Large-Scale WbLS Detector R&D

Applied Antineutrino Physics Workshop
11th October, 2018

Gabriel D. Orebi Gann
UC Berkeley & LBNL
Overview

- Theia detector concept
- Physics program
- Development of detector capabilities
Theia Detector Concept
Cherenkov / Scintillation Separation

Separation in charge, time, wavelength

Methods to enhance separation:

- Ultra-fast photon detection (LAPPDs)
- Delay scintillation light
- Optimize cocktail: scintillation fraction & spectrum (fluor)
- Readout sensitivity
Theia

- Large-scale detector (50-100 kton)
- Water-based LS target
- Fast, high-efficiency photon detection with high coverage
- Deep underground (e.g. Homestake)
- Isotope loading (Gd, Te, Li...)
- *Flexible*! Target, loading, configuration
  
  ➡ Broad physics program!

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Concept paper - arXiv:1409.5864
Theia Physics Program
Physics Program

1. Neutrinoless double beta decay
2. Solar neutrinos (solar metallicity, luminosity)
3. Geo-neutrinos
4. Supernova burst neutrinos & DSNB
5. Source-based sterile searches
6. Nucleon decay
7. Long-baseline physics (mass hierarchy, CP violation)
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Remarkably, the same detector could show that neutrinos and antineutrinos are the same, and that “neutrinos” and “antineutrinos” oscillate differently.
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Antineutrino Detection

• Detect via IBD

• High light yield allows enhanced n tag : 2.2 MeV $\gamma$ from $^1$H
  ▶ Suppress single-event background that limits water Cherenkov

• Higher detection efficiency than Gd-H$_2$O due to high scint. yield

• Reduce NC background that limits LS detectors
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Geo Neutrinos

- Current total geo-ν exposure: < 10kt-yr (KL + Borexino)
- **THEIA**: large statistics in a complementary geographical location
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DSNB

- Enhanced n tag
- Reduced NC background
- Most sensitive search to-date
- Plus NaCl for $\nu$ signal
Supernova

Neutrinos
## Supernova Detection

<table>
<thead>
<tr>
<th>Neutrino Reaction</th>
<th>Percentage of Total Events</th>
<th>Type of Interaction</th>
</tr>
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<tbody>
<tr>
<td>$\bar{\nu}_e + p \rightarrow n + e^+$</td>
<td>88%</td>
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Supernova Detection

- ~15k events for SN at 10 kpc (50 kt volume)
- ~90% events are IBD
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Highly complementary to $\nu_e$-dominated LAr signal
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**Highly complementary to $\nu_e$-dominated LAr signal**

- Enhanced n tag via low threshold scintillation
- Gd reduces n-cap time delay (200μs → 20 μs) ⇒ reduce pile up
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Early warning (PR value)
Neutrinos: long history of exciting physics and technological developments

SNO+: potential to discover the nature of the neutrino, and resolve the matter/antimatter mystery

THEIA: broad program of compelling science

Unique opportunity to combine conventional neutrino physics with rare-event searches in a single, large-scale detector

Critical flexibility to adapt to new directions in the scientific program as the field evolves

Powerful instrument of discovery

Ongoing R&D
WbLS Development

Emission and attenuation [BNL]

Metal loading for broad program [BNL]

e.g. n/γ separation in Gd-LS

Ton-scale demonstrator & production [BNL]

Nanofiltration & materials testing [UC Davis]

WbLS control sample is identical to WbLS not passing through the filter

Permeate’s (sample passing through the filter) absorption spectra consistent with low levels of surfactant but removal of LS
Nanofiltration [UCD]  
A membrane filtration process

Deionization critical for optical transparency
For WbLS: separate water/LS, filter, recombine

Requirements:
1. Separate water/ions from LS
2. Scalable to large volume (high flow rate)
3. No impact on LS light yield

Permeate’s (sample passing through the filter) absorption spectra consistent with low levels of surfactant but removal of LS

WbLS control sample is identical to WbLS not passing through the filter

Threshold Ratio
0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5
Rate (Hz)

Flow Rate (kg/hr.m²)

