CEνNS and the Search for Dark Matter in the LZ experiment

Xin Xiang, Ph.D.
On behalf of LZ Collaboration

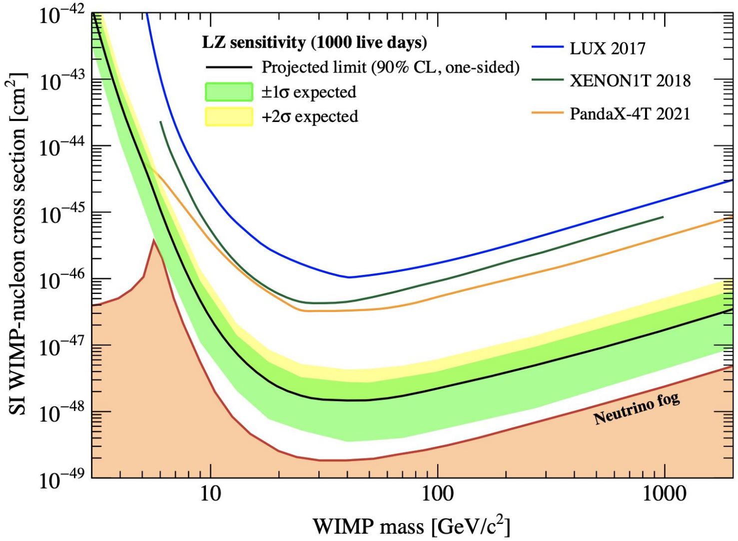
Magnificent CEνNS 2021

Sanford Underground Research Facility
South Dakota Science and Technology Authority
BROWN

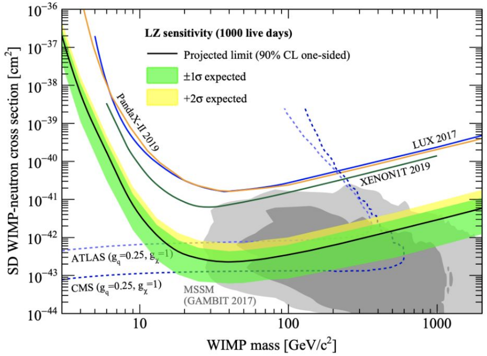
Physics Reach of LZ

- LZ detector is multi-purpose (Swiss-Army-Knife)
- Projected World-leading Dark Matter Sensitivity
  - Full exposure: 15.3 tonne-year
  - SI WIMP-nucleon sensitivity: 1.4×10^{-48} cm^2 @ 40 GeV
  - SD WIMP-neutron (proton) sensitivity: 2.7×10^{-43} (7.1×10^{-42}) cm^2 @ 40 GeV
  - Sub-GeV masses accessible via Migdal effect
- Search of Other DM Candidates:
  - ALPs, hidden photon, mirror DM, etc
- Non-DM Physics
  - Solar axions, supernova neutrinos
  - Neutrino magnetic moment
  - Search of $0\nu\beta\beta$
  - 2νECEC on ^{124}Xe

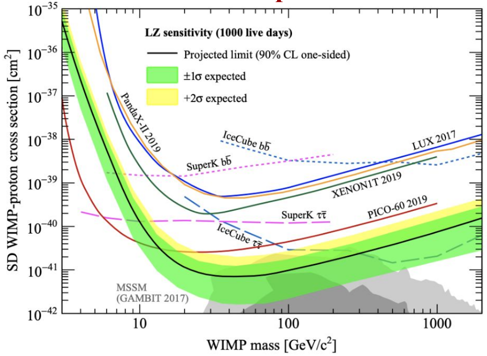
SI WIMP-nucleon



WIMP-neutron

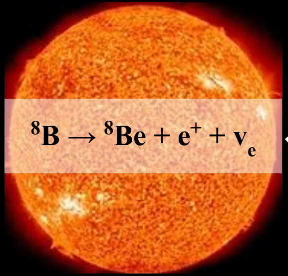


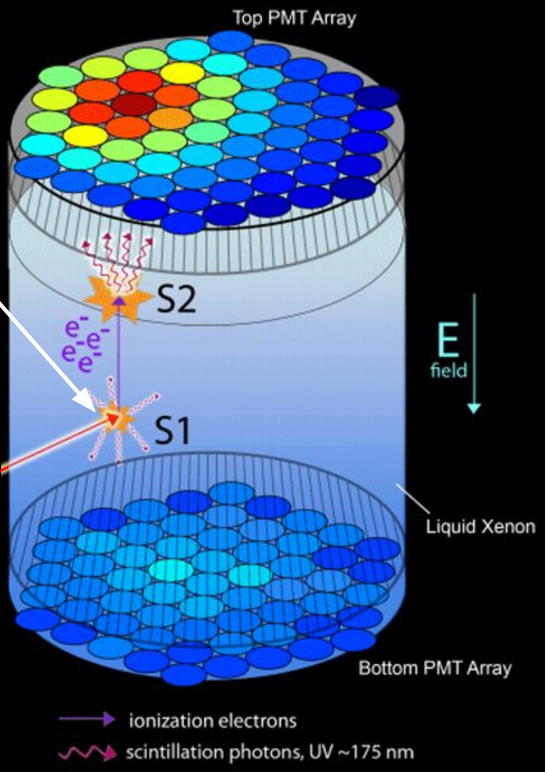
WIMP-proton

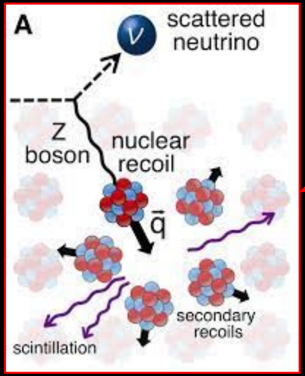


X. Xiang (2021)

Working Principle of a TPC







Coherent ⟶ sees nucleus as a whole
Elastic ⟶ no nuclear excitations

X. Xiang (2021)

Principle of a TPC

- Prompt primary scintillation light at interaction site ⟶ S1
- Ionization electrons are drifted to gas pocket where it produces light via electroluminescence ⟶ S2
- Drift time ⟶ z position at O(mm) precision.
- S2 channel pattern ⟶ (x,y) positions at O(cm) precision
- S2/S1 ratio ⟶ ER/NR Discrimination:
    - S2/S1 ratio depends on dE/dx
    - ER produces relatively more charge than NR

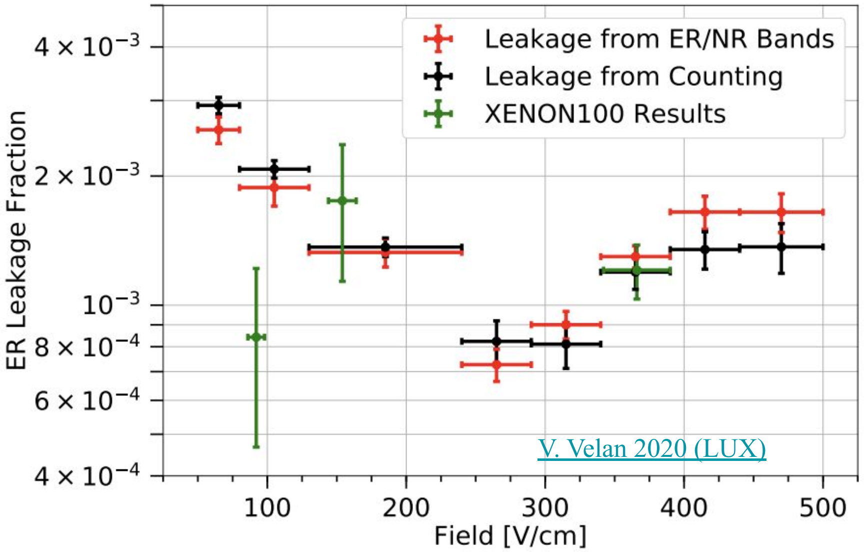
ER/NR Discrimination

Background (ER/NR) to Dark Matter Search:

