Dual Phase LAr Detector R&D for CEvNS Measurements at Reactors

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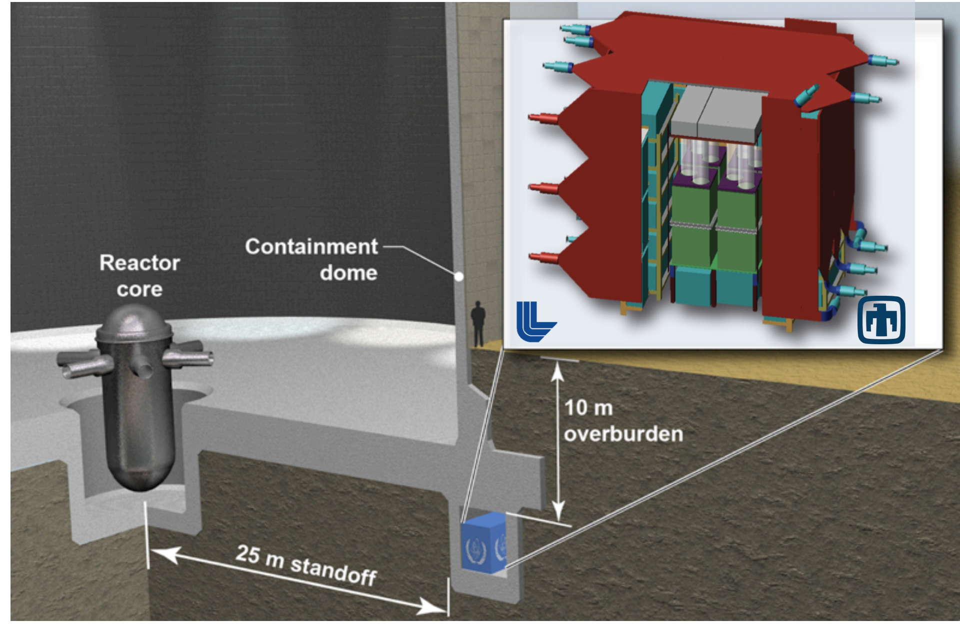
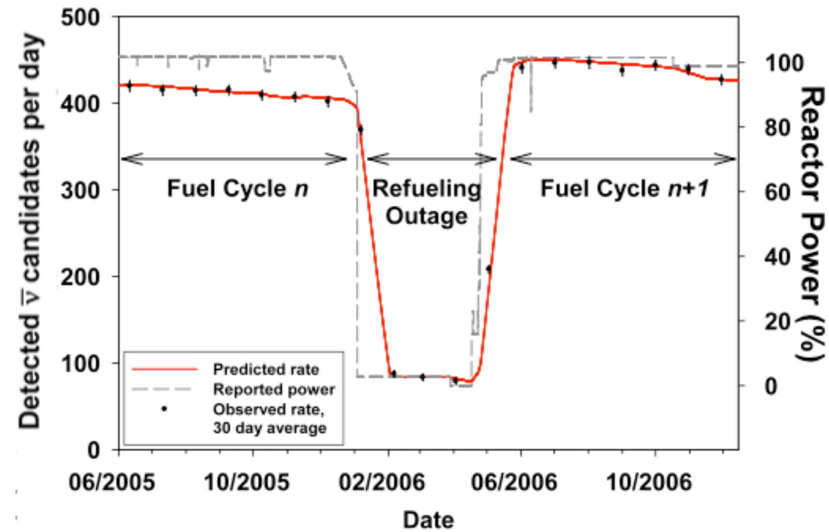
Reactor Monitoring using Antineutrino Detection

- Tools and techniques from neutrino physics have enabled remote unattended reactor monitoring demonstrations, ***using Inverse Beta Decay***
- Provides means to verify reactor operational history & fuel loading
- Aboveground operation and detector footprint are among the utility considerations raised by potential end-users

