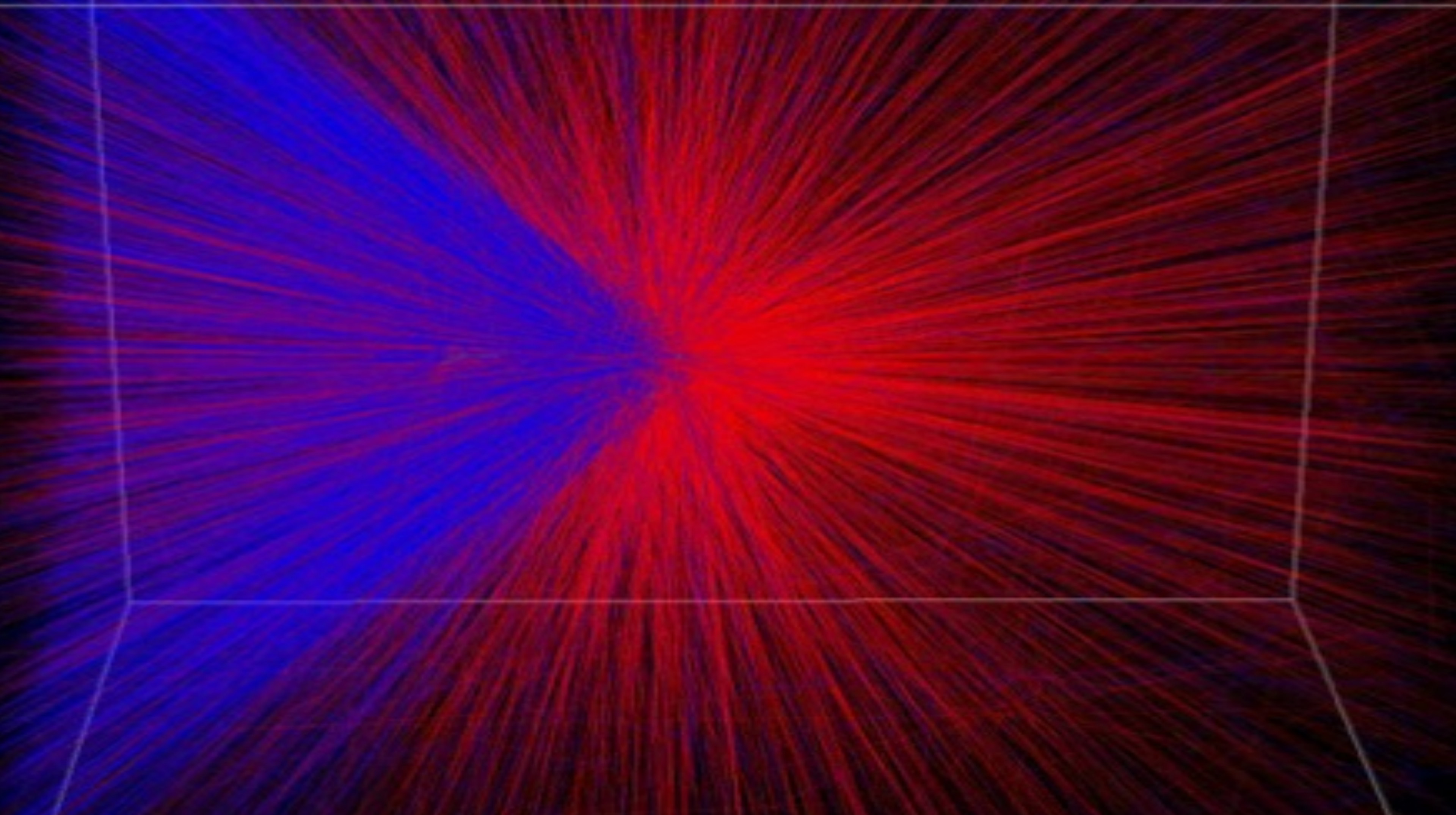
Neutrinoless Double-Beta Decay Sensitivity in Hybrid Detectors → THEIA



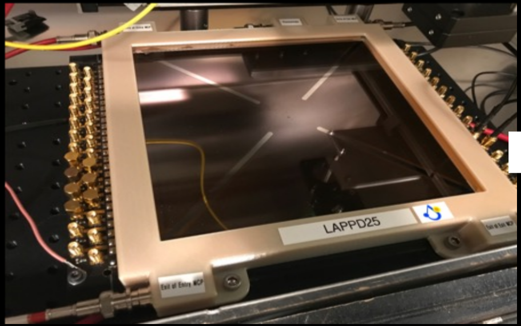
+++ DBD 2022 +++ Lisbon, June 7 +++ Michael Wurm (Mainz) +++

JG|U

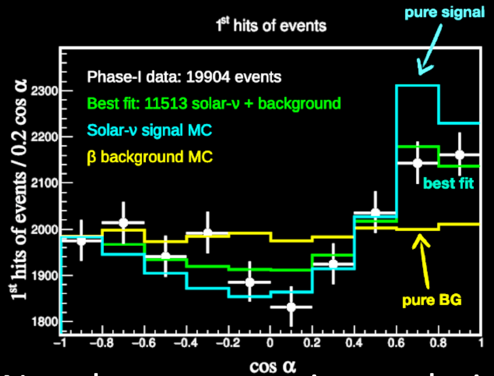
PRISMA

Hybrid Cherenkov/Scintillation Detectors

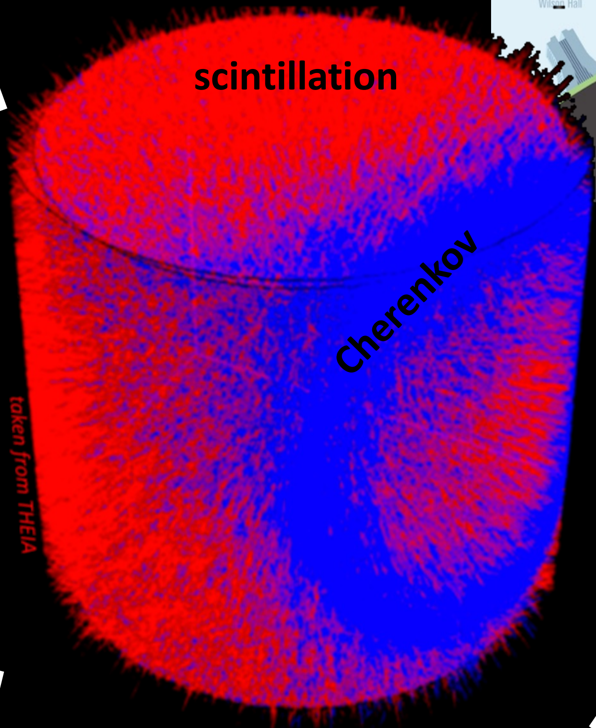
Novel target media:
Water-based/Slow Scintillator



Novel light sensors:
fast PMTs, LAPPDs, dichroicons

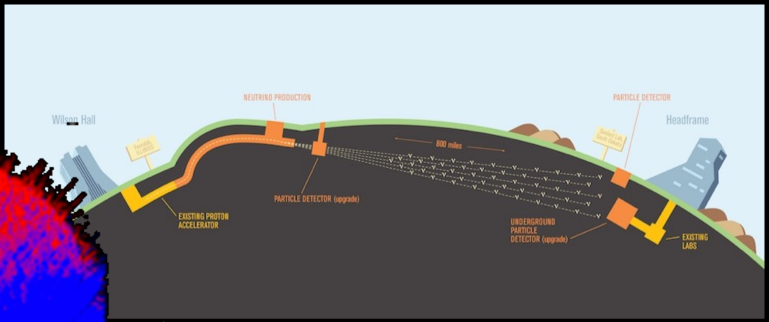


Novel reconstruction techniques



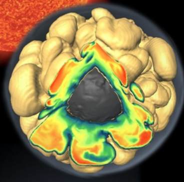
Large volume detector
able to exploit both
Cherenkov+Scintillation
signals

→ **Enhanced sensitivity to broad physics program**



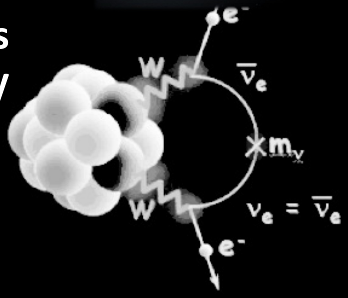
- Long-Baseline Oscillations
- Solar neutrinos

- Supernova neutrinos

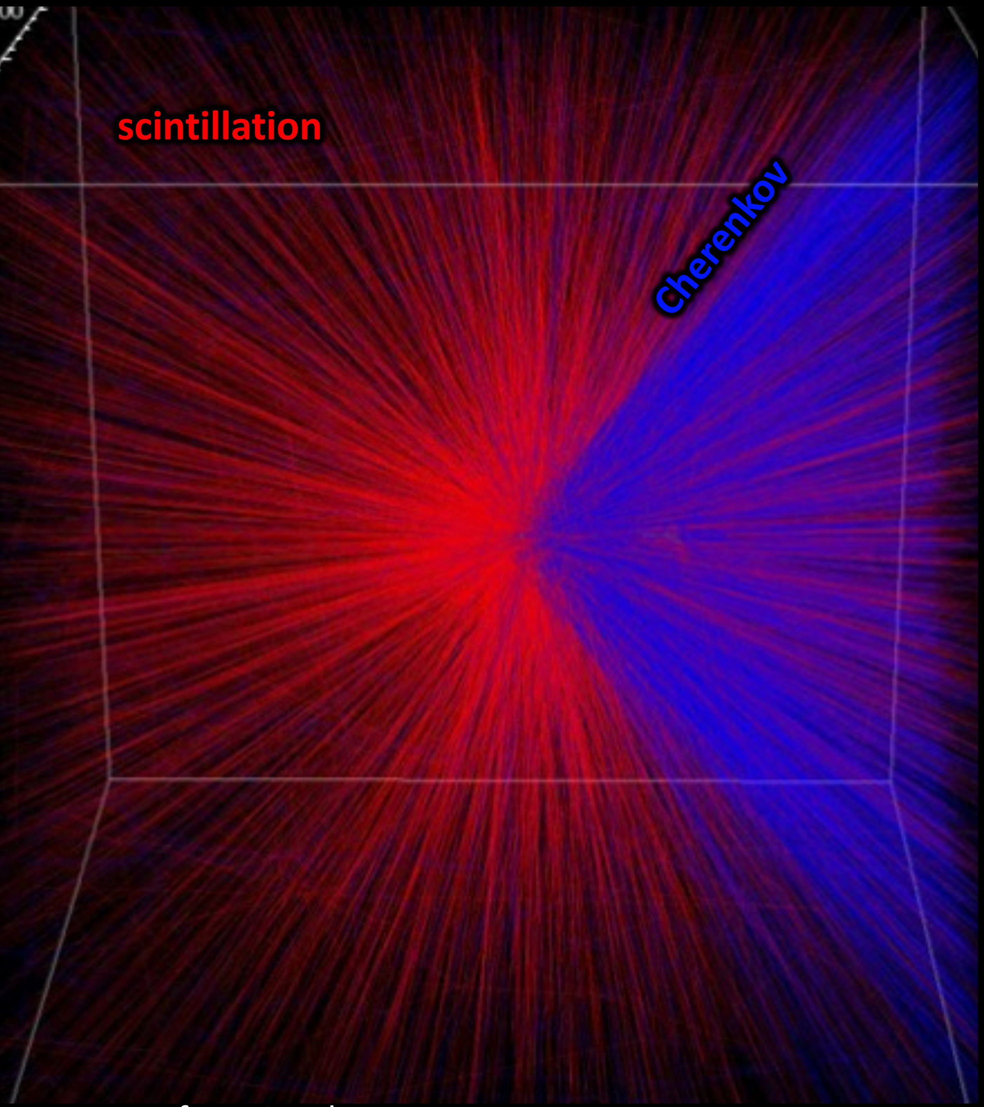


- Diffuse SN neutrinos

- **Neutrinoless Double-Beta Decay**



Hybrid detectors for ββ-decay



courtesy of Ben Land

A large-volume hybrid detector offers

→ like regular LS, **large ββ-isotope mass** can be dissolved in the detector liquid

→ **Scintillation:** good energy resolution, pulse shape discrimination

→ **Cherenkov effect:** (solar neutrino) background discrimination and number of final state particles

→ **C/S ratio:** particle ID

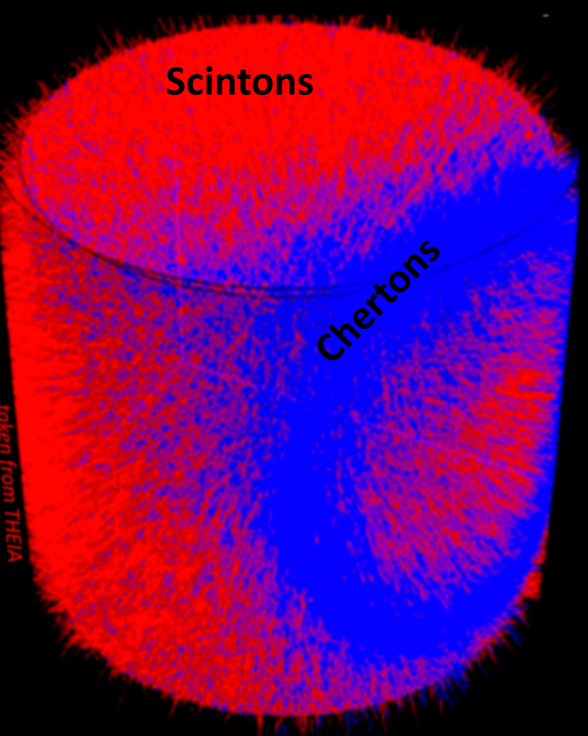
How to extract the Cherenkov signal from scintillation detectors?

→ enhance liquid transparency and/or

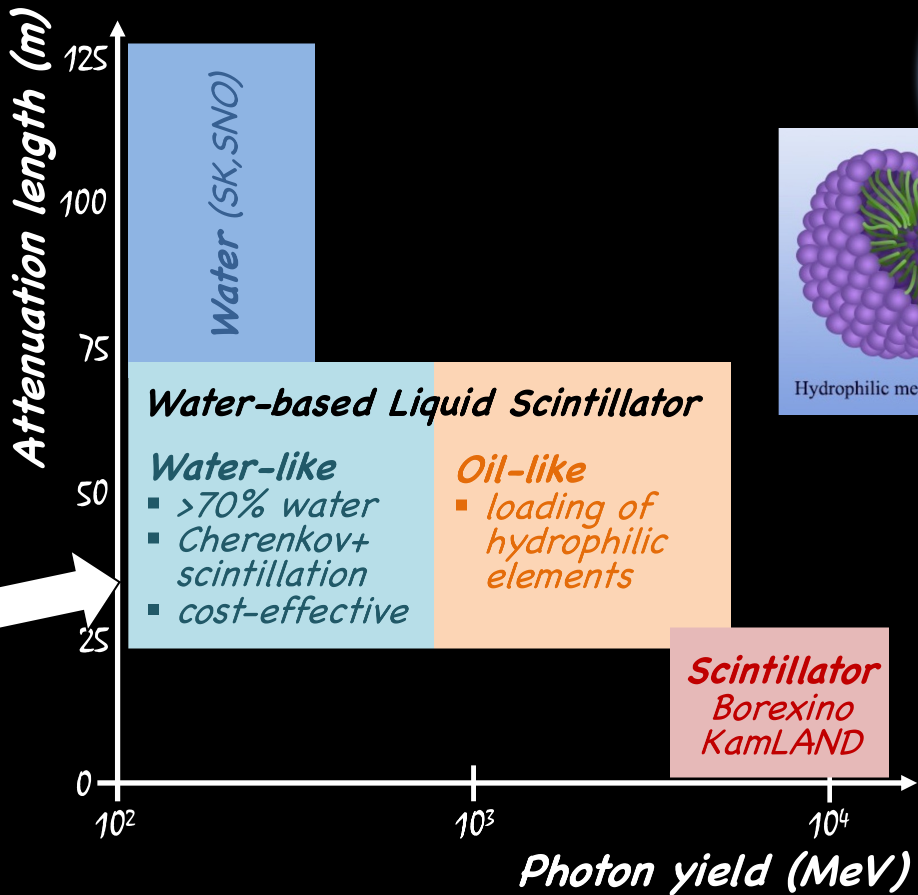
→ slow down scintillation emission

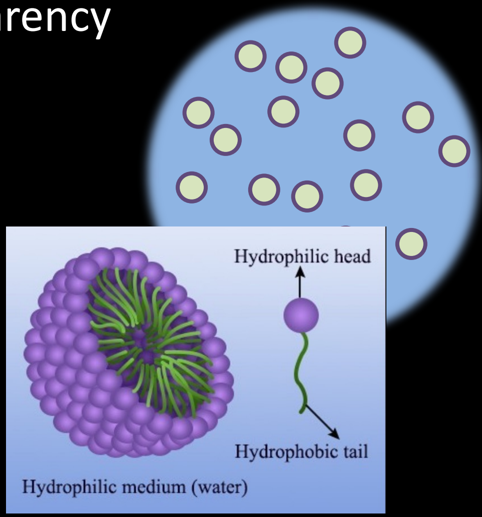
→ Cherenkov/scintillation (C/S) separation

Water-based liquid scintillators (WbLS)

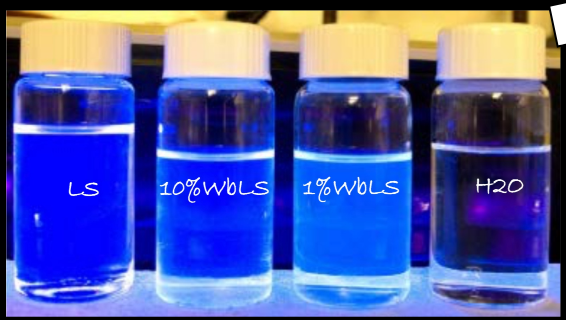


→ WbLS: water + tensid + solvent (LAB) + fluor (PPO)
→ low organic fraction → high transparency





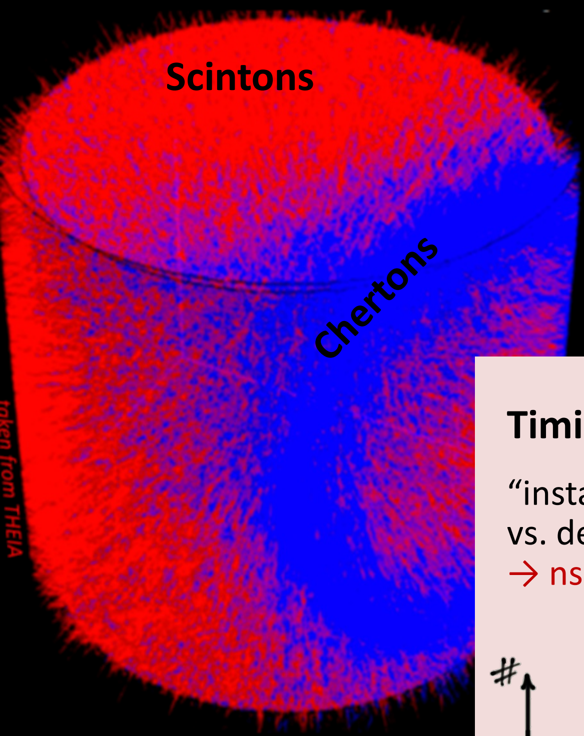
WbLS mycels



Minfang Yeh, BNL

→ for ββ searches, large (or pure) organic phase preferable
→ water content offers additional options for metal loading

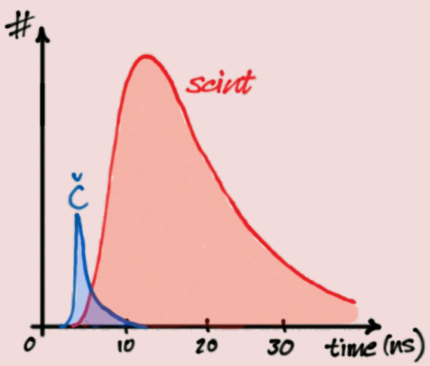
Separating Chertons and Scintons



→ how to resolve the Cherenkov/scintillation signals?

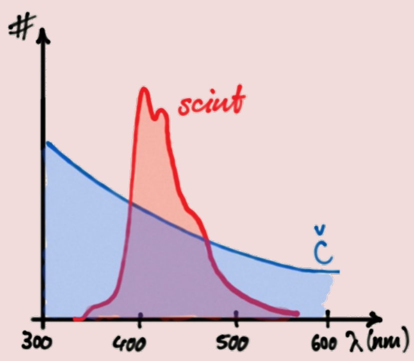
Timing

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



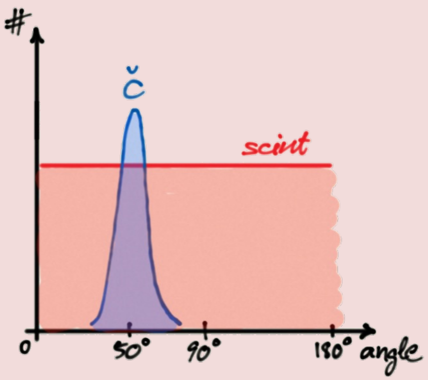
Spectrum

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

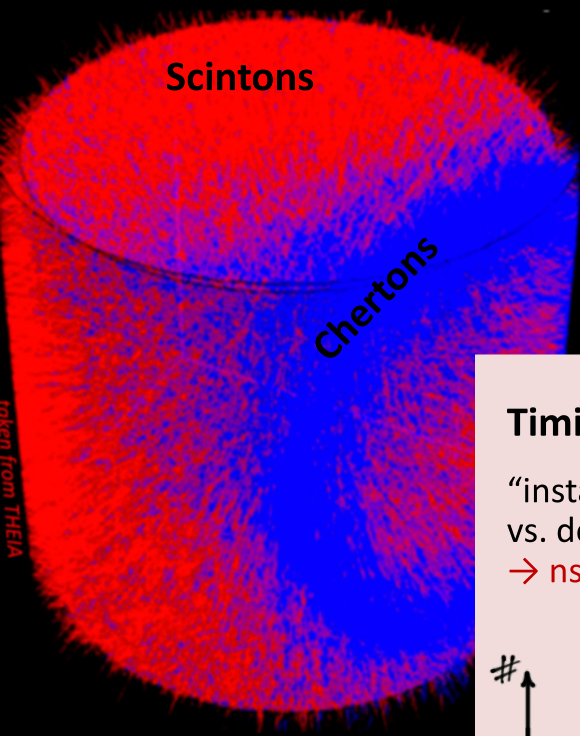


Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity



Separating Chertons and Scintons



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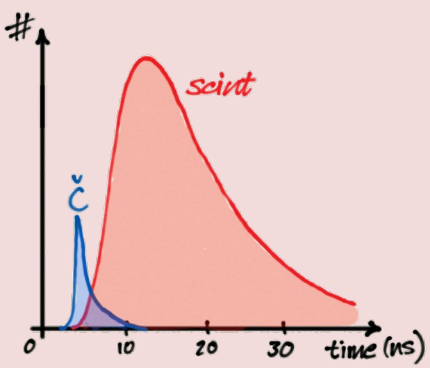
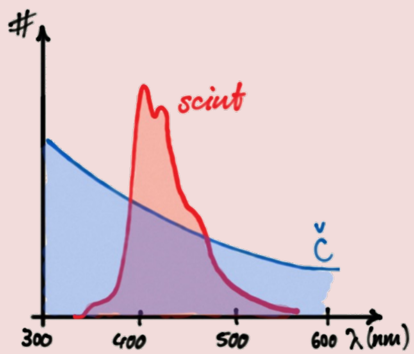


LAPPDs: ~60ps timing

Spectrum

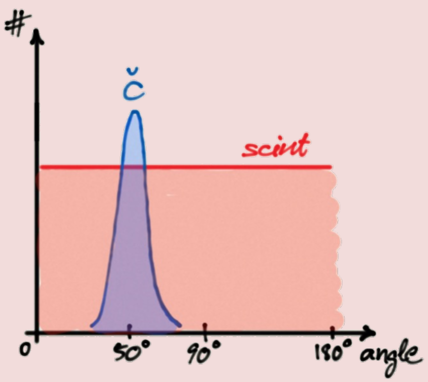
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity



Dichroic filters

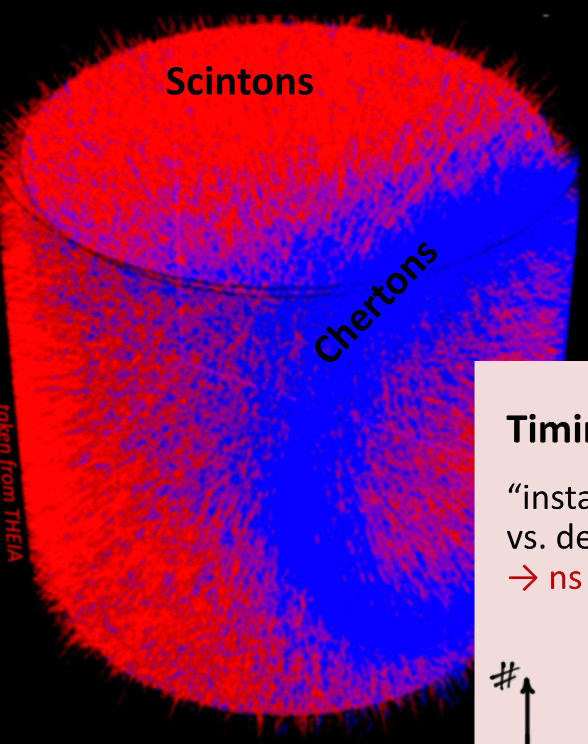
Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity



Standard PMTs

Separating Chertons and Scintons



→ how to resolve the Cherenkov/scintillation signals?

Timing

"instantaneous chertons" vs. delayed "scintons"
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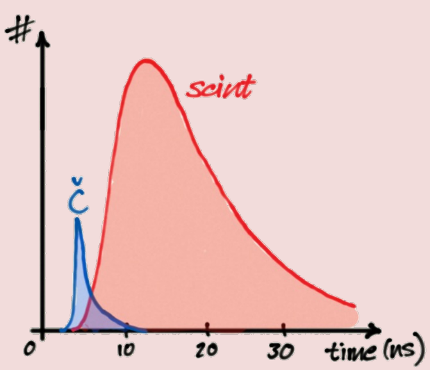
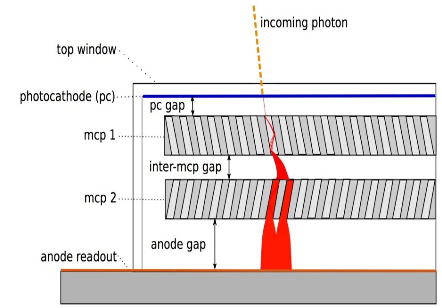
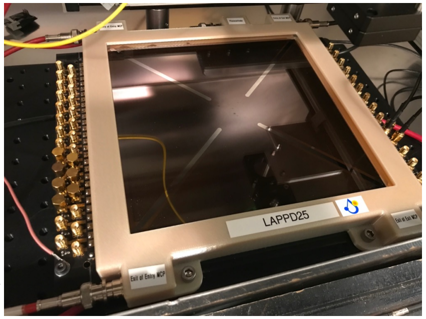


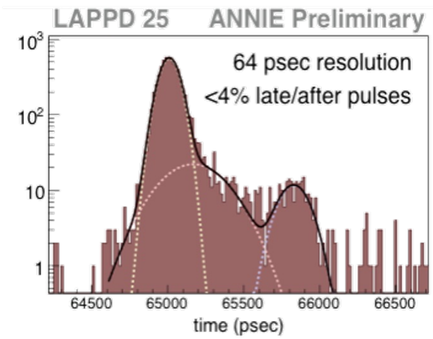
LAPPDs: ~60ps timing

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.

