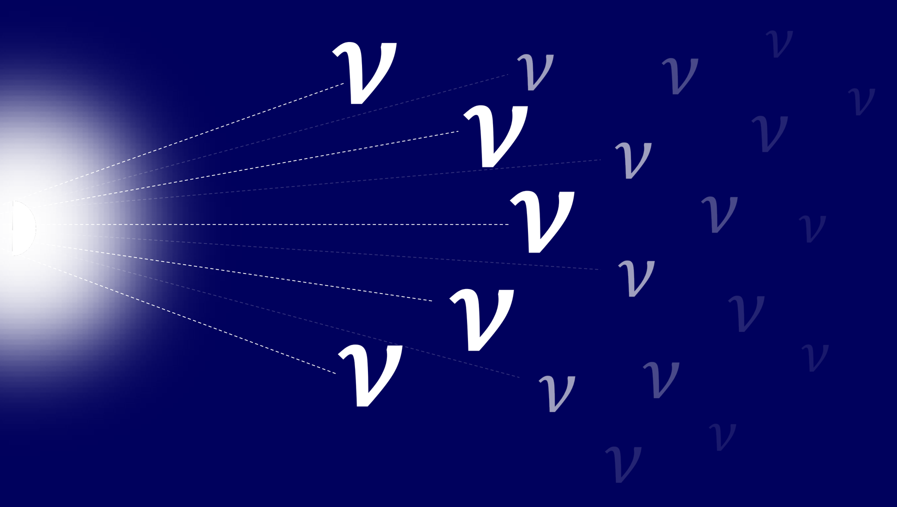
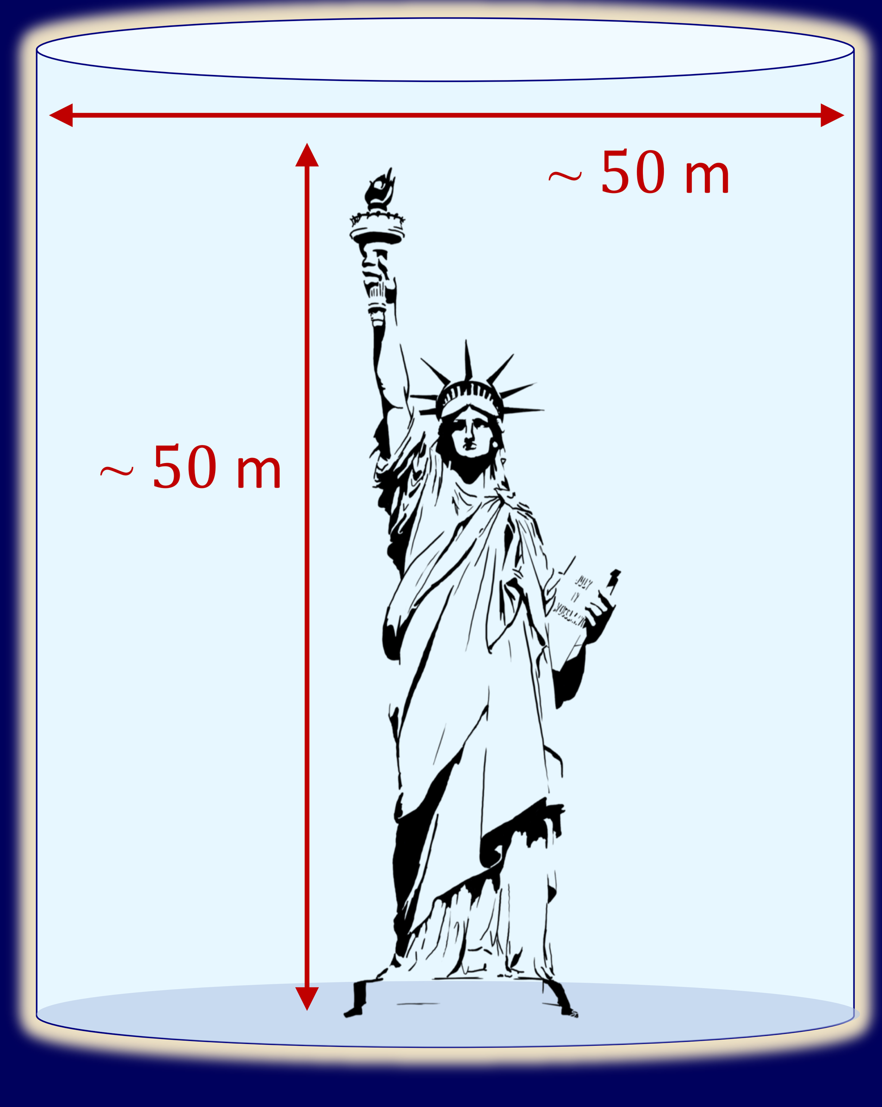


