Theia

A Next-Generation Water-Based LS Detector

NNN 2019

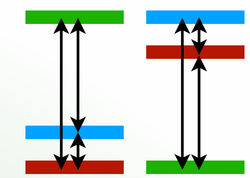
November 9, 2019

Andy Mastbaum
Rutgers University
mastbaum@physics.rutgers.edu

Big Questions

δ_{CP}

Could *CP* violation in neutrino interactions explain the matter/antimatter asymmetry?



What is the ordering of the neutrino masses?

Standard Model Physics

$$\nu \overset{?}{=} \bar{\nu}$$

Is the neutrino its own antiparticle?

What is the mass of the neutrino, and why is it so small?

Beyond the Standard Model

Are there new interactions we could discover via neutrinos?

ν_s

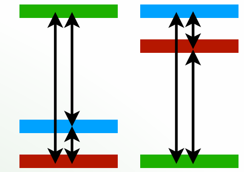
Are there additional neutrinos beyond the known three types?

Big Questions

Long Baseline

δ_{CP}

Could *CP* violation in neutrino interactions explain the matter/antimatter asymmetry?



Long Baseline

What is the ordering of the neutrino masses?

NLDBD

$$\nu \stackrel{?}{=} \bar{\nu}$$

Is the neutrino its own antiparticle?

Standard Model Physics

Beyond the Standard Model

NLDBD
Beta Decay
Cosmology

What is the mass of the neutrino, and why is it so small?

Long Baseline

Are there new interactions we could discover via neutrinos?

ν_s

Short Baseline

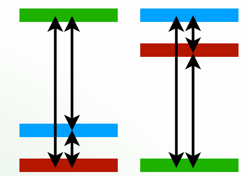
Are there additional neutrinos beyond the known three types?

Big Questions

Long Baseline

δ_{CP}

Could *CP* violation in neutrino interactions explain the matter/antimatter asymmetry?



Long Baseline

What is the ordering of the neutrino masses?

NLDBD

$$\nu \stackrel{?}{=} \bar{\nu}$$

Is the neutrino its own antiparticle?

Standard Model Physics

NLDBD
Beta Decay
Cosmology

What is the mass of the neutrino, and why is it so small?

Beyond the Standard Model

Long Baseline

Are there new interactions we could discover via neutrinos?

ν_s

Are there additional neutrinos beyond the known three types?

Short Baseline

Neutrinos as Messengers

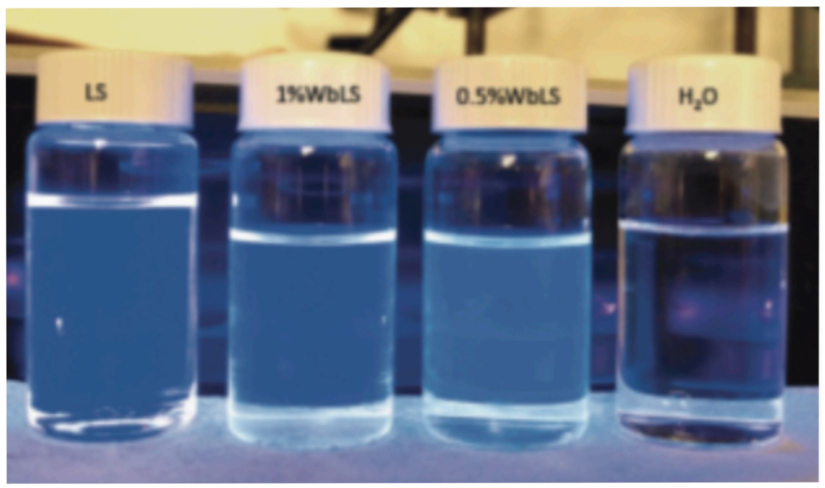
Solar Neutrinos

Geoneutrinos

Supernovae & DSNB

Enabling Technologies

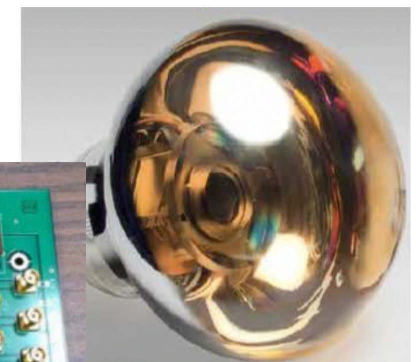
Water-Based Liquid Scintillators	(Ultra-)Fast Photon Detectors	Advanced Vertex Reconstruction

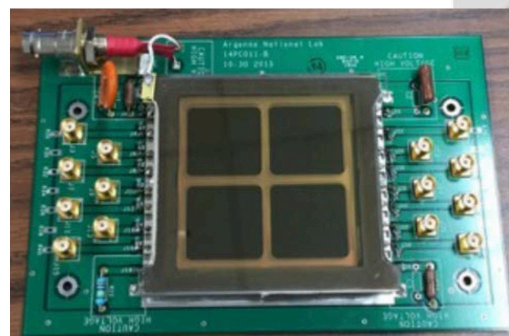


LS 1%WbLS 0.5%WbLS H_2O

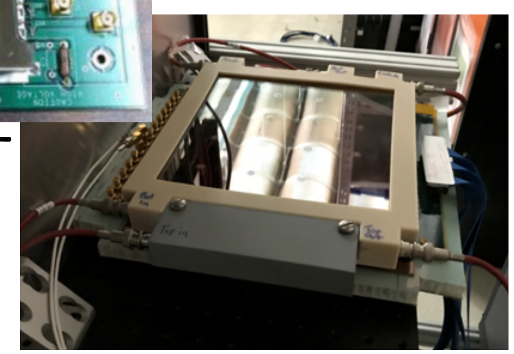
BNL WbLS

PMT

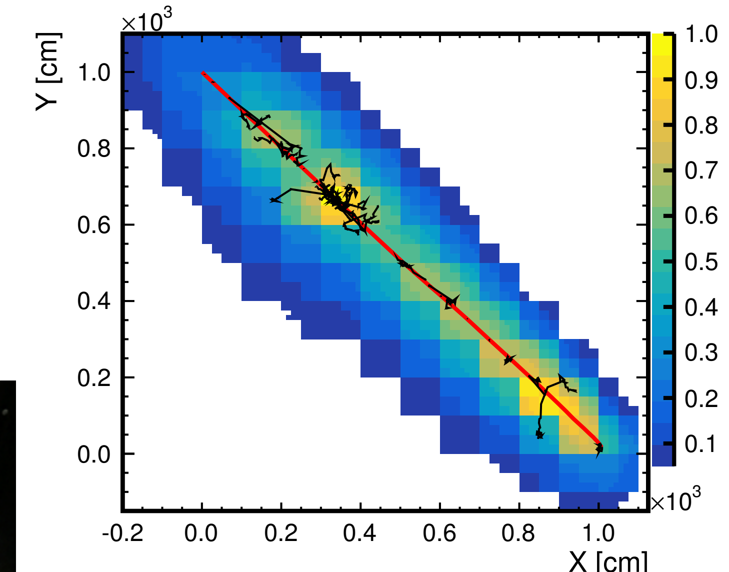




ANL MCP-PMT



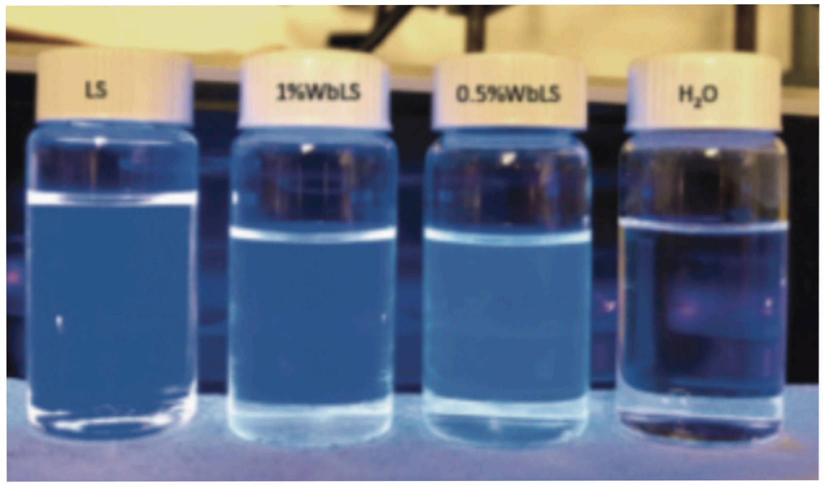
LAPPD (UChicago)



μ track reconstruction
JINST 13, P07005 (2018)

Enabling Technologies

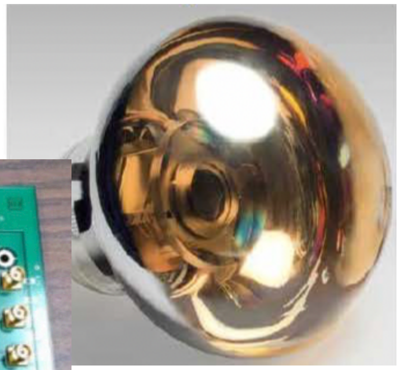
Water-Based Liquid Scintillators	(Ultra-)Fast Photon Detectors	Advanced Vertex Reconstruction

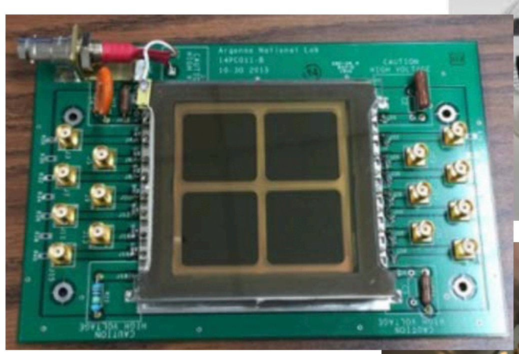


LS 1%WbLS 0.5%WbLS H_2O

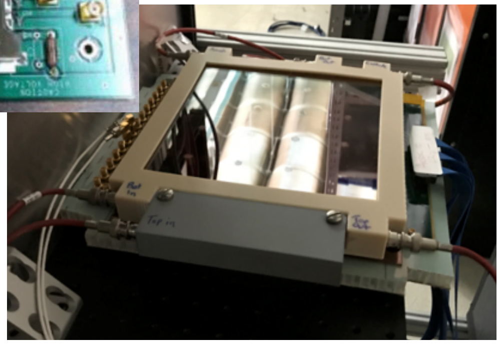
BNL WbLS

PMT

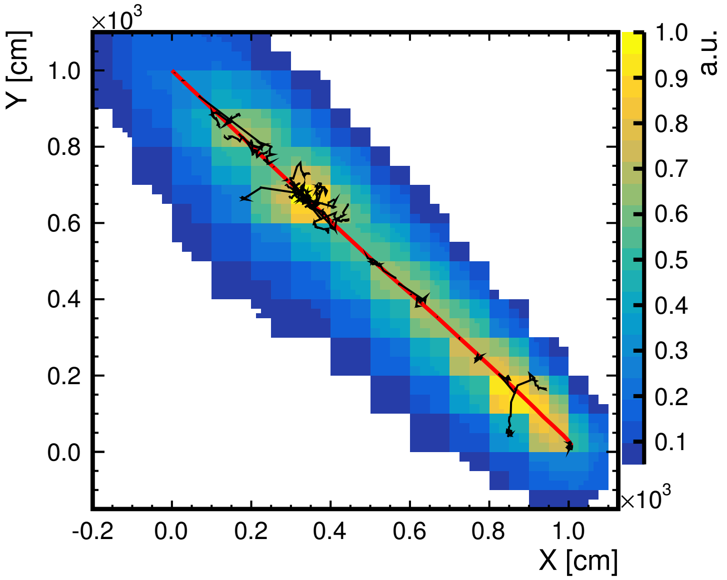




ANL MCP-PMT



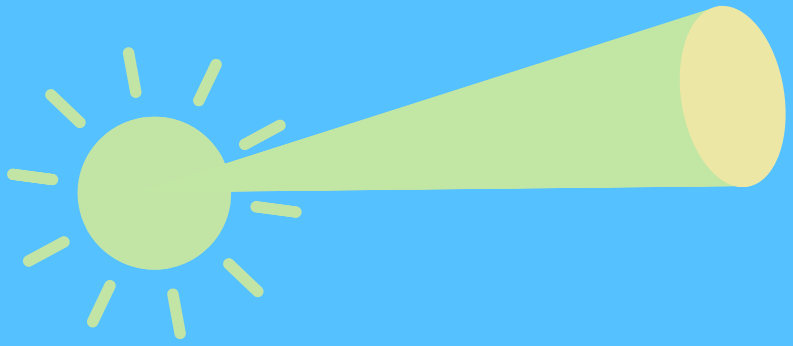
LAPPD (UChicago)



μ track reconstruction
JINST 13, P07005 (2018)

Water-Based Liquid Scintillator

Scintillation Light
Isotropic, threshold-less

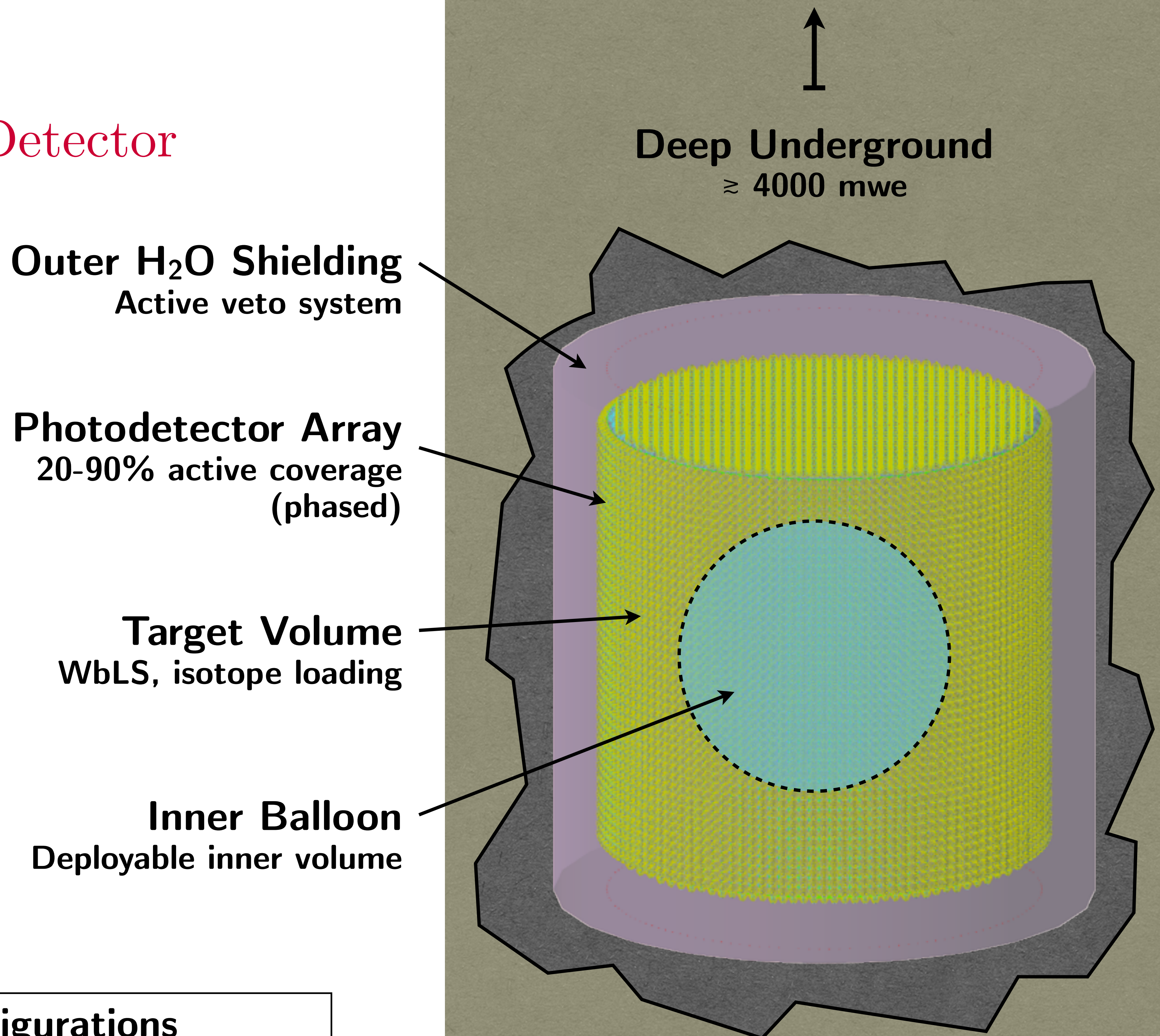


Cherenkov Light
Directional, threshold

Theia

A Next-Generation Detector

A detector combining **large mass**, an **underground location**, **WbLS target**, and **fast photon detectors**