IAEA Report STR-361



Schematic diagram of SONGS1 monitoring detector deployed at the San Onofre Nuclear Generating Station



SONGS1 data (points) compared to expectation (red) showing sensitivity to power history and fuel burnup

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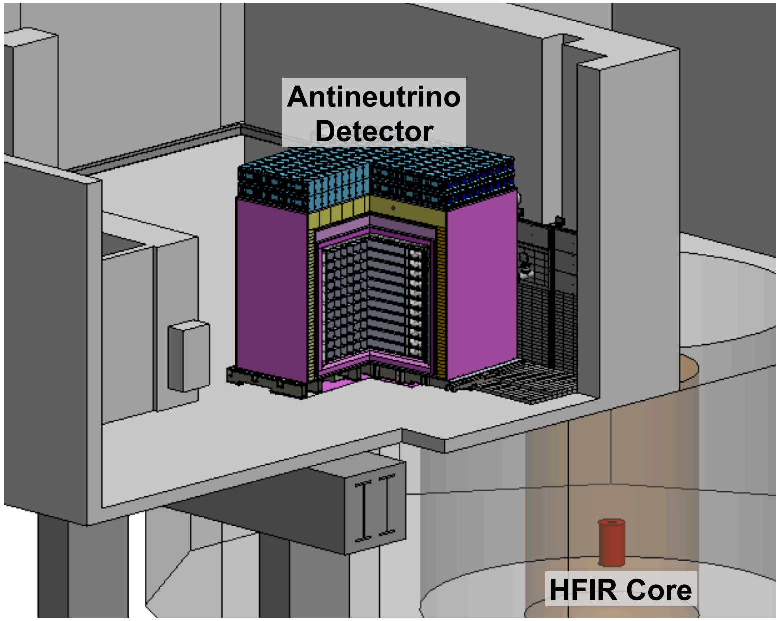
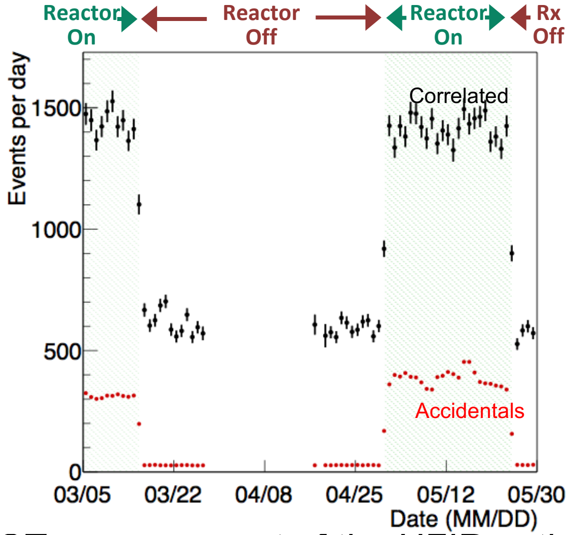


*Schematic diagram of **PROSPECT** experiment at High Flux Isotope Reactor (HFIR), **with almost no overburden***



***PROSPECT** measurement of the HFIR antineutrino flux with >1:1 S:B on the earth's surface*

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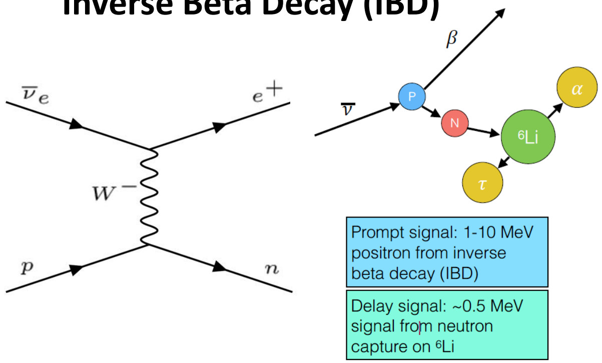
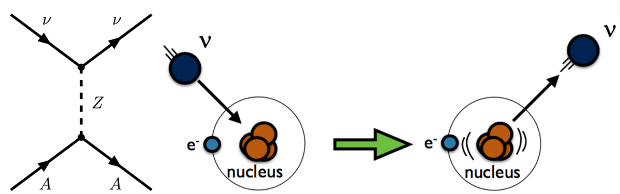
Relative to IBD, Coherent Neutrino Nucleus Scattering has high cross section and can access low energy reactor antineutrino flux

