Neutrino Physics with THEIA

Presented by

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on behalf of the THEIA collaboration

RAL Seminar, 4th November 2020

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

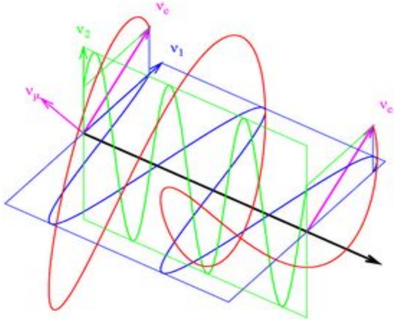
Theia (Θεία): Greek Titan goddess of the radiant blue sky, sight, precious stones and precious metals.

Overview

- **Introduction**
- **Concept and technologies (R&D)**
- **Physics program**
  - Long Baseline
  - Low energy astroparticle physics

Goals of Neutrino Physics

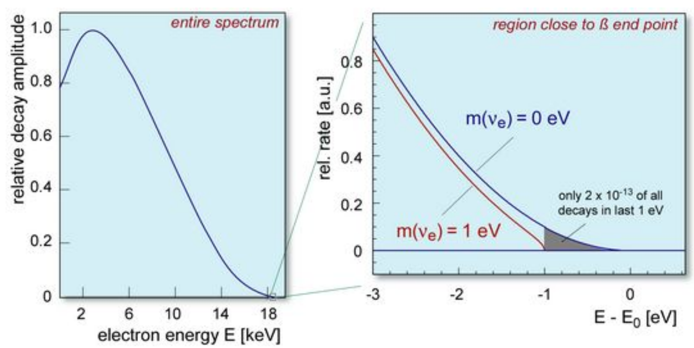
Answer fundamental questions about neutrinos:



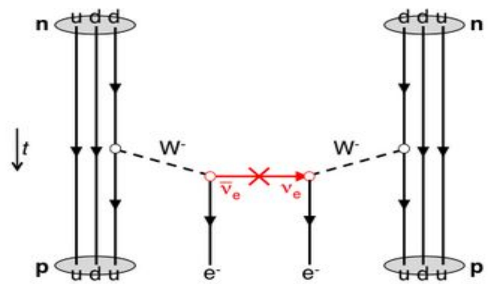
CP-violating phases

Neutrino Mixing:
(including sterile Neutrinos)
Oscillation

Neutrino Mass:
Endpoint of beta-decay



Majorana or Dirac:
Neutrinoless doublebeta-decay (0νββ)

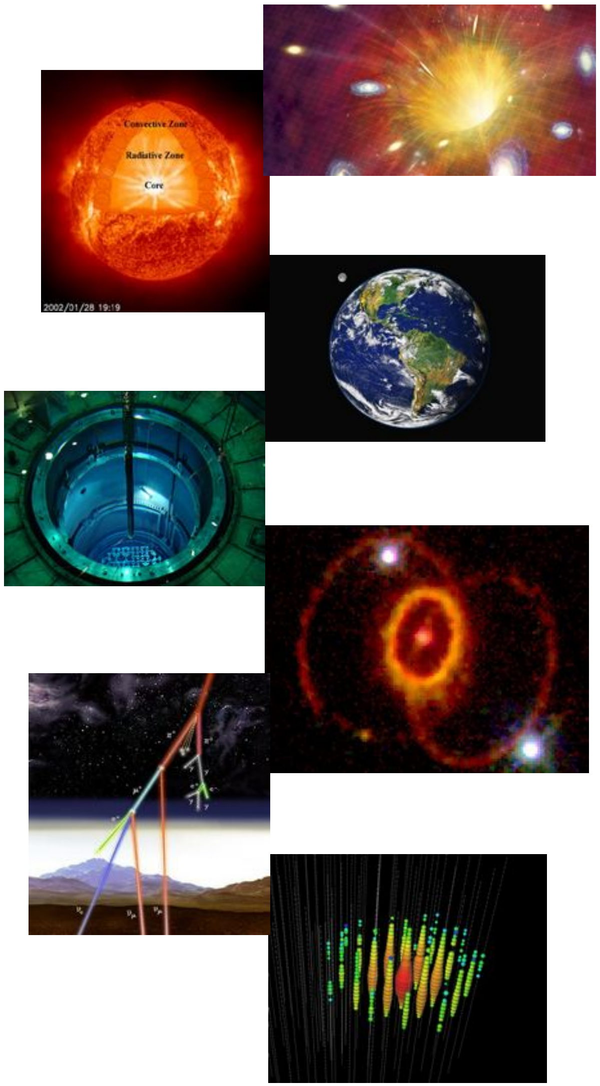


Lepton number violating process

Primary experimental Ansatz

Goals of Neutrino Physics

Use neutrinos as a probe or messenger particle:



10^{-4} eV

Energy

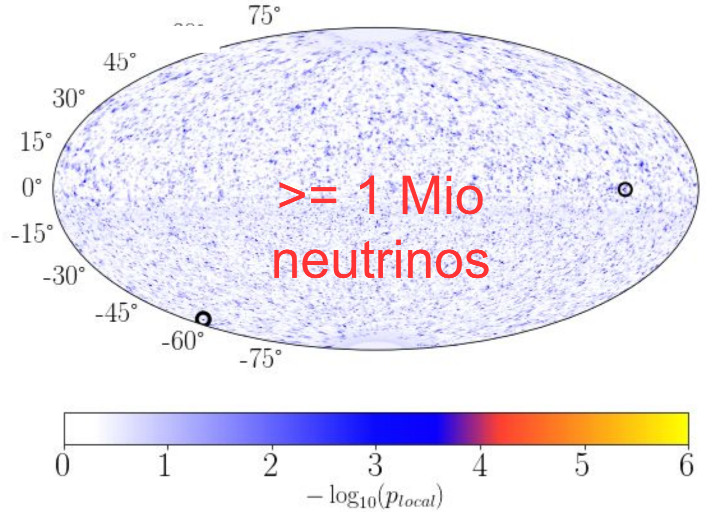
10^{20} eV

- Cosmic Neutrino Background
- Solar Neutrinos
- Geo Neutrinos
- Reactor Neutrinos
- Supernova Neutrinos
- Diffuse Super Nova Neutrino Background (DSNB)
- Atmospheric Neutrinos
- Astrophysical Neutrinos

The Neutrino Revolution: Examples

"I have done a terrible thing, I have postulated a particle that cannot be detected" Wolfgang Pauli (1930)

ICECUBE:
A sky full of Neutrinos



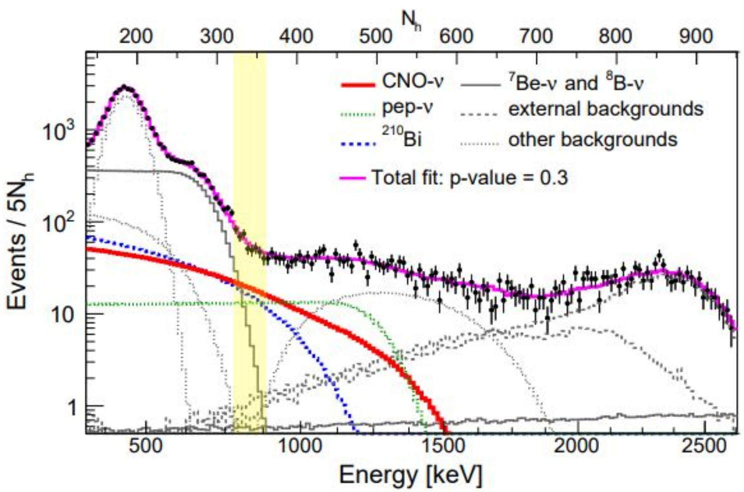
Neutrino energies up to PeV

"New all-sky search reveals potential neutrino sources"

M. G. Aartsen et al. Physical Review Letters 124, 051103 (2020)

Two recent highlights!

Borexino:
Probes the core of the Sun

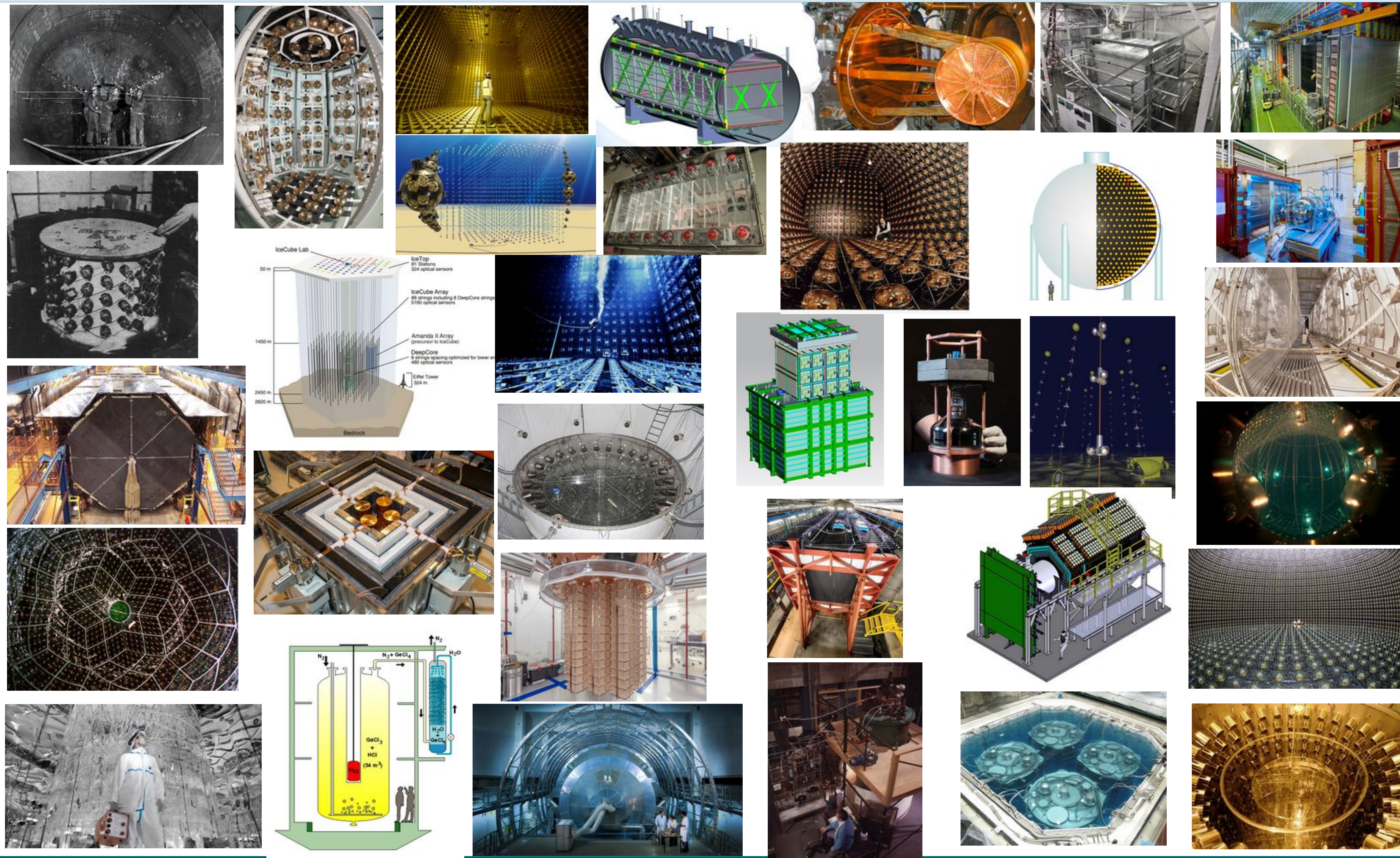


Neutrino energy (MeV)

"First Direct Experimental Evidence of CNO neutrinos"

Agostini, M. et al., June 2020, arXiv:2006.15115

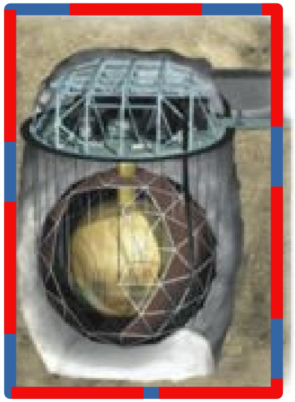
Rich Experimental Landscape



Not a complete picture!

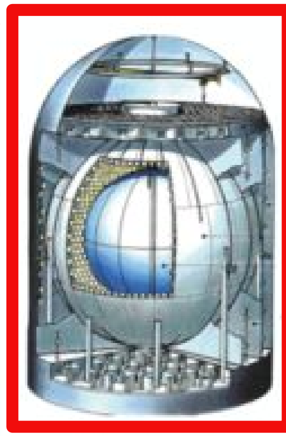
Some Major Contributors

Large homogeneous optical detectors



SNO
/SNO+

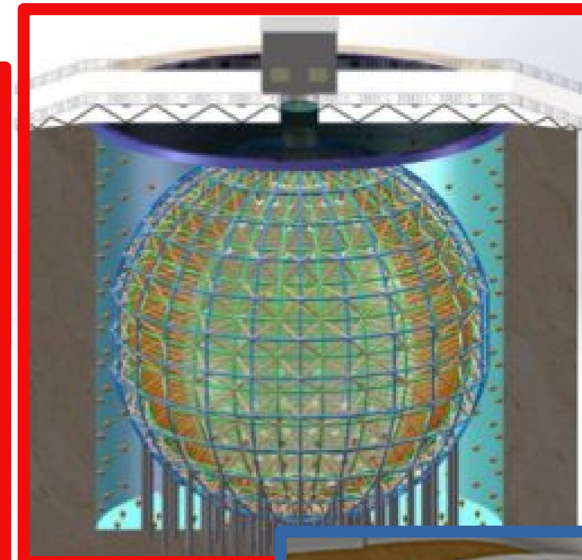
Super-
Kamiokande/
T2K

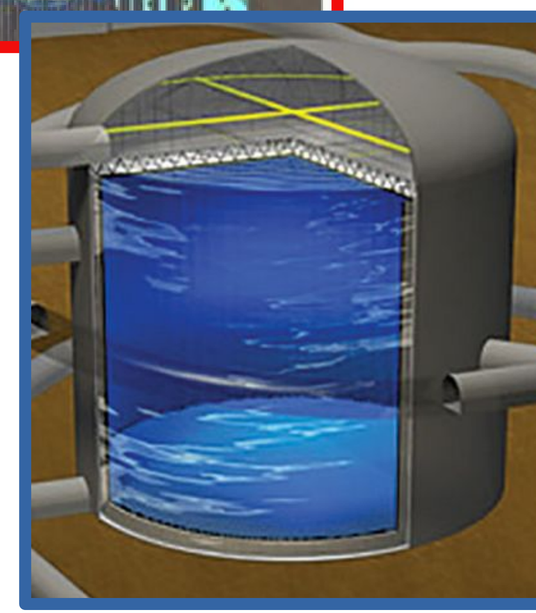


KamLAND
/KamLAND-Zen

Borexino

JUNO
(starting data taking in 2022)





Hyper-
Kamiokande
(starting operation in 2027)

Advantages:

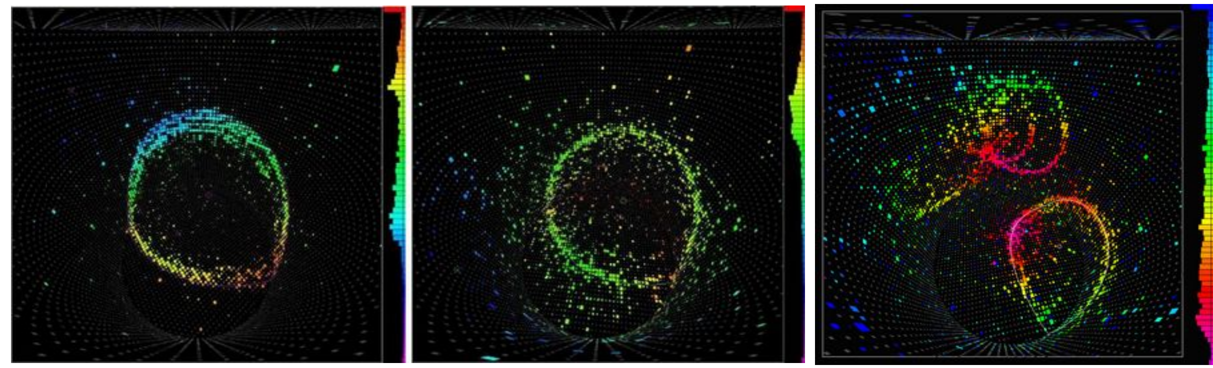
- Large size per cost
- Low threshold
- Fast timing for background reduction
- **Re-configurable as the field progresses**

(Changing or doping the liquid, inserting sub-volumes, using new instrumentation, adding a neutrino source)

Two Detector Types

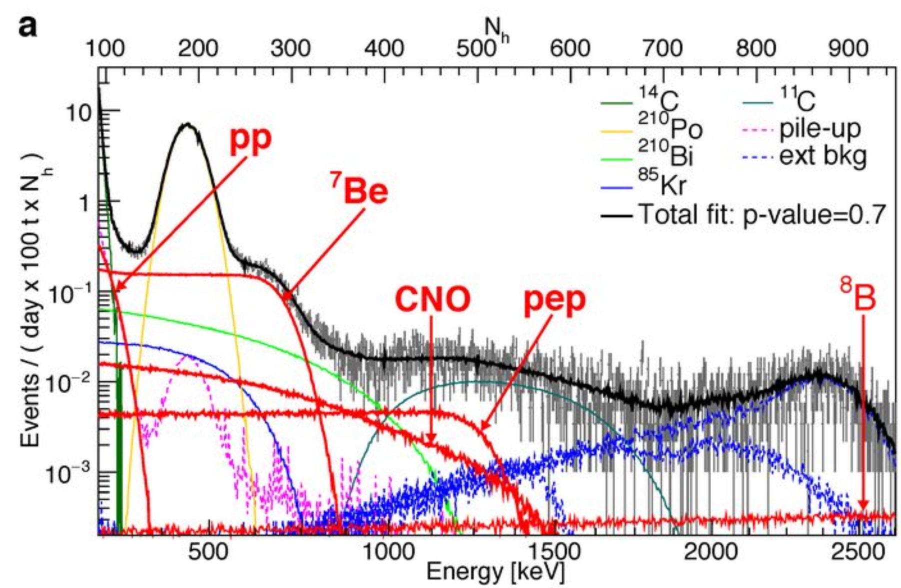
- **Water Cherenkov**
  - Excellent Transparency
    - large size
  - Cheap
  - Directionality
  - Particle ID
  - Potential for large Isotopic Loading

Examples of Chernkov-Rings in Super-Kamiokande



Muon Electron Multi-ring

- **Liquid Scintillator**
  - High light yield
  - Low threshold
  - Good energy resolution
  - Can be radiologically very clean



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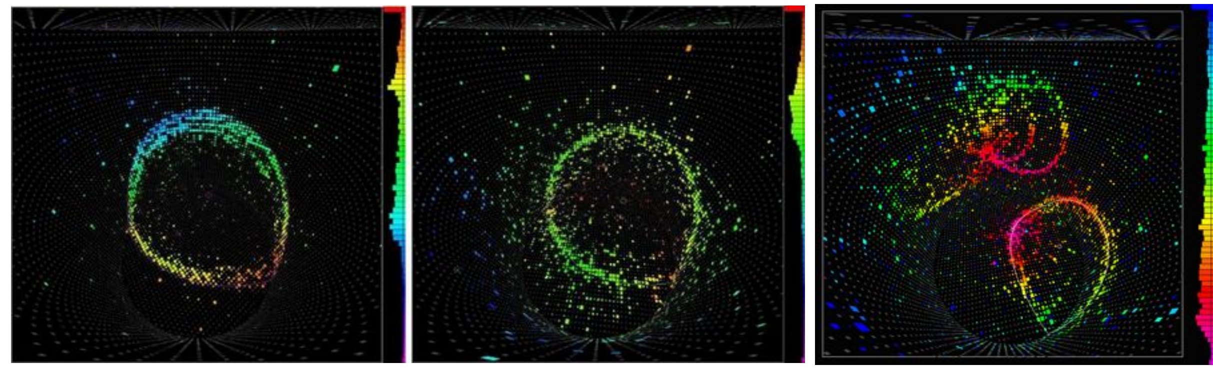
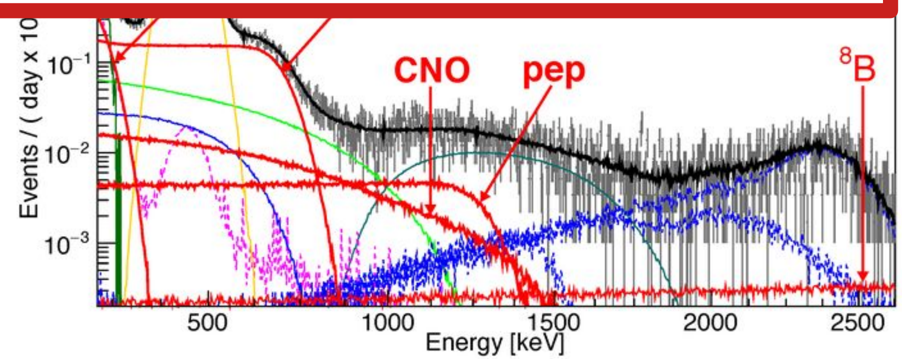


Muon Electron Multi-ring

How to combine the advantages of both?

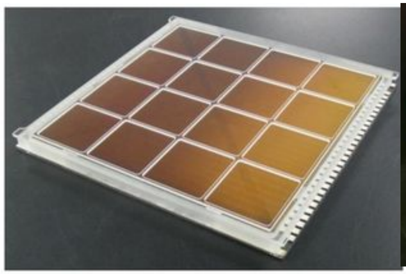
- **Liquid Scintillator**
  - High light yield
  - Low threshold
  - Good energy resolution
  - Can be radiologically very clean

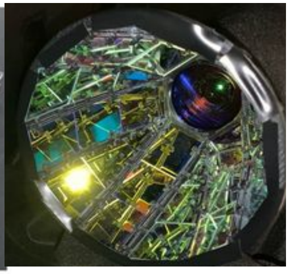


The Theia Project

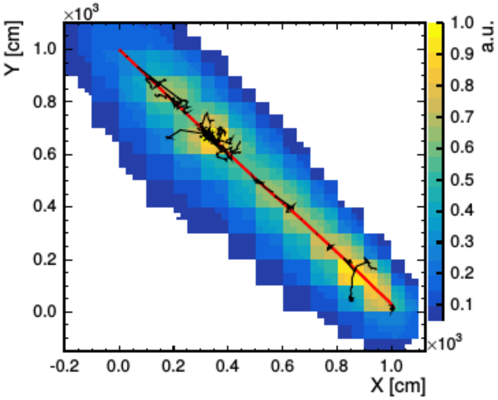
Large volume detector able to **exploit both Cherenkov+Scintillation** signals

Novel target medium: (Wb)LS

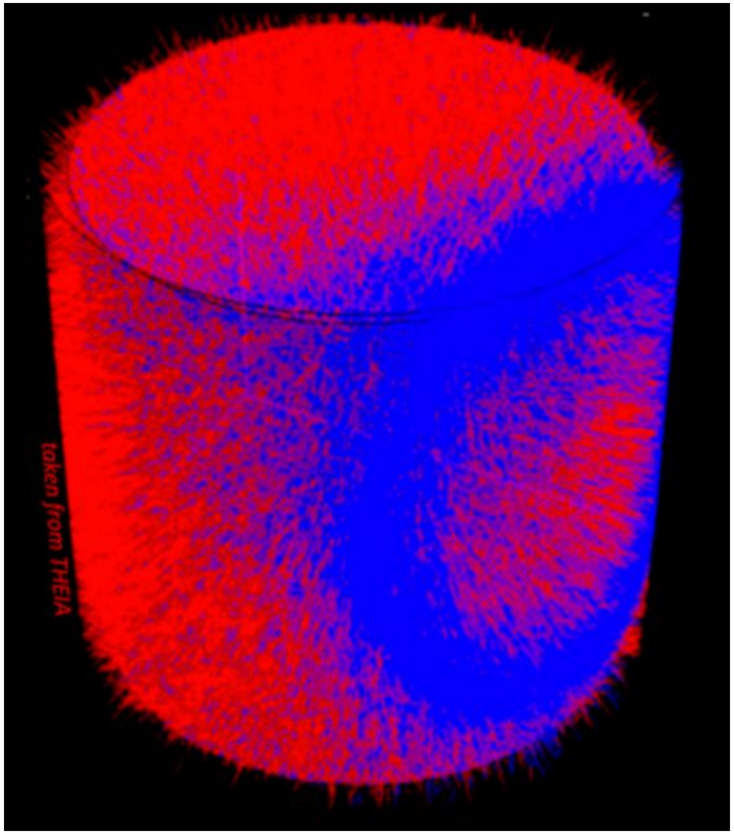




Novel light sensors: LAPPDs, dichroicons



Novel reconstruction methods



M. Askins, et al., Eur.Phys.J.C 80 (2020) 5, 416, arXiv:1911.03501

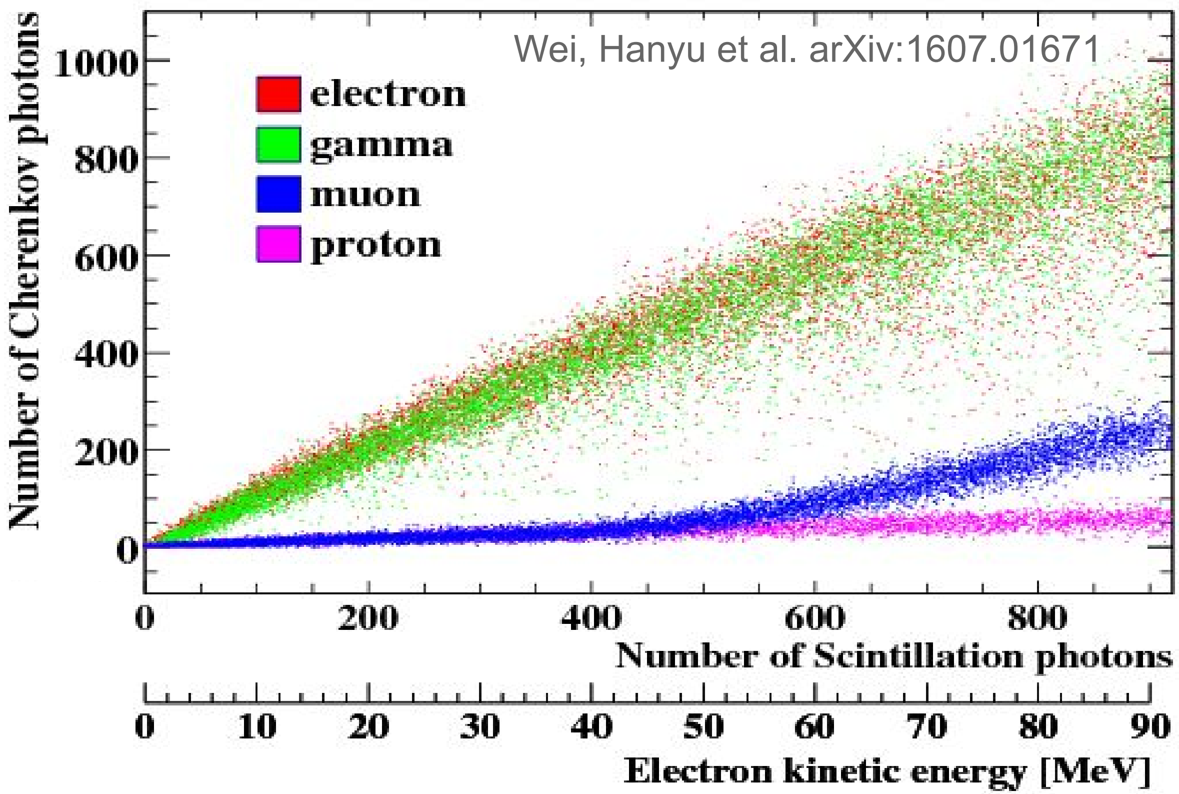
Enhanced sensitivity to broad physics program:

- Long baseline oscillations
- Solar neutrinos
- Supernova neutrinos
- Diffuse SN neutrinos
- Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

Key Aspect

- **Separating Cherenkov & Scintillation light:**
  - Access information from both light species
  - Cherenkov/Scintillation ratio (C/S-ratio)

    → **Enhanced particle discrimination**



Number of Cherenkov- and scintillation photons for different particles in LAB

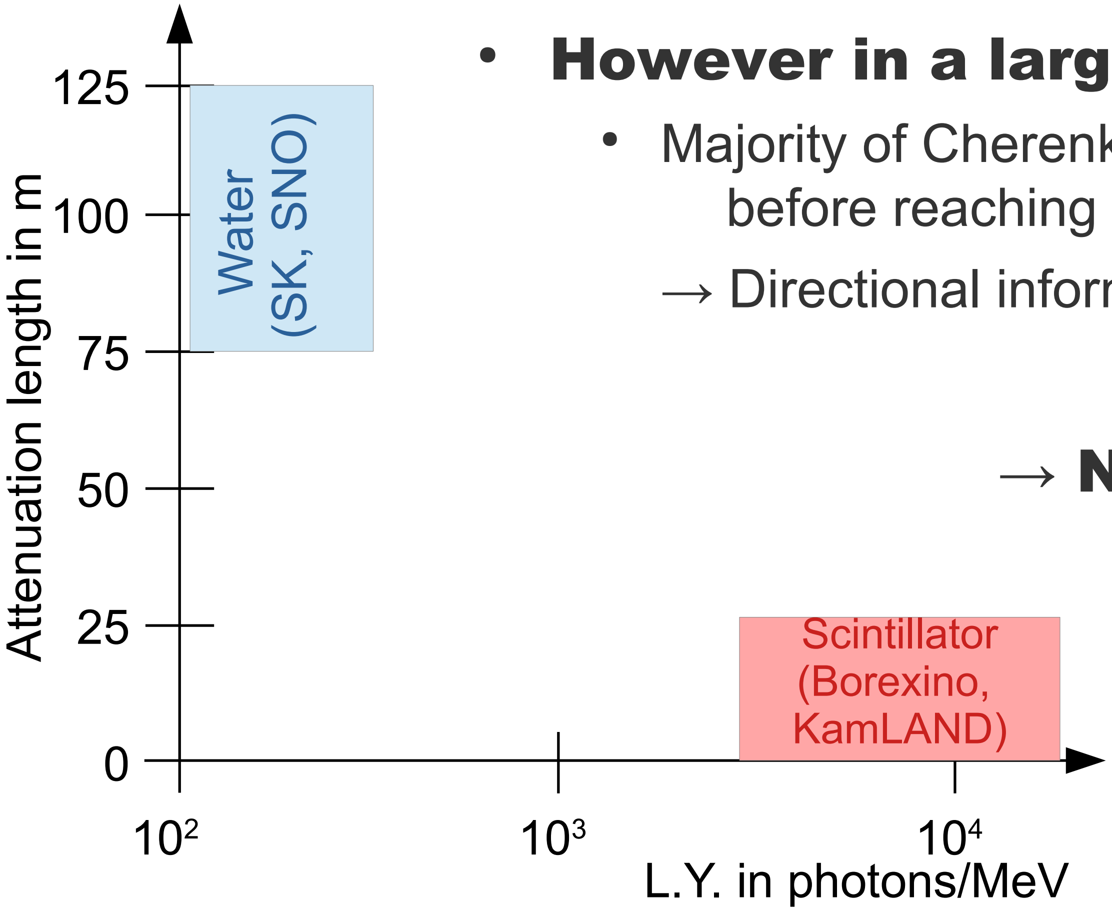
THEIA:

More than just the sum of a Cherenkov & a liquid scintillator detector!

How to Build such a Hybrid Detector?

- **In principle I could take pure liquid scintillator**
  - > 3% of light emitted is Cherenkov-light

    → Hard to see rings in scintillation background



- **However in a large detector**
  - Majority of Cherenkov-photons scattered or absorbed before reaching PMTs

    → Directional information is lost

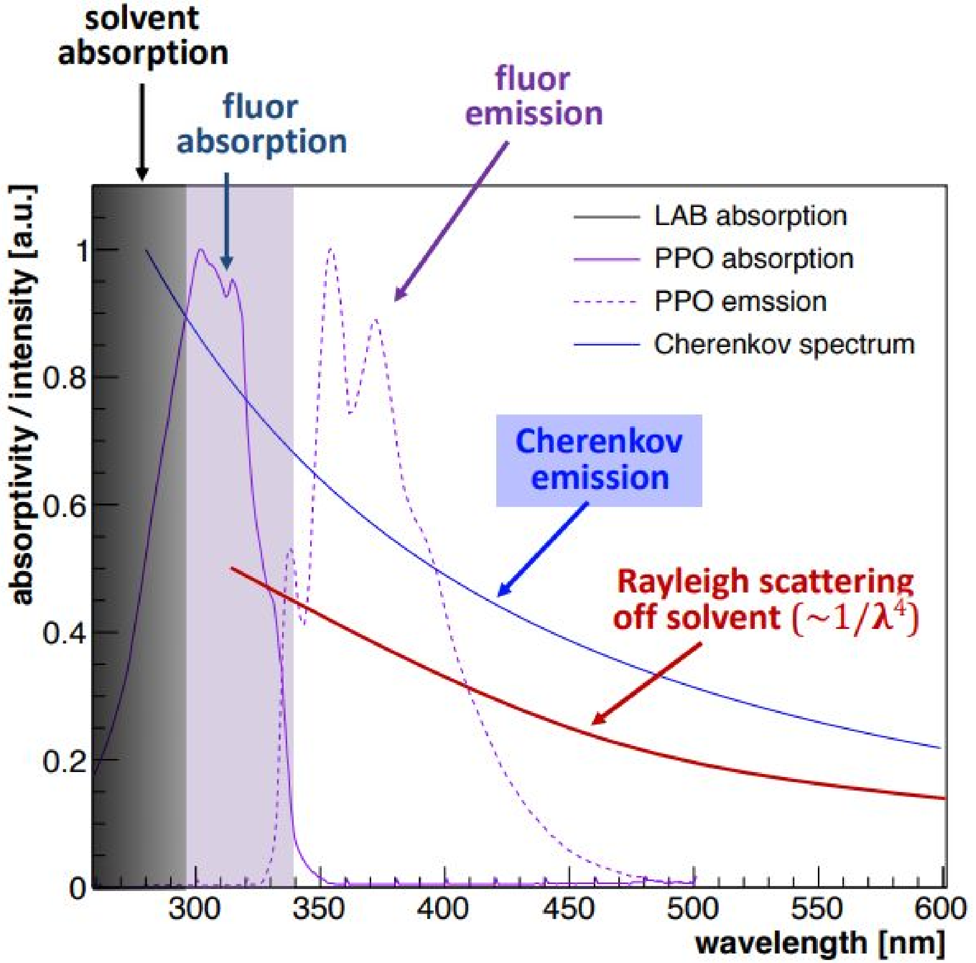
→ **Need to optimize the liquid!**

How to Improve Relative Cherenkov Yield?

- **Reduce Rayleigh scattering**
  - New transparent solvent, e.g. LAB (λ > 20m)
  - Dilution of solvent:
    - Water-based LS
    - Oil-diluted LS (LSND, …)

- **Reduce fluor concentration**
  - Impacts scintillation yield
  - Slows down scintillation

    → Helps separation (see later)



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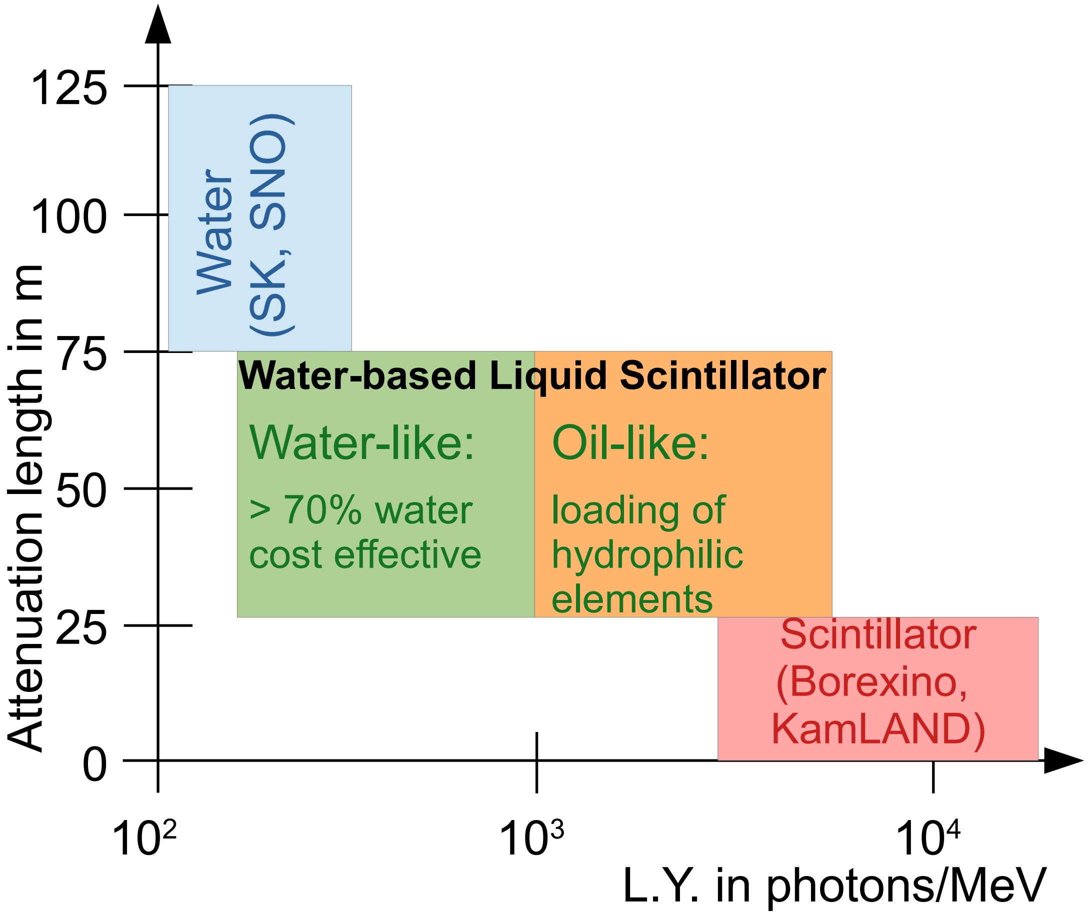
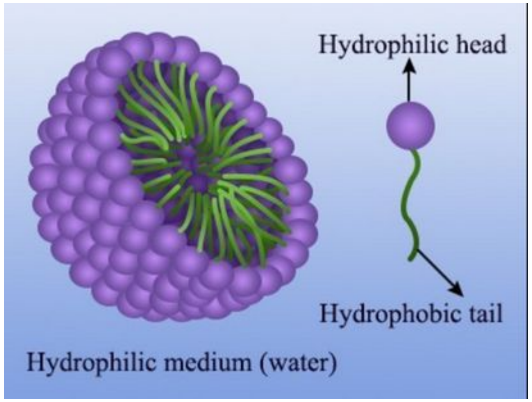


Water-based Liquid Scintillator (WbLS)

- **Idea:** Use a surfactant to generate mycels with oil inside
  - Successful produced at BNL and JGU Mainz
  - BNL already working on production of larger samples
  - Nanofiltration developed at UC Davis
  - Can be loaded with many elements (Li, B, Ca, Zr, In, Te, Xe, Pb, Nd, Sm, Ge, Yb)

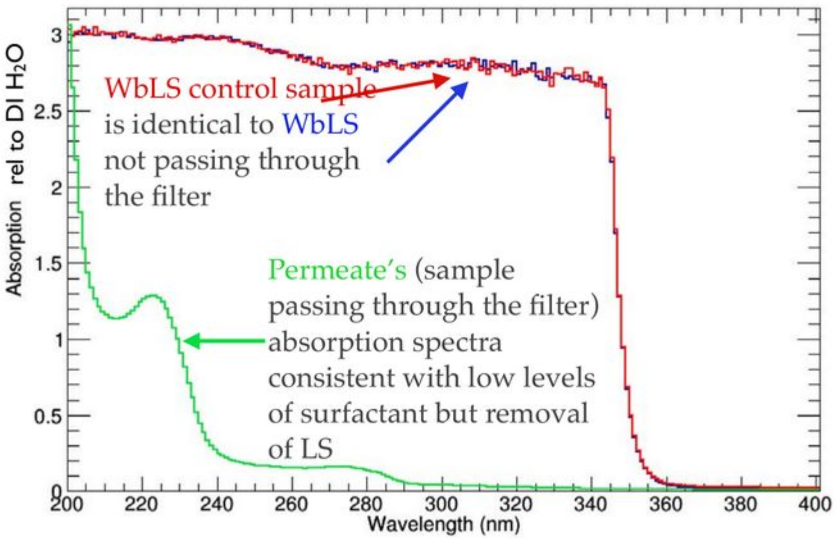


WbLS mycels (nm-scale)

WbLS from Mifang Yeh (BNL)

Hans Steiger (JGU Mainz)

Ton-scale production facility (at BNL)



Results of Nanofiltration (UC Davis)

Cherenkov-/Scintillation Light Separation

3 signatures to separate Cherenkov-Light

Timing

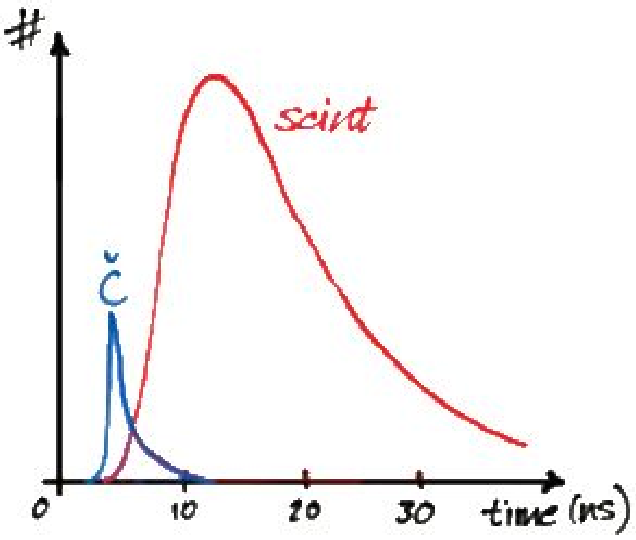
“instantaneous chertons” vs. delayed “scintons”
→ ns resolution or better

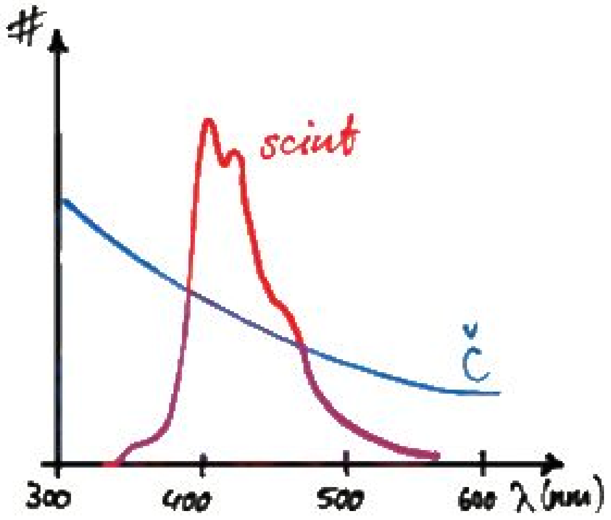
Spectrum

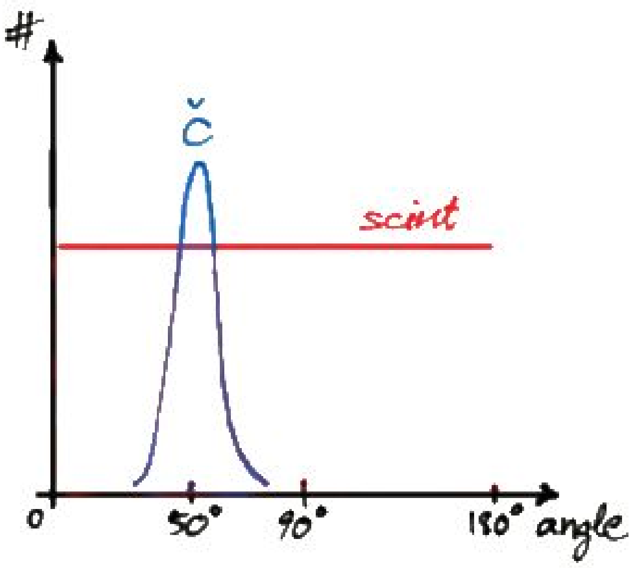
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity

Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity







Courtesy to M. Wurm for this plots!

Time Based Separation

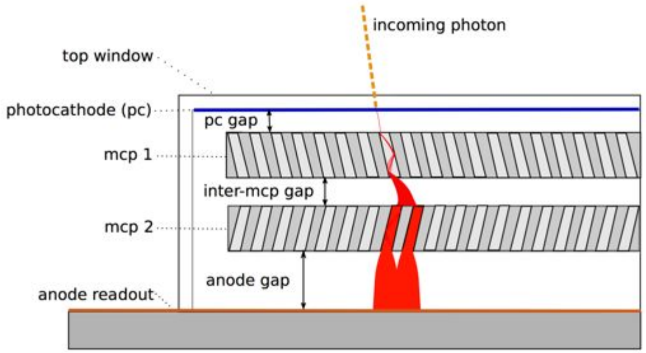
Large Area Picosecond Photon Detectors (LAPPDs)

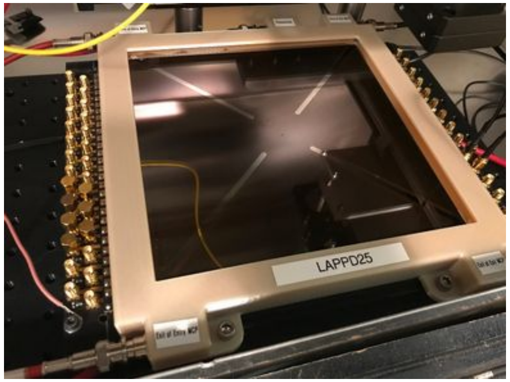
- Area: 20-by-20 cm^2

- Amplification of p.e. by two MCP layers
- Flat geometry

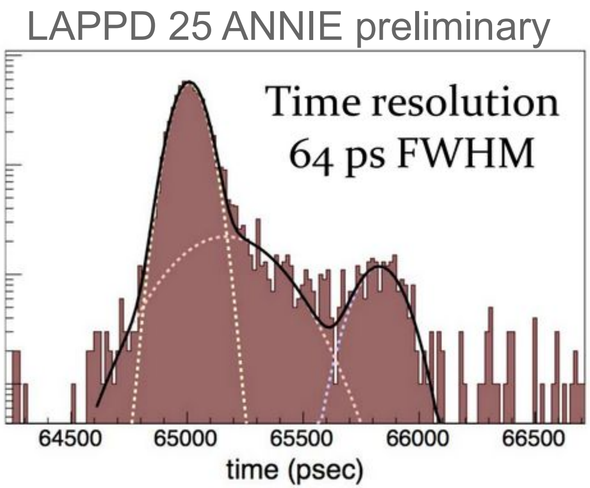
- Ultrafast timing ~65ps
- Spatial resolution <1cm

- Commercial production by Incom, Ltd.

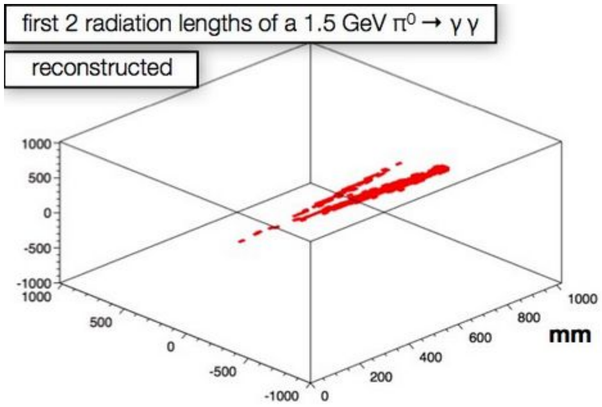




< 4% later/after pulse



144 ps ~ 1 cm in water!