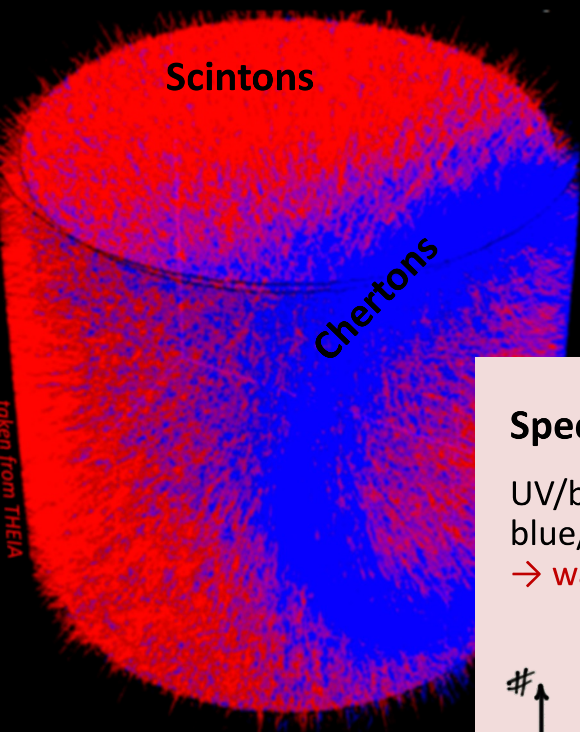


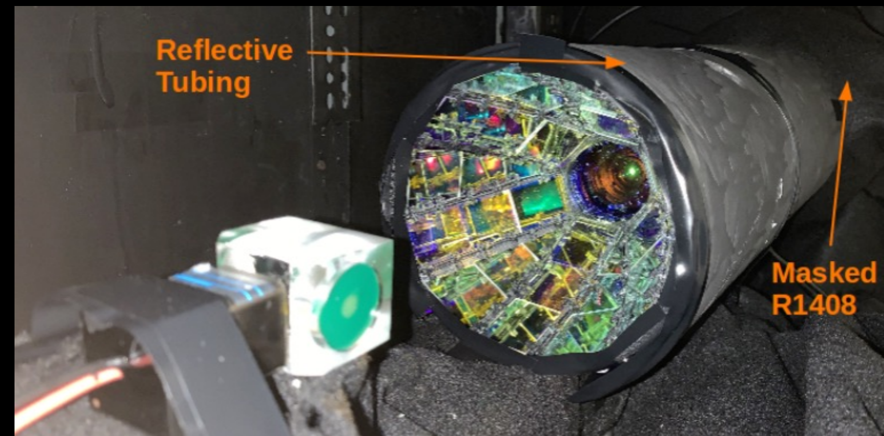




[arXiv:1909.10399]

Separating Chertons and Scintons





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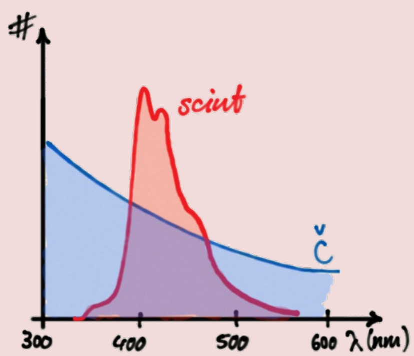
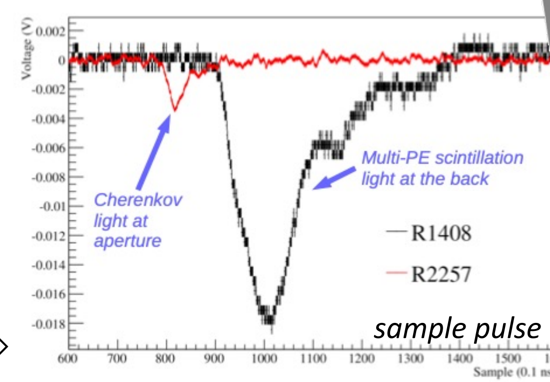
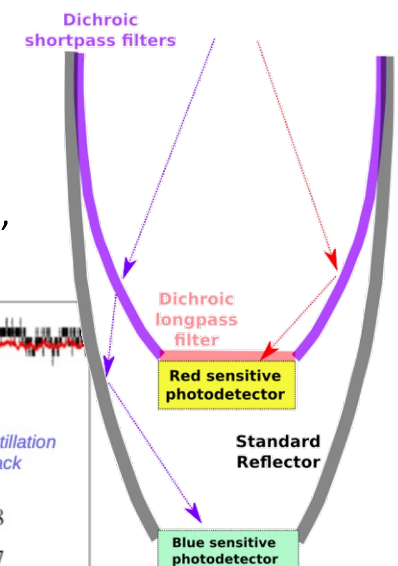


Dichroic filters

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**





Better suited: Slow Scintillators

Starting point: LAB + 2g/l PPO → τ~5ns
→ can be prolonged to facilitate C/S separation

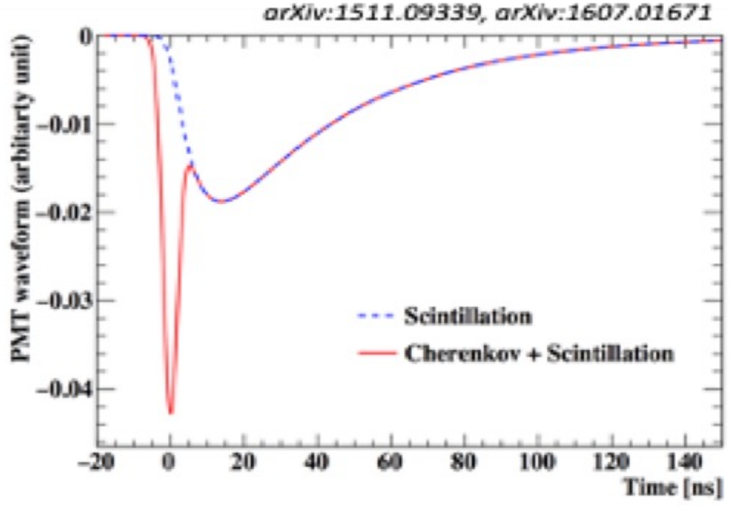
Options

- 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]

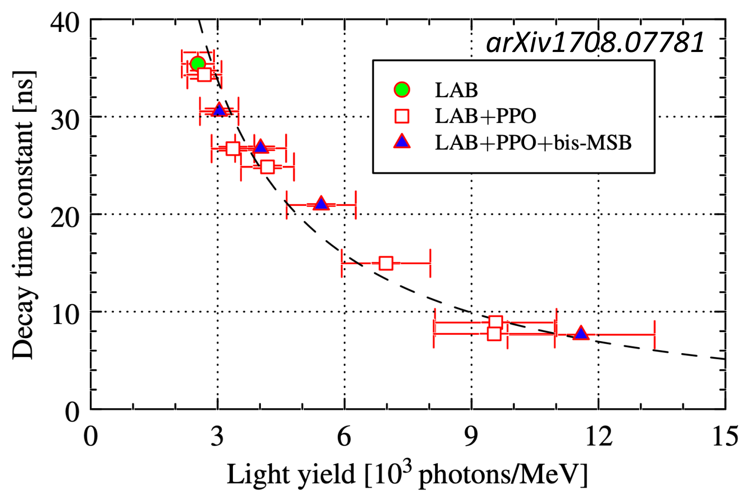
Consequences

- 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

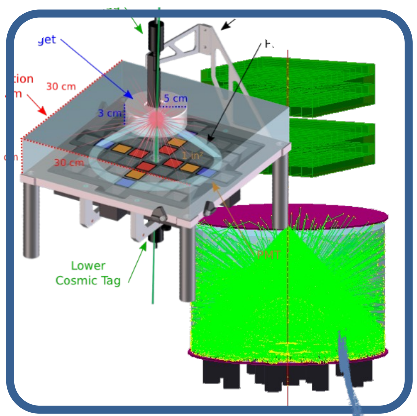


Decay time/LY vs. PPO concentration



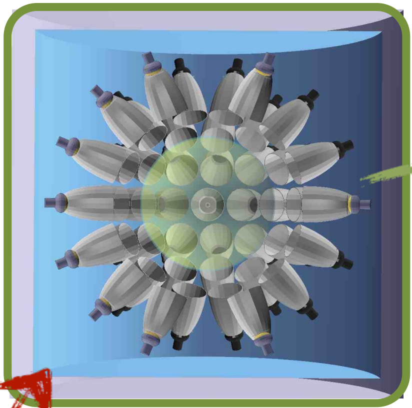
ββ Development Path for Hybrid Detectors

Lab-Scale Setups



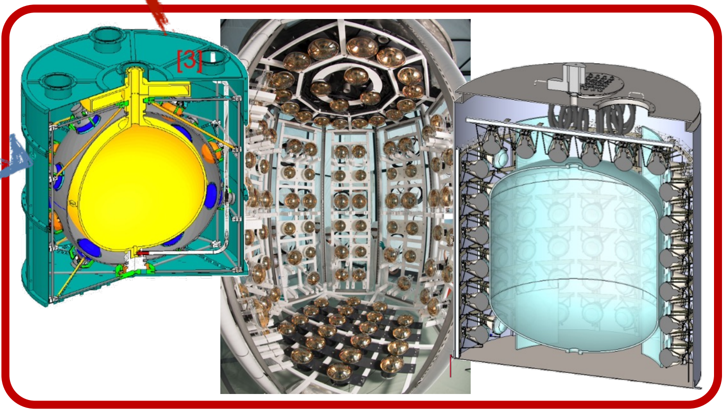
UCB: CHESS
Tsinghua U.
MZ: SCHLYP
MZ/TÜ: DISCO
...

JUNO
OSIRIS

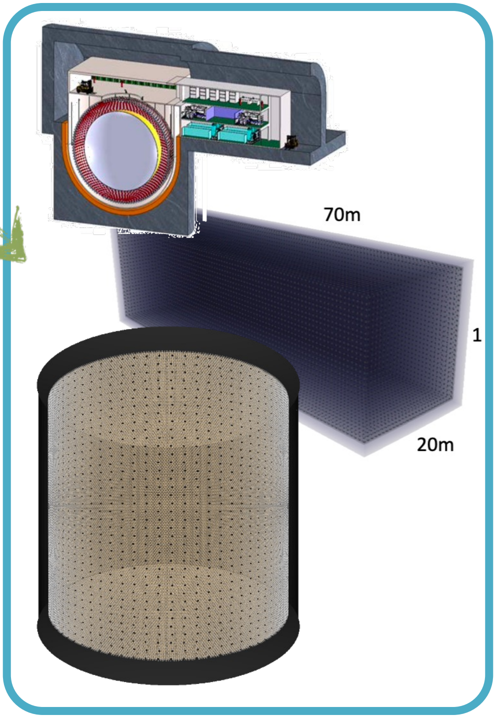


Mid-scale Setups: 2β^+ search?

Ton-Scale Demonstrators



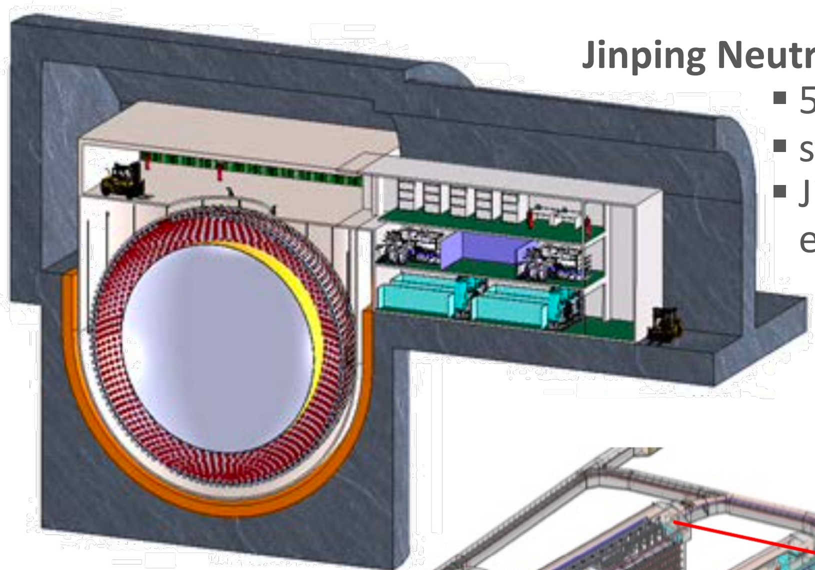
Jinping 1t
ANNIE/SANDI
EOS



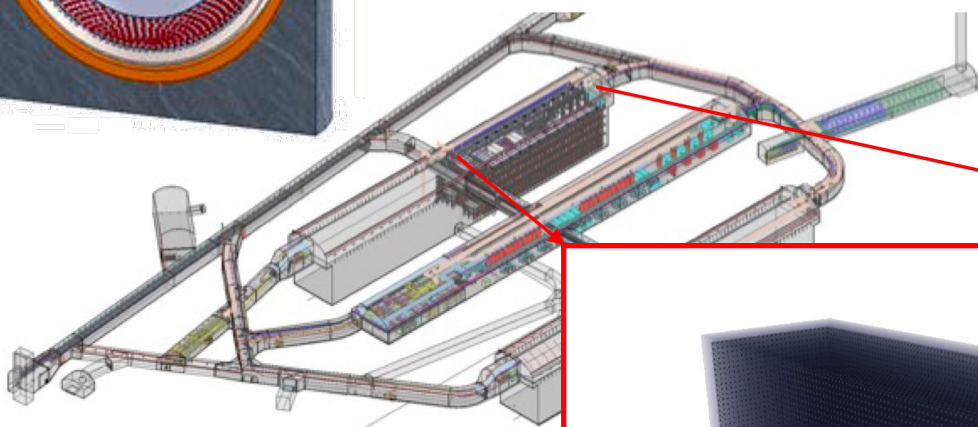
Future full-scale hybrid detectors

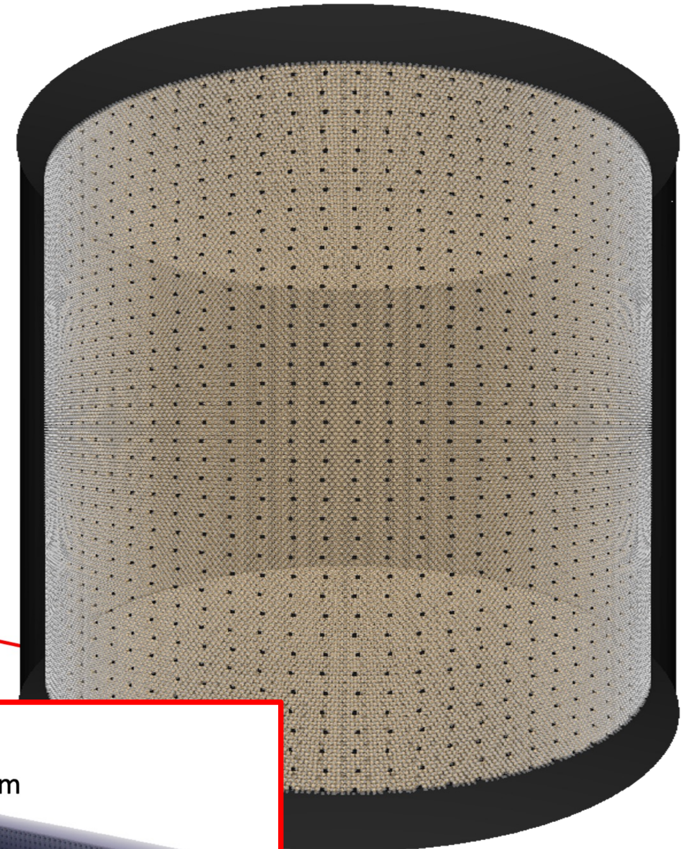
Jinping 500t
Theia 25/100

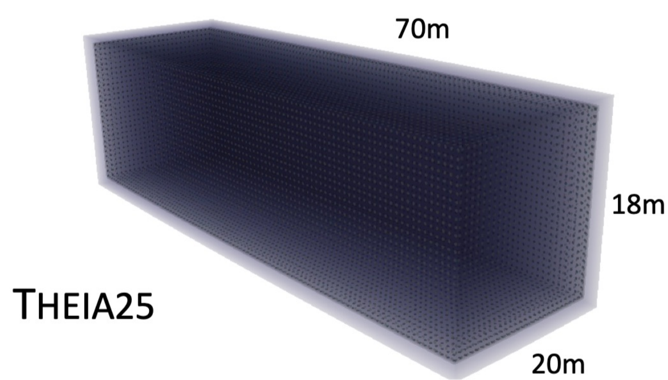
Future Large-Scale Hybrid Detectors



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



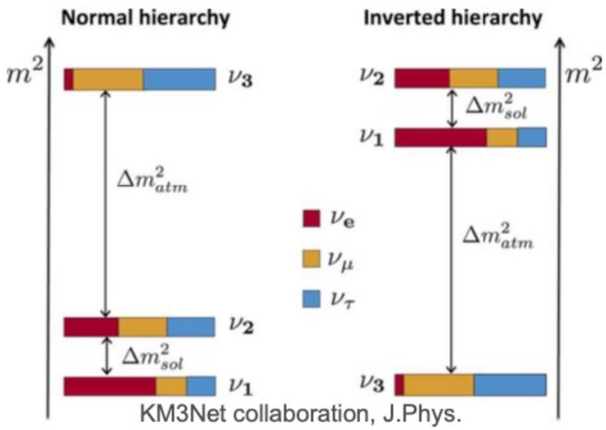




THEIA
- 25kt/100kt
- water-based LS
- SURF >> LBNF
- staged program

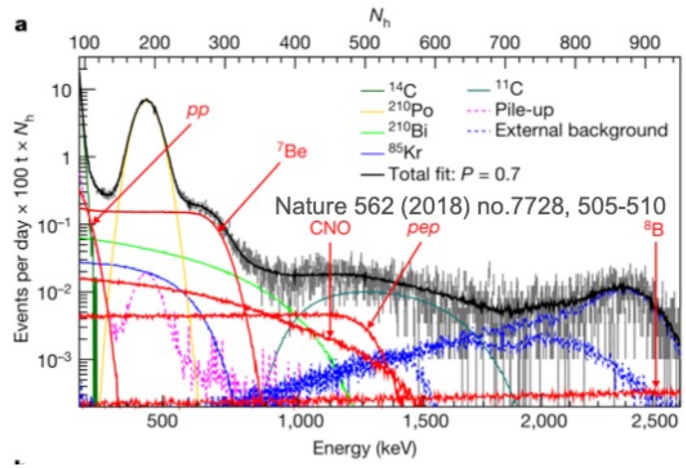
THEIA : Broad Physics Program

Long-baseline physics



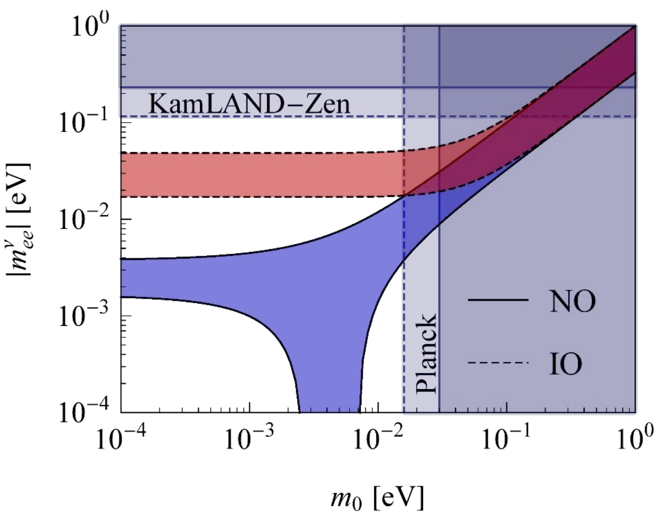
KM3Net collaboration, J.Phys. G43 (2016) no.8, 084001

Solar neutrinos

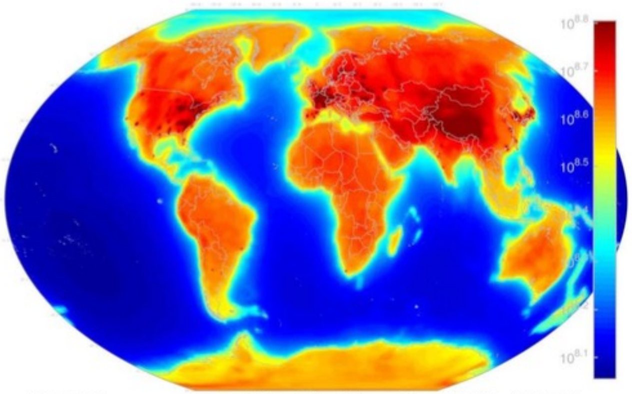


Supernova burst neutrinos & DSNB

Neutrinoless double beta decay

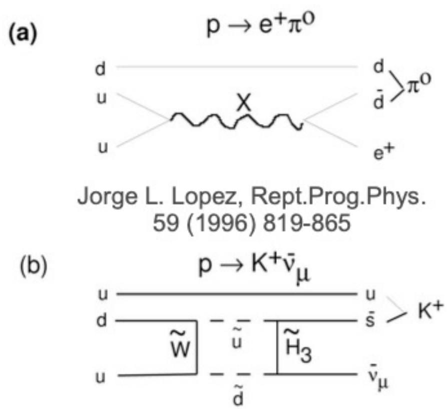


Geo-neutrinos



S.M. Usman, et al., Scientific Rep. 5, 13945 (2015)

Nucleon decay



and more ...

slide by Björn Wonsak

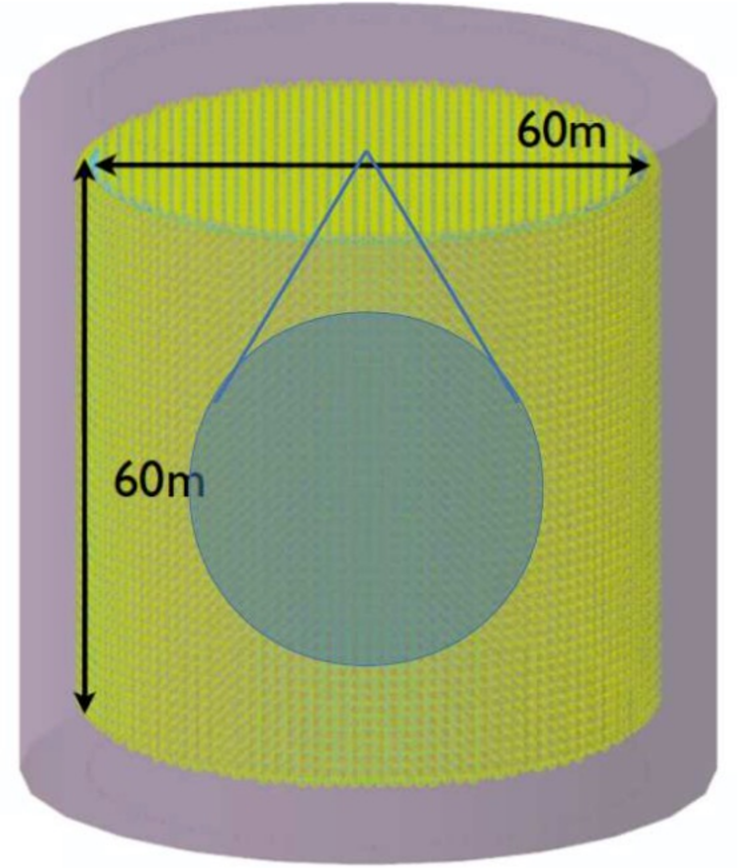
THEIA : ββ-Phase

Default Scenario

KamLAND-Zen style setup with central vessel, separating high light yield (slow-ish?) scintillator with ββ-isotope from surrounding veto volume

Basic assumptions

- balloon/acrylic vessel with 8m radius
- LAB-based scintillator with 2g/l PPO (τ~5ns)
- isotope loading
  - 3% enriched xenon (89.5% in ^{136}Xe, 49.5t)
  - 5% natural tellurium (34.1% in ^{130}Te, 31.4t)
- outside: WbLS with 10% organic fraction
- overburden of SURF: 4300 mwe
- PMT coverage: 90%
  → Light Yield: ~1200 p.e./MeV
  → energy resolution: ~3% at 1 MeV



[arXiv:1911.03501]

THEIA : ββ Background Levels

Background assumptions

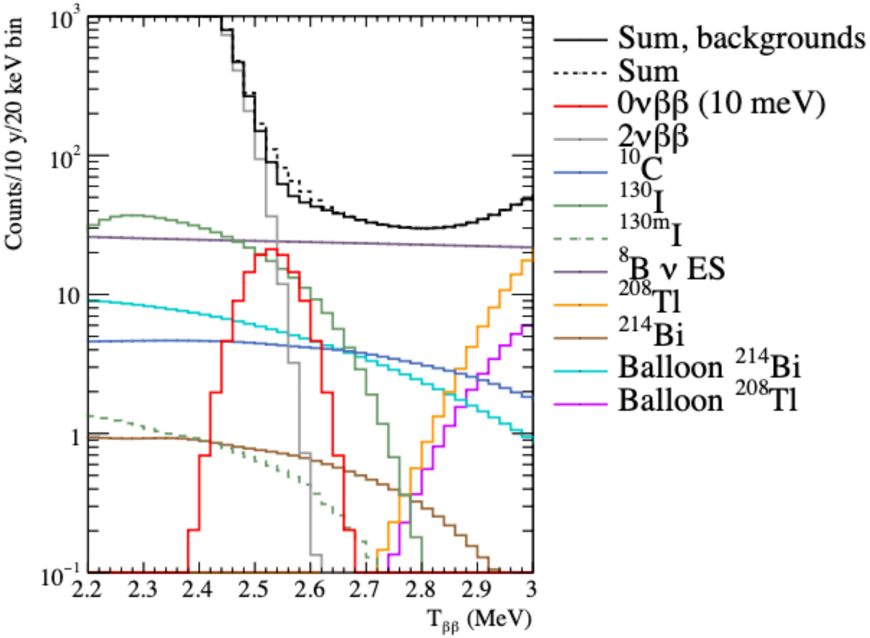
- PID or directionality used to remove 50% of **solar ^{8}B neutrino** events
- **cosmogenic ^{10}C** reduced by 92.5% with threefold coincidence tagging (Bx)
- **activation of ββ isotope** by solar ν's CC but no cosmogenic activiation
- **2ν2β:** asymmetric ROI of [-0.5σ;2σ]
- **LS radiopurity** like Borexino Phase I
- Bi-Po tagging with 99.9% efficiency (to remove ^{214}Bi/^{208}Tl)
- **vessel radiopurity** like KamLAND, fiducial volume with R<7m

	Expected event rates [yr^{-1}]		
Source	**total**	**ROI-Te**	**ROI-Xe**
Solar ^{8}B	500	2.5	2.5
Cosmogenic ^{10}C	2950	13.8	13.8
Te: ^{130}I	155	8.3	
2ν2β	1.2e8	8.0	
Xe: ^{136}Cs	478		0.06
2ν2β	7.1e7		3.8
LS: 1e-17 g/g U	7300	0.4	0.4
1e-17 g/g Th	870	-	-
Nylon Vessel			
1.1e-12 g/g U	1.2e5	2.4	2.7
1.6e-12 g/g Th	2.1e4	0.03	0.01
Total BG-Index [$(t\cdot yr)^{-1}$]		1.1	0.5

