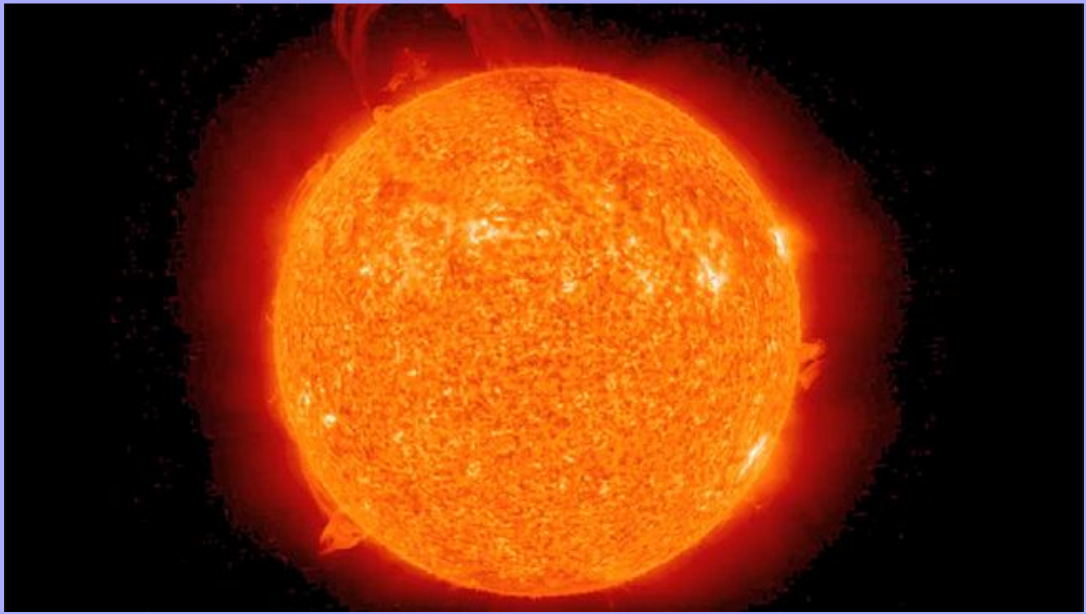
Solar Neutino Physics with Borexino

Rencontres de Physique de La Vallée d'Aoste - 2012

Marco G. Giammarchi
Istituto Nazionale di Fisica Nucleare
Via Celoria 16 – 20133 Milano (Italy)
marco.giammarchi@mi.infn.it
http://pcgiammarchi.mi.infn.it/giammarchi/

1. BOREXINO
2. Be-7 flux measurement
3. B-8 measurement
4. Geoneutrinos
5. Pep first detection
6. Future



1. BOREXINO

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

Detecting Solar Neutrinos means:

1. BOREXINO

2. Be-7 flux measurement

3. B-8 measurement

4. Geoneutrinos

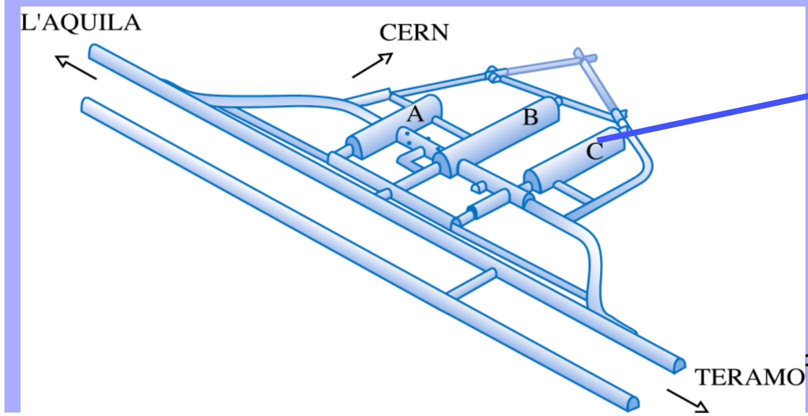
5. Pep first detection

6. Future

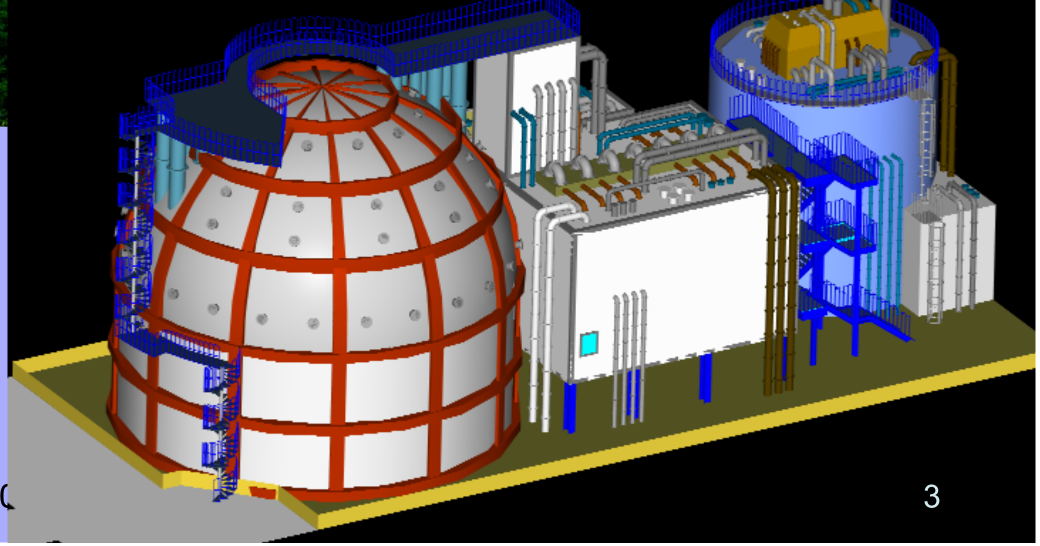
- Low interaction rates: 0.1/1 event/day/ton of target mass
- Low energy (mostly <10 MeV, better if <2 MeV)
- Low threshold and low background
- Underground location to shield from cosmic rays

