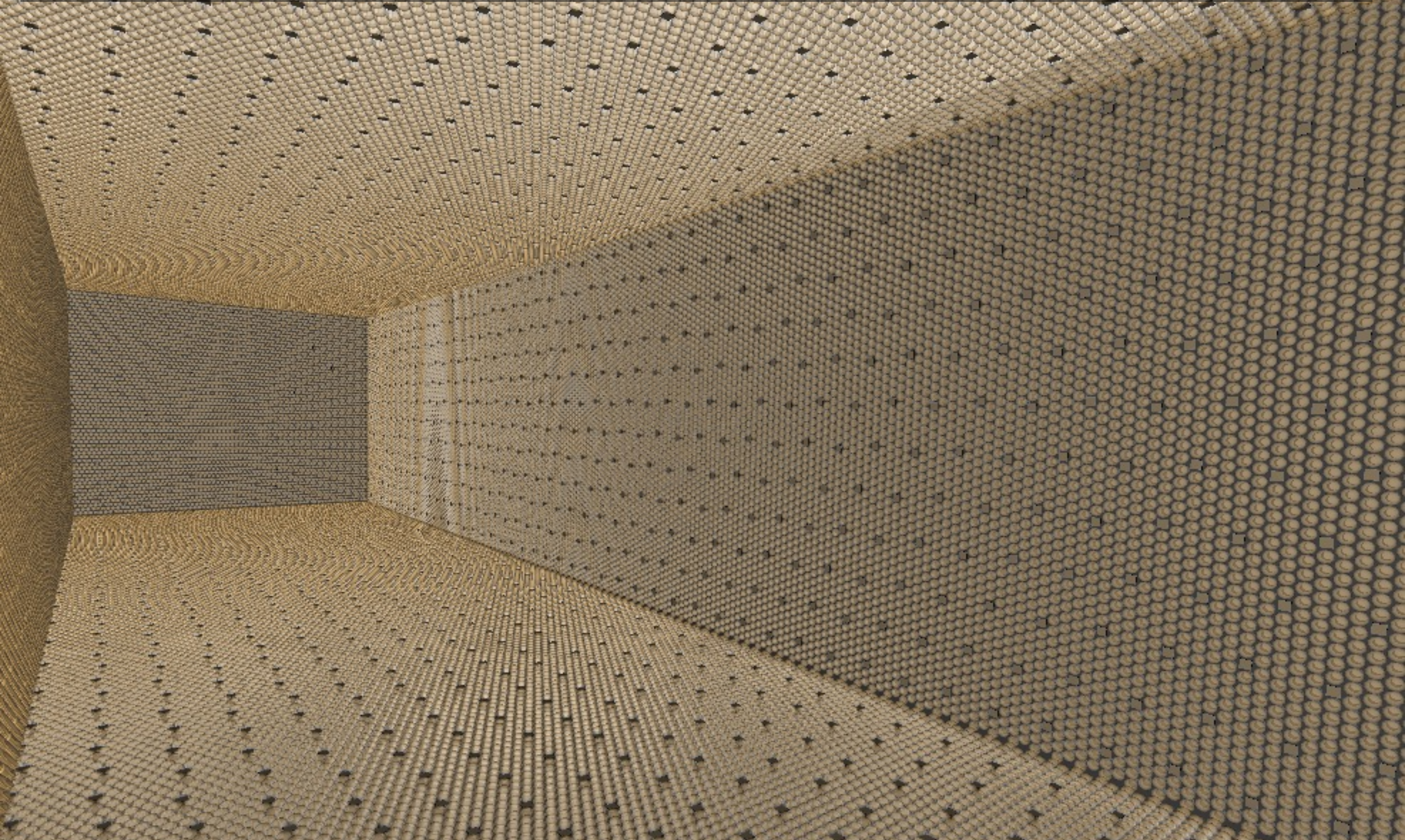
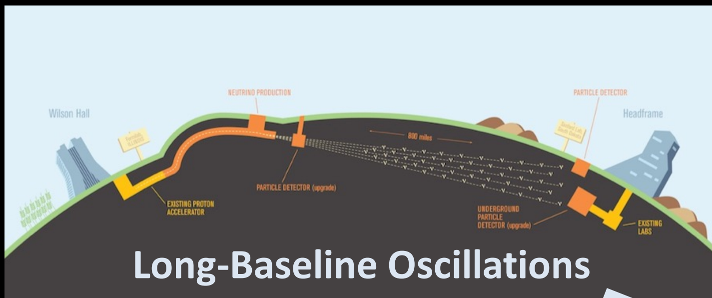
R&D and demonstrators for THEIA



++ DUNE Phase-II Working Group Call ++ June 12, 2023 +++ Michi Wurm (Mainz) ++

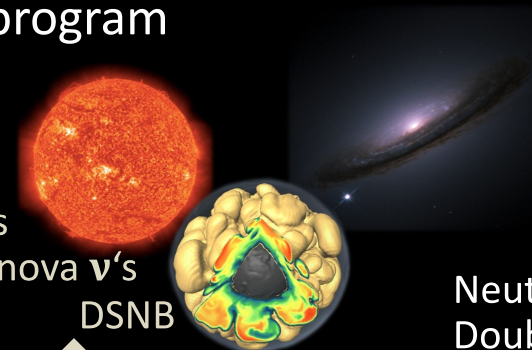
Hybrid Cherenkov/Scintillation Detector

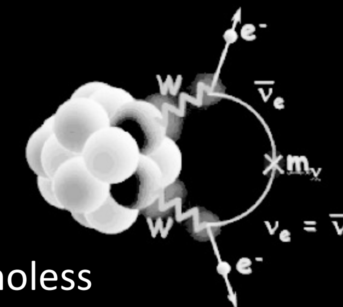
→ Enhanced sensitivity to broad physics program



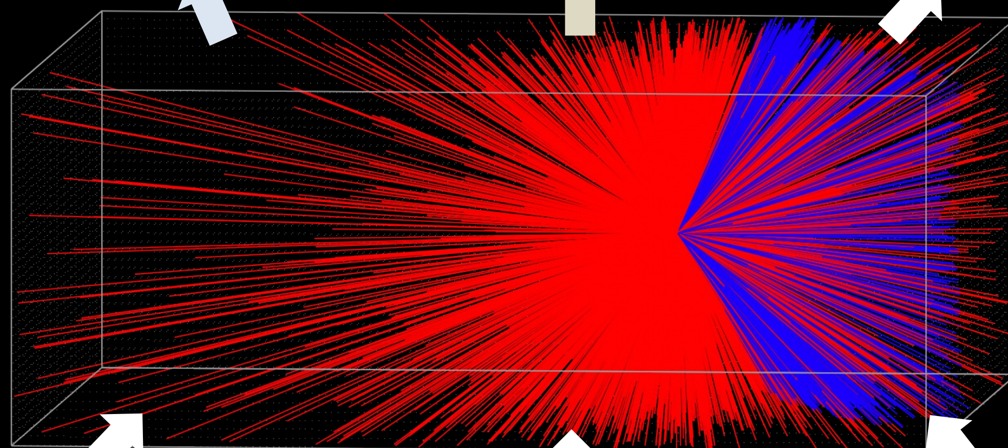
Long-Baseline Oscillations

solar ν's
Supernova ν's
DSNB





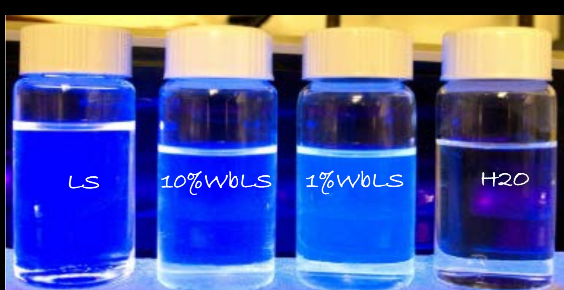
Neutrinoless Double-Beta Decay

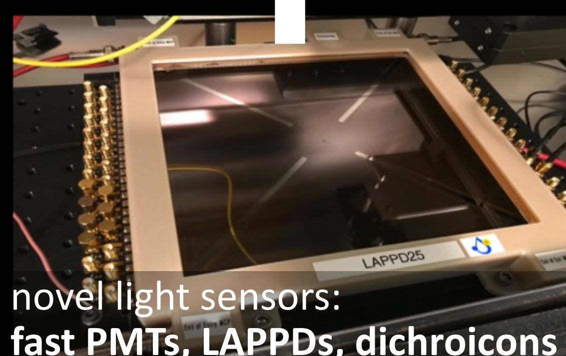


THEIA25

Hybrid Detector able to exploit both **Cherenkov+ Scintillation** signals

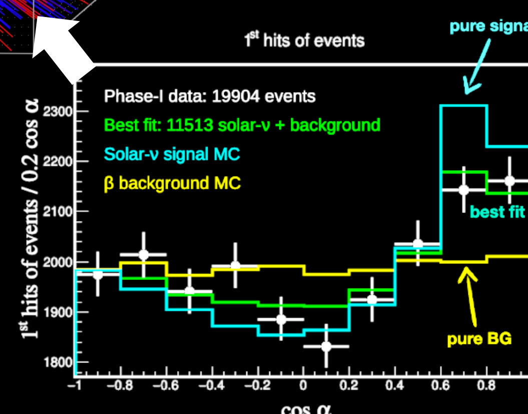
novel target medium:
Water-based Liquid Scintillator



