The Theia physics program & the Eos demonstrator

Logan Lebanowski
for the Theia & Eos collaborations

24th International Workshop on
Next Generation Nucleon Decay & Neutrino Detectors (NNN25)

Sudbury, Ontario
Oct. 3, 2025

Optical neutrino detectors

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

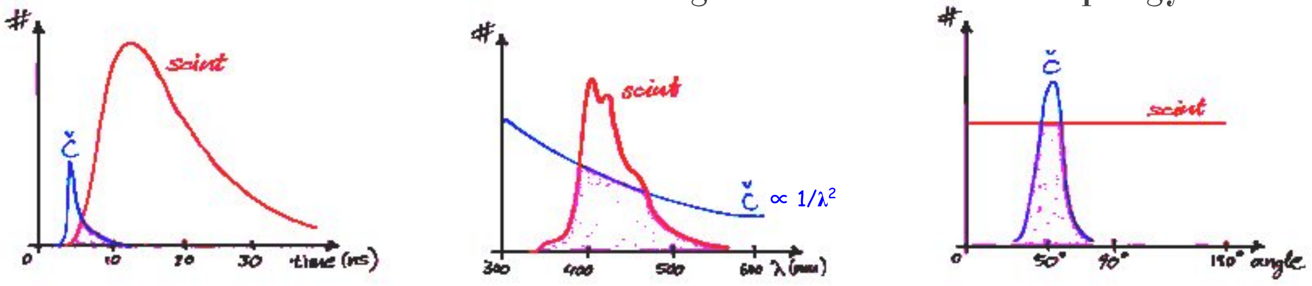
They have observed and made precise measurements of neutrino oscillations, made the most sensitive $0\nu\beta\beta$ search to-date, and enabled studies of neutrinos from the atmos., Earth, Sun, supernovae, reactors, accelerators, AGN/cosmic rays. They have also set leading limits on nucleon decay.

The next generation of optical neutrino detectors will have improved **photosensors** and optimized **optical media**, and some will be able to simultaneously use both scintillation and Cherenkov photons [iNSPIRE:2052358 Future Advances in Photon-Based Neutrino Detectors: A SNOWMASS White Paper, 2025 Hybrid Detector Workshop at UPenn].

Cherenkov + Scintillation

Cherenkov and scintillation photons are distinguishable via

Time **Wavelength** **Topology**



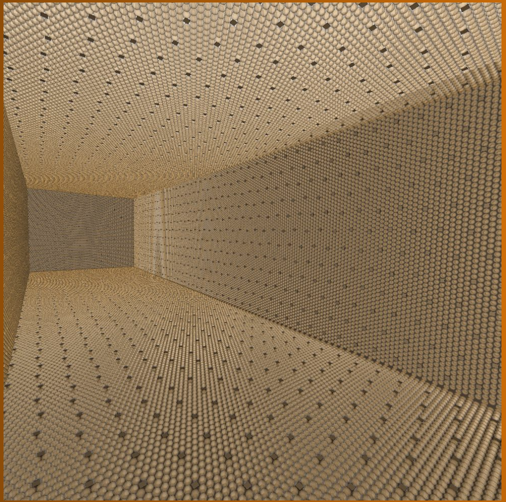
Technologies being developed and demonstrated:

- 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.

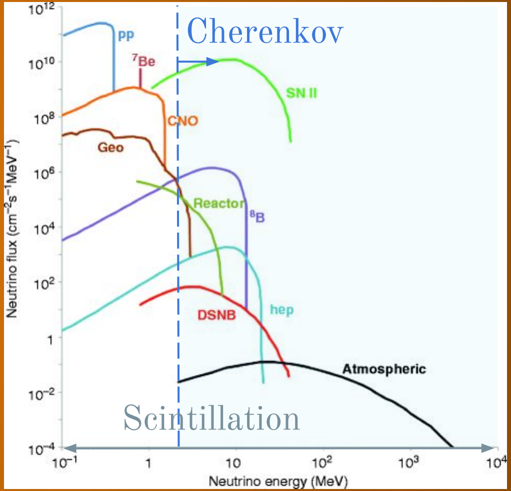
THEIA

A proposed large-scale neutrino detector that would use the direction resolution of Cherenkov light and the remarkable energy resolution and low detection threshold of a scintillator detector to enable a rich program of physics.

25 kt Box



- Novel scintillator
- Fast photosensors
- Spectral sorting



Theia received Gateway-0 approval at SNOLAB, which provides P.M. & eng. support to initiate concept. design.

Planning visit to SURF (1.5 km) Dec'25 to discuss initiating similar effort. Potential private funding.

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.

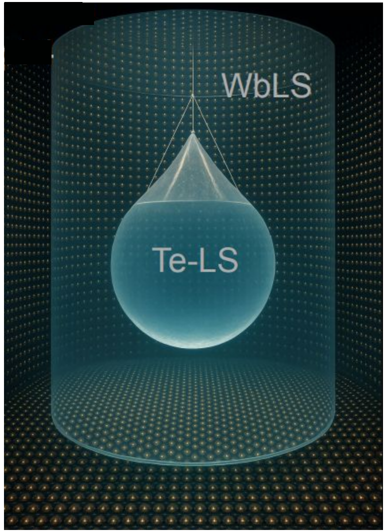
Primary physics goal	Reach	Context
Nucleon decay $p \to \nu K+$ ($\to 3\nu$)	T>1.1 x 10^{34} yrs (T>1.2 x 10^{32} yrs)	Complementary to DUNE, HK, JUNO (sensitive to different modes)
Supernova burst	2° pointing, 5k events (10 kpc)	Complementary to DUNE (ν vs. anti-ν) Improved flavour separation via Cher/scint
Diffuse supernova neutrino background	5σ in 5 yrs	Beyond SK / JUNO due to low threshold, bkg tagging
MSW transition	5σ	Unique handle on bkg rejection via directionality
CNO neutrinos	<12% (2%) Wb(LS)	No concurrent competition
Geoneutrinos	< 5 % (2% stat.)	First high-stats measurement in North America
$0\nu\beta\beta$	$T_{1/2}$ > 1.1 x 10^{28} yrs (90% C.L.)	Beyond ton-scale (further optimization possible)

$0\nu\beta\beta$

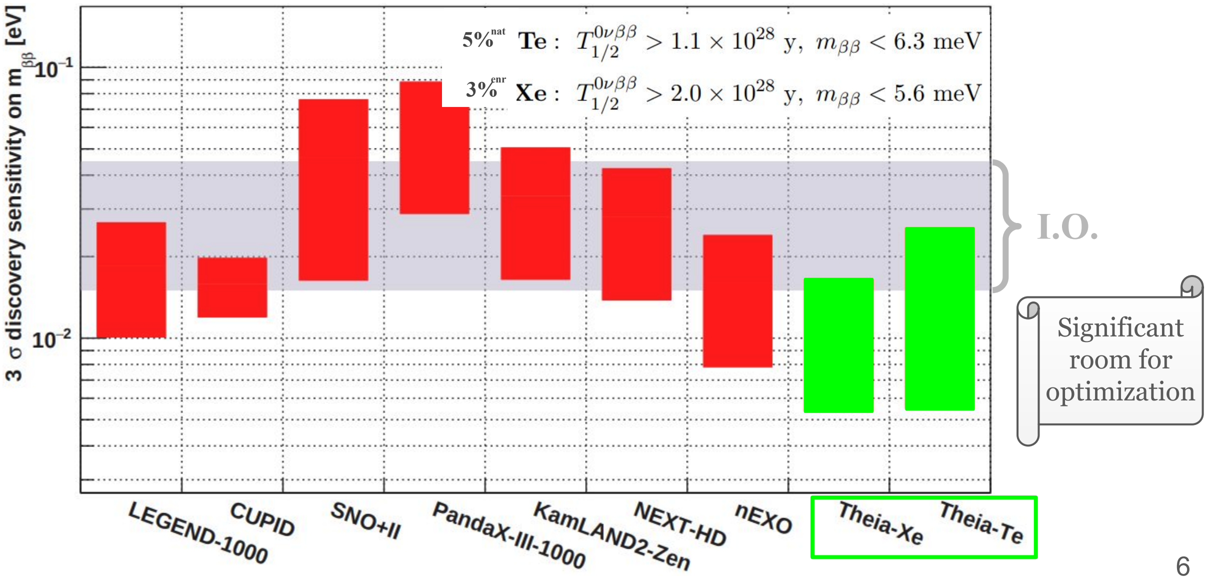
KamLAND-Zen and SNO+ approaches provide high isotope mass and:

- Background fiducialization, characterization before loading, & filtering.
- Isotope can be scaled, removed, enriched, or depleted (in-situ confirmation of signal).
- Cherenkov directionality discriminates on directional sources/backgrounds.
- C/s and improved multisite discrimination will further reduce backgrounds.

