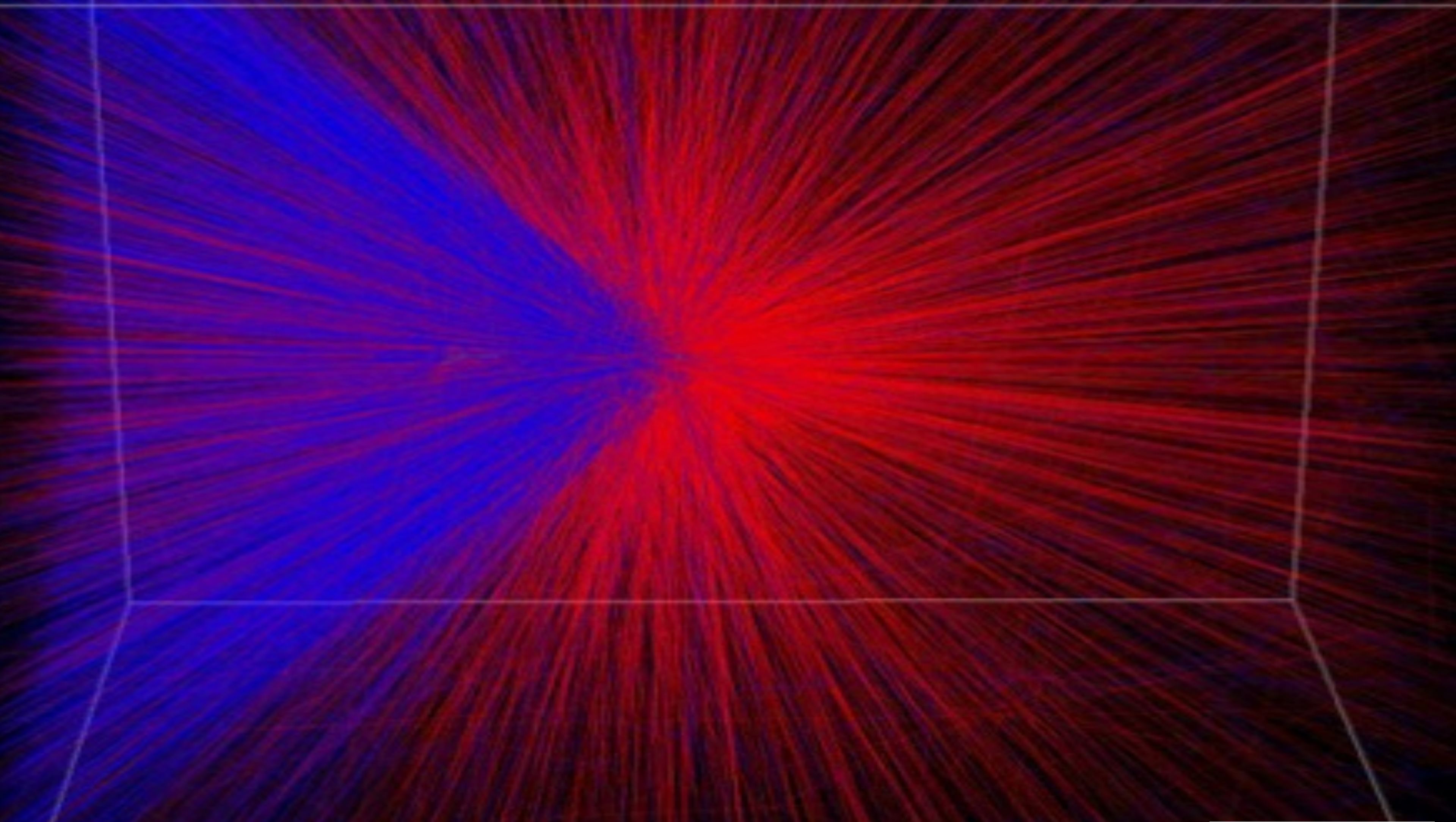
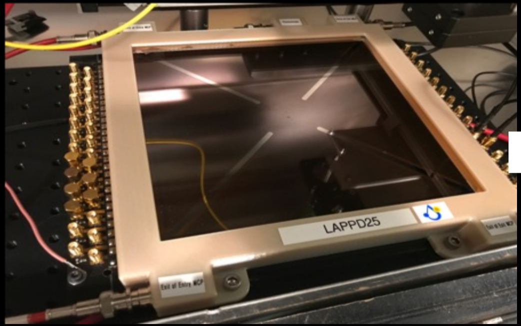
Overview on **Hybrid Cherenkov/Scintillation Detectors**



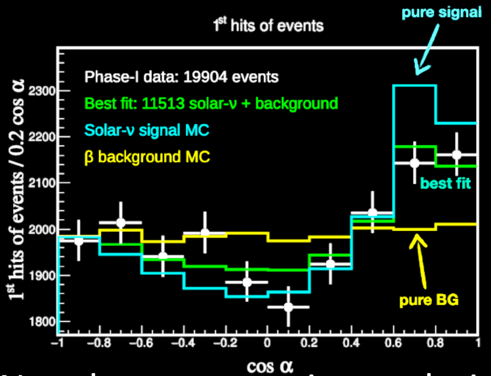
+++ Neutrino 2022 +++ Virtual Seoul, June 3, 2020 +++ Michael Wurm (Mainz) +++

Hybrid Cherenkov/Scintillation Detectors

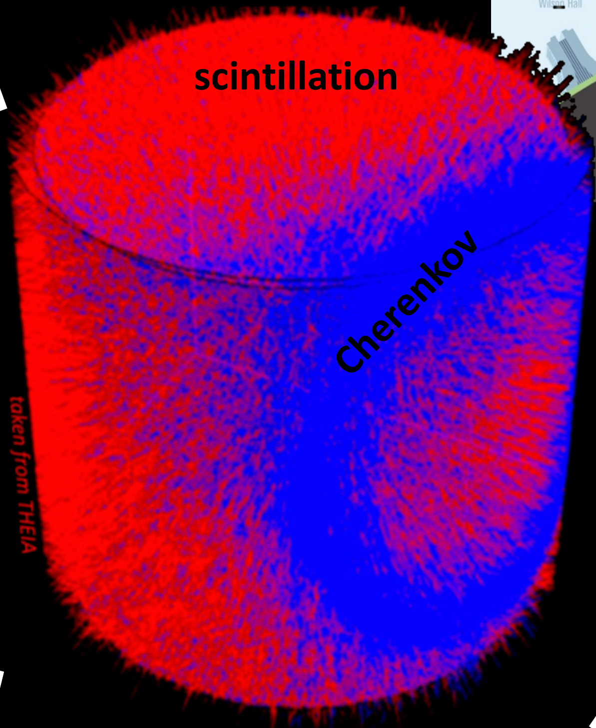
Novel target media:
Water-based/Slow Scintillator



Novel light sensors:
fast PMTs, LAPPDs, dichroicons

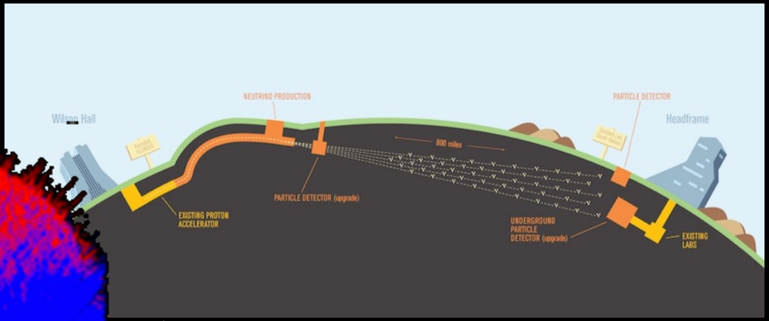


Novel reconstruction techniques



Large volume detector
able to exploit both
Cherenkov+Scintillation
signals

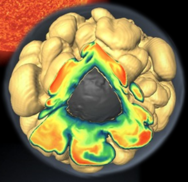
→ **Enhanced sensitivity to broad physics program**



Long-Baseline Oscillations

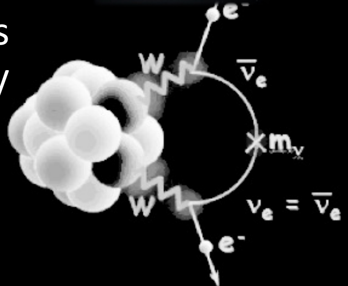
Solar neutrinos

Supernova neutrinos

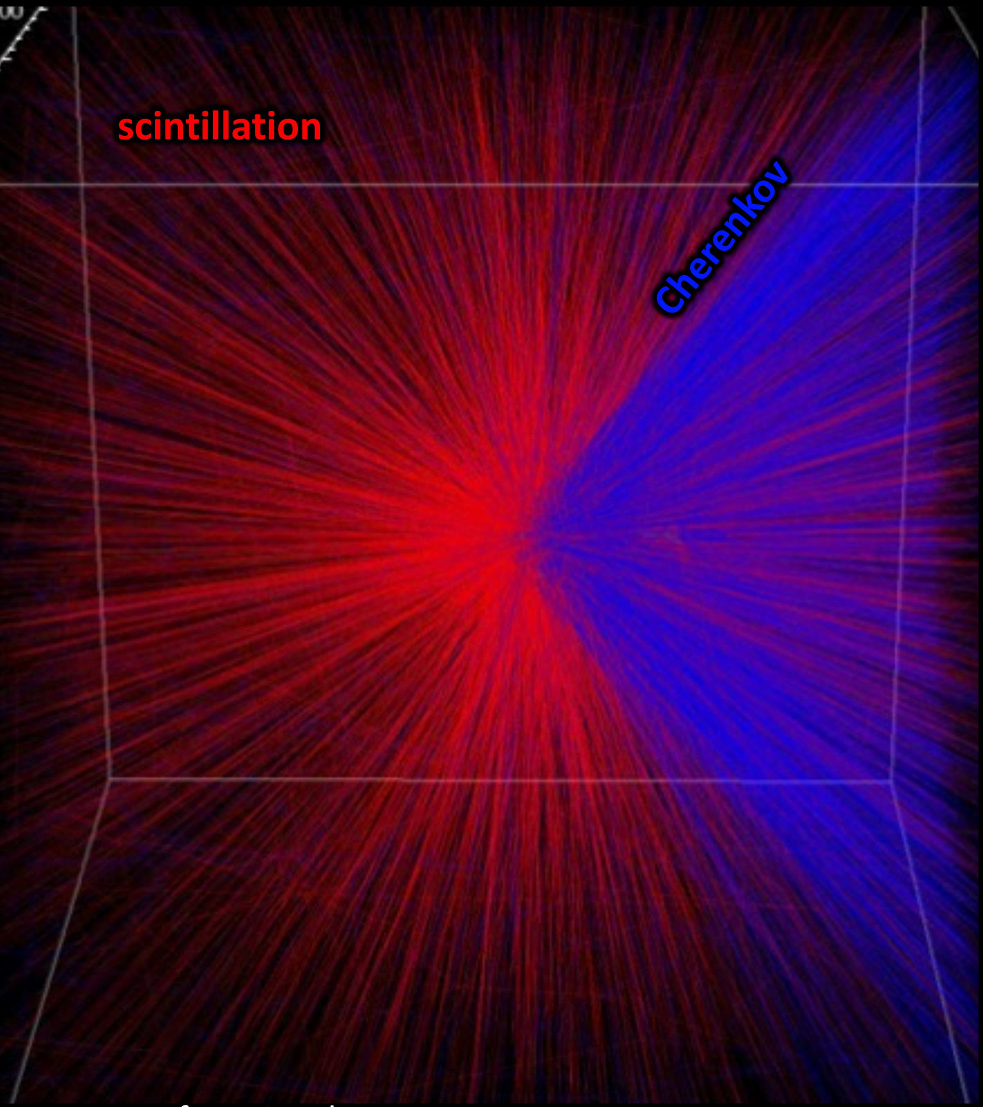


Diffuse SN neutrinos

Neutrinoless
Double-Beta Decay



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?

