清華大學
Tsinghua University

Xe
XENON
Dark Matter Project

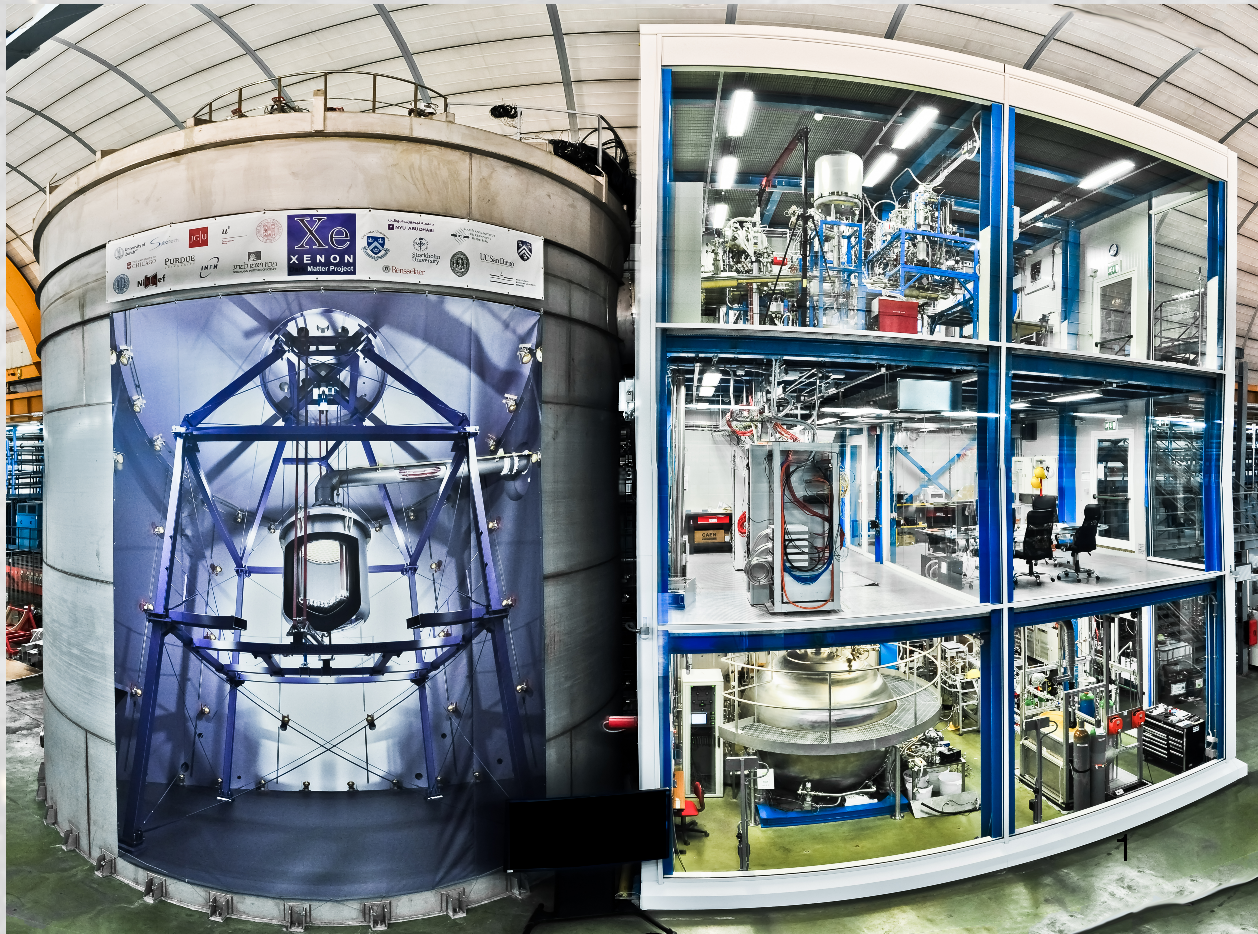
利用XENON1T寻找太阳中微子

高飞，清华大学物理系

On behalf of the XENON Collaboration

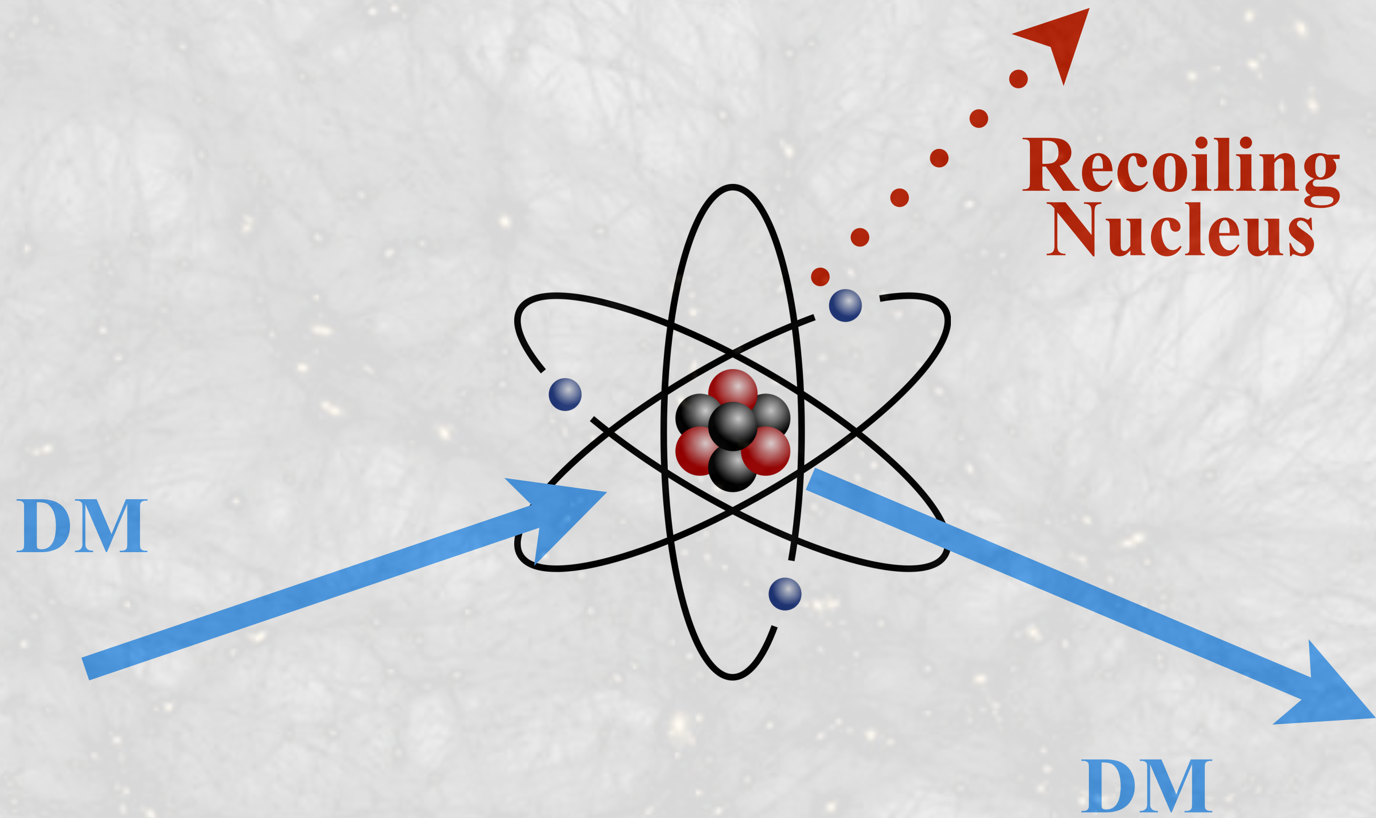
IHEP EPD seminar

Dec 24, 2020



Direct Detection of Dark Matter

- DM mass range: GeV~TeV
- local DM density: 0.3 GeV/cm^3
- Isothermal velocity distribution: v_0~220 km/s
- escape velocity ~544 km/s

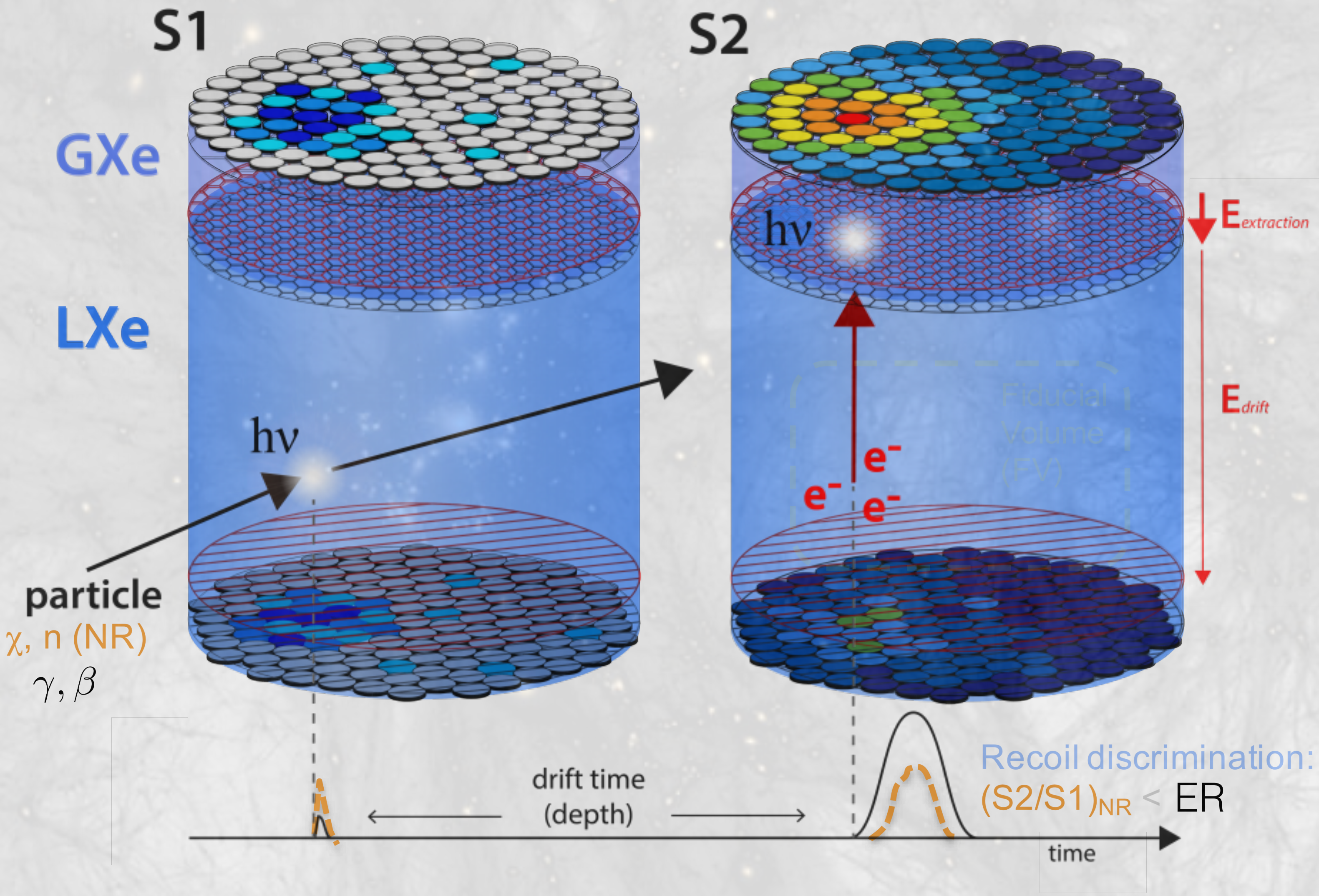


$$\frac{dR}{dE_{nr}} \propto N \frac{\rho_\chi}{2 m_\chi m_r^2} \sigma_N \left| F^2(E_{nr}) \right| \int_{v_{\min}}^{v_{esc}} \frac{f(v)}{v} d^3 v$$

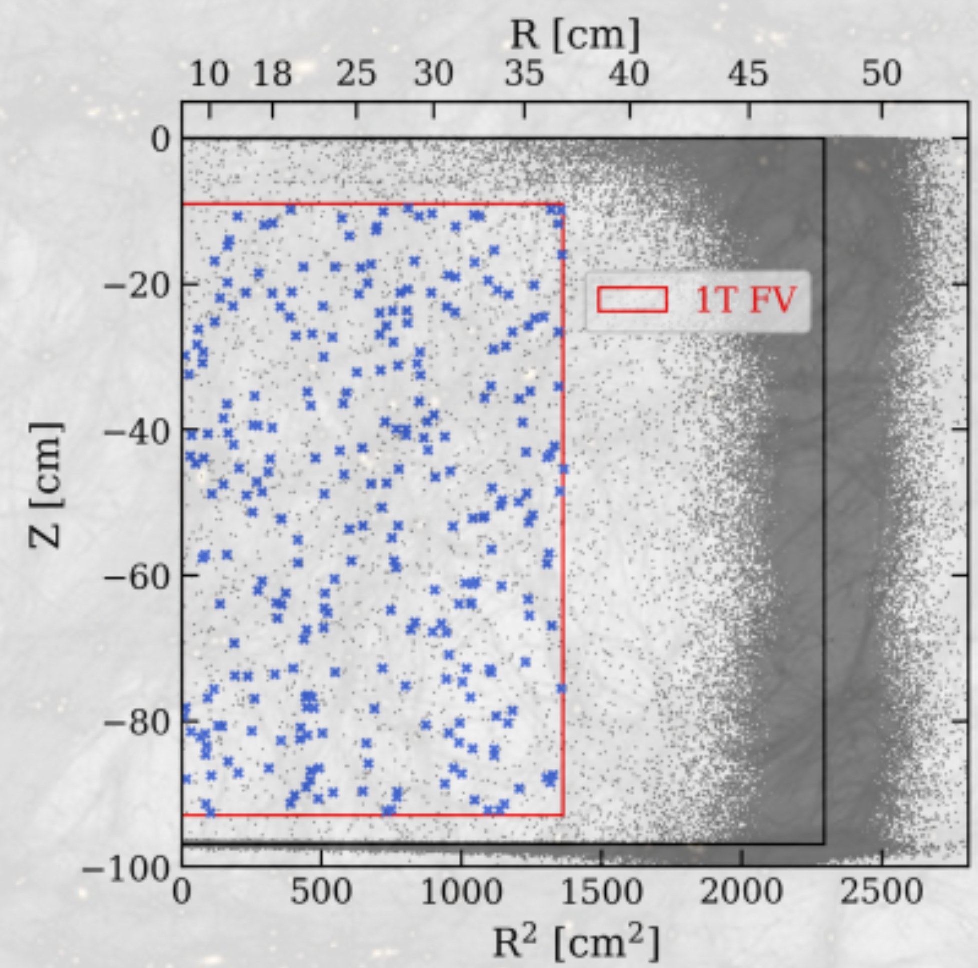
- N: number of targets
- ρ_χ: DM density
- m_χ: DM mass
- σ_N: interaction cross section
- $|F^2(E_{nr})|$: nuclear effects
- $\int \frac{f(v)}{v} d^3v$: WIMP velocity distribution

Two-phase Xe Time Projection Chamber

- **Scintillation light - S1**
- **Ionization electron -S2**



- two signals for each event:
  - 3D event imaging: x-y (S2) and z (drift time)
  - self-shielding, surface event rejection, single vs multiple scatter events



Two-phase Xe Time Projection Chamber

- Scintillation light - S1
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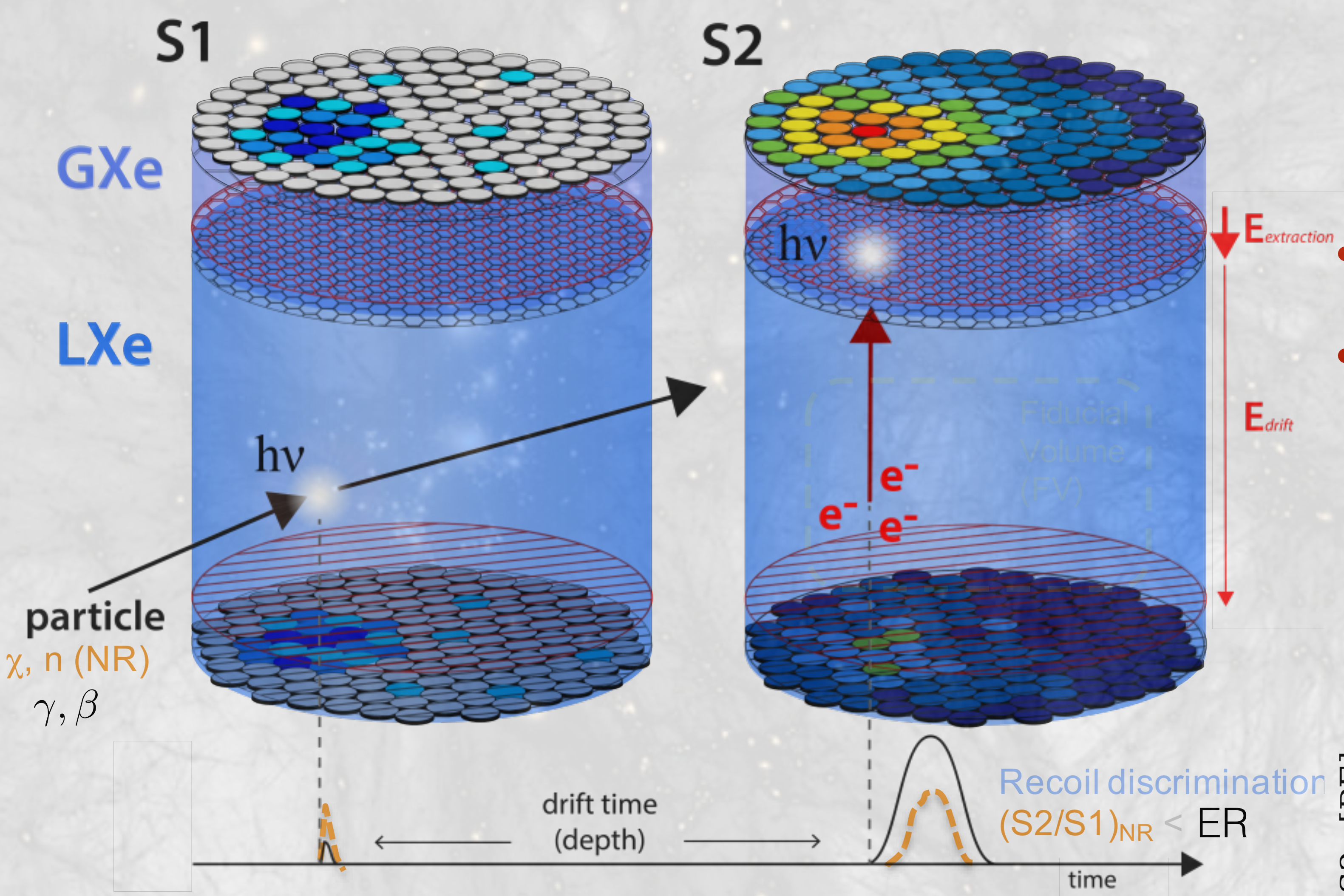
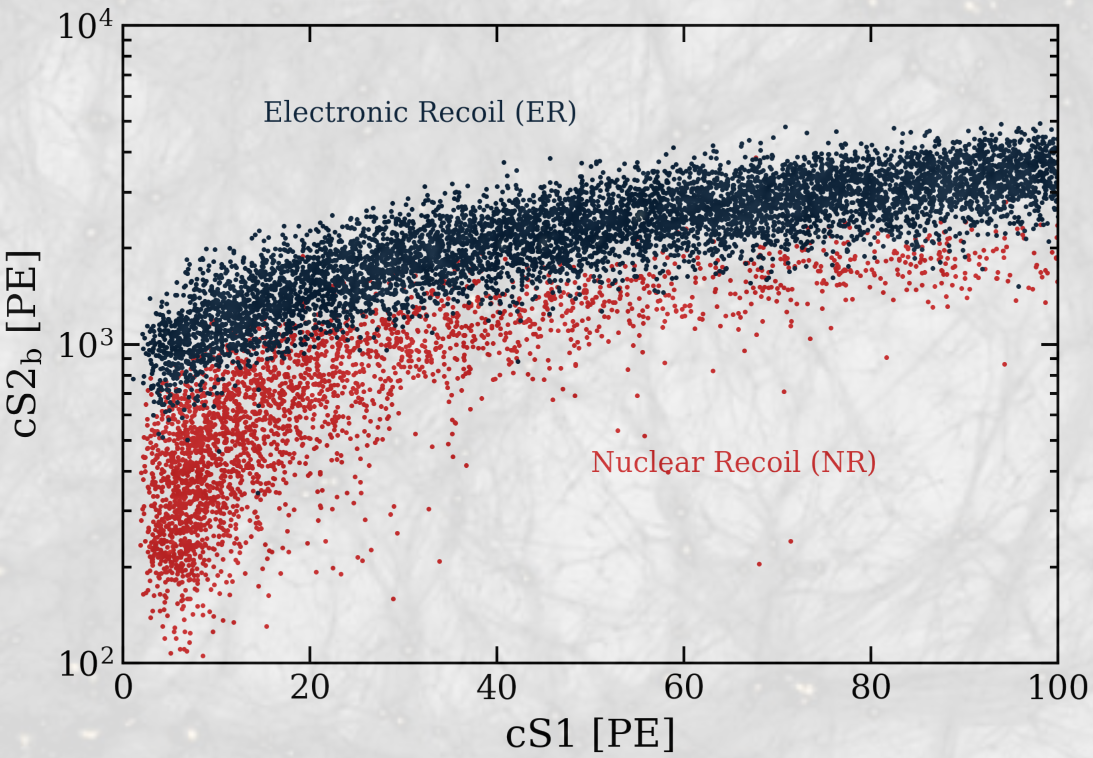


- two signals for each event:
  - 3D event imaging: x-y (S2) and z (drift time)
  - self-shielding, surface event rejection, single vs multiple scatter events
- Energy from S1 and S2 area
- Recoil type discrimination from ratio of charge (S2) to light (S1)



