Neutrino Physics

Josh Klein, University of Pennsylvania

Work on:

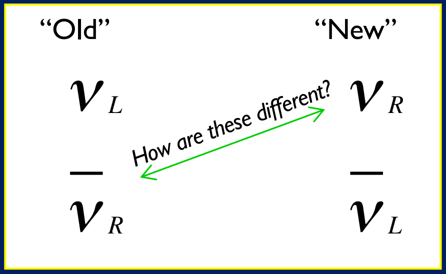
- Neutrinoless double beta decay, solar and reactor νs with SNO+
- Long-baseline ν oscillations with DUNE
- ν interactions and ”sterile” ν searches with SBND
- Plans for future detectors (e.g., Theia)
- Related R&D

Big Questions

1. Are neutrinos Majorana Particles?
2. What is the neutrino mass ordering?
3. Do neutrinos violate (Dirac) CP?
4. Are standard 3-flavor oscillations the whole story?
5. What can we learn about astrophysical objects and events with νs?

Majorana Neutrinos

If neutrinos are not Majorana, we have four neutrino states:



“Old”	“New”
ν_L	ν_R
$\bar{\nu}_R$	$\bar{\nu}_L$

But what’s the *physical* difference between $\bar{\nu}_R$ and ν_R ?

They have:

- Same charge (0)
- Same mass
- Same chirality

They differ only in their “anti”-ness…but “anti”-ness is *not a thing!*

Majorana Neutrinos

If neutrinos are Majorana, then:

1. We need a new mass-generating mechanism
2. We likely have observed low-energy consequences of very high E scale physics
3. We may have an explanation for the matter/antimatter asymmetry
    - “Leptogenesis”
    - Requires Majorana CP phases

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

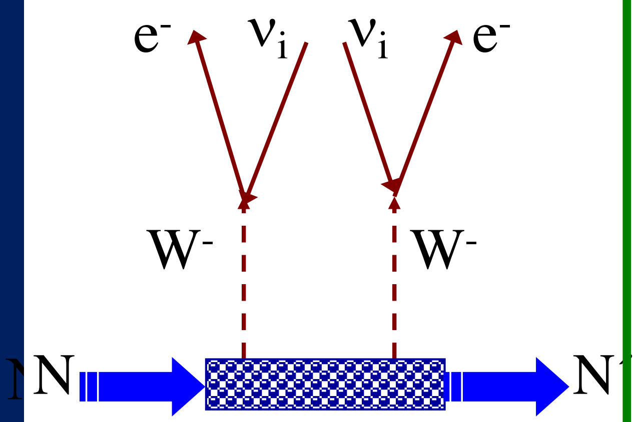
If neutrinos are Dirac, then:

1. Matter and antimatter are *fundamentally* different things
2. We have states that don’t really do much

Majorana Neutrinos

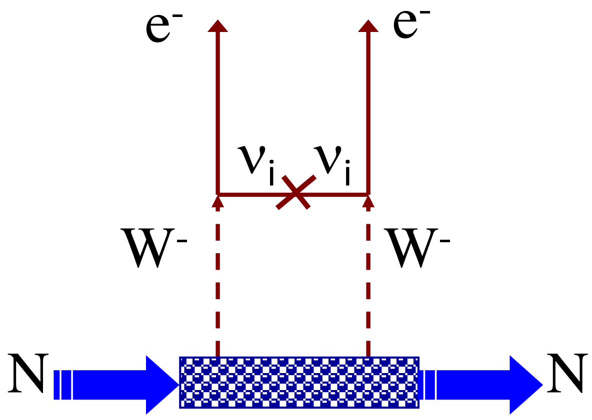
Most practical way of deciding this…

Two-neutrino double beta decay



Rare process with half-lives of ~10^{21} years

Neutrinoless double beta decay



$$T_{1/2} \propto m_{\beta\beta}^2 \sim 10^{27}\ \text{years}$$

Mass is mixed average, including phases

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

$$\left|m_{\beta\beta}\right|^2 = \left|\cos^2\theta_{12}\cos^2\theta_{13}m_1 + e^{2i\lambda_2}\sin^2\theta_{12}\cos^2\theta_{13}m_2 + e^{2i(\lambda_3-\delta_{CP})}\sin^2\theta_{13}m_3\right|^2$$

Large coeffs.