- Internal LXe:
    - ^{222}Rn (target: 2 μBq/kg), ^{220}Rn, ^{85}Kr, ^{136}Xe
- Material γ-rays:
    - ^{238}U, ^{232}Th chains, ^{60}Co, ^{40}K
- Physical: solar *pp* neutrinos
- Detector material: (α,n) & spontaneous fission
- Cosmogenic neutrons
- CEνNS:
    - **Solar ^{8}B, Atmospheric, Diffuse Supernova, Solar *hep***
- Surface backgrounds (α-decays, recoiling nuclei)

LXe TPC has powerful discrimination against ER backgrounds

Discrimination Study from LUX Run 4 Data

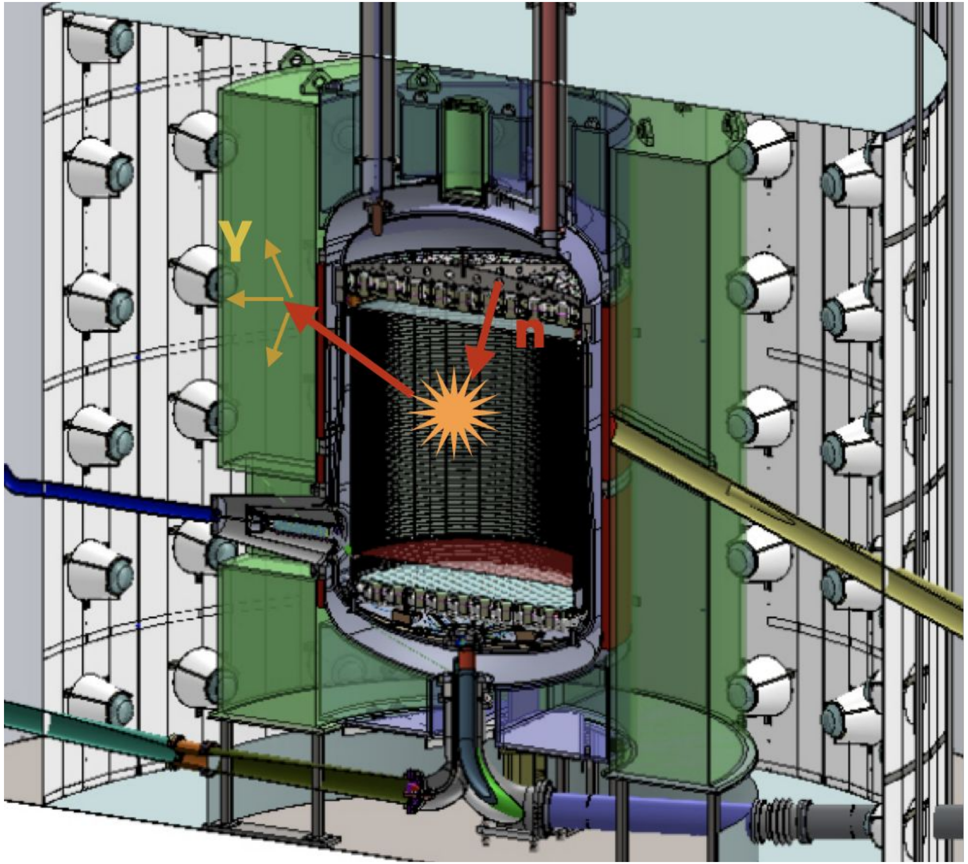


The Veto System

Neutrons are suppressed by shielding & active neutron veto

Three Layers System:

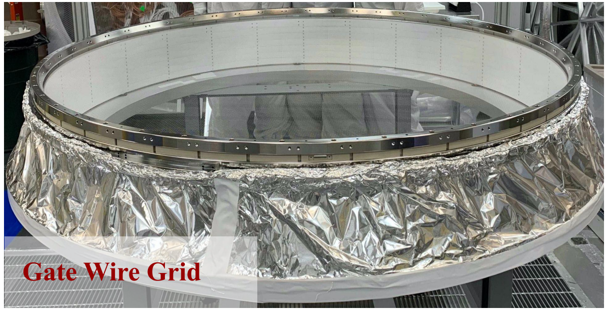
1. A layer of LXe skin in the TPC inner cryostat, monitor by separated PMTs
   a. tagging γ-rays efficiency: **>95%**
2. Acyclic vessels surrounding TPC cryostat
   a. Gd (0.1% doped) loaded LS (Linear Alkyl Benzene)
   b. Neutron captured on Gd followed by emission of 3-5 γ-rays:
      i. $n + {}^{155}Gd \rightarrow {}^{156}Gd + 8.5$ MeV (18%)
      ii. $n + {}^{157}Gd \rightarrow {}^{158}Gd + 7.9$ MeV (82%)
   c. neutron veto efficiency **> 95%**
3. Water Tank as a passive shielding



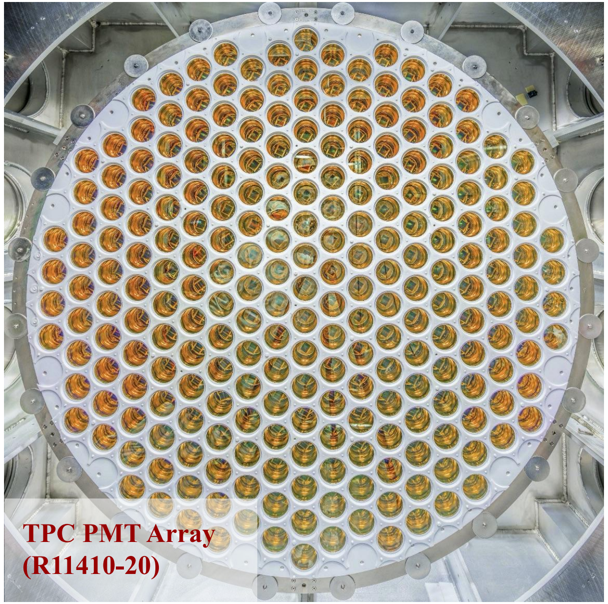
X. Xiang (2021)

