On the road to a broad program of **neutrino physics with THEIA**

Logan Lebanowski
for the Theia collaboration

Berkeley UNIVERSITY OF CALIFORNIA

BERKELEY LAB

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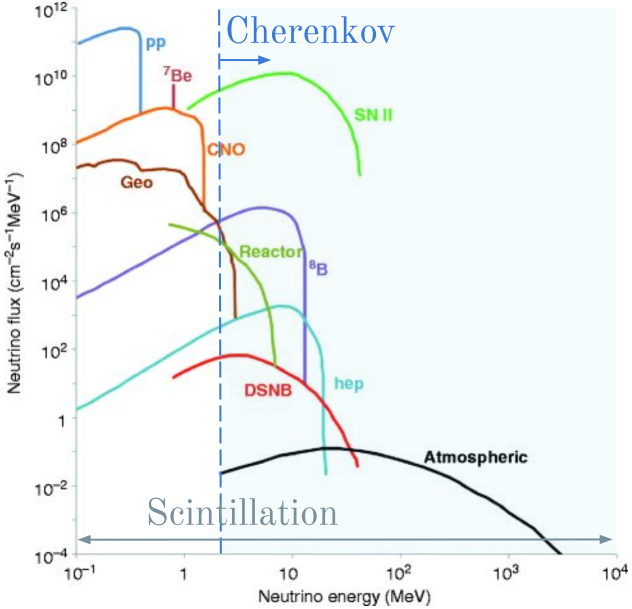
Optical neutrino detectors

Large optical detectors (water Cherenkov and scintillation) have been groundbreaking in neutrino physics and continue to be the primary workhorse for discovery and precision.

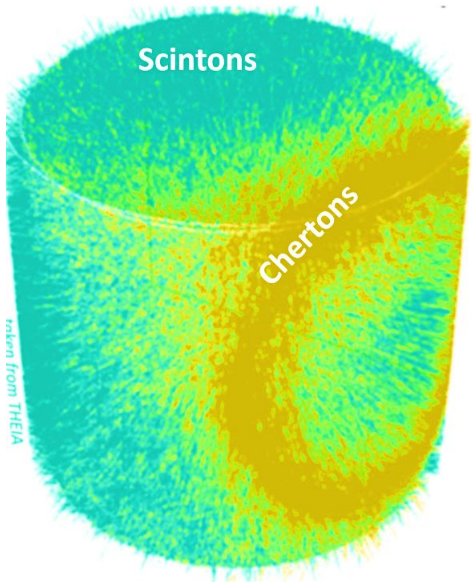
They have observed and made precise measurements of neutrino oscillations, the most sensitive 0**νββ** search, and the study of neutrinos from the atmos., Earth, Sun, supernovae, reactors, accelerators, AGN/cosmic rays.

The next generation of optical neutrino detectors will have improved **photosensors** and optimized **optical media**, some of which will be able to simultaneously use both scintillation and Cherenkov photons [iNSPIRE:2052358 Future Advances in Photon-Based Neutrino Detectors: A SNOWMASS White Paper].

THEIA



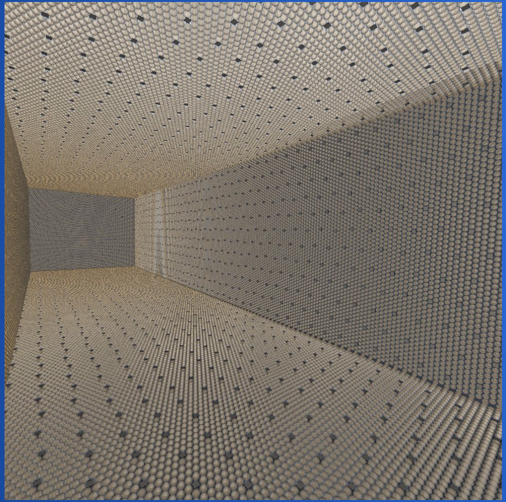
THEIA is a proposed large-scale neutrino detector that would use both Cherenkov and scintillation signals to enable a rich program of fundamental physics, including both low- and high-energy neutrino physics.



Detector

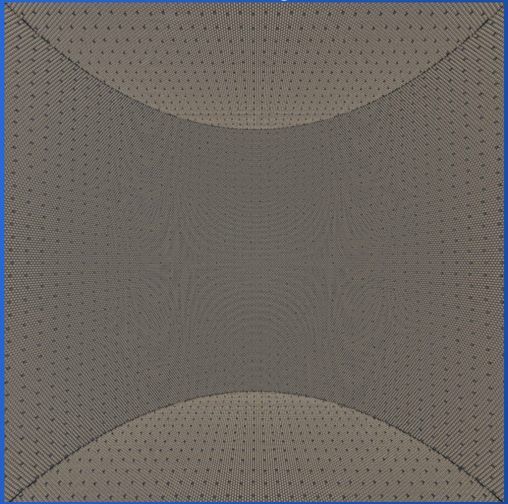
Baseline design to leverage both the direction resolution of the Cherenkov signal and the remarkable energy resolution and low detection threshold of a scintillator detector.

25 kt Box



- Novel scintillator
- Fast photosensors
- Spectral sorting

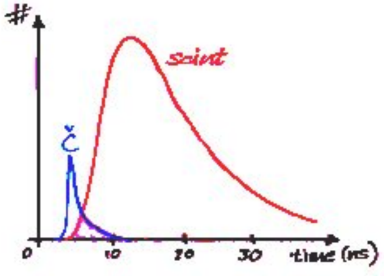
100 kt Cylinder



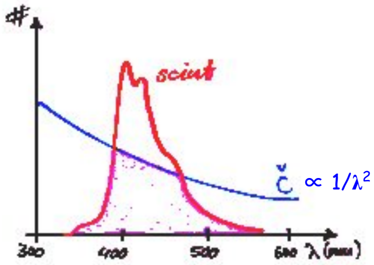
Cherenkov + Scintillation

Cherenkov and scintillation photons are distinguishable via

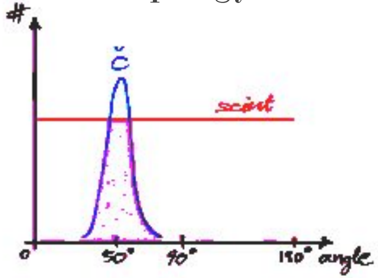
Time



Wavelength



Topology



Addressing the challenges:

- Timing: Resolve timing with fast photosensors, slow scintillators.
- Yields/Attenuation: Adjust scintillation yield and attenuation in novel scint.
- Wavelength: Spectrally sort photons into dedicated photosensors.

These technologies are being demonstrated.

THEIA physics program

The primary design driver will likely be a search for $0\nu\beta\beta$ with sensitivity into the normal mass ordering. Such a detector could also produce leading measurements of solar, geo, supernova burst, diffuse supernova neutrinos, and more.

If located at SURF, it could also measure δ_{CP} and the neutrino mass ordering using high-energy neutrinos from the LBNF neutrino beam.

