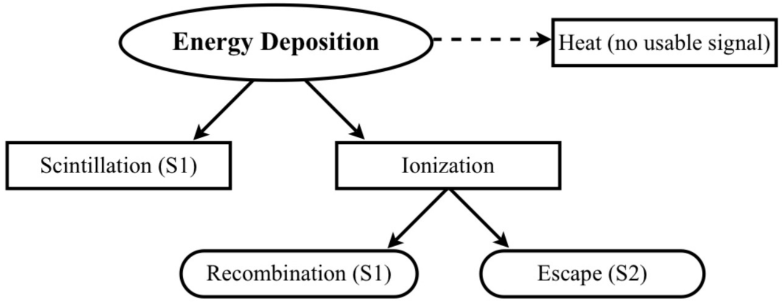
Scintillation Detection in Liquid Noble Elements

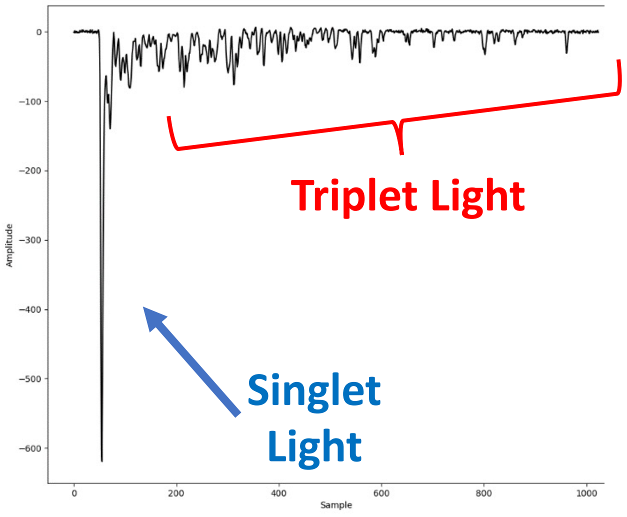
Neutrinos at ORNL Workshop

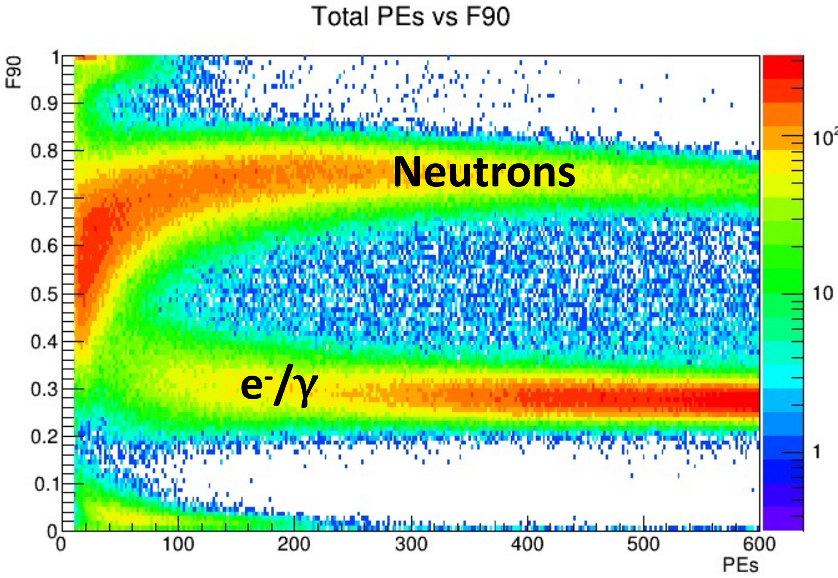
Jacob Daughhetee

12/2/2021

Liquid Noble Element Scintillation







Argon

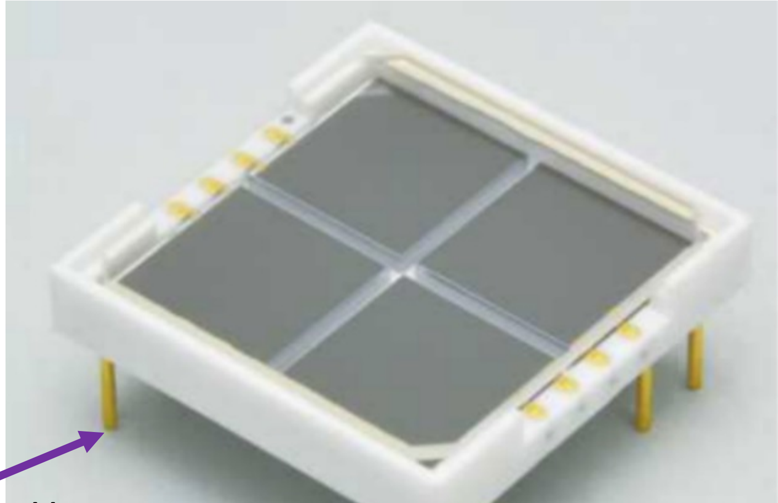
- Yield: 40 photons/keVee
- Emission timescales:
  - 6 ns (singlet)
  - 1.6 μs (triplet)

→ **Pulse Shape Discrimination** (PSD)

- Scintillation light wavelength: **128 nm** (requires wavelength shifting)

Xenon

- Yield: 60-70 photons/keVee
- Emission timescales:
  - 4 ns (singlet)
  - 22 ns (triplet)
- Scintillation light wavelength: **178 nm**



Hamamatsu VUV4 S13371

- **Neon** and **Helium** scintillate as well.
- Shorter wavelengths than Argon (≤ 100 nm).
- Not widely used, but interest in lighter targets could change that.

