清華大學
Tsinghua University

XENON
Dark Matter Project

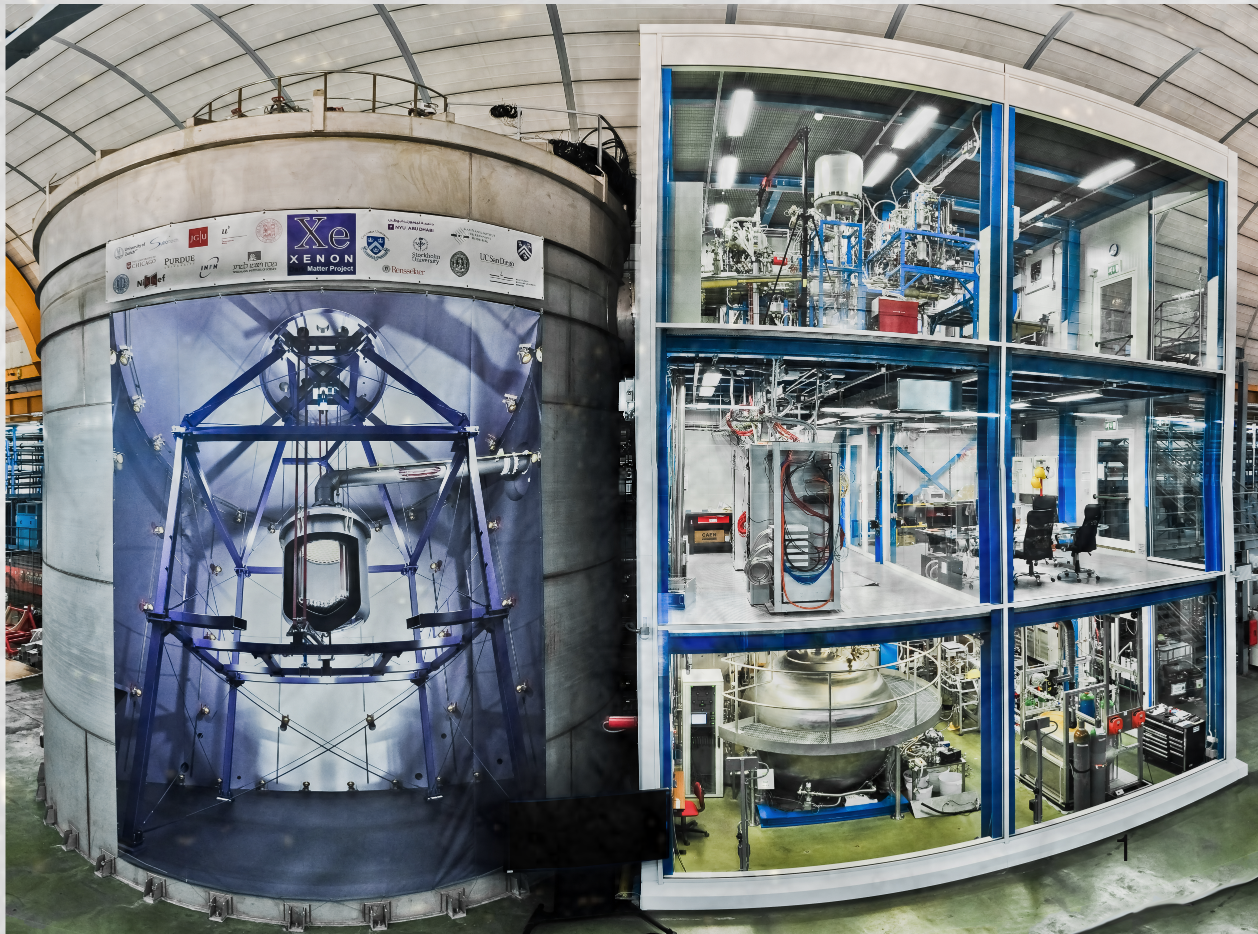
Search for Solar B8 Neutrinos with XENON1T

Fei Gao
Tsinghua University

On behalf of the XENON Collaboration

7th Supernova Neutrino Workshop

Jan 7, 2021



The XENON Collaboration

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

Chicago

UCSD

Rice

Purdue

Tokyo

Nagoya

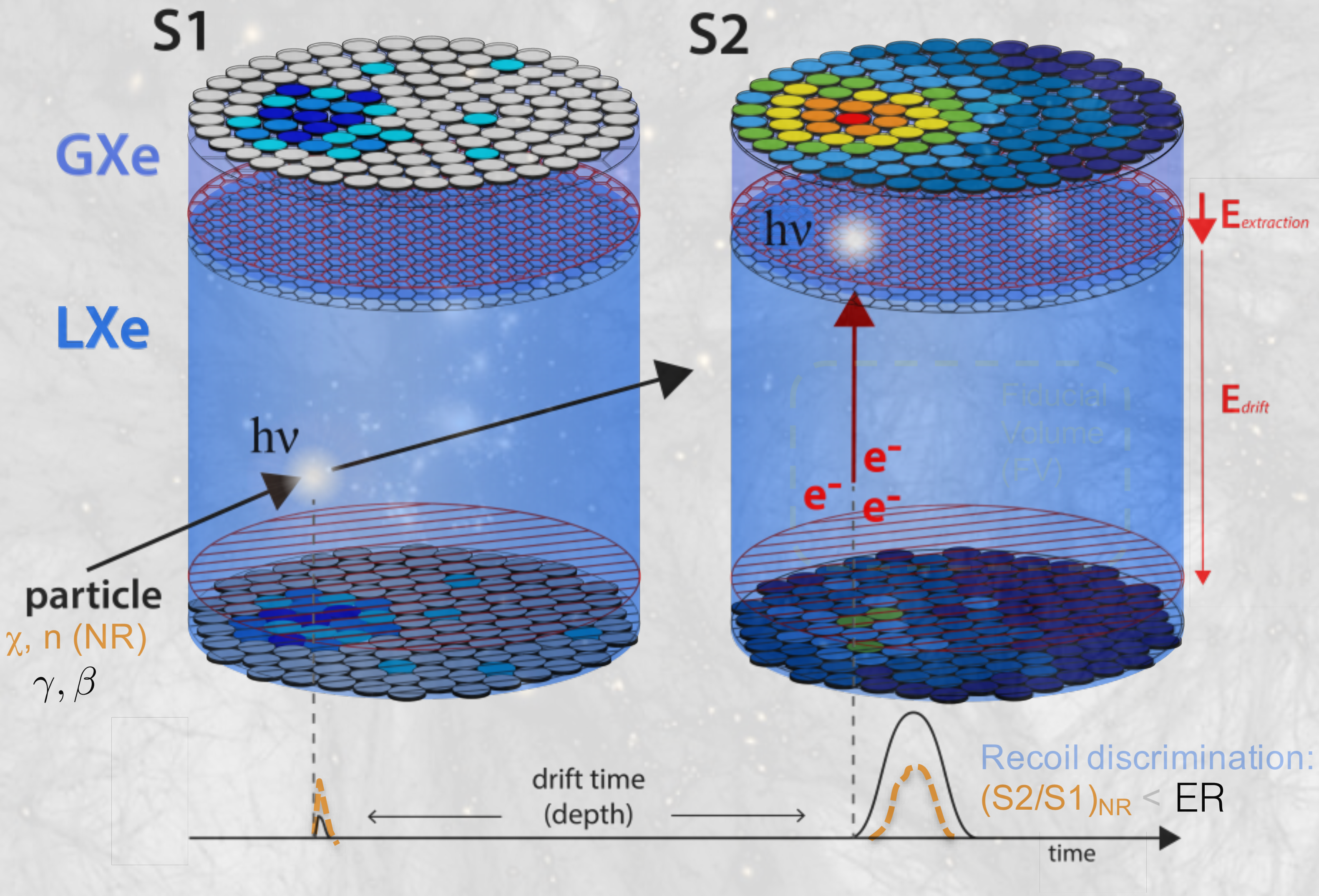
Kobe

NYUAD

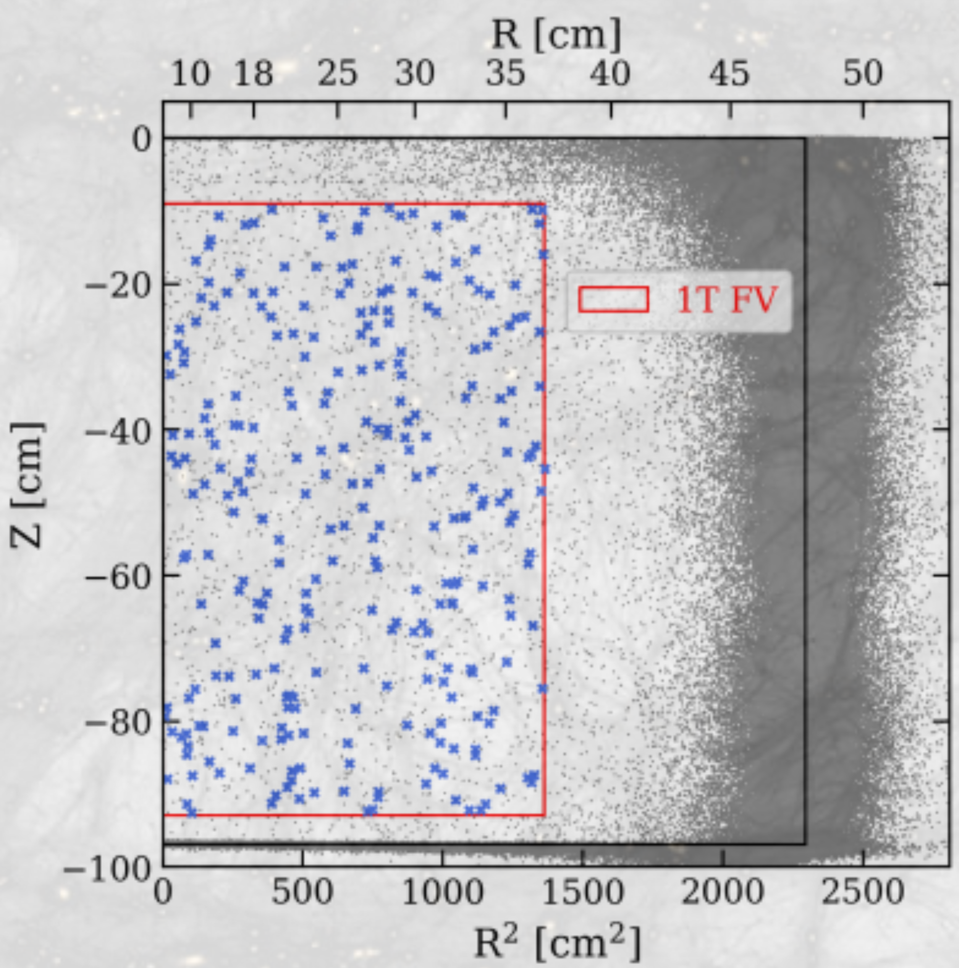
Subatech Coimbra LPNHE IJCLab Torino Bologna L'Aquila LNGS Napoli Weizmann

Two-phase Xe Time Projection Chamber

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

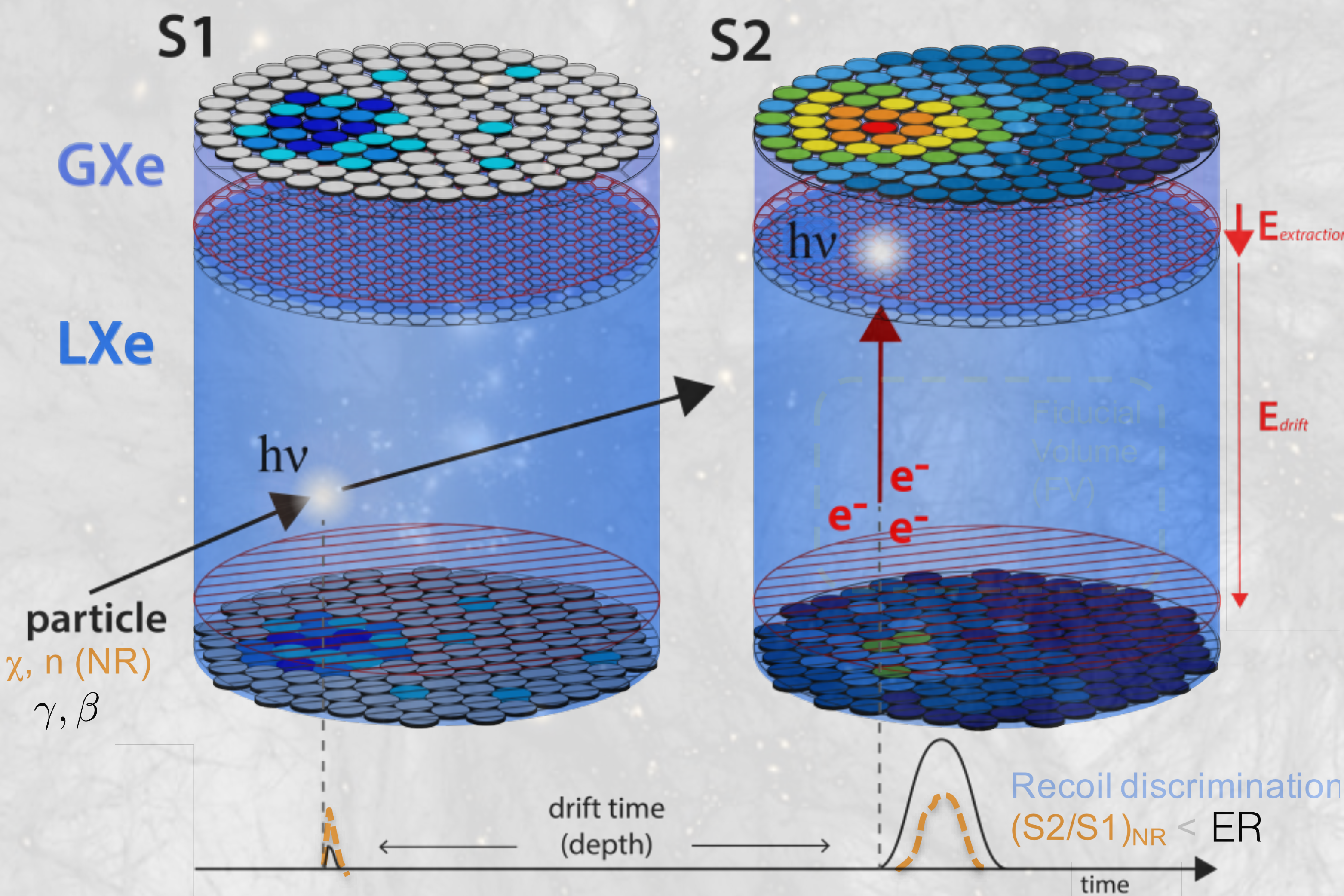


- two signals for each event:
  - 3D event imaging: x-y (S2) and z (drift time)
  - self-shielding, surface event rejection, single vs multiple scatter events

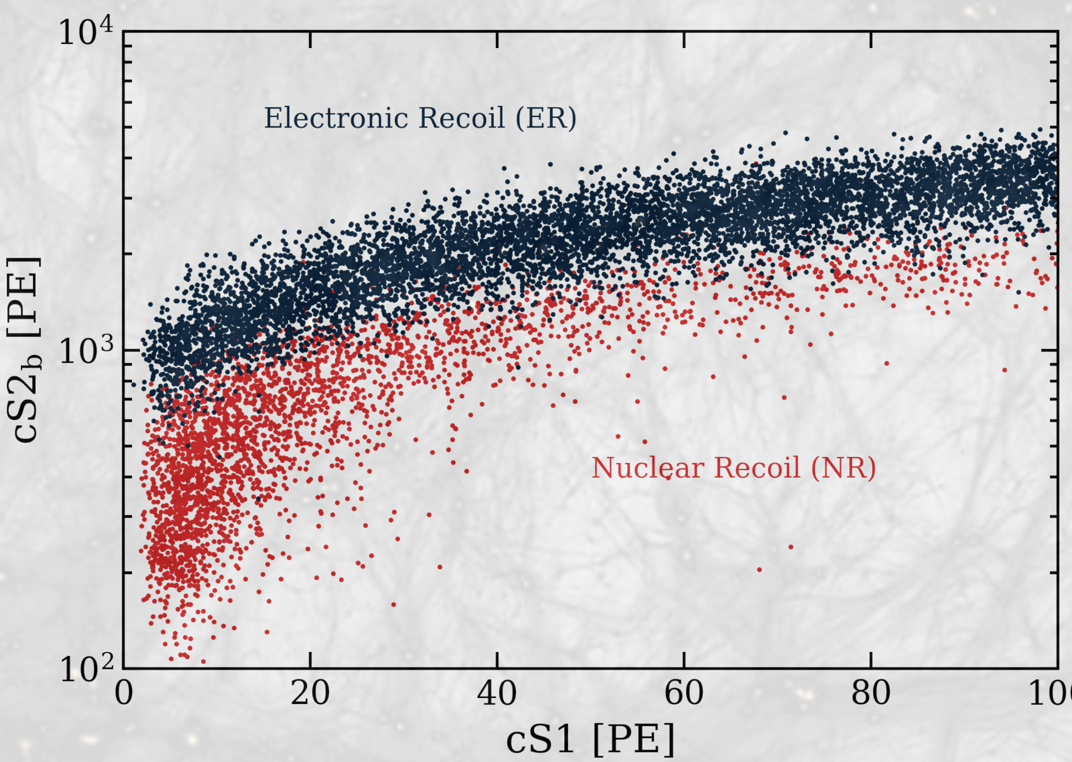


Two-phase Xe Time Projection Chamber

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



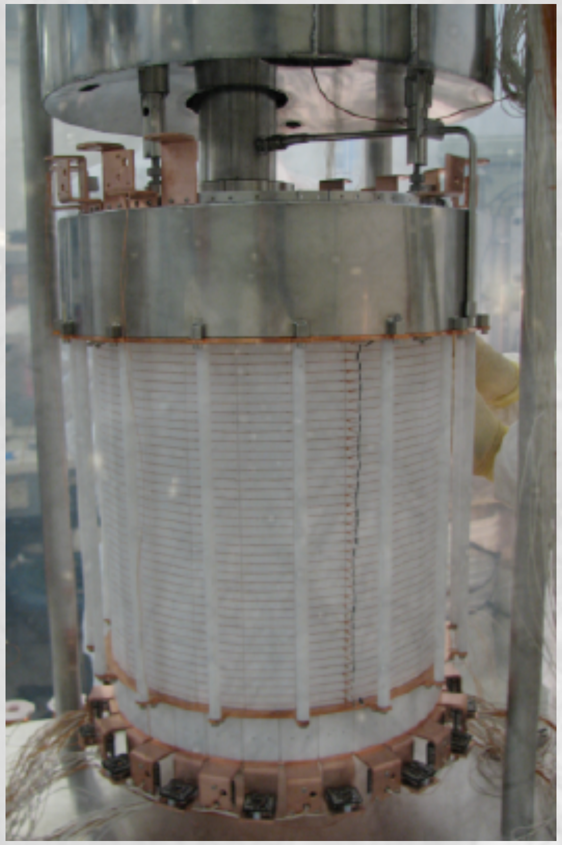
- two signals for each event:
  - 3D event imaging: x-y (S2) and z (drift time)
  - self-shielding, surface event rejection, single vs multiple scatter events
- Energy from S1 and S2 area
- Recoil type discrimination from ratio of charge (S2) to light (S1)