Minimum flow rate required
Photon Sensor Development

“Standard” PMTs

Modular PMTs

MCP-based photosensors

Single-PE pulses FWHM ~ 1.1 ns

Time resolution 64 ps FWHM

Pulse Amplitude

CHESS: CHErenkov-Scintillation Separation

Cosmic muon ring-imaging experiment
Select vertical cosmic muon events
Image Cherenkov ring in Q and T on fast-PMT array
Allows charge- and time-based separation

12 1-inch H11934 PMTs (300ps FWHM, 42% QE)
CAEN V1742 (5GHz)
675 samples (135ns window)
CAEN V1730 (500MHz)
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CHESS Results: LAB/PPO

Typical ring candidate event

NOTE: Rise time = 0.75 ± 0.25 ns

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<tr>
<th></th>
<th>LAB (time)</th>
<th>LAB (charge)</th>
<th>LAB/PPO (time)</th>
<th>LAB/PPO (charge)</th>
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<tbody>
<tr>
<td><strong>Cherenkov detection efficiency</strong></td>
<td>83 ± 3 %</td>
<td>96 ± 2 %</td>
<td>70 ± 3 %</td>
<td>63 ± 8 %</td>
</tr>
<tr>
<td><strong>Scintillation contamination</strong></td>
<td>11 ± 1 %</td>
<td>6 ± 3 %</td>
<td>36 ± 5 %</td>
<td>38 ± 4 %</td>
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</table>
CHESS Results: WbLS

Average of WbLS data set

Charge rings: Clearly seeing scintillation light even in 1% WbLS
WbLS Modelling in CHESS

Extract microphysical parameters by fitting using complete MC model

Detailed geometry
Beta decay generator (90Sr source)

Microphys. simulation:
Birk’s constant [1], LAB/PPO emission spectrum, absorption [2], reemission, T profile

Full photon tracking & optics model
Full PMT geometry: glass, dynode, casing
track photons to dynode

Full calibrated DAQ model:
waveform, gain, TTS

Time Profile

Calibrate method using well-understood LAB/PPO target

Time profile model: 3 exp. decay + rise time

\[ \rho(t) \propto (1 - e^{-t/\tau_r}) \times \sum_{i=1}^{3} A_i e^{-t/\tau_i} \]

- \( \tau_r = 0.7 \text{ ns} \)
- \( \tau_1 = 4.3 \text{ ns} \)
- \( \tau_2 = 16 \text{ ns} \)
- \( \tau_3 = 166 \text{ ns} \)

Good agreement between data and model

- Cerenkov
- Scintillation
- Reemission
- DATA

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Good agreement between data and model

WbLS time profile does not agree!

Faster than LAB/PPO?
Time Profile Measurement

Modify (parameter values in) underlying timing model in simulation

Fit for WbLS time profile

Result of fit (10% WbLS)

Cross-check against other samples

1%, 5% WbLS seem consistent with time profile of 10% cocktail
Preliminary light yield

Note: assumes LAB/PPO wvl emission profile
Fit for WbLS time profile

Method: define LAB/PPO LY
Calibrate setup to LAB/PPO charge collection
Determine LY per WbLS cocktail by data/MC fit
Signal Separation in Theia
Signal Separation in Theia