Photo of the LZ TPC

TPC Assembled



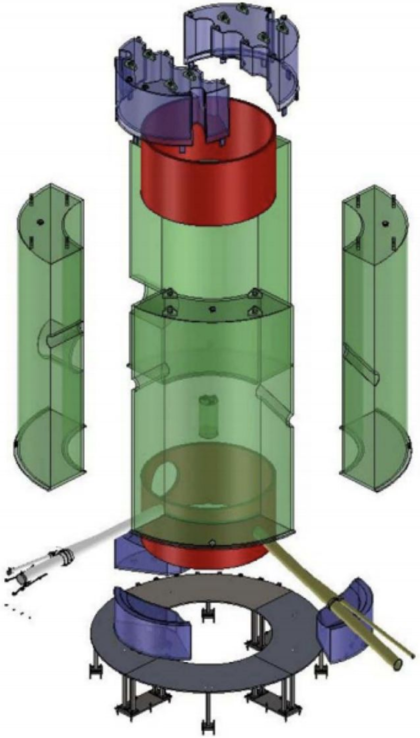
Gate Wire Grid



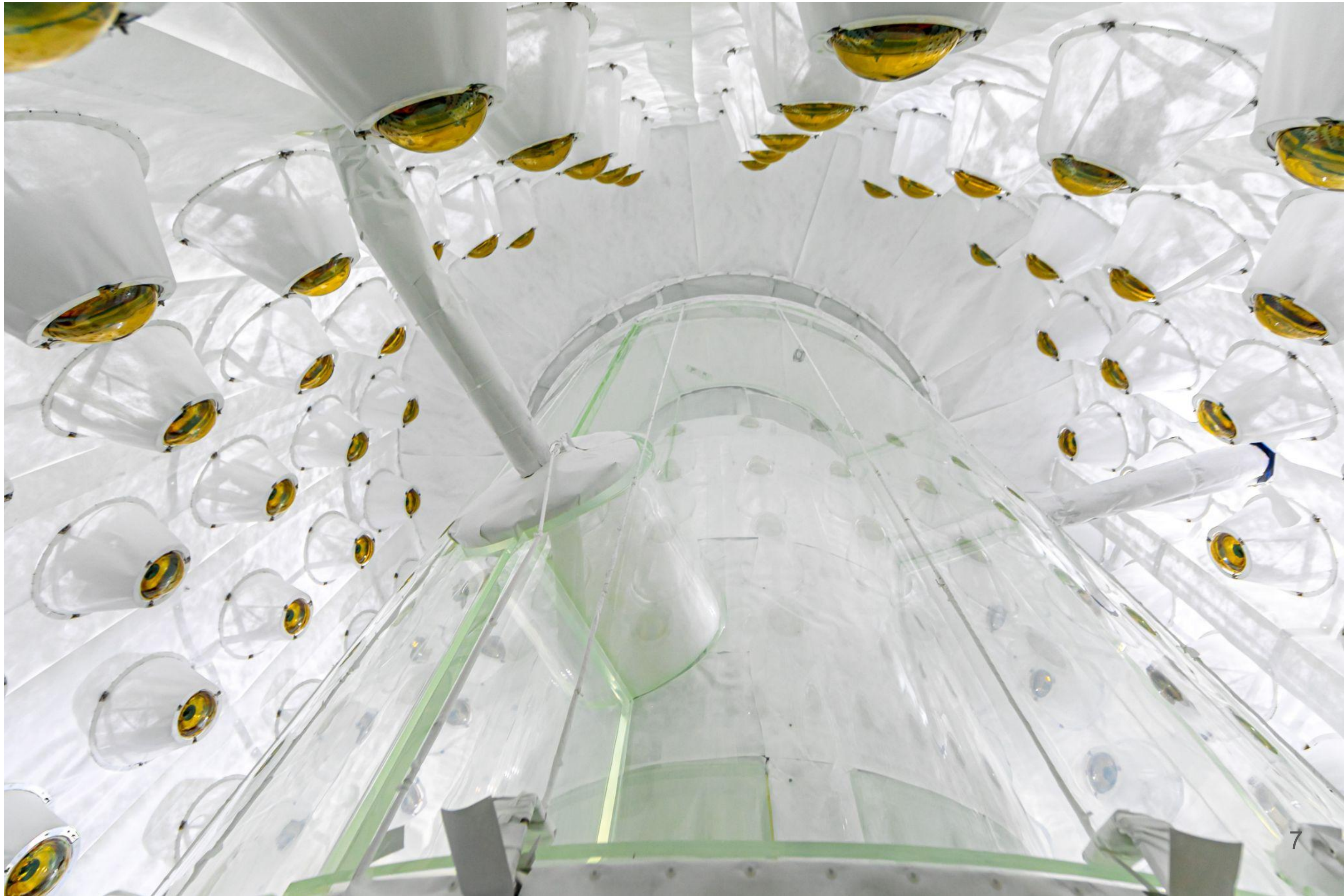
TPC PMT Array
(R11410-20)

TPC as it descends into Ti cryostat

Acyclic Vessels Inside the Water Tank



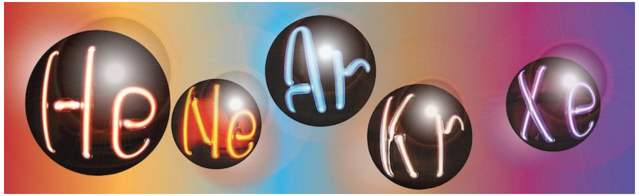
X. Xiang (2021)

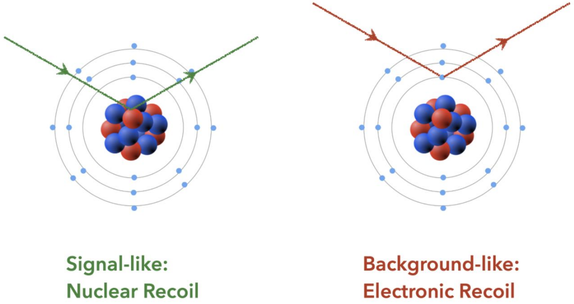


LXe TPC as Neutron Observatory via CEvNS

- LXe is an excellent target for CE*ν*NS
  - Enhanced cross-section due to **~N^2**
  - Sensitive to **sub-keV** CE*ν*NS (high scintillation and ionization yield)
- LXe TPC is optimized for observing rare NR from WIMPs (same as CEvNS signature)
  - Low backgorund (radiopurity & shielding & veto)
  - **S2/S1** (ionization to scintillation ratio) discriminates against Electronic Recoils (ER) events
  - Scalable detector

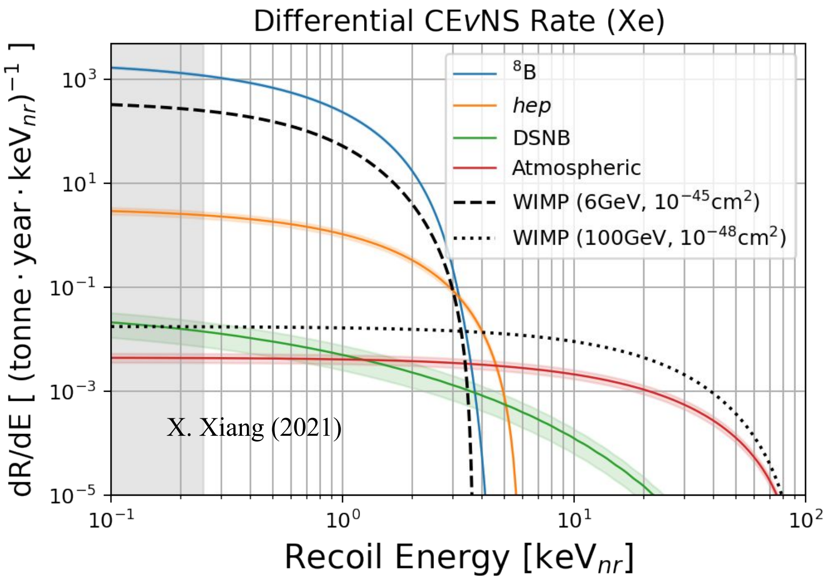
→ **Suitable for observing natural neutrino via CEvNS down to 5 MeV**