The XENON Collaboration

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

Chicago

UCSD

Rice

Purdue

Tokyo

Nagoya

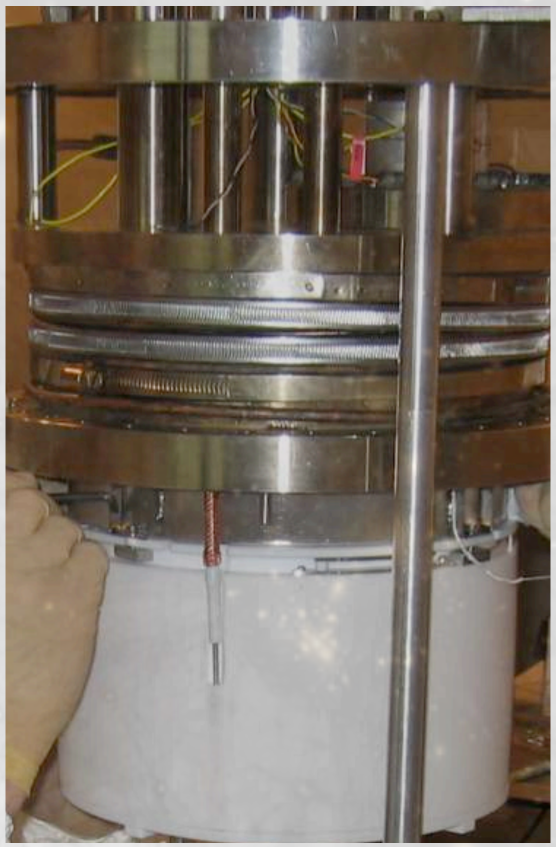
Kobe

NYUAD

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

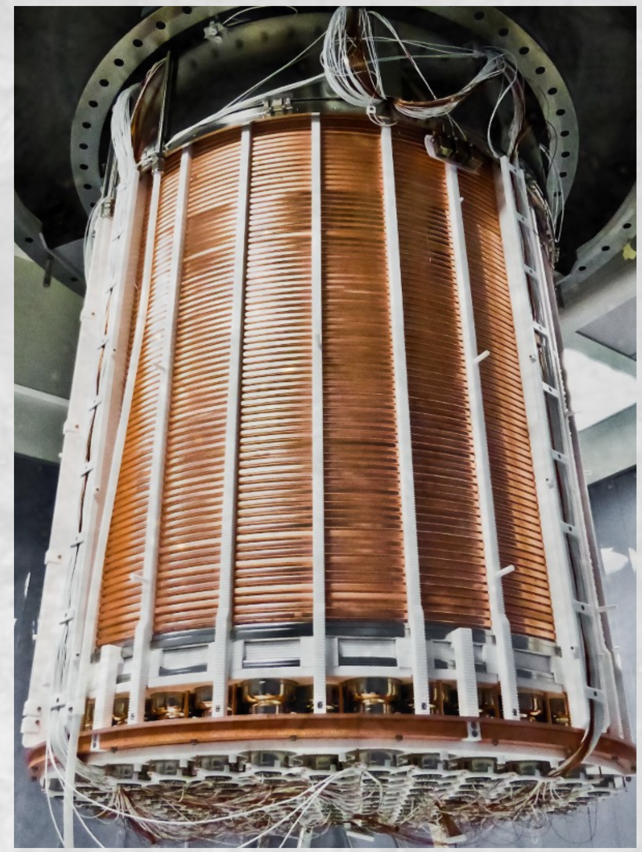
Development of XENON Program

XENON10

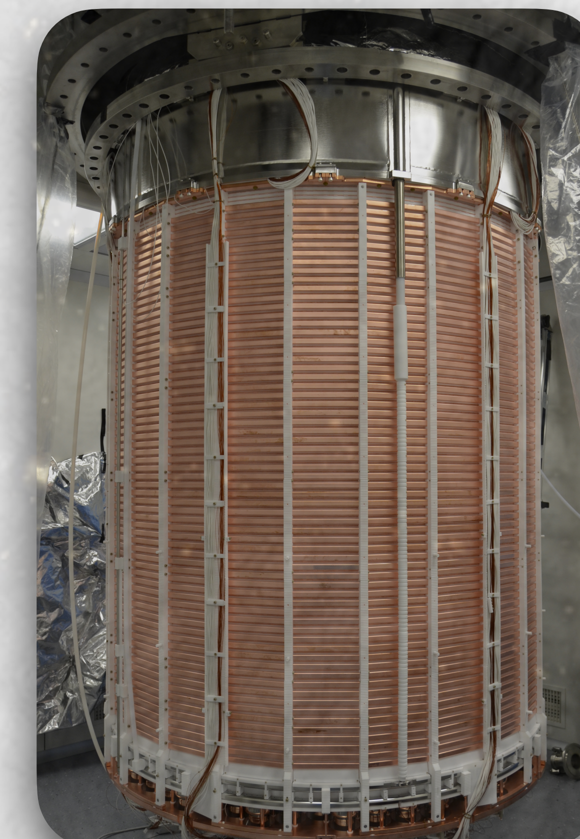


XENON100

XENON1T

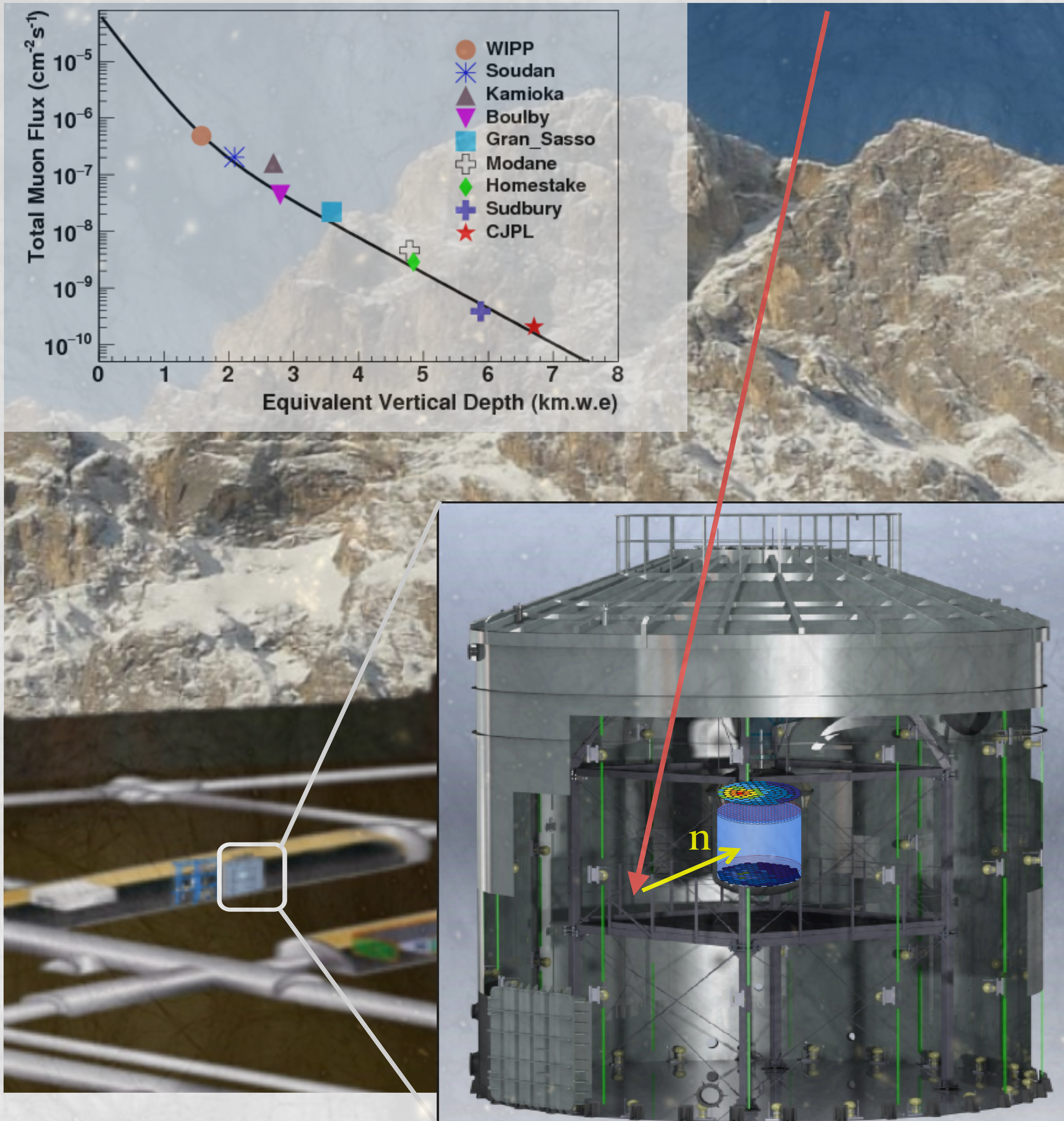


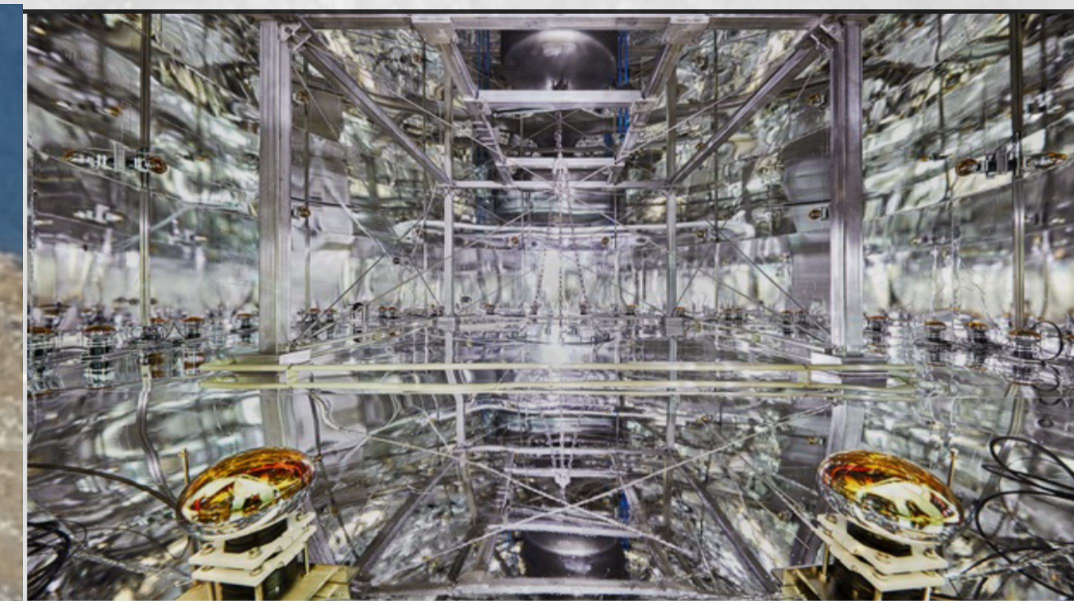
XENONnT

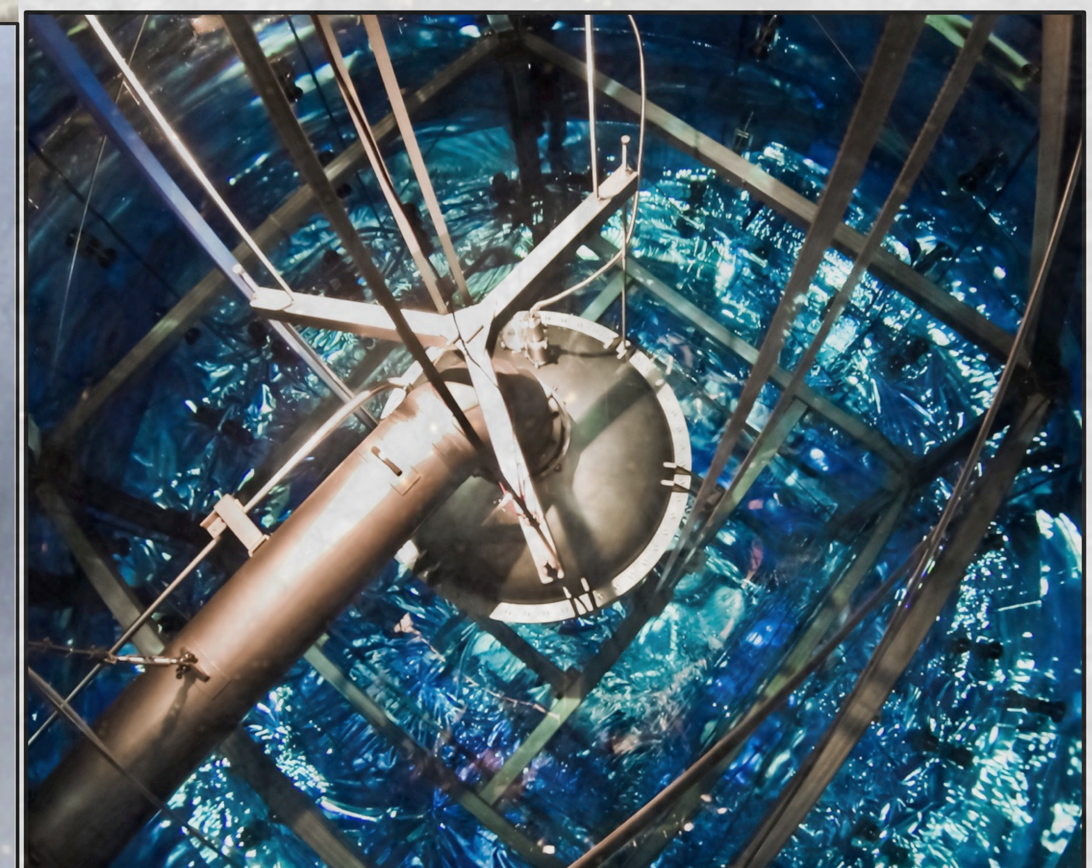


2005-2007	2008-2016	2012-2018	2019-202x
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8.6 ton - 1.5 m drift
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2

Gran Sasso: The XENON1T Shield

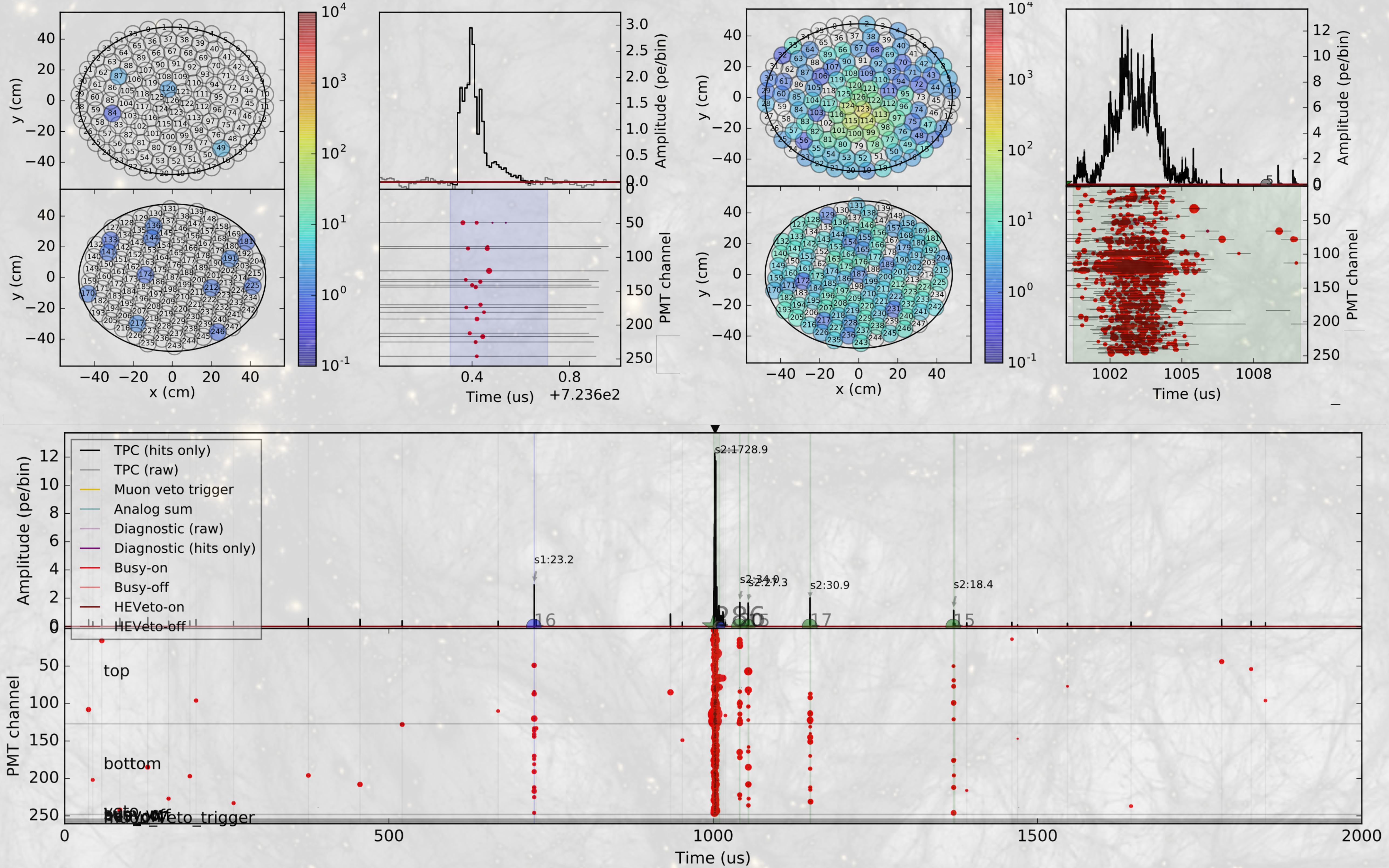






XENON1T: All Systems

A XENON1T Waveform

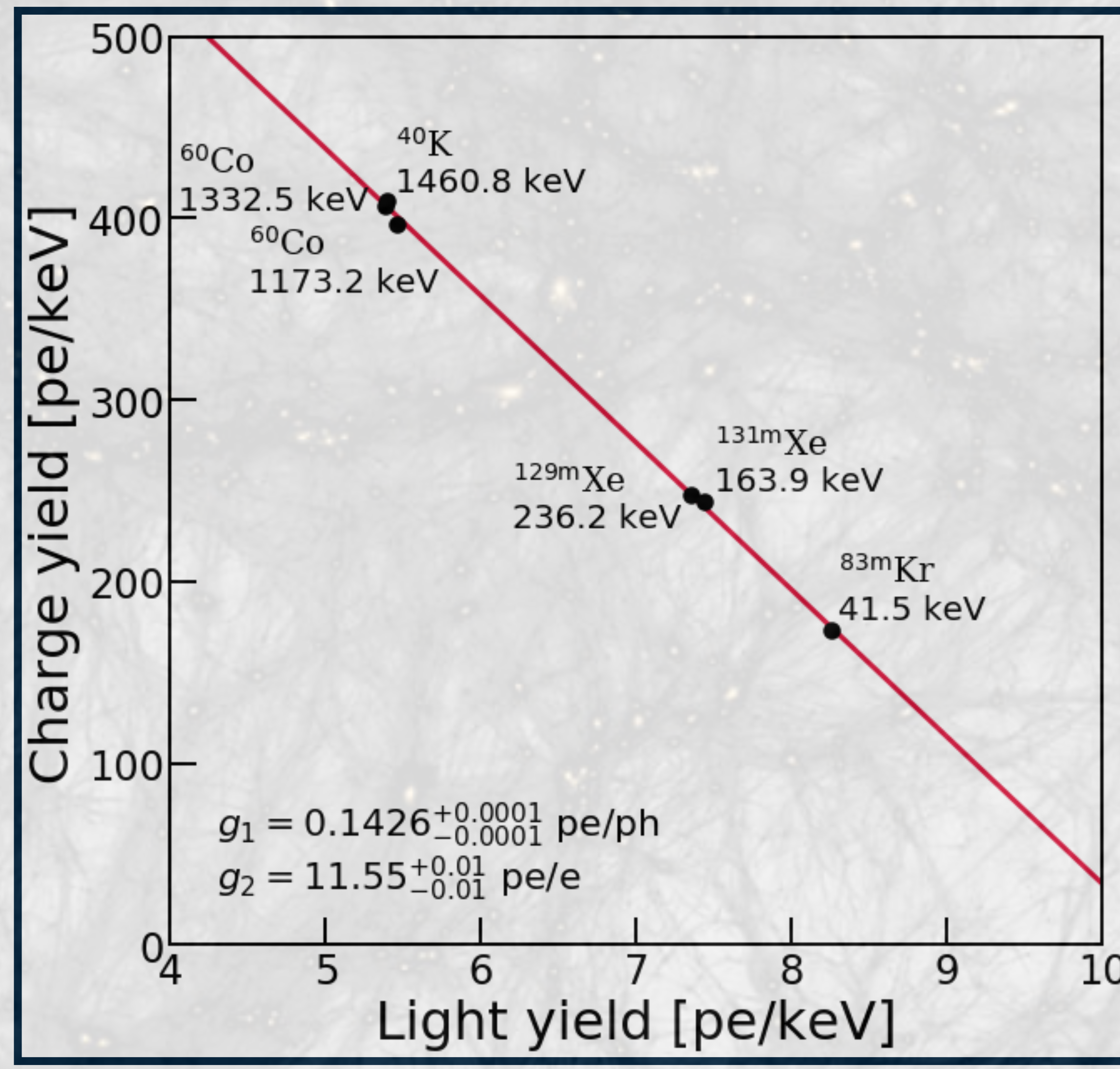


Energy Response in XENON1T

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

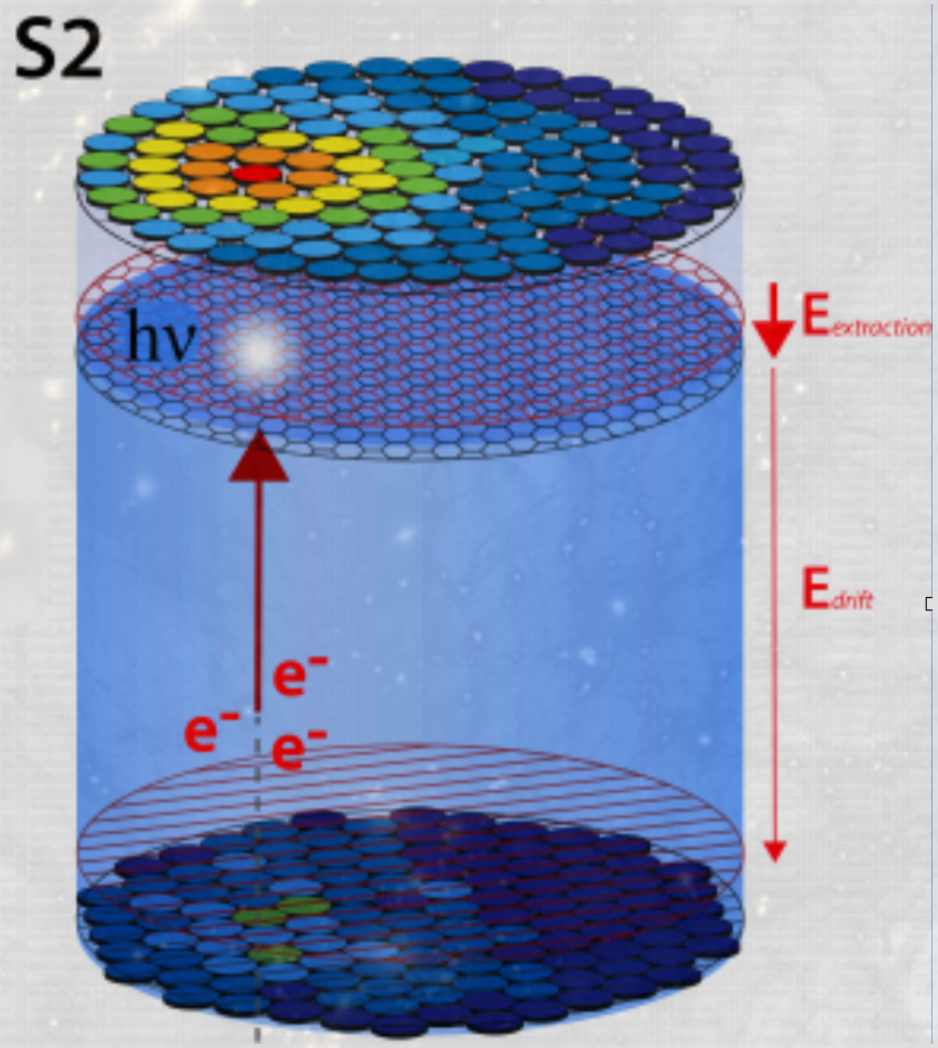
$$\frac{S2}{E} = -\frac{g_2}{g_1}\frac{S1}{E} + \frac{g_2}{W}$$

$$E = W\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$



g1 and g2: detector-specific gain **constants**

Position Reconstruction



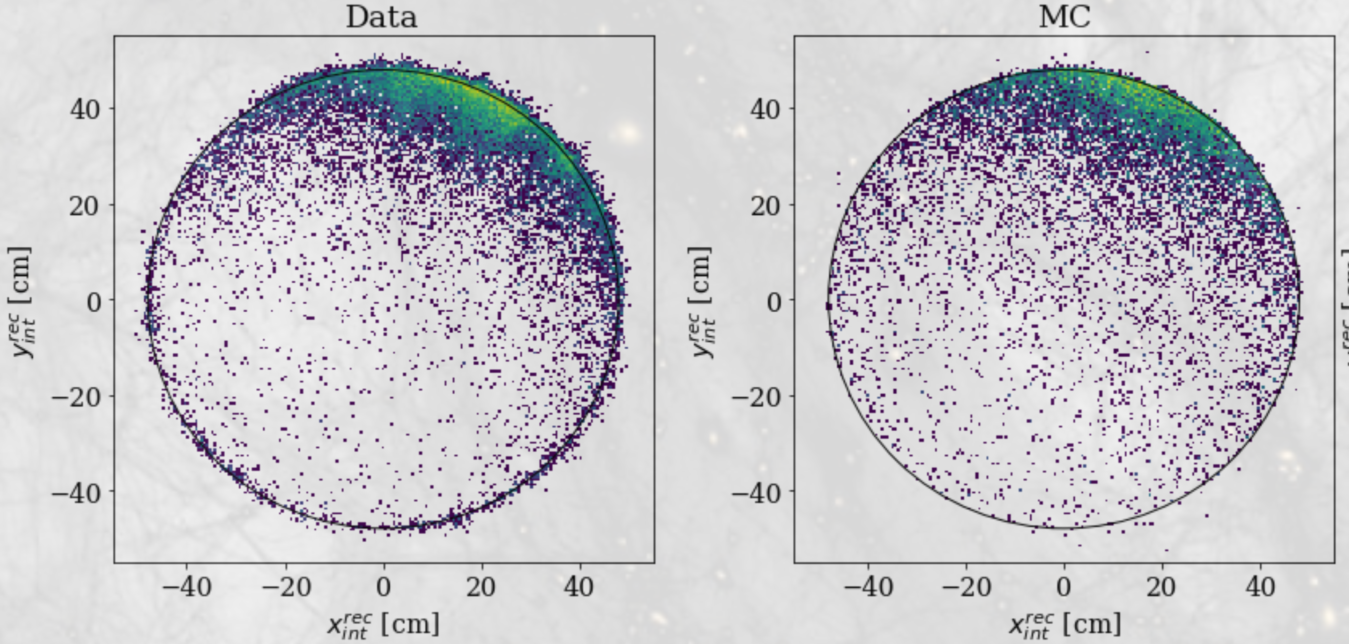
x-y reconstruction via **Machine Learning**:

- **Input:** charge/channel top array
- **Training:** Monte Carlo simulation

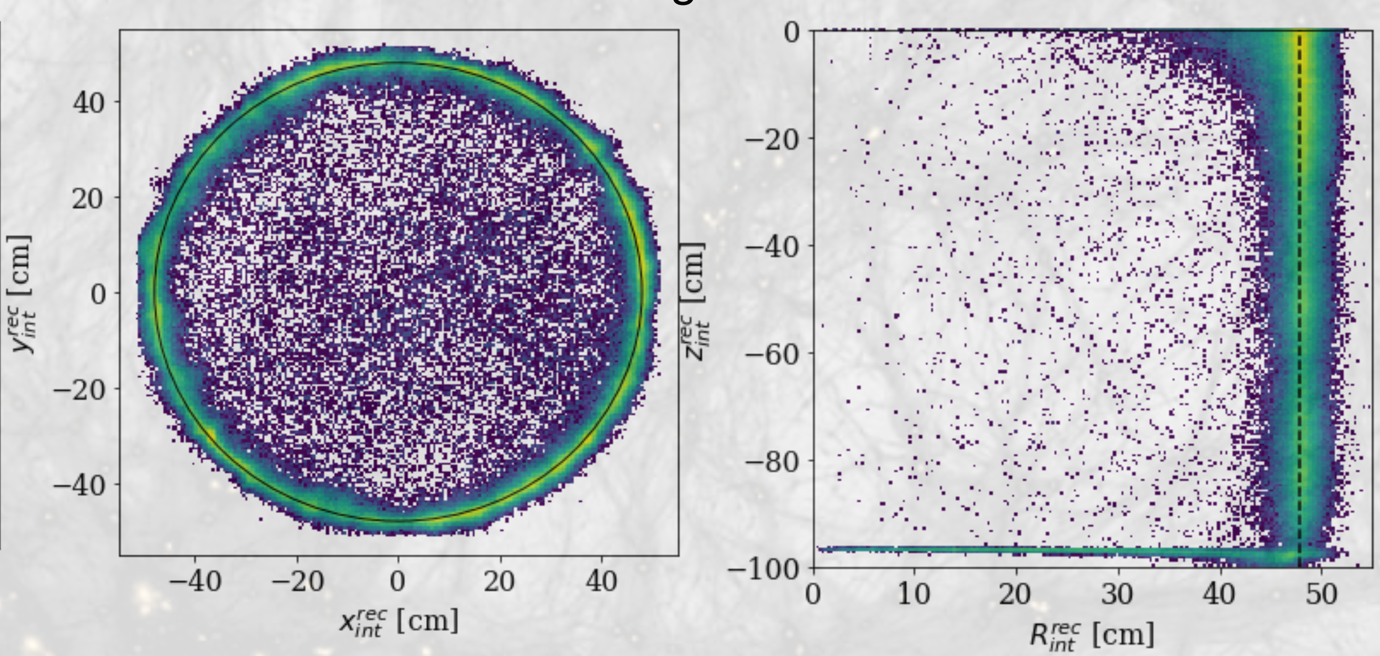
Position resolution

- Position resolution (1-2 cm)
- PMT diameter (7.62 cm)

