First WIMP search results from the XENONnT experiment

GDR DUPhy - Aussois

21th of June, 2023

Dr. Maxime Pierre

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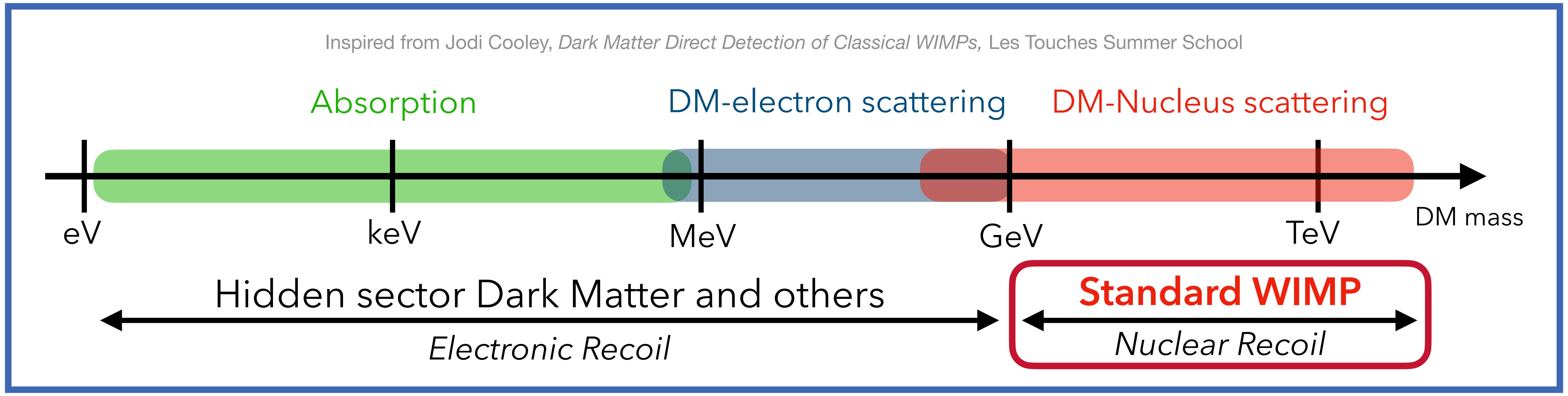
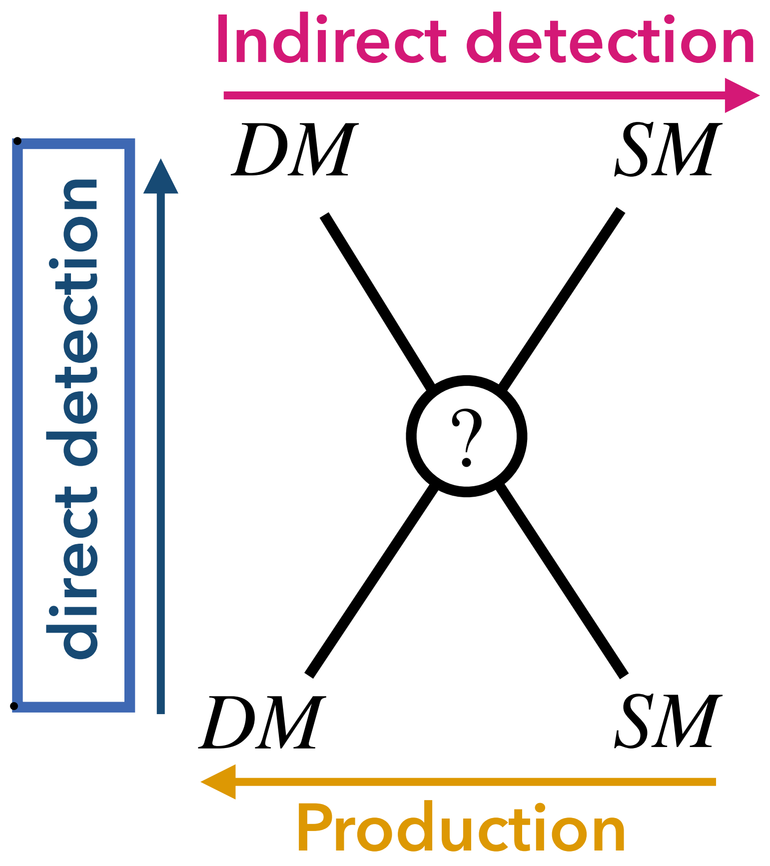
XENONnT Main Goal:

- **Direct detection** of Dark Matter (DM) interaction in ground-based experiment.
- Standard **WIMP** in the **[GeV, TeV] mass range**.
- **Signature:** WIMP **scattering off** a **xenon** target nuclei





Context - Dark Matter Search

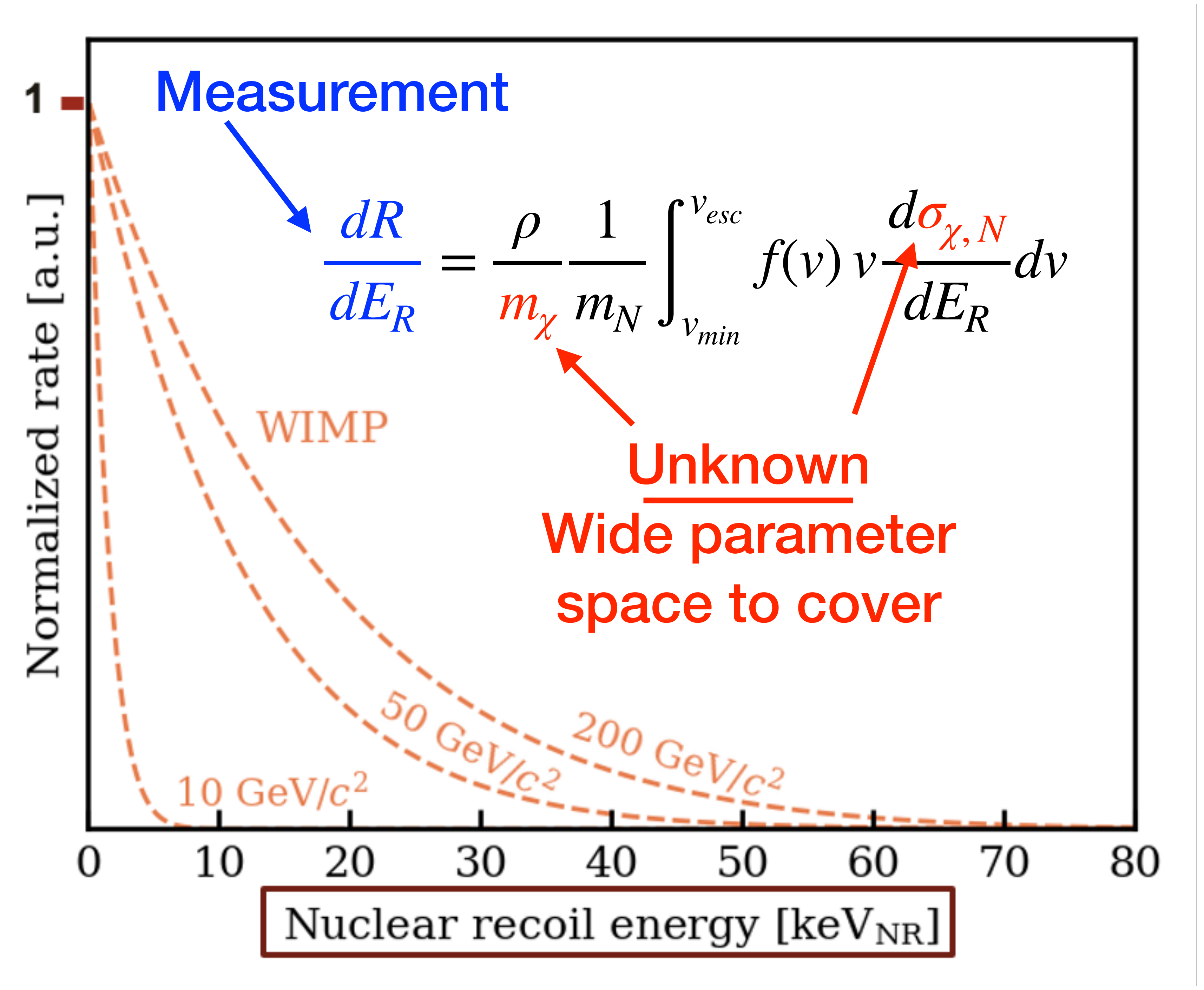
XENONnT Main Goal:

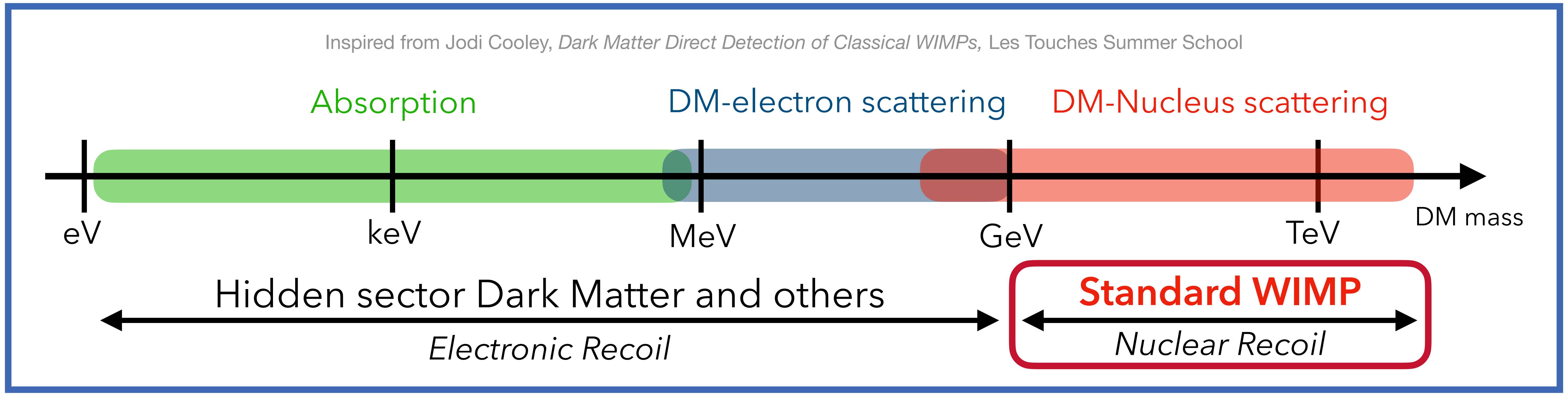
- **Direct detection** of Dark Matter (DM) interaction in ground-based experiment.
- Standard **WIMP** in the **[GeV, TeV] mass range**.
- **Signature:** WIMP **scattering off** a **xenon** target nuclei
  - ➡ **Low-energy nuclear recoil**
  - ➡ Sensitive to **spin-independant** and **spin-dependent** interaction

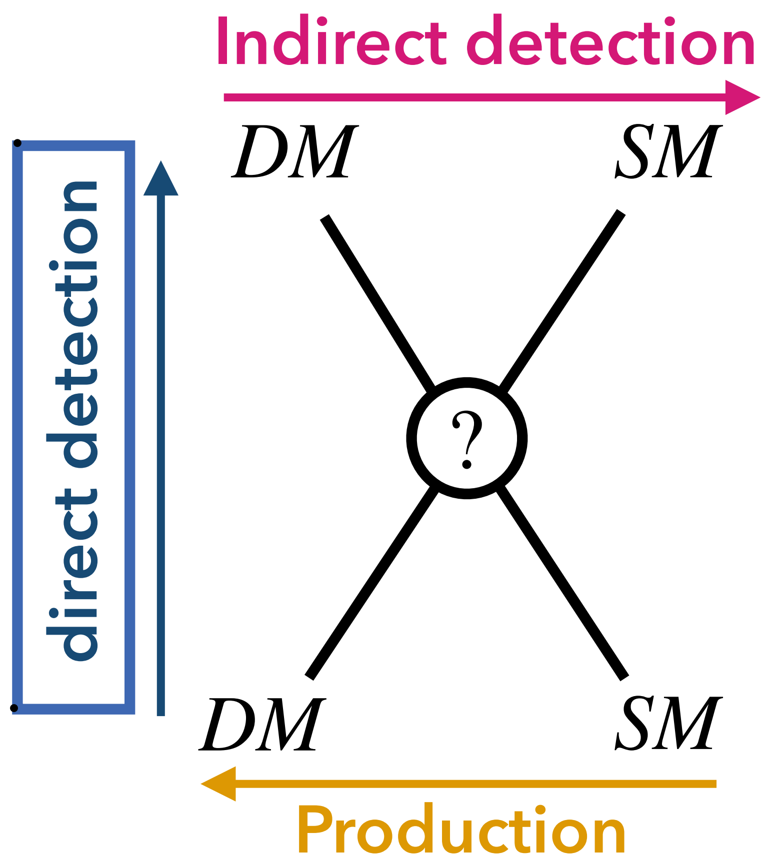
$$\frac{d\sigma_{\chi,N}}{dE_R} = \frac{1}{E_{\max}}\left(\sigma_{SI}F_{SI}^2 + \sigma_{SD}F_{SD}^2\right)$$

^{129}Xe (spin-1/2) | 26.4% n.a.

^{131}Xe (spin-3/2) | 21.2% n.a.







Context - Current Landscape

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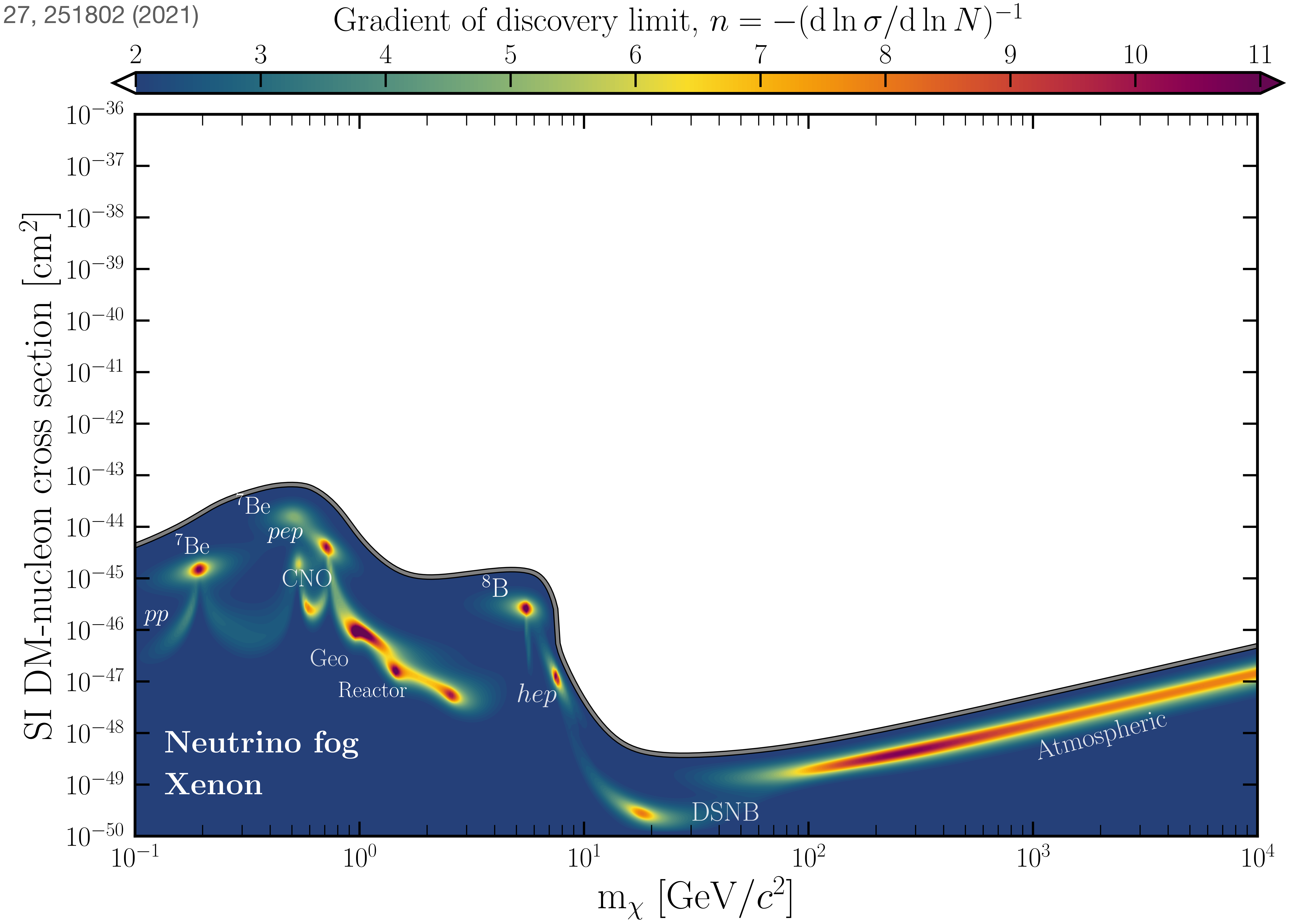
Adapted from PRL 127, 251802 (2021)



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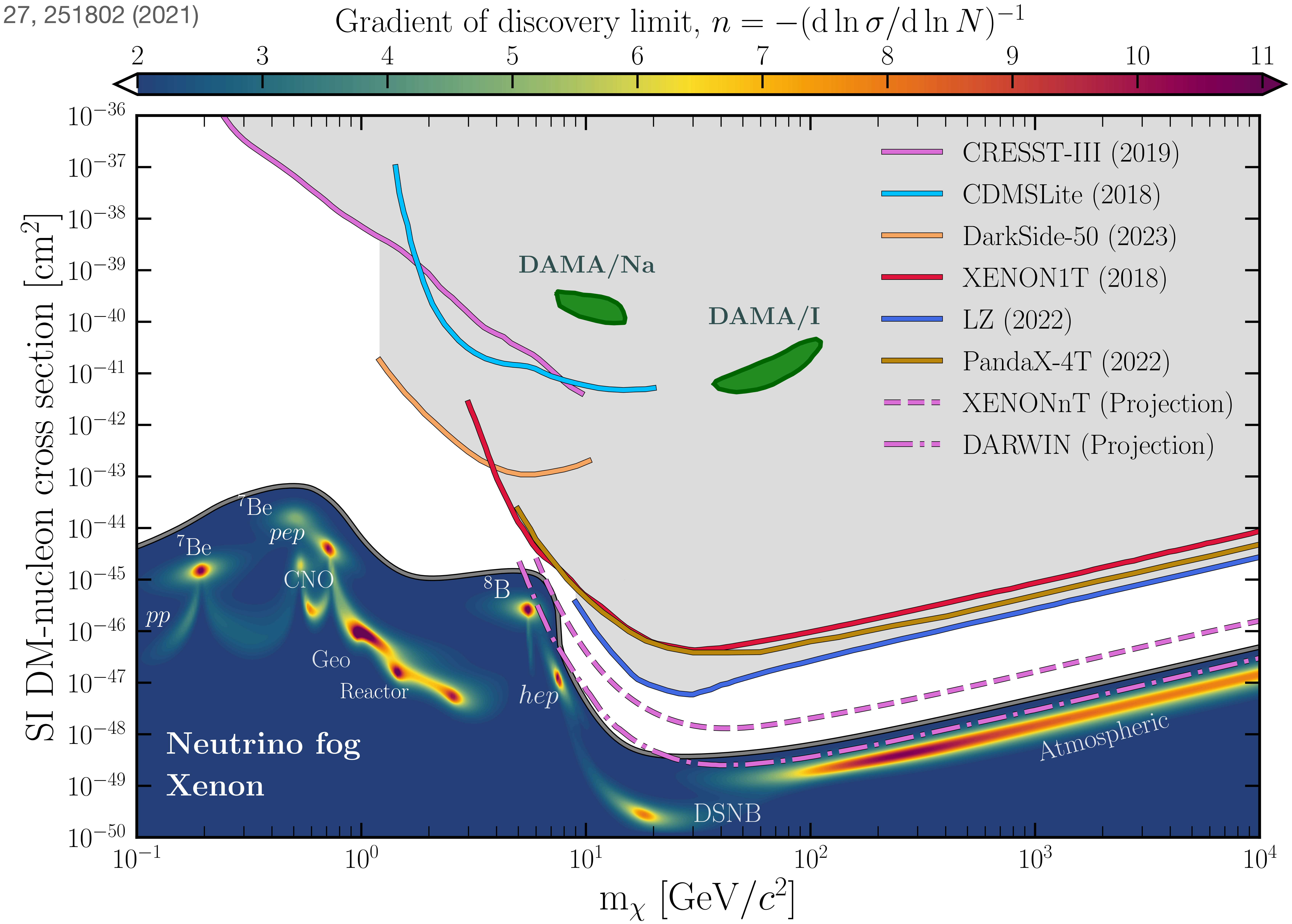

