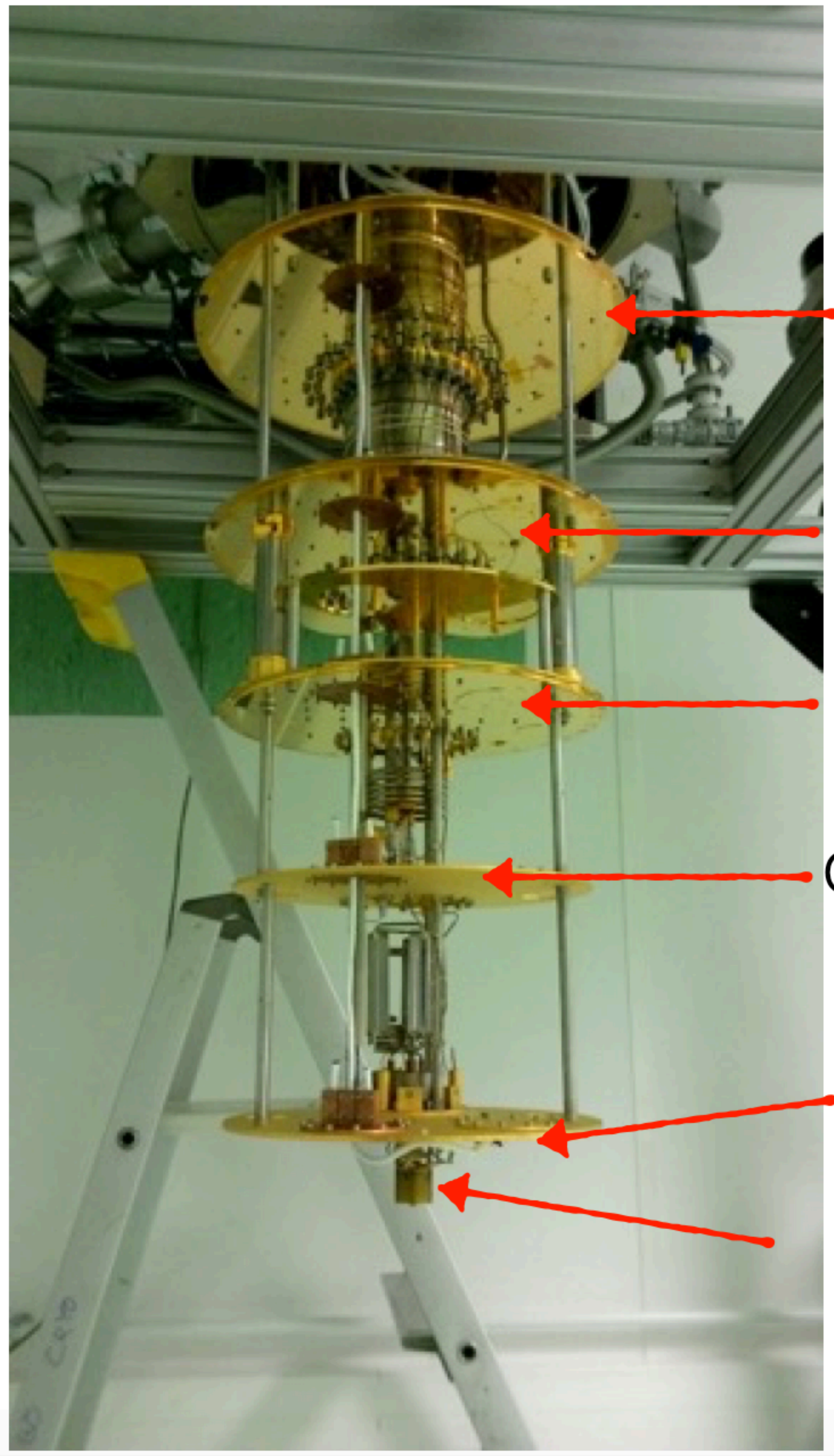
- Efficient **(Self-)shielding** material (Z= 94, ρ_{LXe} ~ 2.9 g/cm^3).
- Relatively easy to operate in liquid phase:
  - Can build compact detector and can be **scaled to largest mass**
  - high boiling point temperature (~178 K at P~ 2 bar) → **"Modest" cryogenic**

XENONnT Cryogenic system



https://xenonexperiment.org/photos/

Multi-stage cooling for cryogenic bolometers



J. Billard, Ecole de GIF (2016)

Why Xenon?

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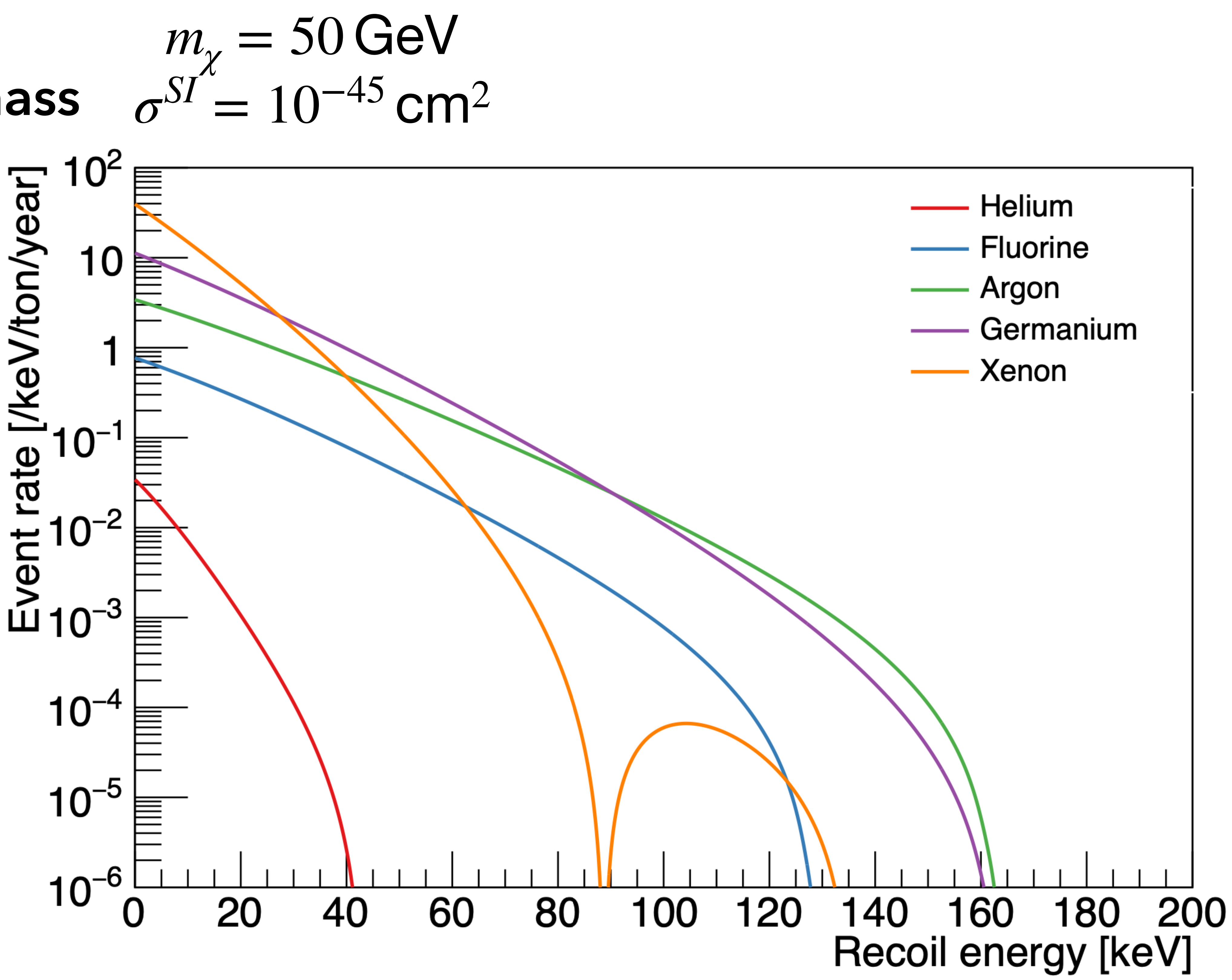

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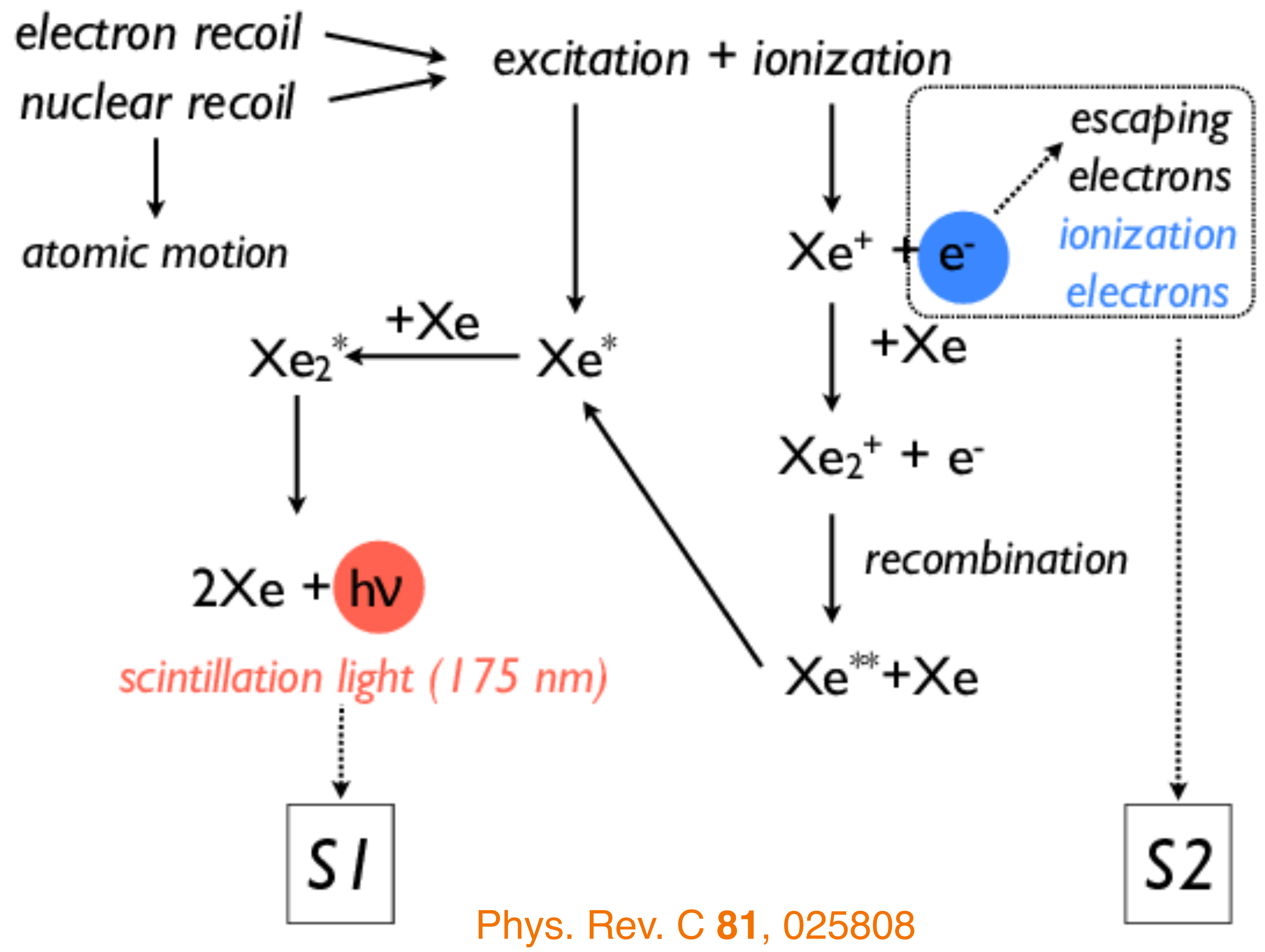
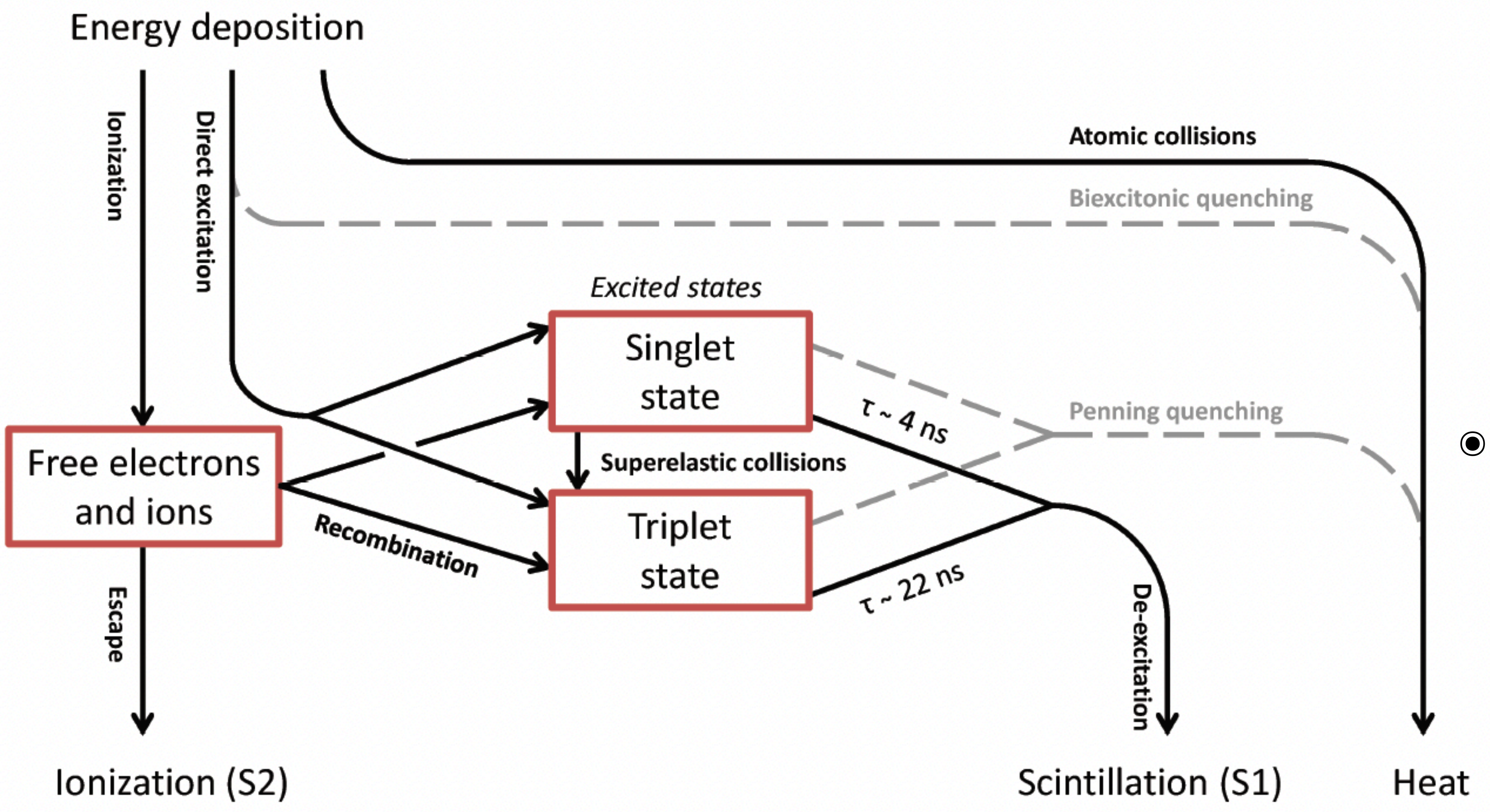
Xenon is transparant to its own scintillation light (VUV photon)!



Phys. Rev. C **81**, 025808

Why Xenon?

Zoom in energy transfer in Xenon:

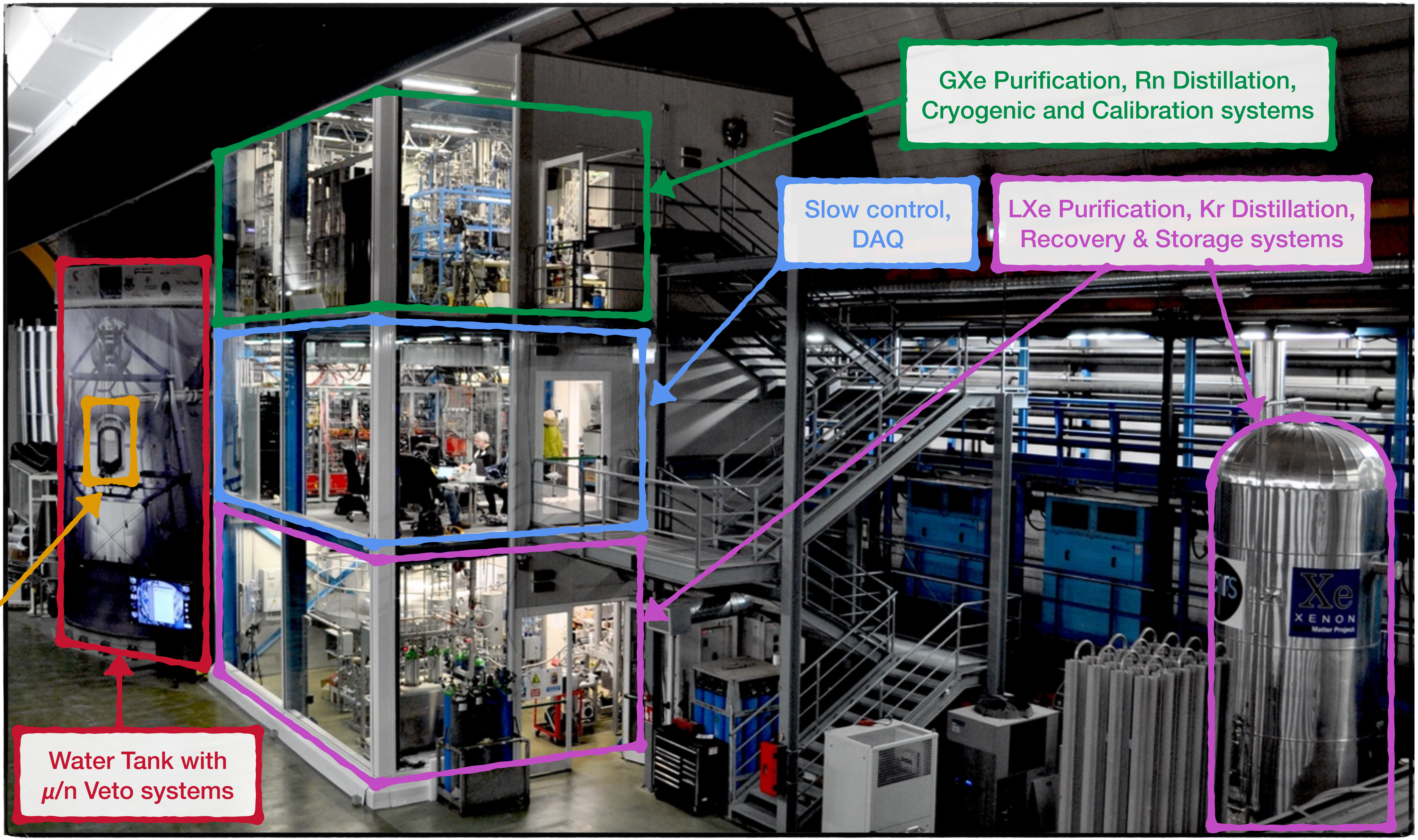


E. Hogenbirk et al., JINST, 13(05):P05016, 2018

- Singlet/Triplet lifetime are very different between Argon (~6 ns, ~1.5μs) and Xenon (~4 ns, ~22 ns)
  - ➡ Scintillation Pulse-Shape
  - ➡ Ratio between two states depends on the energy deposited density distribution (particle dependent) → 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 → ER/NR discrimination

XENONnT Experiment Overview

Not just one detector

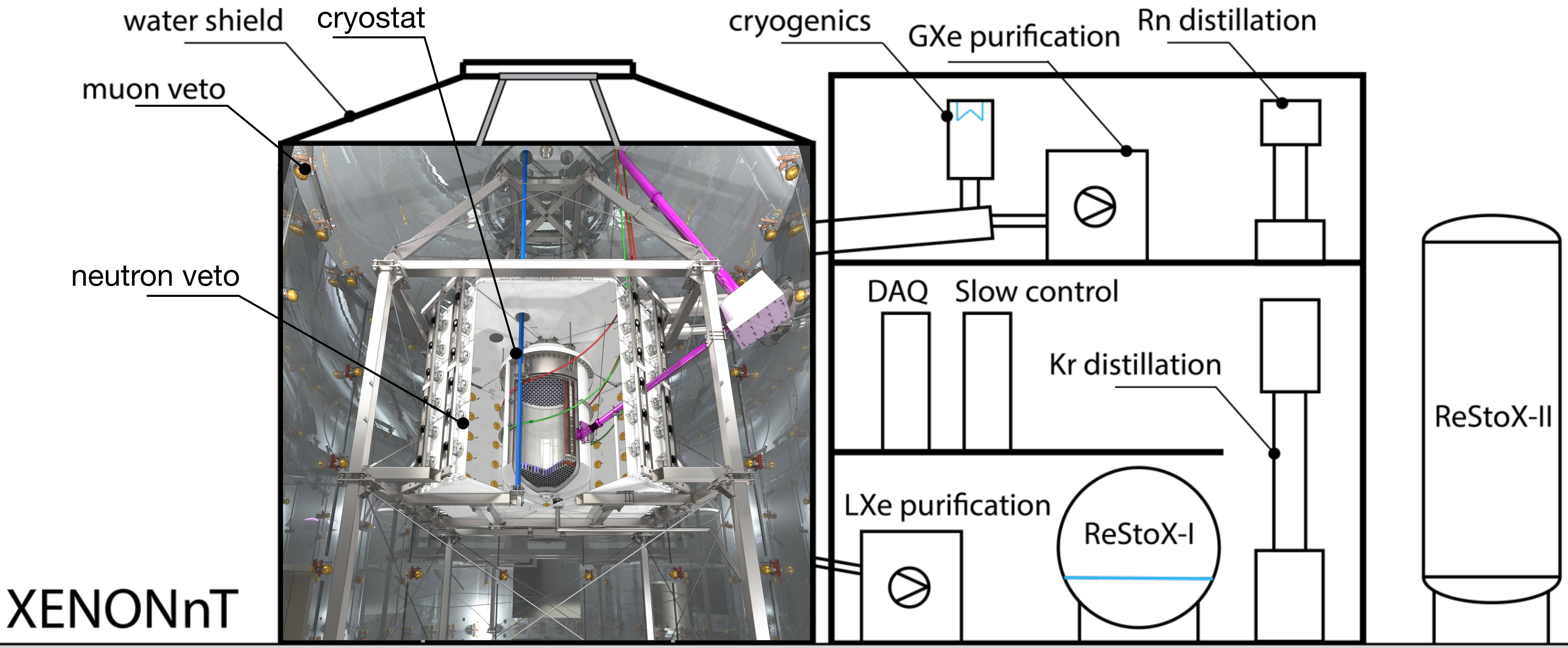


Main Detector:
Dual-Phase Time projection Chamber

Water Tank with μ/n Veto systems

XENONnT Experiment Overview

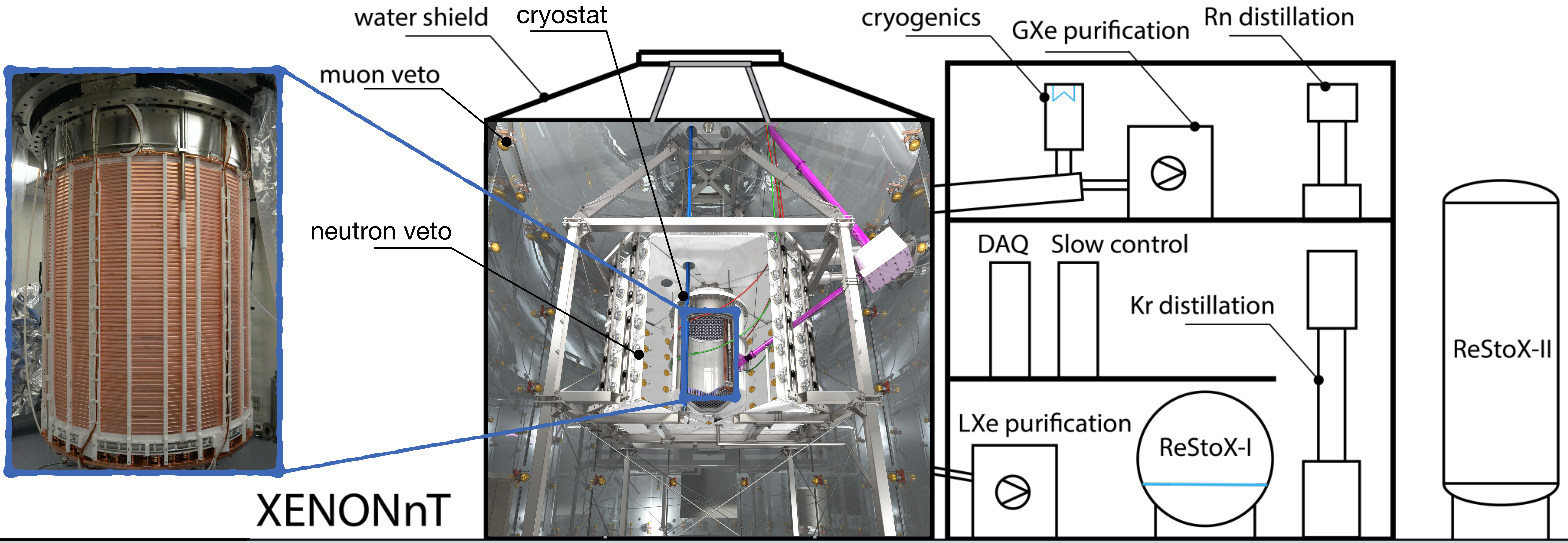
XENON1T UPGRADE



XENONnT Experiment Overview

XENON1T UPGRADE

x3 larger TPC
8.5 t LXe
494 PMTs



XENONnT Experiment Overview

XENON1T UPGRADE

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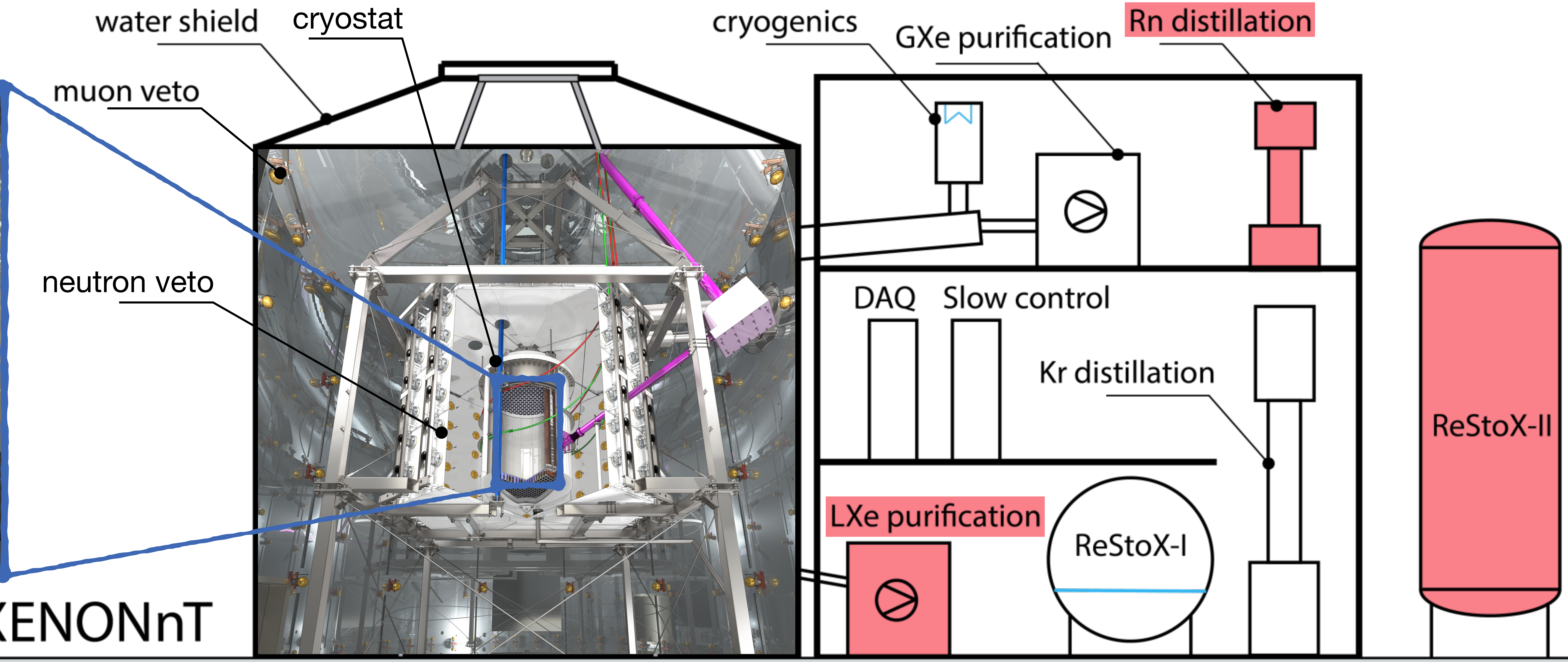
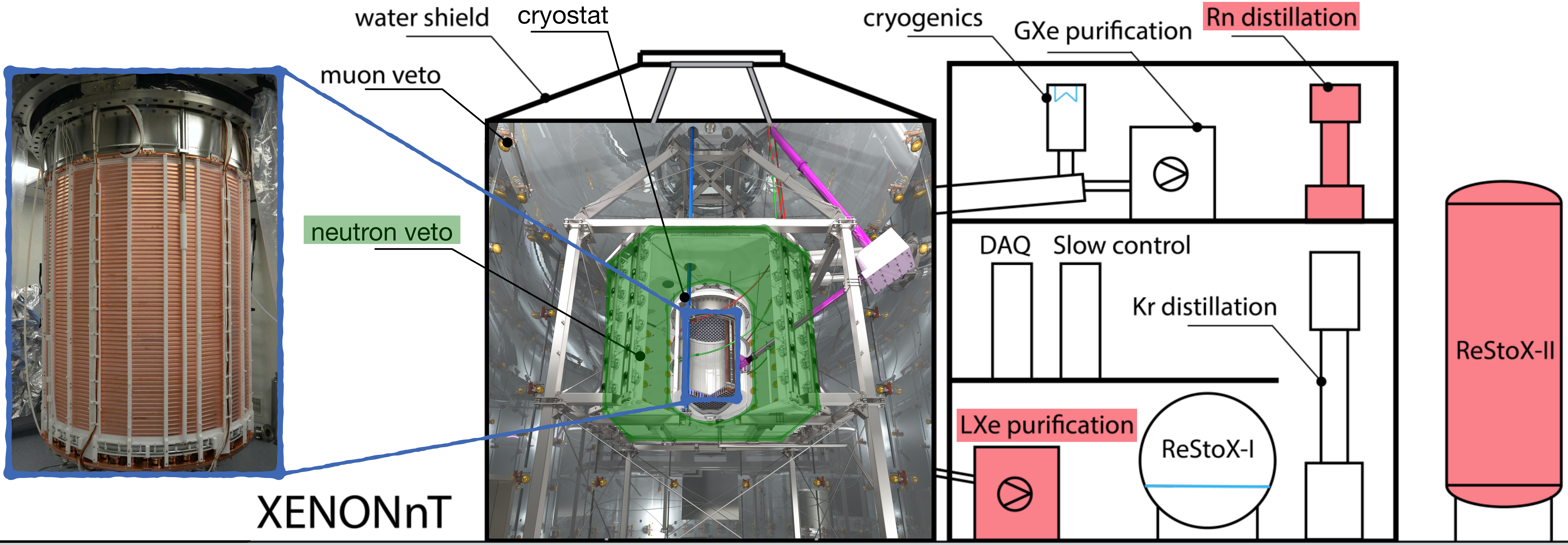
Xenon handling
New purification
& ER bkg. reduction
New recovery/storage



XENONnT Experiment Overview

XENON1T UPGRADE

x3 larger TPC 8.5 t LXe 494 PMTs	**Xenon handling** New purification & ER bkg. reduction New recovery/storage	**Water Cherenkov Neutron Veto** Gd-doping in preparation



XENONnT Experiment Overview

XENON1T UPGRADE

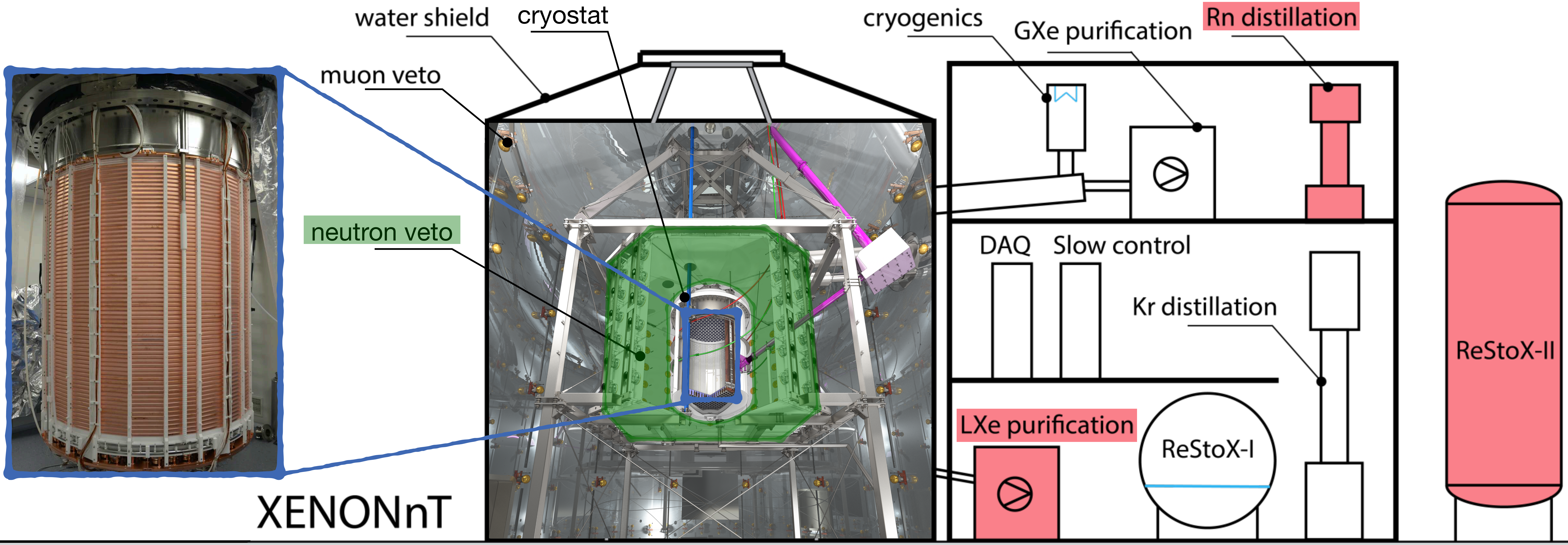
x3 larger TPC
8.5 t LXe
494 PMTs

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

Water Cherenkov Neutron Veto
Gd-doping in preparation

Goal →

More target mass
Reduced background level



XENONnT Experiment Overview

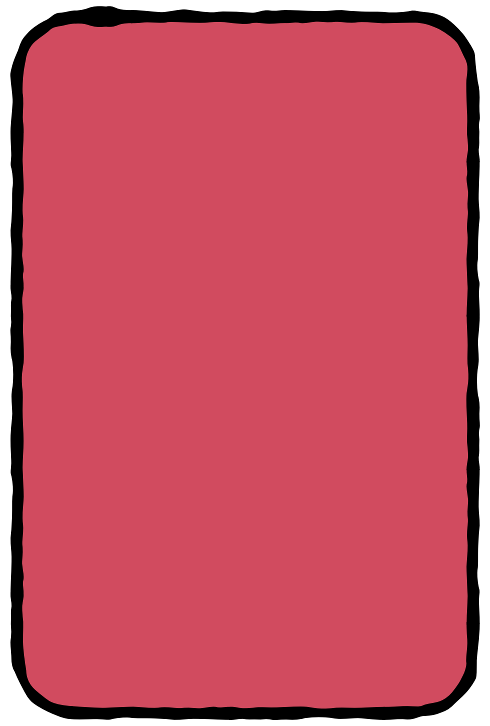
How to achieve an ultra-low background experiments:

XENONnT Experiment Overview

How to achieve an ultra-low background experiments:

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

TPC



XENONnT Experiment Overview

How to achieve an ultra-low background experiments:

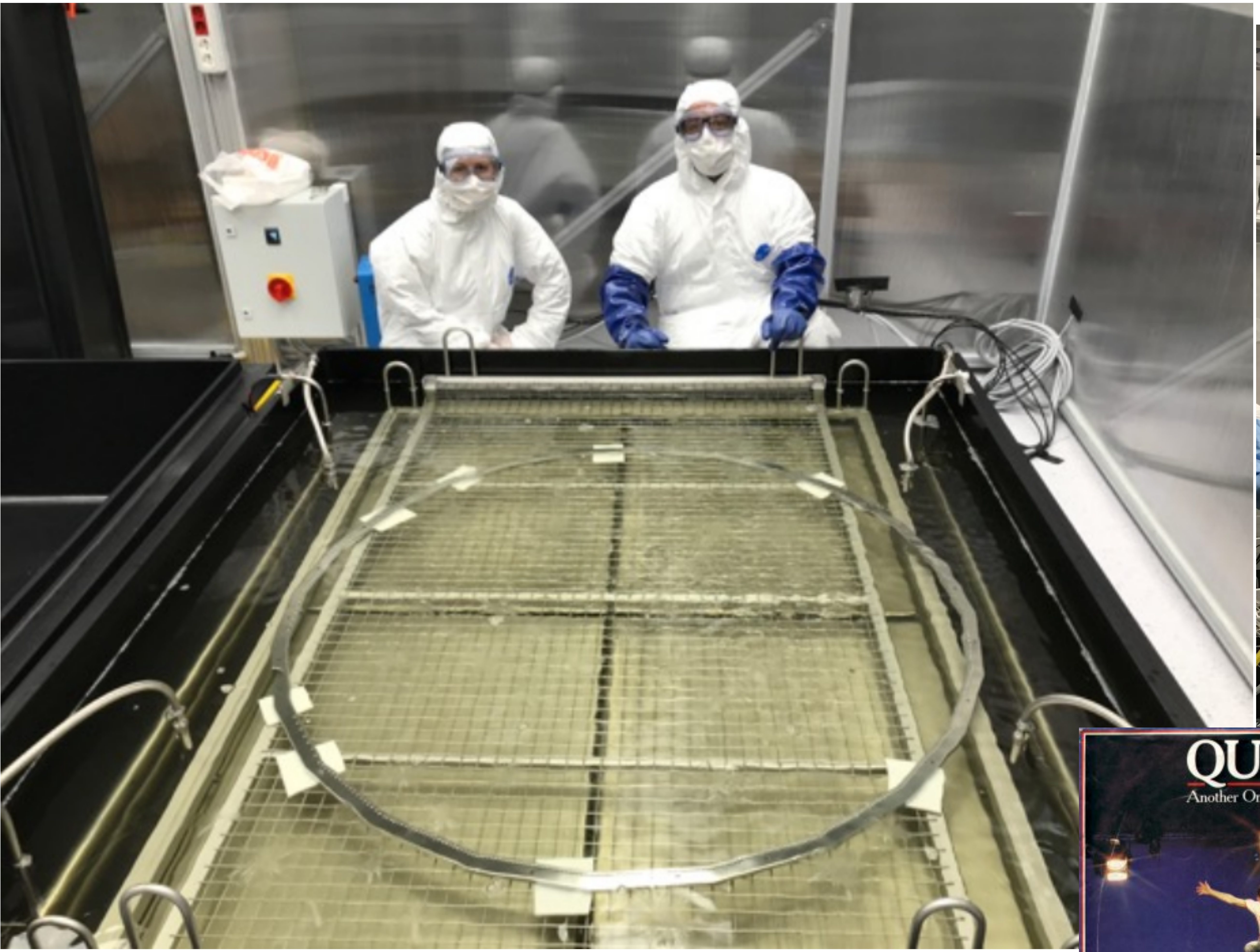
- Material selection/cleaning
    - Screening campaign
    - Cleaning pre-construction

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

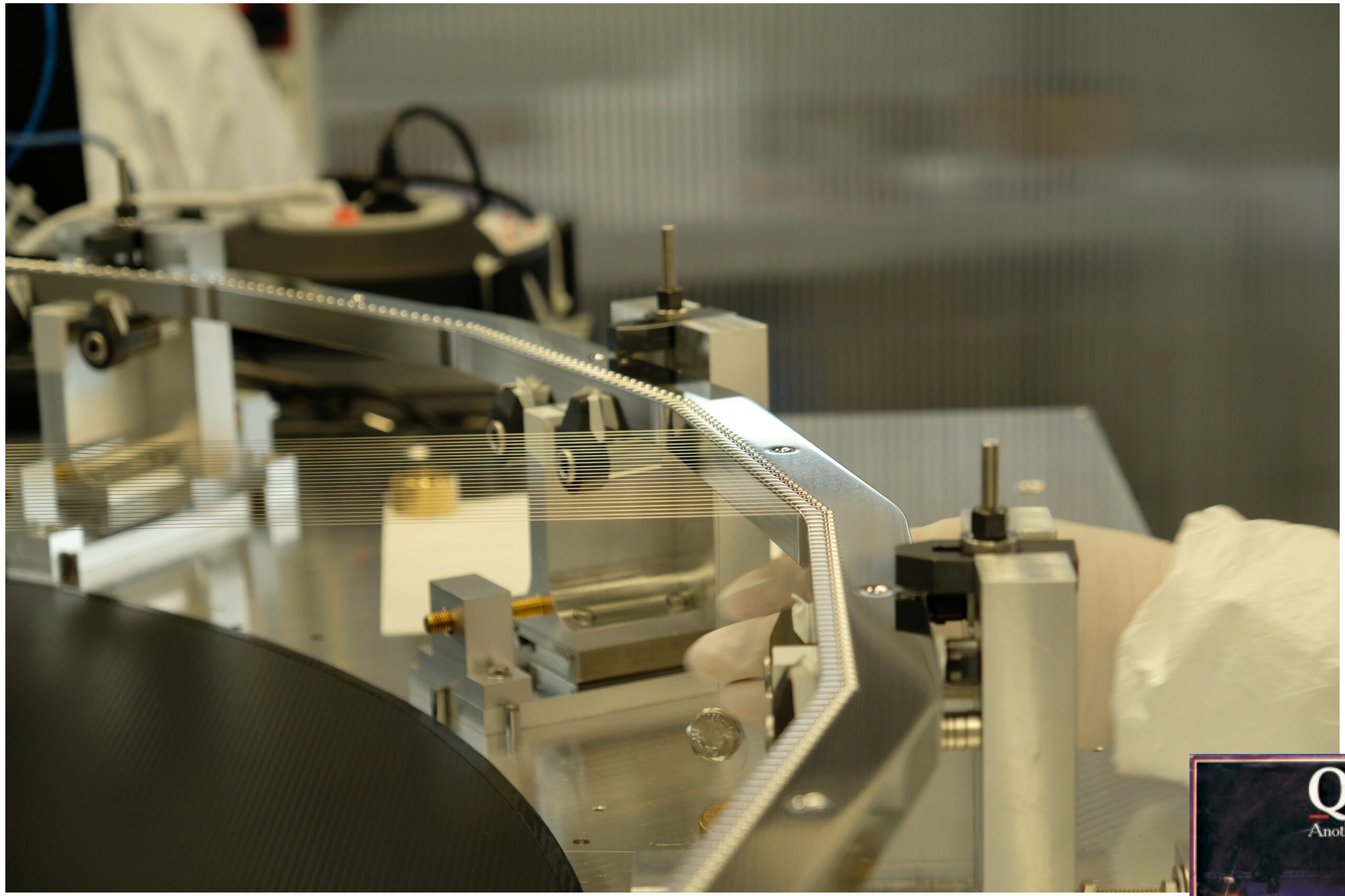
XENONnT Experiment Overview

XENON Collaboration pictures



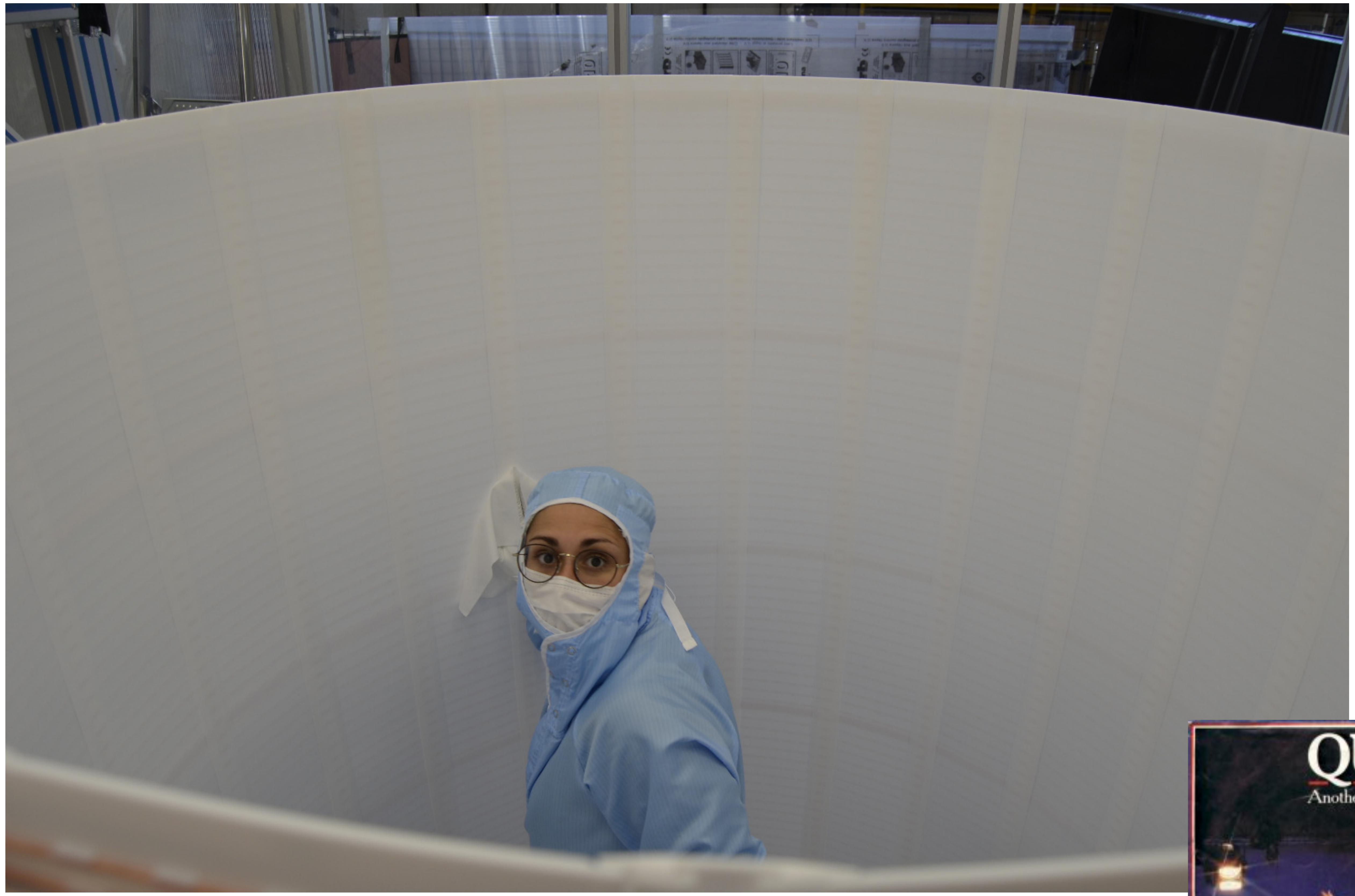
XENONnT Experiment Overview

XENON Collaboration pictures



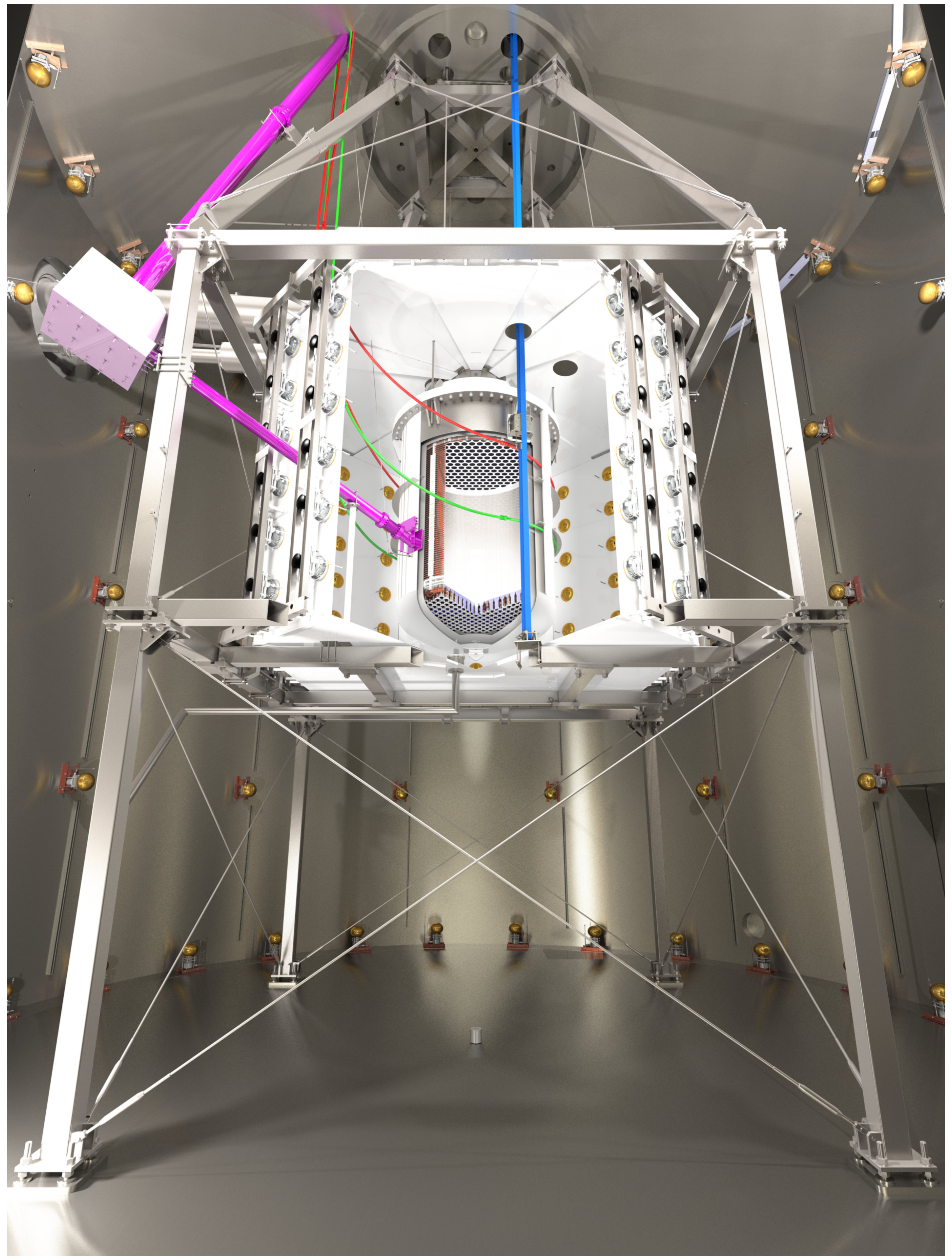
XENONnT Experiment Overview

XENON Collaboration pictures

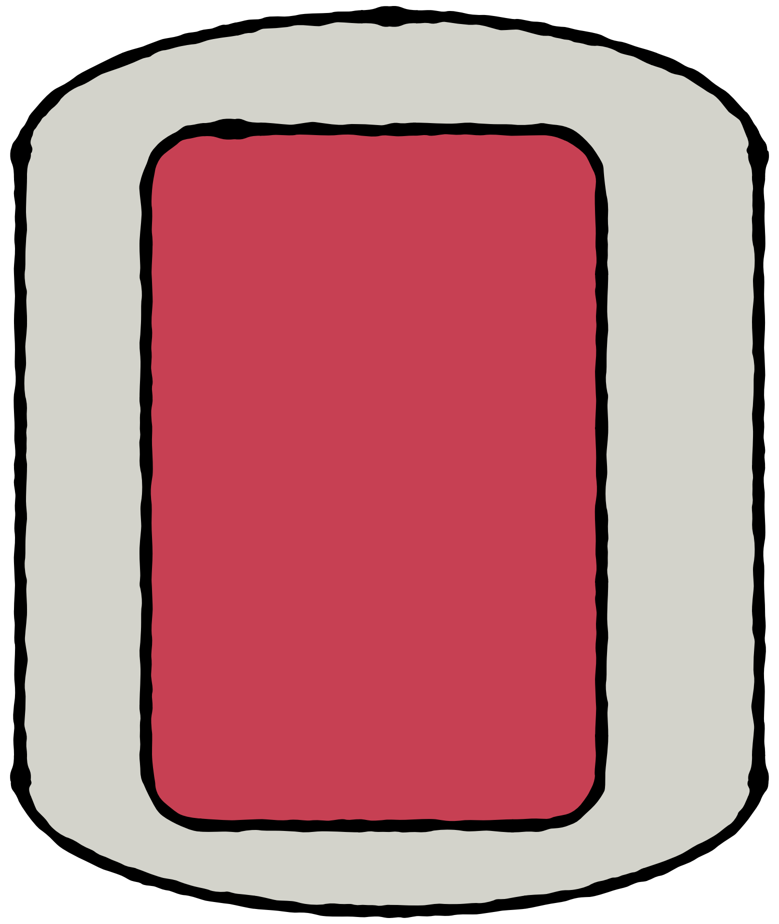


XENONnT Experiment Overview

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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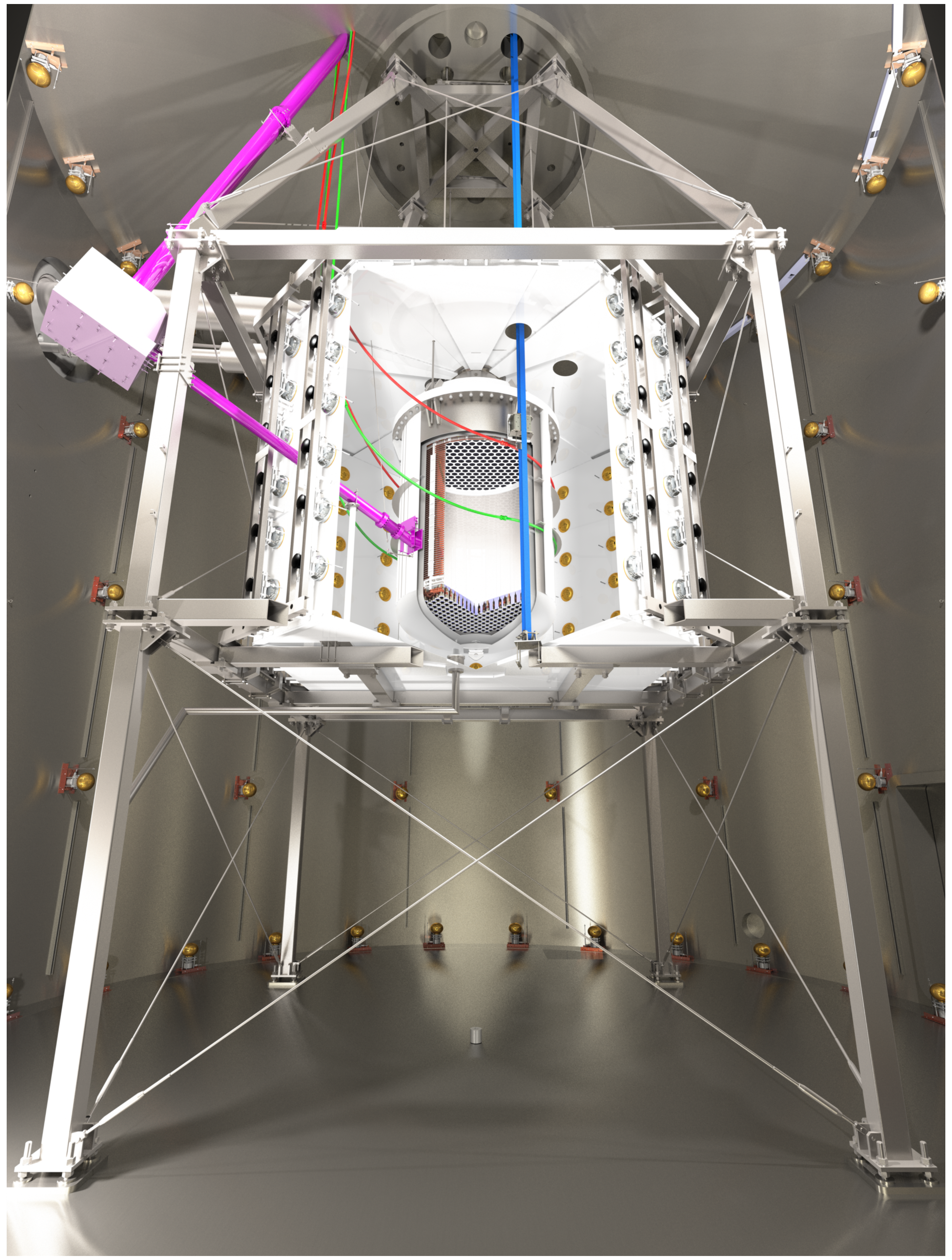
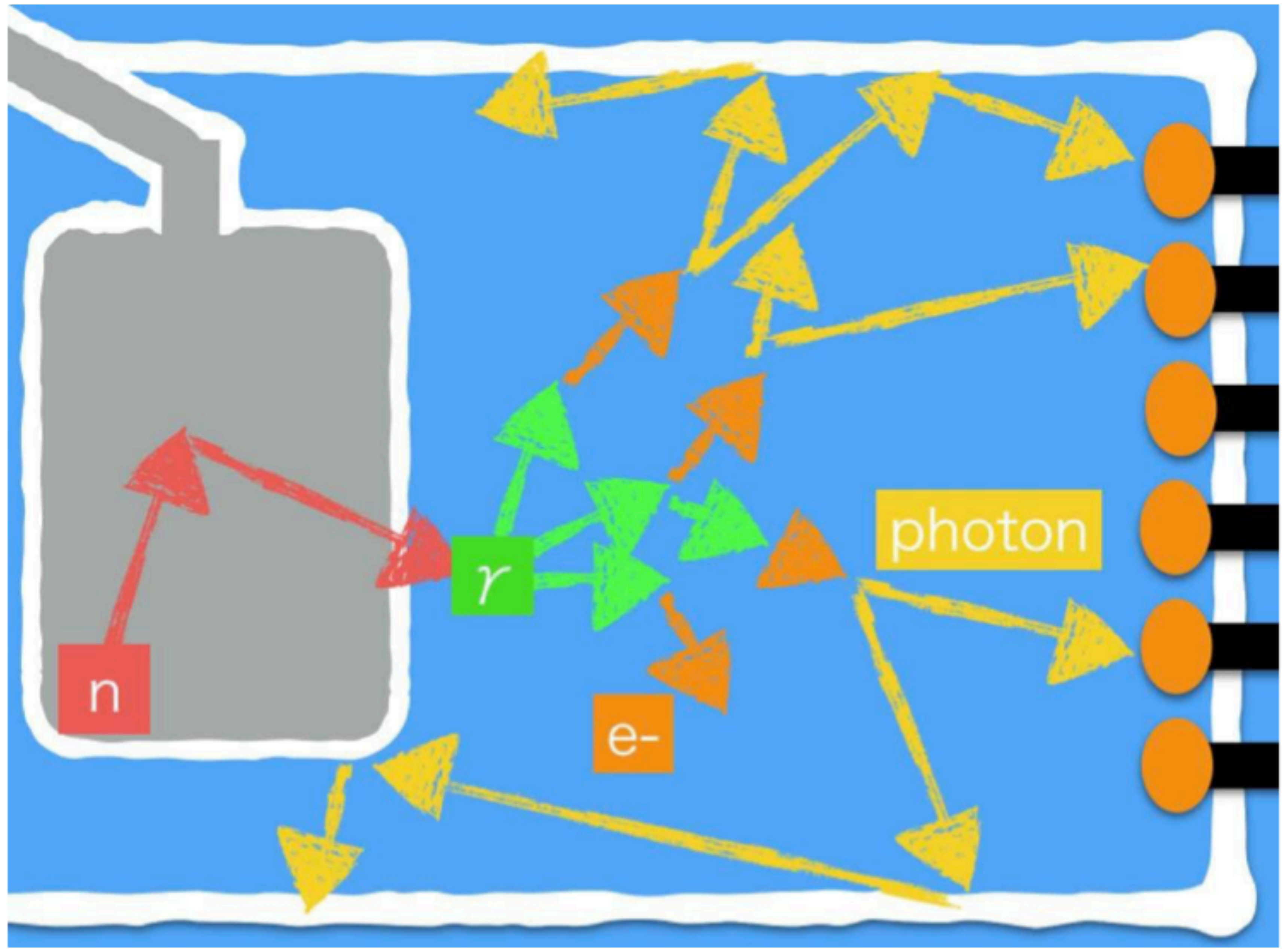
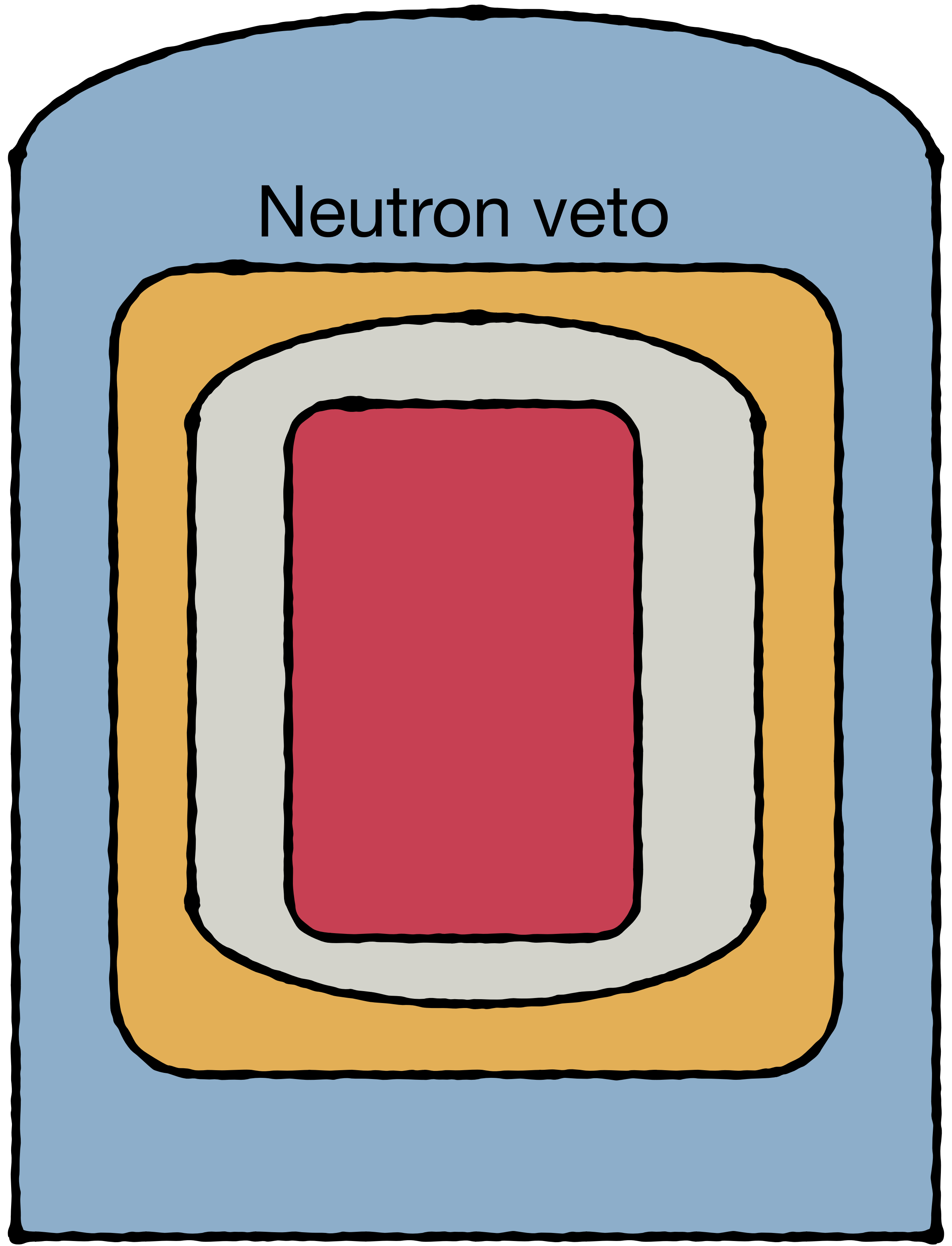


- Material selection/cleaning
- Self-shielding with LXe:
- Active Shielding
  - n-veto | (n,ɣ) capture
  - μ-veto | Cherenkov light



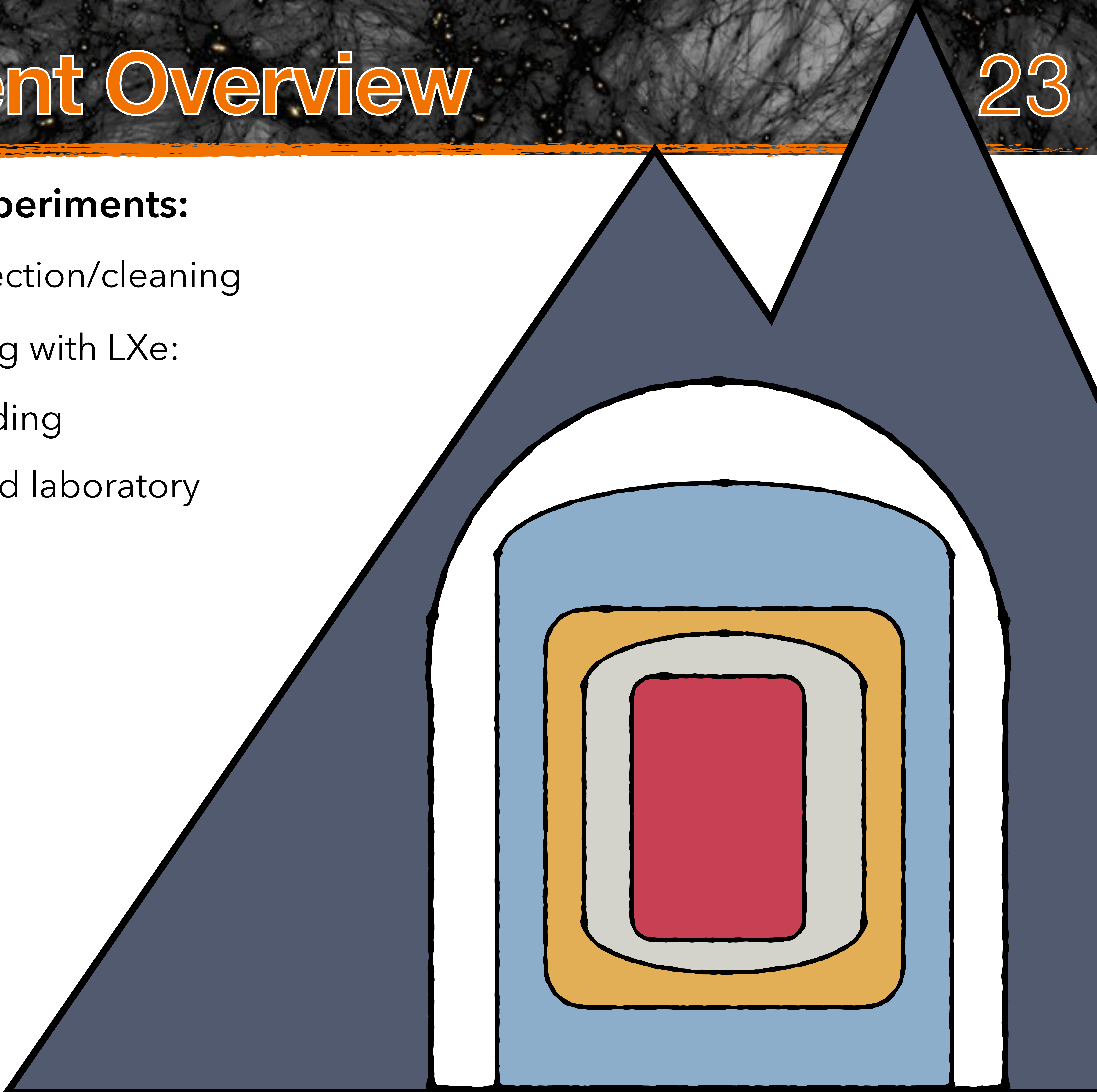


Tag neutrons through the neutron capture on hydrogen which releases a 2.2 MeV gamma

XENONnT Experiment Overview

How to achieve an ultra-low background experiments:

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



XENONnT Experiment Overview

How to achieve an ultra-low background experiments:

