# Antineutrino Detection & Technology

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Lawrence Livermore National Laboratory

# Overview

First – I apologize. I cannot cover everything. Also I cannot rule out a Livermore bias. My excuse is I have to get along with folks when I go back home…… ☺

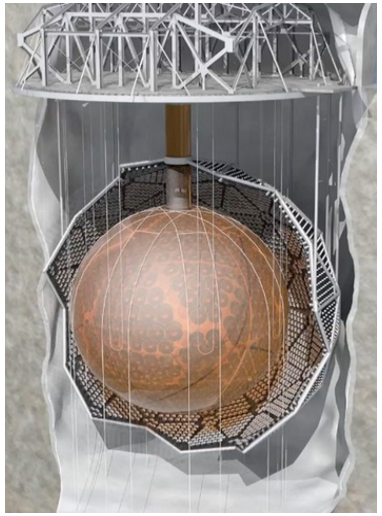
- State of the art – where are we?
- Summary of interaction types – Inverse Beta, Electron scattering, CEvNS
- Needed capabilities?

**Looking forward:**

- Detection materials – new plastics, liquids
- Long-term operation considerations
- Scaling
- Innovative segmented designs
- Photodetection
- Electron scattering and CEvNS
- Summary and the view ahead

# Reactor neutrino experiments – state of the art (deep)

**SNO+**

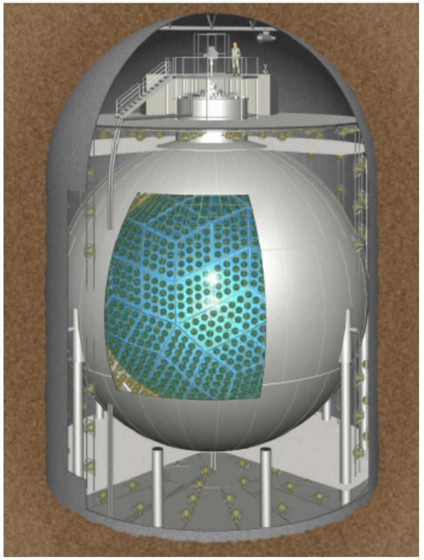


(Pure water phase)

Allega et al.
Phys. Rev. Lett. 130, 091801

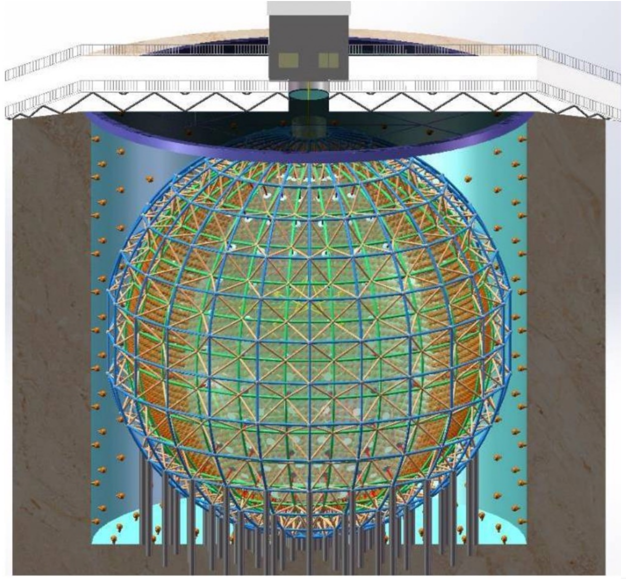
| | **SNO+ water phase** | **KamLAND** | **JUNO** |
|---|---|---|---|
| Target mass | 0.9 kt | 1 kt | 20 kt |
| PMT coverage | 55% (including light concentrators) | 34% | 78% |
| Detection Material | Water | Pseudocumene + min. oil | Linear Alkylbenzene |
| Energy Res. | ~50% @ 1 MeV (est.) | 6.4% @ 1 MeV | 3% @ 1 MeV |
| Purpose | Neutrinoless double beta decay | Measure $\theta_{12}$ | Neutrino mass hierarchy |

**KamLAND**



e.g.
Abe et al.
Phys. Rev. Lett.
100, 221803, (2008)

**JUNO**



e.g.
Angel Abusleme et al. 2022
Chinese Phys. C 46 123001

At > ~1km depth, cosmogenic backgrounds are suppressed.

Pure scintillator (or water) designs are favored for simplicity, long attenuation lengths, large volumes.

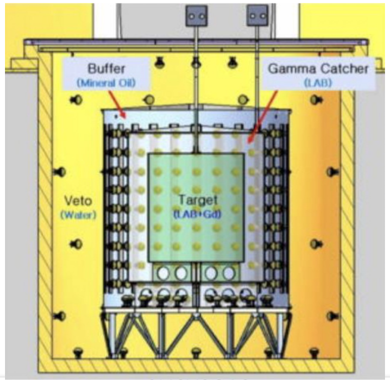
# Reactor neutrino experiments – state of the art (mid depth)
# $\theta_{13}$ experiments in early 2000s.

- Shorter baselines → shallower deployment. Need to work harder to defeat cosmogenic backgrounds.
- E.g. employ gadolinium doping
- Nested scintillator volume designs were in part forced by the characteristics of neutron capture on gadolinium

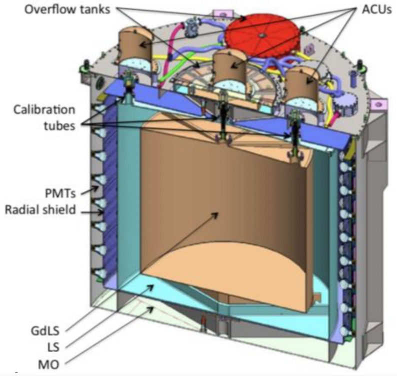
| **Vol Name** | **Material** | **Purpose** |
|---|---|---|
| Target volume | Gd-doped scintillator | Detect the $e^+$ and neutron capture |
| Gamma-catcher | Non doped scintillator | Ensures full energy recovery from Gd-neutron capture |
| Buffer volume | Mineral oil | PMT-related gamma-rays shielded from scintillator |
| Veto | Water | Veto events associated with recent passage of muon |

RENO
Physical Review Letters. **108** (18): 191802
Daya Bay
Physical Review Letters. **108** (17): 171803
Double Chooz
Physical Review Letters. 108, 131801

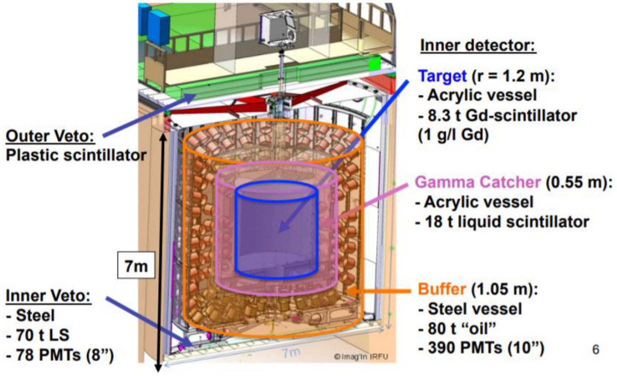
**RENO**



**Daya Bay**



**Double Chooz**

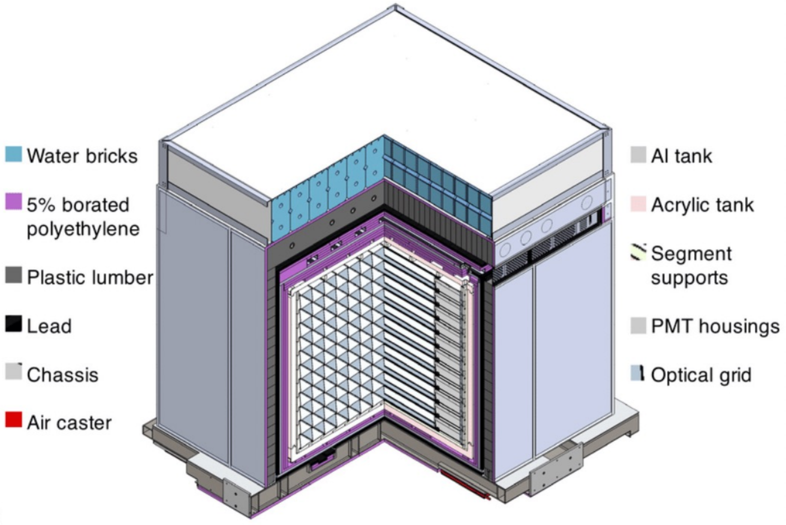


# Reactor neutrino experiments – state of the art (Surface deployments)

- Ultra-short baselines → aboveground deployments.
- Cosmogenic fast neutrons. Topological characteristics (segmentation) and particle ID (PSD) become important
- PROSPECT, MiniChandler → First successful aboveground experiments
- Other significant experiments in the field SOLID, STEREO also rely on segmentation

