Solar Neutrinos, the physics gold mine

Hamish Robertson, NDM12, Nara, June 2012

Solar gold

- Neutrino oscillations, mass, explain the solar neutrino problem.

- Θ_{12} and Θ_{13} accurately known now.

- Solar models very accurate (metals abundance remains in doubt, but minor).

What is the future for solar neutrinos?

- Our challenge is a 1% measurement of the TOTAL neutrino luminosity. Comparison with the electromagnetic luminosity will test for sterile neutrinos and whether there is solar variability, with climate consequences.

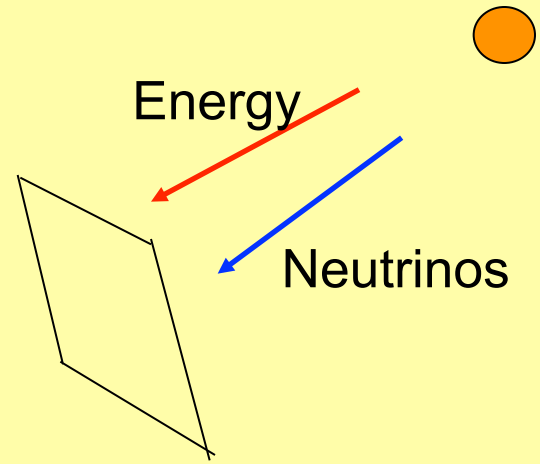
1%

Can we DO that?

Simplicity of the luminosity test:

Energy from Hydrogen Burning:

$4\ p + 2\ e^- \to {}^4He + 2\nu_e + 26.731\ MeV$



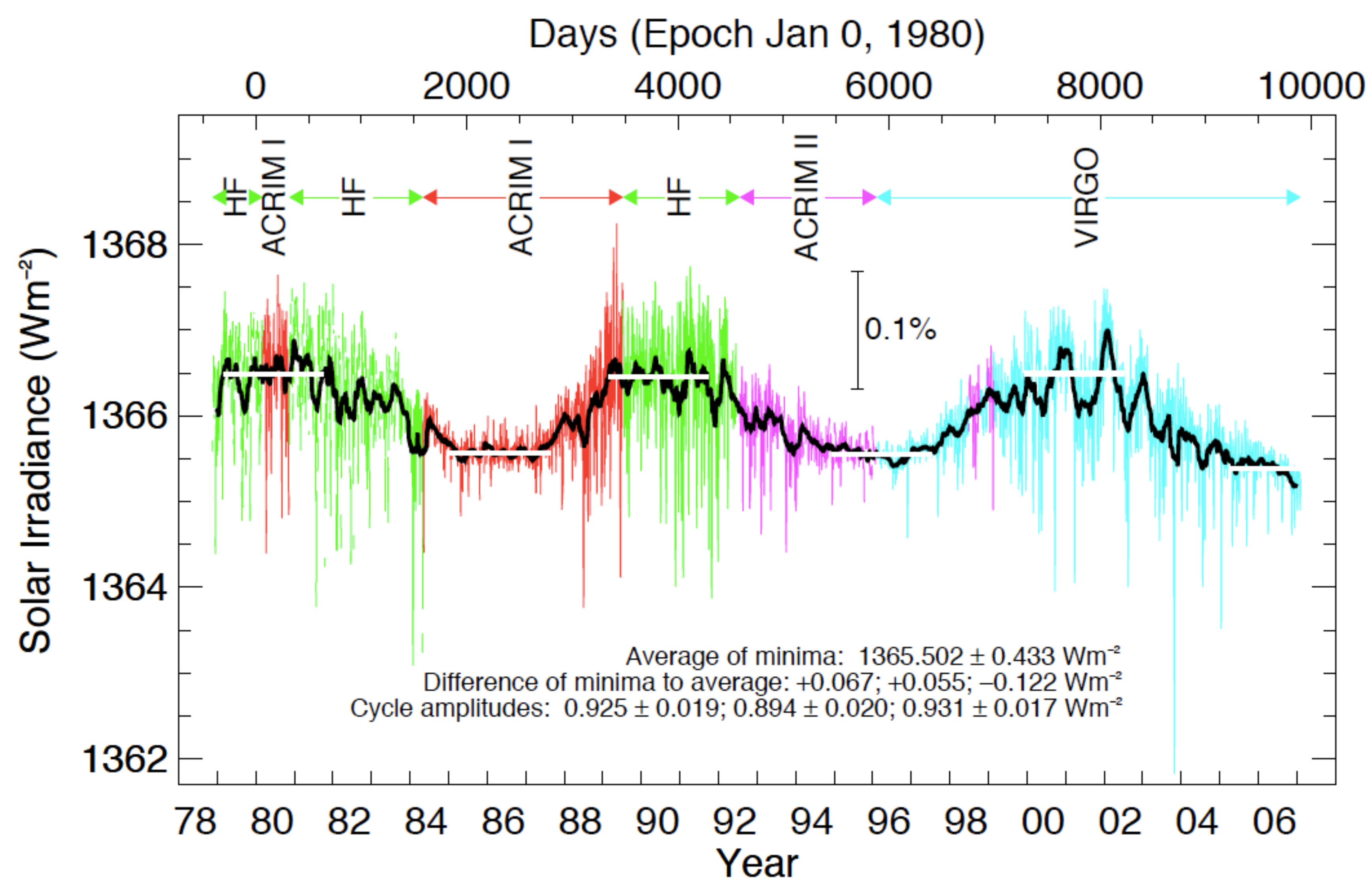
Measured power reaching Earth:

$137\ mW\ cm^{-2} = 8.53 \times 10^{11}\ MeV\ cm^{-2}\ s^{-1}$

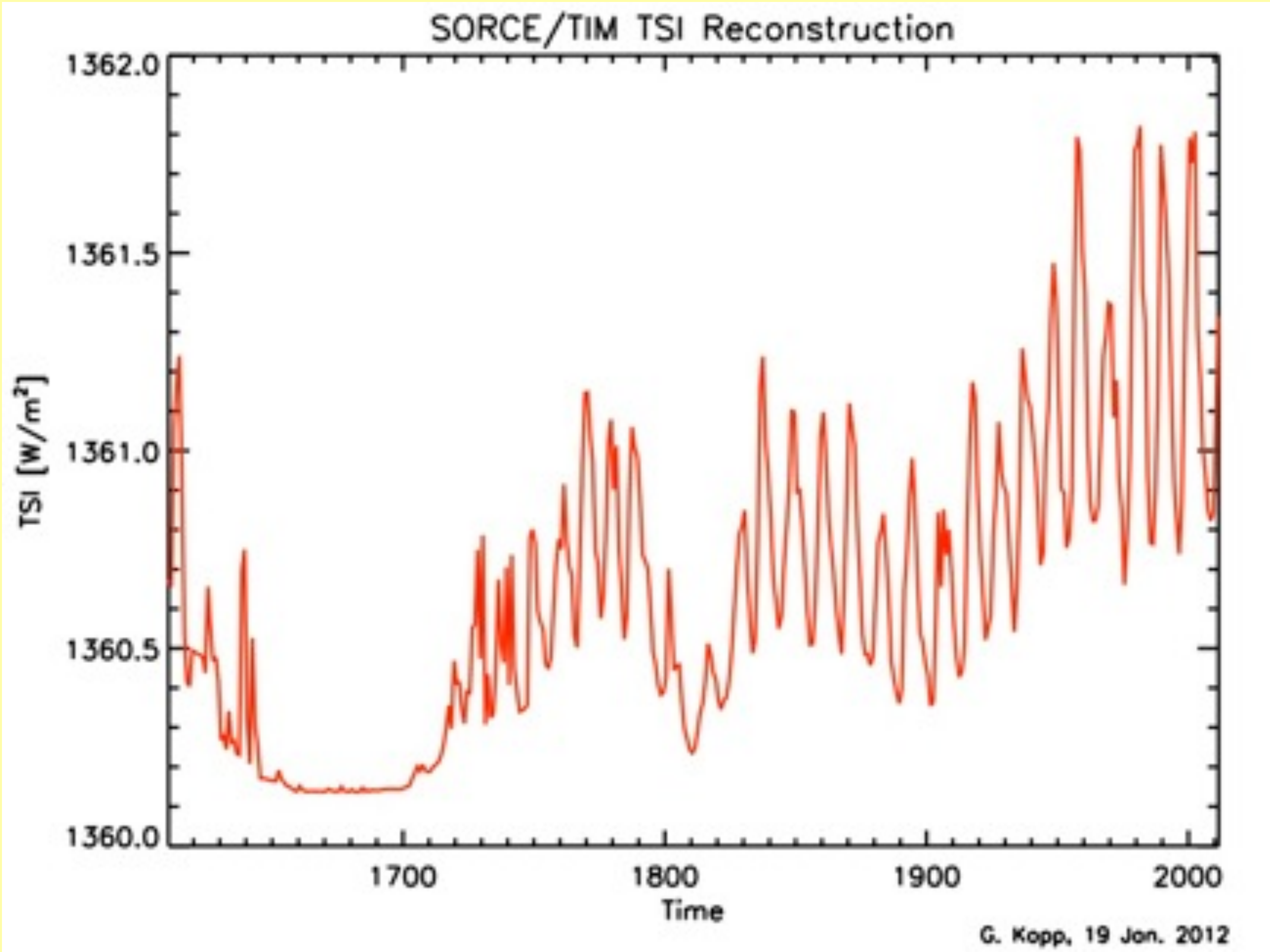
So… the neutrino flux is

$$\frac{2 \times 8.53 \times 10^{11}}{26.731} = \mathbf{6.38 \times 10^{10}}\ \nu_e\ cm^{-2}\ s^{-1}$$

Solar Irradiance



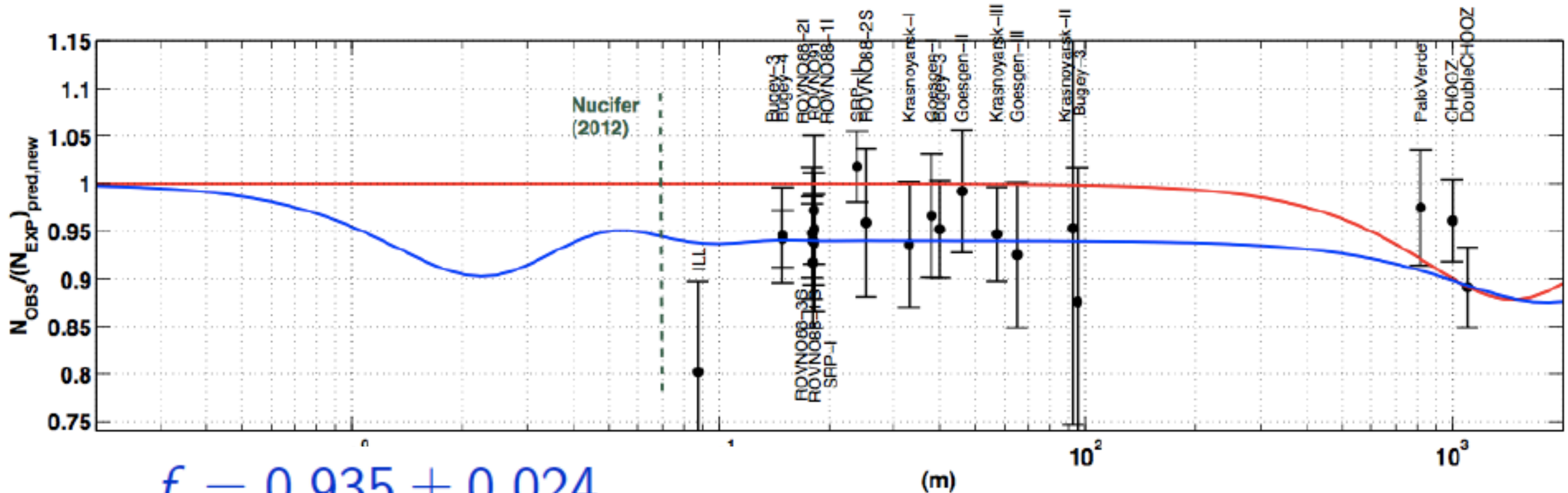
Solar Irradiance from Sunspot Numbers



Kopp & Lean; Geophys. Res. Lett., **38**, L01706 (2011).

