The Theia Neutrino Detector

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Theia Concept

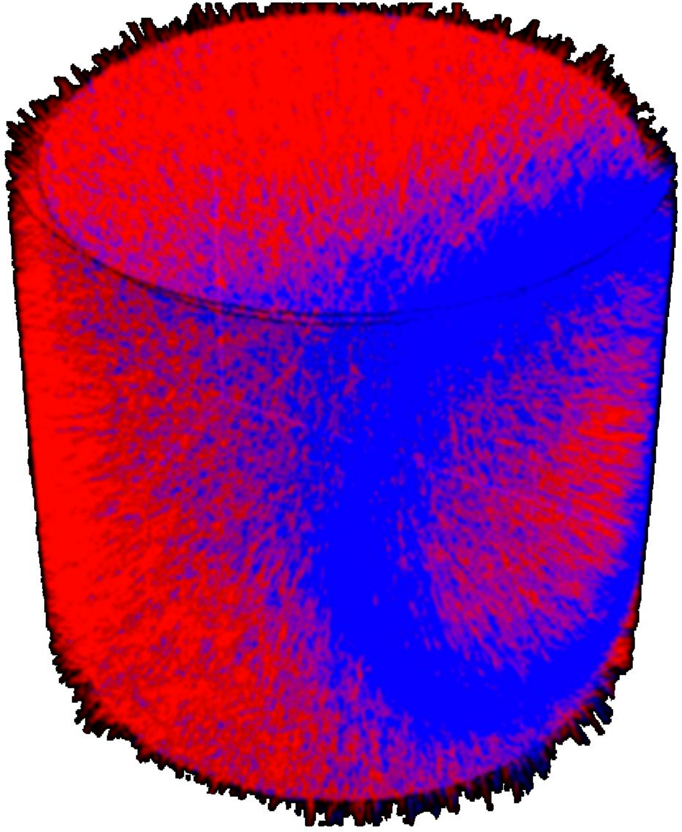
Large volume detector that can make use of both Cherenkov and scintillation photons.

Make use of technological developments on several fronts:

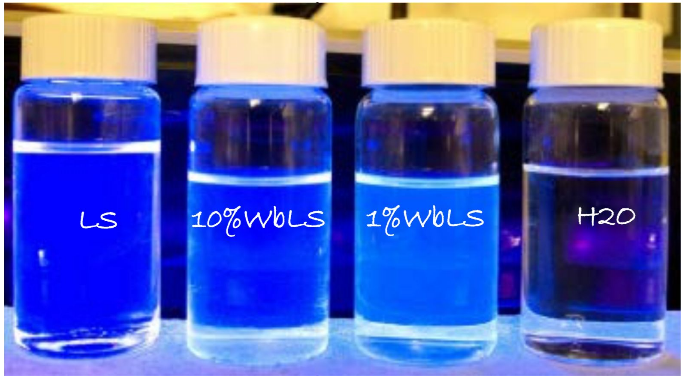
- Novel medium: Water-based liquid scintillator (WbLS)
- Fast, high efficiency photodetectors (fast timing PMTs, LAPPDs, or dichroicons)
- Advanced reconstruction (image recognition using ML and other novel techniques)

For broad range of (mainly) neutrino physics:

- Long baseline oscillations
- Neutrinoless double beta decay
- Supernova neutrinos
- Diffuse SN background
- Solar neutrinos
- Proton decay