- Material selection/cleaning
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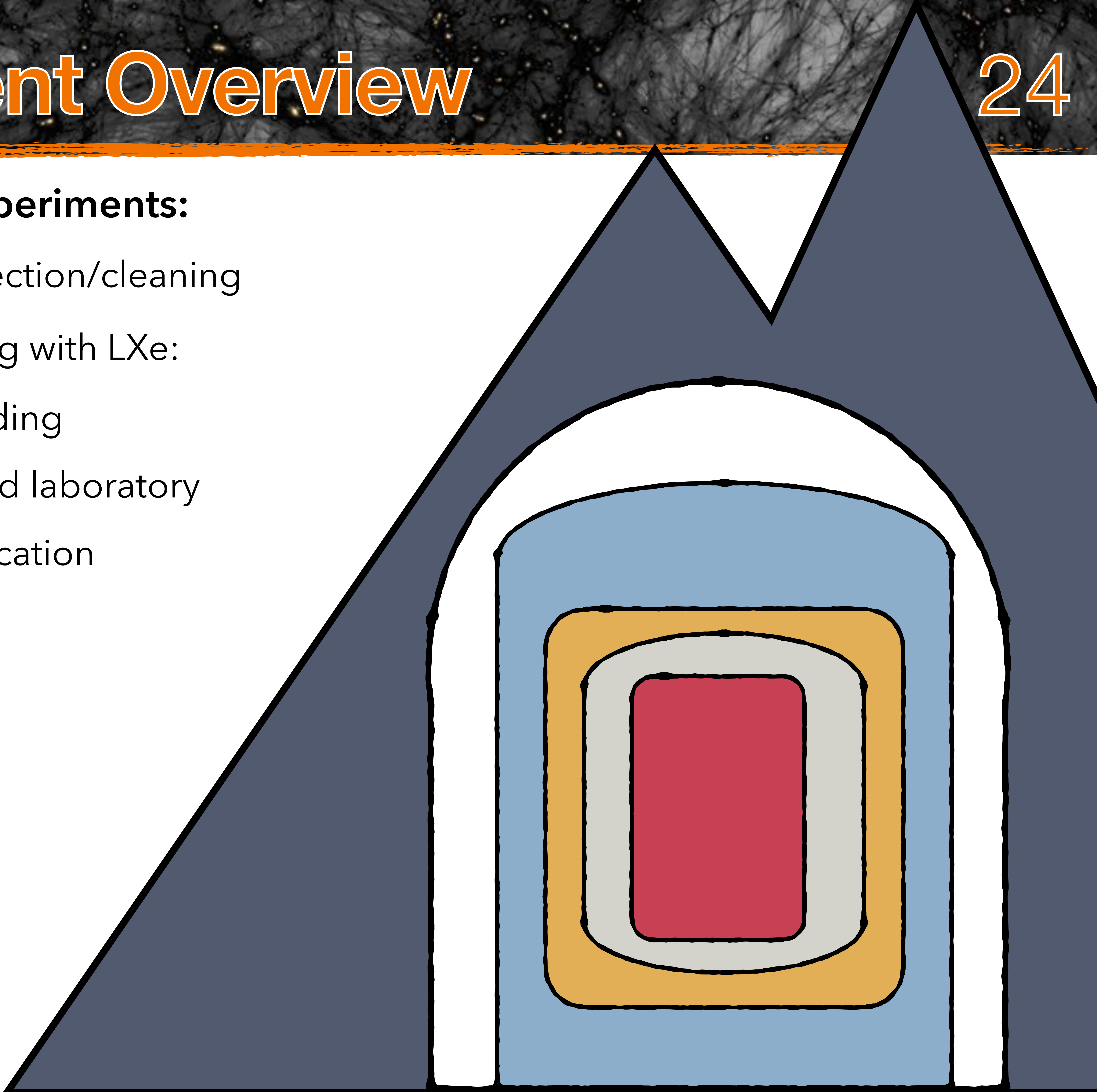
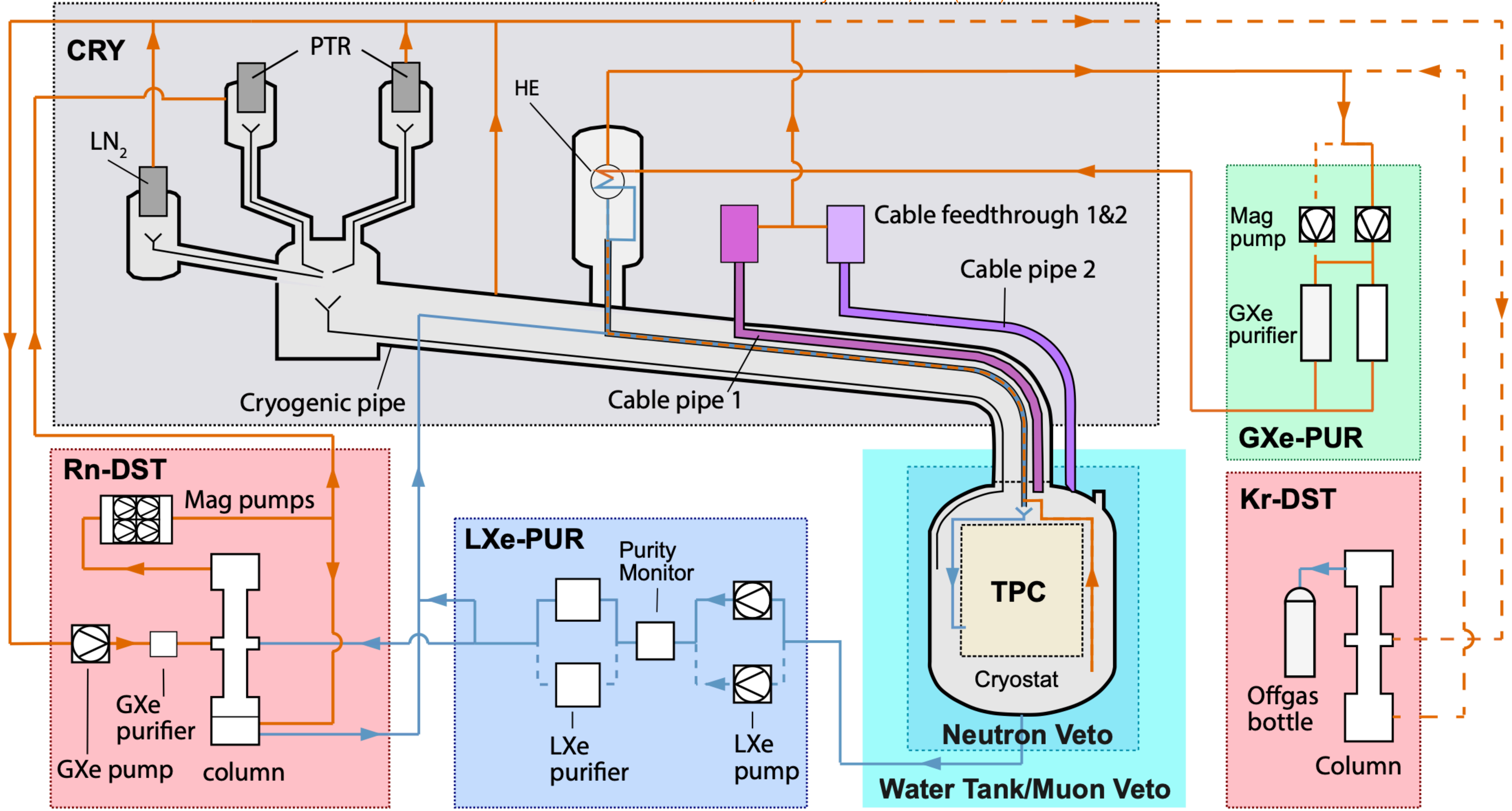
- Target purification



Purification systems

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



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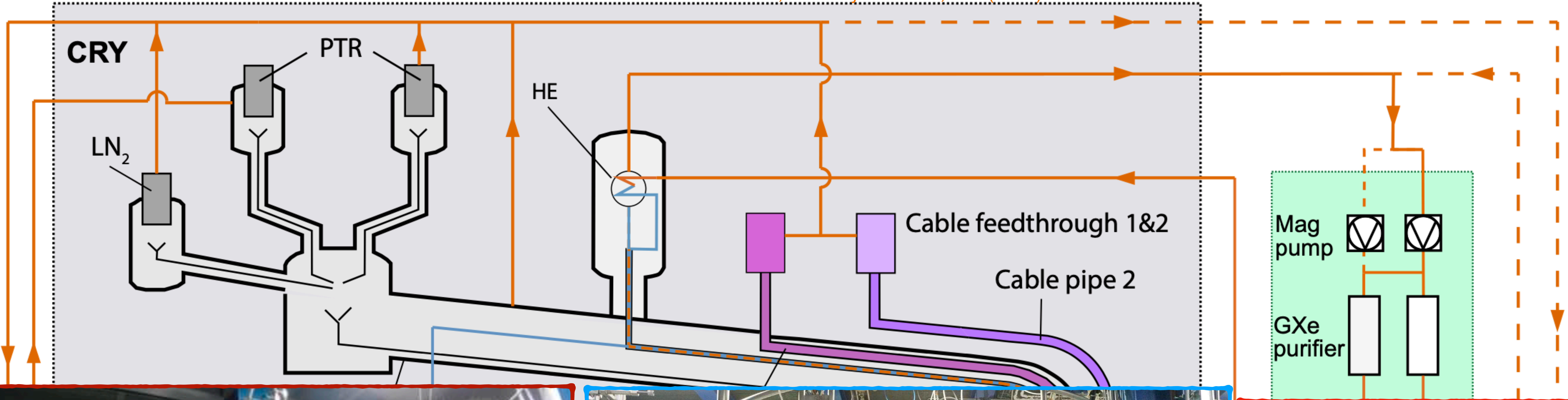
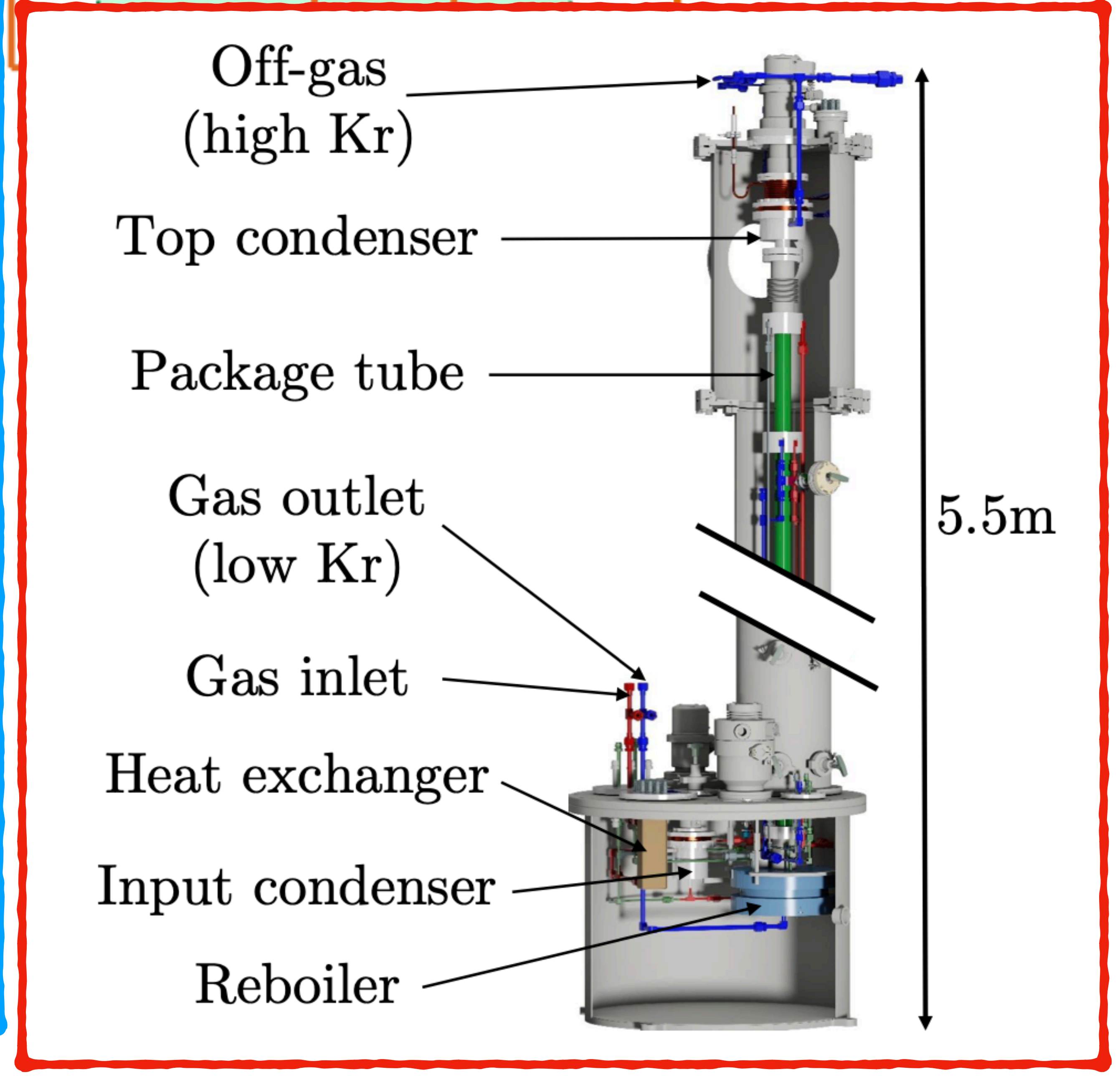
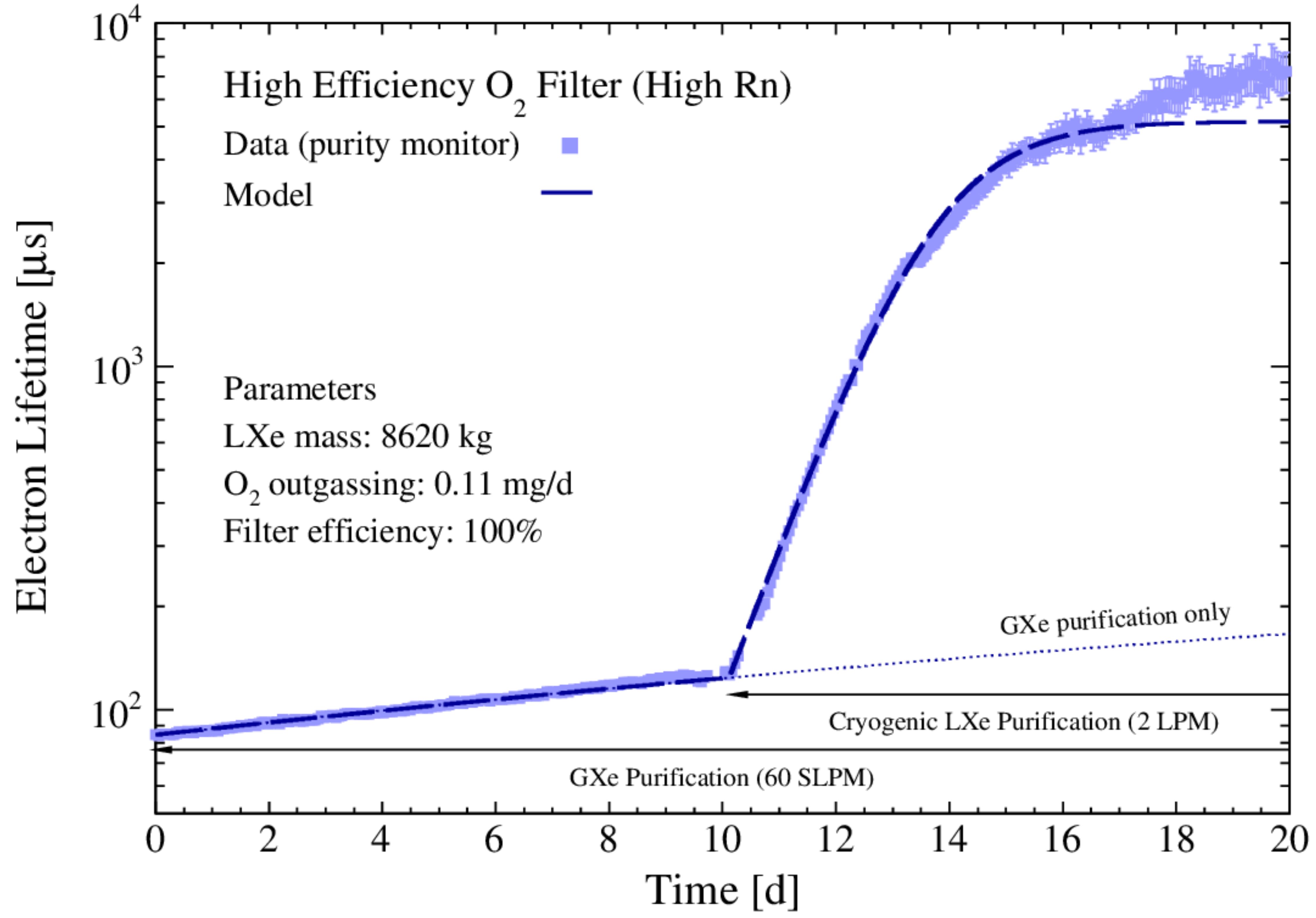
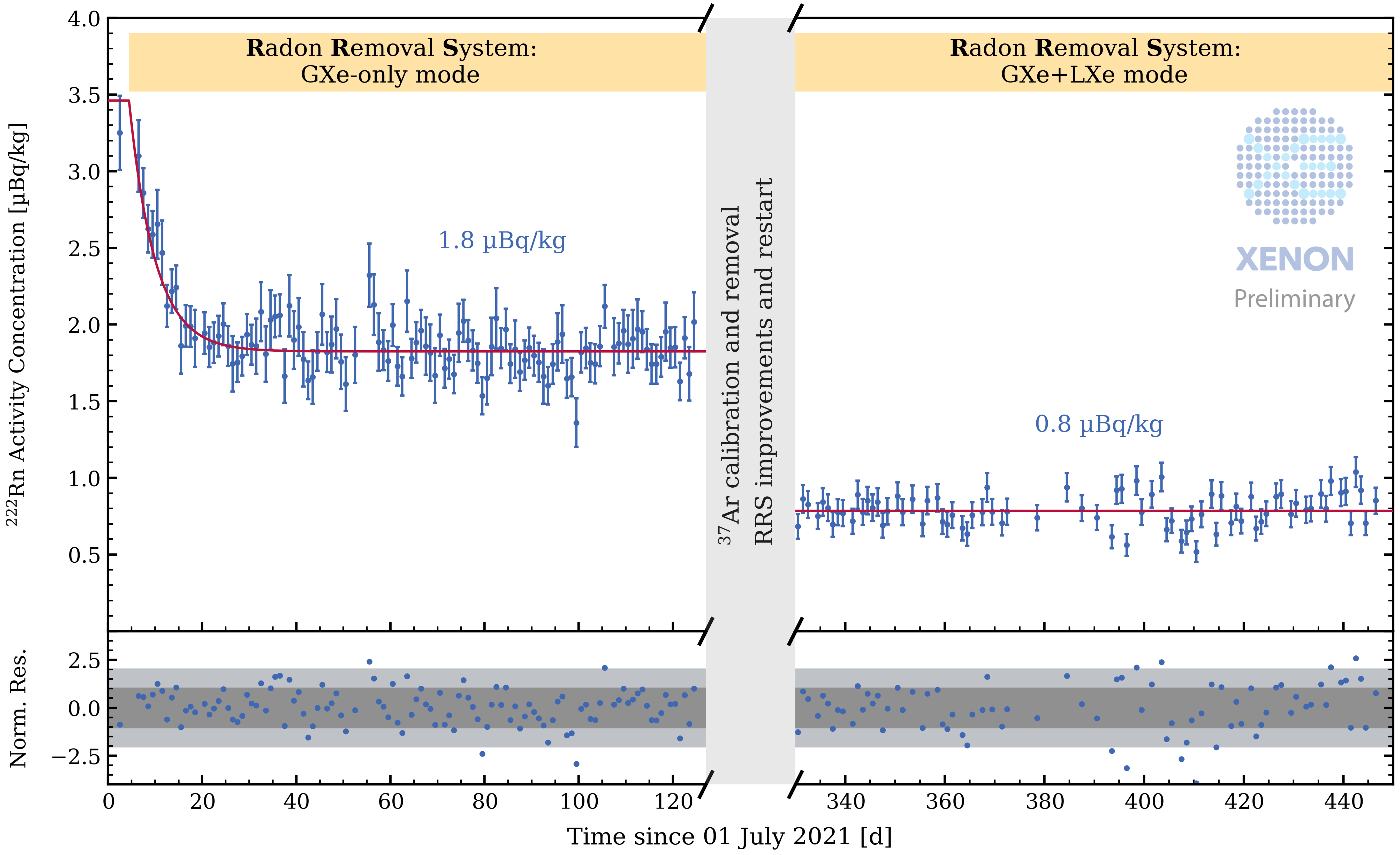




XENON Collaboration, Eur. Phys. J. C (2017) 77: 881

Purification systems





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

XENONnT Experiment Overview

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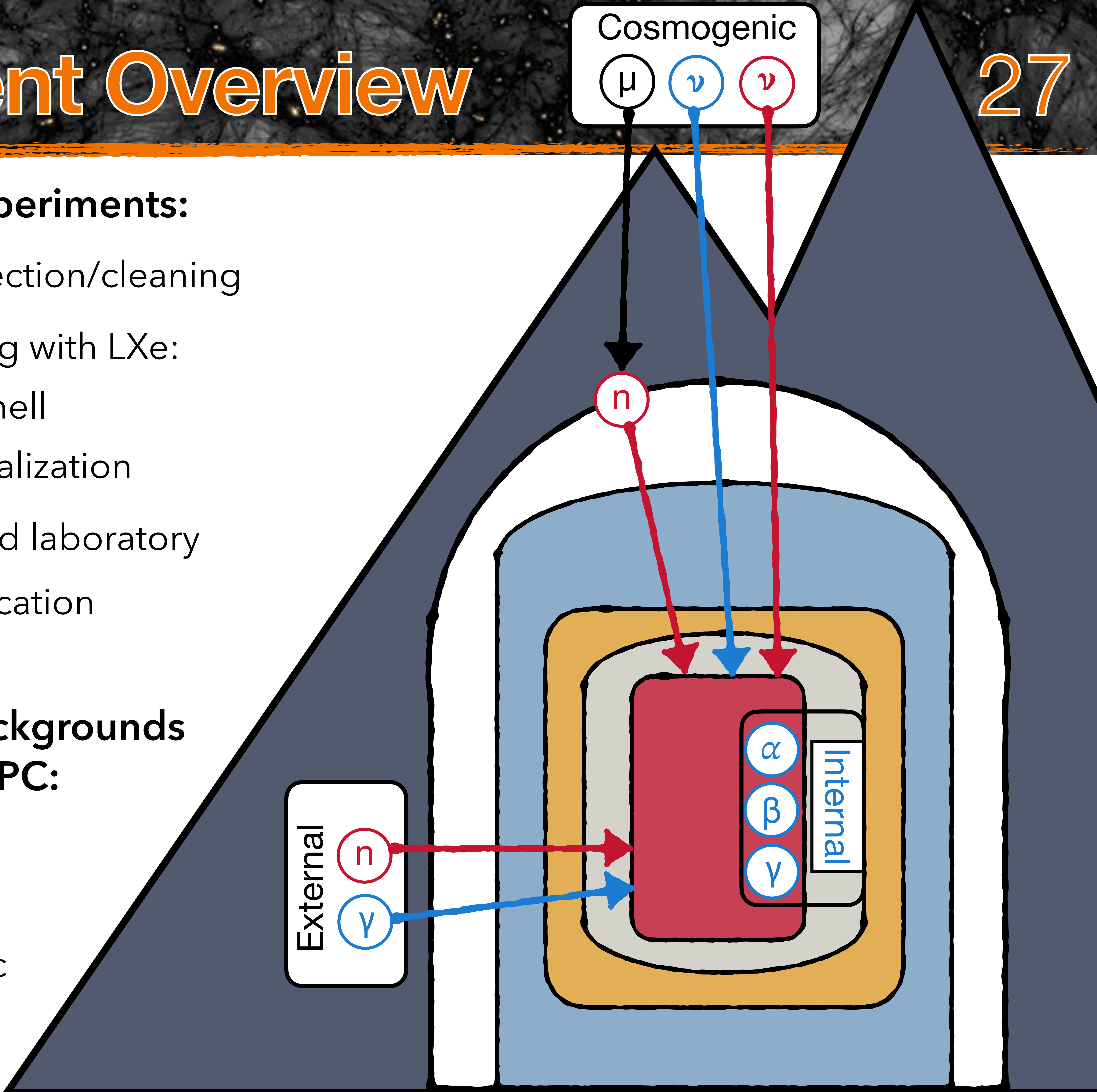
Remaining backgrounds reaching the TPC:

- External
- Internals
- Cosmogenic



Time Projection Chamber

New Larger TPC

- x3 larger volume w.r.t. XENON1T

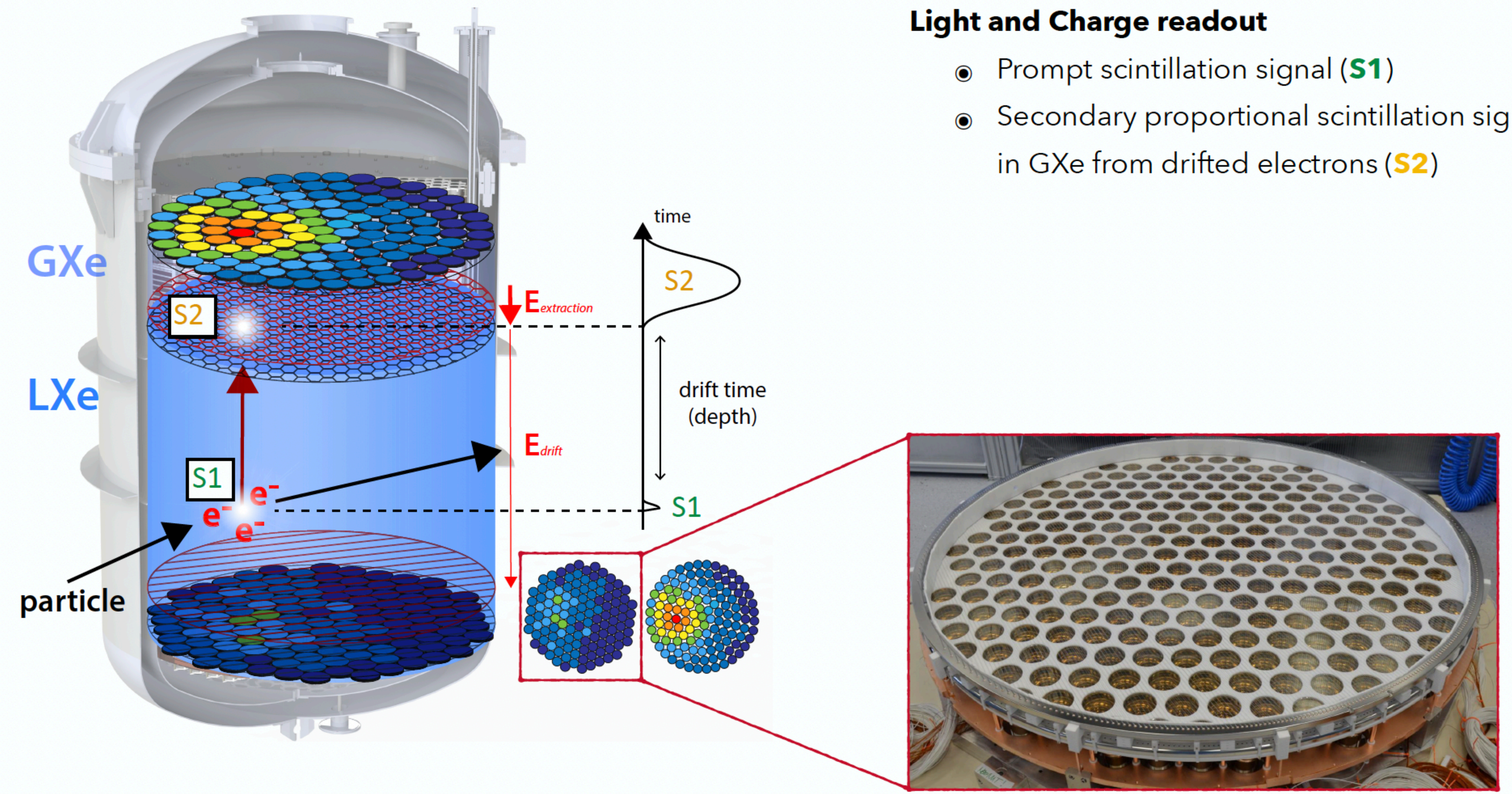
★ 2.0 t → 5.9 t LXe active mass

★ ~1 m → ~1.5 m drift length

★ ~1 m → ~1.3 m diameter

★ 248 → 494 3″ PMTs

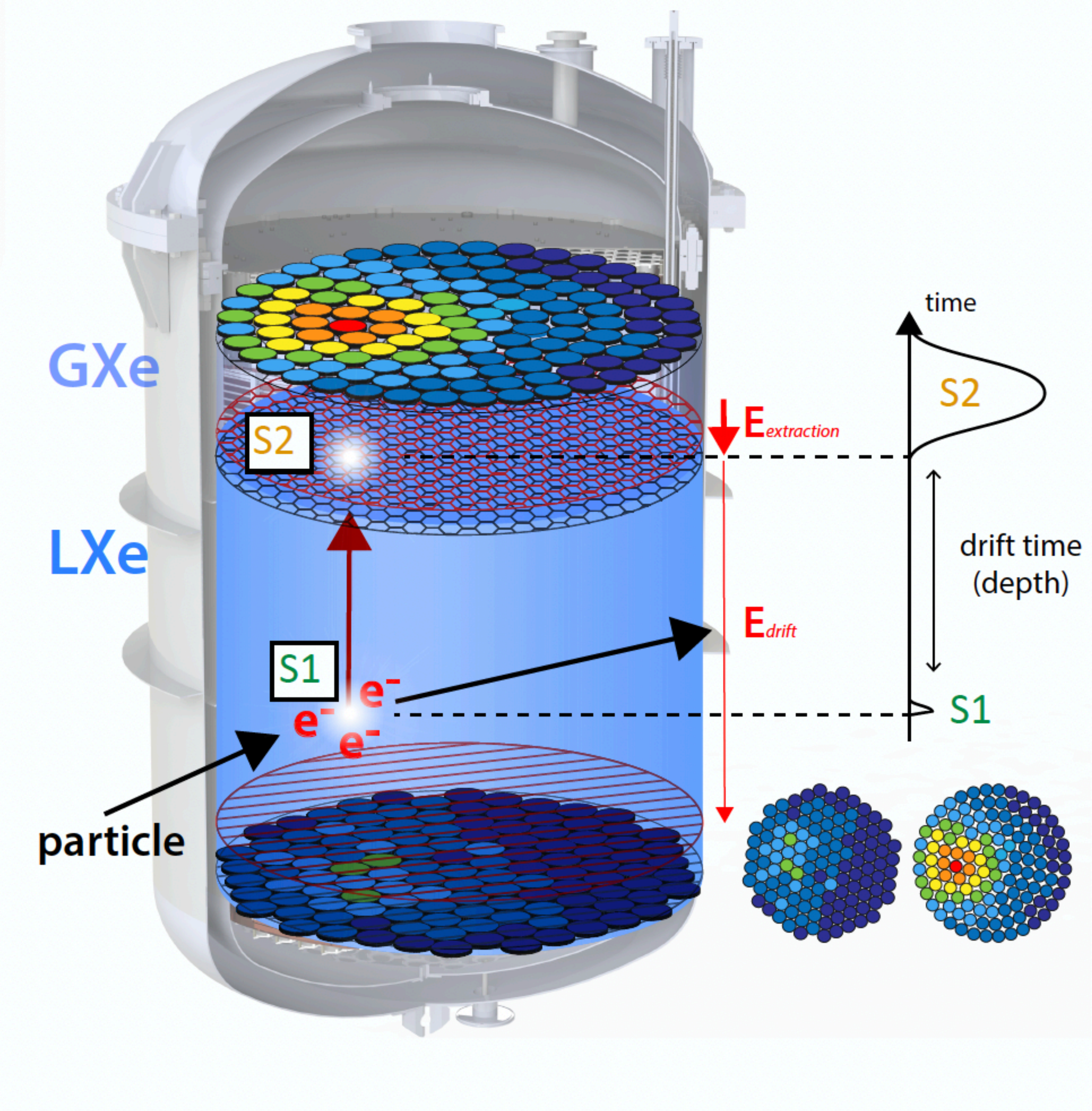
TPC Working Principle



Light and Charge readout

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

TPC Working Principle



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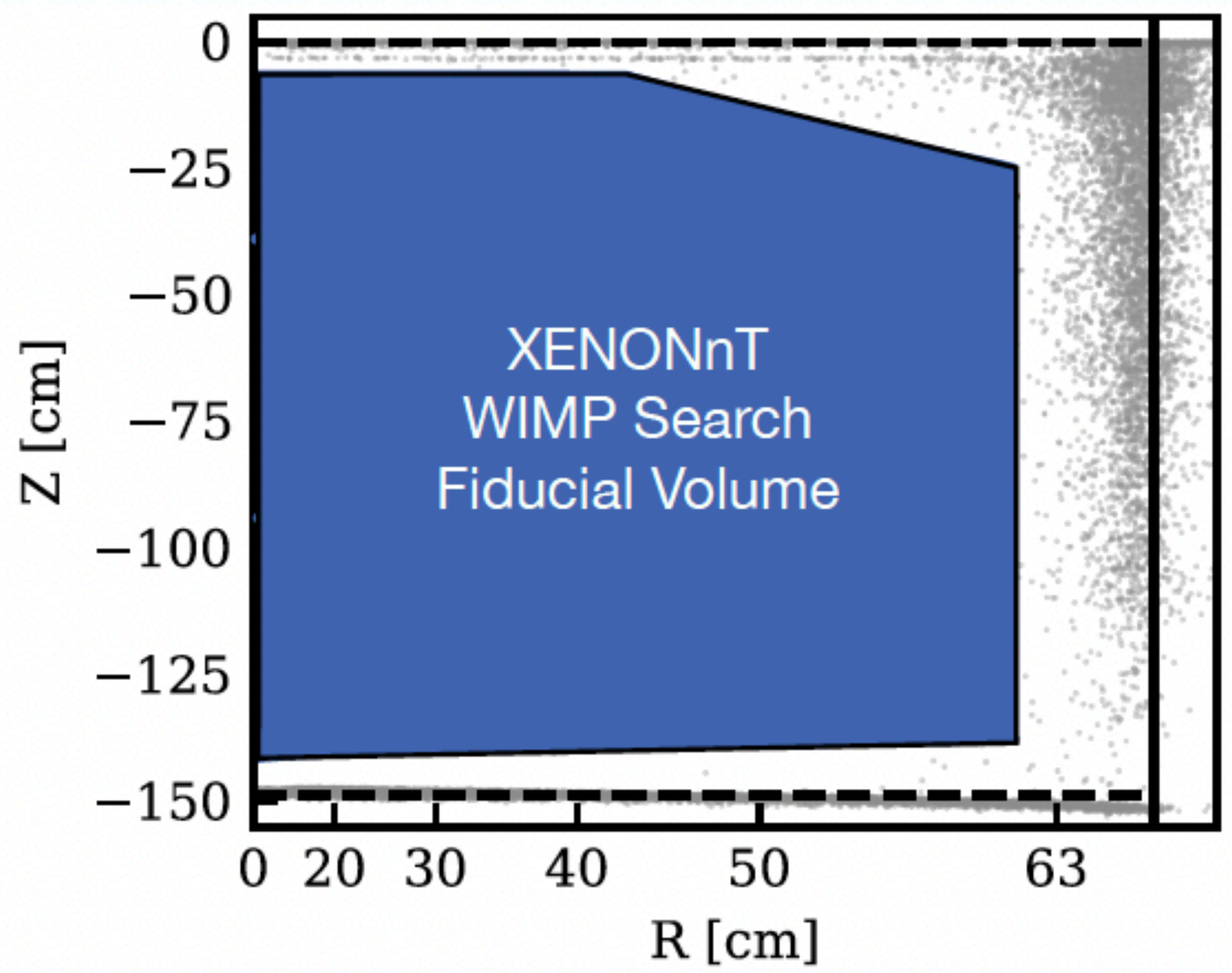
Event reconstruction

