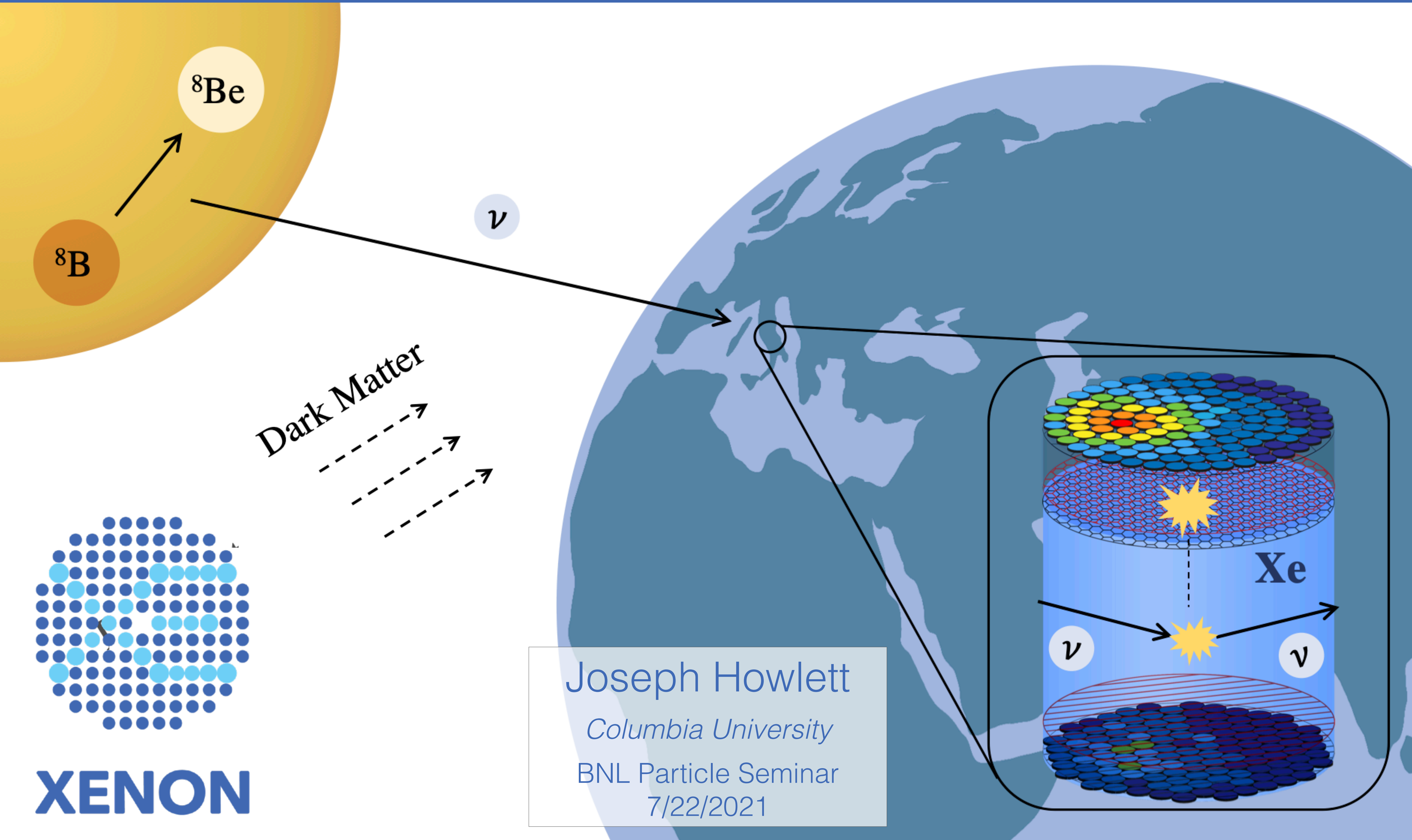
A Gamble in the Fog
Solar ^{8}B Neutrino Search in XENON1T



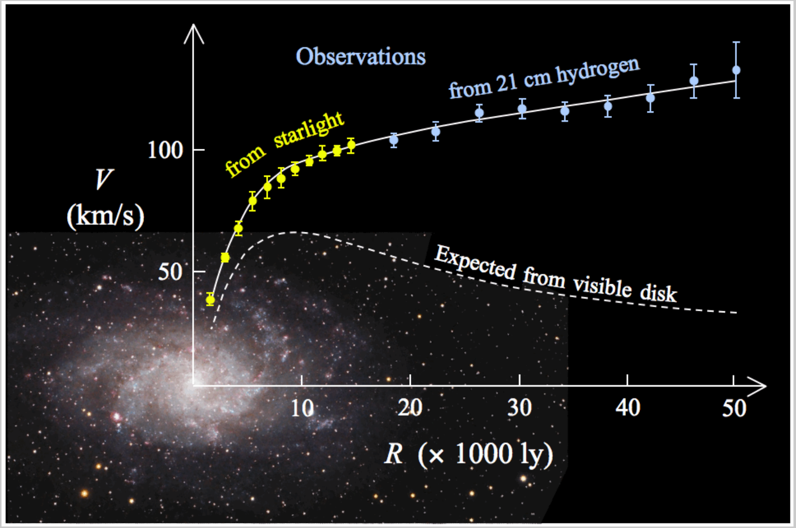
Joseph Howlett

Columbia University

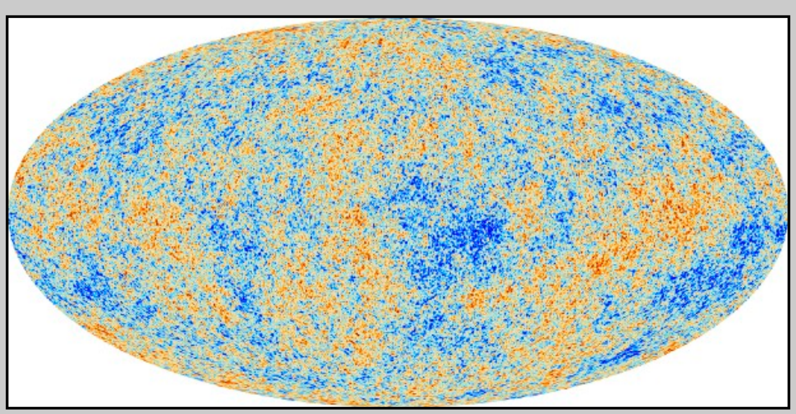
BNL Particle Seminar
7/22/2021

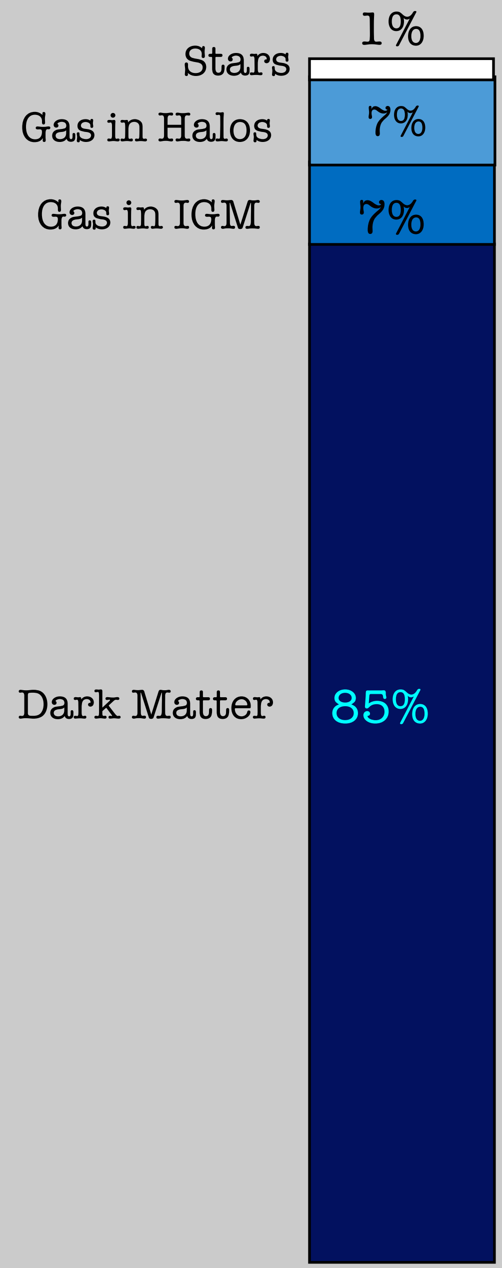
XENON

Dark Matter

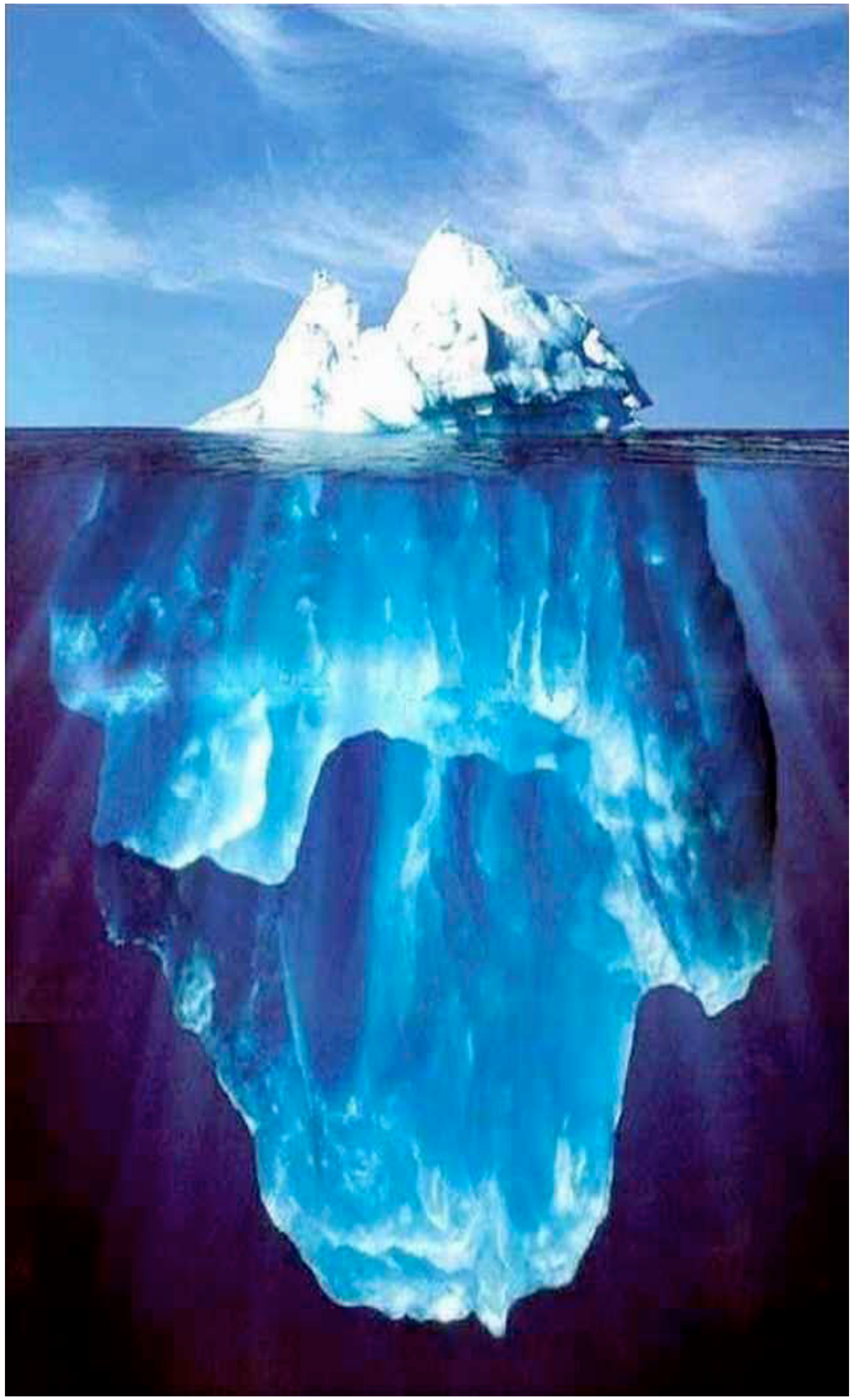


Observations
from 21 cm hydrogen
from starlight
V
(km/s)
100
50
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)



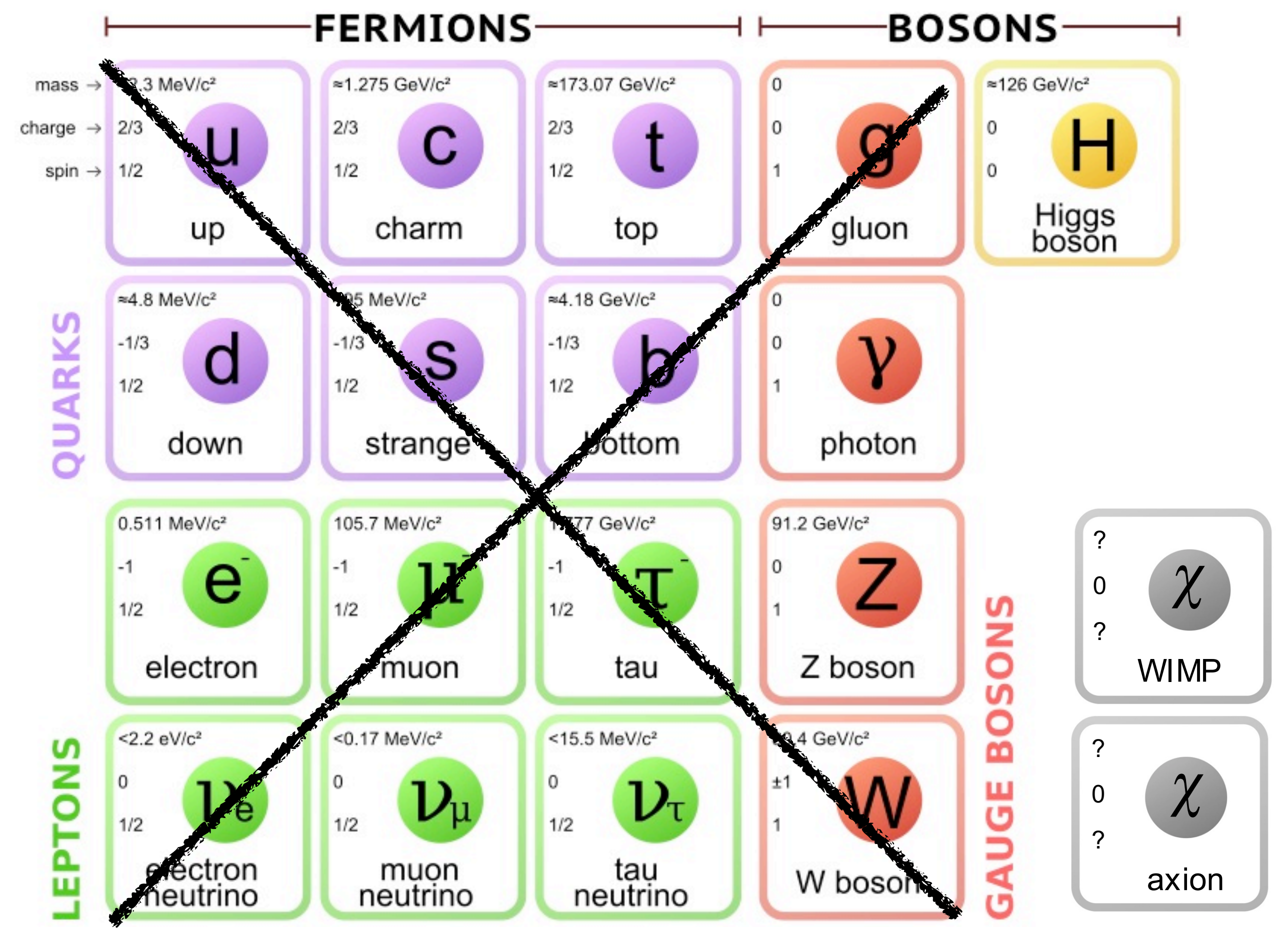


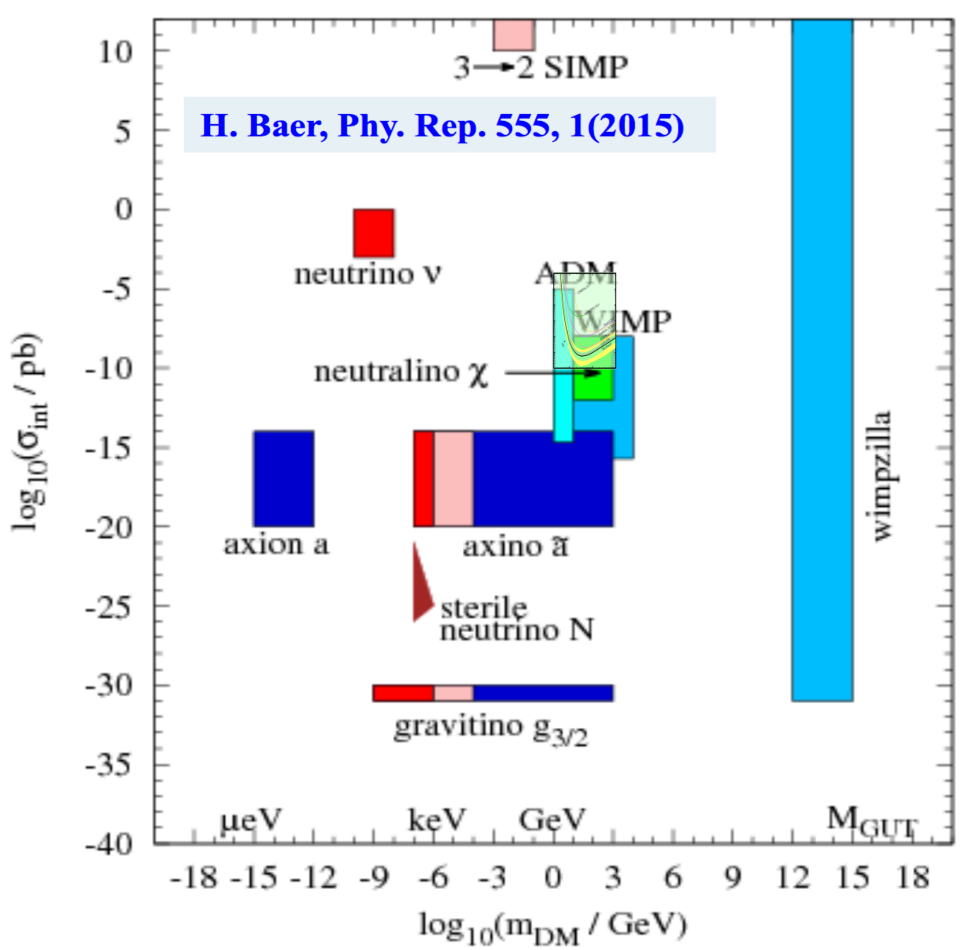
1%
Stars
Gas in Halos
7%
Gas in IGM
7%
Dark Matter
85%

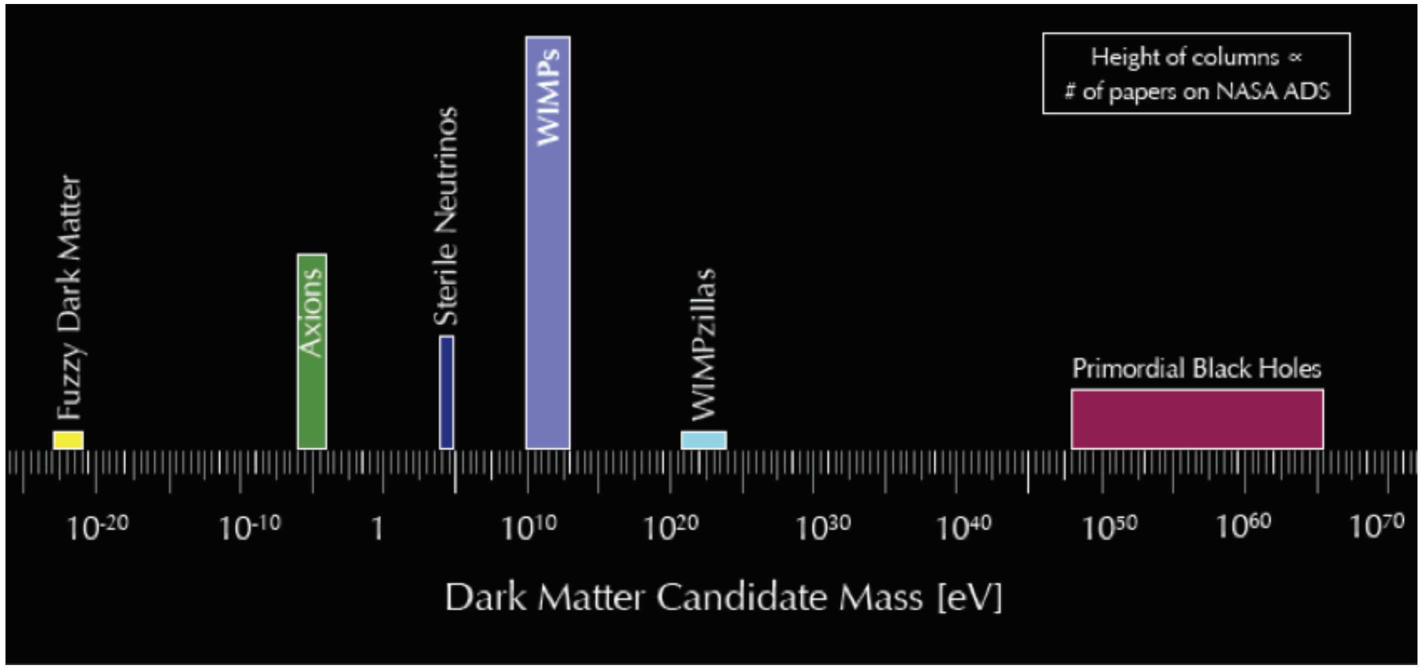


What is Dark Matter?

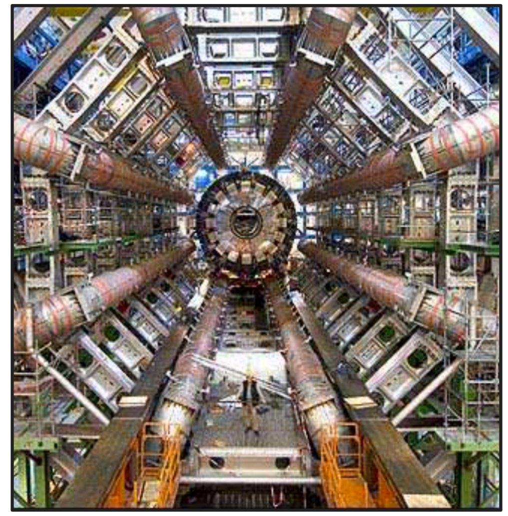
- Neutral: no EM interaction
- Stable: Lifetime > age of the Universe
- Massive: for structure formation
- Interaction besides Gravity ??