Example concept:



THEIA 100 kt for 10 years

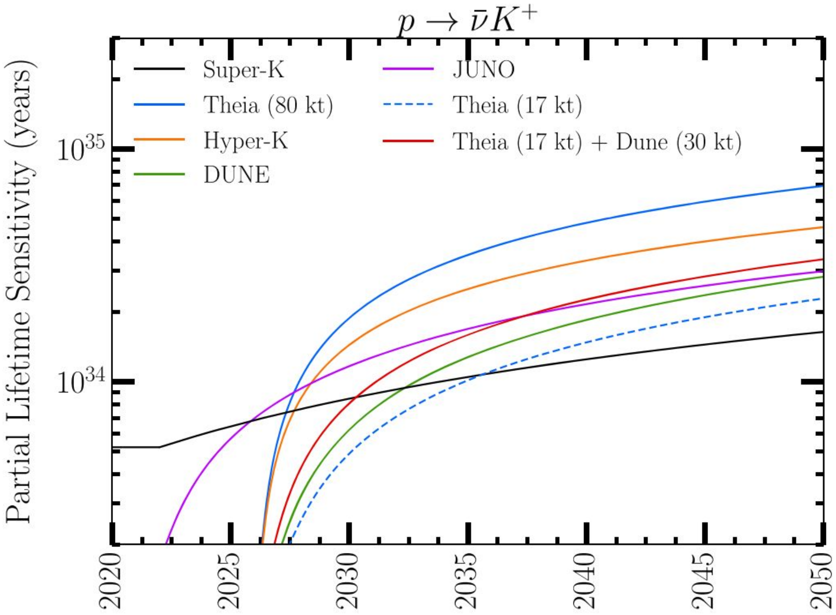


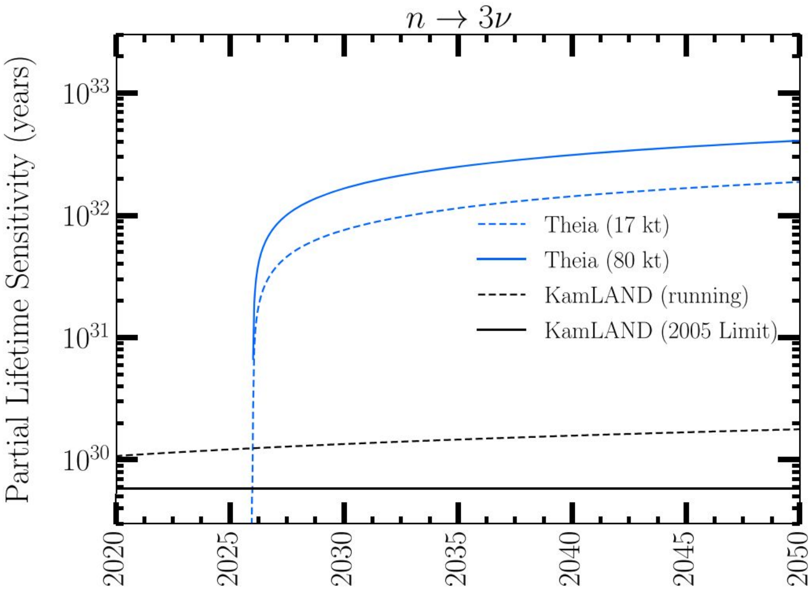
Nucleon decay

Sensitivities comparable to other experiments.

- Can see (K^+) below Cherenkov threshold.
- May benefit from C/s separation & PSD.

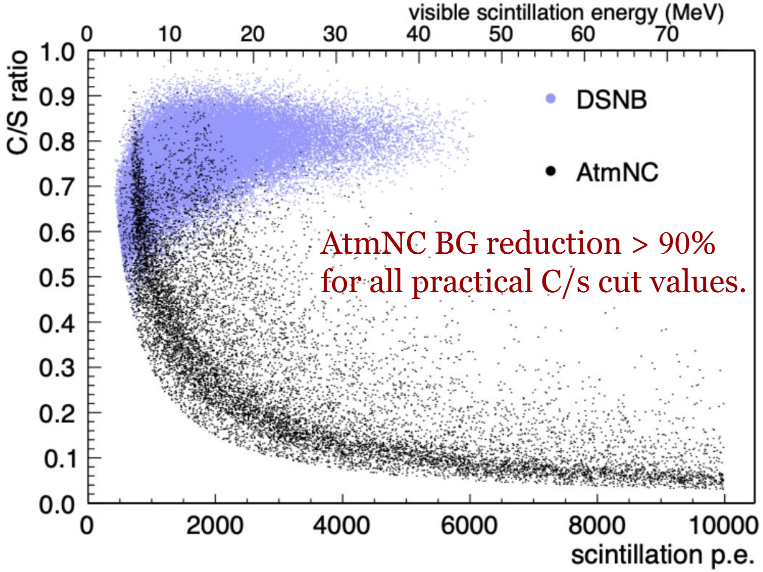
World-leading sensitivities to modes with 'invisible' decay products.
Dominant in some extra dimension GUTs.





Diffuse supernova neutrinos

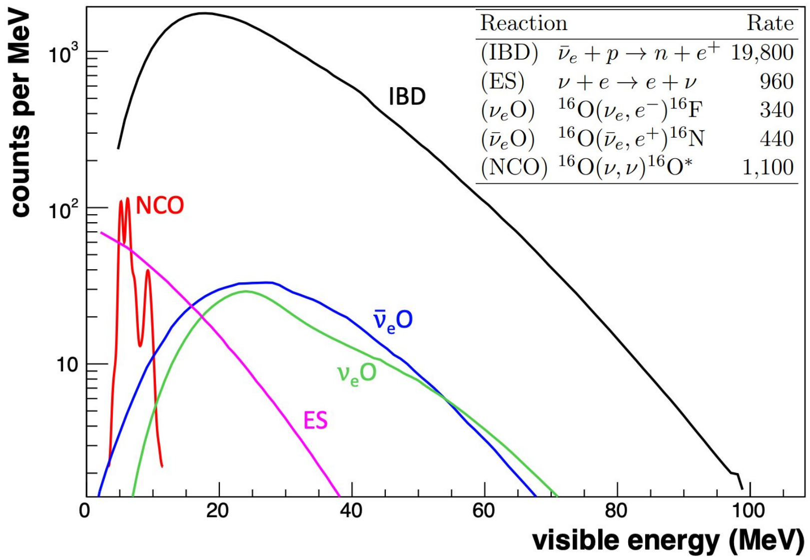
Discovery & spectroscopy to inform astrophys.
Could measure lower energies than SK-Gd/HK.



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



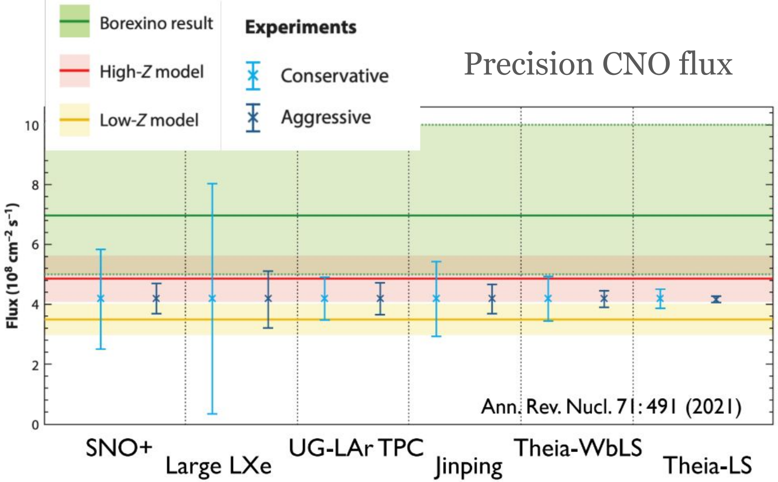
Reaction		Rate
(IBD)	$\bar{\nu}_e + p \to n + e^+$	19,800
(ES)	$\nu + e \to e + \nu$	960
(ν_eO)	$^{16}O(\nu_e, e^-)^{16}F$	340
($\bar{\nu}_e$O)	$^{16}O(\bar{\nu}_e, e^+)^{16}N$	440
(NCO)	$^{16}O(\nu, \nu)^{16}O^*$	1,100

Solar neutrinos

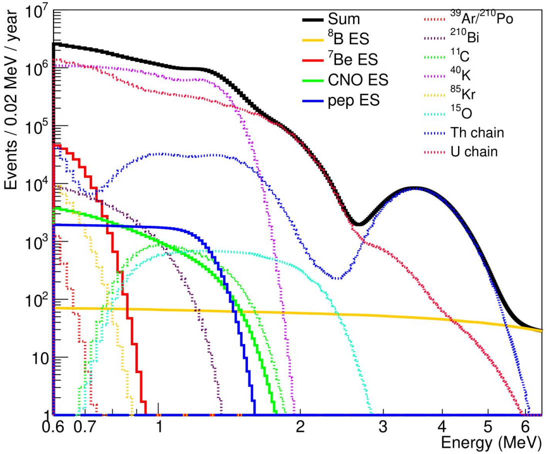
- Test solar models (e.g., metalicity)
    - Precision CNO flux

- Search for new physics (in the 1-5 MeV vacuum-matter transition region).