Inverse Beta Decay (IBD)

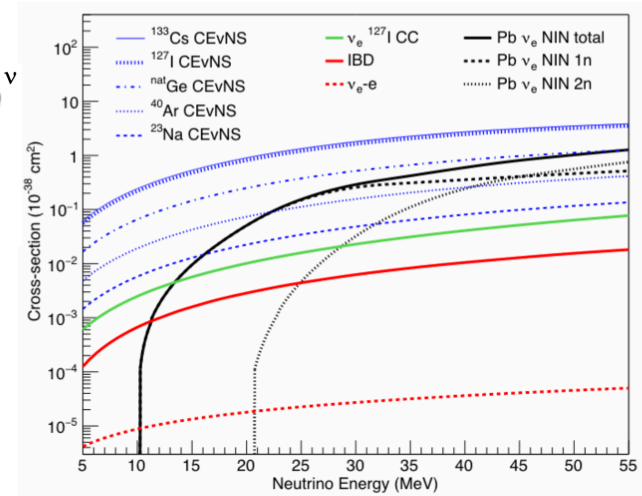


- Charged current interaction with free proton
- 1.8 MeV antineutrino threshold
- Delayed coincidence of products key for background reduction
- Positron energy directly related to antineutrino energy

Coherent Elastic Neutrino Nucleus Scattering



- Neutral current scattering process, where (anti-)neutrinos interact coherently with all neutrons
- High cross section relative to IBD
- Neutrino energy threshold can be low
  - (~1.5 MeV for Xe, ~0.4 MeV for Ar)
- Energy transfer is very low, ~1keV or less



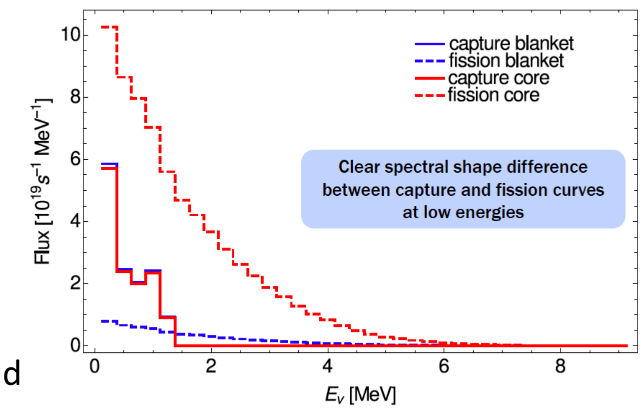
Interaction cross section of different neutrino interaction processes with matter. COHERENT, arXiv:1803.09183

Motivations for reactor antineutrino measurements via CEvNS

- High cross section → potential for smaller footprint
- Low threshold can give sensitivity to non-fission nuclear production signals
- Complementarity to IBD yet to be examined in detail

