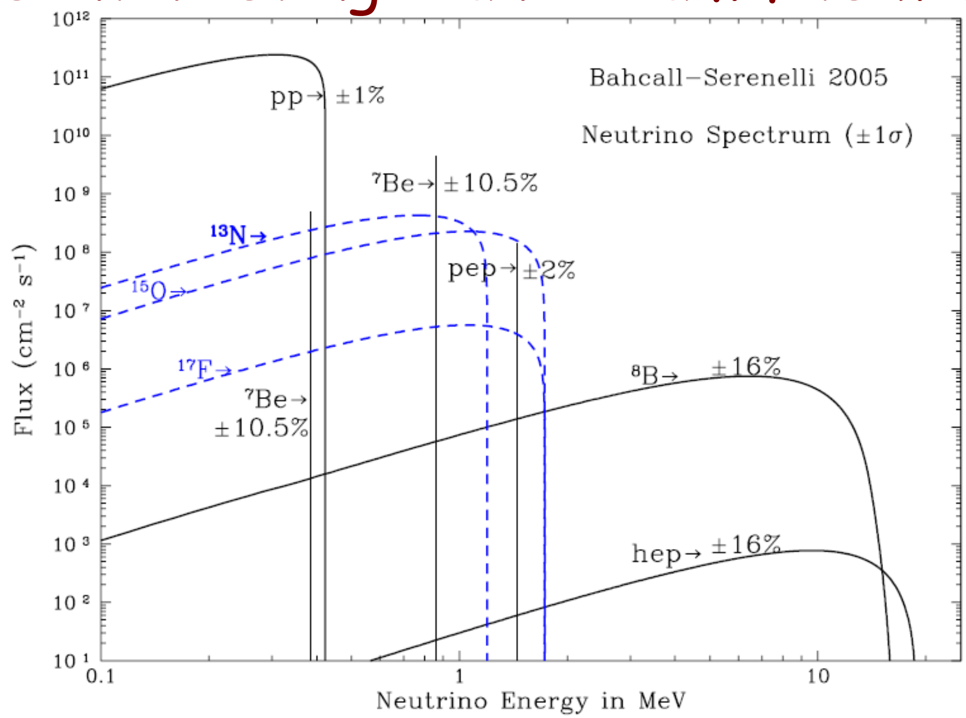
Future
Solar Neutrino Experiments

- **What's Left to Learn**
- **What's needed and what is planned**

Josh Klein, Penn

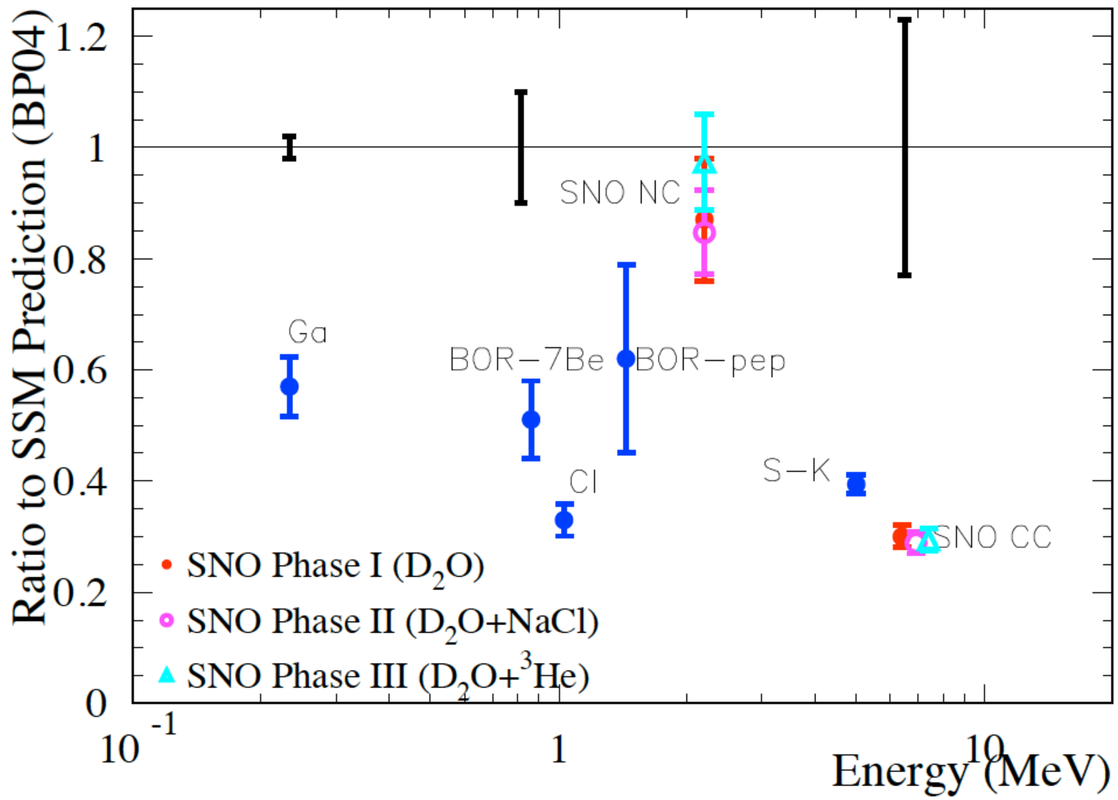
Why Solar νs?

- Broadband and mono-energetic, background-free beam
- Matter effects are crucial and observable
- (and time- and density-varying)
- Source itself is interesting---and beam fits within FY2012

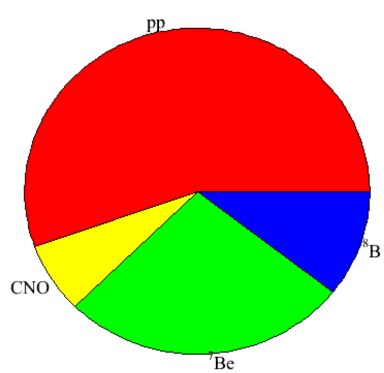


On the other hand, we're stuck with disappearance or inclusive appearance, which limits some of the accessible phenomenology (e.g., CP violation)

