Theia

CIPANP 2018

Neutrino Mass and Neutrino Mixing parallel session

Theia: A multi-purpose water-based liquid scintillator detector

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University of California at Davis

May 30, 2018

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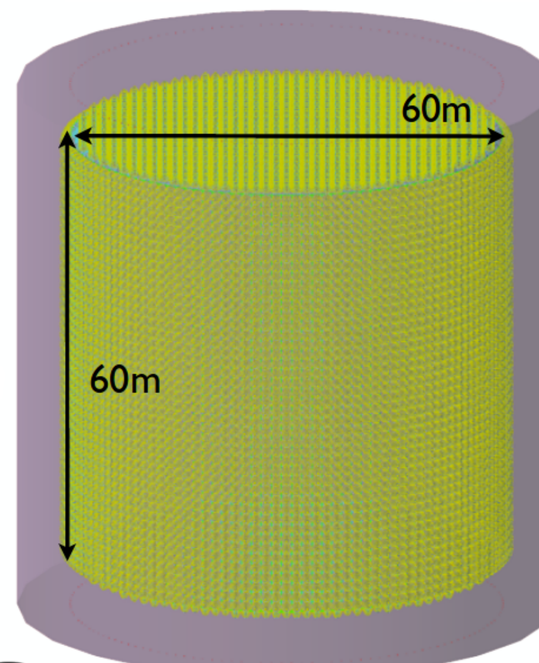
Overview of Theia

Theia

- Greek mythology: Theia (Θεια) is the Titan goddess of light, mother of Helios (Sun), Eos (Dawn), and Selene (Moon)

- **Theia** is a project for a large multi-purpose water-based liquid scintillator detector
- **~50 kilotonnes** of water-based liquid scintillator (**WbLS**)
- **Physics goals**: CP violation, mass hierarchy, solar neutrinos, double-beta decay, sterile neutrinos, geoneutrinos, etc...
- Use of fast-timing photosensors known as **LAPPDs**



Detector image product of RAT-PAC

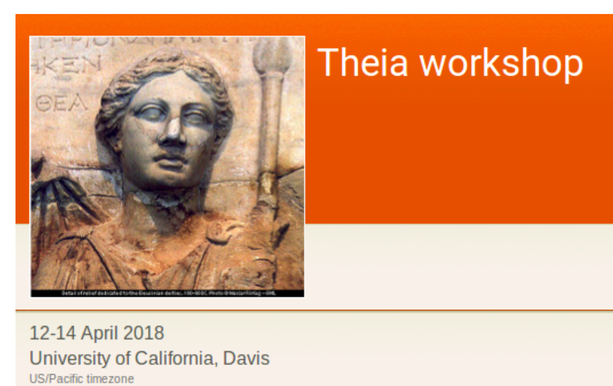
More details: **arXiv:1409.5864**

The Theia proto-collaboration

~60 proto-collaborators in more than 6 countries

4 meetings already occurred (2 in the US, 2 in Germany)

Last meeting (April) was at UC Davis with a large attendance and interests from other collaborations (**ANNIE**, **WATCHMAN**)



Water-based Liquid Scintillator - Basics

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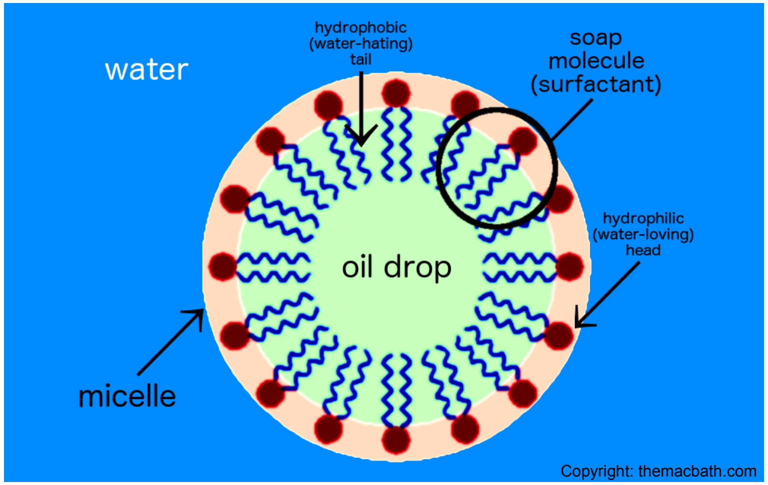
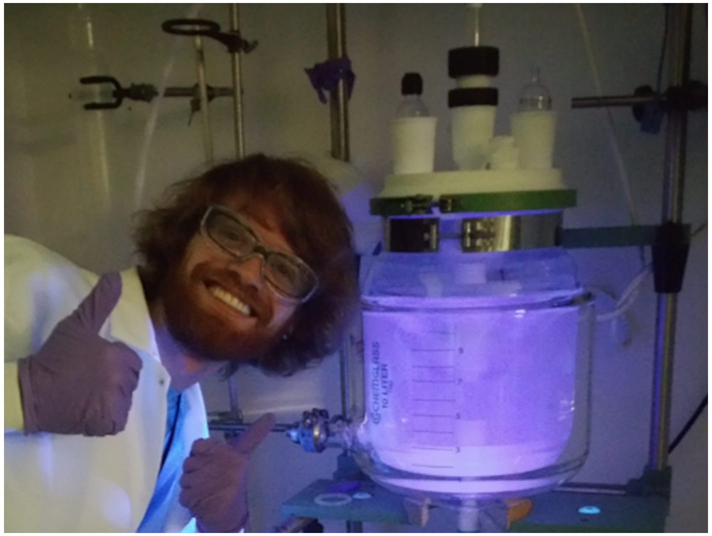
Theia

- **W**ater-**b**ased **L**iquid **S**cintillator (**WbLS**) is a mixture of pure water and oil-based liquid scintillator
- While water and oil don't mix, WbLS is made using a **surfactant** (soap-like) such as PRS* (hydrophilic head and hydrophobic tail) to hold the scintillator molecules in water in a “**micelle**” structure
- **Combines the advantages** of water (low light attenuation, low cost) and liquid scintillator (high light yield)
- Emission of **prompt Cherenkov** light and **delayed scintillation** light
- **Tunable LS content** for a broad range of physics goals
- **Low cost** and **environmentally-friendlier** than pure LS
- Strong R&D effort ongoing at **Brookhaven and Berkeley** Nat. Labs and **UC Davis**



Micelle structure in water

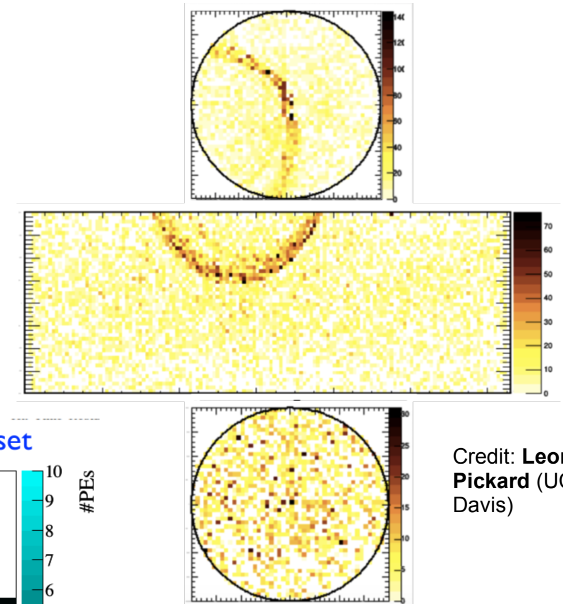


Former UCD graduate student **Morgan Askins** at BNL

*PRS: Linear Alkyl Sulfonate

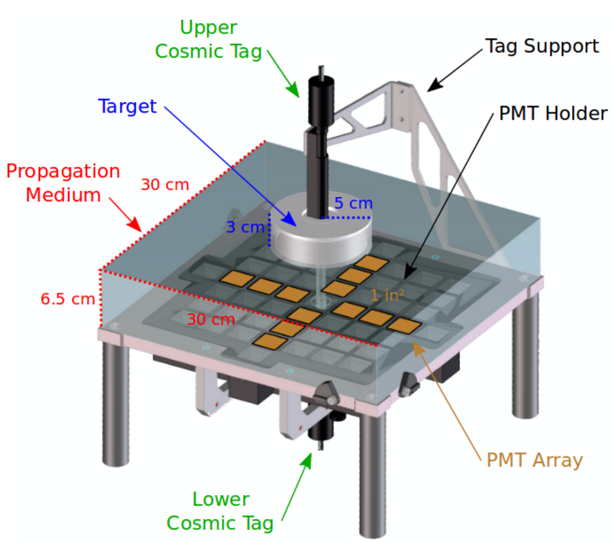
Water-based Liquid Scintillator - Capabilities

- **Time and charge reconstruction** show separation of Cherenkov (directional) and scintillation light (isotropic) in simulations
- Ongoing tests performed with **CHESS** (Eur. Phys. J. C (2017) 77: 811) to **separate both components**

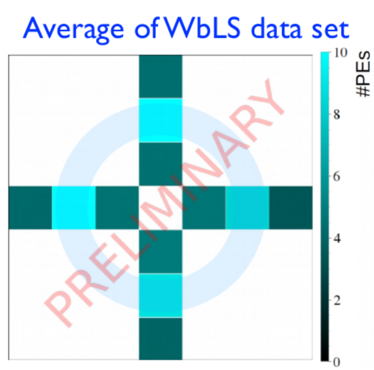


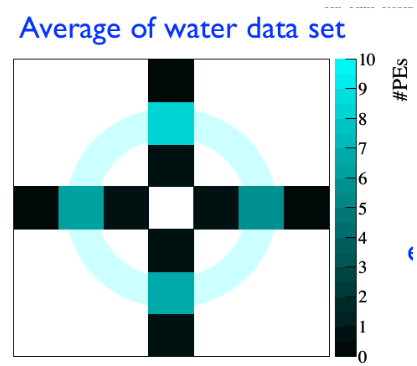
Credit: **Leon Pickard** (UC Davis)

