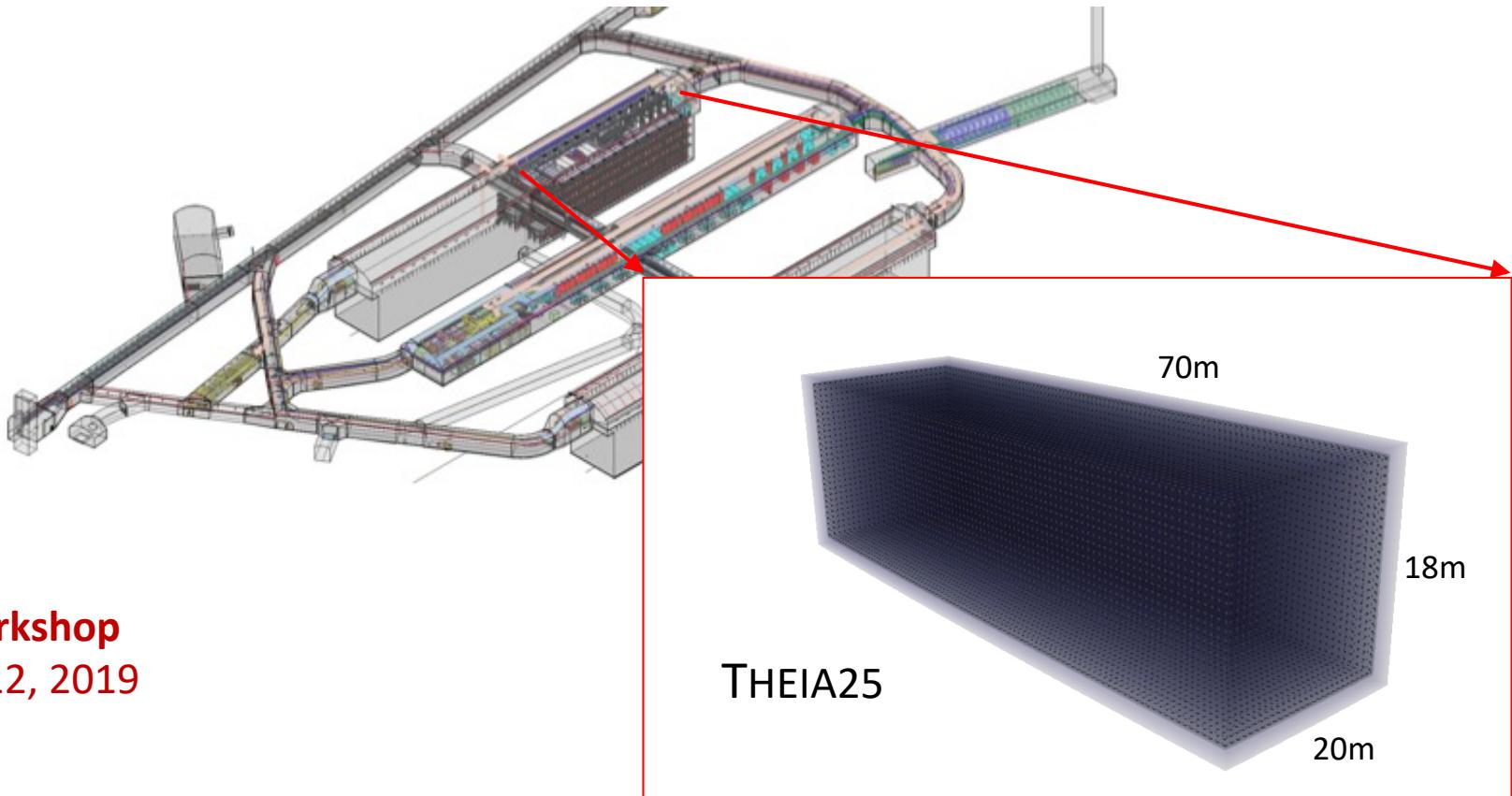


Introduction to THEIA and low-energy neutrino program



MooD Workshop
BNL, Nov 12, 2019

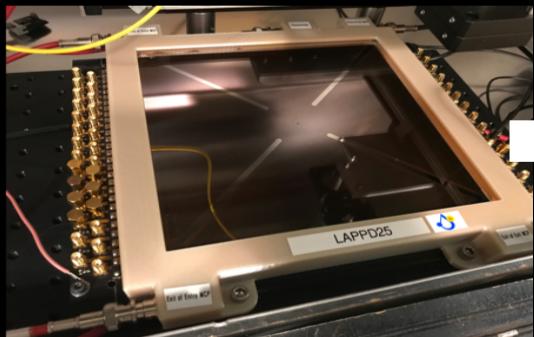
Michael Wurm (JGU Mainz)
for the THEIA proto-collaboration

What is THEIA?

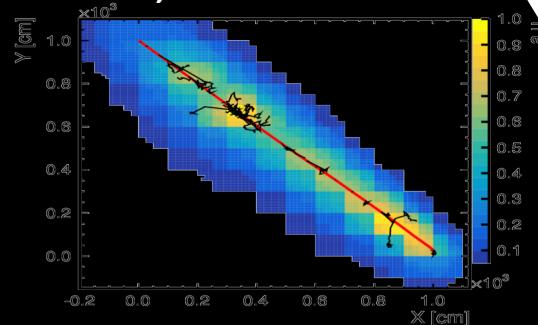
JG|U



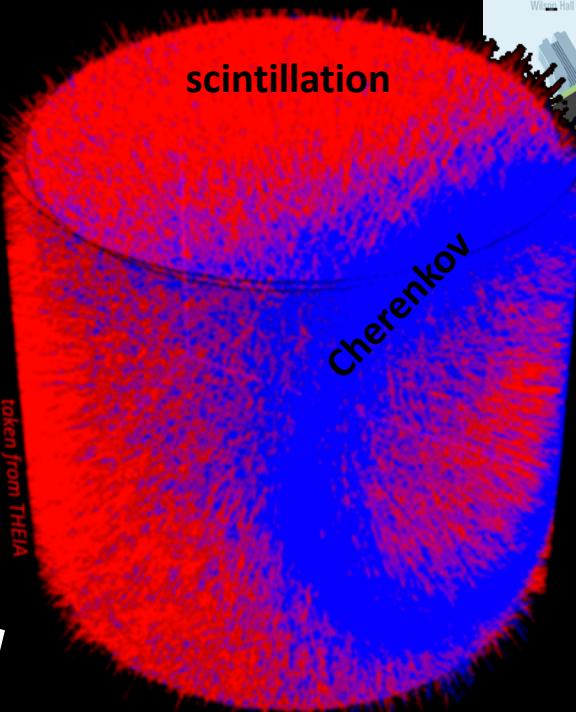
Novel target medium:
Water-based Liquid Scintillator



Novel light sensors:
LAPPDs, dichroicons

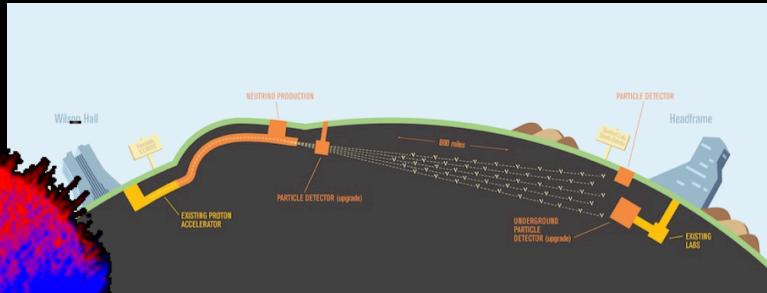


Novel reconstruction techniques

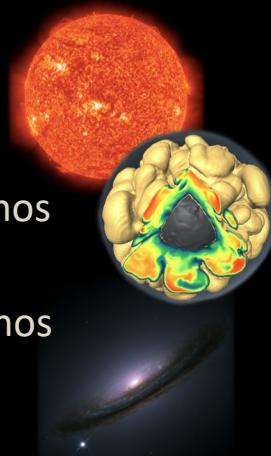


Large volume detector
able to exploit both
Cherenkov+Scintillation
signals

→ Enhanced sensitivity to broad physics program



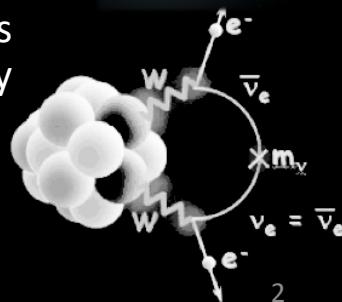
→ Long-Baseline Oscillations



→ Supernova neutrinos

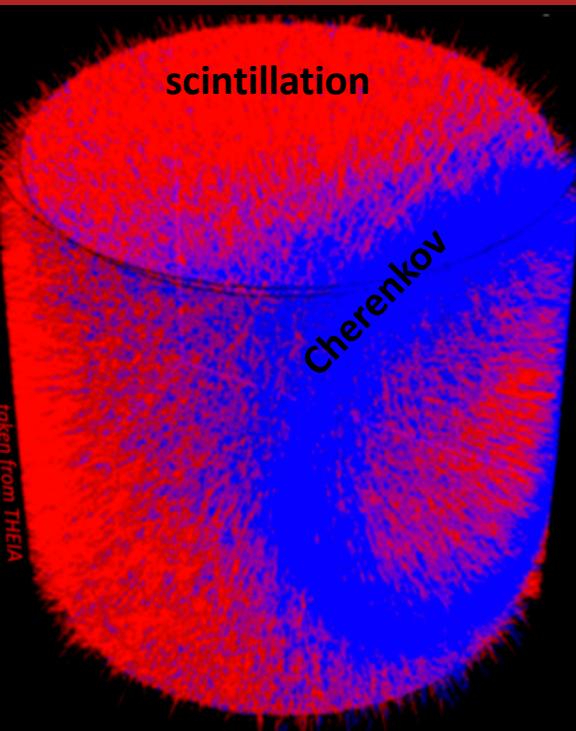
→ Diffuse SN neutrinos

→ Neutrinoless
Double-Beta Decay



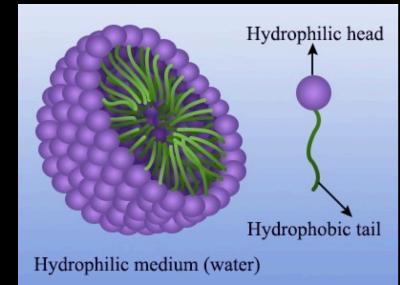
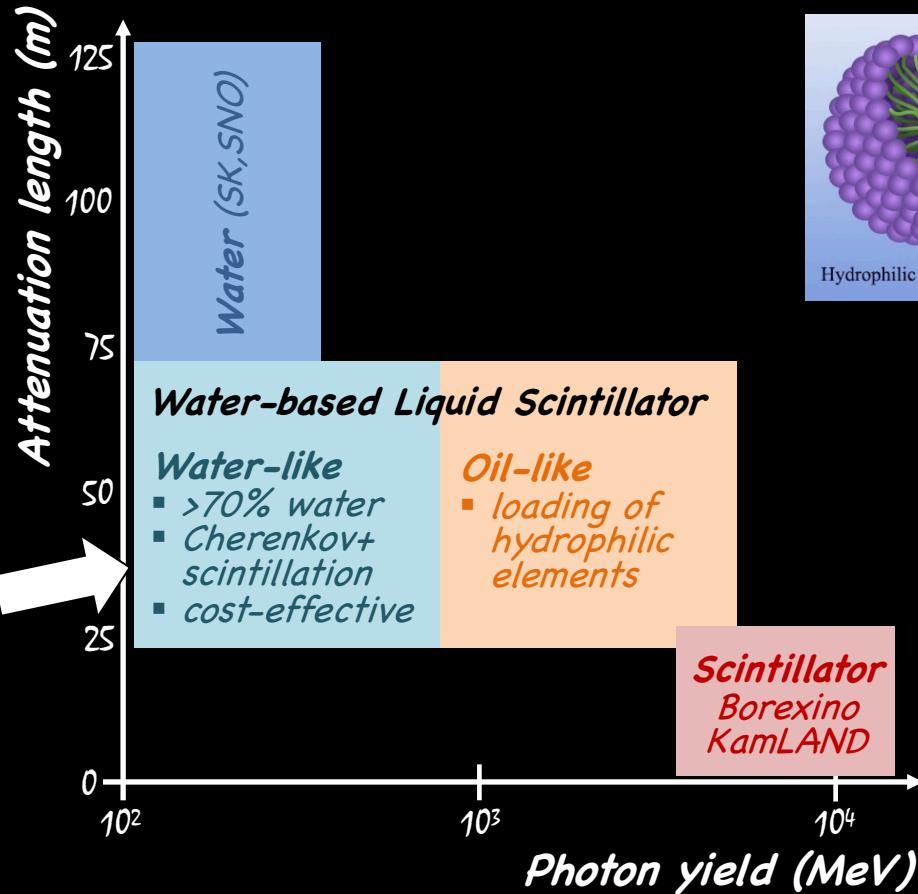
THEIA Technology

JG|U



Sufficiently transparent to extract Cherenkov photons!