The Discovery Potential of Theia

(A Hybrid Cherenkov/Scintillator Detector)

Christopher Grant, Boston University

on behalf of the Theia Collaboration



Approximate scale of the Theia detector (still under investigation)

Neutrino Physics with Theia

Theia is a proposed 50-kiloton-scale detector filled with a novel water-based liquid scintillator (WbLS) and equipped with ultra fast-timing, high-efficiency photosensors (PMTs or LAPPDs). This highly-versatile detector will have the capability to measure neutrinos over an energy range from MeV to GeV, thus enabling a world-leading physics program.

The use of the high-intensity neutrino beam generated at Fermilab's Long Baseline Neutrino Facility (LBNF) is an integral part of the Theia science program. This can be achieved by constructing the Theia detector deep underground (4850 ft) in the LBNF far site, at the Sanford Underground Research Facility.

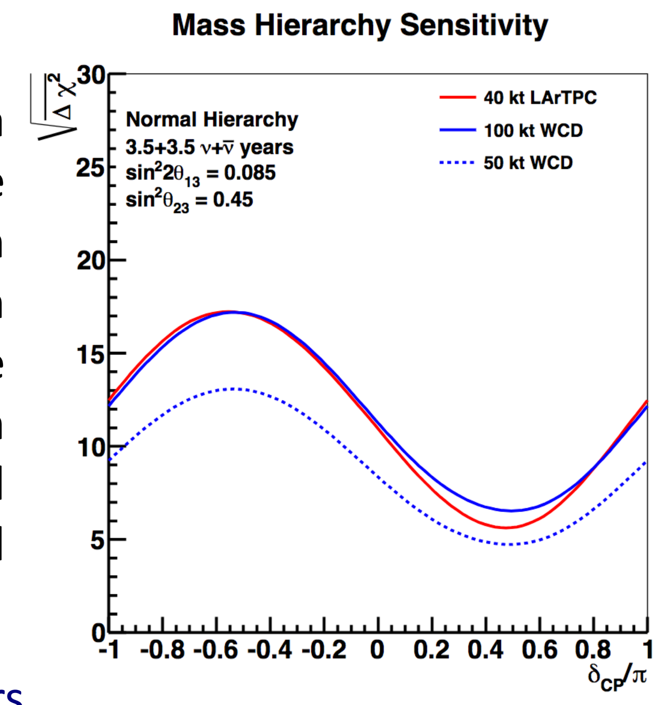
Science Drivers

- Long-baseline physics (CP-violation, mass hierarchy)
- Neutrinoless double beta decay
- Solar neutrinos (metallicity, NSI, luminosity)
- Supernova neutrinos (core-collapse, diffuse SN background)
- Nucleon decay (relatively unexplored modes)
- Geo-neutrinos
- Source-based sterile neutrino searches

The sensitivity of Theia to a subset of critical science drivers is presented below. These studies rely only on PMTs and are not contingent on LAPPDs. More in-depth information on all of topics can be found in the concept paper (arXiv:1409.5864).