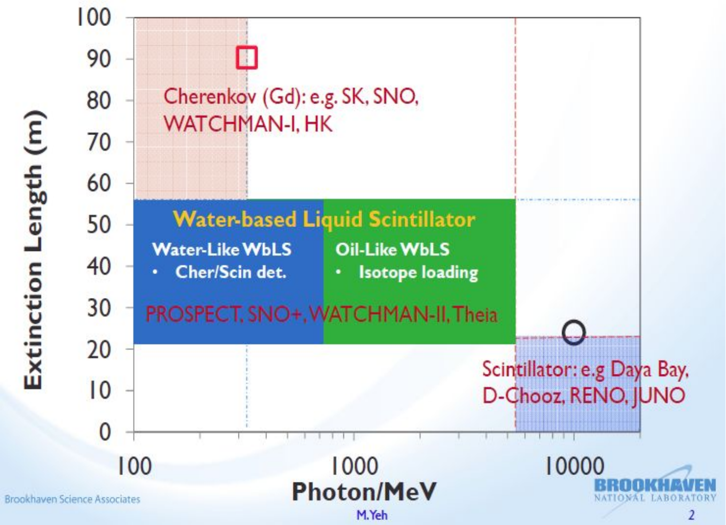
Water-based Liquid Scintillator



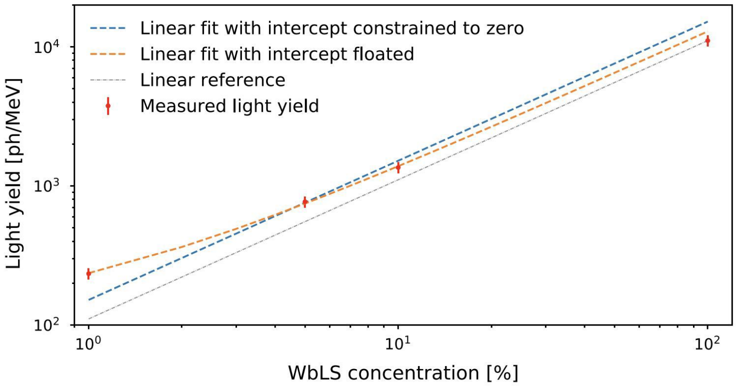
Mixture of liquid scintillator with water.

Provides benefits of both a **liquid scintillator** detector and a **water Cherenkov** detector:

- **Low energy threshold**
- **Good energy resolution**
- **Directional information**
- **Low absorption**



Tunable timing to separate fast (Cherenkov) from slow (scintillation) light and tunable light yield.

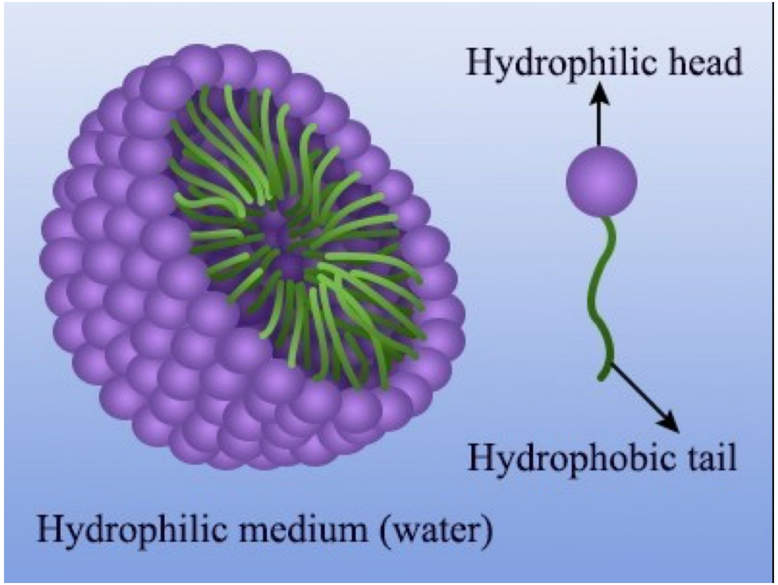


Water-based Liquid Scintillator: Mixing Oil and Water

Water + surfactants + organic scintillator.

Surfactants form “micelles” with scintillator inside.

Same principle as cleaning insoluble materials with detergent and water.



Strong WbLS R&D program ongoing at BNL, UC Berkeley, LBNL, and elsewhere.

See R. Wang’s talk (yesterday) and L. Lebanowski’s talk (a few minutes ago).