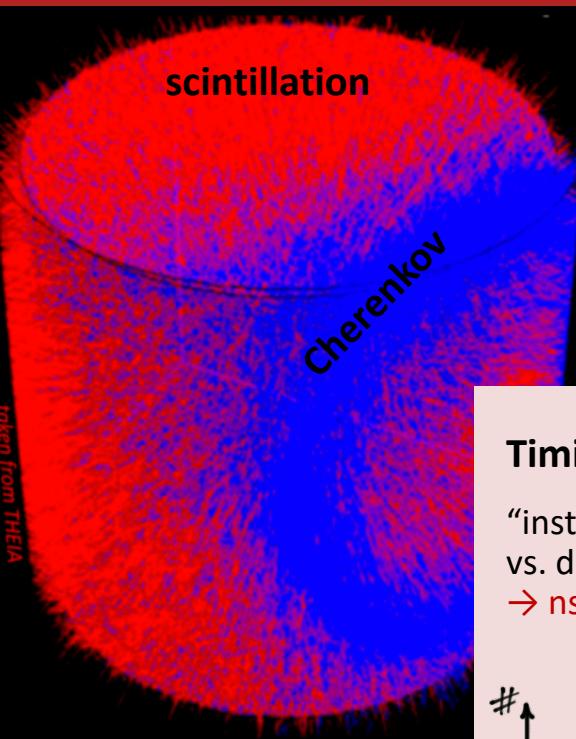
→ how to generate (and preserve!) scintillation and Cherenkov photons?



→ target medium can be adjusted to physics goals!

THEIA Technology

JG|U

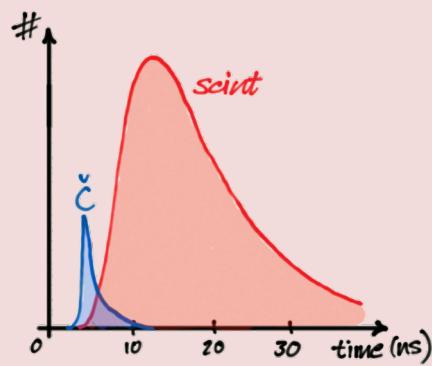


→ how to generate (and preserve!) scintillation and Cherenkov photons?

→ how to separate the Cherenkov/scintillation signals?

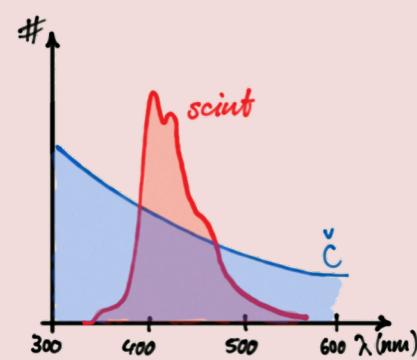
Timing

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



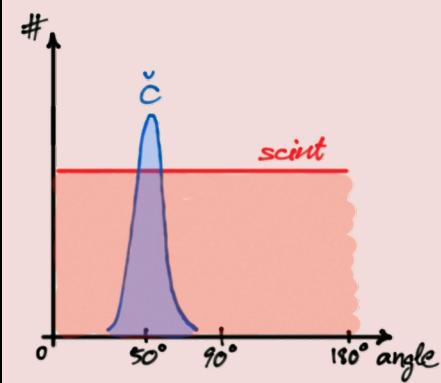
Spectrum

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



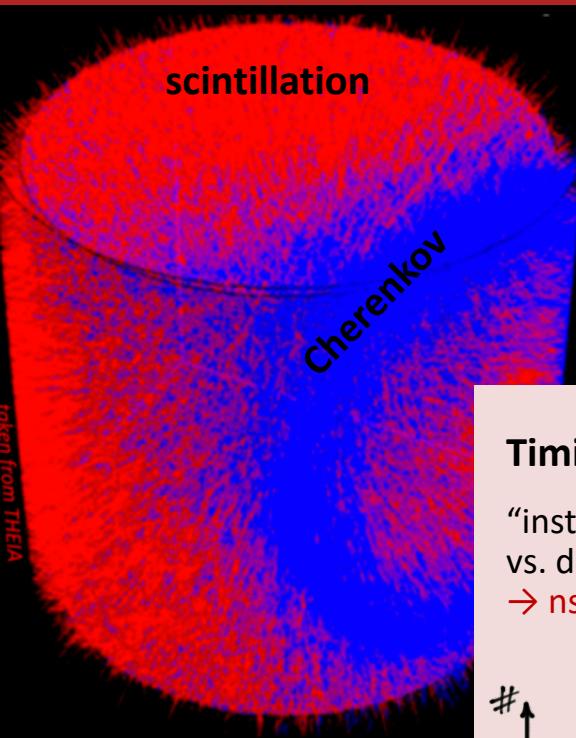
Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity



THEIA Technology

JG|U

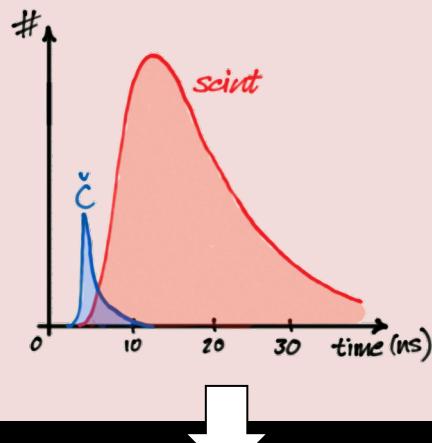


→ how to generate (and preserve!) scintillation and Cherenkov photons?

→ how to separate the Cherenkov/scintillation signals?

Timing

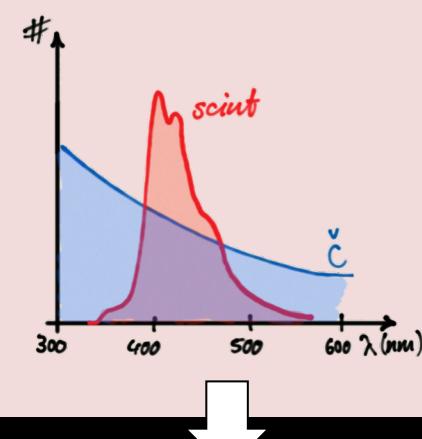
"instantaneous chertons" vs. delayed "scintons"
→ ns resolution or better



LAPPDs: ~60ps timing

Spectrum

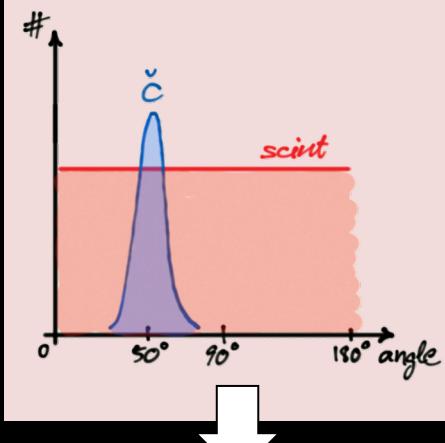
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity



Dichroic filters
→ talk by Tanner Kaptanoglu

Angular distribution

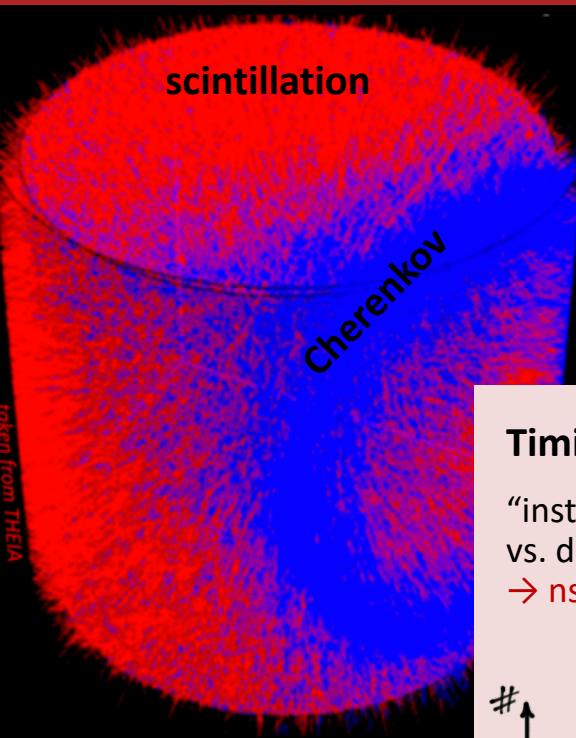
increased PMT hit density under Cherenkov angle
→ sufficient granularity



Standard PMTs

THEIA Technology

JG|U



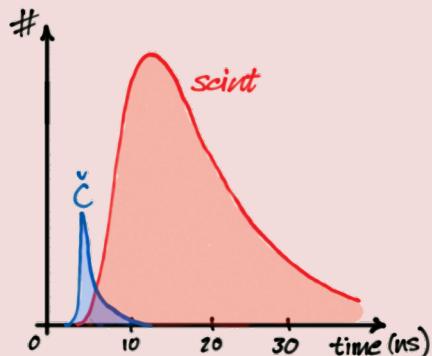
→ how to generate (and preserve!) scintillation and Cherenkov photons?

Cherenkov

→ how to separate the Cherenkov/scintillation signals?

Timing

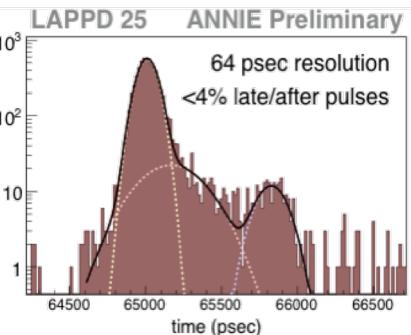
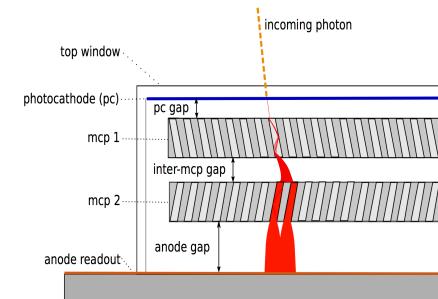
"instantaneous chertons"
vs. delayed "scintons"
→ ns resolution or better



LAPPDs: ~60ps timing

Large Area Picosecond Photon Detectors

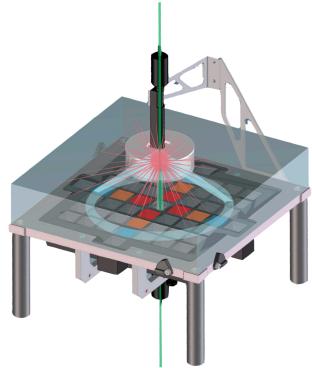
- Area: 20-by-20 cm²
- Amplification of p.e. by two MCP layers
- Flat geometry: ultrafast timing ~65ps
- Strip readout: spatial resolution ~1cm
- Commercial production by Incom, Ltd.