Experimental site

Abruzzo, Italy
120 Km from Rome



Borexino Detector and Plants



Laboratori Nazionali del Gran Sasso

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

The Borexino Detector

Neutrino electron scattering

ν e -> ν e

Scintillator:

270 t PC+PPO (1.4 g/l)

Nylon vessels:

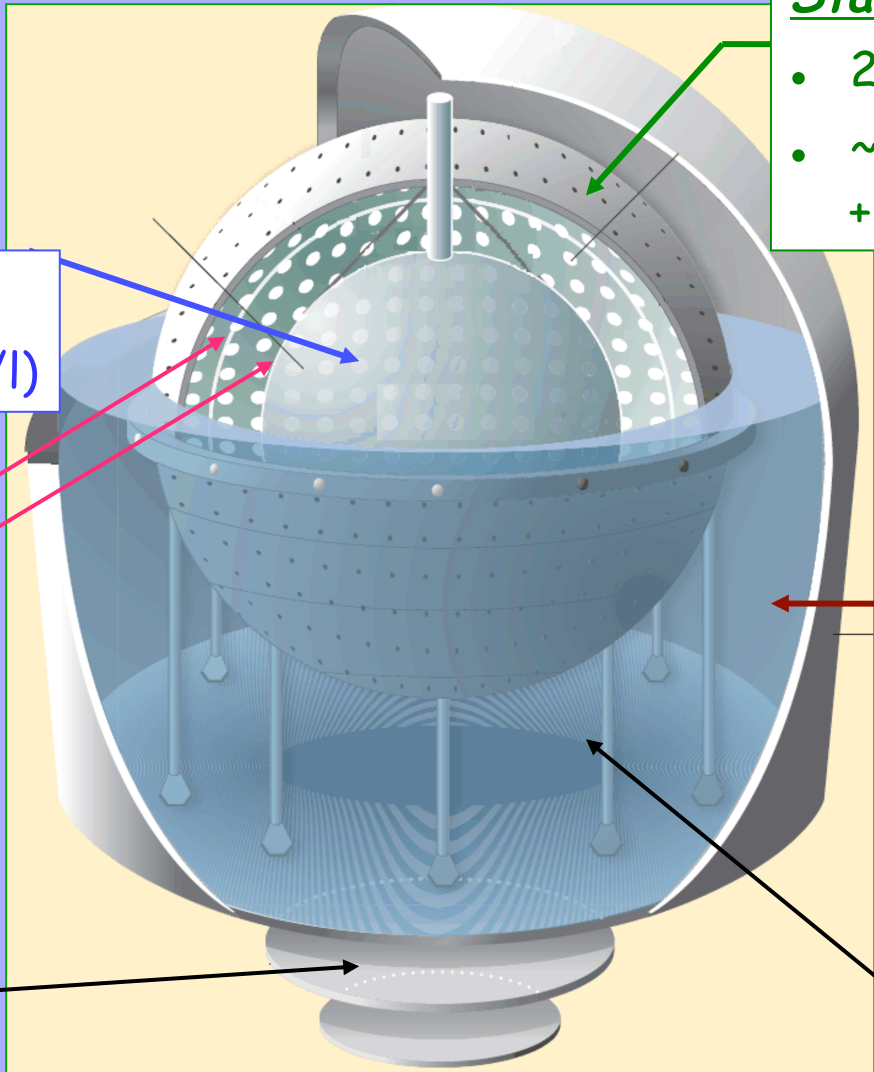
(125 μm thick)