Optical reconstruction of charged particle tracks

See NIM A 814, 19-32 (2016); NIM A 795, 1-11 (2015); NIM A 732, 392-296 (2013); https://psec.uchicago.edu/; A. V. Lyashenko et al., Nucl.Instrum.Meth.A 958 (2020) 162834, arXiv:1909.10399

Ring Based (Angular) Separation

- **Need high granularity**

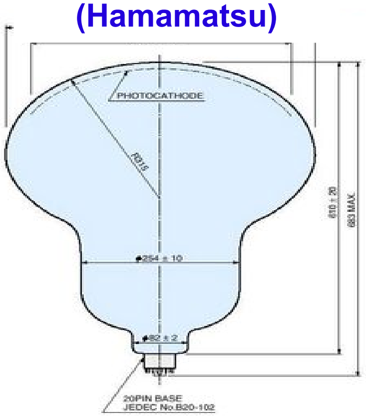
  → Photosensors must be
  - Cheap
  - Efficient
  - Reasonable fast

- Modular PMTs
  (Good compromise of everything)

Water-Cherenkov Test Beam Experiment

- HQE 20” PMTs (Efficient & affordable)

Dynode-PMT (Hamamatsu)

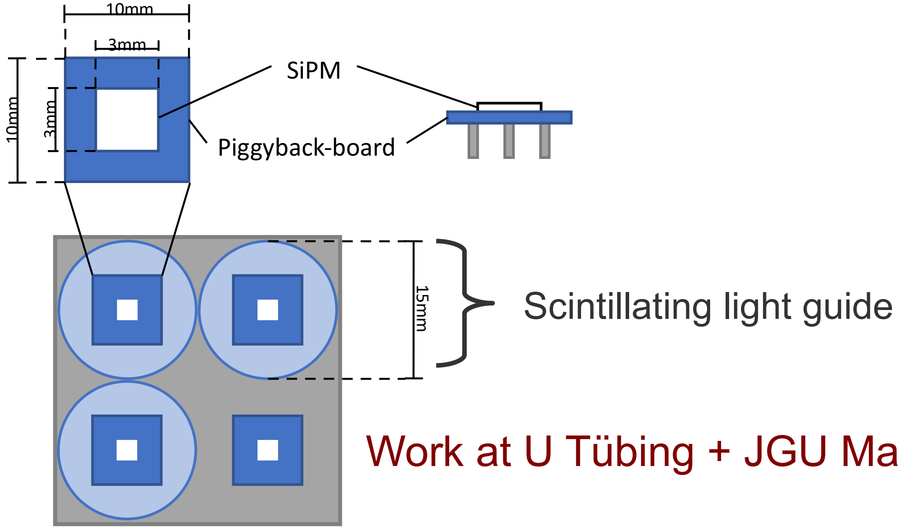


MCP-PMT (NNVT)

QE ~28%: Used in JUNO

Dynode-PMTs: TTS ~ 1ns σ

- SiPM + active light guide
  (Very efficient + increasing affordability)

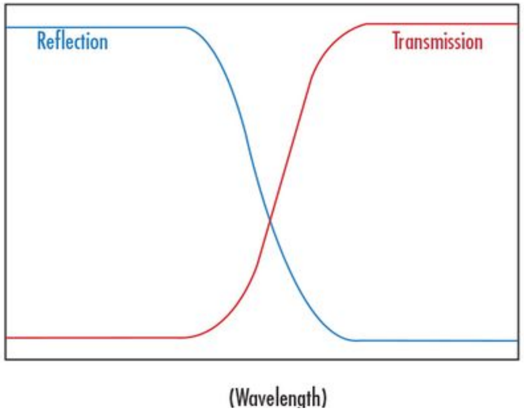


Work at U Tübing + JGU Mainz

Wavelength Based Separation

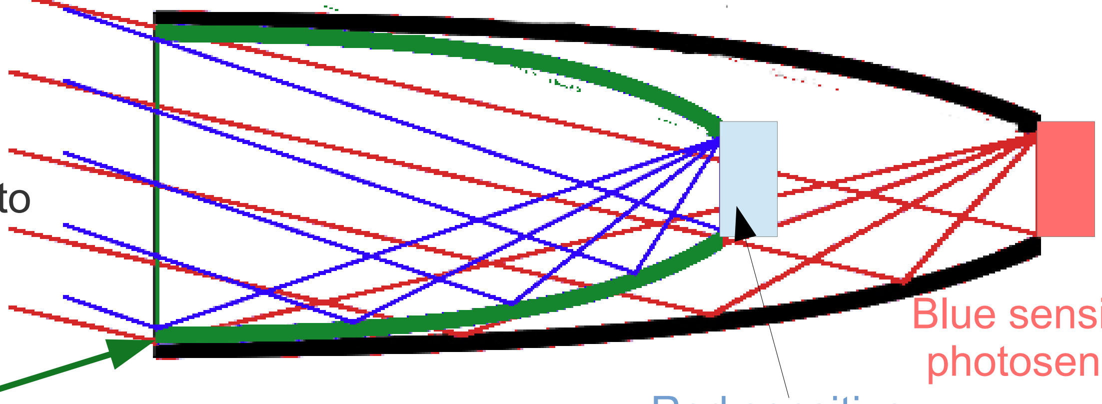
- **Dichroic filter**

  Reflect only light above/below certain wavelength threshold

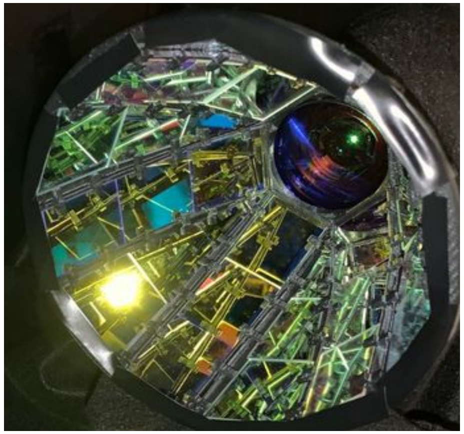


+ Winston cones

Collect light on sensor sensitive to different wavelengths



= Dichroicon



Kaptanoglu, Tanner et al., *JINST* 14 (2019) 05, T05001, arXiv:1811.11587

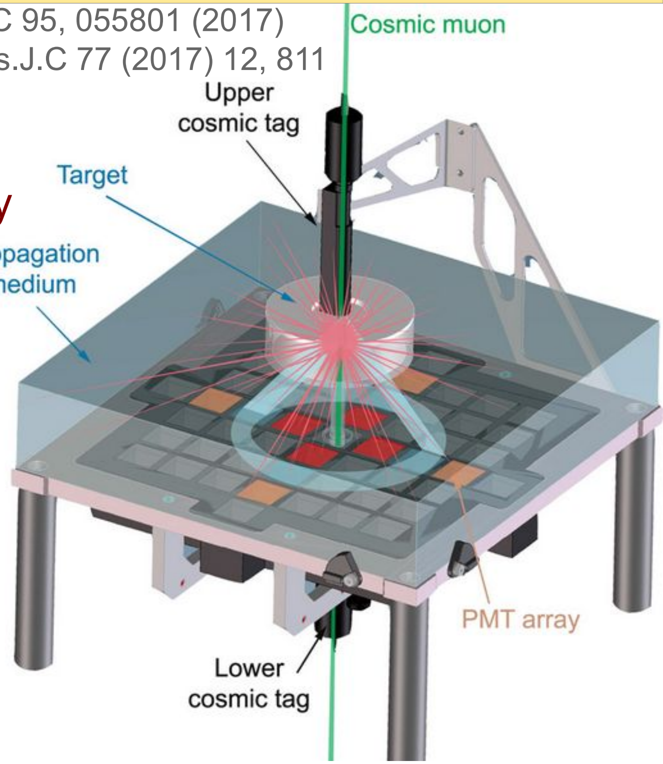
Kaptanoglu, Tanner et al., *Phys.Rev.D* 101 (2020) 7, 072002, arXiv:1912.10333

CHErenkov Scintillation Separation (CHESS)

- Cosmic muon ring-imaging experiment
- Images Cherenkov rings in Q and T on fast PMT-array
- Allows charge and time based separation
- **Results:**
  - Ring and timing pattern clearly visible
  - WbLS faster than pure LAB

Phys. Rev. C 95, 055801 (2017)
also Eur.Phys.J.C 77 (2017) 12, 811

Work at UC Berkeley

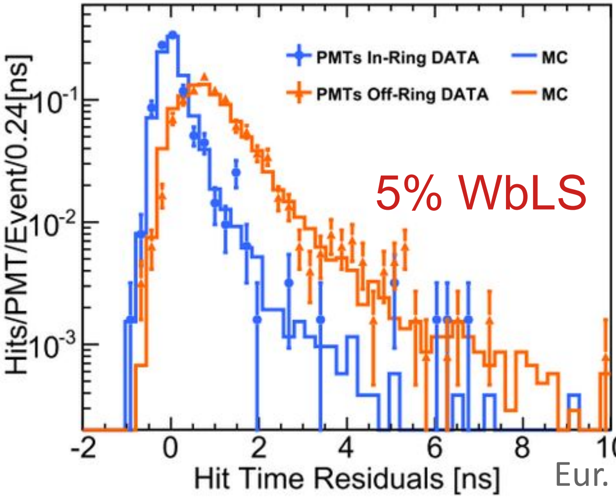


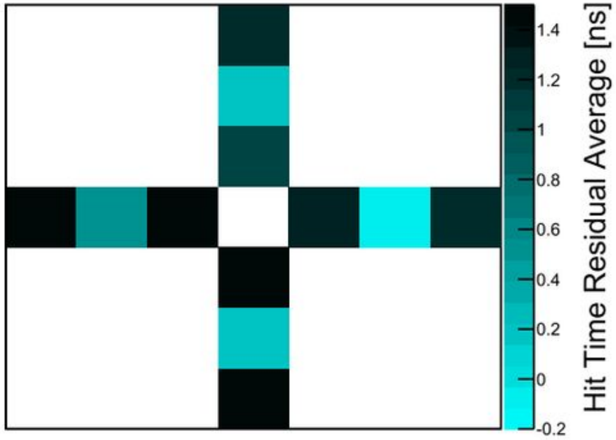
WbLS	1%	5%	10%	LAB + 2g/l PPO
τ_1 [ns]	2.25 ± 0.15	2.35 ± 0.11	2.70 ± 0.16	5.21 ± 0.5*
τ_2 [ns]	15.1 ± 7.5	23.2 ± 3.3	27.1 ± 4.2	16.4 ± 0.6*
R	0.96 ± 0.01	0.94 ± 0.01	0.94 ± 0.01	0.78 ± 0.01*
L.Y. [photon/MeV]	234 ± 30	770 ± 72	1,357 ± 125	11,076 ± 1004

Eur. Phys. Jour. C 80, 867 (2020), arXiv:2006.00173

* T. Marrod´an Undagoitia, Rev. Sci. Instr. 80, 043301 (2009)

Derived first data-driven MC model for WbLS !

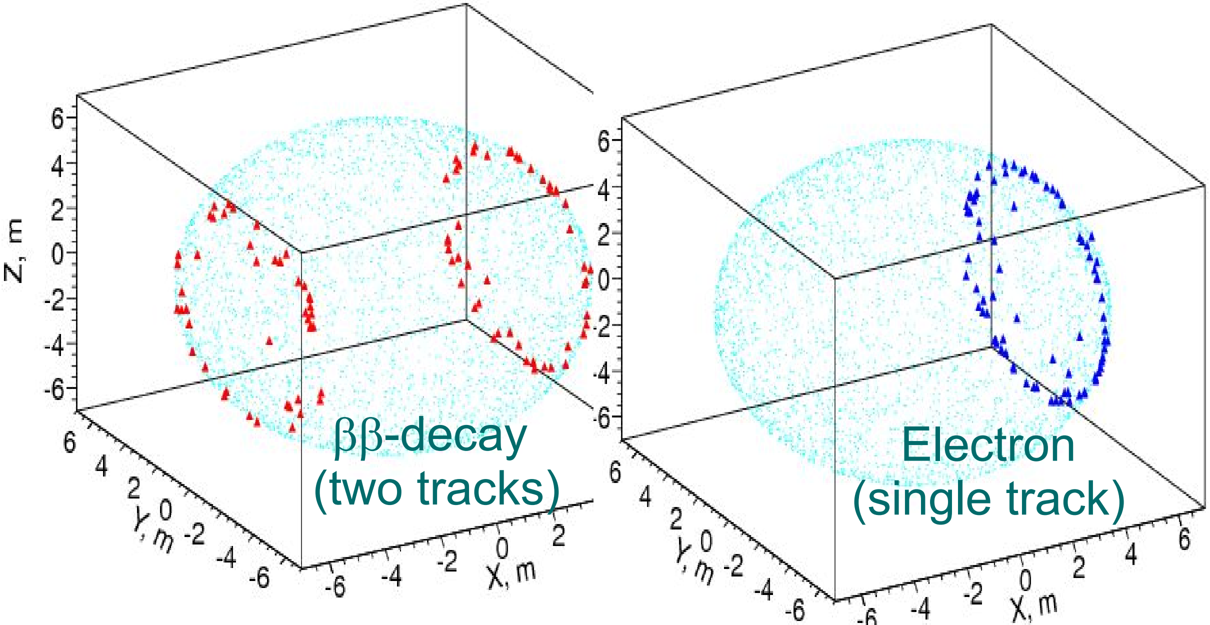




Eur. Phys. Jour. C 80, 867 (2020), arXiv:2006.00173

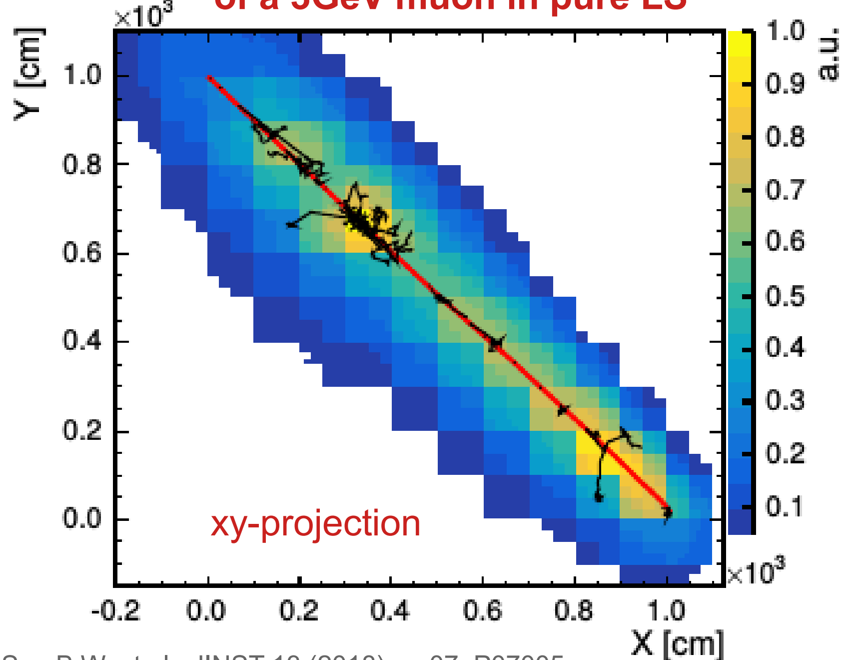
Advanced Computing & Reconstruction Methods

- Reconstruction methods have advanced greatly
  (pulse-shape analysis, machine learning, topological reconstruction)
- Shower identification along tracks possible (dE/dx accessible)
- Cherenkov-light could even revel the two-prong nature of $0\nu\beta\beta$
- Discriminating point-like from non-point like events possible
  (with enough light & good enough timing)



A. Elagin et al., arXiv:1609.09865
(see also R.Jiang and A.Elagin, arXiv:1902.06912)

3D topological reconstruction of a 3GeV muon in pure LS



See B.W. et al., JINST 13 (2018) no.07, P07005

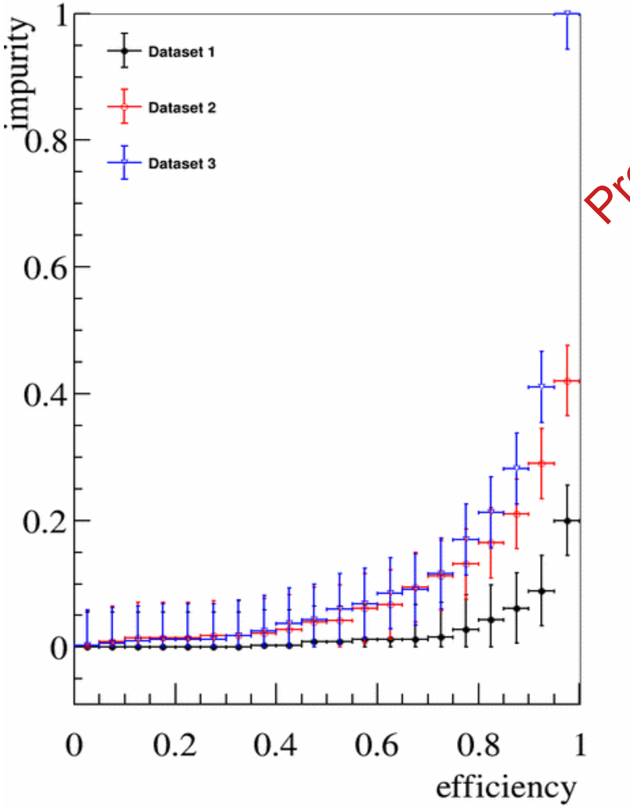
Particle Identification at MeV Energies

- **Data-set 1:** No TTS, perfect vertex, no DCR
- **Data-set 2:** Added TTS and realistic vertex
- **Data-set 3:** Added Dark Count Rate (DCR)

L. Ludhova et al. ArXiv:2007.02687

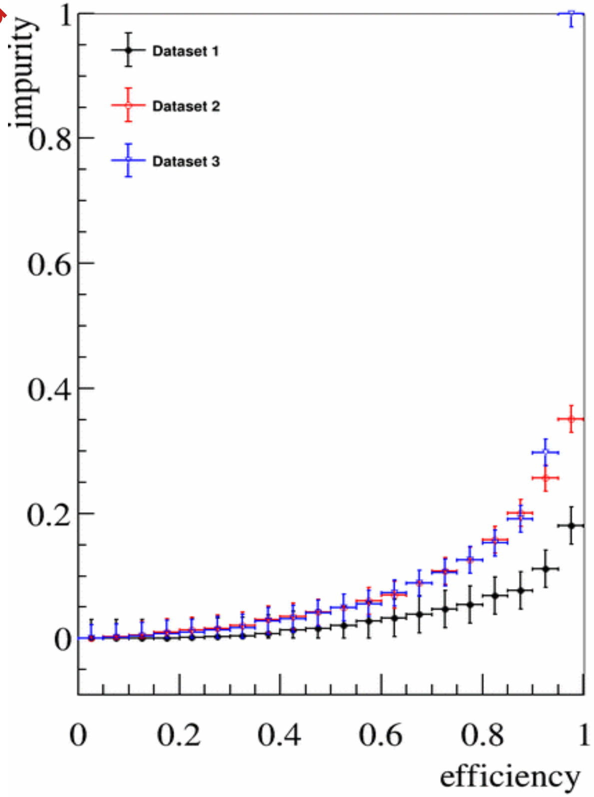
see also BW et et al., doi:10.1142/9789811204296_0028

e+e- discrimination



Preliminary JUNO simulation used

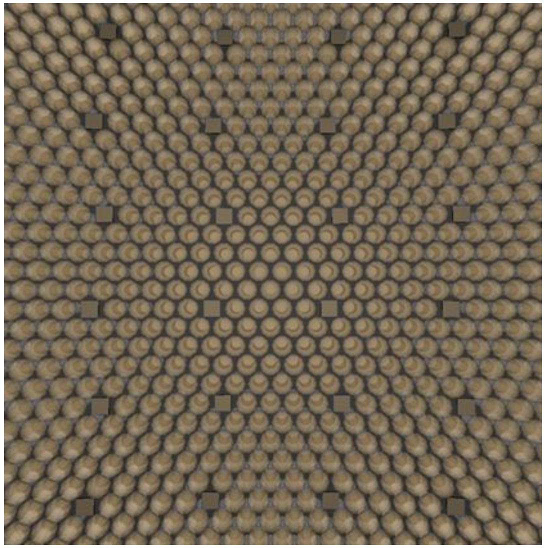
e-/γ discrimination



Gap between data-set 1 and 2 indicates huge potential of good TTS
(good TTS will also affect the vertex resolution)

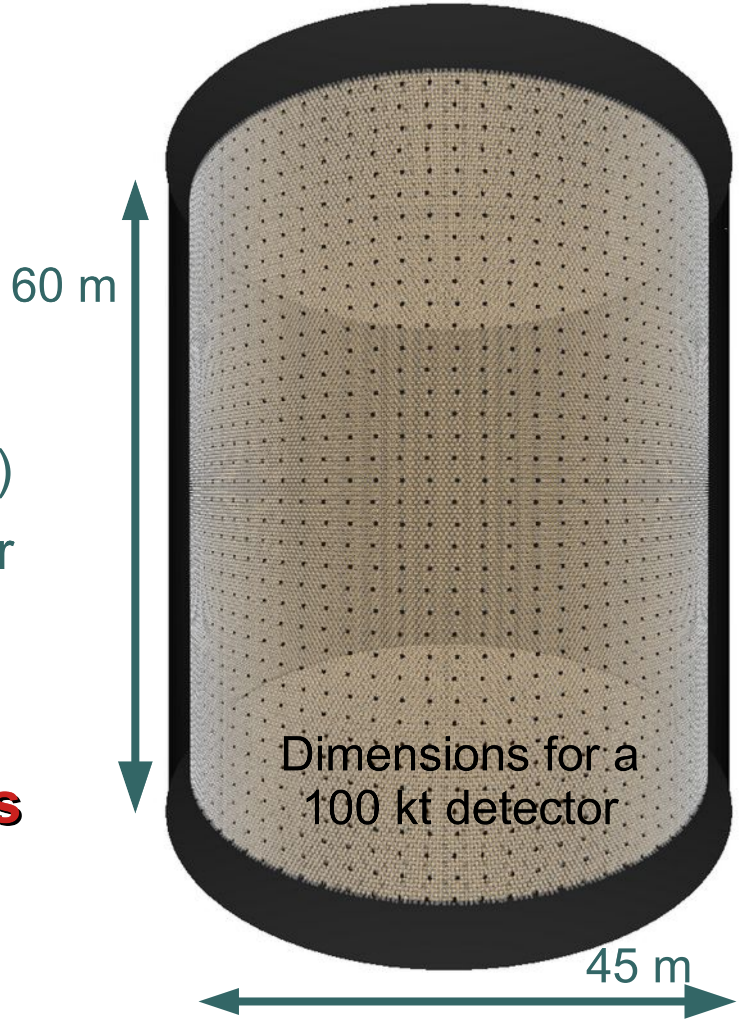
The THEIA Detector

- **Detector specifications:**
  - **Mass:** 25-100 kt (physics and location)
  - **Dimensions:** ~ $(50m)^3$ (WbLS transparency)
  - **Photosensors:** Mix of conventional PMTs (light collection) and LAPPDs (timing)
  - **Location:** Deep lab with neutrino beam (Homestake, Pyhäsalmi, Korean sites, …?)
  - **Isotope loading:** Gd, Te, Li, … (physics, later stage)



→ **Very flexible**

→ **Broad physics program**



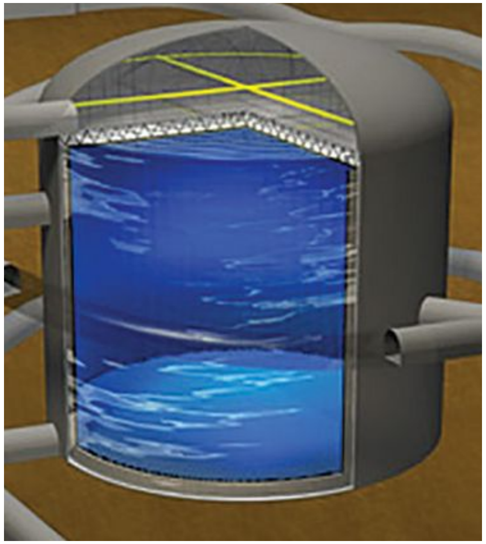
Concept paper: arXiv:1409.5864

White paper: M. Askins et al., Eur.Phys.J.C 80 (2020) 5, 416, arXiv:1911.03501

Future Long-Baseline Neutrino Experiments

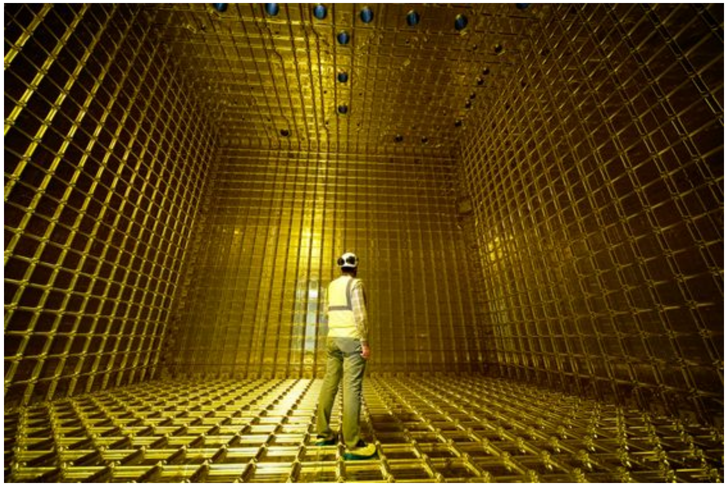
- **THEIA would need a beam to do long-baseline physics**
- **Two upcoming large scale projects:**
  - Hyper-Kamiokande (Hyper-K/HK) & DUNE

Hyper-K



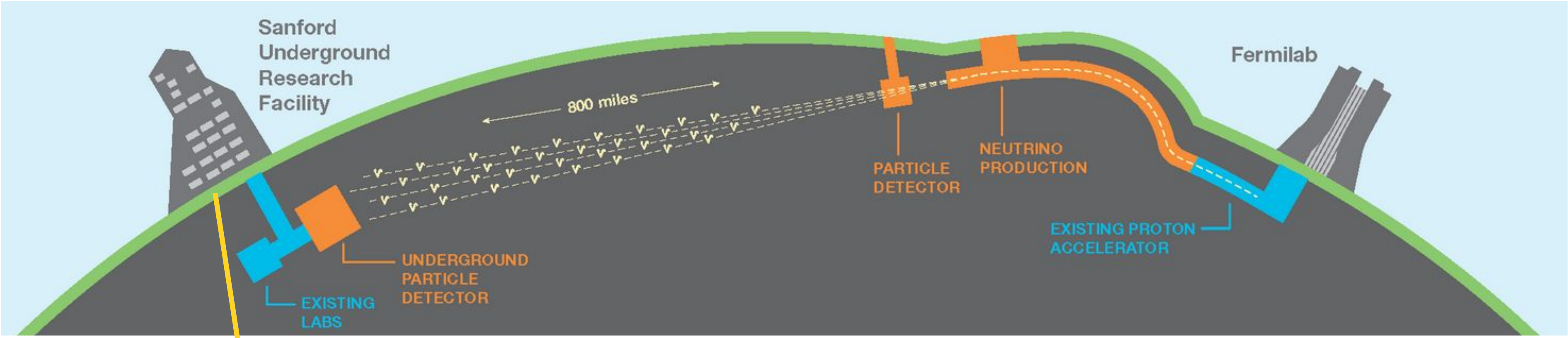
260 kton Water,
starting operation in 2027