THEIA R&D and friends

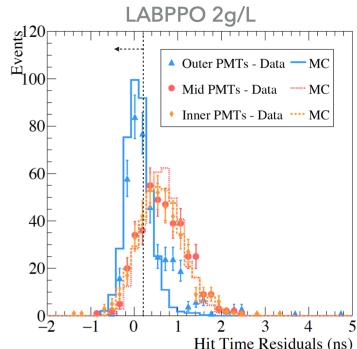
JG|U

Selected examples of on-going R&D:



CHESS setup at UC Berkeley:

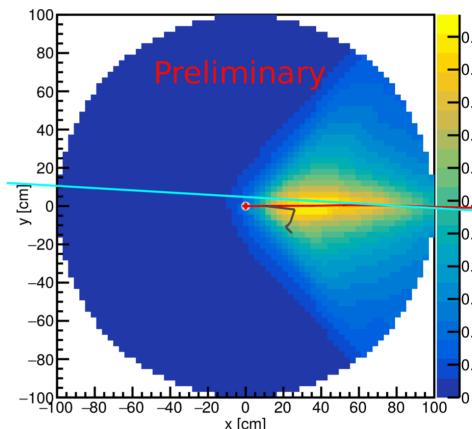
Image Cherenkov rings from WbLS + C/S timing
timing in rings →



Dichroicons at U.Penn

Simultaneous but discriminating detection of chertons & scintons

→ talk by T. Kaptanoglu



Topological reconstruction at U.Hamburg

Using (Wb)LS volume as “photon TPC” by tracking back photons for enhanced emission probability

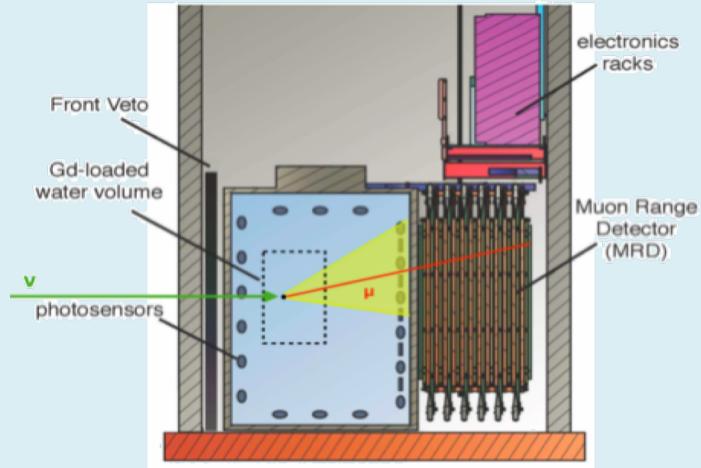
← 0.5GeV μ in WbLS+LAPPDs

THEIA

ANNIE @ Fermilab BNB



→ demonstrator for LAPPDs
→ WbLS upgrade foreseen



WATCHMAN-AIT

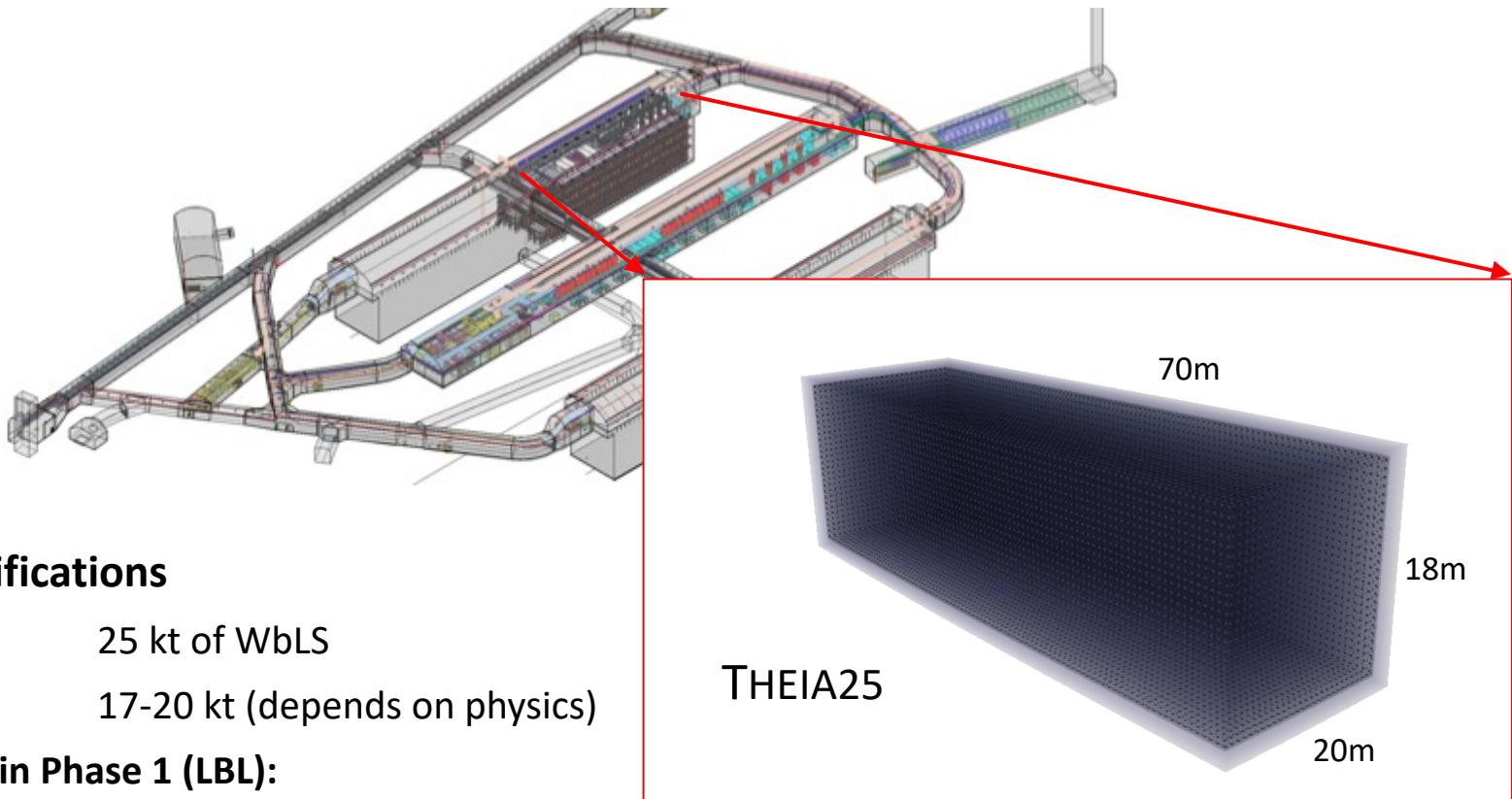
→ test of
THEIA-related
technologies

→ talk by
Adam Bernstein



THEIA25 as the Module of Opportunity

JG|U

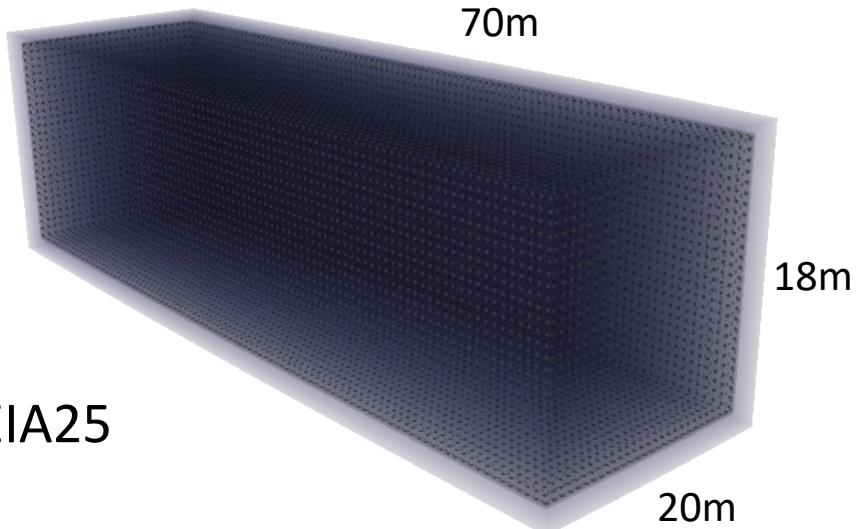


Detector specifications

- **Total mass:** 25 kt of WbLS
- **Fiducial mass:** 17-20 kt (depends on physics)
- **Photosensors in Phase 1 (LBL):**
22,500x 10'' PMTs → 25% coverage w/ high QE
700x 8'' LAPPDs → 3% coverage
→ equals the current photon collection of SK!
- **Background levels:**
Radiopurity (H_2O): $\sim 10^{-15}$ g/g in ^{238}U , ^{232}Th , ^{40}K
Rock shielding: 4300 m.w.e. → muon flux only $\sim 10\%$ of LNGS

THEIA25 : Staged Approach

JG|U



THEIA25

Staged Approach

Phase 1 Long-baseline neutrinos (LBNF)
with "thin" WbLS (1-10%)

Phase 2 Low-energy neutrino
observation with "oily" LS

Phase 3 multi-ton scale $0\nu\beta\beta$ search with
loaded LS in suspended vessel
and added photocoverage

Physics Goals

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

WbLS: Impact on MeV neutrino detection JG|U

Water Cherenkov

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

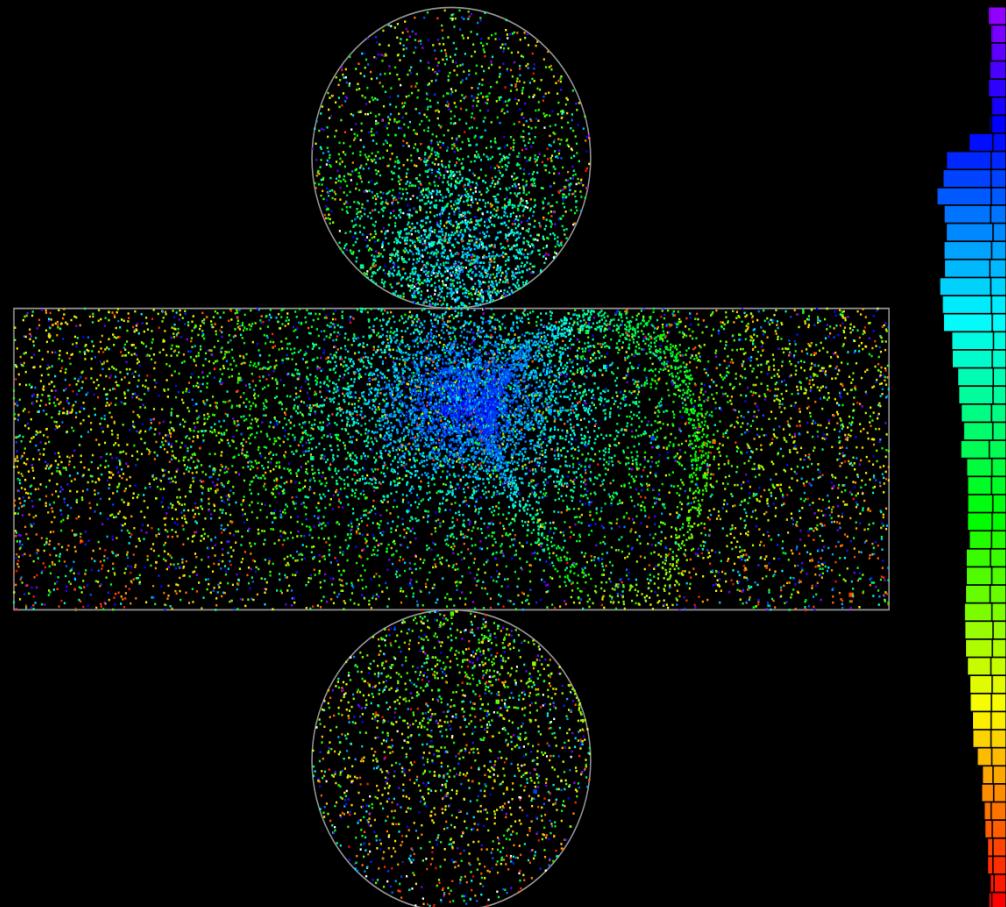


Combined: Particle ID based on
Cherenkov/scintillation (C/S) ratio
(p, α below Č threshold)

