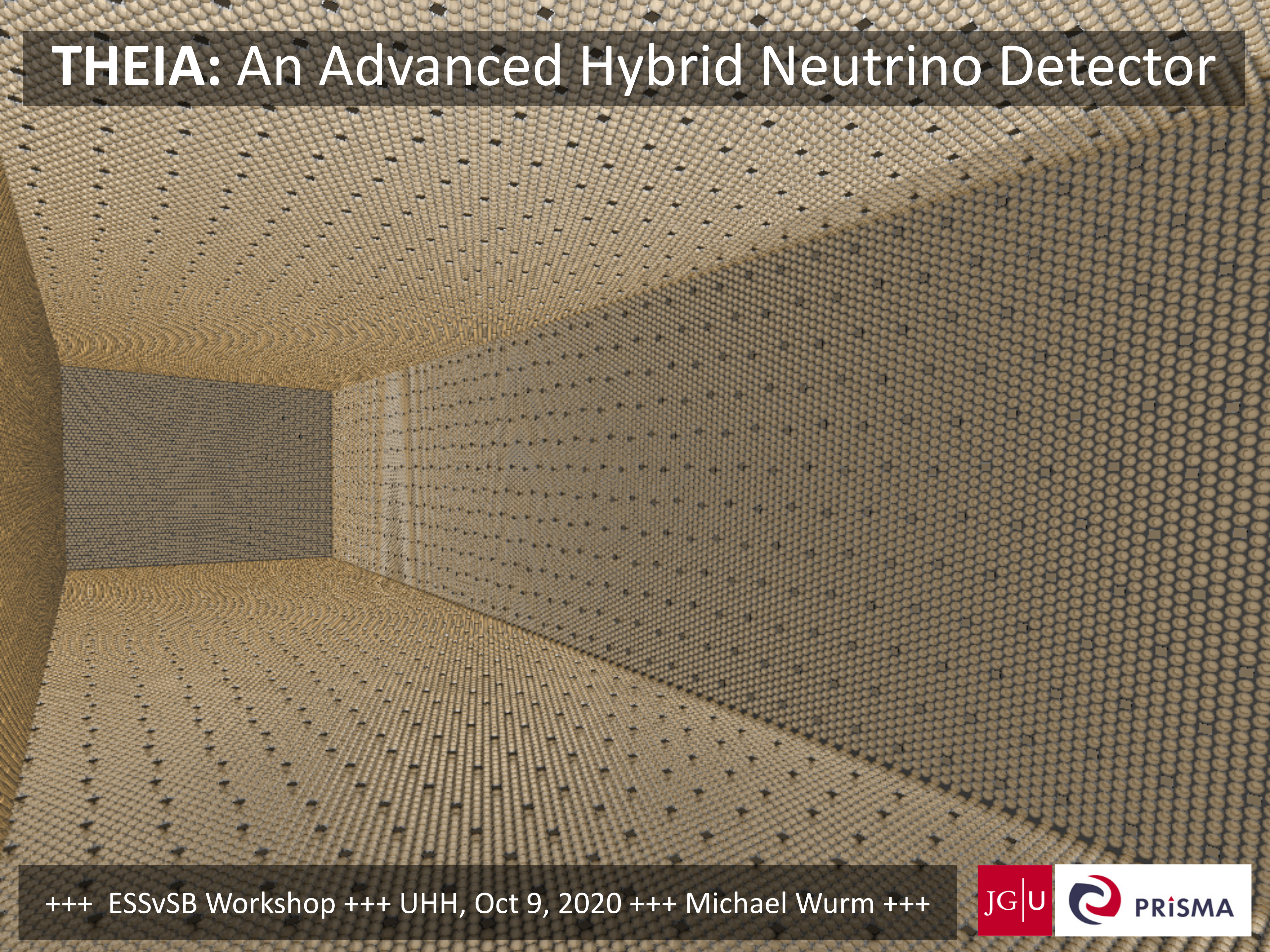
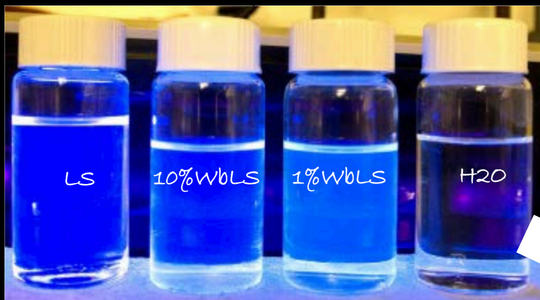
THEIA: An Advanced Hybrid Neutrino Detector

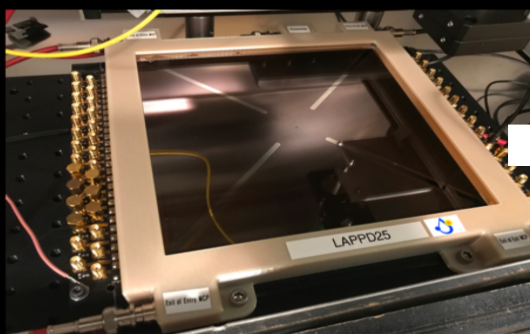


+++ ESSvSB Workshop +++ UHH, Oct 9, 2020 +++ Michael Wurm +++

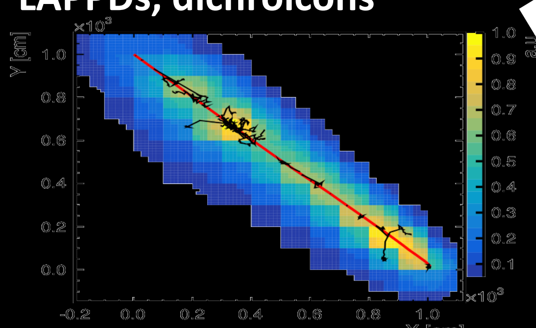
What is THEIA?



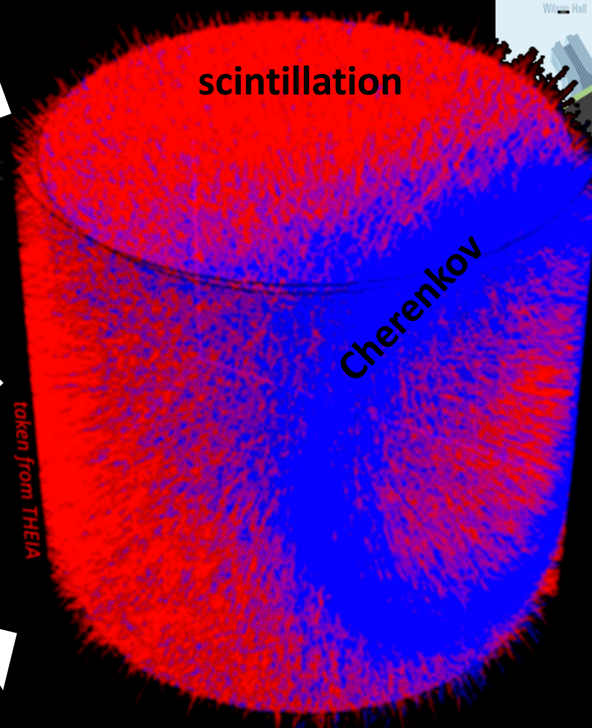
Novel target medium:
Water-based Liquid Scintillator



Novel light sensors:
LAPPDs, dichroicons

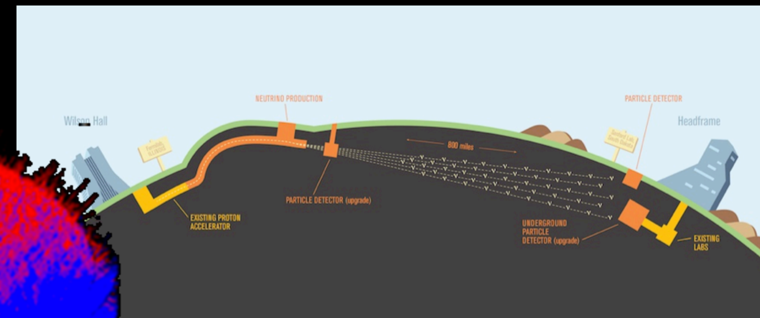


Novel reconstruction techniques



Large volume detector
able to exploit both
Cherenkov+Scintillation
signals

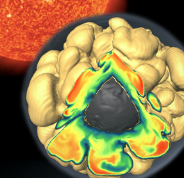
→ Enhanced sensitivity to broad physics program



Long-Baseline Oscillations

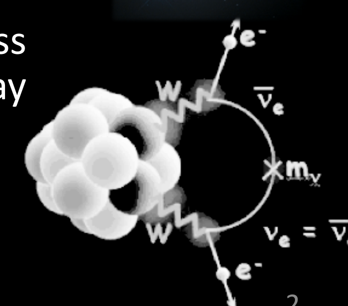
Solar neutrinos

Supernova neutrinos



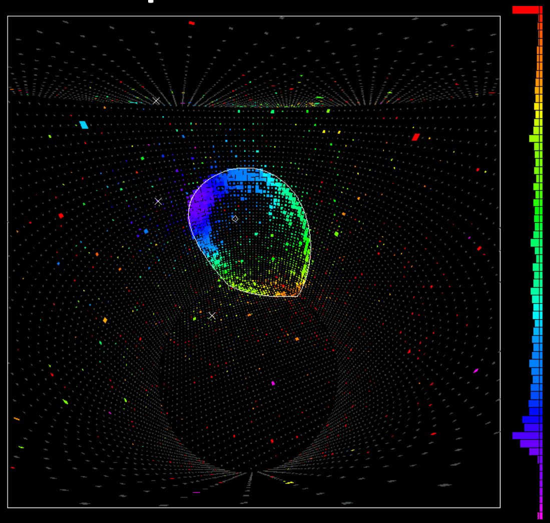
Diffuse SN neutrinos

Neutrinoless
Double-Beta Decay



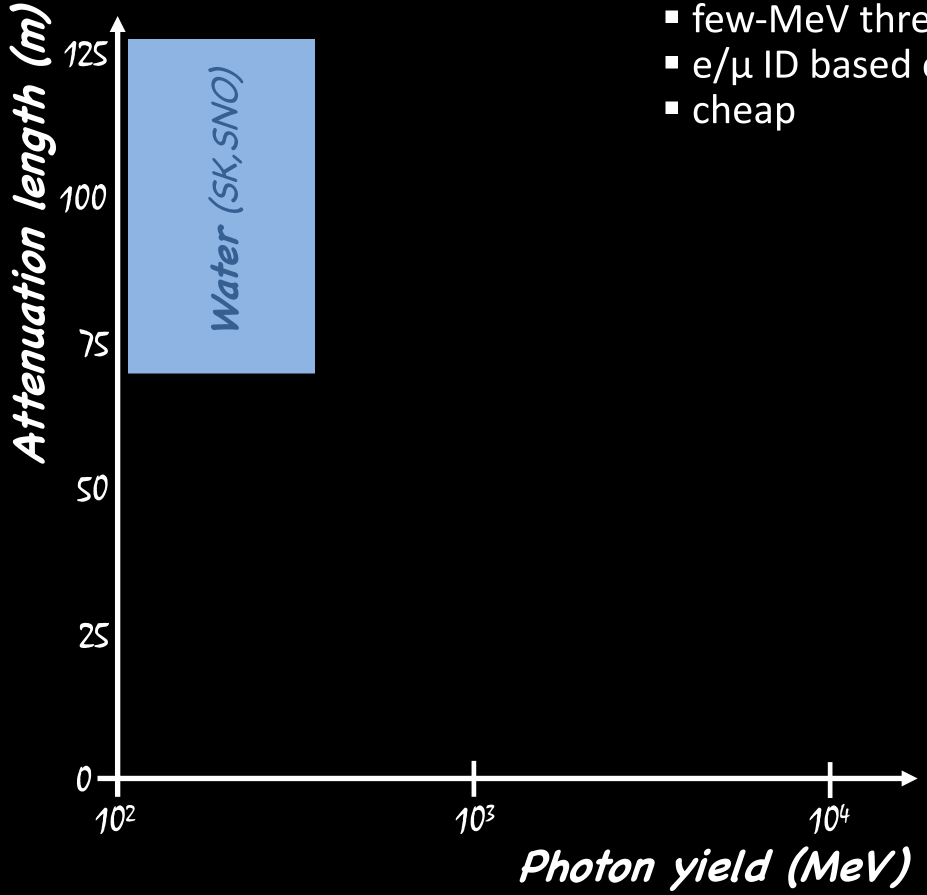
Low-energy neutrino detectors

Super-Kamiokande



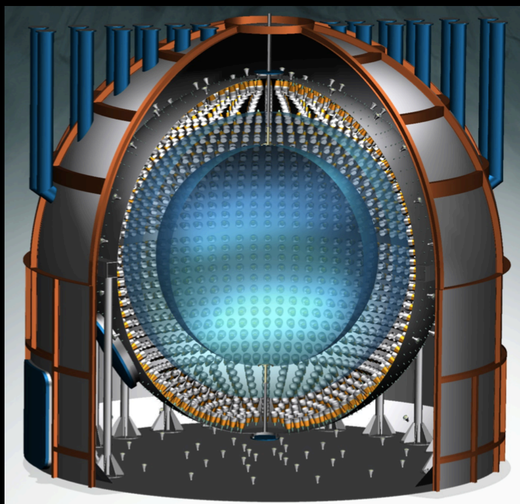
Water Cherenkov Detectors:

- large volume (25kt → 250kt)
- directional reconstruction
- few-MeV threshold
- e/µ ID based on ring fuzziness
- cheap

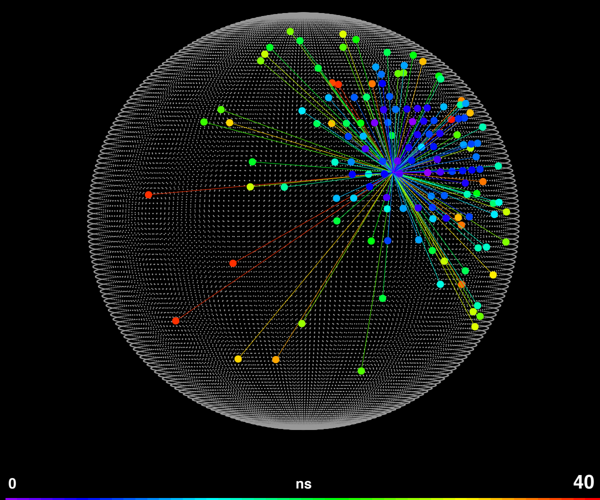


→ **great for >5MeV and sub-GeV neutrinos**

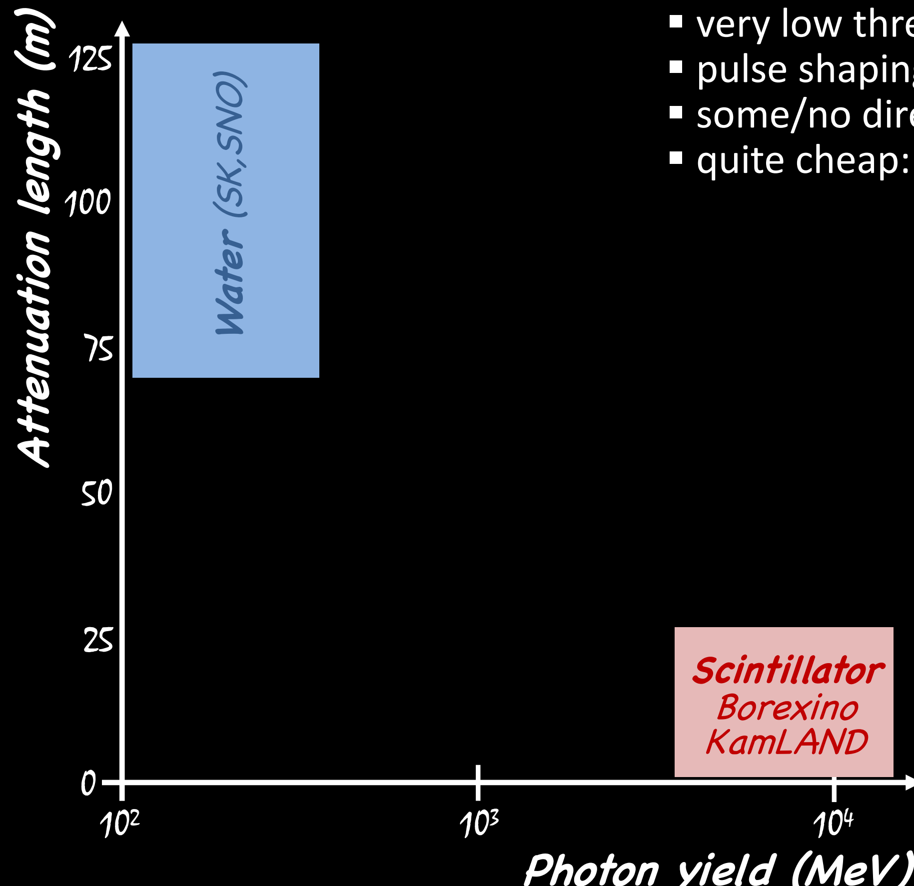
Low-energy neutrino detectors



Borexino



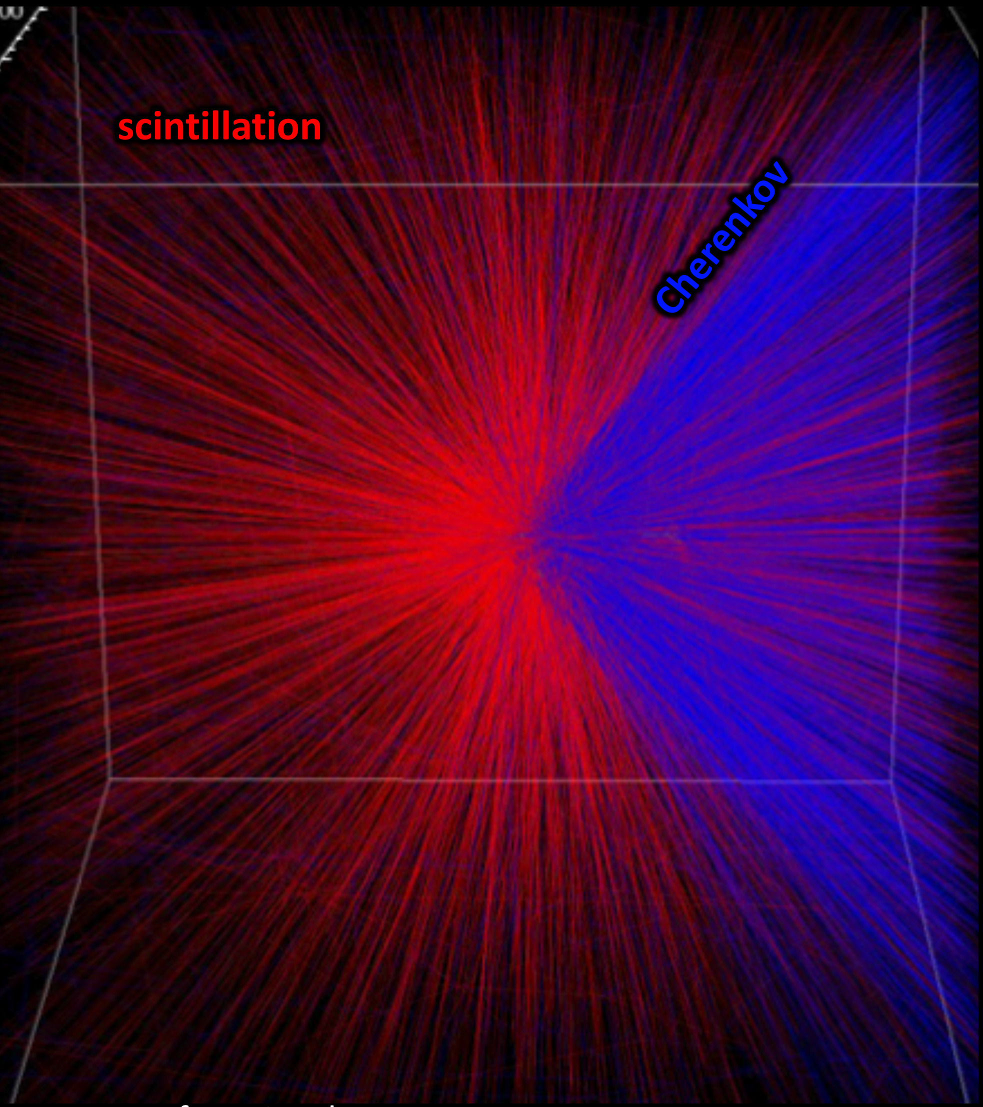
Liquid Scintillator Detectors:



- smaller volume (300t → 1kt)
- excellent energy resolution
- very low threshold: ~150keV
- pulse shaping for α/β/p ID
- some/no directionality
- quite cheap: 1.50 €/kg

→ great for <5 MeV neutrinos

Cherenkov photons in scintillator



courtesy of Ben Land

→ Cherenkov light is particularly useful for reconstruction of direction and (multiple) tracks

→ Cherenkov photons are produced in liquid scintillators (~5%)

→ the majority is scattered or absorbed before reaching PMTs

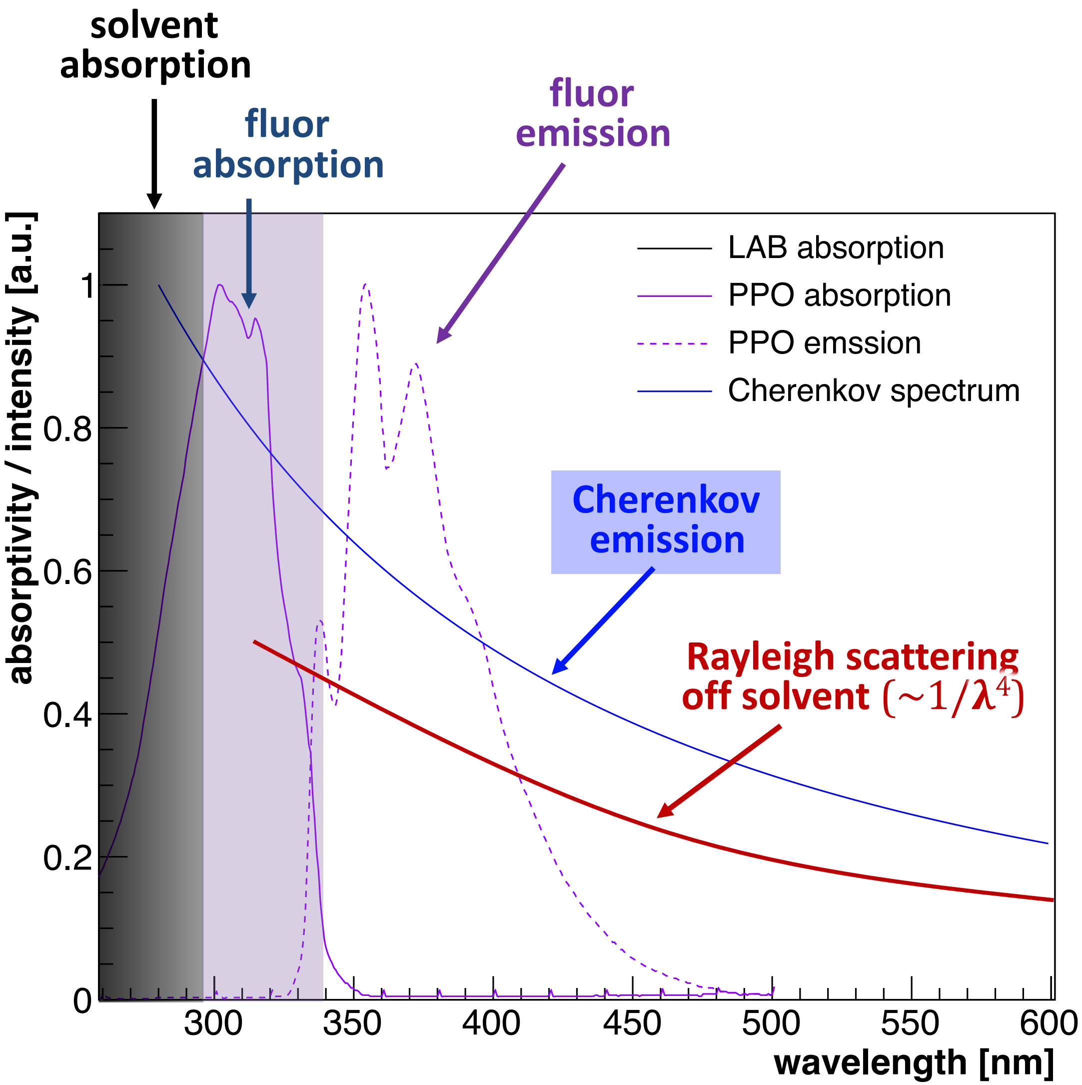
To make use of it:

→ reduce scattering/absorption

→ separation of Cherenkov and scintillation photons

Light propagation in organic scintillators

JG|U



How to improve the (relative) Cherenkov photoelectron yield?

→ **reduce fluor concentration**

- impacts scintillation yield
- slows down scintillation (helps separation, see later)

→ **reduce Rayleigh scattering**

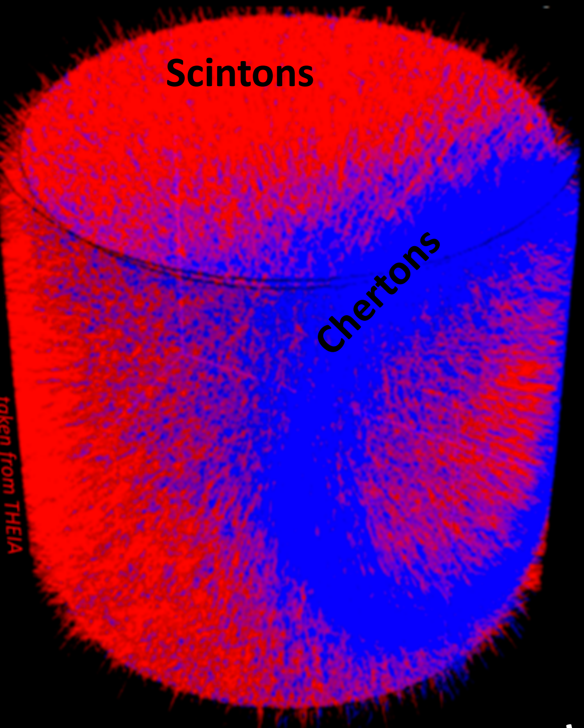
- new transparent solvent, e.g. LAB (~20m)

  and/or

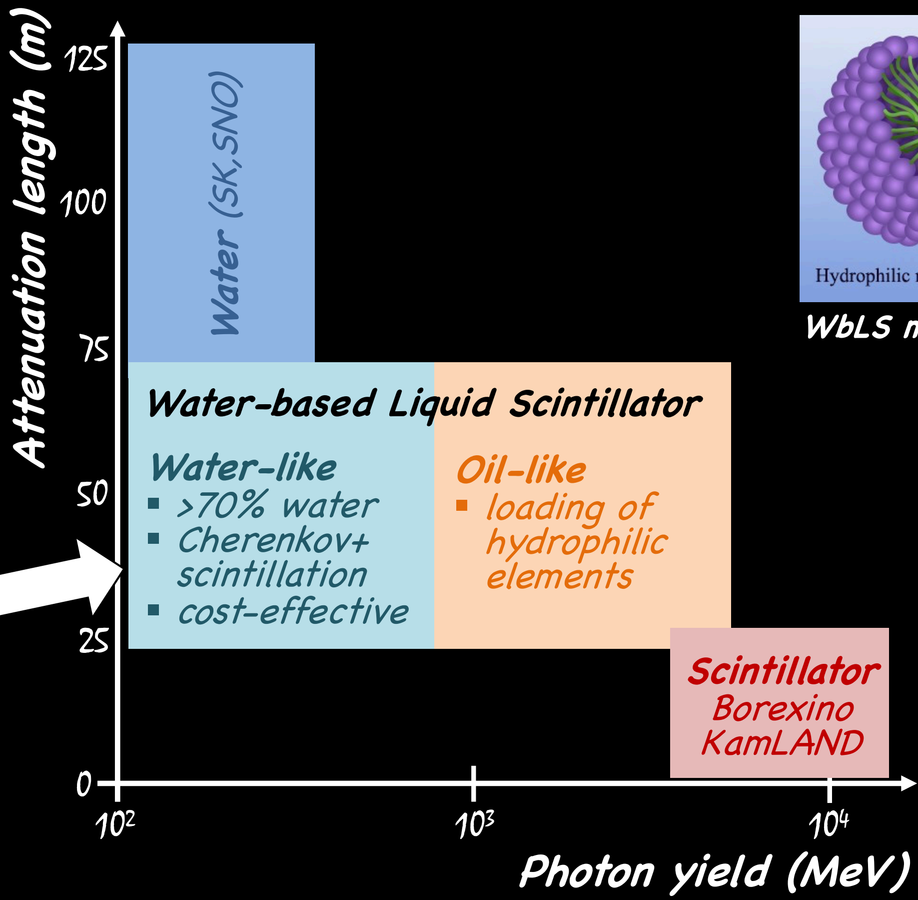
- dilution of solvent: Water-based scintillators Oil-diluted LS (LSND …)

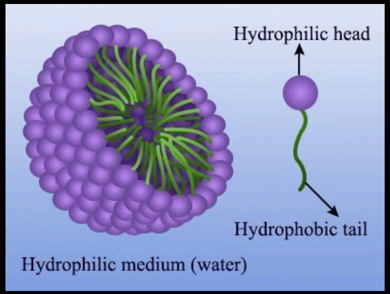
Water-based Liquid Scintillator

JG|U



→ how to generate (and preserve!) scintillation and Cherenkov photons?





WbLS mycels (nm-scale)

Sufficiently transparent to extract Cherenkov photons!

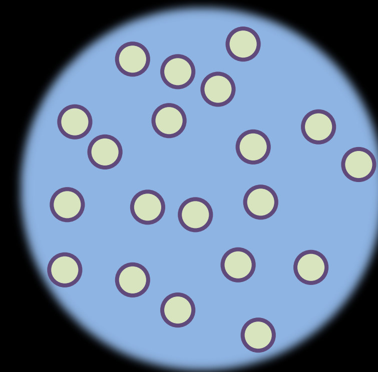
→ properties of target medium can be adjusted to physics goal

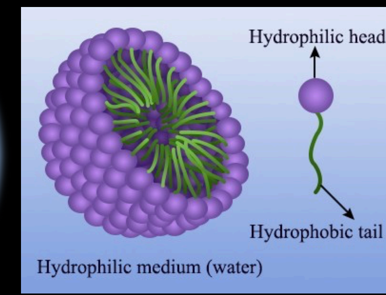
Water-based Liquid Scintillator?

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 nanometer-scale droplets (mycels) of organic LS in the water phase

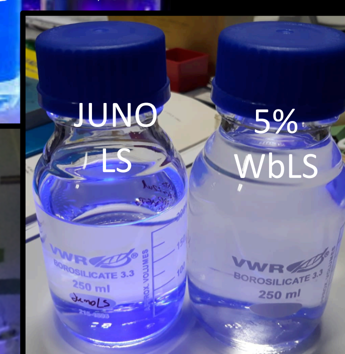
Properties
- very transparent (water)
- some Rayleigh scattering of mycels (size!)
- scintillation! (linear with organic fraction)
- fast timing (LAB→PPO transfer times)





WbLS mycels (nm-scale)

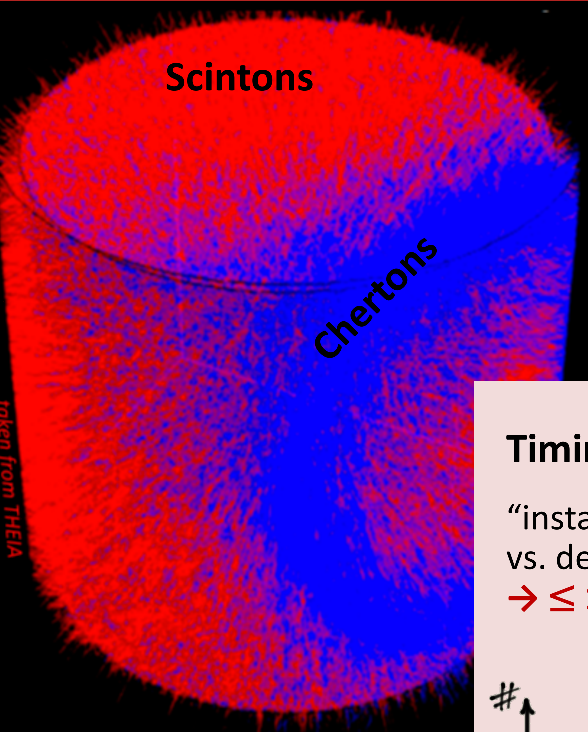
Minfang Yeh, BNL



Hans Steiger, JGU Mainz

UC Davis

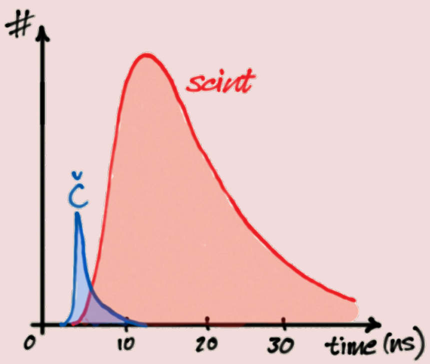
Separating Chertons and Scintons



→ how to resolve the Cherenkov/scintillation signals?

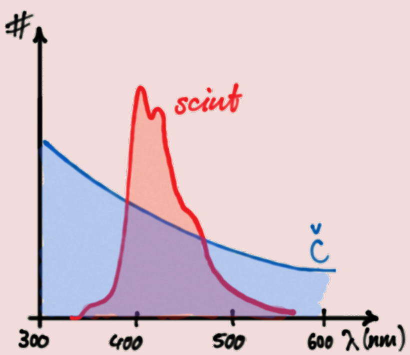
Timing

"instantaneous chertons" vs. delayed "scintons"
→ ≤ 1 nanosec resolution



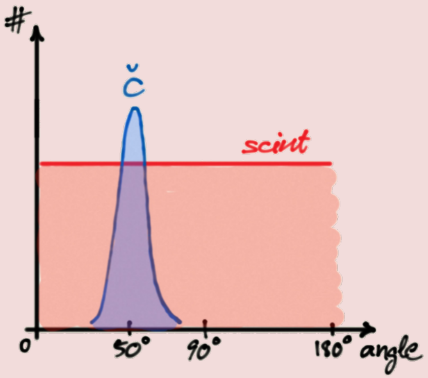
Spectrum

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



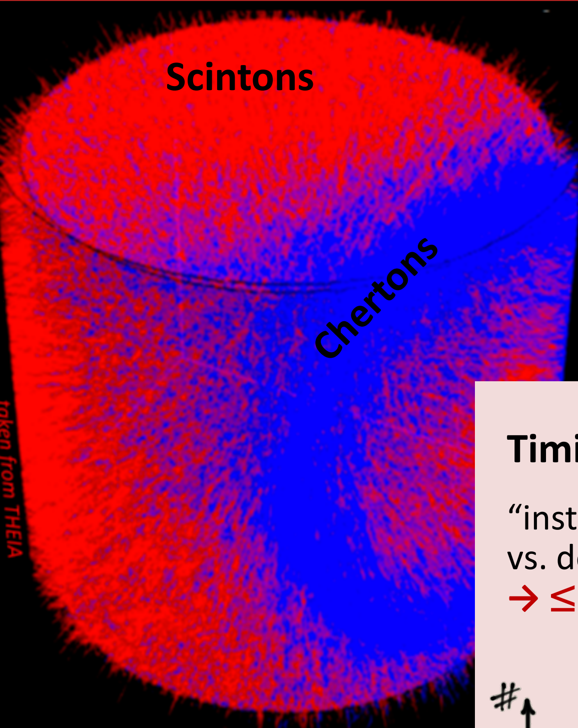
Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity



Separating Chertons and Scintons

JG|U



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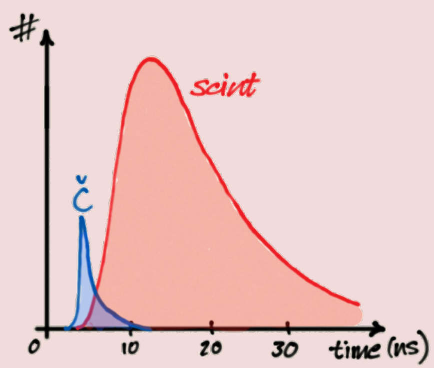

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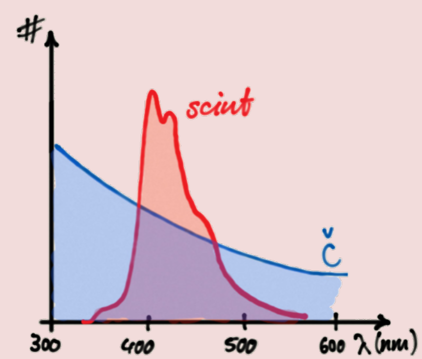

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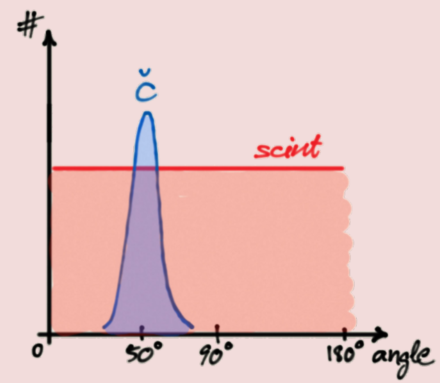


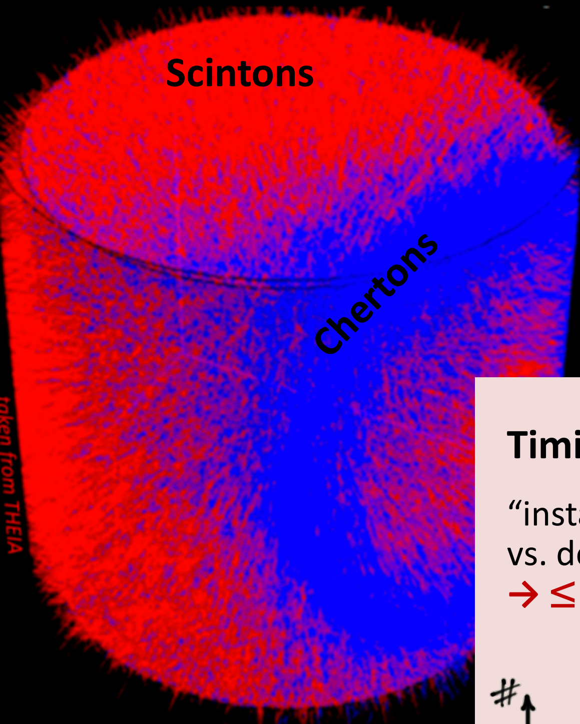
e.g.

LAPPDs: ~60ps timing

Dichroic filters

Standard PMTs

Separating Chertons and Scintons



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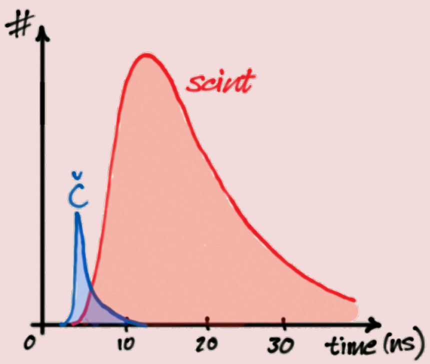
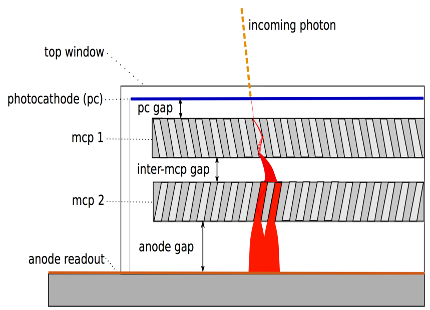
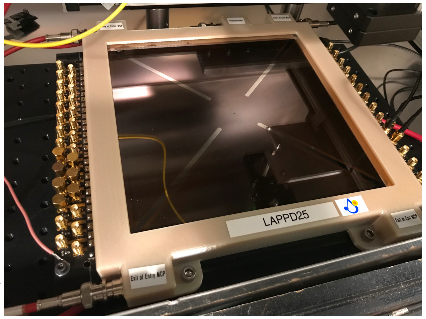


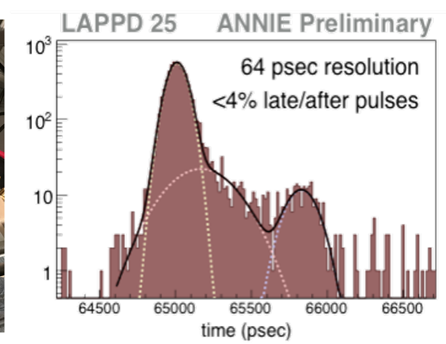
LAPPDs: ~60ps timing

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.