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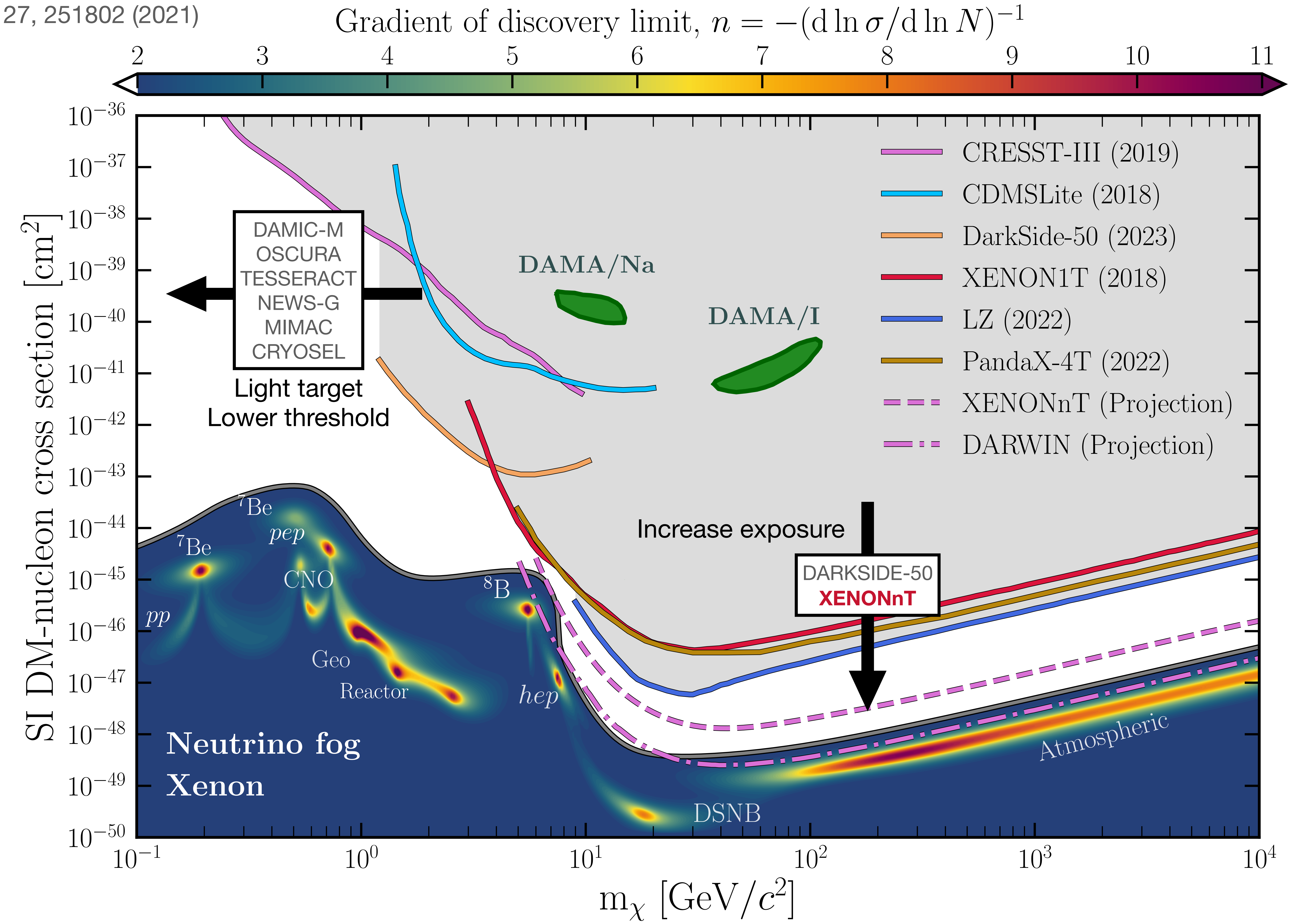

DM Experiment with a dedicated talk in the agenda of the GDR.

The XENON Collaboration

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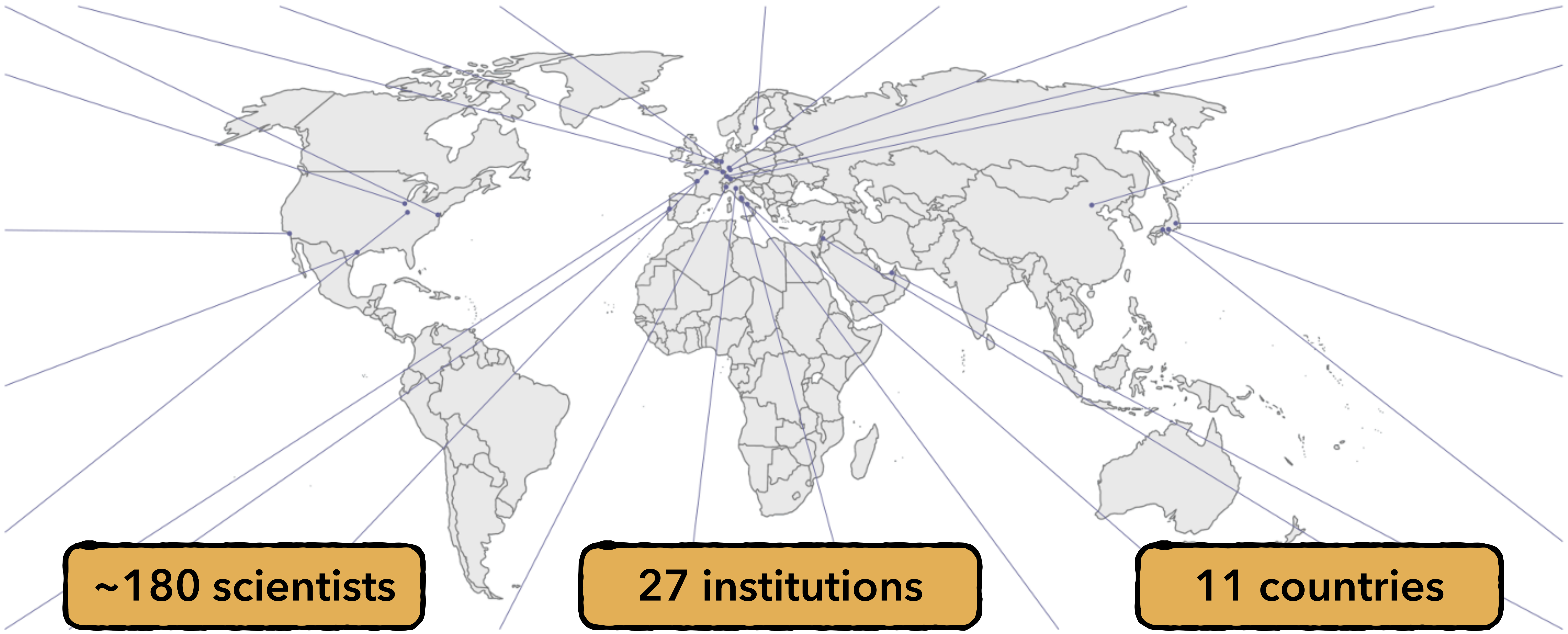
Columbia | KIT | Nikhef | Muenster | Stockholm | Mainz | MPIK, Heidelberg | Freiburg | Zurich

Chicago | UCSD | Rice | Purdue

Tsinghua | Tokyo | Nagoya | Kobe



~180 scientists

27 institutions

11 countries

Subatech | Coimbra | LPNHE | Torino | Bologna | L'Aquila | LNGS | Napoli | Weizmann | NYUAD

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Columbia University
Columbia

KIT Karlsruhe Institute of Technology
KIT

Nikhef
Nikhef

WWU MÜNSTER
Muenster

Stockholm University
Stockholm

JG|U
Mainz

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG
MPIK, Heidelberg

UNI FREIBURG
Freiburg

University of Zurich[UZH]
Zurich

THE UNIVERSITY OF CHICAGO
Chicago

UC San Diego
UCSD

Rice

PURDUE UNIVERSITY
Purdue

清華大学 Tsinghua University
Tsinghua

東京大学 THE UNIVERSITY OF TOKYO
Tokyo

NAGOYA UNIVERSITY
Nagoya

KOBE UNIVERSITY
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Subatech
Subatech

Coimbra

LPNHE PARIS
LPNHE

INFN TORINO
Torino

Bologna

L'Aquila

INFN LNGS
LNGS

Napoli

מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
Weizmann

جامعة نيويورك أبوظبي NYU ABU DHABI
NYUAD

Main Goal: Direct detection of WIMP dark matter candidate

The XENON Program

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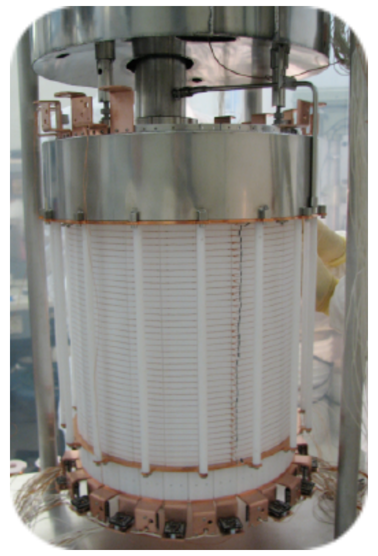
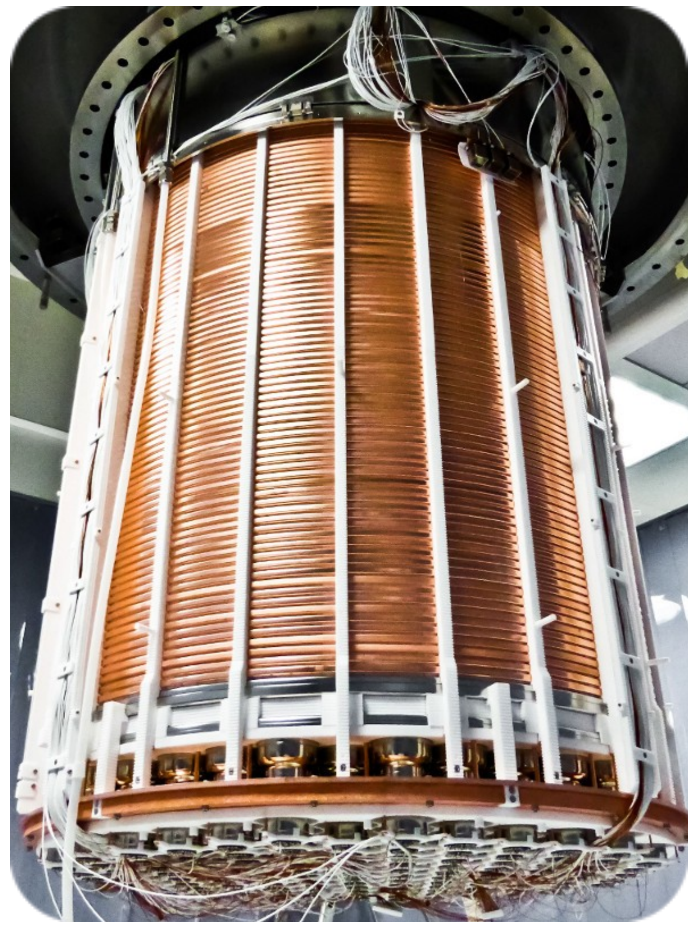
- **Fourth generation of XENON experiment**
  - ➡ Based on the same detection technology: **dual-phase Time Projection Chamber**
  - ➡ Already **demonstrated the scalability** of this technology

Present

Xe XENON10



Xe XENON100



Xe XENON1T

XENONnT

	XENON10	XENON100	XENON1T	XENONnT
Time	2005	2008	2016	**2021**
Active mass	15 kg	62 kg	2000 kg	**5900 kg**

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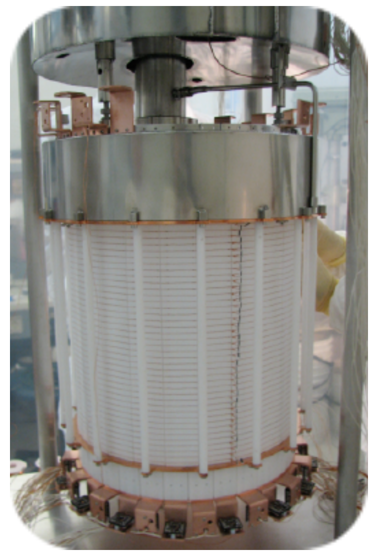
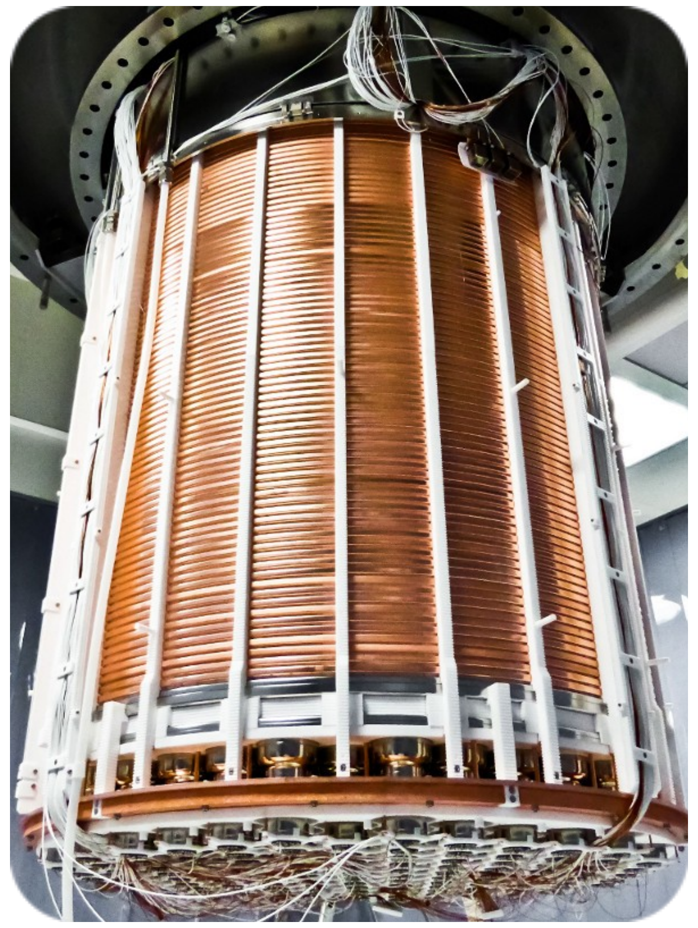
- **Fourth generation of XENON experiment**
  - ➡ Based on the same detection technology: **dual-phase Time Projection Chamber**
  - ➡ Already **demonstrated the scalability** of this technology
- Operating at the **INFN - Laboratori Nazionali del Gran Sasso** (LNGS)
  - ➡ **Underground laboratory with 1500 m overburden** (3600 m.w.e)

Present





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The XENONnT experiment

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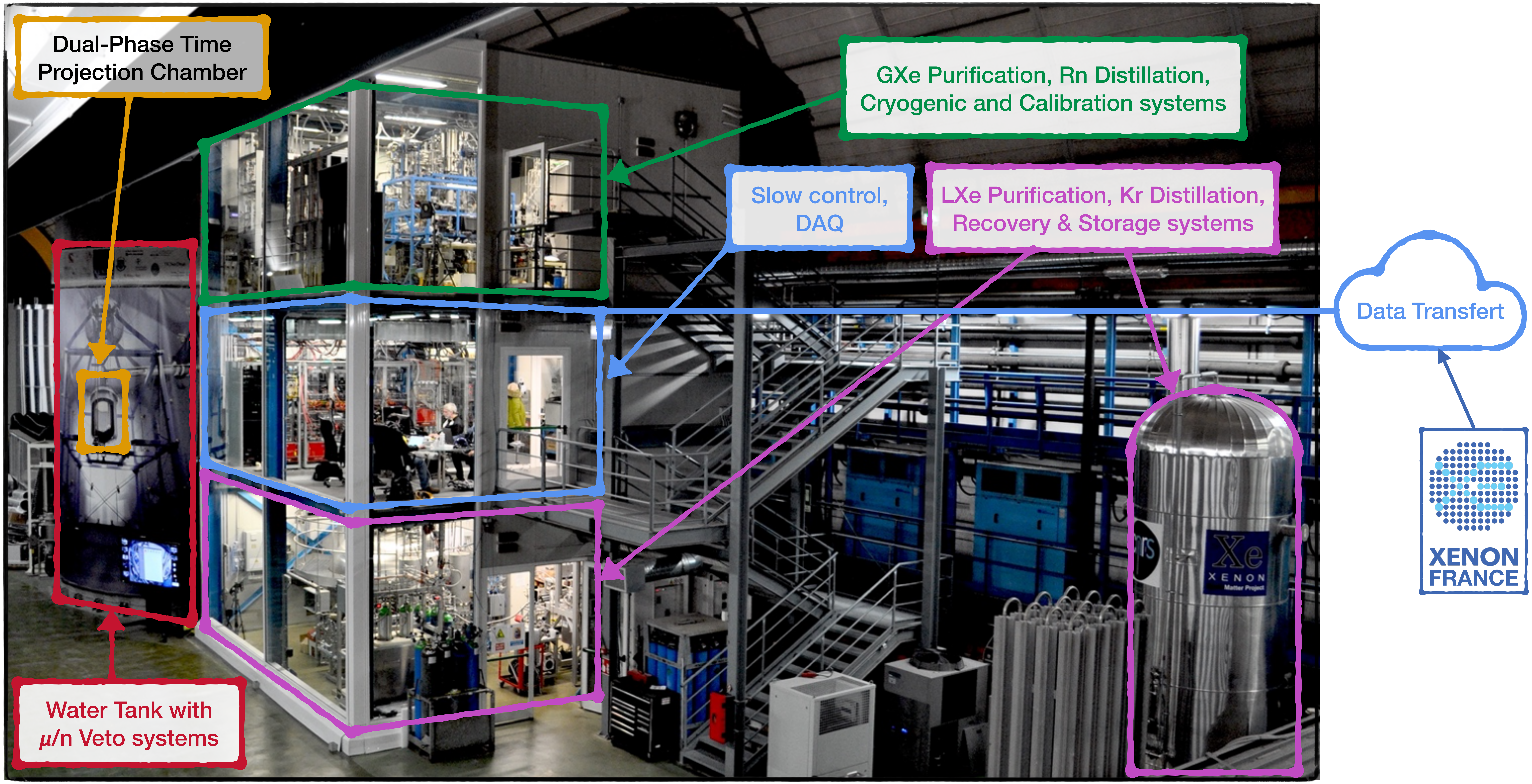

Fast upgrade from XENON1T

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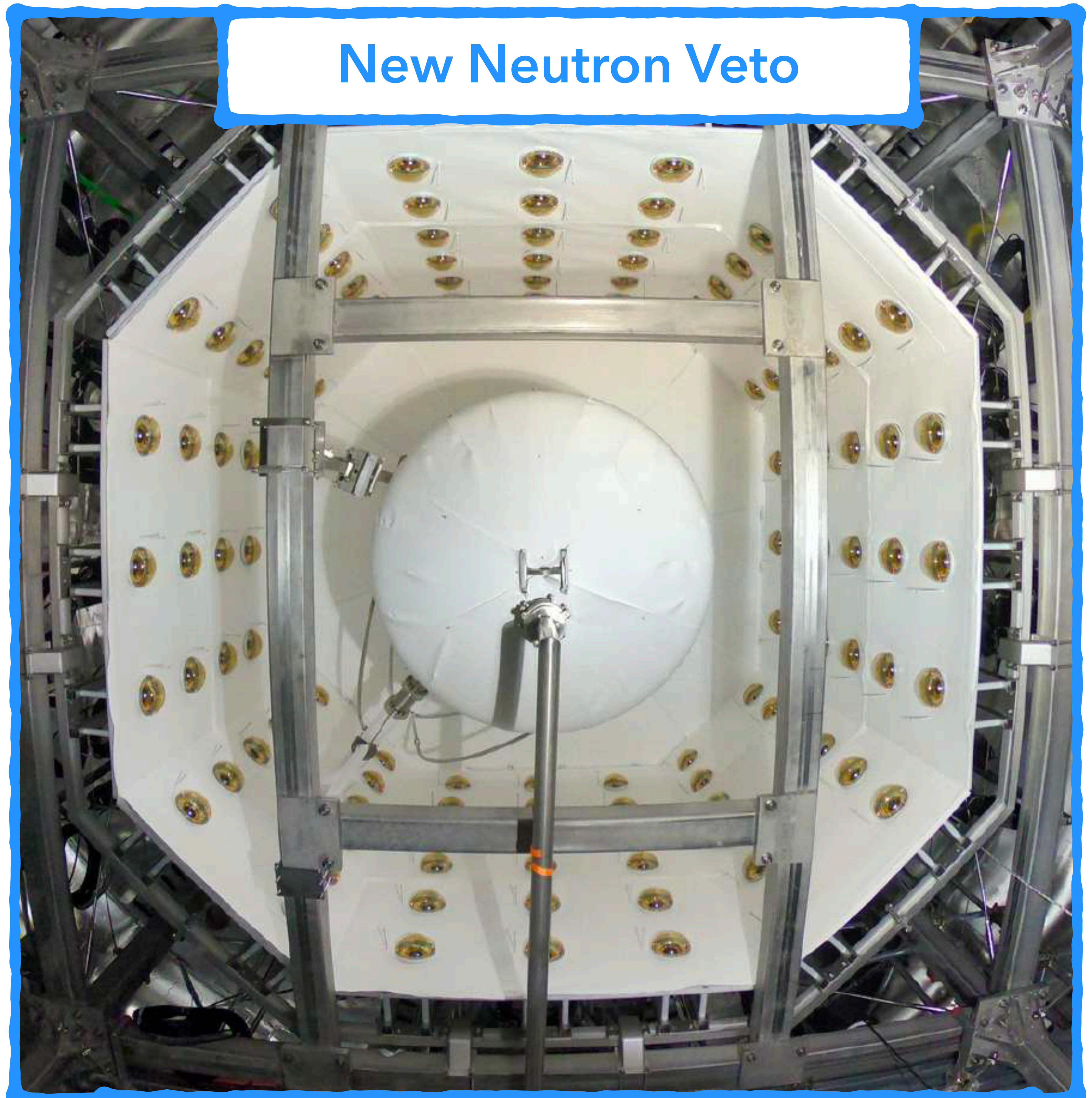
New Radon Distillation Column