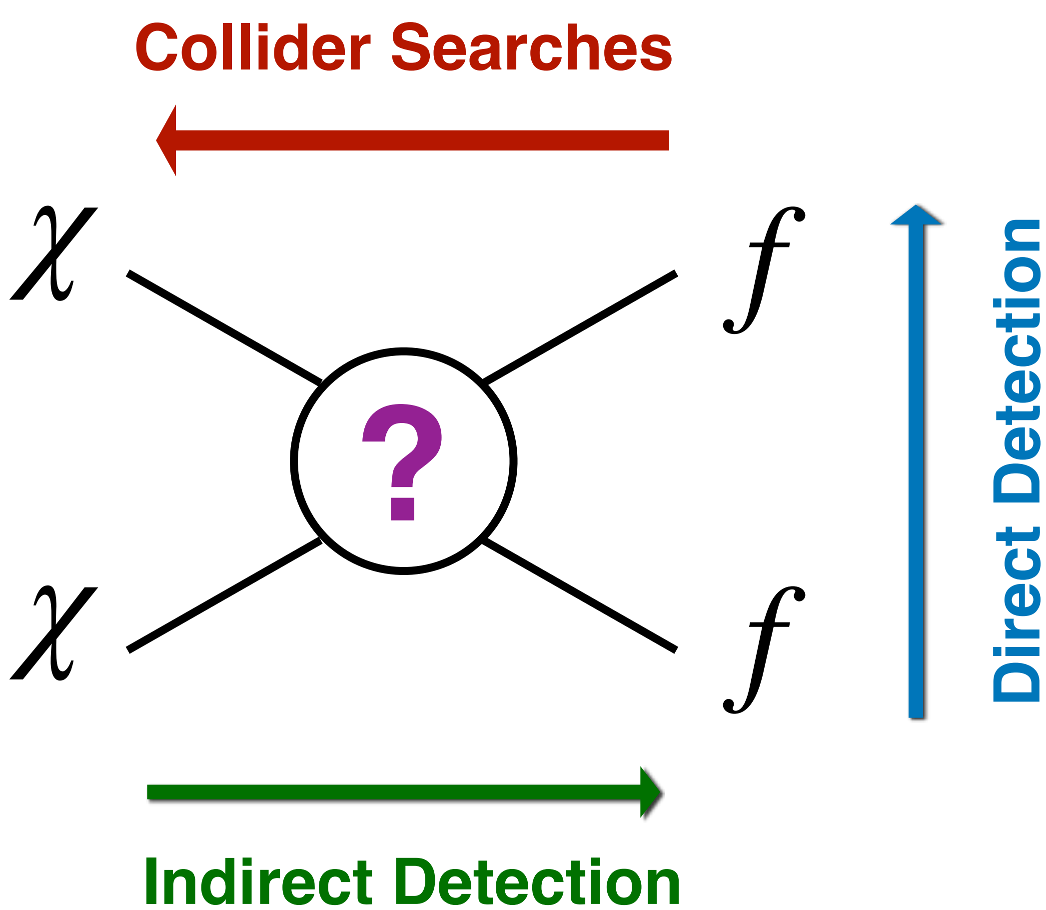




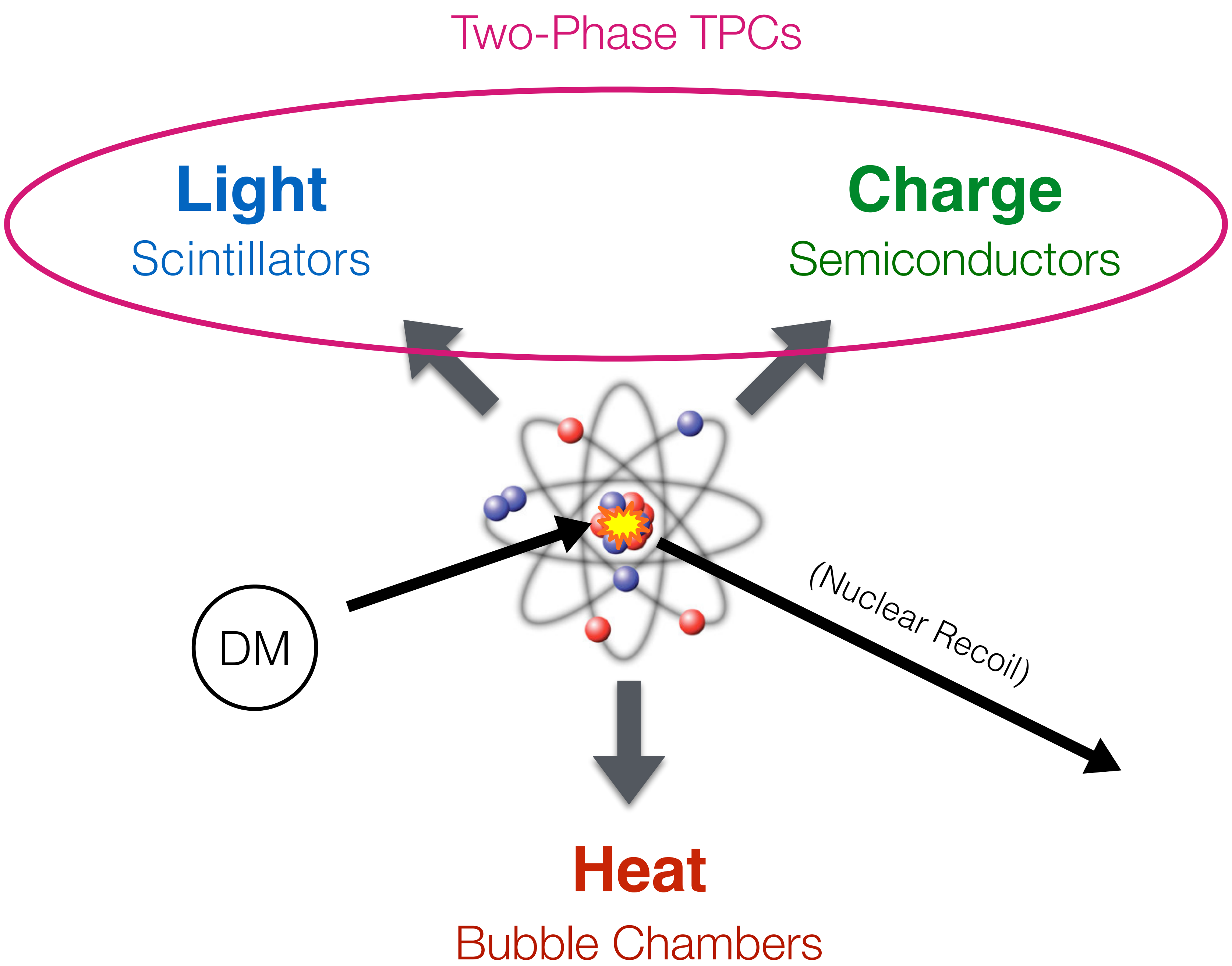


Direct Detection



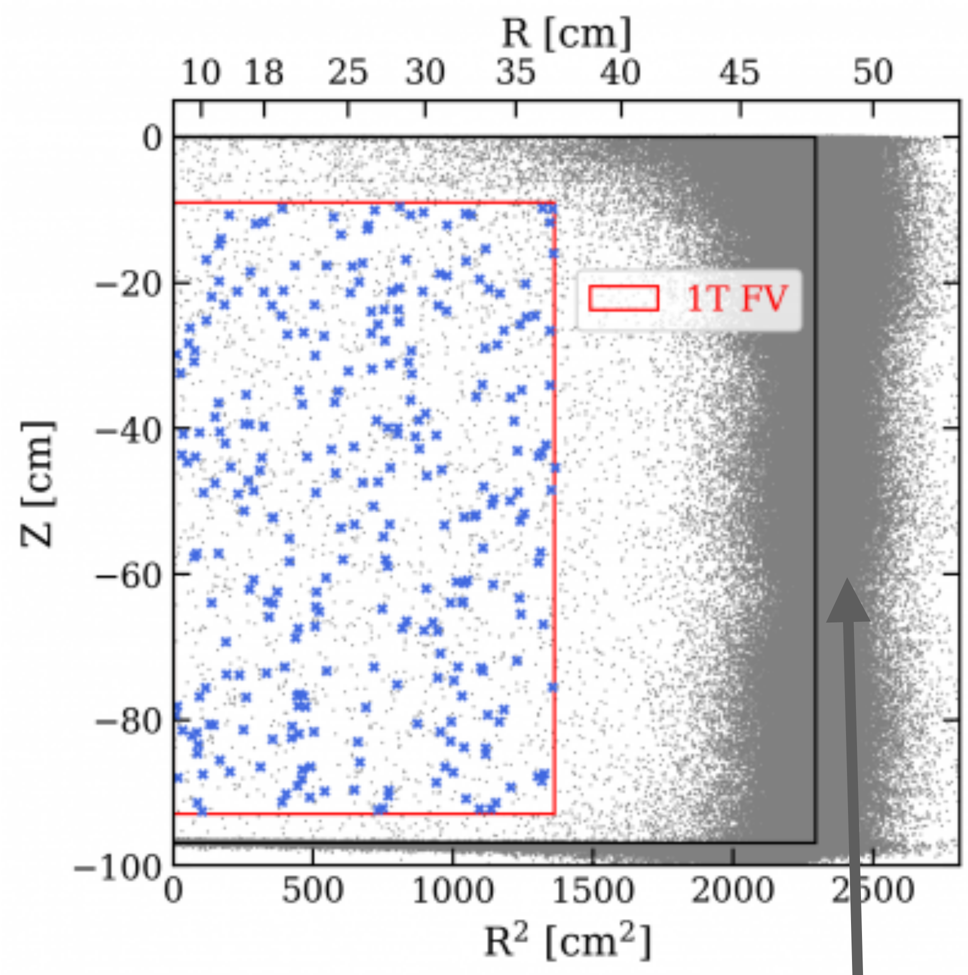


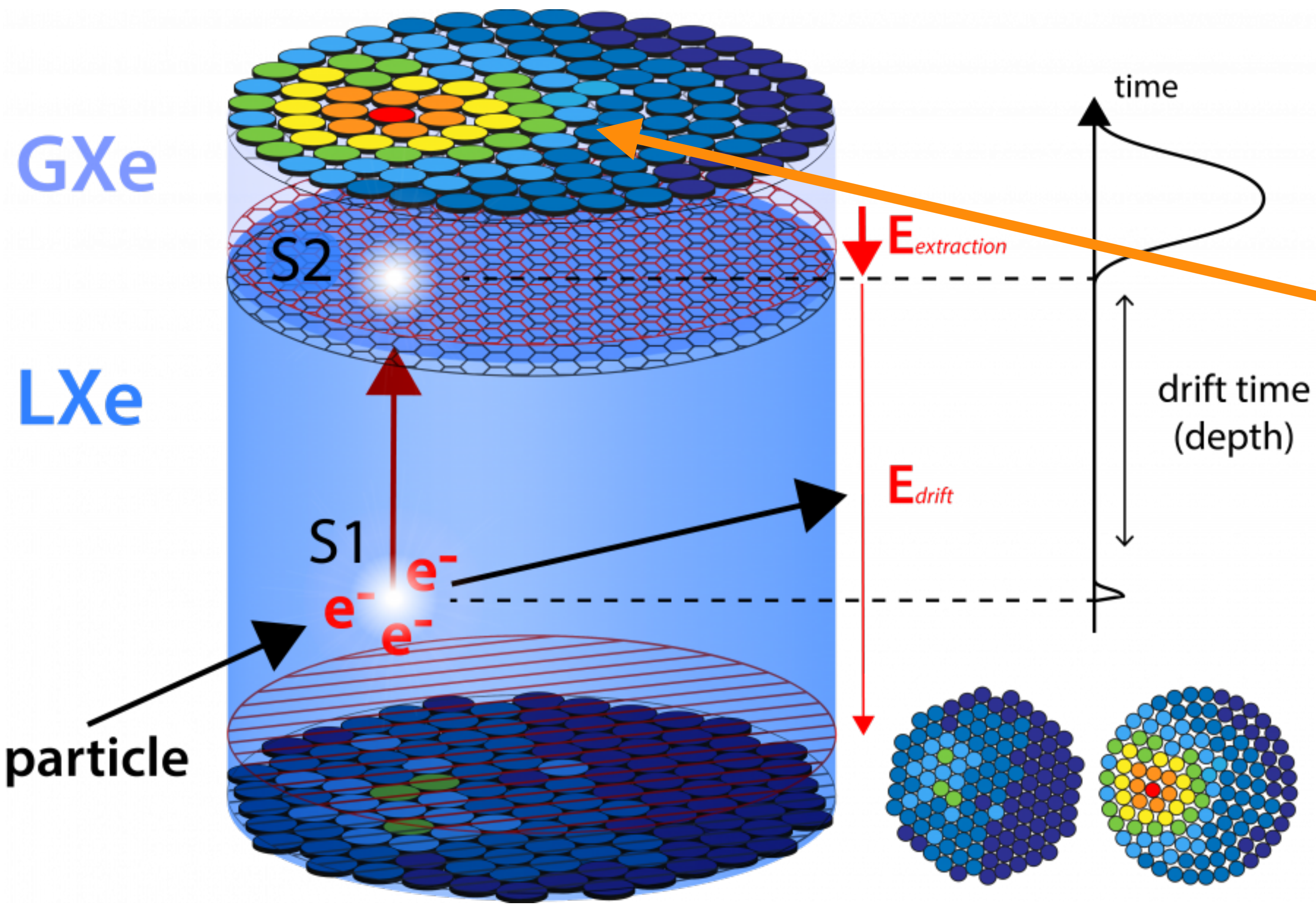
Direct Detection



Dual-Phase TPCs

- Light (S1) is detected by PMT arrays
- Charge is drifted through liquid, extracted into gas - scatters and produces proportional scintillation (S2)

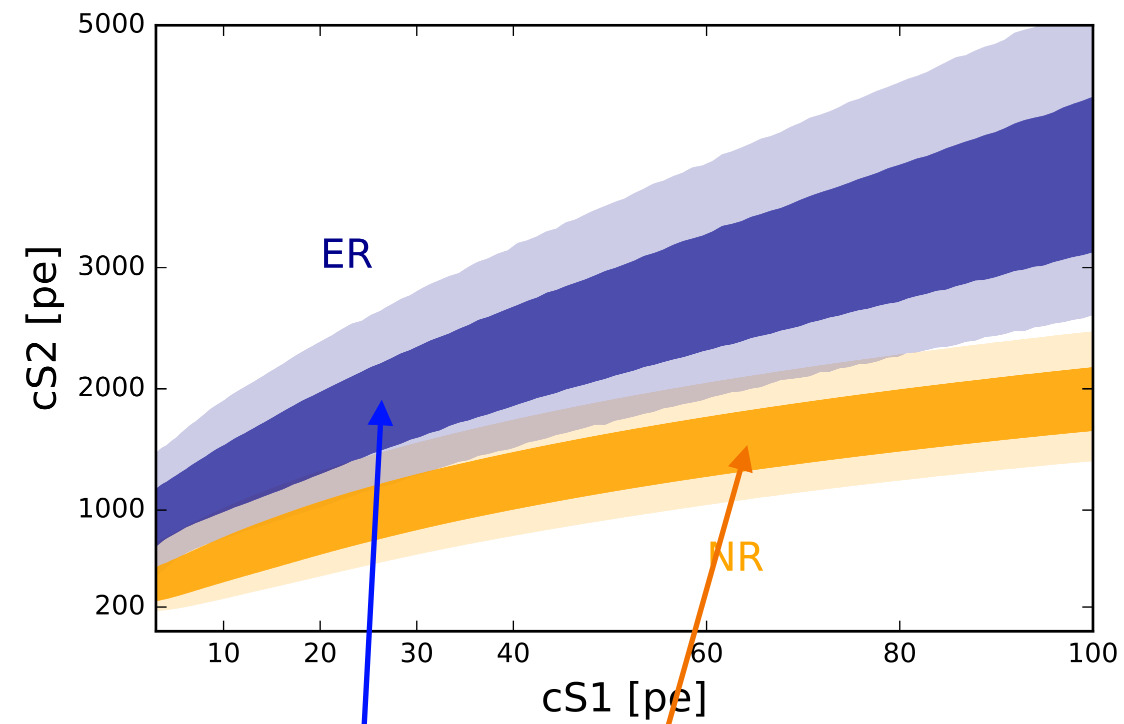


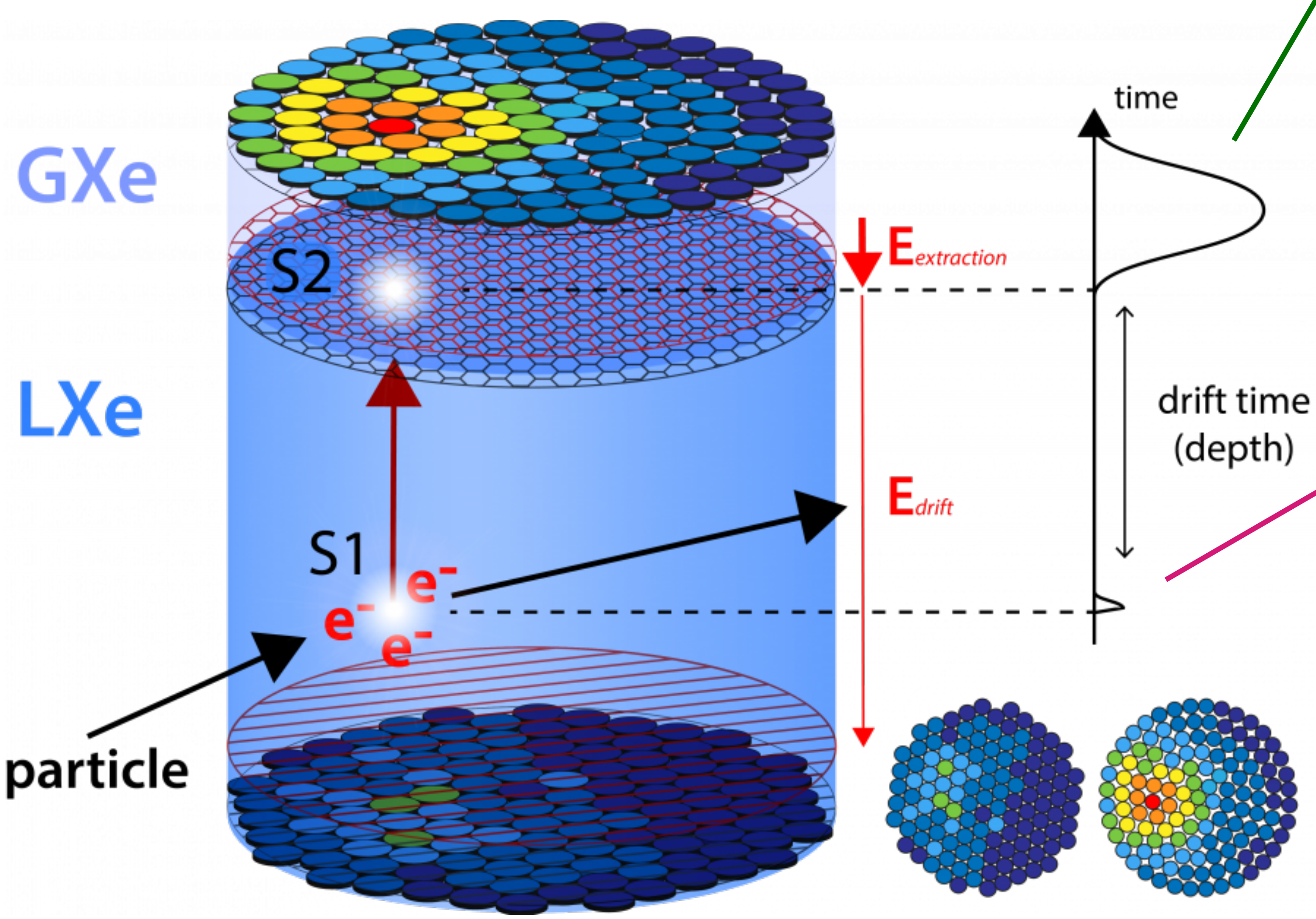


- R from PMT pattern
- Z from drift time
- Self-shielding from gammas
- Fiducialization

Two-Phase TPCs

- Light (S1) is detected by PMT arrays
- Charge is drifted through liquid, extracted into gas - scatters and produces proportional scintillation (S2)





- ERs and NRs have different S2/S1 ratios
- Discriminate WIMPs from dominant (ß) background

XENON Collaboration

27 Institutions

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

Chicago | UCSD | Rice | Purdue

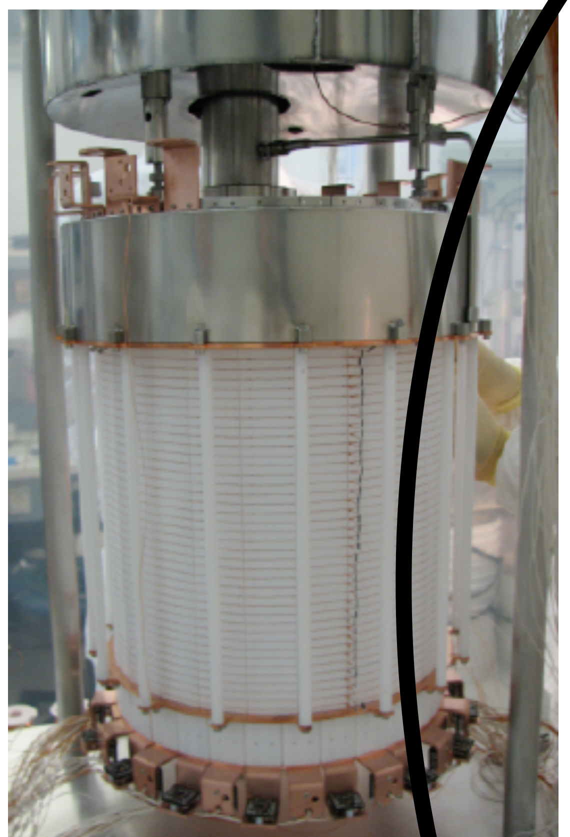
Tsinghua | Tokyo | Nagoya | Kobe

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

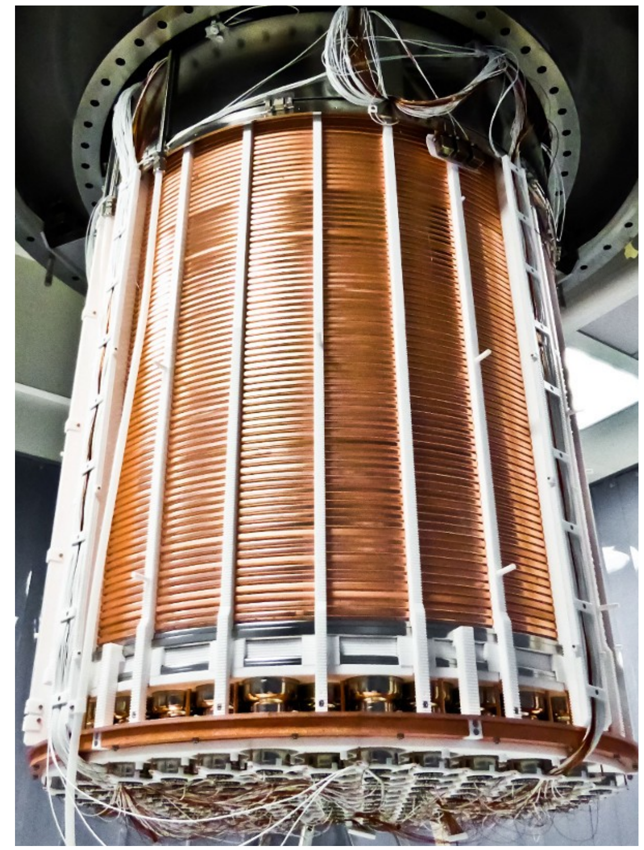
Evolution of XENON

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

XENON1T Systems

WIMP Search Result

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

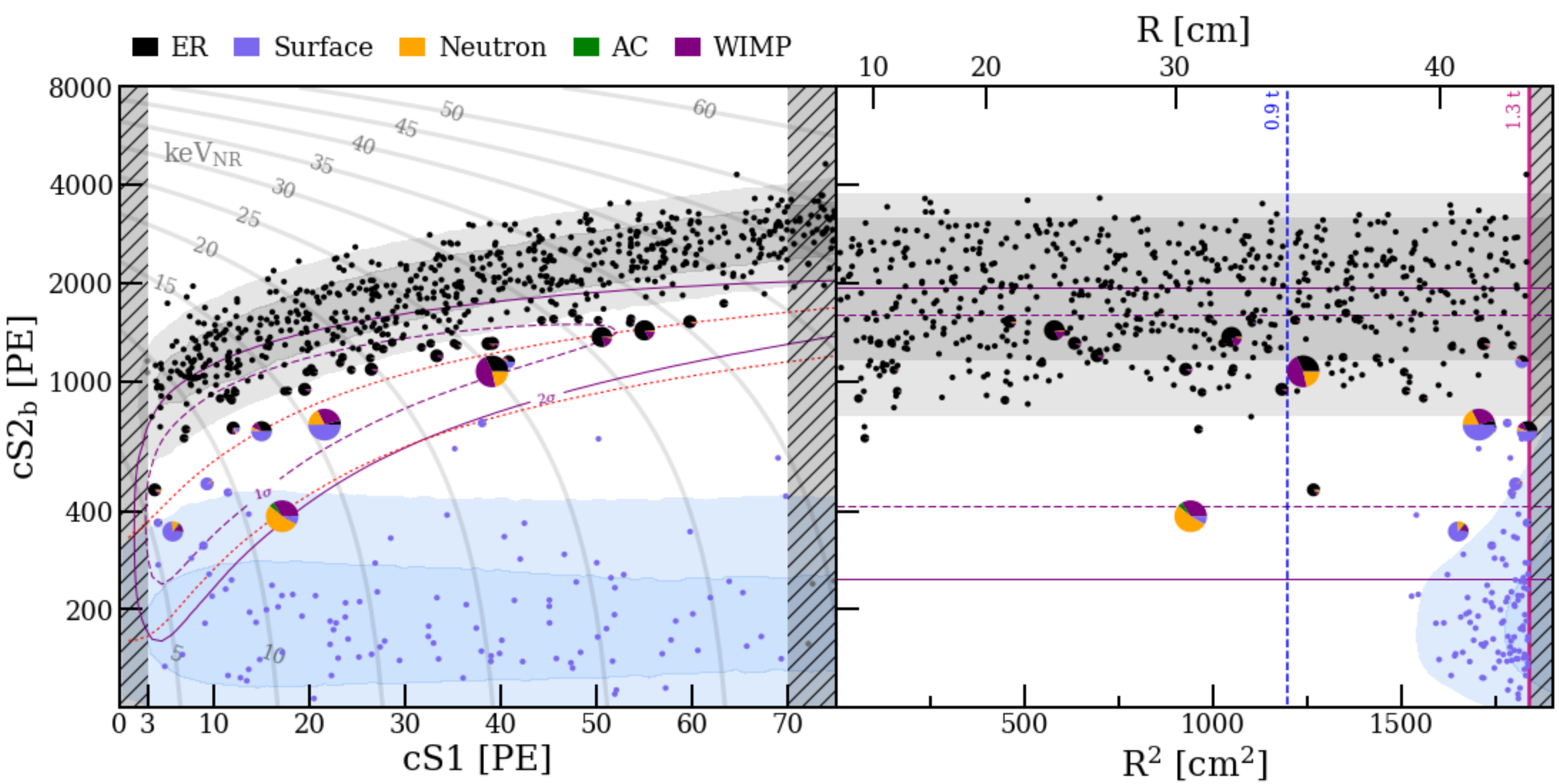
1 Ton x Year Exposure of XENON1T

(blind analysis)

