Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) with Noble Liquids

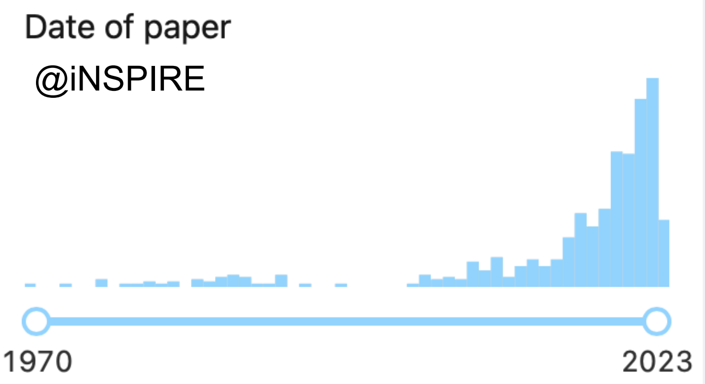
Kaixuan Ni (UC San Diego)

WIN 2023, July 2023, SYSU

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- CEvNS is a standard model process predicted 50 years ago (D.Z. Freedman, 1973) and was first observed by the COHERENT collaboration at the Spallation Neutron Source (SNS) in 2017 [1708.01294]
- Particle physics:
  - weak mixing angle
  - neutrino EM properties: charge radius, magnet moments, millicharge
  - non-standard interactions (NSI), light mediators ….
- Nuclear physics
  - nuclear form factors, neutron radius…
- Astrophysics:
  - Solar neutrinos and supernova neutrinos
- New physics:
  - sterile neutrinos, dark matter
- Applications:
  - nuclear security, reactor fuel (spent fuel) monitoring

$$\frac{d\sigma}{dE_R} = \frac{G_F^2}{4\pi}(N - Z(1-4\sin^2\theta_w))^2 m_N (1 - \frac{m_N E_R}{2E_\nu^2}) F^2(E_R)$$

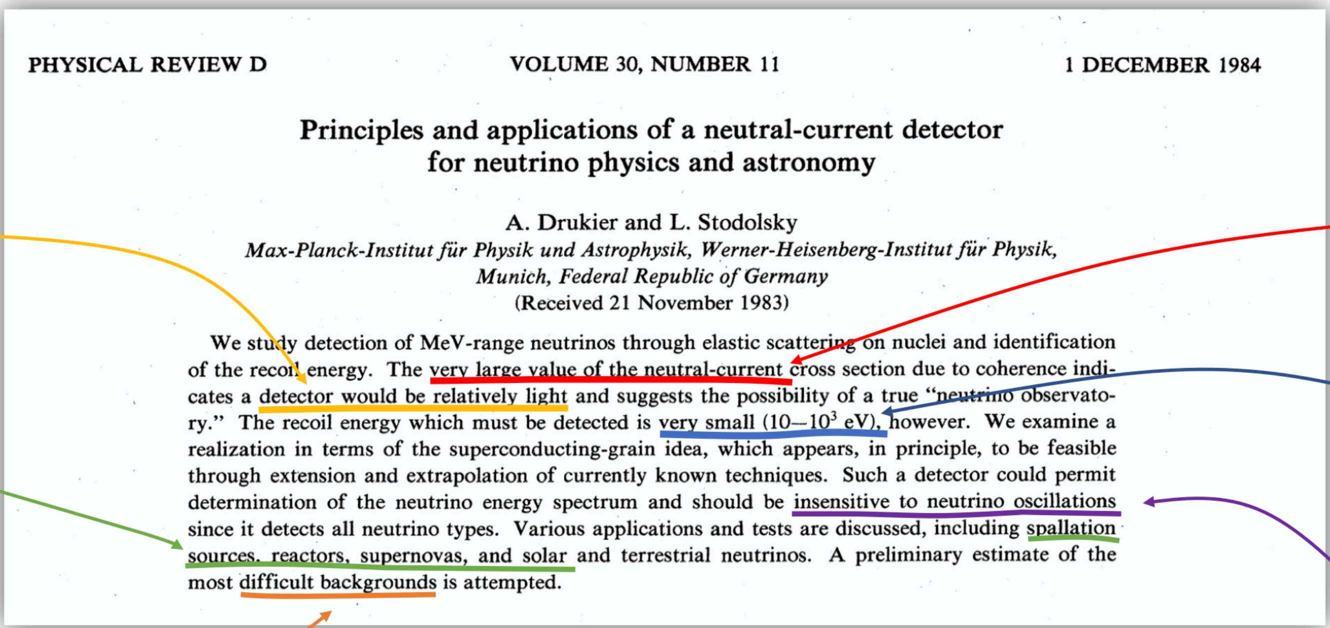


opening talk at Magnificent CEvNS 2023, Munich

Victoria Wagner & Raimund Strauss

Small detectors

experimental ideas


PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky

Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany

(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

CEvNS is strong

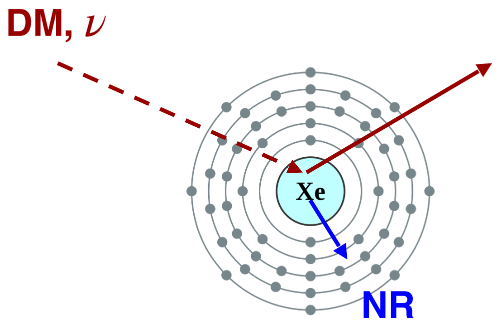
CEvNS is tiny

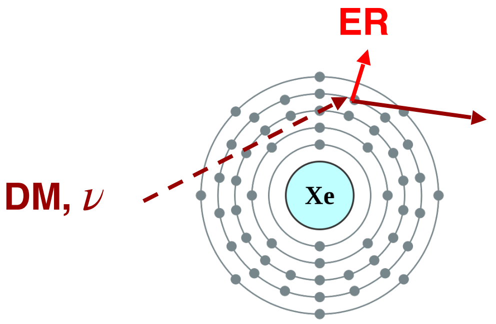
CEvNS is clean

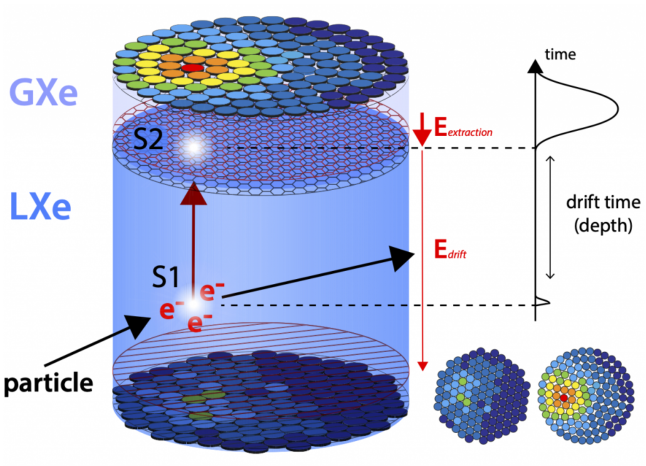
Backgrounds (!)

Dark matter detection technique for neutrino CEvNS

- historically, dark matter detectors were developed to search for *elastic nuclear recoils (NR)* from WIMP interactions.
- the low-background environment of these experiments allows search for other rare events, including DM, that produce *electronic recoils (ER)*.
- these low-threshold detectors makes possible for neutrino detection (e.g. arXiv: 2203.07361 *Coherent elastic neutrino-nucleus scattering: Terrestrial and astrophysical applications*):
  - CEvNS neutrino detection
  - Elastic neutrino-electron scattering (EvES)
  - stopped-pion beams/reactor/geo neutrinos
  - solar/supernova/atmospheric neutrinos





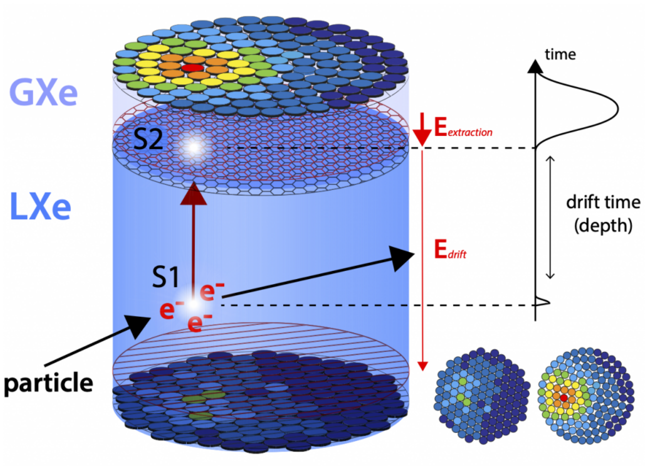


the two-phase (LXe/GXe) time projection chamber (TPC), XENON Collaboration

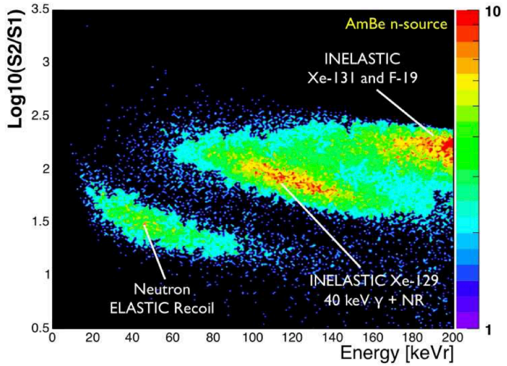
Noble Liquid Detectors

- Noble elements based detectors (in gas or liquid forms) are widely used in particle physics experiments.
- **Noble liquids** (liquified noble gases, specially **liquid argon** and **liquid xenon**) are excellent detection media due to their
  - higher density and larger stopping power (compared to gas)
  - can be purified in-situ (unlike solids)
  - both scintillation/ionization with high yields
  - electron/nuclear recoil discrimination
  - availability in large quantities and scalability
- **Noble liquids** are becoming increasingly attractive targets for dark matter and neutrino experiments

Noble Liquid Detectors



the two-phase (LXe/GXe) time projection chamber (TPC), XENON Collaboration



PRL 97 (2006) 081302

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Noble Liquids as Target for CEvNS

