Solar and Geo Neutrino Physics with Borexino
RICAP - 2013

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1. BOREXINO

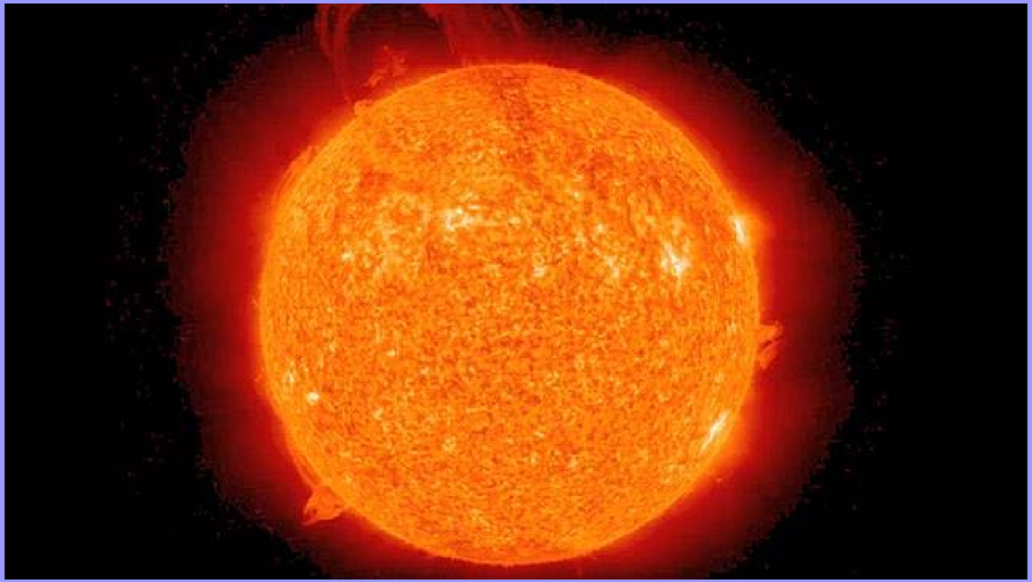
2. Be-7 flux measurement

3. B-8 measurement

4. pep detection and CNO limit

5. Geoneutrinos

6. Future



on behalf of

the Borexino Collaboration

INFN

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1. BOREXINO

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

Detecting Solar Neutrinos (and other rare phenomena) means:

- 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
- Underground location to shield from cosmic rays

Experimental site

Abruzzo, Italy

120 Km from Rome

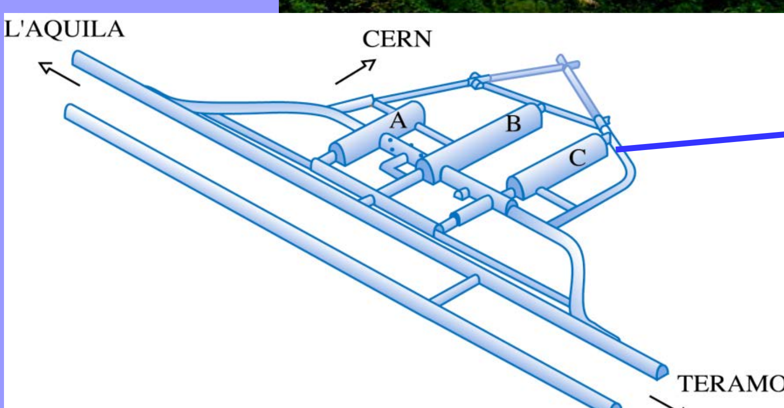
Laboratori Nazionali del Gran Sasso

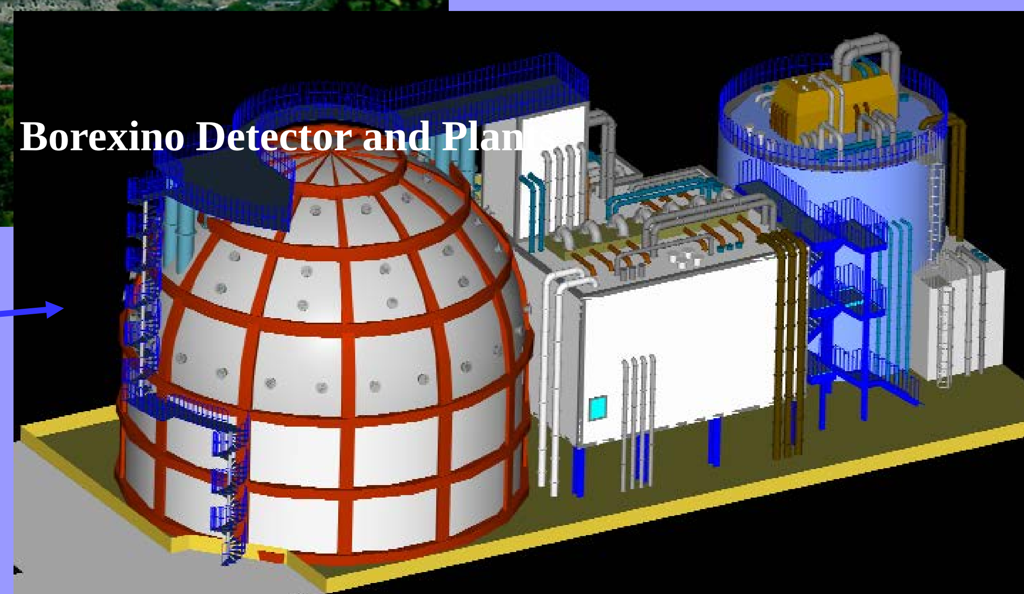
Assergi (AQ) Italy

1400m of rock shielding

~3800 m.w.e.

External Labs





The Borexino Detector

Neutrino electron scattering

$\nu e \rightarrow \nu e$

Scintillator:

270 t PC+PPO (1.4 g/l)

Nylon vessels:

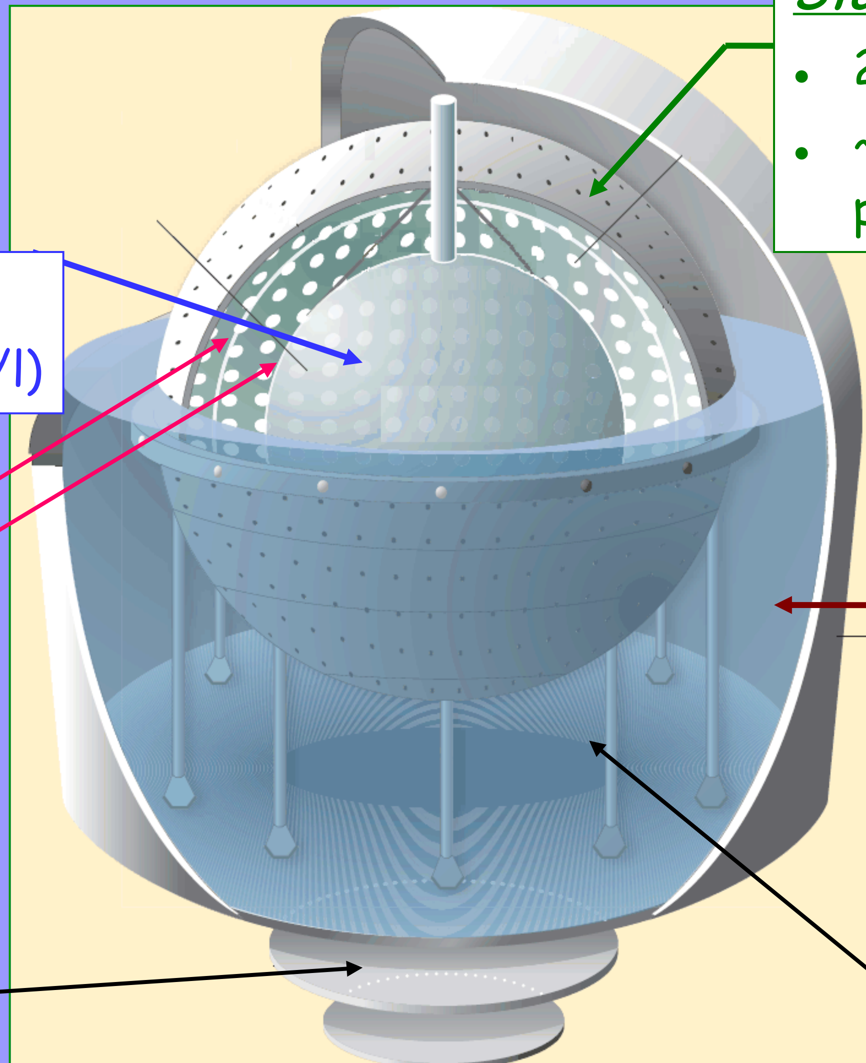
(125 μm thick)