THEIA program

Primary Physics Goal	Reach	Exposure / assumptions
Long-baseline oscillations	$> 5\sigma$ for 30% of δ_{CP} values	524 kt-MW-yr
Supernova burst	$< 1(2)^{\circ}$ pointing accuracy	100(25)-kt detector, 10 kpc
	20,000 (5,000) events	
DSNB	5σ discovery	125 kton-yr
CNO neutrino flux	< 5 (10)%	300 (62.5) kton-yr
Reactor neutrino detection	2000 events	100 kton-yr
Geo neutrino detection	2650 events	100 kton-yr
NLDBD	$T_{1/2} > 1.1 \times 10^{28}$ yr	211 ton-yr ^{130}Te
Nucleon decay $p \to \overline{\nu} K^+$	$T > 3.80 \times 10^{34}$ yr (90% CL)	800 kton-yr

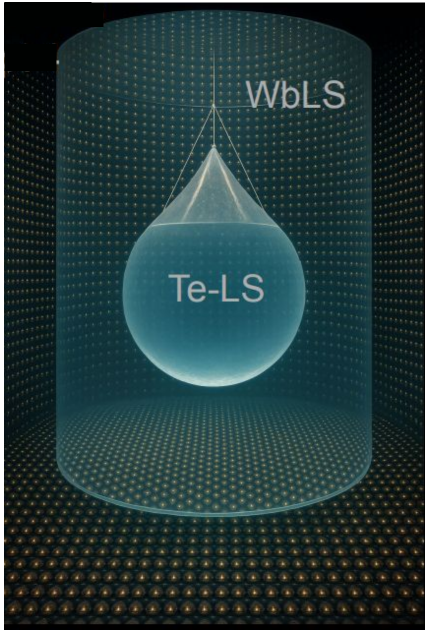
iNSPIRE:2039010

$0\nu\beta\beta$

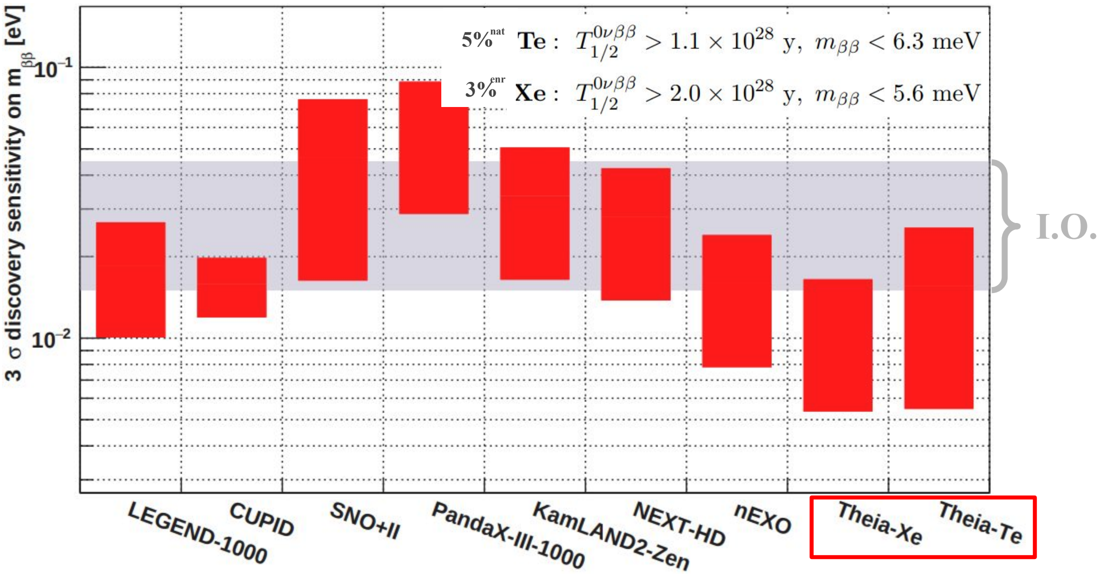
KamLAND-Zen and SNO+ scintillator approaches can provide high mass and have demonstrated advantages (background and isotope control).

Cherenkov directionality offers powerful discrimination of directional sources or backgrounds ⇒ help reduce dominant solar neutrino background.

Example:



THEIA 100 kt for 10 years



Geoneutrinos

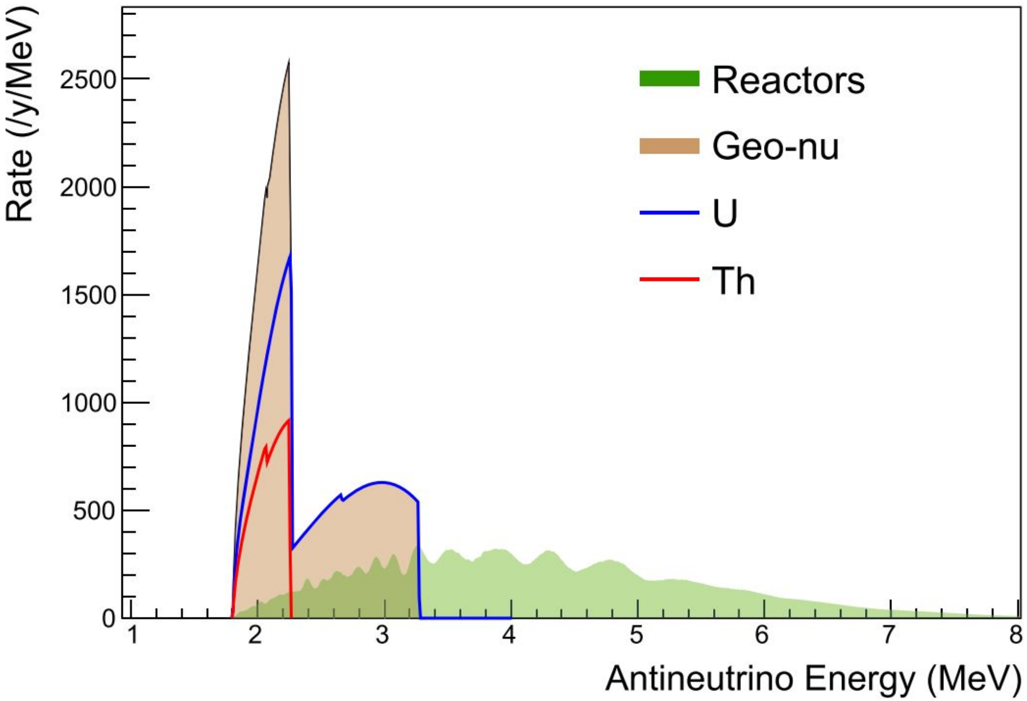
Tests of geo models. Could measure U/Th ratio and improve global picture.

Background likely to be n:

- Atmospheric ν NC-induced
- μ-induced
- (□,n) G.S.

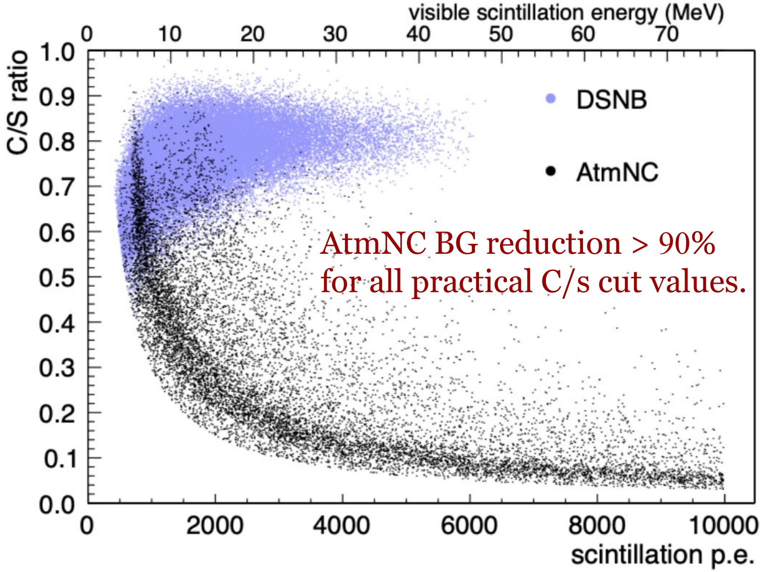
Simple C/s ratio offers powerful discrimination:
heavy particles (□,p,n) produce no Cherenkov at low E ...