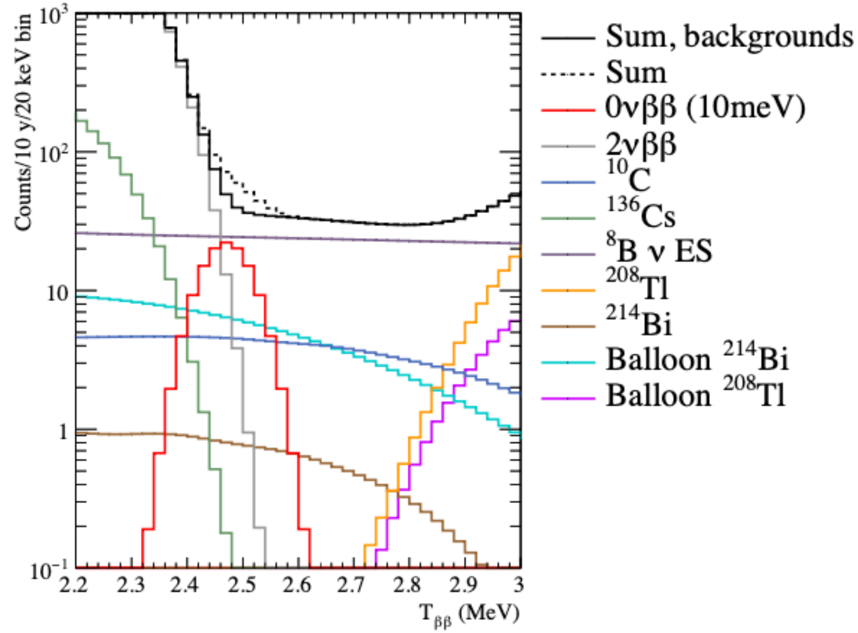
[arXiv:1911.03501

THEIA : Expected ββ Endpoint Spectra

5% ^{nat}Te



3% ^{enr}Xe



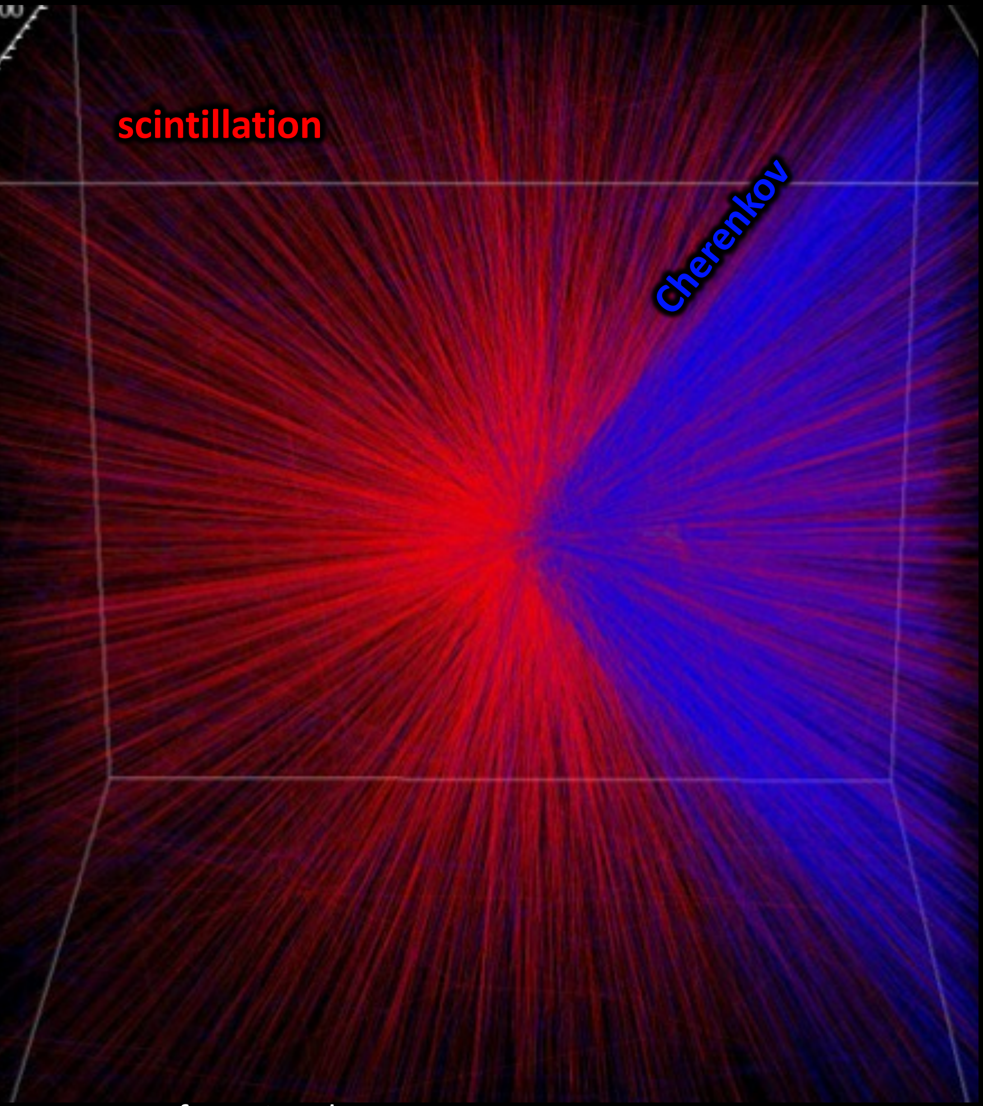
sensitivity based on counting analysis (90% C.L.)

$$\mathbf{Te}: \quad T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{28}\ \mathrm{y}, \ m_{\beta\beta} < 6.3\ \mathrm{meV}$$

$$\mathbf{Xe}: \quad T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{28}\ \mathrm{y}, \ m_{\beta\beta} < 5.6\ \mathrm{meV}$$

[arXiv:1911.03501

Added Value of Hybrid Detectors



courtesy of Ben Land

How to improve beyond the baseline scenario?

Goal: Background discrimination surpassing standard LS detectors

→ **directional reconstruction** to remove solar ^{8}B ν background

→ **two-ring event topology** to provide clear signature of $2\beta^{-}$ decays (discovery)

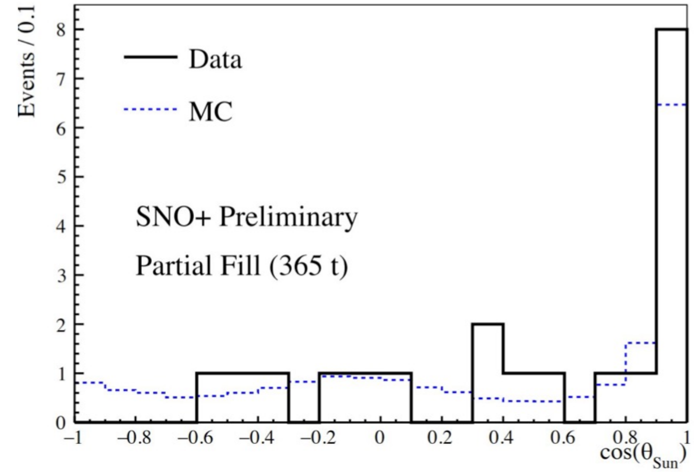
→ **Cherenkov/scintillation ratio** to distinguish e^{-}-γ-e^{+}-$2e^{+}$ events

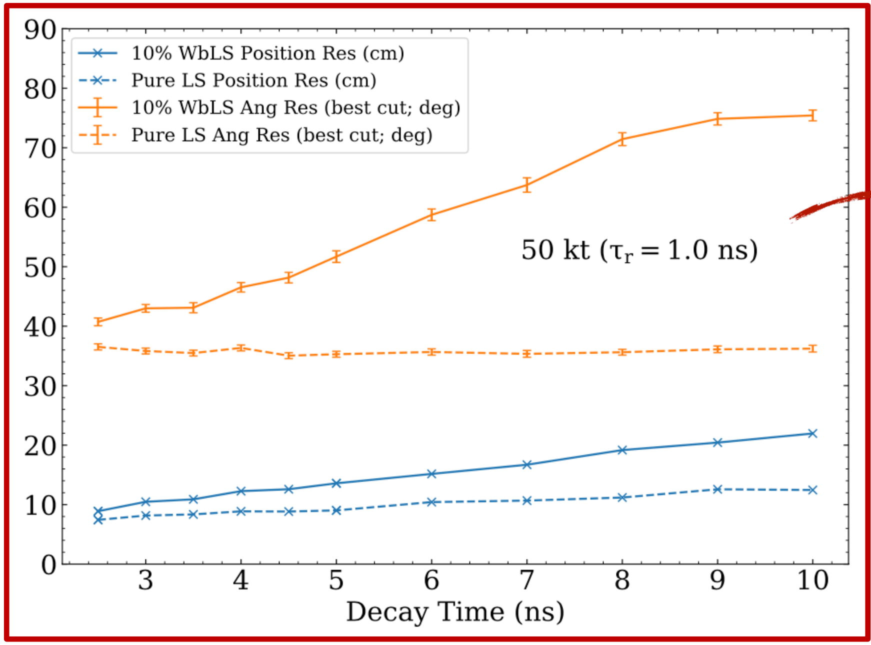
i) solar ^{8}B Directional Cut

LAB+PPO comparatively slow scintillator

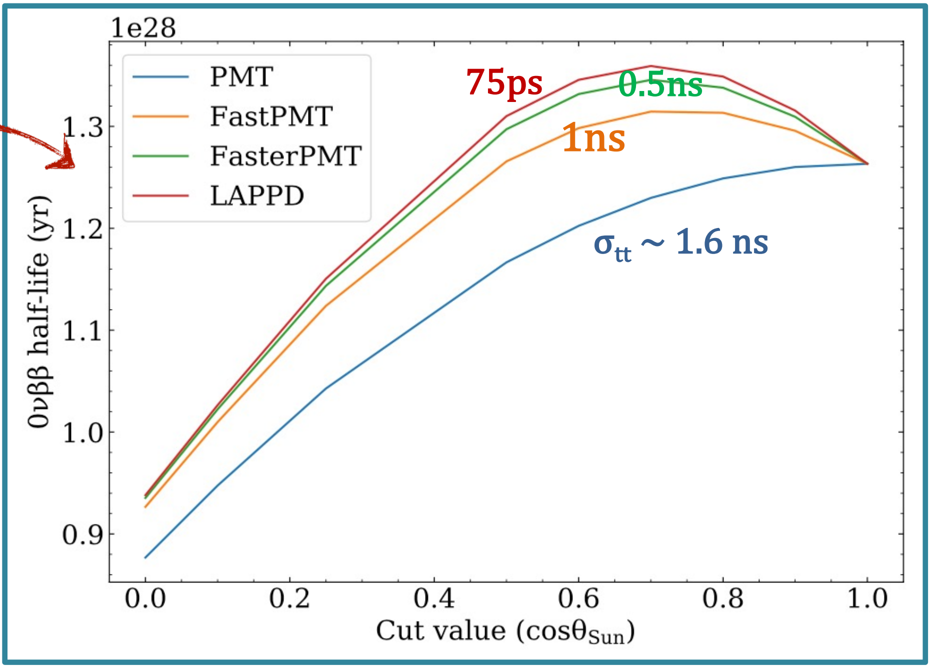
- Cherenkov signature can be used for directional reconstruction of ^{8}B solar ν's
- MC studies suggest that at low energies, slow-ish oLS (τ~5ns) performs better than WbLS

cf. Recent SNO⁺ Result
LAB + 0.6g/l PPO
40% with cosθ>0.8





MC study on low-E angular resolution vs. LS decay time
LAPPD-like time resolution: **LAB-LS outperforms WbLS**



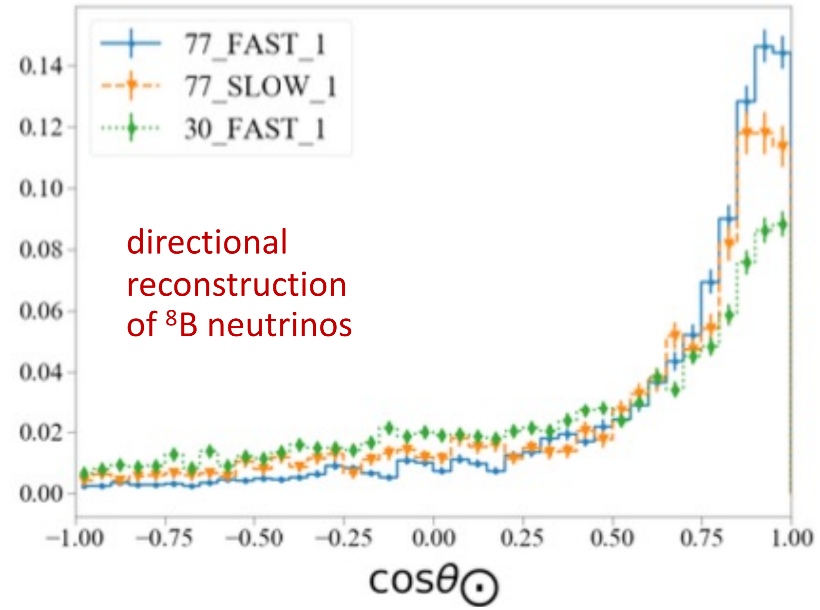
resulting 0ν2β sensitivity → PMT $\sigma_{tt} \leq 1$ns!

[arXiv:2007.14999]

i) Further Improvement with Slow LS?

- study assumes slow LS based on LAB + 4 g/l acenapthene (+ 1mg/l Bis-MSB)
  → decay time of 45 ns
- different configurations studied, good performance found for large coverage (77%) and/or fast PMTs (1ns)

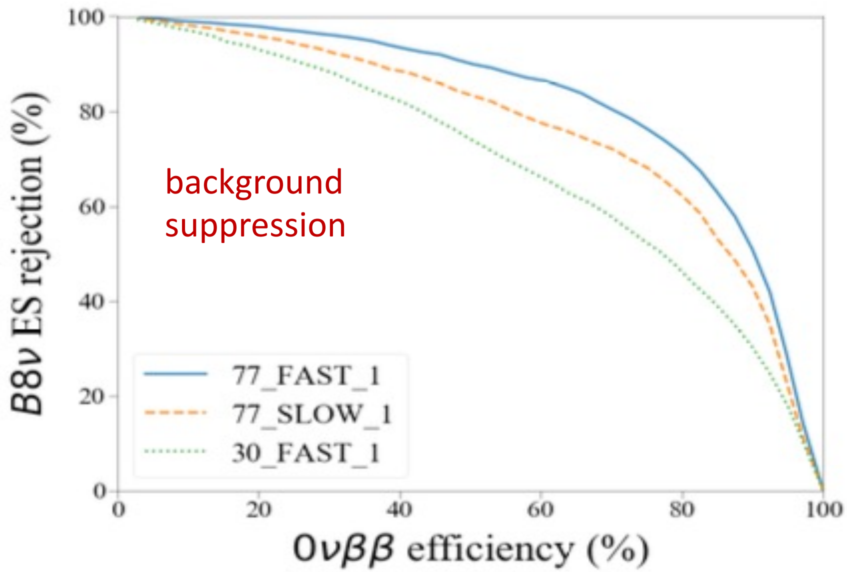
→ for low energies, slow LS probably better choice than fast scintillators



directional reconstruction of ^{8}B neutrinos

detector configurations studied:

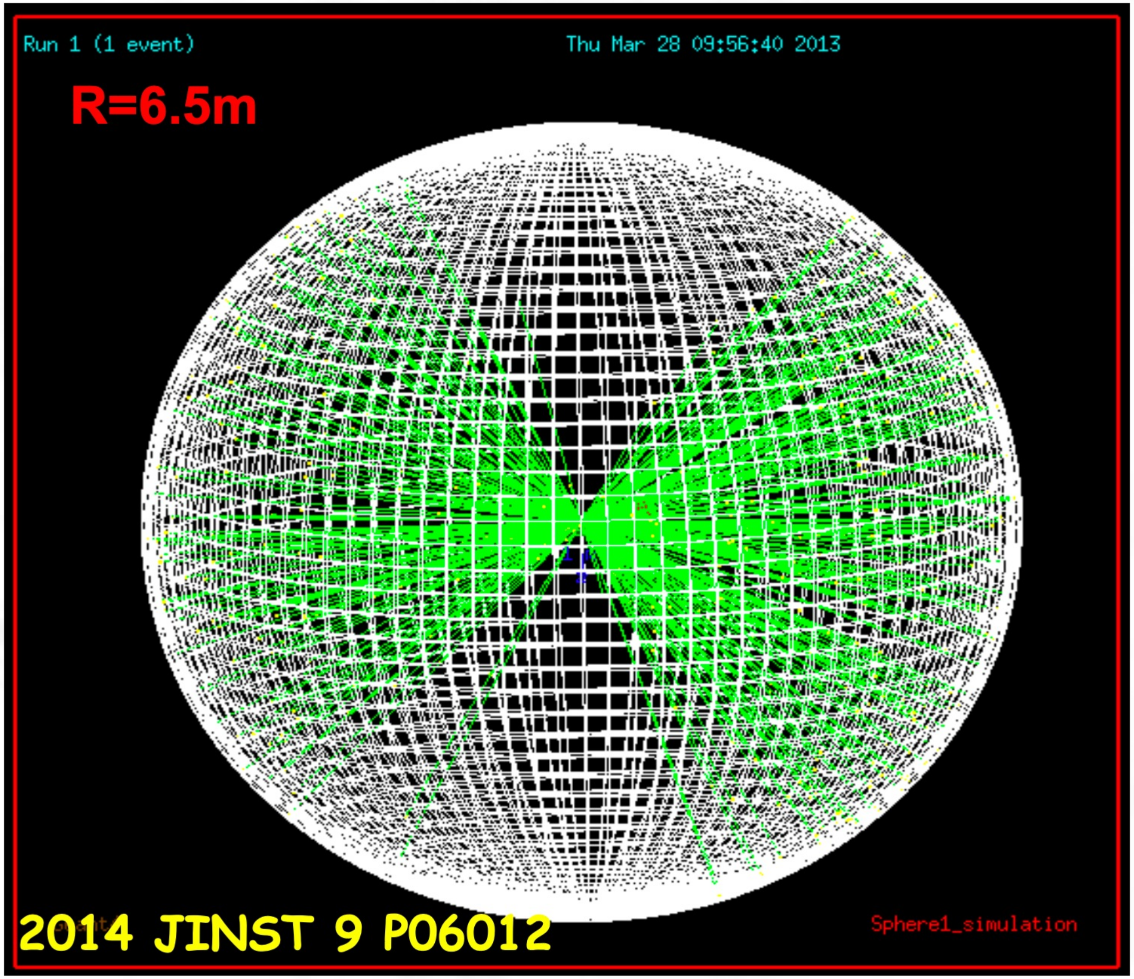
Acronym	% Photocathode coverage	PMT TTS (ns)	bis-MSB (mg/L)	Resulting pe/MeV
77_FAST_1	77	1	1	1000
77_SLOW_1	77	3.7	1	1000
77_SLOW_0	77	3.7	0	500
30_FAST_1	30	1	1	400
30_SLOW_1	30	3.7	1	400
30_FAST_0	30	1	0	200
30_SLOW_0	30	3.7	0	200



background suppression

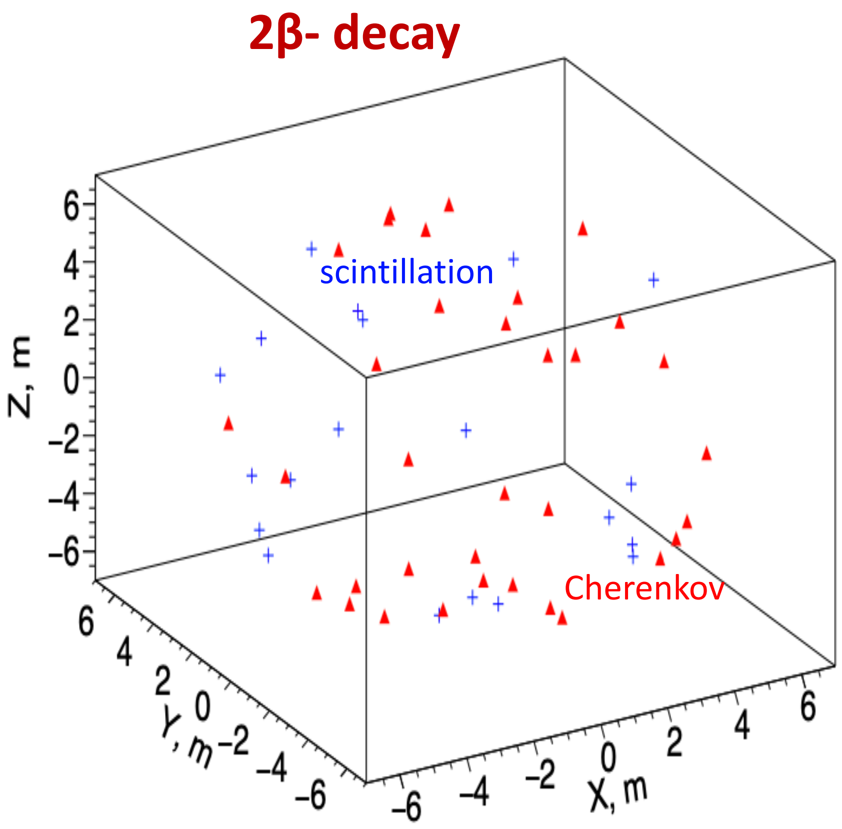
[arXiv:2203.01147]

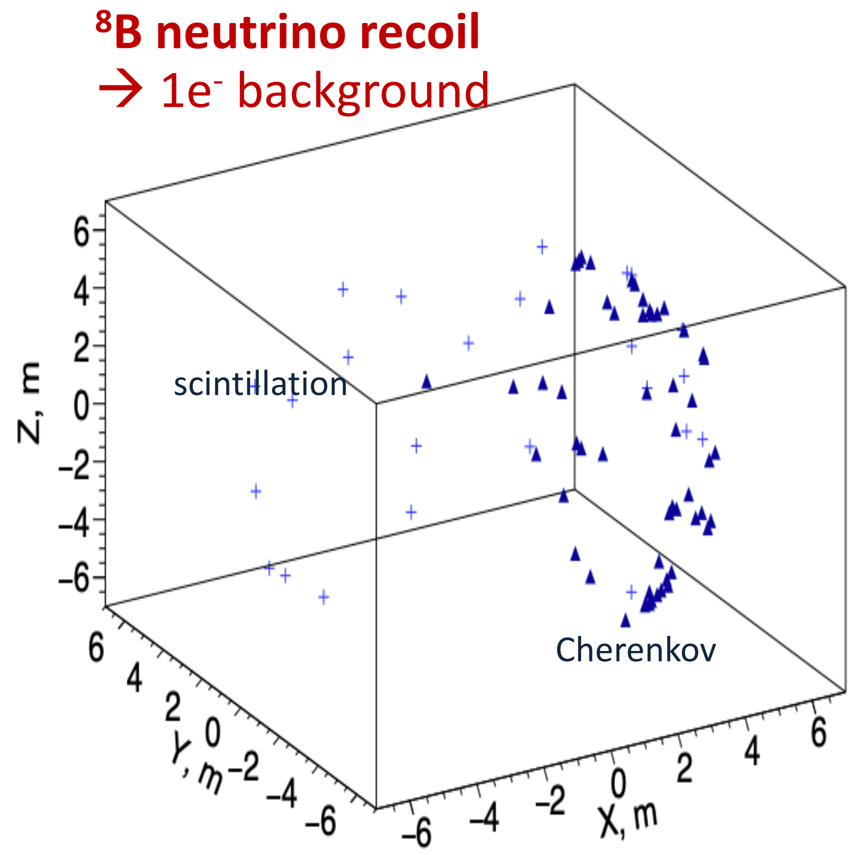
ii) Event Topology with C/S signal



Is there a chance to detect double Cherenkov cone signature from 2β⁻ decays?

ii) Study on 2β⁻/⁸B Recoil Discrimination





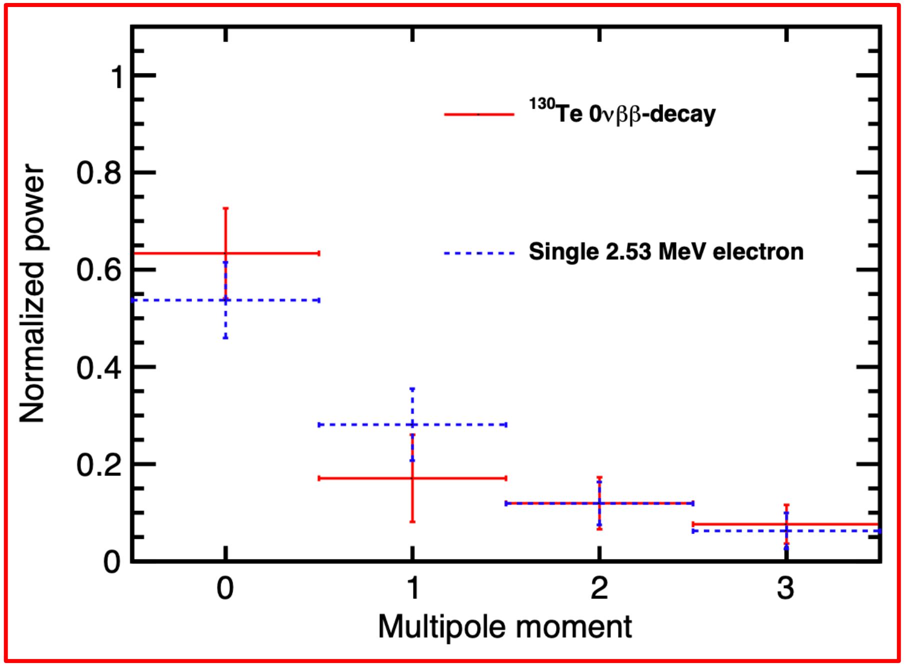
- restrict analysis to early hits
- search for level of asymmetry in the hit pattern
  →analysis based on spherical harmonics

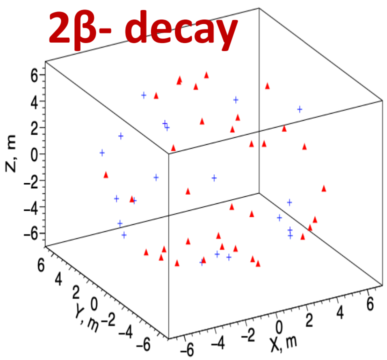
[arXiv:1609.09865]

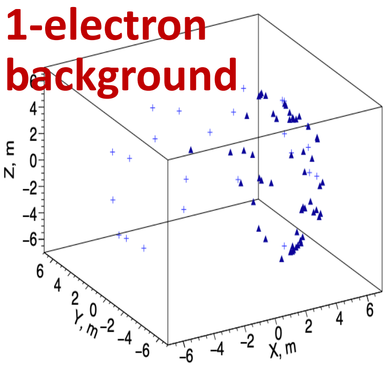
ii) Discrimination with Spherical Harmonics

makes use of direction-independent spherical harmonics

$$S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2$$







[arXiv:1609.09865]

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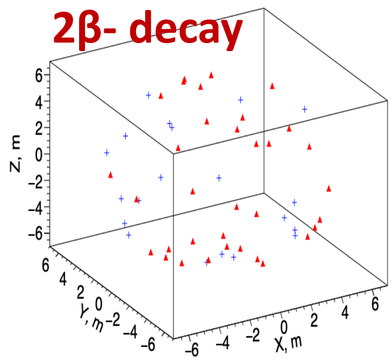

