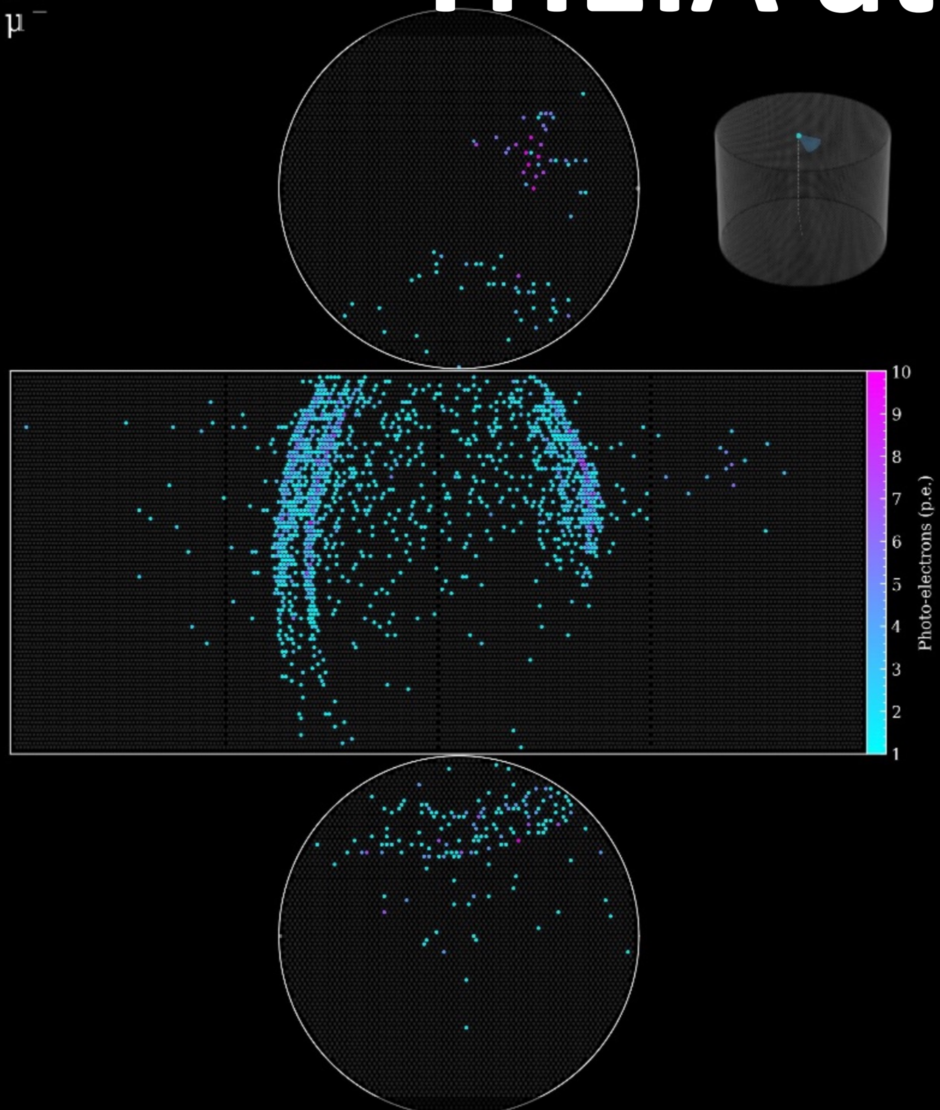
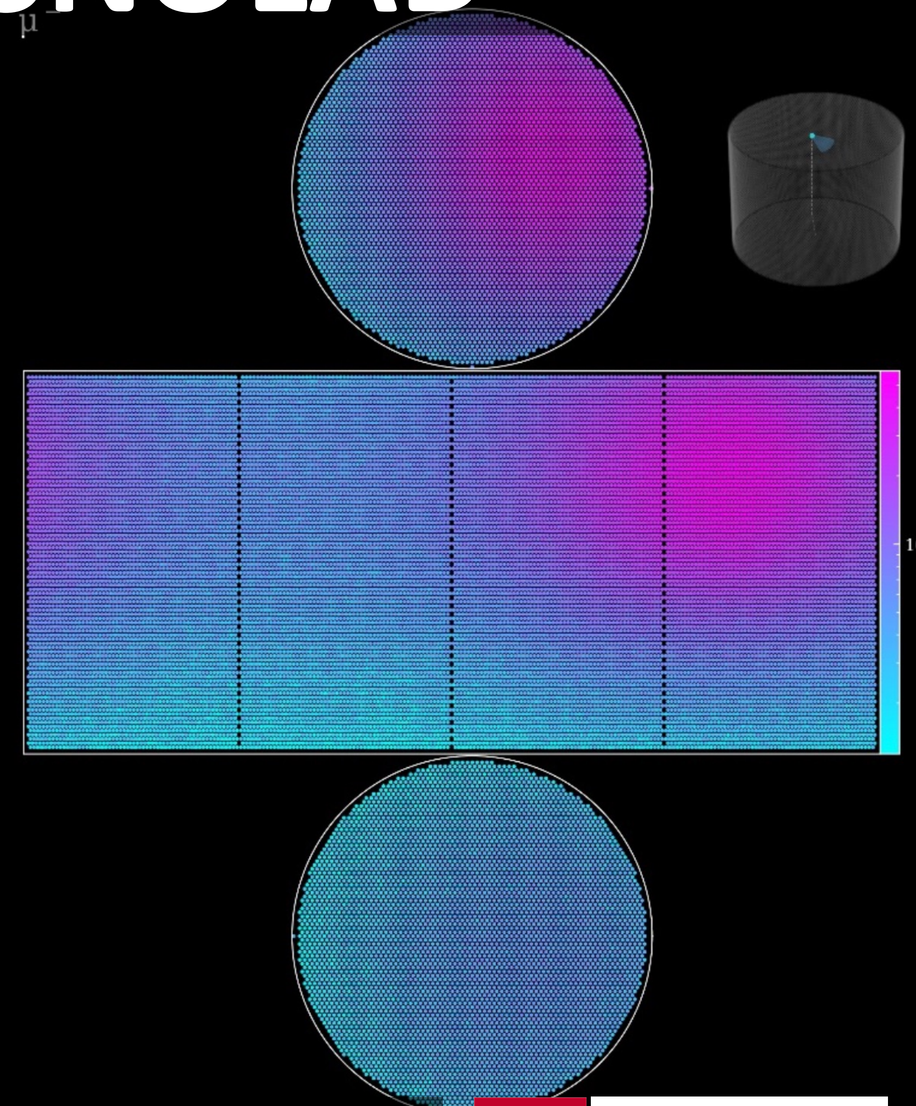
Next-generation Hybrid Cherenkov-Scintillation Detector

THEIA at SNOLAB





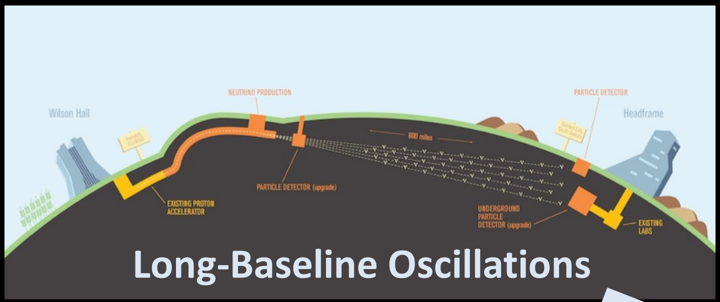
+++ Future Projects Workshop ++ SNOLAB, 29 Apr 2025 +++

++ Michael Wurm (JGU Mainz) for the THEIA consortium ++

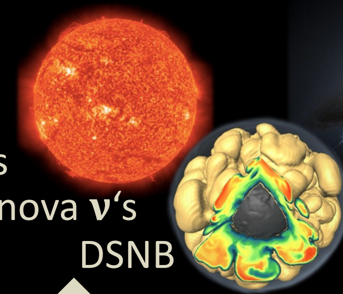
JG|U PRiSMA+

Hybrid Cherenkov/Scintillation Detector

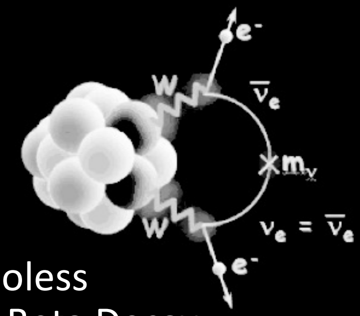
→ Enhanced sensitivity to broad physics program



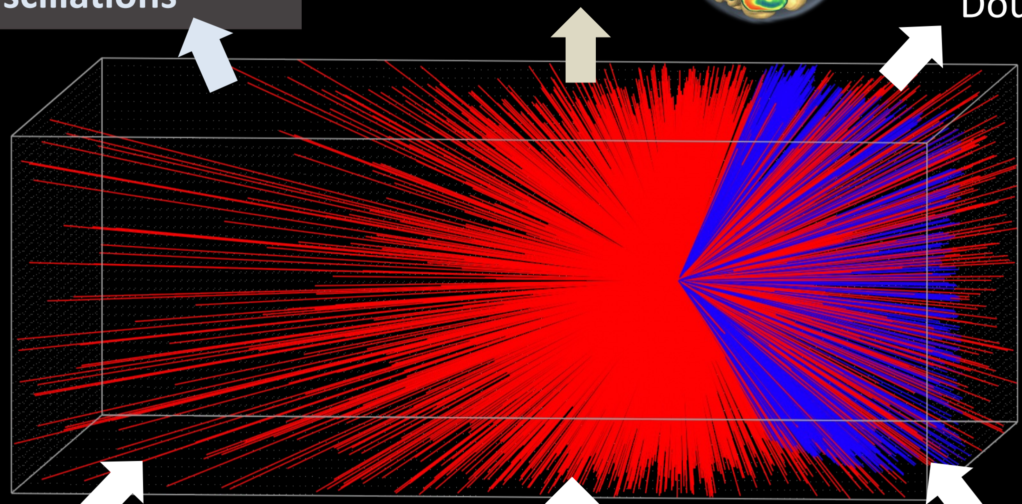
Long-Baseline Oscillations



solar ν's
Supernova ν's
DSNB



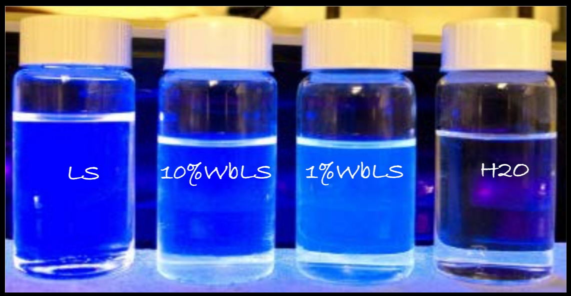
Neutrinoless
Double-Beta Decay



THEIA25

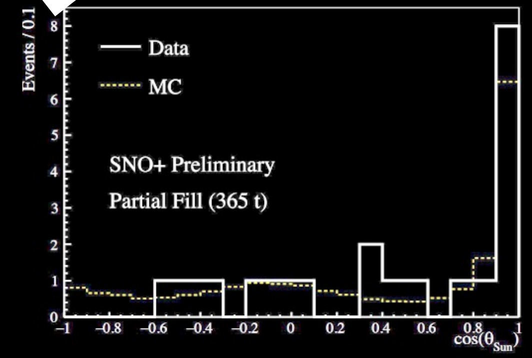
Hybrid Detector able to exploit both **Cherenkov+ Scintillation** signals

novel target medium:
Water-based Liquid Scintillator

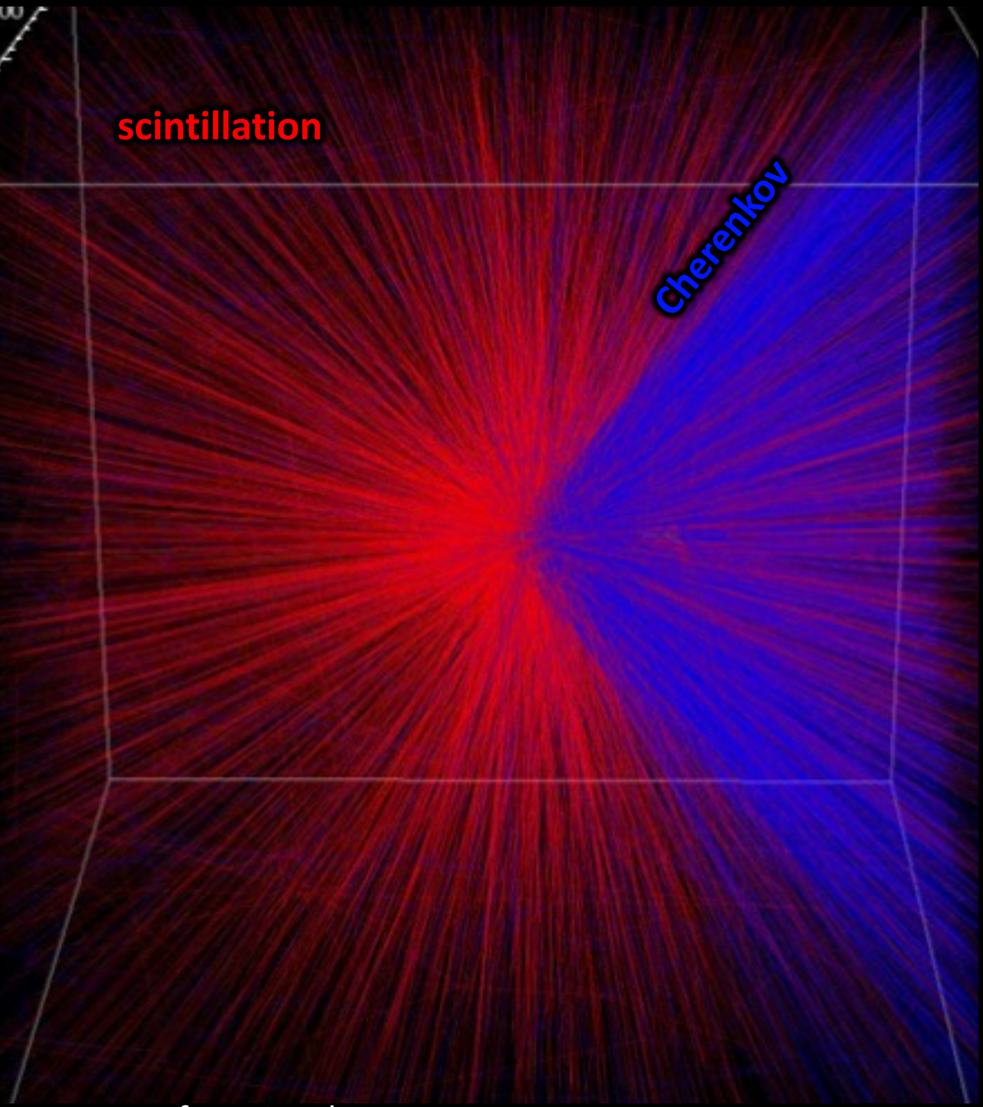


novel light sensors:
fast PMTs, LAPPDs, dichroicons

novel
reconstruction
techniques



Hybrid Cherenkov-scintillation detection



courtesy of Ben Land

MeV-GeV neutrino experiments use

→ **Scintillation:** enables good energy resolution and low thresholds

→ **Cherenkov effect:** particularly useful for reconstruction of direction and (multiple) tracks

→ Cherenkov photons *are* produced in liquid scintillators (~5%), but the majority is scattered or absorbed before reaching PMTs

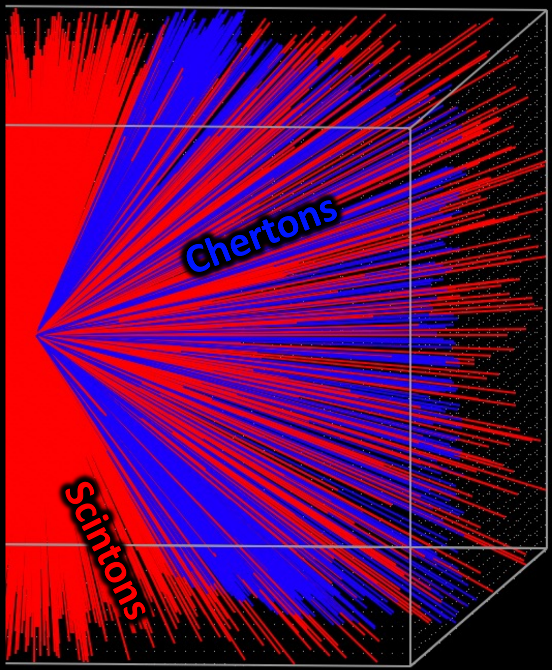
How to extract the Cherenkov signal?

