# Neutrino Physics with THEIA

Presented by

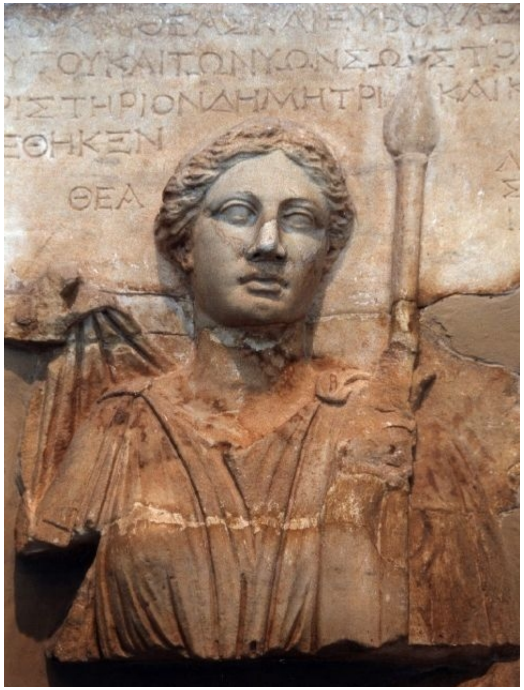
**Björn Wonsak**

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

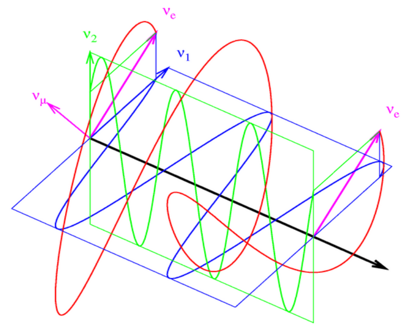
# Goals of Neutrino Physics

## Answer fundamental questions about neutrinos:

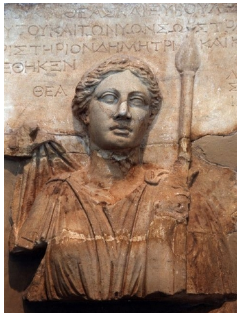
Neutrino Mixing:

(including sterile Neutrinos)

Oscillation

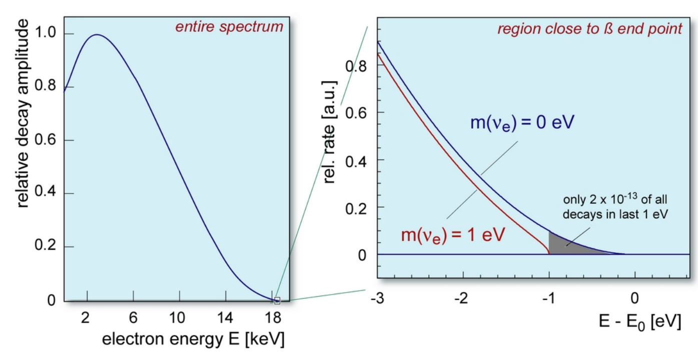



**CP-**violating phases



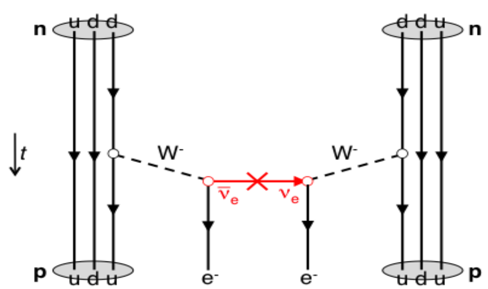
Neutrino Mass:

Endpoint of beta-decay

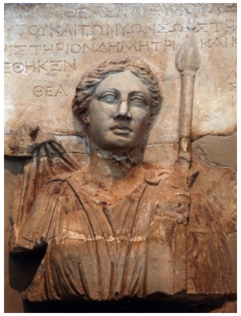



Majorana or Dirac:

Neutrinoless doublebeta-decay ($0\nu\beta\beta$)



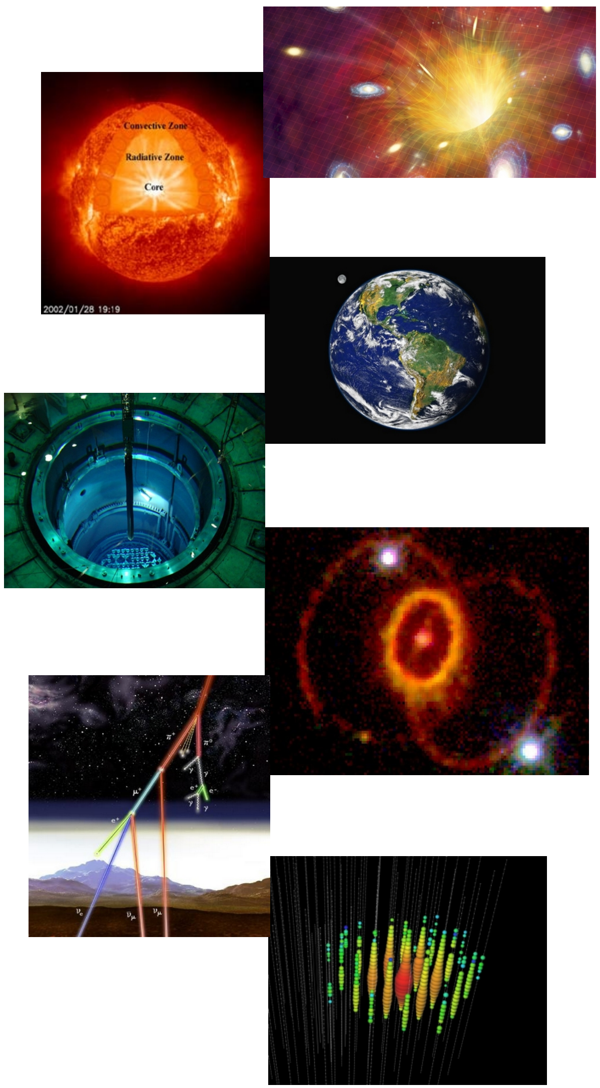

Lepton number violating process



Primary experimental Ansatz

# Goals of Neutrino Physics

## Use neutrinos as a probe or messenger particle:

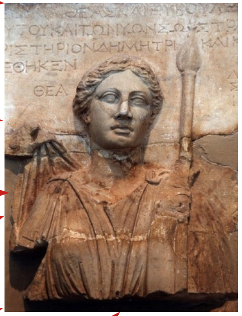



$10^{-4}$ eV

Energy

$10^{20}$ eV

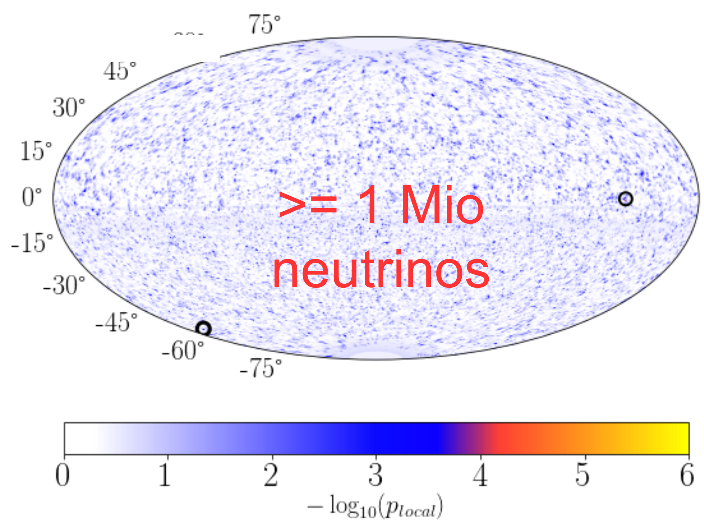
- Cosmic Neutrino Background
- Solar Neutrinos
- Geo Neutrinos
- Reactor Neutrinos
- Supernova Neutrinos
- Diffuse Super Nova Neutrino Background (DSNB)
- Atmospheric Neutrinos
- Astrophysical Neutrinos



# 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**



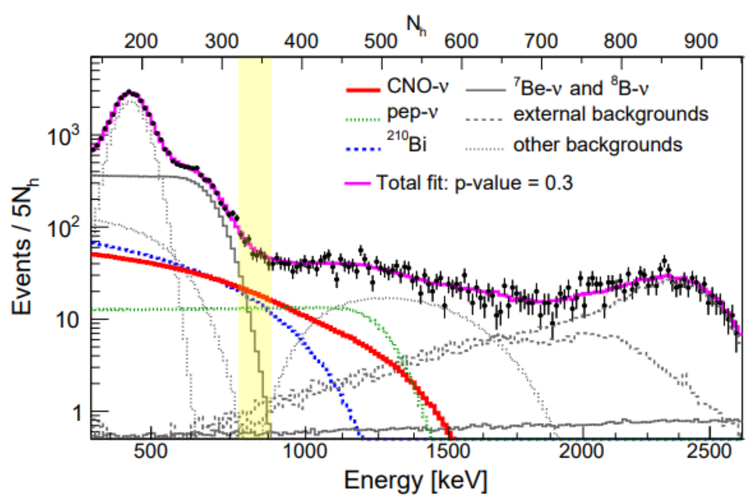

Neutrino energies up to PeV

"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**

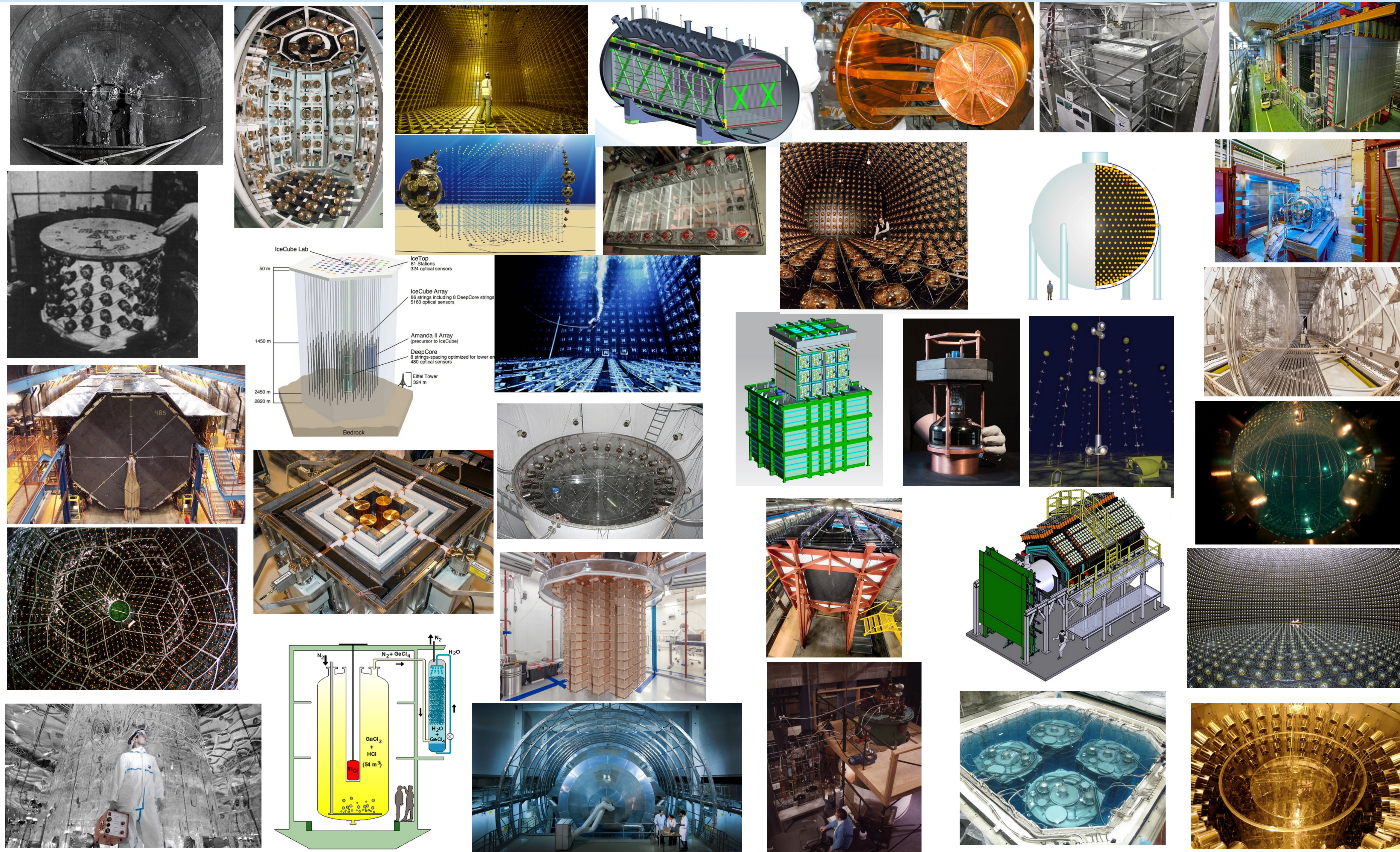



Neutrino energy (MeV)

"First Direct Experimental Evidence of CNO neutrinos"

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

# Rich Experimental Landscape

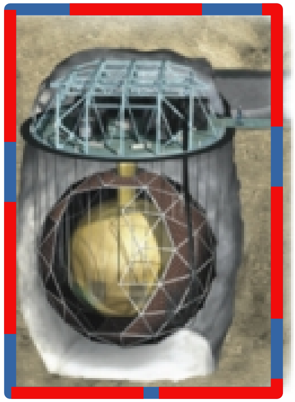




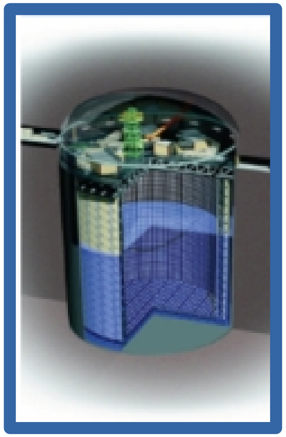

Not a complete picture!

# Some Major Contributors

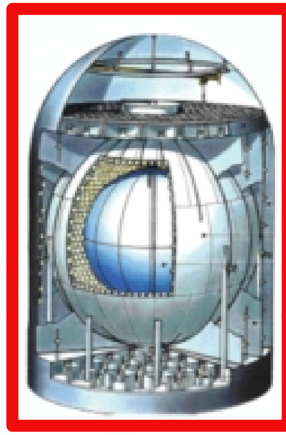
## Large homogeneous optical detectors



SNO
/SNO+

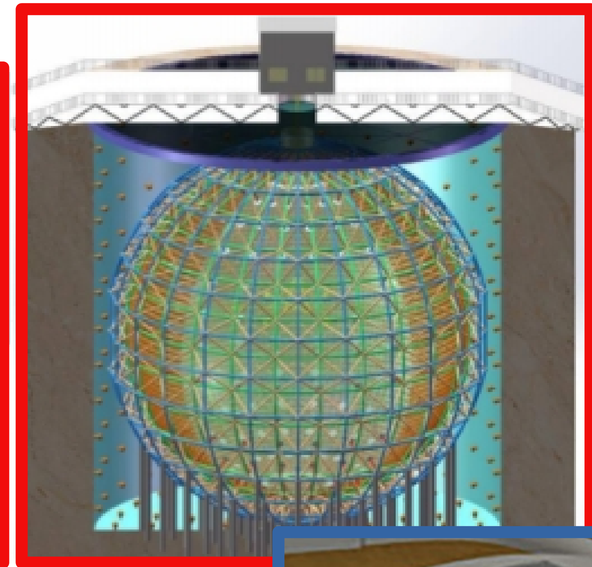


Super-
Kamiokande/
T2K

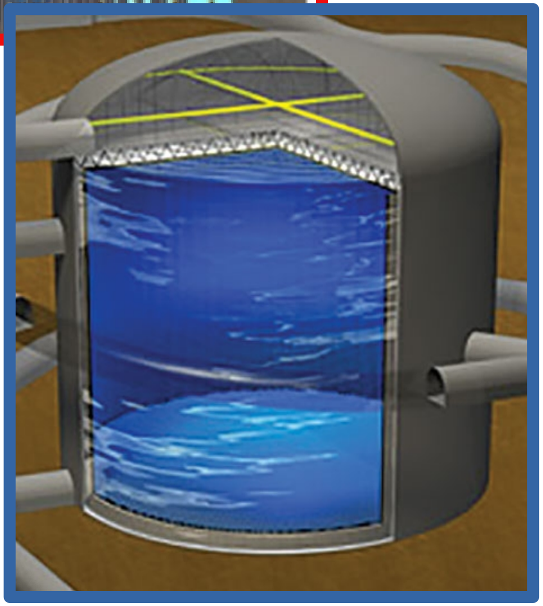


KamLAND
/KamLAND-Zen

Borexino



JUNO
(starting data taking in 2022)



Hyper-
Kamiokande
(starting operation in 2027)

**Advantages:**

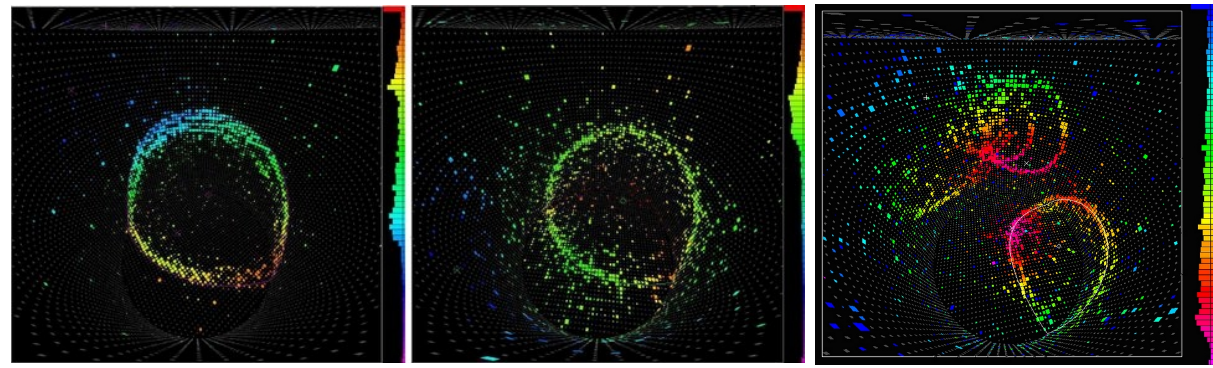
- Large size per cost
- Low threshold
- Fast timing for background reduction
- **Re-configurable as the field progresses**

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

# Two Detector Types

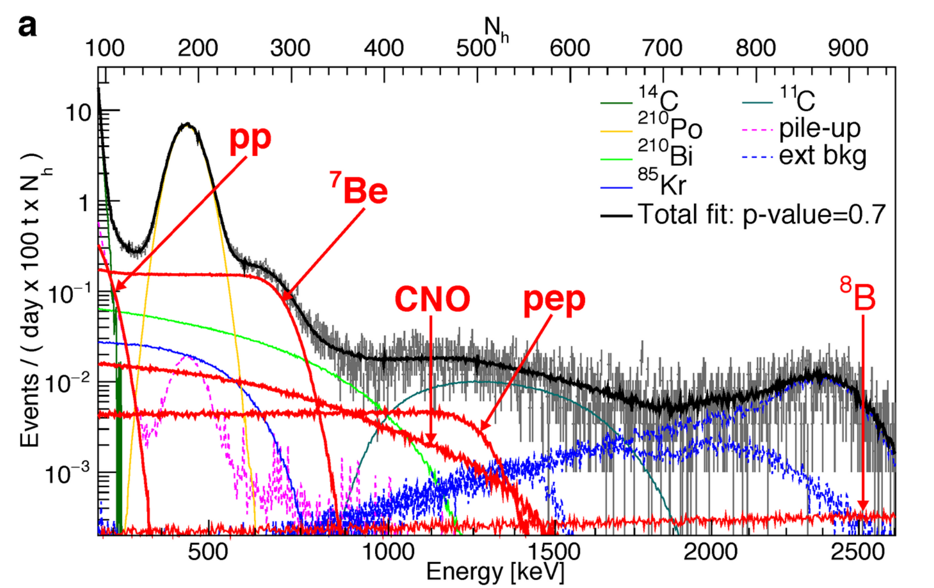
- **Water Cherenkov**
  - Excellent Transparency
    - large size
  - Cheap
  - Directionality
  - Particle ID
  - Potential for large Isotopic Loading

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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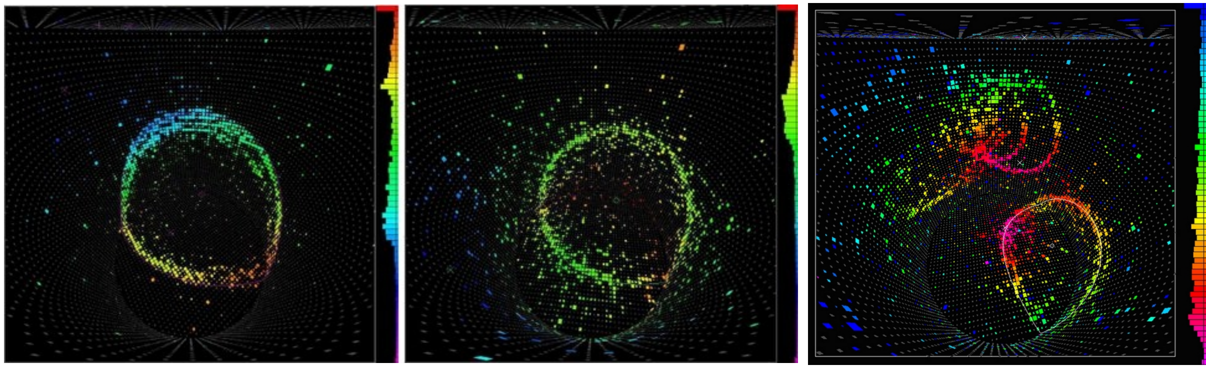

Muon Electron Multi-ring

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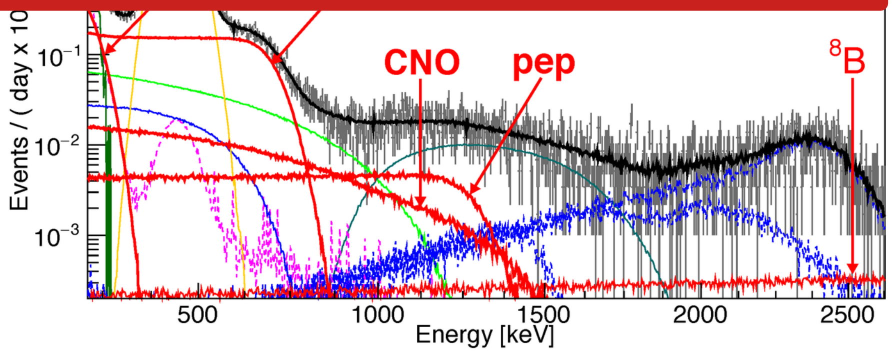
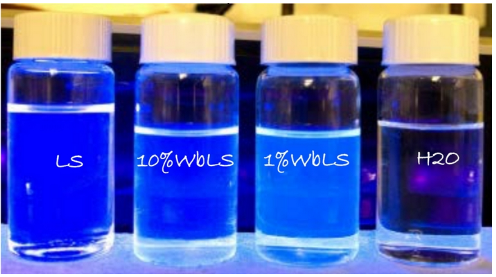
How to combine the advantages of both?

