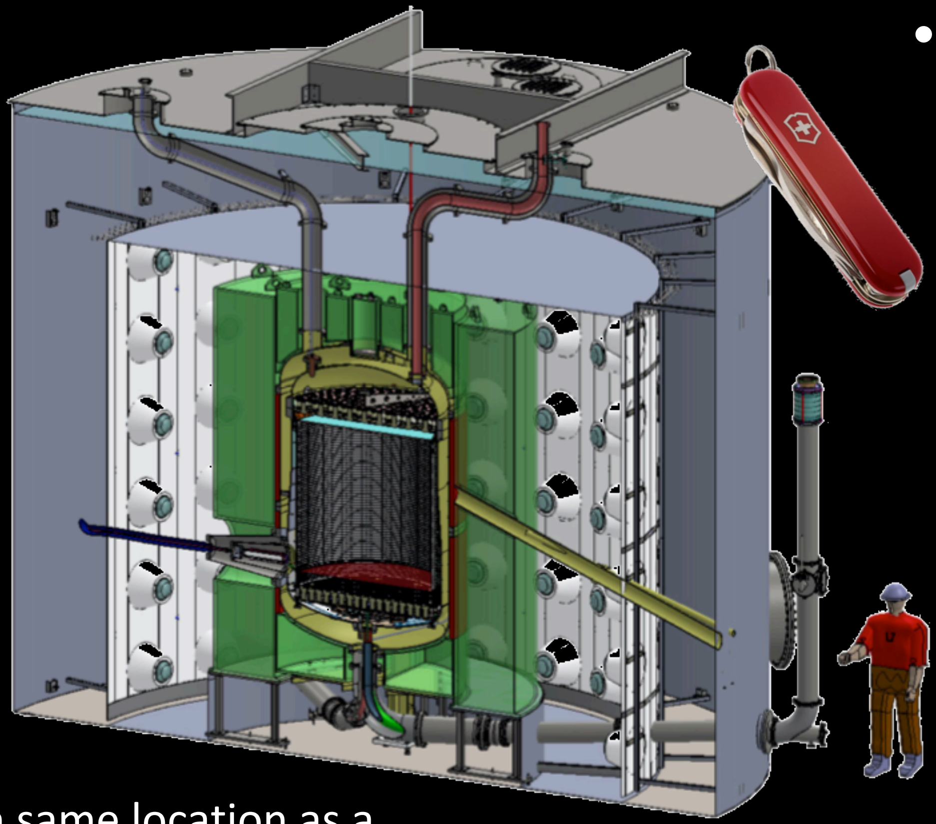
Low-Energy Neutrino Interactions in the LZ Experiment

Matthew Szydagis, UAlbany

May 12, 2022 CoSSURF, SDSMT

What is LZ? (LUX-ZEPLIN)



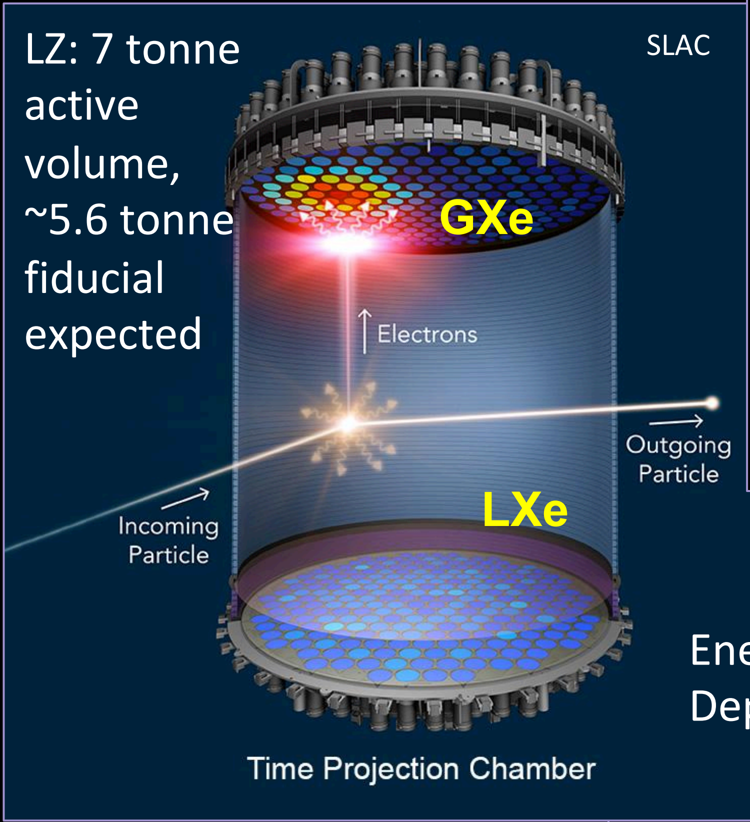
In same location as a predecessor LUX, at the 4850’ level in the Davis cavern, here at

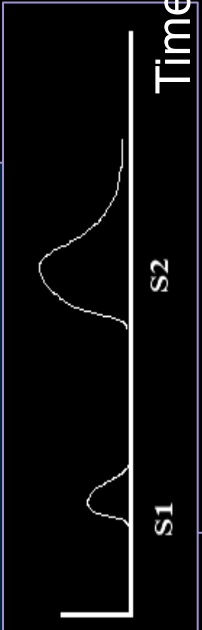
Sanford
Underground Research Facility
South Dakota Science and Technology Authority

- A flagship Dept. of Energy Gen-2 WIMP dark matter direct-detection experiment
  - Running now
- But it can do much more than seek dark matter: a powerful machine with diverse physics objectives
  - 2 great examples are solar neutrinos (^{8}B) and supernova neutrinos
  - But there are many others: axions and other non-WIMP dark matter, neutrinoless double-beta decay, neutrino magnetic moment, atmospheric neutrinos
- Multiple layers
  - Water, Gd-loaded liquid scintillator (OD or outer detector), LXe skin veto, TPC

Two-Phase TPC at the Heart

LZ: 7 tonne active volume, ~5.6 tonne fiducial expected



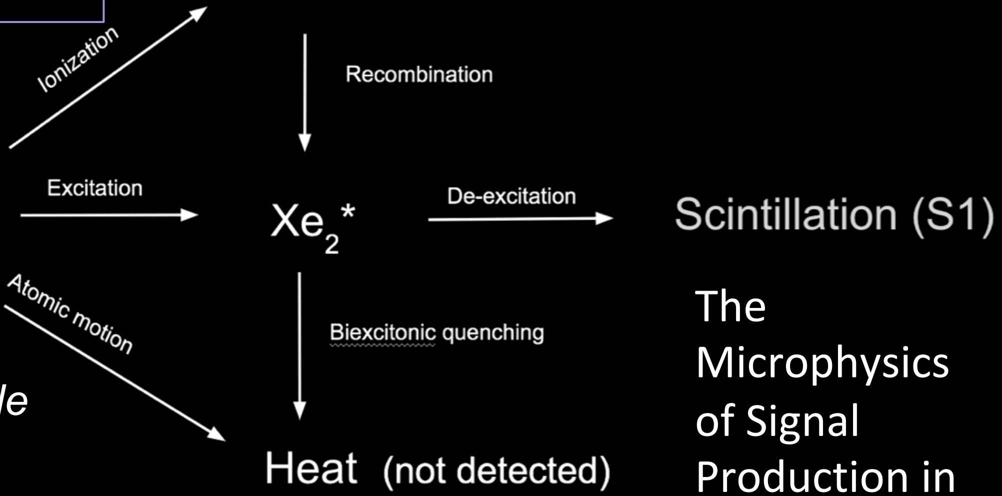


$$E = \frac{W}{L}(n_{ph} + n_e)$$

$$\langle \mathrm{S1c} \rangle = g_1 \langle n_{ph} \rangle \quad \langle \mathrm{S2c} \rangle = g_2 \langle n_e \rangle$$

We typically use "position-corrected" S1 and S2 signals (S1c and S2c), characterizing the "actual" yields to remove the detector-specific variations

Particles that multiply scatter will only provide 1 S1, but 1 S2 for each vertex of scattering



Energy Deposit

Ionization

$Xe^+ + e^-$

Escape

Ionization (S2)

Recombination

Excitation

Xe_2^*

De-excitation

Scintillation (S1)

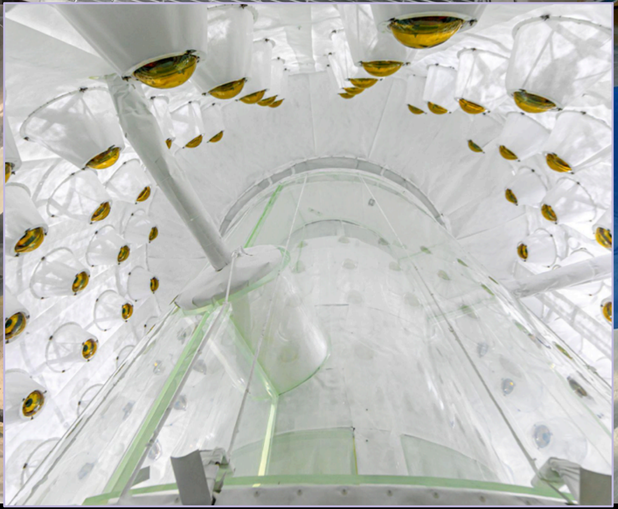
Atomic motion

Biexcitonic quenching

Heat (not detected)

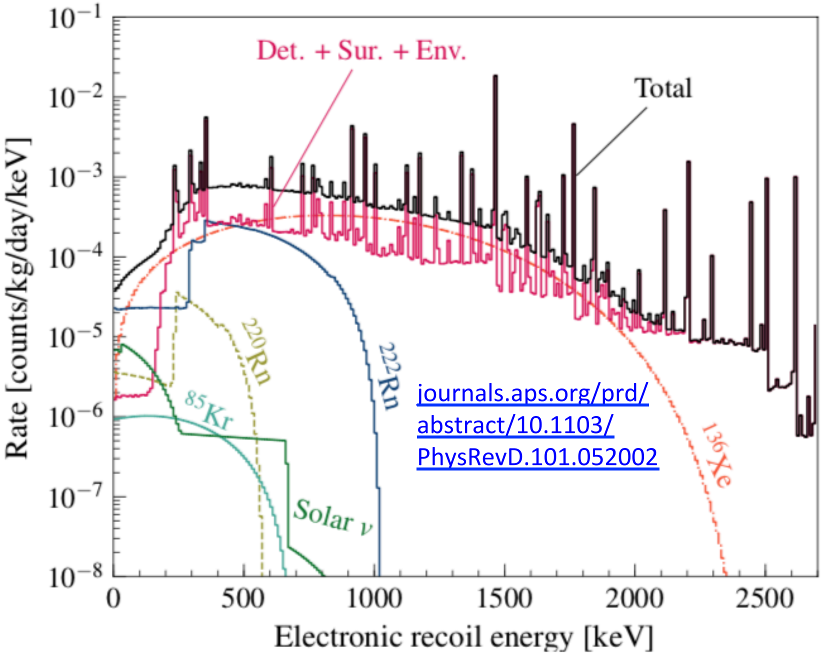
The Microphysics of Signal Production in L(Xe)