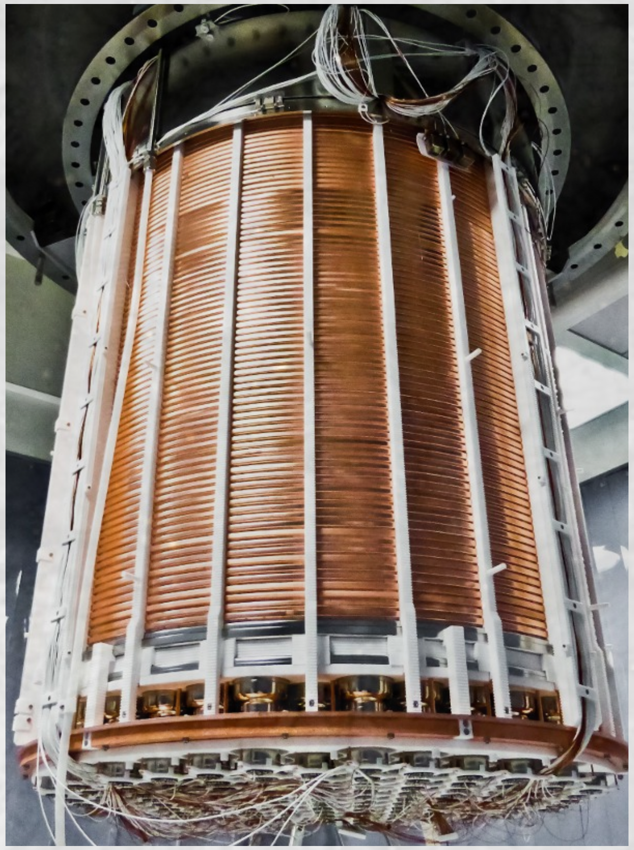
Development of XENON Program

XENON10

XENON100



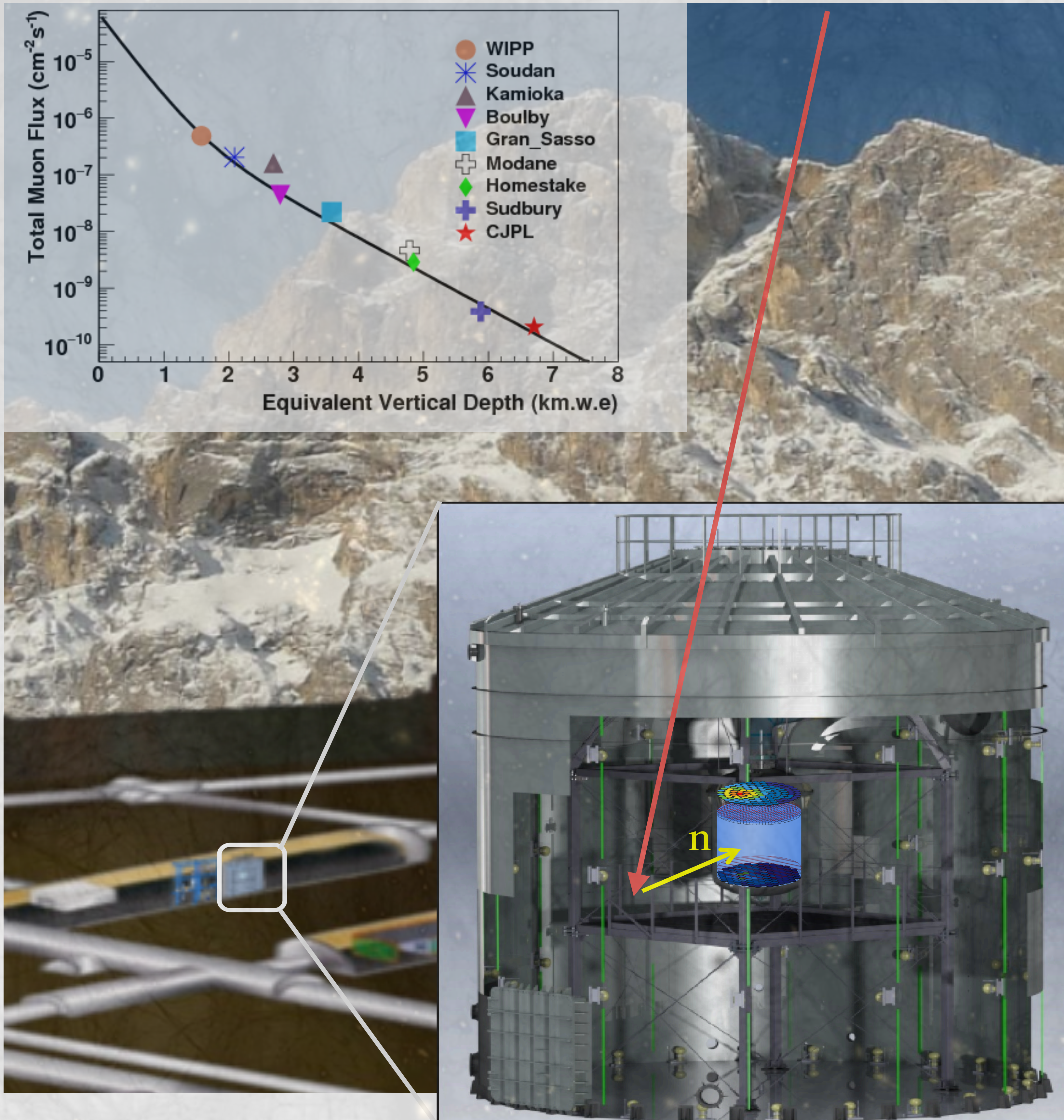
XENON1T

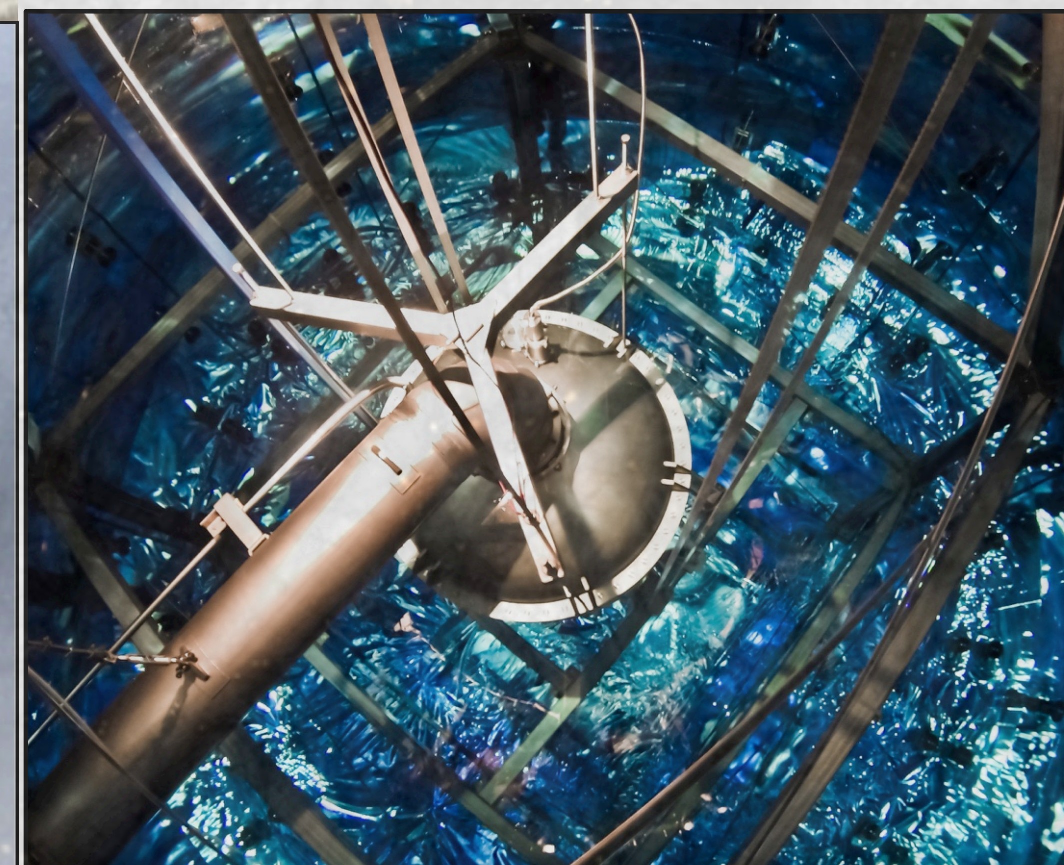


XENONnT

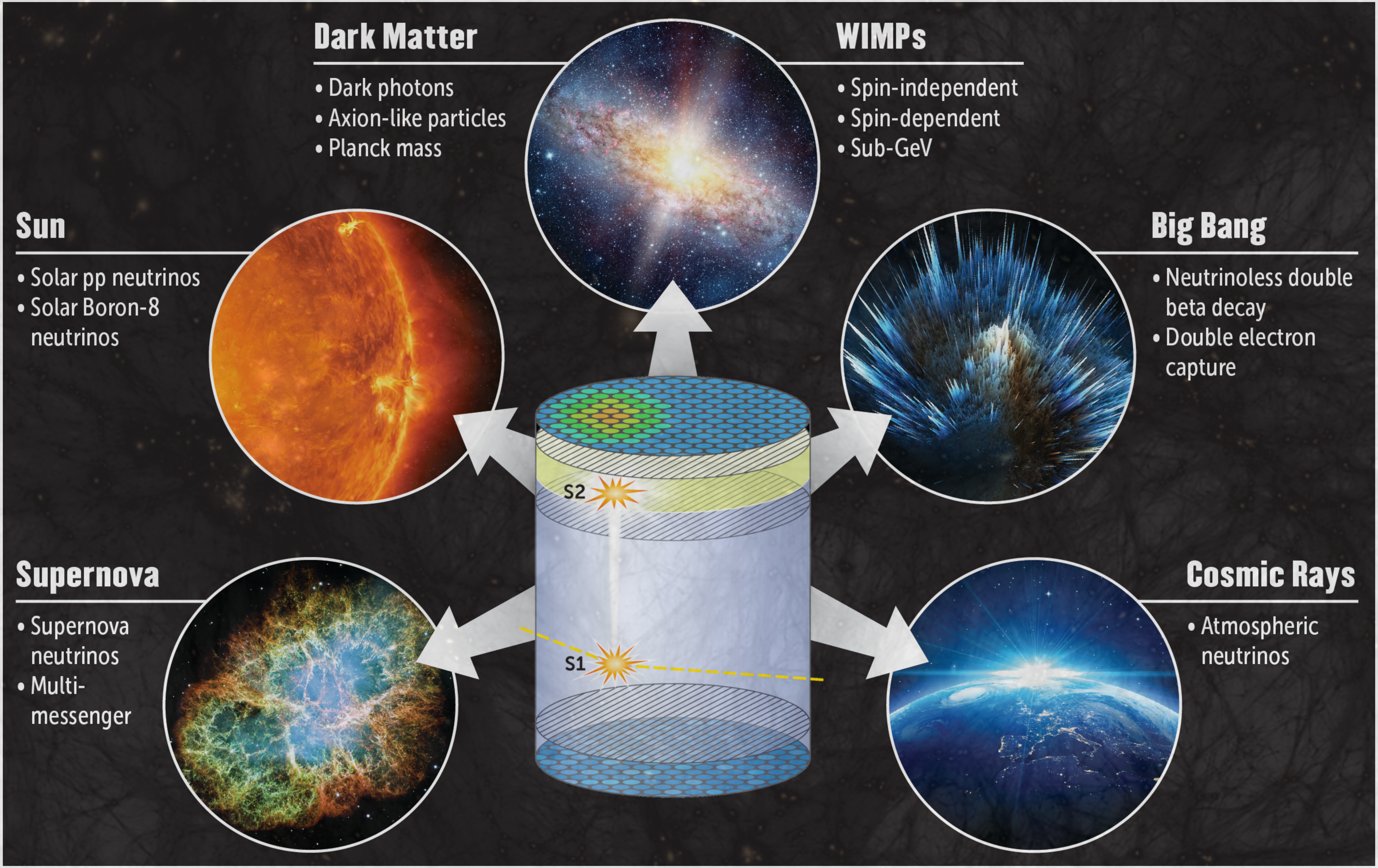
2005-2007	2008-2016	2012-2018	2019-202x
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8.6 ton - 1.5 m drift
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2

Gran Sasso: The XENON1T Shield





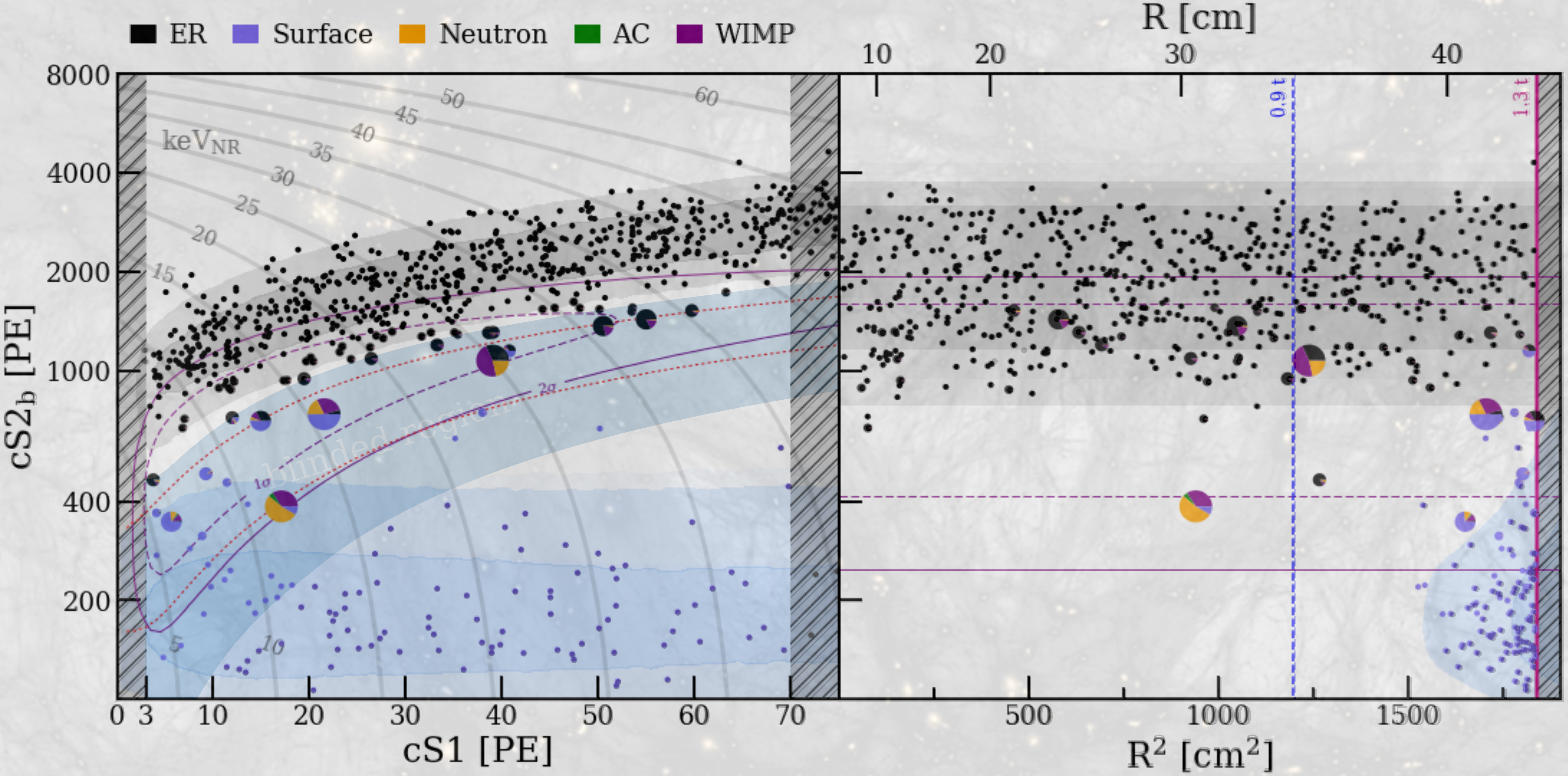
What do We Search in XENON1T?



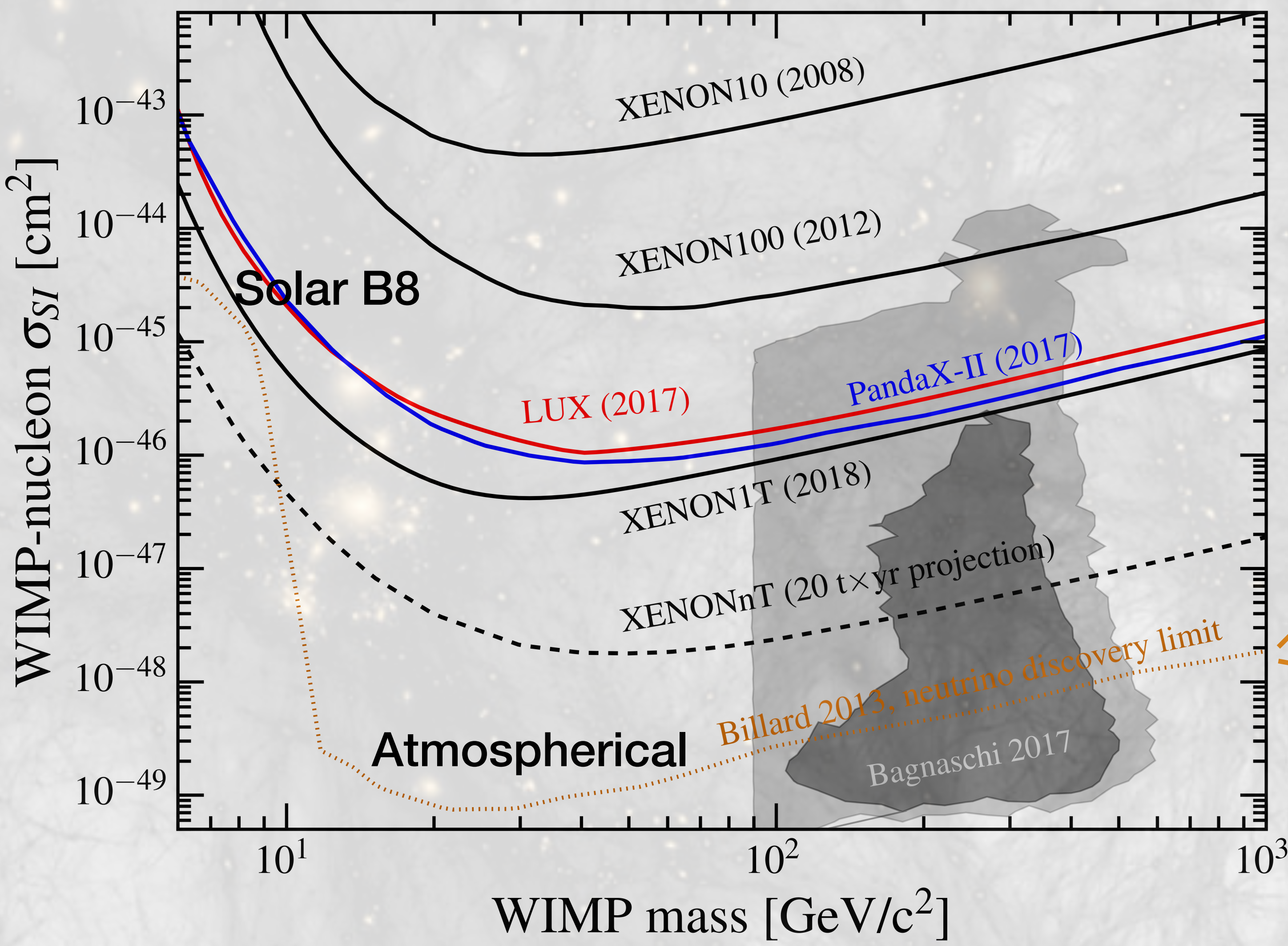
Dark Matter Search Results - 2018

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
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
Data	**739**	**14**	**2**

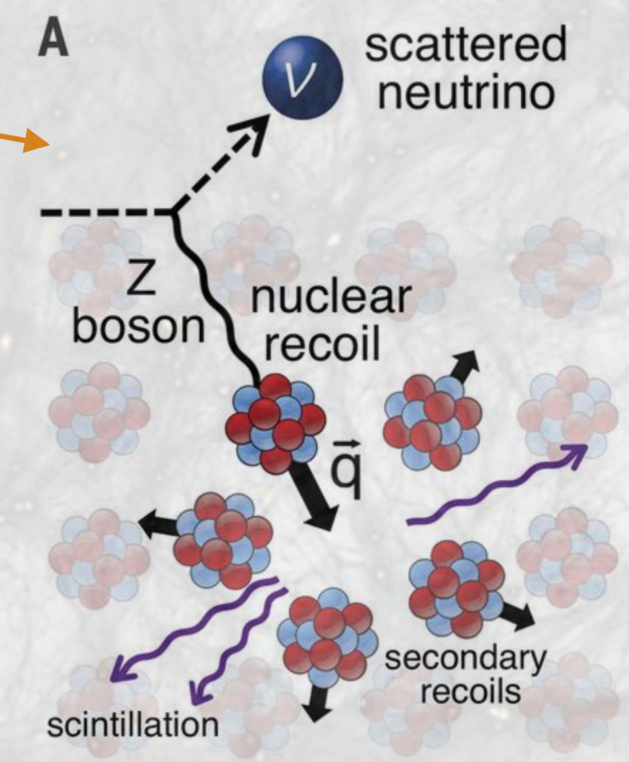


Constrains on Dark Matter



Coherent elastic scattering from neutrinos and DM are indistinguishable!