THEIA 50 kt at SURF



Diffuse supernova neutrinos

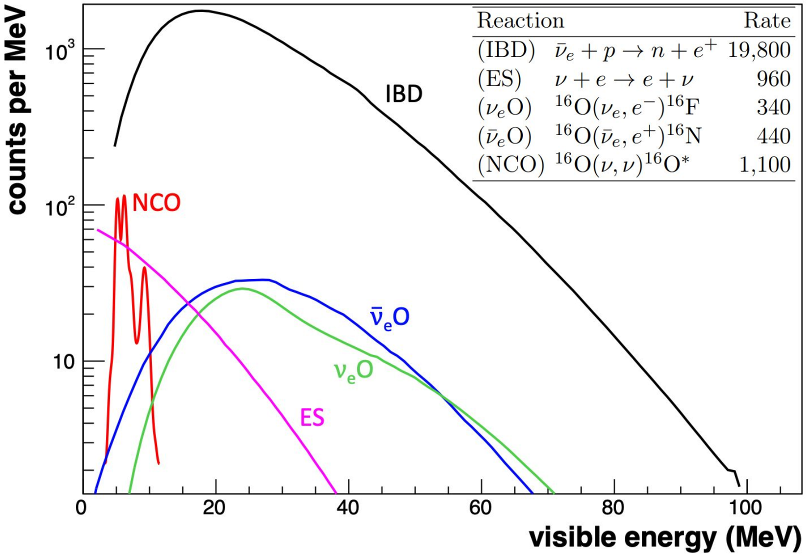
Discovery & spectroscopy to inform astrophys.
Could measure lower energies than SK-Gd/HK.



Supernova burst neutrinos

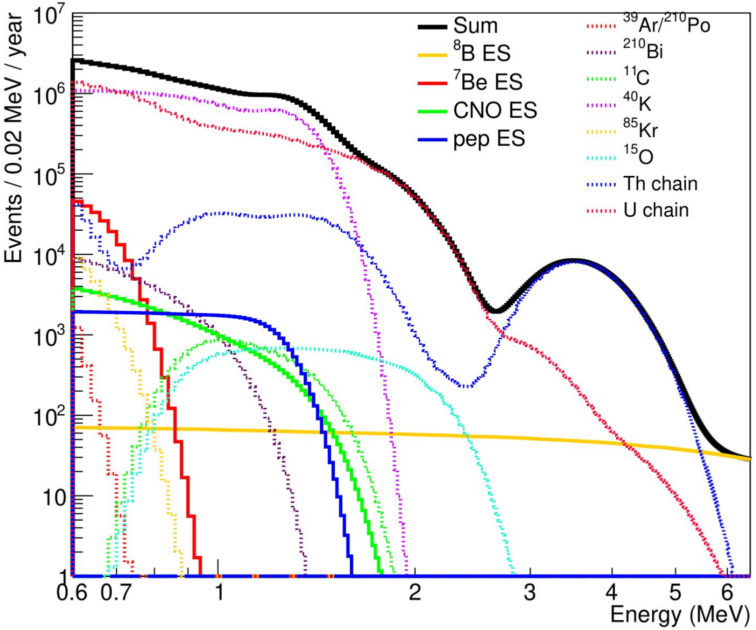
Flavor-resolution & spectral analyses (E & t).
ES can provide pointing < 1° for 100 kt.
Channels complementary to DUNE.
Pre-SN: 3σ detection at 3 kpc.

THEIA 100 kt WbLS at 10 kpc



Solar neutrinos

THEIA 25 kt of 5% WbLS



Test solar models (e.g., metalicity) & search for new physics (e.g., in the vacuum-matter transition region, 1-5 MeV).

Event directionality clearly important.

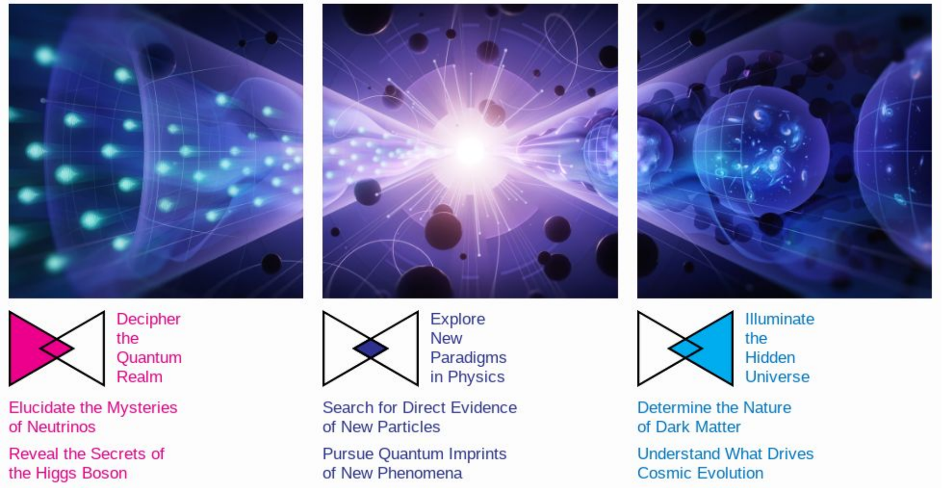
- Advantages of both water Cherenkov (like SK) & scintillator (like Borexino).
- SNO+ and Borexino have demonstrated solar directionality in scintillator.

P5 recommendations

Particle Physics Project Prioritization Panel (P5)

In 2023, P5 presented a 10-year strategic plan for US particle physics, with essential input from the community planning exercise Snowmass 2021.

“We recommend research and development (R&D) toward an advanced fourth detector that could ultimately expand DUNE’s physics program.”



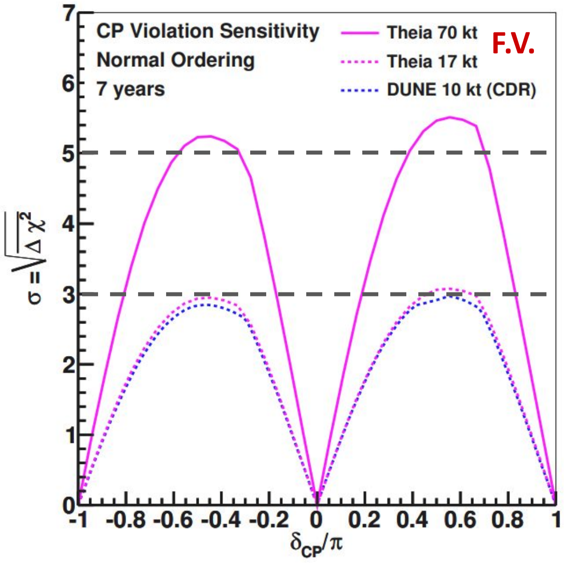
Long-baseline oscillations

At SURF, THEIA would measure GeV neutrinos and antineutrinos from the LBNF neutrino beam. Advanced Cherenkov ring imaging techniques lead to improved particle ID and ring counting, greatly improving BG rejection. Simpler nuclear target (H_2O vs. Ar).

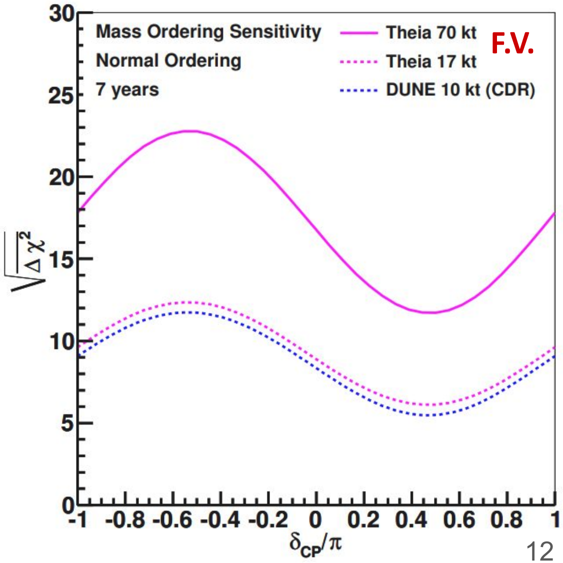
	Energy resolution at 1 GeV
DUNE	(10-20)% [arXiv:2106.04597]
T2K	2.4% (single-ring μ)

Work is ongoing on event reconstruction & updating sensitivity studies.

