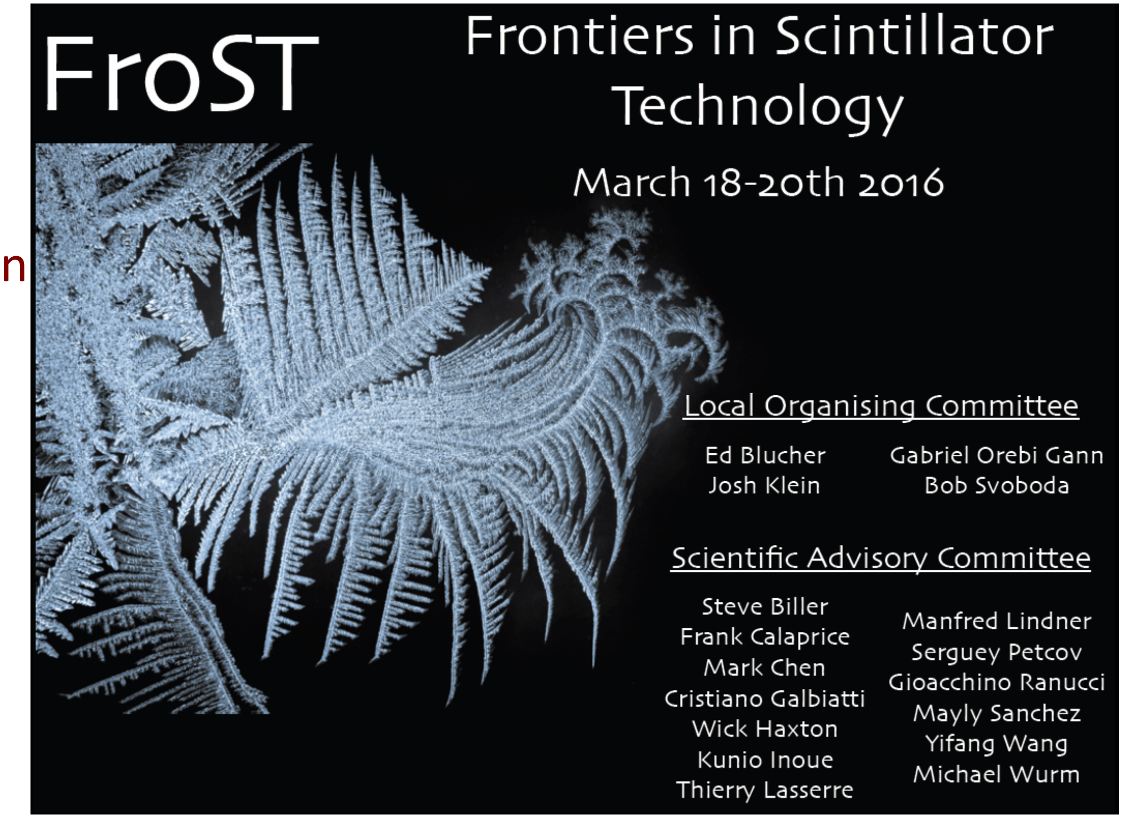
Beyond* [Long Baseline] Neutrino Oscillations with Scintillator-based Detectors

- Opportunity with LBNF and scintillator detector
- Physics motivations and possible program
- Path Forward

Josh Klein, Penn
June 20, FNAL PAC

Scintillator Workshop at FNAL



International representation from:
Daya Bay, RENO, BOREXINO, JUNO, SNO/SNO+, KamLAND/KamLAND-Zen Super-K, NOνA, Double CHOOZ, NuPrism, ANNIE, WATCHMAN, Prospect, LENA,THEIA

Countries:
Canada, China, France, Germany, Italy , Japan, Korea, UK, US

Speakers:
N. Lockyer, G.D. Orebi Gann, P. Huber, E. Worcester, M. Chen,S.D. Biller, M. Smy, M. Vagins, M. Wurm, R. Svoboda, G. Gratta, J. Link, I. Shimizu, S. Manecki, M. Pallavicini, A. Konaka, S-H. Seo, S. Mufson, B. Yu, K. Heeger, M. Hartz, M. Malek, T. Enqvist, A. Cabrera, M. Yeh, L. Bignell, T. Wongjirad, F. Calaprice, S. Li, Z. Wang F. Suekane, Y. Hotta, M. Wetstein, M. Sakai

Beyond LBL Oscillations

Critical Physics of and with Neutrinos

- Majorana vs. Dirac
- Solar neutrinos
- Sterile Neutrinos
- (Nucleon Decay)
- Non-standard interactions
- Mixing angles and mass differences in (1,2) sector
- Geoneutrinos
- Supernova burst neutrinos
- Diffuse supernova (anti)neutrino background

(Clearly this list is not exhaustive)

LBNF will be a world resource hosted in the US---
Investment happening now makes future broad program possible. Depth is crucial.

Broadening the Program

But requirements for various physics goals are in tension:

Physics	Size	Cherenkov Priority	Scintillation Priority	Cleanliness Priority
$0\nu\beta\beta$	~few ktonne	Medium	Very high	Very High
Low E Solar νs (< 1MeV)	~10 ktonne	High	Very high	Very High
High E Solar νs (> 1 MeV)	>50 ktonne	High	Low	High
Geo/reactor anti-νs	~10 ktonne	Low	High	Medium
DSNB anti-ns	>50 ktonne	Low	High	Medium
Long-baseline νs	> 50 ktonne	Very high	Low	Low
Nucleon decay (K+ anti-ν)	> 100 ktonne	High	High	Low

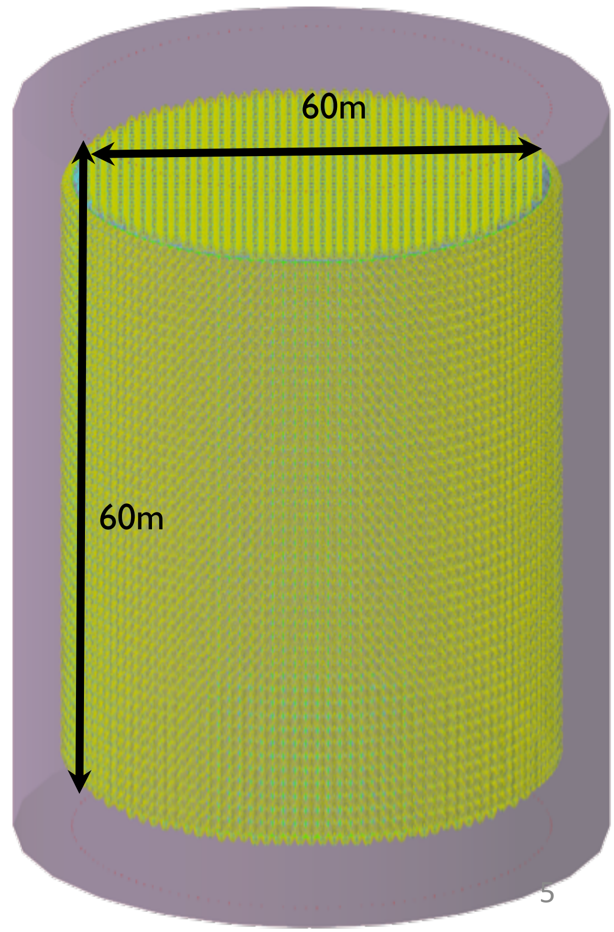
- Low-energy physics wants a clean detector with a lot of light
- High-energy physics wants a big detector with direction reconstruction

Reference Detector "Theia"

Reference Design:

- 50-100 ktonnes WbLS
- Cylindrical geometry
- Up to 80% coverage with photon sensors
- 4800 mwe underground
- Loading of various isotopes (Gd, Li, Te, Xe)
- Ability to deploy inner "bag"

"Forward-looking infrastructure" would allow long-term, phased program to accomplish complete program.



Majorana vs. Dirac

A simple conceptual model

	"Old"		"New" (Have no weak interactions)
"Dirac neutrinos"	ν_L		ν_R
	$\overline{\nu}_R$		$\overline{\nu}_L$

How are these different?

So maybe we only have two states after all:

$$\nu_L \quad \nu_R$$

Which basically means

$$\nu = \overline{\nu}$$ "Majorana neutrinos"

So what?

Majorana vs. Dirac

If neutrinos are Majorana, then:

1. We need a new mass-generating mechanism
   - Simplest term is dimension-5 and not renormalizable!
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

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

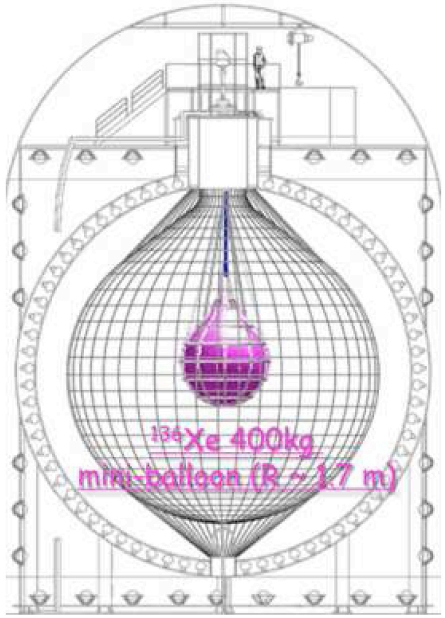
If neutrinos are Dirac, then:

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

$0\nu\beta\beta$ with Liquid Scintillator

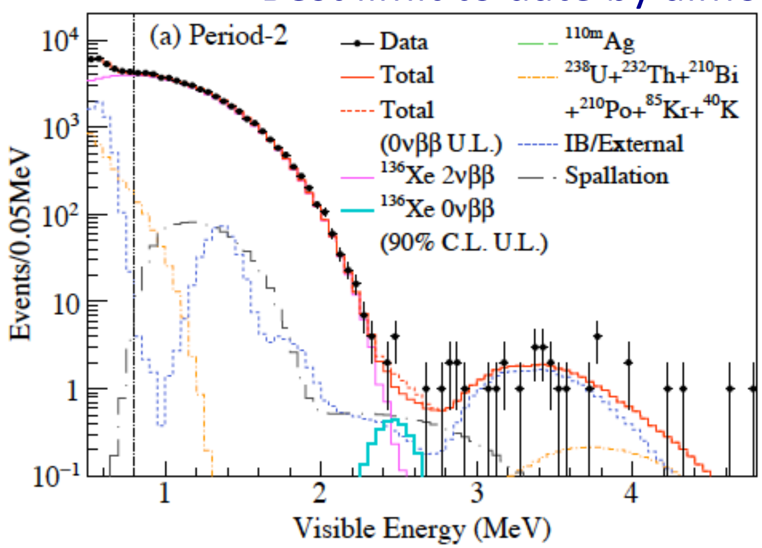
KamLAND-Zen

~100 kg ^{136}Xe (fiducial)

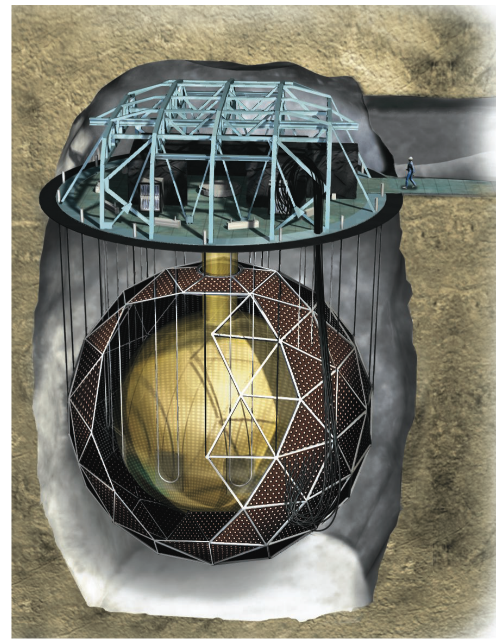


$T_{1/2}$>1.1x10^{26}y 90%CL

Best limit to date by almost x10



SNO+

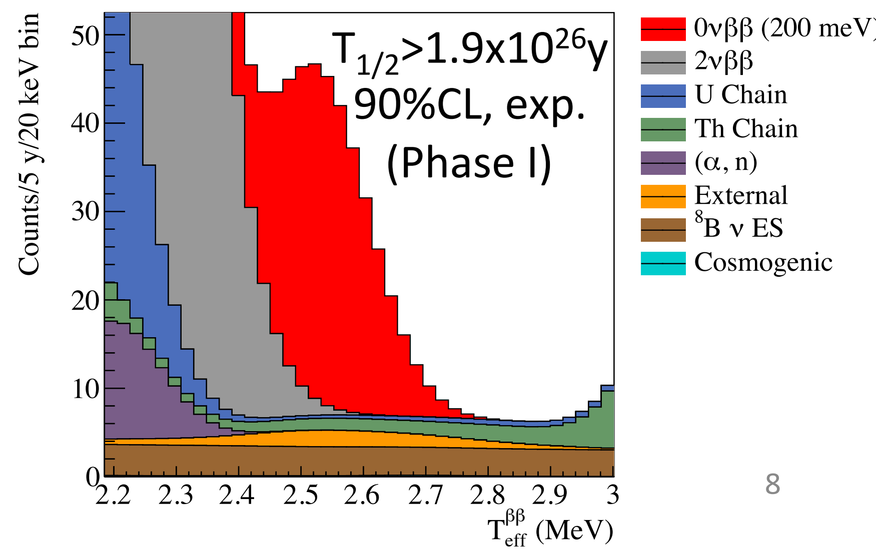


Phase I:

260 kg ^{130}Te (fiducial)

Phase II:

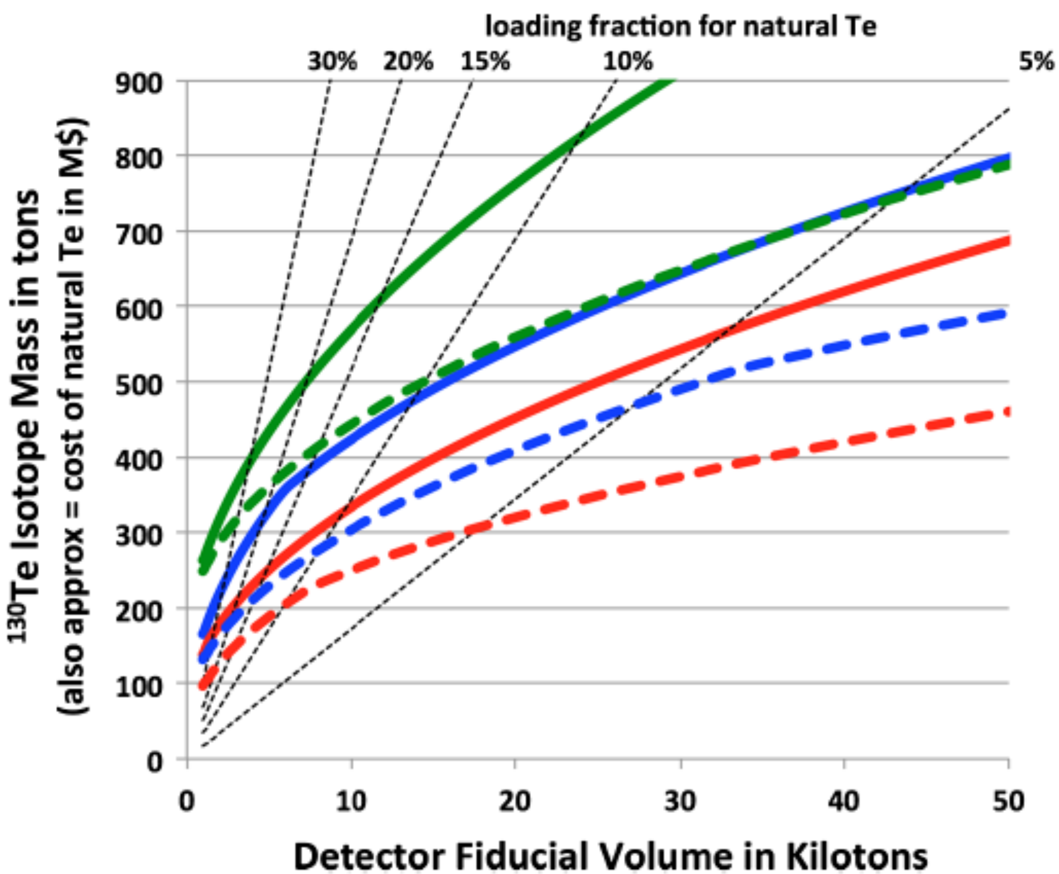
1500 kg ^{130}Te (fiducial)

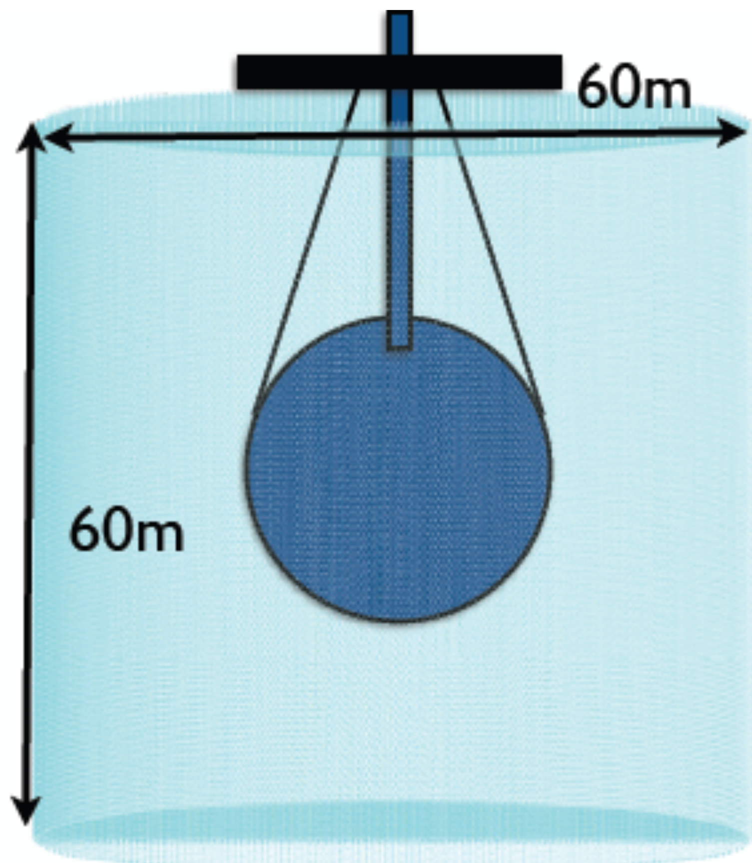


0νββ at THEIA

Going further….