Neutrino sources: Solar neutrinos, atmospherical neutrinos, supernova



How far are We from the Neutrino Floor?

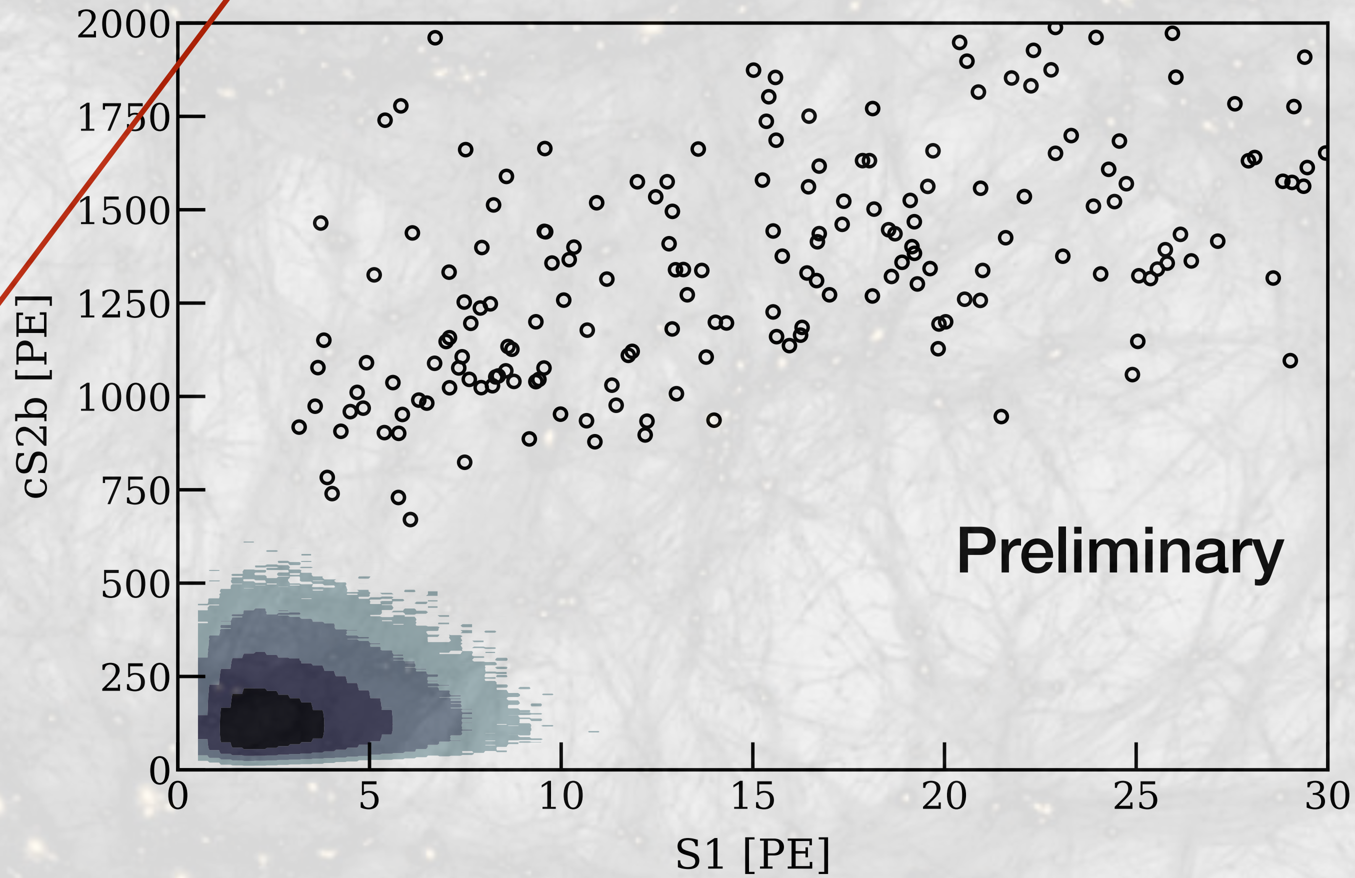
There are ~600 CEvNS recoils from B8 solar neutrinos alone

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

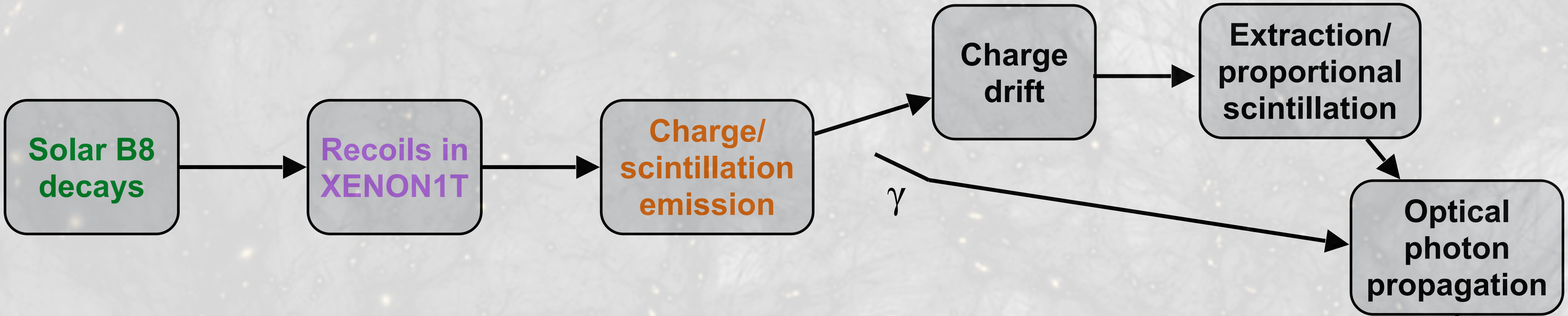
XENON1T WIMP search analysis has low detection efficiency 0.01%

Can we increase the detection efficiency?

Source	1.3 t	1.3 t, NR Ref.
ER	627 ± 18	1.6 ± 0.3
Radiogenic	1.4 ± 0.7	0.8 ± 0.4
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
200 GeV WIMP	3.6	1.7
Data	**739**	**14**



How XENON1T Detect Solar B8 Neutrinos?



Rate

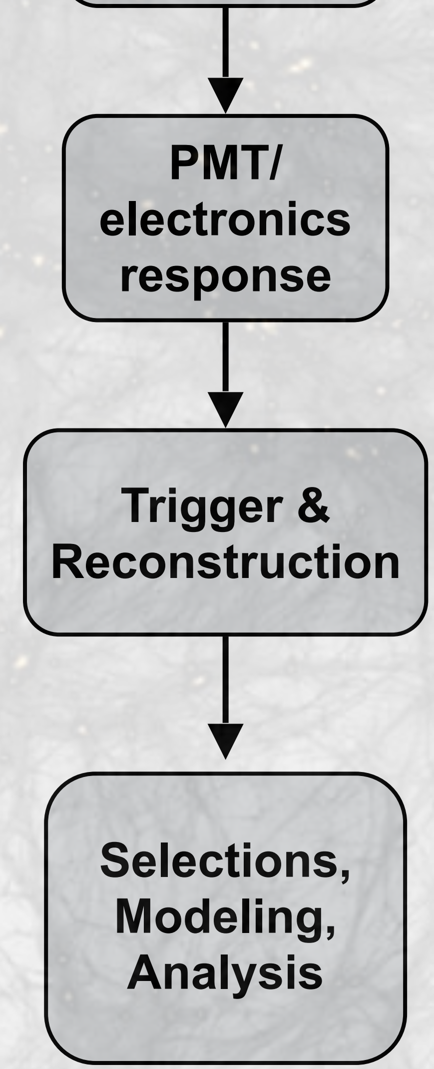
- 8B neutrino flux
- Cross-section

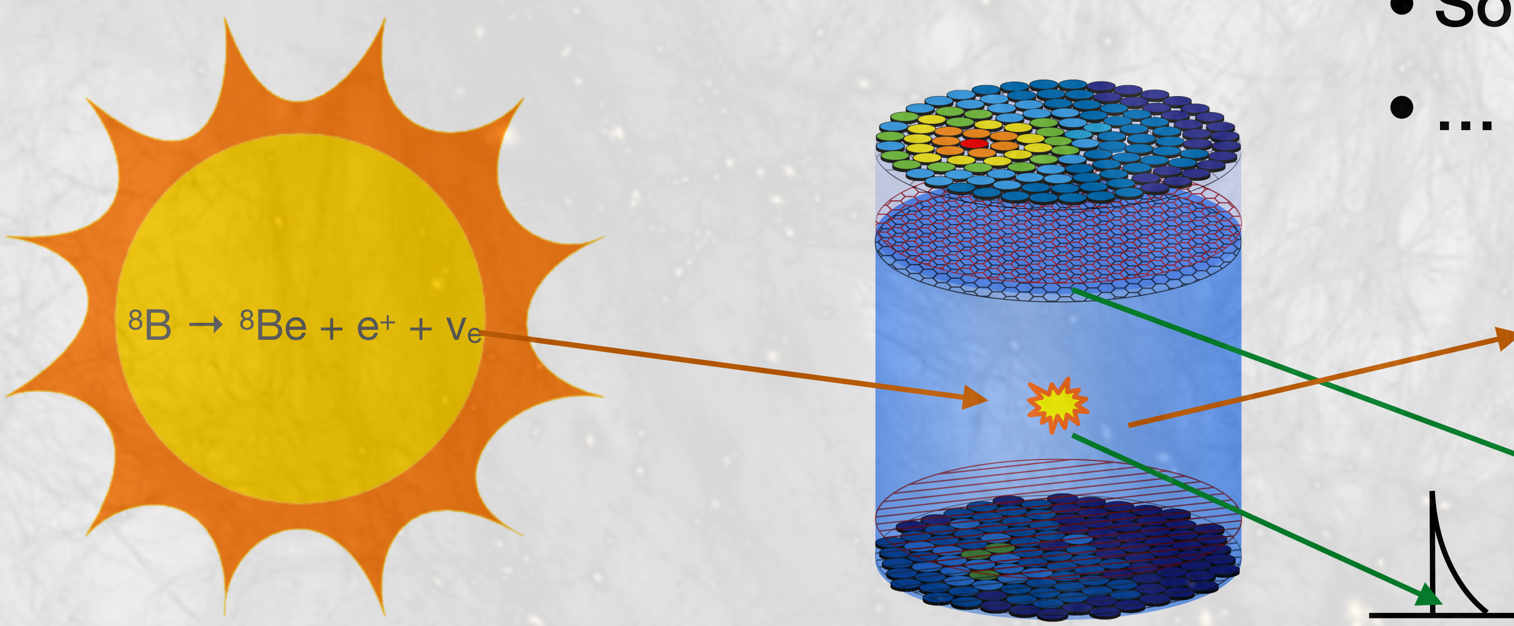
LXe Response

- Charge Yield
- Light Yield???

Detection efficiency??