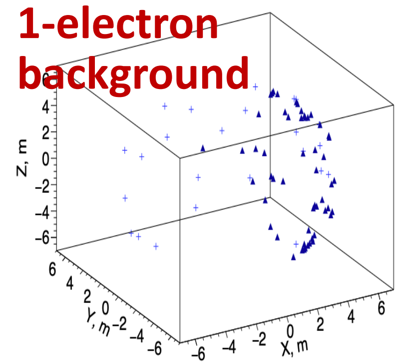

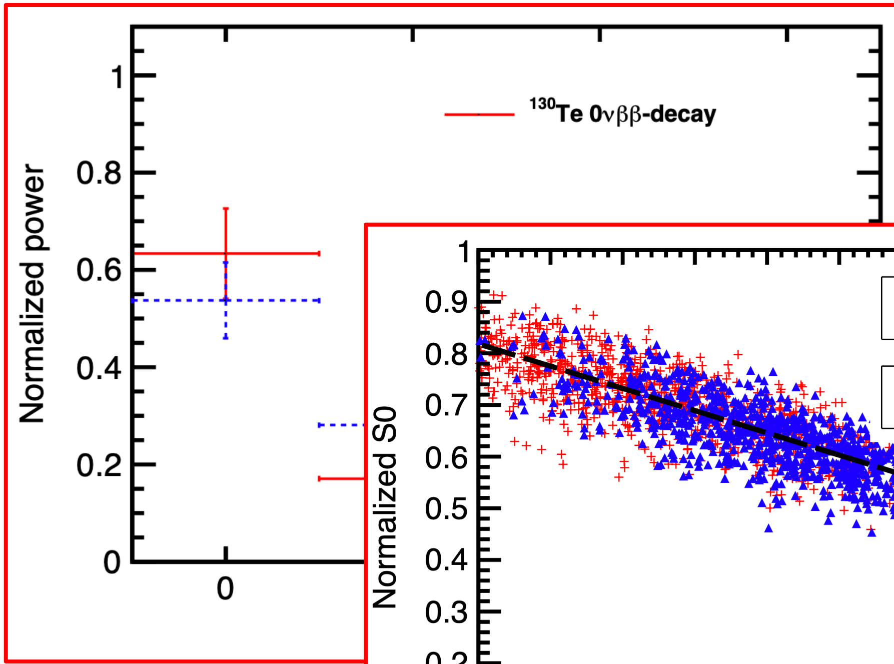

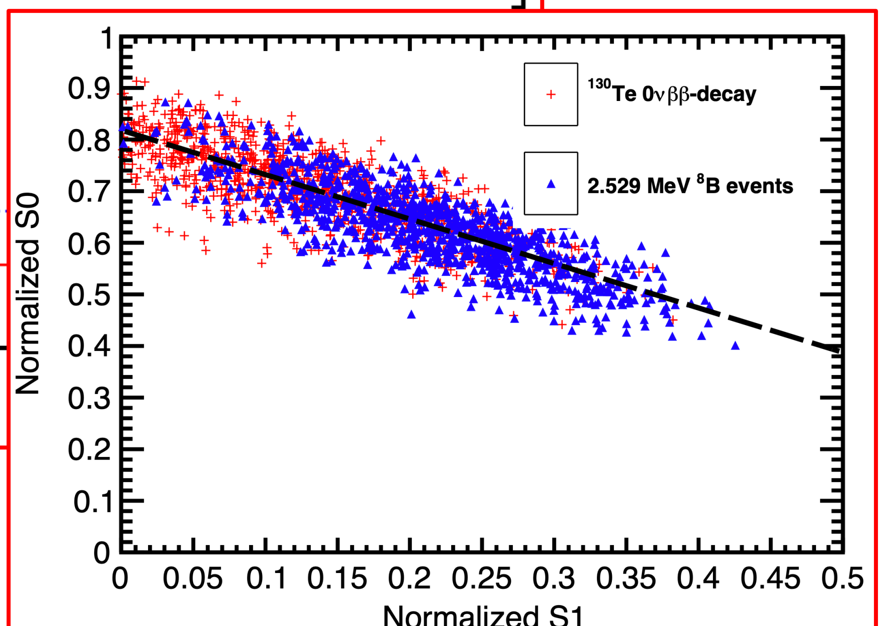

discrimination w/ power S0 vs. S1

[arXiv:1609.09865]

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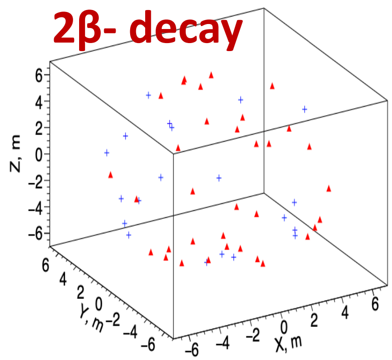
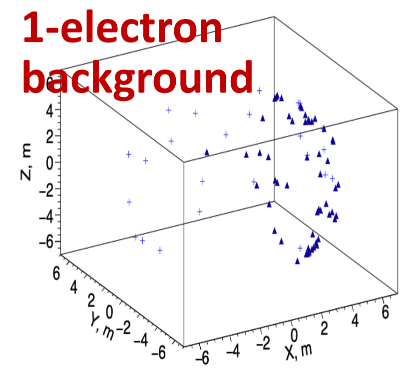
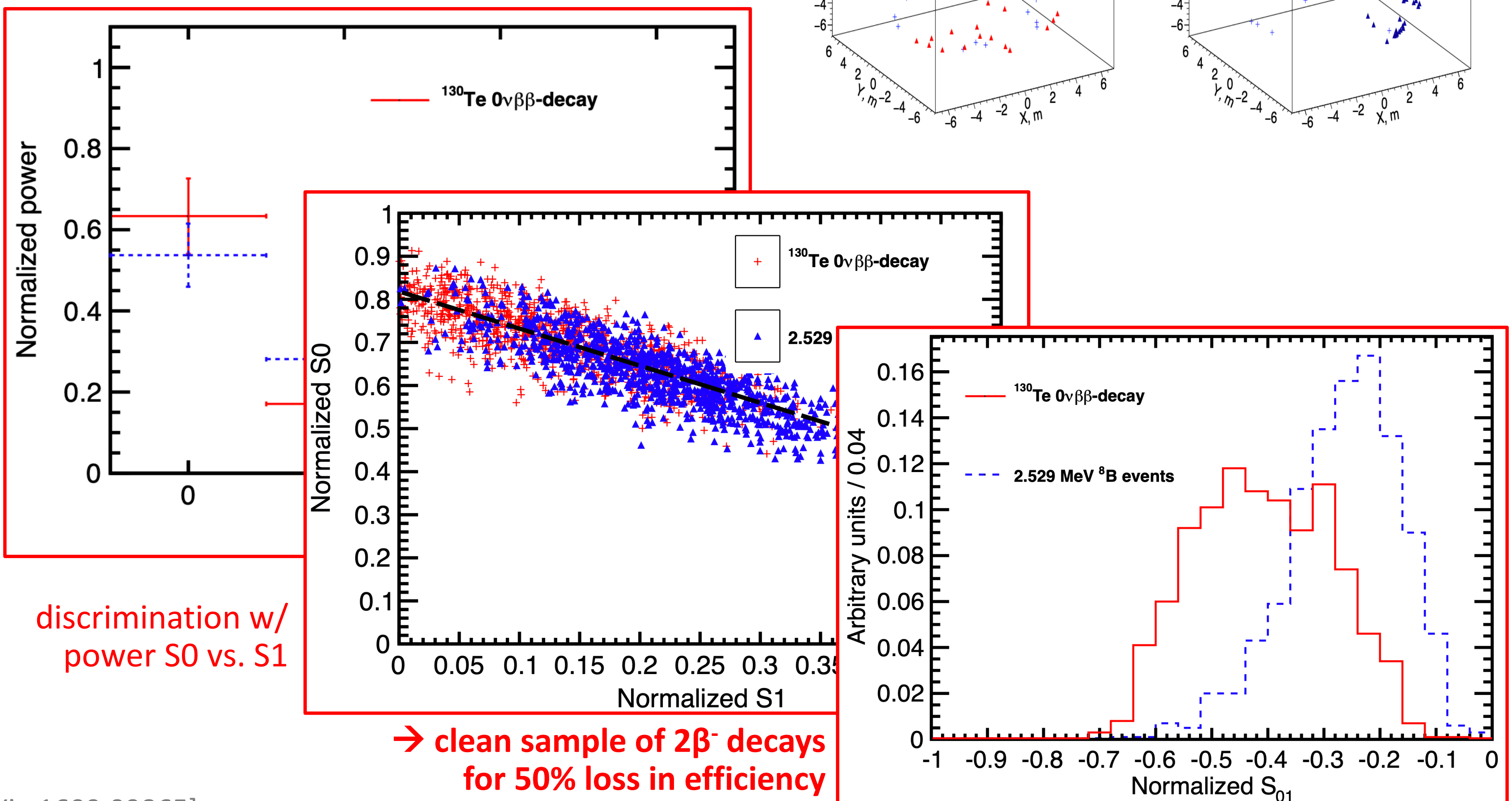
makes use of direction-independent spherical harmonics

$$S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2$$







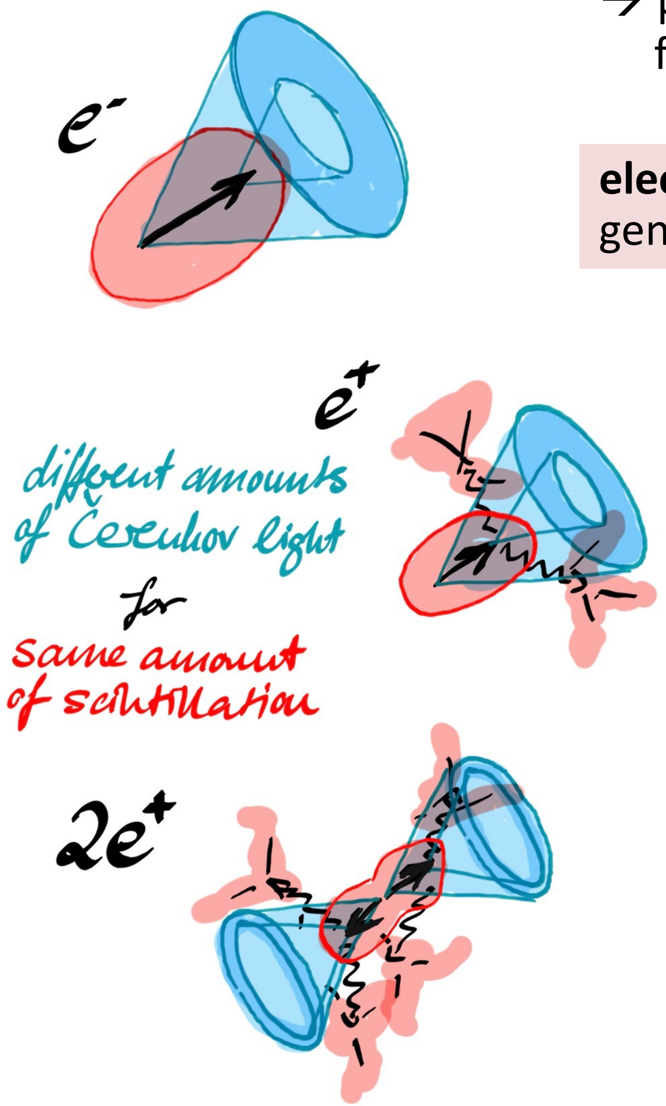
discrimination w/ power S0 vs. S1

→ clean sample of $2\beta^-$ decays for 50% loss in efficiency

[arXiv:1609.09865]

iii) *ne*$^{\pm}$ Discrimination based on C/S ratio

basic idea: low-energy electrons create low/no Chertons
→ particles generating many secondary electrons (γ's,e$^+$) feature a reduced Cherenkov/scintillation C/S ratio!



electron-like: multi-MeV electrons will generate most Cherenkov light

2β$^-$-like: somewhat reduced Cherton yield due to split of energy on two electrons

gamma-like: several Compton electrons with on average lower Cherton yield

positron-like: two 511 keV γ's create LE electrons that generate almost no Chertons

2β$^+$-like: four 511 keV γ's suppress Cherton emission even more.

inreasing Cherenkov/Scintillation ratio

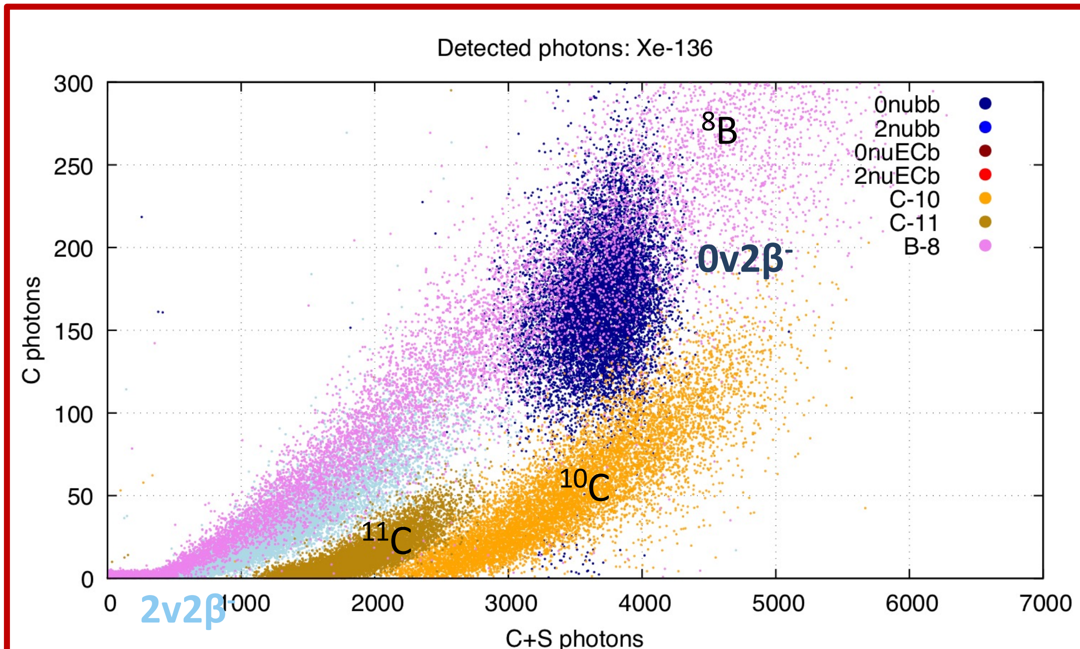
iii) Discrimination based on Cherton counting

basic assumptions:
of MC study

overall light yield: 1500 pe/MeV
~5% of photons are Chertons
~30% can be identified
→ **counting Chertons vs. all photons!**

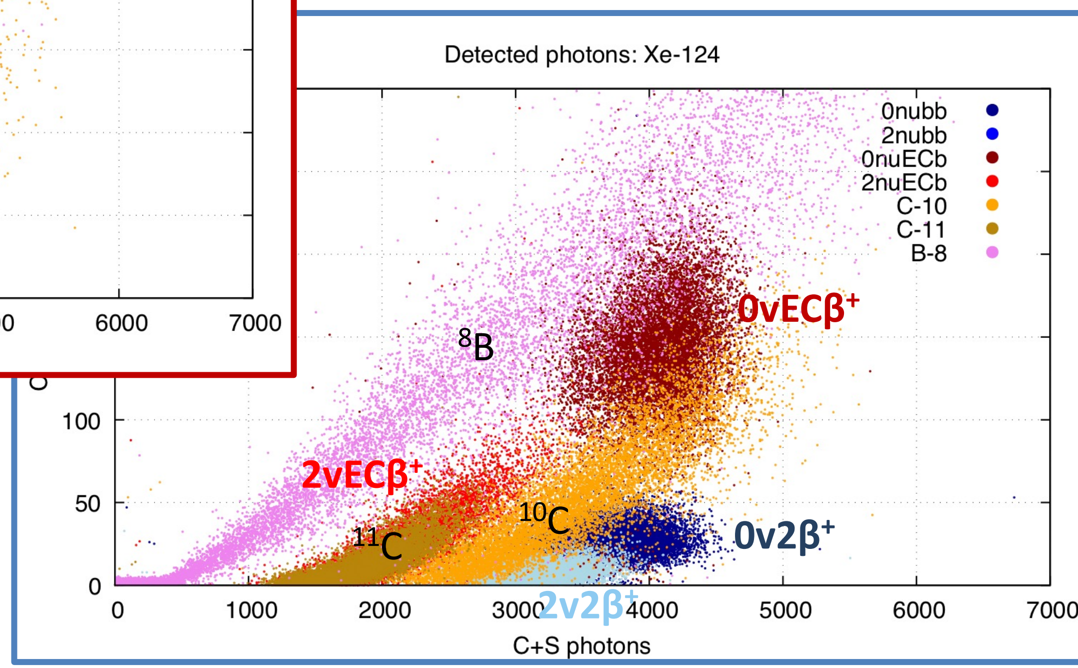
ordered by C/S

- ^{8}B 1e^{-}
- 2β- 2e^{-}
- ^{11}C ECβ^{+} $e^{+} \rightarrow \gamma\gamma$
- ^{10}C 2β^{+} $1e^{+}+\gamma \rightarrow 3\gamma$, $2e^{+} \rightarrow 4\gamma$



^{136}Xe : 2β^{-} decays

^{124}Xe : ECβ^{+}/2β^{+} decays



iii) Discrimination based on Cherton counting

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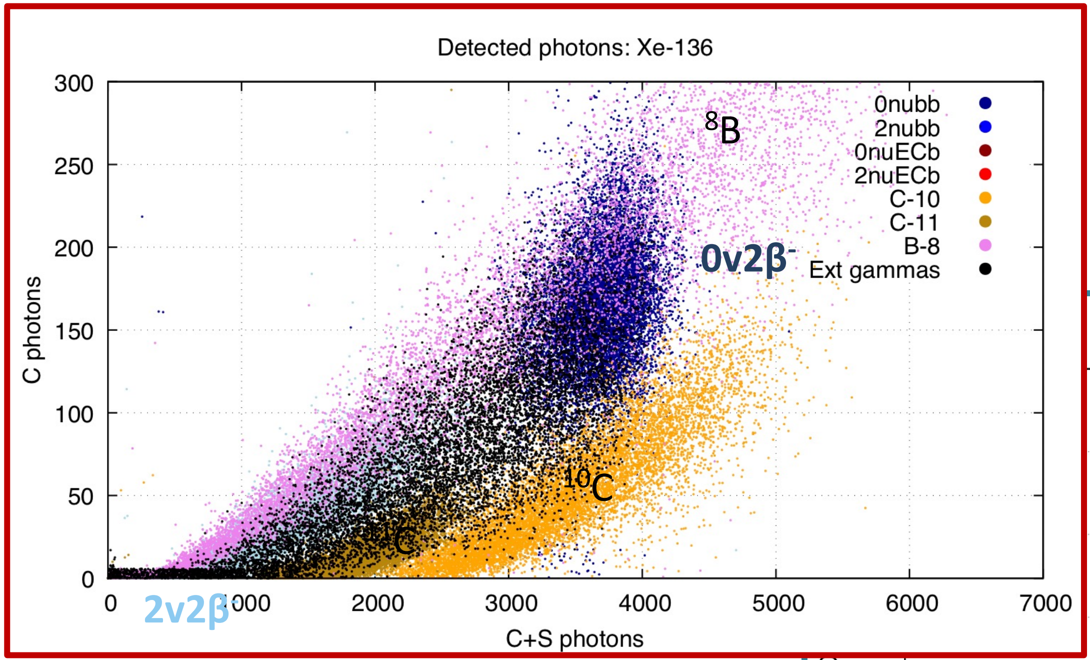
overall light yield: 1500 pe/MeV
~5% of photons are Chertons
~30% can be identified
→ **counting Chertons vs. all photons!**

ordered by C/S

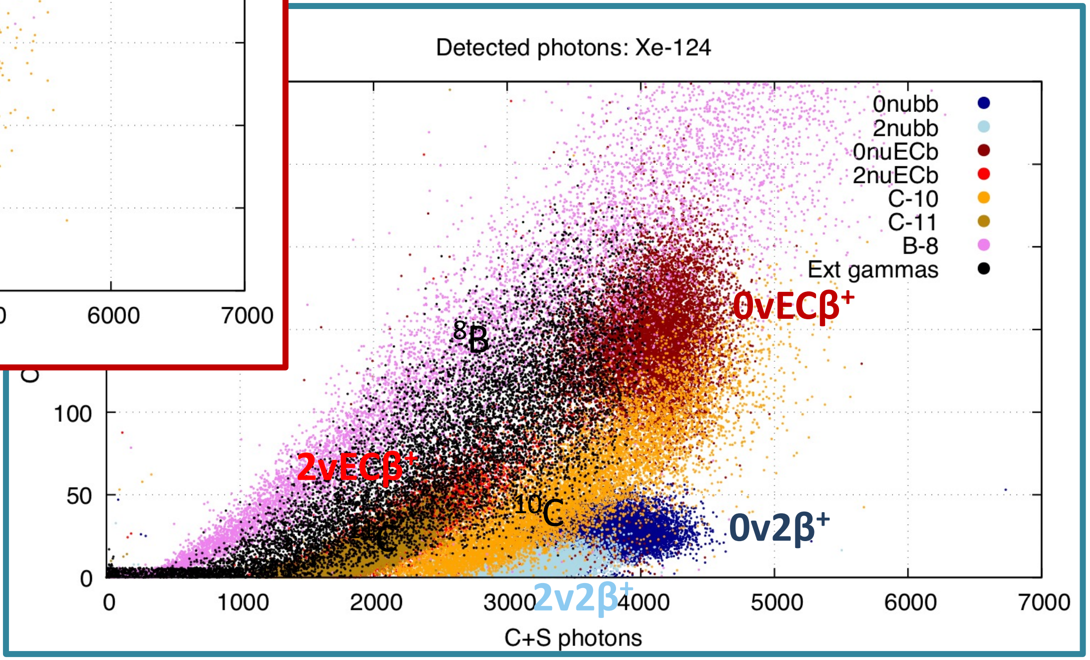
- ^{8}B — $1e^-$
- $2\beta^-$ — $2e^-$
- ^{11}C — $e^+ \to \gamma\gamma$
  $EC\beta^+$
- ^{10}C — $1e^+ + \gamma \to 3\gamma$
  $2\beta^+$ — $2e^+ \to 4\gamma$



^{136}Xe : $2\beta^-$ decays

+ ext. gamma BG

^{124}Xe : $EC\beta^+/2\beta^+$ decays

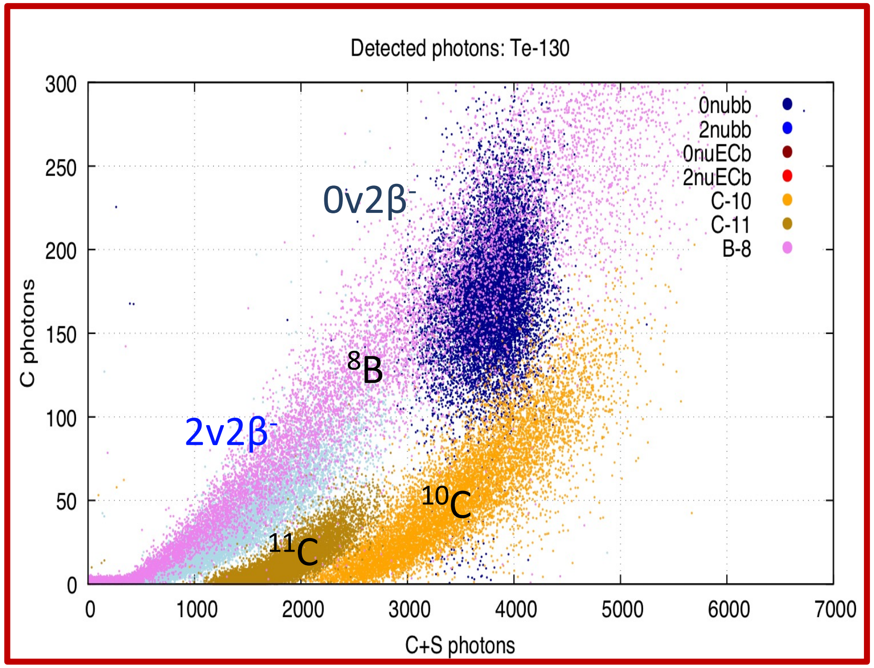


Searches in multi-kt Detectors

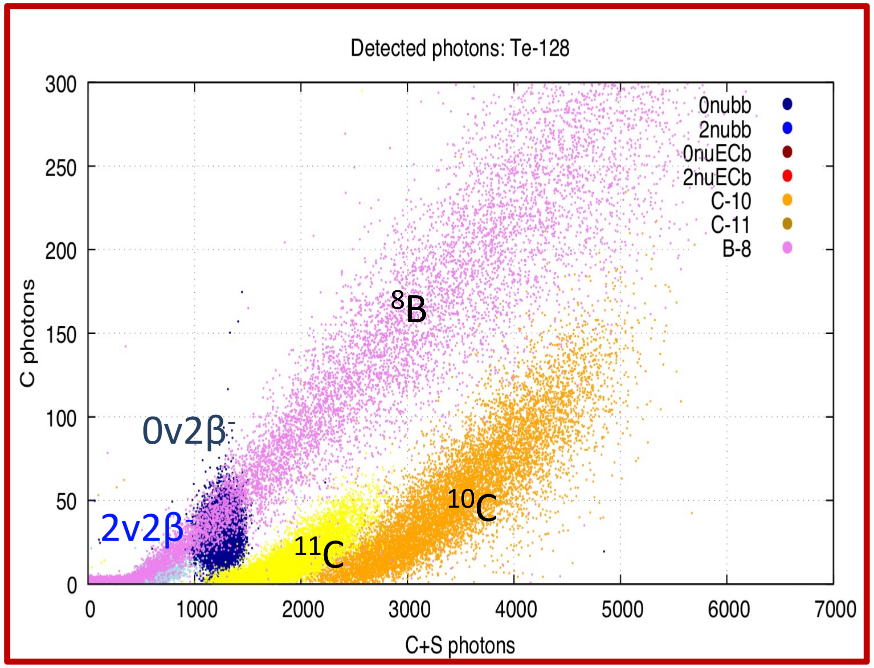
i.e. THEIA, potentially JUNO others

- for $2\beta^-$ searches (Xe, Te), C/S ratio very effective to discriminate LS cosmogenics (^{10}C, ^{11}C)
  → works for all endpoint energies
- for high loading with natural Xe, simultaneous search for $2\beta^-/2\beta^+$ possible
- searches for $0\nu2\beta^+$ decay potentially attractive because $2\nu2\beta^+$ is as well very suppressed
  → less of an issue with BG