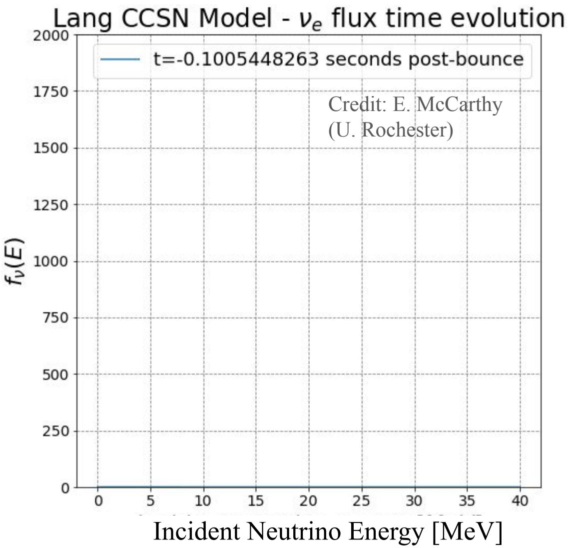




X. Xiang (2021)

CEνNS from Natural Neutrinos





This gif animation does not work in the pdf version

All CEνNS recoil spectra that LZ is capable of seeing

- ^{8}B spectrum is the same as a 6 GeV WIMP
- Atm. spectrum is the same as WIMPs > 100 GeV

Supernova Neutrino

- LZ is a member experiment of the Supernova Neutrino Early Warning System 2.0 (SNEWS 2.0) network.
- Observed signal is a stream of S2 pulses within 10 seconds

X. Xiang (2021)

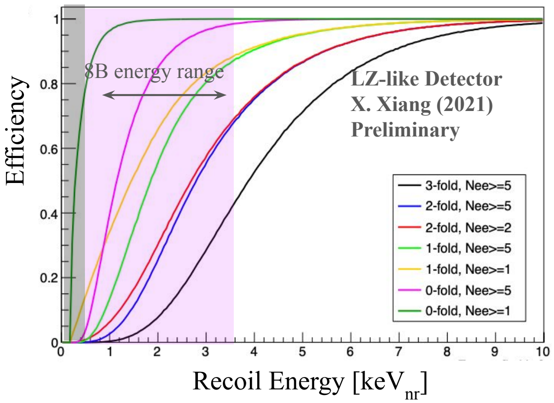
Opportunity: the First ^{8}B Observation via CEνNS

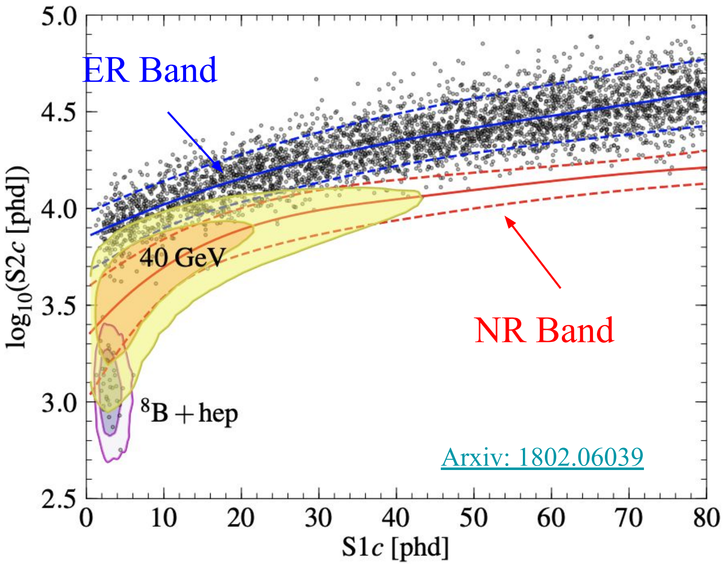
- ^{8}B has never been observed in CEνNS channel. This is exciting!
- Events populate near threshold (purple).
- The expected event rate (FV=5.6e3 kgd) is sensitive to the thresholds (preliminary):
  - LZ threshold (3-fold, $N_{ee} \geqslant 5$): **(2.7 ± 0.69^{yield}) evt/100 day**
  - Lower threshold (2-fold, $N_{ee} \geqslant 5$): **(12 ± 2.3^{yield}) evt/100 day**
- A significant claim is not a matter of if, but a matter of when

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

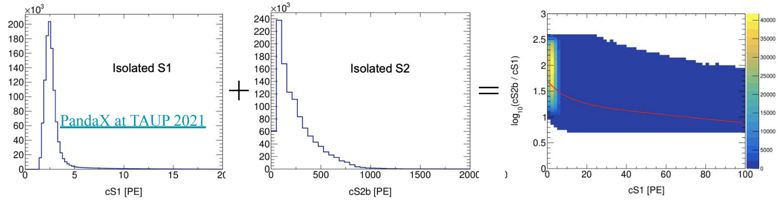
	3-fold (S1 ≥ 3 phd)	2-fold (S1 ≥ 2 phd)	S2-only (0 or 1 phd)
Nee ≥ 8 e-	1.39	5.32	23.6
Nee ≥ 7 e-	1.78	7.1	37.8
Nee ≥ 6 e-	2.23	9.42	58.4
Nee ≥ 5 e-	**2.73**	**12.1**	91.7
Nee ≥ 4 e-	3.25	15.4	142
Nee ≥ 3 e-	3.73	18.8	217

NR Efficiency for Various Thresholds

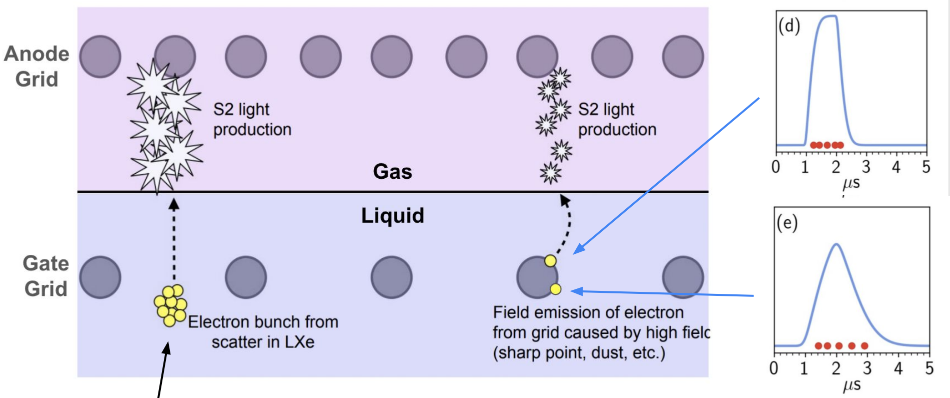


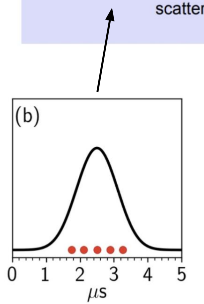


Challenge: Accidental Coincidence



- 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)