Detector Types

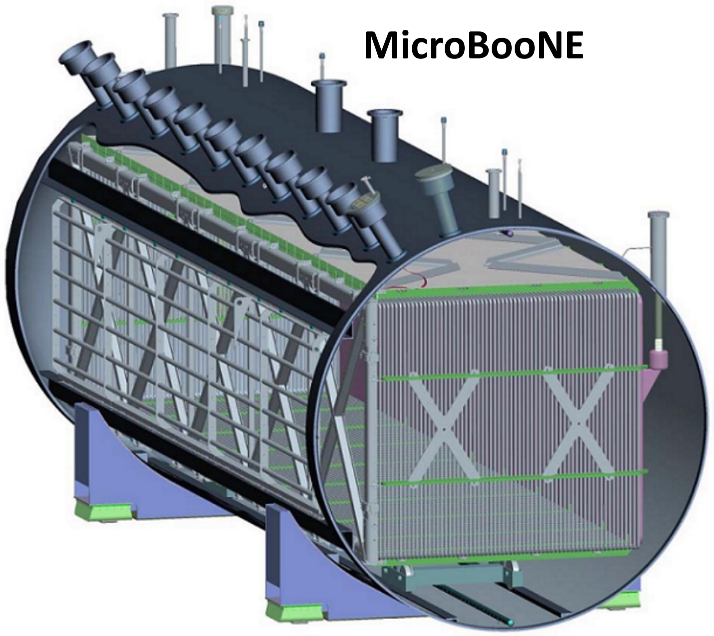
Scintillation Calorimeter

CCM 120 arXiv:2105.14020

- Scintillation channel only
- Timing information for PSD
- Reconstruction *possible* with fast detectors and wavelength shifting.

Time Projection Chamber

MicroBooNE

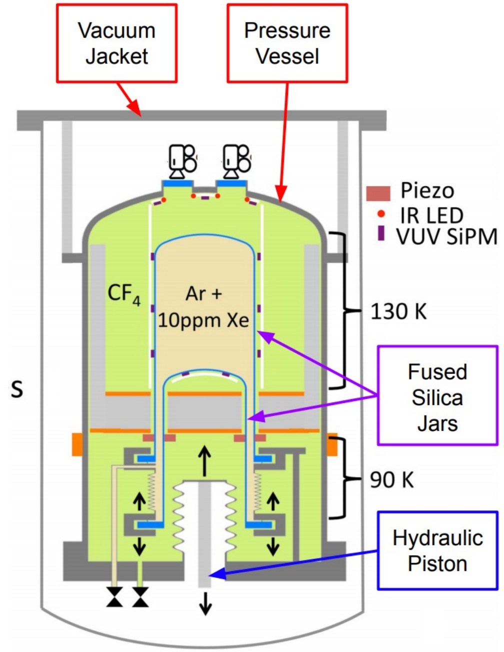


- Scintillation signal used for event triggering
- Ionization charged drifted and collected.
- Allows for 3D reconstruction.
- Single or Dual-phase

Bubble Chamber

SBC

S



Pietro Giampa ICHEP 2020

- Superheated liquid noble element
- Nuclear recoils create nucleation site for bubble creation
- Electrons/Gammas unable to generate bubbles due to insufficient linear energy transfer
- Scintillation signal can identify high-energy recoils

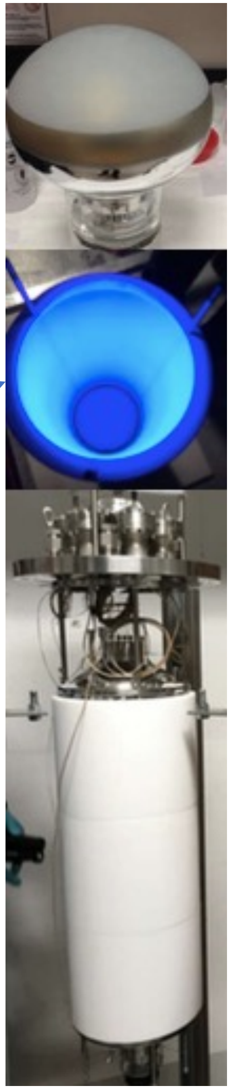
Challenges in Ar Scintillation

- Short wavelength (128 nm) requires wavelength shifting for detection with conventional photosensors.

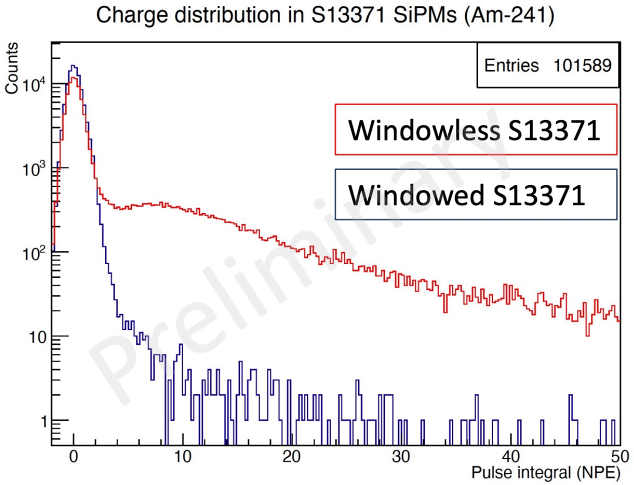
- Several materials available:

Table 1. Fundamental properties of common WLS materials used in LAr detectors: peak emission wavelength (λ_{em}), PLQY, re-emission lifetime (τ), refractive index (n), vapour pressure (p_{sat}), and approximate sublimation temperature (T_m).

Wavelength Shifter	λ_{em} [nm]	PLQY @ 128 nm	τ [ns]	n	p_{sat} [mbar]	T_m [°C]	Comment
TPB	430	0.6 [25]–2 [26]	2	1.7	10^{-11}	204	
p-Terphenyl	350	0.82 [27]	1	1.65		213	PLQY @ 254 nm
bis-MSB	440	0.75–1 [28,29]	1.5	1.7		180	PLQY rel. to TPB
pyrene	470	0.64 [30]	155	1.8	$6{\cdot}10^{-6}$	150	PLQY @ 260 nm
PEN	420	0.4–0.8 [31]	20	1.75	–	270	PLQY rel. to TPB