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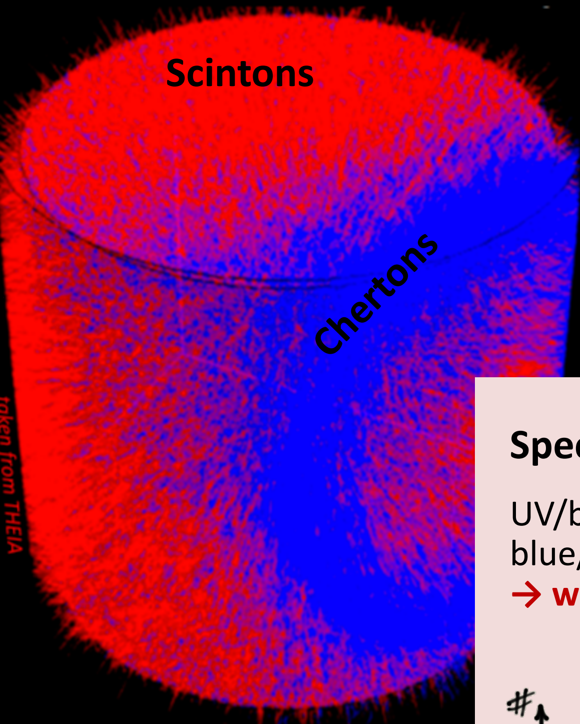

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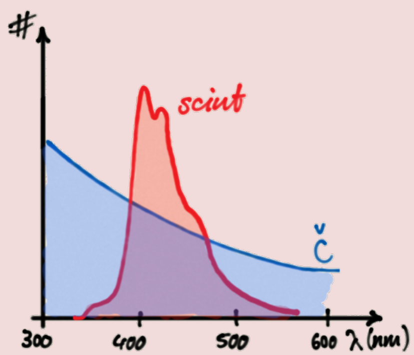
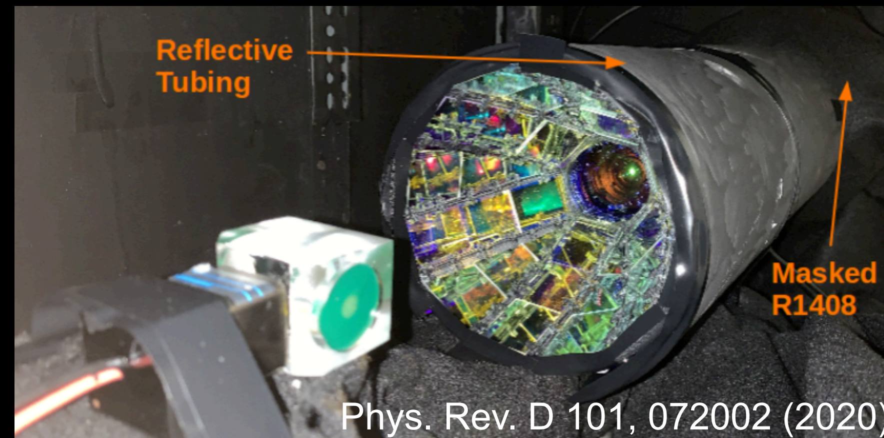
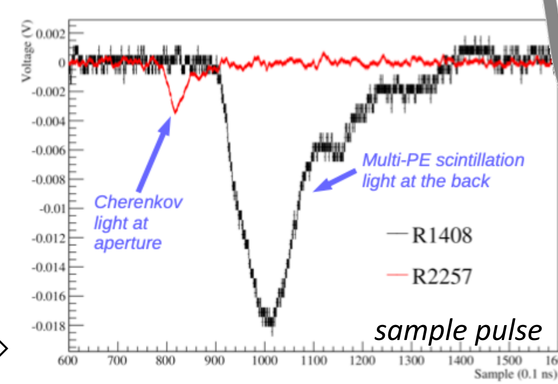


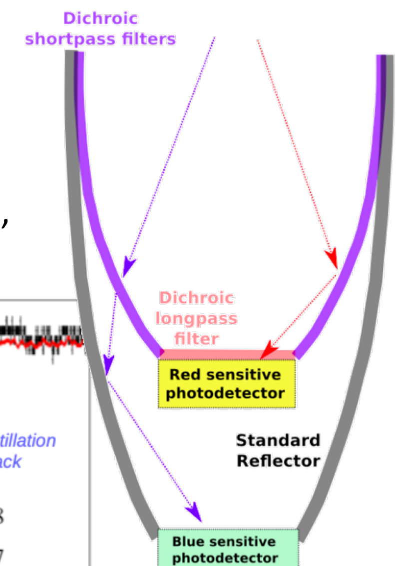
Dichroic filters



Dichroicons (Josh Klein's group @ U Penn)

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

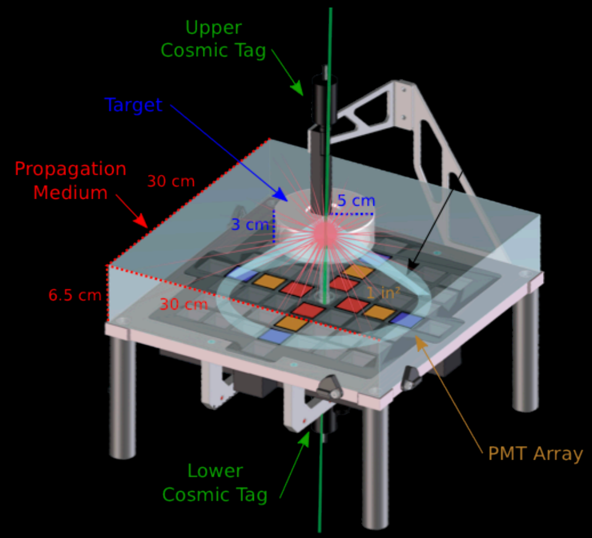




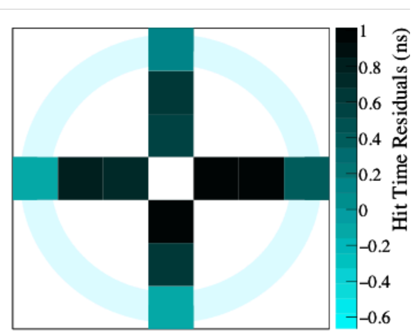
Chertons and Scintons with CHESS

[arXiv:2006.00173]

Setup at UC Berkeley (Gabriel Orebi Gann)



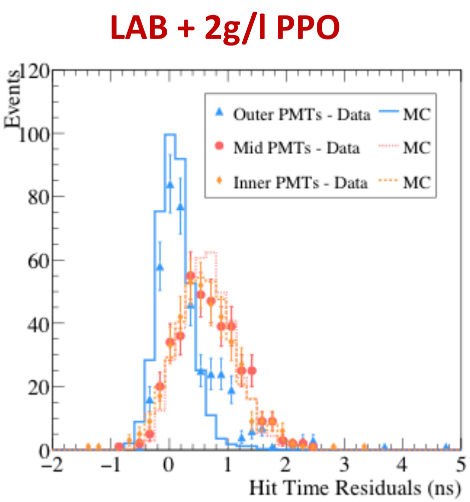
12 1-inch H11934 PMTs (300ps FWHM, 42% QE)
CAEN V1742 (5GHz)
675 samples (135ns window)
CAEN V1730 (500MHz)

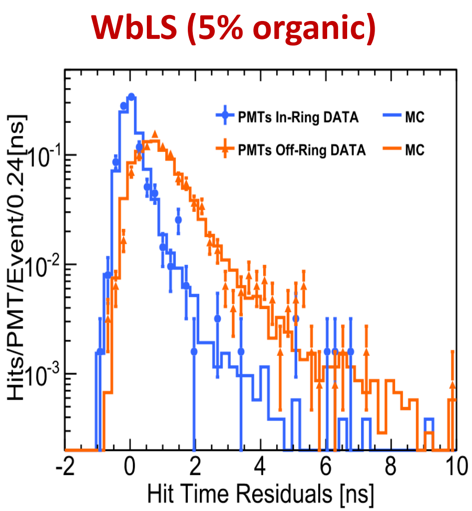


Hit pattern expected on the PMT array for a muon crossing the scintillator target

→ angular and fast timing information

Results for timing distributions in different rings:



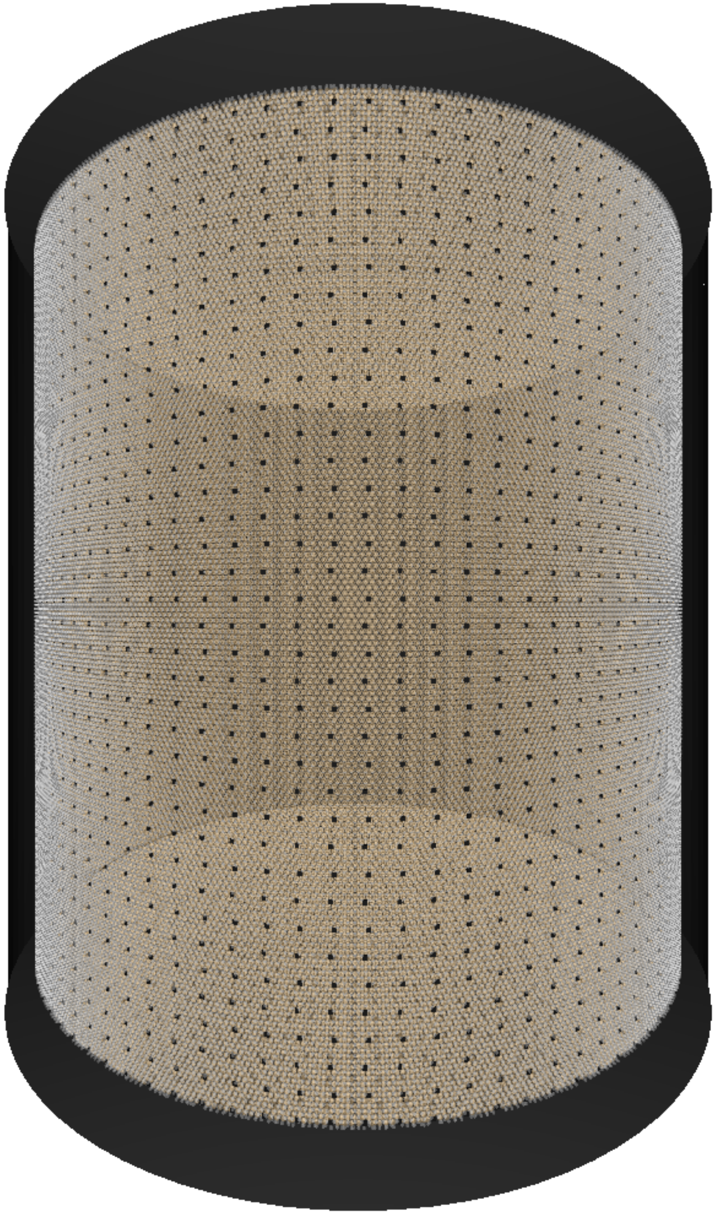


→ **ring and timing pattern clearly visible!**

→ WbLS is found to be faster than pure LAB LS

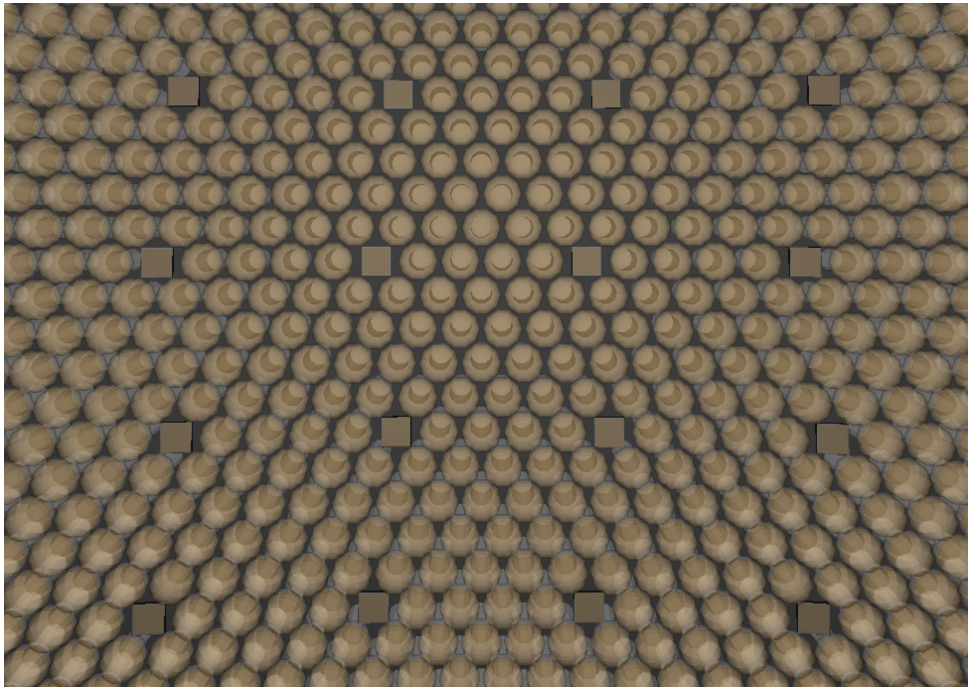
WbLS	1%	5%	10%
τ_1 [ns]	2.25 ± 0.15	2.35 ± 0.11	2.70 ± 0.16
τ_2 [ns]	15.1 ± 7.5	23.2 ± 3.3	27.1 ± 4.2
R_1	0.96 ± 0.01	0.94 ± 0.01	0.94 ± 0.01

THEIA100

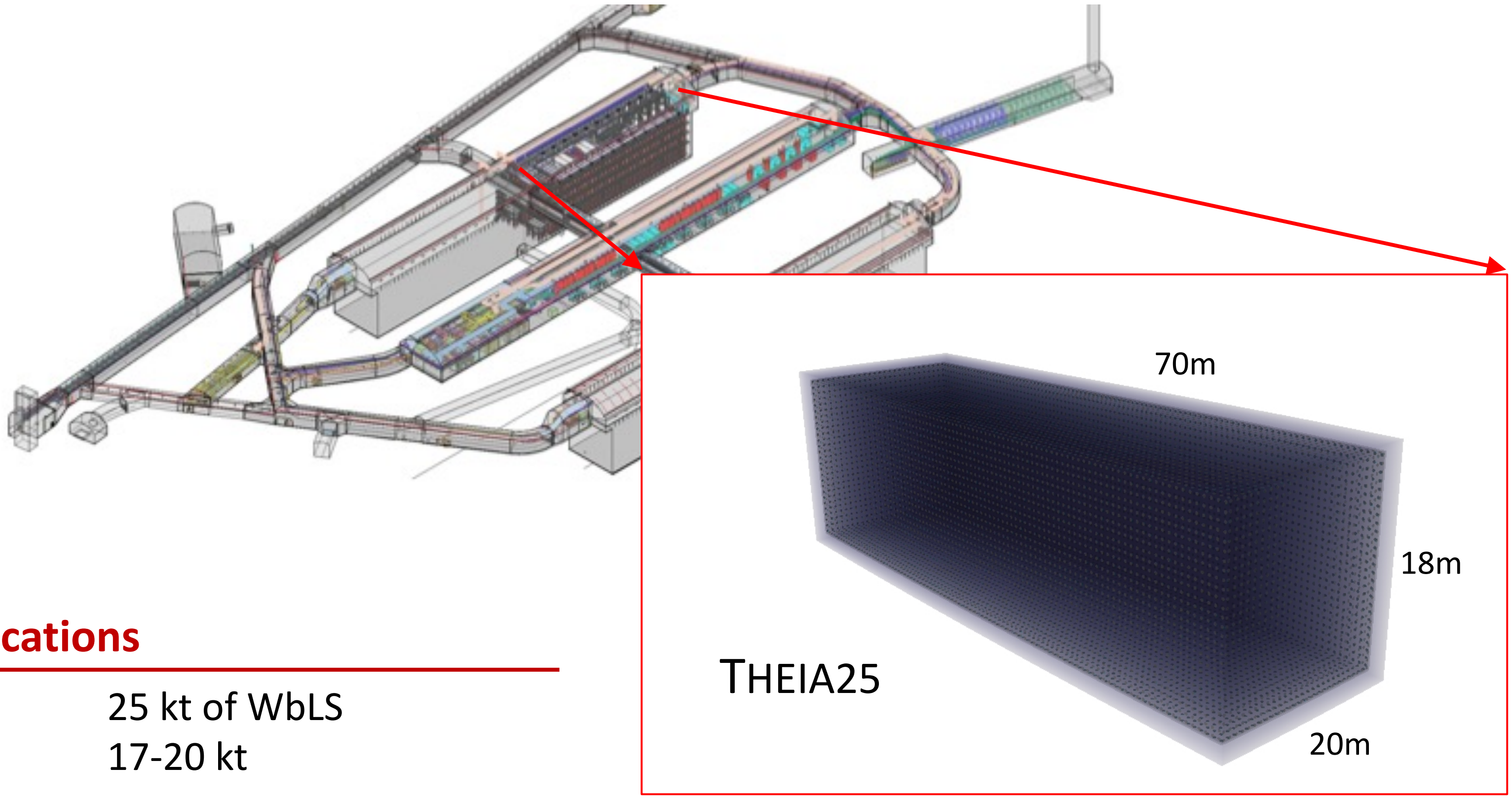


Detector Specifications

- **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 (Homestake, Pyhäsalmi, Swedish sites?)



THEIA25 as Module 4 of DUNE

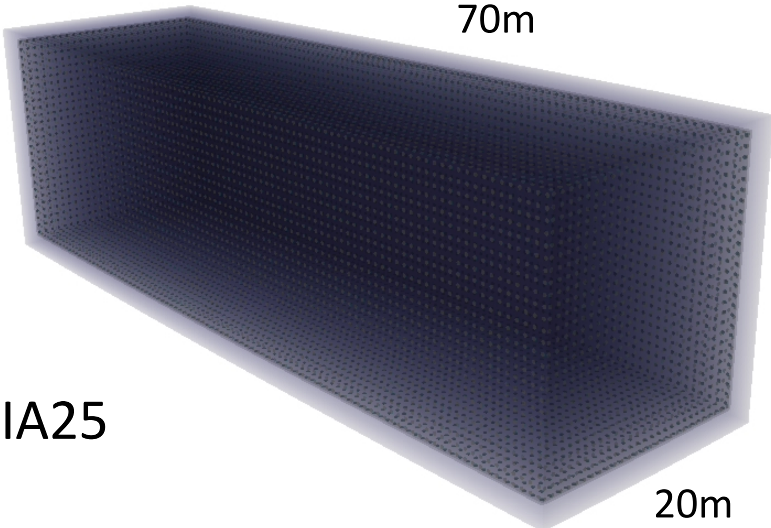


Detector specifications

- **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, 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

THEIA25 : Staged Approach

JG|U



THEIA25

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** $\rightarrow K^+\nu/\pi^0 e^+$
- Supernova neutrinos
- Diffuse SN neutrinos
- Solar neutrinos
- Geoneutrinos
- **$0\nu\beta\beta$ search** on <10meV scale

THEIA in LBNF beam

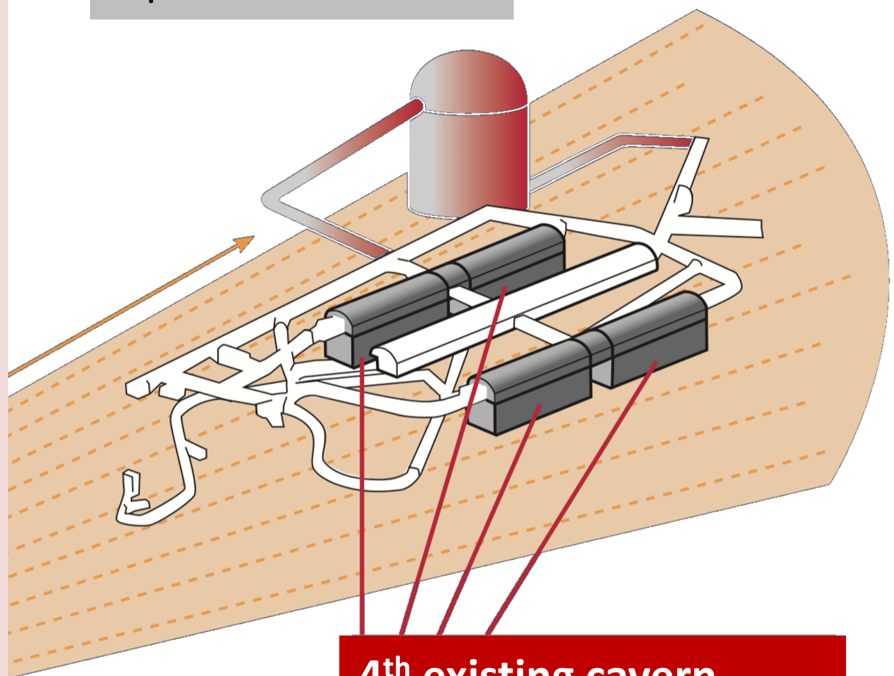
What will a **large WbLS detector** add to the existing LBNF/DUNE program?

