Results from Borexino
26th Rencontres de Blois - 2014

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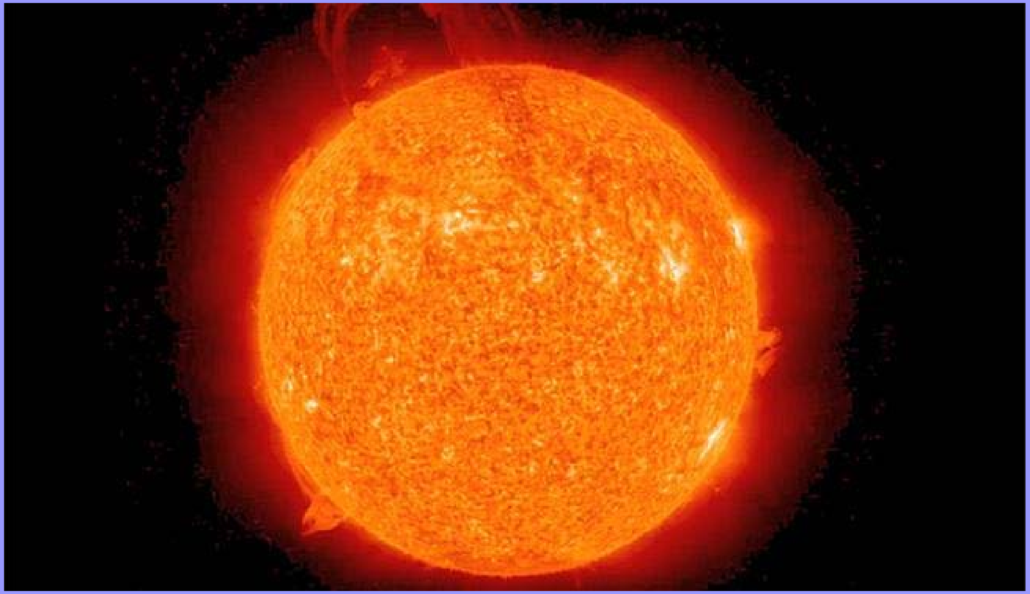
On behalf of the BOREXINO Collaboration
Reporting on the Solar Results only



the Borexino Collaboration

Milano

Heidelberg

Hamburg

Mainz

Gran Sasso

Perugia

Genova

Napoli

TU Dresden

Jagiellonian Kraków

JINR Dubna

Virginia Tech

Houston

Paris

Moscow

Los Angeles

Princeton

UMass Amherst

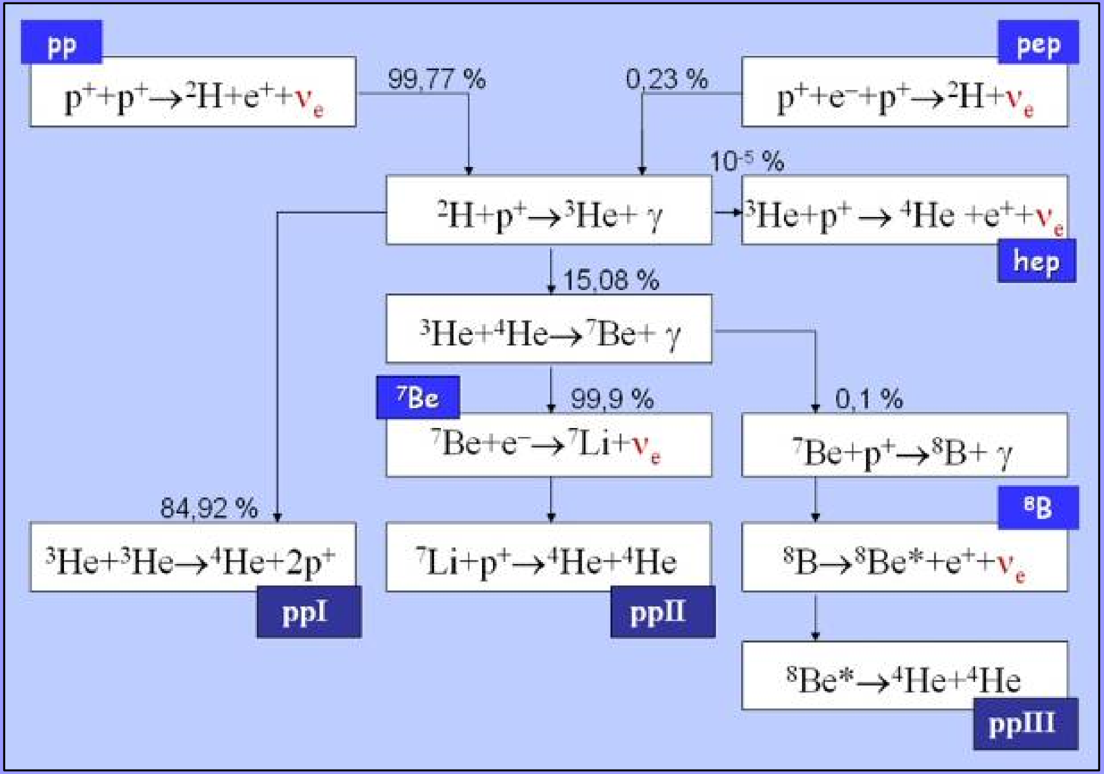
St. Petersburg

Kurchatov Moscow

We believe we understand the Sun

pp-cycle
>99% energy production
5 ν species

CNO-cycle
<1% energy production
3 ν species



pp
$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

0,23 %

pep
$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

$^2H + p^+ \rightarrow {}^3He + \gamma$

10^{-5} %

$^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$
hep

15,08 %

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

^7Be

99,9 %

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

0,1 %

$^7Be + p^+ \rightarrow {}^8B + \gamma$

^8B

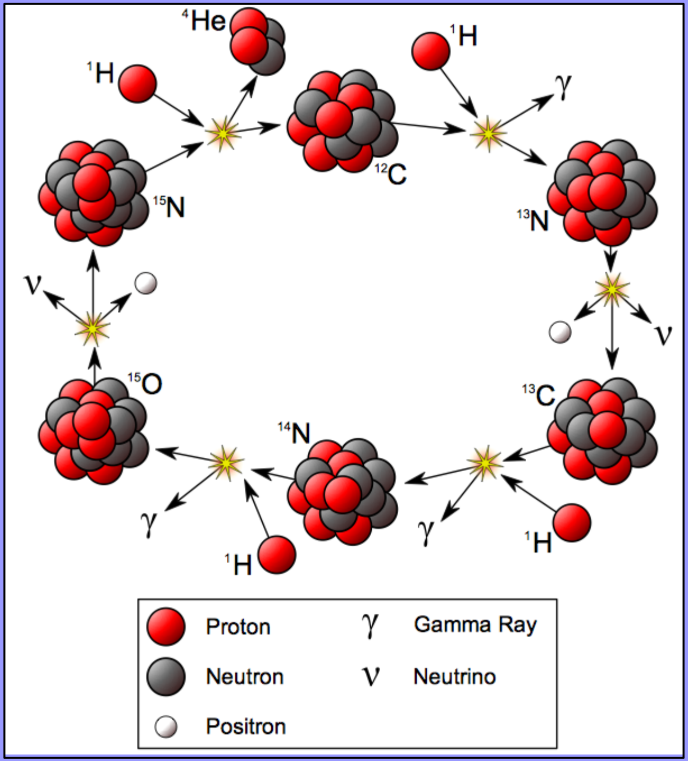
84,92 %

$^3He + {}^3He \rightarrow {}^4He + 2p^+$
ppI

$^7Li + p^+ \rightarrow {}^4He + {}^4He$
ppII

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$^8Be^* \rightarrow {}^4He + {}^4He$
ppIII



Neutrinos are produced in several reactions in both cycles

1. BOREXINO

Borexino is a low background Neutrino Detector for sub-MeV solar Neutrino (and other) studies

Detecting Solar Neutrinos, Geo-neutrinos and other rare phenomena

1. BOREXINO

2. Be-7 flux measurement

3. B-8 measurement

4. pep detection and CNO limit

5. Future

- Main detection reaction: elastic scattering in a scintillator $\nu e^- \rightarrow \nu e^-$
- Low interaction rates: 0.1/1 event/day/ton of target mass
- Low energy (mostly <10 MeV, better if <2 MeV)
- Low threshold and low background (radiopurity)
- Underground location to shield from cosmic rays (10^6 reduction of muon flux)

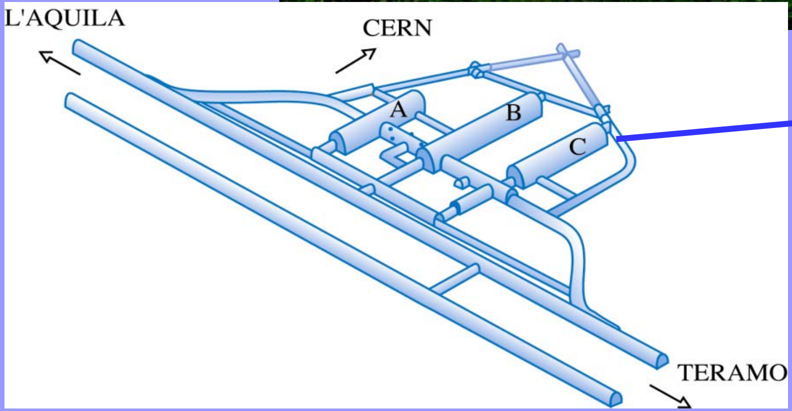
Experimental site

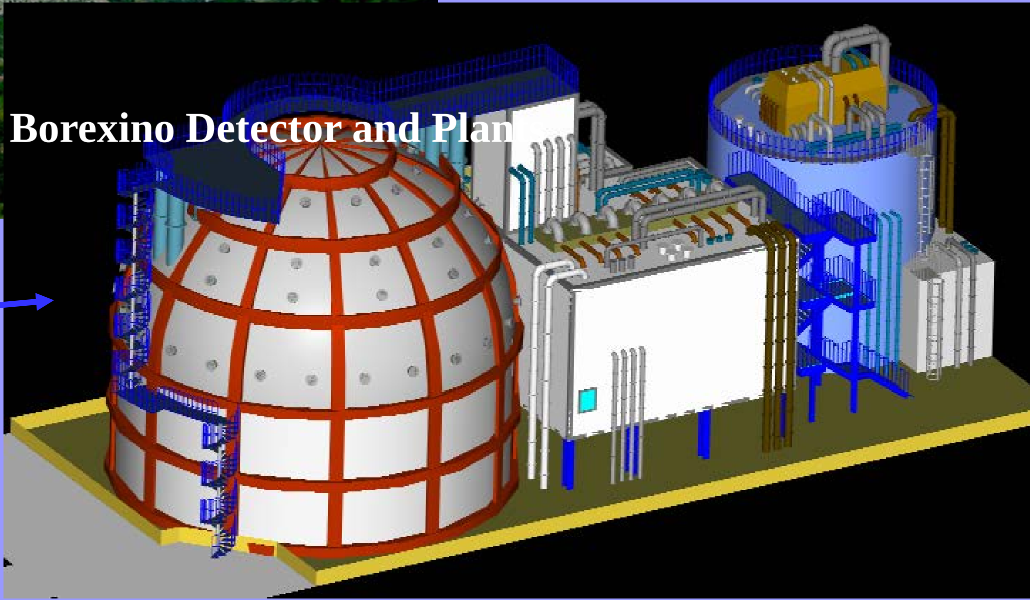
Laboratori Nazionali del Gran Sasso

Assergi (AQ)
Italy
1400m of rock shielding
~3800 m.w.e.

