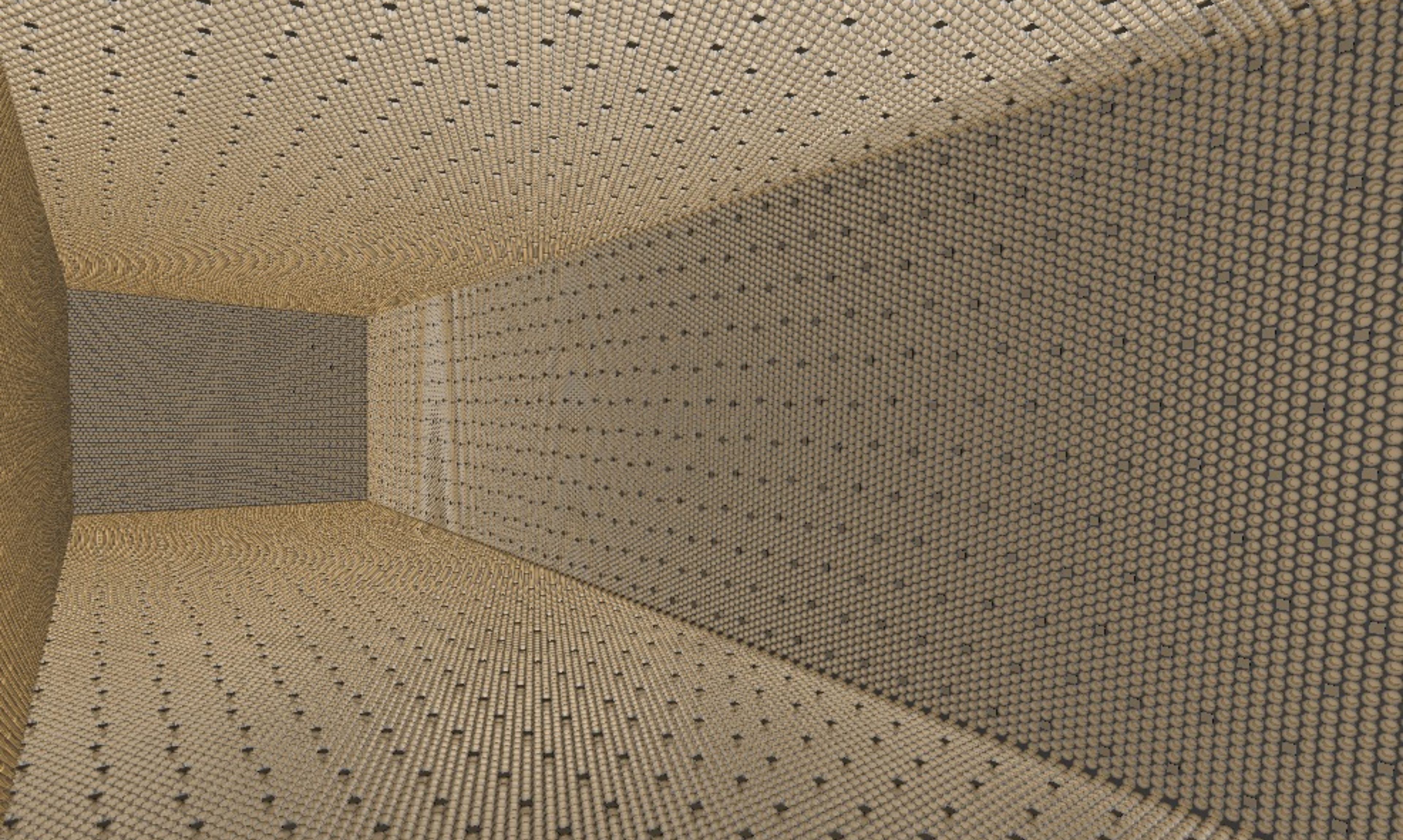
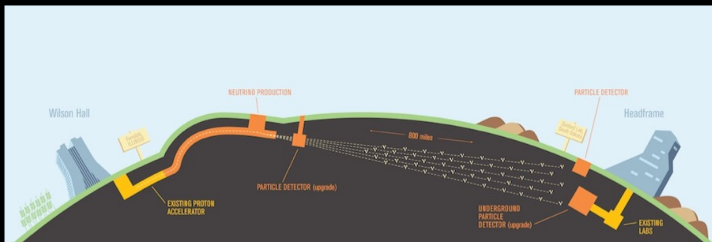
Prospects for DSNB detection in THEIA



++ SN Neutrino Workshop ++ Oak Ridge, Mar 6, 2023 +++ Michael Wurm (Mainz) ++

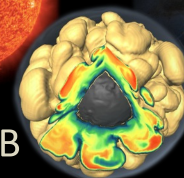
Hybrid Cherenkov/Scintillation Detector

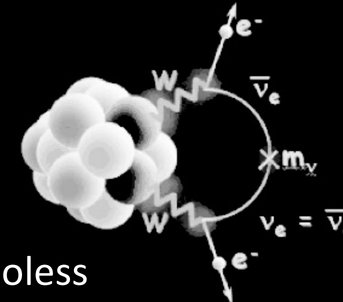
→ Enhanced sensitivity to broad physics program



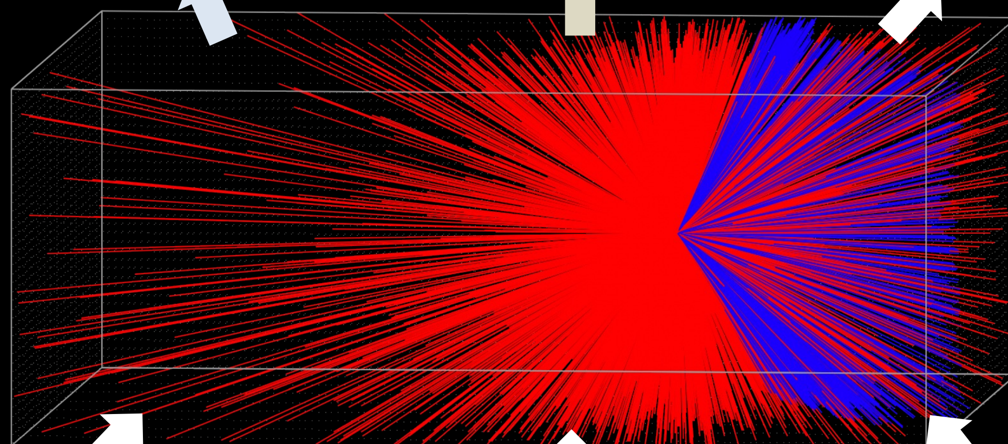
Long-Baseline Oscillations

solar ν's
Supernova ν's
DSNB





Neutrinoless
Double-Beta Decay

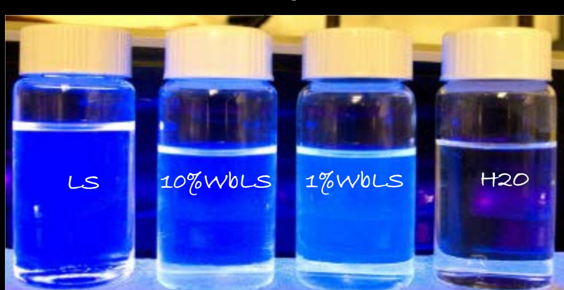


THEIA25

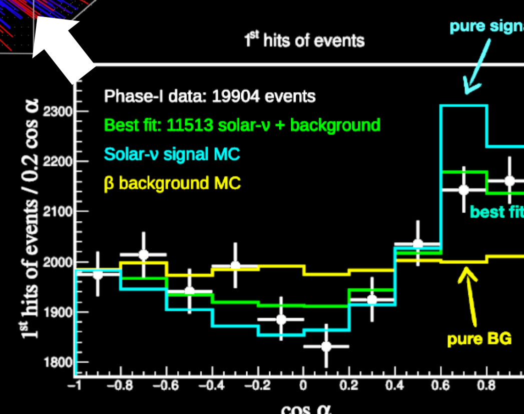
Hybrid Detector able to exploit both **Cherenkov+ Scintillation** signals

novel reconstruction techniques

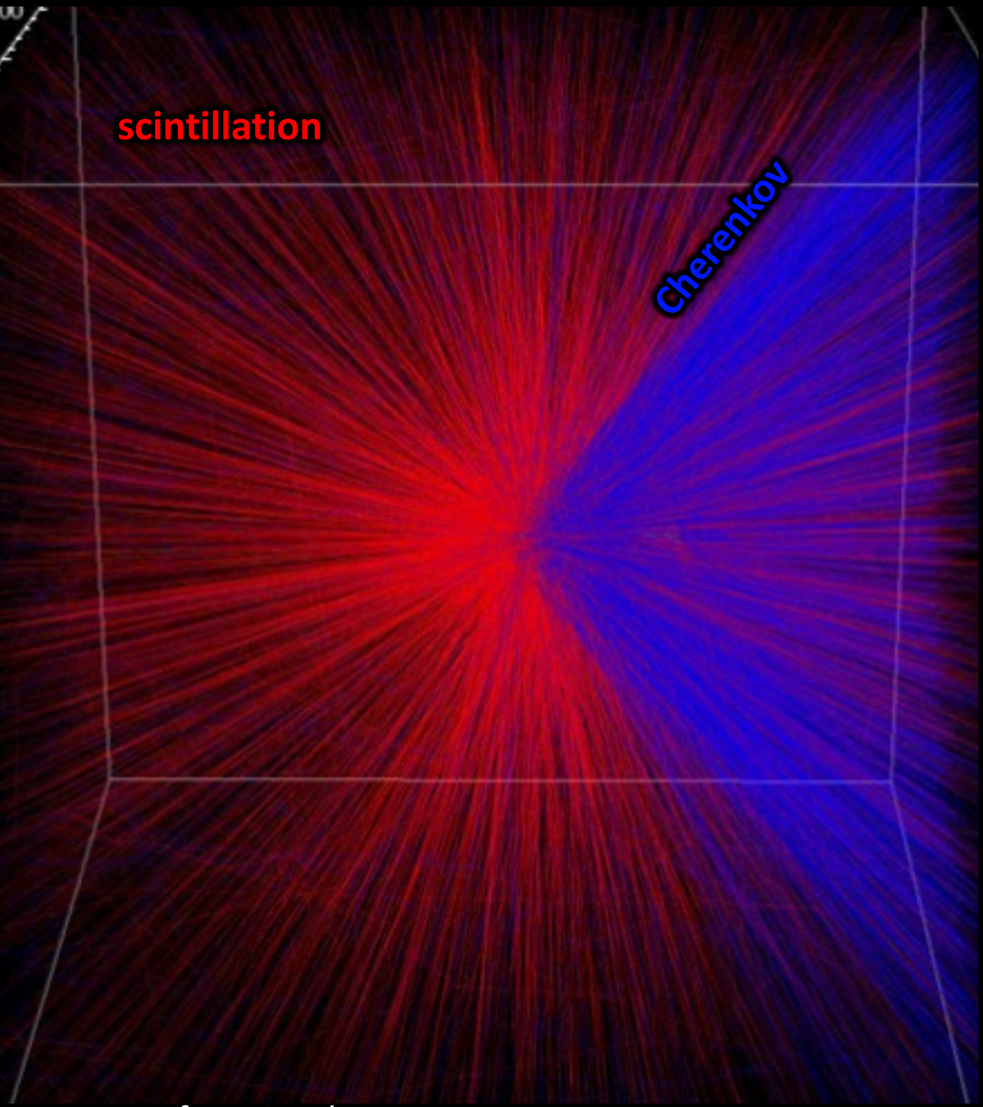
novel target medium:
Water-based Liquid Scintillator



novel light sensors:
fast PMTs, LAPPDs, dichroicons



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?