Solar ν Measurements

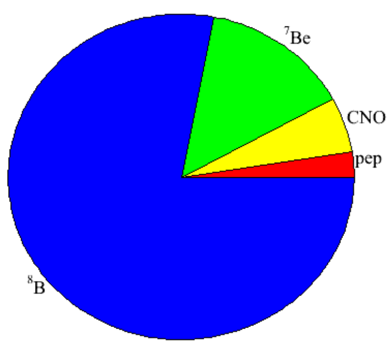


SAGE/GALLEX/GNO



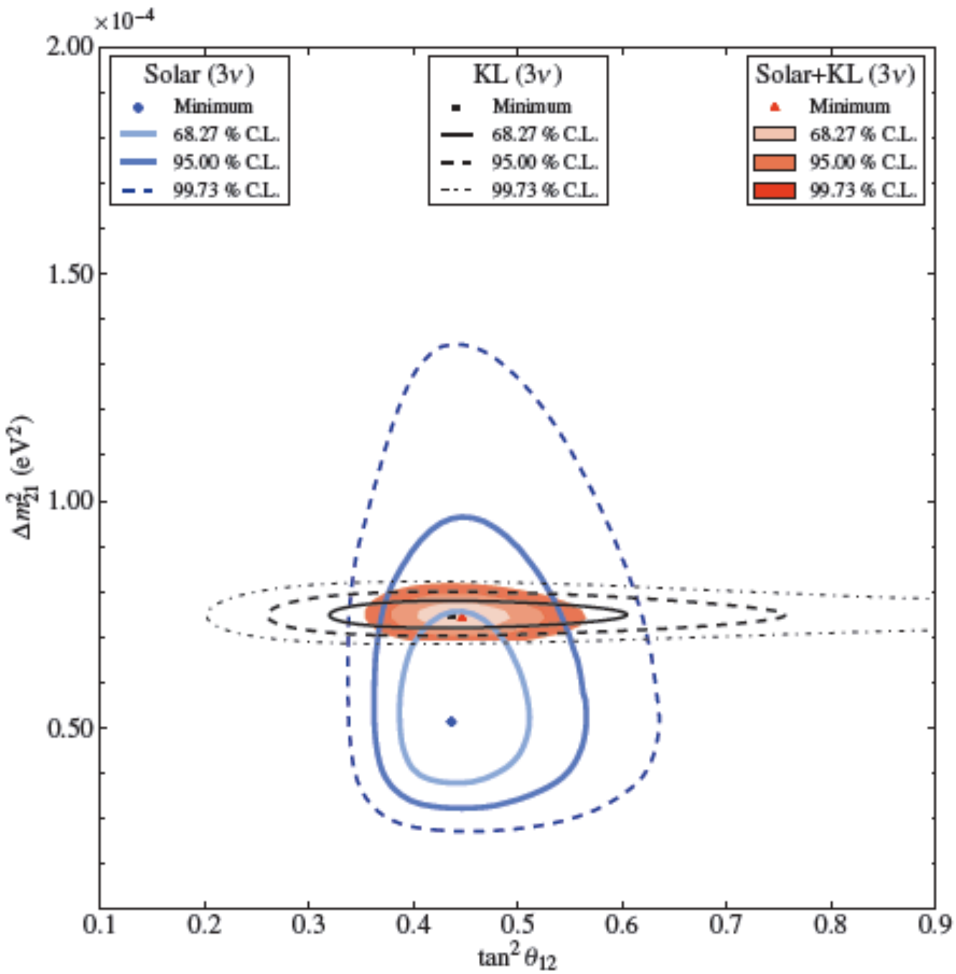
Inclusive measurements

Chlorine



The First Precision Test

Only(?) Standard Model predicts these 2 experimental regimes see the same effect



	KamLAND	Solar
	Reactor	**Solar**
E	2-10 MeV	0.1-15 MeV
L	150 km	1.5 x 10^8 km
MSW	No	Yes
ν	**Anti-ν_e**	**ν_e**

So What Do We Have?

- Clear mixing signal
- General confirmation of Standard Solar Model
- Restriction of parameters to LMA
- First solar test of mixing model (with KamLAND)

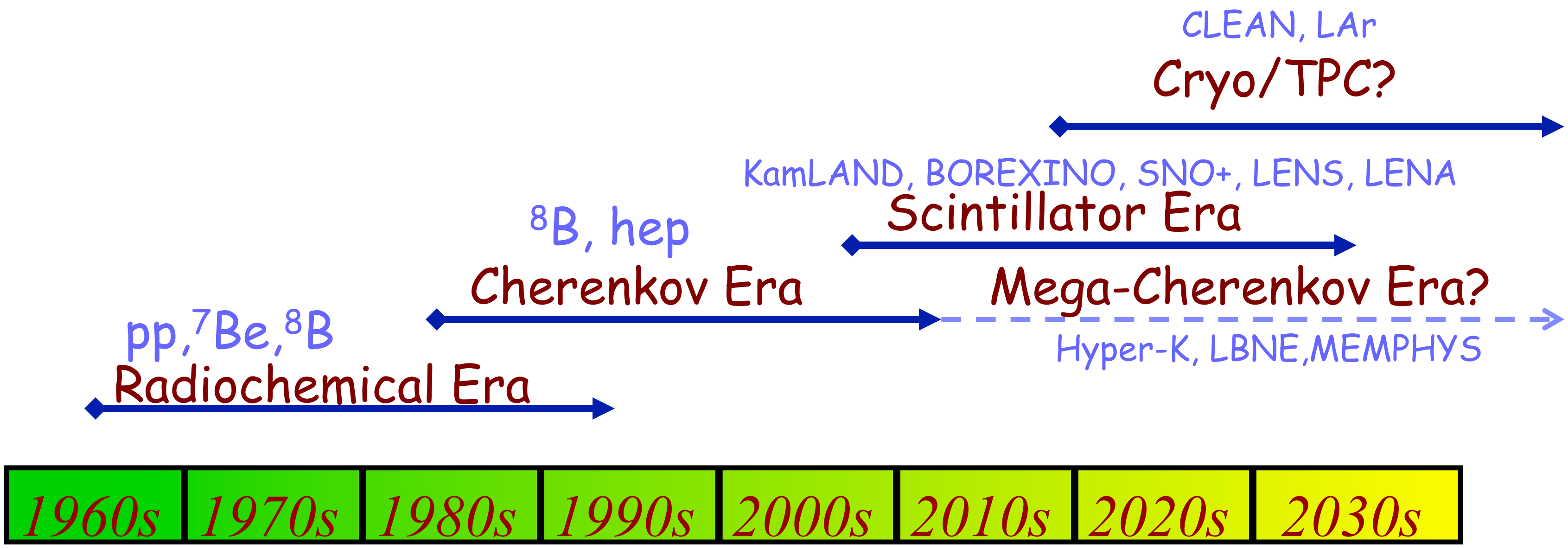
In other words, all the easy stuff is done.

Five Things We Should Measure

(in no particular order)

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

Next Generations



→ Nearly all future experiments are multi-purpose:

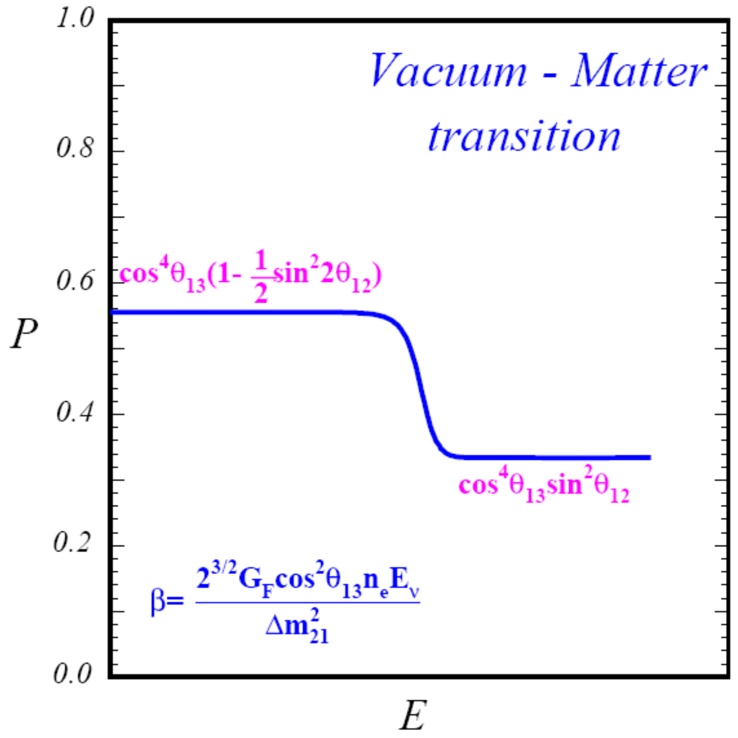
- Dark matter
- $0\nu\beta\beta$
- Reactor anti-νs
- Long baseline/proton decay
- neutrino magnetic moment

Note: The only new, completely-funded experiment is SNO+
BOREXINO, KamLAND, and Super-K will continue