Abruzzo, Italy
120 Km from Rome

External Labs



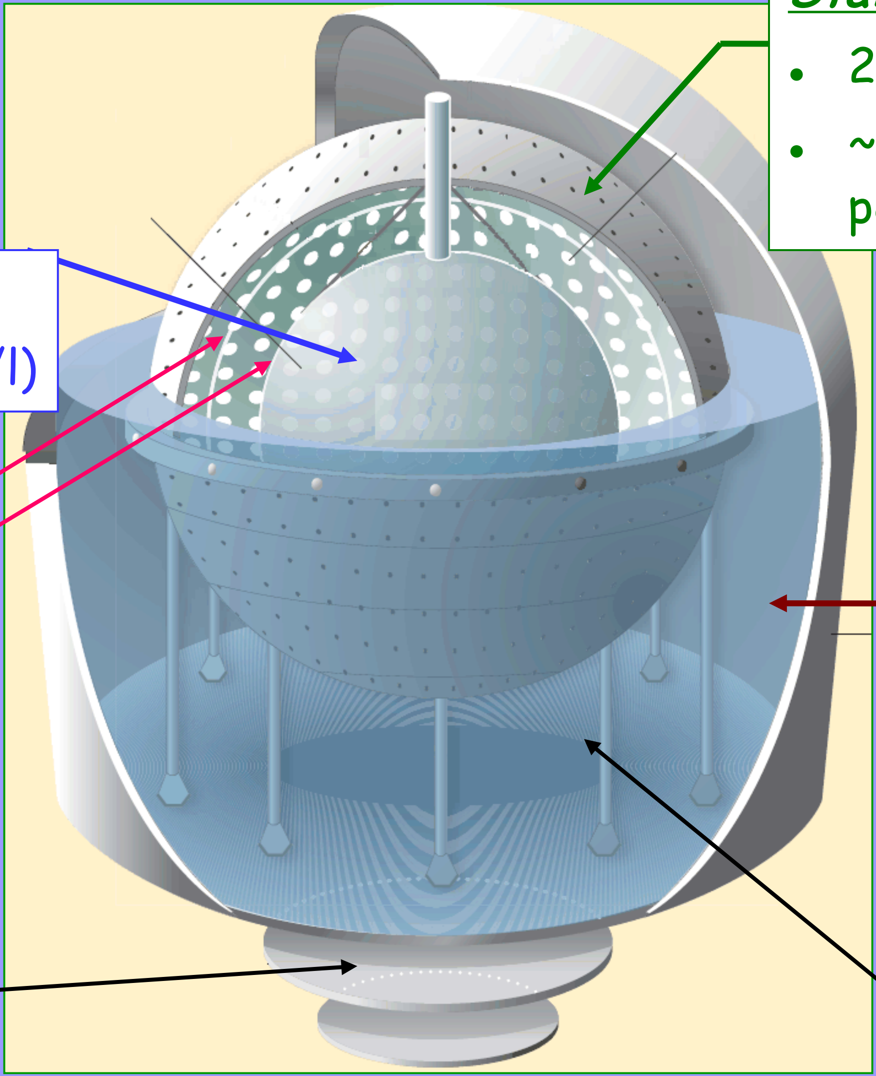


Borexino Detector and Plan

The Borexino Detector

Neutrino electron scattering

νe –> νe



Scintillator:

270 t PC+PPO (1.4 g/l)

Nylon vessels:

(125 μm thick)

Inner: 4.25 m

Outer: 5.50 m

(radon barrier)

Carbon Steel Plates

Stainless Steel Sphere:

- 2212 PMTs
- ~ 1000 m^3 buffer of pc+dmp (light queched)

Water Tank:

γ and n shield

μ water Č detector

208 PMTs in water

2100 m^3

20 legs

Filling phase of the Borexino detector (2007, Laboratorio del Gran Sasso)

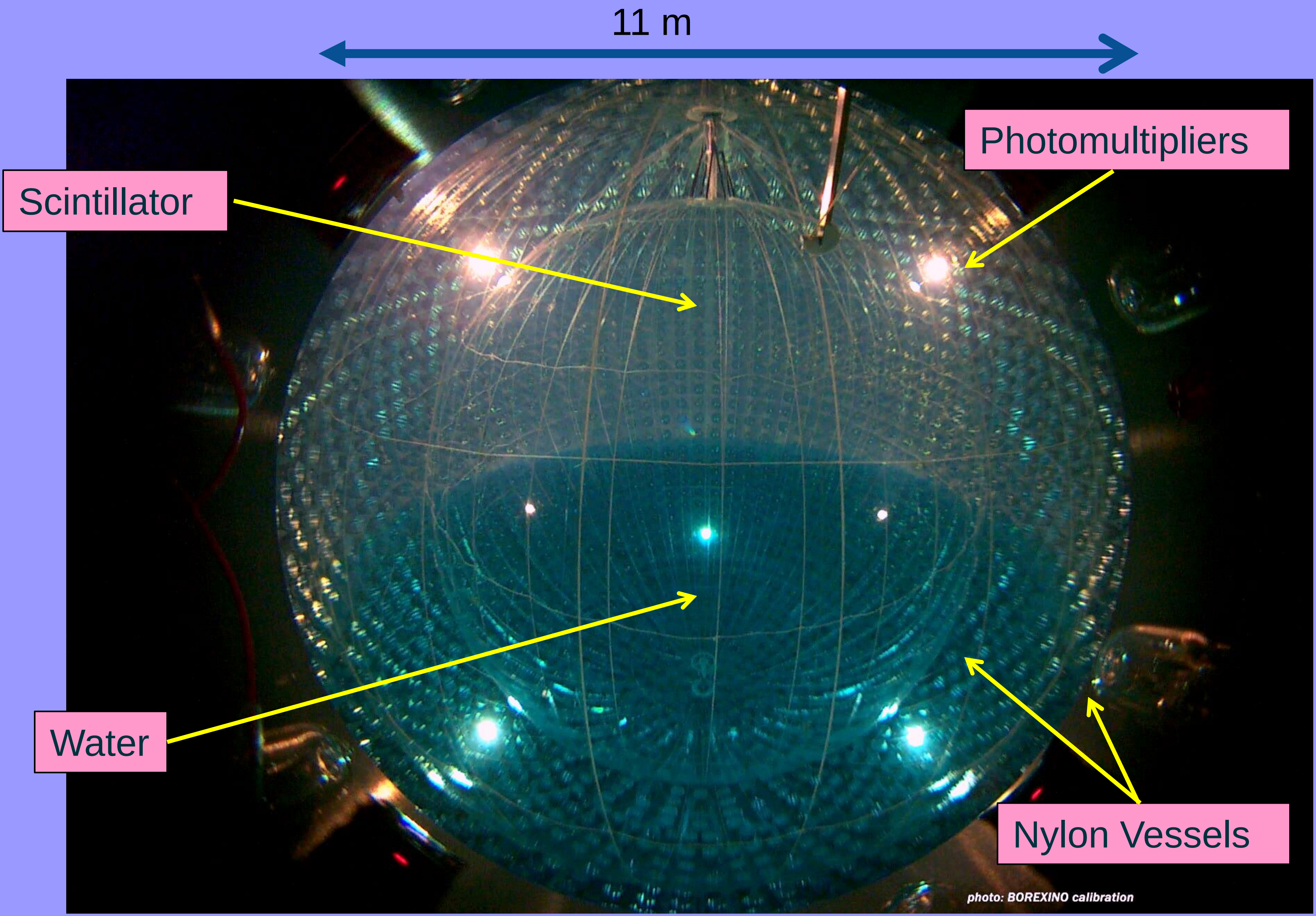
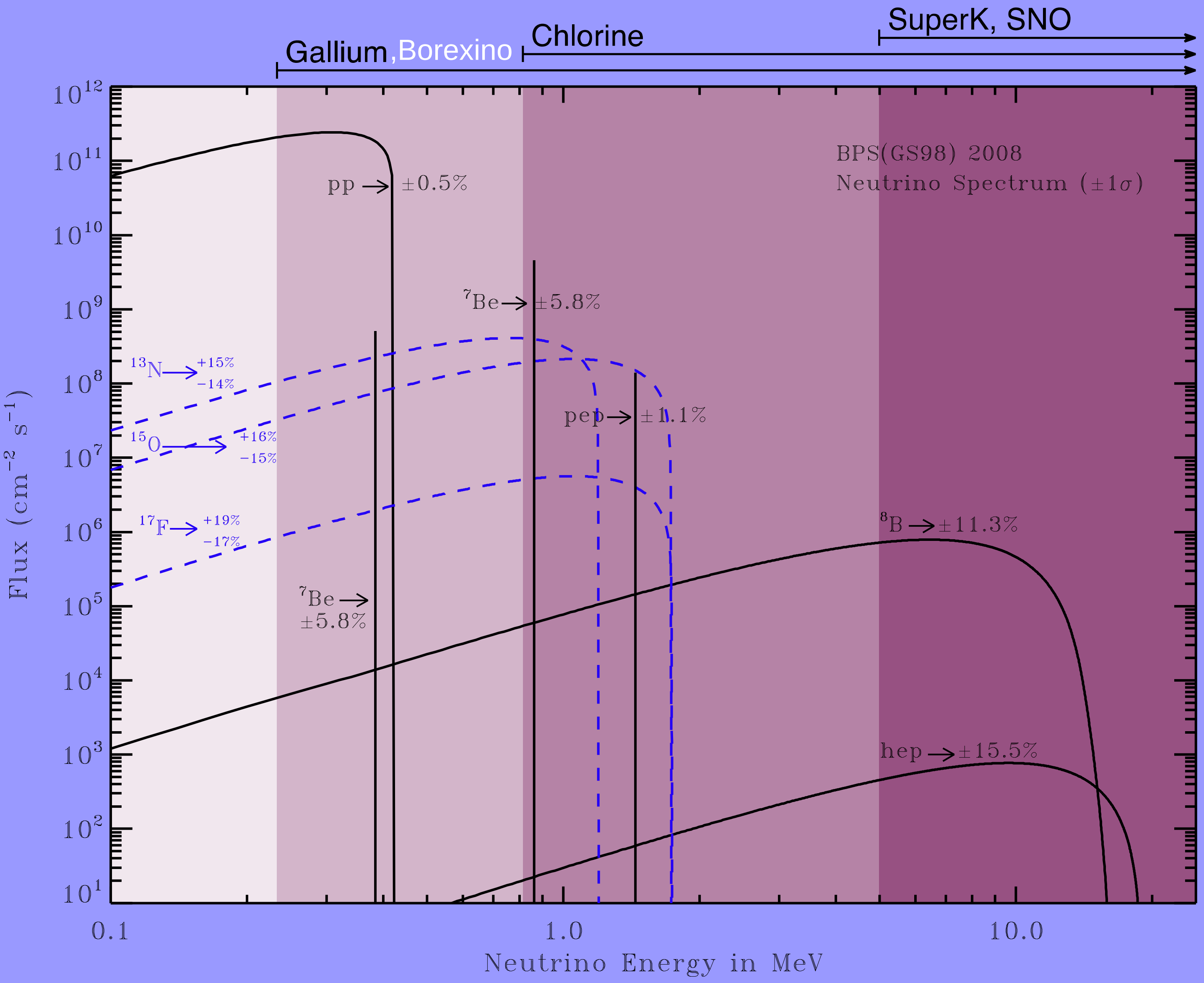
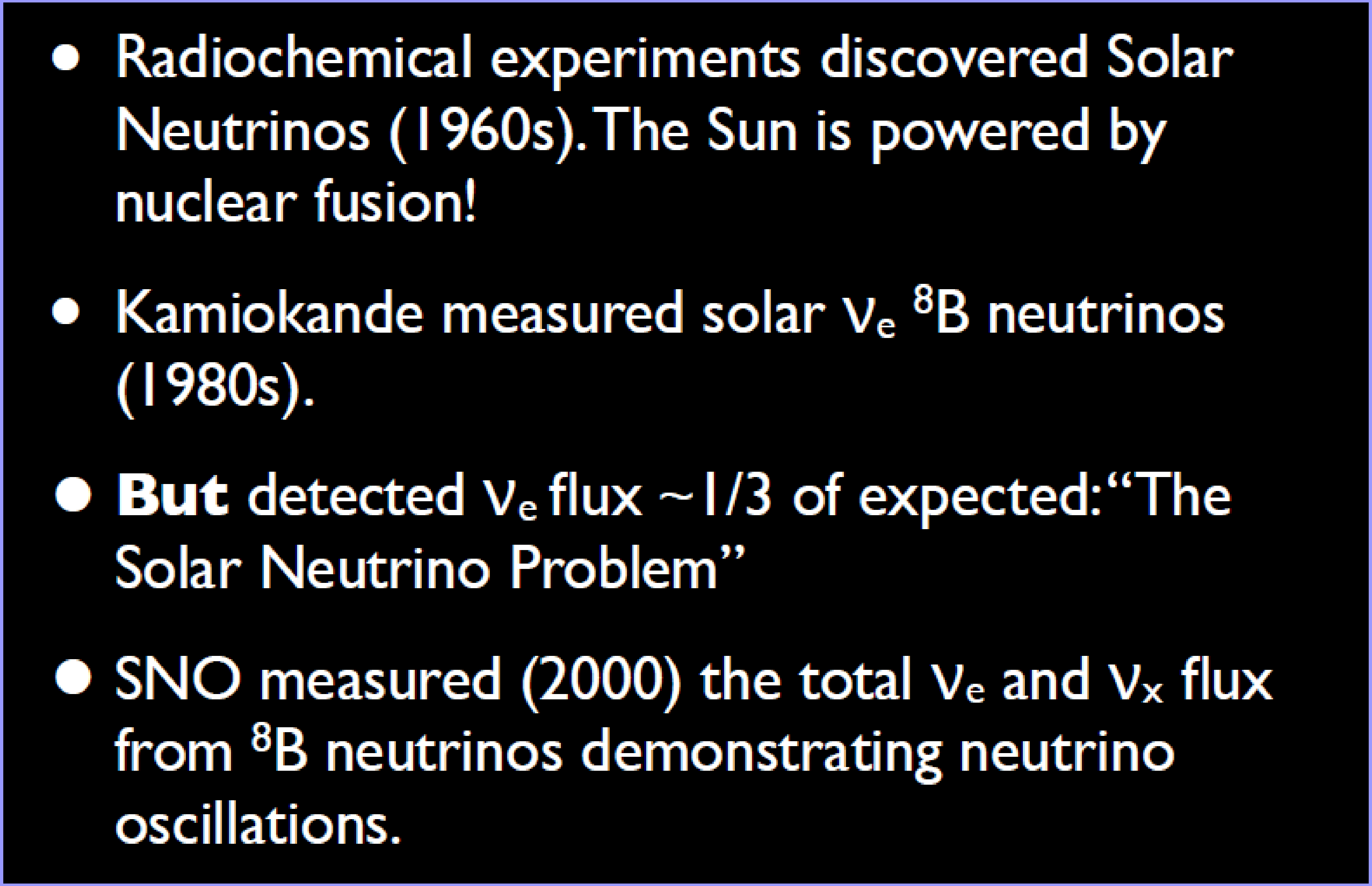