With 1000 pe/MeV (green) or more, can get 90% CL at 2.5 meV!





S.D. Biller, PRD **87,** 071301, (2013)

0νββ at THEIA

Going further….

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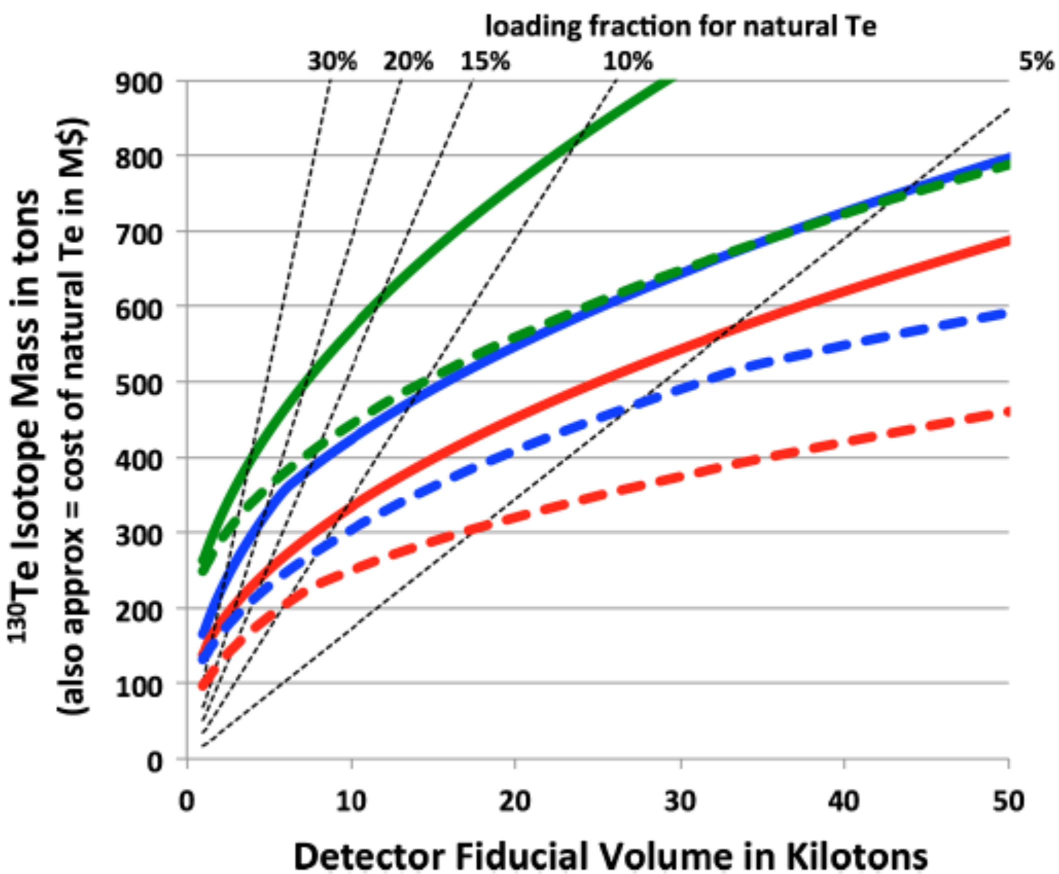
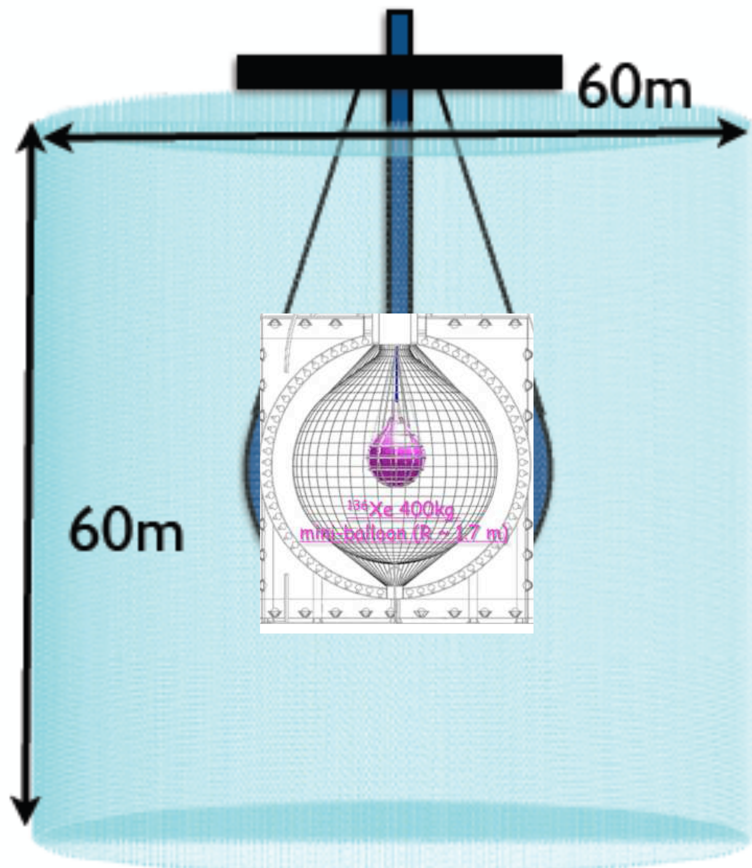
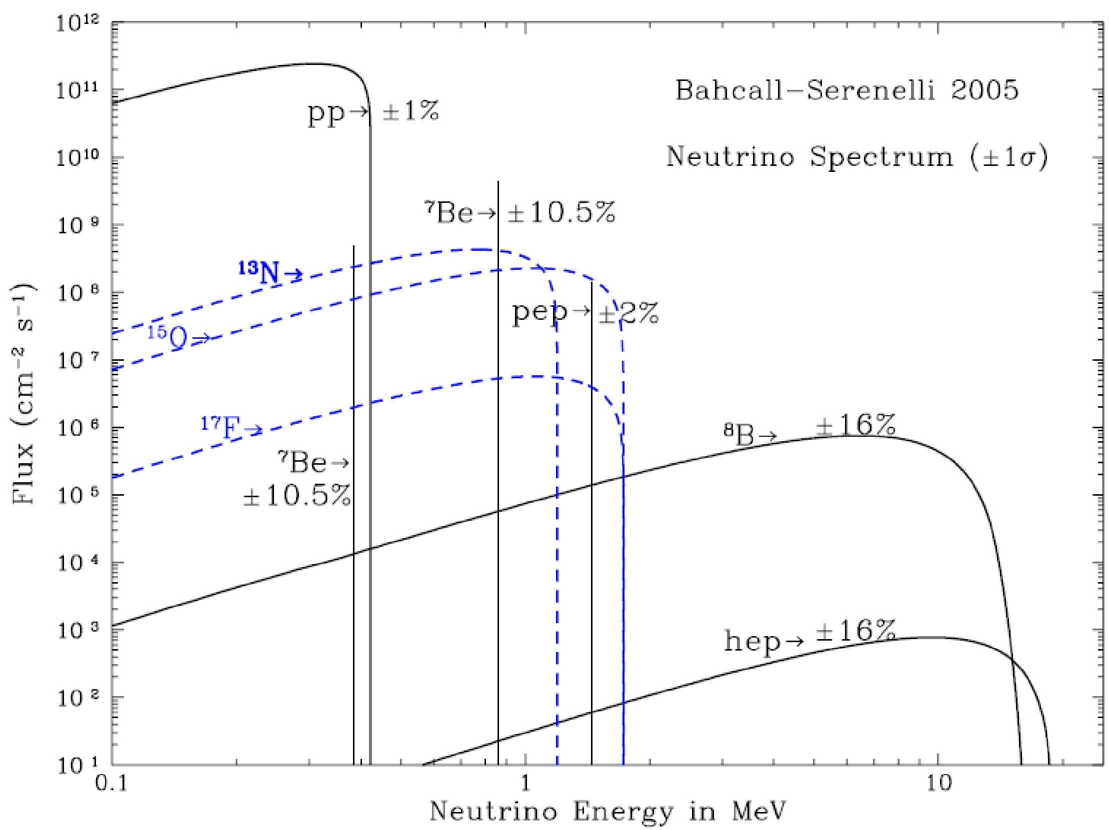




S.D. Biller, PRD **87,** 071301, (2013)

Solar Neutrinos

- Broadband and mono-energetic, background-free ν_e beam
- Flux in some cases measured as precisely as ~3%
- Flux in some cases predicted as precisely as 1%
- Matter effects are crucial and observable
- Source itself is interesting---and beam operations fits within FY2025



Six Things We Should Measure

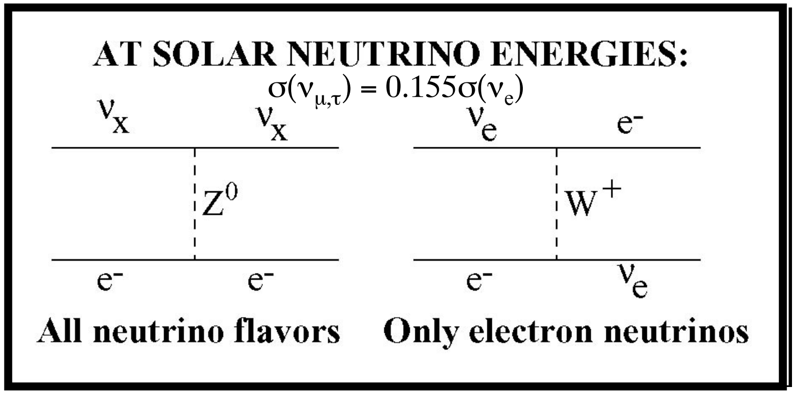
(in no particular order)

1. Vacuum/matter transition region
2. Precision ^{8}B Day/Night asymmetry
3. Exclusive, precision measurement of pep flux
4. Exclusive, precision measurement of CNO flux
5. Exclusive, precision measurement of pp flux
6. Observation of solar hep neutrinos

Physics Drivers:

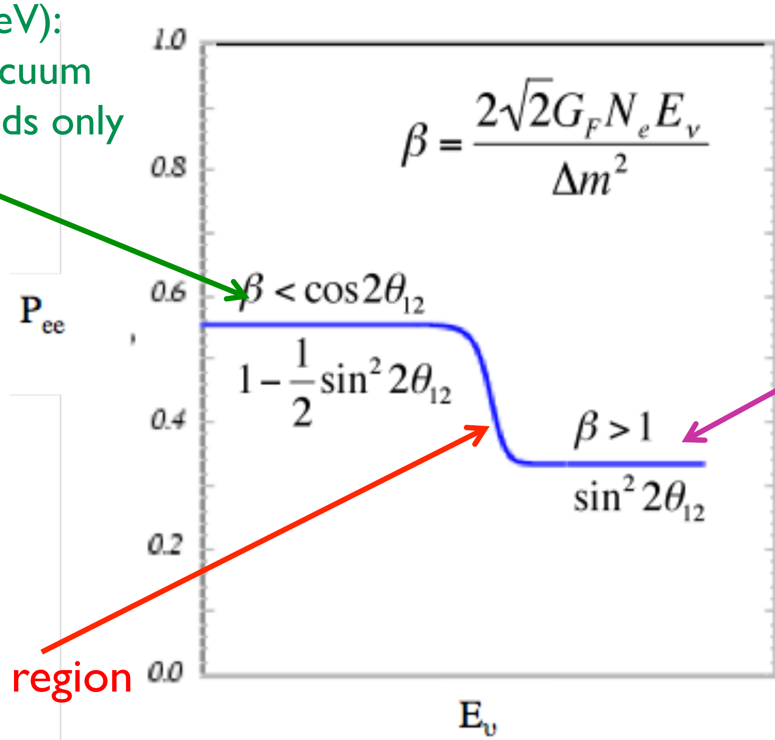
- Exploit the discovery of neutrino mass
- Search for the unknown

Observing MSW Phenomenology



Day/Night ν_e Asymmetry

Low energy (<1MeV): Phase-averaged vacuum oscillations; depends only on θ_{12}



Transition region

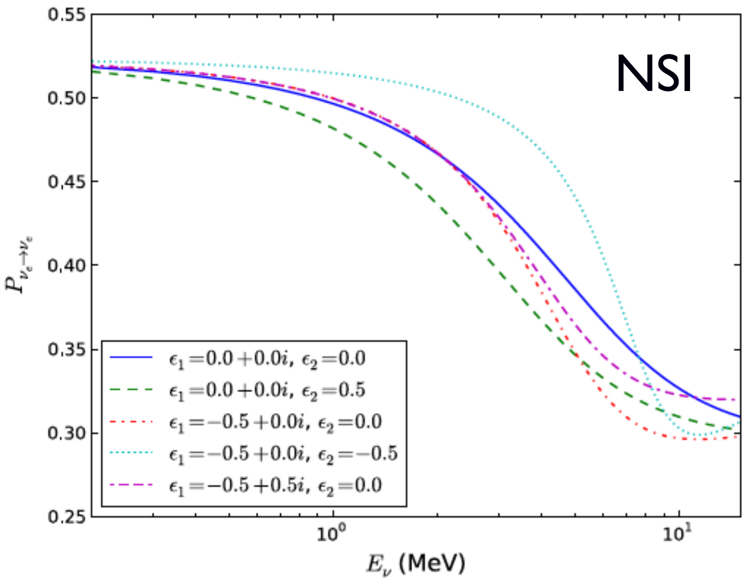
'High' energy (>5MeV): Matter-dominated conversion; depends only on θ_{12}

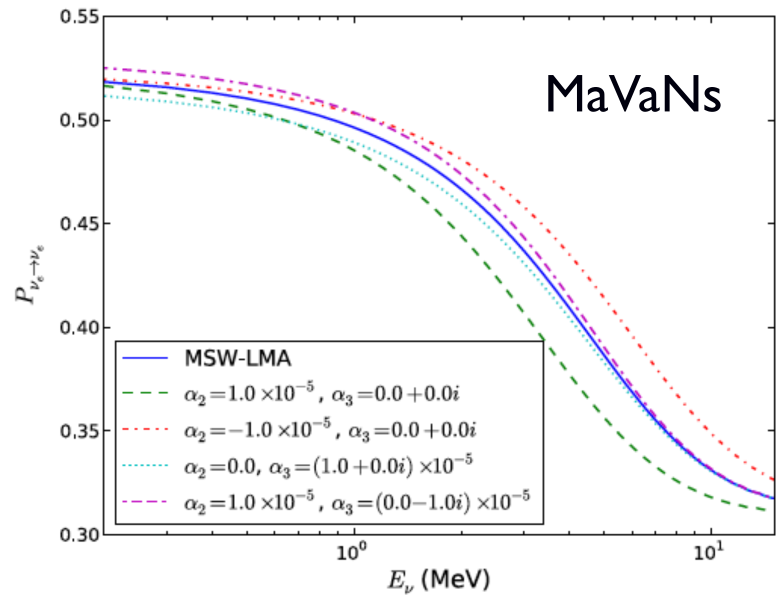
Interferometry on top of interferometry…

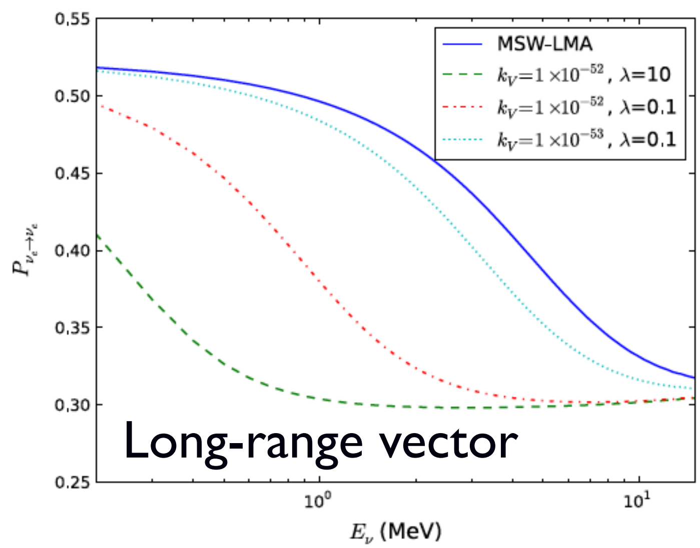
Anything that distinguishes flavor or mass states changes position and width of transition region

Observing MSW Phenomenology

Vacuum/matter transition region



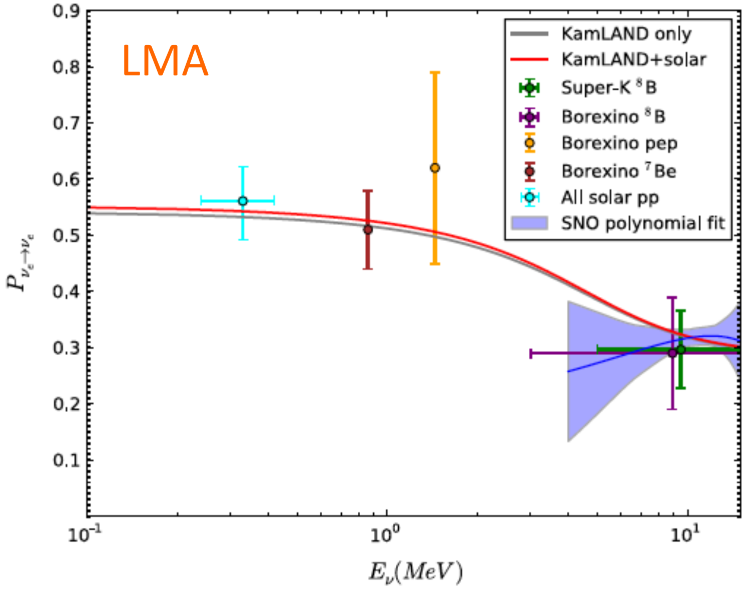


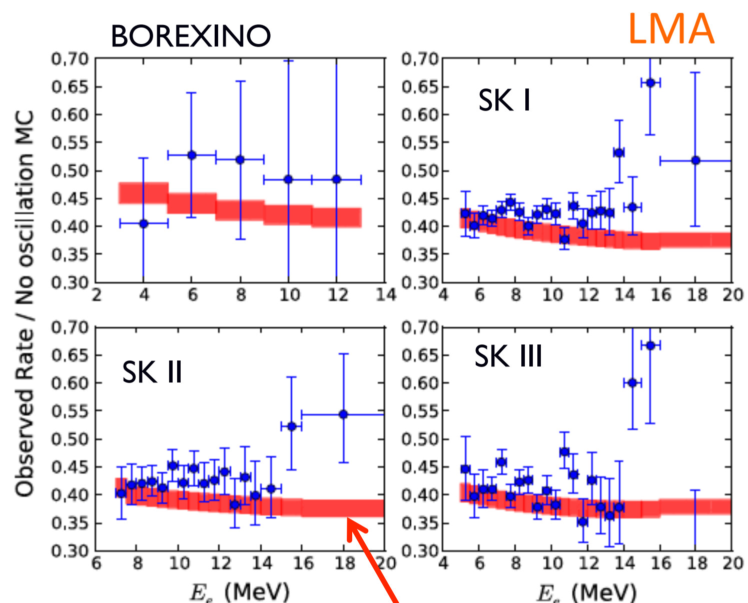


Bonventre, LaTorre, et al.