→ enhance liquid transparency and/or

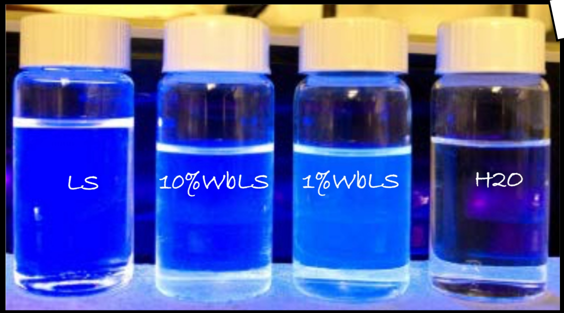
→ slow down scintillation emission

→ Water-based liquid scintillators and slow scintillators

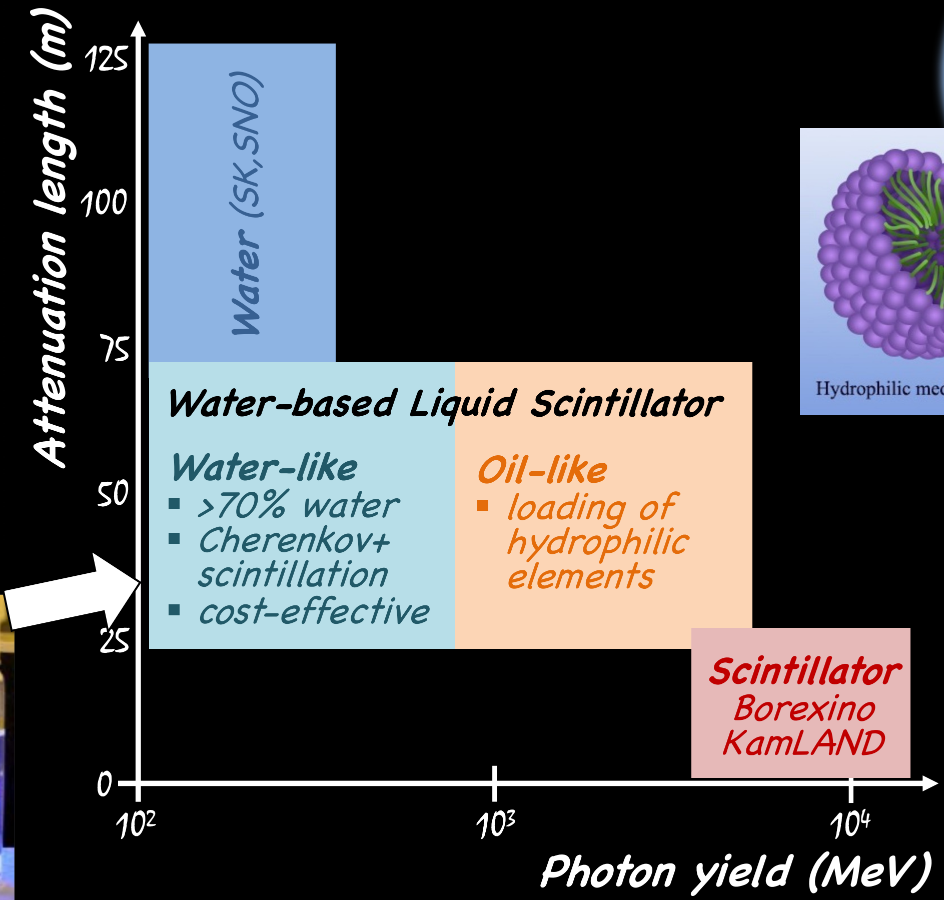
Water-based liquid scintillators (WbLS)

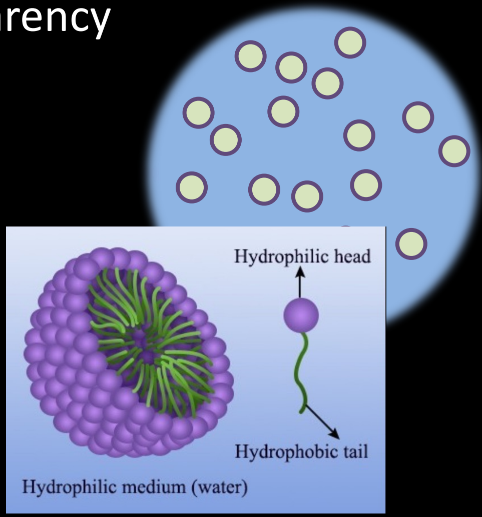


→ WbLS: water + tensid + solvent (LAB) + fluor (PPO)
→ low organic fraction → high transparency



Minfang Yeh, BNL





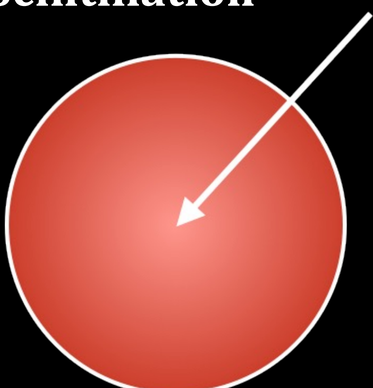
WbLS mycels

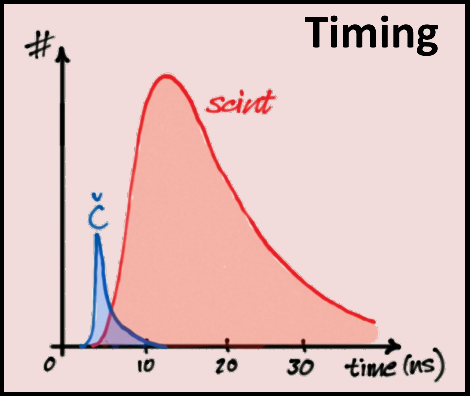
→ **properties of target medium can be adjusted to physics goal**
→ **water content offers additional options for metal loading**

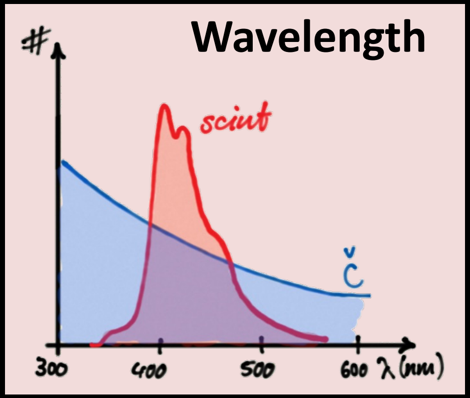
Photo Sensors for Separating Chertons and Scintons

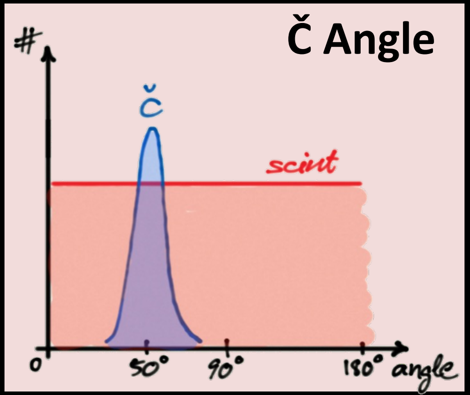
Cherenkov

Scintillation

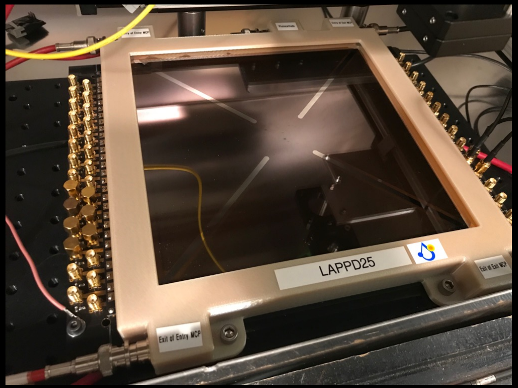






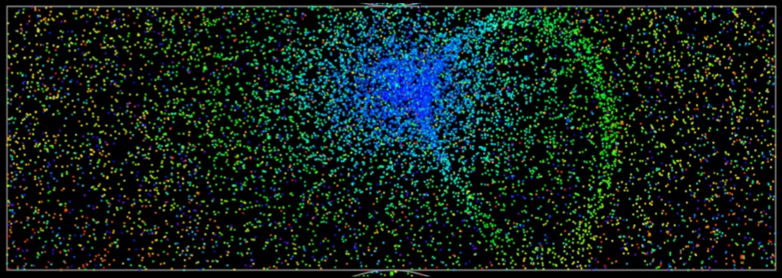


LAPPDs
tts~60ps



Dichroicons
spectral
sorting

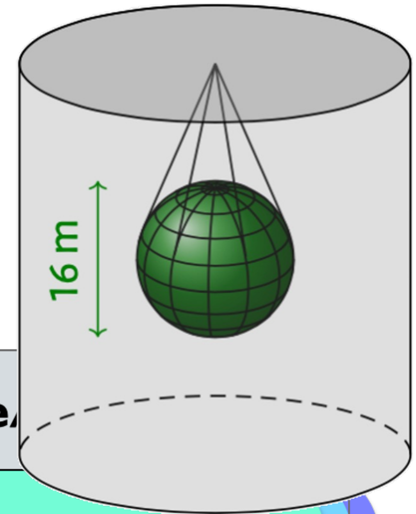
PMT granularity



THEIA's Phased Physics Program

scintillator properties will be adjusted to physics requirements,

e.g. 1% WbLS → 10% WbLS → slow scintillator

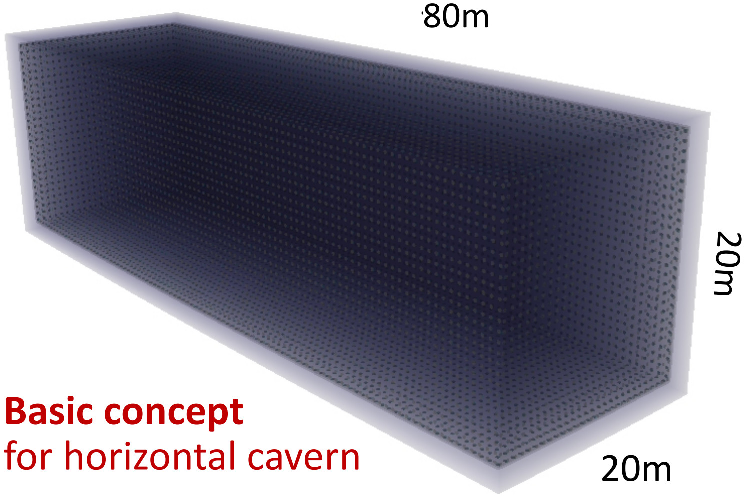


only if located at SURF

start at **SNOLAB** from **Phase II**

Phase	Primary physics goal	Reach	Exposure
I	**Long-baseline oscillations**	>5σ for 30% of δ_{CP}	524kt-MW-year
I	**Nucleon decay $p \rightarrow \bar{\nu} K^+$**	T>3.8 x 10^{34} year	800 kt-year
I	**Supernova burst**	<1(2)° pointing 20K(5K) events	100(25)kt, 10kpc SN
I	**Diffuse Supernova Neutrino**	5σ	125kt-year
II	**CNO neutrinos**	<5(10)%	300(62.5)kt-year
II	**Geoneutrinos**	< 7 %	25 kt-year
III	**$0\nu\nu\beta$**	$T_{1/2}$ > 1.1 x 10^{28} year (90%C.L.)	800 kt-year (Multi-tonne loaded LS in suspended vessel search)

THEIA Detector at SNOLAB

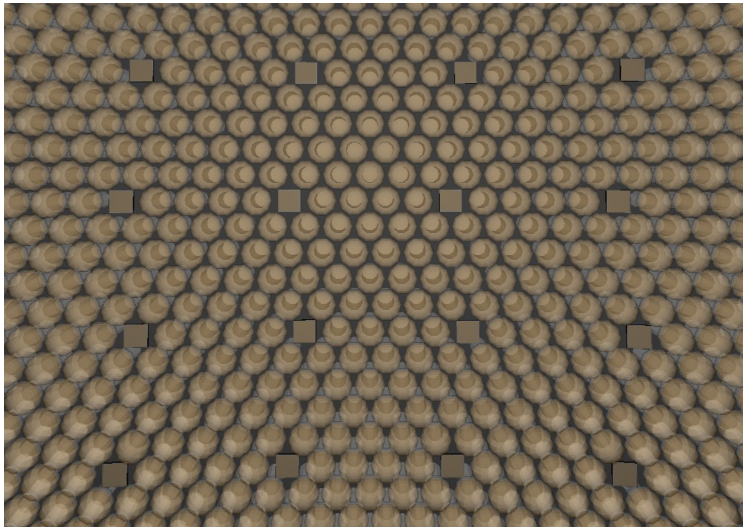


Basic concept
for horizontal cavern

THEIA Detector Specifications

- **Detector mass:** baseline 25 kt → ideal 100 kt
- **Dimensions:** 20m x 20m x 80m → 32,000 m^3
- **Target medium:** WbLS with organic fraction 5-10%
- **Photosensors:** fast PMT array aiming at 40% optical coverage, e.g. 25,000 10''-PMTs, potentially adding LAPPDs/dichroicons
- **ββ phase:** balloon (2,000 m^3) of slow scintillator, re-arrange PMTs to increase coverage

PMT array with interspaced LAPPDs



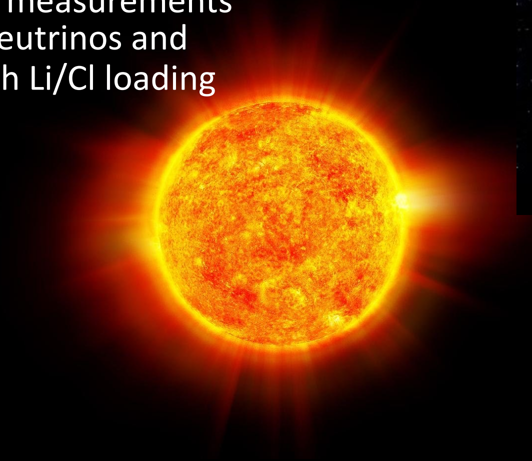
Advantages of SNOLAB as detector site

- **Depth and rock shielding**
  → suppression of muon-induced C/Te spallation isotopes
  → excellent performance for astro-ν & ββ program
- **Infrastructure and experience**
  → existing infrastructure for low-BG experiments
  → ample experience from SNO+