3 MeV $\beta$, 5% WbLS
Signal Separation in Theia

B: Cherenkov, R: Scintillation

3 MeV β, 5% WbLS, 50kt, 90%
Ring Imaging
Ring Imaging

B: Cherenkov, R: Scintillation

1% γs

1 GeV β, 5% WbLS, 50kt, 90%
Ring Imaging

B: Cherenkov, R: Scintillation

1% $\gamma$s

1 GeV $\beta$, 5% WbLS, 50kt, 90%

100% $\gamma$s
<table>
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<tr>
<th>Site</th>
<th>Scale</th>
<th>Target</th>
<th>Measurements</th>
<th>Timescale</th>
</tr>
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<tbody>
<tr>
<td>UChicago</td>
<td>bench top</td>
<td>H2O</td>
<td>fast photodetectors</td>
<td>Exists</td>
</tr>
<tr>
<td>CHIPS</td>
<td>10 kton</td>
<td>H2O</td>
<td>electronics, readout, mechanical infrastructure</td>
<td>2019</td>
</tr>
<tr>
<td>EGADS</td>
<td>200 ton</td>
<td>H2O+Gd</td>
<td>isotope loading, fast photodetectors</td>
<td>Exists</td>
</tr>
<tr>
<td>ANNIE</td>
<td>30 ton</td>
<td>LS</td>
<td>directionality</td>
<td>Exists</td>
</tr>
<tr>
<td>WATCHMAN</td>
<td>1 kton</td>
<td>LS</td>
<td>directionality</td>
<td>2020</td>
</tr>
<tr>
<td>NuDot</td>
<td>1 ton</td>
<td>LS</td>
<td>directionality</td>
<td>2018</td>
</tr>
<tr>
<td>Penn</td>
<td>30 L</td>
<td>(Wb)LS</td>
<td>light yield, timing, loading</td>
<td>Exists</td>
</tr>
<tr>
<td>SNO+</td>
<td>780 ton</td>
<td>(Wb)LS</td>
<td>light yield, timing, loading</td>
<td>2018</td>
</tr>
<tr>
<td>CHESS (LBNL)</td>
<td>bench top</td>
<td>WbLS</td>
<td>signal separation, tracking, reconstruction / light yield, loading, attenuation</td>
<td>Exists</td>
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<tr>
<td>BNL</td>
<td>1 ton</td>
<td>WbLS</td>
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EGADS
Gd loading and purification

BNL 1-t
Water-based liquid scintillator

SNO+
Te loading

WbLS, Gd, LAPPD, HQE PMT, full integration prototype

Note: not an exhaustive list!
THEIA Collaboration

Concept paper - arXiv:1409.5864
Summary

- **THEIA**: broad program of compelling science
- Enhanced capabilities for anti-neutrino detection
- Flexibility to adapt to new directions in the scientific program as the field evolves
- Powerful instrument of discovery
- Rich, exciting program of ongoing R&D
Backup
Transformational Opportunity
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Development of new scintillators e.g. WbLS
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Fast, efficient photodetectors
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Fast, efficient photodetectors

Fully-equipped, deep underground labs (+ beam)
Transformational Opportunity

Development of new scintillators e.g. WbLS

Fast, efficient photodetectors

Advanced computing & reconstruction methods


Fully-equipped, deep underground labs (+ beam)

$\nu, \bar{\nu}$
Transformational Opportunity

Development of new scintillators e.g. WbLS

Fast, efficient photodetectors

New-generation of large-scale, low-threshold, directional detectors

Fully-equipped, deep underground labs (+ beam)


ν, ¯ν
Detector Concept

- New technology with proven methodology

House light-producing target inside large monolithic detector

Novel, breakthrough target medium
Powerful Target Medium

Minfang Yeh et al., BNL

Tune to specific physics goals

Mean Absorption Length (m)

- Cerenkov (e.g. SK, SNO)
- Water-based Liquid Scintillator
  - Water-like
    - >70% H2O
    - Cerenkov Scintillation
    - Cost-effective
  - Oil-like
    - A new loading technology for hydrophilic elements
- Scintillator (e.g. SNO+, Daya Bay)

Photon/MeV
Precision of a Cherenkov Detector

- High transparency: good light collection
- Topological information
  - Particle identification (ring imaging)
  - Directionality
- Metal loading potential

Demonstrated at 1–50 kt-scale (SNO, SuperK)

Leon Pickard, UC Davis
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Electron

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Power of a Scintillation Detector

- High light yield
- Low threshold, sub-Cherenkov-t/h detection
- Good energy & vertex resolution
- “Fast” timing at low threshold: coincidence tag
- Particle identification
- Can be made ultra clean

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Cher / scint ratio provides additional handle on particle ID
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Neutrino

Electron

1+1>2

Cher / scint ratio provides additional handle on particle ID
Cherenkov Calibration

Motivation:
Separate detector light collection efficiency from LS optical properties (light yield, absorption) in a pure LS experiment (SNO+).