Added value for LBL (δ_{CP}) program

- Additional statistics
  ~1.7:1 in mass for WbLS : LAr
- Complementary systematics
  e.g. cross-sections (simpler nuclei)
- hadronic recoils/neutron tagging
  → reduces systematics of energy reco
  → 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

add. THEIA cavern

~50 kt water-based liquid scintillator



4th existing cavern
for 30-kt WbLS detector

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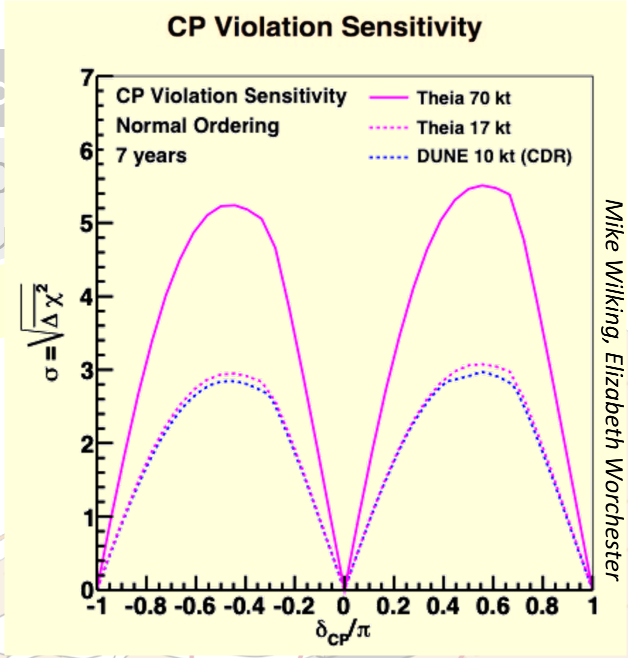

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LBNF facility

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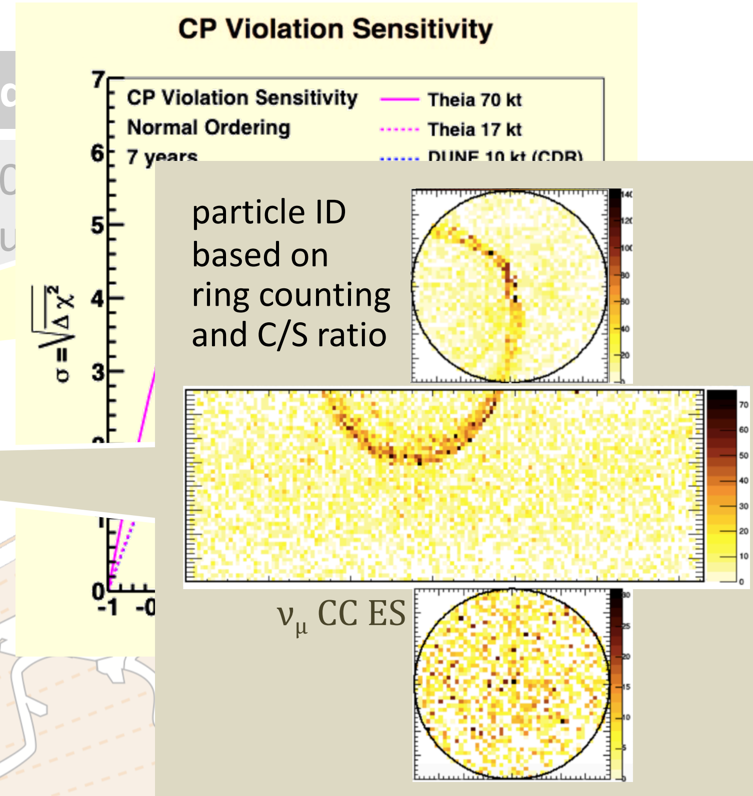

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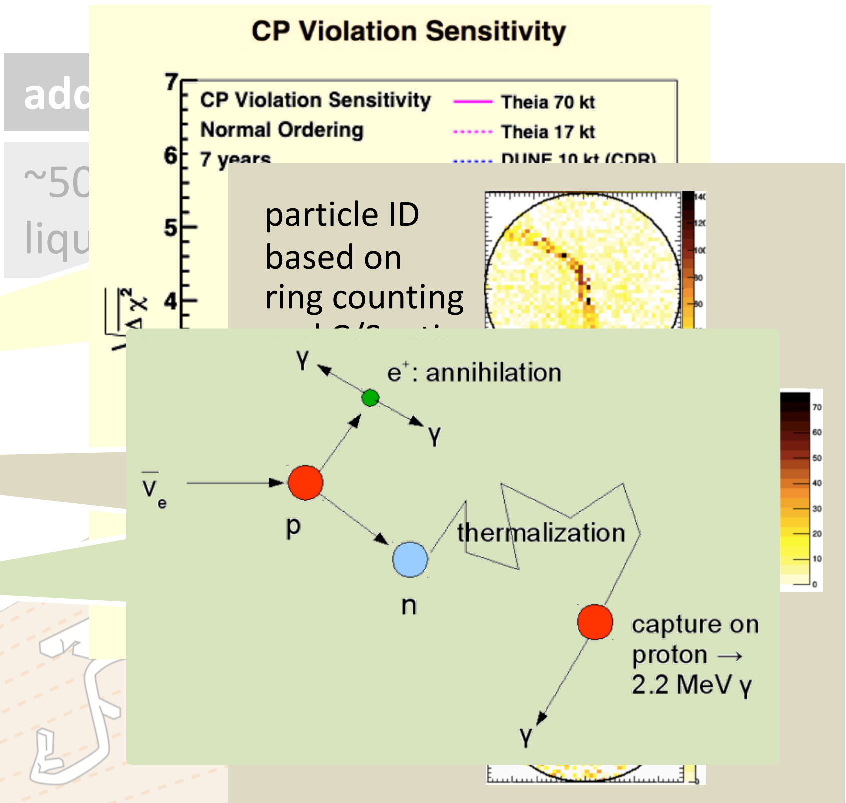

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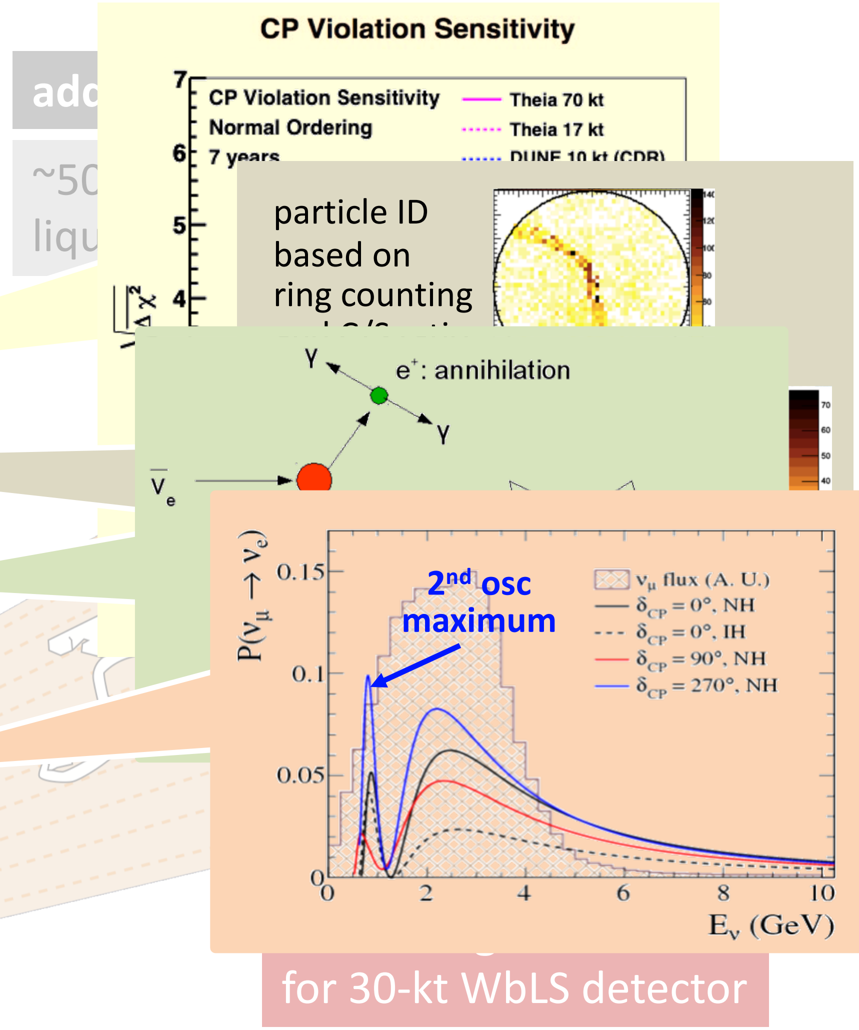
- Fast timing: ν energy measurement using initial π/K time-of-flight difference



THEIA in LBNF beam

What will a large WbLS detector add to the existing LBNF/DUNE program?

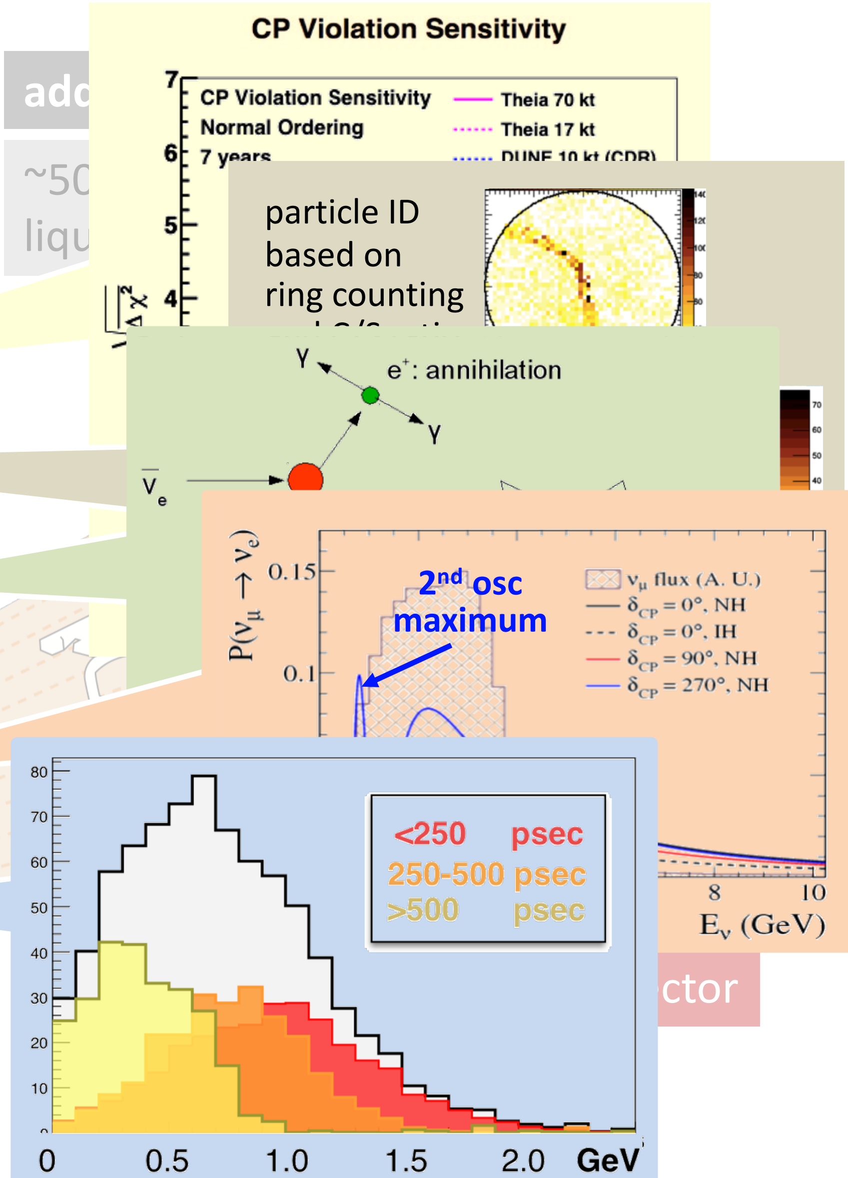
Added value for LBL (δ_{CP}) program

- Additional statistics
  ~1.7:1 in mass for WbLS : LAr
- Complementary systematics
  e.g. cross-sections (simpler nuclei)
- hadronic recoils/neutron tagging
  → reduces systematics of energy reco
  → 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

+

rich low-energy neutrino program

LBNF facility

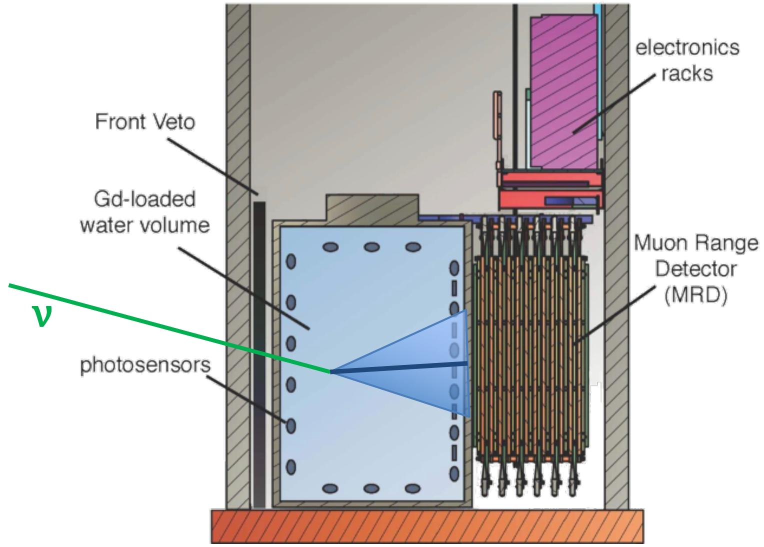


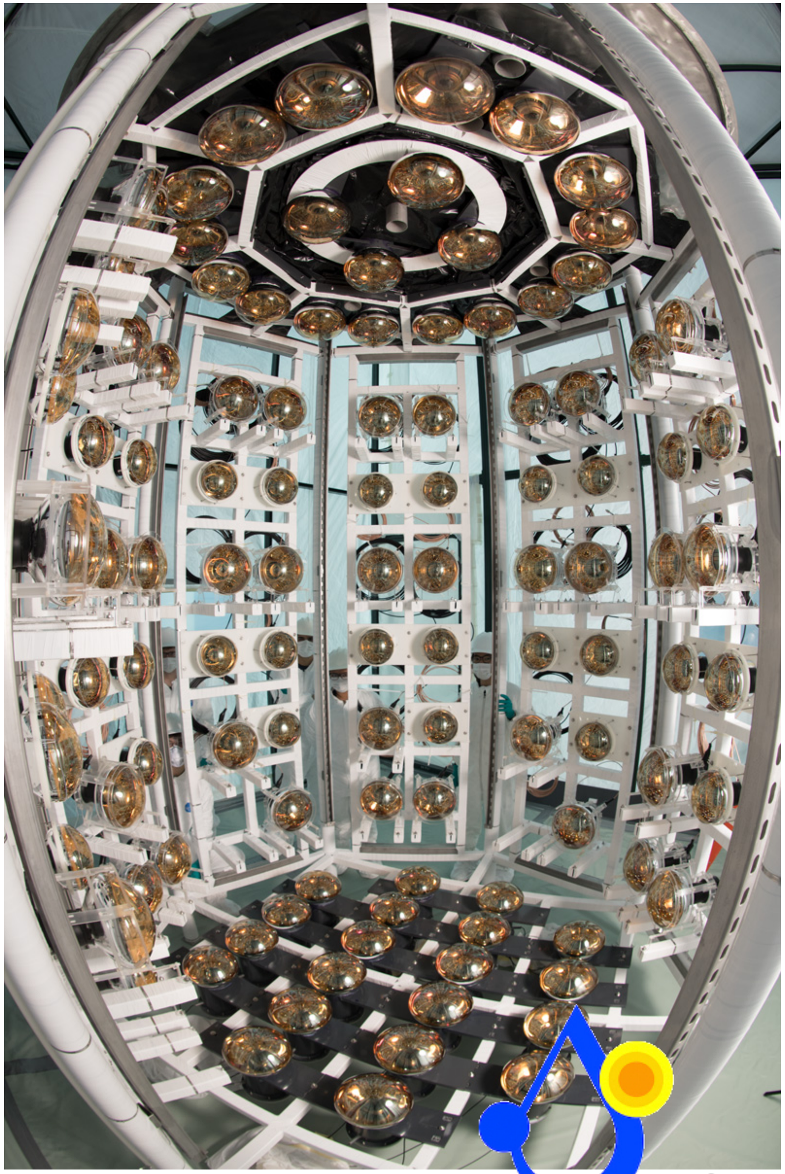
ANNIE at Fermilab

JG|U

ANNIE Phase II

- 26t H_2O+Gd Cherenkov detector, UK+US+DE
- ANNIE measures ν cross sections and neutron multiplicity in Booster Neutrino Beam
- First application of **LAPPDs** in a neutrino beam experiment → study inpact on reco
- Data can be **combined/compared to SBND** → A/O cross-sections from same ν beam





ANNIE at Fermilab

ANNIE Phase II

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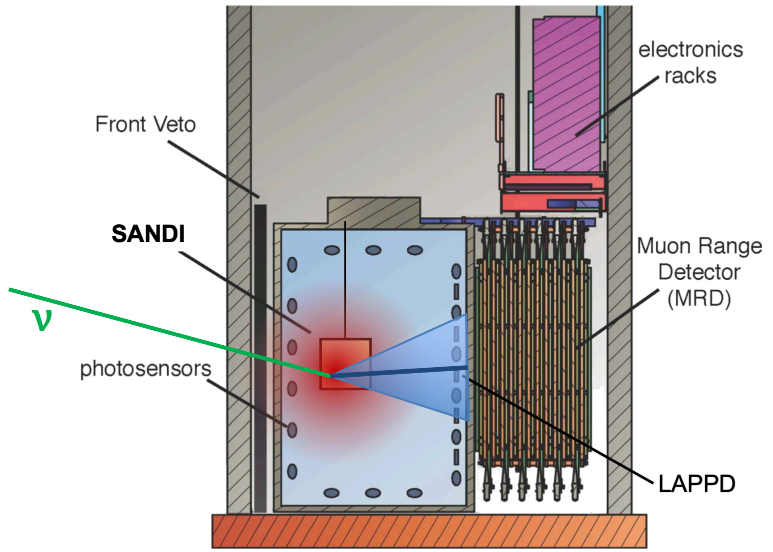


SANDI

planned for summer next year:

- insertion of **acrylic vessel with 0.5t of Gd-loaded WbLS** into the target volume
- study of scintillation signal from **hadronic recoils** → energy reco

ANNIE Phase III

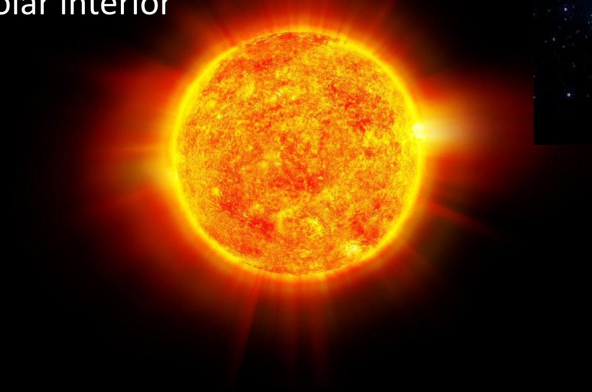
two years from now:

- **full target volume with WbLS** (incl. liquid handling system)
- upgrade to **full LAPPD setup** (20x)
- improved cross-section measurement
- NC backgrounds for DSNB/proton decay measurements

Astrophysical neutrinos at low energies

Supernova Neutrinos
from cooling of
proto neutron star
within the Milky Way

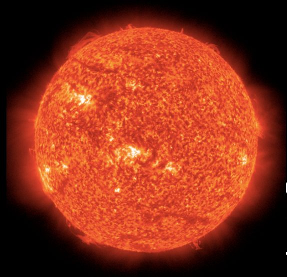
Solar Neutrinos
from H fusion in
solar interior