Astrophysical neutrinos at low energies

Supernova Neutrinos
high statistics and flavor-resolved
observation of neutrino burst

Solar Neutrinos
precision measurements
of CNO neutrinos and
$P_{ee}(E)$ with Li/Cl loading



Diffuse Supernova Neutrinos
average SN neutrino spectrum
fraction of dark/BH-forming SNe

Geoneutrinos
crust/mantle
contributions
U/Th ratio

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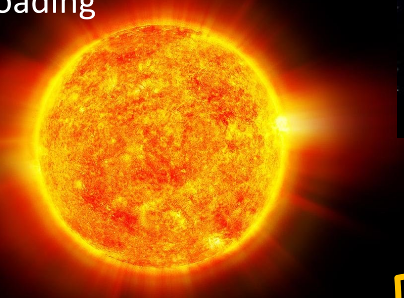
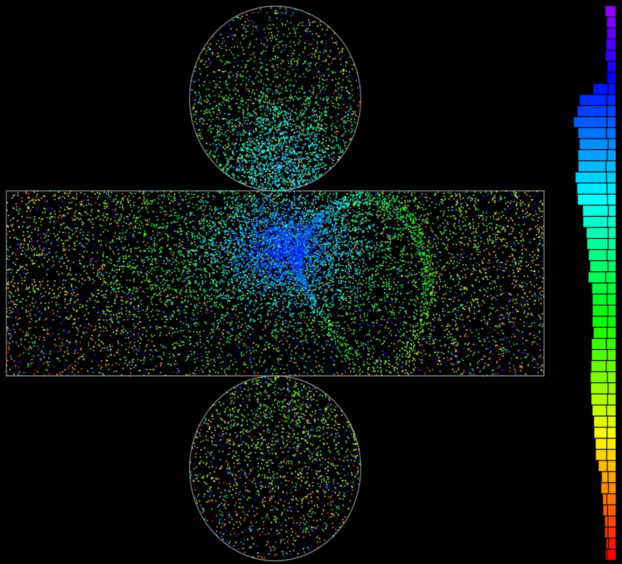


Diffuse Supernova Neutrinos
average SN neutrino spectrum
fraction of dark/BH-forming SNe

Geoneutrinos
crust/mantle
contributions
U/Th ratio

Hybrid detectors offer

- Cherenkov: particle ID, discriminating isotropic BGs
- Scintillation: good energy resolution, low threshold, pulse shape discrimination
- C/S ratio: BG discrimination for particles with low/no Cherenkov light output

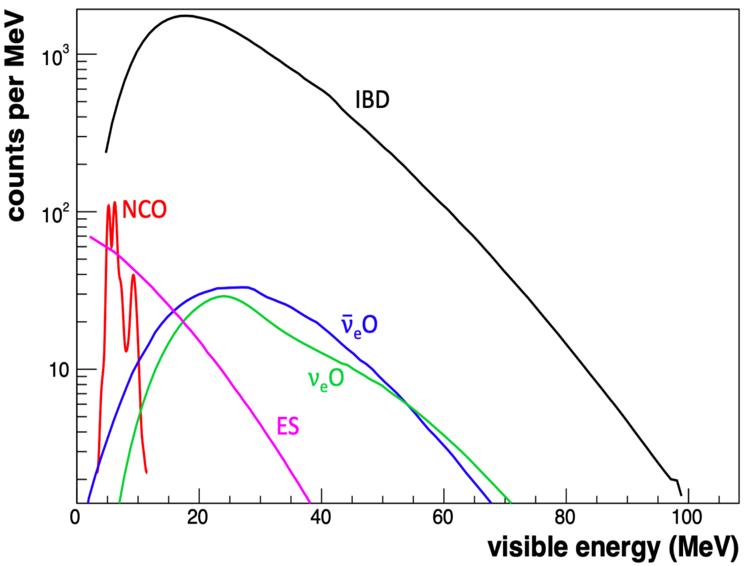


Supernova Neutrinos in THEIA

Event rates for THEIA-25
GVKM SN model @ 10kpc

Reaction		Rate
(IBD)	$\bar{\nu}_e + p \rightarrow n + e^+$	4,950
(ES)	$\nu + e \rightarrow e + \nu$	240
(ν_eO)	$^{16}\mathrm{O}(\nu_e, e^-)^{16}\mathrm{F}$	85
($\bar{\nu}_e$O)	$^{16}\mathrm{O}(\bar{\nu}_e, e^+)^{16}\mathrm{N}$	110
(NCO)	$^{16}\mathrm{O}(\nu, \nu)^{16}\mathrm{O}^*$	275

(Prompt) event energy spectra
assuming 10%of WbLS (200p.e./MeV)

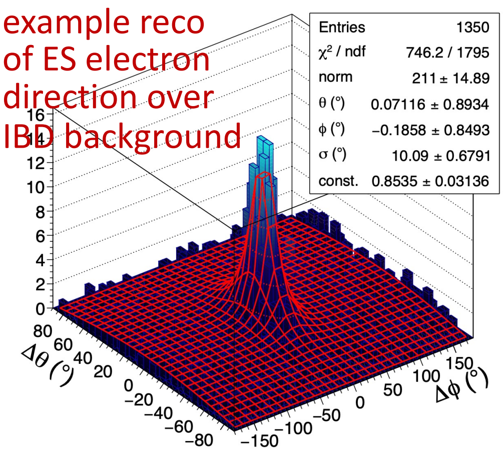


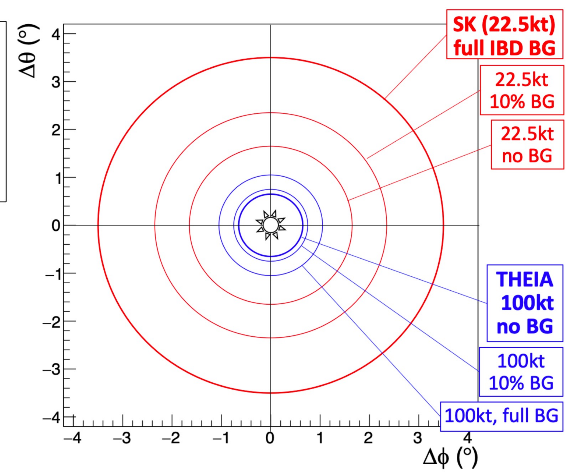
THEIA: High-statistics (~5k events) flavor-resolved information on core-collapse SNe with complementarity to SK, JUNO and DUNE

Note: unlike pure Cherenkov detectors, channels separated based on event signature!

- signal is dominated by IBDs ($\bar{\nu}_e$'s)
- Electron Scattering (ES) and CC on oxygen provide ν_e-specific information
- ES signal: excellent pointing capability, ~2° due to IBD background suppression
- NC on oxygen → all-flavor (ν_e+$\boldsymbol{\nu_\mu}$+$\boldsymbol{\nu_\tau}$) rate

example reco of ES electron direction over IBD background



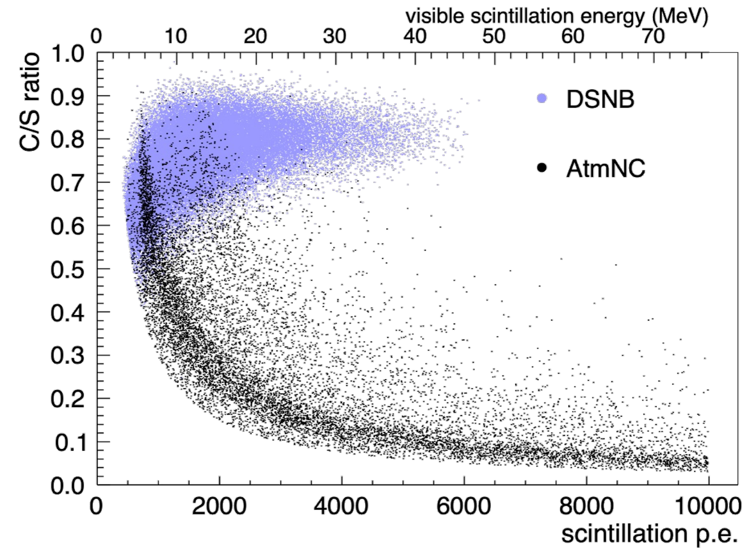


Diffuse Supernova Neutrino Background

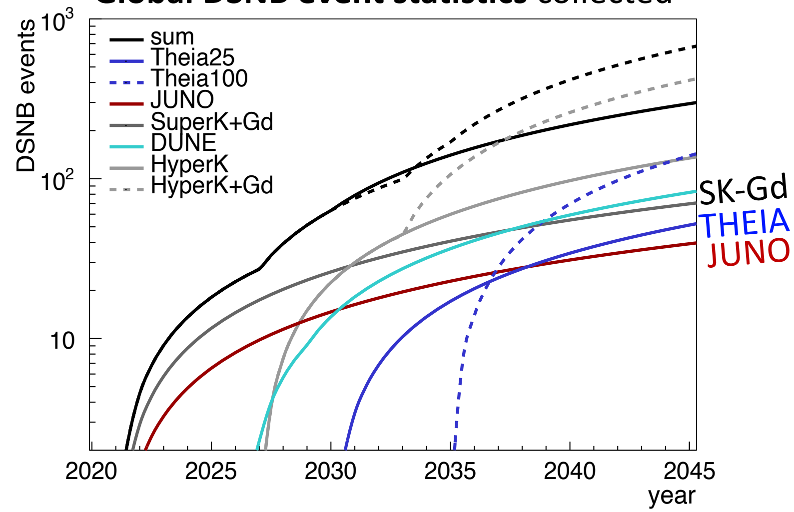
THEIA: Excellent background discrimination and conditions means rapid collection of DSNB statistics and first go at spectroscopy

- In THEIA, $\bar{\nu}_e$ component detectable via IBD, ~5 ev. for 25 kt·yrs on hydrogen
  → *en par* with SK-Gd, HK and JUNO
- THEIA combines discrimination capabilities of Cherenkov and scintillator detectors
- For atmospheric neutrino backgrounds, Cherenkov/scintillation ratio as powerful tool
  → signal efficiency: 80%
  → residual background: 1.3%
  } **S:B > 2:1**
  → will improve BG estimates for water/LS
- THEIA-100: **5σ observation of DSNB in 5 yrs**
- With other experiments, DSNB spectroscopy:
  → average SN neutrino spectrum
  → fraction of dark (black hole-forming) SNe

Cherenkov/scintillation ratio for BG discrimination



Global DSNB event statistics collected



Solar Neutrinos in THEIA

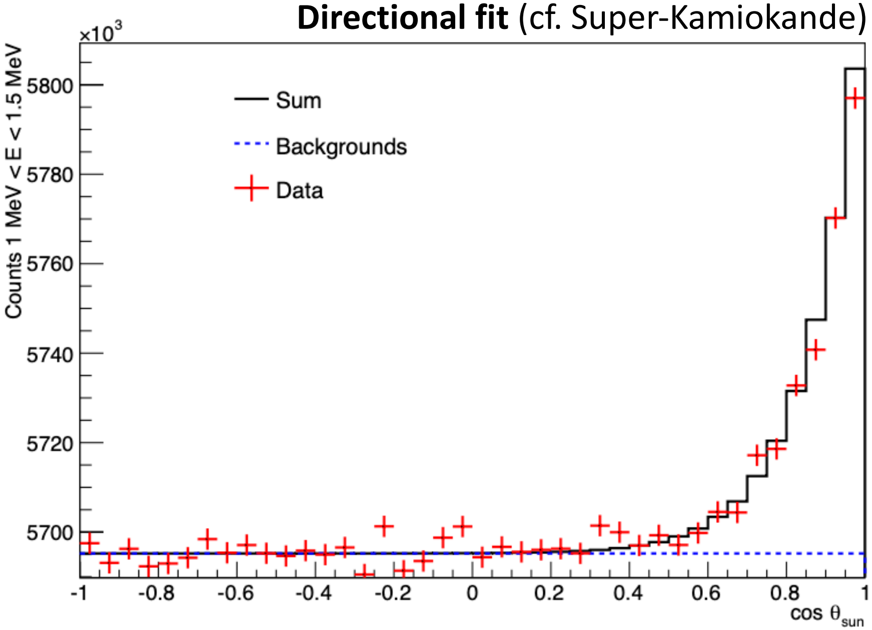
THEIA: Low-energy threshold combined with directionality and/or isotope loading (Li) to perform precision spectroscopy of low-energy solar neutrinos

- Precise measurement of CNO neutrino flux → stellar physics, solar metallicity
- Spectral upturn of low-energy ^{8}B neutrinos → matter effects, BSM physics?