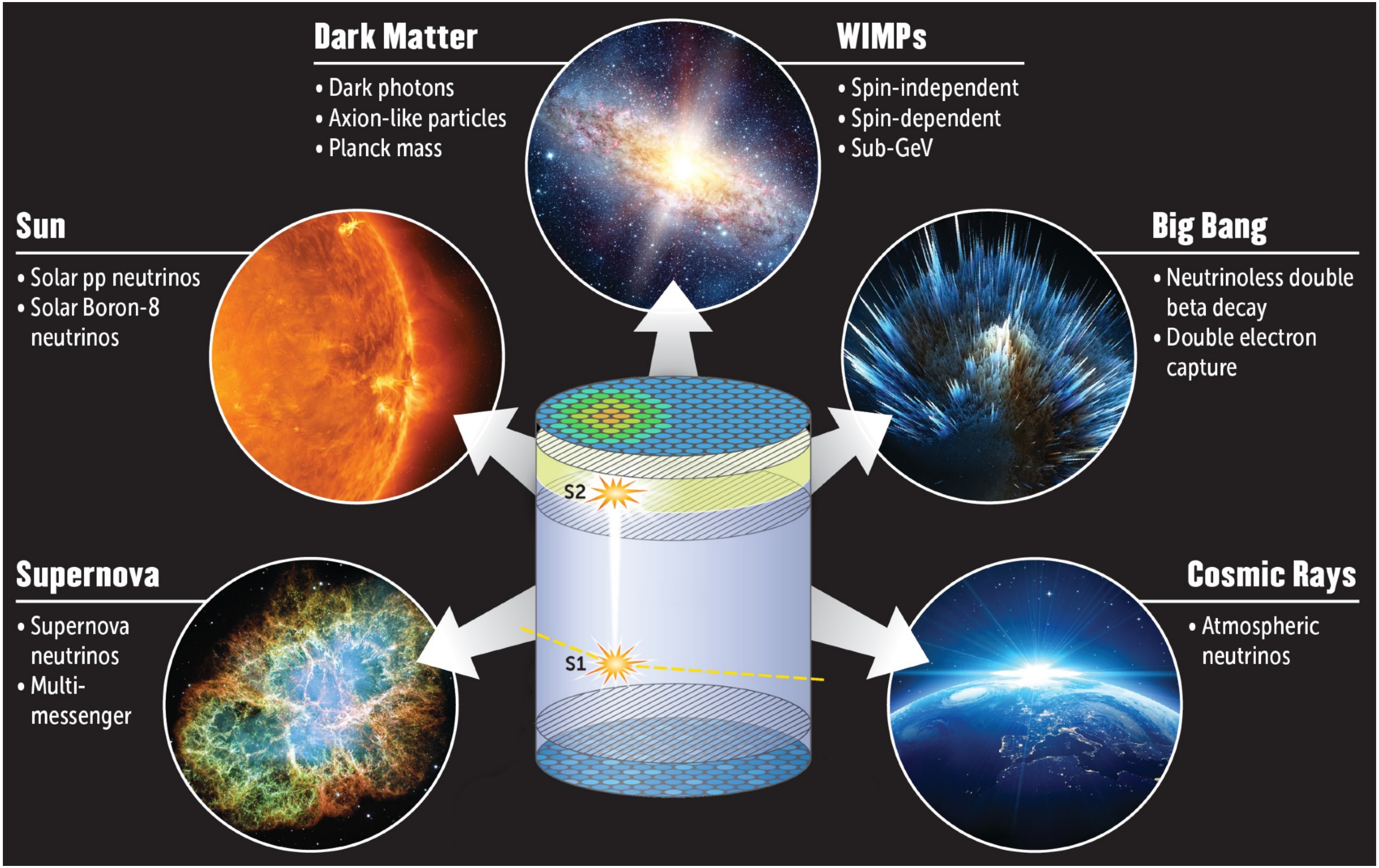
Source	1.3 t	1.3 t, NR Ref.	0.9 t, NR Ref.
ER	627 ± 18	1.6 ± 0.3	1.1 ± 0.2
Radiogenic	1.4 ± 0.7	0.8 ± 0.4	0.4 ± 0.2
CEνNS	0.05 ± 0.01	0.03 ± 0.01	0.02
Accidental	$0.5^{+0.3}_{-0.0}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$
Surface	106 ± 8	4.8 ± 0.4	0.02
Total	735 ± 20	7.4 ± 0.6	1.6 ± 0.3
200 GeV WIMP	3.6	1.7	1.2
Data	**739**	**14**	**2**

No significant excess due to WIMPs

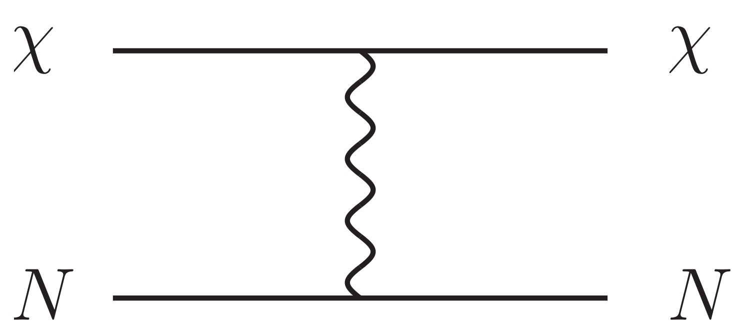
lots of constraints…



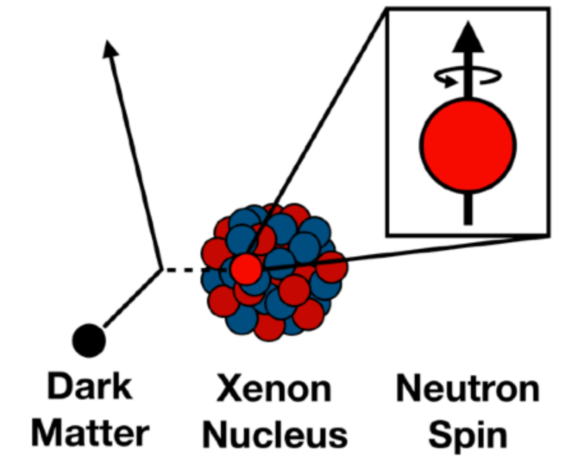
Physics Reach



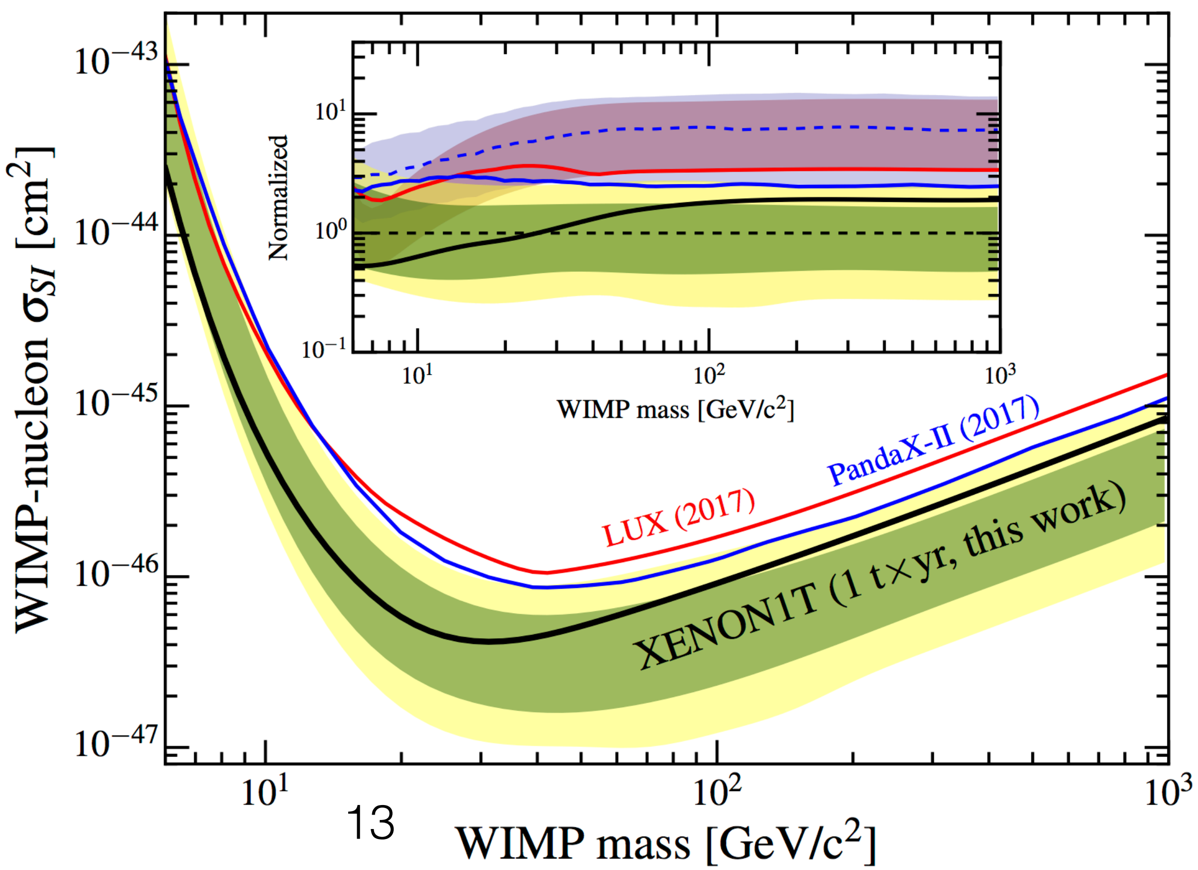
WIMP Constraints

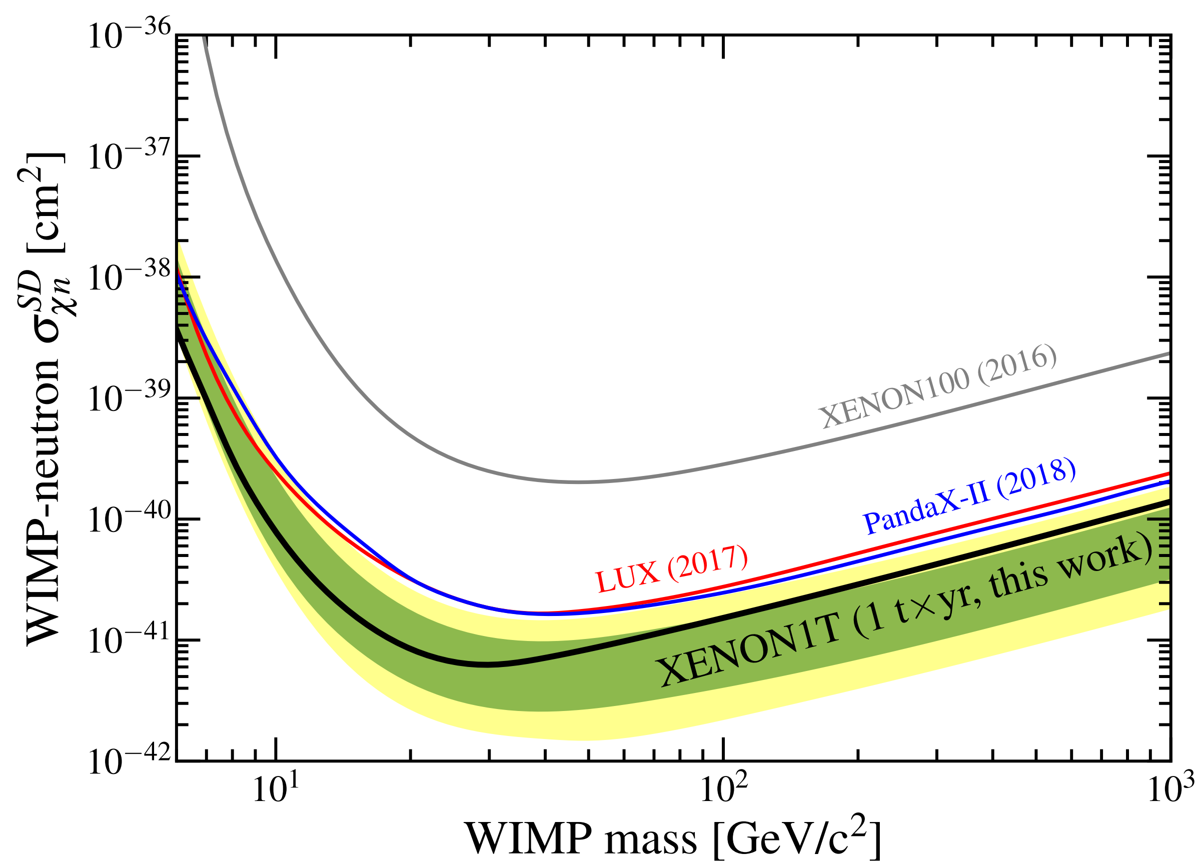


Phys. Rev. Lett. 121, 111302 (2018)



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





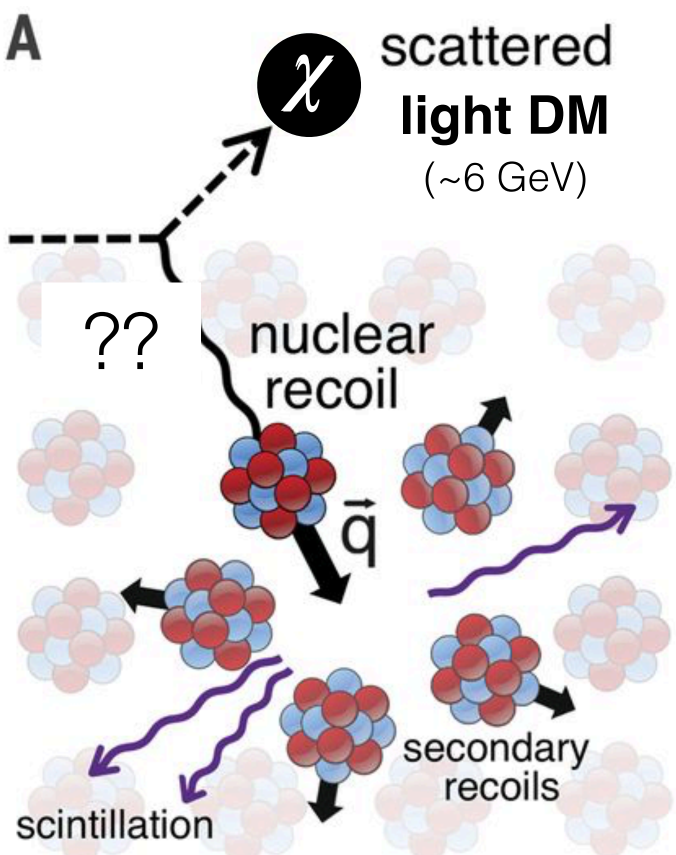
$\sigma < 4.1 \times 10^{-47}$ cm^2 at 30 GeV/c^2

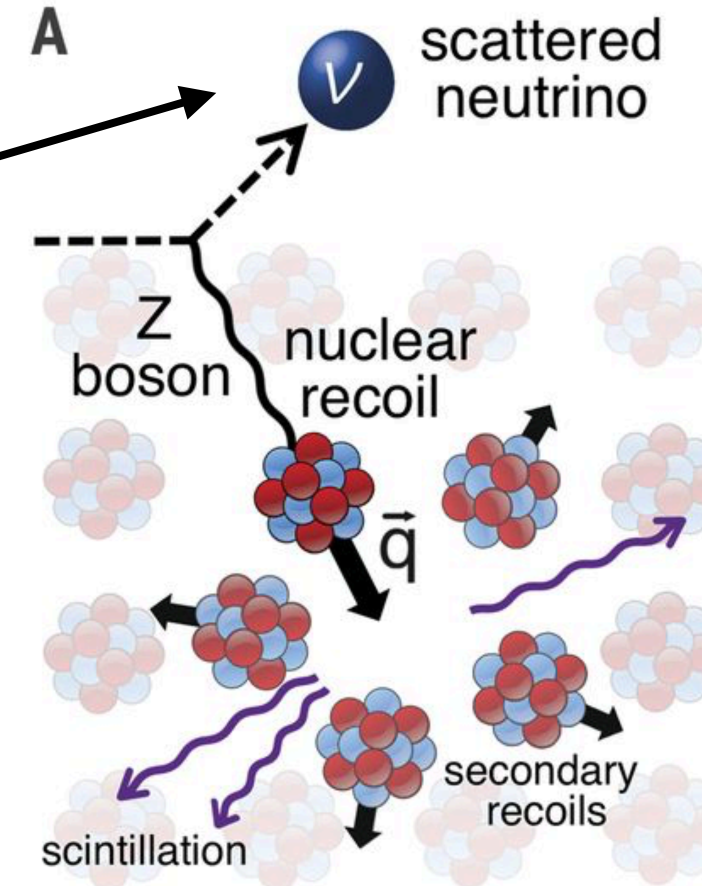
$\sigma < 46.3 \times 10^{-42}$ cm^2 at 30 GeV/c^2

CEvNS looks like WIMPs!

At low momentum-transfer the mediator wavelength is longer than the nuclear radius, neutrinos see the nucleus and not its constituents

- Coherent → sees nucleus as pointlike
- Elastic → no nuclear excitations
- Largely below 3 keV NRs in xenon



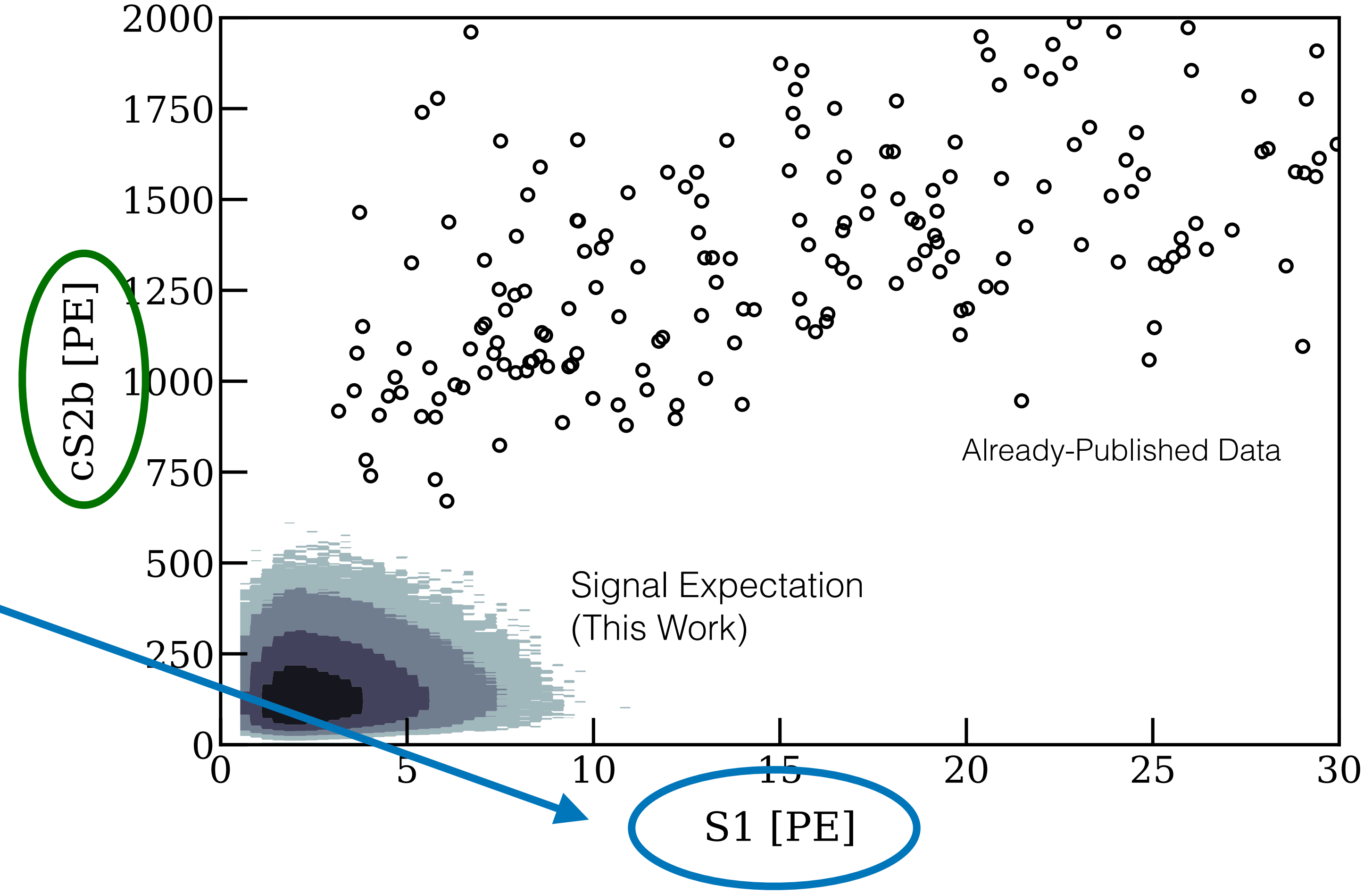


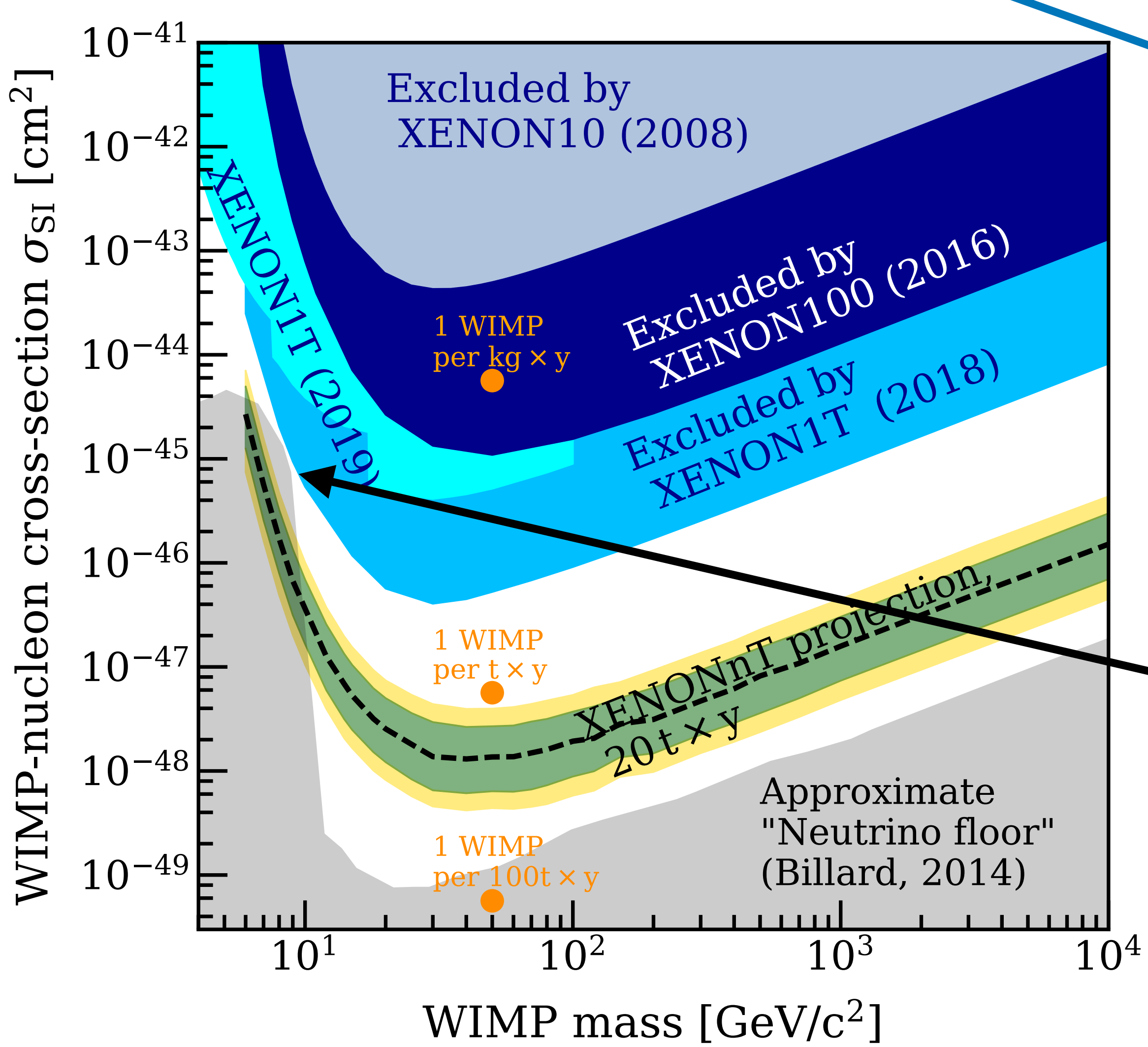
COHERENT Collab., Science **357**, 1123 (2017)