Bonus:
Demonstrate transmission of Cherenkov spectrum through LS target.
NLDBD with Theia

50 kton water-based liquid scintillator detector
High coverage with fast photon detectors
Deep underground
8-m radius balloon with high-LY LS and isotope
7-m fiducial, 3% natTe, 10 years

Builds on critical developments by KLZ & SNO+ collaborations

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<tr>
<td>0νββ (10 meV)</td>
<td>65.6</td>
</tr>
<tr>
<td>2νββ</td>
<td>11.9</td>
</tr>
<tr>
<td>8B Solar ES</td>
<td>132.9</td>
</tr>
<tr>
<td>10C</td>
<td>27.0</td>
</tr>
<tr>
<td>130I</td>
<td>41.3</td>
</tr>
<tr>
<td>130mI</td>
<td>1.5</td>
</tr>
<tr>
<td>208Tl</td>
<td>0.007</td>
</tr>
<tr>
<td>Balloon 214Bi</td>
<td>17.7</td>
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<tr>
<td>Balloon 208Tl</td>
<td>0.63</td>
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<td><strong>Total</strong></td>
<td><strong>232.9</strong></td>
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NLDBD with Theia

7-m fiducial, 3% natTe, 10 years

Counts/1 y/20 keV bin

Sample spectrum

$T_{1/2} > 1.1 \times 10^{28}$ yrs (90% CL)

$m_{\beta\beta} < 6.3$ meV (IBM-2 NME)
Long-Baseline Program

- Large-scale detector at Homestake, in the LBNF beam
- Complementary program to LArTPC (DUNE)
- Build on WCD studies (arXiv:1204.2295)
- Plus advantages from low-threshold scintillation

MH sensitivity for 50kt WbLS alone > 5σ

Study by E. T. Worcester using same GLOBES package used for ELBNF
Open Questions in Solar ν

- Detect CNO neutrinos:
  - Determine solar metallicity
  - Test understanding of heavier main-sequence stars
  - Test postulate of homog. \( T=0 \) Sun
  - Test extent of CN-cycle eqm

![Graph showing δc/c vs. R/R_⊙](image)
Open Questions in Solar $\nu$

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  - Text extent of CN-cycle eqm

- Probe vacuum-matter transition via low-energy $^8B$ spectrum:
  - Confirm MSW
  - Sensitive search for new physics

![Graph showing best fit $P_{ee}$ for fermion-density dependent MaVaN model with $\Delta \chi^2 = 3.4$ and C.L. = 0.81.](image)

**Phys. Rev. D 88 (2013) 053010**
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- High-precision pep flux — luminosity
- High-precision $^7$Be flux — solar T, $\Delta m^2_{21}$ to 0.1%, geo-tomography
- Separation of CNO components
Solar Neutrinos with Theia
Solar Neutrinos with Theia

- Dominant background to CNO $\nu$ measurement: $^{210}\text{Bi}$
Solar Neutrinos with Theia

- Dominant background to CNO ν measurement: $^{210}$Bi
- Theia offers unique low-threshold, directional detection

2D fit in energy and $\cos(\theta_{\text{sun}})$
Solar Neutrinos with Theia

- Dominant background to CNO ν measurement: $^{210}\text{Bi}$
- Theia offers unique low-threshold, directional detection
- Ability to separate Cherenkov and scintillation signals demonstrated in pure LS (LAB + 2 g/L PPO)

![Graph showing events vs. energy]

$2D$ fit in energy and $\cos(\theta_{\text{sun}})$

![Graph showing 2D fit]


PRC 95 055801 (2017)
Theia Detector Parameters

Baseline detector:
5 years
50-kton (x 50% fiducial)
5% WbLS
90% coverage
25° resn
SNO bkg levels in H₂O
  0.1 x Borex value for ⁴⁰K
Borexino-I bkg levels in LS
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Variables considered:
Mass        25 – 50-kton
Target      0.5 – 5% WbLS
Coverage    60 – 90%
Angular resn 25° – 55°
Bkg levels in H₂O x10-10,000
BiPo & α rejection 0 – 95%
Theia Detector Parameters

Baseline detector:
- **5 years**
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- **5% WbLS**
- **90% coverage**
- **25° resn**
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  - **0.1 x Borex value for ⁴⁰K**
- **Borexino-I bkg levels in LS**

Variables considered:
- **Mass** 25 – 50-kton
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Baseline background levels:

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<thead>
<tr>
<th></th>
<th>H₂O level (g/gH₂O)</th>
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<tbody>
<tr>
<td><strong>²³⁵U chain</strong></td>
<td>6.63e−15 [37]</td>
<td>1.6e−17 [35]</td>
</tr>
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<td><strong>²³²Th chain</strong></td>
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</tr>
<tr>
<td><strong>⁴⁰K</strong></td>
<td>6.1e−16⁵</td>
<td>1.3e−18 [36]</td>
</tr>
<tr>
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<td>2.4e−25³</td>
<td>2.4e−25 [36]</td>
</tr>
<tr>
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<td>2.75e−24 [36]</td>
</tr>
<tr>
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<td>3.78e−28³</td>
<td>3.78e−28 [36]</td>
</tr>
<tr>
<td><strong>¹¹C</strong></td>
<td>0</td>
<td>1.0e5 (ev/kT/year) [4]</td>
</tr>
</tbody>
</table>

Superscript:
- "⁵" The **⁴⁰K level in water is taken to be 0.1 × the Borexino measurement [34]
- "³" The **⁸⁵Kr**, **³⁹Ar**, and **²¹⁰Bi** levels in water are taken to be the Borexino measured level in scintillator [36], although levels increased by several orders of magnitude are explored.
Theia Detector Parameters

Baseline detector:
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Variables considered:
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- Coverage: 60 – 90%
- Angular resn: 25° – 55°
- Bkg levels in H₂O: 10-10,000
- BiPo & α rejection: 0 – 95%

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b The ⁸⁵Kr, ³⁹Ar, and ²¹⁰Bi levels in water are taken to be the Borexino measured level in scintillator [36], although levels increased by several orders of magnitude are explored

Angular resolution:
- Expected photon hits in Theia:
  - SNO saw ~36 hits at 5MeV, ~26.7° [31]
  - SuperK ~ 41 hits at 6MeV ~ 35° [32]

Theia Flux Sensitivity

Baseline detector:
- 50-kton target volume (x 50% fiducial)
- 5% WbLS target material
- 90% photocathode coverage
- 25° angular resolution

5 years data taking
- $H_2O$ background levels from SNO
  - exc. 0.1x Borexino value for $^{40}K$
- LS background levels from Borexino-I

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CNO & ²¹⁰Bi signals highly correlated (-0.84) in pure LS fit, errors not accurate

Pull distribution shows unbiased fit for WbLS Theia detector
(mean pull ~0, RMS ~1)

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<tr>
<th>Signal</th>
<th>Normalization sensitivity (%)</th>
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<tbody>
<tr>
<td>$^8$B $\nu$</td>
<td>0.4</td>
</tr>
<tr>
<td>$^7$Be $\nu$</td>
<td>0.4</td>
</tr>
<tr>
<td>pep $\nu$</td>
<td>3.8</td>
</tr>
<tr>
<td>CNO $\nu$</td>
<td>5.3</td>
</tr>
<tr>
<td>$^{210}$Bi</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>11.5</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>10.5</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>0.04</td>
</tr>
<tr>
<td>$^{39}$Ar/$^{210}$Po</td>
<td>21.9</td>
</tr>
<tr>
<td>$^{238}$U chain</td>
<td>0.02</td>
</tr>
<tr>
<td>$^{232}$Th chain</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Detector Parameters

Impact of detector design parameters

<table>
<thead>
<tr>
<th>Target mass</th>
<th>WbLS</th>
<th>Angular resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>25°</td>
</tr>
<tr>
<td>50 kT</td>
<td>0.5%</td>
<td>6.2</td>
</tr>
<tr>
<td>50 kT</td>
<td>1%</td>
<td>6.1</td>
</tr>
<tr>
<td>50 kT</td>
<td>2%</td>
<td>6.2</td>
</tr>
<tr>
<td>50 kT</td>
<td>3%</td>
<td>5.9</td>
</tr>
<tr>
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<tr>
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<td>2%</td>
<td>8.5</td>
</tr>
<tr>
<td>25 kT</td>
<td>3%</td>
<td>8.0</td>
</tr>
<tr>
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<td>7.6</td>
</tr>
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</tr>
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<td>5.9</td>
</tr>
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</tr>
<tr>
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</tr>
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<tr>
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<td>5%</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Impact of detector response (energy systematics)


WbLS R&D, G. D. Orebi Gann
Backgrounds

Directional sensitivity means the fit is very robust to variations in intrinsic background levels.