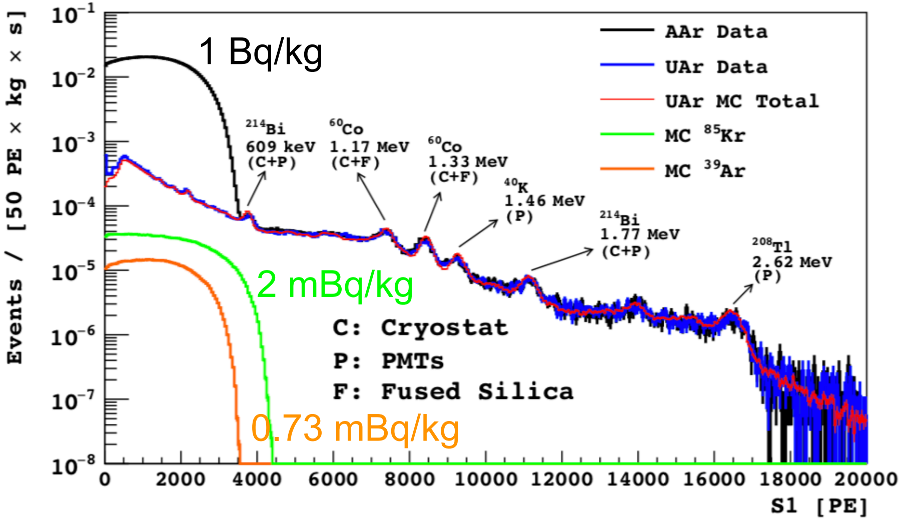
	Liquid Density (kg/L)	Boiling point at 1 bar (K)	W_i (eV) [a]	Electron mobility (cm^2/Vs)[a]	W_{sc} (eV) [a]	Scintillation wavelength (nm)	Long-lived radioactive isotopes	Cost ($/kg)
LHe	0.14	4.2	-	0.03	-	80	none	~$100
LNe	1.2	27	-	0.001	-	78	none	~$500
LAr	1.4	87	23.6	620	19.5	128	^{39}Ar, ^{42}Ar (β)	~$1
LKr	2.4	120	20.5	1200	15	150	^{78}Kr (DEC) ^{81}Kr (EC), ^{85}Kr (β)	~$100
LXe	3.0	165	15.6	2200	13.8	175	^{124}Xe (DEC) ^{136}Xe ($\beta\beta$)	$2000

[a] Aprile, Bolotnikov, Bolozdynya, Doke, *Noble Gas Detectors*

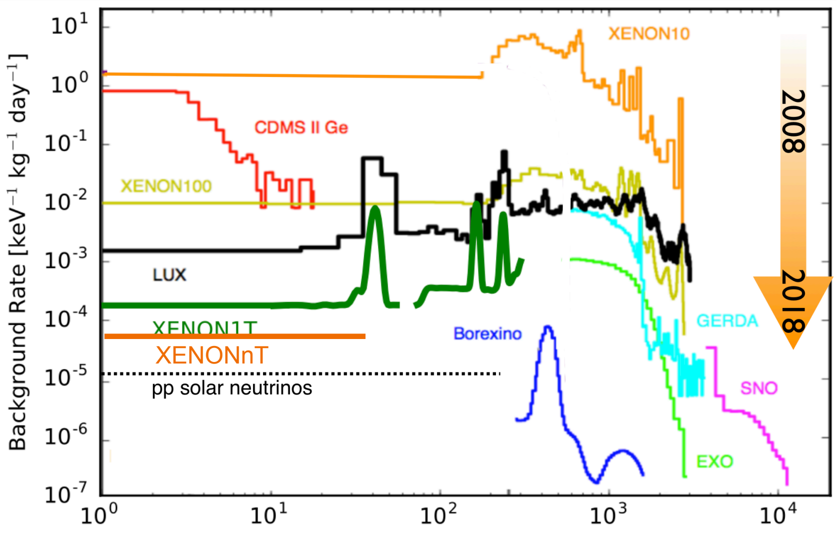
Pro *Con*

Internal background for noble liquids

- **Ar39**: 1 Bq/kg in atmospheric argon to <1 mBq/kg in underground argon
- **Kr85**: 10 ppb Kr/Xe (~0.9 mBq/kg) in commercially available xenon to sub-ppt (1 ppt = 0.1 μBq/kg) by dedicated removal devices (developed by experiments)
- **Rn222**: <1 μBq/kg achieved in XENONnT, 2 μBq/kg in DS-50, 0.2 μBq/kg in DEAP-3600



DarkSide-50, 1510.00702



Thanks to L. Baudis

Techniques to remove trace radioactive gases in noble liquids

LZ: Chromatography Kr Removal System

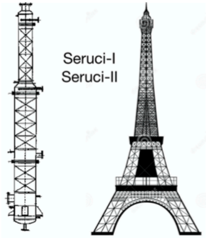
XENONnT: Radon Removal System

XENON1T/nT
Kr distillation column

Industrial Scale Underground Argon (UAr)

Production – URANIA – Cortez, CO, US

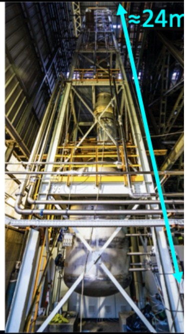
- Industrial scale extraction plant
- Extraction rate: 250-330 kg/day
- Production capability ≈ 120 t over two years for DS-20k
- UAr purity: 99.99%



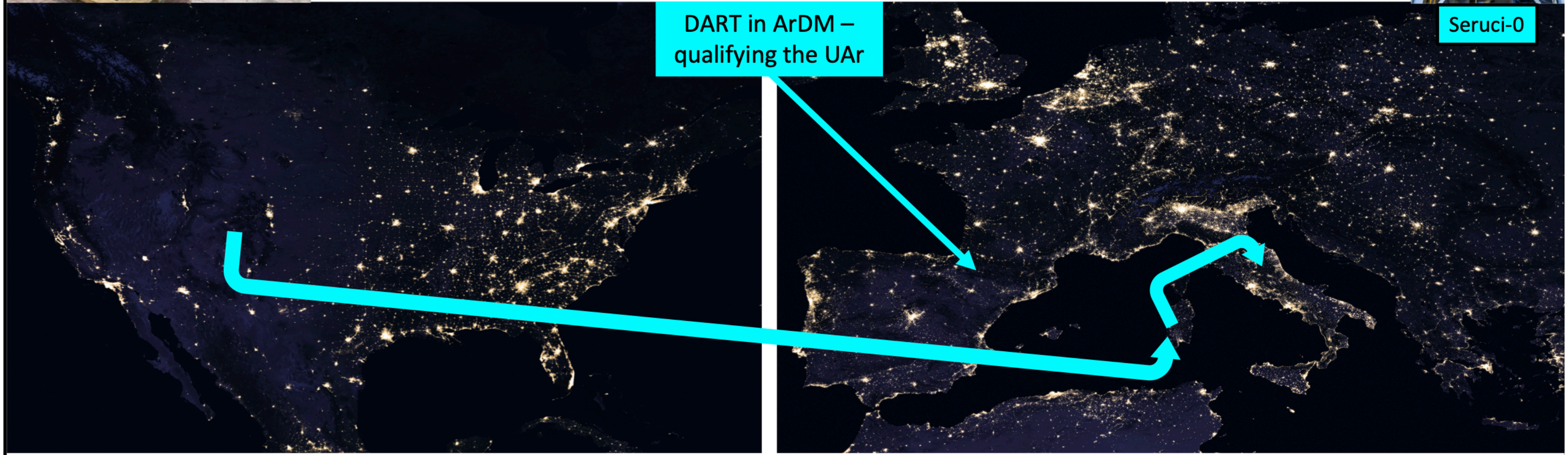
Purification – Aria – Sardinia, IT

Eur. Phys. J. C (2021) 81:359

- Seruci-0 (demonstrator) tested
- 350 m cryogenic distillation column
- O(1 tonne)/day capability
- Resulting UAr purity: 99.999%



Seruci-0

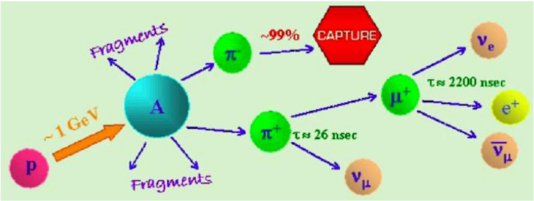


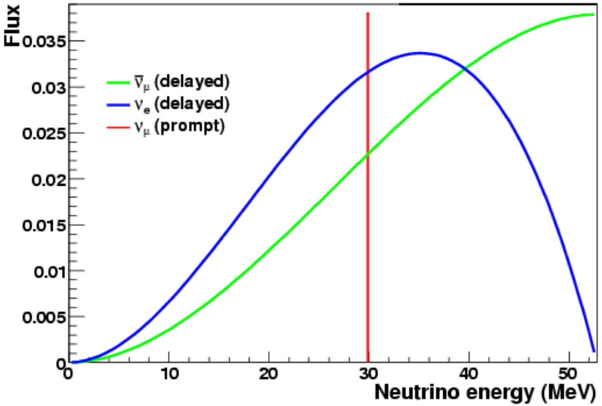
Neutrino Sources and CEvNS Detection

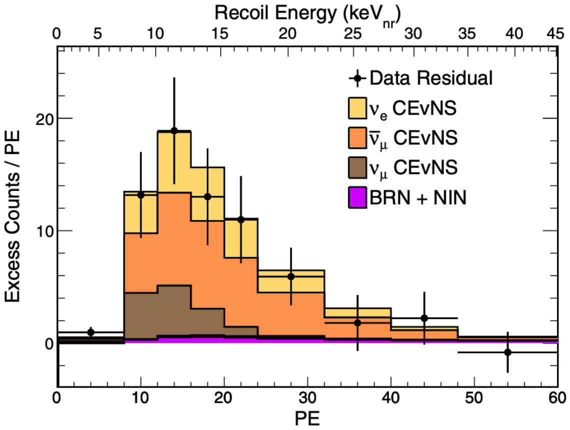
- Neutrinos from SNS
- Solar neutrinos
- Supernova neutrinos
- Reactor neutrinos

Stopped-Pion (DAR) Neutrinos

CEvNS on CsI[Na]: most precise measurement of CEvNS so far.