photo: BOREXINO calibration

Solar Neutrinos: the predicted spectrum



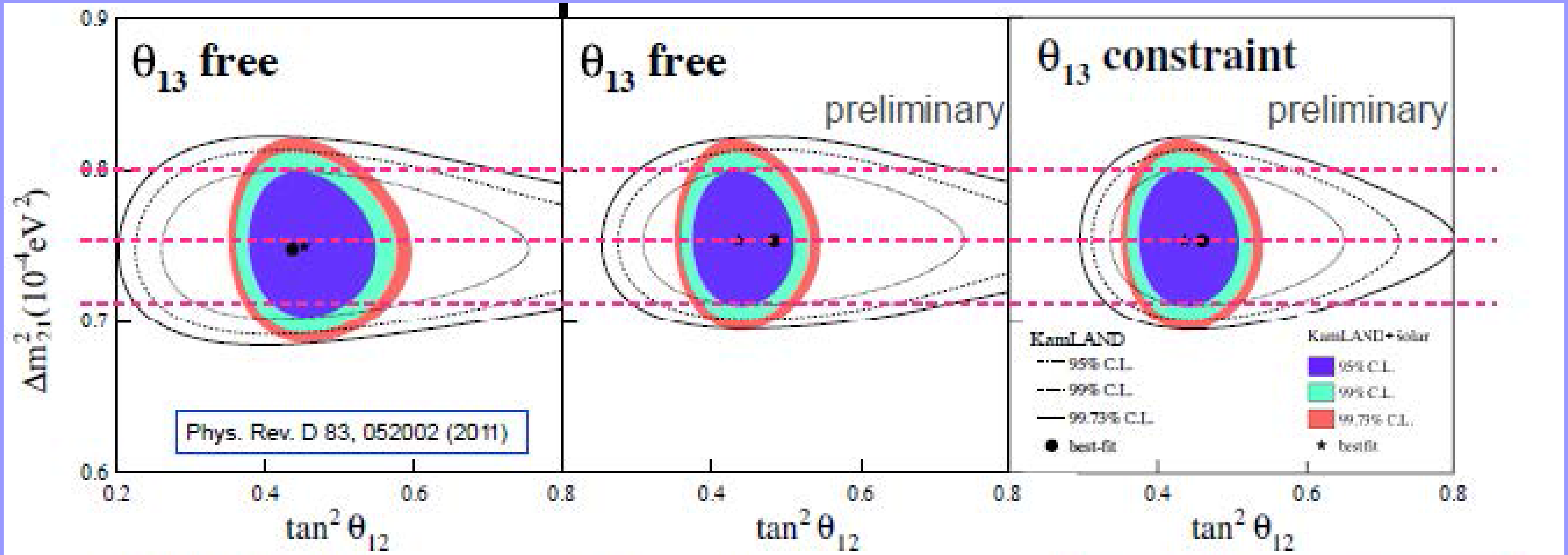
Study of Solar Neutrinos → Solar Neutrino Problem → Neutrino Oscillations



- Radiochemical experiments discovered Solar Neutrinos (1960s). The Sun is powered by nuclear fusion!
- Kamiokande measured solar ν_e ^{8}B neutrinos (1980s).
- **But** detected ν_e flux ~1/3 of expected: "The Solar Neutrino Problem"
- SNO measured (2000) the total ν_e and ν_x flux from ^{8}B neutrinos demonstrating neutrino oscillations.

Neutrino Oscillation Solution

(W. Hiroko's talk at Neutel 2013)



Large Mixing Angle + MSW mechanism in the Sun

Global, 3-lepton flavor analysis

$$\Delta m^2_{12} = \left(7.54^{+0.26}_{-0.22}\right)\times 10^{-5}\ eV^2$$

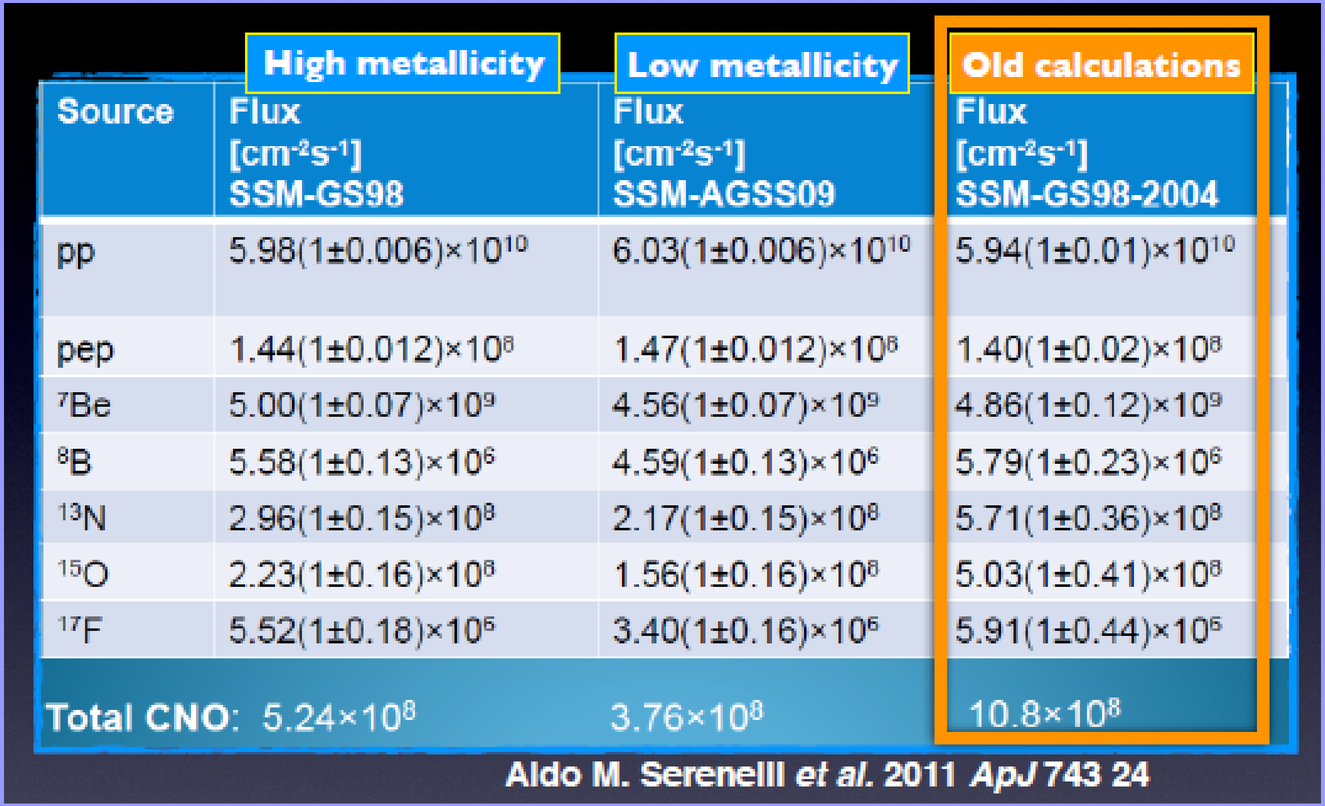
$$\sin^2\theta_{12} = 0.307^{+0.018}_{-0.016}$$

$$\sin^2\theta_{13} = 0.0241 \pm 0.0025$$

However: before Borexino, only radiochemical experiments could observe solar neutrinos below 1 MeV. Real-time experiments were sensible mostly to > 5 MeV

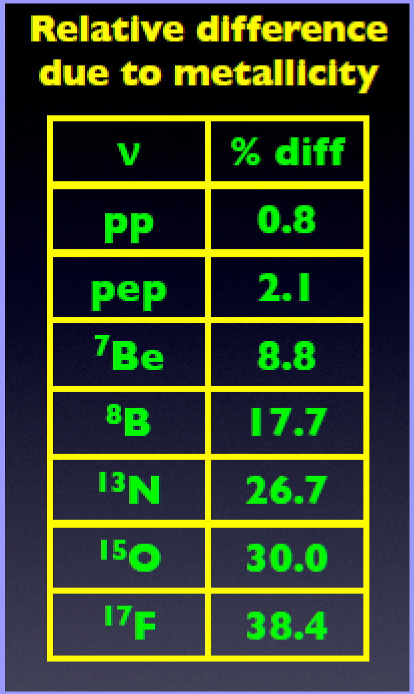
Open Issues

- Is MSW-LMA correct? How well can we test the model?
- Physics beyond the Standard Model can affect the features of the P_{ee} dependence on neutrino energy.
- Probe the P_{ee} transition region.
- How well are solar neutrino fluxes predicted by the SSM? Two competing models High and Low Metallicity.



Source	**High metallicity** Flux [$cm^{-2}s^{-1}$] SSM-GS98	**Low metallicity** Flux [$cm^{-2}s^{-1}$] SSM-AGSS09	**Old calculations** Flux [$cm^{-2}s^{-1}$] SSM-GS98-2004
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	$5.94(1\pm0.01)\times10^{10}$
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	$1.40(1\pm0.02)\times10^{8}$
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	$4.86(1\pm0.12)\times10^{9}$
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	$5.79(1\pm0.23)\times10^{6}$
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$2.17(1\pm0.15)\times10^{8}$	$5.71(1\pm0.36)\times10^{8}$
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	$5.03(1\pm0.41)\times10^{8}$
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	$5.91(1\pm0.44)\times10^{6}$
Total CNO:	5.24×10^{8}	3.76×10^{8}	10.8×10^{8}

Aldo M. Serenelli *et al.* 2011 *ApJ* 743 24



Relative difference due to metallicity

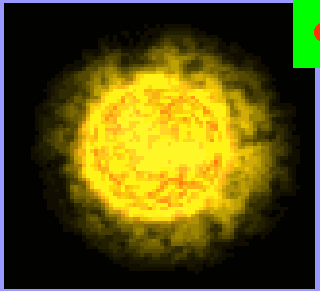
ν	% diff
pp	0.8
pep	2.1
^{7}Be	8.8
^{8}B	17.7
^{13}N	26.7
^{15}O	30.0
^{17}F	38.4

2. Be-7 flux measurement

1. BOREXINO
2. **Be-7 flux measurement**
3. B-8 measurement
4. pep detection and CNO limit
5. Future

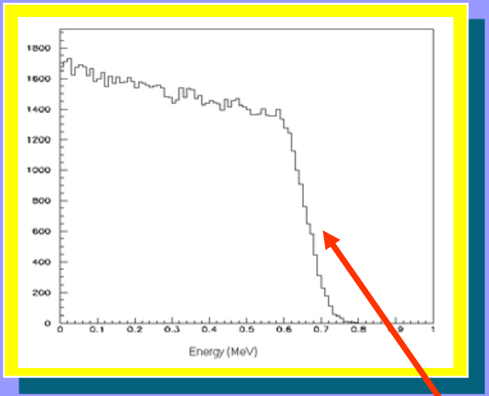
E_ν = 862 keV (monoenergetic)

$\Phi_{SSM} = 4.8 \cdot 10^9\ \nu\ s^{-1}\ cm^2$

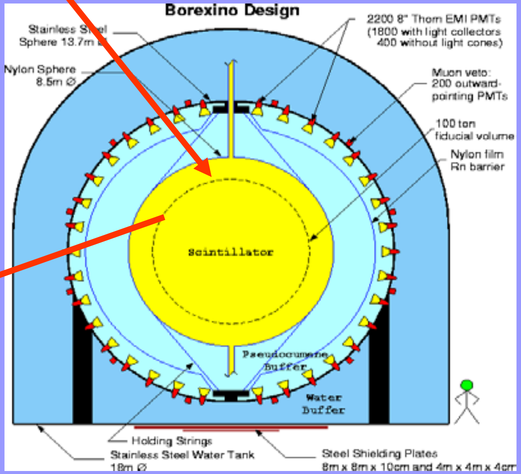


$${}^7Be + e^- \to {}^7Li + \boxed{\nu_e}$$

ν_e ↔ ν_x



Electron recoil spectrum



$$\nu_x + e^- \to \nu_x + e^-\ (x = e, \mu, \tau)$$

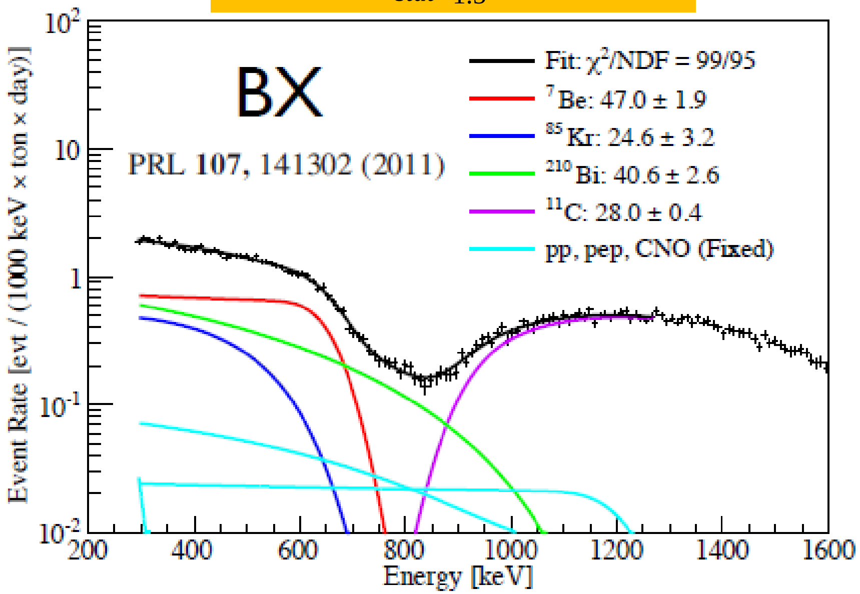
Cross Section ≈ 10^{-44} cm^2 (@ 1 MeV)