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

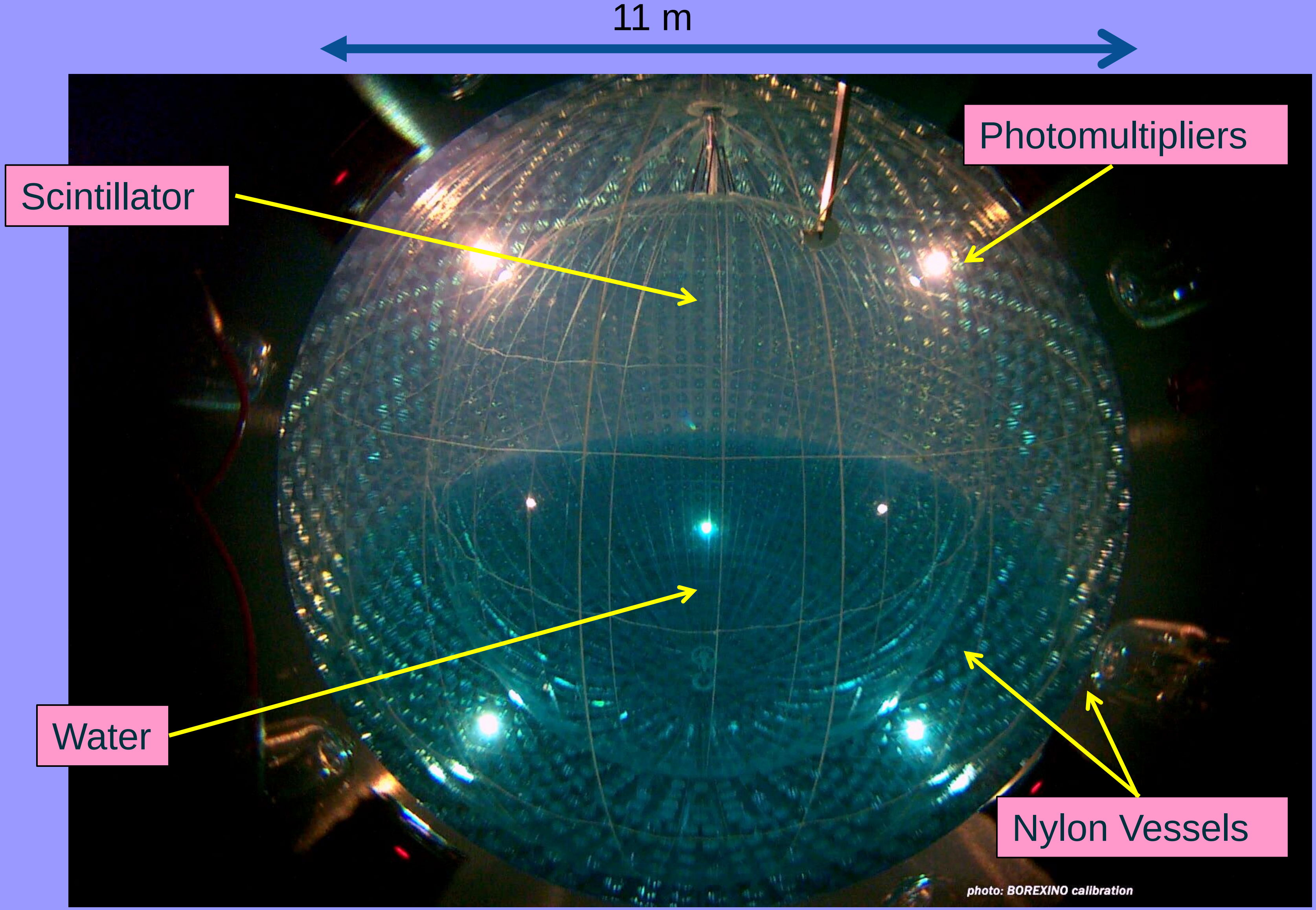
μ water Č detector

208 PMTs in water

2100 m^3

20 legs

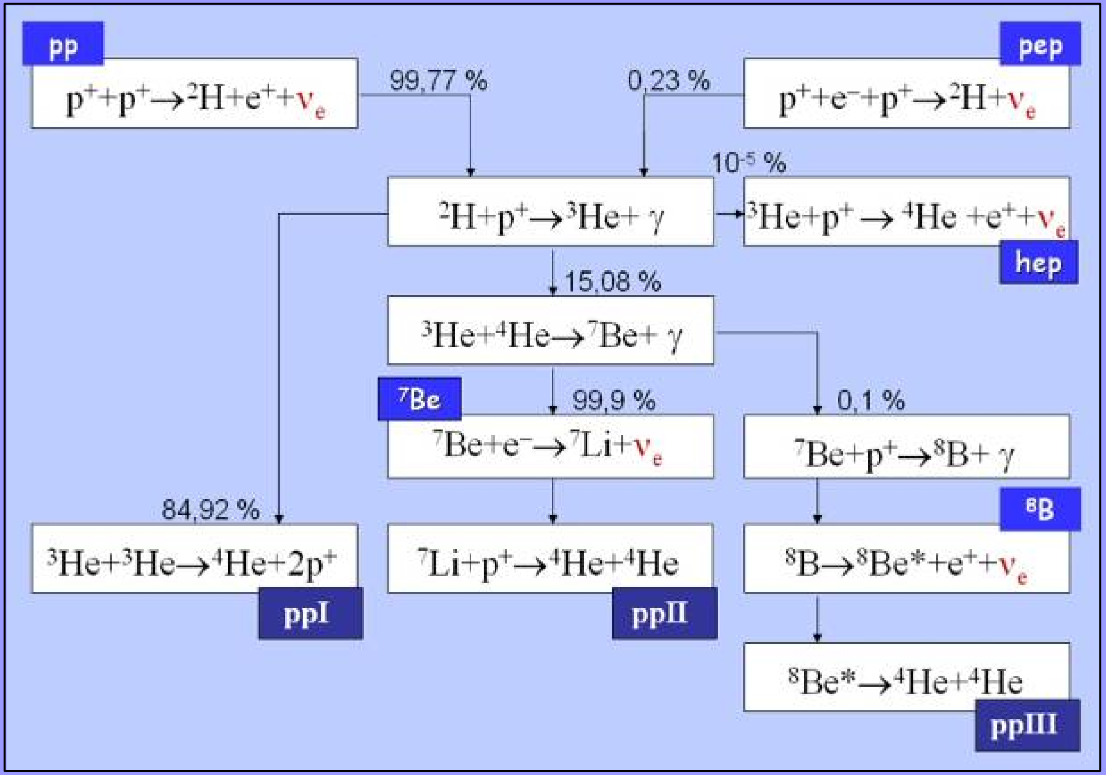
Filling phase of the Borexino detector (2007, Laboratorio del Gran Sasso)

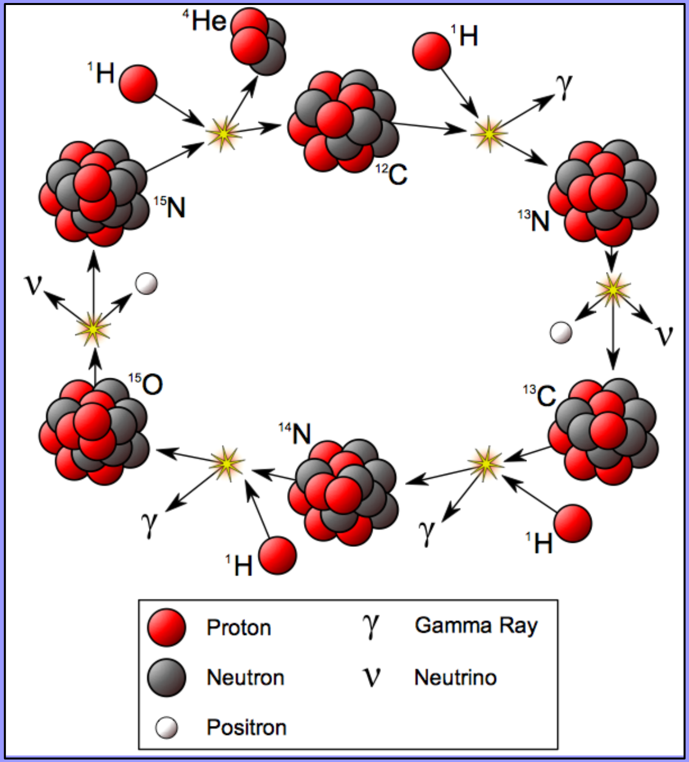


Energy production in the Sun

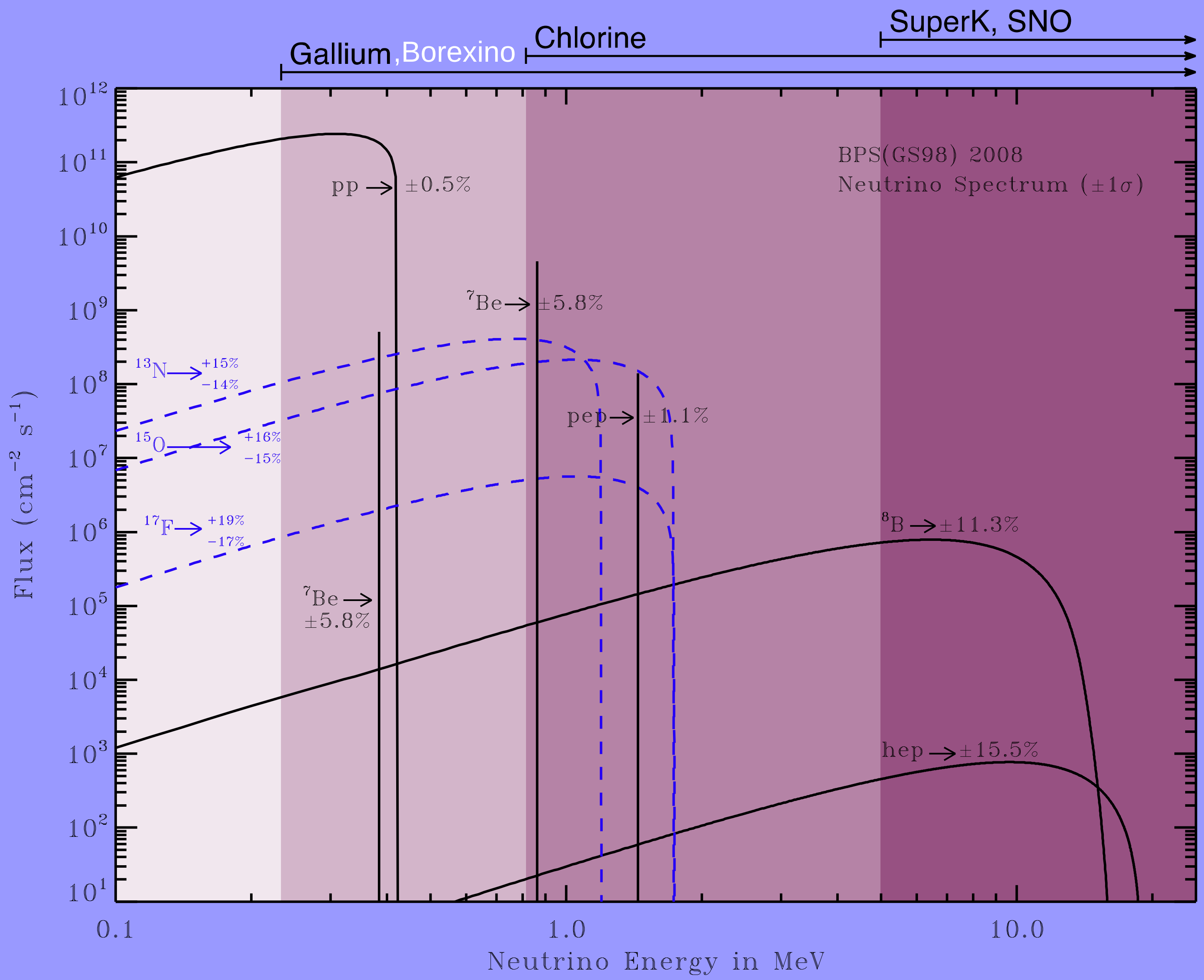
pp-cycle
>99% energy production
5 ν species