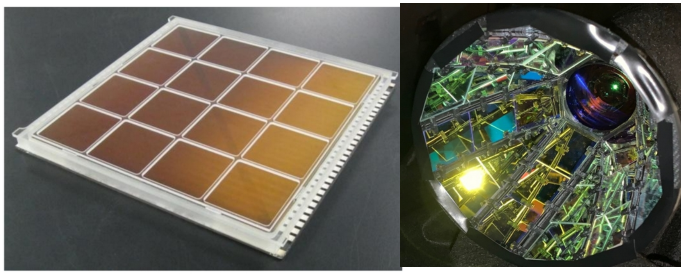


# The Theia Project

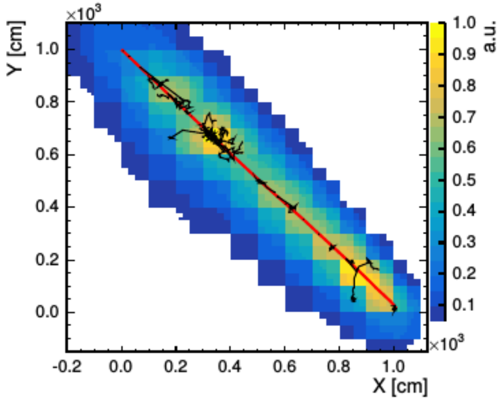
Large volume detector able to **exploit both Cherenkov+Scintillation** signals



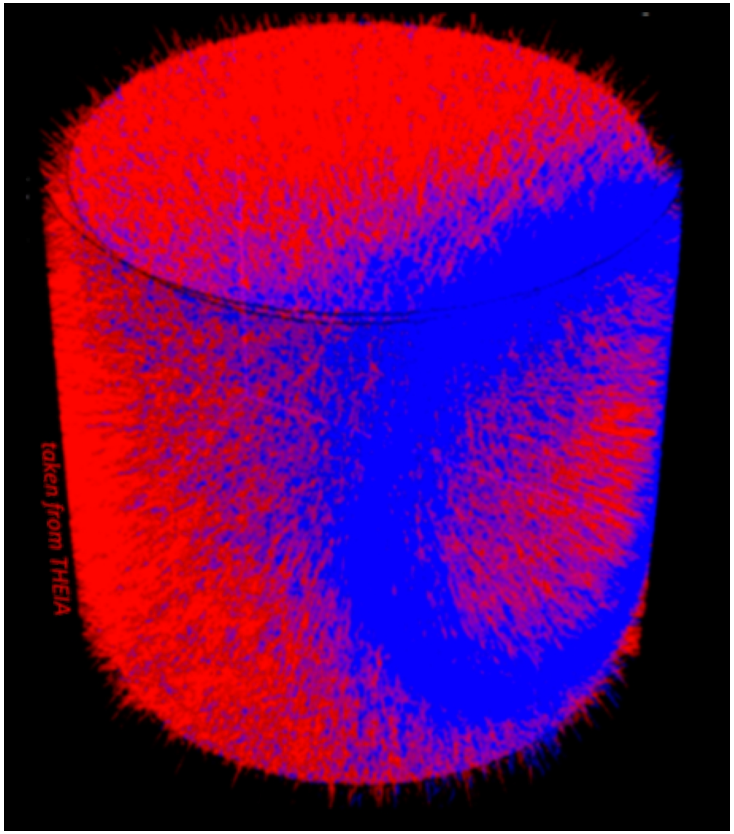

**Novel target medium:** (Wb)LS



**Novel light sensors:** LAPPDs, dichroicons




**Novel reconstruction methods**




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

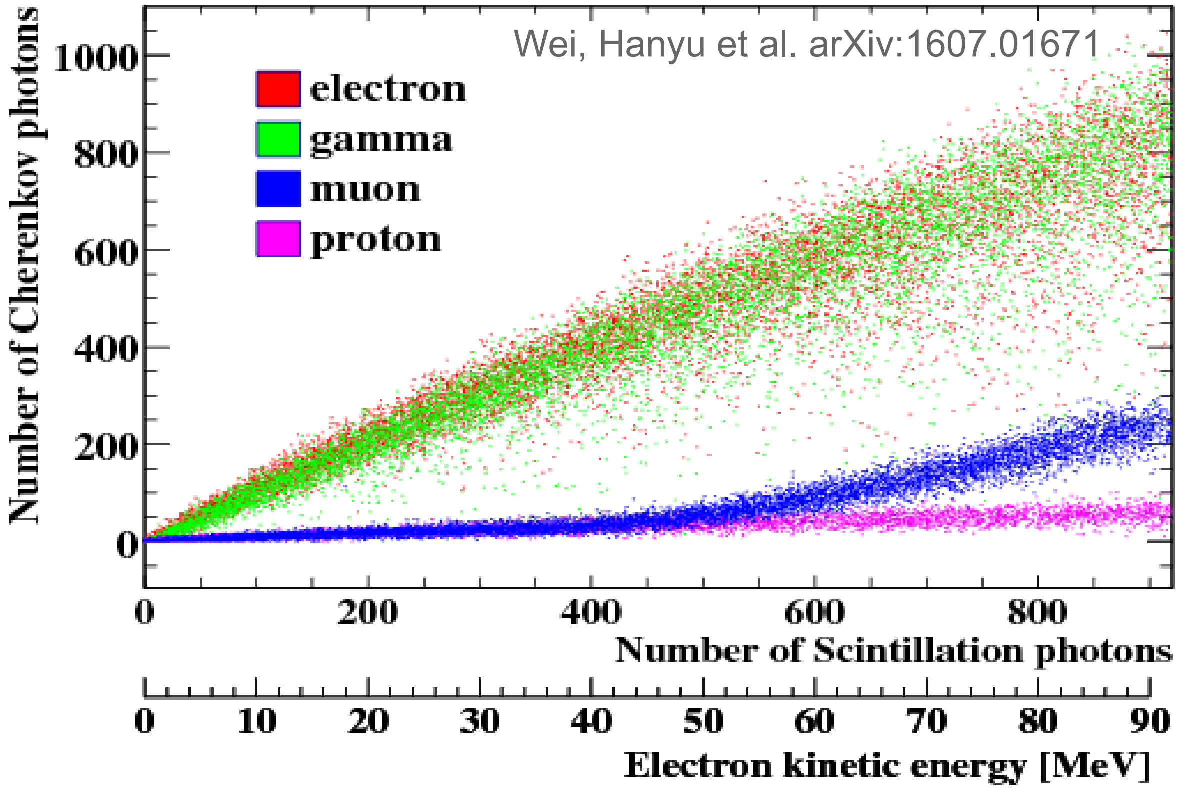
**Enhanced sensitivity to broad physics program:**

- 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 ration (C/S-ratio)

→ **Enhanced particle discrimination**



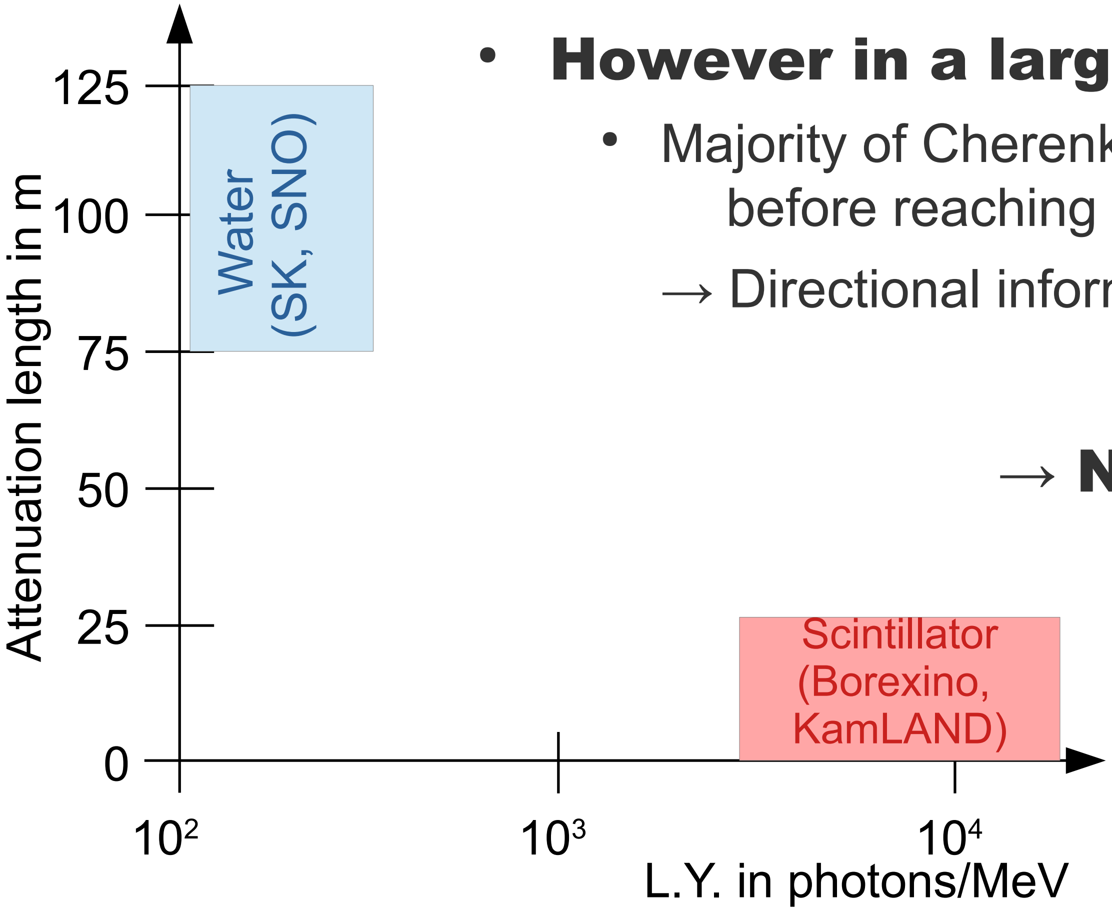

Number of Cherenkov- and scintillation photons for different particles in LAB

**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

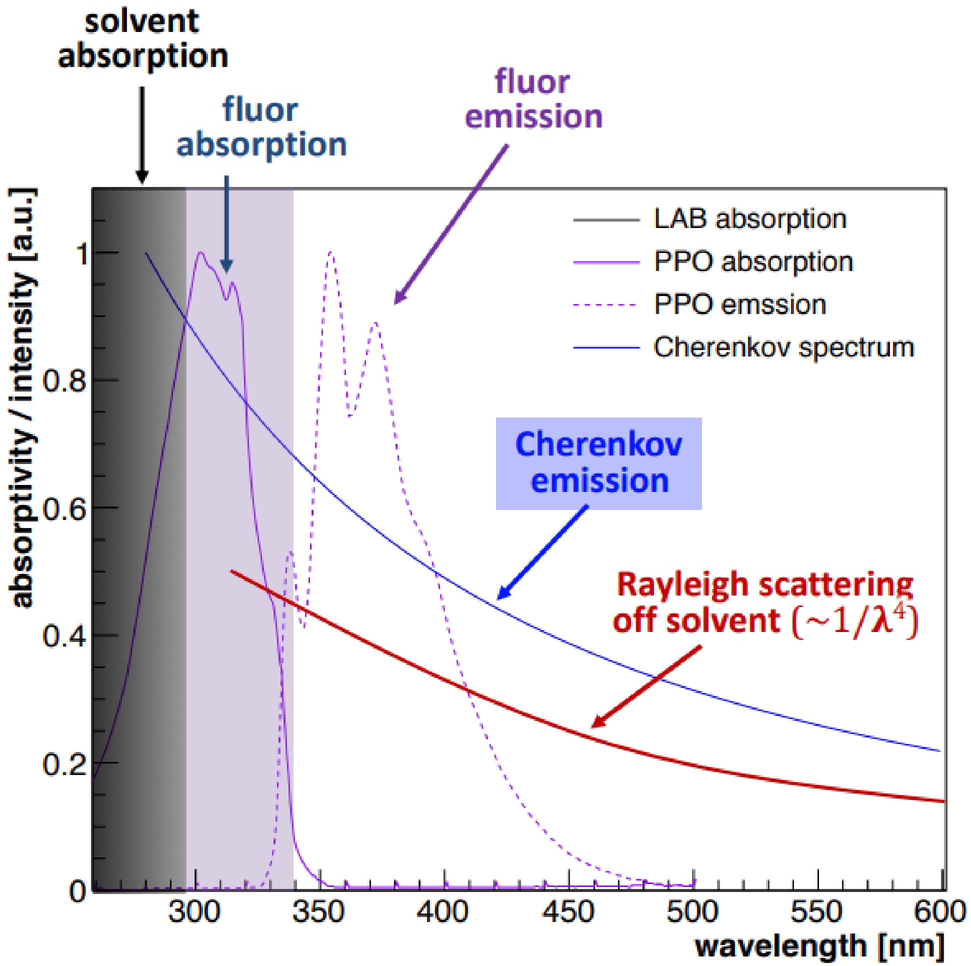
→ **Need to optimize the liquid!**

# How to Improve Relative Cherenkov Yield?

- **Reduce Rayleigh scattering**
  - New transparent solvent, e.g. LAB ($\lambda$ > 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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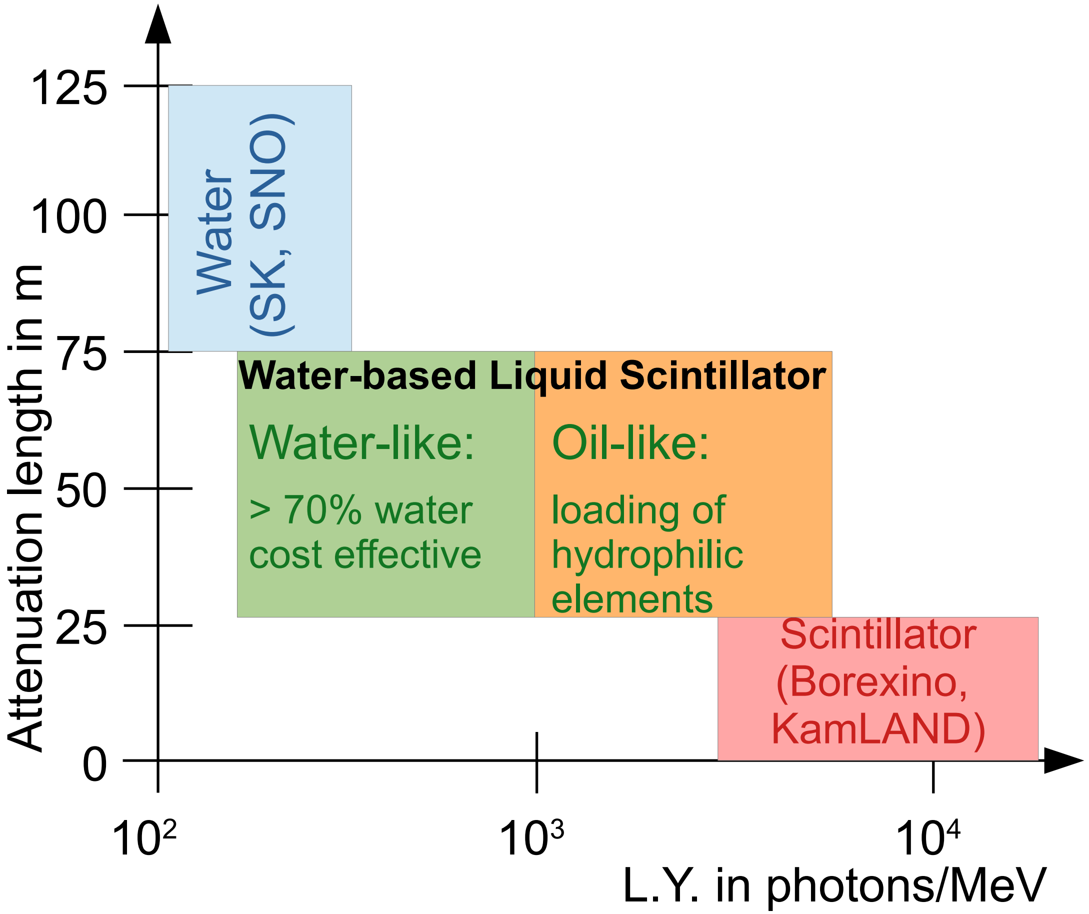


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  - Impacts scintillation yield
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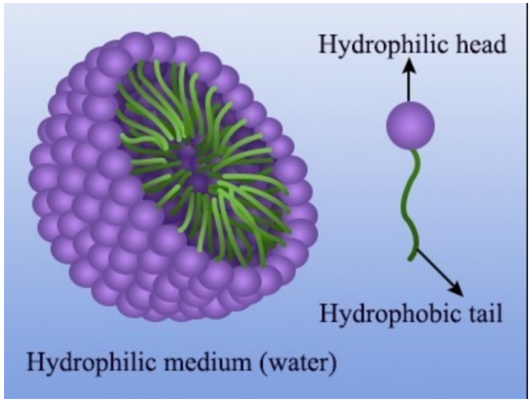
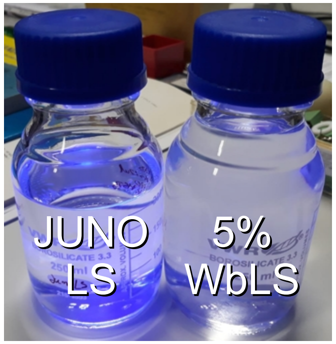
# Water-based Liquid Scintillator (WbLS)

- **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)



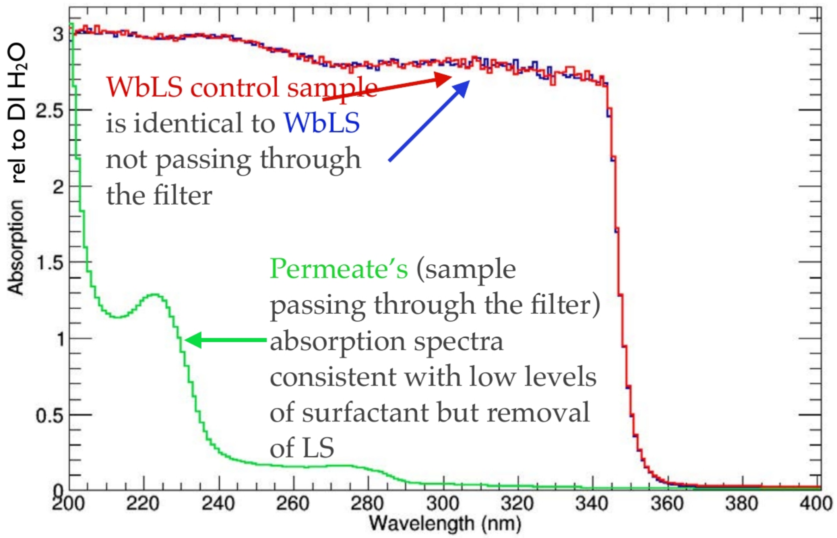

**WbLS mycels (nm-scale)**


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

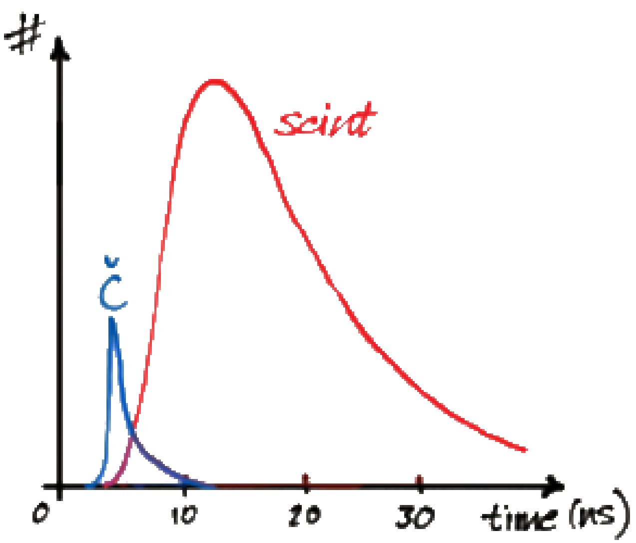
“instantaneous chertons” vs. delayed “scintons”
→ ns resolution or better

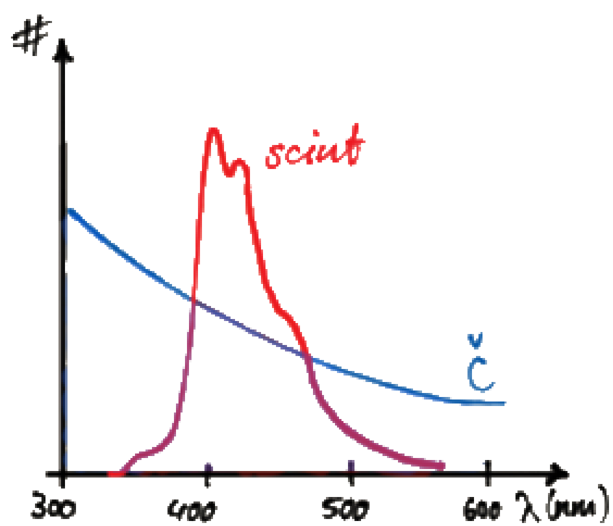
### Spectrum

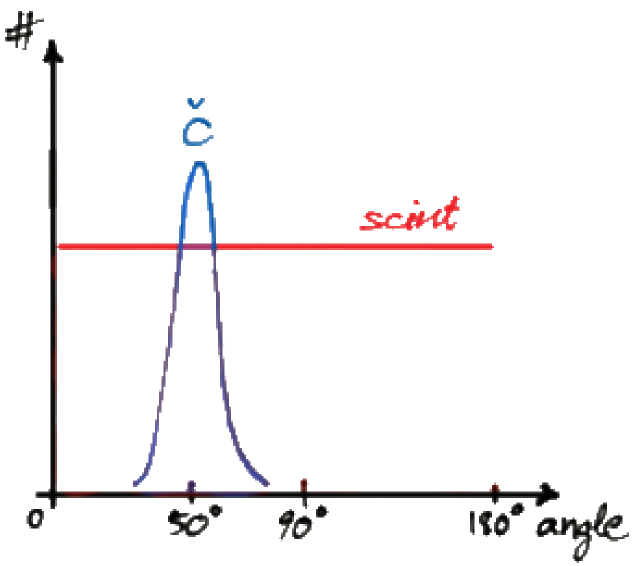
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity

### Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity




Courtesy to M. Wurm for this plots!

# Time Based Separation

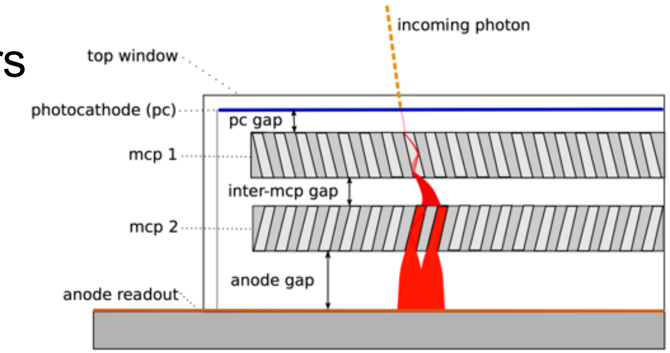
## Large Area Picosecond Photon Detectors (LAPPDs)

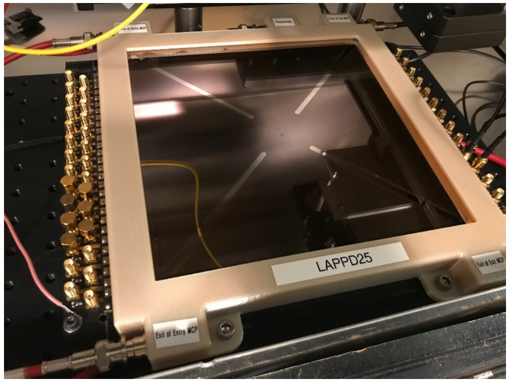
- Area: 20-by-20 $cm^2$

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

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

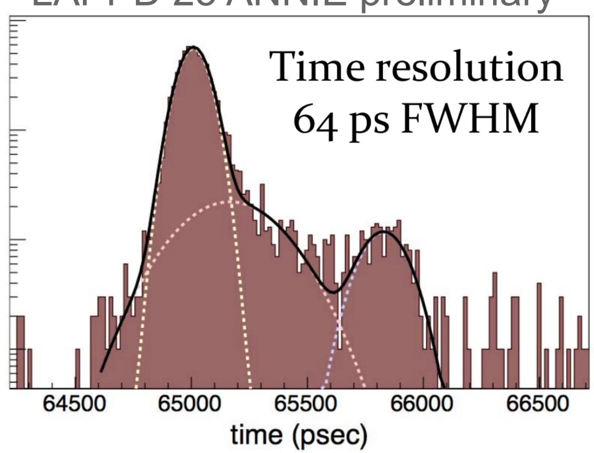
- Commercial production by Incom, Ltd.