PHYSICAL REVIEW D **88**, 053010 (2013)

Other Models



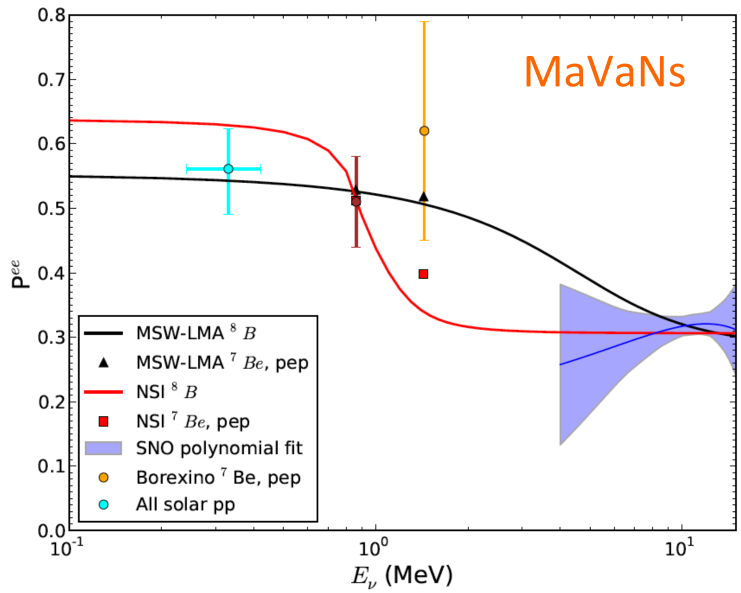


Bonventre, LaTorre, *et al*, Phys. Rev. D 88 (2013) 053010

Best fit for mass-varying neutrinos

$\Delta\chi^2 = 3.3$

C.L. = 0.81



Sensitivity non-standard effects entirely driven by lack of precision ^{8}B data in transition region—

Need low threshold, high statistics!

=Big scintillation detector.

pp/pep and the Sun

Are all energy generation/loss mechanisms accounted for?

With luminosity constraint:

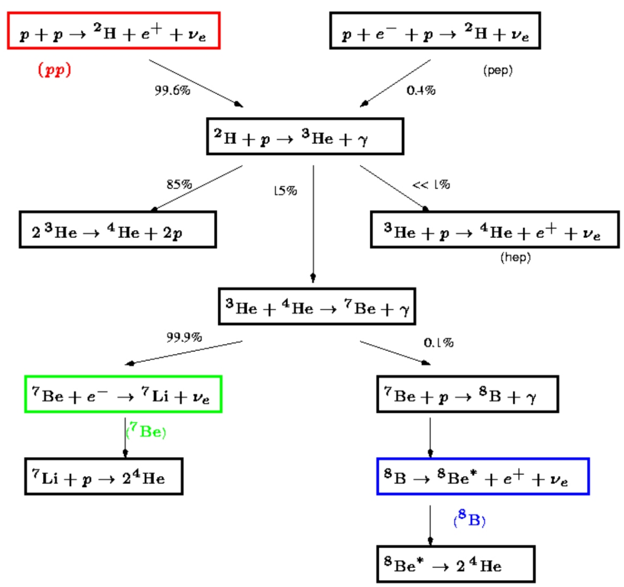
Exp. Uncs.   Theory Uncs.

$$\phi(\mathrm{pp})_{\mathrm{measured}} = (1.02 \pm 0.02 \pm 0.01)\phi(\mathrm{pp})_{\mathrm{theory}}$$
$$\phi(^8\mathrm{B})_{\mathrm{measured}} = (0.88 \pm 0.04 \pm 0.23)\phi(^8\mathrm{B})_{\mathrm{theory}}$$
$$\phi(^7\mathrm{Be})_{\mathrm{measured}} = (0.91^{+0.24}_{-0.62} \pm 0.11)\phi(^7\mathrm{Be})_{\mathrm{theory}}$$

Bahcall and Pinsonneault

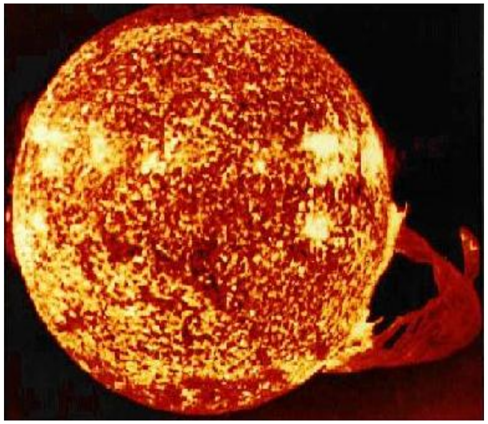
But without constraint: $L_\nu/L_\odot$ known only to 20-40%

→ \`Unitarity' test that integrates over a lot of new physics



CNO and the Sun

The solar `metallicity problem'



the ar. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars. ---John Bahcall, PR, (1964)

- Helioseismology convinced `everyone' that SSM was correct
- Modern measurements of surface metallicity are lower than before
- Which makes SSM helioseismologic predictions wrong

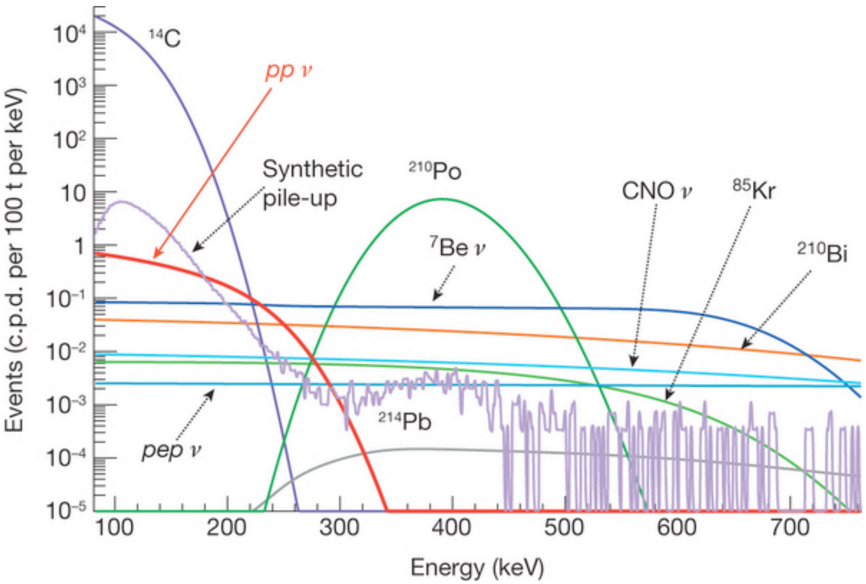
But! CNO neutrinos tell us metallicity of solar core

→ Flux may differ by factor of 2 between old/new metallicity

(Maybe Jupiter and Saturn `stole' metals from solar photosphere?
---Haxton and Serenelli, Astrophys.J. 687 (2008)

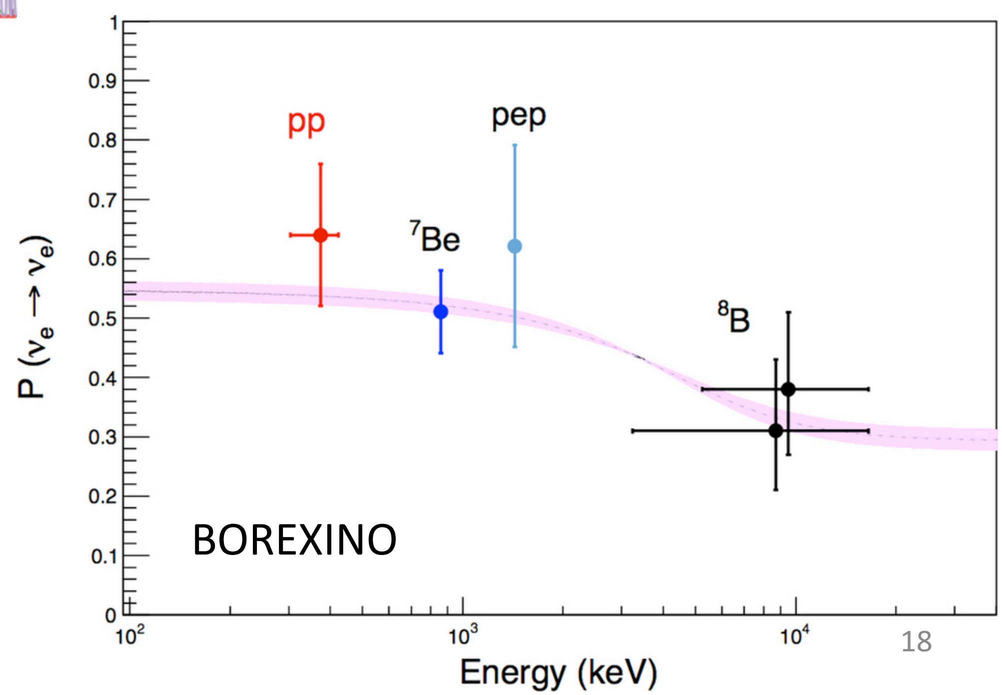
pp Measurements

BOREXINO spectacularly clean…first *exclusive* pp measurement!



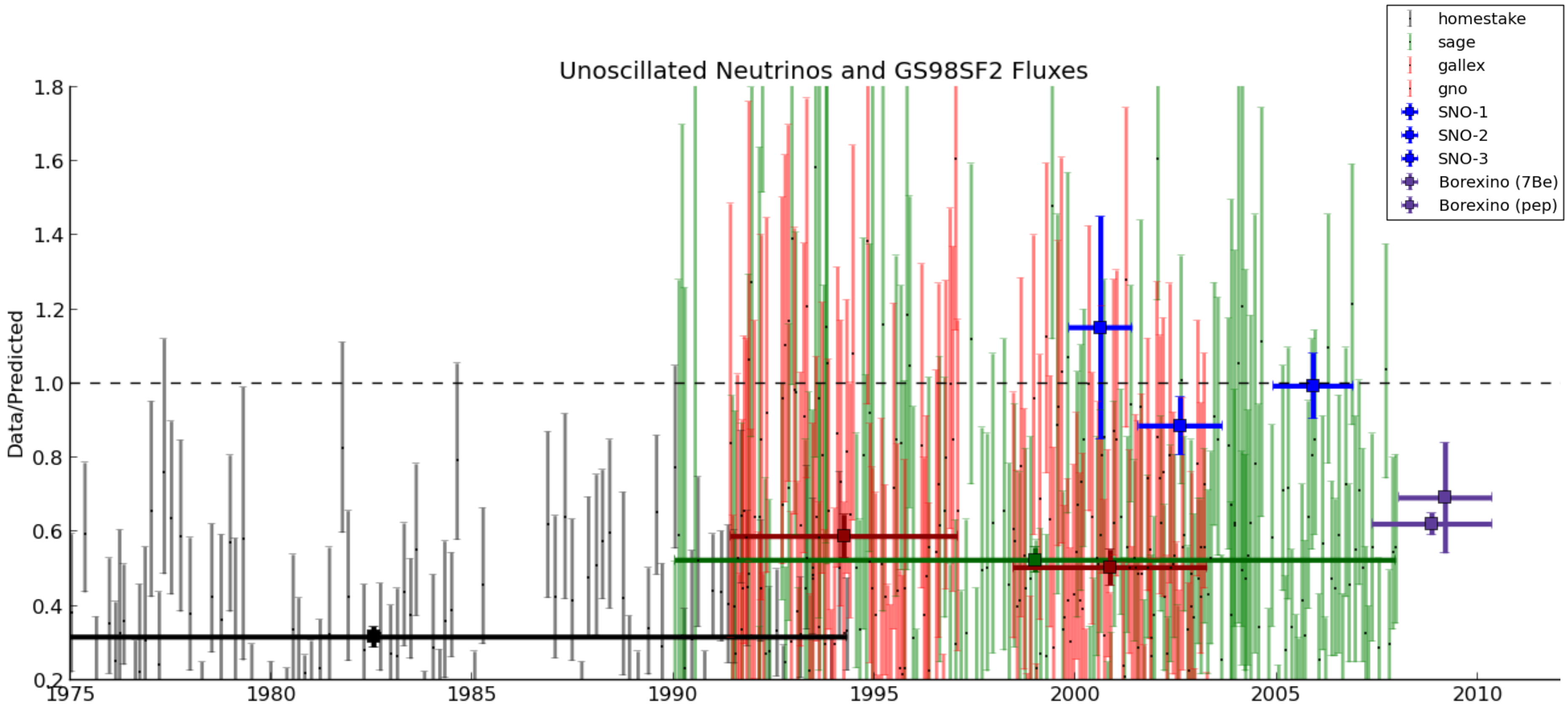
Precision comparable to inclusive Ga experiments

But far from what is needed for precision luminosity test.



The (Very) Recent History of the Solar Core

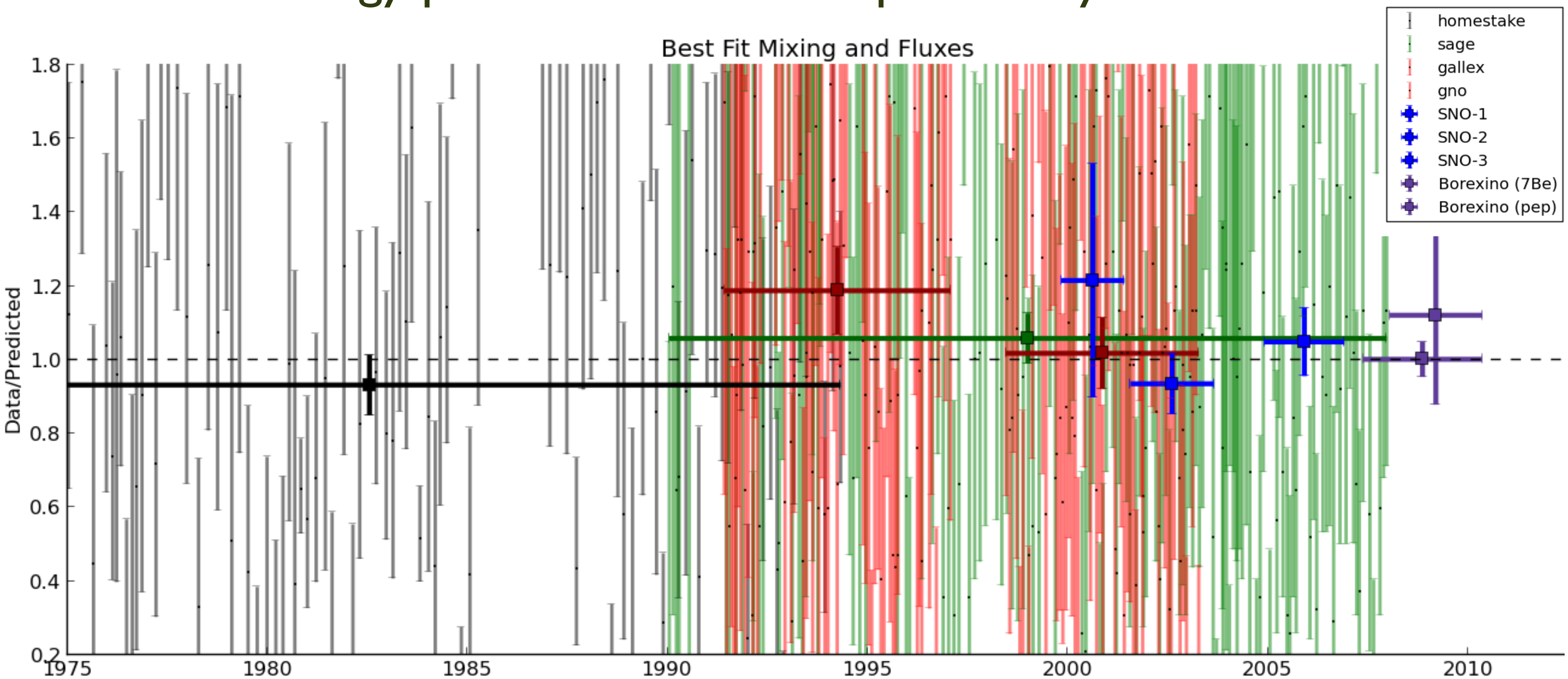
Without mixing correction, this is a history of the Solar Neutrino Problem



A. LaTorre

The (Very) Recent History of the Solar Core

Correcting for mixing angles, this is the stability of solar energy production over the past 45+ years.