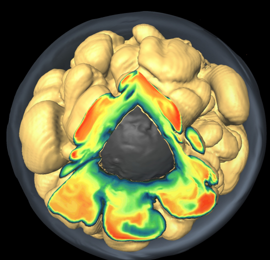
Diffuse Supernova Neutrinos
from core-collapse Supernovae
throughout the Universe

Geoneutrinos
Natural radioactivity
of Earth crust/mantle

Astrophysical neutrinos at low energies



Solar Neutrinos
- Oscillations: spectral upturn solar $\Delta m^2_{21} \neq$ reactor Δm^2_{21} → low-energy ^8B neutrinos
- precision measurement of CNO neutrinos and solar metallicity

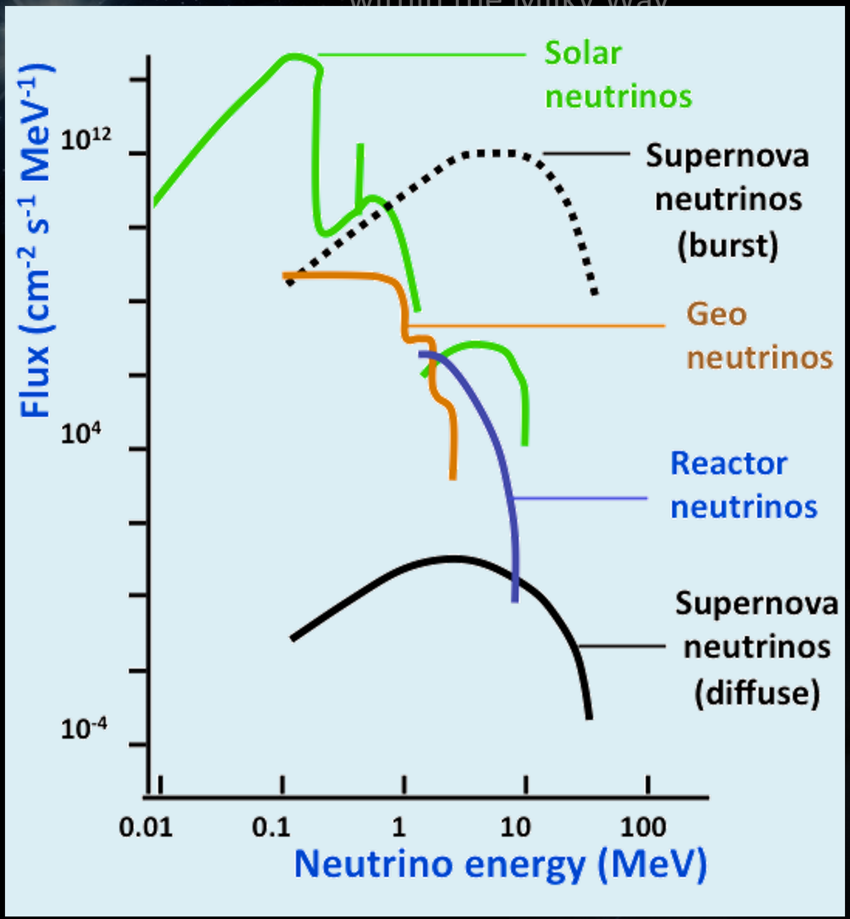


Galactic Supernovae
- prominent antineutrino signal
- NC information on all flavors
- high-accuracy SN pointing
- long range (3ν frm Andromeda)
- sensitive to pre-SN neutrinos

Diffuse SNν background (DSNB)
- excellent background rejection → discovery of the DSNB signal
- average SN neutrino spectrum
- rate of failed/dark Supernovae

Geoneutrinos
- detetermine radiogenic contribution to heat flow
- measure U/Th contributions to crust and mantle
- determine ratio of U and Th

Neutrino Energy Spectrum



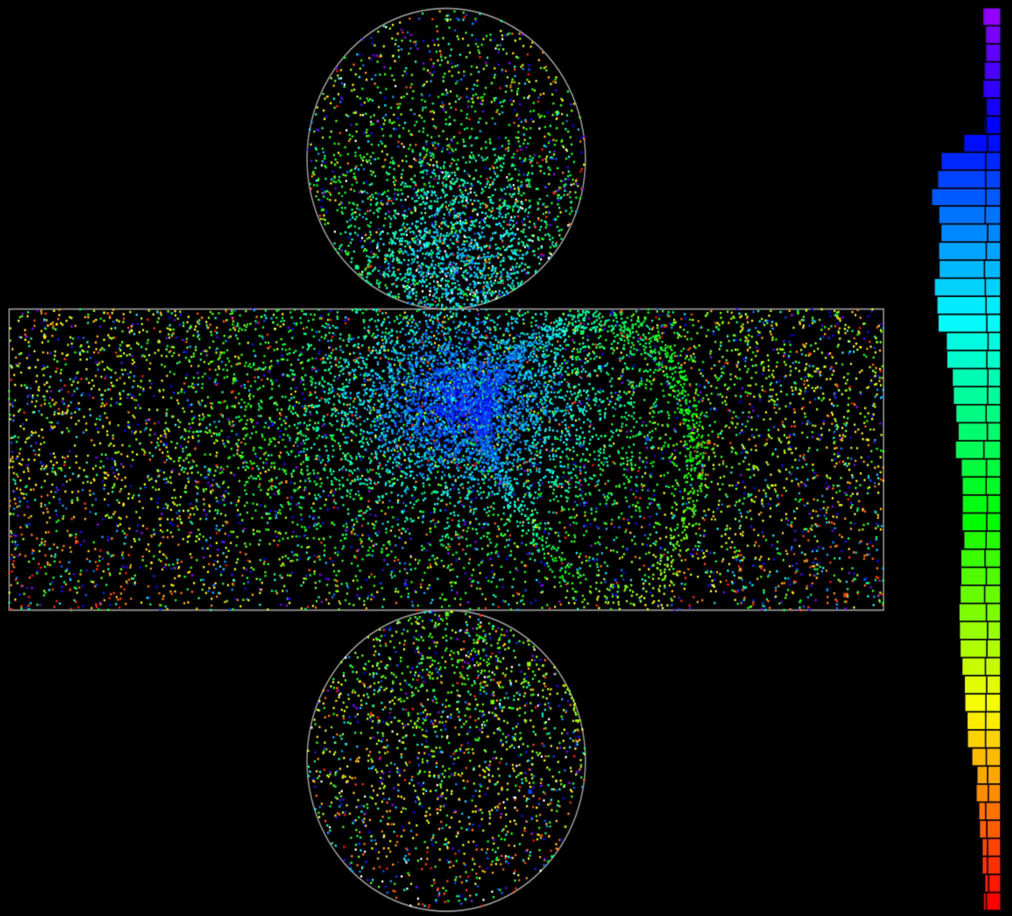
WbLS: Impact on MeV neutrino detection

[arXiv:2007.14999]

Water Cherenkov
- High transparency
  → enhanced light collection
- Directionality from cone reco
- Particle ID from ring counting
- Enhanced metal loading

Combined: Particle ID based on **Cherenkov/scintillation (C/S) ratio** (p, α below Č threshold)

Organic scintillator mycels
- Low (sub-Cherenkov) threshold
- Increased light yield
- Enhanced vertex reconstruction
- Particle ID by pulse shape
- Enhanced cleanliness



Diffuse Supernova Neutrino Background

[arXiv:2007.14705]

DSNB detection:

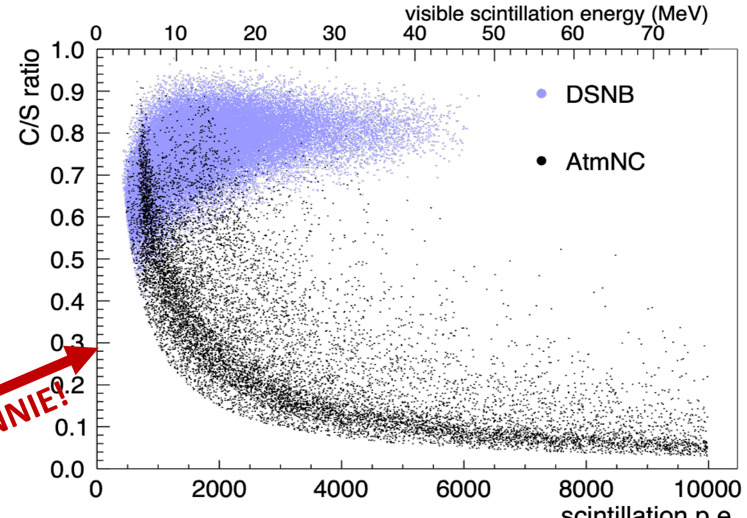
- Low-flux $\mathcal{O}(10^2\ cm^{-2}s^{-1})$ $\bar{\nu}_e$ signal
  → detectable by IBD: ~2 ev. per 10 kt·yrs
- Requires efficient BG discrimination, especially to atmospheric ν NC interactions
- In THEIA:
  - ring counting:
  - **Cherenkov/scintillation ratio**
  - delayed decay tags

→ signal efficiency: 81%
→ residual background: 1.3%

very clean measurement cf. JUNO & SK-Gd

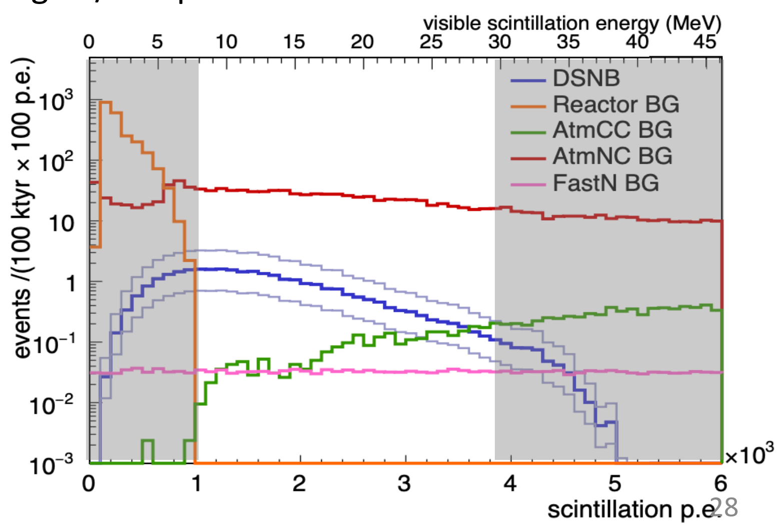
THEIA100: 17 IBDs over 9 BG per year
→ **5σ discovery after 1-2 years**

NC BG data by ANNIE!



Cherenkov/scintillation ratio for BG discrimination

Signal/BG spectra and observation window



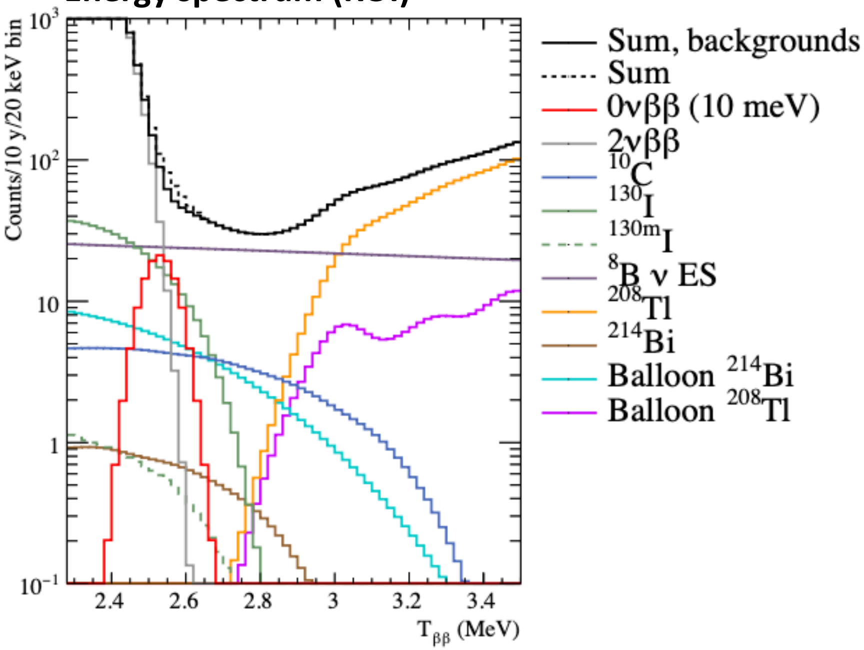
Neutrinoless double-beta decay

Insertion of a sub-volume holding 1.8kt of organic scintillator (LAB+PPO)

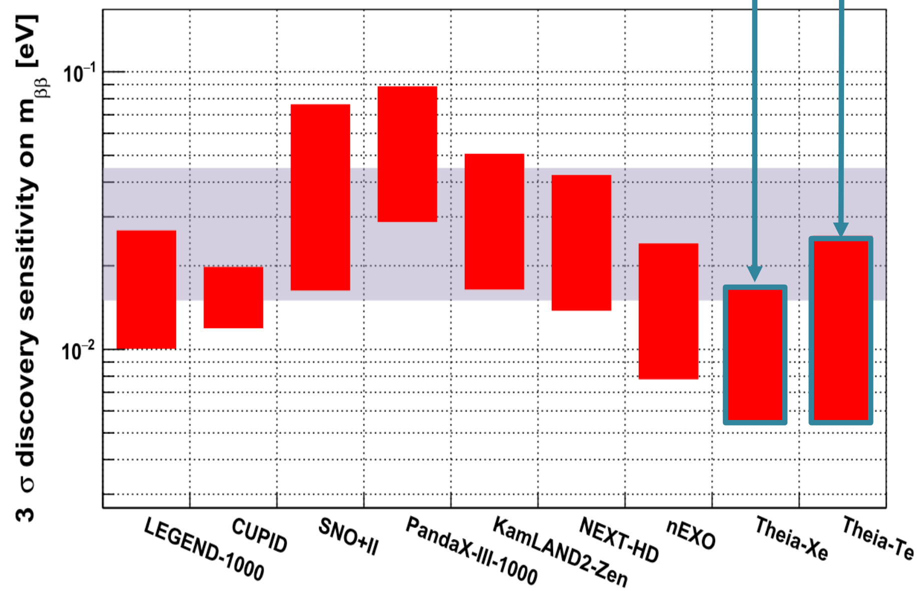
loading: **-- 3% enriched Xe** (89.5%)
-- 5% natural Te (~90t)

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

Energy spectrum (ROI)



Sensitivity (90% CL) from counting analysis:
- **Te:** $T_{1/2} > 1.1 \times 10^{28}$ yrs, $m_{\beta\beta} < 6.3$ meV
- **Xe:** $T_{1/2} > 2.0 \times 10^{28}$ yrs, $m_{\beta\beta} < 5.6$ meV



Plot by Yu. G. Kolomensky using methodology from Agostini, Benato, Detwiler: Phys Rev D96 053001

Further reading: THEIA Whitepaper

EPJC 80, 416 (2020), arXiv:1911.03501

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

THE EURO
PHYSICAL

Regular Article - Experimental Physics

THEIA: an advanced optical neutrino detector

M. Askins[1,2], Z. Bagdasarian[3], N. Barros[4,5,6], E. W. Beier[4], E. Blucher[7], R. Bonventre[2], E. Bourret[2], E. J. Callaghan[1,2], J. Caravaca[1,2], M. Diwan[8], S. T. Dye[9], J. Eisch[10], A. Elagin[7], T. Enqvist[11], V. Fischer[12], K. Frankiewicz[13], C. Grant[13], D. Guffanti[14], C. Hagner[15], A. Hallin[16], C. M. Jackson[17], R. Jiang[7], T. Kaptanoglu[4], J. R. Klein[4], Yu. G. Kolomensky[1,2], C. Kraus[18], F. Krennrich[10], T. Kutter[19], T. Lachenmaier[20], B. Land[1,2,4], K. Lande[4], J. G. Learned[9], V. Lozza[5,6], L. Ludhova[3], M. Malek[21], S. Manecki[18,22,23], J. Maneira[5,6], J. Maricic[9], J. Martyn[14], A. Mastbaum[24], C. Mauger[4], F. Moretti[2], J. Napolitano[25], B. Naranjo[26], M. Nieslony[14], L. Oberauer[27], G. D. Orebi Gann[1,2,a], J. Ouellet[28], T. Pershing[12], S. T. Petcov[29,30], L. Pickard[12], R. Rosero[8], M. C. Sanchez[10], J. Sawatzki[27], S. H. Seo[31], M. Smiley[1,2], M. Smy[32], A. Stahl[33], H. Steiger[27], M. R. Stock[27], H. Sunej[8], R. Svoboda[12], E. Tiras[10], W. H. Trzaska[11], M. Tzanov[19], M. Vagins[32], C. Vilela[34], Z. Wang[35], J. Wang[12], M. Wetstein[10], M. J. Wilking[34], L. Winslow[28], P. Wittich[36], B. Wonsak[15], E. Worcester[8,34], M. Wurm[14], G. Yang[34], M. Yeh[8], E. D. Zimmerman[37], S. Zsoldos[1,2], K. Zuber[38]

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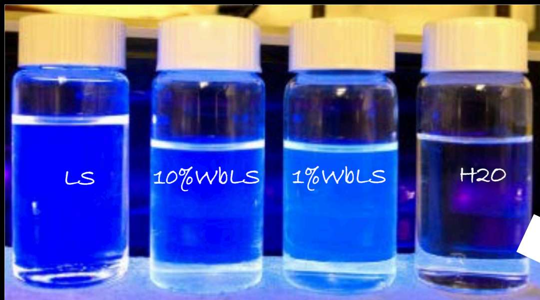
THEIA proto-collaboration:
groups from 35+ institutions and eight countries (CA, CN, DE, FI, IT, KR, UK, US)

More information on:

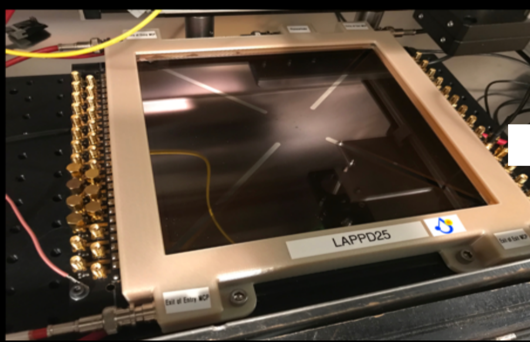
- Detector technology
- Low energy neutrinos, e.g. solar, SN neutrinos
- Nucleon decay
- …

Conclusions

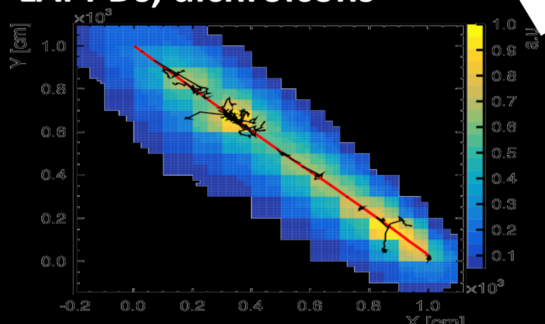
→ **Enhanced sensitivity to broad physics program**



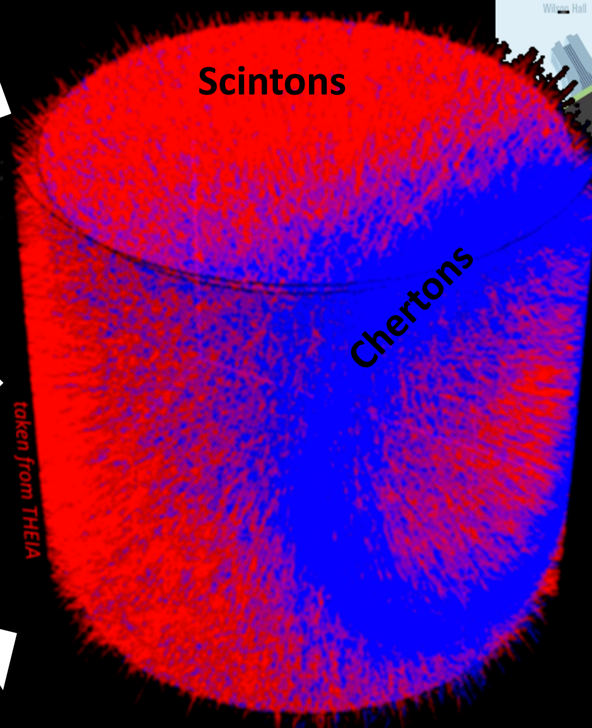
Novel target medium:
Water-based Liquid Scintillator