Image credits: Matt Kapust, SURF; and various LZ Collab members

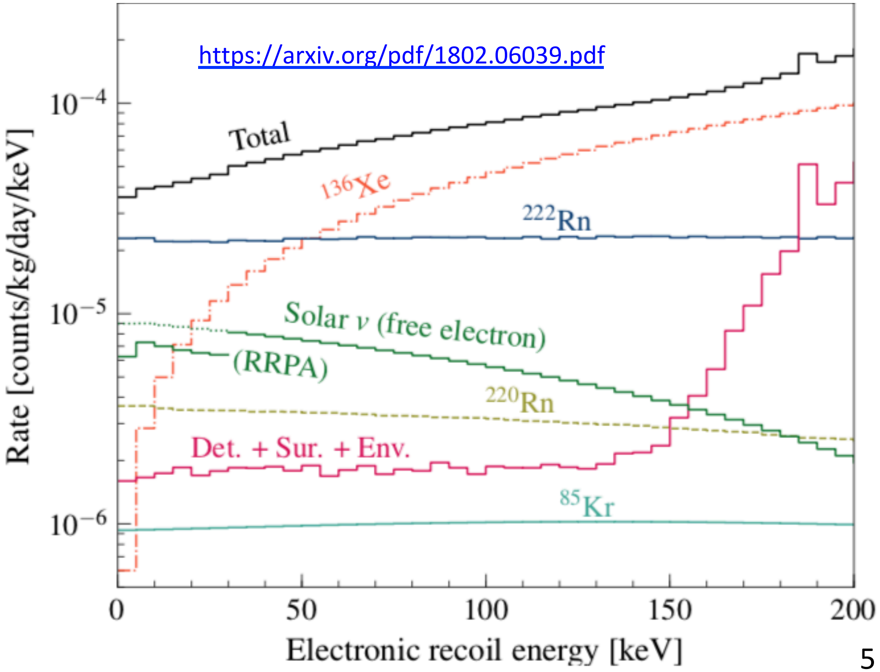


Signals and Backgrounds

- One scientist’s background is another’s signal!
  - Upper plot fuller range, lower plot zoomed in at low energies
  - One individual’s “low energy” (DUNE) is another’s very high (us!)
- If you make a direct dark matter detector big enough you start to become a decent neutrino experiment
  - This is true for both electronic recoils (ER) and nuclear recoils (NR)



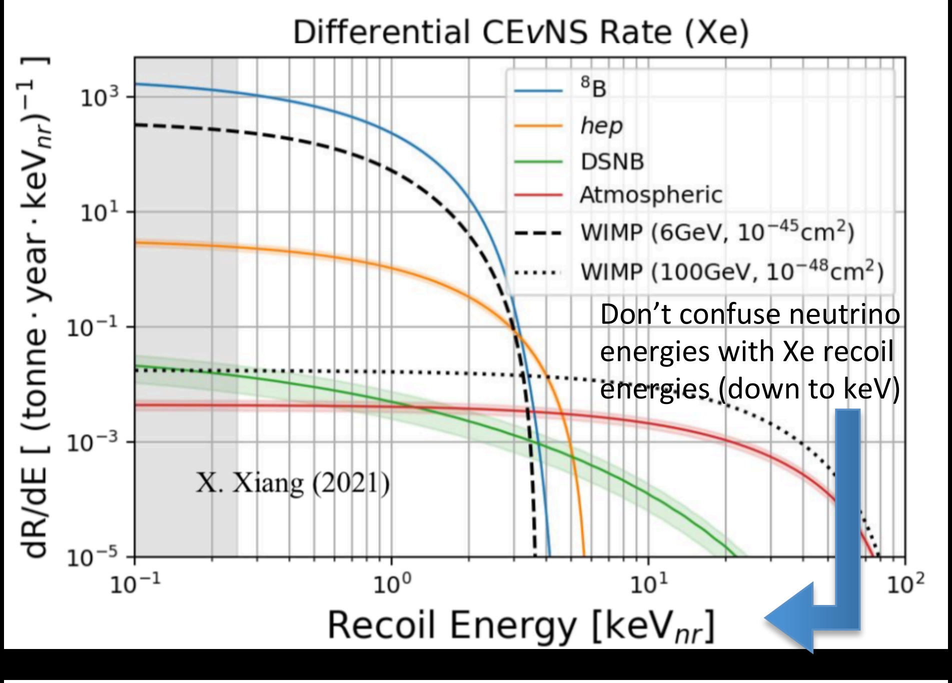
journals.aps.org/prd/abstract/10.1103/PhysRevD.101.052002



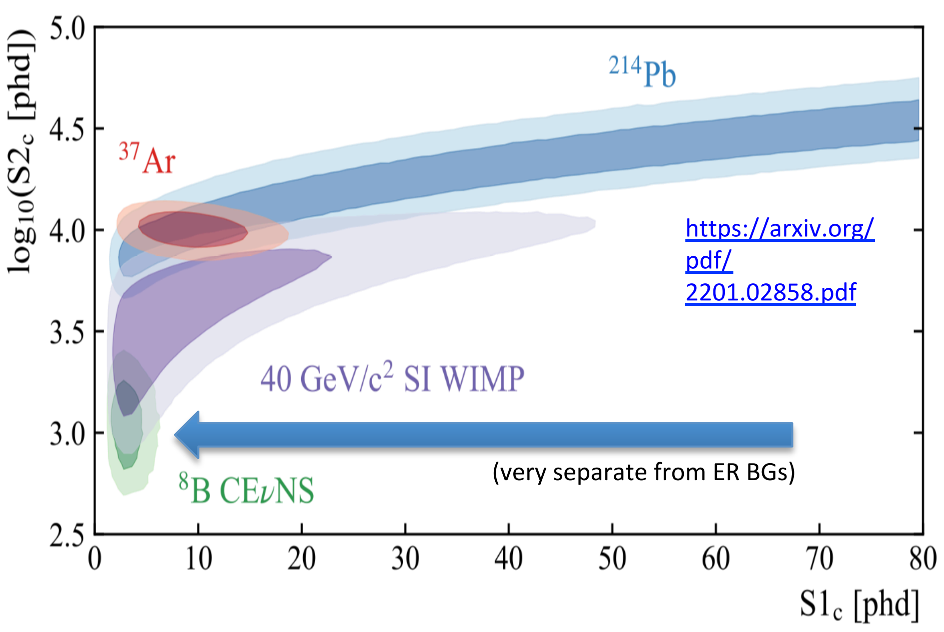
https://arxiv.org/pdf/1802.06039.pdf

Boron-8 (^{8}B)

- Looks like low-mass WIMP (~6 GeV/c^2 in mass). *hep* there too
  - In terms of its falling-exponential-like energy spectrum (of *recoils*)
  - Looks very different (lower) than “standard NR band”
  - Guaranteed new (physics) BG -- as we scaled up from LUX and ZEPLIN
- Expecting ~40 ^{8}B events in 1,000 live-days of LZ
  - Exact number depends on thresholds, and charge and light yields
  - Many more with “S2-only” analysis possible



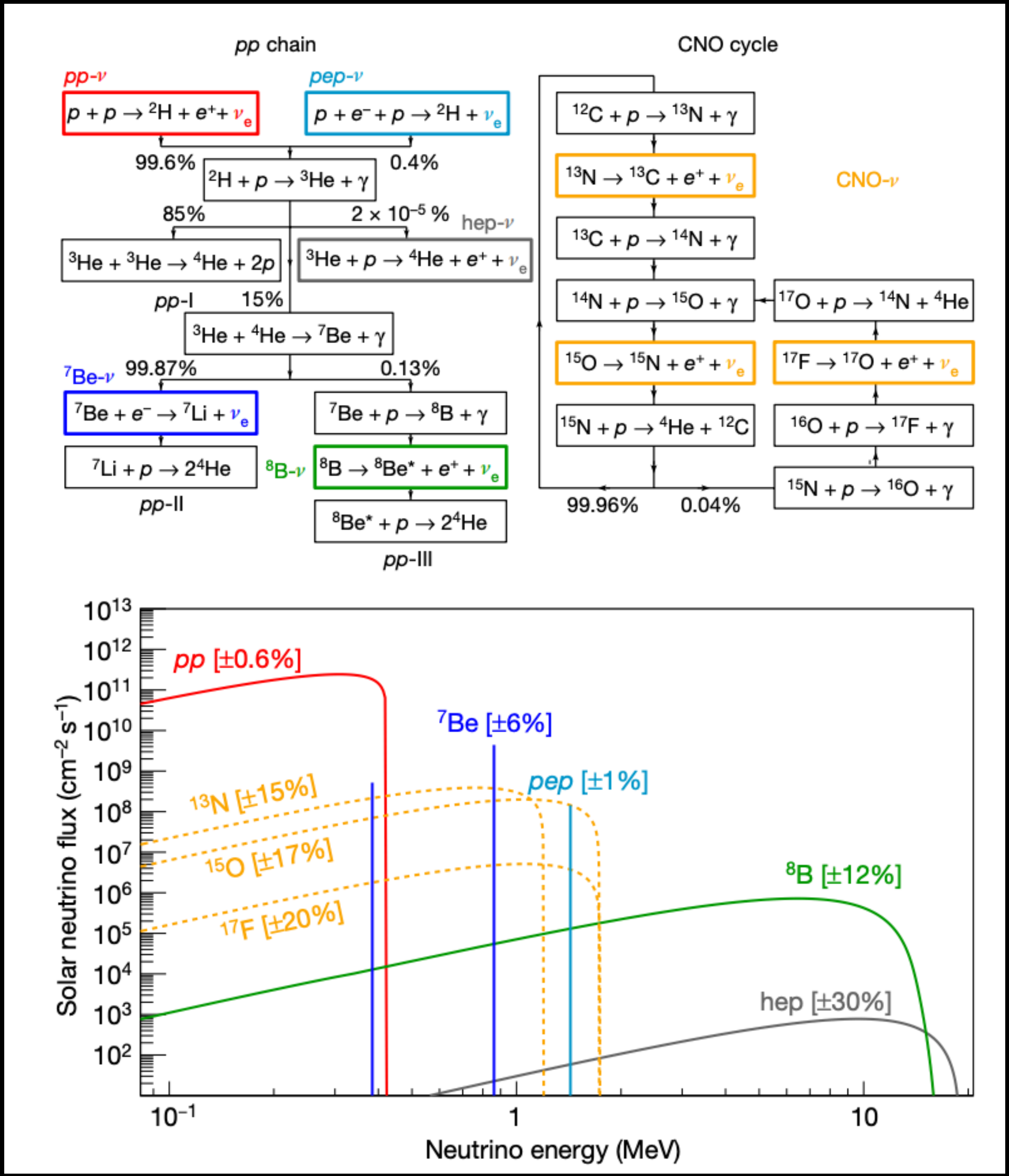
Don’t confuse neutrino energies with Xe recoil energies (down to keV)



https://arxiv.org/pdf/2201.02858.pdf

(very separate from ER BGs)