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

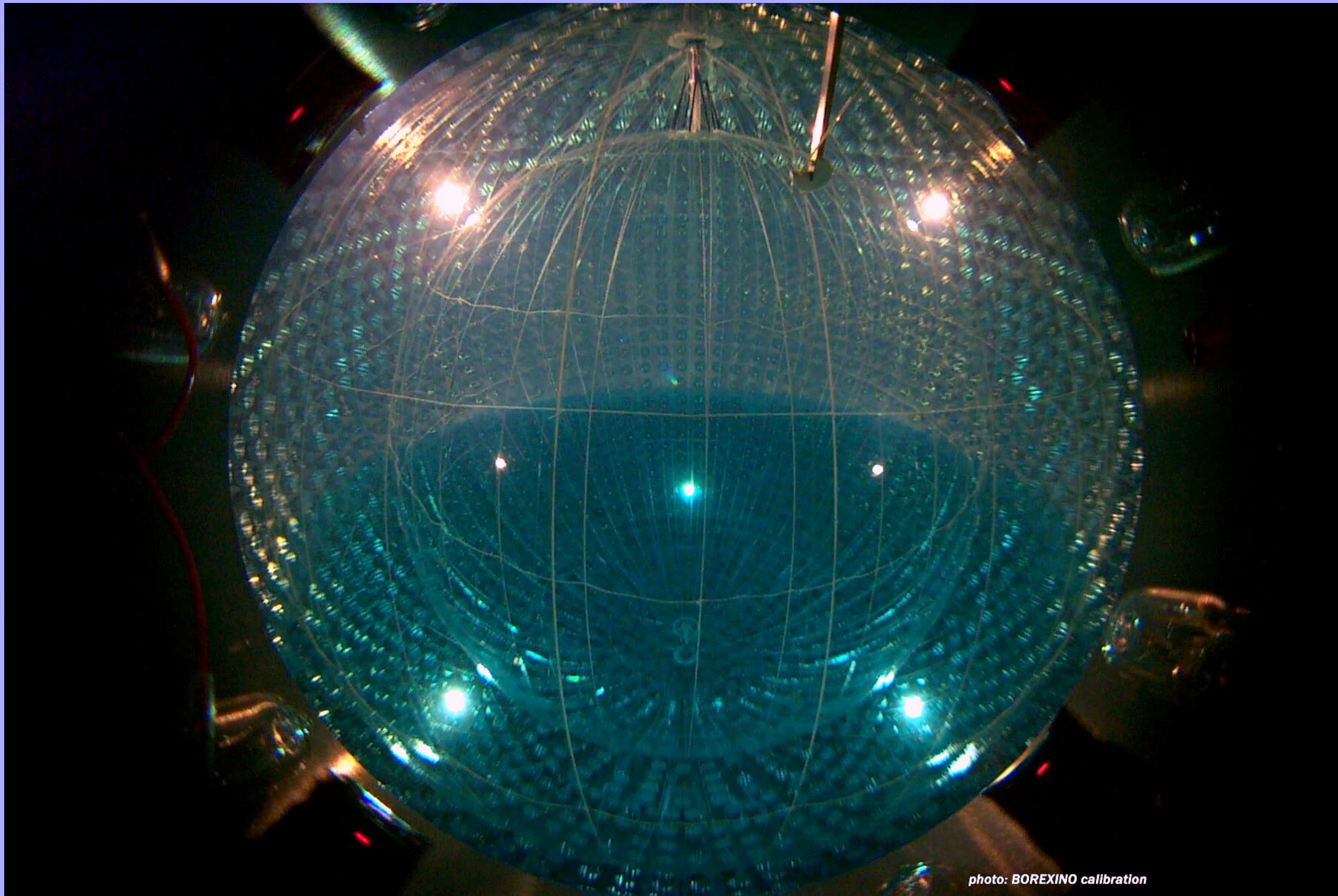
208 PMTs in water

2100 m^3

20 legs

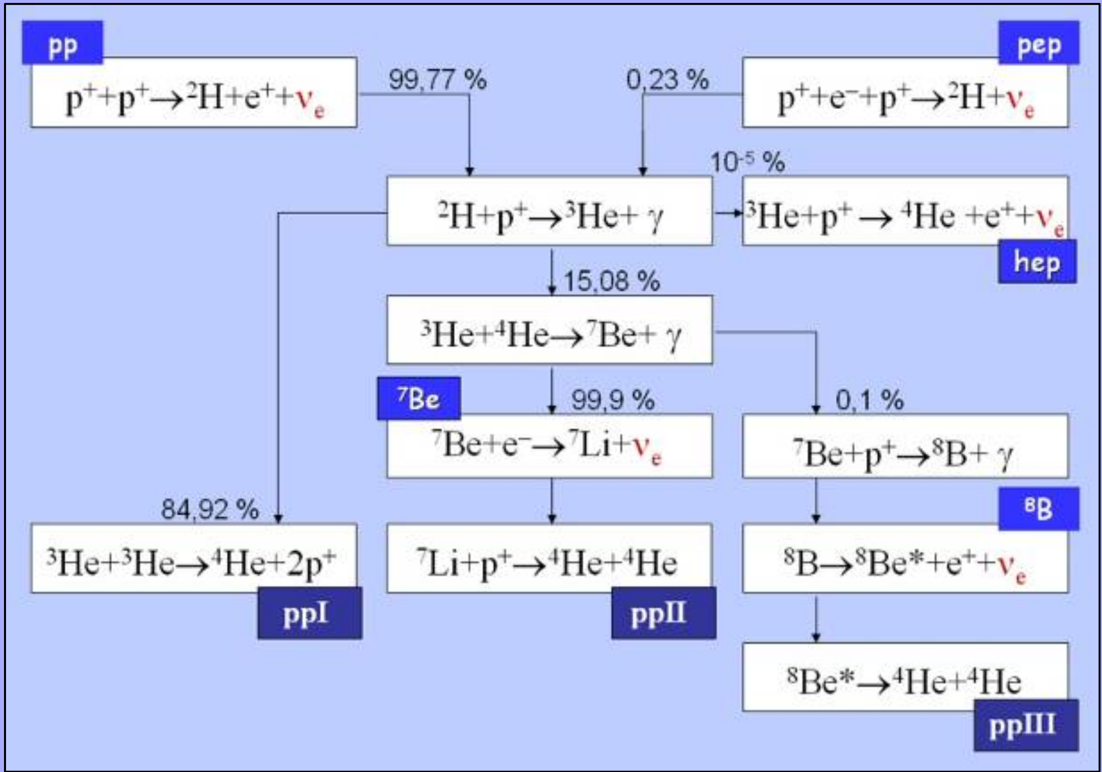
Filling phase of the Borexino detector (2007, Laboratorio del Gran Sasso)