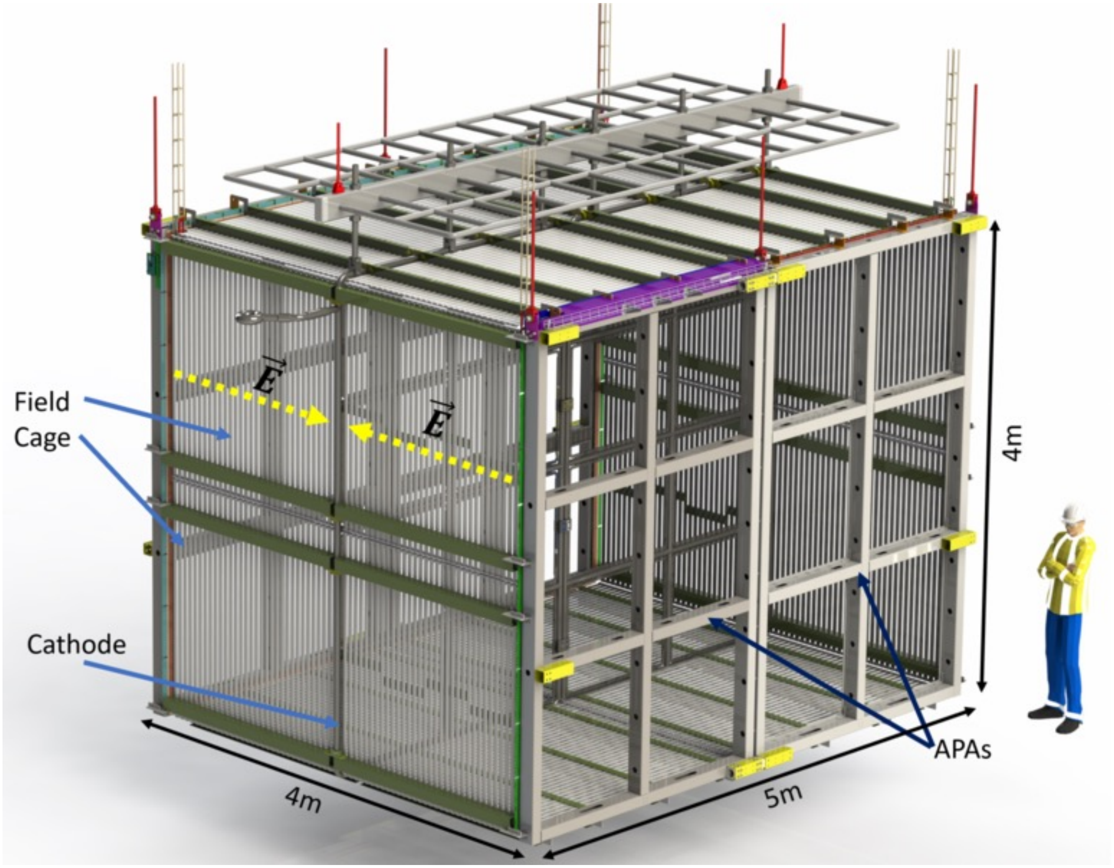
- Other option – VUV sensitivity:



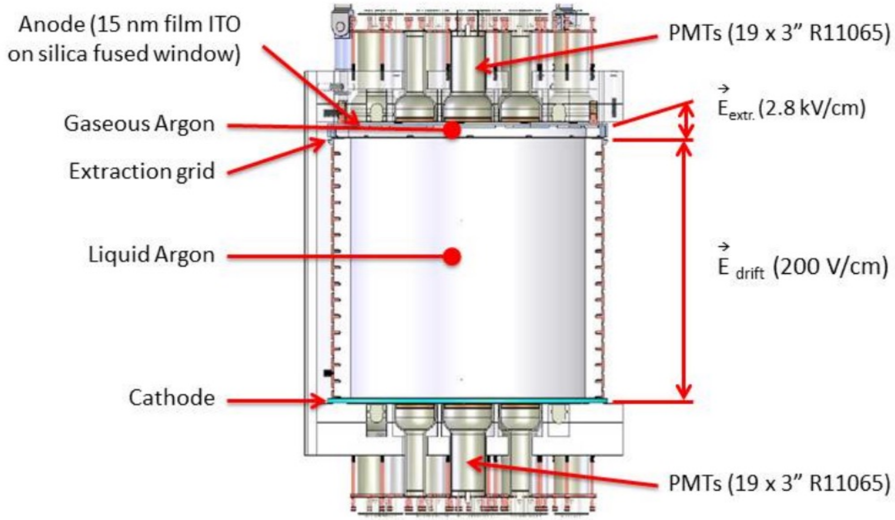
Teal Pershing
LIDINE 2021

Divergent R&D Needs

- Wide range of physics uses results in different priorities for liquid noble element R & D.
- Large experiments looking for scalable low-cost solutions while CEvNS and DM place more emphasis on collection efficiency.
- Desirable aspects often in tension:
  - Cost, Scalability, Stability, Efficiency, Power