Theia100 Concept
100 kton, 80 kton fiducial

Rendering made with RAT-PAC MC

Example Configurations
Theia25 — 25 kton, DUNE module-like
Theia100 — 100 kton, new SURF cavern

Theia

Broad Physics Goals

A mix of high-energy and nuclear physics:

- Long baseline oscillation physics
  - CP violation, mass ordering
- Nucleon decay searches
- Source-based sterile neutrino searches
- Neutrinoless double-beta decay
- Solar neutrinos (metallicity, luminosity)
- Supernova burst neutrinos & DSNB
- Applied antineutrinos, geoneutrinos

A broad program addressing:

- Major interdisciplinary questions across neutrino physics
- Fundamental neutrino physics and neutrino astrophysics, applied antineutrinos
- Physics over 5 orders of magnitude in energy
- LNV (double beta decay) + CPV (long baseline) $\rightarrow$ Leptogenesis

A flexible experimental program:

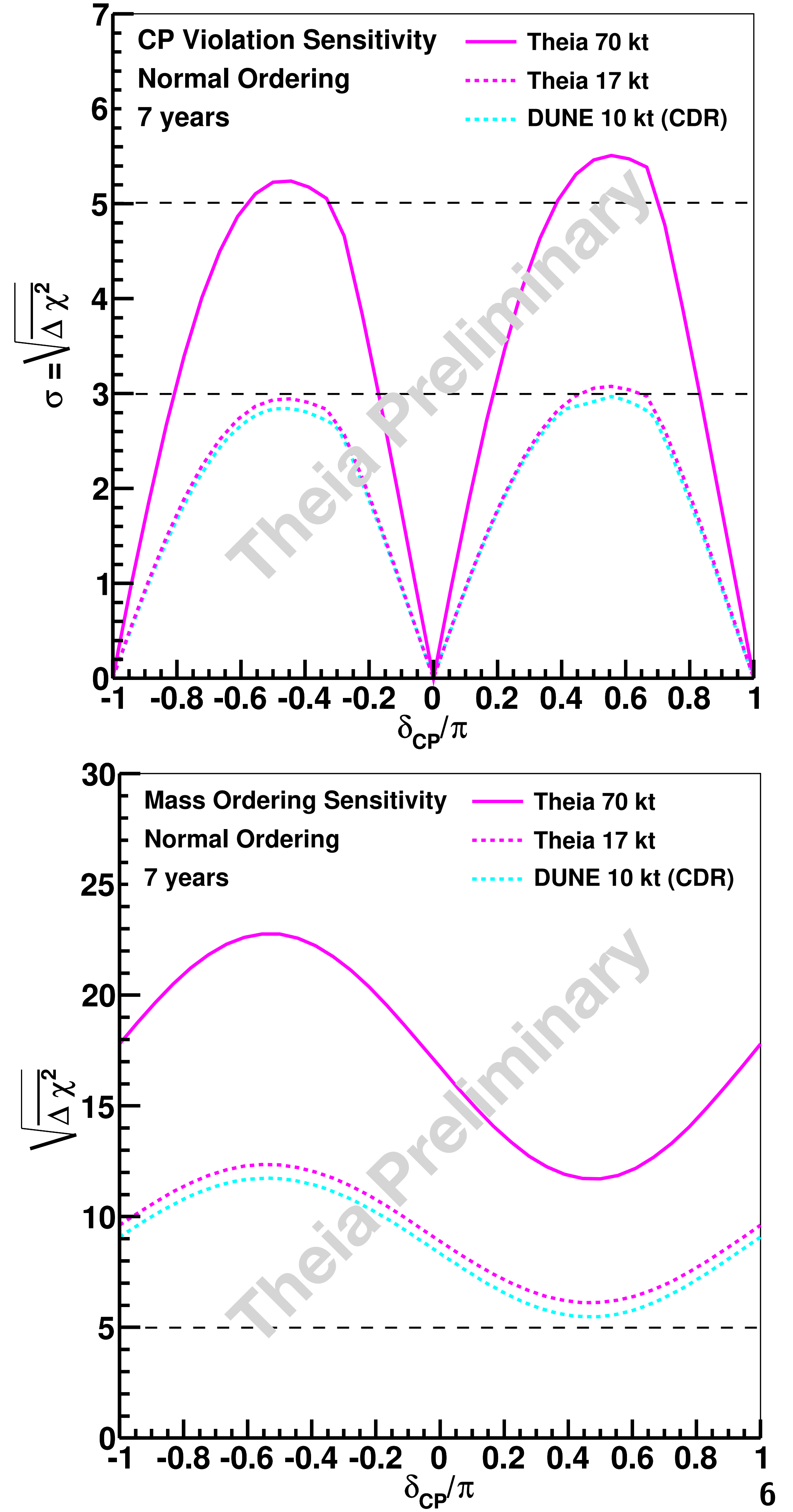
- Staging of detector configuration: isotope loading, scintillator fraction, etc.
- Potential upgrade routes for photon detectors (coverage, uniformity, response)
- A detector that can adapt with new discoveries in the coming decades

Long Baseline

CPV and Mass Ordering

A complementary measurement to DUNE, with the same beam but a different (water) target and different systematics.

- Considered a 25 or 100 kton water target
- Leveraging recent reconstruction improvements
  - Ring counting: 75% NC rejection, reducing π^0
  - e/μ PID: High purity $\nu_e CC\pi^+$ channel
  - High purity multi-ring ν_e samples
- Nine-sample likelihood fit: 1-, 2-, 3-ring with 0/1 Michel for ν mode, 0 Michel for $\overline{\nu}$ mode
- Assumed constraint from additional ν_μ samples
- 2% (5%) systematic on each $\nu_e/\overline{\nu}_e$ signal (background) mode in the fit, per DUNE CDR
- *Additional gains are possible using fast timing, scintillation for improved efficiency, purity, PID*



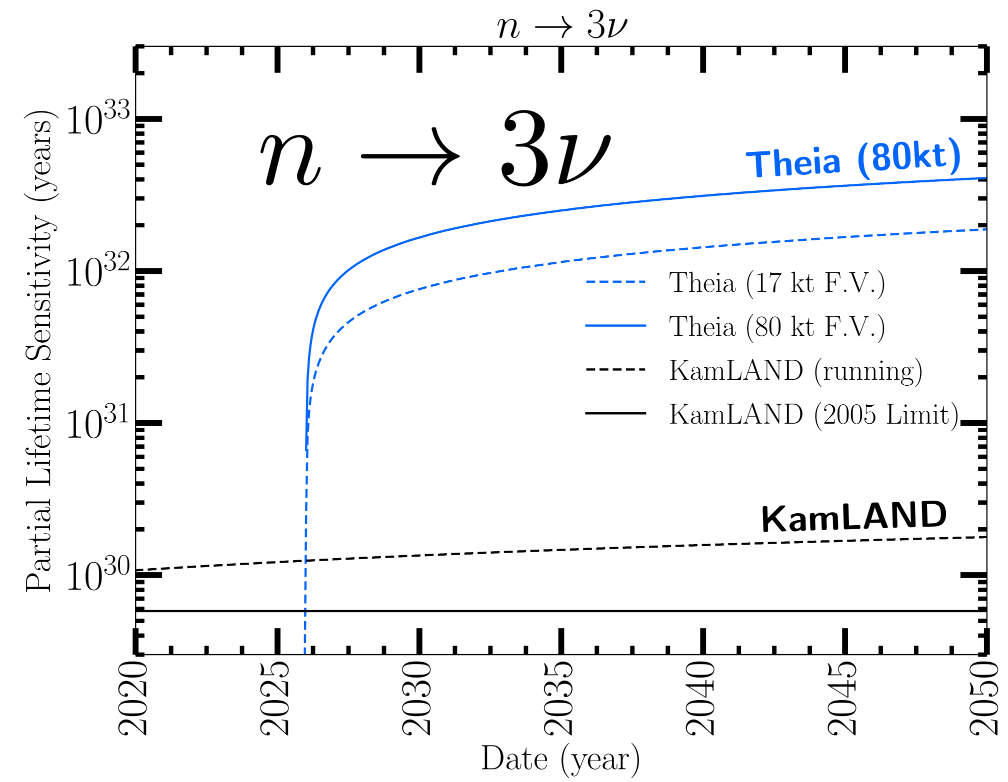
Plots: E.T. Worcester

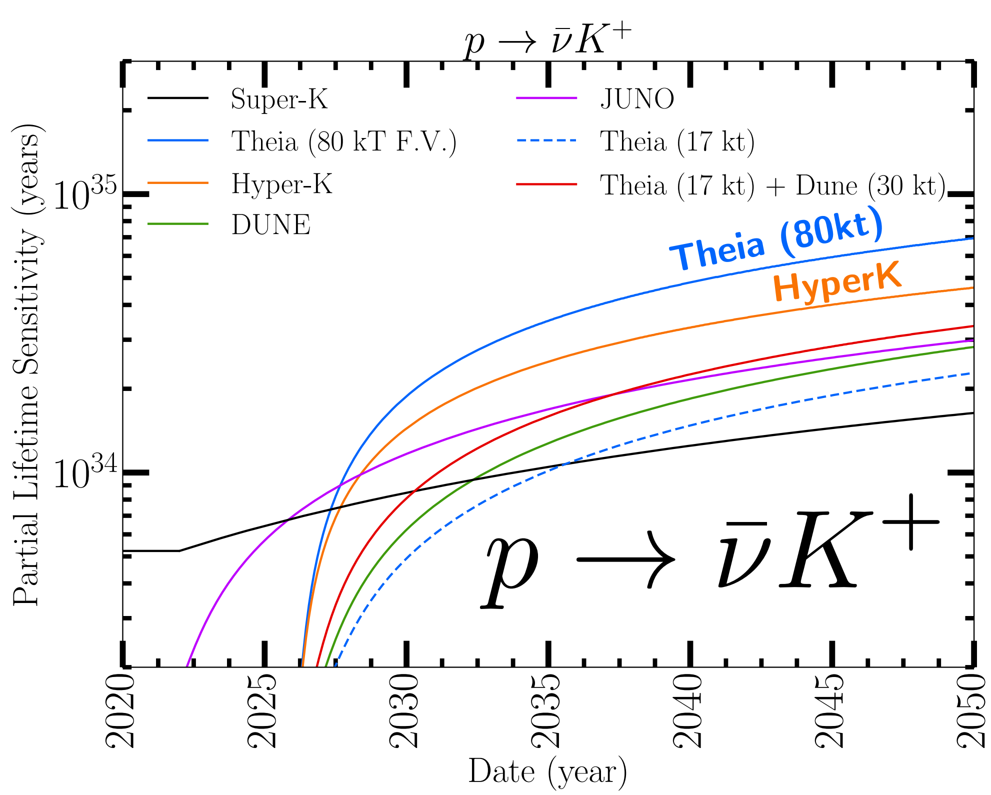
Nucleon Decay

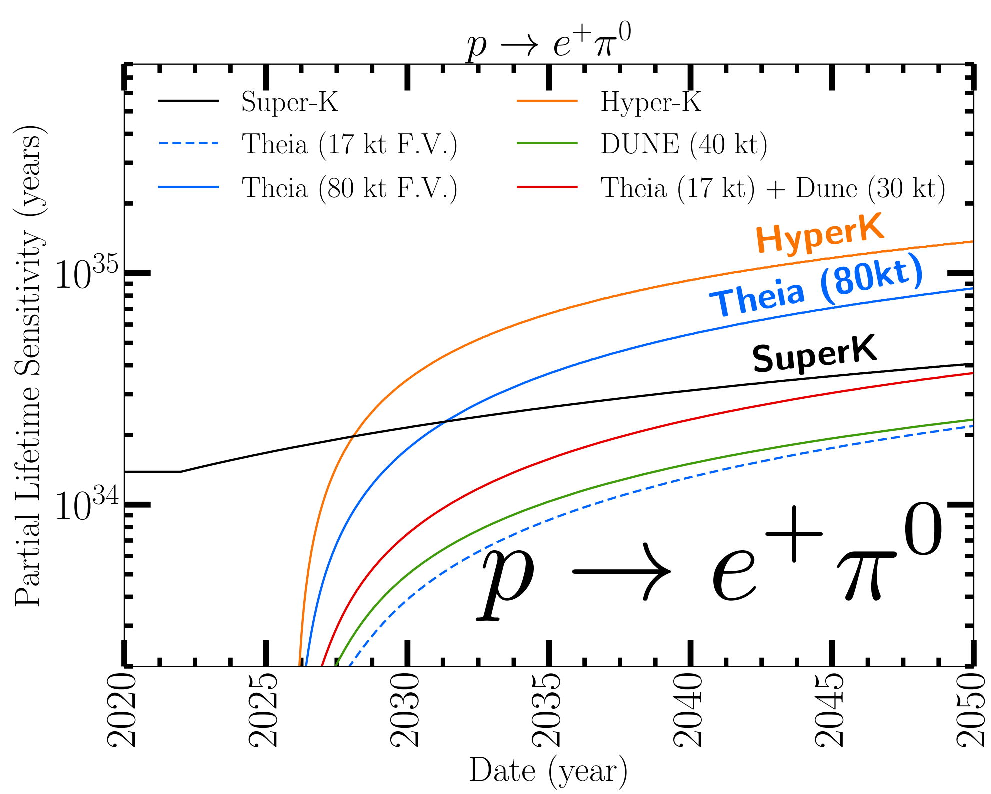
BSM Baryon Number Violation

Low-threshold, low-background BNV search.

- Low threshold and low background due to depth leads to excellent sensitivity for invisible modes
- WbLS allows coincidence search with mesons below Cherenkov threshold (e.g. K^+)
- Complementary to searches in both DUNE and HyperK, leading in invisible







Plots: M. Askins

Solar Neutrinos

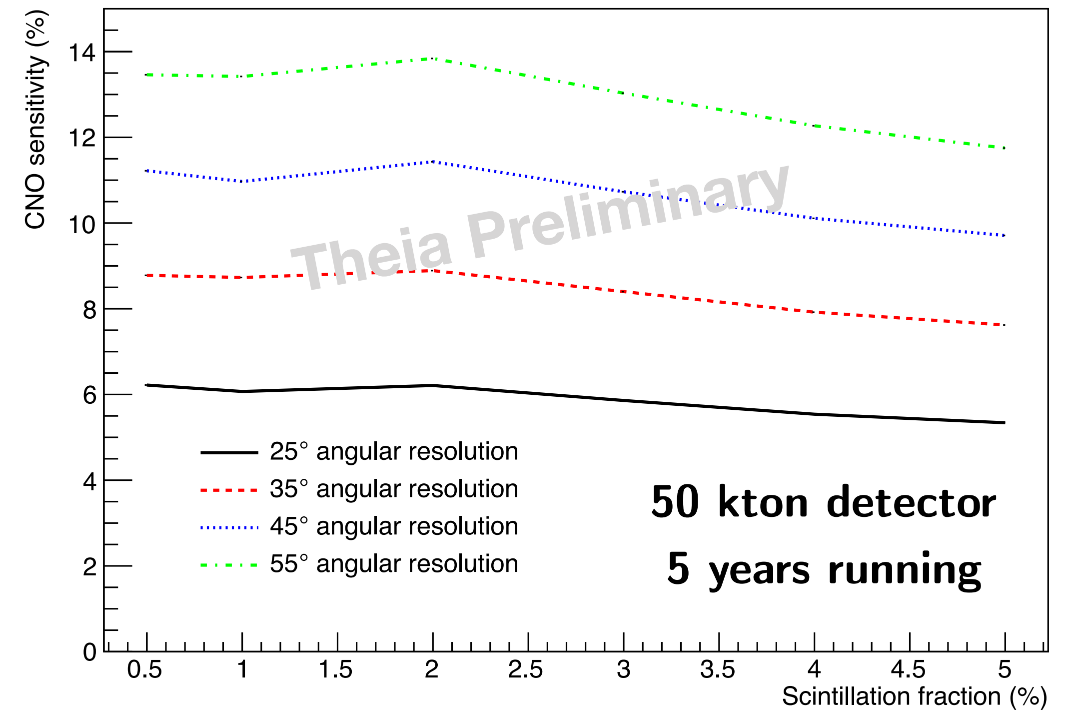
CNO and the MSW Transition

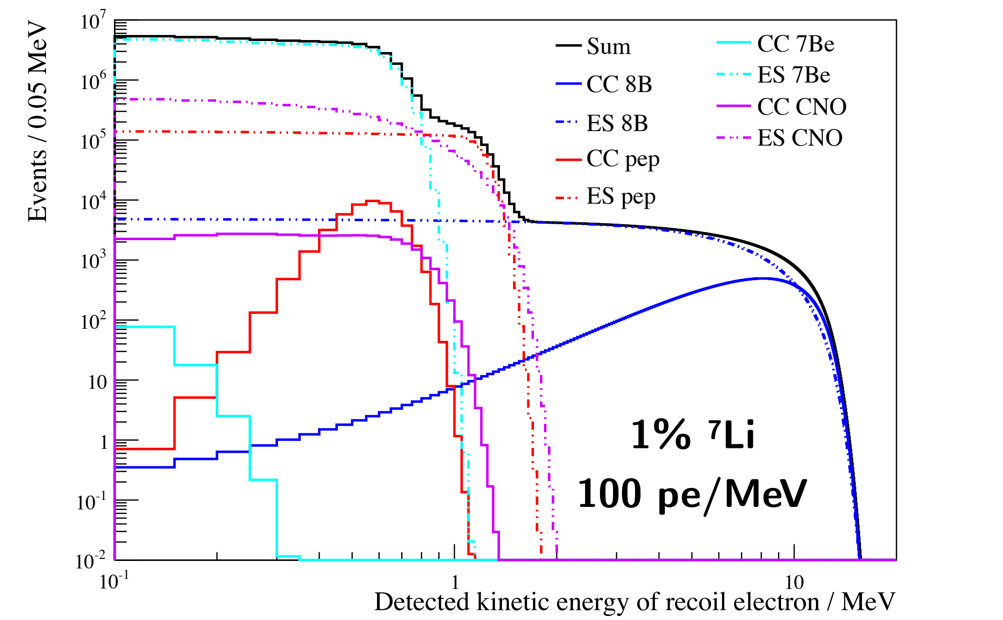
Huge low-energy ES statistics, and potential for CC via isotope loading.