### Sensitivity to $^{40}$K level

<table>
<thead>
<tr>
<th>Signal</th>
<th>Baseline $^{40}$K</th>
<th>$\times 10^{40}$K</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^8$B $\nu$</td>
<td>0.4</td>
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<td>8.6</td>
</tr>
<tr>
<td>CNO $\nu$</td>
<td>5.3</td>
<td>11</td>
</tr>
</tbody>
</table>

### Sensitivity to background levels

<table>
<thead>
<tr>
<th>Fraction of nominal contamination</th>
<th>$^{11}$C</th>
<th>$^{210}$Bi</th>
<th>$^{85}$Kr</th>
<th>$^{39}$Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1x</td>
<td>5.3</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1x</td>
<td>5.3</td>
<td>5.3</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>10x</td>
<td>5.4</td>
<td>5.4</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>100x</td>
<td>5.5</td>
<td>6.0</td>
<td>5.4</td>
<td>5.4</td>
</tr>
<tr>
<td>1000x</td>
<td>–</td>
<td>9.4</td>
<td>5.6</td>
<td>5.4</td>
</tr>
<tr>
<td>10000x</td>
<td>–</td>
<td>–</td>
<td>5.9</td>
<td>5.5</td>
</tr>
</tbody>
</table>

### Sensitivity to background rejection

<table>
<thead>
<tr>
<th>CNO sensitivity (%)</th>
<th>Nominal</th>
<th>No $\alpha$ rejection</th>
<th>No BiPo in-window rejection</th>
<th>No $\alpha$, no BiPo in-window rejection</th>
<th>No $\alpha$, no BiPo rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.3</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Theia Spectral Sensitivity
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1996, W.C. Haxton: isotope loading for CC interaction (water)

“Salty water Cherenkov detectors” W.C. Haxton PRL 76 (1996) 10

arXiv:1409.5864
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Cross section from W.C. Haxton

\[ E_\nu = 3\text{MeV} \]
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Cross sections from J. Bahcall

arXiv:1409.5864
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Unprecedented low-energy statistics (ES)

30kt fiducial
1% 7Li by mass
Conservative
100 pe/MeV

Similar to LENA — Astropart. Phys. 35 (2011) 685-732
+ directionality from Cherenkov

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Enabled by use of WbLS (7Li, CC)

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Spectral Sensitivity (CC)

\[ \cos\theta_\odot < 0.4 \]

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Similar to LENA — Astropart. Phys. 35 (2011) 685-732
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Spectral information could allow separation of constituent CNO components
And potentially detect ecCNO ν

preliminary

CNO shape analysis

arXiv:1409.5864
Directionality

- Toy MC (uniform and isotropic) as function of absn length (PPO fraction)
- Angle between initial photon direction and PMT hit direction (only plotting photons that are absorbed and reemitted)
7Li Loading

\[ ^7Li + \nu_e \rightarrow ^7Be + e^- \quad (Q = 862 \text{ keV}) \]

- Two significant transitions
  - Mixed Fermi / GT transition to GS, threshold = 0.862 MeV
  - Super-allowed GT to 1st ES (\( \sim 430 \) keV), \( \tau \sim 200 \) fs
- Potential to differentiate e\(^-\) from (e\(^-\) + \gamma) using isotropy of PMT hits
- Contribution of the two known precisely from theory
- Precisely known angular distributions - additional discriminant
- NC on 7Li excites 1st ES of 7Li (478 keV), \( \tau \sim 105 \) fs

Credit: W. Haxton
# Requirements

<table>
<thead>
<tr>
<th>Physics</th>
<th>Size</th>
<th>Cherenkov Priority</th>
<th>Scintillation Priority</th>
<th>Cleanliness Priority</th>
</tr>
</thead>
</table>
| $0
\nu\beta\beta$             | ~few ktonne | Medium             | Very high              | Very High            |
| Low E Solar vs (< 1MeV)     | ~10 ktonne | High               | Very high              | Very High            |
| High E Solar vs (> 1 MeV)   | >50 ktonne | High               | Low                    | High                 |
| Geo/reactor anti-vs         | ~10 ktonne | Low                | High                   | Medium               |
| DSNB anti-ns                | >50 ktonne | Low                | High                   | Medium               |
| Long-baseline vs            | > 50 ktonne| Very high          | Low                    | Low                  |
| Nucleon decay (K+ anti-\nu) | > 100 ktonne| High              | High                   | Low                  |
Long-Baseline Program