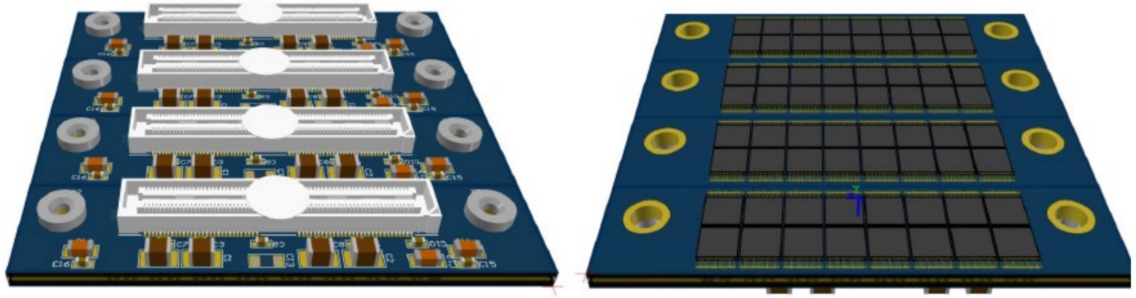
SBND TPC



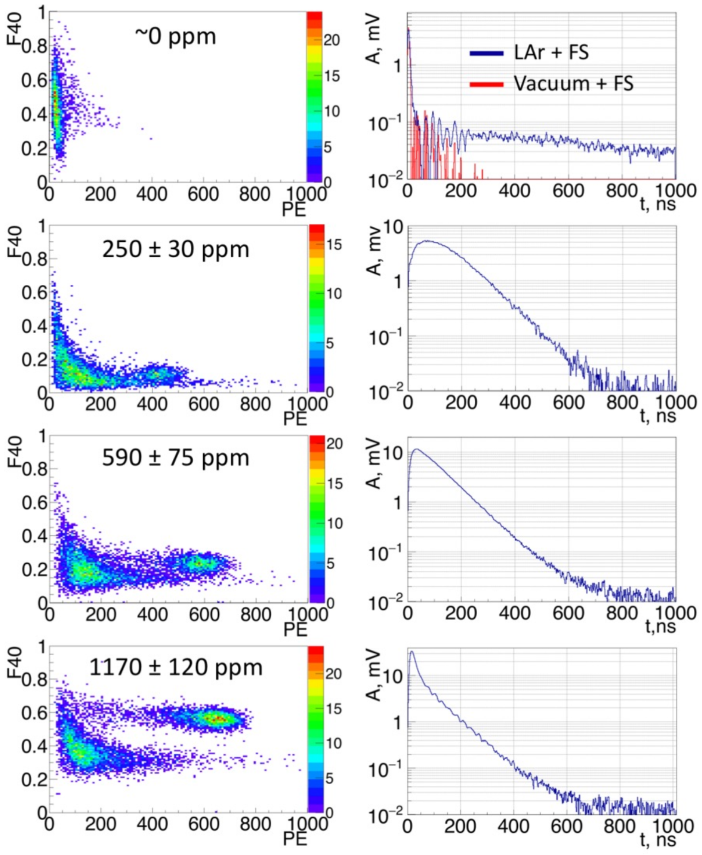
DarkSide-50 Experiment

Scalability

See talk by Lorenzo Fabris



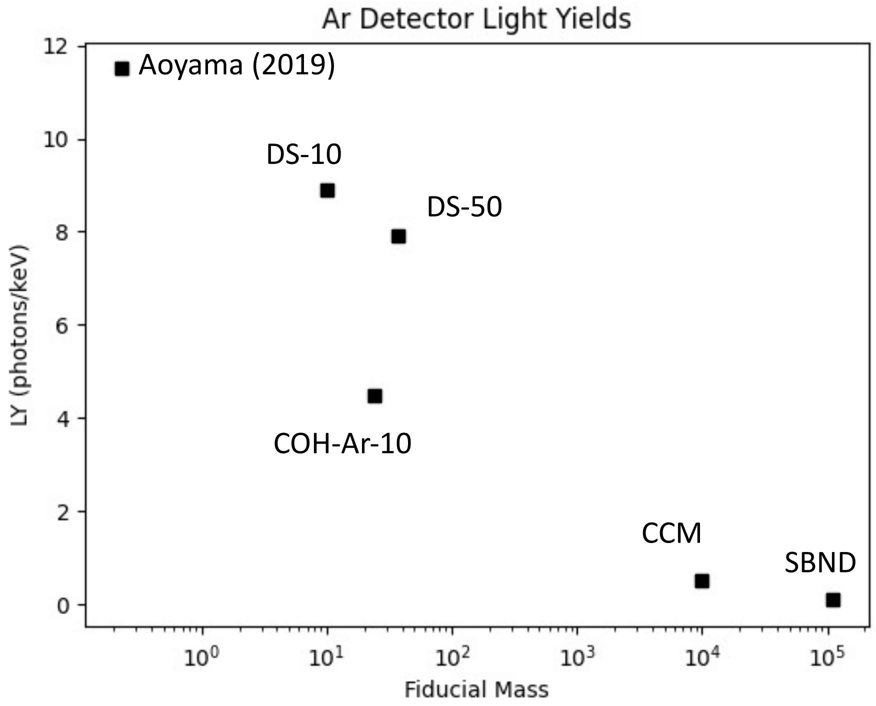
- SiPM arrays offer a detection scheme with lower intrinsic backgrounds than PMTs.
- Large arrays face issues with capacitance, noise, and power consumption!
- Photon-to-Digital Converters may offer a low-power solution which features excellent timing (see talk by Lorenzo Fabris).
- For LAr, achieving an effective and stable wavelength shifting scheme is non-trivial.
- Evaporative coating of TPB on large surfaces is expensive and time consuming. Stability of coatings may be an issue.
- Potential solutions include Xe-doping and the use of polyethylene naphthalate (PEN).