^{130}Te : $2\beta^-$ decays



^{128}Te : $2\beta^-$ decays



Searches in multi-kt Detectors

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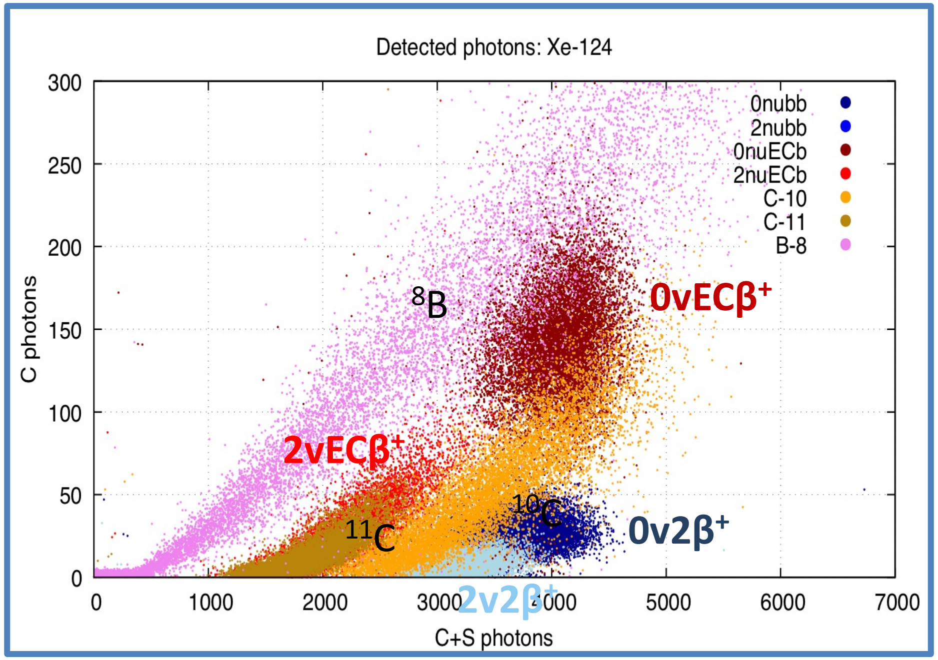
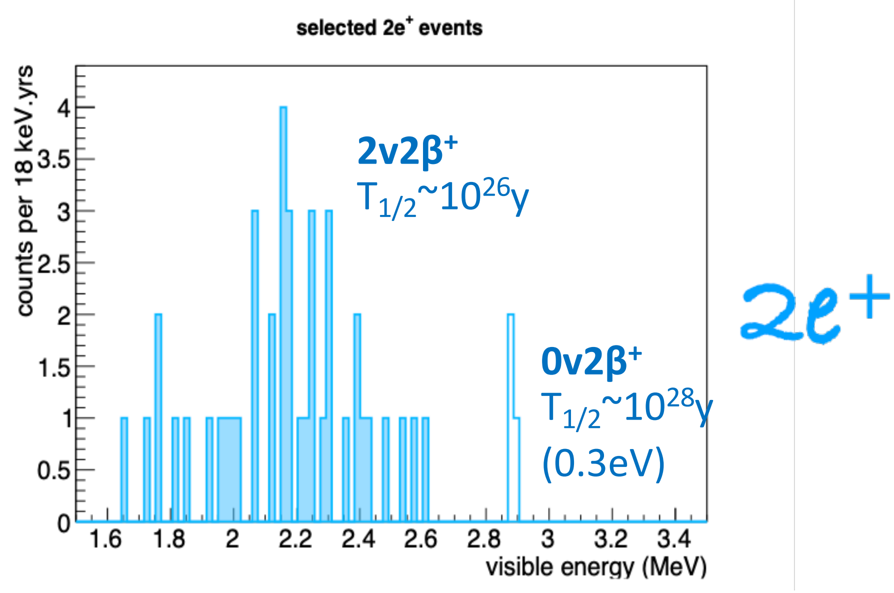
- for high loading with natural Xe, simultaneous search for $2\beta^-/2\beta^+$ possible
- searches for $0\nu 2\beta^+$ decay potentially attractive because $2\nu 2\beta^+$ is as well very suppressed
  → spectral overlap is less of an issue

^{124}Xe : $EC\beta^+/2\beta^+$ decays





Dedicated $2\beta^+$ Search for Mid-Scale Setups?

hybrid detectors especially sensitive to $2\beta^+$
→ current $2\beta^+$ limits are $\mathcal{O}(10^{22})$ yrs

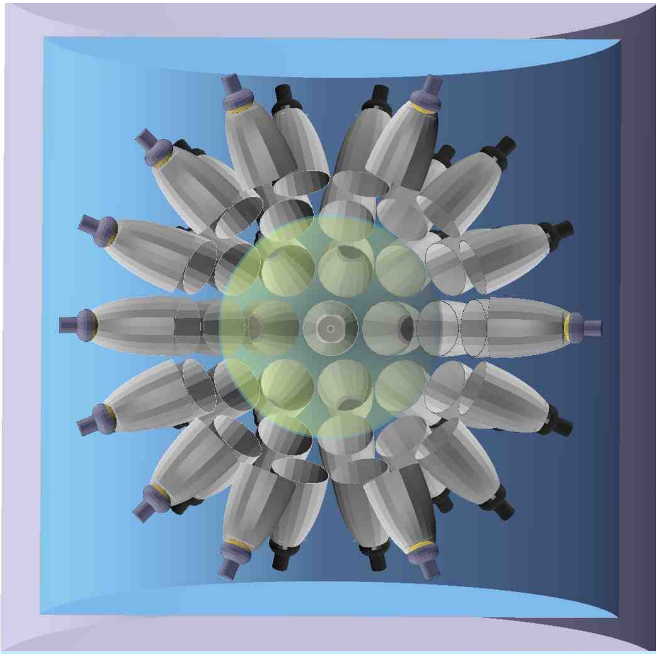
e.g. test measurement with JUNO pre-detector OSIRIS ("CTF") looking for $EC\beta^+/2\beta^+$ of ^{78}Kr

- spectral endpoint at 2.85 MeV (visible)
- 20 tons of slow LS with 2% ^{nat}Kr → 400 kg
- low natural abundance: 0.4% → ^{78}Kr: 1.6 kg
- at 10^{22} yrs: ~10^3 events per year
  → $\mathcal{O}(10^{25})$ yrs for 1 yr of BG-free measuring
- [if enriched to 94% → $\mathcal{O}(10^{28})$ yrs]

→ without enrichment, relatively cheap method to observe $2\nu2\beta^+$ and significantly enhance life time limits on $0\nu2\beta^+$ decay for several isotopes:

^{78}Kr, ^{124}Xe, ^{106}Cd, others?

→ how helpful for 2β/matrix element predictions?



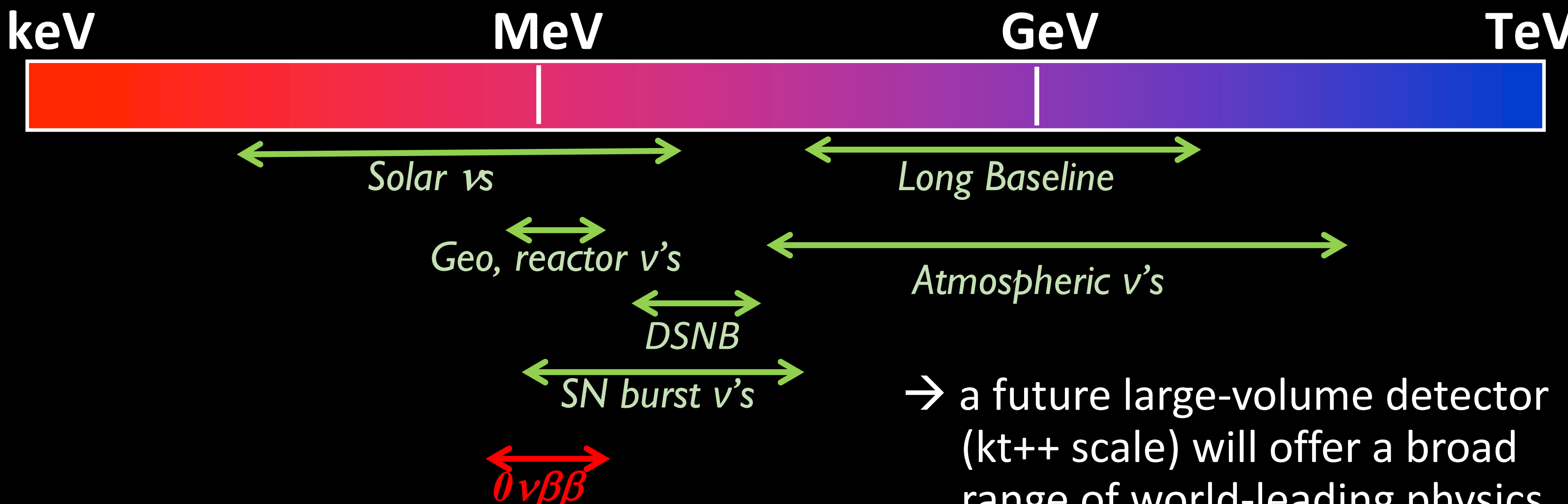
OSIRIS Detector upgrade for 2β

compared to current setup

- additional external shielding (40cm concrete)
- PMTs rearranged (larger distance) & equipped with light cones
  → light yield >10^3 pe/MeV
- spherical (double) balloon to reduce internal γ background
- doubles as solar pp-ν detector

Conclusions

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

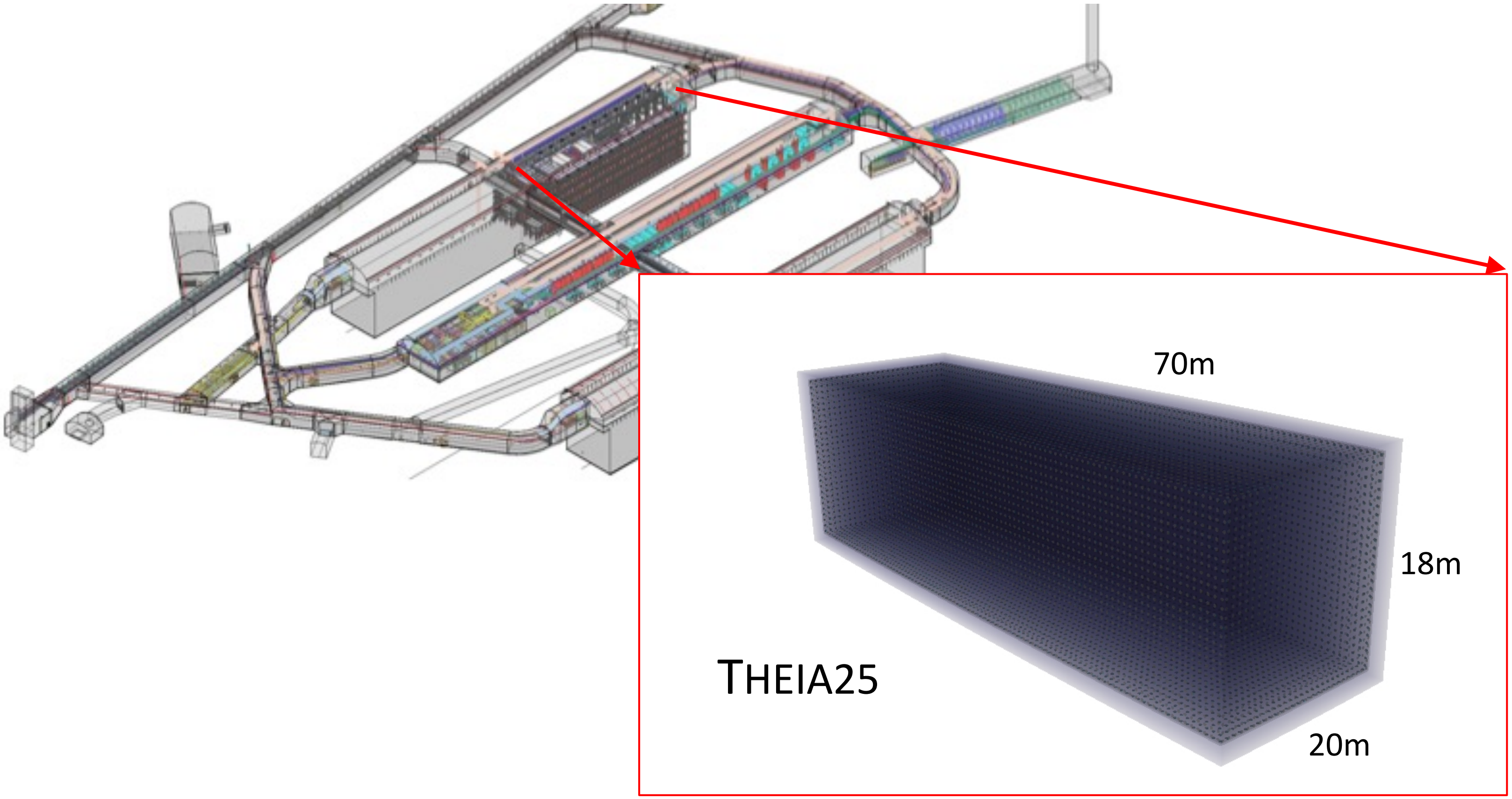


→ a future large-volume detector (kt++ scale) will offer a broad range of world-leading physics

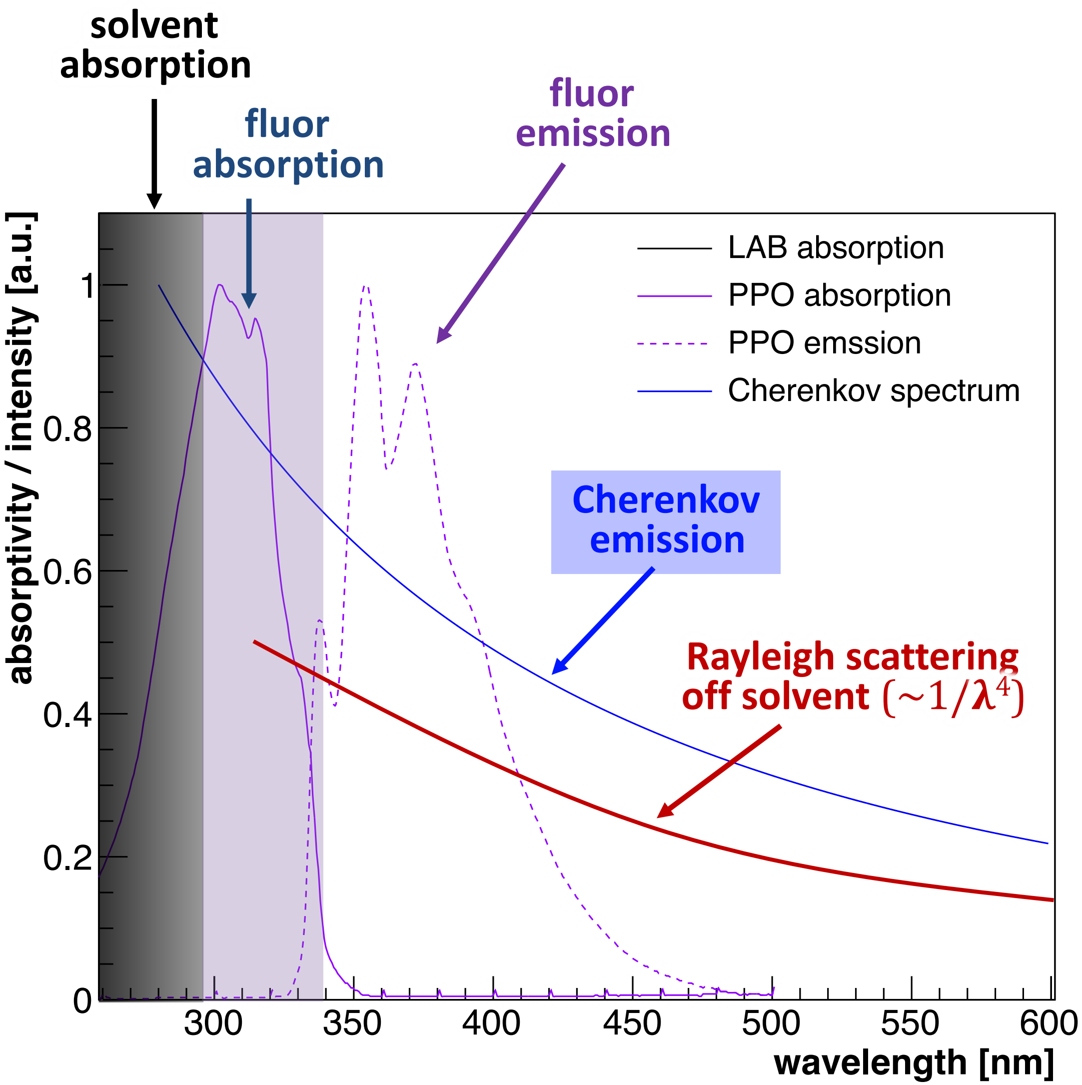
for 2β searches, hybrid detectors offers several possibilities to enhance sensitivity compared to "conventional" scintillator searches

- directional discrimination of 8B neutrinos
- identification of 2β decay topologies based on Cherenkov photon distribution
- $ne^{\pm}$ discrimination based on C/S ratio

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)

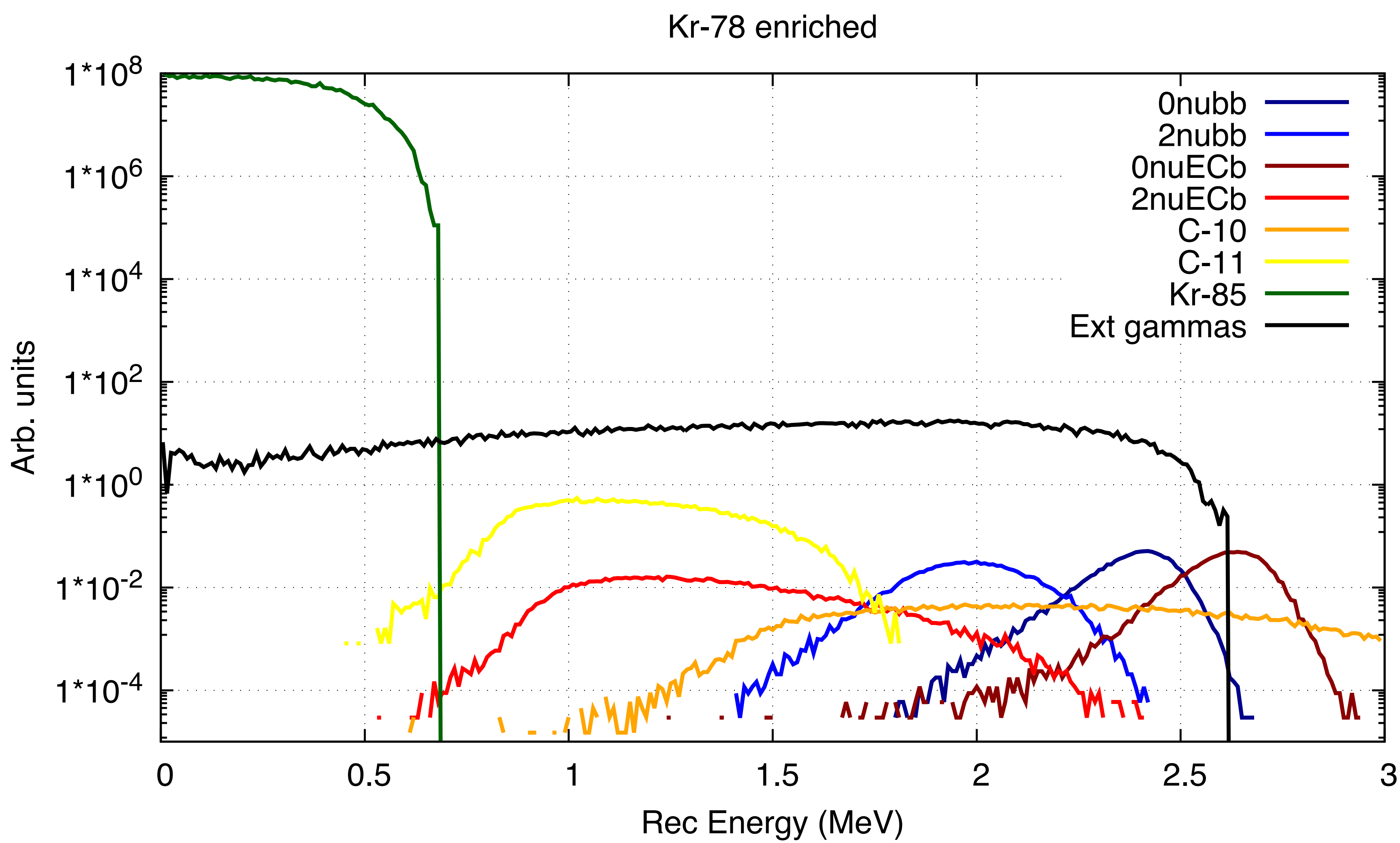
→ **reduce Rayleigh scattering**

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

  and/or

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

SERAPPIS 1D spectra



Receipe for WbLS

Challenges

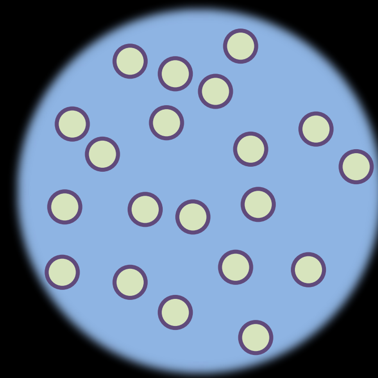
- water does not scintillate
- organic fluorophores do not dissolve in water

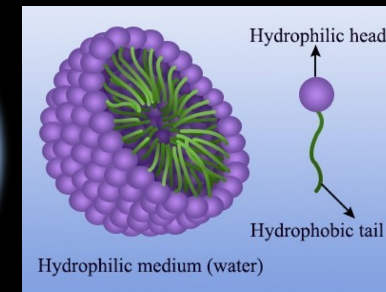
How to overcome this?

- start from usual organic scintillator, i.e. solvent (e.g. LAB) + small concentration of fluorophore (e.g. PPO, several gram/liter)
- add a surfactant (tensid) to create the interface between organic and water phase
- dissolve small droplets (mycels) of organic LS in the water phase

Properties

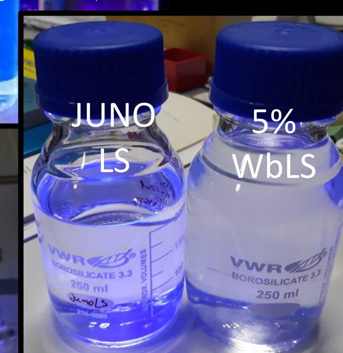
- very transparent (water)
- limited by Rayleigh scattering of mycels (size!)
- scintillation! (linear with organic fraction)
- fast timing (LAB→PPO transfer times)





WbLS mycels

Minfang Yeh, BNL



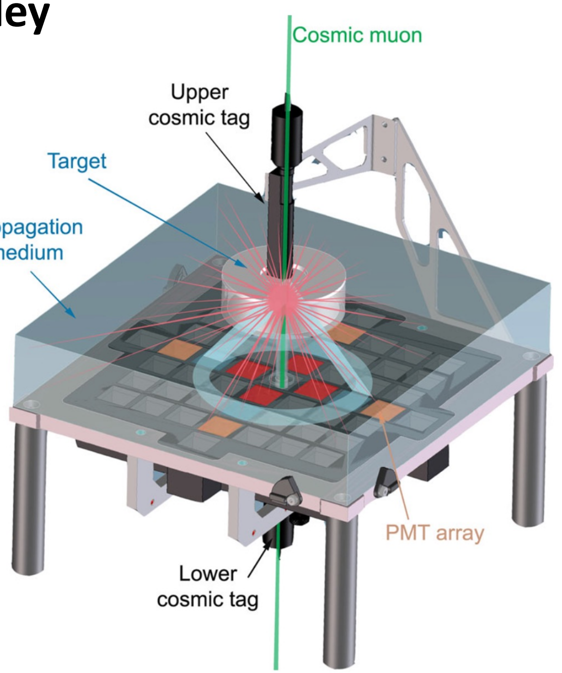
Hans Steiger, Mainz

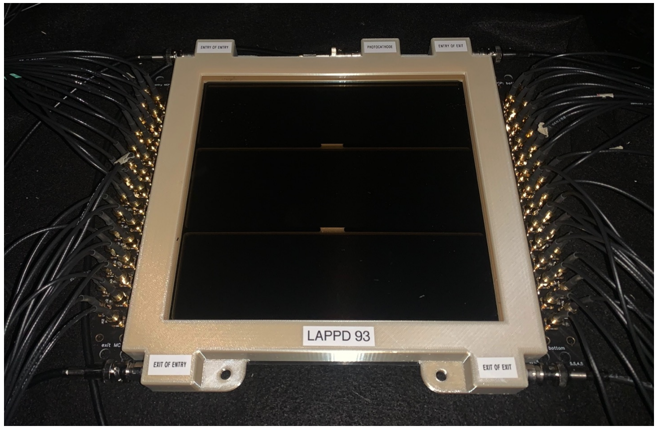
Lab Setups for C/S Separation

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

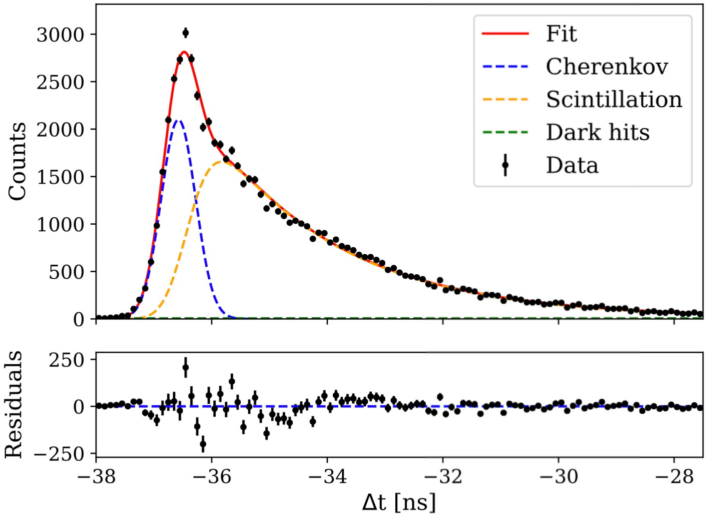
PMT array illuminated by small LS target excited by cosmic muons and radioactive sources

→ C/S separation using hit pattern





WbLS time profile with LAPPD
[arXiv:2110.13222]

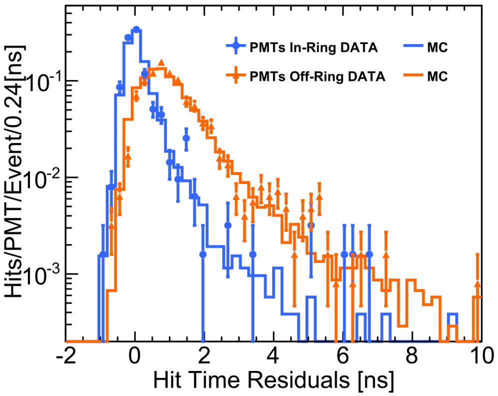


→ C/S separation based on timing

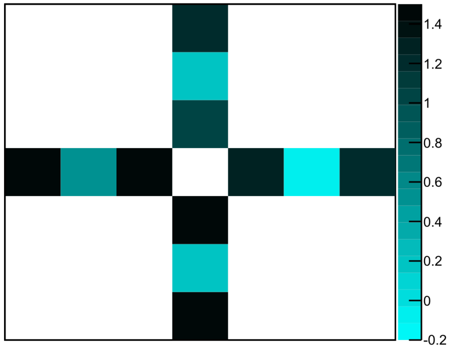
5% WbLS

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

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



PMT hit pattern



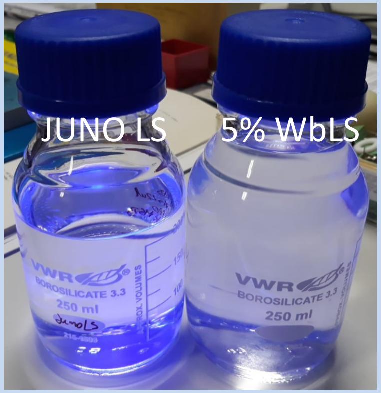
German involvement: R&D on WbLS

WbLS Development at TUM

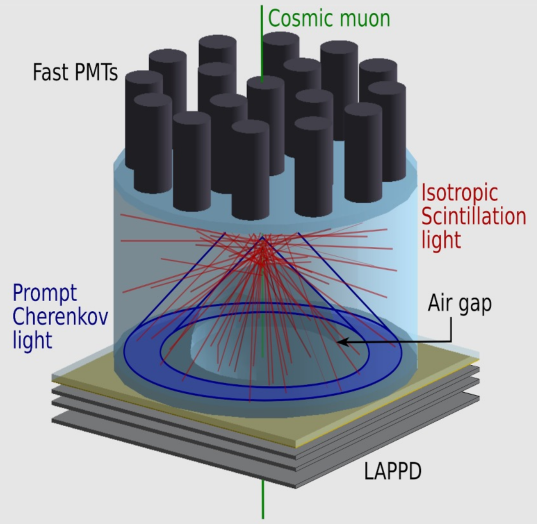
→ systematic study of WbLS composition and properties