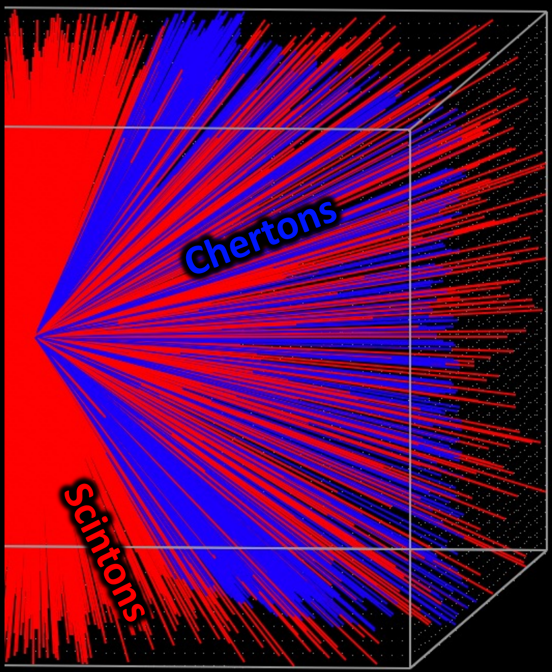
→ enhance liquid transparency and/or

→ slow down scintillation emission

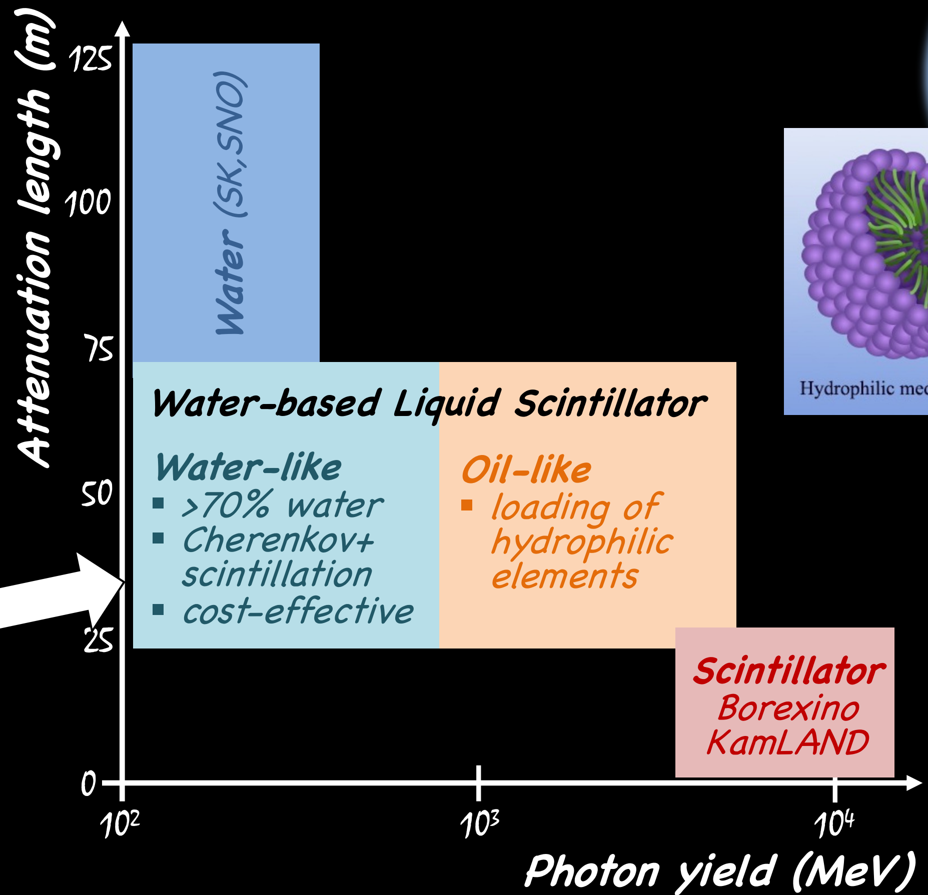
→ Water-based liquid scintillators (GeV) and slow scintillators (MeV)

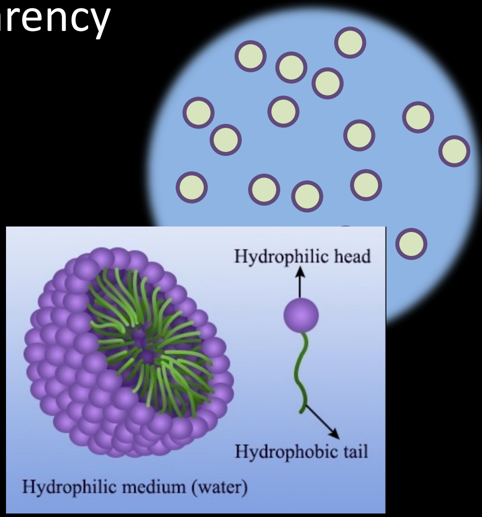
note: some of the following can be tried as well in a large organic LS detector

Water-based liquid scintillators (WbLS)

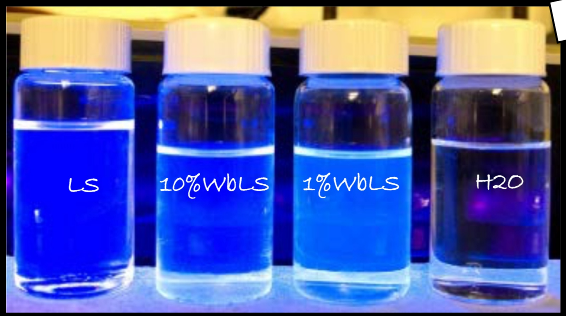


→ WbLS: water + tensid + solvent (LAB) + fluor (PPO)
→ low organic fraction → high transparency





WbLS mycels



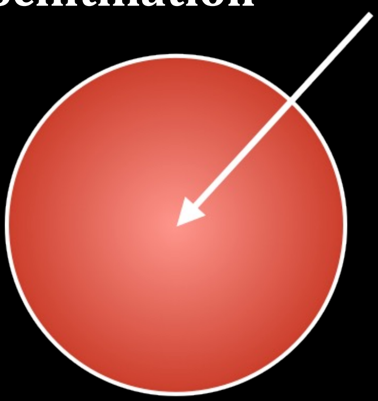
Minfang Yeh, BNL

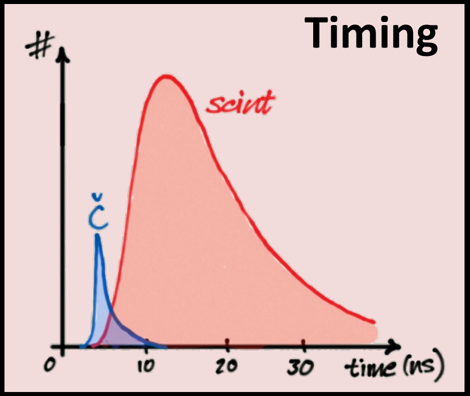
→ properties of target medium can be adjusted to physics goal
→ water content offers additional options for metal loading

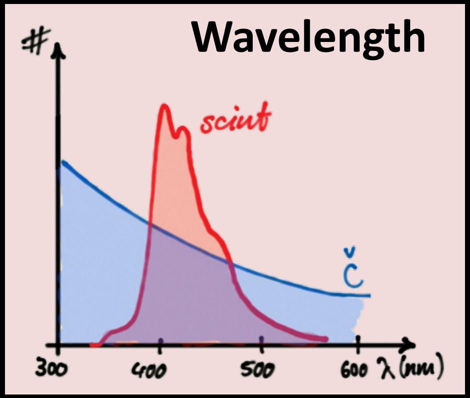
Photo Sensors for Separating Chertons and Scintons