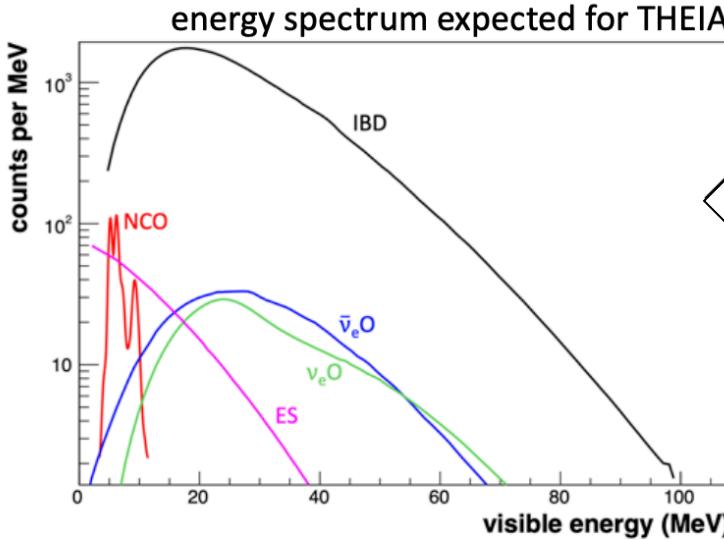


Organic scintillator mycel

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

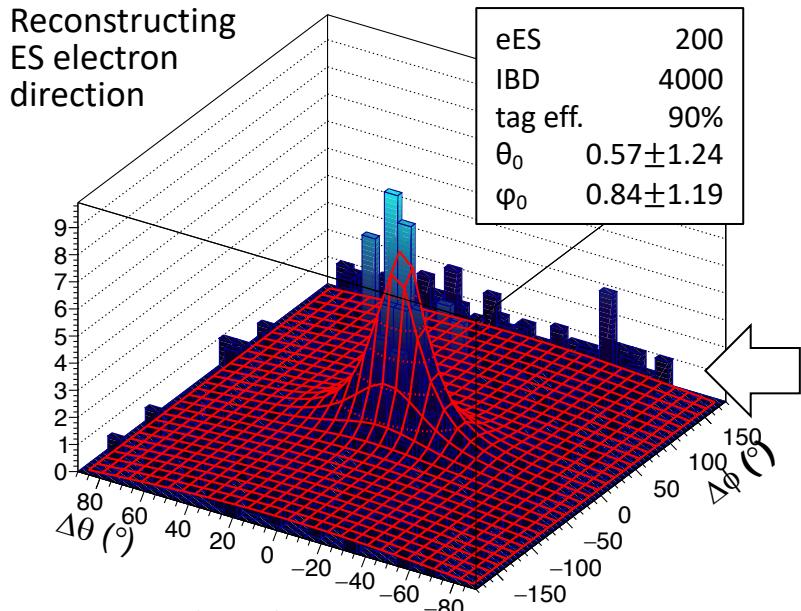


Supernova Neutrinos



Galactic Supernovae (10kpc):

- Expected events: **~5,000, mostly $\bar{\nu}_e$'s** from IBD
- complementary to ν_e signal in argon
- Same location: compare Earth matter effects
- Provide fast trigger for Lar TPCs, especially for far-off Supernovae (LMC: ~ 200 ev. In THEIA)



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

- some all-flavor ($\nu_e + \nu_\mu + \nu_\tau$) information from NC reactions on oxygen
- **Enhanced SN pointing:** $\sim 2^\circ$ based on ES with IBD background subtraction

Diffuse Supernova Neutrino Background

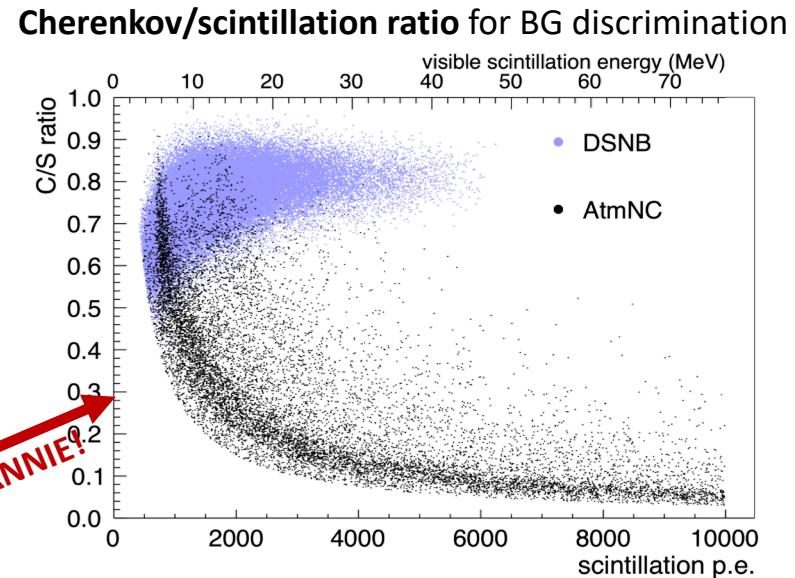
JG|U

DSNB detection:

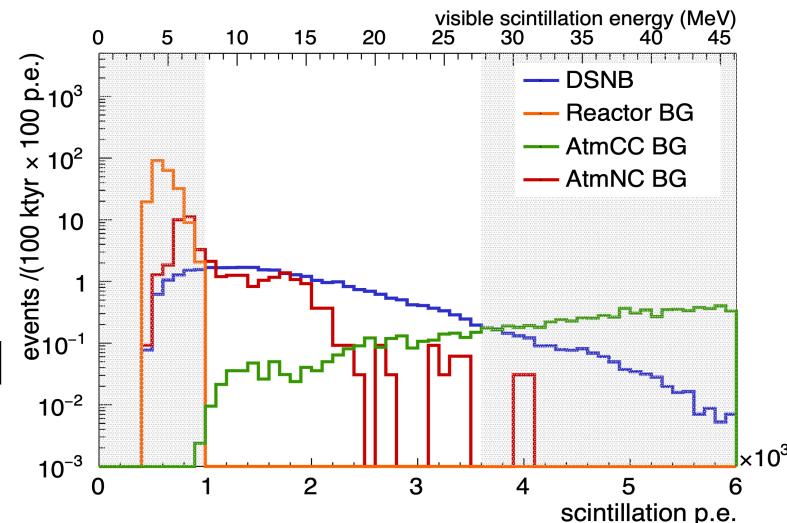
- Low-flux $\mathcal{O}(10^2 \text{ cm}^{-2}\text{s}^{-1})$ $\bar{\nu}_e$ signal
→ detectable by IBD: ~ 2 ev. per $10 \text{ kt}\cdot\text{yrs}$
 - Requires efficient BG discrimination,
especially to atmospheric ν NC interactions
 - In THEIA:
 - ring counting:
 - **Cherenkov/scintillation ratio**
 - delayed decay tags
- signal efficiency: 95%
- residual background: 1.7%

very clean measurement cf. JUNO & SK-Gd

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



Signal/BG spectra and observation window



Solar neutrinos

Objectives:

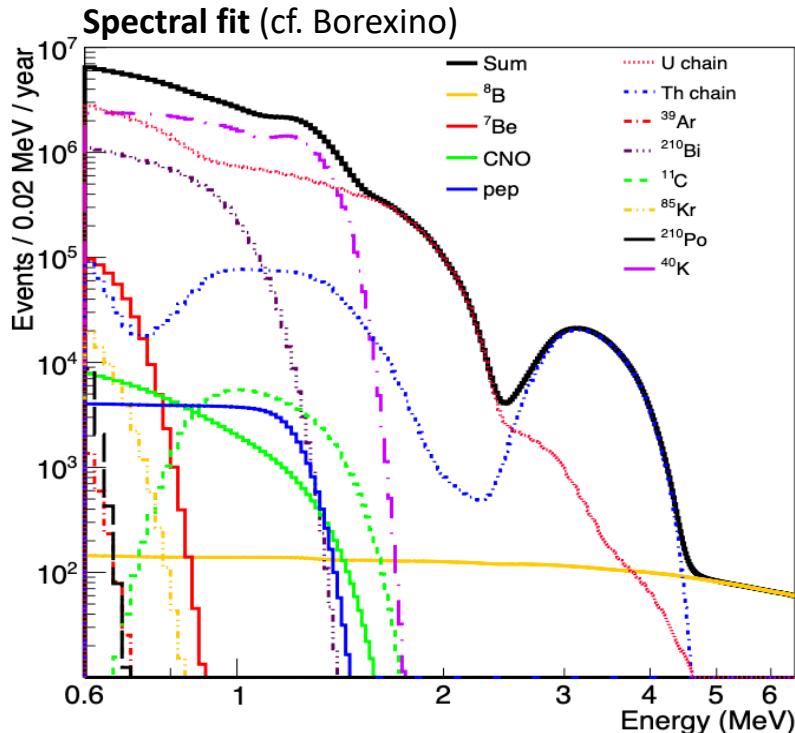
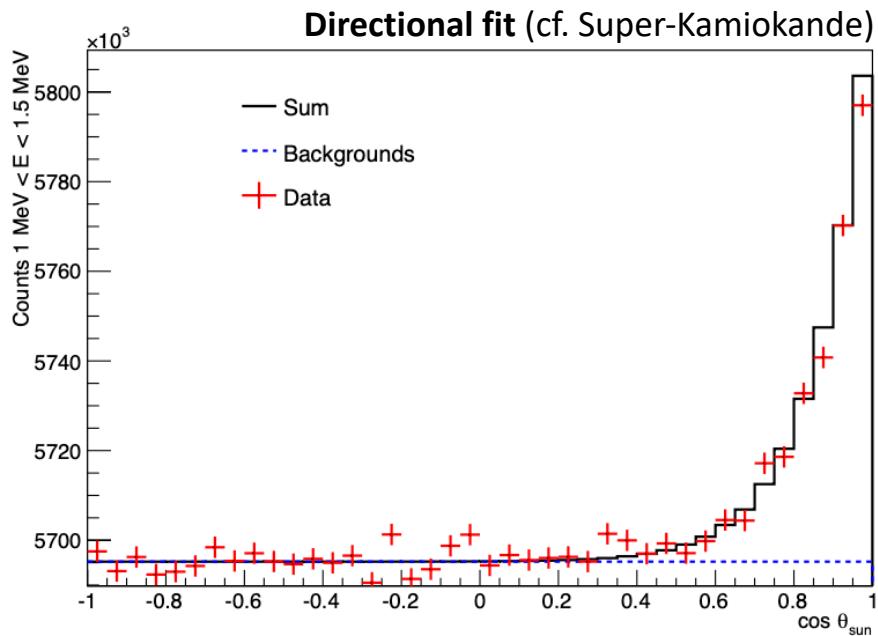
- Precise measurement of CNO neutrino flux
- Spectral upturn of low-energy ^8B neutrinos

◀ stellar physics, solar metallicity
◀ matter effects, BSM physics?

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

- THEIA25: 2D directional & spectral fit

→ **CNO flux at 10% level after 5 yrs**



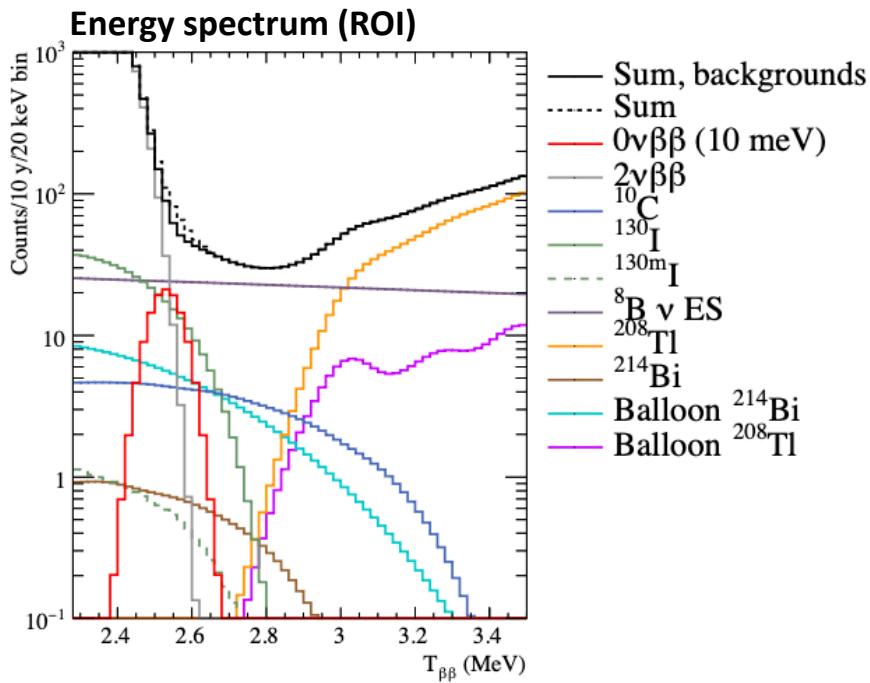
Neutrinoless double-beta decay

JG|U

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

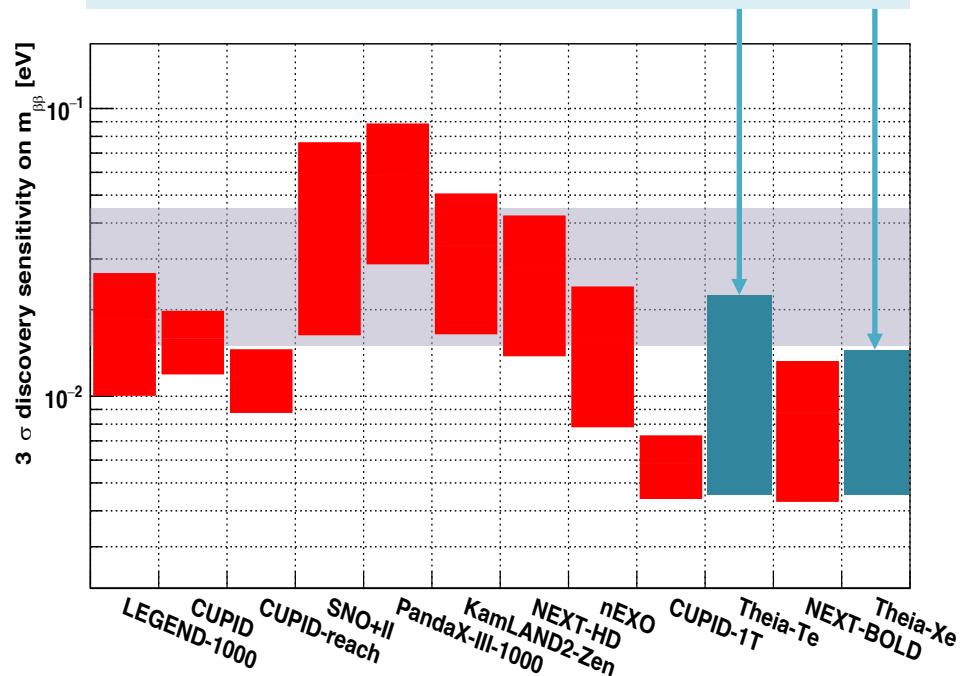
loading:
-- **3% enriched Xe (89.5%)**
-- **5% natural Te (~90t)**

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



Sensitivity (90% CL) from spectral fit:

- **Te: $T_{1/2} > 1.1 \times 10^{28} \text{ yrs}, m_{\beta\beta} < 6.3 \text{ meV}$**
- **Xe: $T_{1/2} > 2.0 \times 10^{28} \text{ yrs}, m_{\beta\beta} < 5.6 \text{ meV}$**



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

THEIA Whitepaper online!