→ new WbLS components: surfactants (Triton-X vs. LAS), solvents (benzene, dioxane)

→ in Mainz: oil-diluted organic LS (heptane, dodecane, hexadecane)



WbLS Cherton/Scinton Test Cell in Mainz



→ C/S discrimination and reco with sub-ns photosensors

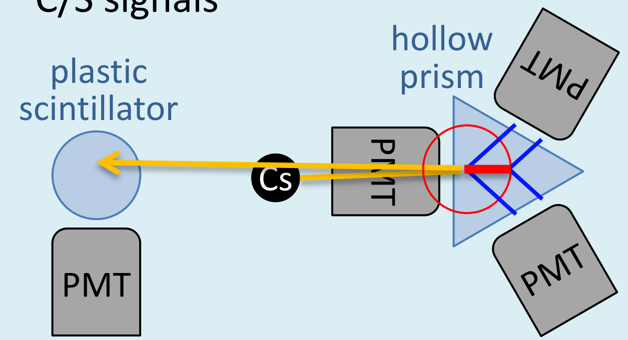
→ light propagation in WbLS over 10-20 cm

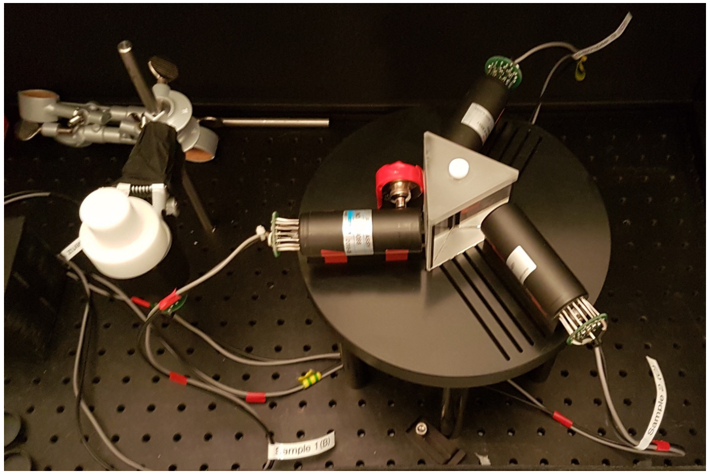
- Cylindrical tank: 10-15l
- Air gap for ring formation
- Changeable photosensors: LAPPDs, SiPMs …
- fast (<1ns) PMT rear array for scinton detection

WbLS Light Yield in Mainz

→ forward-scattered electrons produce Chertons and scintons

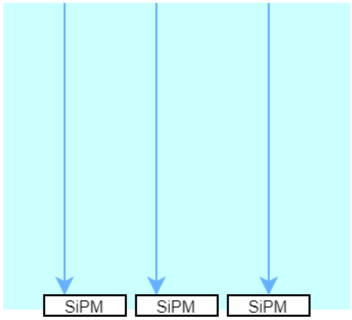
→ rear PMT sees pure scinton signal, front PMTs (tts 300ps) separate C/S signals



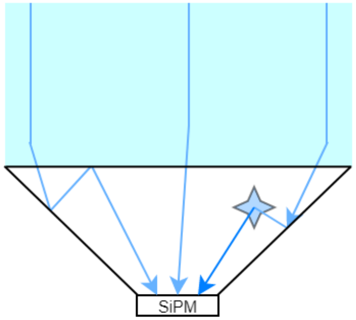


German involvement: Photosensors

Tübingen/Mainz
FZ Jülich (ZEA-2)



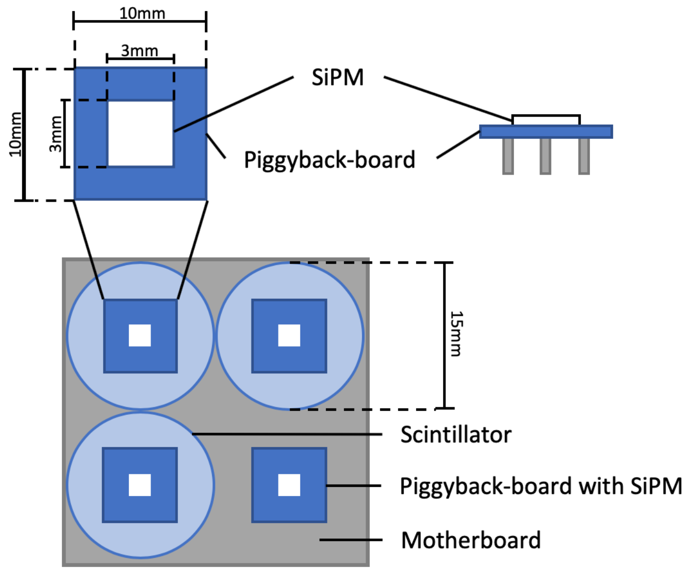
SiPM array



SiPM with active lightguide

Idea: SiPM array with active light guides

- SiPM arrays for sub-nanosec timing
- increased granularity compared to PMTs
- equip SiPMs with cone-shaped scintillators to enhance light collection
  → reduce costs
  → reduce dark noise



Currently: Production of test array in TÜ

- 2x2 array with SiPM mounted on small piggyback boards
- Active light guides:
  - 3 plastic scintillators from Mainz
  - 1 reference channel without guide
- Design of large mother board on-going:
  - Preamplifiers and other electronics
  - Adapters for piggyback boards

Planned: Design of readout electronics for 64-channel array with FZ Jülich/ZEA-2

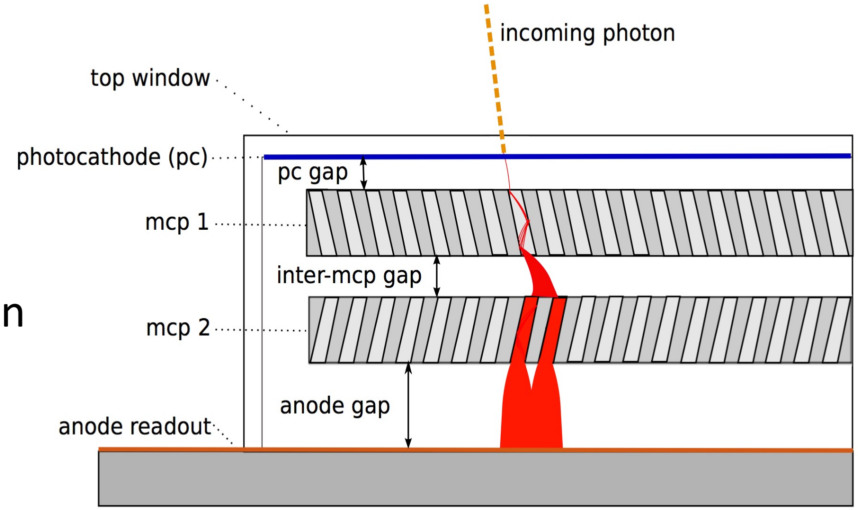
Fast light detectors: LAPPDs

Possible alternative: SiPM arrays
→ JUNO Near Detector
(Björn Wonsak's talk, We)

For fast scintillators (e.g. WbLS),
sub-ns time resolution will be crucial

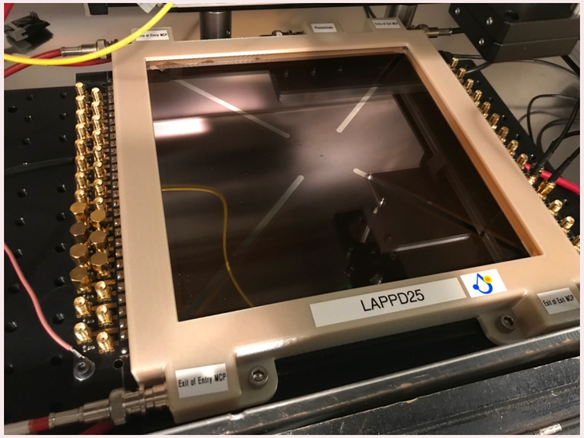
Large-Area Picosecond Photo-Detectors:

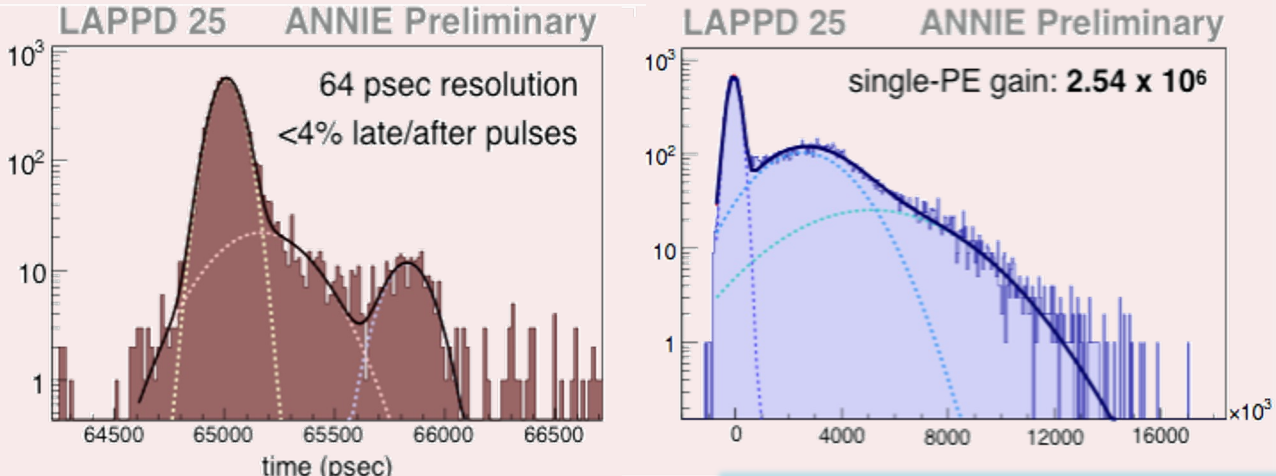
- flat, large area (20cm x 20cm) detectors
- standard photocathode, MCP-based amplification
- time resolution: ~60 ps
- spatial resolution: <1cm
- Manufactured by US company, Incom Inc.



Schematic of LAPPD

LAPPD test for ANNIE





→ posters by A. Elagin, M. Wetstein

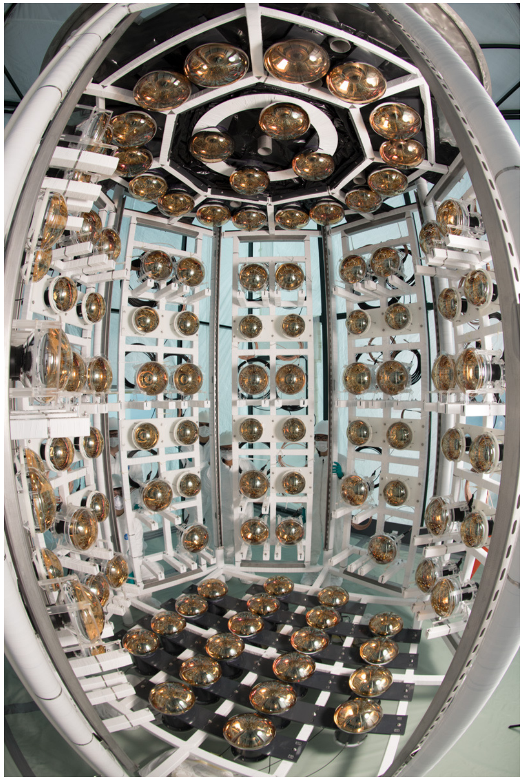
ANNIE Experiment

P0155 P0266

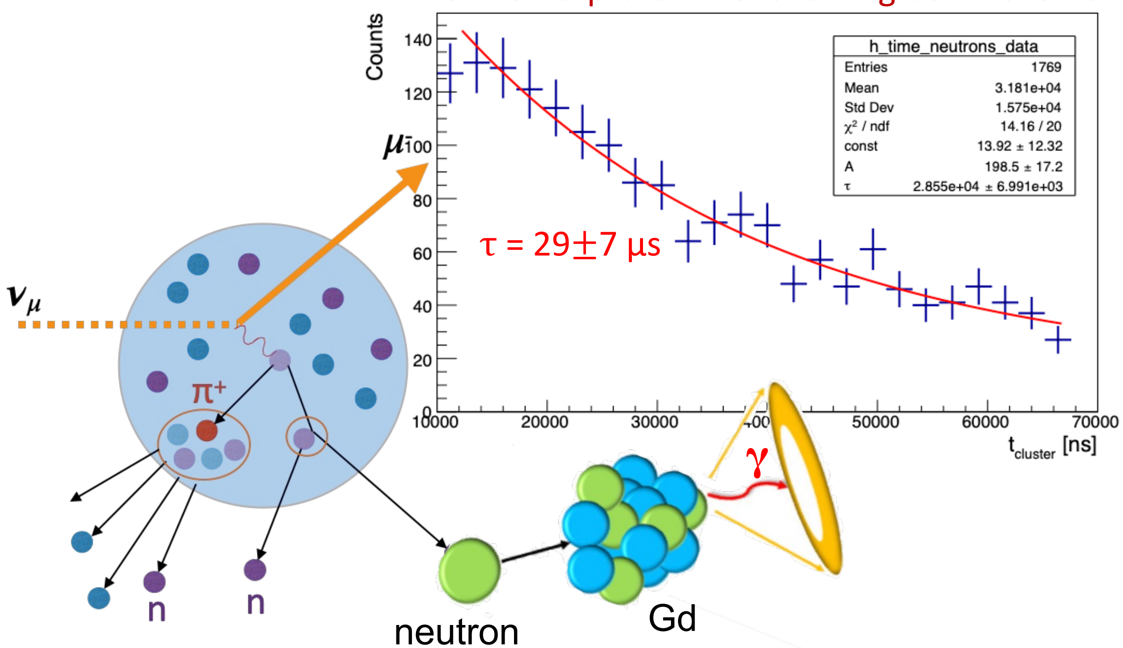
Accelerator Neutrino Nucleus Interaction Experiment

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

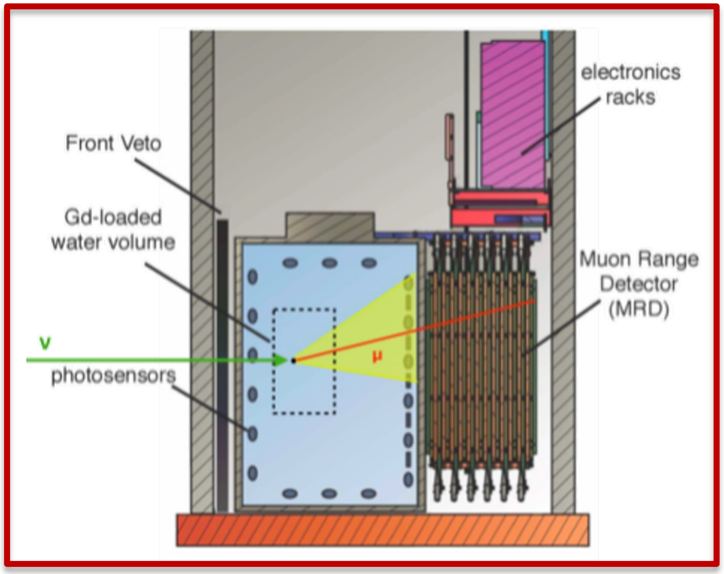
- measurement of GeV neutrino differential cross-sections and neutron multiplicity
- physics data taking started in early 2021
- R&D program for new technologies
  → Gd-water → LAPPDs → WbLS



neutron capture time following beam events

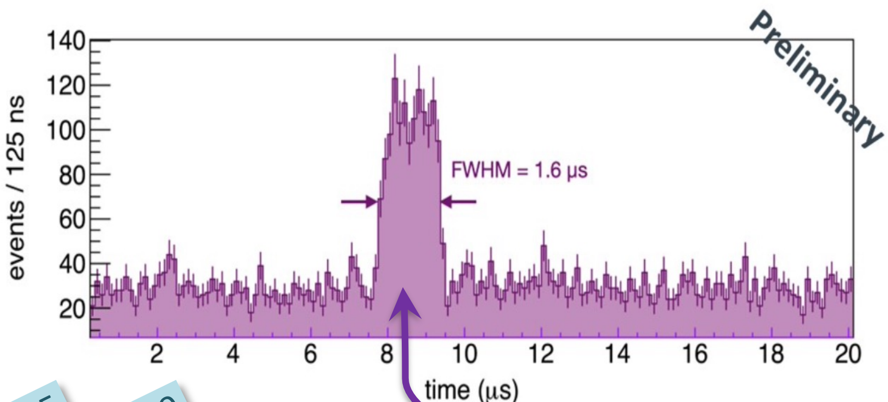


ANNIE Detector Layout



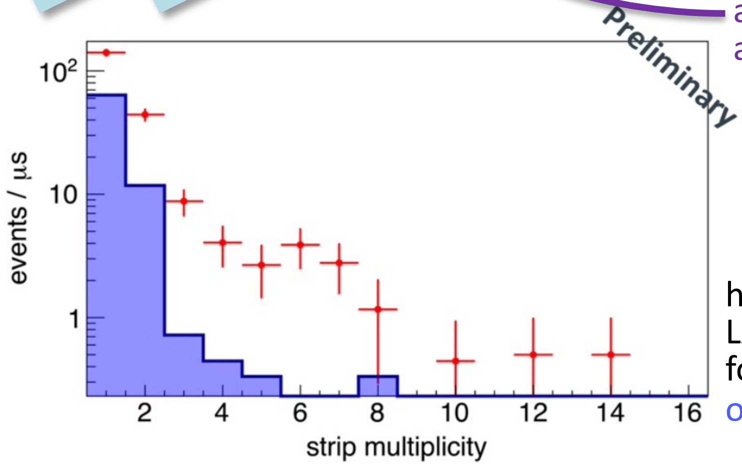
ANNIE: First LAPPD installed

- 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

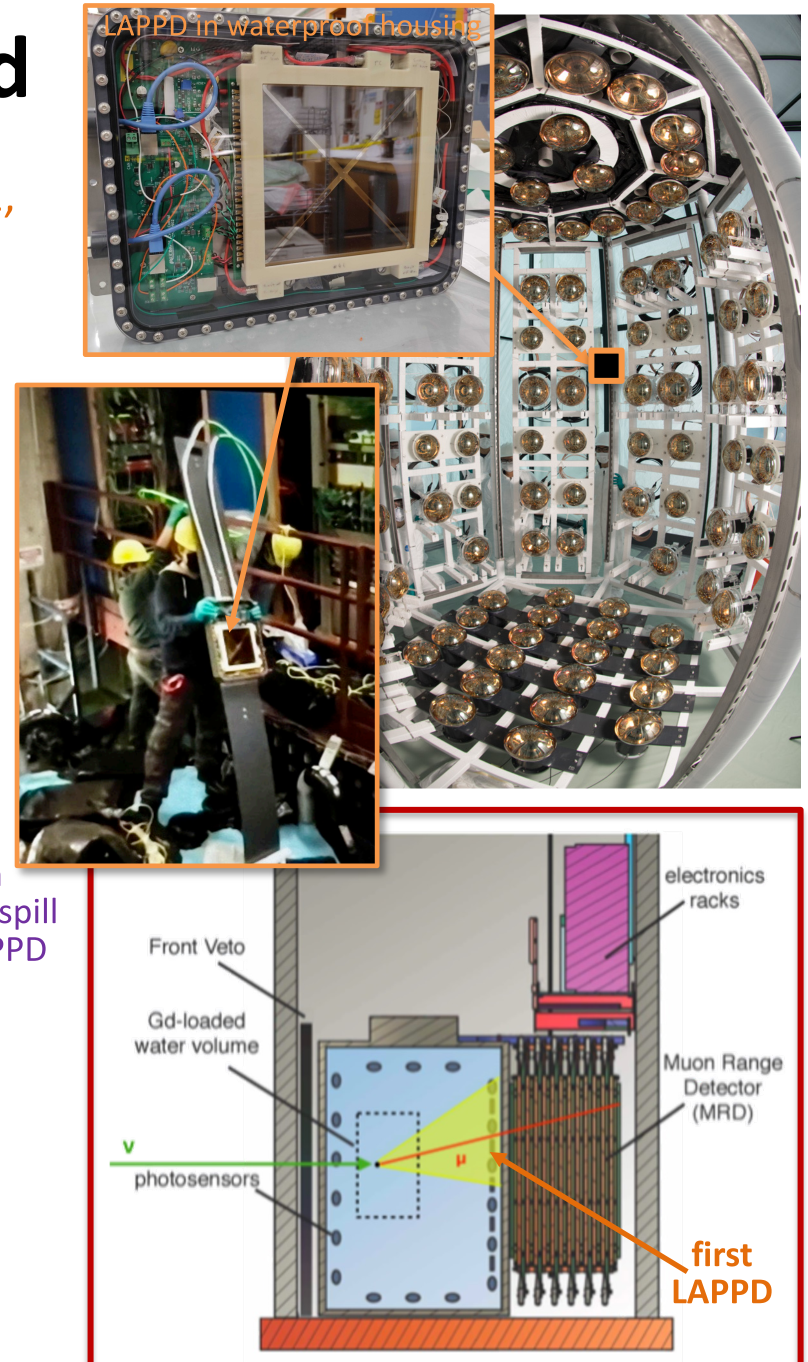


event time distribution around the BNB beam spill as observed by the LAPPD

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

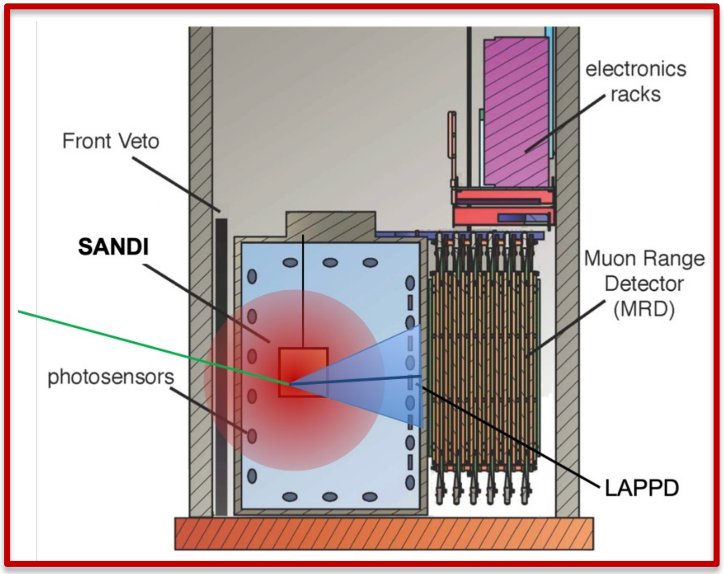
→ test WbLS performance for future use in long-baseline exp.s!