Observing MSW Phenomenology

- Test the model of massive neutrino mixing

Vacuum/Matter Transition



Day/Night ν_e Asymmetry

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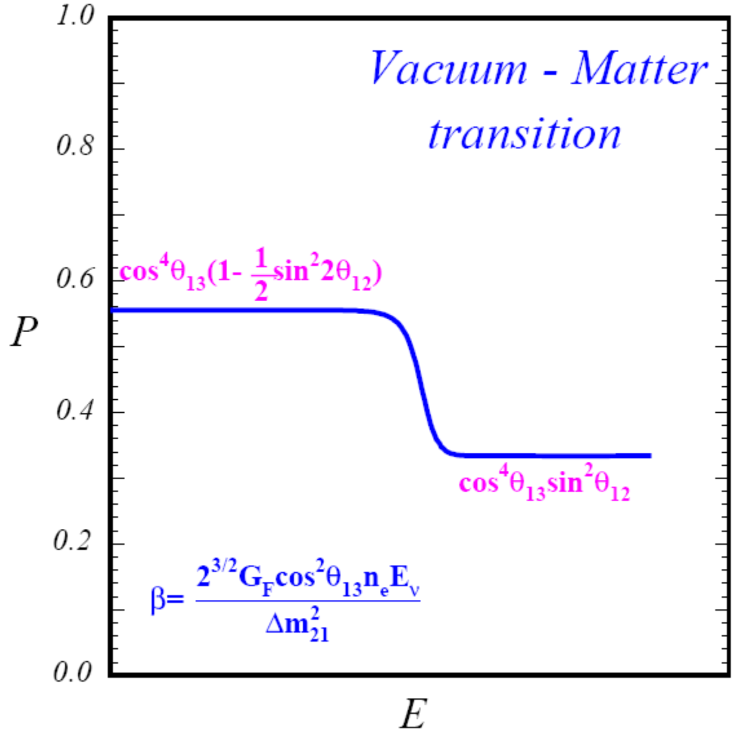

Day/Night ν_e Asymmetry

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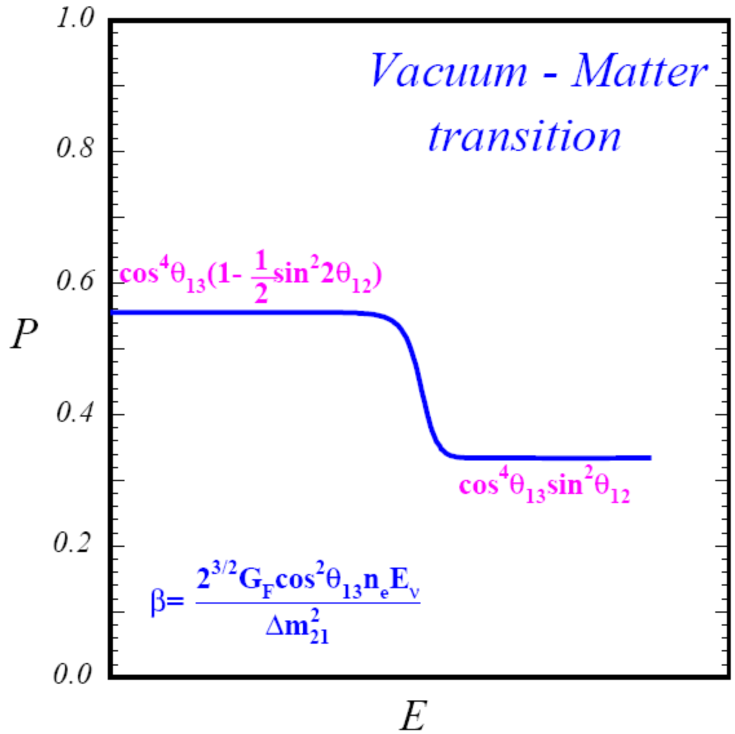
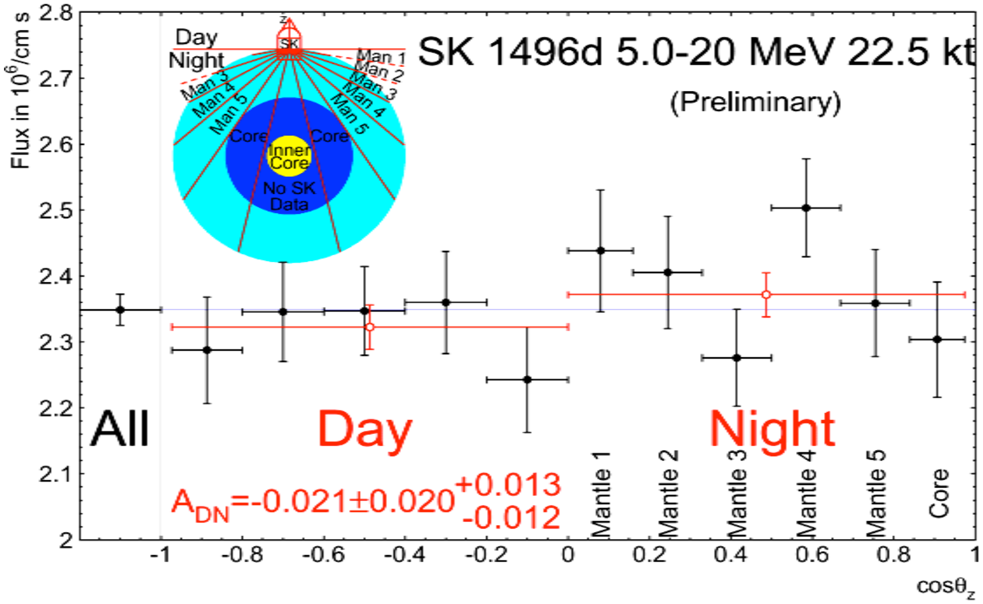


Day/Night ν_e Asymmetry

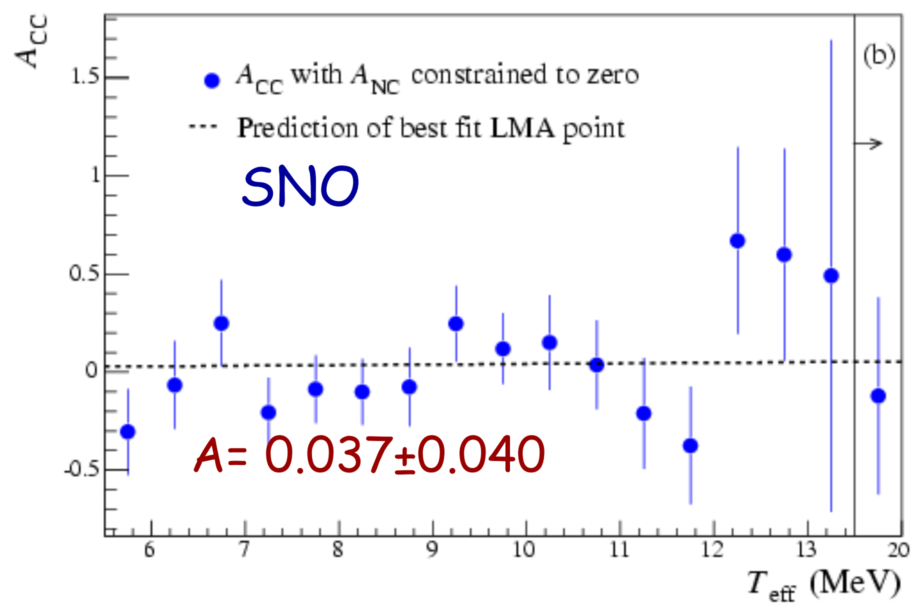
(Can we invert D/N effect to determine Earth density profile?)