JG|U

arXiv:1911.03501

THEIA: An Advanced Optical Neutrino Detector

M. Askins,^{1,2} Z. Bagdasarian,³ N. Barros,^{4,5,6} E.W. Beier,⁴ E. Blucher,⁷ R. Bonventre,² E. Bourret,² E. Callaghan,^{1,2} J. Caravaca,^{1,2} M. Diwan,⁸ S.T. Dye,⁹ J. Eischt,¹⁰ A. Elagin,⁷ T. Enqvist,¹¹ V. Fischer,¹² K. Frankiewicz,¹³ C. Grant,¹³ D. Guffanti,¹⁴ C. Hagner,¹⁵ A. Hallin,¹⁶ C. M. Jackson,¹⁷ R. Jiang,⁷ T. Kaptanoglu,⁴ J.R. Klein,⁴ Yu. G. Kolomensky,^{1,2} C. Kraus,¹⁸ F. Krennrich,¹⁰ T. Kutter,¹⁹ T. Lachenmaier,²⁰ B. Land,^{1,2} K. Lande,⁴ J.G. Learned,⁹ V. Lozza,^{5,6} L. Ludhova,³ M. Malek,²¹ S. Manecki,^{22,18,23} J. Maneira,^{5,6} J. Maricic,⁹ J. Martyn,¹⁴ A. Mastbaum,²⁴ C. Mauger,⁴ F. Moretti,² J. Napolitano,²⁵ B. Naranjo,²⁶ M. Nieslony,¹⁴ L. Oberauer,²⁷ G. D. Orebi Gann,^{1,2} J. Ouellet,²⁸ T. Pershing,¹² S.T. Petcov,^{29,30} L. Picard,¹² R. Rosero,⁸ M. Sanchez,¹⁰ J. Sawatzki,²⁷ S.H. Seo,³¹ M. Smiley,^{1,2} M. Smy,³² A. Stahl,³³ H. Steiger,²⁷ M. R. Stock,²⁷ H. Sunej,⁸ R. Svoboda,¹² E. Tiras,¹⁰ W. Trzaska,¹¹ M. Tzanov,¹⁹ M. Vagins,³² C. Vilela,³⁴ Z. Wang,³⁵ J. Wang,¹² M. Wetstein,¹⁰ M.J. Wilking,³⁴ L. Winslow,²⁸ P. Wittich,³⁶ B. Wonsak,¹⁵ E. Worcester,^{8,34} M. Wurm,¹⁴ G. Yang,³⁴ M. Yeh,⁸ E.D. Zimmerman,³⁷ and K. Zuber³⁸

¹University of California, Berkeley, Department of Physics, CA 94720, Berkeley, USA

²Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720-8153, USA

³Forschungszentrum Jülich Institute for Nuclear Physics Wilhelm-Johnen-Straße 52425 Jülich, Germany

⁴Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104-6396

⁵Universidade de Lisboa, Faculdade de Ciências (FCUL),

Departamento de Física, Campo Grande, Edifício C8, 1749-016 Lisboa, Portugal

⁶Laboratório de Instrumentação e Física Experimental de Partículas (LIP),

Av. Prof. Gama Pinto, 2, 1649-003, Lisboa, Portugal

⁷The Enrico Fermi Institute and Department of Physics,

The University of Chicago, Chicago, IL 60637, USA

⁸Brookhaven National Laboratory, Upton, New York 11973, USA

⁹University of Hawai'i at Manoa, Honolulu, Hawai'i 96822, USA

¹⁰Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA

¹¹Department of Physics, University of Jyväskylä, Finland



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

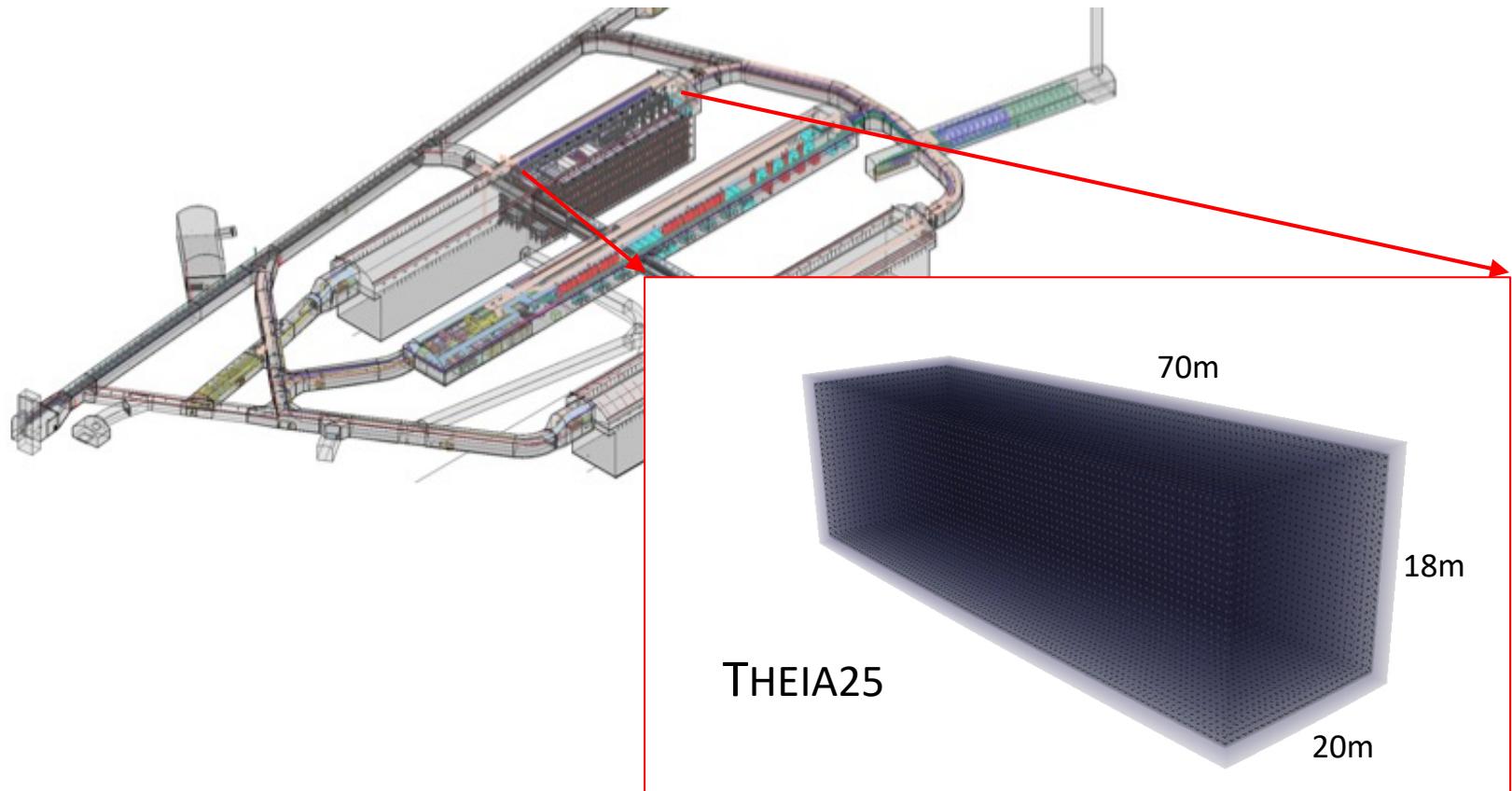
Read more on:

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

→ Mike Wilking's talk

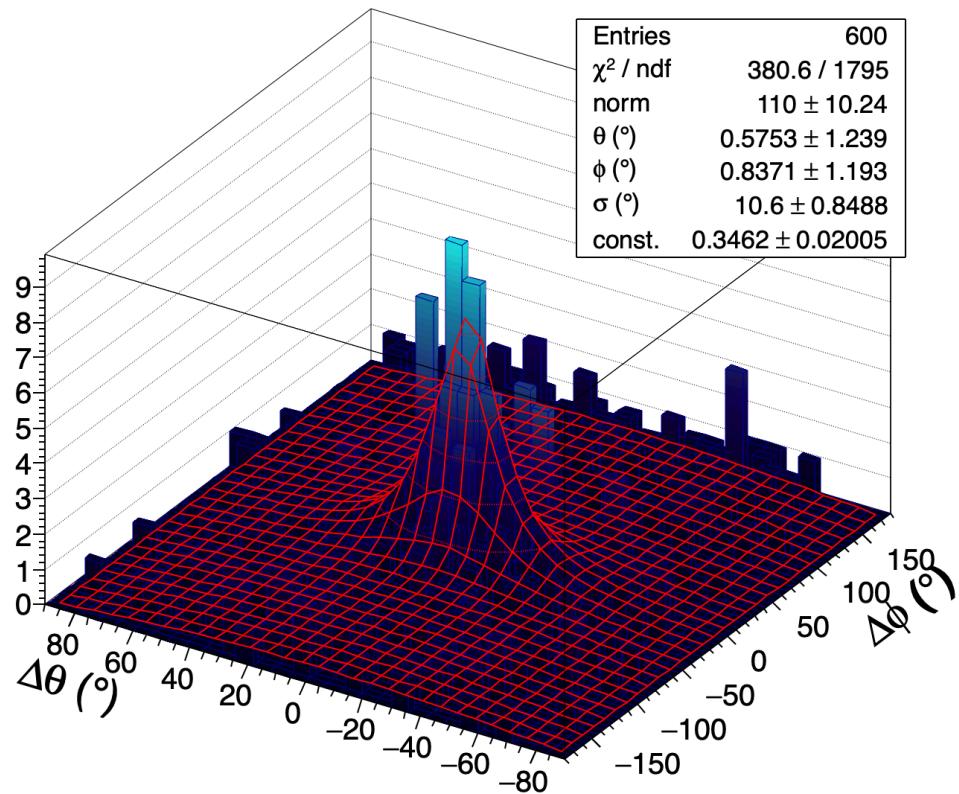
Backup Slides

JG|U



Supernova neutrino pointing

JG|U



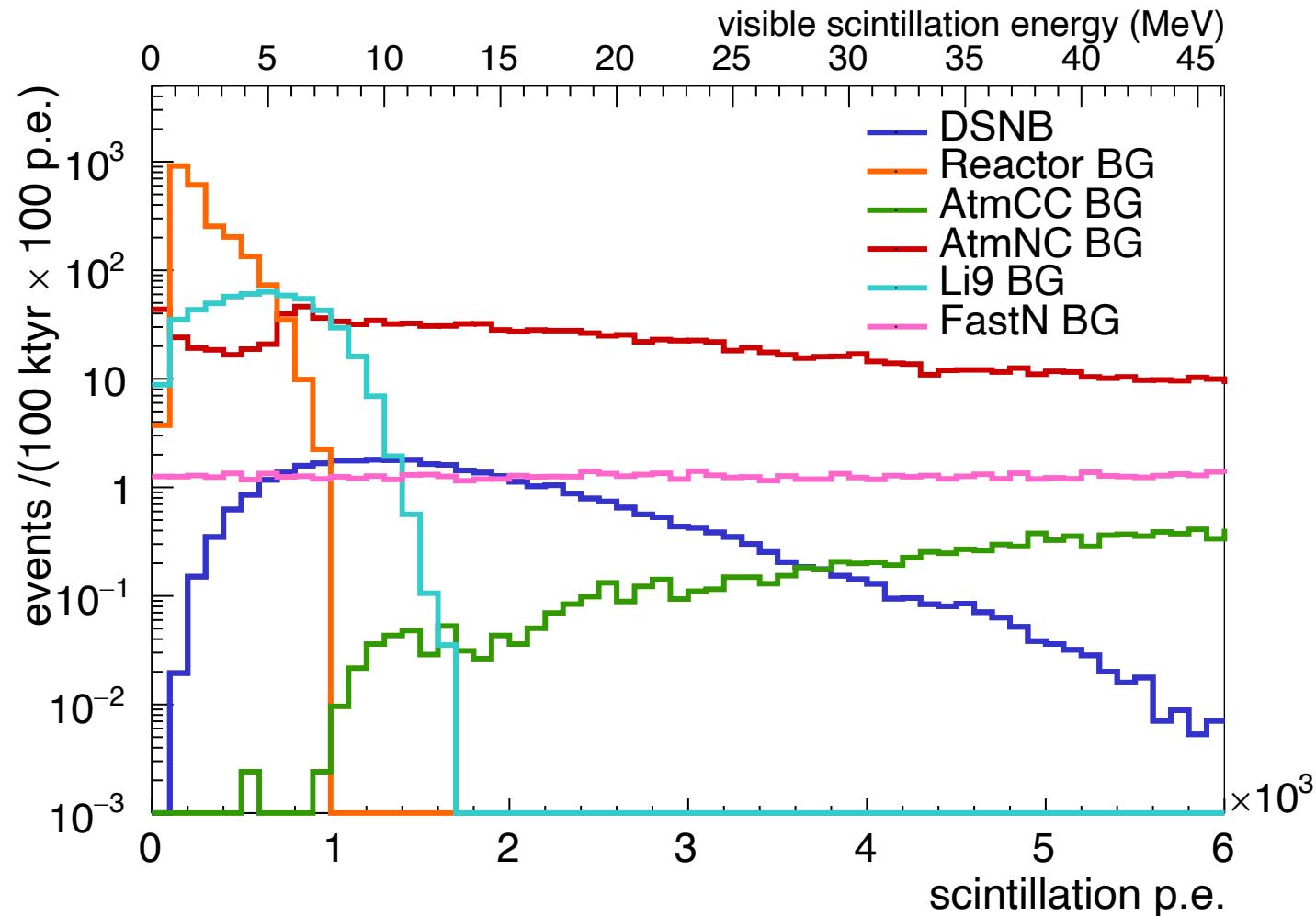
Toy-MC study

- Realistic kinematics for ES
- Flat for IBD (conservative)
- “canonical” SN model (used for JUNO)
- eES events: 200 in 20kt
- IBD events: 4000
- IBD tagging efficiency: $0\% \rightarrow 90\% \rightarrow 100\%$
- Angular resolution (at 10MeV+) $10^\circ \rightarrow 15^\circ \rightarrow 20^\circ$
- Results of a 2D analytical fit:

IBD tag efficiency	Angular resolution		
	10°	15°	20°
0%	1.55	1.55	2.05
90%	1.75	1.95	2.55
100%	2.95	5.45	11.35