Reactor anomaly

Mention et al., 1101.2755



$$f = 0.935 \pm 0.024$$

$$\chi^2_{\min} = 15.7/18 \quad (P = 61\%)$$

$$\chi^2_{f=1} = 23.0/19 \quad (P = 2.4\%)$$

$$\Delta\chi^2_{f=1} = 7.25 \quad (2.7\sigma)$$

T. Schwetz, Nu2012

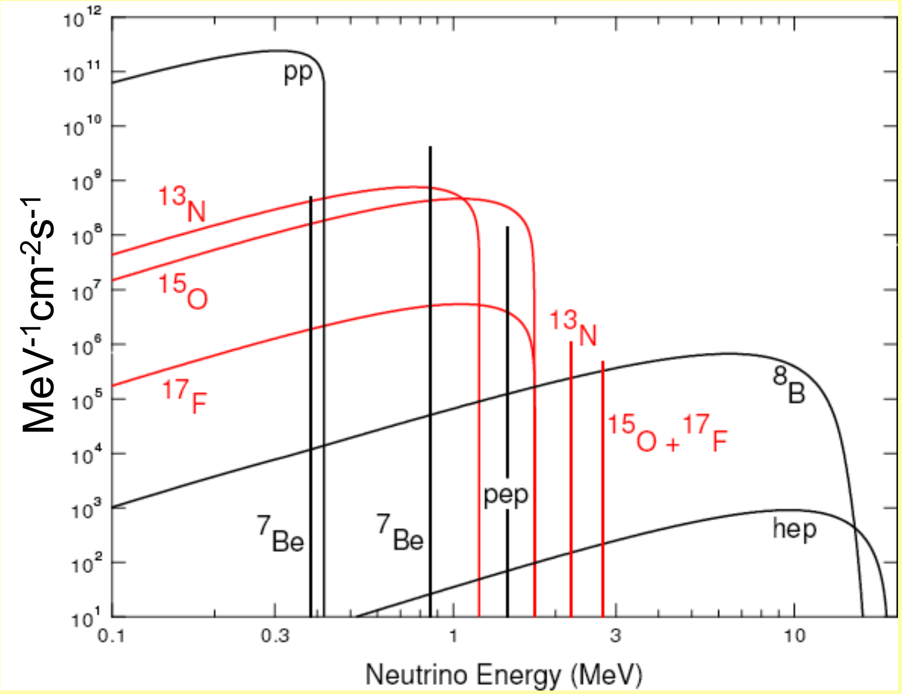
The Neutrino Luminosity

Some corrections and assumptions:--

Residual heat from formation (gravitation, deuterium burning) <<1%

Quasi-static burning (^{3}He, CNO)

The practical problem →



<u>The Luminosity Constraint:</u>

$$\sum_i \eta_i \Phi_i = \frac{2I}{Q}$$

I = 85.31(34) x 10^{10} MeV cm^{-2} s^{-1} (solar irradiance)

What do we need?

Source	η_i
pp	0.9799
pep	0.8917
^{7}Be	0.9352
^{8}B	0.4979
CNO (^{13}N + ^{15}O)	0.9363
hep	0.7609

DATA:

SAGE, Gallex/GNO:

Borexino: 1.6(3) x 10^8 cm^{-2}s^{-1}

Borexino: 4.89(24) x 10^9 cm^{-2}s^{-1}

SNO: 5.25(19) x 10^6 cm^{-2}s^{-1}

Borexino: <3.7 x 10^8 cm^{-2}s^{-1}

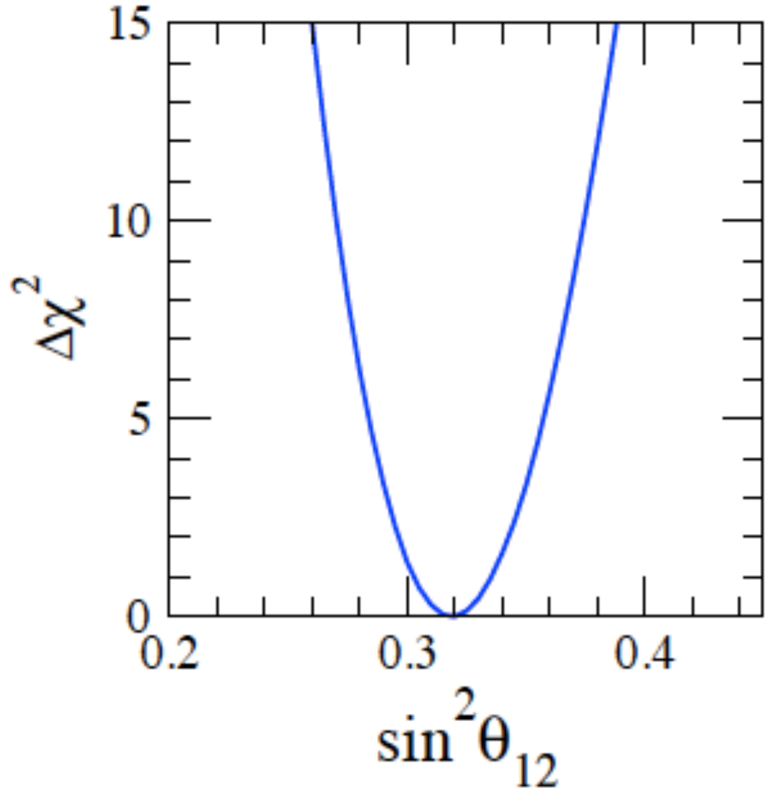
SNO: <2 x 10^4 cm^{-2}s^{-1}

θ_{12} SNO, SK, KamLAND

θ_{13} D-Chooz, Daya Bay, RENO

Recent global analyses

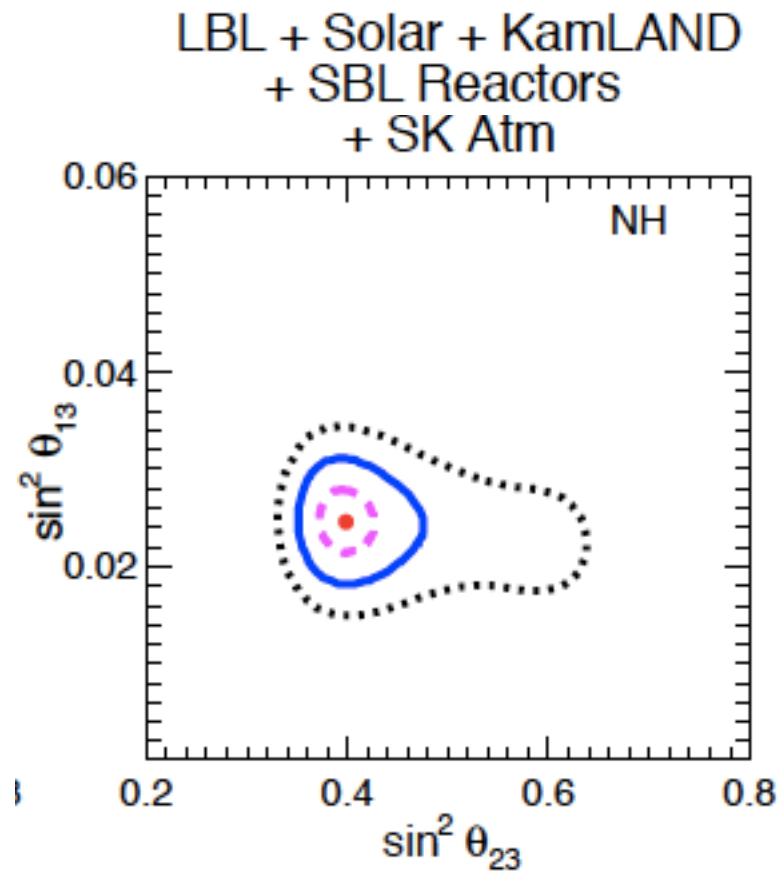
Forero et al. 1205.4018v2



$$\sin^2\theta_{12} = 0.320^{+0.015}_{-0.017}$$

$$\sin^2\theta_{13} = 0.026^{+0.003}_{-0.004}$$

Fogli et al. 1205.5254v2



$$\sin^2\theta_{12} = 0.307^{+0.018}_{-0.015}$$

$$\sin^2\theta_{13} = 0.0245^{+0.0034}_{-0.0031}$$

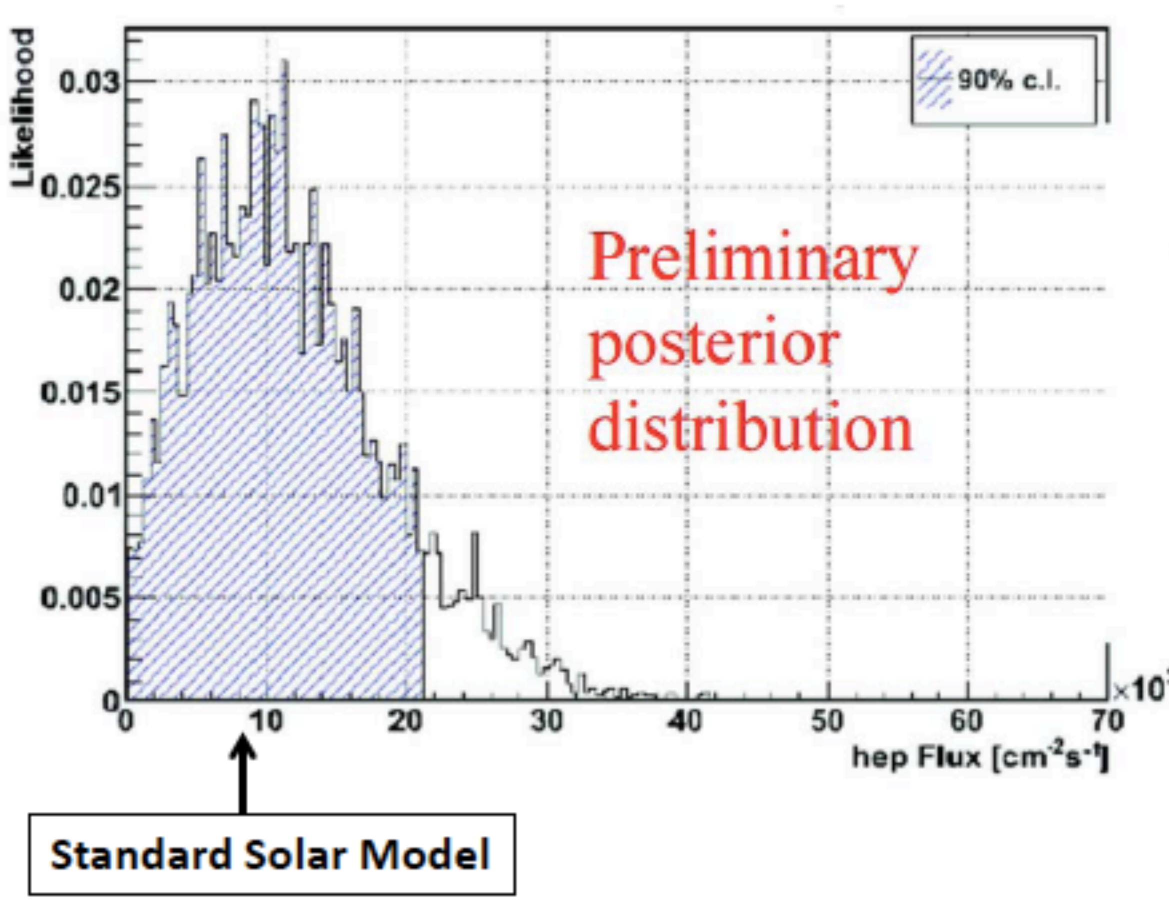
SNO *hep* limit

hep neutrino flux: Chris Howard SNO thesis, to be published

Preliminary MCMC fit to all SNO data.