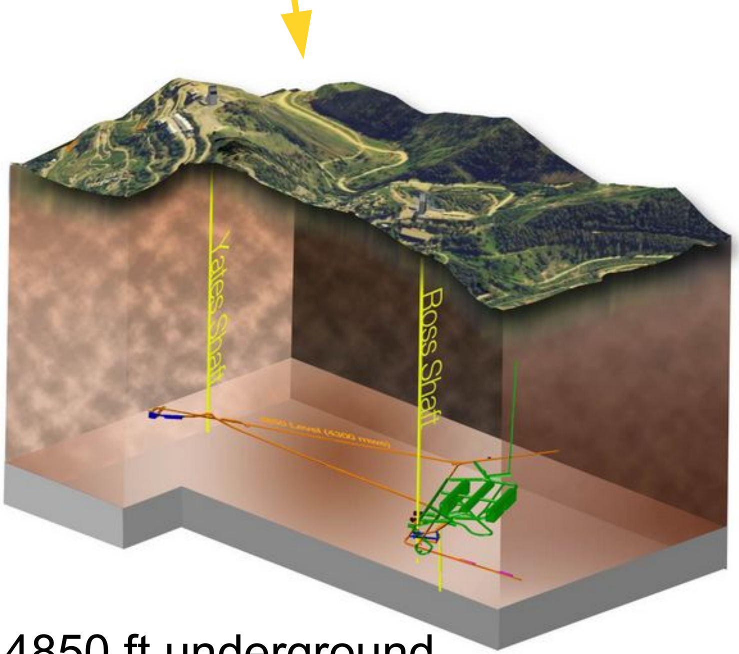
DUNE



3-4 x 10 kton liquid Argon,
beam start 2029

Long Baseline Neutrino Facility (LBNF)



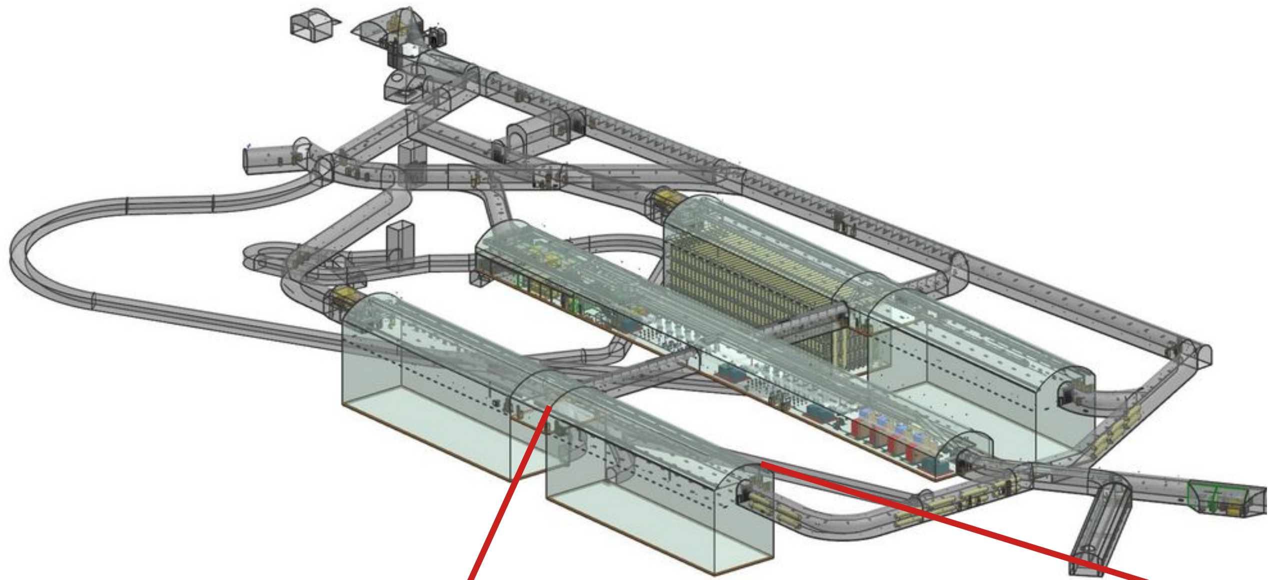


4850 ft underground

<u>SURF (Sanford Underground Research Facility):</u>

- Famous for Homestake experiment
- 1300 km distance to Fermilab
  → large matter effects
- Home of DUNE (4x10kt LAr-detector)
- ~1480 m deep (2300 mwe)
  → muon flux only ~10% of LNGS

Theia and the 4th LBNF Cavern



Detector specifications:

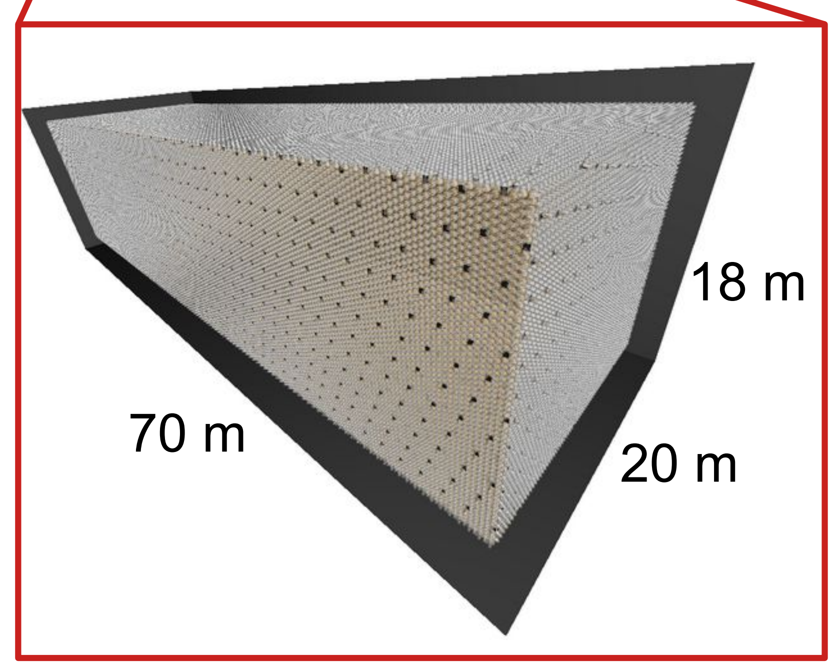
Total mass: 25 kt of WbLS

Fiducial mass: 17-20 kt

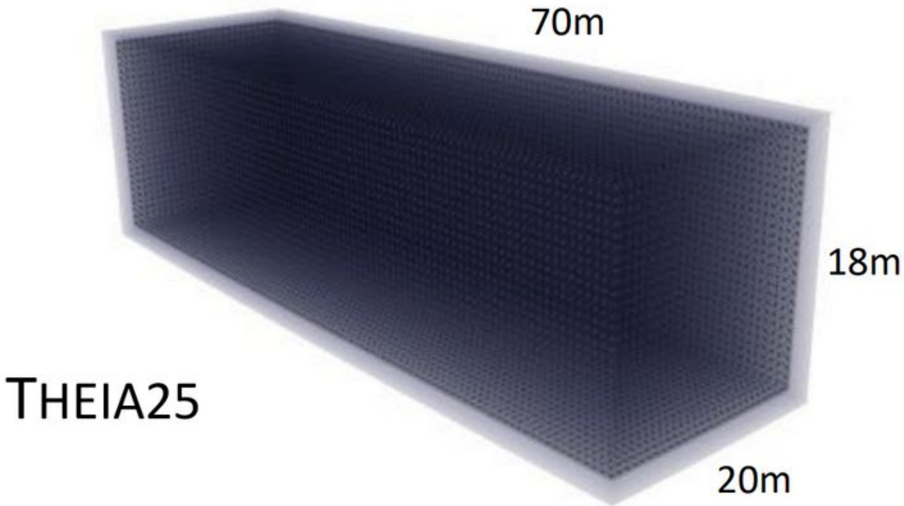
Photosensors:

- 22,500 10” PMTs (high QE) → 25% coverage
- 700 8” LAPPDs → 3% coverage
  - → equals the current photon collection of SK!
  - → upgrade for later phases (solar, $0\nu\beta\beta$)

Background level: ~10^{-15} g/g in ^{238}U, ^{232}Th, ^{40}K
(Borexino: ~10^{-17} - 10^{-18} g/g)



THEIA25: Stage 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

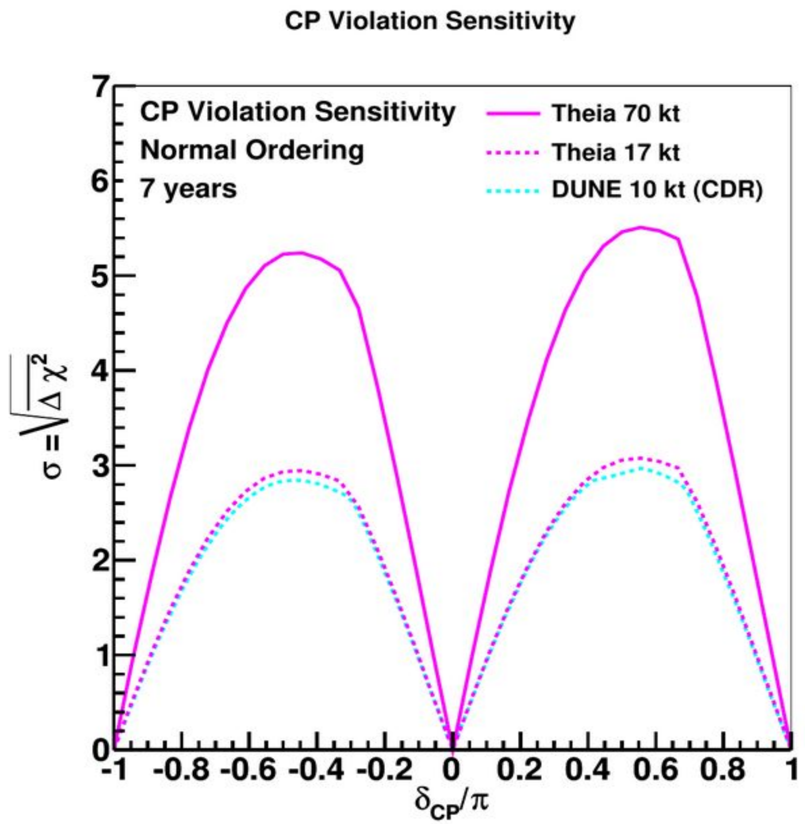
Physics Goals

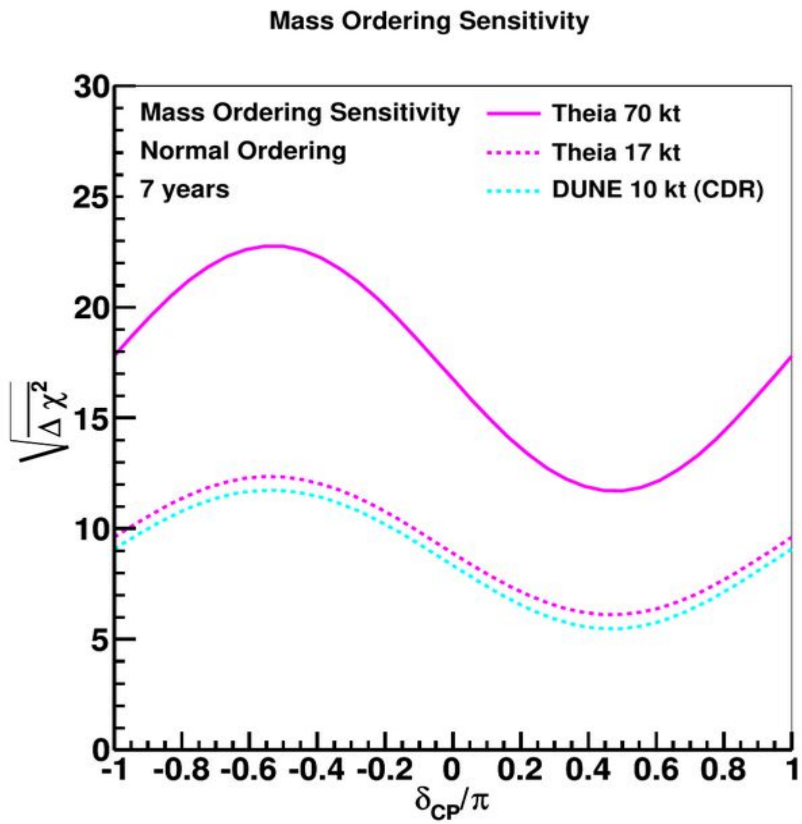
- **Long-Baseline Oscillations**
- **Proton decay** $\rightarrow K^{+}\nu/\pi^{0}e^{+}$
- Supernova neutrinos
- Diffuse SN neutrinos
- Solar neutrinos
- Geoneutrinos
- **$0\nu\beta\beta$ search** on <10meV scale

Courtesy to M. Wurm for this slide!

Neutrino Oscillation Sensitivity of THEIA25

- **Key:** Rejecting NC background ($\nu_\mu + X \rightarrow \nu_\mu + X + \pi_0$; $\pi_0 \rightarrow 2\gamma$)
- SK & HK improved reconstruction methods a lot (using Ring imaging)
- Assumed same efficiencies (ignoring additional benefit expected from WbLS)





THEIA25 equivalent to 1 DUNE module in terms of sensitivity!

Added Value for LBNF (δ_{CP}) Program

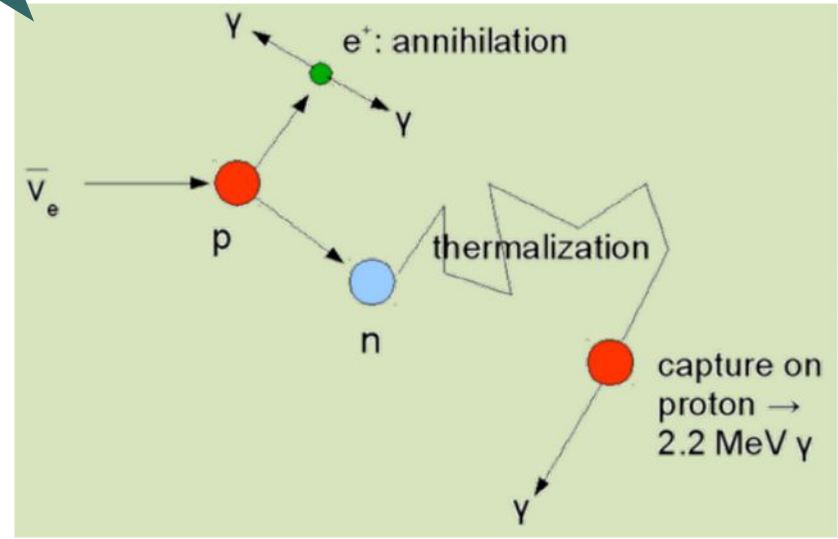
In the end DUNE will be dominated by systematics

Adding different technologies and a different target will be more important than increased statistics!

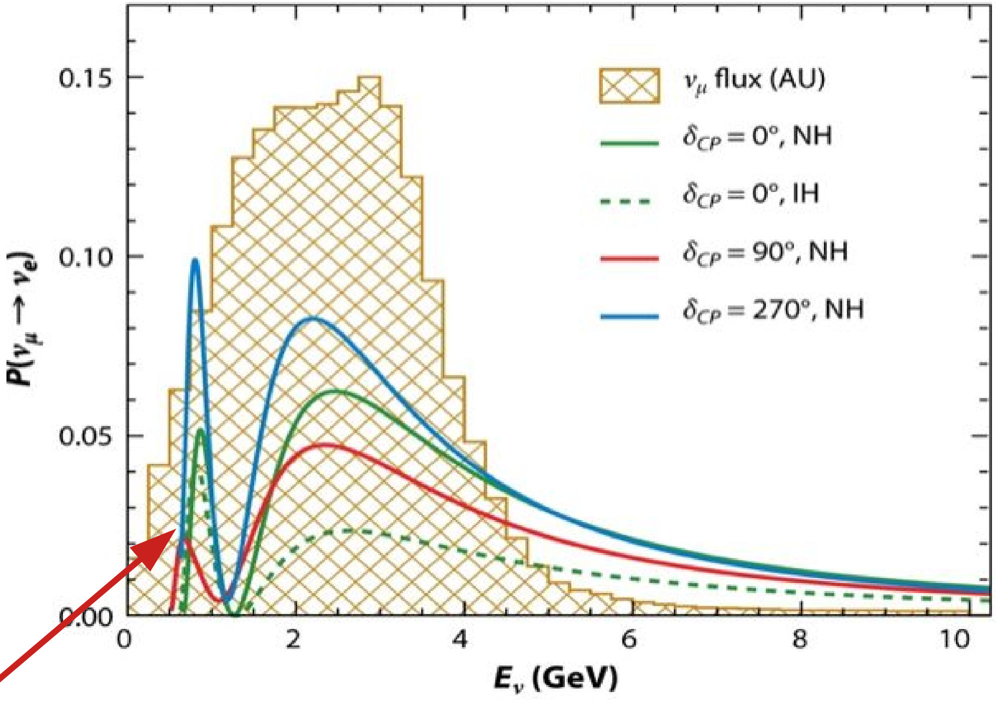
- **Additional statistics**
  - ~1.7:1 in mass for WbLS : LAr
- **Complementary systematics**
  - e.g. cross-sections (simpler nuclei)
- **Hadronic recoils/neutron tagging**

  → reduces systematics of energy reco

  → neutrino/antineutrino discrimination



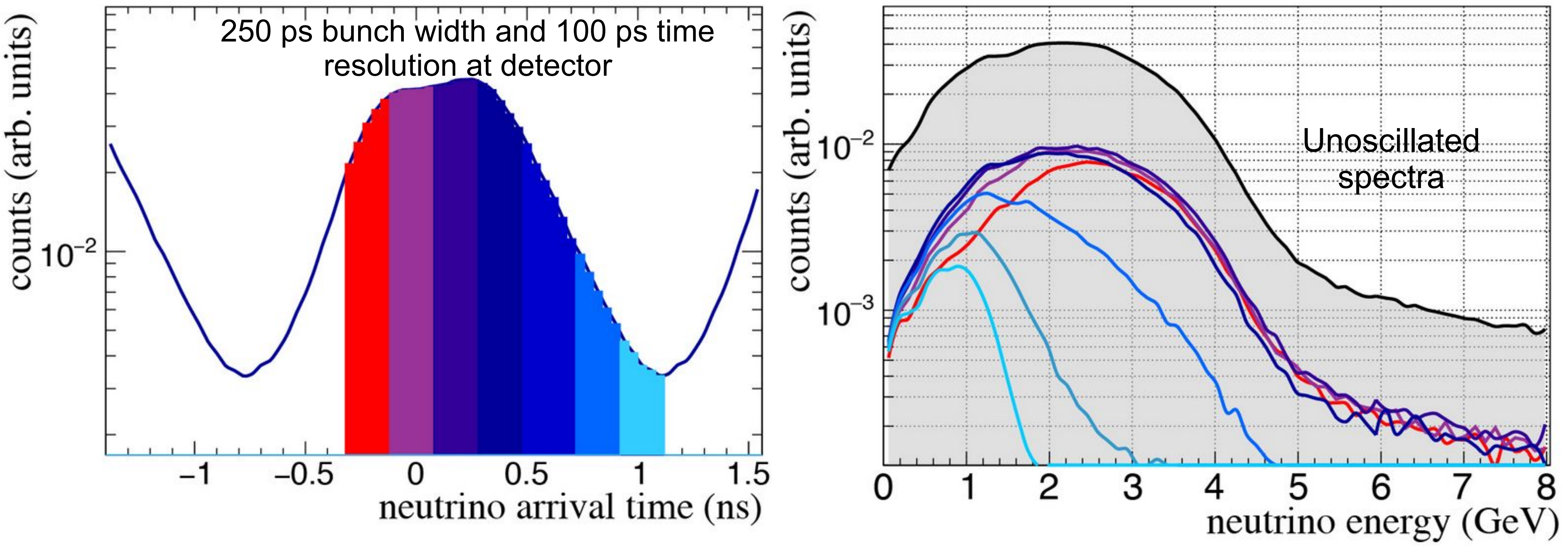
Added Value for LBNF (δ_{CP}) Program



- **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 selection using initial π/K time-of-flight difference

Using Arrival Times at Far Detector

- Low energy Kaons and Pions are slow
  → Neutrinos from their decay arrive later
- Also results in different flavor content for different time slices
- Both helps to disentangle systematics (flux, cross section, reco efficiencies)



Arrival times and energy spectra for the FHC* configuration of the LBNF beam at DUNE

*FHC forward horn current

Low Energy Astrophysics with Neutrinos

Solar Neutrinos
from H fusion in
solar interior

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

Statistics are often more important than systematics

→ Size does matter!

→ Assuming 50 kton (mostly) detector in the following

Diffuse Supernova Neutrinos
from core-collapse Supernovae
throughout the Universe

Geoneutrinos
Natural radioactivity
of Earth crust/mantle

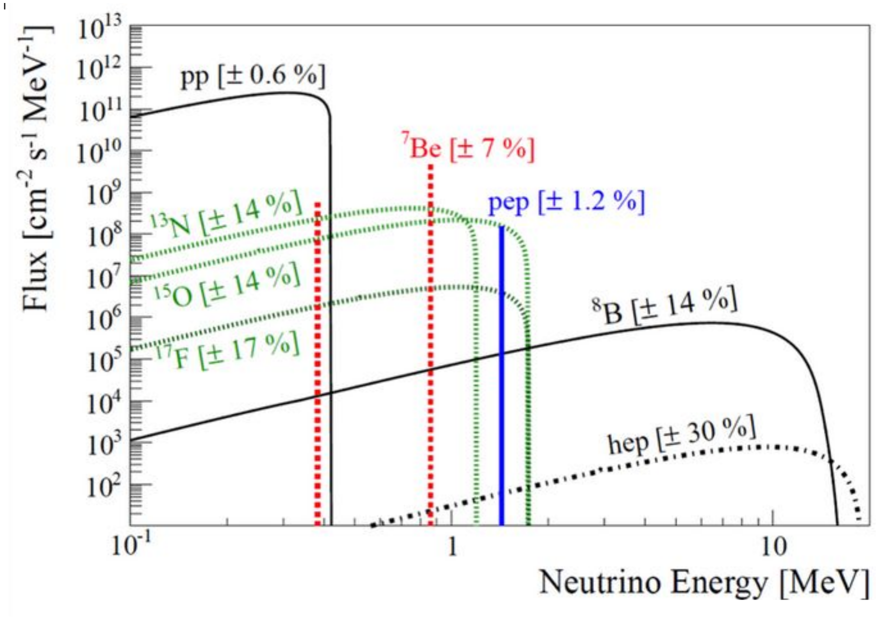
Why Solar Neutrinos?