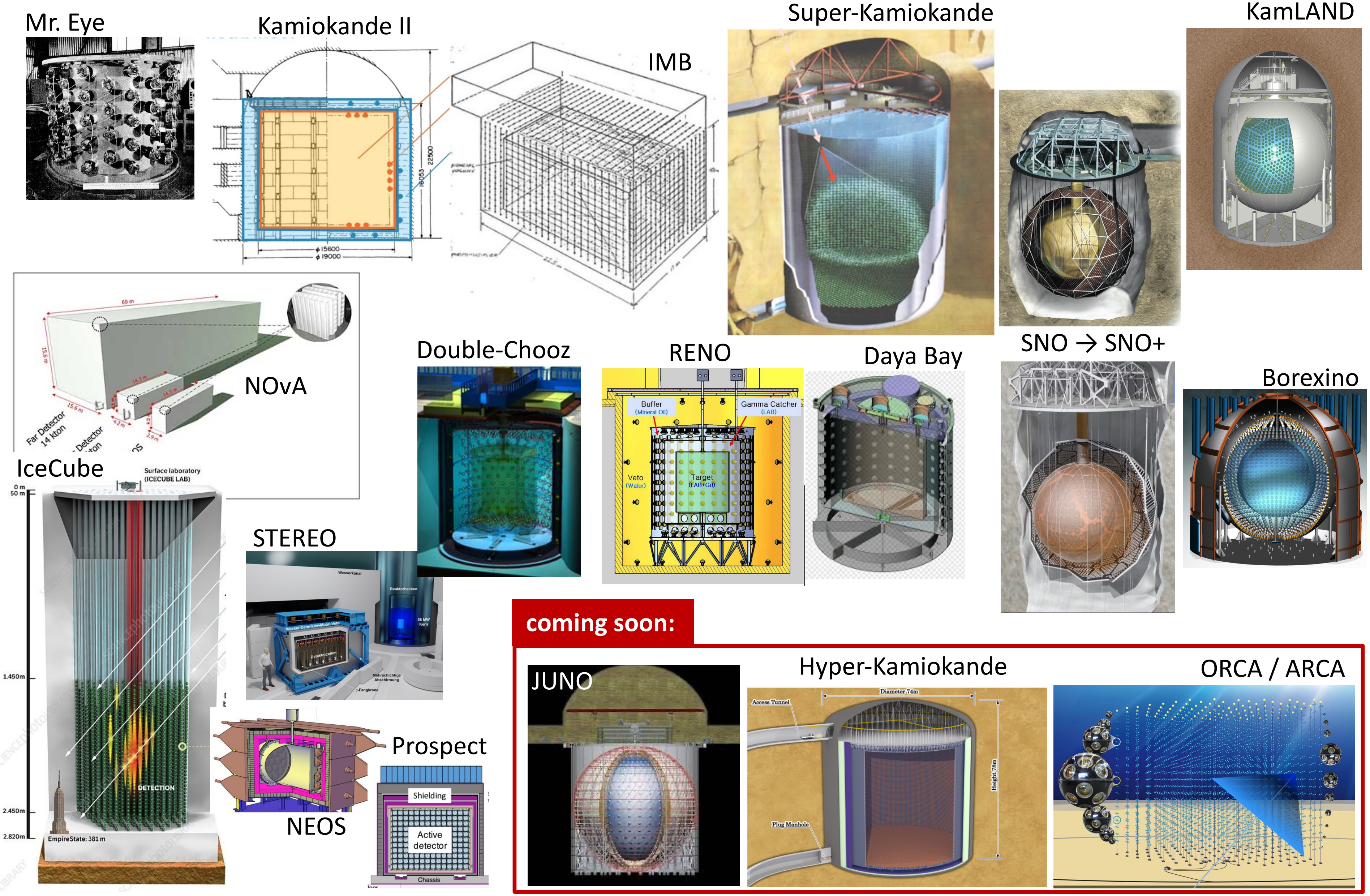


novel light sensors:
fast PMTs, LAPPDs, dichroicons

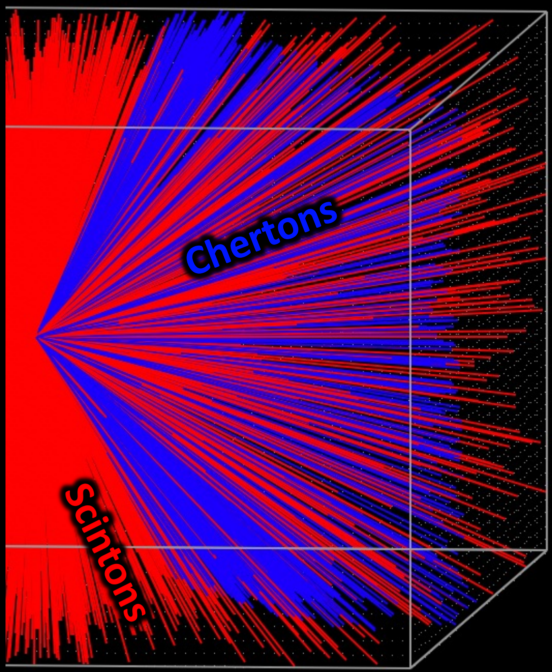
novel reconstruction techniques



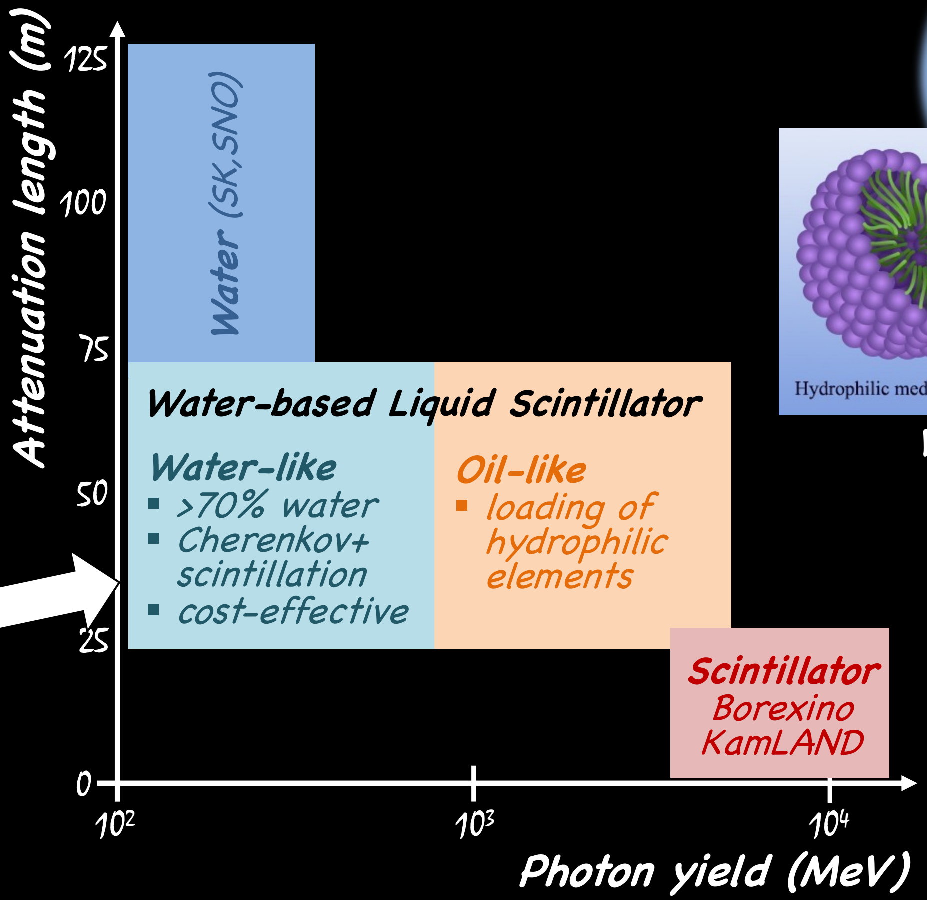
Water/Liquid Scintillator Neutrino Detectors

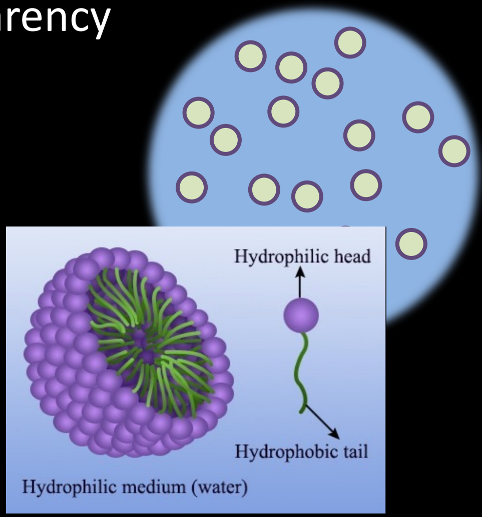


R&D : Water-based liquid scintillators (WbLS)

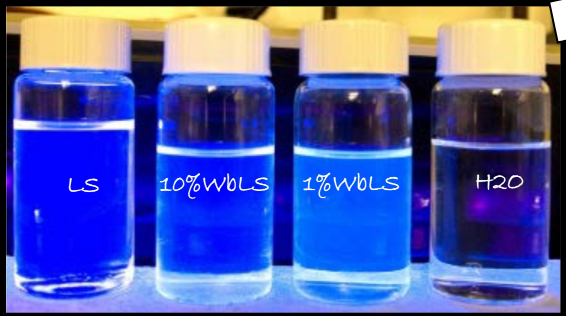


→ WbLS: water + tensid + solvent (LAB) + fluor (PPO)
→ low organic fraction → high transparency





WbLS mycels



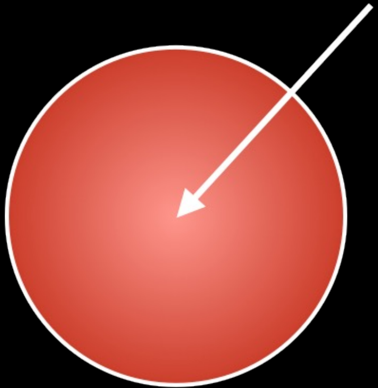
Minfang Yeh, BNL

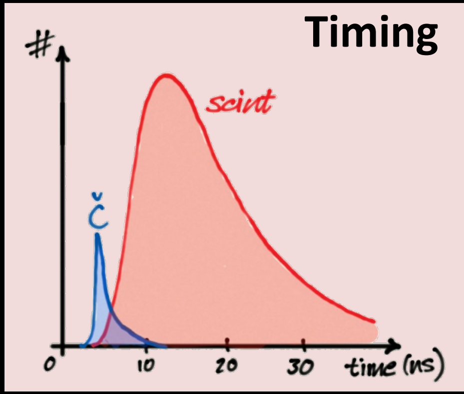
→ properties of target medium can be adjusted to physics goal
→ water content offers additional options for metal loading

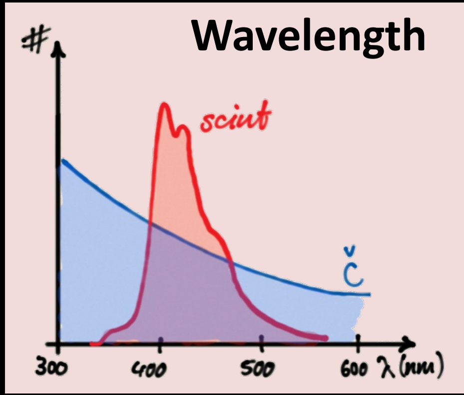
R&D : Sensors for Separating Chertons and Scintons