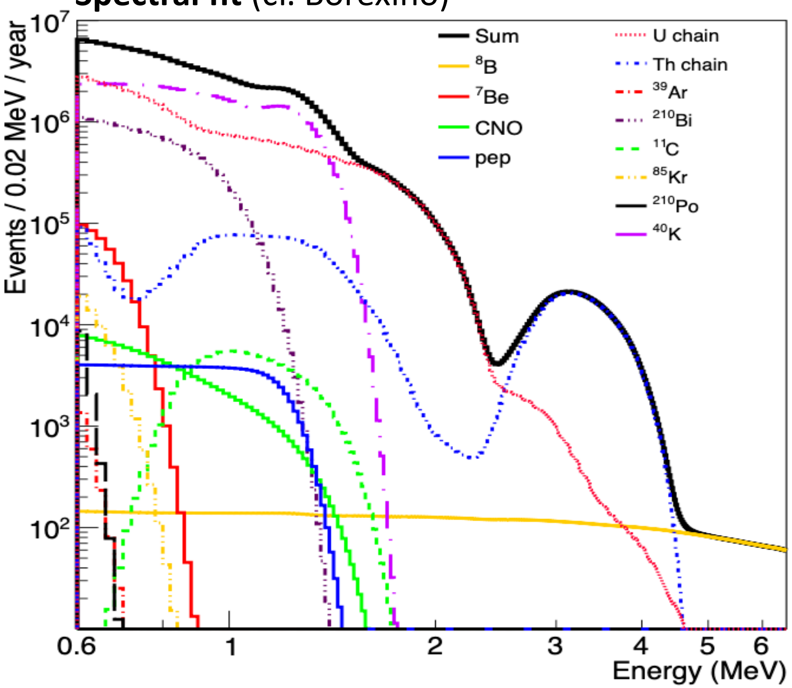
→ require efficient BG discrimination and sufficient light yield in 1-3 MeV range

- THEIA25: 2D directional & spectral fit
  → CNO flux at 10% level after 5 yrs

Directional fit (cf. Super-Kamiokande)



Spectral fit (cf. Borexino)

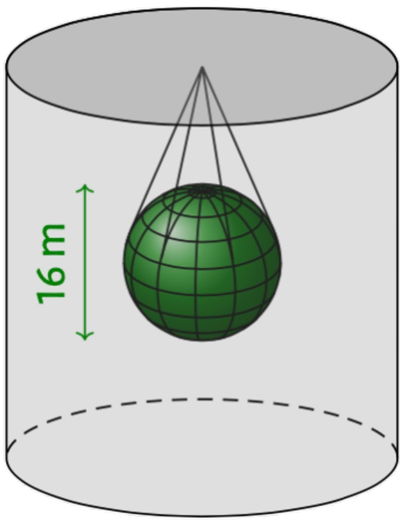


R. Bonventre, G.D. Orebi Gann, Eur. Phys. J. C (2018) 78:435

Second Phase: ββ Search with Theia

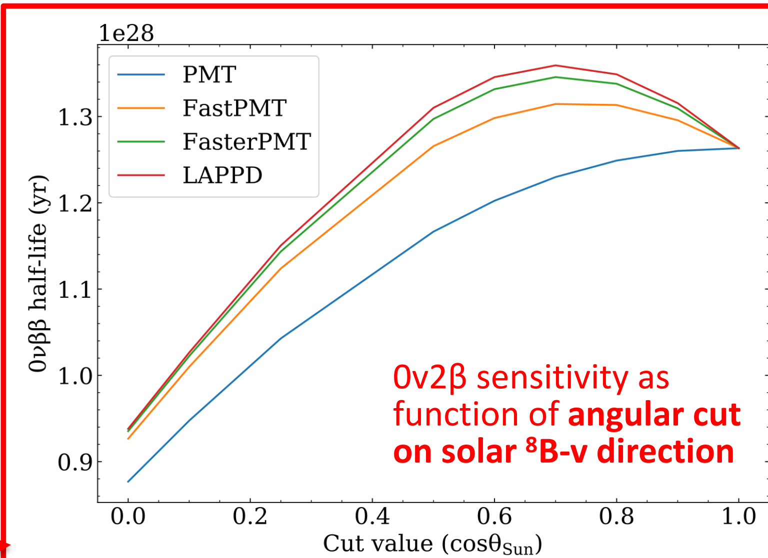
In continuation of SNO+ physics program:

THEIA: 50t of ^{130}Te in 2kt balloon with slow scintillator to reach **mass range $m_{\beta\beta}$~5meV**



Detector geometry

install balloon (2,000 m³) of loaded slow scintillator
→ isotope mass: 30~60 t
→ organic: high light yield
→ high photo-coverage (for WbLS phase)
→ good energy resolution

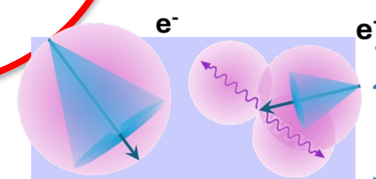


Enhanced background discrimination

- suppression of **solar ⁸B-neutrinos** based on directionality
- hybrid detector offers ratio of Cherenkov to scintillation photons

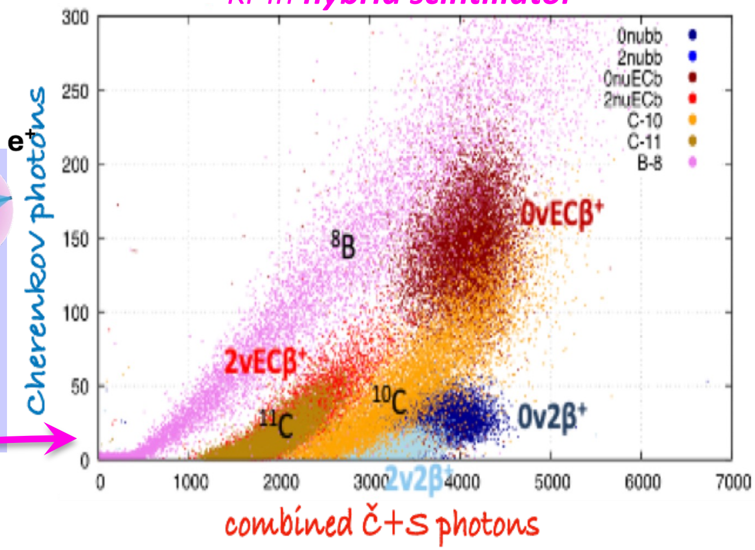
  → e⁺/e⁻/γ discrimination

  → potential 2β⁻/2β⁺ signatures



ratio of Cherenkov to scintillation photons depends on particle type and energy

*Cherenkov-scintillation ratio for ^{78}Kr in **hybrid scintillator***



Neutrinoless Double-Beta Decay Sensitivity

compared to current scintillator-based double-beta experiments

→ substantially larger isotope mass

→ better energy resolution

→ enhanced background discrimination

compared to other experimental techniques

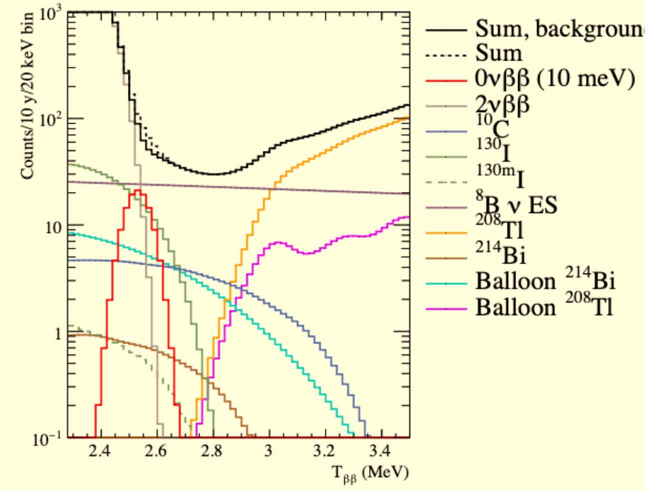
→ sensitivity sufficient to reach into the $m_{\beta\beta}$ mass range of normal ordering

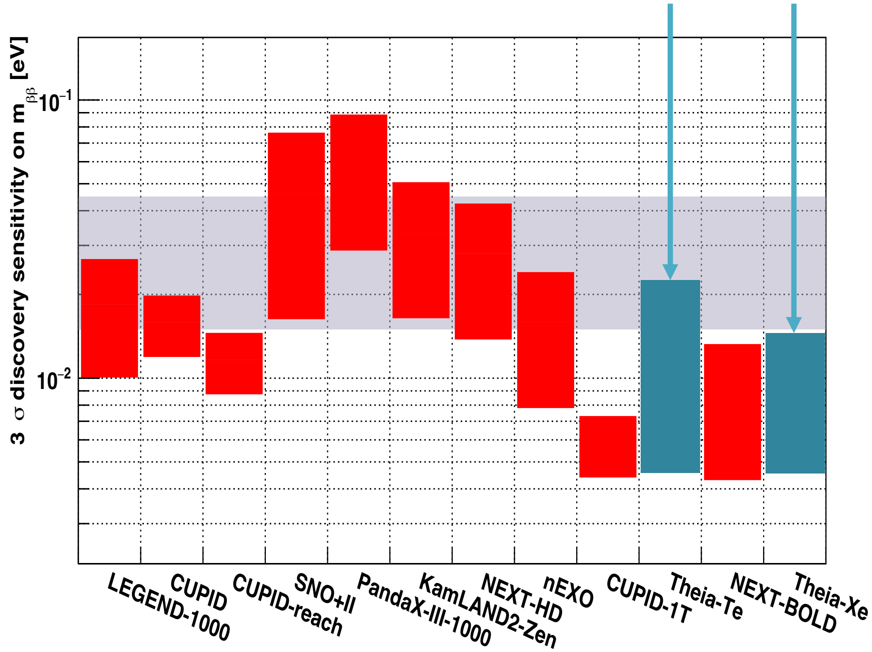
Sensitivity (90% CL)
from spectral fit:

- **Te-130:** $T_{1/2} > 1.1 \times 10^{28}$ yrs, $m_{\beta\beta} < 6.3$ meV
- **Xe-136:** $T_{1/2} > 2.0 \times 10^{28}$ yrs, $m_{\beta\beta} < 5.6$ meV

Assumptions

- 2,000 m^3 of LS
- mass: ~50t
- 1,200 pe/MeV
- $\Delta E/Q_{\beta\beta}$ ~ 1.8%
- ROI BG count: 0.03 events/yr

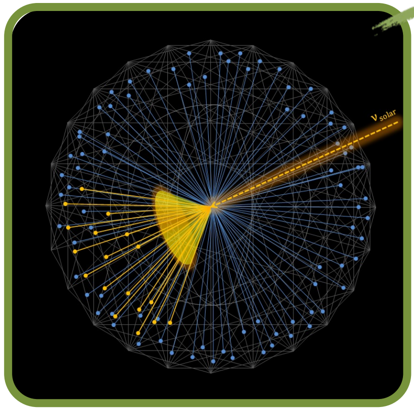




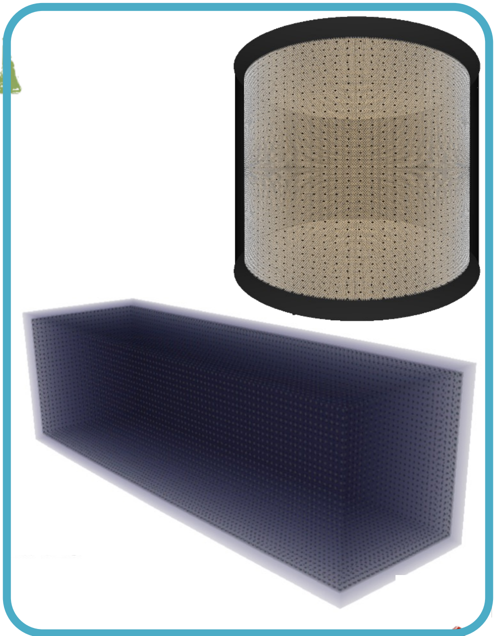
Plot by Yu. G. Kolomensky using methodology from Agostini, Benato, Detwiler: PhysRevD.96.053001

Current Status of Hybrid Scintillator Program

Borexino
SNO+

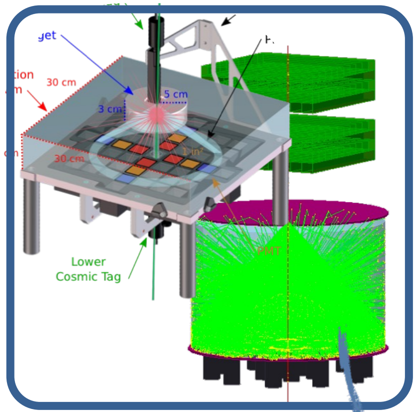


Re-analyzing data from existing LS Detectors



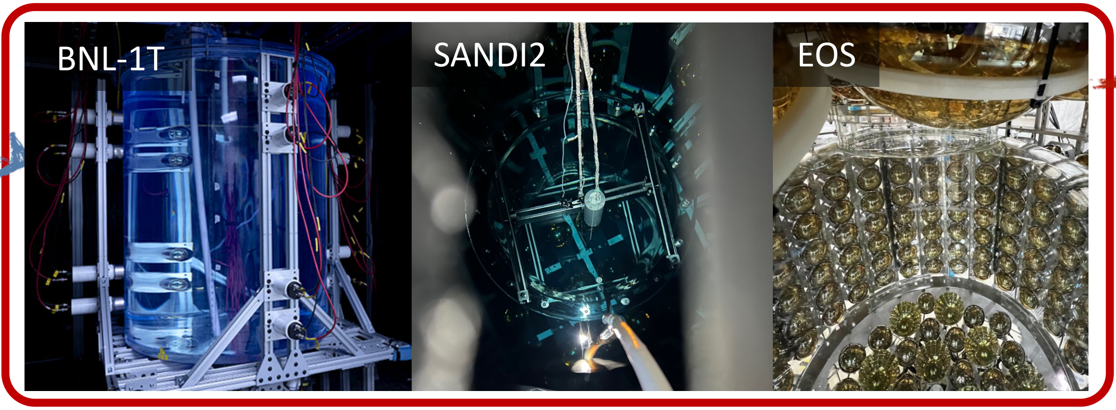
Full-scale THEIA

Lab-Scale Setups



UCB: CHESS
Tsinghua U.
MZ: SCHLYP
MZ/TÜ: DISCO
...

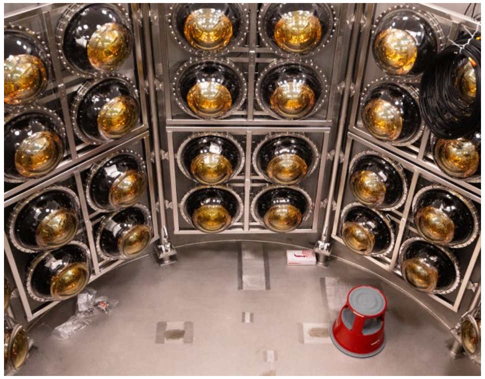
CURRENT MULTI-TON-SCALE SETUPS



BNL Prototypes
SANDI in ANNIE
EOS

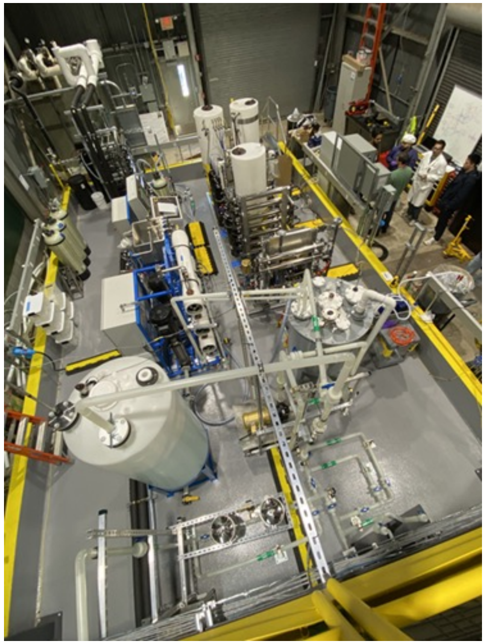
THEIA Community

- **THEIA consortium:** 117 authors, 48 institutions, many groups from US/Germany, *3 Canadian institutes*
- main experimental effort in **demonstrator development**
  - ANNIE WbLS+LAPPDs, GeV reco
  - BNL-1T/30T WbLS circulation/purification
  - EOS MeV reco with WbLS/slow LS
  - BUTTON low-background WbLS
- **plus** large international community working on bench-top experiments for both water-based and slow scintillators
- effort embedded in international R&D programs like DRD2



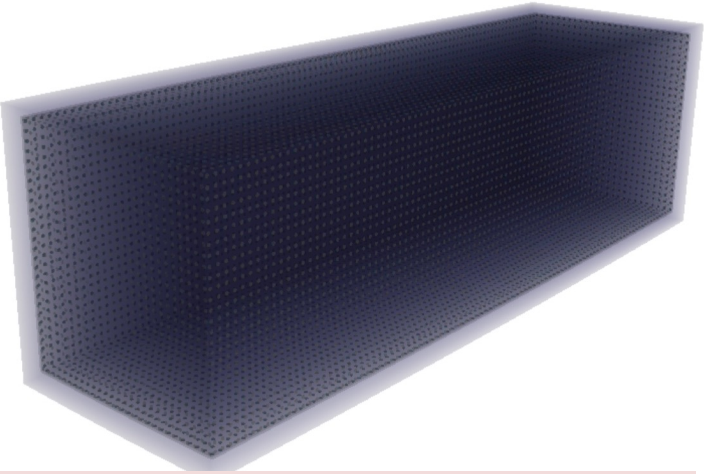
↑ BUTTON (UK): WbLS with low background levels