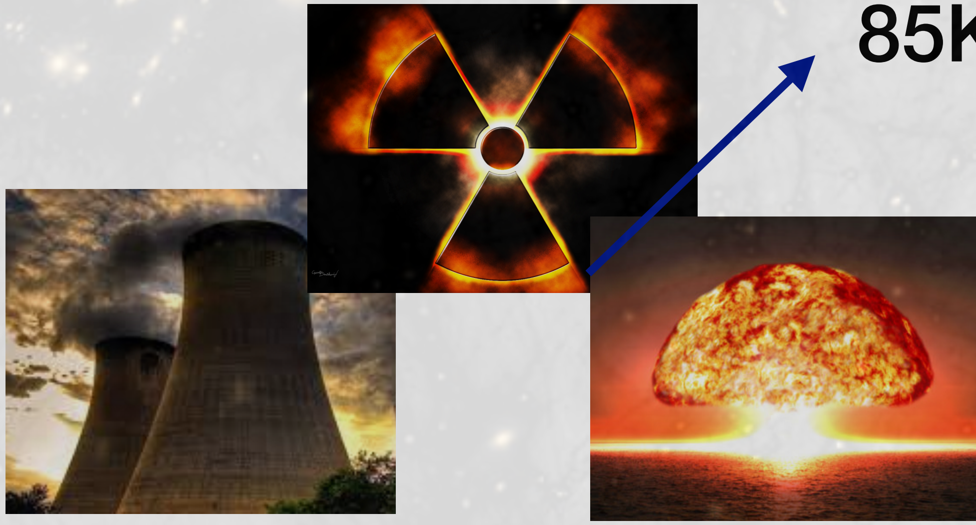
Neutron Generator data



Background data



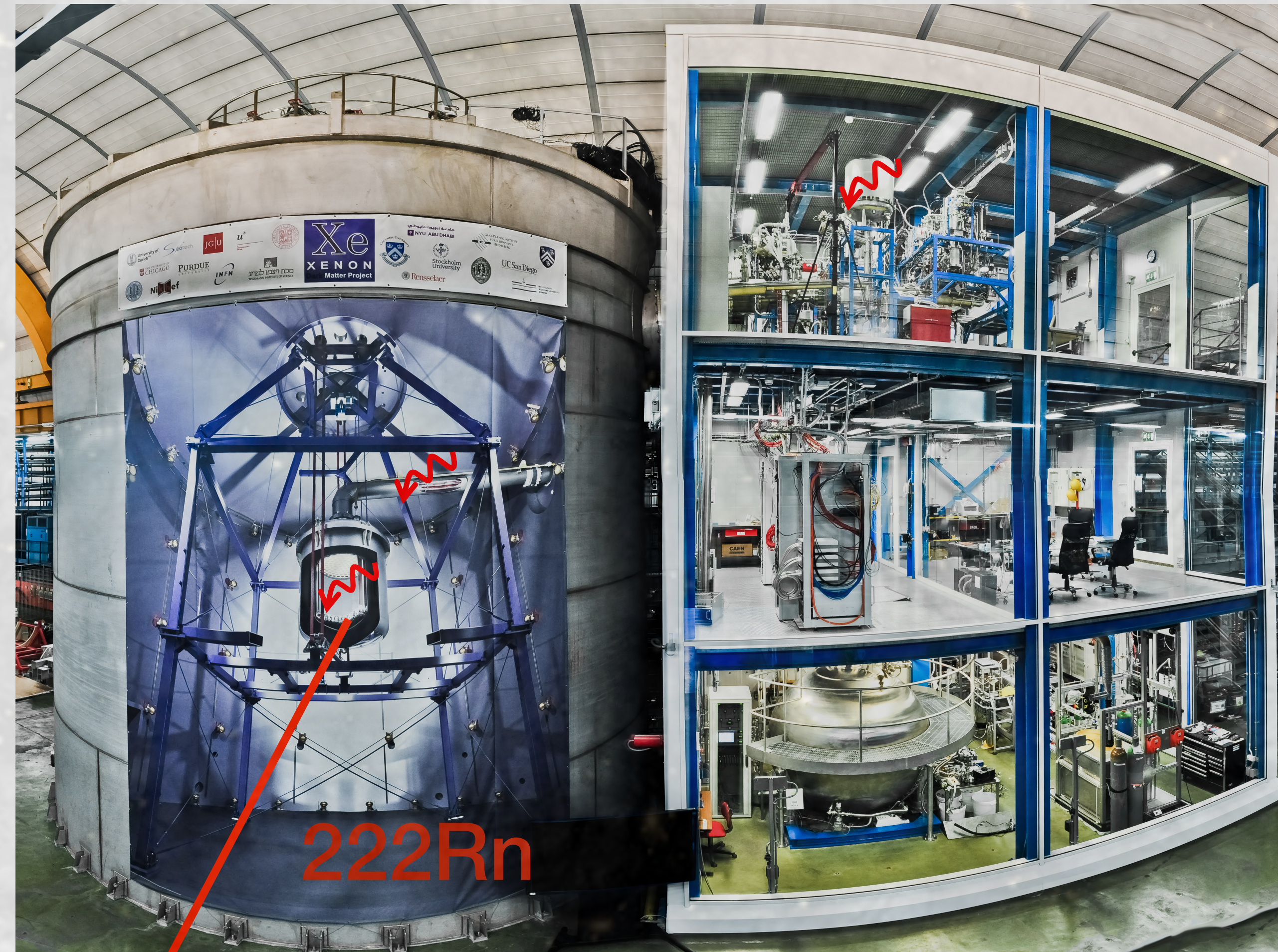
Backgrounds

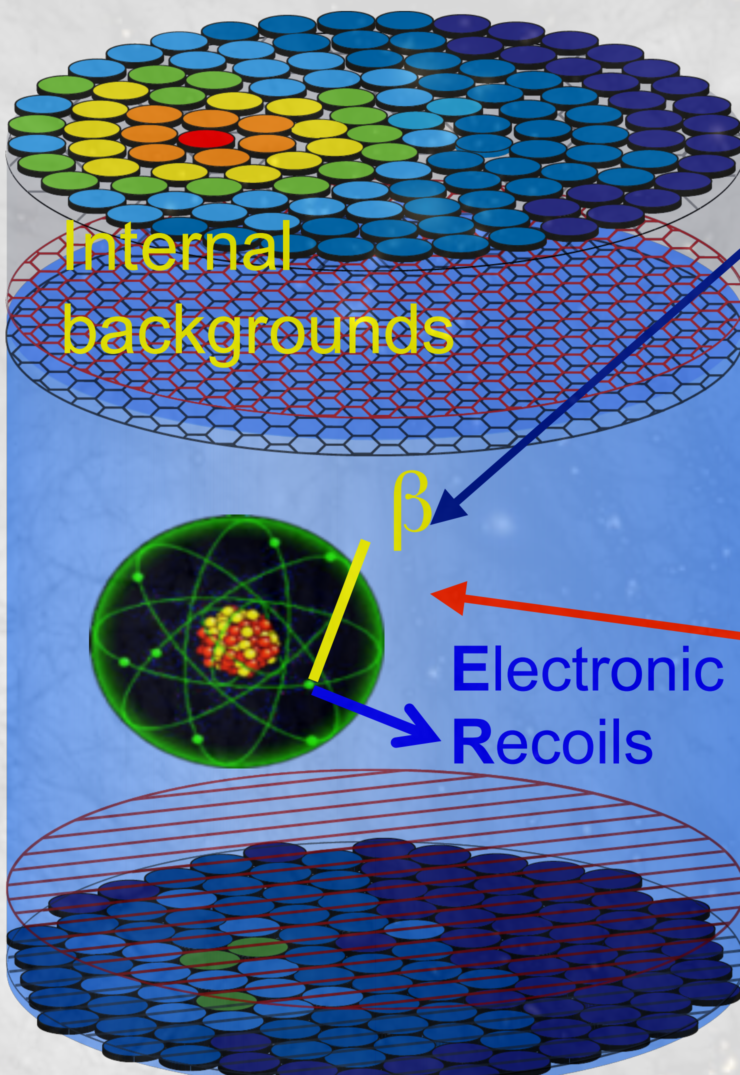


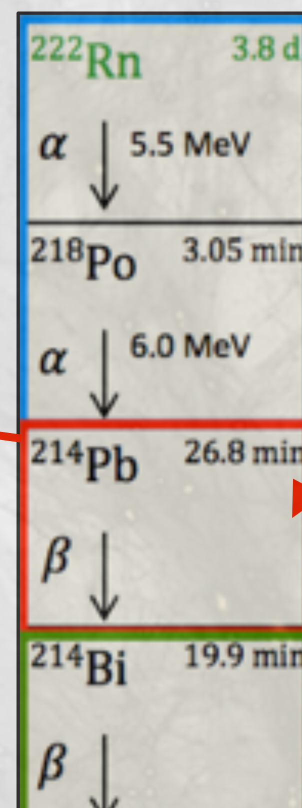
85Kr

Air

Xenon

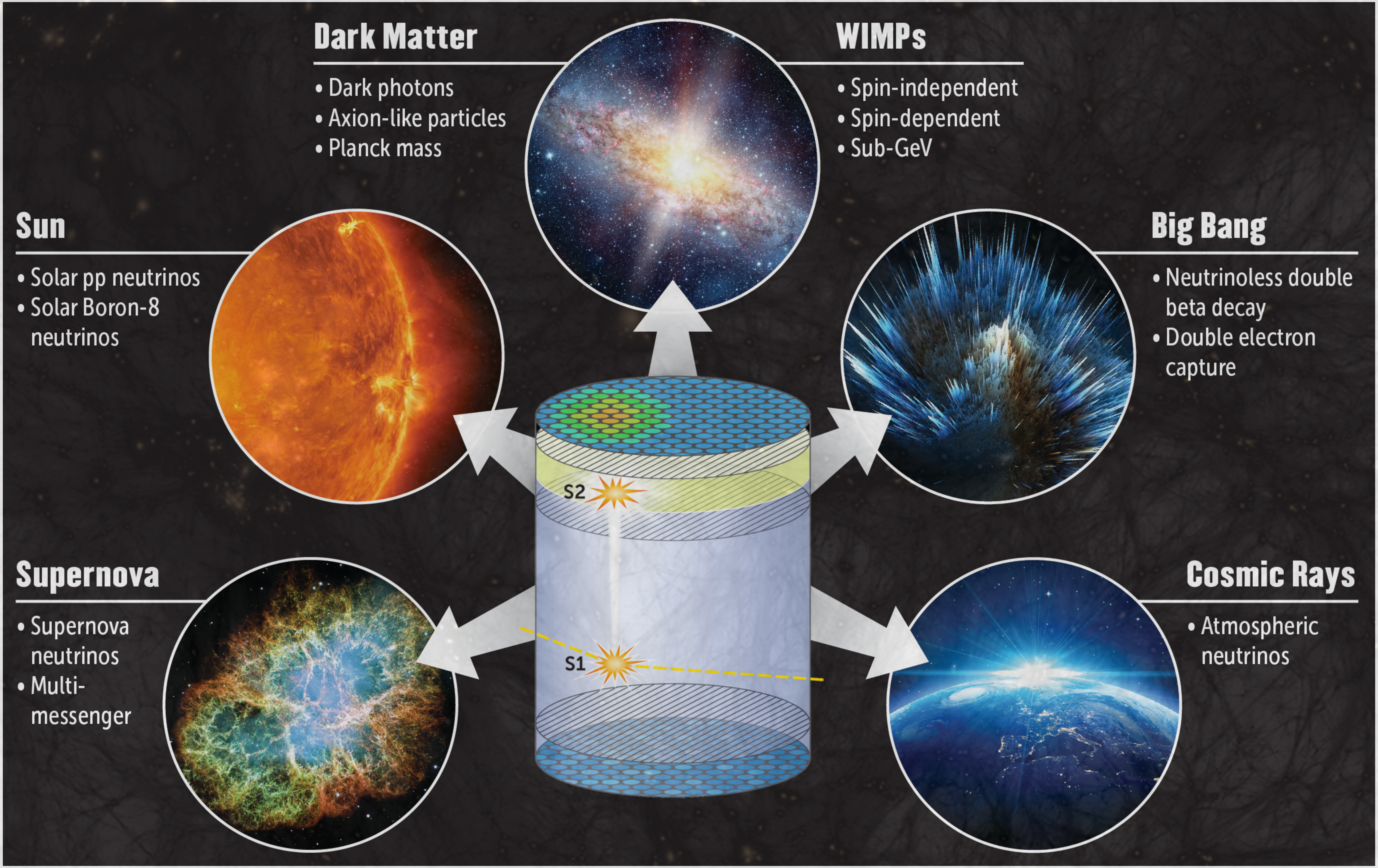






Source	Rate [t^{-1} y^{-1} keV^{-1}]	Fraction [%]
222Rn	**56 ± 6**	75.0
85Kr	**7.7±1.3**	10.3
Solar ν	2.5±0.1	3.3
Materials	8±1	10.7
136Xe	0.8±0.1	1.1
Total	75±8	
Measured	82±5	

What do We Search in XENON1T?

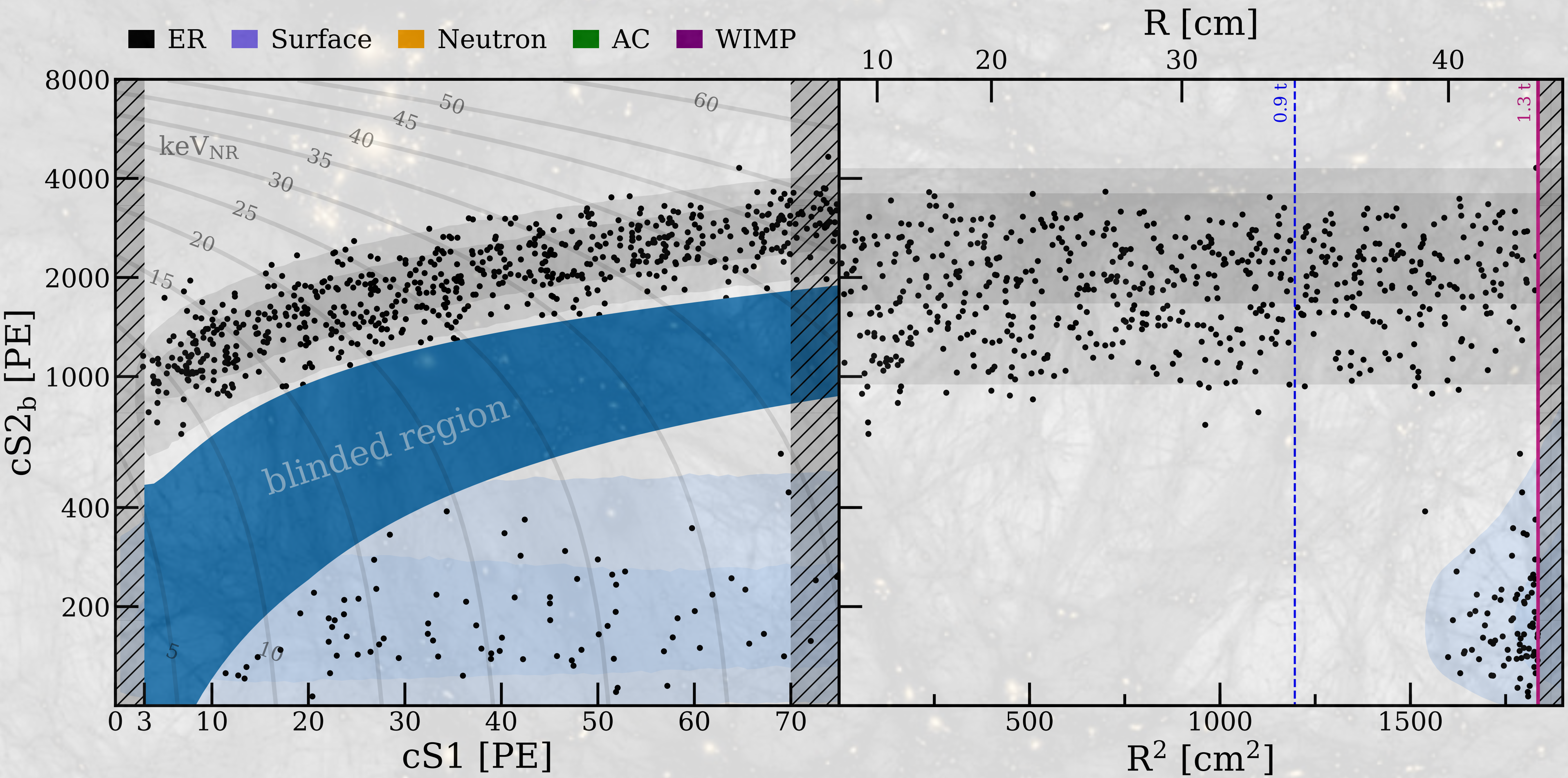


Dark Matter Search: Background Prediction

Blind Analysis

Position dependent modeling

Source	1.3 t	1.3 t, NR Ref.	0.9 t, NR Ref.
ER	627 ± 18	1.6 ± 0.3	1.1 ± 0.2
Radiogenic	1.4 ± 0.7	0.8 ± 0.4	0.4 ± 0.2
CEνNS	0.05 ± 0.01	0.03 ± 0.01	0.02
Accidental	$0.5^{+0.3}_{-0.0}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$
Surface	106 ± 8	4.8 ± 0.4	0.02
Total	735 ± 20	7.4 ± 0.6	1.6 ± 0.3
200 GeV WIMP	3.6	1.7	1.2



Dark Matter Search: Unblinding and Results

No significant Excess!

Source	1.3 t	1.3 t, NR Ref.	0.9 t, NR Ref.
ER	627 ± 18	1.6 ± 0.3	1.1 ± 0.2
Radiogenic	1.4 ± 0.7	0.8 ± 0.4	0.4 ± 0.2
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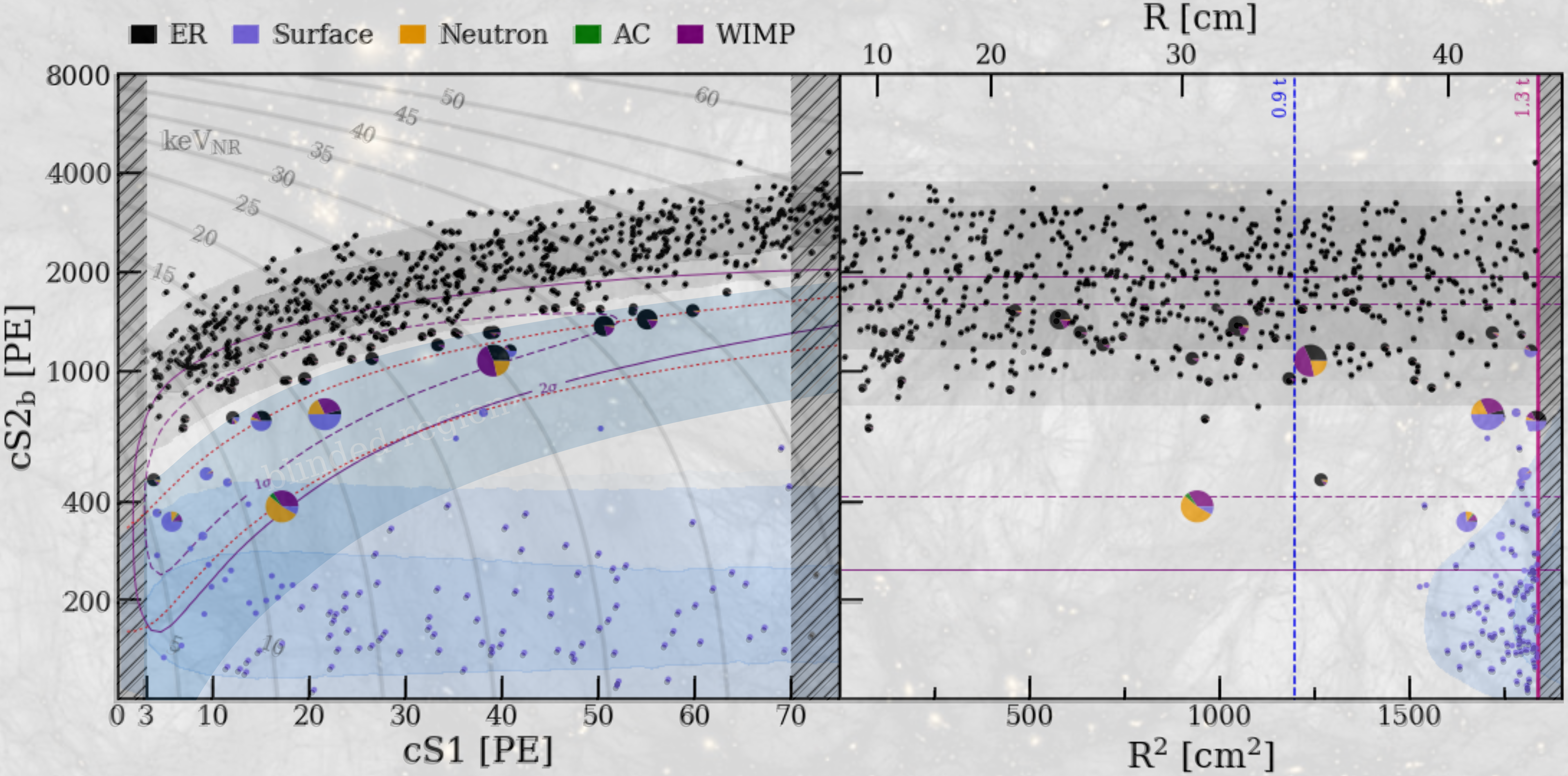
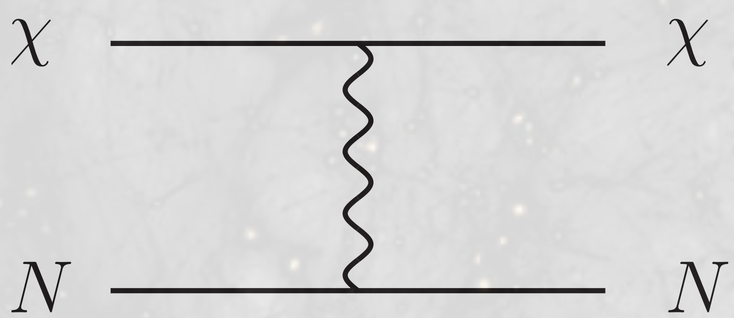
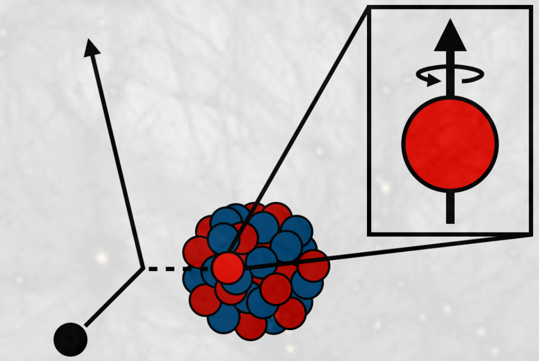
Total	735 ± 20	7.4 ± 0.6	1.6 ± 0.3
200 GeV WIMP	3.6	1.7	1.2
Data	**739**	**14**	**2**

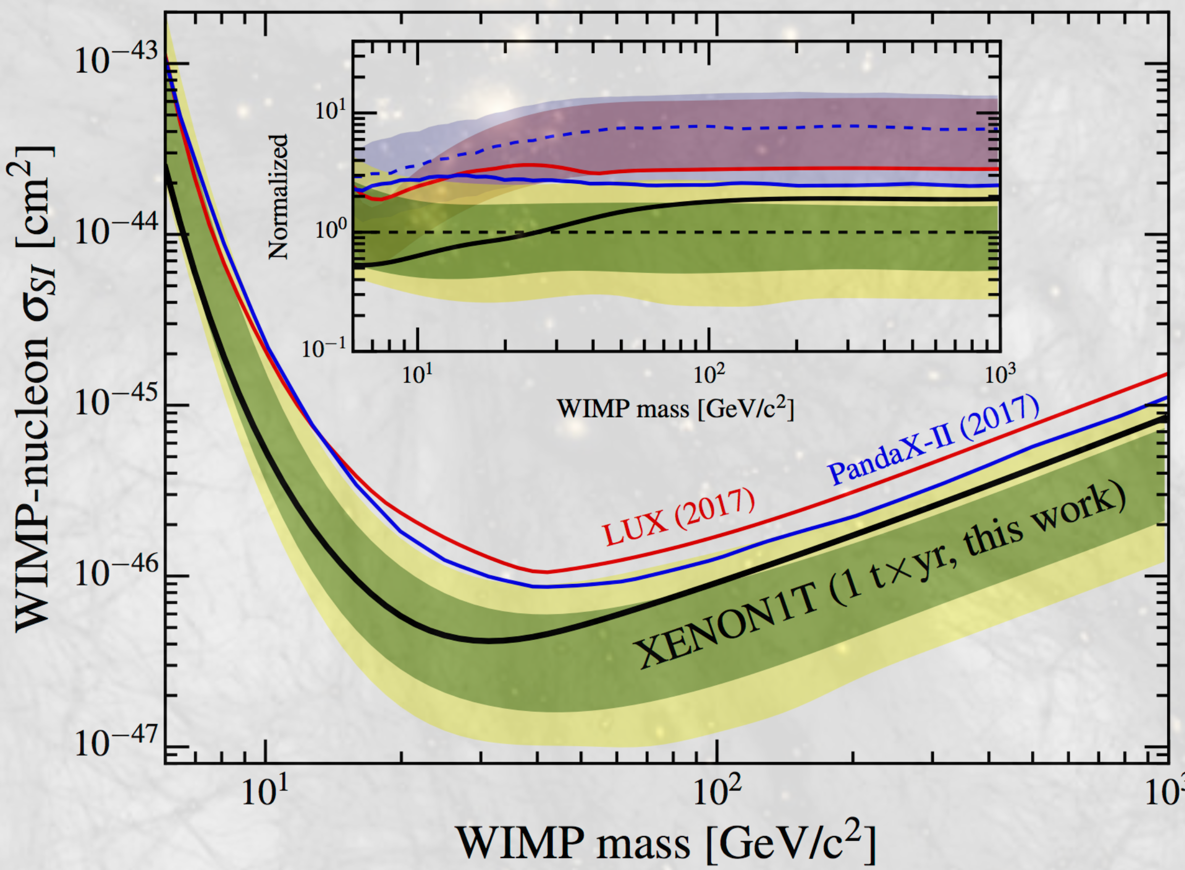


Constraints on Dark Matter Interactions



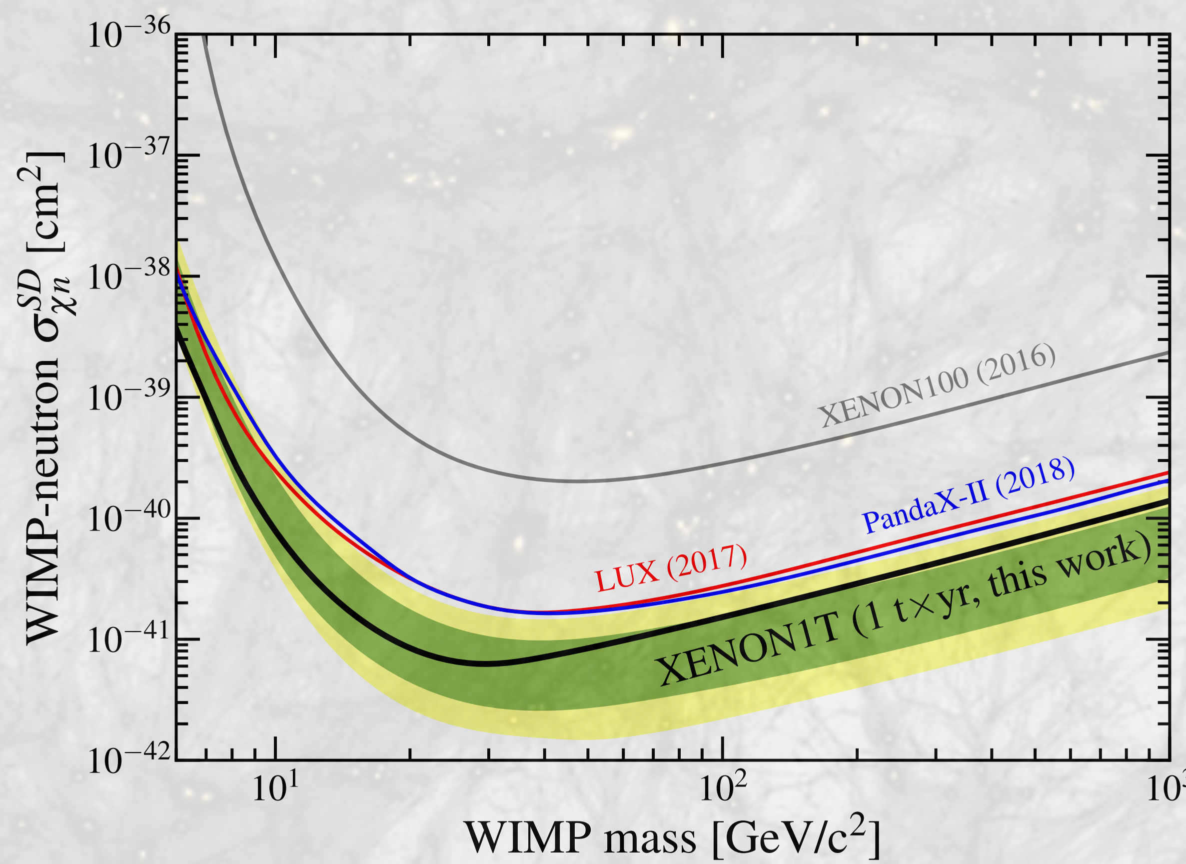


Phys. Rev. Lett. 121, 111302 (2018)