Precision CNO flux



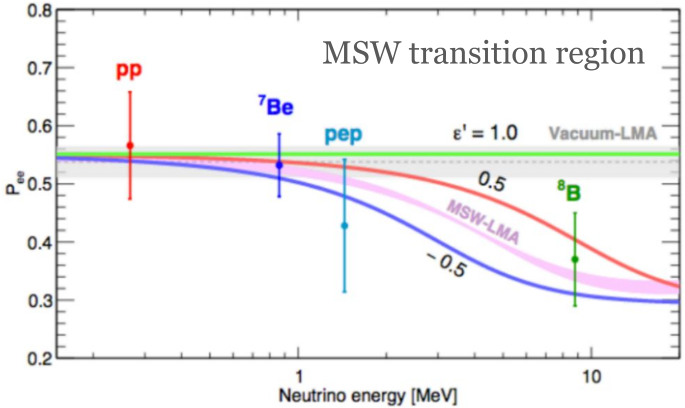
THEIA 25 kt of 5% WbLS



Event directionality important.

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

MSW transition region



Geoneutrinos

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

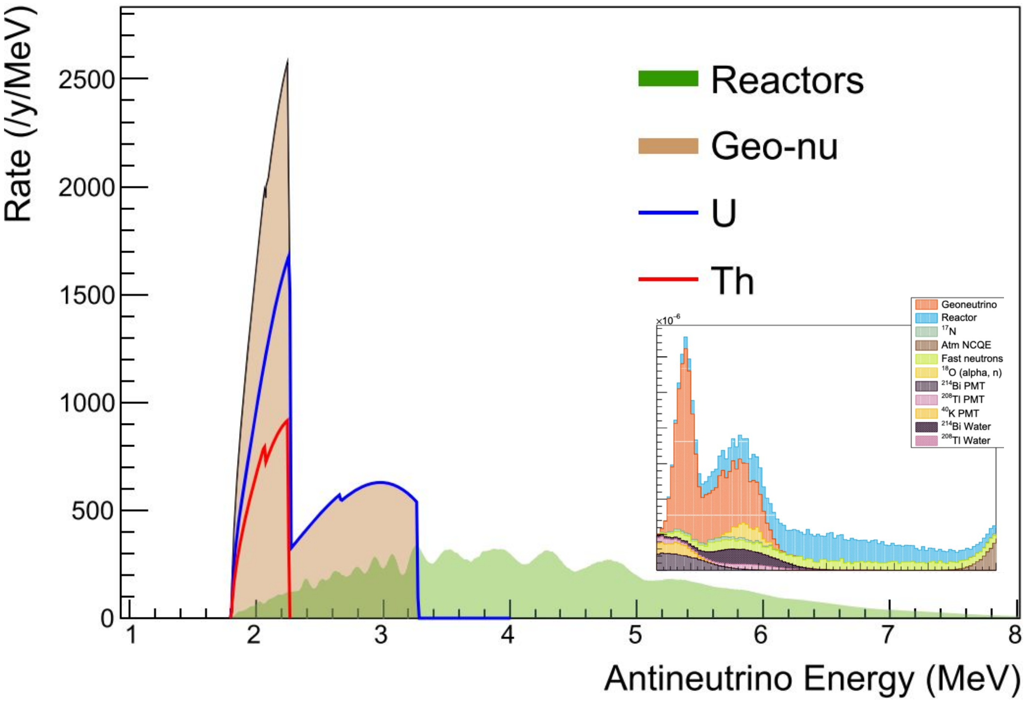
Backgrounds likely to be n:

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

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

At SNOLAB, Theia could improve SNO+ measurement of Δm^2_{21} with reactor ν.

THEIA 50 kt at SURF



Geoneutrinos

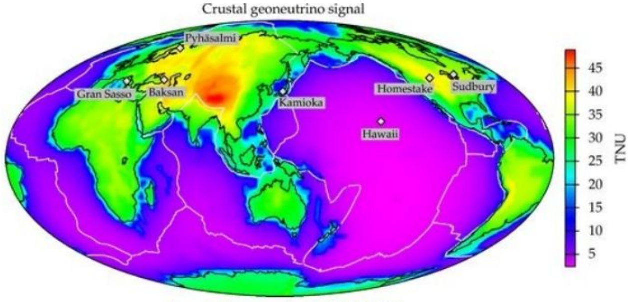
Tests of geo models. Could measure U/Th ratio & improve global picture.

Backgrounds likely to be *n*:

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

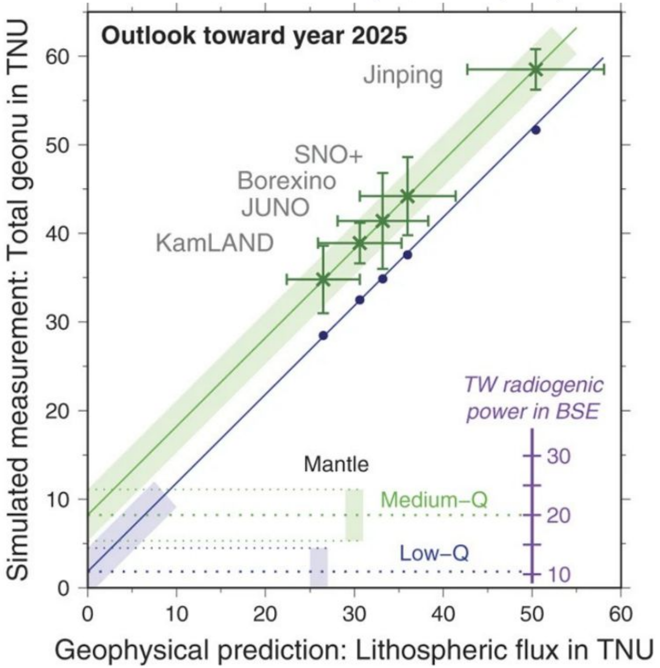
Simple C/s ratio offers powerful discrimination:
heavy particles (α,*p*,*n*) produce no Cherenkov at low *E* ...

At SNOLAB, Theia could improve SNO+ measurement of Δm^2_{21} with reactor *ν*.



inspirehep.net/record/1218471

Šrámek, O. et al. Sci. Rep. 6, 33034 (2016)



Long-baseline oscillations

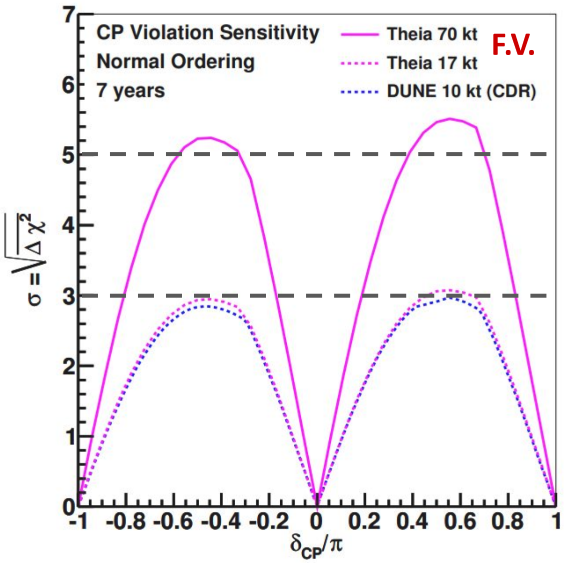
"We recommend R&D toward an advanced fourth detector that could ultimately expand DUNE's physics program."

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).

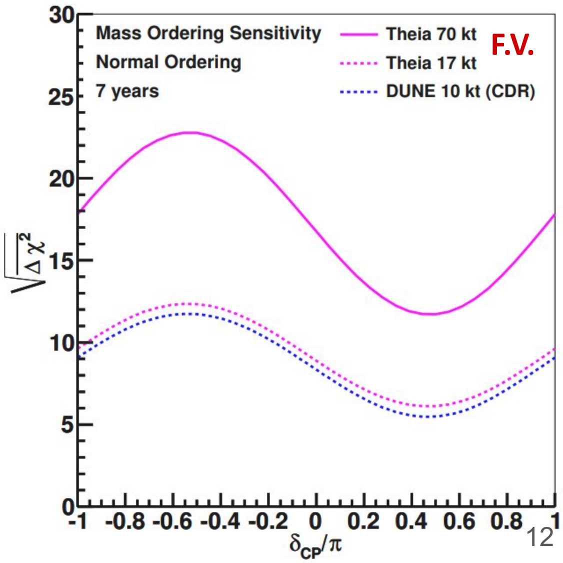
	Energy resolution at 1 GeV
DUNE	(10-20)% [arXiv:2106.04597]
T2K	2.4% (single-ring μ)

Work is ongoing on high-*E* event reconstruction & to update sensitivities.

_CP_ violation sensitivity



Mass ordering sensitivity



On the path to THEIA

There is strong international interest and active, funded R&D & demonstrators.

A suite of detectors are demonstrating technologies and techniques relevant to next-generation neutrino detectors, like Theia.