Simulated CC interaction in WbLS

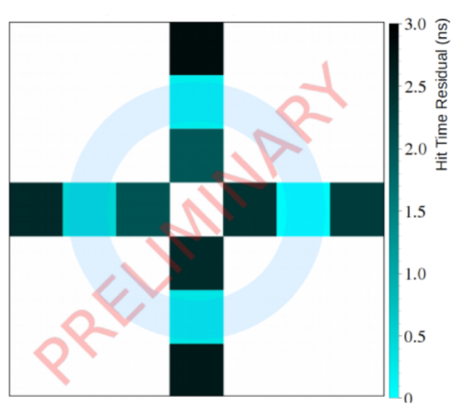


The CHESS setup

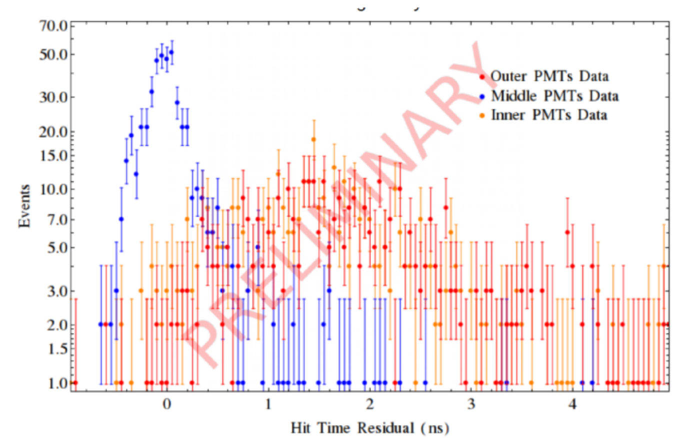




Number of PEs detected



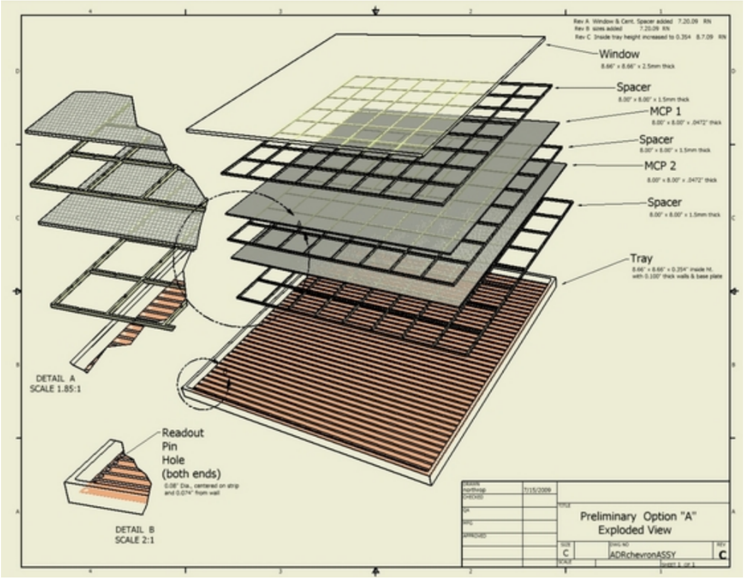
Mean hit time residuals

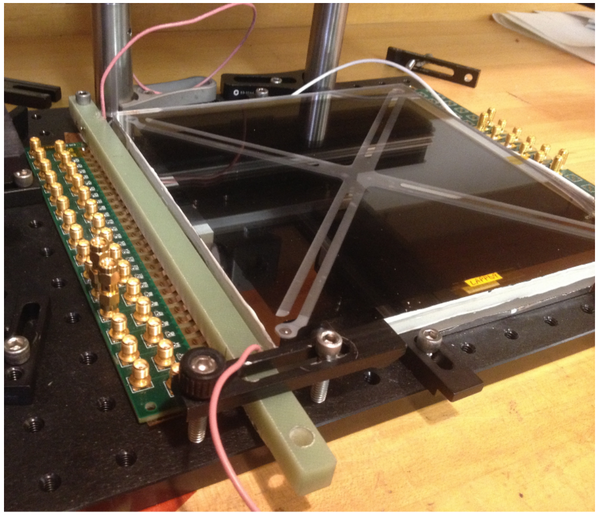


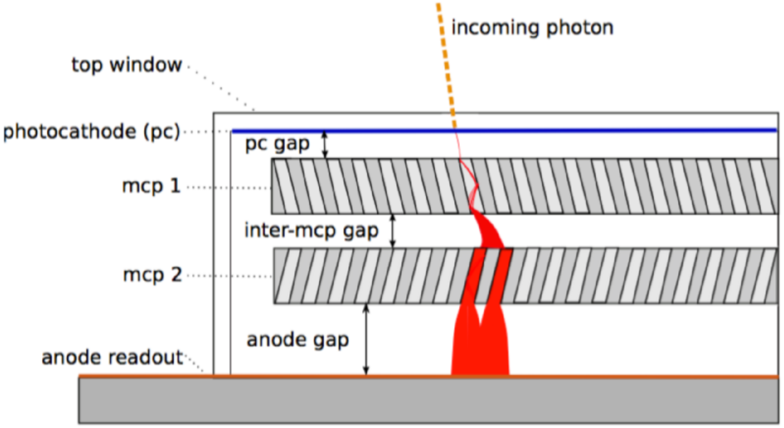
Hit time residuals

Large Area Picosecond PhotoDetectors - Principles

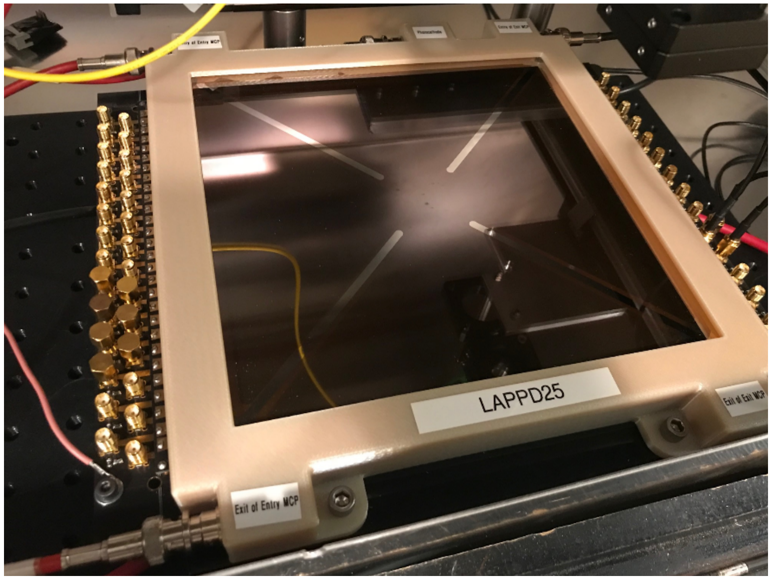
- Large, flat **MCP-based** photosensors
  - Time resolution: **~60 picoseconds**
  - Spatial resolution: **< 1 cm**
- Design includes an **intrinsic PSEC-4 readout** system
- Manufactured by the **Incom company**, being tested extensively at **Iowa State University** and expected to be deployed in the **ANNIE** detector
- **More information**: A Brief Technical History of the Large-Area Picosecond Photodetector (LAPPD) Collaboration, arXiv:1603.01843

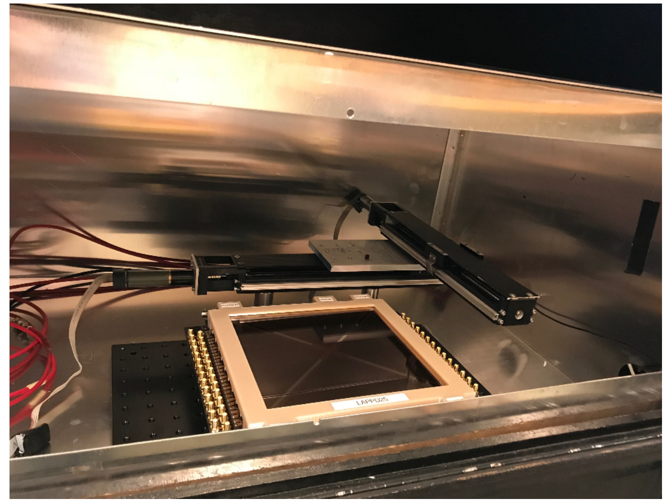


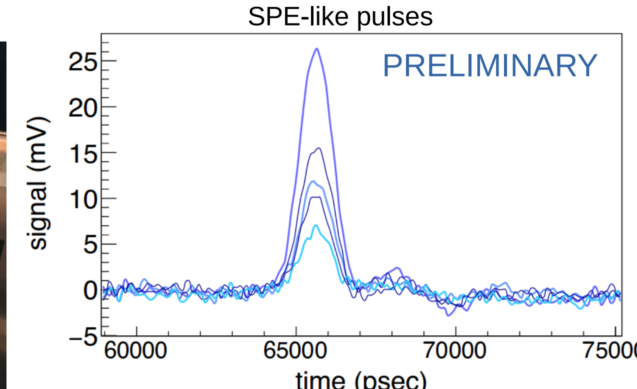


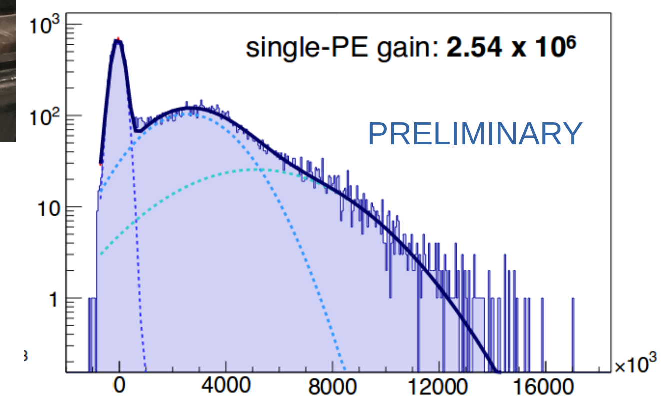


Large Area Picosecond PhotoDetectors- Capabilities

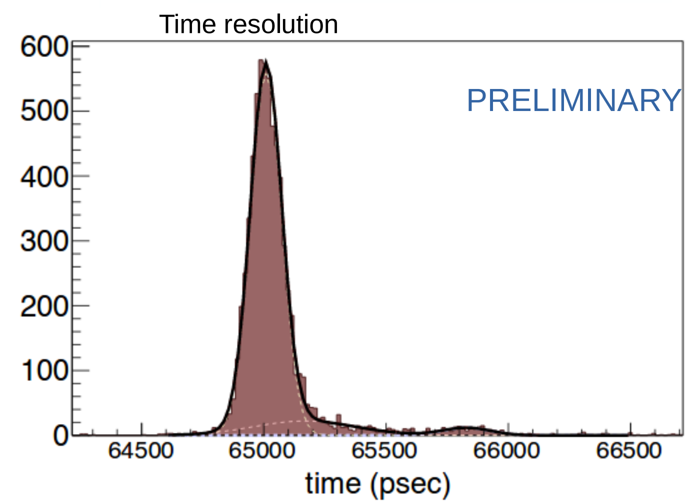








- **LAPPD Tile #25** is the **first one to be deployed in ANNIE**
  → First deployment in an operating neutrino detector
- Being **thoroughly tested** at ISU (gain, time resolution, etc.)
- Preliminary results show a **good behavior** even at lower voltage than expected during nominal operation



Credit: **Matt Wetstein** (Iowa State University)