↓ BNL-30T facility Large-scale WbLS purification



Authors of Theia White Paper: groups from 35+ institutions and eight countries (CA, CN, DE, FI, IT, KR, UK, US)

Estimated Timeline for THEIA



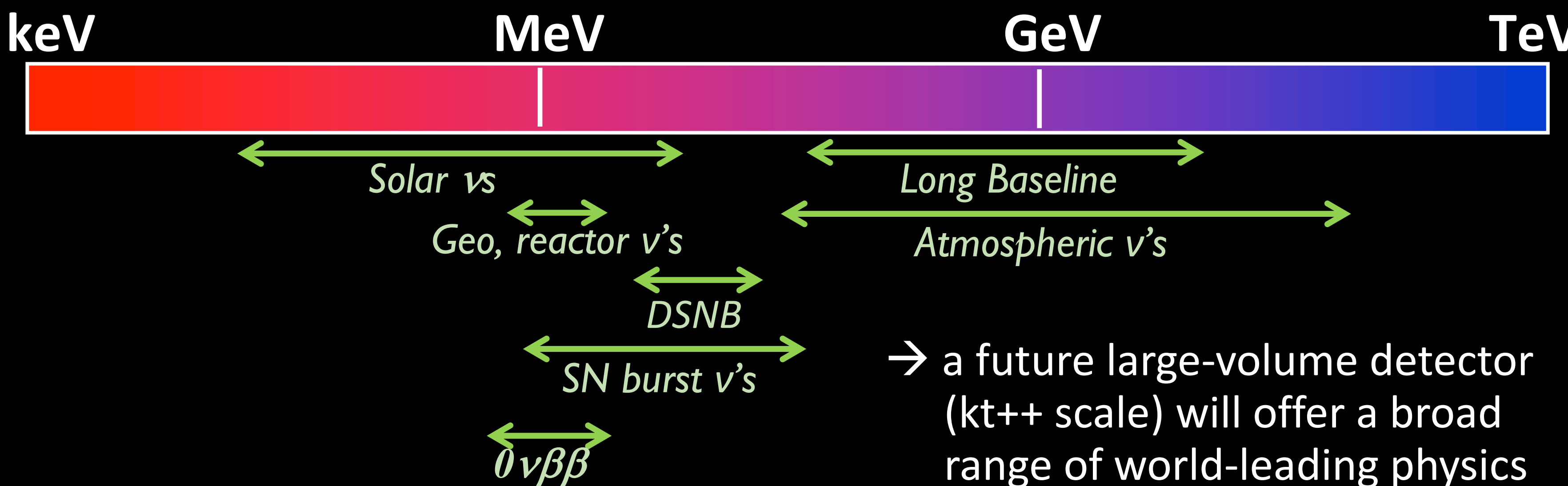
- US/German groups funded for demonstrators but no dedicated funding for a THEIA design
- **from start of preparative funding**
  - conceptual design : 3 yrs
  - technical design : 2 yrs
  - detector construction : 5 yrs
  - → 10 years until start of data taking
- **most relevant additional time scales**
  - preparation of cavern : 5 yrs
  - delivery of 25 kPMTs : 5 yrs
- **duration of operation**
  - astroneutrino program : 10 yrs
  - ββ-search : 5 yrs

Potential SNOLAB support

- **current phase:** general information
- **design phase:** input from lab scientists and significant involvement of lab engineers
- **realization phase:** access for construction crew and scientists for detector installation (25-50)
- **operation phase:** less than 10 people underground

Conclusions

- **hybrid Cherenkov/scintillation detectors** offer a large dynamic range, enhanced event reconstruction and new background discrimination capabilities



→ a future large-volume detector (kt++ scale) will offer a broad range of world-leading physics

- several ton-scale WbLS demonstrators running and providing first physics data
- strong international team with track record from various scintillator experiments ready to start into the design phase for a full-scale detector
- **SNOLAB** is ideal location in terms of background levels, infrastructure and expertise
- **THEIA** can be in many respects *the* continuation of the SNO(+) program at **SNOLAB**

Thank you!

EPJC 80, 416 (2020), arXiv:1911.03501

Eur. Phys. J. C (2020) 80:416
https://doi.org/10.1140/epjc/s10052-020-7977-8

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PHYSICAL

Regular Article - Experimental Physics

THEIA proto-collaboration:
groups from 35+ institutions and eight countries (CA, CN, DE, FI, IT, KR, UK, US)

THEIA: an advanced optical neutrino detector

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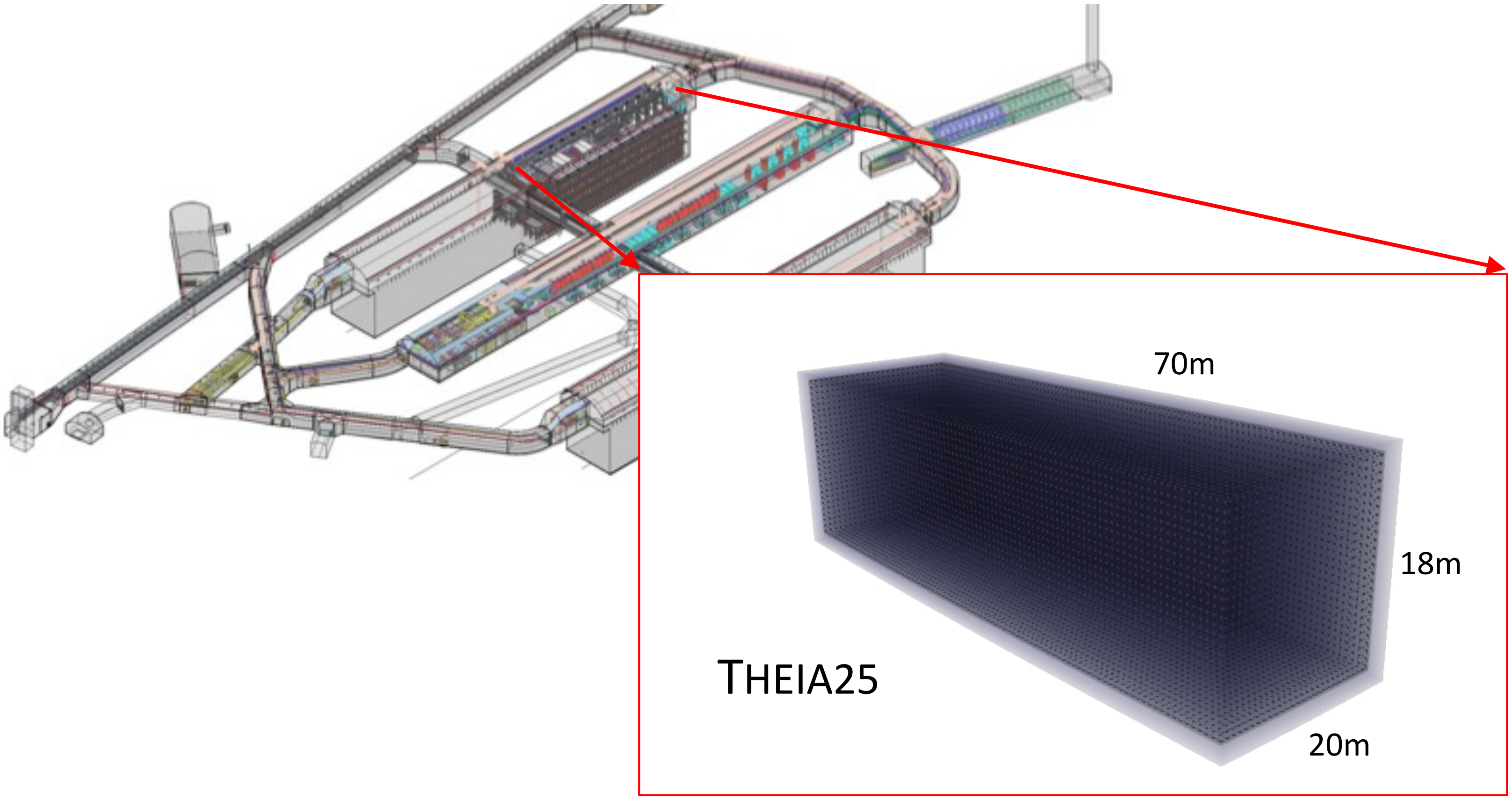
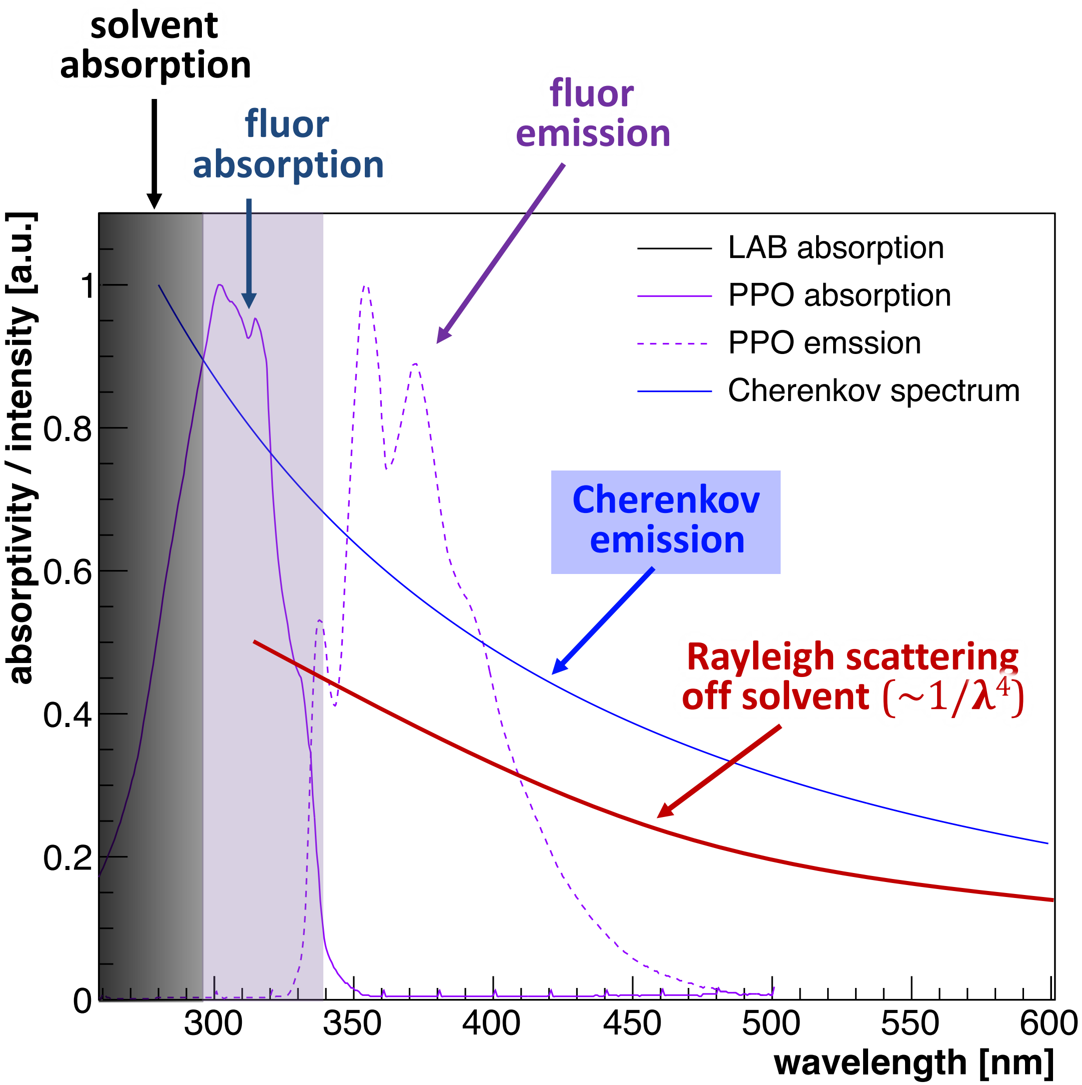
More information on:

- Detector technology
- Long baseline sensitivity
- Low energy neutrino astronomy
- Neutrinoless ββ-decay
- Nucleon decay
- …

Backup Slides



Light propagation in organic scintillators



How to improve the (relative) Cherenkov photoelectron yield?

→ **reduce fluor concentration**

- impacts scintillation yield
- slows down scintillation (good! → see next slide)

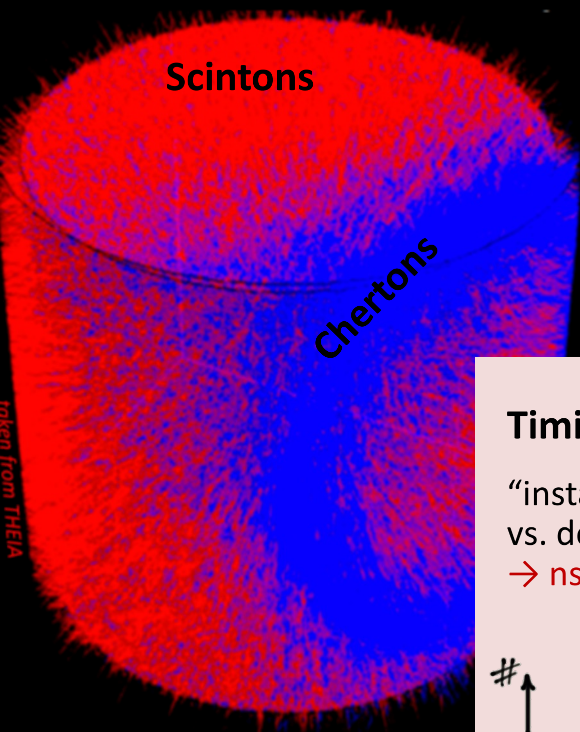
→ **reduce Rayleigh scattering**

- new transparent solvent, e.g. LAB (~20m)

  and/or

- dilution of solvent: Water-based scintillators Oil-diluted LS (LSND …)

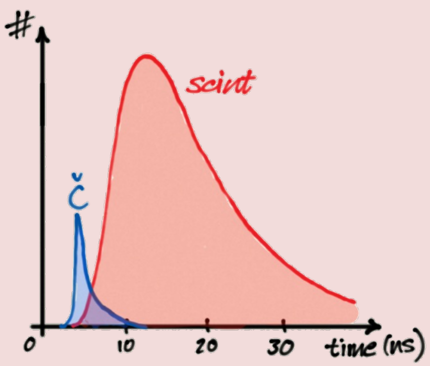
Separating Chertons and Scintons



→ how to resolve the Cherenkov/scintillation signals?