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



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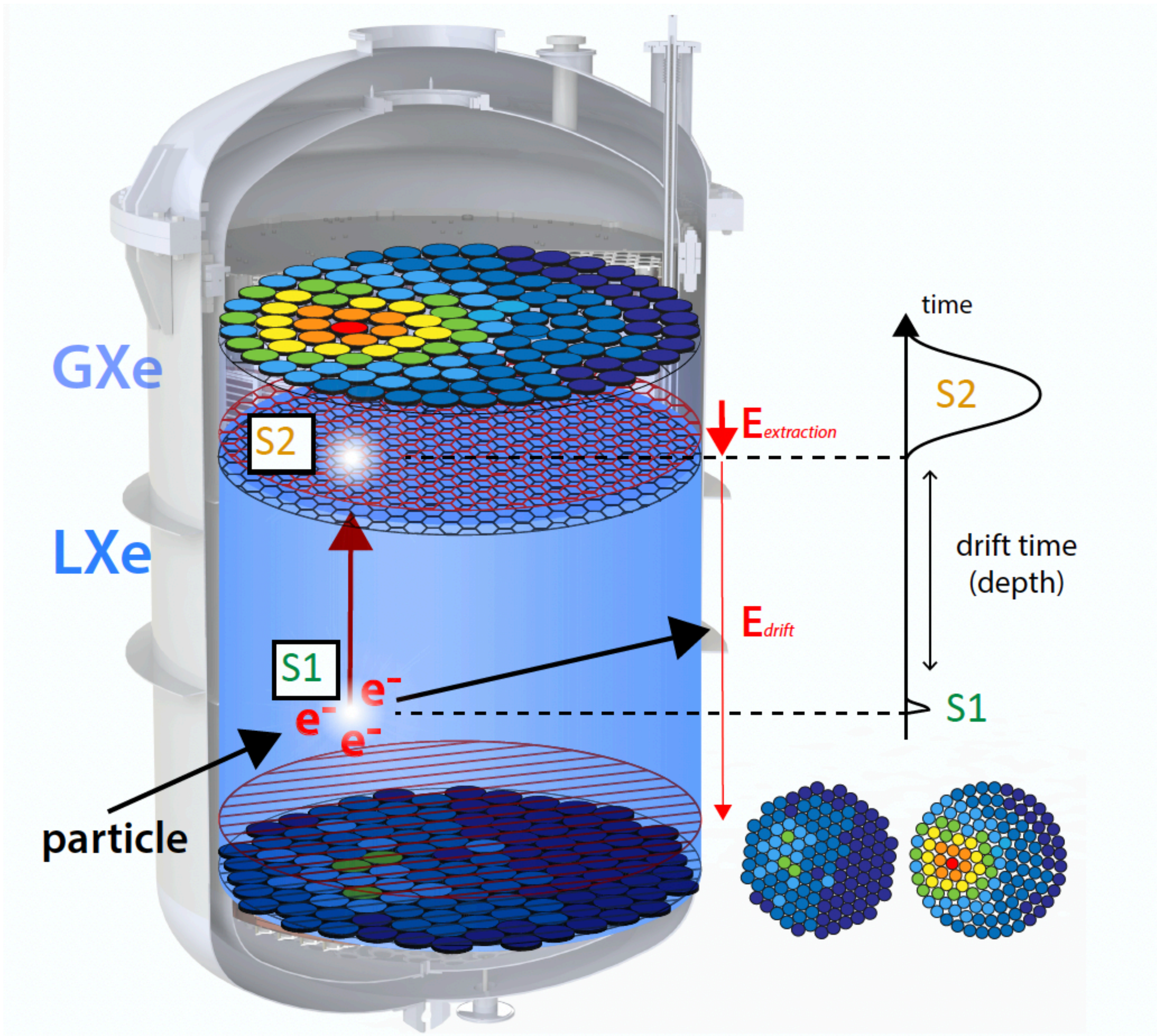

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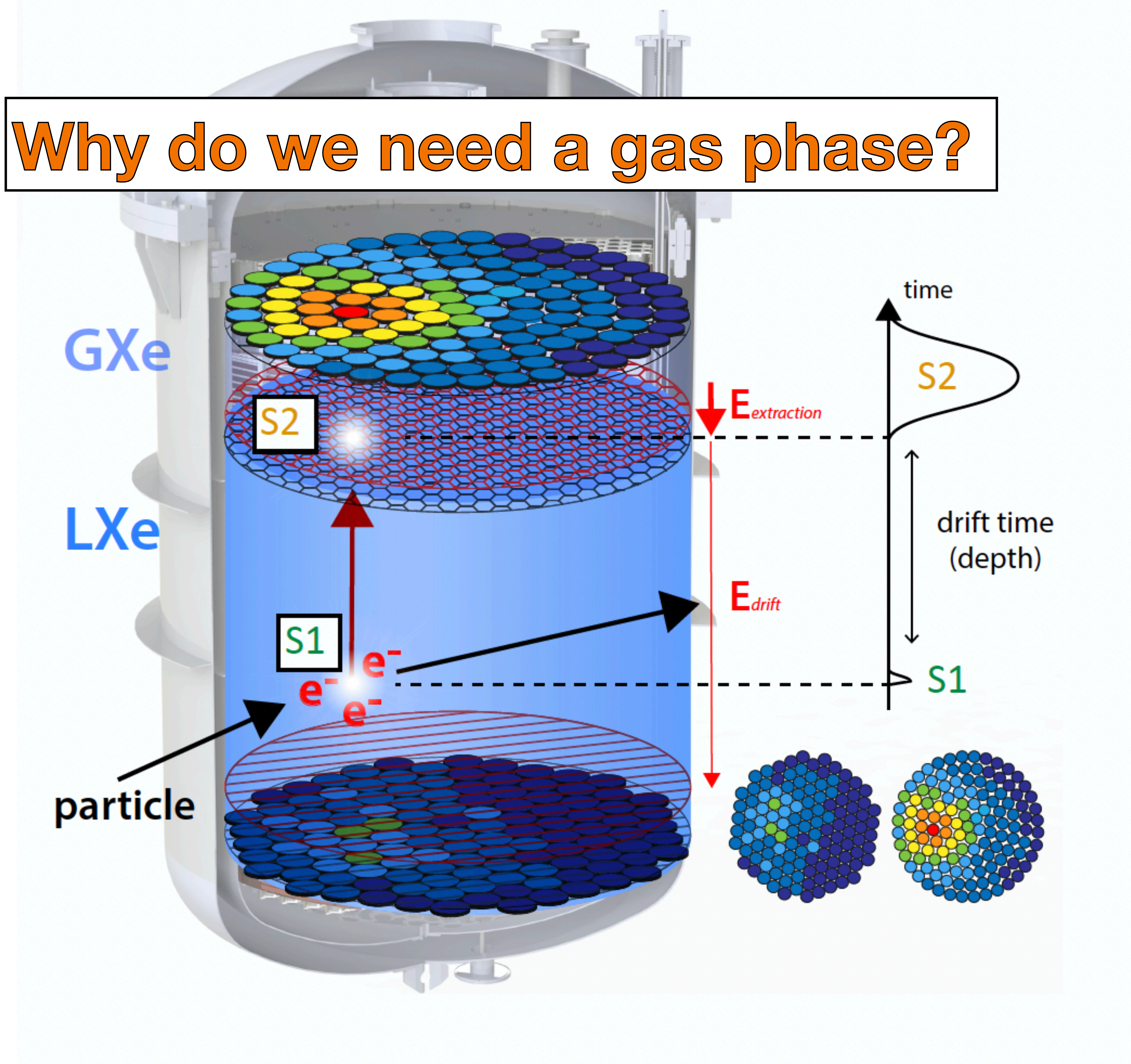
Particle discrimination

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

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

TPC Working Principle



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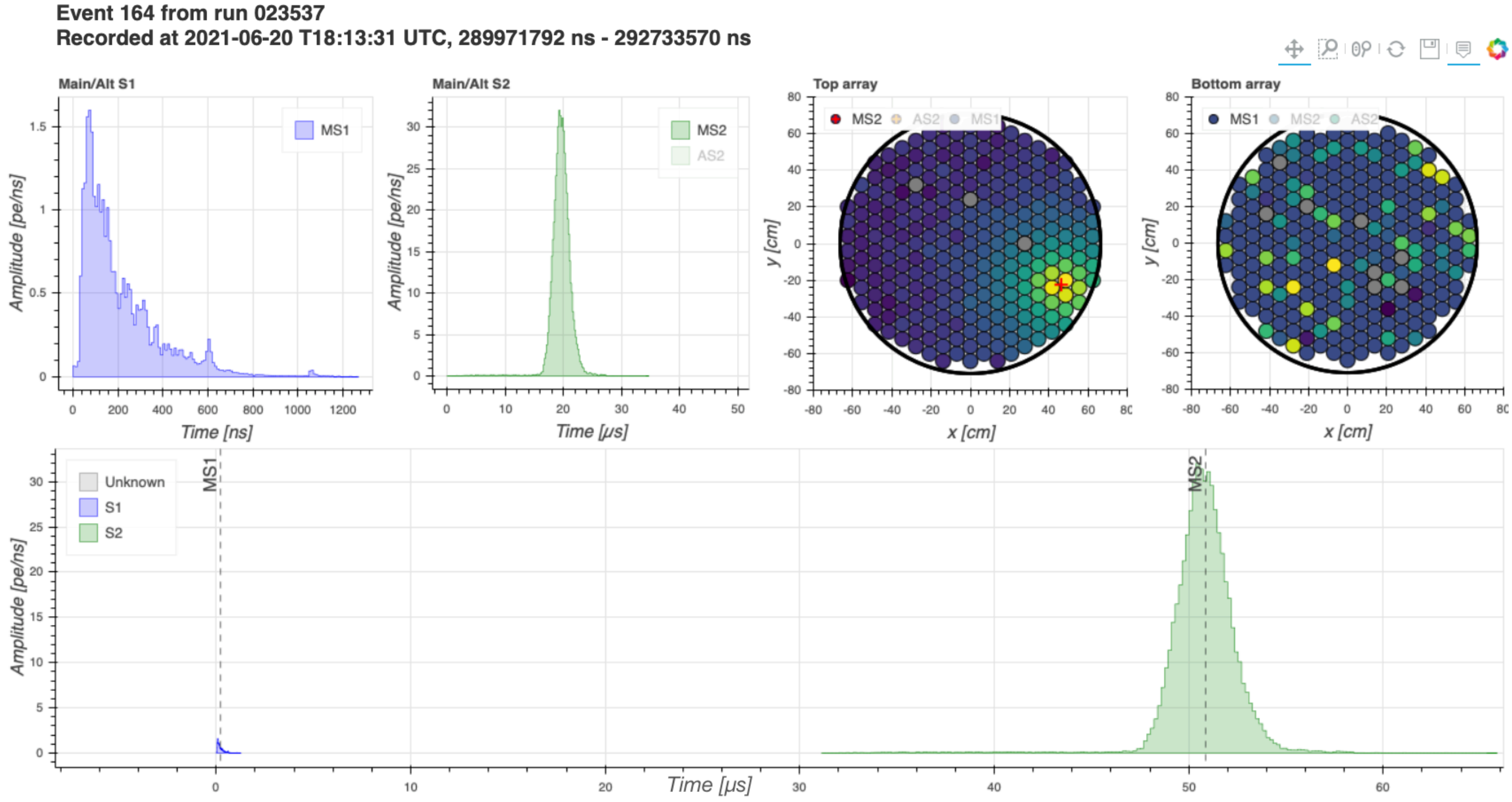
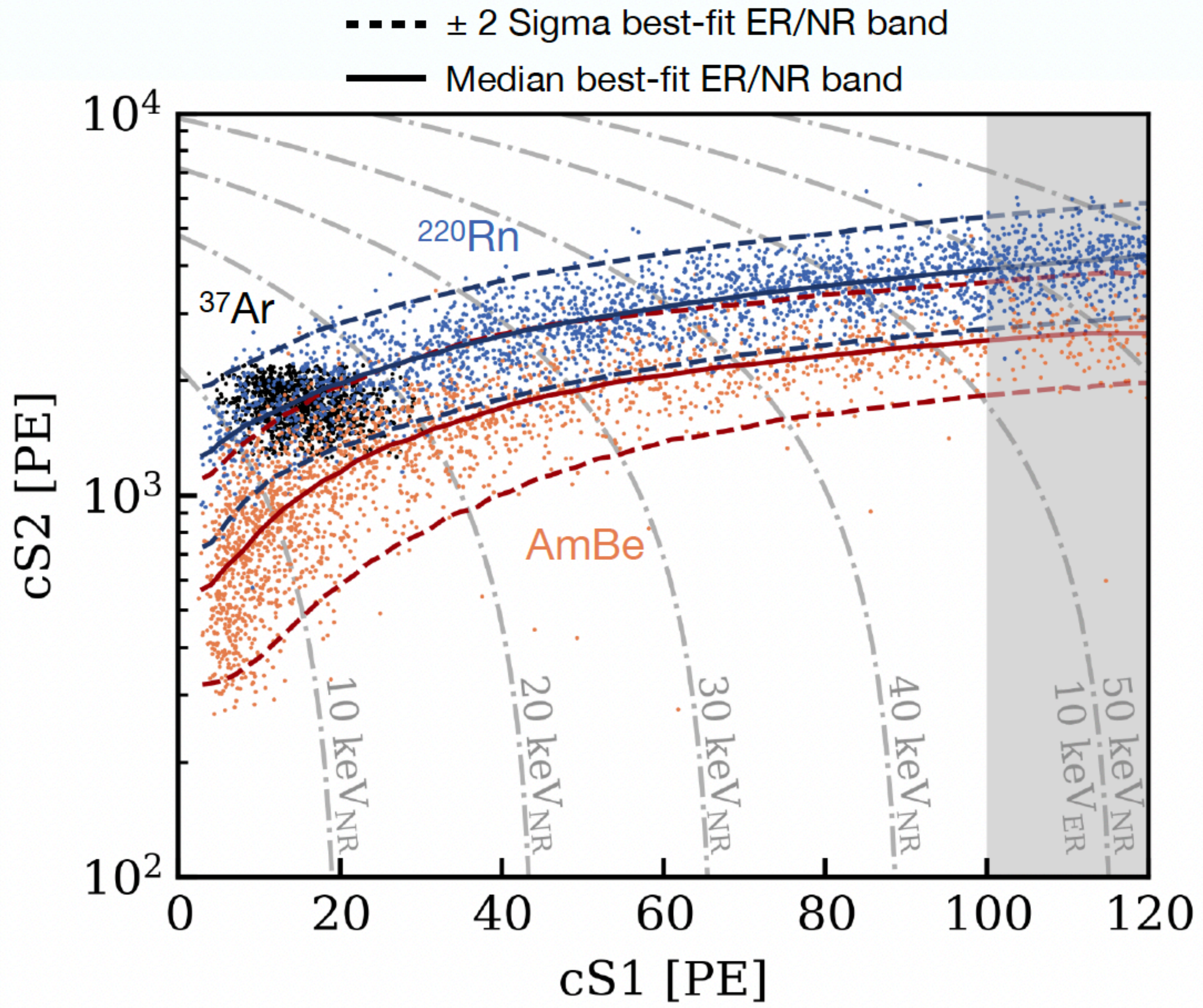
Waveform example



Calibration strategy



Fraction of ER events below NR median is 1.1 %

Signal Characterisation and Correction

- ^{83m}Kr internal calibration source:
  - ➡ 2 successives 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 ~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

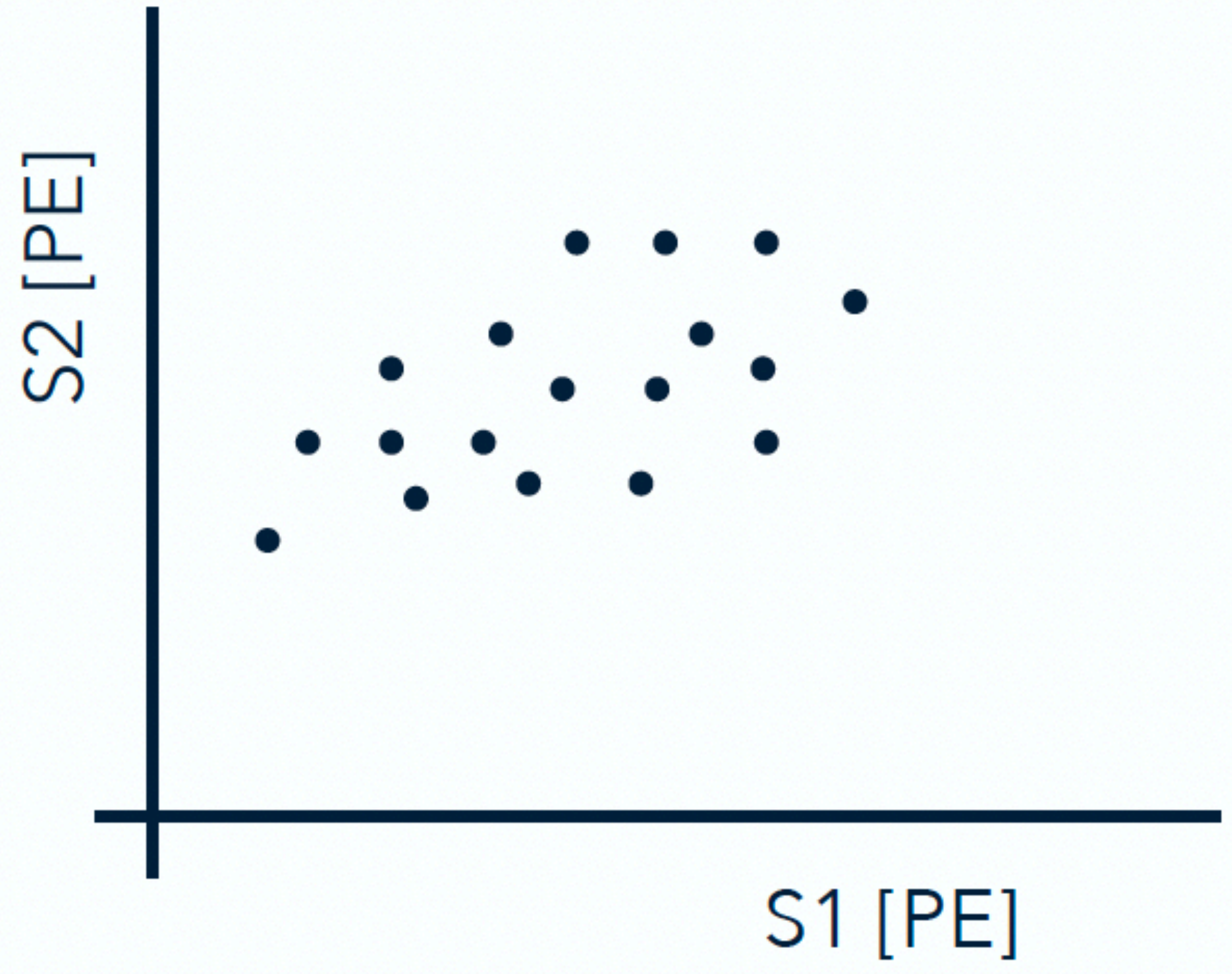
- External AmBe neutron source
  - ➡ Clear NR selection via coincident 4.4 MeV γ in nVeto

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

Energy reconstruction

Combined energy reconstruction from S1 and S2:

2D analysis

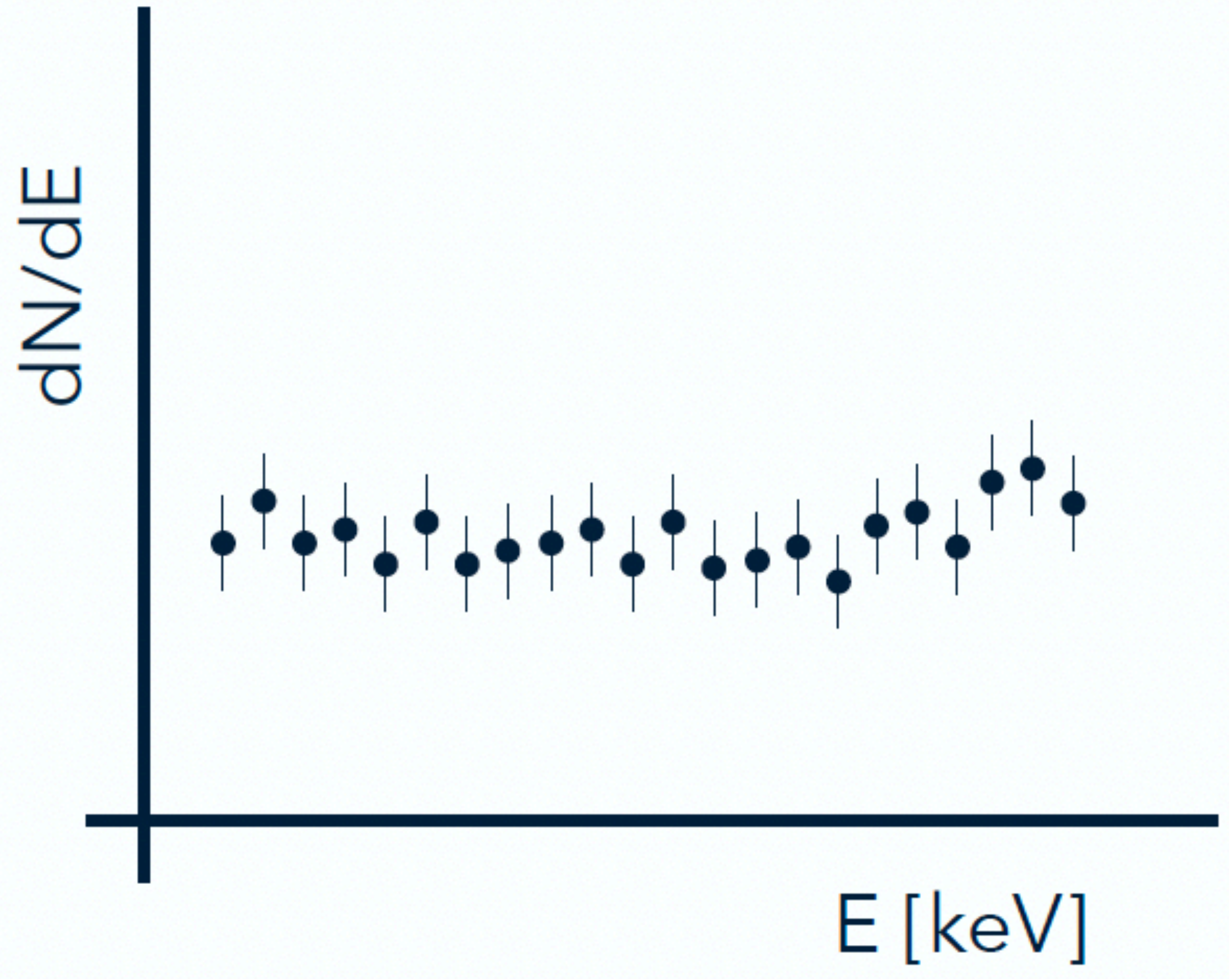


$$W = 13.7 \text{ eV/quantum}$$

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

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

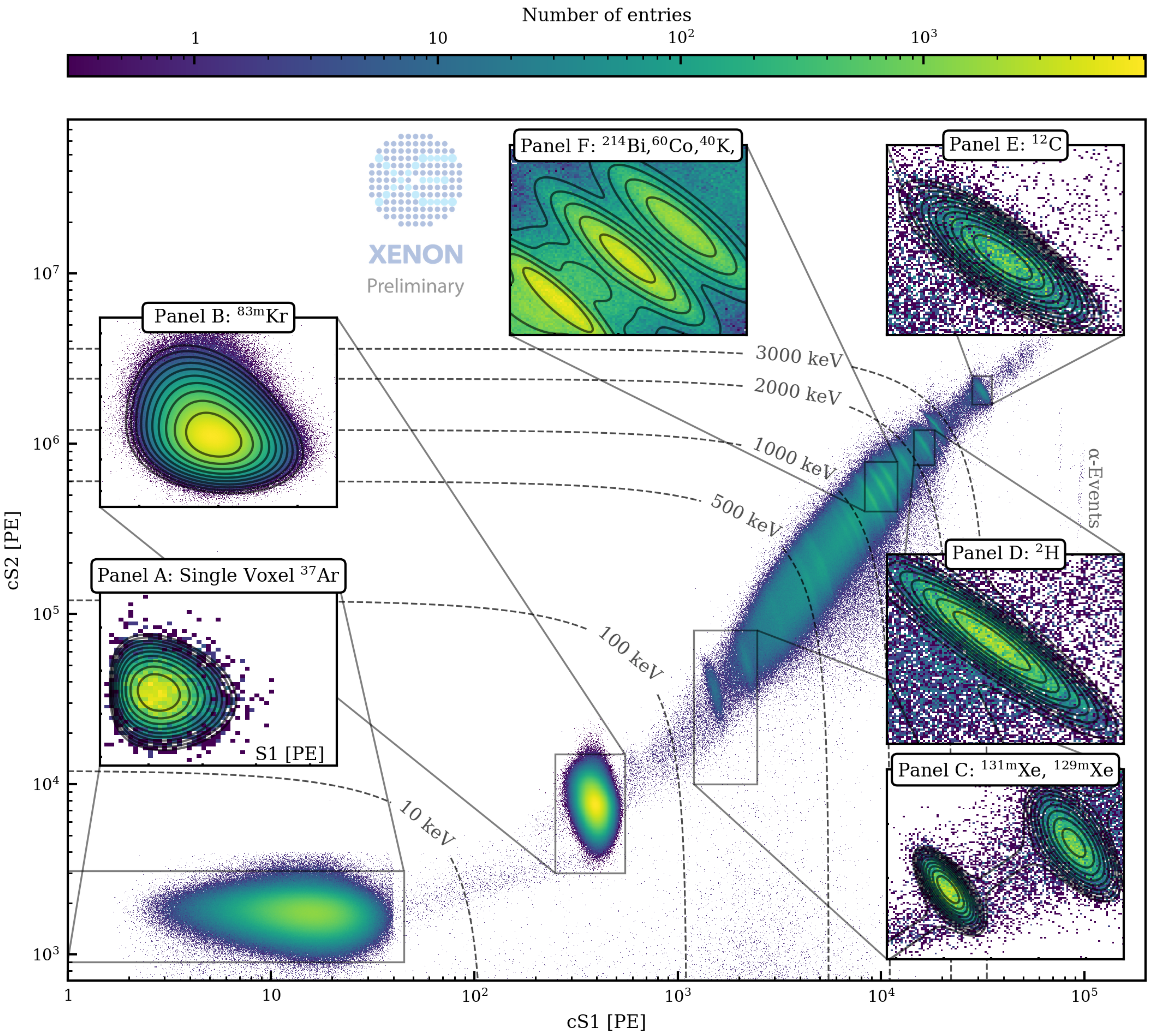
1D analysis

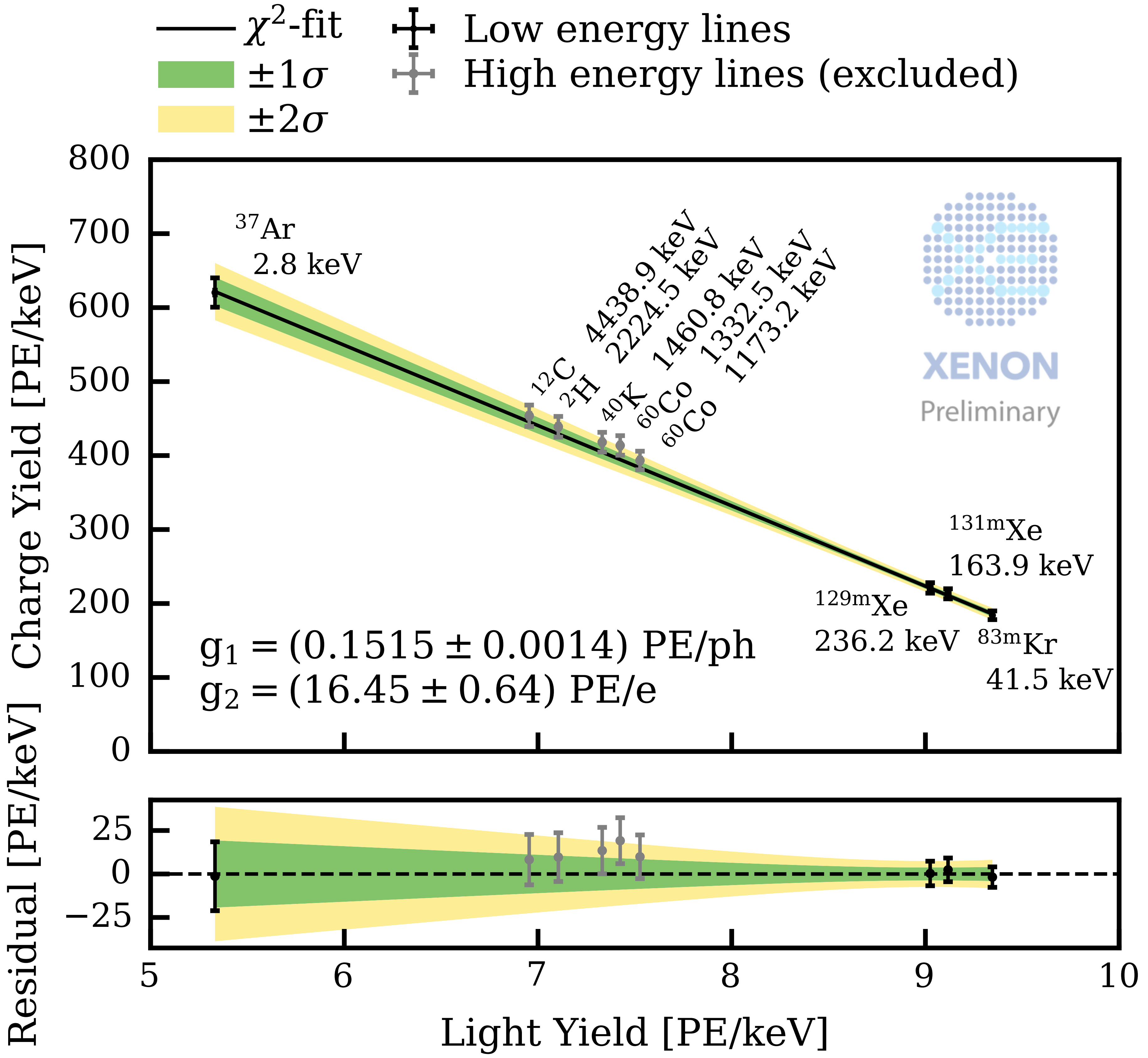


- Energy reconstruction based on detector-dependent parameters:
  - g1: photon detection efficiency.
  - g2: charge amplification factor.