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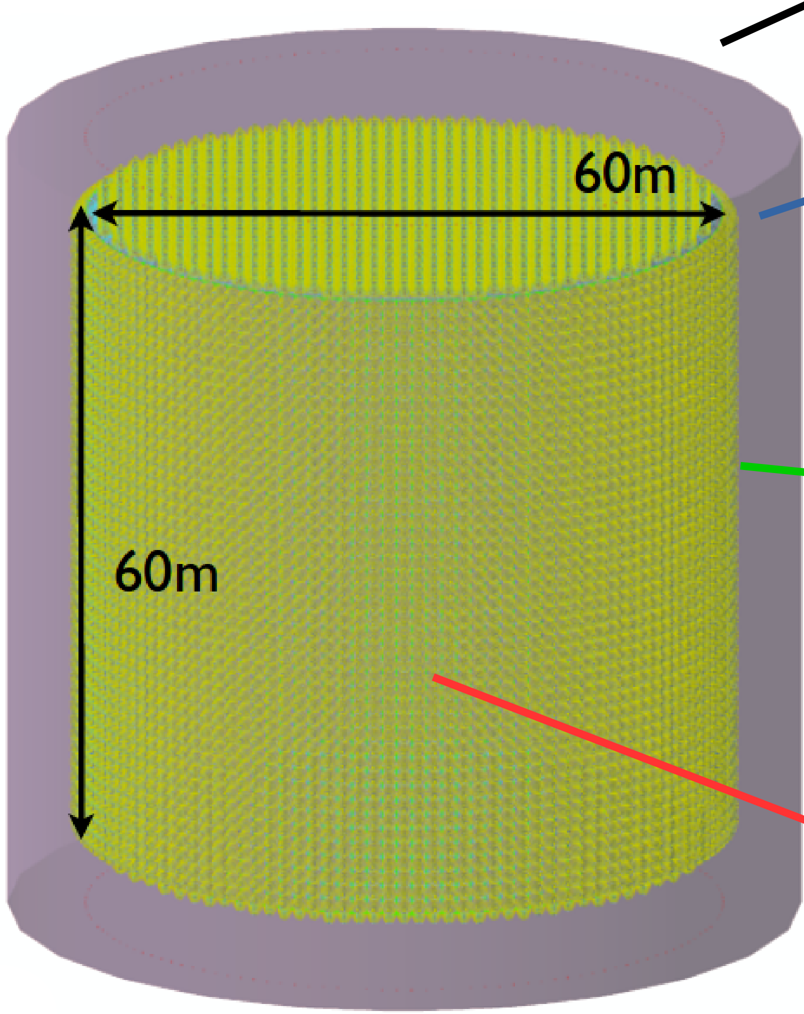
The Theia detector

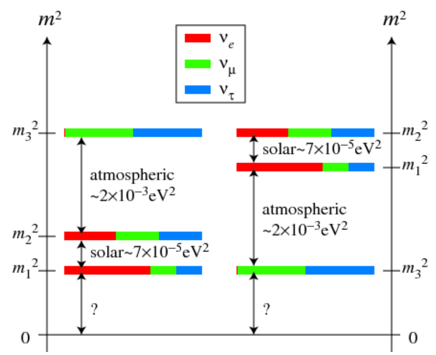
Theia



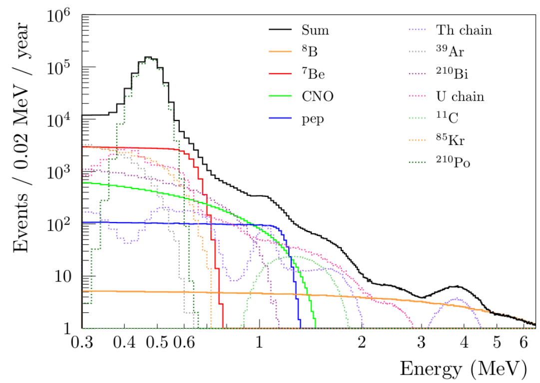
- Underground location (>~ 4000 m.w.e)
- **Outer shielding**:
  - Pure water
  - Instrumented to act as an active veto
- **Support structure**:
  - Diameter/Height ~ 60 meters
  - Holds **> 100000 PMTs** → **90% coverage**
- **Target volume**:
  - Reference design: **Water-based Liquid Scintillator**
  - Possibility to **load metals**
  - Possibility to **deploy inner "bag"**

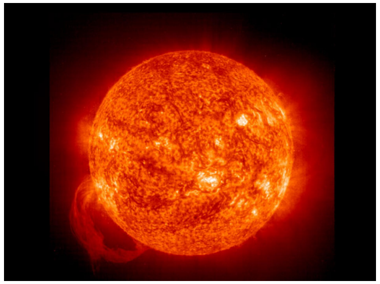
Theia – Physics goals

Long baseline



Solar neutrinos





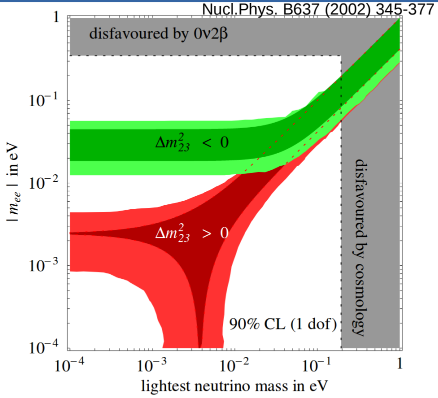
National Geographics

Supernova neutrinos

Wikipedia.com

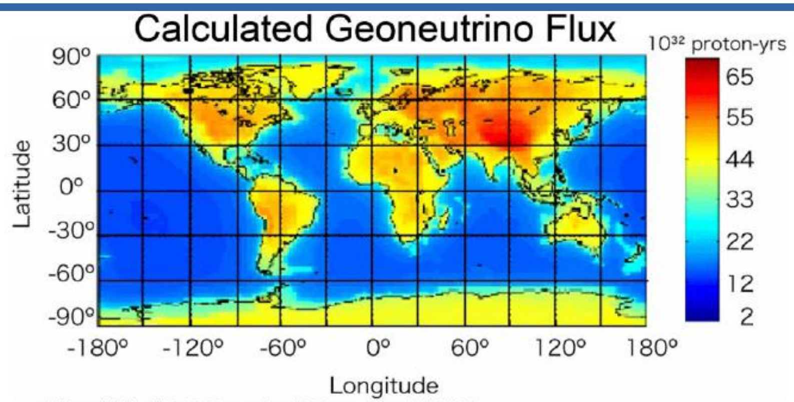
Double-beta decay

Nucl.Phys. B637 (2002) 345-377



Broad range of neutrino physics!

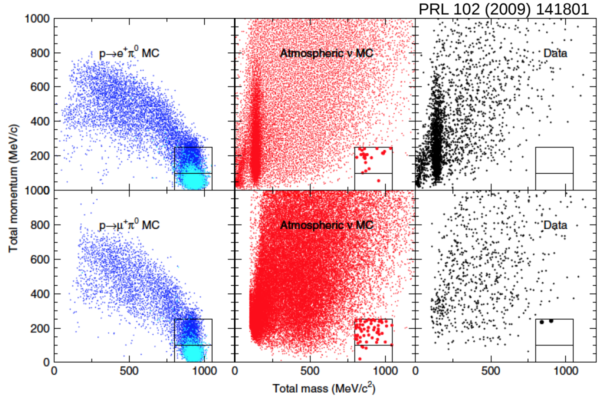
Geoneutrinos



G. Fiorentini, M. Lissia, F. Mantovani, and R. Vannucci, hep-ph/0401085

Nucleon decay

PRL 102 (2009) 141801



… and more !

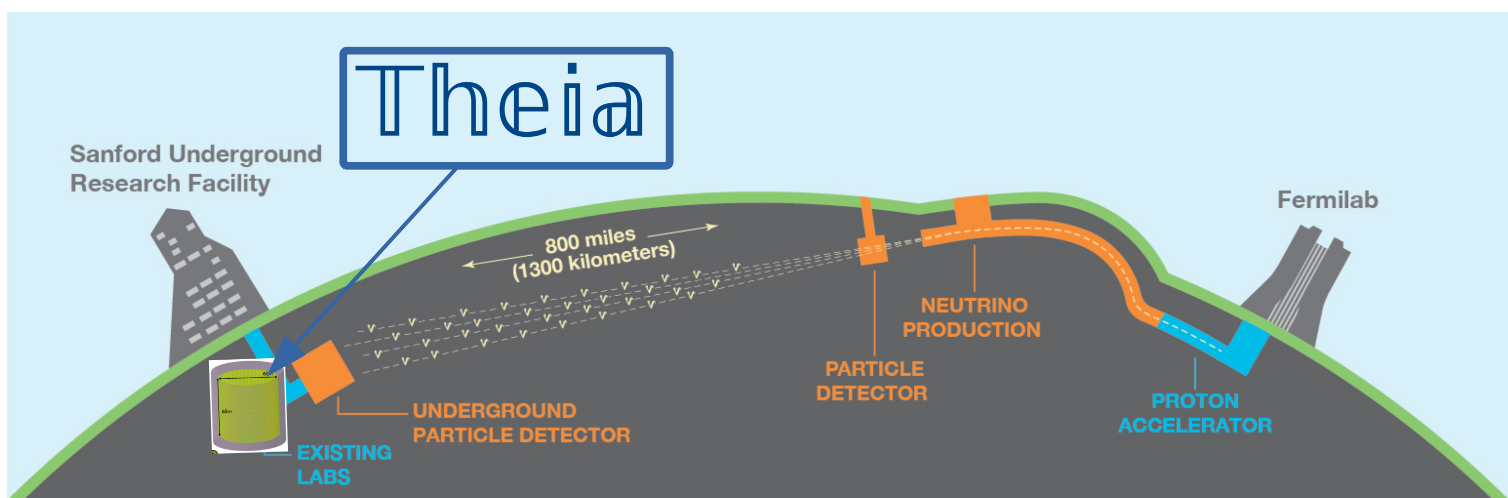
Theia – Long baseline oscillations

- **DUNE**: Four 10-kt liquid argon detectors placed at SURF
    - 4000 m.w.e. overburden
    - High intensity beam from Fermilab 1300 km away

- Another detector using a different detection medium in the DUNE cavern would **increase the sensitivity to CP violation and mass hierarchy** (if not already discovered)