1.8 μBq/kg ^{222}Rn/Xe

New Liquid Xenon Purification

Increased purity > 10 ms e^- lifetime

New Neutron Veto



87 % (~60 %) projected neutron tagging efficiency with Gd-loaded (pure) water

New fast recovery system to handle our larger xenon inventory

Contribution from CNRS

ReStoX 2

Fast upgrade from XENON1T

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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 Detection Principle

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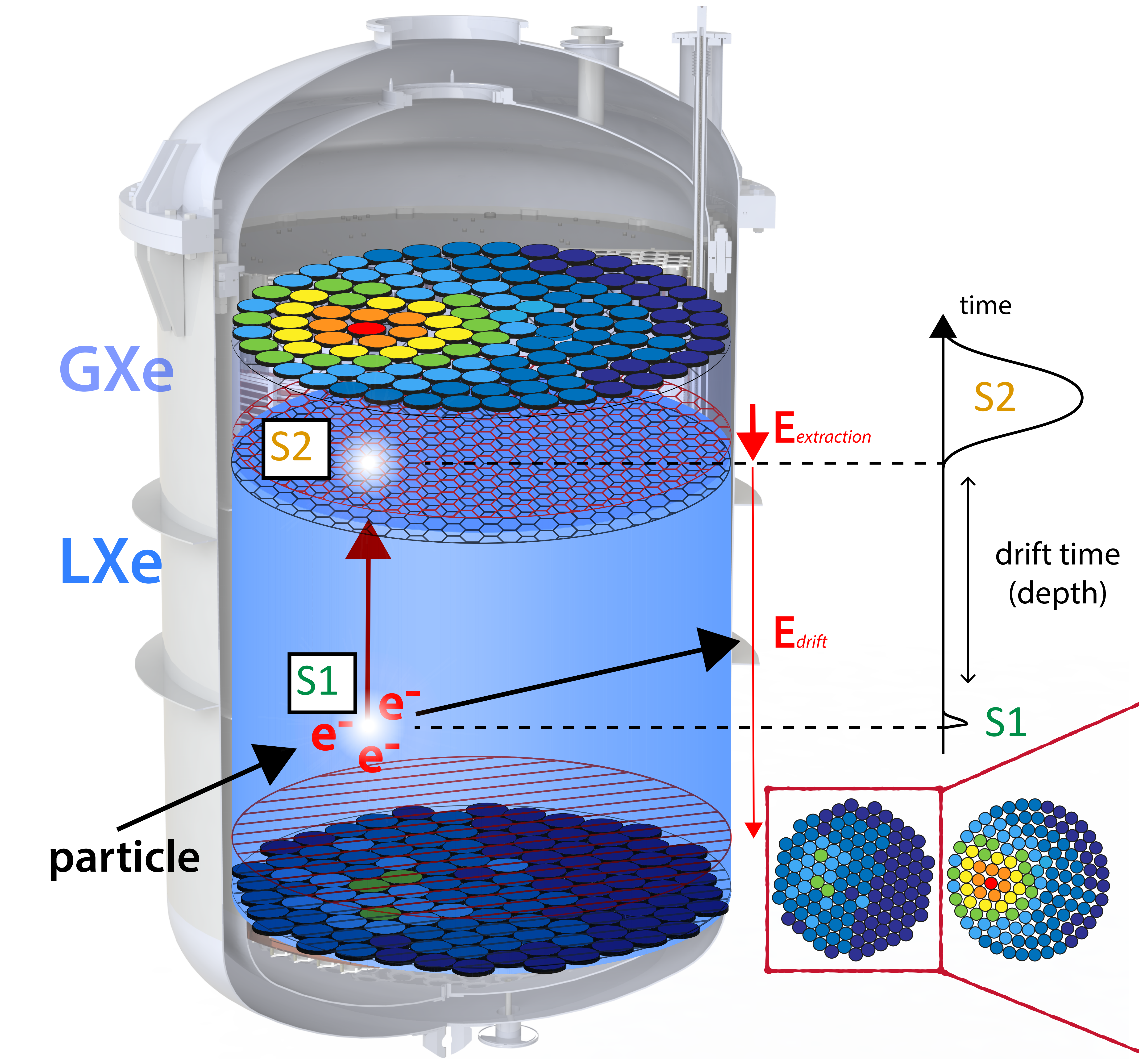
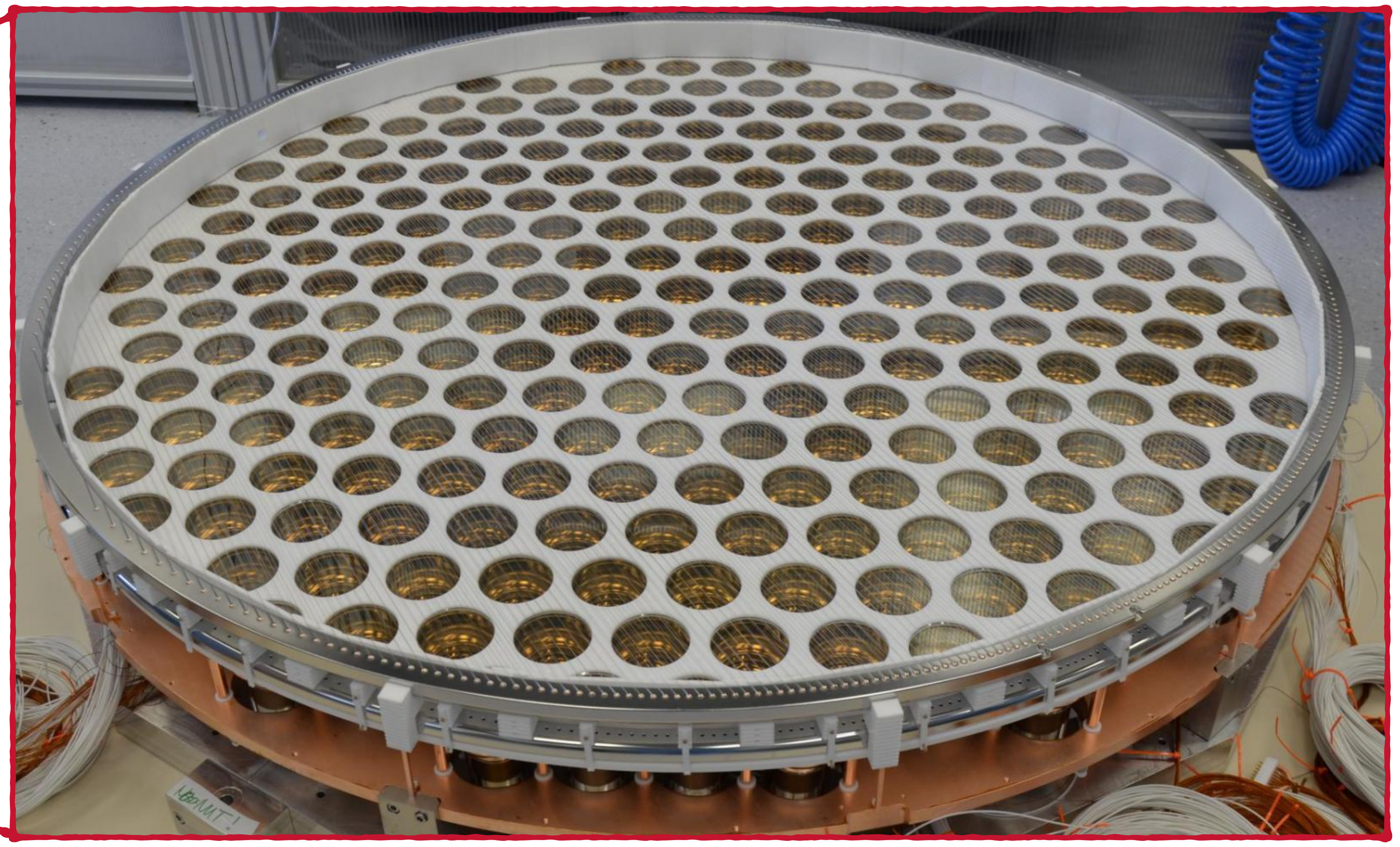
Light and Charge readout

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





TPC Detection Principle

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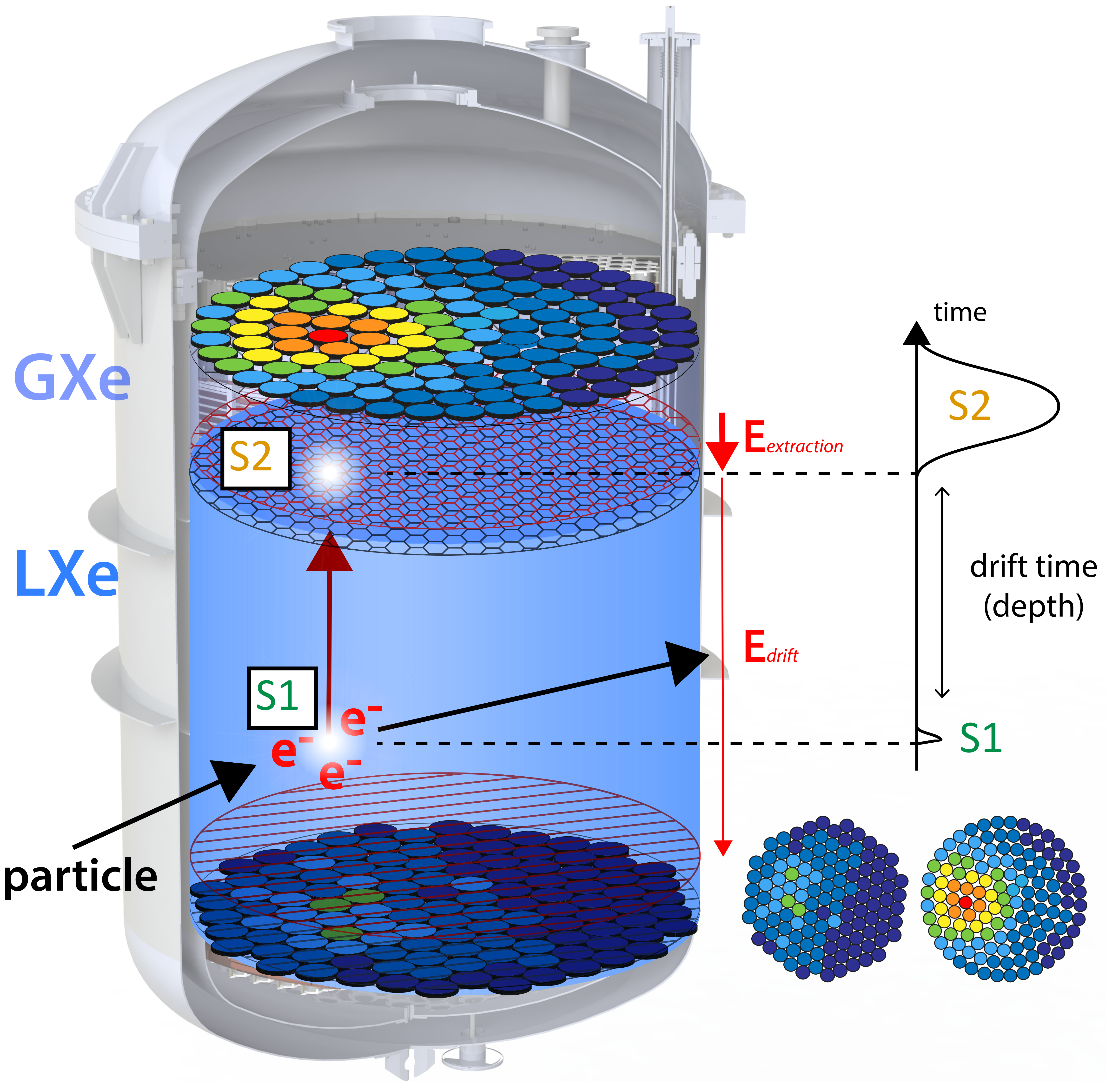
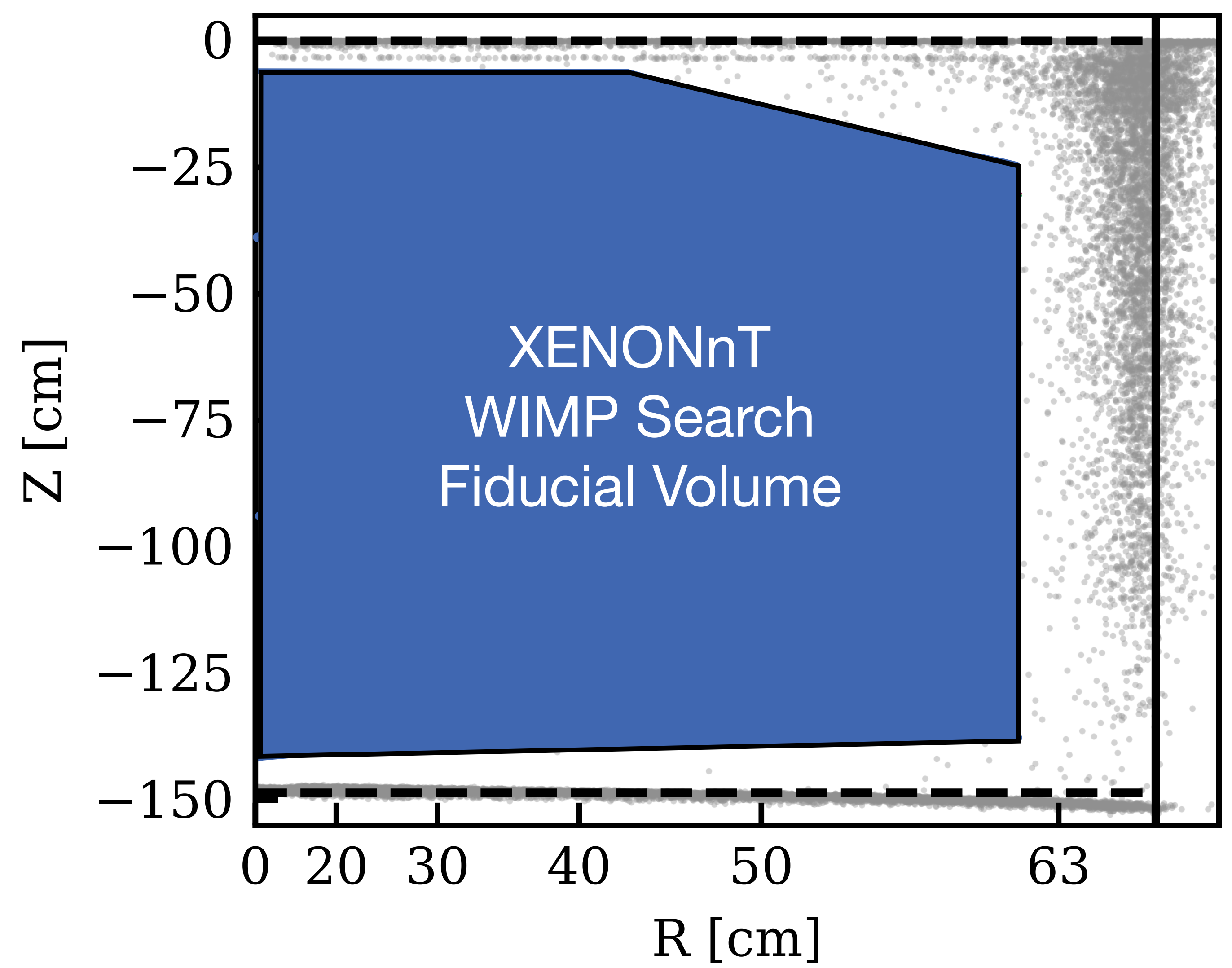


Light and Charge readout

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

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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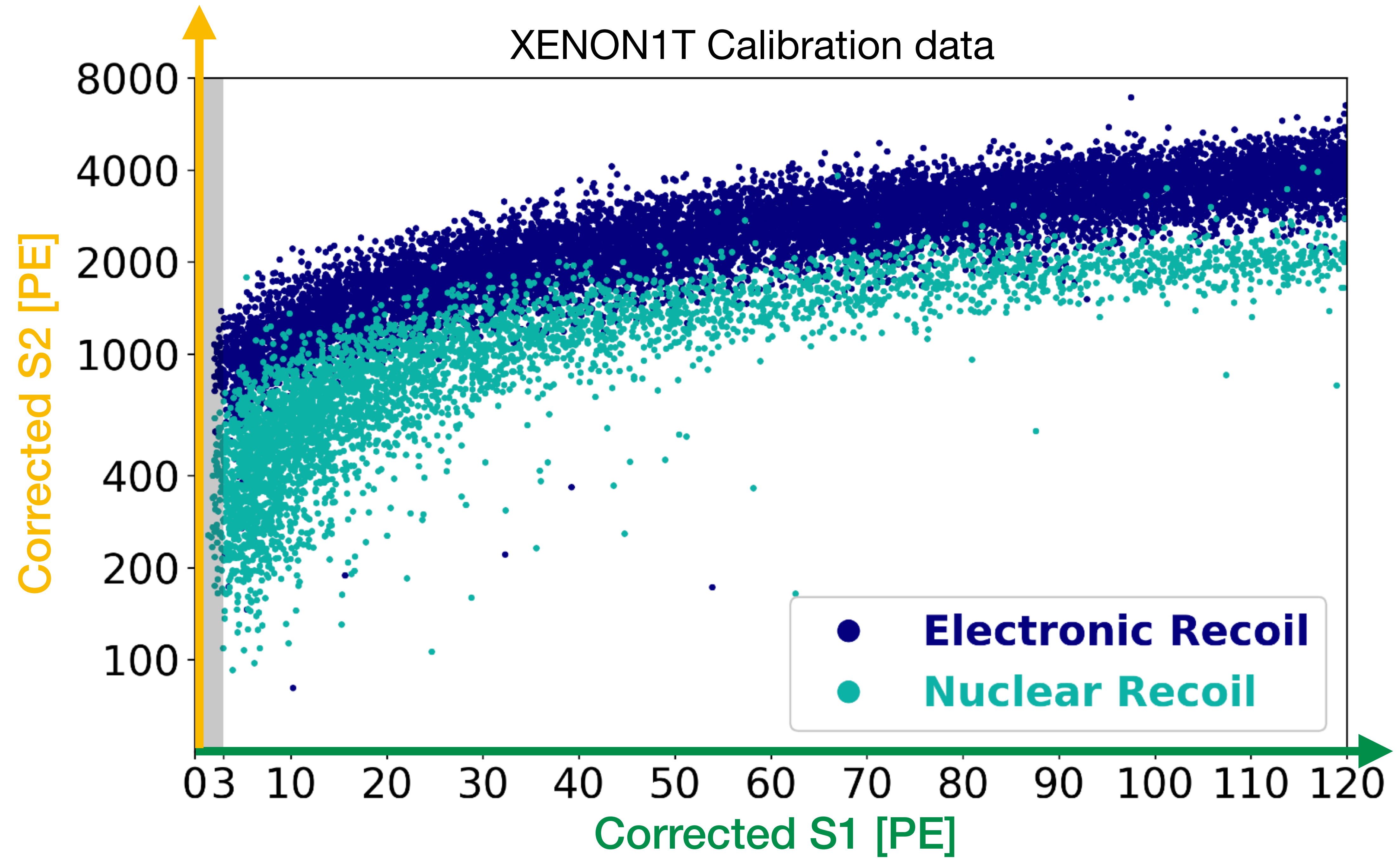