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

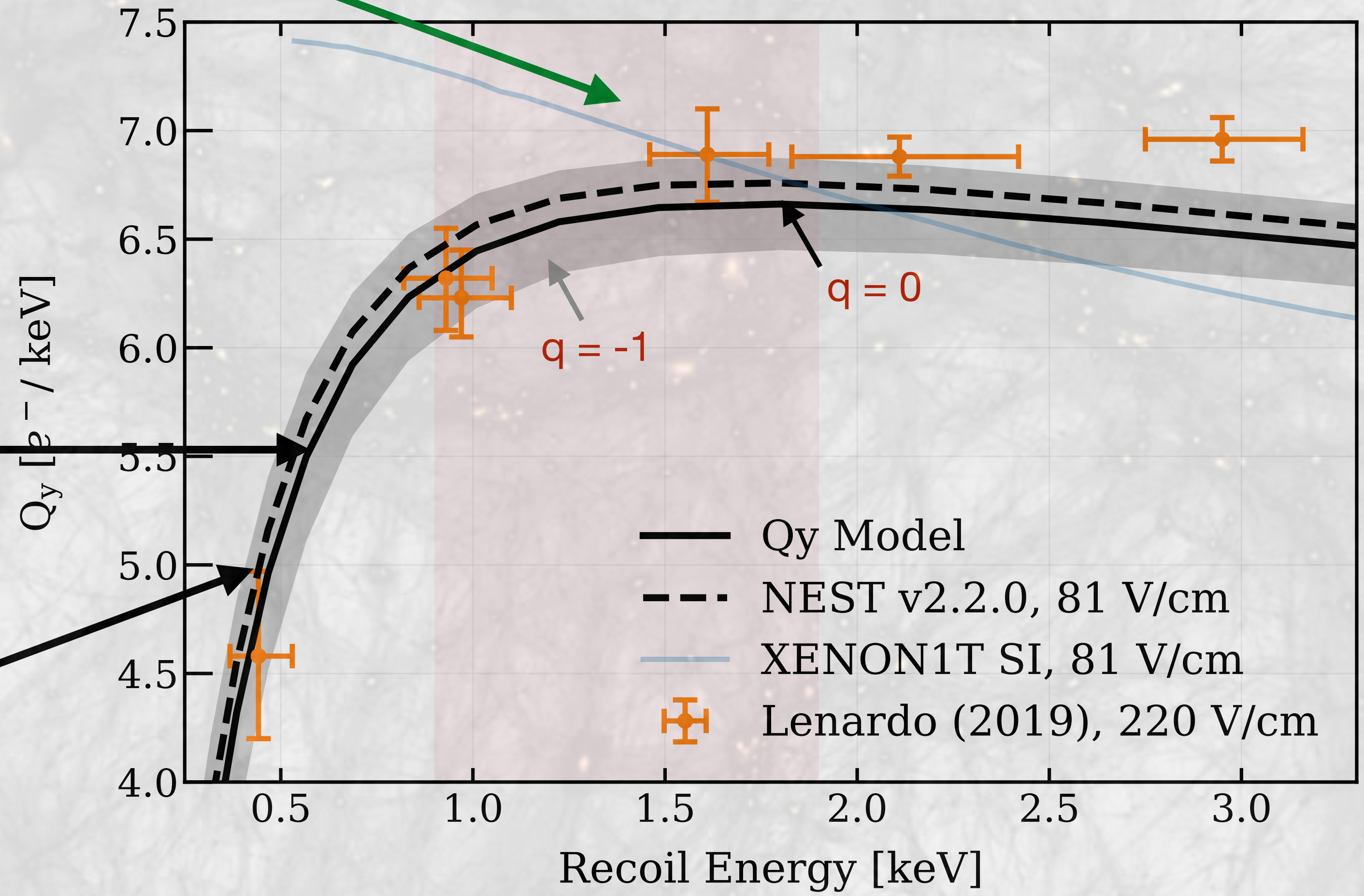




Ionization Yields for Nuclear Recoils

Precise measurement of ionization yields is available from LLNL data

arXiv:2012.02846

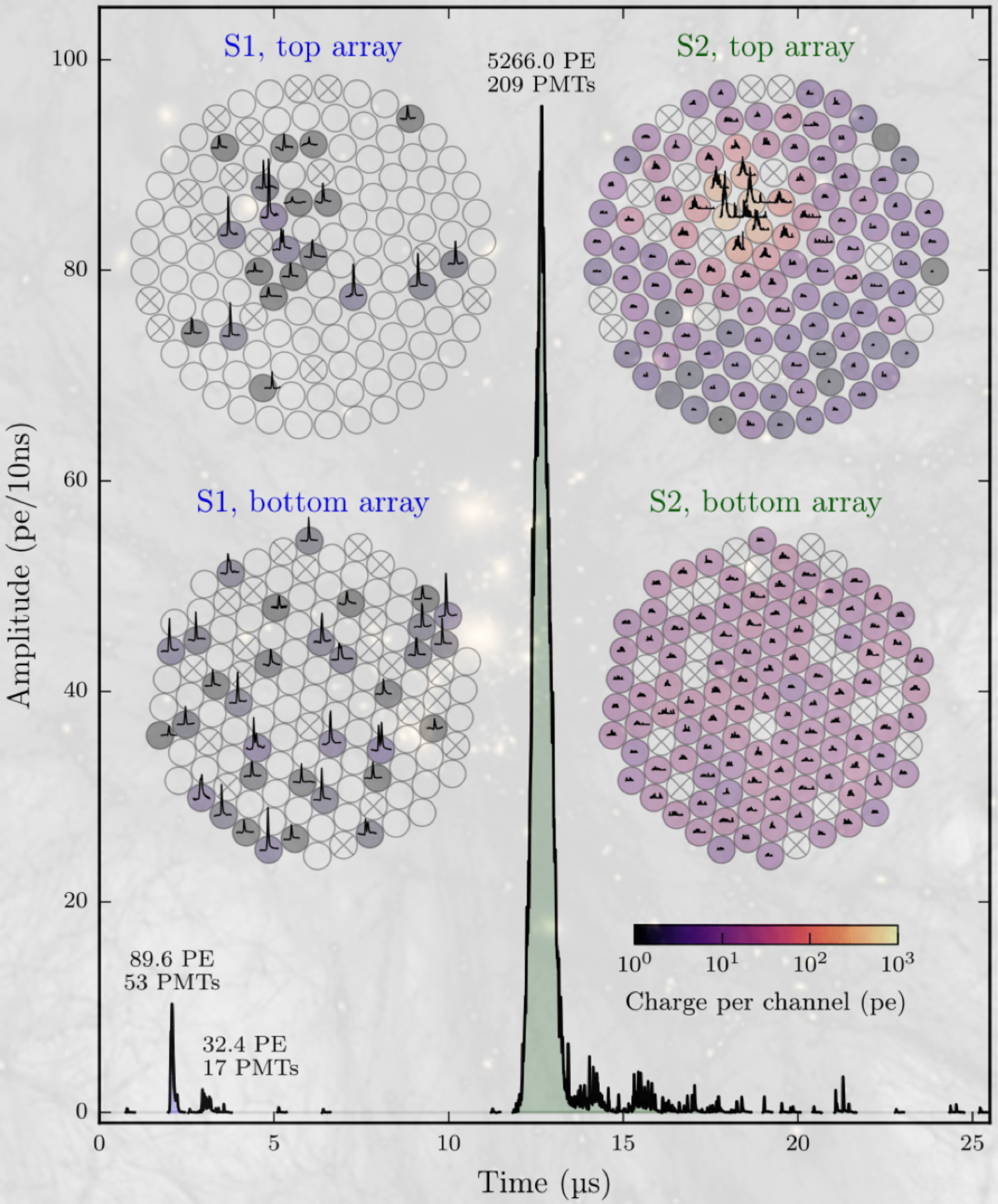


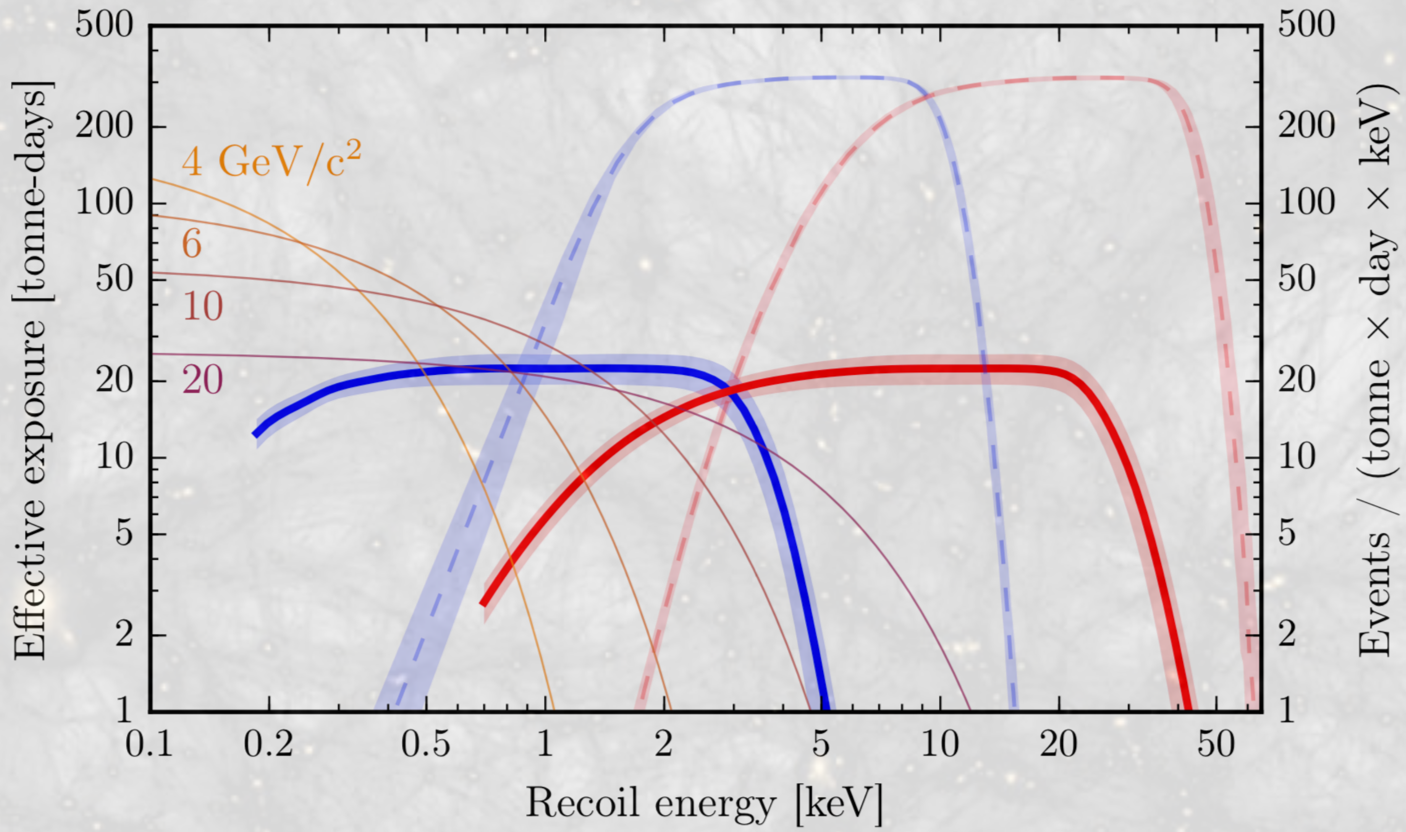
NEST model agrees with data

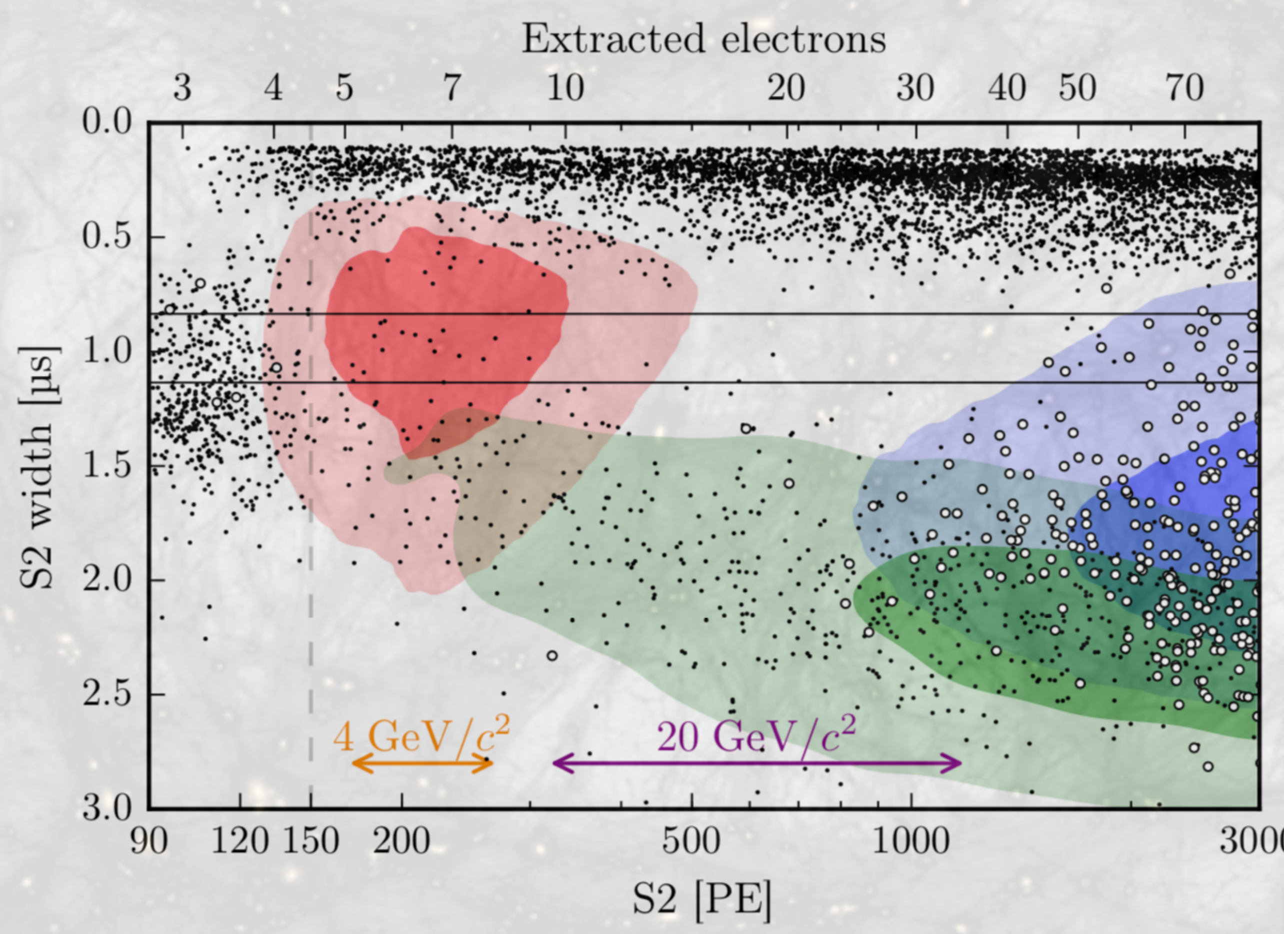
Uncertainty is subdominant compared with other factors

Lower the Energy Threshold: S2-only

Fig. credits to J. Aalber

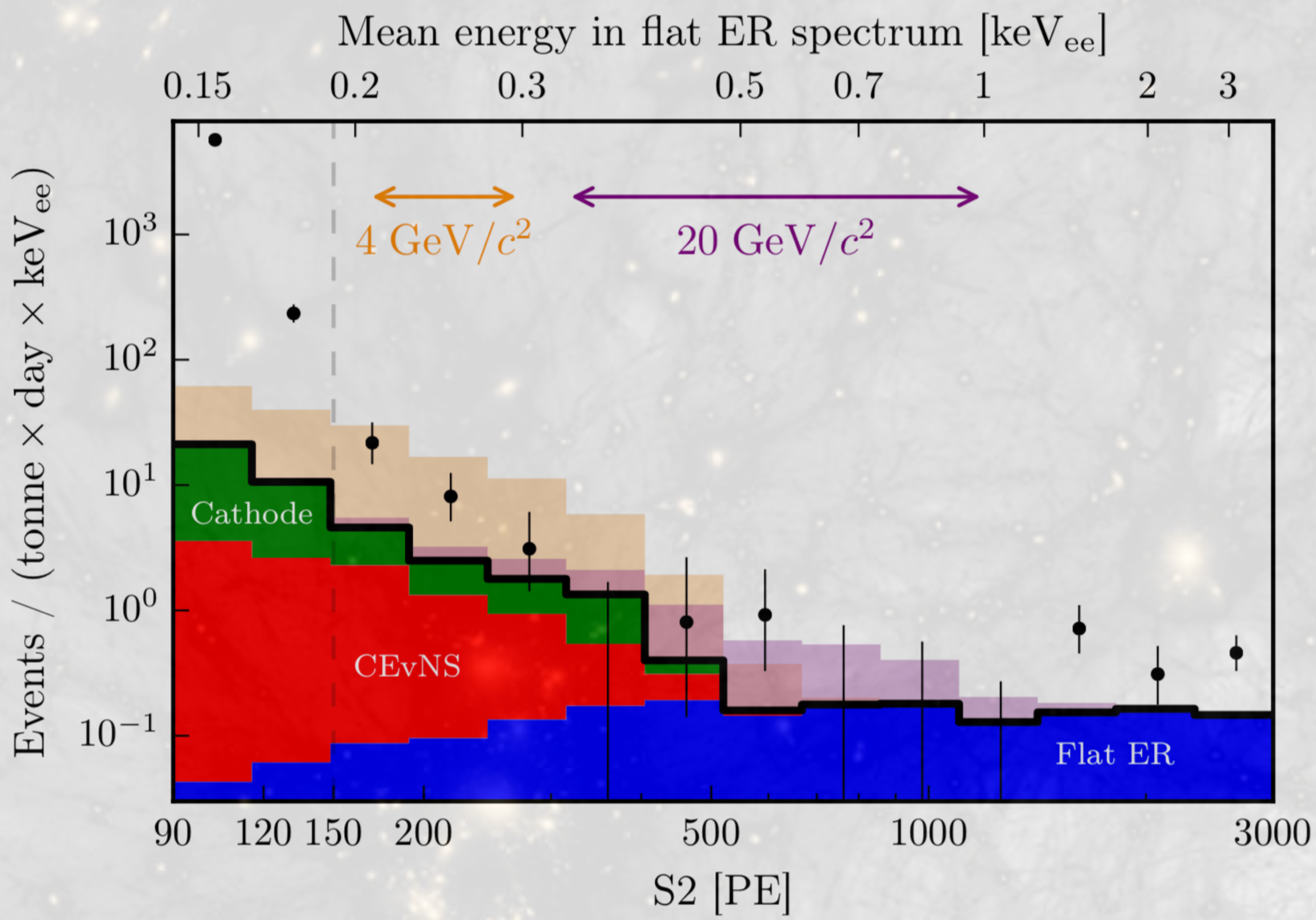






XENON1T, PRL 123 251801 (2019)

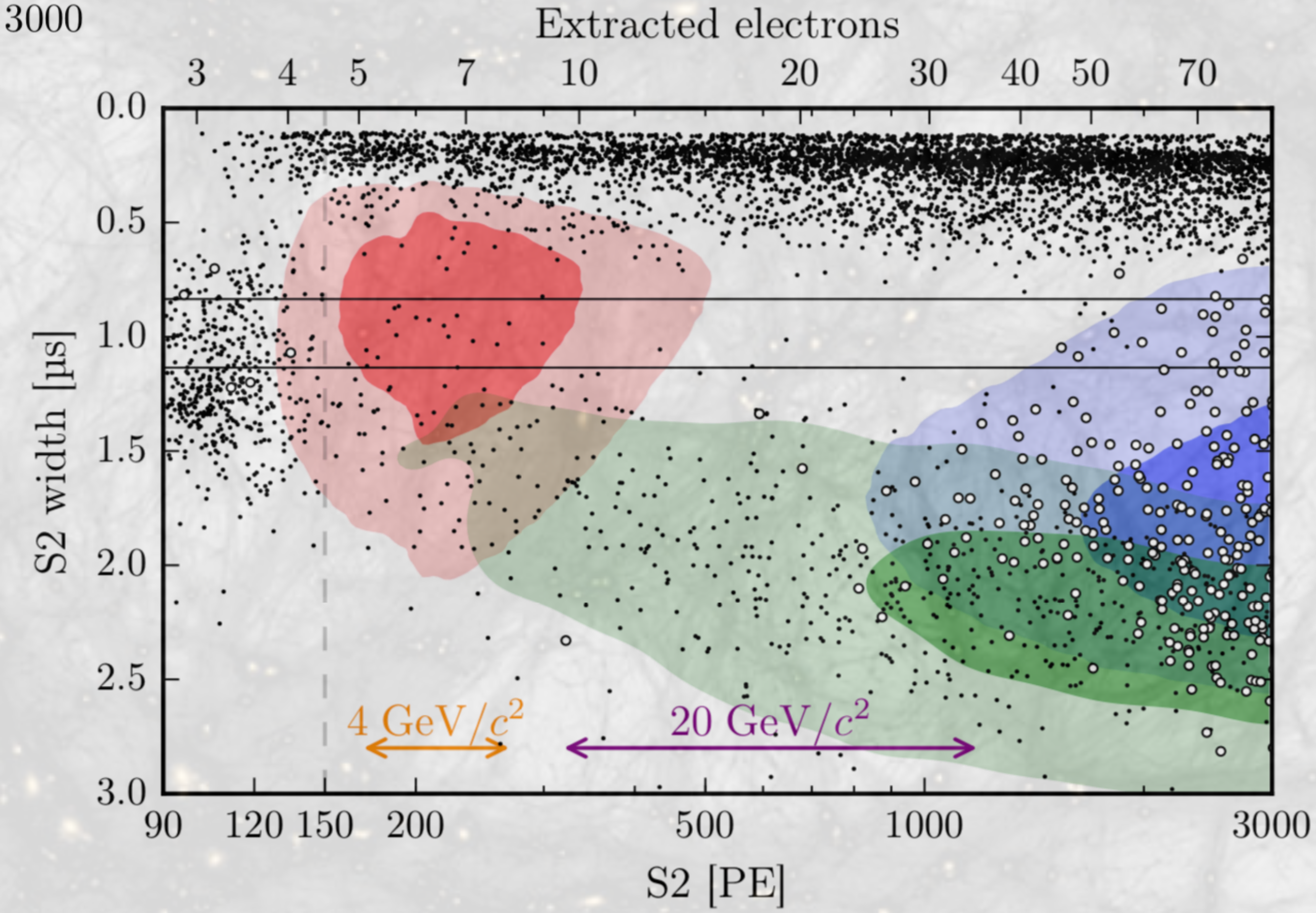
Have we Detected B8 CEvNS?



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

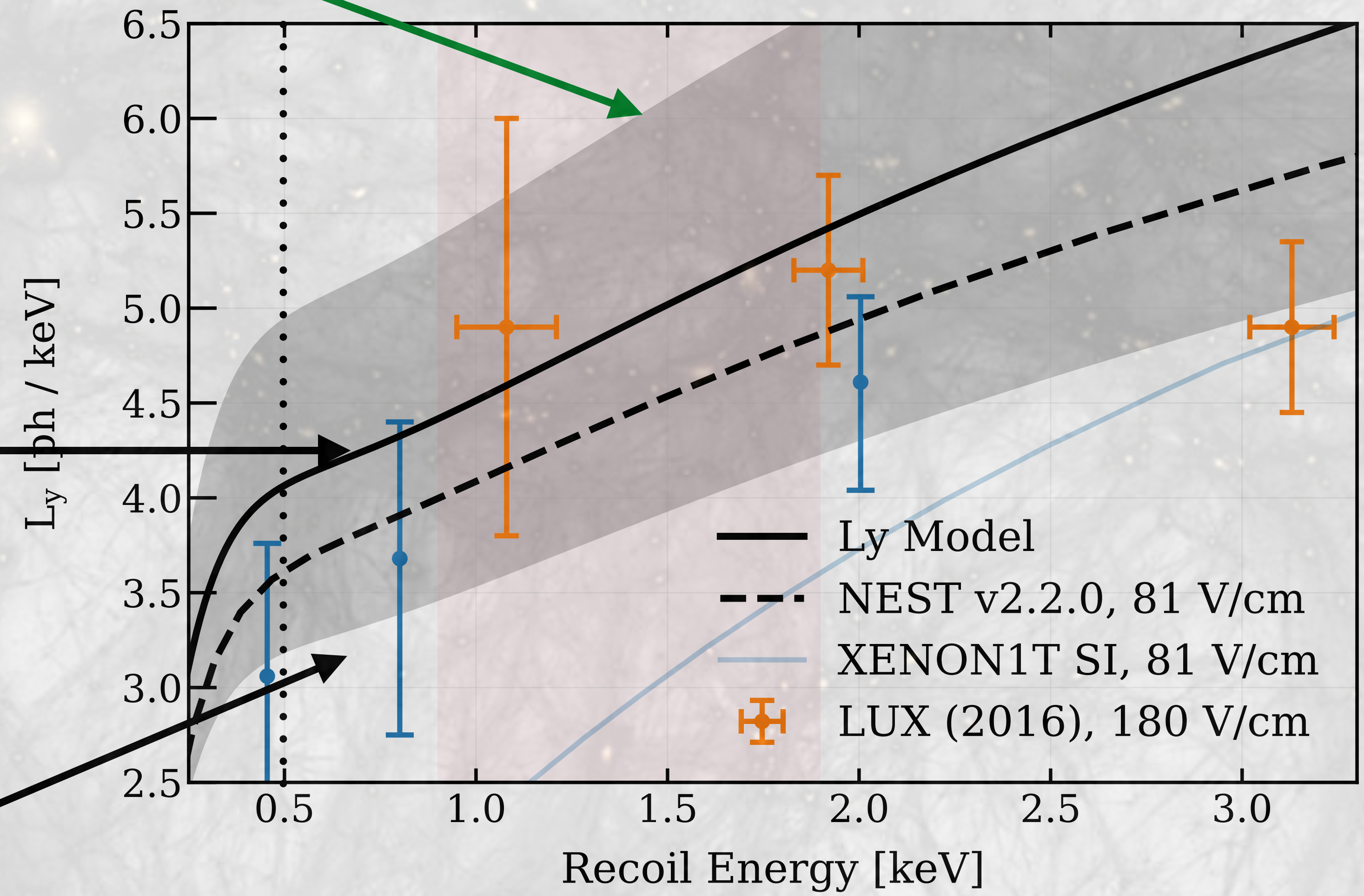


Scintillation Yields for Nuclear Recoils

LUX D-D calibration is the most precise measurement at this energy!

arXiv:2012.02846

We scaled the NEST model to describe the average scintillation yields



A large uncertainty bands is used, which can accommodate the measurements

Search for CEvNS with both S1 and S2?

There are ~600 CEvNS recoils from B8 solar neutrinos alone

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

Source	1.3 t	1.3 t, NR Ref.
ER	627 ± 18	1.6 ± 0.3
Radiogenic	1.4 ± 0.7	0.8 ± 0.4
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

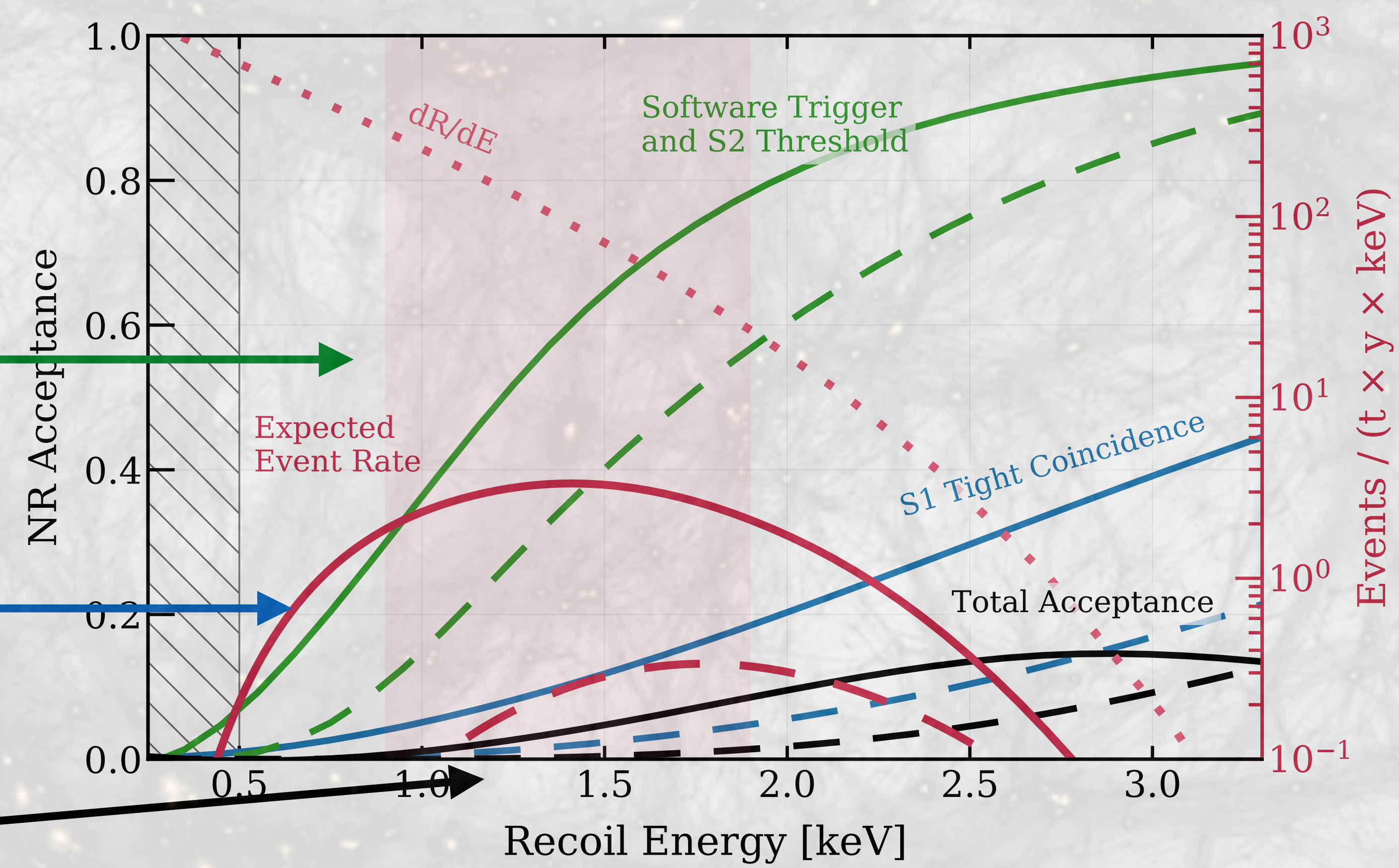
arXiv:2012.02846

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

S2 threshold: S2 > ~~200~~ 120PE

S1 threshold: ~~Three~~ Two PMTs seeing light within 50ns

Additional cuts ~~not~~ optimized for CEvNS



How does Background Change?