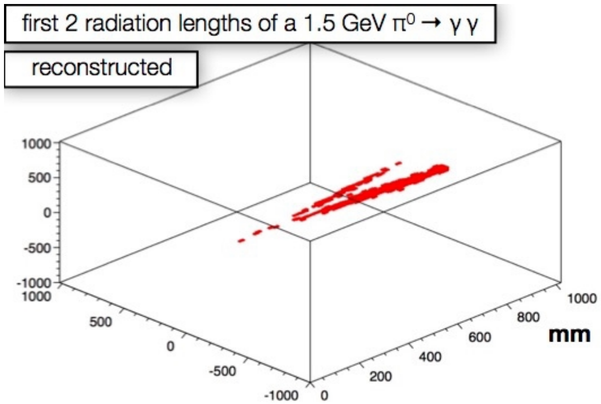




LAPPD 25 ANNIE preliminary

< 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

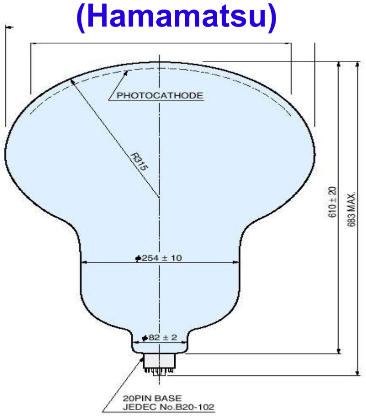
# Ring Based (Angular) Separation

- **Need high granularity**

  **→ Photosensors must be**
  - Cheap
  - Efficient
  - Reasonable fast

- HQE 20” PMTs (Efficient & affordable)

Dynode-PMT (Hamamatsu)

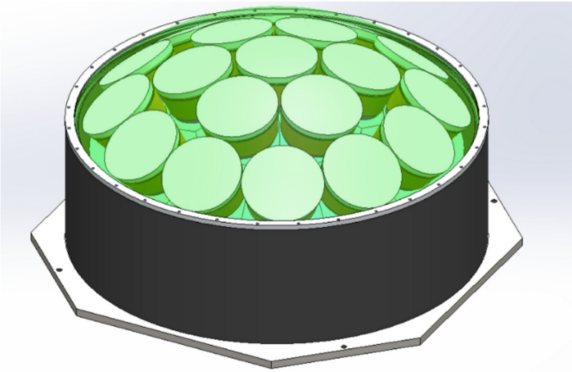



MCP-PMT (NNVT)

QE ~28%: Used in JUNO

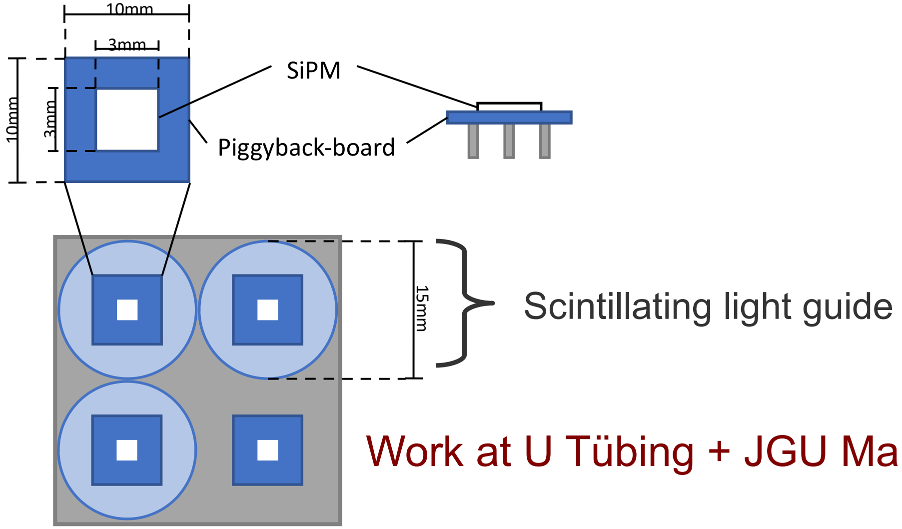
Dynode-PMTs: TTS ~ 1ns $\sigma$

- Modular PMTs
  (Good compromise of everything)



Water-Cherenkov Test Beam Experiment

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

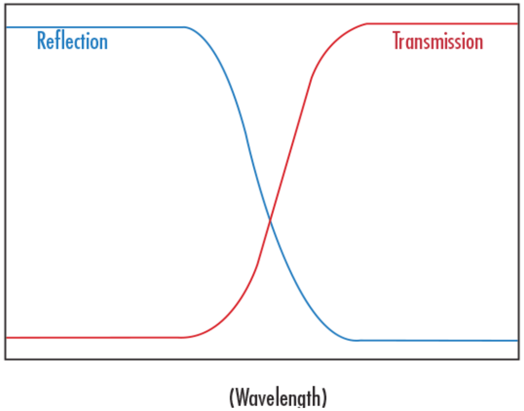



Work at U Tübing + JGU Mainz

# Wavelength Based Separation

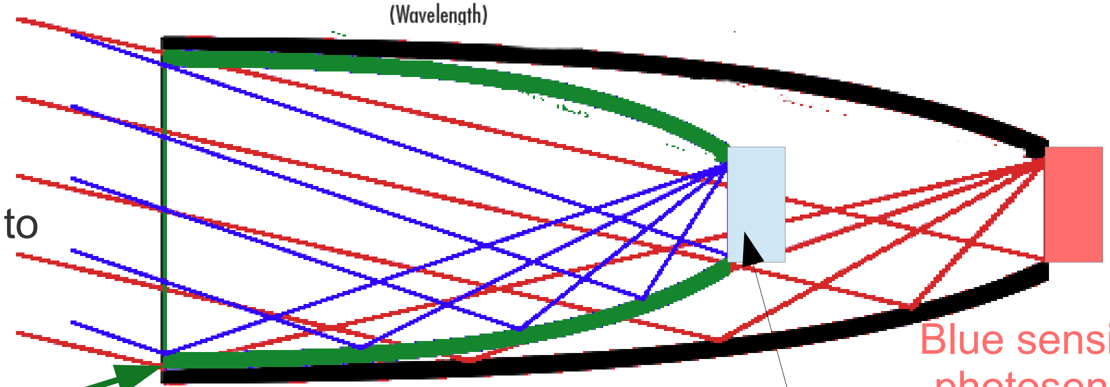
- **Dichroic filter**

  Reflect only light above/below certain wavelength threshold

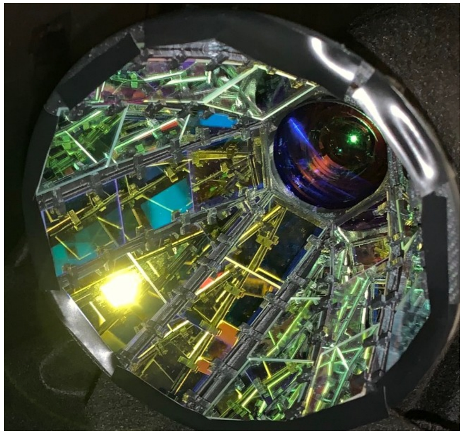



## + Winston cones

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

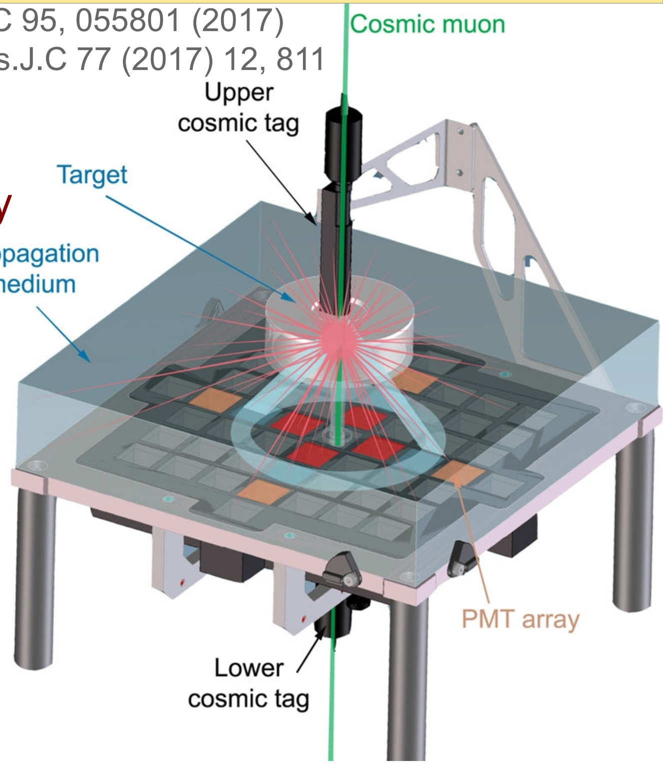
# CHErenkov Scintillation Separation (CHESS)

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

- Cosmic muon ring-imaging experiment
- Images Cherenkov rings in Q and T on fast PMT-array
- Allows charge and time based separation

Work at UC Berkeley

- **Results:**
  - Ring and timing pattern clearly visible
  - WbLS faster than pure LAB

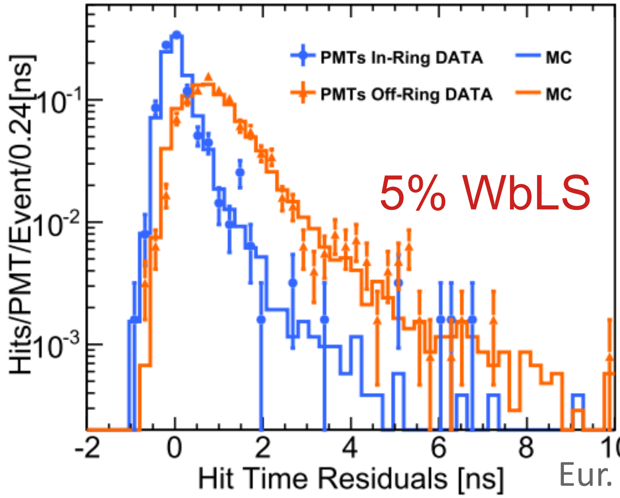


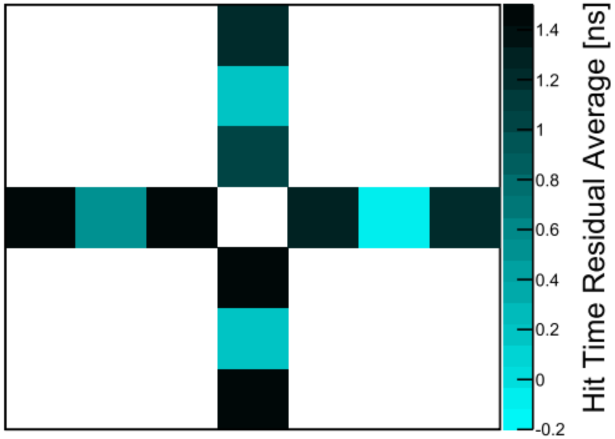

| WbLS | 1% | 5% | 10% | LAB + 2g/l PPO |
|---|---|---|---|---|
| $\tau_1$ [ns] | 2.25 ± 0.15 | 2.35 ± 0.11 | 2.70 ± 0.16 | 5.21 ± 0.5* |
| $\tau_2$ [ns] | 15.1 ± 7.5 | 23.2 ± 3.3 | 27.1 ± 4.2 | 16.4 ± 0.6* |
| R | 0.96 ± 0.01 | 0.94 ± 0.01 | 0.94 ± 0.01 | 0.78 ± 0.01* |
| L.Y. [photon/MeV] | 234 ± 30 | 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 !**

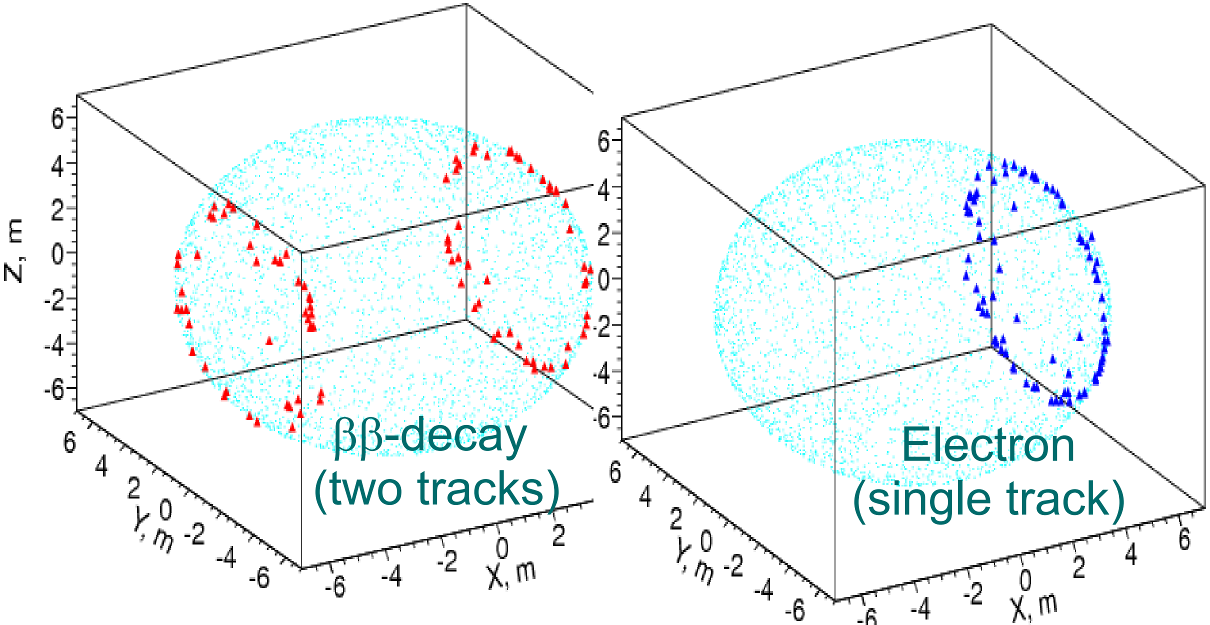



Eur. Phys. Jour. C 80, 867 (2020), arXiv:2006.00173

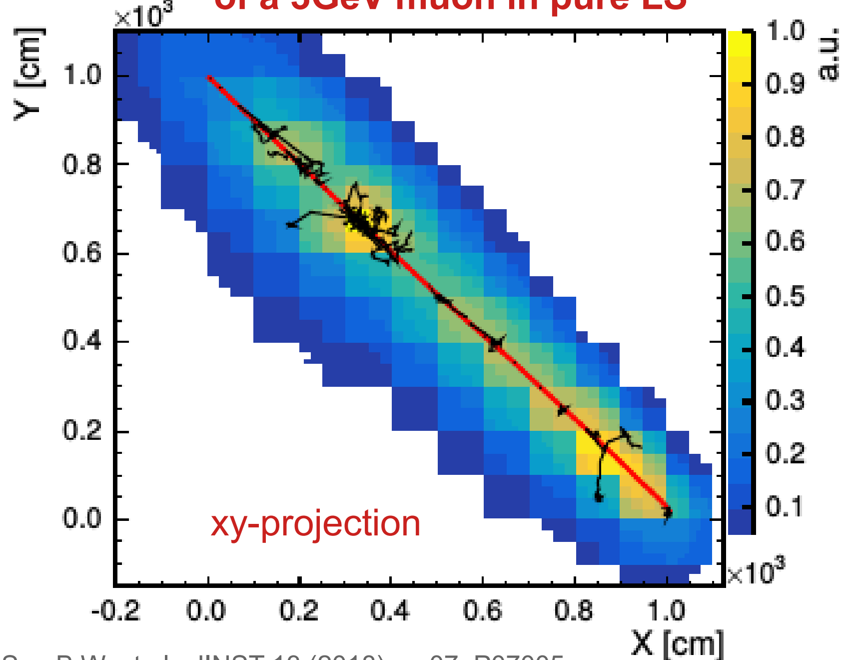
# Advanced Computing & Reconstruction Methods

- 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

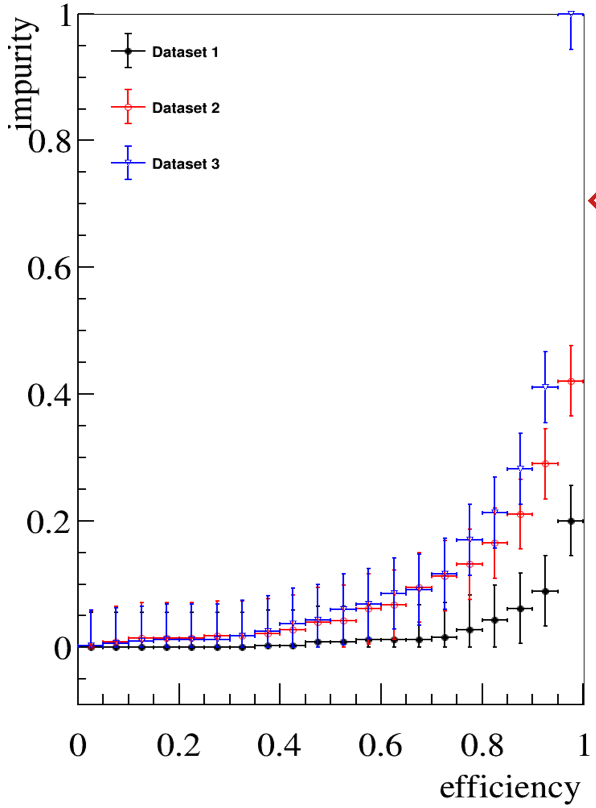
# Particle Identification at MeV Energies

- **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

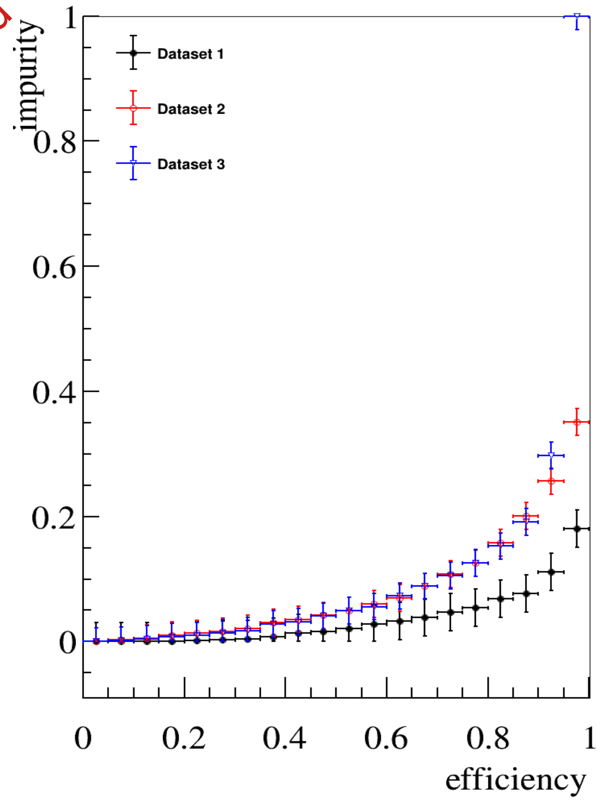
see also BW et et al., doi:10.1142/9789811204296_0028

e+e- discrimination




Preliminary JUNO simulation used

e-/γ discrimination

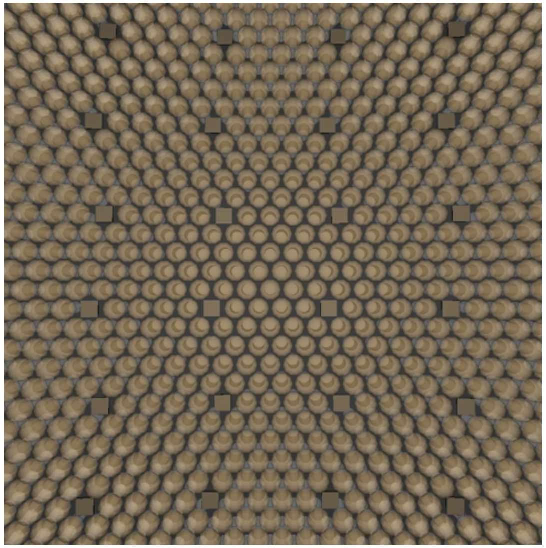



**Gap between data-set 1 and 2 indicates huge potential of good TTS**

(good TTS will also affect the vertex resolution)

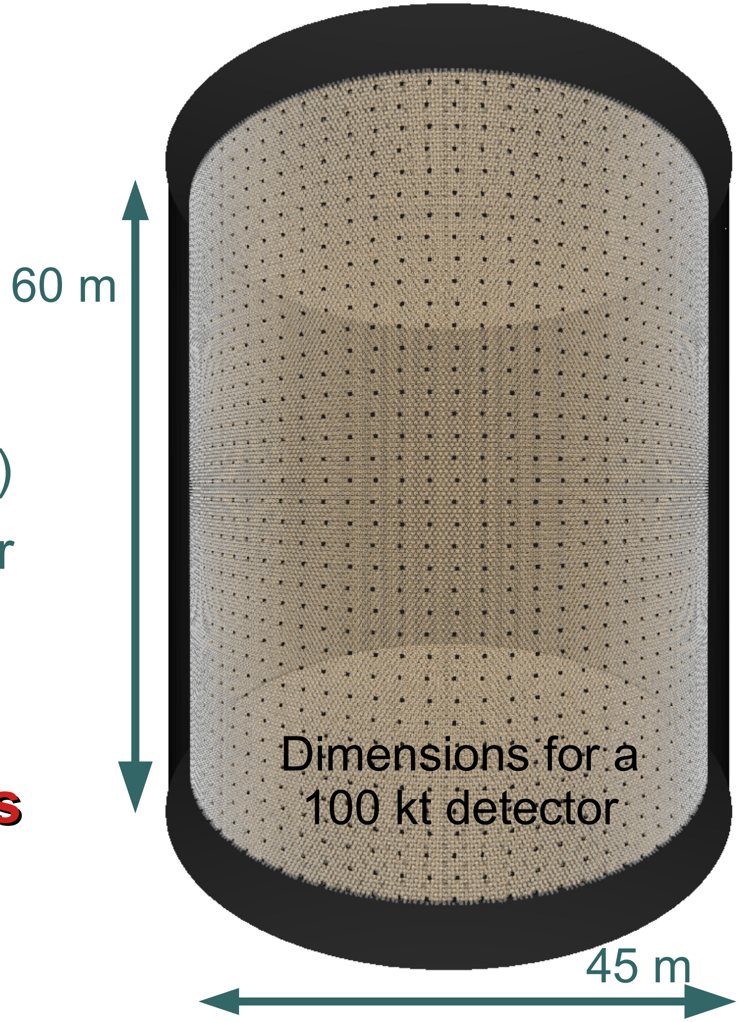
# The THEIA Detector

- **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

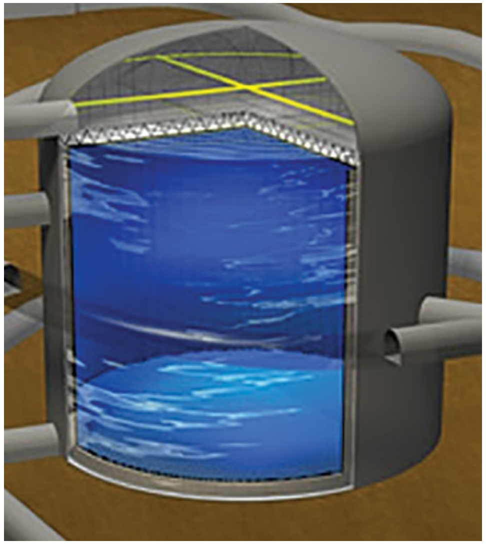
**White paper:** M. Askins et al., Eur.Phys.J.C 80 (2020) 5, 416, arXiv:1911.03501

# Future Long-Baseline Neutrino Experiments

- **THEIA would need a beam to do long-baseline physics**

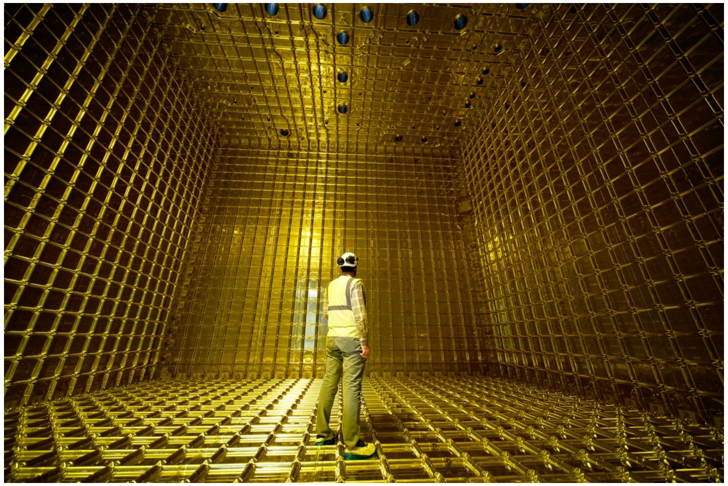
- **Two upcoming large scale projects:**
  - Hyper-Kamiokande (Hyper-K/HK) & DUNE