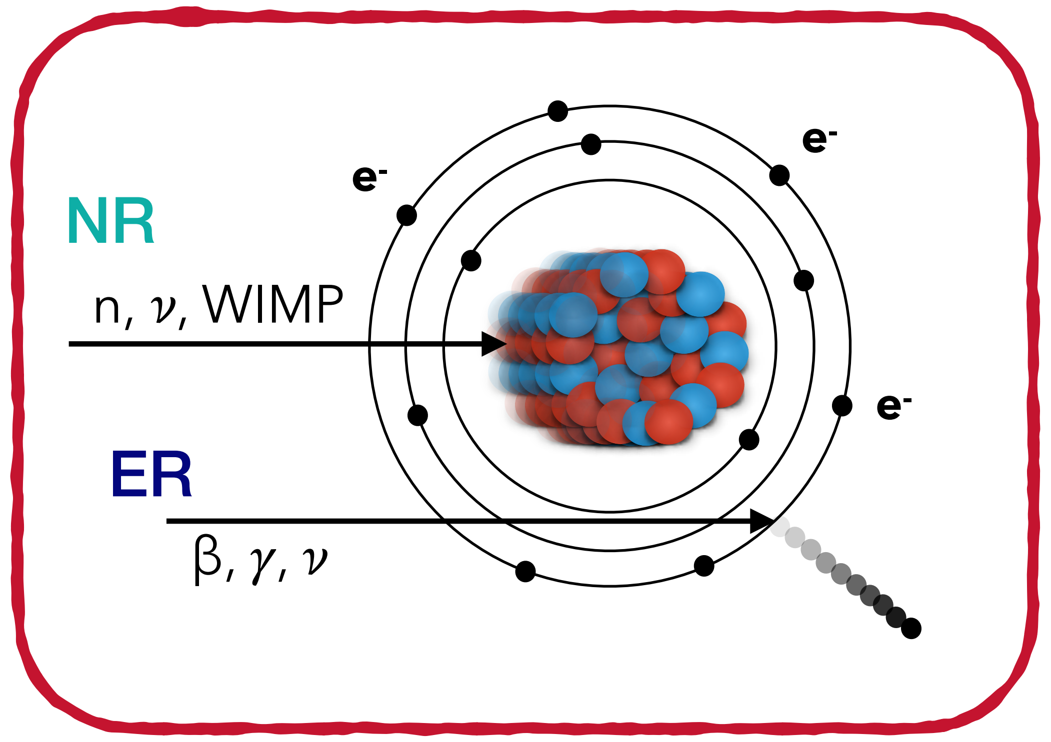

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Particle discrimination

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

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

XENONnT - Science Run 0

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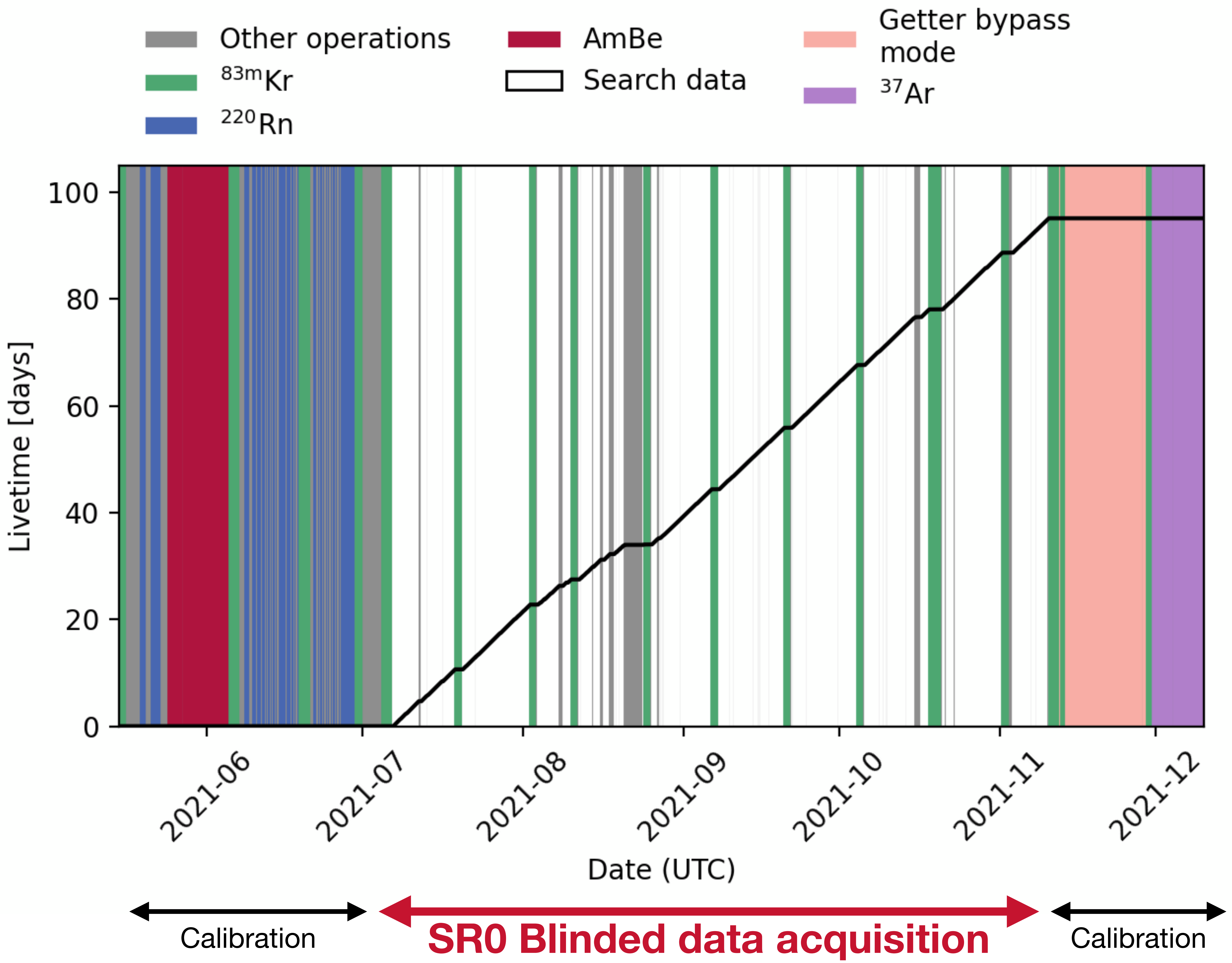

Science run summary

- July 6 to Nov 10, 2021 (97.1 days)
- 95.1 days lifetime corrected
- 4.18 ± 0.13 tonnes Fiducial Volume
- Exposure: 1.1 tonne-year
- **Blinded data analysis**

Detector configuration

- Drift field: 23 V/cm
- Extraction field: 2.9 kV/cm (~50% e^- extr. eff.)
- 477 out of 494 PMTs working (~3.4% loss)
- **LY & CY stable at 1% and 1.9% respectively during blinded data taking**

XENON FRANCE

➡ More about data quality monitoring in XENONnT with Quentin Pellegrini Talk, Friday @ 11:00

Detector Calibration

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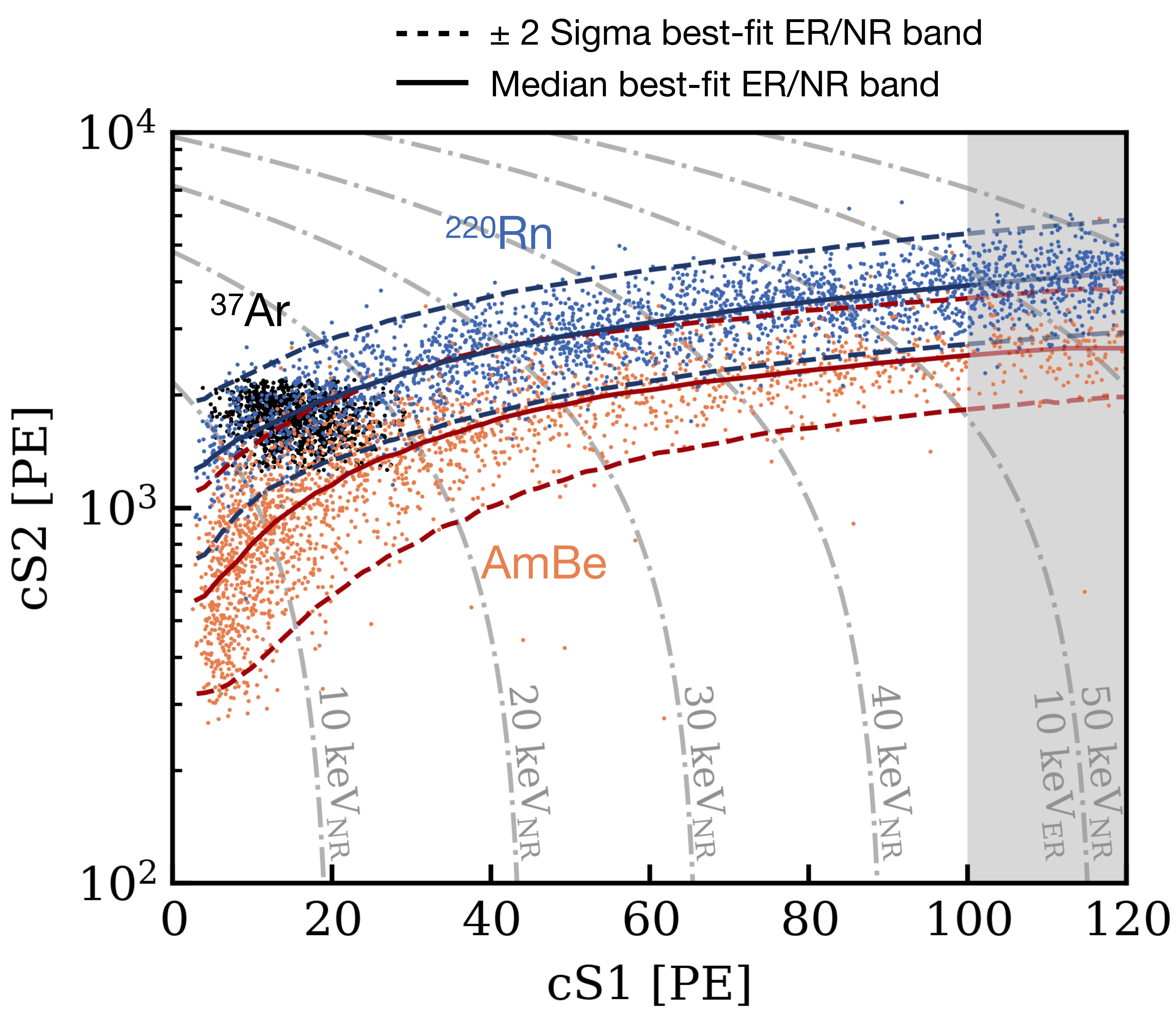

Fraction of ER events below NR median is 1.1 %

Signal Characterisation and Correction

- ^{83m}Kr internal calibration source:
  - ➡ 2 successives IC @ 32.2 keV & 9.4 keV
  - ➡ Building block of the signal correction
  - ➡ Details in an upcoming analysis paper

Selection

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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

Threshold & Efficiency

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Detection efficiency

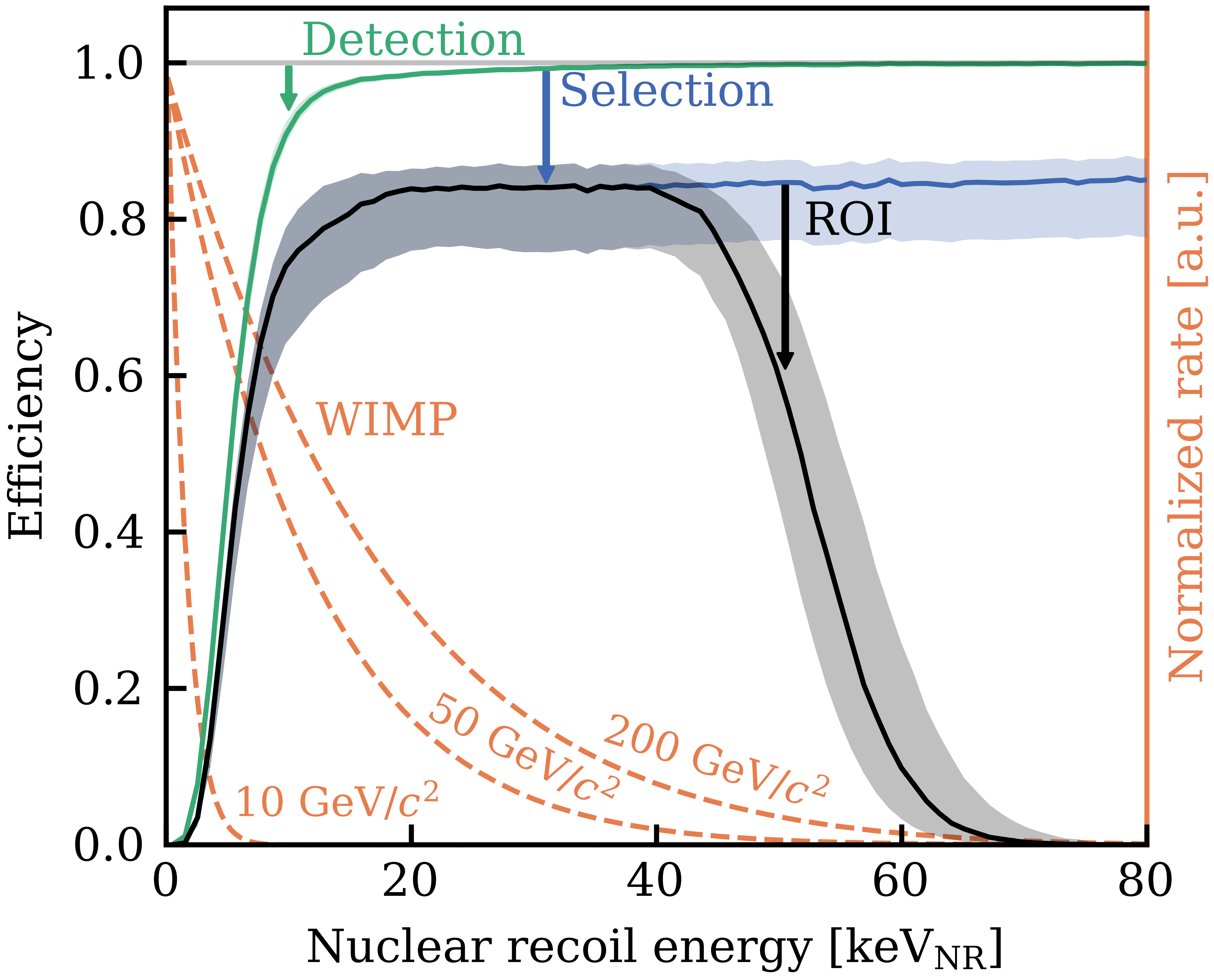
- Threshold driven by a 3-fold PMT coincidence for S1
- Validation with waveform simulation and data-driven methods

Selection efficiency

- Select Single Scatter interaction
- Quality cut evaluated using calibration data
  - ➡ Details in an upcoming analysis paper

Region of Interest (ROI)

- cS1: [0, 100] PE
- cS2: [$10^{2.1}$, $10^{4.1}$] PE



Signal and Background Models

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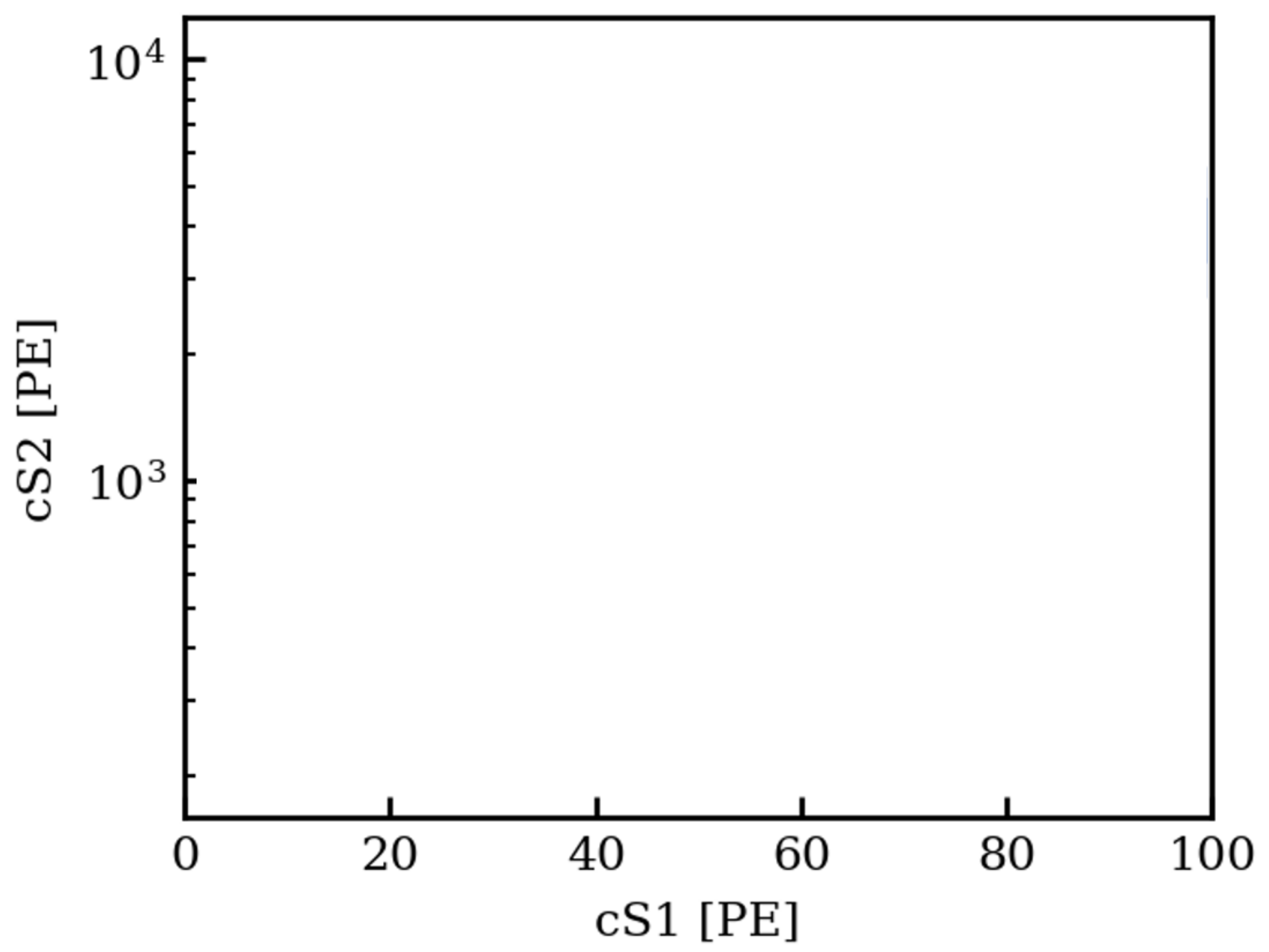

Signal and Background Models

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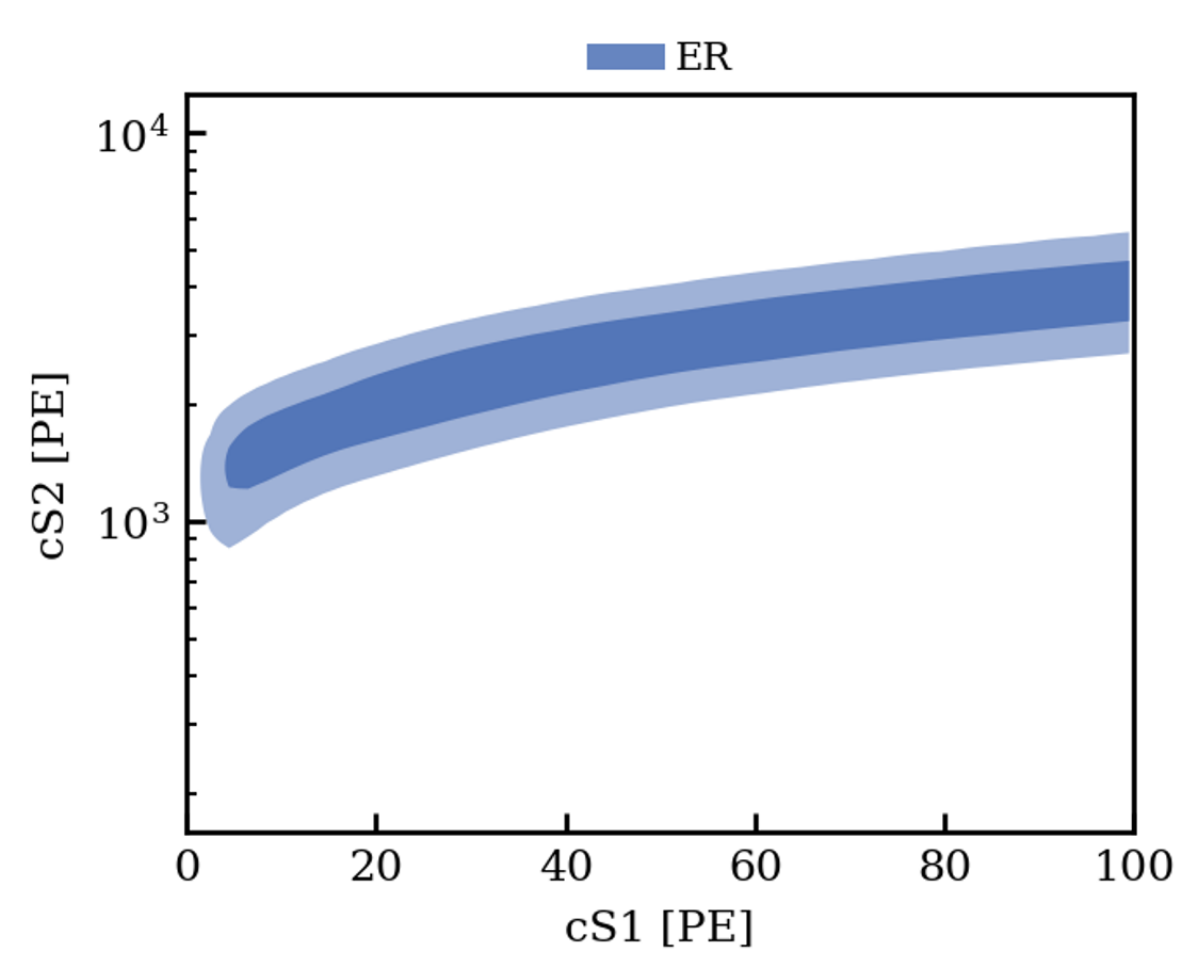
Electronic recoils