11 m

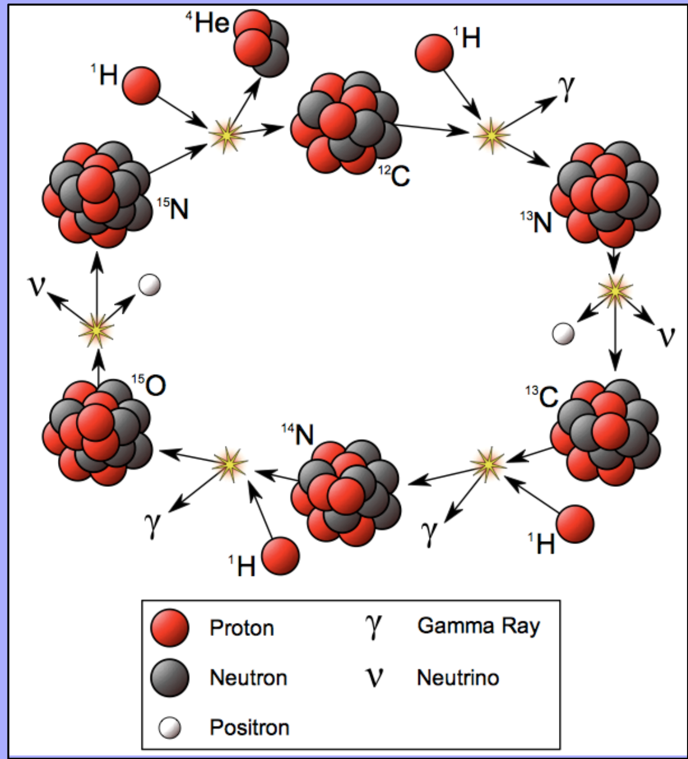


Energy production in the sun

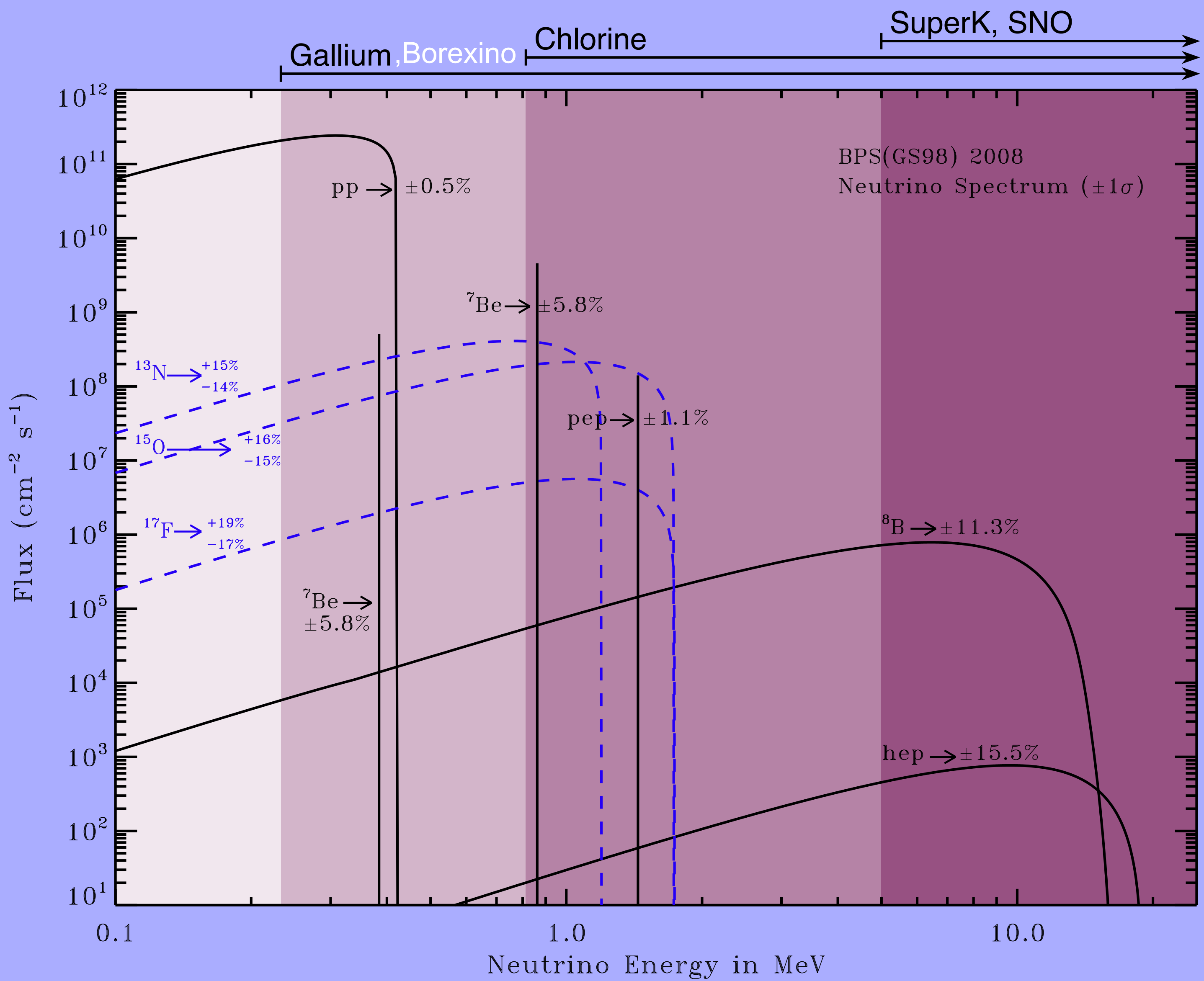
PP-chain
>99% energy production
5 νspecies