**Hyper-K**



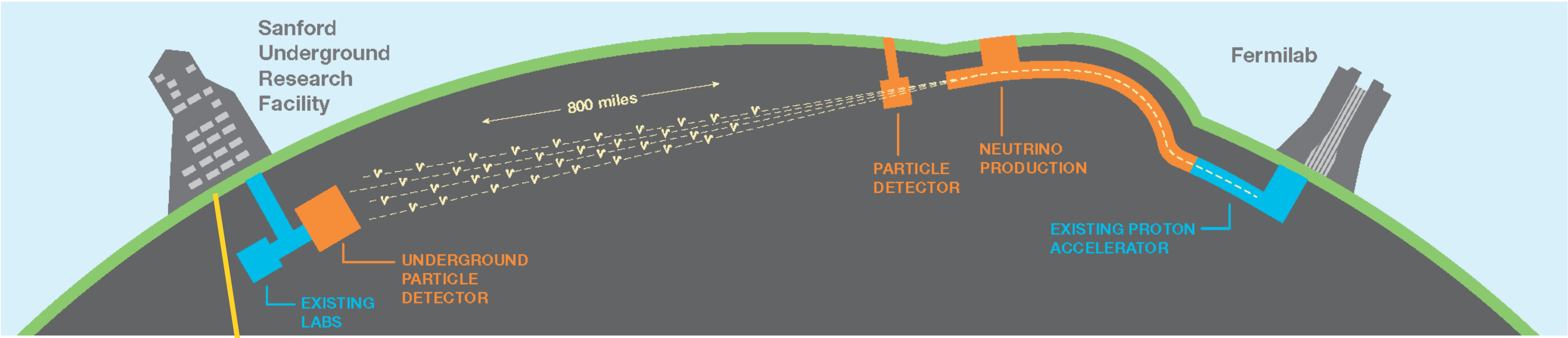
260 kton Water,
starting operation in 2027

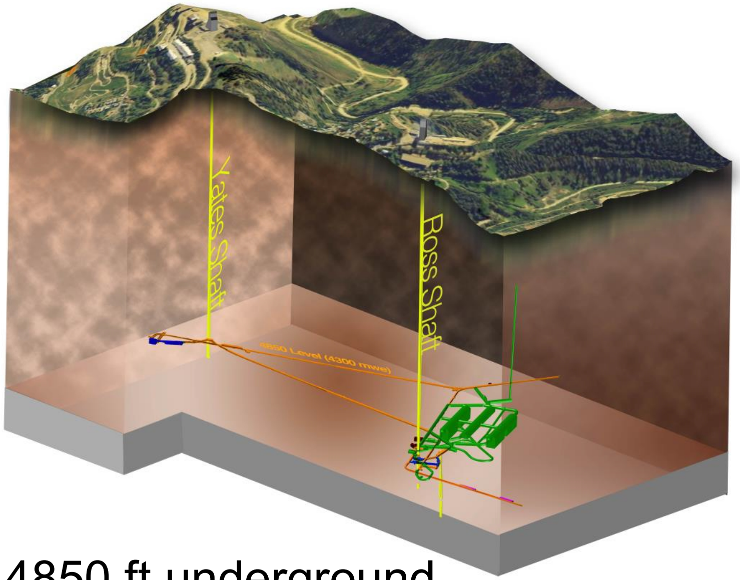
**DUNE**



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

# Long Baseline Neutrino Facility (LBNF)



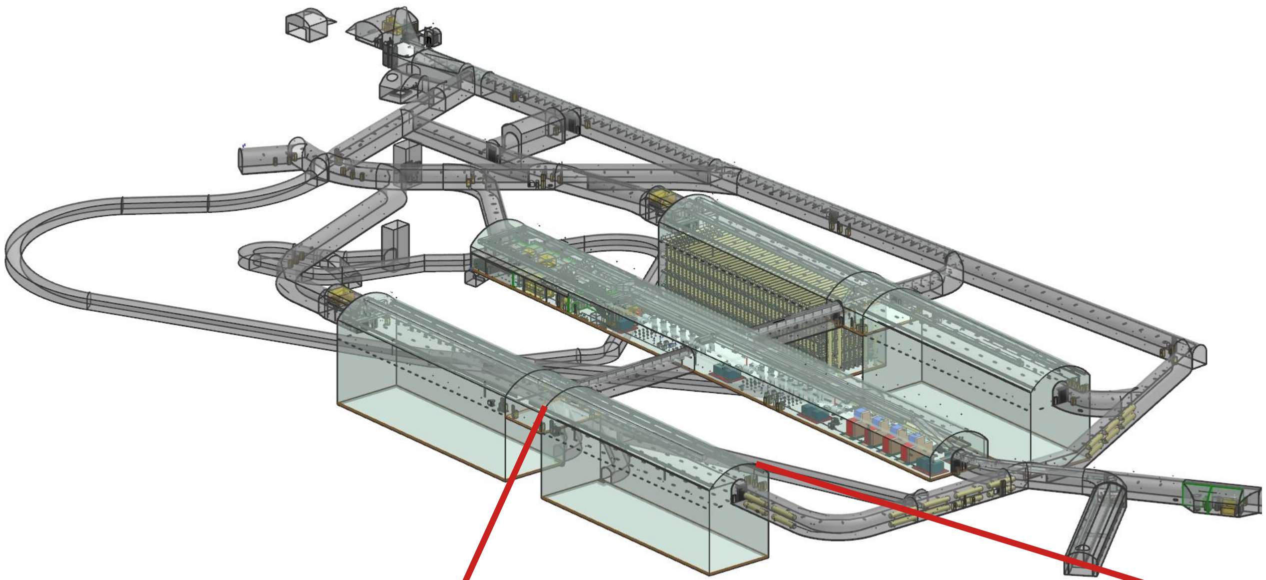



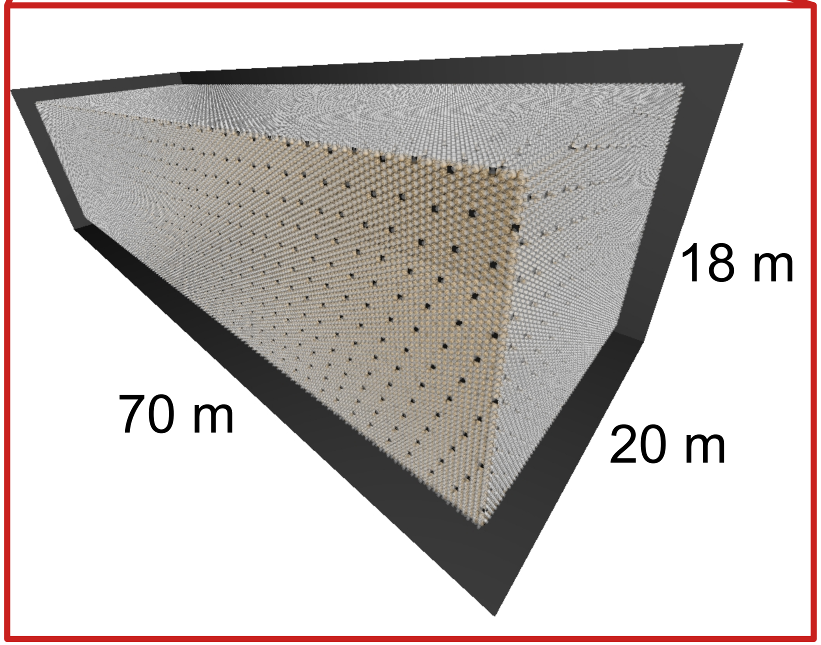

4850 ft underground

**<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

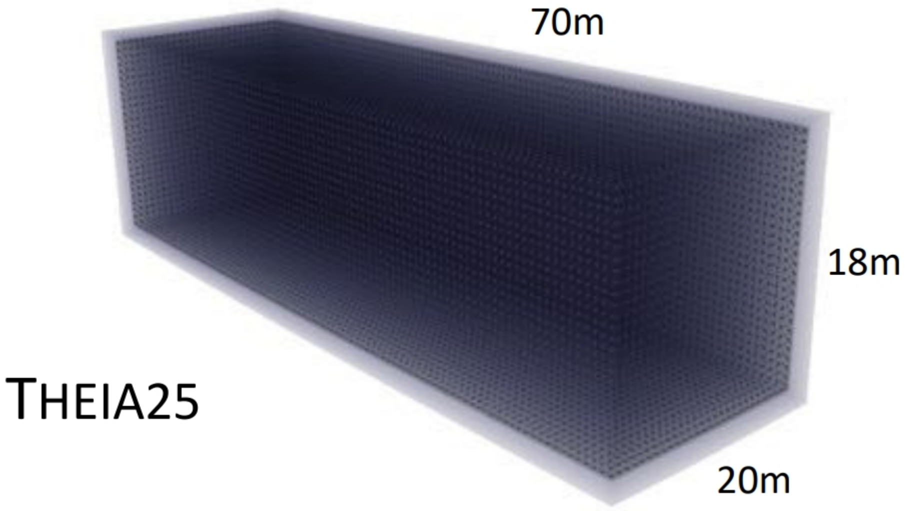
**Photosensors:**

- 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 |

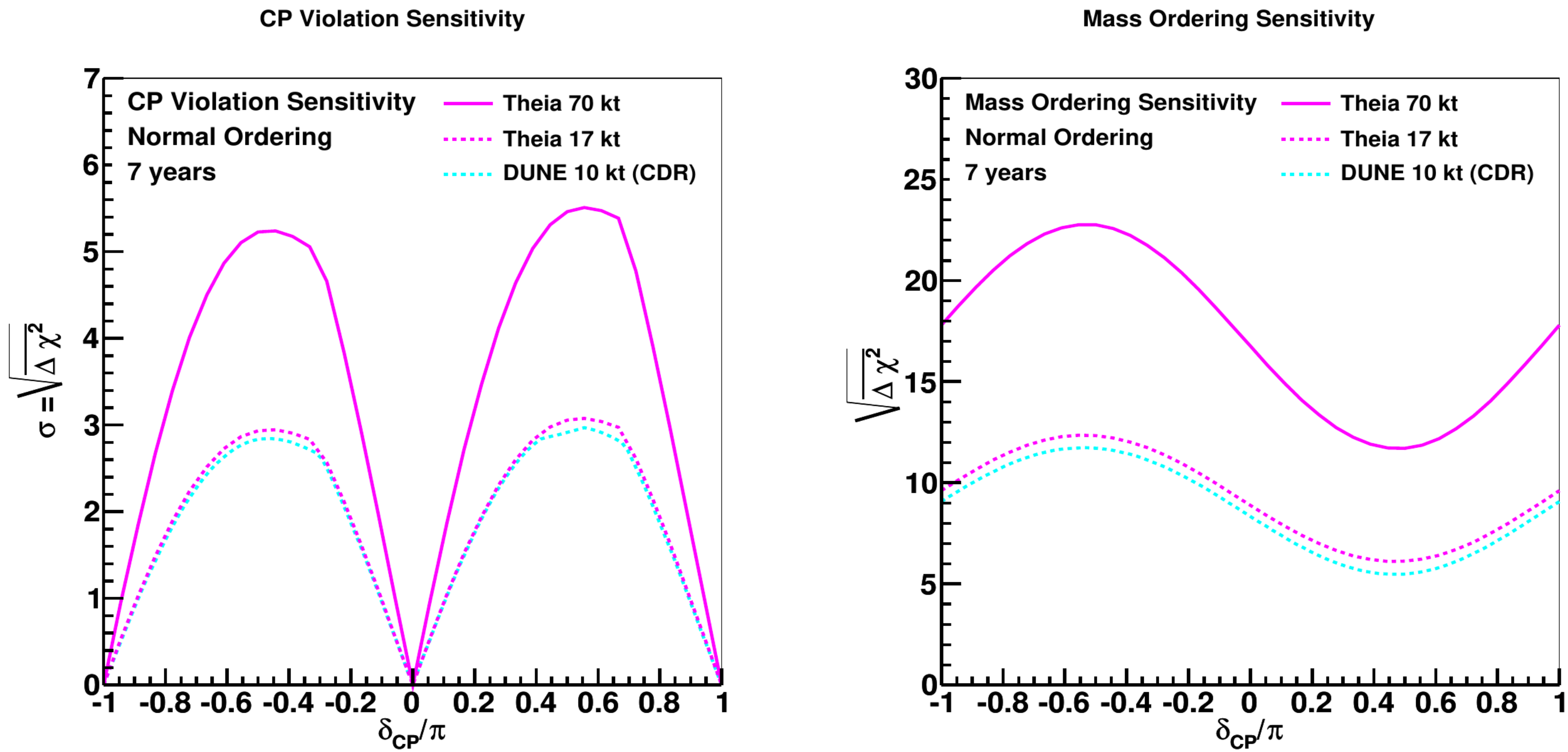
**Physics Goals**

- **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 ($\delta_{CP}$) Program

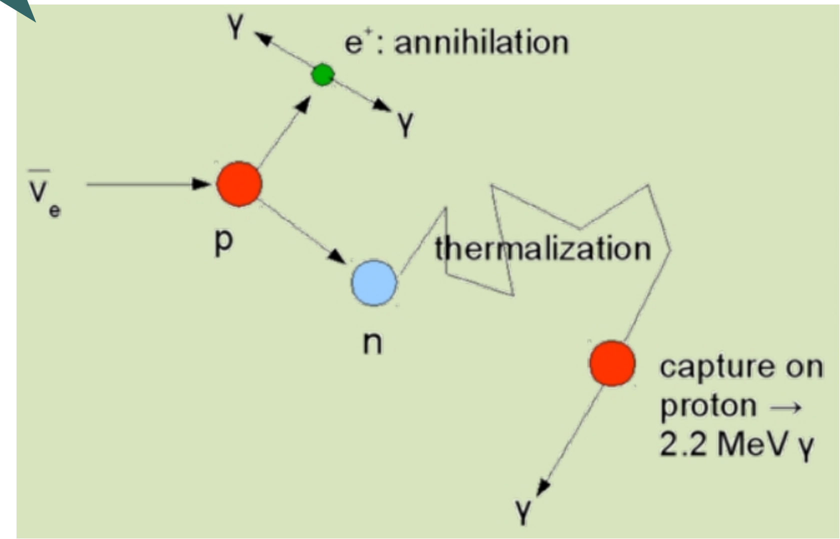
- **Additional statistics**
  - ~1.7:1 in mass for WbLS : LAr
- **Complementary systematics**
  - e.g. cross-sections (simpler nuclei)
- **Hadronic recoils/neutron tagging**

  → reduces systematics of energy reco

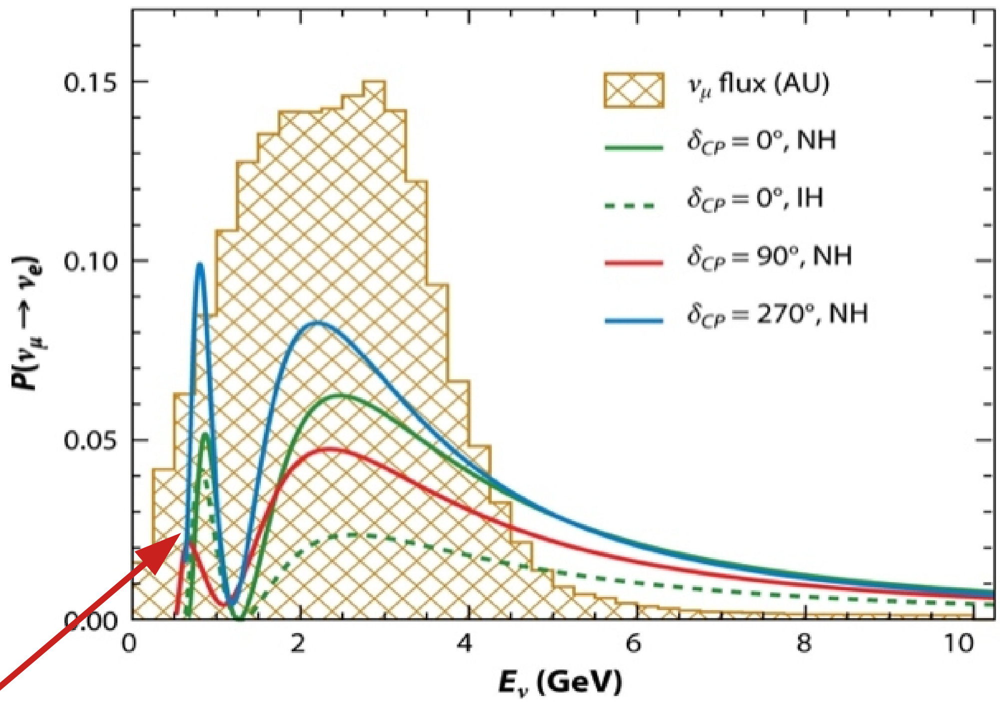
  → neutrino/antineutrino discrimination

**In the end DUNE will be dominated by systematics**

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



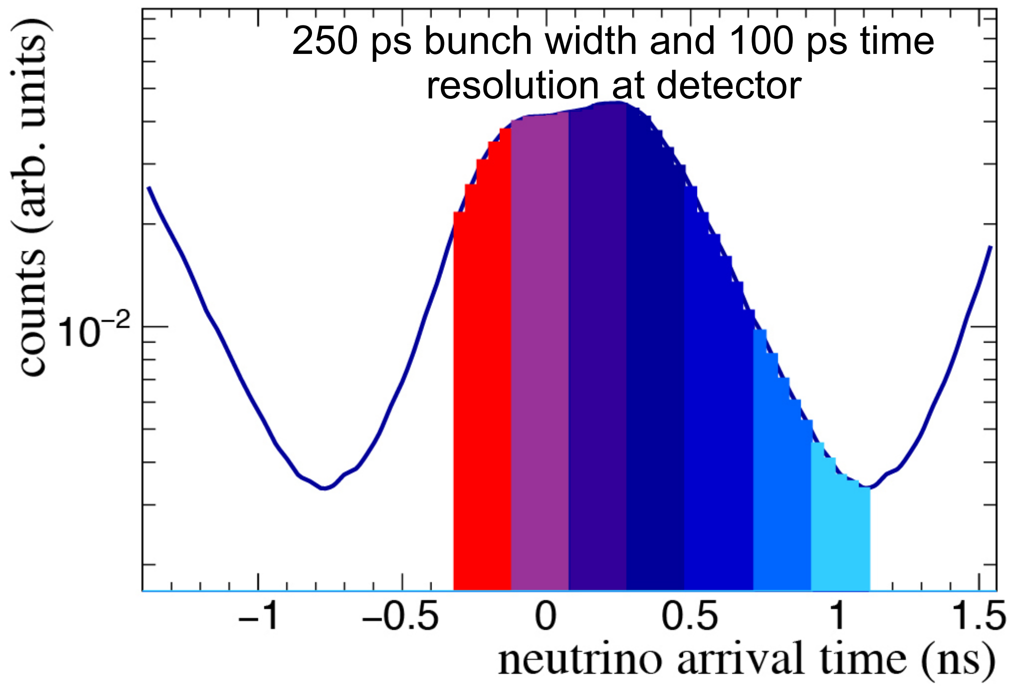
# Added Value for LBNF ($\delta_{CP}$) Program

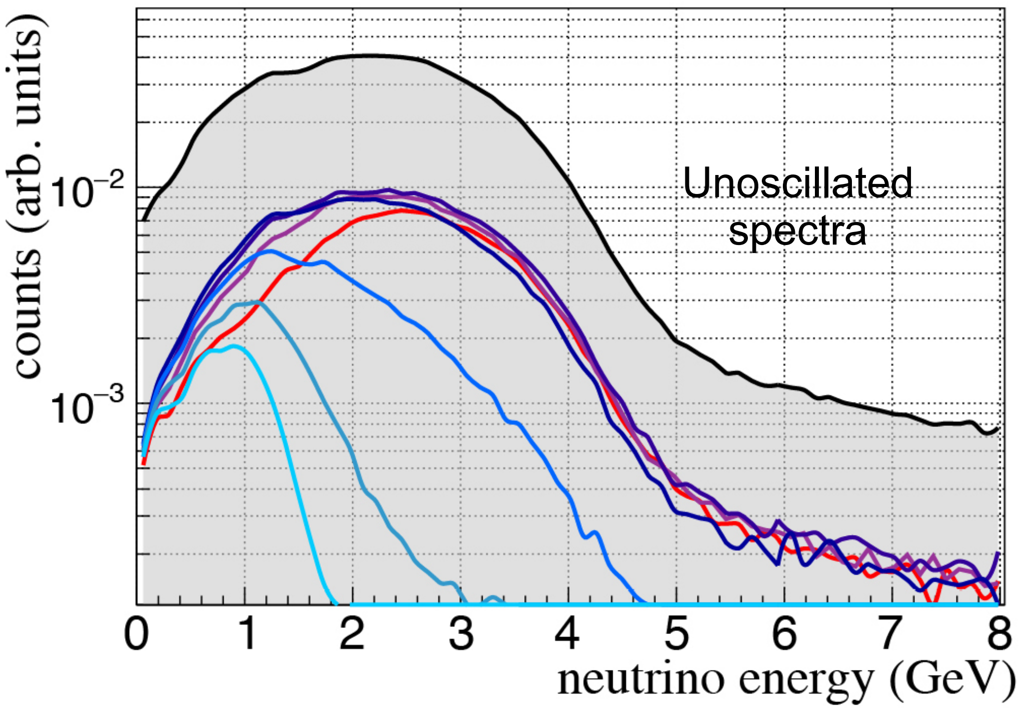



- **Additional statistics**
  - ~1.7:1 in mass for WbLS : LAr
- **Complementary systematics**
  - e.g. cross-sections (simpler nuclei)
- **Hadronic recoils/neutron tagging**
  - → reduces systematics of energy reco
  - → neutrino/antineutrino discrimination
- **Improved energy resolution for low energies (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)



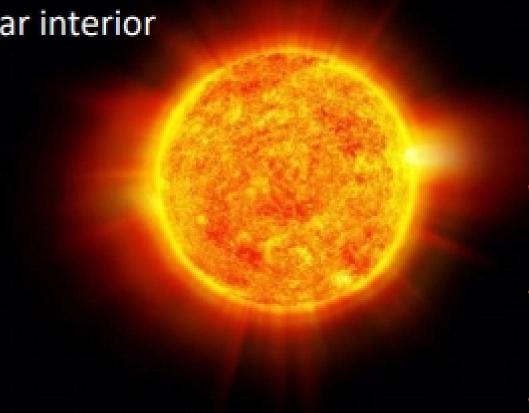

Arrival times and energy spectra for the FHC* configuration of the LBNF beam at DUNE

*FHC forward horn current

# Low Energy Astrophysics with Neutrinos

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

**Solar Neutrinos**
from H fusion in
solar interior



**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

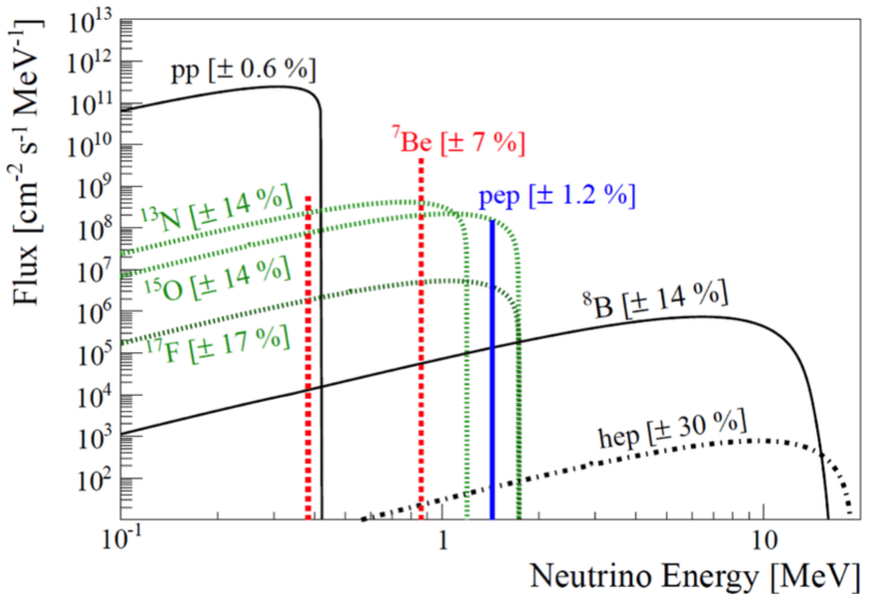
    → Accurately measure CNO flux

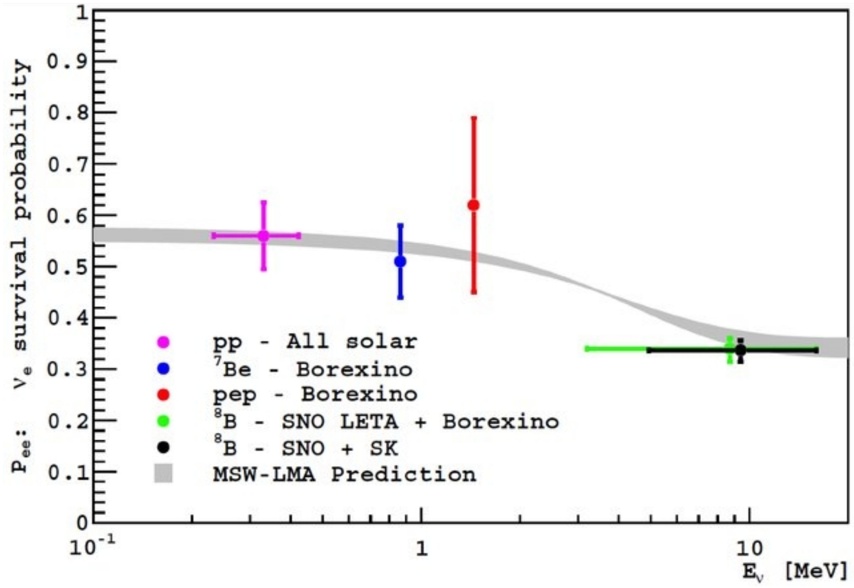
  - Test predictions MSW-Oscillations

    → 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 $\nu$ | 3.8 |
| CNO $\nu$ | 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