***CP* violation sensitivity**



Mass ordering sensitivity



The road to THEIA

A broad demonstrator program is underway that is enabling extrapolations of the technology performance and enhanced reconstruction techniques to a large-scale detector like Theia.

Addressing the challenges C/s discrimination:

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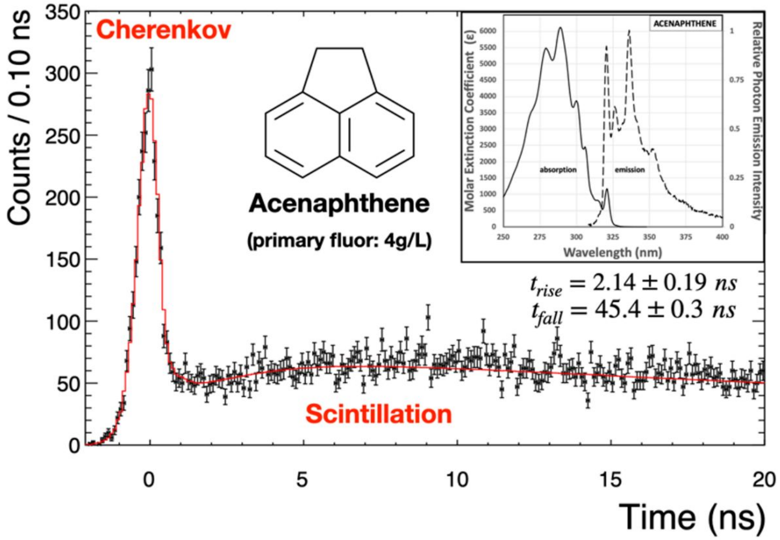
- Yields/Attenuation: Adjust scintillation yield and attenuation in novel scint.
- Wavelength: Spectrally sort photons into dedicated photosensors.

New directions in directionality

Some specific efforts:

- **Slow fluors**
- Large area ps photodetectors (LAPPDs)
- Dichroic light concentrator (dichroicon)
- Water-based LS (WbLS)
- New PMTs, SiPMs, …



[iNSPIRE:2052358]

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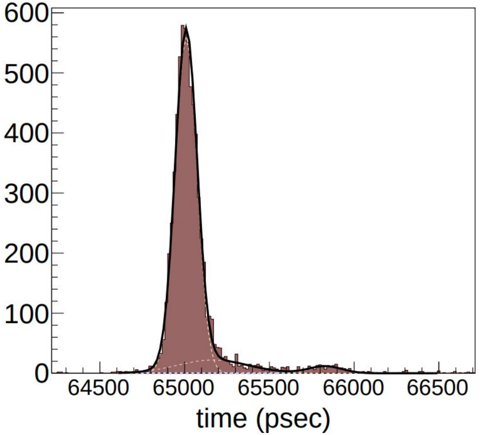

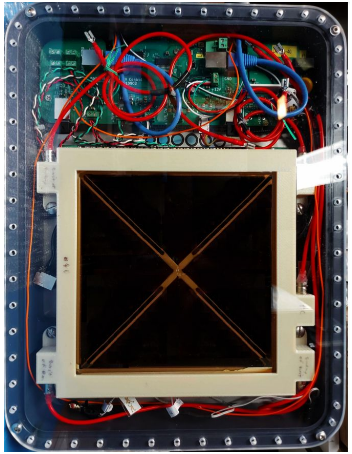

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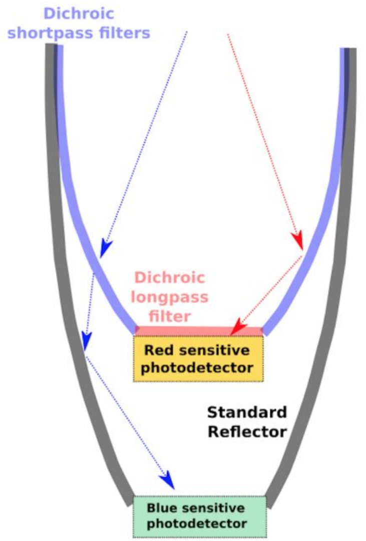

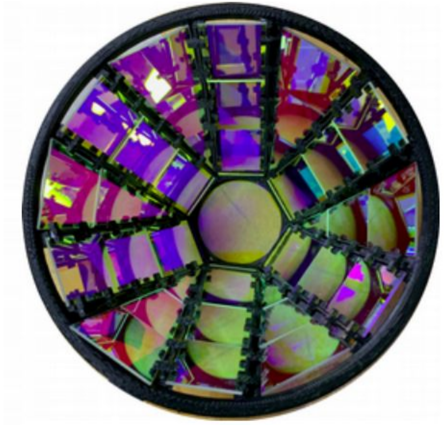

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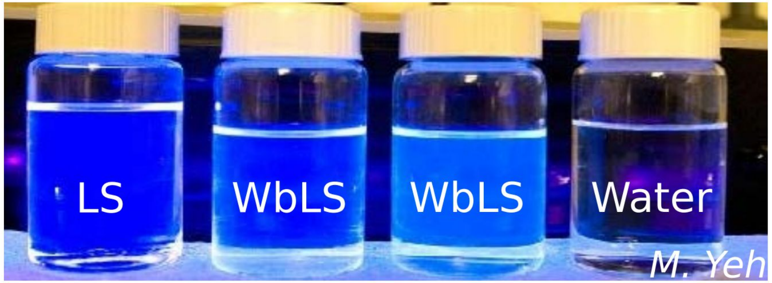
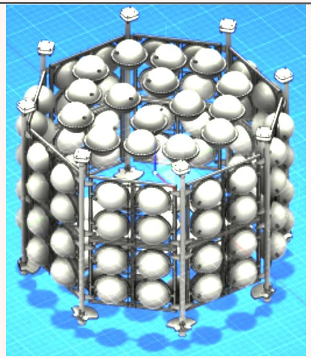


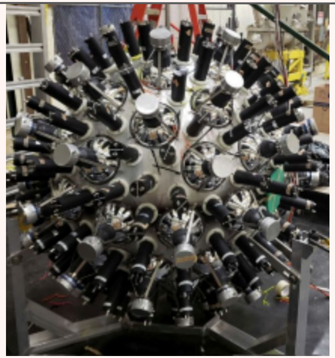
[iNSPIRE:2052358]

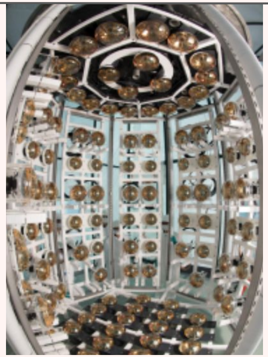
Technology demonstrators

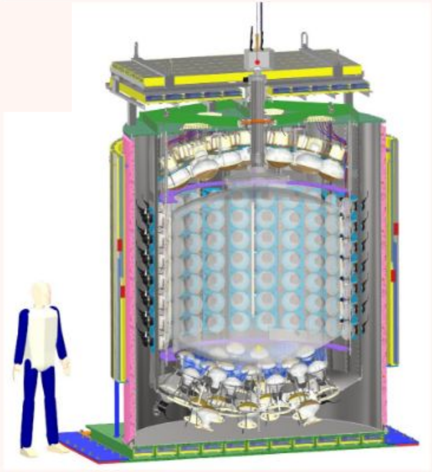
- **BNL: optics + engineering demonstrator (30 ton)**
  - Ton-scale production
  - Optical transparency in an operating detector
  - Optical stability over time
  - Recirculation of WbLS (nanofiltration)