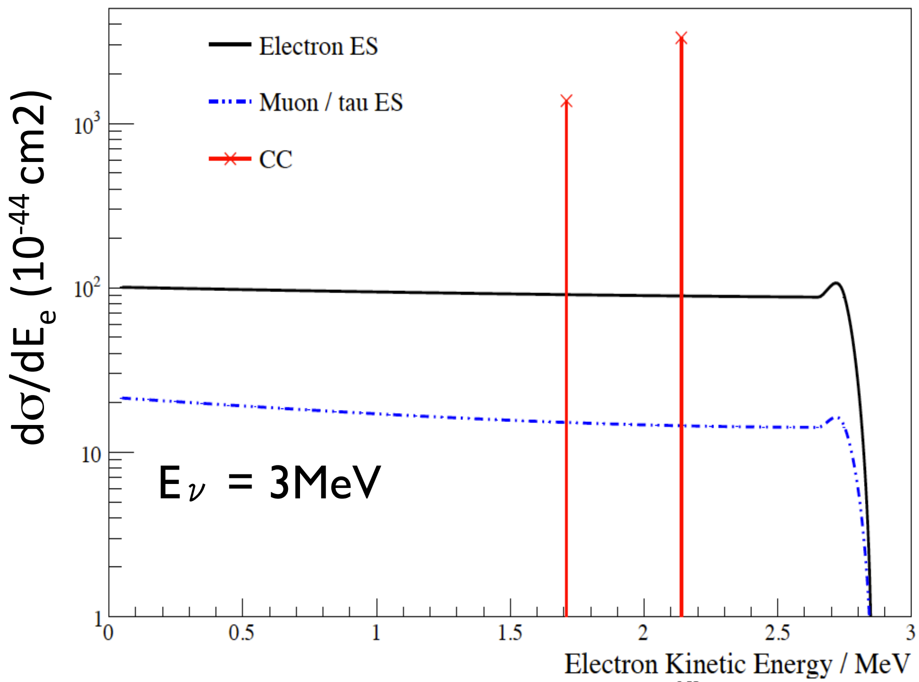


A. LaTorre

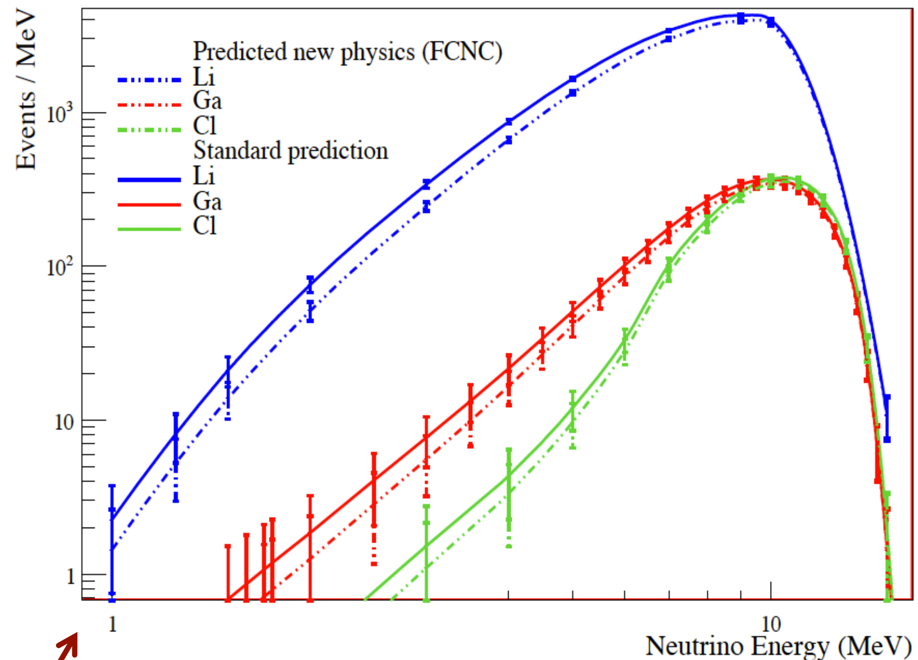
Solar νs in Liquid Scintillator

"Salty water Cherenkov detectors" W.C. Haxton PRL 76 (1996) 10

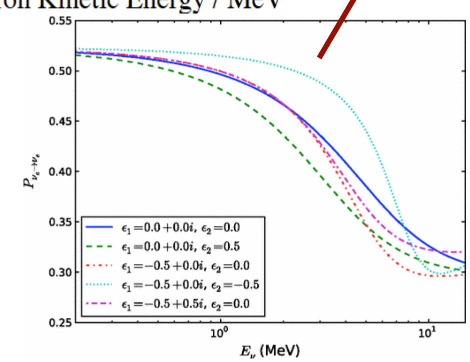
Loading with (e.g.) ^{7}Li provides CC cross section with narrow dσ/dE.



Makes models easy to distinguish

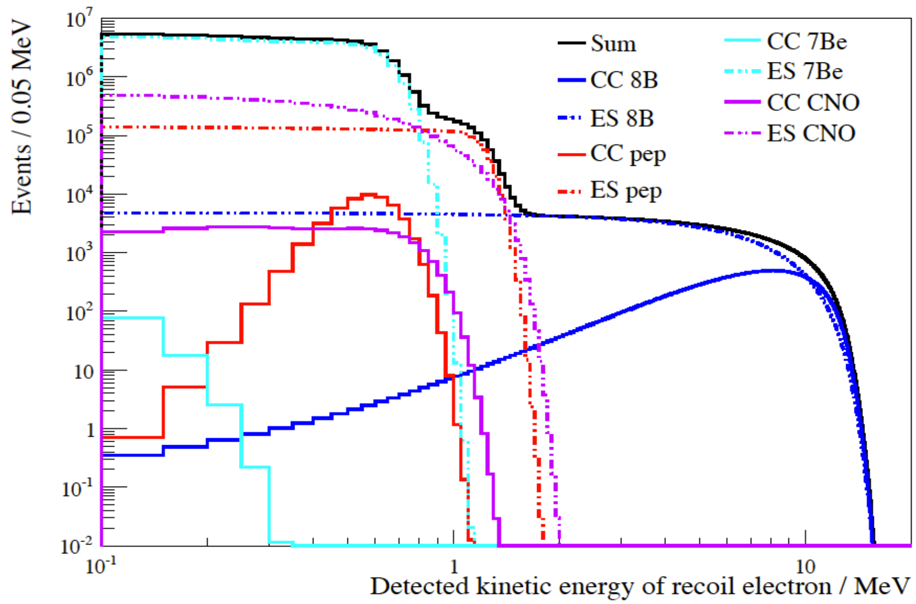


G. D. Orebi Gann (Berkeley)

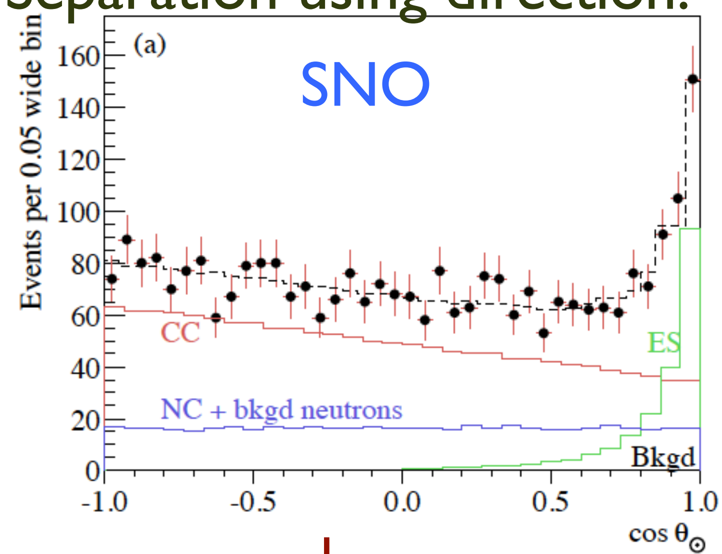


Solar νs in Water-based Liquid Scintillator

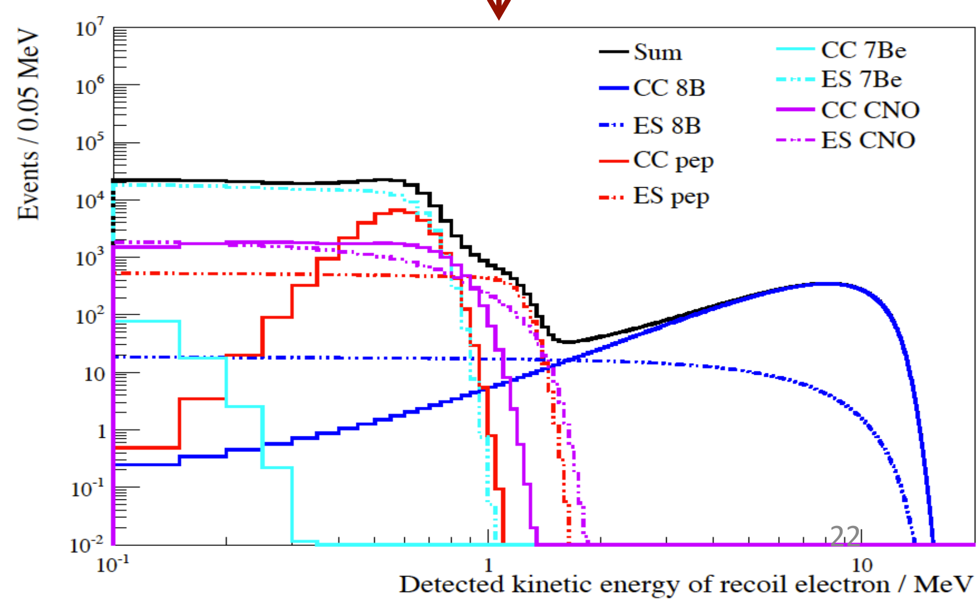
Low-energy solar νs also now possible via CC and ES:



Separation using direction:



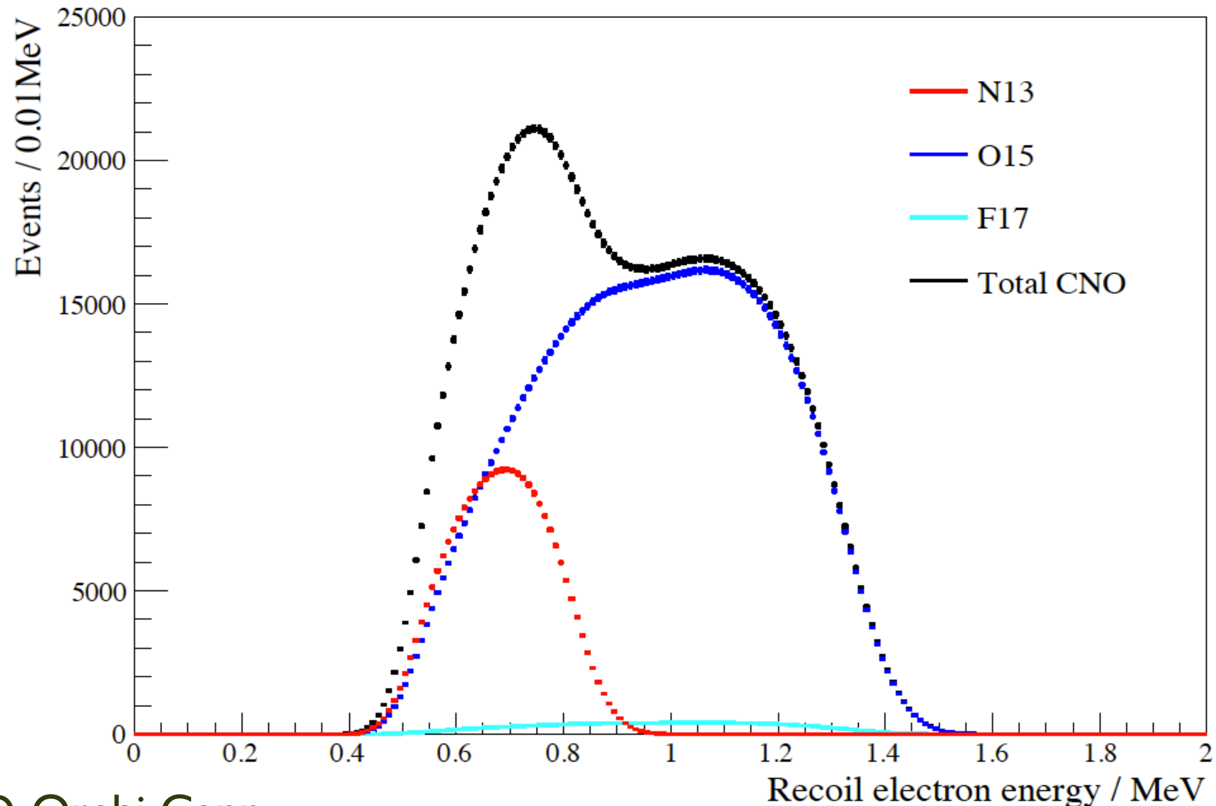
G.D. Orebi Gann



CC+ES also yields total flux via NC component of ES

Solar νs at THEIA

CC spectral sensitivity might also allow shape separation of CNO components

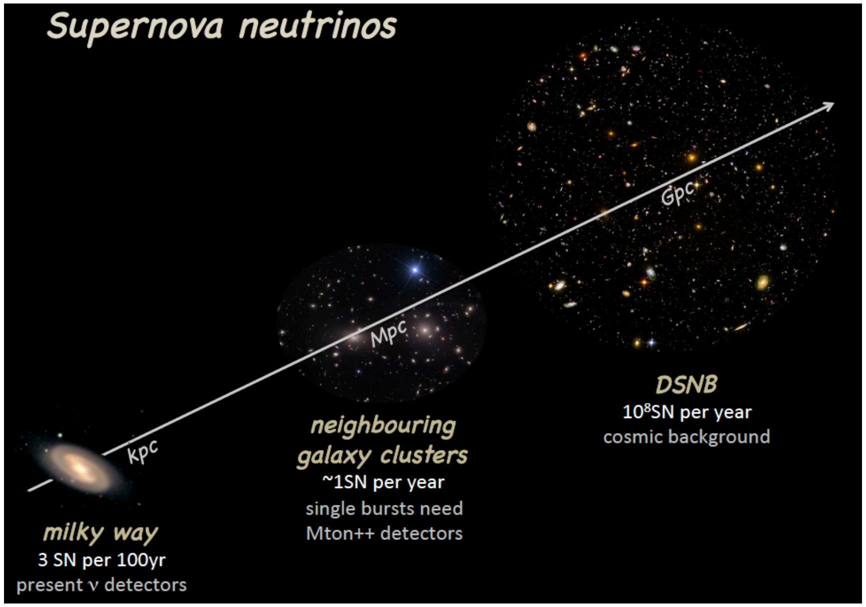


G.D. Orebi Gann

What about *pp*?

About 5×10^6 events/year in 50 ktonne!

Diffuse Supernova (Anti)Neutrino Background

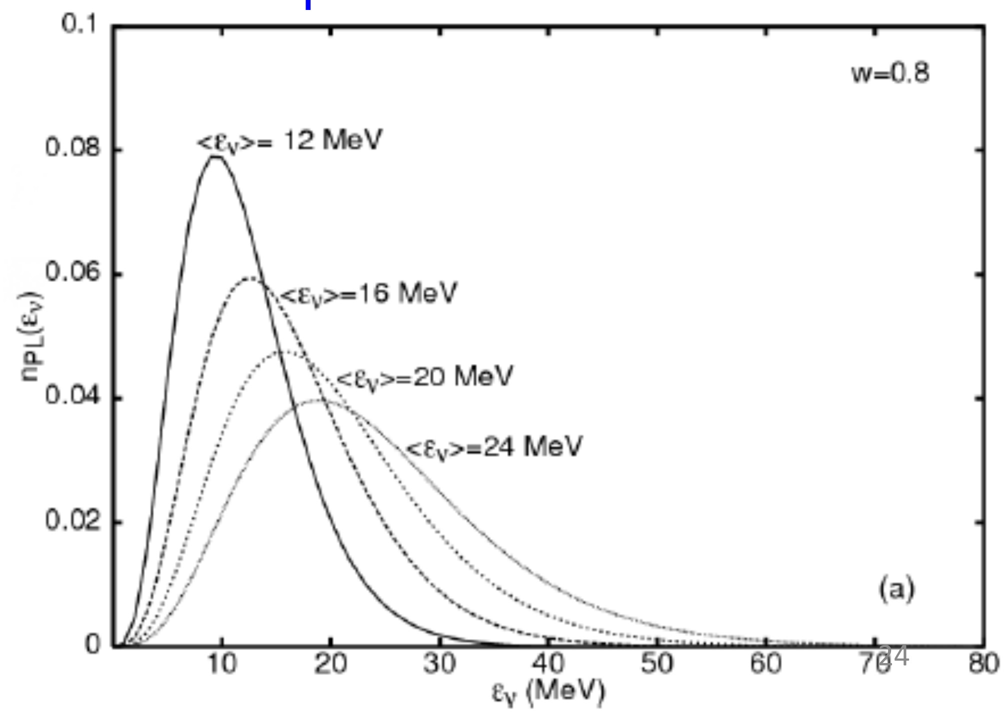


Why wait for a supernova burst?