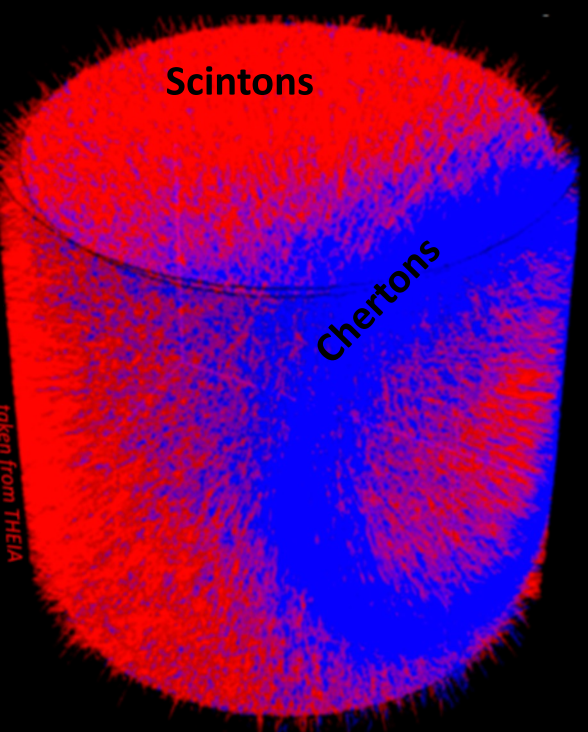
→ enhance liquid transparency and/or

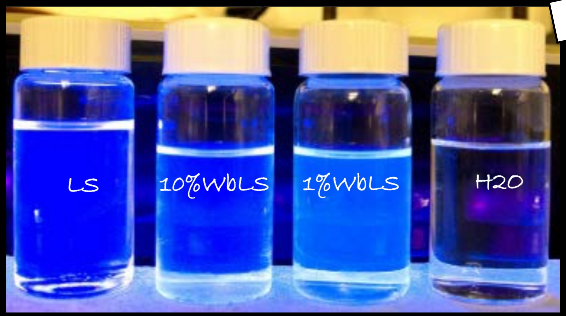
→ slow down scintillation emission

→ Cherenkov/scintillation (C/S) separation

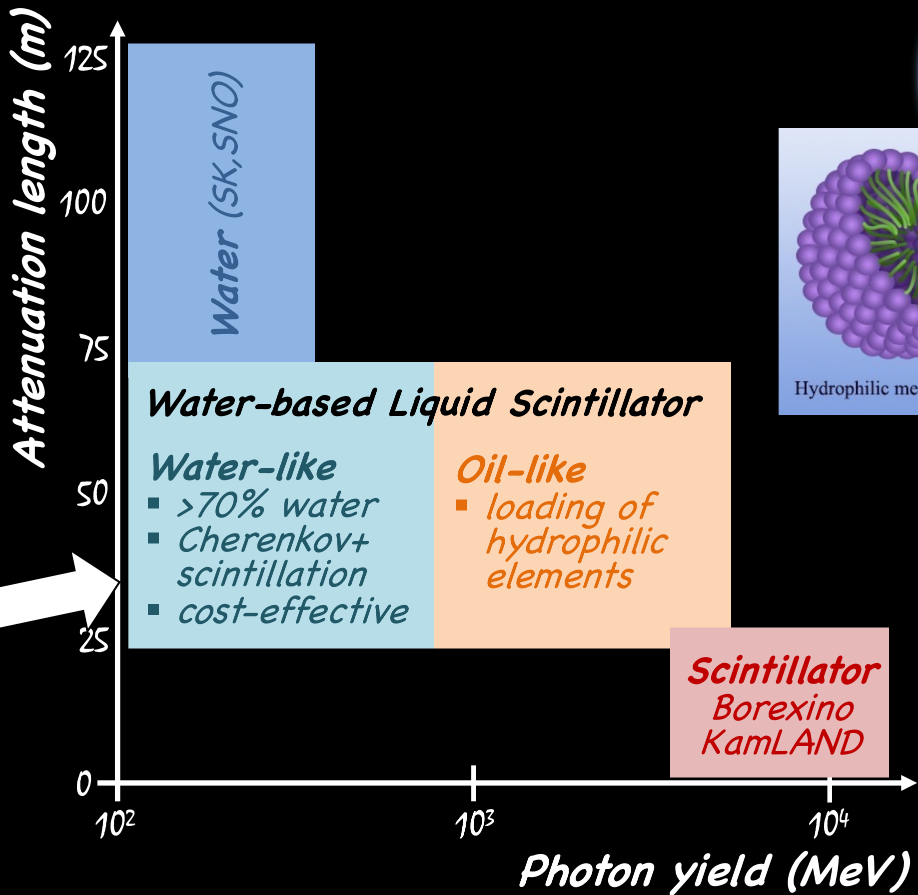
Water-based liquid scintillators (WbLS)

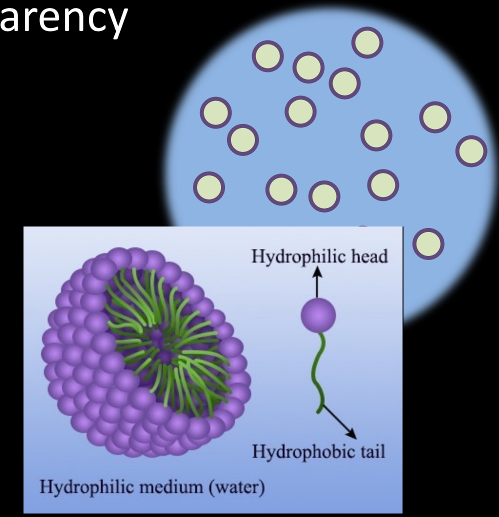
→ WbLS: water + tensid + solvent (LAB) + fluor (PPO)
→ low organic fraction → high transparency