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)

X. Xiang (2021)

The ^{8}B Rate Uncertainties

CEvNS Recoil Rate → Produced Quanta photon/electron → Observables S1 & S2

Neutrino Flux
- 4.4% uncertainty [SNO, Broxino]

Cross-section
- Helm’s form factor ~ 1 for ^{8}B

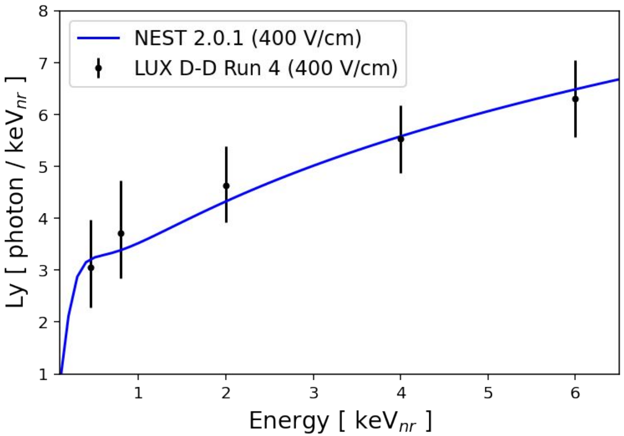
NEST* Yield Model
- Def. # of quanta created per energy deposition
- **Light yield (Ly)**
- Charge yield (Qy)

(S1, S2) Detection Threshold → NR Efficiency

Signal Detection Efficiency
- Electron survival probability during the drift (e-life ~ 850 μs)
- g1: probability of a photon being detected (g1 ~ 0.12)
- g2: avg. number of electroluminescence photons per electron (g2 ~ 80 phd/e)

The best NR calibration data:
- Ly: LUX Run4 calibration (Huang 2020)
- Qy: Livermore measurement (Xu 2019)

Ly is the highest source of systematics.



$$\langle S1 \rangle = E_r \times Ly \times g1$$
$$\langle S2 \rangle = E_r \times Qy \times g2$$

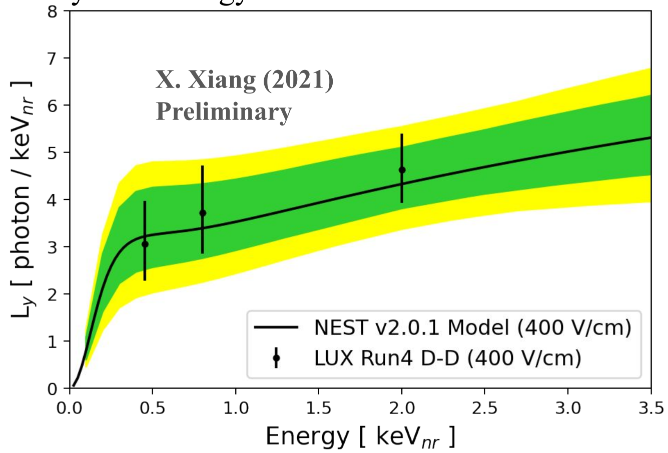
X. Xiang (2021)

*NEST stands for Noble Element Simulation Techniques

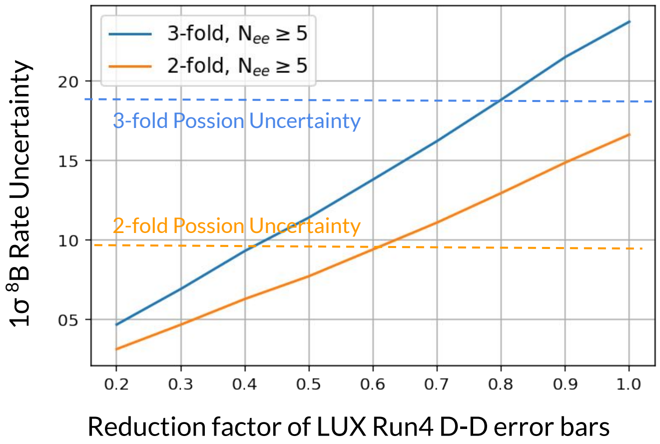
The Ly Uncertainty

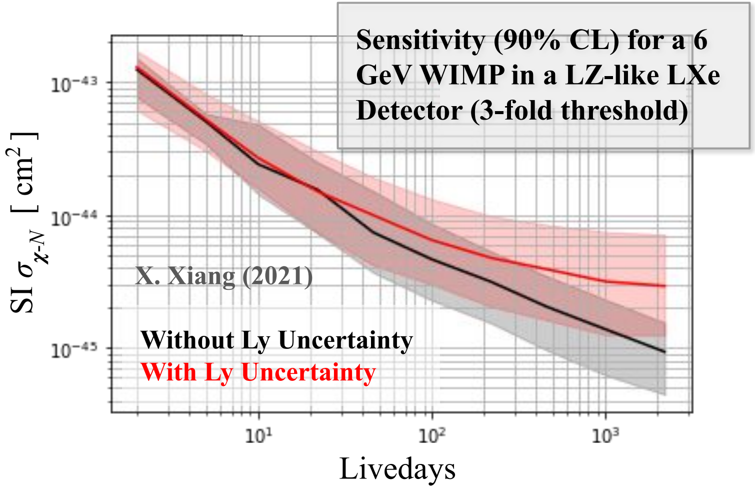
- The Ly uncertainty for low-energy NRs is studied
    - Uncertainty in 8B Rate (preliminary): **~ 25%** (3-fold) **~18%** (2-fold)
    - Ly variation affects both WIMPs and CE*v*NS (correlated)
- In comparison, Qy uncertainty for N_{ee}> 5 threshold: 6%
- The effect on the proj. sensitivity is investigated:
    - **Earlier saturation at high exposure**
    - **Short-term (<100 days) effect is subdominant to Poisson fluctuation**
- Low-energy NR calibration requirement is quantified.

Ly Low-energy Error Based on LUX D-D data



NR Calibration Requirement for a 15.3 tonne-year exposure in a LZ-like detector



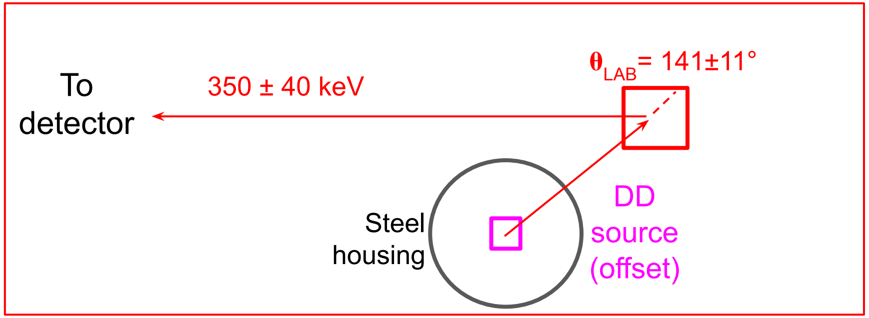


X. Xiang (2021)

Mitigation Strategy - DD Calibration

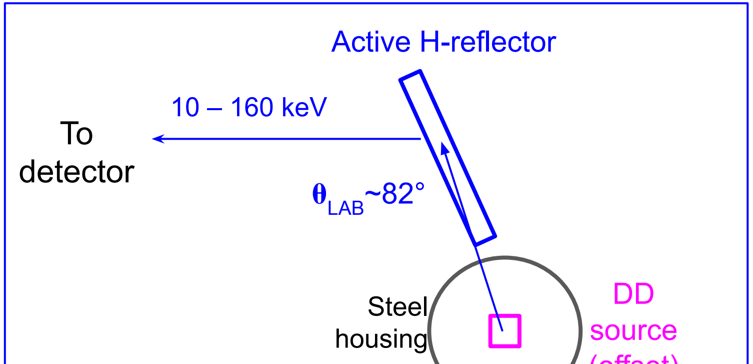
Direct DD Mode:

- 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 keV$_{nr}$** recoil energy with per-event ToF-tagged neutron KE.