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



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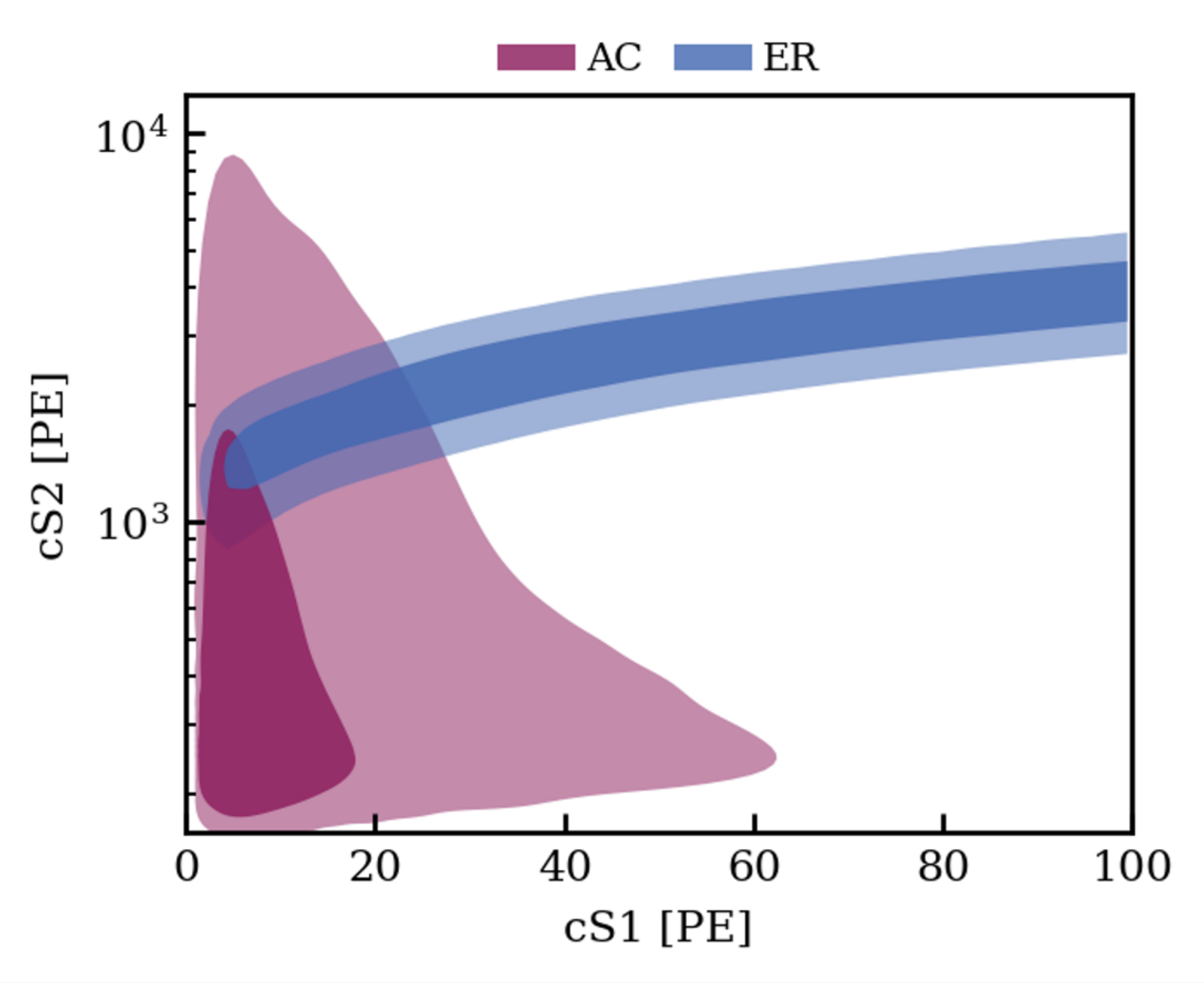
Accidental Coincidence

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



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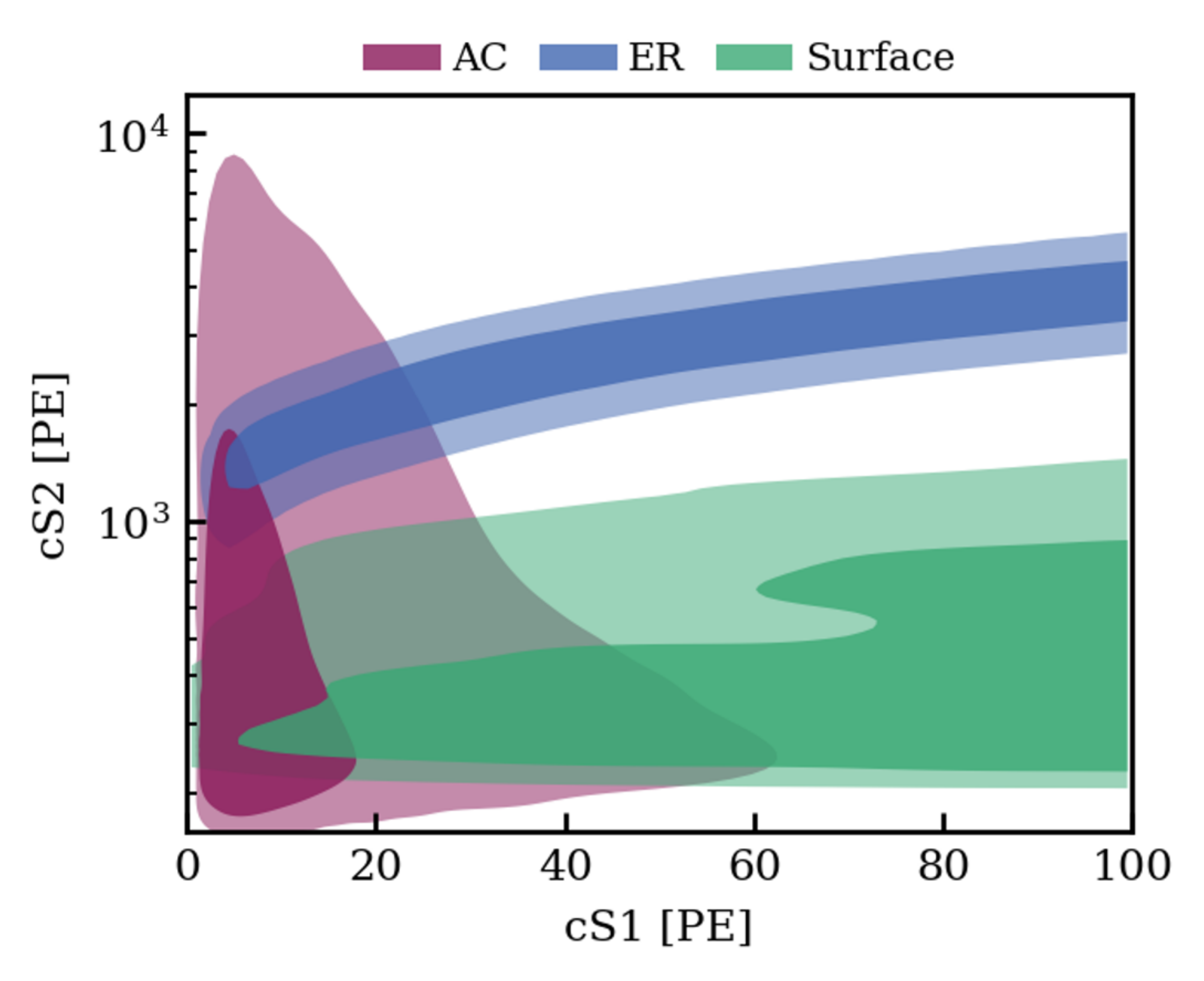
Surface

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



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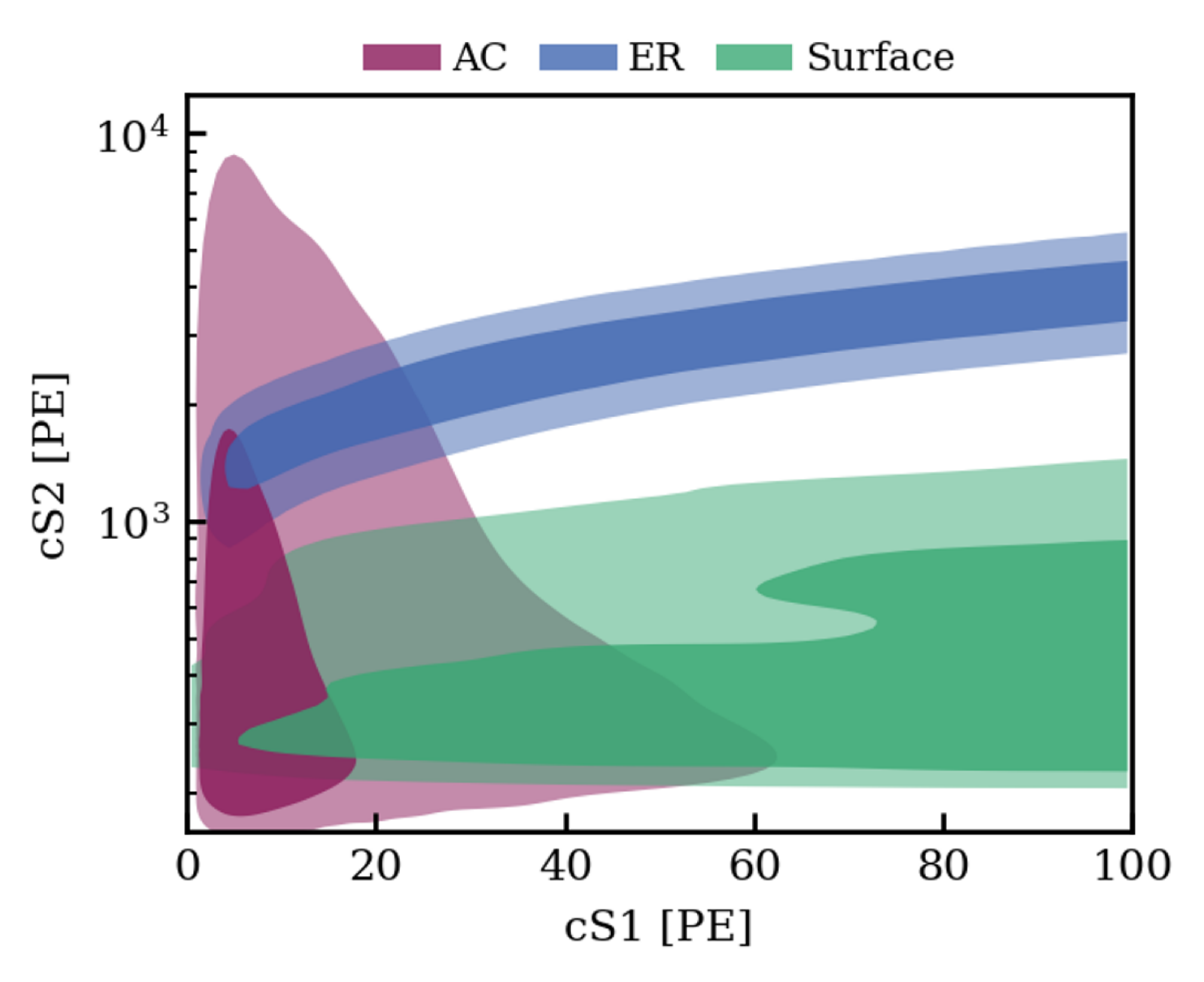
Nuclear recoils

- Radiogenic neutrons spontaneous fission & (α, n)-reactions
  - ➡ Rate prediction from NV tagging ~ 1.1 events
- Cosmogenics are negligible after μVeto
- ^{8}B CEνNS constrained by flux



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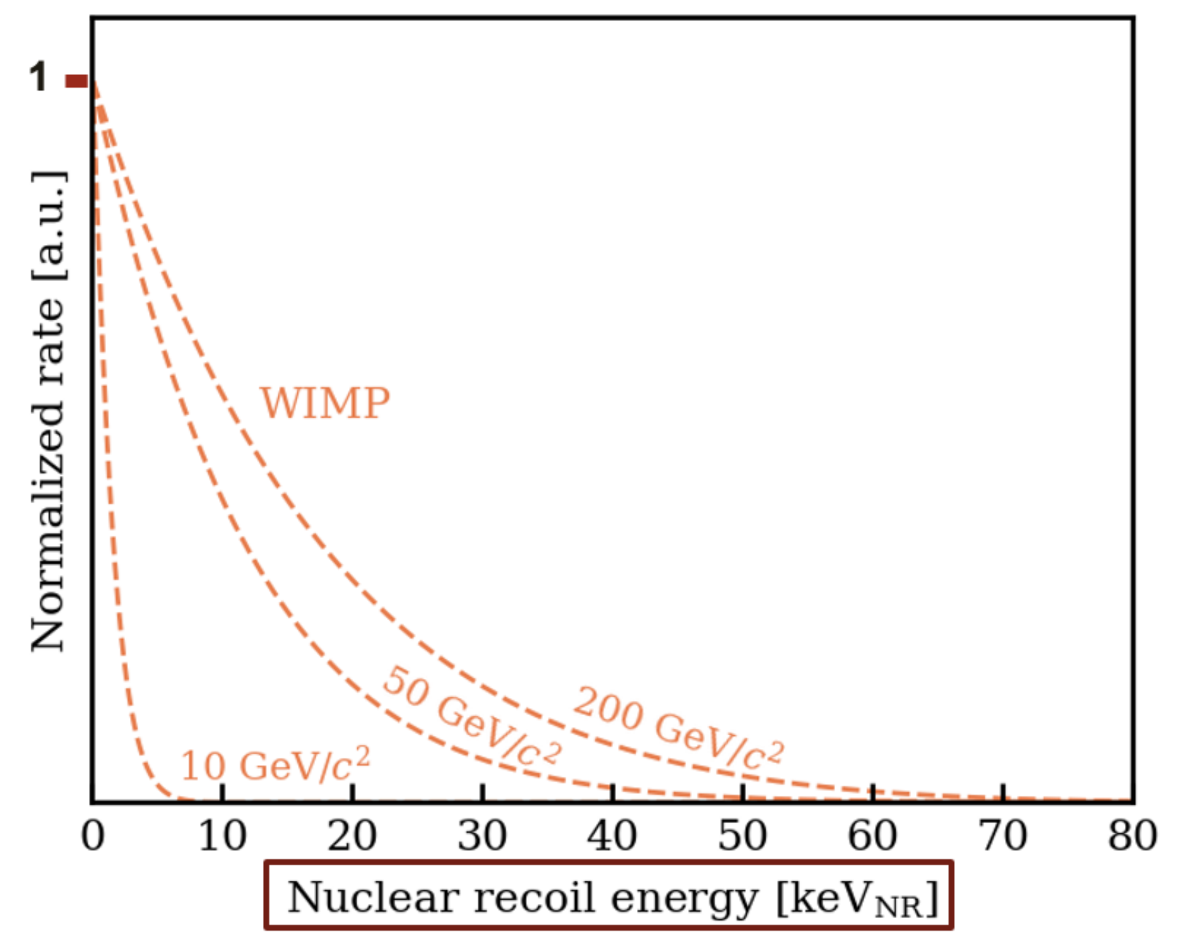
WIMP Signal Model



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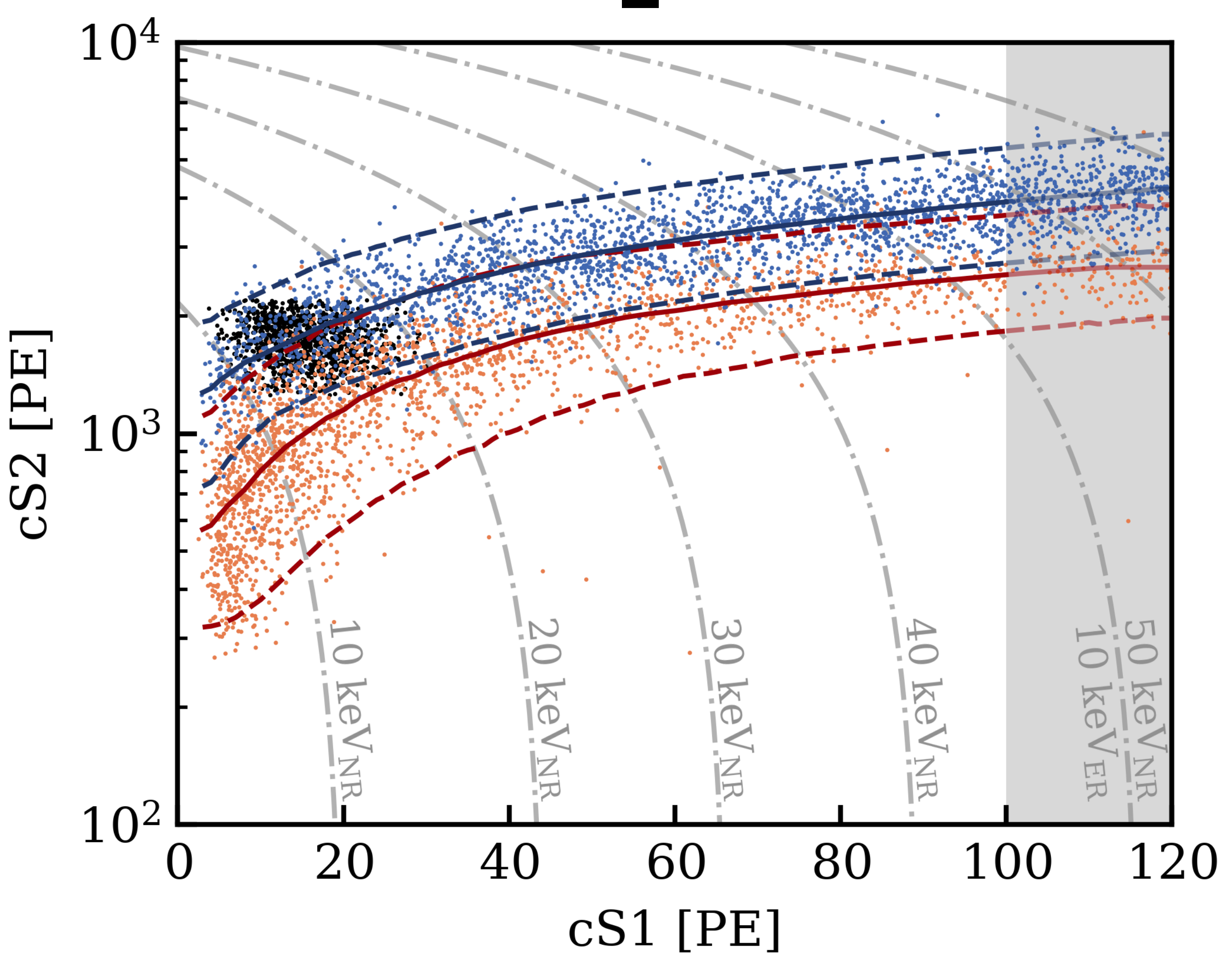
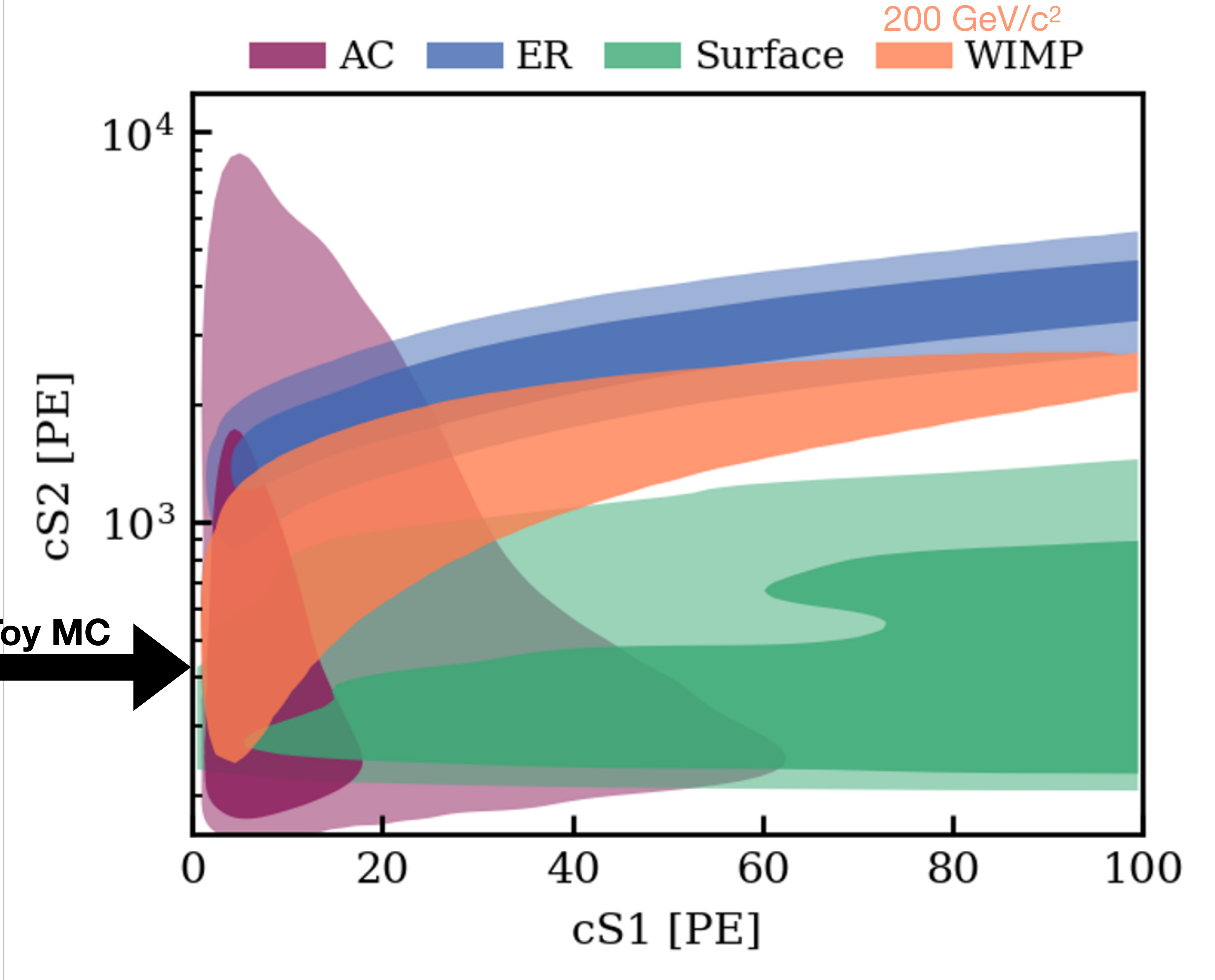