Minfang Yeh, BNL

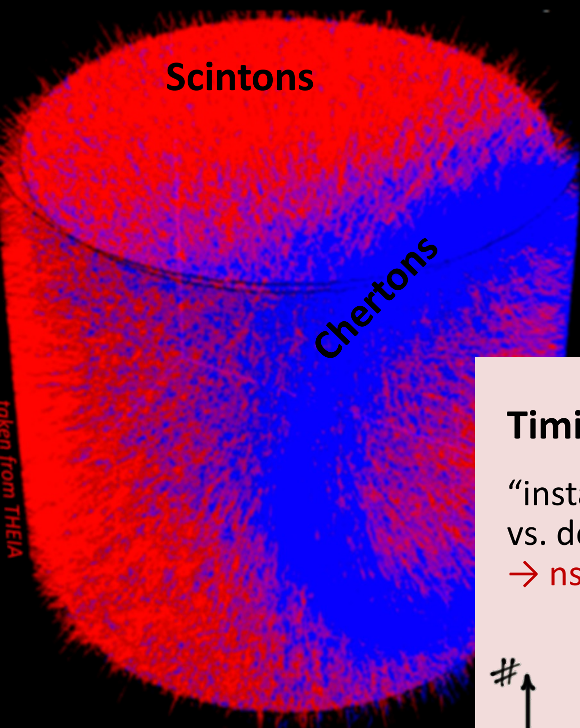




WbLS mycels

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

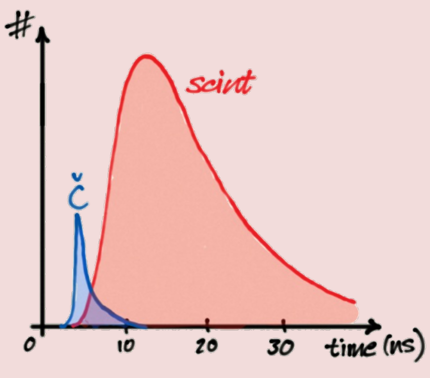
Separating Chertons and Scintons



→ **how to resolve the Cherenkov/scintillation signals?**

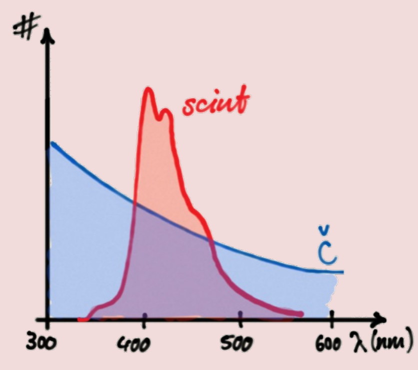
Timing

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



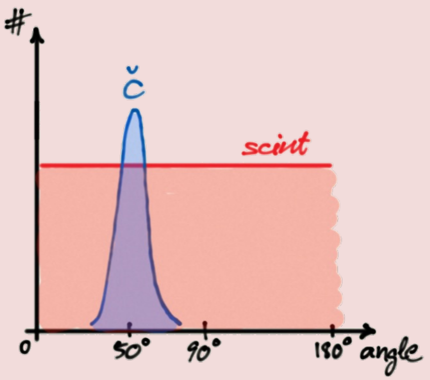
Spectrum

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

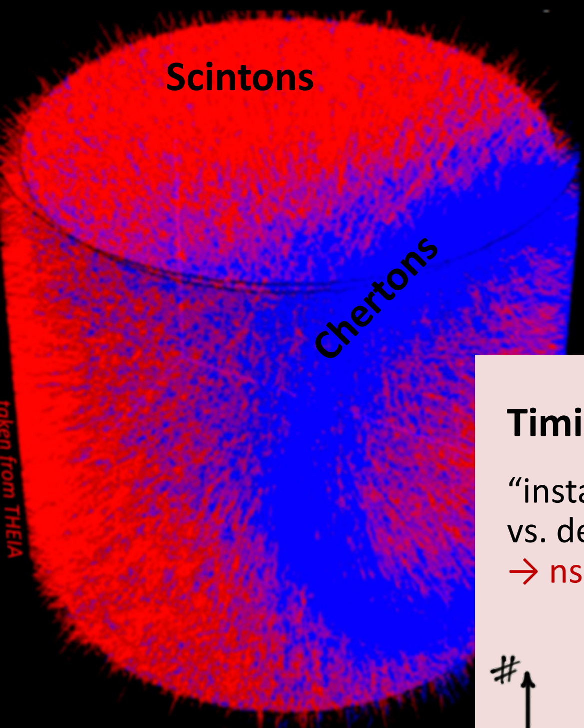


Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity



Separating Chertons and Scintons



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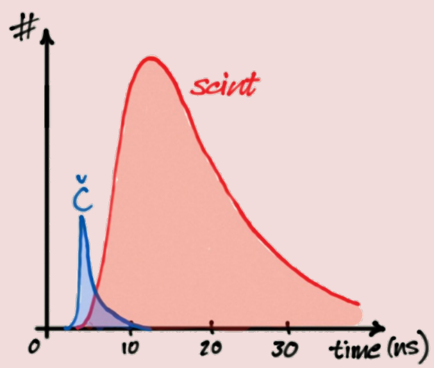
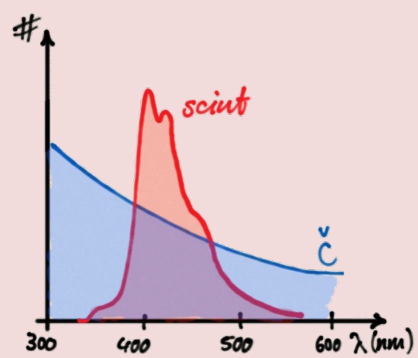


LAPPDs: ~60ps timing

Spectrum

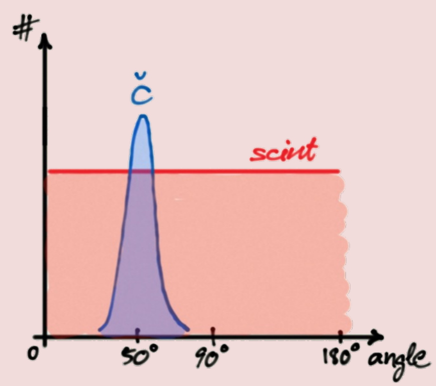
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity



Dichroic filters

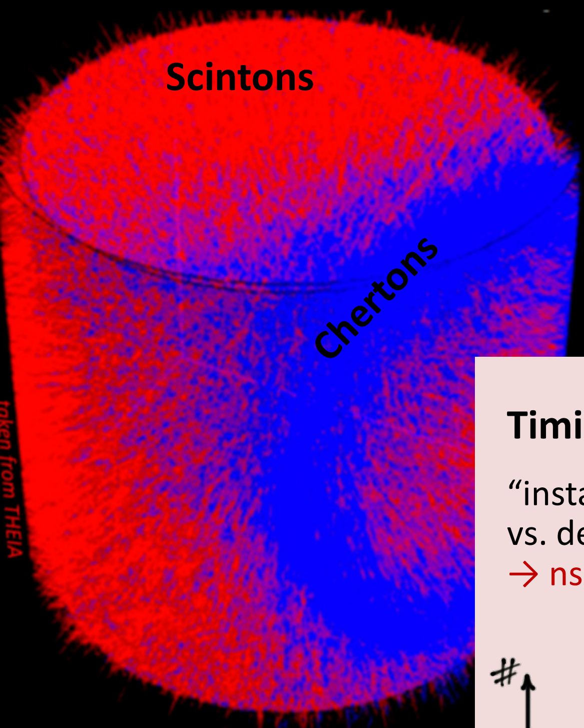
Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity



Standard PMTs

Separating Chertons and Scintons



→ how to resolve the Cherenkov/scintillation signals?

Timing

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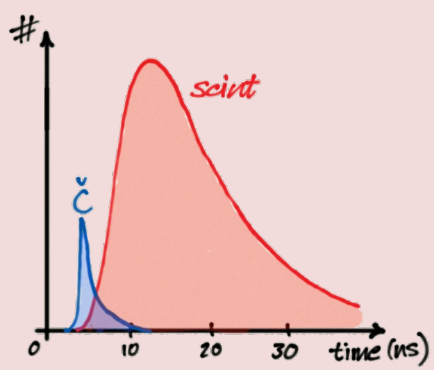
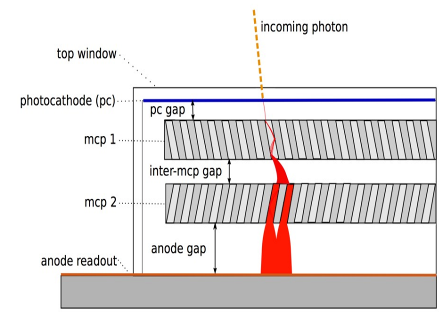
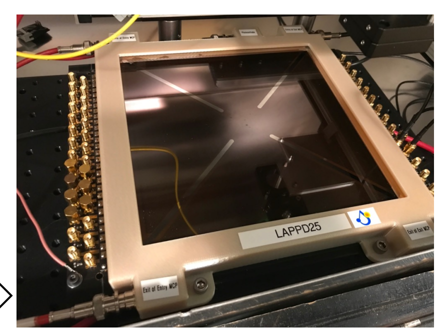


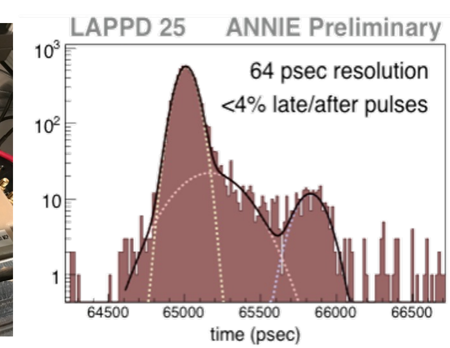
LAPPDs: ~60ps timing

Large Area Picosecond Photon Detectors

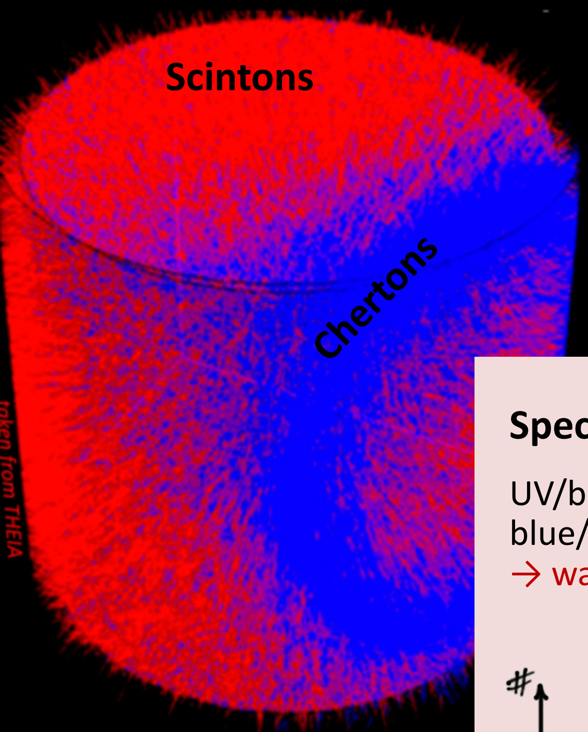
- Area: 20-by-20 cm^2
- Amplification of p.e. by two MCP layers
- Flat geometry: ultrafast timing ~65ps
- Strip readout: spatial resolution ~1cm
- Commercial production by Incom, Ltd.







Separating Chertons and Scintons



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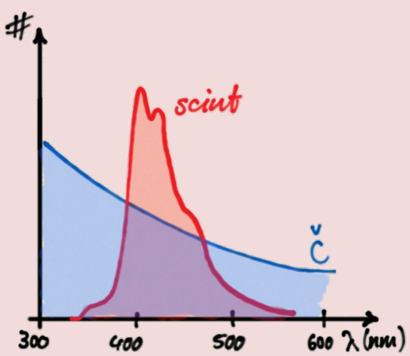
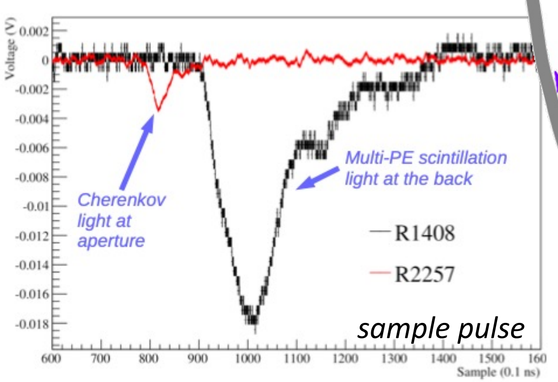
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity

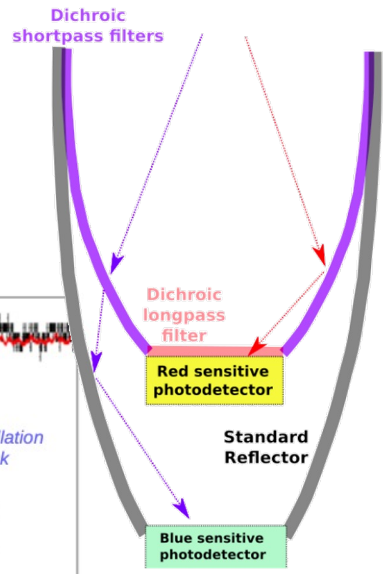


Dichroic filters

Dichroicons [add Ref]