Separation of Cherenkov and Scintillation Signals

Large Area Picosecond Photon Detectors (LAPPDs)

Dichroic filters

PMTs

Timing

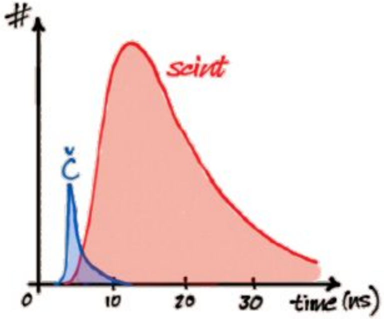
"instantaneous chertons" vs. delayed "scintons"
→ ns resolution or better

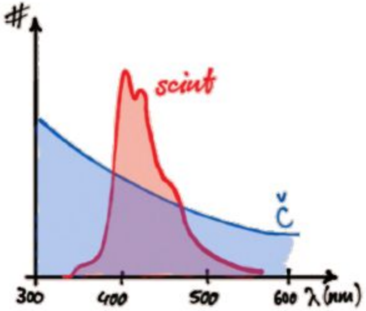
Spectrum

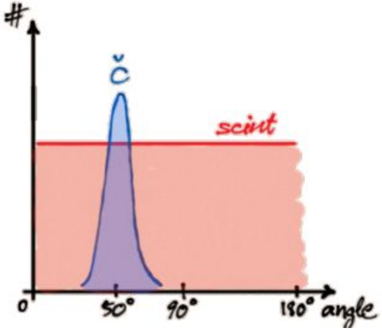
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity

Angular distribution

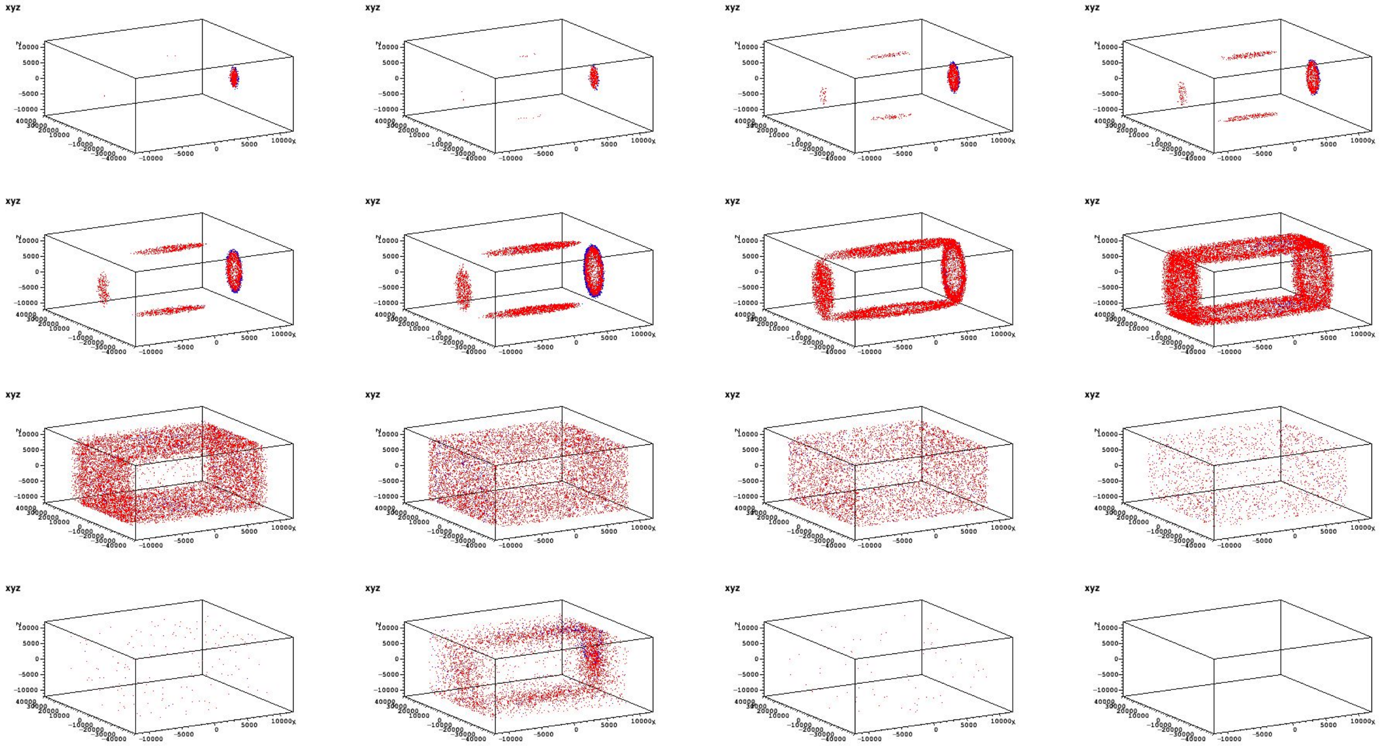
increased PMT hit density under Cherenkov angle
→ sufficient granularity