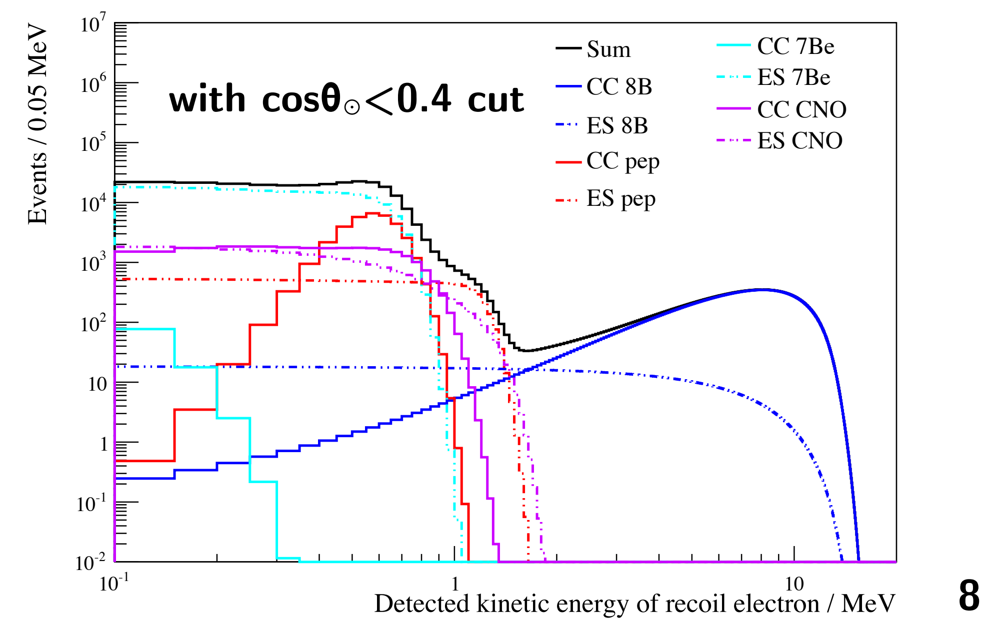
Goals

- Detect CNO neutrinos to constrain solar metallicity, model for heavy main sequence stars
- Precision probes of MSW matter-vacuum transition: MSW check and new physics searches

- Low-energy ES measurements
  - 5% WbLS, 90% coverage, ~25° angular res.
  - 2D maximum likelihood analysis using reconstructed energy and solar direction
  - 5-10% measurement of CNO fluxes achievable
- Charged Current measurements
  - Potential to load ^{7}Li: ^{7}Li(ν_e,e)^{7}Be, 862 keV
  - High precision possible on E_ν by tagging excited state decay γ







Plots: G. Orebi Gann, R. Bonventre   See Eur. Phys. J. C 78 (2018) 435 (ES) and arXiv:1409.5864 (CC)

Supernova Neutrinos

Supernova Burst Detection

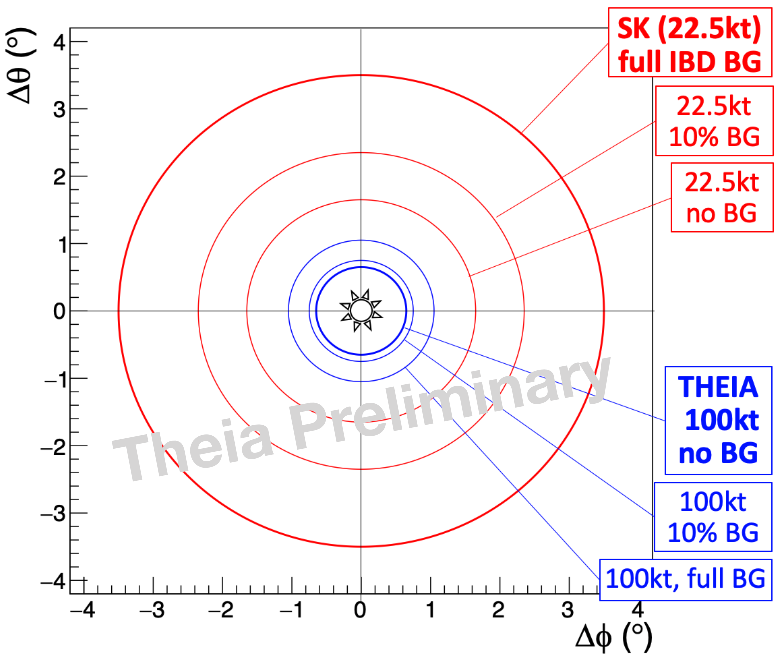
Multi-channel SNe detection with a high statistics antineutrino sample.

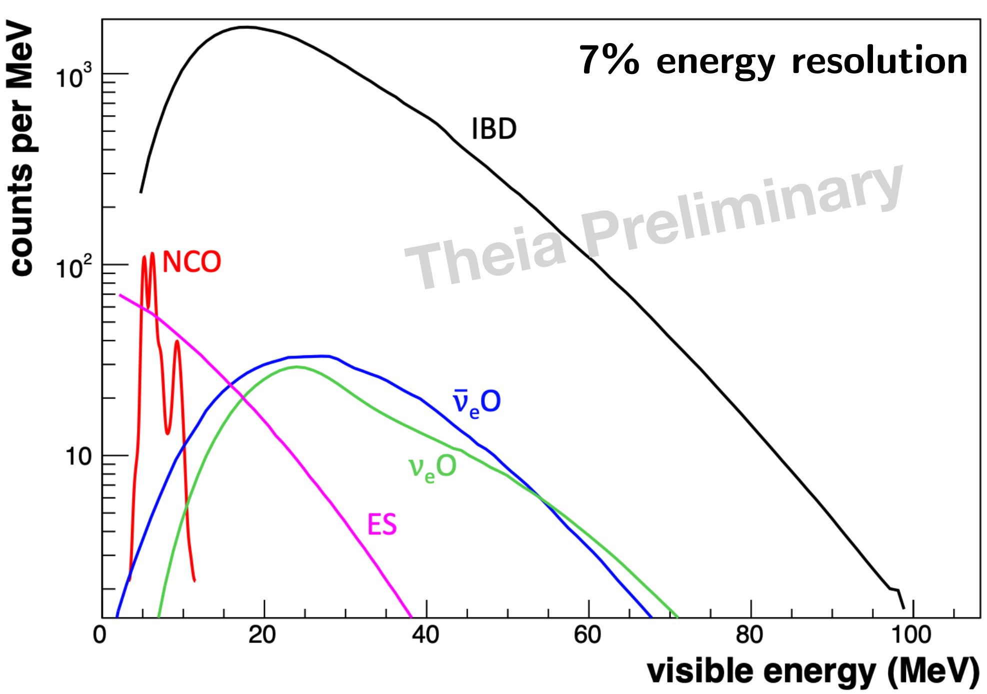
- Primary signal (88%) is $\overline{\nu}_e$ IBD
  - Complementary to ν_e detection in DUNE
- Scintillation improves low-threshold neutron tag
- Low background ES channel → pointing
  - Potential to add low-energy νp ES channel
- CC & NC channels → burst timing, ν mixing
- Provides a capable SNe early warning trigger

Reaction		Rate
(IBD)	$\bar{\nu}_e + p \rightarrow n + e^+$	19,800
(ES)	$\nu + e \rightarrow e + \nu$	960
(ν_eO)	$^{16}\mathrm{O}(\nu_e, e^-)^{16}\mathrm{F}$	340
($\bar{\nu}_e$O)	$^{16}\mathrm{O}(\bar{\nu}_e, e^+)^{16}\mathrm{N}$	440
(NCO)	$^{16}\mathrm{O}(\nu, \nu)^{16}\mathrm{O}^*$	1,100

10kpc, GVKM, SNOwGLoBES

Pointing resolution better than 1° achievable thanks to large ES statistics and good intrinsic resolution (1σ ~ 10°)





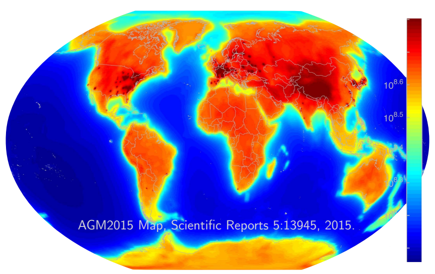
Antineutrinos

From Earth and Beyond

High efficiency IBD detection with improved background rejection.

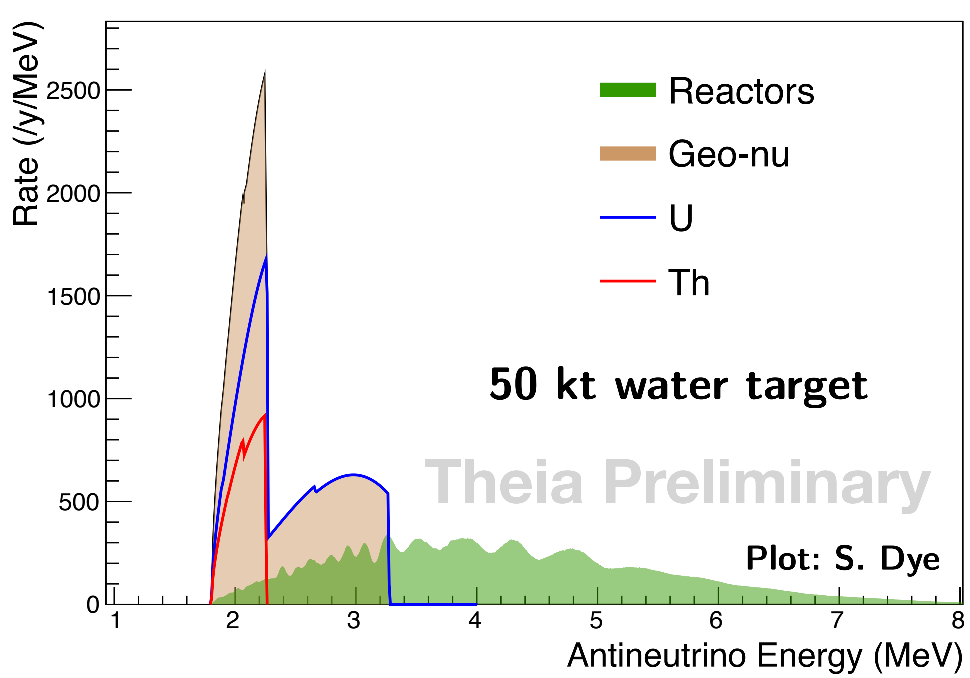
High light yield and C+S enables:

- Tag on 2.2 MeV ɣ from ^{1}H, reducing single-event backgrounds in WCDs
- Reduced in NC backgrounds vs. LS detectors
- Higher efficiency than Gd-H_2O IBD detection with improved background rejection.

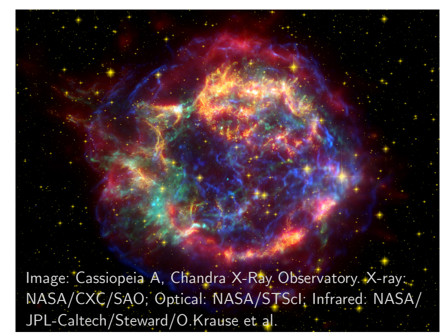


Geoneutrinos

Antineutrinos from U and Th chain reactions driving the radiogenic heating of Earth

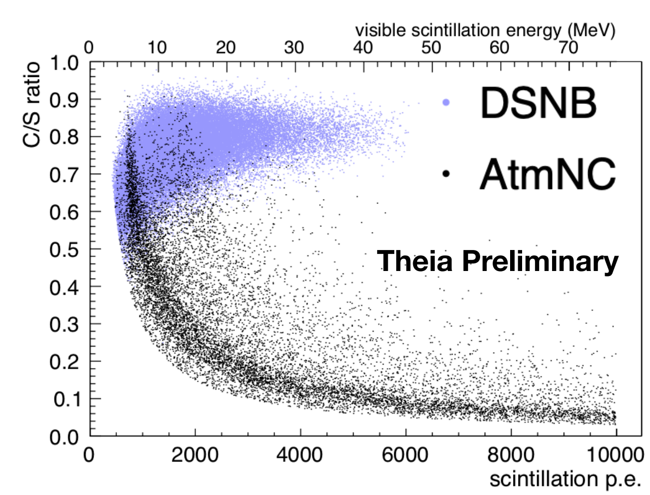


- High statistics
- Complementary to KL, Borexino
- Potential for directionality

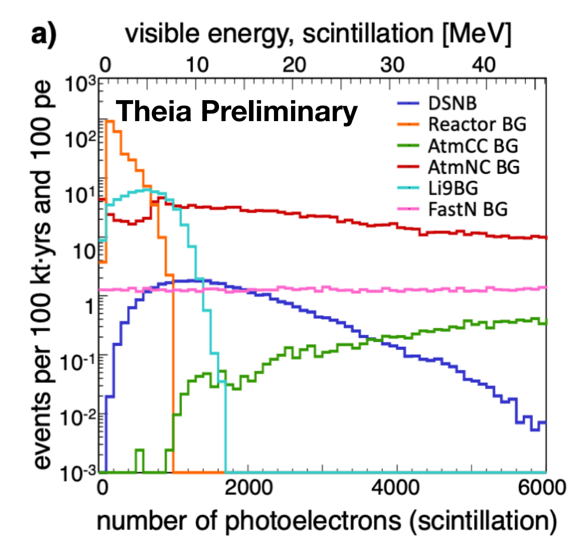


Diffuse Supernova Neutrino Background

Diffuse neutrino flux from past core-collapse supernovae



NC background rejection via Cherenkov/scintillation light ratio (>98%)



Plots: M. Wurm, J. Sawatzki

Significant background reduction through C/S ratio, ring counting, and coincidence cuts

Potential for 5σ in 1 (5) y for Theia100 (Theia25)
O(100) events in 5 y in Theia100

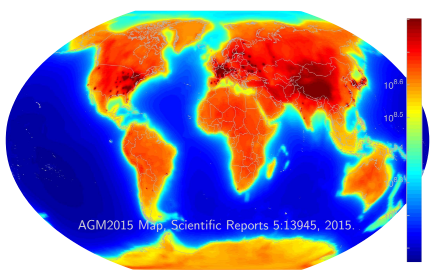
Antineutrinos

From Earth and Beyond

High efficiency IBD detection with improved background rejection.