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





Alternative: Slow Scintillators

General idea

organic scintillators modified for slow(er) scintillation emission

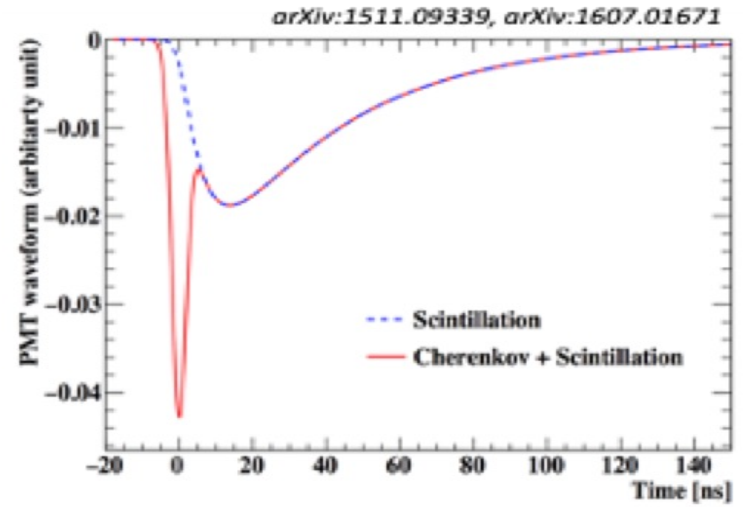
Options

- 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]

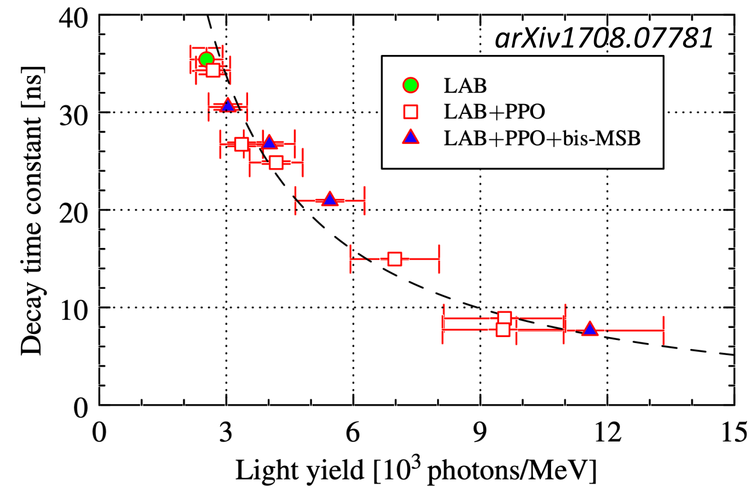
Consequences

- 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

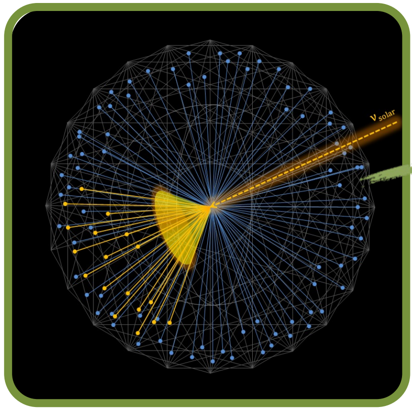


Decay time/LY vs. PPO concentration



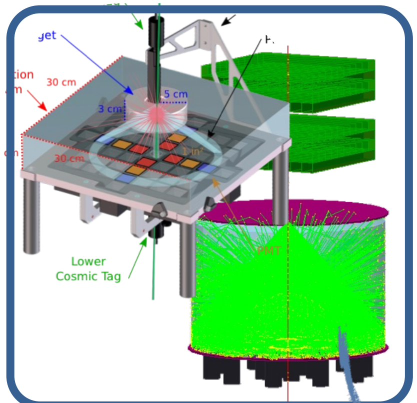
Development Path of Hybrid Detectors

Borexino
SNO+



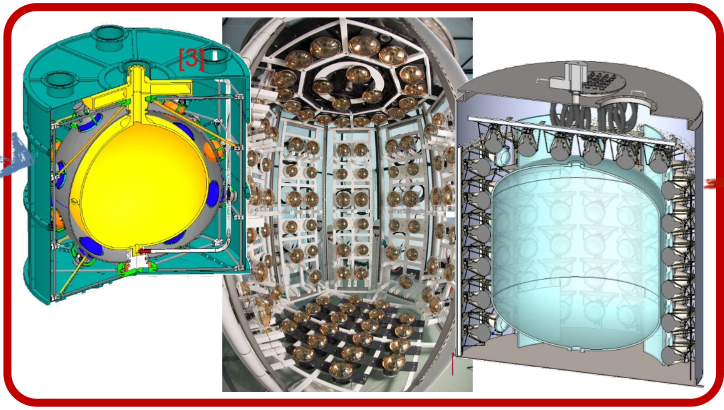
Re-analyzing data from existing LS Detectors

Lab-Scale Setups

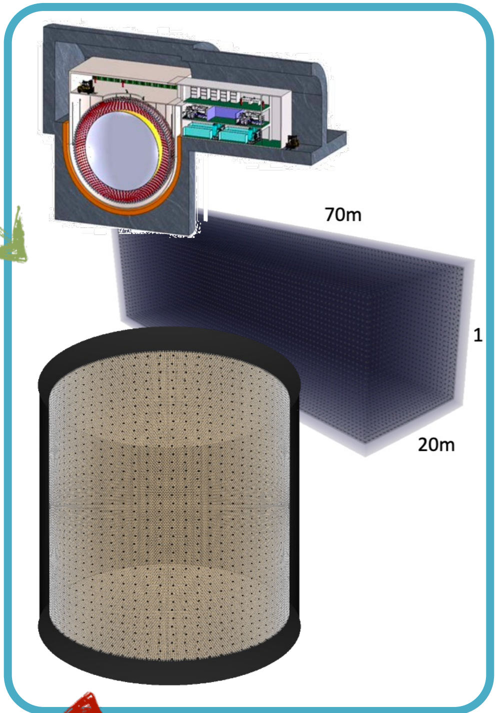


UCB: CHESS
Tsinghua U.
MZ: SCHLYP
MZ/TÜ: DISCO
...

Ton-Scale Setups



Jinping 1t
ANNIE/SANDI
EOS



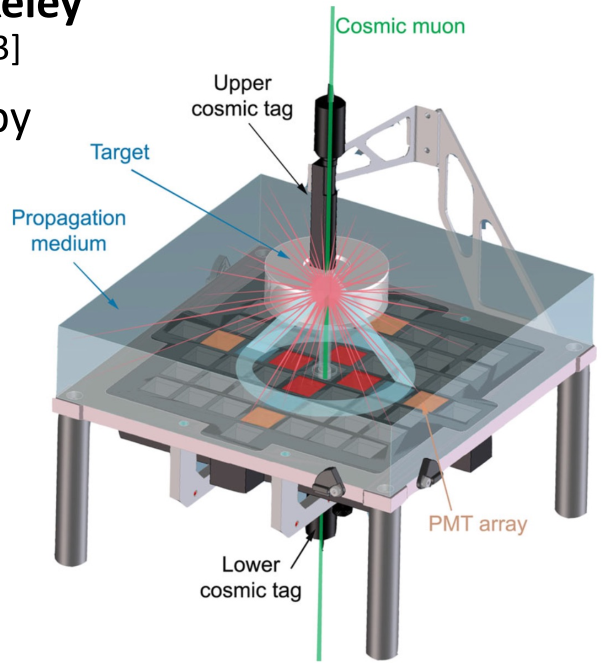
Future full-scale hybrid detectors
Jinping 500t
Theia 25/100

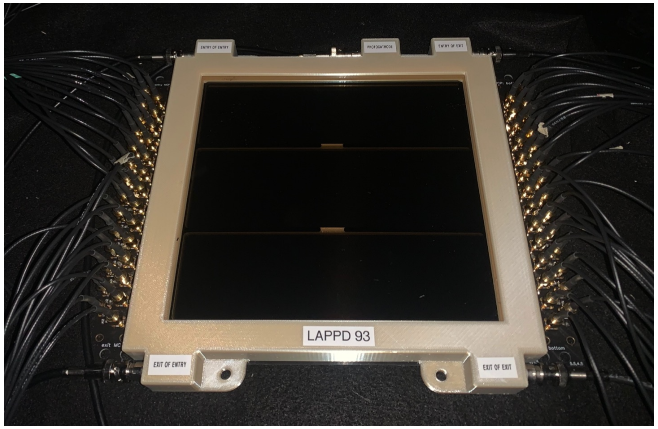
Lab Setups for C/S Separation

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

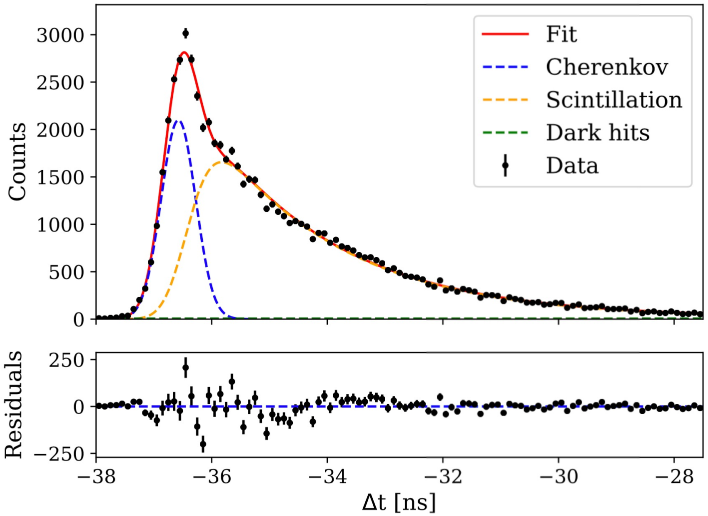
PMT array illuminated by small LS target excited by cosmic muons and radioactive sources

→ C/S separation using hit pattern

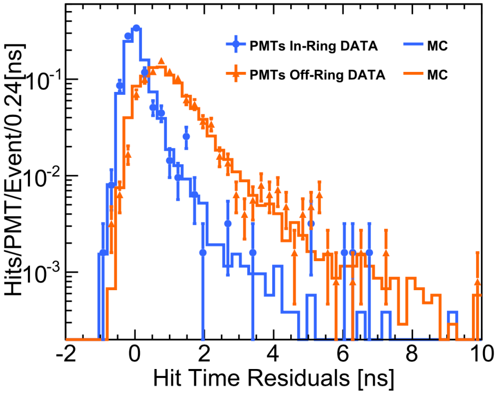




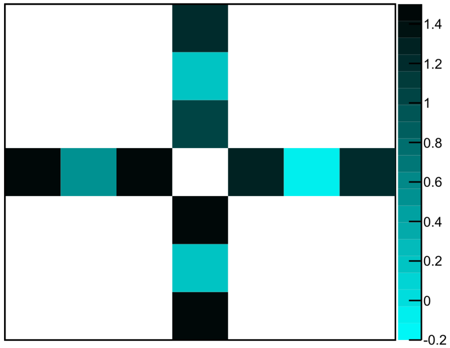
WbLS time profile with LAPPD
[arXiv:2110.13222]