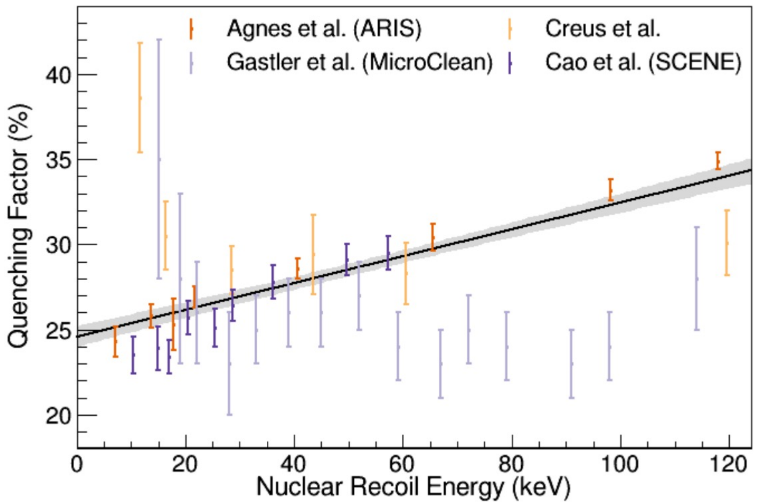


D. Akimov et al 2019 JINST 14 P09022

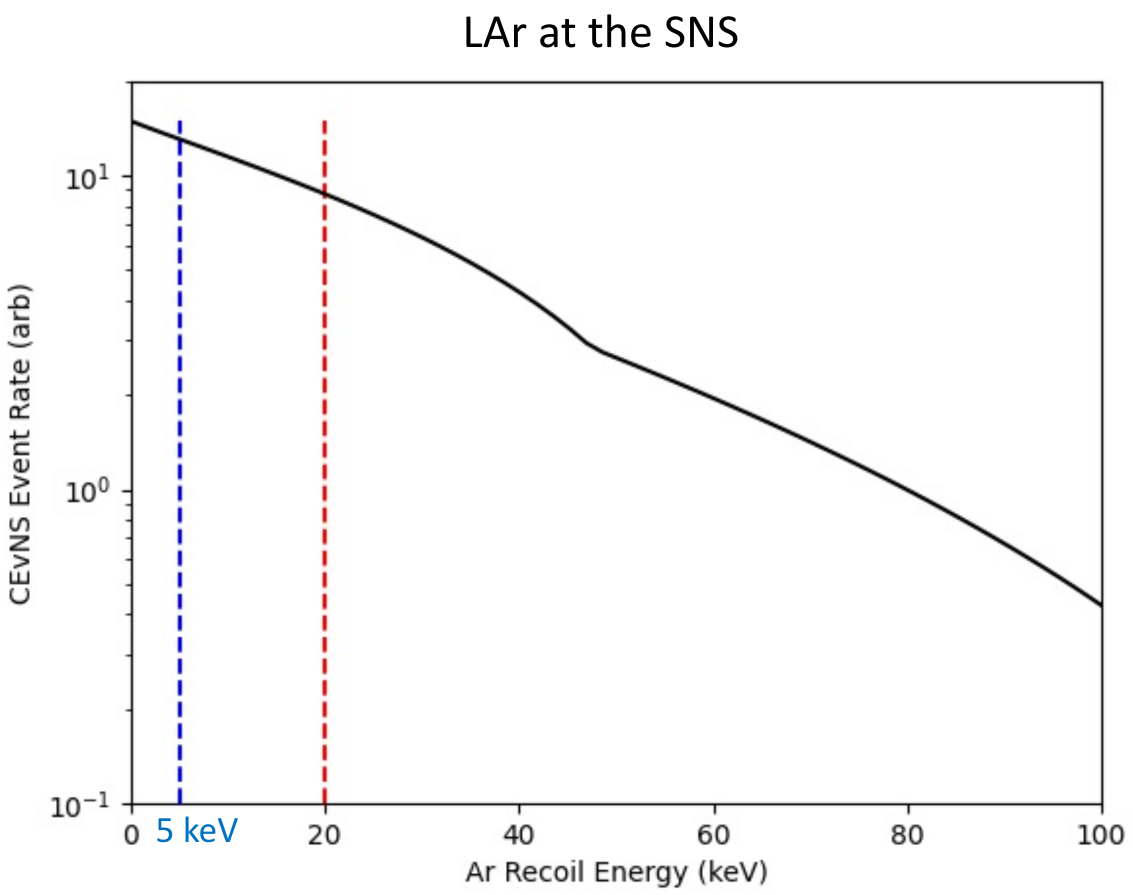
Maximizing Efficiency

- Pushing to lower thresholds requires increased scintillation efficiency.
- Highest light yields achieved so far have employed TPB+PMT schemes.
- Can similar (or better) light yields be reached with Xe-doping? What about without TPB?
- Maximizing photo-coverage is an obvious option, can more effective reflective surfaces be used?
- As thresholds are lowered, understanding of the nuclear recoil response will be essential – linearity of performance with energy not guaranteed!





Physics Potential of Improved Scintillation Detection

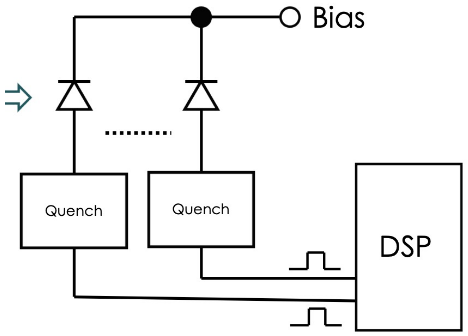


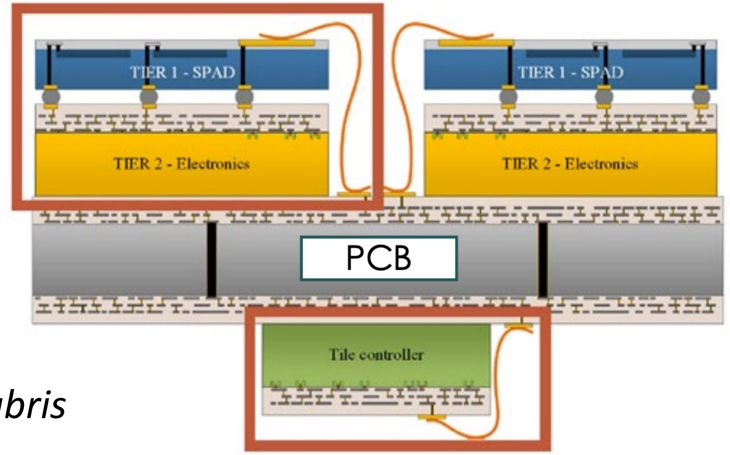
70% Event Rate Increase

- Improved light efficiency allows for lower recoil thresholds.
- Sensitivity to larger portion of CEvNS spectrum at π-DAR sources – enabling tests for NSI.
- Effects of a large neutrino magnetic moment will largely manifest at energies below current / planned threshold for LAr scintillation at the SNS.
- Improved PSD (essential for detectors using atmospheric Ar or subject to ER backgrounds).
- If methods are scalable, superior event timing and reconstruction for TPCs.

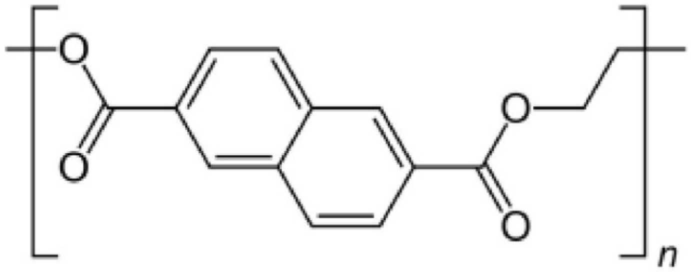
R&D at ORNL

- Ample opportunity for scintillation R&D at ORNL.
- Opportunity to test methods and technologies by synthesizing ongoing activities with existing LAr experiment.
- Demonstration of PDC operation in cryogenic environment will be of high interest to large-scale experiments!
- Possibility of branching out into new directions:
  - Alternative WLS
  - Exploring reconstruction and machine learning
  - Scintillation bubble chamber at HFIR?