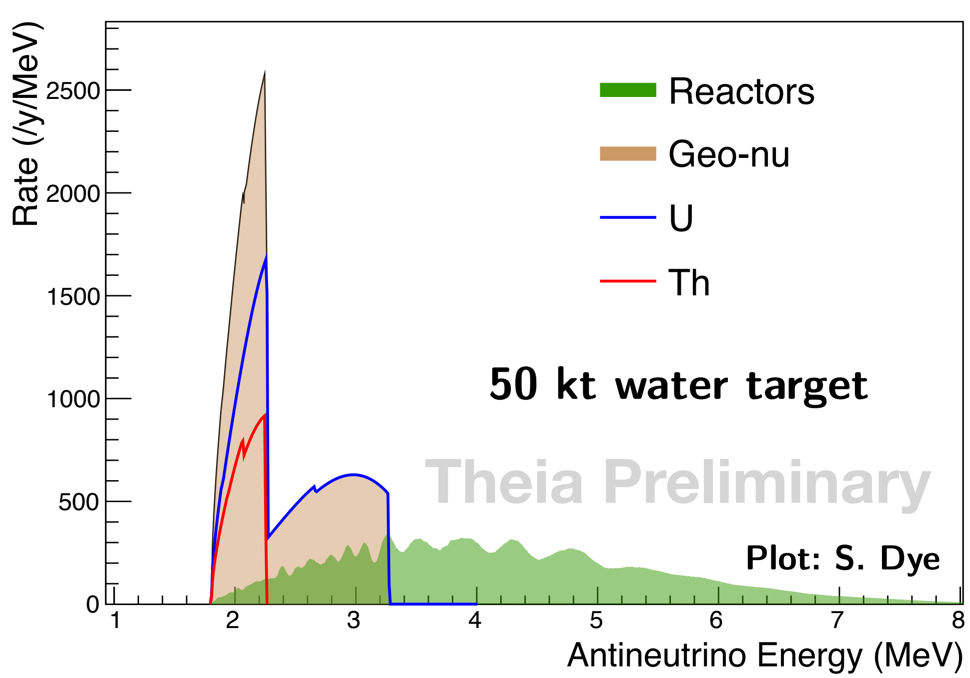
High light yield and C+S enables:

- Tag on 2.2 MeV γ from ^{1}H, reducing single-event backgrounds in WCDs
- Reduced in NC backgrounds vs. LS detectors
- Higher efficiency than Gd-H_2O IBD detection with improved background rejection.

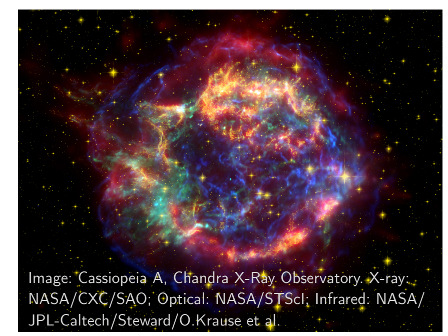


Geoneutrinos

Antineutrinos from U and Th chain reactions driving the radiogenic heating of Earth

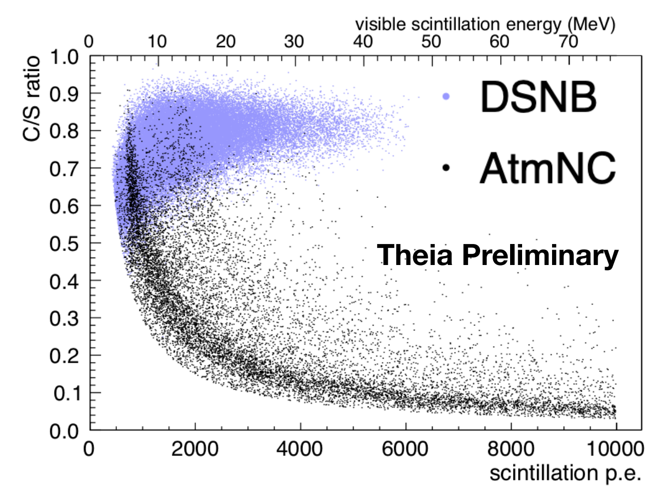


- High statistics
- Complementary to KL, Borexino
- Potential for directionality

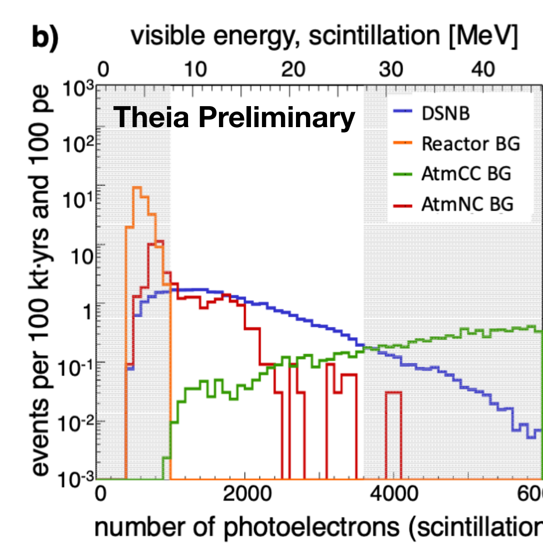


Diffuse Supernova Neutrino Background

Diffuse neutrino flux from past core-collapse supernovae



NC background rejection via Cherenkov/scintillation light ratio (>98%)



Plots: M. Wurm, J. Sawatzki

Significant background reduction through C/S ratio, ring counting, and coincidence cuts

Potential for 5σ in 1 (5) y for Theia100 (Theia25)
O(100) events in 5 y in Theia100

Neutrinoless Double Beta Decay

Majorana Neutrinos & LNV

A very large isotope mass deployed in a liquid scintillator target volume.

- ⌀16 m LAB-PPO filled inner balloon
- Loading ^{nat}Te or ^{enr}Xe (or ^{100}Mo, ^{82}Se, ^{150}Nd)
- Backgrounds due to ^{8}B solar neutrinos, $2\nu\beta\beta$, LS contamination, and detector materials
- Single-bin Feldman-Cousins counting analysis

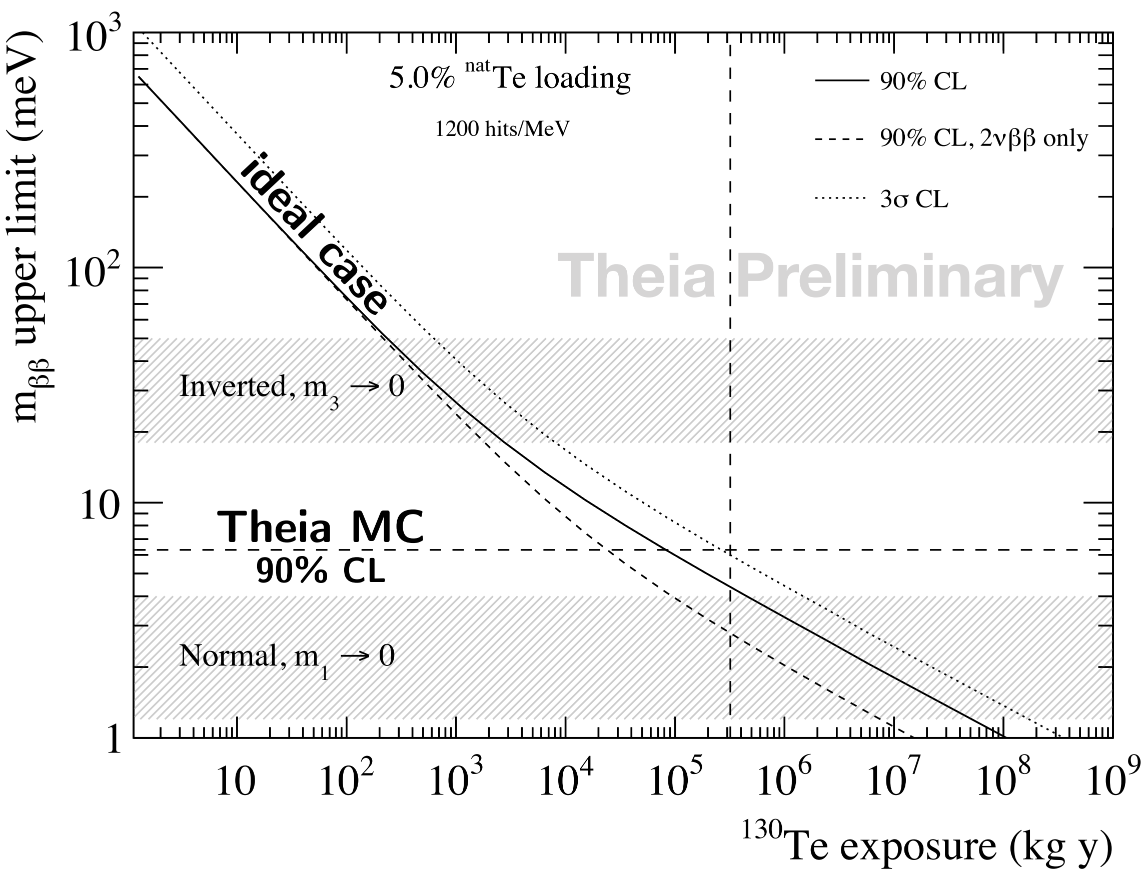
Expected 90% CL Sensitivity

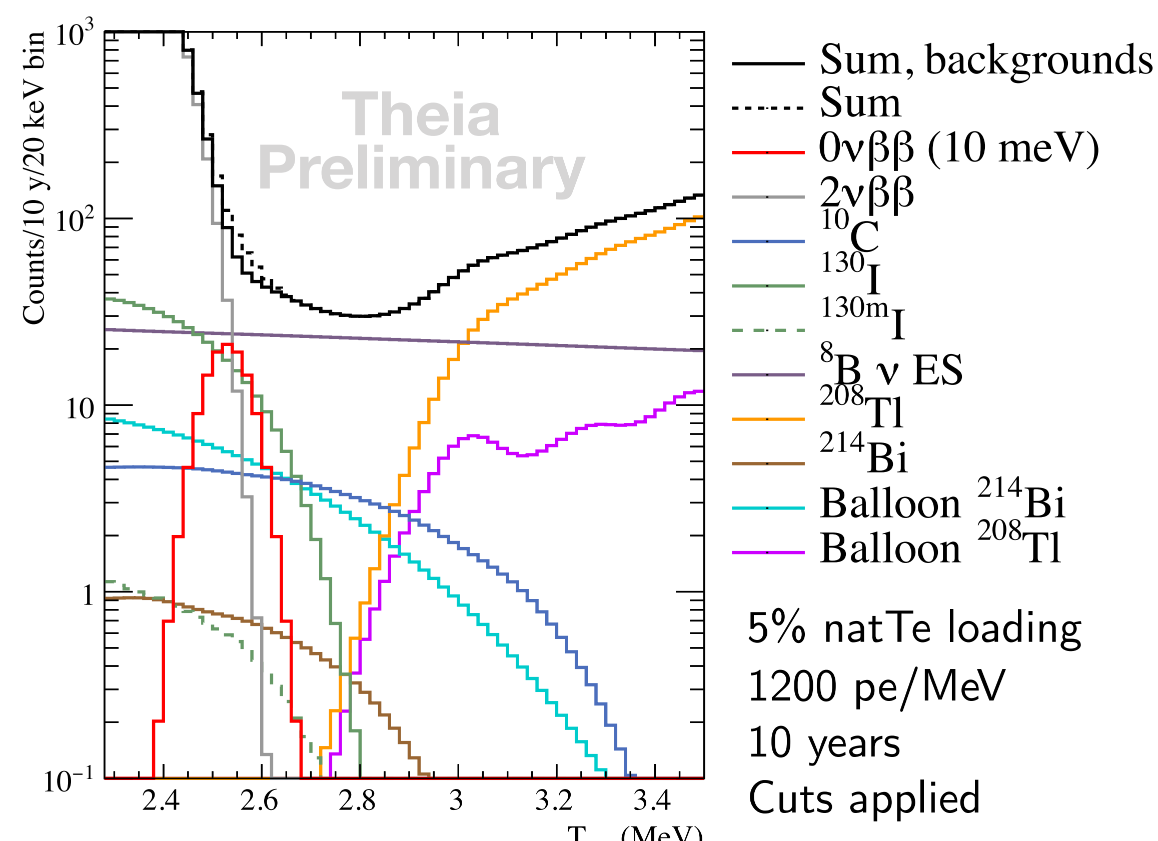
5% ^{nat}Te Loading
$T_{1/2} > 1.1\times10^{28}$ y, $m_{\beta\beta} < 6.3$ meV

3% ^{enr}Xe Loading* (89.5%)
$T_{1/2} > 2.0\times10^{28}$ y, $m_{\beta\beta} < 5.6$ meV

(IBM-2 NME, g_A=1.269)

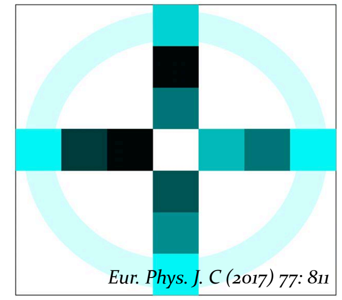
* ~10× annual global production





R&D Program

Overview



CHESS: CHErenkov-Scintillation Separation at LBL

BROOKHAVEN NATIONAL LABORATORY

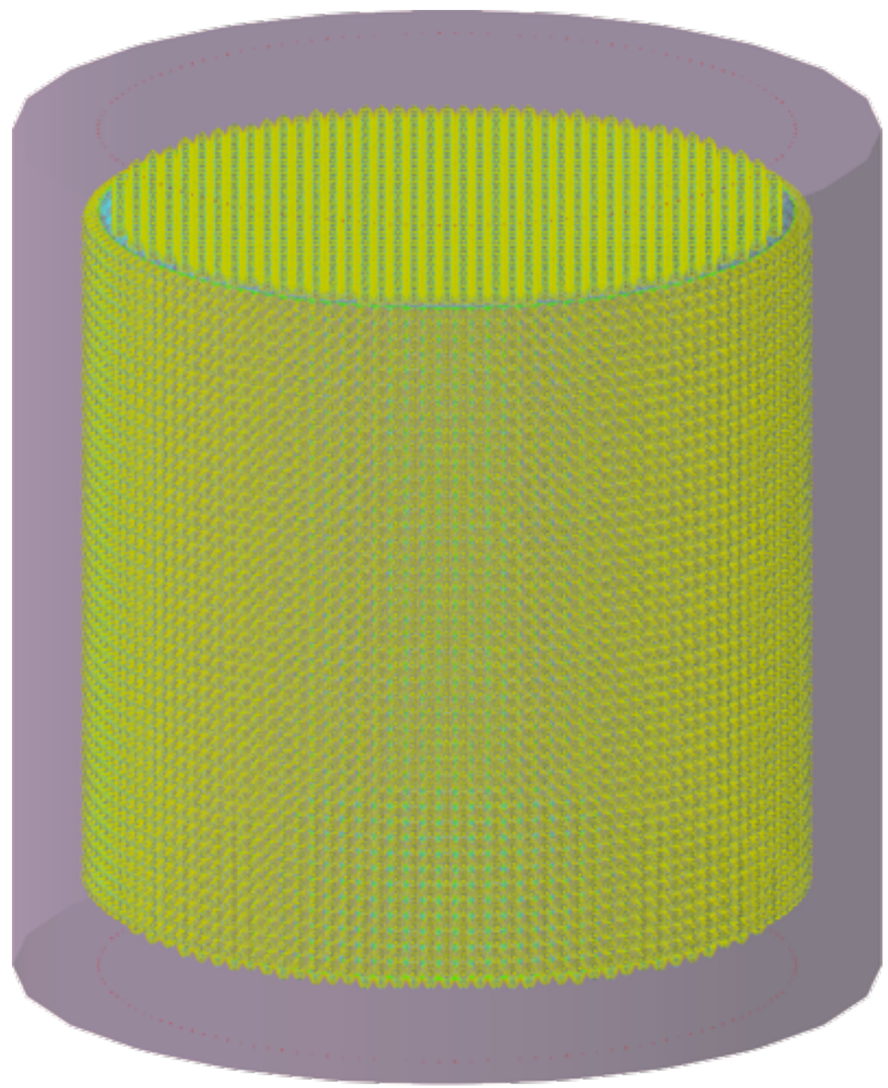
Scintillator development

annie

LAPPDs, reconstruction
WbLS target possible

Penn University of Pennsylvania

WbLS optical properties
Dichroic light concentrators



WATCHMAN

Antineutrinos
PMTs, WbLS

Berkeley University of California / Berkeley Lab

LS Cherenkov/Scintillation
WbLS + LAPPDs
Proton light yield

Germany Group:
(Hamburg, Mainz, München, Tübingen)
WbLS & photon detection R&D, 4 GS + 1 PD