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



PMT hit pattern



→ C/S separation based on timing

5% WbLS

rise time: 209±10 ps

fast decay time: 2.25±0.01 ns

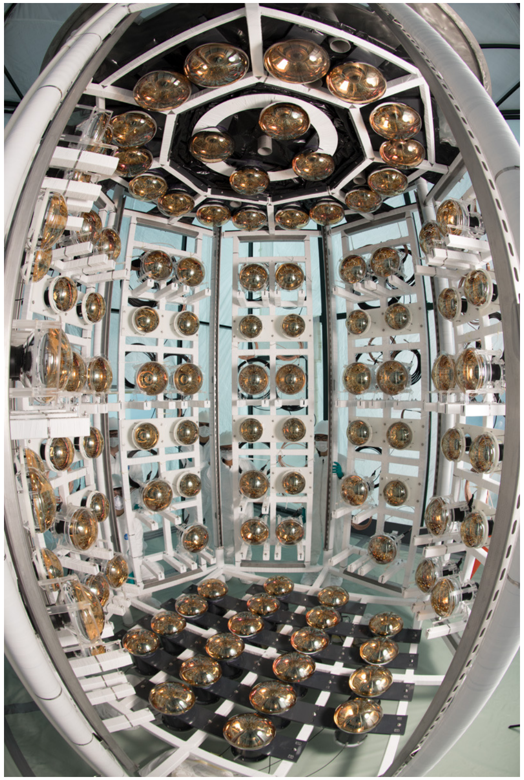
ANNIE Experiment

P0155 P0266

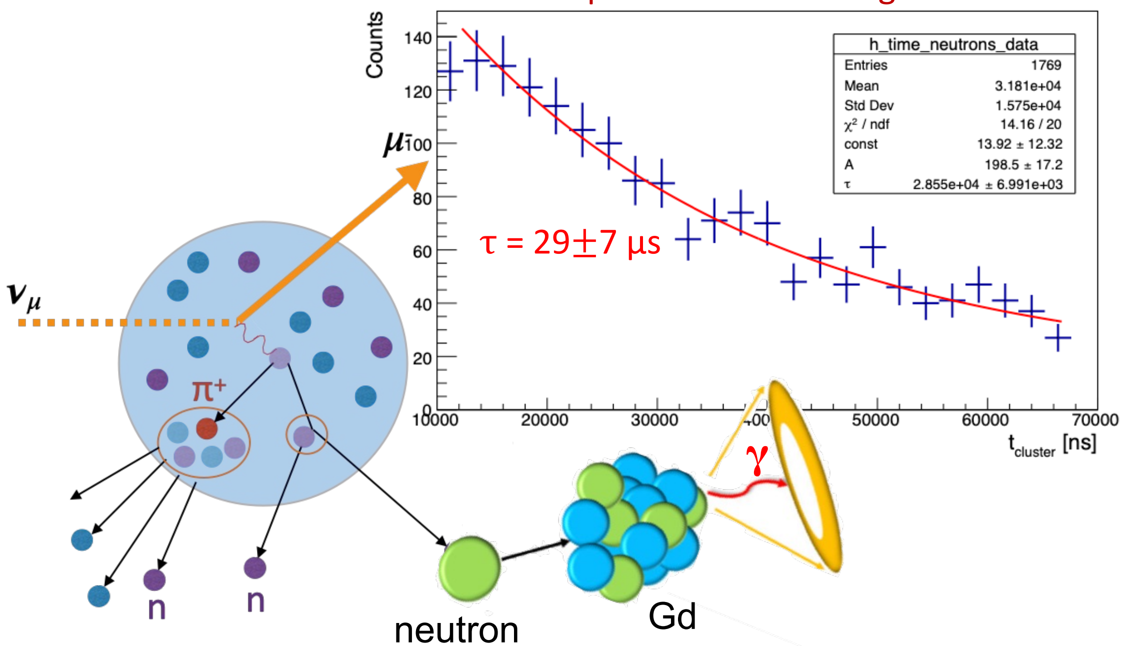
Accelerator Neutrino Nucleus Interaction Experiment

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

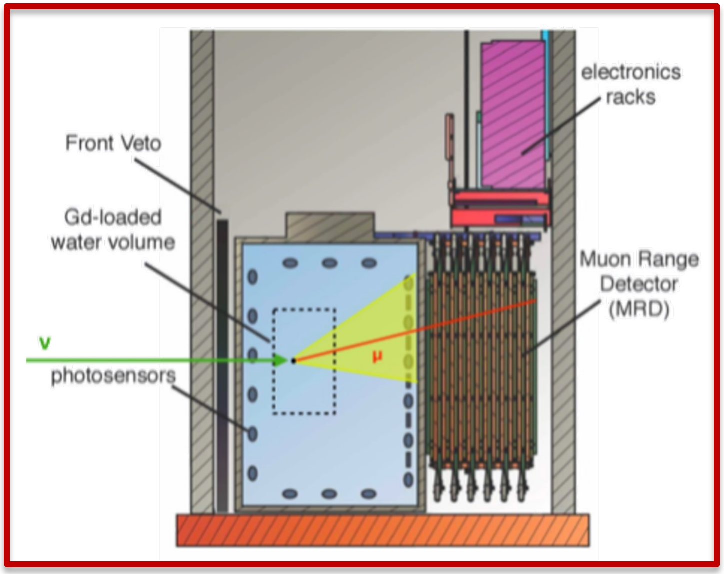
- measurement of GeV neutrino differential cross-sections and neutron multiplicity
- physics data taking started in early 2021
- R&D program for new technologies
  → Gd-water → LAPPDs → WbLS



neutron capture time following beam events

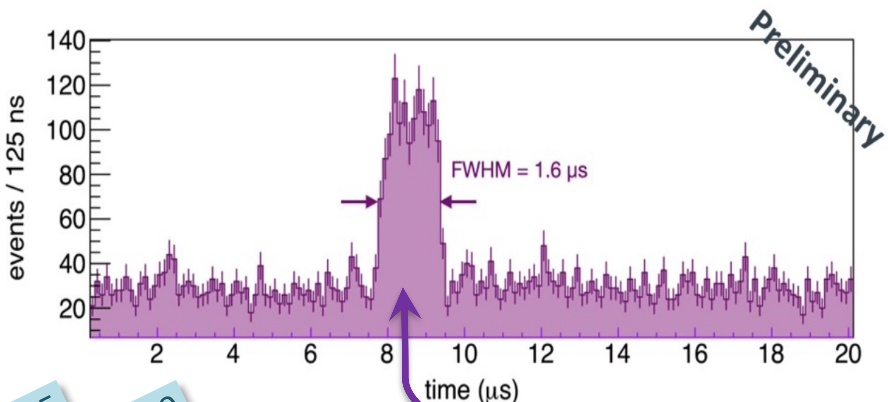


ANNIE Detector Layout



ANNIE: First LAPPD installed

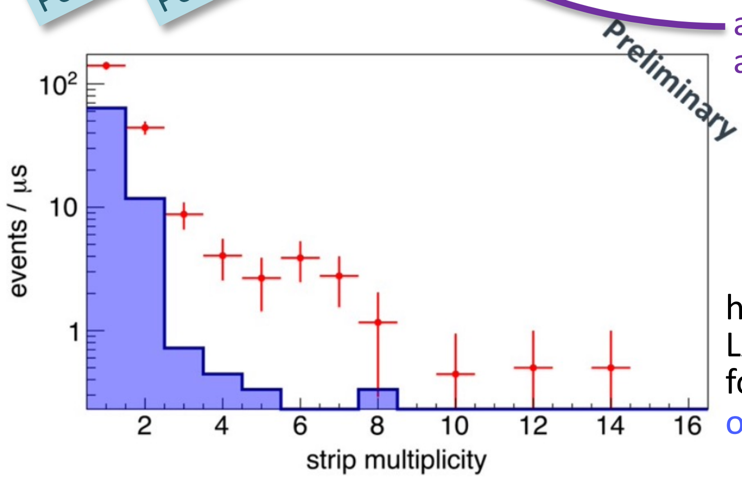
- major milestone: 1st LAPPD installed in March 2022, detected first light from neutrinos
- currently: *in-situ* timing calibration
- 4+ LAPPDs more to be installed for next beam year



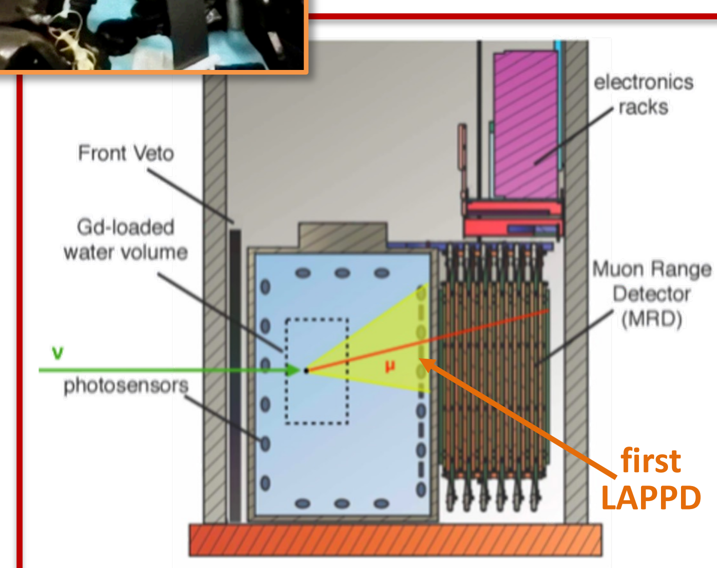
event time distribution around the BNB beam spill as observed by the LAPPD

P0565

P0699



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

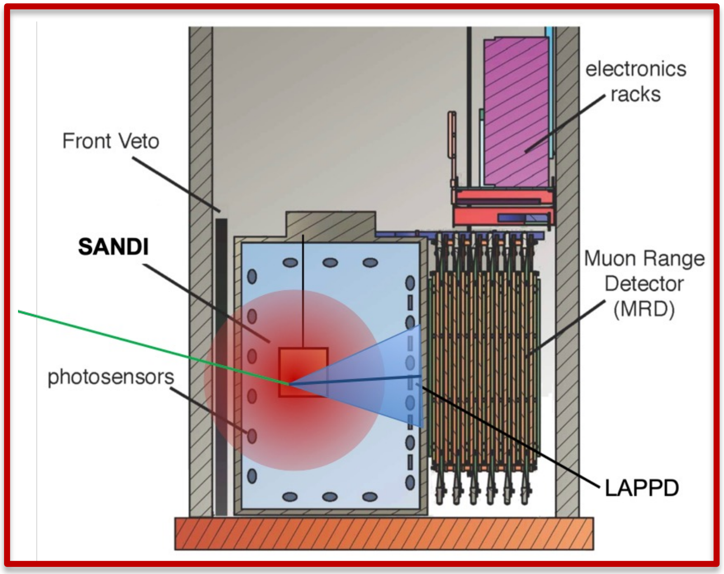
→ test WbLS performance for future use in long-baseline exp.s!