COHERENT, PRL 2022

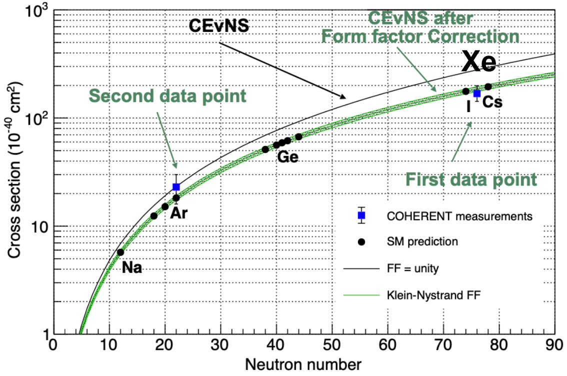
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ PROMPT

$$\downarrow$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies between 0 and $m_\mu/2$ DELAYED (2.2 μs)

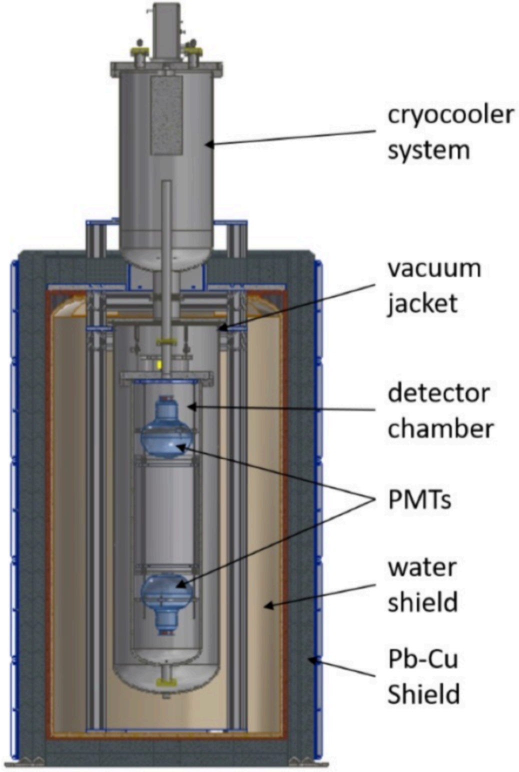


Typical flux: ~0.13 per flavor per proton at the SNS

Kate Scholberg

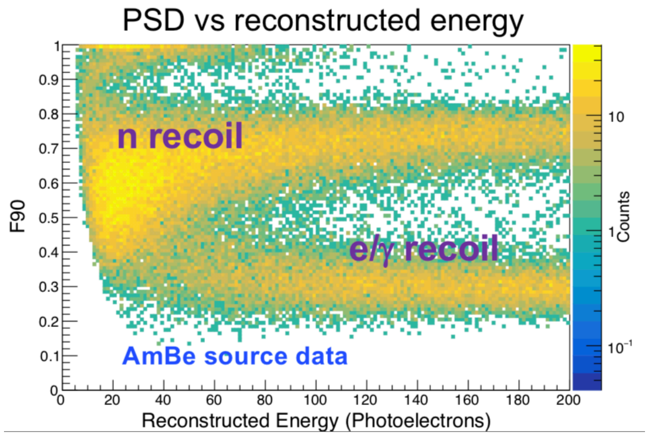
Jason Newby, CEvNS 2023

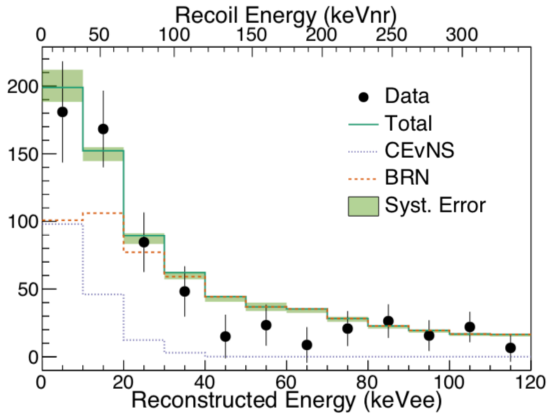
COHERENT - LAr at SNS



CENNS-10

- 24-kg fiducial volume LAr
- 2 x 8” Hamamatsu PMTs with 18% QE at 400 nm
- TPB coated side reflectors/PMTs
- Light yield: 4.6 PE/keVee
- Production run at SPS 2017-19
- dominant background from ^{39}Ar, with remainder from surround gammas
- 10^4-fold suppression due to pulsed SNS beam, and 10^2-fold suppression by PSD.
- First measurement of CEvNS on Argon - PRL 2021

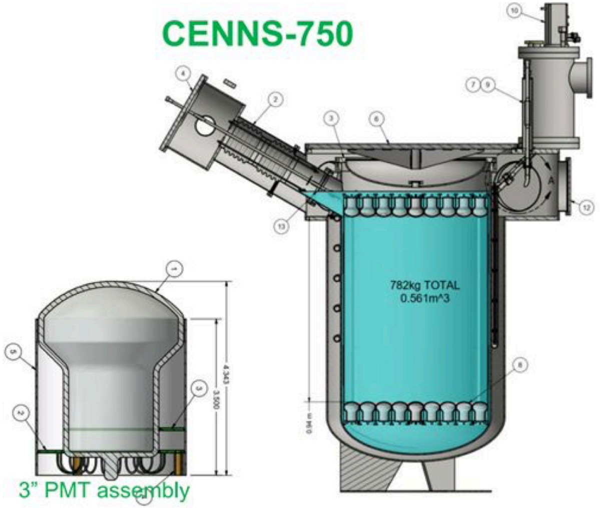


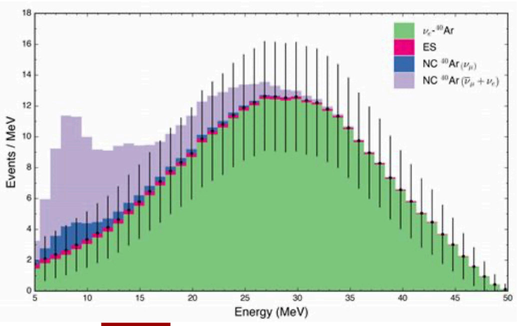


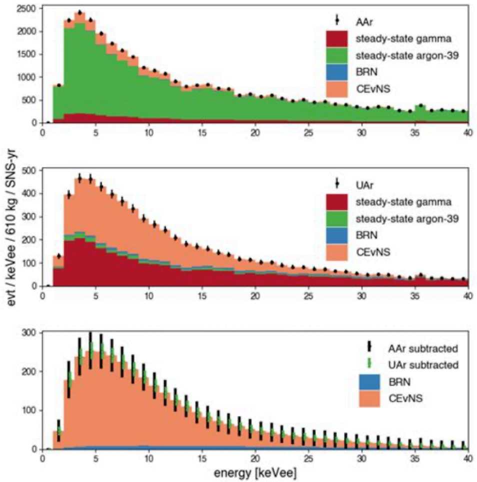
Precision measurement of CEvNS with Argon

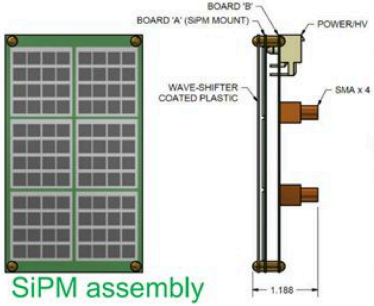
COH-Ar-750

- 610 kg fiducial volume
- Attain same ~20 keVnr threshold
- 3000 CEvNS per SNS-year
- ~400 CC/NC inelastic events per SNs-year
- R&D of cryostat, photodetectors
- Exploring ^{39}Ar-depleted underground argon





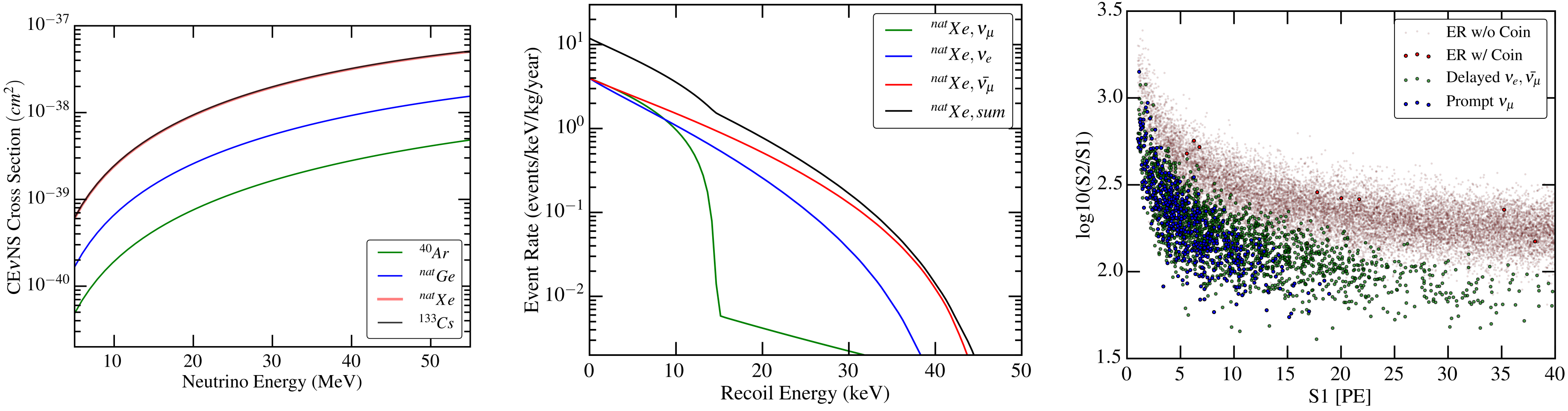




Daniel J Salvat, LIDINE 2021

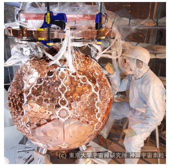
Prospects of liquid xenon to measure CEvNS at SNS

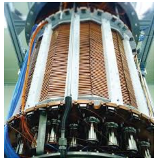
- LXe detector technology is well advanced to detect the Nuclear Recoils from SNS neutrinos via CEvNS.
- CEvNS will soon become the dominant background for LXe-based dark matter detectors (PandaX-xT, DARWIN/XLZD)



Expected CEvNS spectrum (left) and response (right) in a XENON100-like two-phase xenon detector. (figures by Fei Gao)

The LXe detector (r)evolution



PandaX-4T

XENONnT (6T)

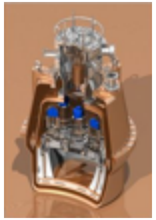
LZ (7T)

~2000 — Concept of using LXe for DM Detection

DAMA/LXe, ZEPLIN-I, XMASS, XENON

2007 — First Results from Two-Phase Xe detectors (~10-kg)

XENON10, ZEPLIN-II/III


2010 — G1 Experiments (100-1000 kg)