UC DAVIS University of California

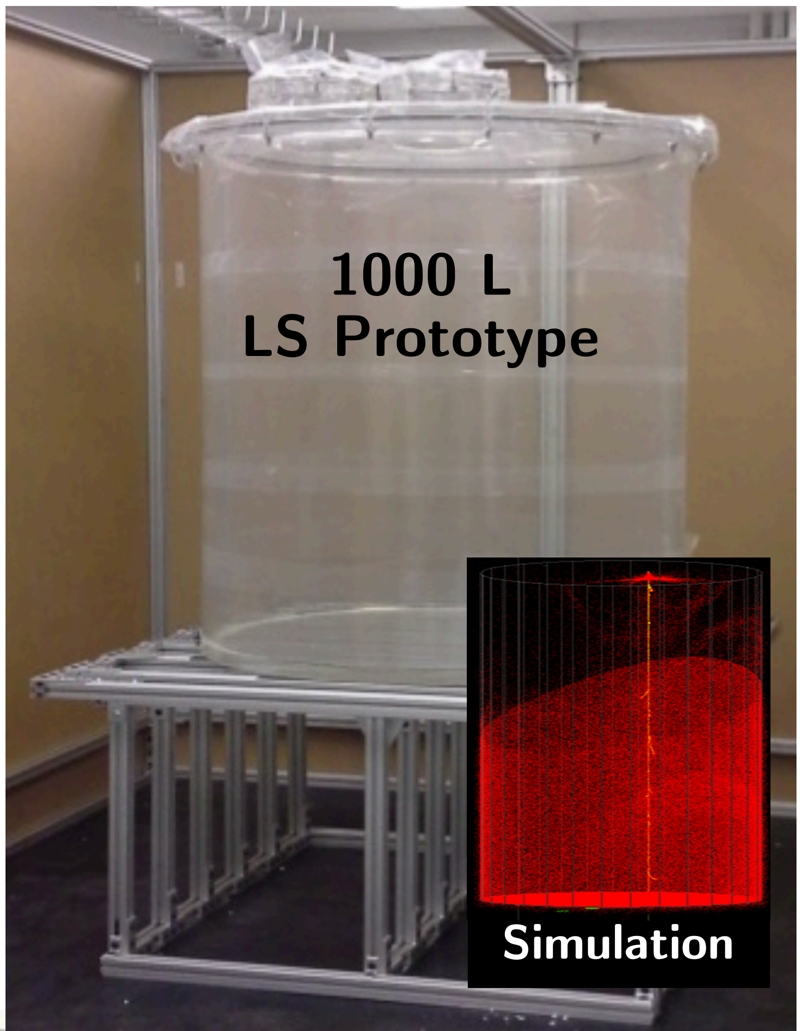
Purification, nanofiltration

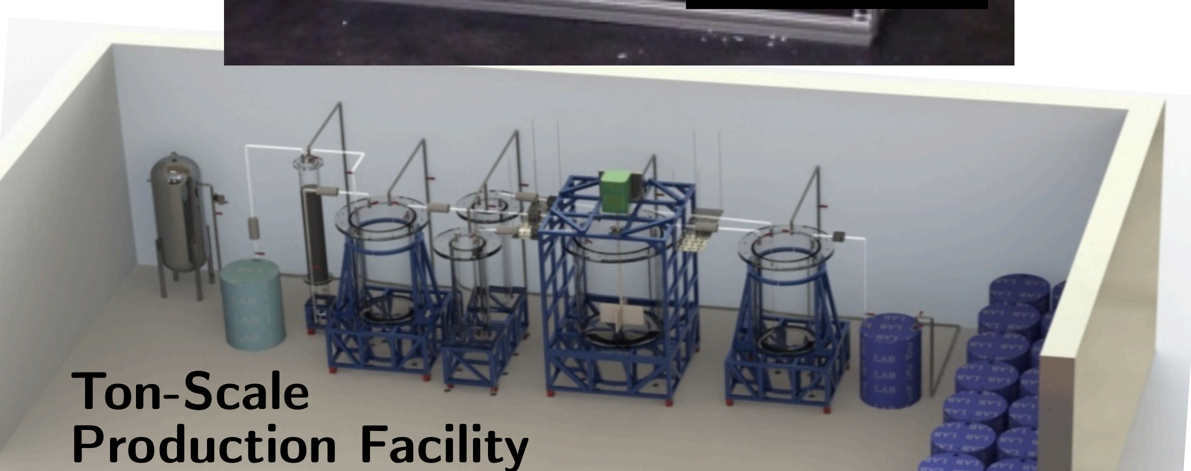
UK Group: Planning 2 ton test tank WbLS and photon detection systems

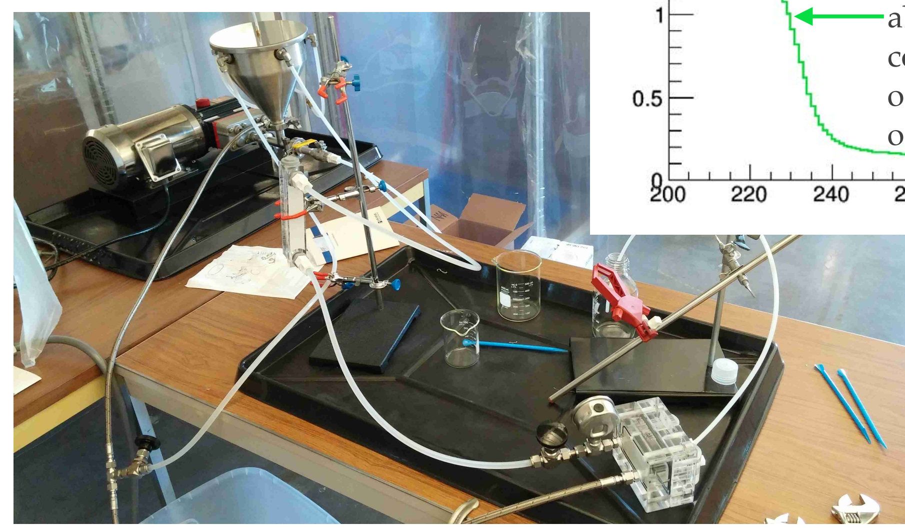
not an exhaustive list!

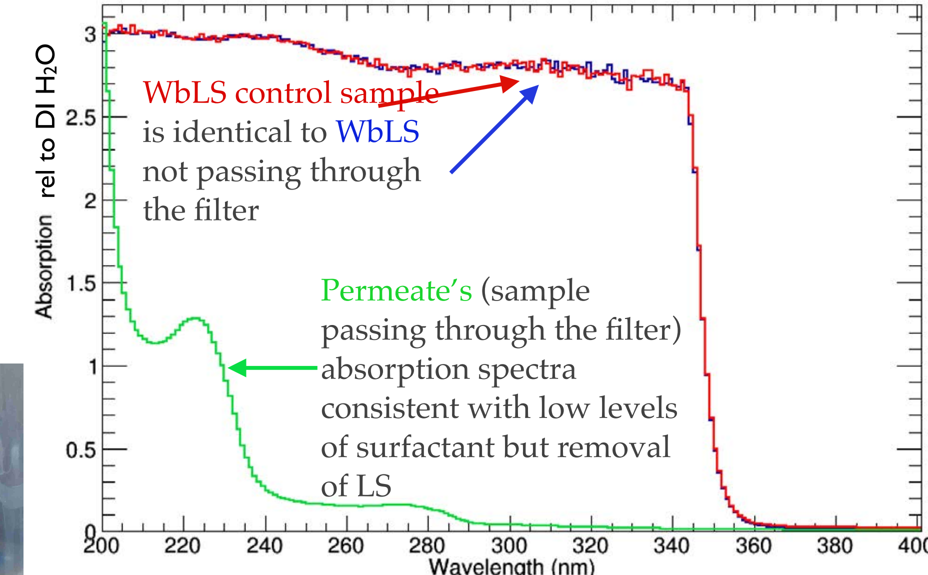
Water-Based Liquid Scintillator

Target R&D



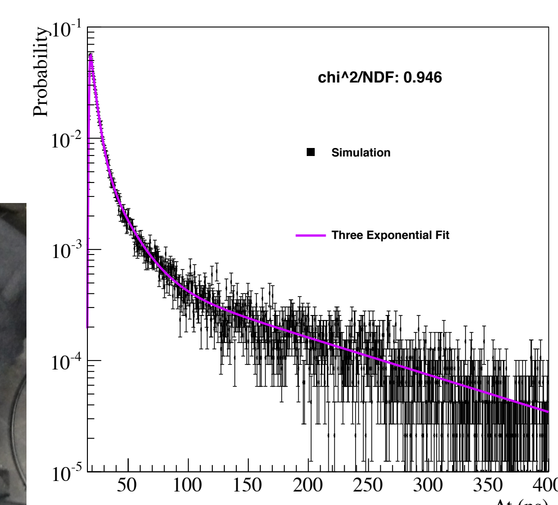






nm-scale membrane filtration process

Separate and DI water for optical transparency



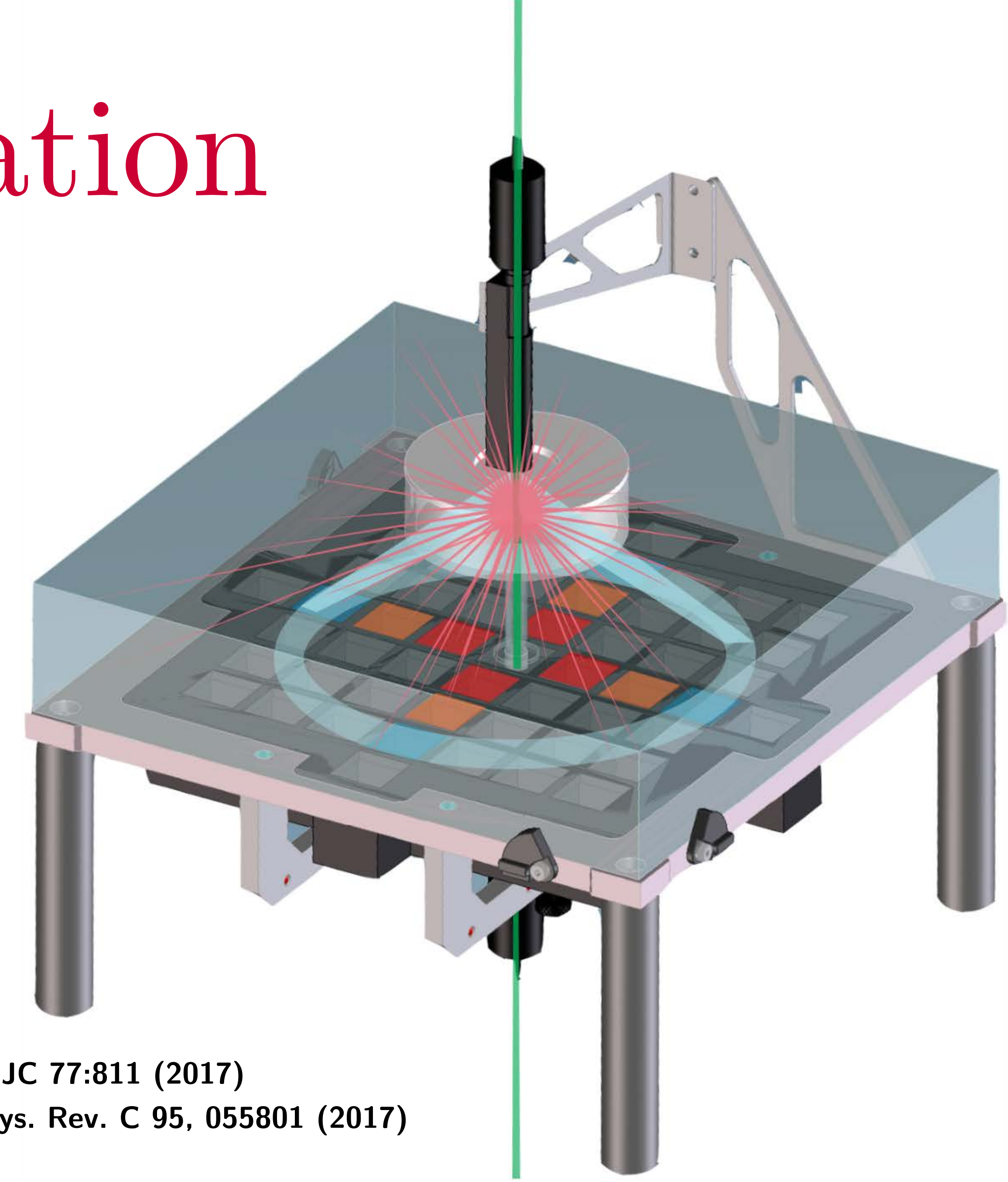
Scintillator timing and optics

Cherenkov & Scintillation

CHESS at LBL

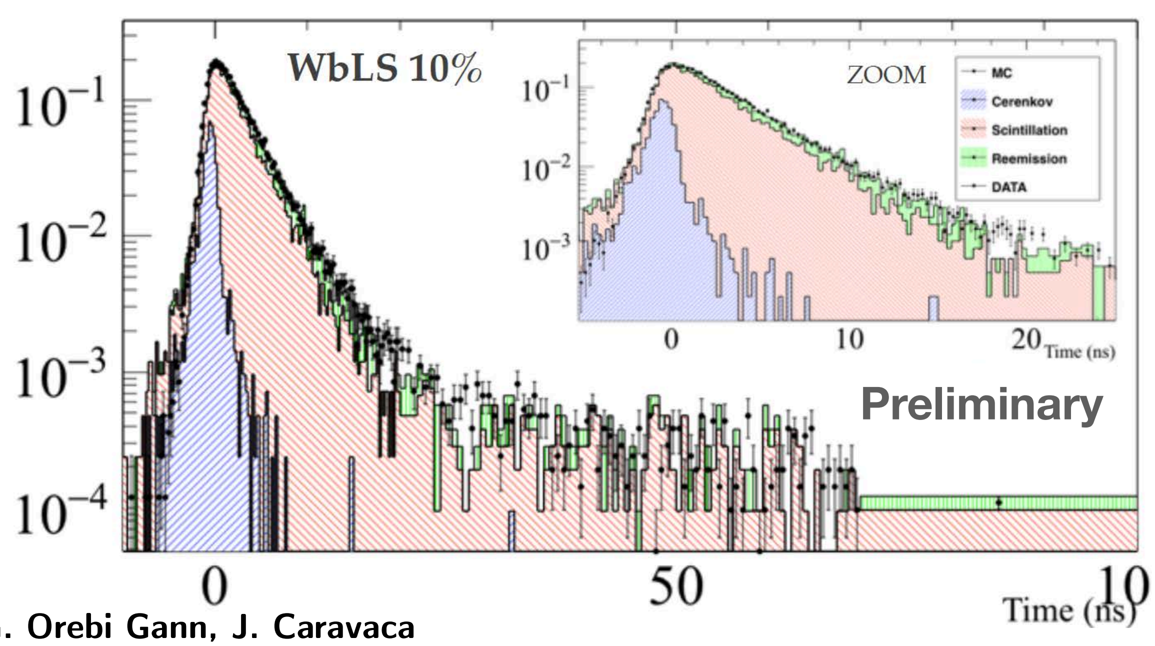
A cosmic muon ring imaging experiment.