- **Design studies ongoing**

DEEP UNDERGROUND NEUTRINO EXPERIMENT

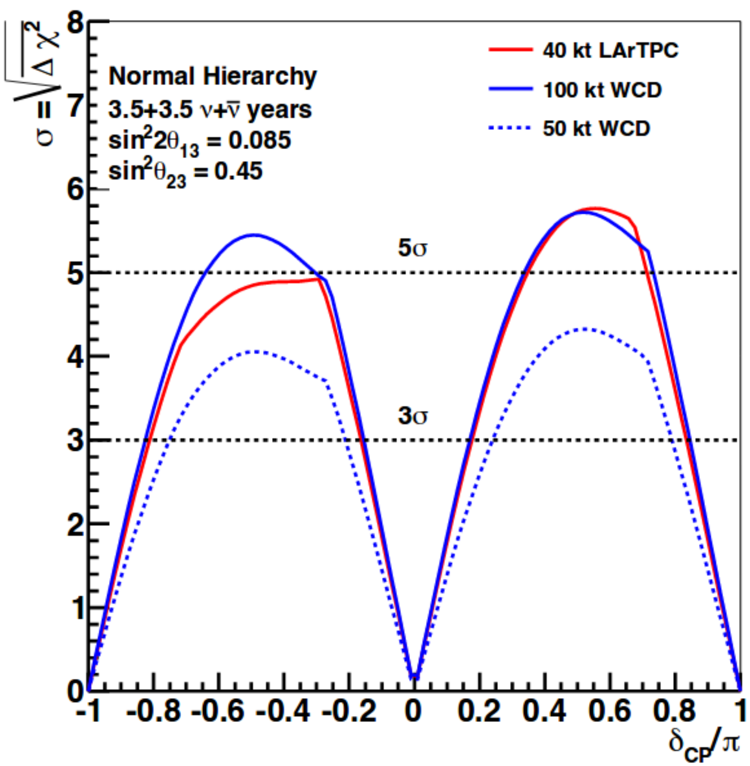


Theia – Long baseline oscillations

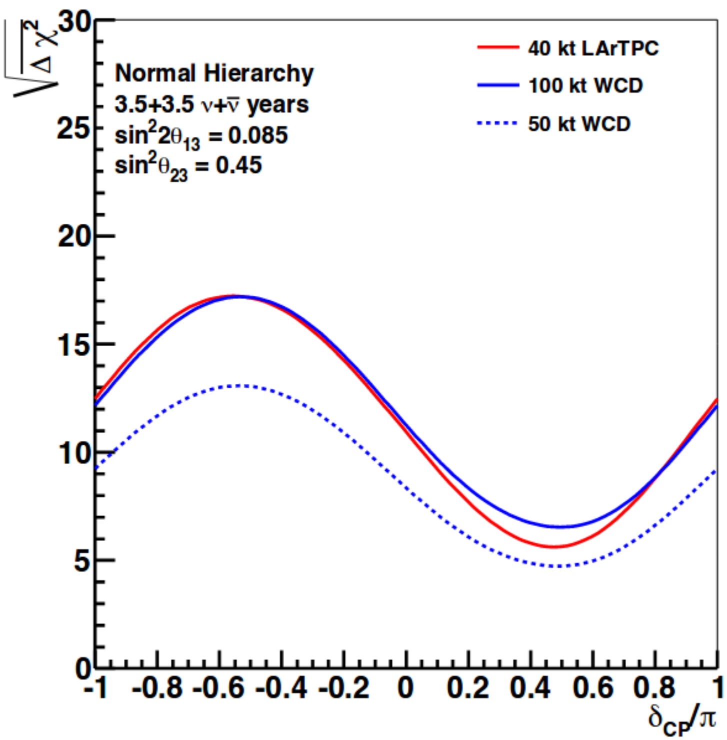
- The addition of a **50-kt water Cherenkov detector next to DUNE** increases the sensitivity to the missing neutrino oscillation parameters:
  - CP violation: **5σ over 50% of the δ_{CP} range**
  - Mass hierarchy: **> 5σ the whole δ_{CP} range**

- However, this is a **conservative scenario for Theia+DUNE**:
  - Increased background rejection
  - Reconstruction of missing energy (neutrons)
  - Fast timing sensors

CP Violation Sensitivity

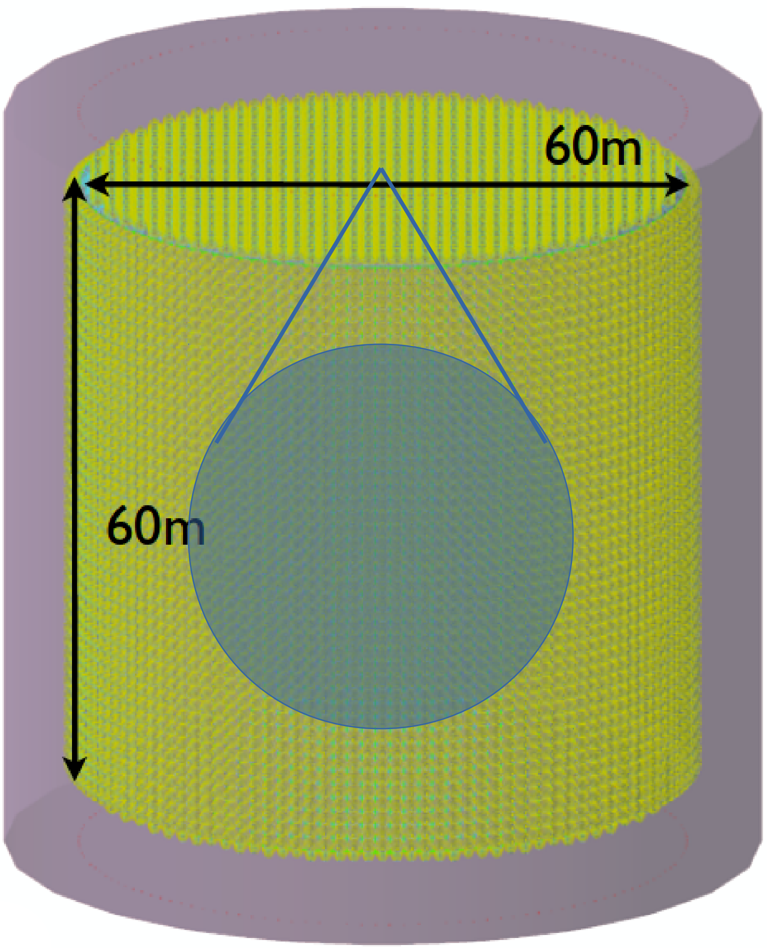


Mass Hierarchy Sensitivity

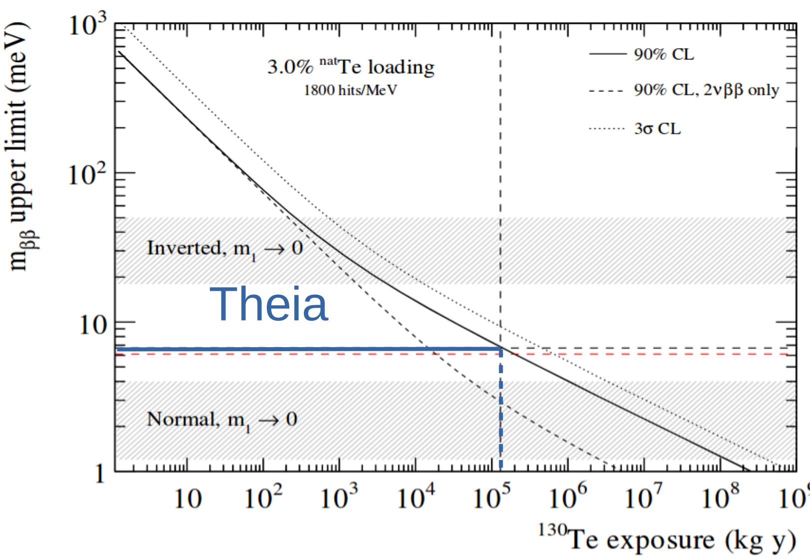


Theia – Double-Beta Decay

- $0\nu2\beta$ approaches:
  - **Entire detector** filled with WBLS loaded with a 2β isotope
    → "SNO+-like"
  - **Only inner balloon** filled but with a higher concentration of 2β isotope
    → "KamLAND-Zen-like"
- **Fiducialization** and **tagging techniques** (triple coincidence, directionality, etc..) greatly reduce backgrounds
- Isotopes in consideration: **^{136}Xe and ^{130}Te**
- **Goal: Reach $T^{0\nu2\beta}_{1/2}$ ~ 10^{28} years**



Assumptions:
- 8 m balloon
- 3% Te loading
(300 tonnes)



Limit on $T^{0\nu2\beta}_{1/2}$ = 1.2 x 10^{28} years

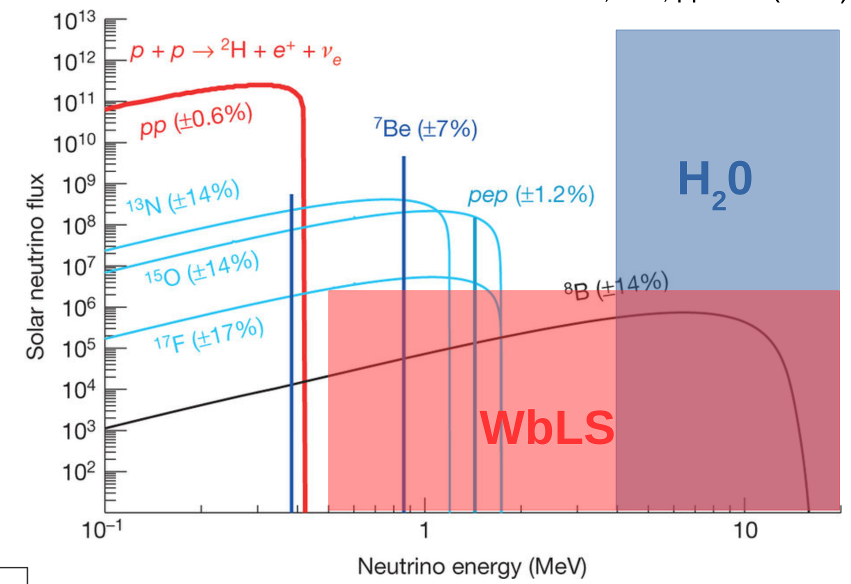
Theia will completely probe the IH part of the mass phase space!

… and start probing the NH part with a higher isotope loading!