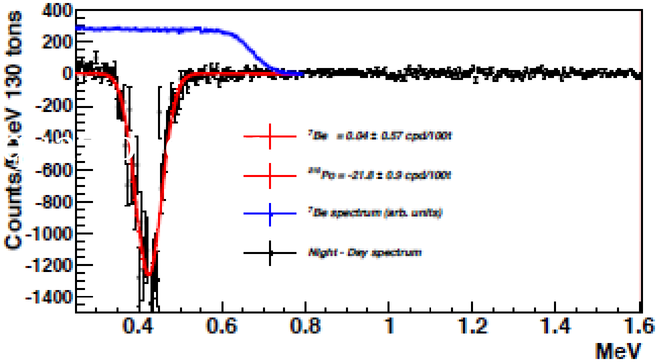
^{7}Be neutrinos

- Large flux: 100 times larger than ^{8}B.
- Flux predicted with 7% uncertainty.
- Mono-energetic E = 862 keV.

Day/Night Asymmetry

$$46.0 \pm 1.5_{stat}{}^{+1.6}_{-1.5}\ c/d{\cdot}100\ t$$





$$2\,\frac{\Phi_n-\Phi_d}{\Phi_n+\Phi_d} = 0.001 \pm 0.0012_{st} \pm 0.007_{syst}$$

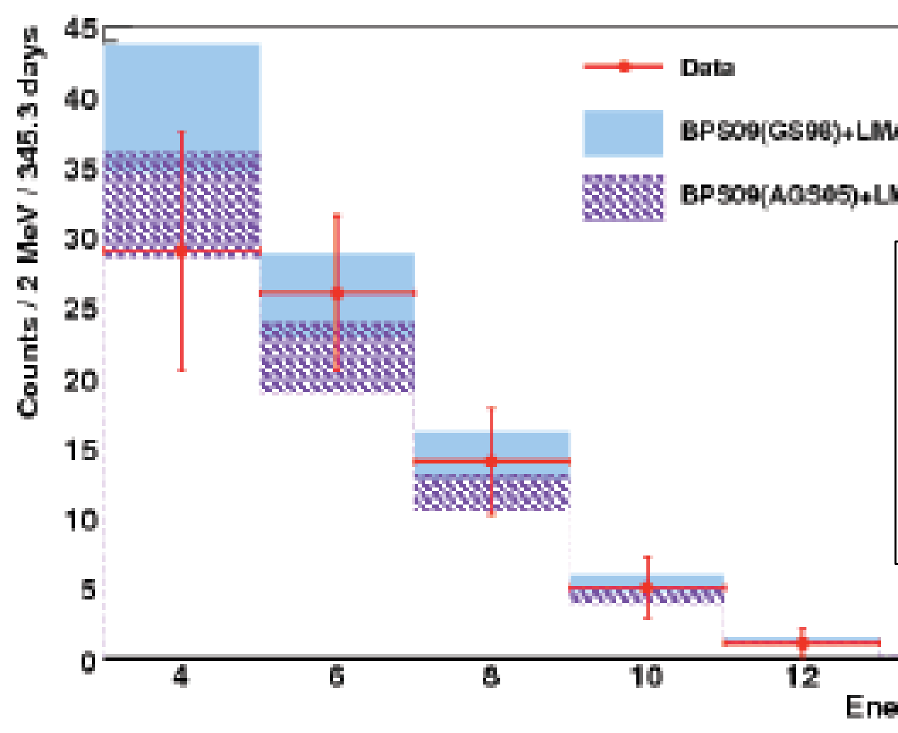
^{7}Be ν_e flux: **LMA**

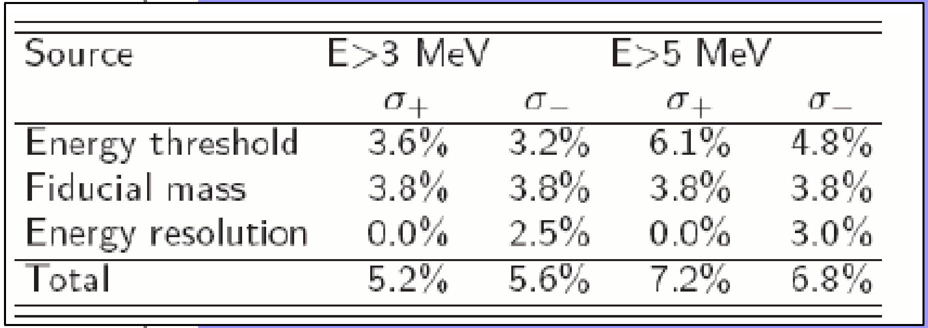
$$\Phi = (4.84 \pm 0.24) \times 10^9\ cm^{-2} s^{-1}$$

3. B-8 measurement

Analysis with 3 MeV threshold
Borexino rate : ≈ 0.2 cpd / (100 tons)
Backgrounds:
- Muons, Neutrons
- External background
- Fast cosmogenics
- C-10, Be-11
- Tl-208,Bi-214

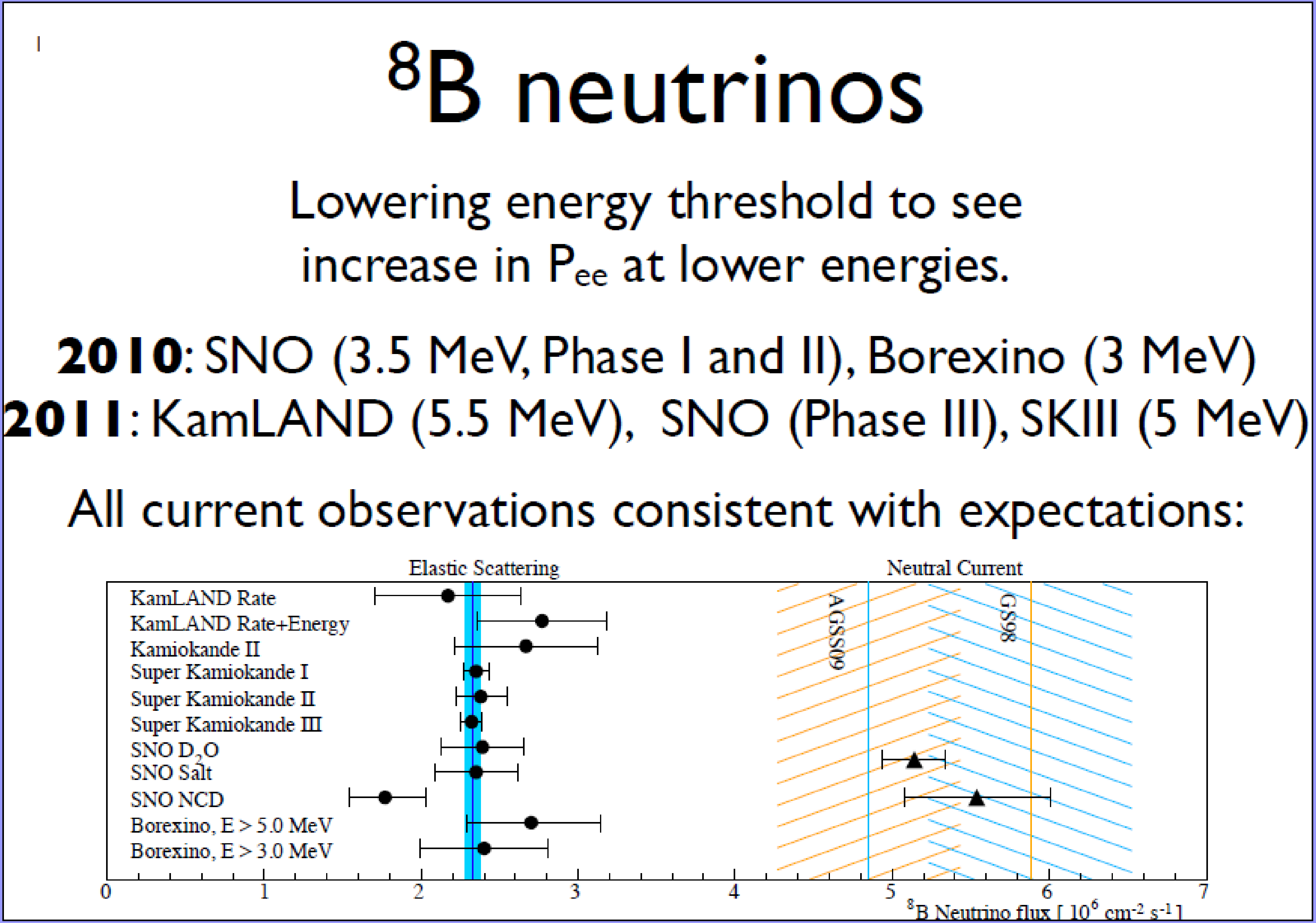
1. BOREXINO
2. Be-7 flux measurement
3. **B-8 measurement**
4. pep detection and CNO limit
5. Future





Source	E>3 MeV		E>5 MeV	
	σ_+	σ_-	σ_+	σ_-
Energy threshold	3.6%	3.2%	6.1%	4.8%
Fiducial mass	3.8%	3.8%	3.8%	3.8%
Energy resolution	0.0%	2.5%	0.0%	3.0%
Total	5.2%	5.6%	7.2%	6.8%

$$R=0.22\pm0.04(stat)\pm0.01(syst)\ cpd/100t\ \ (above\ 3\ MeV)$$



^{8}B neutrinos

Lowering energy threshold to see increase in P_{ee} at lower energies.

2010: SNO (3.5 MeV, Phase I and II), Borexino (3 MeV)
2011: KamLAND (5.5 MeV), SNO (Phase III), SKIII (5 MeV)

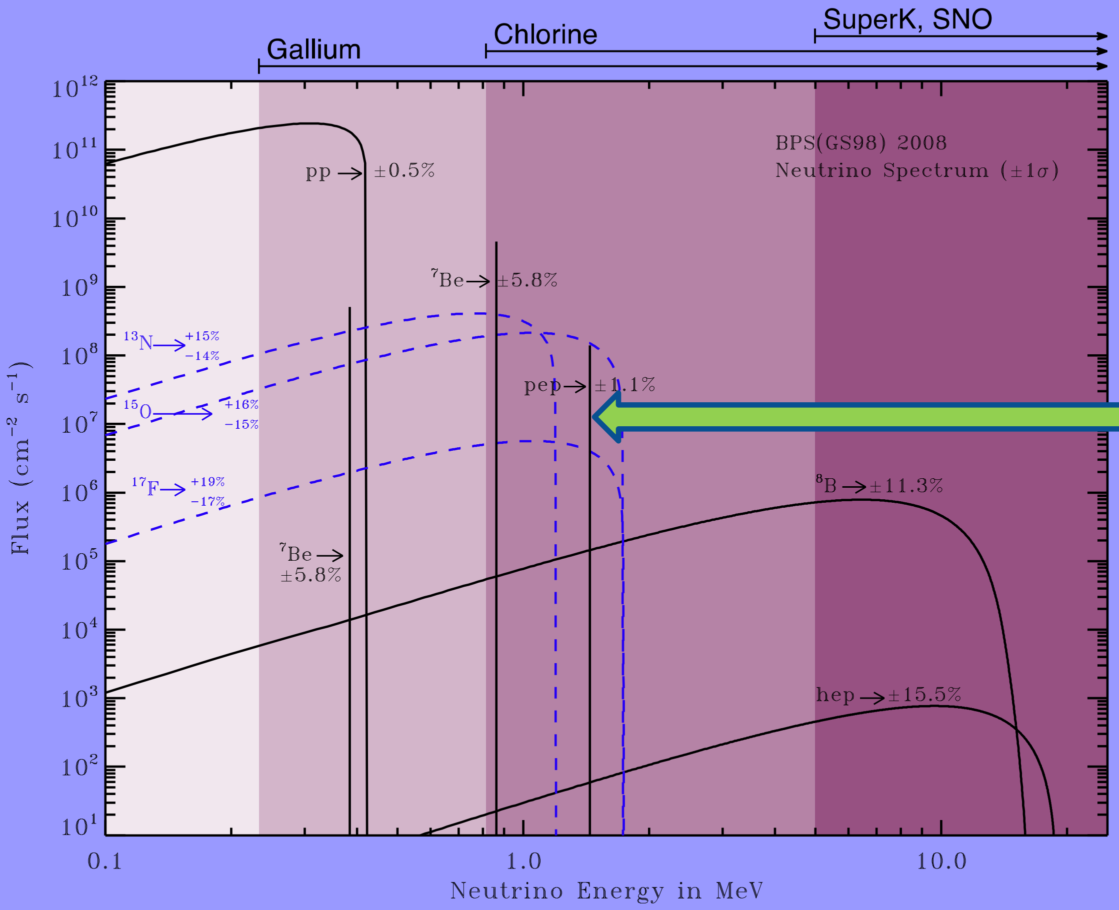
All current observations consistent with expectations:

4. pep detection and CNO limit

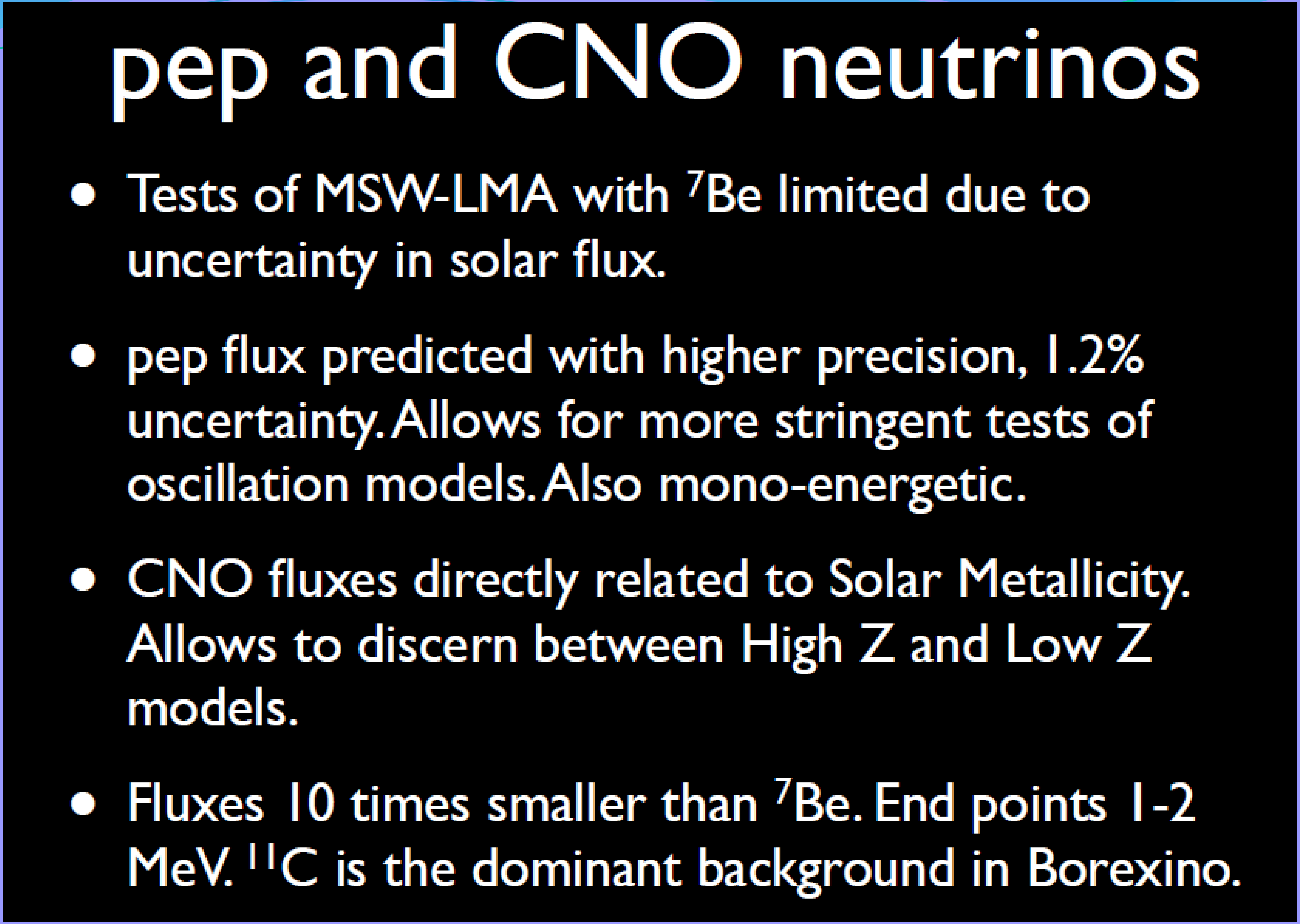
Pep reaction

$$p + e^{-} + p \to d + \nu_e$$

1. BOREXINO
2. Be-7 flux measurement
3. B-8 measurement
4. **pep detection and CNO limit**
5. Future



Monoenergetic 1.44 MeV neutrinos

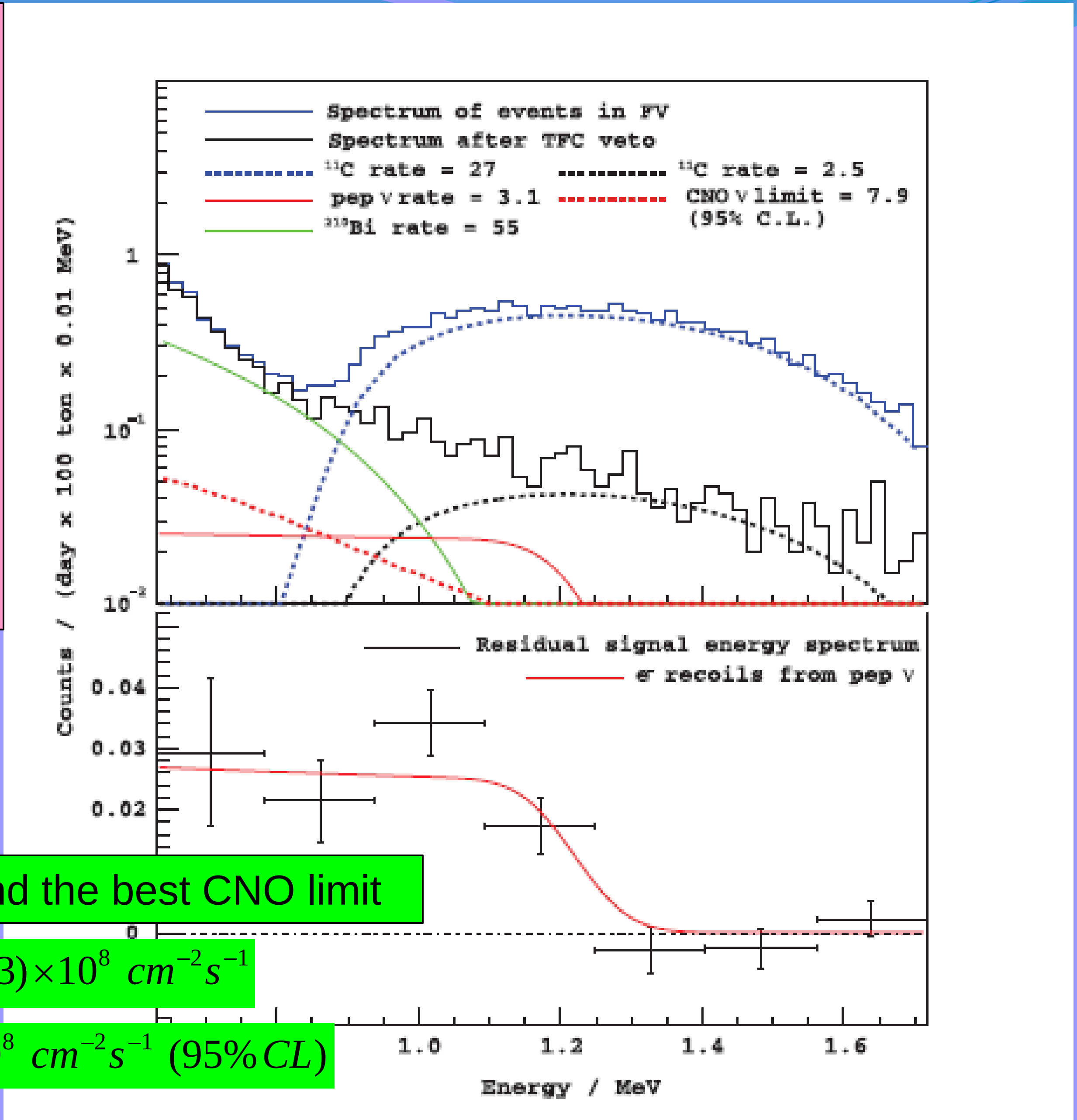


pep and CNO neutrinos

- Tests of MSW-LMA with ^{7}Be limited due to uncertainty in solar flux.
- pep flux predicted with higher precision, 1.2% uncertainty. Allows for more stringent tests of oscillation models. Also mono-energetic.
- CNO fluxes directly related to Solar Metallicity. Allows to discern between High Z and Low Z models.
- Fluxes 10 times smaller than ^{7}Be. End points 1-2 MeV. ^{11}C is the dominant background in Borexino.

C-11 reduction strategy:

- Threefold coincidence (muon,neutron,C11)
- Pulse shape discrimination electron/gamma/positron (Ps formation)
- Multivariate fit with also energy and position