Determined through severals calibrations

Energy reconstruction

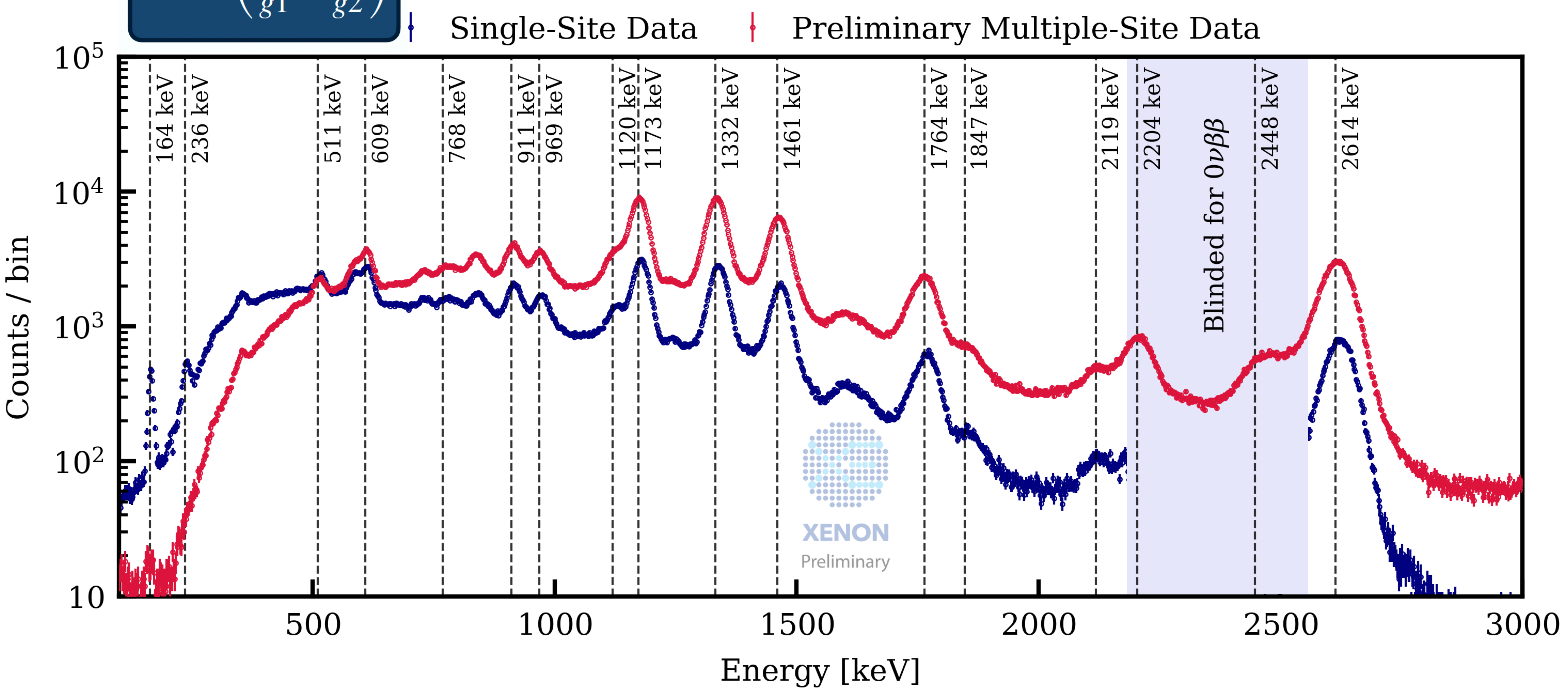




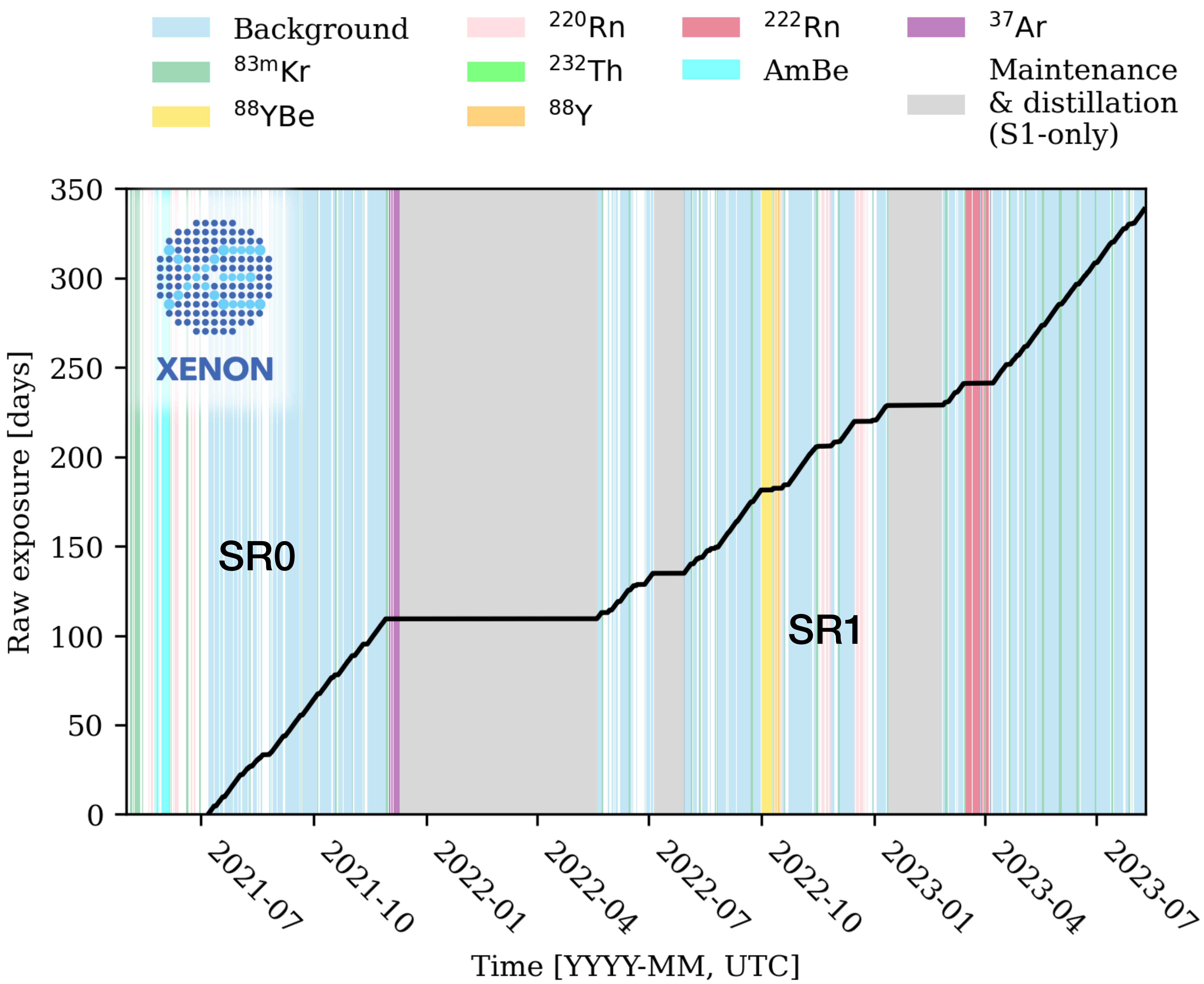
- Derive Light and Charge Yield from multiple mono-energetic lines and infer g1/g2 to build our energy scale

Energy reconstruction

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

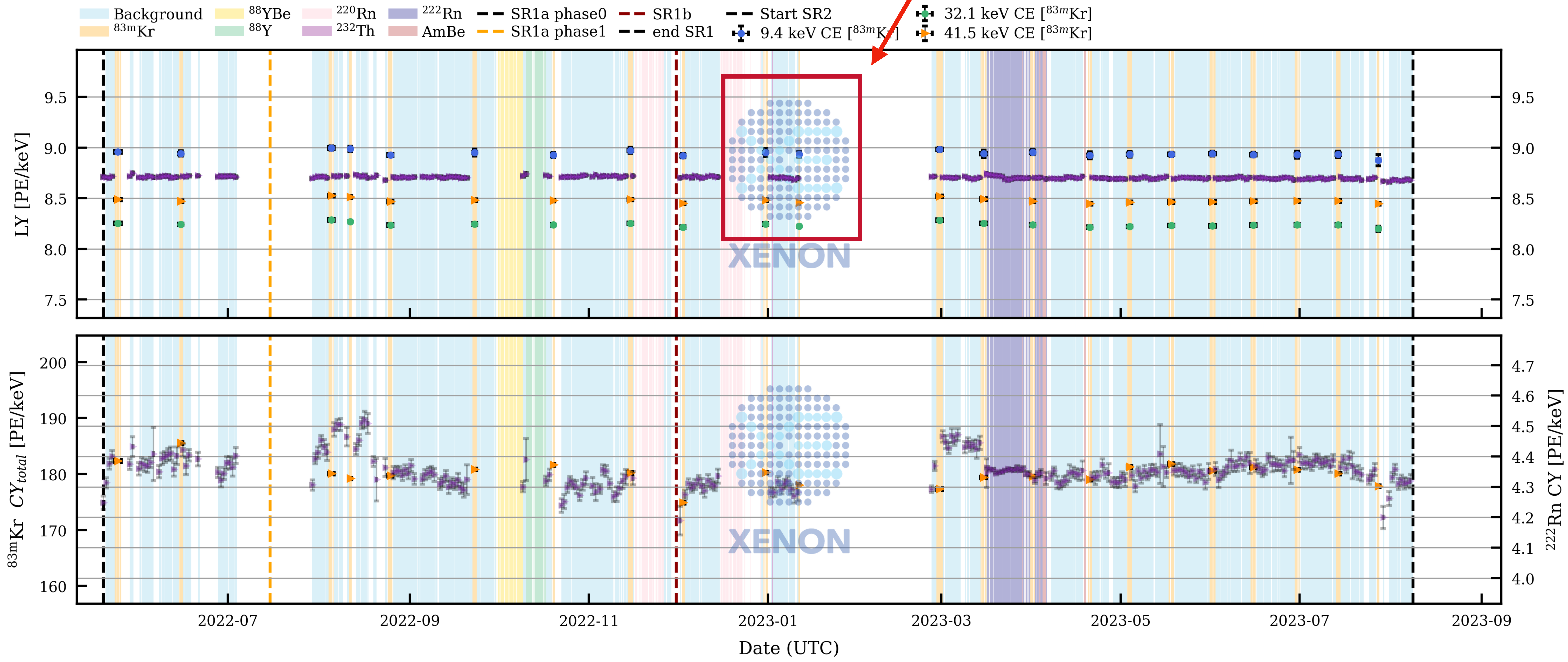


XENONnT First Science runs



Dark Matter in the Milky Way:

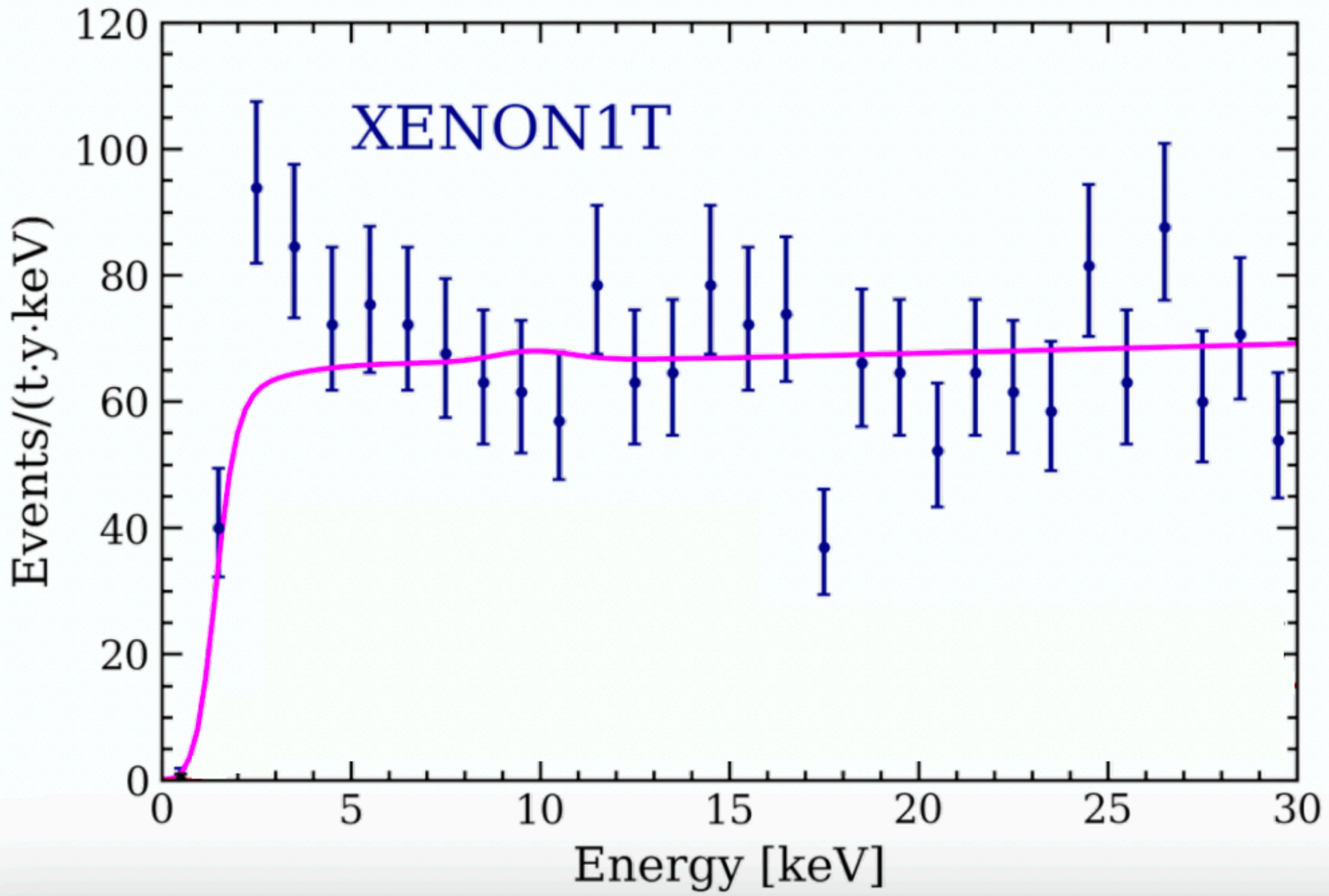
Might look sad, but the stability is actually good :)



First XENONnT results

Why look at ER first?

- **Excess of ER events < 30keV observed in XENON1T corresponding to a 3.3 σ fluctuation** (PRD 102, 072004)
  - ➡ Background: tritium β-decay, or…
  - ➡ Physics: solar axion, ALPs, ν magnetic moment
- **XENONnT could give a final answer in few months**



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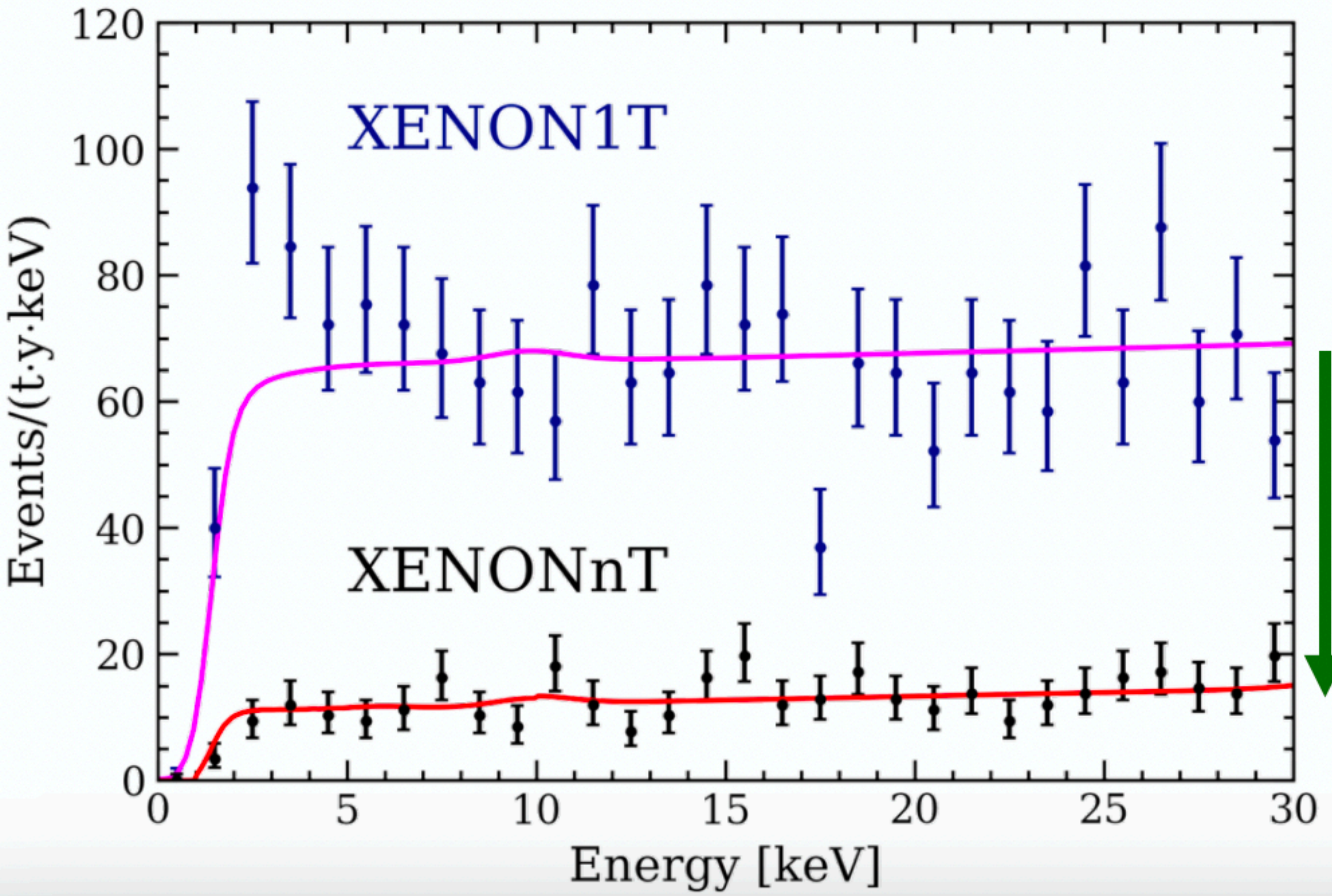
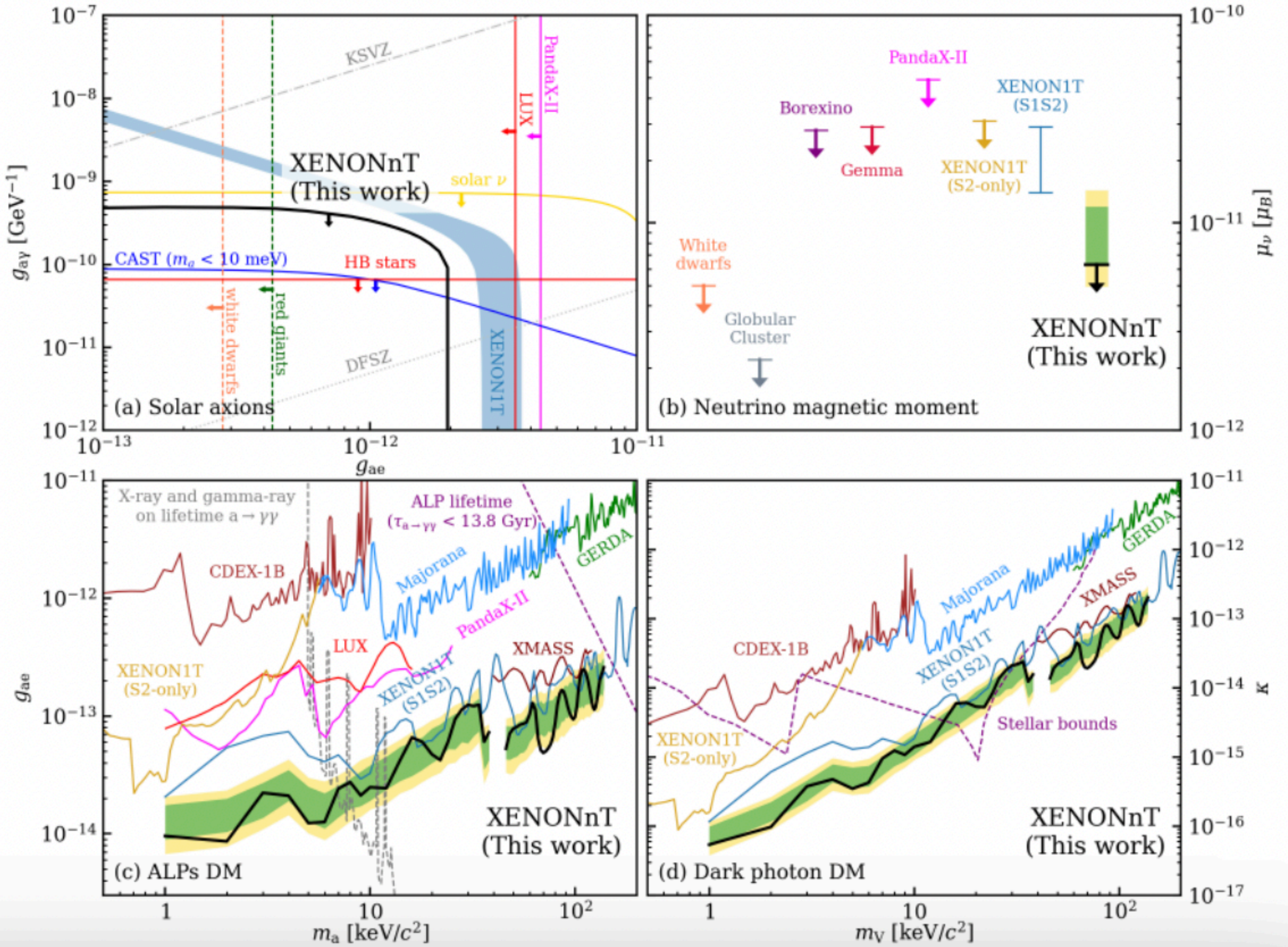


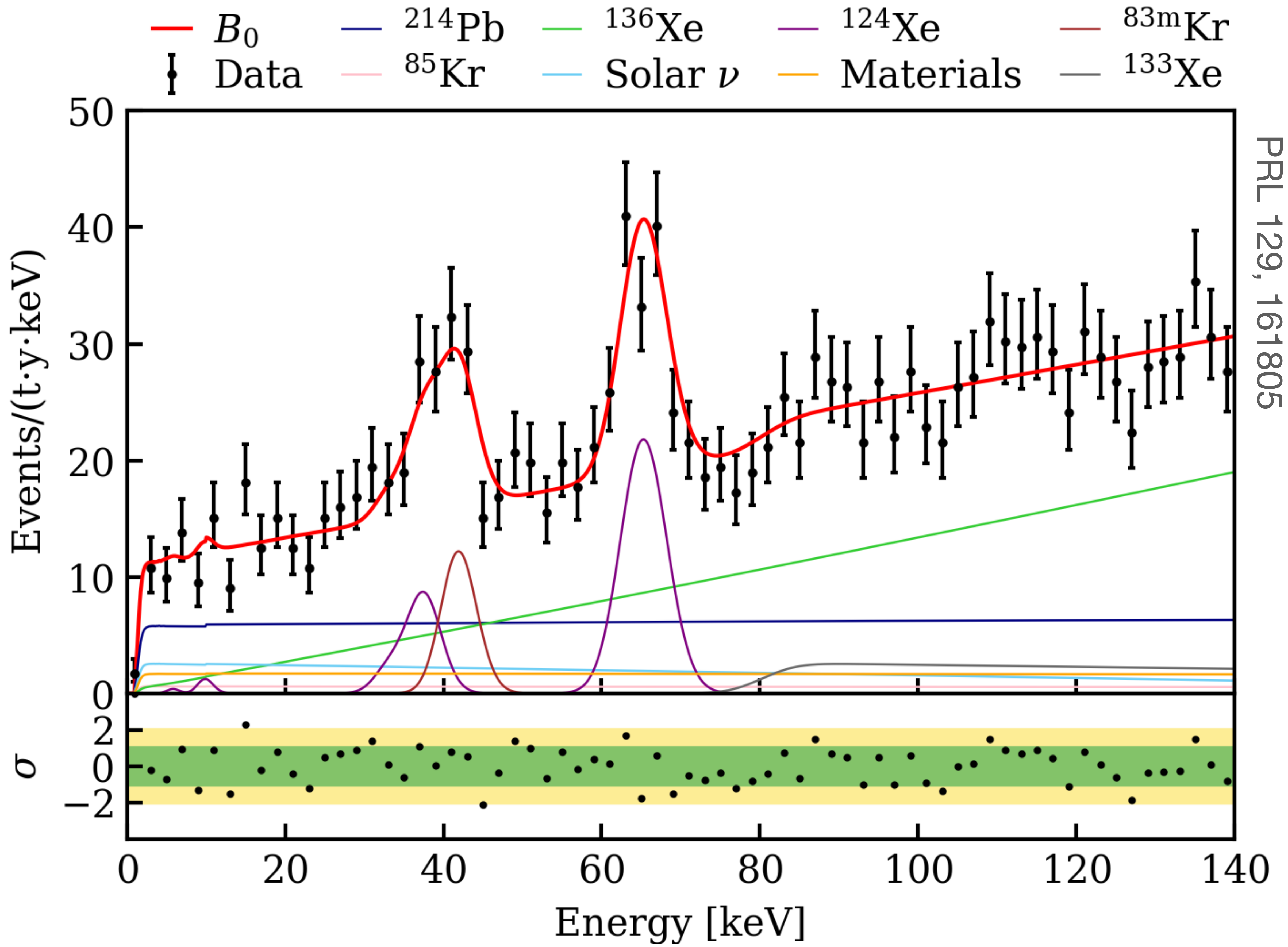
~16 events/(t.y.keV)

Lowest ER rate achieved with such detector

Result from XENONnT SR0

- **No excess found** in XENONnT and an excess of the XENON1T magnitude is **excluded at 8.6** σ.
- **Set new limits on physics model** PRL 129, 161805 (2022)





PRL 129, 161805

SR0 Results | Low-Electronic Recoil

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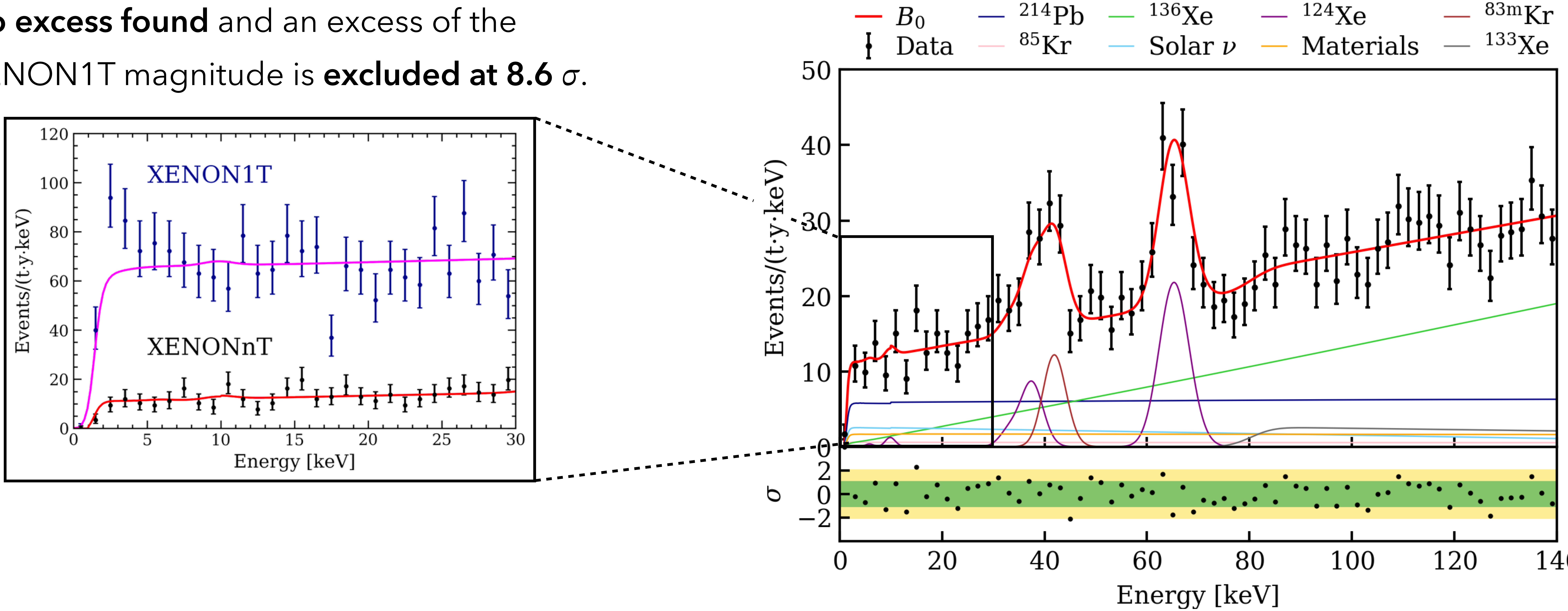

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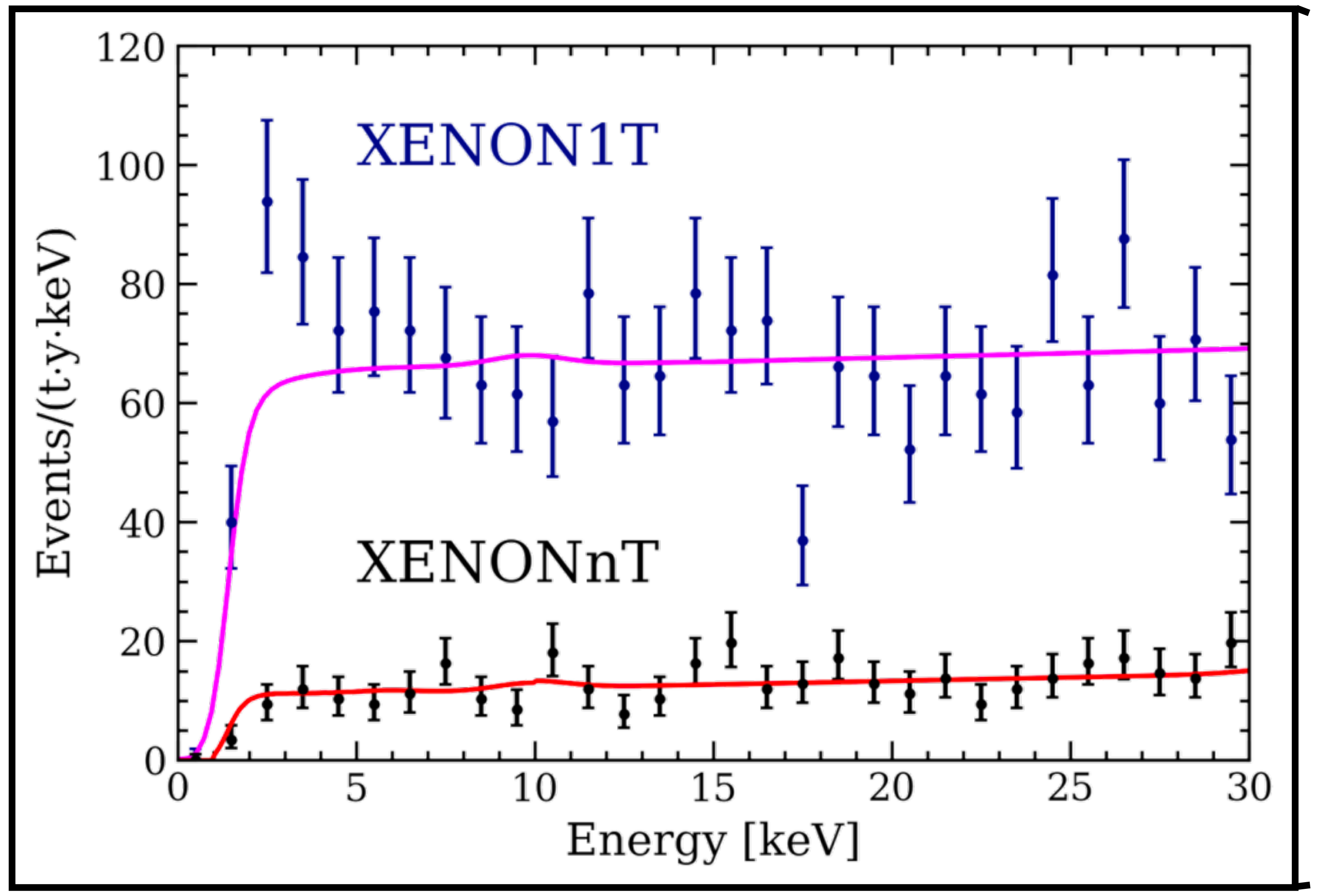

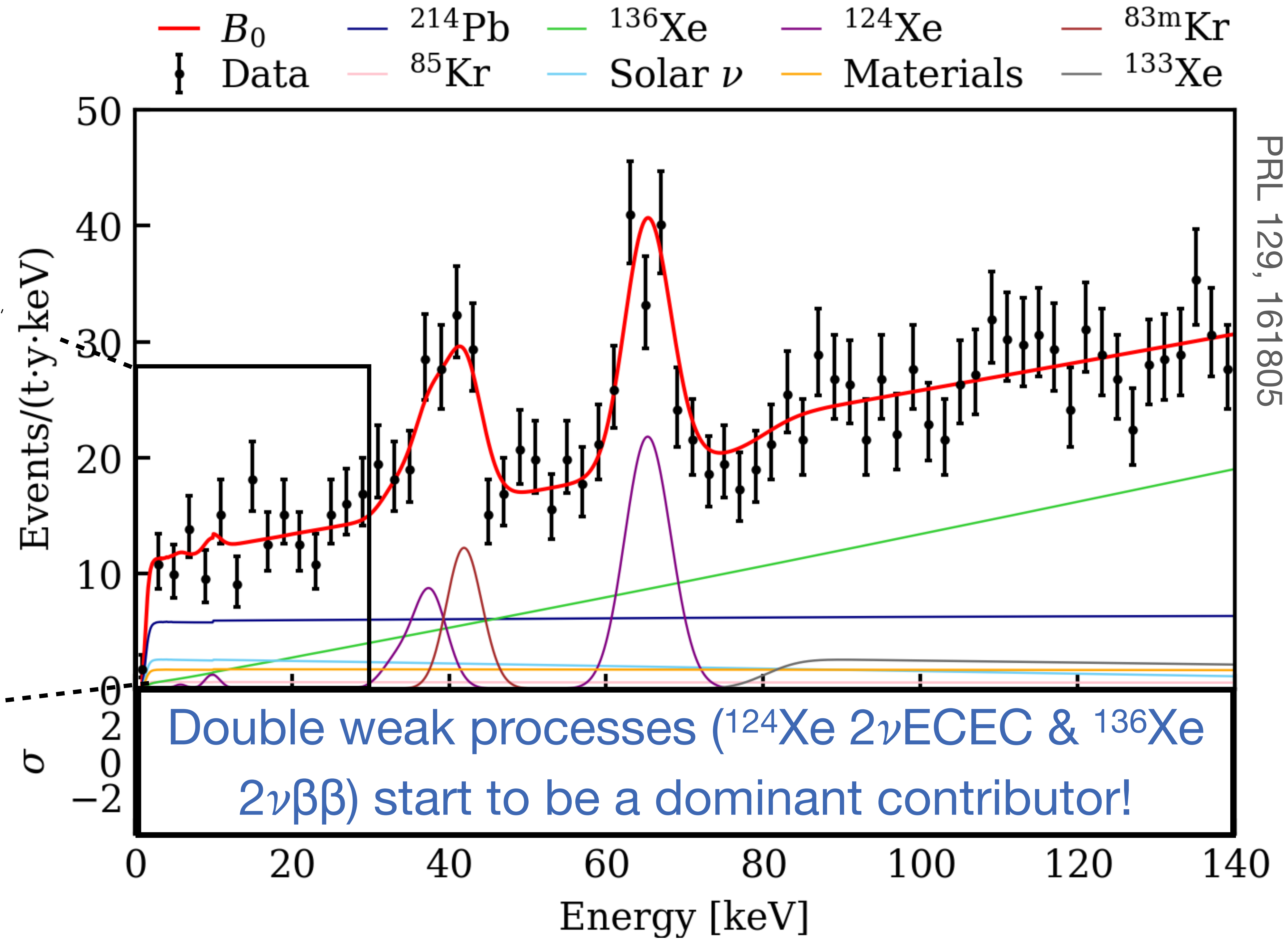

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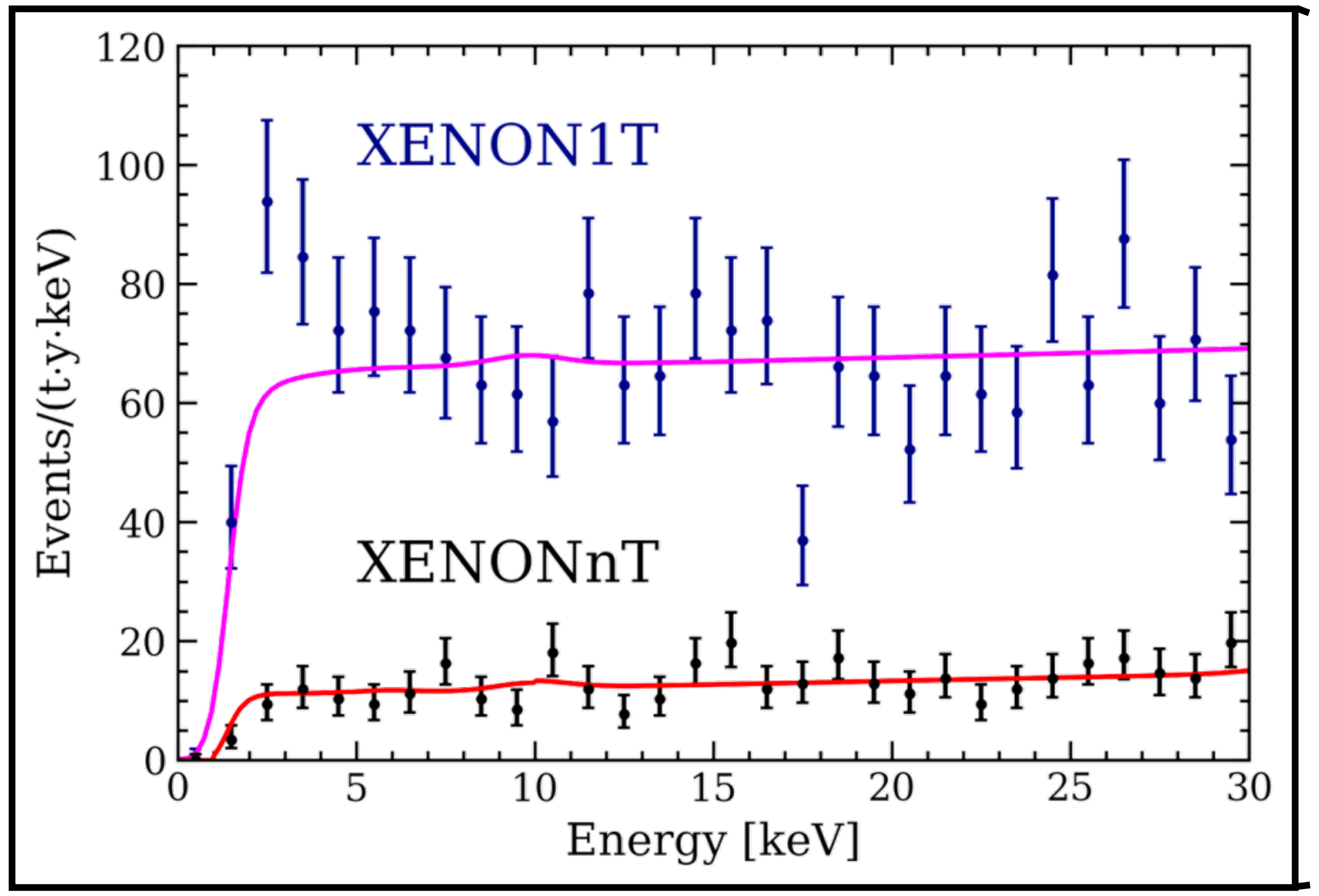
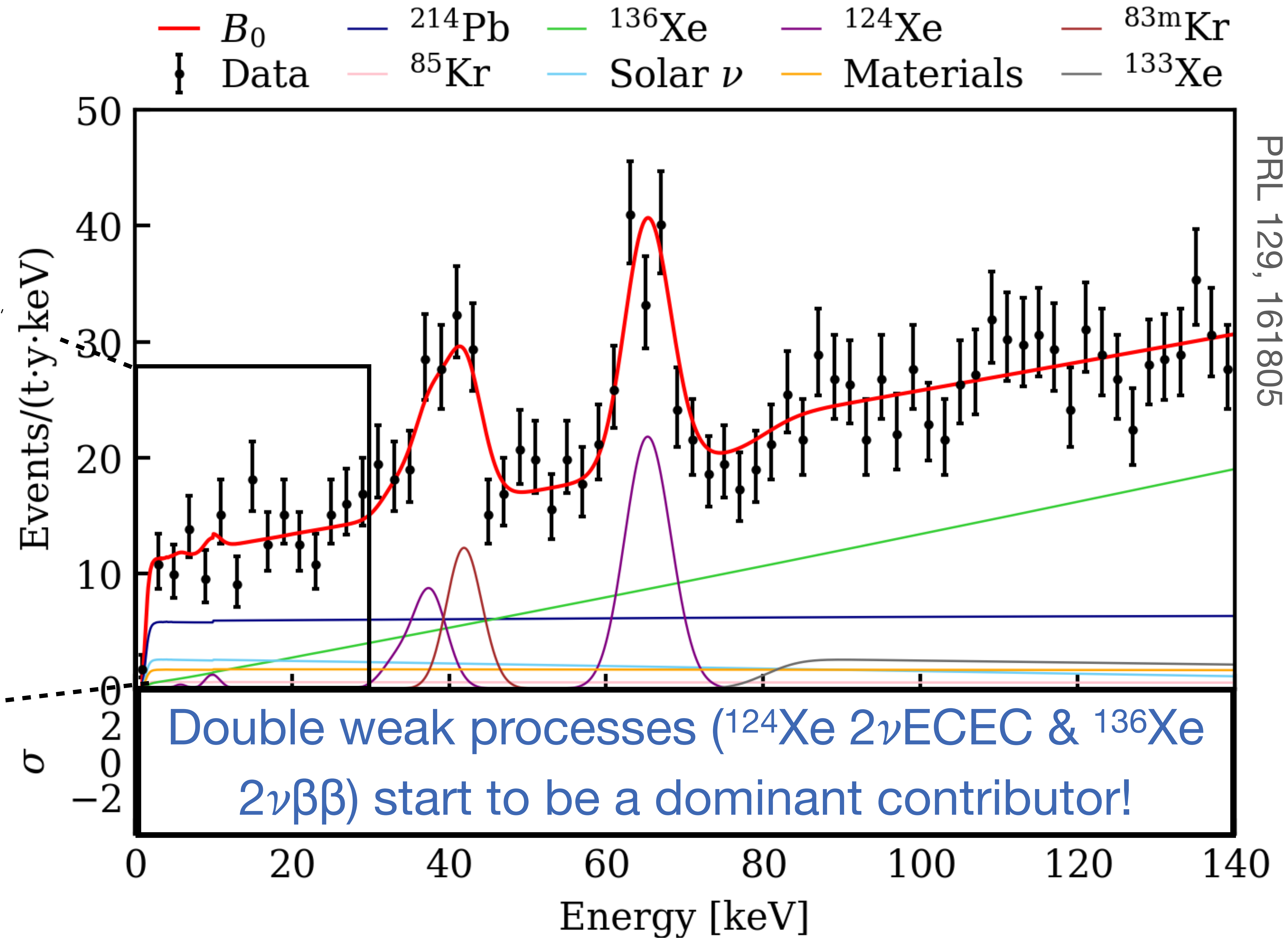