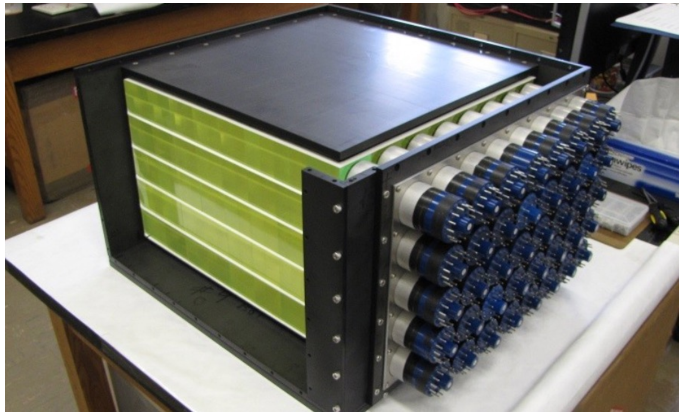
**PROSPECT detector**

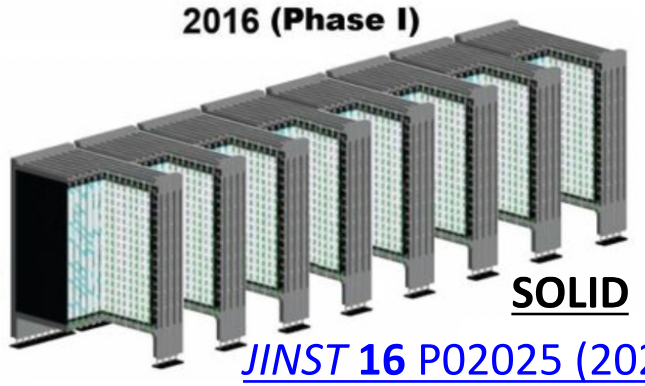
Physical Review Letters 131, 021802 (2023)



**MiniCHANDLER**

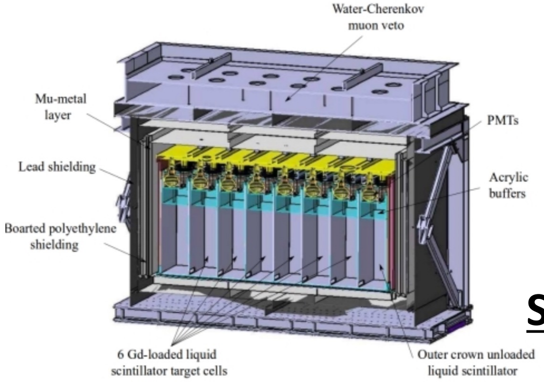
Physical Review Applied 13, 034028 (2020)





**SOLID**

*JINST* **16** P02025 (2021)



**STEREO**

Physical Review D 102, 052002 (2020)

# Interaction Types

**IBD:**

- Up until now, simple inverse beta decay (IBD) has dominated the antineutrino detection field.
- $\bar{\nu}_e$ + p → $e^+$ + n

But there are other options. As technologies continue to improve, ES and CEvNS may become more relevant

**Electron Scattering:** $\bar{\nu}_e$ + $e^-$ → $\bar{\nu}_e$ + $e^-$

- The interaction of choice for low energy solar neutrino detection at Super-K, allows access to antineutrino direction

**CEvNS:** $\bar{\nu}_e$ + N → $\bar{\nu}_e$ + N

- Increases the interaction cross-section by ~100x relative to IBD. But observable – low E nucleus

# Needed capabilities?

In recent years, enormous progress has been made producing detectors capable of aboveground deployment.
What is still missing now?

# Needed capabilities?

**For nonproliferation:**

- we still don't have (quite) a stand alone detector that can be parked next to a reactor for monitoring purposes – watch this space ☺
- We've seen above ground detection at ~10-20m. Sensitivity to lower fluxes?
- Better particle ID for aboveground and shallow deployments
- Directionality?

**For science:**

- We are very close to having a relic supernova detector – Super-K
- Geoneutrino and mass hierarchy sensitivity breakthroughs – JUNO
- Better particle ID in beam experiments
- Directionality

In this talk I will go over some of the more relevant near-future technologies likely to get us closer to some of these capabilities

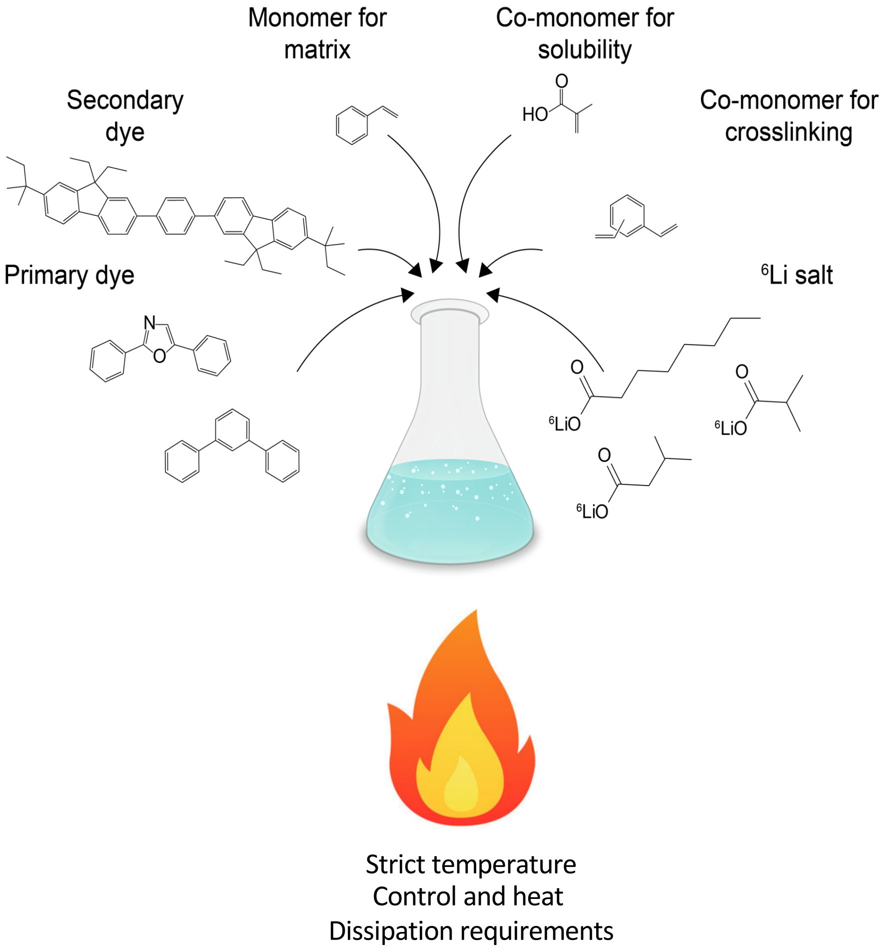
# Where to from here?