CNO-cycle
<1% energy production
3 ν species





Solar Neutrino 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.

(W. Hiroko's talk at Neutel 2013)

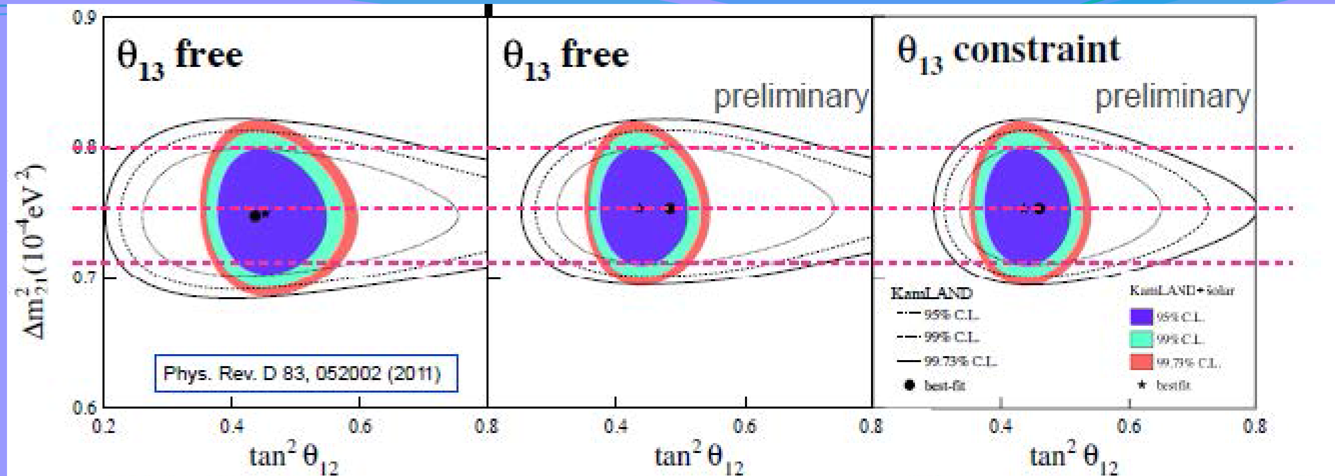
Neutrino Oscillation Solution

KamLAND+Solar+Theta13

$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5} \mathrm{eV}^2$

$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$

$\sin^2\theta_{13} = 0.023^{+0.002}_{-0.002}$



2011 Today Today

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

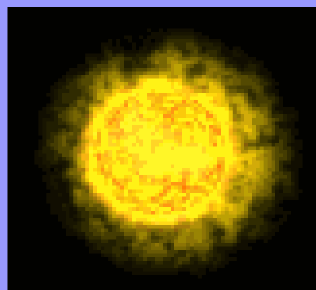
Open Issues →

- 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.

2. Be-7 flux measurement

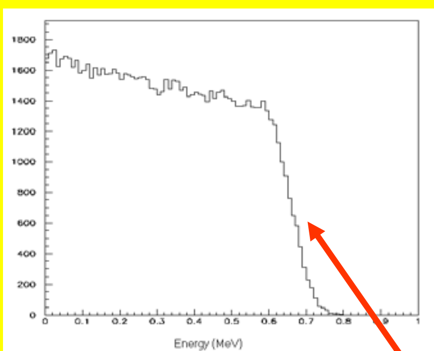
E_ν = 862 keV (monoenergetic)

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

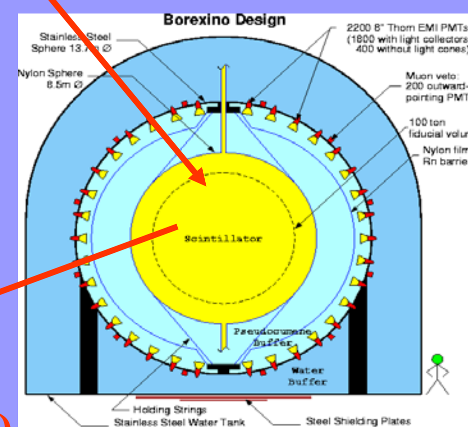


$$^7Be + e^- \rightarrow {}^7Li + \nu_e$$

ν_e ↔ ν_x



Electron recoil spectrum



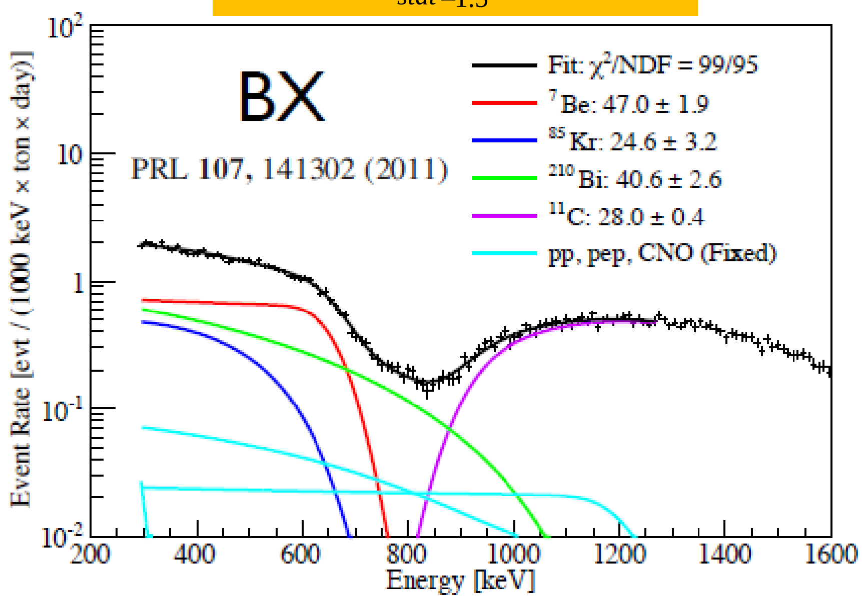
$$\nu_x + e^- \rightarrow \nu_x + e^-\ (x = e, \mu, \tau)$$

