$0\nu\beta\beta$ into the normal ordering with Theia

Berkeley
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for the Theia collaboration

BERKELEY LAB

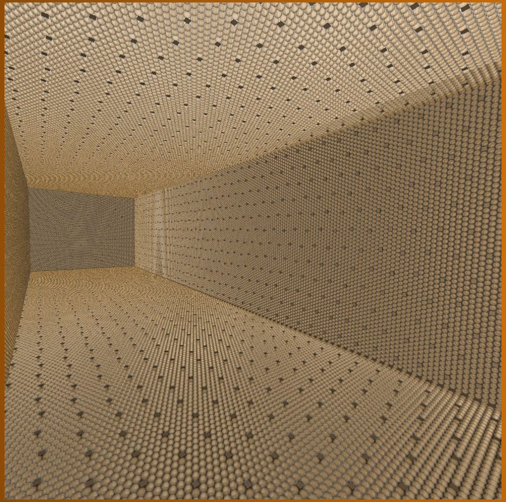
ENT½ENTE
Extreme Nuclear Half-Life Efforts: New Theories and Experiments

Sudbury, Ontario Sep. 30, 2025

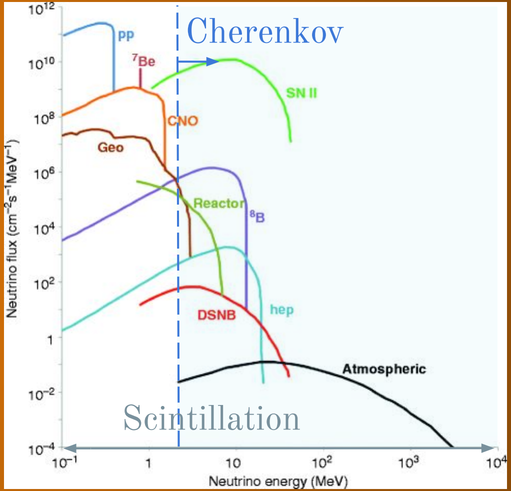
THEIA

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

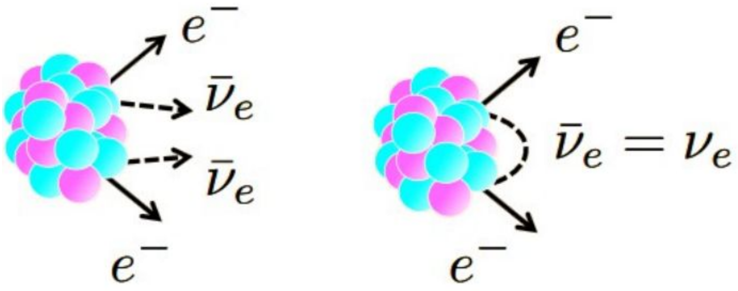


Theia received Gateway-0 approval at SNOLAB, which provides P.M. & eng. support to initiate concept. design.

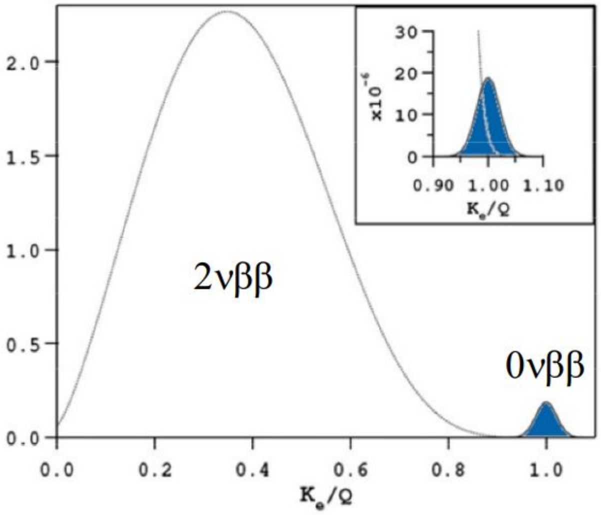
Planned visit to SURF Dec'25 to discuss initiating a similar effort. Potential for private funding.

$0\nu\beta\beta$ decay

Neutrinoless double beta decay would violate lepton number conservation, and could occur if neutrinos are Majorana particles.



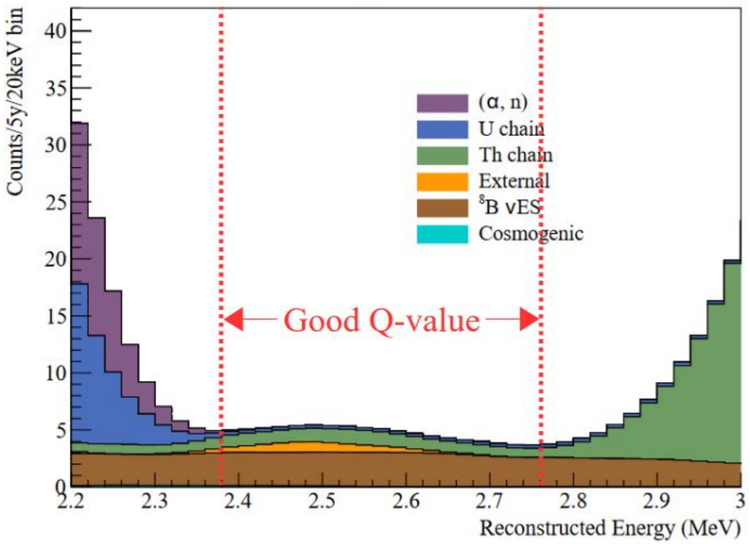
beta decay: $n \rightarrow p + e^- + \overline{\mathbf{v}}_e$



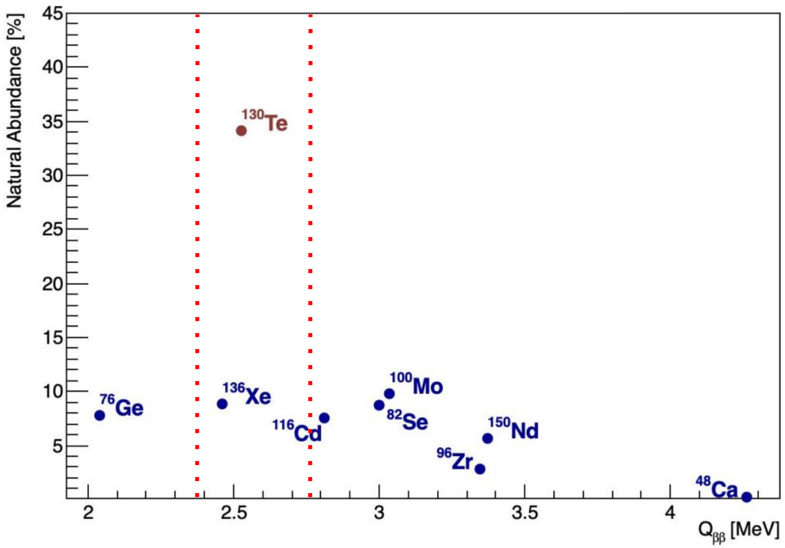
$2\nu\beta\beta$ decay in scintillator

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

Backgrounds (SNO+)