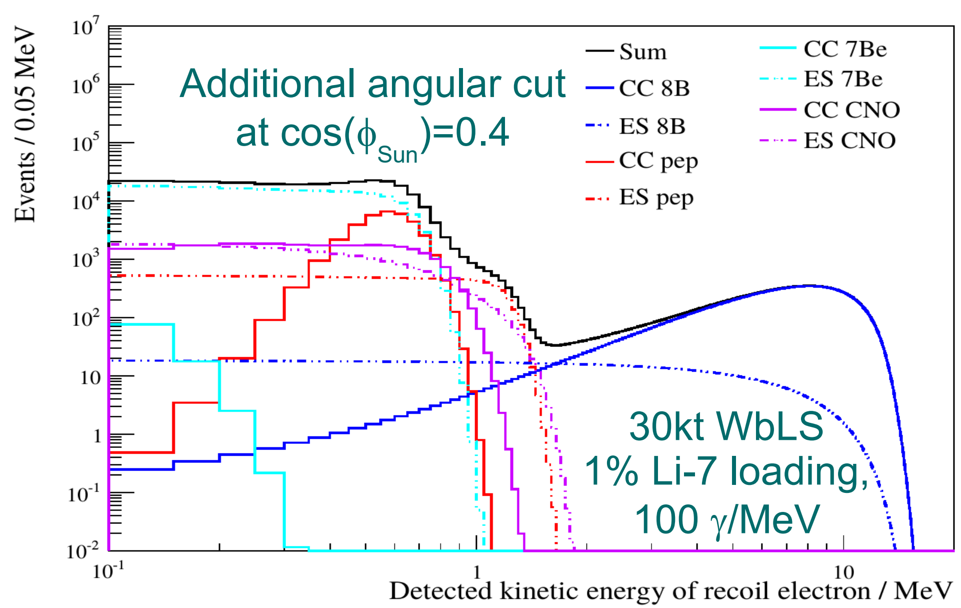
- Li-loading makes CC-channel accessible

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

  - 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

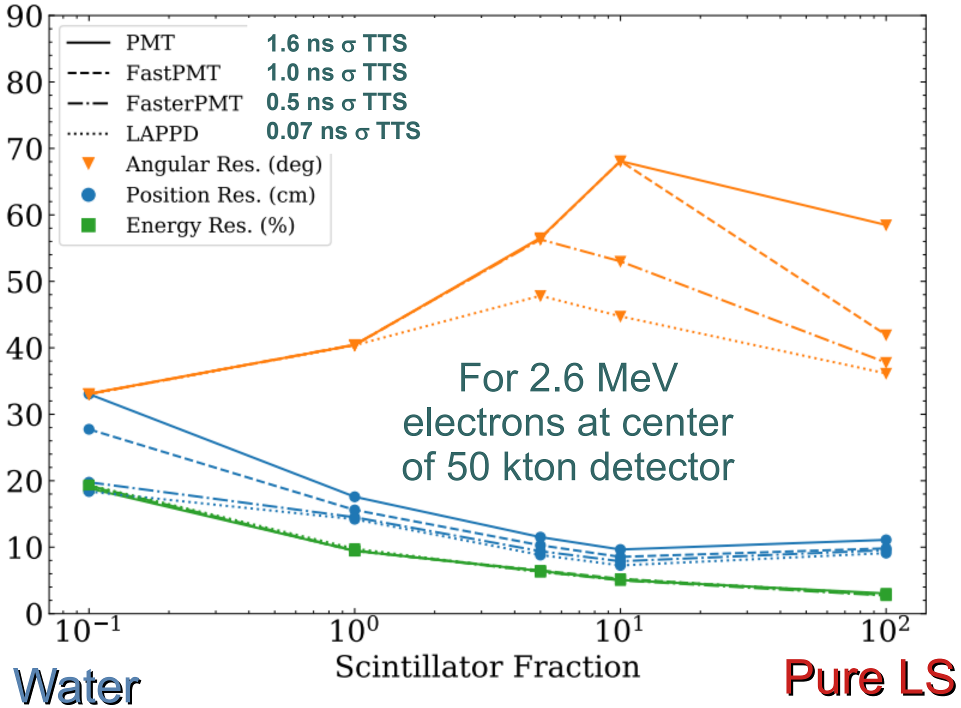


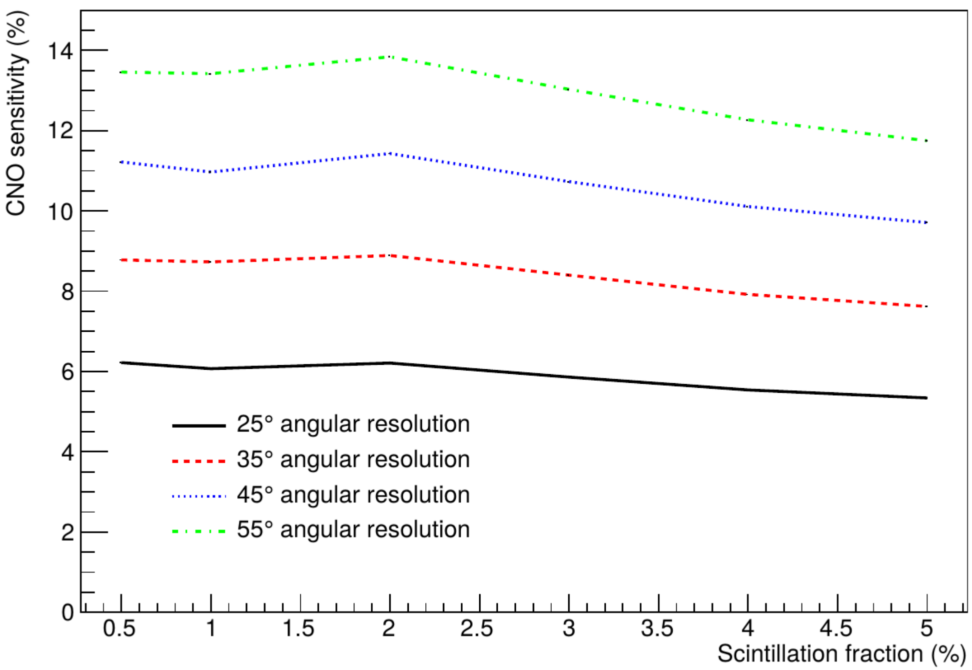
# Helping Solar Neutrinos with Directionality

- 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



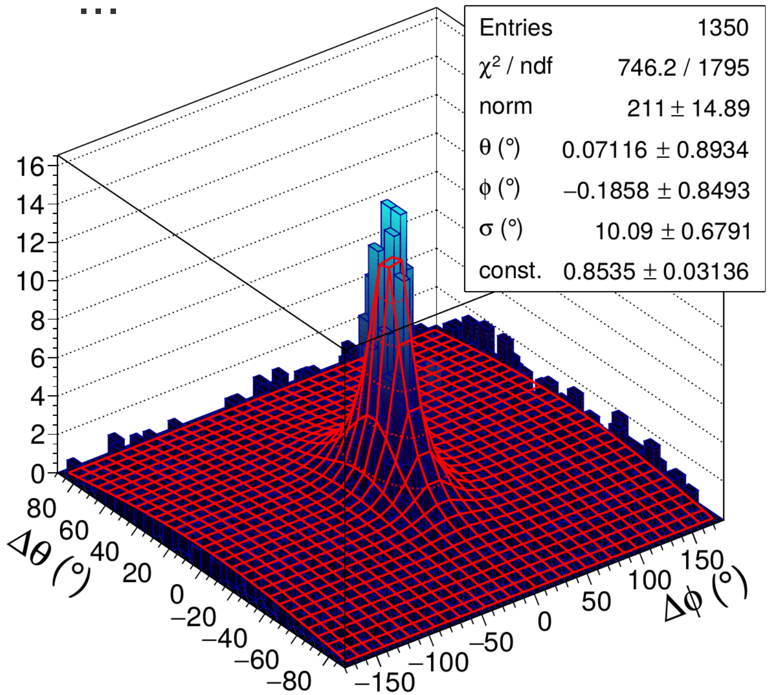

B. Land, et al., arXiv:2007.14999, July 2020

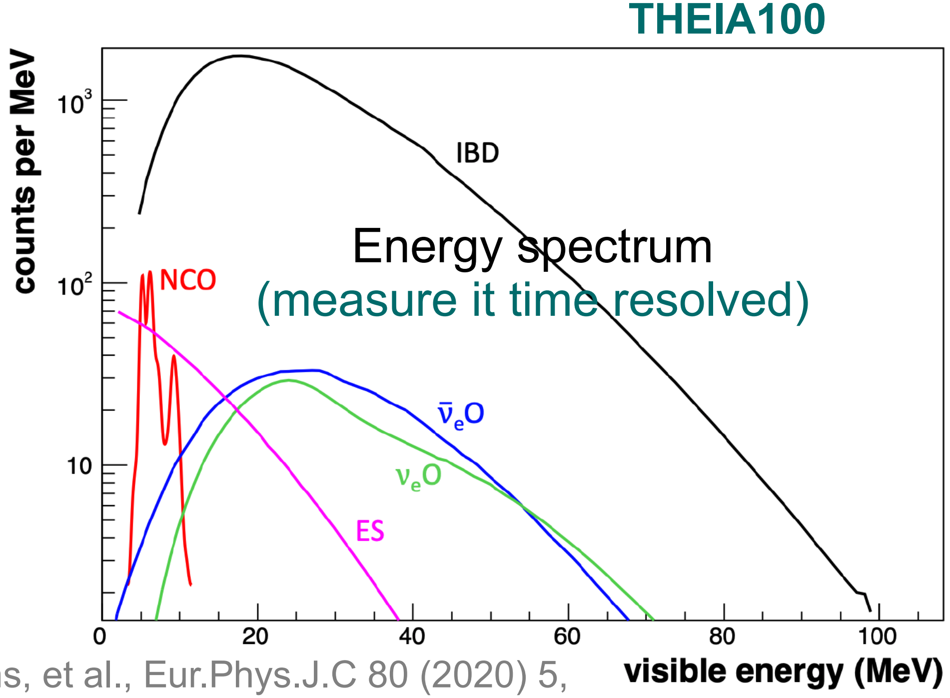
# Supernova Neutrinos in THEIA

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




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

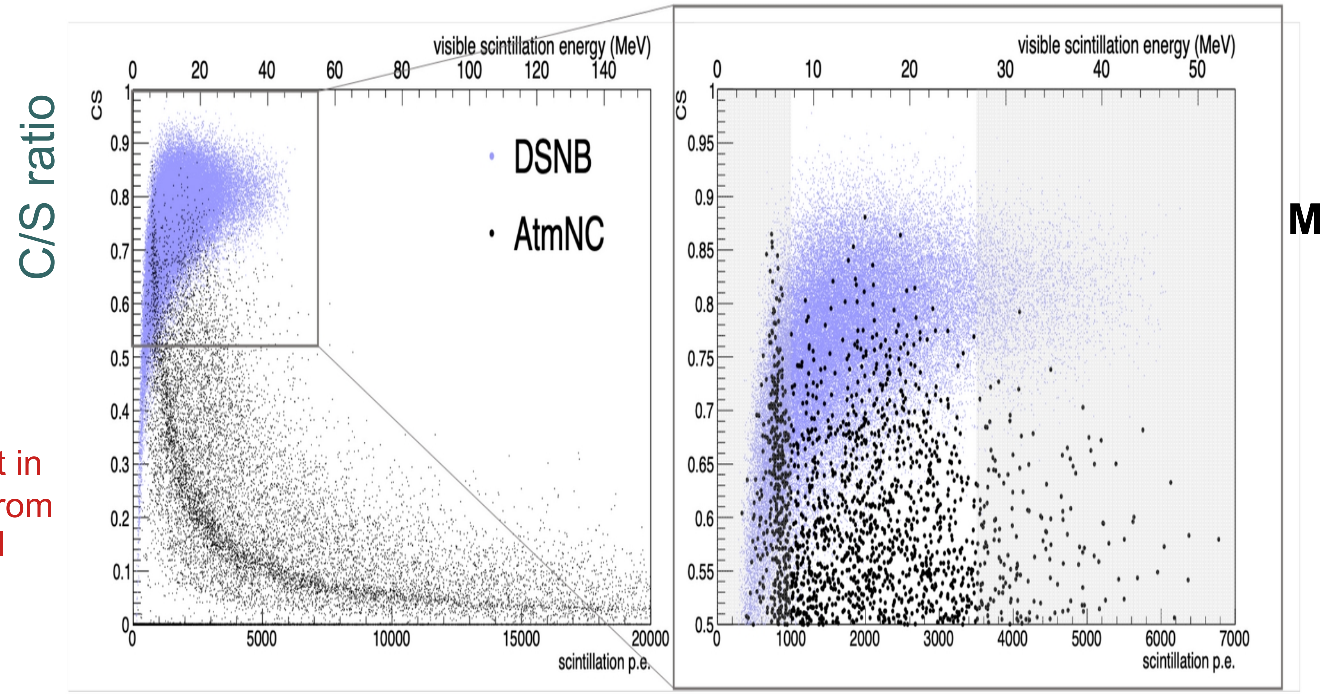
M. Askins, et al., Eur.Phys.J.C 80 (2020) 5, 416, arXiv:1911.03501

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

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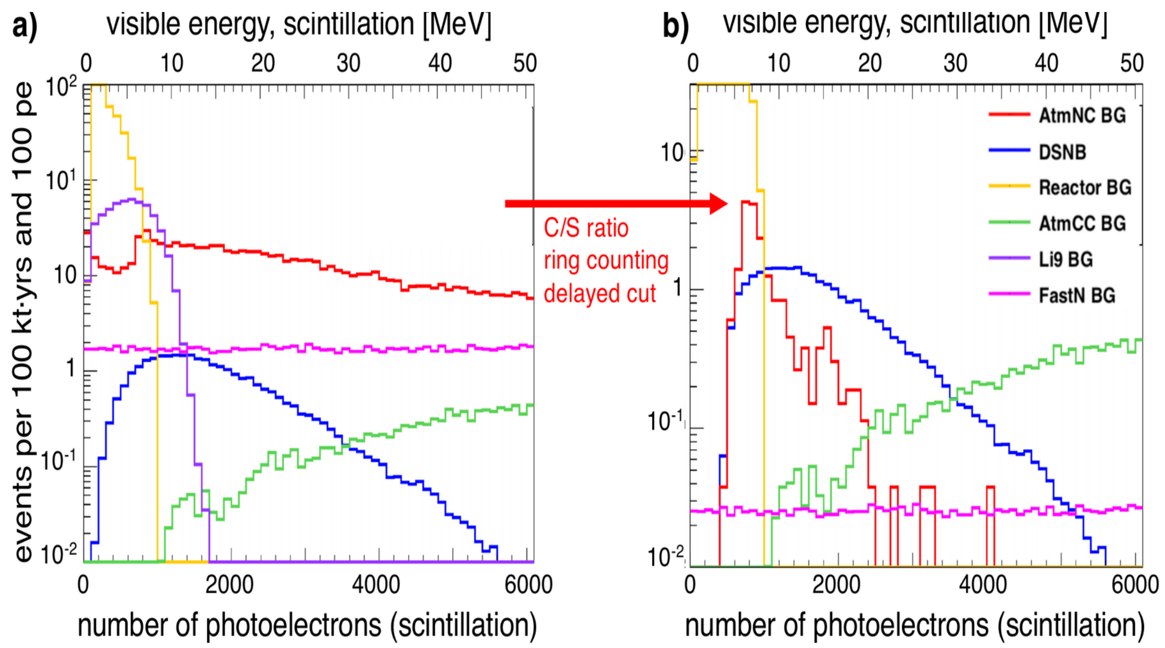
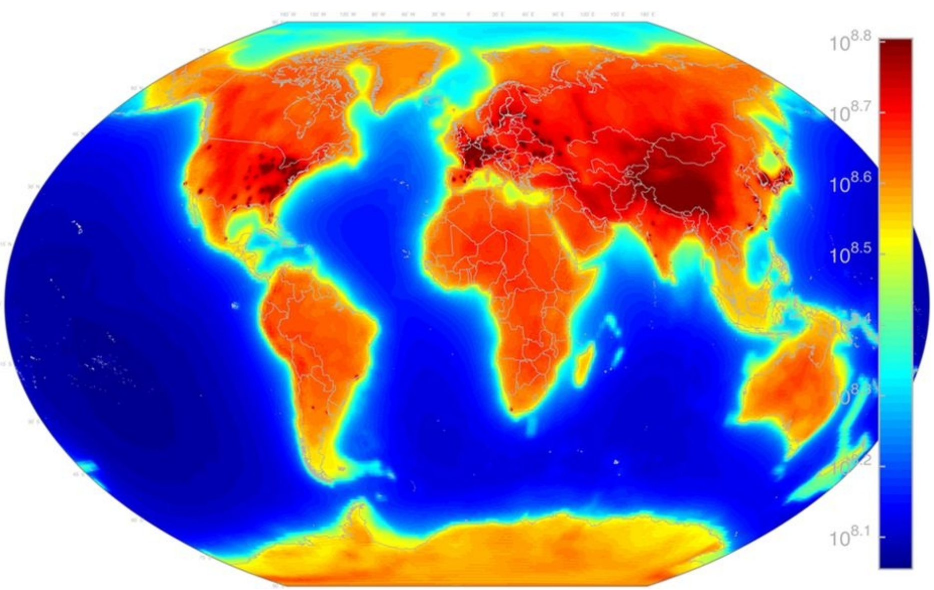
J. Sawatzki, et al., arXiv::2007.14705, July 2020



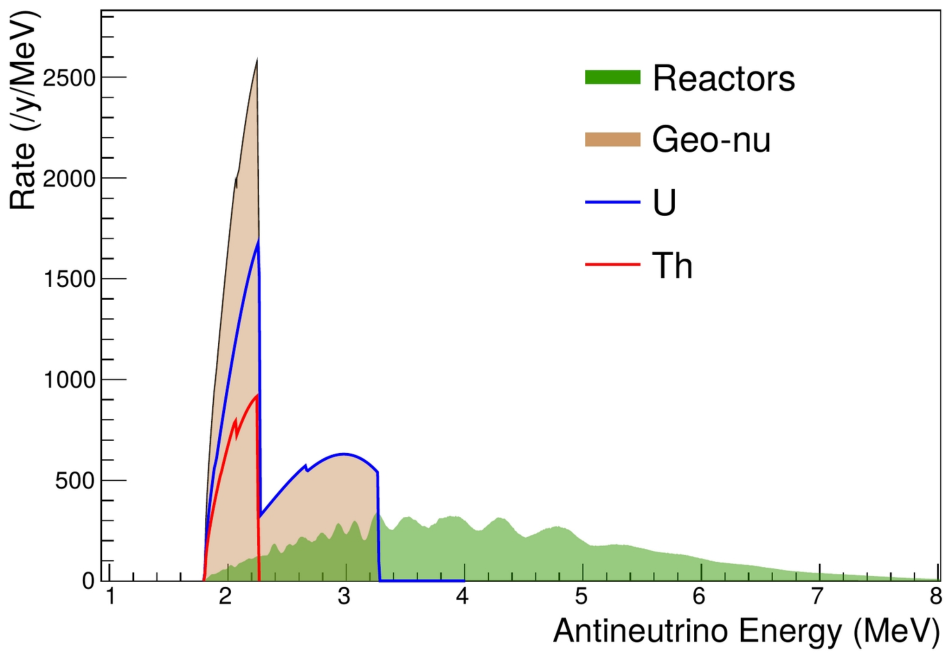

17kt fiducial mass

# 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



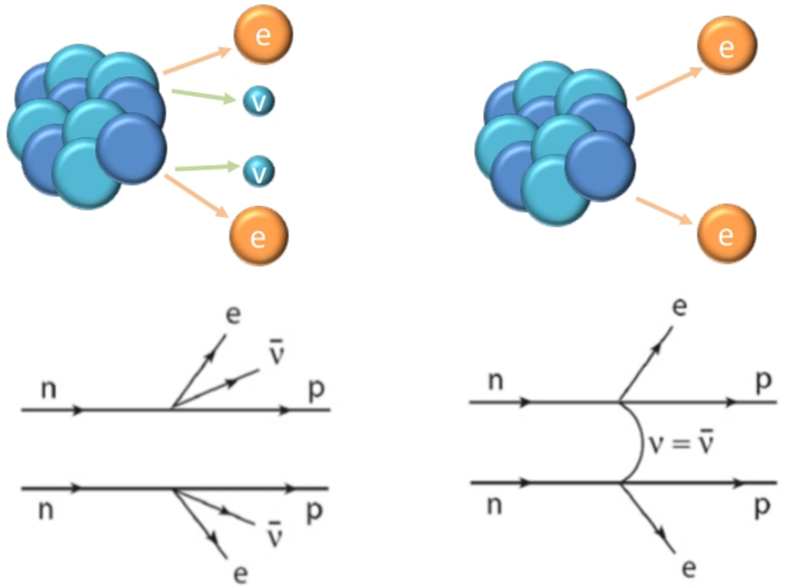

S.M. Usman, et al., Scientific Rep. 5, 13945 (2015)




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

# The Neutrino-less Double Beta Decay ($0\nu\beta\beta$)

- 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

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

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

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

# $0\nu\beta\beta$ 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, $2\nu\beta\beta$, LS contamination and detector materials

After 10 years, THEIA100

**Expected 90% CL Sensitivity**

**5% $^{nat}$Te Loading**

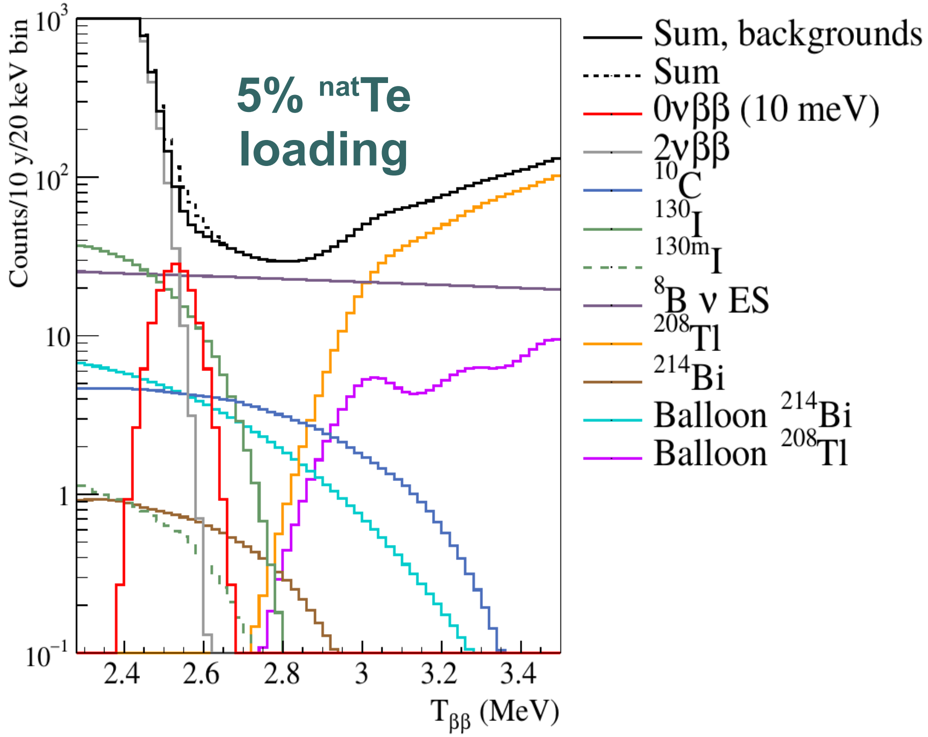
$T_{1/2} > 1.1\times10^{28}$ y, $m_{\beta\beta} < 6.3$ meV