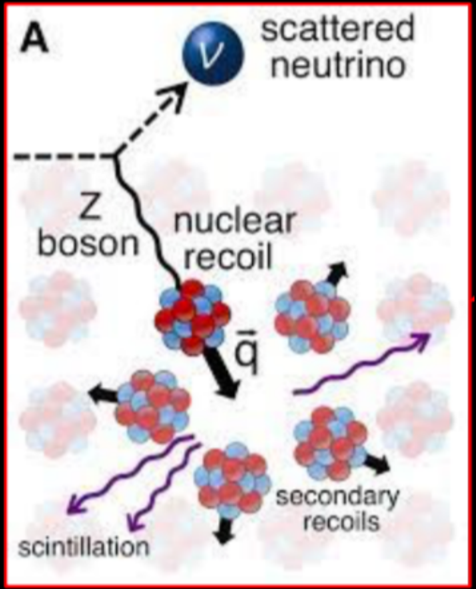
Standard Solar Cycle



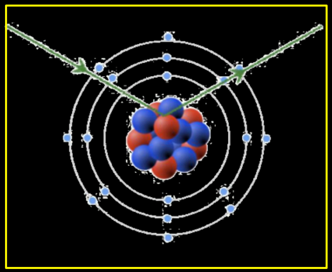
- Where are the Boron-8 neutrinos coming from?
- Overview, left: https://www.nature.com/articles/s41586-018-0624-y.pdf (Figure 1)

Solar Physics => Beyond Standard Model Physics

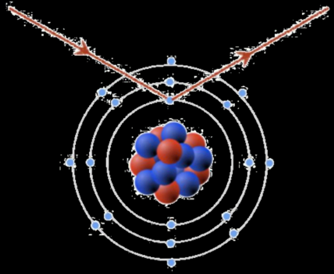
$^8B \rightarrow {}^8Be + e^+ + \nu_e$



For ^{8}B, CEνNS in general



Signal-like:
Nuclear Recoil

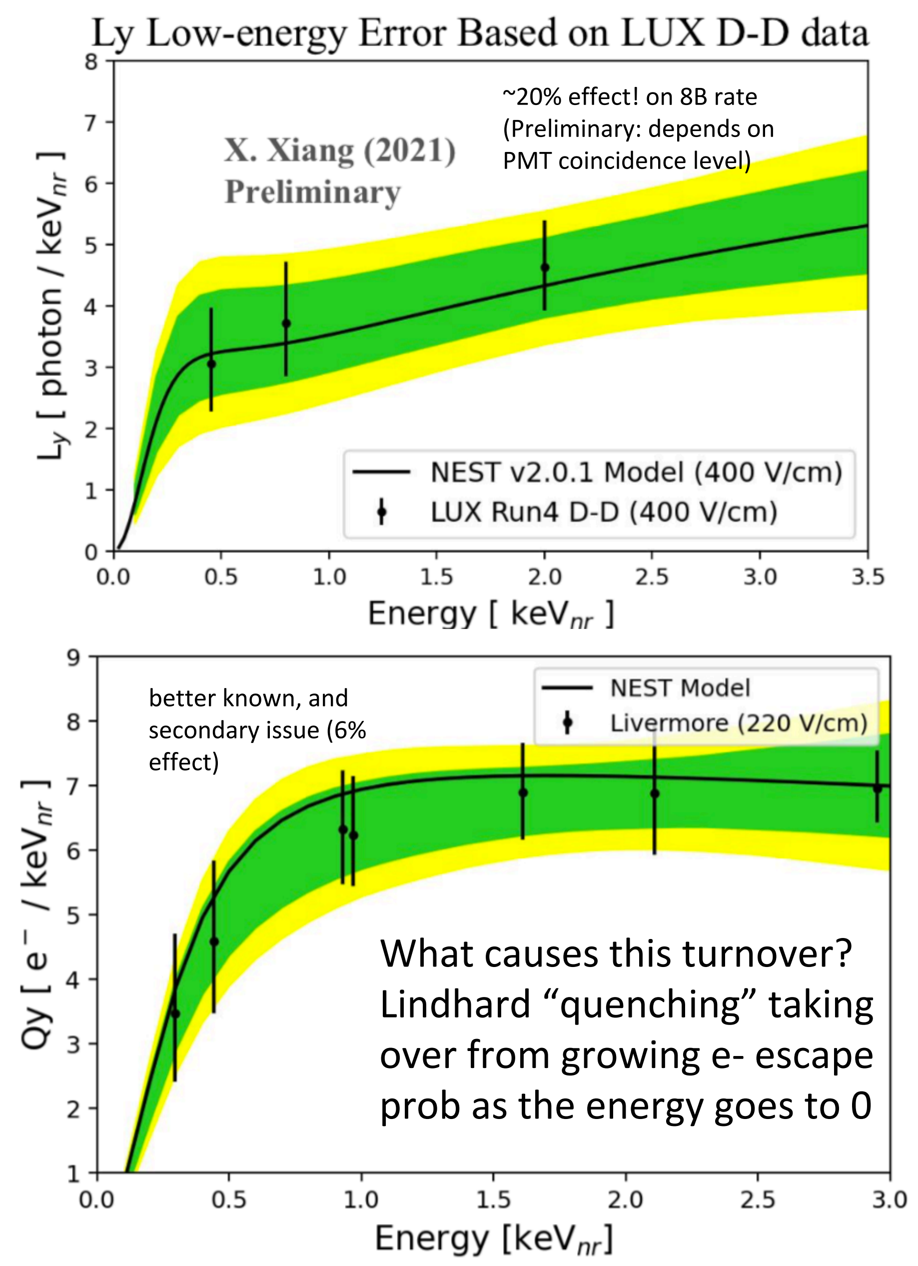


Background-like:
Electron(ic) Recoil

Discrimination of these very solid, and well understood: https://doi.org/10.1103/PhysRevD.102.112002

- May be able to check solar model (how much of different kinds of nuclear fusion). Neutral current -> total ^{8}B rate
- As well as look for deviations from the Standard Model cross-section for CEνNS for ^{8}B neutrinos in LXe and/or NSI (non-standard interactions)? Nuclear physics form factor ~1
  - NSI from excess of events; light sterile neutrino from deficit
- First, light & charge yield uncertainties must be addressed

How Many Quanta?



~20% effect! on 8B rate (Preliminary: depends on PMT coincidence level)

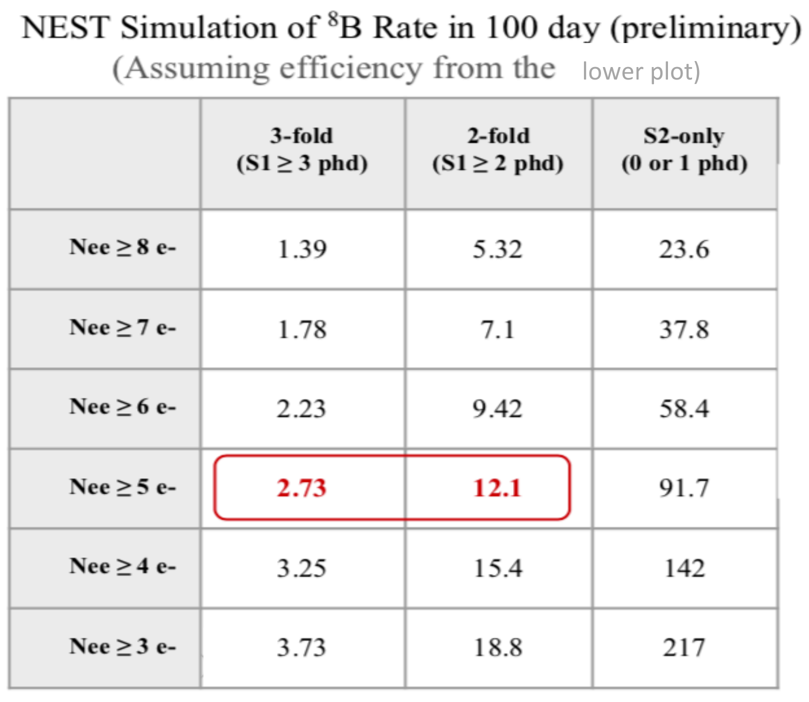
better known, and secondary issue (6% effect)

What causes this turnover? Lindhard "quenching" taking over from growing e- escape prob as the energy goes to 0

- ^{8}B neutrinos may provide "natural" constraint!
  - Will have to disentangle from NSI-caused differences in flux
  - Can combine with other calibrations for help (D-D, D reflector, H reflector, ^{88}YBe)
  - 4.4% uncertainty on the flux from SNO, Borexino
- The biggest issue is light yield: the uncertainty at low *E*'s
  - And what is the value period below 0.5 keV?
  - Does it stay flat or go up? (unlikely, even if possible mathematically)
- Other challenges: BGs
  - Accidental coincidence (of rogue S1s and S2)
  - Single/multiple-e-'s boiling out

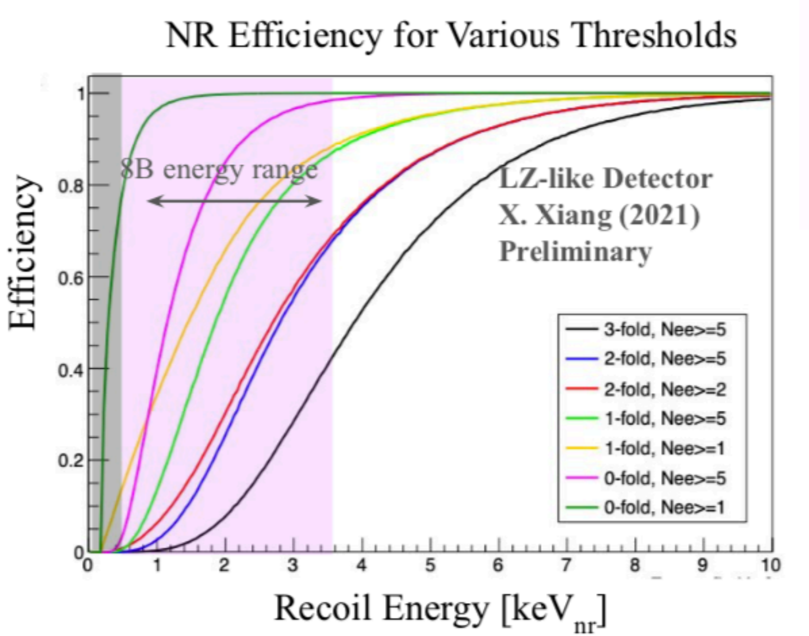
https://doi.org/10.1103/PhysRevD.102.092004 (LUX)

#Photons, Electrons => # ^{8}B events in LZ



NEST Simulation of ^{8}B Rate in 100 day (preliminary)
(Assuming efficiency from the lower plot)

	3-fold (S1 ≥ 3 phd)	2-fold (S1 ≥ 2 phd)	S2-only (0 or 1 phd)
Nee ≥ 8 e-	1.39	5.32	23.6
Nee ≥ 7 e-	1.78	7.1	37.8
Nee ≥ 6 e-	2.23	9.42	58.4
Nee ≥ 5 e-	**2.73**	**12.1**	91.7
Nee ≥ 4 e-	3.25	15.4	142
Nee ≥ 3 e-	3.73	18.8	217