# New materials – $^{6}$Li-doped PSD plastic scintillator

- Invented 2013

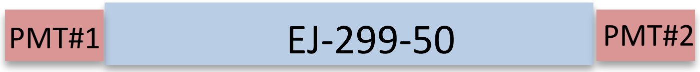
[Zaitseva et al. NIMA – V729, P747 (2013)](#)

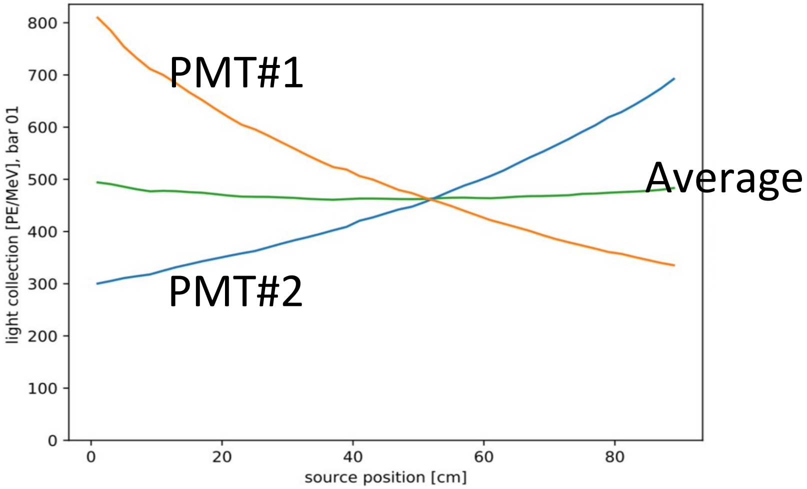
- Multi-liter volumes are now available from Eljen Technologies (EJ-299-50)
- Key ingredients – scintillating monomer (styrene or vinyl toluene), ~30% PPO (primary dye, provides PSD), secondary dye
- $^{6}$Li salt dissolved within an organic co-monomer – methacrylic acid.
- Cross-linker to strengthen polymerization



# $^6$Li-doped PSD plastic scintillator - performance

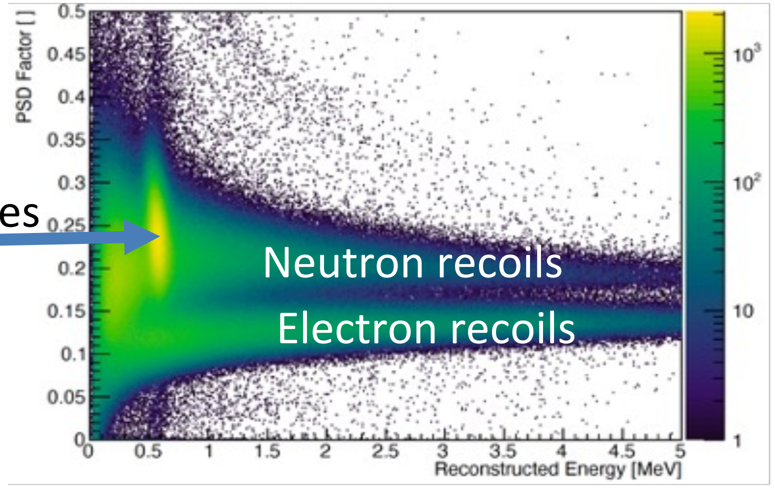
Bar experimental setup





- Light output ~65% of EJ 200 (a non PSD standard) – ~6000 Photons/MeV
- Attenuation lengths ~90 cm
- Shown is typical attenuation and PSD performance from a 6cm x 6cm x 100cm bar
- 2-inch PMTs at both ends
- Bar wrapped with mirror-like material
- Collimated gamma-ray source

Neutron captures on $^6$Li



See talk by Cristian Roca

# $^6$Li-doped PSD plastic scintillator – long term performance

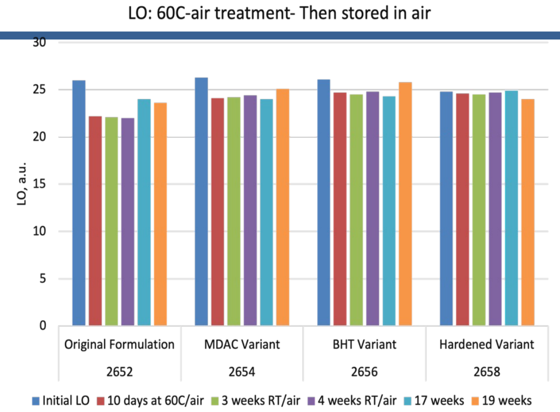
**Yellowing update:**

- Earlier iterations of PSD plastic scintillator have shown a tendency to interact with oxygen – causing yellowing, and reduced light output
- e.g. EJ-276, EJ-299-33
- If you have bought one of these you know….
- The new version (EJ-299-50) performs much better
- Over ~1 year time-scales – no yellowing observed
- Within EJ-299-50 we are testing further improvements

**Scintillator sweating/outgassing:**

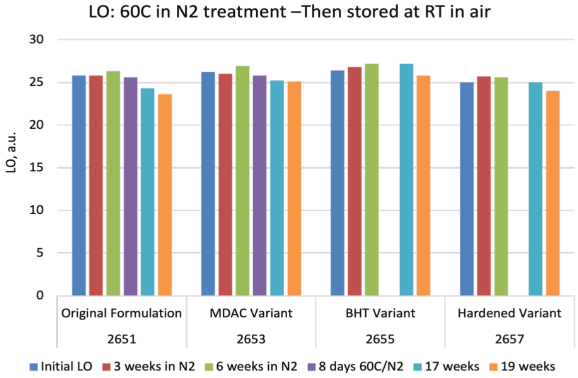
- 30% PPO doesn't polymerize. It slowly diffuses out of the plastic into the air
- If trapped near scintillator – PPO crystals can form
- Crystals can interfere with light propagation along a bar
- Degradation ~6-9 months timescale
- Crystal formation can be defeated by bonding a layer of plastic on the scintillator

See talk by Cristian Roca



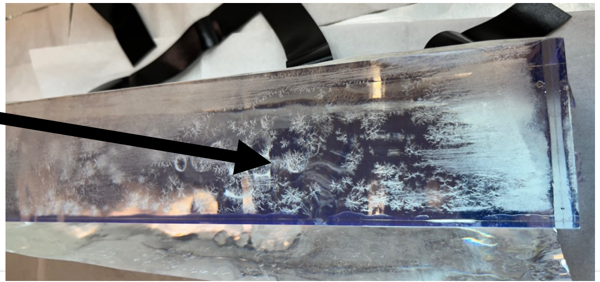
Effect of ageing on light output in air:

- 4 variants tested. 3 with antioxidants added, 1 "hardened" variant.
- Antioxidants degrade less in ageing tests
- Antioxidant+hardener shows little if any ageing effect

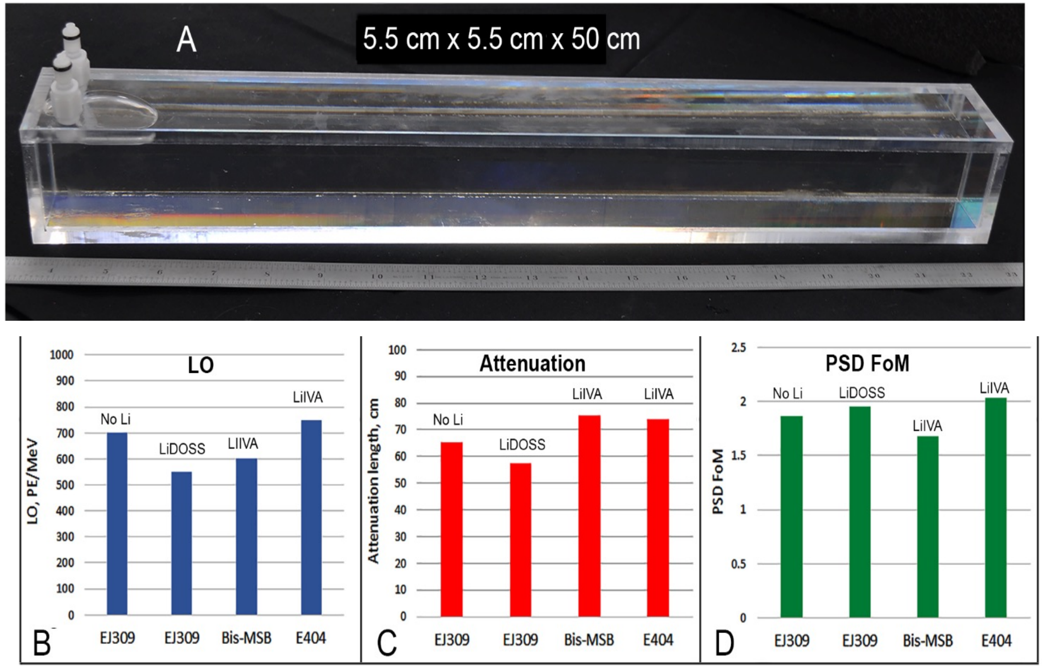


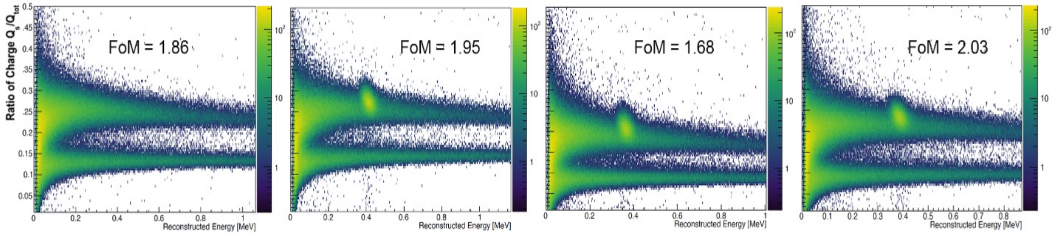
Effect of ageing on light output in nitrogen:

- Same variants show little if any ageing under nitrogen



# New materials – $^6$Li-doped PSD liquid scintillator





EJ-309 EJ-309 + 6LiDOSS Bis-MSB + 6LiIVA E404 + 6LiIVA

<u>Motivation:</u>

- Previous $^6$Li-doped PSD liquid scintillators (e.g. PROSPECT) relied upon dissolving $^6$Li salt in water, then mixed throughout liquid scintillator via an emulsion
- Work associated with dissolving $^6$Li in organic compounds directly (with no need for emulsions) grew out of the plastic scintillator work - which provided capability to directly dissolved in scintillator

<u>Light output, PSD and attenuation Tests:</u>

- Acrylic test cells – same dimensions as ROADSTR scint. bars – 5.5cm x 5.5cm x 50cm
- Cells wrapped with specular reflective wrapping
- Tests directly comparable to PSD plastic tests
- 2-inch PMTs mounted at both ends of each cell.
- $^6$Li organic compounds appear to not negatively impact scintillator light output

**Note: $^6$Li-doped PSD liquid scintillator is actively being evaluated as a possible fill for PROSPECT 2**

See talk by Tomi Akindele

# Opaque scintillating materials

**LiquidO Concept:**

- Liquid scintillator with very long absorption length, and very short scattering length combined with wavelength shifting fibers to extract light from the medium
- In principle, enhanced event reconstruction (3D imaging)

**Outstanding questions:**

- Energy resolution? – drivers will be photo-statistics + distance to fiber
- How to handle proliferation of channels

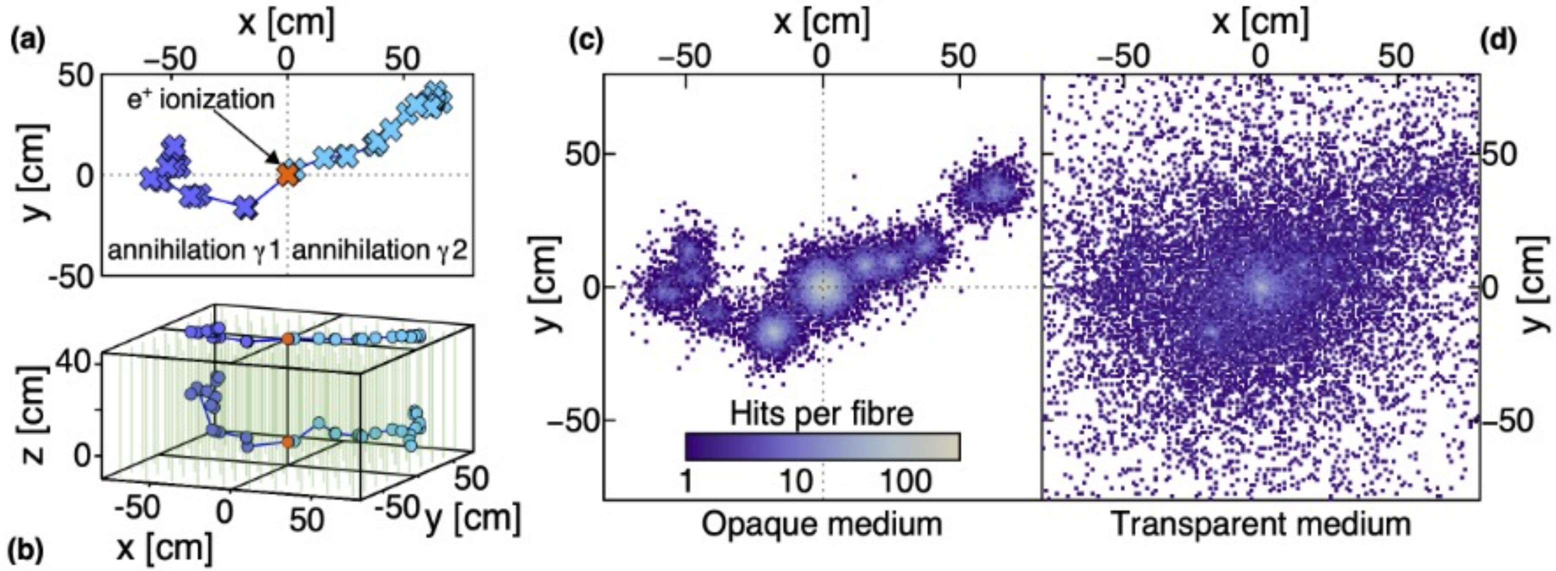
**Plans for the future:**

- Larger prototypes
- Optimization of liquid (scattering length, minimizing absorption)

**Long term plan:**

- SuperChooz (~10 kton, ~1km from Chooz reactors)

## Simulations:



**1 MeV $e^+$:**

(a): 2D representation

(b): 3D representation

(c): reconstruction (5mm scattering length)

(d): transparent scintillator

See Nature Communication Physics, **4**, Article number 273 (2021)

# WbLS

Invented by Minfang Yeh at BNL

[NIMA, V660, issue 1, (2011), P51]()

**Concept:**

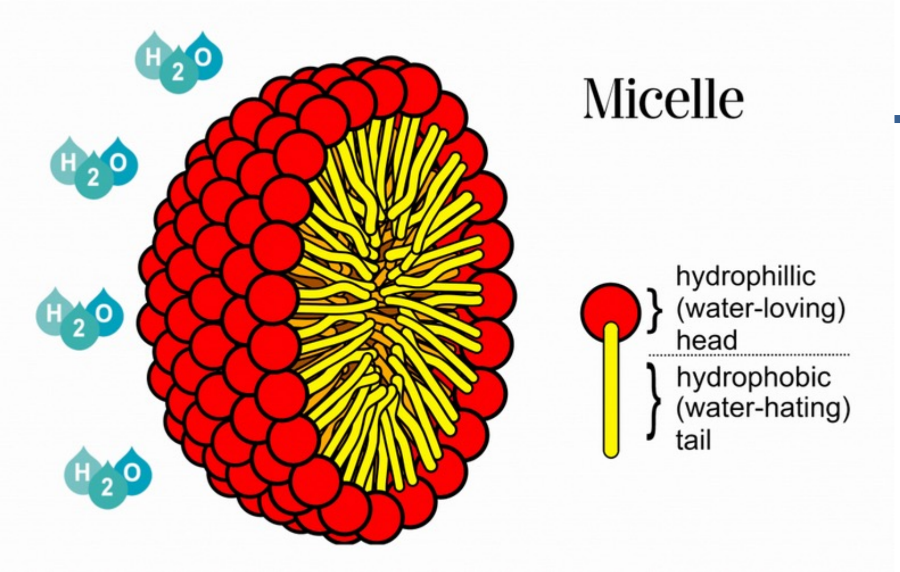
- Emulsion of organic scintillator shielded from water inside micelle structures
- Fraction of scintillator to water can be tuned for your application (anywhere from 1% to 10s%)
- Particle ID via Cherenkov/scintillation separation
- Dopants such as gadolinium can be added to the water

**Proposed experiments:**

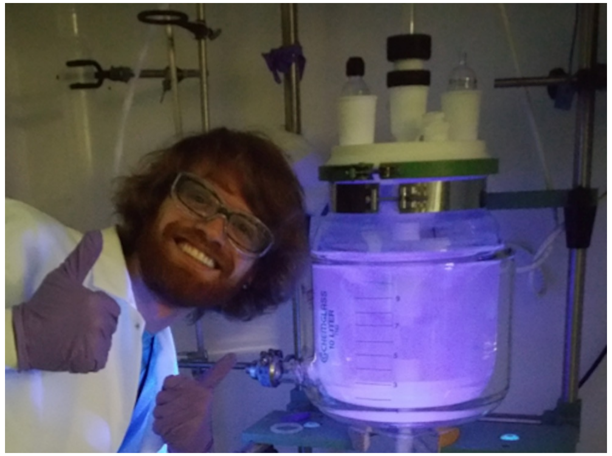
- 400L Deployed in ANNIE
- Proposed for WATCHMAN, EOS, BUTTON and Theia