- Tag cosmics using scintillator detectors
- Target vessel: LS, WbLS, H_2O, etc.
- Image using a fast PMT array
- Study isotropic/ring component: precise charge and timing information
- Calibrated via radioactive sources

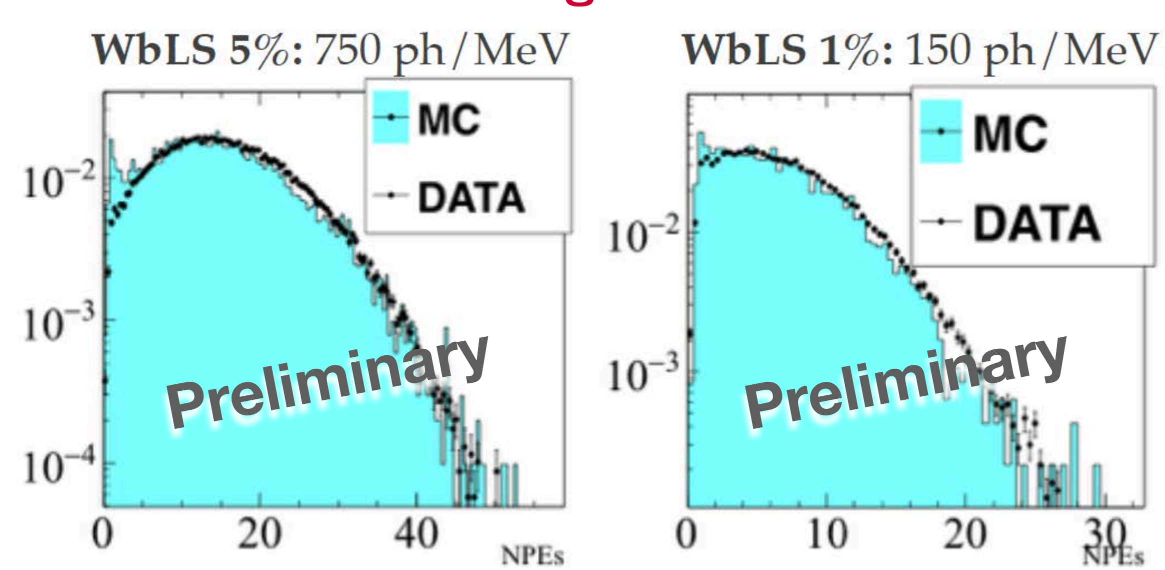


EPJC 77:811 (2017)
Phys. Rev. C 95, 055801 (2017)

WbLS Scintillation Timing



WbLS Scintillation Light Yield



Plots: G. Orebi Gann, J. Caravaca

Photon Detection

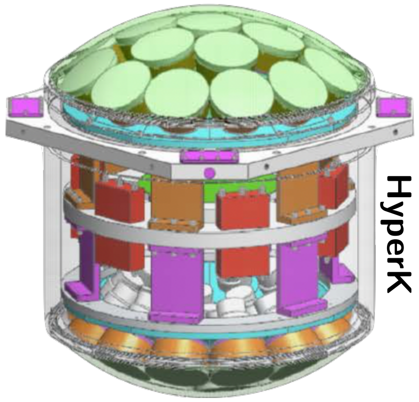
Overview

Goals:

- Observed light yield ~1200 p.e./MeV for LS
- High photocathode coverage (90%)
- High quantum efficiency
- Fast timing for Cherenkov/scintillation separation and optical tracking
- Cost effective/pathways for future upgrades

Large-Area PMTs

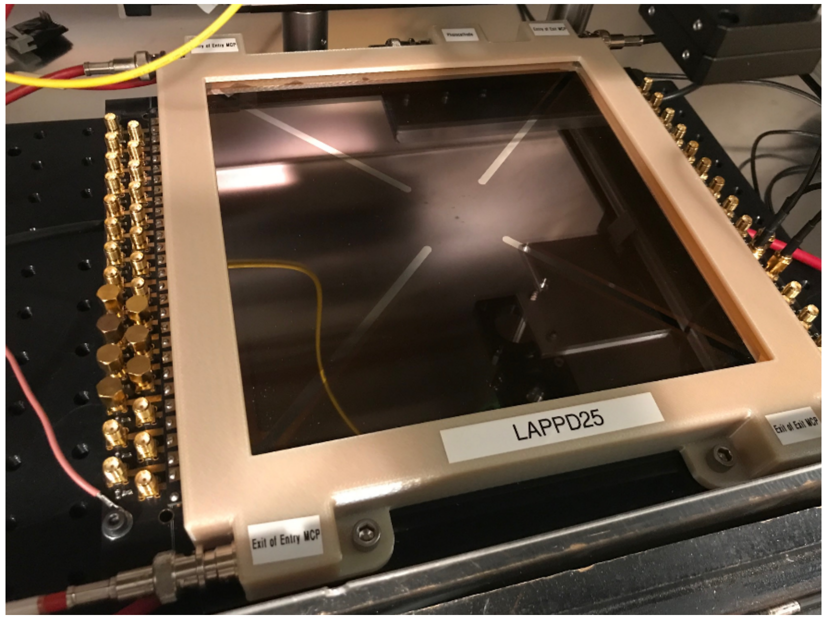
- High efficiency
- Sub-ns timing
- Cost effective



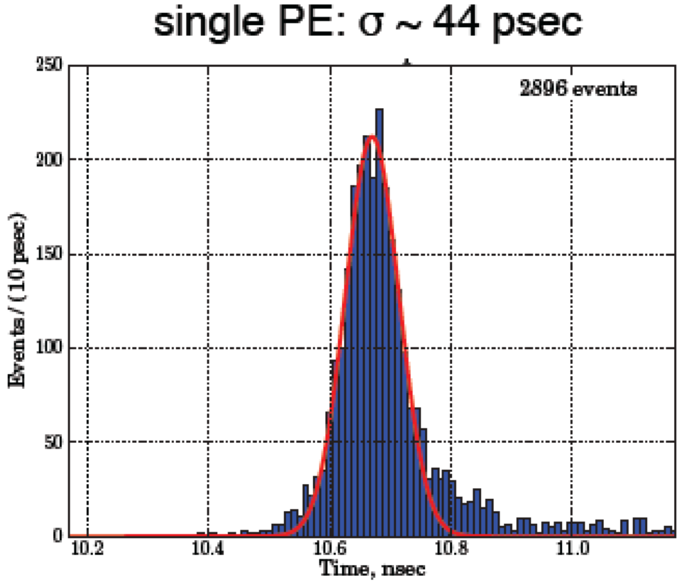
Modular PMTs

- High density
- Fast timing
- Flexible response

See HK talks!

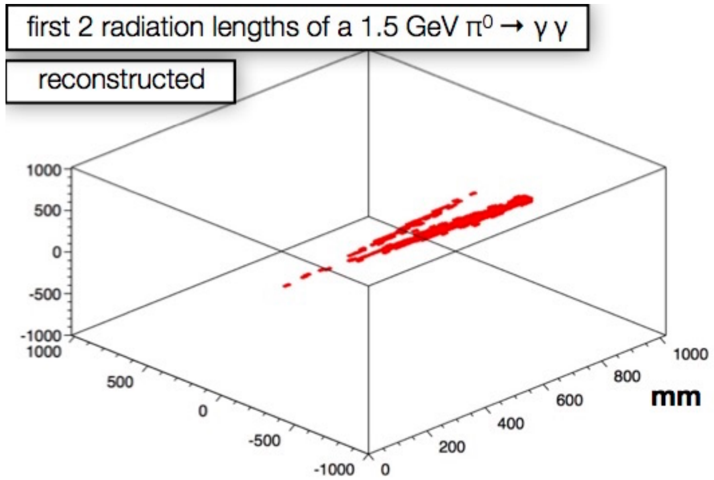


Large Area Picosecond Photo-Detectors



144 ps ~ 1 cm in water!

Optical reconstruction of charged particle tracks

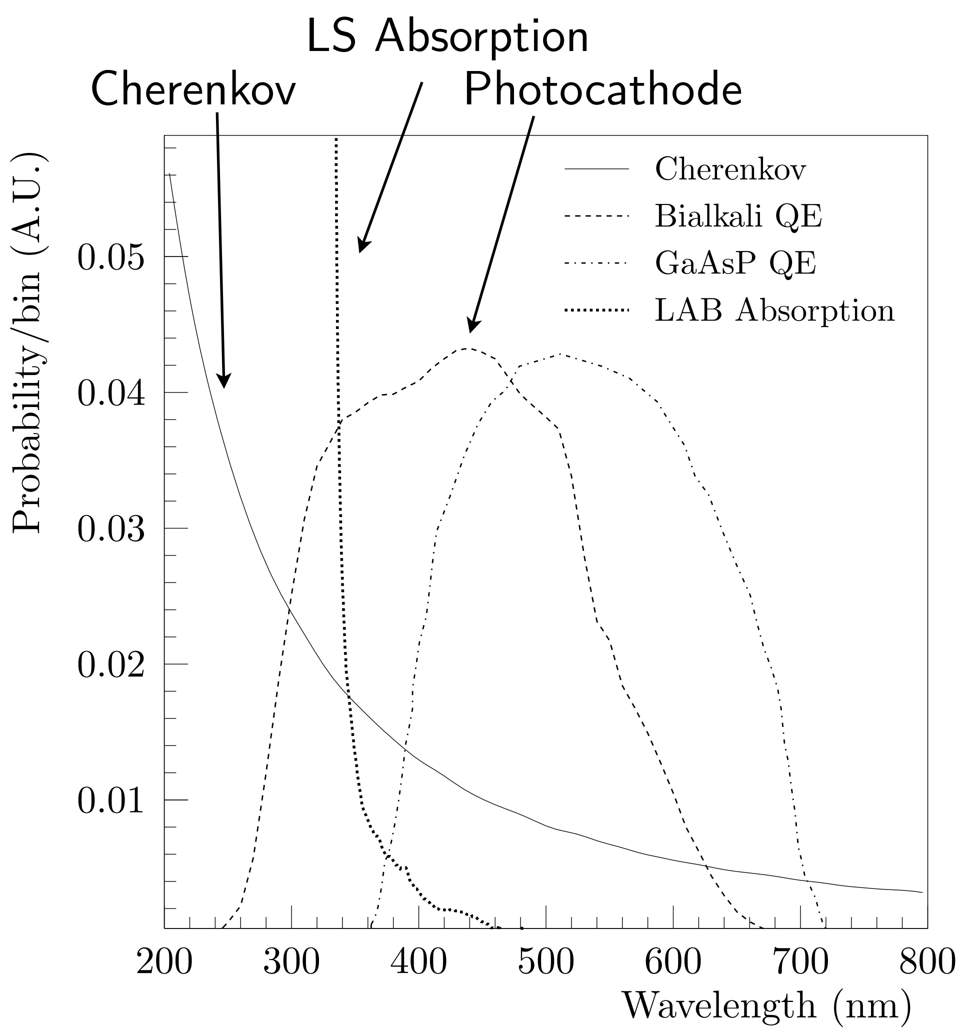


See NIM A 814, 19-32 (2016); NIM A 795, 1-11 (2015); NIM A 732, 392-296 (2013); https://psec.uchicago.edu/

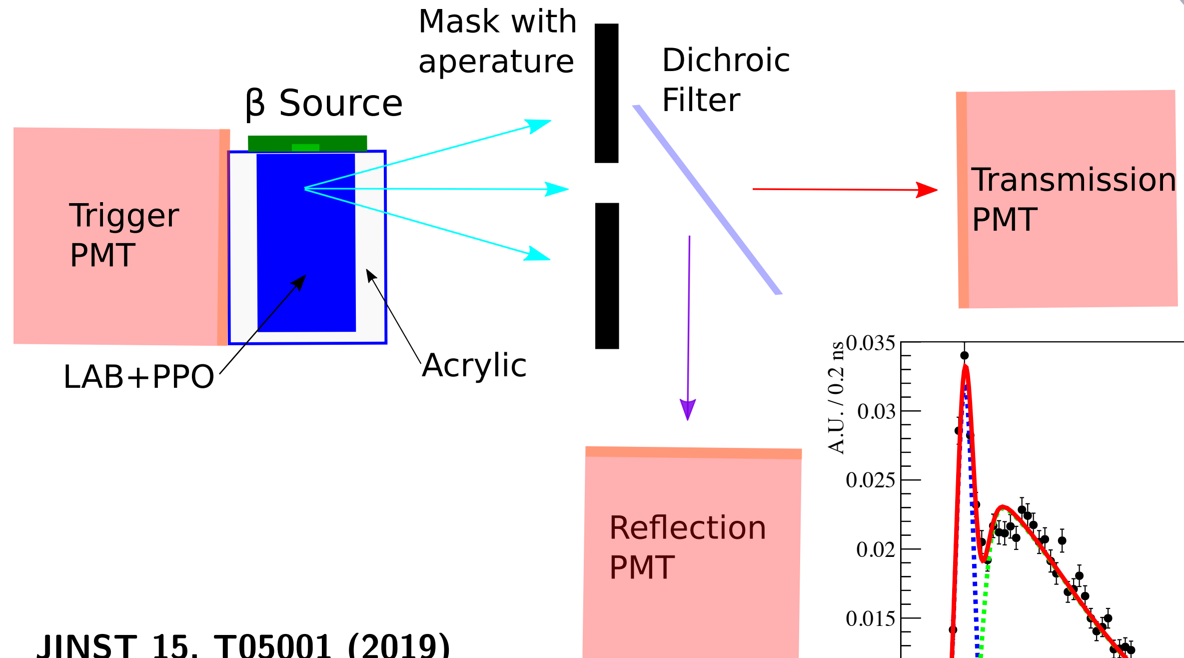
Photon Detection

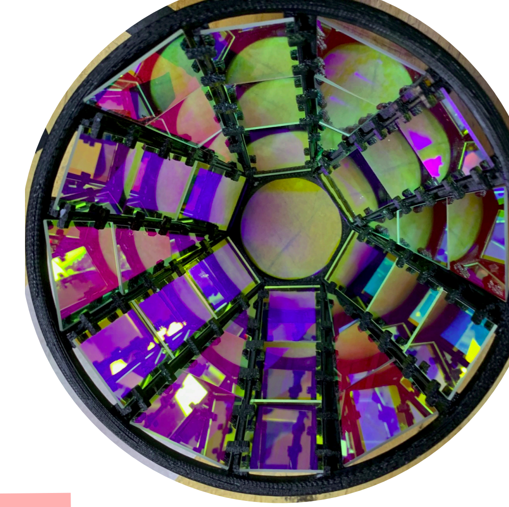
Spectral Dependence

1. **Cherenkov production is fast relative to scintillation**
   Early photons are Cherenkov-rich
2. **Most Cherenkov photons are absorbed by the LS**
   The valuable direct photons are in the long-wavelength tail.

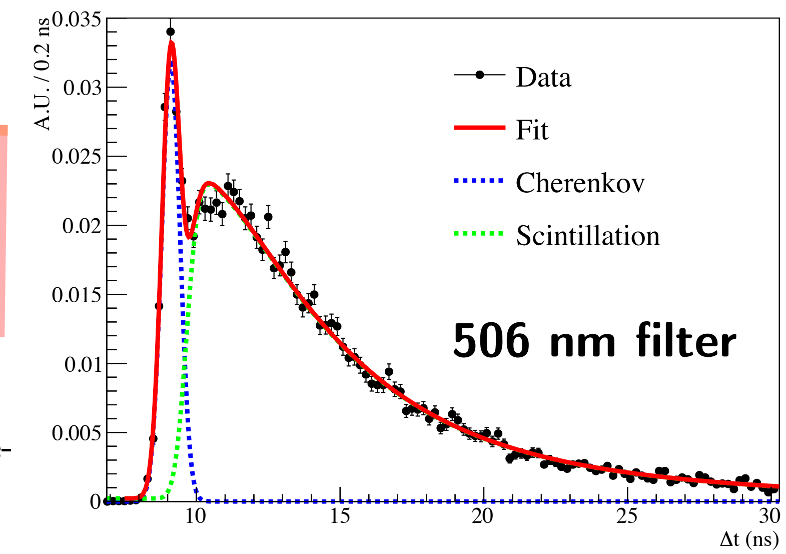


Dichroic Filtering





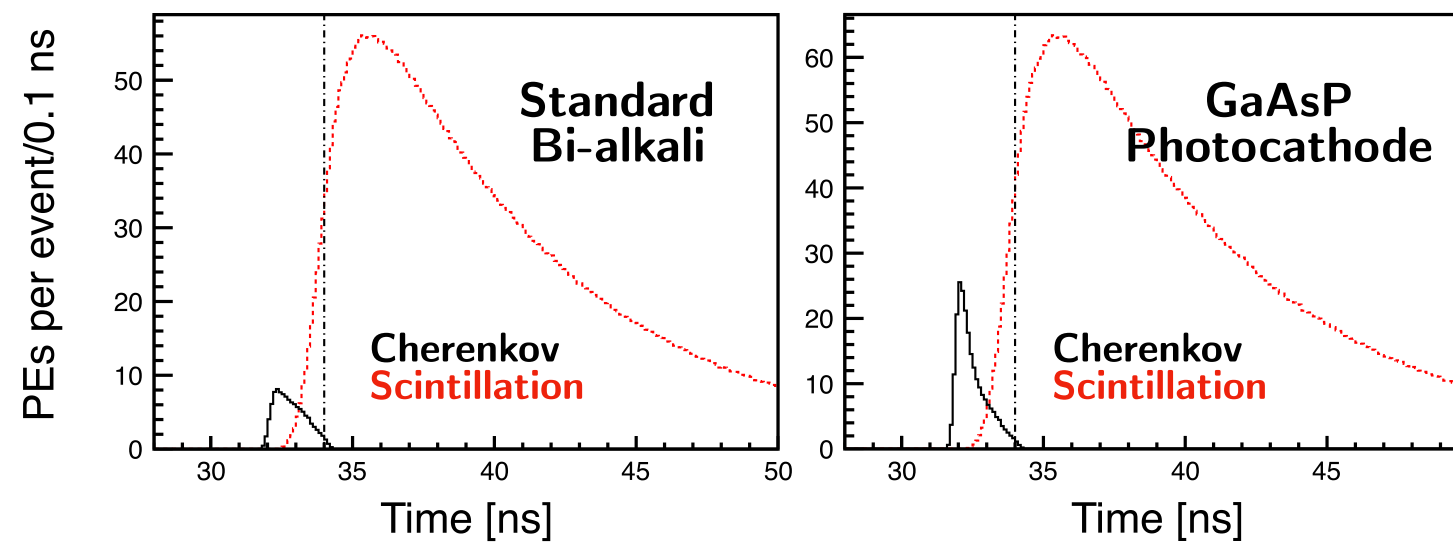
Dichroic Winston cone
T. Kaptanoglu, DPF19