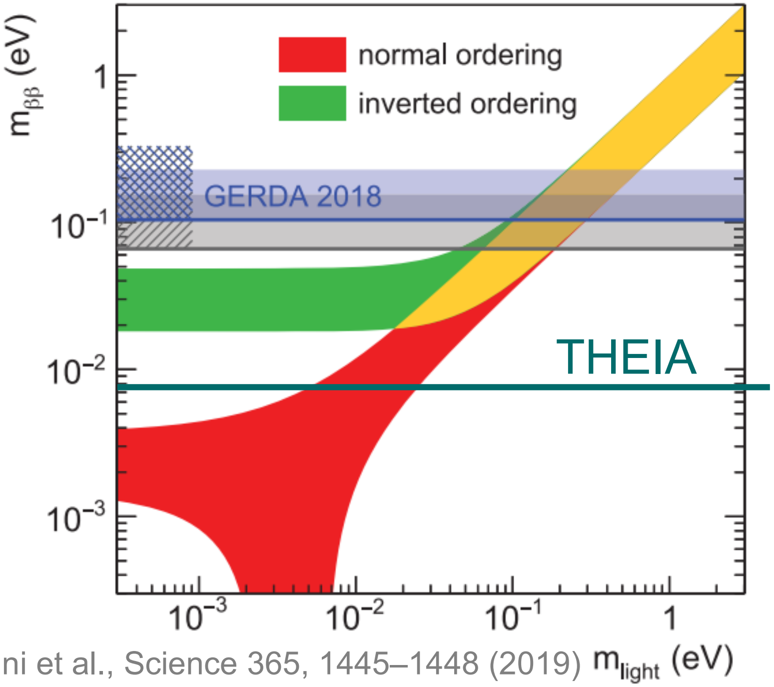
**3% $^{enr}$Xe Loading*** (89.5%)

$T_{1/2} > 2.0\times10^{28}$ 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 $\sigma_T$, 23% QE, 19.6% coverage)

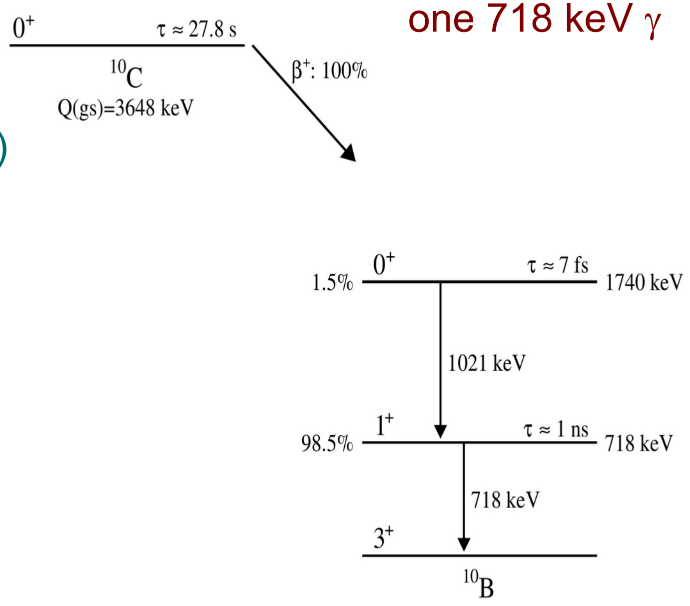
→ 62% bkg reduction at 90% signal efficiency

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 $\gamma$



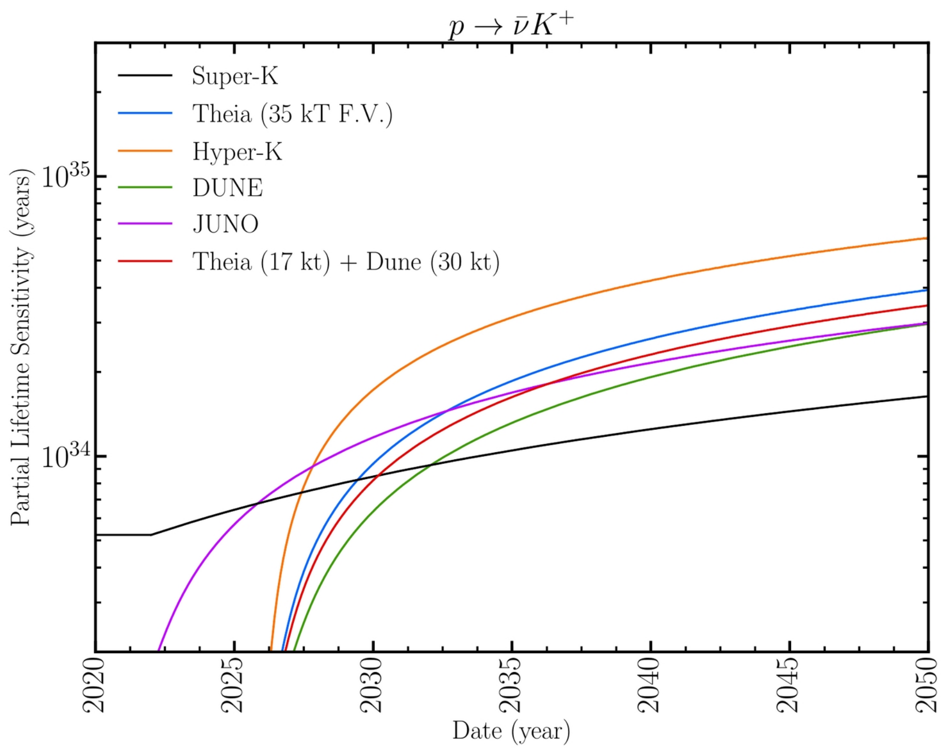

- $^{10}$C is background (bkg) for solar-$\nu$ and $0\nu\beta\beta$
- I see similar potential for $^{130}$I ($0\nu\beta\beta$ bkg)

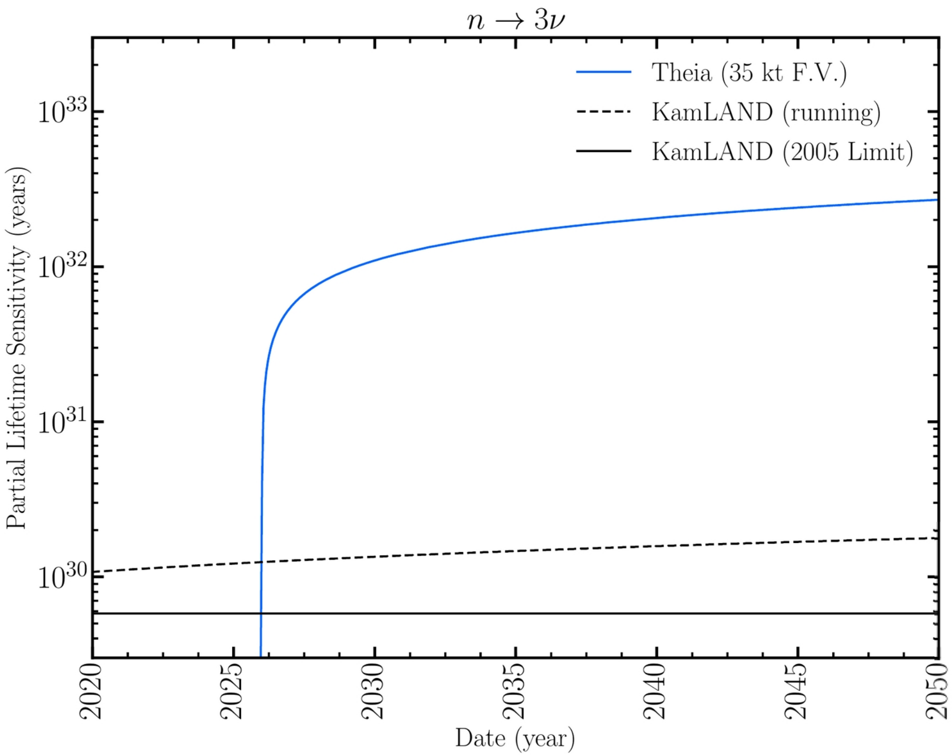
**Has not been included in current study!** (used only three-fold coincidence)

# Nucleon Decay with THEIA

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

n → 3ν → One 6.18 MeV γ from excited nucleus

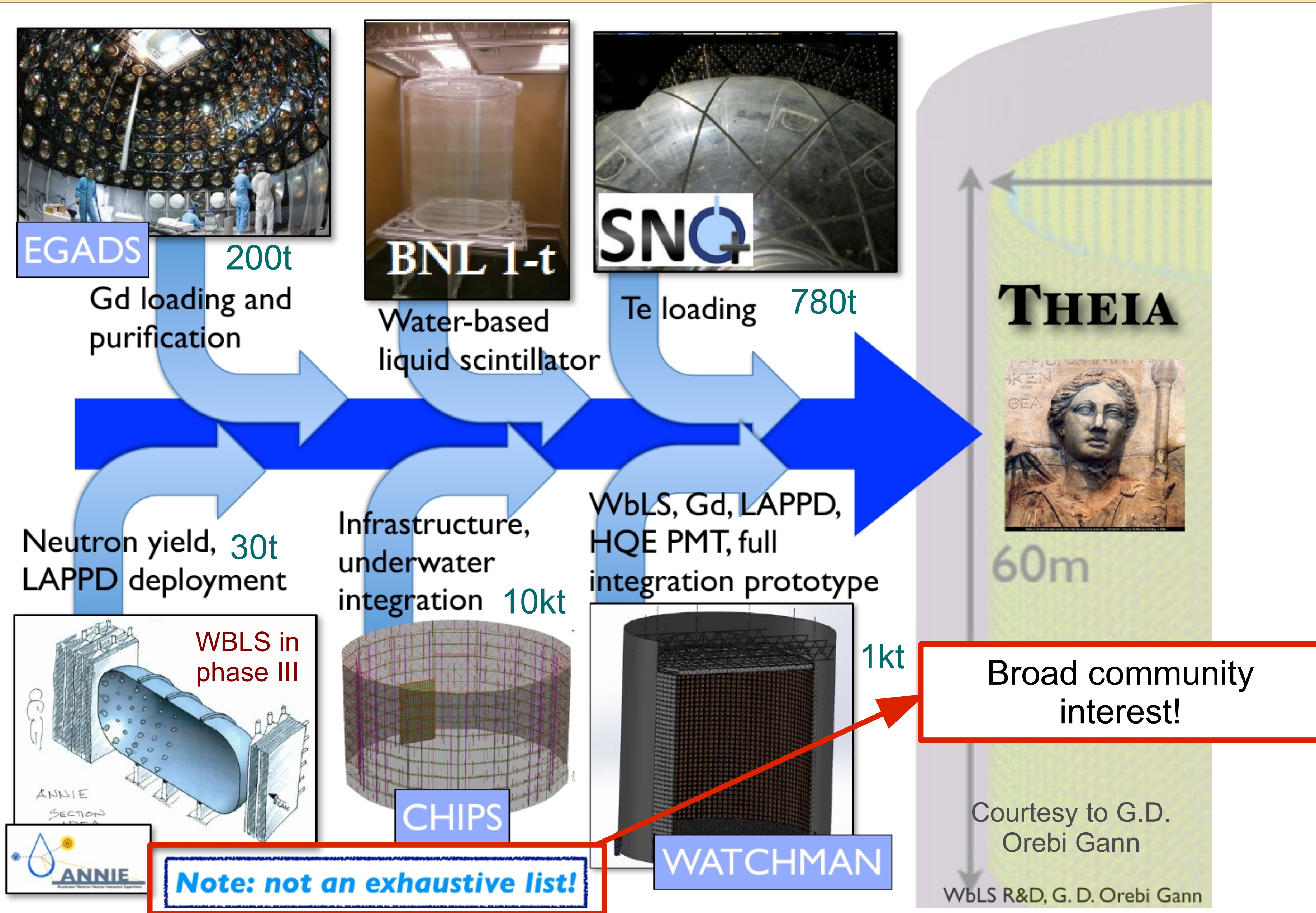



→ **Complementary to competitors** (DUNE & HyperK)

**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

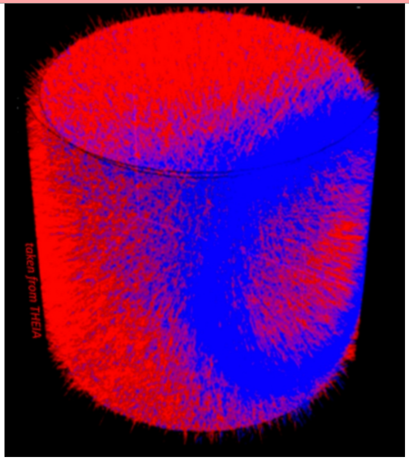
**US**
Brookhaven NL
Boston U.
U. Chicago
Colorado U.
Cornell U.
U. Hawaii
Iowa State
Lawrence
Berkeley NL
LSU
MIT
U. Penn
Stony Brook
SURF
Temple
UC Berkeley
UC Davis

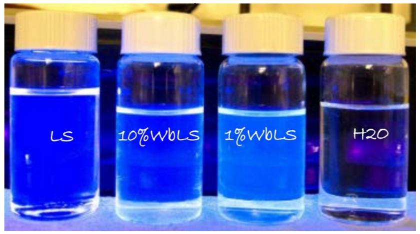
**More collaborators welcome!**

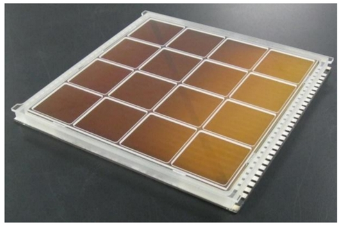
# Summary/Conclusions

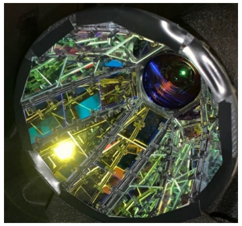
- **THEIA:**
  - Combining advantages of Water-Cherenkov & Liquids Scintillator detectors
  - Using new technologies (WbLS, LAPPDs, Dichroicons, advanced reconstruction, …)

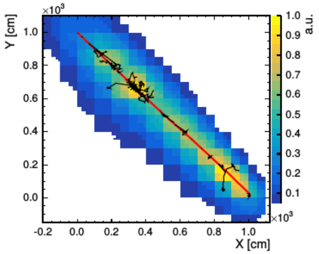
    → **Complementary to existing and upcoming large-scale projects**



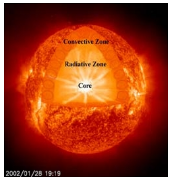


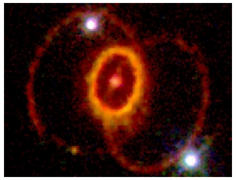



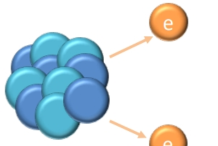


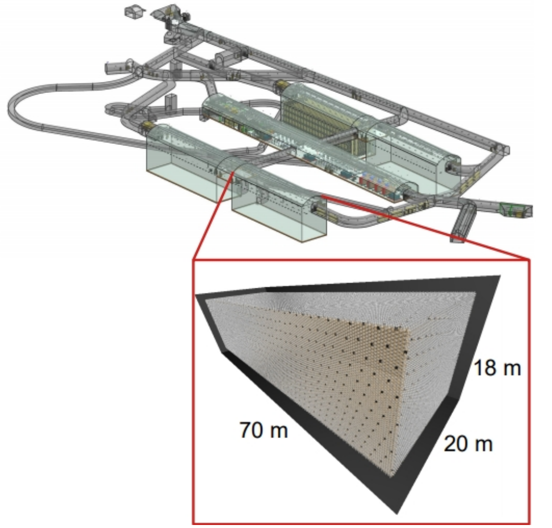



- **Physics case:**
  - Enhanced sensitivity to a broad physics program **(long-baseline physics, solar neutrinos, Supernova neutrinos, DSNB, $0\nu\beta\beta$)**
  - THEIA25 makes an excellent match for the 3 DUNE modules






- **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]

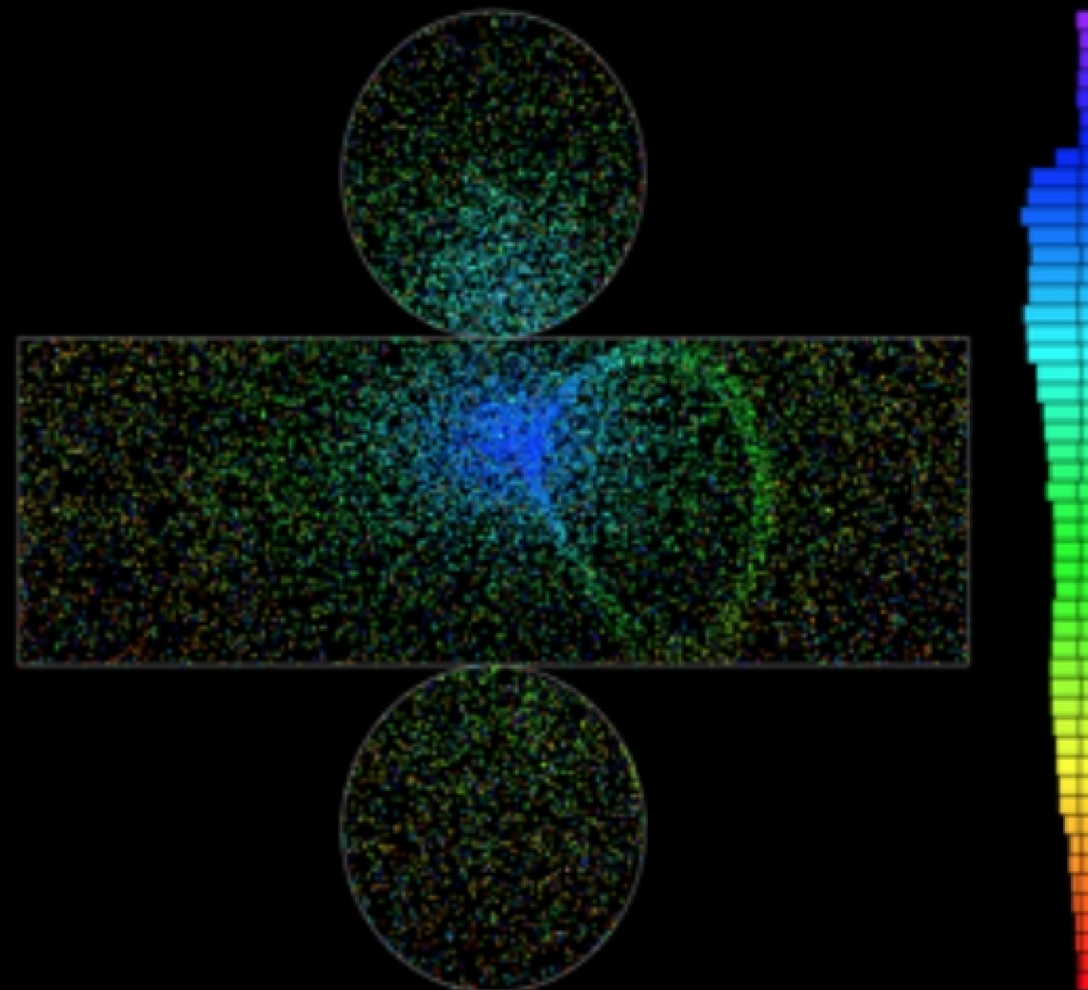
**Water Cherenkov**
- High transparency
  → enhanced light collection
- Directionality from cone reco
- Particle ID from ring counting
- Enhanced metal loading

↓

**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



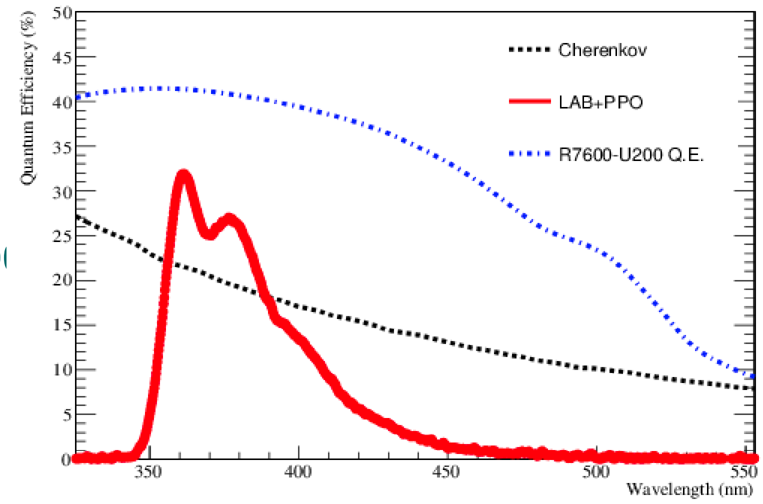
# Cherenkov-Light Separation by Wavelength

- Using dichroic filter

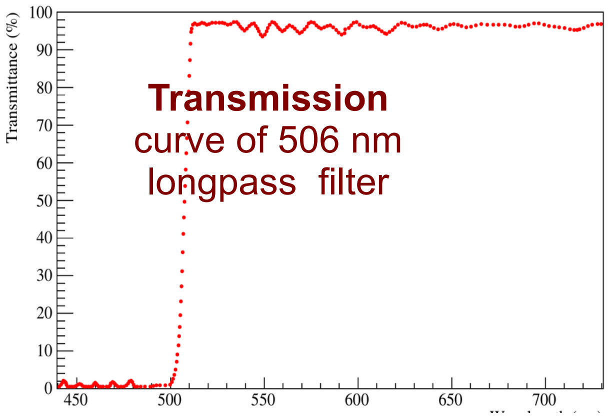
  (transmitting above or below a certain threshold, reflecting the rest)

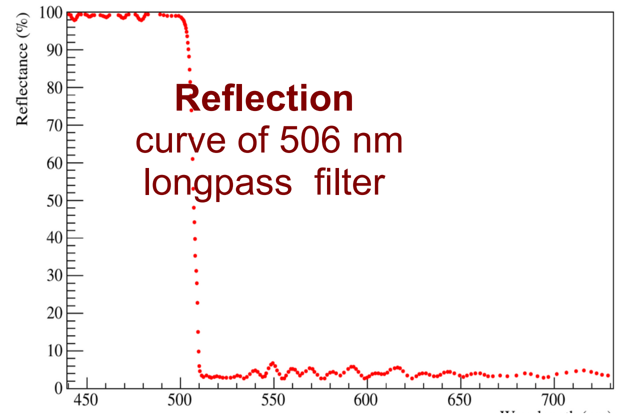
- Optimal Cut for LAB-PPO (2g/l): 450 nm

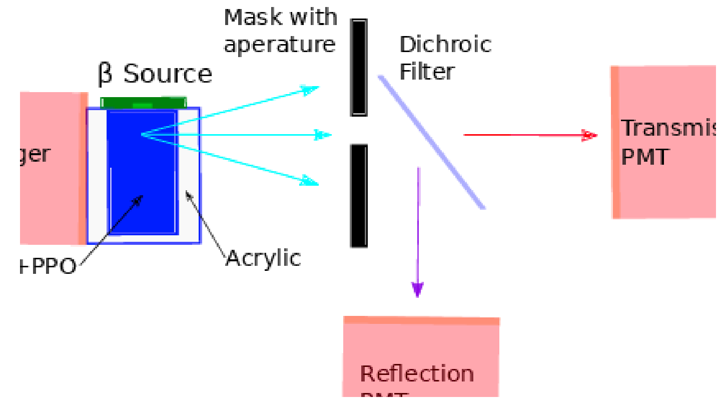
  Full description in T. Kaptanoglu et al., JINST 14 (2019) no.05, T050