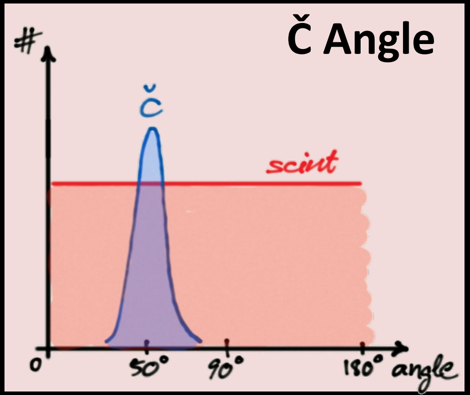
Cherenkov

Scintillation

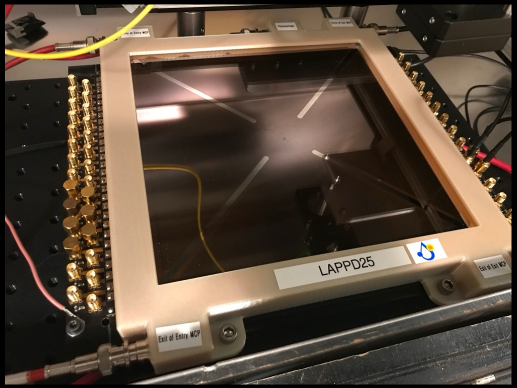






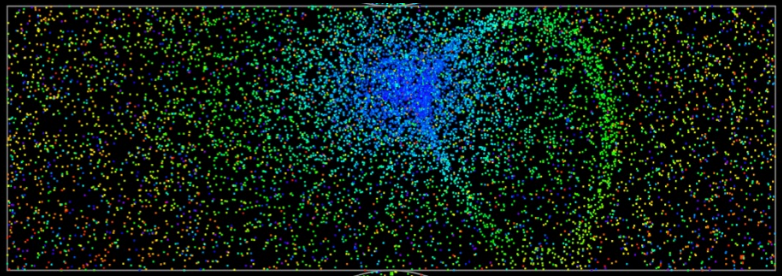


LAPPDs
tts~60ps

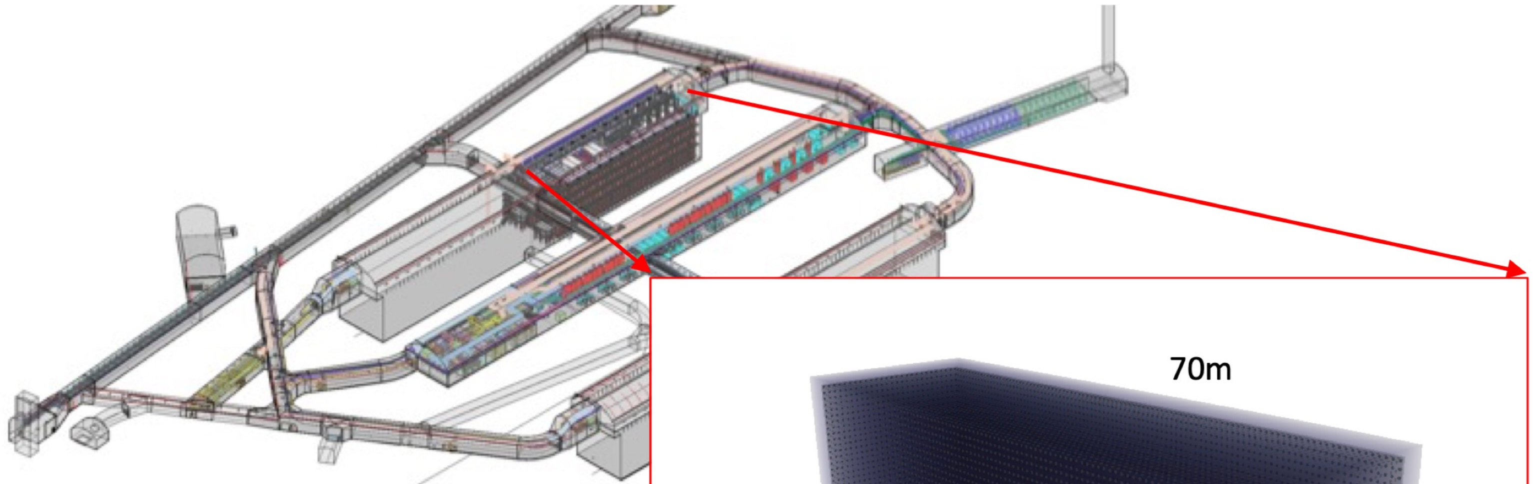


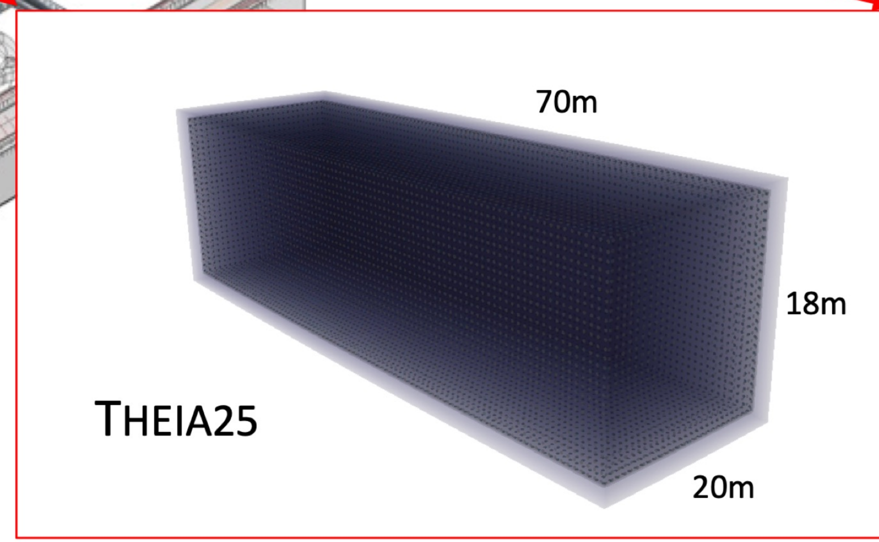
Dichroicons
spectral
sorting

PMT granularity



THEIA25 as DUNE Module of Opportunity

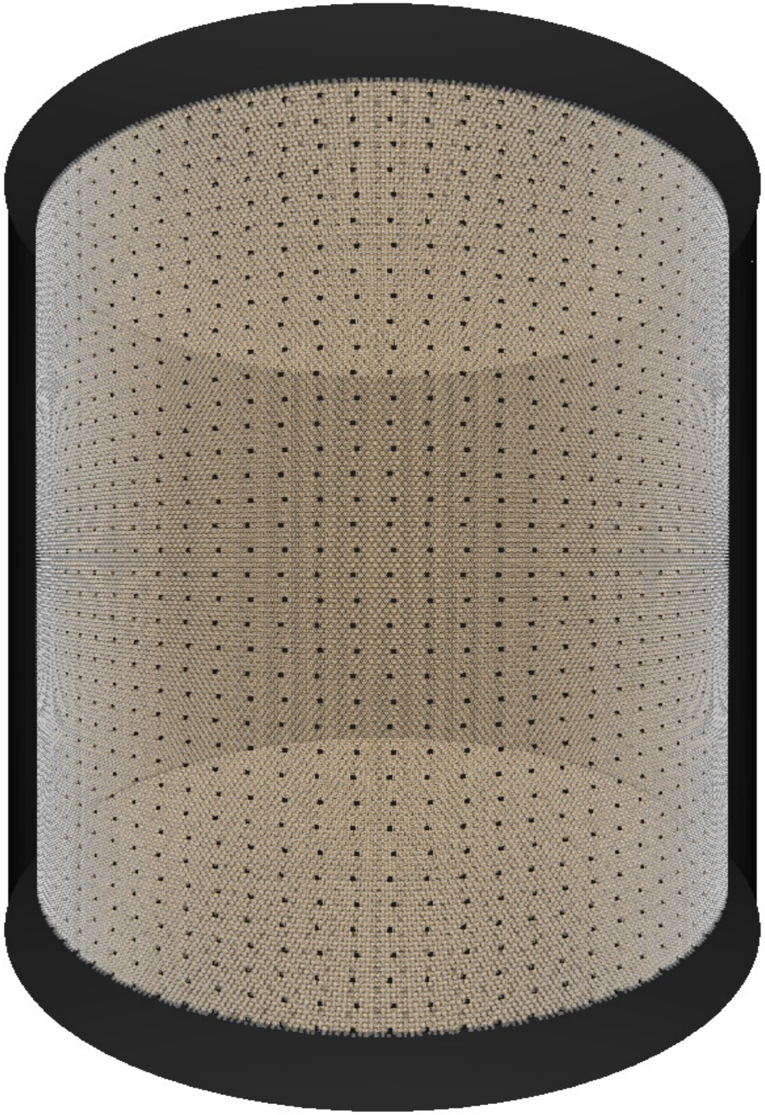




Detector specifications

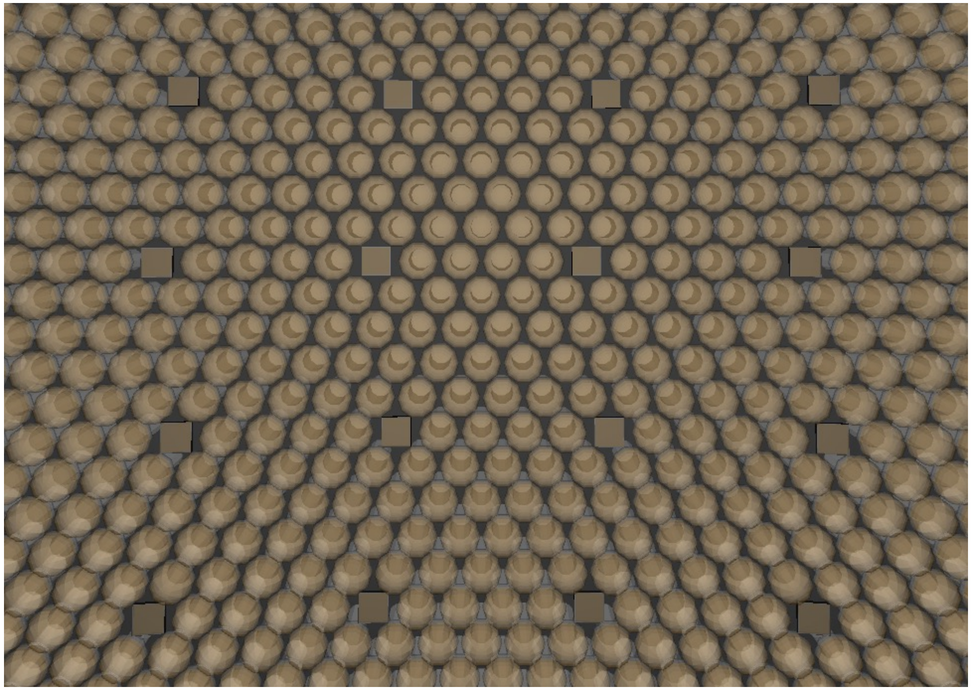
- **Total mass:** 25 kt of WbLS
  Fiducial mass: 17-20 kt
- **Photosensors:**
  22,500x 10'' PMTs 25% coverage w/ high QE → equals the current photon collection of SK!
  700x 8'' LAPPDs ~3% coverage → upgrade for later phases (solar, 0νββ)
- **Background levels:**
  Radiopurity (H_2O): ~10^{-15} g/g in ^{238}U, ^{232}Th, ^{40}K
  Rock shielding: 4300 m.w.e. → muon flux at SURF only ~10% of LNGS