JINST 15, T05001 (2019)

T. Kaptanoglu, July 11 Detector Parallel Session "The Dichroicon: Spectral Photon Sorting For Large-Scale Cherenkov and Scintillation Detectors"

Red-Sensitive Photocathodes



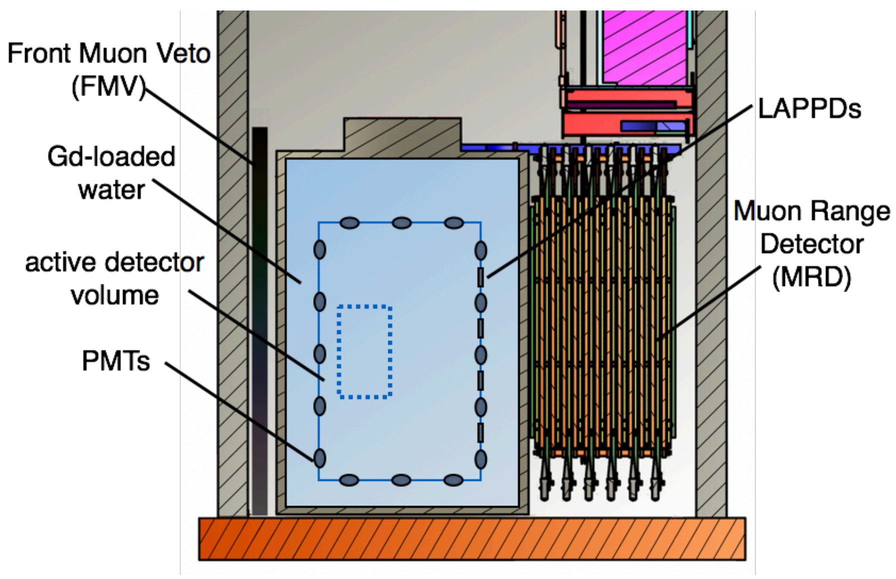
JINST 9, P06012 (2014)

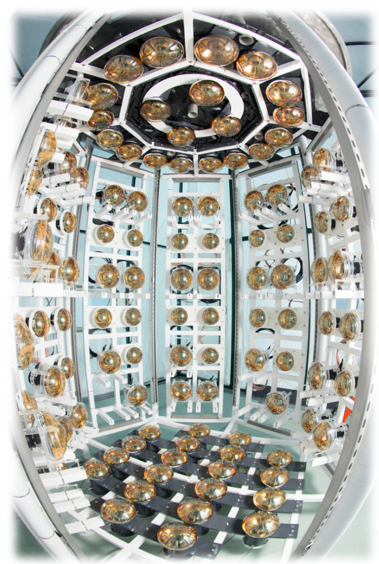
Complementary Programs

"Friends of Theia"

Existing programs pilot key Theia technologies, building up to full scale

ANNIE: Accelerator Neutrino-Nucleus Interaction Experiment

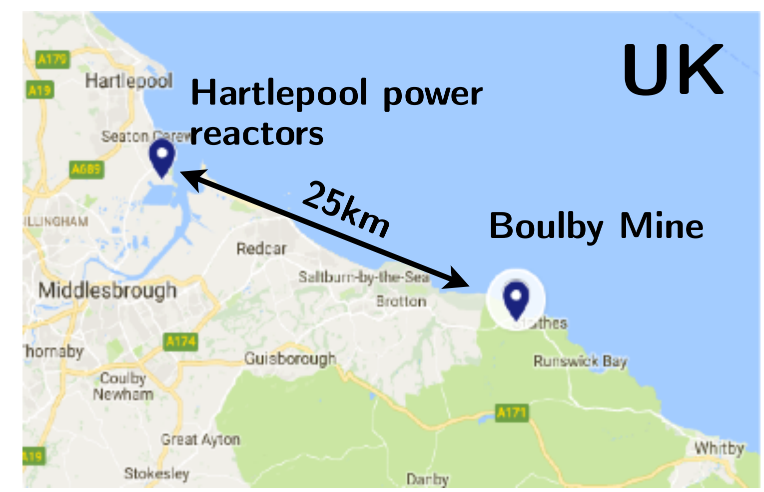




26 tonne water Cherenkov detector in the FNAL Booster Neutrino Beam

- First to deploy LAPPDs in water
- Materials & compatibility testing
- Reconstruction technique development
- Potential for WbLS loading

WATCHMAN: WATer Cherenkov Monitor for Anti-Neutrinos



"Advanced Instrumentation Testbed"
Phase I, reactor monitoring mission

- Materials testing, integration, DAQ
- Reconstruction development
- Possible for large-scale WbLS loading
- Advanced photon sensor R&D

Adapted from R. Malek

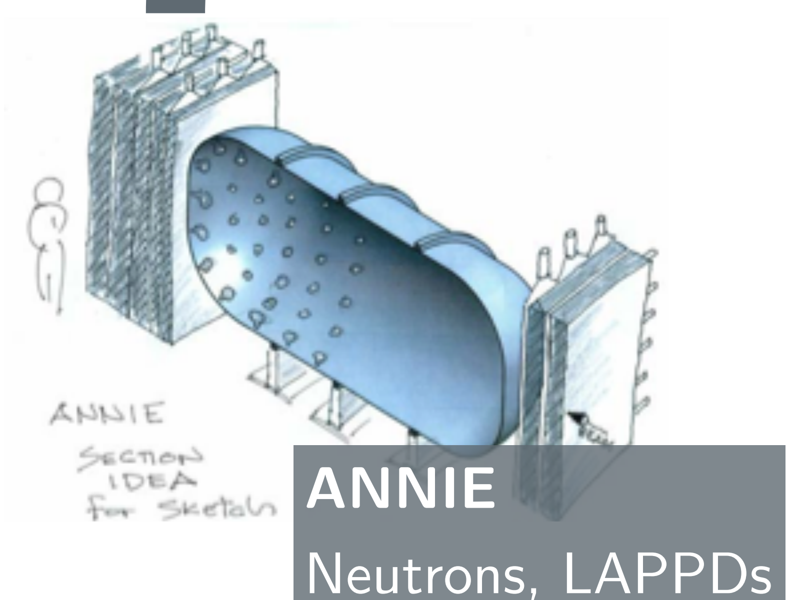
Detector Programs

Complementary R&D

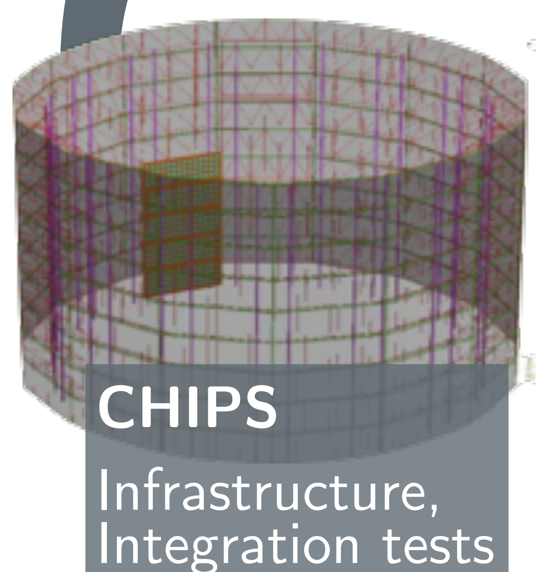
arxiv:1908.11532

bnl.gov/chemistry/NNC

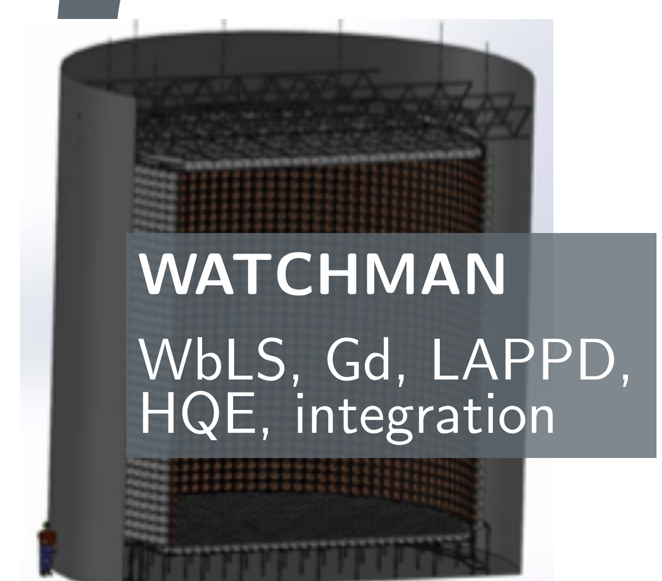
snoplus.phy.queensu.ca



annie.fnal.gov



chipsneutrino.org



arxiv:1502.01132

Slide adapted from G. Orebi Gann

Summary & Outlook

Compelling Physics via Novel Technologies

Enabling Technologies

- Water-Based LS target
- Cherenkov + Scintillation
- Fast photodetectors
- Advanced reconstruction

Broad Physics

- LBL: CPV + mass ordering
- Nucleon decay
- Geoneutrinos
- Supernova burst & DSNB
- Source-based sterile searches
- Neutrinoless Double-Beta Decay

- The convergence of technologies presents a transformational opportunity to address several major open questions in neutrino physics
- High level of complementarity with the existing program, including DUNE and LBNF
- The flexibility of target and detection mechanisms means a detector that can evolve with the field for decades to come

Thank You!

Questions?

Advanced Scintillator Detector Concept (ASDC) Whitepaper → arxiv:1409.5864

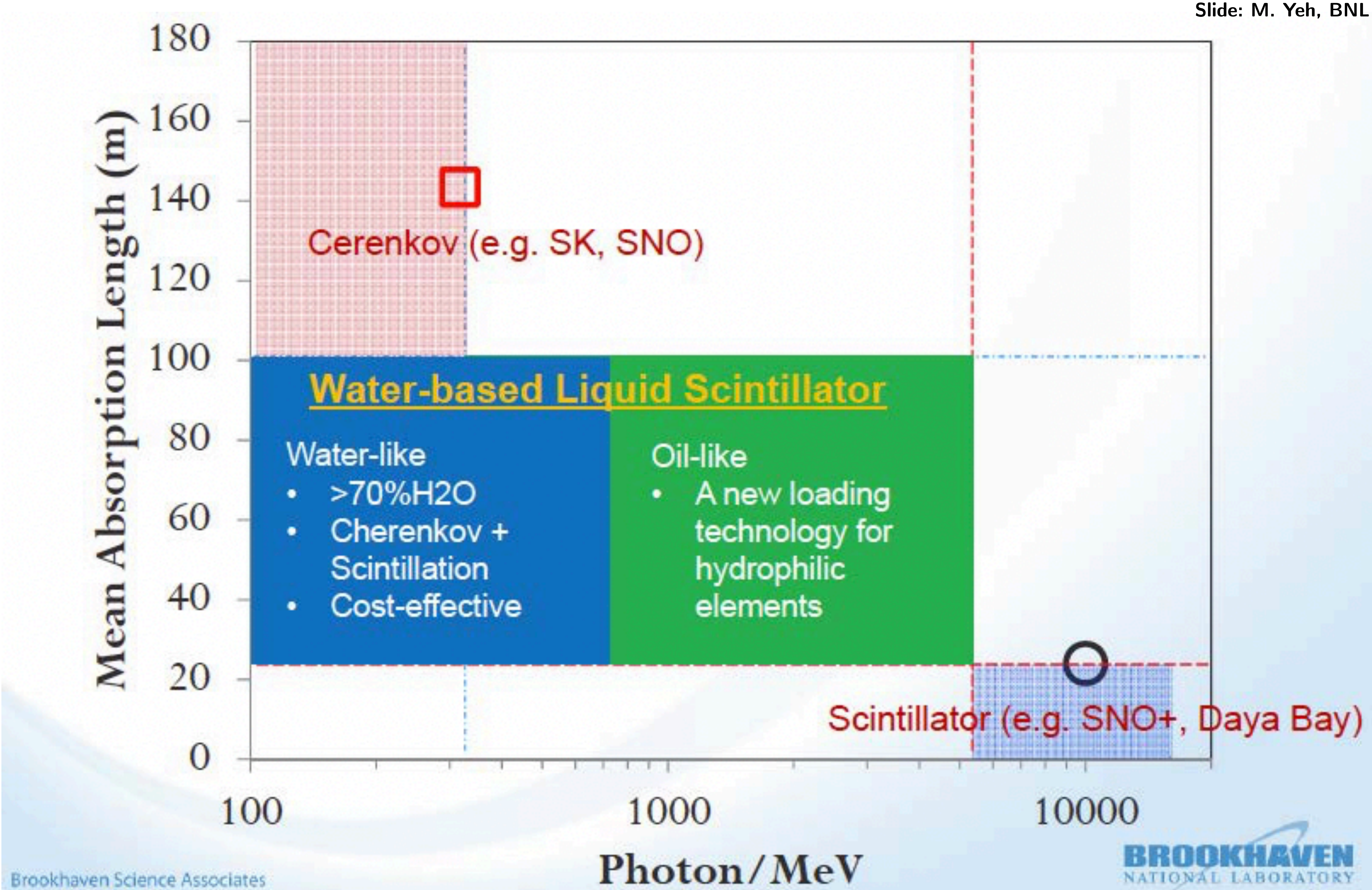
Theia whitepaper in preparation

FroST – Topical Workshop for Theia, JGU Mainz

Water-Based LS

Cherenkov/Scintillation Tuning

Slide: M. Yeh, BNL



Liquid Scintillator

Advantages & Challenges

Liquid Scintillator detectors have been deployed and proposed to study a broad array of topics:

- Long-baseline neutrinos and beams
- Neutrinoless double beta decay (and related)
- Solar neutrinos
- Reactor $\bar{\nu}$ and geoneutrinos
- Supernova and diffuse SN background neutrinos
- Sterile neutrinos

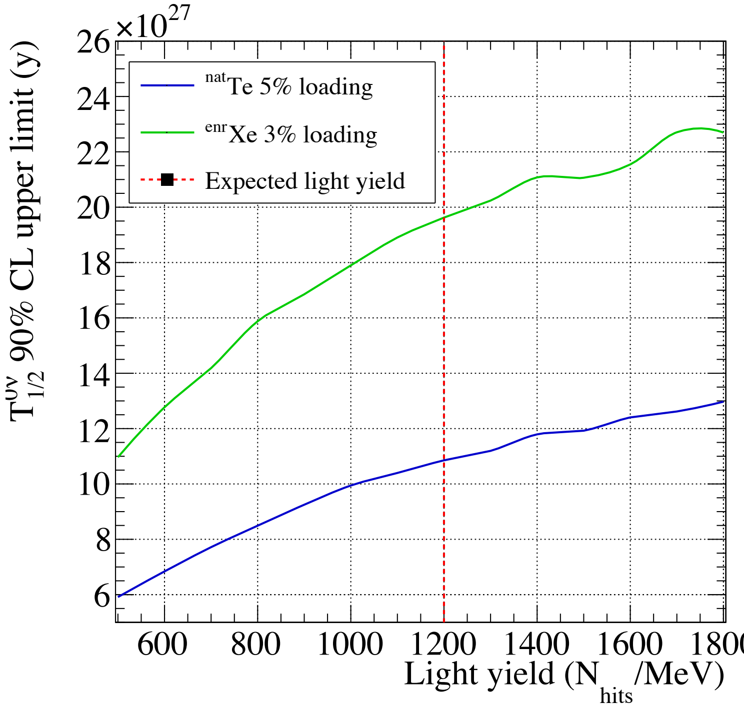
:)	:(
Low threshold, large target mass, self-shielding, loading options	*Energy resolution, optics, cost, lack of directionality*