"Relics" from all supernovas since Big Bang are detectable.

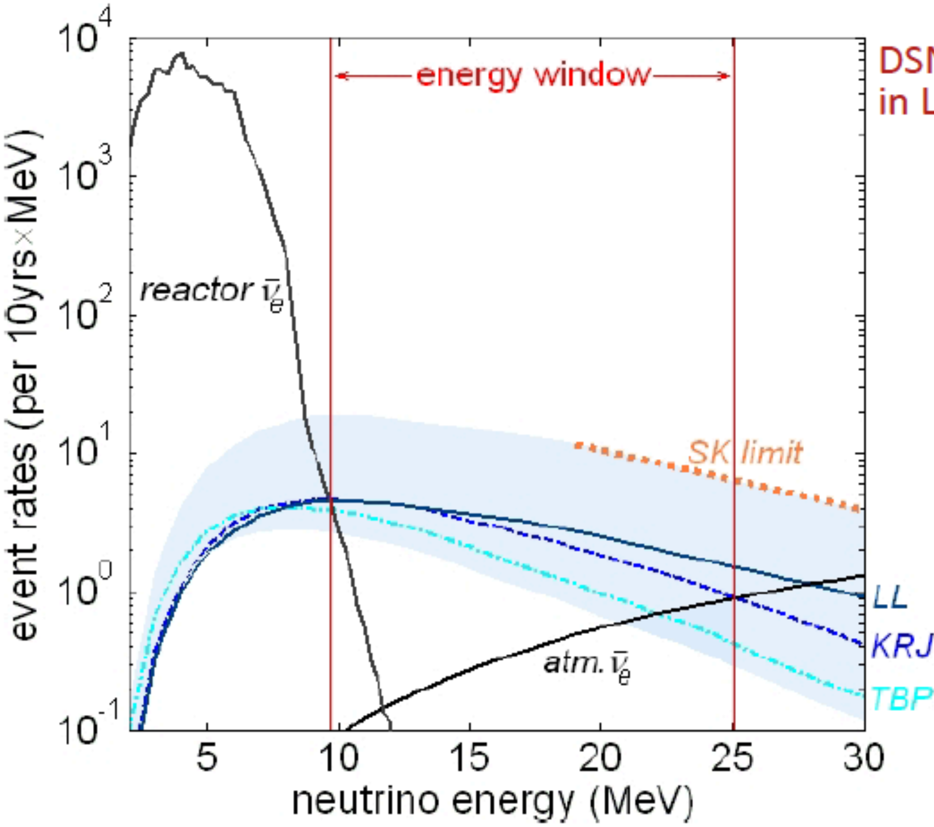
About 1 event/10kt/year.

Observed spectrum depends on supernova mechanism



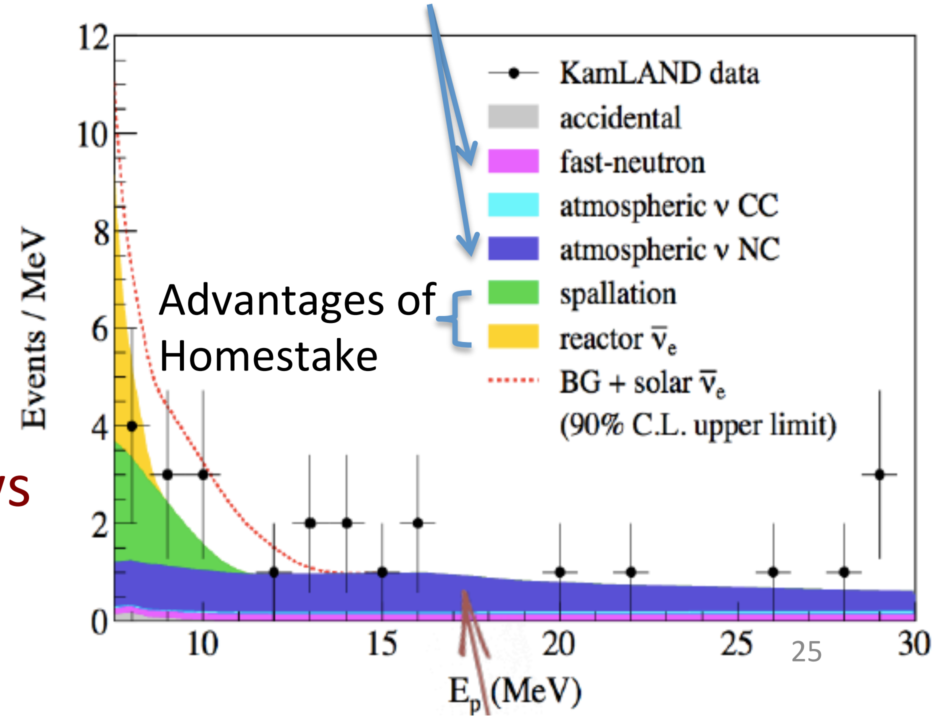
M. Wurm

Diffuse Supernova (Anti)Neutrino Background



DSNB detection in LENA (2006)

Big advantage of LS is "free" neutron tags and low threshold---
Provides background rejection



Pulse-shape discrimination also allows rejection of non-electron events.

M. Wurm

Geoneutrinos

Electron antineutrinos from U, Th, K decay in the Earth

Assay the Earth by looking at the “antineutrino glow”

Expect 4 events/month/ktonne

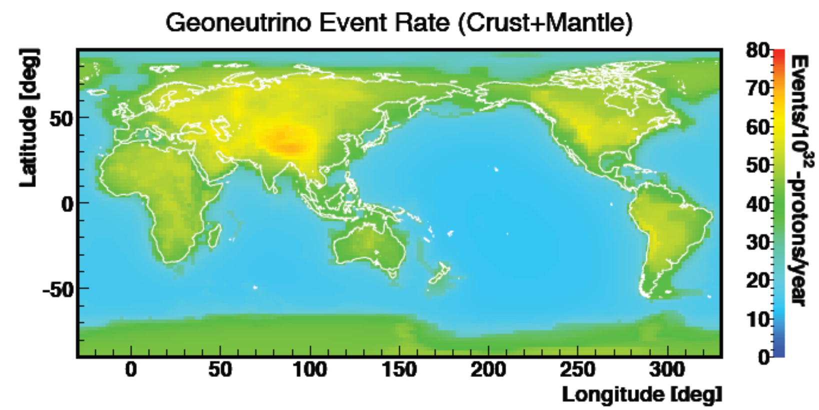
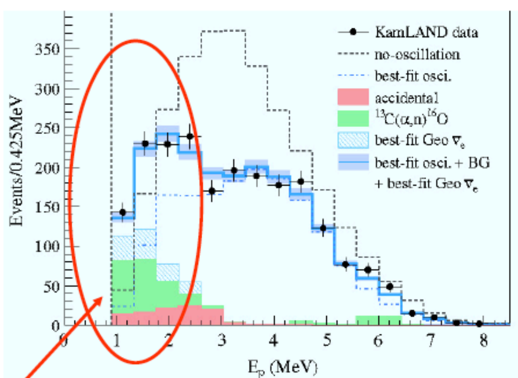


Image: S. Enomoto

Current total geo-ν exposure < 10 kt-yr (KamLAND+BOREXINO)



Geoneutrinos are contained in the low energy part of the spectrum.

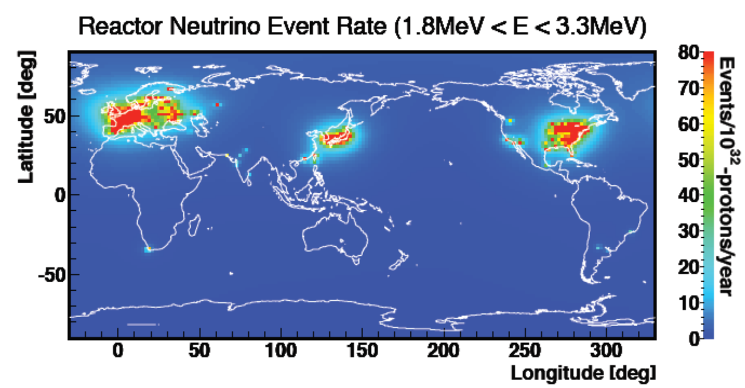
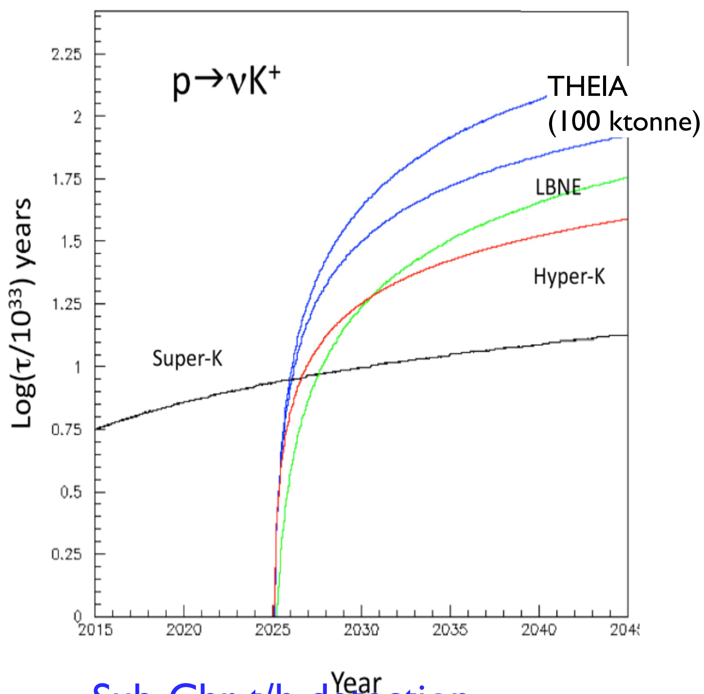


Image: S. Enomoto

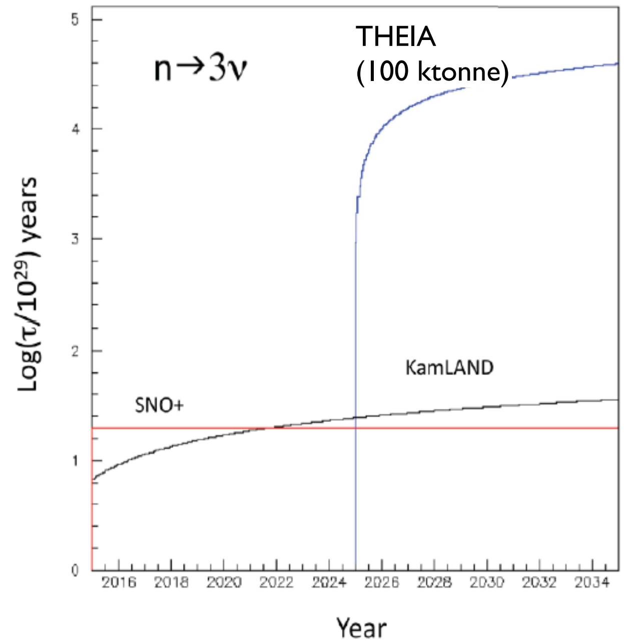
G. Gratta

Nucleon Decay with THEIA

Scintillation light allows observation of K+, as well as de-excitation γs from "invisible" decay modes.



Sub-Chr t/h detection
⇒ Directly visible K^+
A 50 ktonne THEIA+DUNE ~ 100 ktonnes



R. Svoboda

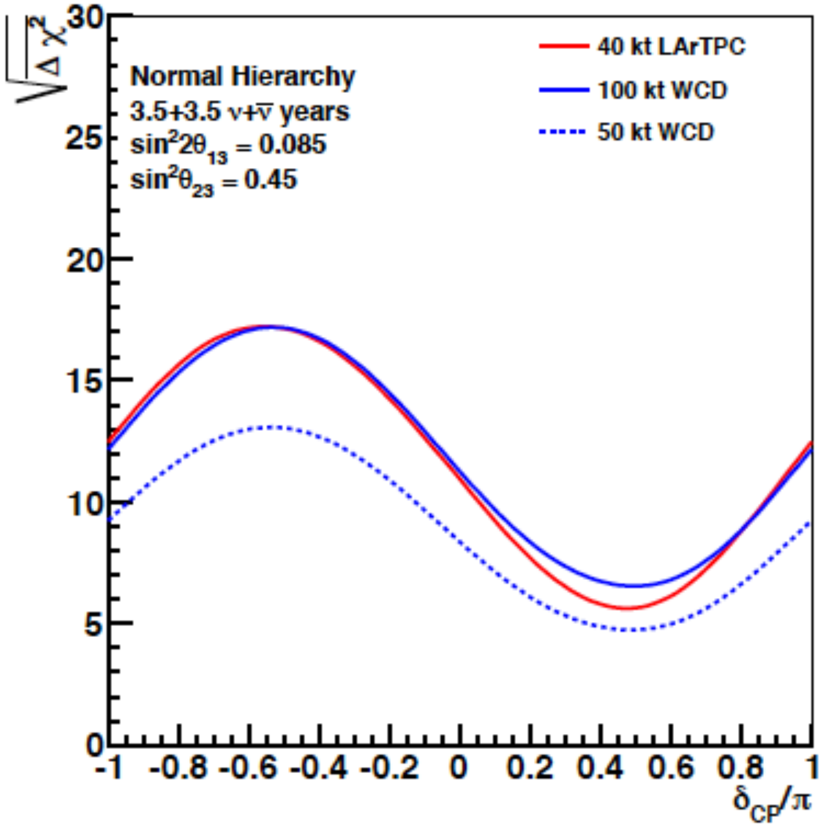
Deep, low threshold
De-excitation γs observaiable via Cher or Scint

For $p \rightarrow e^+\pi^0$ mode, not likely to be competitive with Super-K/Hyper-K unless THEIA can be made > 200 ktonne

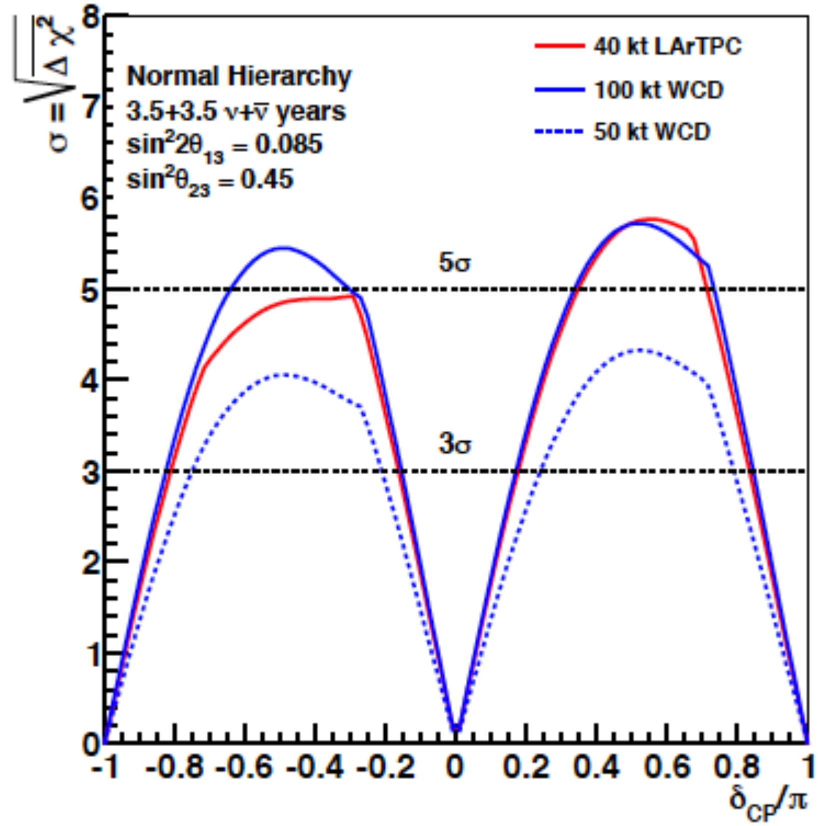
$*$

Large-scale photon detector (H_2O, WbLS, LS) would enhance LBL program

Mass Hierarchy Sensitivity



CP Violation Sensitivity



100 kt far-detector with WCD-like performance in LBNF beam yields similar sensitivity to 40-kt DUNE LAr TPC.

E. Worcester

Or 50 kt H_2O=20 kt LAr

Getting to the Full Program

Physics program covers 5 orders of magnitude in E_ν.

Detector must be:

- Ultra-clean from start
- Able to contain varied targets
  - H_2O
  - Water-based LS
  - LS
  - Li-loaded, Te-loaded, …
- Able to include inner balloon
- Able to upgrade photon detectors

Getting to the Full Program

Physics program covers 5 orders of magnitude in E_ν.