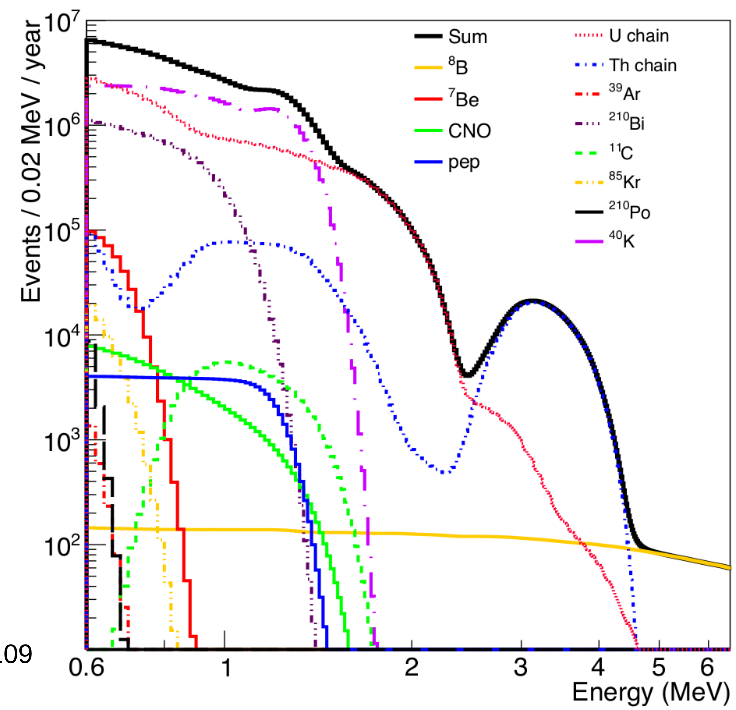
Theia – Solar neutrinos

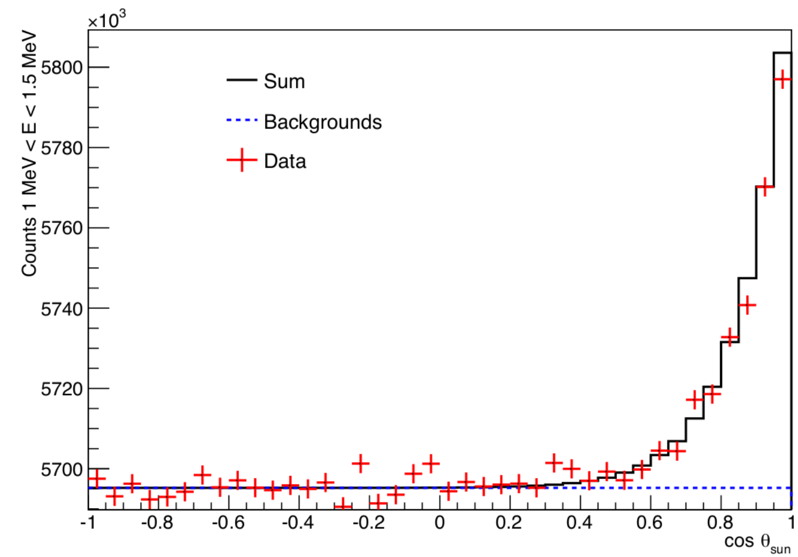
- The addition of scintillation dramatically **lowers the detection threshold**
  - Increases sensitivity to a wider range of solar ν's
  - Keeps directional information with Cherenkov
- Measuring the CNO and pep components of the solar flux allows to:
  - Study **solar metallicity**
  - Study **neutrino oscillations** and matter effects

Nature, 512, pp. 383 (2014)



Predicted solar neutrino spectra for:
- 50 kT Theia with 5% WbLS
- 5 years
- 90% coverage
- 25° resolution
- Borexino and SNO background levels





R. Bonventre & GDOG, arXiv: 1803.07109
Accepted to Eur. Phys. Jour.

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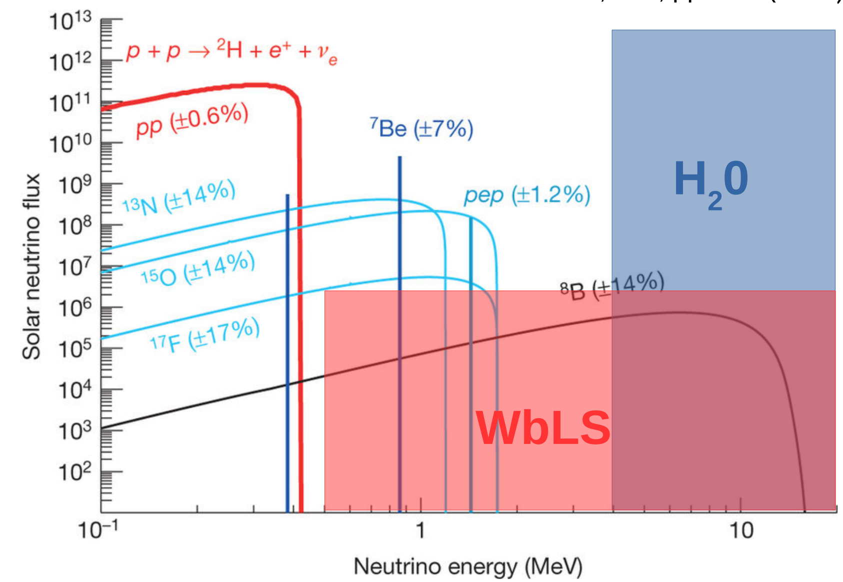
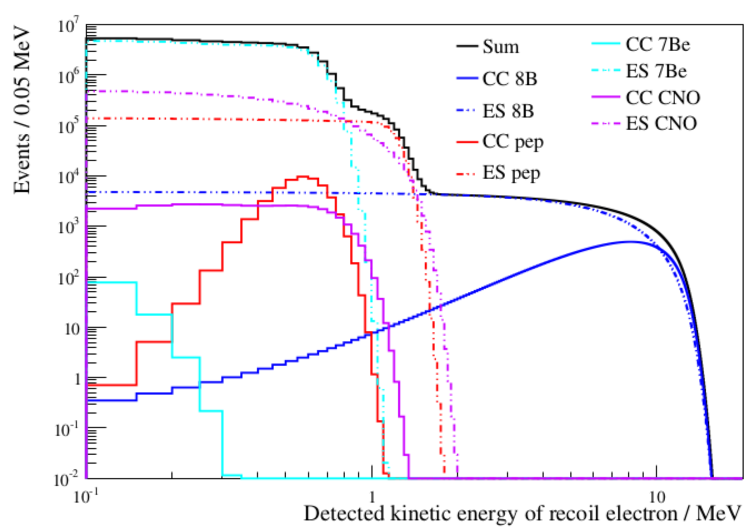
- Measuring the CNO and pep components of the solar flux allows to:
  - Study **solar metallicity**
  - Study **neutrino oscillations** and matter effects
- Isotope loading (^{7}Li, ^{71}Ga, ^{37}Cl) allows the detection of **charged current interactions** and not only elastic scatterings

Nature, 512, pp. 383 (2014)

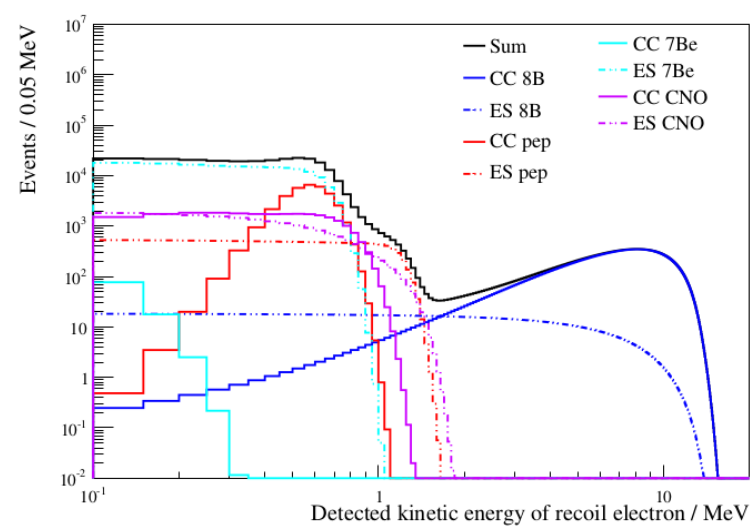


Predicted solar neutrino spectra in 30 kT Theia loaded with 1% ^{7}Li

More details: arXiv:1409.5864

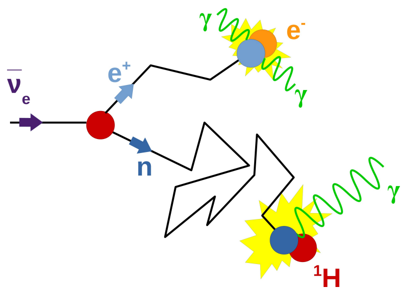


No directionality cut

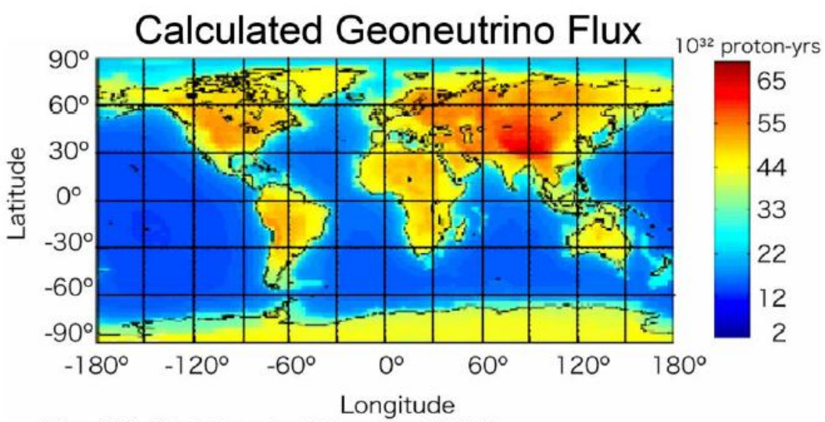


Directionality cut (to cut ES events)

Theia – Geoneutrinos and supernovae



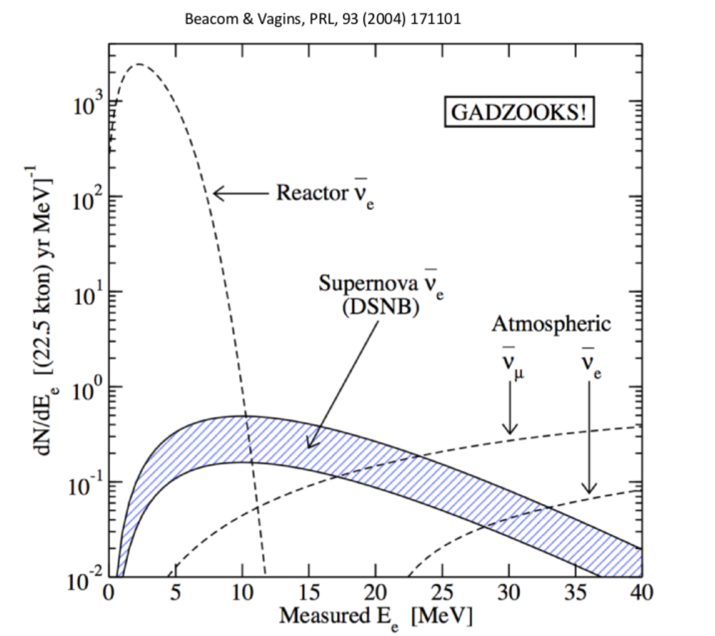
Antineutrinos detected through **Inverse Beta Decay** on H
→ Coincidence (e^+,n)



G. Fiorentini, M. Lissia, F. Mantovani, and R. Vannucci, hep-ph/0401085

- A total of ~100 geoneutrinos have been detected by Borexino and KamLAND so far
- Given its size and low threshold, Theia would detect **the same number in a few months**
- Beneficial isotope loading: **Gd, Li, B**

- **~8000 events** for a 10 kpc SN
- Ability to tag IBD neutrons:
  → Selection of ES events and good angular reconstruction (~3°)
  → Crucial input for astronomers



- **Diffuse Supernova Background**:
  → About 1 event/10kt/year expected

Conclusion and take-home message

- **Theia** is a large water-based liquid scintillator detector with a **impressively broad range of physics goals**

- **Water-based Liquid Scintillator** combines the **advantages of both water and liquid scintillator:** directionality, light yield, optical properties, cost, etc..