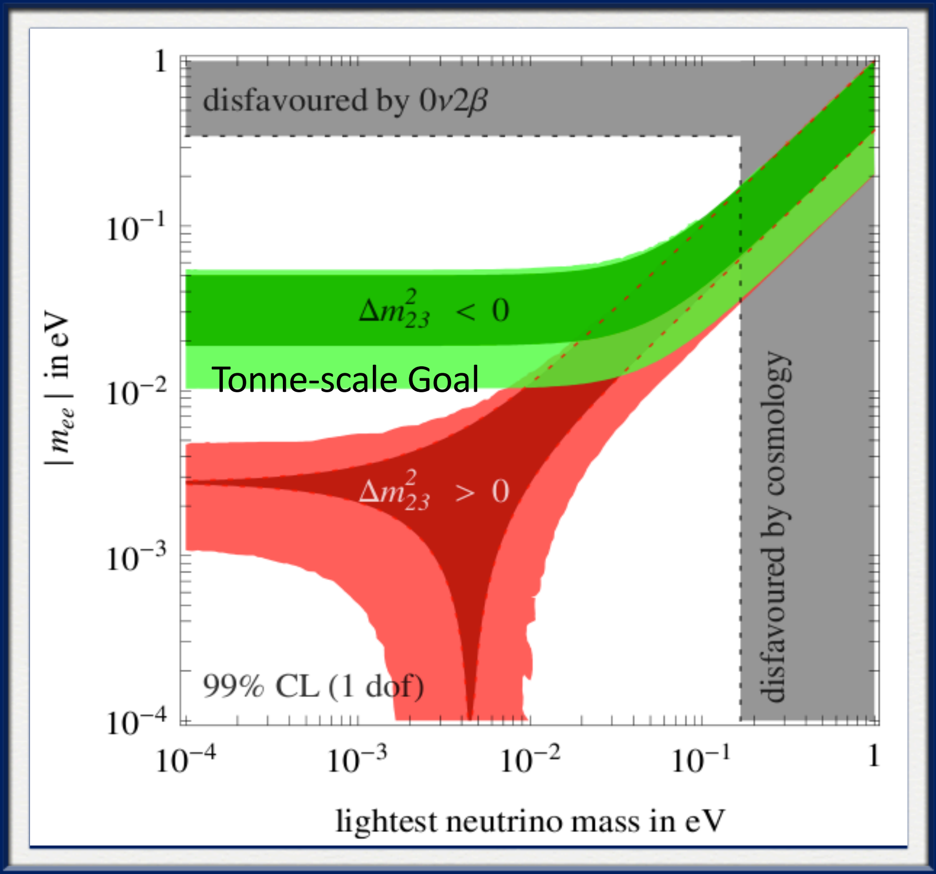
Small coeff.

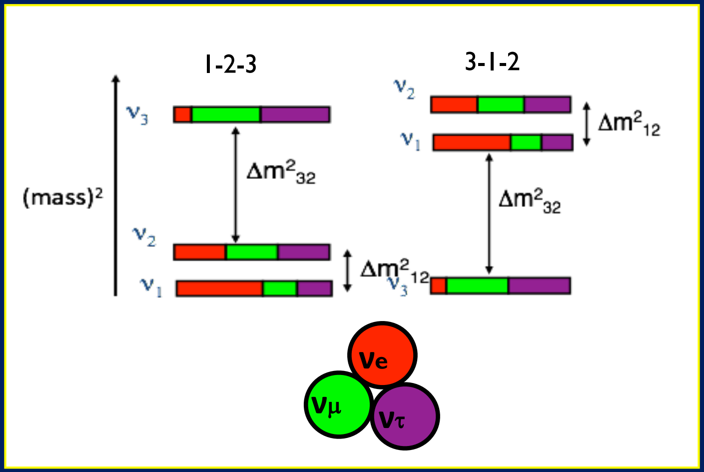
Fortunately, Avogadro's number is very big, so 10^{27} years ~ 1 tonne of isotope

Unfortunately, we don't know $m_{\beta\beta}$, or even which m_i is biggest.

Majorana Neutrinos and the Neutrino Mass Ordering

Interpretation of a null result depends on mass ordering of neutrinos





Neutrino Mass Ordering and Dirac CP Violation

Long Baseline Neutrino Oscillations

Extremely rich phenomenology:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}
\end{aligned}
$$

CP violating phase

$$
\begin{aligned}
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \boxed{\sin\delta \cdot} \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \boxed{\frac{a}{\Delta m_{31}^2}} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

Sign of neutrino ordering from matter effects

"All the neutrinos, all the time"

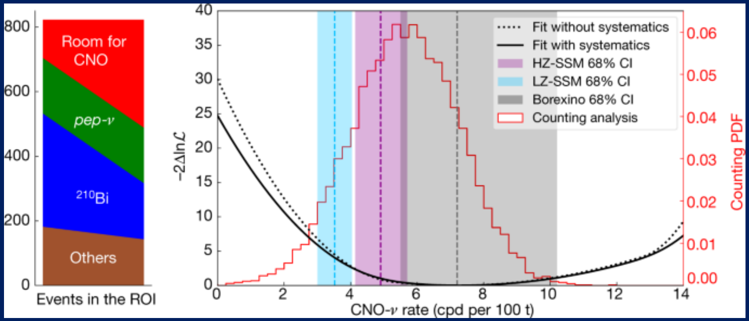
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

$$a = 2\sqrt{2} G_F n_e E$$

$$\mathcal{A}_{cp}(E_\nu) \approx \frac{\cos\theta_{23} \sin 2\theta_{12} \sin\delta}{\sin\theta_{23} \sin\theta_{13}} \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) + \text{matter effects.}$$