A possible phased program:

I. Water-based LS+20% photon coverage
   - High-E solar, long-baseline νs, supernova burst

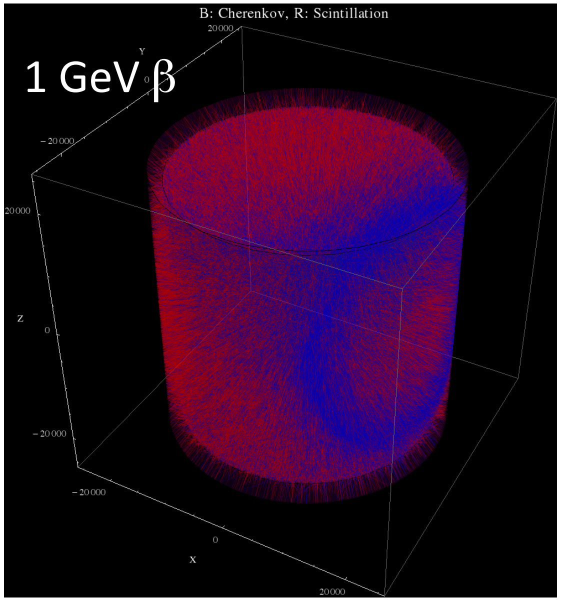
II. Richer scintillator mix, 80% fast photon coverage, Li-loaded
   - Low E solar, MSW transition, DSNB, geo-ν

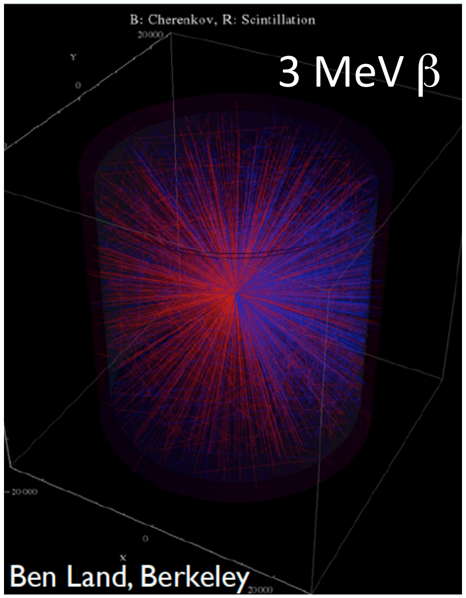
III. Inner balloon, Te or Xe-loaded liquid scintillator
   - $0\nu\beta\beta$ with sensitivity toward normal hierarchy regime

Getting to the Full Program

Critical questions:

- How well can Cherenkov/Scintillation separation be done?





- What photon sensors to use? (LAPPDs, PMTs, hybrid-PMTs…?)
- How good is direction reconstruction and particle ID?
- Can very large clean bag be built for $0\nu\beta\beta$?
- Where should it go?
- Cost?

Path Forward Toward THEIA

THEIA "Interest Group" formed with concept paper:

Advanced Scintillator Detector Concept (ASDC): arXiv:1409.5864

A Concept Paper on the Physics Potential of Water-Based Liquid Scintillator

J. R. Alonso,[1] N. Barros,[2] M. Bergevin,[3] A. Bernstein,[4] L. Bignell,[5] E. Blucher,[6] F. Calaprice,[7] J. M. Conrad,[1] F. B. Descamps,[8] M. V. Diwan,[5] D. A. Dwyer,[8] S. T. Dye,[9] A. Elagin,[6] P. Feng,[10] C. Grant,[3] S. Grullon,[2] S. Hans,[5] D. E. Jaffe,[5] S. H. Kettell,[5] J. R. Klein,[2] K. Lande,[2] J. G. Learned,[11] K. B. Luk,[8,12] J. Maricic,[11] P. Marleau,[10] A. Mastbaum,[2] W. F. McDonough,[13] L. Oberauer,[14] G. D. Orebi Gann*,[8,12,†] R. Rosero,[5] S. D. Rountree,[15] M. C. Sanchez,[16] M. H. Shaevitz,[17] T. M. Shokair,[18] M. B. Smy,[19] A. Stahl,[20] M. Strait,[6] R. Svoboda,[3] N. Tolich,[21] M. R. Vagins,[19] K. A. van Bibber,[18] B. Viren,[5] R. B. Vogelaar,[15] M. J. Wetstein,[6] L. Winslow,[1] B. Wonsak,[22] E. T. Worcester,[5] M. Wurm,[23] M. Yeh,[5] and C. Zhang[5]

50 authors, 23 institutions, lots of experience: Borexino, DUNE, KamLAND, SNO, Double CHOOZ, SNO+, Daya Bay, LENA, KamLAND-Zen, MiniBOONE, Super-Kamiokande, WATCHMAN, ANNIE, T2K....

Brookhaven National Laboratory
University of California, Berkeley
University of California, Davis
University of California, Irvine
University of Chicago
Columbia University
University of Hawaii at Manoa
Hawaii Pacific University
Iowa State University
Lawrence Berkeley National Laboratory
Los Alamos National Laboratory
University of Maryland
MIT
University of Pennsylvania
Princeton University
Sandia National Laboratories
Virginia Polytechnic Inst. & State University
University of Washington
RWTH Aachen University
TUM, Physik-Department
University of Hamburg
Johannes Gutenberg-University Mainz

Proto-collaboration meeting in Germany being discussed for Fall 2016

Conclusions

- Long-baseline Neutrino Facility is a great opportunity
- Broad program of physics possible with new scintillator technology
- Phased program could cover 5 orders of magnitude in energy
- (And could significantly enhance long-baseline oscillation program)

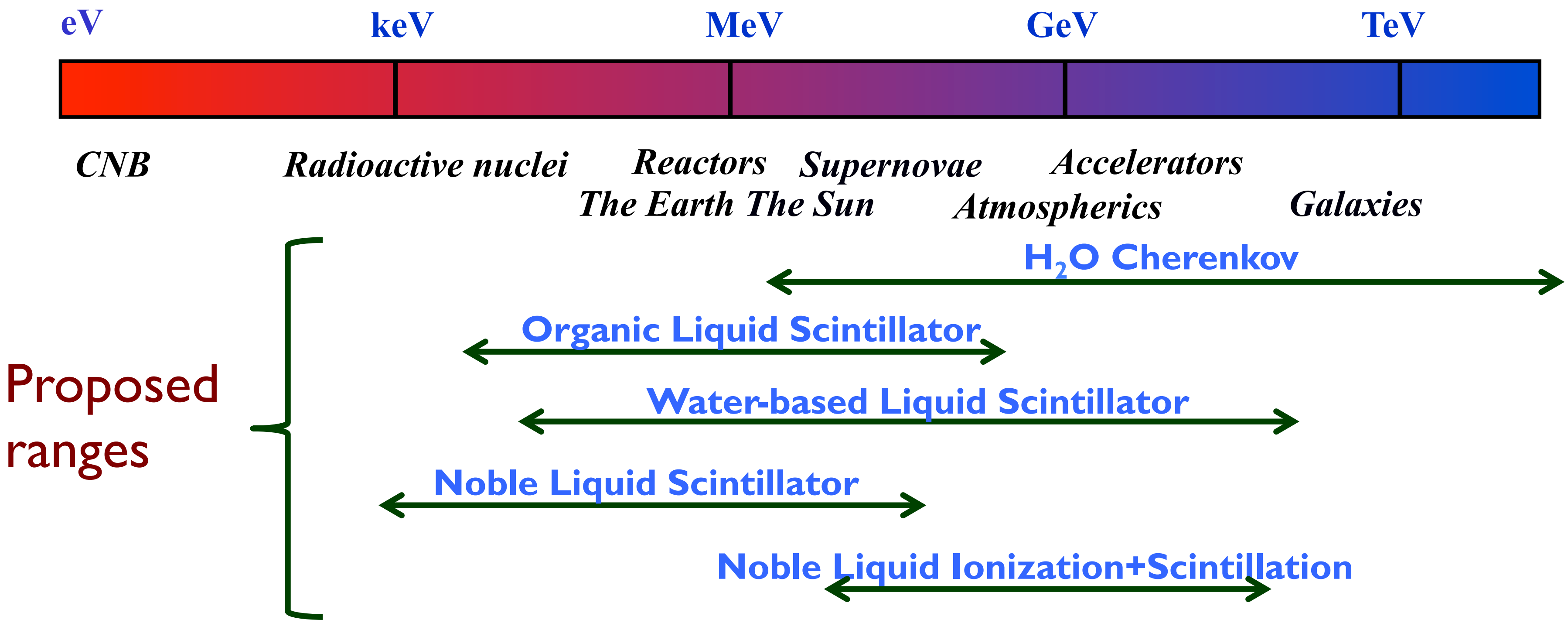
P5:

"…the U.S. to host a large water Cherenkov neutrino detector, as one of three additional high-priority activities, to complement the LBNF liquid argon detector, unifying the global long-baseline neutrino community to take full advantage of the world's highest intensity neutrino beam. The placement of the water and liquid argon detectors would be optimized for complementarity. This approach would be an excellent example of global cooperation and planning" – P5 (Scenario C)

Liquid Scintillator or Water-based Liquid Scintillator satisfies these goals but with an even broader program.

Backups

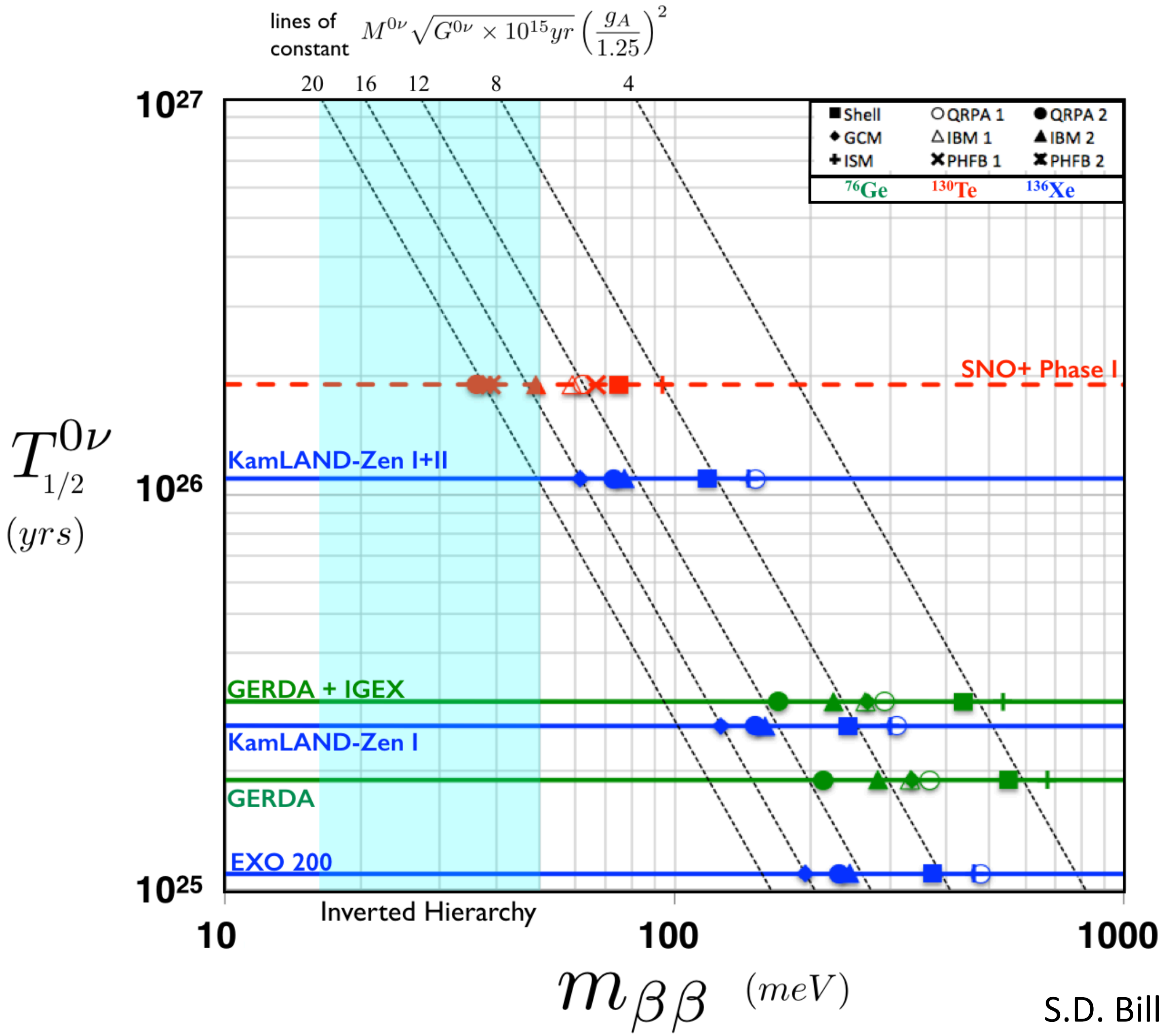
Broadening the Program



New Technologies---

- Scintillator cocktails (including water-based)
- Fast photon detector timing
- High-efficiency photon detection
- Advanced reconstruction methods

Allow a rich low-energy program of neutrino physics
(+ complement the high-energy program)



lines of constant $M^{0\nu}\sqrt{G^{0\nu}\times 10^{15}yr}\left(\frac{g_A}{1.25}\right)^2$
20 16 12 8 4
Shell QRPA 1 QRPA 2
GCM IBM 1 IBM 2
ISM PHFB 1 PHFB 2
^{76}Ge ^{130}Te ^{136}Xe
SNO+ Phase I
KamLAND-Zen I+II
GERDA + IGEX
KamLAND-Zen I
GERDA
EXO 200
Inverted Hierarchy
10^{27}
10^{26}
10^{25}
$T^{0\nu}_{1/2}$ (yrs)
10 100 1000
$m_{\beta\beta}$ (meV)

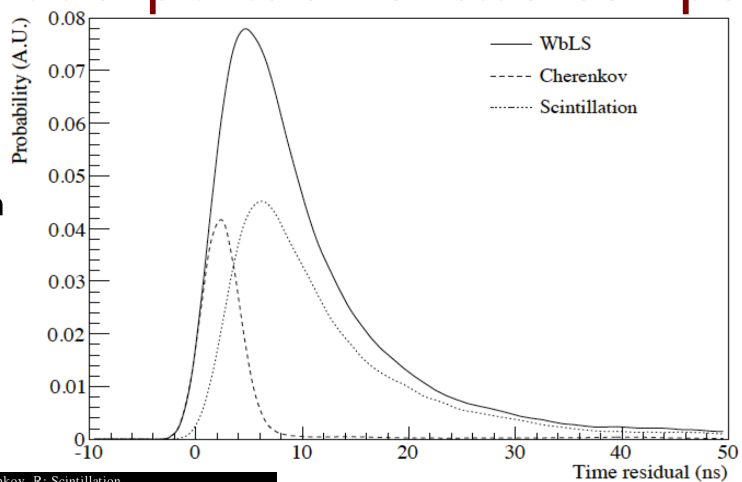
S.D. Biller

Water-based Liquid Scintillator

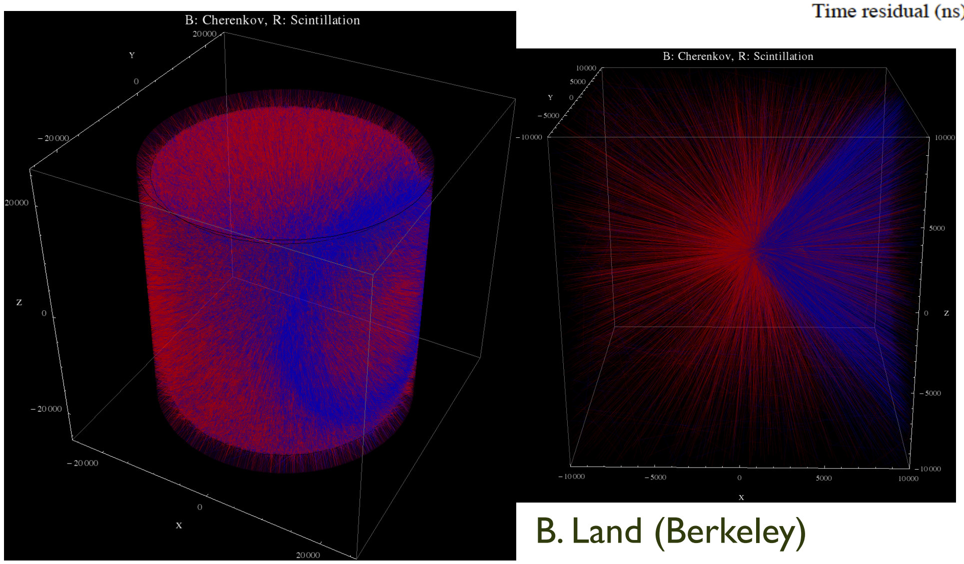
Cherenkov/Scintillation Separation

- Long extinction length means detector can be large
- About ½ of Cherenkov light absorbed or scattered
- But separation of two components still possible

A. Mastbaum (Penn)



THEIA



B. Land (Berkeley)

Cherenkov ID scales like

$$R_{s/c} \sim \frac{\gamma_C}{\gamma_S}\frac{t_{jitt}}{\tau_{scint}}\rho(\cos\alpha_C)R(\lambda)$$

t_{jitt} = transit time spread of PD
τ_{scint} = scintillation time constant
γ_C=number of Cherenkov photons
γ_S=number of scintillation photons
$\rho(\cos\alpha_c)$ = angular weighting function
$R(\lambda)$=spectral response function