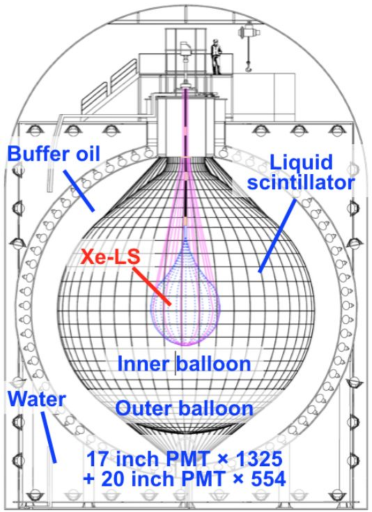
$2\nu\beta\beta$-decay isotopes



$0\nu\beta\beta$ search - KamLAND-Zen 800

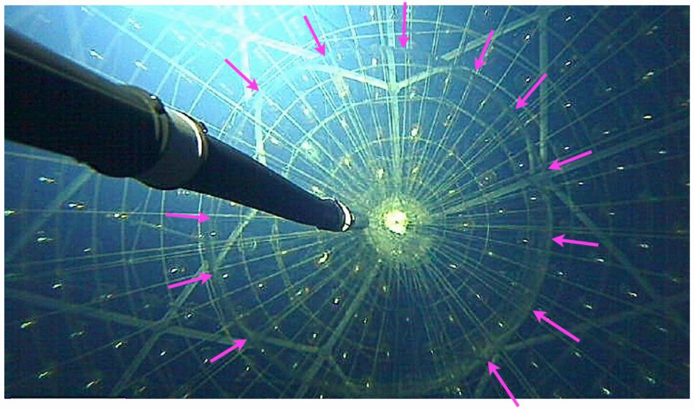
Located in the Kamioka Observatory, Japan, KamLAND-Zen augments the KamLAND detector with a Xe-LS-filled balloon to search for $0\nu\beta\beta$.

Has produced the most sensitive $0\nu\beta\beta$ search to-date.



Mass	1 kton (total), 745 kg (^{136}Xe)
Scintillator	0.82 decane + 0.18 PC + 2.4 g/L PPO + 3.13% Xe
Energy Resolution	6.7% @ 1 MeV
Overburden	1.0 km (~20,000 μ/day)

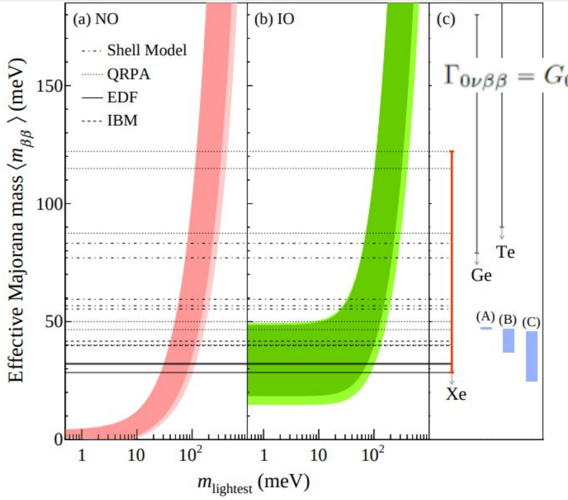
*The mini-balloon, indicated by arrows, is 3.1m in diameter.



Tohoku Univ.

0νββ decay rate is proportional to the square of the effective Majorana neutrino mass $\langle m_{\beta\beta}\rangle \equiv |\Sigma_i U^2_{ei} m_{\nu i}|$.

KamLAND-Zen 800



$$\Gamma_{0\nu\beta\beta} = G_{0\nu} \left|\mathcal{M}_{0\nu}\right|^2 \left|m_{\beta\beta}\right|^2$$

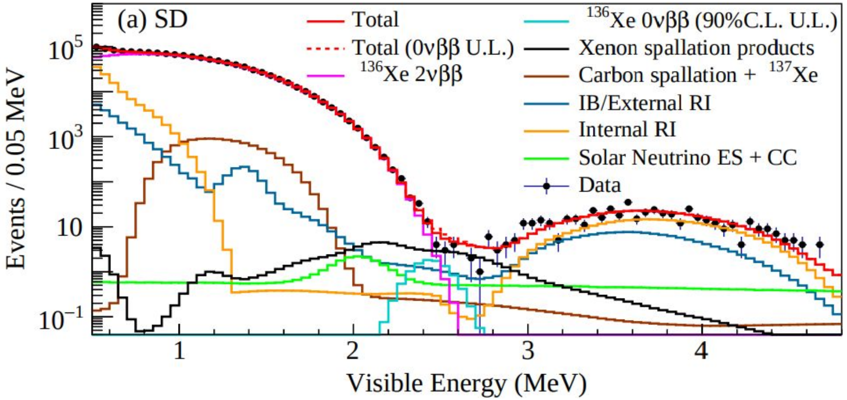
With 745 kg of ^{136}Xe, the 2.1 ton-yr exposure leads to a lower limit for the half-life;

$$T^{0\nu}_{1/2} > 3.8 \times 10^{26} \text{ yr (90\% C.L.).}$$

This half-life corresponds to a range of upper limits on effective Majorana neutrino mass; 28-122 meV.

Limited by cosmogenic spallation backgrounds.

KamLAND2-Zen will use 1 ton of Xe with several detector upgrades, and is scheduled to start in 2027.



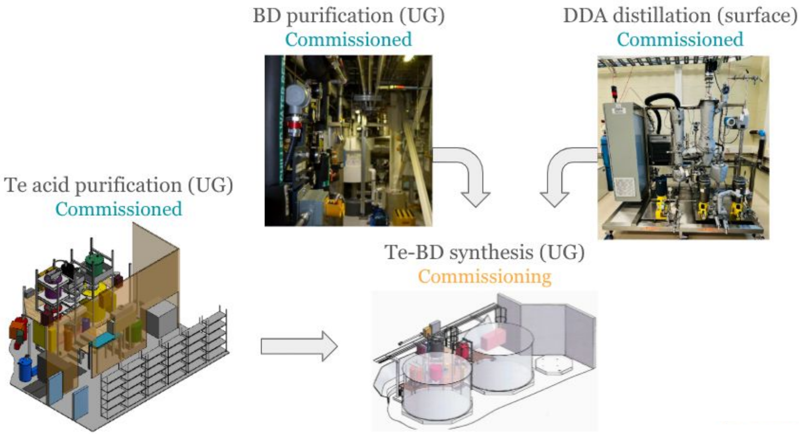
[iNSPIRE:2799242]