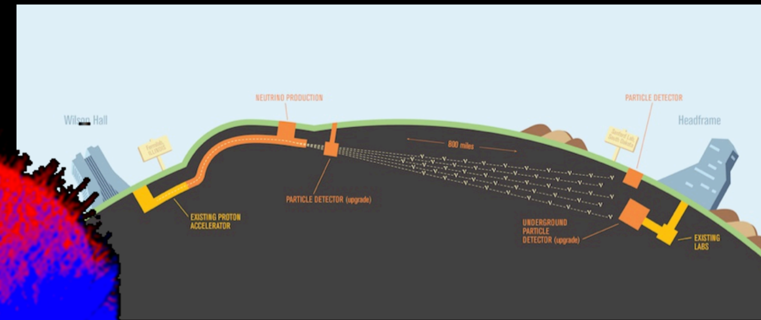


Novel light sensors:
LAPPDs, dichroicons



Novel reconstruction techniques

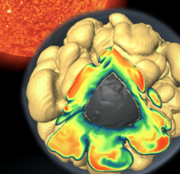




Long-Baseline Oscillations

Solar neutrinos

Supernova neutrinos

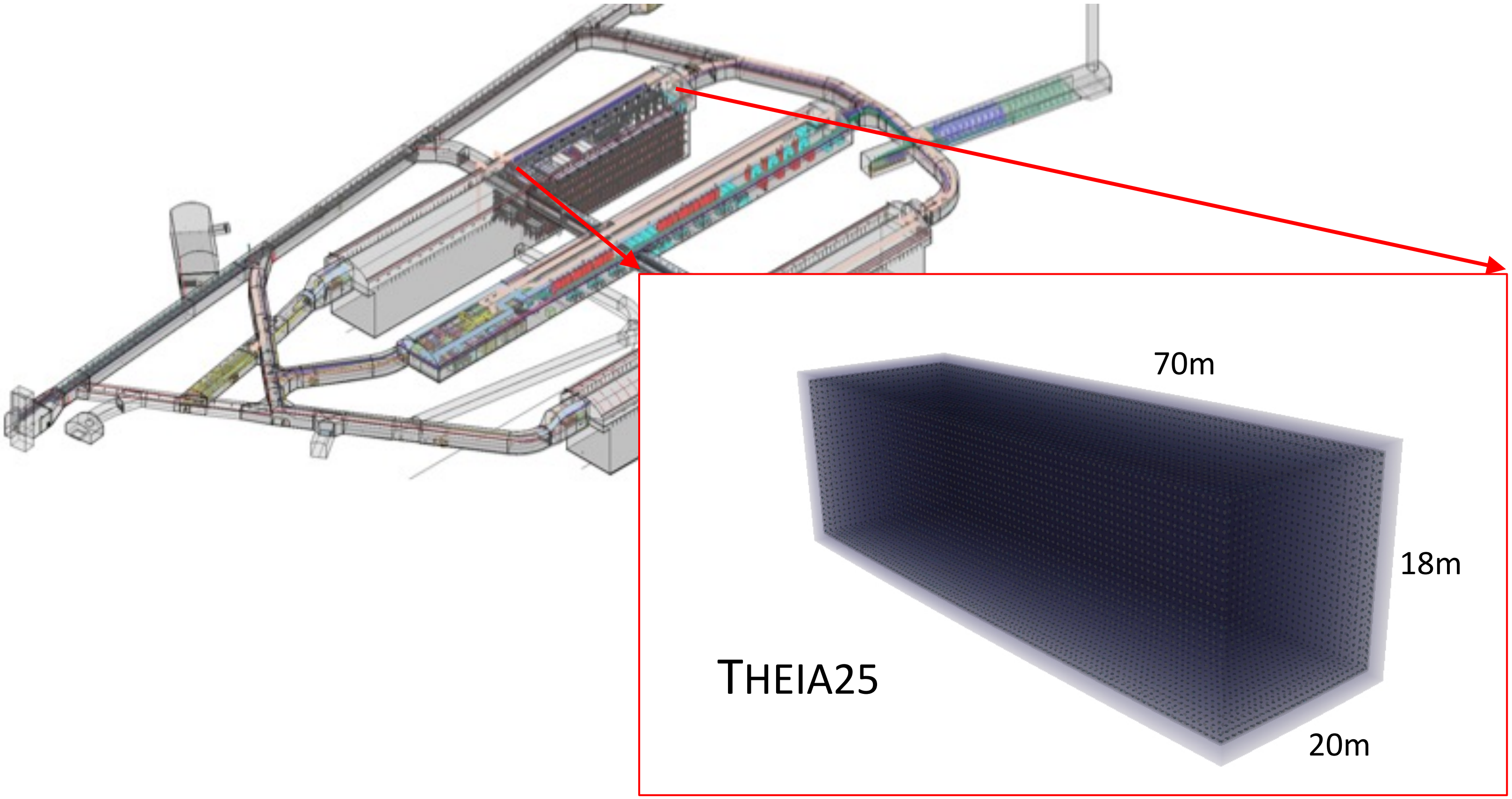


Diffuse SN neutrinos

Physics case for THEIA:

- WbLS technology offers complementary capabilities to existing and upcoming large-scale neutrino projects.
- THEIA25 makes an excellent match for the 3 DUNE modules.

Backup Slides



DUNE Near Detector vs. THEIA?

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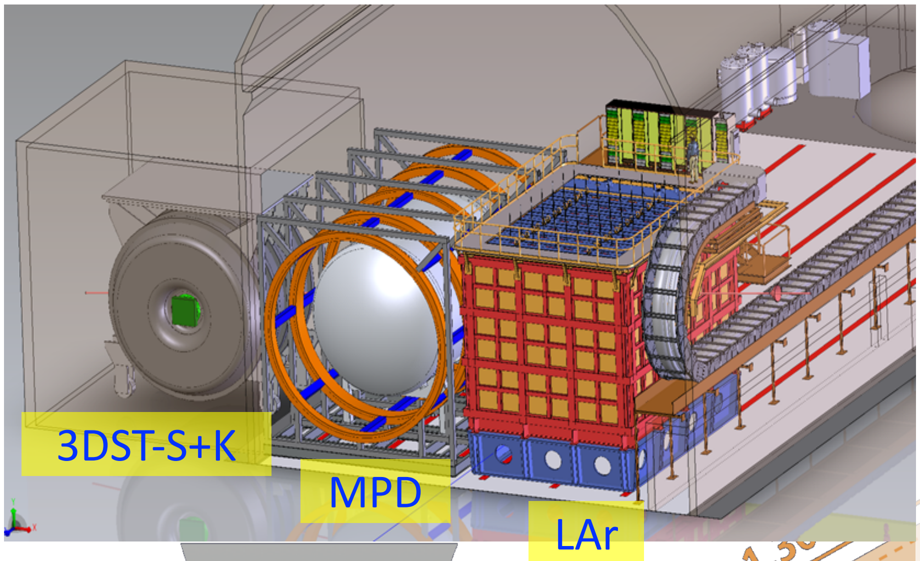
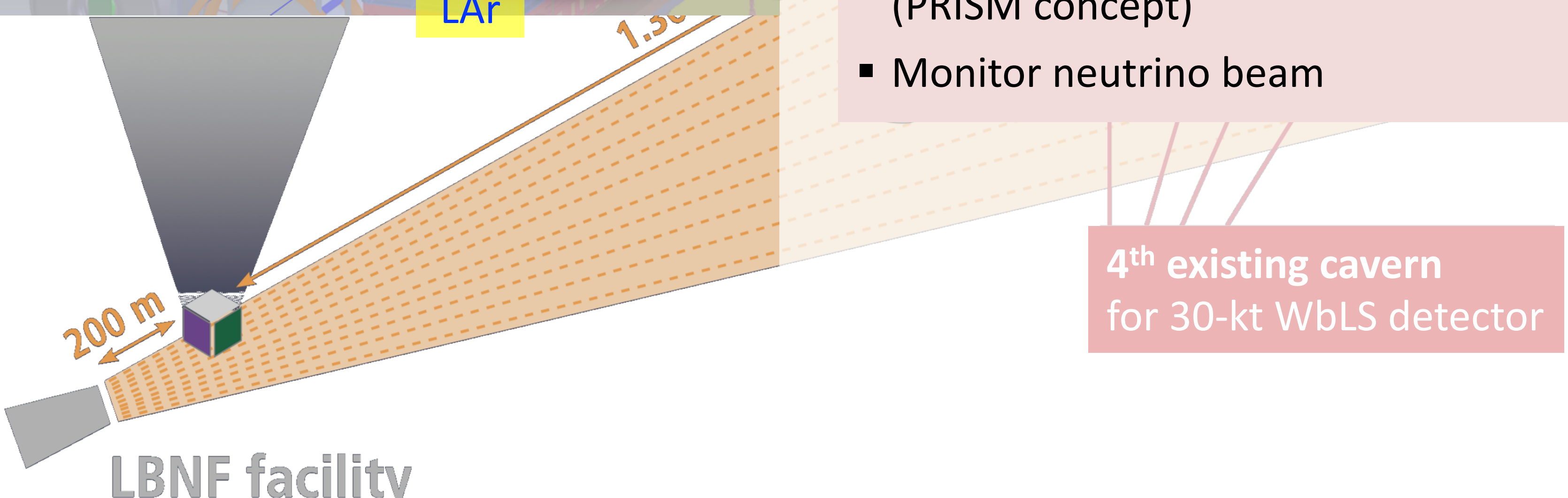
DUNE Near Detector Complex



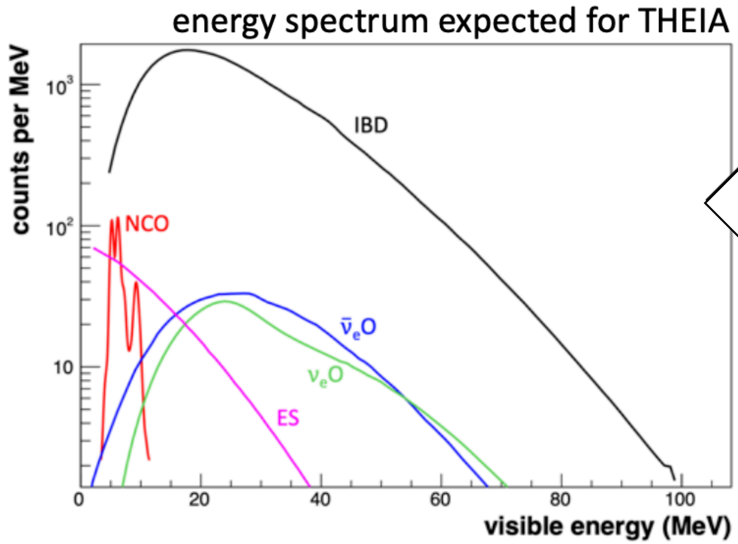
DUNE ND uses agron as target isotope
→ does this configuration suit THEIA?

Up to a point, yes!

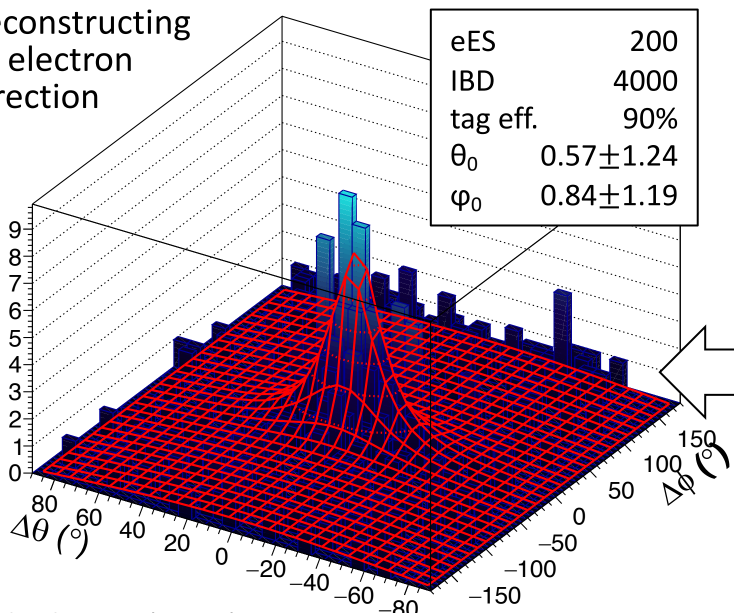
- Predict neutrino spectrum at Far Site
- Measure the neutrino energy
- Measure cross-sections on oxygen (?)
- Measure neutrino flux
- Measure under different angles (PRISM concept)
- Monitor neutrino beam



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

Solar neutrinos

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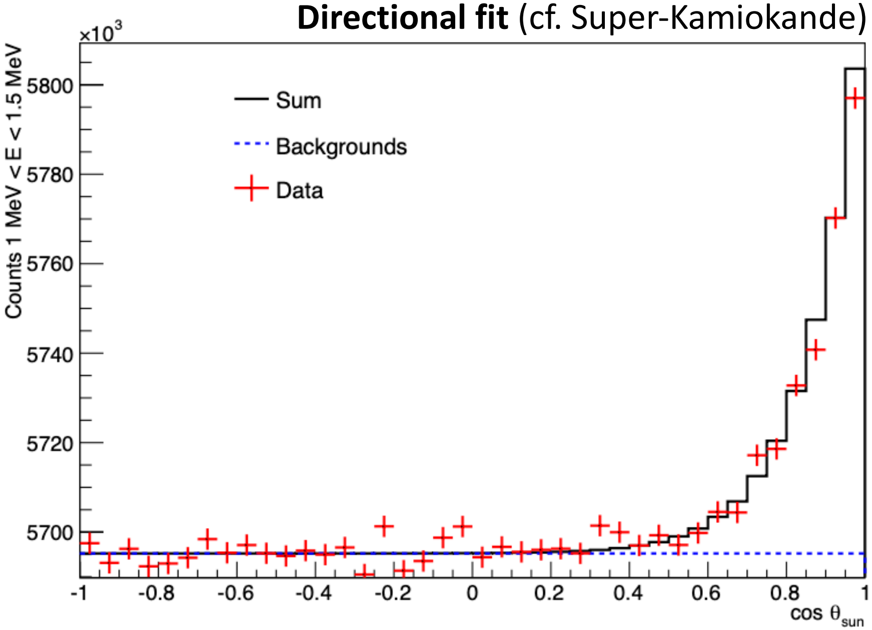
Objectives:

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

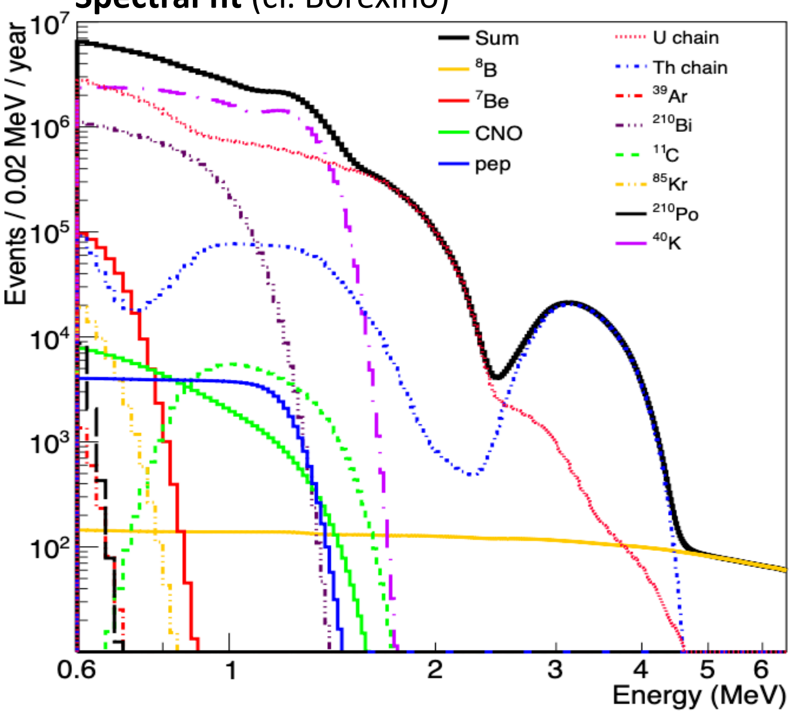
→ require efficient BG discrimination and sufficient light yield in 1-3 MeV range

- 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

pre-Supernova neutrinos

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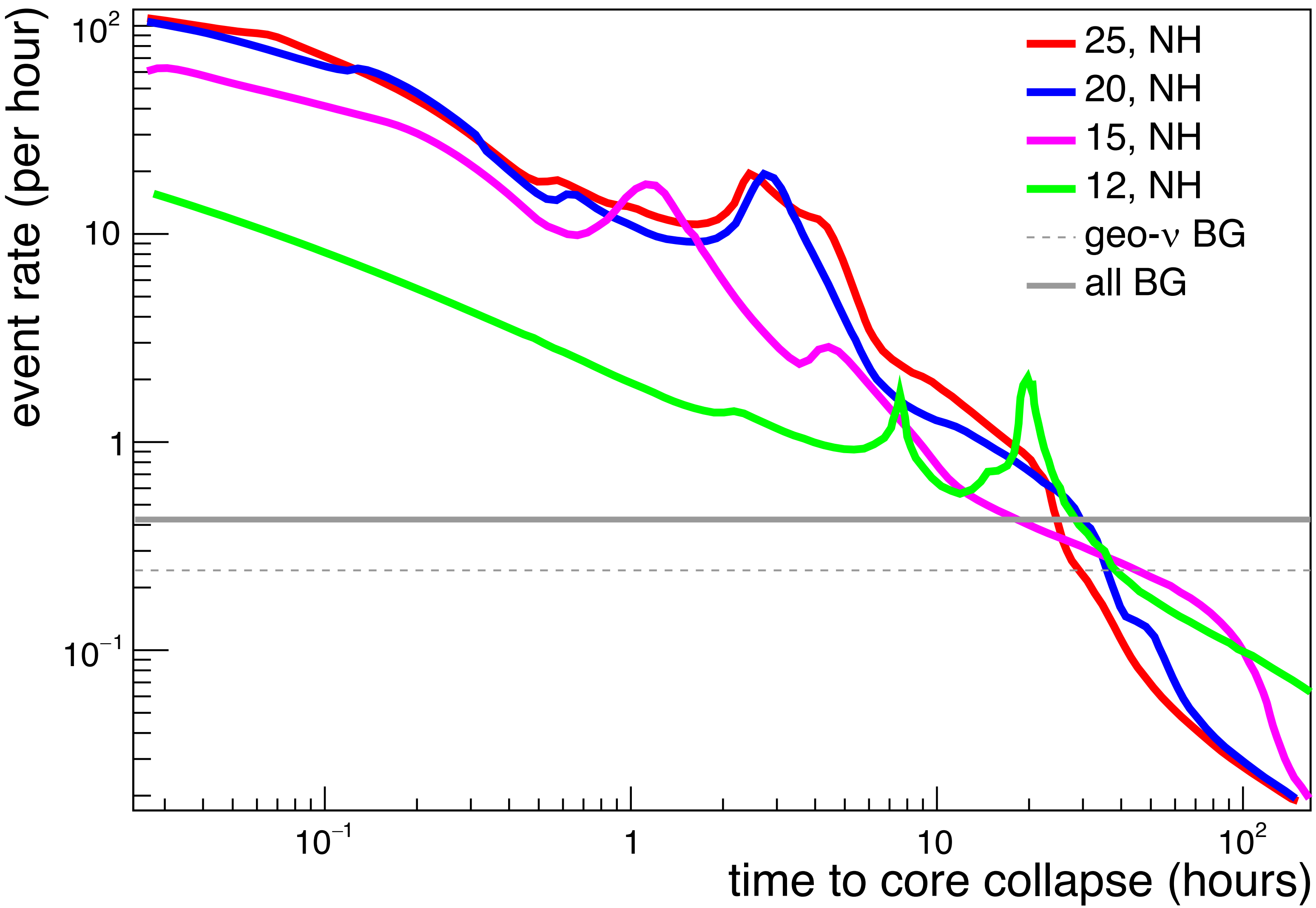