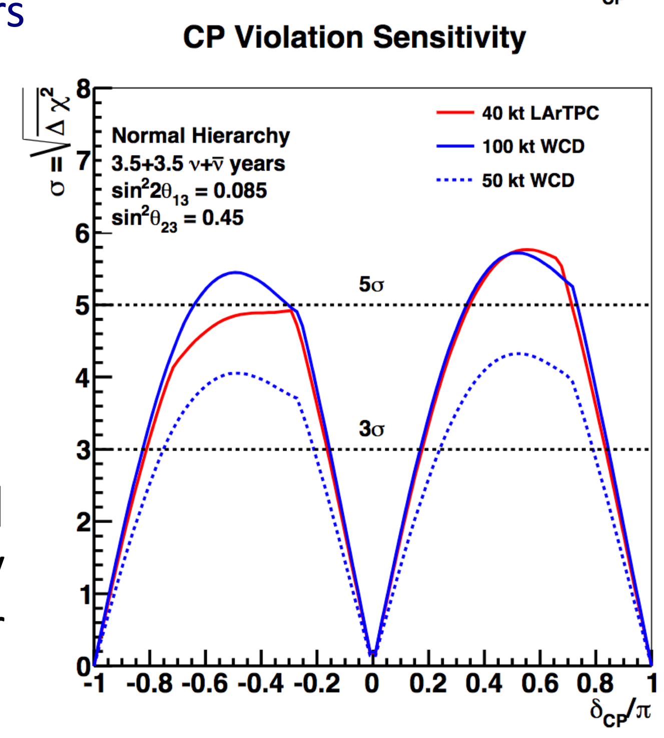
Long-Baseline Oscillations

Long-baseline (LBL) neutrino measurements in a WbLS-filled detector would complement those made by DUNE liquid argon Time Projection Chambers. The small loss of Cherenkov light in WbLS compared to pure water is believed to have very little impact on LBL sensitivity (based on previous experience from Super-Kamiokande I and II), but the optimal fraction of LS in WbLS required for sufficient ring imaging is yet to be determined.



However, scintillation and fast-timing photosensors could provide the following enhancements:

- Identification of hadrons below Cherenkov threshold (better ν_e CC π^+ selection)
- Enhanced final state neutron tagging ($\nu/\bar{\nu}$ separation)
- Improved reconstruction with fast-timing and new algorithms (reduce NC π^0 backgrounds)



Studies have been performed using GLoBES [1,2] configurations from the LBNE water Cherenkov detector [3] with ring imaging performance similar to Super-Kamiokande[4].

Sensitivities to the mass hierarchy and δ_{CP} are shown in the upper and middle right, respectively. These assume NC backgrounds are reduced to 25% of the level achieved with Super-Kamiokande selection efficiency (based on T2K experience [5]), but has not yet been demonstrated for the LBNF beam. A 100 kt Theia would have similar sensitivity to the mass hierarchy and δ_{CP} as the DUNE 40 kt LArTPC.

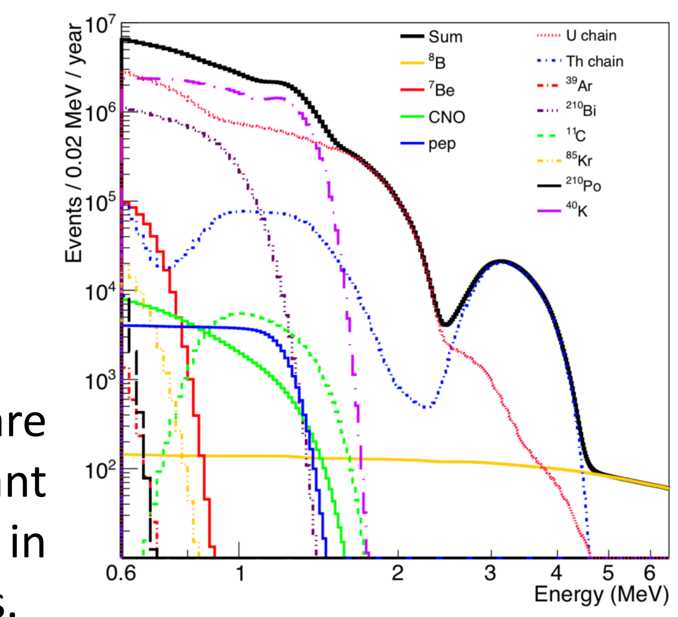
[1] arXiv:hep-ph/0407333 [3] arXiv:1204.2295 [5] K. Abe et al. (The T2K Collaboration), Phys. Rev. Lett. 112, 061802
[2] arXiv:hep-ph/0701187 [4] R. Wendell et al. (The Super-Kamiokande Collaboration), Phys. Rev. D 81, 092004