SANDI vessel at Davis

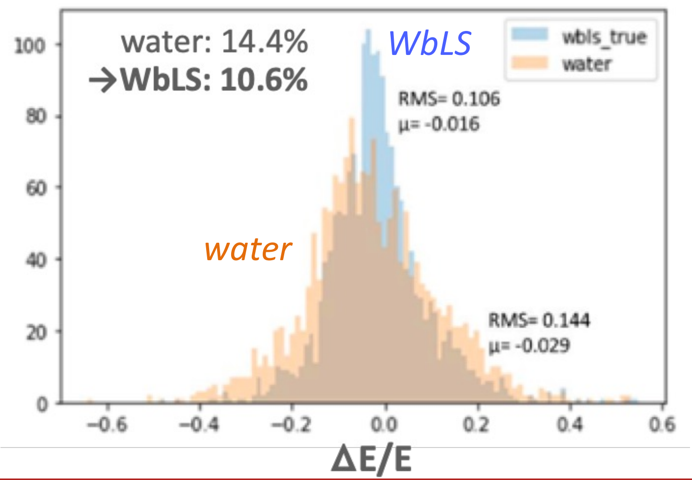
Preparations are on-going

- 3‘ x 3‘ vessel already on-site at Fermilab
- (Gd-loaded) WbLS to be produced at BNL (M. Yeh)

ANNIE vs. SANDI WbLS vessel



MC with idealized reco and machine learning

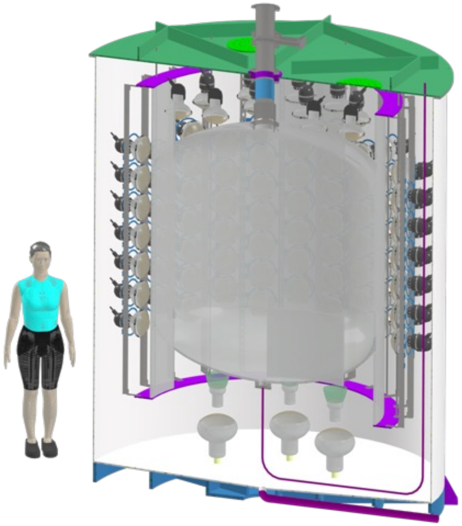


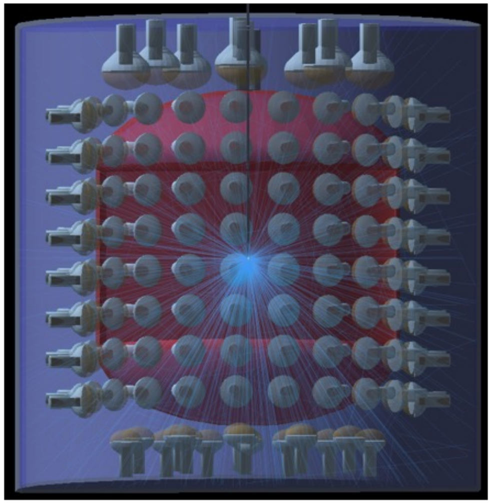
EOS: WbLS performance demonstrator

Detector Layout

- stand-alone hybrid detector
- target mass: 4 ton (water, WbLS, LS)
- 200 fast 8'' PMTs (tts of 900 ps) with CAEN V1730 readout
- plus deployment of 4 dichroicons for spectral sorting

→ start in 2023/24 (UC Berkeley)





4-ton WbLS demonstrator detector for MeV energy regime

Demonstrator program

- event reconstruction using hybrid Cherenkov/scintillation signatures
- validate models to support large-scale detector performance predictions

P0093

P0443

closely connected to BNL effort on a 30-ton tank for demonstration of WbLS production, transparency and stability

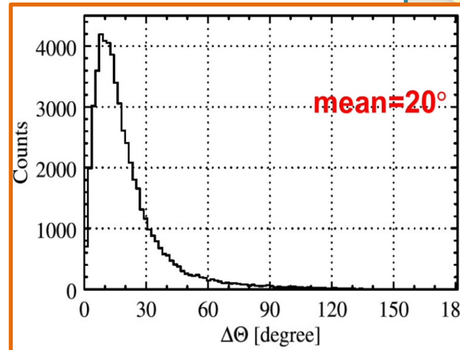
Jinping 1-Ton Prototype

fast 8'' MCP-PMT

P0485
P0506

Detector Layout

- acrylic sphere containing 1t of slow scintillator
- fast 8'' PMTs for light read-out
  (new fast MCP-PMT being developed, σ_{tts}=1.5ns)
- detector running since 2018

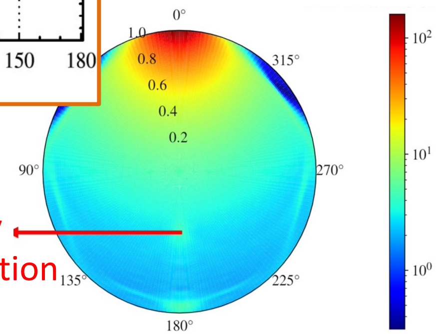


angular resolution for cosmic muons

Project program

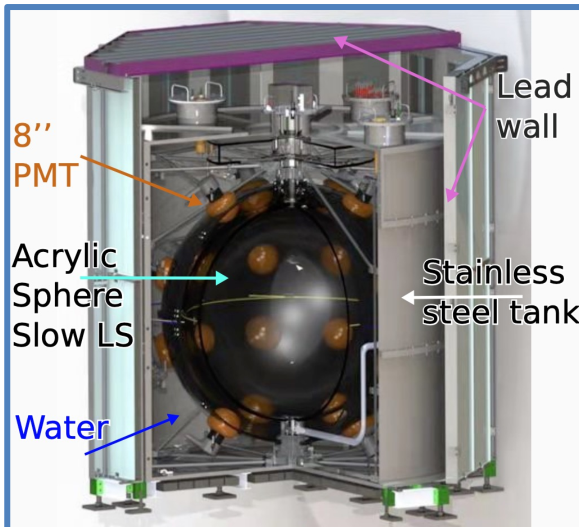
- event reconstruction in slow scintillator
- background levels in Jinping laboratory and radiopurity of detector materials

P0533
P0354
P0413
P0478



study of low-energy LS event reconstruction incl. total reflection

liquid handling system @ Jinping



Directionality in present-day scintillator detectors

BOREXINO

- 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!

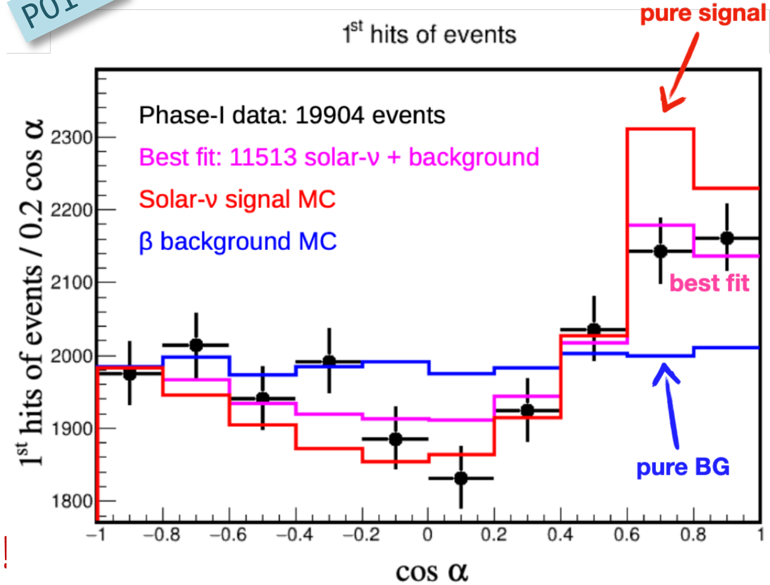


photo: BOREXINO calibration

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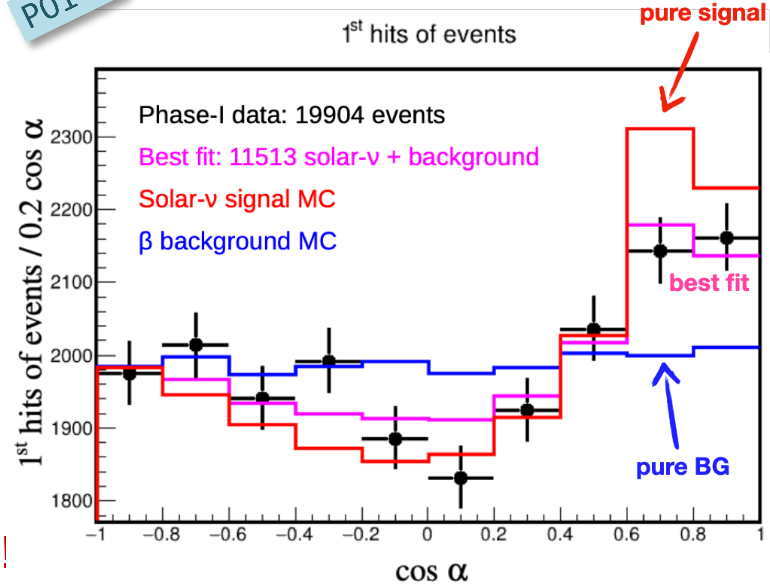
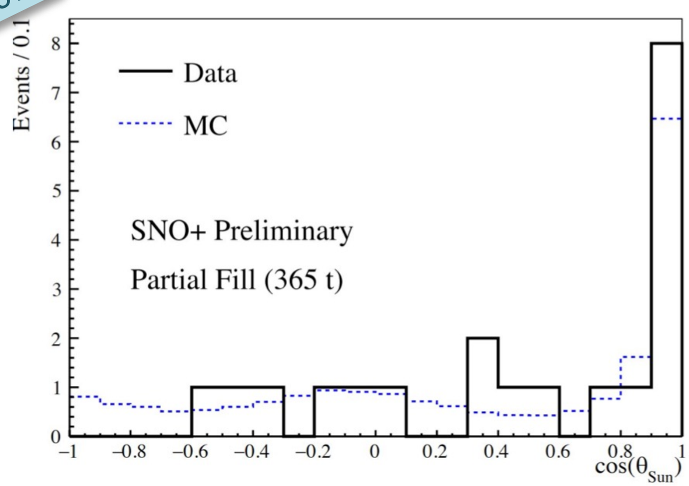
P0142