$0\nu\beta\beta$ search - SNO+

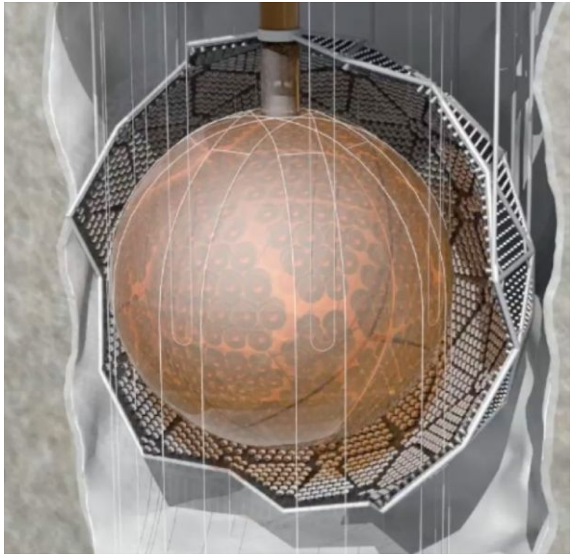
Located in SNOLAB, Canada, SNO+ repurposes the SNO detector to use Te-loaded LS to search for $0\nu\beta\beta$.

- This approach allows all detector and scintillator backgrounds to be characterized prior to isotope deployment.

$0\nu\beta\beta$ phase planned to start in 2026.



Mass	0.78 ktons (total), 1.3 tons (^{130}Te)
Scintillator	LAB + PPO (2.2 g/L) + bis-MSB (2.2 mg/L) + {^{nat}Te(0.5%)-ButaneDiol + DDA(0.2%)}
Energy Resolution	≈7% @ 1 MeV
Overburden	2.0 km (~70 μ/day)



SNO+ sensitivities

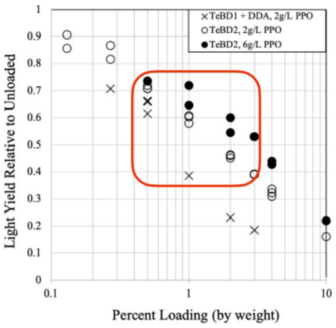
Initial 0.5% Te

A 3-year counting analysis of 1330 kg of ^{130}Te yields $T^{0\nu}_{1/2} > 2 \times 10^{26}$ yr (90% C.L.).

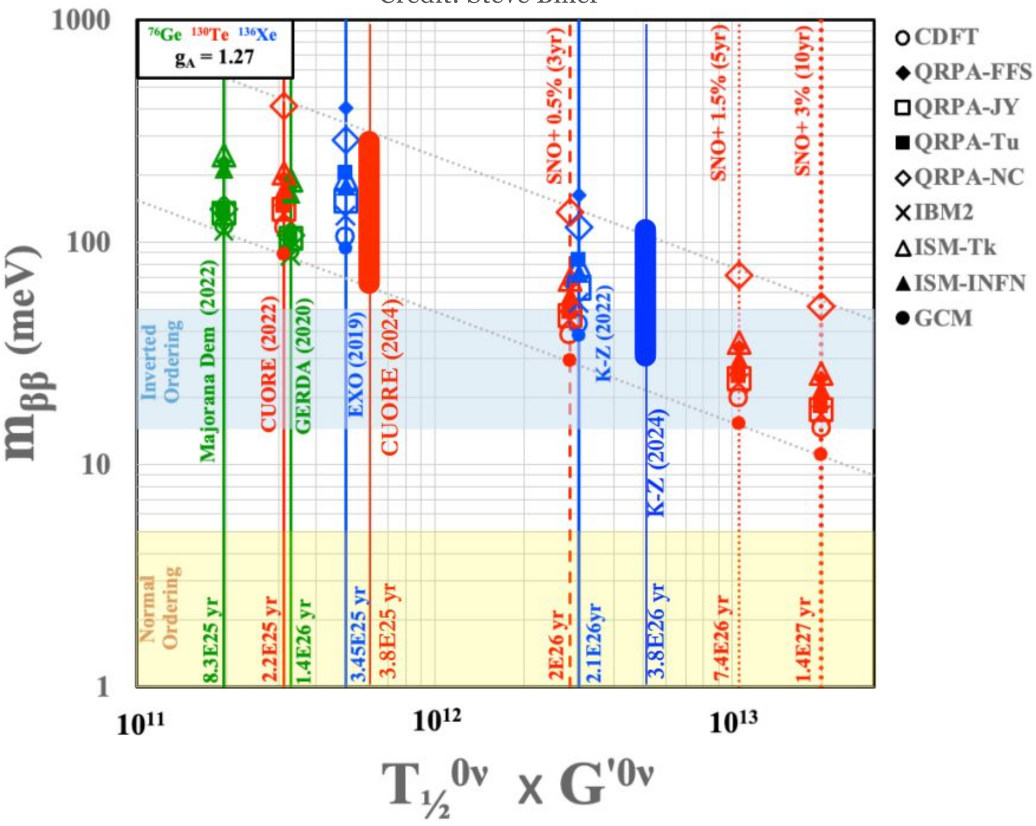
Later 1.5% Te

A 5-year counting analysis of 4000 kg of ^{130}Te yields $T^{0\nu}_{1/2} > 7.4 \times 10^{26}$ yr (90% C.L.).

R&D has shown that Te loading can be increased.



Credit: Steve Biller



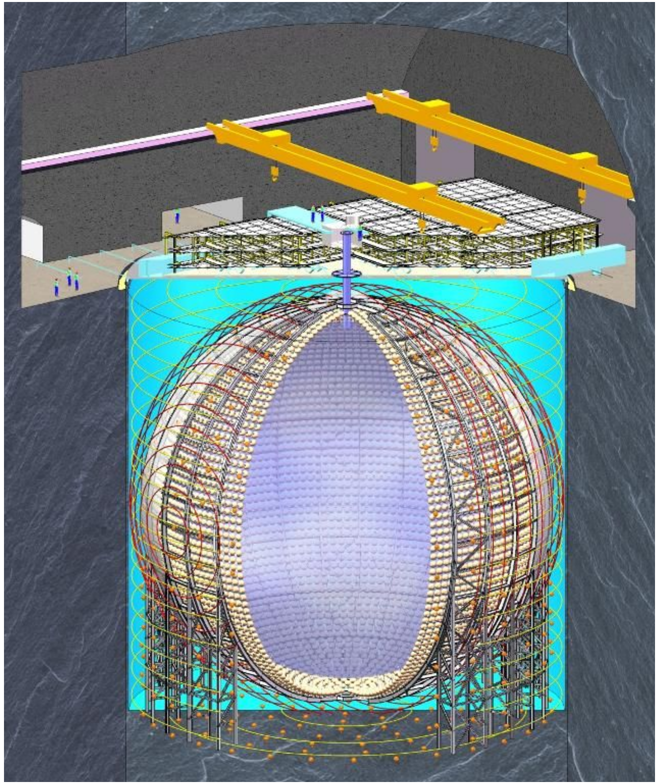
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}|M^{0\nu}|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2 \qquad m_{\beta\beta} = \left|\sum_{k=1}^{3} m_k U_{ek}^2\right|$$

JUNO

Located in Guangdong, China, JUNO is the largest scintillator detector to-date. Began taking data Aug. 2025.