^{8}B solar neutrinos produce an *indistinguishable background* for low-mass WIMP searches!

Why so few?

^{8}B CEvNS falls far below our previous science analysis threshold in both scintillation and ionization





This background becomes more important as we push further down in parameter space

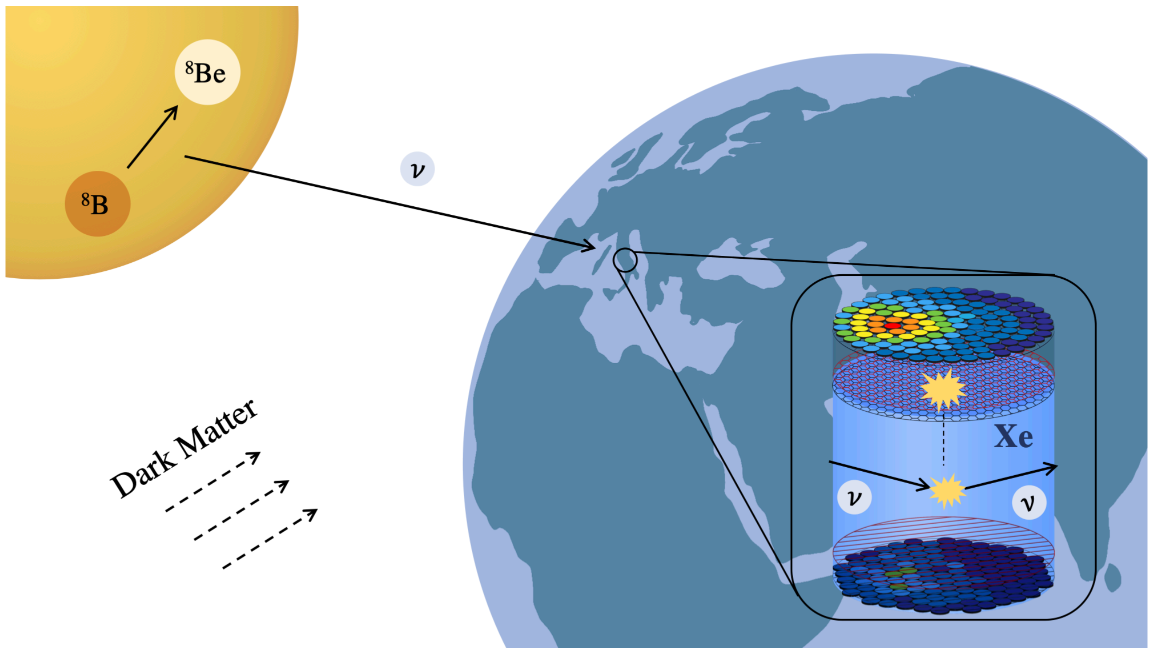
Can we look for it?

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

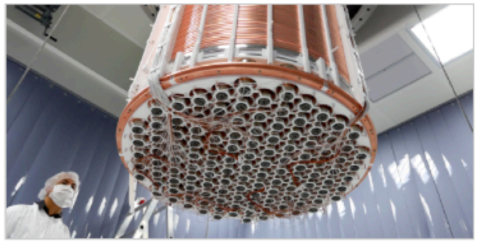
Source	1.3 t	1.3 t, NR Ref.
ER	627 ± 18	1.6 ± 0.3
Radiogenic	1.4 ± 0.7	0.8 ± 0.4
CEvNS	**0.05 ± 0.01**	0.03 ± 0.01
Accidental	$0.5^{+0.3}_{-0.0}$	$0.10^{+0.06}_{-0.00}$
Surface	106 ± 8	4.8 ± 0.4
Total	735 ± 20	7.4 ± 0.6
200 GeV	3.6	1.7
Data	**739**	**14**

~ 0.01% acceptance!

Phys. Rev. Lett. 126, 091301 (2021) — Editor's Suggestion



Featured in *Physics Magazine*



RESEARCH NEWS

Neutrinos Rising from the Floor

June 29, 2021

A neutrino background that could confound dark matter searches is now becoming an opportunity for probing new physics. **Read More »**

Rate

number of recoils

Xenon Response

number of observables

Detection Efficiency

energy threshold

CEvNS

Rate

number of recoils

- ^{8}B neutrino flux
- Cross-section (SM)

Xenon Response

number of observables
(conservative model used)

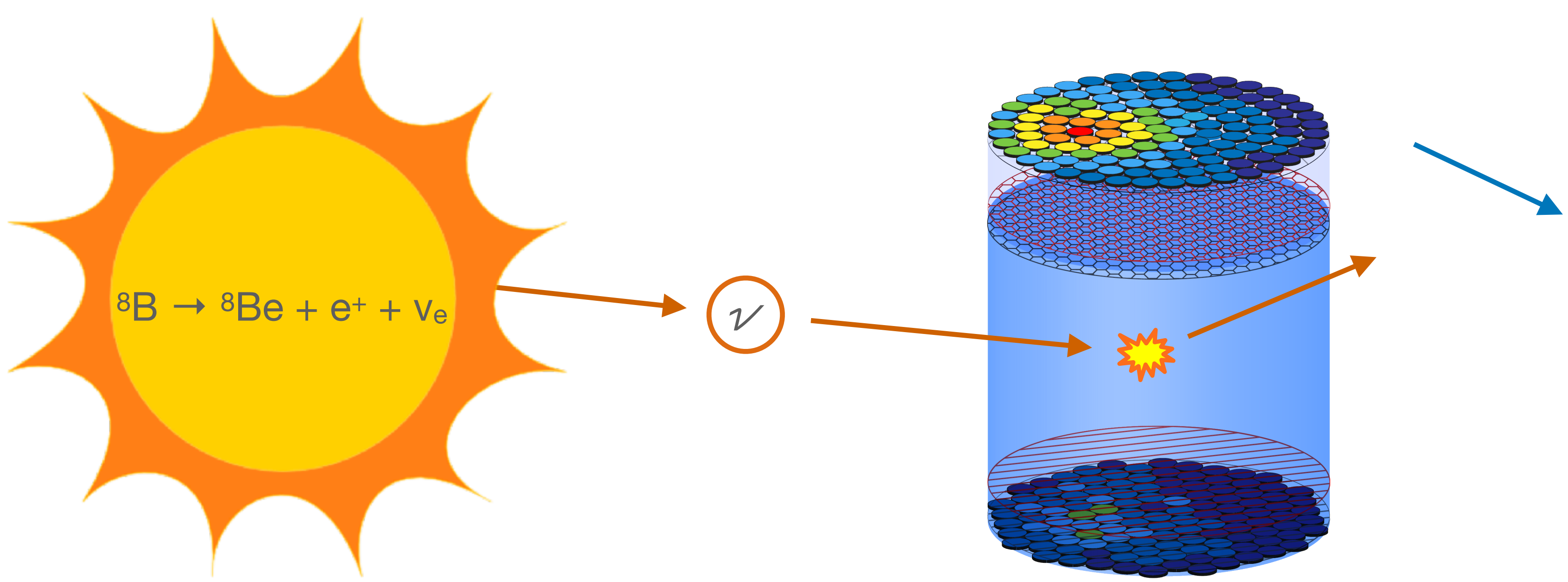
- Charge Yield
- Light Yield

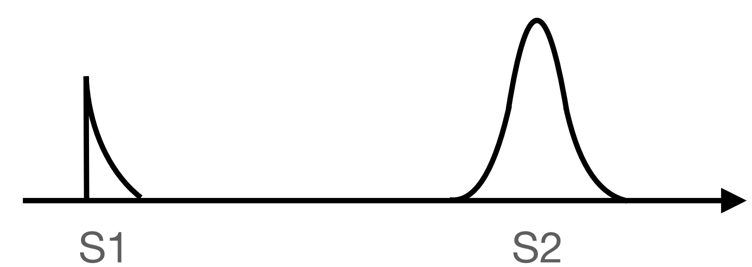
Detection Efficiency

energy threshold
(set high to cut background)

- PMT Coincidence
- Software Event Trigger

Solar ^{8}B Decay → Recoil in LXe → Quanta Production → Quanta Detection





How can we detect?

Rate

number of recoils

↑

Constrain w/ ^{8}B flux measurements (5% uncertainty) and SM cross-section

Xenon Response

number of observables (conservative model used)

↑

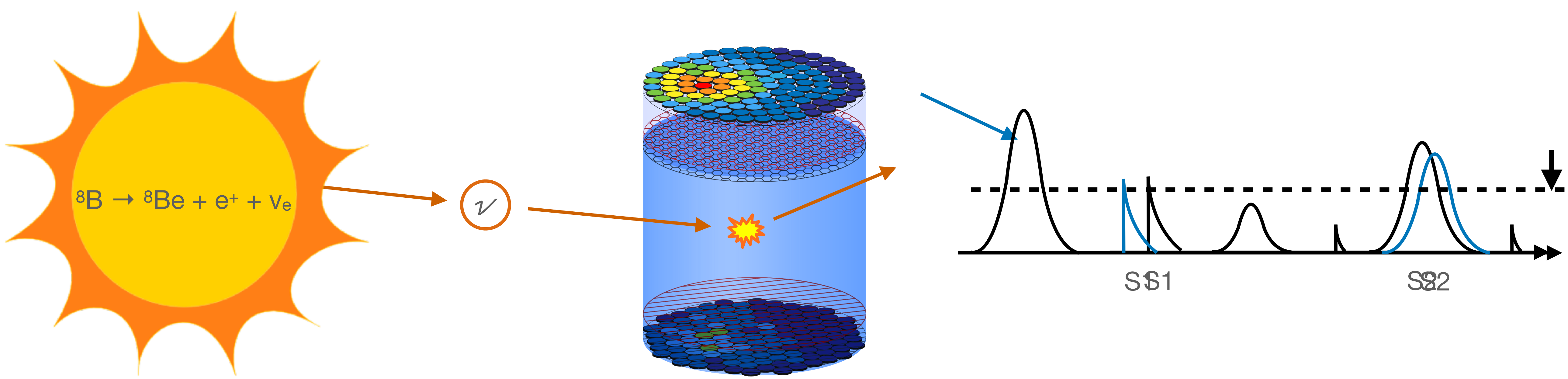
Model w/ data from other LXe experiments (20% uncertainty)

Detection Efficiency

energy threshold (set high to cut background)

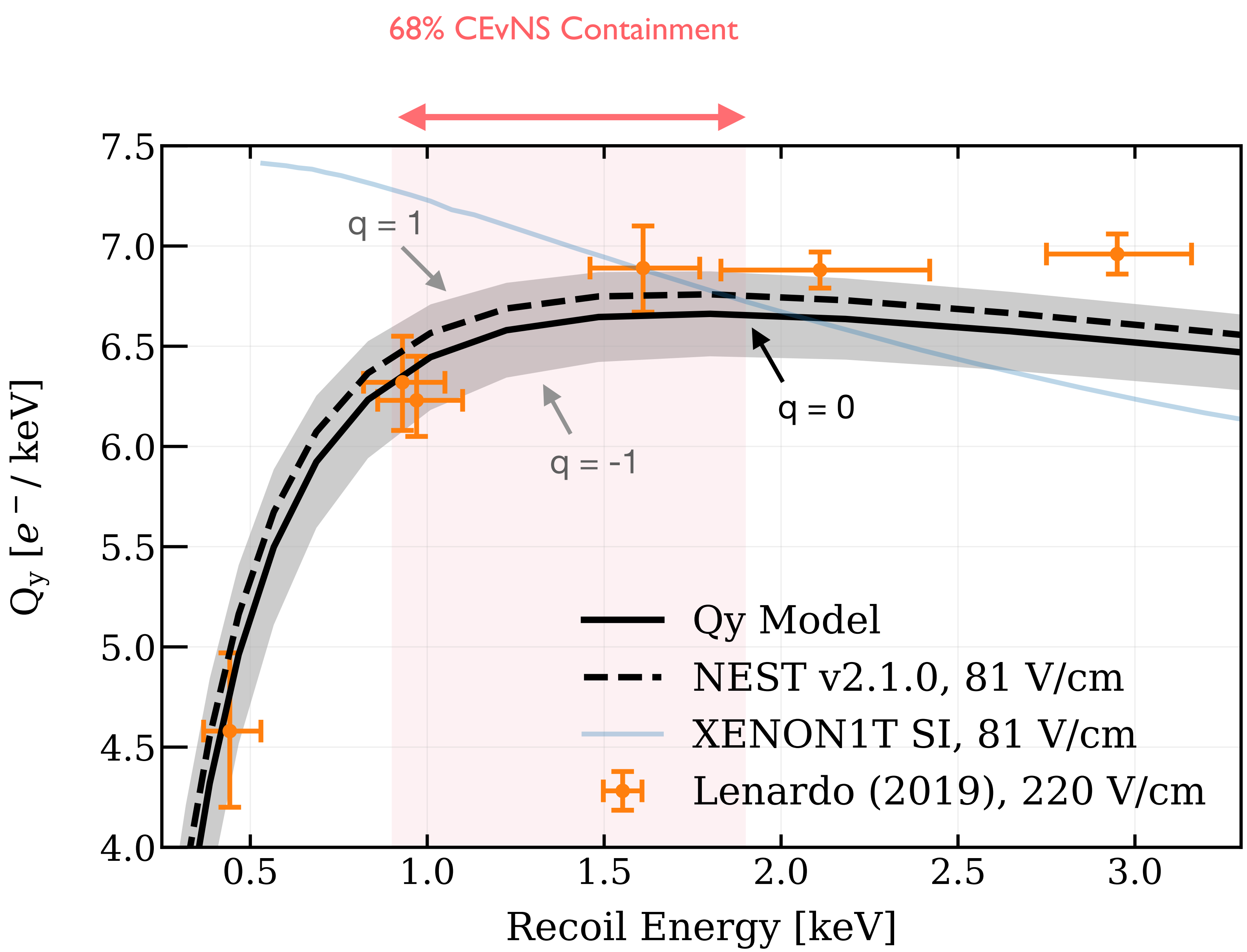
↑

Improve by lowering the energy threshold



Charge Yield

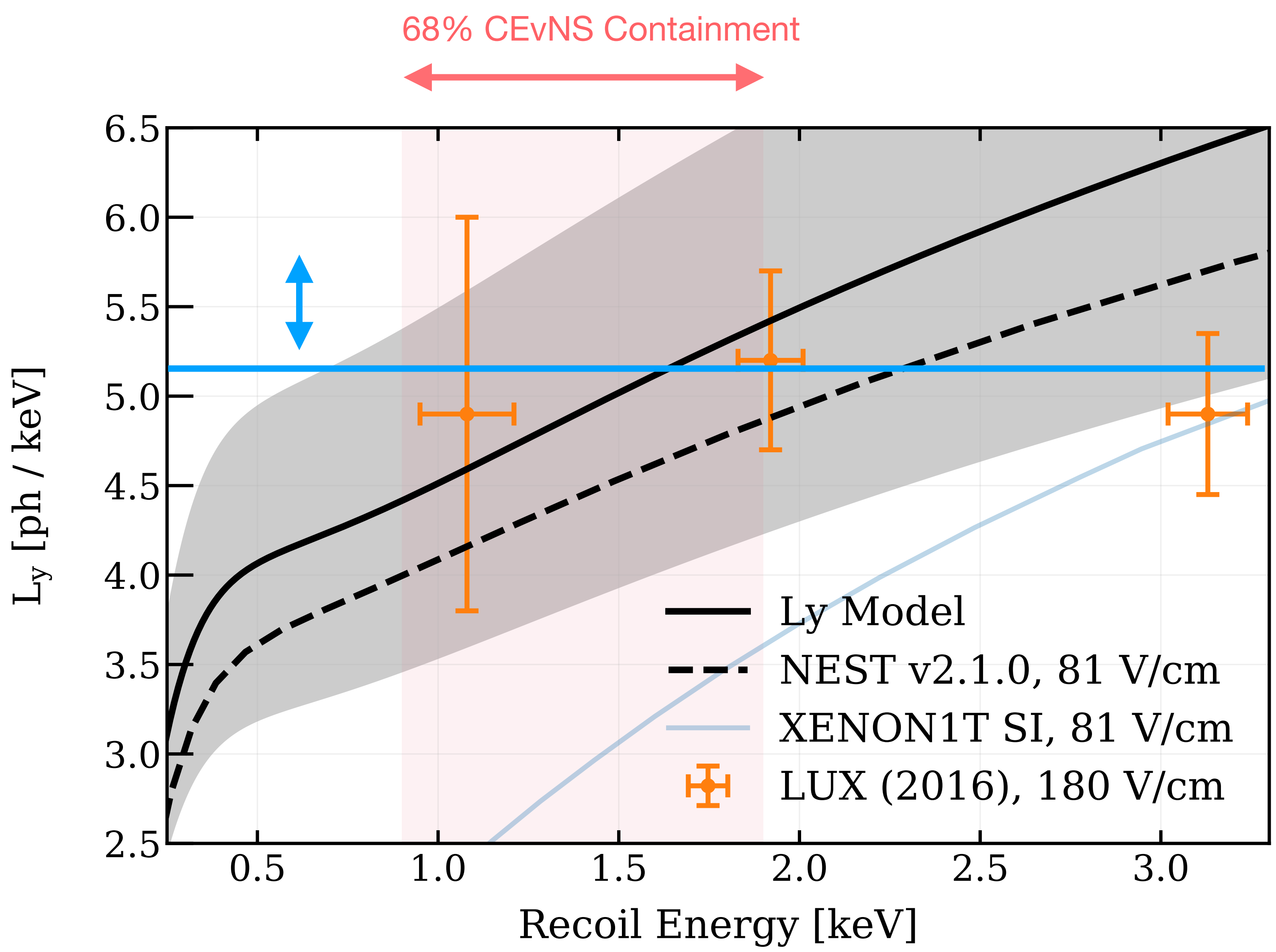
- Need a model that matches measurements at CEvNS energies
- **Existing model** (NEST) additionally constrained through correlations with higher-energy data
- “Interpolation parameter” **q** is introduced to scale the curve within the NEST Qy uncertainty
- Fit to the data within 68% CEvNS containment, rescaled to units of sigma



NR Response

Light Yield

- Need a model that matches measurements at CEvNS energies
- Far more uncertain than Qy
- **Existing model** (NEST) less reliable



Two Models Used:

1. Scale NEST curve by a free parameter: **CEvNS search, new physics searches**
2. Single-valued Ly: **Constraining Ly**

CEvNS

Solar 8B Decay → Recoil in LXe → Quanta Production → Quanta Detection

Rate

number of recoils

- 8B neutrino flux
- Cross-section (SM)

Xenon Response

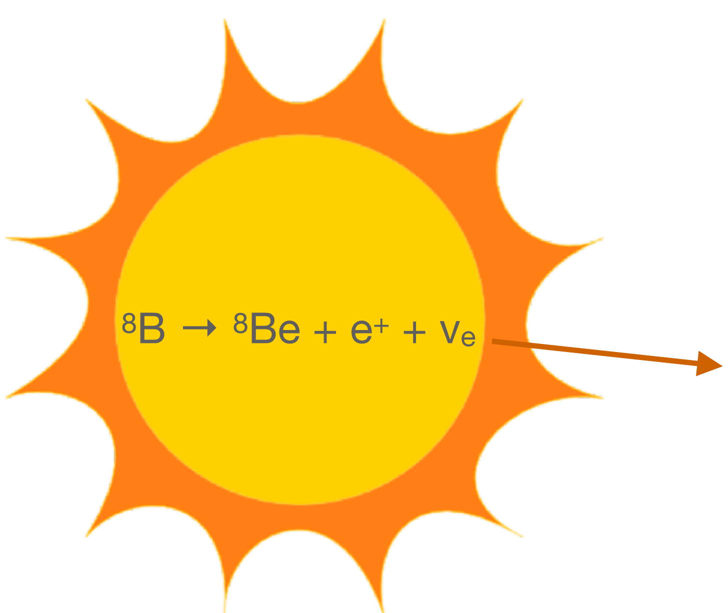
number of observables

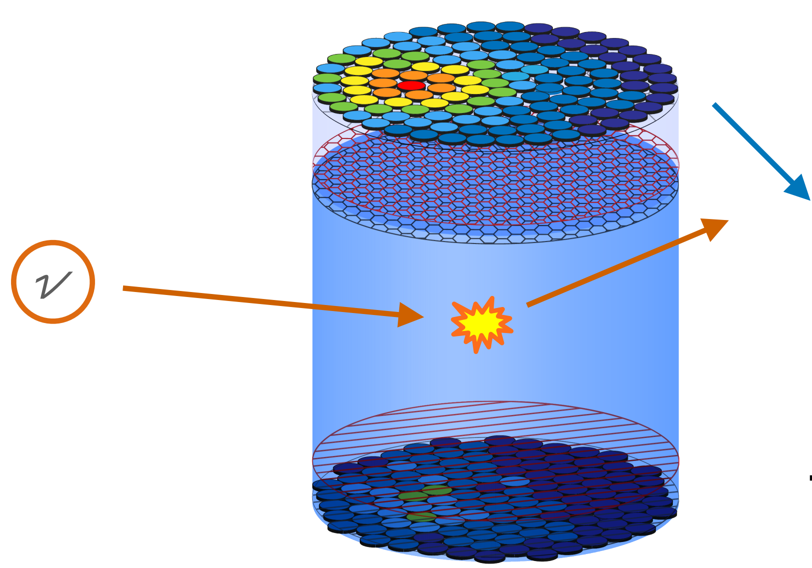
- Charge Yield
- Light Yield
- Response Cutoff