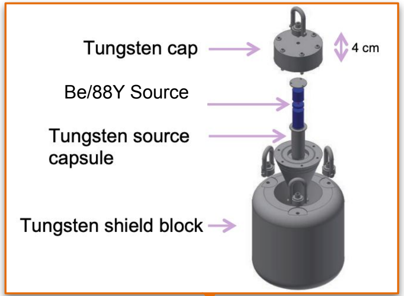


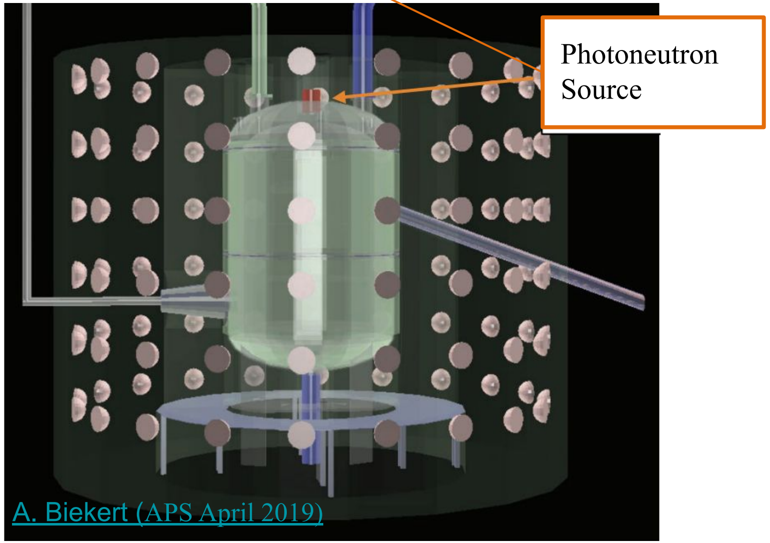
W. Taylor (CPAD 2021)

H-Reflector Mode:

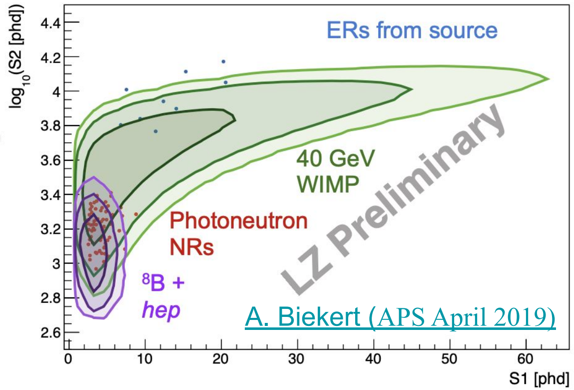
- Forward-scattering near 90 degrees off hydrogenous scintillator (EJ200) generates **10-160 keV** neutron KE range.
- Time-of-flight (ToF) between H-reflector scintillator and TPC permits per-neutron KE reconstruction
- Delivers ~**700 “golden” single-scatter** events /keV/day in **0.3-4.8 keV$_{nr}$**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

Mitigation Strategy - Photoneutron Calibration



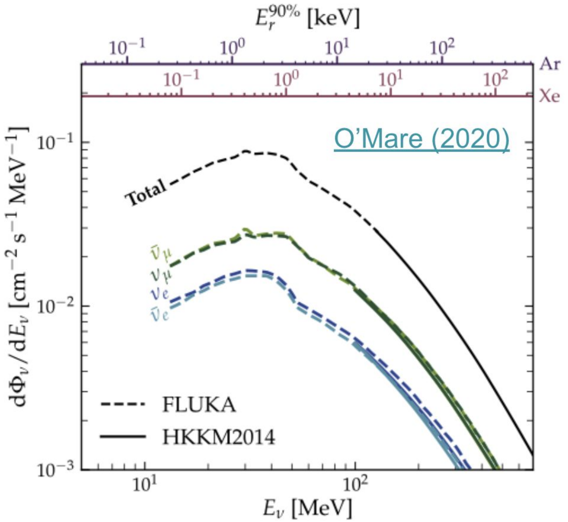


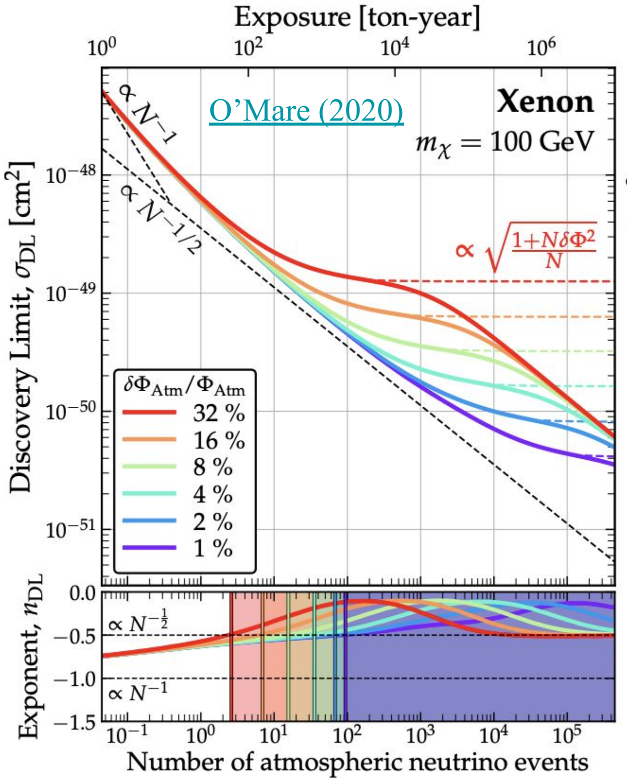
- (γ, n) reaction
  - Match γ energy to Q-value → low-energy n
  - Small cross-section → 10^4:1 γ-n yield → Tungsten shielding
- ^{88}Y-Be source:
  - 3.7 MBq ^{88}Y MeV-scale γ-rays
  - $E_n \sim E_\gamma + Q \rightarrow \sim 470$ n/s, $E_n \sim 153$ keV
  - Single-scatter NR endpoint: 4.6 $\mathrm{keV_{nr}}$
- For more info, see: [A. Biekert (APS April 2019)]



Proposed as DM calibration: J. I. Collar. PRL, 110(21), 2013.