SANDI vessel at Davis

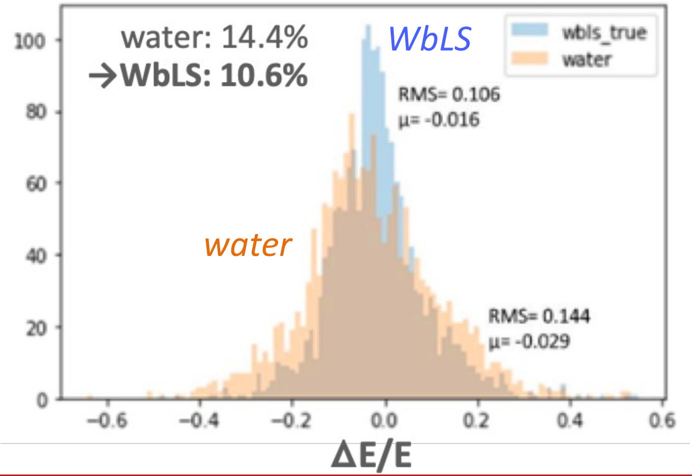
Preparations are on-going

- 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

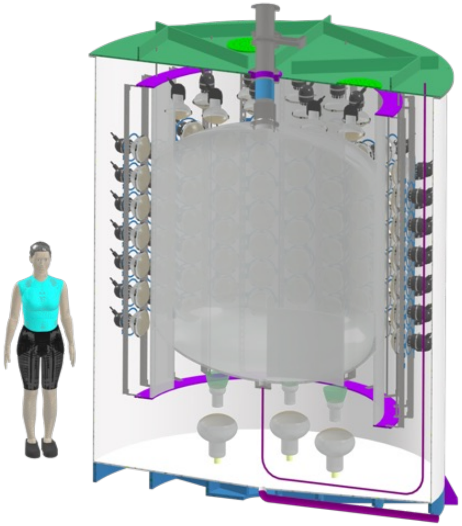
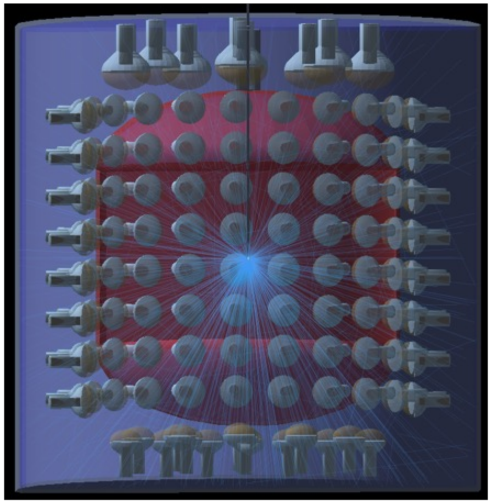


EOS: WbLS performance demonstrator

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

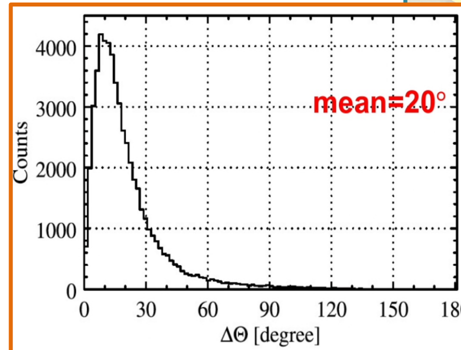
P0093 P0443


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

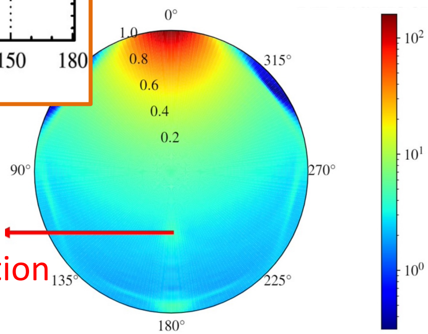
Jinping 1-Ton Prototype

fast 8‘‘ MCP-PMT

P0485
P0506



angular resolution for cosmic muons



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

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

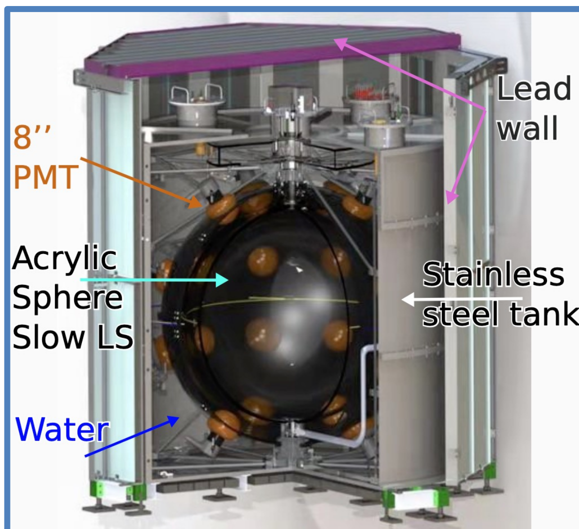
Project program

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

→ demonstrator for future 500t detector

P0533
P0354
P0413
P0478

liquid handling system @ Jinping



Directionality in present-day scintillator detectors

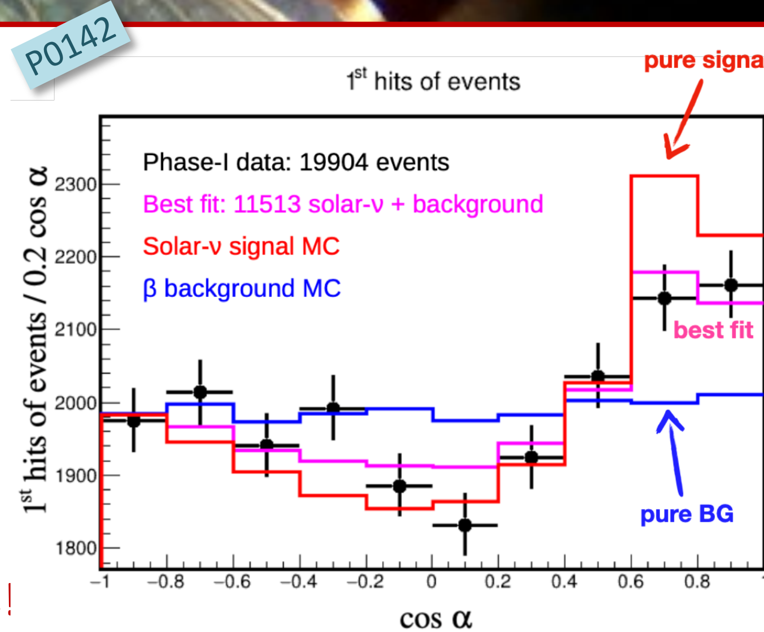
BOREXINO

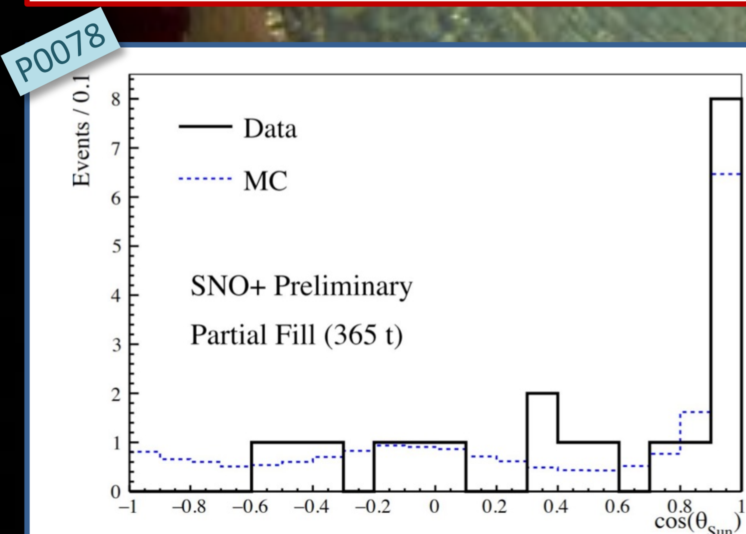
- new analysis technique tested in the spectral region of sub-MeV solar ^{7}Be neutrinos
- CID: use *integrated* angular distributions of early PMT hits relative to direction of the Sun

→ 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!





SNO+

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

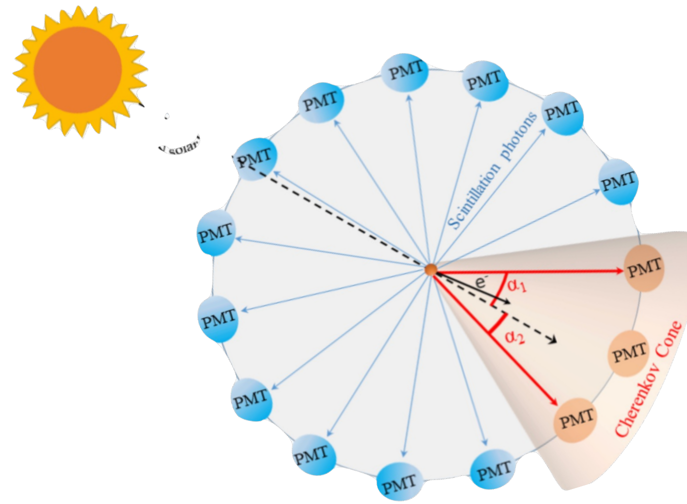
→ first demonstration of *event-by-event directional reconstruction* of solar ^{8}B neutrinos in slow scintillator

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

photo: BOREXINO calibration

Directionality in Borexino

- new analysis technique tested in the spectral region of sub-MeV solar ^{7}Be neutrinos
- Borexino is not optimized for this task
  → main difficulty: only 1 out of 300 photons detected is of Cherenkov origin



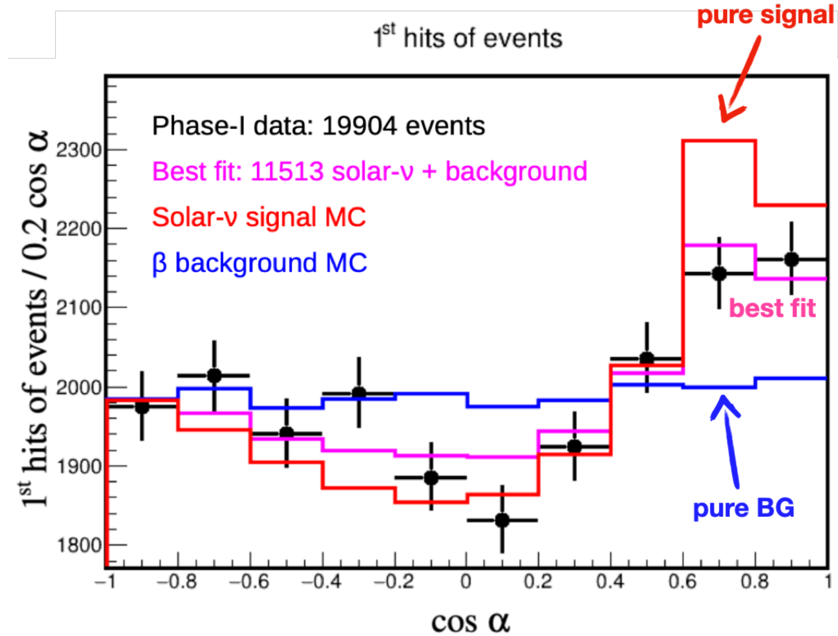
CID method

- cut on early hit times (enriches to 8% Cherenkov),
- use *integrated* angular distributions of PMT hits relative to Sun position

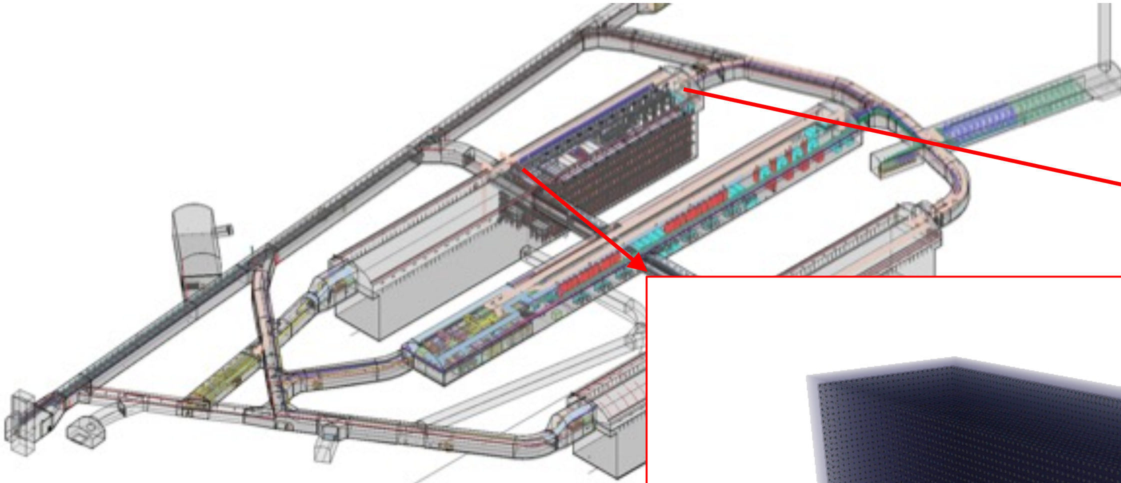
Result

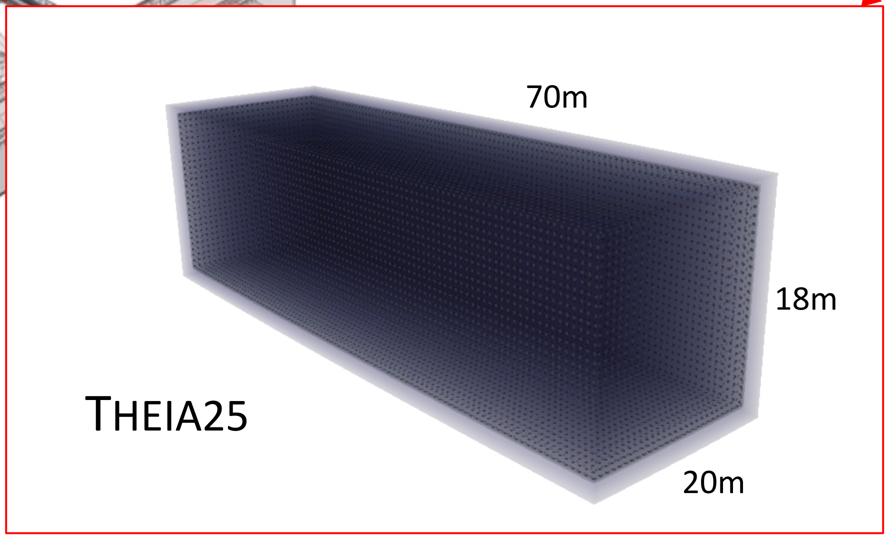
- observation of significant **(>6σ!)** angular excess caused by Cherenkov photons
- corresponding neutrino rate: $1.13^{+0.22}_{-0.25}$ of SSM prediction (incl. oscillations)

→ first directional detection of sub-MeV solar neutrinos!



THEIA25 as Module 4 of DUNE

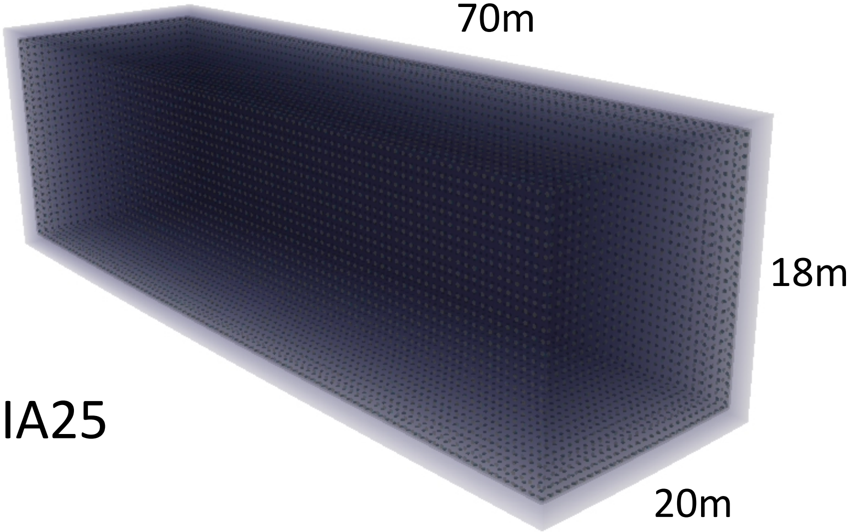




Detector specifications

- **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, $0\nu\beta\beta$)
- **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

THEIA25 : Staged Approach



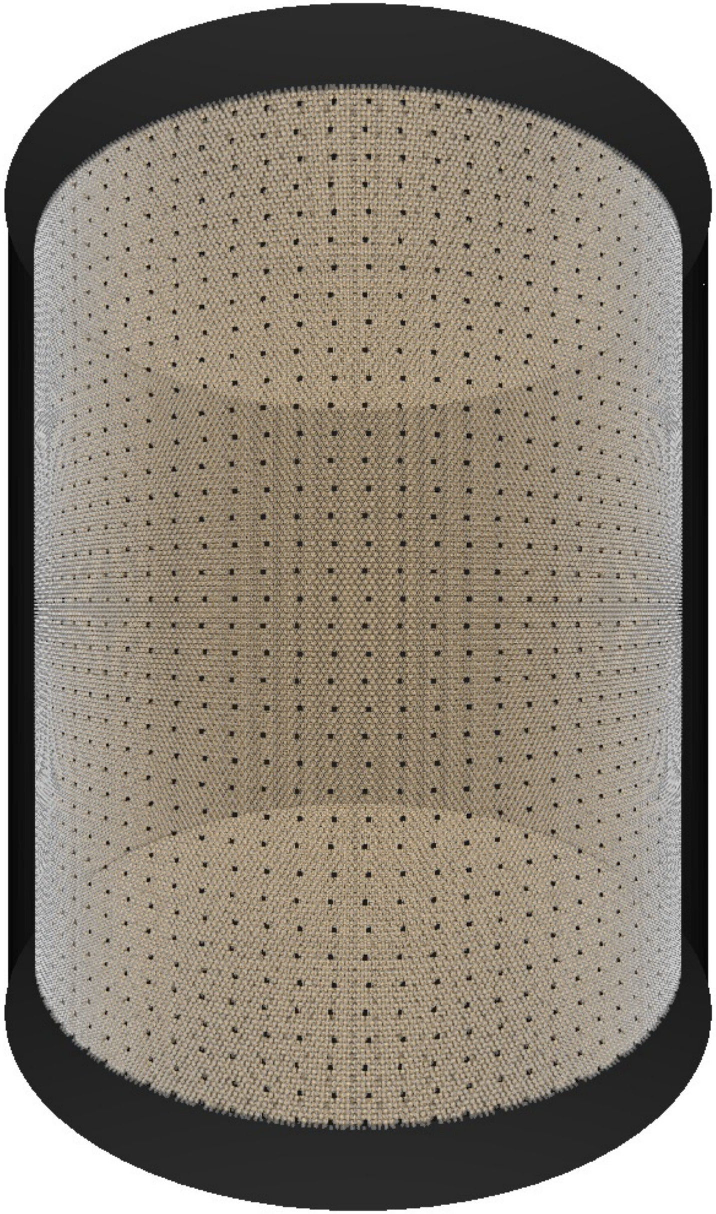
Staged Approach

Phase 1	Long-baseline neutrinos (LBNF) with ”thin” WbLS (1-10%)
Phase 2	Low-energy neutrino observation with “oily” LS
Phase 3	multi-ton scale $0\nu\beta\beta$ search with loaded LS in suspended vessel and added photocoverage

Physics Goals

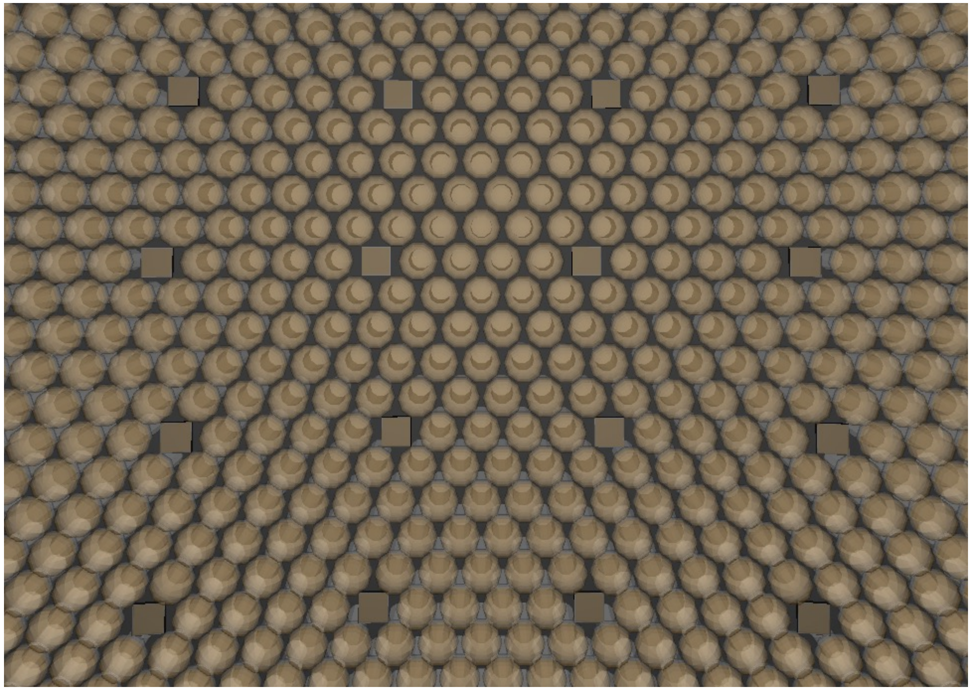
- **Long-Baseline Oscillations**
- **Proton decay** → $K^+\nu/\pi^0e^+$
- Supernova neutrinos
- Diffuse SN neutrinos
- Solar neutrinos
- Geoneutrinos
- **$0\nu\beta\beta$ search** on <10meV scale

Future full physics stage: THEIA



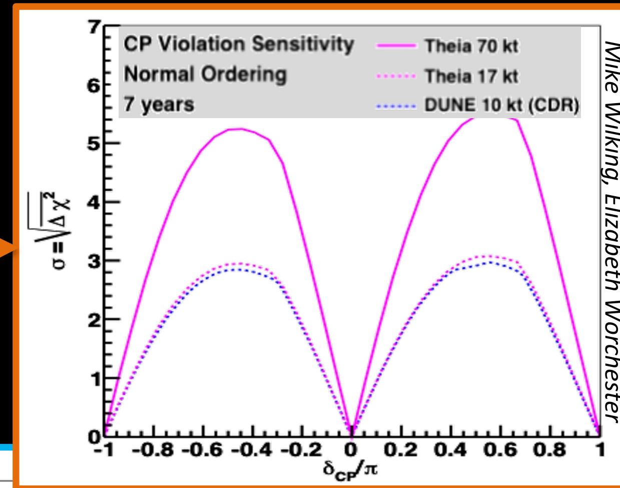
Detector Specifications

- **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 (Homestake/SURF comes to mind)



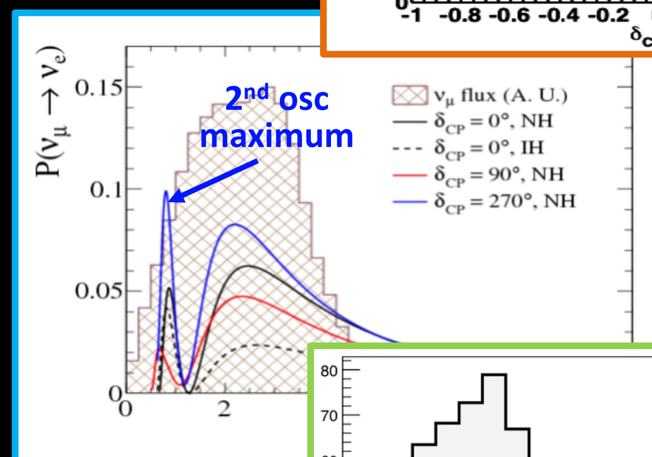
Hybrid Detectors for Long-Baseline Neutrinos

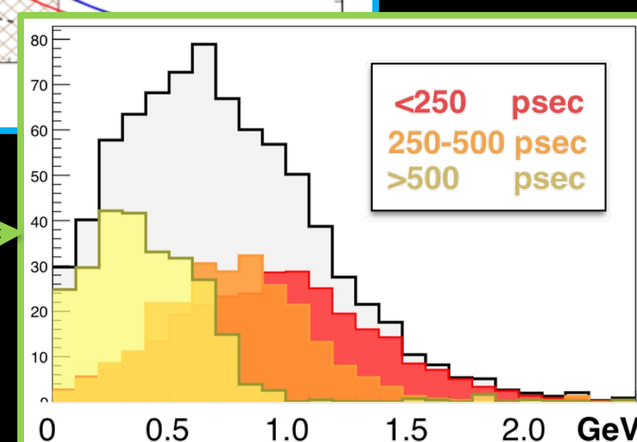
e.g. in context of **DUNE Module of Opportunity:** What would a **large WbLS detector** add to the existing liquid-argon modules?



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

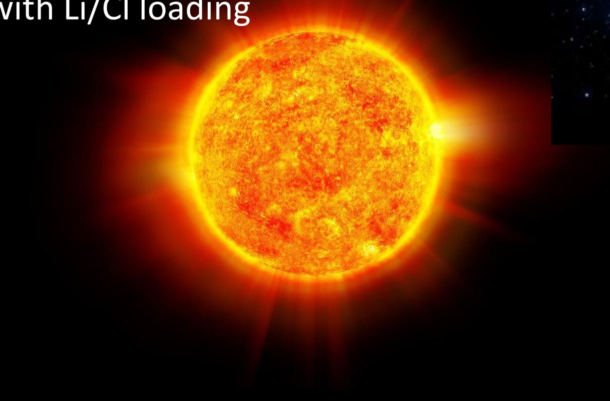




Astrophysical neutrinos at low energies

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

Astrophysical neutrinos at low energies

Supernova Neutrinos
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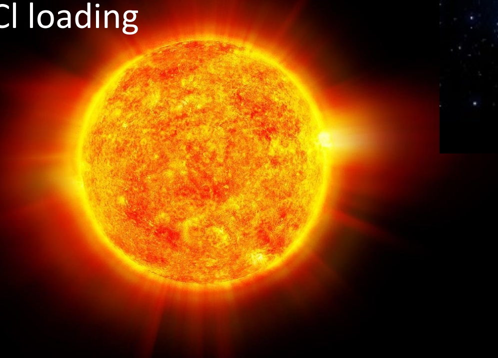
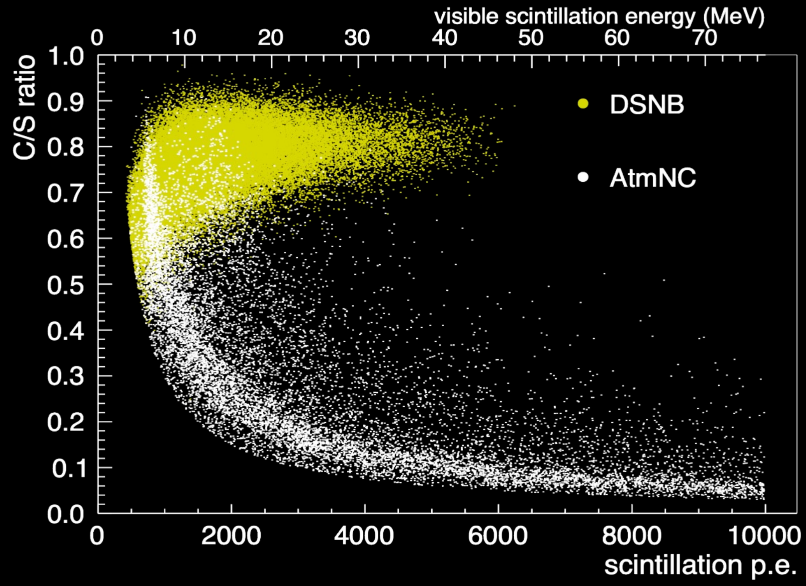


Diffuse Supernova Neutrinos
C/S-based discrimination
of atmospheric NC events

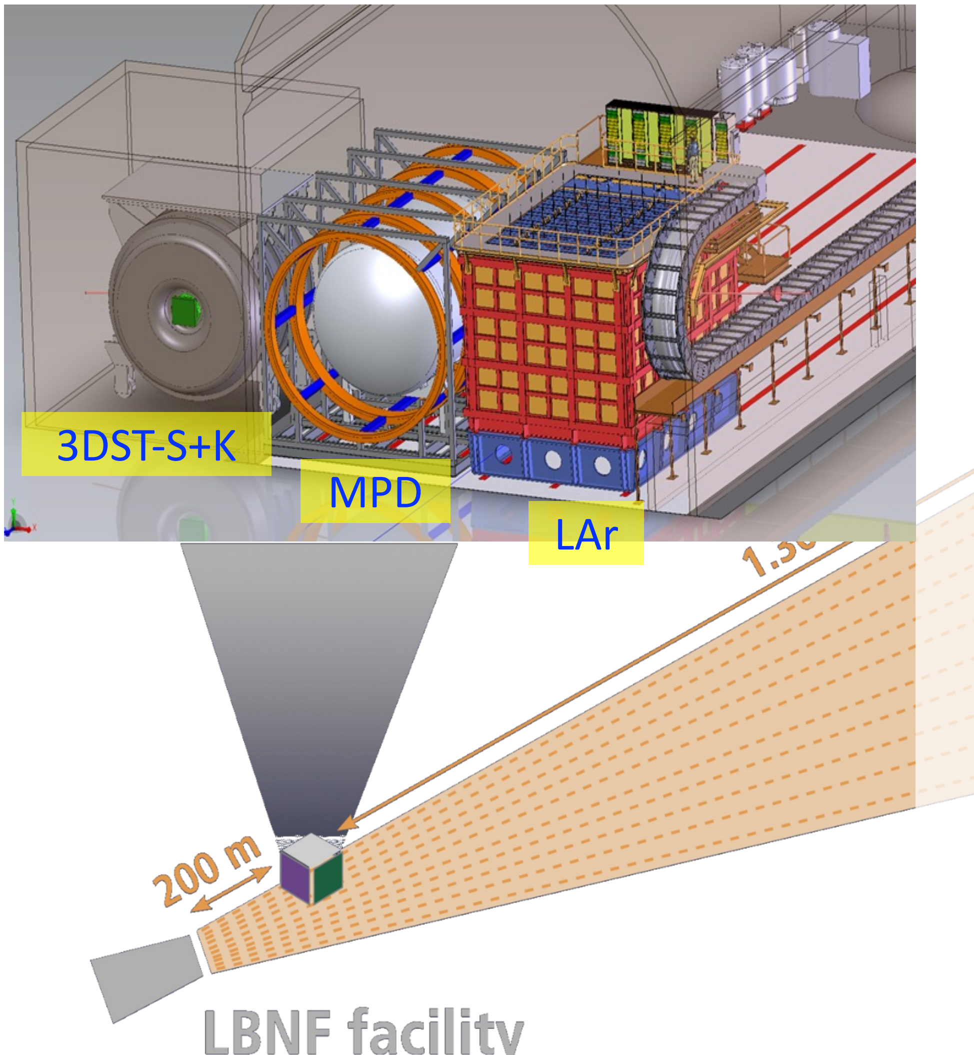
→ excellent S:B ratio



Geoneutrinos
crust/mantle contribution
U/Th ratio

DUNE Near Detector vs. THEIA?