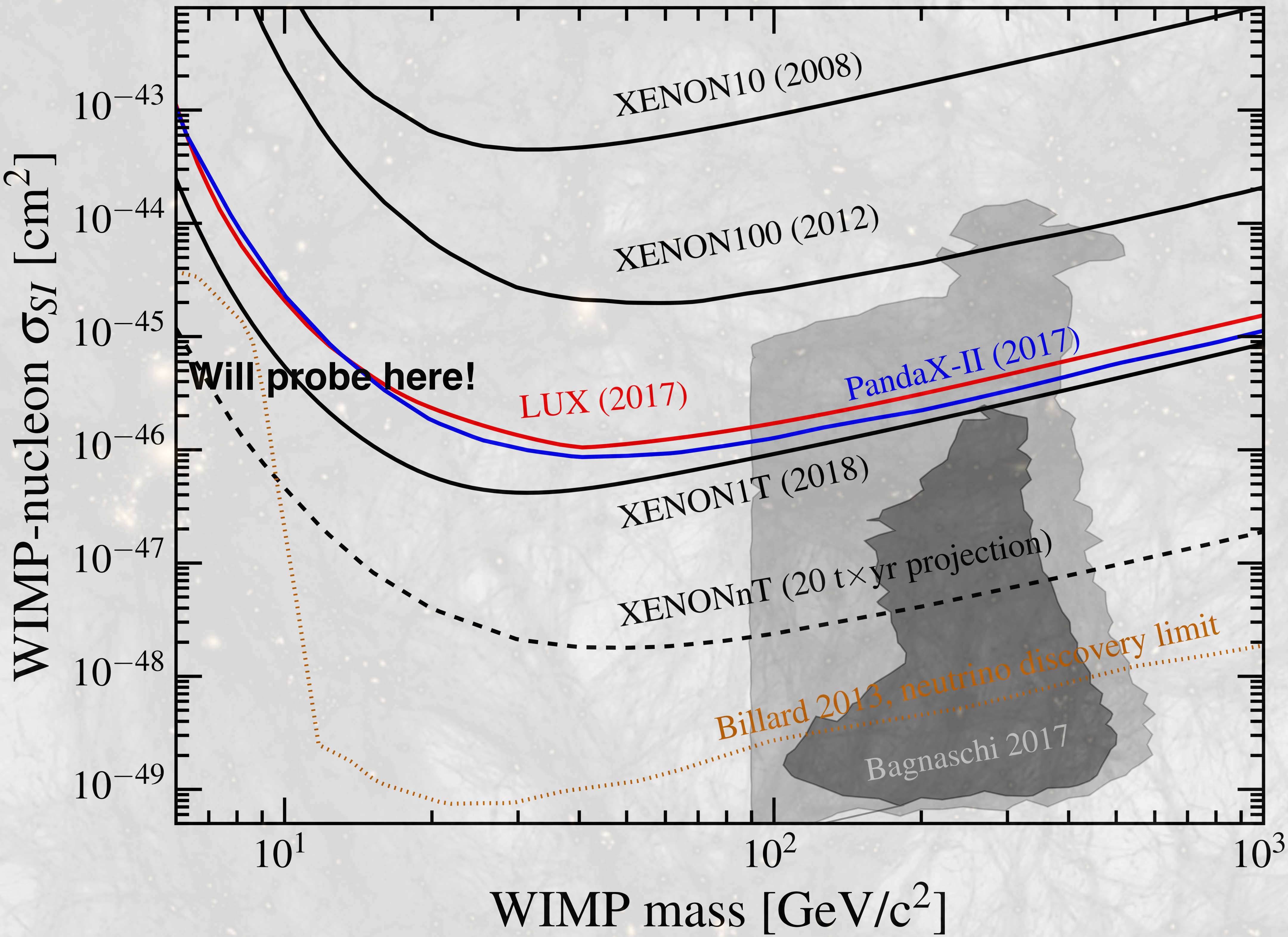
σ < 4.1 x 10^{-47} cm^2 at 30 GeV/c^2

Phys. Rev. Lett. 122, 141301 (2019)



σ< 46.3 x 10^{-42} cm^2 at 30 GeV/c^2

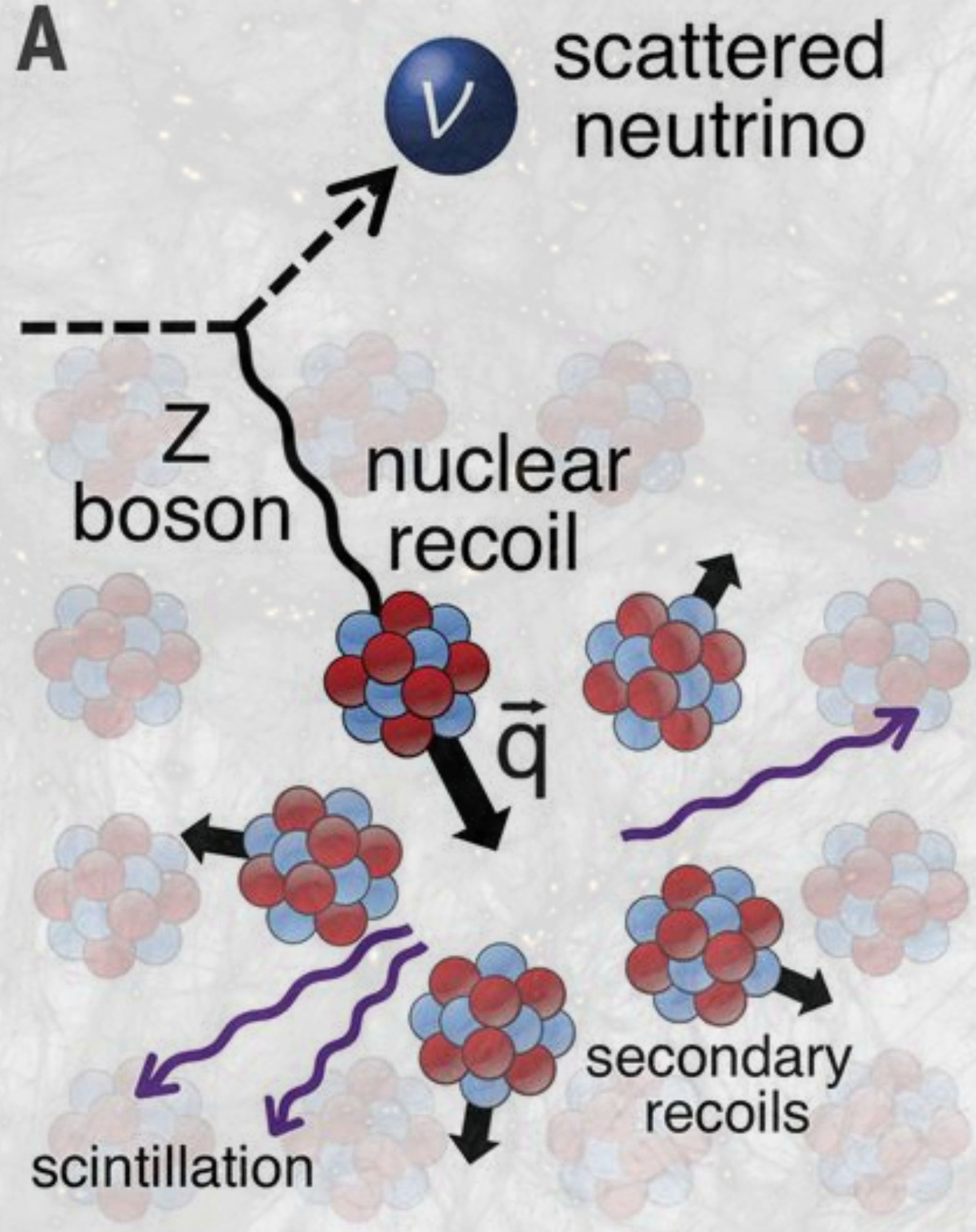
How can We Reach the Neutrino "Floor"



What is the “Neutrino Floor”

Coherent elastic scattering from neutrinos and DM are indistinguishable!

Neutrino sources: Solar neutrinos, atmospherical neutrinos, supernova



COHERENT Collab., Science 357, 1123 (2017)

How far are We from the Neutrino Floor?

There are ~600 CEvNS recoils from B8 solar neutrinos alone

$$R = \phi(\nu) \times \sigma_\nu \times N_{Xe} \times \text{exposure}$$
$$\simeq 600\,\text{events}/(\text{tonne} \times \text{year})$$

XENON1T WIMP search analysis has low detection efficiency 0.01%

Can we increase the detection efficiency?

Source	1.3 t	1.3 t, NR Ref.
ER	627 ± 18	1.6 ± 0.3
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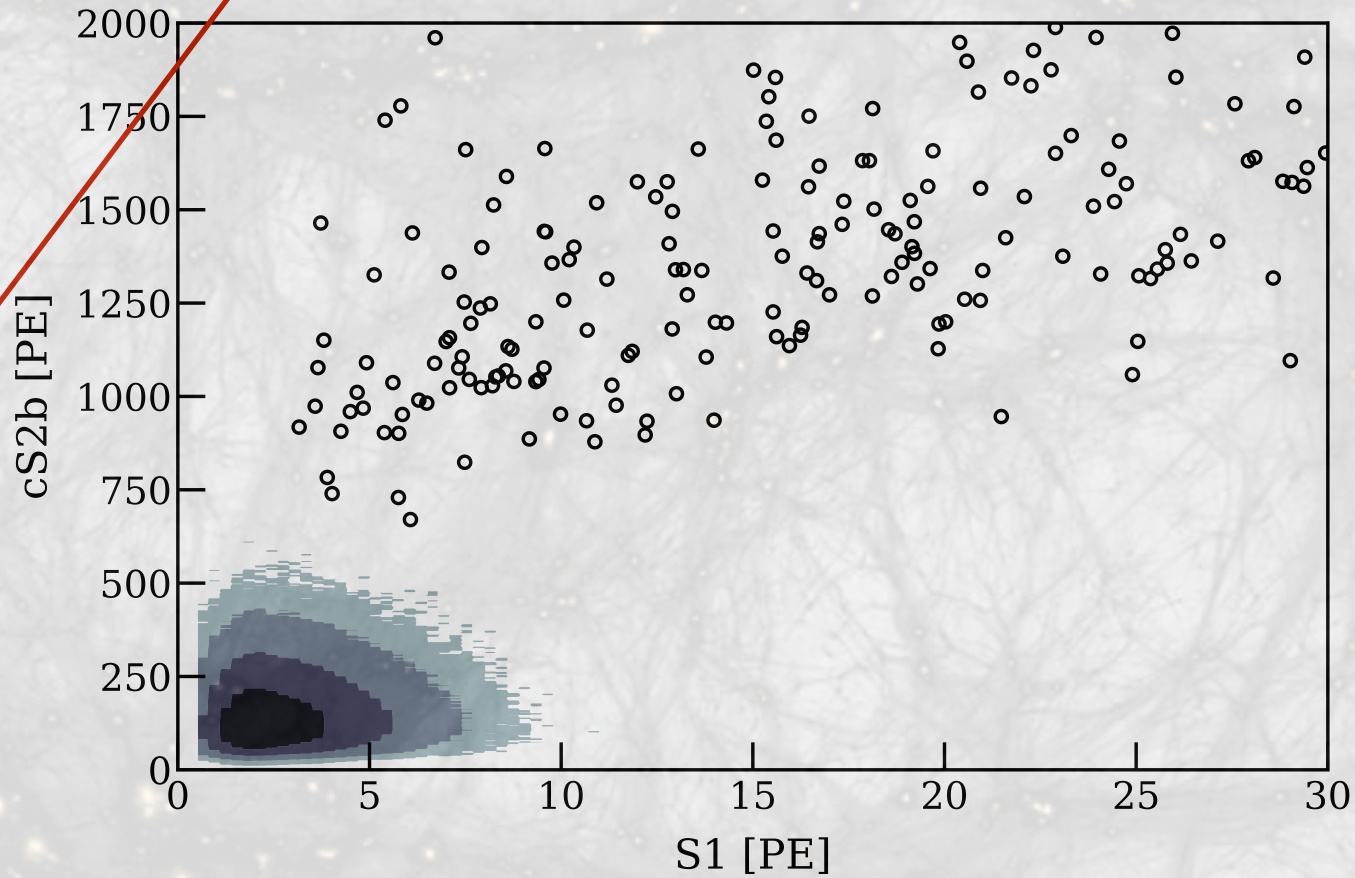


How XENON1T Detect Solar B8 Neutrinos?

Solar B8 decays → Recoils in XENON1T → Charge/ scintillation emission → Charge drift → Extraction/ proportional scintillation → Optical photon propagation

Charge/ scintillation emission → γ → Optical photon propagation

Optical photon propagation → PMT/ electronics response → Trigger & Reconstruction → Selections, Modeling, Analysis

Rate

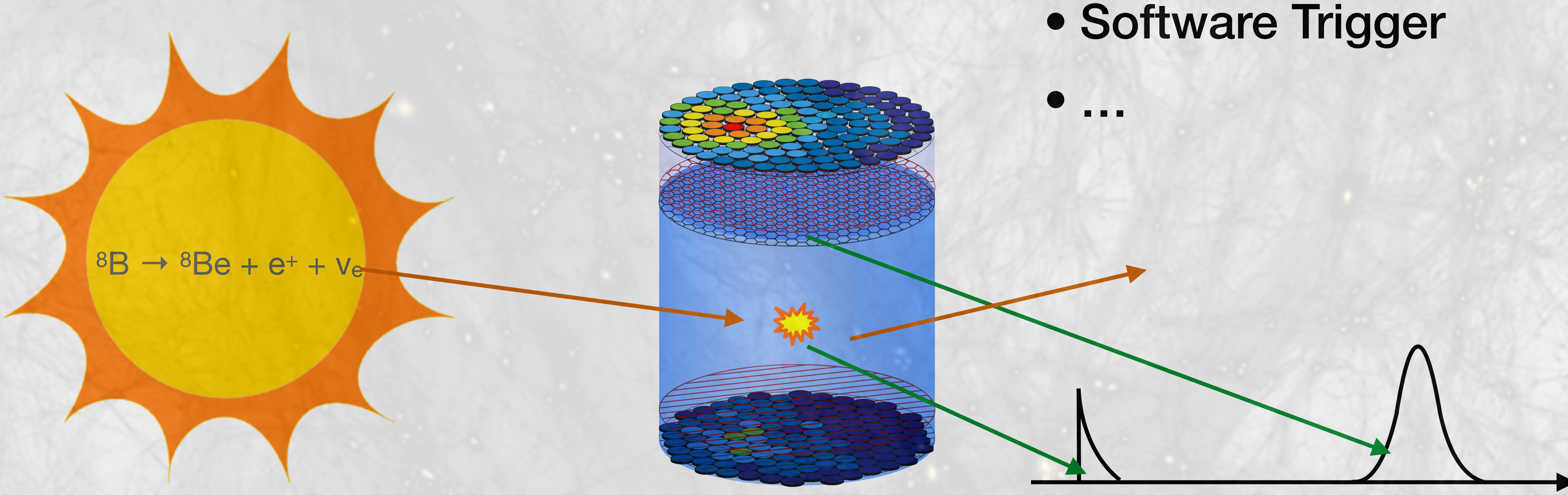
- 8B neutrino flux
- Cross-section

LXe Response

- Charge Yield
- Light Yield

Detection efficiency

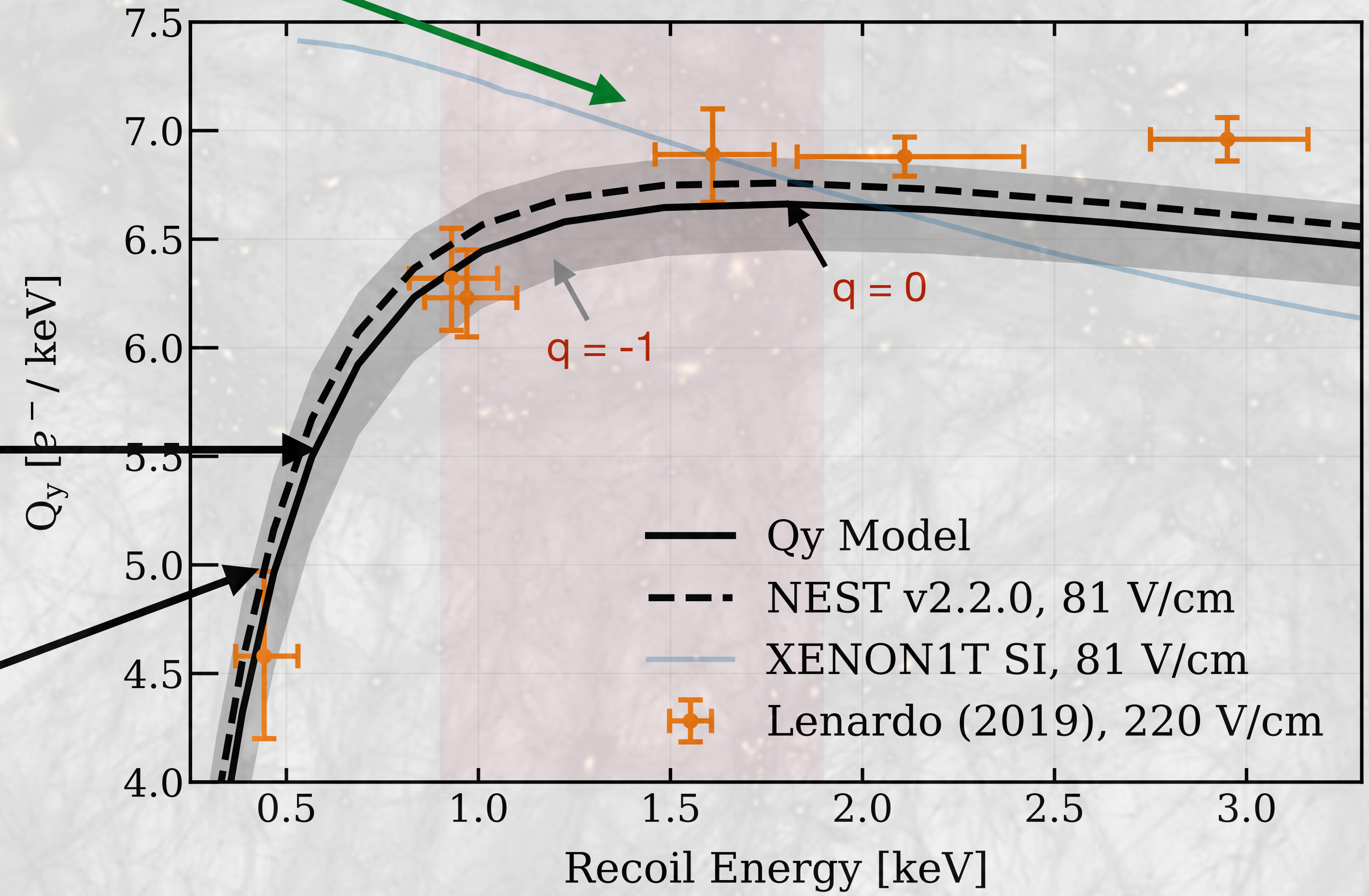
- LXe Purity
- PMT Coincidence Requirement
- Software Trigger
- ...



Ionization Yields for Nuclear Recoils

Precise measurement of ionization yields is available from Lenardo et. al

arXiv:2012.02846



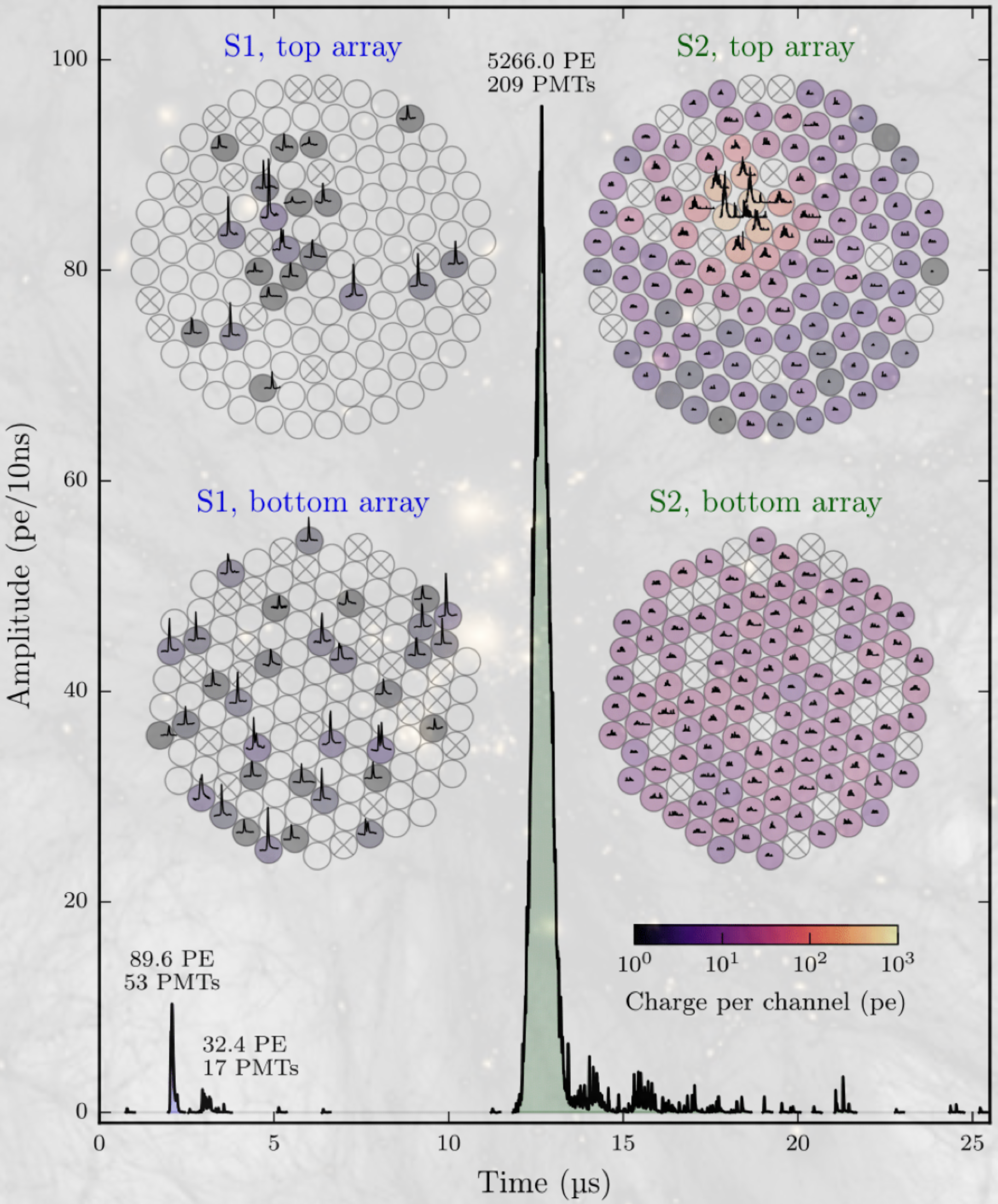
NEST model is agreeing with low energy measurements

Uncertainty is subdominant compared with other factors, such as the scintillation response