**R&D:**

- Continuous purification of water needed for long term deployment



UC Davis
https://svoboda.ucdavis.edu/rd-projects/water-based-liquid-scintillator



# WbLS – PSD and potential for organic doping

**Concept:**

- Increased organic fraction (10s%)
- PSD sensitivity
- $^6$Li doping can be added to the organic component rather than the water

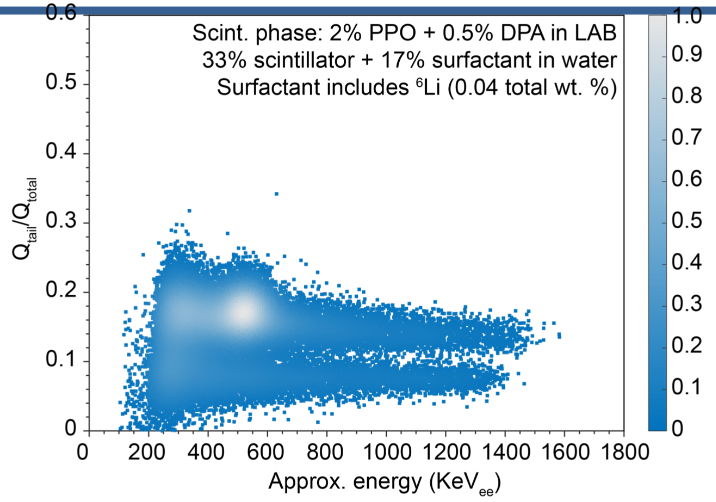
**R&D:**

- Early stage – currently testing whole parameter space for concentrations of surfactant/scintillator/water that result in clear liquid
- R&D to scale up production commences in 2024

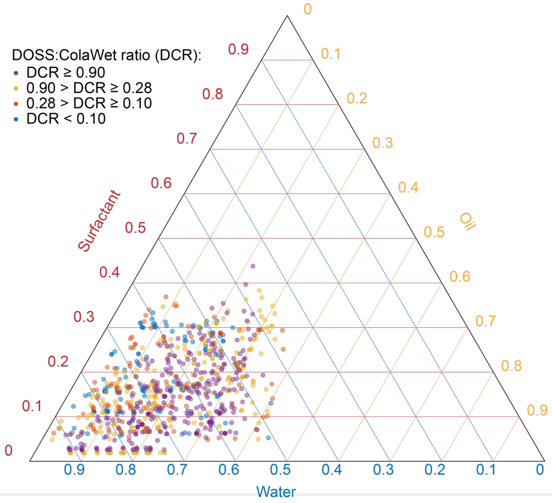
**Purification:**

- The use of pure DI water may have implications for purification (good? Bad?, R&D question)

See talk by Tomi Akindele


Scint. phase: 2% PPO + 0.5% DPA in LAB
33% scintillator + 17% surfactant in water
Surfactant includes $^6$Li (0.04 total wt. %)

T. Akindele, M. Ford, N. Zaitseva



# Long term material performance of new materials

**WbLS:**

- Bacteria multiplies just great in water. So all water-based materials must be continually purified to maintain clarity
- Water is a great solvent – dissolves your detector! - so it must be continually purified to remove ions
- R&D to separate water/organics on a large scale continues at UC Davis and BNL

**WbLS (PSD):**

- Undoped water may help purification process? Not sure.

**$^6$Li-doped PSD plastic:**

- Oxygen induced yellowing which plagued earlier iterations appears to be small/manageable now
- PPO outgassing/sweating appears manageable over ~1 year timescale. Testing mitigations for MAD

**$^6$Li-doped PSD liquid:**

- Long term stability and materials compatibility may be improved relative to PROSPECT. Needs further testing to confirm

# Scaling

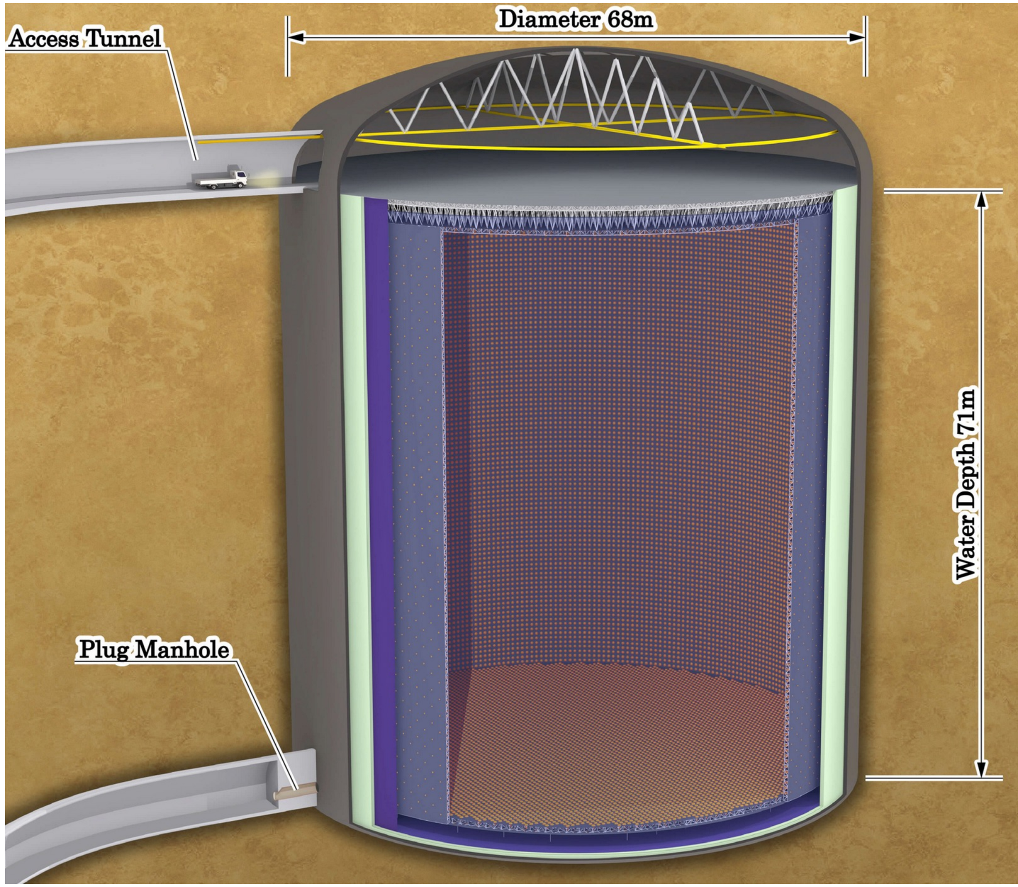
**To set the scale:**

- Water Cherenkov and Gd-H2O – up to 50-260 kton (Super-K and Hyper-K)

**New scintillators:**

- $^6$Li-doped PSD plastic – 1-5 liters per item
- $^6$Li-doped PSD liquid scintillator – R&D questions being addressed now
- WbLS – currently being scaled to ~30 tons. Scaling to kilotons depends on purification R&D (UC Davis and BNL)
- PSD WbLS – purification R&D needed

**260 kton Hyper-Kamiokande detector**



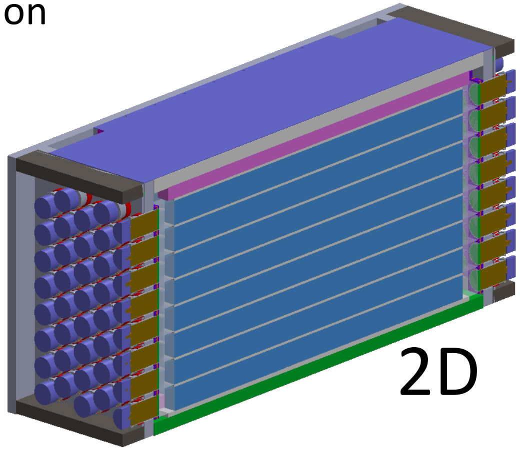
The Hyper-Kamiokande design report

# Mobile, above-ground deployments

- Nonproliferation and reactor operator communities have identified use-cases for neutrino detectors, as summarized in NuTools (called for aboveground and mobile capability)
- Plastic materials are ideal for mobile applications
- PROSPECT and MiniChandler have shown that PSD and segmentation help reduce cosmogenic neutron backgrounds by
  - Identifying pulse shape and topological characteristics of signal and background
  - providing accurate position reconstruction – distance cuts, fiducialization
  - Enhances efficient photon detection