Timing

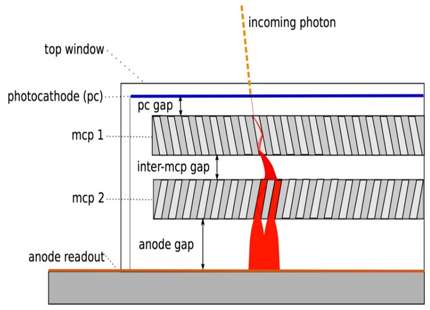
"instantaneous chertons" vs. delayed "scintons"
→ ns resolution or better

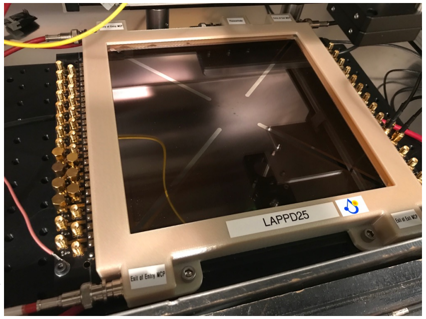


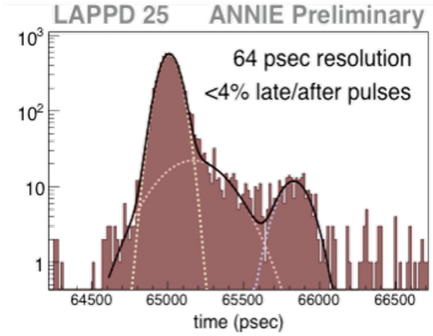
LAPPDs: ~60ps timing

Large Area Picosecond Photon Detectors

- Area: 20-by-20 cm^2
- Amplification of p.e. by two MCP layers
- Flat geometry: ultrafast timing ~65ps
- Strip readout: spatial resolution ~1cm
- Commercial production by Incom, Ltd.

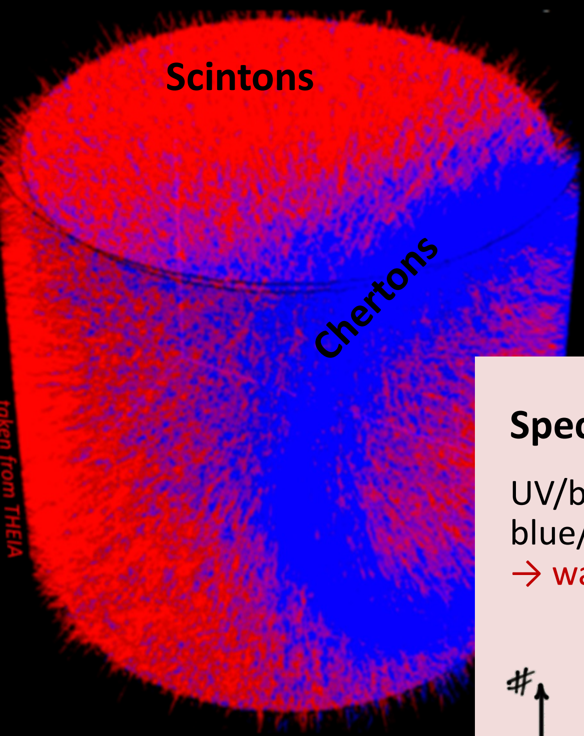






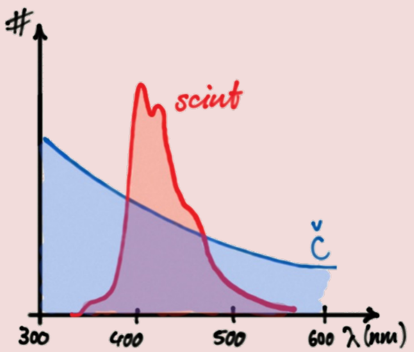
[arXiv:1909.10399]

Separating Chertons and Scintons



Spectrum

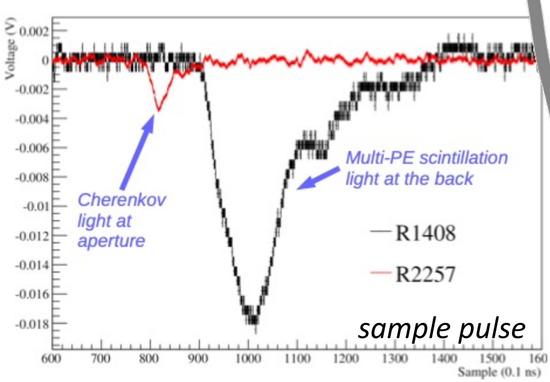
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity

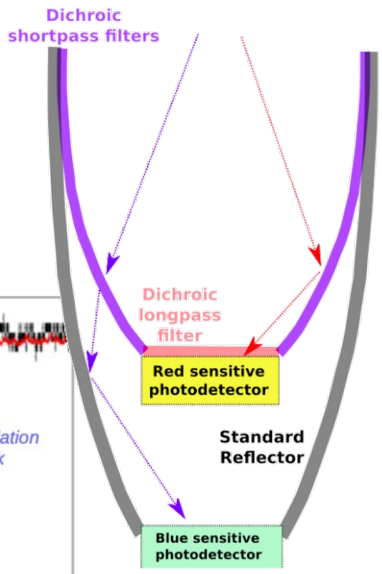


Dichroic filters

Dichroicons [arXiv:1912.10333]

- two PMTs in sequence separated by a Winston cone assembled from shortpass filters (<460nm)
- front PMT collects **Chertons**, back PMT **scintons**



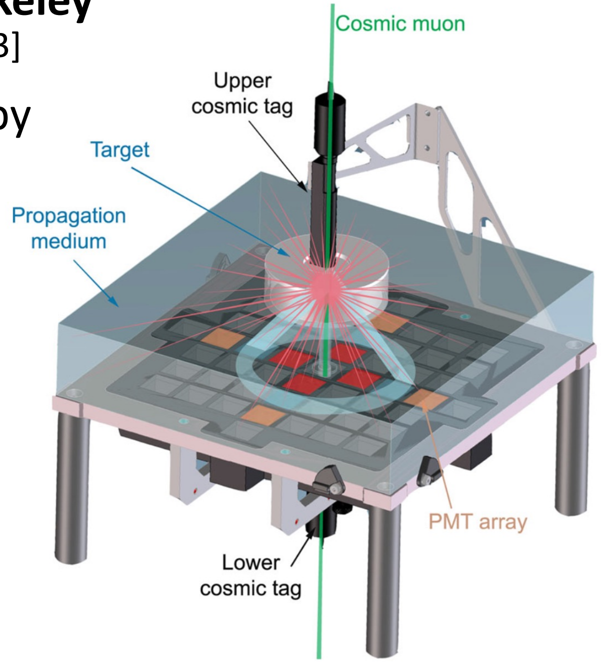


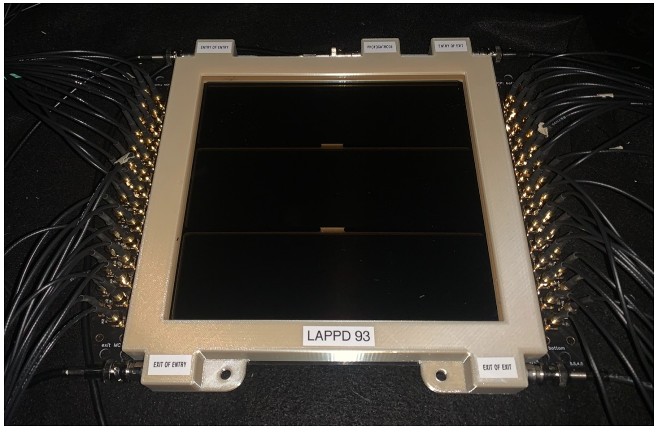
Lab Setups for C/S Separation

CHESS Setup at UC Berkeley
[arXiv:1610.02011,2006.00173]

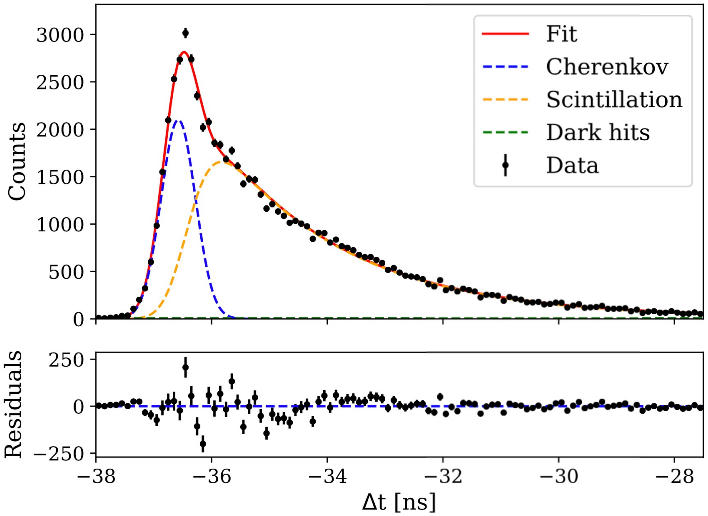
PMT array illuminated by small LS target excited by cosmic muons and radioactive sources

→ C/S separation using hit pattern



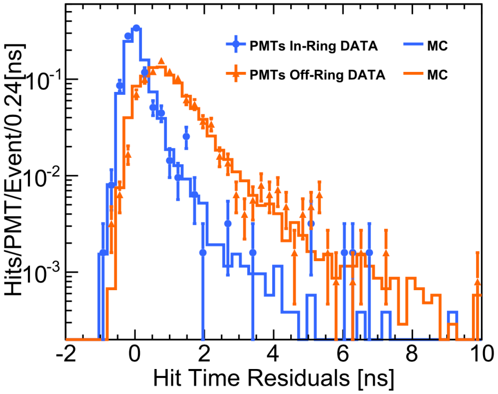


WbLS time profile with LAPPD
[arXiv:2110.13222]

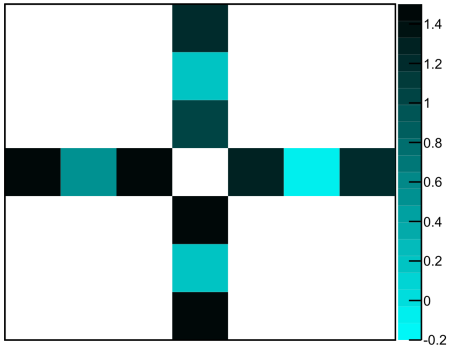


→ C/S separation based on timing

Result for 5%-WbLS:
timing of C/S components



PMT hit pattern

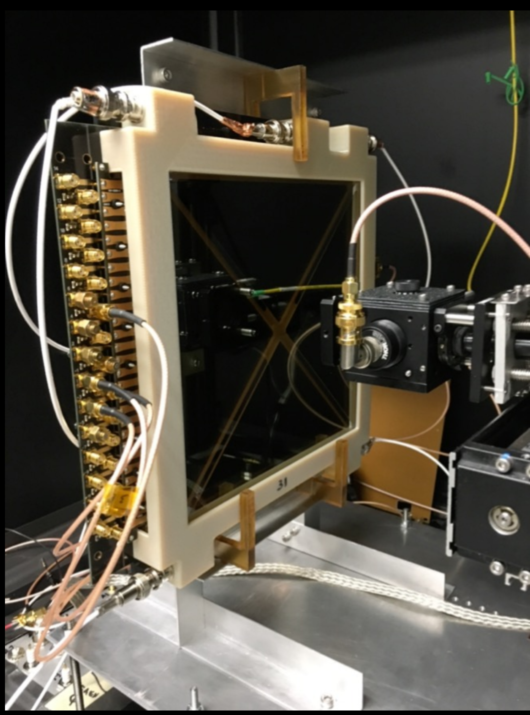


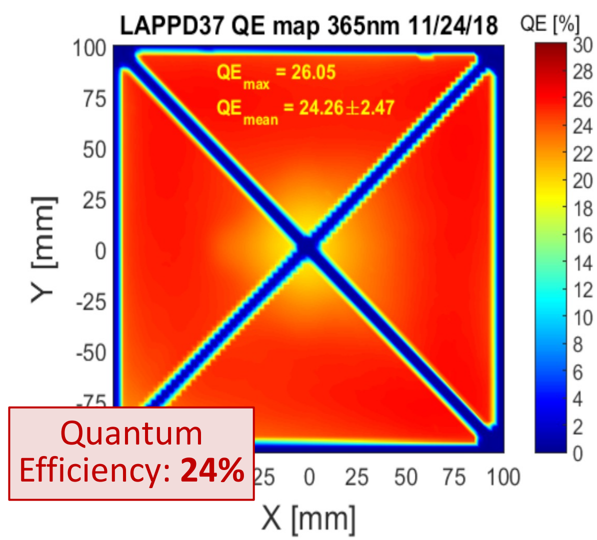
5% WbLS

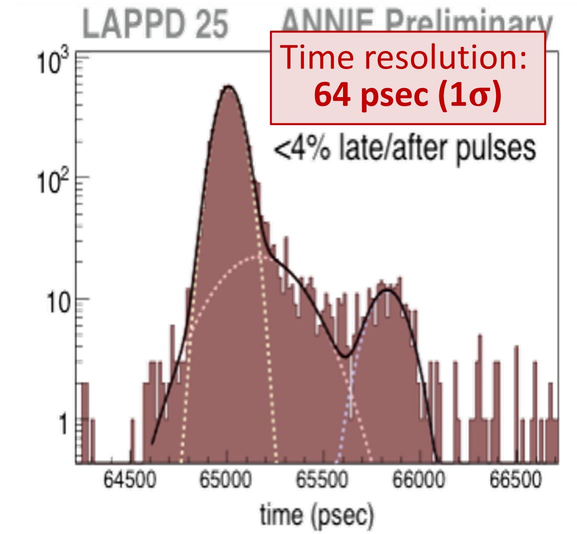
rise time:	209±10 ps
fast decay time:	2.25±0.01 ns

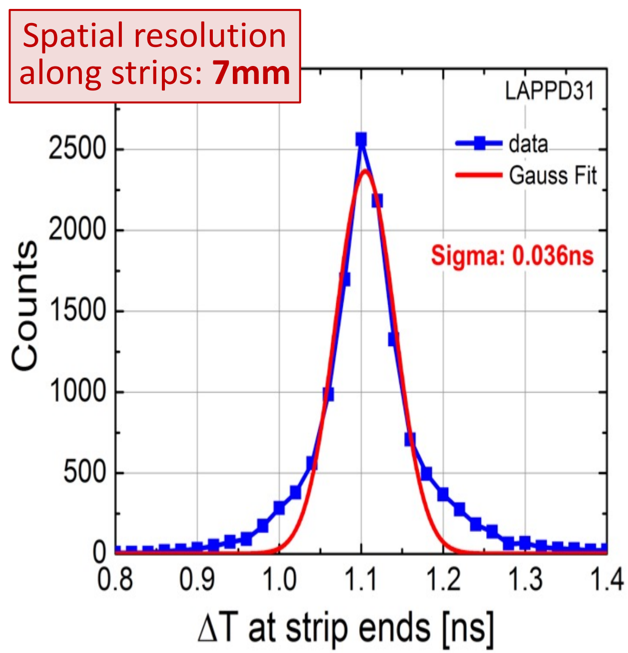
LAPPD Performance

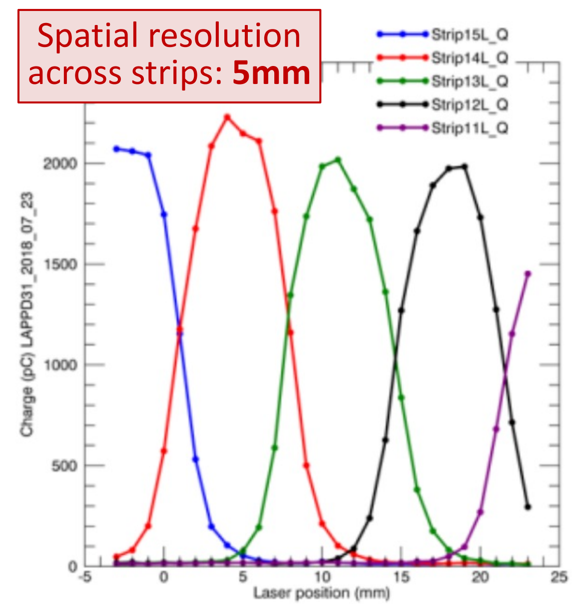
- uniformly flat light sensor, p.e. amplified by two stacked MCP layers
  → excellent timing!
- LAPPDs produced commercially by Incom (several 10s per year)