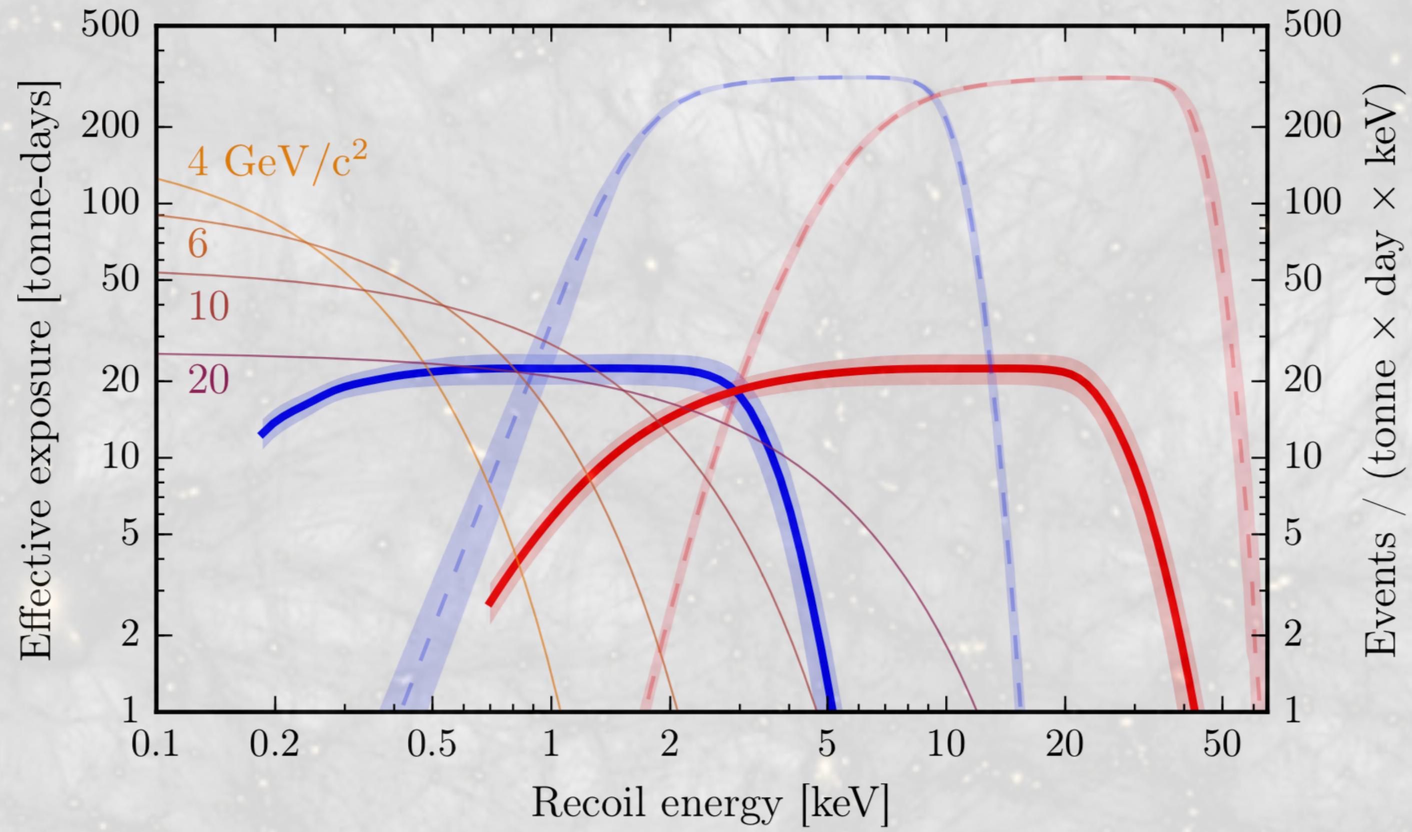
One interpolation parameter, **q**, is used to account for the uncertainty

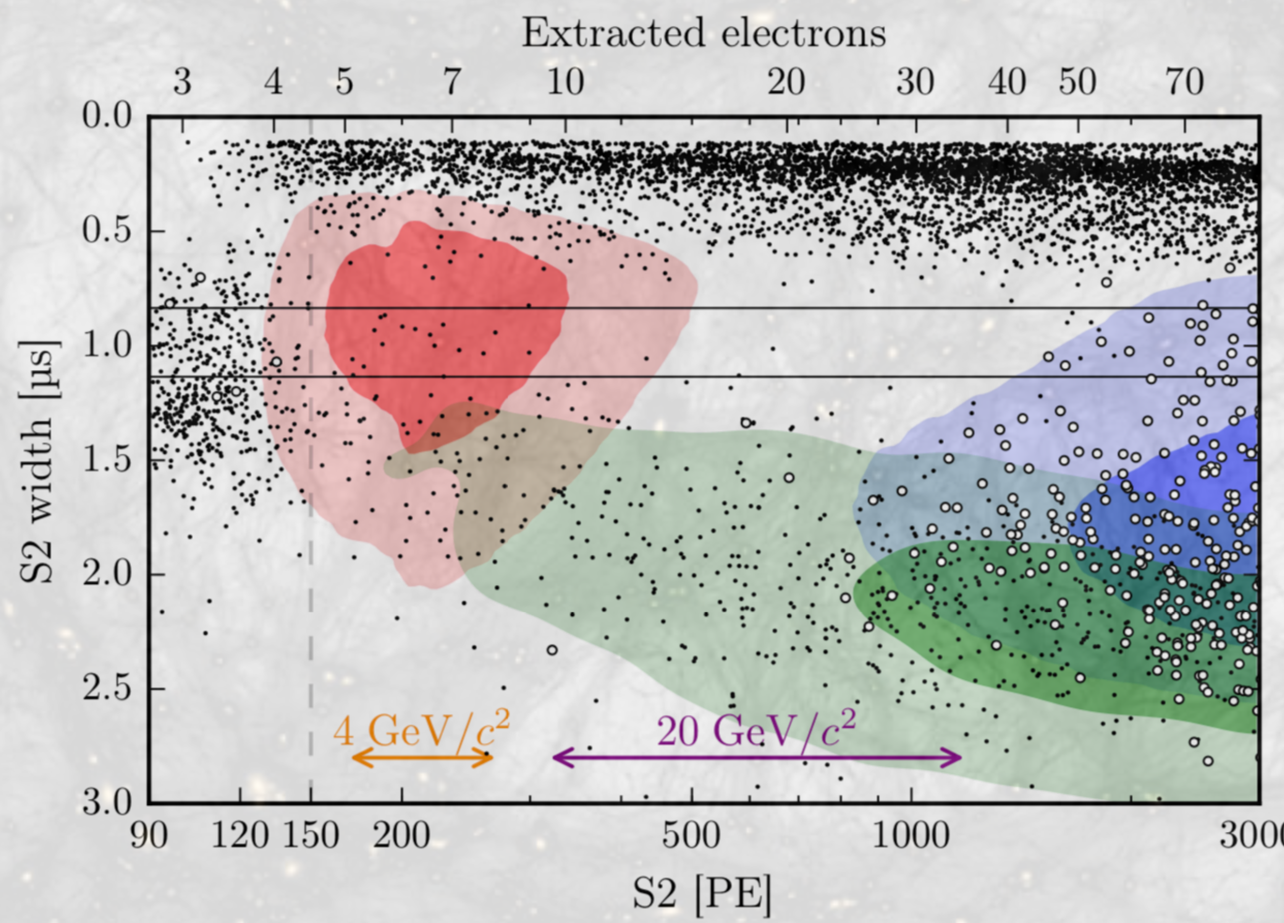
Lower the Energy Threshold: S2-only

Fig. credits to J. Aalber

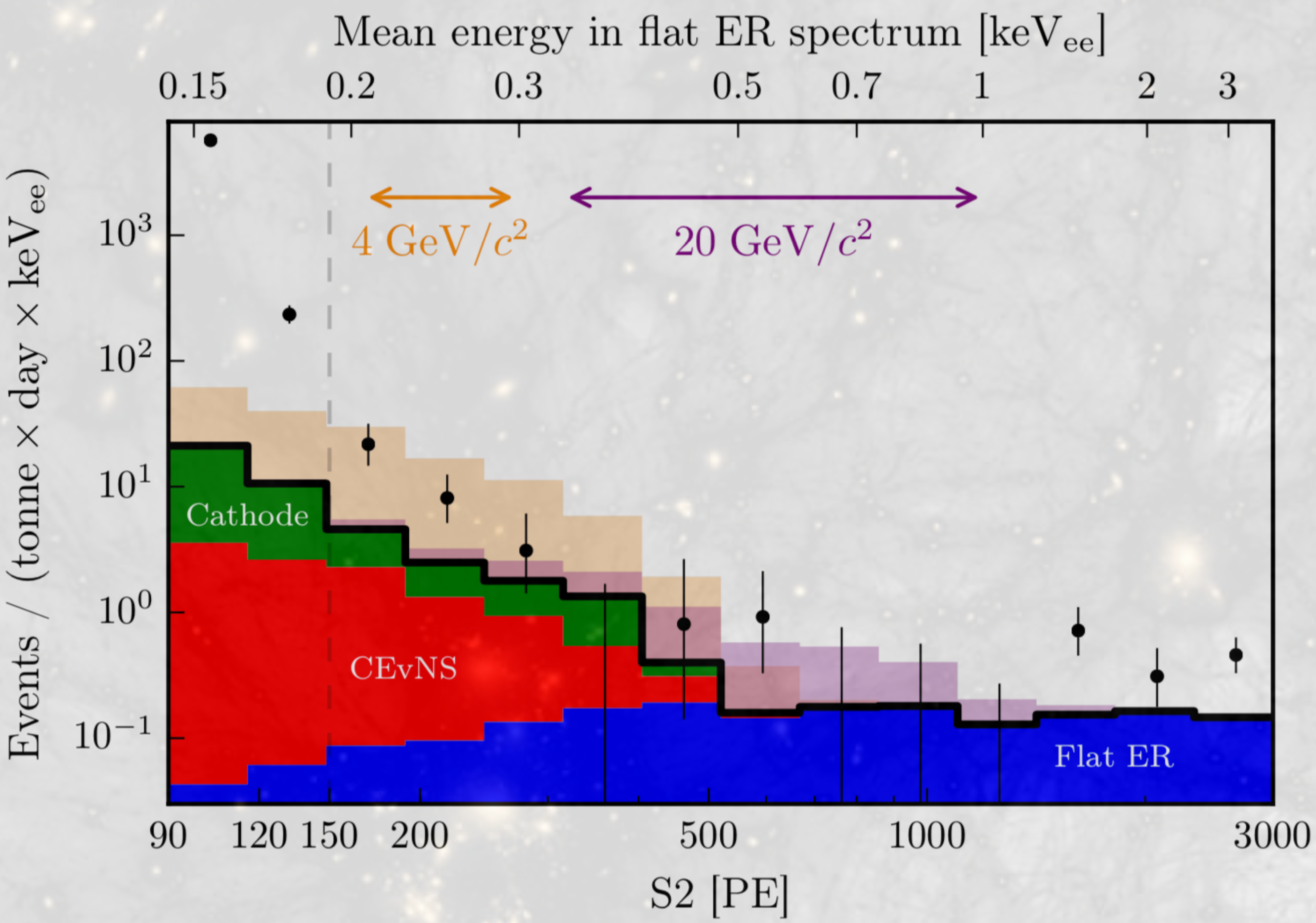


XENON1T, PRL 123 251801 (2019)





Have we Detected B8 CEvNS?

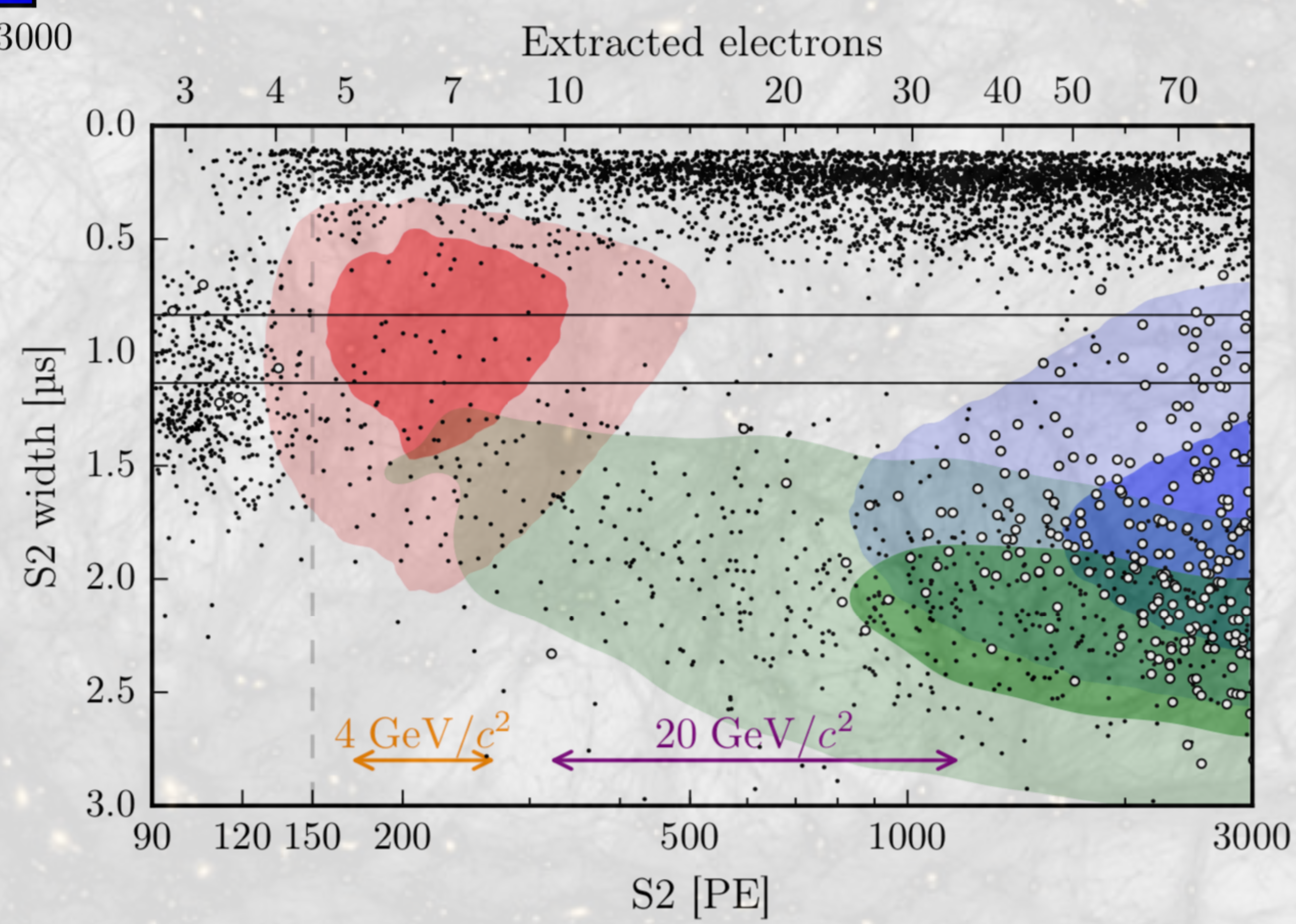


The analysis doesn't have a complete modeling of background

Existing instrumental background on the grids leads to tight selections, and low detection efficiency as well

It became limit setting analysis

Though we expect 2.0±0.3 CEvNS events in the optimal ROI



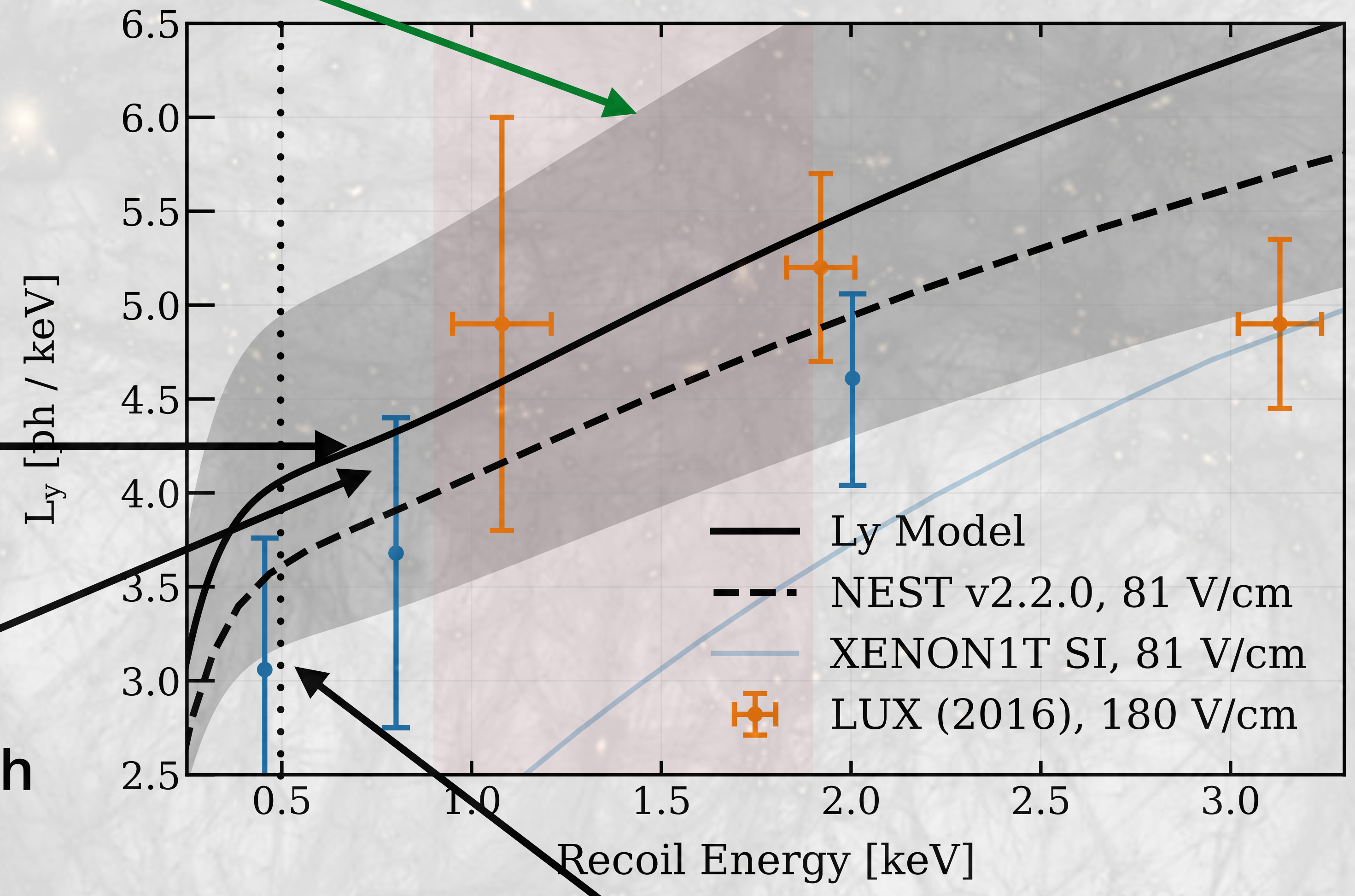
Scintillation Yields for Nuclear Recoils

Measurement of scintillation yields is quite uncertain. Only efforts across the LUX collaboration/collaborators

arXiv:2012.02846

We scaled the NEST model to describe the average scintillation yields, which agrees with existing measurements

A large uncertainty bands is used, which can accommodate all available measurements



Unpublished measurement from Dr. Dongqing Huang's thesis available down to 0.5 keV, we made a cut off here

Search for CEvNS with both S1 and S2?

There are ~600 CEvNS recoils from B8 solar neutrinos alone

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$$\simeq 600\,\text{events}/(\text{tonne} \times \text{year})$$

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CEvNS	**0.05 ± 0.01**	0.03 ± 0.01
Accidental	$0.5\ ^{+0.3}_{-0.0}$	$0.10\ ^{+0.06}_{-0.00}$
Surface	106 ± 8	4.8 ± 0.4
Total	735 ± 20	7.4 ± 0.6

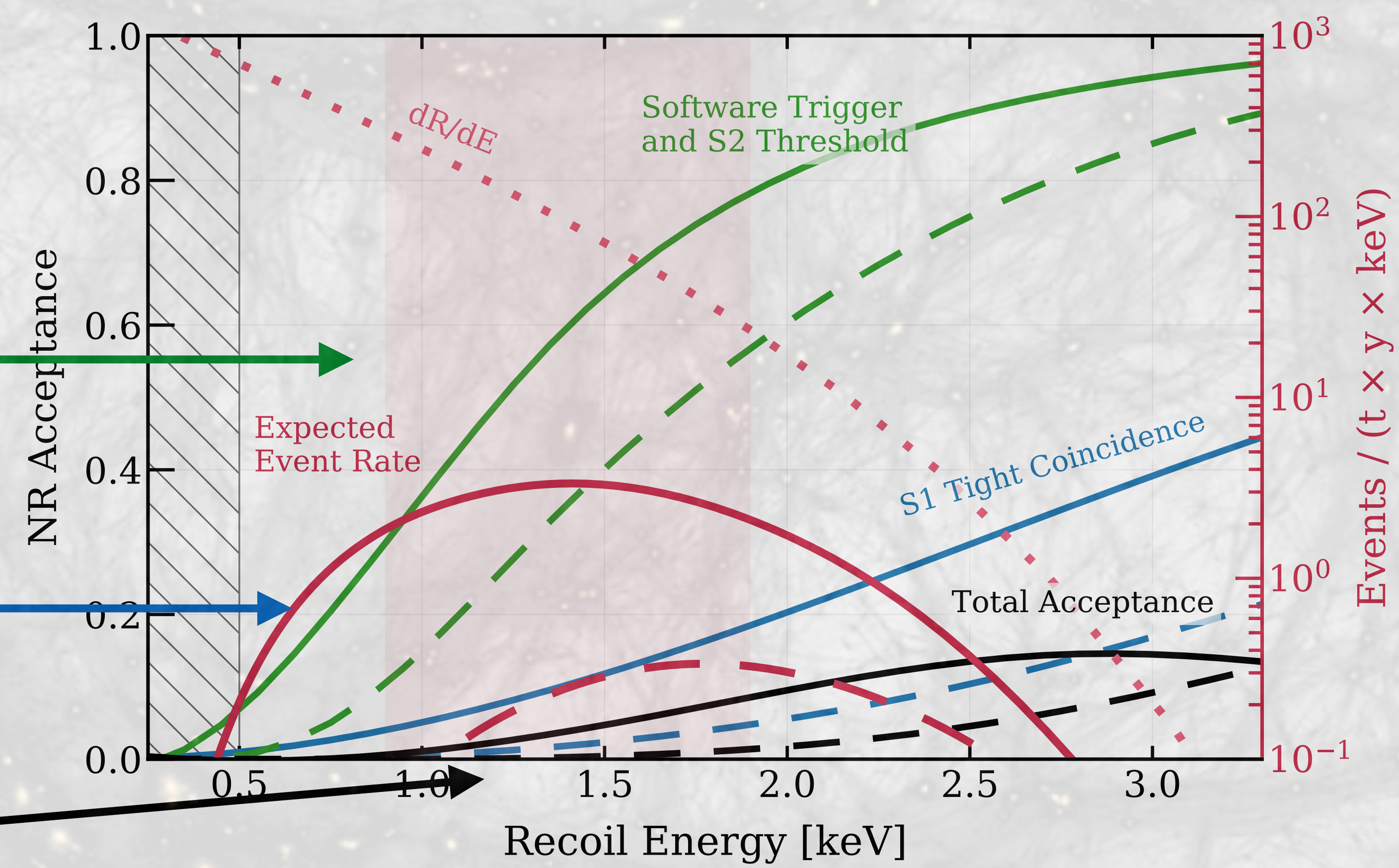
arXiv:2012.02846

Can we increase the detection efficiency to ~1%? o(5) CEvNS

S2 threshold: S2 > ~~200~~ 120PE to ensure reconstruction quality and to suppress background

S1 threshold: ~~Three~~ Two PMTs seeing light within a typical S1 window (50ns)

Additional cuts ~~not~~ optimized for CEvNS



What are the Knowns and Unknowns?

Solar B8 decays → Recoils in XENON1T → Charge/ scintillation emission → Charge drift → Extraction/ proportional scintillation → Optical photon propagation → PMT/ electronics response → Trigger & Reconstruction → Selections, Modeling, Analysis

Charge/ scintillation emission → γ → Optical photon propagation

Rate

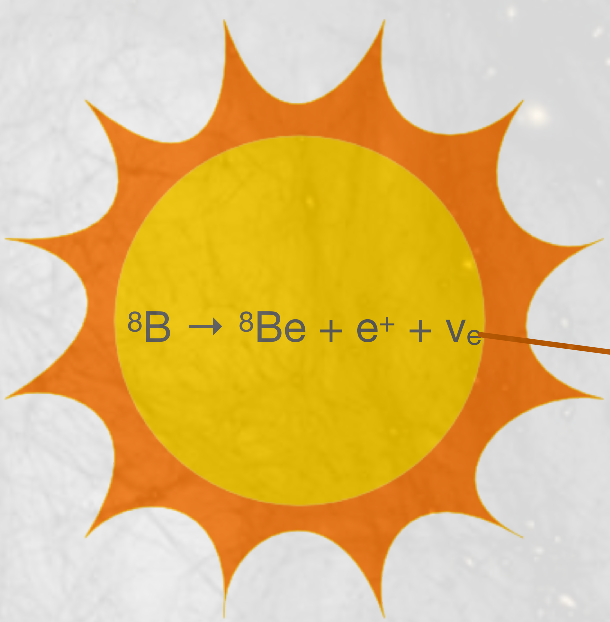
- 8B neutrino flux
- Cross-section

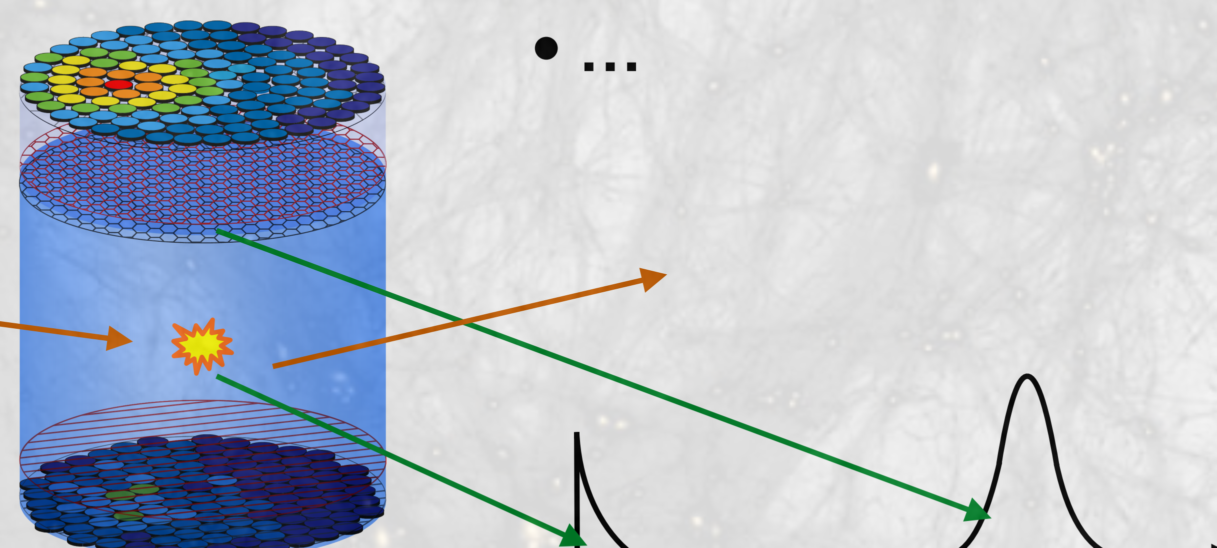
LXe Response

- Charge Yield
- Light Yield???