Observing MSW Phenomenlogy

`Unlucky' Parameters so far…

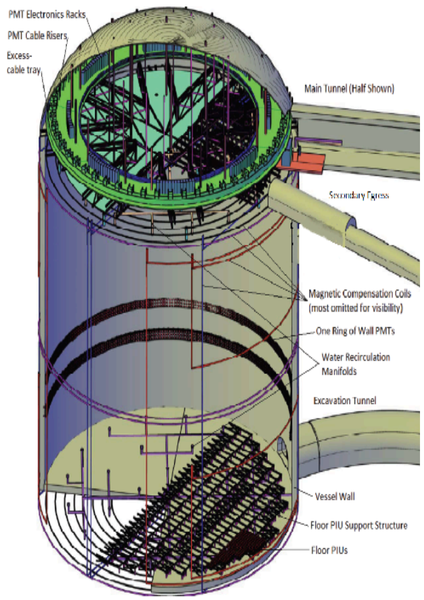


No Day/Night yet

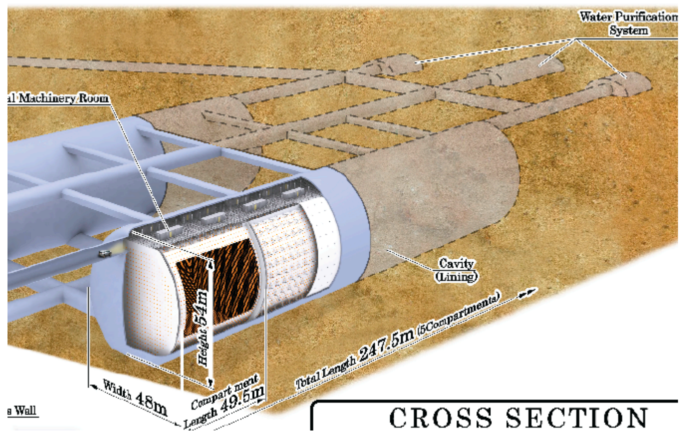


Hyper-Sized H_2O Cherenkov

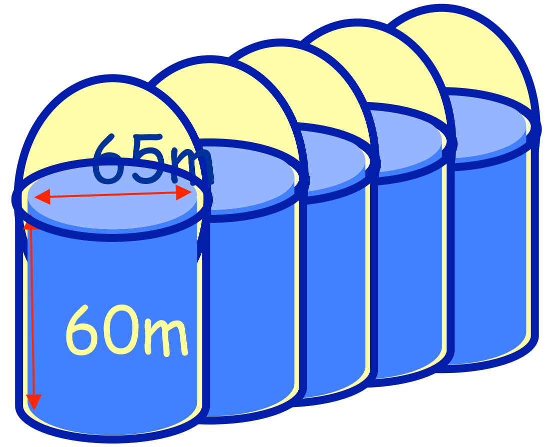
Day/Night Asymmetry



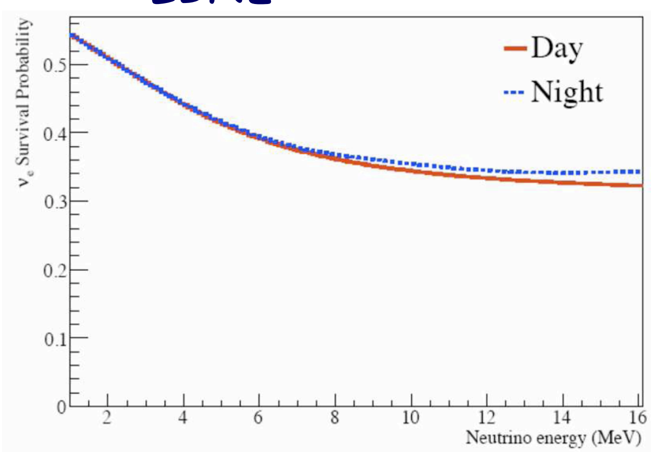
LBNE



Hyper-Kamiokande



MEMPHYS



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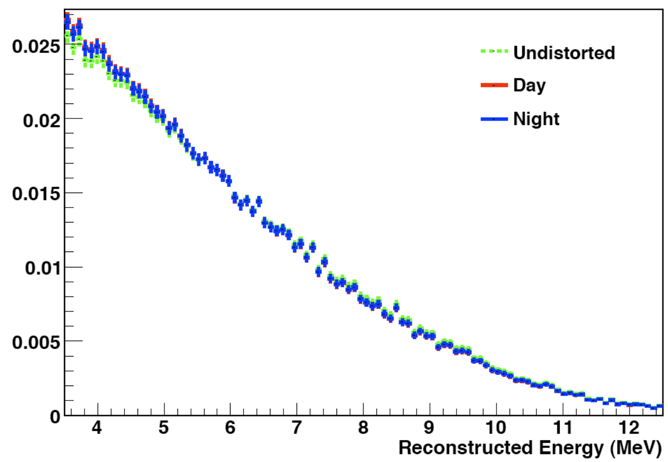


Expect a tiny (~2%) effect, mostly at high energies (but smeared out by ES)

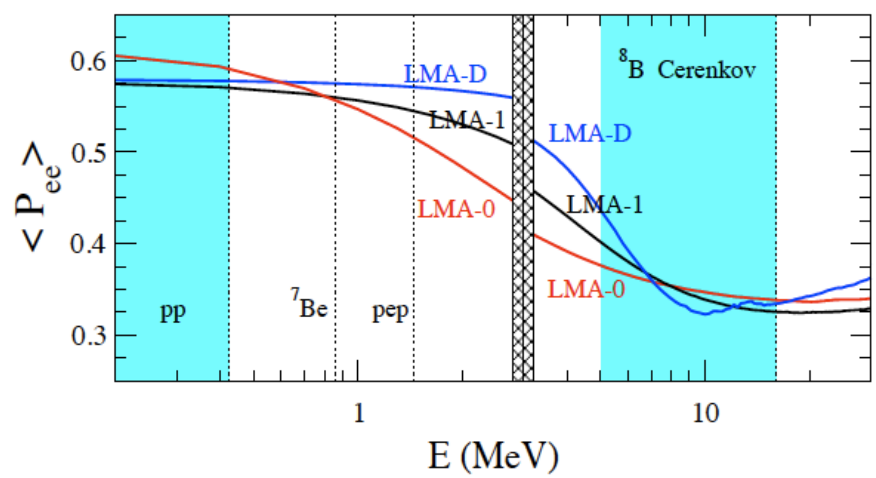
Reasonable threshold is 7 MeV for 30% photocathode coverage;
Should get ~40 events/day/100kton, so perhaps 3σ signal in few years, before systematics