- **Long baseline** program is **complementary to DUNE's** and could be happening in parallel

- Theia would provide **world leading measurements** in a wide range of physics goals

- Theia benefits from other existing and/or funded experiments such as **ANNIE** and **WATCHMAN**

THANK YOU FOR YOUR ATTENTION

BACK-UP

Water-based Liquid Scintillator - Tunability

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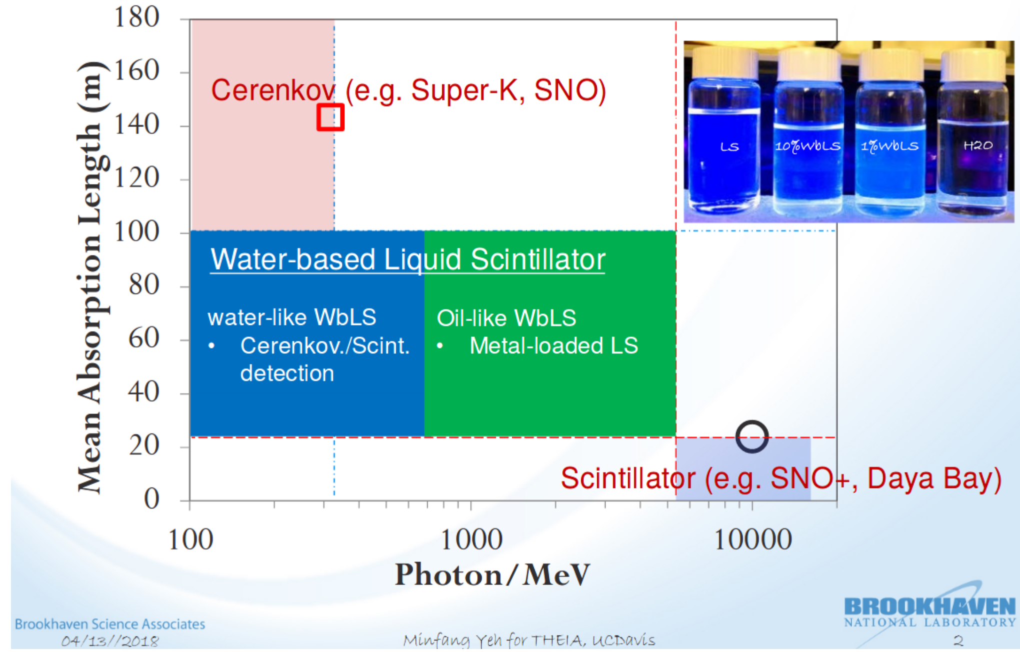
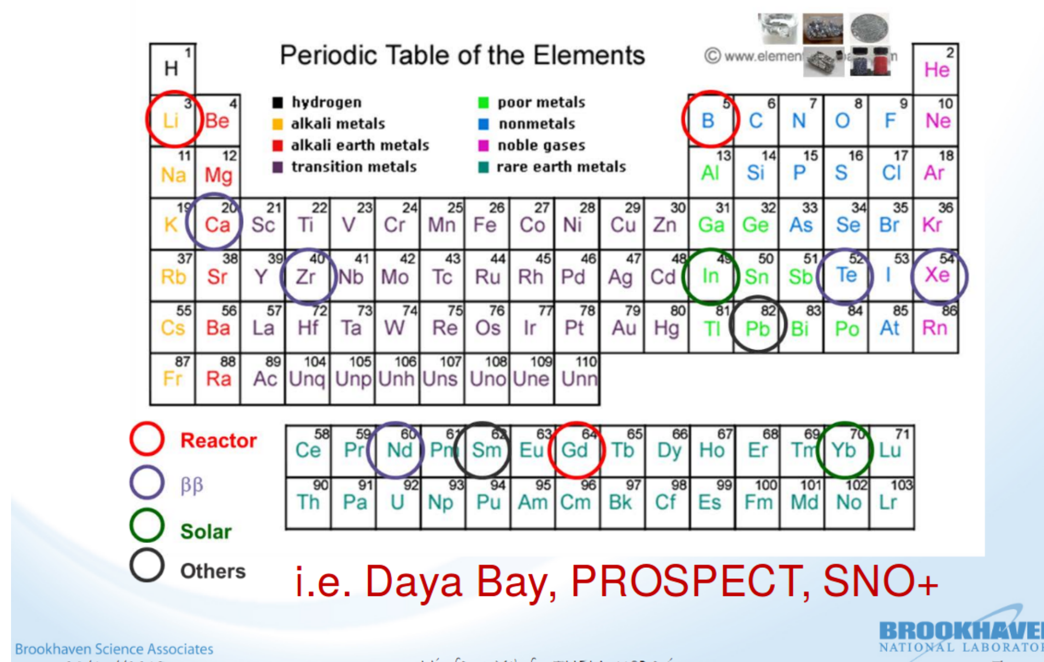
- Different applications might require different levels of scintillation and Cherenkov light:
  - **Low energy physics** (~MeV) → High LS content (> 20%) and **oil-like WbLS**
  - **Beam physics** (~GeV) → Lower LS content (< 20%) and **water-like WbLS**



- **Isotope loading** (Li, Gd, Te, etc..) has been performed on both water and LS

- **Hydrophilic elements** would be the easiest to load (e.g. Gadolinium compounds)

- Metal-loaded WbLS would help a broad range of neutrino experiments:
  - **Reactor** (neutron sensitivity): Gd, Li, B
  - **Double-beta decay**: Te, Nd, Xe



Water-based Liquid Scintillator - Purification and compatibility

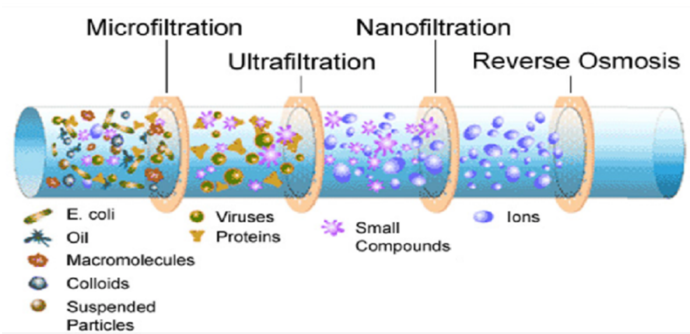
- **Nanofiltration**: Filtration process using membranes to separate water and organic components (micelles)
  - Widely used in the food industry
  - Allows water to go through the membrane **without damaging the micelles**
  - **Scalable** with reasonable flow rate

- Water will then be purified using a regular de-ionizing process

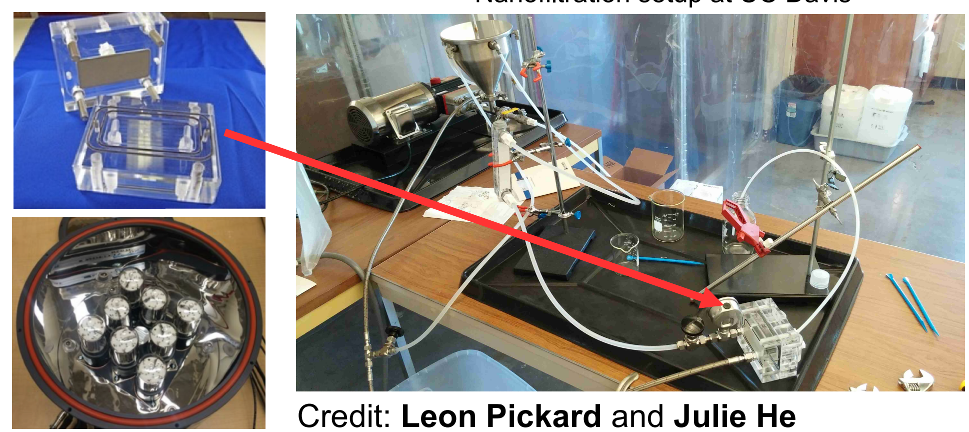
- **Work at UC Davis**:
  - Small-scale nanofiltration apparatus
  - Post-filtration absorbance and light yield measurements to ensure wbLS hasn't been damaged

- Since surfactant might be aggressive on some materials, all materials must undergo a **compatibility test beforehand**

Nanofiltration principle

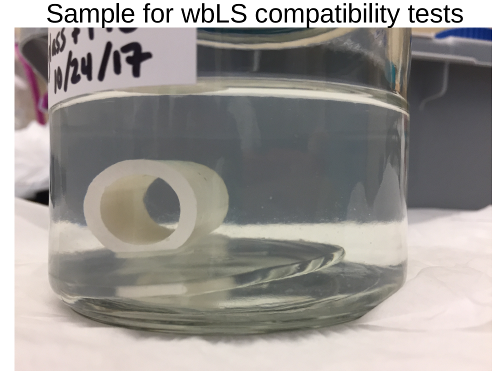


Nanofiltration setup at UC Davis

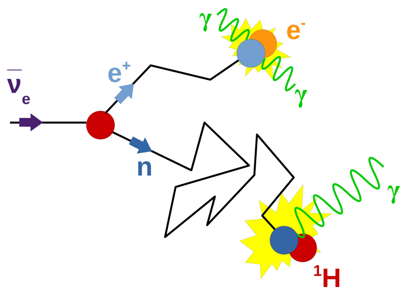


Credit: **Leon Pickard** and **Julie He** (UC Davis)