Challenges

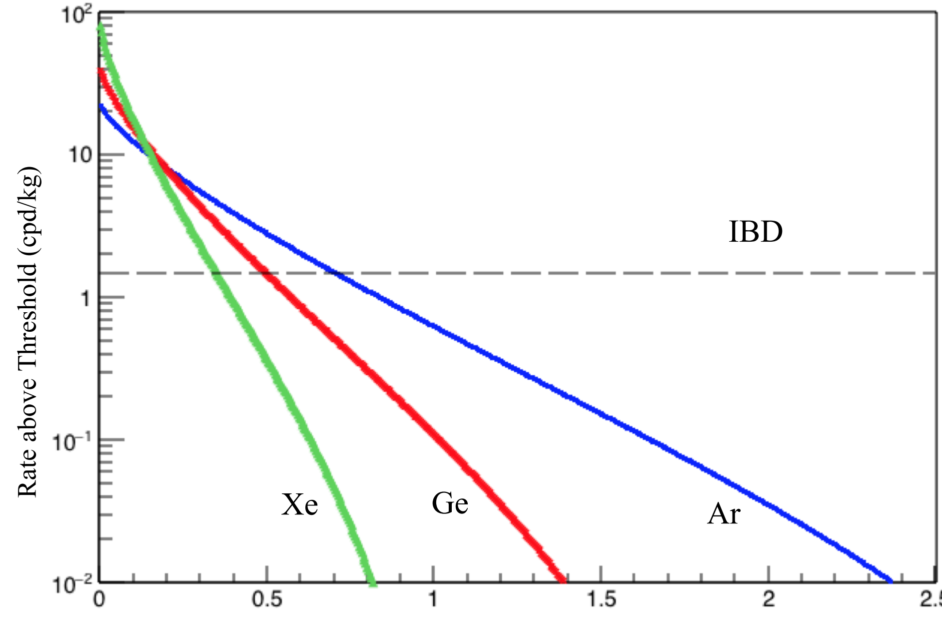
- Single, small energy deposition signal requires very low threshold and background
- Relatively complex detectors (cryogenics, etc)
- Compared to accelerator ν source, low energy (<10 MeV) and no timing reference



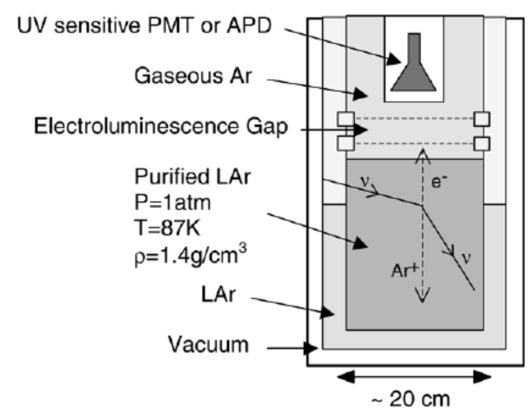
Cogswell & Huber, Science & Global Security (2016)

Selection of Detection Medium for CEvNS @ Reactor

- CEvNS event rate depends strongly on the achievable threshold
  - Signal amplitude advantage of light nuclei weighed against cross section enhancement for heavier nuclei
- Ar/Xe/Ge detectors have comparable CEvNS rates at ~200eVnr threshold
- Reasonable to compare to 1 ton-scale IBD detectors
  - A CEvNS detector will require mass of O(100kg) to achieve rates comparable to ton-scale IBD detectors
- At LLNL, we have focused on noble-liquid TPCs due in part to the ability to scale in mass with relative ease



Estimated CEvNS rate in different detector medium for a reactor of 1GWe with 25m standoff