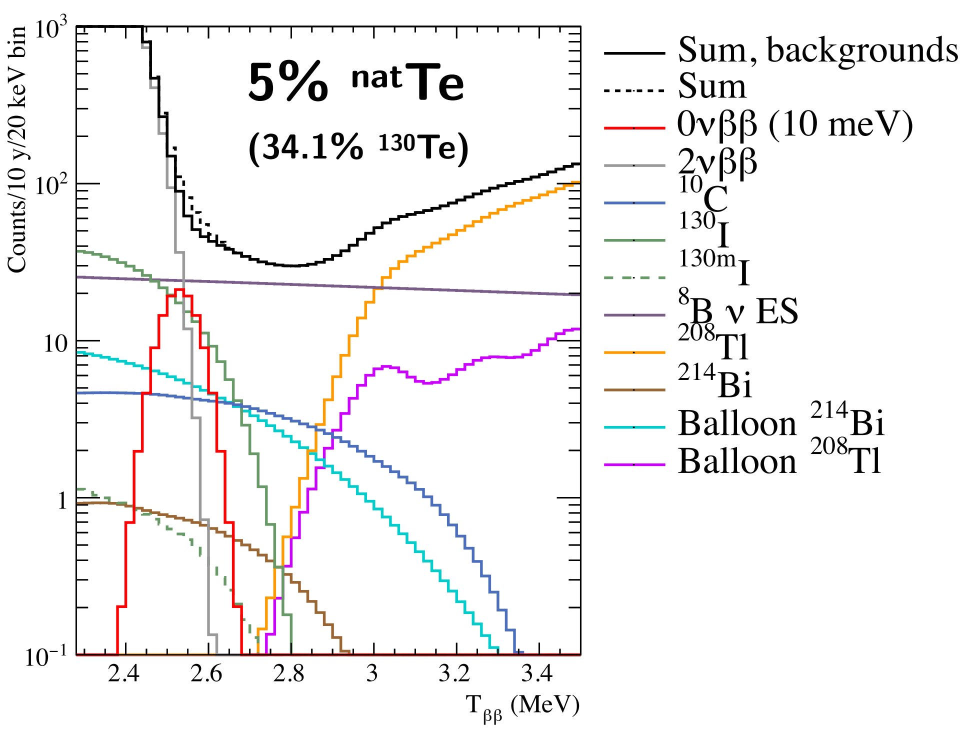
Neutrinoless Double Beta Decay

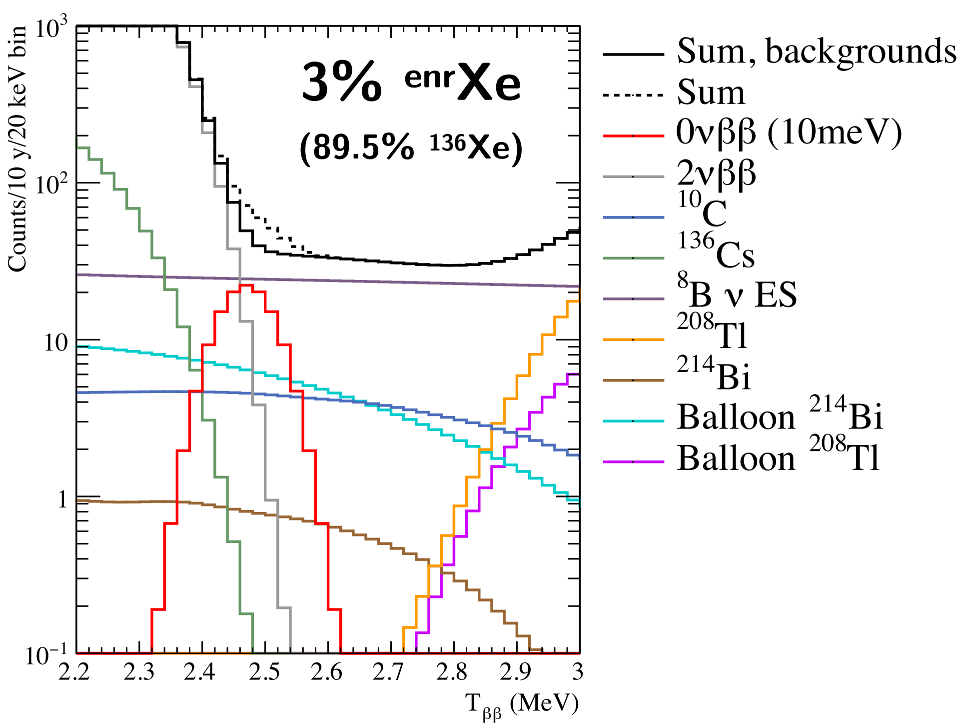
Majorana Neutrinos & LNV

Source	Target level	Expected events/y	Events/ROI·y 5% ^{nat}Te	Events/ROI·y 3% ^{enr}Xe
Balloon ^{10}C		500	2.5	2.5
^{8}B neutrinos (normalization from [45])		2950	13.8	13.8
^{130}I (Te target)		155 (30 from ^{8}B)	8.3	-
^{136}Cs ($^{\text{enr}}$Xe target)		478 (68 from ^{8}B)	-	0.06
$2\nu\beta\beta$ (Te target, $T_{1/2}$ from [46])		1.2×10^{8}	8.0	-
$2\nu\beta\beta$ ($^{\text{enr}}$Xe target, $T_{1/2}$ from [47, 48])		7.1×10^{7}	-	3.8
Liquid scintillator	^{214}Bi: 10^{-17} g_U/g	7300	0.4	0.4
	^{208}Tl: 10^{-17} g_{Th}/g	870	-	-
Nylon Vessel [49, 50]	^{214}Bi: $< 1.1\times10^{-12}$ g_U/g	1.2×10^{5}	3.0	3.4
	^{208}Tl: $< 1.6\times10^{-12}$ g_{Th}/g	2.1×10^{4}	0.03	0.02

TABLE IV: Dominant background sources expected for the NLDBD search in THEIA. The assumed loading is 3% for Xe, for a ^{136}Xe mass of 49.5 t, and 5% for Te, for a ^{130}Te mass of 31.4 t. The events in the ROI/yr are given for a fiducial volume of 7 m and an asymmetric energy range around the Q-value of the reaction (*see text*). A rejection factor of 92.5% is applied to ^{10}C, of 99.9% to ^{214}Bi, of 50% to the balloon backgrounds, and of 50% to the ^{8}B solar neutrinos.







LY: 1200 pe/MeV
10 years livetime
7 m fiducial volume
H_2O bkg.: SNO
LS bkg.: 0.1x Borexino
75% signal efficiency

Rejection:

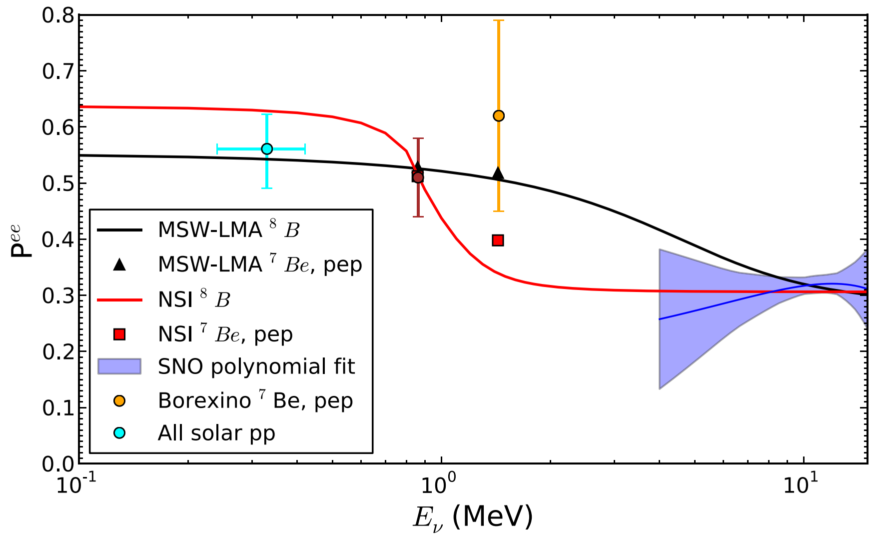
- 92.5% ^{10}C
- 99.9% ^{214}Bi
- 50% external
- 50% ^{8}B solar ES

Solar Neutrinos
Questions & Motivation

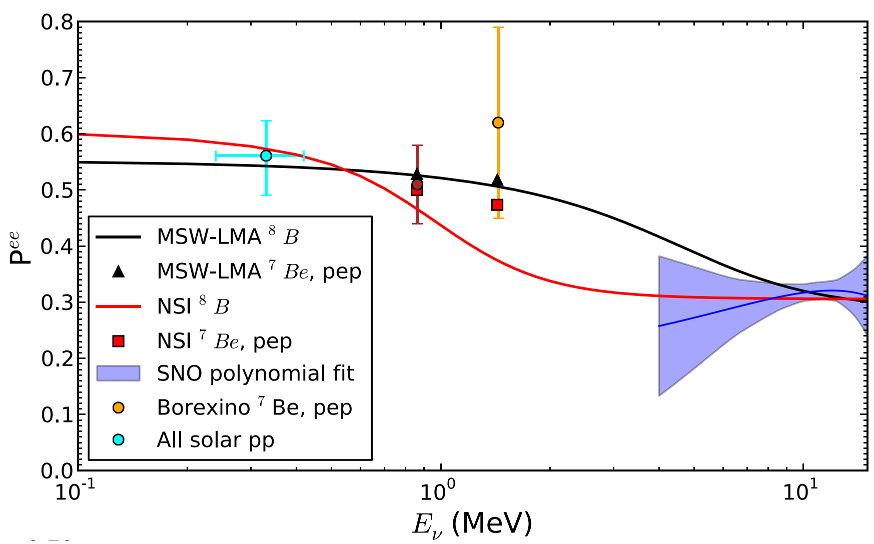
- Measurement of MSW matter-vacuum transition region, $E_\nu \sim 1$ MeV
  - Understand experimental tension
  - Confirmation of MSW model
  - Search for new physics (NSI) $\rightarrow$
- High-precision *pp* fluxes
  - *pep* (luminosity)
  - ^{7}Be (temperature, tomography)
  - *hep* (unmeasured)
- CNO fluxes
  - Solar metallicity
  - Modeling of heavier main-sequence stars

Example NSI Fits

PRD 88, 053010 (2013)



Fermion-density dependent MaVaN



Scalar long-range force

Requirements

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

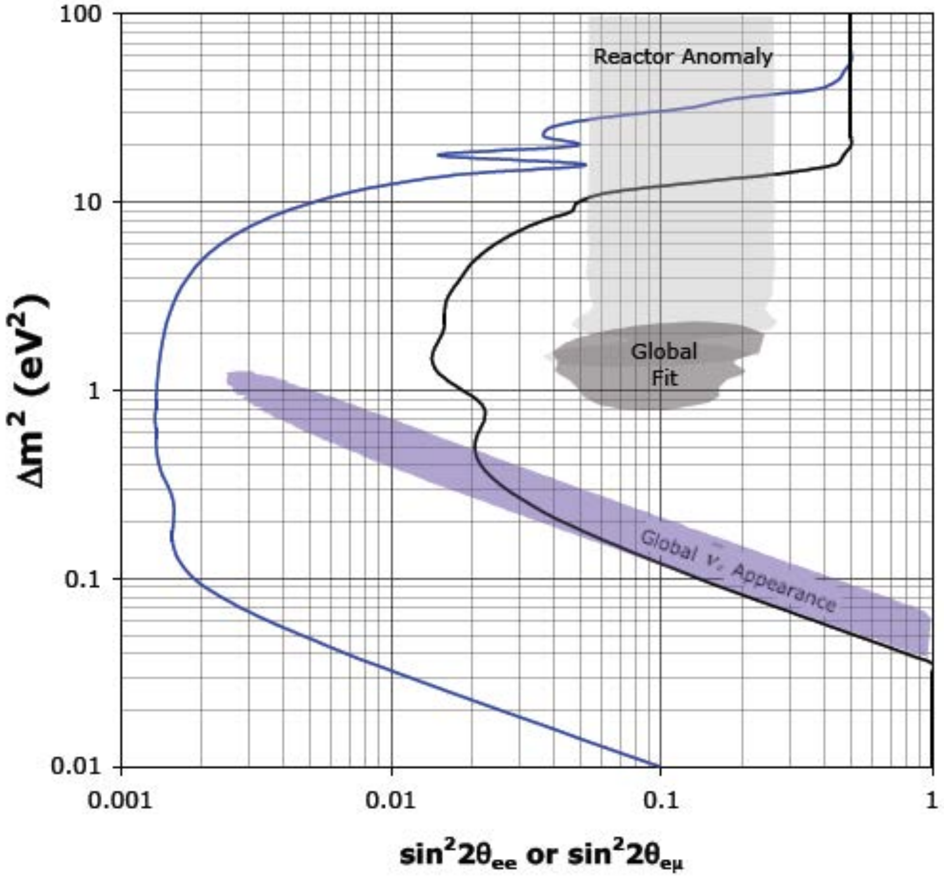
From G.D. Orebi Gann

Sterile Neutrinos

Source-Based VSBL Oscillations

- Potential to deploy an intense DAR source near the Theia detector
- E.g. ^{8}Li DAR such as IsoDAR
- Response requirements: E~15% E, r~50 cm
- Case study →
  - 5 years live time
  - Fiducial 1 kt (black) / 20 kt (blue)
- Could reduce backgrounds using a $2n$ tag with a *heavy* water based LS (HWbLS)

arxiv:1409.5864



Advanced Reconstruction
Examples

see B. Wonsak et al., Solar Neutrinos, pp. 445-463 (2019)

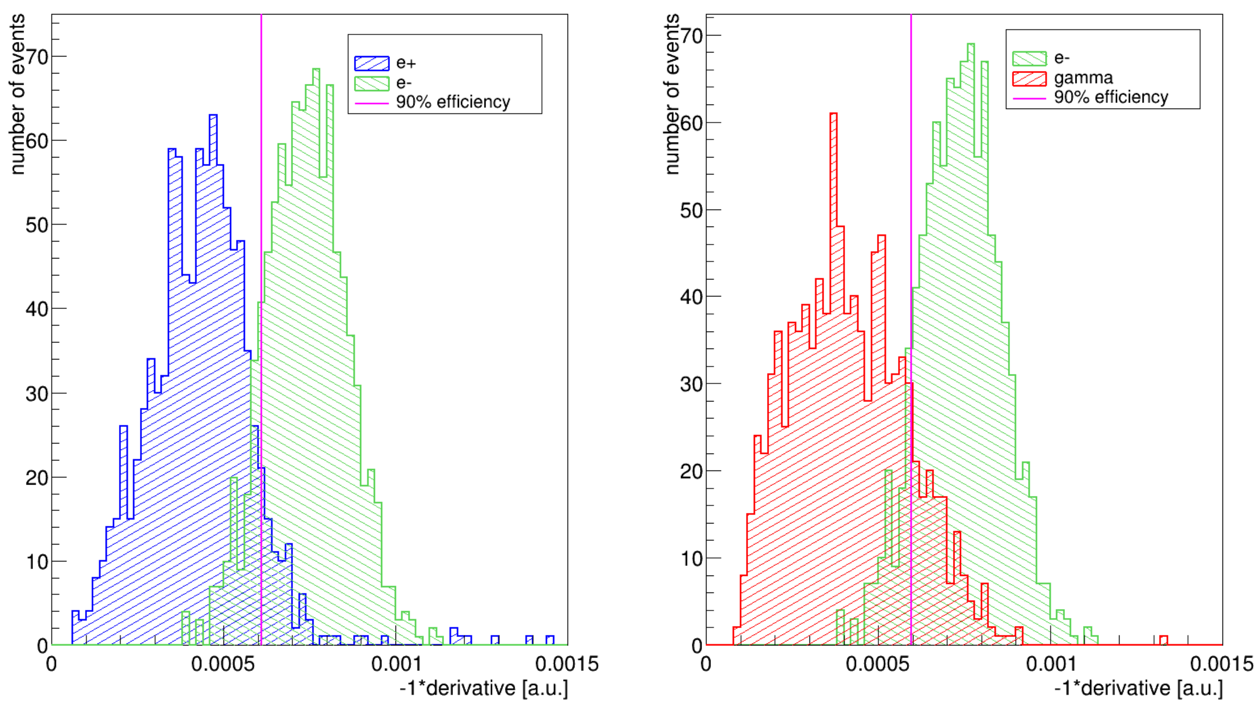


FIG. 2: Maximum derivative of the radial profile of the 3D-topological reconstruction at 2 MeV in JUNO for (left) electrons and positrons and (right) electrons and gammas [63].

Examples:

- **Cherenkov + Scintillation**
  - **MiniBooNE**
  - **LSND**
- **Likelihood approaches**
  - **fiTQun (SK): multi-track, PID**
- **Topological reco**
  - **Tracking with C+S**
  - **Low-energy topology (SS/MS, e/gamma)**
- **Spherical harmonics & DL approaches**
  - **60% C10 rejection, 90% NLDBD eff.**

Angular resolution 0.3–0.8 rad
100 ps photodetector timing
2.5 MeV simulated electrons
see R. Jiang and E. Elagin, arXiv:1902.06912

FIG. 3: Simulation of a liquid scintillator detector similar to KamLAND-Zen, but equipped with 100 ps time resolution photo-detectors. Details about the simulation can be found in [60] (Left): The inner product between the reconstructed direction and the true electron direction for simulation of 10,000 one-track background events. (Right): The mean value of the inner product distribution as a function of photo-coverage.