Optimum Layout: THEIA100

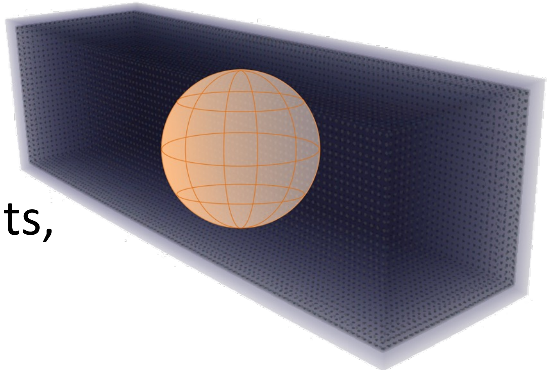


Detector Specifications

- **Detector mass:** ca. 100 kt
- **Dimensions:** 50-by-50 m (WbLS transparency)
- **Photosensors:** mix of conventional PMTs (light collection) and LAPPDs (timing)
- **Location:** deep lab with neutrino beam (e.g. new cavern at SURF)



THEIA : Phased Physics Program



scintillator properties will be adjusted to physics requirements,

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

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

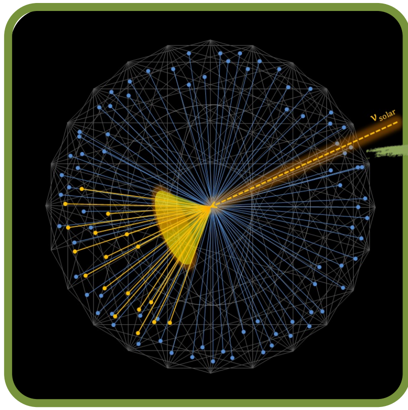
I

II

III

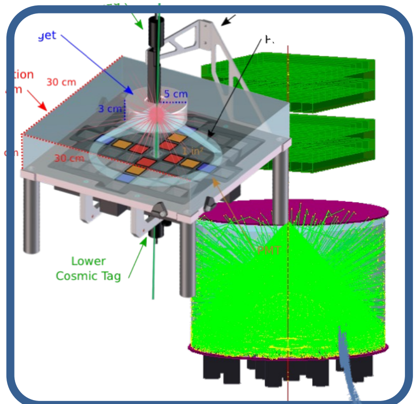
Development Path of Hybrid Detectors

Borexino
SNO+



Re-analyzing data from existing LS Detectors

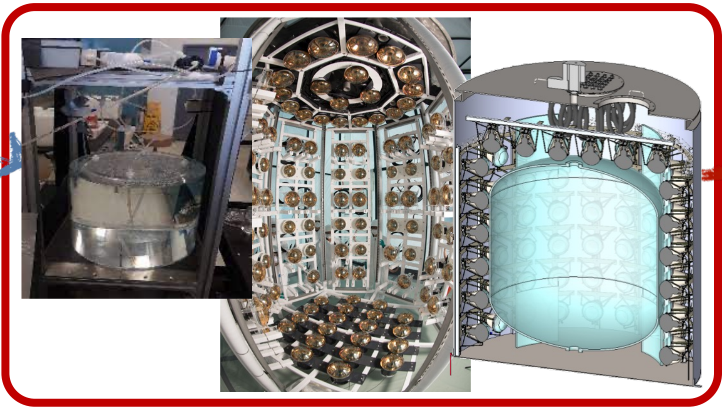
Lab-Scale Setups

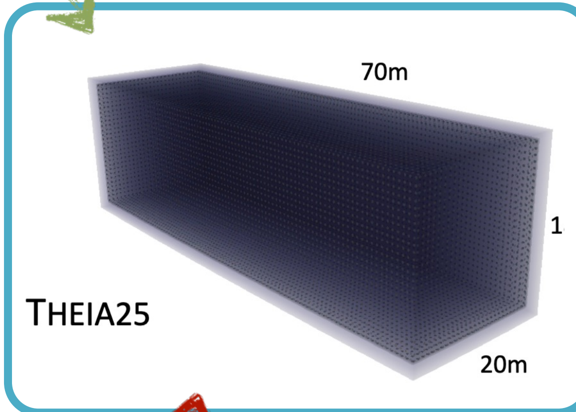


UCB: CHESS
MZ: SCHLYP
MZ/TÜ: DISCO
...

Ton-Scale Setups

BNL
ANNIE/SANDI
EOS





Future full-scale hybrid module

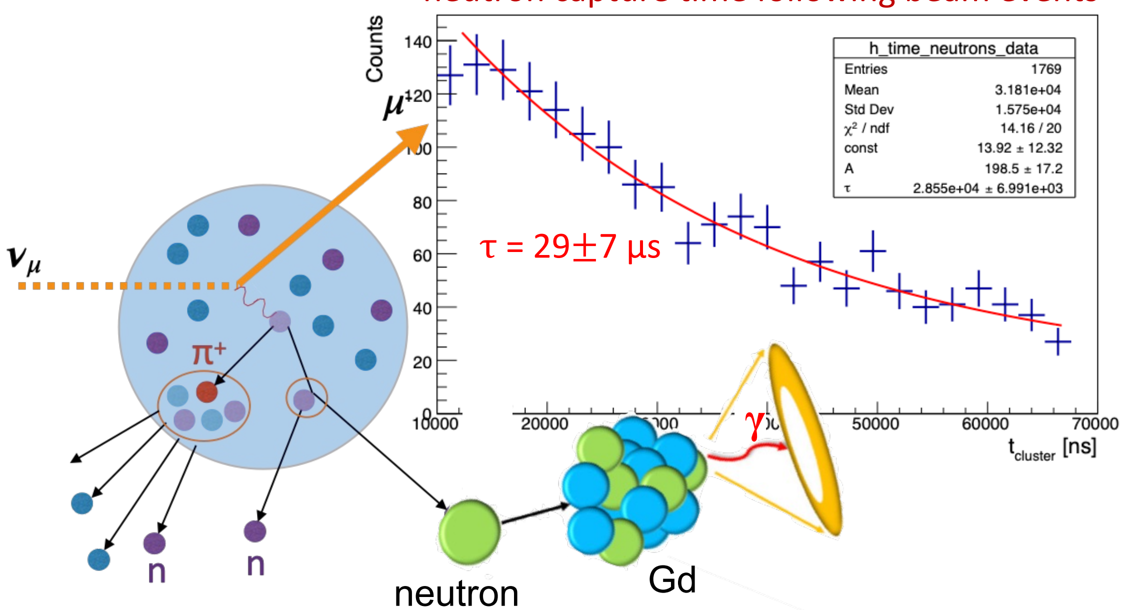
ANNIE Experiment

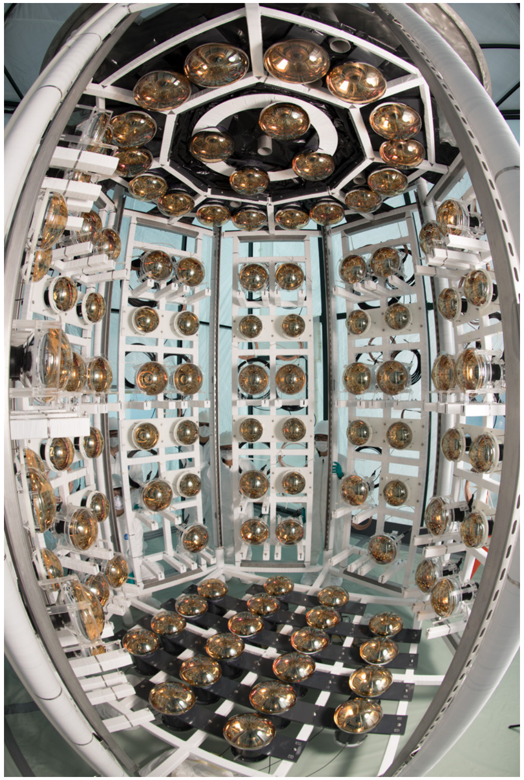
Accelerator Neutrino Nucleus Interaction Experiment

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

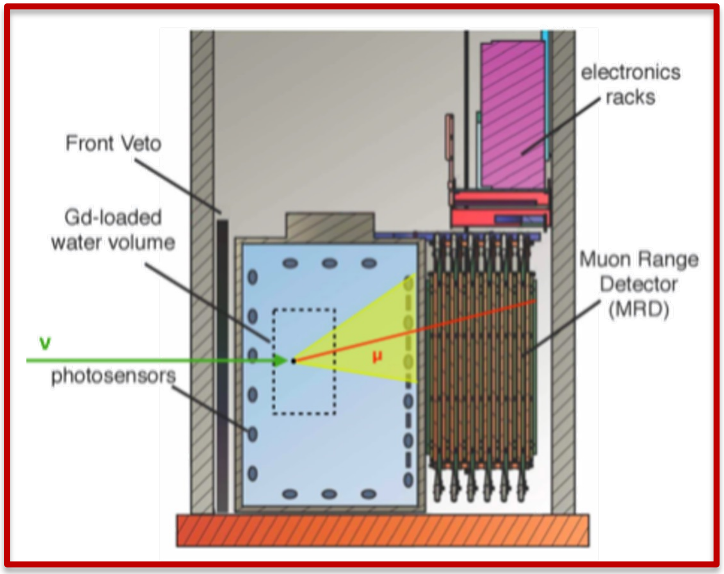
- measurement of GeV neutrino differential cross-sections and neutron multiplicity
  → **data to understand NC background rates for DSNB**
- physics data taking started in early 2021
- R&D program for new technologies
  → Gd-water → LAPPDs → WbLS