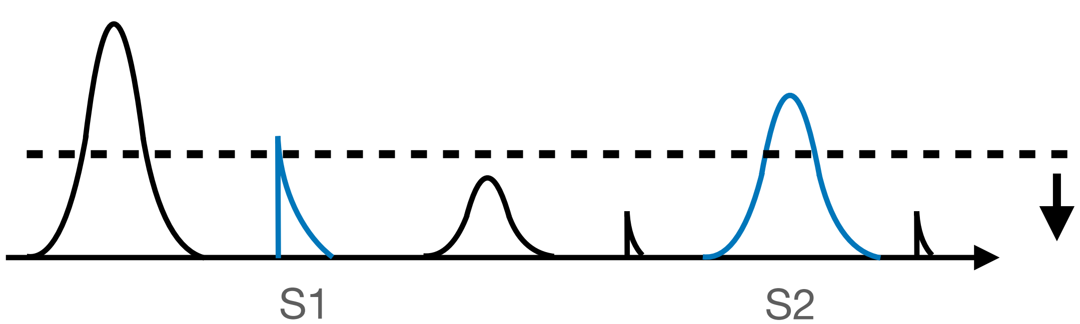
Detection Efficiency

energy threshold
(set high to cut background)

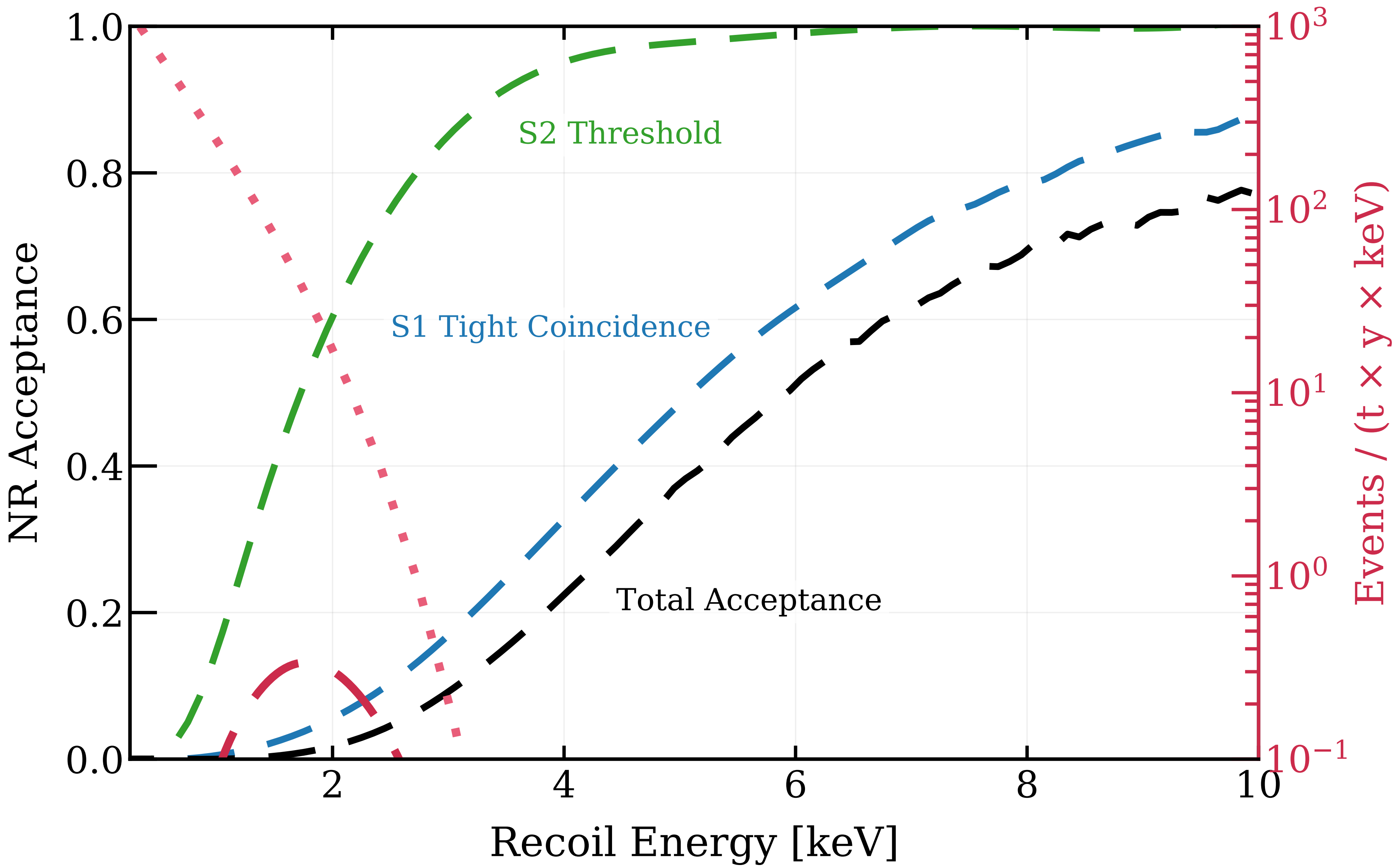
- PMT Coincidence Requirement
- Software Event Trigger







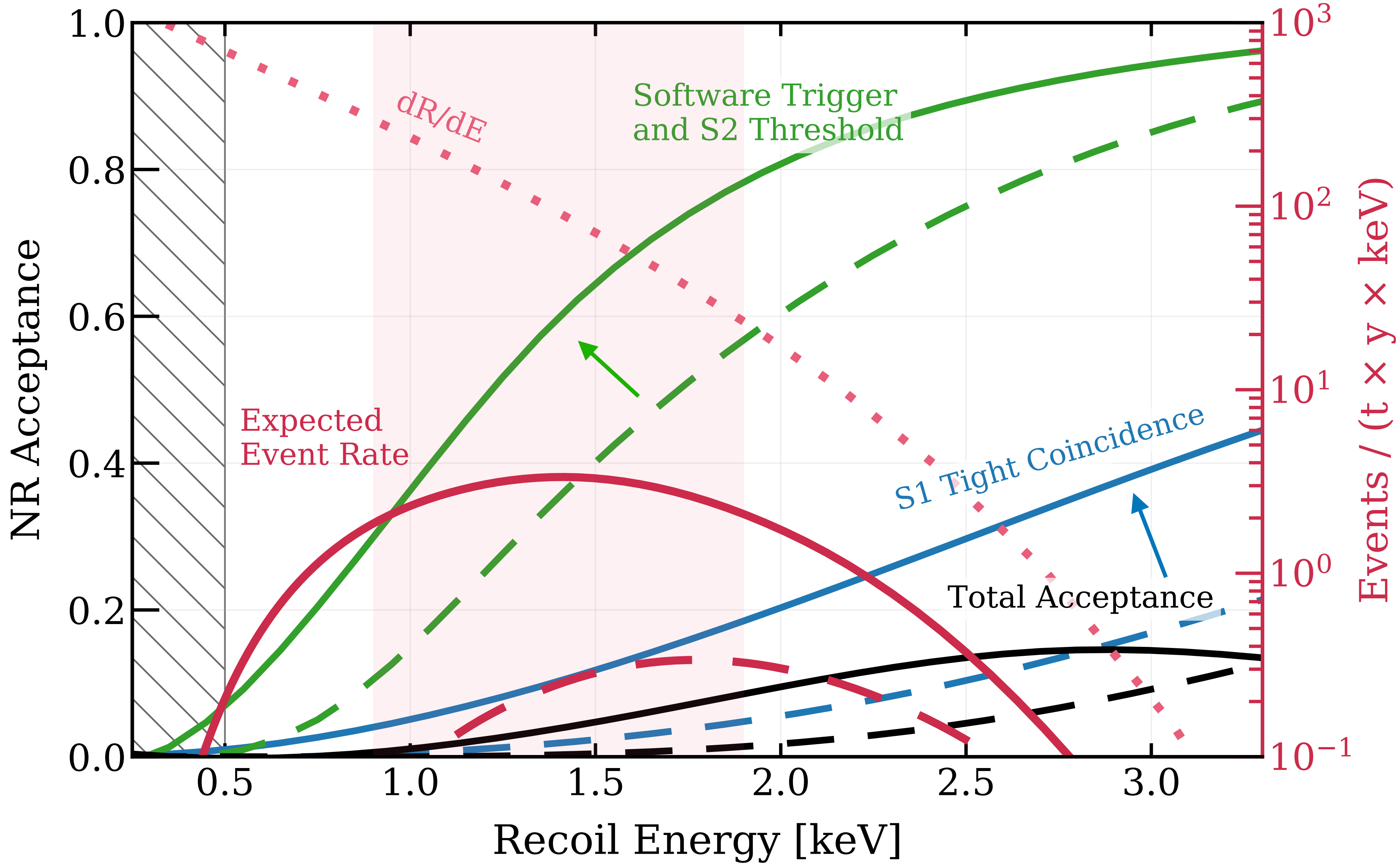
NR Acceptance



Two Effects Define Our Energy Threshold:

1. S1 “Tight Coincidence”: **Three PMTs** see light within 50ns
2. Software Event Trigger: Require **S2s > 200 PE** for 100% trigger efficiency

NR Acceptance



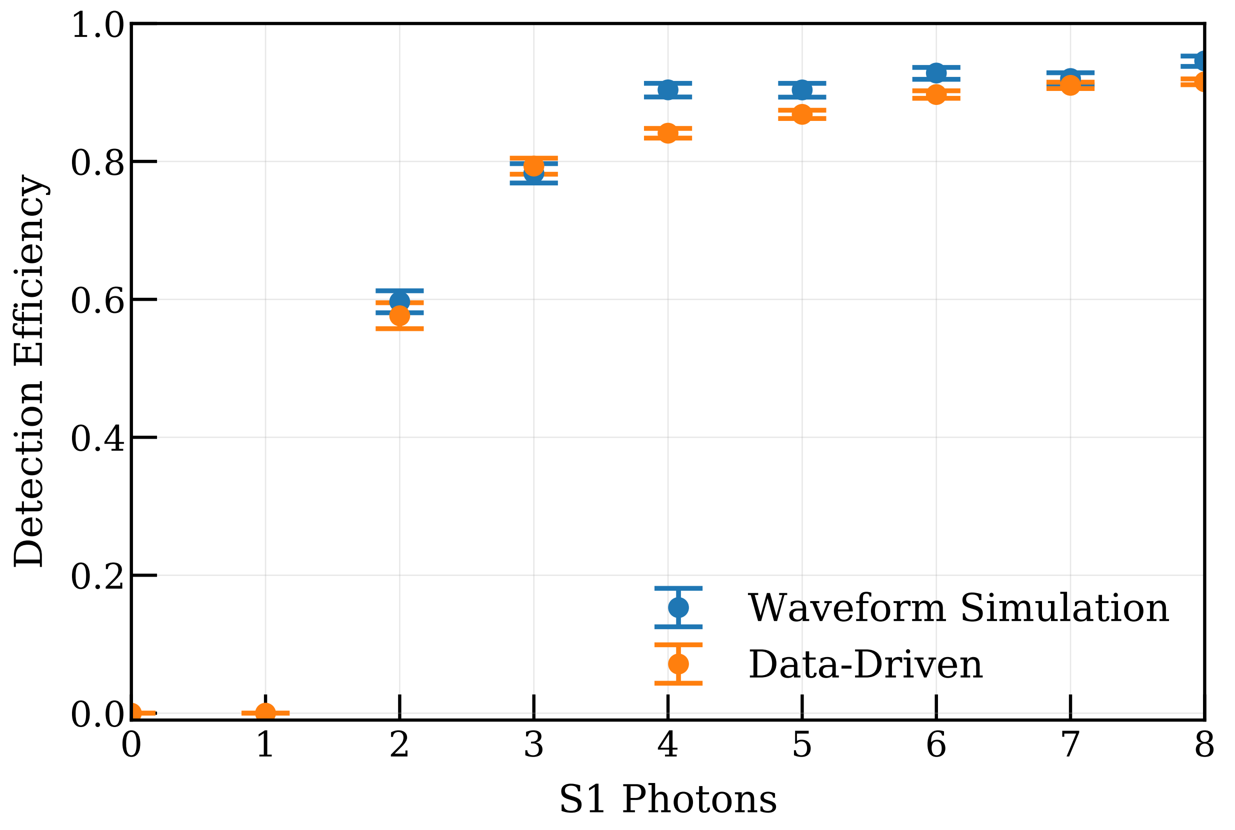
Two Effects Define Our Energy Threshold — We Modify Both:

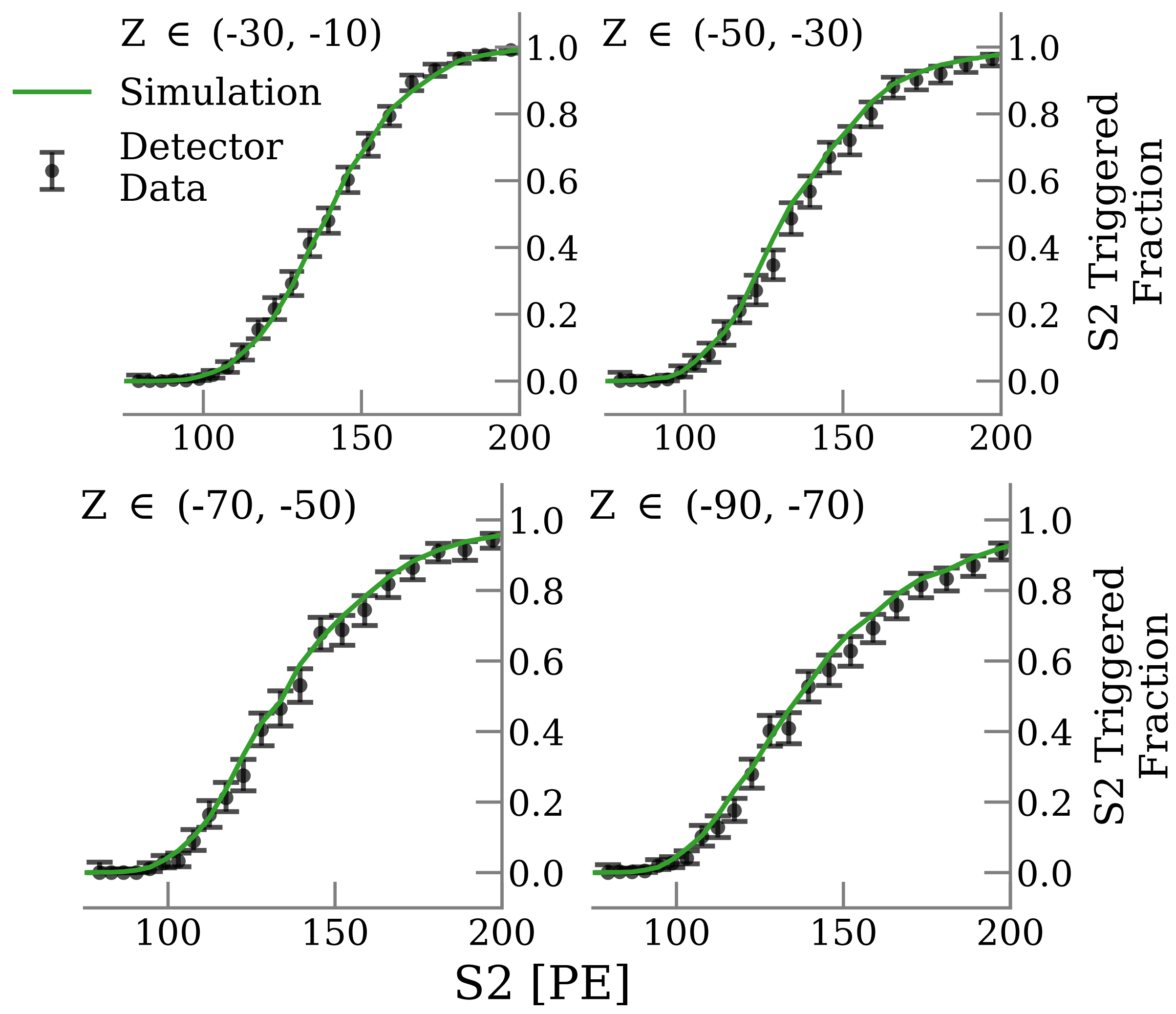
1. S1 "Tight Coincidence": ~~Three~~ **Two PMTs** see light within 50ns
2. Software Event Trigger: Require **S2s > ~~200~~ 120 PE**, **no longer ensuring** the event makes a trigger

NR Acceptance

S1 Detection Efficiency

- Small S1s are simulated with the waveform simulator
- Cross-checked with data-driven approach by bootstrapping from large S1s



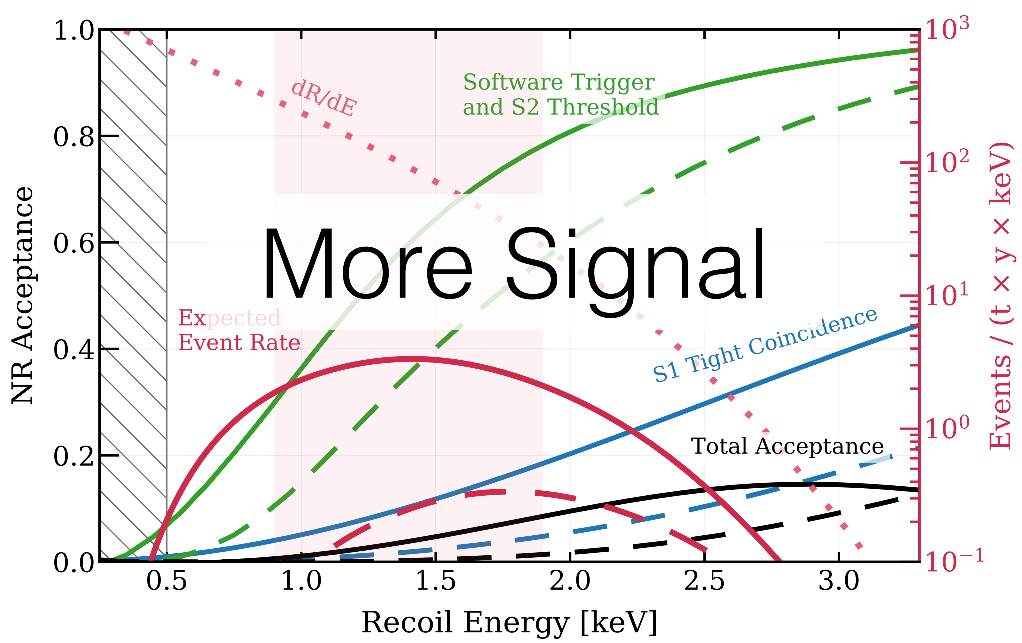


Trigger Efficiency

- Small S2s are simulated with the waveform simulator and passed through the event builder
- Validated against S2s extracted from events where S1 created the trigger
- Position dependence included

Backgrounds

Lowered Threshold



More Signal

More Background!

Backgrounds

Four Backgrounds Modeled in XENON1T:

1. Accidental Coincidence (AC)
2. Electronic Recoils (^{214}Pb beta decay)
3. Radiogenic Neutrons
4. ~~**"Surface" Events**~~ → Reduced to < 0.04 events by R < 37cm cut

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

Backgrounds

Four Backgrounds Modeled in XENON1T:

1. Accidental Coincidence (AC)
2. Electronic Recoils (^{214}Pb beta decay)
3. **Radiogenic Neutrons**
4. ~~“Surface” Events~~

Very low but correlated with CEvNS through systematics (yields) so we model to be safe

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

Backgrounds

Four Backgrounds Modeled in XENON1T:

1. Accidental Coincidence (AC)
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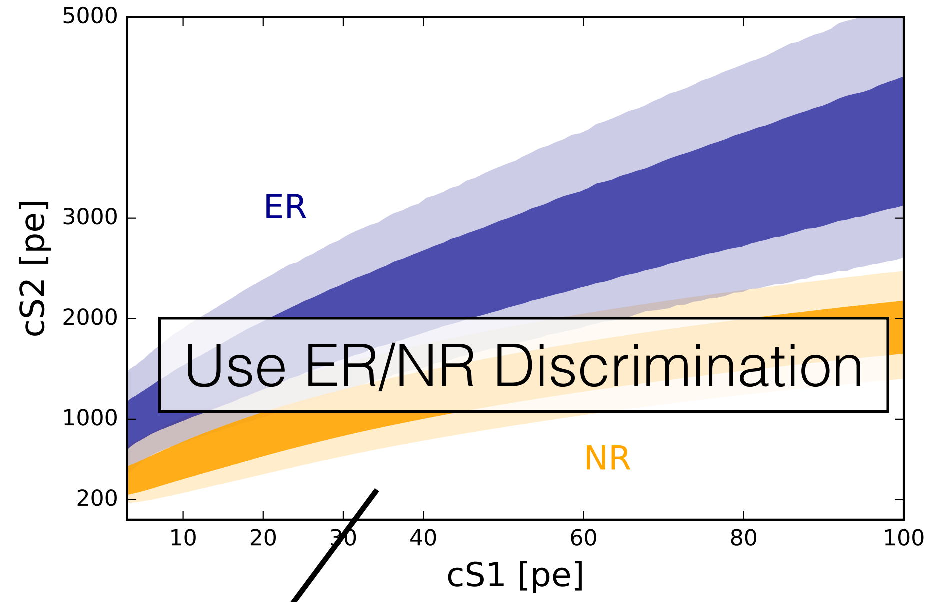

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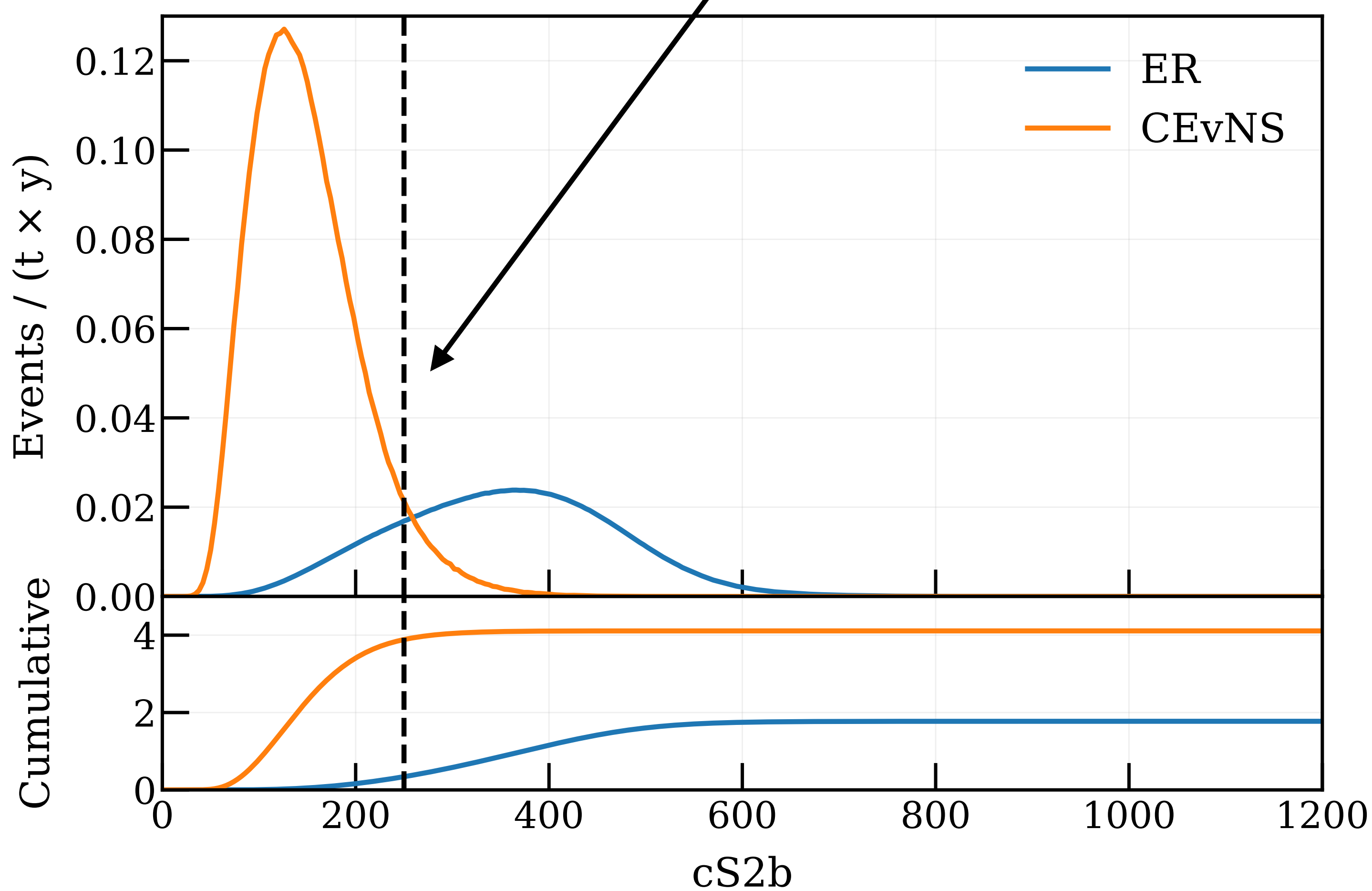


Backgrounds: AC

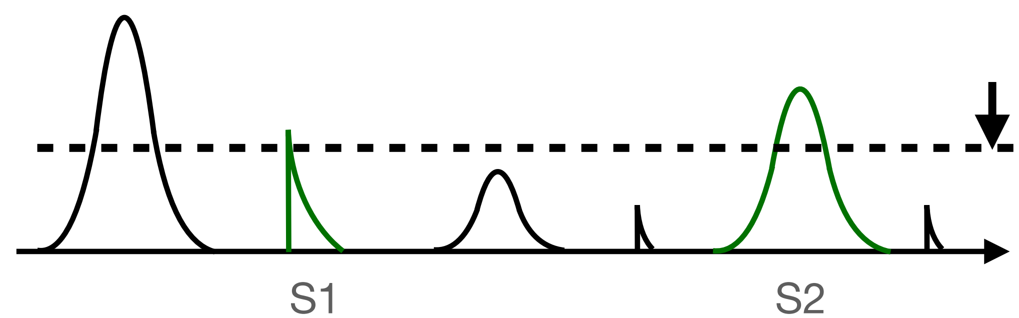
Isolated S1s due to e.g. spurious firing of 2+ PMTs…

… get paired with isolated S2s

1. Accidental Coincidence (AC)

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

Reduced tight-coincidence requirement and **S2 threshold** lead to ~100x increase!