- Large-scale detector at Homestake, in the LBNF beam
- Complementary program to LArTPC (DUNE)
- Build on WCD studies (arXiv:1204.2295)

Images from arXiv:1204.2295
Long-Baseline Program

- Large-scale detector at Homestake, in the LBNF beam
- Complementary program to LArTPC (DUNE)
- Build on WCD studies
  (arXiv:1204.2295)

- Ring-imaging of a water Cherenkov detector
- Particle ID from Cher/scint separation
- n and low-E hadron detection (low threshold)
  - reduce wrong-sign component (nu vs anti-nu)
  - reduce NC background by detecting $\pi^0 \rightarrow \gamma\gamma$
- Large size $\rightarrow$ sensitivity to 2nd oscn max
Long-Baseline Sensitivity

Study by E.T. Worcester using same GLOBES package used for ELBNF

Synergy with LAr TPC
Independent systematics
High-energy events

~300 kt-MW-yr exposure (40kt LAr)

Performance competitive with 40kt LAr TPC !!
Long-Baseline Sensitivity

Synergy with LAr TPC
Independent systematics
High-energy events

MH sensitivity for 50kt WbLS alone > 5σ

Study by E.T. Worcester using same GLOBES package used for ELBNF
Sterile Neutrinos
Sterile Neutrinos

- Deploy $^8\text{Li}$ decay-at-rest (IsoDAR)
  - 13MeV endpoint (above r/a)
  - Required detector response: 15% (E) & 50cm (R)
  - 5 yrs, 1kt (black) / 20kT fid. (blue)

- Heavy-water based LS: 2n tag (reduce bkg in IBD searches)

Figs from arXiv:1409.5864
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Nucleon Decay

- Large, deep, very clean
- Enhanced n tag
- Sub-Cherenkov threshold detection
- Sensitive to several modes

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Sub-Chr t/h detection ⇒ Directly visible $K^+$

Figs from arXiv:1409.5864
Application of Signal Separation

Photon arrival times in kton-scale LS detector

Composition of early-time sample
Application of Signal Separation

- Photon arrival times in kton-scale LS detector
- Composition of early-time sample
- Spherical harmonics analysis of “idealised” events

Application of Signal Separation

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NLDBD  8B solar nu

Spherical harmonics analysis of “idealised” events

Signal/background discrimination

Application of Signal Separation

Photon arrival times in kton-scale LS detector

Spherical harmonics analysis of “idealised” events

Composition of early-time sample

Signal/background discrimination

NLDBD 8B solar nu

MCP Development [ANL]

Argonne 6X6 cm MCP-PMT on custom readout board

- Argonne routinely producing 6X6 cm² functional detectors with K₂CsSb photocathode
- New IBD-1 design allows HV optimization, as biasing individual components possible
- In addition to assembly of photo-detectors, laser testing facility available and photocathode research ongoing.
- Performance:
  - Gain > 10⁷
  - Quantum efficiency ~ 15%
  - Time resolution including the laser jitter: σ ~ 35 ps
  - Position resolution along anode strip: < 1 mm
  - Rate capability > 1 MHz/cm² for single photoelectrons

B. Wagner et al., Argonne NL
1. 2nd-gen Optical TPC design e.g. for NLDBD
2. 2nd-gen control card; multi-buffered PSEC4 ASIC
3. Photodetector development, working with INCOM

1. Top seal (glass complete, ceramic underway)
2. High resolution pad anodes for LHC (NIM)
3. Monolithic high-bandwidth ceramic body
4. PMT-style batch production (w. INCOM)
5. High-QE photocathode in-situ synthesis

A. Elagin & master glassblower Joe Gregar

Gen-II Margherita Dual-Vacuum facility
Ceramic base tiles from 4 vendors

H. Frisch et al., Chicago