Hagmann & Bernstein, IEEE Trans.Nucl.Sci. 51 (2004) 2151

Detection approach pursued at LLNL: Dual Phase Noble Liquid TPCs

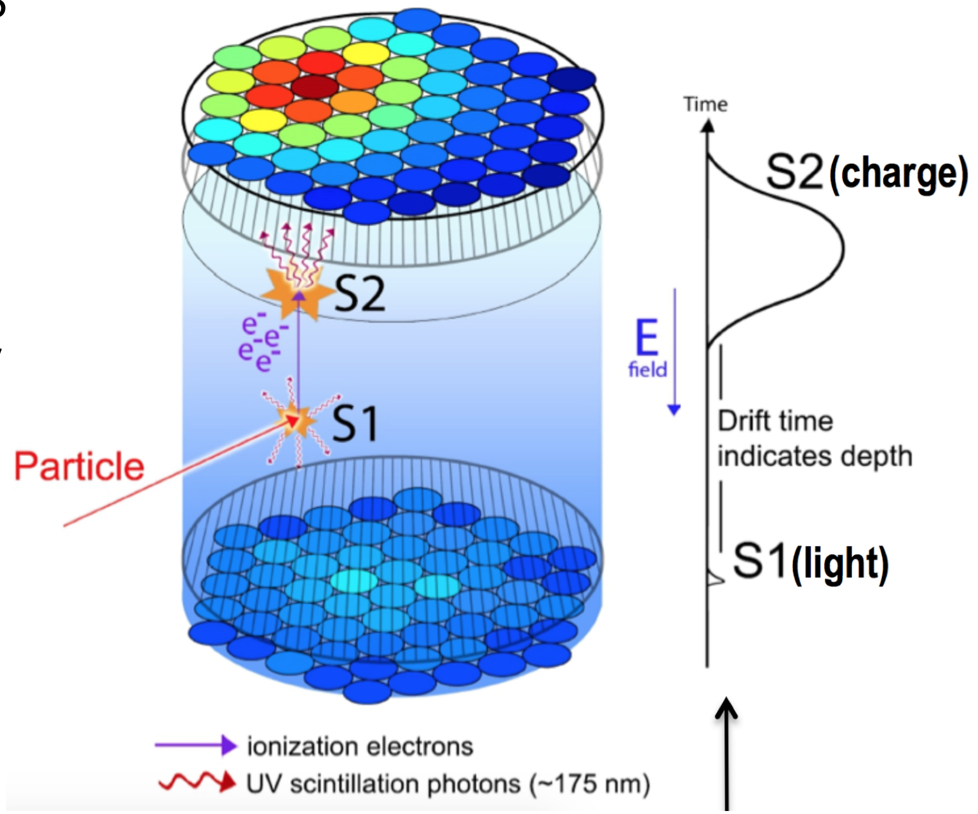
Reactor CEvNS signals are similar to WIMP dark matter search signals:

- Nuclear recoils at low energy
- Relatively low event rate

Dual-phase noble liquid TPCs have demonstrated high dark matter sensitivity

- Low radioactivity
- Single ionization electron threshold
- Scalable

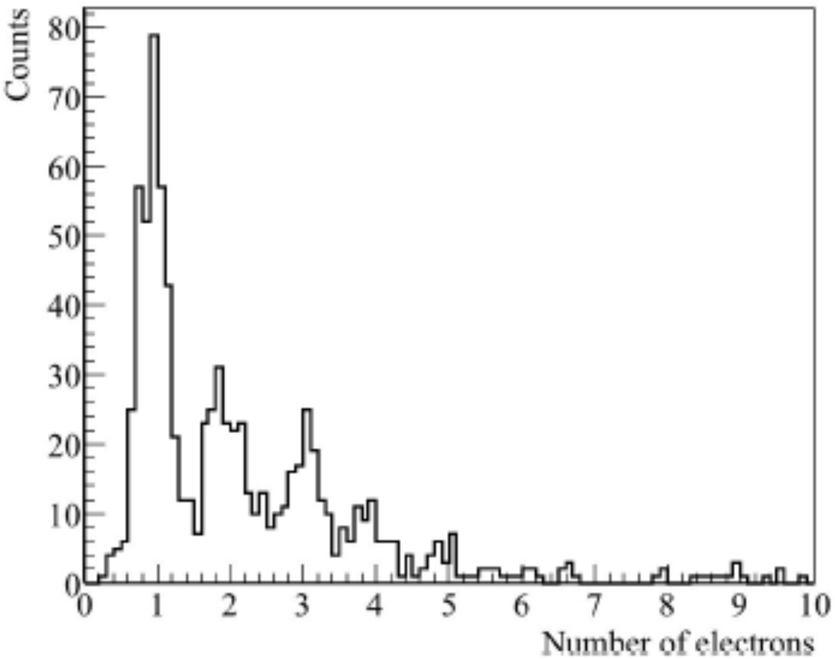
Reactor CEvNS signals unlikely to produce detectable S1 light, but feasible to rely on ‘amplified’ S2 signal



An illustration of signal generation in a dual-phase xenon TPC detector. For reactor CEvNS events, only charge signals are expected.