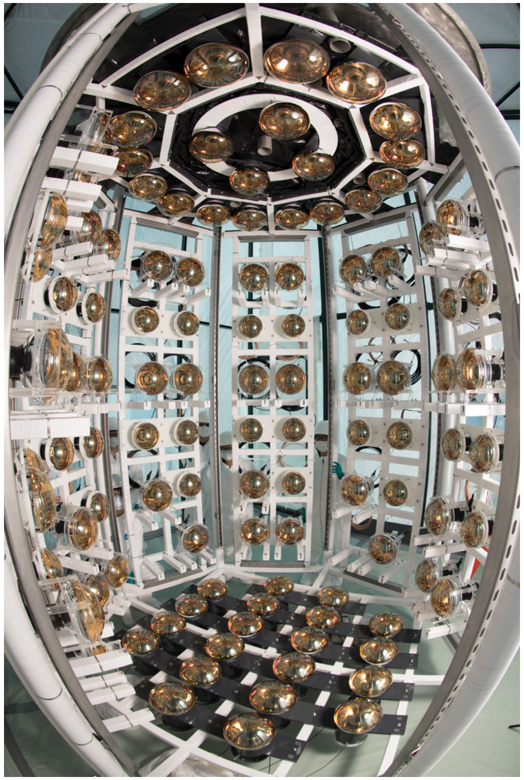








ANNIE Experiment

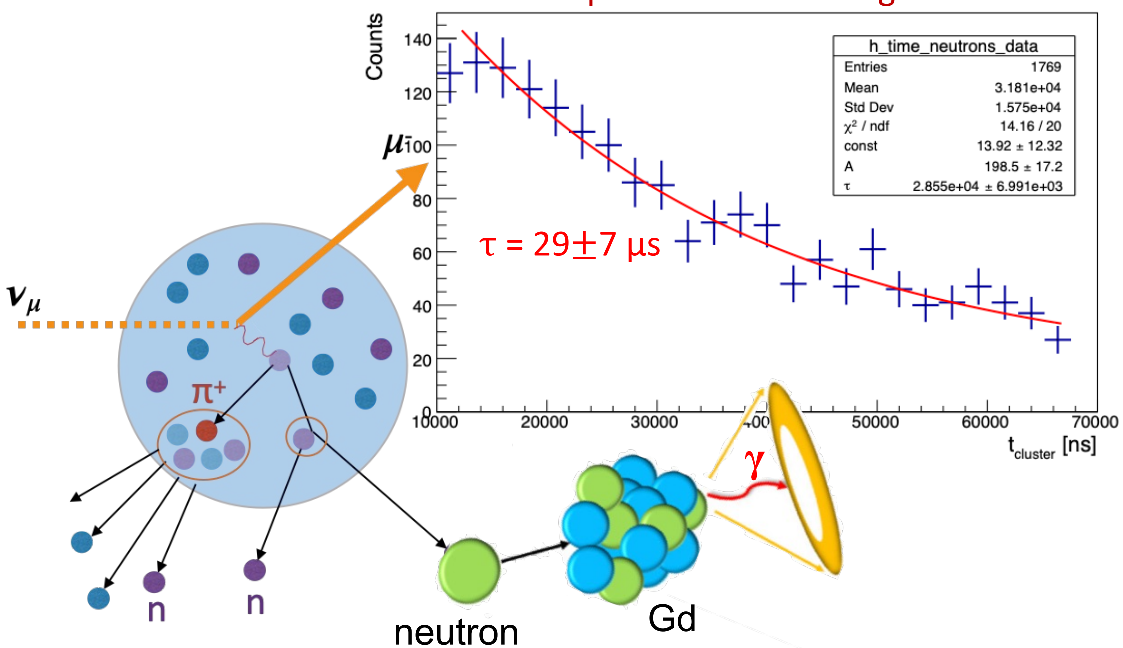


Accelerator Neutrino Nucleus Interaction Experiment

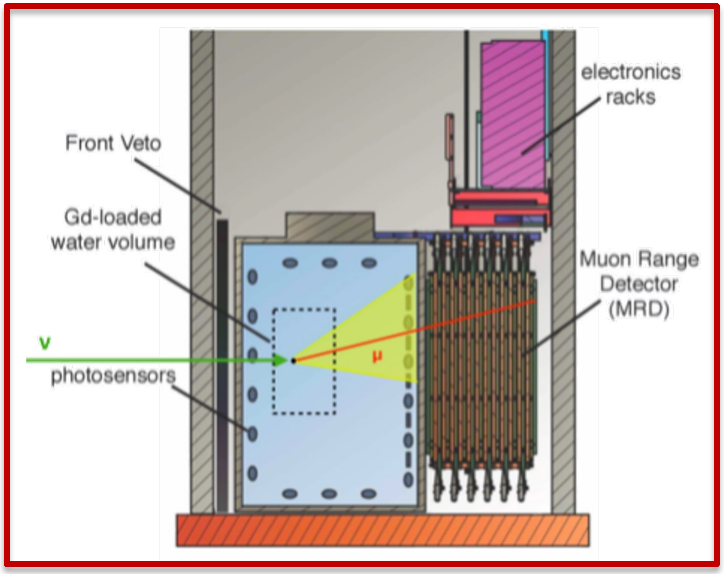
27-ton (Gd-loaded) Water Cherenkov Detector running in the **Fermilab BNB neutrino beam**

- measurement of GeV neutrino differential cross-sections and neutron multiplicity
- physics data taking started in early 2021
- R&D program for new technologies → Gd-water → LAPPDs → WbLS

neutron capture time following beam events

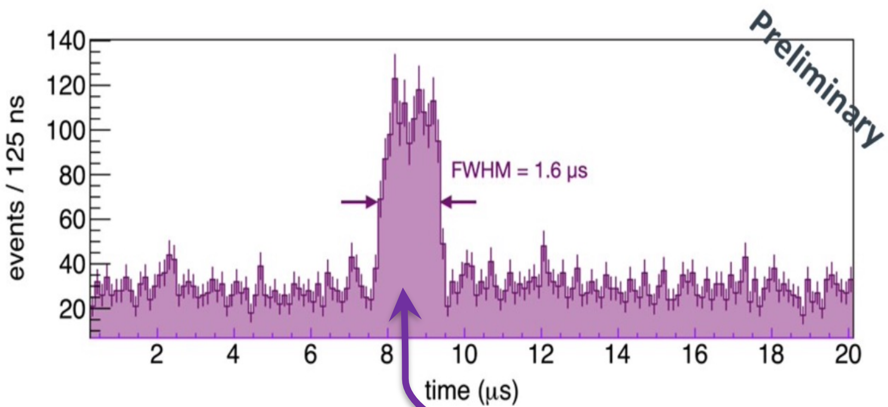


ANNIE Detector Layout

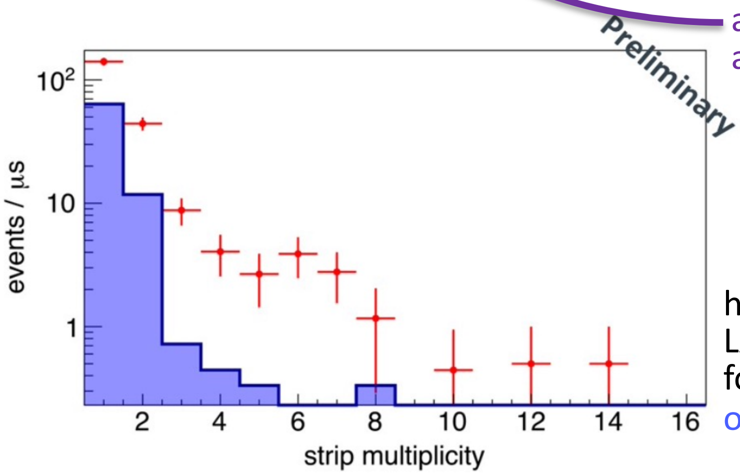


ANNIE: First LAPPD installed

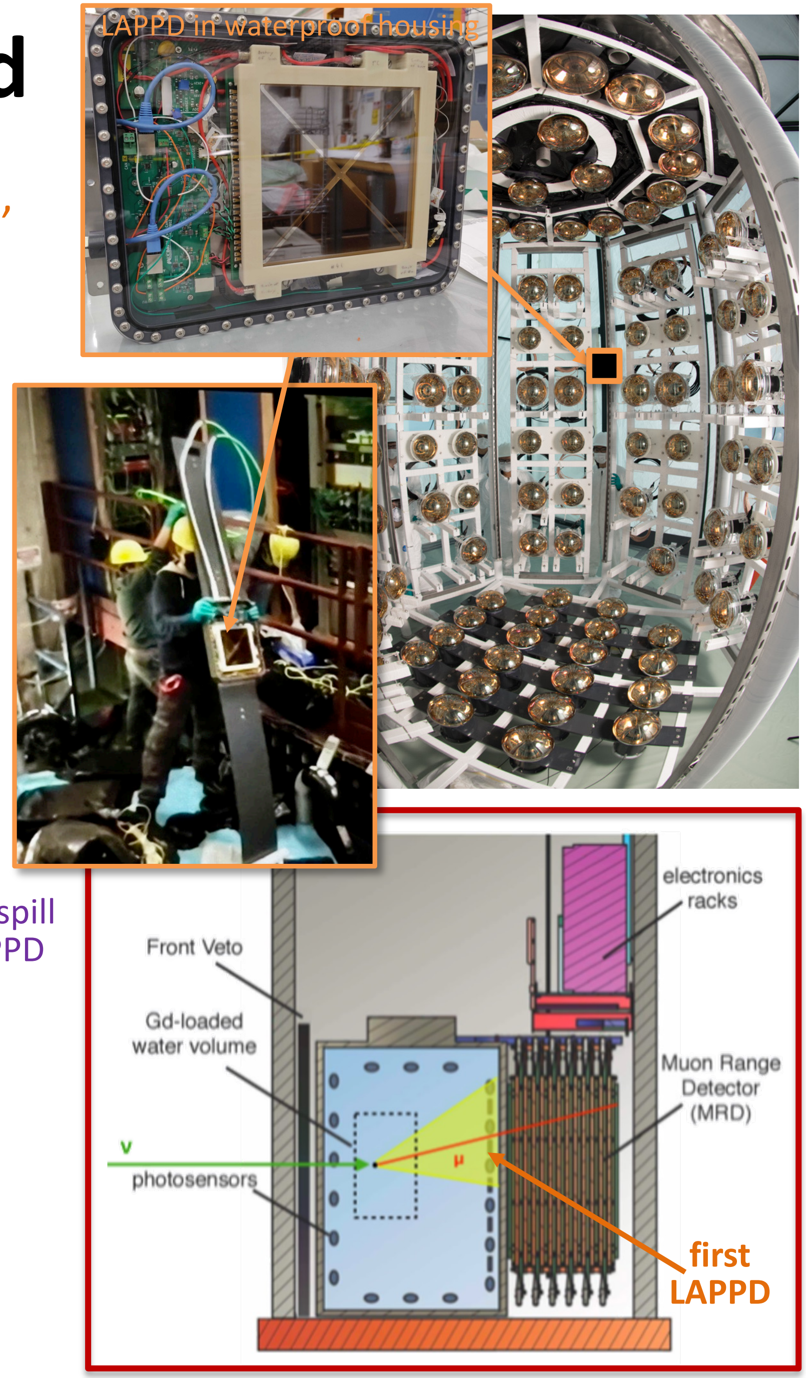
- major milestone: 1st LAPPD installed in March 2022, detected first light from neutrinos
- 4+ LAPPDs more are currenlty installed



event time distribution around the BNB beam spill as observed by the LAPPD



hit multiplicity on LAPPD strip readout for on-beam and off-beam events



ANNIE+SANDI: WbLS test deployment

→ **next step: SANDI**
acrylic vessel with 365 kg of WbLS submerged in ANNIE

- resolve scintillation light from hadronic recoils, improve neutrino energy determination
- higher light output for neutron captures on gadolinium
→ improved neutron detection efficiency & vertex reco
- first attempt of C/S separation for neutrinos with LAPPDs

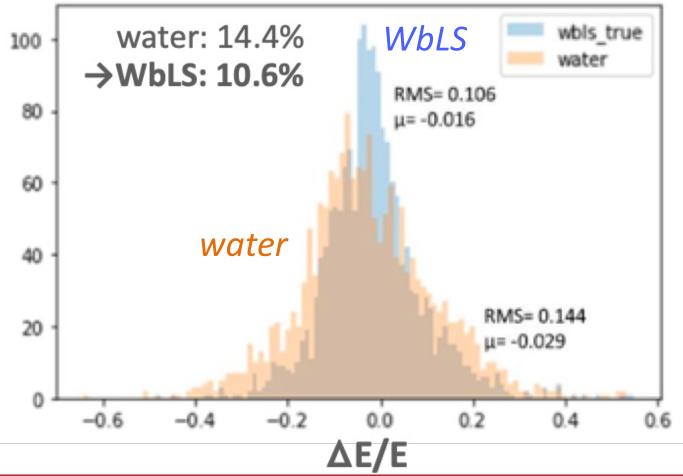
→ test WbLS performance for future use in long-baseline exp.s!