Solar Neutrinos

Neutrinos from nuclear fusion reactions in the Sun offer a unique picture of the solar interior. The Sun's varying density induces an adiabatic flavor conversion as neutrinos propagate outwards and offers channels for new physics (eg. sterile neutrinos, flavor-changing neutral currents). Furthermore, a measurement of the CNO neutrino flux could resolve an ongoing dispute between the Standard Solar Model and helioseismology, known as the "Solar Metallicity Problem".

Solar neutrino sensitivity studies for Theia [5] use the following assumptions:

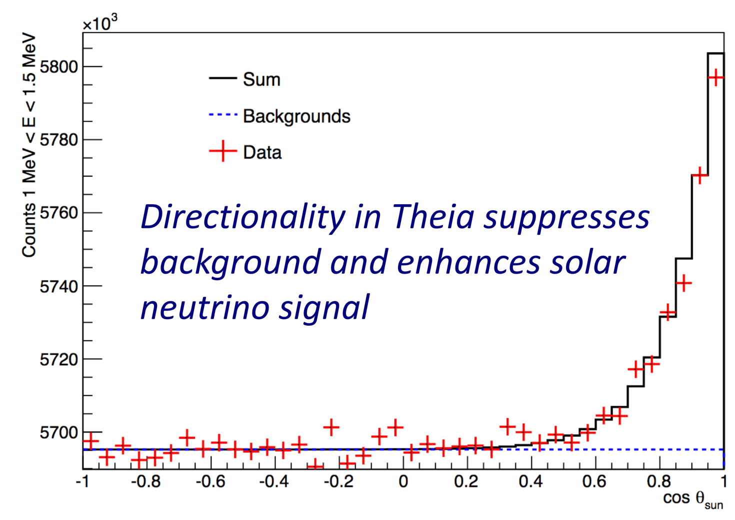
- 50 kt total mass (50% fiducial cut applied) exposed 5 years
- WbLS (5% LS and 95% water)
- 90% photocathode coverage (roughly 10^5 PMTs)
- Angular resolution of 25°
- SNO background levels used as input for water
- Borexino background levels used as inputs for LS
- Impact of all the above parameters was explored



Simulated spectra (ν-electron elastic scattering) are shown on the right, where ^{210}Bi is the dominant background for CNO neutrinos. Directionality in WbLS can be used to suppress these backgrounds.

LS % in WbLS	Angular Resolution 25°	35°	45°	55°
0.1%	6.2	8.8	11.2	13.5
1%	6.1	8.7	11.0	13.4
2%	6.2	8.9	11.4	13.8
3%	5.9	8.4	10.7	13.0
4%	5.5	7.9	10.1	12.3
5%	5.3	7.6	9.7	11.8

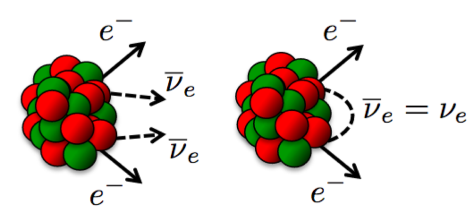
CNO flux sensitivity (%) as a function of angular resolution (background rejection) for the study described above.



Directionality in Theia suppresses background and enhances solar neutrino signal

[5] R. Bonventre and G. D. Orebi-Gann, arXiv:1803.07109 (accepted in Eur. Phys. J. C)

Neutrinoless Double Beta Decay



The Dirac/Majorana nature of the neutrino could be probed by loading with a $0\nu\beta\beta$ isotope (in the full detector volume or concentrated in a containment vessel). Investigations of Theia's $0\nu\beta\beta$ sensitivity (still in early stages) have focused on an 8 meter diameter balloon containing 3% loading by weight natural Tellurium (34% abundance of ^{130}Te) in LS (LAB+PPO).