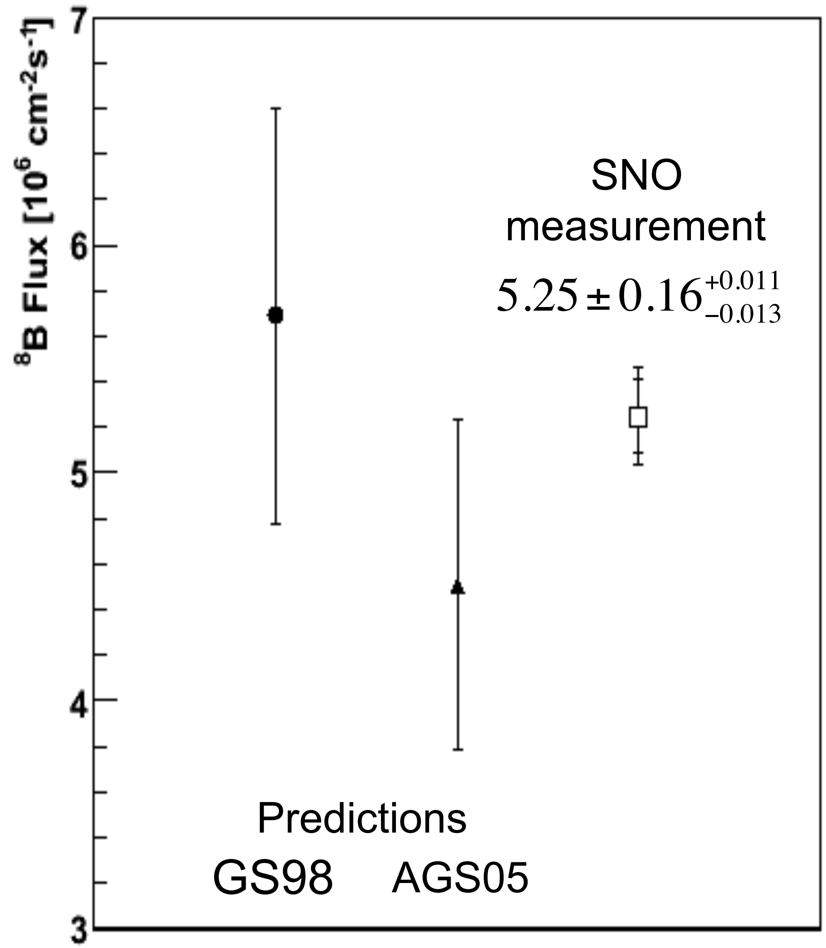
Limit of 22 x 10^3 cm^{-2}/s (90%)

Consistent with
SSM: 8 x 10^3 cm^{-2}/s



^{8}B Solar Neutrino Flux

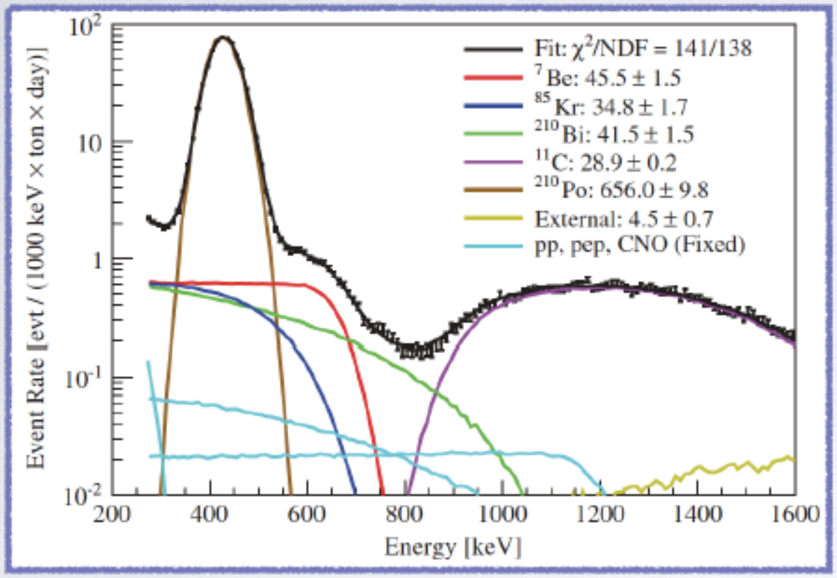
B. Aharmim et al. 1109.0763v1



^{7}Be RATE (II)

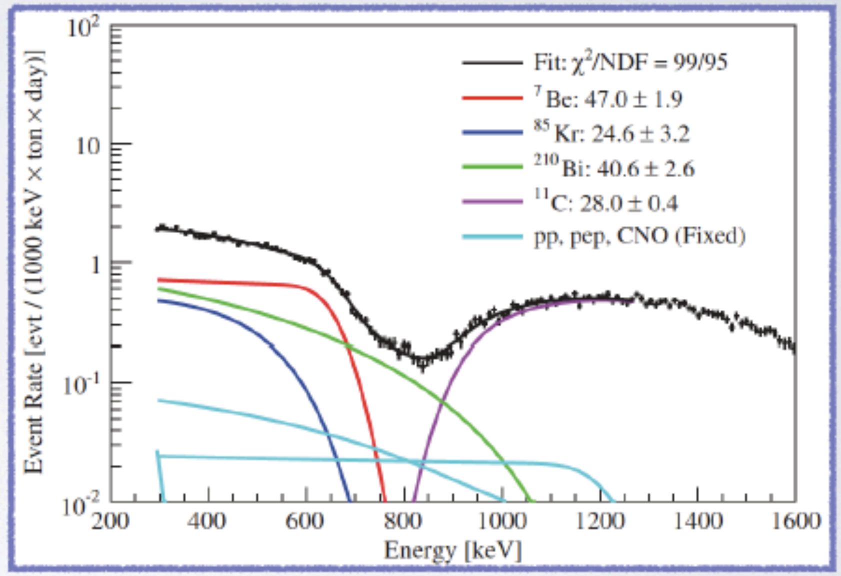
- Two approaches to control systematic errors due to analysis procedure:

Monte Carlo fit to the spectrum, no α/β ^{210}Po peak subtraction



Phys. Rev. Lett. 107, 141302, 2011

Analytical fit to the spectrum, after α/β ^{210}Po peak subtraction



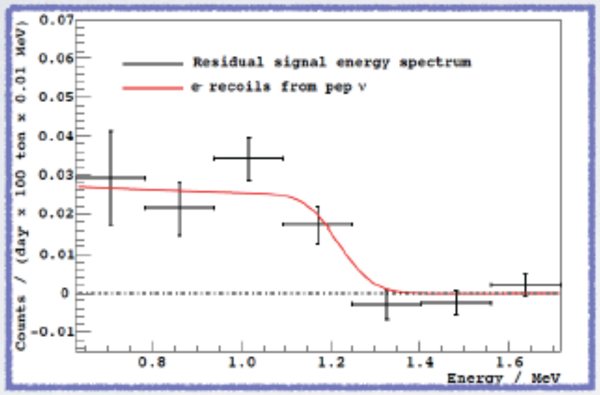
- Very Consistent results, small difference included in sys. uncertainty
- Rate for 100 t target:
  - **46.0 ± 1.5 (stat) ± 1.5 (sys) c d^{-1}**

Source	%
Trigger efficiency and stability	< 0.1
Live time	0.04
Scintillator density	0.05
Fiducial volume	+0.5 -1.3
Fit methods	2
Energy response	2.7
Sacrifice of cuts	0.1
Total	**+3.4 -3.6**

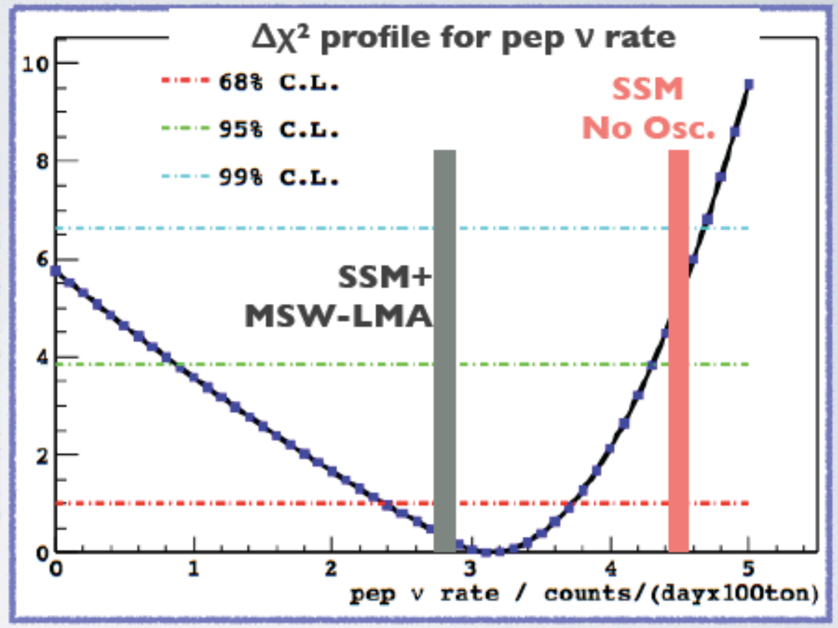
FIRST DETECTION OF PEP NEUTRINOS (ν)

- Rate: **3.1 ± 0.6$_{(stat)}$ ± 0.3$_{(sys)}$ cpd/100 t**

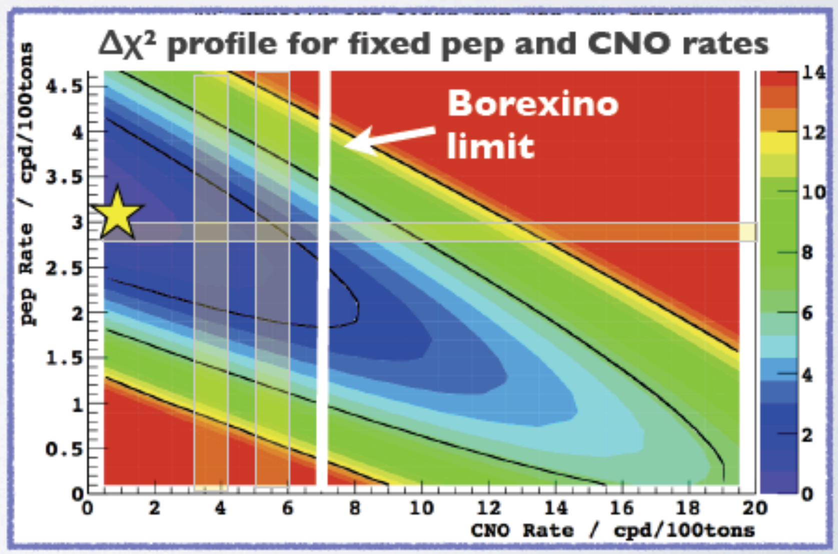
PRL 108, 051302 (2012)