neutron capture time following beam events



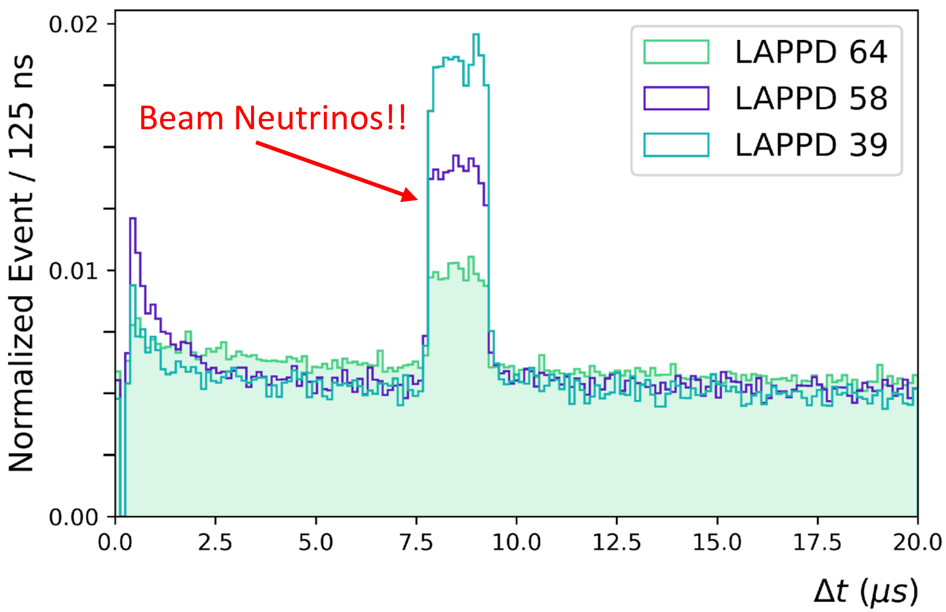


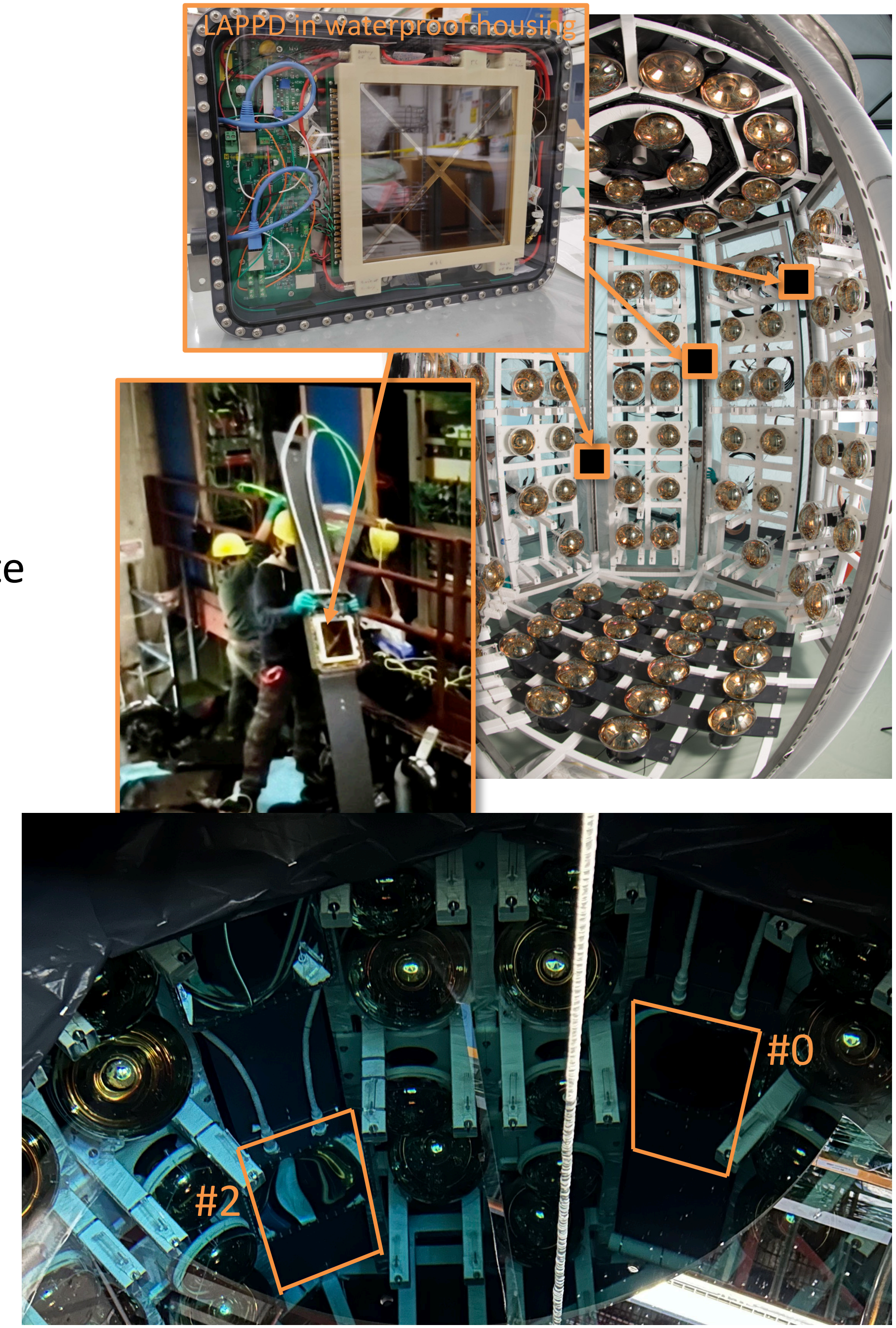
ANNIE Detector Layout



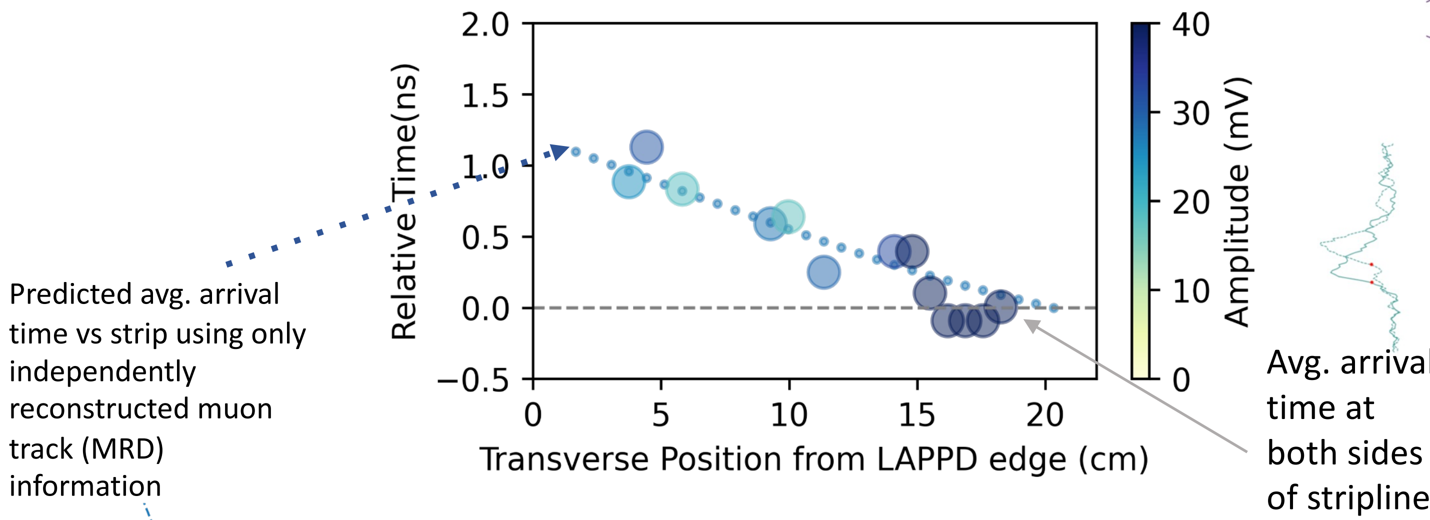
LAPPDs in ANNIE

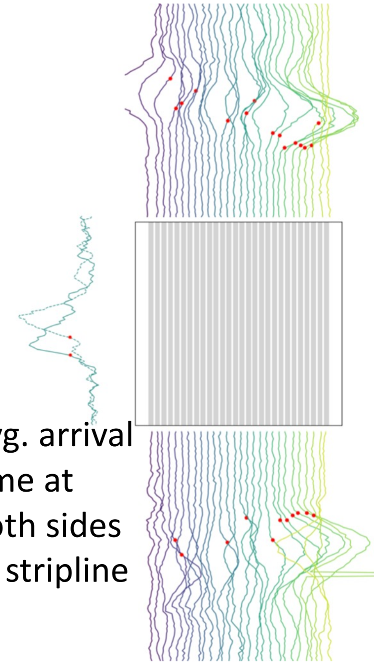
- first LAPPD deployed in 2022
- commissioning: integration with PMT system and MRD, time calibration, trigger integration
- by now, three LAPPDs (#0-2) up and running
- LAPPD #3 and #4 being characterized
- in context of WbLS/SANDI: aim to demonstrate time separation of Cherenkov and fast (~2ns!) scintillation component