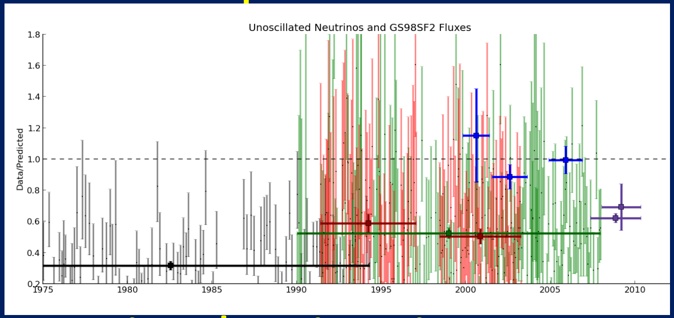
Neutrinos as Astrophysical Messengers

- Is the Sun as metal poor as it looks? If so, where did metals go…?



Borexino, *Nature*

- Are the Sun's core fusion processes stable with time?



A. LaTorre

- Does the Sun's neutrino luminosity agree with its total energy output?
- What will the next galactic supernova tell us about neutrinos, and supernovae?
- What do all the past supernovae tell us about stars?

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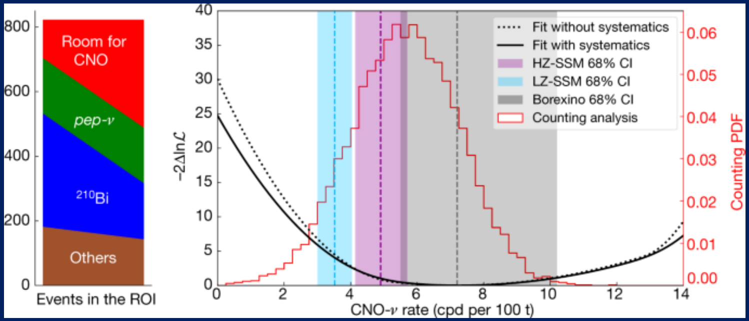

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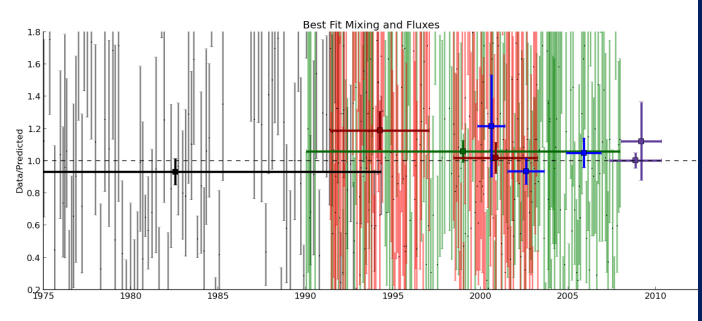

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A Broad Program…

With very different requirements…

Solar νs

Geo, reactor $\bar{\nu}$

DSNB

SN burst νs

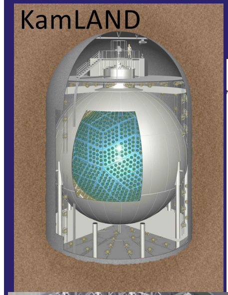
$0\nu\beta\beta$

Long Baseline

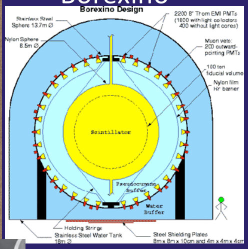
Atmospherics

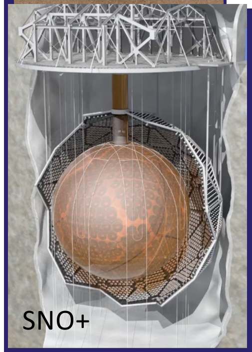
Extragalatic νs

KamLAND



Borexino





SNO+

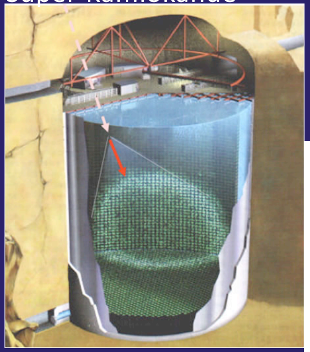
Requirements:

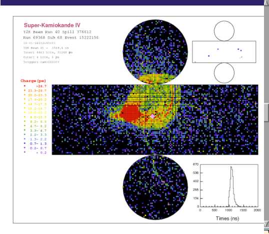
- Low radio backgrounds
- Excellent energy resolution
- Directional information

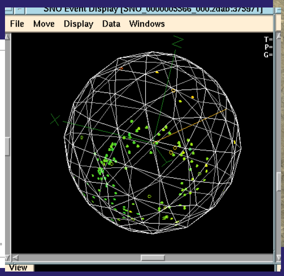
Requirements:

- Excellent PID
- Directional information
- Very big detector
- A beam

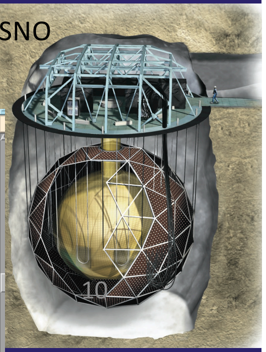
Super-Kamiokande





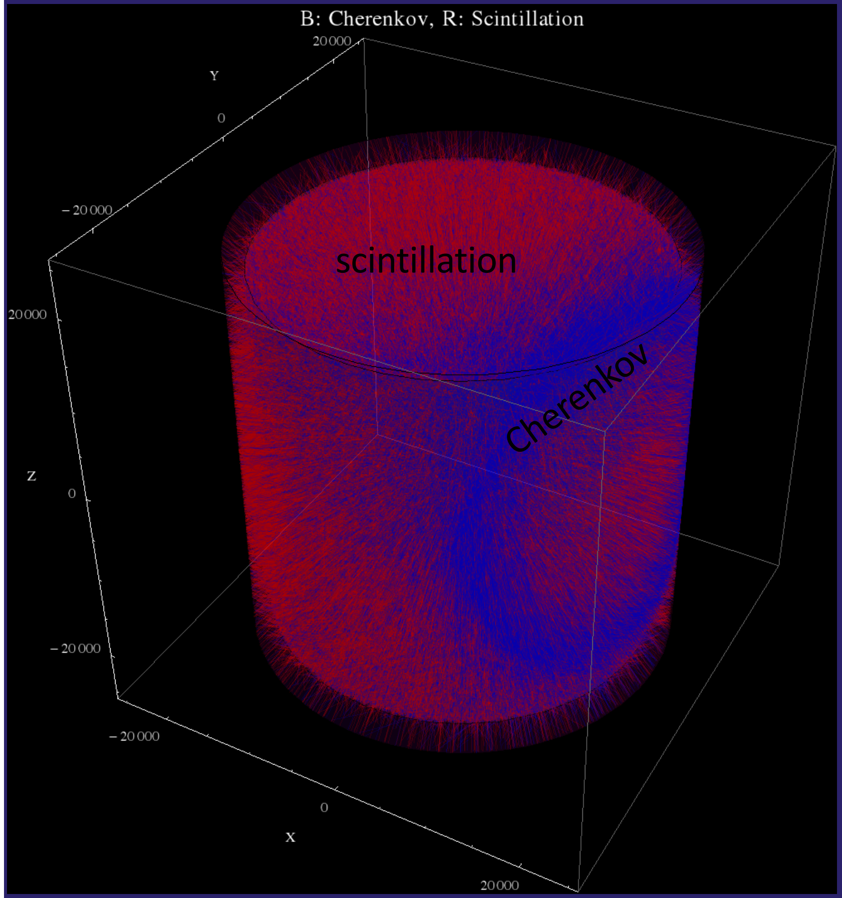


SNO



THEIA

Hybrid Cherenkov/Scintillation



Cherlight:

- Solar/SN direction
- Particle ID at high and low energies
- Measurement of velocity and path length

Scintlight:

- Energy resolution
- Particle ID at low energies
- Measurement of dE/dx

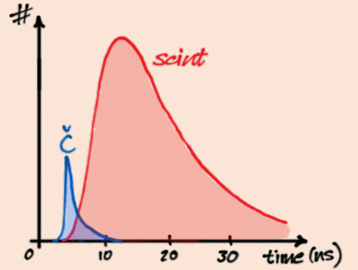
THEIA

Many new technologies for discriminating “chertons” from “scintons”

Timing

“instantaneous chertons” vs. delayed “scintons”