$0\nu\beta\beta$ Half-life:

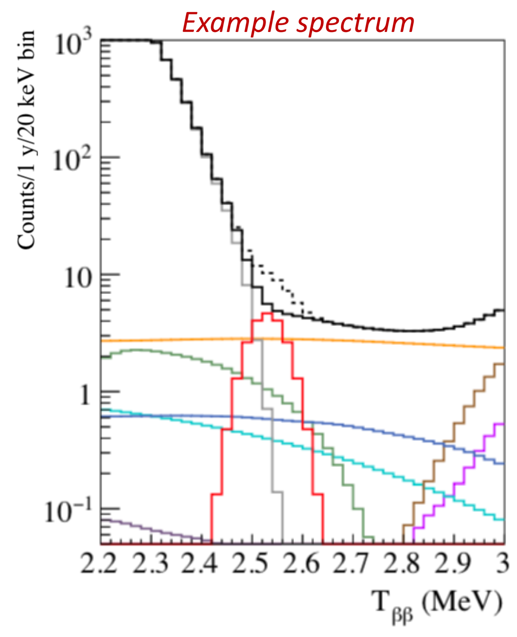
$$(T^{0\nu}_{1/2})^{-1} = G|M|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Effective Majorana mass; Phase space factor; Nuclear matrix element; Electron mass

MC simulations use the following inputs:

- Light yield of 1800 hits/MeV (90% PMT coverage)
- 7 meter fiducial volume (~12.5 tons ^{130}Te)
- Energy ROI of 2.51 – 2.60 MeV
- Total live time of 10 years
- 50% reduction of ^{8}B solar ES with topology

Example spectrum

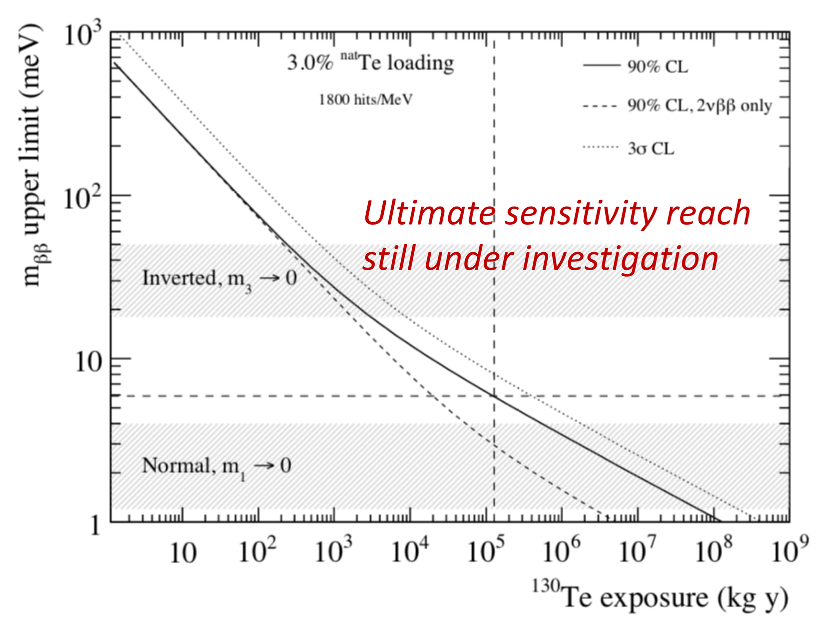


Signal	Events
$0\nu\beta\beta$ (15 meV)	147.3
$2\nu\beta\beta$	11.9
^{8}B Solar ES	132.9
^{10}C	27.0
^{130}I	41.3
^{130m}I	1.5
^{208}Tl	0.007
Balloon ^{214}Bi	17.7
Balloon ^{208}Tl	0.63
Total	232.9

Results for one test-case scenario:

- $T^{0\nu}_{1/2} > 1.1{\times}10^{28}$ years at 90% C. L.
- $m_{\beta\beta} < 6.3$ meV at 90% C. L. with IBM-2 nuclear matrix element