Significant advances have been made in Noble Liquid TPCs, especially in LXe

- Overlap with needs and goals of dark matter community
- See, e.g. RED100 talk yesterday
- Thresholds less than a single ionization electron (SE) threshold achieved, with good SE resolution
- Possible sources of SE background identified and now being intensively studied:
    - Impurity-related
    - Unextracted electrons
    - Photoionization electrons
    - Metal surface emissions

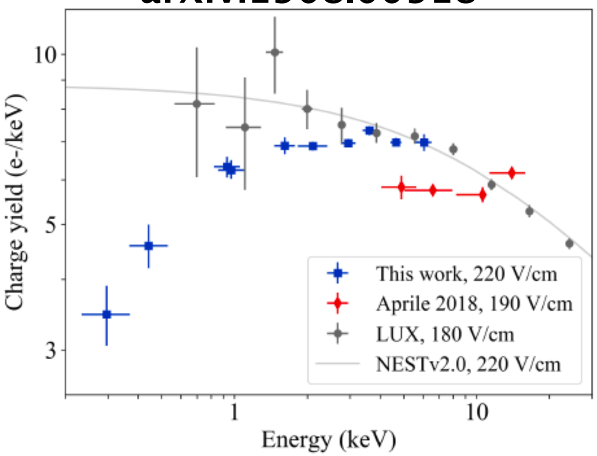


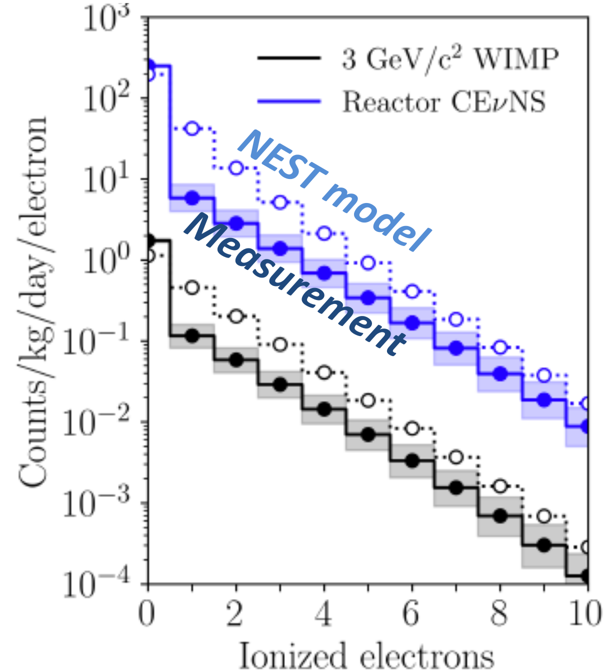
Ionization electron spectrum of XeNu detector used in arXiv:1908.00518

Recent LXe Low Energy Recoil Measurement

- Ability to observe CEvNS from reactor flux is very dependent on low energy quenching factors
- Recent LLNL-lead measurement in LXe reinforces indication of higher quenching than previously assumed in the energy region relevan to CEvNS at reactors
- A large fraction of CEvNS interactions produce no ionization electrons in LXe
- For our group, reinforces motivation to examine LAr for reactor focused efforts