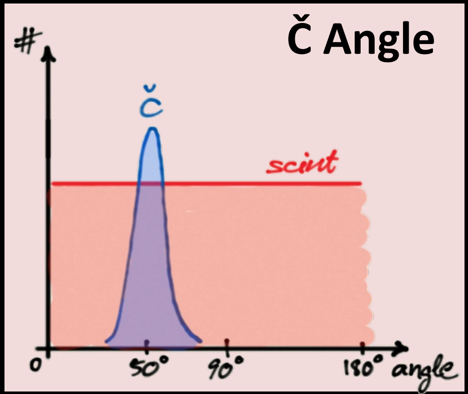
Cherenkov

Scintillation

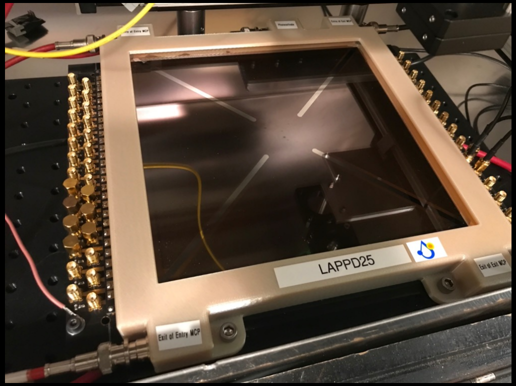






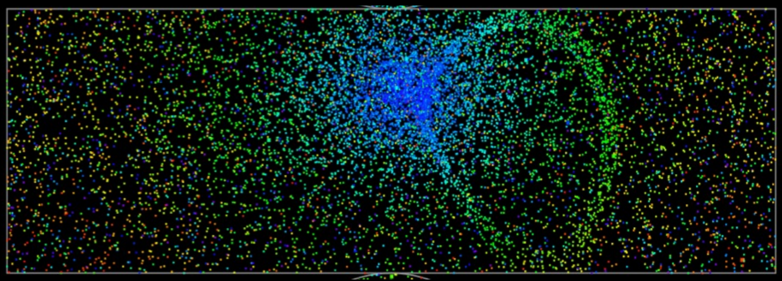


LAPPDs
tts~60ps

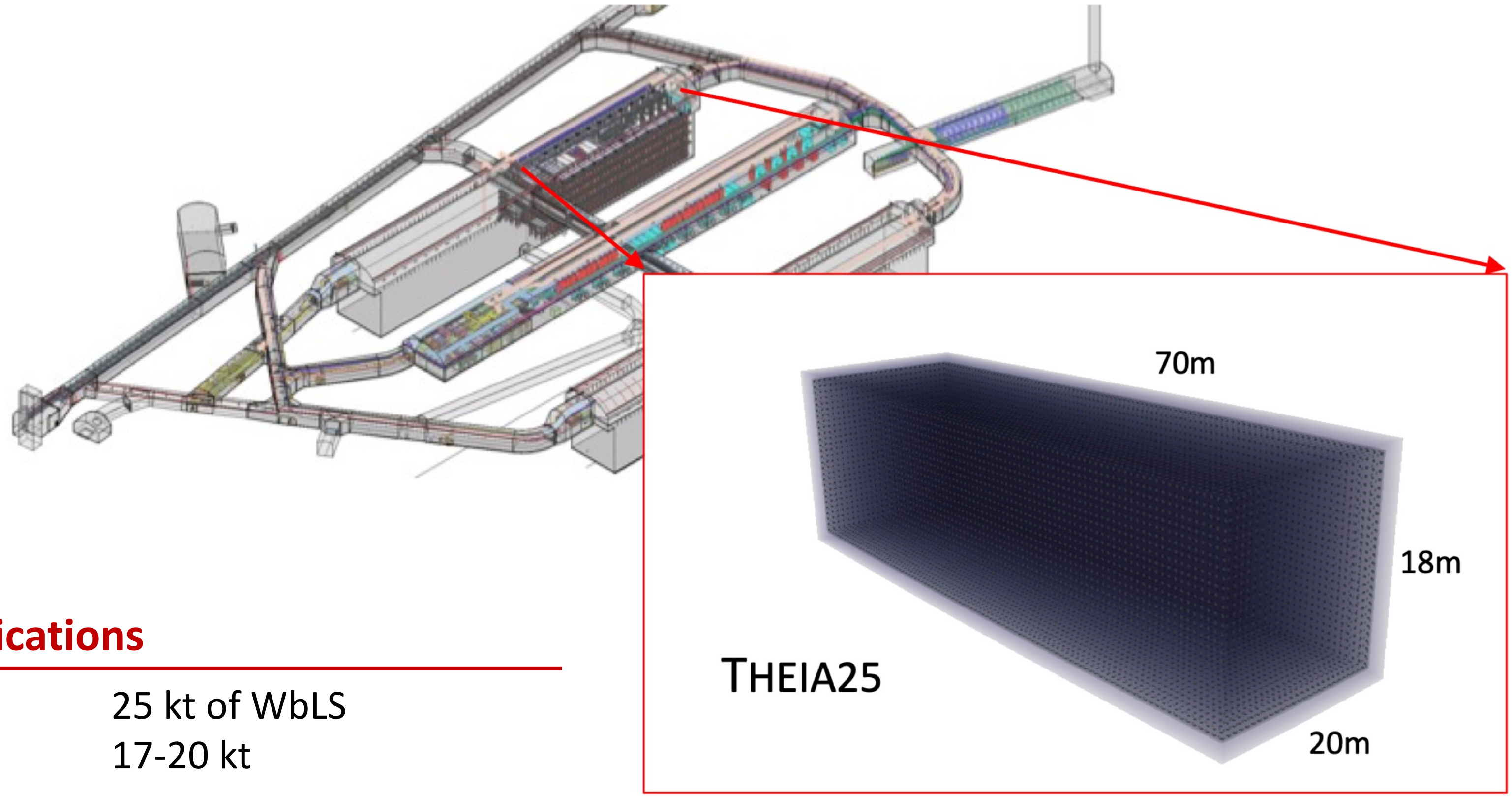


Dichroicons
spectral
sorting

PMT granularity



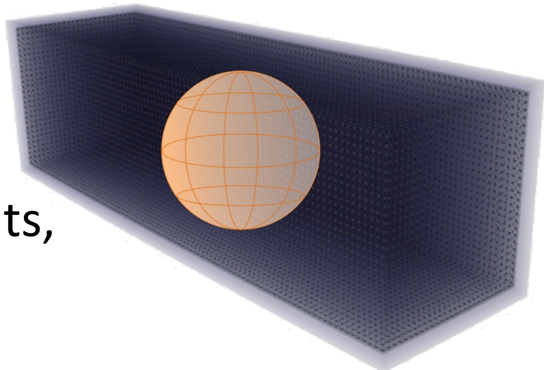
THEIA25 as DUNE Module of Opportunity



Detector specifications

- **Total mass:** 25 kt of WbLS
  Fiducial mass: 17-20 kt
- **Photosensors:**
  22,500x 10'' PMTs — 25% coverage w/ high QE → equals the current photon collection of SK!
  700x 8'' LAPPDs — ~3% coverage → upgrade for later phases (solar, 0νββ)
- **Background levels:**
  Radiopurity (H_2O): ~10^{-15} g/g in ^{238}U, ^{232}Th, ^{40}K
  Rock shielding: 4300 m.w.e. → muon flux at SURF only ~10% of LNGS

THEIA : Phased Physics Program



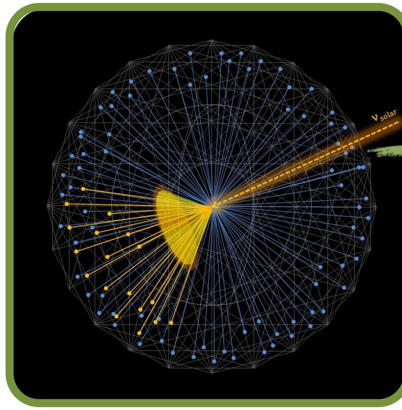
scintillator properties will be adjusted to physics requirements,

e.g. 1% WbLS → 10% WbLS → slow scintillator

Phase	Primary physics goal	Reach	Exposure/assumptions
I	**Long-baseline oscillations**	>5σ for 30% of δ_{CP}	524kt-MW-year
I	**Nucleon decay $p \to \bar{\nu} K^+$**	T>3.8 x 10^{34} year	800 kt-year
I	**Supernova burst**	<1(2)° pointing 20K(5K) events	100(25)kt, 10kpc SN
I	**Diffuse Supernova Neutrino**	5σ	125kt-year
II	**CNO neutrinos**	<5(10)%	300(62.5)kt-year
II	**Geoneutrinos**	< 7 %	25 kt-year
III	**$0\nu\nu\beta$**	$T_{1/2}$ > 1.1 x 10^{28} year (90%C.L.)	800 kt-year (Multi-tonne loaded LS in suspended vessel search)

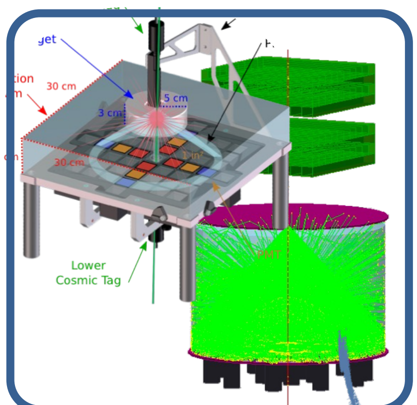
Development Path of Hybrid Detectors

Borexino
SNO+

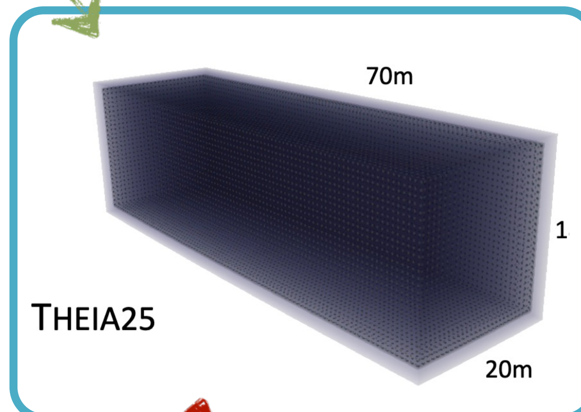


Re-analyzing data from existing LS Detectors

Lab-Scale Setups



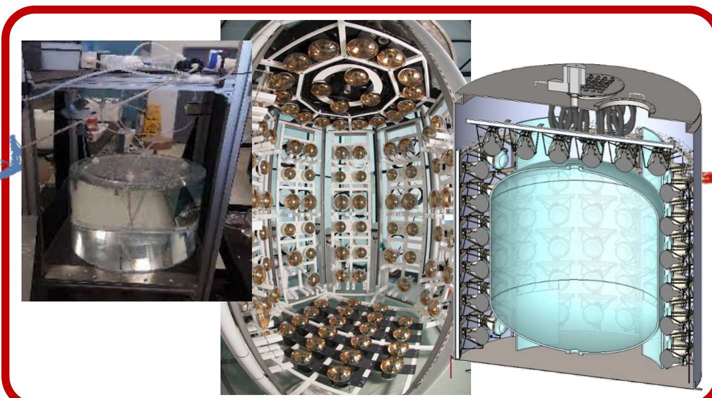
UCB: CHESS
MZ: SCHLYP
MZ/TÜ: DISCO
...