Lorenzo Fabris

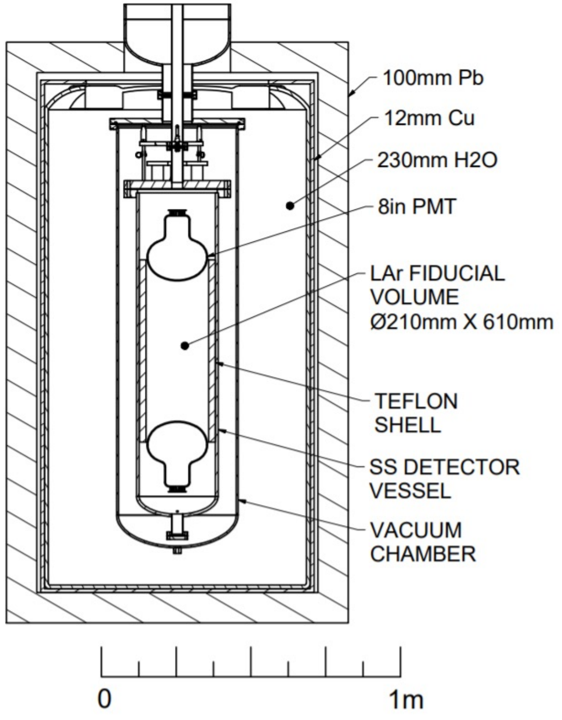


Chemical structure for polyethylene naphthalate

See talk by Brennan Hackett

Noble Elements at the SNS

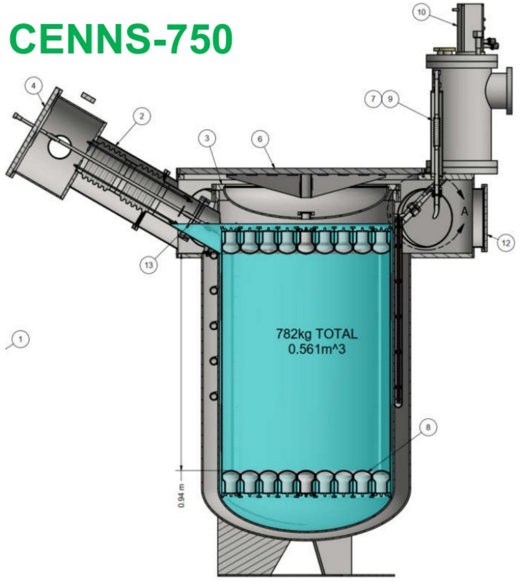
FTS (Present)



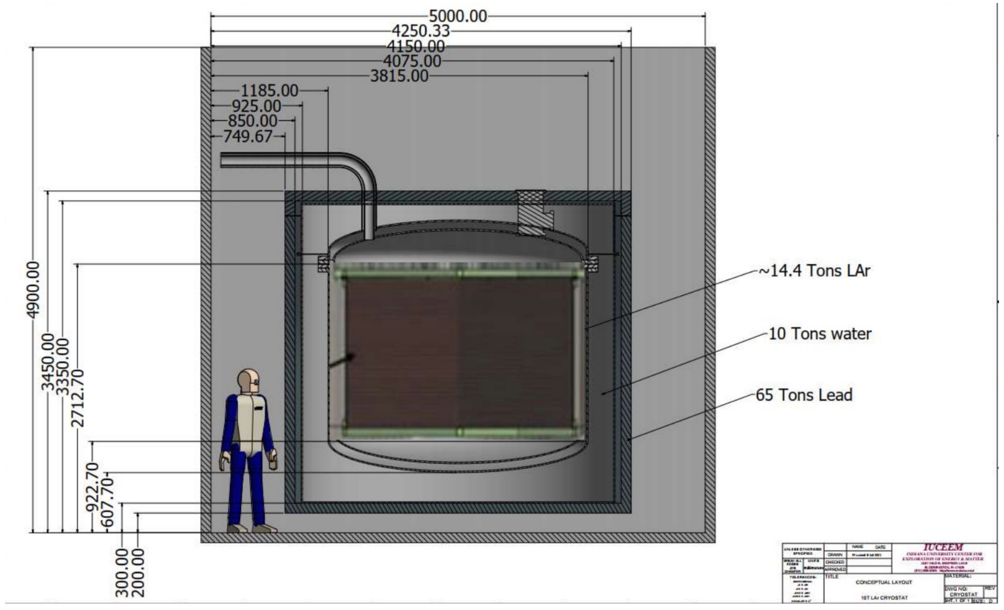
FTS (Future?)