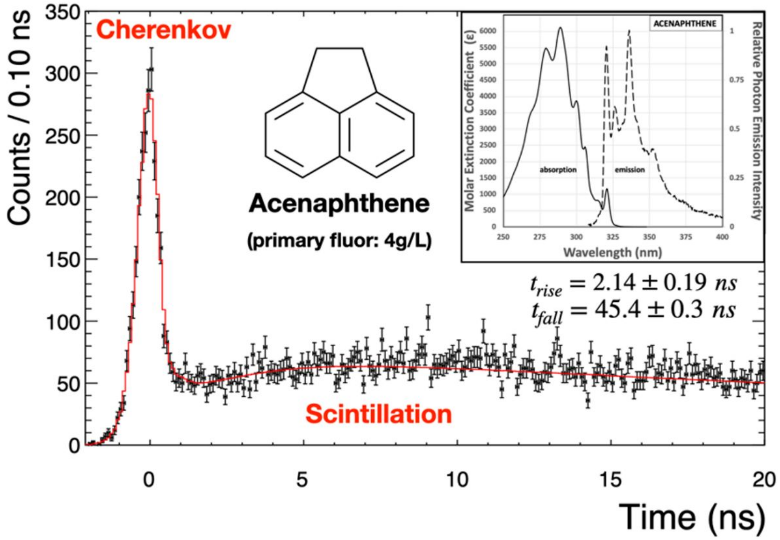
Technologies addressing the challenges of C/s discrimination:

- Timing
- Yields/Attenuation
- Wavelength

Next-generation technologies

Some specific efforts:

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

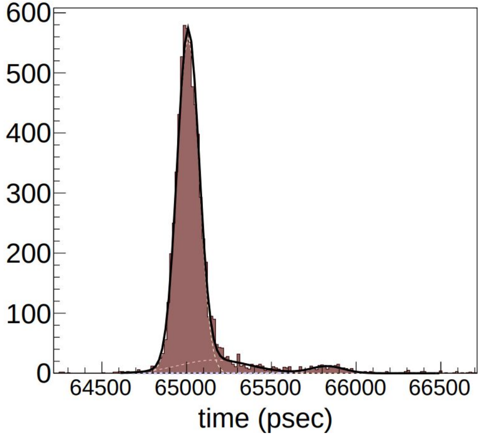


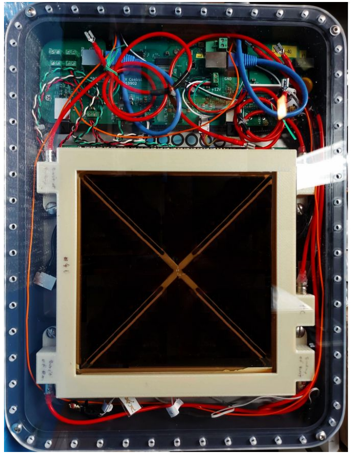
[iNSPIRE:2052358]

Next-generation technologies

Some specific efforts:

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



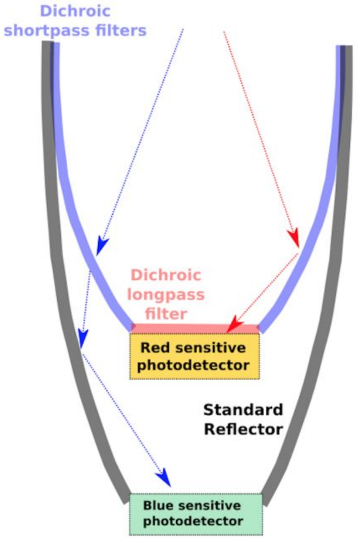


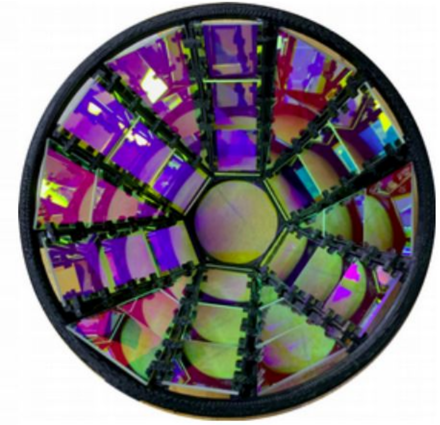
[iNSPIRE:2052358]

Next-generation technologies

Some specific efforts:

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



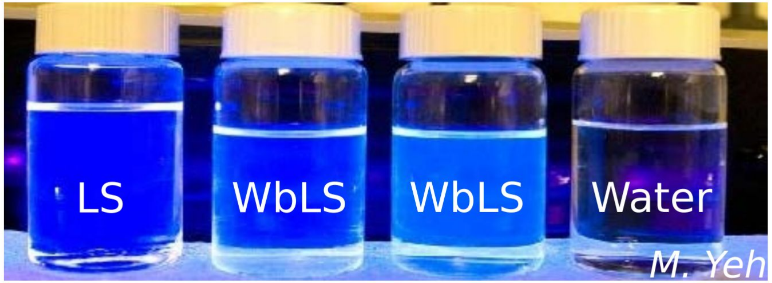


[iNSPIRE:2052358]

Next-generation technologies

Some specific efforts:

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

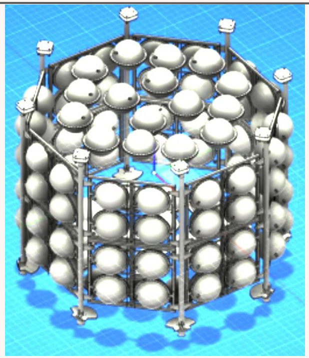


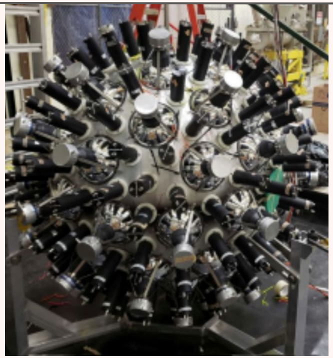
[iNSPIRE:2052358]

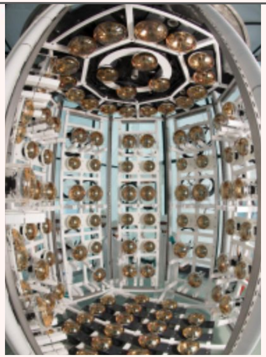
Technology demonstrators

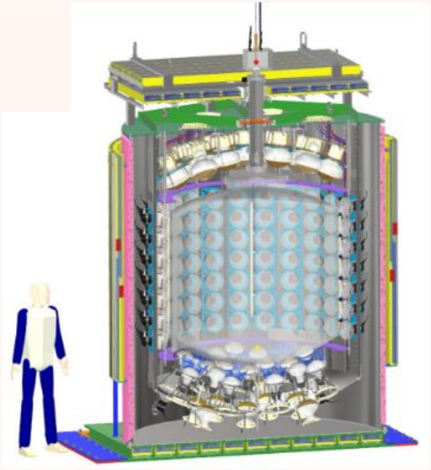
- **BNL: optics + engineering demonstrator (30 ton)**
  - Ton-scale production
  - Optical transparency in an operating detector
  - Optical stability over time
  - Recirculation of WbLS (nanofiltration)

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









- **Boulby: BUTTON**
  - Underground demonstration
  - Low background purification

Delaware: NUDOT

- Isotope loading, quantum dots
- Fast photosensors & readout

FNAL: ANNIE

- Beam deployment with LAPPDs
- High-energy neutrino event reconstruction

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 from novel scintillators for event reconstruction and analysis. [iNSPIRE:2513648]

Results are being
- interpreted in the context of nuclear nonproliferation.
- extrapolated to larger-scale detectors to inform designs.

USA

BERKELEY LAB, Penn, Lawrence Livermore National Laboratory, BOSTON UNIVERSITY, PennState, BROOKHAVEN NATIONAL LABORATORY, Fermilab, RUTGERS, IOWA, BARTOSZEK ENGINEERING, SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY, University of Colorado Boulder

Germany

JOHANNES GUTENBERG UNIVERSITÄT MAINZ, PRiSMA+, TECHNISCHE UNIVERSITÄT MÜNCHEN

Turkey

Portugal

LIP, UNIVERSIDADE D COIMBRA

Finland

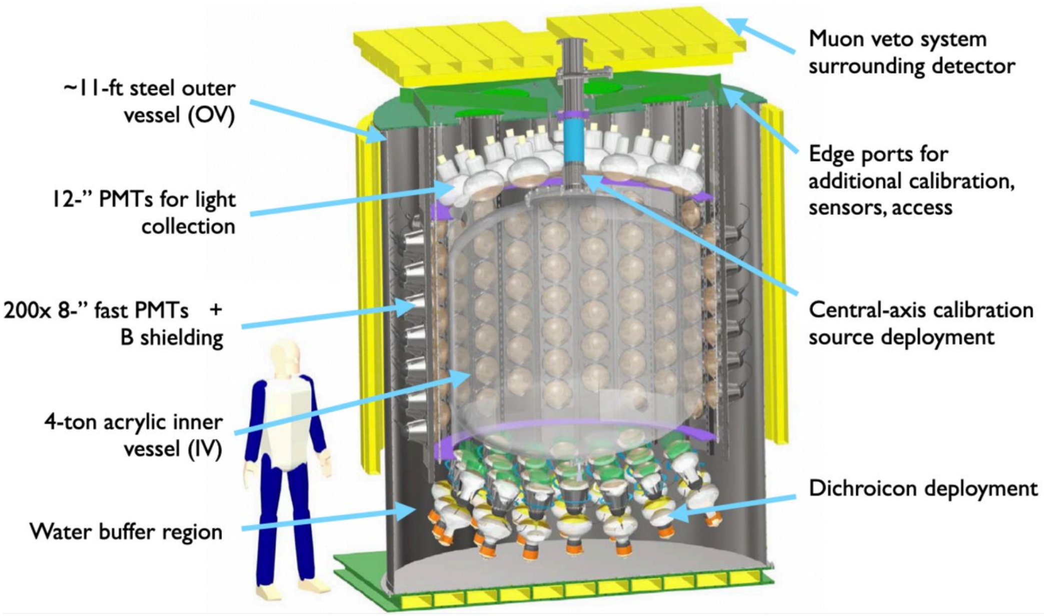
JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ

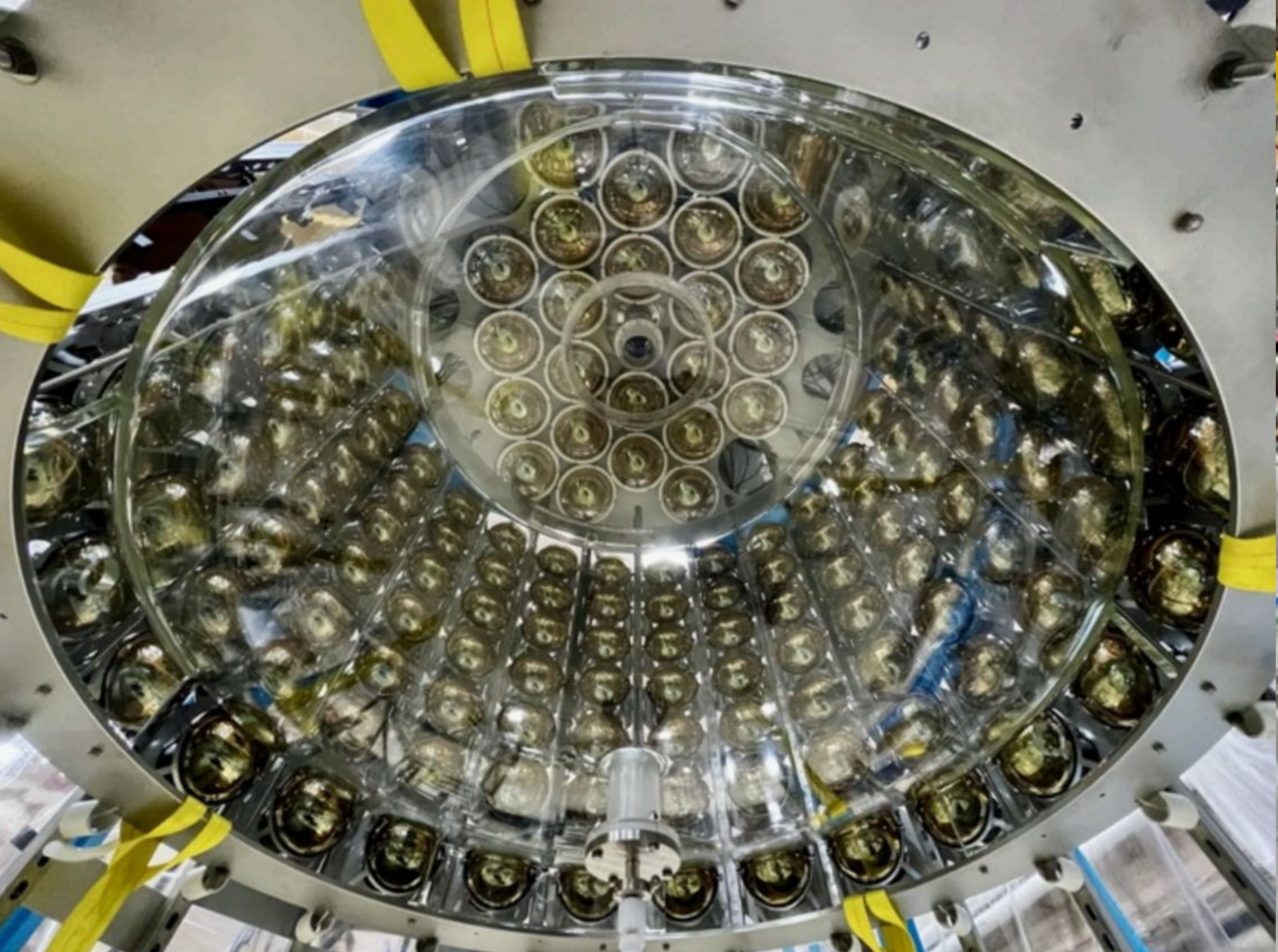
Canada

SNOLAB

Eos detector

- 20-tonne steel vessel filled with water.
- 4-tonne acrylic vessel filled with water in early 2024.
    - Currently filled 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.



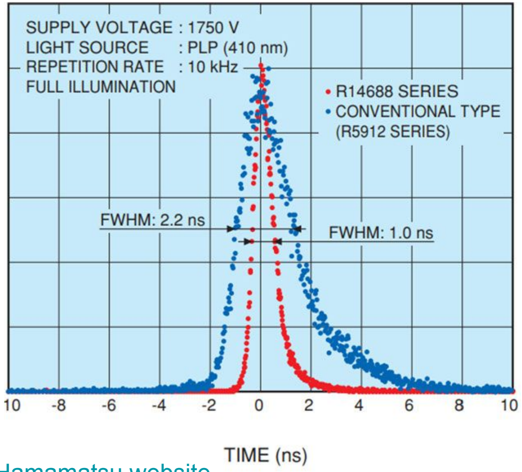


Hamamatsu R14688-100 PMTs

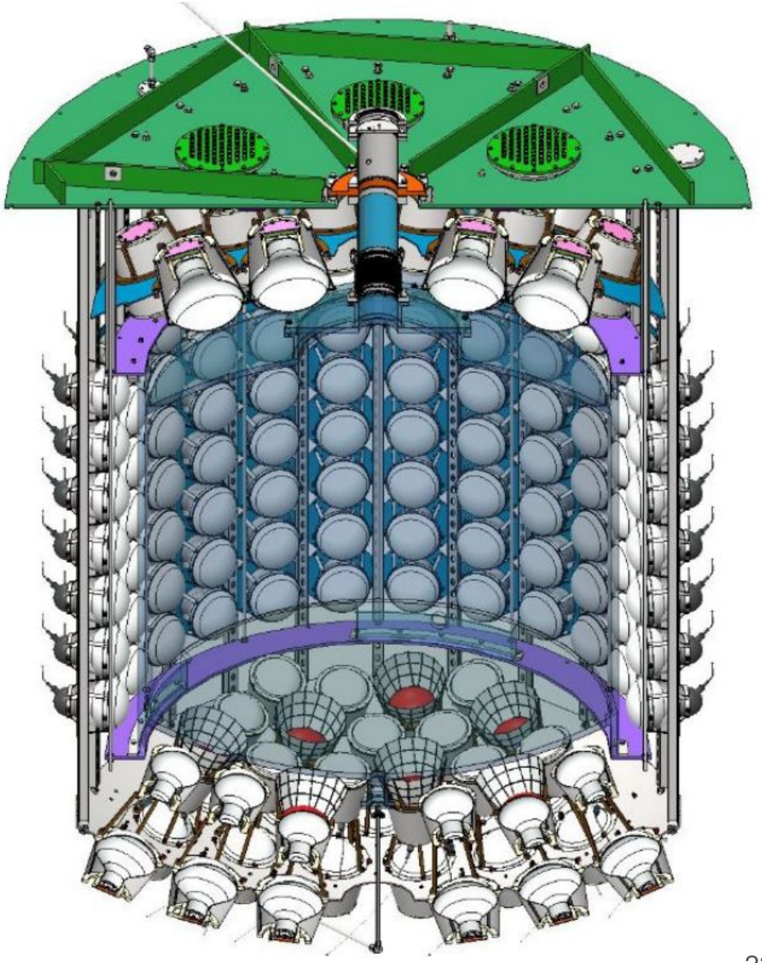
- **168 8” R14688-100 PMTs on the sides (barrel)**
- 24 12” R11780 at the top
- **36 8” R14688-100 PMTs at bottom**
- 13 10” R7081 PMTs at bottom in dichroicon array

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.