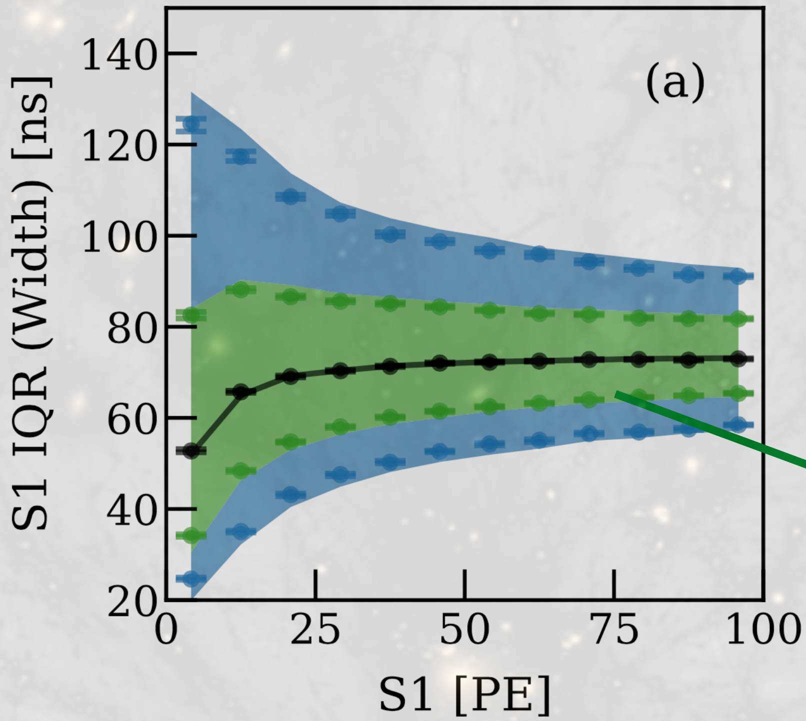
Detection efficiency??

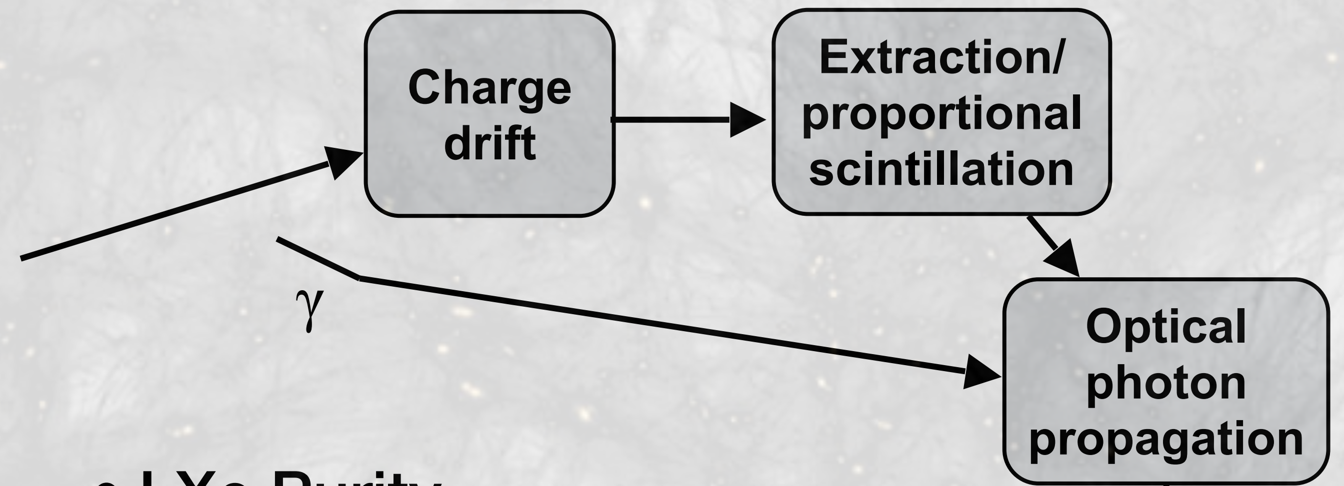
- LXe Purity
- PMT Coincidence Requirement
- Software Trigger
- ...



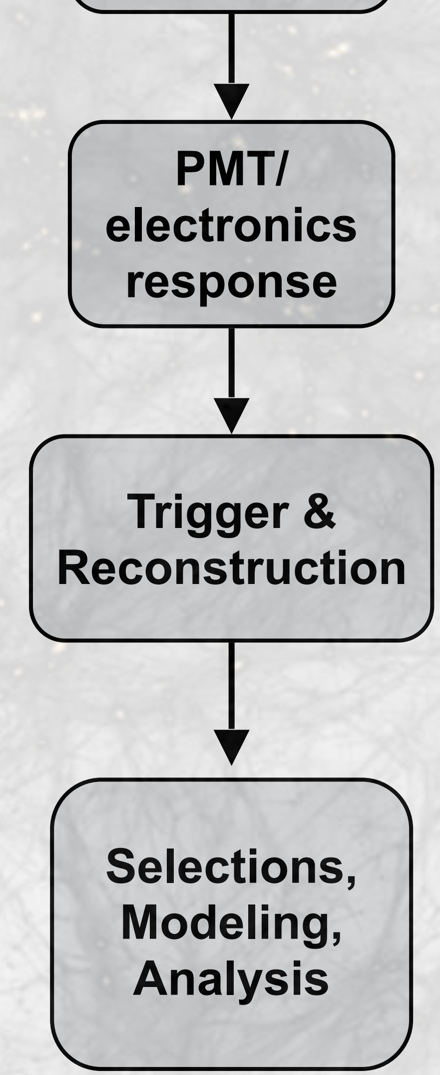


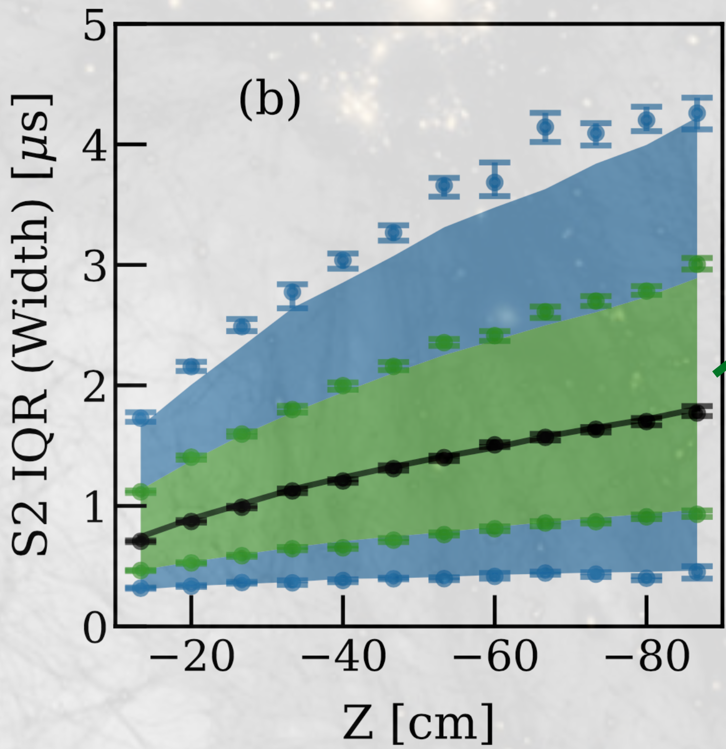
Modeling Efficiency through Waveform Simulation

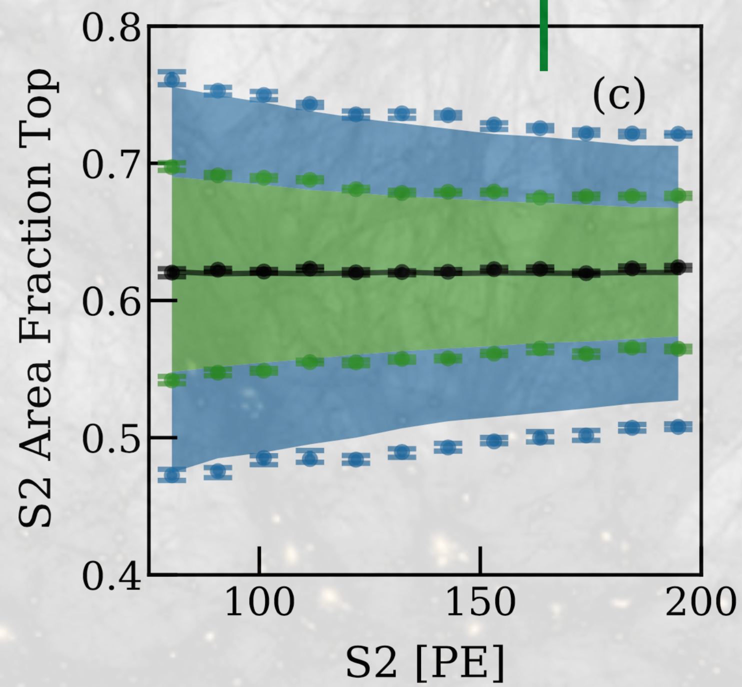




- LXe Purity
- PMT Coincidence Requirement
- Software Trigger
- ...



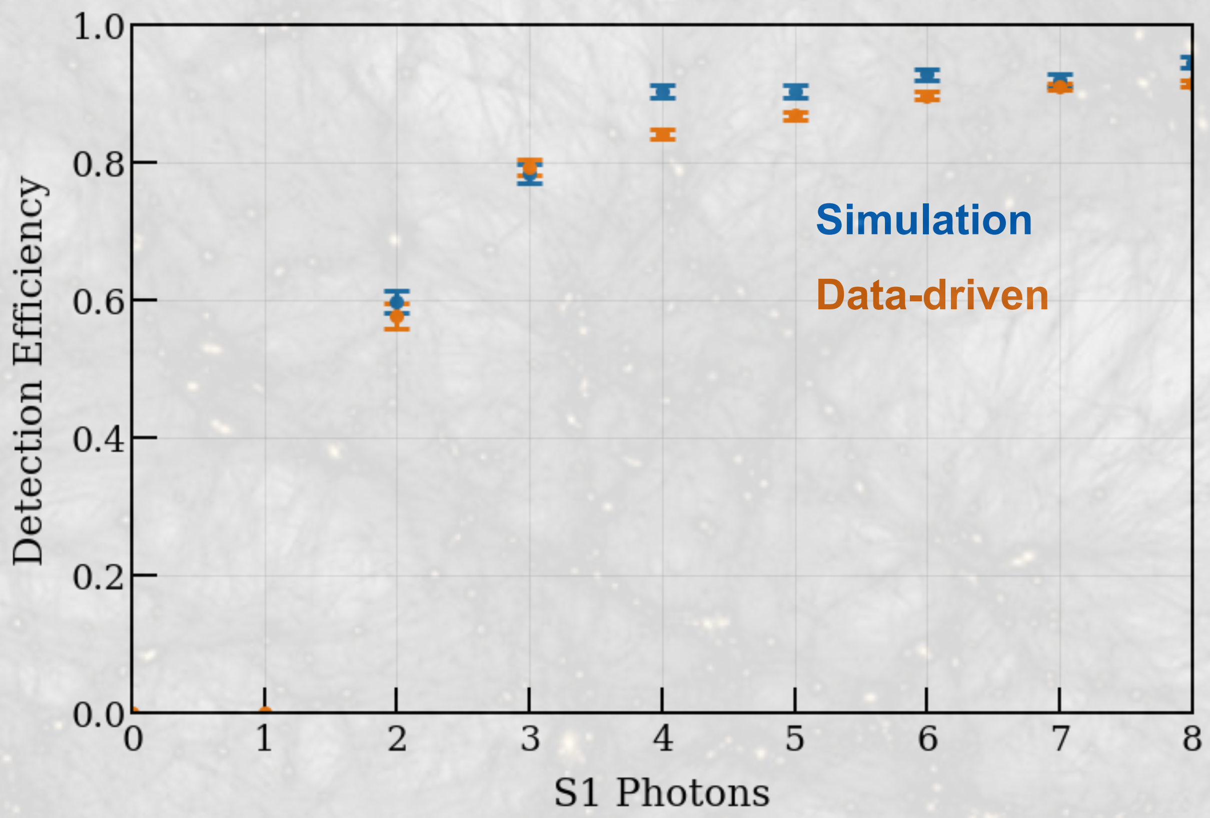




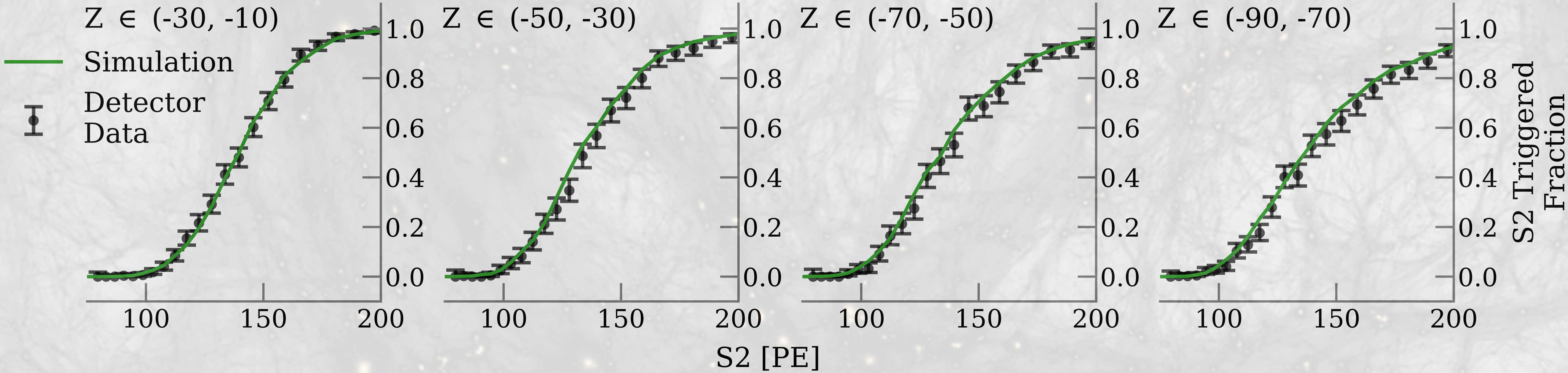
Modeling the Detection Efficiencies

S1 efficiency is well validated

CEvNS will produce mostly 2 and rarely 3 photons. Our S1 ROI is defined by Photons (hits) instead of PE



S2 efficiency is well validated by Surface events, down to 80PE! Our CEvNS S2 threshold is 120PE.



How does Background Change?

Analysis ROI

- S1: 2 or 3 hits
- S2: 120 - 500 PE
- R < 37 cm
- Other selections

AC background increased by two orders of magnitude, due to 2-PMTs coincidence and lower S2 threshold (dominant)

ER background is small, due to tight ROI (additional selection on cS2b<250PE)

Neutron background is small, due to tight ROI

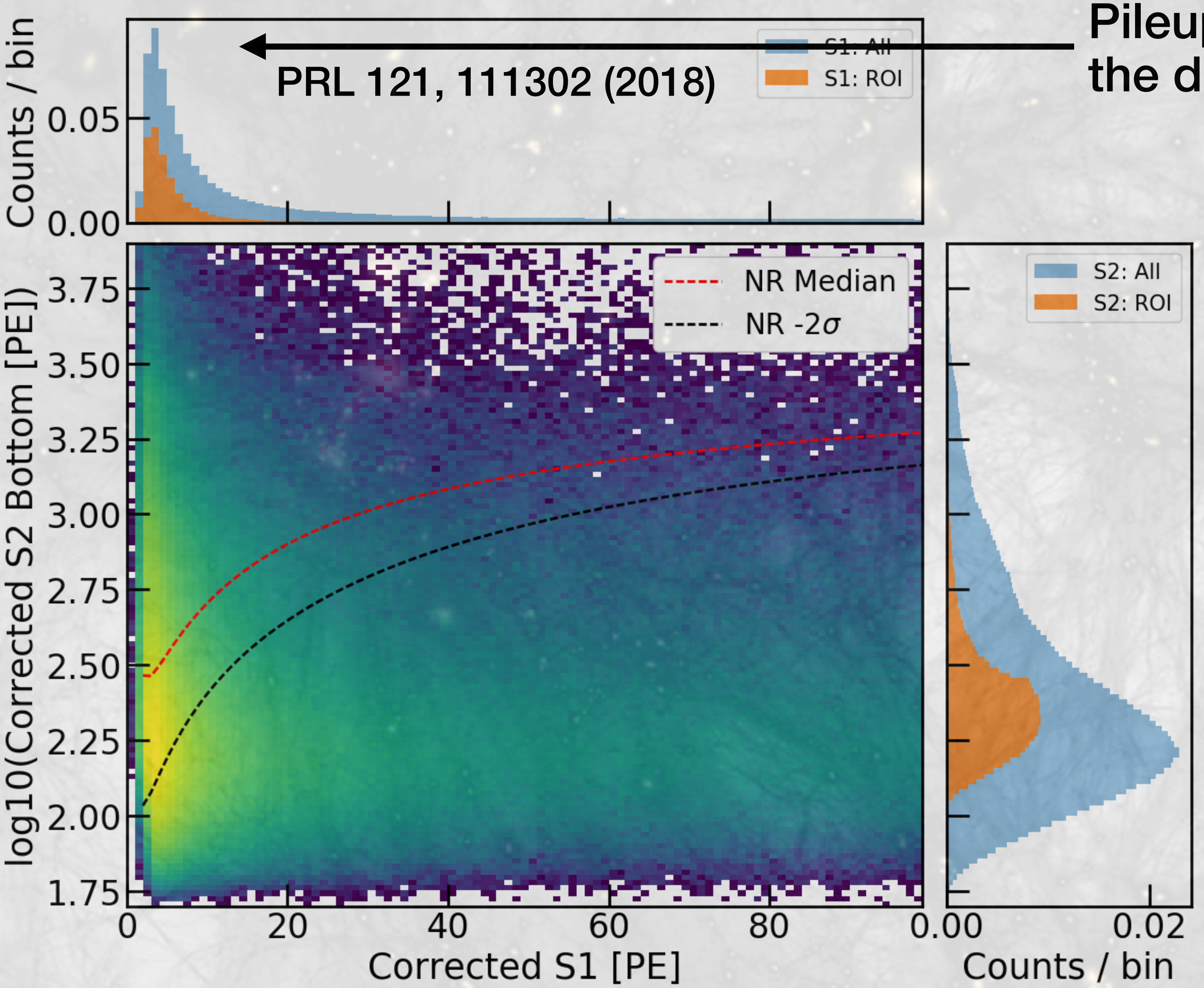
Surface background is negligible due to small fiducial volume

arXiv:2012.02846

Source	Expectation
CEvNS	**2.25**
Accidental	5.14
ER	0.21
Radiogenic	0.03
Surface	Negligible
Total	7.65

The Accidental Coincidence Background

AC background: Accidental coincidence of S1 and S2 peaks are mis-reconstructed as an event



Pileup of PMT's spontaneous counts was the dominating source of S1 peak

S1-only peak rate increased by >20 times by lower the PMT coincidence from 3 to 2

S2 rate also increased due to lower S2 threshold.

Conclusion: We need new ideas to suppress the AC background!

AC Background Suppression: I

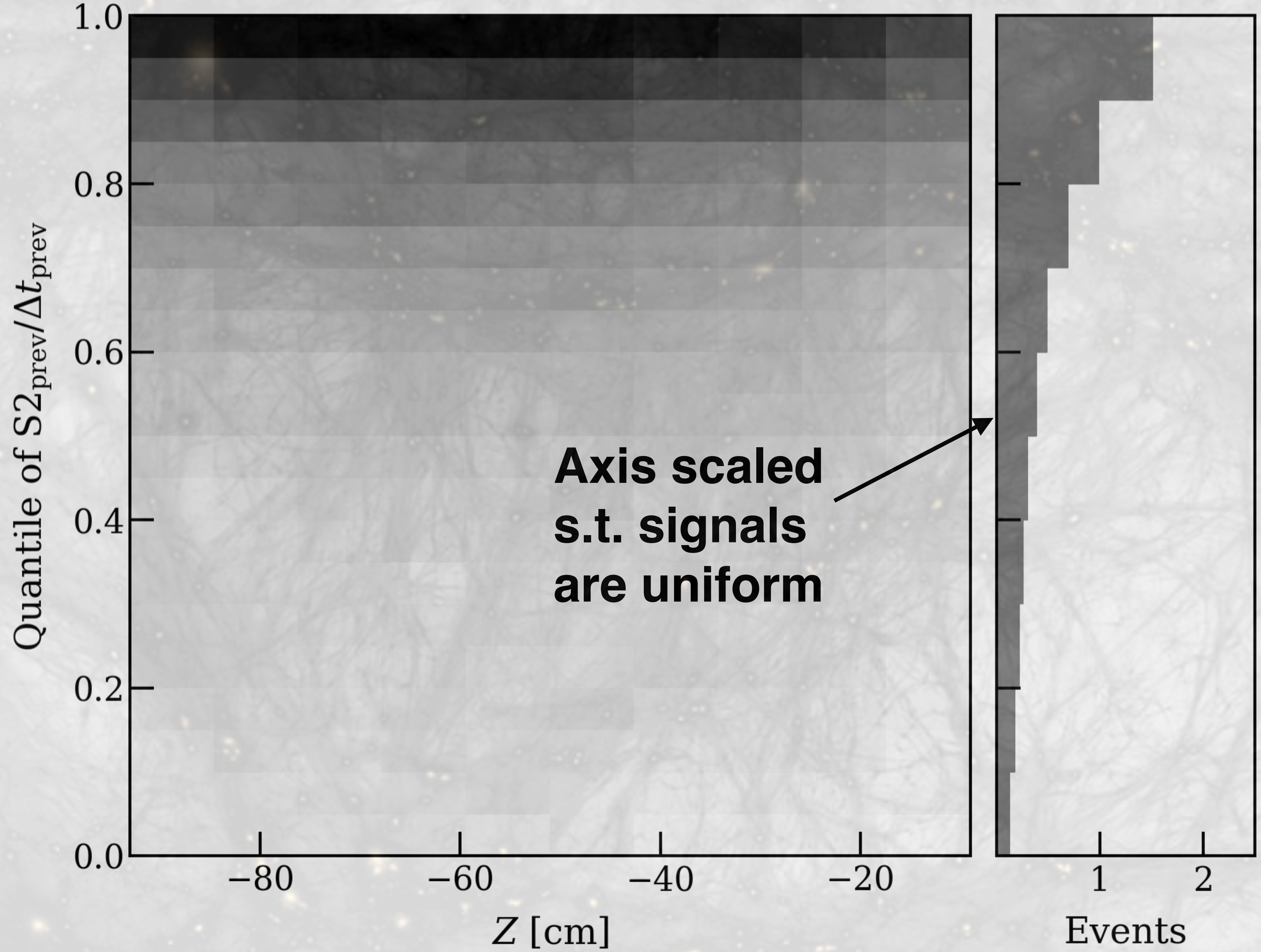
High energy events induce large AC background afterwards

- S1: higher rate of lone-hits (reasons unclear to us)
- S2: higher rate of single electron emissions and hence their pileups
  - Suppressed by a position correlation cut

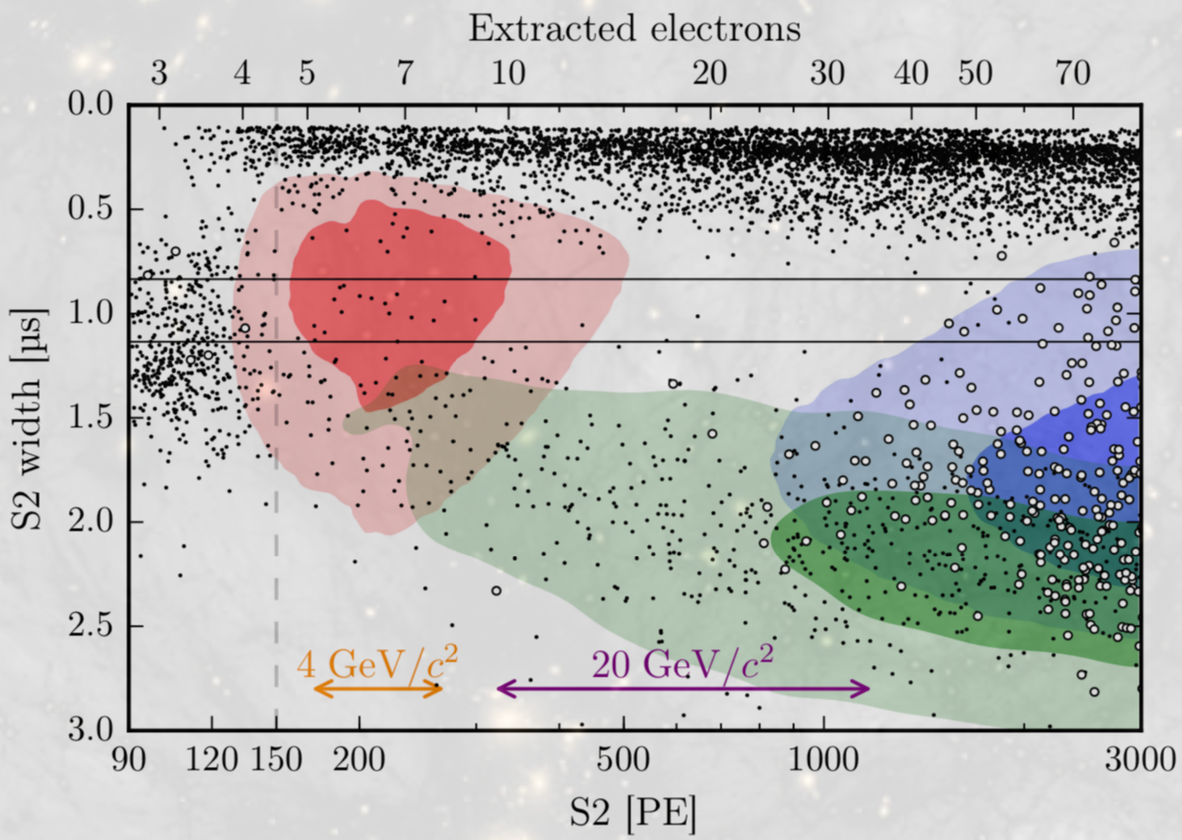
Reduce the impact of a high energy event, we define a cut on: $S2_{prev}/\Delta t_{prev}$

- S1: 65% reduction ->11.2 Hz
- S2: 0.7mHz, 1/3 of XENON1T SR1
- Ensure no correlations of S1 and S2s