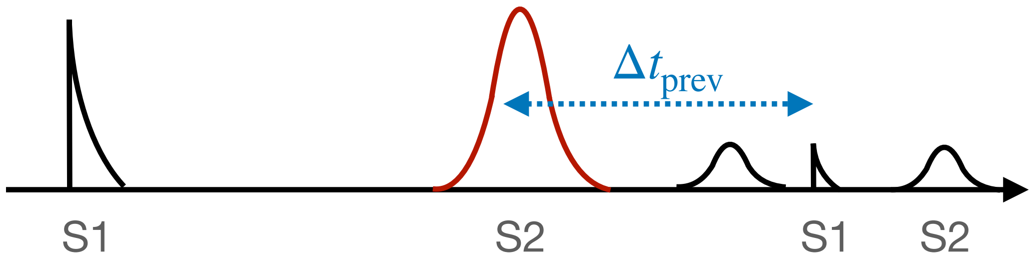


many new cuts required to suppress to this level…

AC Suppression: I

High energy events lead to subsequent AC events

- S1: More spurious PMT hits (unclear why)
- S2: More single electrons

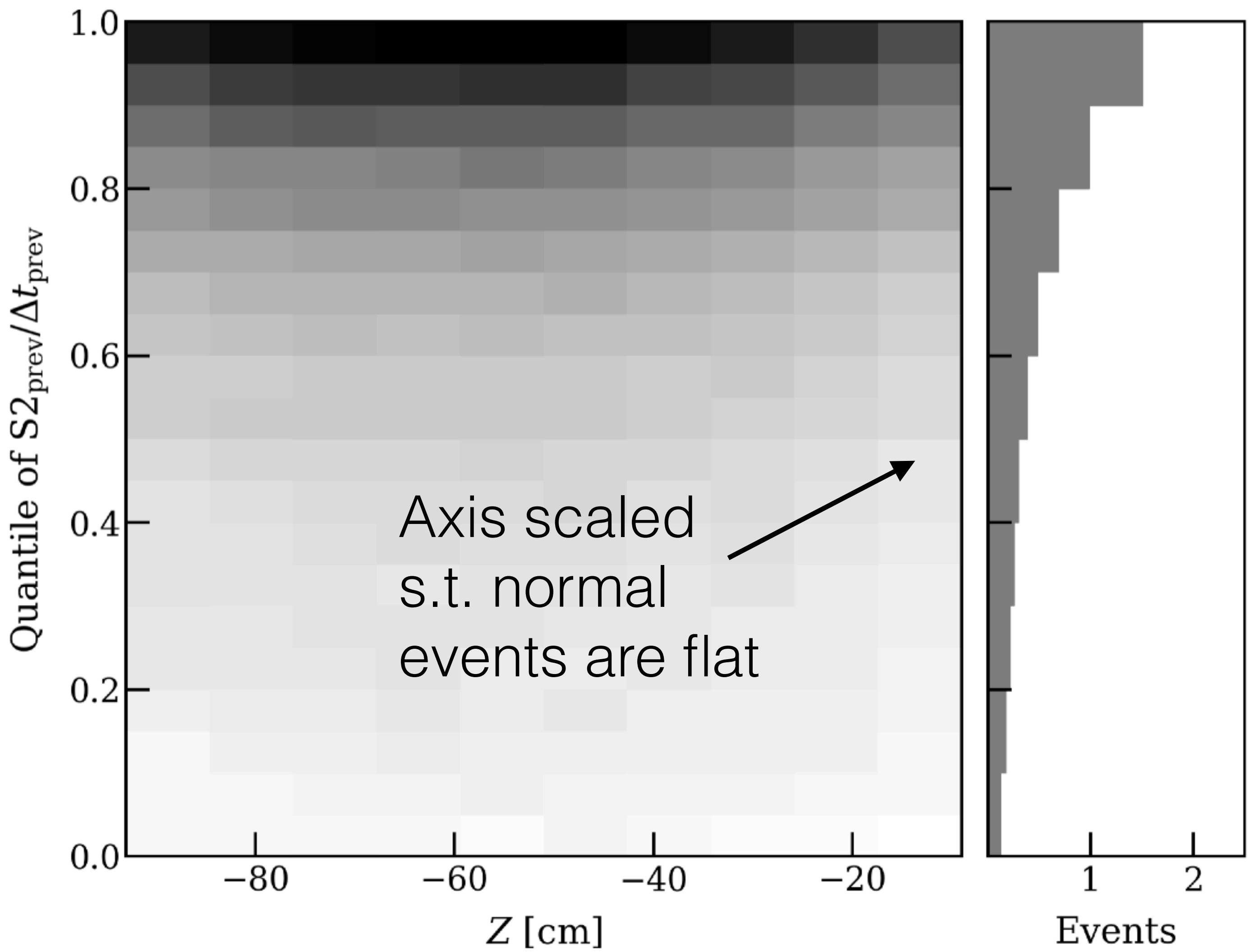


Reduced by cut on X&Y of preceding event

The **larger** the previous event and…

…the **sooner** the suspect event follows it, the more likely it is AC:

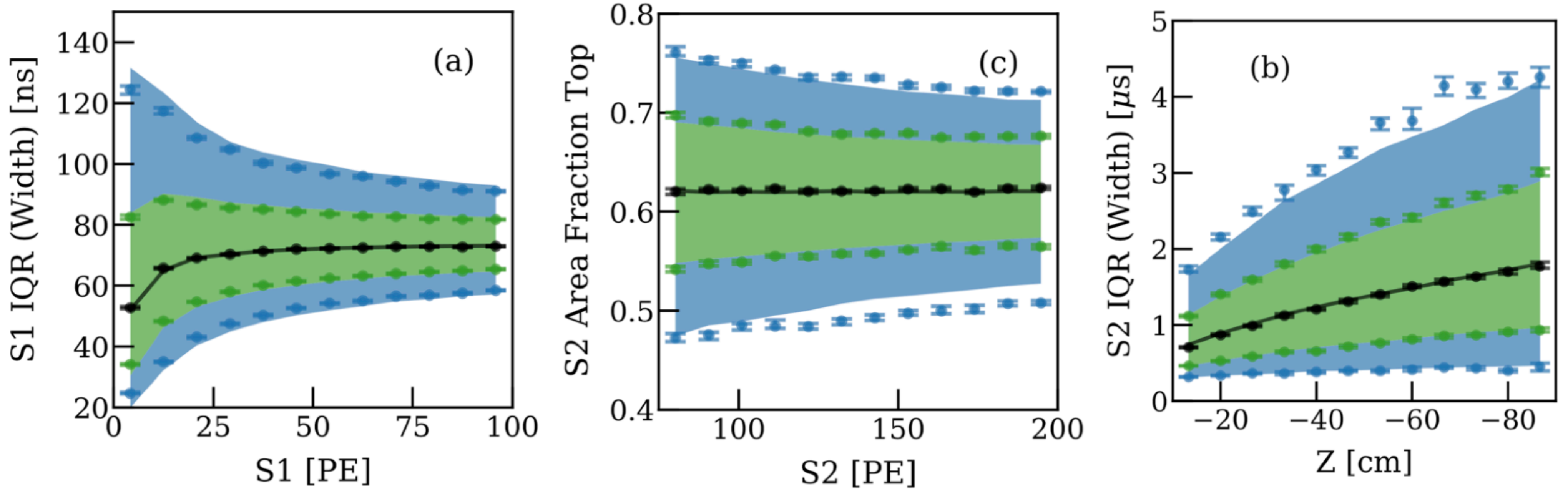
Define FoM: $S2_{prev} \,/\, \Delta t_{prev}$



- S1: 65% rejection → 11.2 Hz
- S2: 0.7 mHz (1/3 of SI result)
- Removes S1-S2 correlations

Signal acceptance: 82%

AC Suppression: II



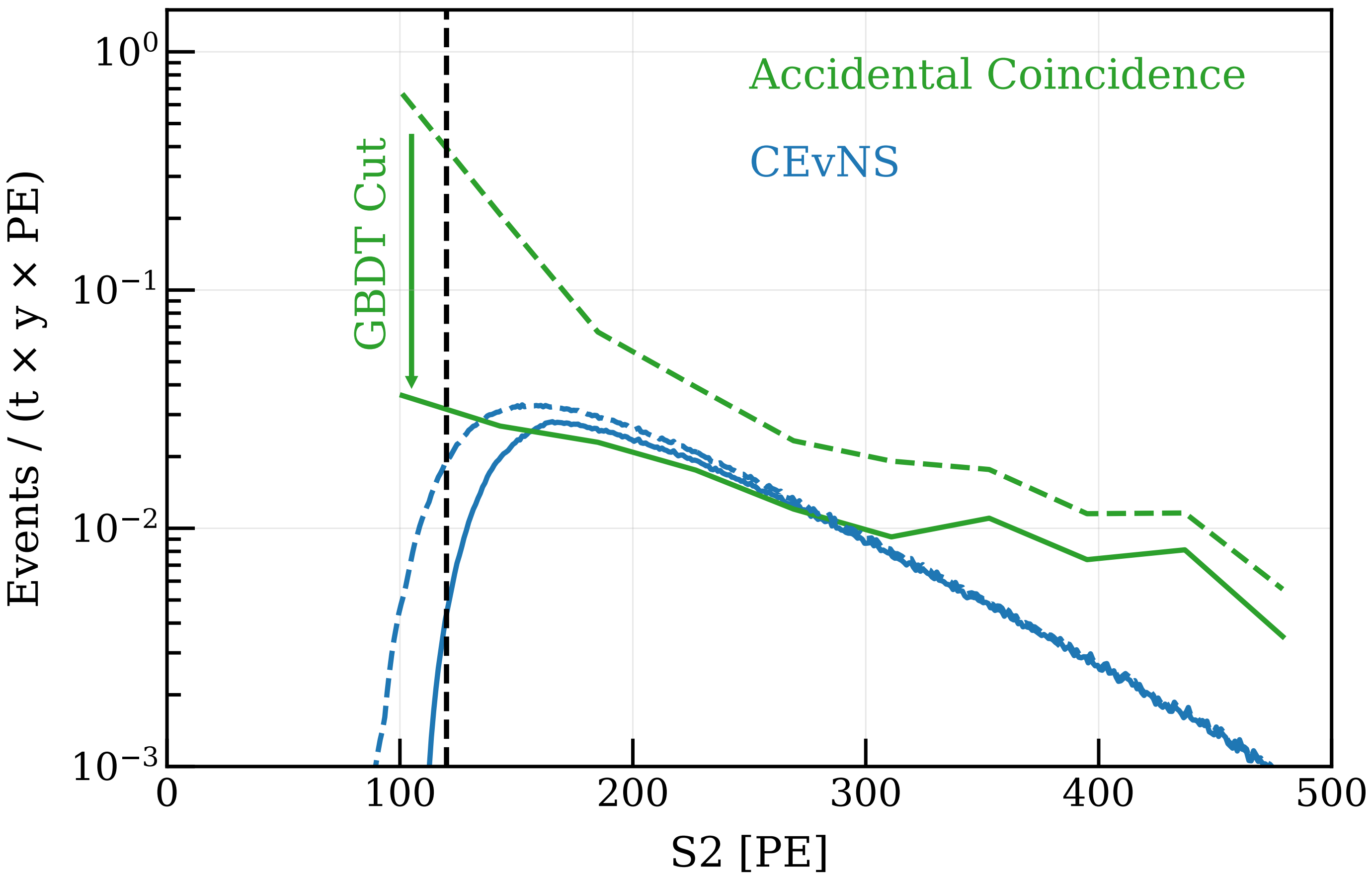
Use:

1. S2 Size
2. S2 Width
3. S2 Top/Total
4. Depth

Gradient **B**oosted **D**ecision **T**ree (ensemble classifier)

Training Data:

- Waveform simulation for signal
- Randomly-combined isolated S1s and S2s for AC



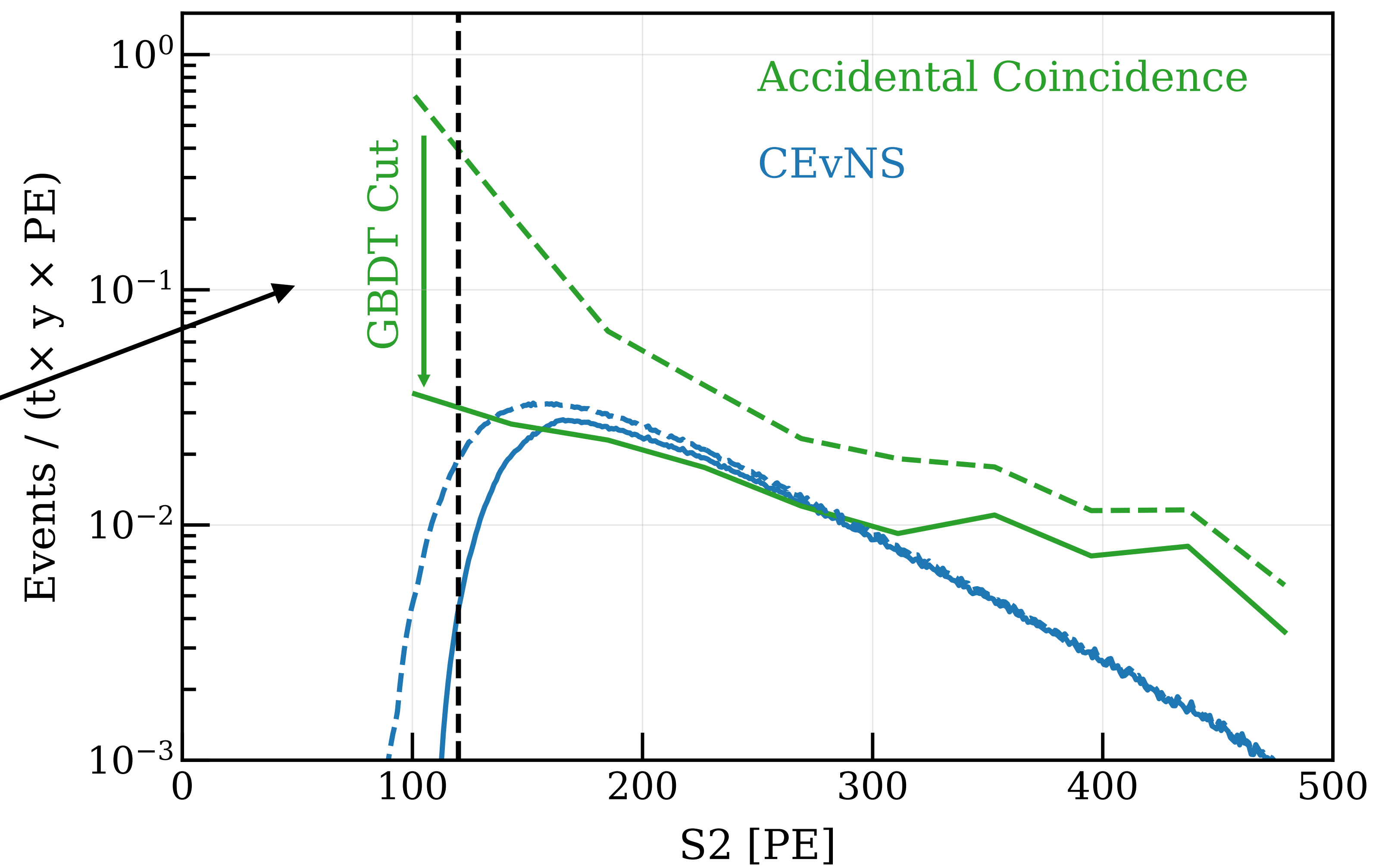
Sidebands

Control Region: Approx. zero CEvNS events have S2 < 120 PE

Use to check AC prediction

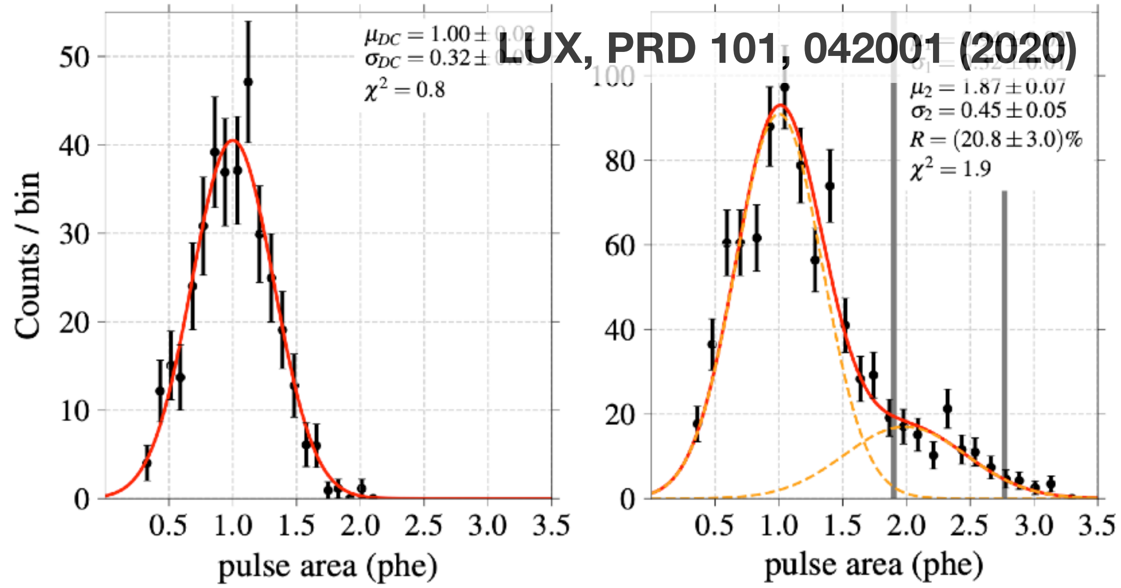
AC Validation Region: Vast majority of events failing GBDT cut are AC

Use to check AC model



AC Suppression: III

Isolated S1s composed of dark counts **rarely contain > 2 PE hits** (1/100)



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

Two "**L**argest **H**it **A**rea" Bins: LHA < 2 PE; LHA ≥ 2 PE

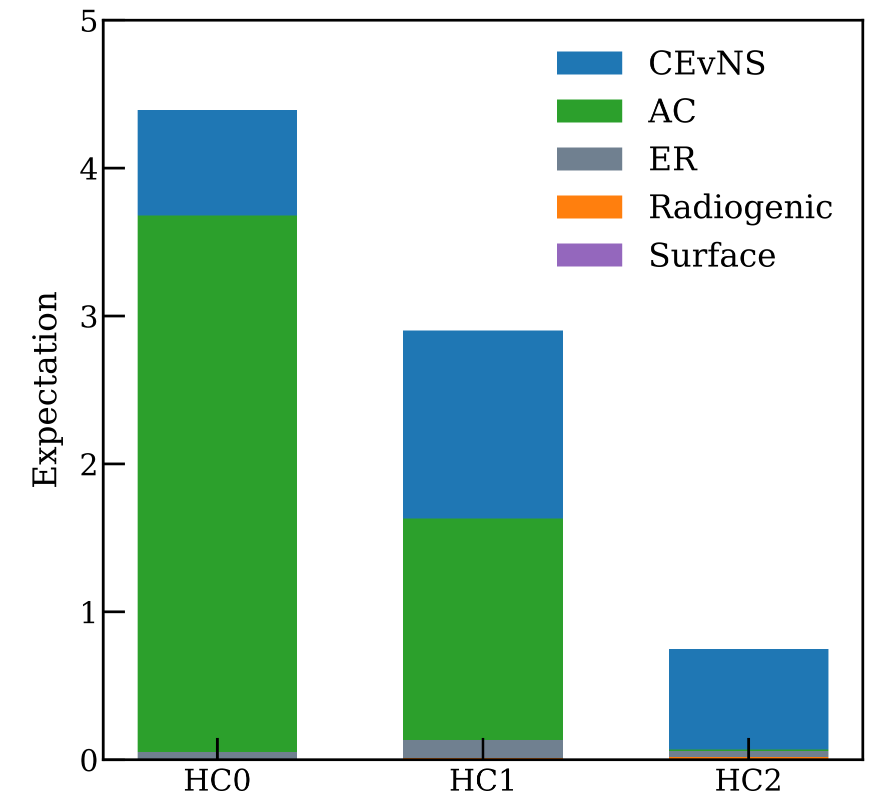
Isolated S1s are roughly **evenly distributed across PMTs**, and **rarely contain three PMTs**; Signal S1s are **larger** and prefer **bottom PMTs**

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

HC0: 2 Hits, 1+ in the top array 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