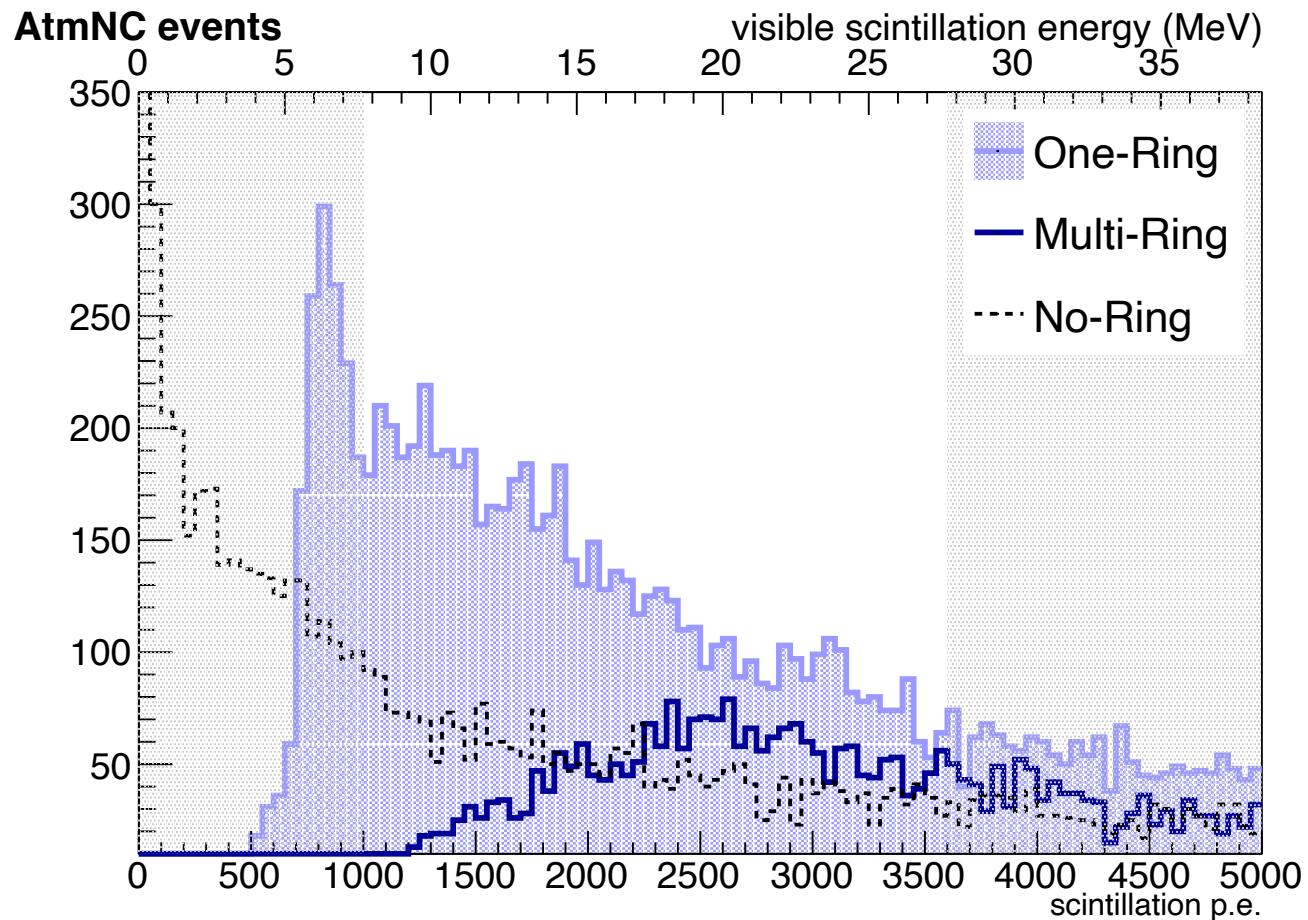
DSNB – spectrum before cuts

JG|U



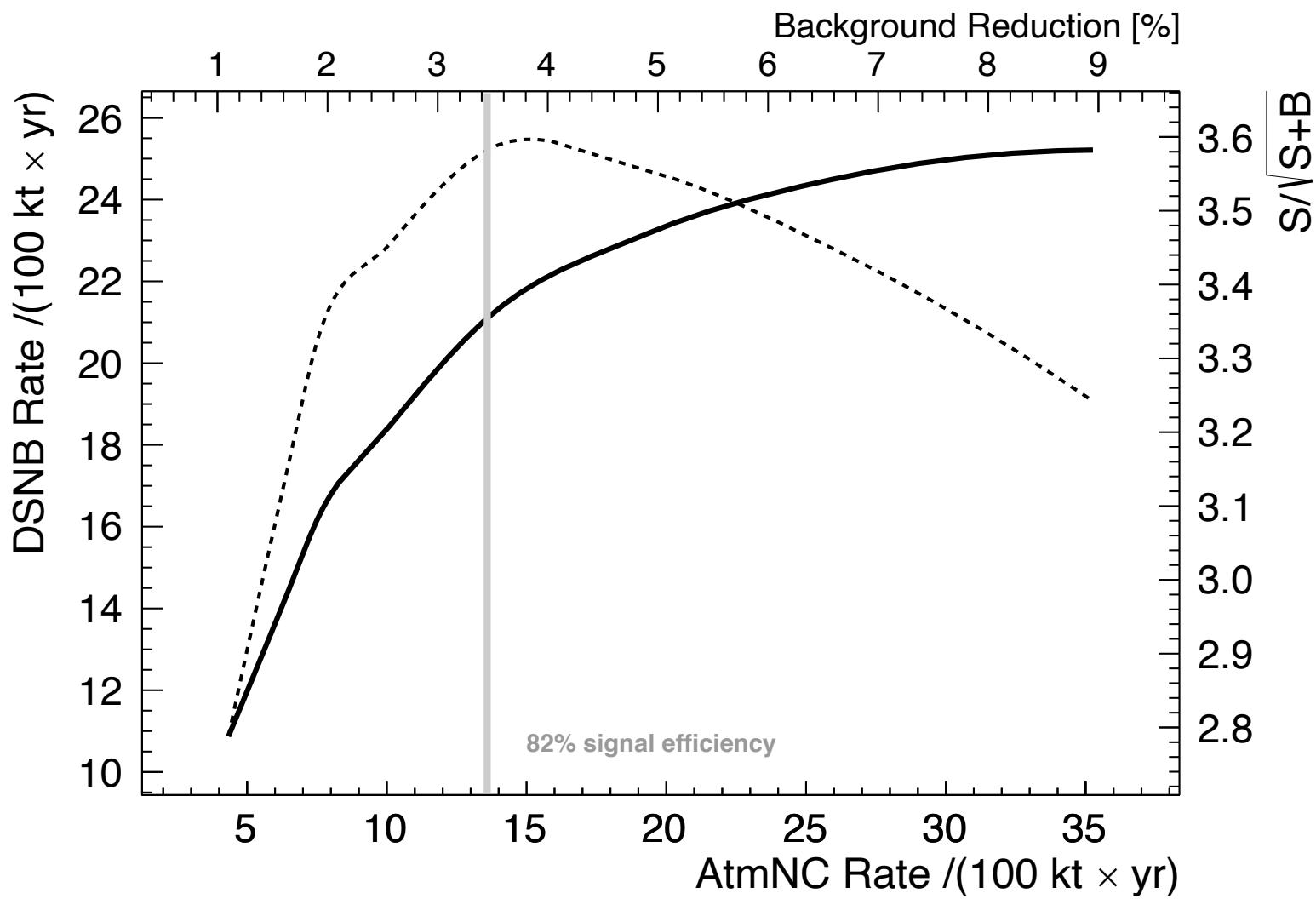
DSNB Ring Counting

JG|U



DSNB C/S ratio background rejection

JG|U



DSNB Delayed decay tags

JG|U

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

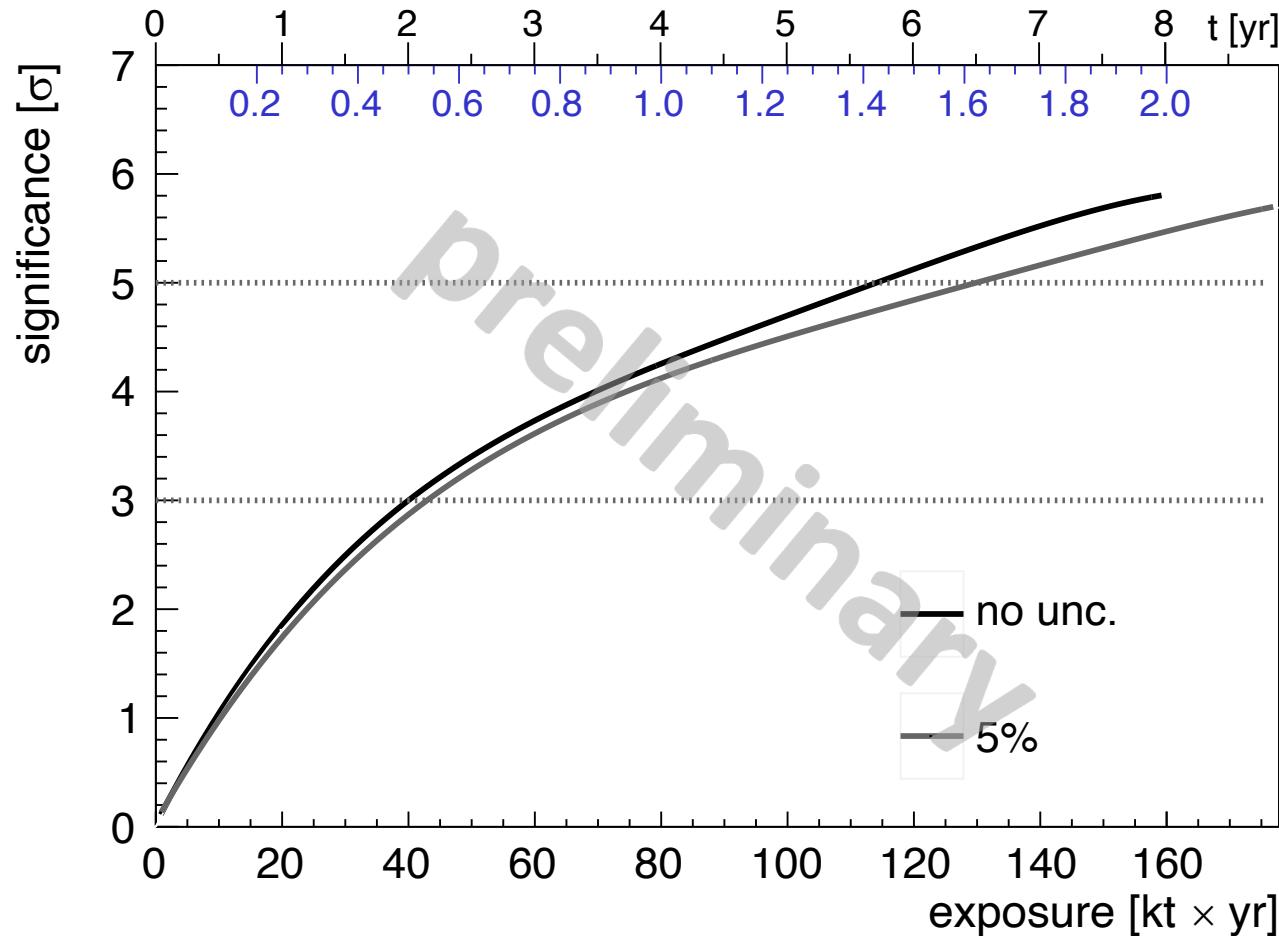
DSNB Signal and Background Rates

JG|U

Spectral contribution after FV cut Li veto delayed decays single-ring C/S cut					
DSNB signal	25.9	25.7	25.7	24.5	24.5
Reactor neutrinos	—	—	—	—	—
Atmospheric CC	2.0	2.0	2.0	1.9	1.9
Atmospheric NC	689	682	394	25.9	13.6
βn -emitters (${}^9\text{Li}$)	55	—	—	—	—
fast neutrons	0.8	0.8	0.8	—	—
Signal-to-background	0.03	0.04	0.07	0.9	1.6

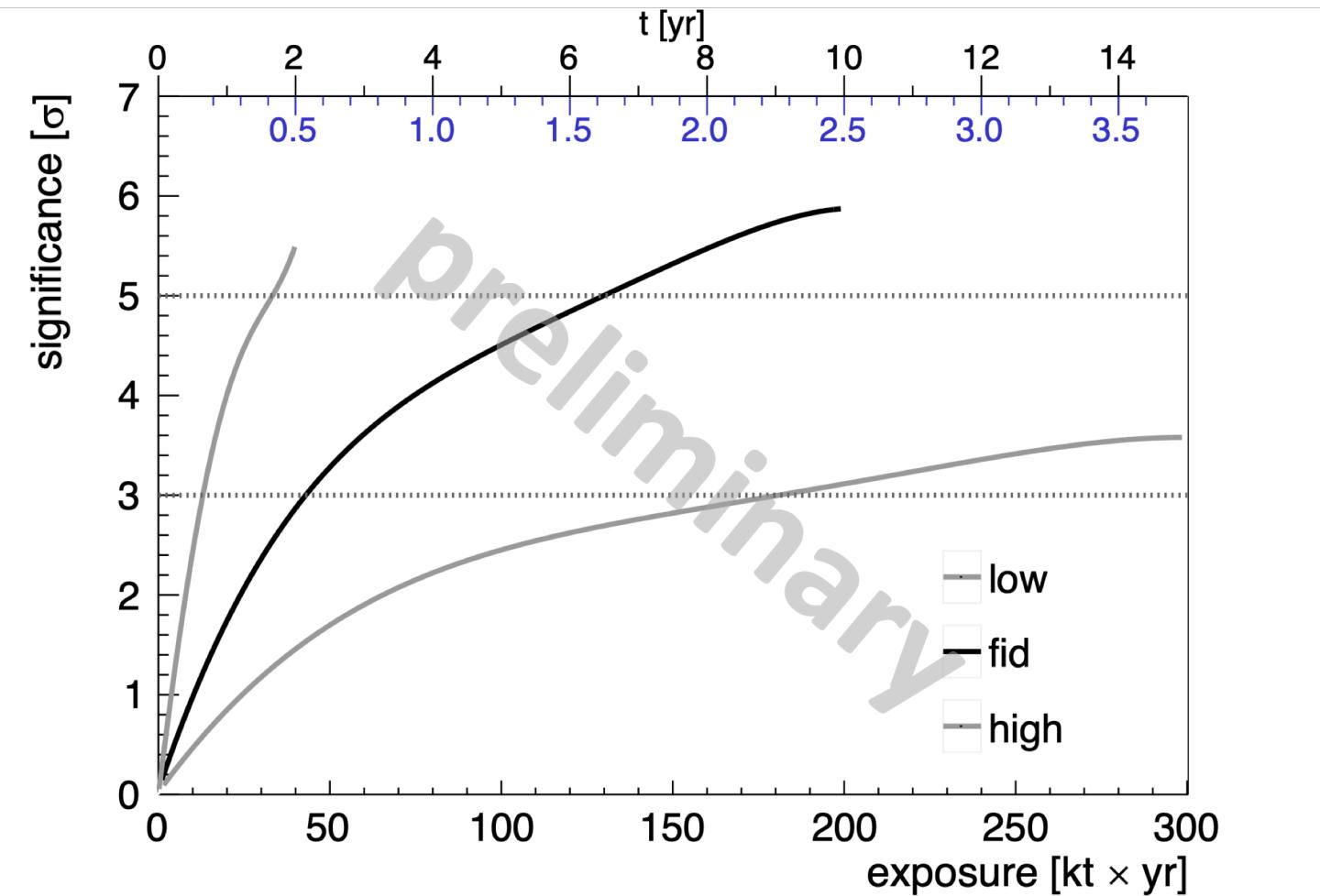
DSNB Sensitivity : BG discrimination

JG|U

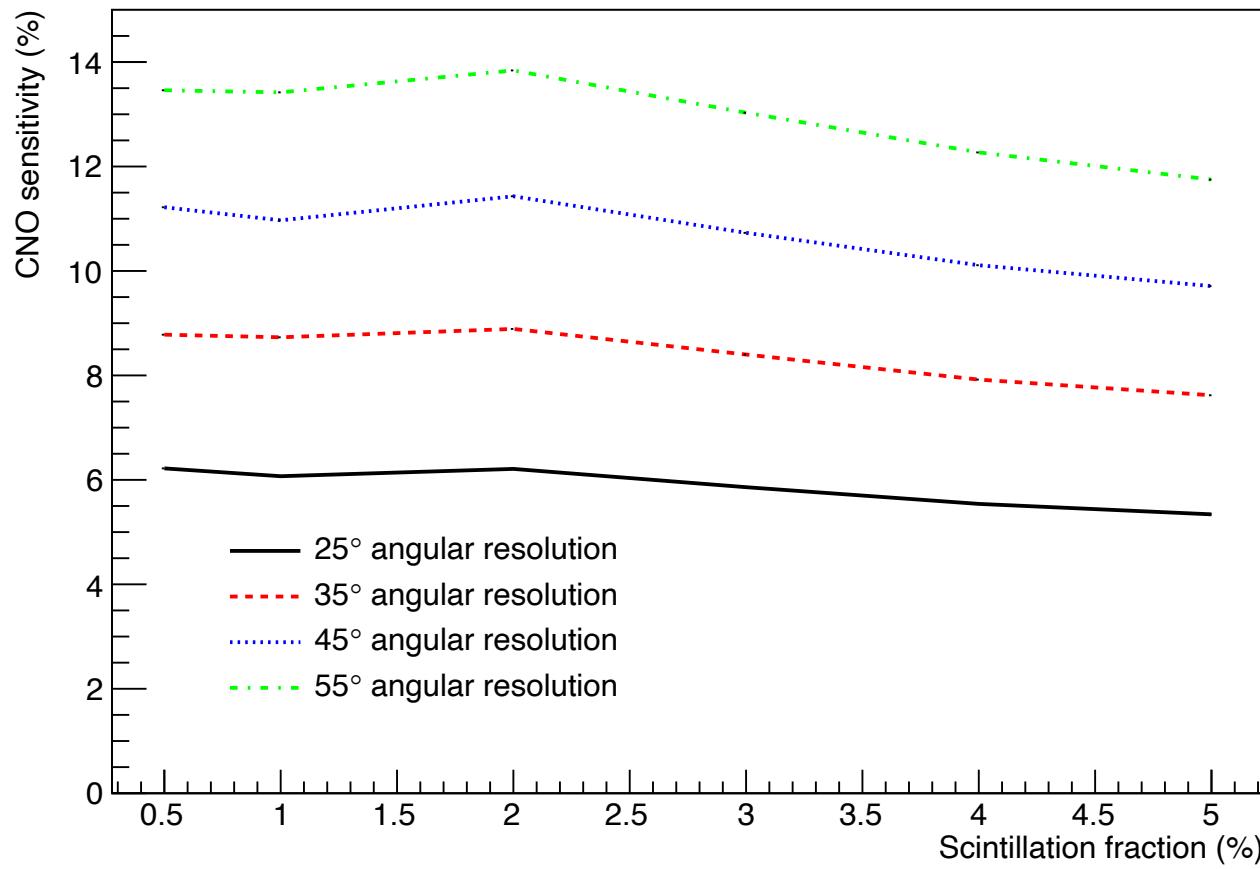


DSNB Sensitivity : DSNB models

JG|U



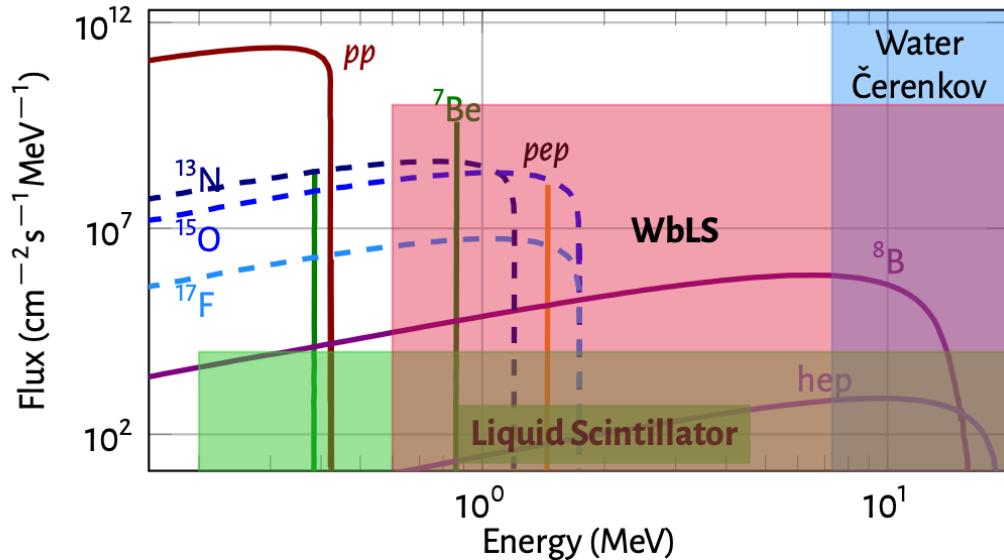
Solar : angular resolution & WbLS fraction JG|U