**M**obile
**A**ntineutrino
**D**emonstrator

MAD will be a
hybrid (2D + 3D) detector



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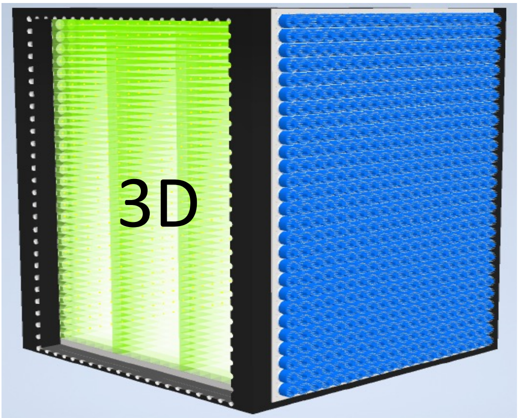


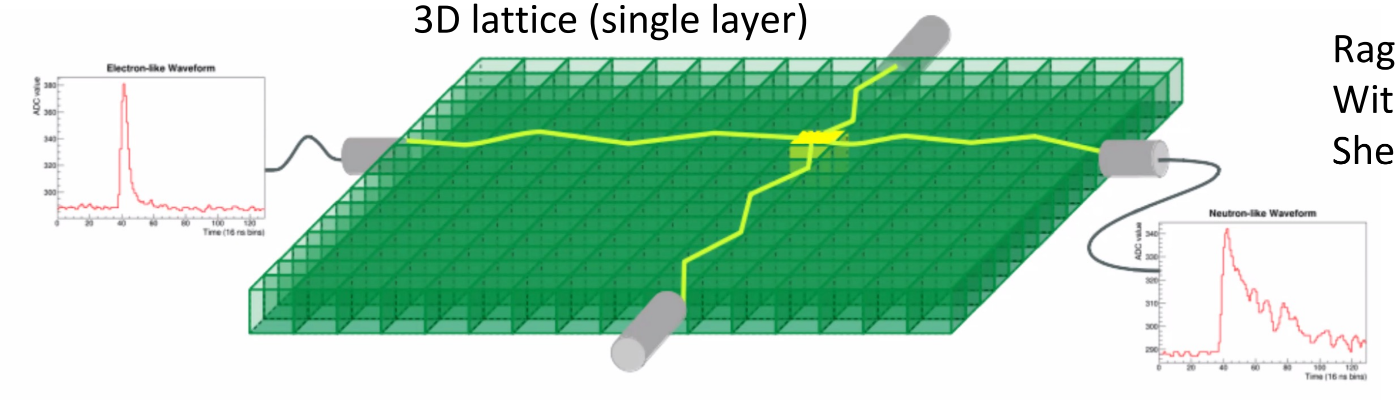
See talk by
Nathaniel Bowden

3D does better at topological event characterization. 2D incorporates PSD for fast neutron rejection

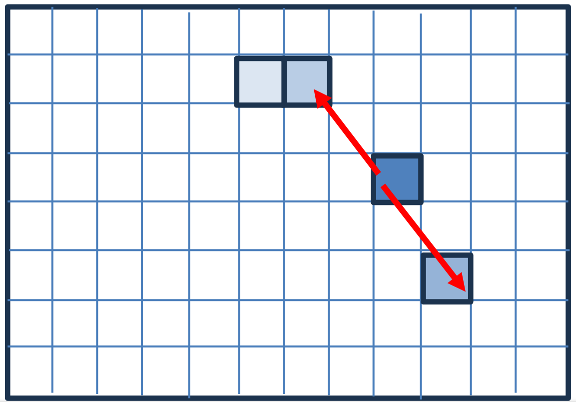
# 3D Segmentation

The goal of 3D topology selection is to identify patterns that are consistent with the Compton scattering of the back-to-back, electron-positron annihilation gammas

3D lattice (single layer)



Raghavan optical lattice
With EJ 426 scintillator
Sheets for neutron capture



Idealized primary
Energy deposit (positron)
And 2x .511 MeV gamma-rays

MiniCHANDLER talk
by Keegan Walkup

# Photodetection – LAPPDs

## available from Incom (https://incomusa.com/lappd/)

**Concept:**

- Position sensitive photon detector with 10s ps timing resolution over 20cm x 20cm area

**Why is development slow?:**

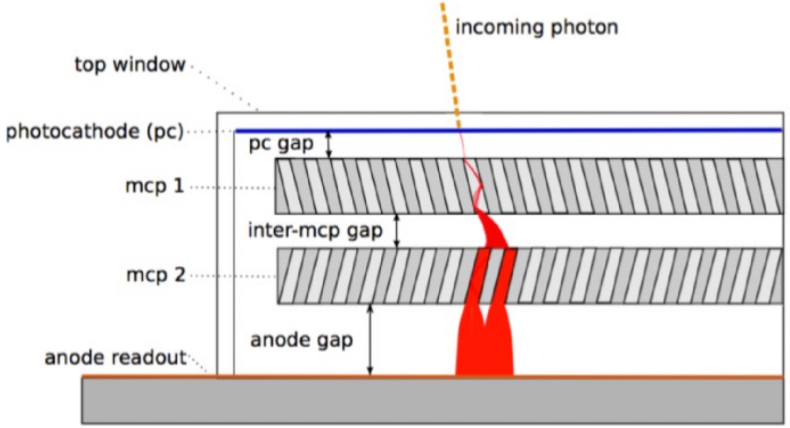
- Readouts are taking a while to catch up to the capabilities that LAPPDs provide
- Need to digitize signal at the LAPPD, not at a distant rack of digitizers
- Speed, # channels, heat dissipation

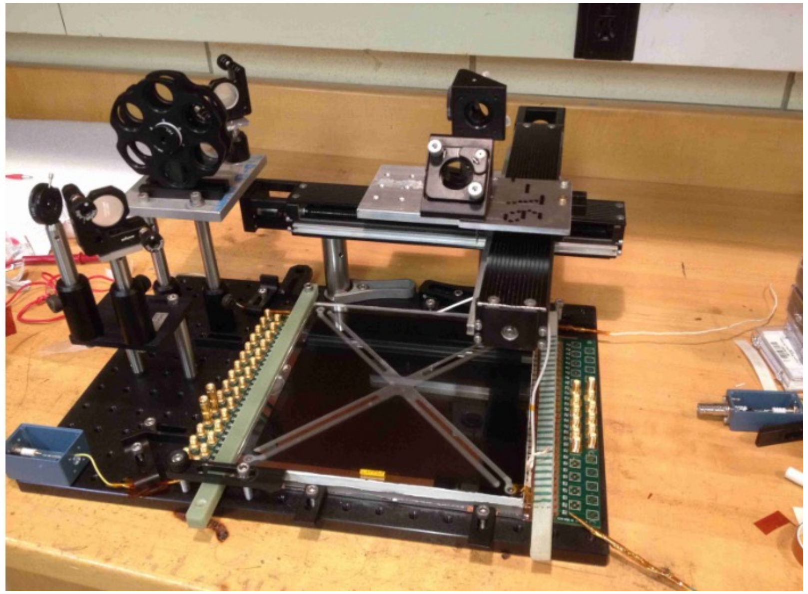
**Solutions:**

- ANNIE has been testing a prototype
- BUTTON will be soon

ANNIE
https://annie.fnal.gov/

BUTTON
IoP HEPP & APP Conference, 3rd April 2023





# Photodetection – large area SiPMs

**Concept:**

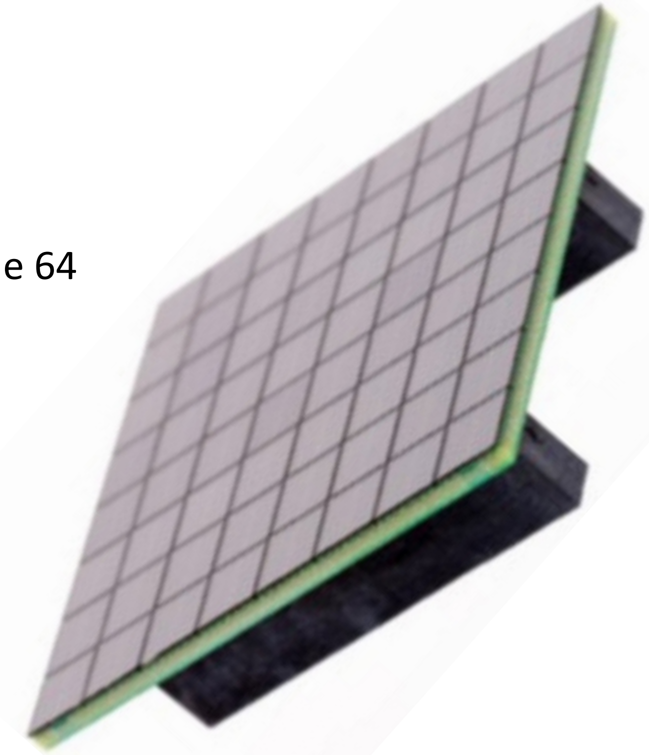
- Packed 2D array of microcells – each a single photon avalanche photodiode (SPAD)
- > ~100k SPADs/pixel
- High photon detection efficiency
- Manufacturable with CMOS technology at standard Silicon mass production technology facilities