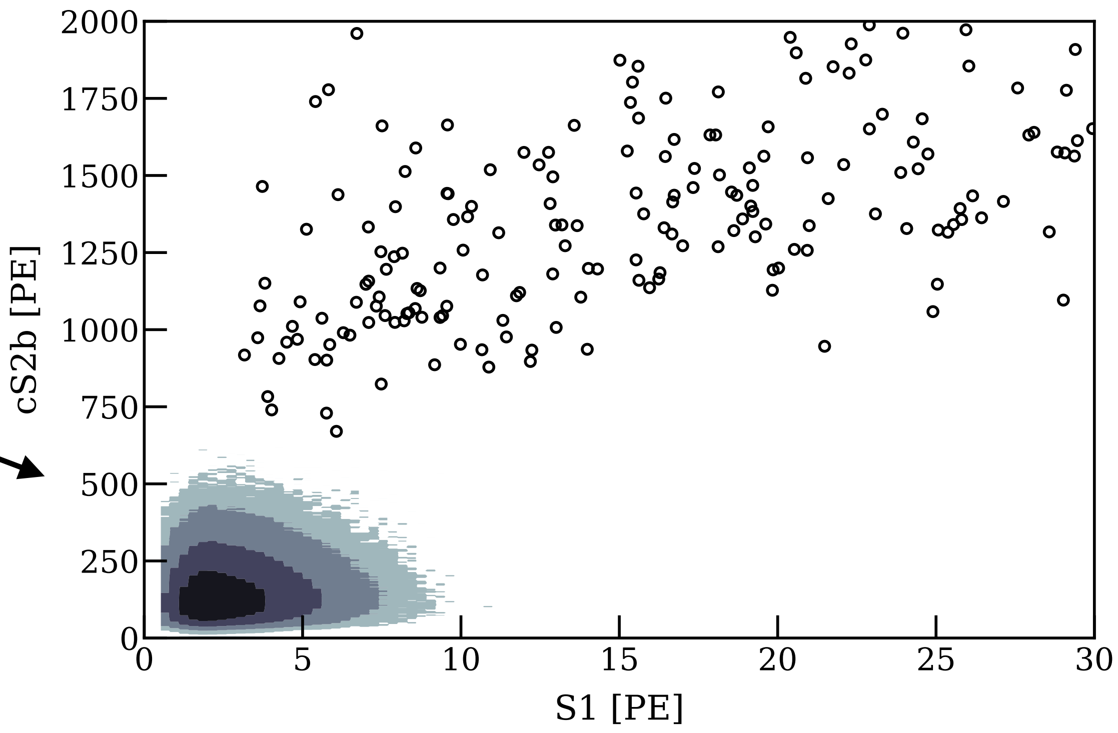
Unblinding Procedure

1. Investigate **Control Region** (80 PE < S2 < 120 PE)
   - Revise Selections
2. Unblind **AC Validation Region** (Invert GBDT Cut)
   - Test GoF
3. Unblind ROI

5% of CEvNS expectation overlaps with previous data

↓

“blind” analysis



Control Region Investigation

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

Expected: 27.7 ± 1.4

Observed: 27

Four of these had two hits on a single PMT → likely PMT afterpulses

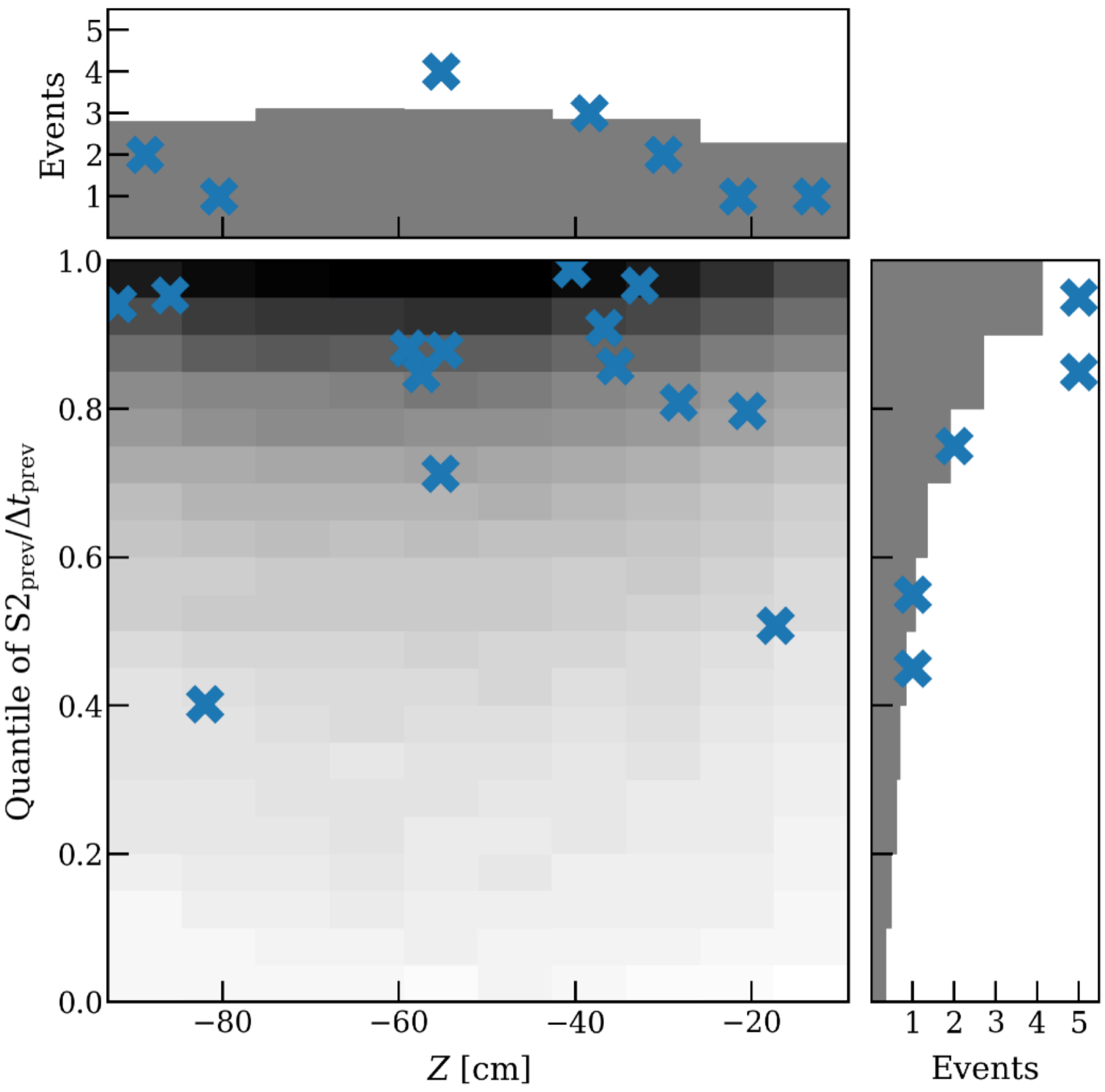
↳ New cut (> 99% acceptance)

Expected: 27.7 ± 1.4

Observed: 23

→ Good agreement!

Based on relative disagreement, conservative 20% AC rate uncertainty is used in the inference



GoF Scores:

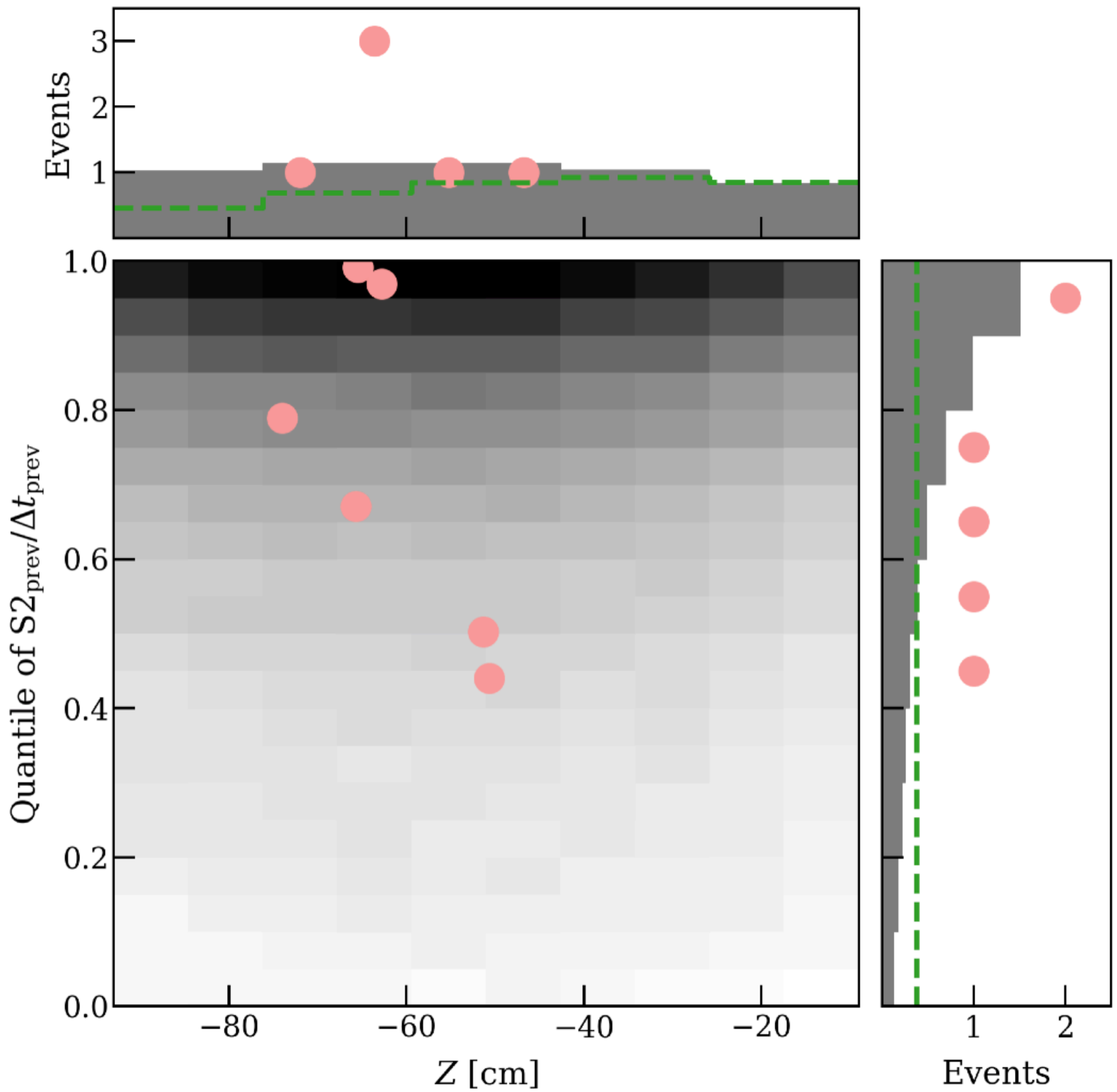
Continuous Axes: p = 0.33

Six (HC x 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**

Science Unblinding

Data consistent with AC background (p > 0.05)



GoF Scores:

Continuous Axes: p = 0.72

Six (HC x LHA) bins: p = 0.64

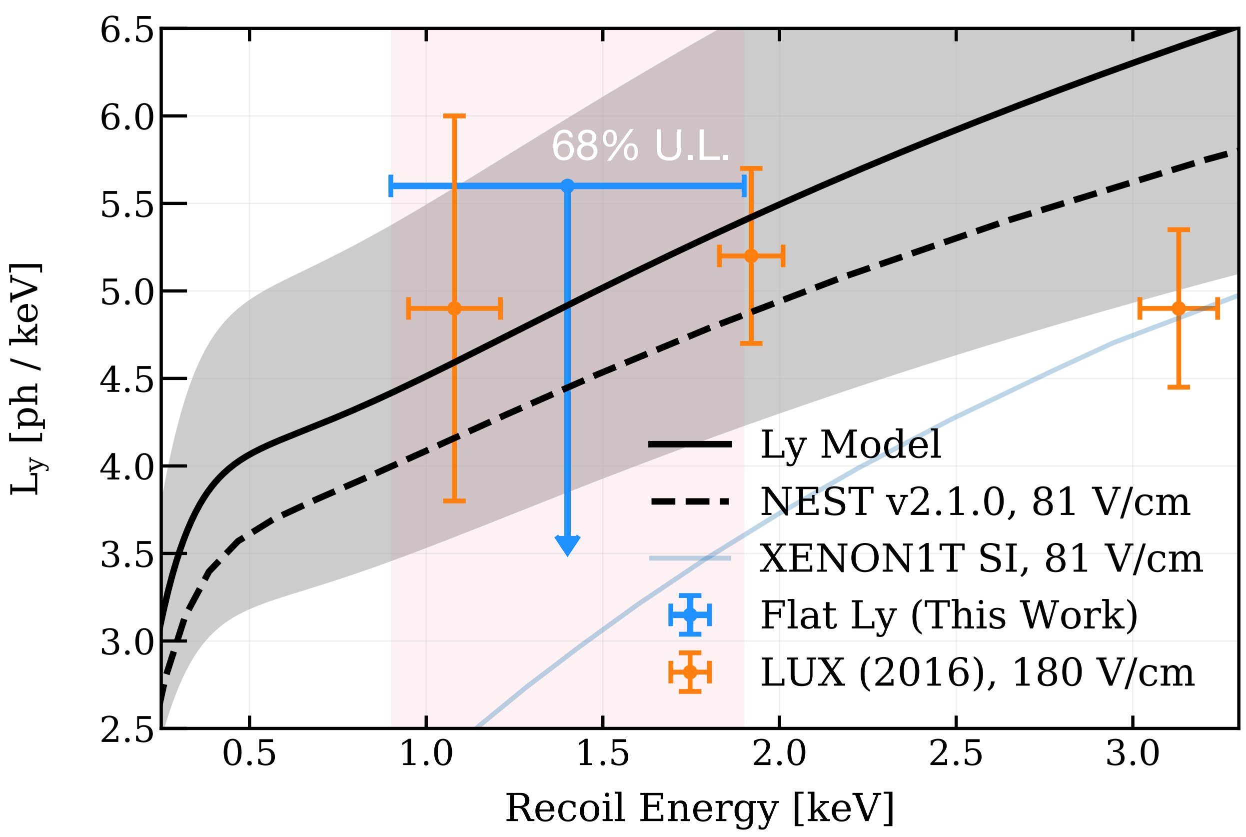
HC	LHA	BG	Signal	Observed
0	≥ 2	0.10	0.13	0
0	< 2	3.58	0.46	4
1	≥ 2	0.06	0.25	0
1	< 2	1.58	0.84	2
2	≥ 2	0.02	0.18	0
2	< 2	0.05	0.39	0
	Total:	**5.38**	**2.25**	**6**

CEvNS Constraints

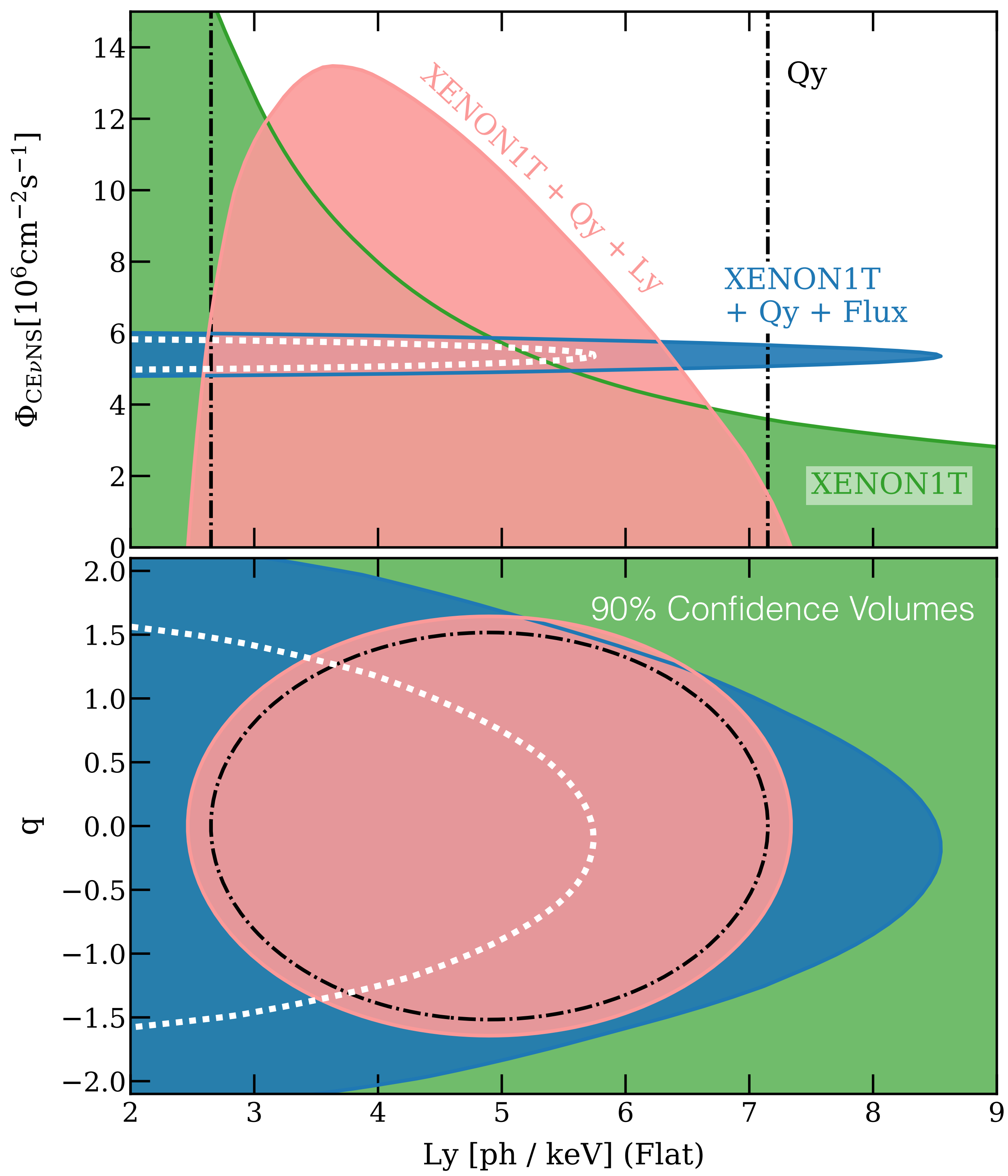
Combination with various external data to learn about the solar flux and xenon response

Yield data (LUX / Livermore) + XENON1T → **Flux < 1.4 x 10^{-7} / cm^2 s**

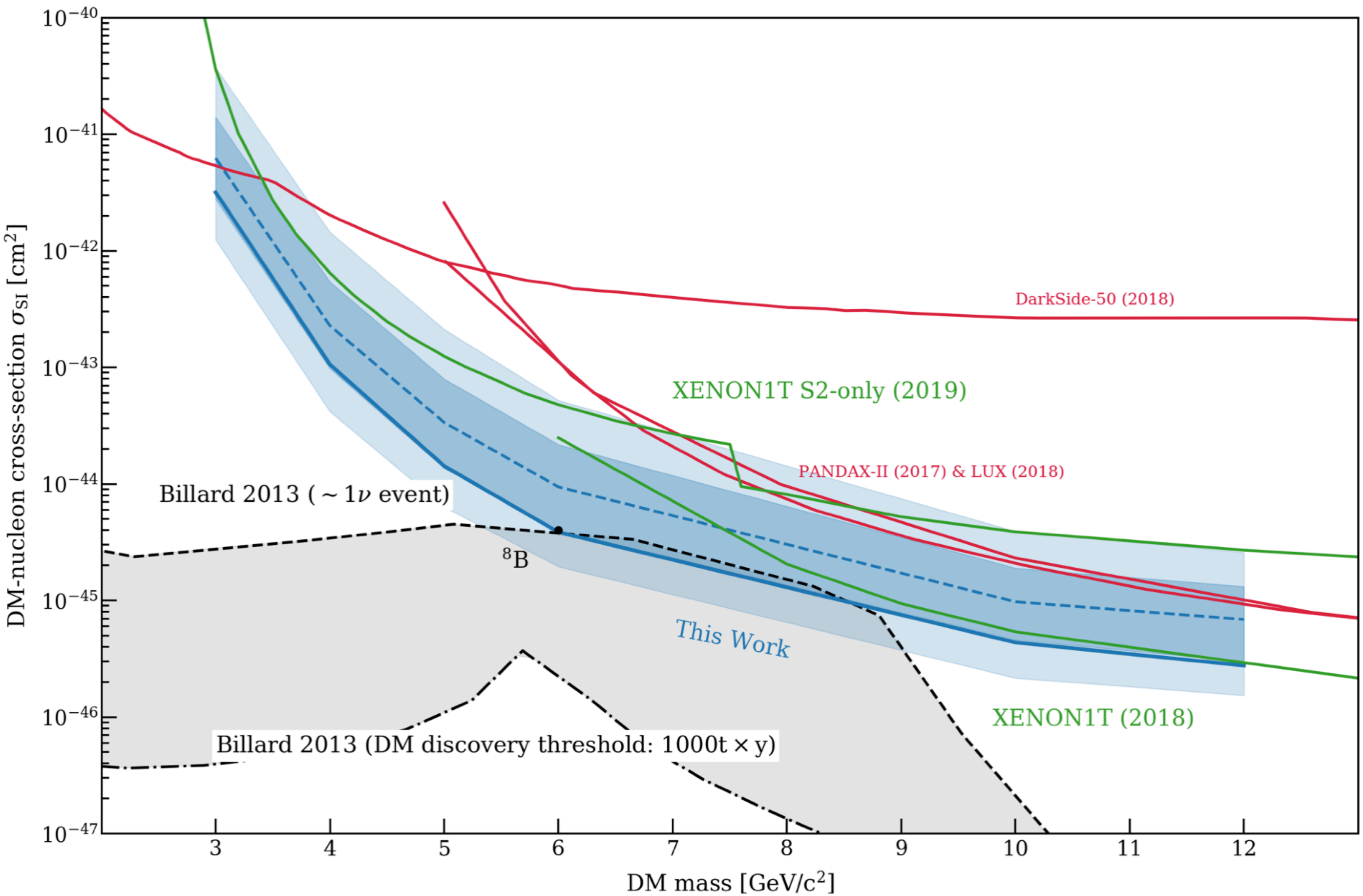
Flux (Borexino) + Qy (Livermore) + XENON1T → **Ly < 8.5 ph / keV**



(Single-Valued Ly)