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

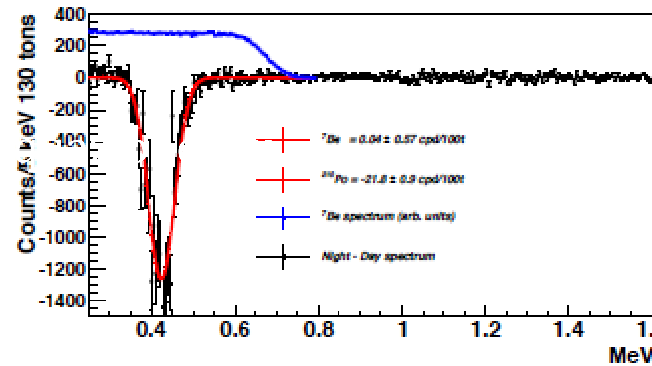
^{7}Be neutrinos

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

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



Day/Night Asymmetry



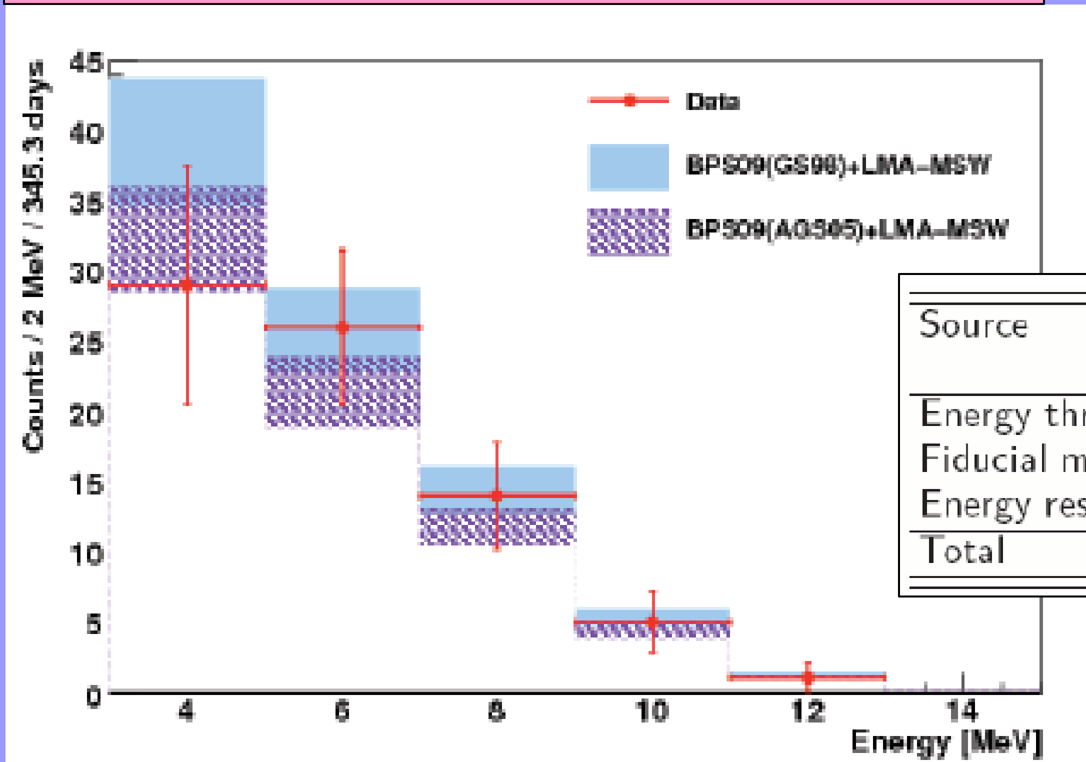
$$2\,\frac{\Phi_n - \Phi_d}{\Phi_n + \Phi_d} = 0.001 \pm 0.0012_{stat} \pm 0.007_{syst}$$

^{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



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%

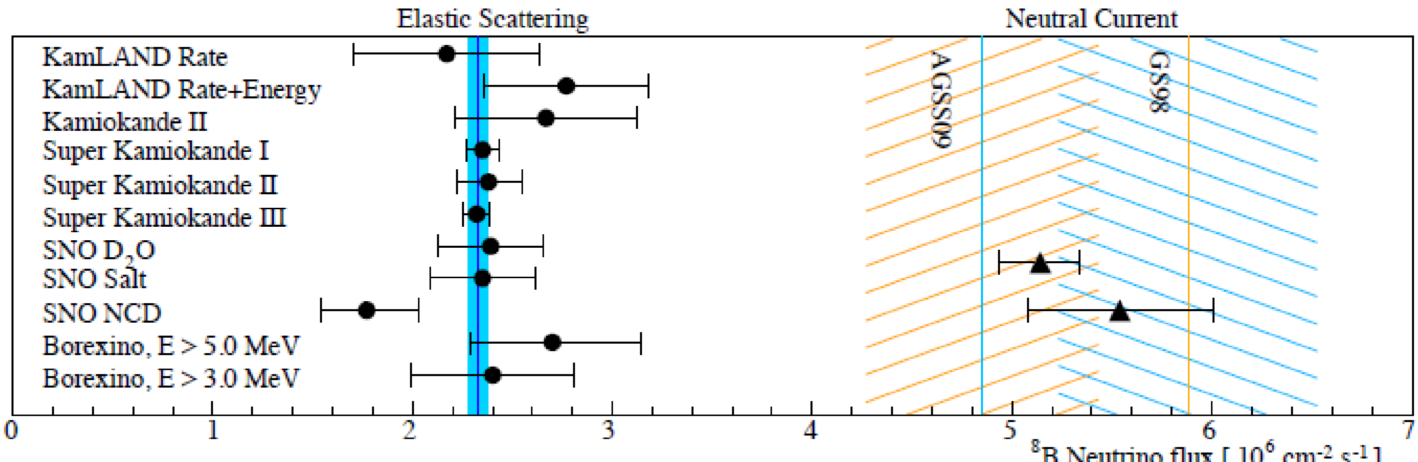
$$R = 0.22 \pm 0.04(stat) \pm 0.01(syst)\ cpd/100t\ \ (above\ 3\ MeV)$$

^{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)

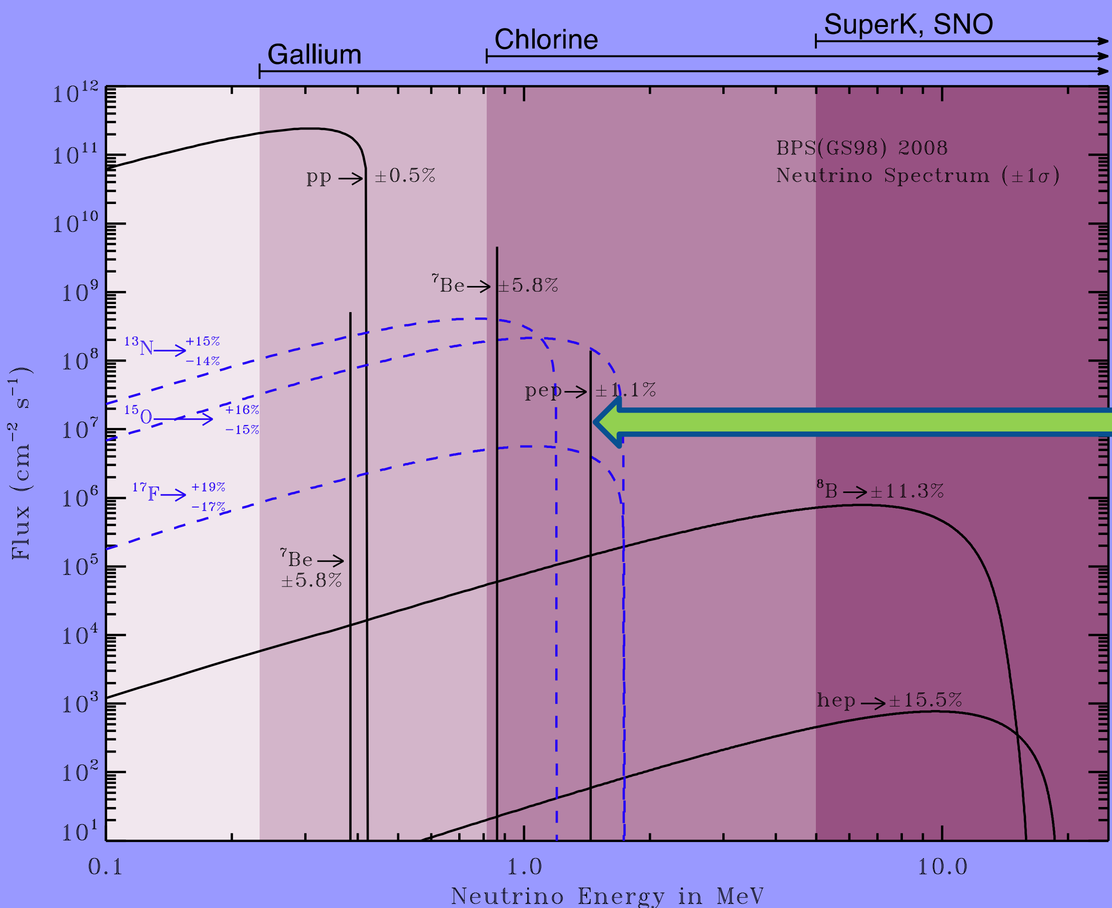
All current observations consistent with expectations:



4. pep detection and CNO limit

Pep reaction

$$p + e^- + p \rightarrow d + \nu_e$$



Monoenergetic 1.44 MeV neutrinos

1. BOREXINO
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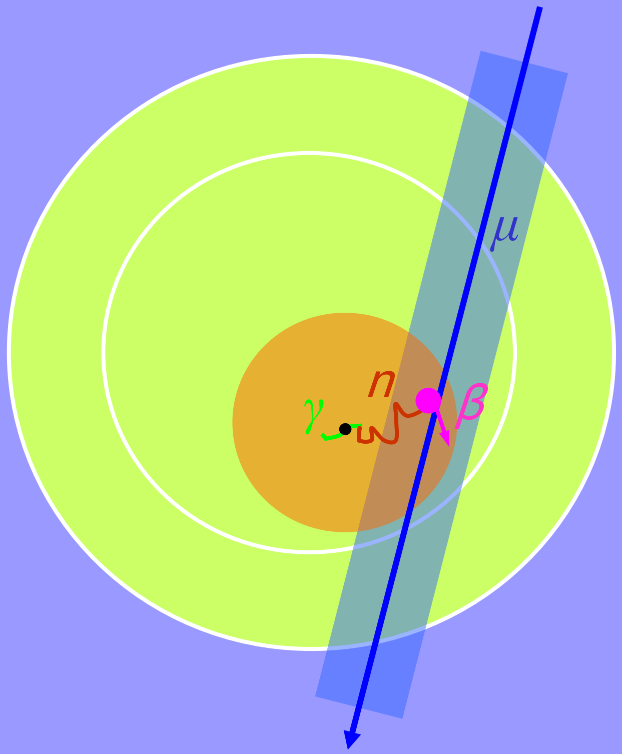
4. **pep detection and CNO limit**
5. Geoneutrinos
6. Future

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.