→ ns resolution or better

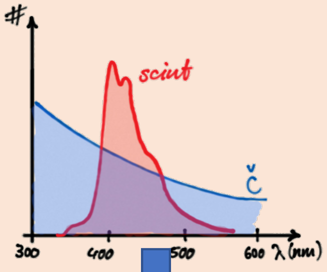


M. Wurm

Spectrum

UV/blue scintillation vs. blue/green Cherenkov

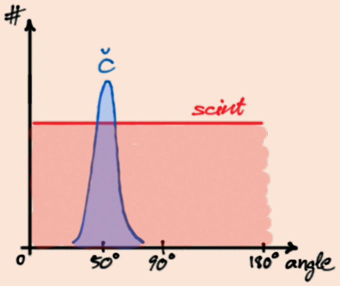
→ wavelength-sensitivity



Angular distribution

increased PMT hit density under Cherenkov angle

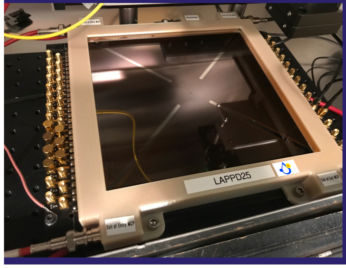
→ sufficient granularity

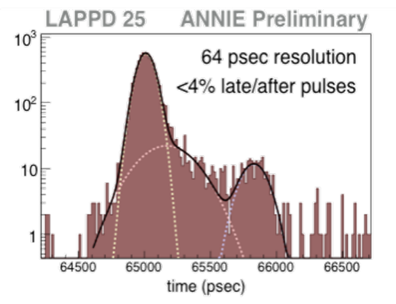


Multiple independent handles achieve:

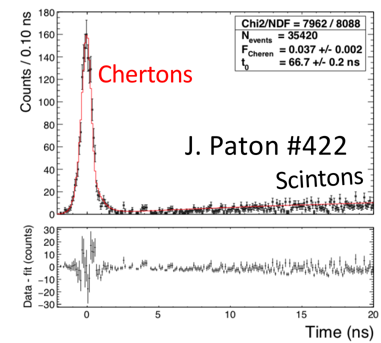
- **90% purity for Chertons**
- **Little loss of scintons**

LAPPDs



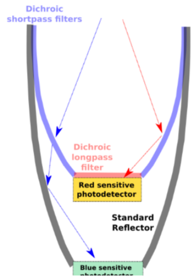


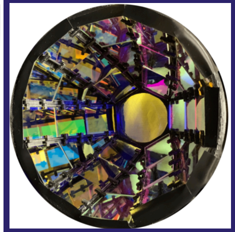
Slow Fluors

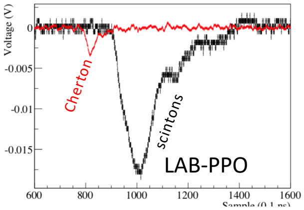


Biller, Leming, Paton NIMA 972 (2020) 164106

Spectral sorting--Dichroicons



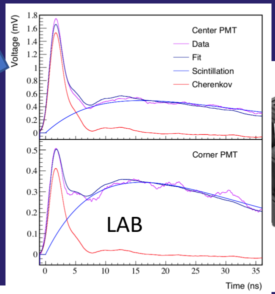


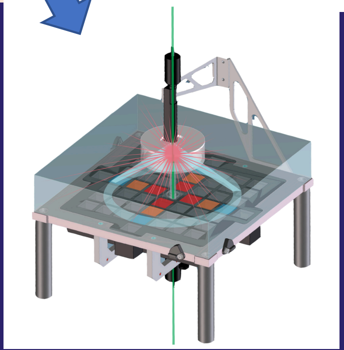


Kaptanoglu et al, PRD 101 (2020) 7, 072002

FlatDot measurements

Gruszko et al, JINST 14 (2019) 02, P02005

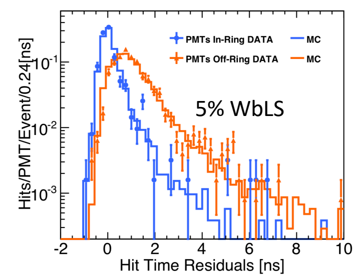


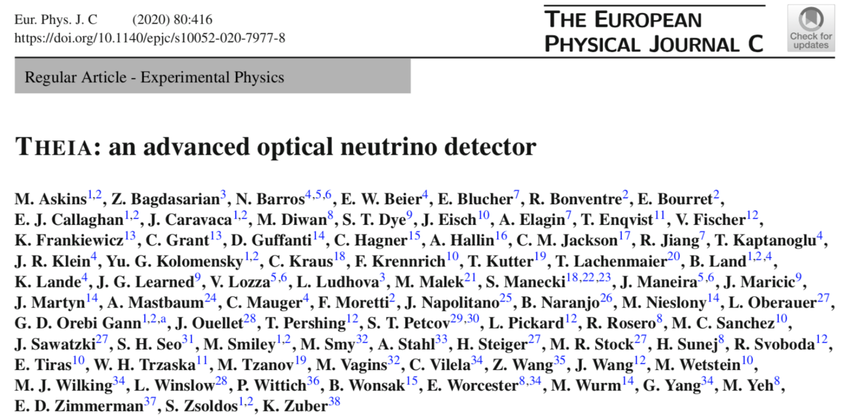


Caravaca et al, EPJC (2017) 77:811

CHESS Measurements

Caravaca et al, arXiv2002.00173(2020)