XENON100, LUX, PandaX-I/II, XMASS

2017 — Results from the first ton-scale LXe detector

XENON1T

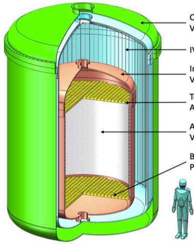
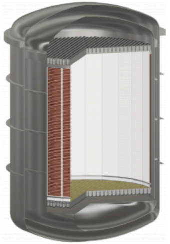
2020 — G2 Experiments (1-10 Ton, two-phase)

XENON1T/nT, PandaX-4T, LZ

2025 — G3 Experiments (40~80 T)

PandaX-xT

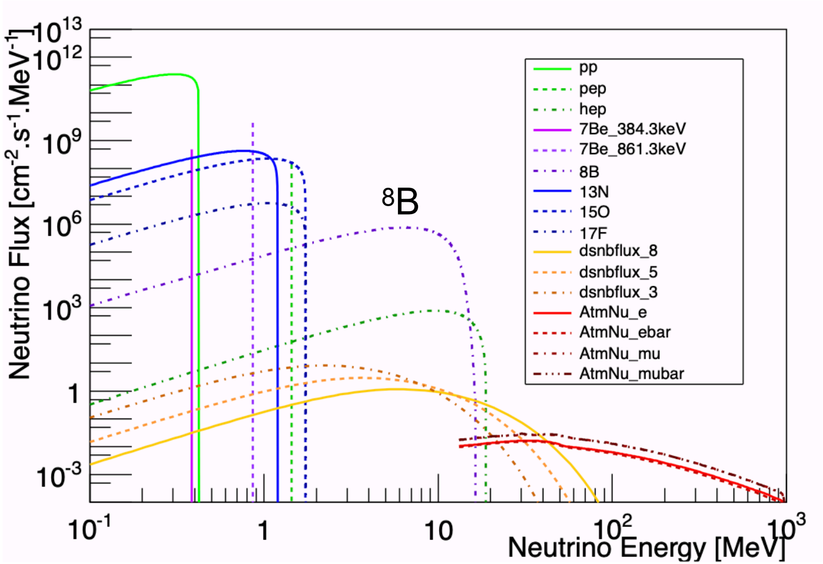
XLZD (XENON/LZ/DARWIN)

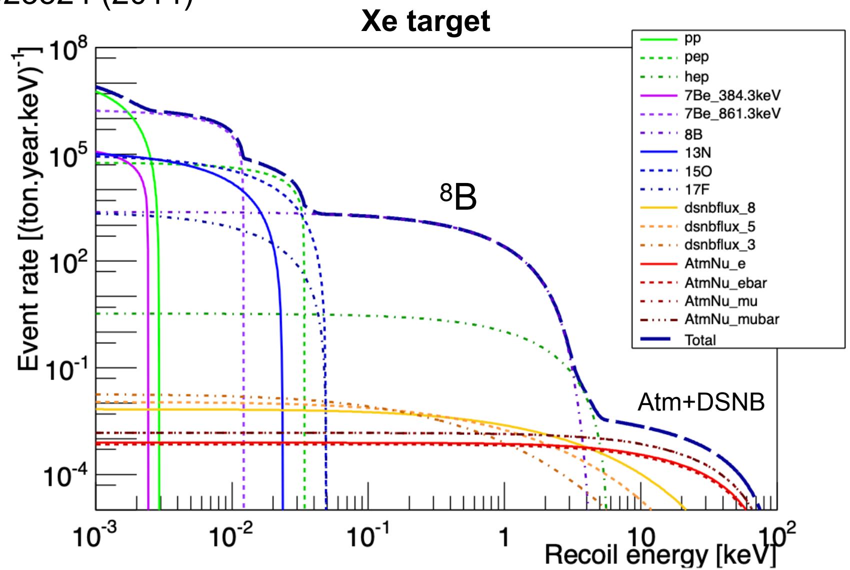



Applications:
LXe for reactor neutrino CEvNS

Solar neutrinos CEvNS as bkg/signal in DM detectors

Billard et al., PRD 89, 023524 (2014)

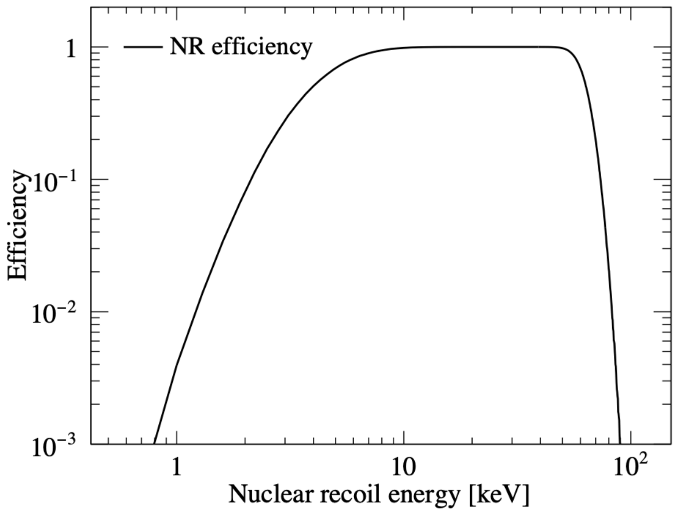


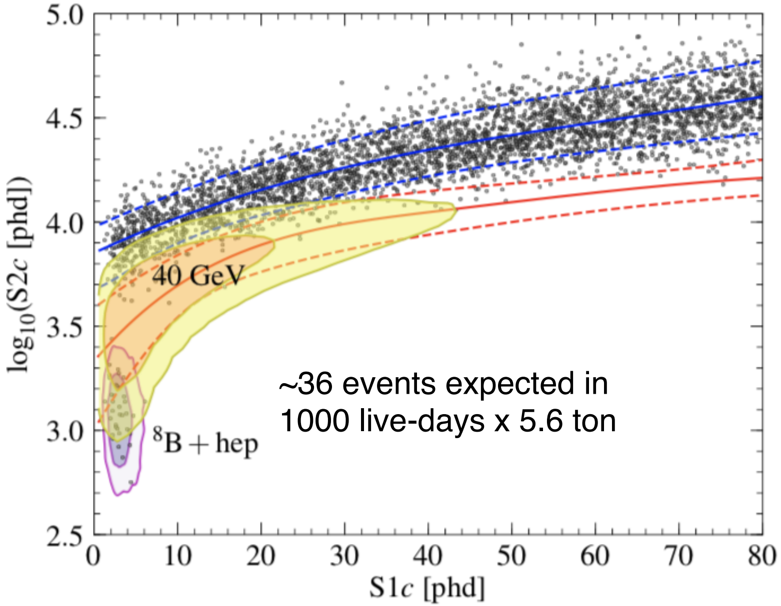


- the dominant solar neutrino CEvNS events are below 1 keV (NR), extremely challenging to detect
- the current generation LXe detectors should see 10-100 events (depending on energy threshold) with the exposure at ~ton-year.

Solar neutrinos interaction with Noble Liquids via CEvNS

solar neutrino CEvNS projection plot from LZ (arXiv:1802.06039)



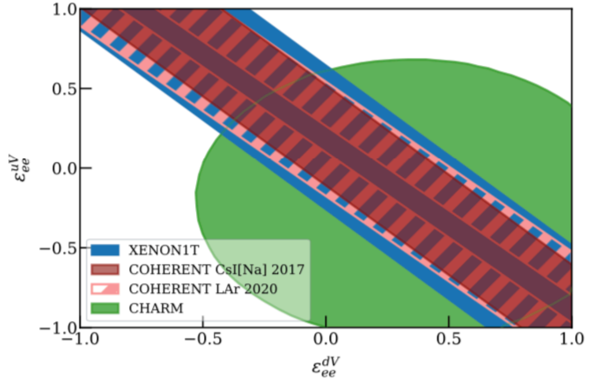


~36 events expected in 1000 live-days x 5.6 ton

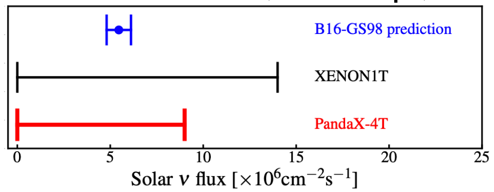
Search for CEvNS from ^{8}B solar neutrinos

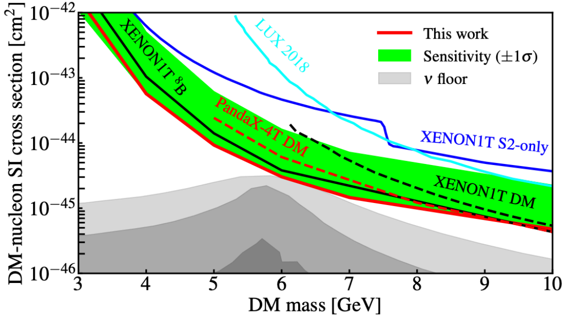
- Searching for CEvNS signals from solar neutrinos was first performed with **XENON1T** 0.6 t-y data [PRL 126, 091301, 2021]
- **PandaX-4T** performed such searches recently with 0.48 t-y data and provides so far the best constraints [PRL 130, 021802, 2023]
- Such searches also provide leading constraints on low mass dark matter at ~3-10 GeV/c²
- With more data under taking, **PandaX-4T**, **XENONnT** and **LZ** will very likely detect solar neutrinos via CEvNS in the next few years.

constraints the non-standard vector couplings between the electron neutrino and quarks (XENON1T)