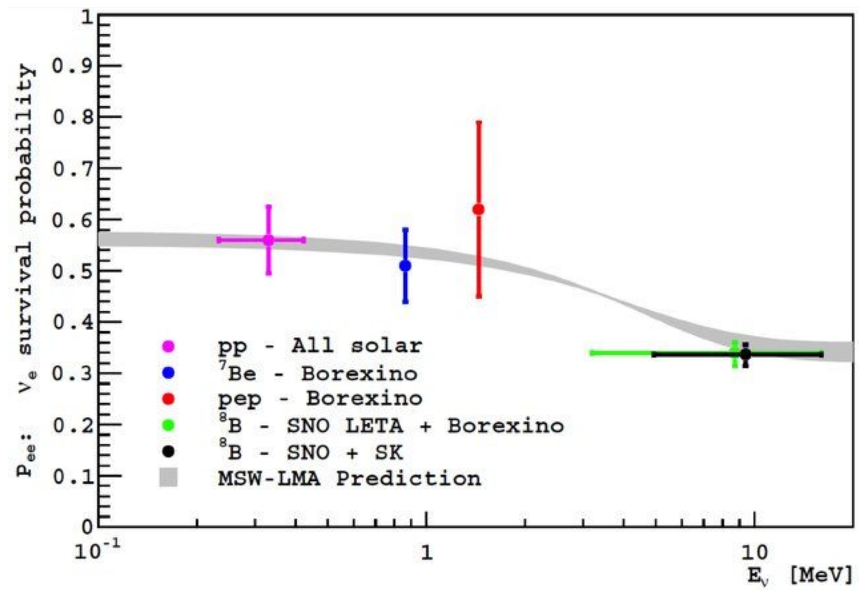
- **Main goals:**
  - Distinguish high- and low metallicity solar models

    → Accurately measure CNO flux
  - Test predictions MSW-Oscillations

    → Look at transition region between vacuum and matter dominated oscillations
  - Precision test of solar models

    (Need to understand the Sun, if we want to understand other stars)





Solar Neutrinos with THEIA

- Large statistic and low background

  → High precision on neutrino fluxes

Signal	Normalization sensitivity (%)
$^{8}B\ \nu$	0.4
$^{7}Be\ \nu$	0.4
pep ν	3.8
CNO ν	5.3
^{210}Bi	0.1
^{11}C	11.5
^{85}Kr	10.5
^{40}K	0.04
$^{39}Ar/^{210}Po$	21.9
^{238}U chain	0.02
^{232}Th chain	0.05

assuming 5% WbLS, 90% coverage, 25% angular resolution

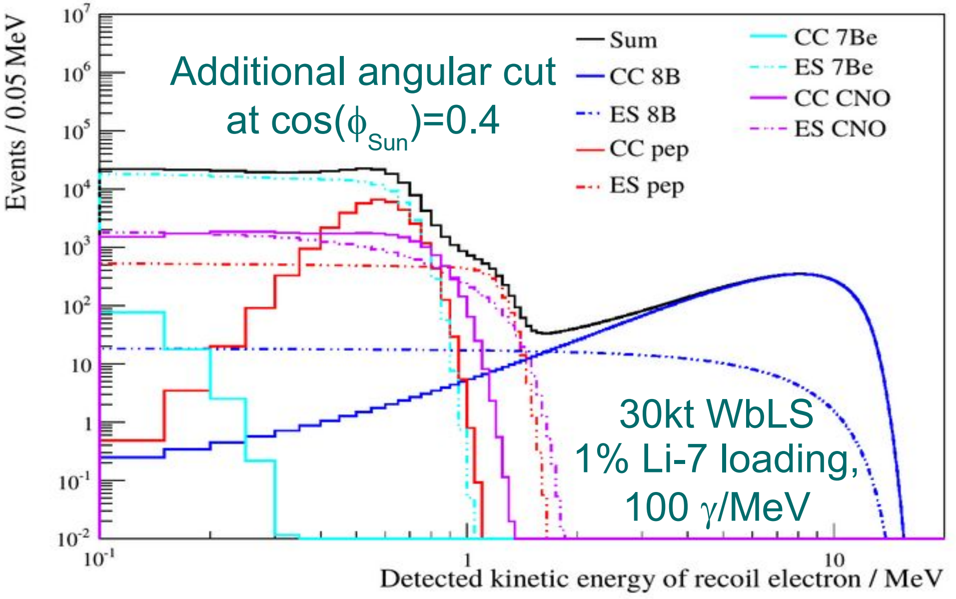
- Li-loading makes CC-channel accessible

$$^{7}Li + \nu_e \rightarrow {}^{7}Be + e^- \quad (\mathrm{Q} = 862\ \mathrm{keV})$$

  - Sharply peaked differential cross-section

    → Almost all incident energy transferred to the scattered electron.
  - Only two transitions possible to
    - ground state of ^{7}Be
    - first excited state of ^{7}Be (430 keV)

  → High precision possible on Eν by tagging excited state decay γ

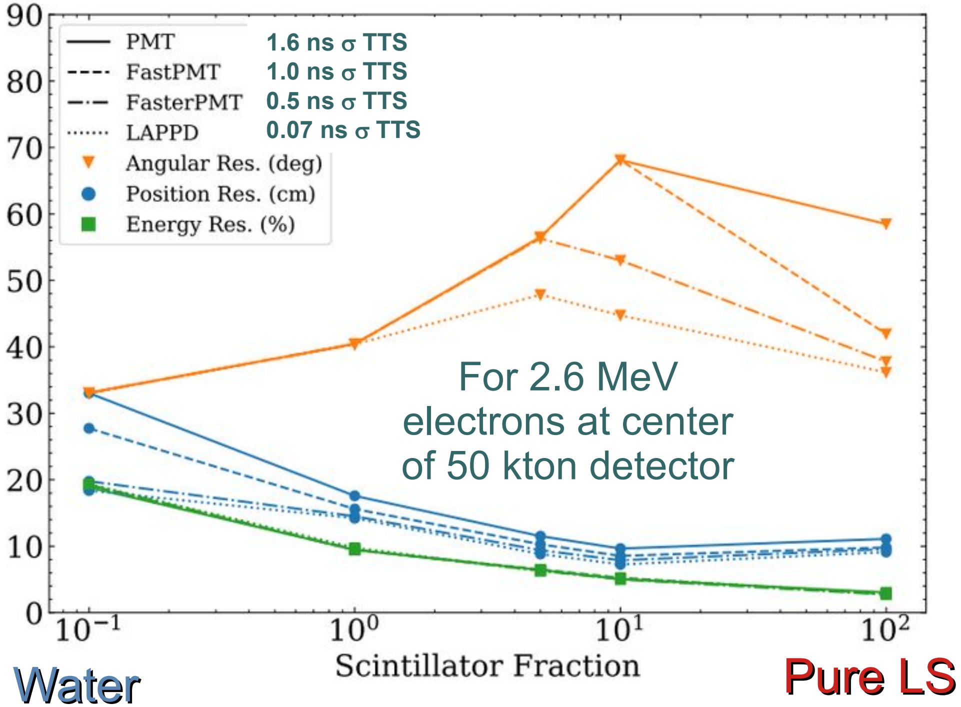


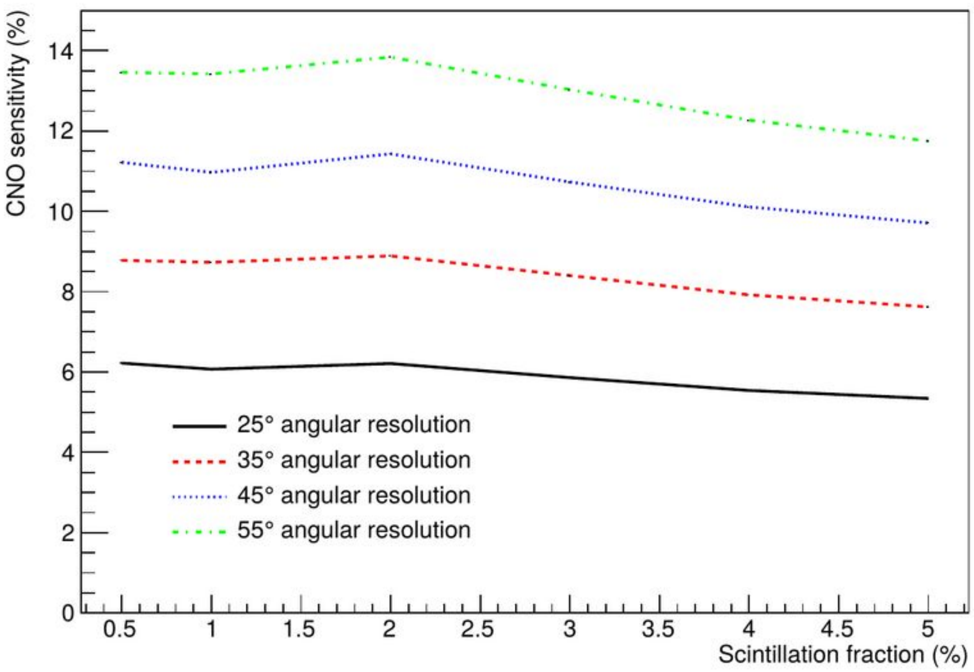
Helping Solar Neutrinos with Directionality

- Used MC model for WbLS derived from CHESS data to study reconstruction of direction (+ position & energy)

  → Fast timing key for high scintillator fraction

- Solar neutrino do elastic scattering → Directionality for background rejection





B. Land, et al., arXiv:2007.14999, July 2020

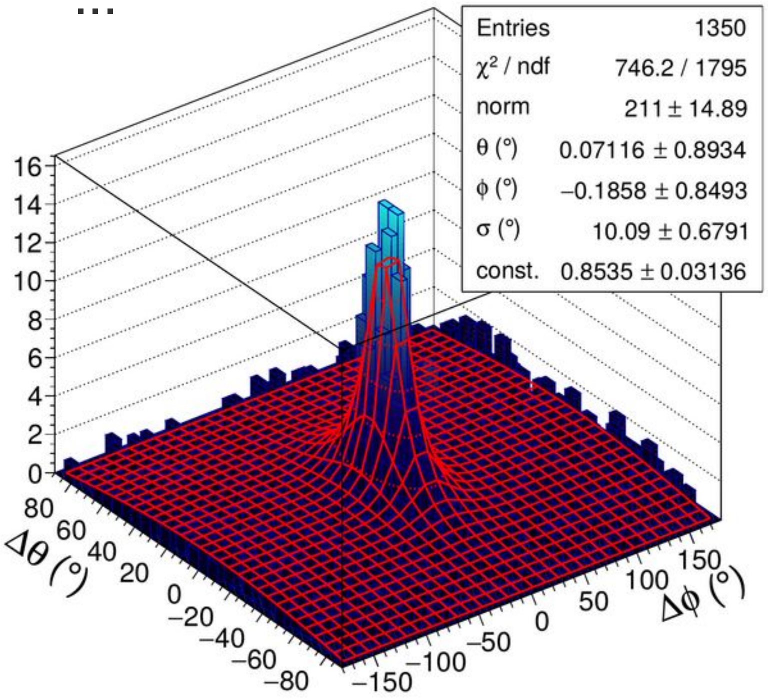
Supernova Neutrinos in THEIA

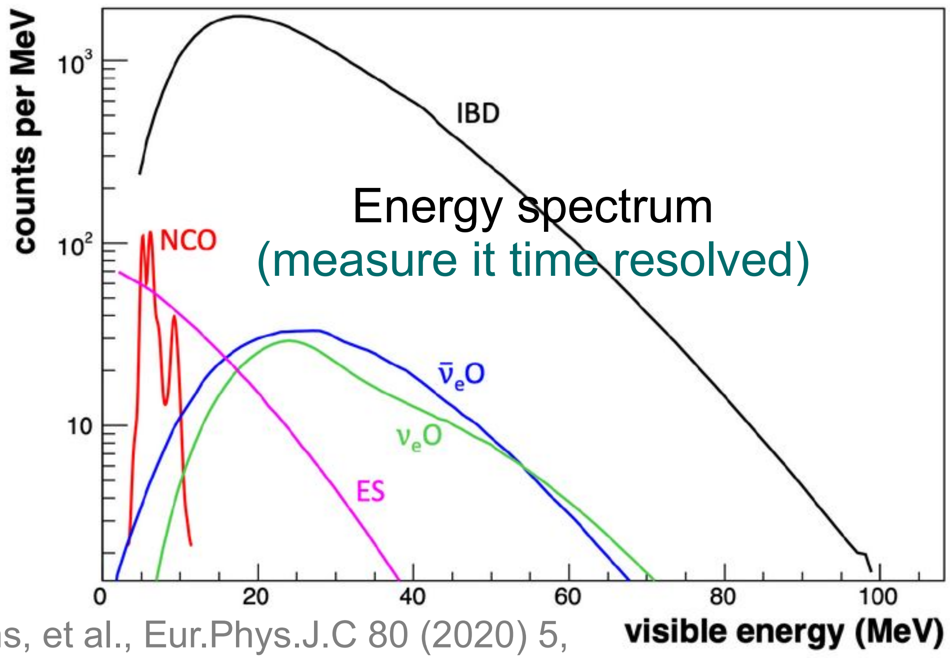
- **Core-collapse SN at 10kpc**
- **Opens new physics window:**
  - Test SN models
  - Information about MH
  - Multi-messenger astronomy
  - Early warning with precise pointing (< 1°)
  - ...

Huge statistics + Flavour information

Reaction		Rate
(IBD)	$\bar{\nu}_e + p \to n + e^+$	19,800
(ES)	$\nu + e \to e + \nu$	960
$(\nu_e\mathrm{O})$	$^{16}\mathrm{O}(\nu_e, e^-)^{16}\mathrm{F}$	340
$(\bar{\nu}_e\mathrm{O})$	$^{16}\mathrm{O}(\bar{\nu}_e, e^+)^{16}\mathrm{N}$	440
(NCO)	$^{16}\mathrm{O}(\nu, \nu)^{16}\mathrm{O}^*$	1,100

THEIA100





M. Askins, et al., Eur.Phys.J.C 80 (2020) 5, 416, arXiv:1911.03501

DSNB with THEIA

- **Combines neutrino signal of past SN**
- **Encoded information:**
  - Star formation rate
  - Average core-collapse neutrino spectrum
- **Advantage THEIA:**
  - Pulse-shape discrimination, ring-counting, C/S-ratio

    → 5σ conceivable after 5 yr

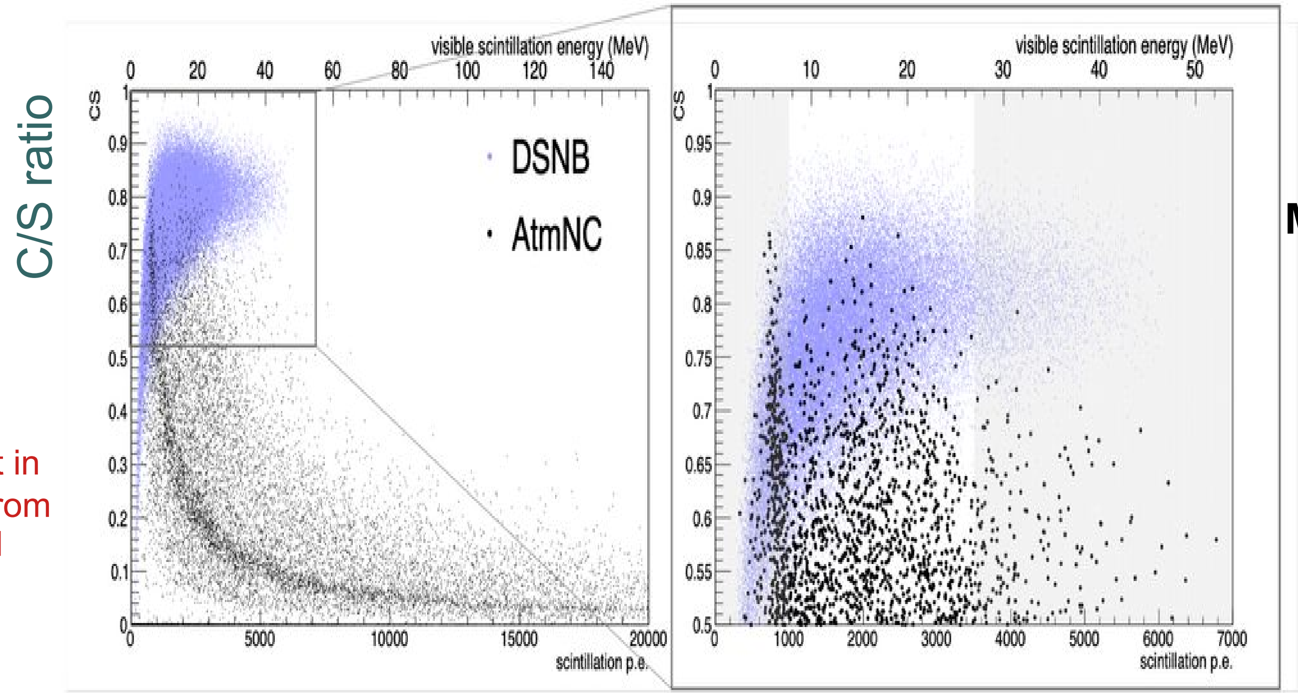
M. Askins, et al., Eur.Phys.J.C 80 (2020) 5, 416, arXiv:1911.03501

see also J. Sawatzki, et al., arXiv::2007.14705, July 2020

Signal:

Same as for SN
(mostly IBD)

Important: Enough light in WbLS to tag 2.2 MeV γ from neutron capture on ^{1}H



Main background:

Atmospheric NC reactions

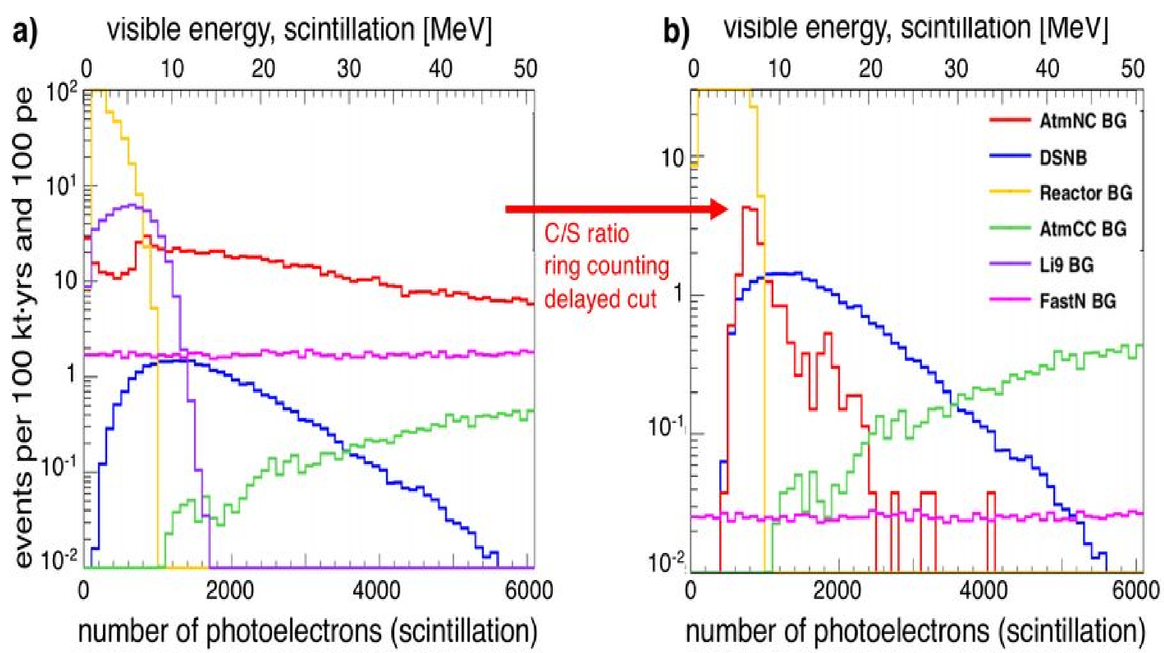
Mostly hadronic

DSNB with THEIA

- **Combines neutrino signal of past SN**
- **Encoded information:**
  - Star formation rate
  - Average core-collapse neutrino spectrum
- **Advantage THEIA:**
  - Pulse-shape discrimination, ring-counting, C/S-ratio

    → 5σ conceivable after 5 yr

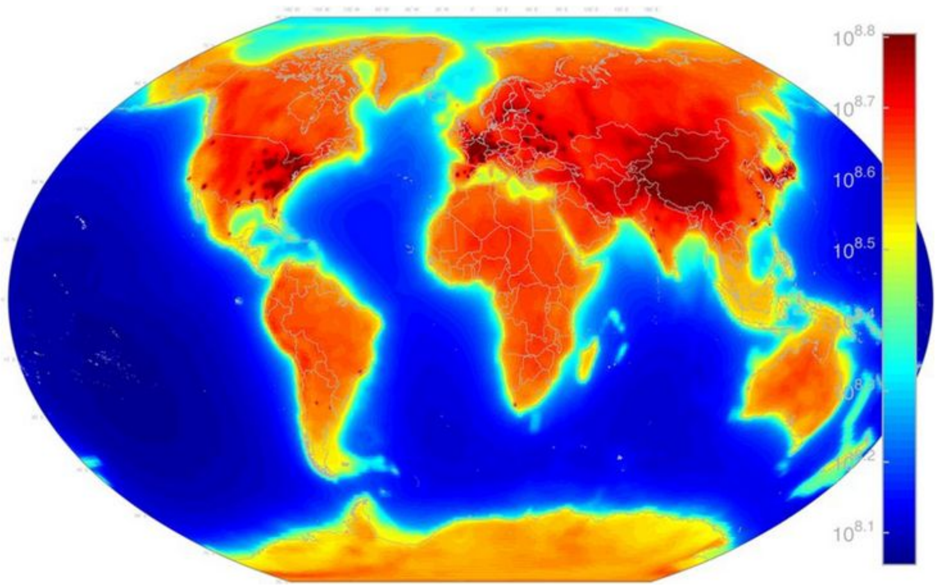
J. Sawatzki, et al., arXiv::2007.14705, July 2020



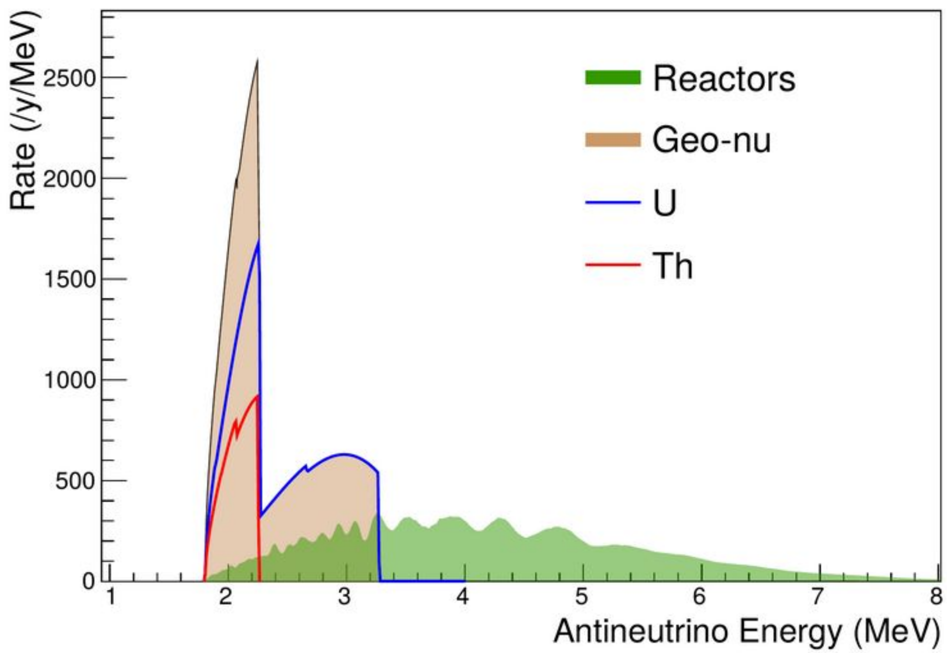
17kt fiducial mass

Geo-Neutrinos with THEIA

- Thousands of Geo-neutrino events per year
  → Precise measurement of Th & U components in spectrum (to test geophysical models)
- Expected rate would be 2σ greater than the KamLAND rate after 1 year (at SURF)
  → First evidence for surface variation of flux possible



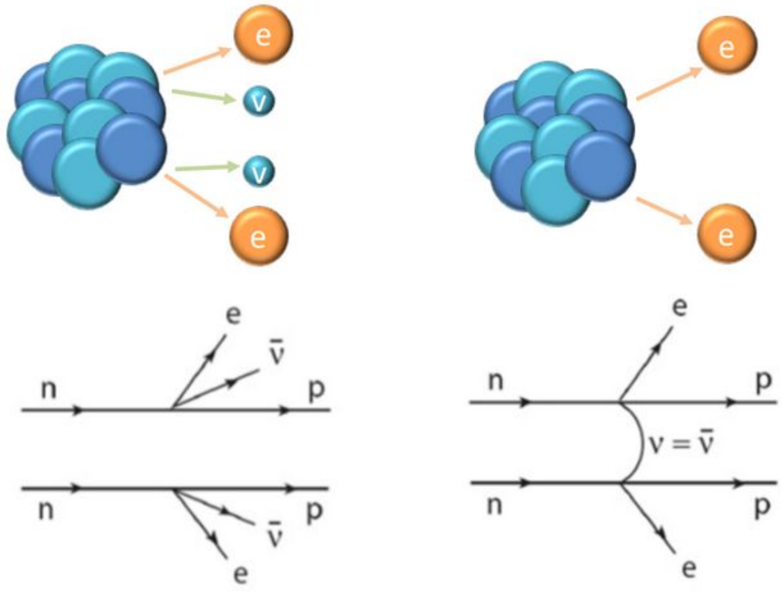
S.M. Usman, et al., Scientific Rep. 5, 13945 (2015)



M. Askins, et al., Eur.Phys.J.C 80 (2020) 5, 416, arXiv:1911.03501

The Neutrino-less Double Beta Decay (0νββ)

- Discovery would proof Majorana character of neutrinos
- Only possible for isotopes that can undergo normal double beta decay



The rate of this process depends on the **effective mass (m_{ee})** of the **electron** neutrino

$$|m_{ee}| = \left|\sum U_{ei}^2 \, m_i\right|$$

also denoted at $m_{\beta\beta}$

- **Signature:** Peak at Q-value of decay
- **Key:**
  - Good energy resolution
  - Extremely low background

0νββ in THEIA

- **Very large isotope mass deployed in liquid scintillator**
- 8 m radius LAB-PPO filled ballon
- Loading ^{nat}Te or ^{enr}Xe (or ^{100}Mo, ^{82}Se, ^{150}Nd)
- Backgrounds due to ^{8}B solar neutrinos, 2νββ, LS contamination and detector materials