Sample for wbLS compatibility tests



Theia – Reactor neutrinos



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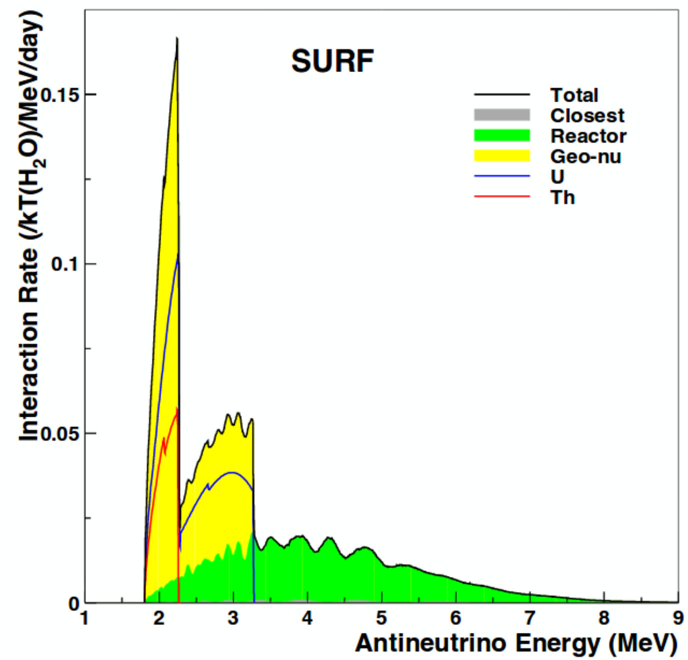
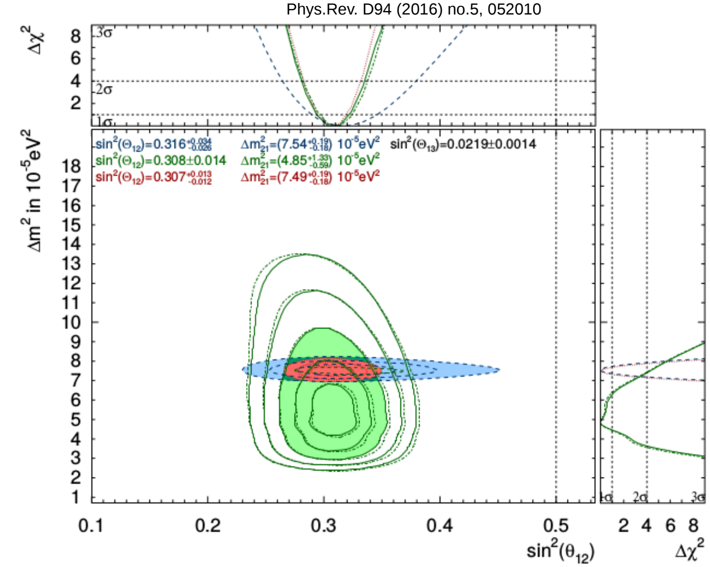


- About 22 reactor neutrinos (and 30 geoneutrinos) expected per kt per year at SURF
- 30 kt Theia → **~650 IBD reactor events per year**
- Possibility to **measure Δm^2_{12}** using reactor neutrinos
- Comparison with Δm^2_{12} measured using solar neutrinos **in the same detector**
- Theia could provide an answer to the **existing solar/reactor tension** (1.5σ) on Δm^2_{12}

Phys.Rev. D94 (2016) no.5, 052010



Theia – Sterile neutrinos

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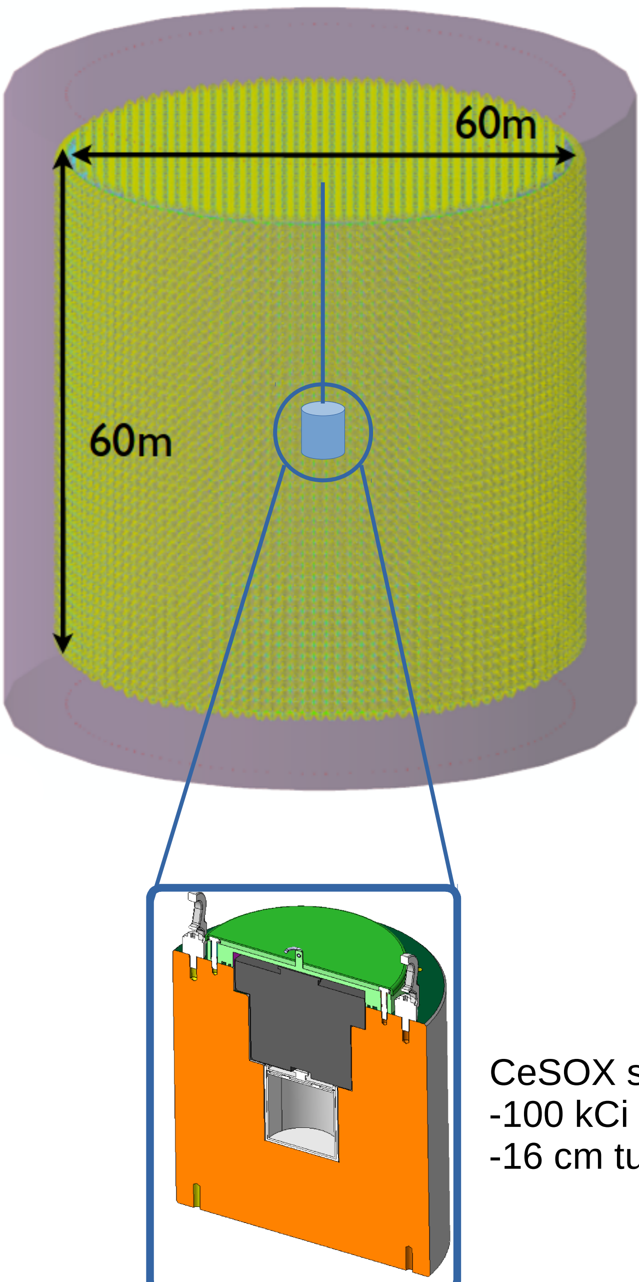
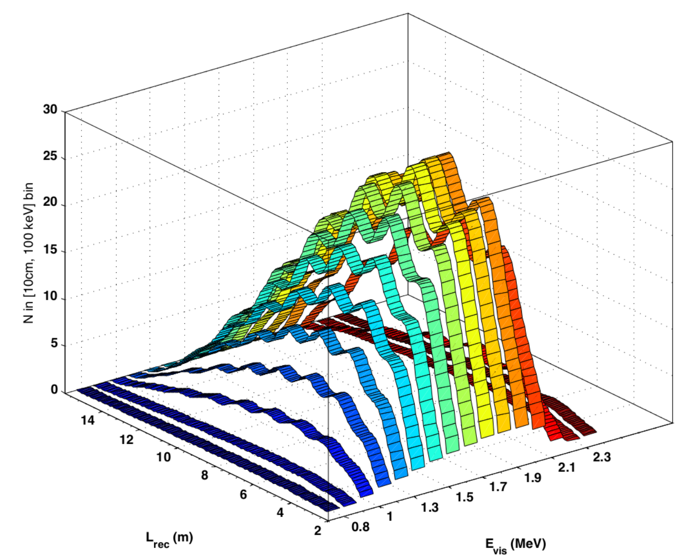


CeSOX source design:
-100 kCi ^{144}Ce-^{144}Pr
-16 cm tungsten shield

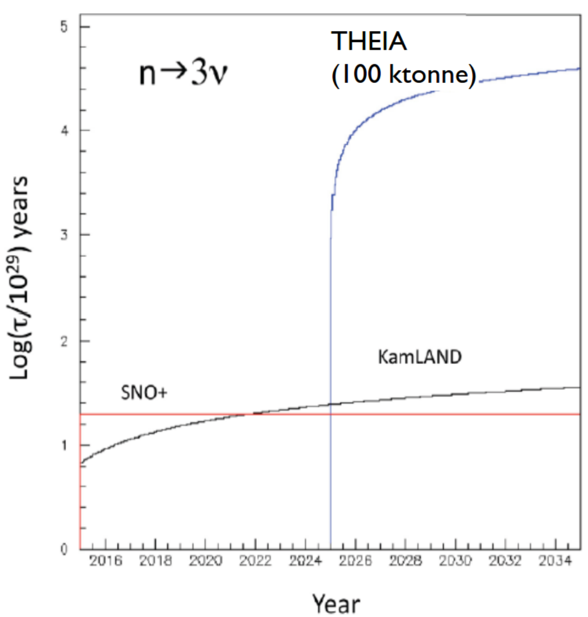
- Hypothetical **eV-scale sterile neutrino** whose existence is accessible through **short baseline oscillations**
- Concept from **CeSOX/CeLAND** (Phys.Rev.Lett. 107 (2011) 201801):
  - Intense radioactive source in or next to Theia
  - Observation of a deficit and a spectral distortion as a function of distance
  - Requires good energy and position reconstruction
- **IsoDAR/DAEδALUS**: High intensity ^{8}Li decay at rest

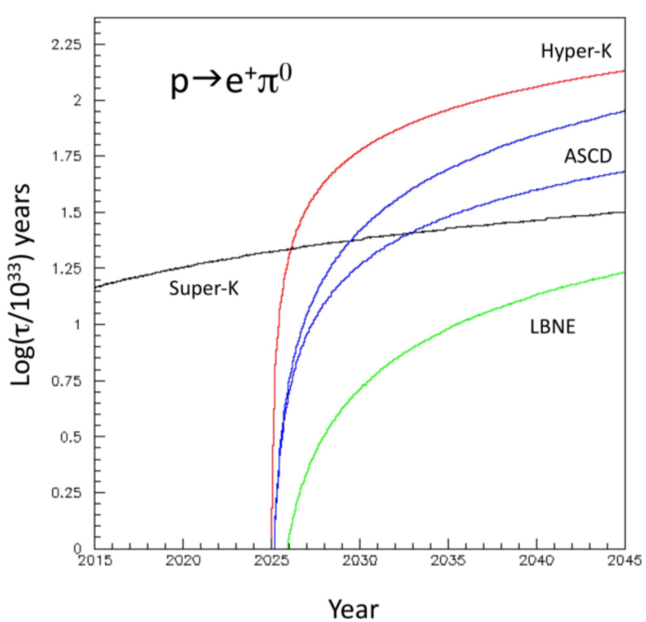
Energy spectrum distortion as a function of distance in CeSOX

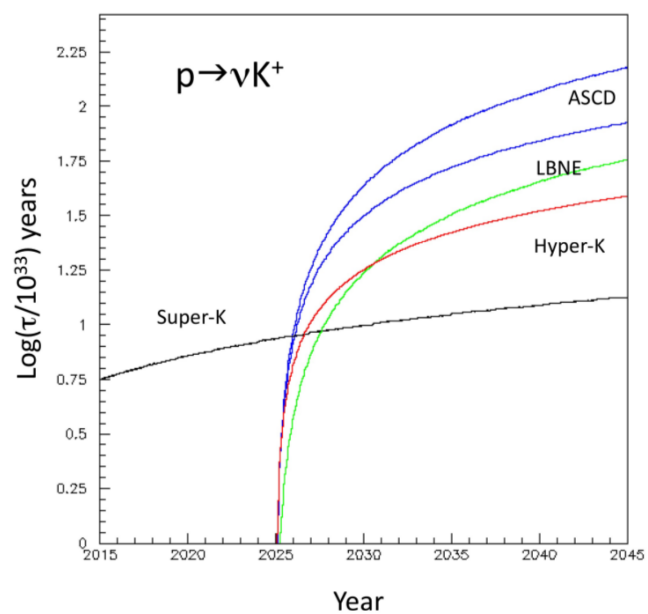


Theia – Nucleon decay searches

- **Huge size**, **deep location** and **scintillation light** make Theia an impressive nucleon decay detector
- Scintillation light allows the **observation of K⁺** created upon a proton decay as well as the gammas emitted upon an **invisible neutron or proton decay** (~6 MeV)
- **Neutron tagging** enhances Theia's sensitivity for proton decay and can be further improved by **isotope loading**