PRL 129, 161805

- **Measurement of the 2νECEC half-life of ^{124}Xe** with improved uncertainties compare to XENON1T.

SR0+SR1 XENON1T: $T_{1/2}^{2\nu ECEC} = \left(1.1 \pm 0.2_{stat} \pm 0.1_{sys}\right) \times 10^{22}\,\mathrm{yr}$

SR0 XENONnT: $T_{1/2}^{2\nu ECEC} = \left(1.18 \pm 0.13_{stat} \pm 0.14_{sys}\right) \times 10^{22}\,\mathrm{yr}$

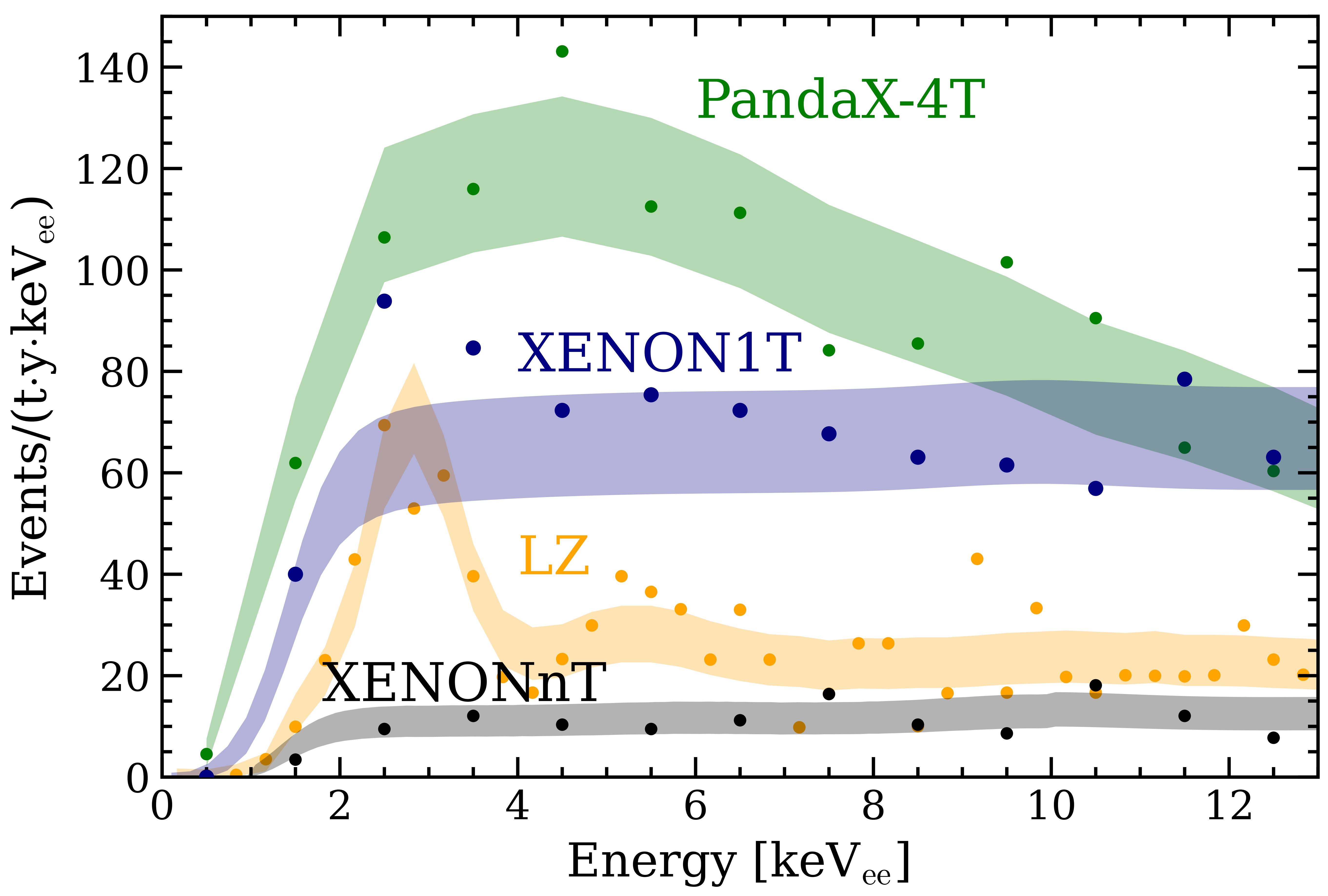
Comparison with our competitors

PandaX-4T, PRL 129, 161804 (2022)

XENON1T, PRD 102, 072004 (2020)

LZ, PRL 131, 041002 (2023)

XENONnT, PRL 129, 161805 (2022)



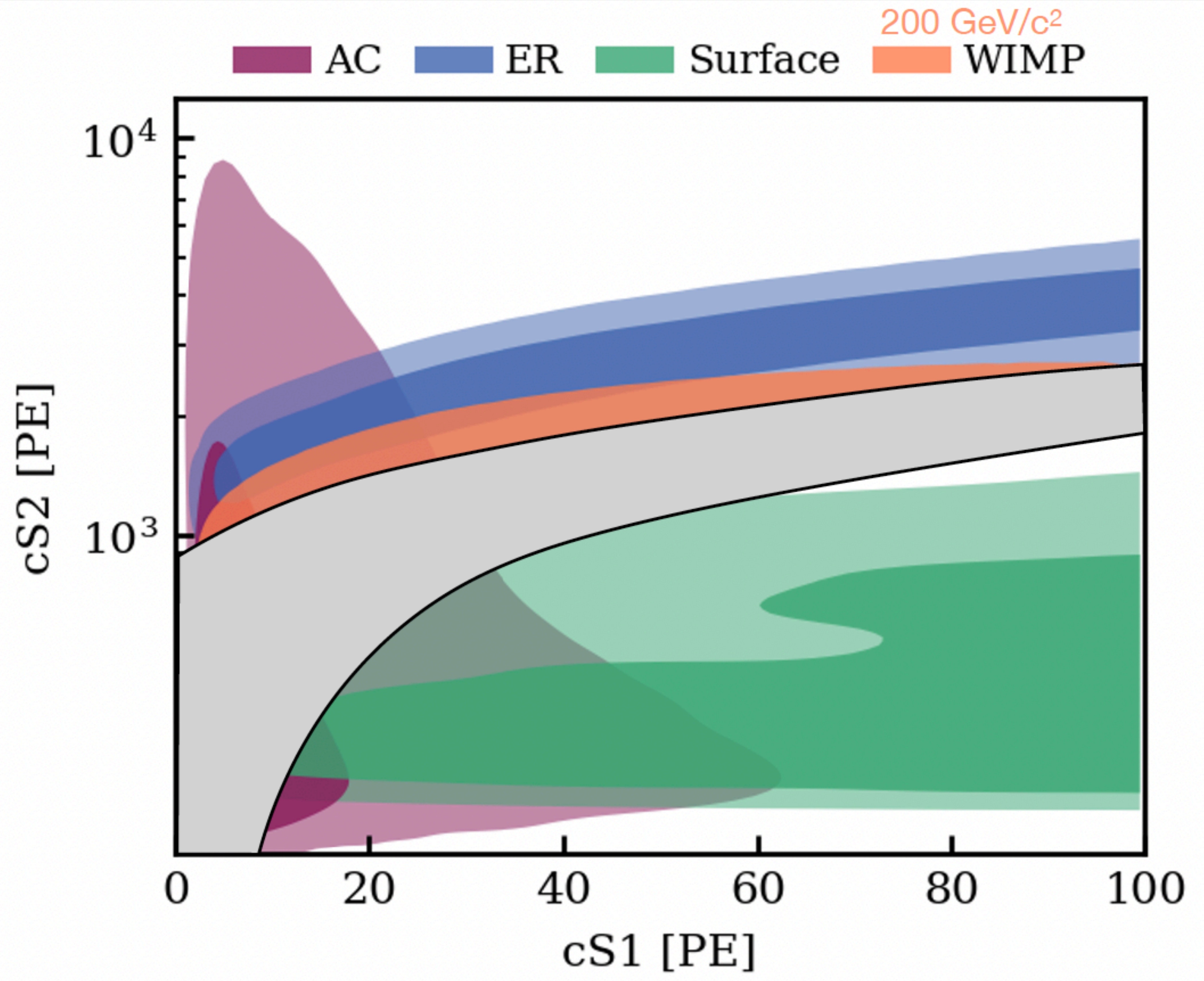
Background model in cS1/cS2 space:

Electronic recoils
- Dominated by β-decay of ^{214}Pb (intrinsic to the LXe target)
- Suppressed by ER/NR discrimination

Accidental Coincidence
- Random pairing of isolated S1 & S2 signals
- Suppressed by dedicated analysis cuts

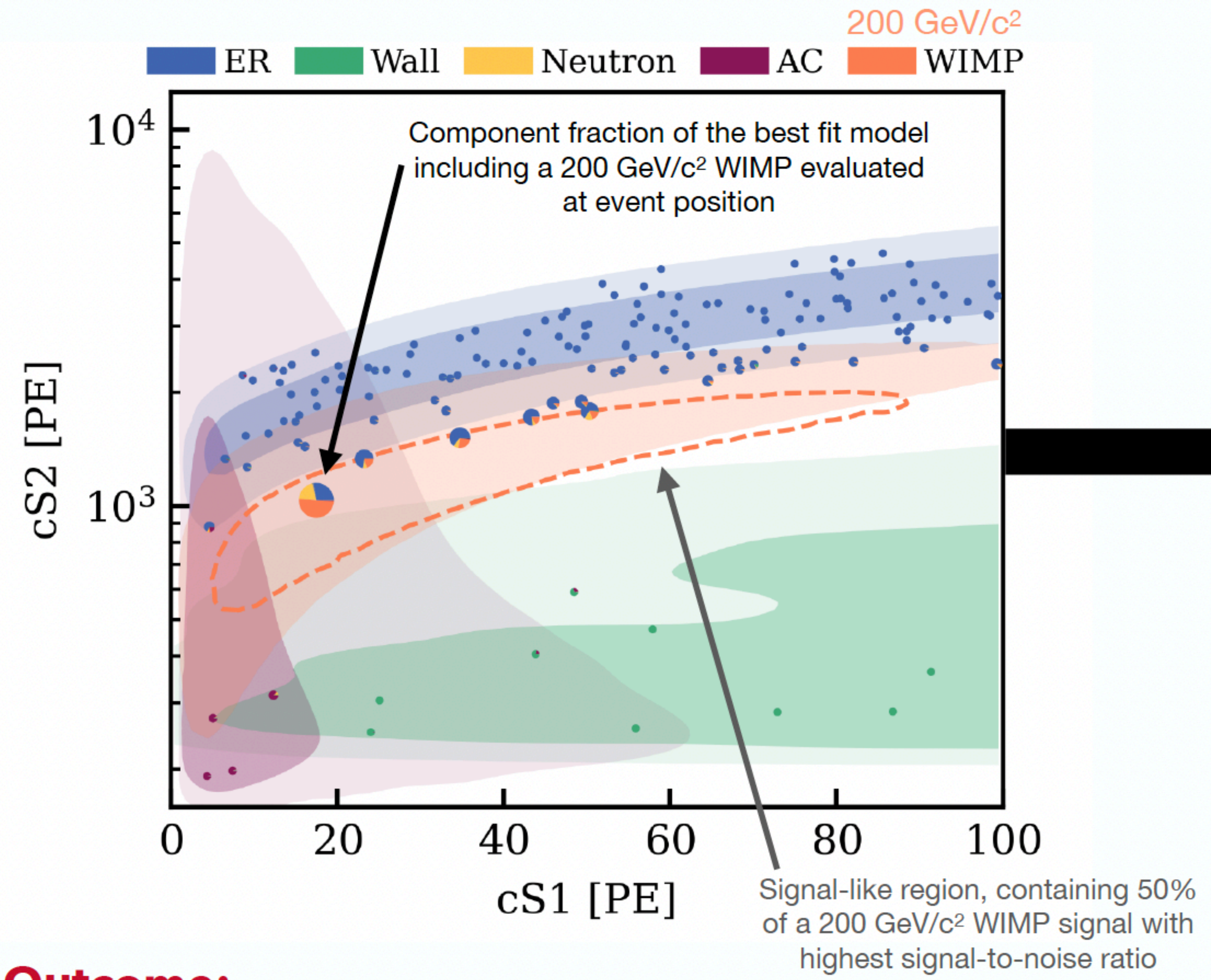
Surface
- ^{210}Pb plate-out on PTFE walls of the TPC
- Suppressed by FV.

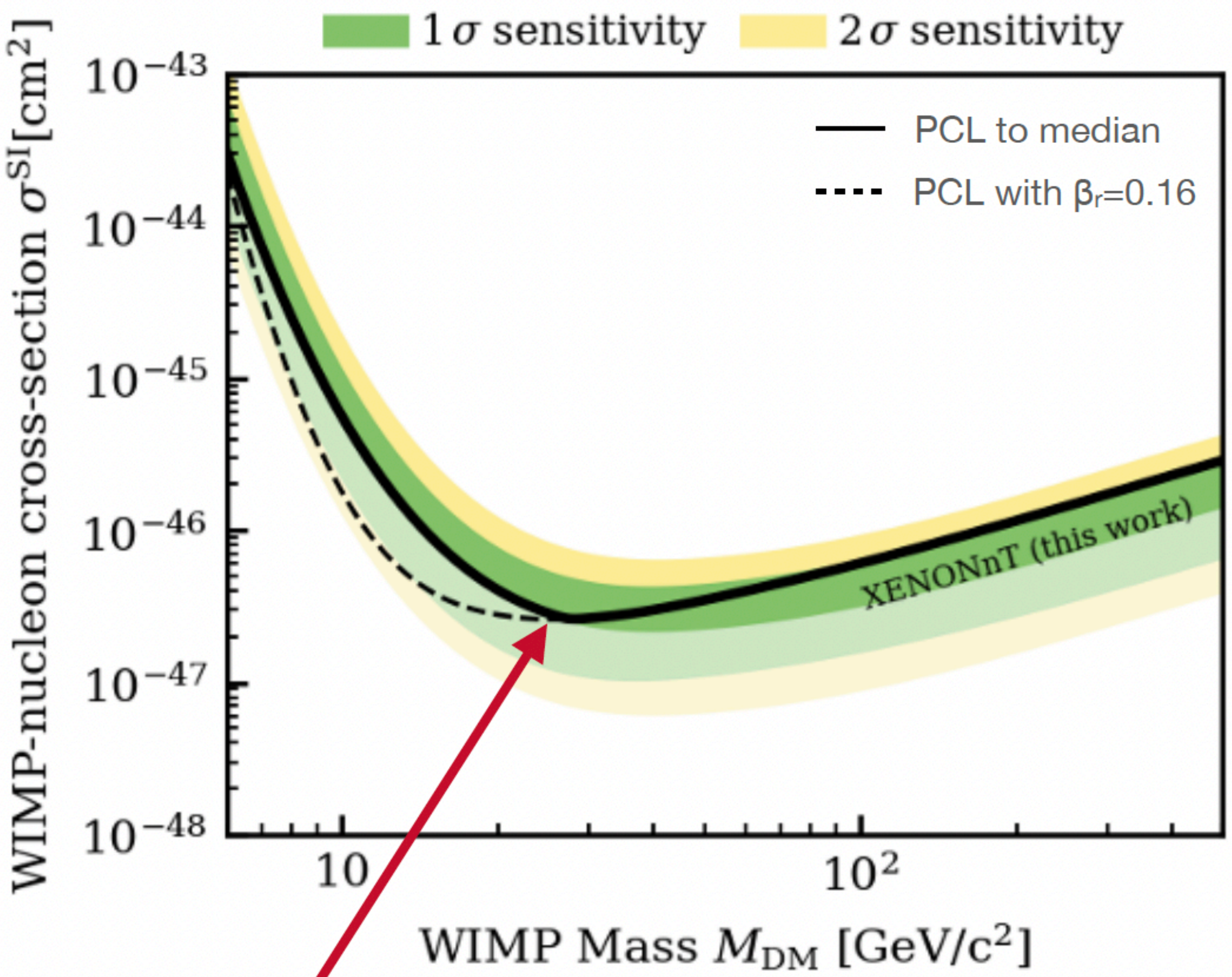
Nuclear recoil (same shape as WIMP)
- Radiogenic neutrons spontaneous fission & (α, n)-reactions
- ^{8}B CEνNS constrained by flux



We are performing a blinded data analysis!

SR0 Results | WIMPs





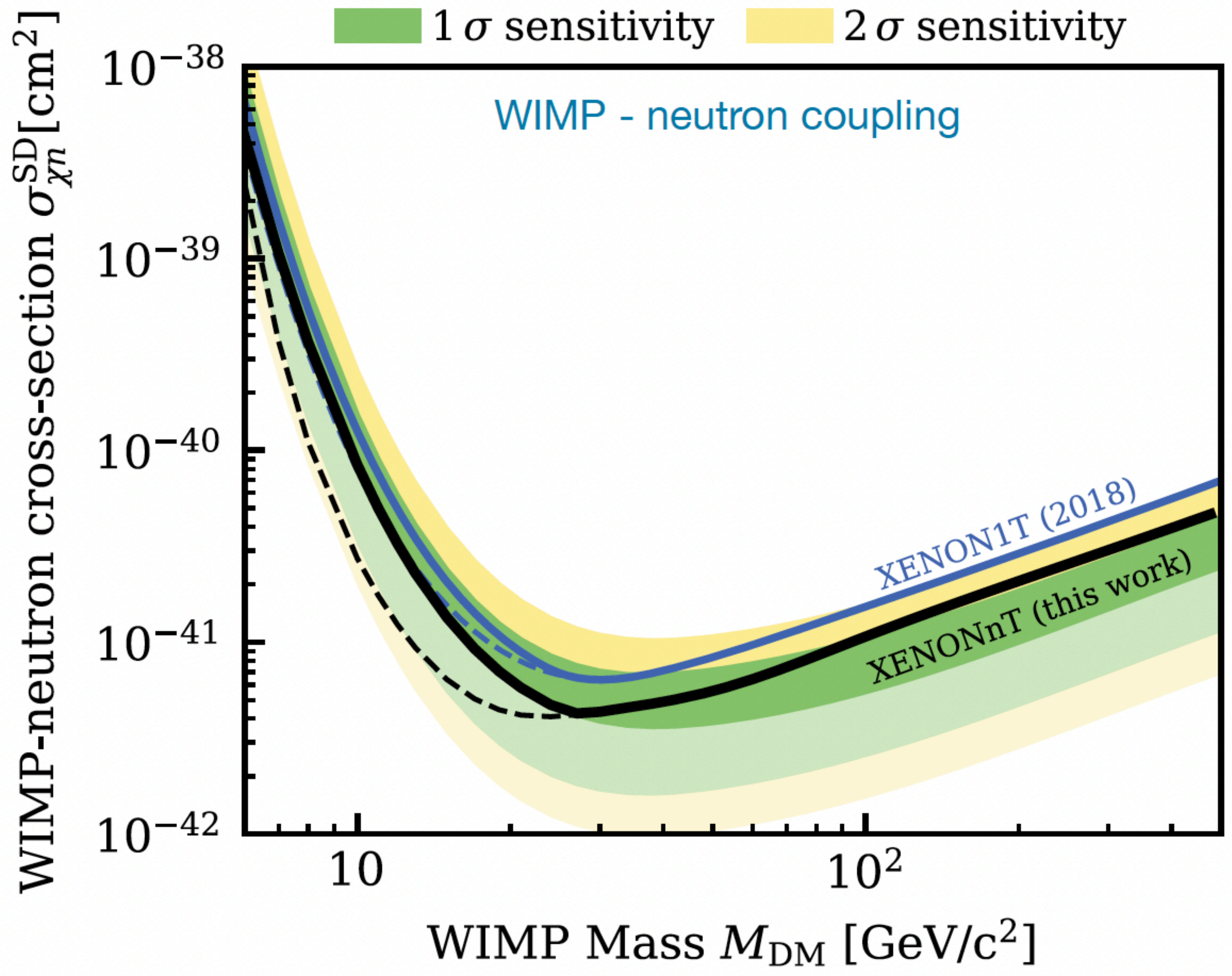
Outcome:

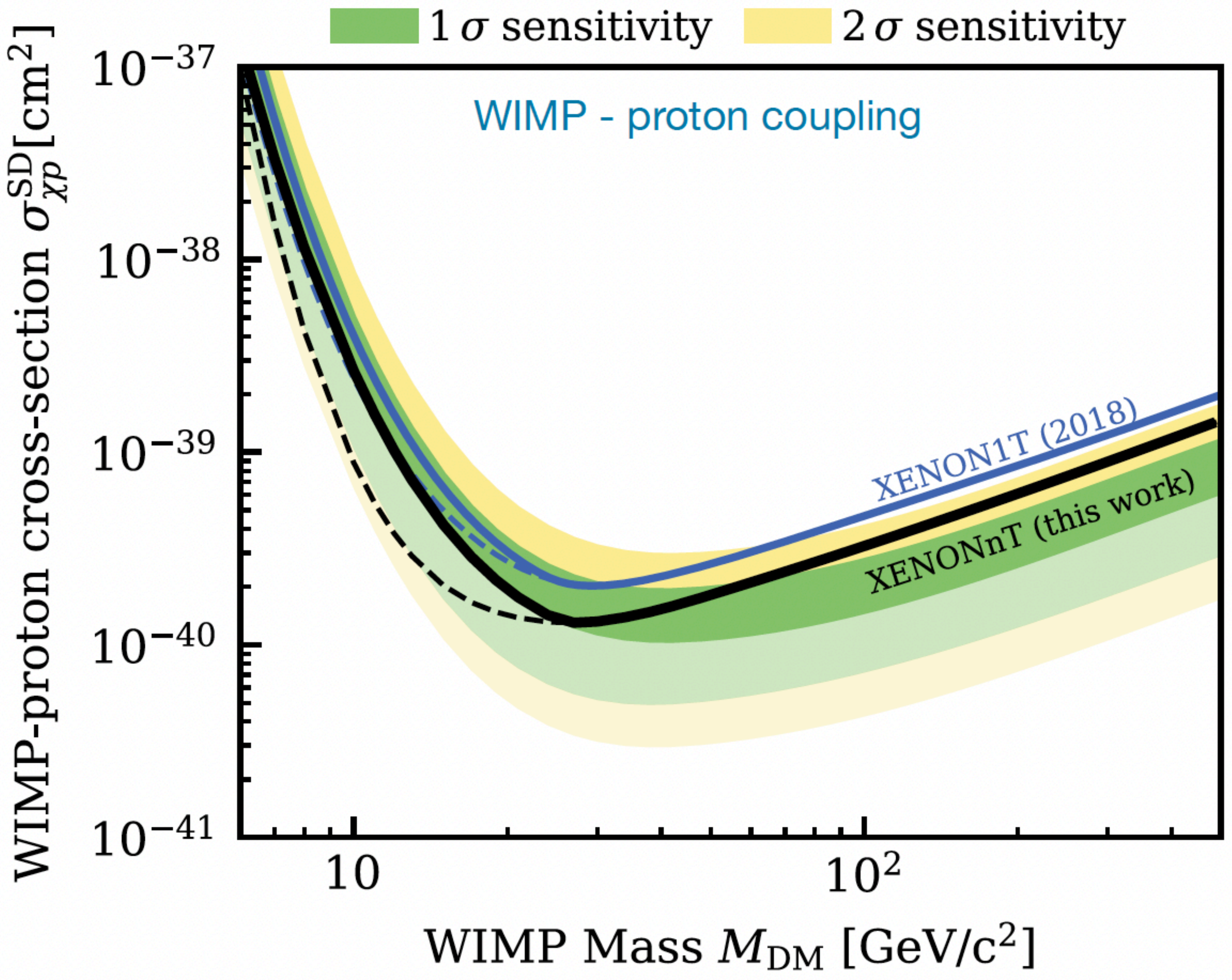
- 152 events in ROI, 16 in blinded region
- Profile log-likelihood-ratio test statistic
  - ➡ **No significant excess observed**

Strongest limit: 2.6 x 10^{-47} cm² (90% C.L.) @ 28 GeV/c² PRL 131, 041003 (2023)

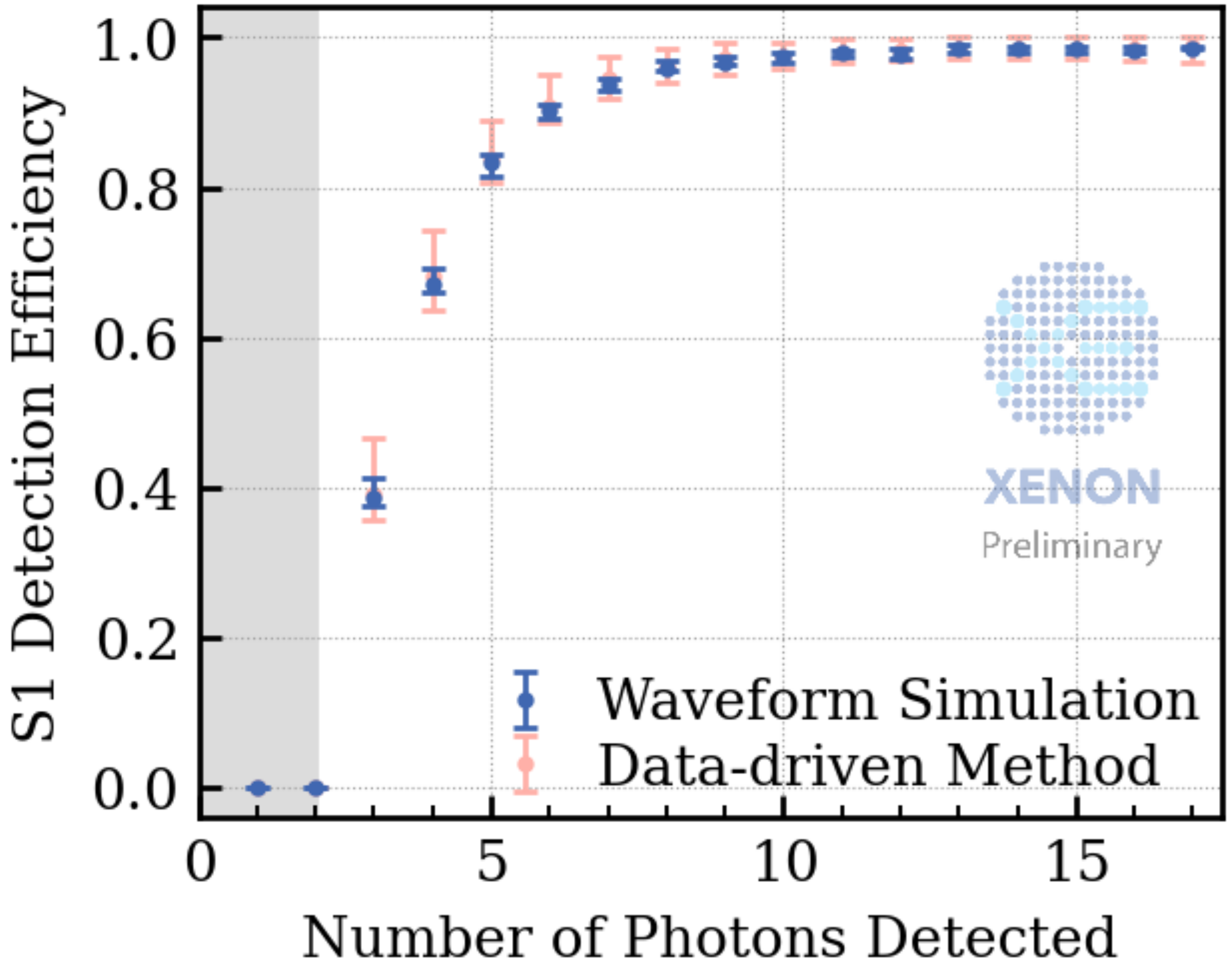
SR0 Results | WIMPs

Reinterpreting results as a purely spin-dependent coupling to ^{129}Xe and ^{131}Xe





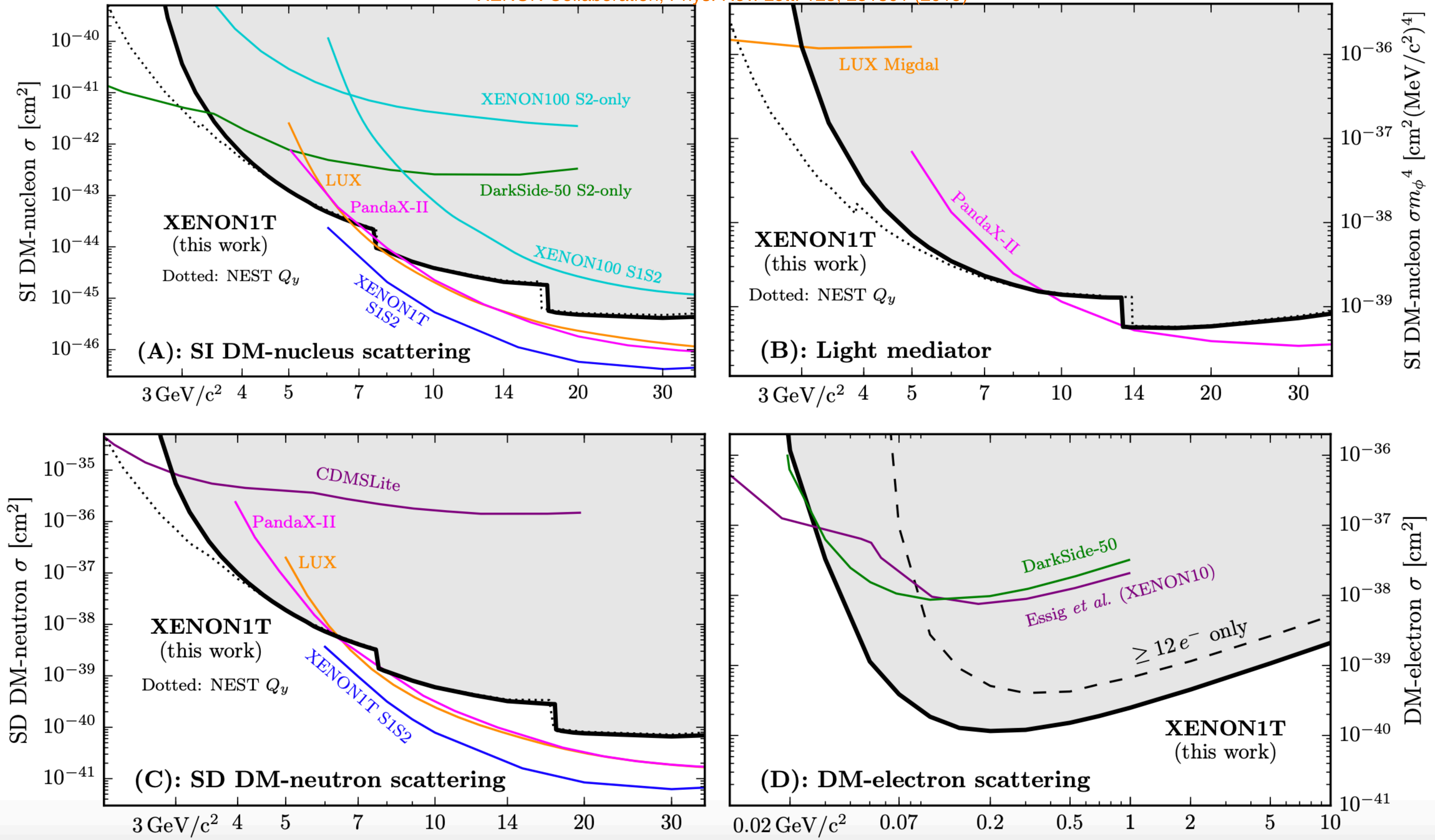
How to go to lower DM masses?