**Limitations:**

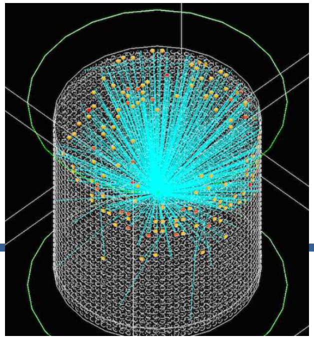
- High dark rates limit use for single PE detection over large areas
- SiPM technology is well ahead of readout hardware – lack of readout boards that can digitize a whole 64 channel SiPM is a problem. But this problem on the way to being solved

**Solutions?:**

- Digital SiPMs enable a digital readout of each and every SPAD hit
- Solves the readout board problem by digitizing on the SiPM itself
- ~90% dark noise is produced by ~10% of the SPADs (noisy ones can be identified digitally)

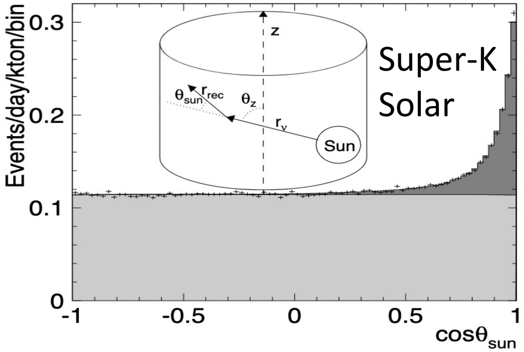


# Other options - $\bar{\nu}_e$ Electron scattering

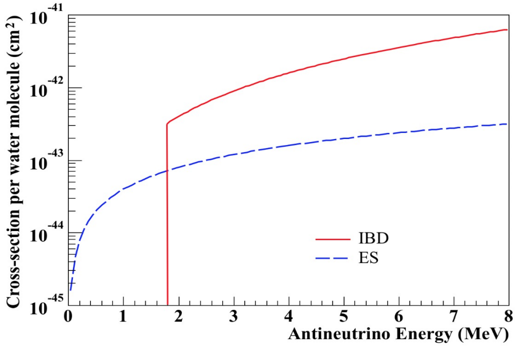


**Pros:**

- Directional
- purification to the required level is possible in principle with today's technology. There is low hanging fruit for further improvement



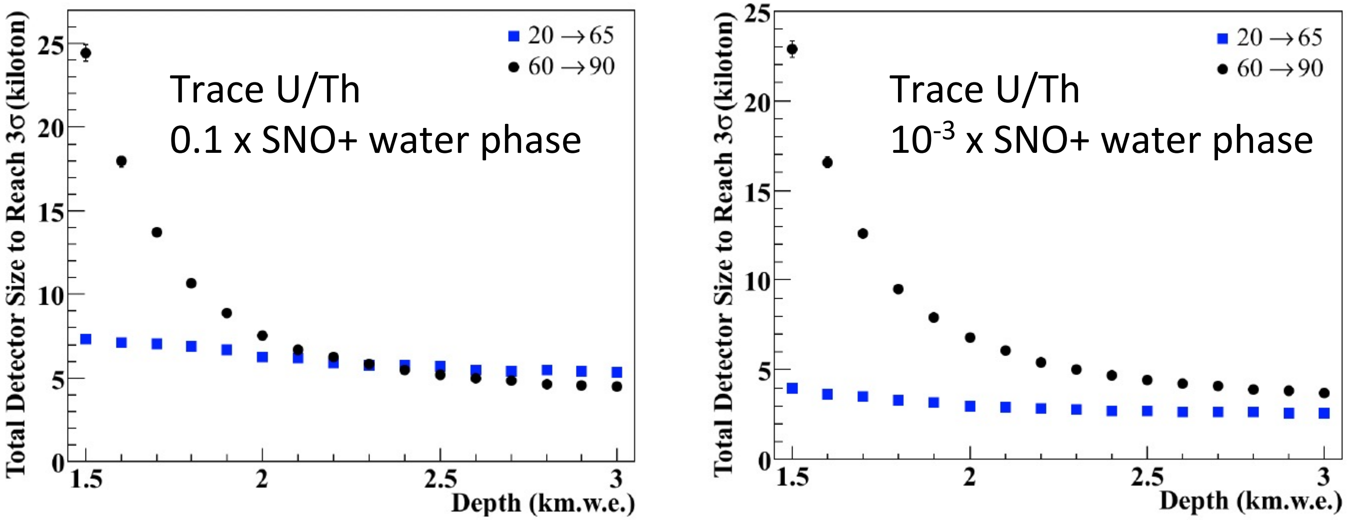
ES versus IBD cross sections



**Cons:**

- Requires purification to better than (SNO) $10^{-14}$ g/g U/Th, or (SNO+ water phase) $10^{-15}$ g/g U/Th
- Antineutrino cross section and pointing not quite as good as for solar neutrinos. Reactor spectrum softer than solar spectrum

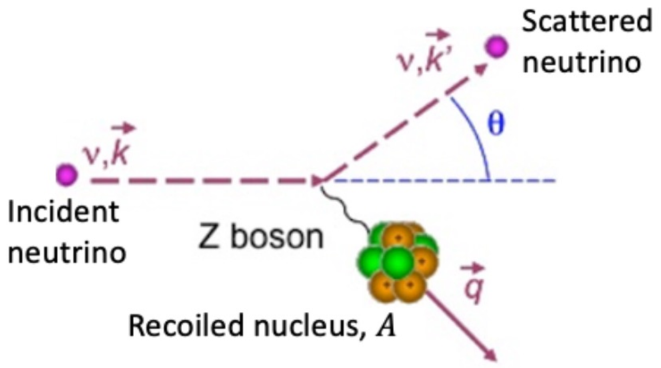
At 13km baseline (Perry reactor/WATCHMAN distance)



In principle this is doable, with further progress on water purification….
But is directionality needed?

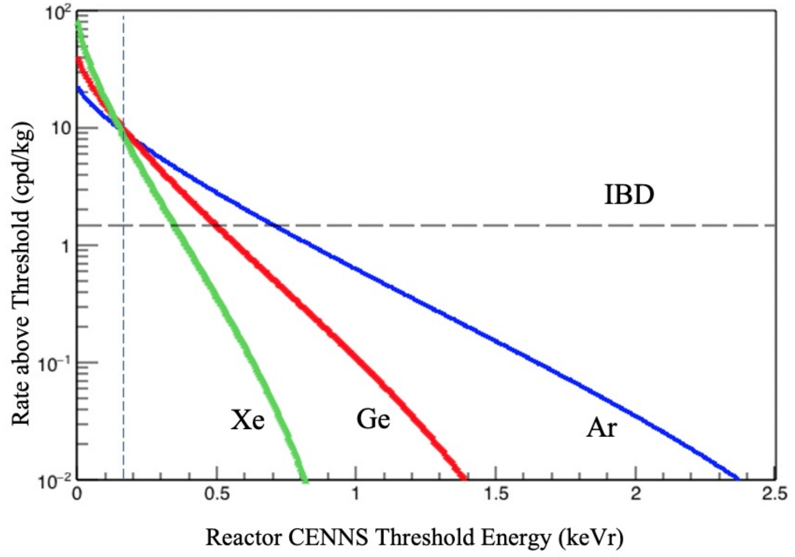
NIMA, Volume 841, (2017), P130

# Other options – Coherent elastic neutrino/nucleus scattering (CEvNS)



**<u>Various technologies are on the table:</u>**

- <u>Scintillator crystals</u> – COHERENT (CsI(Na)), NEON (NaI(Tl)), ($CaWO_4$), PALEOCCENE (crystal defects)
- <u>High purity germanium detectors</u> – CONUS(+), Dresden, nuGEN , TEXONO
- <u>Noble liquids</u> – LUXE (xenon), CHILLAX (xenon doped argon)
- <u>Low-noise fully depleted CCDs</u> - CONNIE
- <u>Bolometers</u> – Ricochet