After 10 years, THEIA100

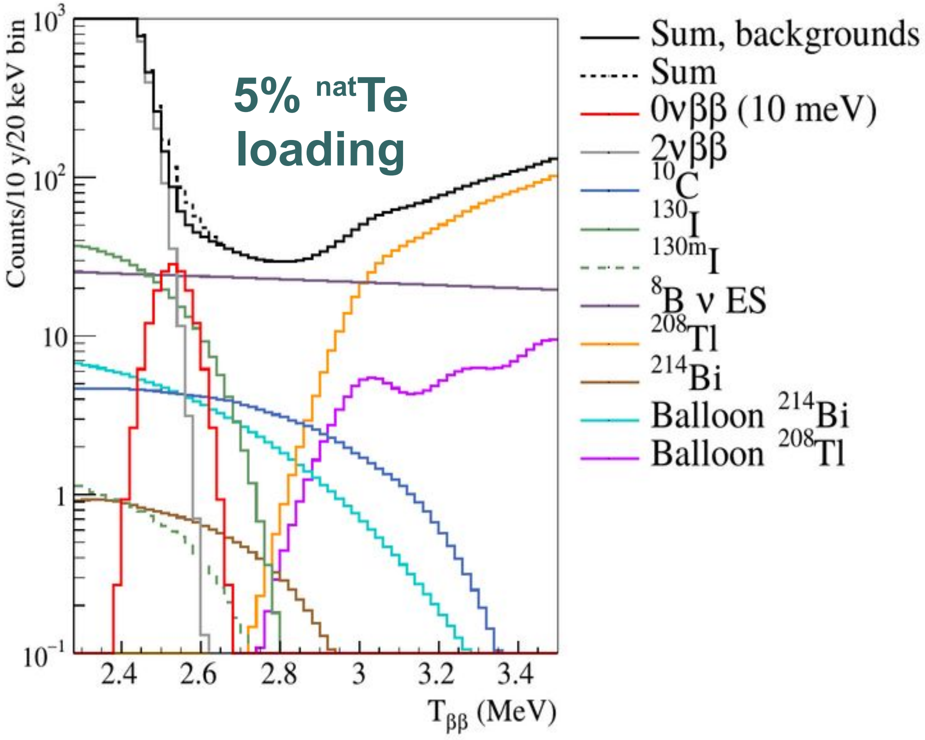
Expected 90% CL Sensitivity

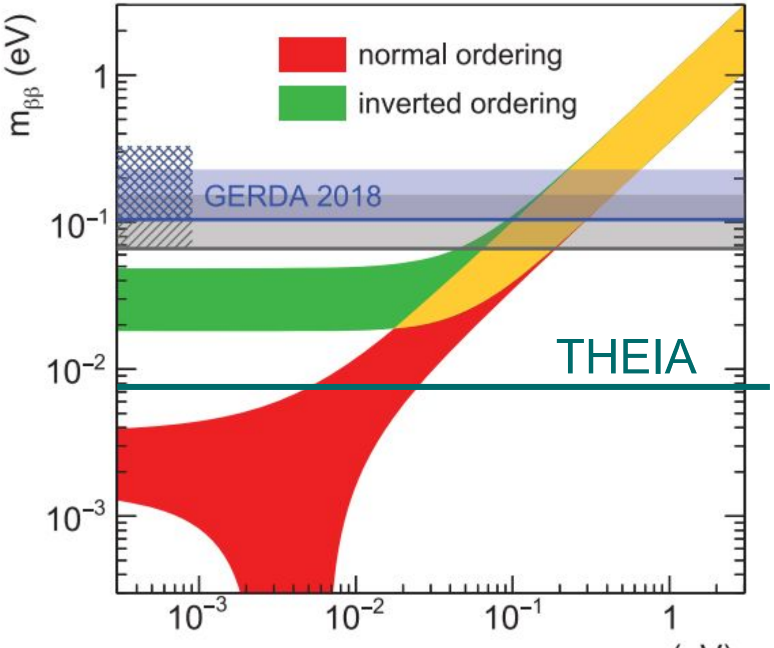
5% ^{nat}Te Loading
$T_{1/2} > 1.1\times10^{28}$ y, $m_{\beta\beta} < 6.3$ meV

3% ^{enr}Xe Loading* (89.5%)
$T_{1/2} > 2.0\times10^{28}$ y, $m_{\beta\beta} < 5.6$ meV

(IBM-2 NME, g_A=1.269)

* ~10× annual global production





Agostini et al., Science 365, 1445–1448 (2019)

Machine Learning Example: C-10

- Studied in A. Li et al. , arXiv:1812.02906
- Using a Convolutional Neural Network (CNN)
- In KamLAND-like detector (~1ns σ_T, 23% QE, 19.6% coverage)

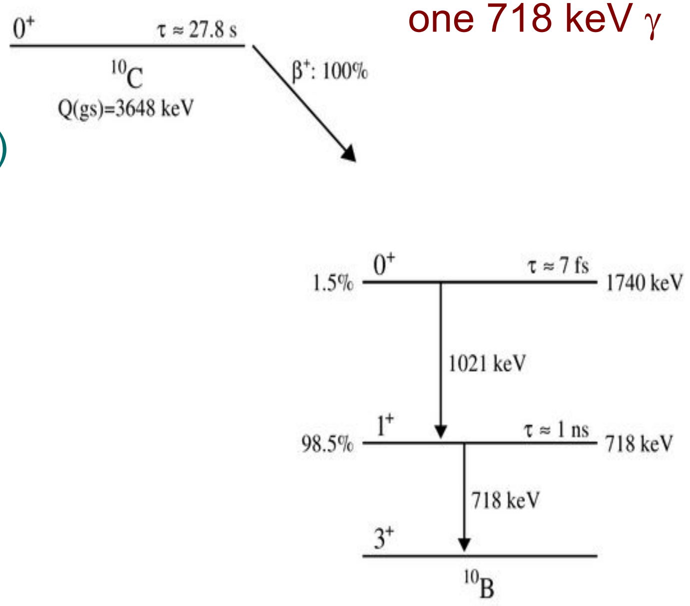
  → 62% bkg reduction at 90% signal efficiency

  82% with ~3.4x light collection (36.2% QE, 42% coverage)

  98% for perfect light collection

  (time delay of ortho-positronium decay not used)

One positron + at least one 718 keV γ



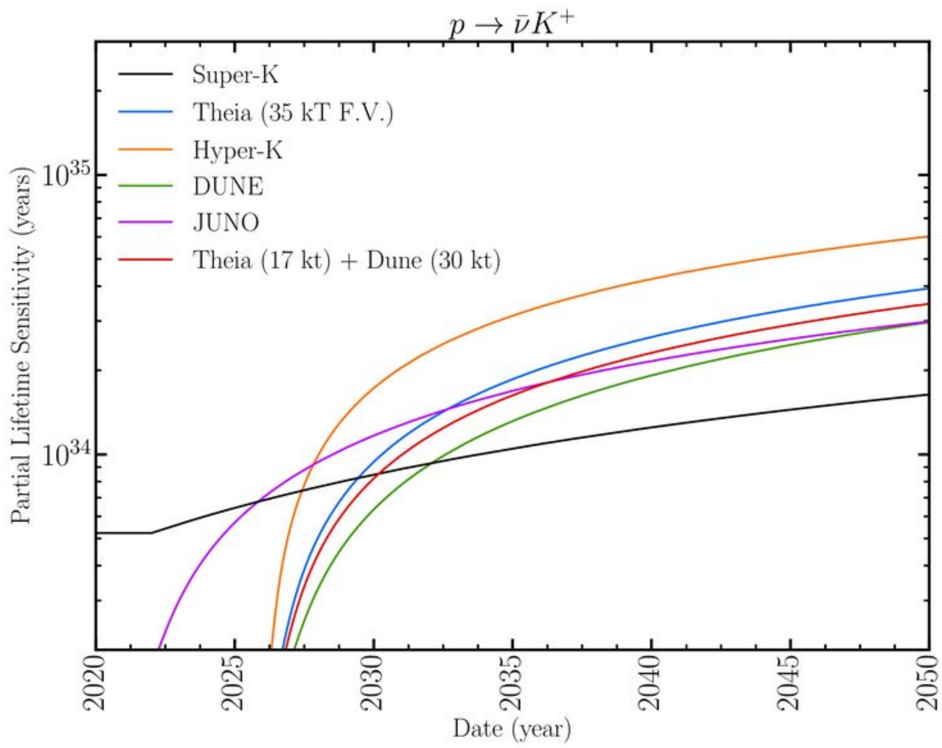
- ^{10}C is background (bkg) for solar-ν and $0\nu\beta\beta$
- I see similar potential for ^{130}I ($0\nu\beta\beta$ bkg)

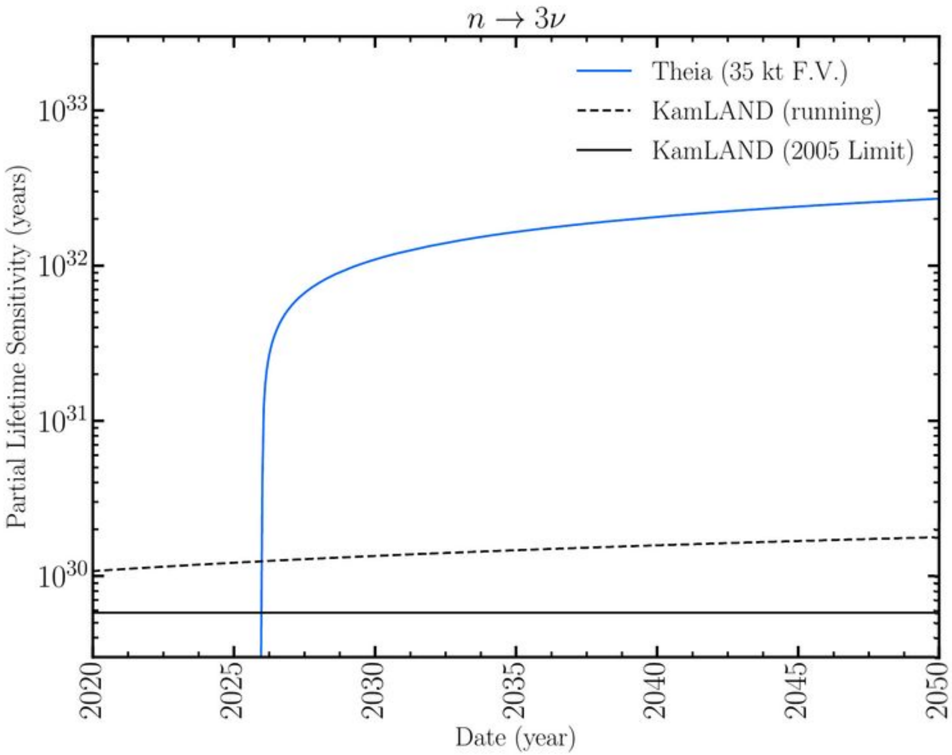
Has not been included in current study! (used only three-fold coincidence)

Nucleon Decay with THEIA

- **THEIA advantage:** low threshold + low background
- **Triple coincidence:** $p \to \bar{\nu} K^+ \to$ Kaon decay $\to$ decay of decay product
- **Invisible decay of oxygen nucleus:**

  $n \to 3\nu \to$ One 6.18 MeV γ from excited nucleus

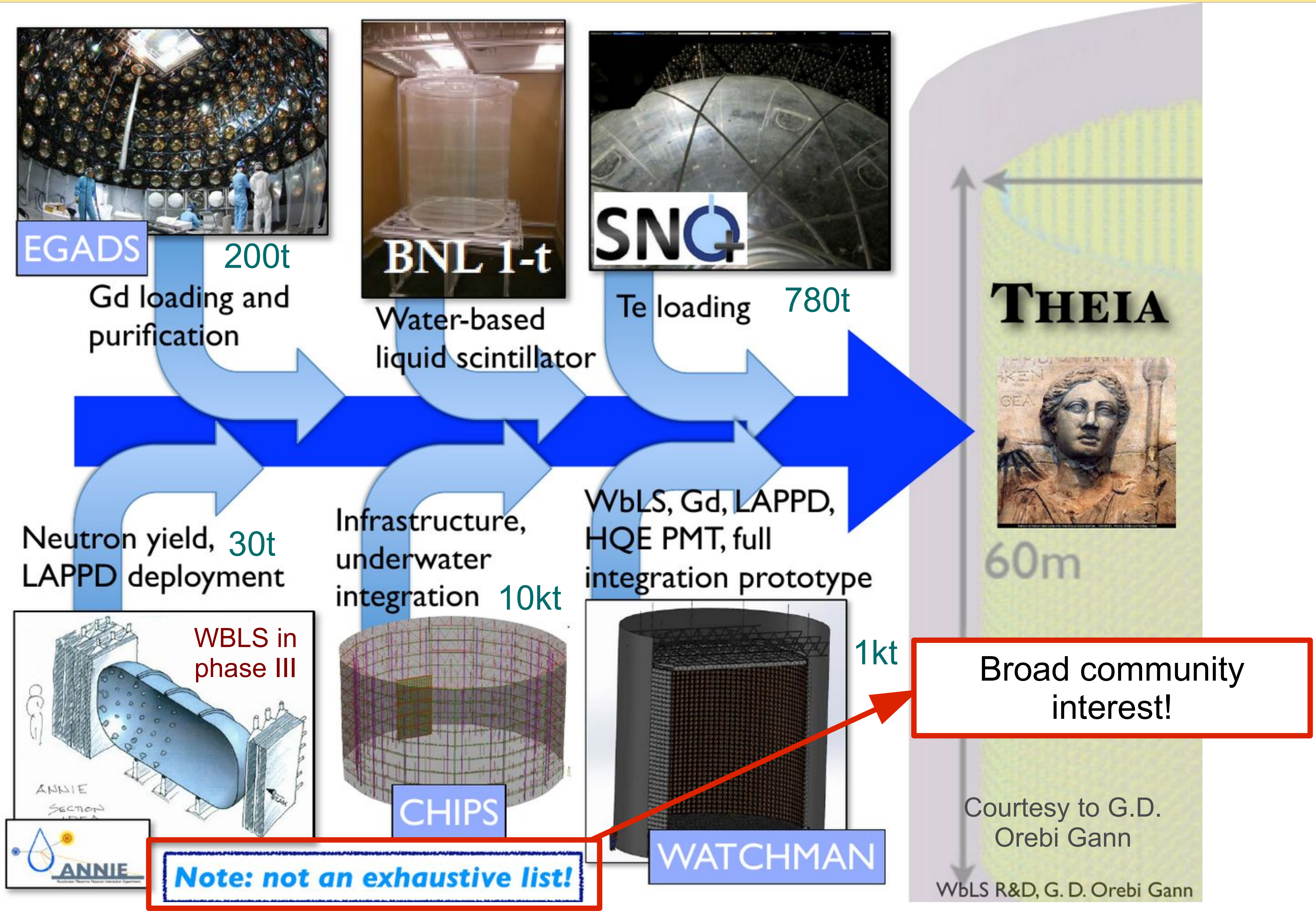




→ **Complementary to competitors** (DUNE & HyperK)

Leading in invisible decay

Using Other Experiments as R&D Testbeds



THEIA Interest Group

Canada
Alberta
Laurentian
Queens
Toronto

China
Tsinghua

Finland
Jyvaskyla
Oulu

Germany
Aachen
Dresden
Juelich
Mainz
TU Munich
U. Hamburg

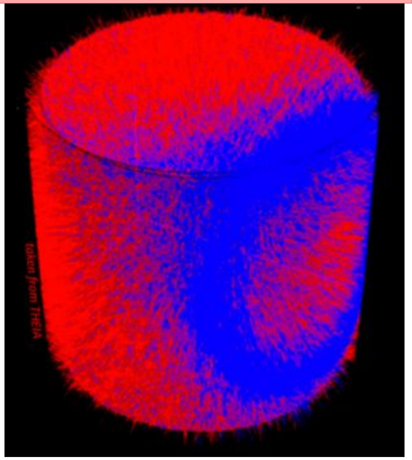
Portugal
LIP

UK
Sheffield

US
Brookhaven NL
Boston U.
U. Chicago
Colorado U.
Cornell U.
U. Hawaii
Iowa State
Lawrence
Berkeley NL
LSU
MIT
U. Penn
Stony Brook
SURF
Temple
UC Berkeley
UC Davis

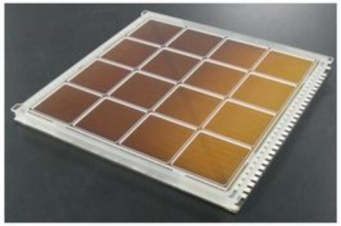
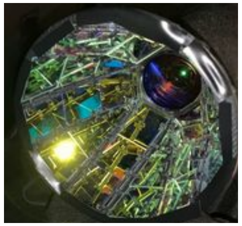
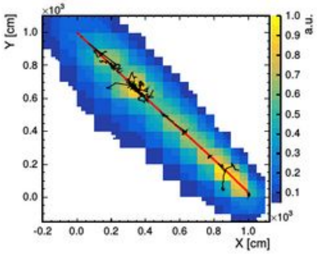
More collaborators welcome!

Summary/Conclusions



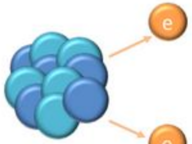
- **THEIA:**
  - Combining advantages of Water-Cherenkov & Liquids Scintillator detectors
  - Using new technologies (WbLS, LAPPDs, Dichroicons, advanced reconstruction, …)

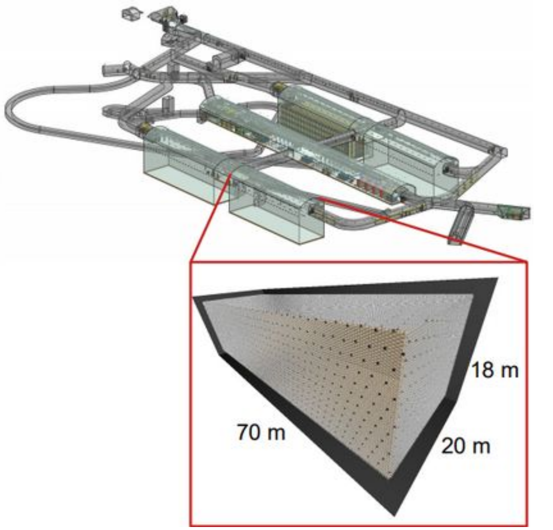
  → **Complementary to existing and upcoming large-scale projects**

- **Physics case:**
  - Enhanced sensitivity to a broad physics program **(long-baseline physics, solar neutrinos, Supernova neutrinos, DSNB, $0\nu\beta\beta$)**
  - THEIA25 makes an excellent match for the 3 DUNE modules





- **Surrounded by a large R&D program**

  (Advanced reconstruction, liquid & sensor development, demonstrators, ...)

- **Large community interest**

Please have a look at our White Paper:

M. Askins, et al., Eur.Phys.J.C 80 (2020) 5, 416, arXiv:1911.03501

Backup slides

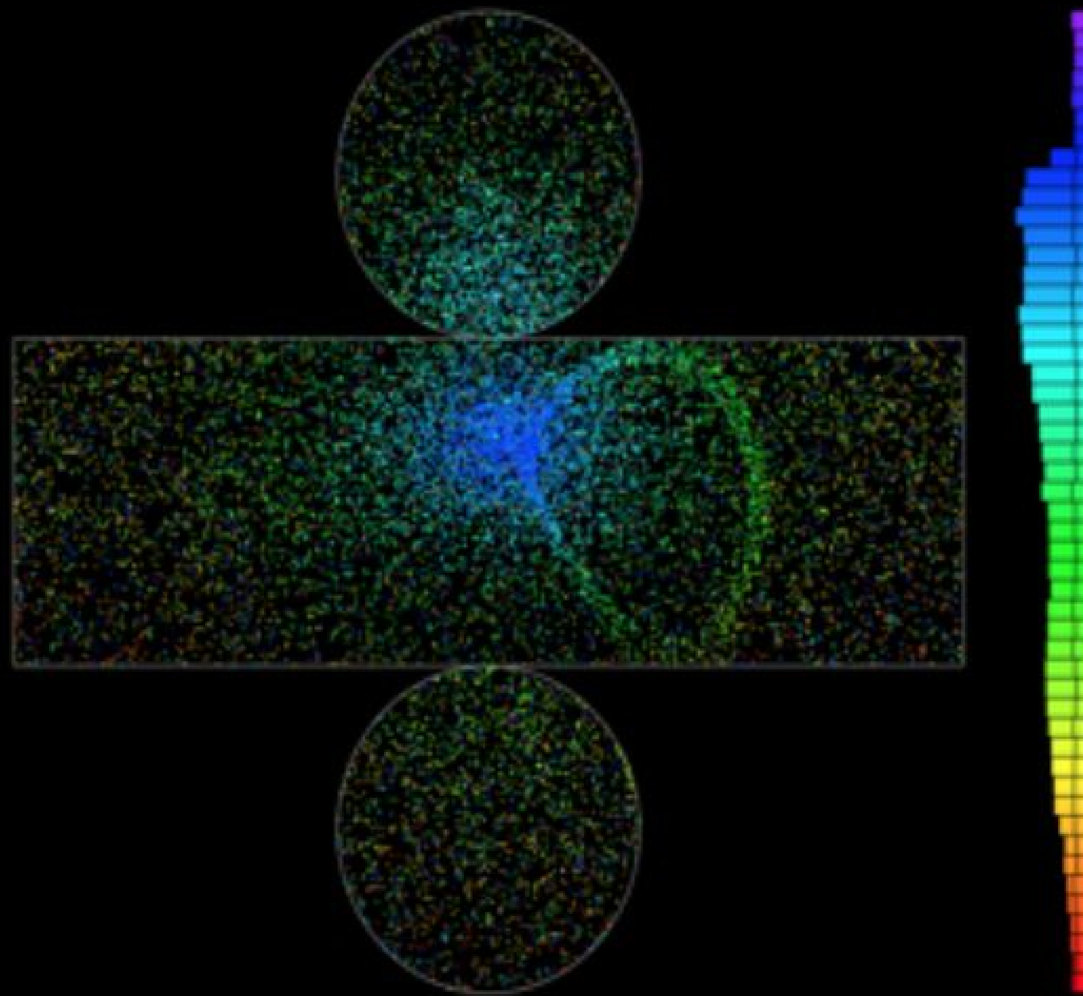
Advantages of WbLS at MeV Energies

[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



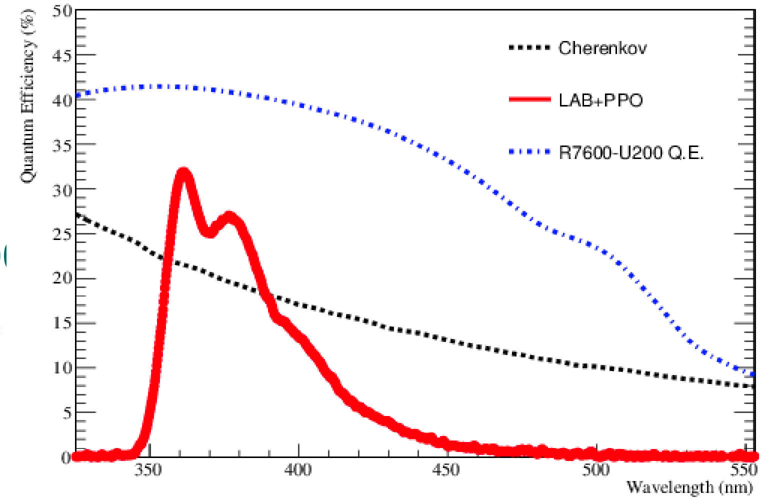
Cherenkov-Light Separation by Wavelength

- Using dichroic filter

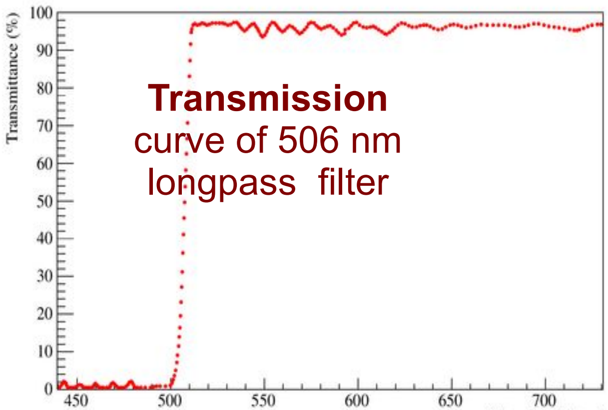
  (transmitting above or below a certain threshold, reflecting the rest)

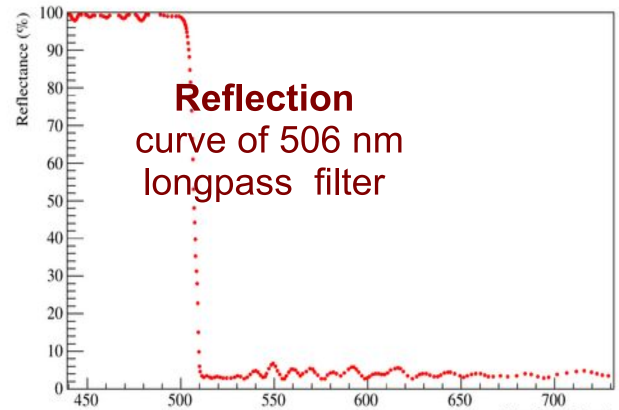
- Optimal Cut for LAB-PPO (2g/l): 450 nm

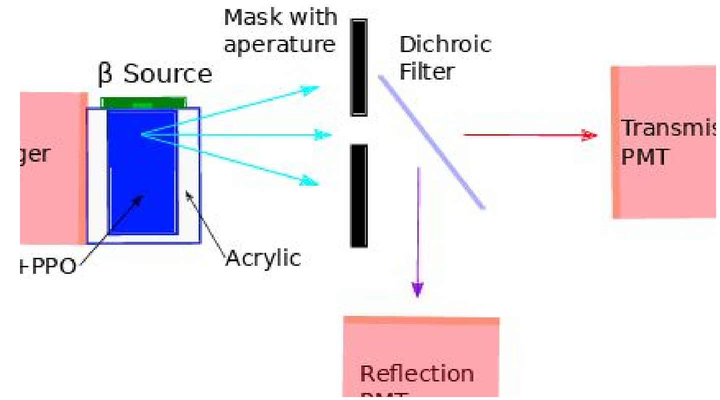
  Full description in T. Kaptanoglu et al., JINST 14 (2019) no.05, T050

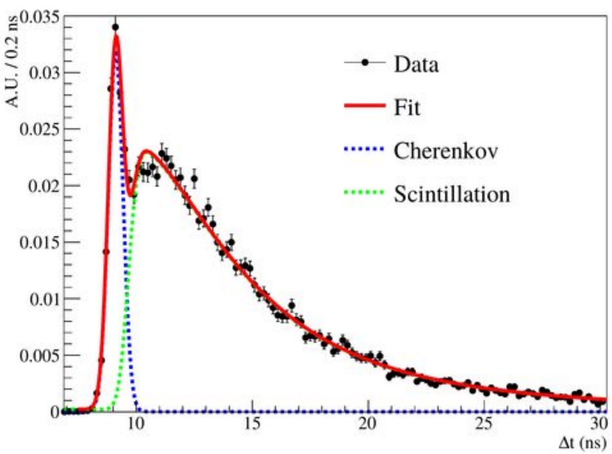


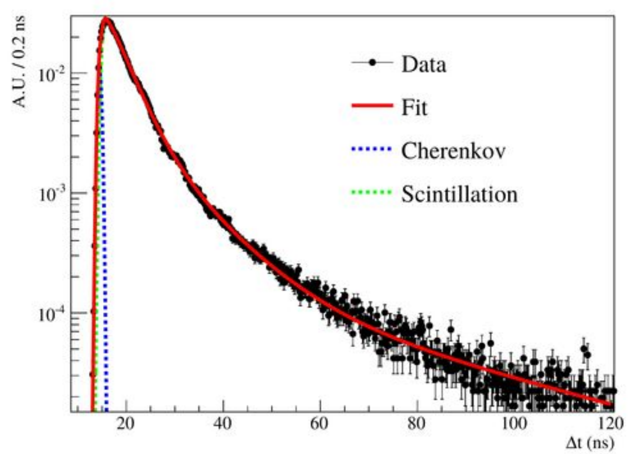
T. Kaptanoglu et al., JINST 14 (2019) no.05, T05001