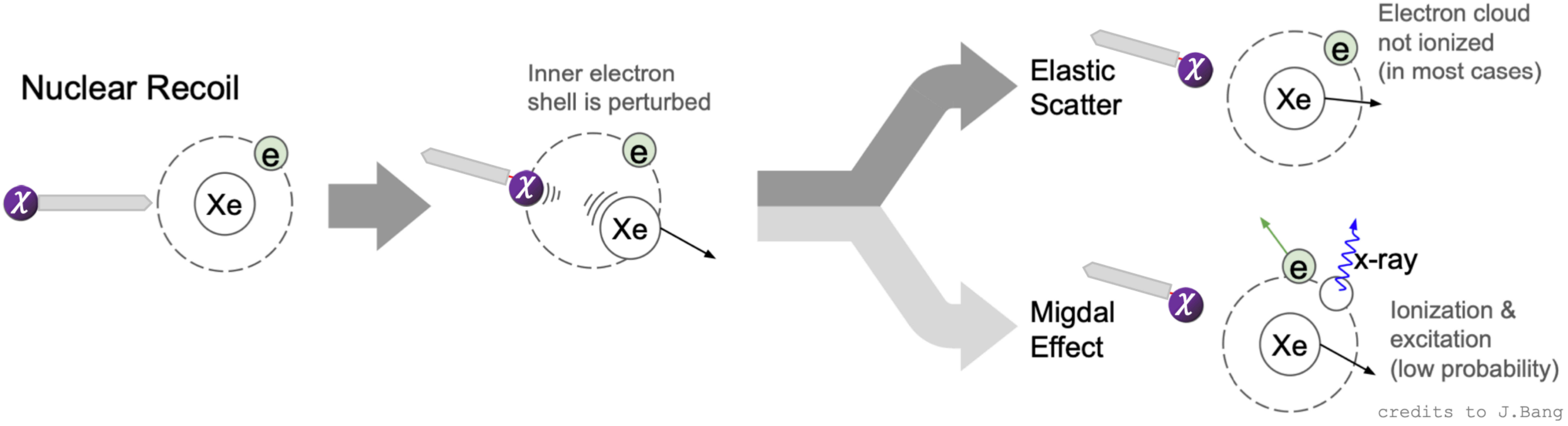
- Energy threshold driven by requirements on the minimal size of S1/S2 signals considered to build an event (interaction)
  - We ask signal to have at least 3 photon detected (3 hit) to be considered as a valid S1
  - Lead to an threshold in energy (from reconstruction) ~ 1 keV
- **To lower the energy threshold, one can**:
  - Lower this requirement
  - Or remove completely the S1 requirement
- **Cost: Larger background**

Ionisation signal only | XENON1T results

XENON Collaboration, Phys. Rev. Lett. 123, 251801 (2019)



Or to use Migdal effect

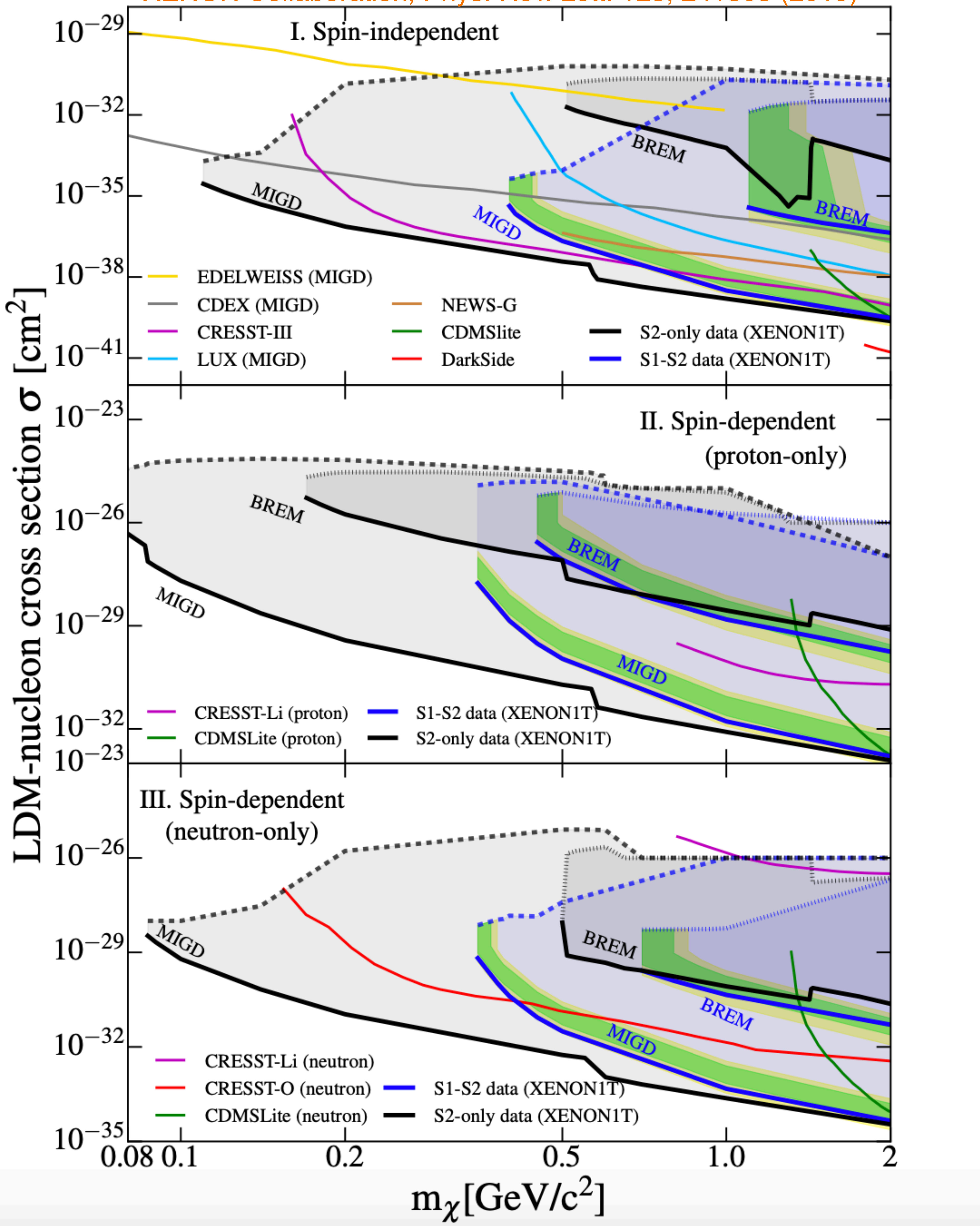


K. Schäffner, TAUP 2023

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

Migdal effect | XENON1T results

XENON Collaboration, Phys. Rev. Lett. 123, 241803 (2019)



Future perspective

Towards a multi-ton scale xenon observatory

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

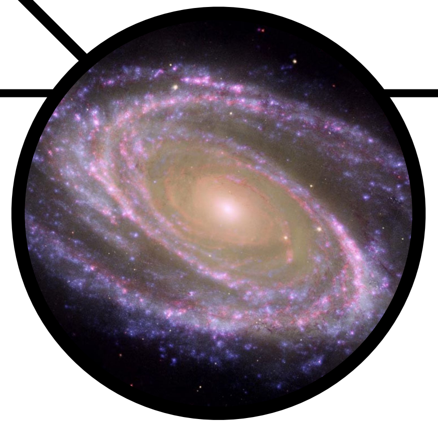
Community Whitepaper

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

Application to neutrino physics

XENON Physics Program



WIMPs DM candidate

- Spin-independent
  - ➡ **PRL 131, 041003**
  - ➡ PRL 119, 181301
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- Spin-dependent
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  - ➡ PRD 103, 063028

Other DM candidate

- Light DM
  - ➡ PRL 123, 241803
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- Heavy DM
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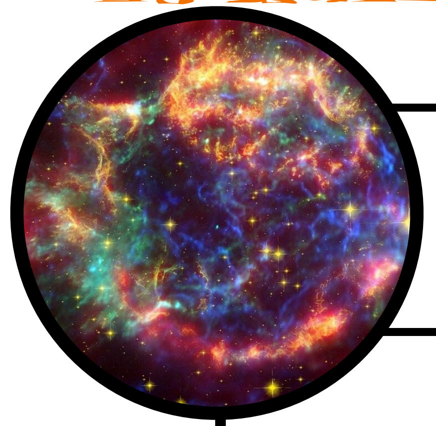
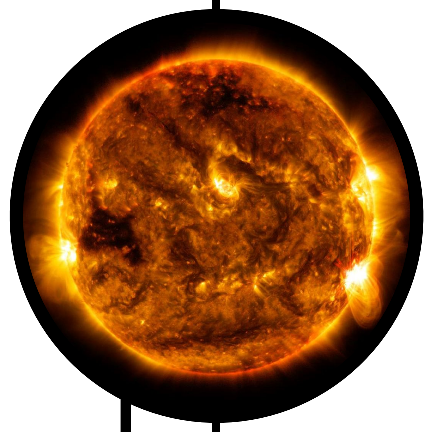
XENONnT latest results

Primary goal → DM direct detection at low-energy recoil in our xenon target

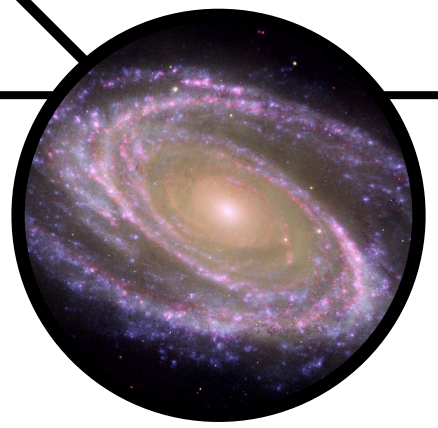
XENON Physics Program



- Supernova neutrinos
  - ➡ PRD 94,103009



- Solar ^{8}B CEvNS
  - ➡ PRL 126, 091301
- Solar pp neutrinos
  - ➡ EPJC 80:1133
- Solar axions
  - ➡ PRD 102, 072004



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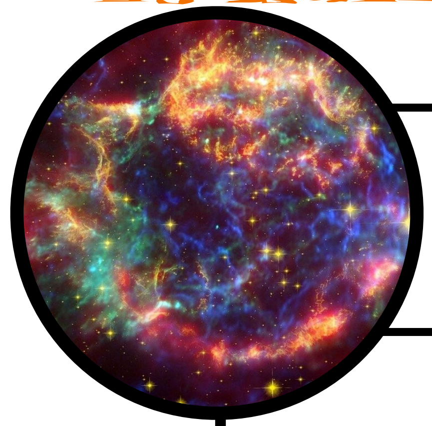

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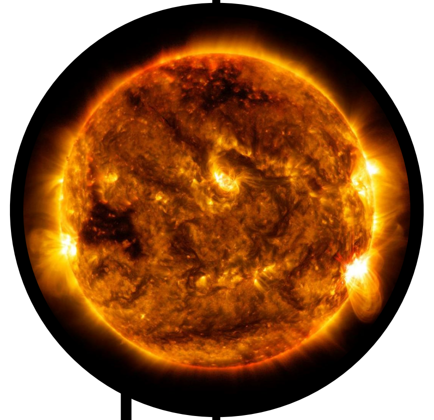

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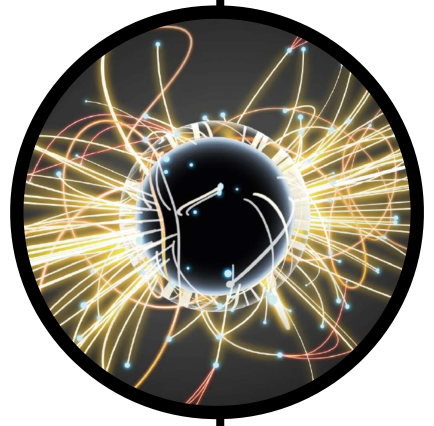
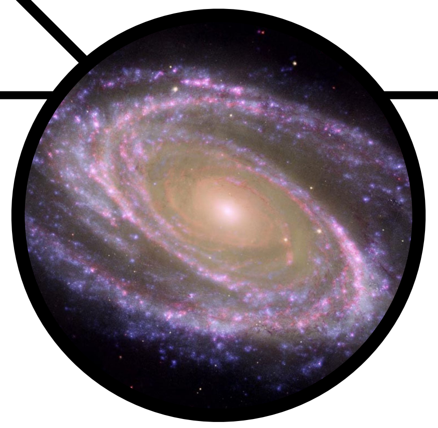
Double Weak Decay



- ^{124}Xe 2νECEC capture
  - ➡ PRL129, 161805
  - ➡ PRC 106, 024328
  - ➡ Nature 568, 532
- ^{136}Xe $0\nu\beta\beta$ decay
  - ➡ PRC 106, 024328
  - ➡ EPJC 80:785
- ^{124}Xe $2/0\nu(EC,\beta^{+})$ decay
  - ➡ EPJC 80:1161
- $^{136/4}Xe$ $2/0\nu\beta\beta$ decay
  - ➡ PRL 125, 171801
  - ➡ PRD 102, 051701
  - ➡ PRD 103,055019
- …



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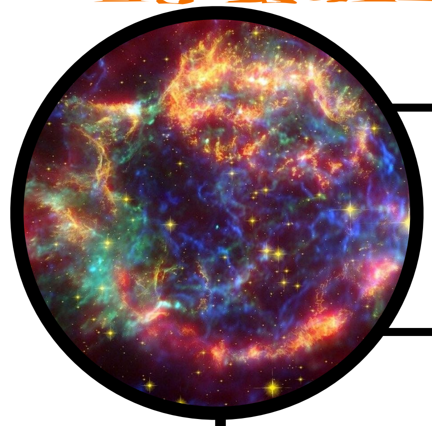
Lower background level → open new physics channel… up to the MeV scale

XENON Physics Program



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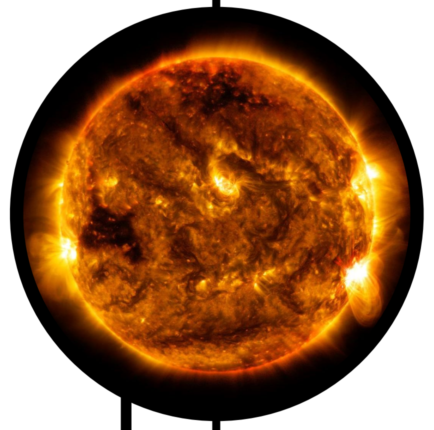

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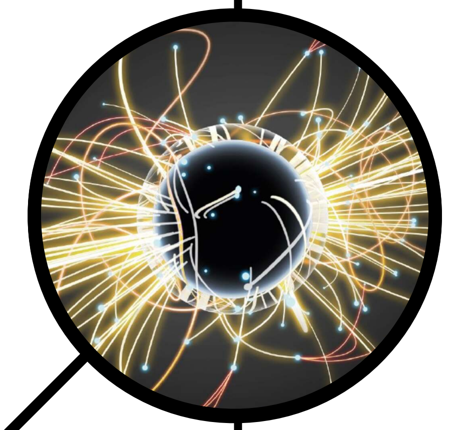

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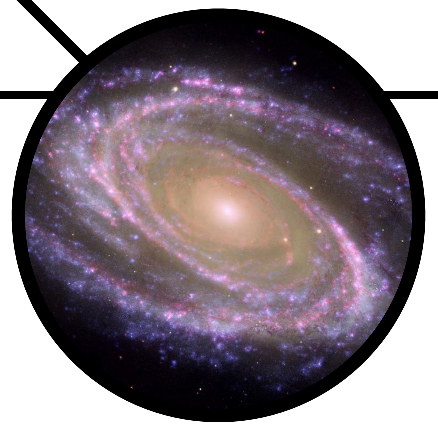

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High energy search in a detector design for low energy rise challenges

Solar neutrinos

Neutrino Interaction:

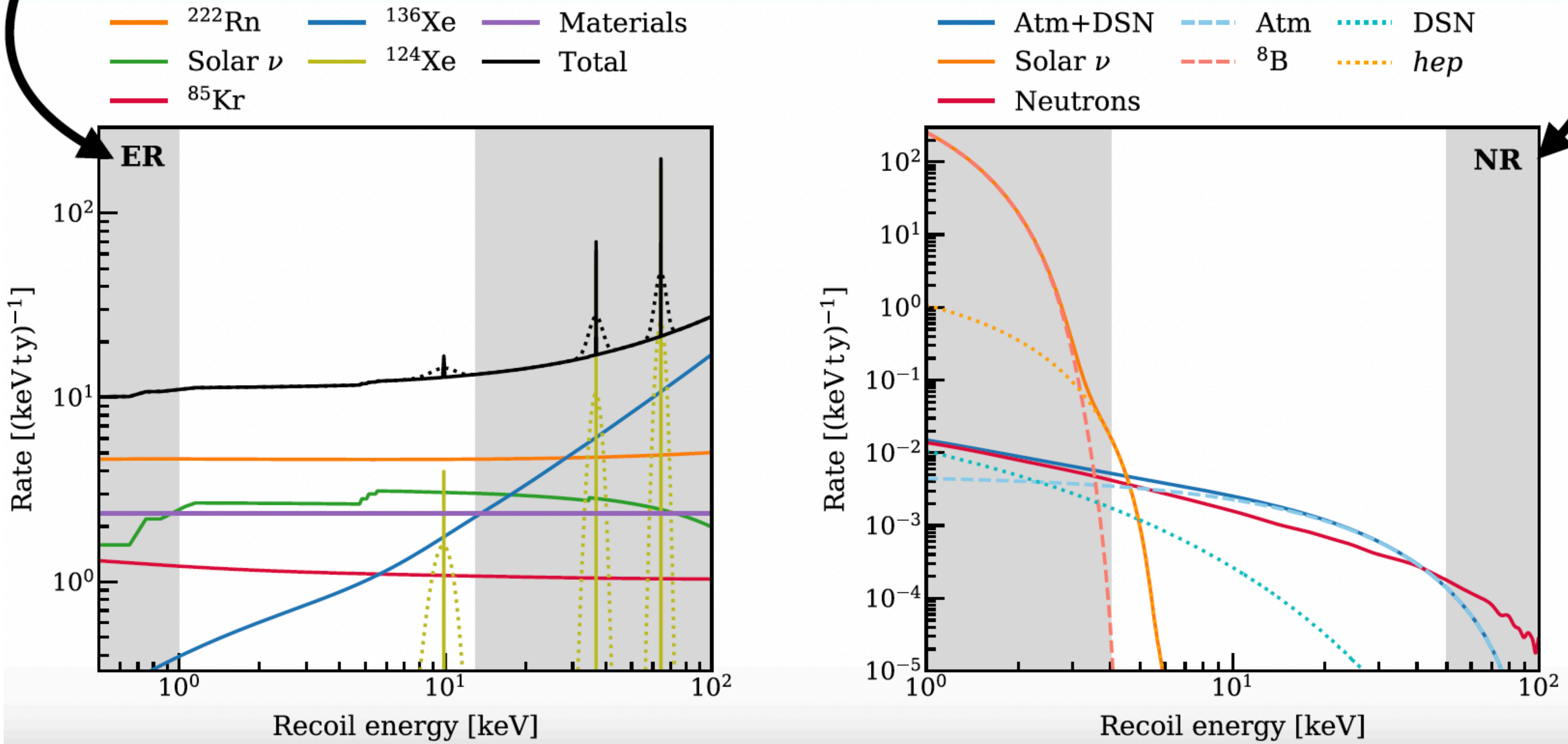
Electroweak interaction
Charged and Neutral Current
(CC & NC)

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)
Neutral Current (NC)

$$\frac{\mathrm{d}\sigma\left(E_\nu, E_\mathrm{R}\right)}{\mathrm{d}E_\mathrm{R}} \propto N^2$$

N: Number of neutrons
→ Xe suitable for CEvNS

XENONnT WIMP background projection

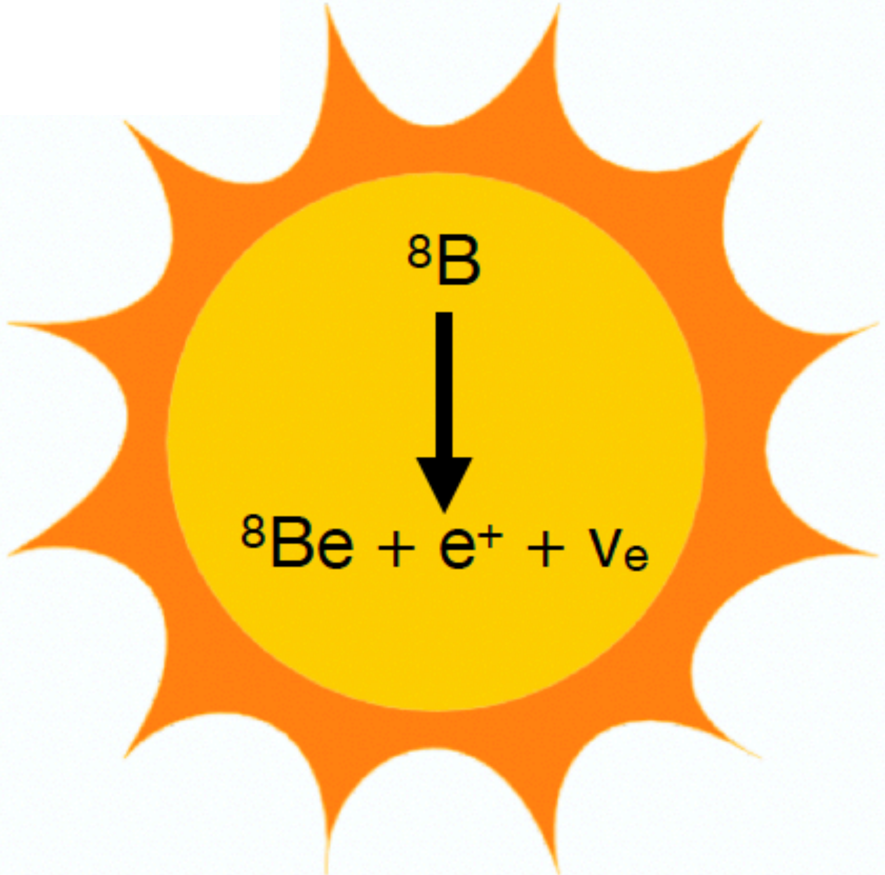


- Irreducible Background source for direct detection DM experiments.
- Already relevant in XENONnT.
- Can be seen as a signal too .

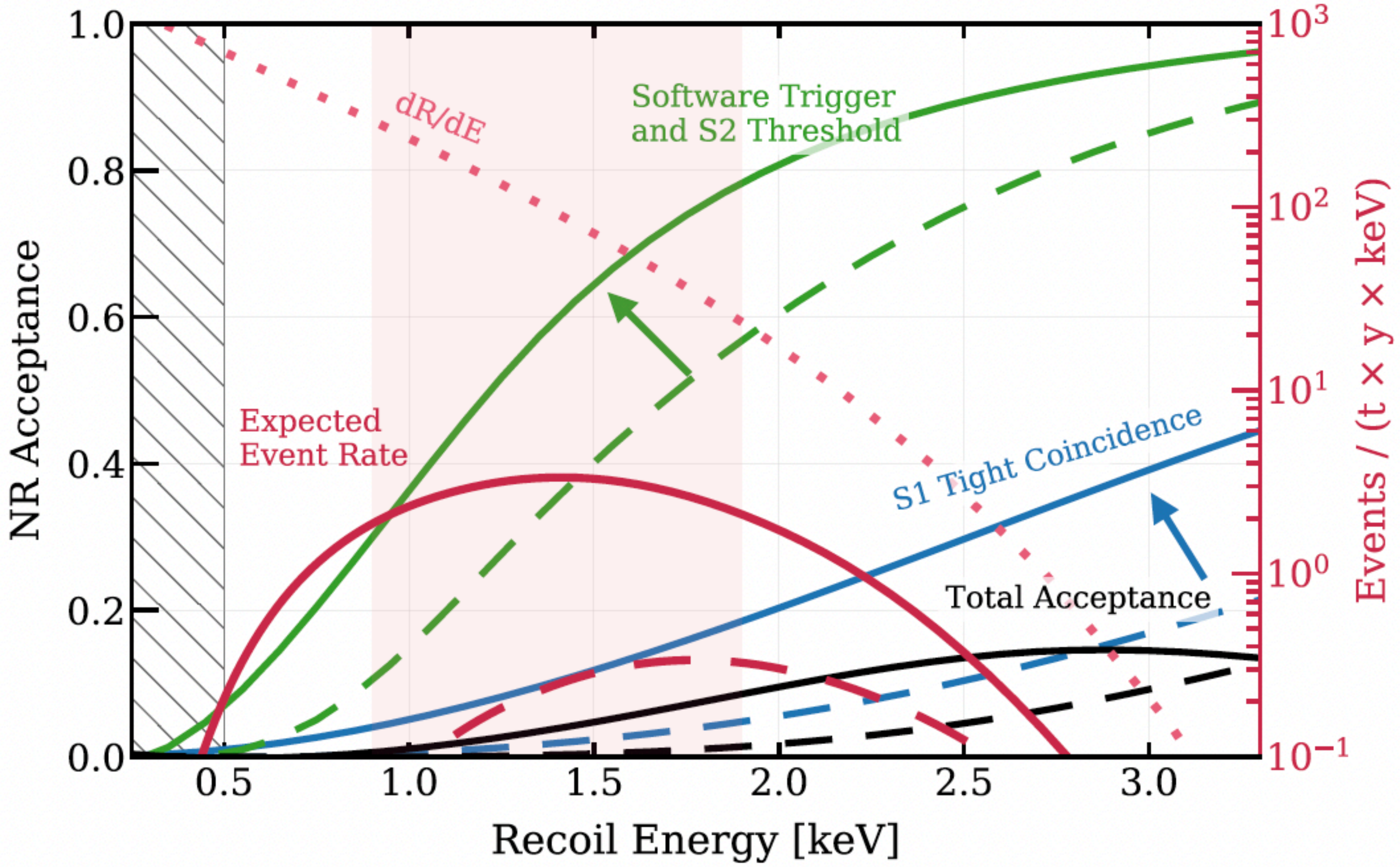
JCAP 11, 031 (2020) | ARXIV:2007.08796

REFERENCES

^{8}B solar neutrinos



- In XENON1T ^{8}B CEvNS falls far belov our previous analysis threshold.
  - 0.01% signal acceptance!
- Improvements in energy threshold required.



REFERENCES

PRL 126, 091301 (2021) | ARXIV:2012.02846

Lowering Energy Threshold :

- Energy threshold driven by:
  - S1 tight coincidence: ~~3~~ → 2 PMTs see light within 50 ns
  - S2 threshold: Require S2s > ~~200~~ → 120 PE (4 e-)
- 100-fold increase in Accidental Coincidences background:
  - High energy events → subsequent AC events.
  - Compensated with ML-classifier cut.

Isolated S1s due to e.g. spurious firing of 2+ PMTs…

…get paired with **isolated S2s**

PRL 126, 091301 (2021) | ARXIV:2012.02846

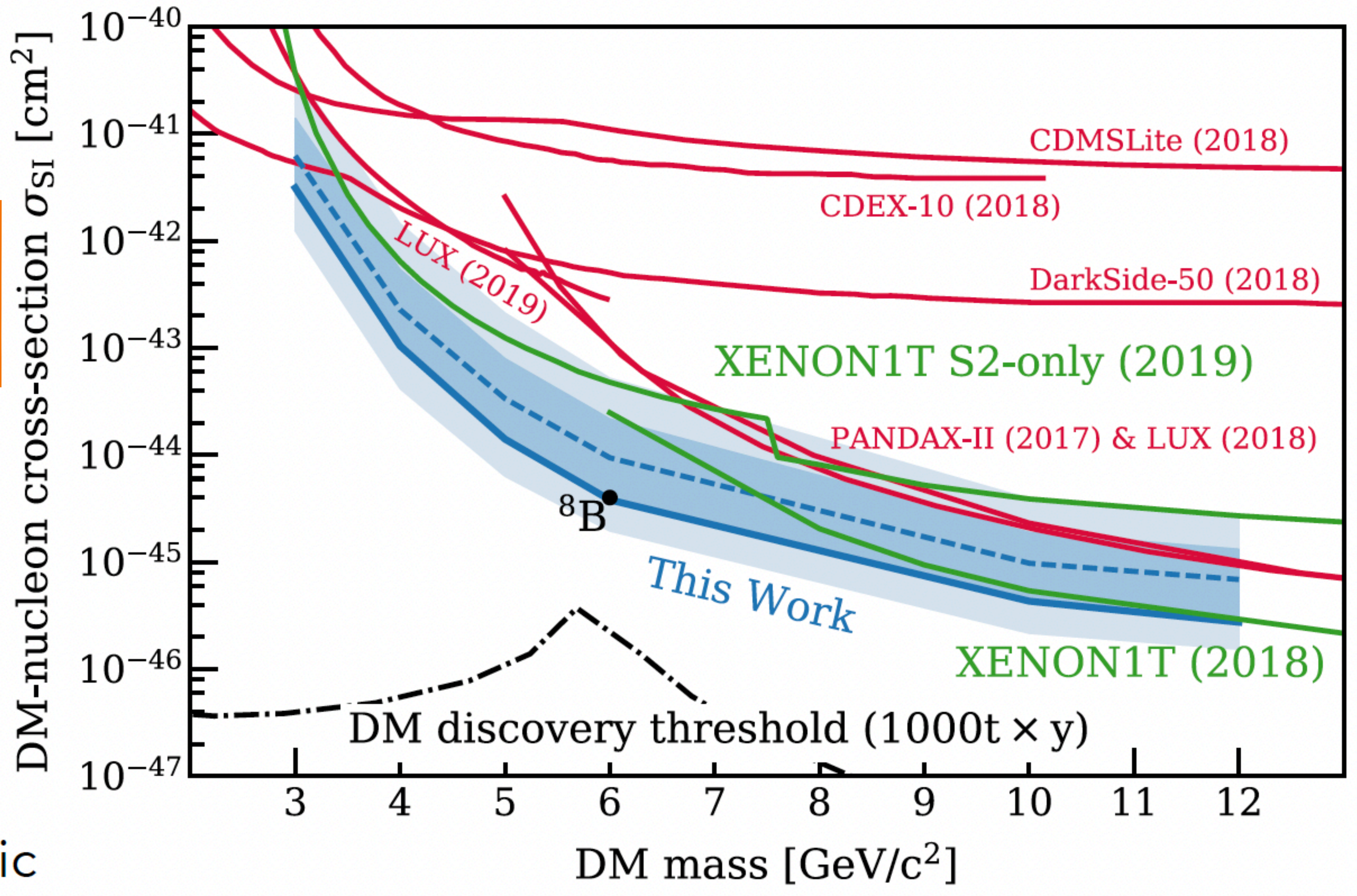
REFERENCES

XENON1T Result:

- No positive detection of CEvNS signal in XENON1T:
  - Use lowered threshold to set **improved low-mass WIMP limits down to 3 GeV/c²**.