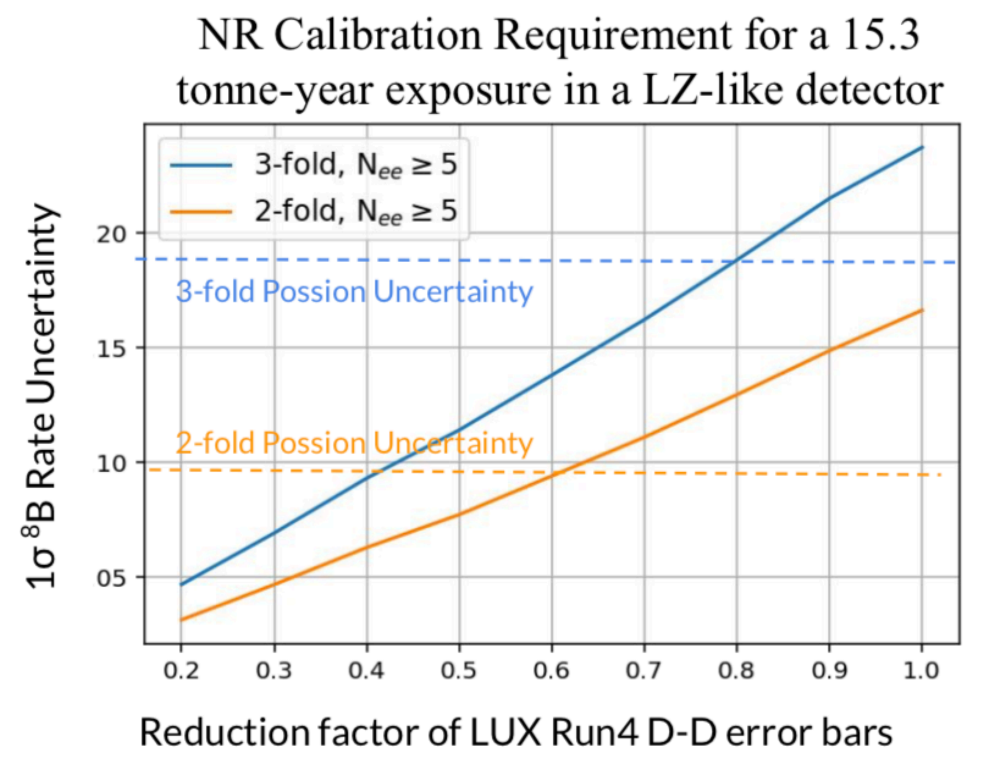


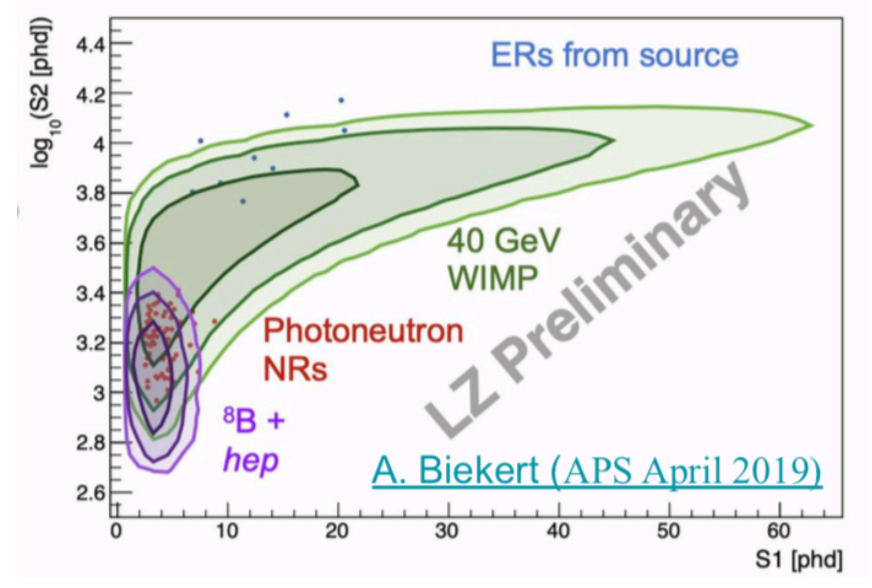
NR Efficiency for Various Thresholds

- Catching only the tail end of 8B bubbling up above the nominal threshold of few keV (NR)
- Nevertheless, a discovery and measurement is practically inevitable, given LZ's planned run time (at least 1,000 live-days)
- "Tricks" we can play
  - Lower PMT coincidence if only for part of detector and/or temporarily
  - Much more: https://doi.org/10.1103/PhysRevLett.122.131301, https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.042001, https://arxiv.org/abs/1904.08979, https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.012011, https://arxiv.org/abs/2101.08753
- 2PE effect => 1 S1, light-element doping (to lower the threshold, not increase cross-section: Hugh Lippincott, HydroX), Migdal effect, ionization-channel-only searches, machine learning, et al.

Sources of Uncertainties

- Last slide was all averages or expectation values
- Need to beat down both the statistical uncertainties and systematics
  - Latter includes the intrinsic uncertainties from calibration: see right plot
  - More calibrations (like more D-D, so just more stats/events) but also more diverse types
- Poisson fluctuations for small counts, on top of being at tail of (not perfect Gaussian) distribution

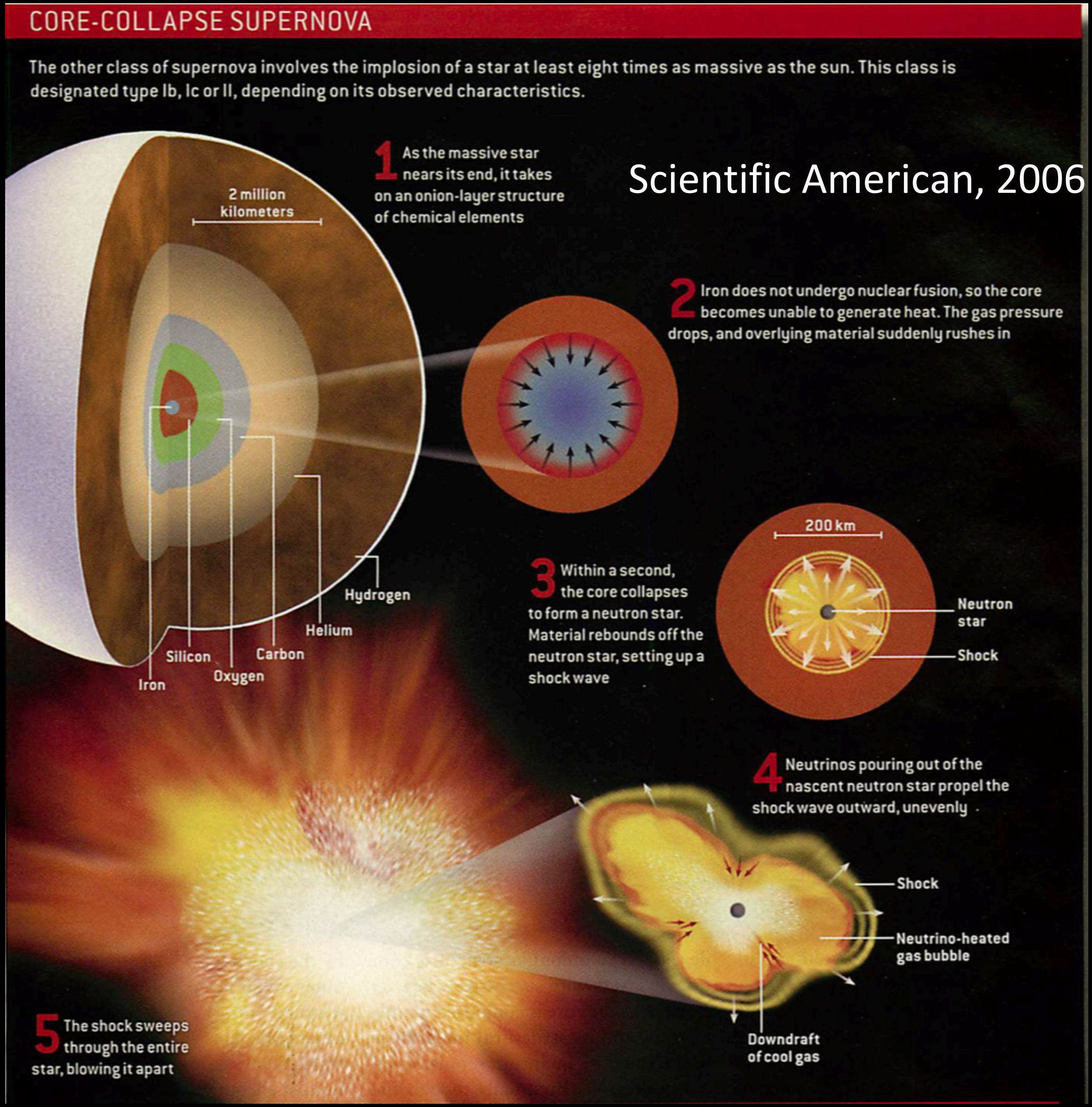




A. Biekert (APS April 2019)

Switching Gears to Different Stars:

Boom!



CORE-COLLAPSE SUPERNOVA

The other class of supernova involves the implosion of a star at least eight times as massive as the sun. This class is designated type Ib, Ic or II, depending on its observed characteristics.

1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements

2 Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in

3 Within a second, the core collapses to form a neutron star. Material rebounds off the neutron star, setting up a shock wave

4 Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly

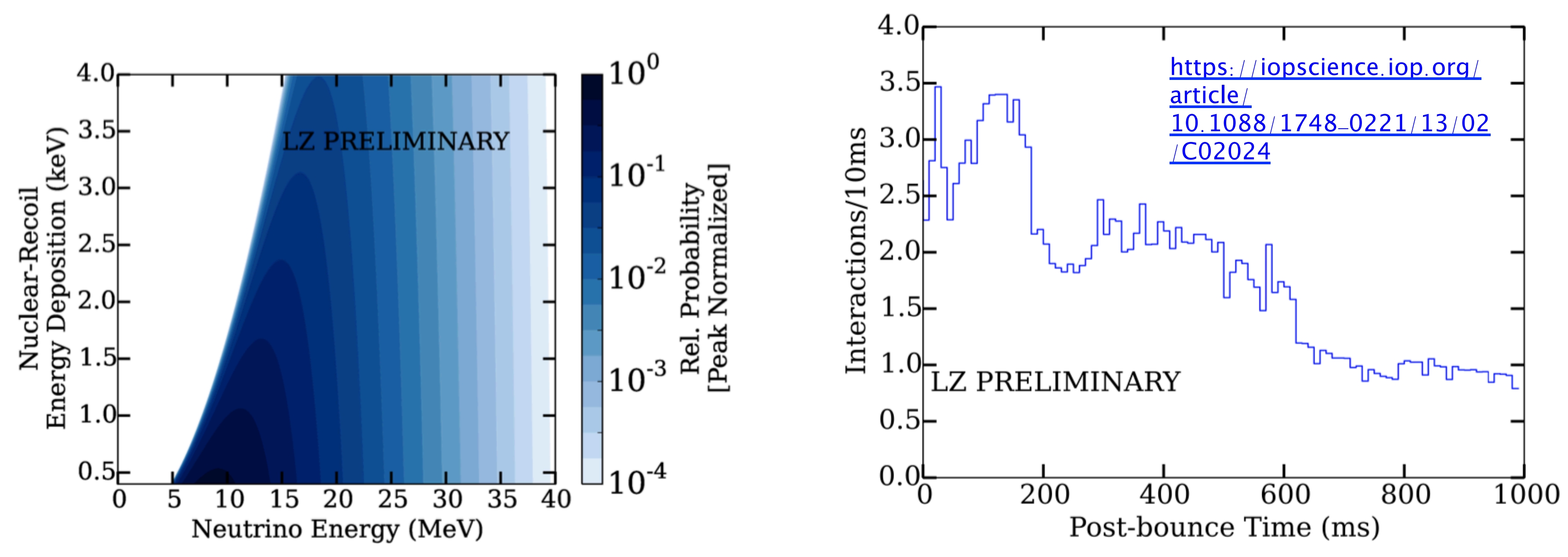
5 The shock sweeps through the entire star, blowing it apart