Future full-scale hybrid module

Ton-Scale Setups

BNL
ANNIE/SANDI
EOS



Program for 1-ton Demonstrators (1/3)

For Long-Baseline Experiments

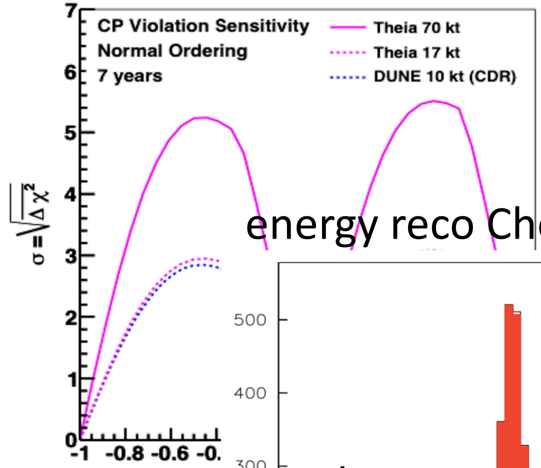
demonstrate improved detector performance compared to pure water Cherenkov detector

- scintillation makes recoil hadrons visible
  → better energy estimator
  → better vertex reco

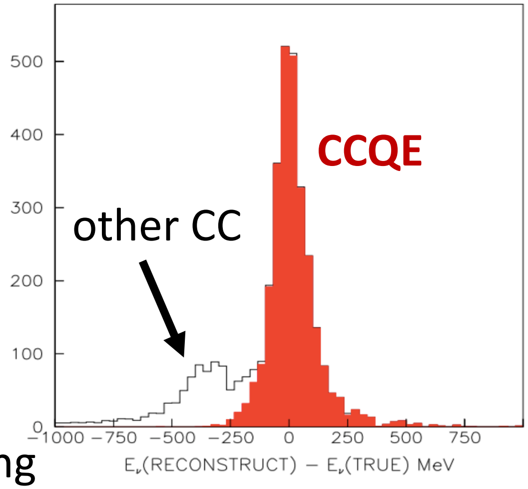
- scintillation/Gd-loading offers handle to detect final-state neutrons
  → better energy estimation (range?)

- accurate event timing
  → neutrino energy
  (via TOF of π/K in decay pipe)

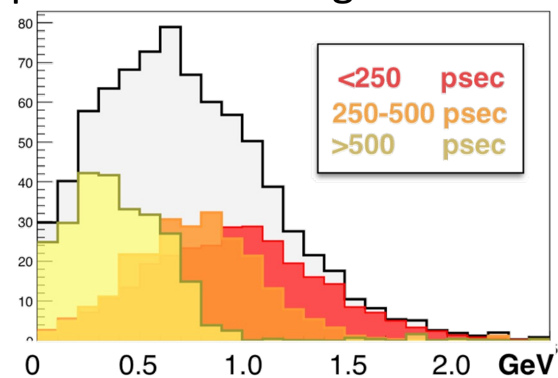
sensitivity of WbLS module



energy reco Cherenkov only



psec event timing



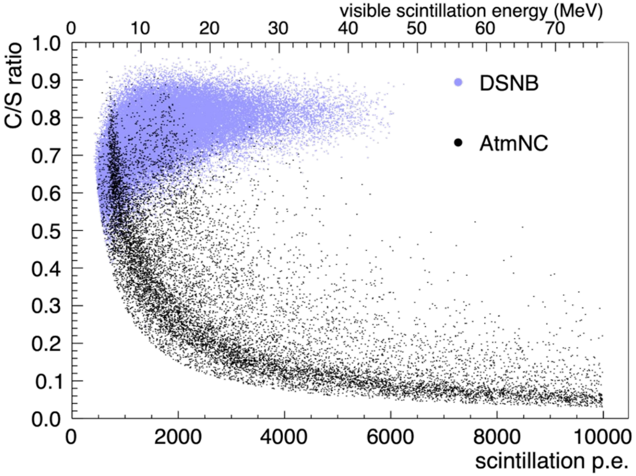
Program for 1-ton Demonstrators (2/3)

For Low-Energy Detection

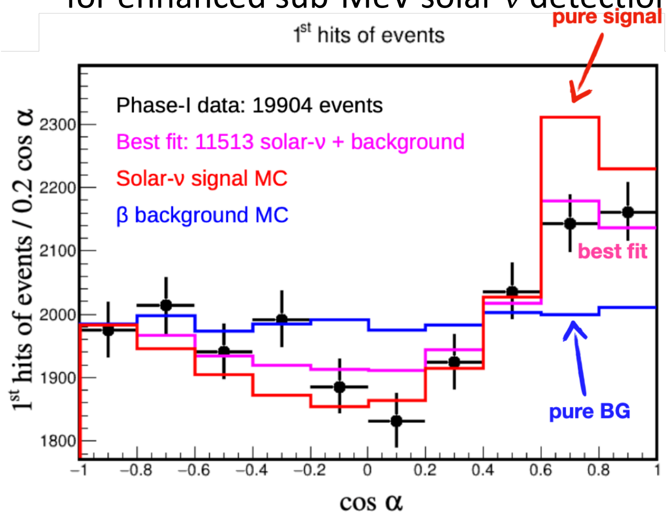
demonstrate added value of hybrid detection cf. water and liquid scintillator

- Particle ID using Cherenkov/scintillation ratio (reject protons and α's)
- Sub-MeV directional reconstruction using cumulative event distributions (CID)
- Improved directional reconstruction for >MeV neutrinos due to isotropic light component
- Neutron tag for SN neutrinos
  → improved pointing capabilities

Cherenkov/scintillation ratio for BG discrimination (here: diffuse SN ν's)



cumulative angular PMT distributions for enhanced sub-MeV solar ν detection

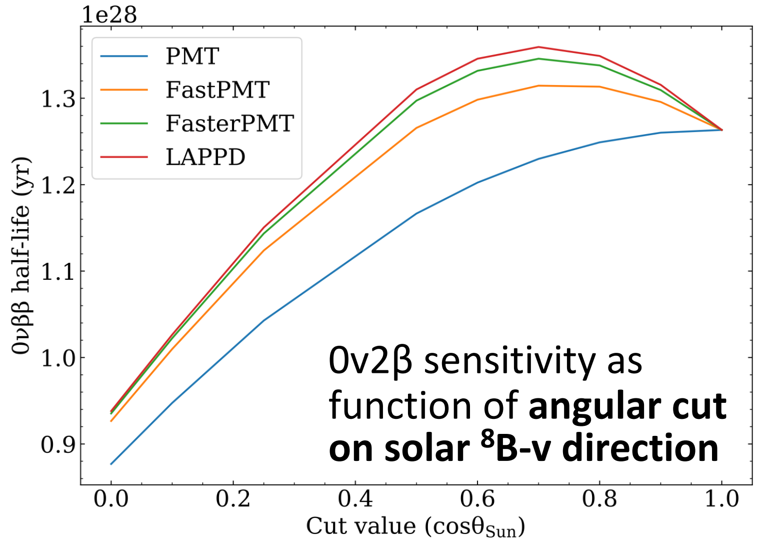


Program for 1-ton Demonstrators (3/3)

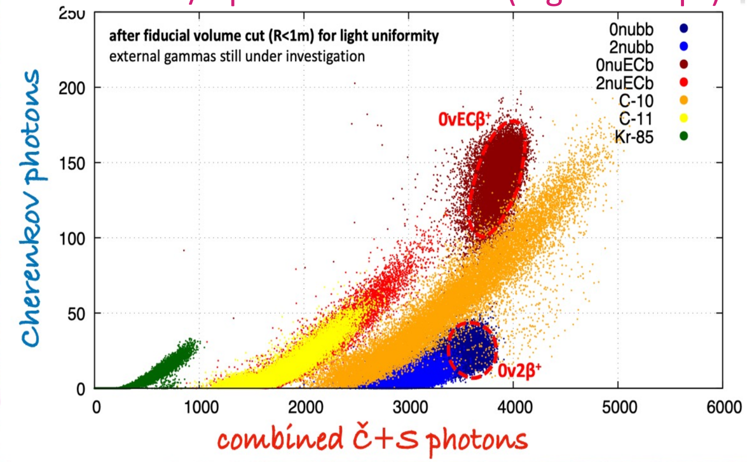
For Neutrinoless Double-Beta Decay

show path to >10-ton scale experiments with excellent background discrimination

- high metal loading factors in water while maintaining high light yield & transparency
- use directionality to suppress solar ^{8}B-ν background
- discrimination of e^- vs. e^+ vs. γ events based on Cherenkov/scintillation ratio
- identify 2β signals vs. 1β backgrounds based on isotropy of Cherenkov light emission



MC study: signal separation based on MC-truth C/S photons detected (e.g. ^{124}Xe-2β$^+$)



WbLS properties and loading

basic properties by now well-understood based on various lab-scale experiments

- light yield (vs. organic fraction)
- fluorescence times (tunable)
- transparency (mycel size)

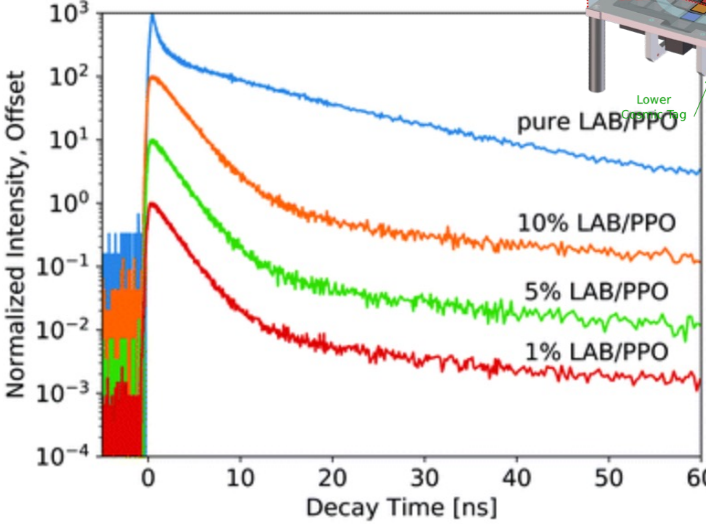
effort turning towards loading of WbLS with **good metal ions**

- for neutron detection: Gd
- for solar neutrino detection: Li
- for $0\nu\beta\beta$: Ca, Kr, Te

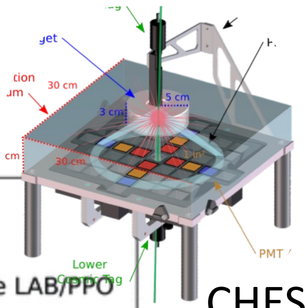
and removing **ionic impurities**

- Fe ions leeched from vessel walls
- online purification (nano-filtration) circulating the WbLS