Cherenkov and Scintillation Light



600 MeV muon

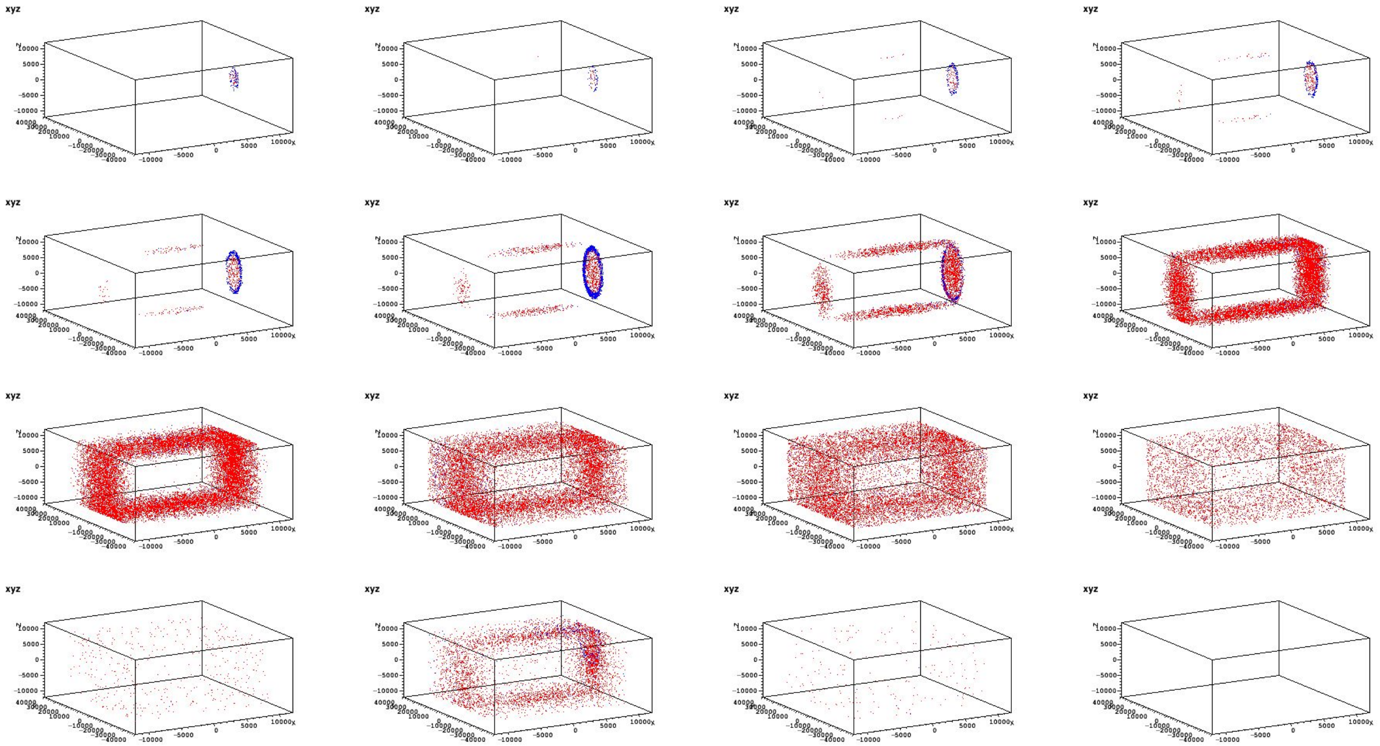
2 ns decay time

Scintillation light

Cherenkov light

2 ns time interval, except last three figures 100 ns interval

Cherenkov and Scintillation Light



600 MeV muon

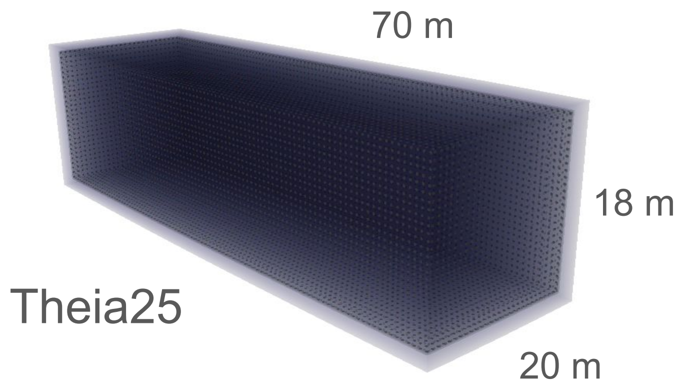
45 ns decay time

Scintillation light

Cherenkov light

2 ns time interval, except last three figures 100 ns interval

Detector Options and Staging



Two options considered in Theia white paper:

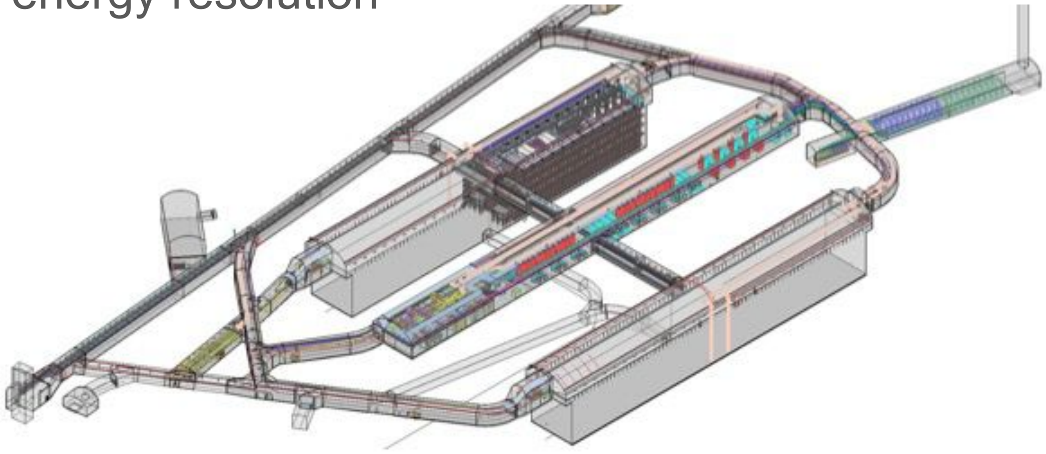
- Theia100 (50 m x 50 m diameter)
- Theia25 (designed to fit in the 4th DUNE cavern)

	Detector configuration	Physics goals
Phase I	1-10% WbLS	Long baseline (δ_{CP},θ_{23},Δm_{23}^2), proton decay, SN neutrinos, diffuse SN background
Phase II	Higher concentration WbLS, increased photocoverage	As above + solar neutrinos, geoneutrinos
Phase III	Add inner balloon of LAB + PPO	Neutrinoless double beta decay

WbLS for DUNE Physics

Theia complements the LAr program at DUNE in several ways:

- Offers a different nuclear target, with different systematics.
- Offers a *simpler* nuclear target, meaning reduced FSI systematics and simpler event topology (less DIS).
- Improved low-energy resolution
- Fast Timing