- No oscillations excluded at **97% c.l.**
- Absence of pep solar ν excluded at 98%



- Assuming MSW-LMA:
  - Φ_{pep} = 1.6 ± 0.3 10^8 cm^{-2} s^{-1}
- CNO limit obtained assuming pep @ SSM
  - **CNO rate < 7.1 cpd/100 t (95% c.l.)**



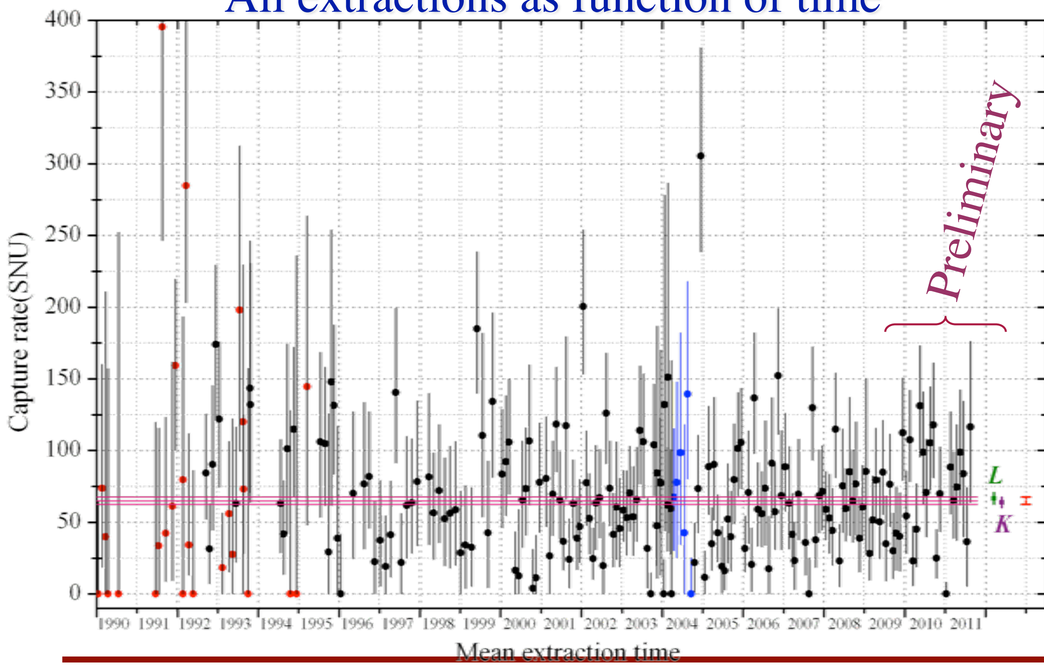
Presently SAGE is the only experiment sensitive to the *pp* neutrinos

It has the longest almost uninterrupted time of measurements among operating solar neutrino experiments

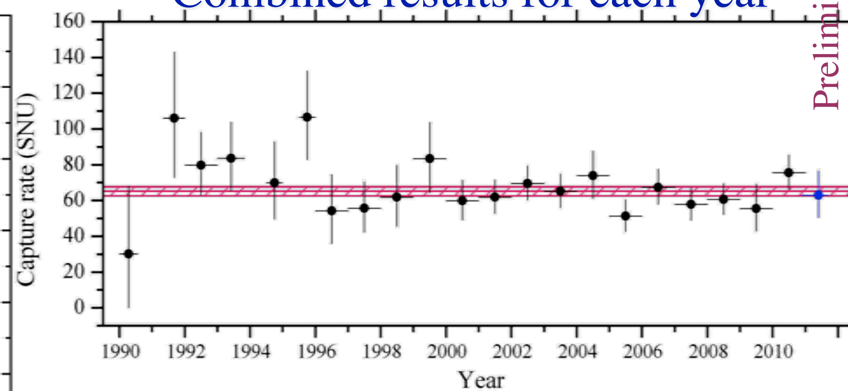
20.6 year period (1990 – 11.2011): 214 runs, 396 separate counting sets

$$\text{Result}: \quad 64.5\,^{+2.7}_{-2.7}\,(\text{stat})\,^{+2.6}_{-2.8}\,(\text{syst})\,\text{SNU} \qquad \text{or} \quad 64.5\,^{+3.7}_{-3.9}\,\text{SNU}$$

All extractions as function of time



Combined results for each year



(1 SNU = 1 interaction/s in a target that contains 10^{36} atoms of the neutrino absorbing isotope).

SAGE continues to perform regular solar neutrino extractions every four weeks with ~50 t of Ga

Luminosity measurement plan

Only two fluxes are significant, *pp* and ^{7}Be. Others are ~1% or less.

A neutral-current measurement at low energies seems out of reach for the foreseeable future.

Therefore we must use CC and/or ES measurements and oscillation parameters to deduce the total active flux.

For a 1% measurement:

- precisely known cross-sections
- precisely known oscillation parameters (we have 5%)
- high statistics
- low systematics

Four possible strategies

1. Make direct measurements of *pp* and ^{7}Be by ES.
2. Use *pep* measurement by ES to determine *pp* by calculation.
3. Use *pep* measurement by ES to normalize a CC measurement of *pp* and ^{7}Be.
4. Use available data and validate the model.

Precise cross sections required

- Elastic scattering is very precisely known.
- CC reactions to ground states known by detailed balance.
- CC reactions can be calibrated with sources.

- Distribution is a continuum.
- Radiochemical rates include excited states.
- Intense sources, geometrical factors are complications.

Neutrino-electron scattering

't Hooft PLB37, 1971

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2(1-\frac{T}{E_\nu})^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

T is electron kinetic energy, and:

$$\frac{2G_F^2 m_e}{\pi} = 1.7233 \times 10^{-44}\ \mathrm{cm}^2$$

Electron neutrinos:

$$g_L = \sin^2\theta_W + 1/2 = 0.73119(14)$$

$$g_R = \sin^2\theta_W = 0.23119(14)$$

Mu, tau neutrinos:

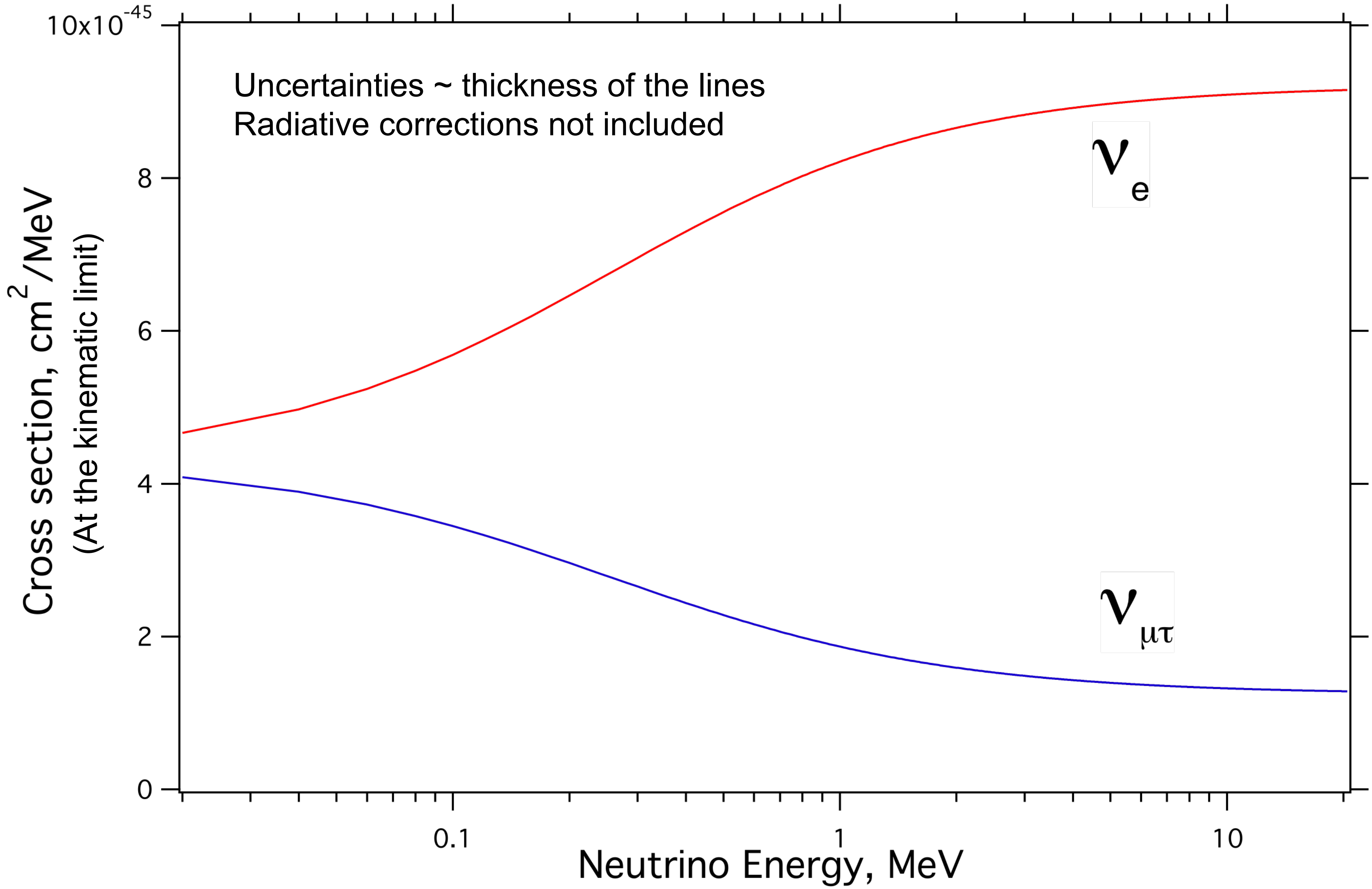
$$g_L = \sin^2\theta_W - 1/2 = -0.26881(14)$$

$$g_R = \sin^2\theta_W = 0.23119(14)$$

Kinematic limit:

$$T \leq \frac{2E_\nu^2}{2E_\nu + m_e}$$

Neutrino – electron scattering



The ES `miracle'

The rate observed in an experiment where both electron and non-electron flavors are present is

$$R \sim [\sigma_e P_{ee} + \sigma_{\mu\tau}(1 - P_{ee})]\,\Phi$$
$$= [P_{ee}(\sigma_e - \sigma_{\mu\tau}) + \sigma_{\mu\tau}]\,\Phi$$

where P_{ee} is the electron neutrino survival probability, σ_α is the differential cross section for scattering of flavor α, and Φ is the active flux.

$$\frac{d\Phi}{\Phi} = -\left[1 + \frac{\sigma_{\mu\tau}}{P_{ee}(\sigma_e - \sigma_{\mu\tau})}\right]^{-1} \frac{dP_{ee}}{P_{ee}}$$

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Flux	E_ν MeV	$\frac{d\Phi}{dP_{ee}}\frac{P_{ee}}{\Phi}$
pp	0.42	- 0.513
^{7}Be	0.86	- 0.616
pep	1.44	- 0.651

The ES `miracle' 2

$$P_{ee} = (1 - \sin^2\theta_{13})^2(1 - 2\sin^2\theta_{12} + 2\sin^4\theta_{12}) + \sin^4\theta_{13}$$
$$\equiv (1 - S_{13})(1 - 2S_{12} + 2S_{12}^2) + S_{13}^2$$