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

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



τ (n capture): ~250μs

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

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

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

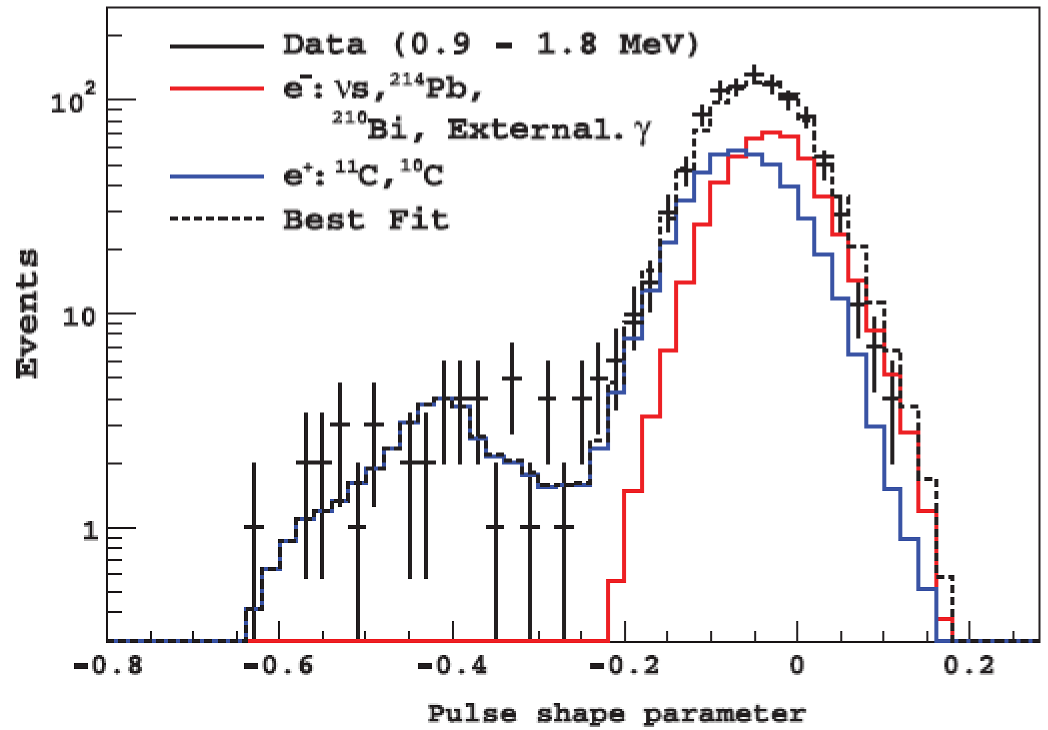
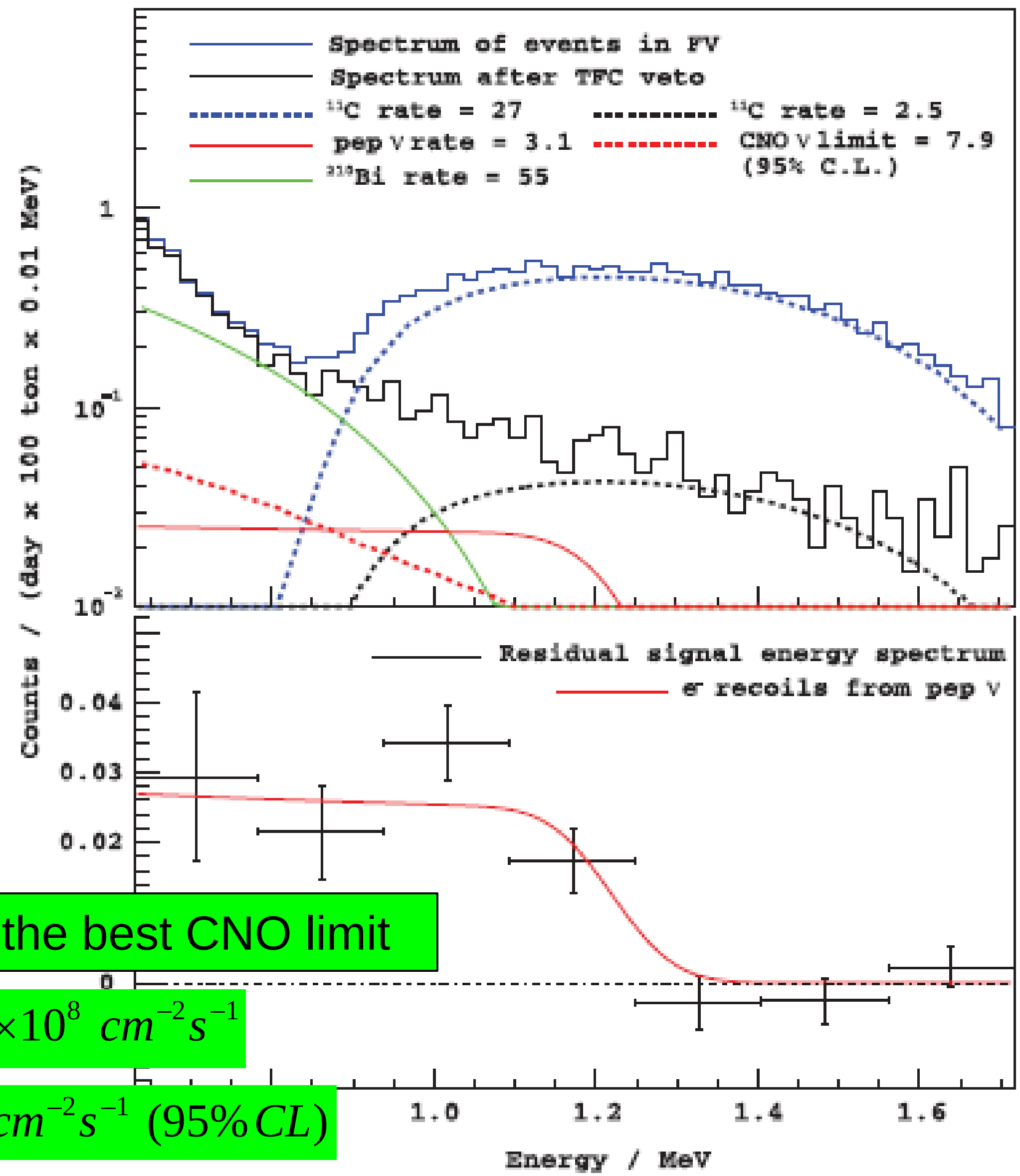


FIG. 2 (color). Experimental distribution of the pulse-shape parameter (black data points). The best-fit distribution (dashed black line) and the corresponding e^- (solid red line) and e^+ (solid blue line) contributions are also shown.

C-11 reduction strategy:

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

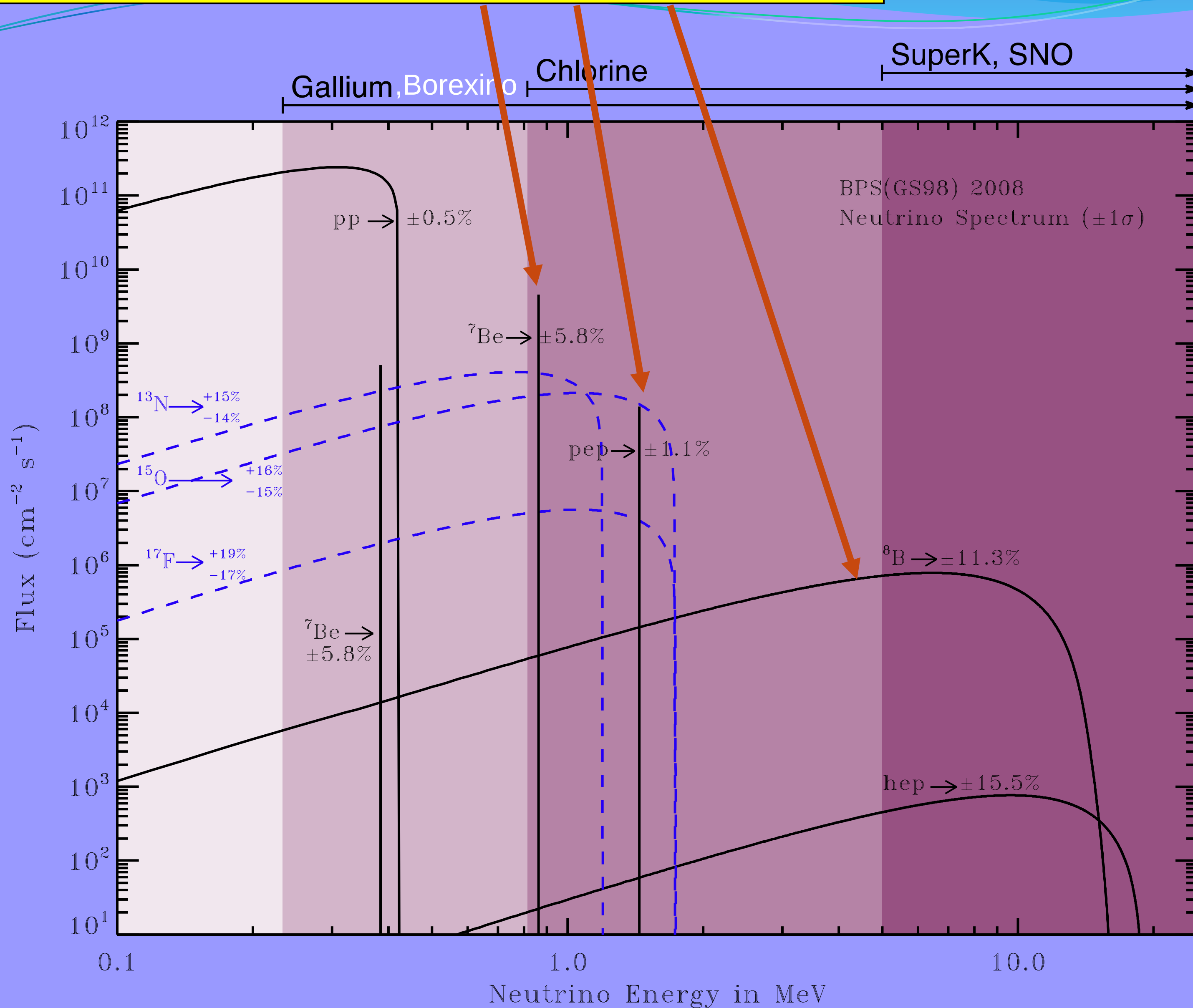


First pep measurement and the best CNO limit

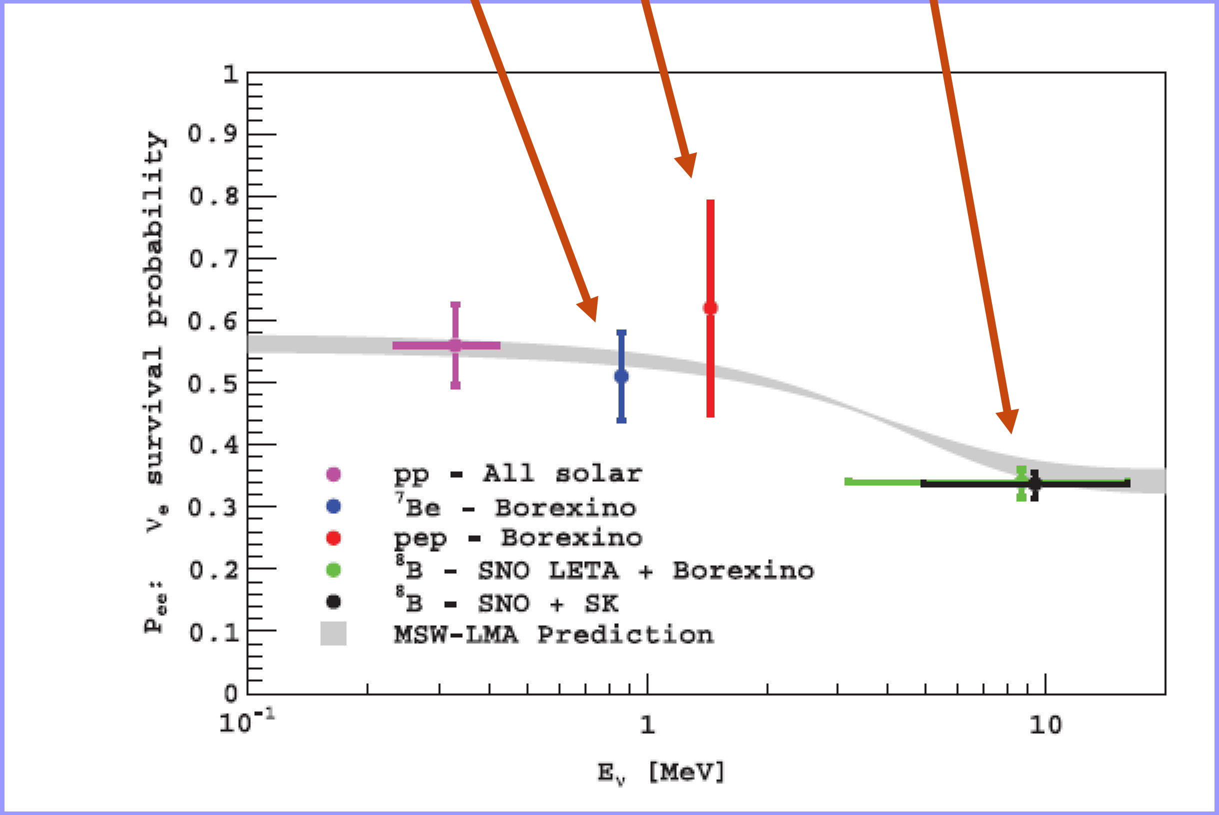
$$\Phi_{pep}\,(MSW-LMA) = (1.6 \pm 0.3)\times 10^{8}\ cm^{-2}s^{-1}$$

$$\Phi_{CNO}\,(MSW-LMA) < 7.7\times 10^{8}\ cm^{-2}s^{-1}\ (95\%\,CL)$$

Solar neutrino components measured by Borexino



Neutrino Oscillations properties measured by Borexino



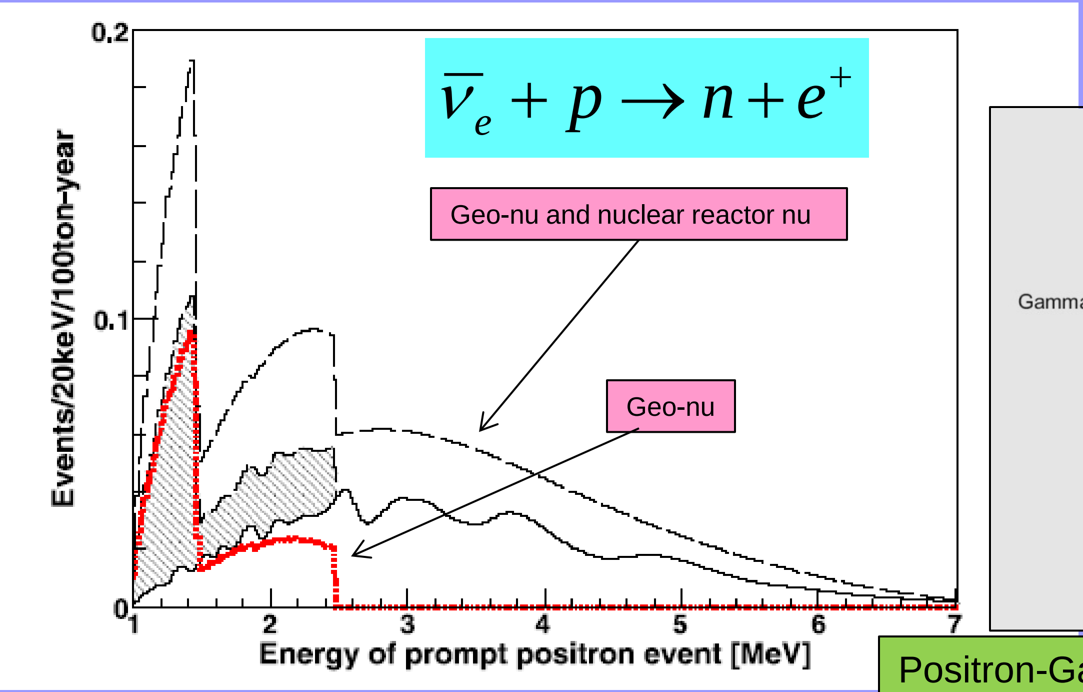
Solar electron neutrino survival probability as a function of neutrino energy
LMA-MSW with standard neutrino interactions

5. Geoneutrinos

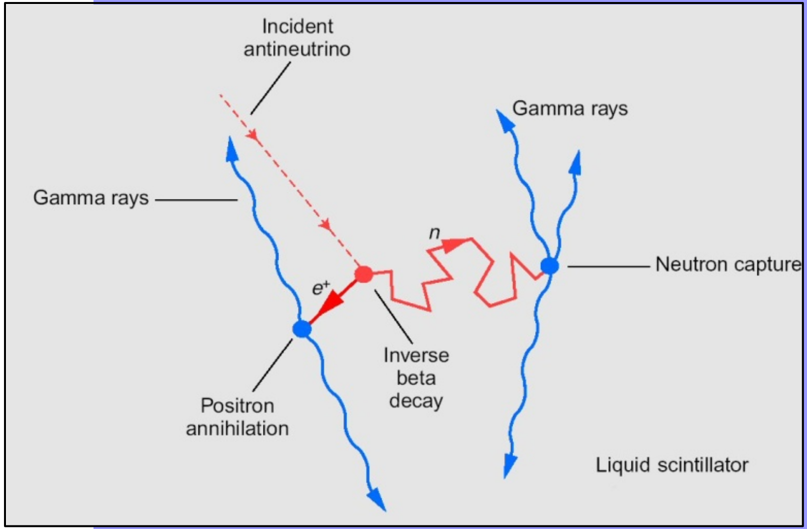
AntiNeutrinos emitted in beta decays of naturally occurring radioactive isotopes in the Earth's crust and mantle

Moderate Nuclear Reactors bkgd at LNGS

Detection by Inverse Beta Decay (1.8 MeV thr.)



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



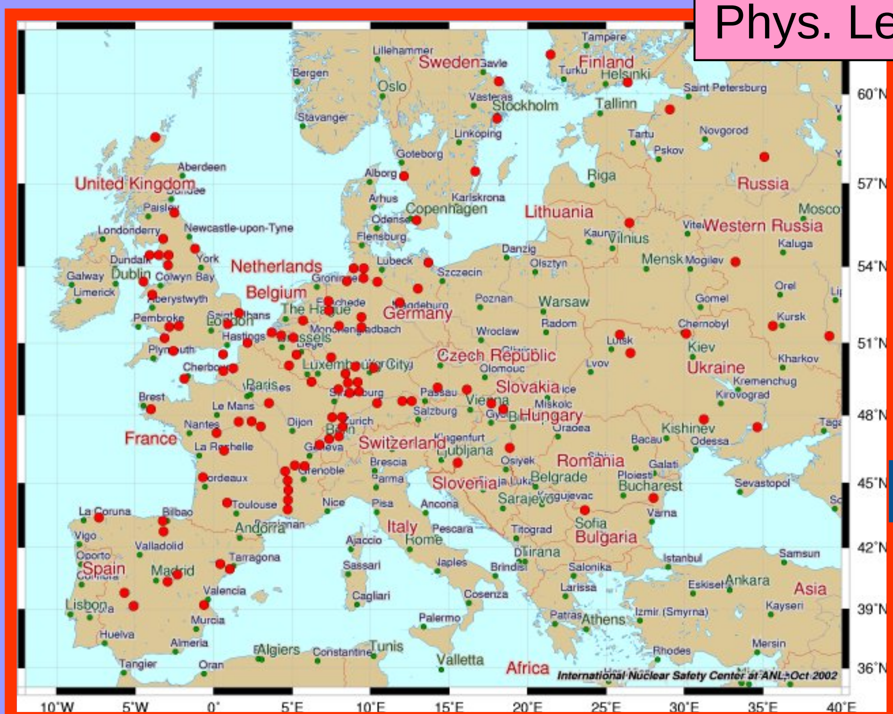
Positron-Gamma (2.2 MeV) delayed coincidence