- JUNO will make the most precise measurements of several neutrino oscillation parameters using reactor neutrinos and attain leading sensitivities in studies of neutrinos from various sources.
- JUNO is also actively investigating a future $0\nu\beta\beta$ phase.

Mass	20 ktons
Scintillator	LAB + PPO (2.5 g/L) + bis-MSB (3 mg/L)
Energy Resolution	3.0% @ 1 MeV
Overburden	0.70 km (~350,000 μ/day)



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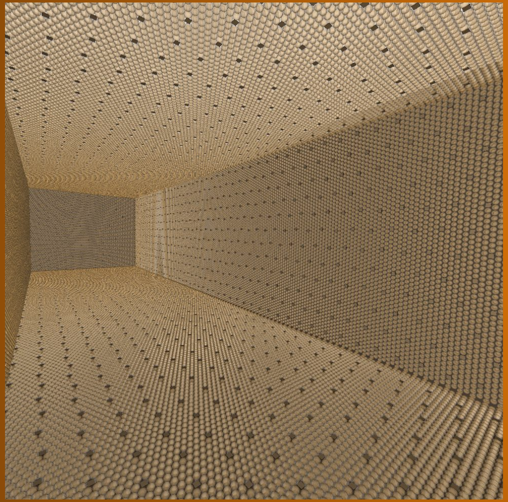

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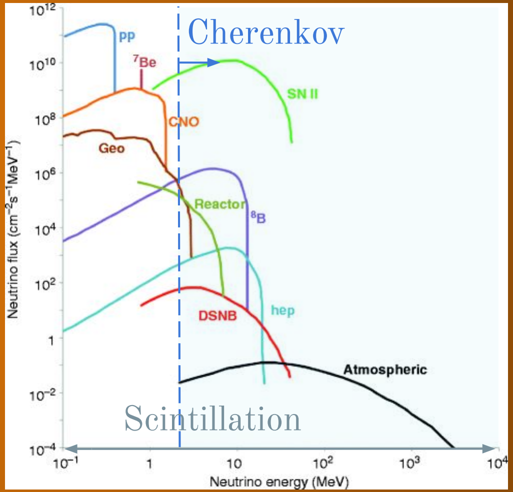

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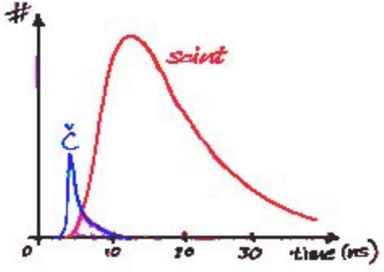
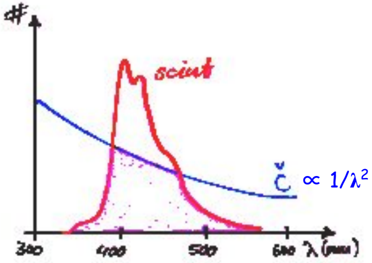
Cherenkov + Scintillation

Cherenkov and scintillation photons are distinguishable via

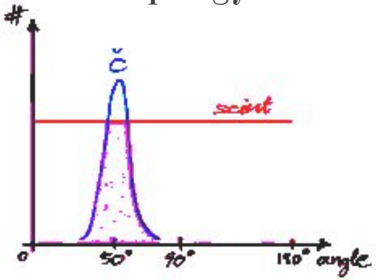
Time



Wavelength



Topology



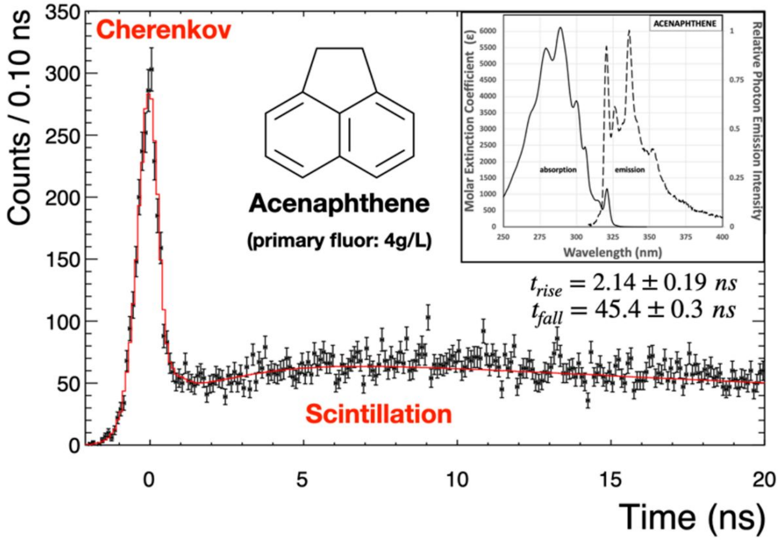
Technologies being developed and demonstrated:

- 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.

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]

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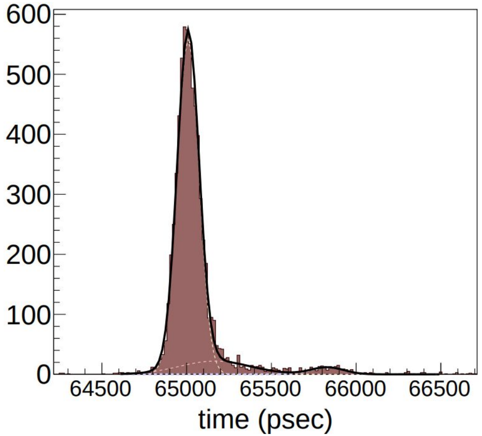

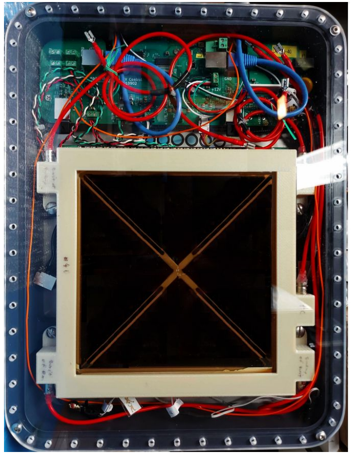

[iNSPIRE:2052358]

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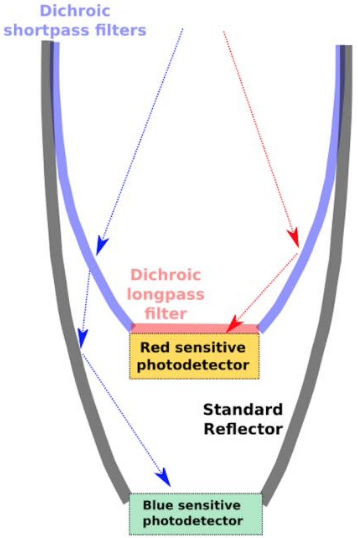