Toy MC



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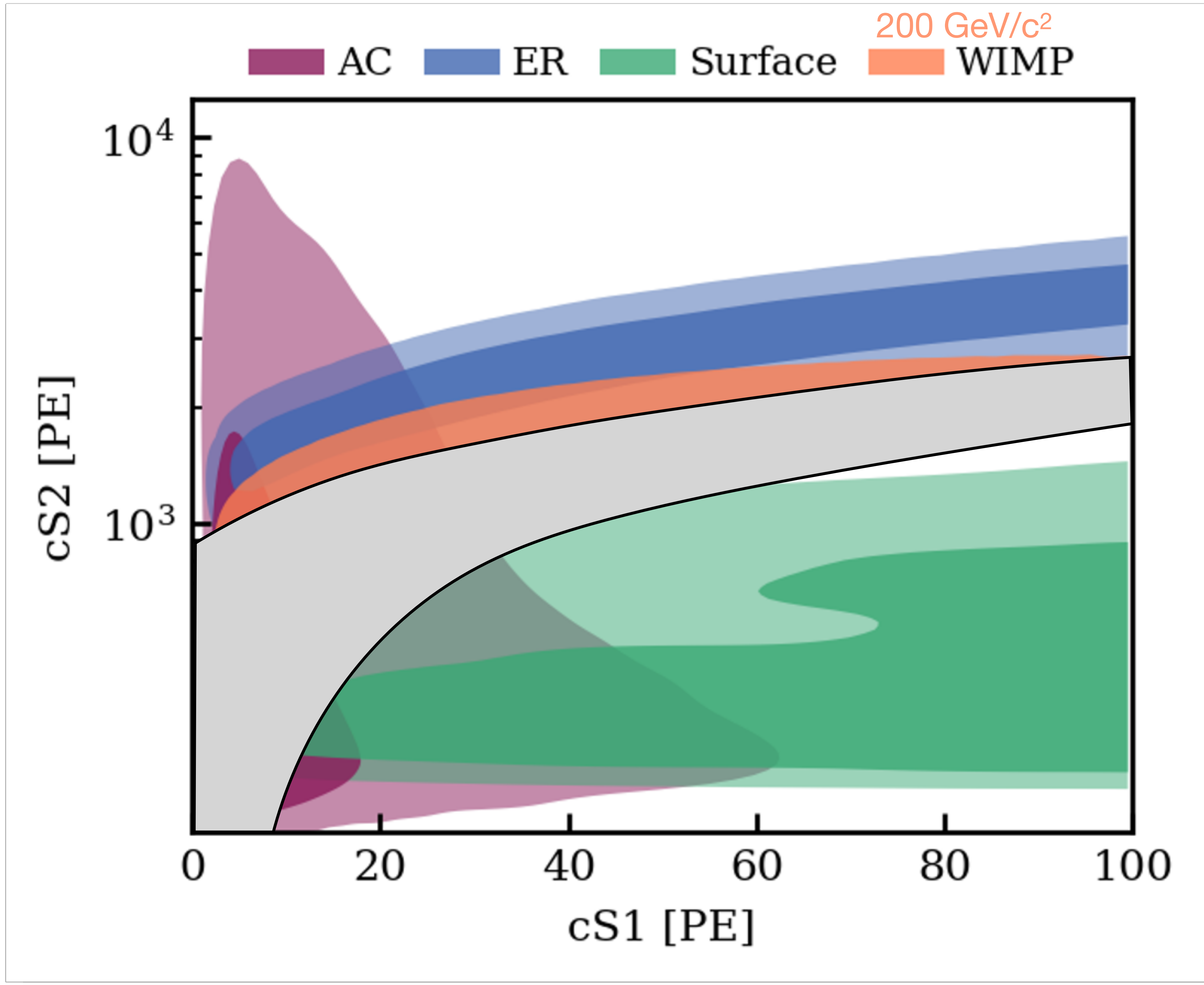

We are performing a blinded data analysis!

WIMP results

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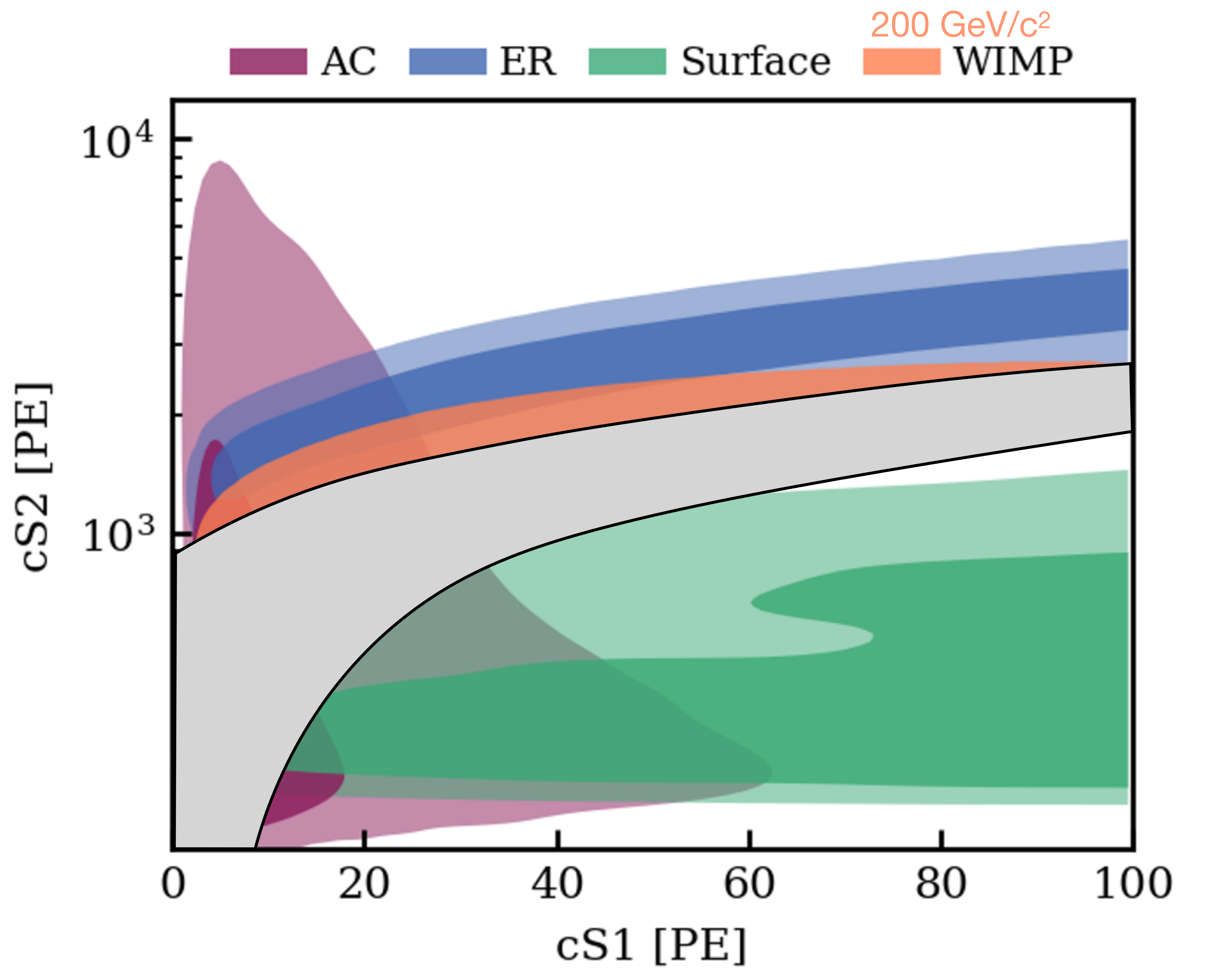
	Expectation
ER	134
Neutrons	$1.1^{+0.6}_{-0.5}$
CEvNS	0.23 ± 0.06
AC	4.3 ± 0.2
Surface	14 ± 3
Total	154
200 GeV/c² WIMP	-
Observed	-

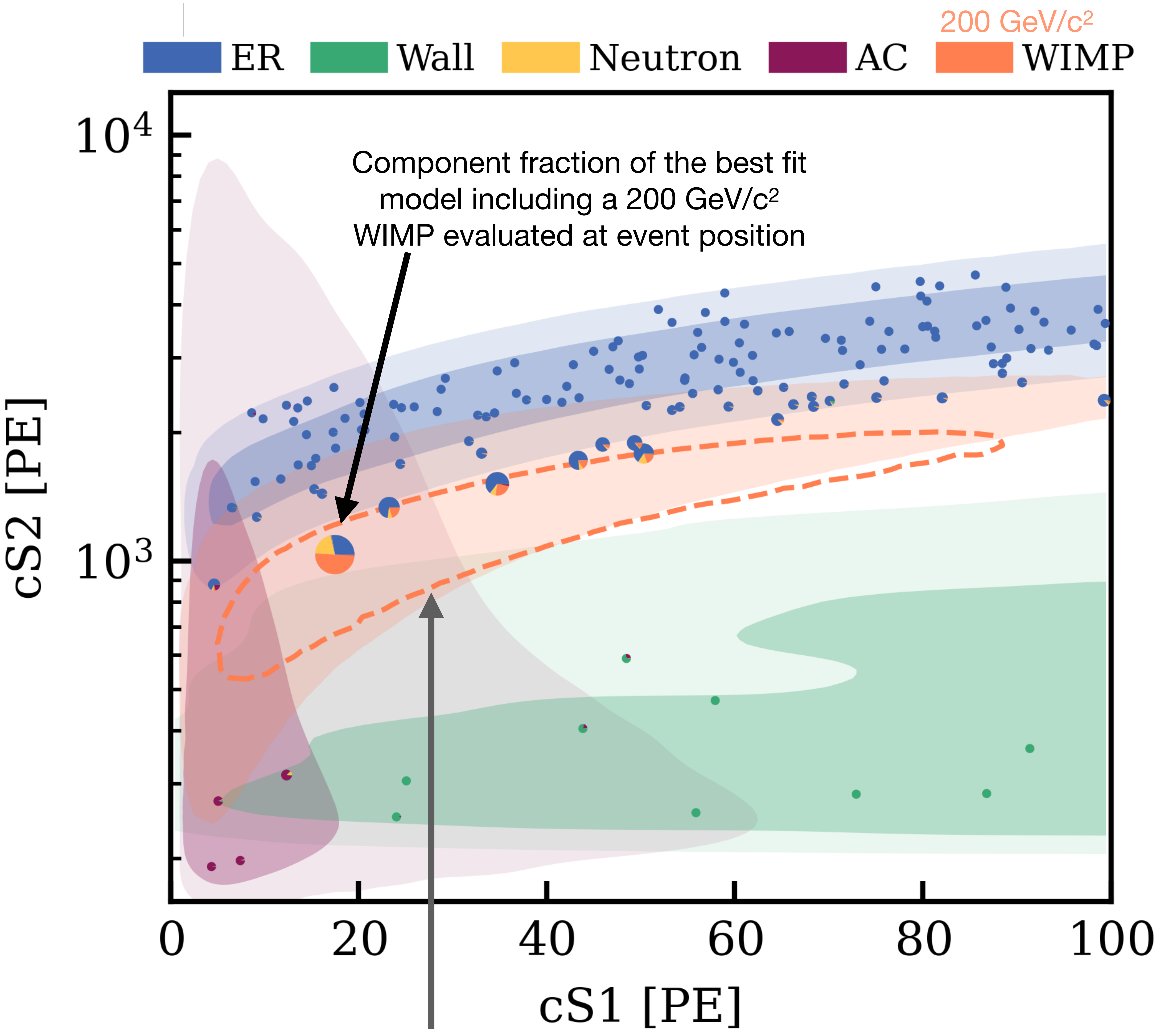


WIMP results

Unblinding

	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/c² WIMP	-	2.4
Observed	-	152

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



Signal-like region, containing 50% of a 200 GeV/c² WIMP signal with highest signal-to-noise ratio

WIMP spin-independent limit

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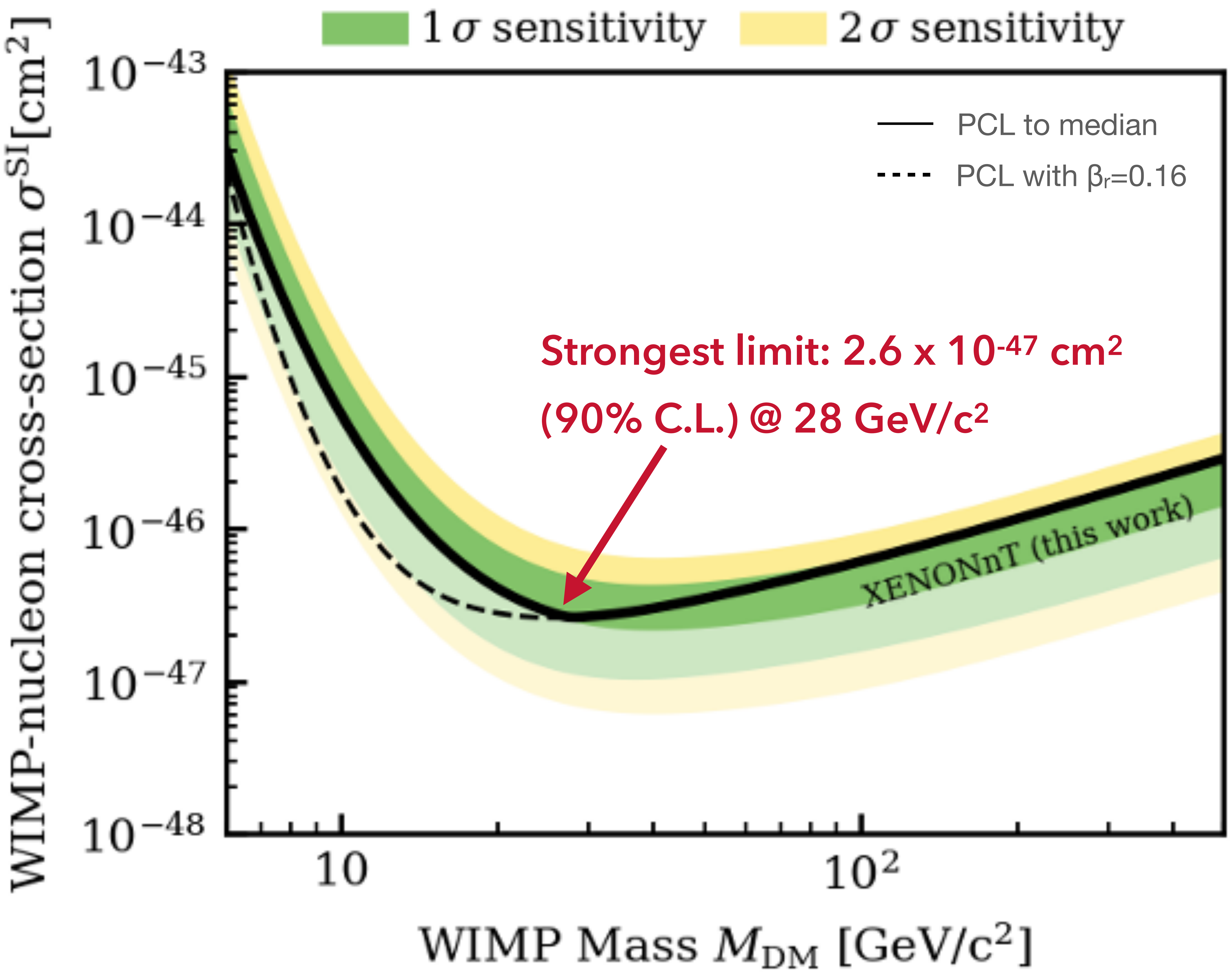
- **Community had agreed on prescriptions for Power-Constrained Limit (PCL)** [1]
  - ➡ **Wrong prescription for PCL critical threshold β_r** in [1] (β_r = 0.16), defined on discovery power instead of rejection power w.r.t. [2]
  - ➡ Choice of minimum rejection power of 50% (β_r = 0.50) , i.e. **constrain limit to median of sensitivity band**
  - ➡ **Conservative choice** before the community re-discuss the topic and agree on a specific value



[1] D. Baxter et al, "Recommended conventions for reporting results from direct dark matter searches" [EPJC 81 (2021)]

[2] G. Cowan, K. Crammer, E. Gross, O. Vitells, "Power-Constrained Limits". arxiv:1105.3166