- **LBNL: performance demonstrator (EoS)**
  - Full event reconstruction in (Wb)LS
  - Performance dependence on %LS, PMT properties
  - Particle ID
  - Background studies









- **Boulby: BUTTON**
  - Underground demonstration
  - Low background purification
  - Potential for scale-up

Delaware: NUDOT

- Isotope doping, quantum dots
- Fast photosensors & readout

FNAL: ANNIE See talk by Jingbo Wang

- Beam deployment with LAPPDs
- High-energy neutrino event reconstruction
- Potential for Phase III (fun WbLS fill)

Eos program

National Nuclear Security Administration

Based at UC Berkeley and LBNL, Eos is demonstrating state-of-the-art detection technologies to simultaneously utilize scintillation and Cherenkov photons in event reconstruction and analysis. [iNSPIRE:2513648]

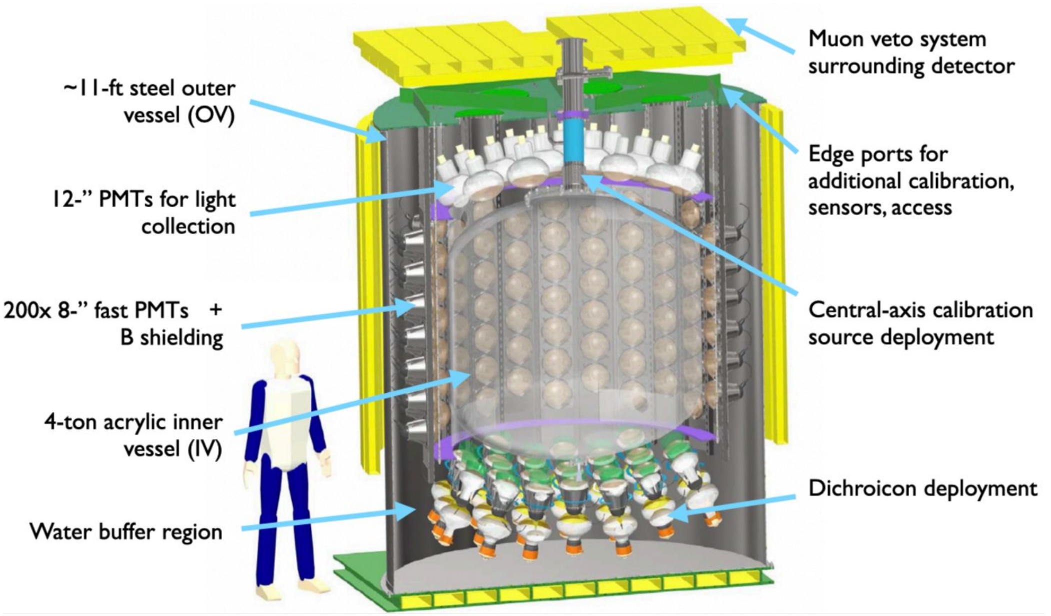
USA | Germany | Portugal | Finland | Turkey | Canada

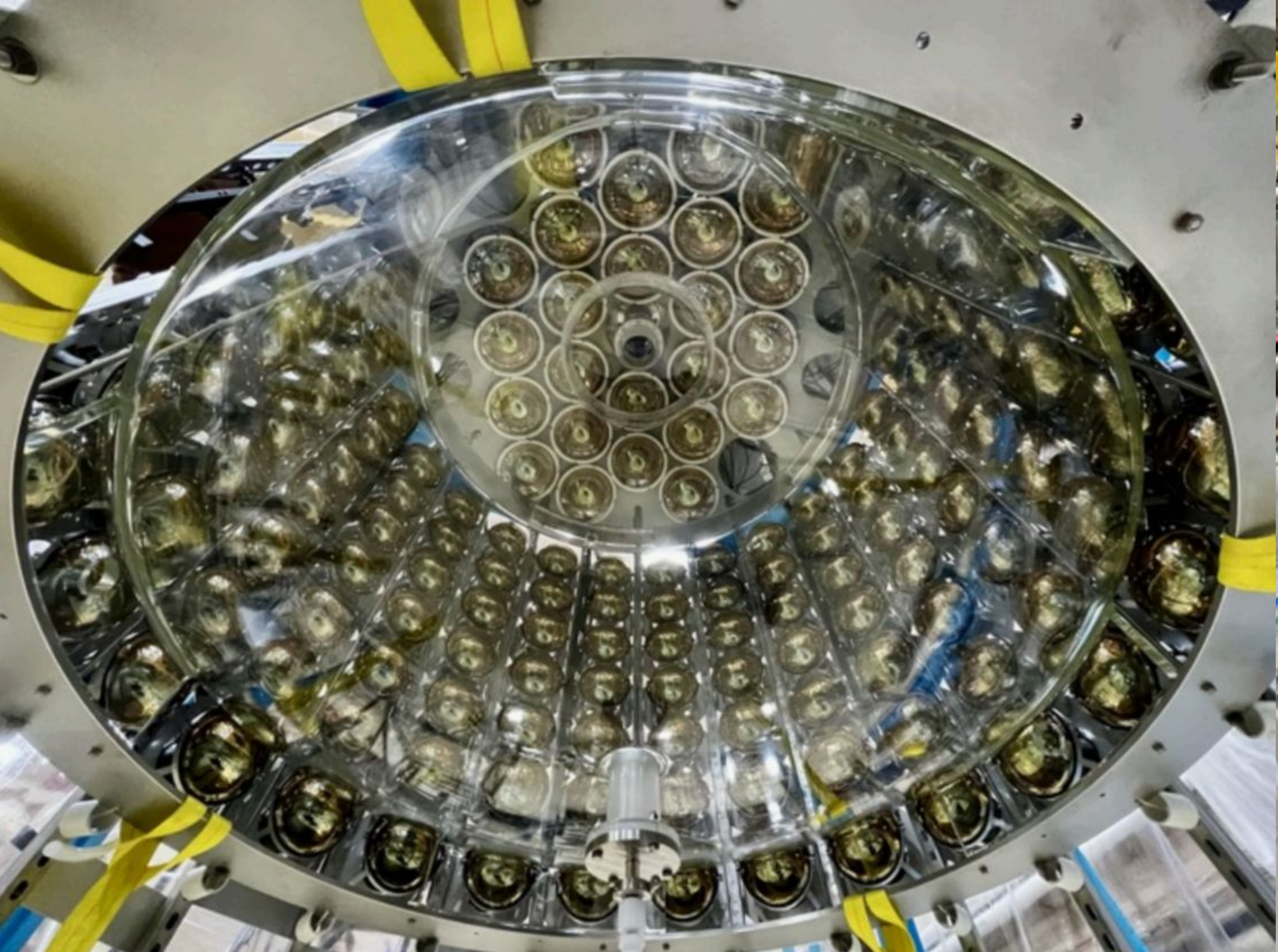
Results are being

- interpreted in the context of nuclear nonproliferation.
- extrapolated to larger-scale detectors and directly inform designs and operations.

Eos detector

- 20-tonne steel vessel filled with water.
- 4-tonne acrylic vessel filled with water in early 2024.
    - Currently filling with water-based liquid scintillator.
- 204 state-of-the-art fast PMTs.
- 12 dichroic light concentrators.
- Vertical calibration deployments.
- Embedded optical fibers.
- Surrounding muon trackers.
- CAEN V1730 readout,
  custom HV & trigger.