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

THE EUROPEAN PHYSICAL JOURNAL C

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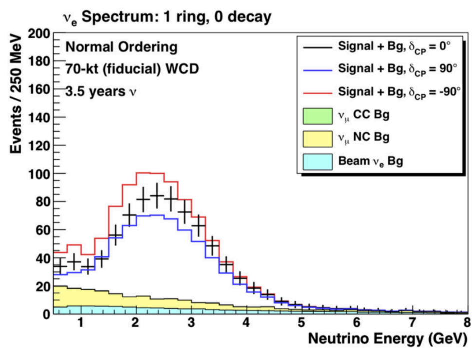
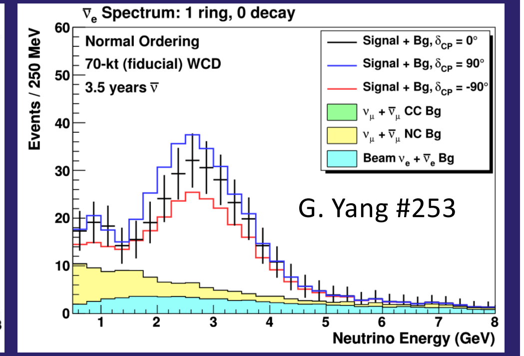
Regular Article - Experimental Physics

THEIA: an advanced optical neutrino detector

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

THEIA Long-baseline oscillations

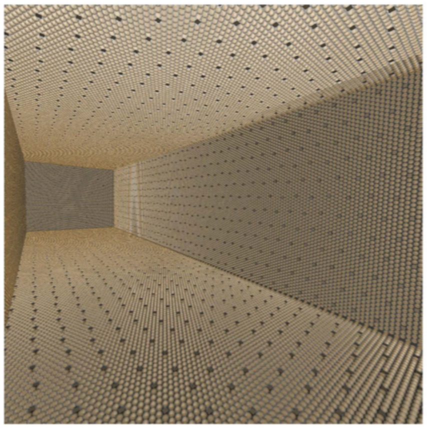




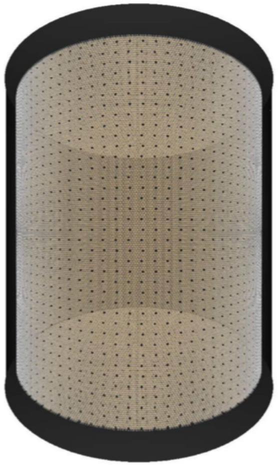
G. Yang #253

Examined two detectors @ LBNF:

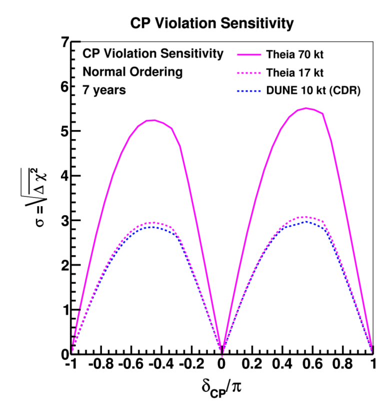
THEIA-25 (kt)

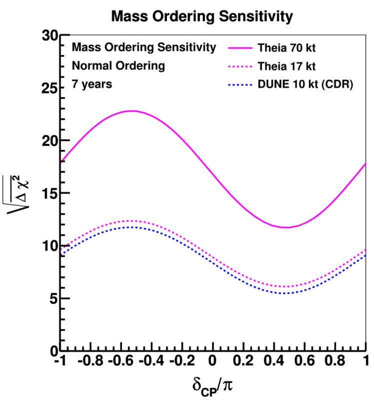


THEIA-100 (kt)



Assumes
- LBNF beam
- Super-K like performance
- Scintons ignored
- T2K-like reconstruction ("fitQUN")
- Includes multi-ring events
- Systematics like DUNE CDR
- Carbon targets in Near Detector



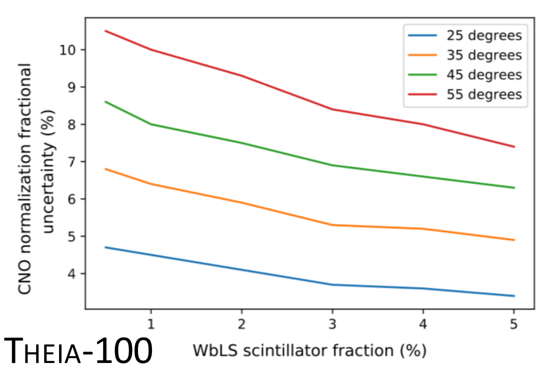


THEIA-25 (17 kt fid.) ~ Single DUNE 10 kt
THEIA-100 (70 kt fid) > 3 σ CP sensitivity over large fraction of phase space