Analysis ROI

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

AC background increased significantly due to lower threshold (dominant)

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

Neutron background is small, due to tight ROI

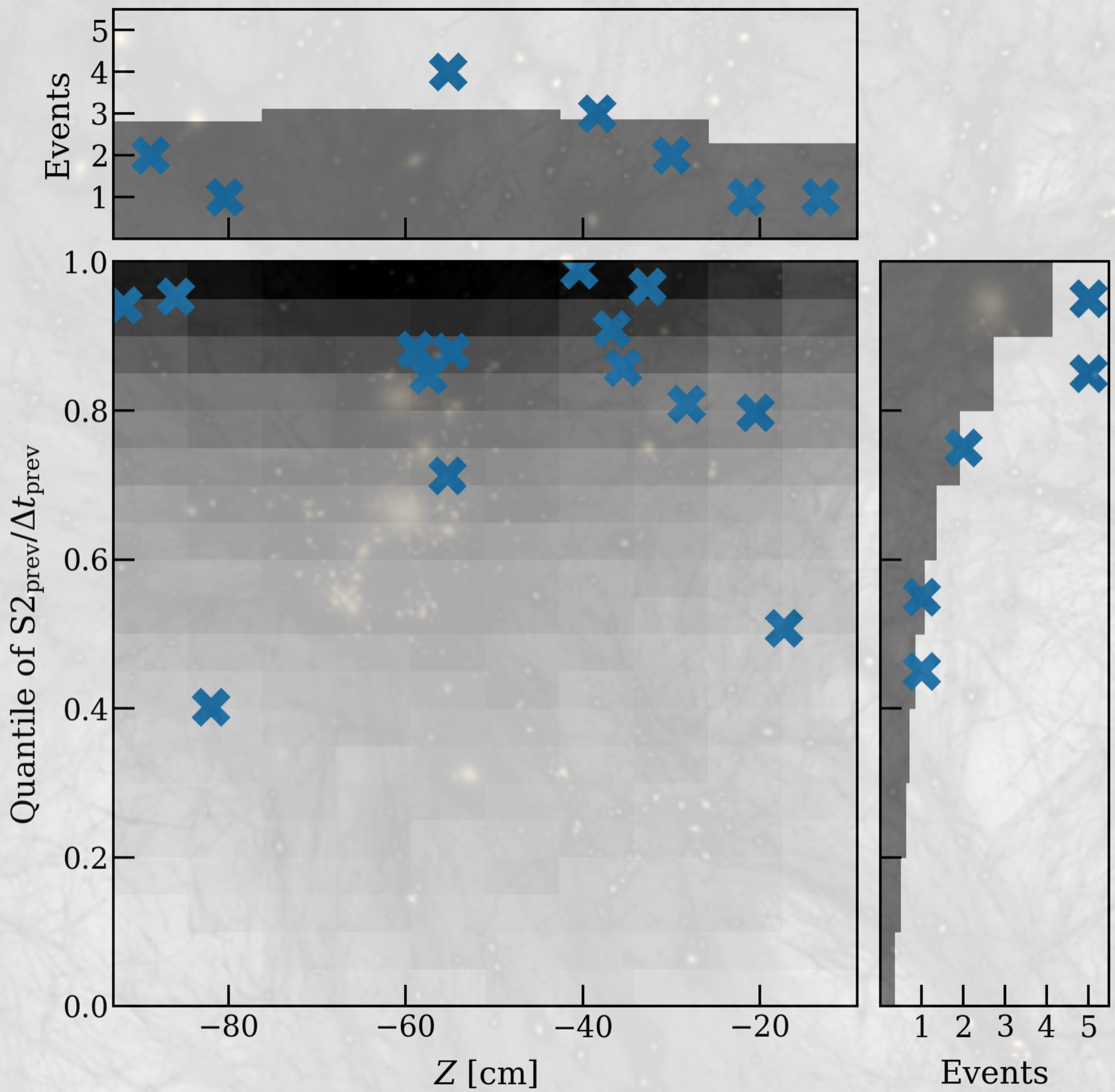
Surface background is negligible due to small fiducial volume

arXiv:2012.02846

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

Unblinding of Validation Data

Data consistent with AC background (p > 0.05)



GoF Scores:

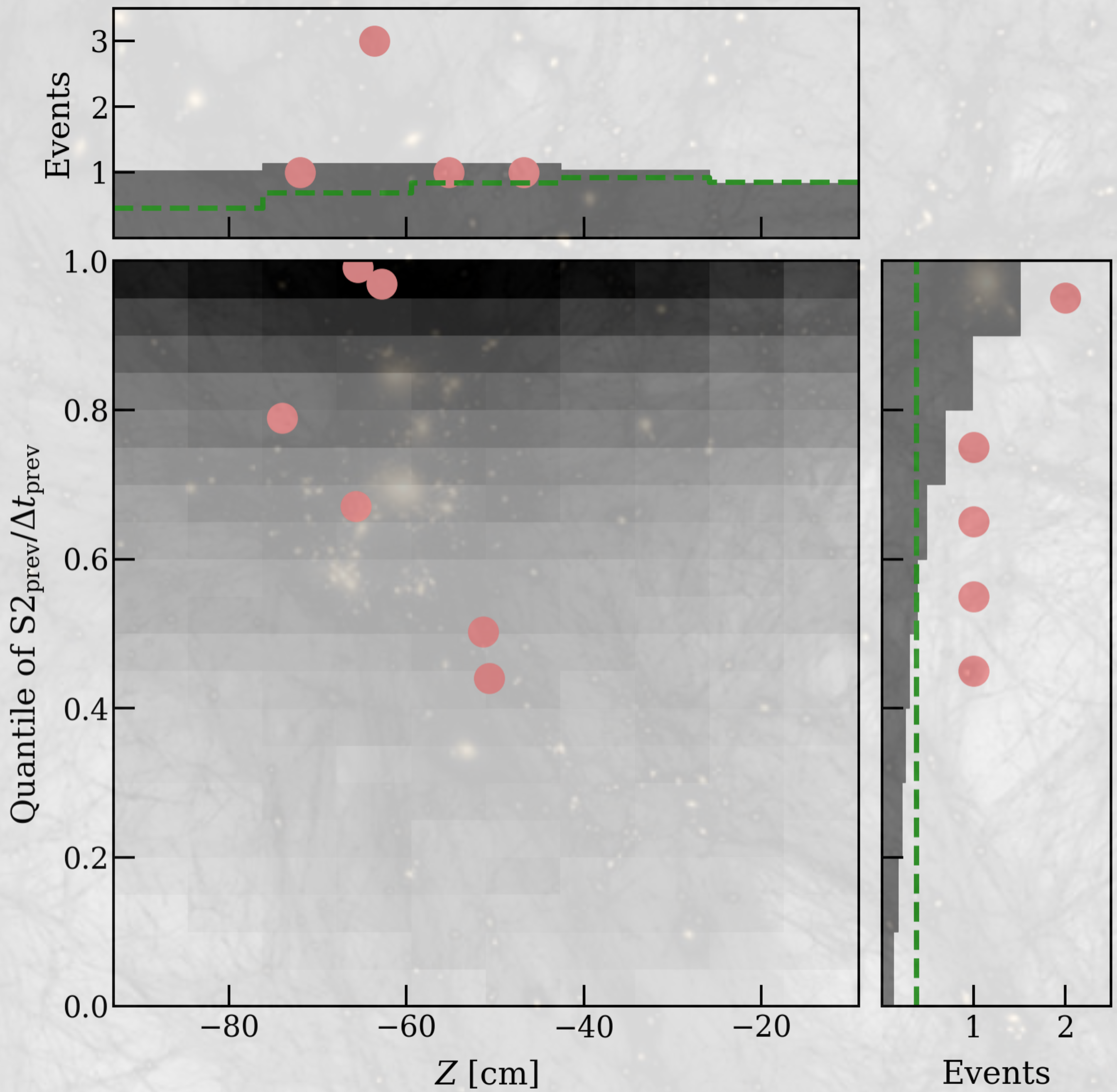
Continuous Axes: p = 0.33

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**

Unblinding of Science Data

Data consistent with AC background (p > 0.05)



GoF Scores:

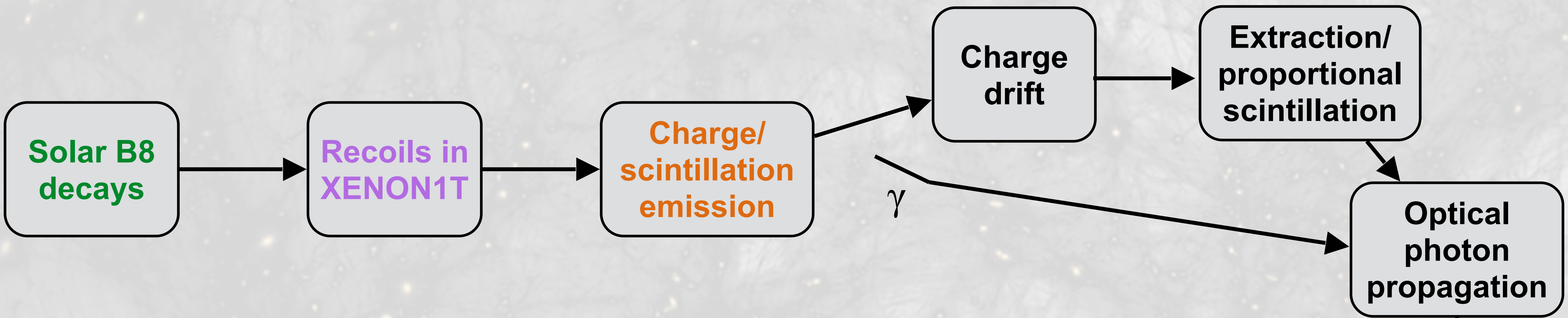
Continuous Axes: p = 0.72

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

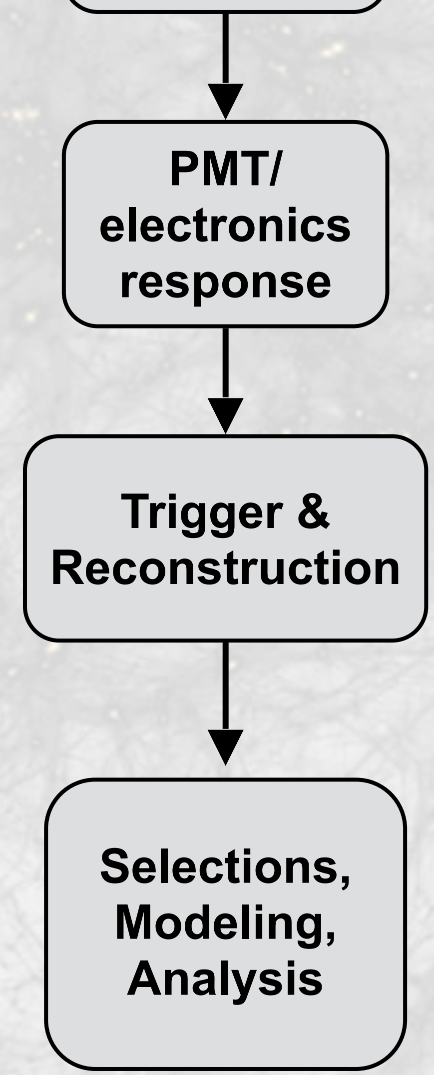
- 8B neutrino flux
- Cross-section

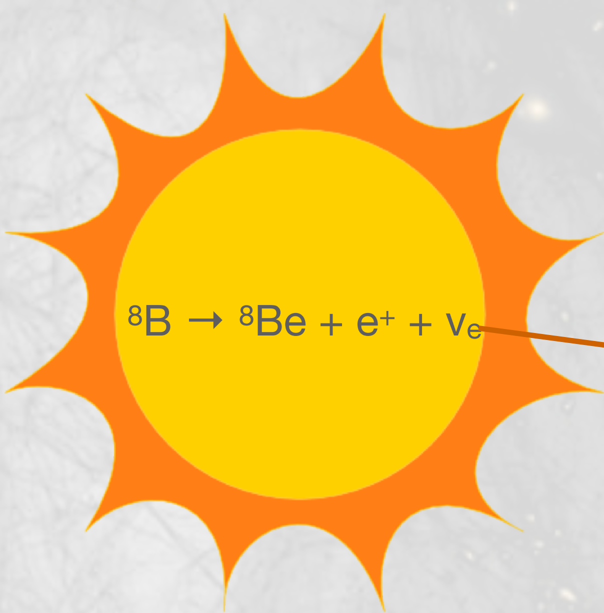
LXe Response

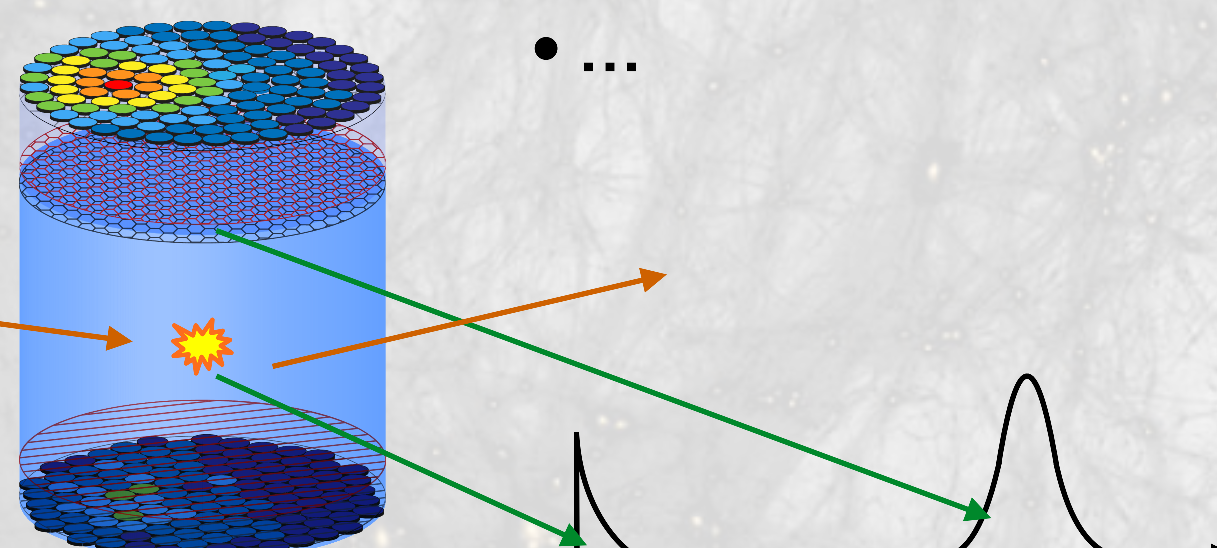
- Charge Yield
- Light Yield???

Detection efficiency

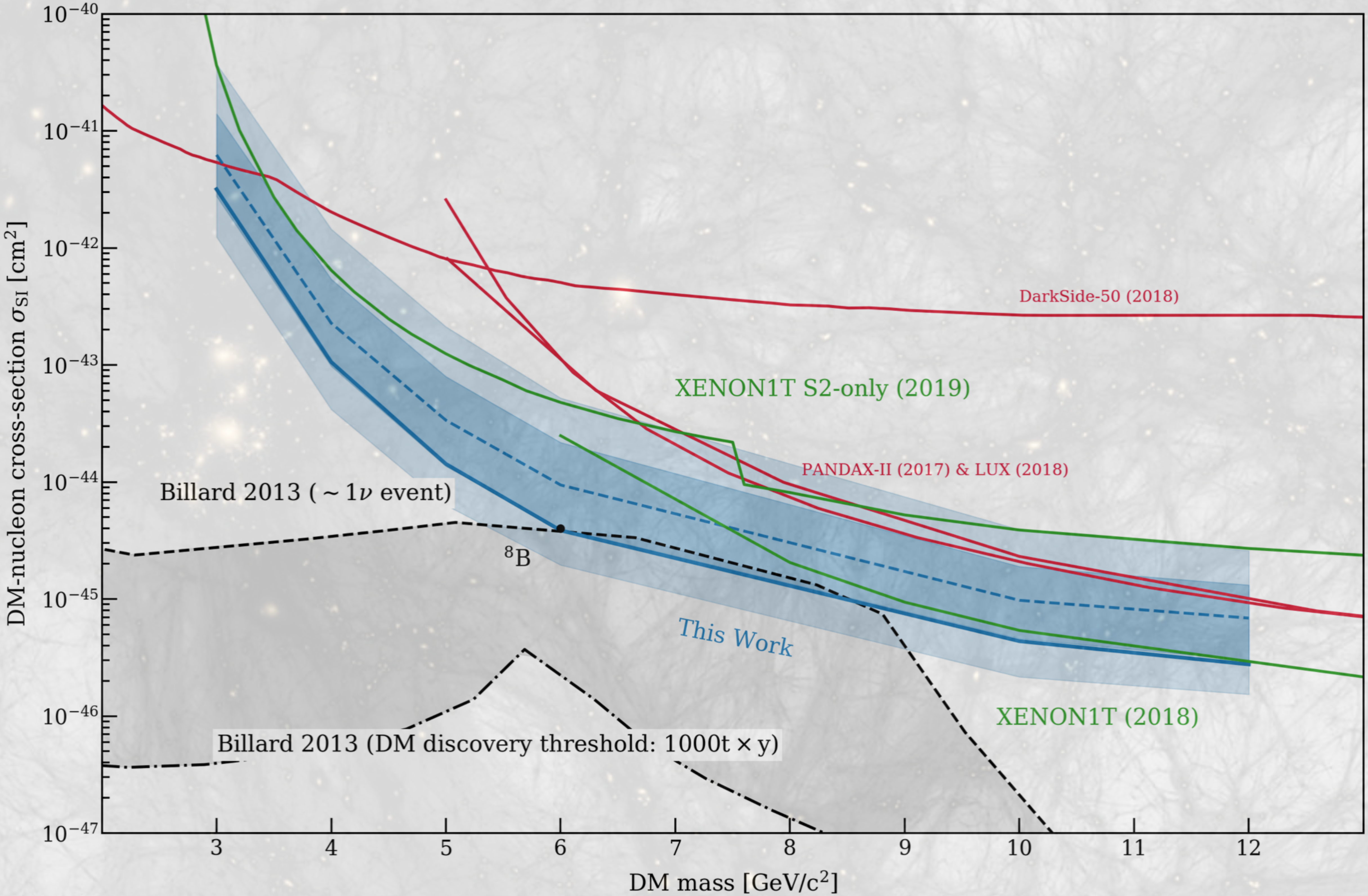
- LXe Purity
- PMT Coincidence Requirement
- Software Trigger
- ...