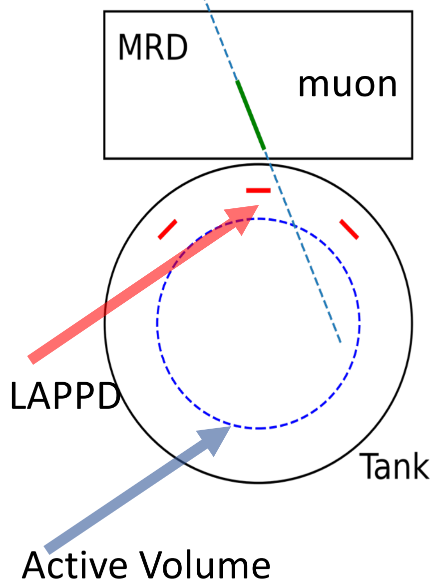




LAPPD Imaging and Timing Capabilities

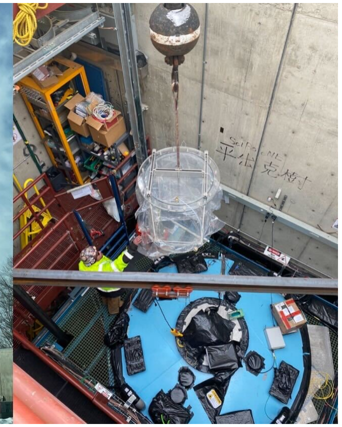


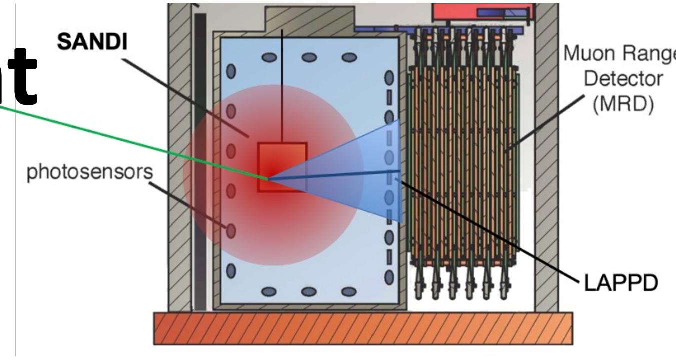


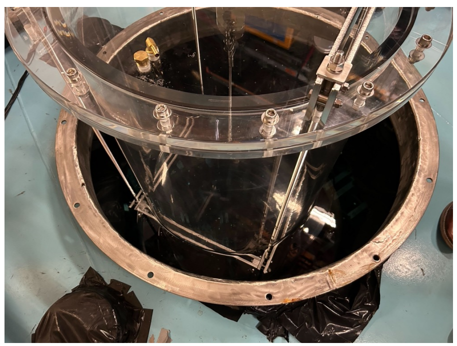


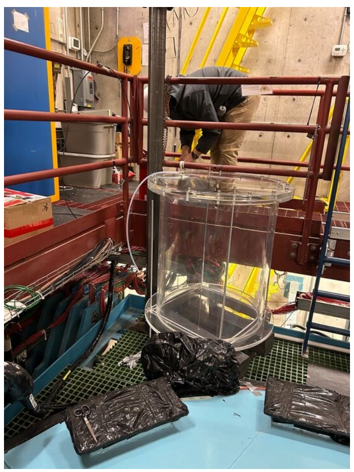
- LAPPDs are capable of reconstructing simultaneous time and spatial gradient of light on their surface.
- Study shows that a single LAPPD can independently constrain track parameters and resolve sub-ns timing structure.
- First step toward full 3D reconstruction and absolute timing benchmarks

ANNIE WbLS test deployment









SANDI vessel & support frame inserted in Jan

Insertion of vessel inside ANNIE tank in March

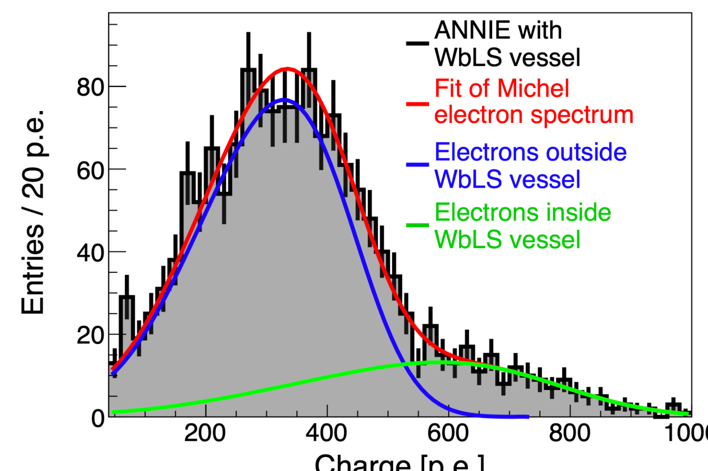
removed in May after taking 2 months worth of beam data

SANDI Acrylic Vessel

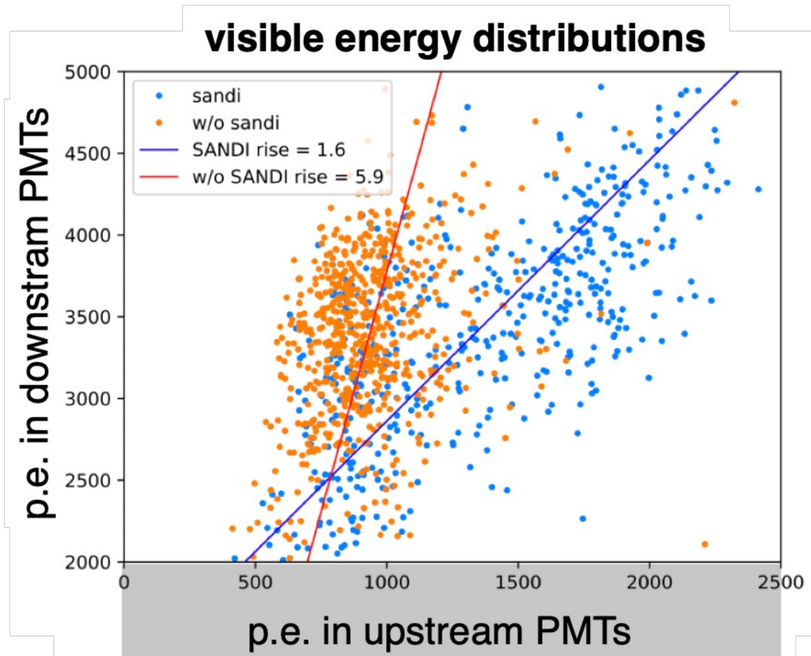
- cylinder holding 365 kg of WbLS submerged in ANNIE water tank

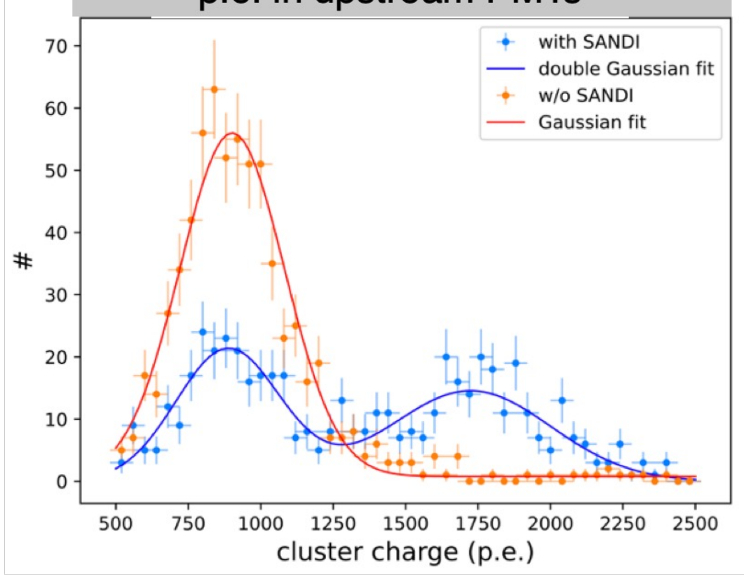
→ **first run (March 2023):**

- WbLS produced at BNL: 0.5% organic fraction
- estimate observed light yield: ~80% of Cherenkov output



First Neutrinos Detected in WbLS

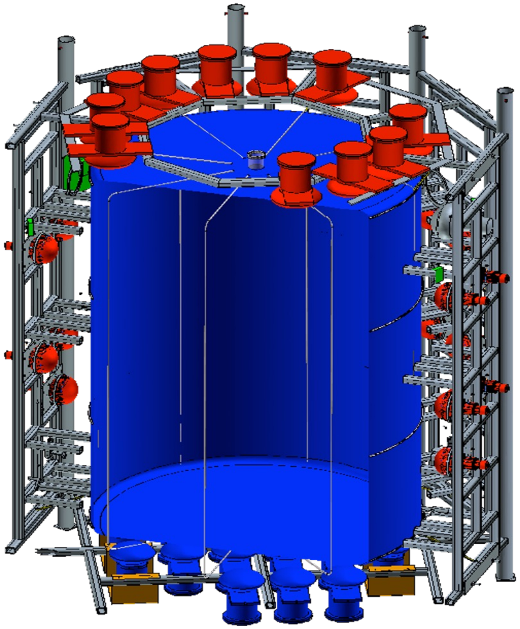




- comparison of **pure water** (orange) and **SANDI WbLS data** (blue)
- additional population of SANDI events with higher light output
- best visible in upstream ("back") PMTs that see mostly scintillation photons
- effective scintillation light ouput ~80% of Cherenkov (from Michel electrons)

What's next?

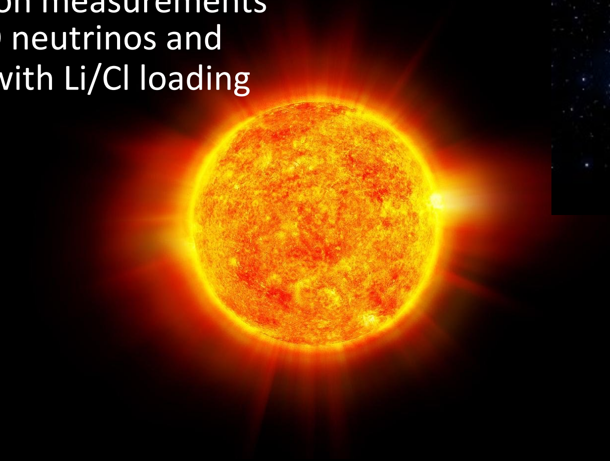
- 2^{nd} SANDI deployment with Gd-loaded WbLS
  → *next week*
- prepare to deploy full-volume (8t WbLS) nylon vessel
  → full event reco
  → hadronic recoils
  → neutron ranging



Astrophysical neutrinos at low energies

Supernova Neutrinos
astrophysics of core collapse
(exotic) oscillation effects

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



Diffuse Supernova Neutrinos
red-shift dep. Supernova rate
average SN neutrino spectrum