The survival probability depends on the oscillation parameters as follows:

$$\frac{dP_{ee}}{P_{ee}} = \frac{-2S_{12} + 4S_{12}^2}{P_{ee}}\frac{dS_{12}}{S_{12}}$$
$$\frac{dP_{ee}}{P_{ee}} = \frac{-S_{13}(1 - 2S_{12} + 2S_{12}^2) + 2S_{13}^2}{P_{ee}}\frac{dS_{13}}{S_{13}}$$

With the current best-fit values, $S_{12} = 0.307(17)$ and $S_{13} = 0.0245(32)$, the logarithmic derivative ratios are,

$$\frac{dP_{ee}}{P_{ee}} = -0.422\frac{dS_{12}}{S_{12}}$$
$$\frac{dP_{ee}}{P_{ee}} = -0.028\frac{dS_{13}}{S_{13}}$$

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Flux	E_ν MeV	Flux Uncert. %
pp	0.42	1.22
^{7}Be	0.86	1.45
pep	1.44	1.54

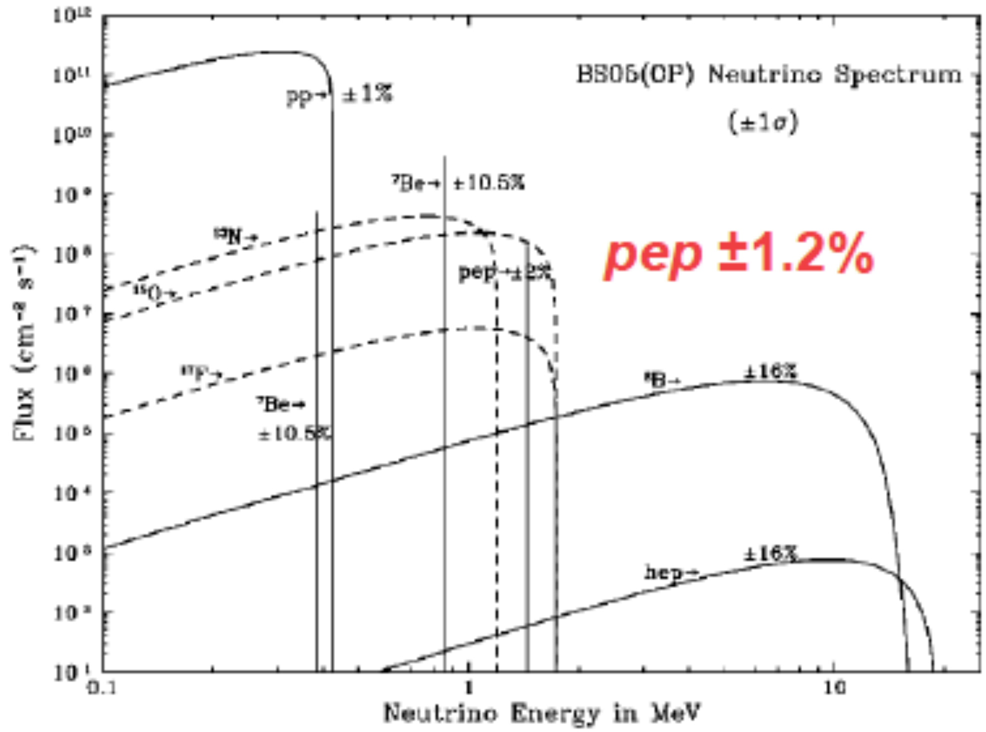
Determination of the neutrino luminosity

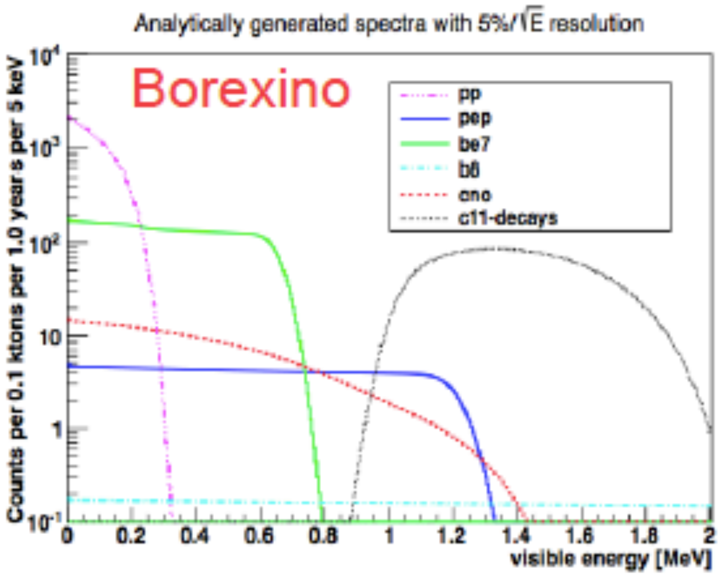
Gonzalez-Garcia et al. 0910.4584v4:

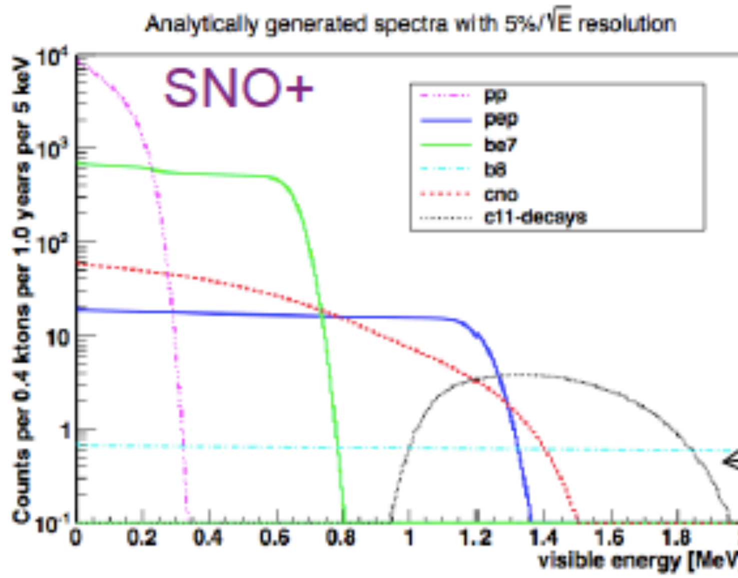
$$\frac{L_\odot(\text{neutrino-inferred})}{L_\odot} = 1.00 \pm 0.14 \left[{}^{+0.37}_{-0.34}\right].$$

SNO+

- will detect pep solar neutrinos without cosmogenic ^{11}C background (in Borexino and KamLAND)
  - $R = \Phi \, P_{ee} \, \sigma$
  - known flux, known cross section
  - thus measurement probes the neutrino survival probability with few% precision

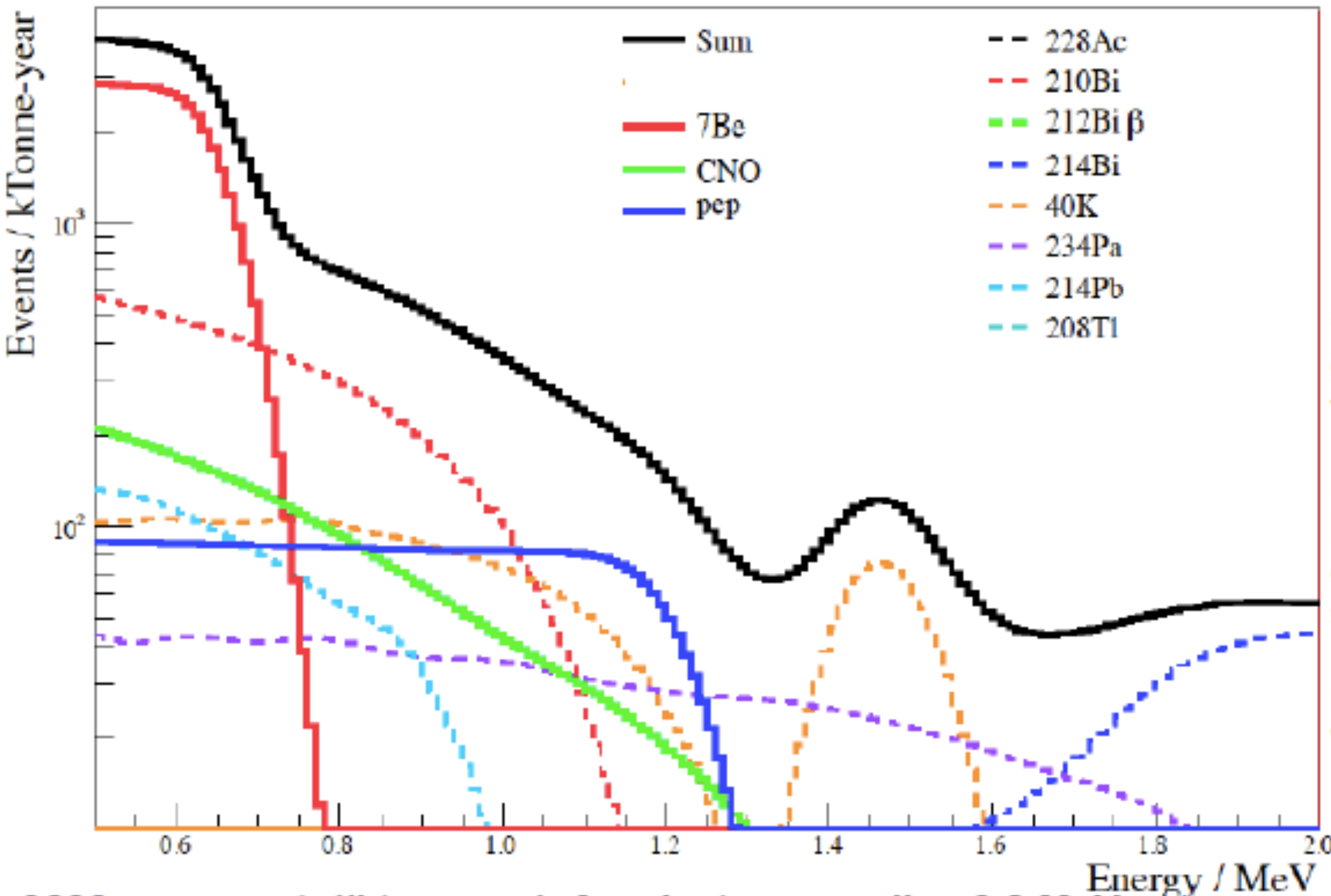






^{11}C background can be cut further using muon tracks.

SNO+ pep and CNO Solar Neutrino Signals



CNO measurement goal: ±10% after 3 years.

Control of ^{210}Bi background is essential through strong control of Rn, Pb, use of metal scavengers, water extraction.