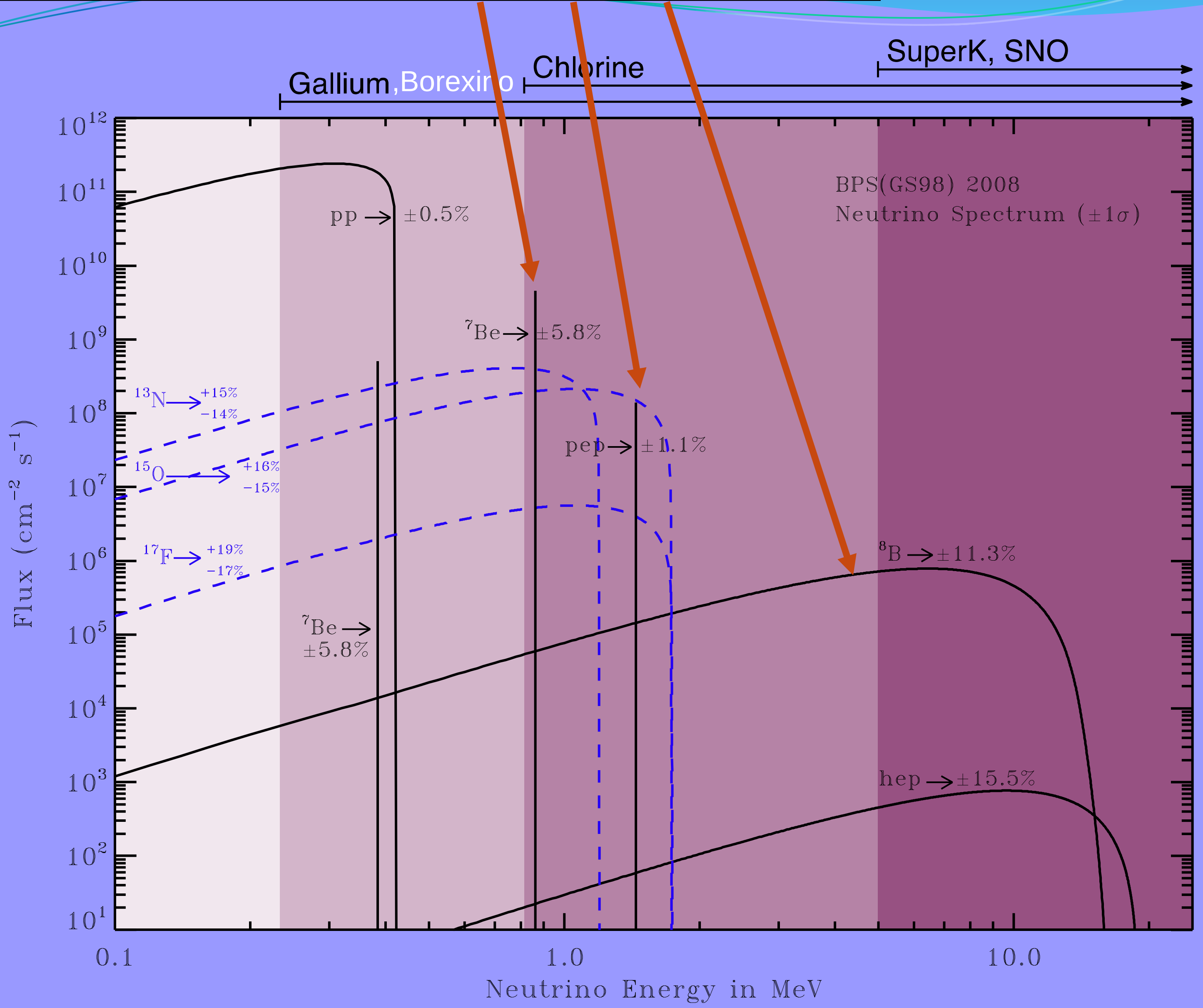


First pep measurement and the best CNO limit

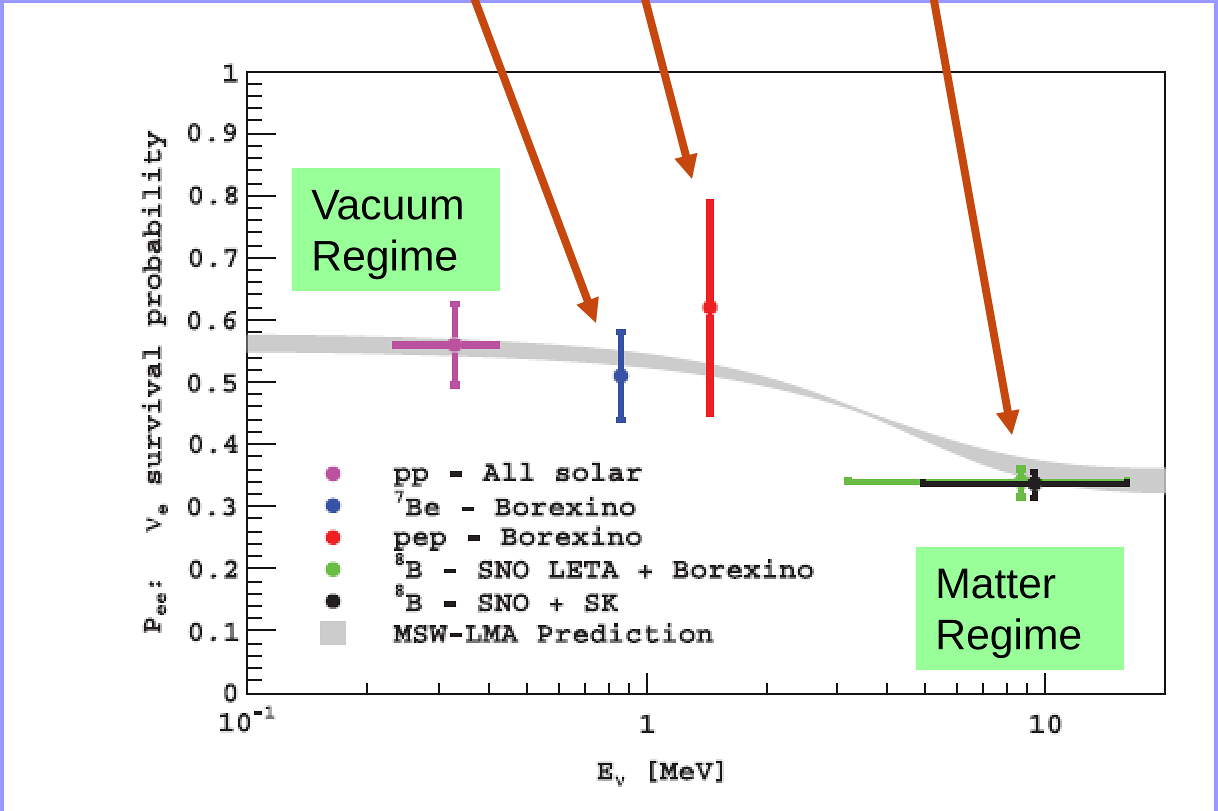
$$\Phi_{pep}\,(MSW-LMA)=(1.6\pm0.3)\times10^{8}\ cm^{-2}s^{-1}$$

$$\Phi_{CNO}\,(MSW-LMA)<7.7\times10^{8}\ cm^{-2}s^{-1}\ (95\%\,CL)$$

Solar neutrino components measured by Borexino



Neutrino Oscillations properties measured by Borexino



Solar electron neutrino survival probability as a function of neutrino energy
LMA-MSW with standard neutrino interactions

6. Future (summary)

1. BOREXINO
2. Be-7 flux measurement
3. B-8 measurement
4. pep detection and CNO limit
5. **Future**

Borexino Phase II (solar neutrinos):

- pp detection
- CNO study

Cycles of Purification (Water Extraction) :

- Reduce ^{85}Kr and ^{210}Bi affecting the pep and CNO analyses
- Kr background reduced to a negligible rate
- Bi-210 reduced (tens of counts/day 100 tons) and possibly studied by means of the time evolution of Po-210 rate.

CNO detection

CNO reactions are responsible for less than 1% of the Sun energy generation

However, this cycle should be dominant for higher mass stars (higher temperatures)

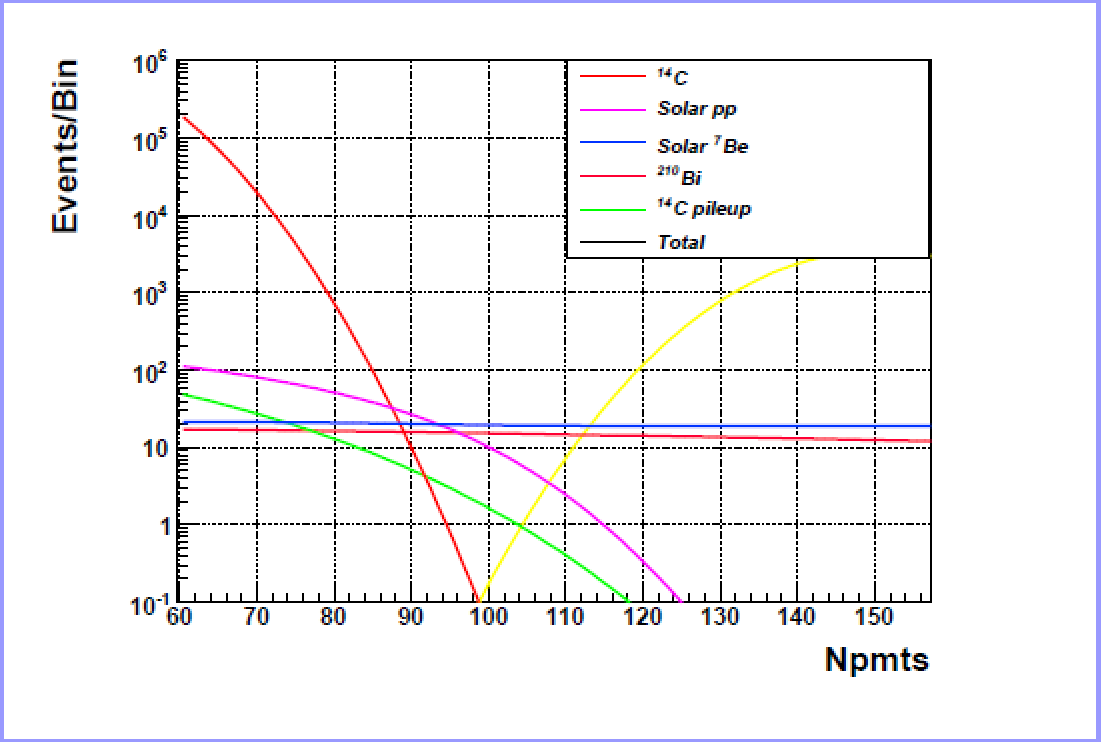
Given their small flux and low energy, neutrinos from CNO have never been measured directly.

pp detection

They make up more than 90% of the total flux and have never been directly observed.

Main source of background is C-14 and its pileup effect.

C-14 spectral shape and pileup



Thank you for your attention (& selected bibliography)

• G. Alimonti et al., Nucl. Instr. & Methods A600 (2009) 568	Detector
• C. Arpesella et al., Phys. Lett. B 568 (2008) 101 • C. Arpesella et al., Phys. Rev. Lett. 101 (2008) 091302 • G. Bellini et al., Phys. Rev. Lett. 107 (2011) 141302 • G. Bellini et al., Phys. Lett. B 707 (2012) 22	Be-7
• G. Bellini et al., Phys. Rev. D 82 (2010) 033006	B-8
• G. Bellini et al., Phys. Lett. B 687 (2010) 299 • G. Bellini et al., Phys. Lett. B 722 (2013) 295	Geo v
• G. Bellini et al., Phys. Rev. Lett 108 (2012) 051302	pep

Backup Slides

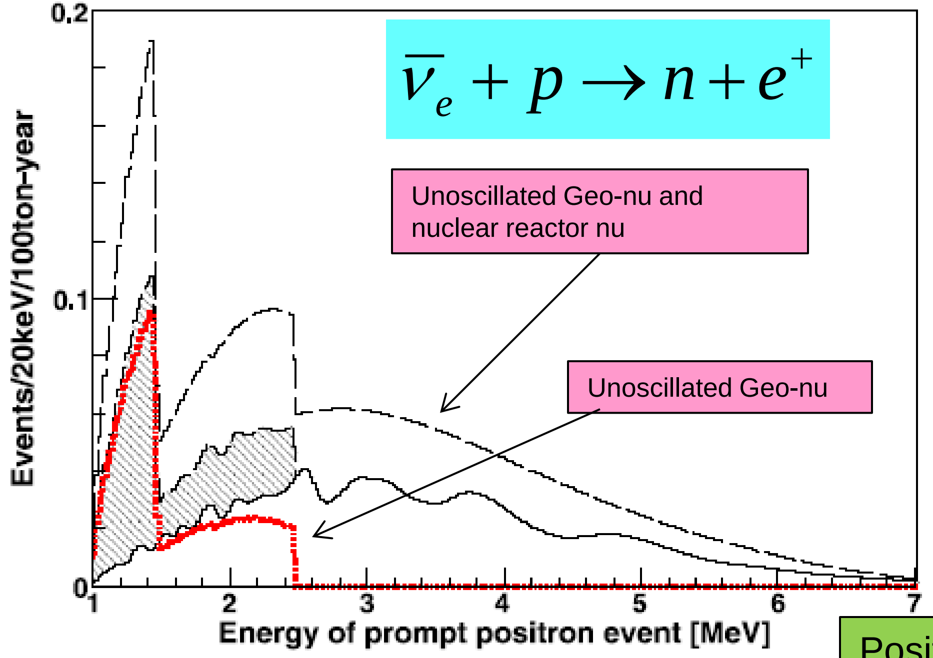
5. Geoneutrinos

AntiNeutrinos emitted in beta decays of naturally occurring radioactive isotopes in the Earth’s crust and mantle

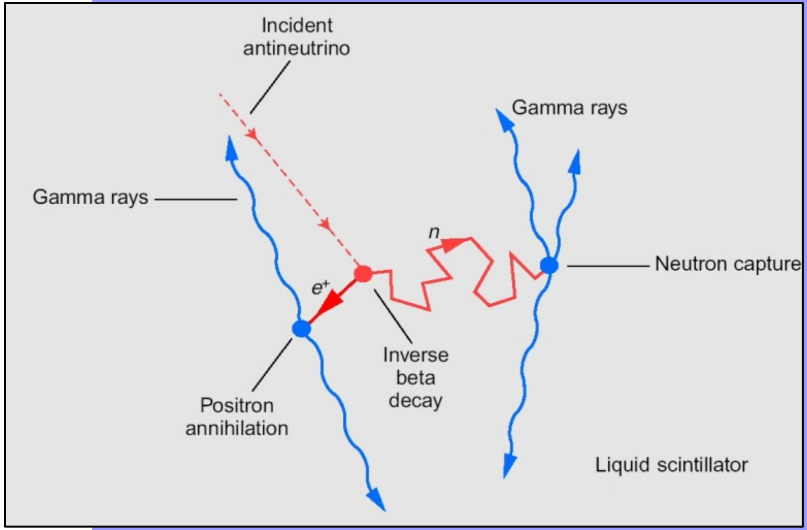
Moderate Nuclear Reactors bkgd at LNGS

Detection by Inverse Beta Decay (1.8 MeV thr.)