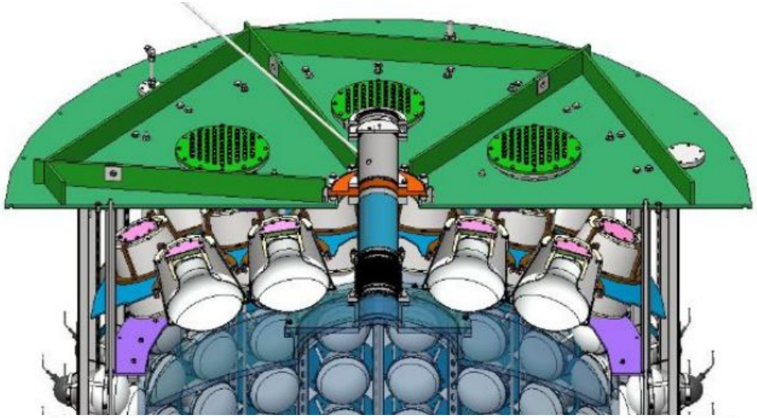


Hamamatsu website



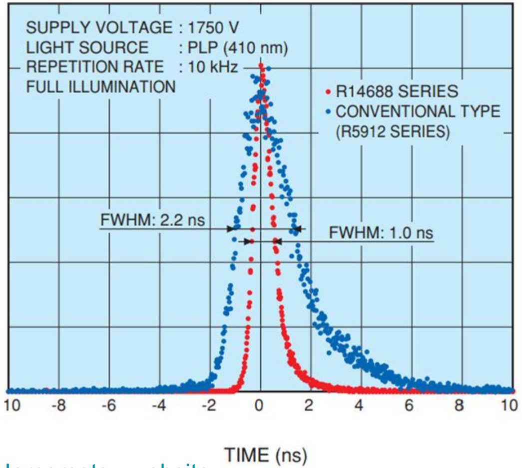
Hamamatsu R14688-100 PMTs

- **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

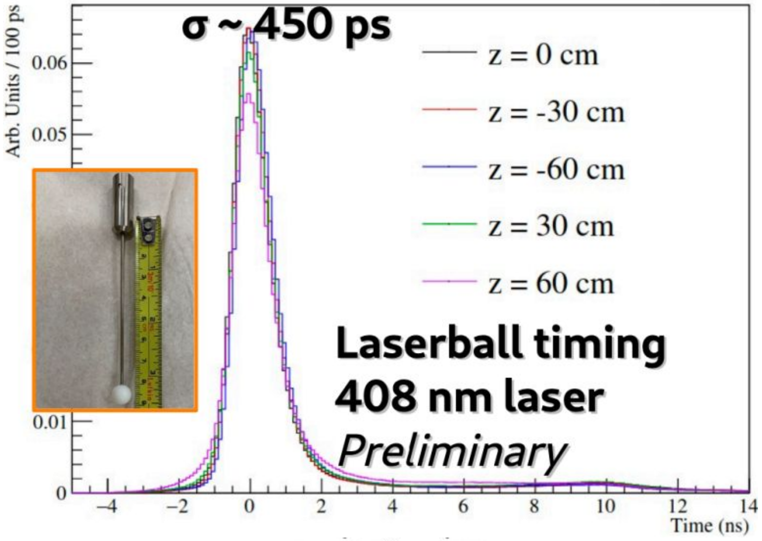


First deployed in Eos, the 204 R14688’s have been measured with a picosecond laser to have a 450-ps **σ** in transit-time.

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



Hamamatsu website

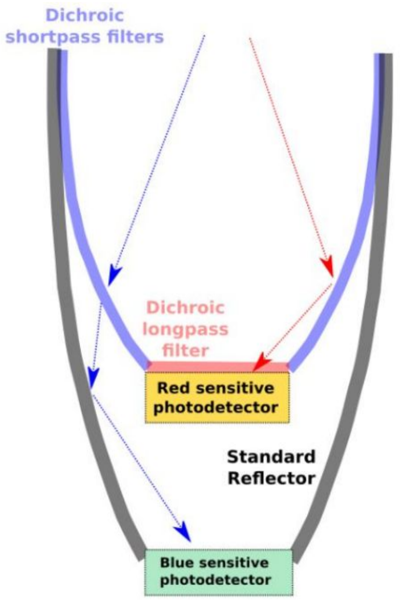


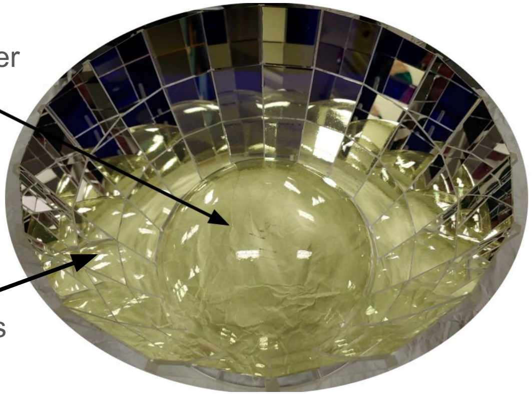
Dichroic light concentrators

Parabolic concentrators 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 transmitted scintillation light.
- The dichroic filters have a cut-on wavelength around 450 nm.
- Tuning and validating model. Will evaluate impact to reconstruction and PID.



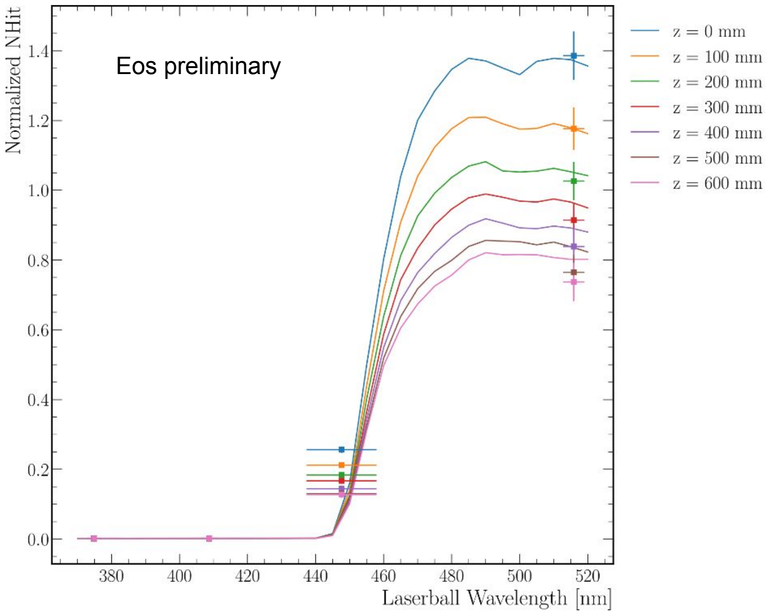


Dichroic light concentrators

Parabolic concentrators 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 transmitted scintillation light.
- The dichroic filters have a cut-on wavelength around 450 nm.
- Tuning and validating model. Will evaluate impact to reconstruction and PID.



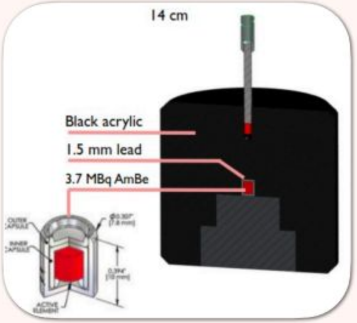
Eos calibration sources

Laserball

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

AmBe

- 4.4 MeV gamma coincident with neutron



Cosmics

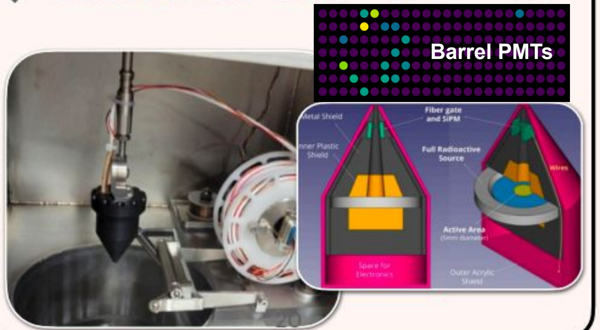
- Michel electron and neutron followers

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

Eos calibration sources - Th source

Th decay chain. Only γ's escape, dominated by the ^{208}Tl 2.6-MeV γ.

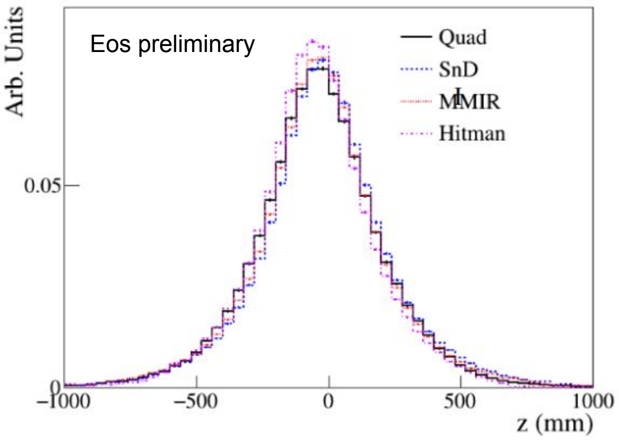
Used to study event reconstruction performance (position, direction, energy) and calibrate PMT efficiency scale.

In water, four different position reconstructions give compatible results (two are likelihood-based and one uses machine learning).

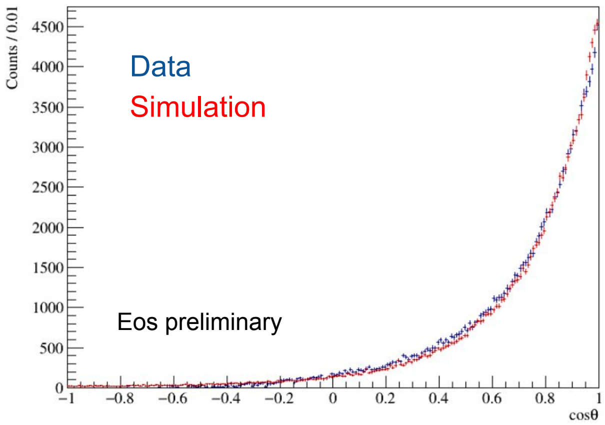
Simple direction reconstruction shows good data-MC agreement.

- $\cos\theta$ is the product of reconstructed direction and direction in which γ position is reconstructed.

Position



Direction



Eos calibration sources - directional sources

Collimated β's from ^{90}Sr (2.3 MeV) and ^{106}Ru (3.5 MeV).