3600 *pep* events/(kton·year), for electron recoils >0.8 MeV
goal: <u>±5% total uncertainty</u> after 3 years (including systematic and SSM)

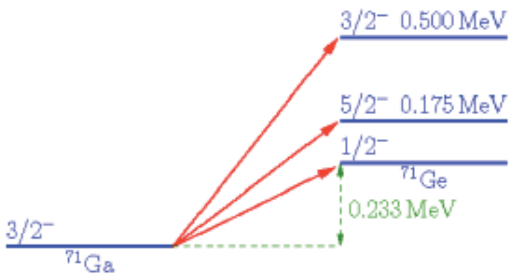
pep and *pp* closely related

$$R_{p+e+p} \cong 5.51 \times 10^{-5} \rho (1 + X) T_6^{-1/2} (1 + 0.02 T_6) R_{p\text{-}p}$$

Bahcall & May, Ap. J. 155 (1969)

The Gallium cross section

the reaction $\nu_e + ^{71}\text{Ga} \to ^{71}\text{Ge} + e^-$
can proceed to the ground state or
through excited states of ^{71}Ge



$$\sigma^x = \sigma^x_{\text{g.s.}} \left(1 + a_x \frac{\text{BGT}_{175}}{\text{BGT}_{\text{g.s.}}} + b_x \frac{\text{BGT}_{500}}{\text{BGT}_{\text{g.s.}}}\right) \qquad (x = \text{Cr, Ar})$$

previous calculations based on estimates of GT strengths
Bahcall hep-ph/9710491, Haxton nucl-th/9804011

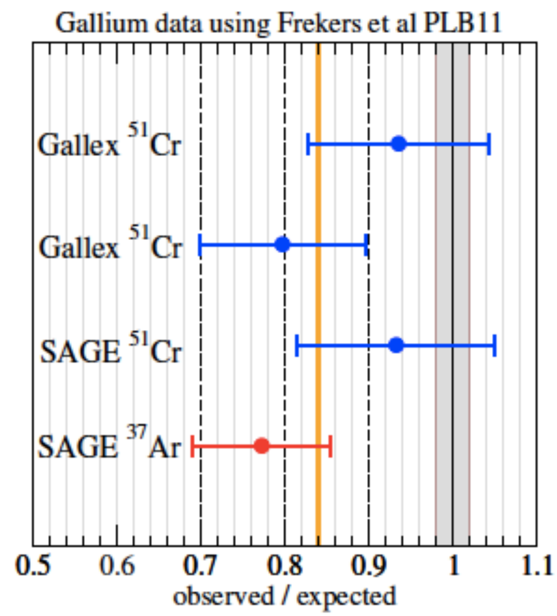
recent measurement of $^{71}\text{Ga}(^3\text{He}, t)^{71}\text{Ge}$ D. Frekers et al., PLB 706, 134 (2011):

$$\frac{\text{BGT}_{175}}{\text{BGT}_{\text{g.s.}}} = 0.0399 \pm 0.0305 \qquad \frac{\text{BGT}_{500}}{\text{BGT}_{\text{g.s.}}} = 0.207 \pm 0.016$$

$\Rightarrow$ contribution of $7.2 \pm 2.0\%$ from excited states (for ^{51}Cr)

Gallium data

D. Frekers et al., PLB 706, 134 (2011) BGT determinations lead to a correction of ratios relative to Bahcall expectation by factor 0.982 (0.977) for Cr (Ar) sources



combined fit: $\chi^2_{\rm min} = 2.3/3\,\text{dof}$ $\quad r = 0.84^{+0.054}_{-0.051}$ $\quad \Delta\chi^2_{r=1} = 8.7\,(2.9\sigma)$

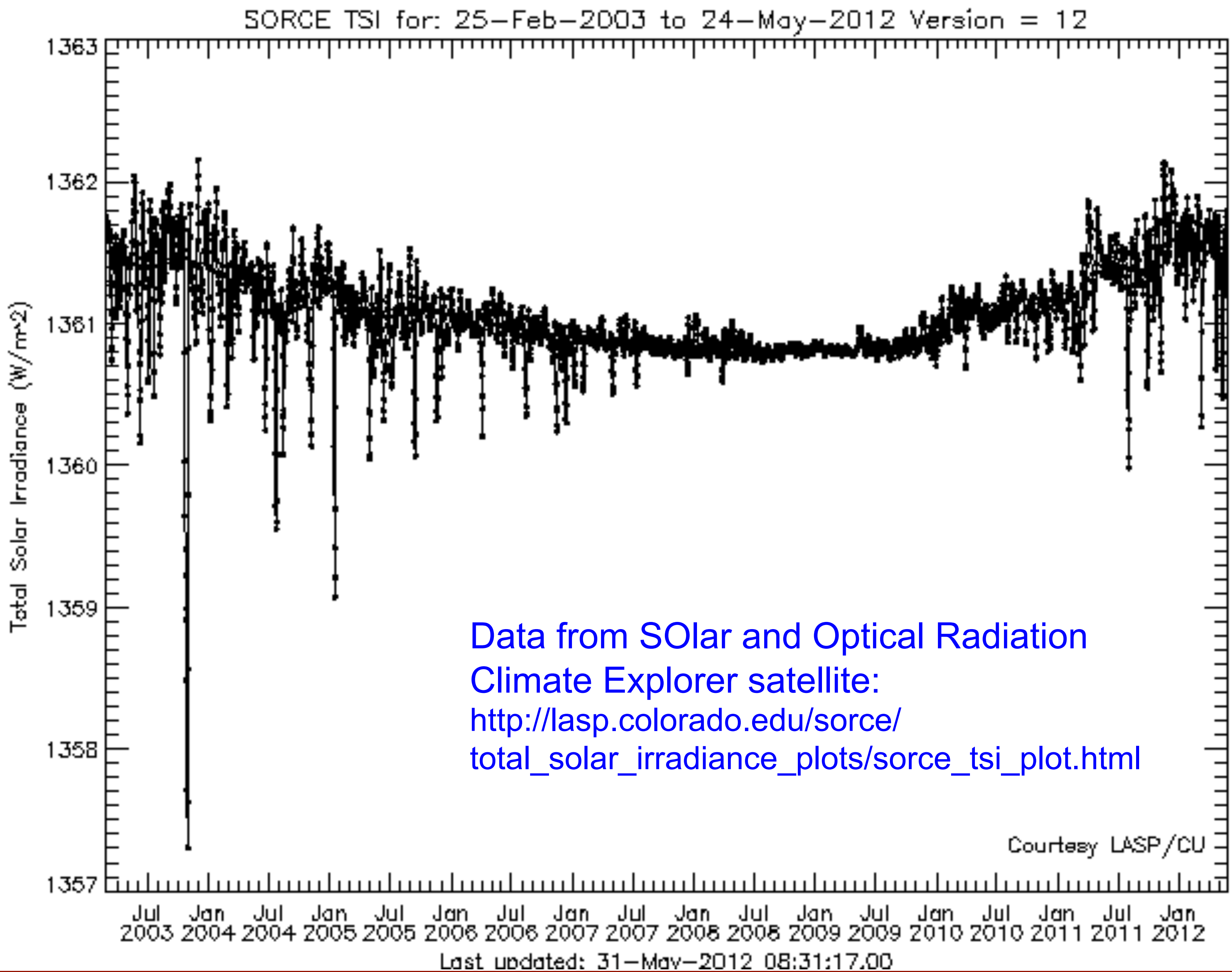
Using the neutrino luminosity

Electromagnetic Luminosity	85.35×10^{10}	MeV cm^{-2} s^{-1}
Sum of known fluxes x η_i (not Ga)	4.89×10^{9}	cm^{-2} s^{-1}
`Predicted' pp flux	$6.01(3) \times 10^{10}$	cm^{-2} s^{-1}
GS98	5.98×10^{10}	cm^{-2} s^{-1}
AGSS09	6.03×10^{10}	cm^{-2} s^{-1}
Use Ga data	$6.30(47) \times 10^{10}$	cm^{-2} s^{-1}
Neutrino Luminosity scaled by Reactor Anomaly	$79.8(20) \times 10^{10}$	MeV cm^{-2} s^{-1}
`Predicted' pp v_a flux	$5.59(15) \times 10^{10}$	cm^{-2} s^{-1}
Difference	$0.71(49) \times 10^{10}$	cm^{-2} s^{-1}

Summary

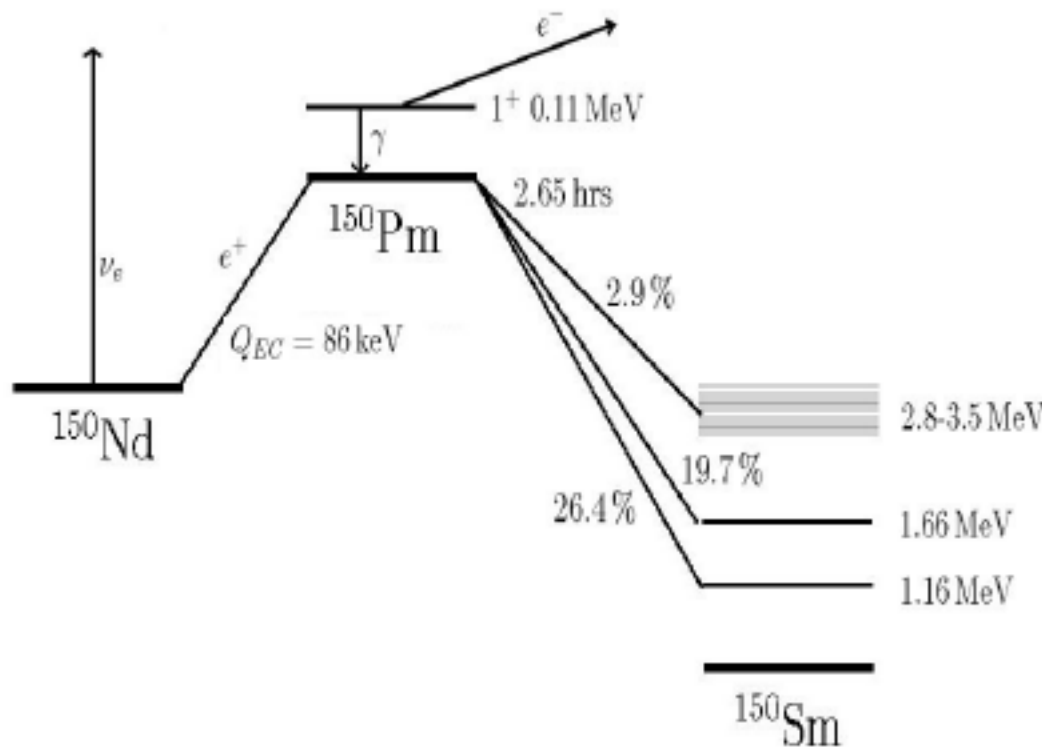
- A ~1% measurement of the ν luminosity appears achievable. We need a good *pp* or *pep* measurement by ES.
- Current data with Ga and no SSM disfavors reactor anomaly at ~90% CL.
- Strong tension between solar and source data for Ga experiments.