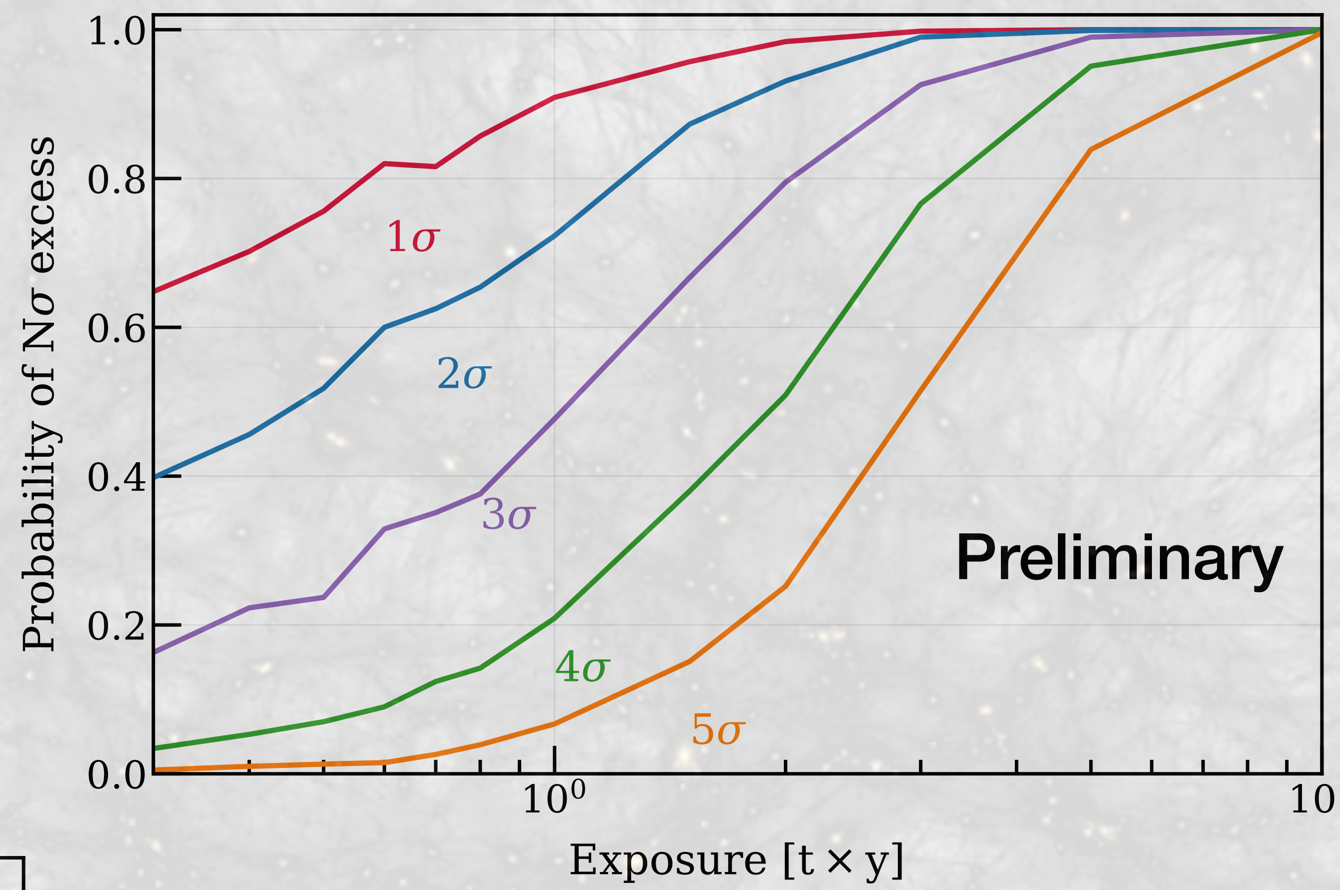


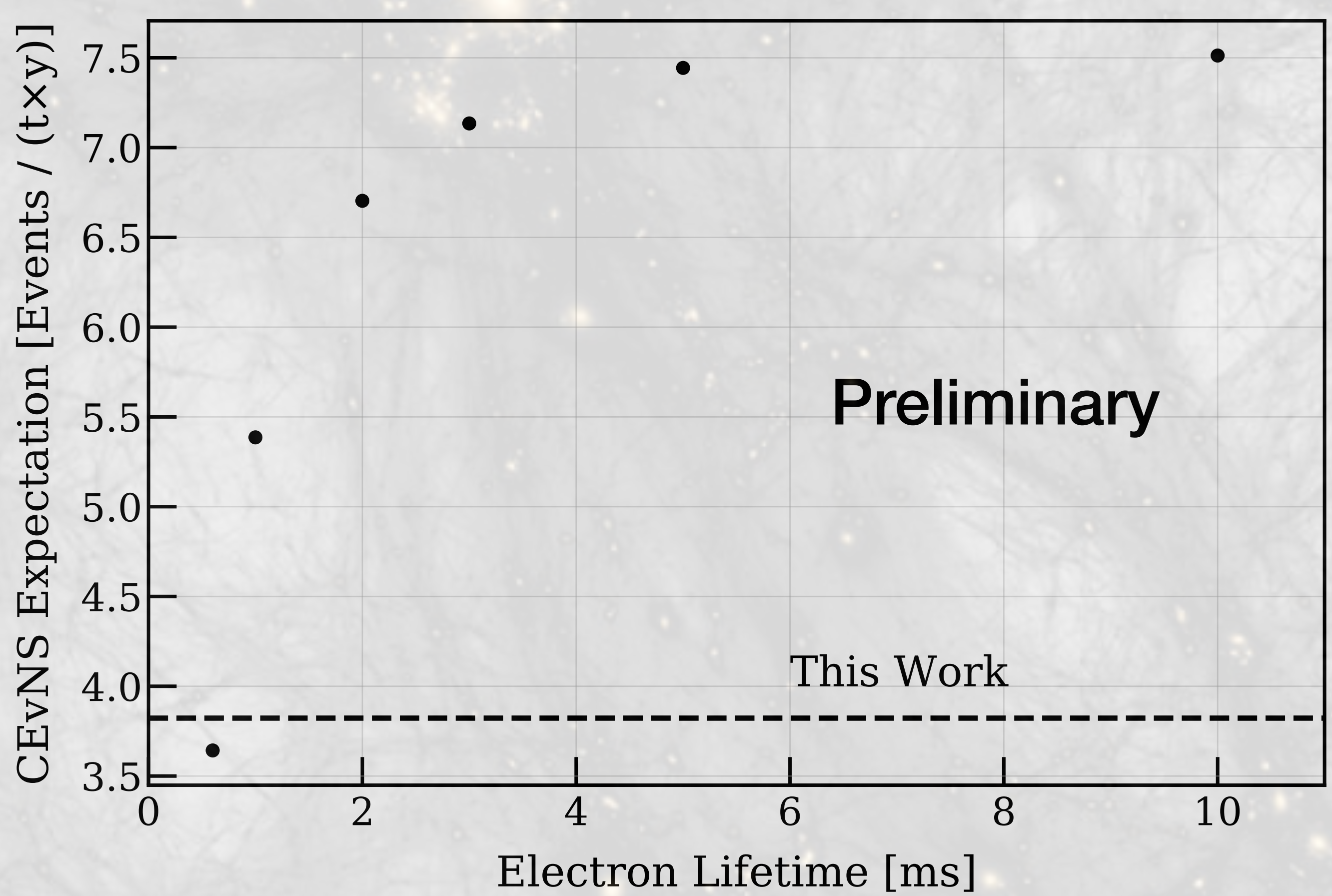
New constraints on light Dark Matter



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)

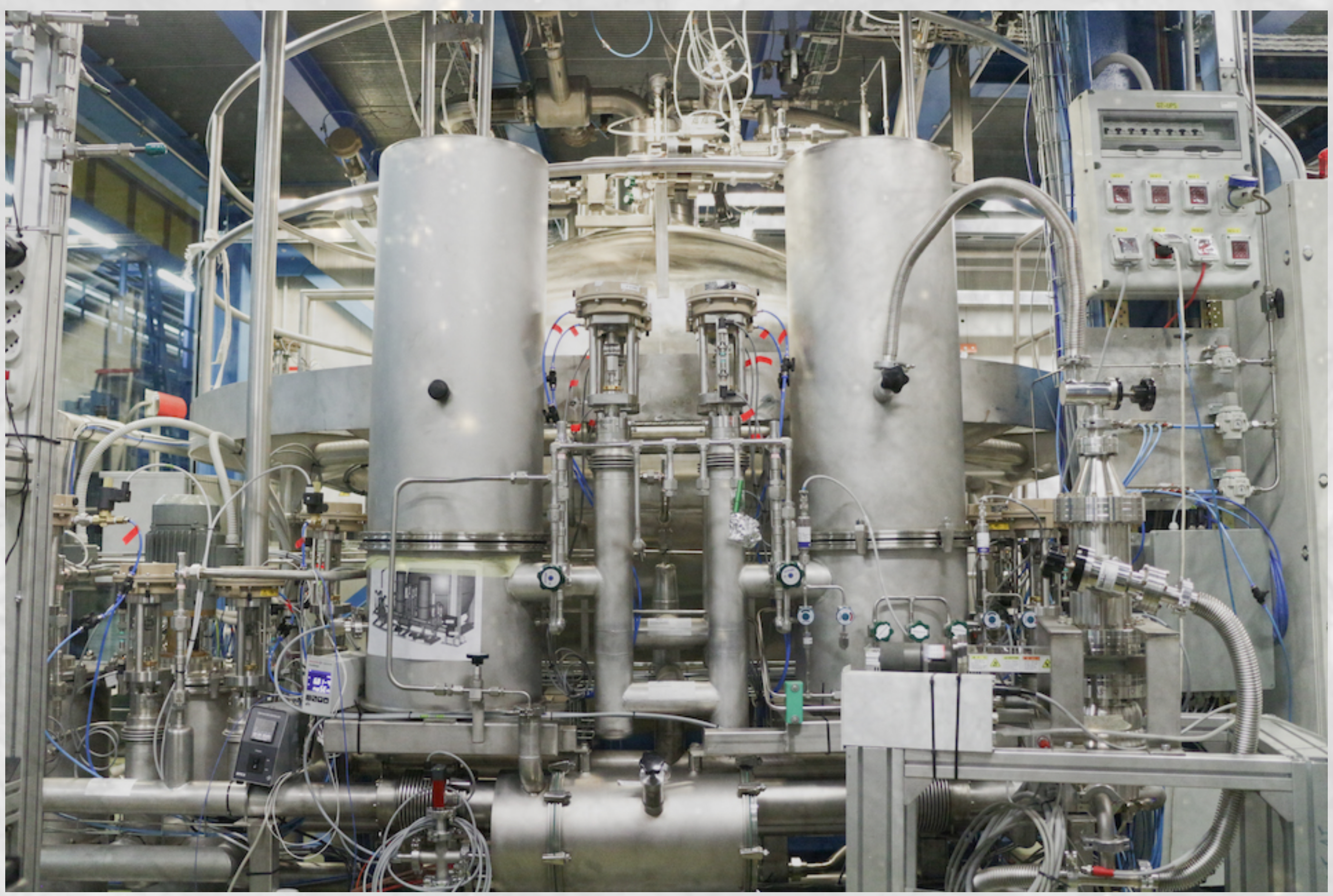
Precision of LXe response calibration is important to constrain the flux of solar neutrinos and other new physics (non-standard interactions and dark matter)

What’s Next? - XENONnT

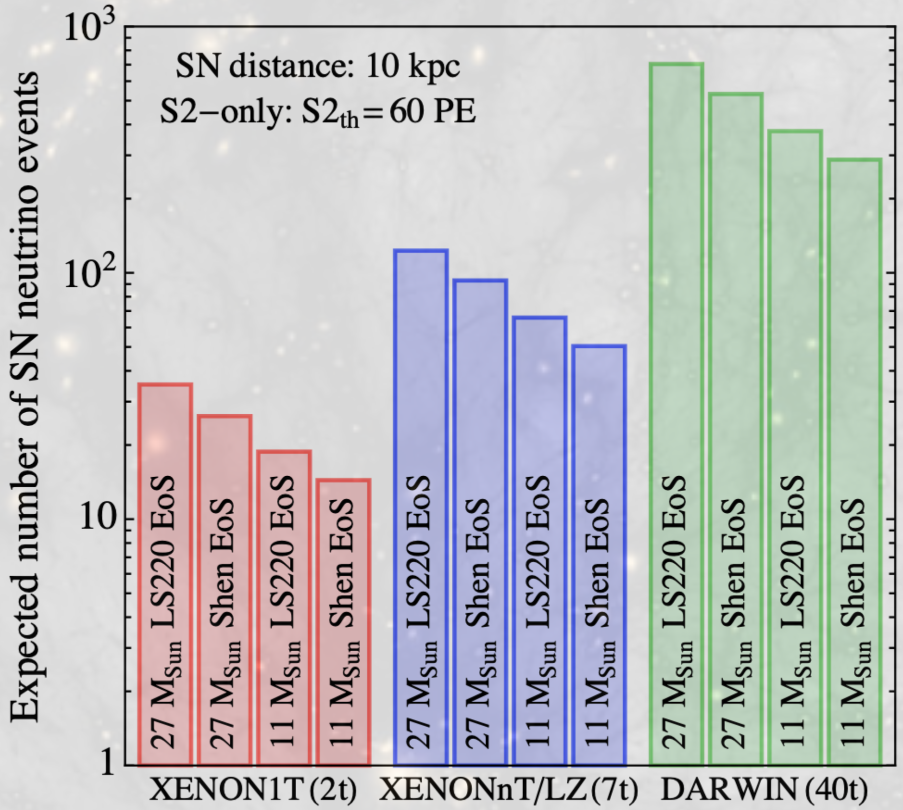
~4 times larger fiducial mass

~1/6 background level

Now: Under Commissioning!



XENONnT: Prospect on Supernova

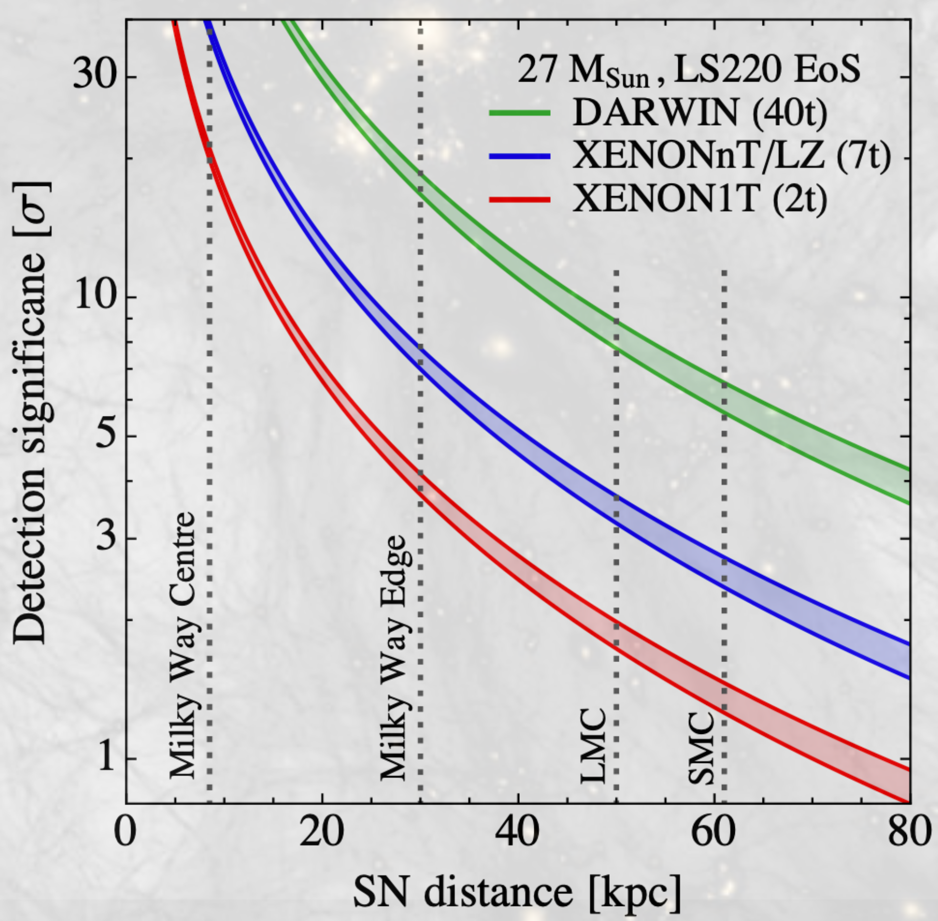


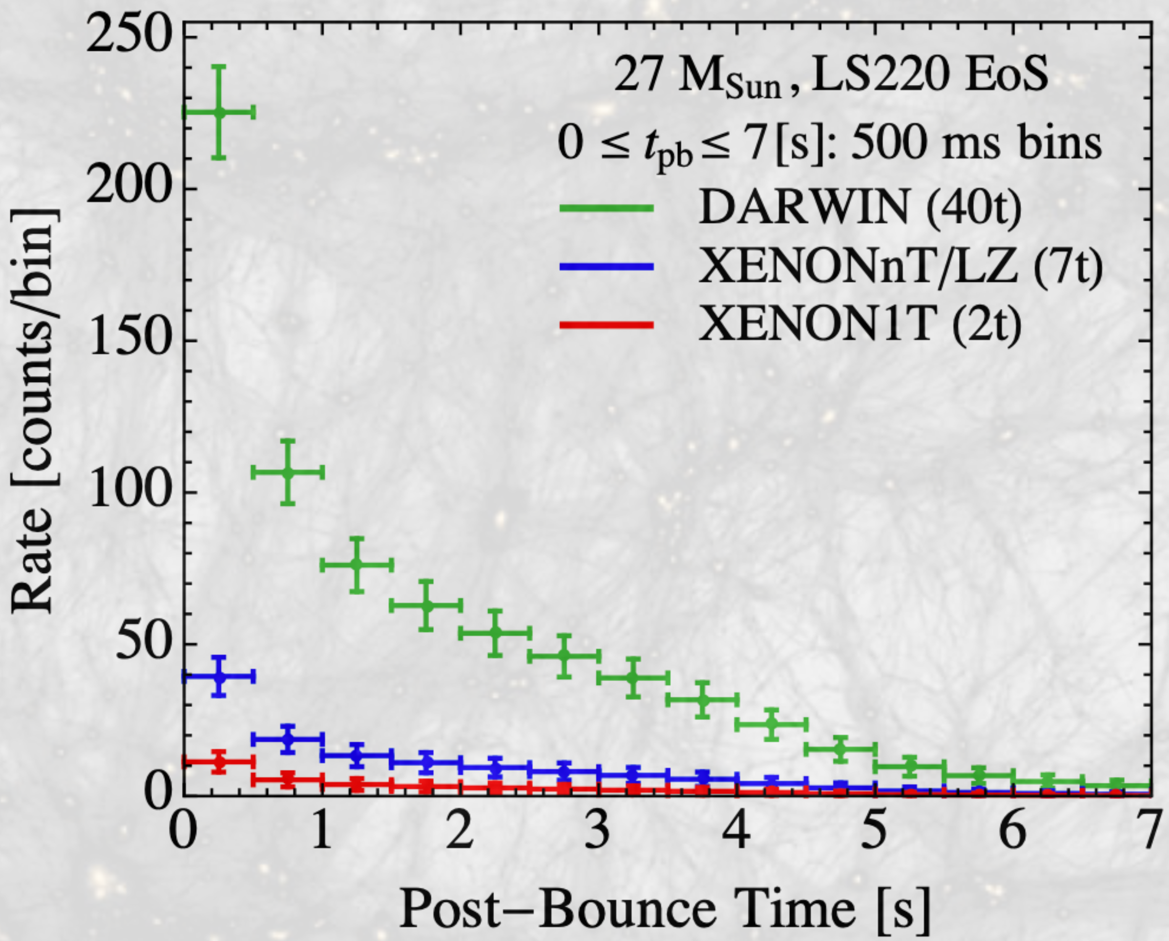
R. Lang et al, PRD 94, 103009, 2006

XENON has a close collaboration with SNEWS-2.0, and will receive trigger from it.