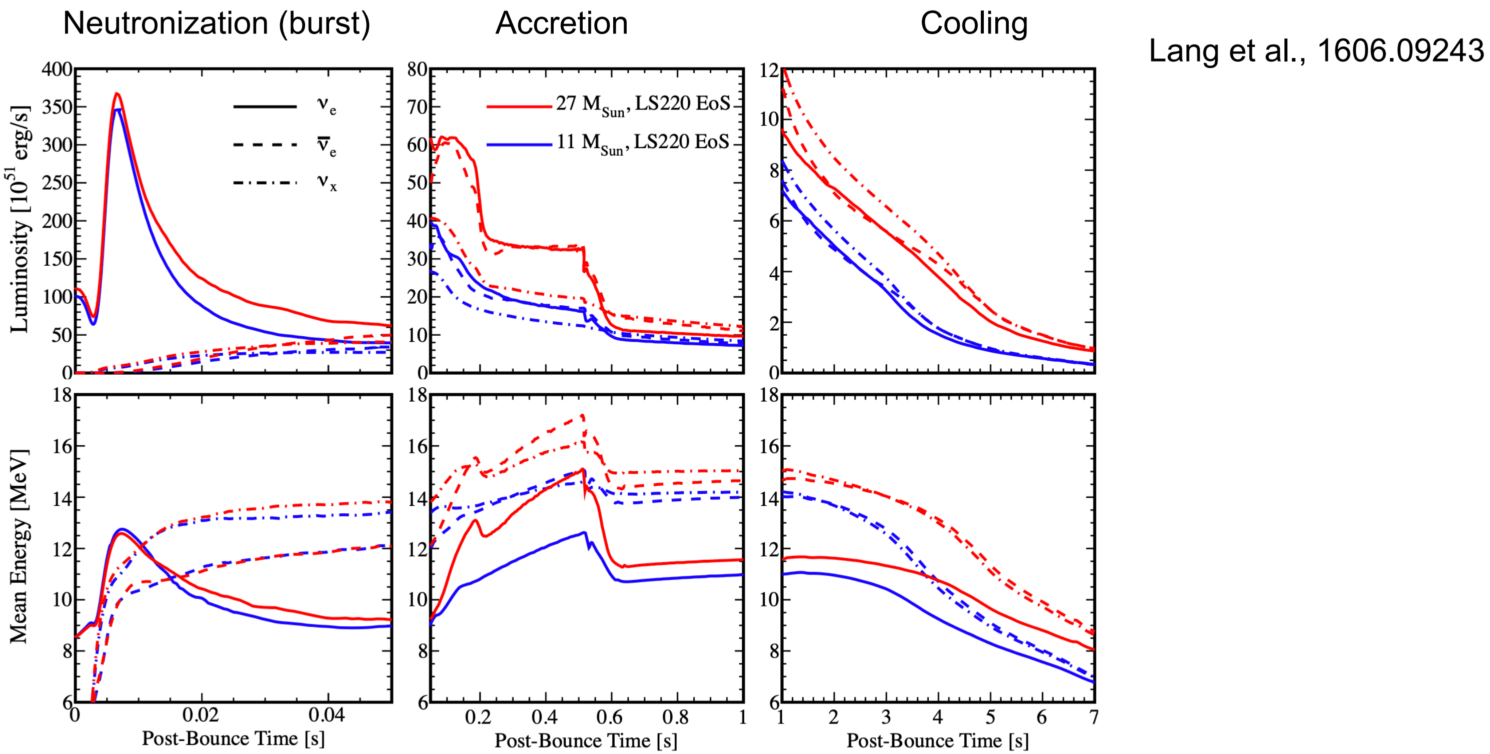


constraints on solar neutrino CEvNS and low-mass dark matter (PandaX-4T)





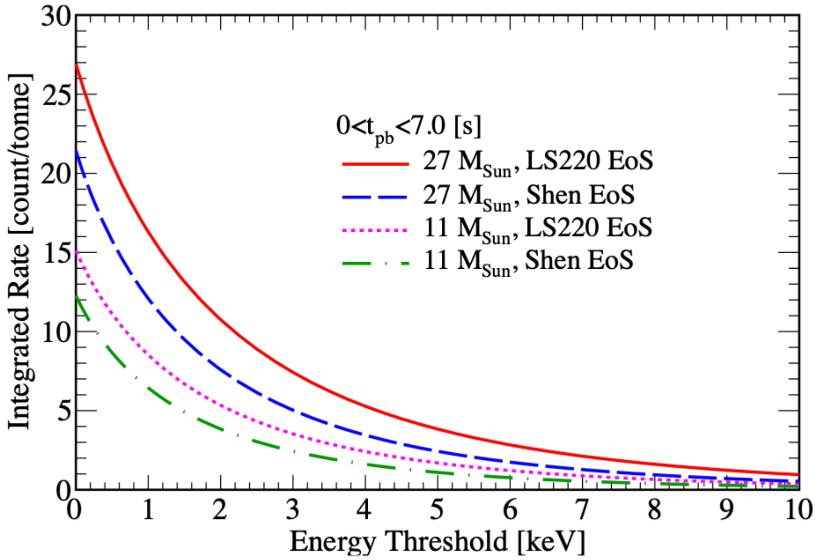
Supernova neutrino detection with noble liquids

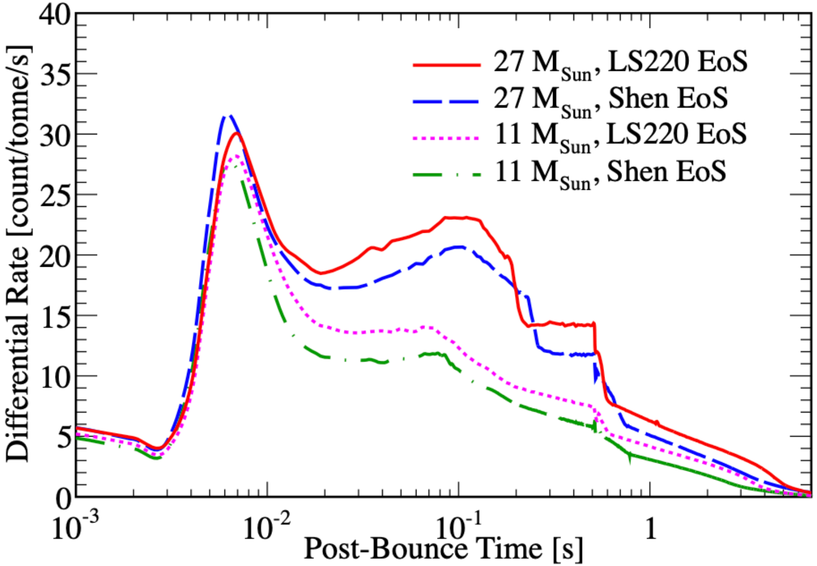


- Neutrinos from core-collapse supernovae bring crucial information on the stellar interiors and allow studying new physics of neutrinos [Manibrata Sen, SNvD 2023@LNGS]

Supernova neutrino detection in liquid xenon

Lang et al., 1606.09243

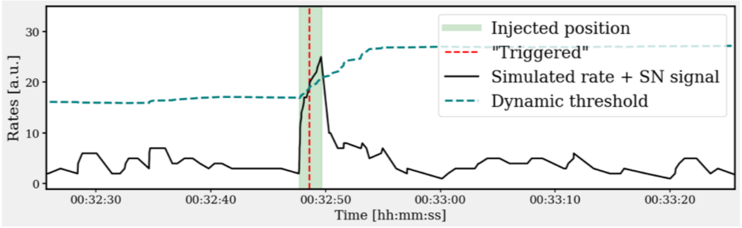


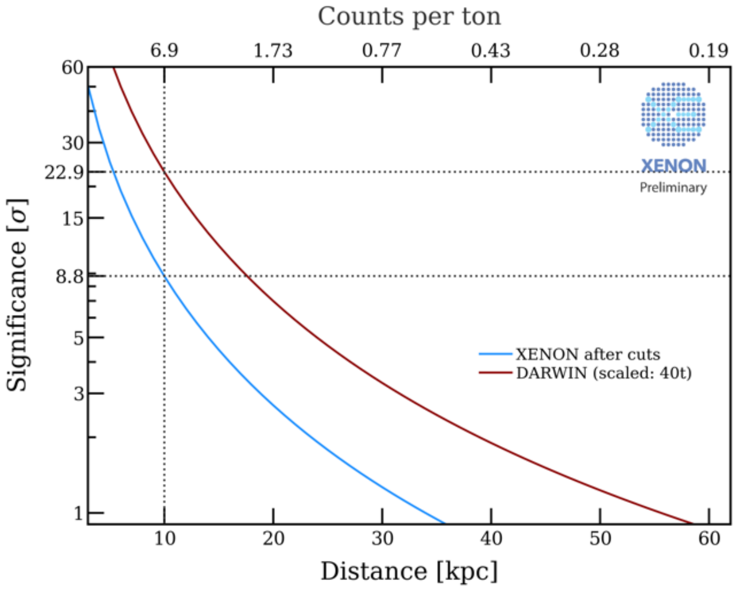


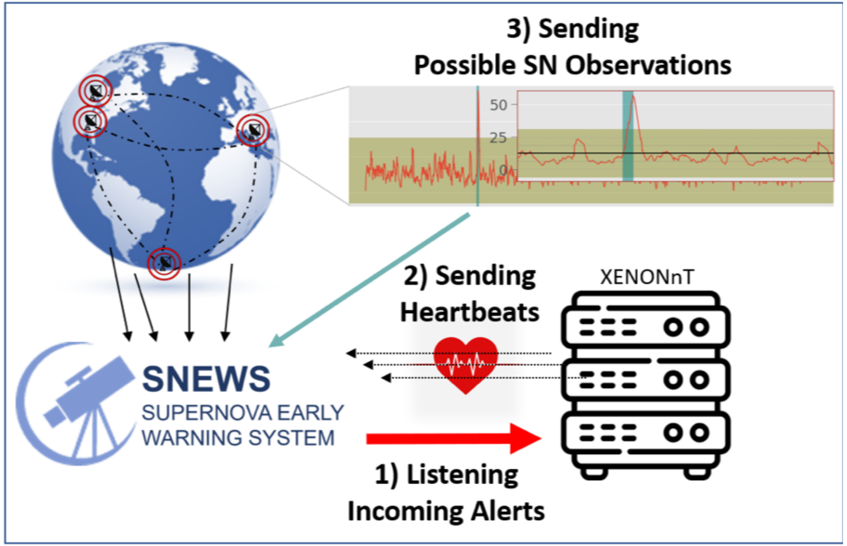
- The nuclear recoil (CEvNS) detection channel is sensitive to all neutrino flavors, allowing reconstruction of total explosion energy emitted into neutrinos

Supernova neutrino detection with large noble liquid detectors

simulated signal and sensitivity (M. Kara/XENON)





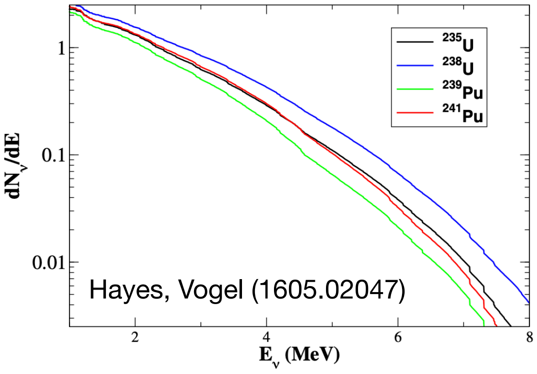


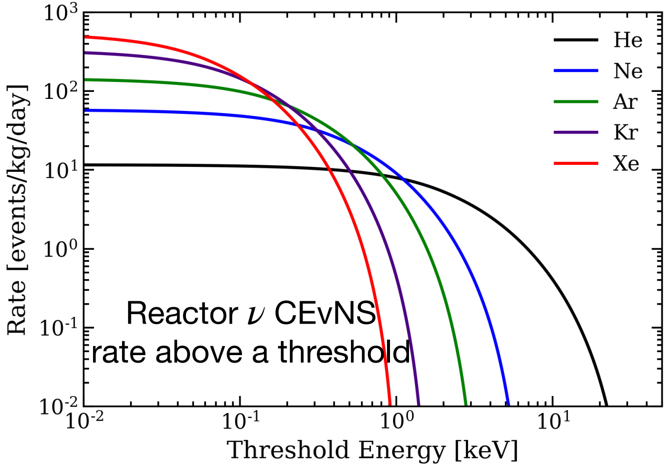
- see studies of supernovae neutrino CEvNS detection by XENONnT/DARWIN, DS-20k, LZ at SNvD 2023@LNGS.