CNO-cycle
<1% energy production
3 νspecies



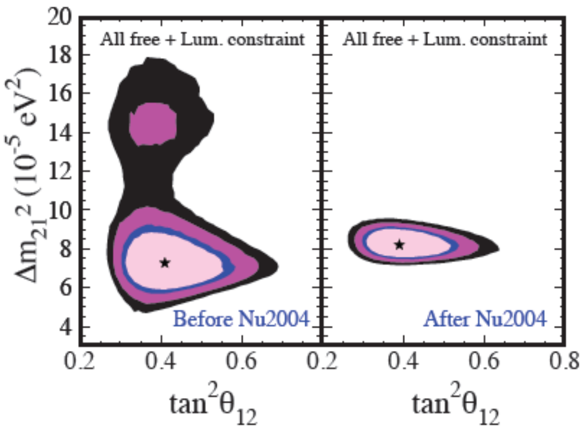
Solar Neutrino Spectrum

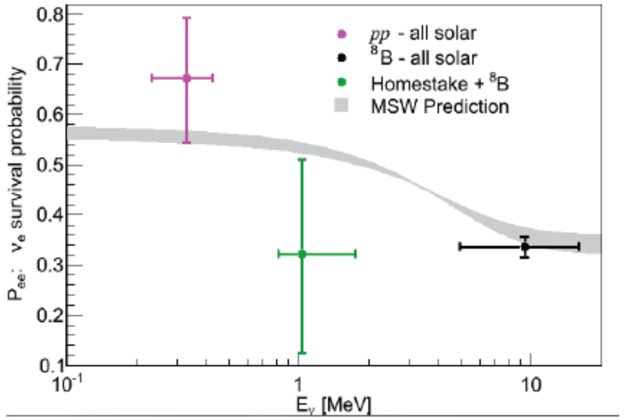


Study of Solar Neutrinos → Solar Neutrino Problem → Neutrino Oscillations

- Radiochemical experiments discovered Solar Neutrinos (1960s). The Sun is powered by nuclear fusion!
- Kamiokande measured solar ν_e ^8B 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 ^8B neutrinos demonstrating neutrino oscillations.

Neutrino Oscillation Solution





MSW-LMA solution

Oscillations parameters Δm^2 and $\tan^2\theta$ constrained from solar + KamLAND reactor data

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

1. BOREXINO

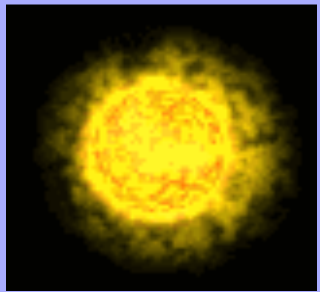
2. Be-7 flux measurement

3. B-8 measurement

4. Geoneutrinos

5. Pep first detection

6. Future

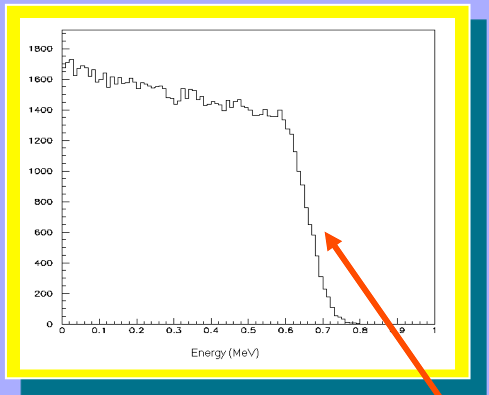


E_ν = 862 keV (monoenergetic)