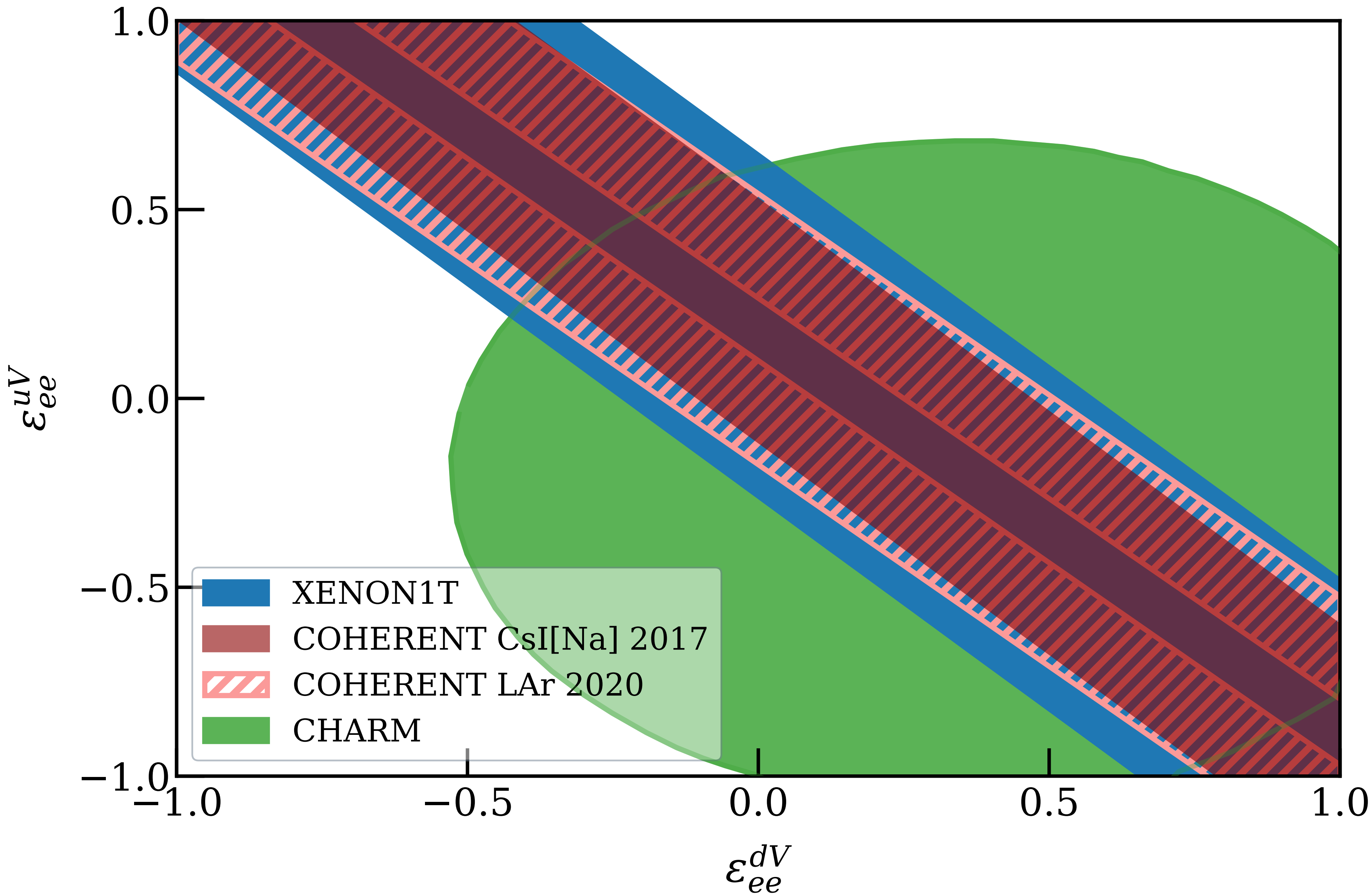
WIMP Constraints



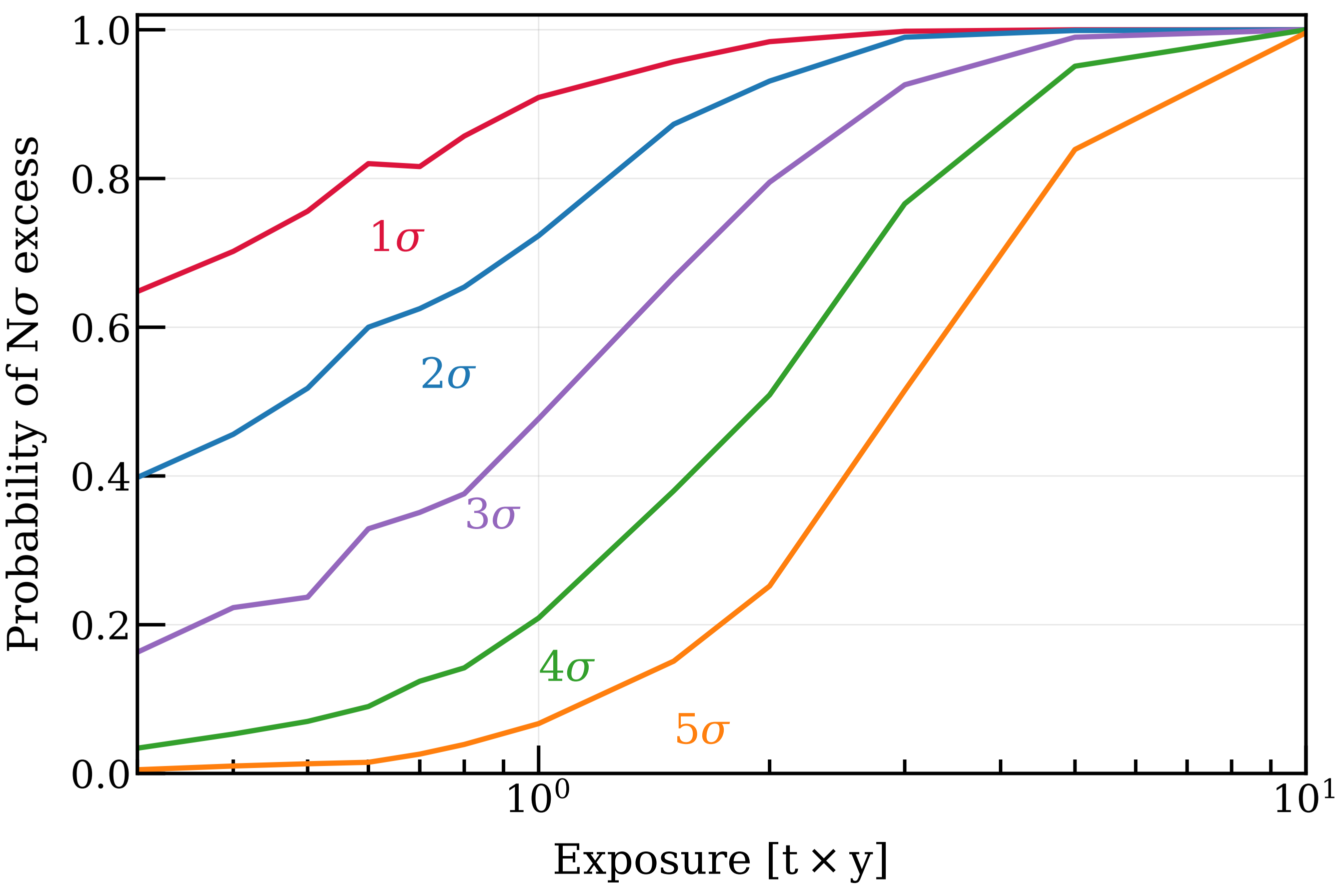
Neutrino Constraints

Relax SM CEvNS cross-section → constrain non-standard neutrino couplings to quarks

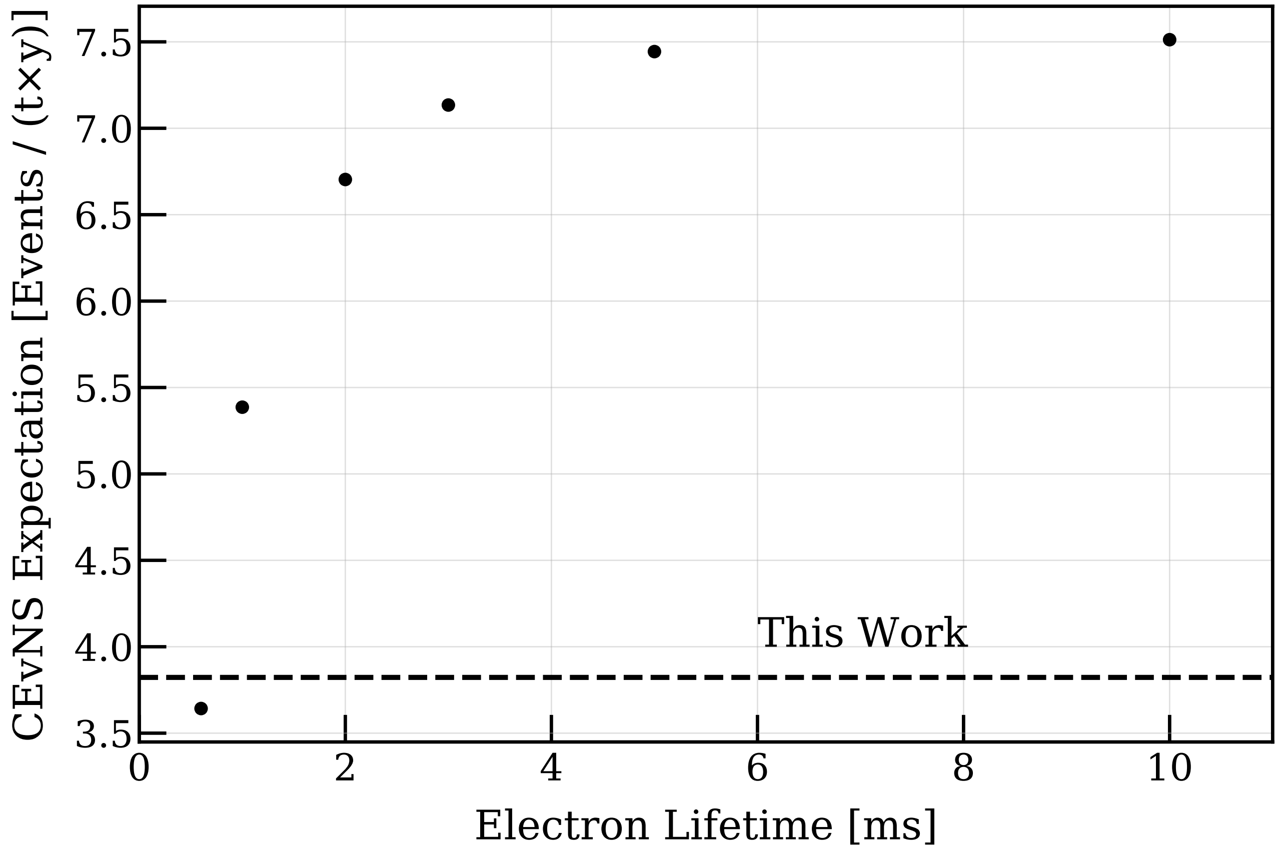
$$Q_w \to \widetilde{Q}_w = N(1 + 2\epsilon_{ee}^{uV} + 4\epsilon_{ee}^{dV}) + Z(4\sin^2\theta_w - 1 + 4\epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})$$



Looking Forward

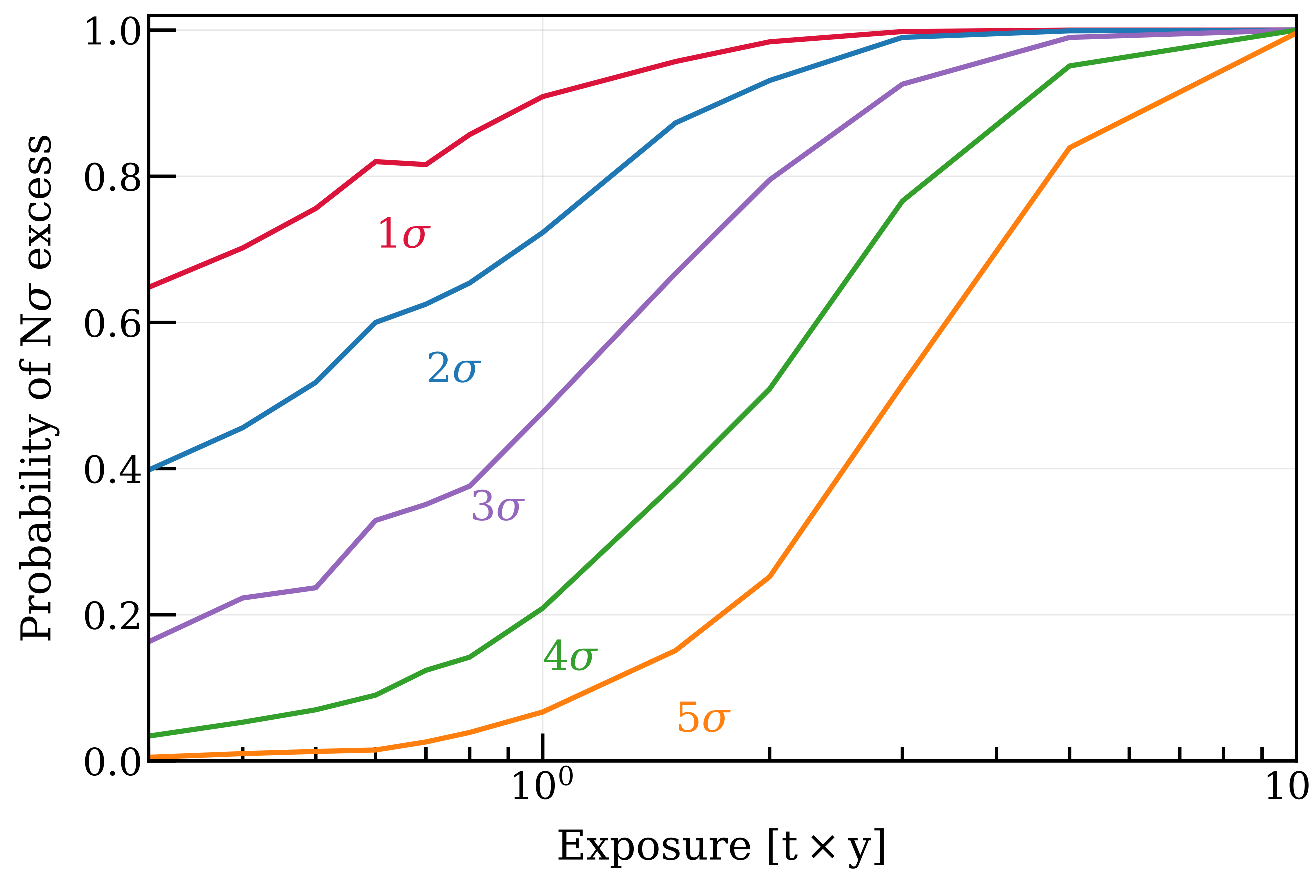


Heavily statistics-limited — few t-y greatly increases the discovery power



Profiling over the constrained yields and considering CEvNS as a background improves low-mass DM limits

XENONnT: Coming Soon!



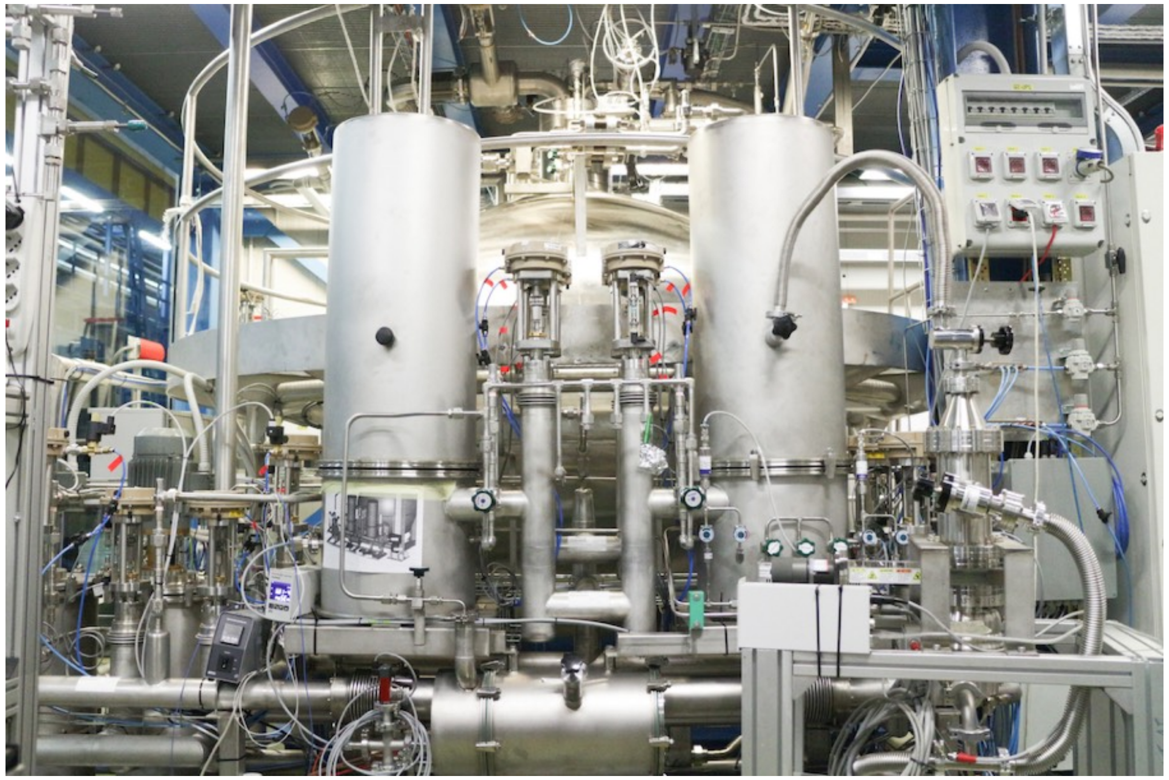
Commissioning since early 2021

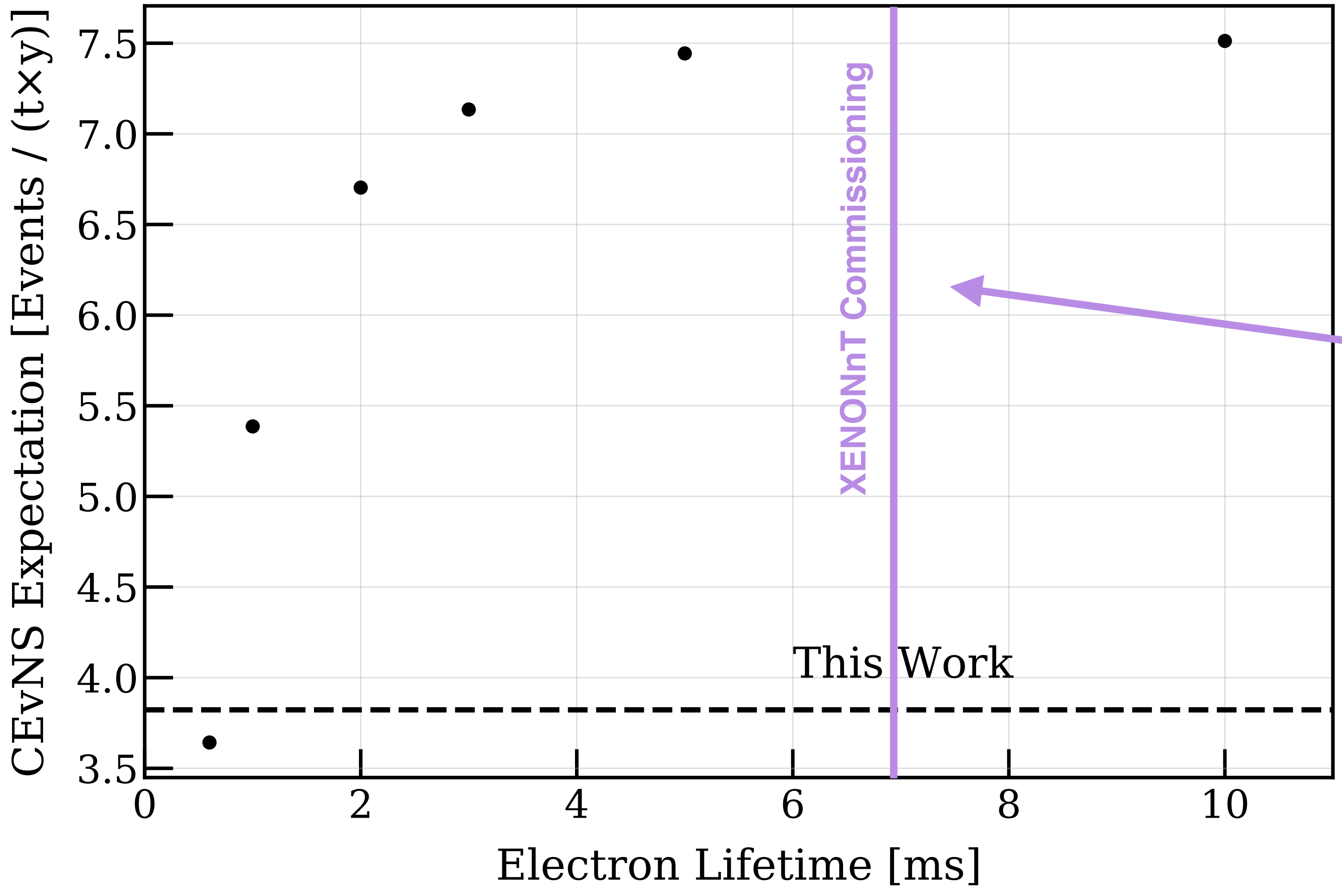
- 4x higher fiducial mass
- Lower ER background

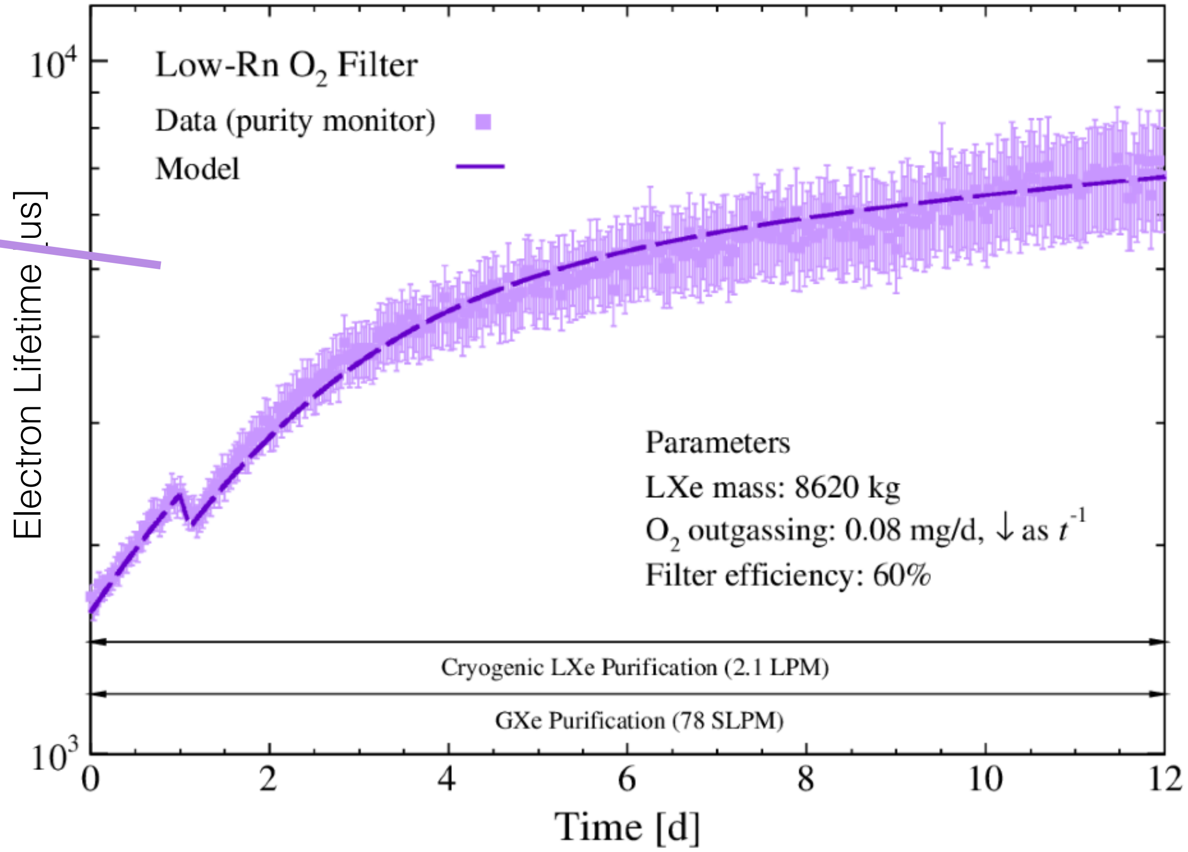
XENONnT: Coming Soon!

Commissioning since early 2021

Liquid xenon pumps and cryogenic filtration enable much faster purification







Summary

- Increased discovery power achieved (20% chance of 3-sigma, 50% of 2-sigma) but no such luck
- Non-detection allows constraints on nuisance parameters, including a competitive Ly U.L.
- World-leading limit for low-mass (3-10 GeV) DM
- Discovery potential very high for next generation (coming soon!)
- High electron lifetime and mitigation of AC background essential
- Low-energy LXe light yield calibration would improve DM sensitivity