SANDI vessel at Davis

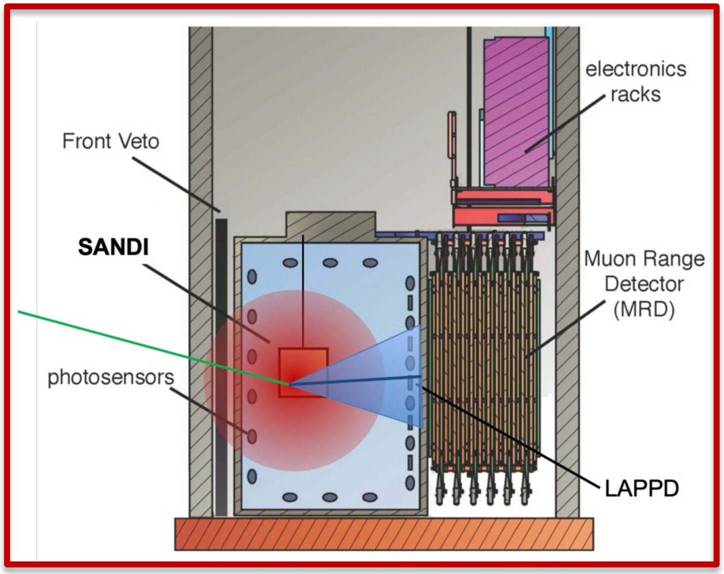
Preparations are on-going

- 3‘ x 3‘ vessel & WbLS (BNL, M. Yeh) already on-site
- deployment before end of November

MC with idealized reco and machine learning
– resolution dominated by Muon Range Detector



ANNIE vs. SANDI WbLS vessel



EOS: WbLS performance demonstrator

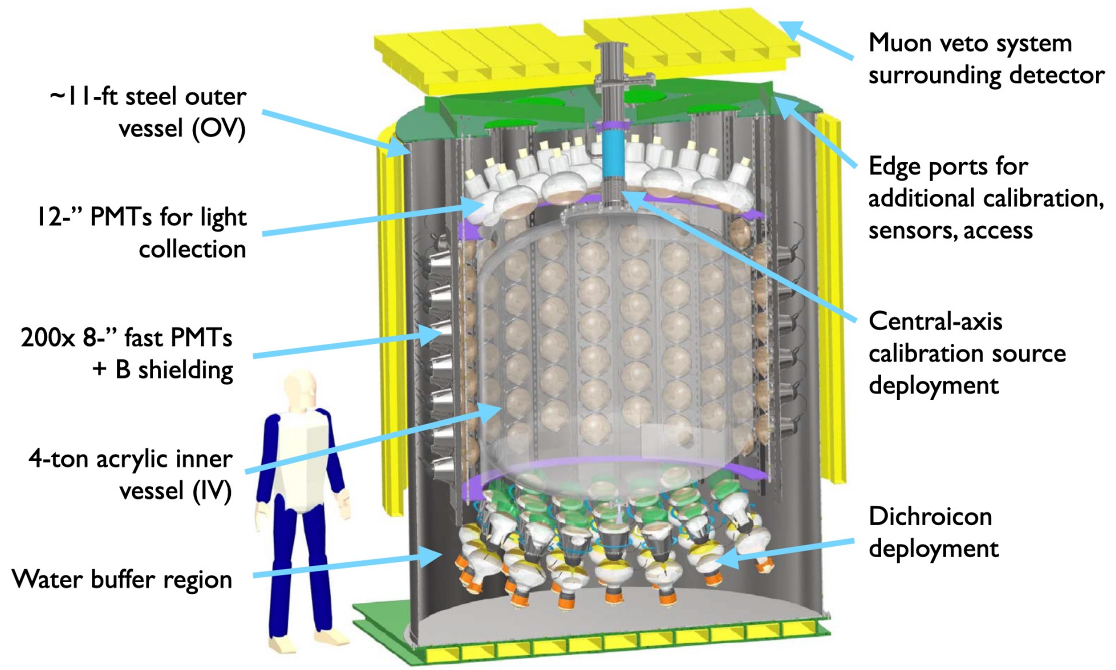
- Stand-alone hybrid detector optimized for MeV energy reconstruction
- Demonstrate event reconstruction using hybrid Cherenkov + scintillation signatures
- Validate models to support large-scale detector performance predictions
- Provide a flexible testbed to demonstrate impact of novel technology: targets, photon detectors, readout, reconstruction algorithms

→ Start of installation this summer at UC Berkeley

→ Closely coupled to 30-ton demonstrator at BNL for WbLS production & stability

EOS Detector Layout

- stand-alone hybrid detector
- target mass: 4 ton of water, WbLS or slow scintillator
- 200 fast 8'' PMTs: tts of 900 ps
- CAEN V1730 readout
- plus deployment of 10 dichroicons for spectral sorting



Alternative: Slow Scintillators

General idea
organic scintillators modified for slow(er) scintillation emission

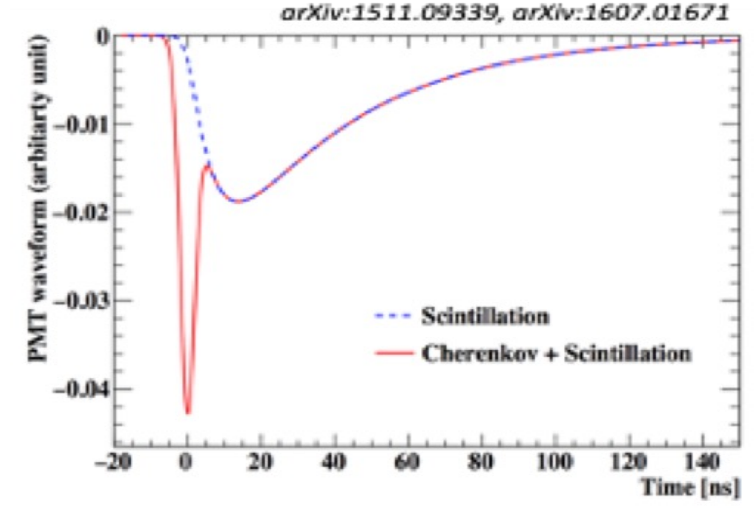
Options

- reduce primary fluor (i.e. PPO) content
  → longer emission but lower light yield
  [Z. Guo et al., arXiv:1708.07781]
- slow fluors selected for long emission times, e.g. di-phenyl-antracene/hexatriene
  [Steve Biller et al., arXiv:2001.10825]
- use co-solvent to slow light transfer to fluor
  [Hans Steiger]

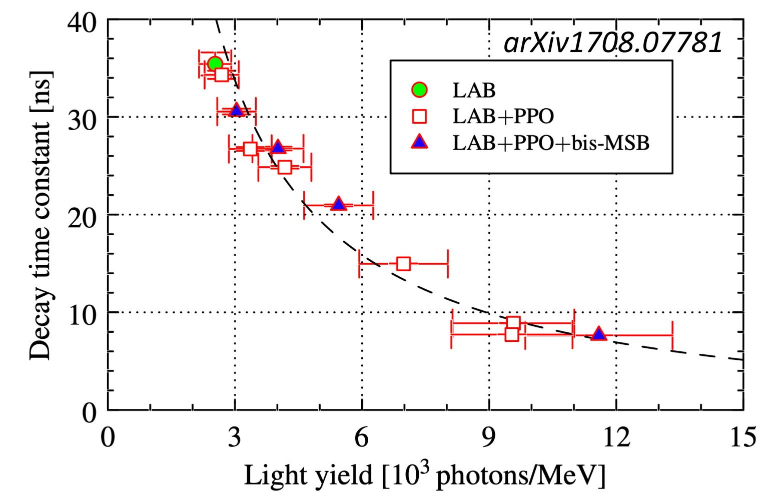
Consequences

- C/S separation can rely on regular PMTs
- high scintillation light yields can be maintained
- quality of vertex reconstruction (and with this indirectly C/S separation) suffers
  → effects have to be balanced

Slow Scintillator – Example Pulse



Decay time/LY vs. PPO concentration



Directionality in present-day scintillator detectors

BOREXINO

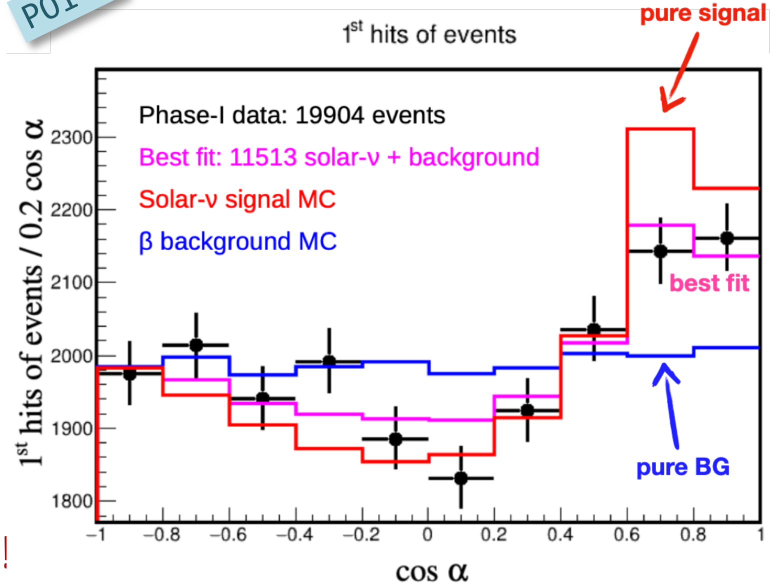
P0142

- new analysis technique tested in the spectral region of sub-MeV solar ^{7}Be neutrinos
- CID: use *integrated* angular distributions of early PMT hits relative to direction of the Sun

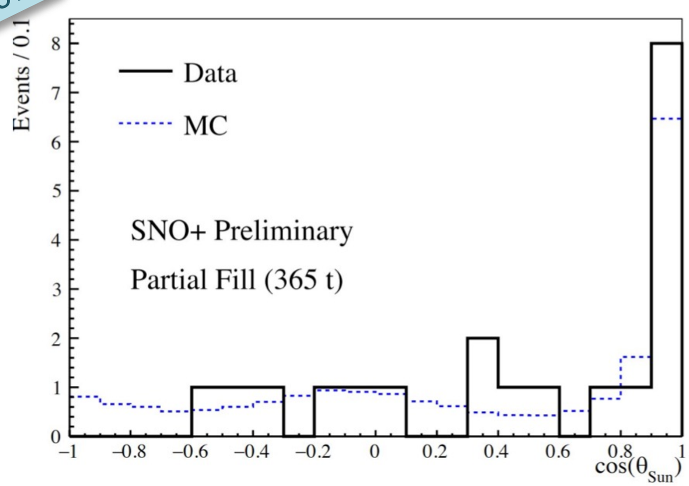
→ observation of significant **(>6σ!)** angular excess caused by Cherenkov photons

→ rate: $1.13^{+0.22}_{-0.25}$ of (oscillated) SSM prediction

first directional detection of sub-MeV solar neutrinos!



P0078



SNO+

- partial fill of detector with 365 t of slow scintillator: LAB + 0.6 g/l PPO

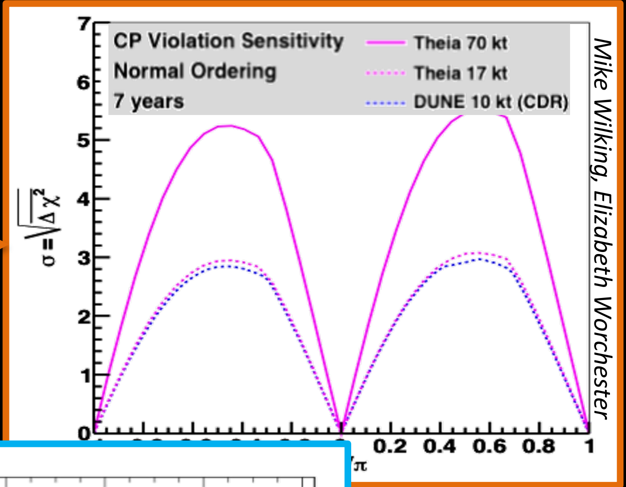
→ first demonstration of *event-by-event directional reconstruction* of solar ^{8}B neutrinos in slow scintillator

- MC/data: ~40% of events with E>5MeV are reconstructed with $\cos\theta_{Sun}$>0.8

photo: BOREXINO calibration

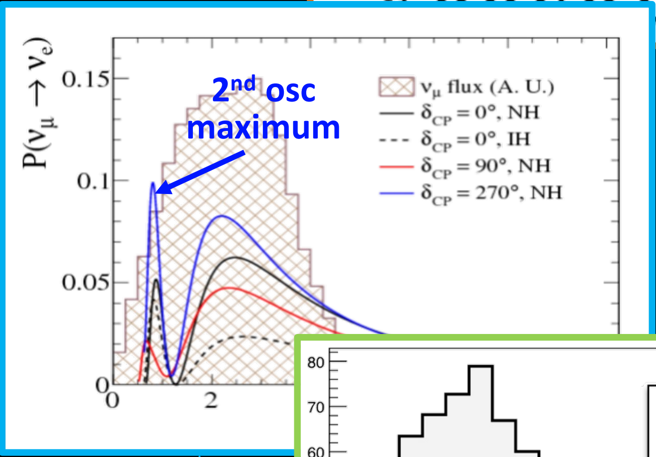
Hybrid Detector for Long-Baseline Neutrinos

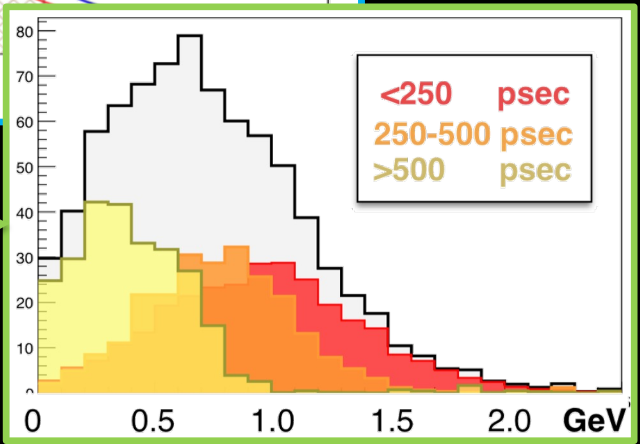
As the fourth **DUNE Module of Opportunity:** What would a **large WbLS detector** add to the existing liquid-argon modules?



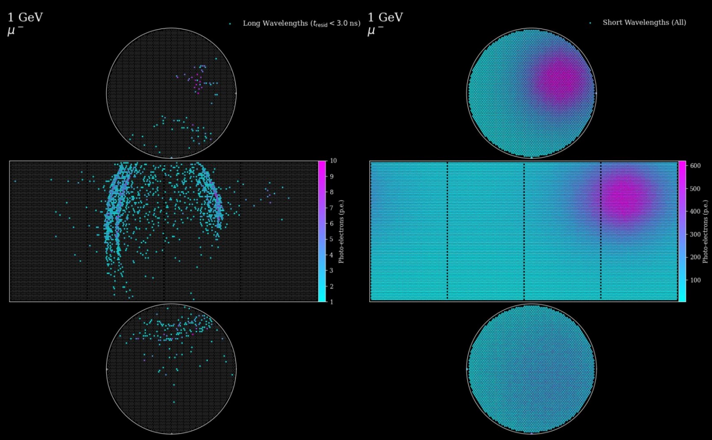
Added value for a δ_{CP} measurement

- Comparable statistics
  ~1.7:1 in mass for WbLS : LAr
  but better active volume ratio
- Complementary systematics
  e.g. cross-sections (simpler nuclei)
- Neutron tagging/recoils in final state
  → aids energy reco of hadronic recoils
  → neutrino/antineutrino discrimination
- Improved energy resolution for low energies (2nd oscillation maximum)
- Fast timing: ν energy measurement using initial π/K time-of-flight difference





Reconstruction with FiTQun



FiTQun: maximum likelihood reconstruction tool for final state particle types and kinematics, officially used in T2K, Super-K and Hyper-K

Current FitQun Performance

- factor 4 suppression of π^0 background compared to previous SK algorithms
- fits up to six Cherenkov rings simultaneously
- up to now: designed and used by Water Cherenkov detectors

FitQun for event reconstruction in WbLS

- expectation: scintillation light will not degrade Cherenkov ring reconstruction
- improvements in vertex resolution, sub-Cherenkov PID and neutrino energy reco
  [https://indico.kps.or.kr/event/30/contributions/233/]

Further development plans

- Simulation with RATPAC: tool for scintillation sim → particle profiles for FiTQun
- Include Scintillation signal in FiTQun profile builder and fitter
- Performance evaluation: Fit for neutrino interactions in WbLS with FiTQun

[Performance in Theia: arXiv:1911.03501]