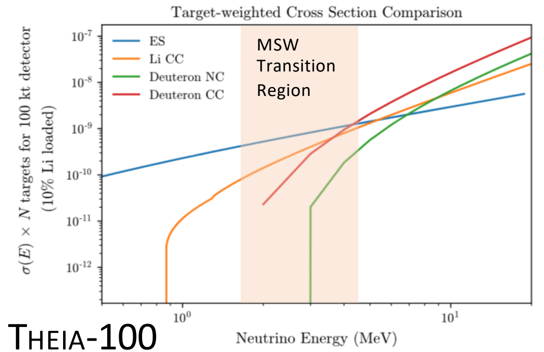
Phased program to increase light yield, Cher/Scint separation

THEIA ν astrophysics

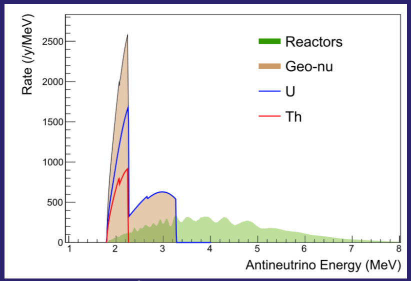
Precision CNO measurement via pointing



Possibility of CC on ^{7}Li for ^{8}B and SN

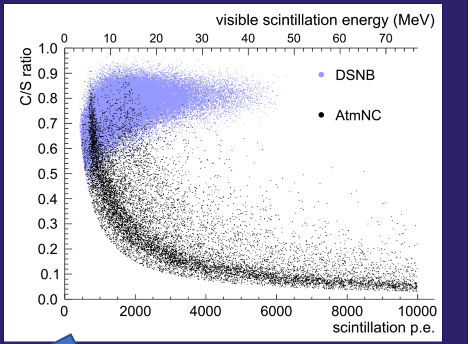


"Clean" geo-neutrino signal

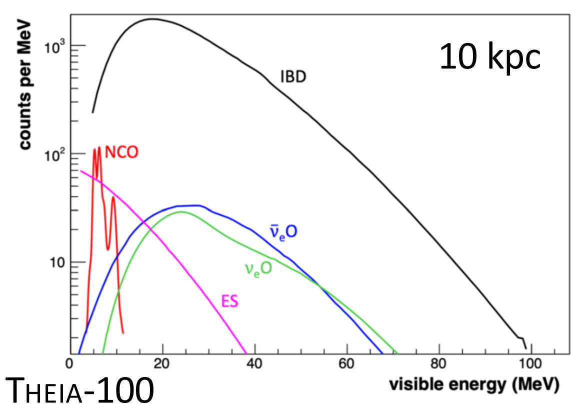


Allows U/Th measurement

DSNB Background rejection exploiting Cher/Scint Ratio

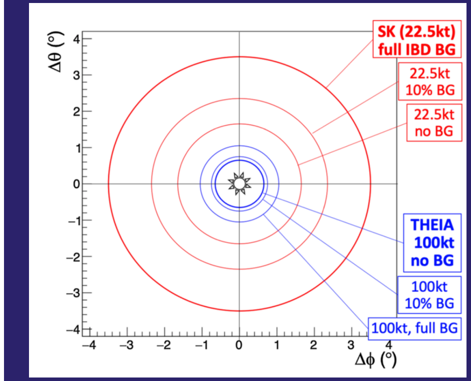


SN Burst neutrino spectra



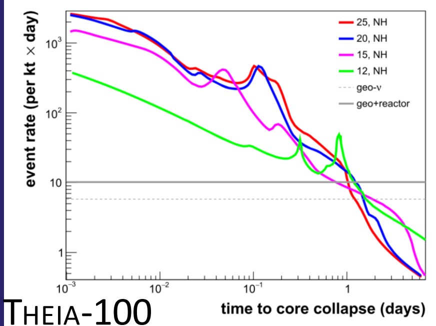
- ~200 events total from LMC
- IBD tagging via n capture
- Literally complementary to LAr