R&D Testing:
- Xe-doping
- SiPMs
- Retrofit and Redeployment

CENNS-750



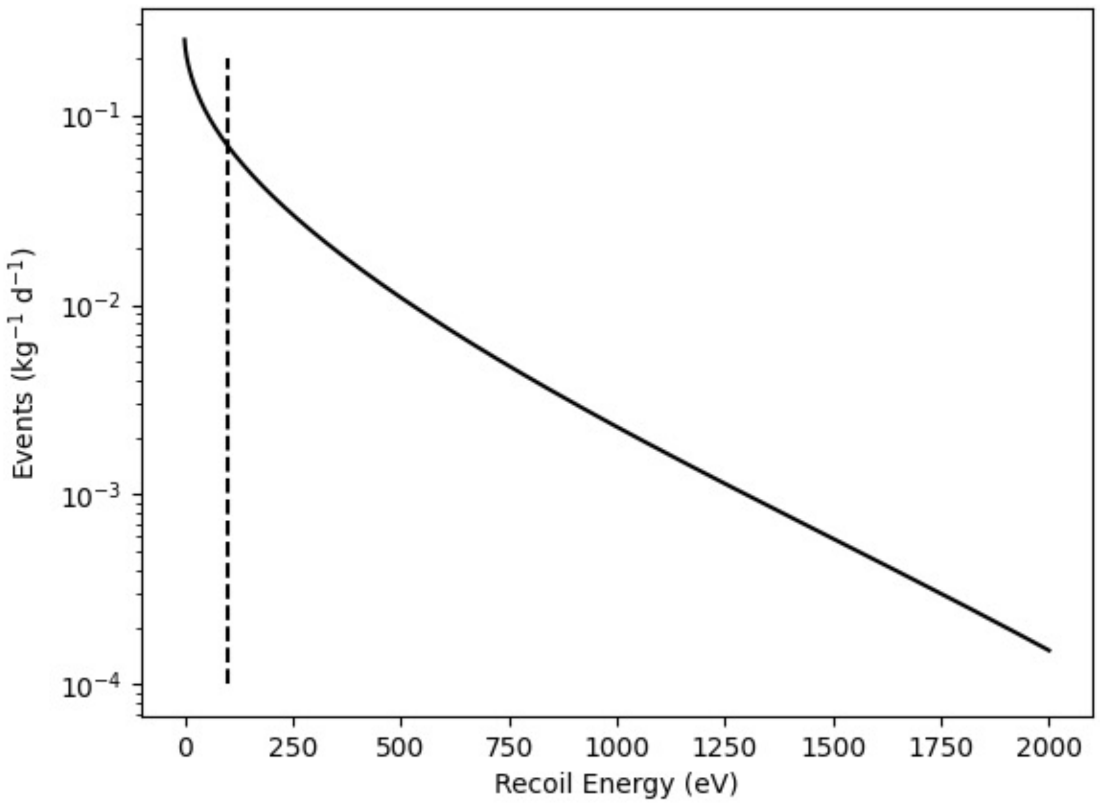
STS

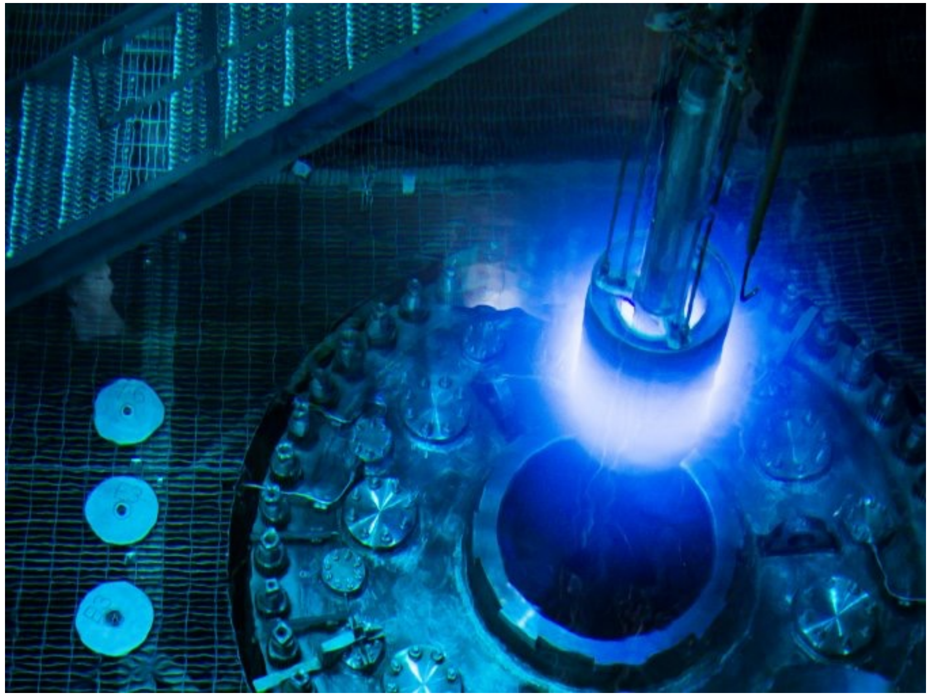


10t scale LAr (or LXe) at TPC

Noble Elements at HFIR?