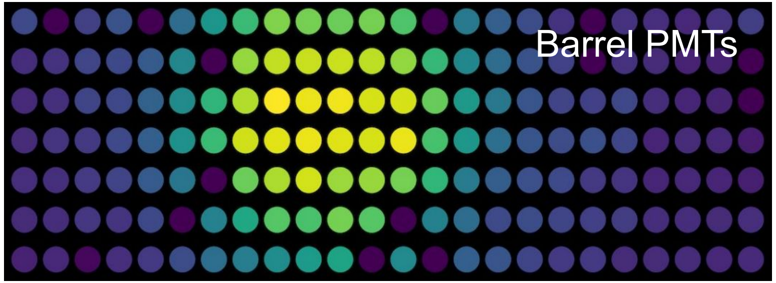
Used to study event direction reconstruction at various polar & azimuthal orientations.

- Triggering on scintillating fibers viewed by two Silicon PhotoMultipliers (SiPMs) will provide definitive evaluations of direction reconstruction in target scintilllators.

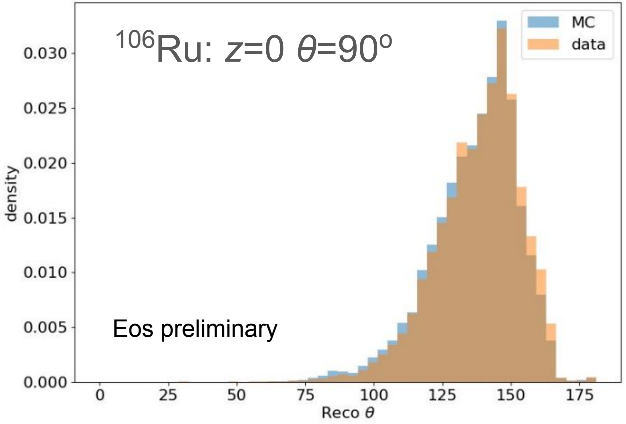
In water, directionality is clear and data-MC agreement is good.

- Reco θ is the angle between reconstructed direction and source direction.

θ=90°



Direction



Novel scintillators

The Eos detector has been characterized with a water target.

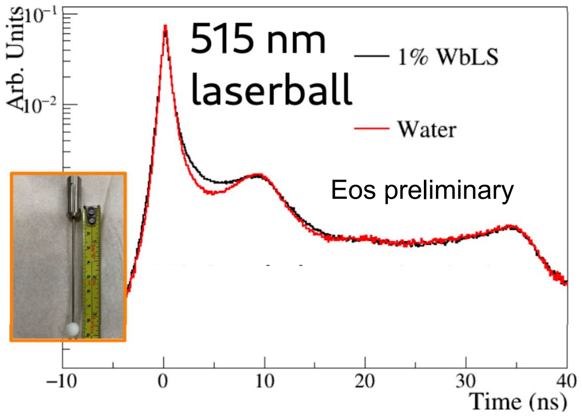
- Papers forthcoming.

Eos is currently measuring 1% water-based scintillator.

- Scintillation yield comparable to Cherenkov yield.
- Timing shows minimal change.
- New reconstruction/calibrations/sources in preparation.

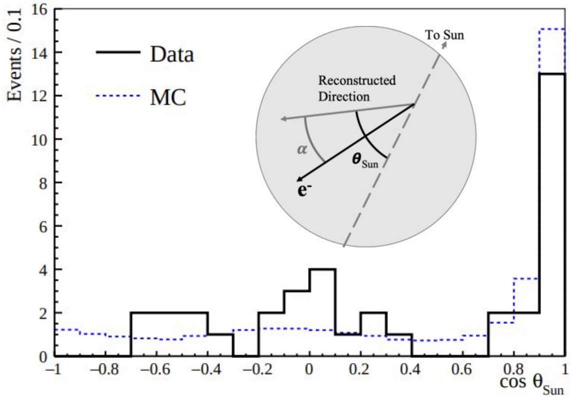
Planned scintillator deployments through 2026.

- 2% & 3% WbLS this year.
- LAB+PPO - common cocktail [0.6 g/L @ SNO+].
    - Scan concentrations of PPO to adjust scintillation timing and photon yield.
        - Slower - maximal C/s separation.
        - Faster - optimal spatio-temporal resolution.
- Possible additives (DIN, …) or deployed samples.



SNO+ LAB + 0.6 g/L PPO [iNSPIRE:2696627]

Direction of individual solar neutrinos > 5 MeV.

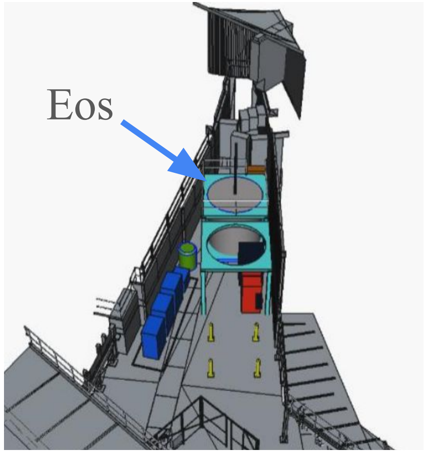


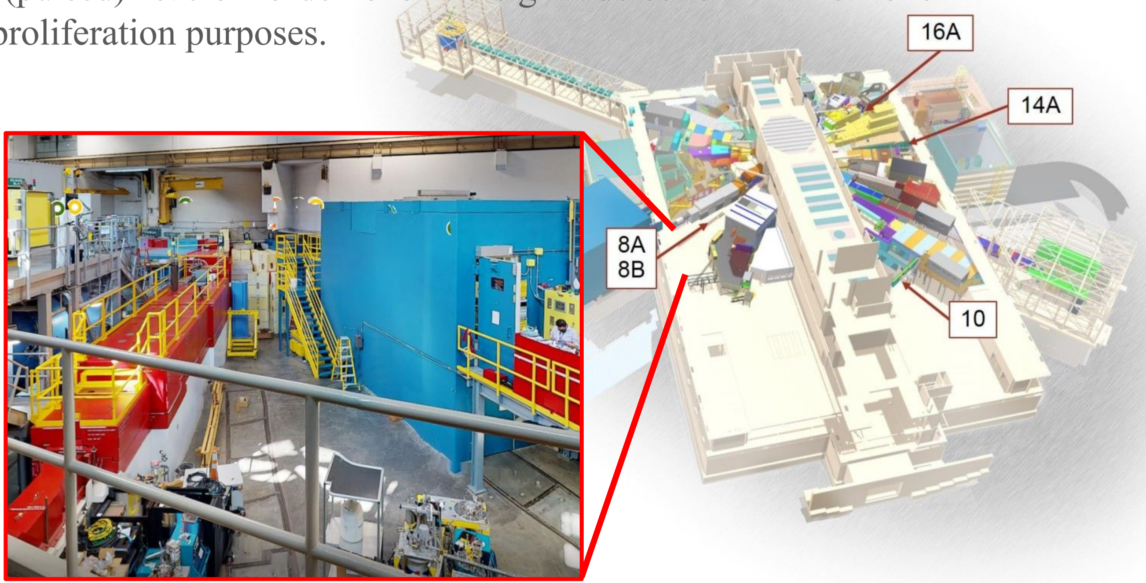
Eos at a neutrino source

Eos is investigating redeployment at the Spallation Neutron Source (ORNL) in 2027.

- Further technical demonstrations: measure low-energy neutrinos (5e7 $\nu cm^{-2}s^{-1}$ @ 10’s of MeV) with hybrid technologies, discriminate charged-currents (C, O) & elastic scatters.
- Bonus physics program: cross section measurements, BSM searches, bkg characterization.

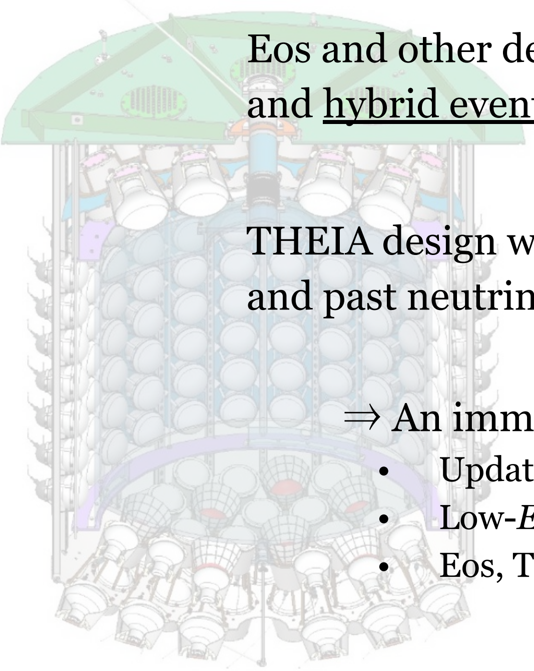
Eos could also be deployed at a (pulsed) reactor to demonstrate signal detection in a realistic background environment for nonproliferation purposes.