Scientific American, 2006

- Neutronization spike
  - Useful for multilateration
- Possible black hole formation (vs. neutron star: mass dependent)

Core-Collapse Supernova Explosion

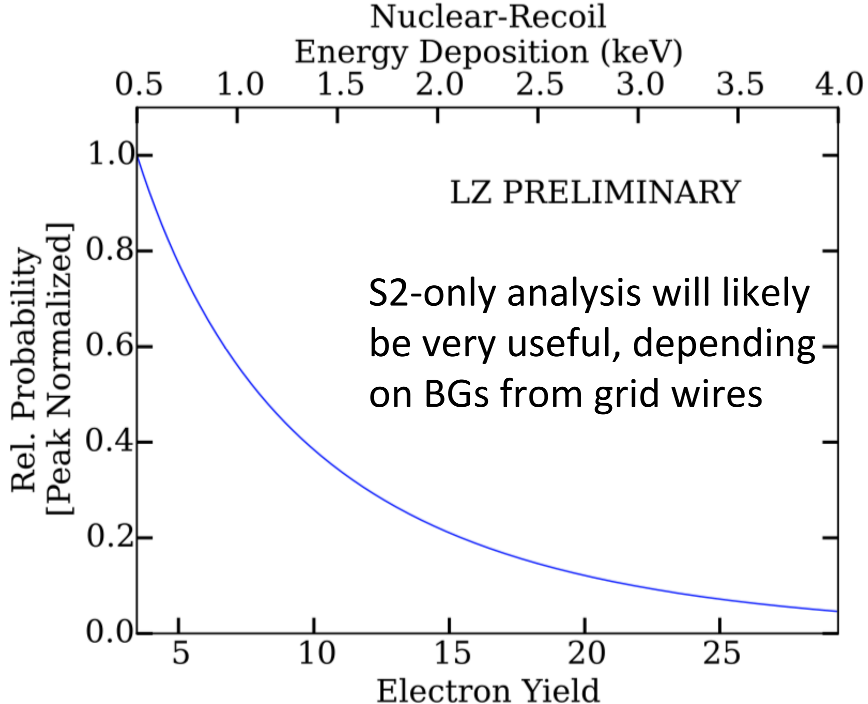
- *(Left)* The relative probability distribution for a neutrino energy deposition in LXe. We present the case where the incident neutrino flux has an average *E* of 10 MeV and a spectral profile from the accretion phase.
- *(Right)* The expected neutrino interaction rate in LZ from a 27 solar-mass supernova (SN) at 10 kpc assuming a detection energy threshold of 0.5 keV (aggressive). About 184 ± 13 ν interactions are expected in the first second and 357 ± 19 in total.



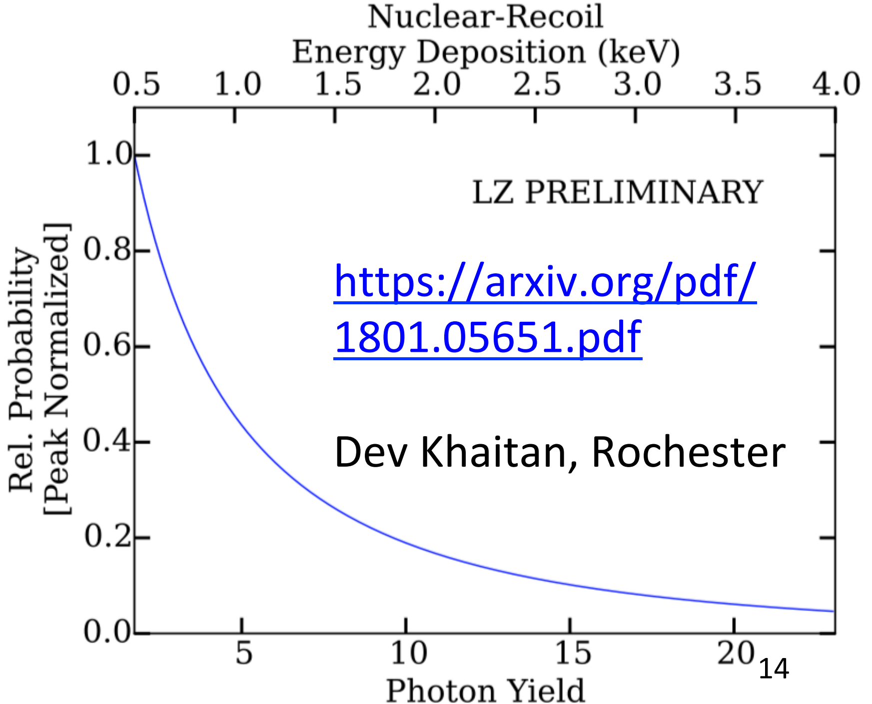
https://iopscience.iop.org/article/10.1088/1748-0221/13/02/C02024

Supernova Neutrino Signal in LZ

- The e^- *(Left)* and photon *(Right)* yields, predicted by NEST (taking mean yields models at face value sans errors, fluctuations) for an incident ν spectrum with an average *E*=10 MeV and spectral profile from the accretion phase.
- Just like in DUNE, right at threshold, but many orders of magnitude lower in energy. (A **unique** window on SNs?)

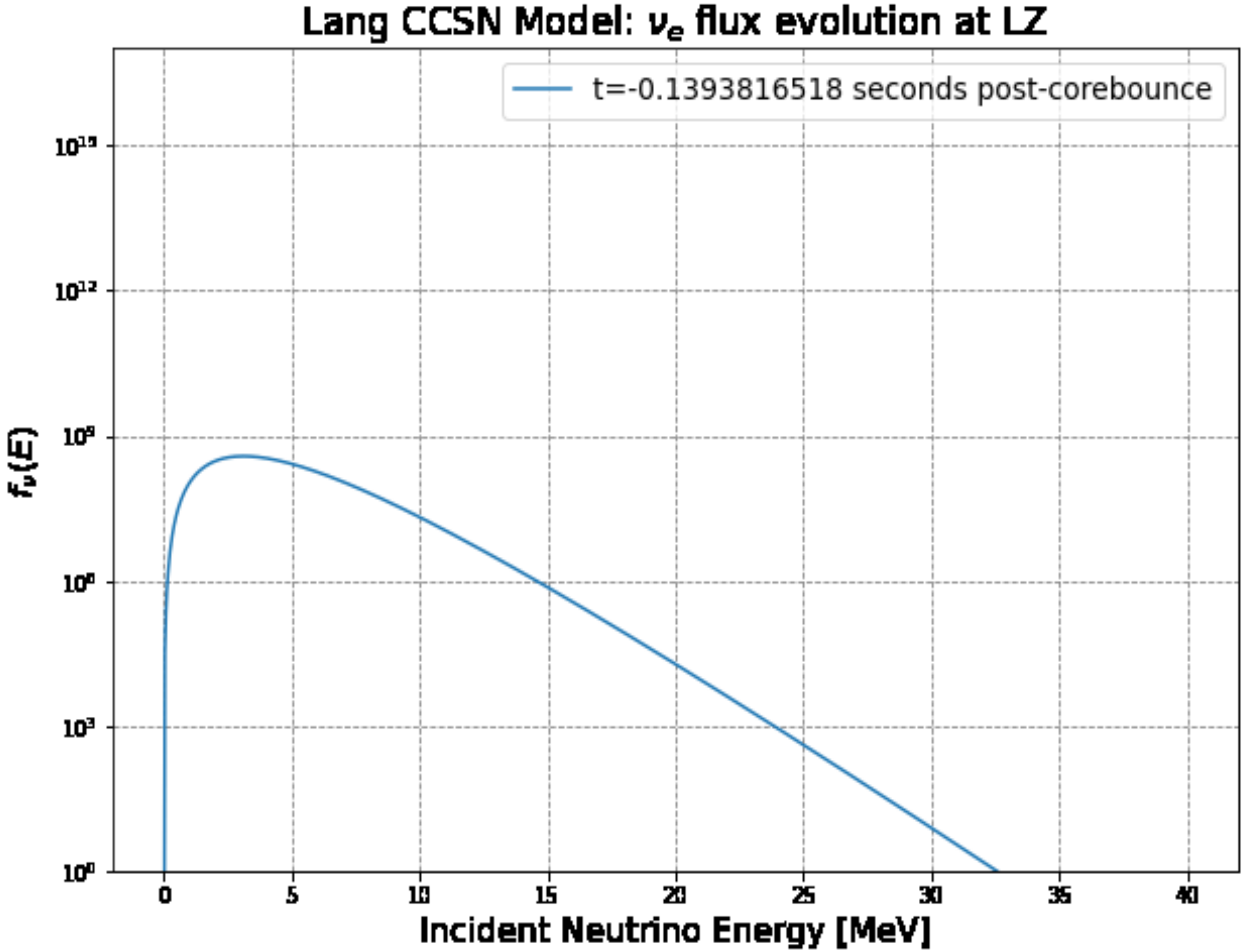


S2-only analysis will likely be very useful, depending on BGs from grid wires



https://arxiv.org/pdf/1801.05651.pdf

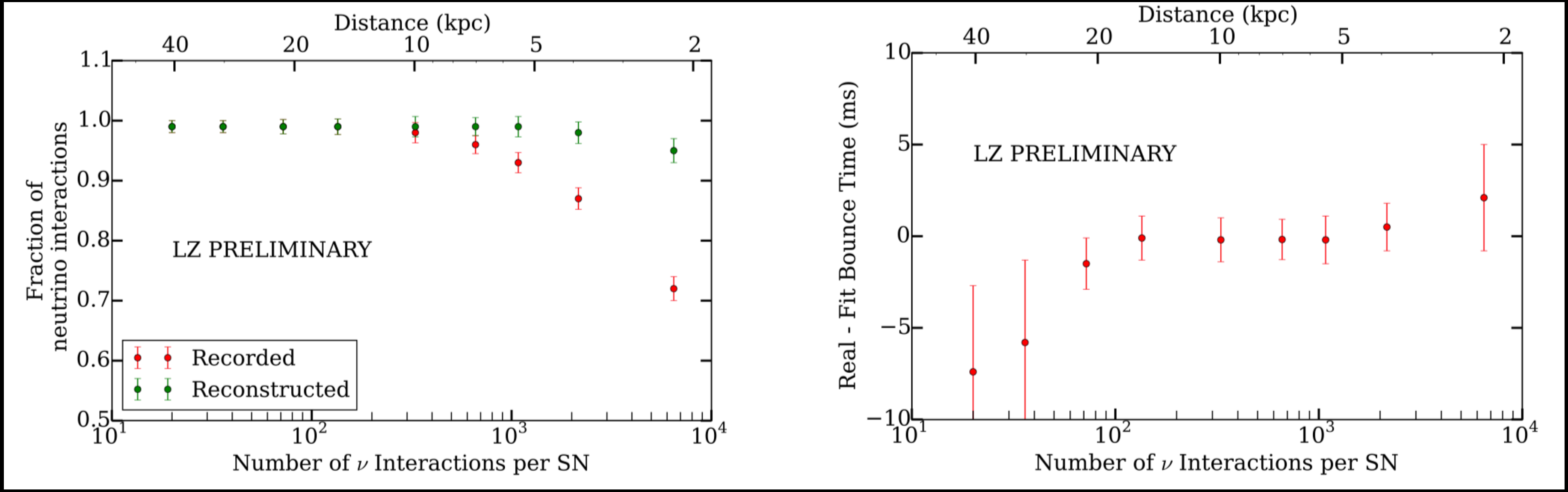
Dev Khaitan, Rochester



Animated gif (PPT file only)