P0078



SNO+

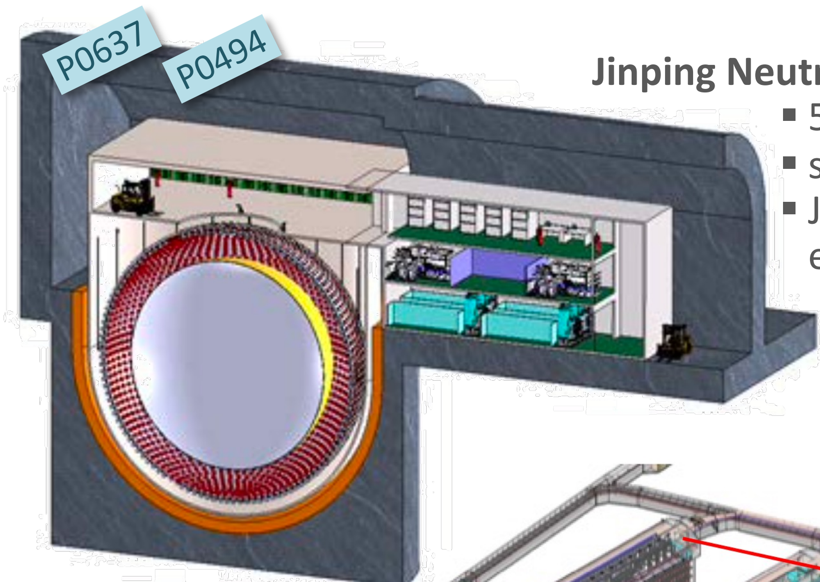
- partial fill of detector with 365 t of slow scintillator: LAB + 0.6 g/l PPO

→ 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 $\cos\theta_{Sun}>0.8$

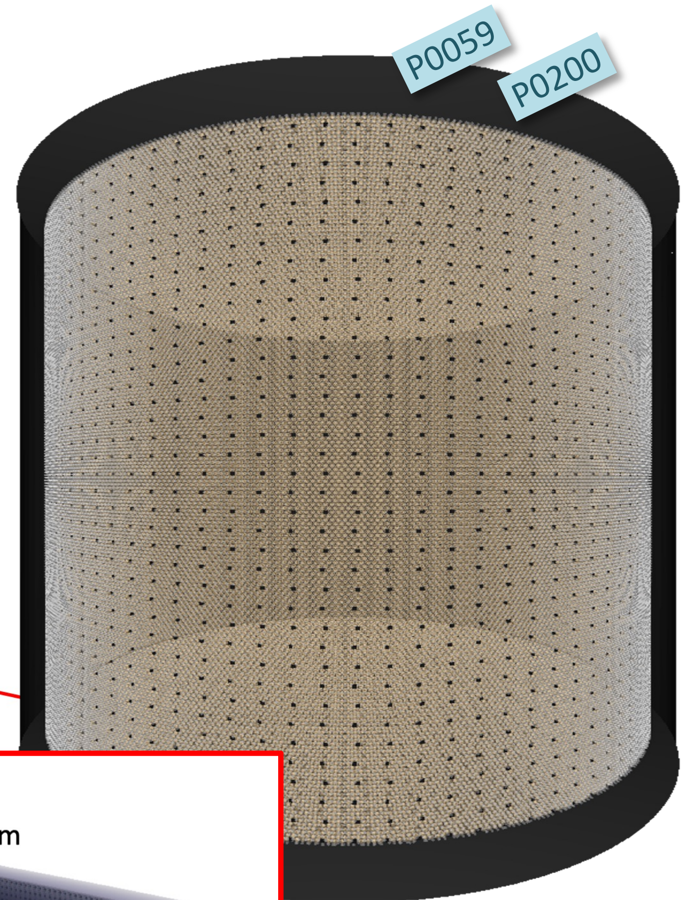
photo: BOREXINO calibration

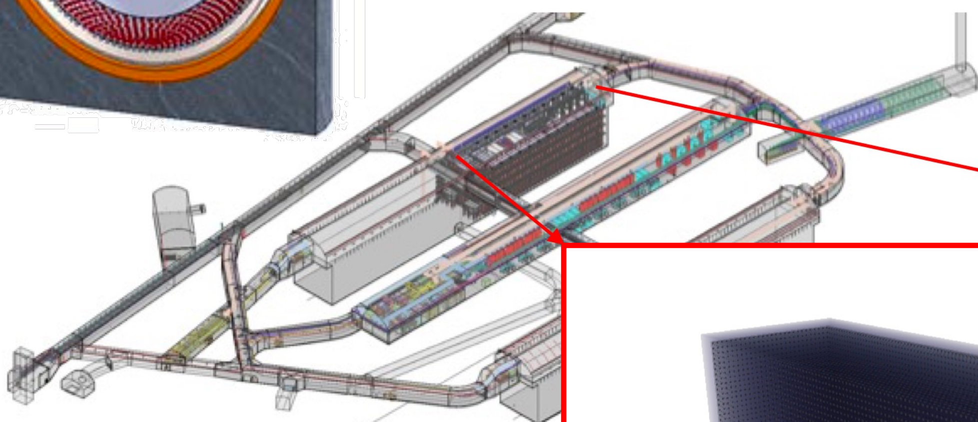
Future Large-Scale Hybrid Detectors

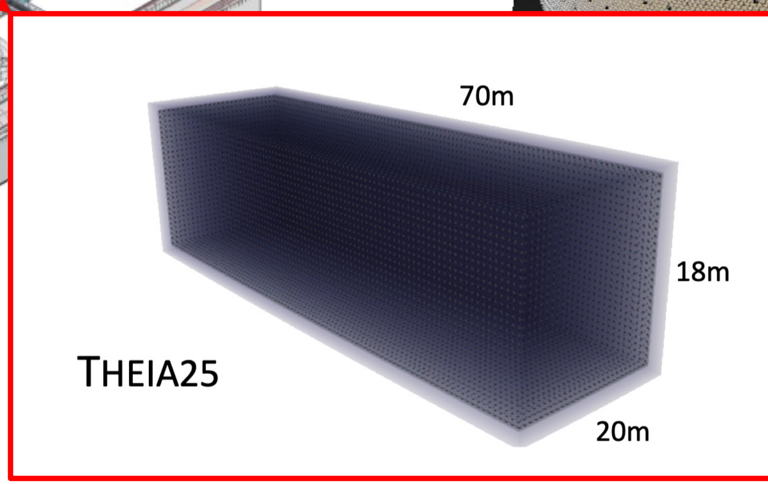


Jinping Neutrino Experiment

- 500t → 4kt
- slow scintillator
- Jinping lab >> excellent shielding





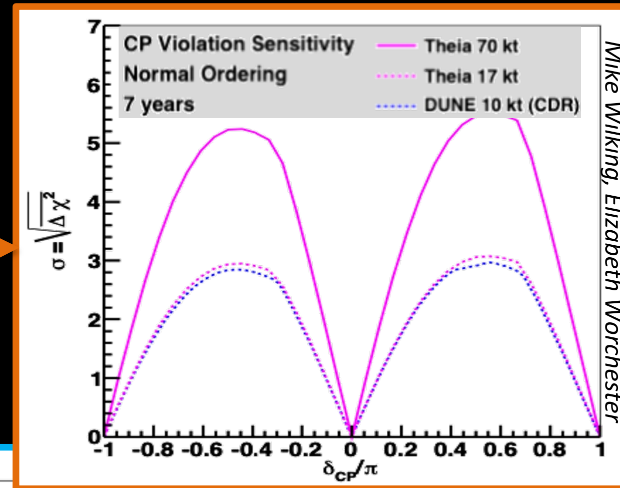


Theia

- 25kt/100kt
- water-based LS
- SURF >> LBNF
- several stages

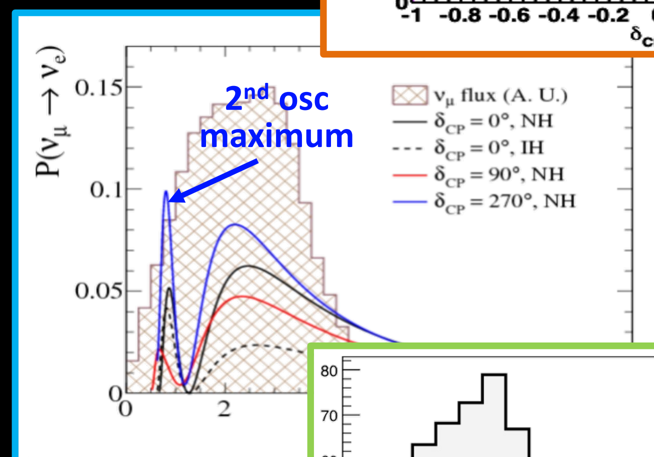
Hybrid Detectors for Long-Baseline Neutrinos

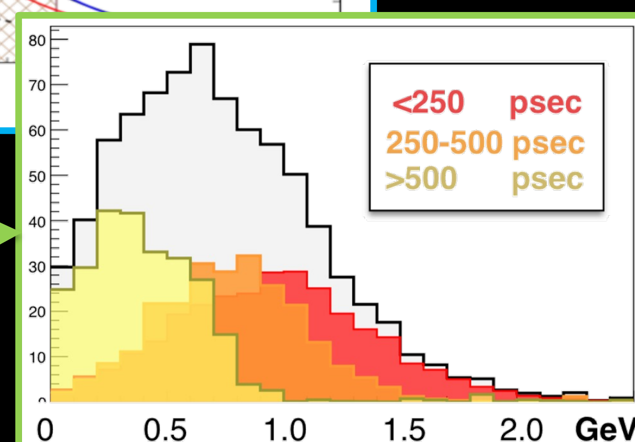
e.g. in context of **DUNE Module of Opportunity:** What would a **large WbLS detector** add to the existing liquid-argon modules?