Solar neutrinos – ${}^7\text{Li}$ loading

JG|U

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

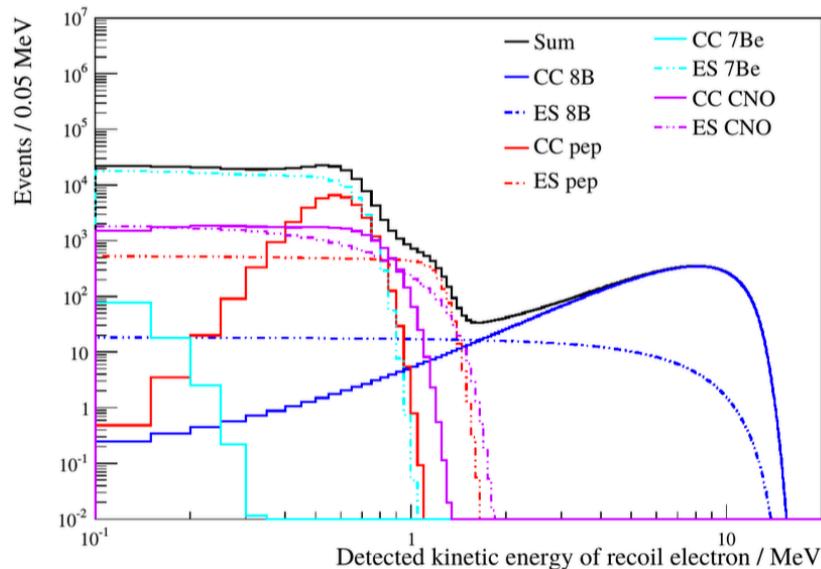


Solar ν CC interaction
Possible loading with ${}^7\text{Li}$
 $\nu_e + {}^7\text{Li} \rightarrow {}^7\text{Be} + e^-$

($Q = 862 \text{ keV}$)

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

- ▶ Improved spectral separation
- ▶ Separation of CNO components



$0\nu\beta\beta$ study for THEIA50

JG|U

Goal:

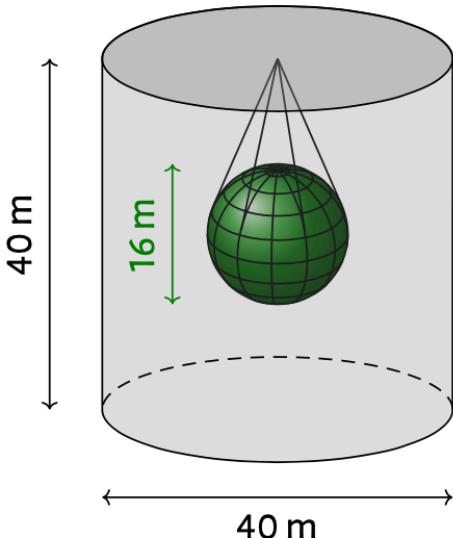
Cover IO space

Reach NO region

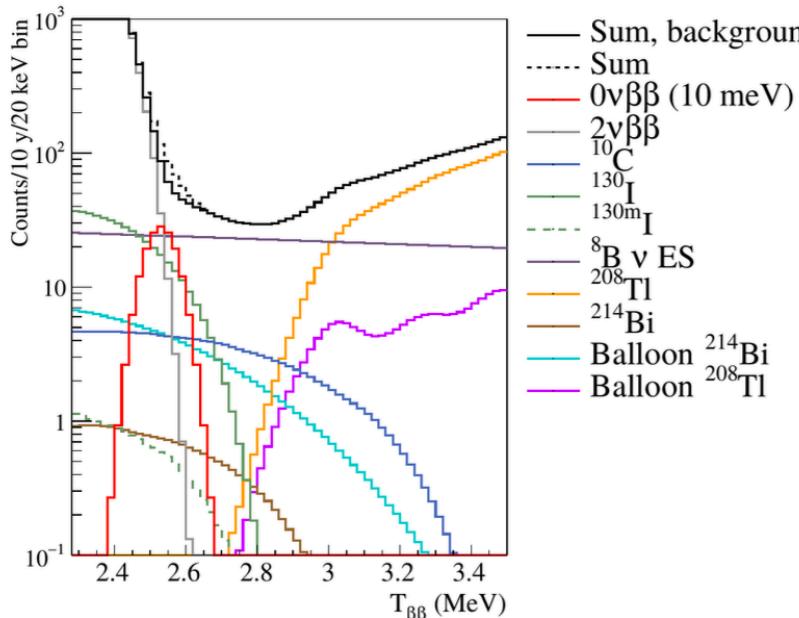
2 possible approaches:

► KamLAND/Zen like

► SNO+ like



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



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

Rejection power > 50% to cover IO

→ Need large photocoverage and
high QE photodetectors

compensate worsening of directionality in pure LS

Expected sensitivity (90% C.L.)

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

0νββ backgrounds

JG|U

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

Antineutrino spectrum

JG|U

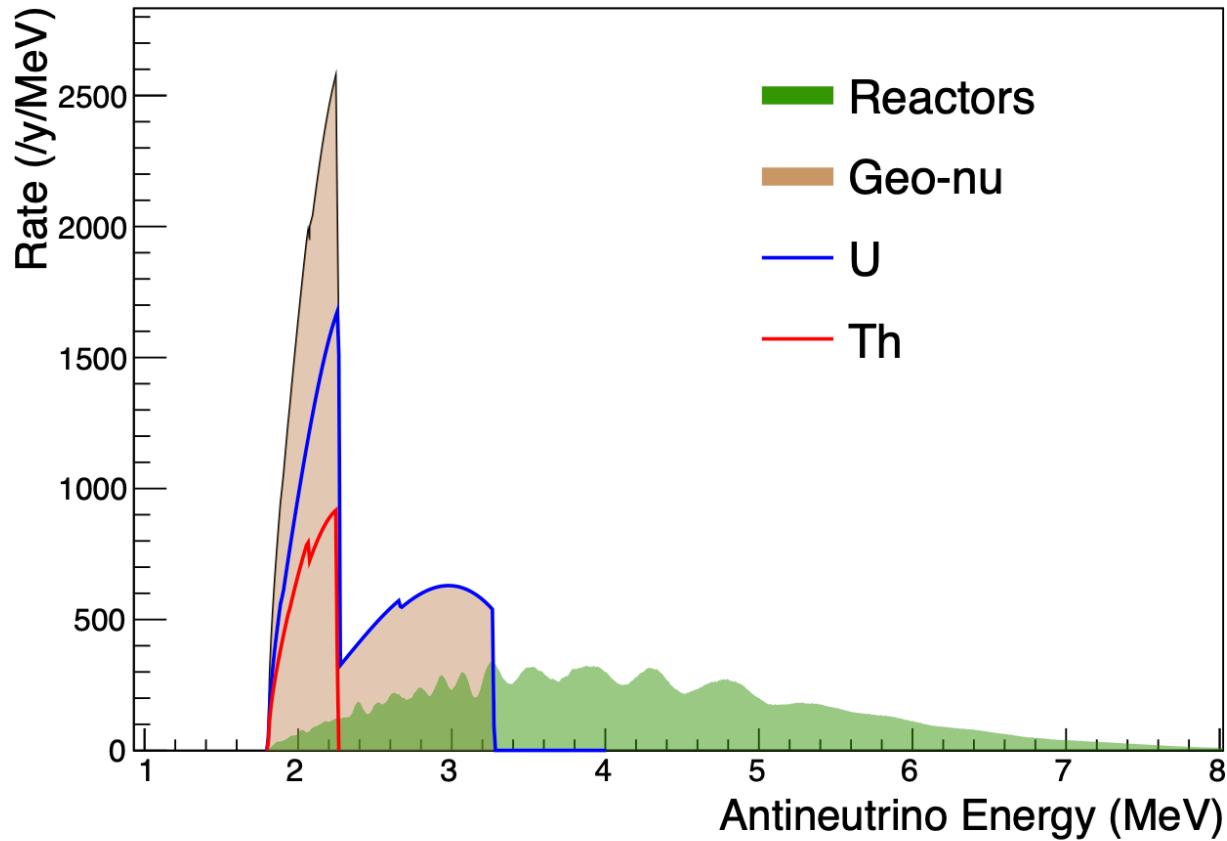


FIG. 15: The detected energy spectrum of the predicted rate of antineutrinos from nuclear power reactors and Earth, assuming a 50 kT water target.

Proton decay sensitivity

JG|U

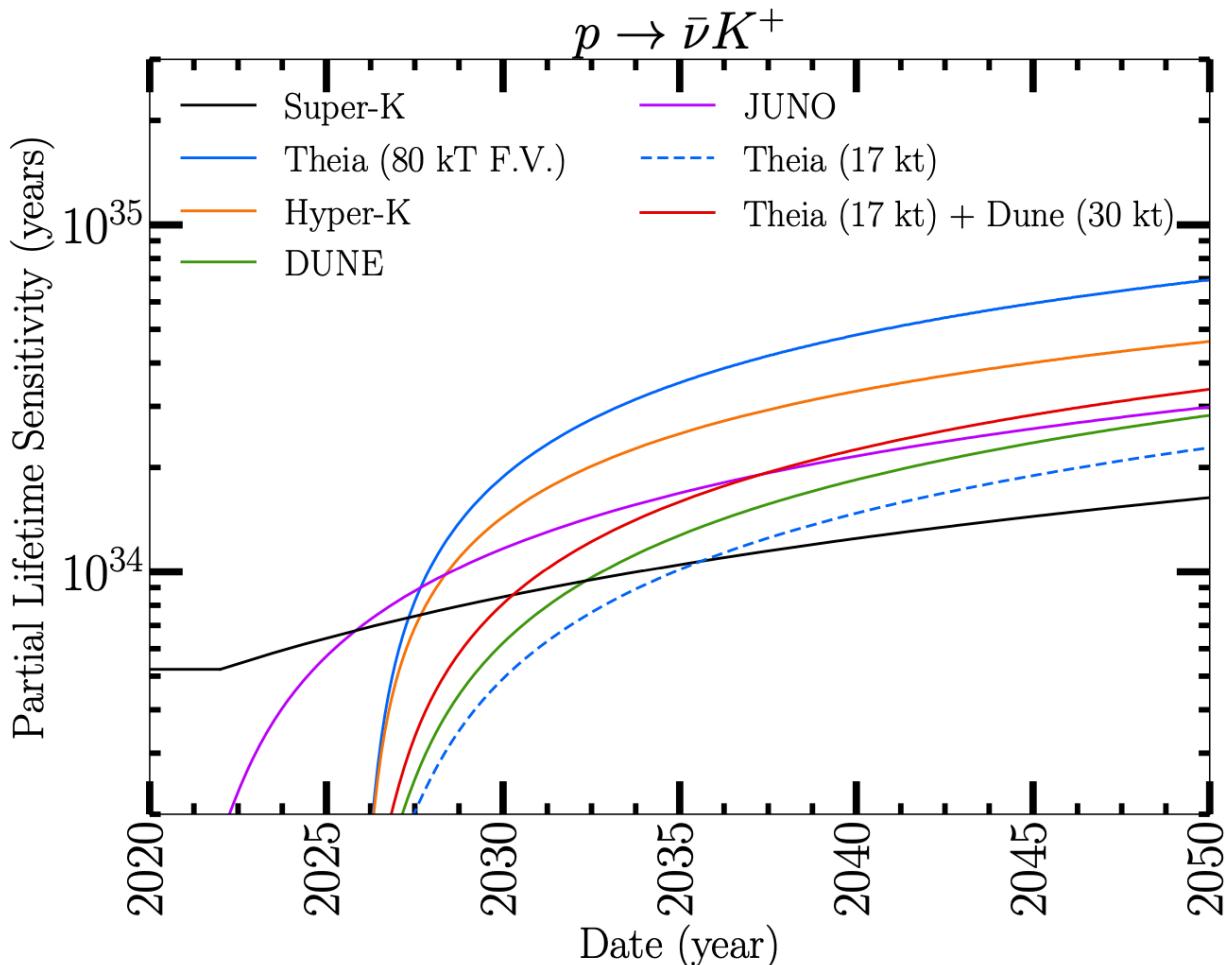


FIG. 19: Sensitivity for $p \rightarrow \bar{\nu} K^+$ is highest for THEIA, closely followed by the Hyper-K detector, whereas JUNO and DUNE will perform similarly. The inclusion of THEIA in the fourth Dune cavity would provide an enhancement to this mode over the full 40-kt Dune.