Future Prospects and Challenges

- Large noble liquid detectors for dark matter search are capable to detect CEvNS from solar and supernova neutrinos
- Two-phase XeTPC with both S1 and S2 will detect handful of events
- Lowering the S1 threshold, or removing the S1 requirement, will improve the event statistics significantly, but at the same time facing a challenging background with S2-only signal
- Similar challenges for applications in detecting reactor neutrinos via CEvNS

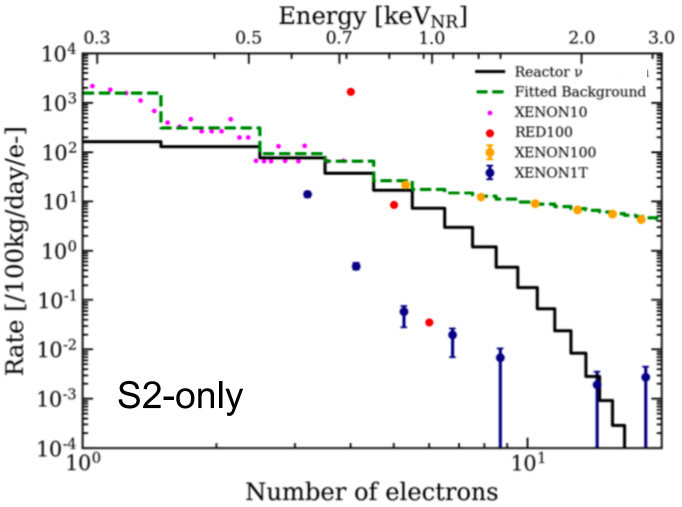
Marching down to detect reactor neutrinos via CEvNS





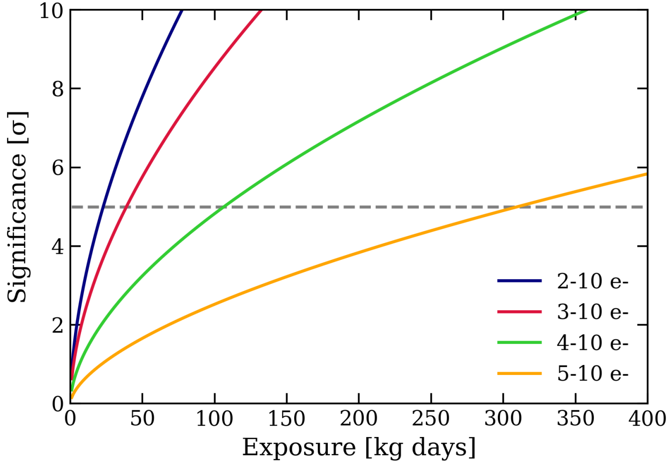
- based on reactor antineutrino spectrum from Hayes, Vogel (1605.02047), normalized to a flux of 6×10^{12} cm^{-2}s^{-1} (~25 m from a 3 GWth reactor)
- ~10 events/kg/day expected at nuclear recoil energy threshold of **0.1~1.0 keV**
- A compact (movable) neutrino detector with 10~100 kg liquid target: **>100 neutrino events/day**
- LXe/LAr are very promising targets.

Sensitivity of LXe to Reactor neutrino CEvNS



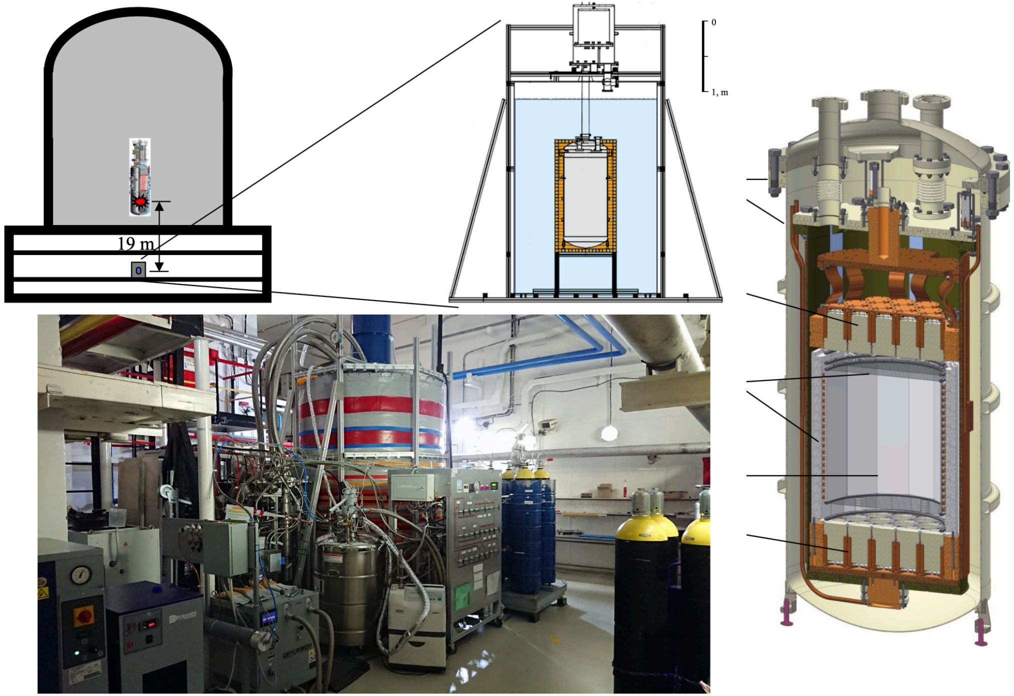
CEvNS Sensitivity (LXe)

Universe 2021, 7, 54



- sub-keV nuclear recoil threshold detector needed for reactor neutrino CEvNS
- for noble liquids, S2-only (ionization) is possibly the only way to achieve such a low threshold: most events liberate only a few ionization electrons
- **achieving an ultra-low threshold and suppressing the background at single electron (SE) level** will significantly improve the sensitivity

RED-100 at Kalinin Nuclear Power Plant (KNPP)



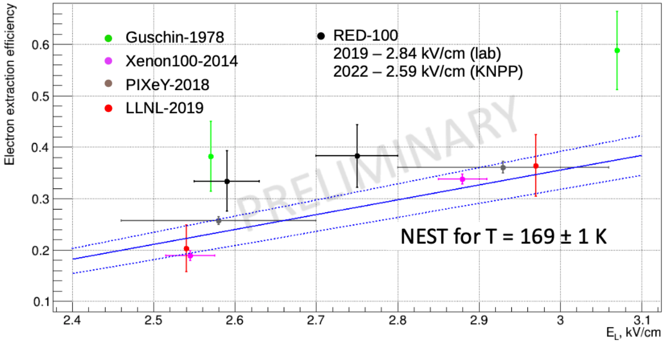
Rudik Dmitrii, RED-100 experiment

- Two-phase liquid xenon detector
- ~200kg of LXe (~100 kg in FV)
- 26 R11410 PMTs (19 top + 7 bottom)
- 19 m from the reactor core (3 GW)
- 65 m.w.e over burden
- Antineutrino flux: ~1.35e13 /cm^2/s
- First run (Jan-Feb, 2022) completed
- no sig. correlation in external background rate with reactor operation
- **dominant background: delayed single e- (and multiple electrons)**
- plan to use LAr to substitute LXe

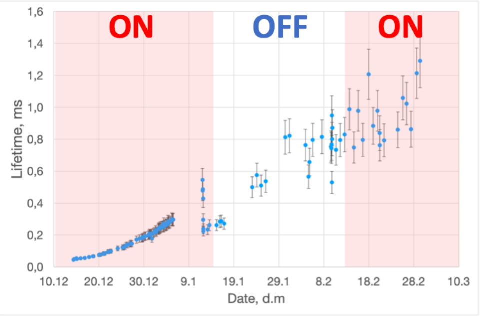
RED-100 Sensitivity

- The most significant influence on CEvNS response prediction
  - Electron extraction efficiency (absolute measurements based on NEST predicted charge yeild)
  - Electrons lifetime
- GEANT4 + ANTS2 simulations of the CEvNS prediction
- RED-100 sensitivity in the region 5-6 electrons is ~33 times lower than SM predicted CEvNS rate

Electron extraction efficiency



Electrons lifetime

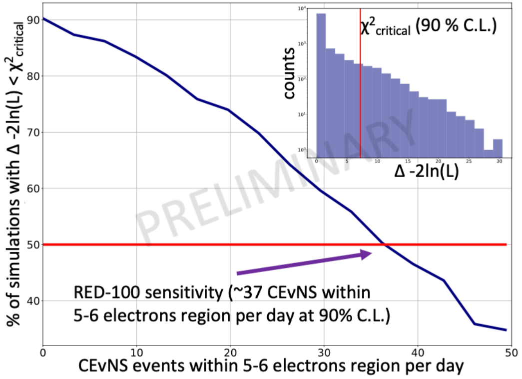


Background rate and CEvNS prediction /~65 kg LXe / day (Preliminary)

Number of e-	4	5	6
background	6375	236	27
CEvNS	3.1*	0.6*	0.1*

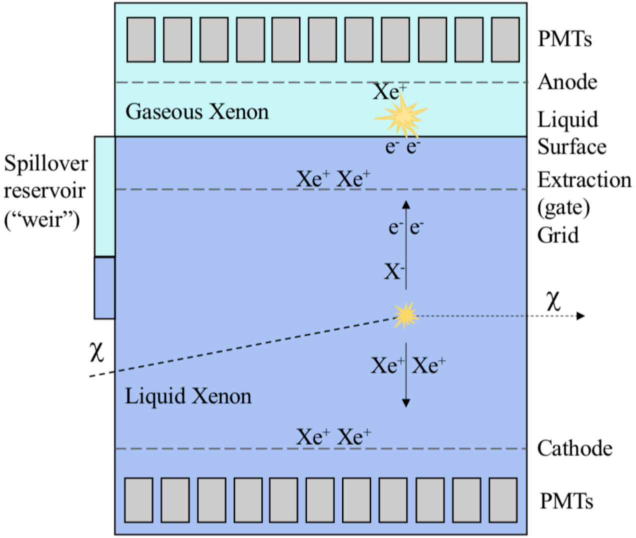
*Uncertainties on prediction numbers are under calculation
Current estimation is 30%