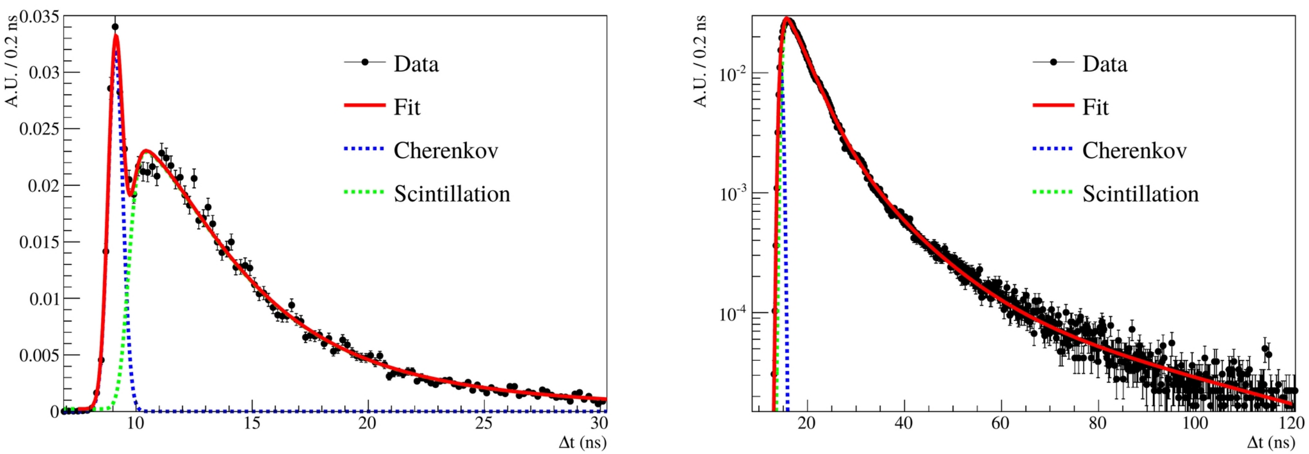



T. Kaptanoglu et al., JINST 14 (2019) no.05, T05001



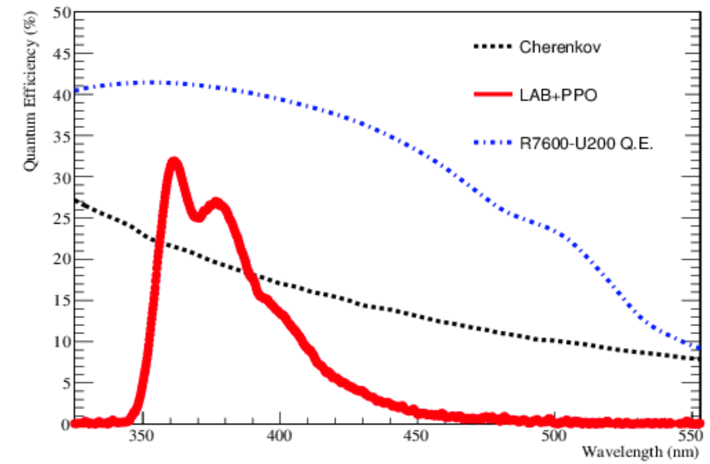

Measured time profile of **transmitted (left)** and **reflected (right)** light from LAB-PPO

# Cherenkov-Light Separation by Wavelength

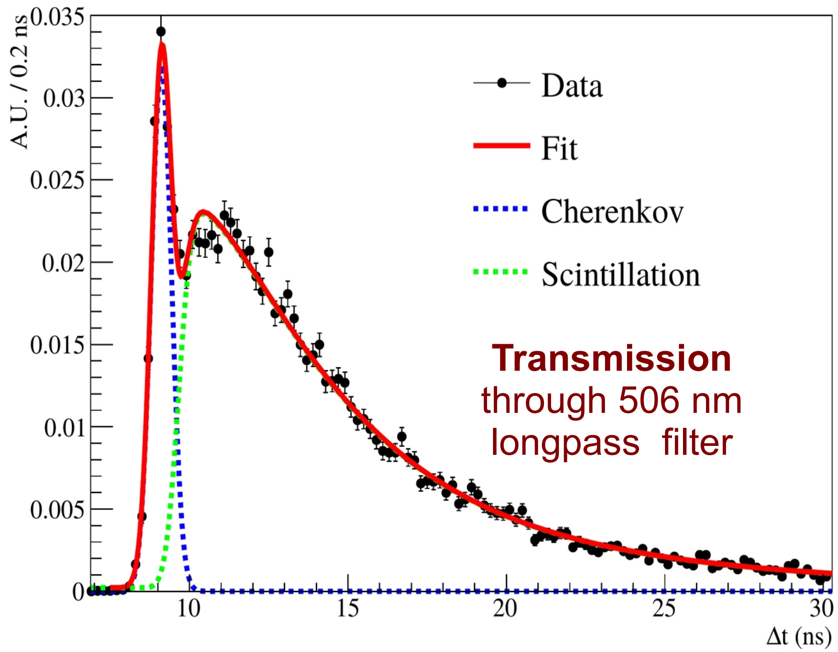
- Using dichroic filter

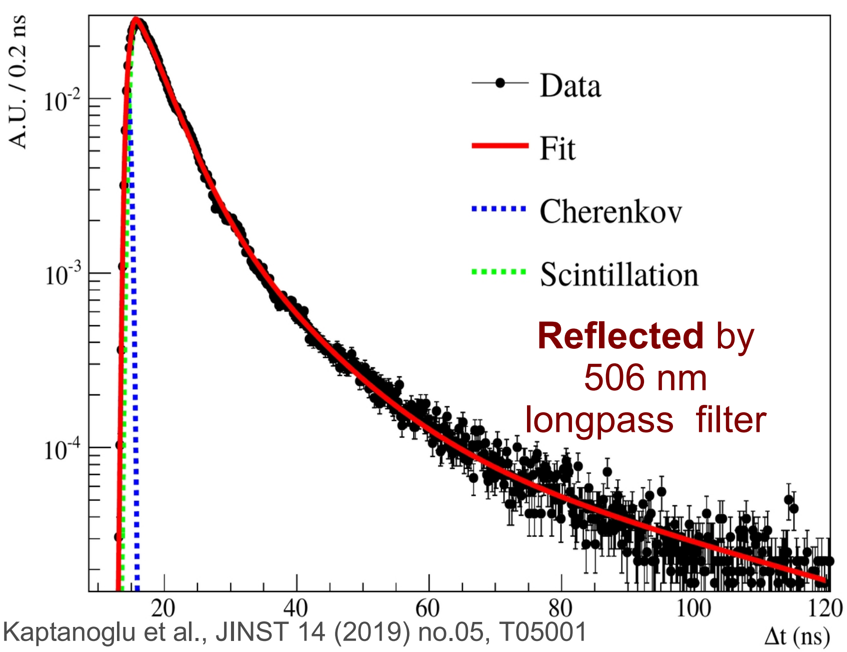
  (transmitting above or below a certain threshold, reflecting the rest)
- Optimal cut for LAB-PPO (2g/l): 450 nm

  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



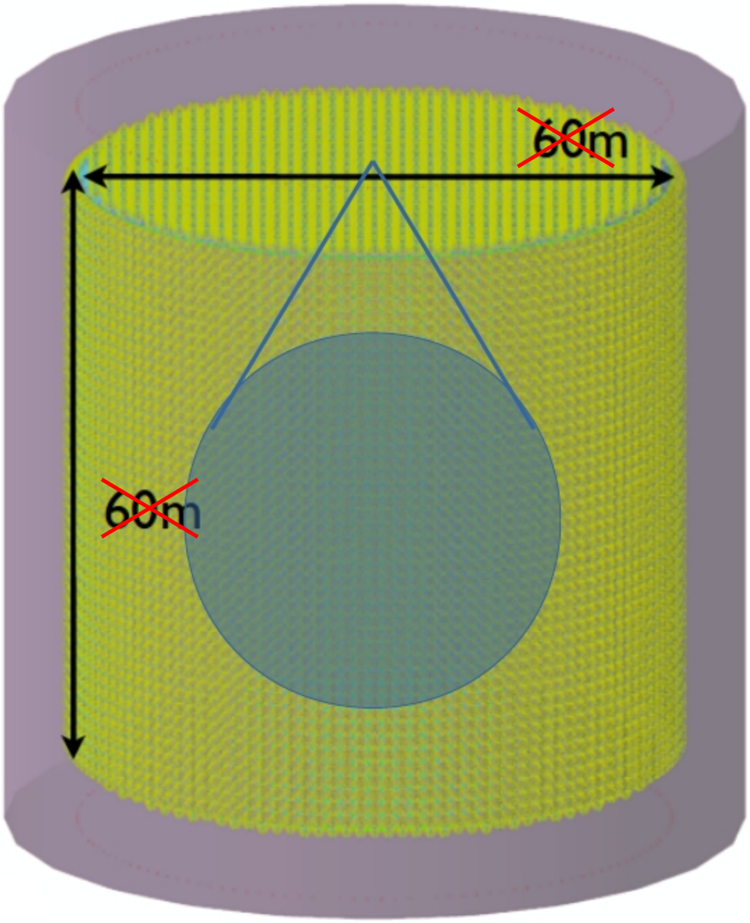




T. Kaptanoglu et al., JINST 14 (2019) no.05, T05001

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 $0\nu\beta\beta$

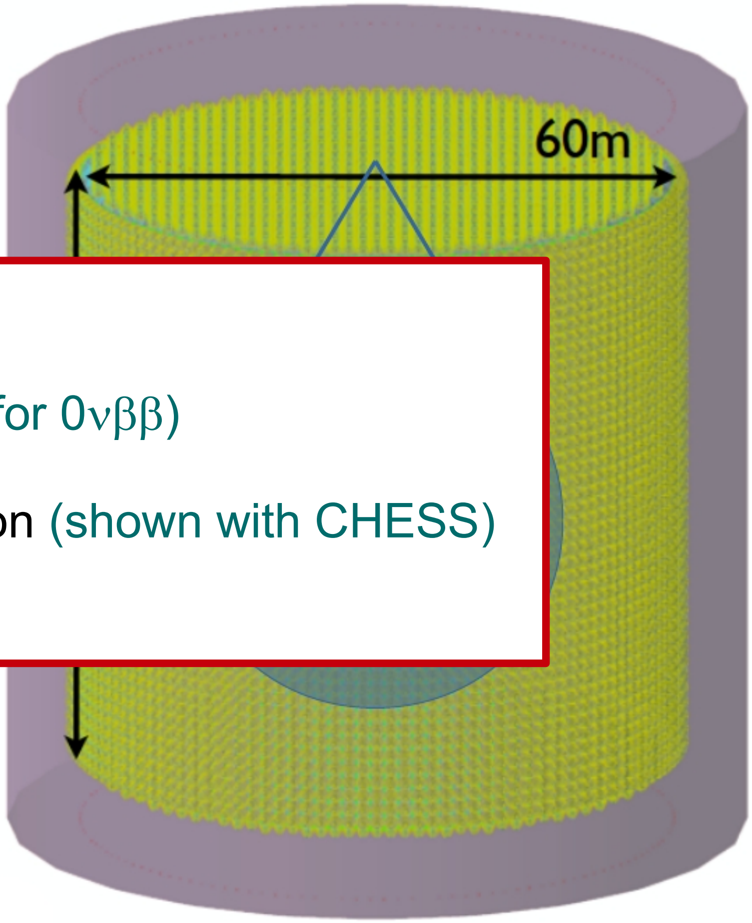
- **Assumption used for sensitivity study**
  - Detector mass 50 ktons
    (20 m fiducial radius, 40 m high)
  - Balloon with 8m radius (7m fiducial radius)
    - Filled with LAB + PPO (2g/l)

**Reason for LAB-PPO:**

High light yield → good energy resolution (crucial for $0\nu\beta\beta$)

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

  - 90% PMT coverage
    → ~1200 $\gamma$/MeV → $\Delta E$ ~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)

**ROI: -σ/2 → 2σ**

| 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]) | | $1.2\times10^{8}$ | 8.0 | - |
| $2\nu\beta\beta$ ($^{enr}$Xe target, $T_{1/2}$ from [46, 47]) | | $7.1\times10^{7}$ | - | 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: $< 1.1 \times 10^{-12}$ $g_U/g$ | $1.2\times10^{5}$ | 2.4 | 2.7 |
| | $^{208}$Tl: $< 1.6 \times 10^{-12}$ $g_{Th}/g$ | $2.1\times10^{4}$ | 0.03 | 0.01 |

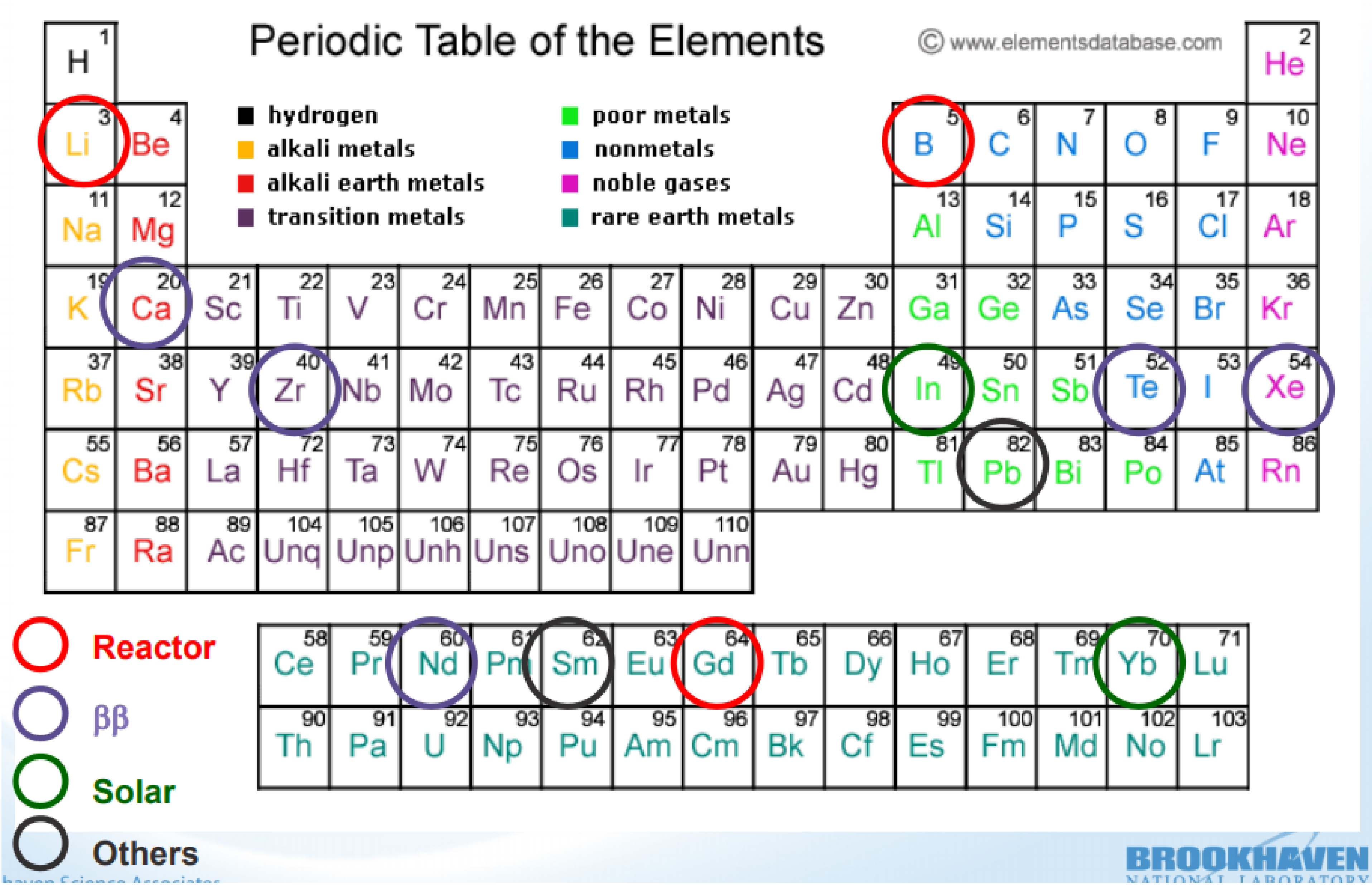
**Total bkg-index :** in evts/(t ·y)

1.1 (Te) 0.5 (Xe)

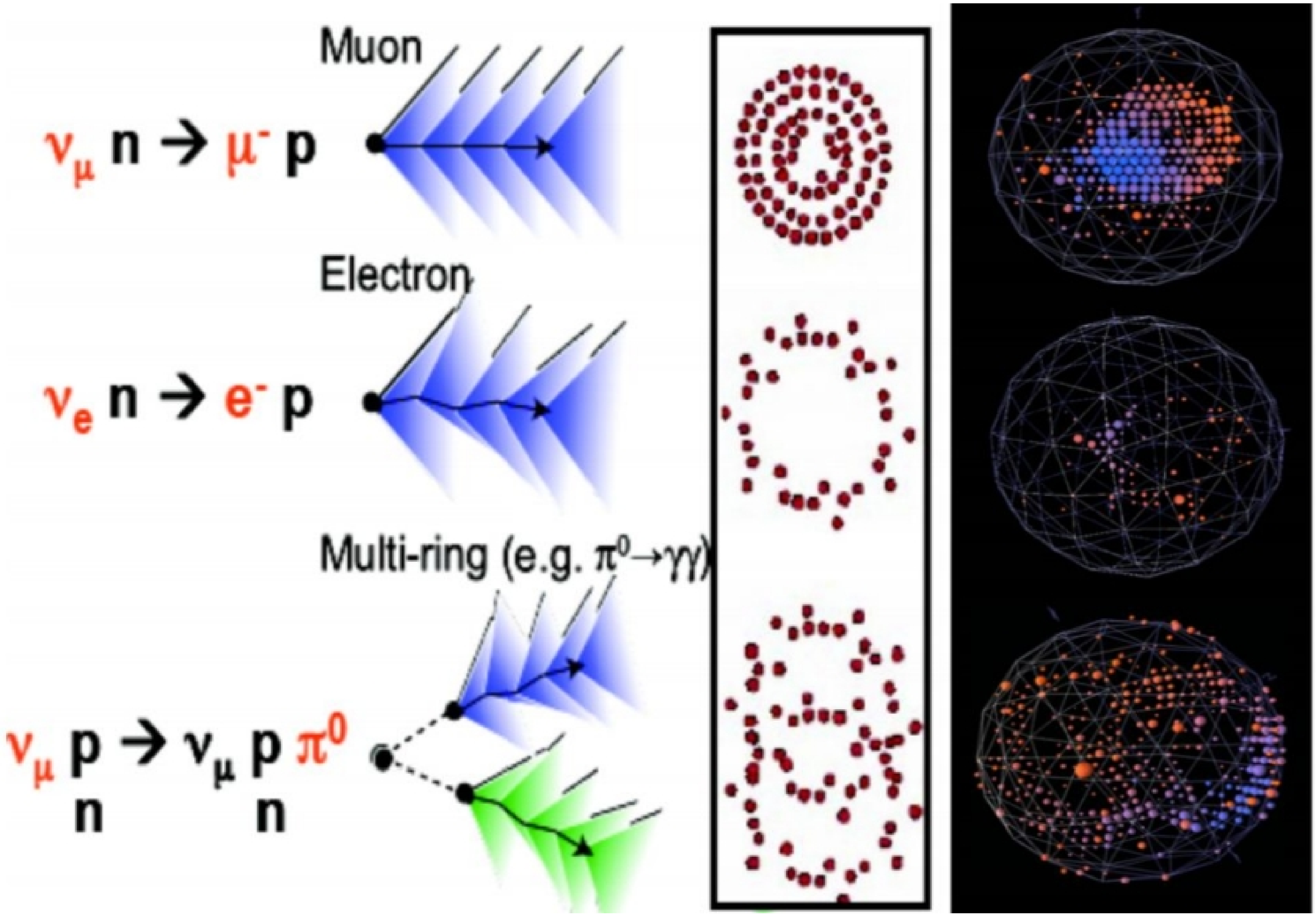
(per ton of Te-130/Xe-136 in full volume)

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

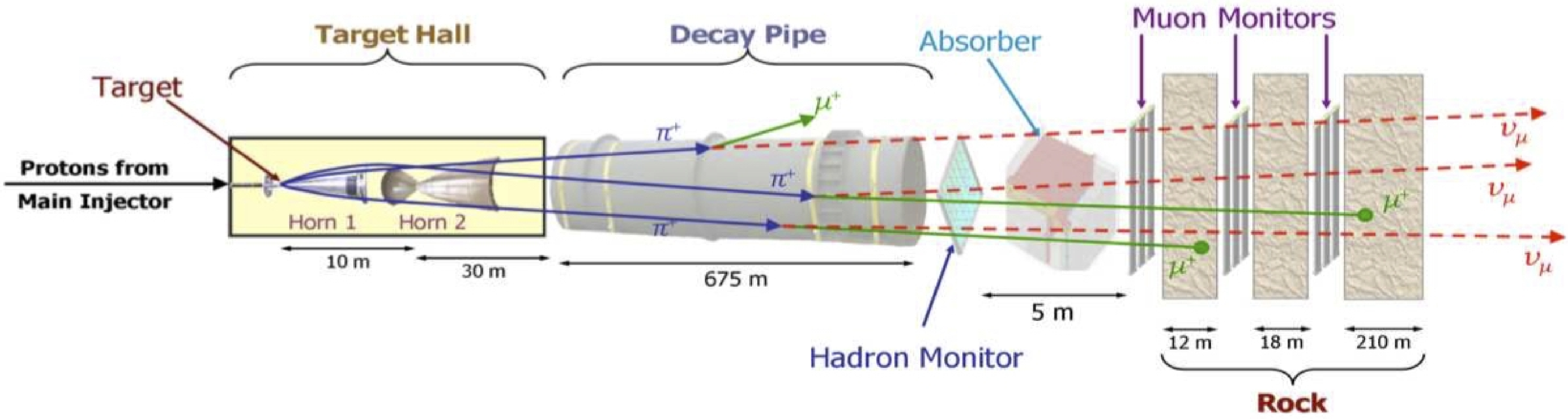
# Isotope Loading of Liquid Scintllator



# Particle ID with Ring-Imaging



# Neutrino Beam Picture



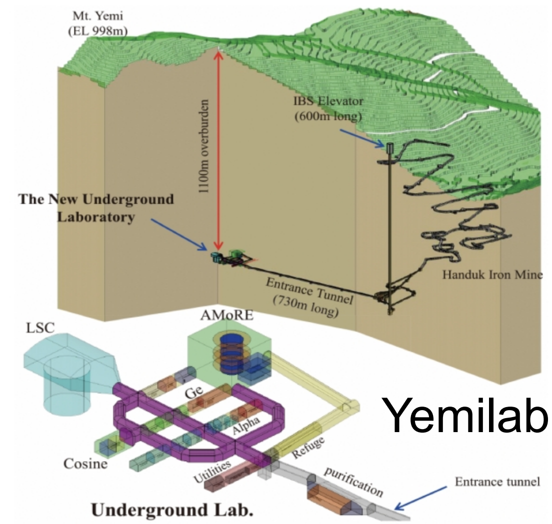
# Neutrino Teleskope at Yemilab (Korea)

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

**Yemilab: Under construction**

New underground lab in Korea

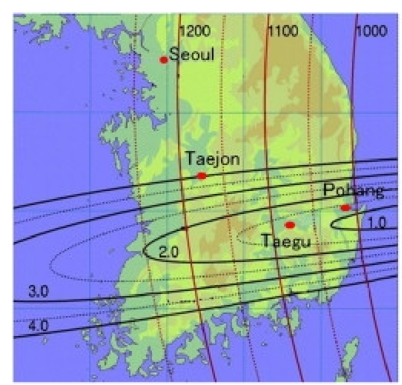
Will have space for a 50 kton WbLS detector