Comparison with recent results

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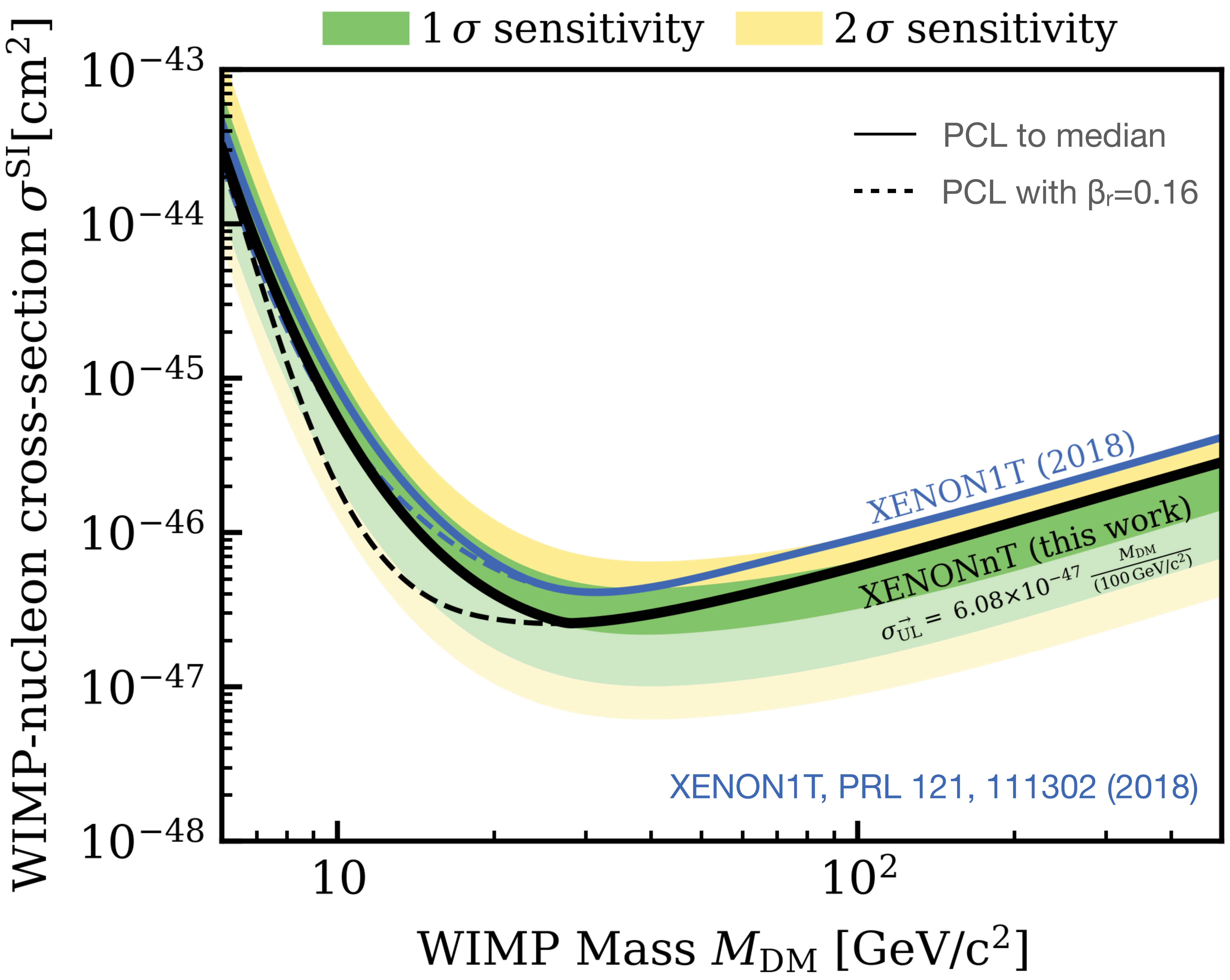
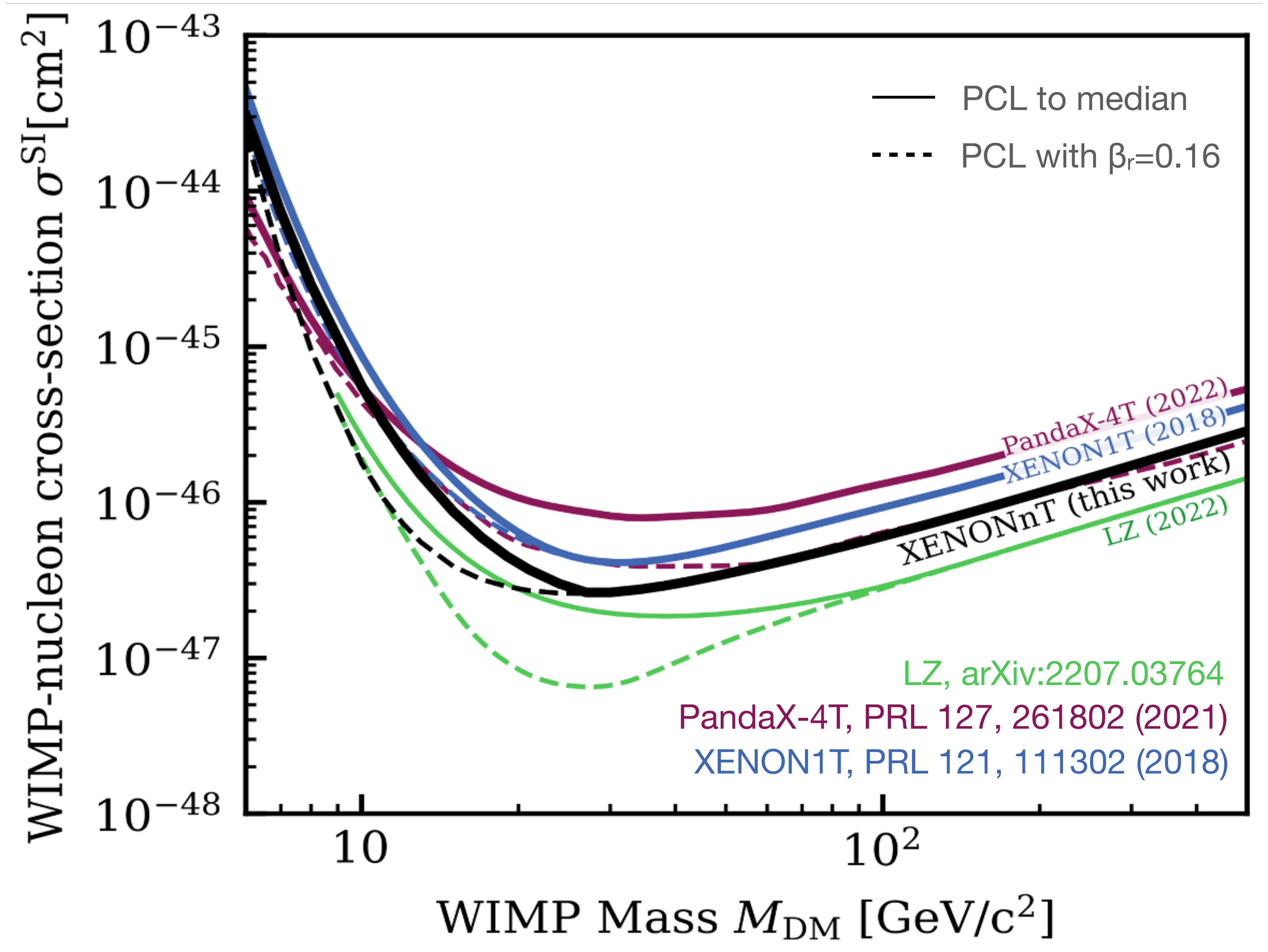
From **blinded** analyses



Improved w.r.t. XENON1T by a factor x1.6 with a similar exposure

From **non-blinded** analyses



Same PCL applied to results of other recent LXe experiments

Conclusion & Outlook

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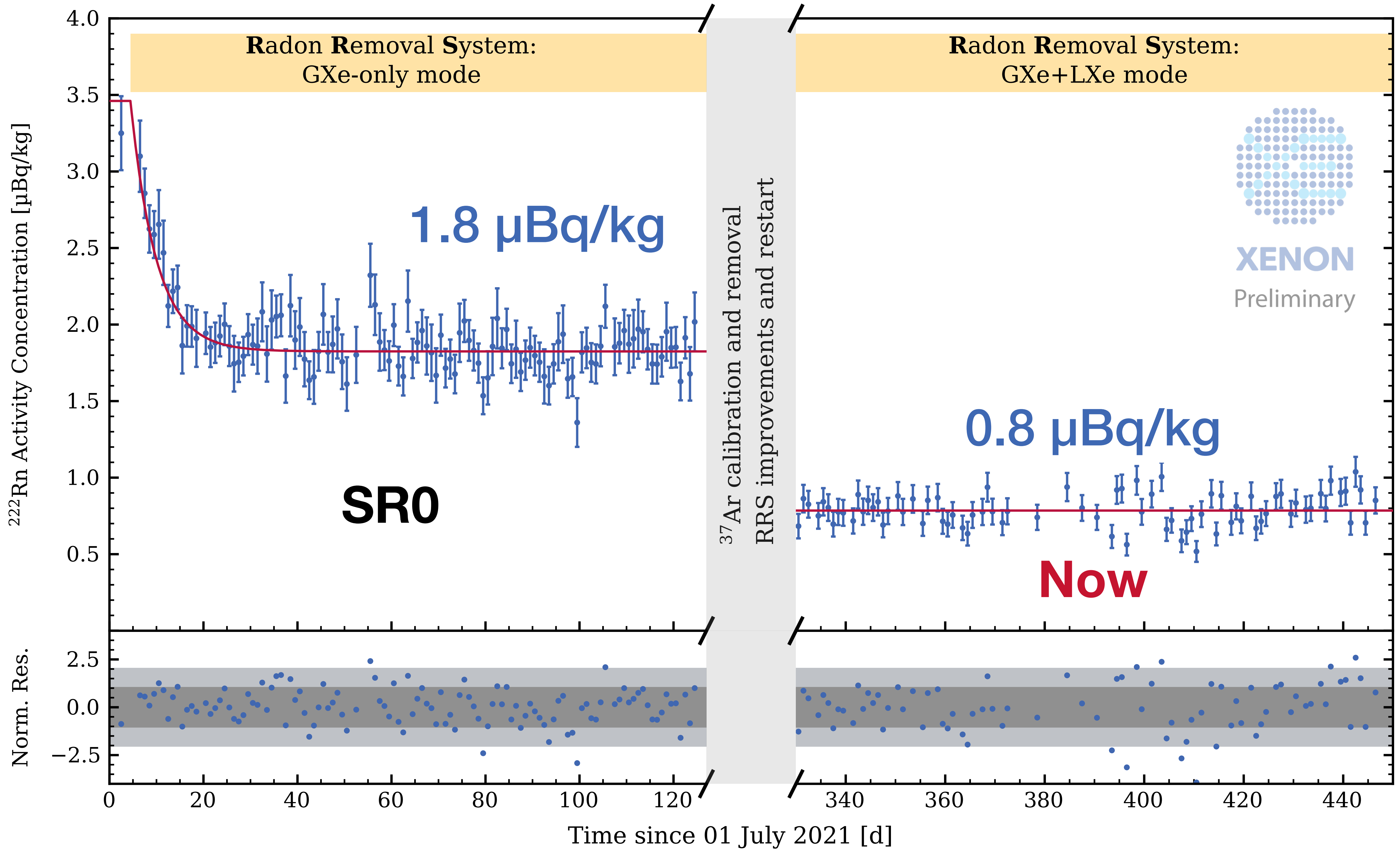
Summary

- **XENONnT SR0** → blinded Dark Matter search with 1.1 t x yr exposure
- **SI limit of 2.6 x 10^{-47} cm² (90% C.L.) @ 28 GeV/c²**
- **Unprecedented low-ER background**
  - ➡ ~ 16 events / (t . y . keV)

XENONnT WIMP result
arXiv:2303.14729

Prospects

- Further reduction of ER background by improved radon distillation flow path
- Gd-loaded water in the nVeto will improve our neutron tagging efficiency
- And even more physics!



Even more physics to come!

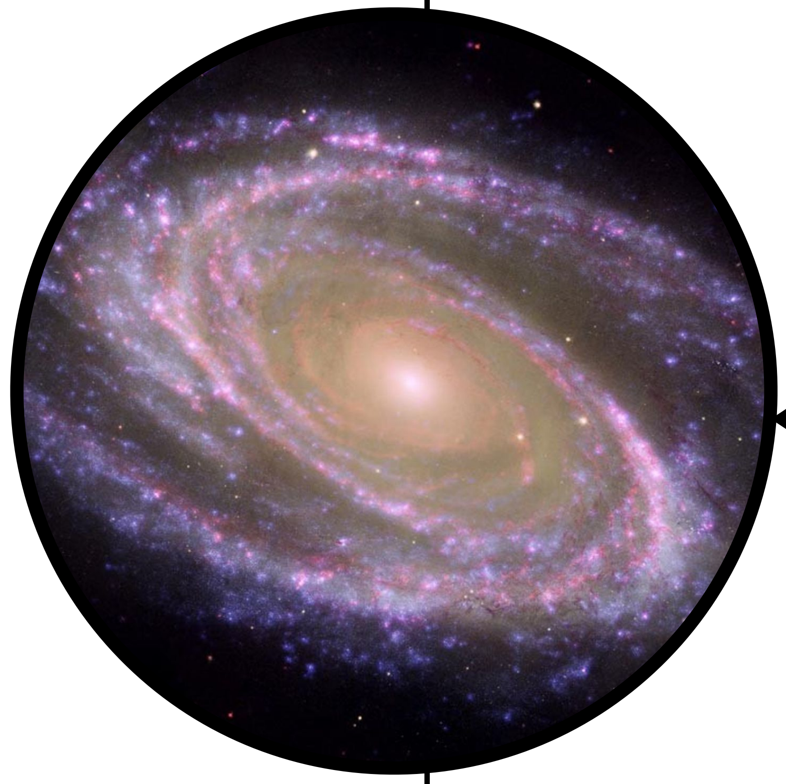
Maxime Pierre
maxime.pierre@nikhef.nl

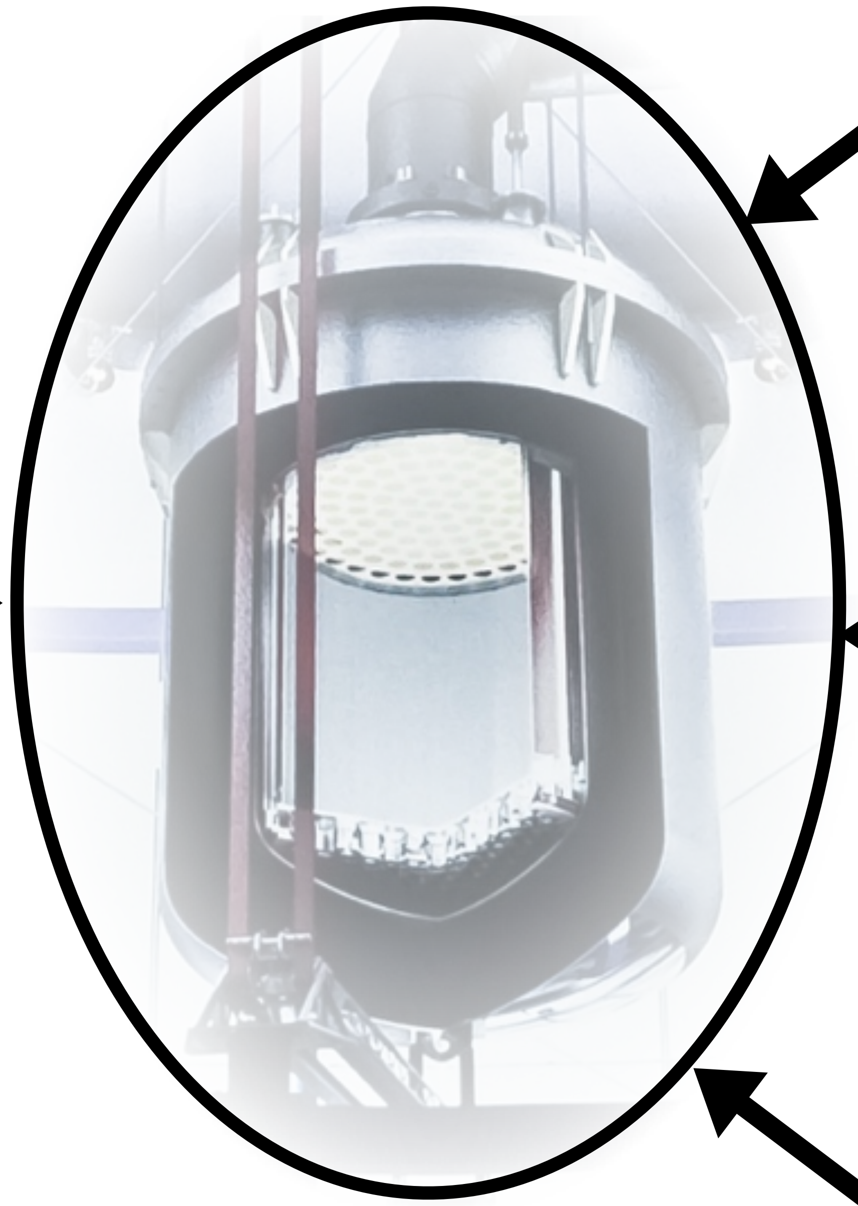
WIMPs

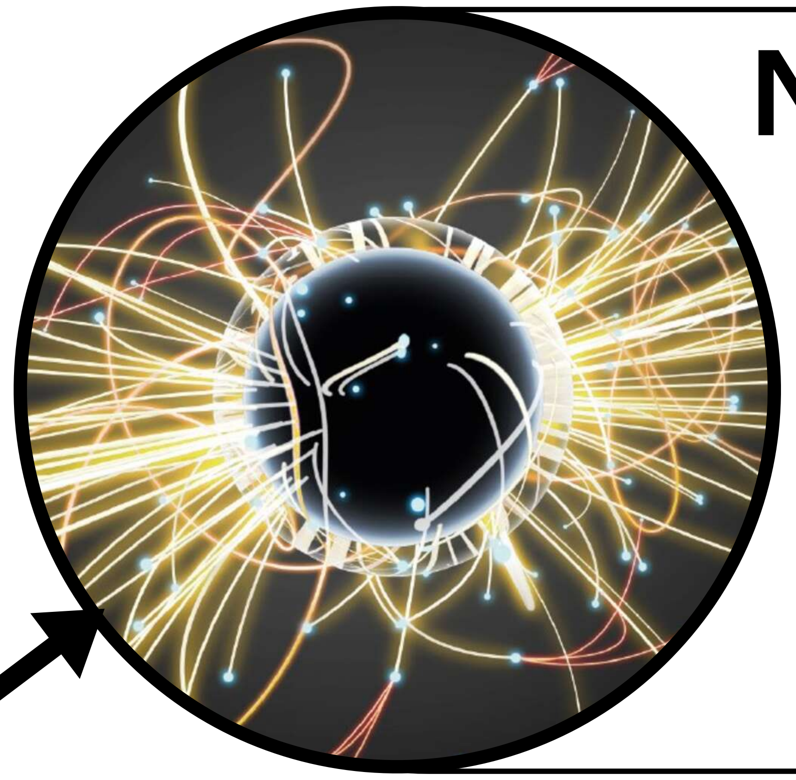
- Spin-independent
  - ➡ PRL 119, 181301
  - ➡ PRL 121, 111302
- Spin-dependent
  - ➡ PRL 122, 141301
- Sub-GeV
  - ➡ PRL 122, 071301
  - ➡ PRD 103, 063028

Dark Matter

- Light DM
  - ➡ PRL 123, 241803
  - ➡ PRL 123, 251801
- Bosonic DM
  - ➡ PRD 102, 072004

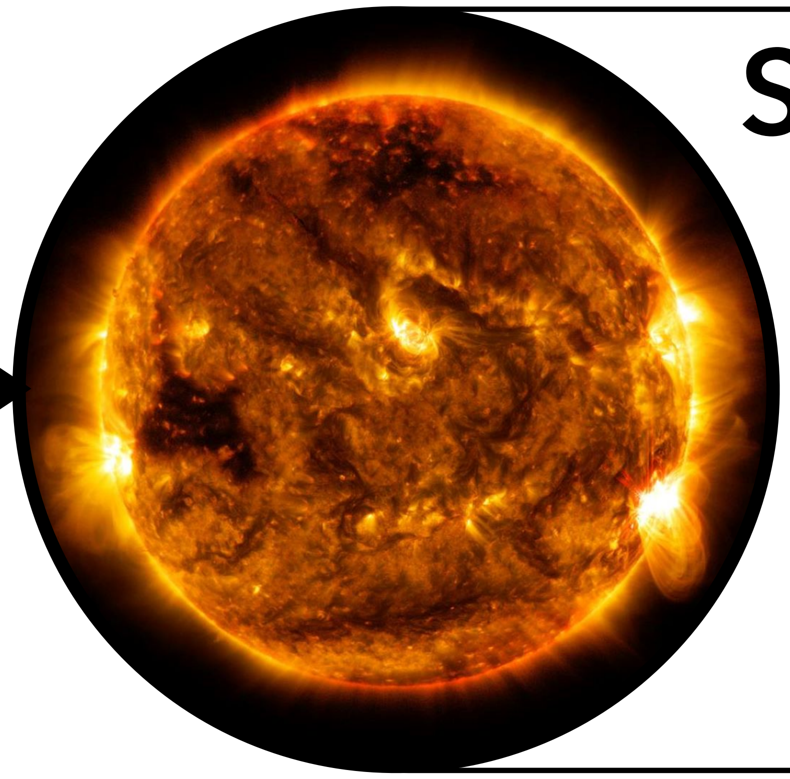






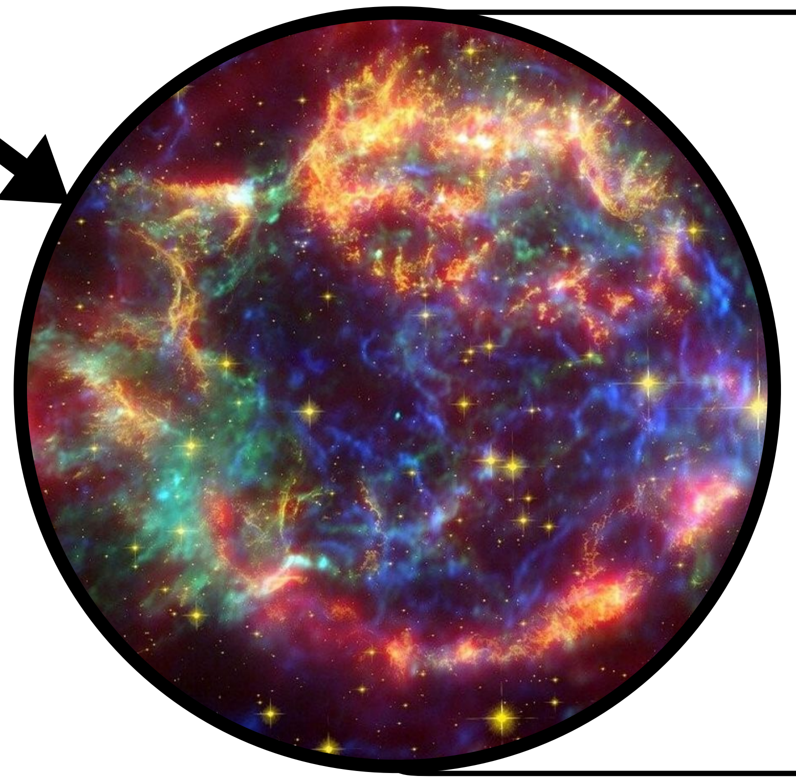
Nuclear/Particle Physics

- 2νECEC capture
  - ➡ Nature 568, 532
- $0\nu\beta\beta$ decay
  - ➡ EPJC 80:785 (2020)



Sun

- Solar ^{8}B CEvNS
  - ➡ PRL 126, 091301
- Solar pp neutrinos
  - ➡ EPJC 80:1133 (2020)
- Solar axions
  - ➡ PRD 102, 072004



Supernova

- Supernova neutrinos
  - ➡ PRD 94,103009
- **Follow Daniel Layos talk, Thursday @ 14:00**

XENON FRANCE

Contribute to the broadening of the physics goal of XENONnT

Even more physics to come!