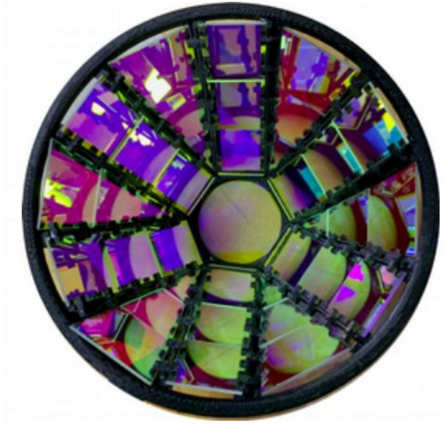

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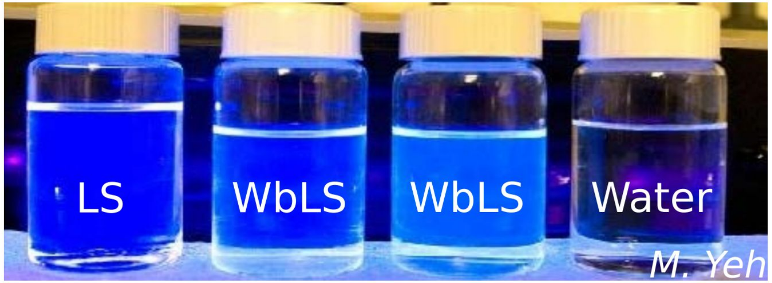
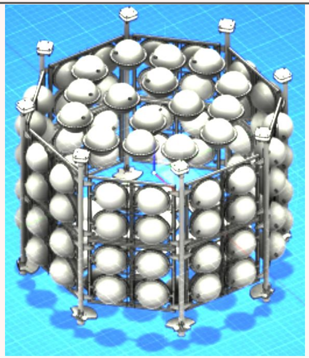


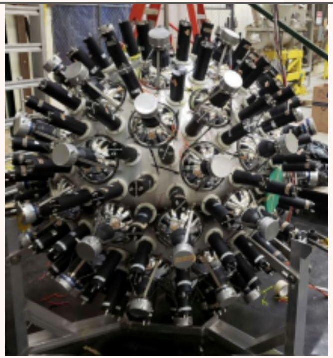
[iNSPIRE:2052358]

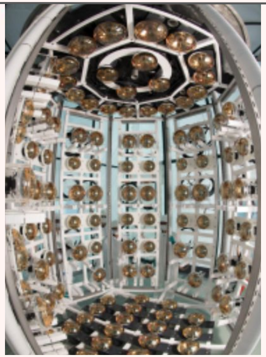
Technology demonstrators

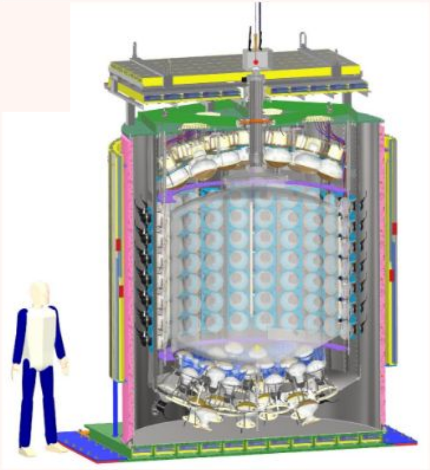
- **BNL: optics + engineering demonstrator (30 ton)**
  - Ton-scale production
  - Optical transparency in an operating detector
  - Optical stability over time
  - Recirculation of WbLS (nanofiltration)

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









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

Delaware: NUDOT

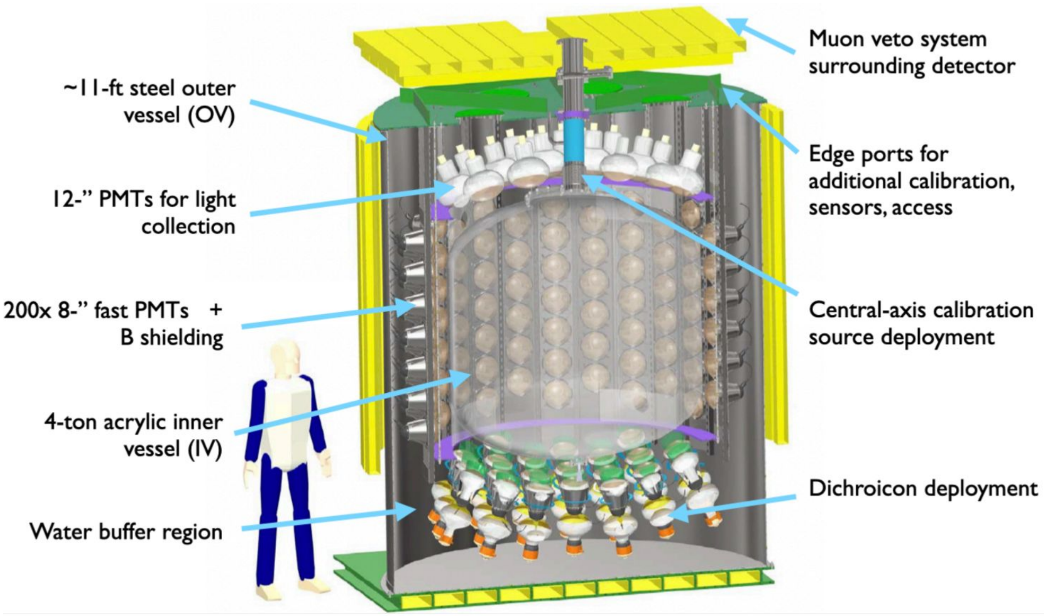
- Isotope loading, quantum dots
- Fast photosensors & readout

FNAL: ANNIE

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

Eos 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.