Sensitivity calculations

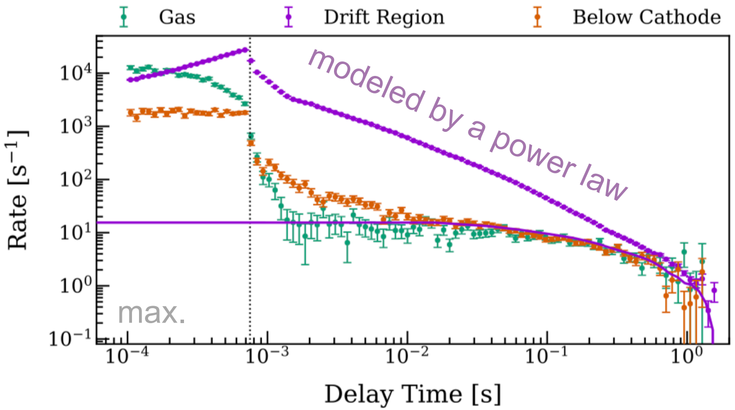


Delayed Single electron (SE) background in two-phase xenon detectors

2004.07791



XENON1T (2112.12116) SE rate following energy depositions,
Also seen in LUX (2004.07791), ASTERiX (2103.05077) etc.



Two plausible sources of these single electrons:

1) delayed release of electrons attached to impurities in LXe (improve liquid purity)
2) delayed emission of electrons trapped at liquid-gas interface (push higher the extraction field, or remove the liquid-gas interface!)

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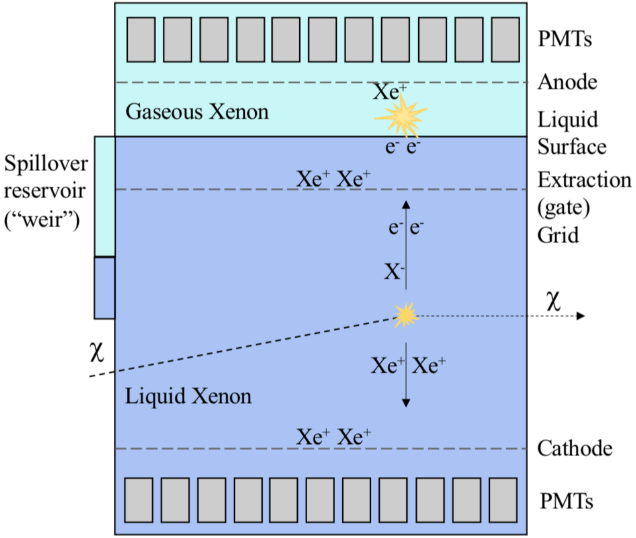

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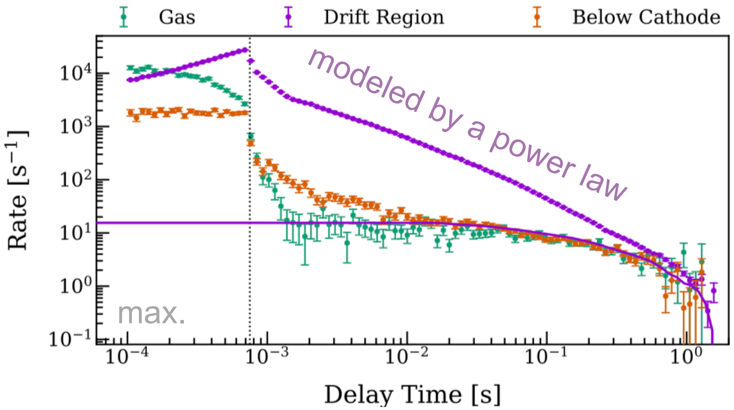

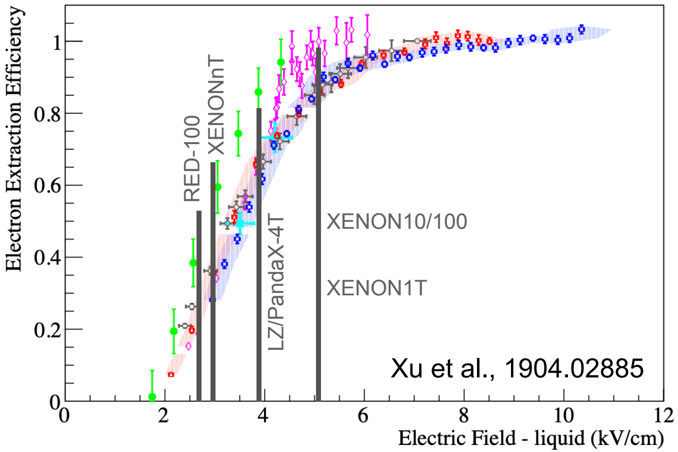

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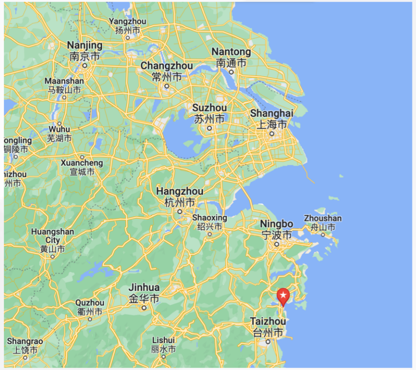
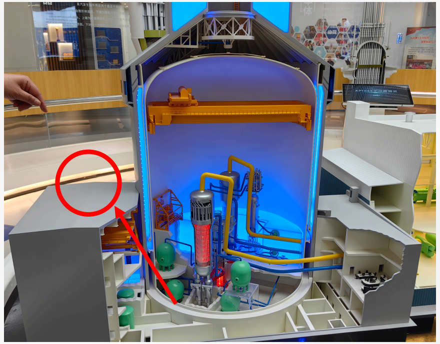
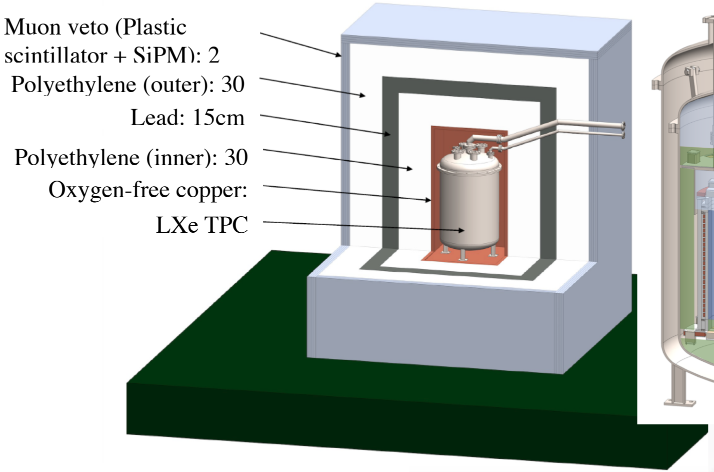
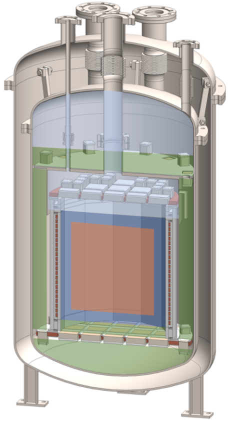
RELICS





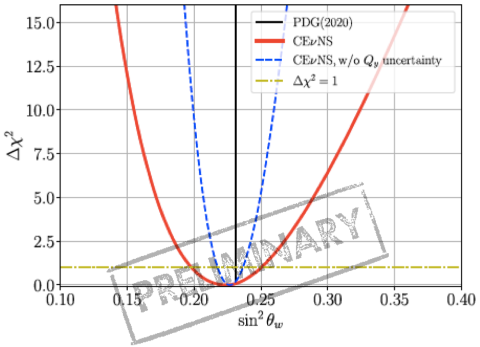
Proposed operation location for RELICS, right outside of containment building.

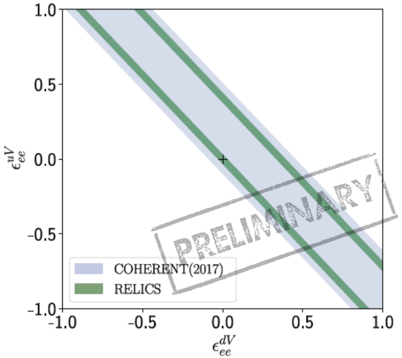




- ✓ Power ~3GW;
- ✓ Distance to Core ~ 25m;
- ✓ Expected **ν** flux ~ 1e13 **ν**/cm²/s.