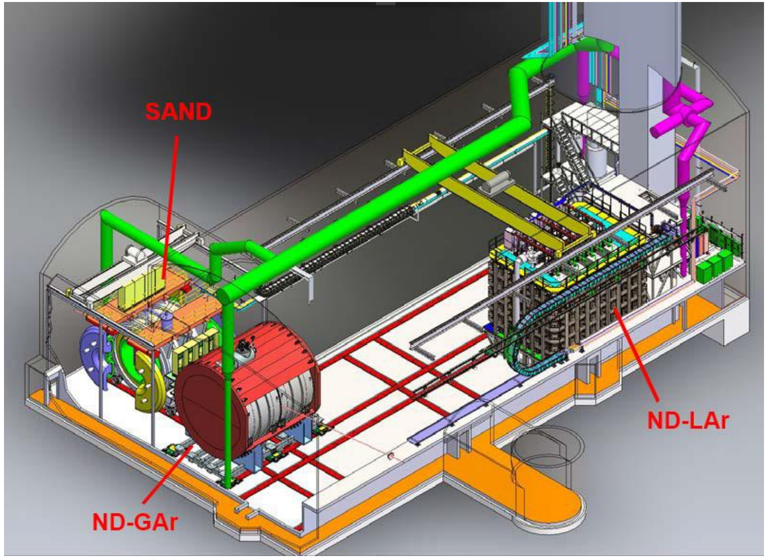
Can Theia25 offer the same LBL sensitivity as LAr?

Theia offers many advantages as a DUNE module of opportunity, but unless it can achieve the same LBL physics as a LAr module, it is dead on arrival.

Initial sensitivity studies assuming performance as pure water and using GLoBEs are promising.

But these studies need to be repeated with more realistic simulation and reconstruction, and a more powerful fitter.

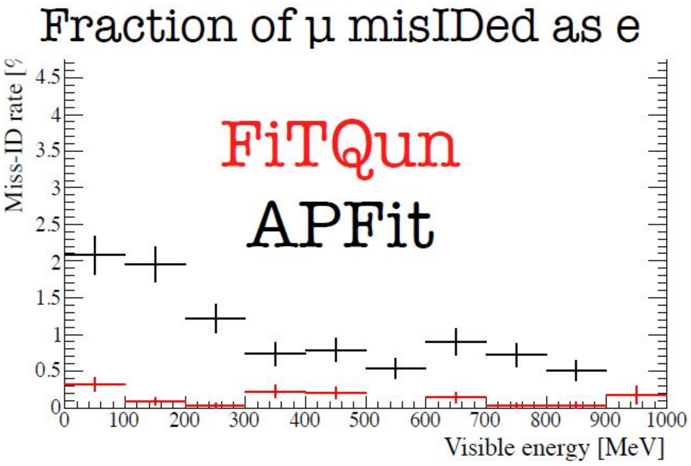
These studies will allow us to set requirements on the near detector - what is needed to adequately constrain the systematics?



Advances in Cherenkov Reconstruction

Ancient history: Studies of a water Cherenkov detector in the LBNF beamline were done for LBNE (DUNE's predecessor).

But (scintillator aside) reconstruction has come a long way since then!



New reconstruction software called FiTQun developed for SK and T2K.

Improvements in e/μ discrimination, NC rejection, multi-ring reconstruction.

Machine learning techniques under development.

Energy Reconstruction for WbLS

Several avenues being explored concurrently:

FitQun

FitQun for WbLS (U. Minn.)

Fast Reconstruction (G. Yang)

Machine Learning

Final Reconstruction Method

Fast Energy Reconstruction

Fast energy reconstruction by G. Yang:

Measure energy of particles over Cherenkov threshold from Cherenkov rings

Remaining particles measured calorimetrically.

E.g. for ν_μ CCQE: Calorimetric energy = Total scintillation light - muon energy equivalent scintillation light.