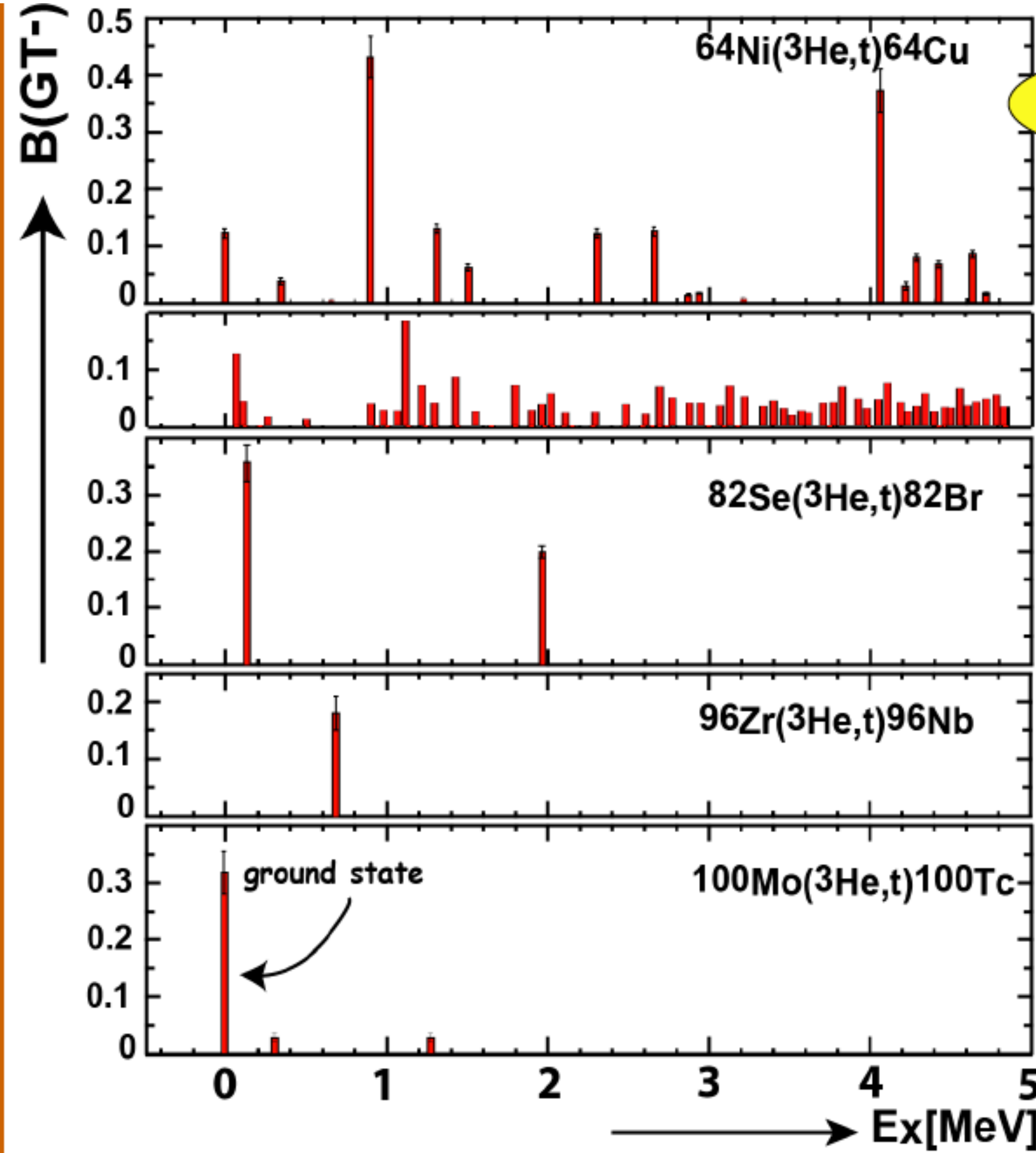
FIN


SORCE TSI for: 25-Feb-2003 to 24-May-2012 Version = 12
Total Solar Irradiance (W/m^2)
1363
1362
1361
1360
1359
1358
1357
Jul 2003 Jan 2004 Jul 2004 Jan 2005 Jul 2005 Jan 2006 Jul 2006 Jan 2007 Jul 2007 Jan 2008 Jul 2008 Jan 2009 Jul 2009 Jan 2010 Jul 2010 Jan 2011 Jul 2011 Jan 2012
Last updated: 31-May-2012 08:31:17.00
Courtesy LASP/CU
Data from SOlar and Optical Radiation Climate Explorer satellite:
http://lasp.colorado.edu/sorce/total_solar_irradiance_plots/sorce_tsi_plot.html

A Low-Threshold Solar Neutrino Target

K. Zuber PLB 709, 6 (2012).





^{64}Zn(εε, εβ+)

^{76}Ge(β-β-)

^{82}Se(β-β-)

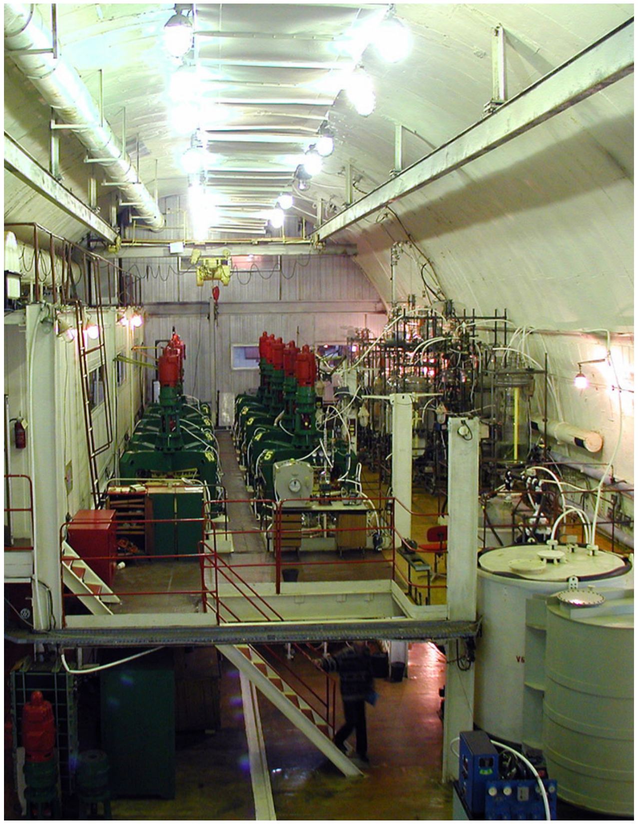
^{96}Zr(β-β-)

^{100}Mo(β-β-)

reduced spreading of GT strength

D. Frekers, 2011 (INT)

SAGE
Baksan, Russia



50 tons of metallic Ga

1990-2011, running

214 runs (Jan 1990 – Dec 2011) give the result: **$64.5^{+3.7}_{-3.8}$ SNU**

GALLEX/GNO
Gran Sasso, Italy

30 tons of Ga

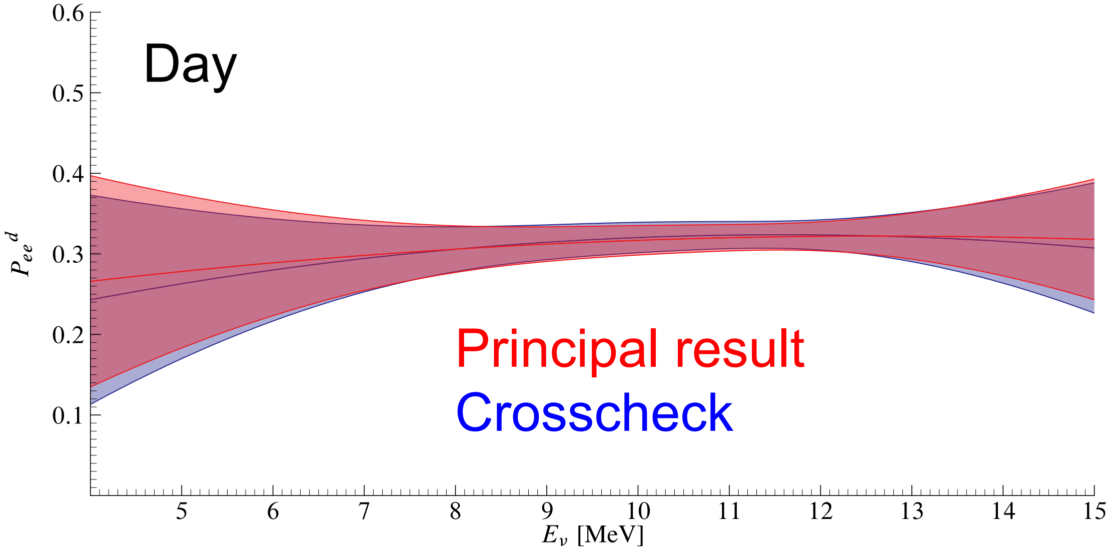
(103 tons of $GaCl_3$ acidic solution)

1991-2003

123 runs (May 1991 – Apr 2003) give the result: **67.5 ± 5.1 SNU**

The weighted average of the results of all Ga experiments is now 66.1±3.1 SNU

Survival Probability



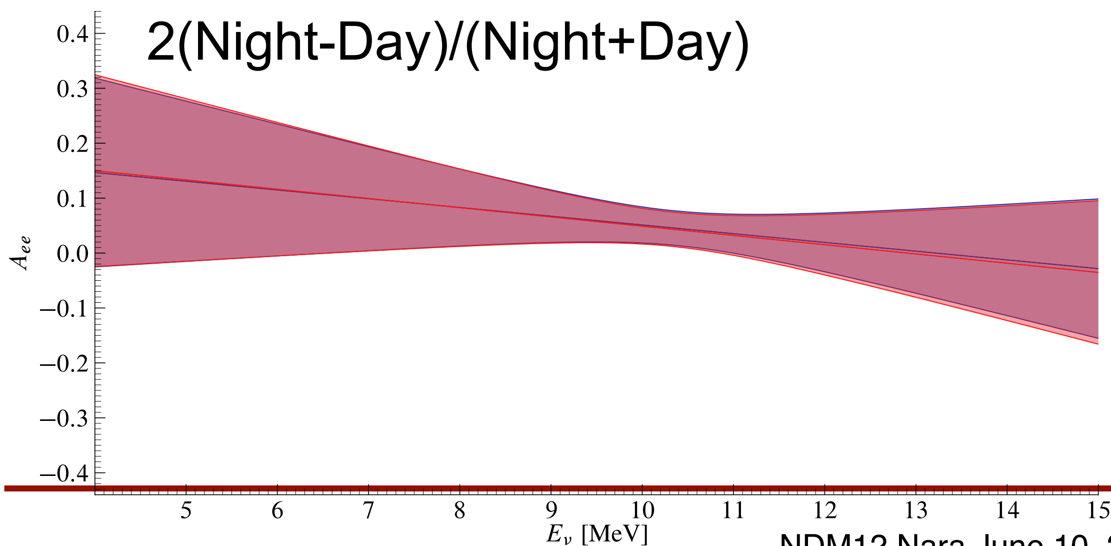
$c_0 = 0.317 \pm 0.016 \pm 0.009$

$c_1 = 0.0039^{+0.0065}_{-0.0067} \pm 0.0045$

$c_2 = -0.0010 \pm 0.0029^{+0.0014}_{-0.0016}$

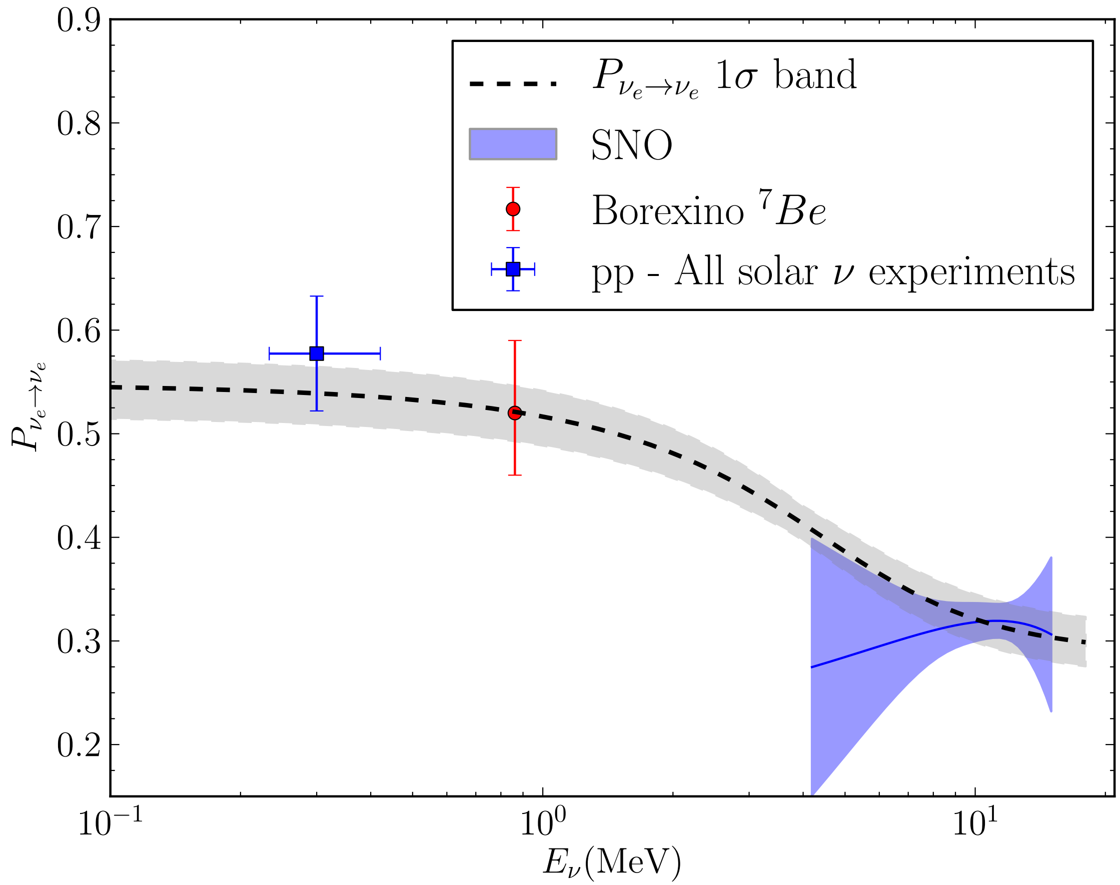
$a_0 = 0.046 \pm 0.031^{+0.014}_{-0.013}$