ASCD: Theia 100kT WbLS (+neutron tagging)

Cherenkov/Scint with CHESS

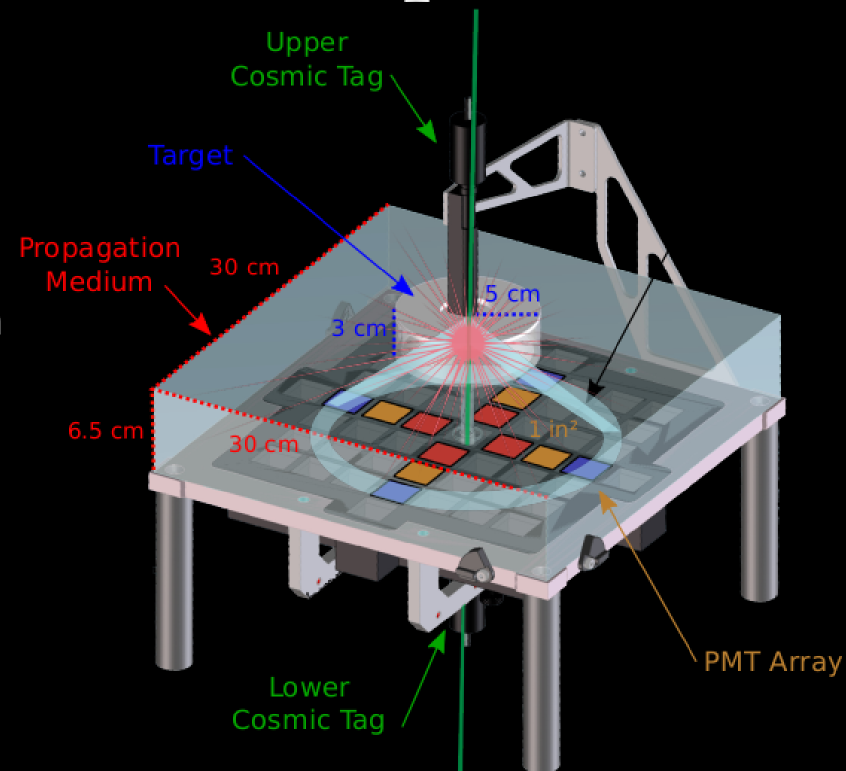
Berkeley group, PRC 95 055801 (2017)

CHESS:
CHErenkov-Scintillation Separation

Select vertical cosmic muon events

Image Cherenkov ring in Q and T on fast-PMT array

Allows charge- and time-based separation



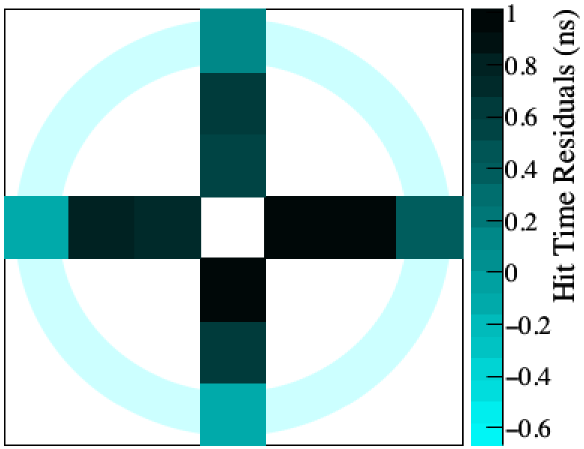
12 1-inch H11934 PMTs (300ps FWHM, 42% QE)
CAEN V1742 (5GHz)
675 samples (135ns window)
CAEN V1730 (500MHz)

From Gabriel Orebi-Gann (UC Berkeley/LBNL)

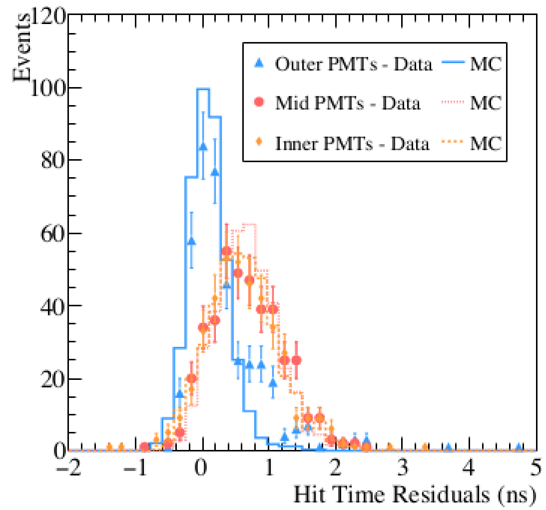
Cherenkov/Scint with CHESS

Berkeley group, Eur. Phys. J. C (2017) 77:811

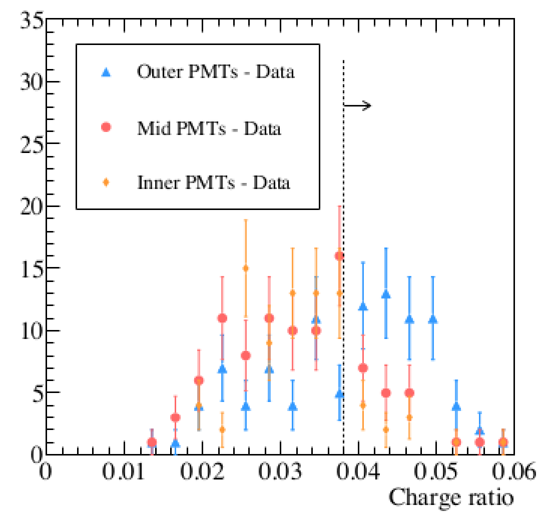
CHESS Results: LAB / PPO



Typical ring candidate event



Time at fixed threshold
Corrected by ToF,
channel delays



Ratio of charge in prompt, 5ns window to charge in total (135ns) window

NOTE: Rise time = 0.75 ± 0.25 ns

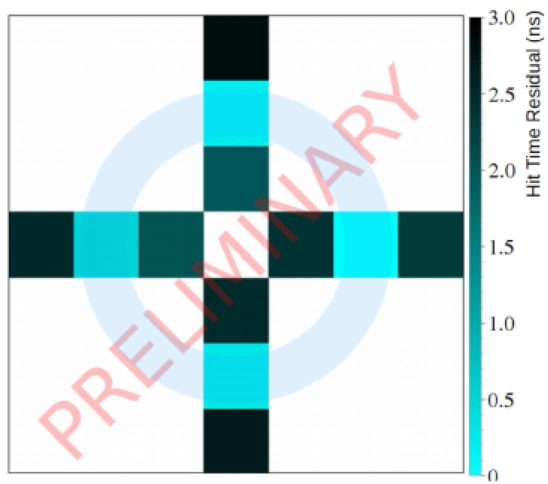
	LAB (time)	LAB (charge)	LAB/PPO (time)	LAB/PPO (charge)
Cherenkov detection efficiency	83 ± 3 %	96 ± 2 %	70 ± 3 %	63 ± 8 %
Scintillation contamination	11 ± 1 %	6 ± 3 %	36 ± 5 %	38 ± 4 %

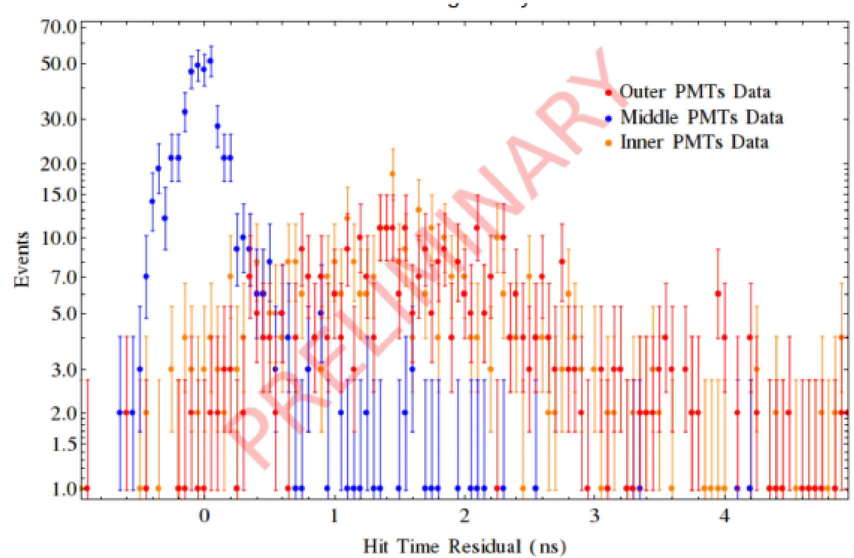
From Gabriel Orebi-Gann (UC Berkeley/LBNL)

Cherenkov/Scint with CHESS

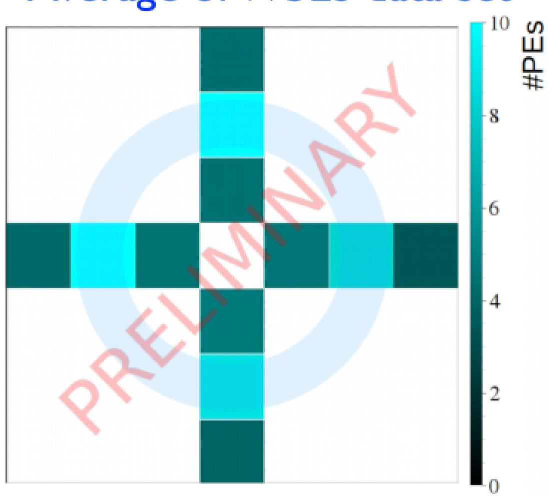
Theia

CHESS Results: 1% WbLS

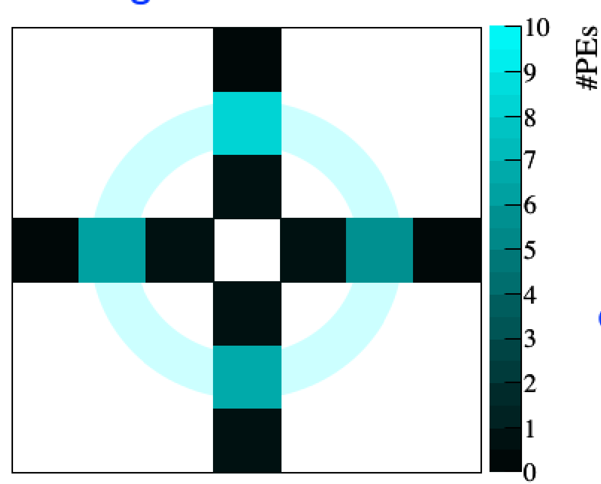




Average of WbLS data set



Average of water data set



Charge rings:
Clearly seeing scintillation light even at 1% LS fraction

From Gabriel Orebi-Gann (UC Berkeley/LBNL)