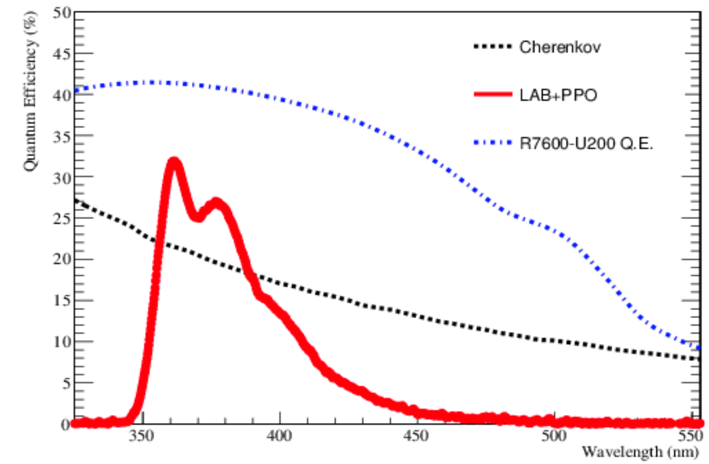
Measured time profile of **transmitted (left)** and **reflected (right)** light from LAB-PPO

Cherenkov-Light Separation by Wavelength

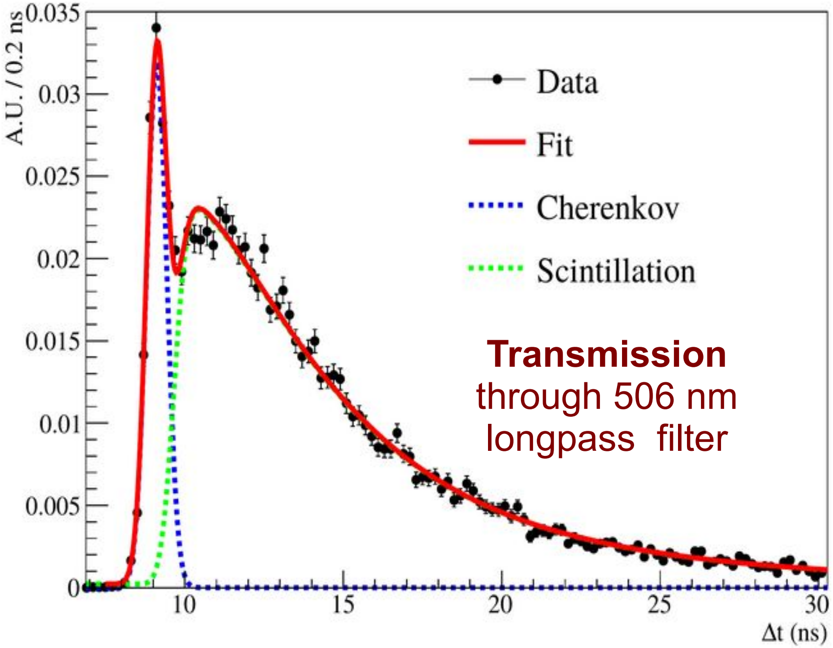
- Using dichroic filter

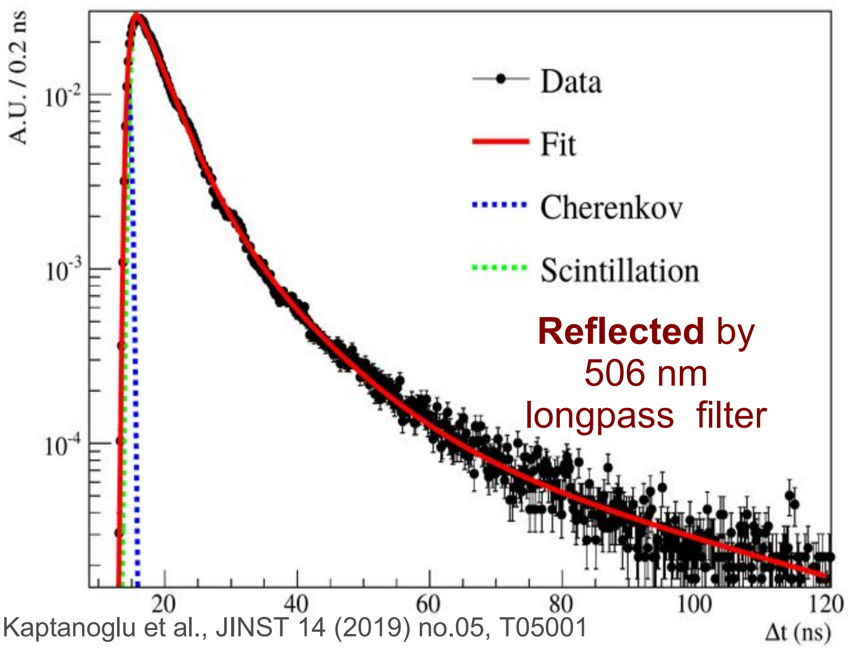
  (transmitting above or below a certain threshold, reflecting the rest)
- Optimal cut for LAB-PPO (2g/l): 450 nm

  Full description in T. Kaptanoglu et al., JINST 14 (2019) no.05, T05001
- Studying application as light concentrator (U. Penn.)



T. Kaptanoglu et al., JINST 14 (2019) no.05, T05001



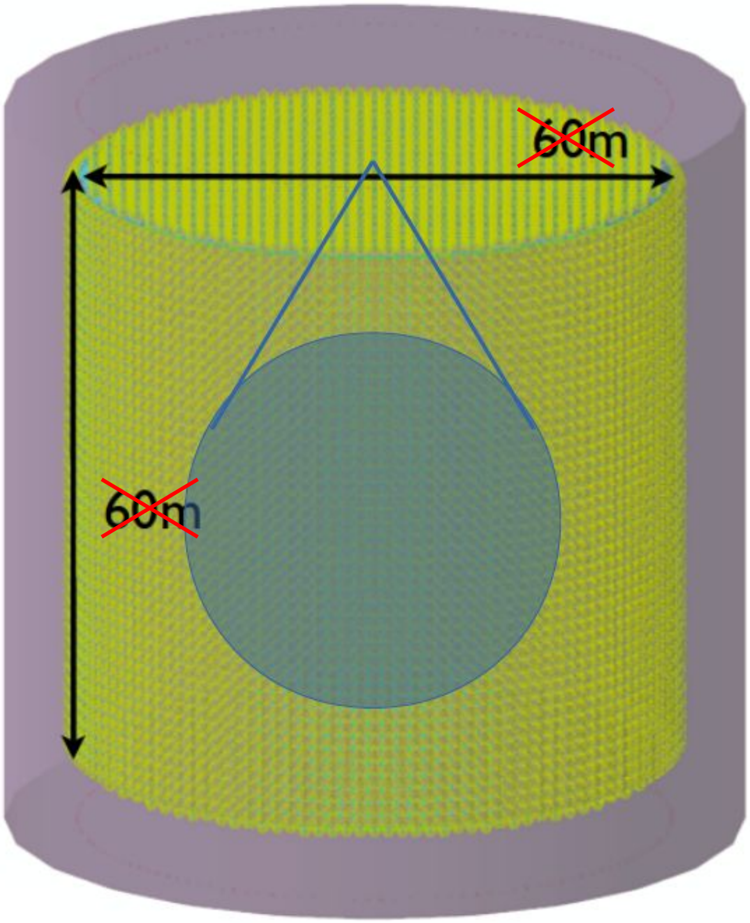


T. Kaptanoglu et al., JINST 14 (2019) no.05, T05001

Measured time profile of **transmitted (left)** and **reflected (right)** light from LAB-PPO

Theia for 0νββ

- **Assumption used for sensitivity study**
  - Detector mass 50 ktons
    (20 m fiducial radius, 40 m high)
  - Balloon with 8m radius (7m fiducial radius)
    - Filled with LAB + PPO (2g/l)
  - Two loading schemes:
    - 3% enriched Xenon (89.5% in 136 Xe)
    - 5% natural Tellurium (34.1% in 130 Te)
  - Outside balloon: WBLS with 10% LAB-PPO
  - Overburden: 4300 m.w.e. (Homestake)
  - 90% PMT coverage
    → ~1200 γ/MeV → ΔE ~3% at 1MeV
    (conservative underestimation for Xe light yield)



Dimensions not to scale!

Theia for 0νββ

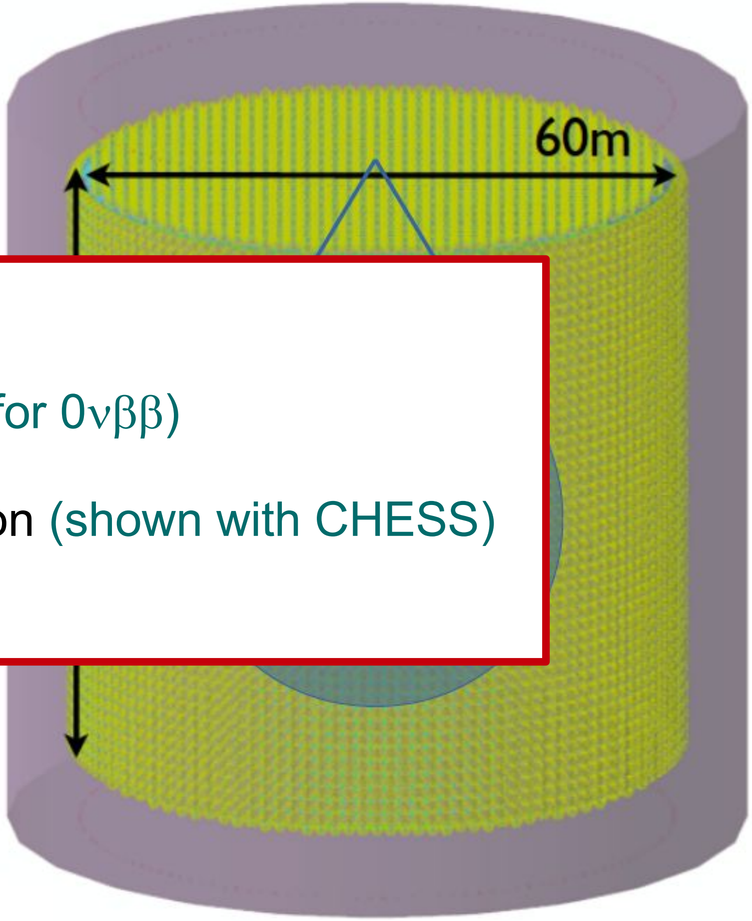
- **Assumption used for sensitivity study**
  - Detector mass 50 ktons
    (20 m fiducial radius, 40 m high)
  - Balloon with 8m radius (7m fiducial radius)
    - Filled with LAB + PPO (2g/l)

Reason for LAB-PPO:

High light yield → good energy resolution (crucial for 0νββ)

+ fast light sensors still allow Cherenkov-Separation (shown with CHESS)

  - 90% PMT coverage
    → ~1200 γ/MeV → ΔE ~3% at 1MeV
    (conservative underestimation for Xe light yield)



Background (bkg) Assumptions

- Assuming Borexino phase II/KamLand-like radioactive contamination (LS/Balloon)
- Delayed Bi-Po-coincidences with 99.9% bkg reduction (Bi-214)
- Careful control of cosmogenic activiation of loading material (→ negligible bkg)
- Three-fold coincidence technique with 92.5% bkg reduction (C-10, efficiency from Borexino)
- Fiducial volume cut for external sources + additional 50% bkg reduction
- Activation by CC-interactions of solar neutrinos on loading material (I-130 & Cs-136)
- PID used to remove 50% of B-8 bkg (see R.Jiang and A.Elagin, arXiv:1902.06912)

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 [44])		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 [45])		1.2×10^{8}	8.0	-
$2\nu\beta\beta$ (^{enr}Xe target, $T_{1/2}$ from [46, 47])		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 [48, 49]	^{214}Bi: $< 1.1\times10^{-12}$ g_U/g	1.2×10^{5}	2.4	2.7
	^{208}Tl: $< 1.6\times10^{-12}$ g_{Th}/g	2.1×10^{4}	0.03	0.01

ROI: -σ/2 → 2σ

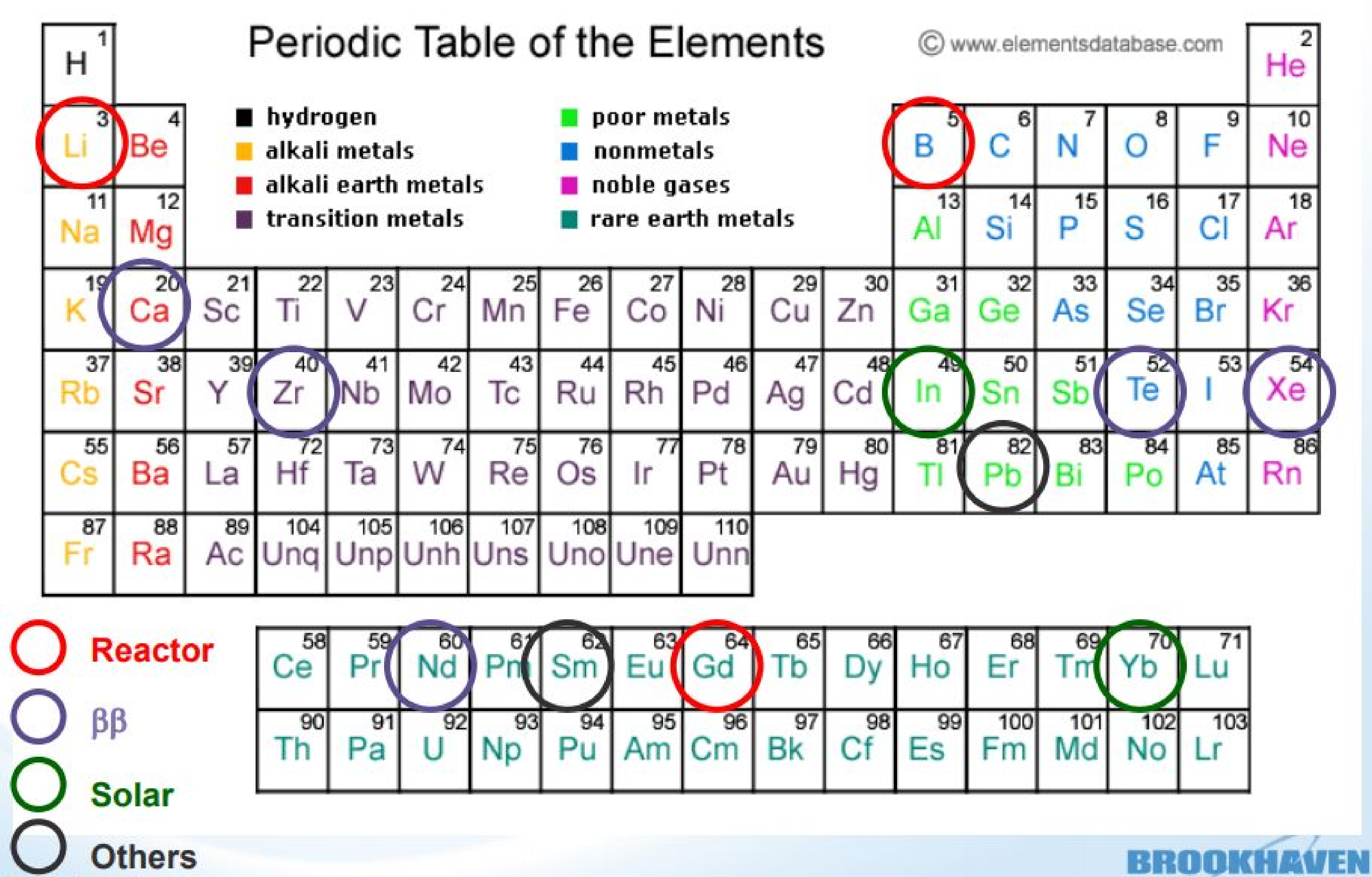
Total bkg-index : in evts/(t ·y)

1.1 (Te) 0.5 (Xe)

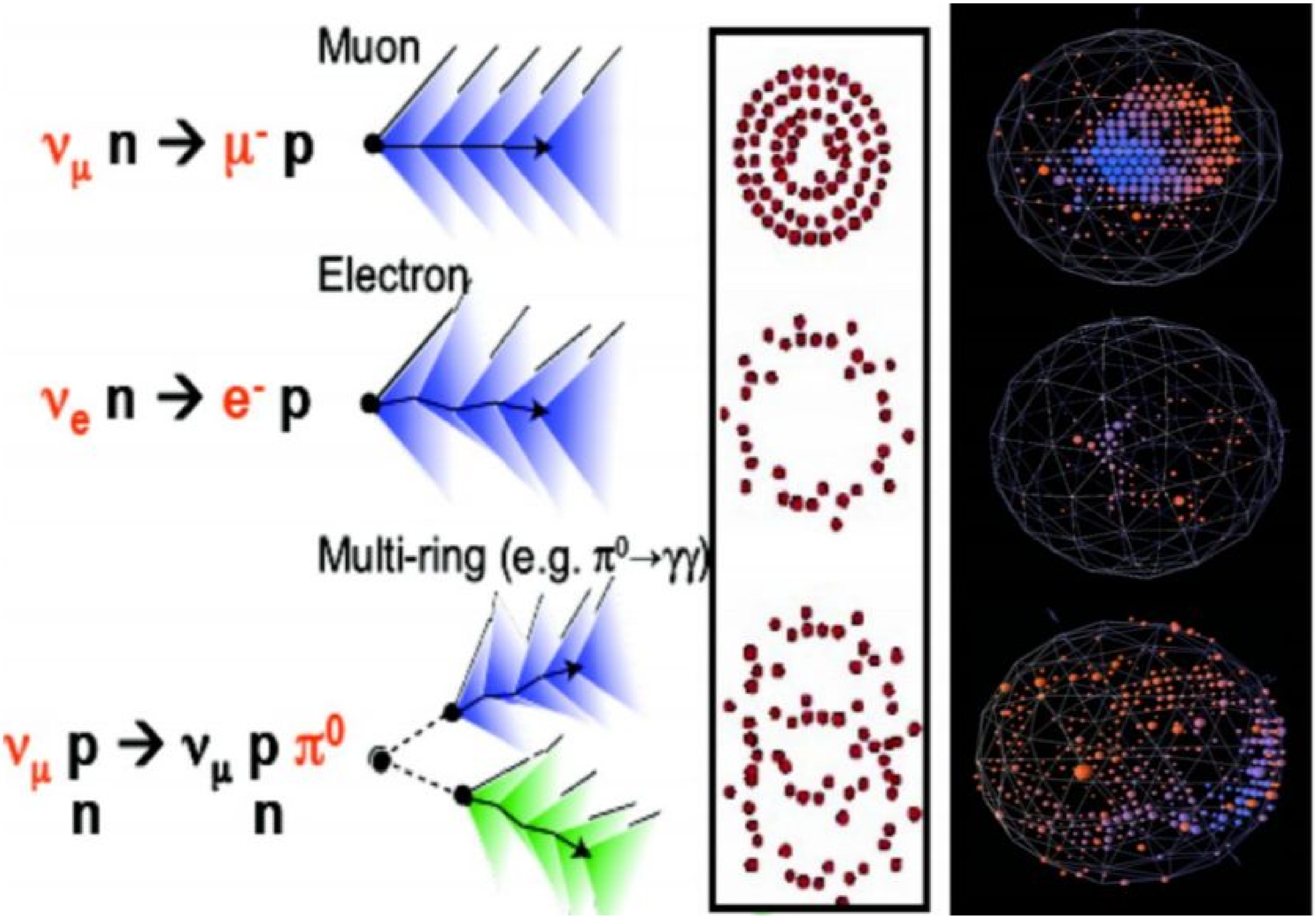
(per ton of Te-130/Xe-136 in full volume)

Theia White Paper, to be published soon
(Courtesy to V. Lozza, A. Mastbaum & L. Winslow)

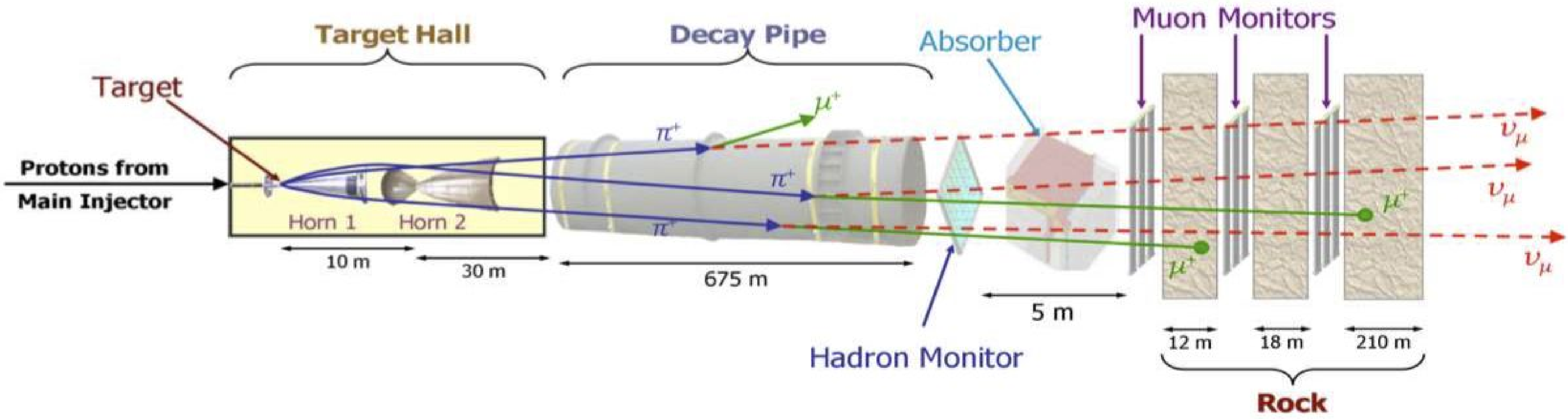
Isotope Loading of Liquid Scintllator



Particle ID with Ring-Imaging



Neutrino Beam Picture



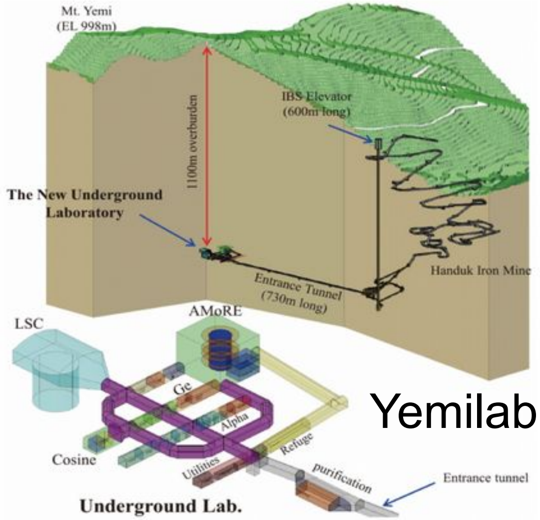
Neutrino Teleskope at Yemilab (Korea)

Seon-Hee Seo, arXiv:1903.05368v1, Mar 2019

Yemilab: Under construction

New underground lab in Korea

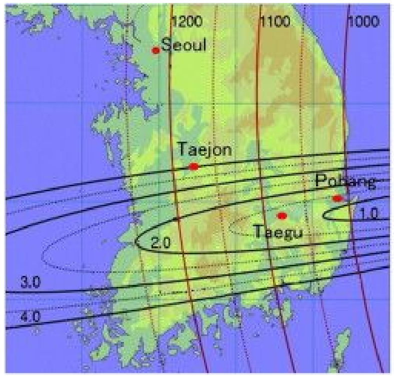
Will have space for a 50 kton WbLS detector



Korean Neutrino Observatory (KNO): Proposed

Hyper-K 2nd detector in Korea, a.k.a. T2HKK

260 kiloton water Cherenkov detector



J-PARC

Solar Neutrinos at Yemilab

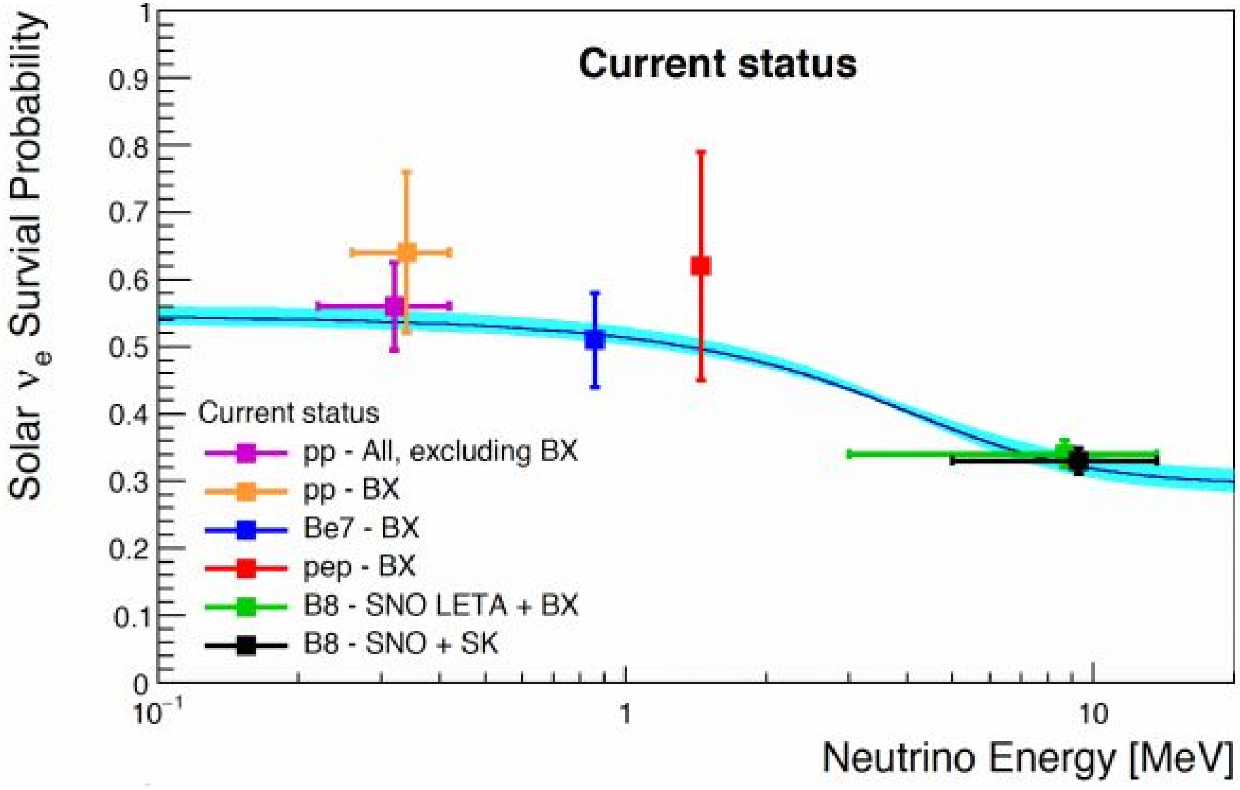
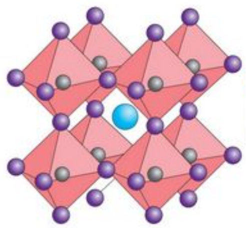
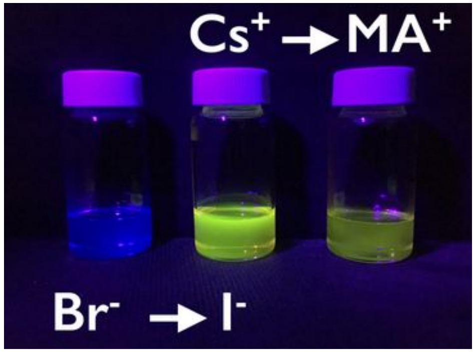


FIG. 6: Solar neutrino survival probability vs. neutrino energy in MeV. Squares with error bars represent solar neutrino fluxes from current measurements by Borexino, SNO and SK. A cyan band represents expected solar neutrino survival probability from standard solar neutrino model with MSW effect. With 4∼5 kiloton WbLS detector at Yemilab it might be possible to reduce the uncertainties to the level of the expected one (cyan band).