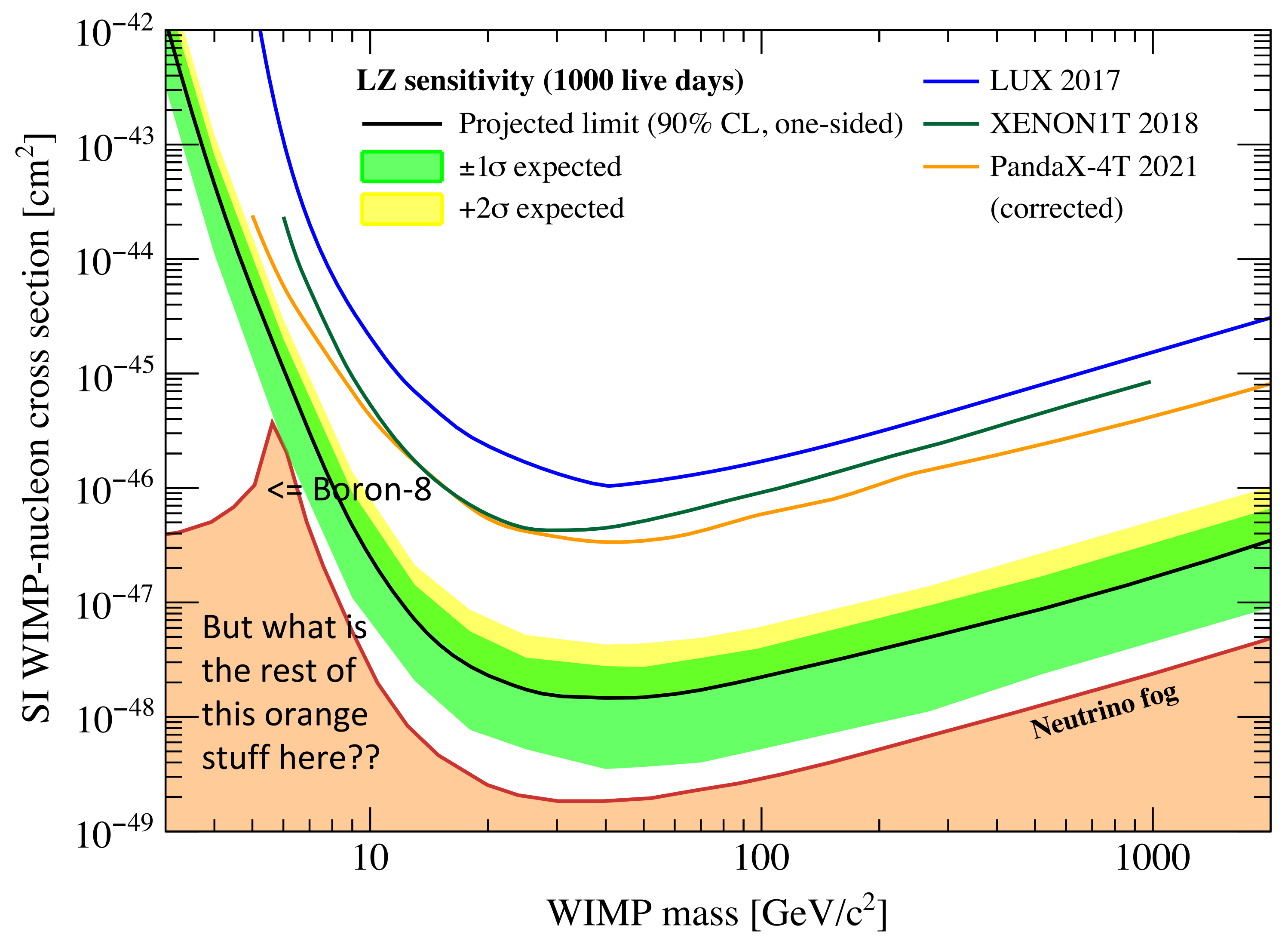
Elise McCarthy, Rochester

Conclusions on Supernovae

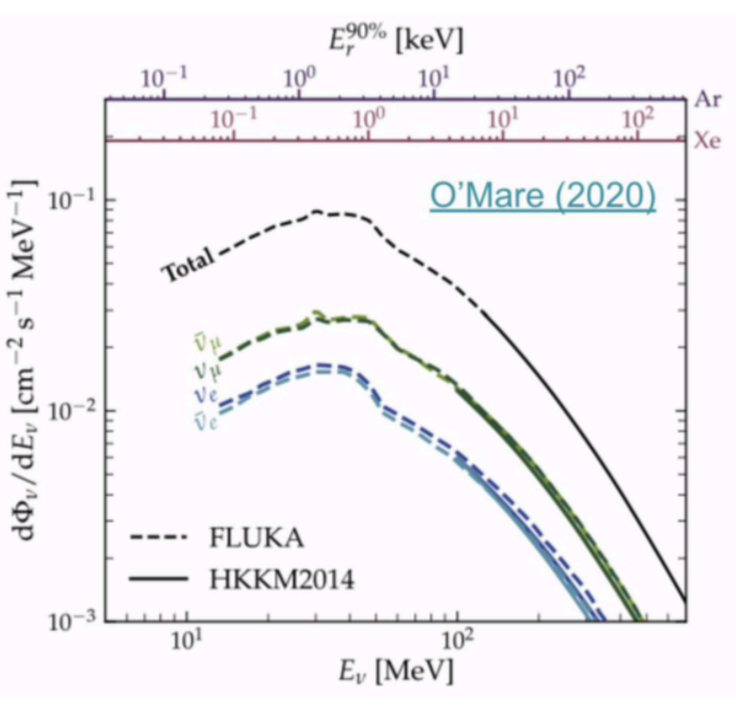


- *(Left)* Fraction of recorded *(red)* and reconstructed *(green)* neutrino interactions. This fraction is presented versus number of neutrino interactions and distance from a 27 solar-mass SN (Betelgeuse 11 solar masses, 0.2 kpc away)
- *(Right)* Recon bounce *t* of SN. The error bars in both plots indicate the statistical error associated with the simulated population. (Note 1987a was 51.4 kpc, ~20 solar mass)
- LZ is part of SNEWS. (Perhaps we are "due" for a SN?? :)

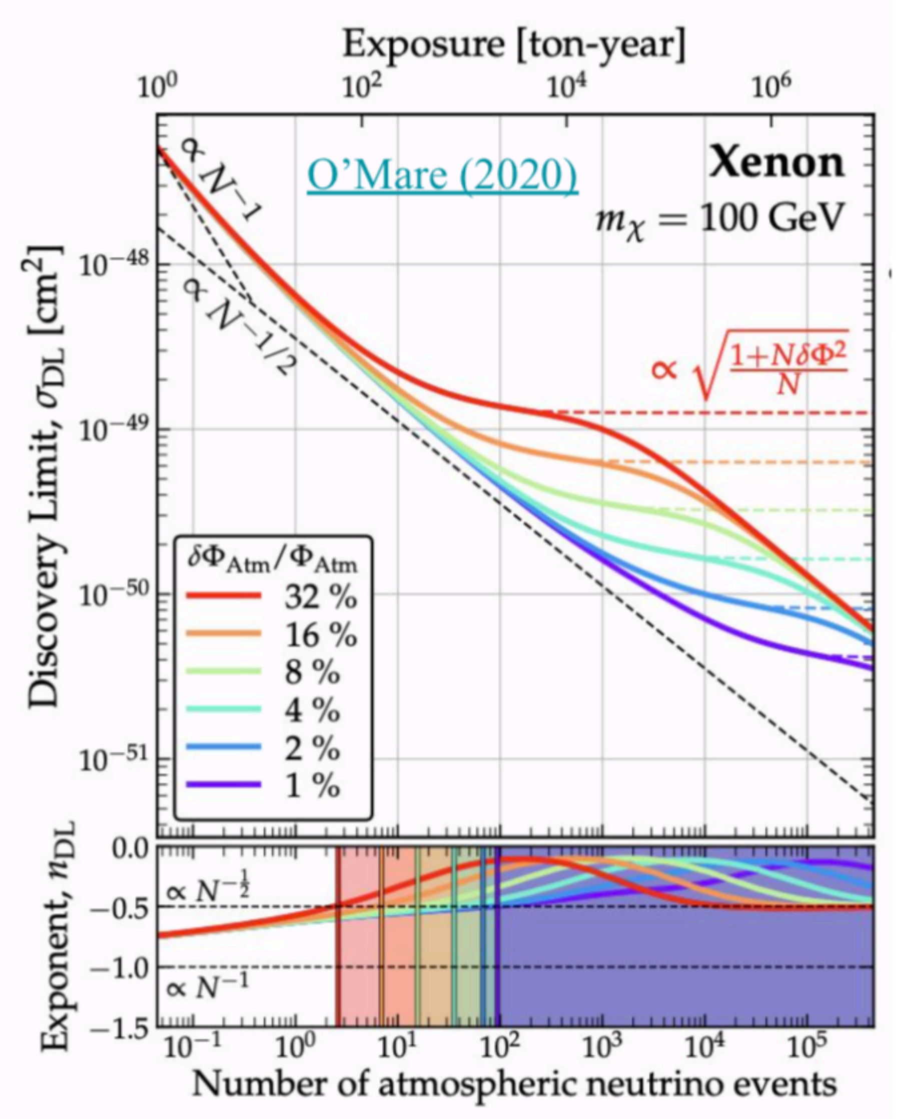
Atmospheric Neutrinos, Inside the "Fog"



Atm. ν Uncertainty



- Currently 20% @neutrino energies < 0.1 GeV (or 15% for < 1 GeV overall)
  - Theory (journals.aps.org/prd/abstract/10.1103/PhysRevD.83.123001). No measurements (sub-GeV)
- Future constraints: DUNE, HyperK, JUNO, others



Summary

- LZ does more than just WIMPs, and does more than just dark matter (direct detection) in general
  - Two-phase (primarily liquid) Xenon TPC
- CEνNS
  - Boron-8 from the Sun and supernova neutrino bursts from core-collapse supernovae
  - Atmospheric neutrinos within the fog or floor
- Coherent neutrino scattering in LZ useful for many different kinds of physics -- from nuclei and atoms to the Sun and supergiant stars
- Future (G3?) pp solar, CNO (charge current), hep

LZ (LUX-ZEPLIN) Collaboration

35 Institutions: 250 scientists, engineers, and technical staff

@lzdarkmatter

https://lz.lbl.gov/

- Black Hills State University
- Brandeis University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Auth.
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University at Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Wisconsin, Madison

(here today!)

me!

US UK Portugal Korea


LZ Collaboration Meeting – September 8–11, 2021

Thanks to our sponsors and participating institutions!