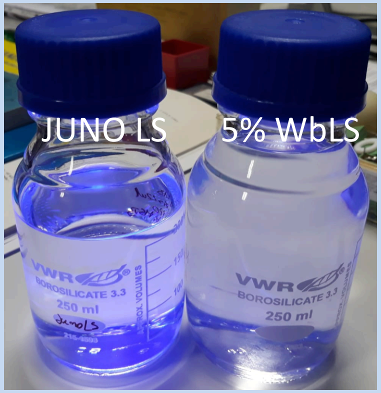
R&D in Germany: WbLS

WbLS Development at TUM

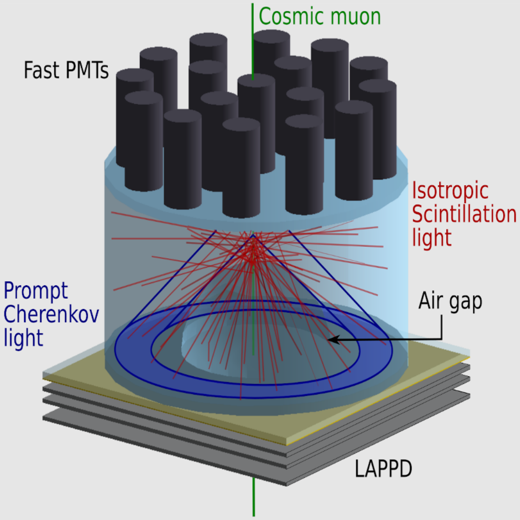
→ systematic study of WbLS composition and properties

→ 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

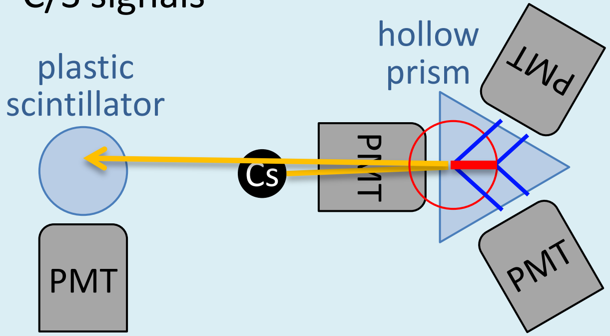
→ light propagation in WbLS over 10-20 cm

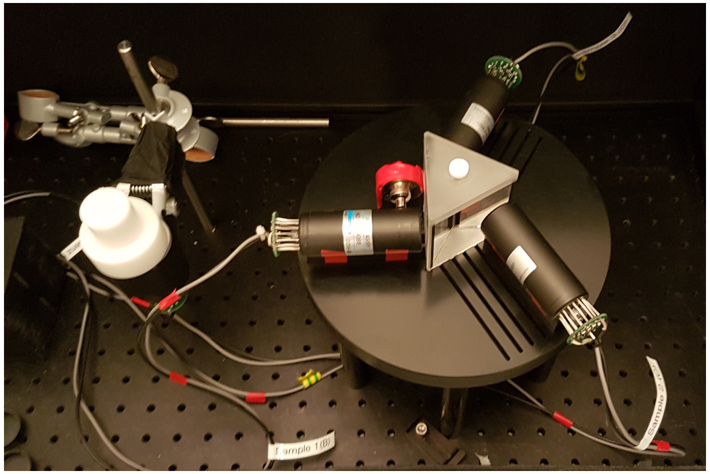
- Cylindrical tank: 10-15l
- Air gap for ring formation
- Changeable photosensors: LAPPDs, SiPMs …
- fast (<1ns) PMT rear array for scinton detection

WbLS Light Yield in Mainz

→ forward-scattered electrons produce Chertons and scintons

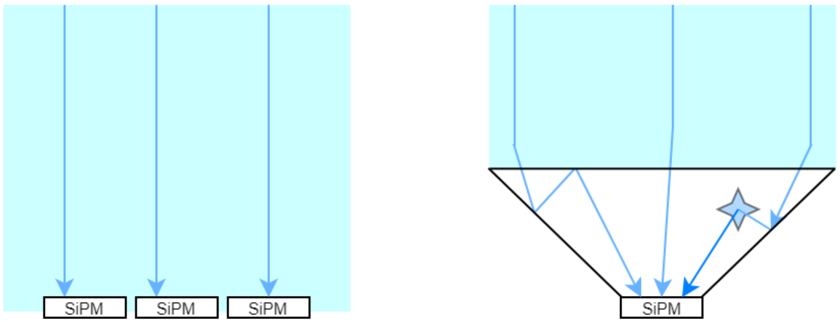
→ rear PMT sees pure scinton signal, front PMTs (tts 300ps) separate C/S signals





R&D in Germany: Photosensors

Tübingen/Mainz
FZ Jülich (ZEA-2)

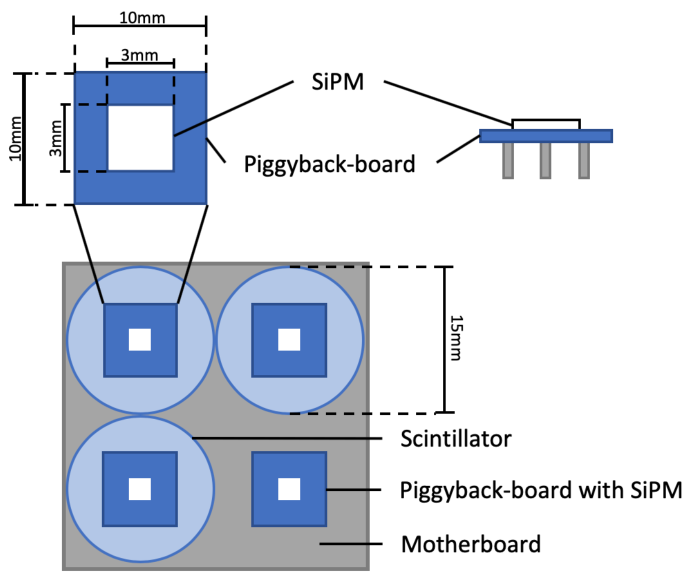


SiPM array

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

R&D in Germany: Reconstruction

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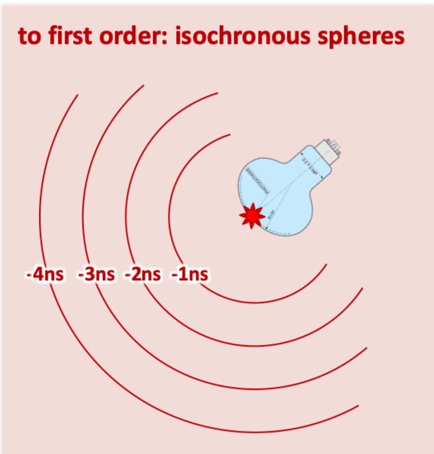
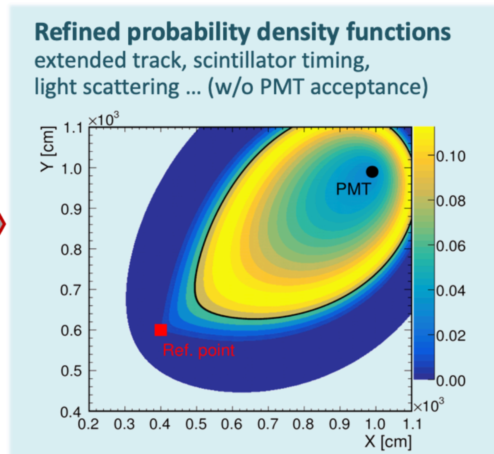
Topological Reconstruction

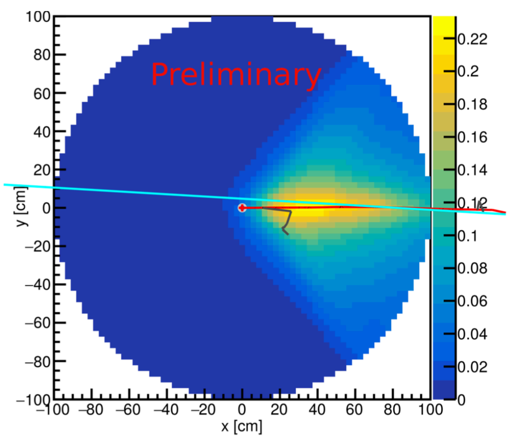
Basic idea: Propagate photons (hits) backward in time to find regions of maximum overlap of emission probability





B. Wonsak *et al.*, arXiv:1803.08802

→ iterative process using probability mask to sharpen image



First application to WbLS

- ANNIE-sized detector filled with WbLS
- inclusion of Chertons in emission model

← result for 0.5GeV muon including LAPPD information

annie

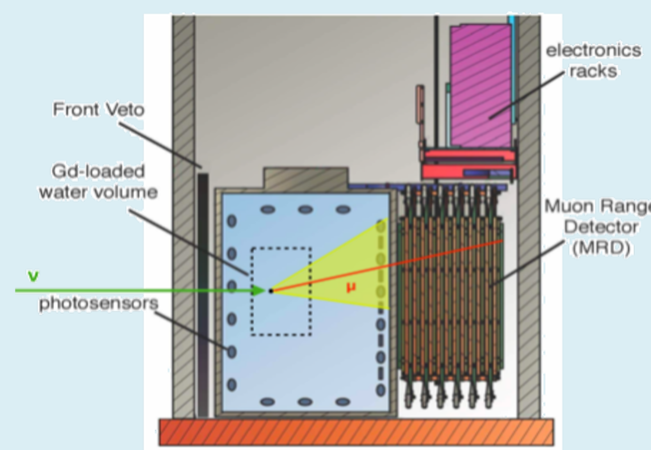
Contribution to ANNIE Upgrade

→ Acrylic Vessel for WbLS deployment

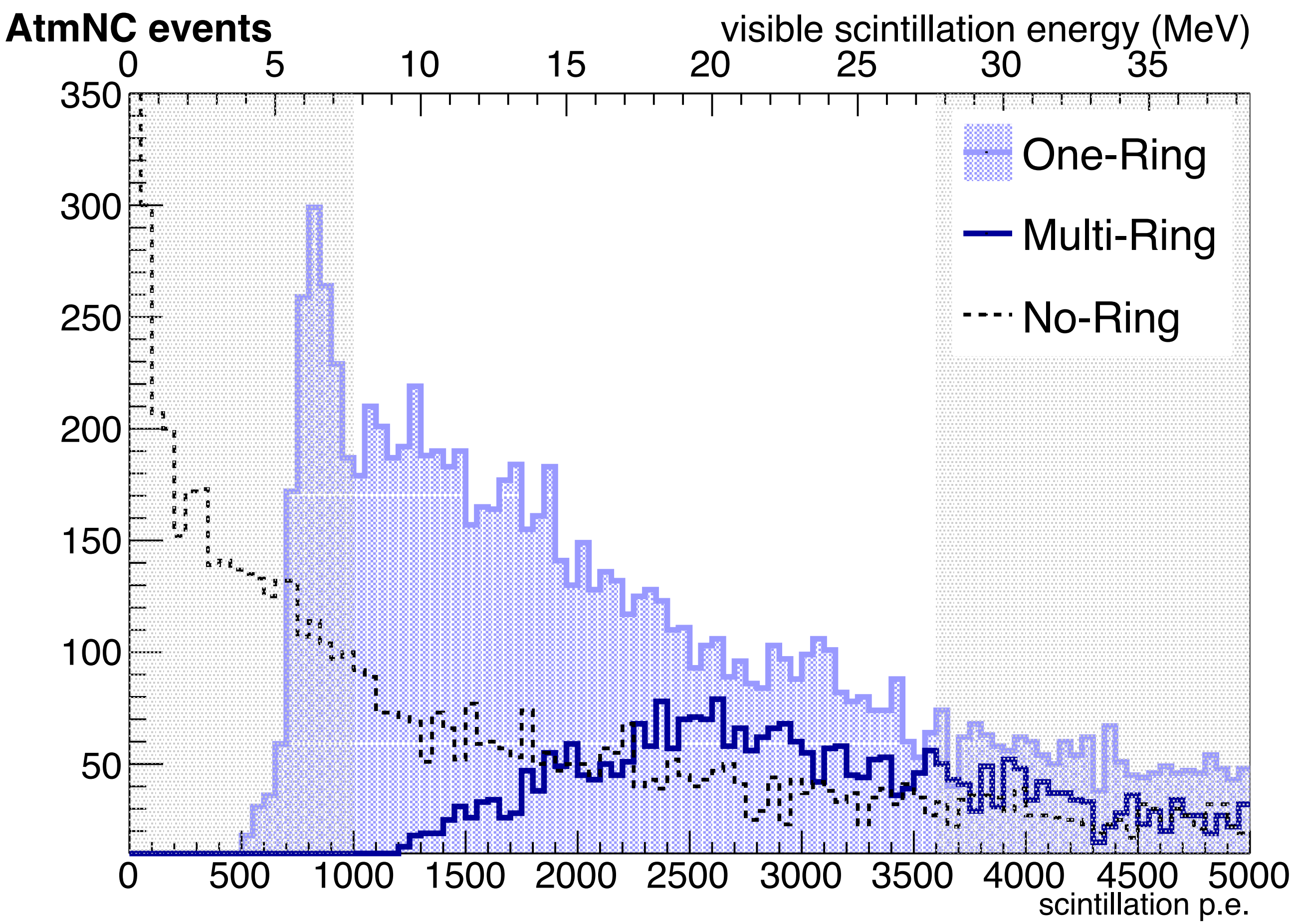
→ contribute to WbLS handling: online purification?

→ SiPM array : first test detector for ANNIE Phase 3?

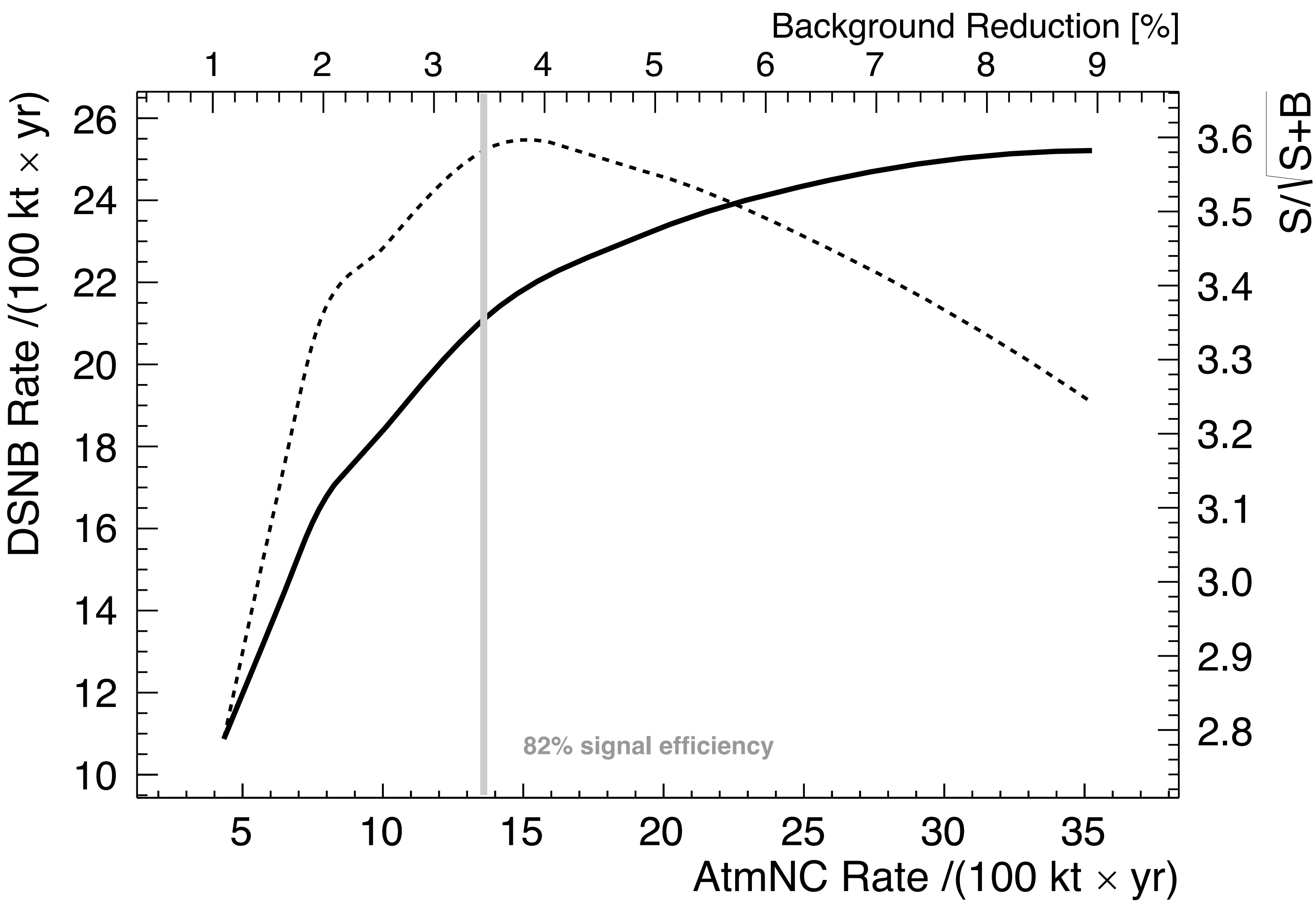
→ test of novel reco algorithms



DSNB Ring Counting



DSNB C/S ratio background rejection



DSNB Delayed decay tags

Reaction channel	Branching Ratio	
(1) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + {}^{15}\mathrm{O}$	45.9%	← taggable
(2) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + \mathrm{p} + {}^{14}\mathrm{N}$	19.7%	
(3) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + 2\,\mathrm{p} + {}^{13}\mathrm{C}$	14.7%	
(4) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + \mathrm{p} + \mathrm{d} + {}^{12}\mathrm{C}$	9.1%	
(5) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + \mathrm{p} + \mathrm{d} + \alpha + {}^{8}\mathrm{Be}$	2.0%	
(6) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + 3\,\mathrm{p} + {}^{12}\mathrm{B}$	1.8%	← taggable
(7) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + \alpha + {}^{3}\mathrm{He} + {}^{8}\mathrm{Be}$	1.6%	
(8) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + \mathrm{p} + \alpha + {}^{10}\mathrm{B}$	1.4%	
(9) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + 2\,\mathrm{p} + \alpha + {}^{9}\mathrm{Be}$	1.2%	
other reaction channels	2.6%	

DSNB Signal and Background Rates

JG|U

	100 kt·yrs exposure			
Spectral component	basic cuts	single-ring	C/S cut	delayed decays
DSNB signal	21.6	21.6	17.6 (17.3)	17.4 (17.1)
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)