Thank you for your attention!

Dark Matter

WIMPs

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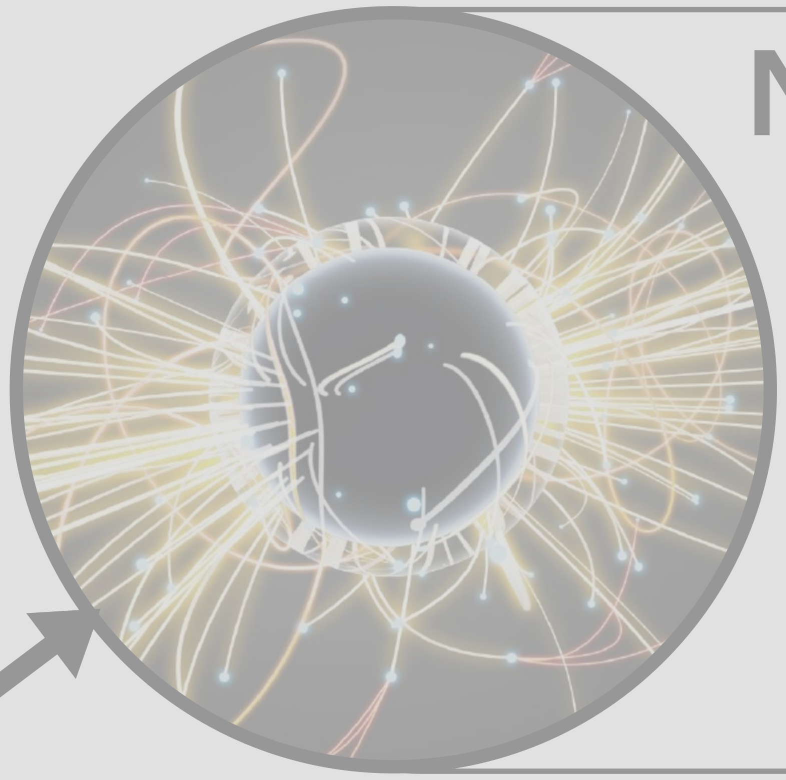

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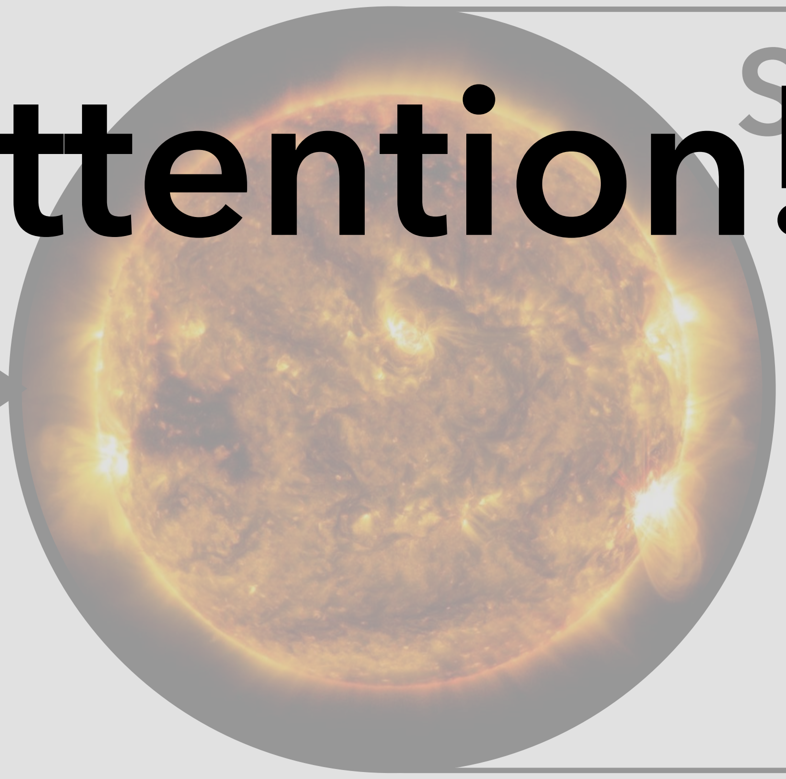

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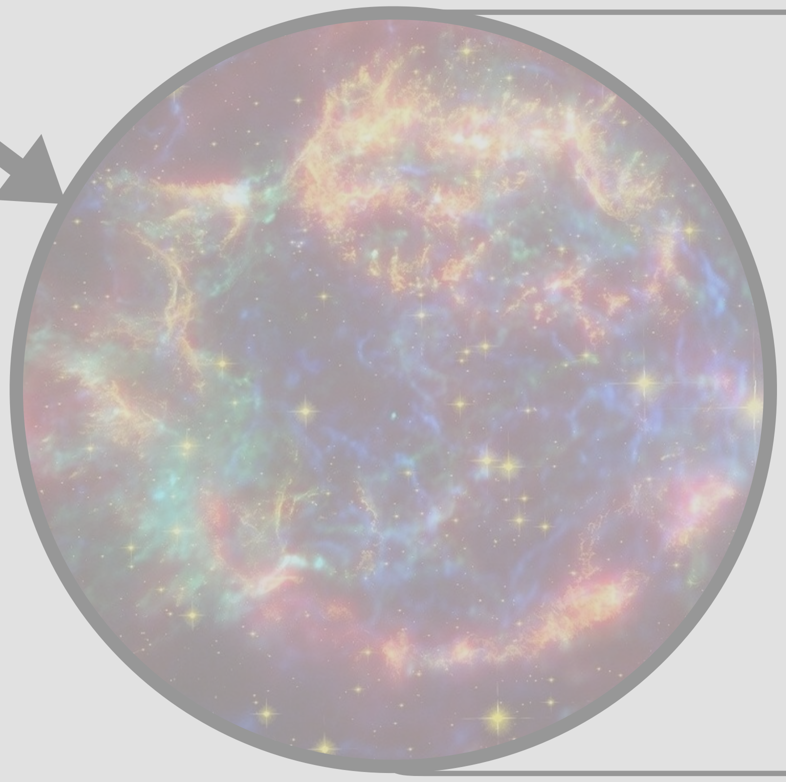

Supernova

- Supernova neutrinos
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XENON FRANCE

Contribute to the broadening of the physics goal of XENONnT

Back-up: WIMP spin-dependent limits

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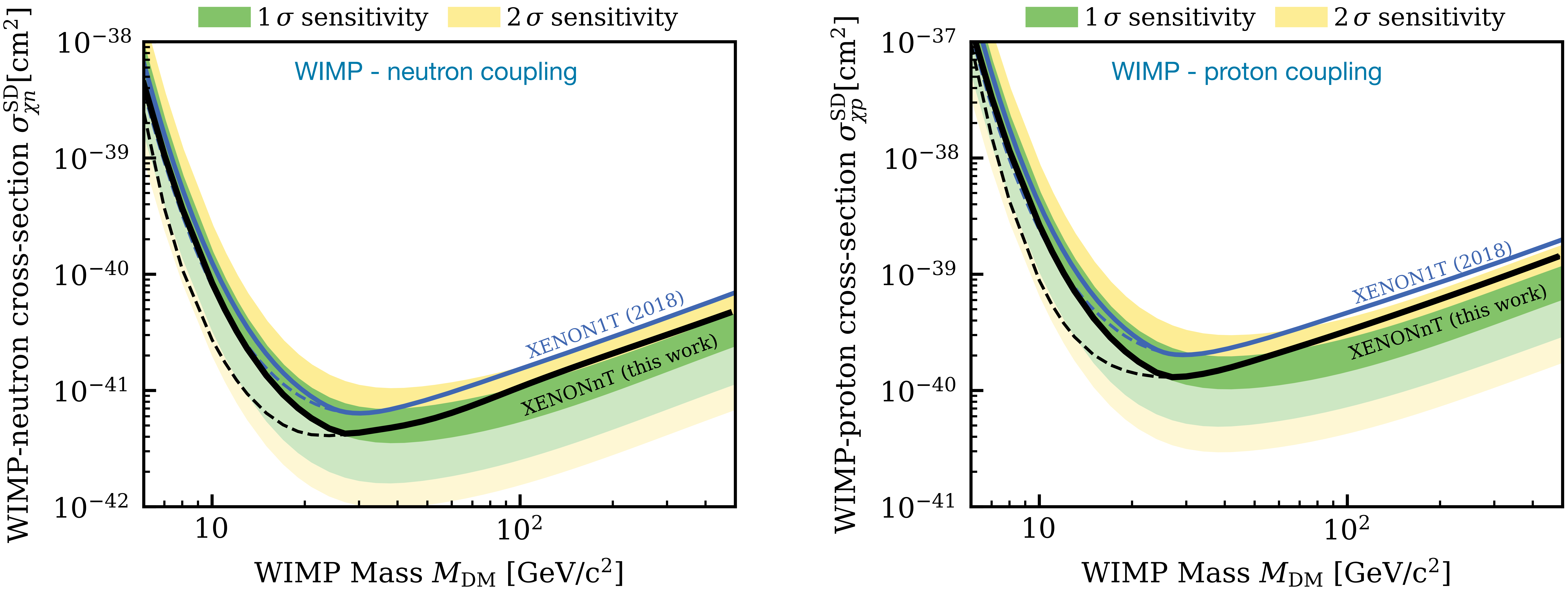
Reinterpreting results as a purely spin-dependent coupling to ^{129}Xe and ^{131}Xe



Back-up: Inference

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$$q(\sigma) = -2\log\frac{L(\sigma,\hat{\hat{\theta}})}{L(\hat{\sigma},\hat{\theta})}$$

Nuisance parameter

Science data Likelihood term

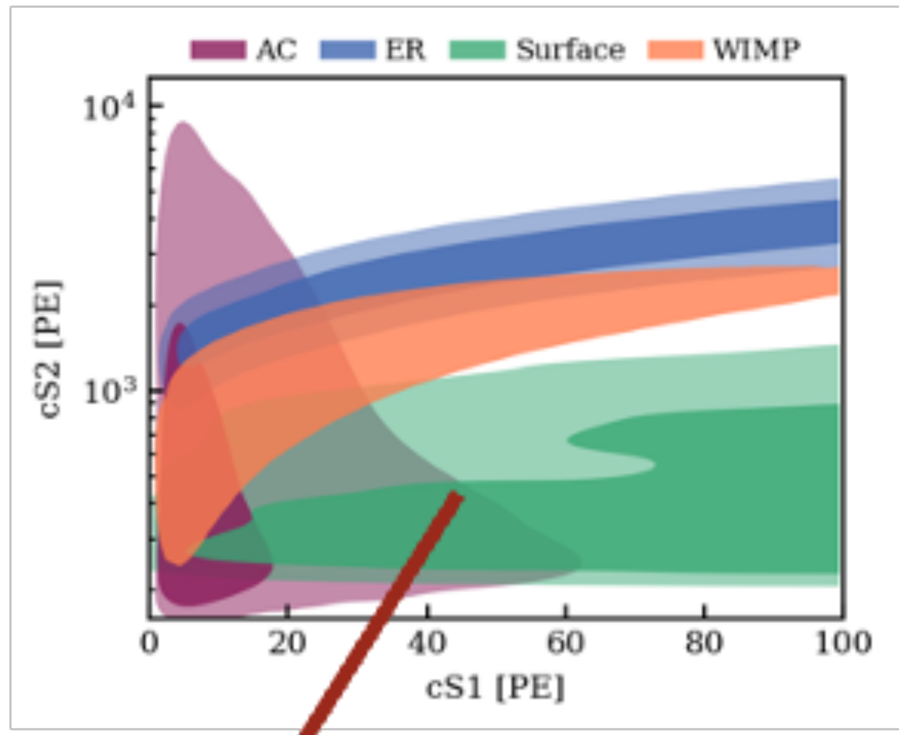
ER calibration term to constraint shape uncertainty

Auxiliary likelihood for nuisance parameters like background rates

$$L_m(\mu_c) = N(\mu_c \,|\, \widehat{\mu_c}, \sigma_c)$$

$$\log L(\sigma,\theta) = \sum_{i=\{near,\,far\}} \log L_{SR0,i}(\sigma,\boldsymbol{\theta}) + \log L_{cal}(\boldsymbol{\theta}) + \sum_m \log L_m(\theta_m)$$

Cross section



Expected number of events from component

$$L_{SR0,i}(\sigma,\theta) = \mathrm{Pois}\big(N_{SR0,i} \,|\, \mu_{tot}(\sigma,\theta)\big) \sum_c \frac{\mu_c(\sigma,\theta)}{\mu_{tot}(\sigma,\theta)} \cdot f_c(\vec{x_i}|\theta)$$

WIMP mass enters through μ_{WIMP}

total sum over all components

Credit: Daniel Wenz

Back-up: Energy reconstruction

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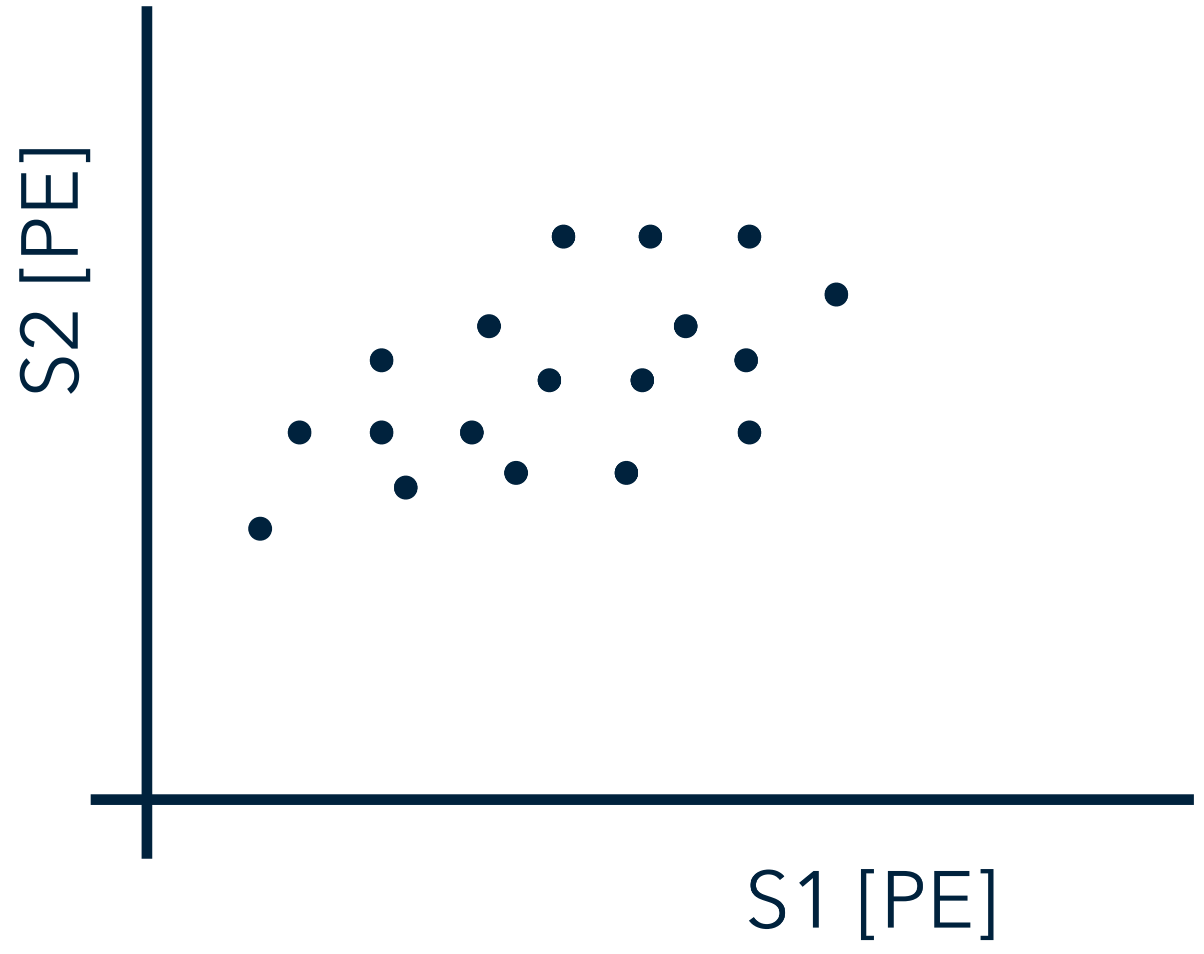
Combined energy reconstruction from S1 and S2:

2D analysis

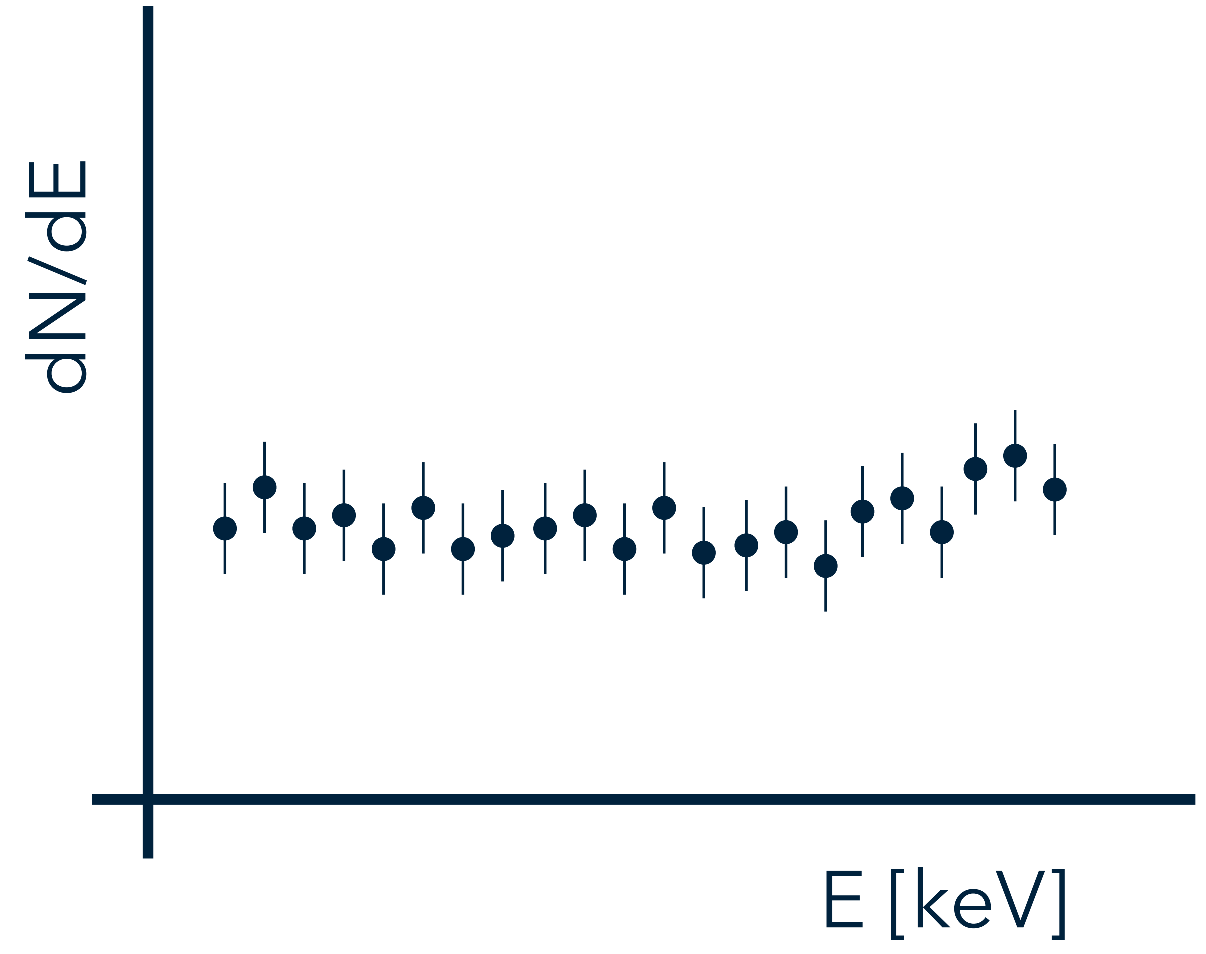


$$W = 13.7 \text{ eV/quantum}$$

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

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

1D analysis



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

→ **Determined through severals calibrations**