U.S. Department of Energy
Office of Science

UKRI Science and Technology Facilities Council

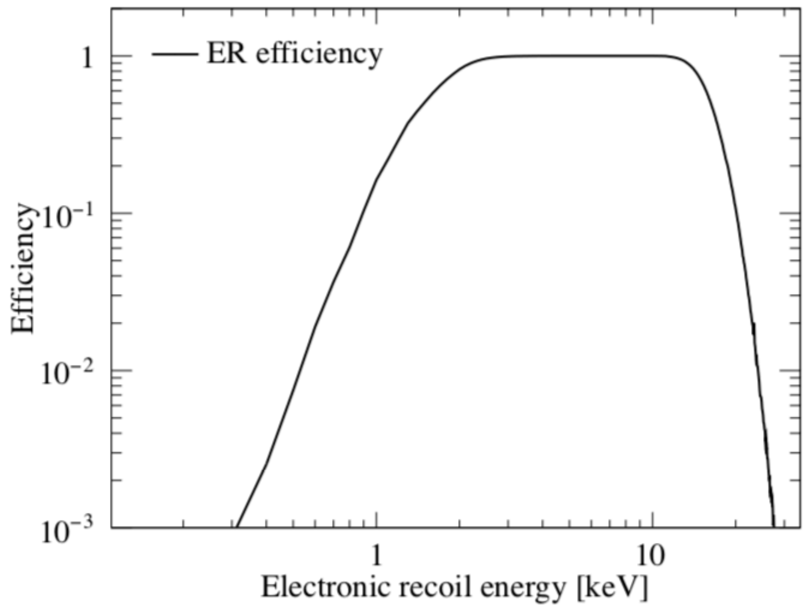
Sanford Underground Research Facility
South Dakota Science and Technology Authority

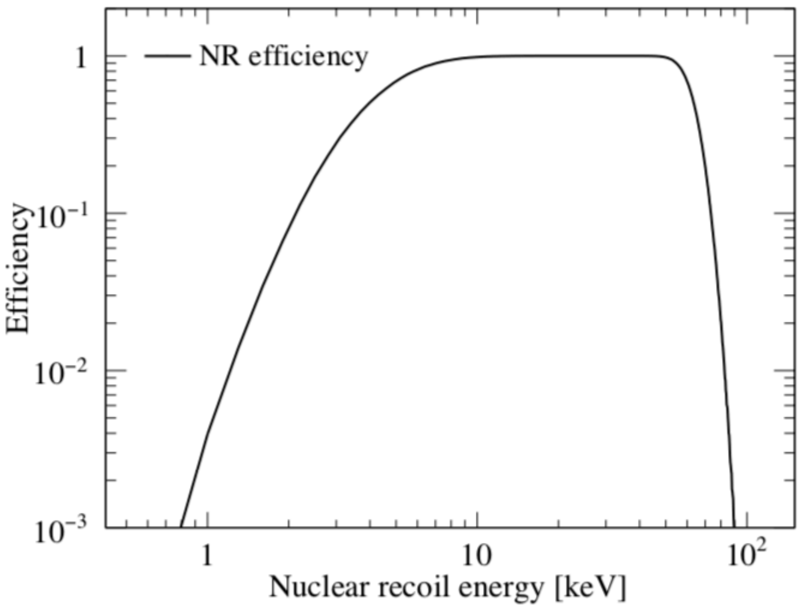
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

ibs Institute for Basic Science

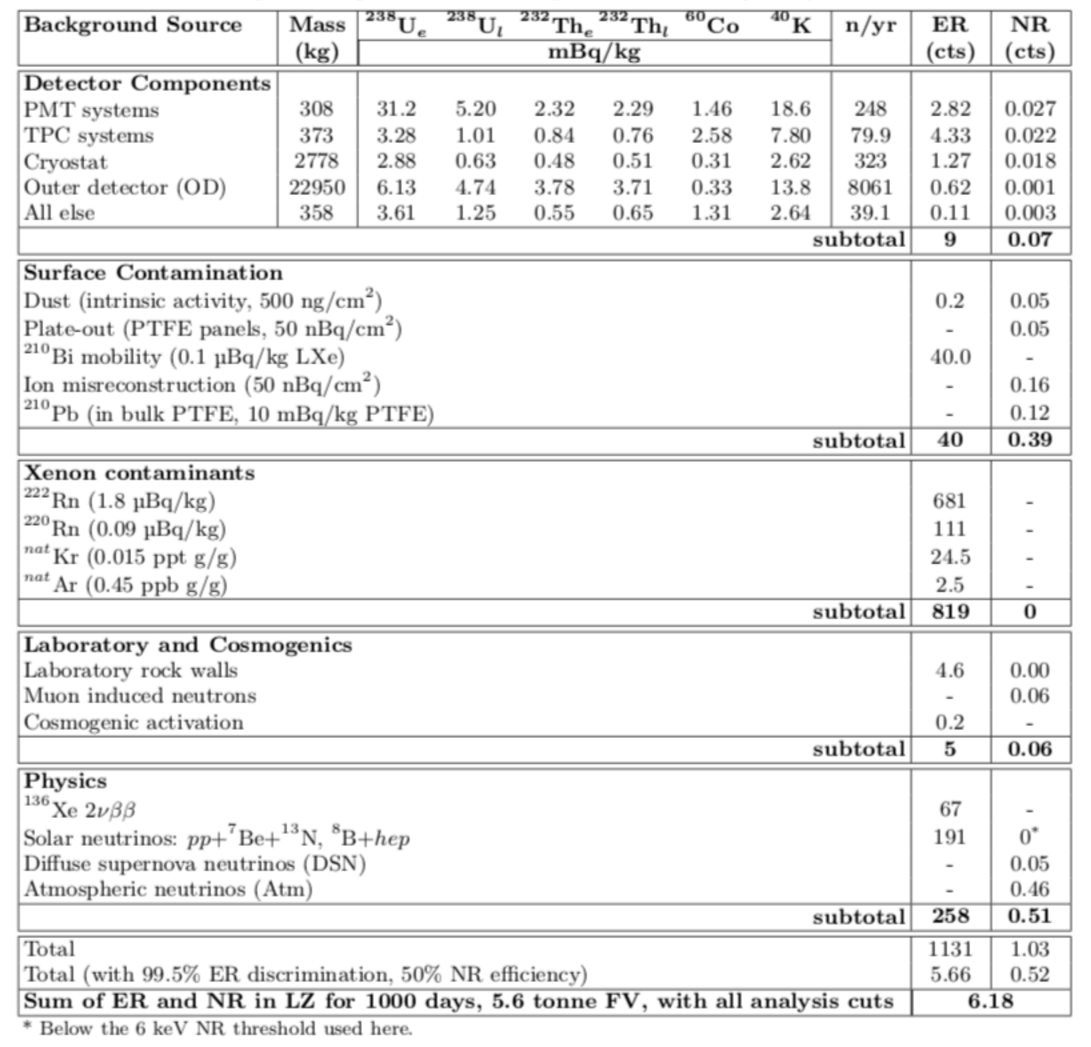
Backup

LZ (Projected, Simulated) Efficiencies





Backgrounds

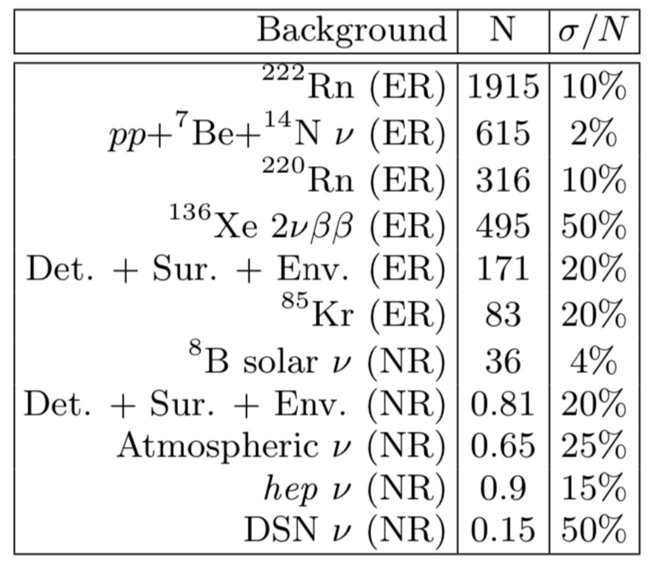


Background Source	Mass (kg)	$^{238}\mathrm{U}_e$	$^{238}\mathrm{U}_l$	$^{232}\mathrm{Th}_e$	$^{232}\mathrm{Th}_l$	$^{60}\mathrm{Co}$	$^{40}\mathrm{K}$	n/yr	ER (cts)	NR (cts)
		mBq/kg								
Detector Components										
PMT systems	308	31.2	5.20	2.32	2.29	1.46	18.6	248	2.82	0.027
TPC systems	373	3.28	1.01	0.84	0.76	2.58	7.80	79.9	4.33	0.022
Cryostat	2778	2.88	0.63	0.48	0.51	0.31	2.62	323	1.27	0.018
Outer detector (OD)	22950	6.13	4.74	3.78	3.71	0.33	13.8	8061	0.62	0.001
All else	358	3.61	1.25	0.55	0.65	1.31	2.64	39.1	0.11	0.003
								subtotal	**9**	**0.07**
Surface Contamination										
Dust (intrinsic activity, 500 ng/cm^2)									0.2	0.05
Plate-out (PTFE panels, 50 nBq/cm^2)									-	0.05
^{210}Bi mobility (0.1 µBq/kg LXe)									40.0	-
Ion misreconstruction (50 nBq/cm^2)									-	0.16
^{210}Pb (in bulk PTFE, 10 mBq/kg PTFE)									-	0.12
								subtotal	**40**	**0.39**
Xenon contaminants										
^{222}Rn (1.8 µBq/kg)									681	-
^{220}Rn (0.09 µBq/kg)									111	-
^{nat}Kr (0.015 ppt g/g)									24.5	-
^{nat}Ar (0.45 ppb g/g)									2.5	-
								subtotal	**819**	**0**
Laboratory and Cosmogenics										
Laboratory rock walls									4.6	0.00
Muon induced neutrons									-	0.06
Cosmogenic activation									0.2	-
								subtotal	**5**	**0.06**
Physics										
^{136}Xe $2\nu\beta\beta$									67	-
Solar neutrinos: pp+^{7}Be+^{13}N, ^{8}B+hep									191	0^*
Diffuse supernova neutrinos (DSN)									-	0.05
Atmospheric neutrinos (Atm)									-	0.46
								subtotal	**258**	**0.51**
Total									1131	1.03
Total (with 99.5% ER discrimination, 50% NR efficiency)									5.66	0.52
Sum of ER and NR in LZ for 1000 days, 5.6 tonne FV, with all analysis cuts									**6.18**	

* Below the 6 keV NR threshold used here.