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

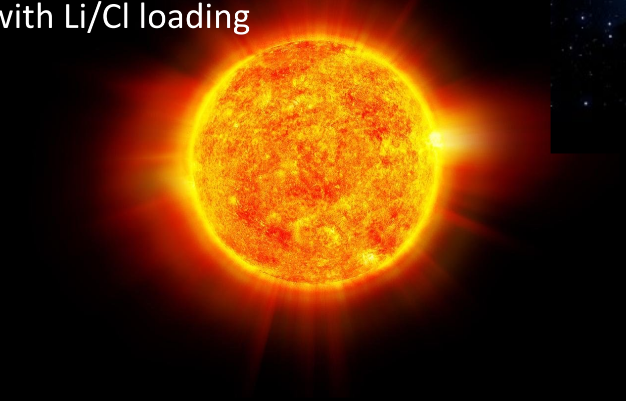




Astrophysical neutrinos at low energies

Supernova Neutrinos
high-statistics $\bar{\nu}_e$ signal
resolved detection channels
excellent pointing
pre-SN signal

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



Diffuse Supernova Neutrinos
C/S-based discrimination
of atmospheric NC events

Geoneutrinos
crust/mantle contribution
U/Th ratio

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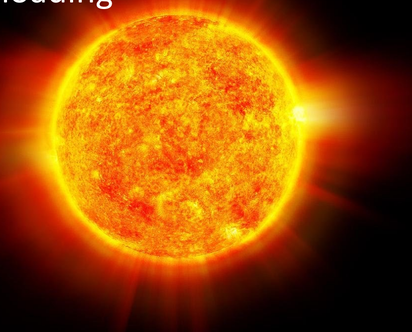
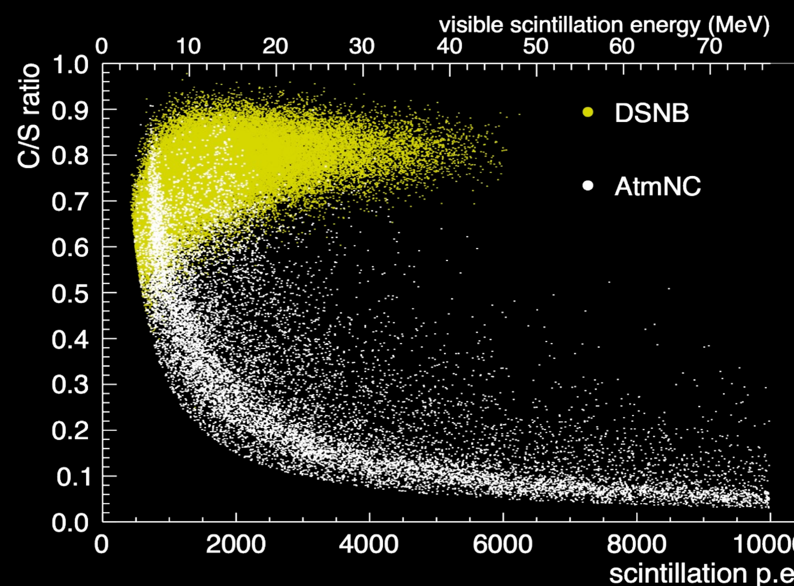


Diffuse Supernova Neutrinos
C/S-based discrimination
of atmospheric NC events

→ **excellent S:B ratio**



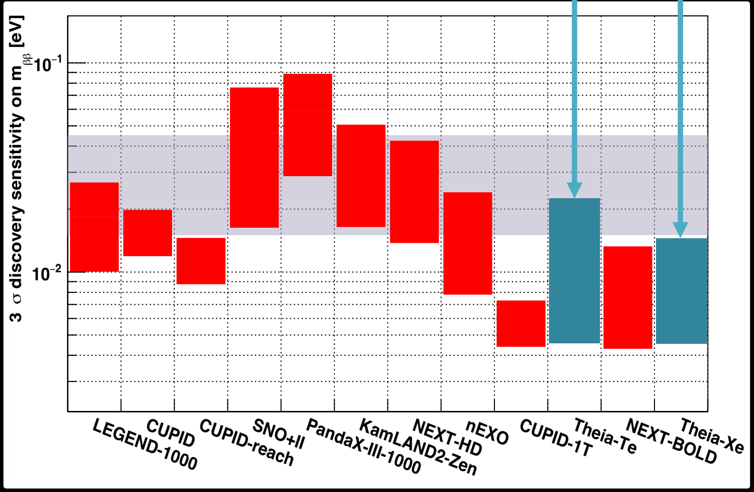
Geoneutrinos
crust/mantle contribution
U/Th ratio

Neutrinoless Double-Beta Decay

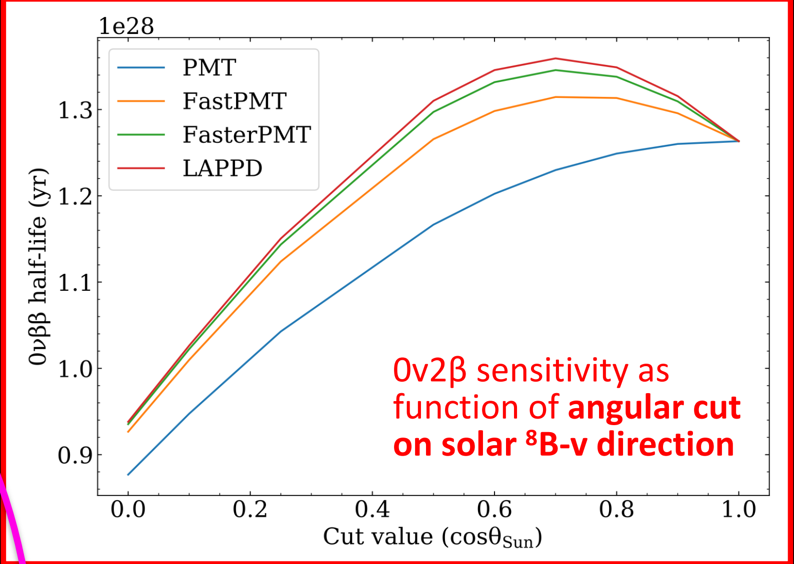
→ **Enhanced background discrimination**
- suppression of solar ^{8}B-ν background
- based on C/S ratio
  - ○ $e^+/e^-/\gamma$ discrimination
  - ○ potential $2\beta^-/2\beta^+$ signatures

→ sensitivity in large-scale detector can reach $m_{\beta\beta}$ in range of normal mass ordering

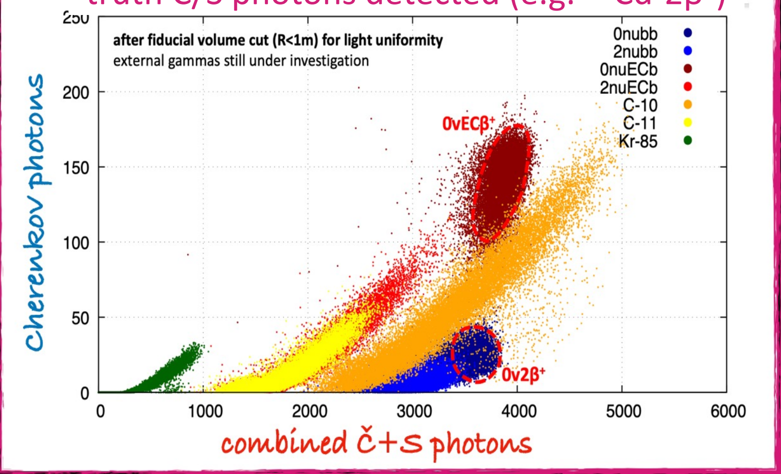
Sensitivity (90% CL) from spectral fit:
- **Te:** $T_{1/2} > 1.1\times10^{28}$ yrs, $m_{\beta\beta} < 6.3$ meV
- **Xe:** $T_{1/2} > 2.0\times10^{28}$ yrs, $m_{\beta\beta} < 5.6$ meV



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

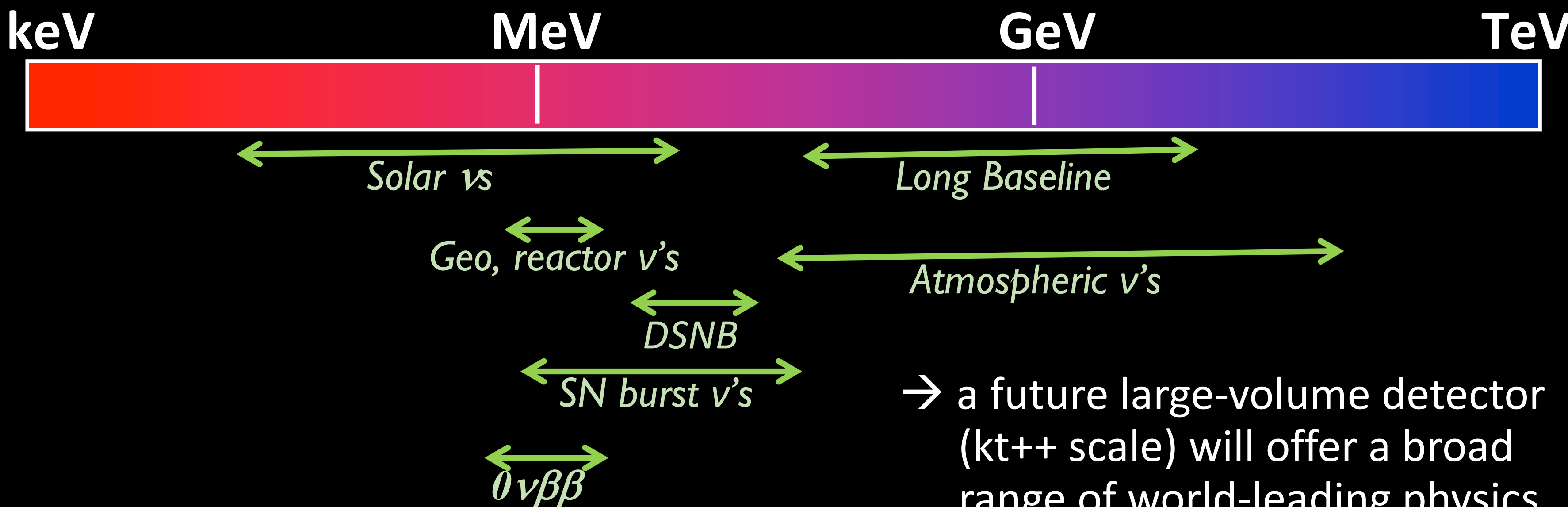


MC study: signal separation based on MC-truth C/S photons detected (e.g. ^{106}Cd-2β$^+$)



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

- with ANNIE, EOS and Jinping prototype, three ton-scale demonstrator experiments are either running or close to completion and provide first physics data
- data of existing scintillator neutrino experiments can be re-evaluated with hybrid detection methods to enhance physics reach