Geoneutrinos
crust/mantle
contributions
U/Th ratio

Astrophysical neutrinos at low energies

Supernova Neutrinos
astrophysics of core collapse
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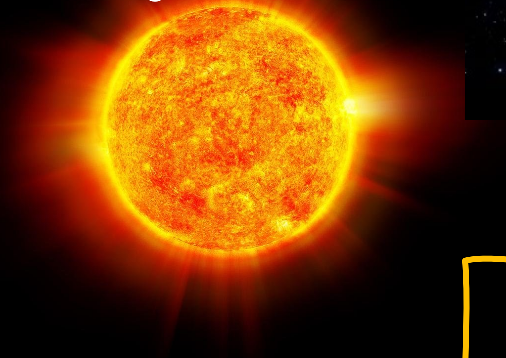
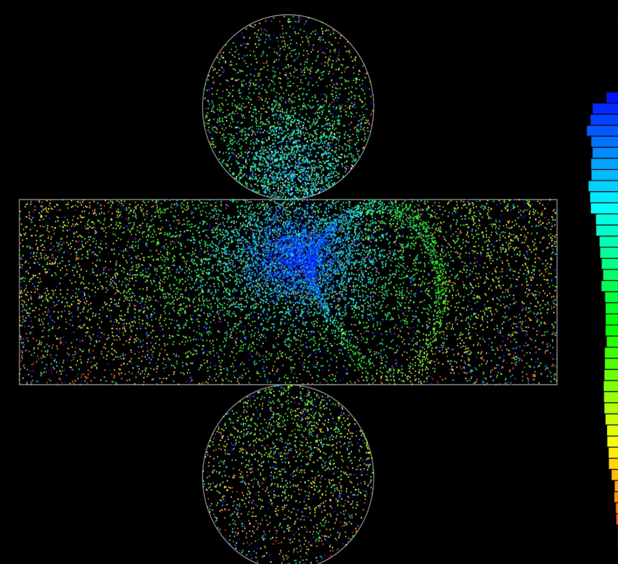


Diffuse Supernova Neutrinos
red-shift dep. Supernova rate
average SN neutrino spectrum

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



DSNB Signal (and Backgrounds) in THEIA

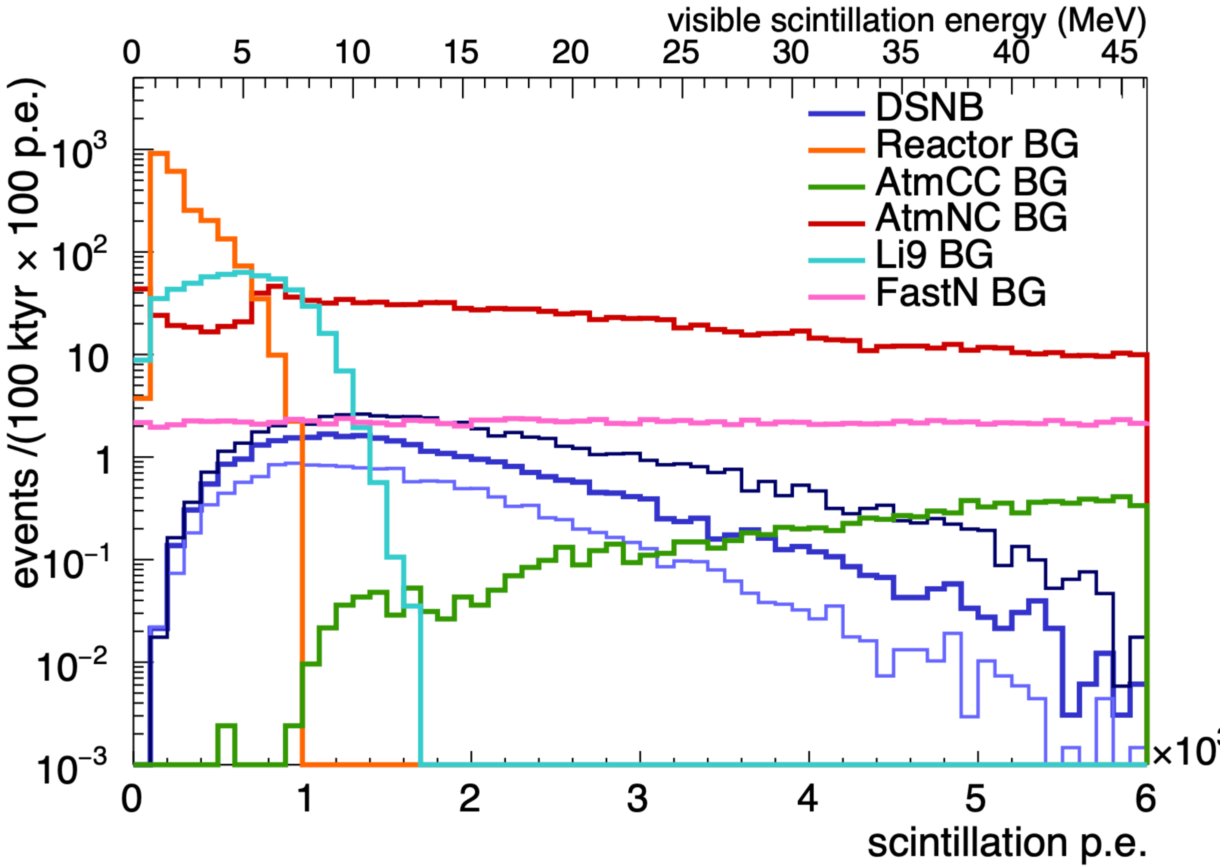
all following slides based on Sawatzki, Wurm, Kresse (2021)

- (raw) signal and backgrounds in WbLS are not very different from organic LS
  → cross-sections for ν interactions/μ spallation on carbon/oxygen comparable
- main backgrounds: atmospheric ν NC reaction, fast neutrons

raw event spectrum
(without background discrimination)

assumes 5% WbLS at SURF/4800 mwe

neutron tag from H capture

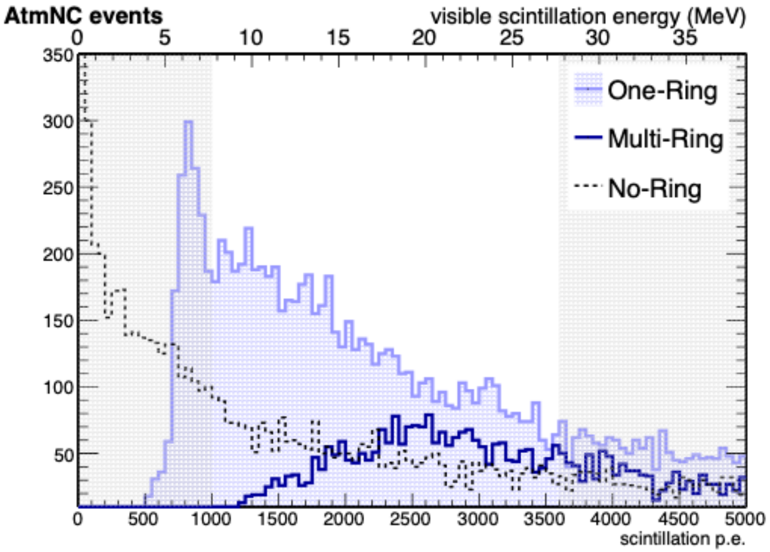


Background Reduction in a Hybrid Detector

- Downside: presence of scintillation makes hadronic recoils/decay products visible!
  → background levels as in JUNO

- Upside: detection can use background discrimination techniques of BOTH Cherenkov and scintillation detectors

- BG discrimination techniques available:
  - muon/neutron tagging (^{9}Li)
  - fiducial volume (fast neutrons, FN)
  - scintillation pulse shape (atm.NC, FN)
  - delayed decays (atm.NC)
  - Cherenkov ring counting (atm.NC)
  - **AND:** Cherenkov/scintillation ratio



Example: Ring-Counting
to tag atmospheric NC BG

Cherenkov-Scintillation Ratio

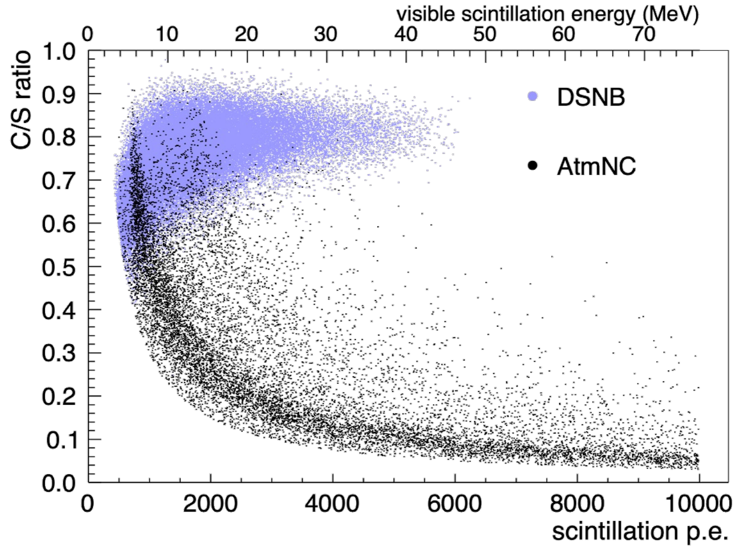
- basic idea:
  - signals from IBD positrons feature a high amount of Cherenkov light compared to their scintillation output
  - low-energy protons, alphas etc. produce next to no Cherenkov light

→ great tool to discriminate
Fast Neutrons (recoil protons) and
Atm. NC Interactions (nuclear fragments)

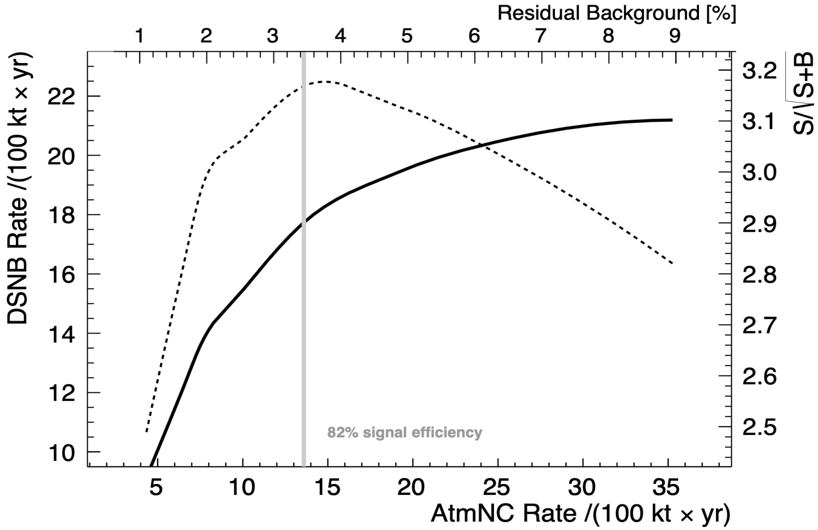
- residual from events with excited oxygen nuclei emitting 6 MeV gammas (c.f. SK-Gd)
- discrimination efficiency can be tuned depending on C/S ratio cut