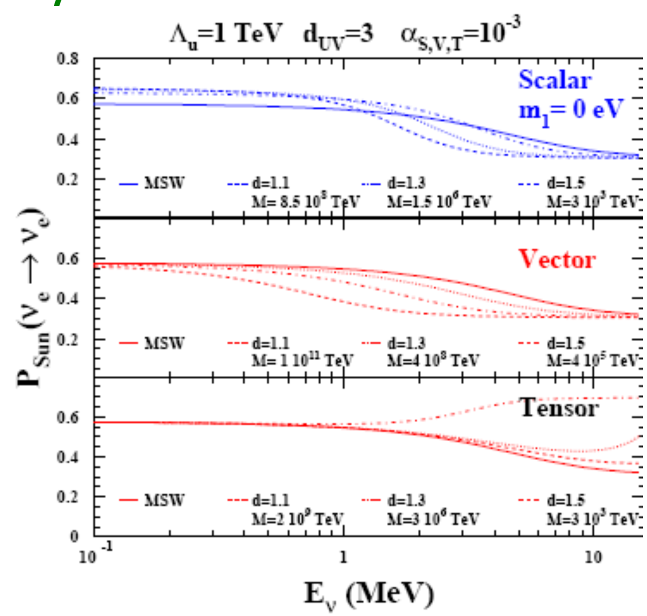
Observing MSW Phenomenology

Vacuum/matter transition region

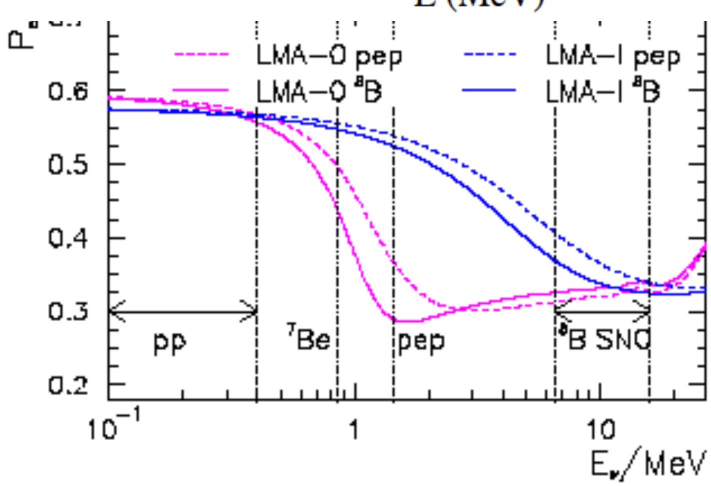
Nonstandard effects can be enhanced by MSW-like resonance

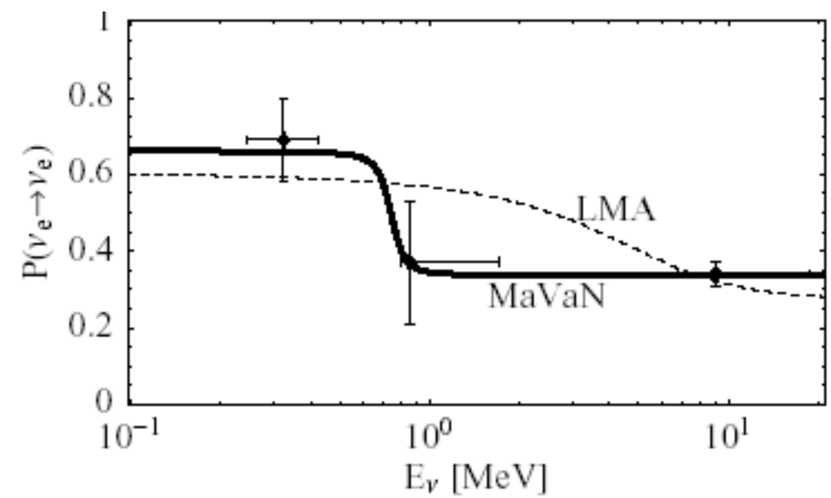
Miranda, Tortola, Valle, JHEP 0610 (2006)





M. C. Gonzalez-Garcia, P. C. de Holanda, E. Masso and R. Zukanovich Funchalc, JCAP 0701 (2007)



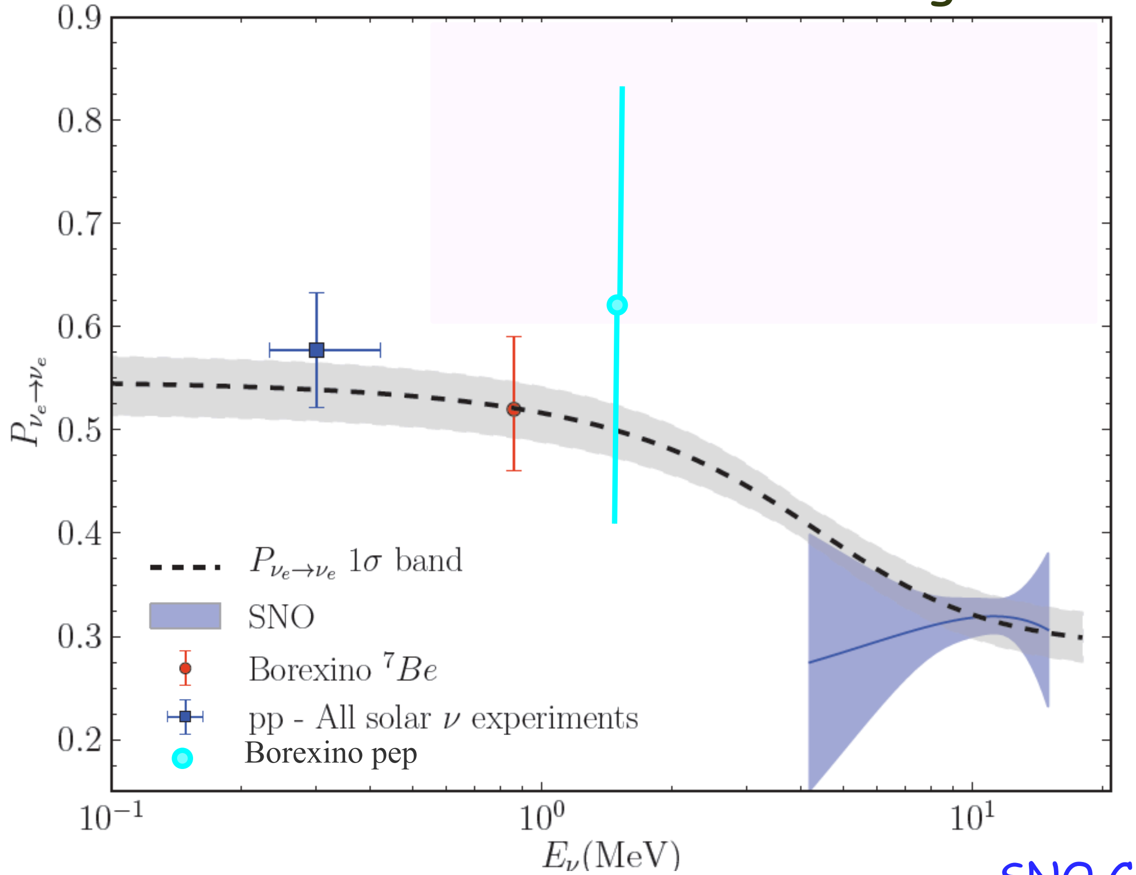


Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Barger, Huber, Marfatia, PRL95, (2005)