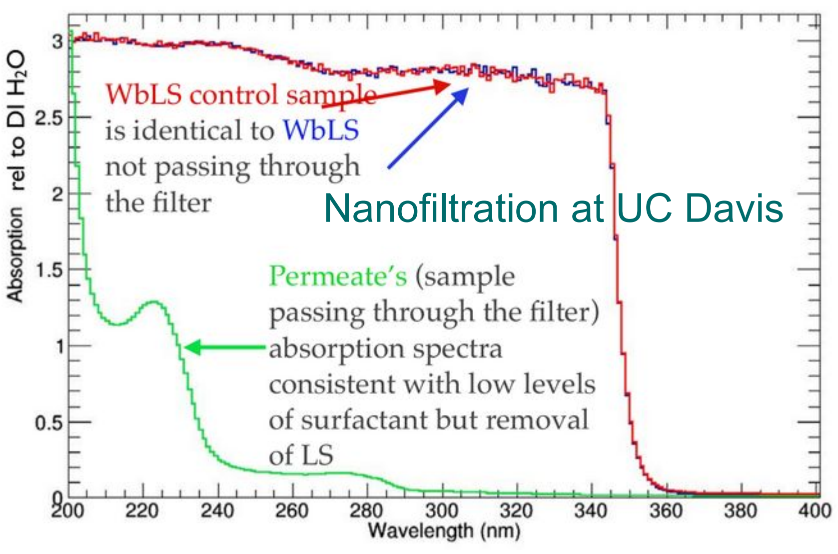
Improving Liquid Properties

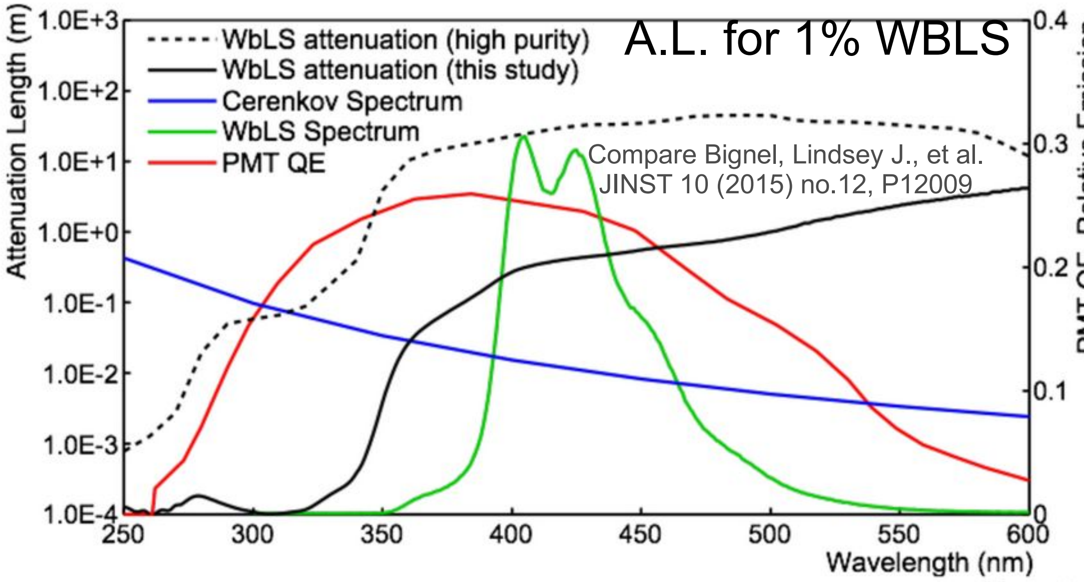
- **Development of scintillating liquids**
  - WBLS (Brookhaven NL, JGU Mainz, TU Munich)
  - Isotope loading (BNL, MIT) (Li,B,Ca,Zr,In,Te,Xe,Pb,Nd,Sm,Ge,Yb)
  - Oil-diluted LS (JGU Mainz)
- **Characterization** (Brookhaven NL, JGU Mainz, TU Munich, ...)
  - Optical properties (Emission, attenuation, ..)
  - Timing properties (Time spectrum, ortho-positronium, ...)
- **Filtering methods** (Attenuation, radiopurity)
  - Nanofiltration (UC Davis)
  - JUNO-test facility achieved A.L > 23 m (LAB + PPO + bis-MSB)





Nanocrystal-Doped Liquid Scintillator arXiv:1908.03564



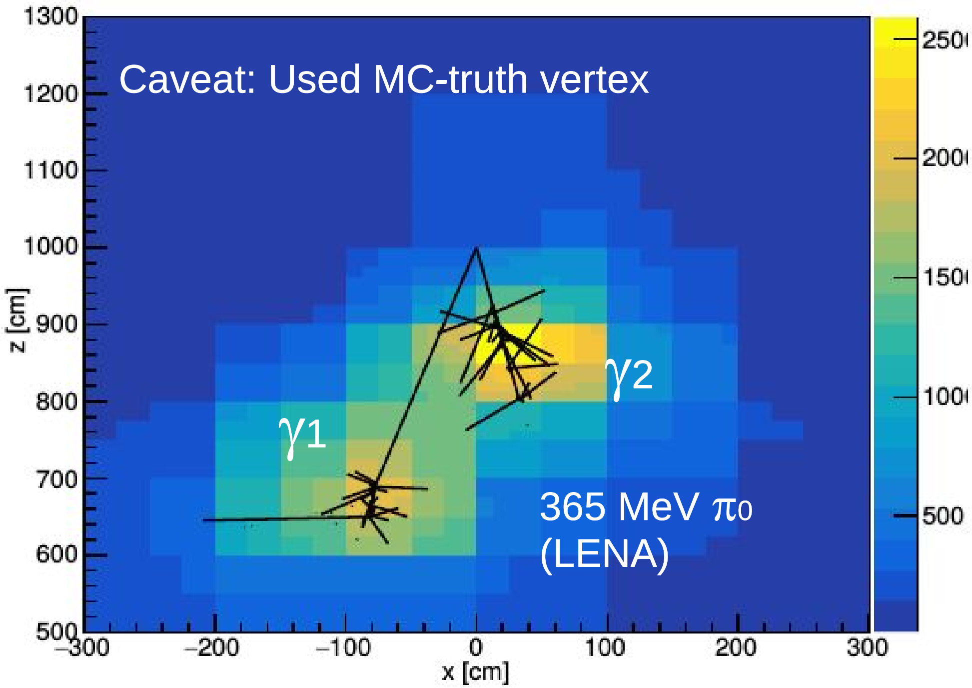


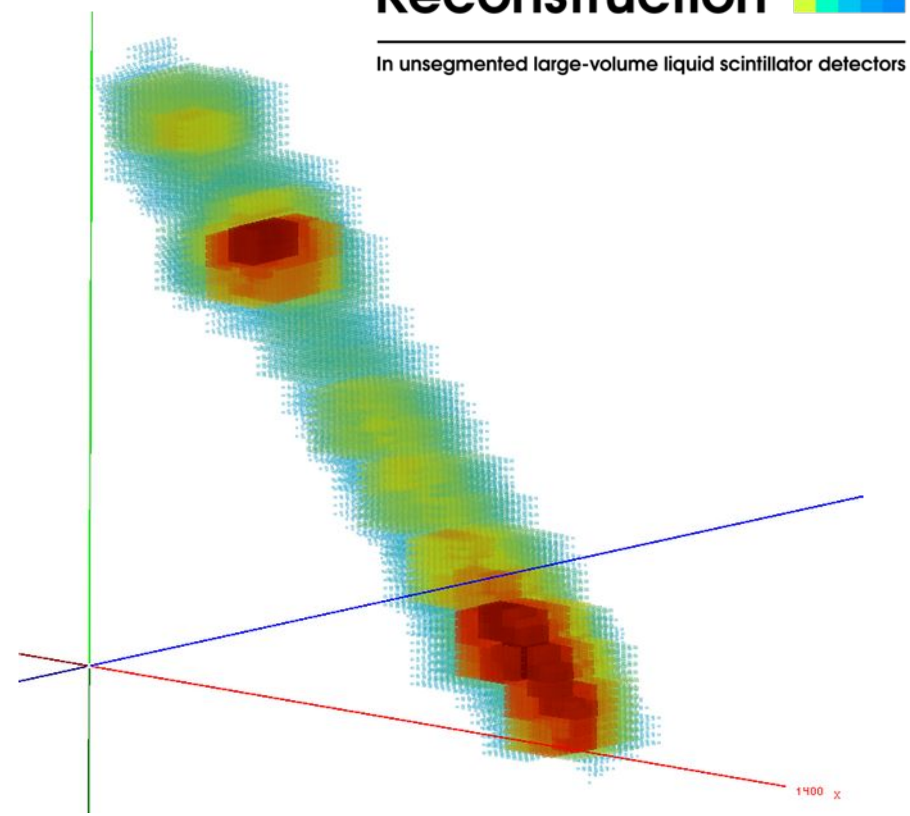
Goals at GeV Energies

- **Non-ML methods:** Full topological reconstruction can reveal many details
- **But:** Very computing intensive & lack robustness in some cases
- **Question:** Can ML do better?

Topological Reconstruction

In unsegmented large-volume liquid scintillator detectors

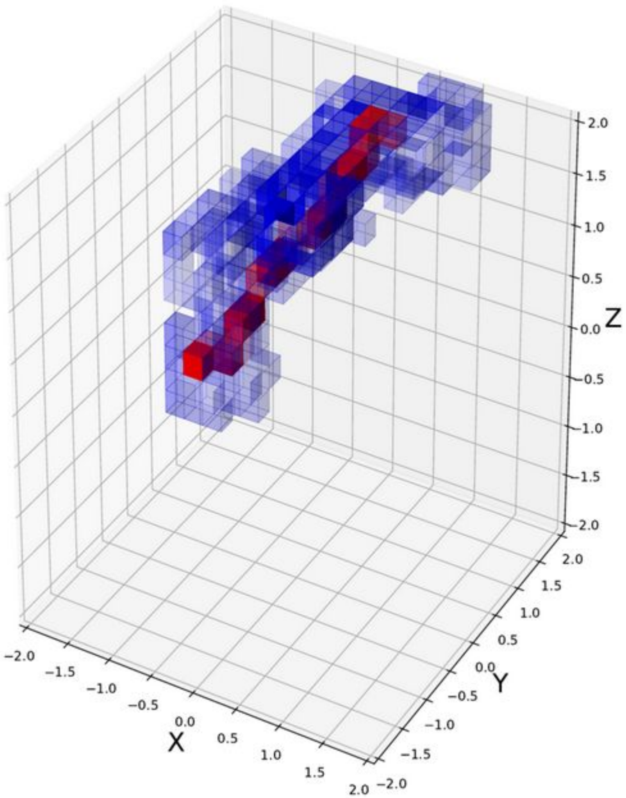




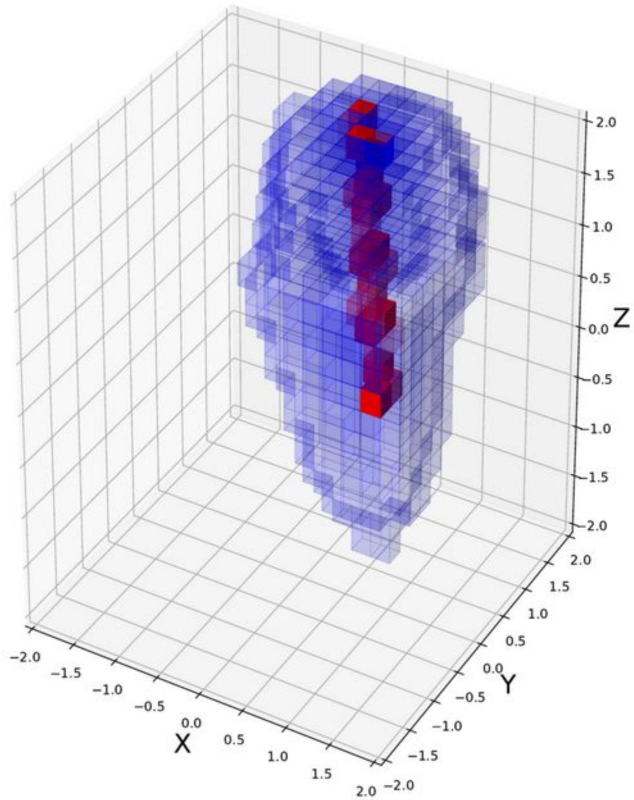
Outlook: First Results Voxel Reconstruction

Red: MC Truth
Blue: Network output

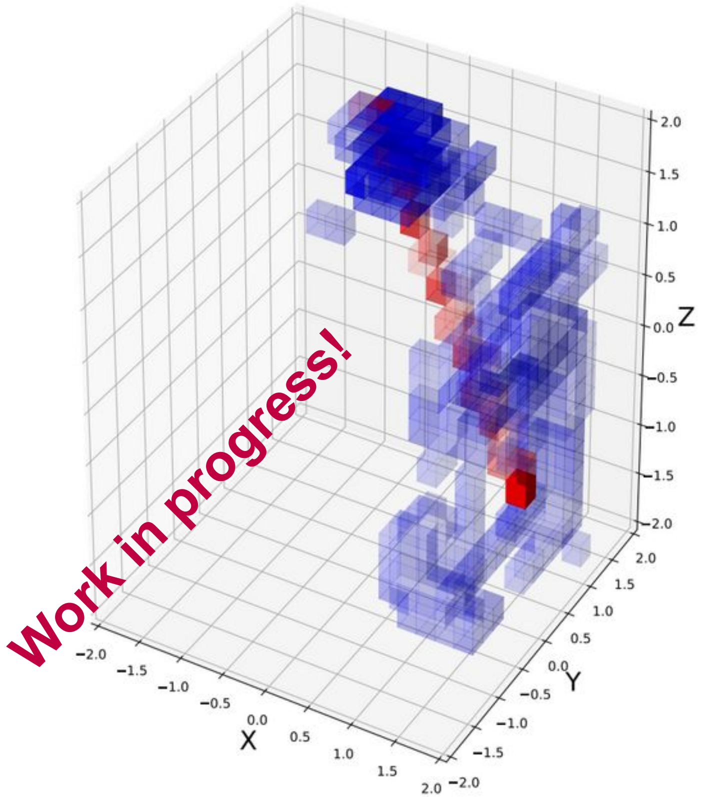
Using L1-regularization in loss function



Result of homogeneous network



Result after propagation layers



Result heterogeneous network (after training)

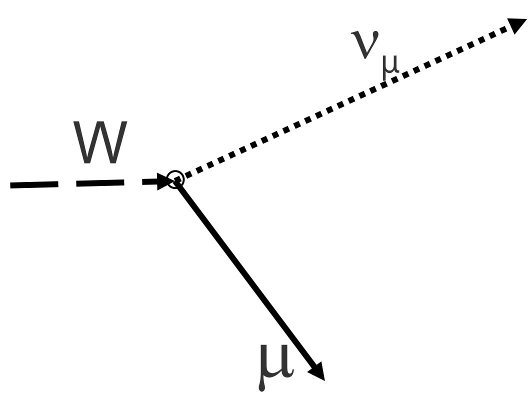
Neutrino Oscillations (Simplified)

Flavour eigenstates
ν_μ, ν_τ **with** θ_{23}

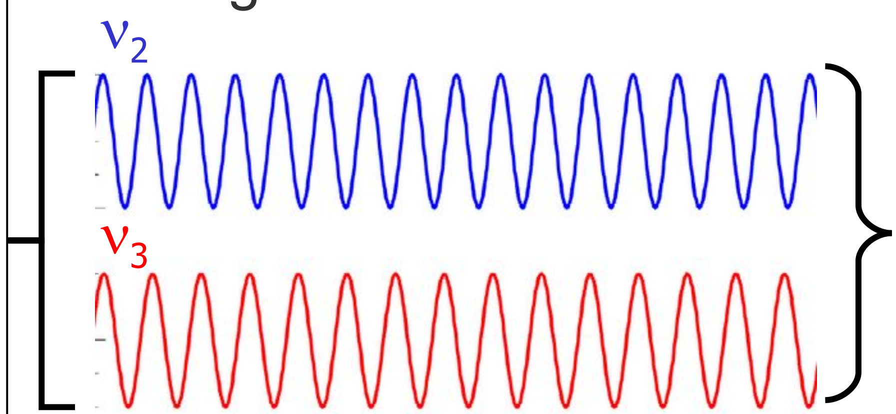
$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{23} & s_{23} \\ -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates
ν_2, ν_3 **with** m_2, m_3

Source creates flavour eigenstates



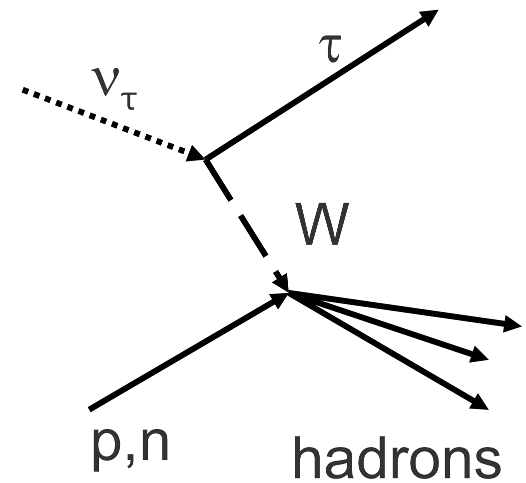
Propagation determined by mass eigenstates



$$\omega_{2,3} = E_{2,3} = \sqrt{p^2 + m_{2,3}^2}$$

Slightly different frequencies
→ phase difference changes

Detector sees flavour eigenstates



Which flavour we measure depends on phase difference!

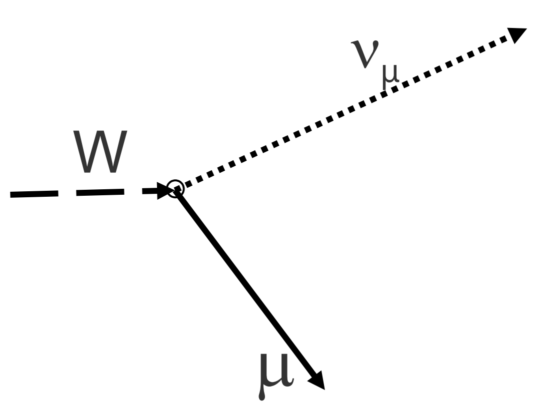
Neutrino Oscillations (Simplified)

Flavour eigenstates
ν_μ, ν_τ with θ_{23}

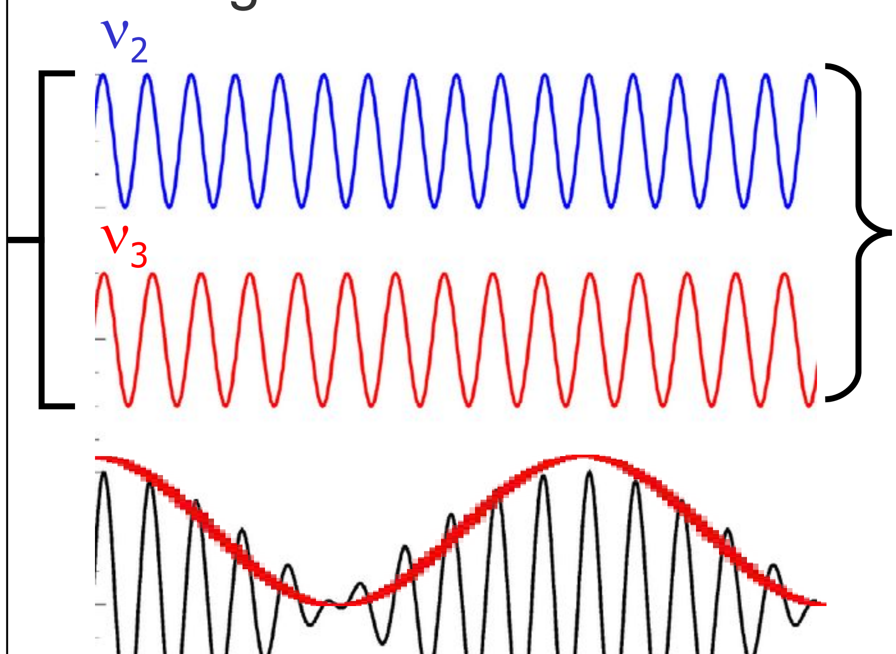
$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{23} & s_{23} \\ -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates
ν_2, ν_3 with m_2, m_3

Source creates flavour eigenstates

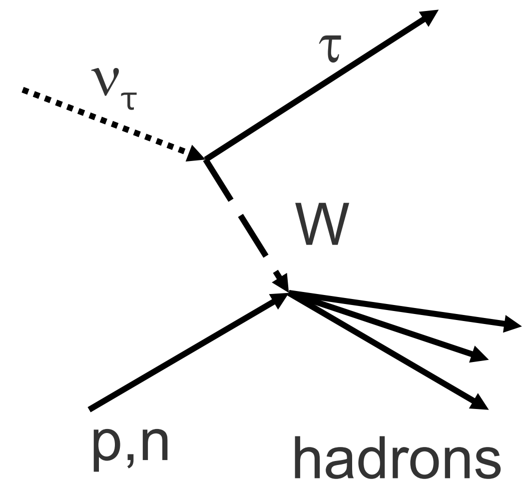


Propagation determined by mass eigenstates



Oscillation frequenzy depends on $\Delta m^2_{23} = m^2_2 - m^2_3$

Detector sees flavour eigenstates



Parametrisation of Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

$\theta_{23}=\theta_{atm}$ | $\theta_{13}=\theta_R$, δ | $\theta_{12}=\theta_{sol}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

In addition: If neutrinos are Majorana particles

$$M = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

2 CP-violating Majorana phases α_1,α_2

Not visible in Oscillations

Mass Ordering

Two mass-differences:

$\Delta m^2_{solar} = \Delta m^2_{21} \approx 7.5 \cdot 10^{-5} eV^2$,

$|\Delta m^2_{atm}| = |\Delta m^2_{32}| \approx 2.5 \cdot 10^{-3} eV^2$

One sign unknown

→ Two mass orderings possible

“Normal” hierarchy

“Inverted” hierarchy