Reduced the exposure to 0.6 ton-year



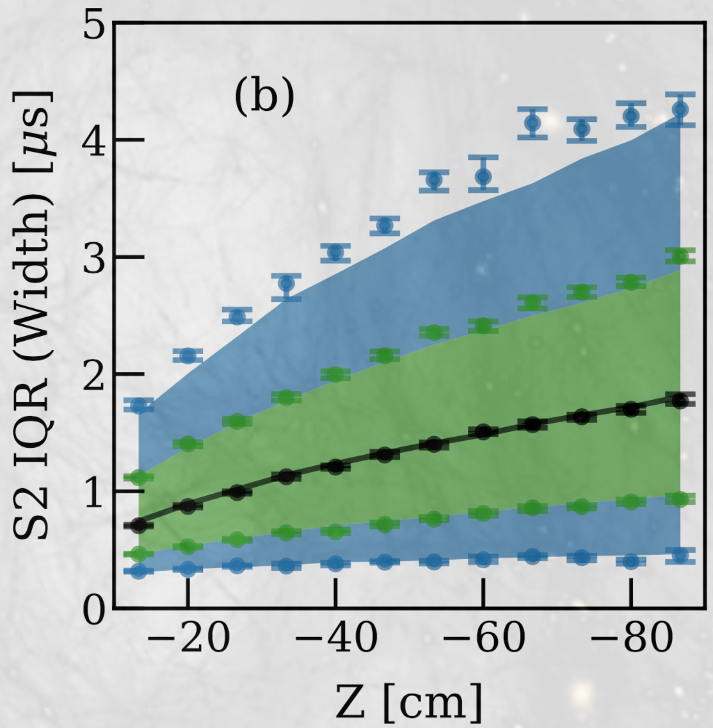
AC Background Suppression: II

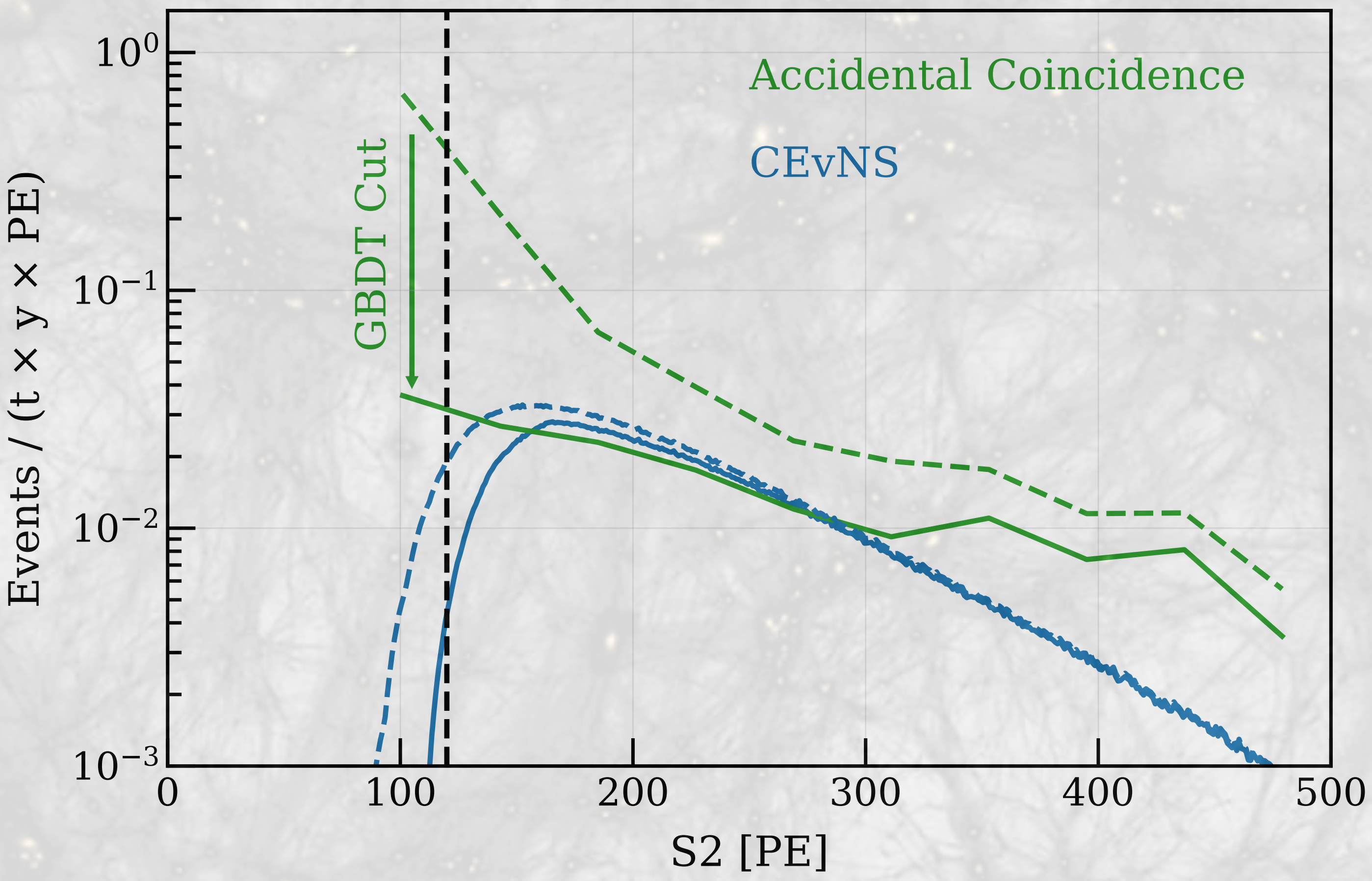


Gradient **B**oosted **D**ecision **T**ree ensemble classifier for an optimal discrimination

GBDT significantly (~65%) reduced the AC background, while keeping ~85% of CEvNS

AC events has different distributions in spaces like: S2, S2 width, S2 area fraction on Top, depth (Z)



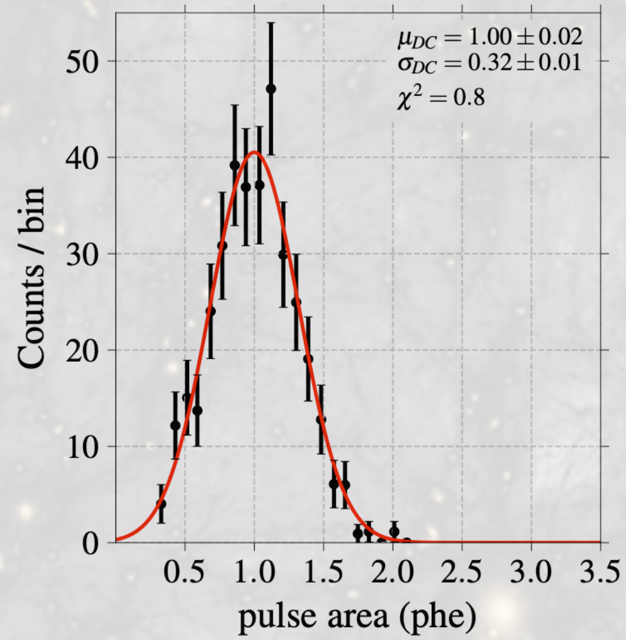


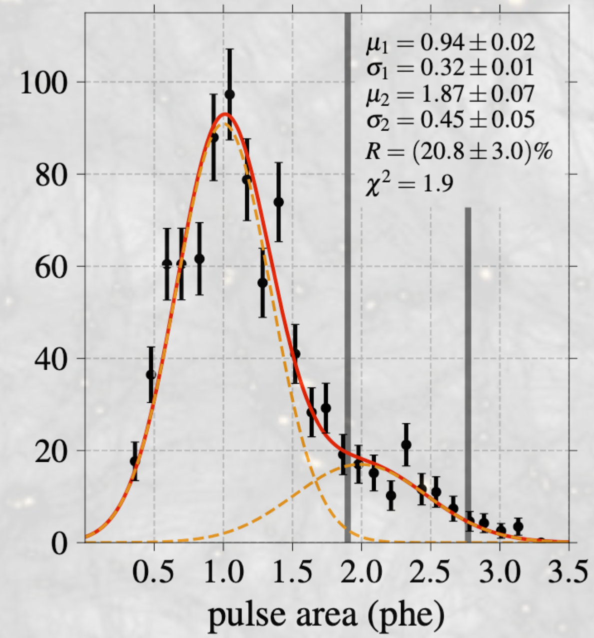
CEvNS rarely has S2s below 120PE: data with S2 below 120PE is used as a Control region

AC Background Suppression: III

LUX, PRD 101, 042001 (2020)

Isolated S1s composed of dark counts **rarely contain >2 PE** hits





Signal S1s have a **~20% DPE** probability per hit

Two "**L**argest **H**it **A**rea" Bins

LHA < 2 PE; LHA ≥ 2 PE

Isolated S1s composed of dark counts are roughly **evenly distributed across PMTs**, and **rarely contain three PMTs**

Signal S1s usually reflect downward toward **bottom PMTs**

Three "**H**it **C**ategory" Bins

HC0: 2 Hits, 1+ in the top array of PMTs → Very AC-like

HC1: 2 Hits, 0 in the top array of PMTs → More Signal-like

HC2: 3 Hits (anywhere) → Very Signal-like

Analysis Strategy

Analysis Dimensions:

- S1: 1-6 PE
  - LHA 2 bins (LHA < 2 PE; LHA ≥ 2 PE)
  - HC 3 bins (HC0, HC1, HC2)
- S2: 120 - 500 PE, 10 bins
- R < 37 cm, Z in [-93 cm, -9 cm] (10 bins)
- $S2_{\mathrm{prev}}/\Delta t_{\mathrm{prev}}$ 10 bins

Analysis Procedure:

1. Study and validate AC background in the **Control Region**
   - develop new selections if needed
2. Unblind AC Validation Region (**Inverted GBDT Cut**)
   - Require GoF p-values > 0.05 for:
     a. Six HC + LHA combinations (summed over other axes)
     b. Three “continuous” dimensions (summed over HC + LHA)
3. Full **unblinding**

Control Region

80 PE < S2 < 120 PE: Very low signal expectation (<1%), High AC

Expected: 27.7 ± 1.4 conservative 5% systematic uncertainty

Observed: 27

4 of 27 had two hits on a single PMT → likely PMT after-pulses

↪ New cut (> 99% acceptance)

Expected: 27.7 ± 1.4 →

Observed: 23 →

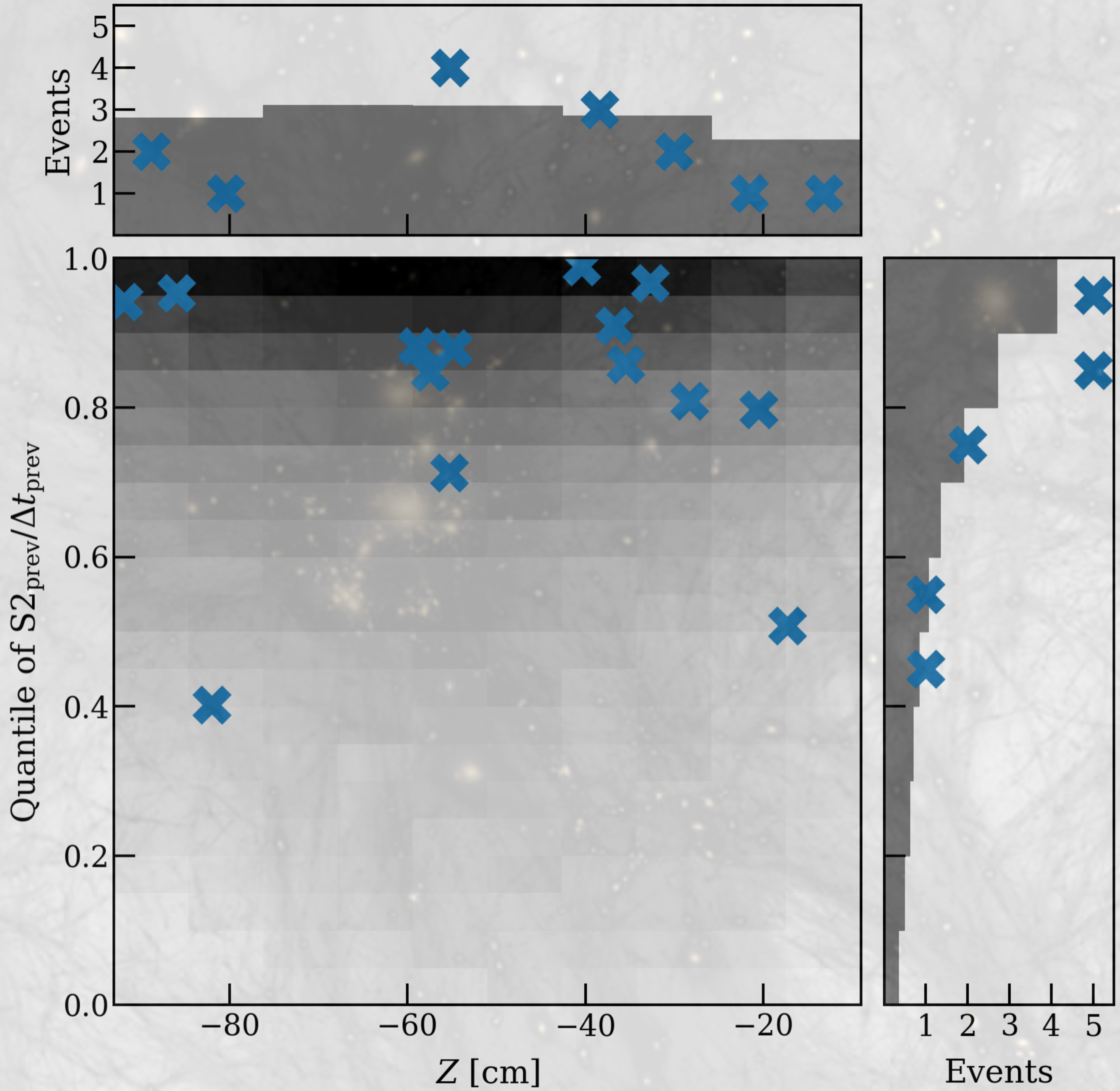
Decent agreement!!

Even if we normalize the model based on observation, the uncertainty is 20%

Super conservative 20% uncertainty is used in the inference —> doesn't have impact on the discovery potential!

Validation Data

Data consistent with AC background (p > 0.05)



GoF Scores:

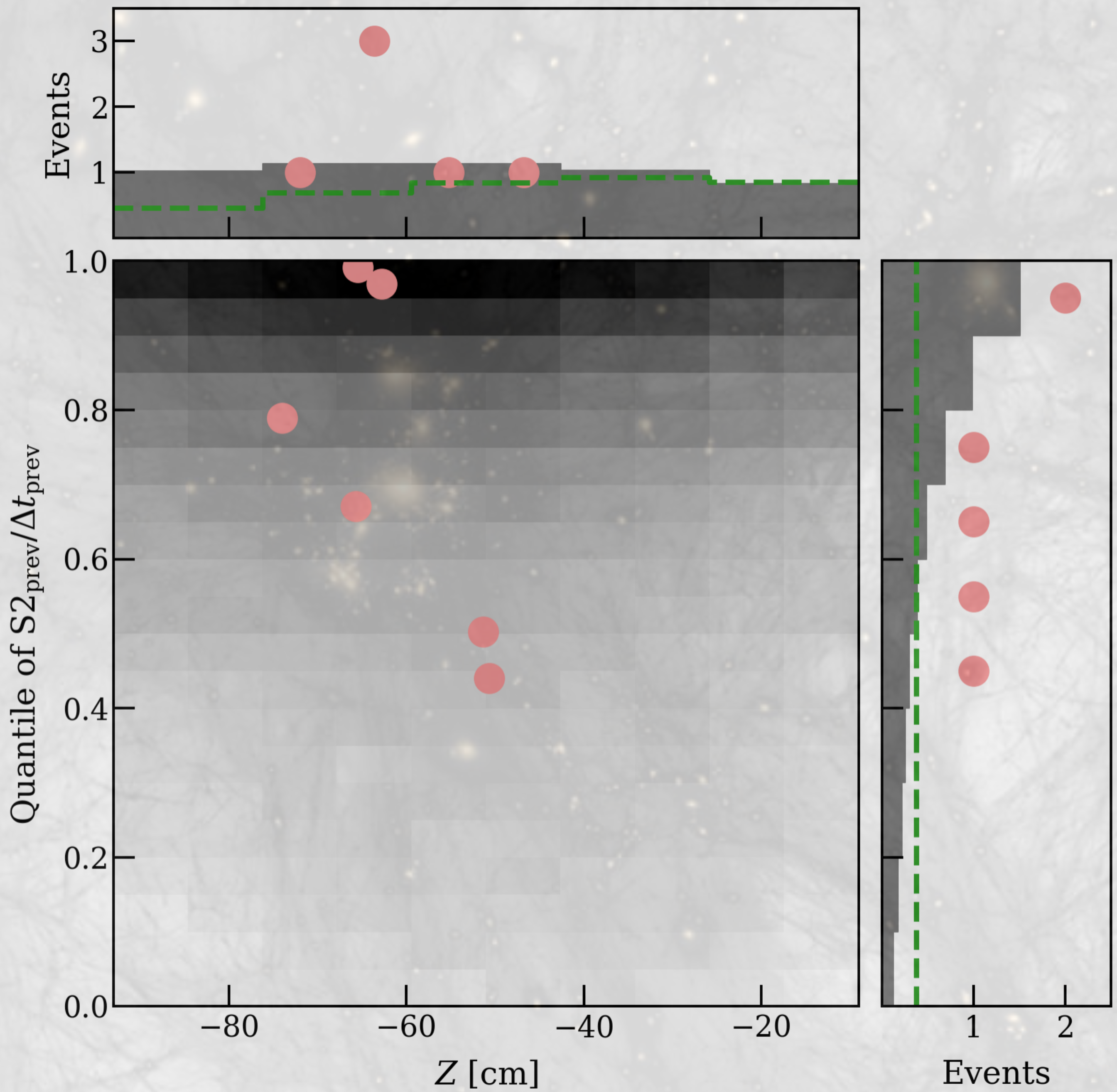
Continuous Axes: p = 0.33

Six HC + LHA bins: p = 0.95

HC	LHA	Expected	Observed
0	≥ 2	0.23	0
0	< 2	9.37	10
1	≥ 2	0.07	0
1	< 2	3.93	4
2	≥ 2	0.00	0
2	< 2	0.03	0
	Total:	**13.63**	**14**

Results from Unblinding

Data consistent with AC background (p > 0.05)



GoF Scores:

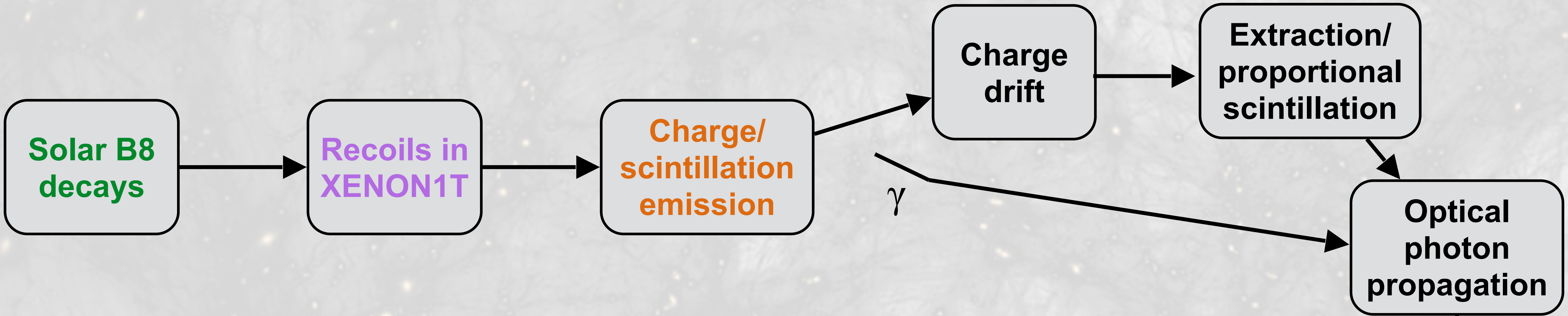
Continuous Axes: p = 0.72

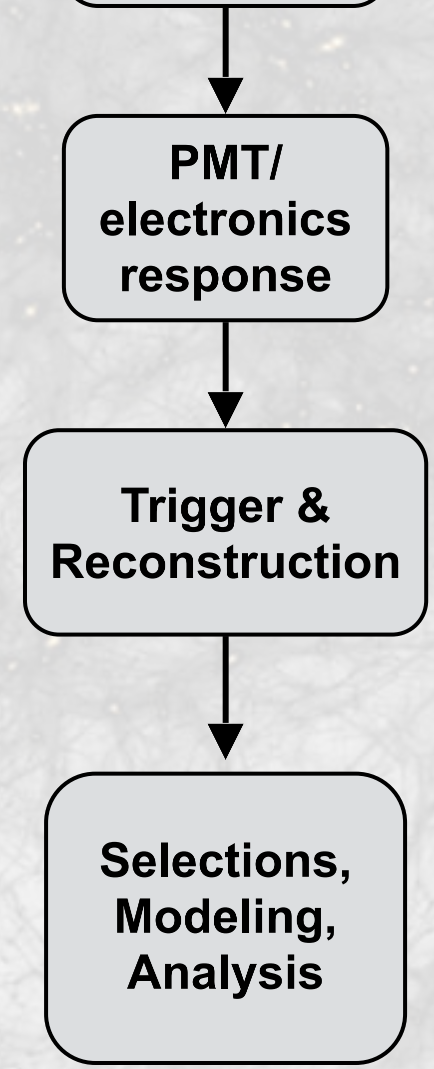
Six HC + LHA bins: p = 0.64

arXiv:2012.02846

HC	LHA	BG	Signal	Observed
0	≥ 2	0.10	0.13	0
0	< 2	3.58	0.46	4
1	≥ 2	0.06	0.25	0
1	< 2	1.58	0.84	2
2	≥ 2	0.02	0.18	0
2	< 2	0.05	0.39	0
	Total:	**5.38**	**2.25**	**6**

What can We Learn from XENON1T Data?





Rate

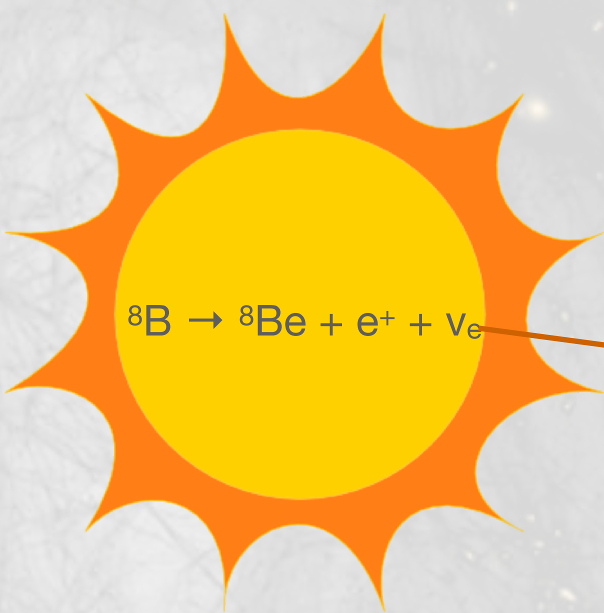
- 8B neutrino flux
- Cross-section

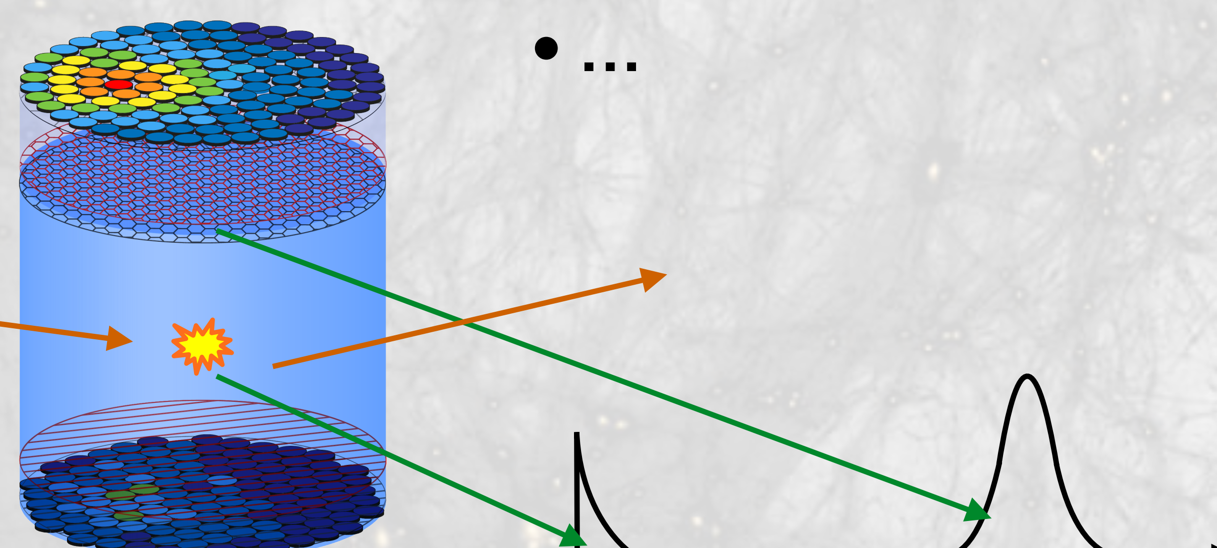
LXe Response

- Charge Yield
- Light Yield???