DUNE Near Detector Complex



DUNE ND uses **agron** as target isotope
→ does this configuration suit THEIA?

Up to a point, yes!

- Predict neutrino spectrum at Far Site
- Measure the neutrino energy
- Measure cross-sections on oxygen (?)
- Measure neutrino flux
- Measure under different angles (PRISM concept)
- Monitor neutrino beam

Solar neutrinos

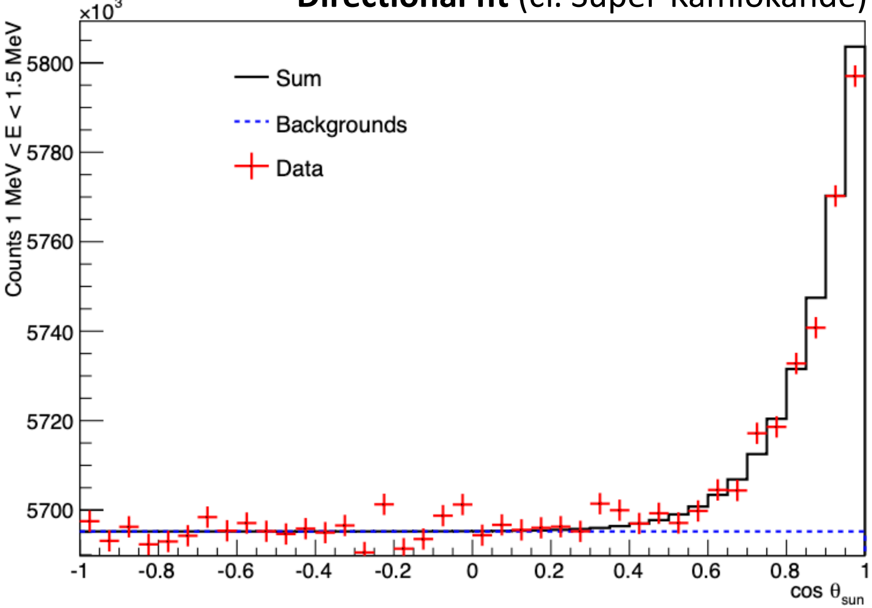
Objectives:

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

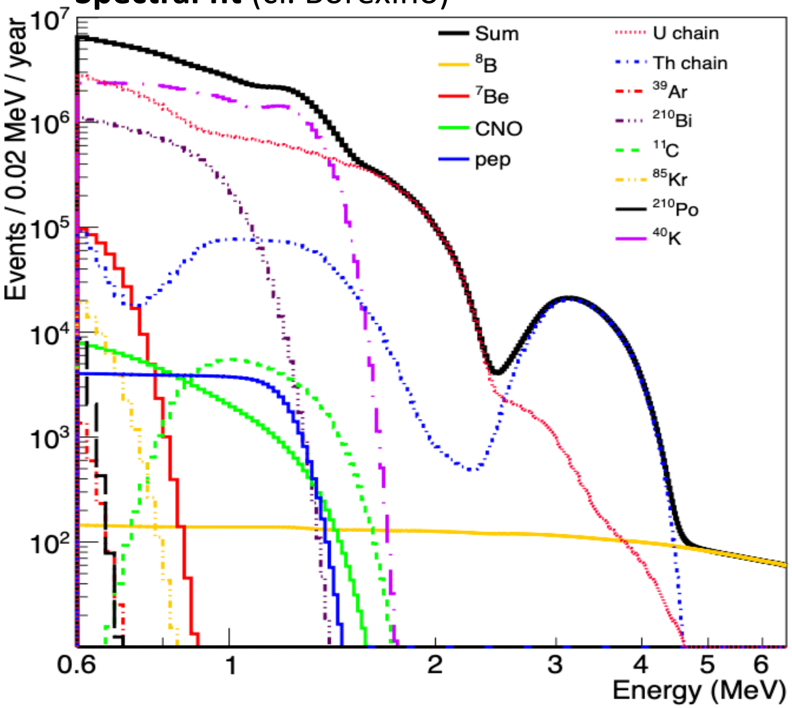
→ require efficient BG discrimination and sufficient light yield in 1-3 MeV range

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

Directional fit (cf. Super-Kamiokande)

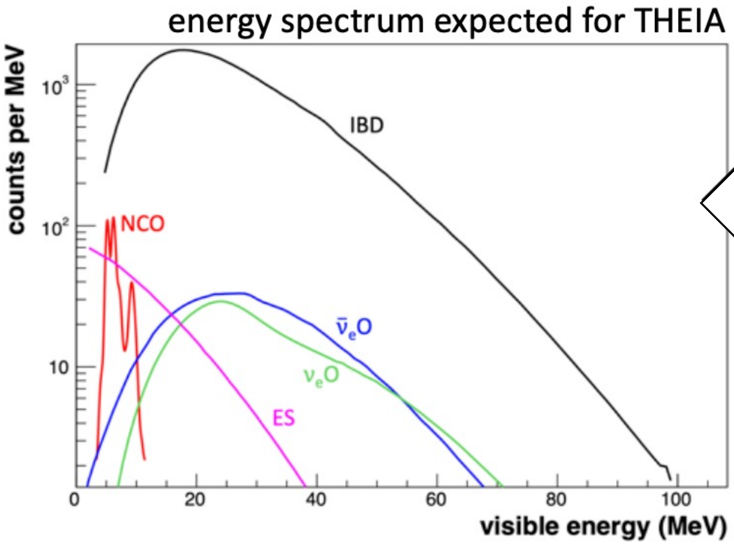


Spectral fit (cf. Borexino)

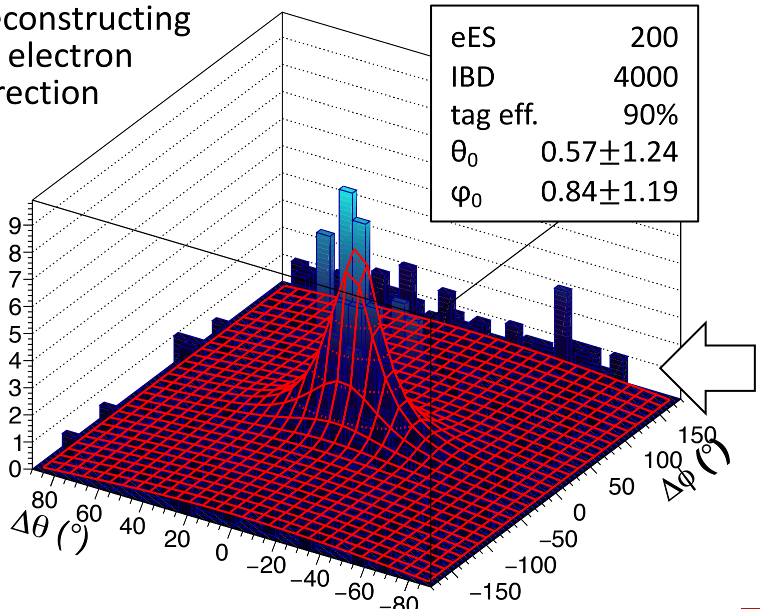


R. Bonventre, G.D. Orebi Gann, Eur. Phys. J. C (2018) 78:435

Supernova Neutrinos in THEIA25



Reconstructing ES electron direction



Galactic Supernovae (10kpc):

Expected events: **~5,000, mostly $\bar{\nu}_e$'s** from IBD

- complementary to ν_e signal in LAr
- Same location as DUNE Far Detectors: compare Earth matter effects in $\nu/\bar{\nu}$ channels
- Provide fast trigger for Lar TPCs, especially for far-off Supernovae (LMC: ~200 events in THEIA)

Detection channels can be separated due to **neutron & delayed decay tags**

- some all-flavor (ν_e+ν_μ+ν_τ) information from NC reactions on oxygen
- **Enhanced SN pointing:** ~2° based on ES with IBD background subtraction

Diffuse Supernova Neutrino Background

DSNB detection:

- Low-flux $\mathcal{O}(10^2\ \mathrm{cm}^{-2}\mathrm{s}^{-1})$ $\bar{\nu}_e$ signal
  → detectable by IBD: ~2 ev. per 10 kt·yrs
- Requires efficient BG discrimination, especially to atmospheric ν NC interactions
- In THEIA:
  - ring counting:
  - **Cherenkov/scintillation ratio**
  - delayed decay tags

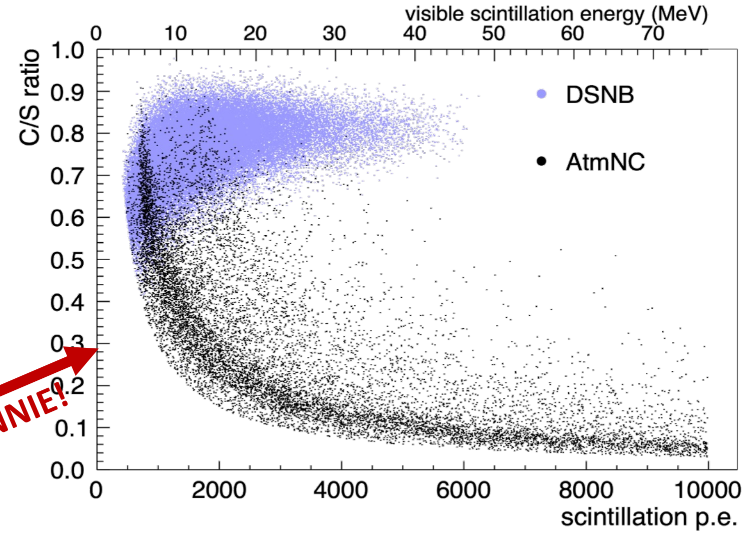
→ signal efficiency: 95%
→ residual background: 1.7%

very clean measurement cf. JUNO & SK-Gd

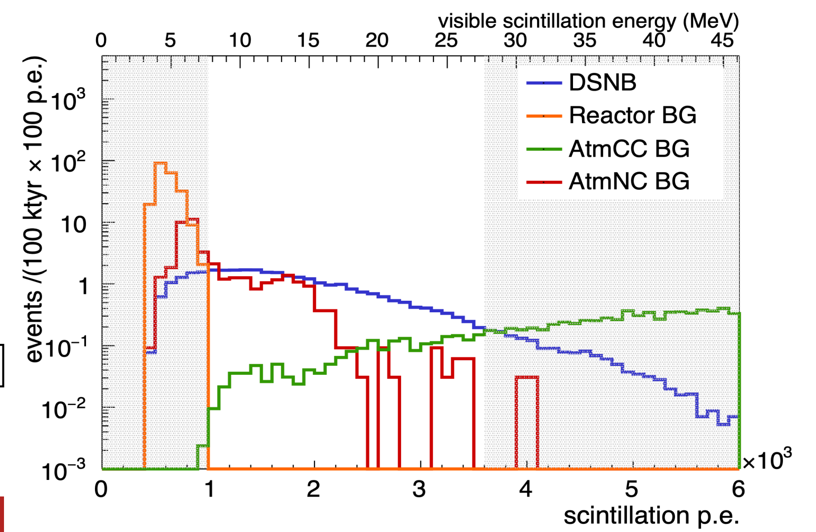
THEIA25: 5 IBDs over 2.7 BG per year
→ **5σ discovery after 6 years**

NC BG data by ANNIE!

Cherenkov/scintillation ratio for BG discrimination

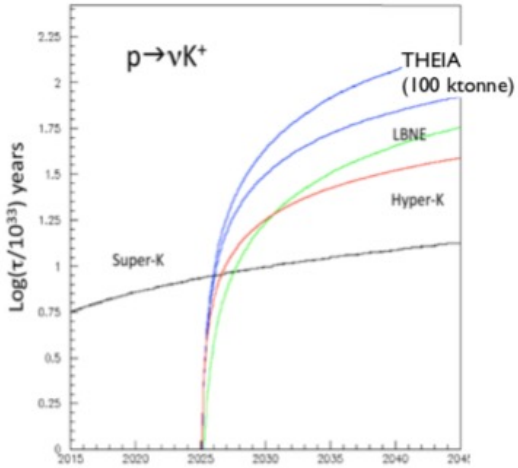


Signal/BG spectra and observation window

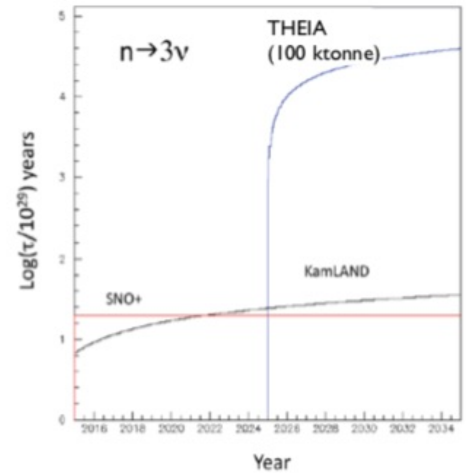


THEIA Proton decay sensitivity

Scintillation light allows observation of K+, as well as de-excitation γs from "invisible"decay modes.



Sub-Chr t/h detection
⇒ Directly visible K⁺
A 50 ktonne THEIA+DUNE ~ 100 ktonnes



R. Svoboda

Deep, low threshold
De-excitation γs observaiable via Cher or Scint

For p→$e^+\pi^0$ mode, not likely to be competitive with Super-K/Hyper-K unless THEIA can be made > 200 kton

Neutrinoless double-beta decay

Insertion of subvolume holding
1.8kt of organic scintillator (LAB+PPO)

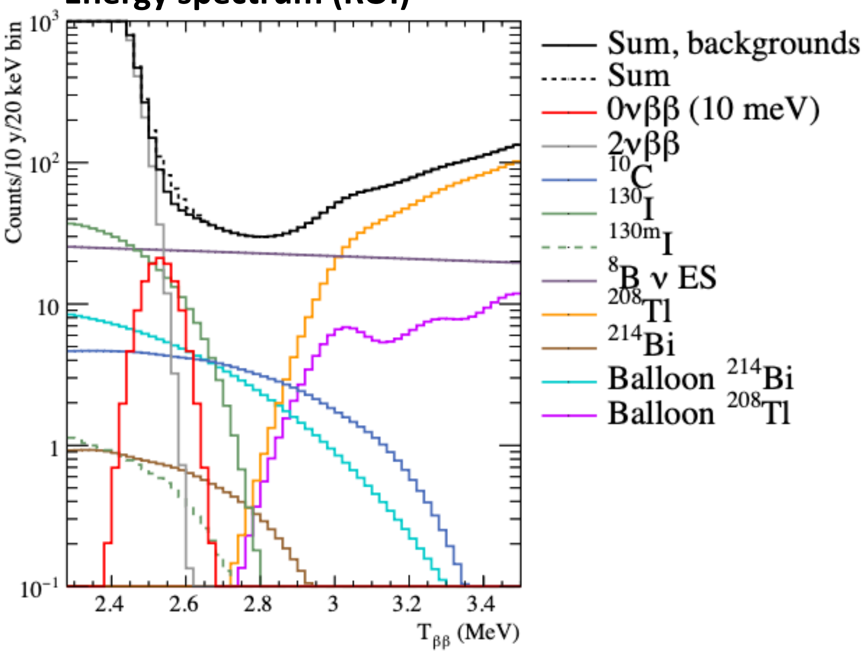
loading: -- **3% enriched Xe** (89.5%)
-- **5% natural Te** (~90t)

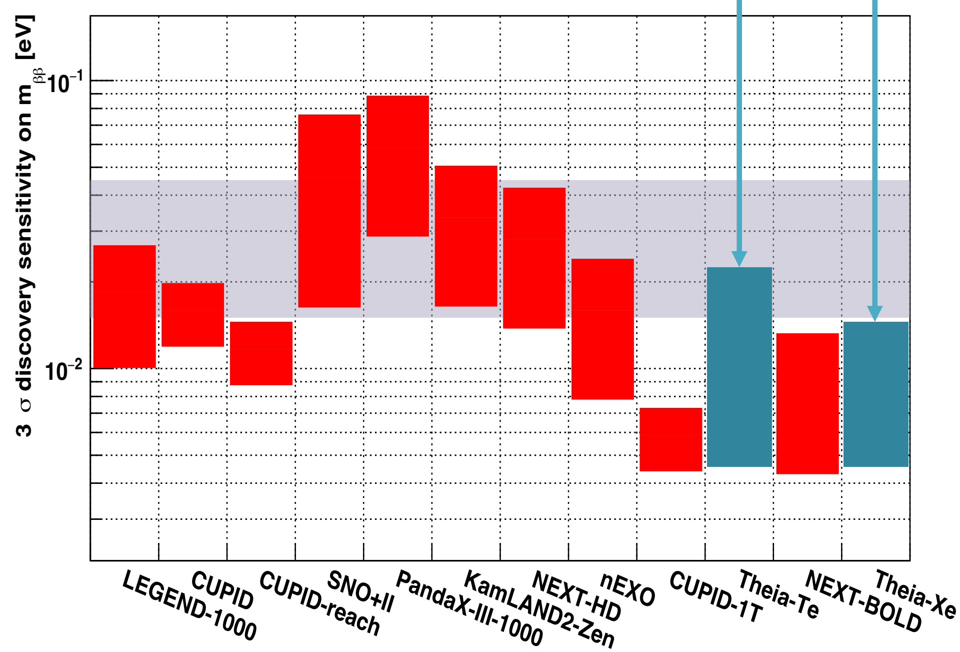
enhanced photo-cov. 1200 pe/MeV (cf. JUNO)
→ **3% energy resolution**

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

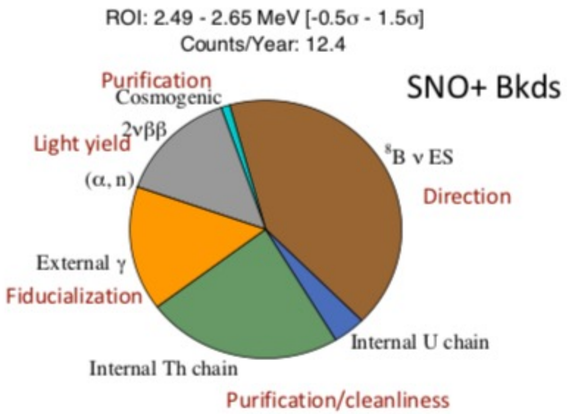
Energy spectrum (ROI)

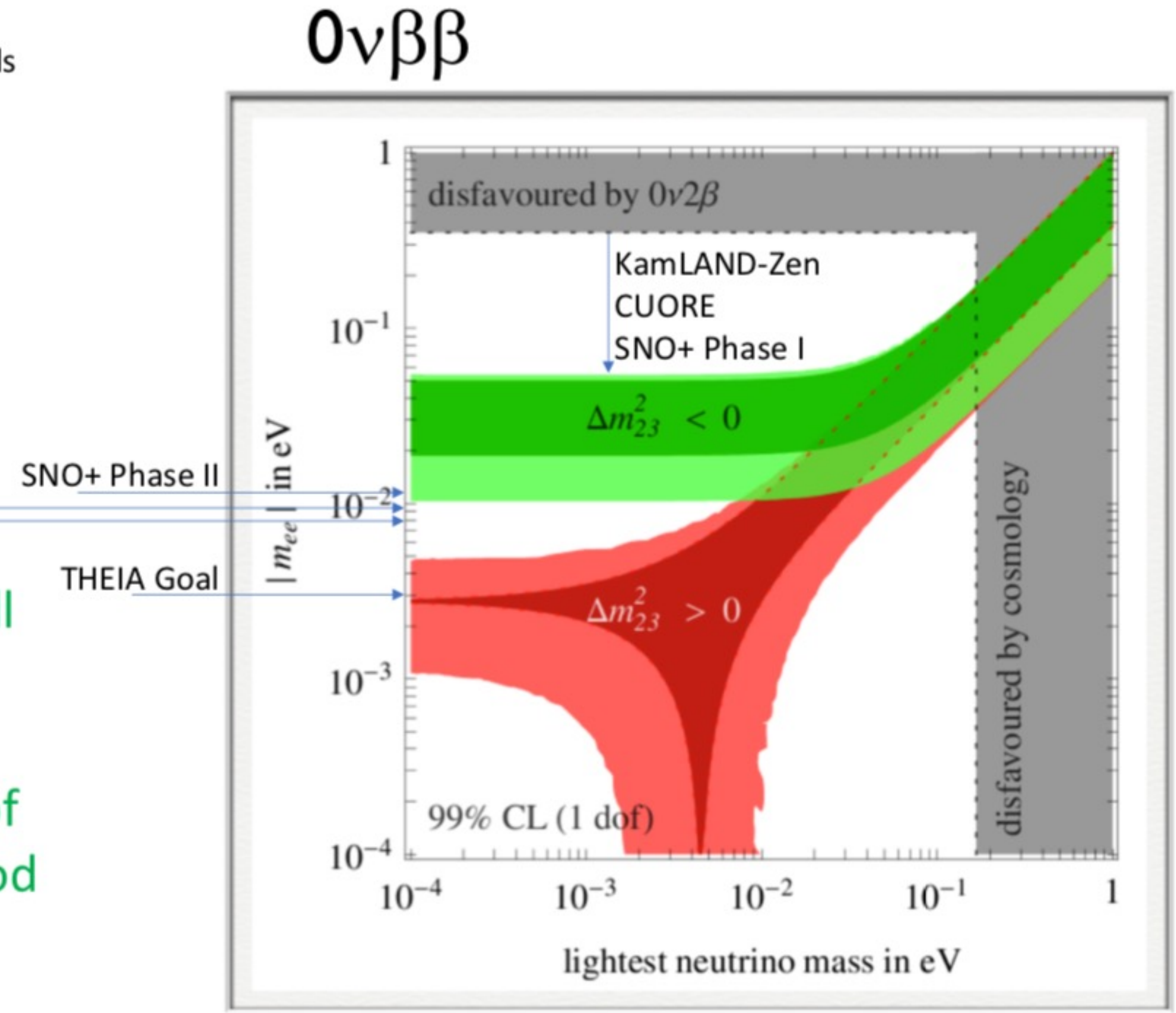




Plot by Yu. G. Kolomensky using methodology from Agostini, Benato, Detwiler: PhysRevD.96.053001

0νββ in very large LS volumes





Getting below 5 meV will require > 10 tonnes of isotope, a small fiducial volume, and reduction of backgrounds though good resolution (2ν) and direction (⁸B)

THEIA Whitepaper online!

arXiv:1911.03501

THEIA: An Advanced Optical Neutrino Detector

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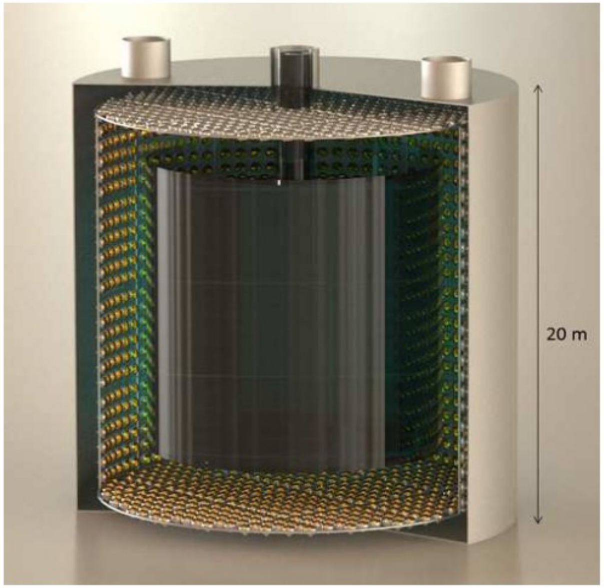
THEIA proto-collaboration:
groups from 35+ institutions and eight countries (CA, CN, DE, FI, IT, KR, UK, US)

More information on:

- Detector technology
- Low energy neutrinos, e.g. geoneutrinos
- Nucleon decay
- LBL oscillations
- …

Slow LS in Jinping Neutrino Experiment

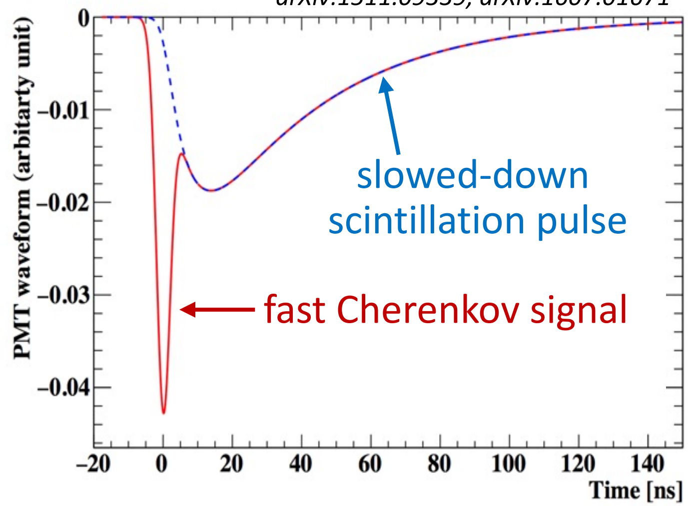


Jinping Neutrino Experiment

- 2-5 kt of conventional LS, low fluor concentration
- conventional PMTs, but high optical coverage
- located at Jinping underground laboratory: 8000 mwe overburden

→ **solar & geo-neutrinos**

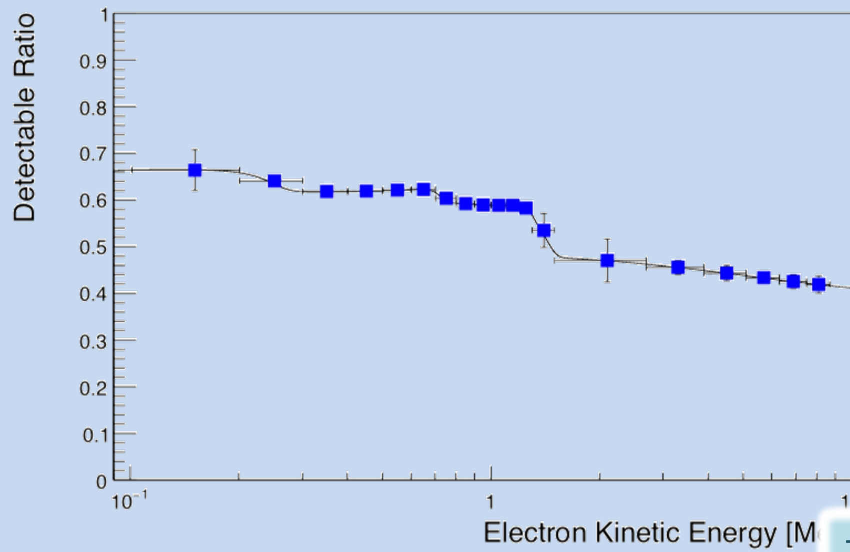
arXiv:1511.09339, arXiv:1607.01671



Slow LS:
LAB + 0.1 g/l PPO

- slowed-down scintillation signal
- reduced scintillation output
- slightly improved transparency

Solar ν_e survival probability (Jinping Experiment)



LoI Jinping NE, arXiv:1602.01733

→ **We:** talk by Chen Shaomin