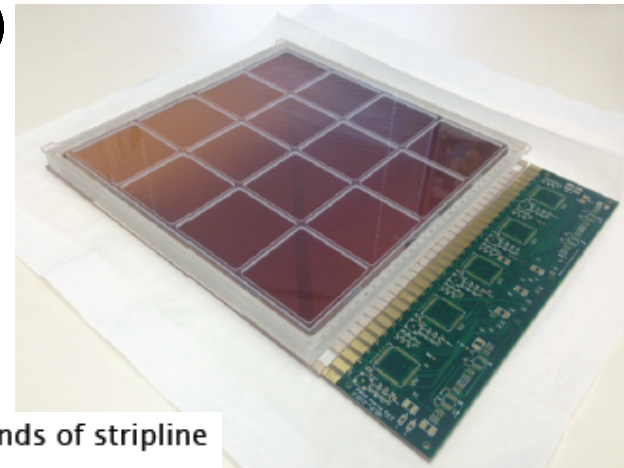
So for a 4% scintillation fraction, standard PMTs, no use of angular information, and equal spectral response for C and S, $R_{s/c}$~ 0.25

Water-based Liquid Scintillator

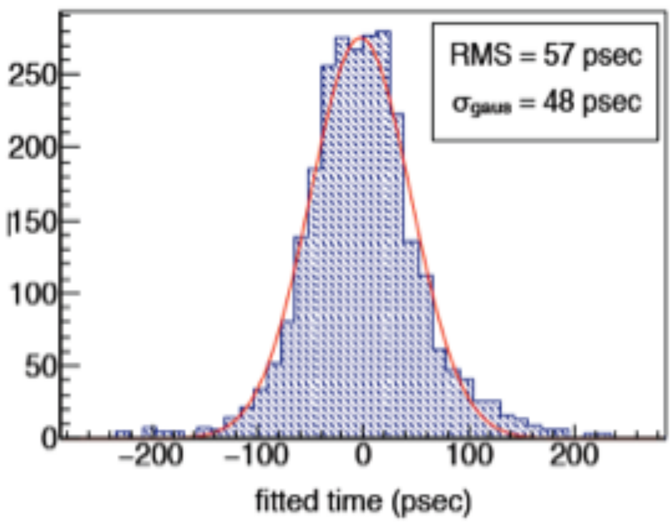
Improved Photon Sensors

Large Area Picosecond Photodetectors (LAPPDs)

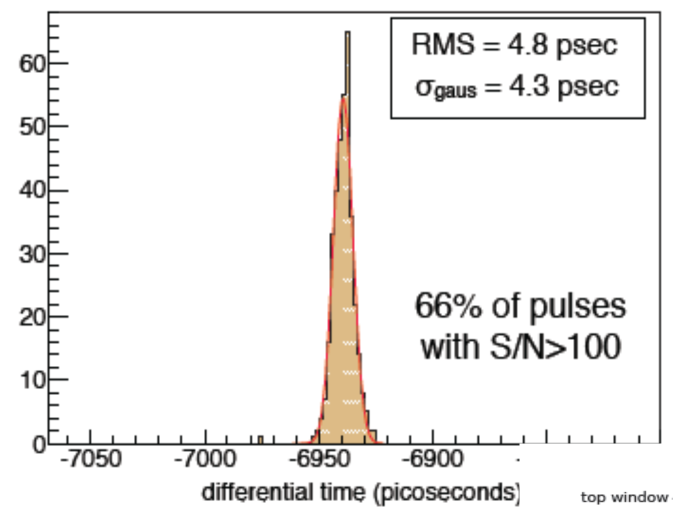
- Large, flat-panel MCP-based photosensors
- 50-100 ps time resolution (<1cm spatial)
- working readout system

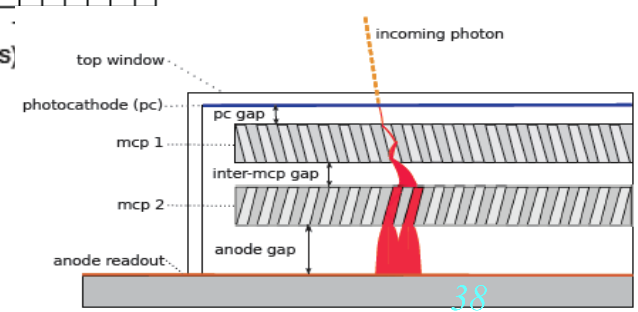


single photoelectron absolute time resolution



differential time resolution between 2 ends of stripline





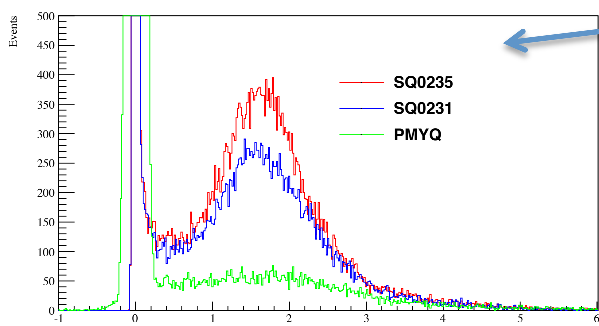
M. Wetstein

Water-based Liquid Scintillator

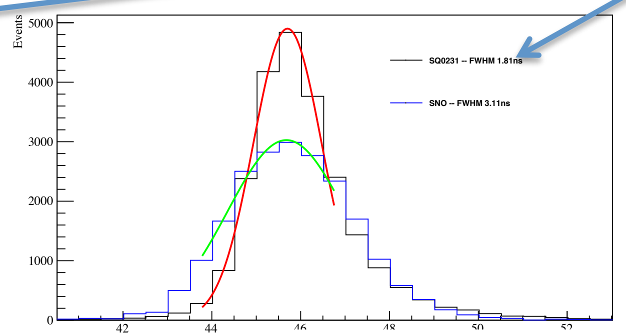
Improved Photon Sensors

Good for scintillation and water Cherenkov detectors also.

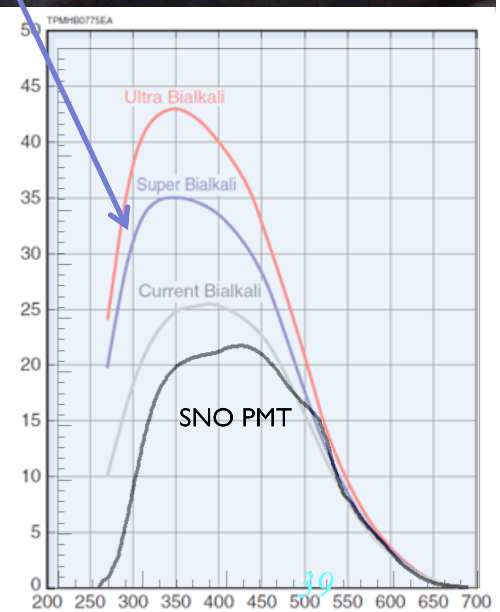
12" HQE (Hamamatsu)	11" HQE (ETL)	10" HQE (Hamamatsu)	8" standard (ETL)	8" HQE (Hamamatsu)	SNO PMT



Chage (pC)



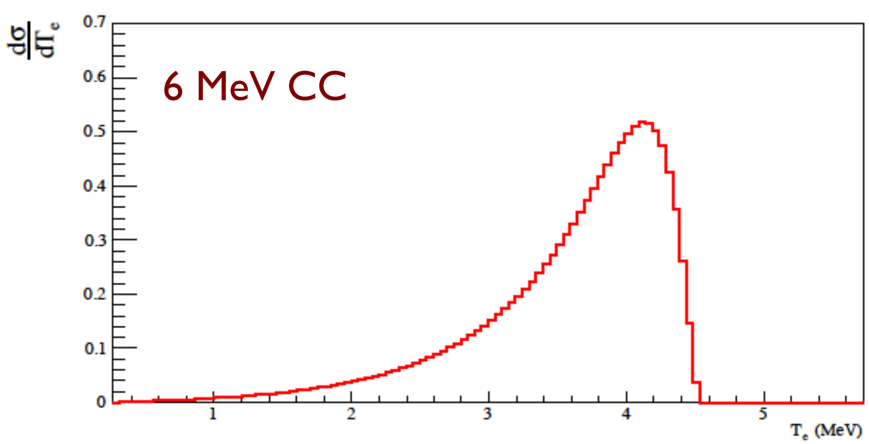
Time residuals (ns)

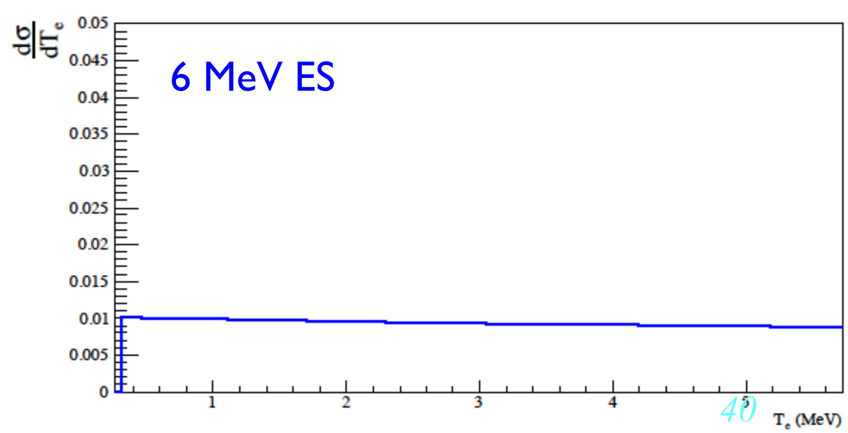


T. Kaptanoglu, Penn

Solar ν Technological Challenges

Physics	Threshold	Size	Resolution	CC/ES	Cleanliness
pp/luminosity constraint	100 keV	>10 tonnes	Moderate	Either	Extremely high
CNO νs	500 keV	> 1 ktonne	Very good	CC	Extremely high
pep	1 MeV	> 1 ktonne	Good	Either	High
MSW transition	1 MeV	> 50 ktonnes	Excellent	CC	High
Day/Night	10 MeV	> 50 ktonnes	Good	Either	Moderate
hep νs	10 MeV	> 10 ktonnes	Excellent	CC	Moderate





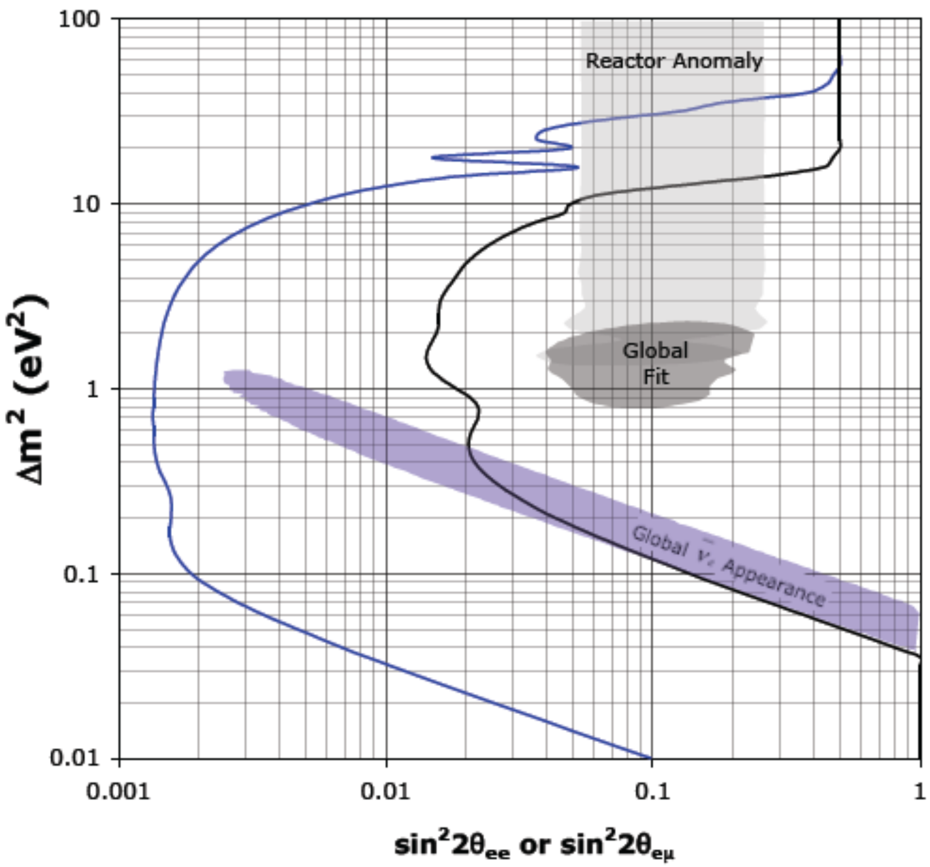
Planned Demonstrations

Site	Scale	Target	Measurements	Timescale
UChicago	bench top	H2O	fast photodetectors	Exists
CHIPS	10 kton		electronics, readout, mechanical infrastructure	2019
EGADS	200 ton	H2O+Gd	isotope loading, fast photodetectors	Exists
ANNIE	30 ton			2016
WATCHMAN	1 kton			2019
UCLA/MIT	1 ton	LS	fast photodetectors	2015
Penn	30 L	(Wb)LS	light yield, timing, loading	Exists
SNO+	780 ton			2016
LBNL	bench top	WbLS	light yield, timing, cocktail optimization, loading, attenuation, reconstruction	Early 2015
BNL	1 ton			Summer 2015
WATCHMAN-II	1 kton			2020

Sterile νs with THEIA

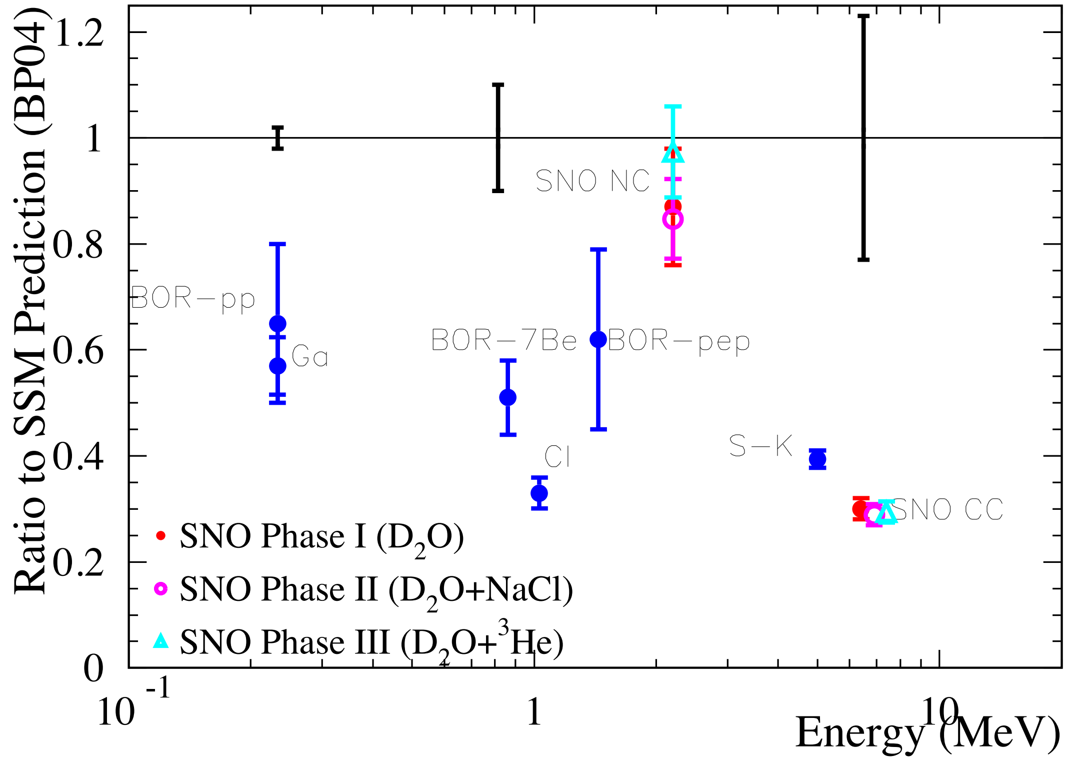
If "reactor anomaly" persists....

- ISODAR uses ^8Li with 13 MeV endpoint
- Could potentially resolve oscillation pattern within single detector
- Need 15% σ_E and 50 cm σ_R

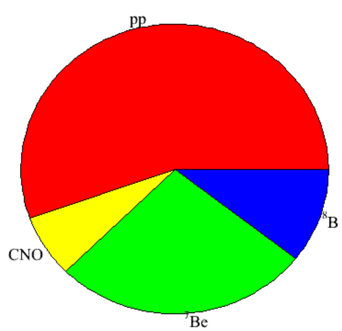


Solar Neutrinos

Measurements

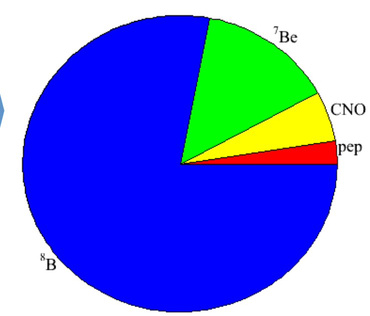


SAGE/GALLEX/GNO



Inclusive measurements

Chlorine



Aren't we done here?

Solar Neutrinos
Physics

Not really.