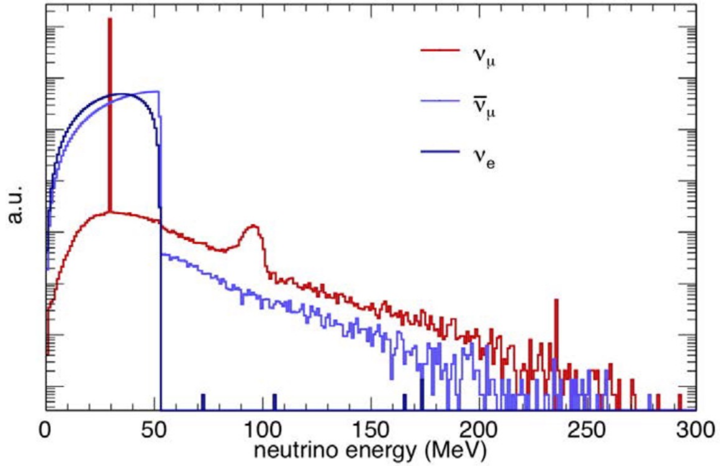


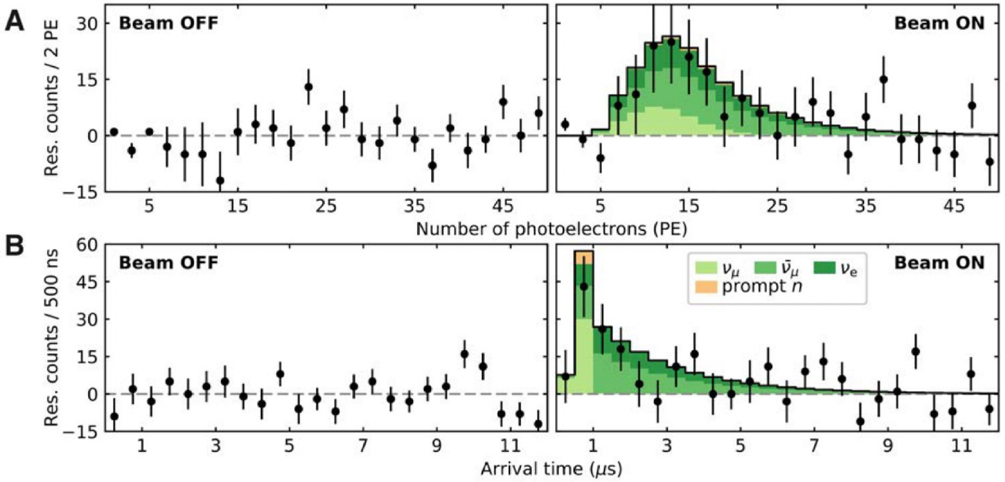
# CEvNS

**Coherent result (2017):**

- First observation of coherent scattering
- Source – the SNS neutrino beam
    - Neutrino energies are much higher than for reactor neutrinos
- Single 14.6 kg CsI(Na) crystal
- Sensitive down to a few keV nucleus recoil energy – few photoelectrons
- Probably can't reach reactor antineutrino energies (100s eV)

See [Science, V357, Issue 6356, P1123, (2017)]()



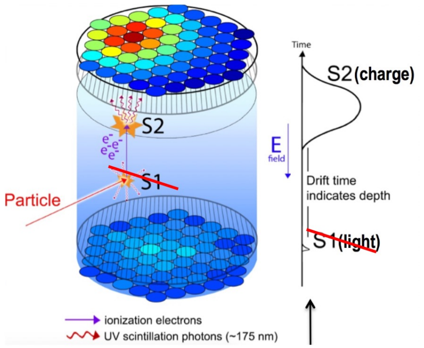


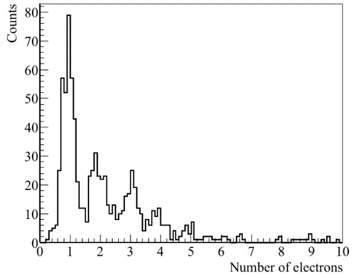
# CEvNS

**CHILLAX (noble liquids):**

- The approach is to combine argon and xenon
  - advantageous energy transfer provided by scattering on argon
  - Better scintillation of xenon
- Handling xenon in the gas phase is non trivial

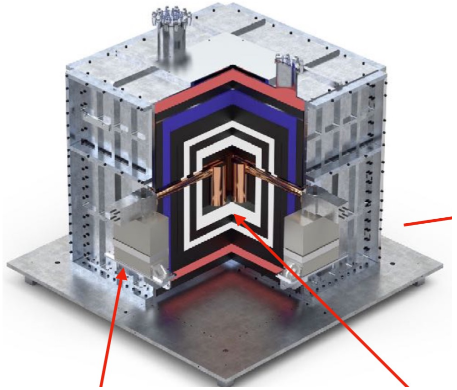
See Jingke Xu Neutrino seminar, Fermilab, April 7th, 2022





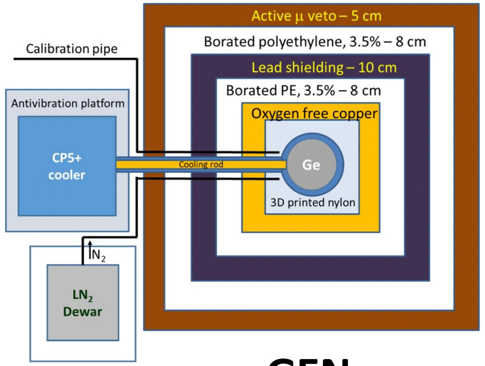
**CONUS(+) νGEN (Germanium):**

- Best prospect of low enough energy threshold (~200 eV)
- Scalability beyond ~few kg?



**CONUS(+)**

Germany - 3.7kg, 17m
(3.9 GWt)



**νGEN**

Russia – 1.4kg, 11m,
(3.1 GWt)

**My brief (ill-informed) Take aways on CEvNS future:**

- Germanium low threshold detectors may get to reactor detection first – but difficult to scale
- Noble liquids look promising long term – easier to scale

# Summary

**Near future technologies to look forward to:**

- Mobile above ground reactor antineutrino detection
- Stable $^6$Li-doped PSD plastic scintillator
- Stable $^6$Li-doped PSD liquid scintillator
- Position sensitive photon detection via LAPPDs and Low(er) dark rate SiPMs (via digital SiPMs)
- If the challenges of purifying WbLS are overcome
  - Large water-based Cherenkov-scintillator detectors

**One day?:**

- Reactor directionality via electron scattering and Cherenkov
- Reactor antineutrino coherent scattering
- Vast tiled walls of photon detectors with fast timing and ~cm position resolution

# Backups

# IBD - other isotopes

On argon_40, threshold is 7.5 MeV → not for reactors, can be considered for supernova detection

Argon_38 threshold 4.9 MeV → possible

He_3 threshold 18.6 keV → yes

Na_23 threshold 4.4 MeV → possible

O_16 threshold 10.4 MeV → No

C_12 threshold 13.4 MeV → No

Cs_133 threshold 0.4 MeV → Yes

# 2D Segmentation

# Purification

# Photodetection - PMTs

## SuperChooz : ~9 700 m³

**common technology but not methodology**

- scintillator: ✓ (improvement?)
- fibres: ✓
- light collection: ✓ (improvement?)
- photo-detector: ✓ (now SiPM)
- MeV optimisation → **R&D**

**SuperChooz (~10 kton)** similar dimensions, shape and technology to **NOvA (~14 kton)**

**Location**:

The Chooz A reactor cavern. ~ 1km from Chooz reactors

# Application, Depth, Location