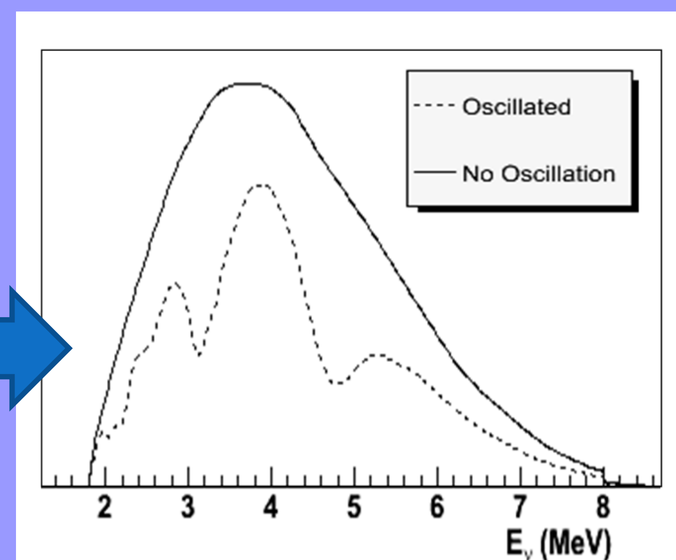
Search for positron/neutron-capturedelayed coincidences in the Borexino detector

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



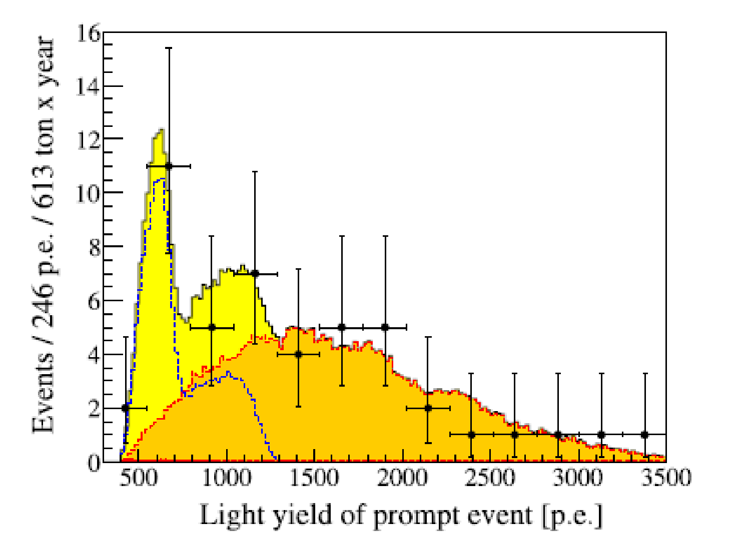


1353 days in Borexino: antineutrino geo analysis

Nuclear Reactor component :

Found : 21 events above geo endpoint

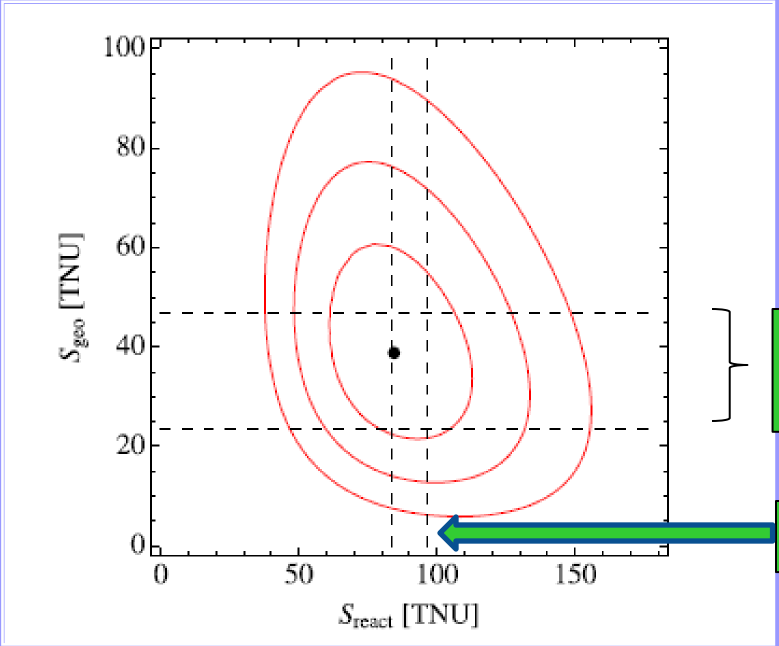
Expected : 22.0 +- 1.6



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

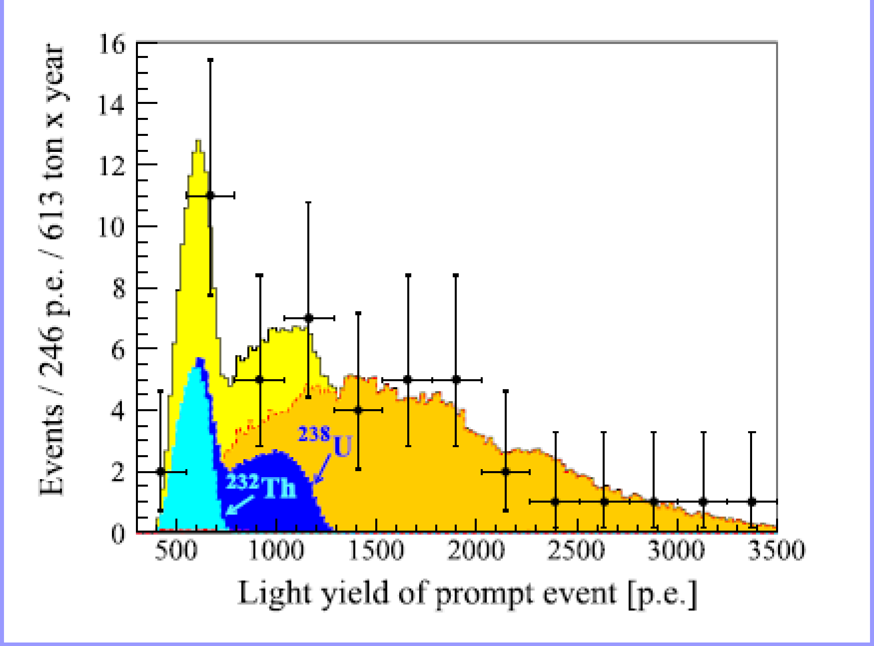
$$\Phi(U) = (2.4 \pm 0.7) \times 10^6\ cm^2 s^{-1}$$

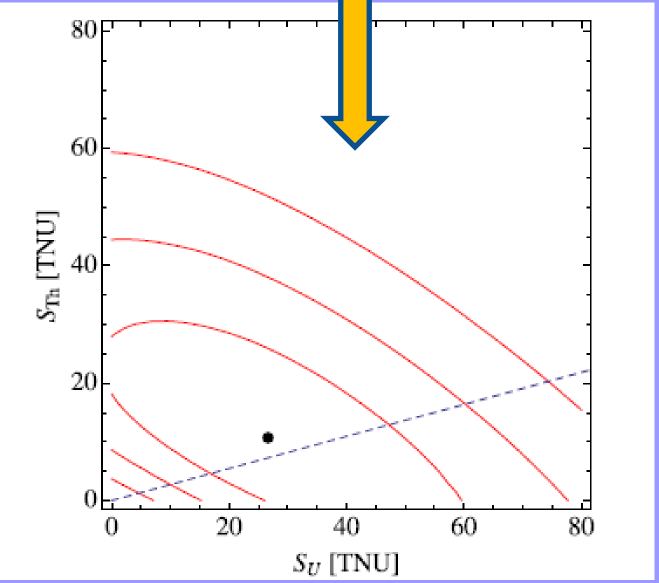
$$\Phi(Th) = (2.0 \pm 0.6) \times 10^6\ cm^2 s^{-1}$$

If U,Th contributions are left free:

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

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





6. Future (summary)

Borexino Phase II :

- pp detection
- CNO study
- Sterile Neutrino search (SOX)