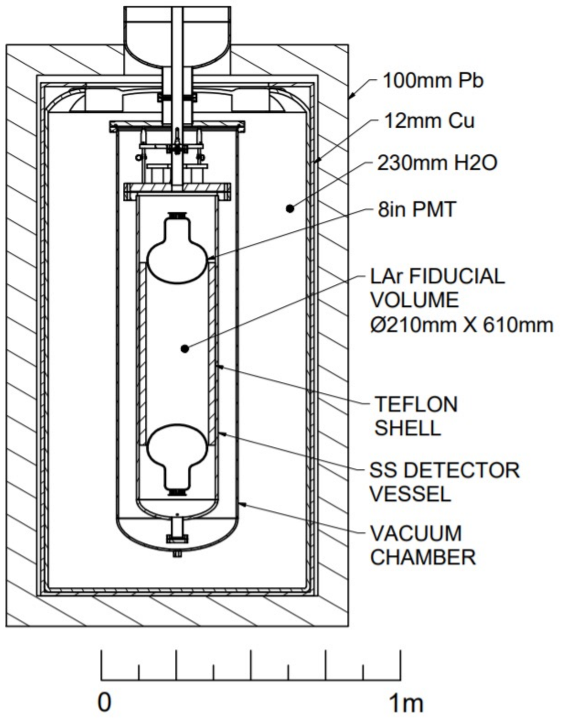
Ar Recoil Spectrum @ 7.9 meters

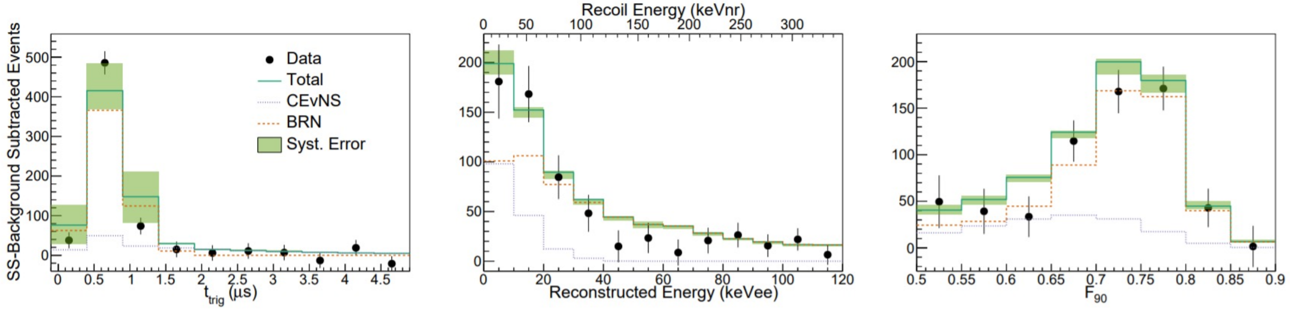




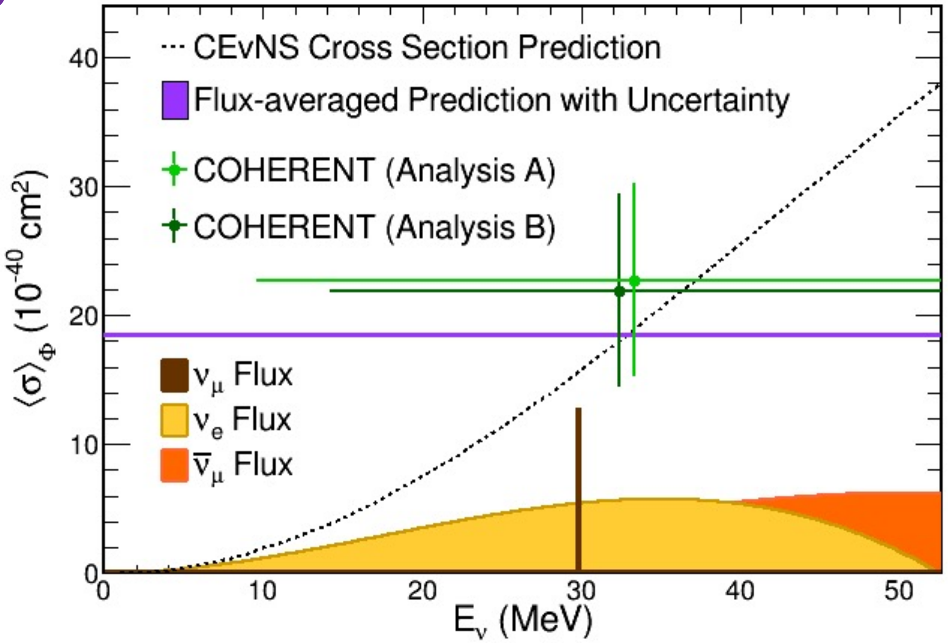
- Scintillating bubble chamber at HFIR capable of large CEvNS event rate: 9.7 events kg^-1 d^-1 for Ar
- Xenon chamber with similar threshold would also feature a large rate.
- Detection of scintillation light can veto neutron-induced recoils; very low background.
- No spectral information for CEvNS BUT could operate with varying threshold.

COH-Ar-10 Testbed

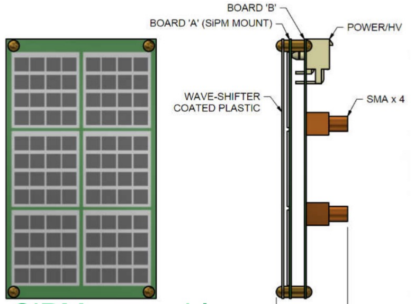




arXiv:*2003.10630*



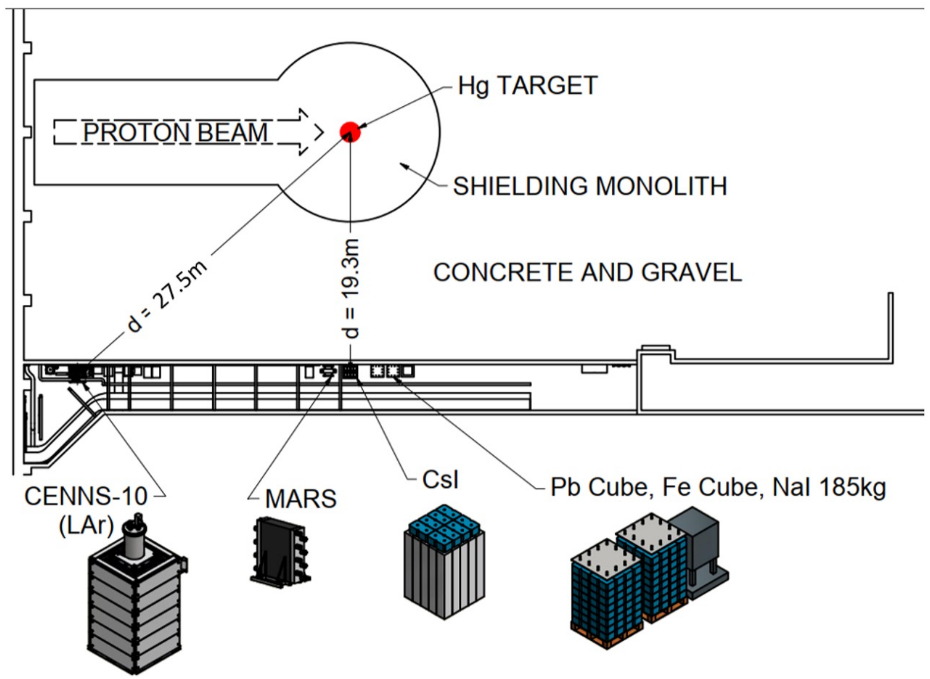
- COH-Ar-10 has completed primary physics data taking (GWhr accumulated).
- Plans for some testing going forward (Xe-doping, SiPMs, etc.)
- Potential for retrofit to demonstrate scintillation R&D?



SiPM assembly

COH-Ar-10 Testbed

- Potential deployment of a re-vamped COH-Ar-10 featuring improved recoil threshold.
- More optimal location in the alley would yield a higher event rate *and* lower prompt neutron backgrounds.
- Low threshold (~5 keVnr) enables searches for anomalous neutrino magnetic moment.
- Sensitivity to more of the CEvNS spectrum allows for test of expected spectral shape and other possible NSI effects.
- Successful design can be incorporated to future LAr detectors at the FTS and STS.



OAK RIDGE National Laboratory

Summary

- Prolific use of liquid noble elements in physics has spurred a large amount of R&D effort; a lot of these efforts overlap, but not all experiments share the same priorities.

- LAr detectors searching for DM (cosmological or accelerator-produced) and CEvNS interactions benefit greatly from increased scintillation efficiency (potentially opening up new searches).

- Integrating ongoing detector and materials development at ORNL with LAr infrastructure at the SNS presents an excellent opportunity to develop new methods for scintillation detection.

- Retrofit and redeployment of COH-Ar-10 in Neutrino Alley could provide a demonstration of detection scheme performance while yielding interesting physics results.