→ here: 82% efficiency at 3% residual BG

Cherenkov/scintillation ratio for BG discrimination



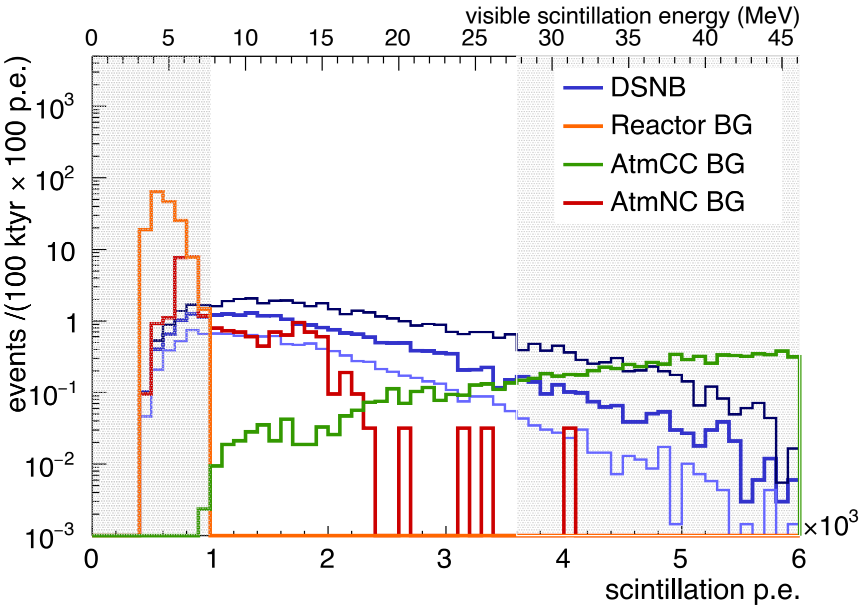
Selection efficiency: BG reduction vs. signal



Signal and Background after Discrimination

Background rejection techniques used:

- basic cuts (e.g. 1 delayed neutron, μ veto)
- selection of single-ring events
- selection of events with high C/S ratio
- rejection of events with delayed decays
- combined signal efficiency: >80%
  residual background ratio: 1.3%
- note: this does not yet use pulse shape!



Signal/BG spectra in observation window

	100 kt·yrs exposure			
Spectral component	basic cuts	single-ring	C/S cut	delayed decays
DSNB signal	21.7	21.7	17.7 (17.4)	17.5 (17.2)
Atmospheric CC	2.0	2.0	1.7 (1.6)	1.7 (1.6)
Atmospheric NC	682	394	13.6 (14.6)	7.4 (7.9)
fast neutrons	0.8	0.8	–	–
Signal efficiency	1	1	0.82 (0.81)	0.81 (0.80)
Background residual	1	0.58	0.022 (0.024)	0.013 (0.014)
Signal-to-background	0.03	0.05	1.2 (1.1)	1.9 (1.8)
Signal significance	0.8	1.1	3.1 (3.0)	3.4 (3.3)

Number of events after BF cuts: basic selection (e.g. 1 delayed neutron), single-ring cut, C/S cut, delayed decays (event rates in brackets for THEIA-25 geometry) – pulse shape discrimination not used!

THEIA in the DSNB landscape

Individual sensitivity of THEIA:

THEIA25: 3.4 IBDs over 1.9 BG per year
→ **3σ evidence after 4 years**

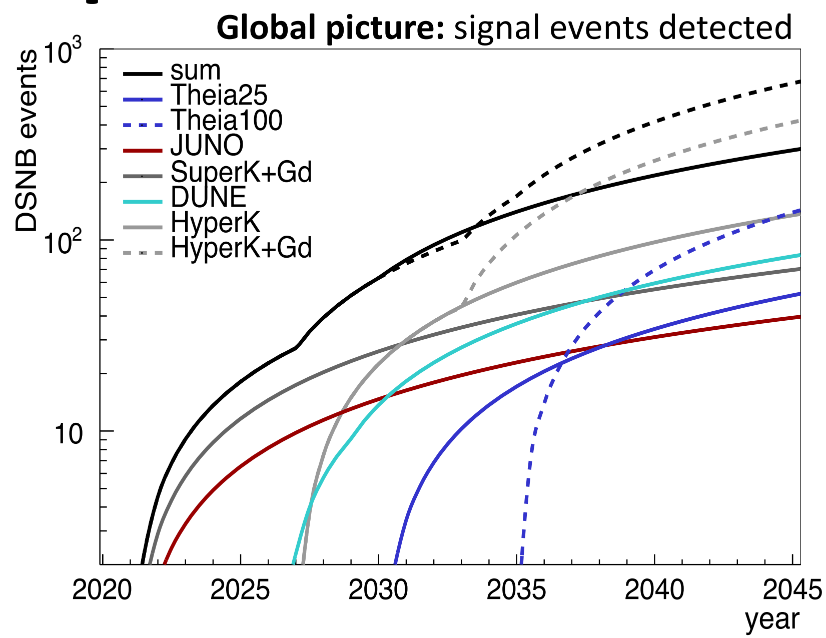
THEIA100: 14 IBDs over 7 BG per year
→ **5σ evidence after 3 years**

In the global picture:

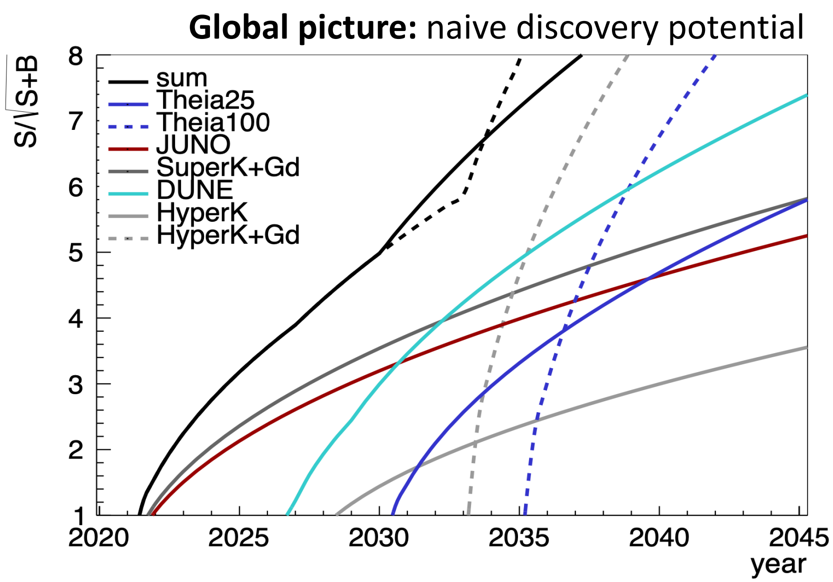
→ **THEIA25** would add to the overall event statistics and help to reduce background systematics

→ **THEIA100** would quickly (10-year scale) accumulate 100s of events, permitting **spectroscopy of the DSNB** with good energy resolution & low background

Global picture: signal events detected

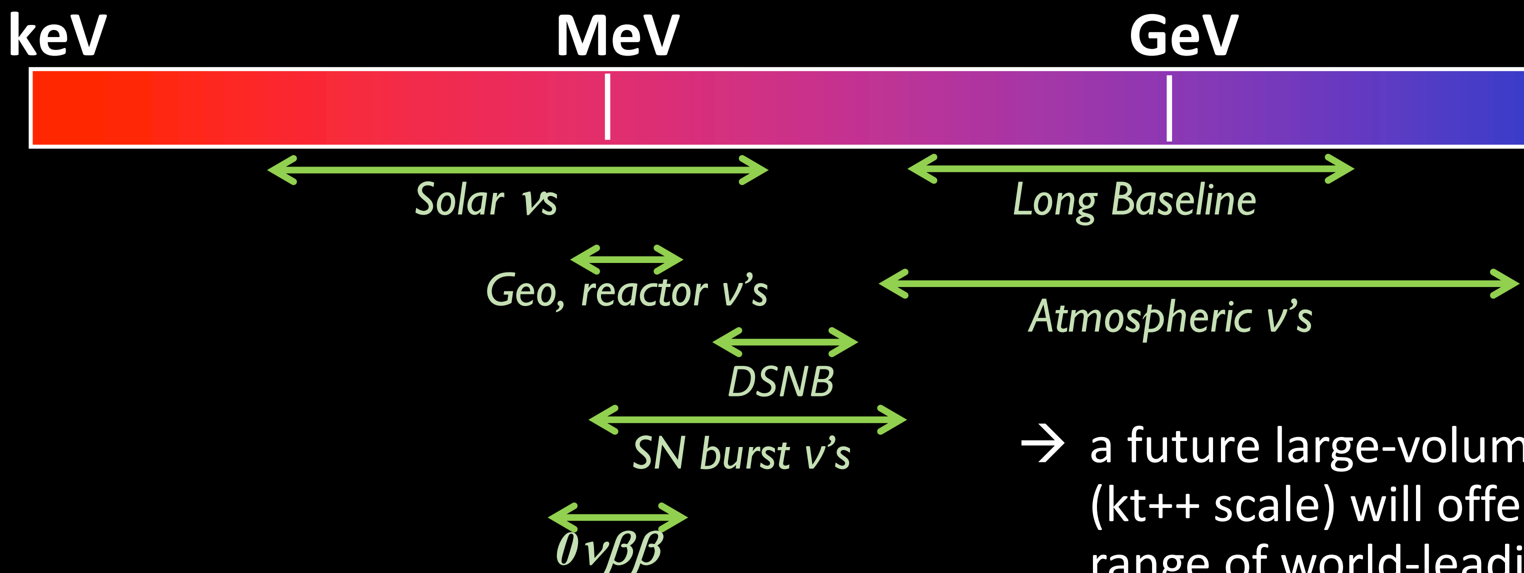


Global picture: naive discovery potential



Conclusions

- **As a hybrid Cherenkov/scintillation detectors, THEIA** offers 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

→ additional BG discrimination capabilities provide excellent sensitivity for the DSNB

- with ANNIE, EOS, BNL and BUTTON detectors, (multi-)ton scale demonstrator experiments are upcoming or running and will provide first physics data

Thank you!

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Regular Article - Experimental Physics

THEIA: an advanced optical neutrino detector

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

More information on:

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