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

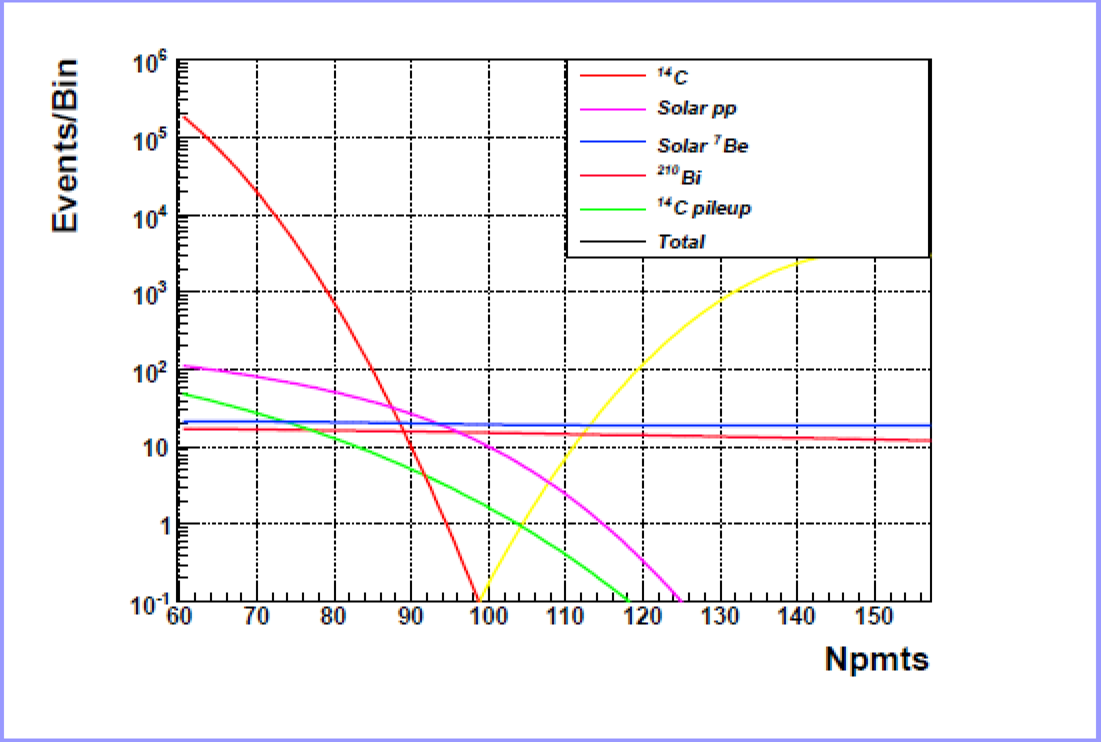
Given their small flux and low energy, neutrinos from CNO have never been measured directly.

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

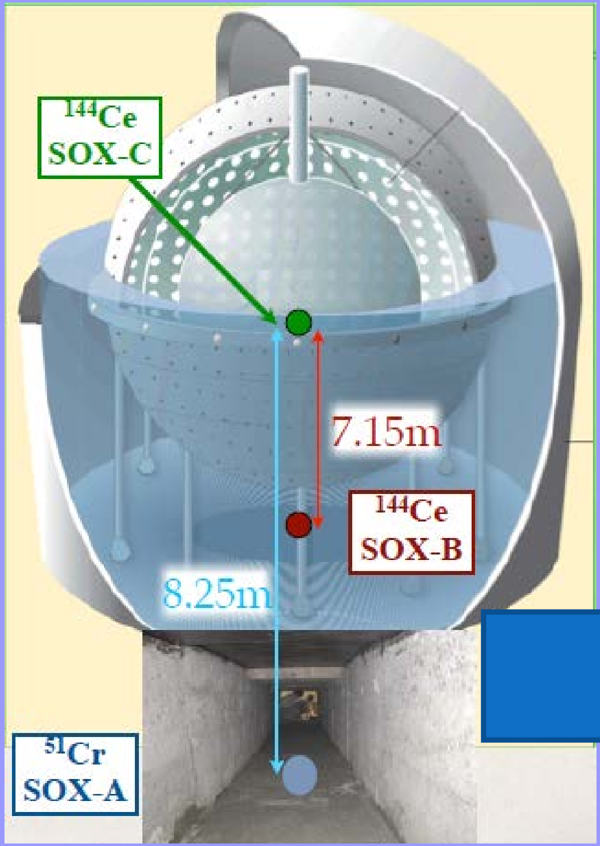


Short distance neutrino Oscillations with BoreXino (SOX)

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

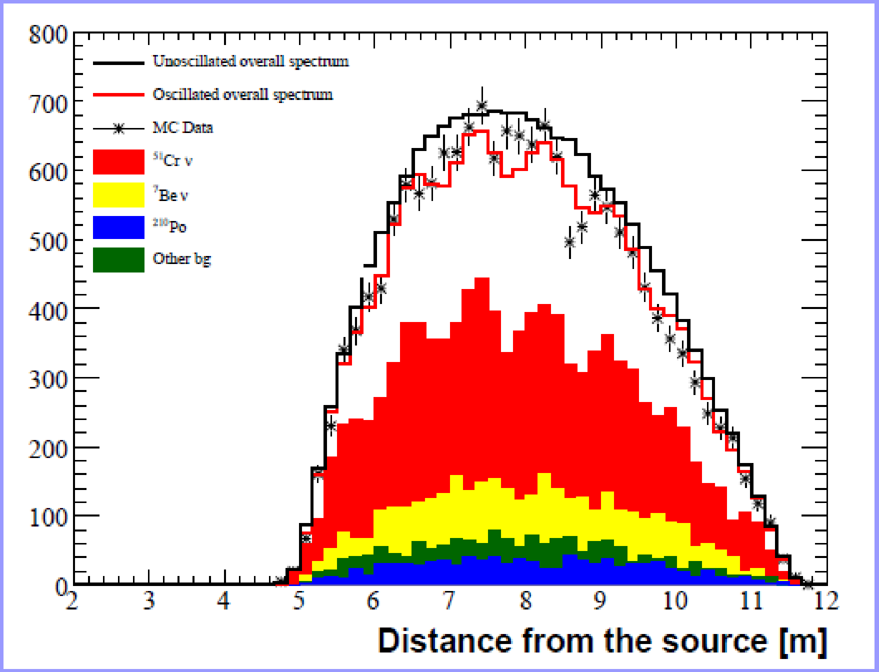
A fourth (sterile) neutrino? («Gallium», «Reactor», «LSND-MiniBoone» anomalies)

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



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

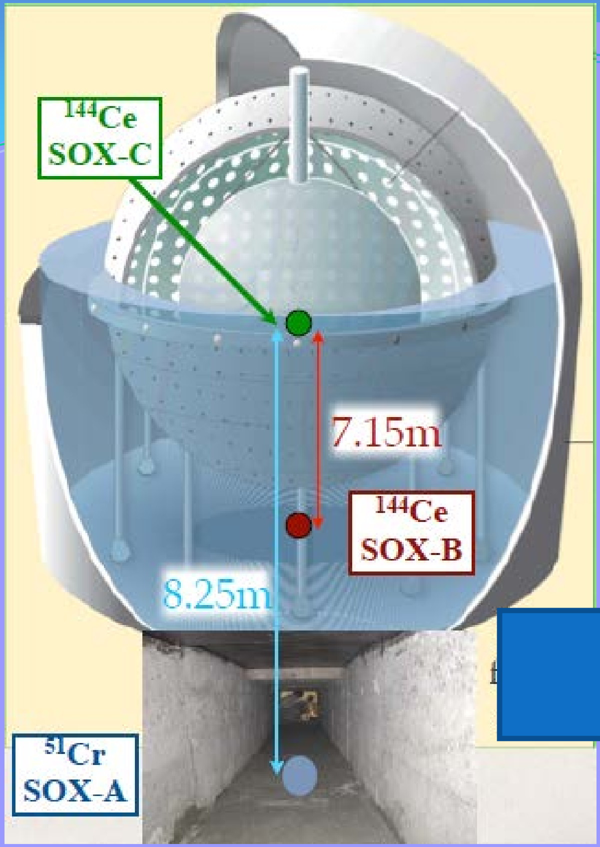
L/E of the order of eV^2

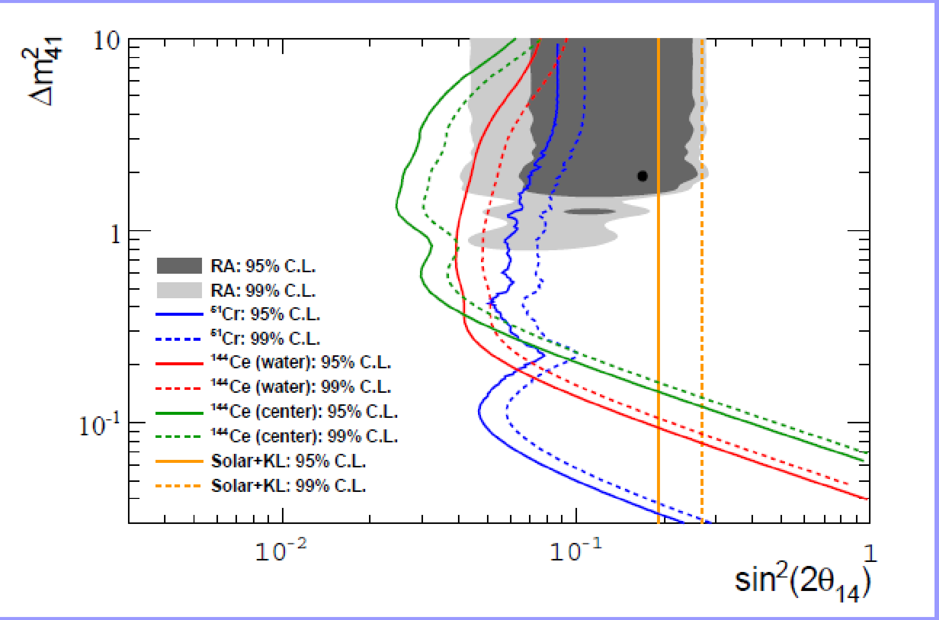


A. The Cr-51 source, with an activity of ~10 Mci

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

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 ν
• G. Bellini et al., Phys. Rev. Lett 108 (2012) 051302	pep

Neutrino Oscillations

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

atmospheric $\quad s_{ij} = \sin\theta_{ij} \quad c_{ij} = \cos\theta_{ij}$ $\quad$ solar

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

θ_{atm} $\quad$ θ_{13}, δ $\quad$ θ_{sol}

PMNS neutrino mixing matrix, analogous to CKM matrix for quarks

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

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

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

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