XENON has sensitivity to single electrons, and can record most of CEvNS interactions from supernova

We'd like to provide a flavor blinded measurement of neutrino flux for the community





Summary

XENON1T is the most sensitive dark matter experiment to date

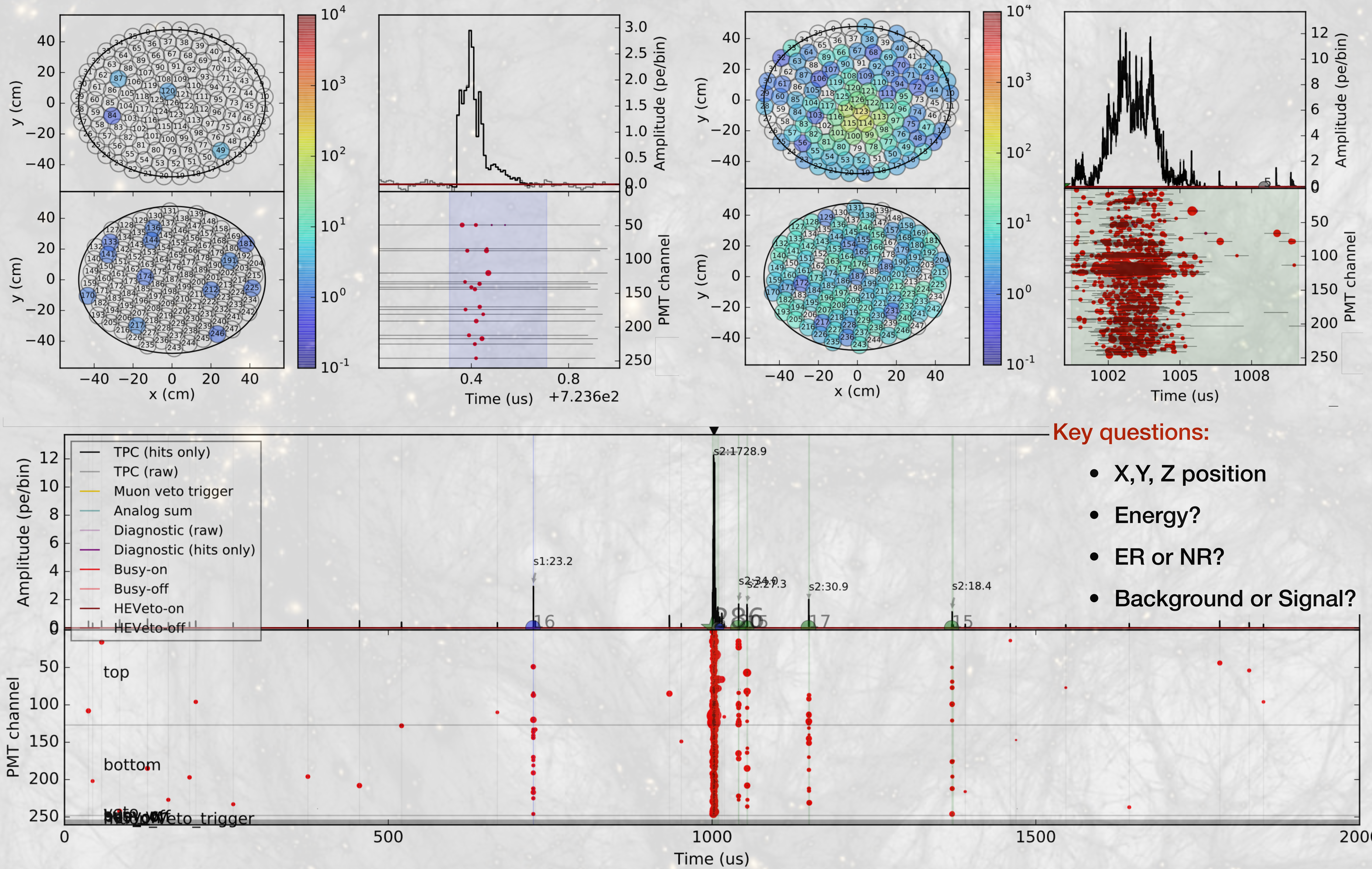
The XENON1T data is used to search for Coherent Elastic Scattering of Solar B8 neutrinos.

Future experiments such as PandaX4T, LZ and XENONnT have high discovery potential of Solar Neutrinos.

And we are prepared for a supernova too!

Thanks for your attention!

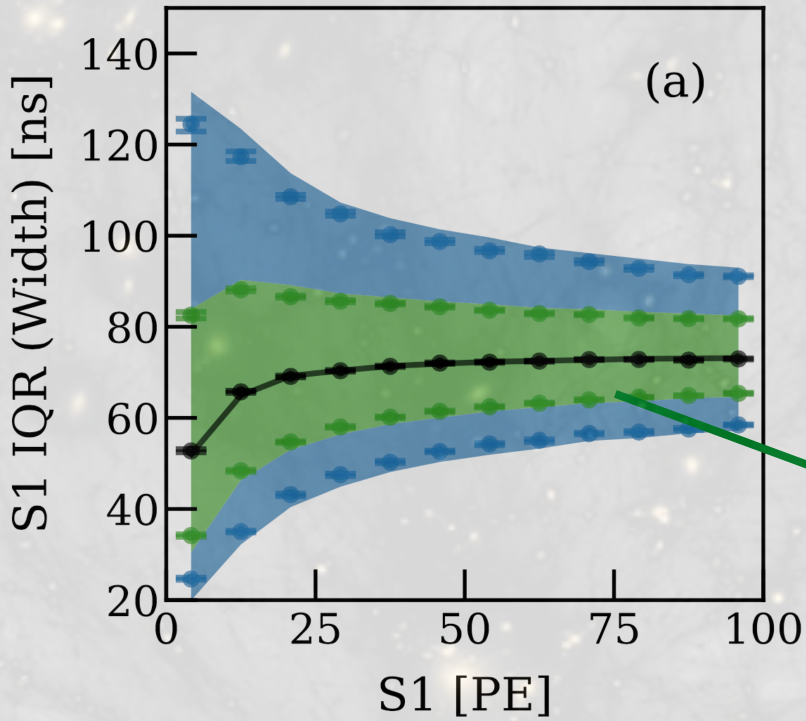
A XENON1T Waveform

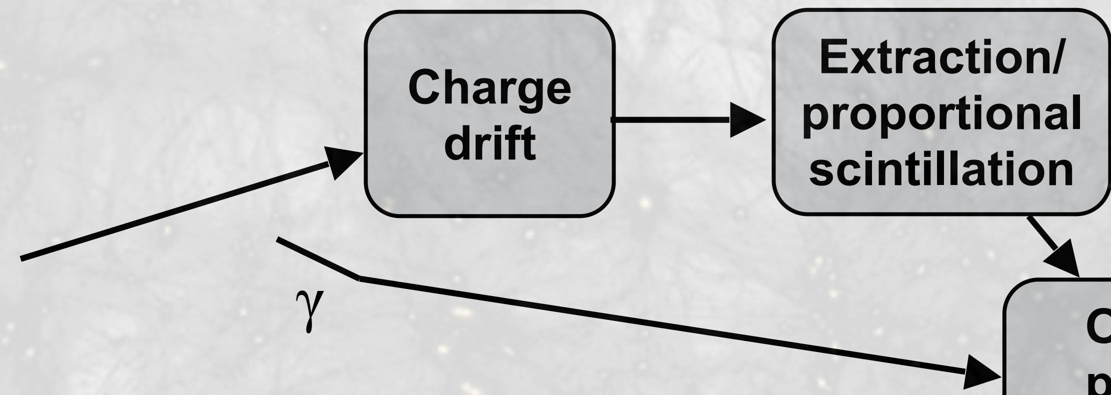
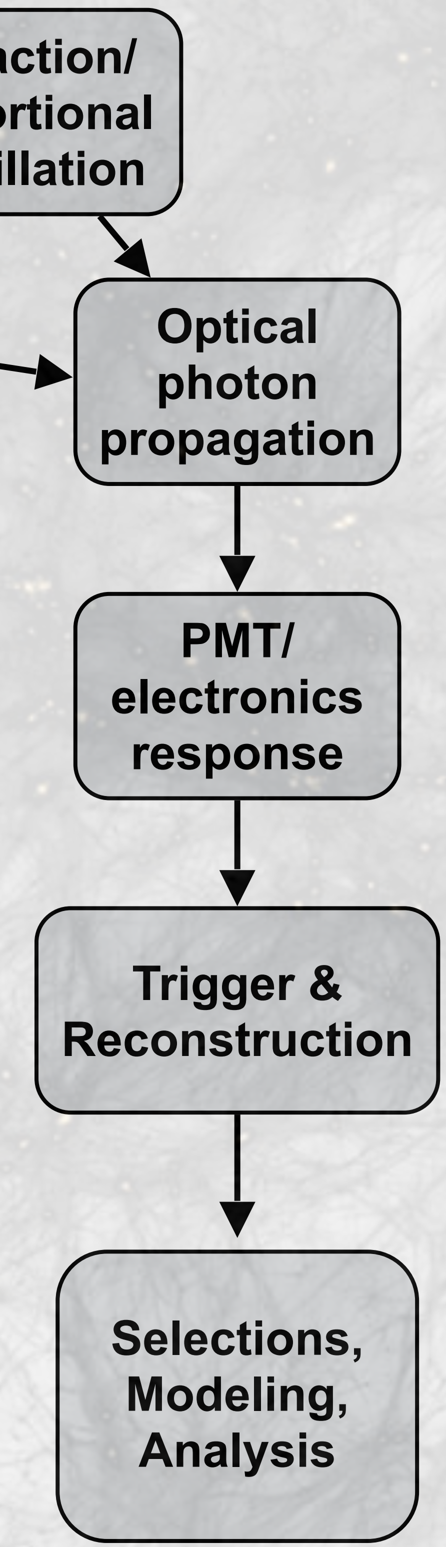


Key questions:

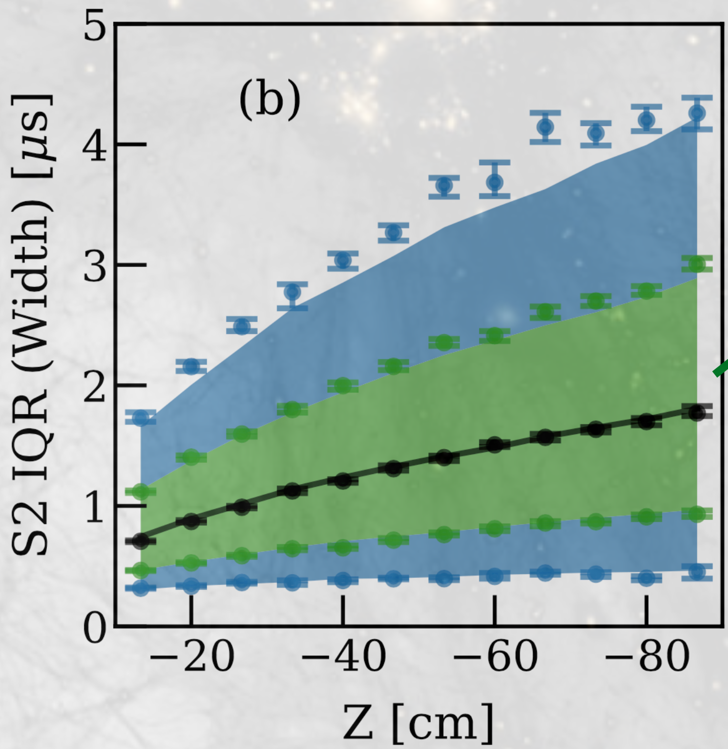
- X,Y, Z position
- Energy?
- ER or NR?
- Background or Signal?

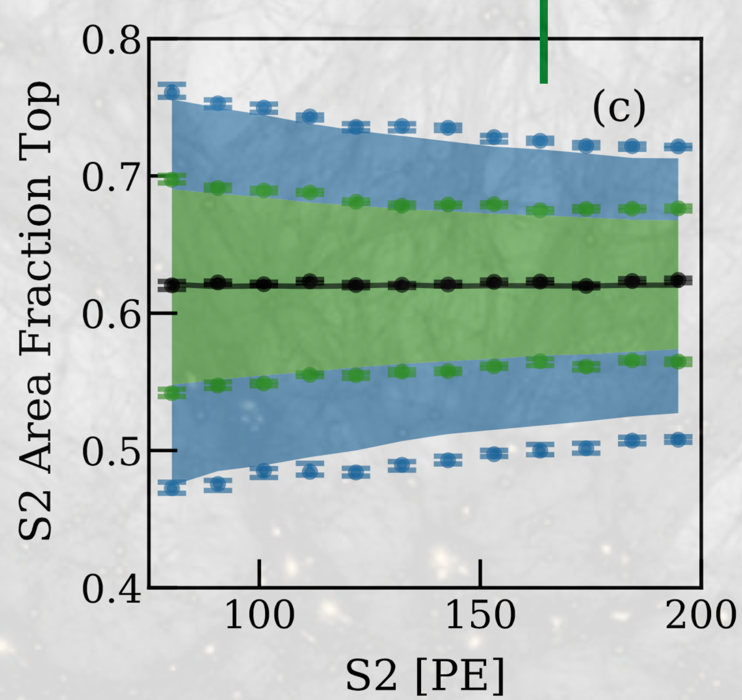
Modeling Efficiency through Waveform Simulation



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

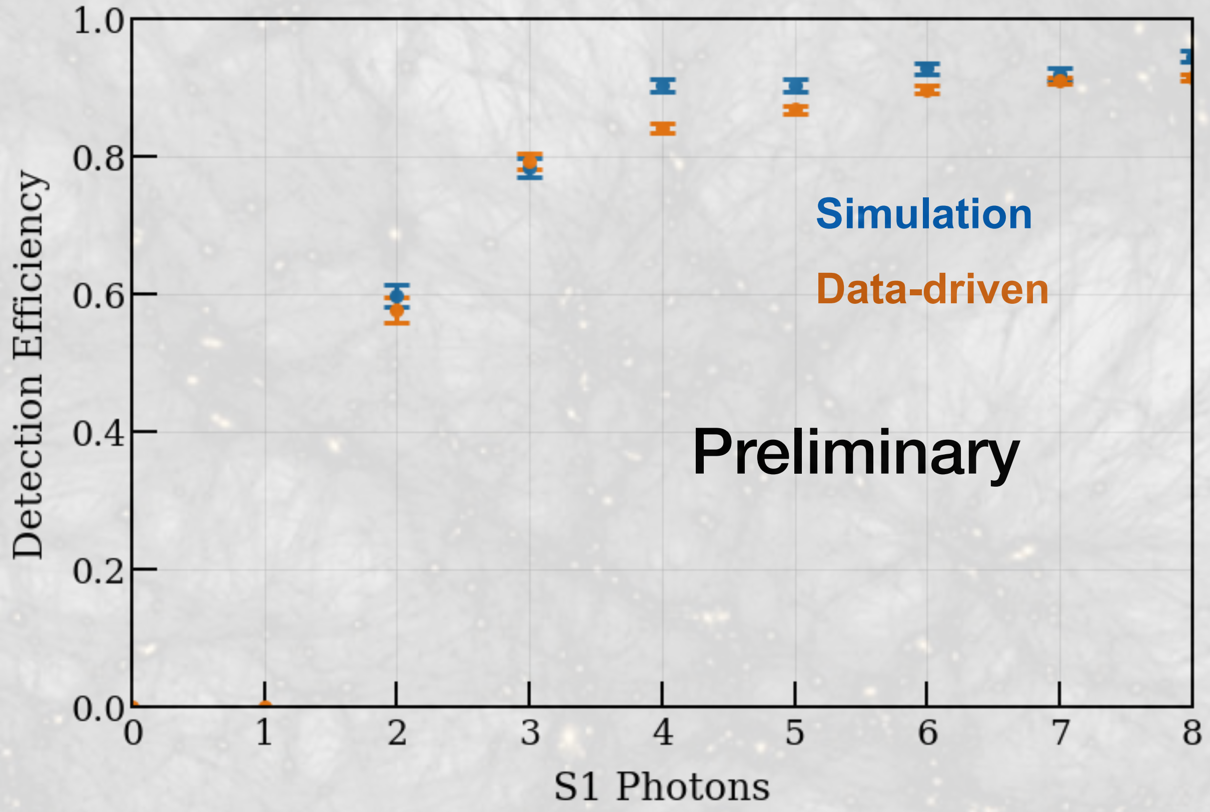




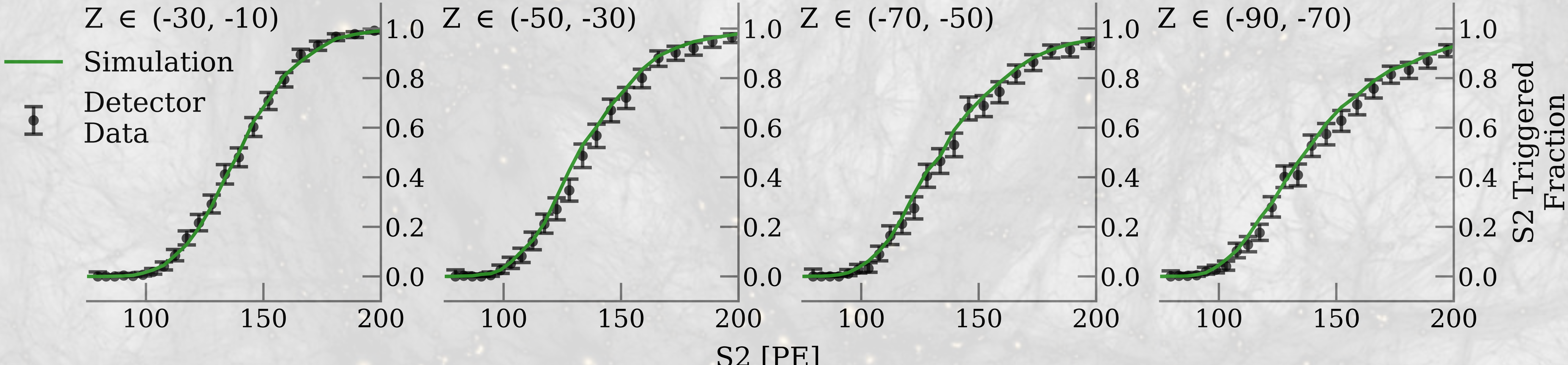
Modeling the Detection Efficiencies

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.