Observing MSW Phenomenology

Vacuum/matter transition region

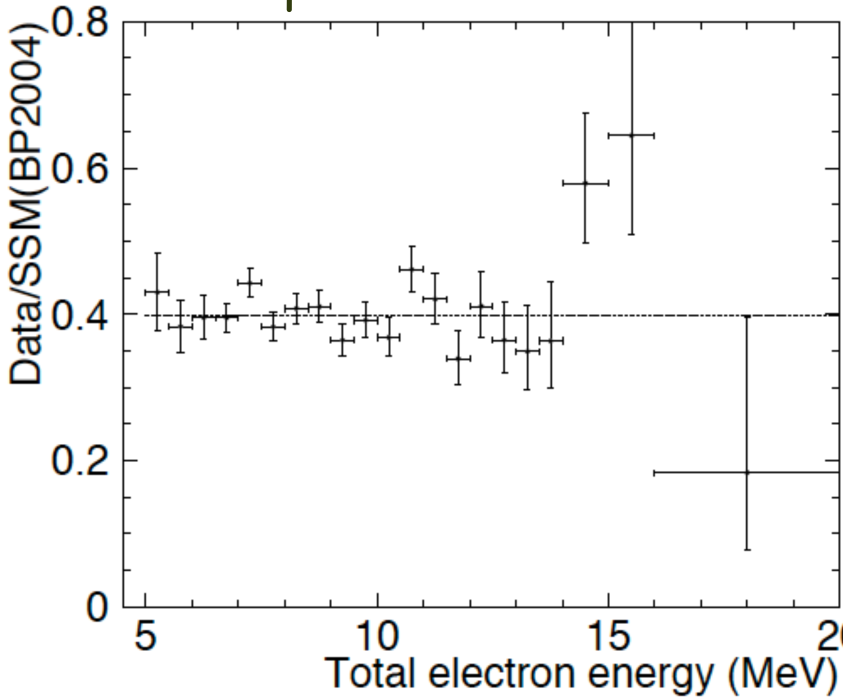


SNO Collaboration

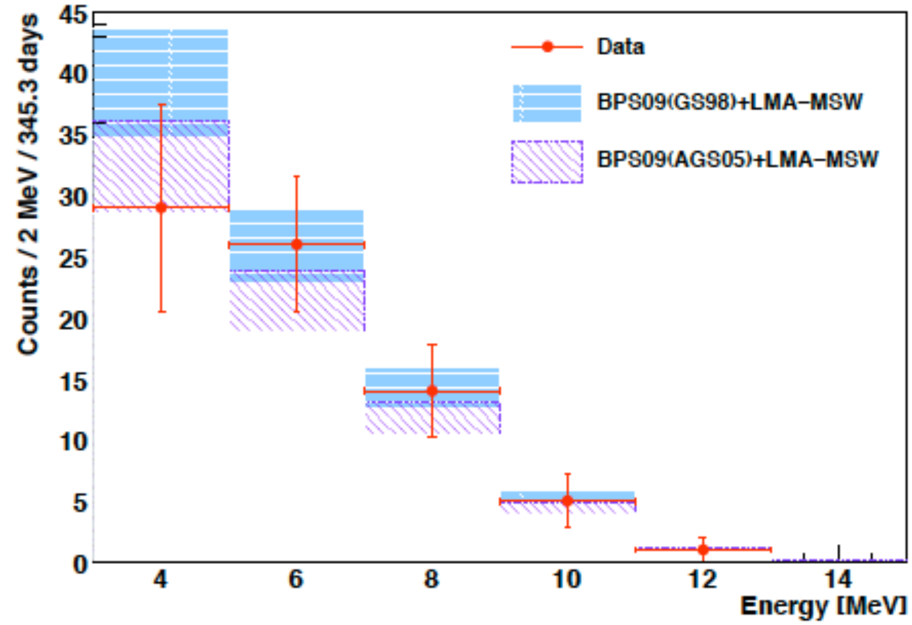
Observing MSW Phenomenology

Vacuum/matter transition region

Super-K III



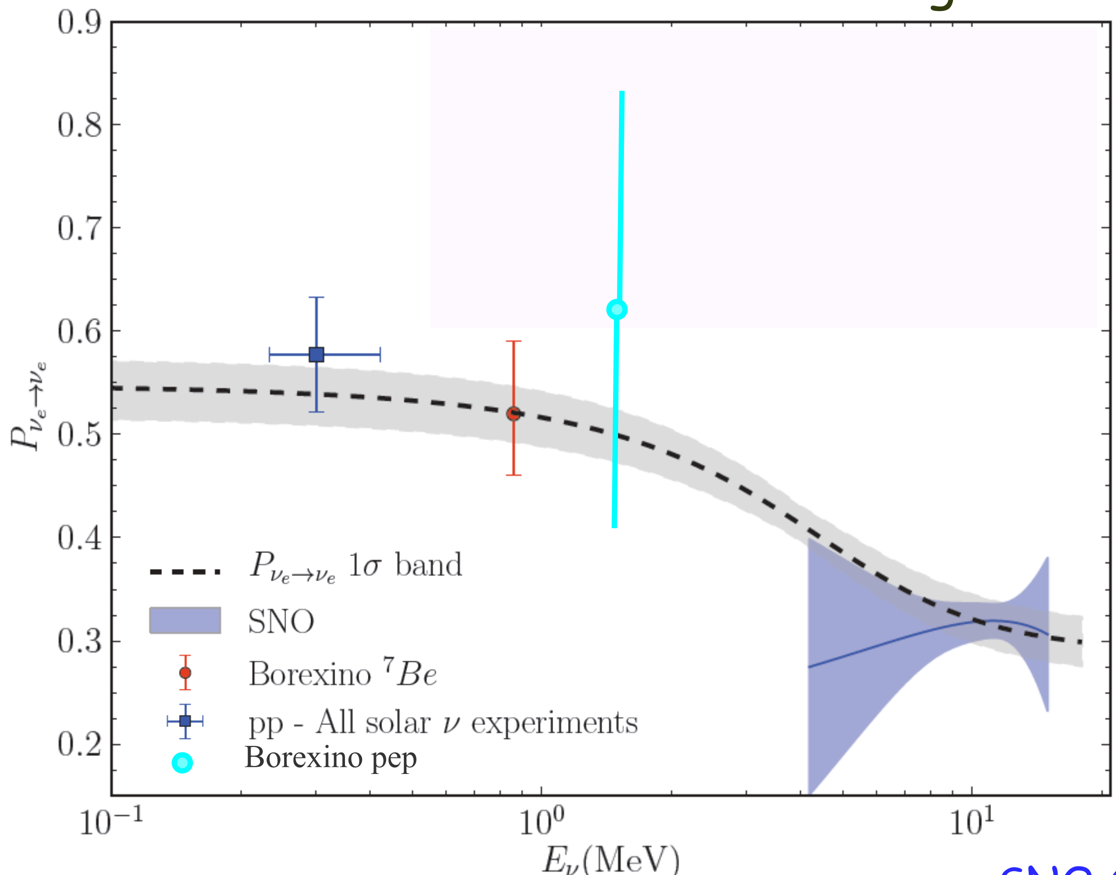
BOREXINO ^{8}B



(Would be nice if everyone published E_{ν}-dependent survival probabilities)

Observing MSW Phenomenology

Vacuum/matter transition region



SNO Collaboration

This is a little frustrating.

Solar νs give us our only huge, observed matter effect.
The situation is ripe for a precision measurement program.

Observing MSW Phenomenology

Only experiments capable of probing 1.5-4 MeV transition region are BOREXINO, KamLAND, and SNO+, LENA, via ES which is a poor way of measuring $P_{ee}(E_\nu)$

Ideas?

- Deuterated scintillator: ~$10 trillion for 1 kton (not really, but…)
- Water-soluble scintillator in D_2O: Good Luck!
- How about…C_2Cl_4 (`Davis fluid') dissolved in scintillator?