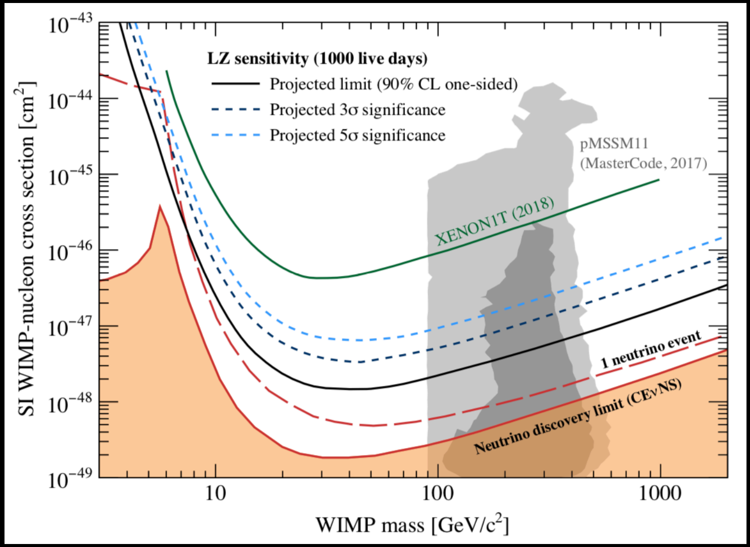
TABLE IV. Eleven background types considered in the PLR analysis, along with the integrated counts in the LZ 1000 day WIMP search exposure and the systematic uncertainties on their normalizations, included as nuisance parameters in the PLR. Counts are for the WIMP search ROI (S1 with $\geq 3-$fold coincidence, $\mathrm{S1}_c < 80$ phd and uncorrected $\mathrm{S2} > 415$ phd): approximately 1.5–15 keV for ERs and 4–60 keV for NRs; and after application of the single scatter, skin and OD veto, and 5.6 tonne fiducial volume cuts.

TABLE IV. Eleven background types considered in the PLR analysis, along with the integrated counts in the LZ 1000 day WIMP search exposure and the systematic uncertainties on their normalizations, included as nuisance parameters in the PLR. Counts are for the WIMP search ROI (S1 with $\geq 3-$fold coincidence, $\mathrm{S1}_c < 80$ phd and uncorrected $\mathrm{S2} > 415$ phd): approximately 1.5–15 keV for ERs and 4–60 keV for NRs; and after application of the single scatter, skin and OD veto, and 5.6 tonne fiducial volume cuts.



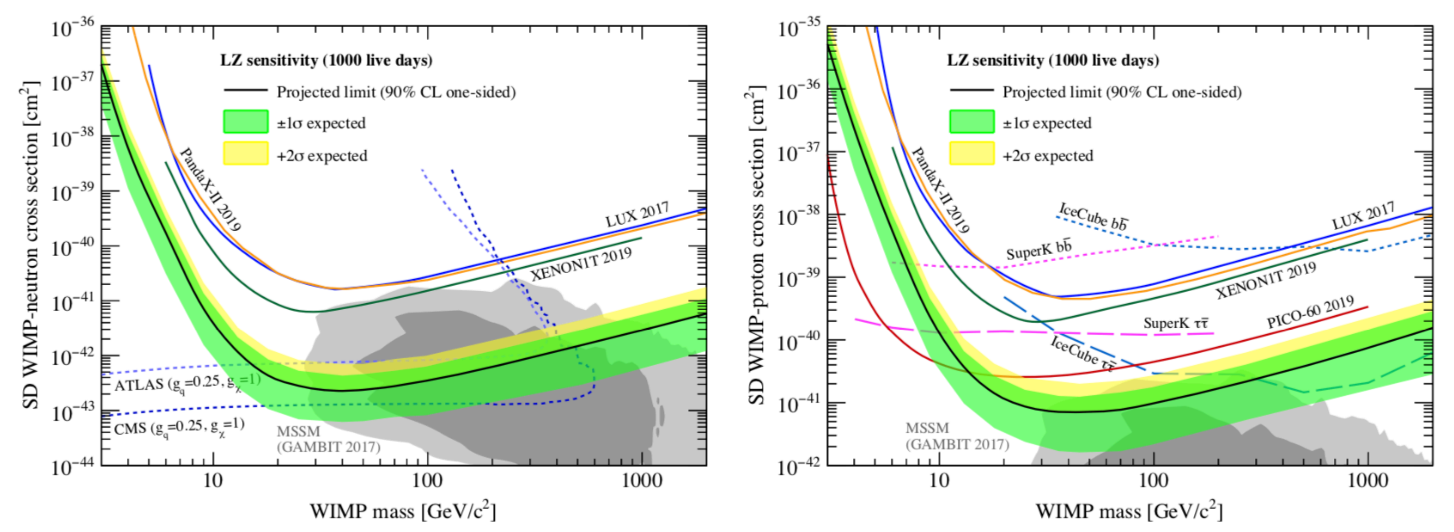
Background	N	σ/N
^{222}Rn (ER)	1915	10%
pp+^{7}Be+^{14}N ν (ER)	615	2%
^{220}Rn (ER)	316	10%
^{136}Xe $2\nu\beta\beta$ (ER)	495	50%
Det. + Sur. + Env. (ER)	171	20%
^{85}Kr (ER)	83	20%
^{8}B solar ν (NR)	36	4%
Det. + Sur. + Env. (NR)	0.81	20%
Atmospheric ν (NR)	0.65	25%
hep ν (NR)	0.9	15%
DSN ν (NR)	0.15	50%

Discovery Potential, SD Sensitivities

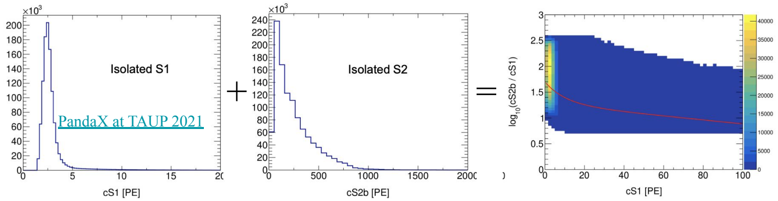


(above “limit” of course)

(EFT operator searches also possible)

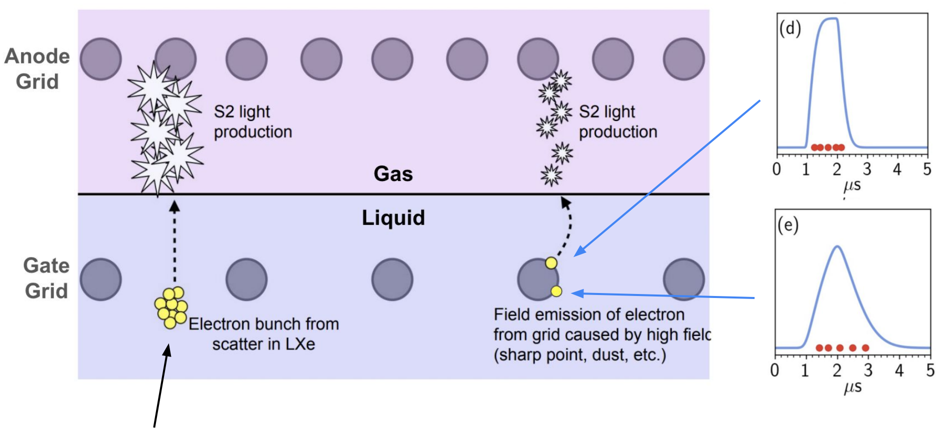


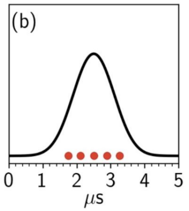
Challenge: Accidental Coincidence



- An accidental coincidence event occurs when an isolated S1 randomly pile-up with an isolated S2
- Possible sources of isolated S1:
  - Dark count pile up
  - Cherenkov in PMT windows / PTFE wall
  - Energy deposition occurs in non-drifting region
- Possible sources of isolated S2:
  - field electron emission from gate and cathode grids
  - delayed electron emission following S2s (ex. electron trapped at liquid surface or captured by impurity)
  - radiogenic grid emission
- Data-driven Modeling
  - Find isolated S1 events and isolated S2 pulse, and randomly pair them up (top plots)

X. Xiang (2021)





BDT technique in LUX (K. Oliver-Mallory 2020):

- (b): Longitude electron diffusion → S2 pulses from bulk LXe are symmetric (b)
- (d) (e): Non-linear field fringing → S2 pulses from grid surface are asymmetric

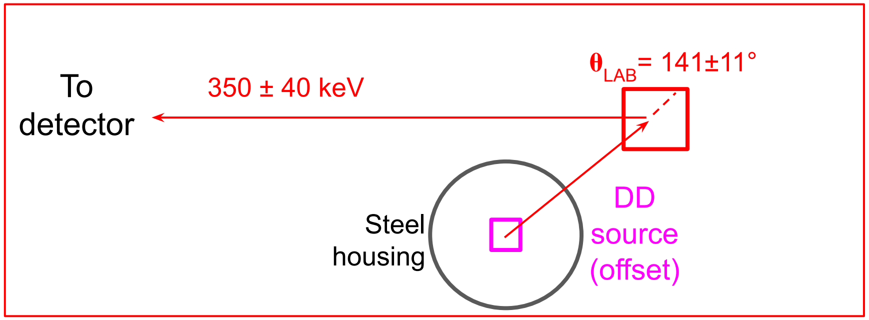
- Features & Rejection:
  - Asymmetric S2 pulse shape (Machine Learning)
  - Drift time is uncorrelated to electron diffusion (Drift time vs S2 width)
  - Correlate with PMT that has abnormally high DC rate (PMT tagging)

DC = Dark Count

Mitigation Strategy - DD Calibration

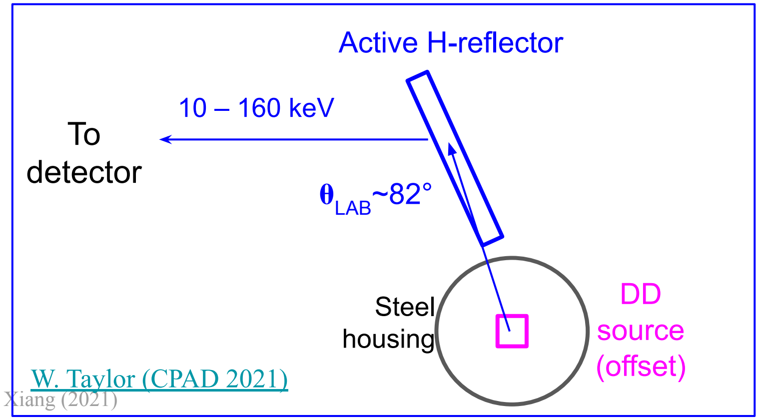
Direct DD Mode:

- Monoenergetic 2.45 MeV neutrons from the deuterium-deuterium (DD) fusion in the generator
- Neutron production pulsed width of **12 us** (HWHM)



D-Reflector Mode:

- Backward-scattering from deuterated scintillator (EJ315) generates **350±40 keV** neutron KE peak (HWHM)
- Time-of-flight (ToF) tag between D-reflector scintillator and TPC permits per-neutron KE reconstruction
- Delivers ~**600 "golden" single-scatter** events /keV/day in **1-10.6 $\mathbf{keV_{nr}}$** recoil energy with per-event ToF-tagged neutron KE.



W. Taylor (CPAD 2021)

X. Xiang (2021)

H-Reflector Mode:

- Forward-scattering near 90 degrees off hydrogenous scintillator (EJ200) generates **10-160 keV** neutron KE range.
- Time-of-flight (ToF) between H-reflector scintillator and TPC permits per-neutron KE reconstruction
- Delivers ~**700 "golden" single-scatter** events /keV/day in **0.3-4.8 $\mathbf{keV_{nr}}$** recoil energy with per-event ToF-tagged neutron KE.