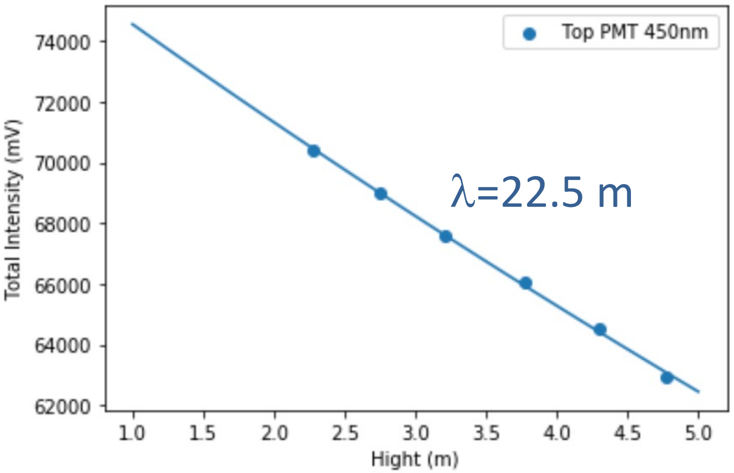
scintillation yield & time constants



CHESS



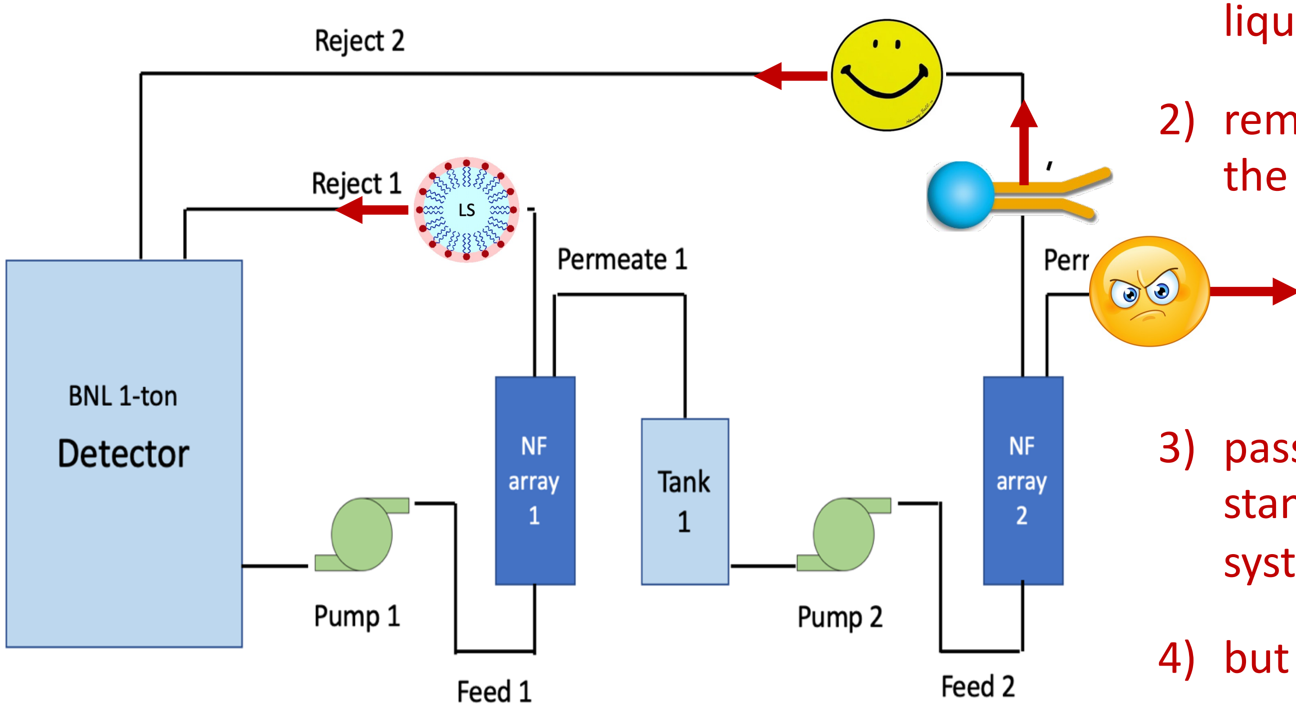
ANNIE-WbLS transparency



SAMD

BNL prototypes

basic concept: separate the organic components from water in order to clean the water



Basic procedure

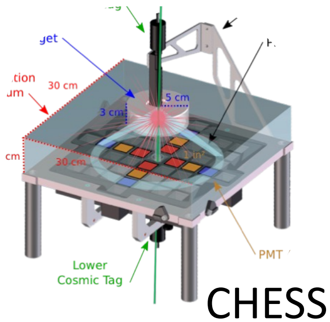
1) remove the micelles from the liquid without disrupting them
2) remove ”free“ surfactant from the permeate of NF array 1
3) pass the “bad“ ions to a standard water purification system for removal
4) but keep the good ions

→ mostly implemented for the BNL 1-ton demonstrator

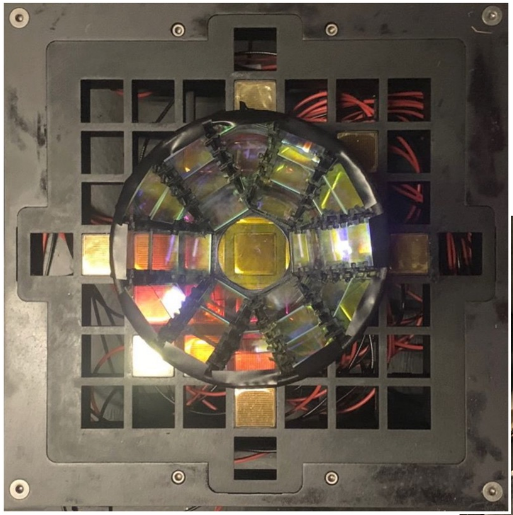
→ meanwhile constructing 30-ton prototype

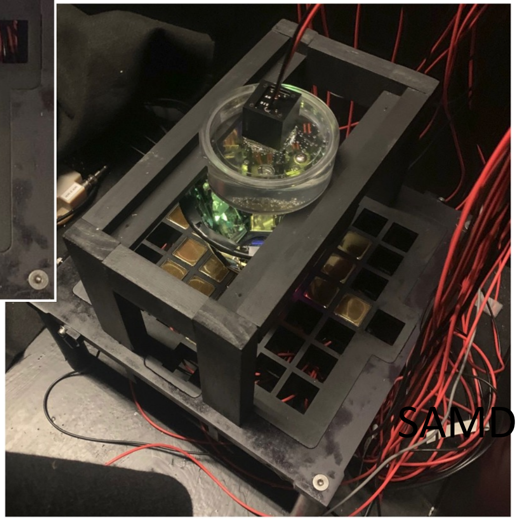
Dichroicon Tests at CHESS

- spectral sorting by focusing either short or long wavelengths to center PMT
- underlying PMT array records deselected photons
- selection purity C/(C+S) based on fit to photon time distribution