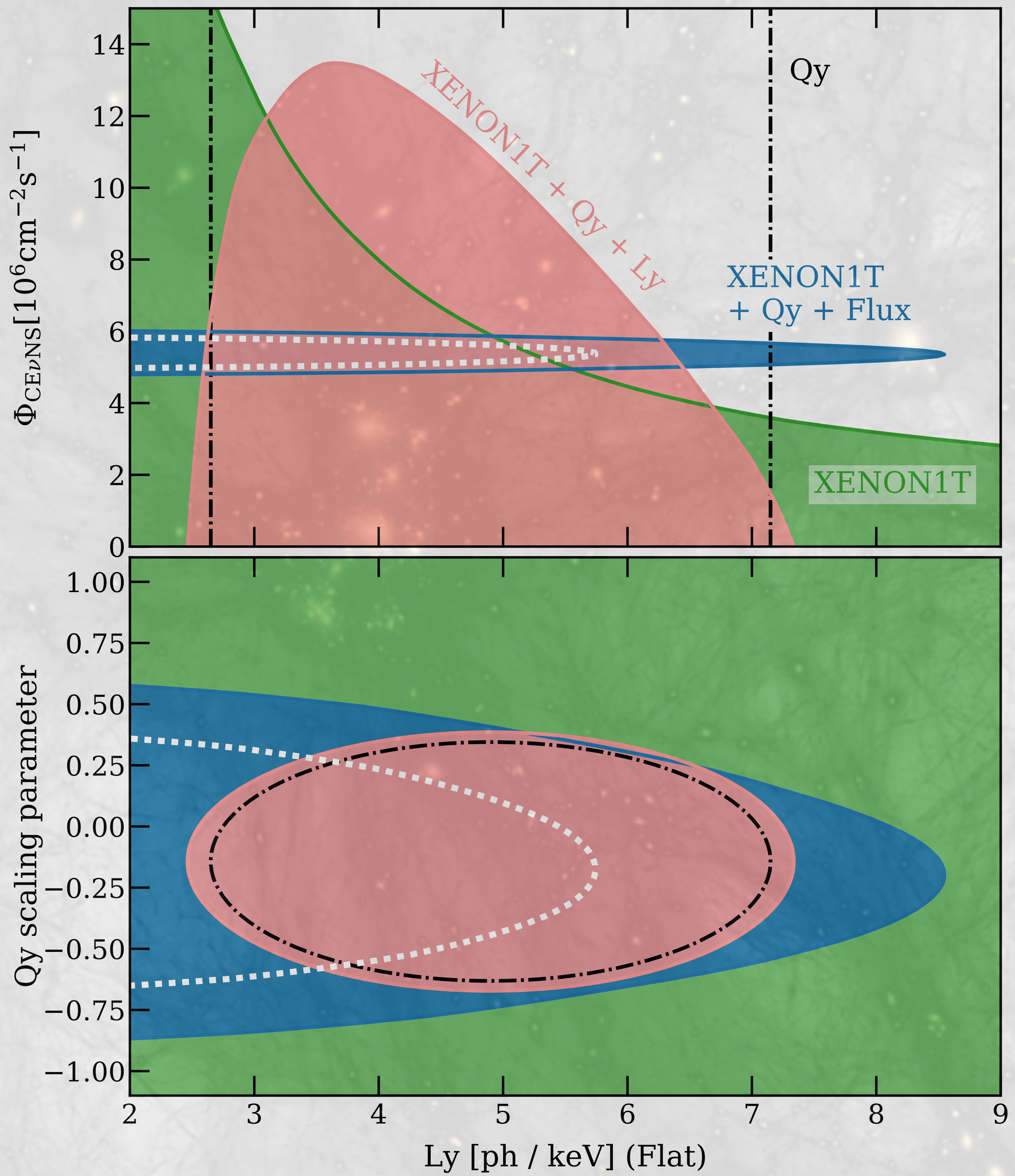
Detection efficiency

- LXe Purity
- PMT Coincidence Requirement
- Software Trigger
- ...





Constraints on the "Standard" Physics



Constraints on the solar B8 neutrino flux and the response of LXe to nuclear recoils

(Use Single-Valued Ly)

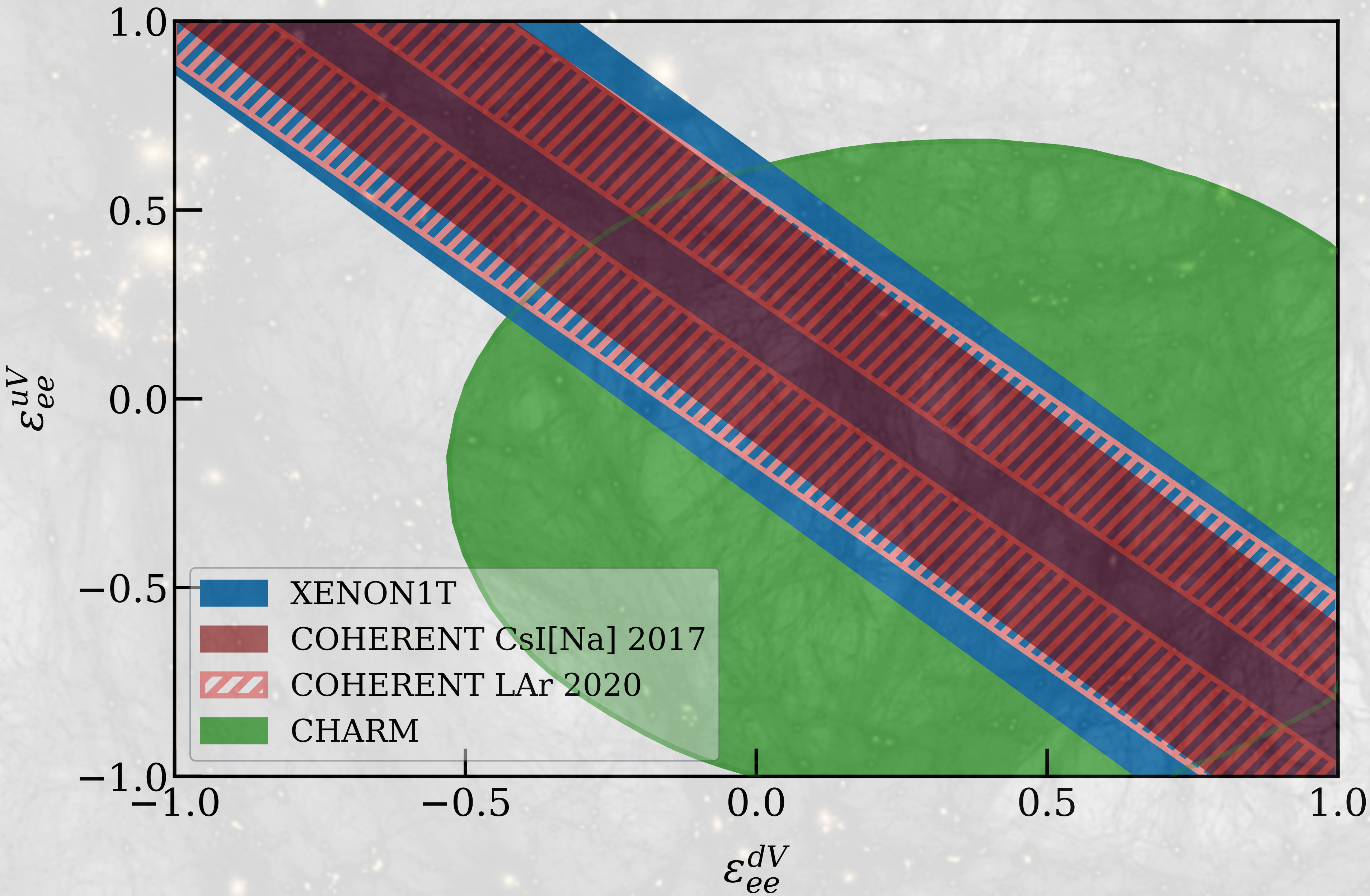
Yield data (LUX / Livermore)
+ XENON1T → **Flux < 1.4e-7 / cm² s**
first independent constraint on solar B8 neutrino flux through **CEvNS** process

Flux (Borexino/SNO) + Qy (Livermore)
+ XENON1T → **Ly < 8.5 ph / keV**

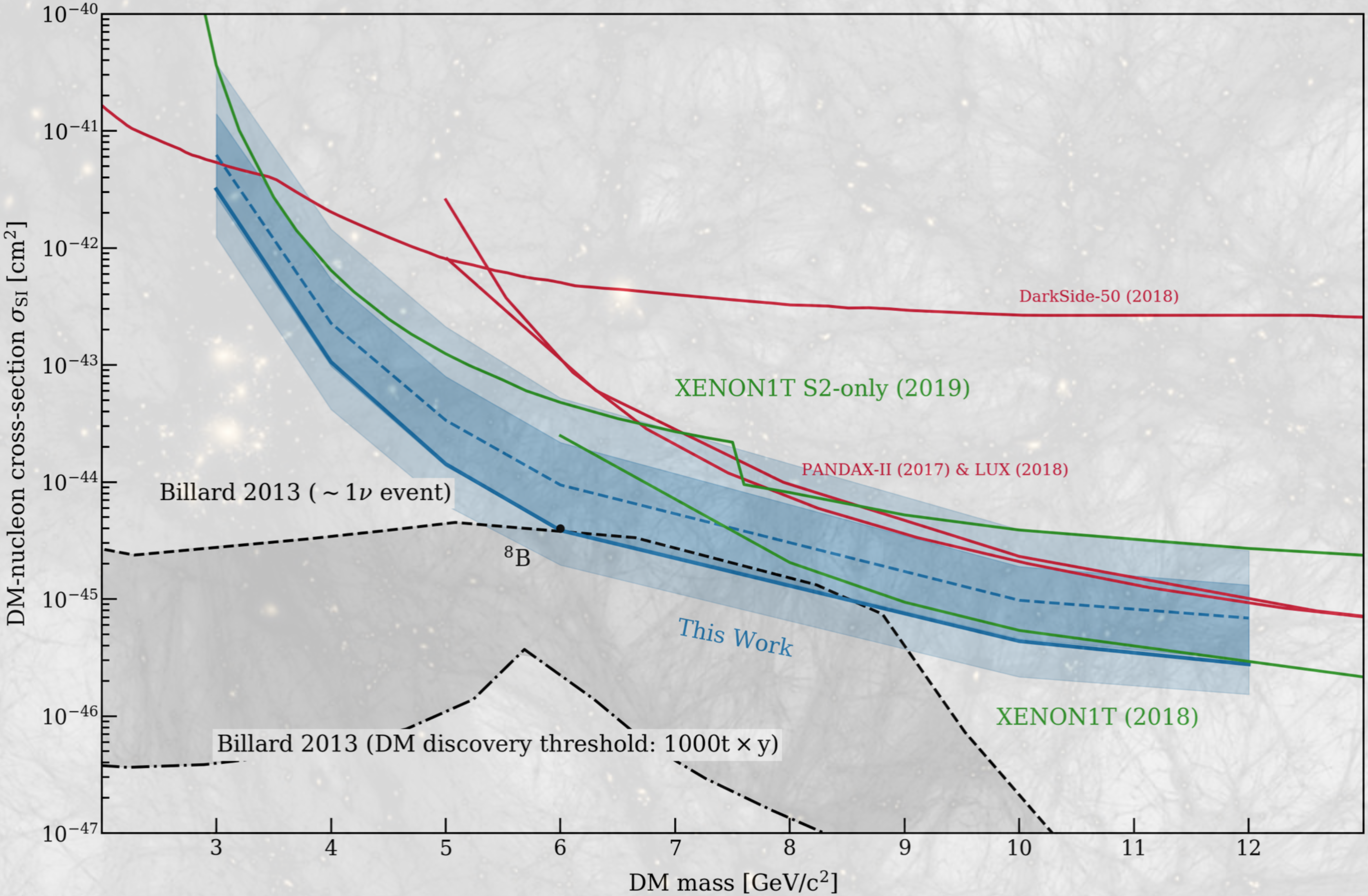
Constraints on "new" physics

$$\frac{\mathrm{d}\sigma}{\mathrm{dE_r}} = \frac{G_F^2}{4\pi}\mathrm{Q_w^2 M}\left(1 - \frac{\mathrm{ME_r}}{2\mathrm{E}_\nu^2}\right)\mathrm{F(E_r)}^2$$

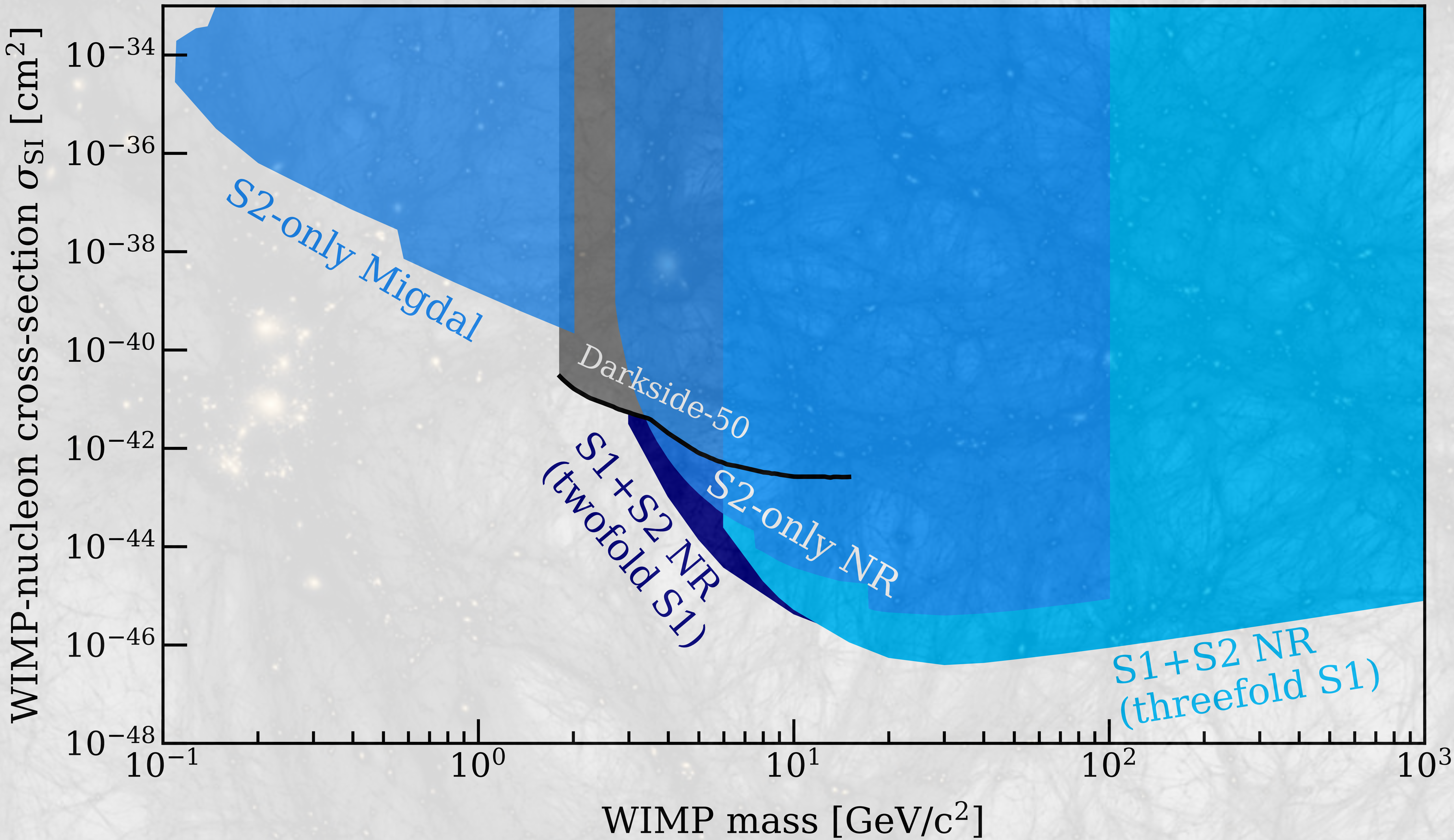
$$Q_w \to \widetilde{Q}_w = N(1 + 2\epsilon_{ee}^{uV} + 4\epsilon_{ee}^{dV}) + Z(4\sin^2\theta_w - 1 + 4\epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})$$



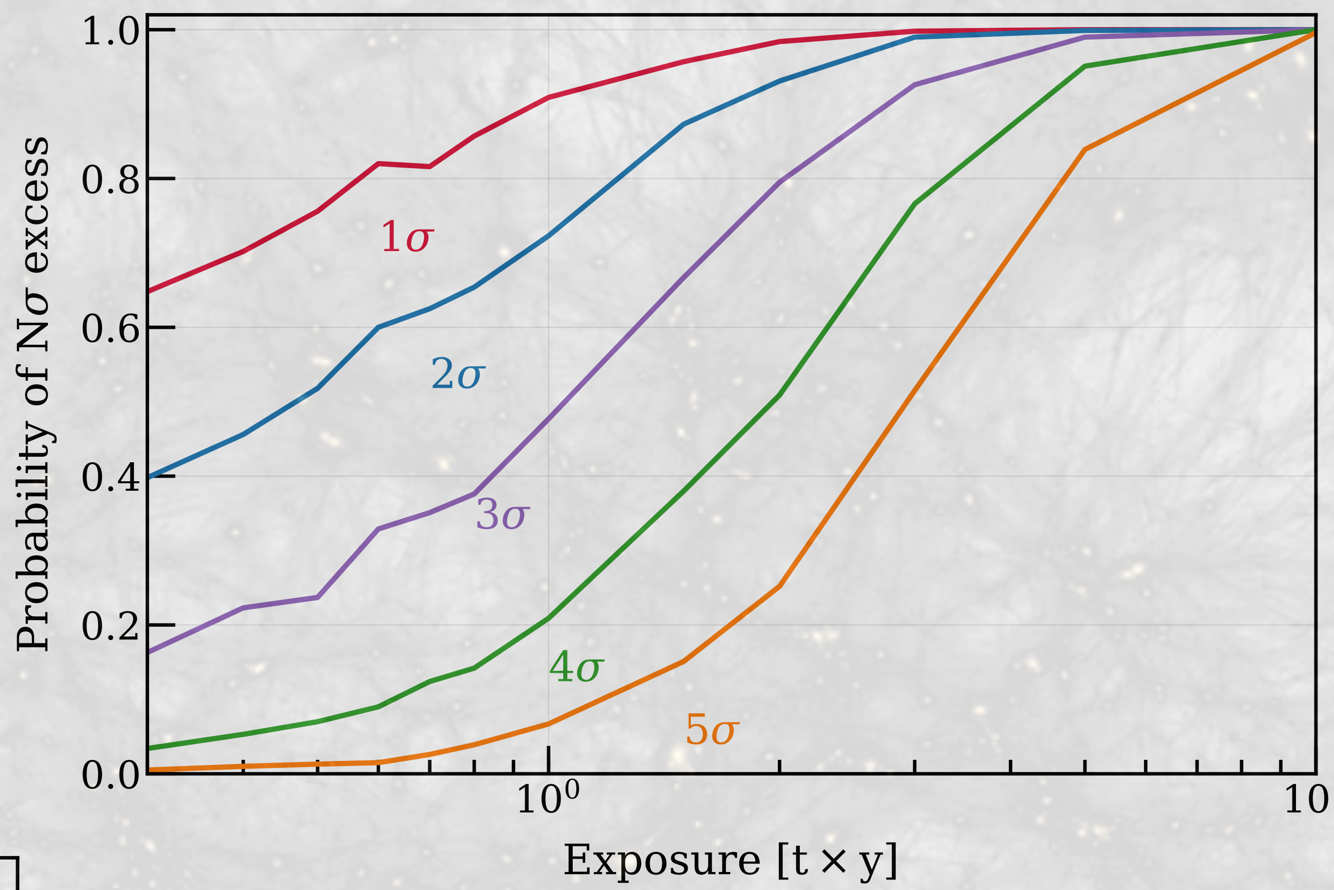
New constraints on light Dark Matter



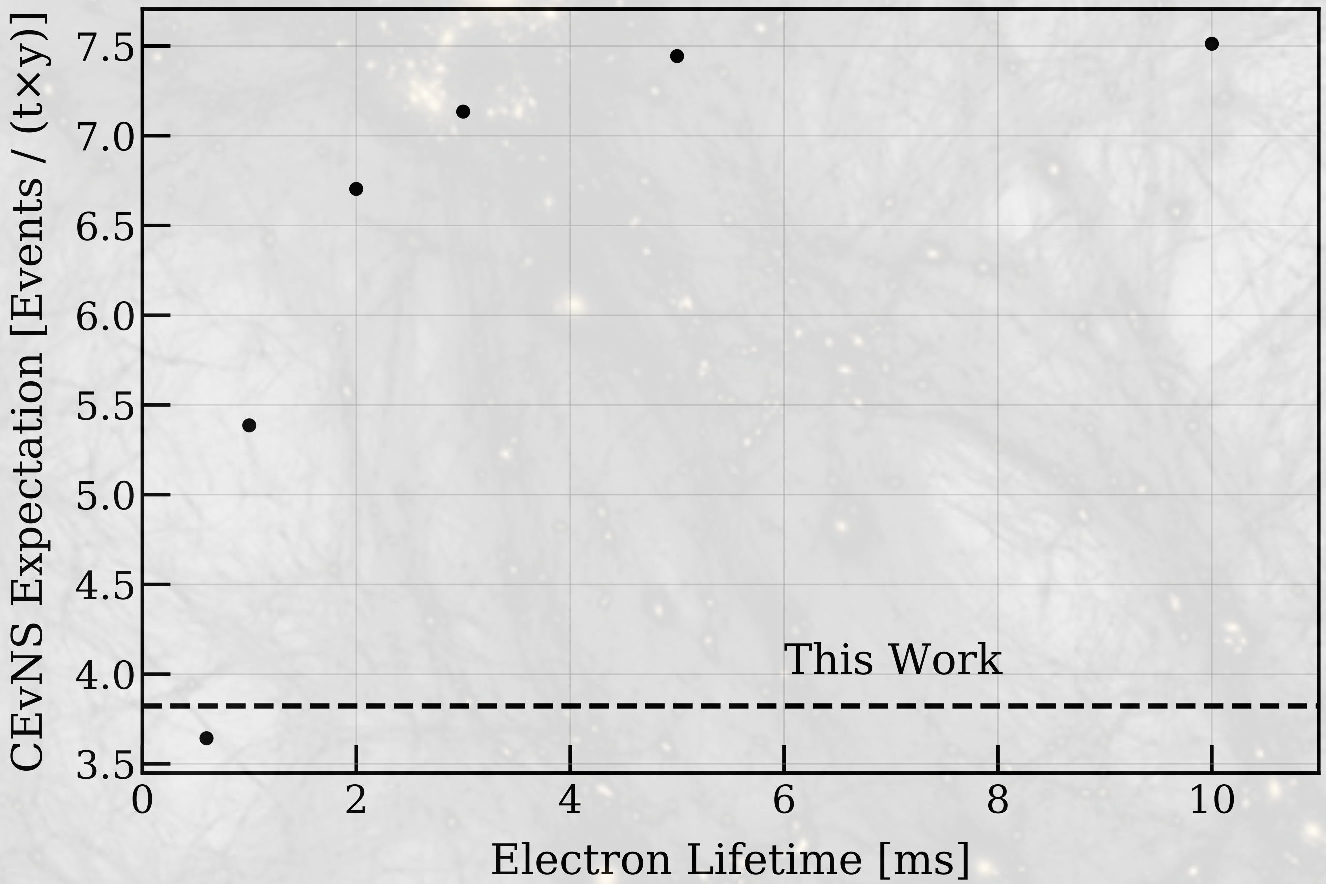
The new Dark Matter Landscape



How to Find More CEvNS?



Discovery potential scales with exposure at the XENON1T signal to background ratio. LZ, PandaX-4T and XENONnT all have significant discovery potential!



Increasing light and charge detection efficiency is critical (e.g. electron lifetime)

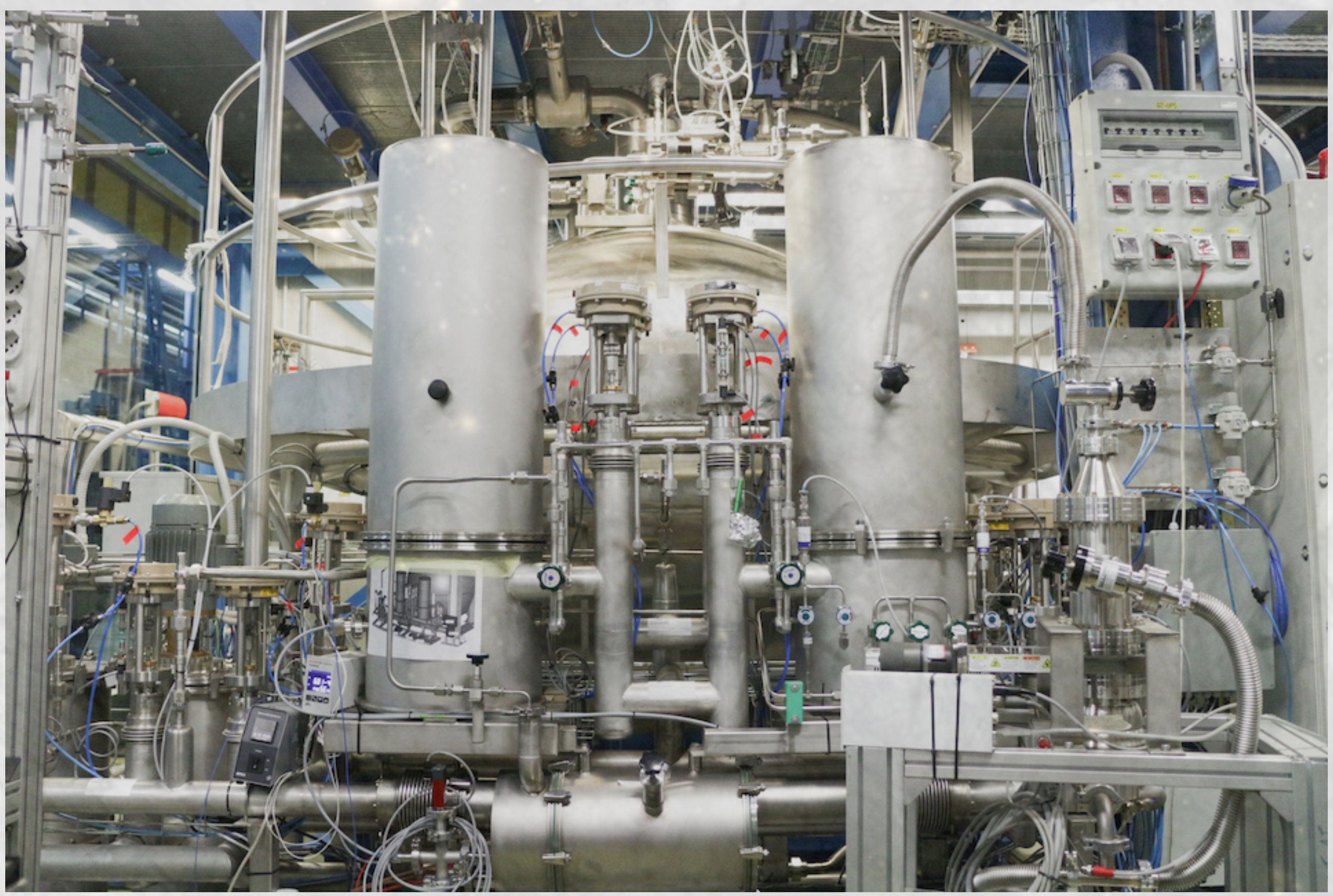
Precision of LXe response calibration is important to constrain the flux of solar neutrinos and other new physics (non-standard interactions and dark matter)

What’s Next? - XENONnT

~4 times larger fiducial mass

~1/6 background level

Now: Under Commissioning!



Summary

XENON1T is the most sensitive dark matter experiment to date

The XENON1T data is used to constrain a variety of physics:

- World leading limits on dark matter interactions
- First search for Scattering of Solar B8 neutrinos
- ...

Future experiments such as PandaX4T, LZ and XENONnT have high discovery potential of these signals

Thanks for your attention!