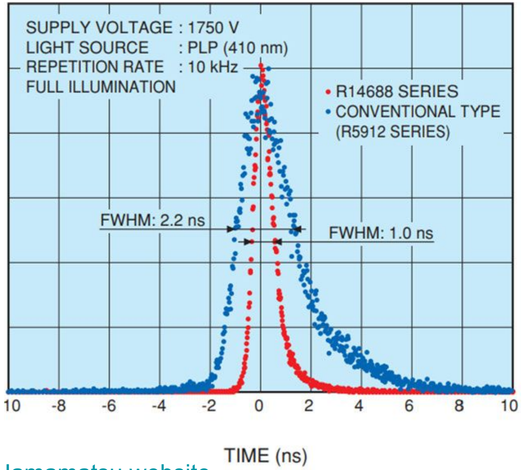


Hamamatsu R14688-100 PMTs

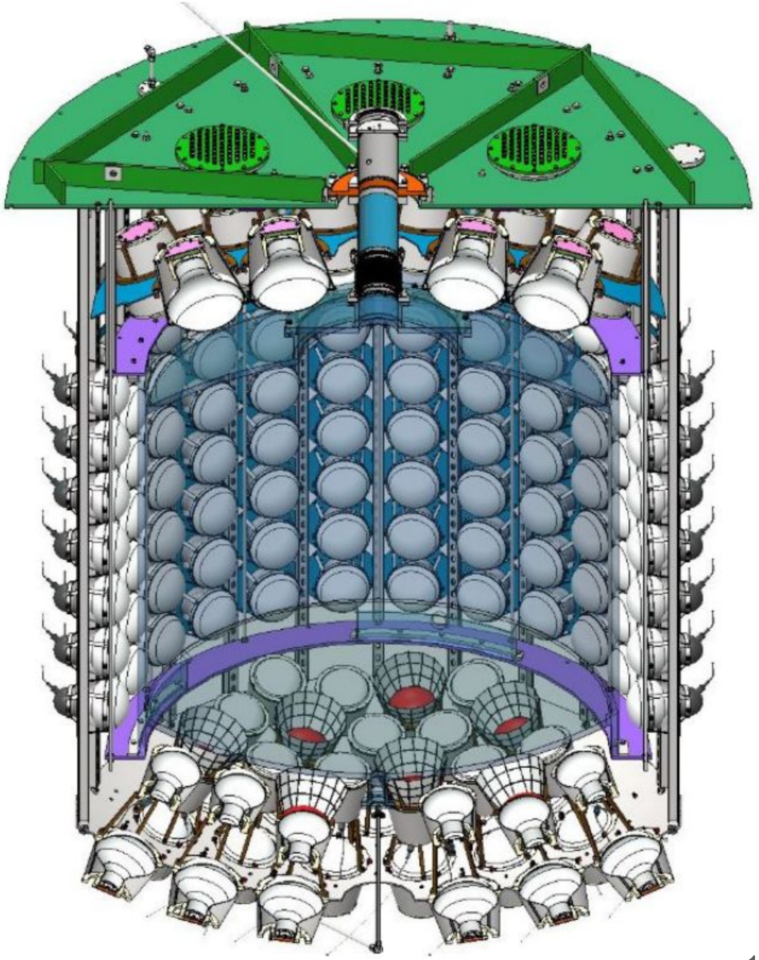
- **168 8” R14688-100 PMTs on the sides (barrel)**
- 24 12” R11780 at the top
- **36 8” R14688-100 PMTs at bottom**
- 13 10” R7081 PMTs at bottom in dichroicon array

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.

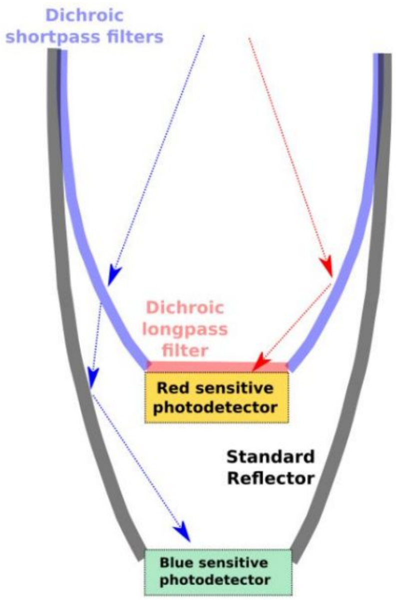


Hamamatsu website



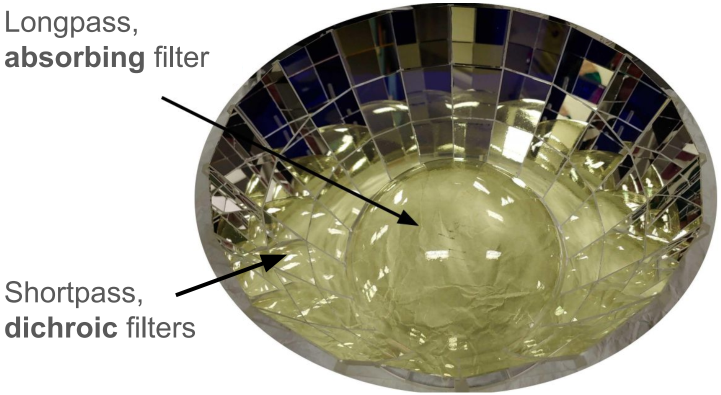
Dichroic light concentrators

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.



Novel scintillators

Eos is currently measuring 1% water-based scintillator.

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

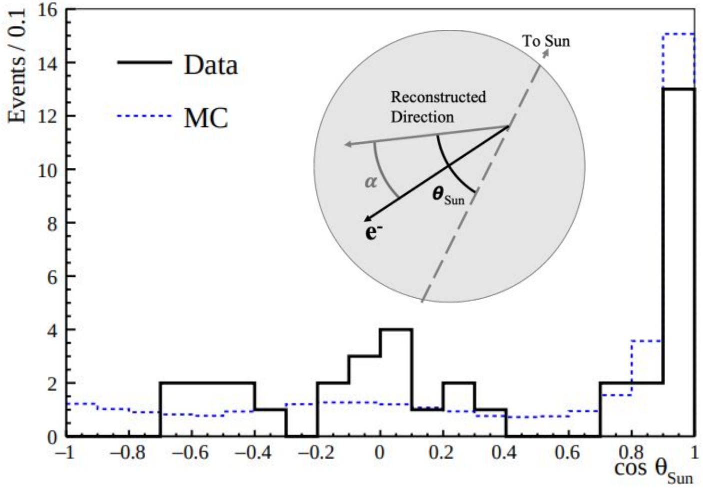
Planned scintillator deployments.

- 2% & 3% WbLS this year.
- LAB+PPO - common cocktail [0.6 g/L @ SNO+].
- Slow scintillator - maximal C/s separation by timing.
- Fast scintillator - optimal spatio-temporal resolution.

SNO+ LAB + 0.6 g/L PPO

Direction of individual solar neutrinos > 5 MeV.

[iNSPIRE:2696627]



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.