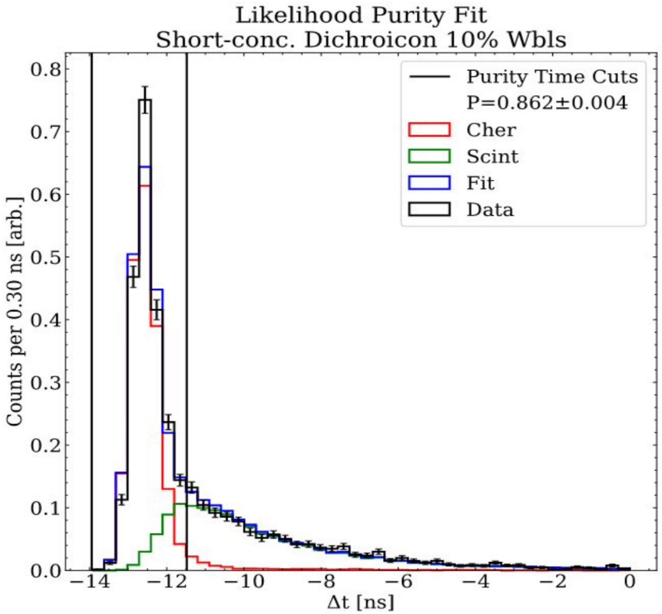


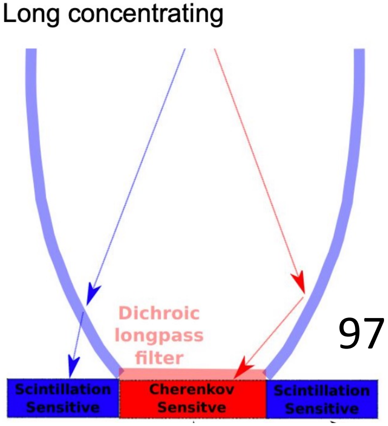
CHESS



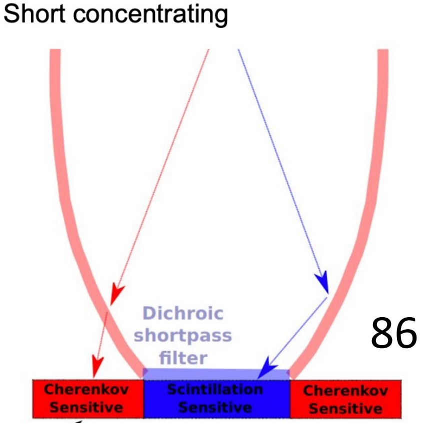


SAMD





97.8%



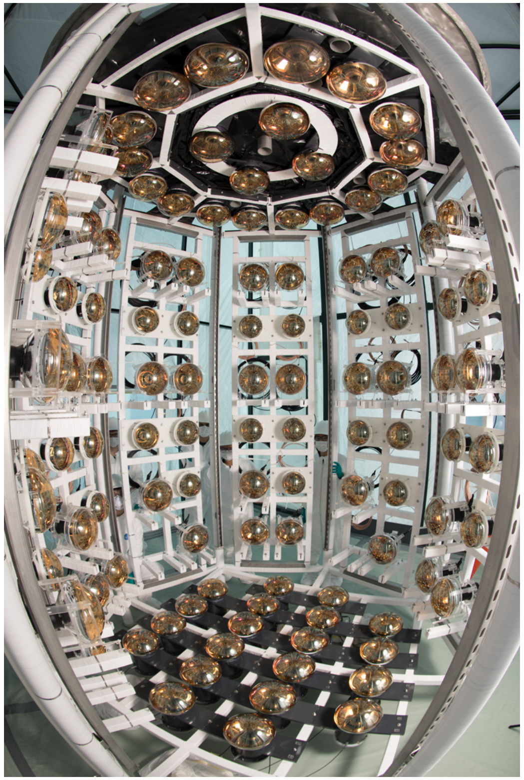
86.2%

ANNIE Experiment

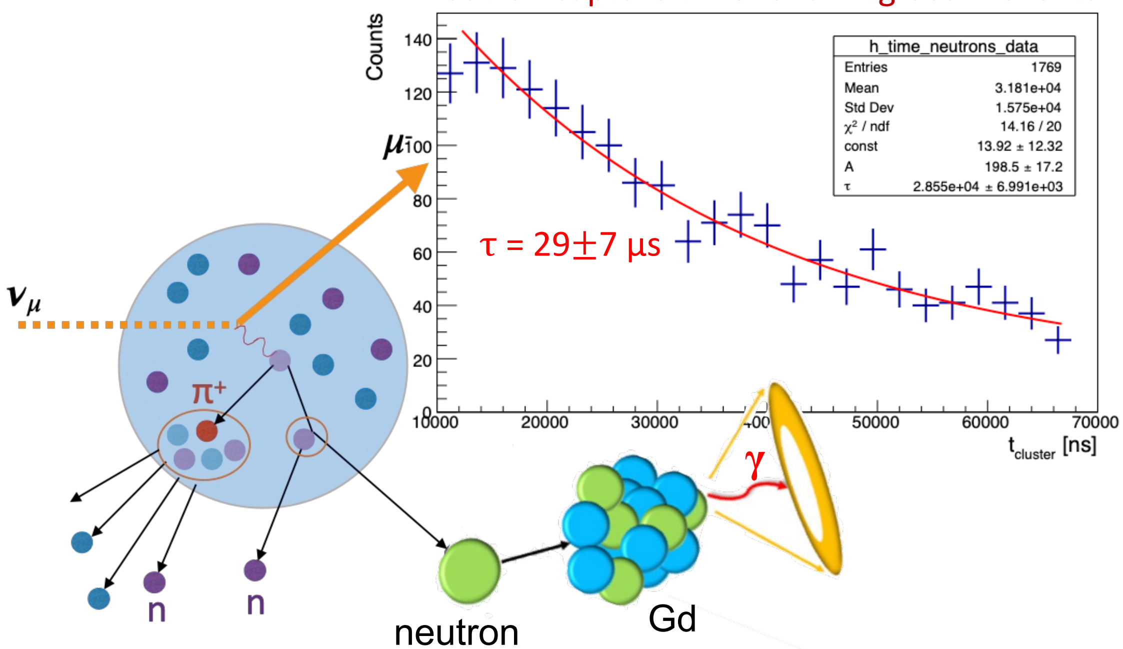
Accelerator Neutrino Nucleus Interaction Experiment

27-ton (Gd-loaded) Water Cherenkov Detector running in the **Fermilab BNB neutrino beam**

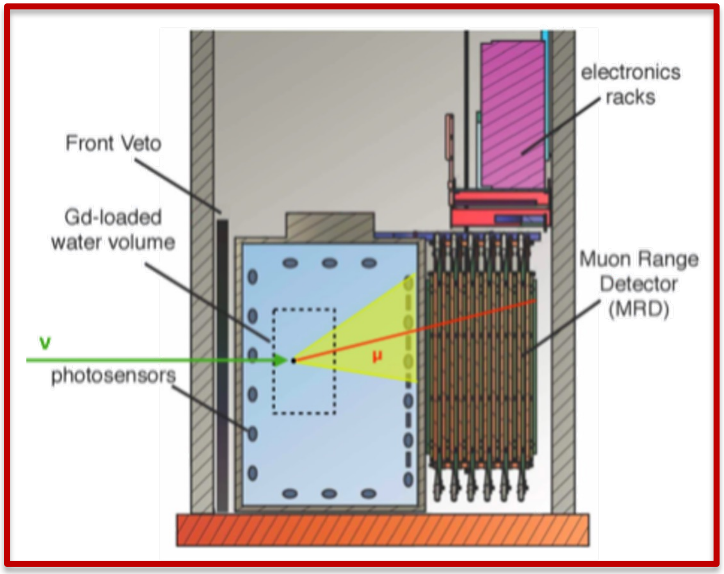
- measurement of GeV neutrino differential cross-sections and neutron multiplicity
- physics data taking started in early 2021
- R&D program for new technologies
  → Gd-water → LAPPDs → WbLS



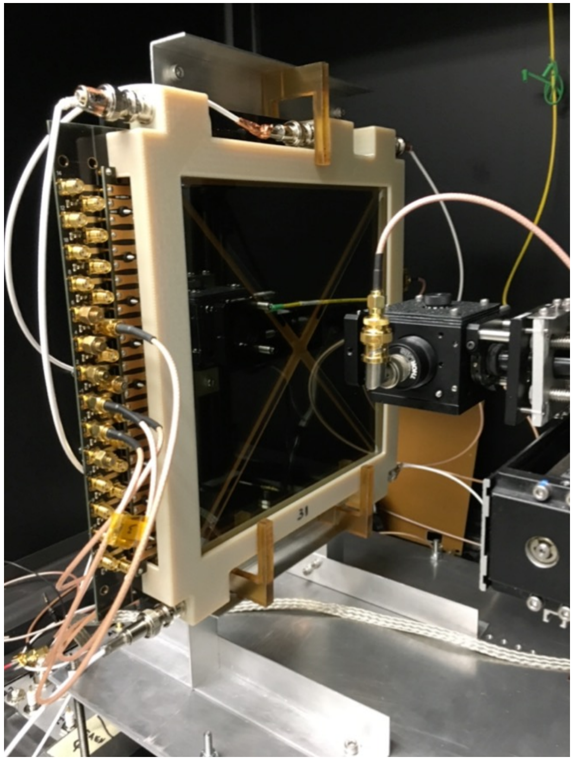
neutron capture time following beam events

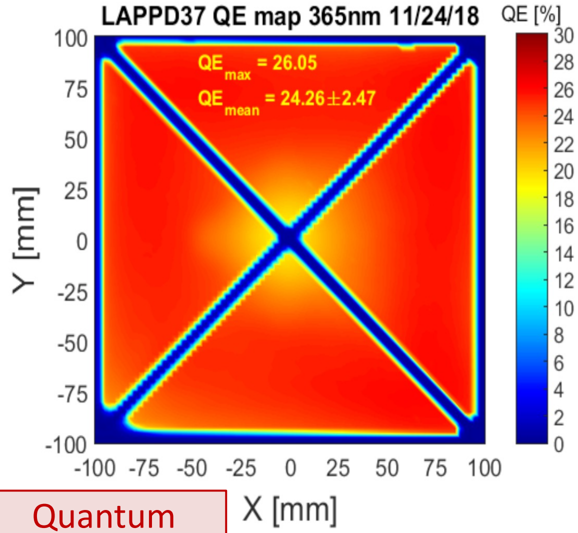


ANNIE Detector Layout



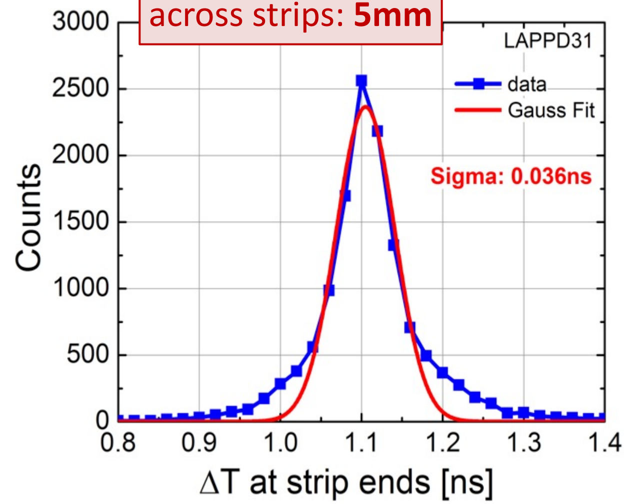
LAPPD Performance – s.p.e. response

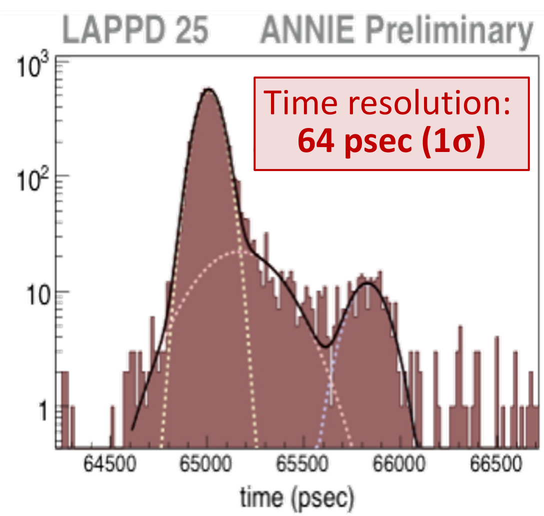




Quantum Efficiency: **24%**

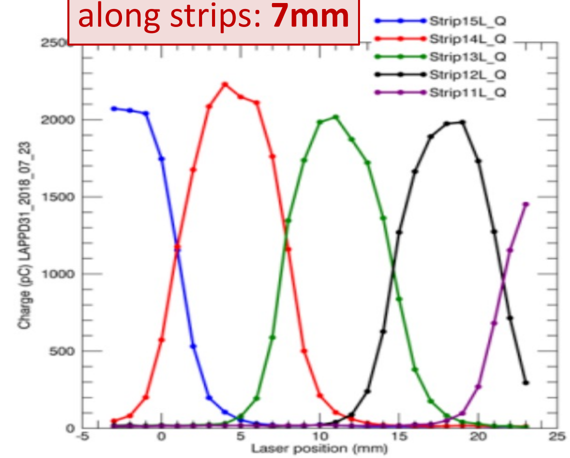
Spatial resolution across strips: **5mm**





Time resolution: **64 psec (1σ)**

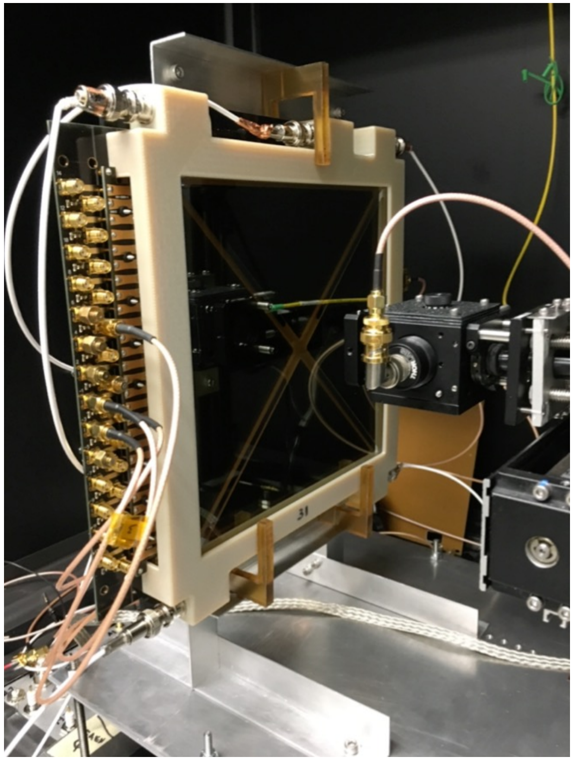
Spatial resolution along strips: **7mm**