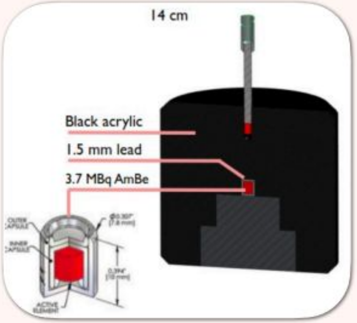
Eos calibration sources

Laserball

- Isotropic light source
- Picosecond lasers
- Four wavelengths (374, 408, 442 and 515 nm)

AmBe

- 4.4 MeV gamma coincident with neutron



Cosmics

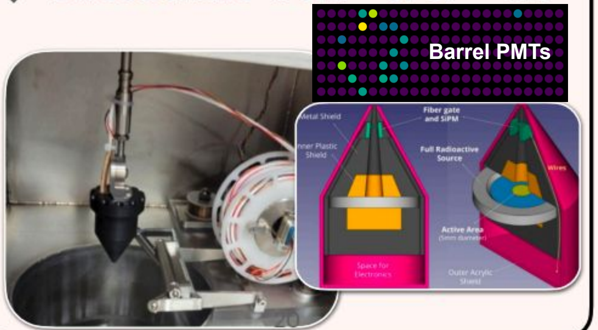
- Michel electron and neutron followers

Cherenkov

- ^{90}Sr source in UVT acrylic housing
- Cherenkov only light production

Directional

- Directional e$^-$ from ^{90}Sr or ^{106}Ru



Thorium

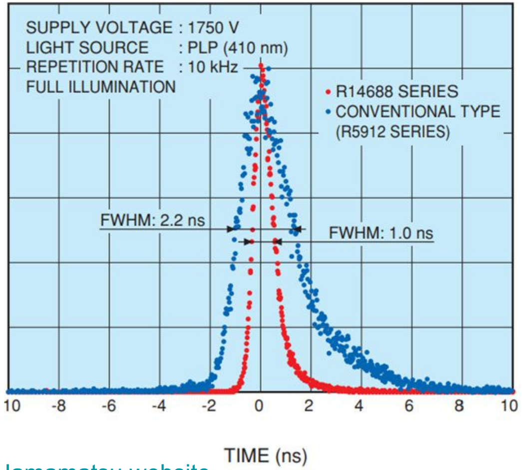
- Primarily 2.6 MeV gammas from ^{208}Tl

Hamamatsu R14688-100 PMTs

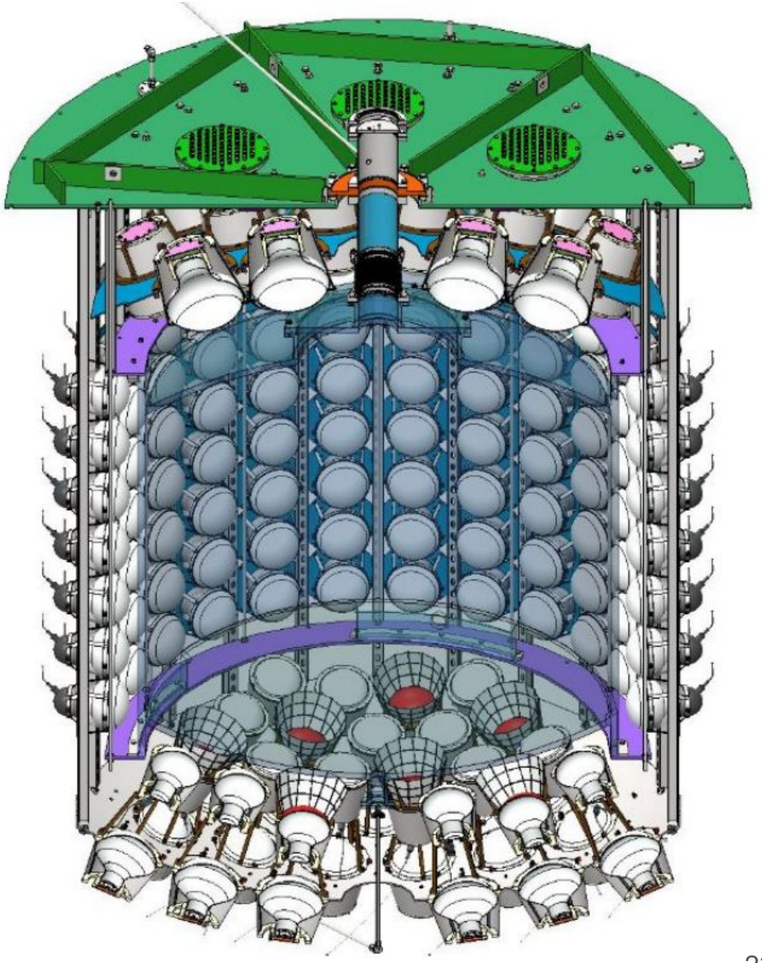
- **168 8” R14688-100 PMTs on the sides (barrel)**
- 24 12” R11780 at the top
- **36 8” R14688-100 PMTs at bottom**
- 13 10” R7081 PMTs at bottom in dichroicon array

First deployed in Eos, the 204 R14688’s have been measured with a picosecond laser to have a 450-ps **σ** in transit-time.

- >2 times better than predecessor R5912.
- Very helpful to distinguish C/s light.



Hamamatsu website



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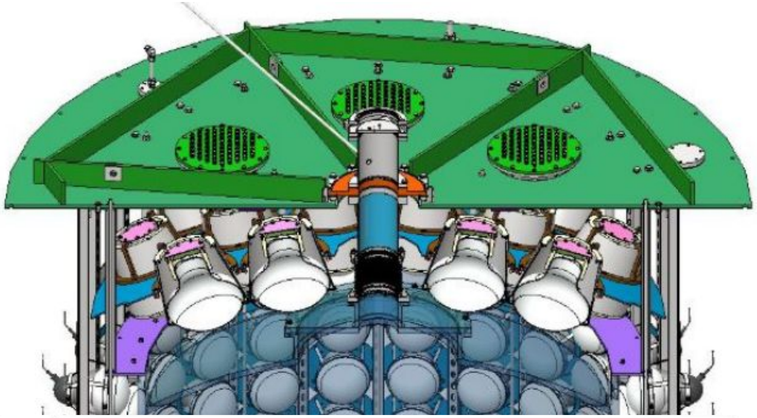

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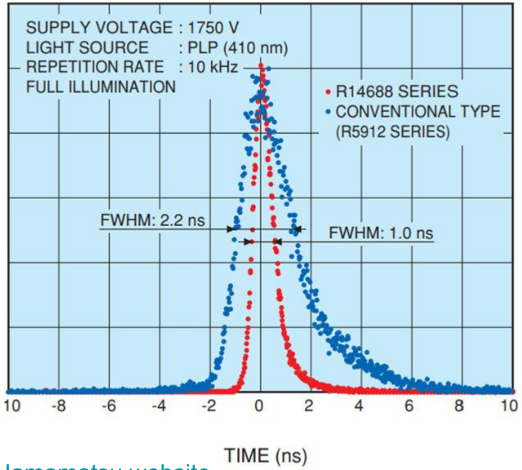