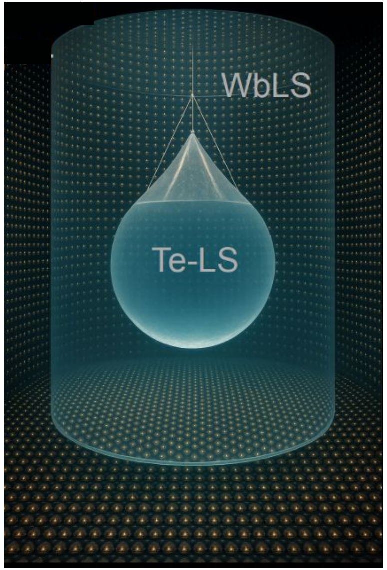
Primary physics goal	Reach	Context
Nucleon decay $p \to \nu K^+$ ($\to 3\nu$)	T>1.1 x 10^{34} yrs (T>1.2 x 10^{32} yrs)	Complementary to DUNE, HK, JUNO (sensitive to different modes)
Supernova burst	2° pointing, 5k events (10 kpc)	Complementary to DUNE (ν vs. anti-ν) Improved flavour separation via Cher/scint
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)

$0\nu\beta\beta$ search
Theia

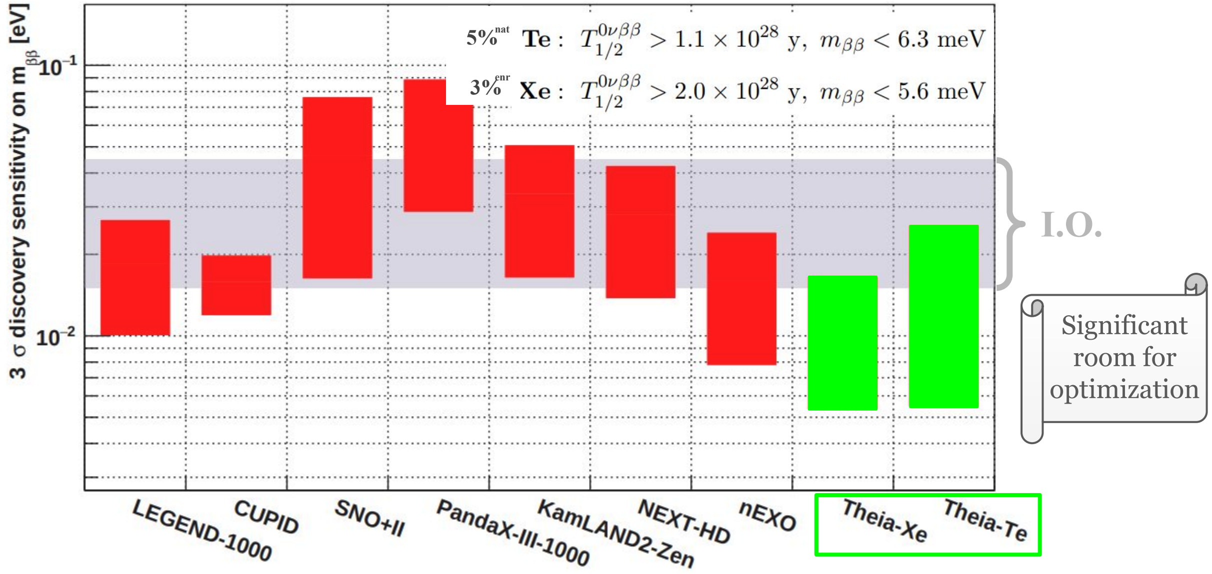
KamLAND-Zen & SNO+ approaches provide high isotope mass and:

- Background fiducialization, characterization before loading, and filtering.
- Isotope can be scaled, removed, enriched, or depleted (in-situ confirmation of signal).

Example concept:

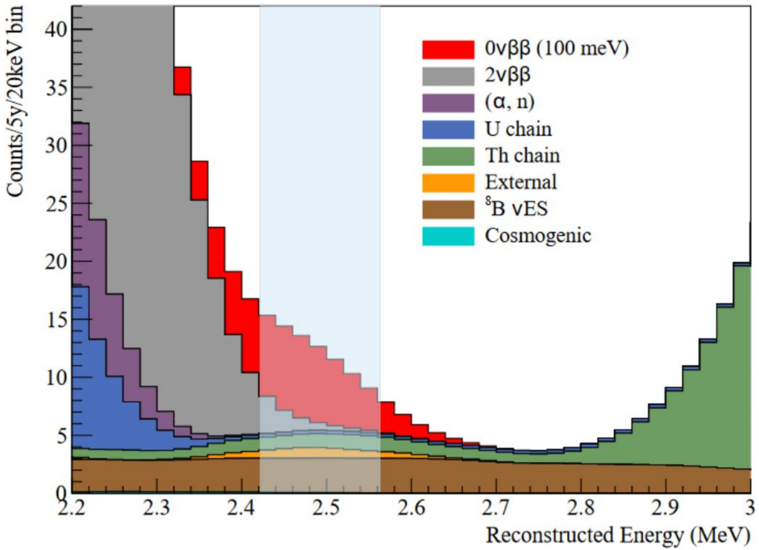


THEIA 100 kt for 10 years



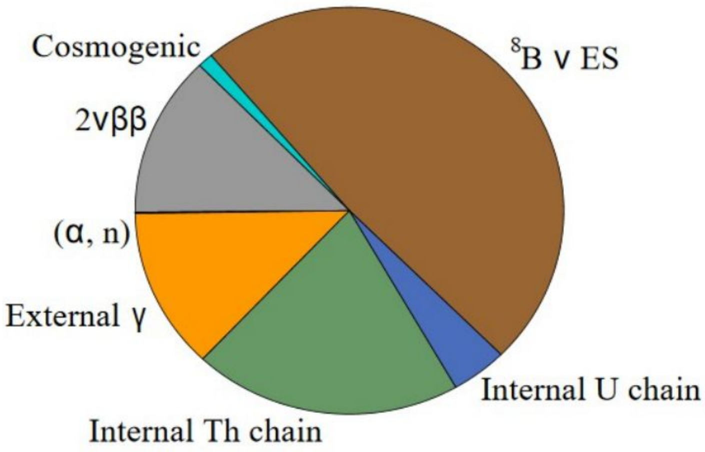
$0\nu\beta\beta$ search with 0.5% Te in SNO+

Looking for **$0\nu\beta\beta$ events** at the endpoint of the **double beta decay spectrum**.



Backgrounds

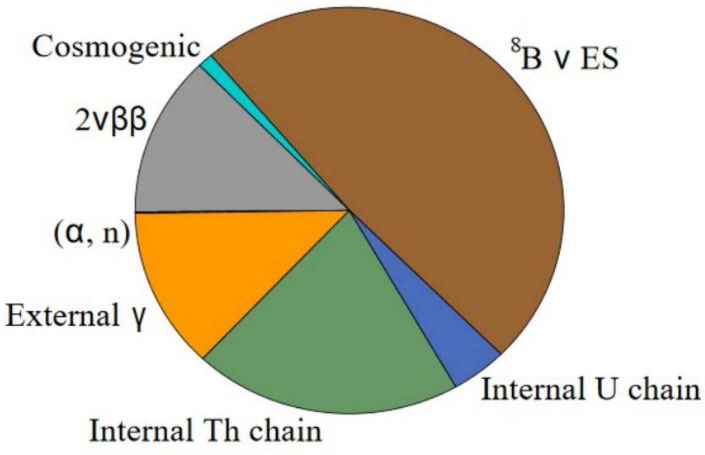
ROI: 2.42-2.56 MeV [-0.5σ - 1.5σ], 3.3 m FV, 9.47 counts/yr.