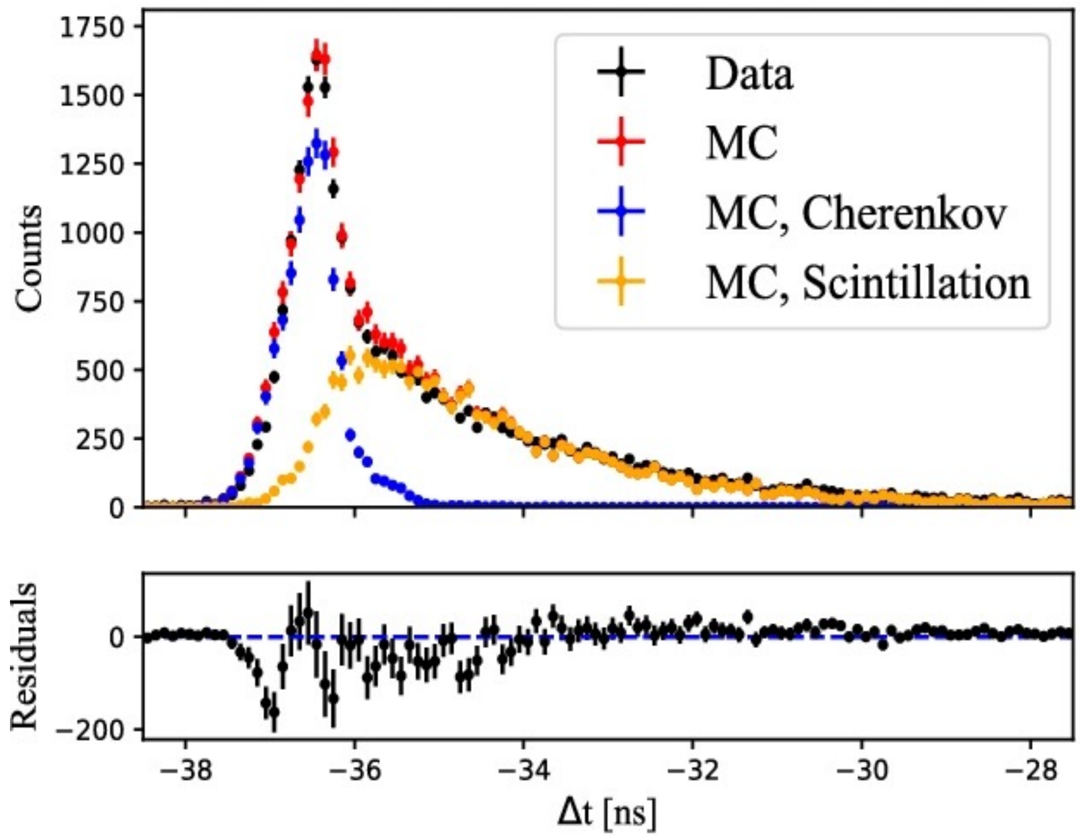


LAPPD performance tests

- lab tests: excellent time and spatial resolution
- on-site tests (Lab-6) in dark box with final ANNIE electronics: <200 ps

LAPPD Performance – C/S separation





LAPPD performance test in CHESS

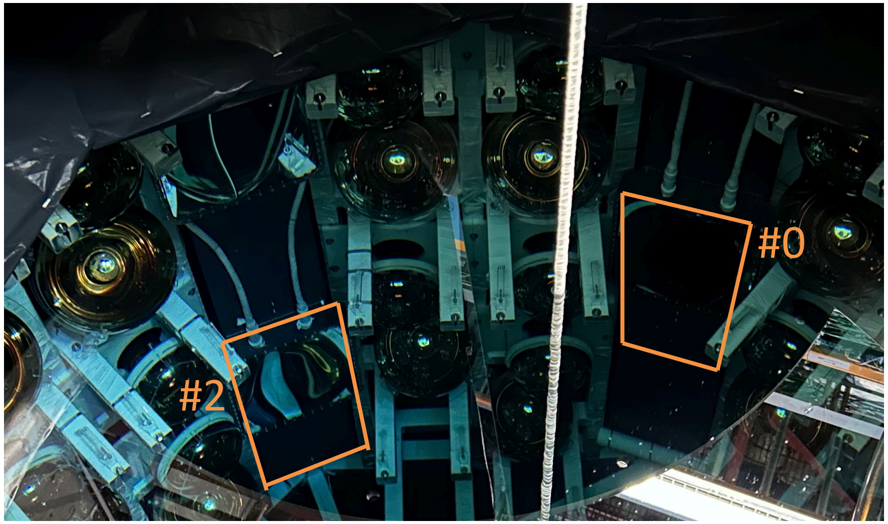
→ timing is sufficient to separate Cherenkov from fast scintillation (τ~2ns) component!

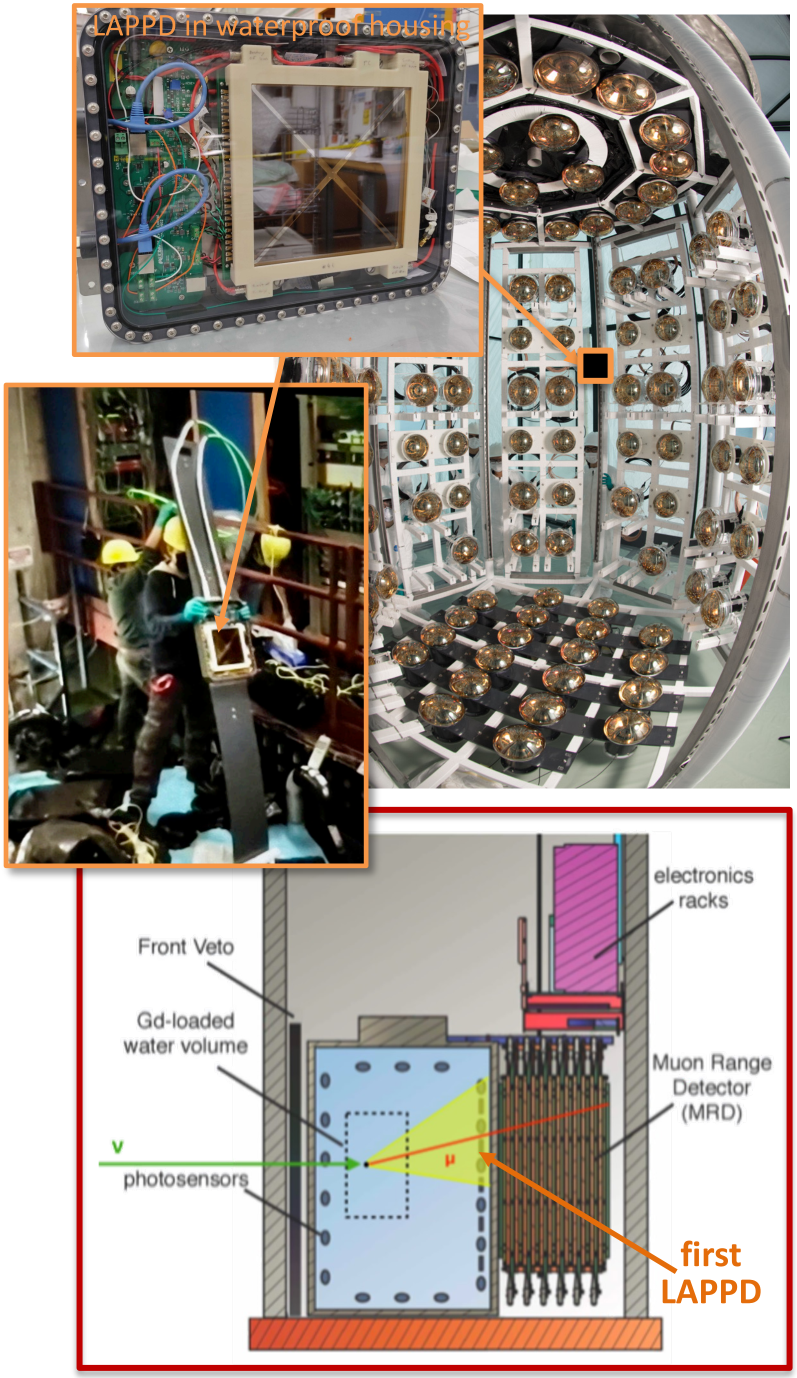
LAPPDs in ANNIE

- LAPPDs are mounted with PSEC electronics directly attached in waterproof housing
- LAPPD #0 installed in March 2022, detected first light from neutrinos
- LAPPDs #1 and #2 installed in February 2023, data aquisition with multiple LAPPDs

→ currently: time synchronisation and combination of LAPPD with PMT data

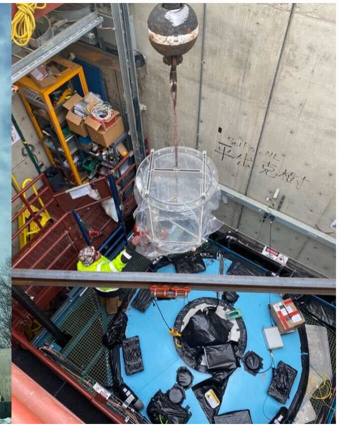
- LAPPDs #3 and #4 underway





ANNIE+SANDI: First WbLS test deployment



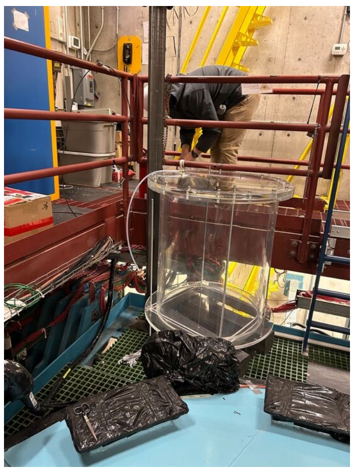


SANDI Acyrlic Vessel

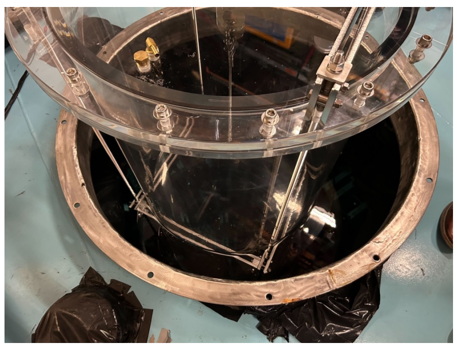
- cylinder holding 365 kg of WbLS submerged in ANNIE water tank
- WbLS produced at BNL

→ **goals of first run:**

- detect scintillation of hadrons
- use LAPPDs for C/S separation
- detect neutron capture on H
- show general compatibility for second GdWbLS run