$a_1 = -0.016 \pm 0.025^{+0.010}_{-0.011}$

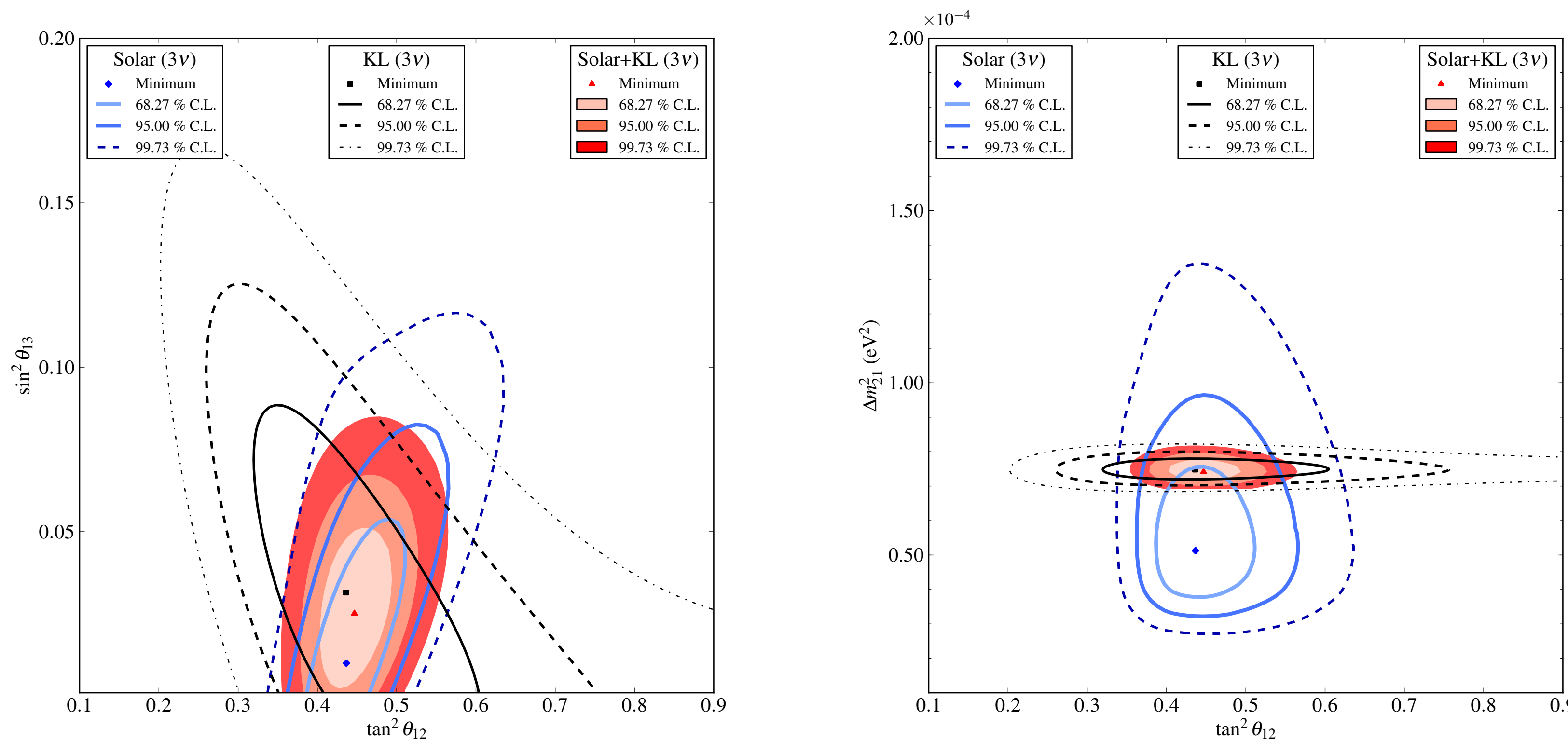


Approximately 20% improvement over previous analysis.

MSW Solution



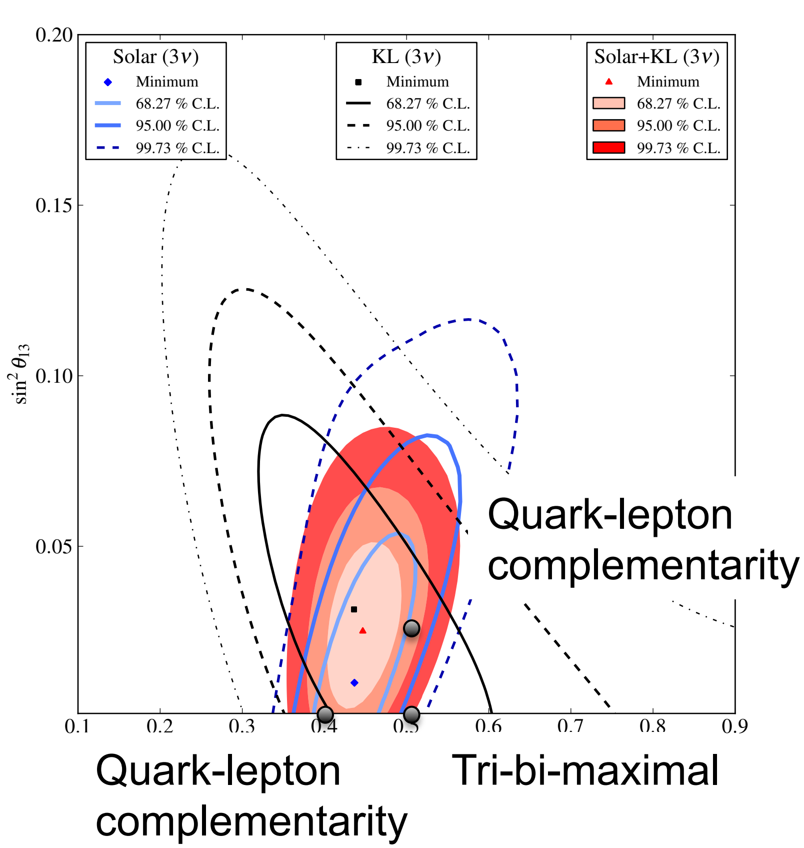
Oscillation Parameters

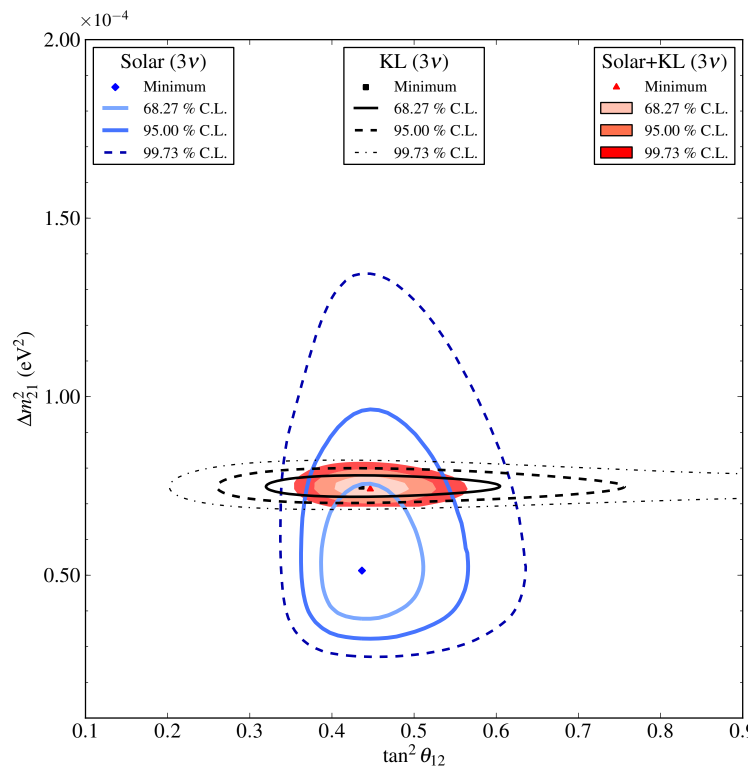


$\tan^2\theta_{12} = 0.446^{+0.030}_{-0.029}$ $\Delta m^2_{21} = \left(7.41^{+0.21}_{-0.19}\right)\times 10^{-5}\,\mathrm{eV}^2$ $\sin^2\theta_{13} = 0.0251^{+0.0176}_{-0.0146}$

< 0.0534 (95%C.L.)

Oscillation Parameters





Solar Neutrino Experiments ca. 2002

Solar Neutrino Experiments												
		Fiducial Mass		Threshold, keV			BP00 Rates per year					
Expt.	Type	Tons	of	ES	CC	NC	pp +pep	^{7}Be	^{8}B	CNO	Event Eff. %	Start
Cl-Ar	Radioch.	135	^{37}Cl		814		14	72	363	26	16	1968
Kamioka	Cerenkov	680	water	7000					120		100	1985
SAGE	Radioch.	23	^{71}Ga		233		181	86	31	22	25	1990
Gallex	Radioch.	12	^{71}Ga		233		94	45	16	11		1991
SuperK	Cerenkov	22000	water	5000					10200		100	1996
GNO	Radioch.	12	^{71}Ga		233		94	45	16	11		1998
SNO	Cerenkov	2000	water	5000					1100		100	1999
		200	^{2}H		6400				10000		100	1999
		200	^{2}H			2223			5000		50	1999
KamLAND	Scintillator	1000	scintillator									2001
Borexino	Scintillator	100	scintillator	250				20000				2002
HERON	L He rotons, Scintillator	5	He	100			3025	1500	2	125	80	
TPC	Gas TPC	7	He	180			4000					
CLEAN	Scintillator	12.5	Ne	100			9000					
XMASS	Scintillator		Xe									
LENS	Scintillator	5	^{176}Yb		301,445		570	400	32	136		
MOON	Scintillator	3.3	^{100}Mo		168		409	129	14	34	20	
Cl	Hybrid	2200	^{37}Cl		814		230	1200	5900	420	16	
GaAs	Ionization		^{71}Ga									
LiF	Bolometer	0.9	^{7}Li		862	487	27	29			100	