$0\nu\beta\beta$ backgrounds - handles in Theia

- Cherenkov directionality discriminates on directional sources/backgrounds.
- C/s and improved multisite discrimination will further improve sig./bg.

Directionality from Cherenkov:
solar ν, external bgs., multi-particle decays.



Cherenkov/scintillation ratio:
$\beta/\gamma/n(p)/\alpha$ discrimination.

Improved timing resolution (PSD, multi-site D):
$\beta/\gamma/n(p)/\alpha$, multi-particle decays.

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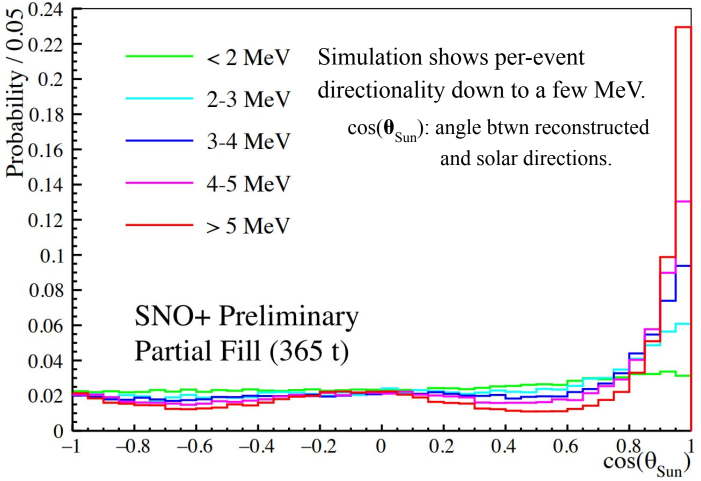
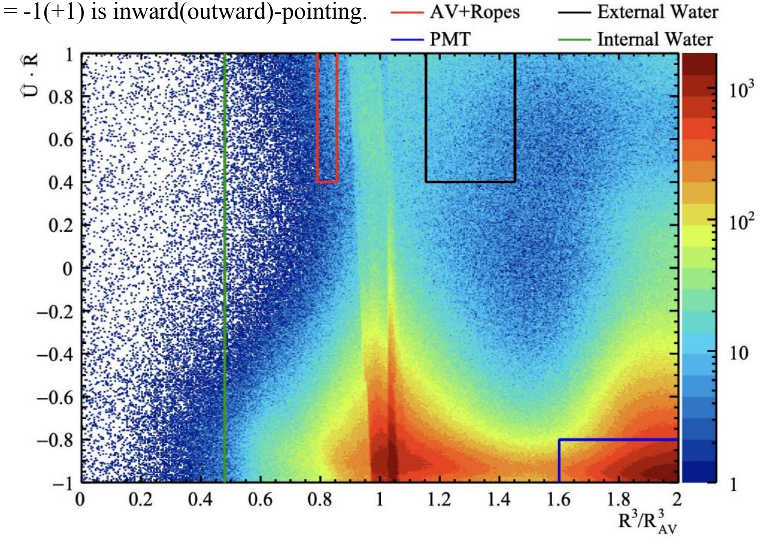


SNO+ discriminated on external backgrounds by their inward-pointedness.
U·R = -1(+1) is inward(outward)-pointing.



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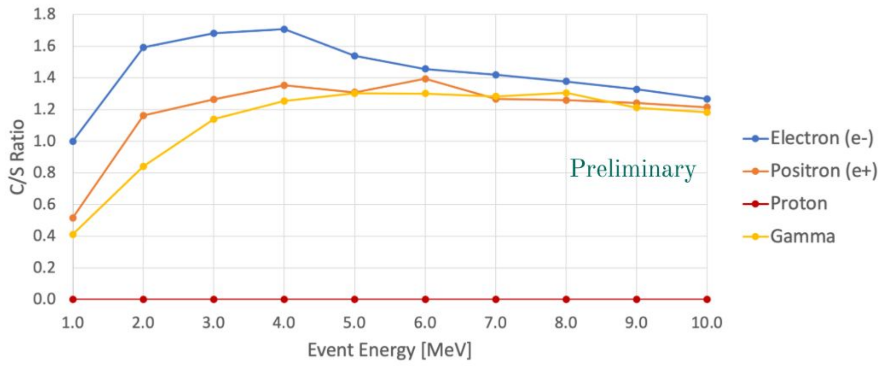
Example in LAr

Cher. on uncoated PMTs (20 ns) / # scint. on coated PMTs.



$0\nu\beta\beta$ backgrounds - handles in Theia

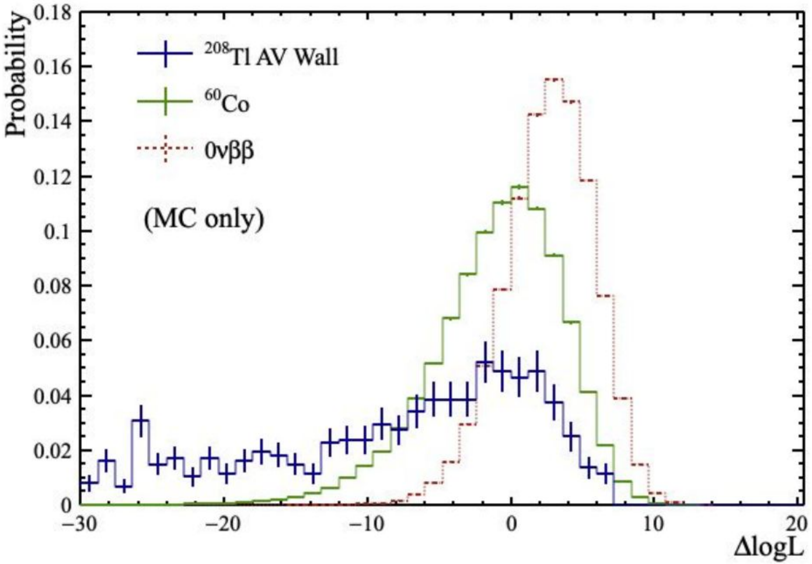
- Cherenkov directionality discriminates on directional sources/backgrounds.
- C/s and improved multisite discrimination will further improve sig./bg.

Directionality from Cherenkov:
solar ν, external bgs., multi-particle decays.

Cherenkov/scintillation ratio:
$\beta/\gamma/n(p)/\alpha$ discrimination.

Improved timing resolution (PSD, multi-site D):
$\beta/\gamma/n(p)/\alpha$, multi-particle decays.

SNO+



Outlook

THEIA

THEIA is a next-generation scintillator detector whose technologies and techniques are being demonstrated and informing the design.

THEIA at SNOLAB

THEIA will utilize Cherenkov & scintillation signals to enable an immense physics program of discovery and precision.

- Aiming to reach $0\nu\beta\beta$ into the normal mass ordering.