Very recent news ;)

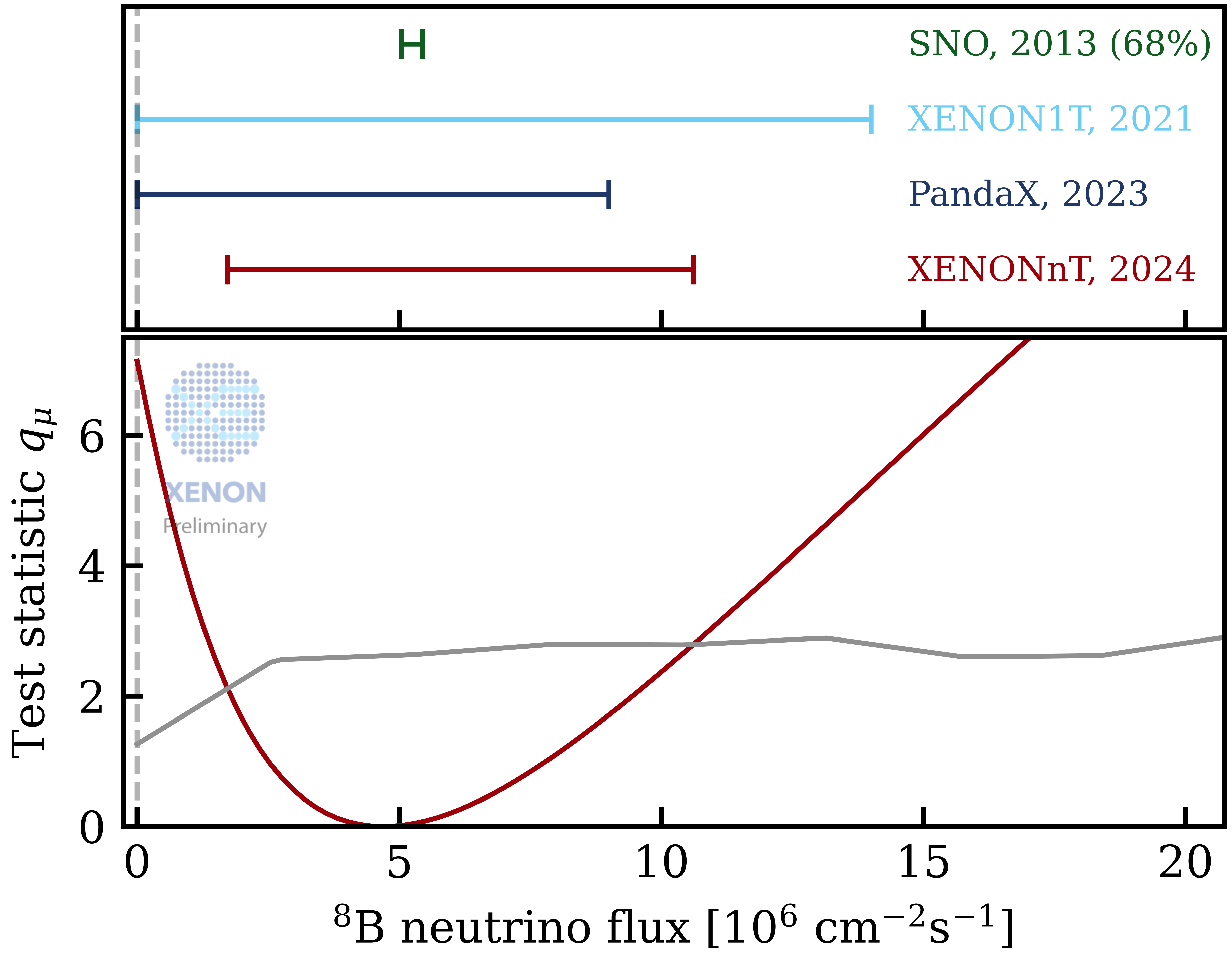
- First observation of CEvNS events from ^{8}B solar neutrinos is **highly expected with XENONnT.**



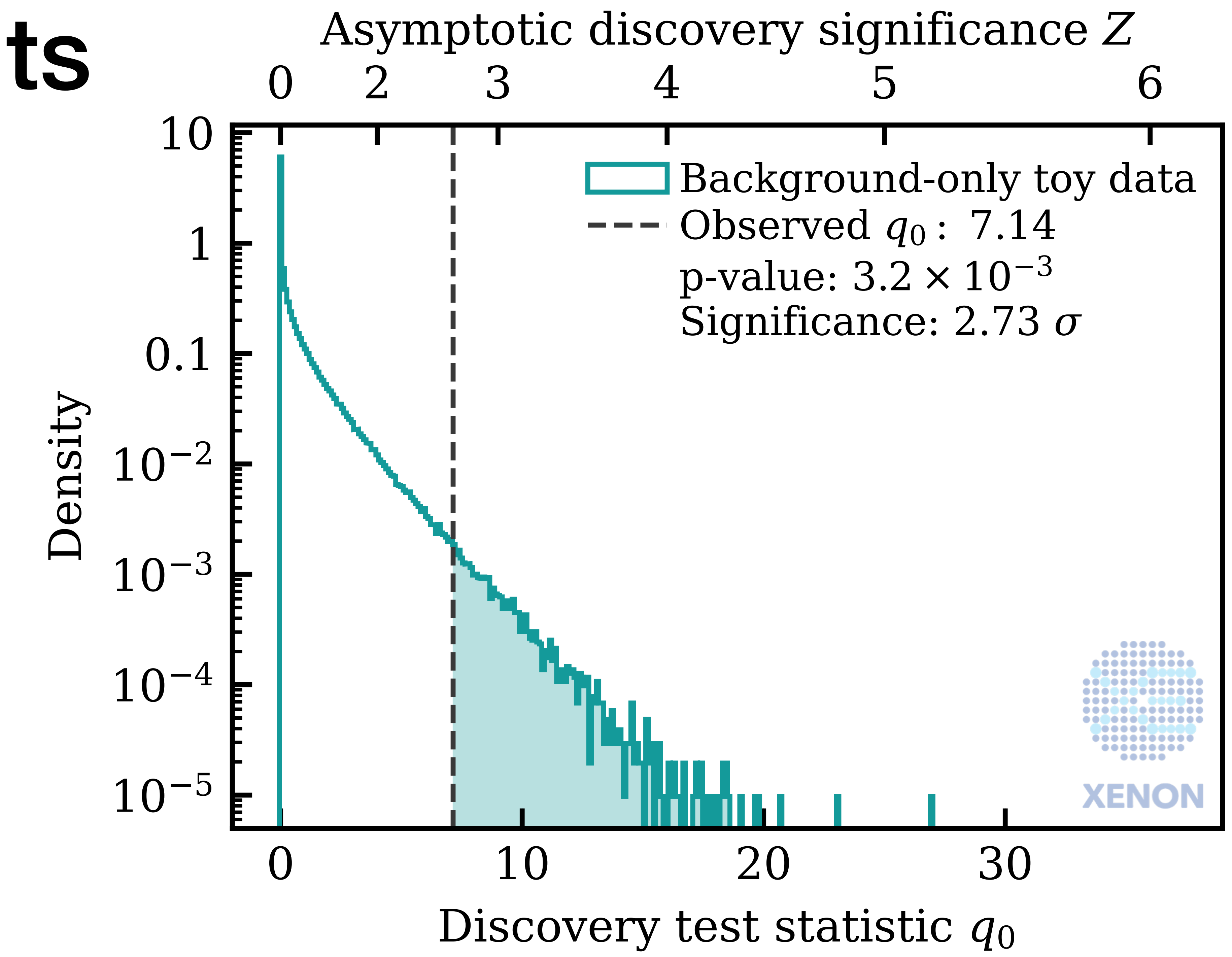
Next generation perspectives:

- Precise measurement of the neutral current component of the solar ^{8}B neutrino flux.
- Hep branch, Diffuse supernova, and Atmospheric neutrinos will be no longer negligible.

XENONnT Solar ^{8}B CEvNS Search Results



F. Gao, on behalf of XENON Collaboration, IDM 2024

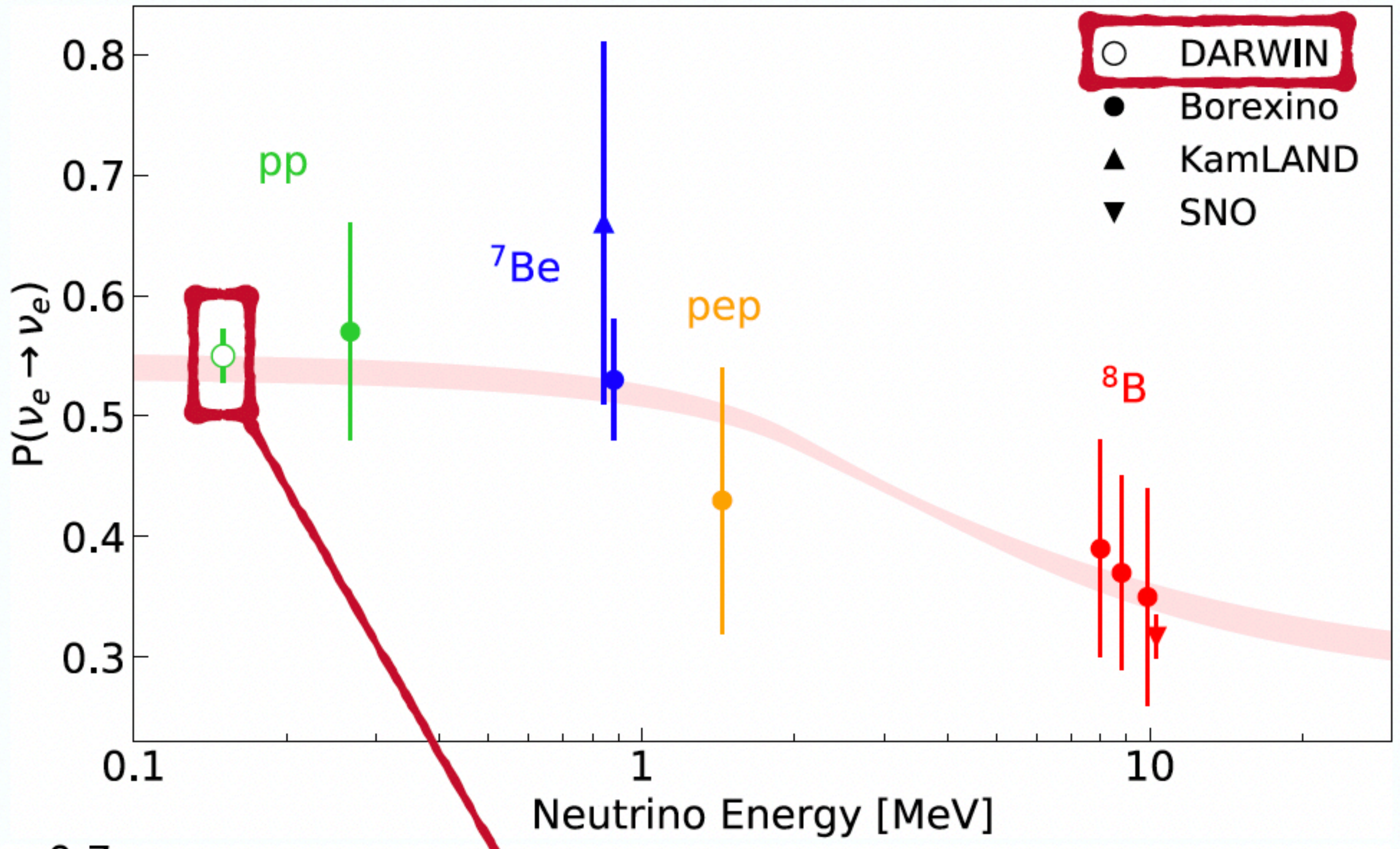


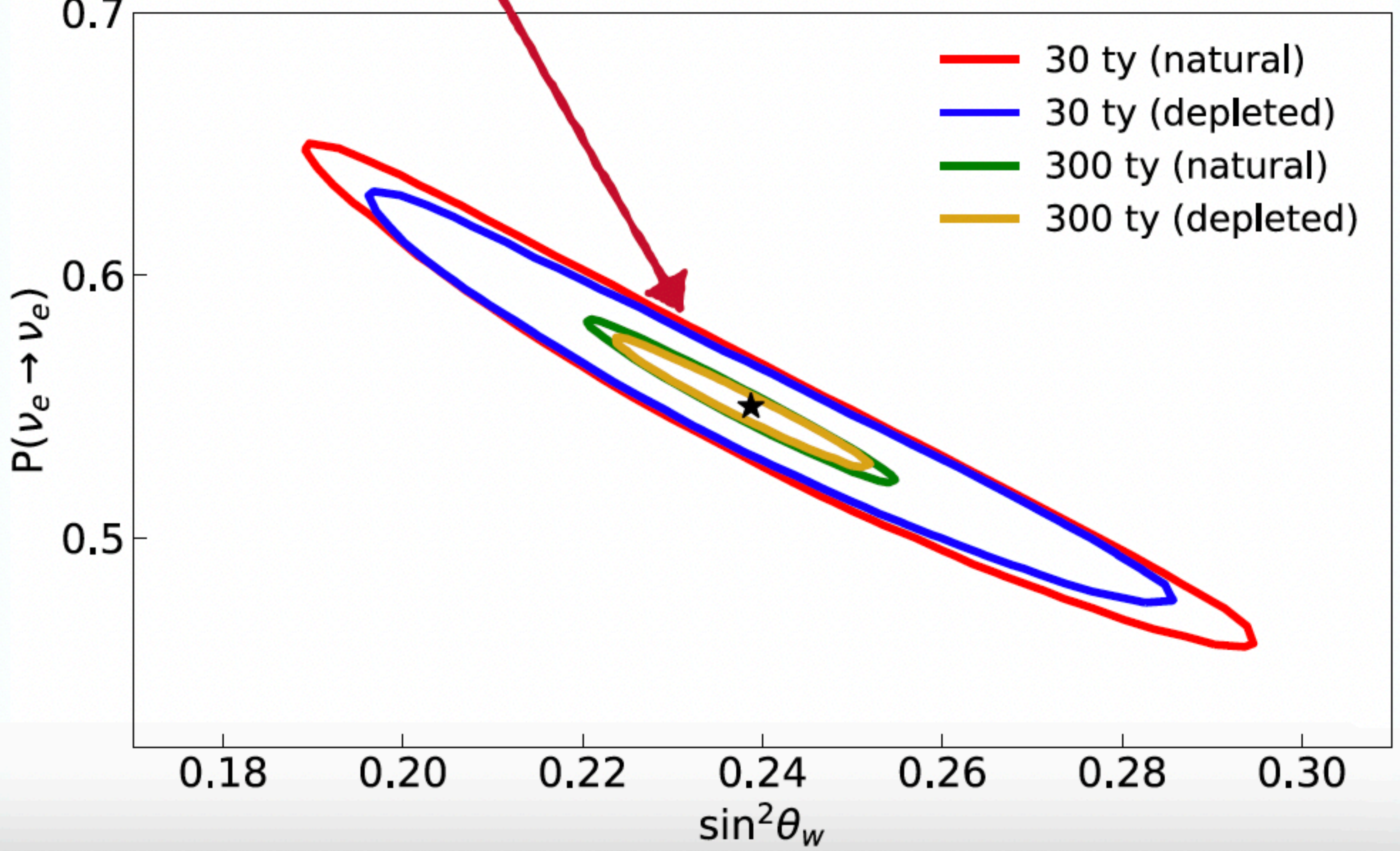
- We have measured the solar ^{8}B neutrinos via CEvNS in XENONnT at 2.73σ
- The first CEvNS measurement with Xe!
- The first astrophysical neutrino measurement via CEvNS

- **Excellent precision in solar neutrino flux measurement:**
  - 0.15 % precision for pp neutrino.
  - 1 % for ^{7}Be neutrino
  - Scenario: 30 t FV mass (300 t.yr exposure)
  - Assuming 0.1 μBq/kg ^{222}Rn/Xe concentration

Precise measurements of electronic solar neutrino survival probability and electroweak mixing angle using pp neutrino

- **First measurement of $\sin^2\theta_W$ in this energy range**, but with larger uncertainty than those at higher energies.
  - $\sin^2\theta_W$ uncertainty → 5.1 %
  - P_{ee} uncertainty → 4.0 %

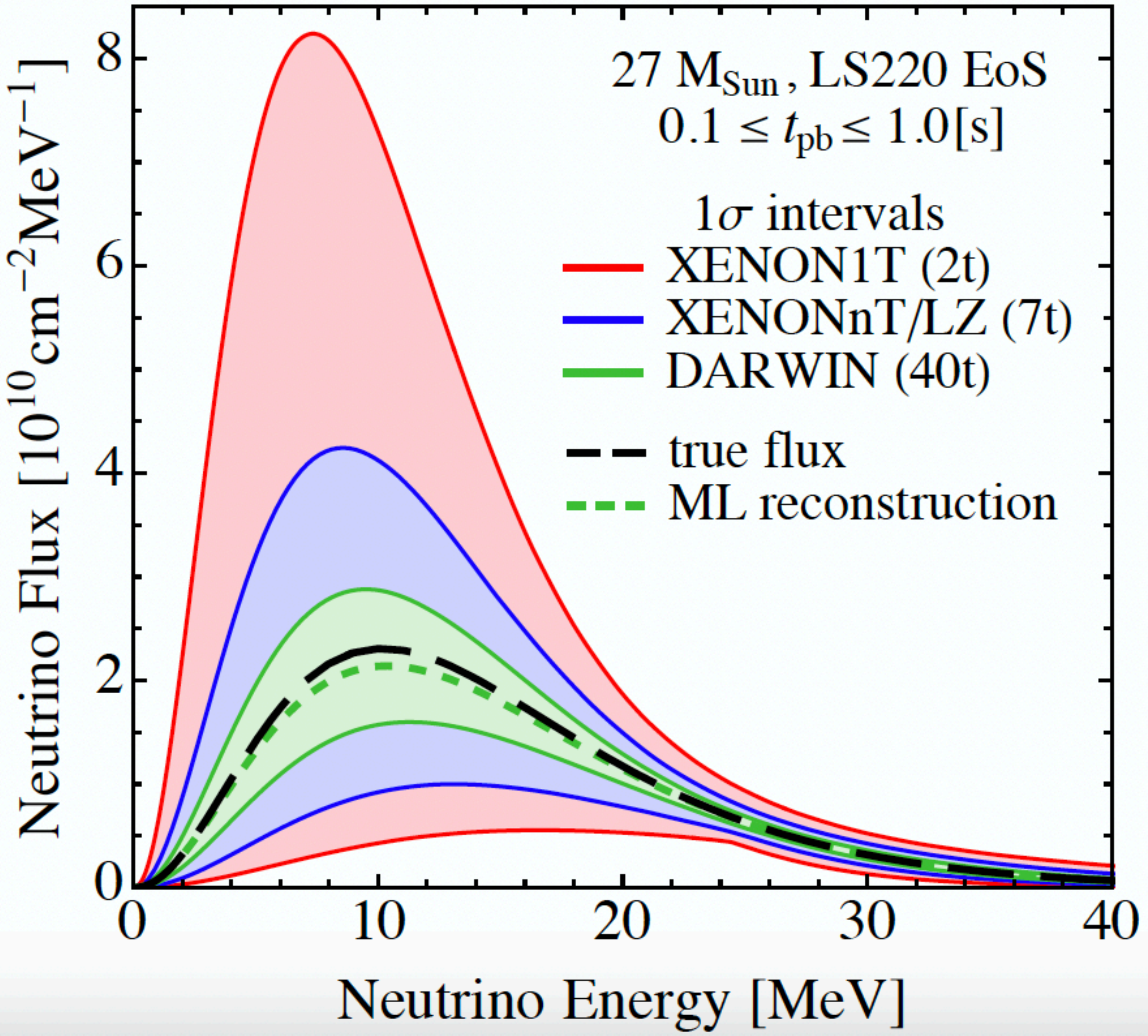


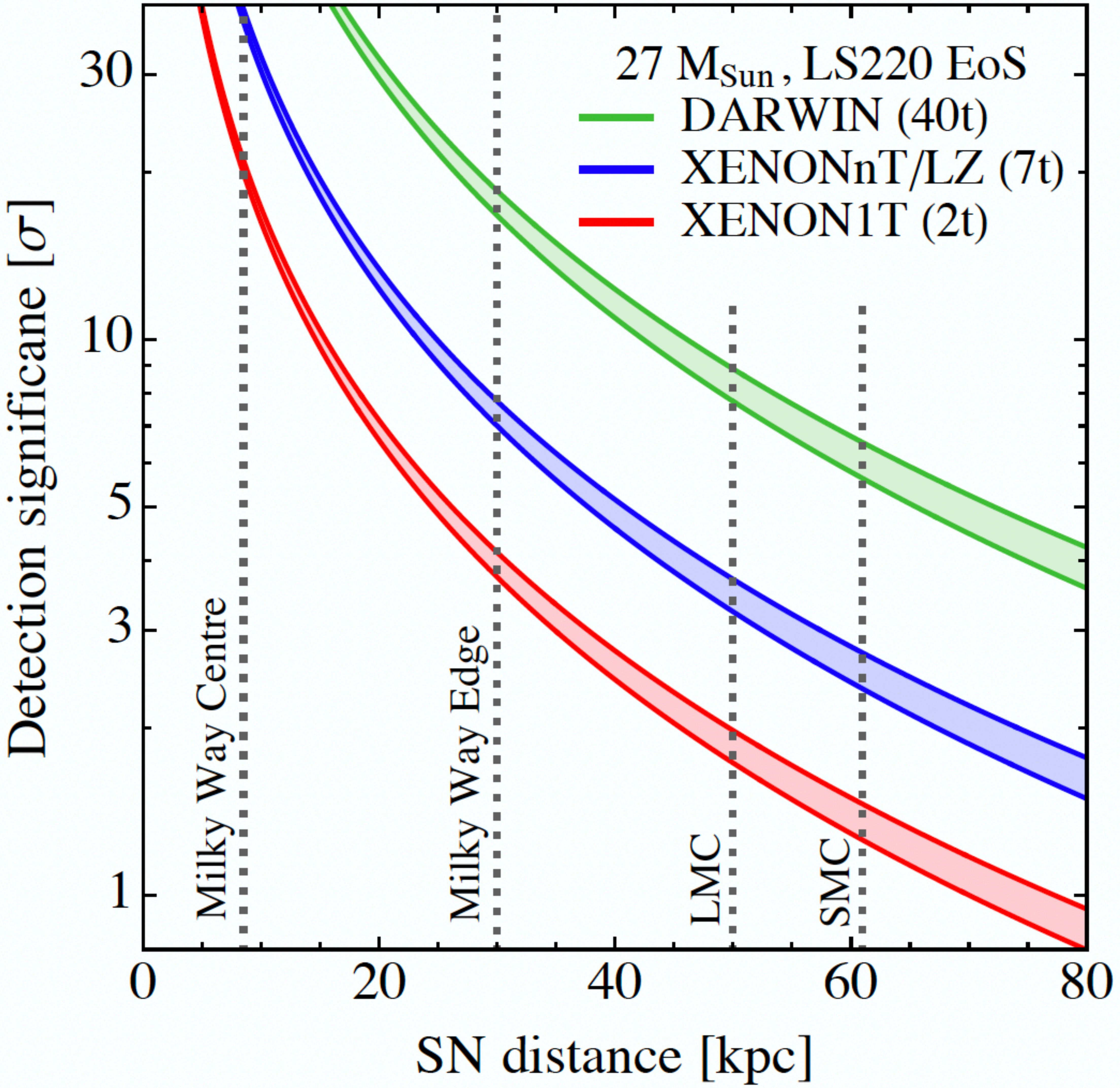


REFERENCES | EPJC 80:1133 (2020) | ARXIV:2006.03114

Supernovae

- **Flavor blinded measurement** of neutrino flux **through CEvNS** events for the community .
- **Contribution to** the upgraded SuperNova Early Warning System (**SNEWS-2.0**) with XENONnT and DARWIN.





Interest in Double-Weak processes

1

Probe BSM physics

- Neutrinoless processes (e.g. $0\nu\beta\beta$ decay) can shed light on the true nature of neutrino (Dirac/Majorana) and explain matter/anti-matter asymmetry in the Universe.

2

Help to test nuclear models

- Second-order weak processes offer an opportunity to constrain NME calculation, which suffer from large uncertainties (≠ nuclear model).

3

Because we can!

- Xenon isotopes undergoing double weak processes (^{124}Xe, ^{134}Xe, ^{136}Xe) are naturally present in our detector!
- Our detector is sensitive to their signal. → Electronic Recoil.
- It can be a potential source of background for other physics channels. → It needs to be understood.

$$\frac{1}{T_{1/2}^{2\nu\beta\beta}} = \left(g_A^{\mathrm{eff}}\right)^4 \left|M_{GT}^{2\nu}\right|^2 G^{2\nu}$$

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = g_A^4\, G^{0\nu} \left|M^{0\nu}\right|^2 \left|f\left(m_i, U_{ei}\right)\right|^2$$

Effective axial-vector coupling

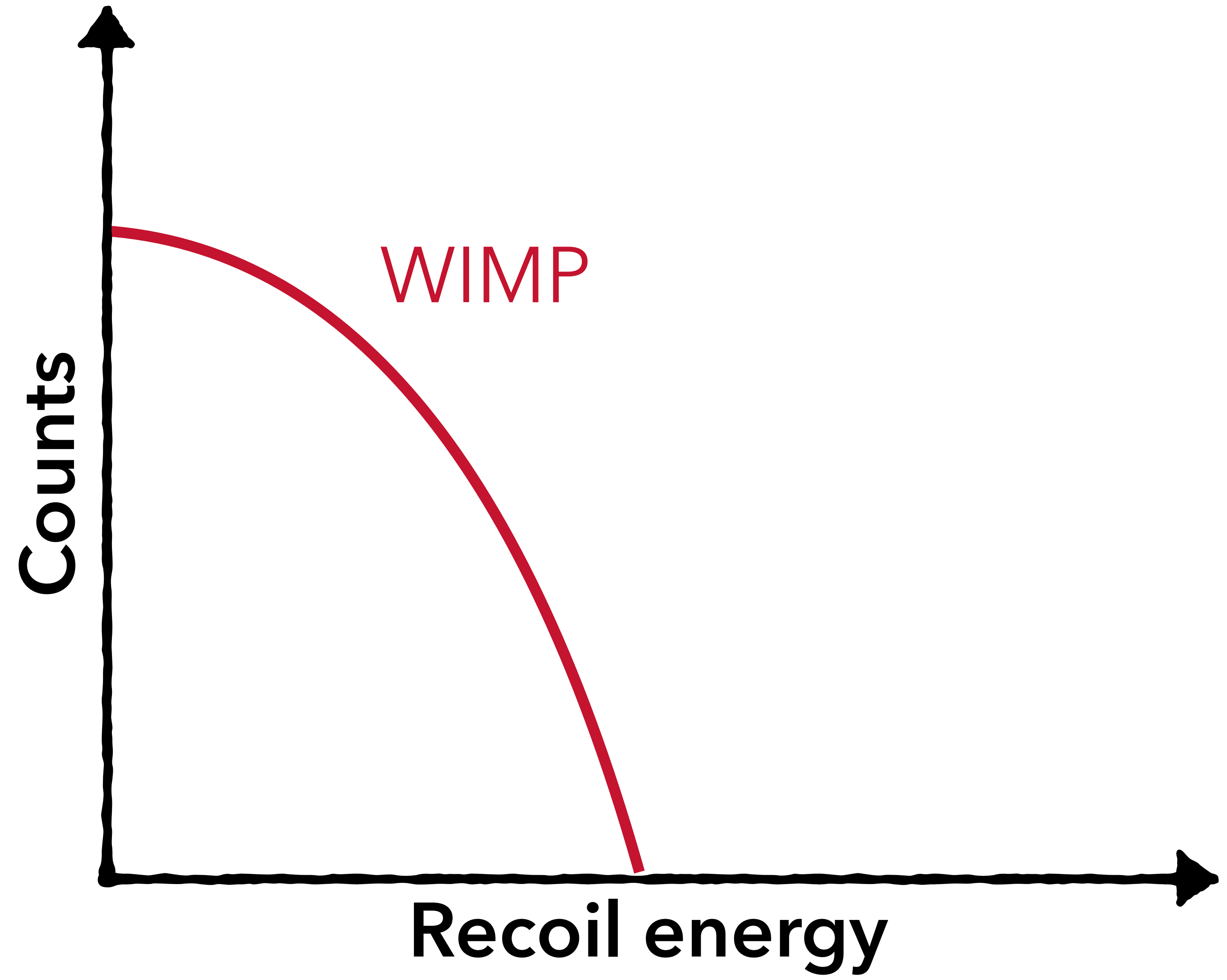
Nuclear Matrix Element (NME)

Phase Space Factor (PSF)

BSM physics driving the decay

Neutrinoless double beta decay search

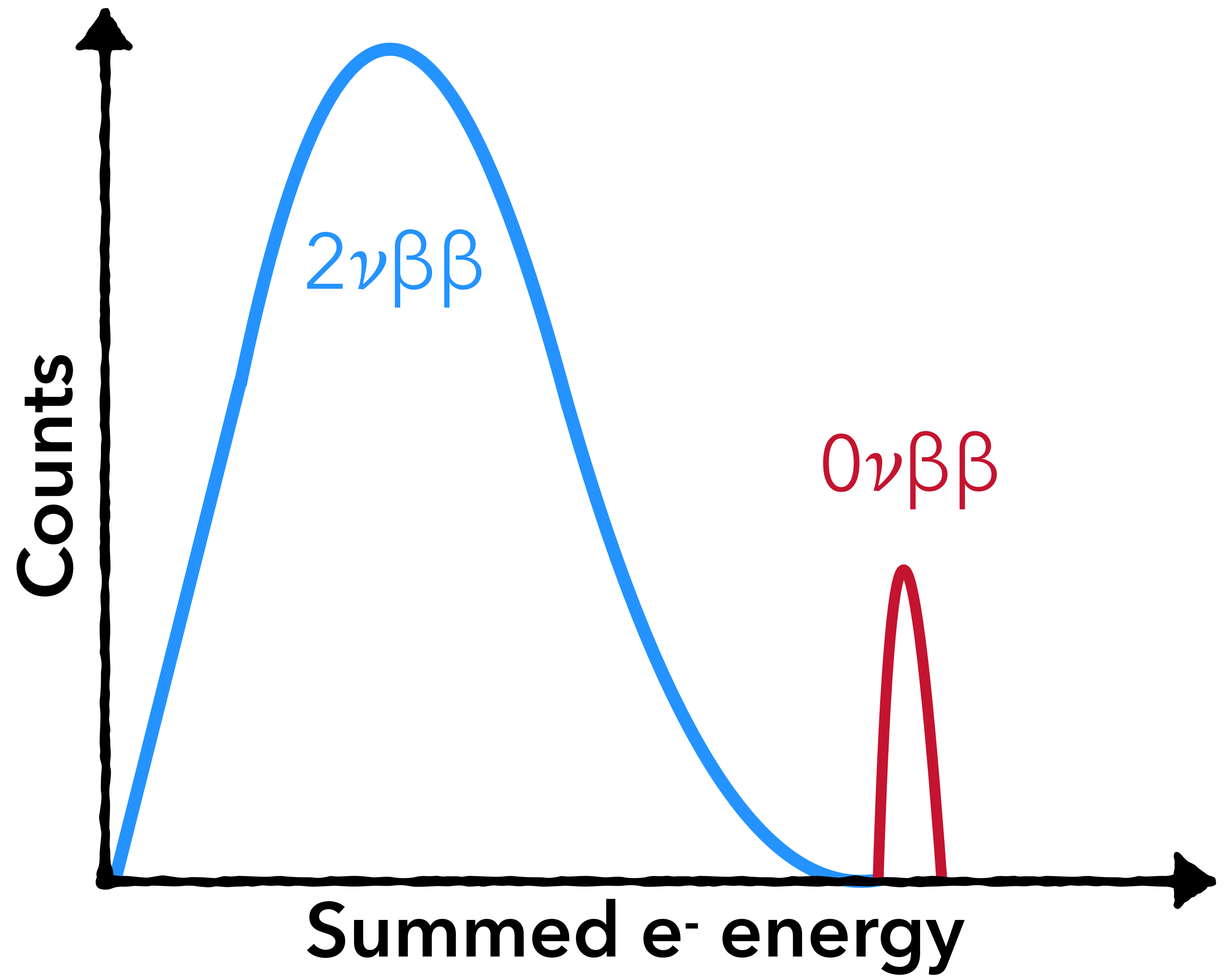
Dark Matter direct detection:



- Signature of DM interaction: WIMP-nucleus scattering → **Nuclear recoil**.
- Recoil energy at the ~ **keV scale**.

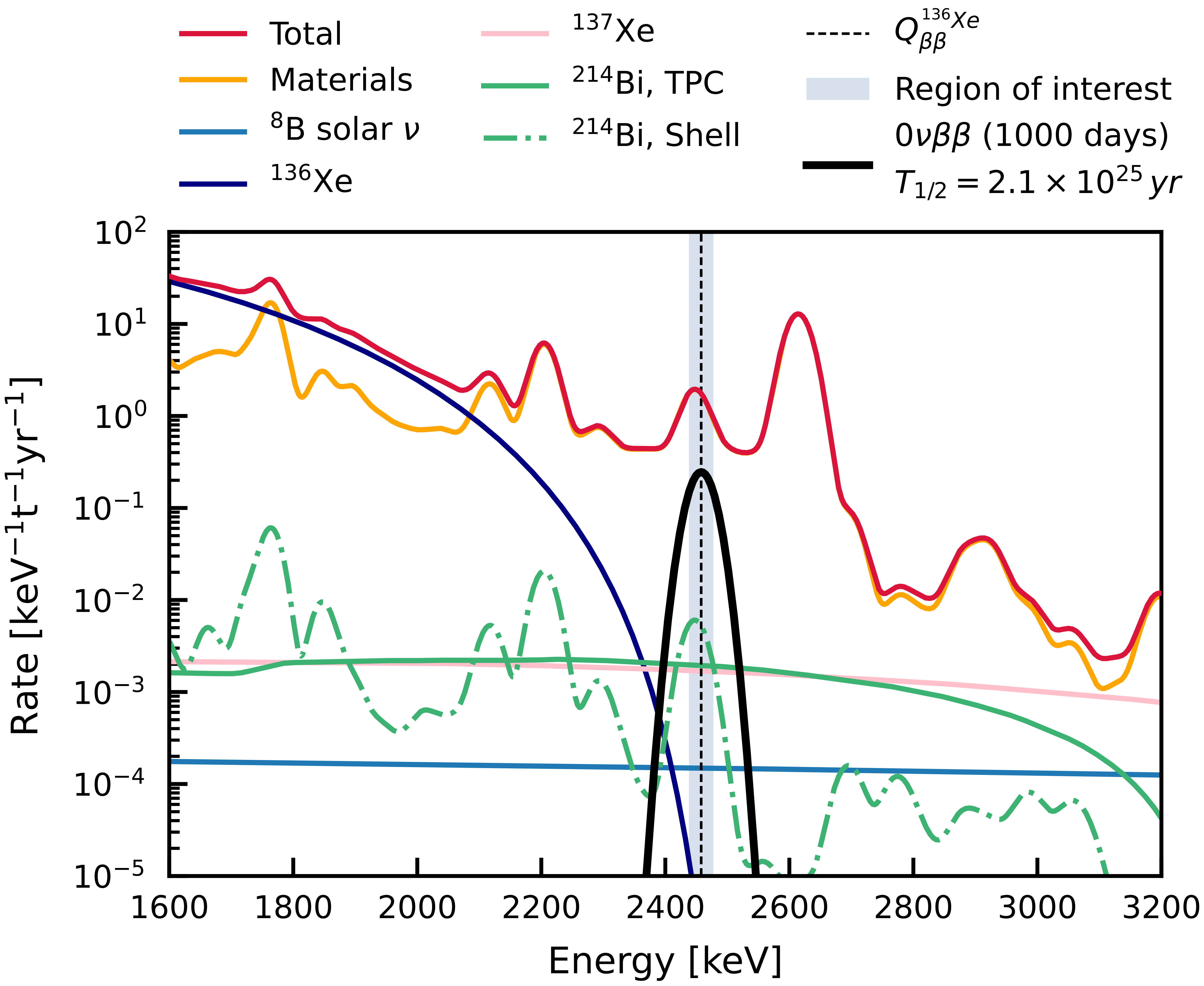
Neutrinoless double beta decay:

$$2\nu\beta\beta : \ (A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
$$0\nu\beta\beta : \ (A,Z) \rightarrow (A,Z+2) + 2e^-$$



- Signature of double-β decay: energy deposition from the two emitted electrons → **Electronic recoil**.
- Q-value of the process ($Q_{\beta\beta}$) ~ **MeV scale**.

Neutrinoless double beta decay search



- Main background from Bi214 gammas from the materials
- $2\nu\beta\beta$ spectrum dominant below 2 MeV

  → New era of precise measurements of the spectrum with high statistics

- Lower limit at 90 % CL from profiled likelihood ratio

$$T_{1/2}^{0\nu\beta\beta} = \ln 2 \times \frac{N_A \times \eta_{Xe136} \times \mathrm{P_{SS}}}{A_{0\nu\beta\beta} \times M_A}$$

Neutrinoless double beta decay search

- Not yet competitive with dedicated $0\nu\beta\beta$ experiments:
  - ➡ Non-enriched target.
  - ➡ Materials optimization for DM search (SS Cryostat).

- **It demonstrates the potential for future xenon DM experiments.**
  - ➡ The next generation of xenon DM experiment (e.g. DARWIN/ XLZD) can approach the sensitivity of dedicated $0\nu\beta\beta$ experiments.

STRENGH

Simultaneous search for DM and $0\nu\beta\beta$ decay in a single detector