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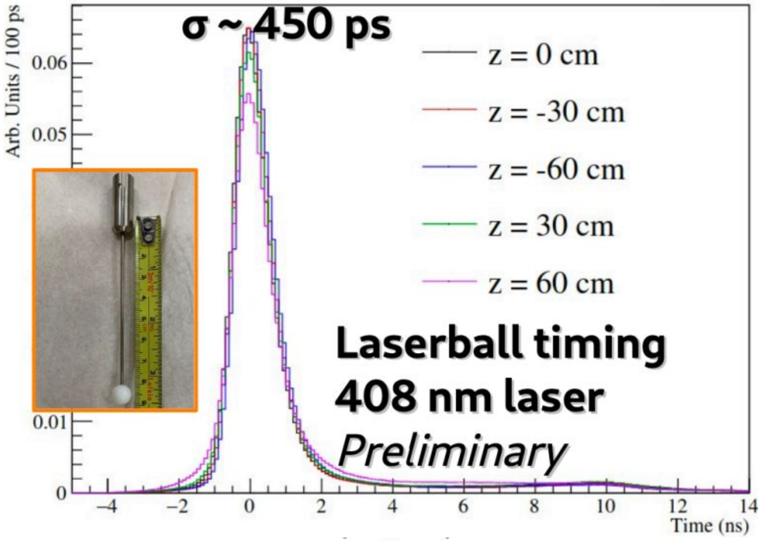
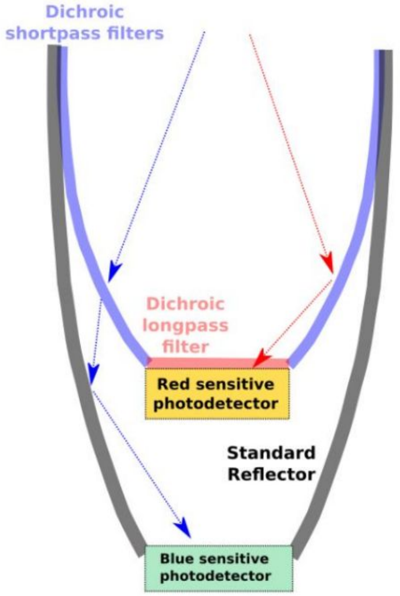


Dichroic light concentrators

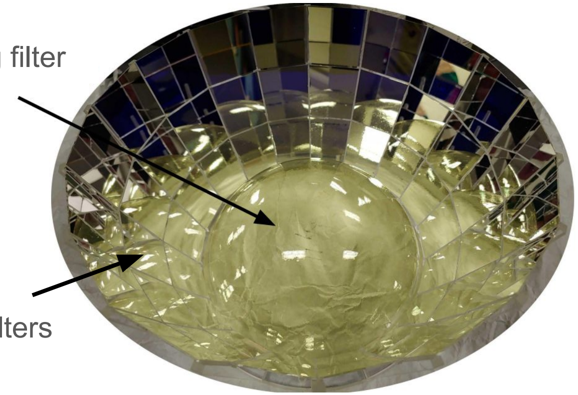
Using a parabolic concentrator built from dichroic filters, sort longer-wavelength (Cherenkov-rich) photons and shorter-wavelength (scintillation-rich) photons toward two different photosensors.



In Eos,

- 12 dichroicons are installed at the bottom.
- An array of 13 10” PMTs are arranged behind them to detect the passing scintillation light.
- The dichroic filters have a cut-on wavelength around 450 nm.
- Tunging and validating model. Will evaluate impact to reconstruction and PID.

Longpass, **absorbing** filter



Shortpass, **dichroic** filters

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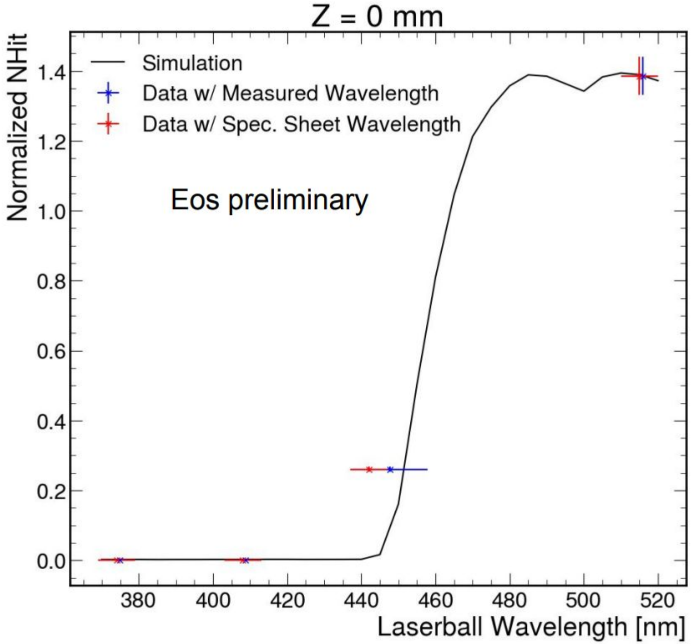
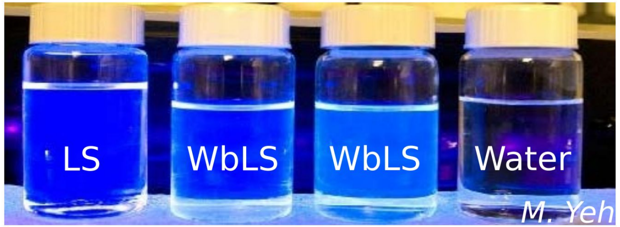
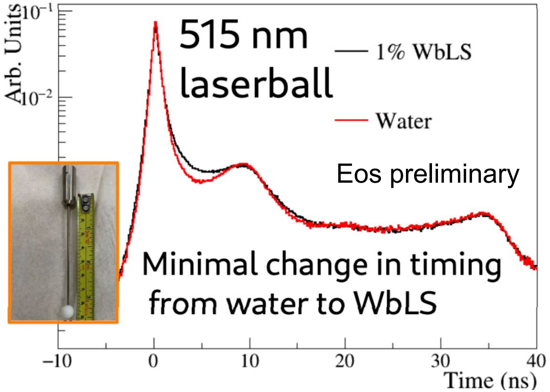


Novel scintillators



Brookhaven National Lab

Eos has completed its water phase.

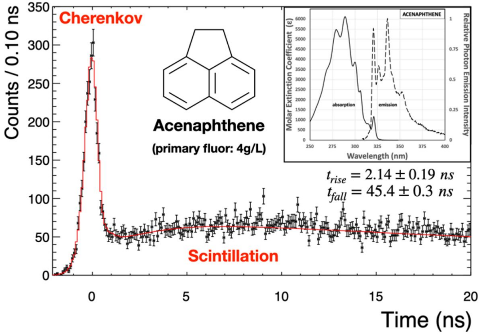


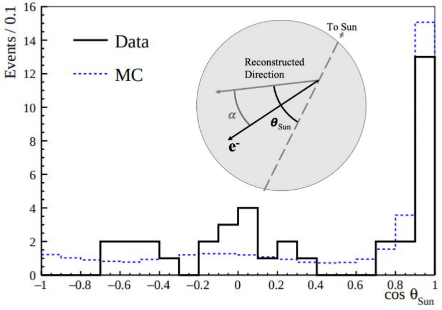
Eos has briefly measured 1% water-based scintillator.

- Scintillation yield comparable to Cherenkov yield.
- Timing showed minimal change.

Planning future scintillator deployments.