arXiv:1908.00518

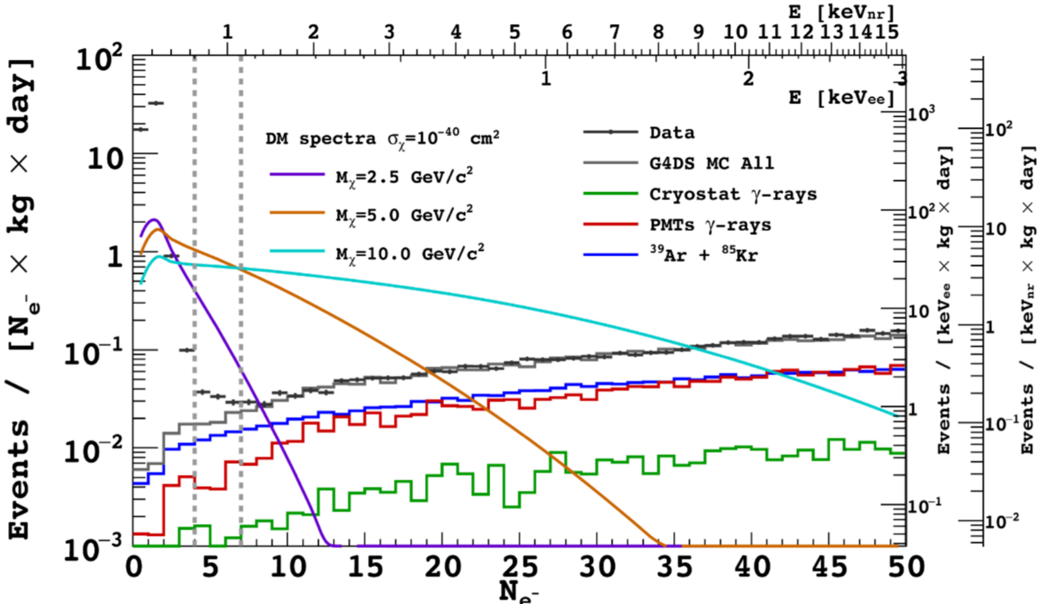




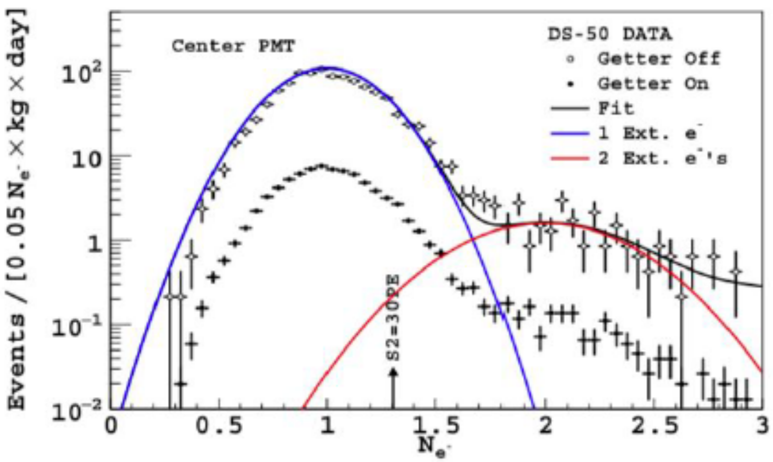
See: Brian Lenardo's talk this afternoon

Challenges for Reactor CEvNS detection via LAr TPCs

- Nuclear recoil signal at low energies not well calibrated
  - <6 keV for Ar
- Background in this energy region not thoroughly studied
  - Radioactive background
  - Instrumental background
  - Cosmogenic background for near-surface operations
- LAr instrument response not yet at levels achieved in LXe
  - UV Ar emissions and long decay timescale present a technical challenge