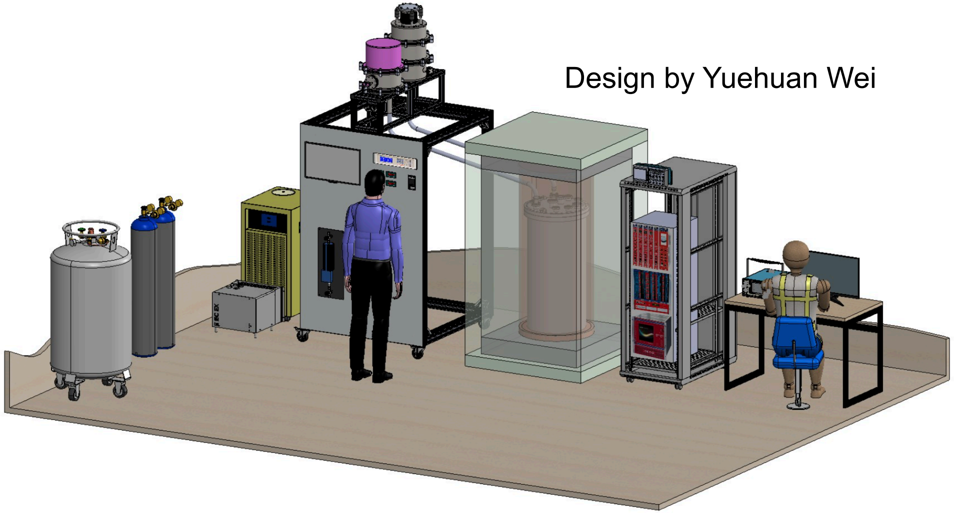
See *Qing Lin*'s talk (7/5)





- ✓ 30-kg fiducial volume;
- ✓ TPC+diving bell with 4**π** LXe veto;
- ✓ Shielded by copper, PE and lead;
- ✓ Muon veto requires >99% tagging eff.;

NUXE: a single-phase LXe/LAr detector for reactor ν CEvNS



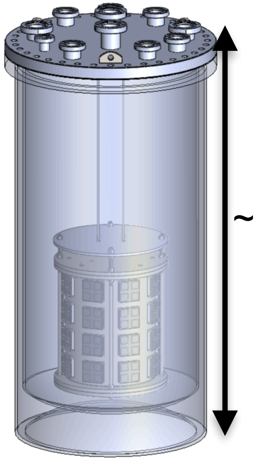
Design by Yuehuan Wei

- **50-100 kg** LXe or (Xe-doped LAr) Proportional Scintillation Counter (PSC) with **single e- sensitivity**
- **single-phase**: NO liquid-gas interface to trap/delay electrons
- **ultra-clean** liquid target: reduce impurity related SE background
- **ultra-low threshold (2e-)**: **~100 events/day** reactor neutrinos via CEvNS

A multi-purpose (LXe or LAr) cryogenic system

NUXE @ UCSD

single-phase PSC: simpler detector than dual-phase



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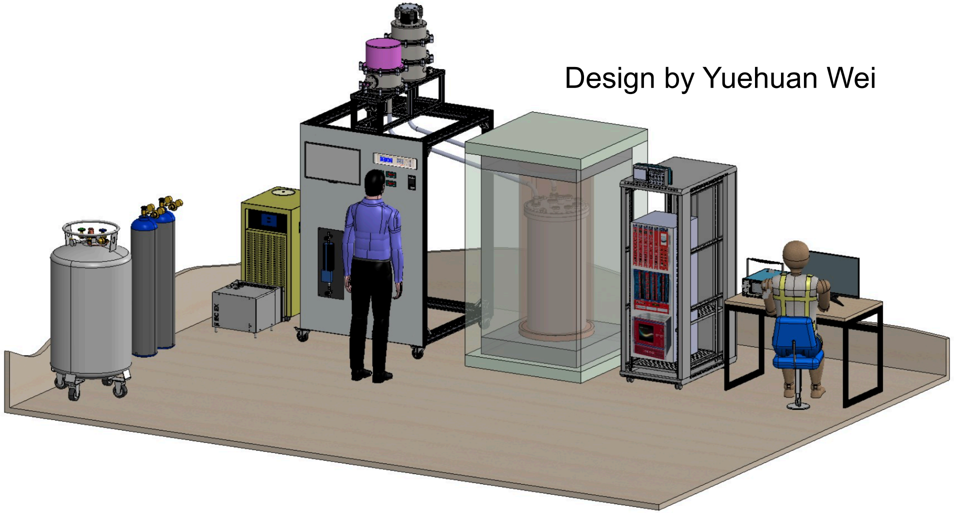

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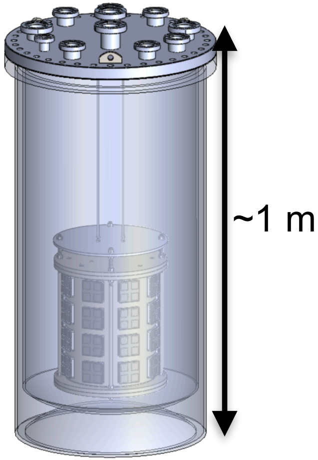

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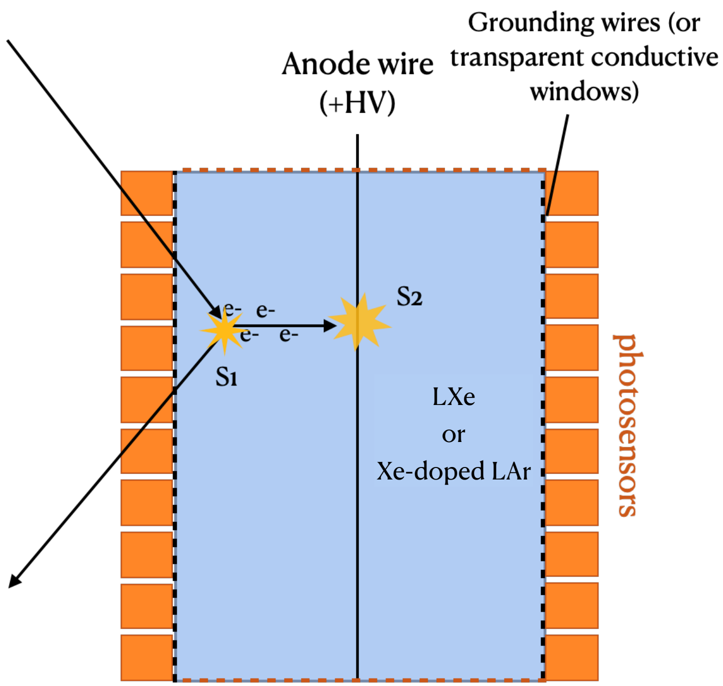
➡Other proposals for reactor CEvNS with LAr: CHILLAX; **SBC** 2101.08785; talk by Yong-peng Zhang (7/5)

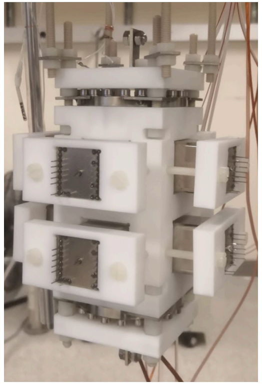
Single-phase LXe (or LAr) to reach single-electron sensitivity

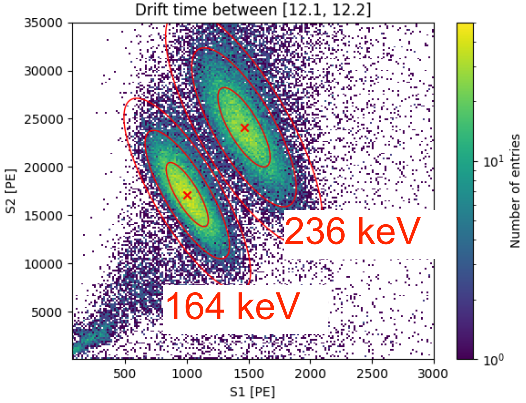


- **Generating proportional scintillation (S2) directly in liquid xenon** was studied by several groups (e.g. Aprile et al., 1408.6206) and recently gained more interest (F. Kuger et al. 2112.11844) for the next generation liquid xenon observatory.
- A simpler cylindrical detector design (thin anode wire in the center) was **first proposed by Qing Lin (2102.06903, JINST).** This design is well suited for detecting reactor ν CEvNS.
- **No liquid-gas interface:** S2 generated on the thin anode wire, no interface to trap electrons
- **Faster liquid-phase purification possible (no gas phase)**
- **More photosensor coverage, no reflection at liquid/gas interface:** higher light collection (lower S1 threshold)

Demonstration of a Single-Phase LXe Proportional Scintillation Counter

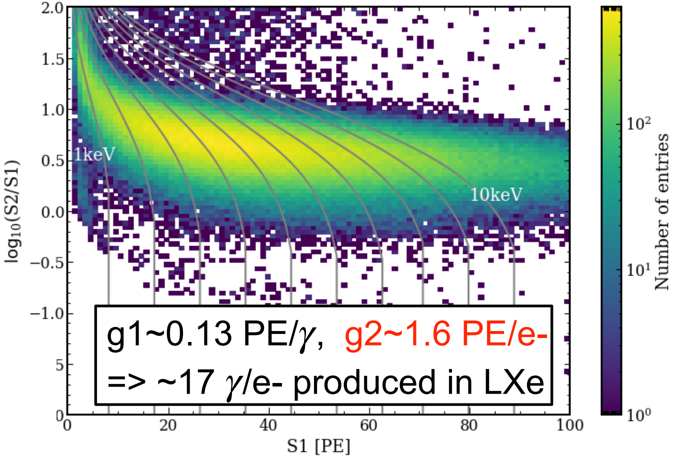
a LXePSC (600g active target) viewed by 8 R8520 PMTs (Y.Wei et al. 2111.09112)



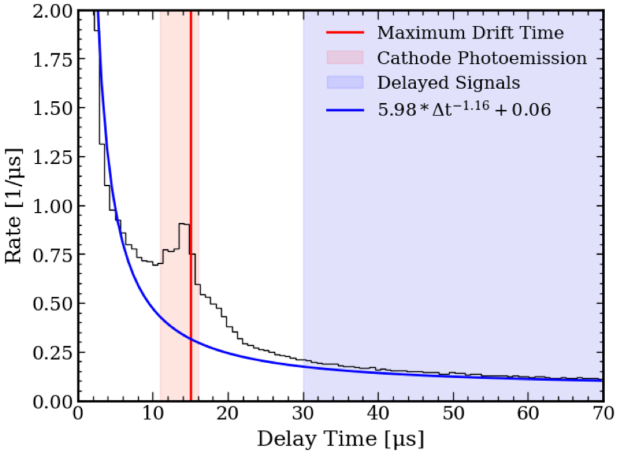


Recent work at UCSD (J.Qi et al. 2301.12296)

Low energy electron recoils from tritium beta decay detected.



delayed 1-2 PE signals



- Delayed 1-2 PE signals show a steeper power law (-1.16) compared to that observed in XENON1T (-0.7), less likely dominated by delayed "electrons".
- More recently achieved g2 ~ 3 PE/e- (preliminary, calibrated with neutron activated Xe lines, left)

Summary

- Noble liquid detectors are well developed for CEvNS detection (thanks to the development of dark matter detection techniques)
- **Will ultra-low threshold noble liquid detectors make another (r)evolution in low-energy neutrino experiments?**
- Promising CEvNS detection with noble liquids:
    - precision measurement with 750-kg LAr detector at SNS
    - in a few years: first detections of solar neutrinos via CEvNS (PandaX-4T, LZ, XENONnT)
    - in 5~10 years: detections of reactor neutrinos via CEvNS (RELICS, NUXE etc.)
    - in a few decades: first detection of supernova neutrinos via CEvNS (DS-20k/ARGO, PandaX-xT, XLZD)