(this is only one of many possible configurations - limits could be improved with further optimization)

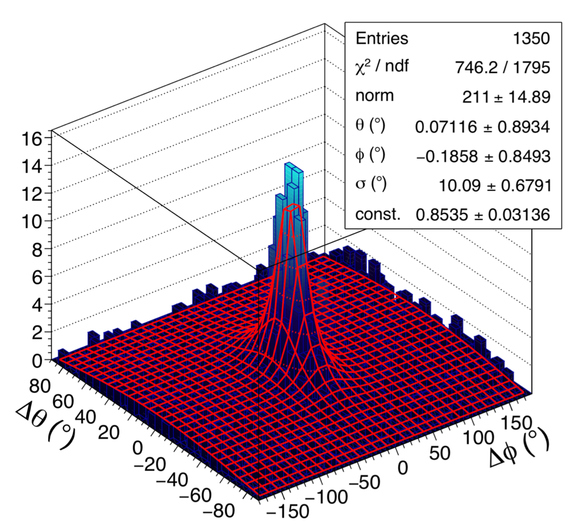


Ultimate sensitivity reach still under investigation

Higher isotope loading and increased suppression of backgrounds with the help of improved directionality could push $m_{\beta\beta}$ sensitivity into the Normal Hierarchy.

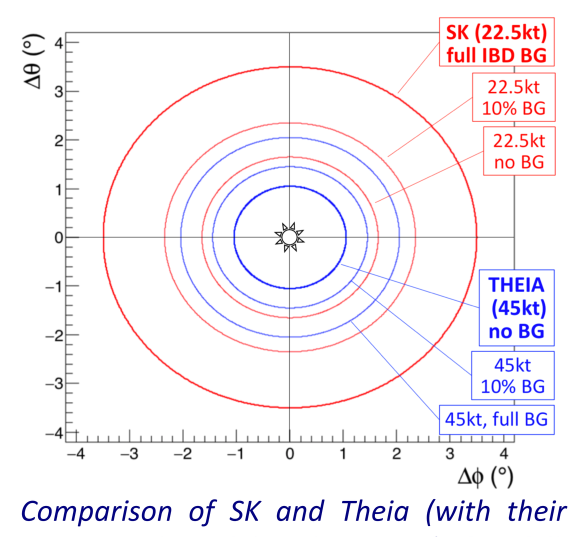
Supernova Neutrinos

Theia would observe more than 10,000 events from a core-collapse supernova (SN) at a distance of 10 kpc from Earth. WbLS provides high-efficiency tagging of neutrons and will enable low-threshold detection of inverse beta decay (IBD) reactions from SN ν_e. Sensitivity studies for measuring the diffuse SN neutrino background in Theia are still on-going (stay tuned!). An investigation into the SN-pointing capability of Theia is presented here.



Analytical fit to the SN direction in a toy MC study for Theia.

Cherenkov light provides the capability to point back to the supernova via ν-electron elastic scattering (ES). For example, Super-Kamiokande (SK) can point back to a SN at 10 kpc distance with ~3.2° accuracy [6]. IBD reactions give very little directional information and are a background for ES events. Theia, with WbLS, will be able to tag and separate IBD events from ES events (also possible in SK doped with Gd).



Comparison of SK and Theia (with their corresponding fiducial masses) for full, 90%, and zero background discrimination.

Reaction	Events
$\bar{\nu}_e + p \rightarrow e^+ + n$	10,000
$\nu_x + e^- \rightarrow \nu_x + e^-$	350
$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + X$	10
$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + X$	100

Number of detected events in Theia for 45 kt fiducial volume. The Wilson model [6] of a SN at 10 kpc distance is assumed and oscillations are not included.

Toy MC study for SN neutrinos in Theia assumes:

- Angular resolution of 10° for electrons
- Only ES and IBD events in the simulated data
- ES events fit with 2D exponential decay function
- Flat IBD background
- Resolution corresponds to 68.5% of the fitted event distribution

[6] K. Abe, et al. Astroparticle Physics 81 (2016) 39-48 [7] T. Totani et al., Astrophys. J. 496, 216 (1998)