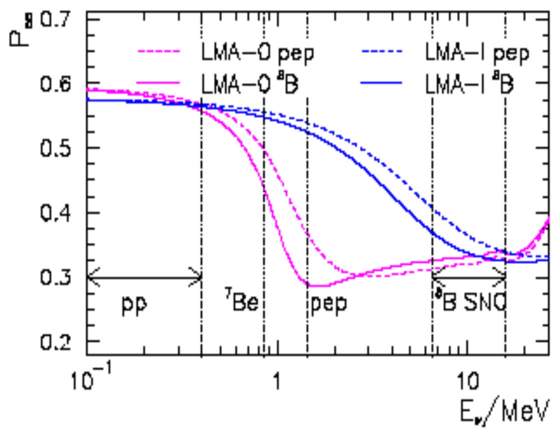
Important measurements still to make:

- Look for new physics in vacuum/matter transition region
- Understand solar system formation using…neutrinos?
- Look for new stellar energy generation/loss mechanisms
- Keep watching

Solar Neutrinos

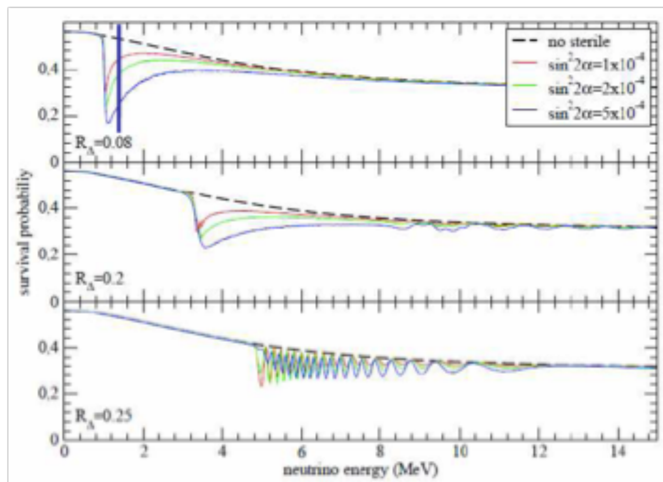
Vacuum/Matter Transition

Non-standard interactions (flavour changing NC)



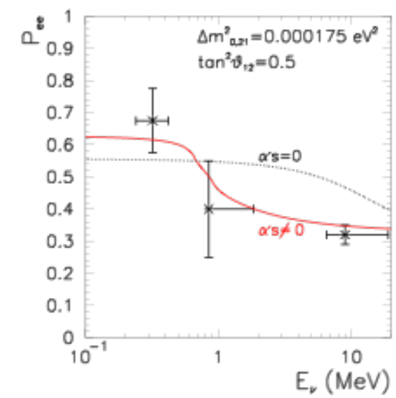
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



Holanda & Smirnov
PRD 83 (2011) 113011

Mass varying neutrinos (MaVaNs)



M.C. Gonzalez-Garcia, M. Maltoni
Phys Rept 460:1-129 (2008)

Interferometry on top of interferometry…
Anything that distinguishes flavor or mass states changes position and width of transition region

A Tremendous Opportunity

Evolution of LBNE into DUNE@LBNF is transformational:

A long-baseline beam aimed at a deep underground lab is a vision it has taken many decades to realize.

(*Pace* NuMI+SOUDAN)

PHYSICAL REVIEW D VOLUME 15, NUMBER 3 1 FEBRUARY 1977

Neutrino oscillations and the number of neutrino types*

A. K. Mann and H. Primakoff
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19174
(Received 7 July 1976; revised manuscript received 27 September 1976)

A brief treatment of neutrino oscillations, generalized to an arbitrary number of neutrino types, is given as the basis for design of a feasible experiment to search for neutrino oscillations using the neutrino beam produced at a high-energy proton accelerator.

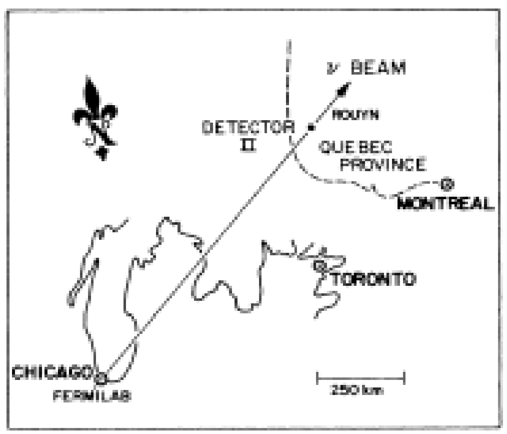


FIG. 4. Approximate geography of the proposed experiment. The present ν beam at Fermilab is directed 38°13′52″ east of north as indicated roughly.

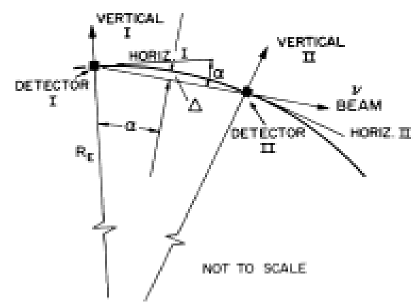
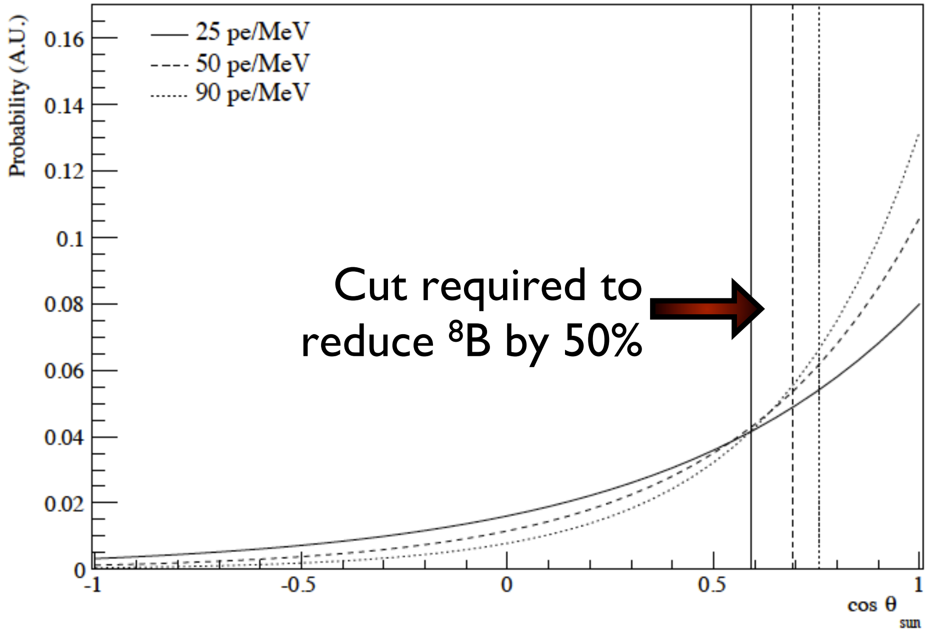


FIG. 1. Geometry of a feasible experiment. If the distance between detectors I and II is 1000 km, then $\alpha = 0.078$ rad and $\Delta = 19$ km. R_E is the radius of the earth $= 6.4 \times 10^3$ km.

0νββ at THEIA



Directionality will allow reduction of dominant ^{8}B background---size eliminates backgrounds from PMTs and walls.

A. Mastbaum (Penn)

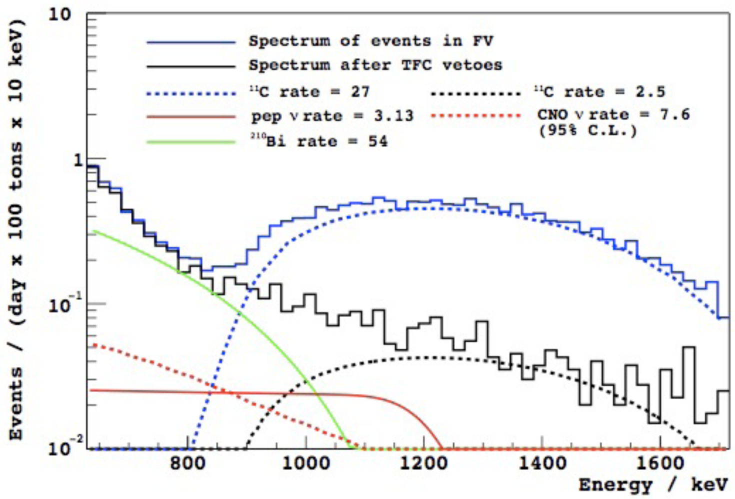
A 1% loading of ^{nat}Te will achieve 15meV criterion

	ΔE (%)	f_{iso} (%)	M_{iso} (tons)	b (cts/MeV·ton·y)	$\widehat{T}^{0\nu}_{1/2}$ (10^{26} y)	$\widehat{m}_{\beta\beta}$ (meV)
SNO+[4]	4.5	0.3	0.16	775	0.85	75
SNO+	3.6	3.0	2.4	260	6.6	27
CUORE[5]	0.2	–	0.74	0.01	0.76	78
CUORE	0.2	–	0.74	0.001	2.4	44
WbLS	5.0	1.0	100	930	19.5	**15**
WbLS	5.0	3.0	300	850	35.5	11

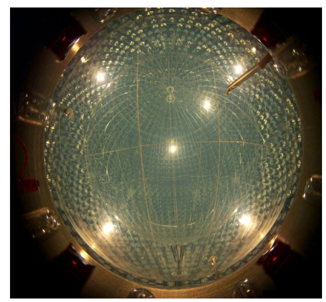
$t = 10$ y

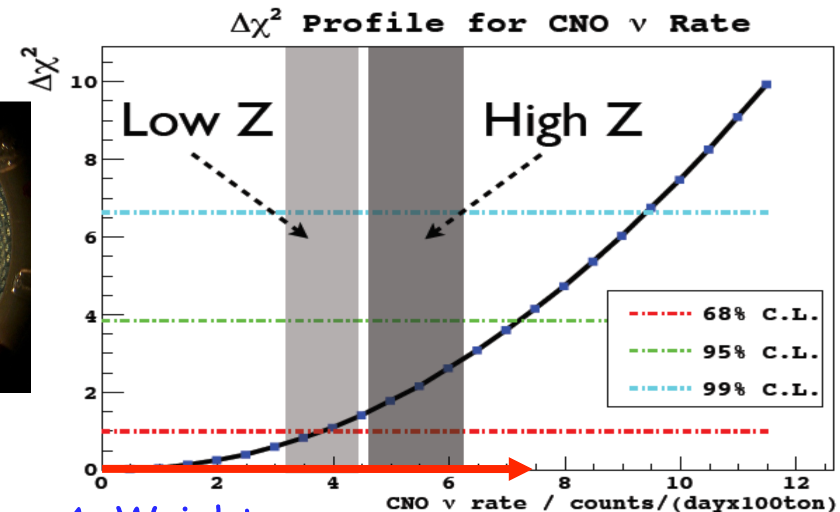
CNO Measurements

BOREXINO has placed limits but no clear signal yet



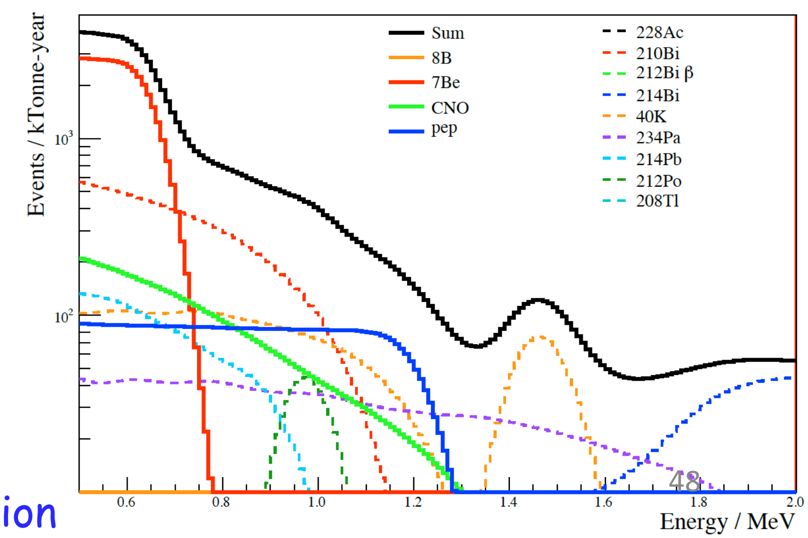
A. Wright





A. Wright

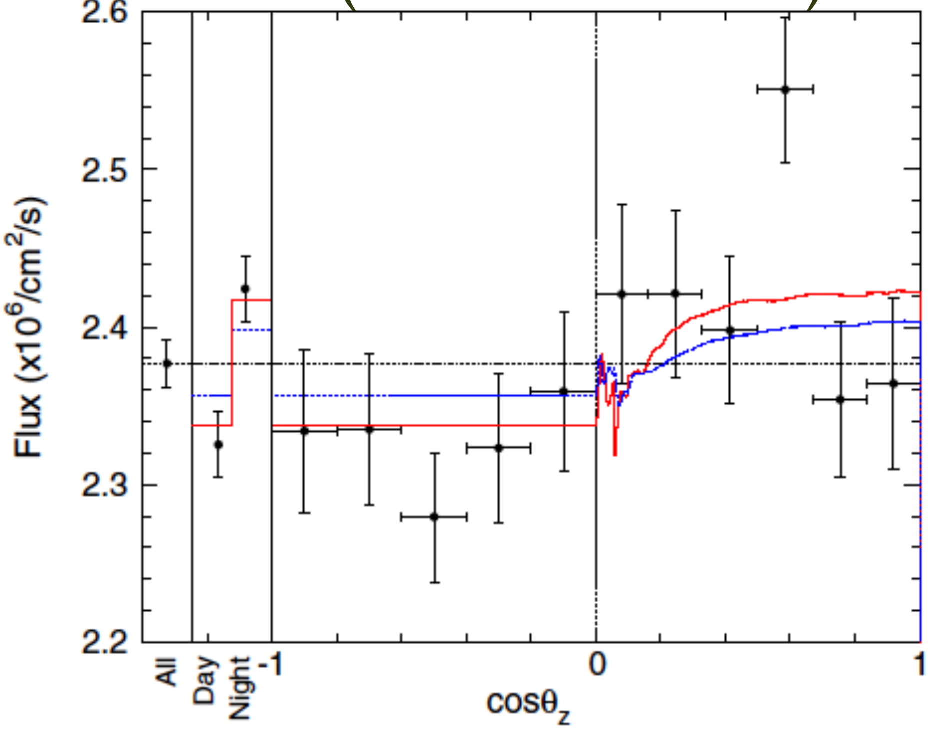
SNO+ will not have ^{11}C background but still separation of CNO from ^{210}Bi is VERY hard.



SNO+ Collaboration

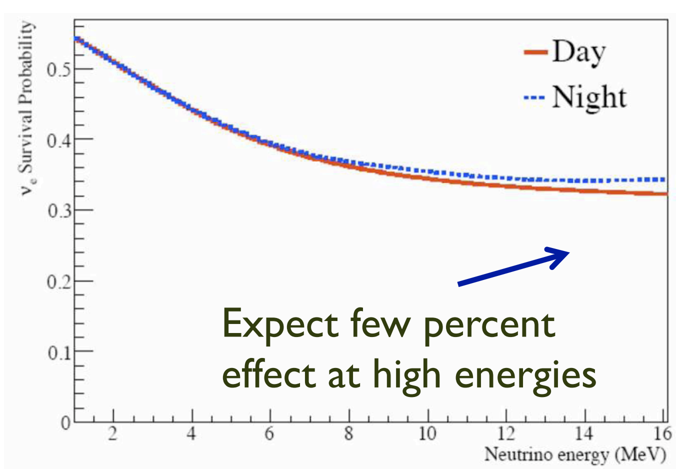
Observing MSW Phenomenlogy

2.7 σ (from unbinned fit)

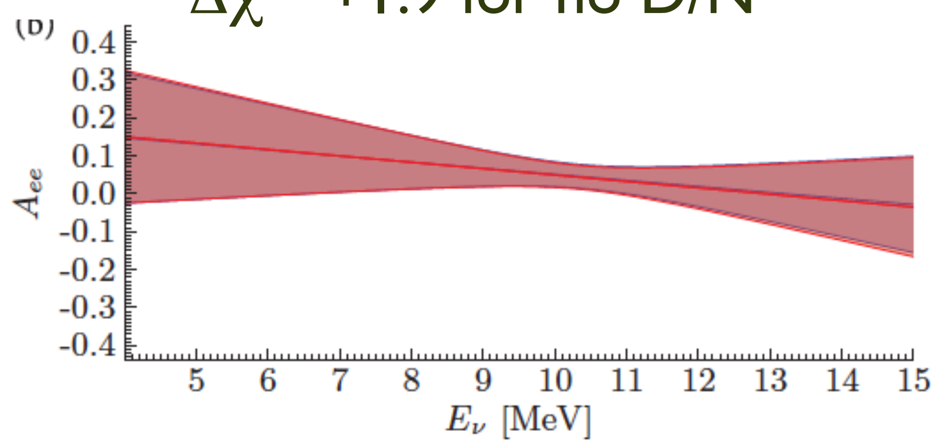


Super-Kamiokande, PRL **112** 091805

Hint of Day/Night Effect from Super-Kamiokande, but statistics make this very hard.



$\Delta\chi^{2}$= +1.9 for no D/N



SNO, PRC **88** 025501

Lot of work on this
already done by LENA

Supernova Bursts

- ~12k events for 10kpc Supernova in 50 ktonne
- Scintillation light makes n tag easy for IBD
- Gd makes n tag even better (200 μs becomes 20μs)

Neutrino Reaction	Percentage of Total Events	Type of Interaction
$\overline{\nu}_e + p \rightarrow n + e^+$	88%	Inverse Beta
$\nu_e + e^- \rightarrow \nu_e + e^-$	1.5%	Elastic Scattering
$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^-$	<1%	Elastic Scattering
$\nu_x + e^- \rightarrow \nu_x + e^-$	1%	Elastic Scattering
$\nu_e +^{16} O \rightarrow e^- +^{16} F$	2.5%	Charged Current
$\overline{\nu}_e +^{16} O \rightarrow e^+ +^{16} N$	1.5%	Charged Current
$\nu_x +^{16} O \rightarrow \nu_x + O^*/N^* + \gamma$	5%	Neutral Current

NC elastic scattering of p may also be visible by scintillation light.

Literally complementary to LAr (anti-ν_e vs. ν_e)
Better resolution than Super-K, allows some discrimination of signals