Atmospheric Neutrino and the Neutrino Floor (Fog)

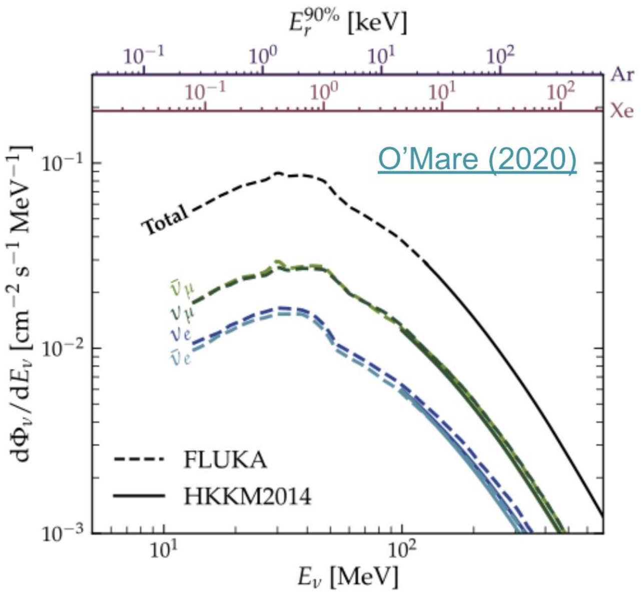


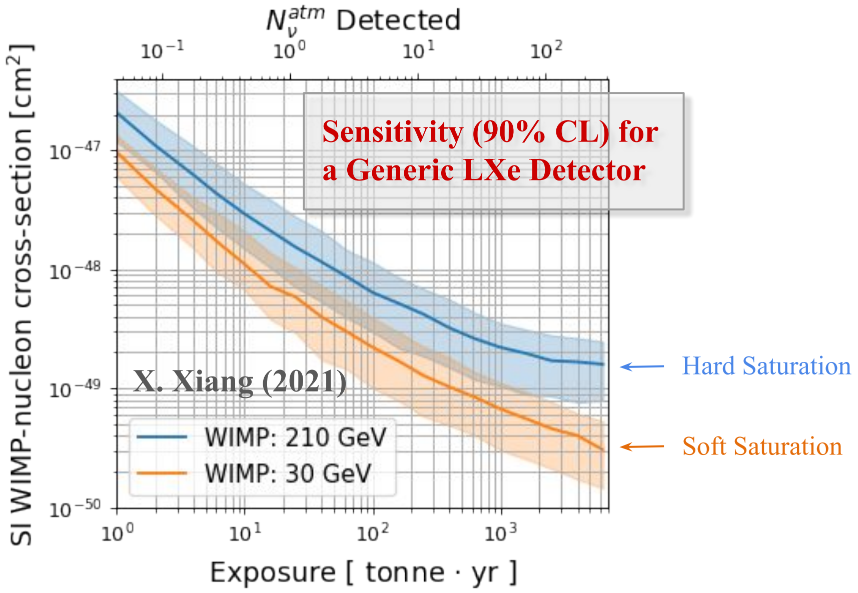


Atm. Neutrino Uncertainty:

- Current 20% (E_ν<100 MeV), 15% (E_ν<1 GeV) u/c comes from calculation [Honda 2011]. No direct experimental measurement for sub-GeV *atm*.
- Future experimental constraint (not necessarily a completed list):
  - *DUNE [K. J. Kelly 2019] :0.1 - 1* GeV range
  - *Hyper- Kamiokande* [Z. Li 2017], 100 MeV - 10 TeV
  - *JUNO [G. Settanta 2019], 0.1 GeV - 10 GeV range, projected u/c: 10% to 25%*

Atmospheric Neutrino and the Neutrino Floor (Fog)





Atm. Neutrino Flux Uncertainty:

- Current **20% (E_ν<100 MeV)**, 15% (E_ν<1 GeV) u/c from calculation [Honda 2011]. No direct experimental measurement for sub-GeV.
- Future experimental constraint (not necessarily a completed list):
  - *DUNE [K. J. Kelly 2019] :0.1 - 1* GeV range
  - *Hyper- Kamiokande* [Z. Li 2017], 100 MeV - 10 TeV
  - *JUNO [G. Settanta 2019], 0.1 GeV - 10 GeV range, projected u/c: 10% to 25%*

Effect on WIMP Sensitivity (neutrino floor/fog)

- An generic LXe detector simulated by NEST
  - NR efficiency curve is similar to LZ (slide 10, black curve)
  - Total ER leakage: 10^{-4} below NR median
- Backgrounds considered (Rn is ignored):
  - Atmospheric neutrino (20% u/c)
  - *pp* neutrinos
  - ^{136}Xe $2\nu\beta\beta$ (N.A., $T_{1/2} = 2.11 \times 10^{21}$ yr [EXO-200])
- PLR Setting:
  - Two-sided, Frequentist, μ_s>0, ... [arxiv: 2105.00599]

X. Xiang (2021)

Summary

- Ton-scale LXe detector is sensitivie MeV-scale natural neutrinos via CEvNS
- Opportunity for LZ to make the first detection of 8B in CEvNS channel
- CEvNS presents challenges for WIMP searches
  - Above 100 GeV: hard neutrino floor (fog) due to atm. uncertainty
  - 4-10 GeV: neutrino floor (fog) due to ^{8}B uncertainties (light yield)
    - Short-term impact is subdominat to Poisson fluntation .
    - Long-term impact on sensitivity → **improvement in light yield measurement is crucial**
  - 10 GeV - 100 GeV: soft neutrino floor (fog) due to different spectrum shape between WIMP and atm neutrinos
- Next Generation Liquid Xenon experiment may (aside from WIMP search) measure:
  - solar *pp (Weinberg's angle* $sin^2\theta_W$*)* via electron scattering
  - ^{8}B *(*NC NSI*)* via CEvNS
  - *CNO* (Solar metallicity) via Charge Current

Acknowledgements - Thank You!

@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 Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- 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

US UK Portugal Korea

Thanks to our sponsors and participating institutions!