Then E_ν = Muon energy + calorimetric energy

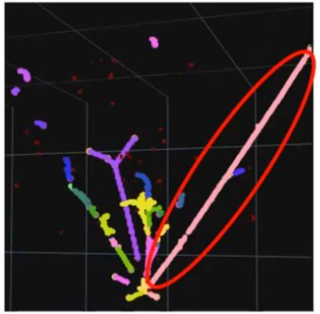
Similarly, if a pion is over Cherenkov threshold, then E_ν = Muon energy + pion energy + calorimetric energy

Fast Energy Reconstruction

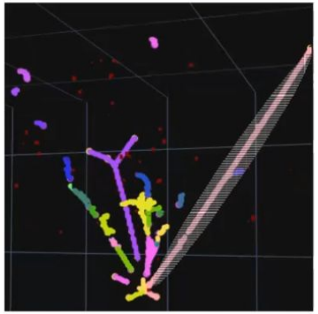
Note that this is the same logic as used by DUNE for LAr!

Neutrino energy = Muon energy + everything else (calorimetric)

$$E_\nu(\nu_\mu) = \text{[muon energy (range)]} + \text{[everything else (calorimetric)]}$$



muon energy
(range)



everything else
(calorimetric)

Fast Energy Reconstruction: Energy Resolution

Energy resolution			
Decay time	μ-only using Cherenkov	μ and π using Cherenkov	μ, π and p using Cherenkov
2 ns	12.7%	9.209%	9.112%
15 ns	12.4%	8.989%	9.10%
45 ns	11.51%	7.844%	8.301%

Compare DUNE LAr: Preliminary energy resolution of 20% for ν_μ CC

Note that these are both preliminary results! But the simpler topology of events in water offers some promise as compared to argon.

Sensitivity

Sensitivities previously produced with GLoBES, assuming pure water performance (at right).

Study in progress:

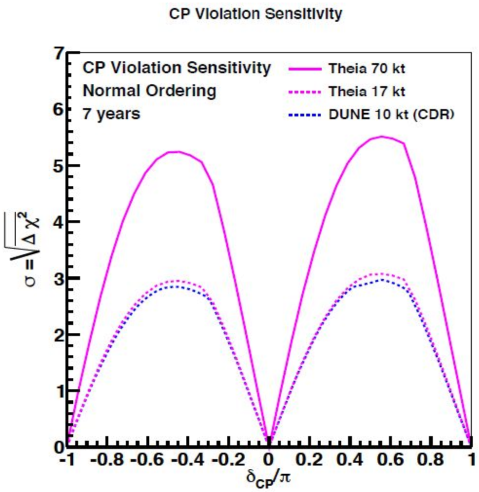
New simulation → new reconstruction → new fitter

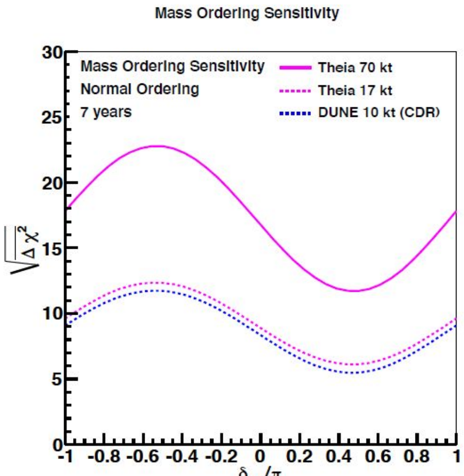
Various fitters available - preliminary fits done in Cafana.

Aiming to use MaCh3 fitting framework, which DUNE has moved to.

However, full MaCh3 fits take a long time.

→ Developing a fast fitter for MaCh3 to allow us to run samples with many parameter choices and get fast fits.





Summary

- WbLS shows great promise for combining the best of scintillation and Cherenkov detectors.
- Theia offers an extraordinarily broad physics reach: long baseline measurements, $0\nu\beta\beta$ decay, proton decay, solar neutrinos, geoneutrinos, SN neutrinos, …
- Theia also offers complementarity with DUNE LAr physics by allowing a different nuclear target without sacrificing sensitivity for oscillation physics.
- A strong, multi-pronged R&D program exists in support of WbLS.
- New reconstruction tools in development.
- Full oscillation sensitivity study in progress.