**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

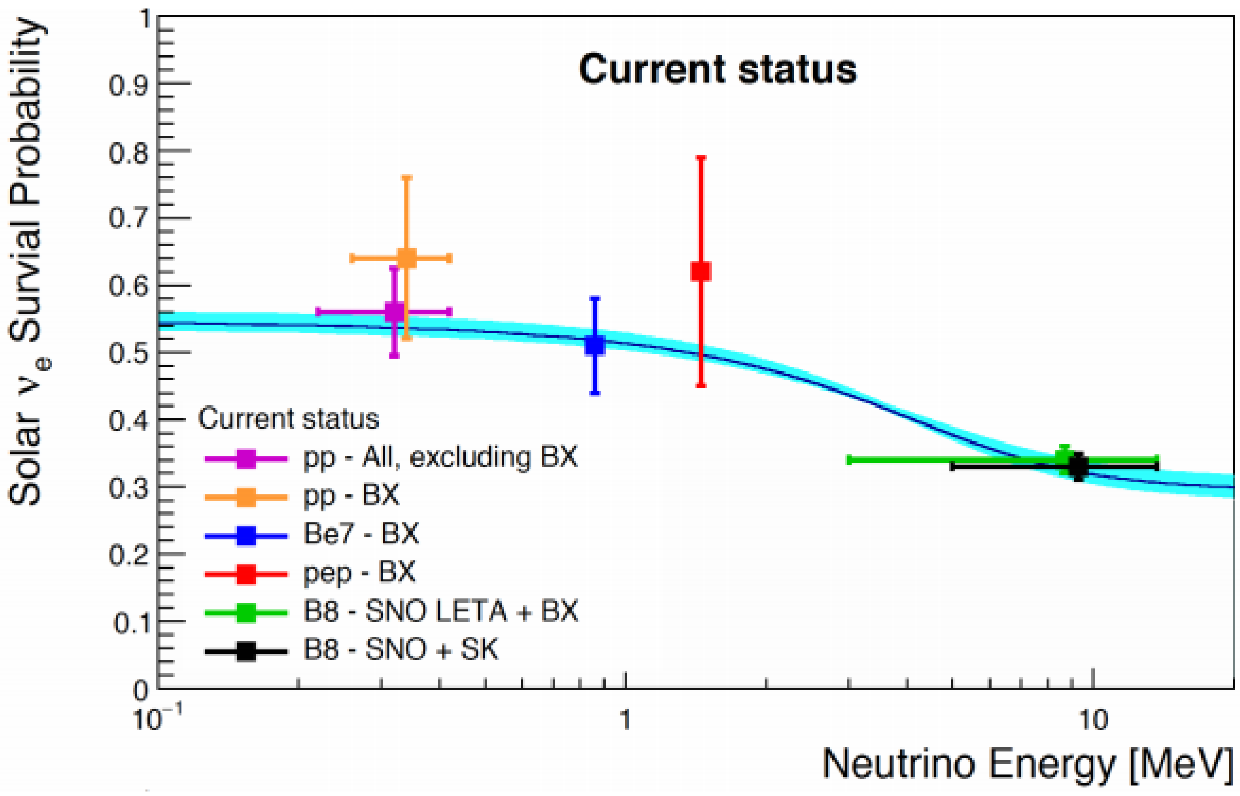
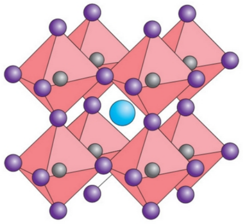
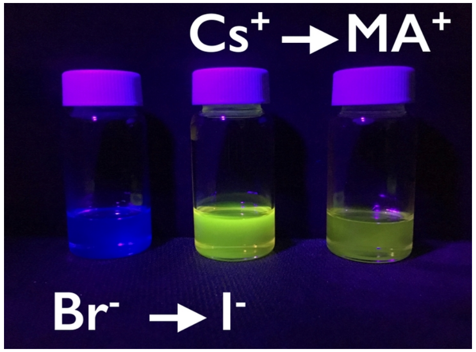



FIG. 6: Solar neutrino survival probability vs. neutrino energy in MeV. Squares with error bars represent solar neutrino fluxes from current measurements by Borexino, SNO and SK. A cyan band represents expected solar neutrino survival probability from standard solar neutrino model with MSW effect. With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

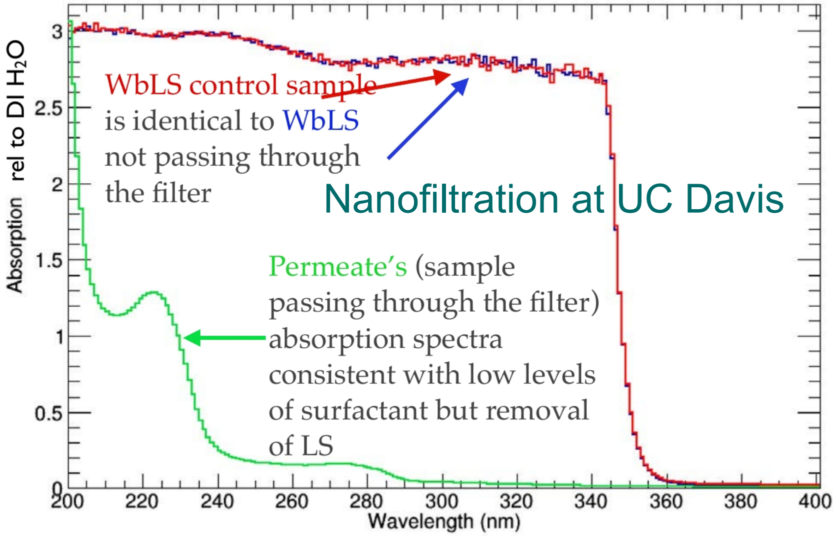
# Improving Liquid Properties

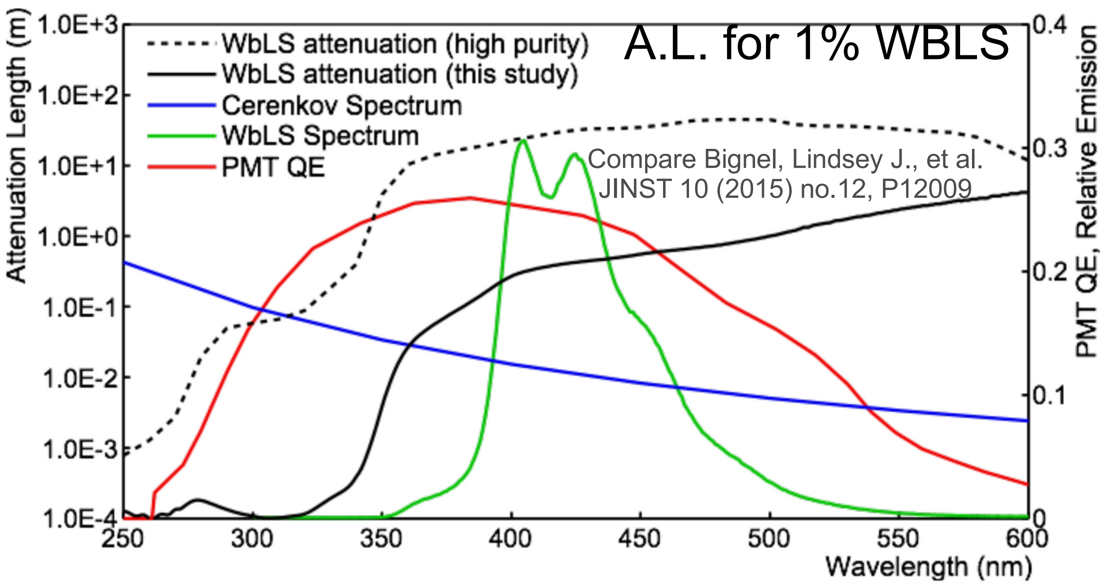
- **Development of scintillating liquids**
  - WBLS (Brookhaven NL, JGU Mainz, TU Munich)
  - Isotope loading (BNL, MIT) (Li,B,Ca,Zr,In,Te,Xe,Pb,Nd,Sm,Ge,Yb)
  - Oil-diluted LS (JGU Mainz)
- **Characterization** (Brookhaven NL, JGU Mainz, TU Munich, ...)
  - Optical properties (Emission, attenuation, ..)
  - 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)





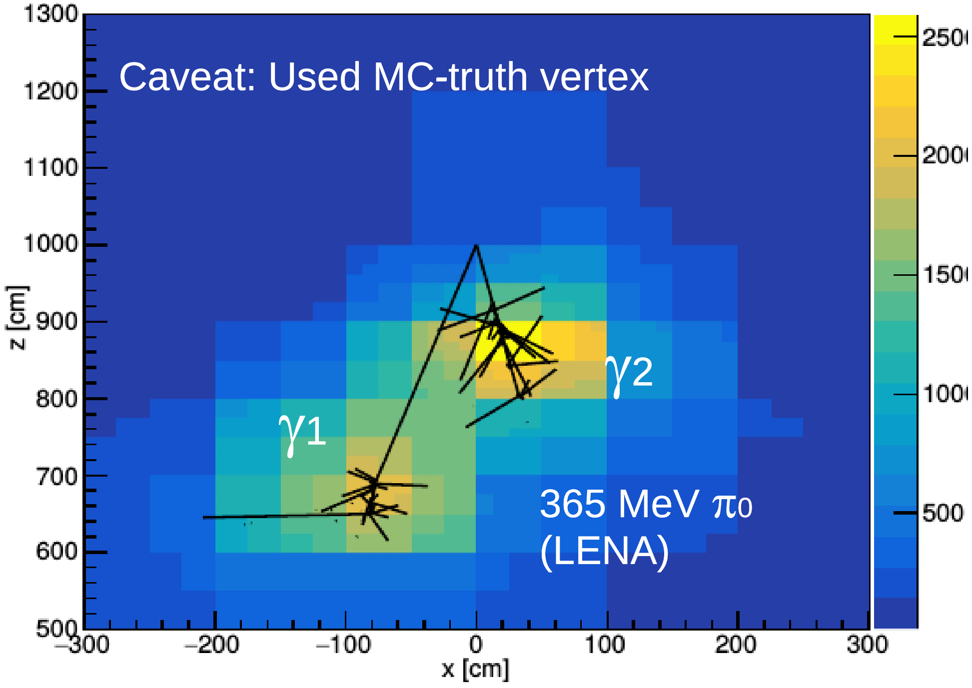

Nanocrystal-Doped Liquid Scintillator arXiv:1908.03564



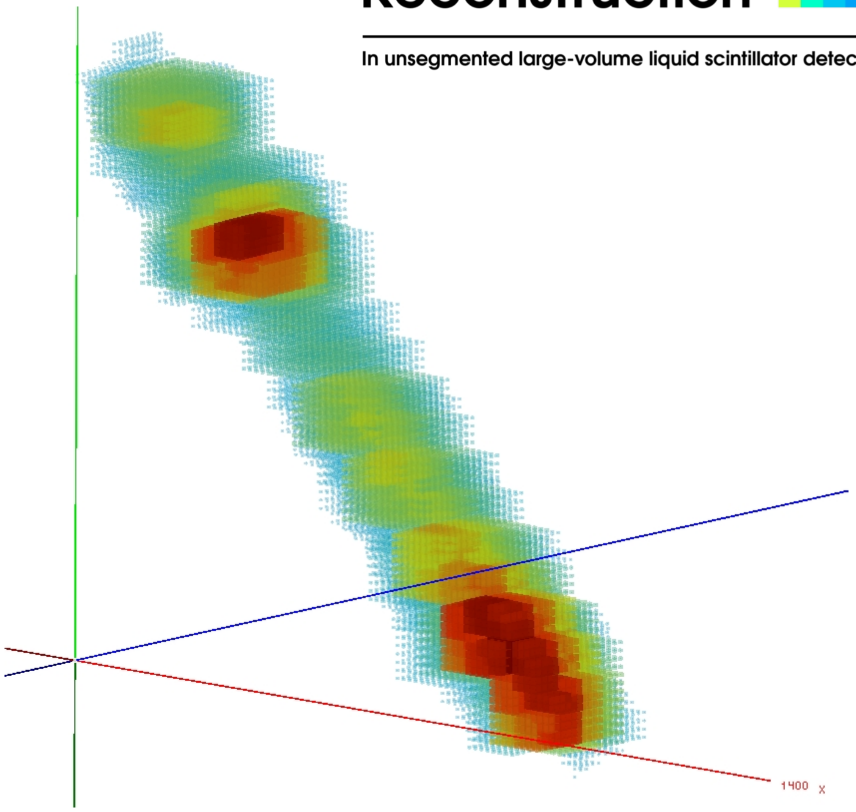
# Goals at GeV Energies

- **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

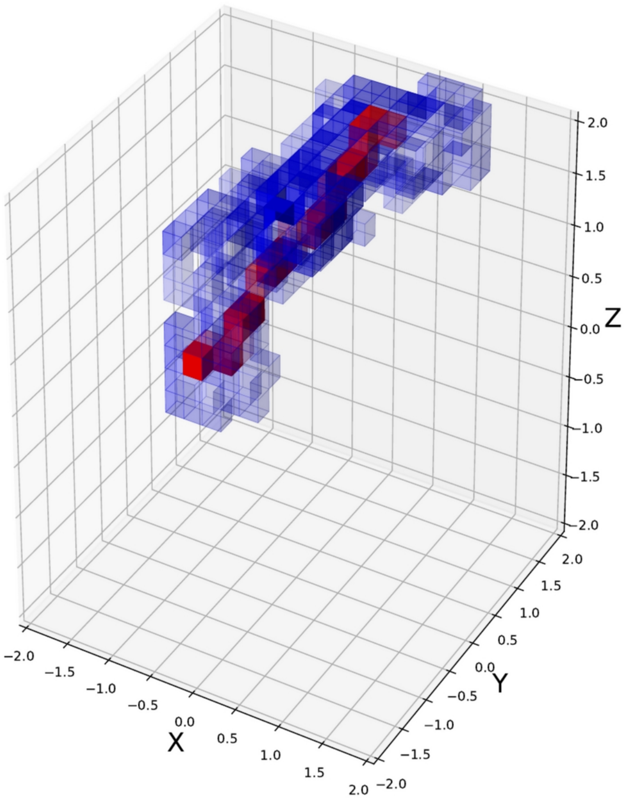
In unsegmented large-volume liquid scintillator detectors



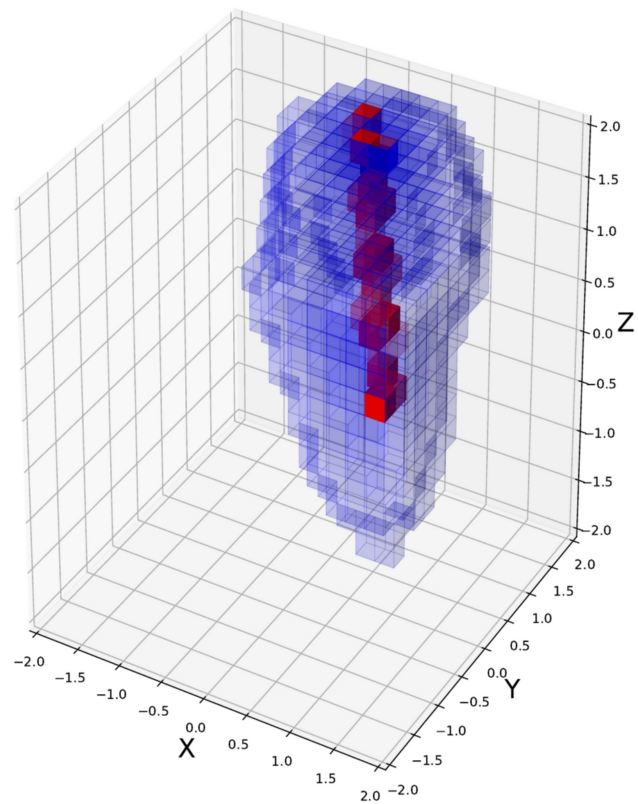
# Outlook: First Results Voxel Reconstruction

**Red:** MC Truth
**Blue:** Network output

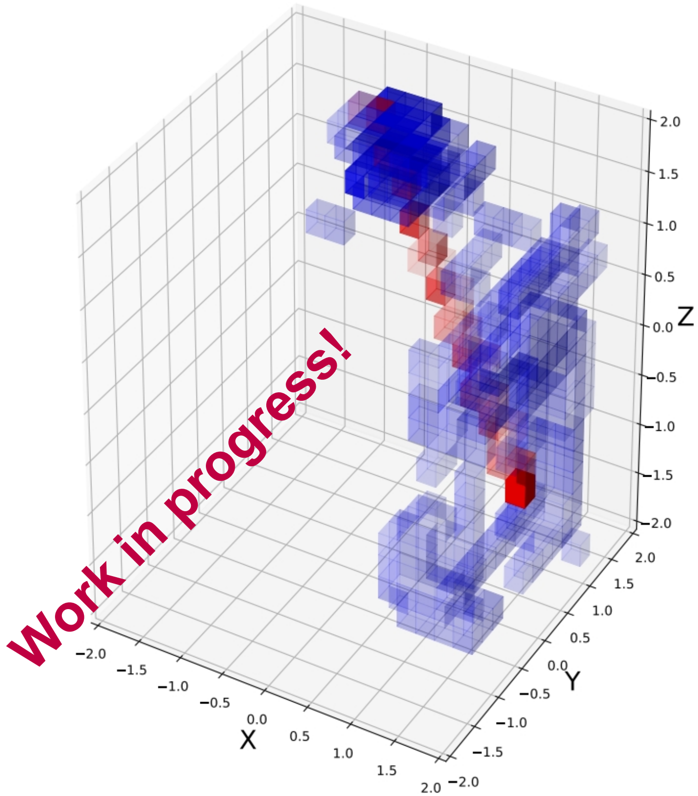
Using L1-regularization in loss function




Result of homogeneous network




Result after propagation layers




Result heterogeneous network (after training)

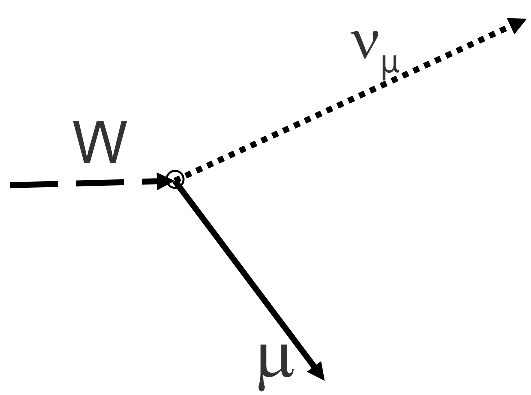
# Neutrino Oscillations (Simplified)

**Flavour eigenstates**
$\nu_\mu$, $\nu_\tau$ **with** $\theta_{23}$

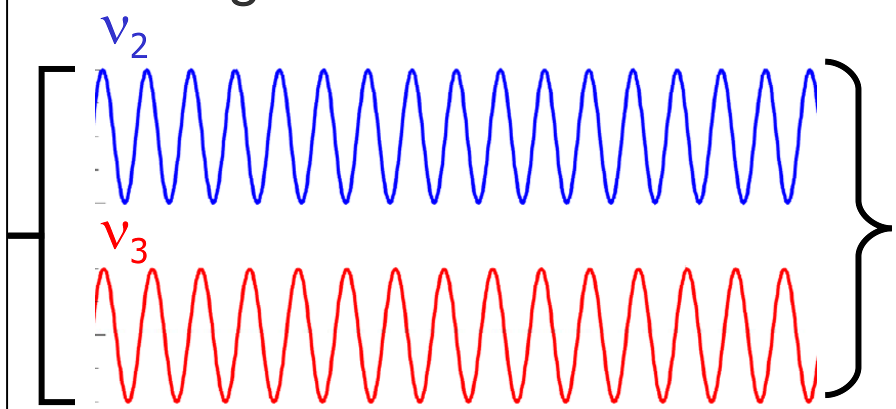
$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{23} & s_{23} \\ -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

**Mass eigenstates**
$\nu_2$, $\nu_3$ **with** $m_2$, $m_3$

Source creates flavour eigenstates



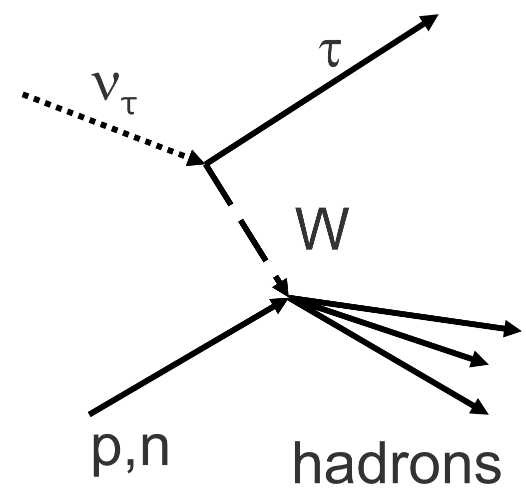

Propagation determined by mass eigenstates




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

Slightly different frequencies
→ phase difference changes

Detector sees flavour eigenstates




Which flavour we measure depends on phase difference!

# Neutrino Oscillations (Simplified)

**Flavour eigenstates** $\nu_\mu$, $\nu_\tau$ **with** $\theta_{23}$

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**Mass eigenstates** $\nu_2$, $\nu_3$ **with** $m_2$, $m_3$

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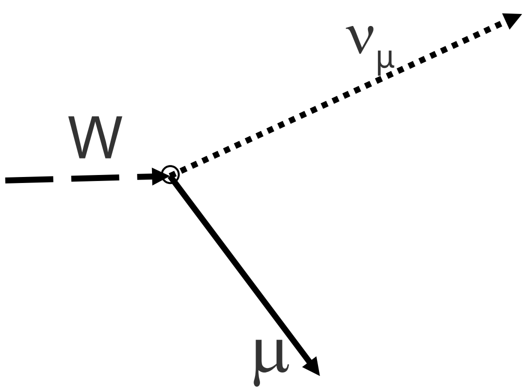
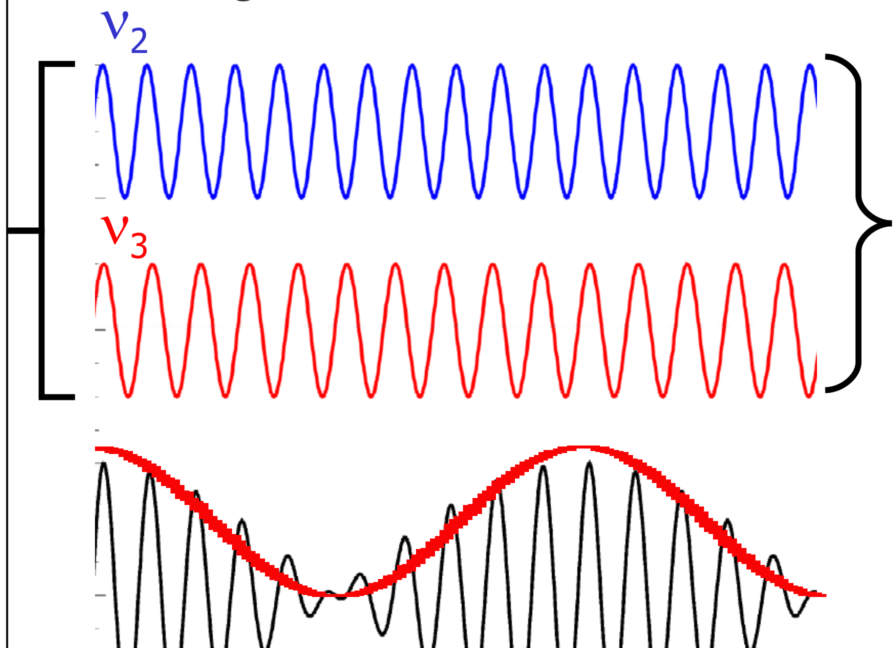
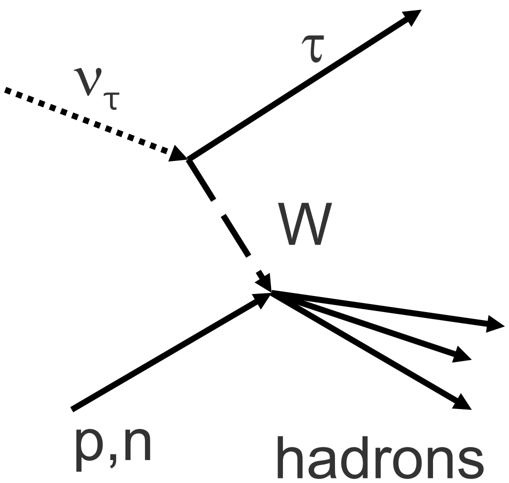



Propagation determined by mass eigenstates




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:

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

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

**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 $\alpha_1, \alpha_2$

Not visible in Oscillations

# Mass Ordering

**Two mass-differences:**

$\Delta m^2_{solar} = \Delta m^2_{21} \approx 7.5\cdot10^{-5}eV^2$,

$|\Delta m^2_{atm}| = |\Delta m^2_{32}| \approx 2.5\cdot10^{-3}eV^2$

**One sign unknown**

**→ Two mass orderings possible**

“Normal” hierarchy

“Inverted” hierarchy