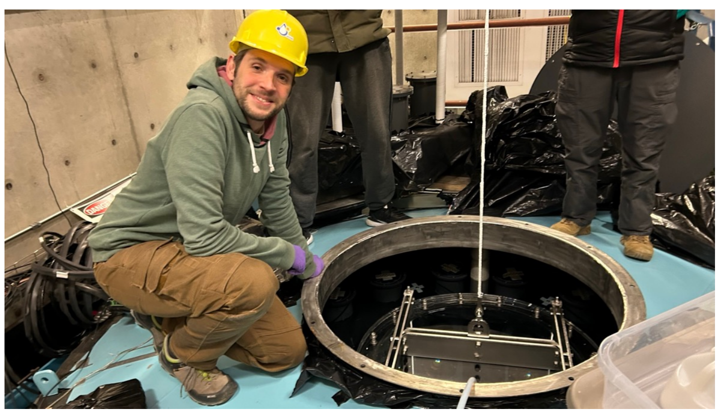


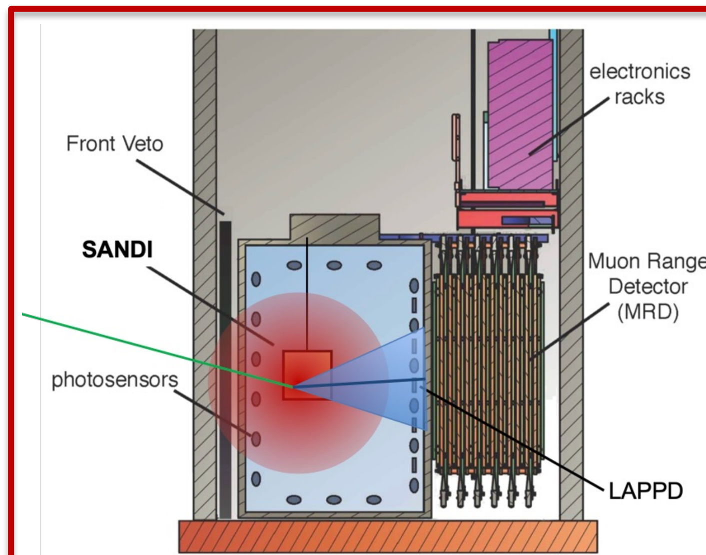
removed in May after taking 2 months worth of beam data



SANDI vessel & support frame inserted in Jan

Insertion of vessel inside ANNIE tank in March





EOS: WbLS performance demonstrator

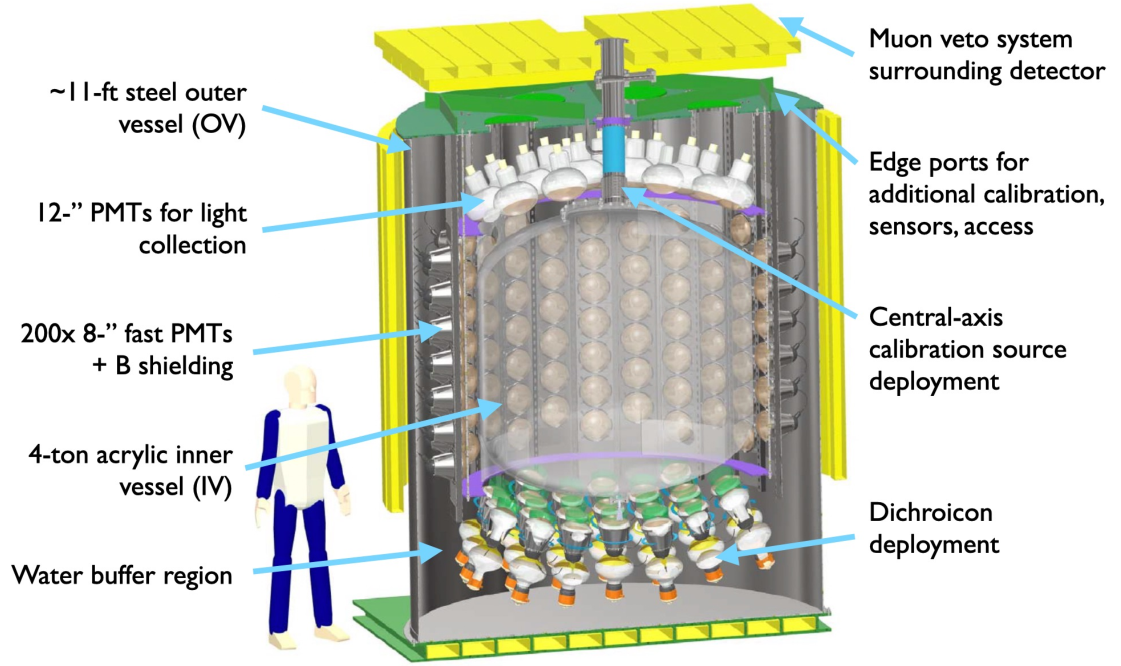
- Stand-alone hybrid detector optimized for MeV energy reconstruction
- Demonstrate event reconstruction using hybrid Cherenkov + scintillation signatures
- Validate models to support large-scale detector performance predictions
- Provide a flexible testbed to demonstrate impact of novel technology: targets, photon detectors, readout, reconstruction algorithms

→ Start of installation this summer at UC Berkeley

→ Closely coupled to 30-ton demonstrator at BNL for WbLS production & stability

EOS Detector Layout

- stand-alone hybrid detector
- target mass: 4 ton of water, WbLS or slow scintillator
- 200 fast 8“ PMTs with tts of 900 ps (FWHM)
- CAEN V1730 readout
- plus deployment of 10 dichroicons for spectral sorting



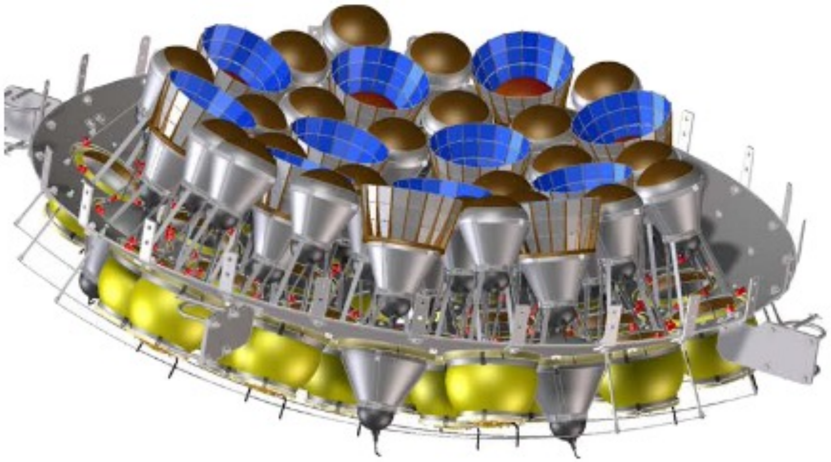
Progress on EOS Assembly

Good progress over the last months

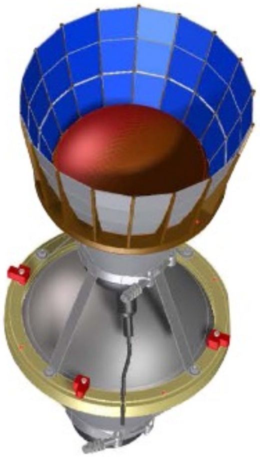
- most of the design work done,
  all long lead-time items ordered
- steel tank and acrylic vessel delivered
- half of 200 very fast 8‘‘ Hamamatsu
  PMTs received, testing on-going
- digitizers & HV boards received

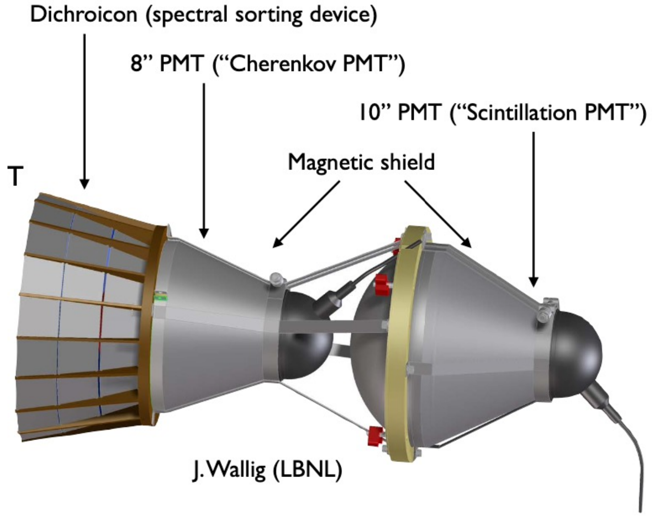
→ detector filling planned for early 2024

EOS outer steel and inner acrylic tanks



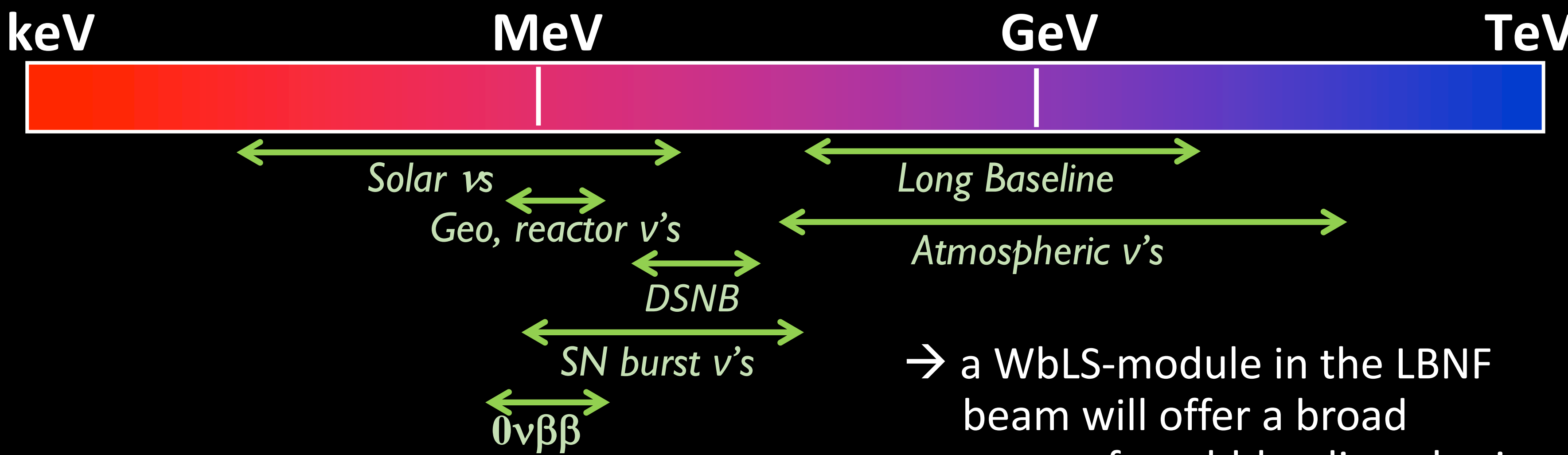
lower PMT array with integrated Dichroicons





Conclusions

- **hybrid Cherenkov/scintillation detectors** offer a large dynamic range, enhanced event reconstruction and new background discrimination capabilities



→ a WbLS-module in the LBNF beam will offer a broad range of world-leading physics

- good progress of R&D on individual components (WbLS, LAPPDs, Dichroicons ...)
- ton-scale experiments ANNIE/SANDI, EOS & BNL prototypes demonstrate combination of components and identify challenges appearing at larger scales

→ will provide the full range of technical information required for a THEIA25 design