1. BOREXINO
2. Be-7 flux measurement
3. B-8 measurement
4. pep detection and CNO limit
5. **Geoneutrinos**
6. Future



$$\overline{\nu}_e + p \rightarrow n + e^+$$



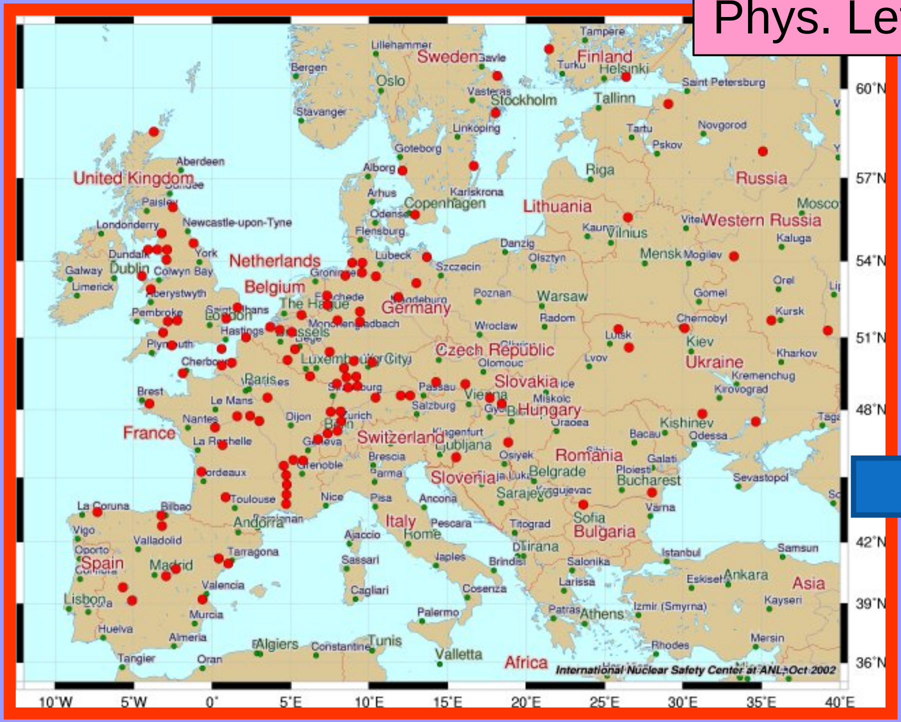
Positron-Gamma (2.2 MeV) delayed coincidence

Search for positron/neutron-capturedelayed coincidences in the Borexino detector

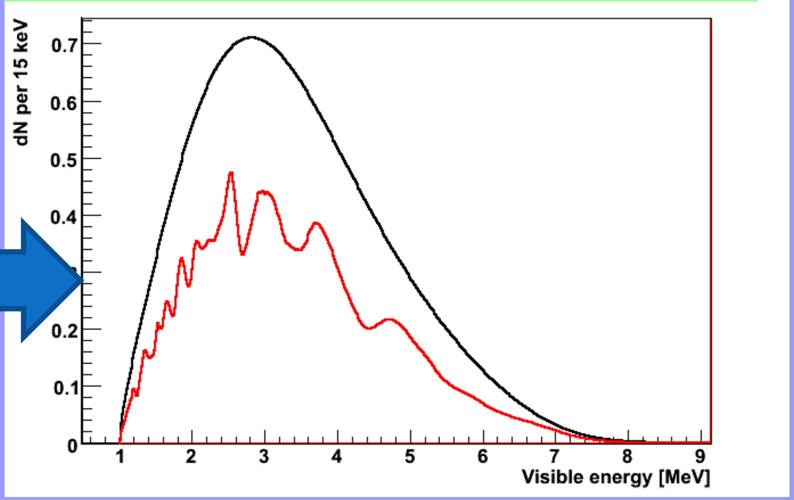
Main background sources:

- Li-9, He-8, untagged muons, accidentals………
- And of course nuclear reactors
- First observation published in 2010

New analysis based on 1353 days of data
Phys. Lett. B 722 (2013) 295



Reactor antineutrinos at LNGS

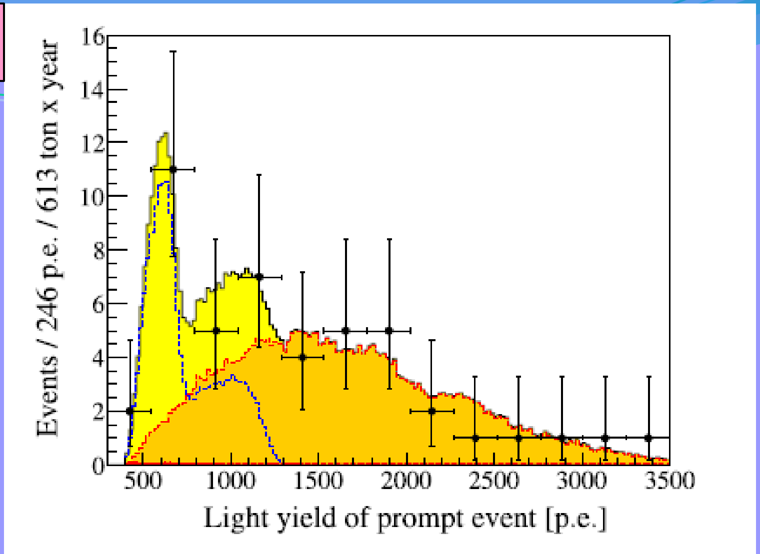


1353 days in Borexino: antineutrino geo analysis

Nuclear Reactor component :

Found : 21 events above geo endpoint

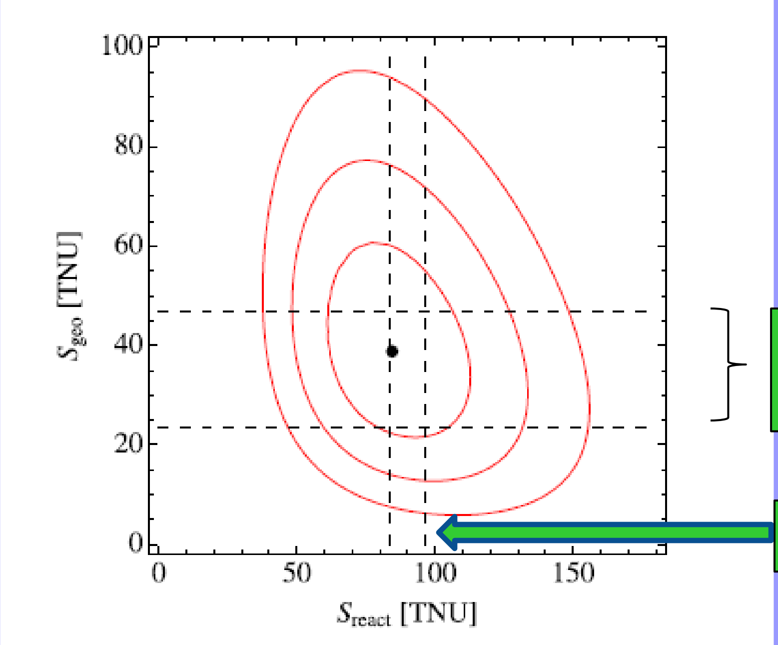
Expected : 22.0 +- 1.6



Geoneutrinos vs Reactor neutrinos:

Free parameters
- Weight of Geo nu
- Weight Reactor nu

Th/U = 3.9 fixed
(condhritic value)



68.27%, 95.45%, 99.73% Confidence level contour plots for geo and reactor neutrinos

Extreme expectations of BSE (Bulk Silicate Earth) model

Reactor signal expectation

(1 TNU = 1 Terrestrial Neutrino Unit = 1 event/year/10^{32} protons)

Best fit values:

$$N_{geo} = (14.3 \pm 4.4) \qquad S_{geo} = (38.8 \pm 12.0) \; TNU$$

$$N_{reac} = 31.2^{+7.0}_{-6.1} \qquad S_{rea} = 84.5^{+19.3}_{-16.9} \; TNU$$

Geofluxes →

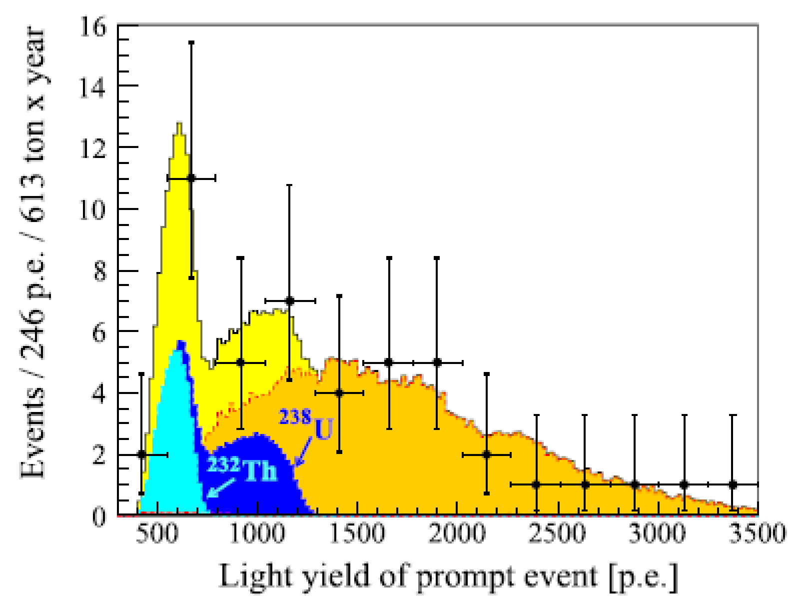
$$\Phi(U) = (2.4 \pm 0.7) \times 10^{6} \; cm^{2} s^{-1}$$

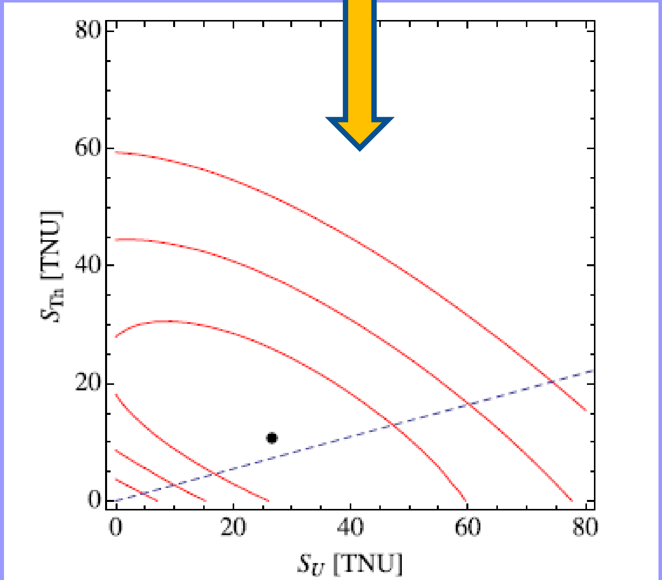
$$\Phi(Th) = (2.0 \pm 0.6) \times 10^{6} \; cm^{2} s^{-1}$$

If U,Th contributions are left free:

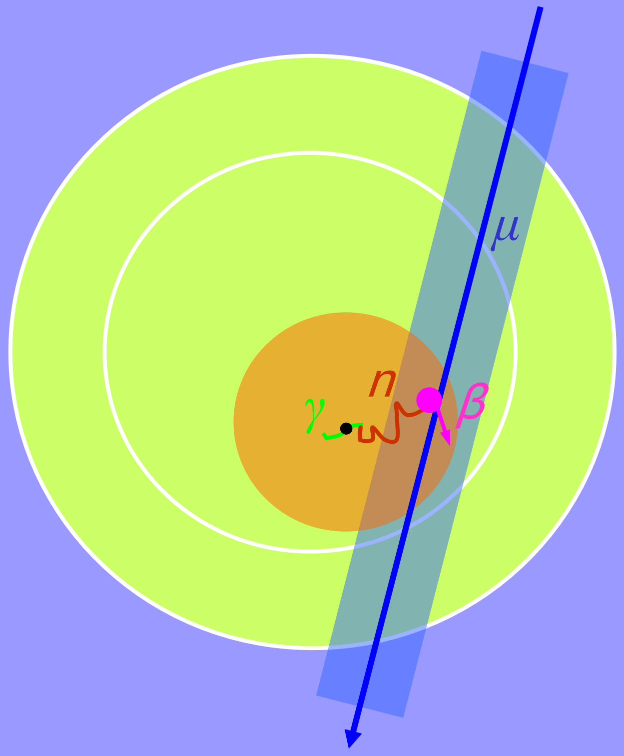
$$\Phi(U) = (2.1 \pm 1.5) \times 10^{6} \; cm^{2} s^{-1}$$

$$\Phi(Th) = (2.6 \pm 3.1) \times 10^{6} \; cm^{2} s^{-1}$$





Going for pep and CNO: ^{11}C tagging



$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$$

τ (n capture): ~250μs

$$\boldsymbol{n + p \rightarrow d + \gamma_{2.2MeV}}$$

$$\boldsymbol{{}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e}$$

τ (^{11}C): ~30min

The main background for *pep* and CNO analysis is ^{11}C, a long lived (τ=30min) cosmogenic β^+ emitter with ~1MeV end-point (shifted to 1-2MeV range)

^{11}C Production Channels:

[Galbiati et al., Phys. Rev. C71, 055805, 2005]

1. 95.5% with n: (X,X+n)
   - X = γ, n, p, $\pi^{\pm}$, $e^{\pm}$, μ.
2. 4.5% *invisible* :
   - (p,d); (π^+,π^0+p).