U.S. Department of Energy Office of Science

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

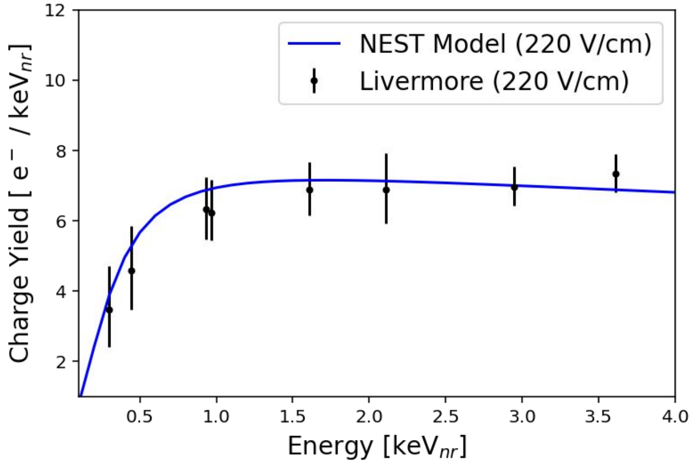
Institute for Basic Science

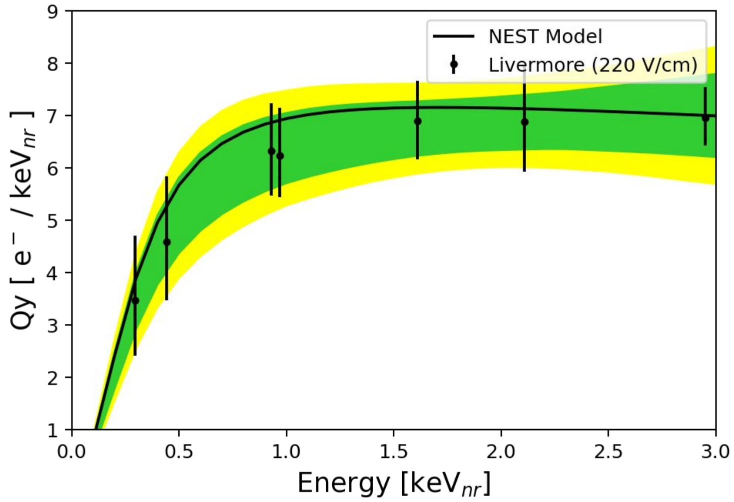
Backup

Charge Yield

Livermore (2020) measurement significantly brings down the Qy uncertainty, comparing to Ly

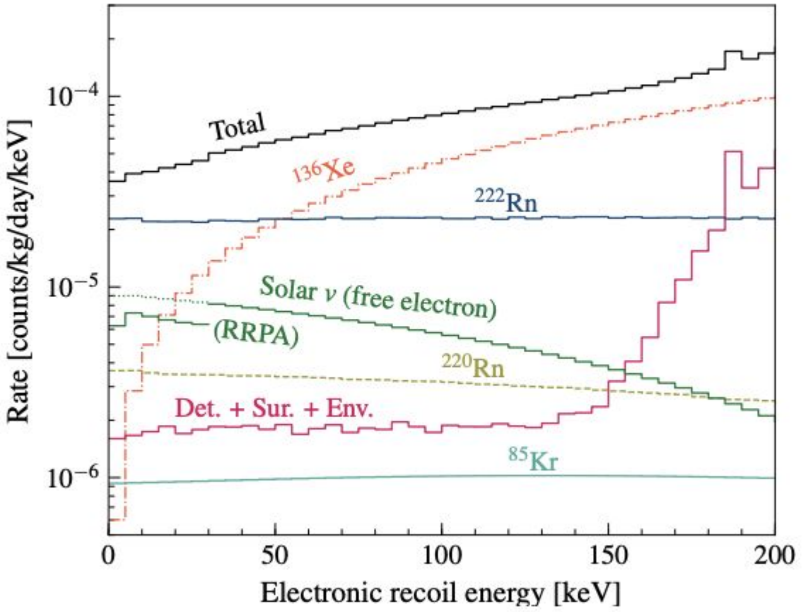
The expected ^{8}B rate varies ~6% due to Qy variation.

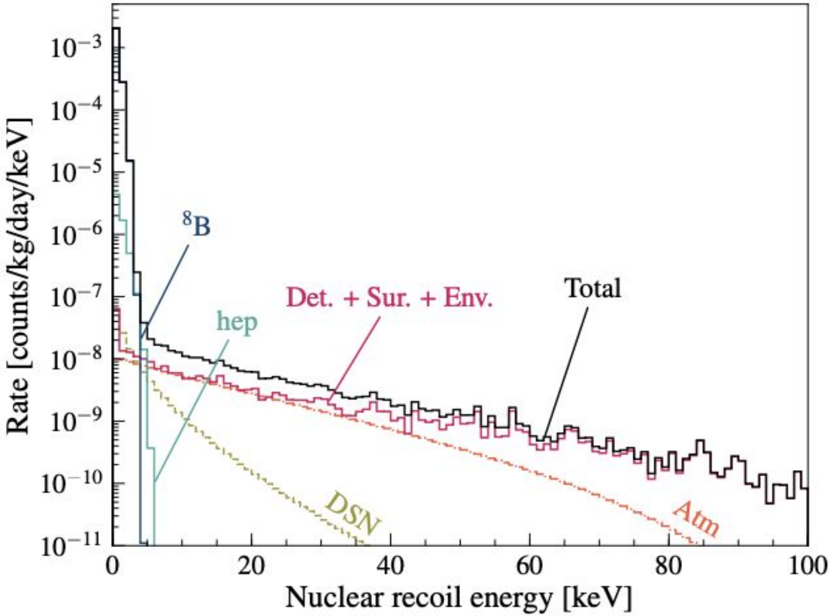




X. Xiang (2021)

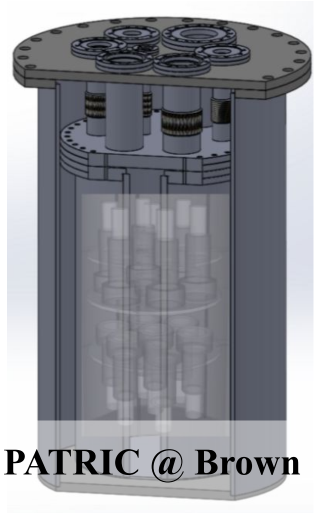
Background Energy Spectra

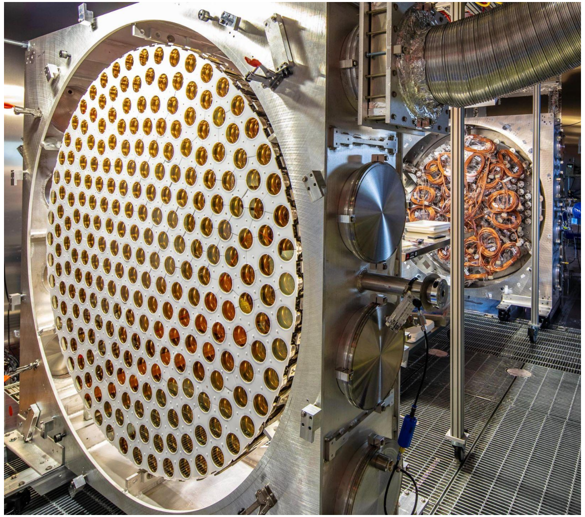


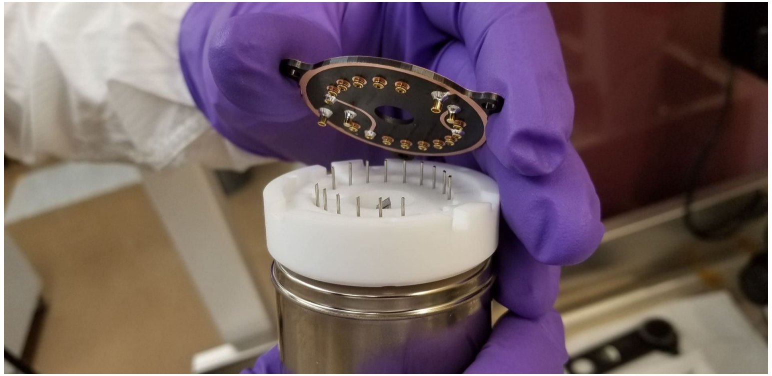


X. Xiang (2021)

PMT Arrays







X. Xiang (2021)