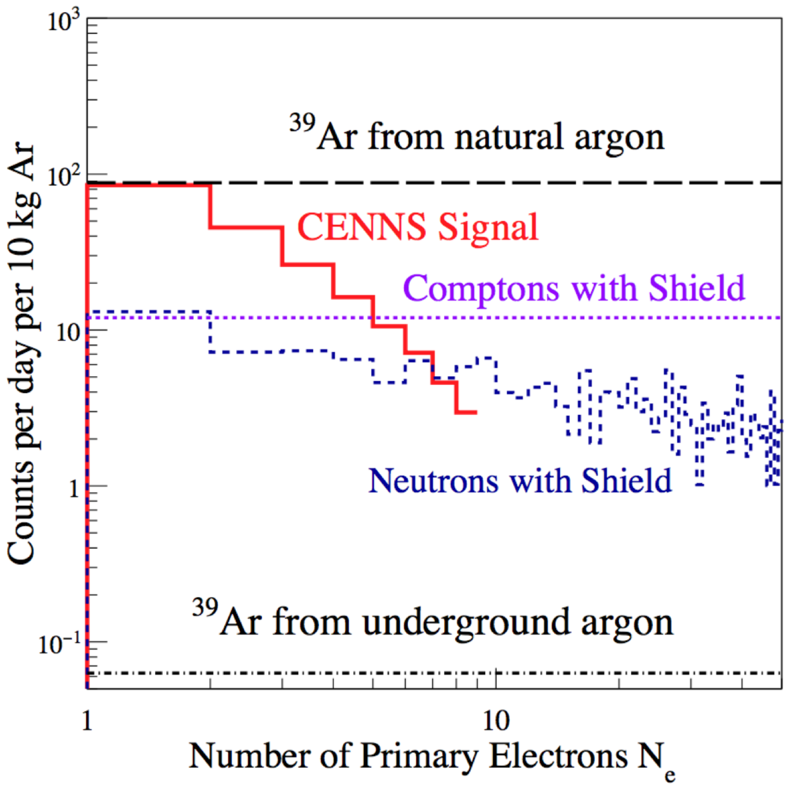
Low-energy spectrum measured by the DarkSide50 experiment -- Note the sharp background increase below 3 e-. [Phys. Rev. Lett. 121, 081307 (2018)]



SE spectrum in DarkSide50 experiment -[Phys. Rev. Lett. 121, 081307 (2018)]

Intrinsic Ar-39 background must (and can) be addressed

- Reactor CEvNS signals in Ar TPCs with atmospheric argon will be overwhelmed by 39Ar decay
  - Cosmogenic $^{40}Ar(n, 2n)^{39}Ar$
  - High rate ~1 Bq/kg
- Argon from some underground sources may have drastically lower ^{39}Ar concentration
- Xu, et al, [Astroparticle Physics 66, 53-60]
- DarkSide50, [Physical Review D 93 (8), 081101]



Estimated reactor CEvNS rate in comparison with that of background (LLNL). [IEEE Trans.Nucl.Sci. 51 (2004) 2151-2155]

Plans for LAr Dual Phase TPC R&D at LLNL

- New LDRD project has just started to LLNL
  - Apply recently expertise from recent LXe to LAr
- Push towards SE resolution and sensitivity in LAr
  - WLS and reflectors increase light collection but decrease position resolution
- Perform low threshold quenching factor measurement, similar to that recently completed for LXe
- Investigate hypothesized SE background sources in LAr

Conclusion

- Reactor antineutrinos provide information relevant for monitoring of nuclear reactors
  - This has been demonstrated using IBD
  - Unique information may be available from CEvNS, plus the high cross section is attractive

- For CEvNS measurement at reactors, LAr Dual Phase TPCs are an attractive approach

- Recent advances in LXe, primarily motivated by dark matter searches, make this a good time to reexamine LAr in CEvNS context, with an emphasis on improved:
  - Single ionization electron sensitivity
  - Knowledge of quenching
  - Understanding of single ionization electron background sources

- Historically, much of the work in our group motivated by CEvNS for reactor monitoring, but we are also interested in developing any scientific opportunities for Reactor CEvNS measurements using Noble Liquid TPCs