SN pointing ~ 2 degrees

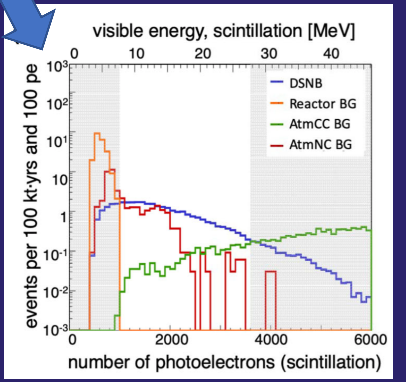


Burst Trigger latency ~100 ns

Pre-SN burst neutrinos



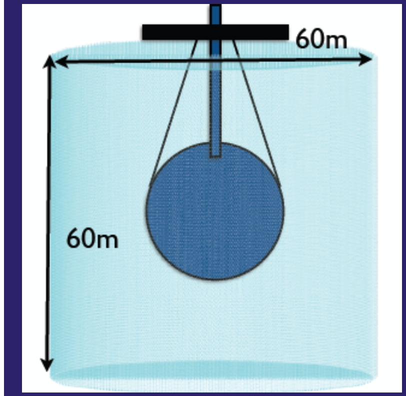
Low reactor/geo background--
3 σ detection 1 day before SN out to 3.3 kpc



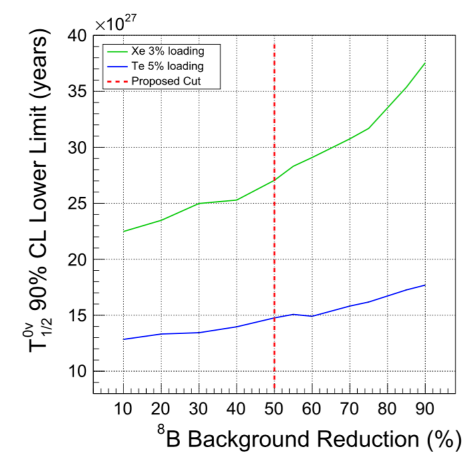
THEIA Beyond the Standard Model

Neutrinoless Double Beta Decay

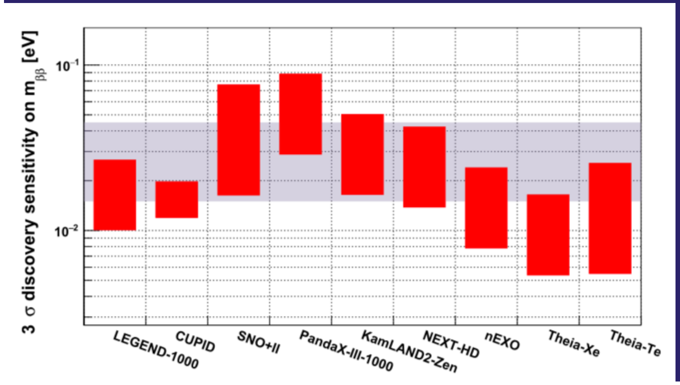
Requires inner containment bag for high LY scintillator



Dominant ^{8}B ν background reduced by pointing



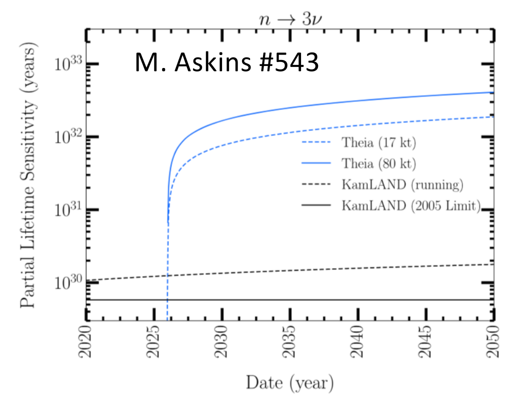
$T_{1/2} > 10^{28}$ y in 10 y for Te loading



Assumes:

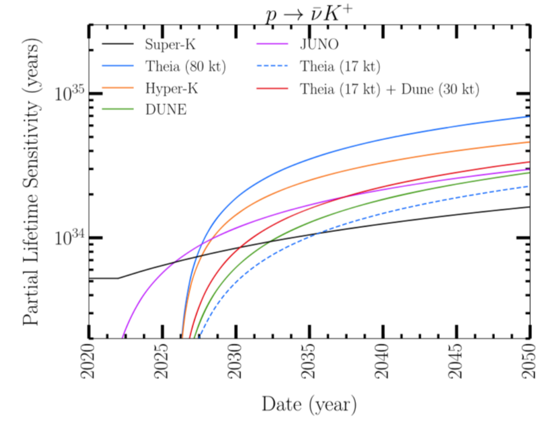
- 5% loading of ^{nat}Te
- 3% energy resolution at endpoint
- 50% removal of ^{8}B ν background

Nucleon Decay



Size and scintillation light provides excellent sensitivity to “invisible modes”

Detection of K$^+$ via scintillation light



What’s Needed?

- Depth (>=4850 ft should do fine)
- Beam like the LBNF beam
- A large cavity (17 ktonnes---100 ktonnes, depending on science goals)
- New technology (fluors/scintillators, dichroicons, fast timing, loading)
- Very clean environment
- A forward-looking infrastructure for a phased program