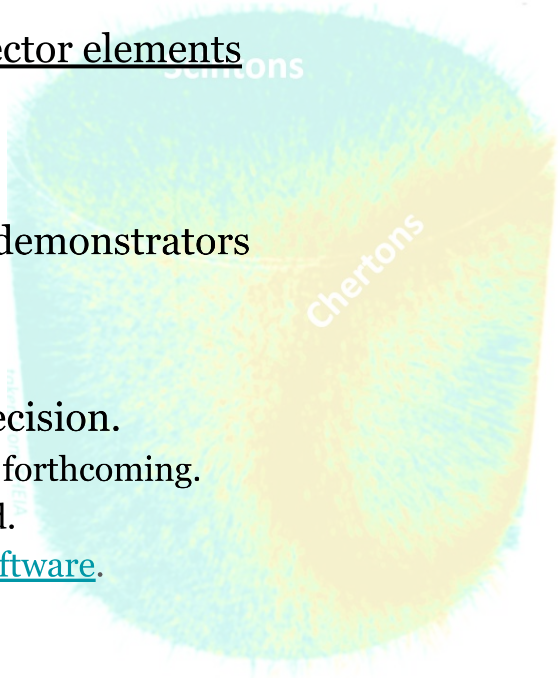


Outlook

Eos



THEIA



Eos and other demonstrators are characterizing <u>novel detector elements</u> and <u>hybrid event reconstruction</u>.

THEIA design work is ongoing based on input from these demonstrators and past neutrino experiments.

THEIA at SNOLAB

$\Rightarrow$ An immense physics program of discovery and precision.

- Updates on high-*E* reconstruction and sensitivities are forthcoming.
- Low-*E* and Simulation working groups recently created.
- Eos, Theia, and others use & develop the ratpac-two software.

Cherenkov detectors

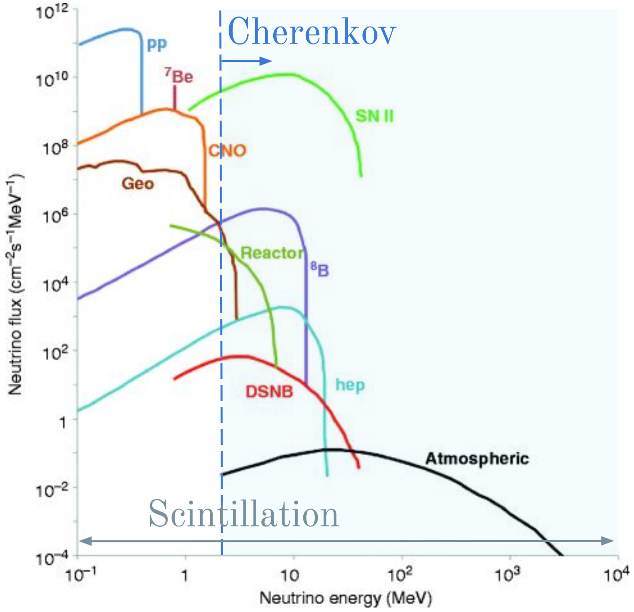
Neutrino oscillations were first observed with atmospheric and solar neutrinos in water Cherenkov detectors [SK, SNO].

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].

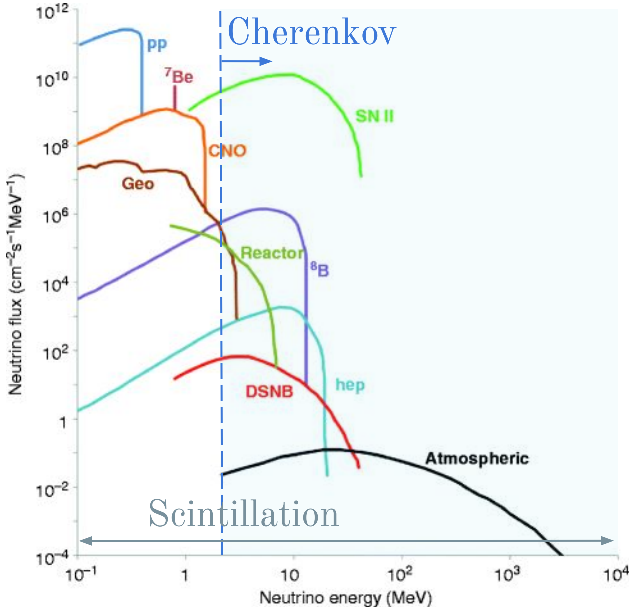
The most sensitive search for $0\nu\beta\beta$ uses scintillation in LXe [KamLAND-Zen].

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.

iNSPIRE:1090322



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

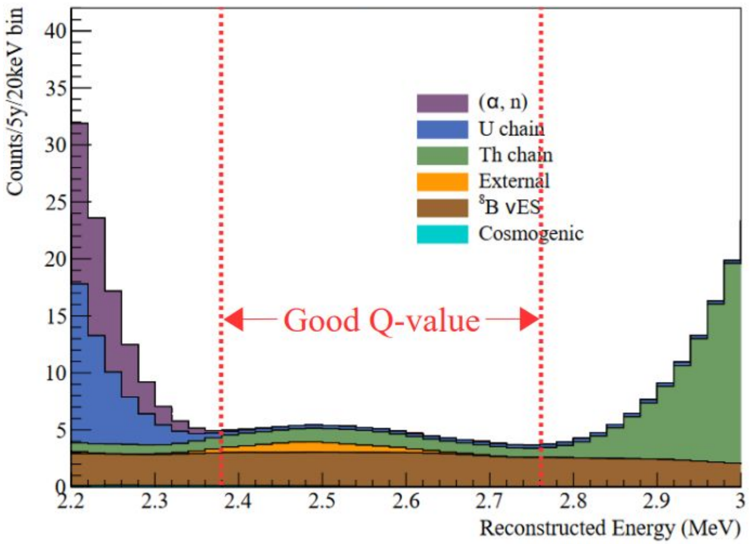
Primary Physics Goal	Reach	Exposure / assumptions
Long-baseline oscillations	$> 5\sigma$ for 30% of δ_{CP} values	524 kt-MW-yr
Supernova burst	$< 1(2)^\circ$ pointing accuracy	100(25)-kt detector, 10 kpc
	20,000 (5,000) events	
DSNB	5σ discovery	125 kton-yr
CNO neutrino flux	< 5 (10)%	300 (62.5) kton-yr
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

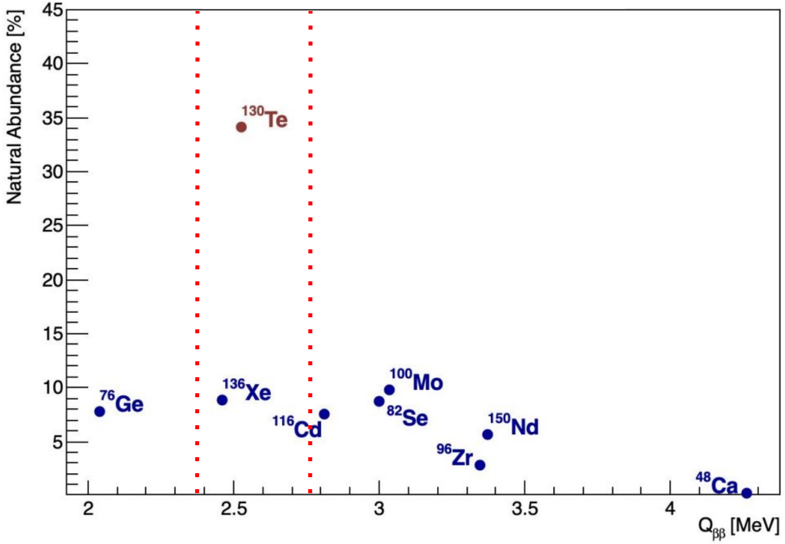
$2\nu\beta\beta$ decay in scintillator

Select a $2\nu\beta\beta$-decay isotope with a favorable endpoint energy.

Backgrounds (SNO+)



$2\nu\beta\beta$-decay isotopes

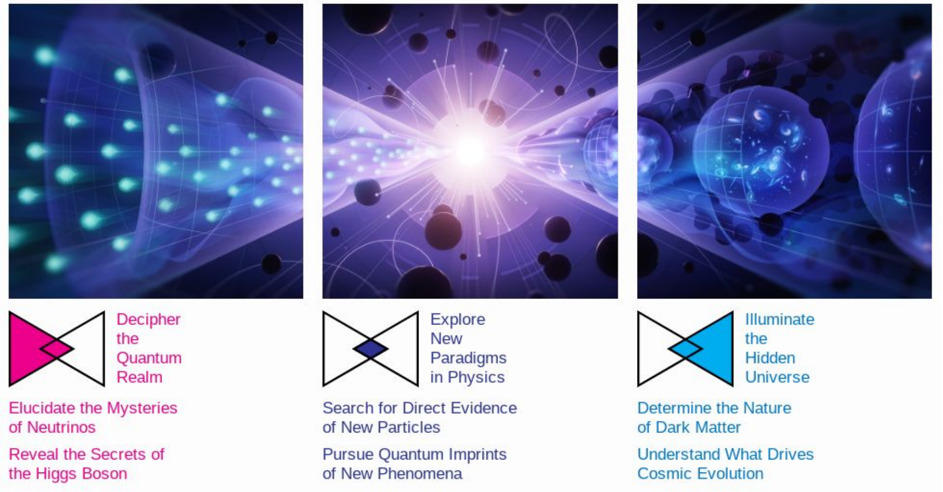


P5 recommendations

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.”



Eos calibration sources (2)

Other analyses underway and sources under development

- external PuBe
- muons
- laser pointers
- tagged Th
- camera