$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e^- \quad (\mathrm{threshold}\ \ 814\ \ \mathrm{keV})$$

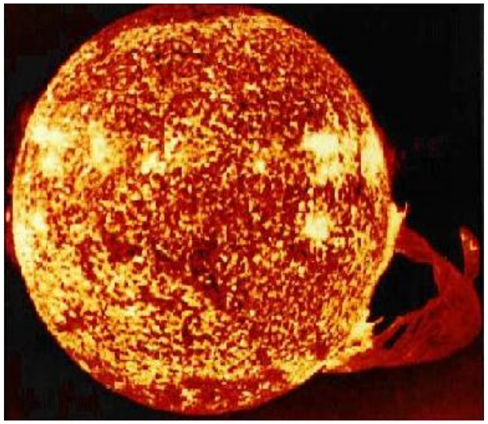
(or maybe just with Cherenkov light? n=1.5…)

- Anything else?

More precision on pep will help here (BOREXINO, SNO+, LENA)

CNO and the Sun

The solar `metallicity problem'



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

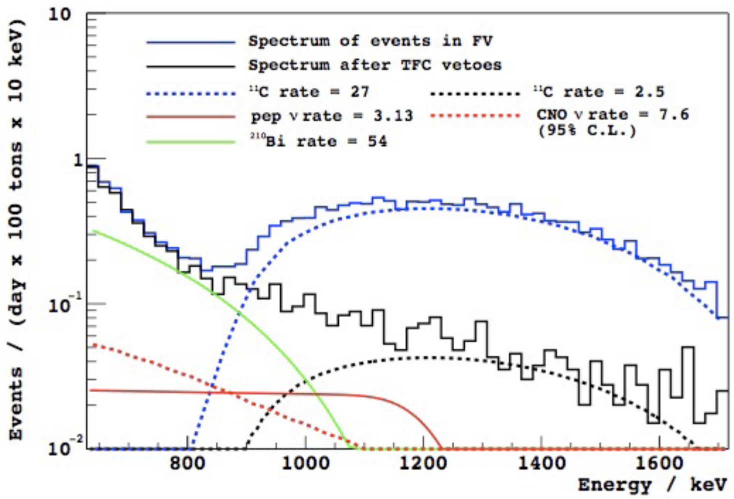
But! CNO neutrinos tell us metallicity of solar core

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

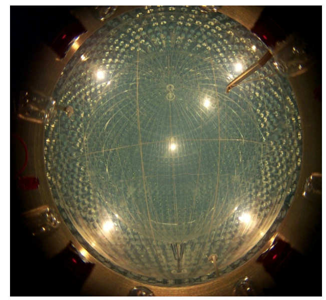
(Maybe Jupiter and Saturn `stole' metals from solar photosphere?
---Haxton and Serenelli, Astrophys.J. 687 (2008)

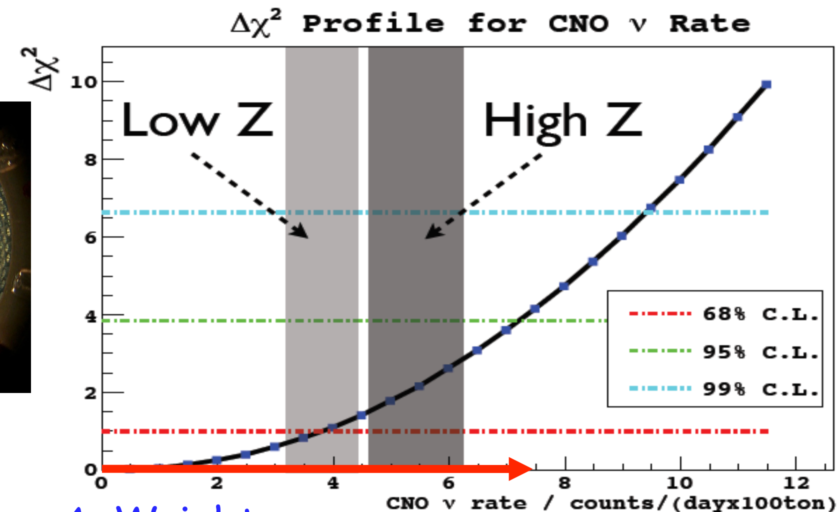
CNO Measurements

BOREXINO has placed limits but no clear signal yet



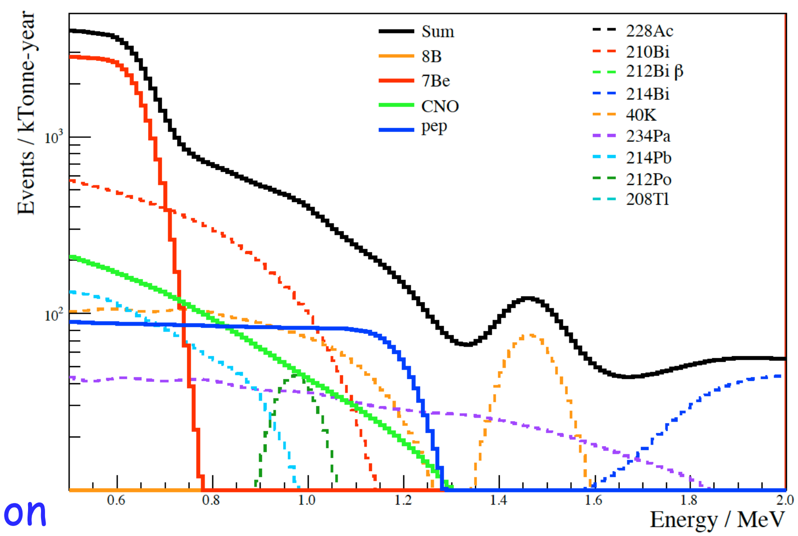
A. Wright





A. Wright

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



SNO+ Collaboration

pp/pep and the Sun

Are all energy generation/loss mechanisms accounted for?

With luminosity constraint: Exp. Uncs. Theory Uncs.