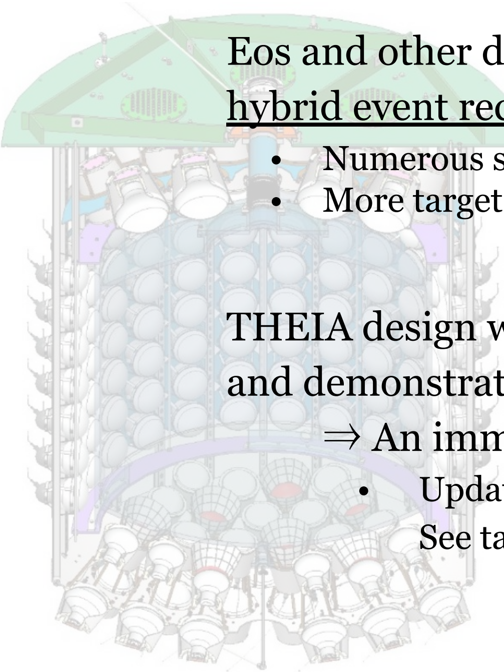
- Slow fluors
- LAB+PPO [SNO+ iNSPIRE:2696627]
- …





Summary

Eos



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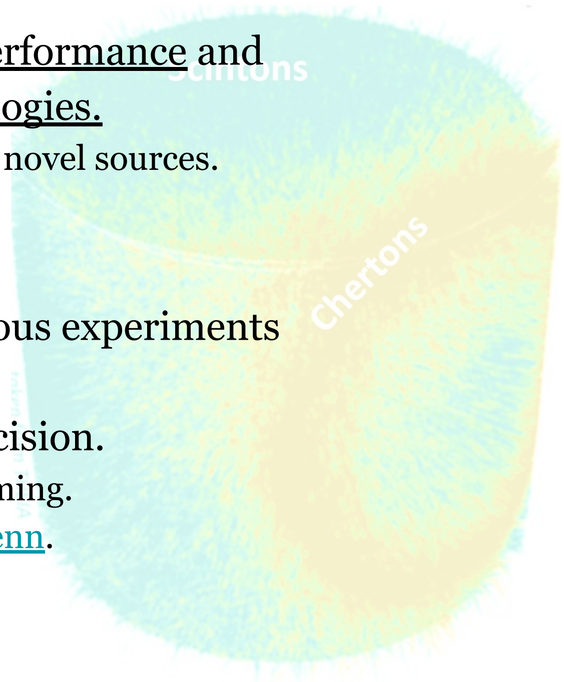


Eos and other demonstrators are characterizing detector performance and hybrid event reconstruction with the latest detector technologies.

- Numerous sources and established methodologies, along with novel sources.
- More target liquids will be tested in Eos.

THEIA design work is ongoing based on input from numerous experiments and demonstrators.

⇒ An immense physics program of discovery and precision.

- Updates on reconstruction and sensitivities are forthcoming.
  See talks at last week's hybrid detector workshop at UPenn.

Cherenkov detectors

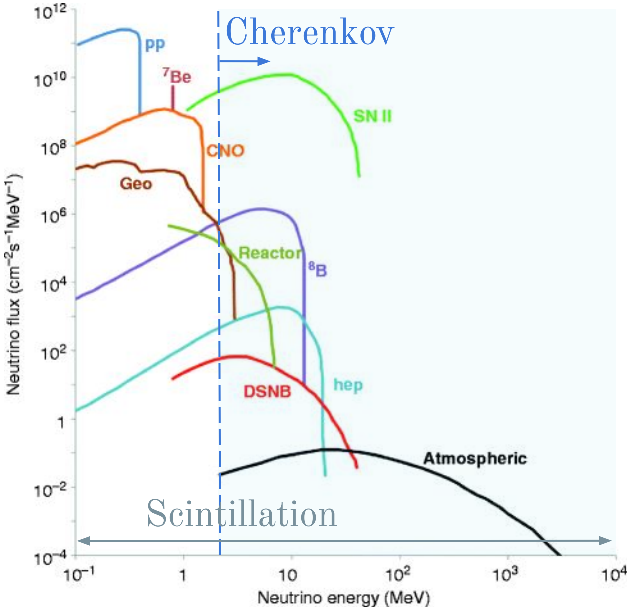
Neutrino oscillations were first observed with atmospheric and solar neutrinos in water Cherenkov detectors [SK, SNO].

Neutrino oscillations of solar, atmospheric, and accelerator neutrinos studied with Cherenkov detectors have produced leading measurements of θ_{12} [SNO, SK], θ_{23} [T2K, KM3NeT, SK, IceCube], Δm^2_{32} [T2K, IceCube], and δ_{CP} [T2K, SK].

Cherenkov detectors have also been used to study neutrinos from

- **Active Galactic Nuclei / Cosmic ray** [IceCube],
- **Supernova 1987a** [Kamiokande, IMB].

iNSPIRE:1090322



Scintillator detectors

The neutrino was first observed using scintillation signals [1956, Reines & Cowan].

Neutrino oscillations of reactor and accelerator neutrinos studied with scintillator detectors have produced leading measurements of θ_{13} [DB], θ_{23} [NOvA, MINOS+], Δm^2_{32} [DB, NOvA, MINOS+], Δm^2_{21} [KamLAND], and δ_{CP} [NOvA].

The most sensitive search for $0\nu\beta\beta$ uses scintillation in LXe [KamLAND-Zen].

Scintillator detectors have also been used to study neutrinos from

- the **Earth** [KamLAND, Borexino, SNO+],
- the **Sun** [Borexino, ...],
- **Supernova 1987a** [Baksan],

... scintillators also produce Cherenkov photons.

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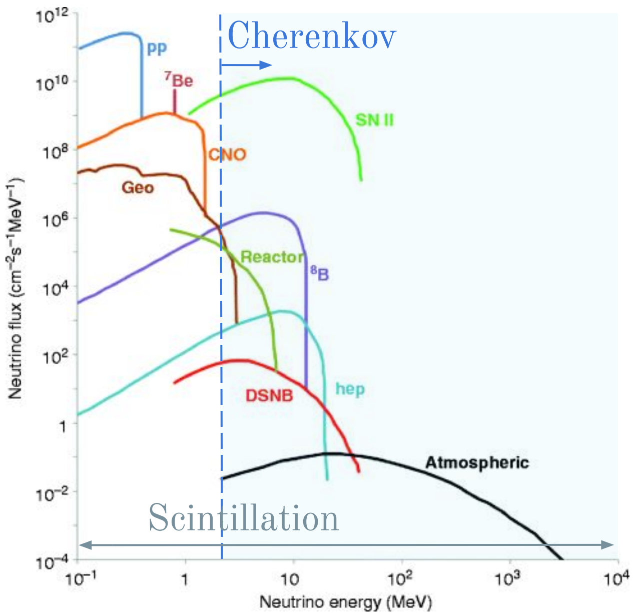
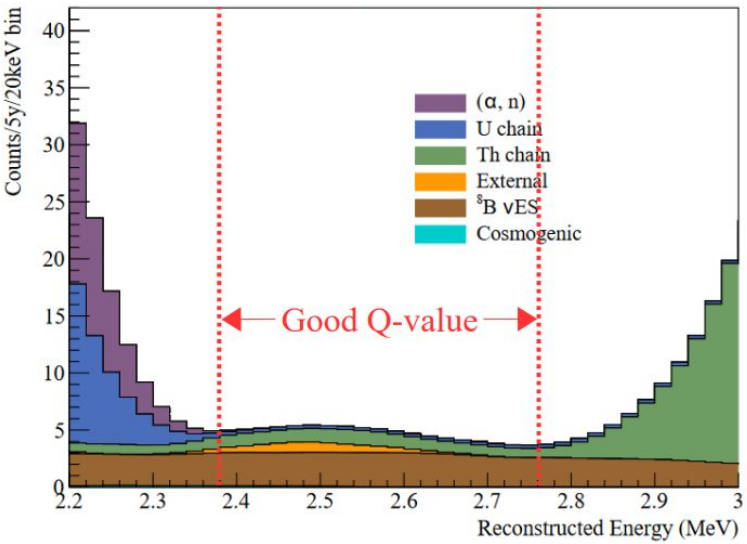


$2\nu\beta\beta$ decay in scintillator

Need a $2\nu\beta\beta$-decay isotope with a favorable Q-value.

Backgrounds (SNO+)



2νββ isotopes