AC Background Suppression: I

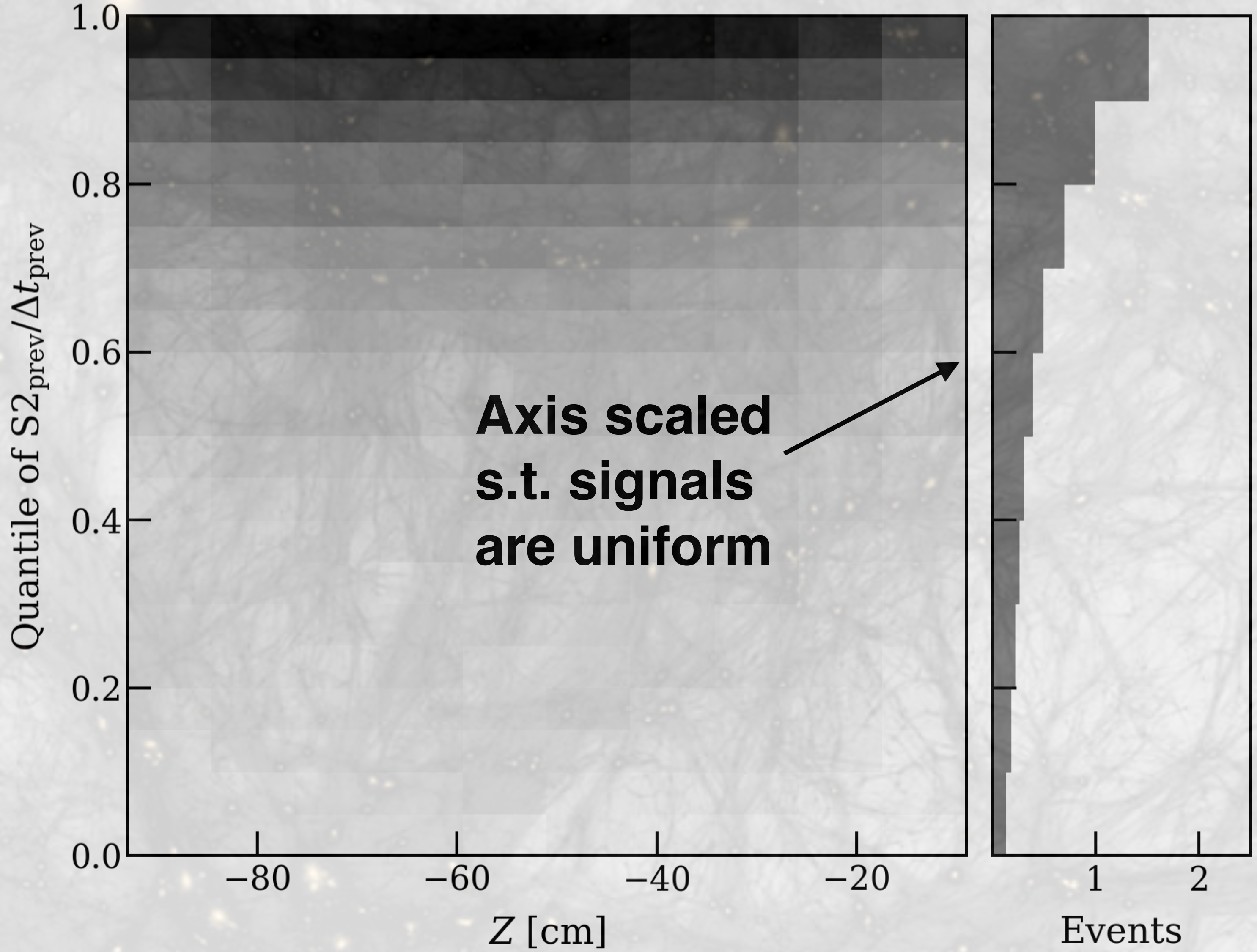
High energy events induce large AC background afterwards

- S1: higher rate of lone-hits (unclear why)
- S2: More single electron emissions
    - Suppressed by a position correlation cut

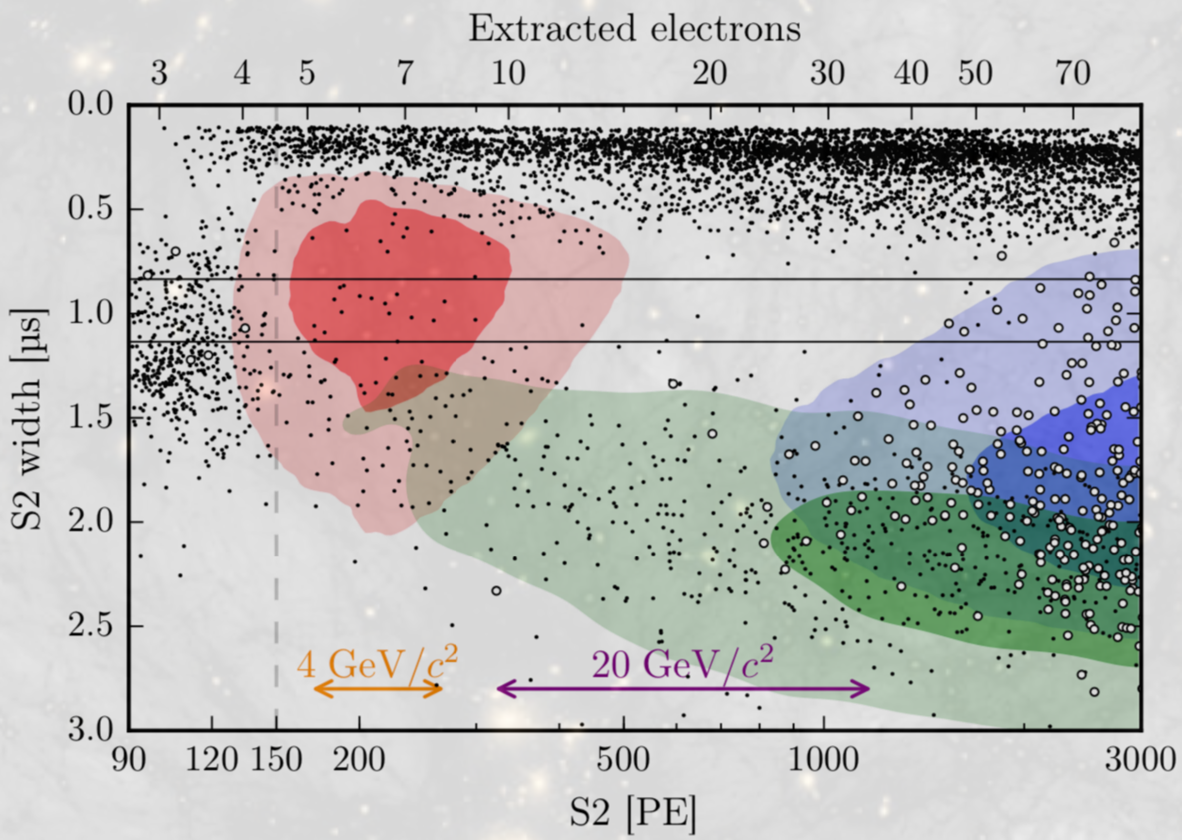
Reduce the impact of a high energy event, we define a cut on: $S2_{\text{prev}}/\Delta t_{\text{prev}}$

- S1: 65% reduction ->11.2 Hz
- S2: 1.0mHz, ~1/3 of XENON1T SR1
- Ensure no correlations of S1 and S2s

Reduced the exposure to 0.6 ton-year

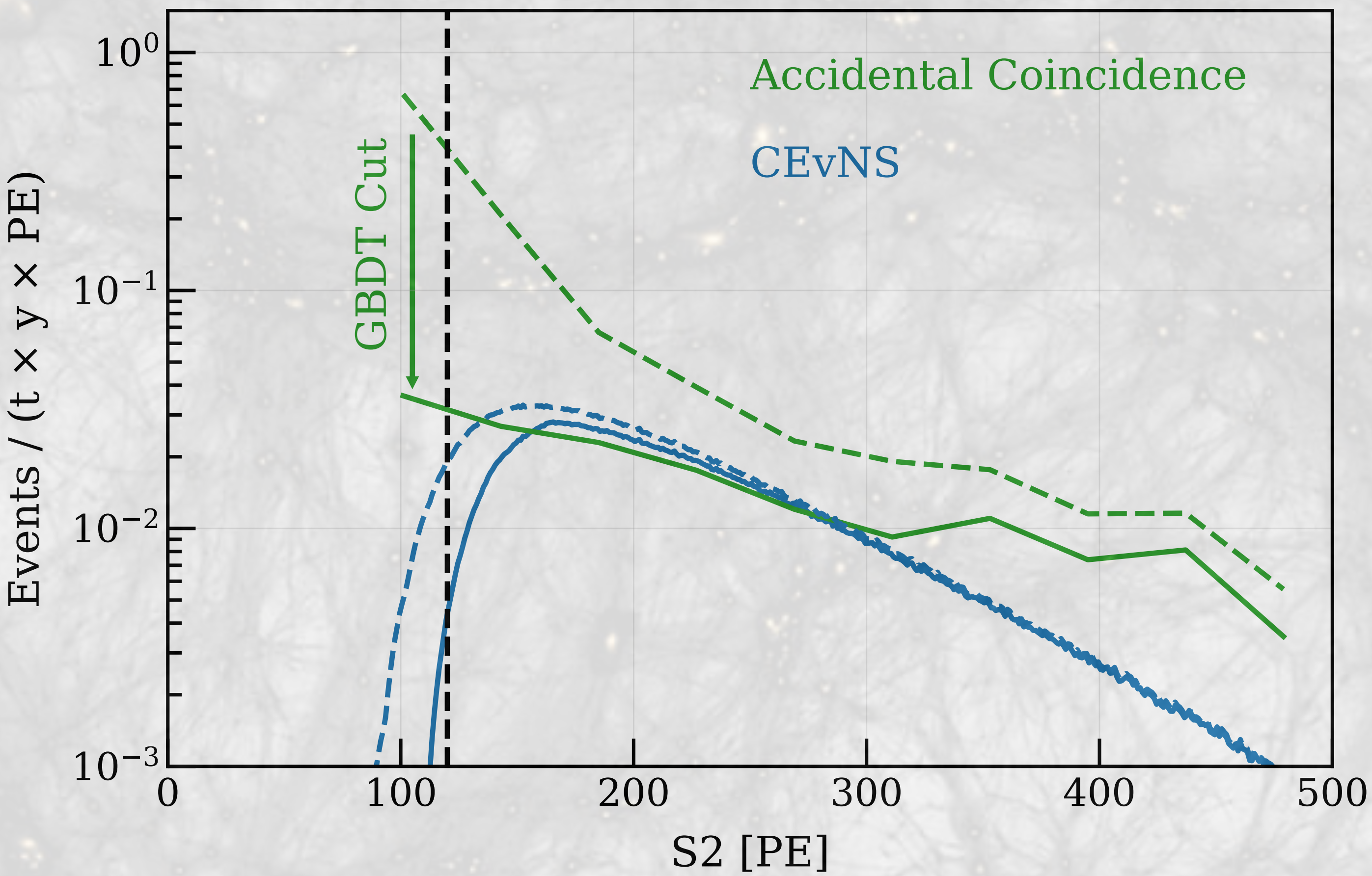


AC Background Suppression: II

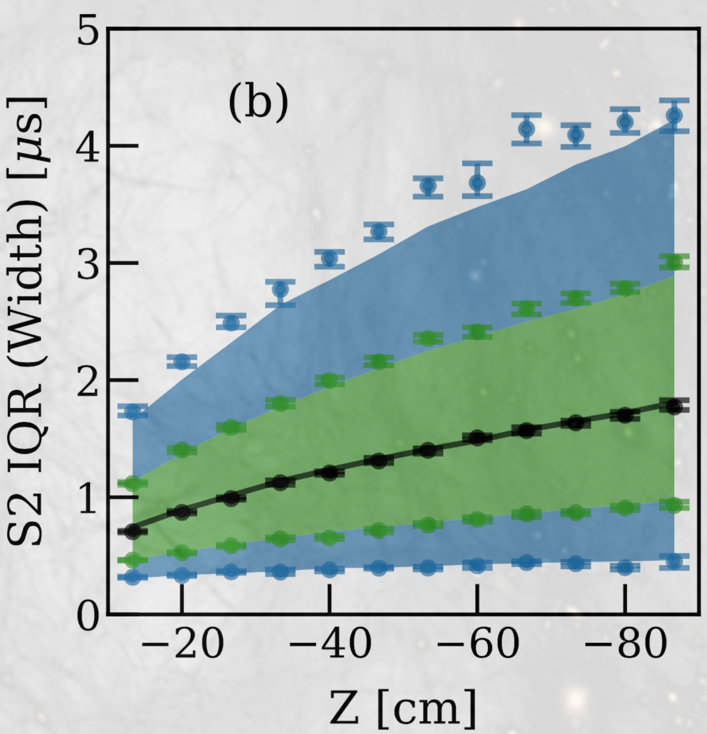


Gradient **B**oosted **D**ecision **T**ree ensemble classifier for an optimal discrimination

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



AC events has different distributions in spaces like: S2, S2 width, S2 Top/Total, depth (Z)

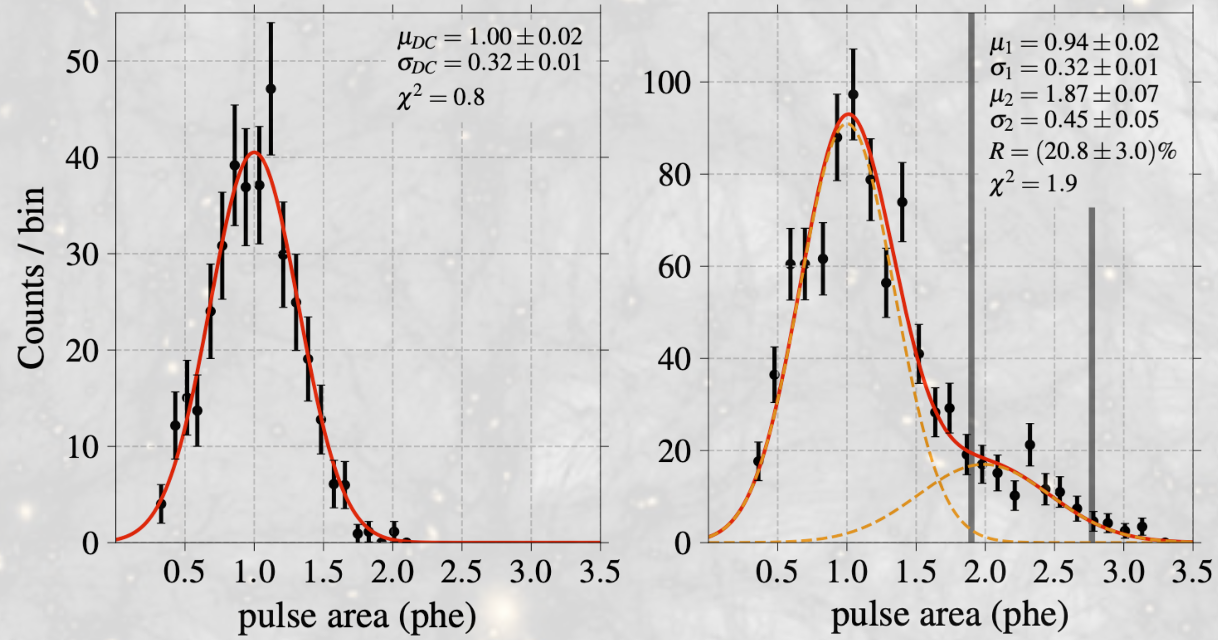


CEvNS rarely has S2s below 120PE: data with S2 below 120PE is used as a Control region

AC Background Suppression: III

LUX, PRD 101, 042001 (2020)

Isolated S1s **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

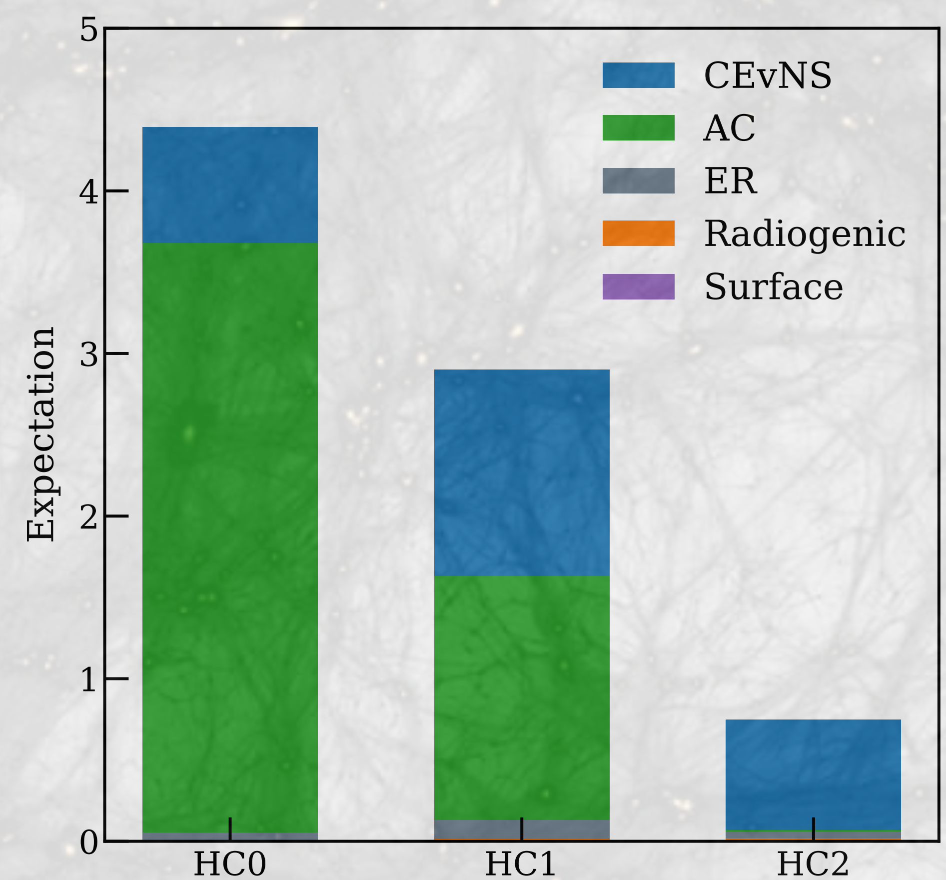
Isolated S1s are roughly **evenly distributed across PMTs**, and **rarely contain three PMTs,** Signal S1s are larger and prefer **bottom PMTs**

Three “**H**it **C**ategory” Bins

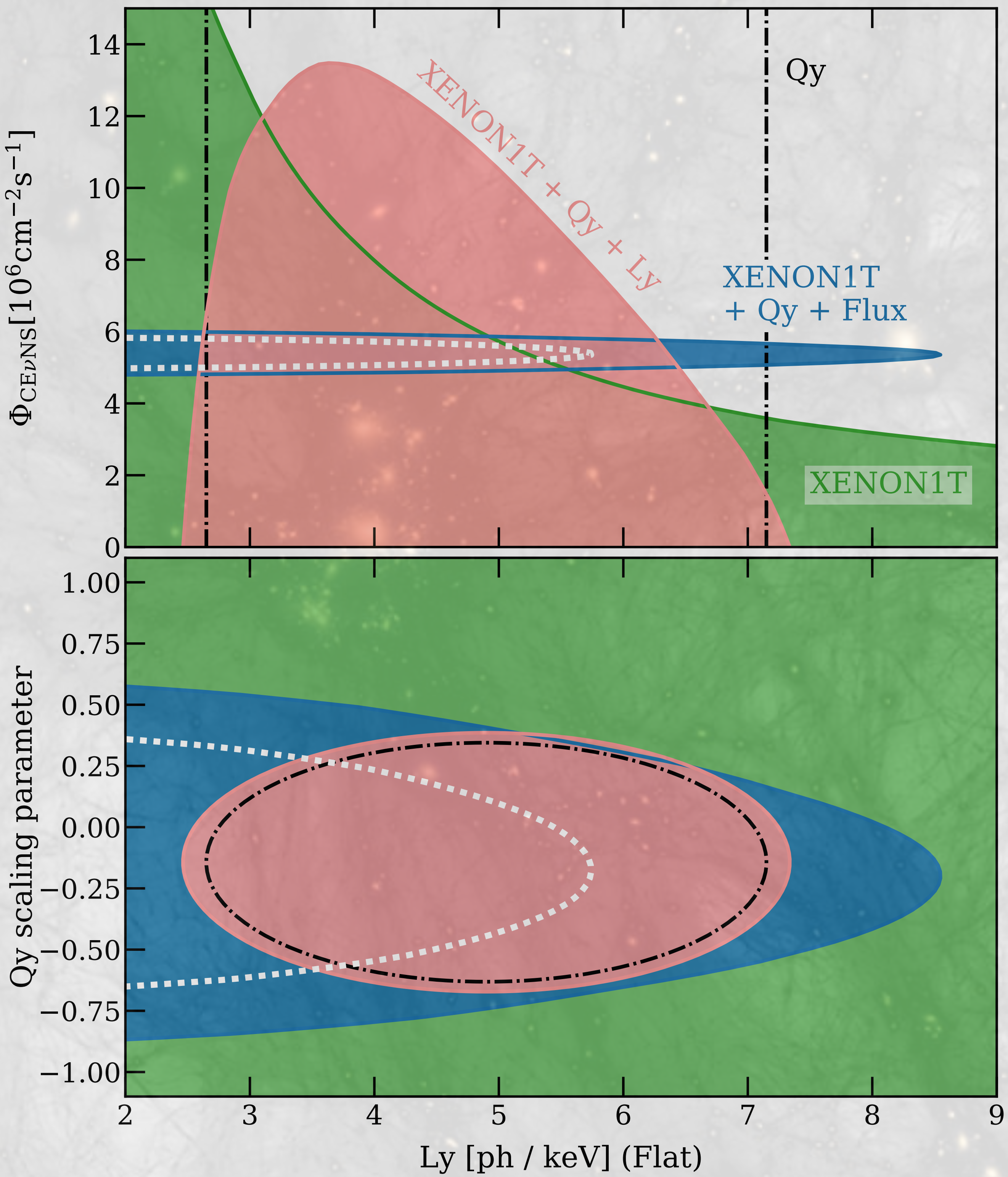
HC0: 2 Hits, 1+ in the top array → Very AC-like

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

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



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 < 1.4e7 / cm² s**
first independent constraint on solar B8 neutrino flux through **CEvNS** process

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