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

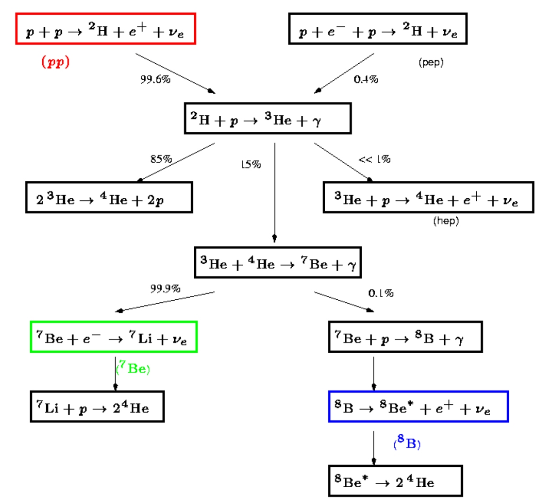
Bahcall and Pinsonneault

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

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

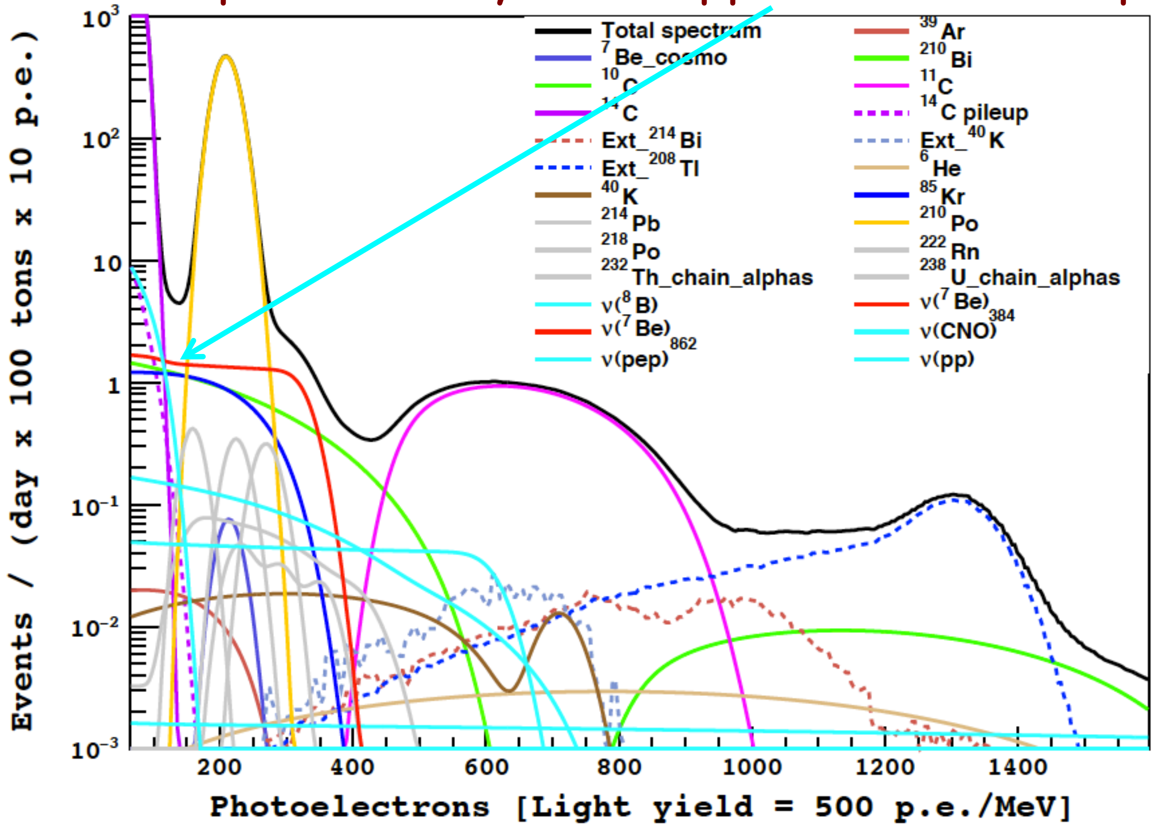
most sensitive to pp flux, but also pep

And high intensity: >10^{10}/cm^2-s on Earth



pp Measurements

BOREXINO spectacularly clean…pp measurement possible?



A. Wright

SNO+? Maybe if ^{14}C and ^{85}Kr are as good as BOREXINO, and light yield as good or better…event rate is ~10,000 pp scatters/year; 1000s in window between ^{14}C and ^{210}Po

pp Measurements

LENS

$$\nu_e + {}^{115}In \rightarrow e^- + (\tau = 4.76\mu s)2\gamma + {}^{115}Sn$$

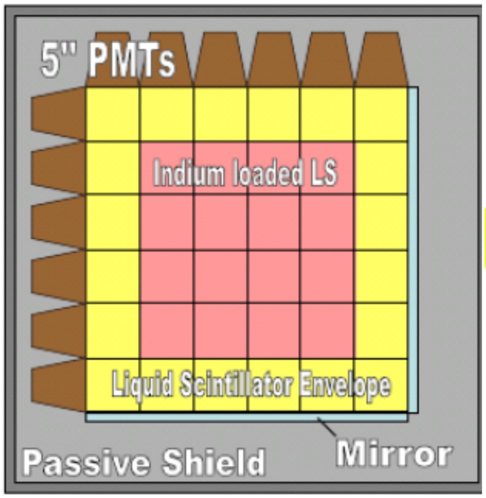
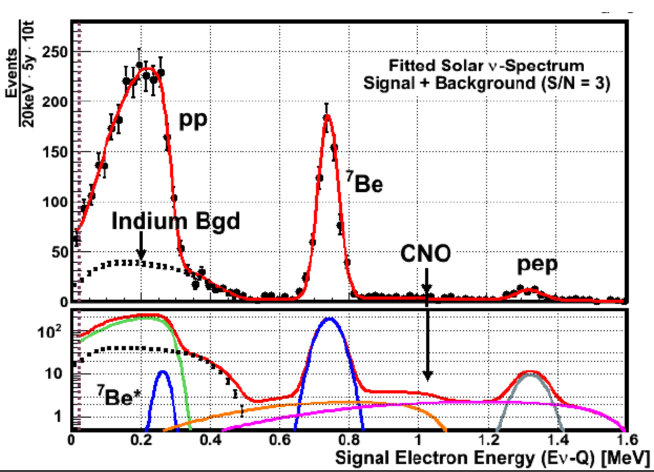
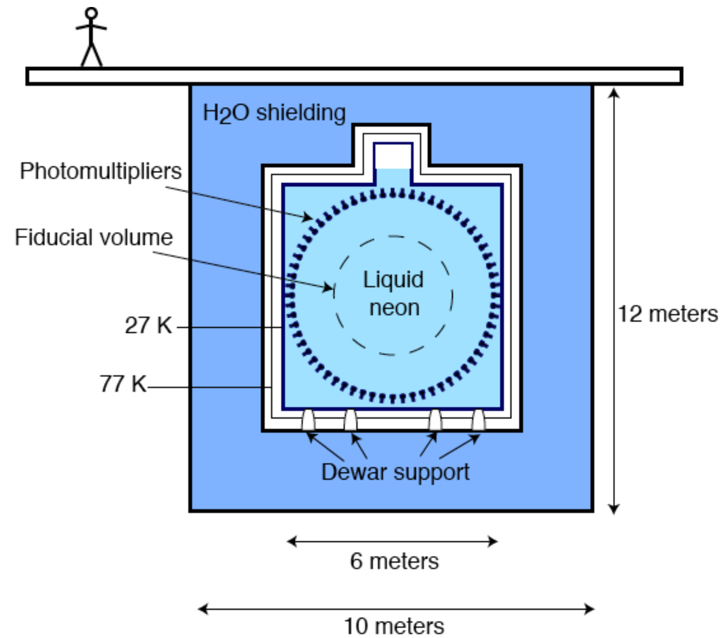


Fig. 12 Schematic design of MINILENS

CC reaction with Q=114 keV



CLEAN



ES only but precision perhaps better than 1%

Survey of Planned Experiments

Experiment	Detection Reaction	Targeted Solar νs	Technology	Other Physics	Status
KamLAND	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	^{7}Be	Liq. scintillator	Reactor νs, geo-νs	^{8}B results
SNO+	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pep, CNO	Liq. scintillator	0νββ, geo-νs	Construction
LENS	$\nu_e + {}^{115}In \rightarrow e^- + 2\gamma + {}^{115}Sn$	pp, ^{7}Be, pep	In-doped liq. scintillator	----------	Prototype bkd studies
XMASS	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp	Scintillation in cryogenic Xe	dark matter, 0νββ	800 kg stage in design
CLEAN	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp	Scintillation in cryogenic Ne	dark matter (DEAP/CLEAN)	0.1 and 1 ton construction
MOON	$\nu_e + {}^{100}Mo \rightarrow e^- + {}^{100}Tc$	pp, ^{7}Be, pep	Scintillator/ Fiber sandwich	0νββ	Prototype for 0νββ
LENA	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp, ^{7}Be, pep, CNO	50 kton Liq. scintillator	0νββ	Design, site selection
XAX	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp	Scintillation in cryo. Xe+Ar	dark matter, 0νββ	Design and simulation
Mega-H_2O	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	^{8}B, hep	H_2O Cerenkov	P-dk, LBL νs	Design, sim.

Summary

• Some very interesting physics and astrophysics left to do
• Not very many new experiments underway, but many planned
• We've gotten incredibly lucky with what Nature provided, worth exploiting it
• Also, we may want to be sure someone continues watching…