^{11}C rate = (28.5 ± 0.5) cpd

exp. pep rate ~ 3cpd

Going for pep and CNO: positronium

Electron/Positron discrimination due to Ps formation in positron events (D. Franco, G. Consolati and D. Trezzi, Phys. Rev. C 83 (2011) 015504

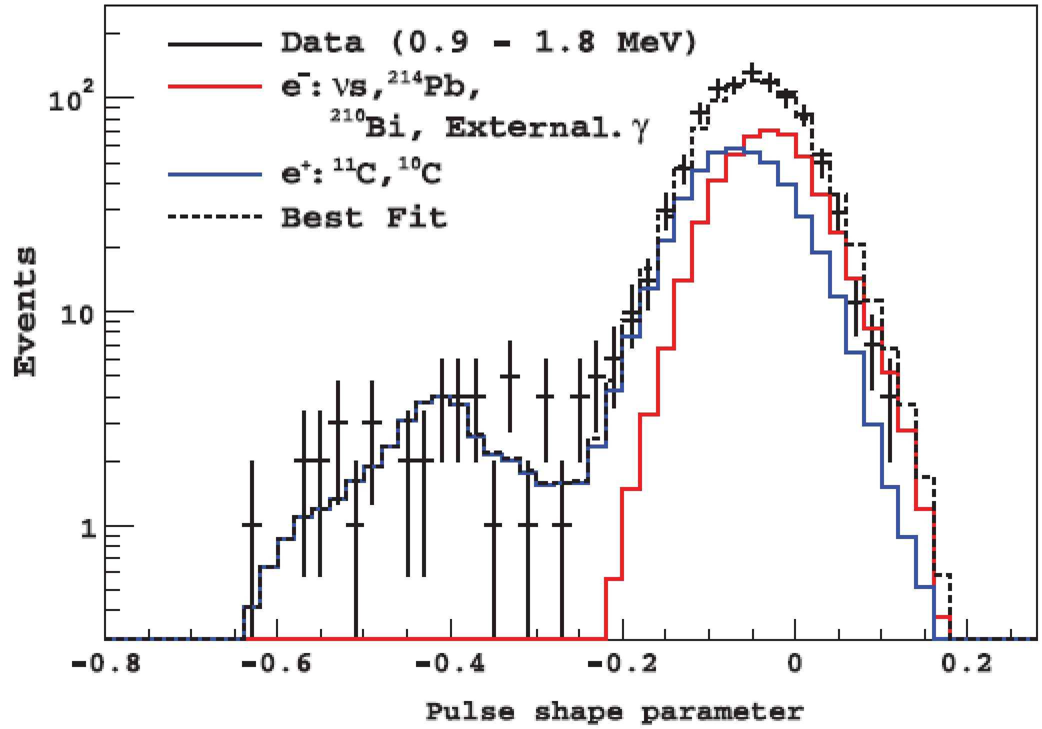
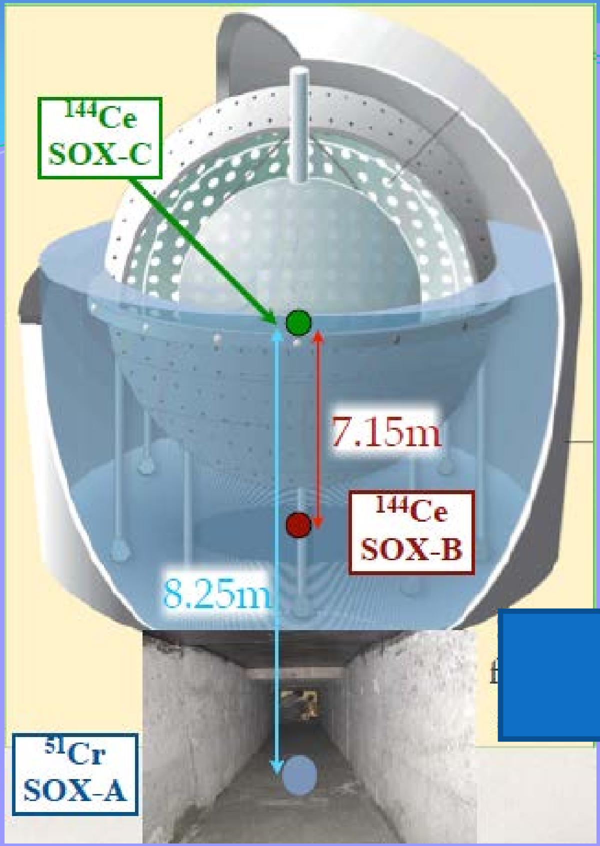


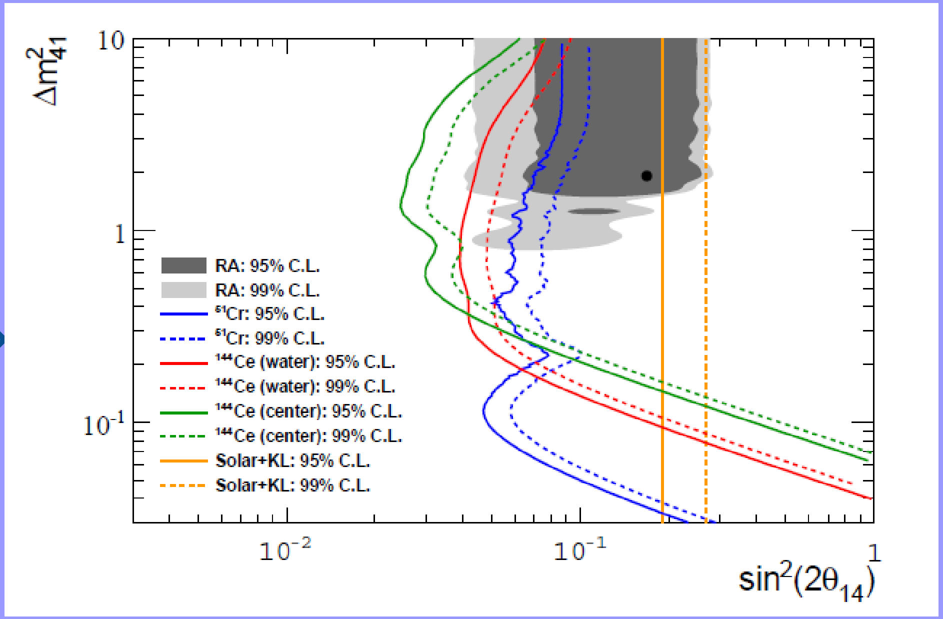
FIG. 2 (color). Experimental distribution of the pulse-shape parameter (black data points). The best-fit distribution (dashed black line) and the corresponding e^- (solid red line) and e^+ (solid blue line) contributions are also shown.

A. The Cr-51 source, with an activity of ~10 Mci

Obtained by irradiation of Cr-50 .

3-months experiment to be performed in 2015





B. A Ce-144 antineutrino source can be used. Due to the antineutrino tag, the activity could be much smaller, in the 80 kCi range.

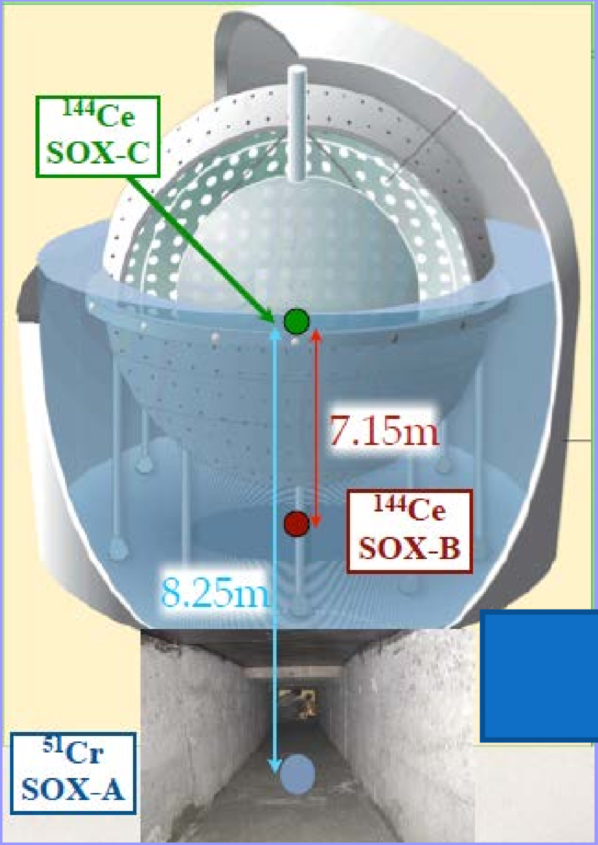
C. The Ce-144 source positioned at the center of the detector

Short distance neutrino Oscillations with BoreXino (SOX)

Experimental anomalies which are difficult to accomodate in a simple 3-flavor scenario

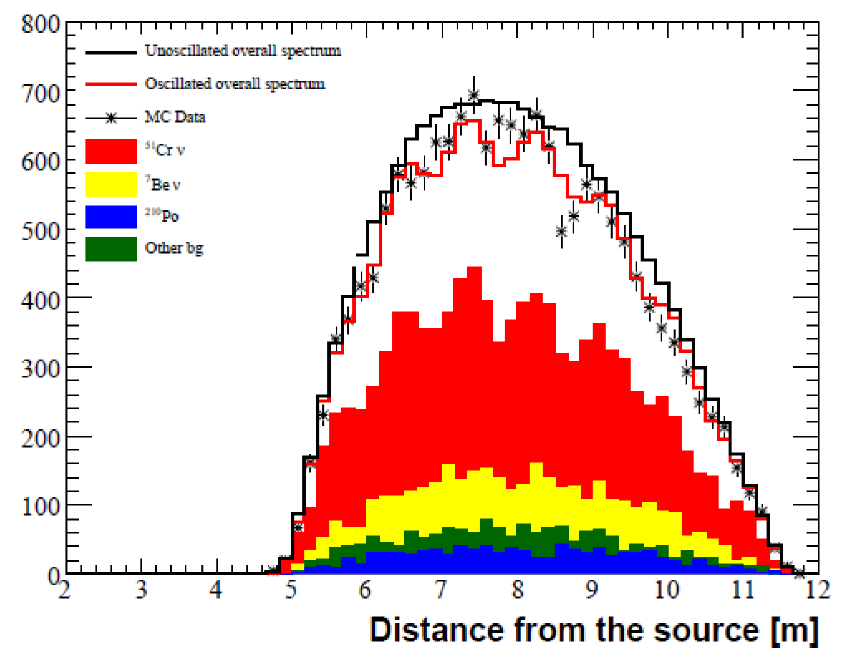
A fourth (sterile) neutrino? («Gallium», «Reactor», «LSND-MiniBoone» anomalies)

Borexino can be used to perform a short baseline experiment with neutrino source



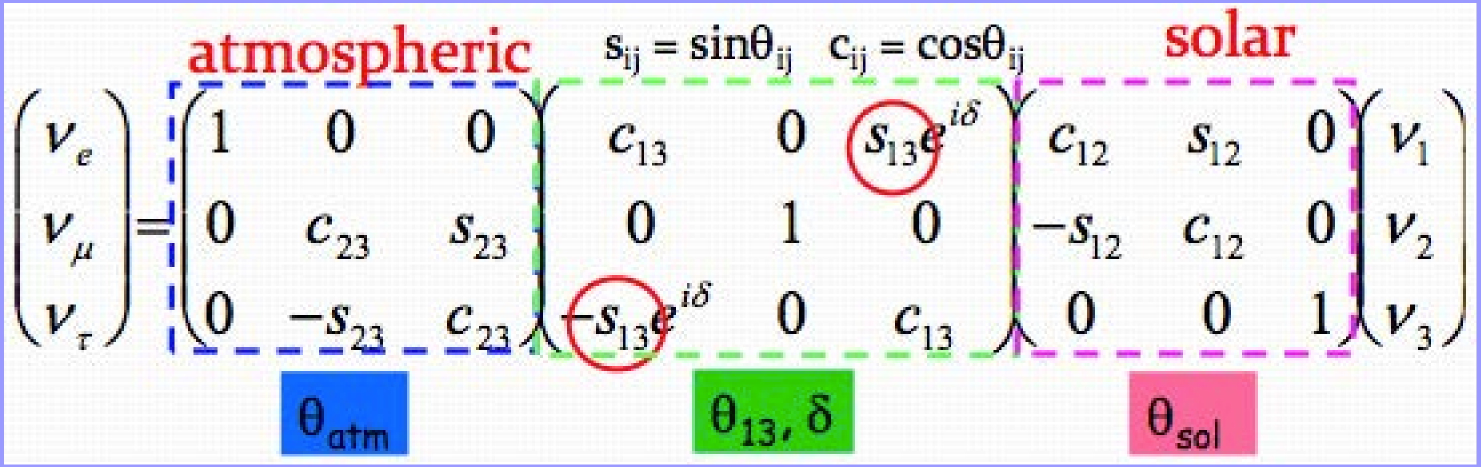
Exploration of parameters in the plane $(\Delta m^2_{14}, \sin^2 2\vartheta_{14})$

L/E of the order of eV^2



Neutrino Oscillations

$$|\nu_l\rangle = \sum_{i=1}^{3} U_{li}|\nu_i\rangle$$



$s_{ij} = \sin\theta_{ij}$ $c_{ij} = \cos\theta_{ij}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

PMNS neutrino mixing matrix, analogous to CKM matrix for quarks

$\sin^2(2\theta_{12}) = 0.861^{+0.026}_{-0.022}$

$\Delta m^2_{21} = (7.59 + -0.21) \times 10^{-5}\ eV^2$

$\sin^2(2\theta_{23}) > 0.92$ [i]

$\Delta m^2_{32} = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$

$0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$

Solution of the Solar Neutrino Problem is neutrino oscillation with matter (MSW) effect at Large Mixing Angle (LMA)

$$P_{ee} = 1 - \sin^2 2\theta \sin^2 (\Delta m^2 L/4E_\nu)$$