DSNB Sensitivity : Other projects

JG|U

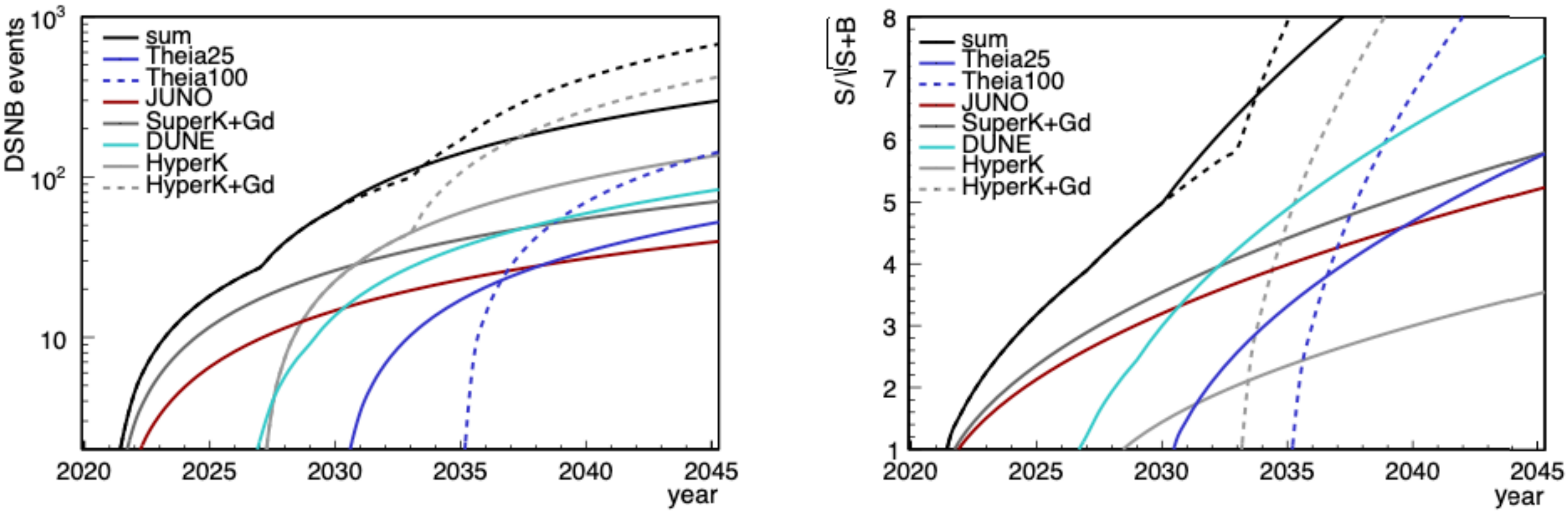
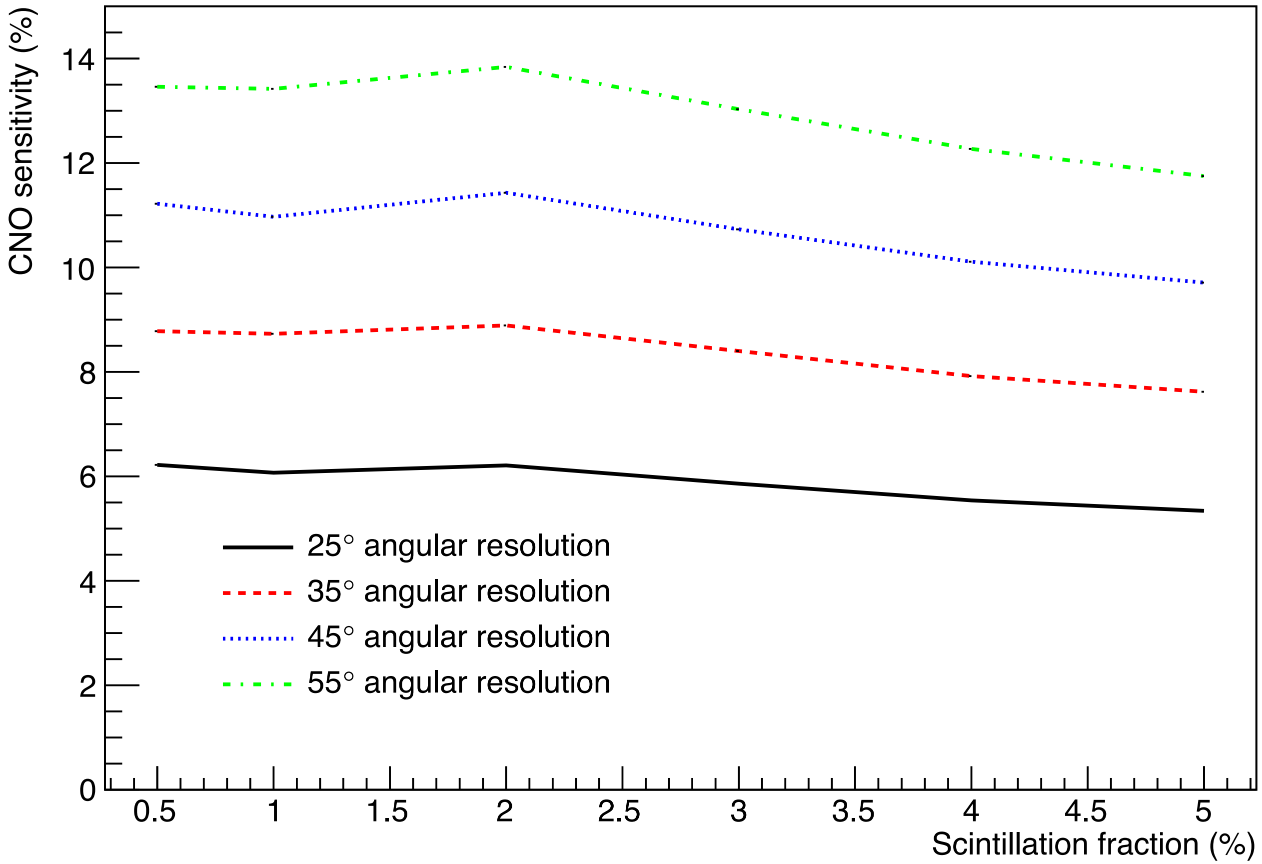


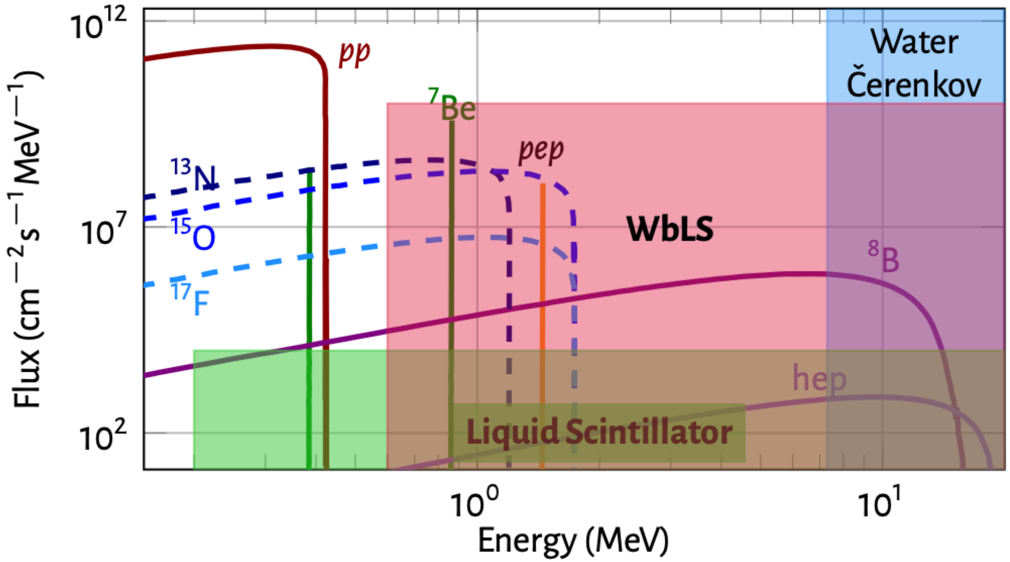
FIG. 10. Projections for the signal rates (left panel) and signal significance (right panel) of the relevant DSNB observatories over the next two decades. Optimistic scenarios correspond to dashed lines. The optimistic sum includes Theia100, and a second tank for Gd-loaded HyperK. DUNE is not added to the overall sum, due to different neutrino channel. Assuming a start of data taking in 2035, Theia100 soon dominates the scene regarding both collected signal statistics and significance of the detection. Theia25 makes a slower start but provides an increasingly relevant contribution over ten years of data taking. See the text for a more detailed discussion.

Solar : angular resolution & WbLS fraction



Solar neutrinos – ^{7}Li loading

- Water Čerenkov (SK + SNO): $\nu(^8\text{B})$
- LS (Borexino): Low Energy ν (*pp*, *pep*, ^{7}Be)
- **WbLS**: interesting energy region
  - CNO neutrinos
    Very relevant for solar and stellar physics
  - ^{8}B neutrino upturn
    Exotic oscillation behaviour



Solar ν CC interaction

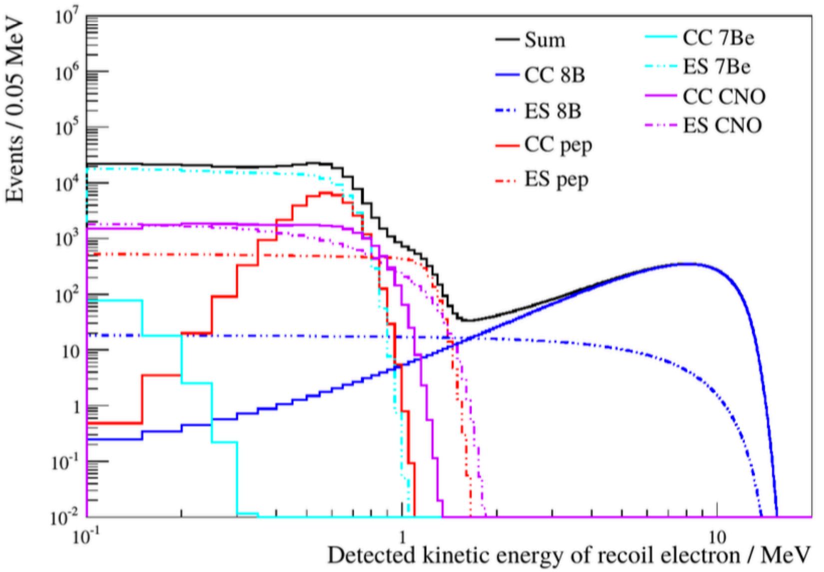
Possible loading with ^{7}Li

$$\nu_e + {}^7\text{Li} \rightarrow {}^7\text{Be} + e^-$$

(Q = 862 keV)

Less statistics than ES signal, but almost direct measurement of ν_e energy

- Improved spectral separation
- Separation of CNO components

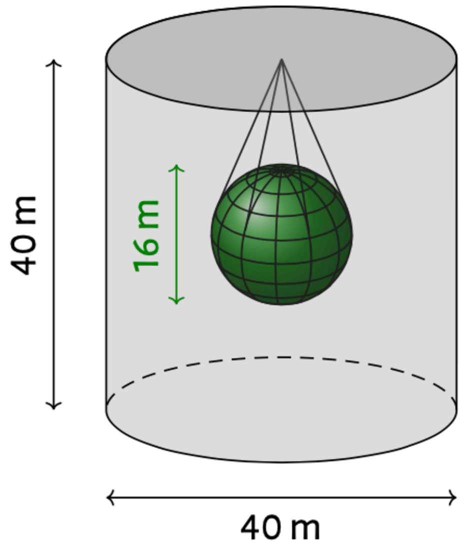


0νββ study for THEIA50

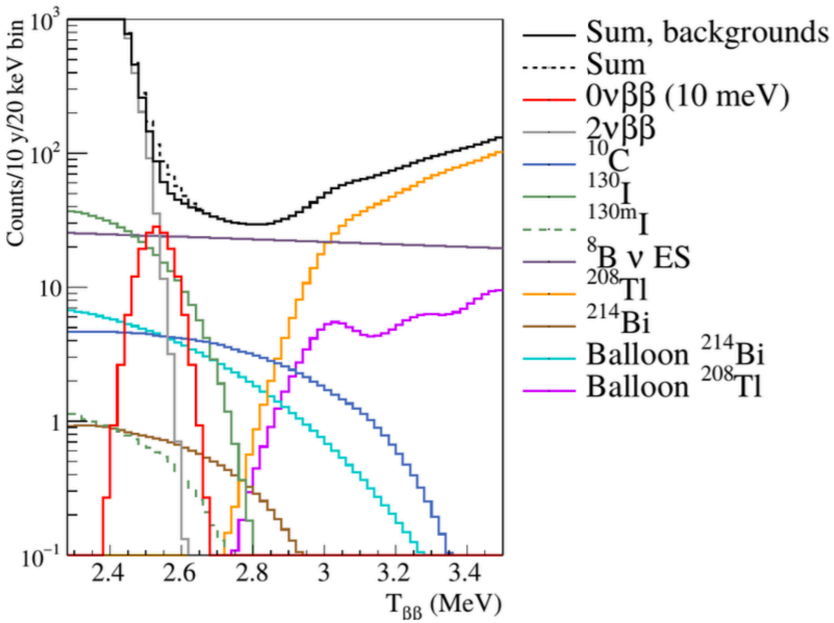
JG|U

Goal:
Cover IO space
Reach NO region

2 possible approaches:
▶ KamLAND/Zen like
▶ SNO+ like



- 50 kton detector
- 90% photocoverage
- Vessel filled with Ultra-pure LAB+PPO ($\sigma_E \simeq 3\%/\sqrt{E}$)
- Loading
  - 5% natural Te (34.1% in ^{130}Te)
  - 3% enriched Xe (89.5% in ^{136}Xe)



Dominant $\nu(^8\mathrm{B})$ **solar neutrino ES background**

Rejection power > 50% to cover IO
↪ Need large photocoverage and high QE photodetectors
compensate worsening of directionality in pure LS

Expected sensitivity (90% C.L.)

- Te: $T_{1/2}^{0\nu\beta\beta} > 1.5 \times 10^{28}$ y, $m_{\beta\beta} < 5.4$ meV
- Xe: $T_{1/2}^{0\nu\beta\beta} > 2.7 \times 10^{28}$ y, $m_{\beta\beta} < 4.8$ meV

0νββ backgrounds

Source	Target level	Expected events/y	Events/ROI·y 5% ^{nat}Te	Events/ROI·y 3% ^{enr}Xe
Balloon ^{10}C		500	2.5	2.5
^{8}B neutrinos (normalization from [107])		2950	13.8	13.8
^{130}I (Te target)		155 (30 from ^{8}B)	8.3	-
^{136}Cs (^{enr}Xe target)		478 (68 from ^{8}B)	-	0.06
$2\nu\beta\beta$ (Te target, $T_{1/2}$ from [108])		1.2×10^{8}	8.0	-
$2\nu\beta\beta$ (^{enr}Xe target, $T_{1/2}$ from [109, 110])		7.1×10^{7}	-	3.8
Liquid scintillator	^{214}Bi: 10^{-17} g_U/g	7300	0.4	0.4
	^{208}Tl: 10^{-17} g_{Th}/g	870	-	-
Nylon Vessel [111, 112]	^{214}Bi: $< 1.1\times10^{-12}$ g_U/g	1.2×10^{5}	3.0	3.4
	^{208}Tl: $< 1.6\times10^{-12}$ g_{Th}/g	2.1×10^{4}	0.03	0.02

Antineutrino spectrum

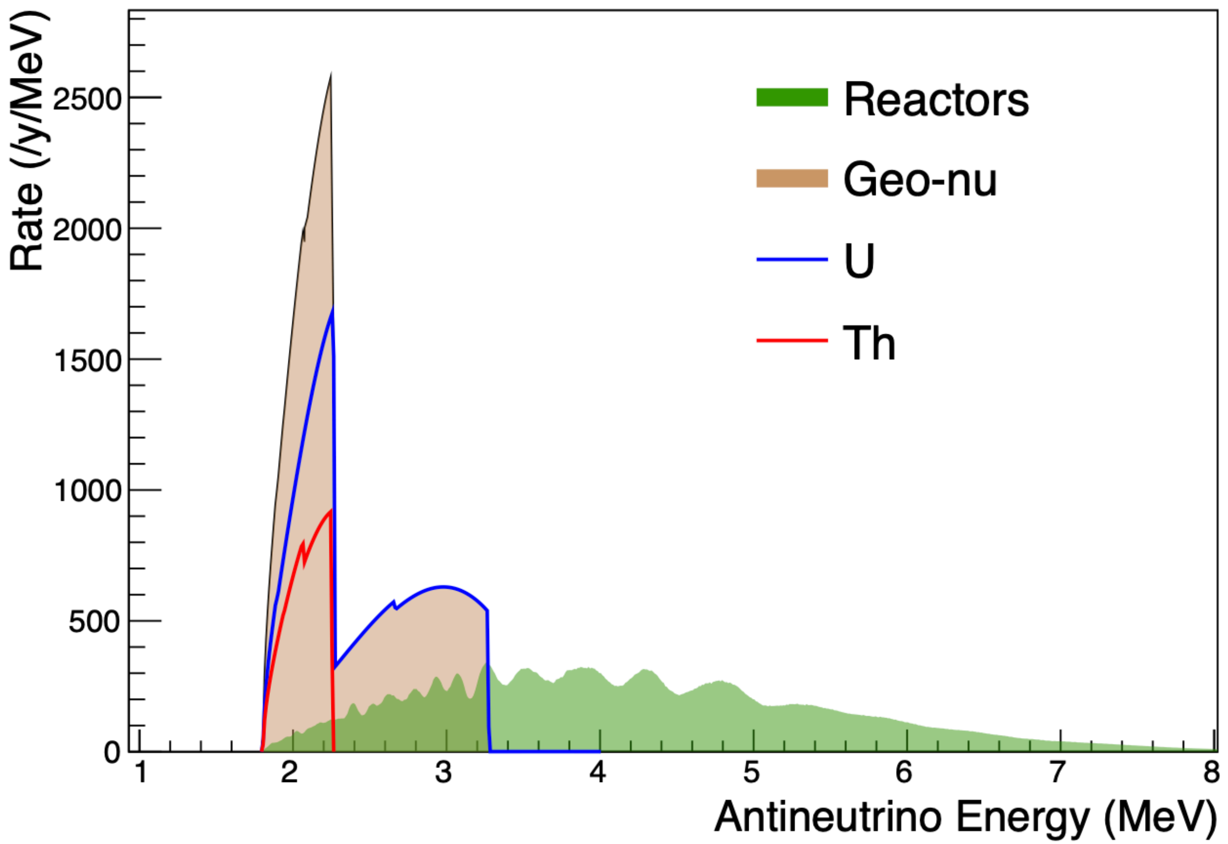


FIG. 15: The detected energy spectrum of the predicted rate of antineutrinos from nuclear power reactors and Earth, assuming a 50 kT water target.

Proton decay sensitivity

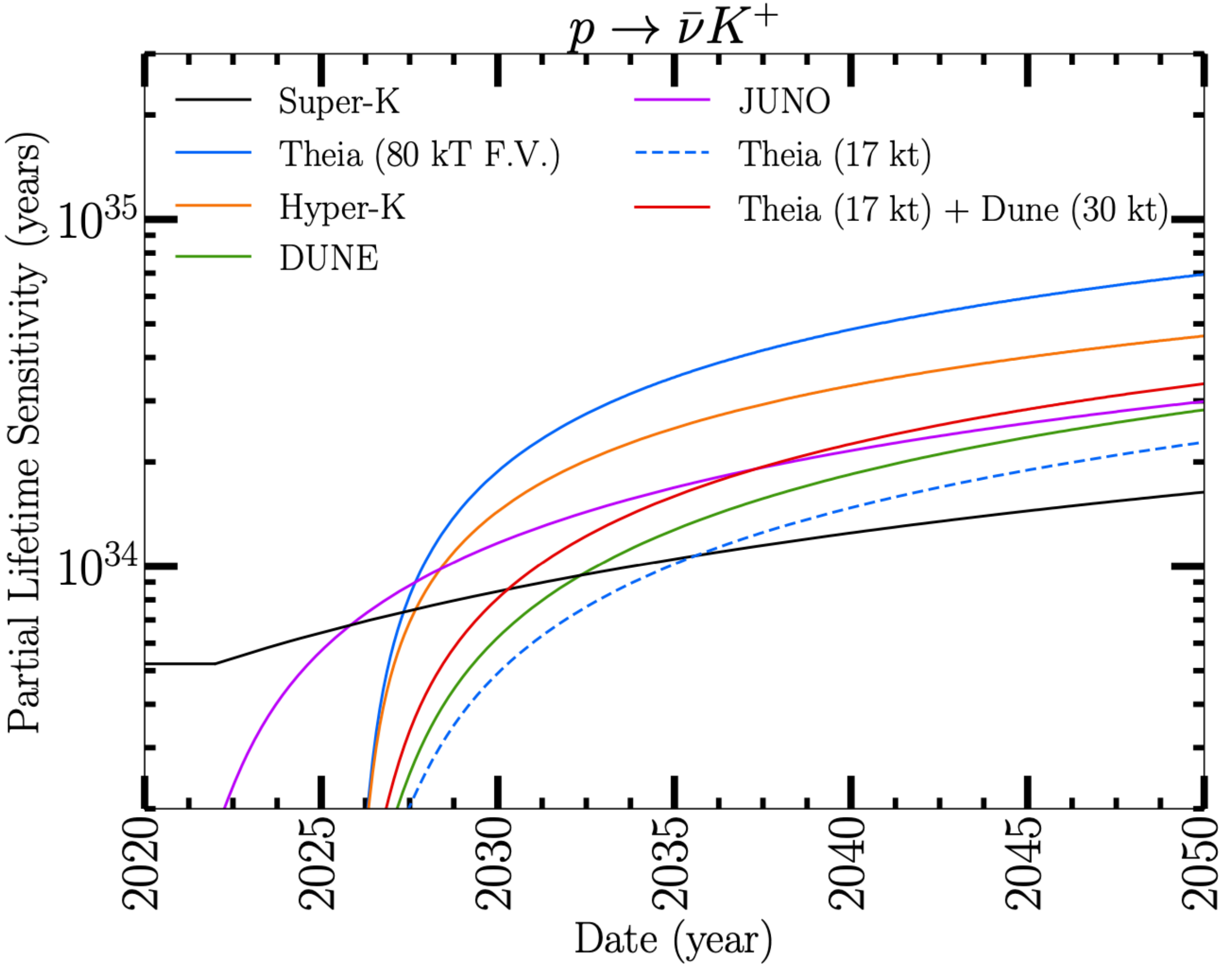


FIG. 19: Sensitivity for $p \to \bar{\nu}K^+$ is highest for THEIA, closely followed by the Hyper-K detector, whereas JUNO and DUNE will perform similarly. The inclusion of THEIA in the fourth Dune cavity would provide an enhancement to this mode over the full 40-kt Dune.