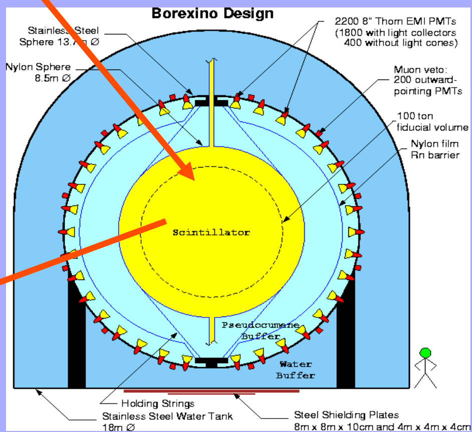
$\Phi_{SSM} = 4.8 \cdot 10^9\ \nu\ s^{-1}\ cm^2$

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

ν_e ↔ ν_x



Electron recoil spectrum



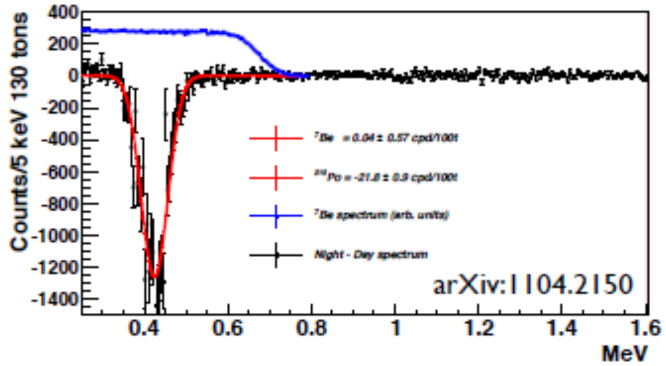
$$\nu_x + e^- \rightarrow \nu_x + e^- \ (x = e, \mu, \tau)$$

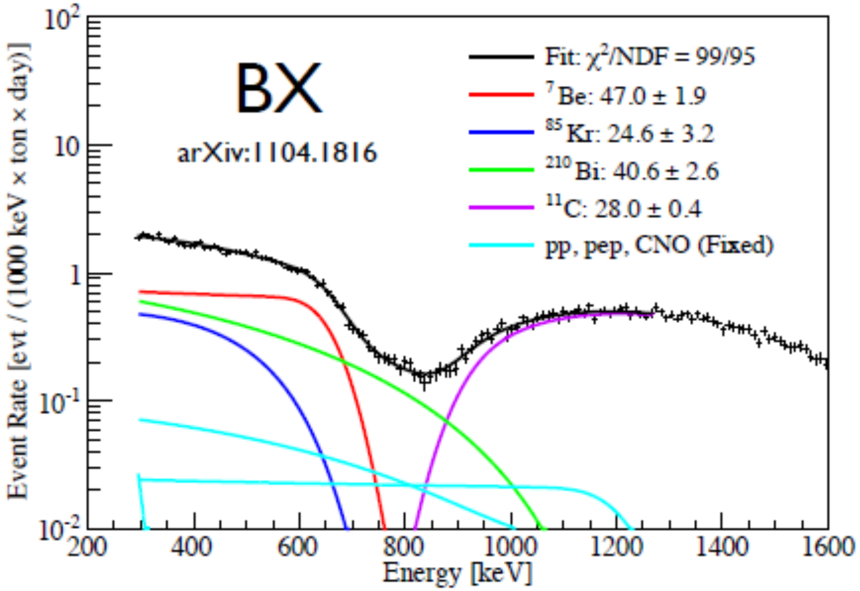
Cross Section ≈ 10^{-44} cm^2 (@ 1 MeV)

^{7}Be neutrinos

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

<u>Day/Night Asymmetry</u>





$$2\frac{\Phi_n-\Phi_d}{\Phi_n+\Phi_d} = 0.001 \pm 0.014$$

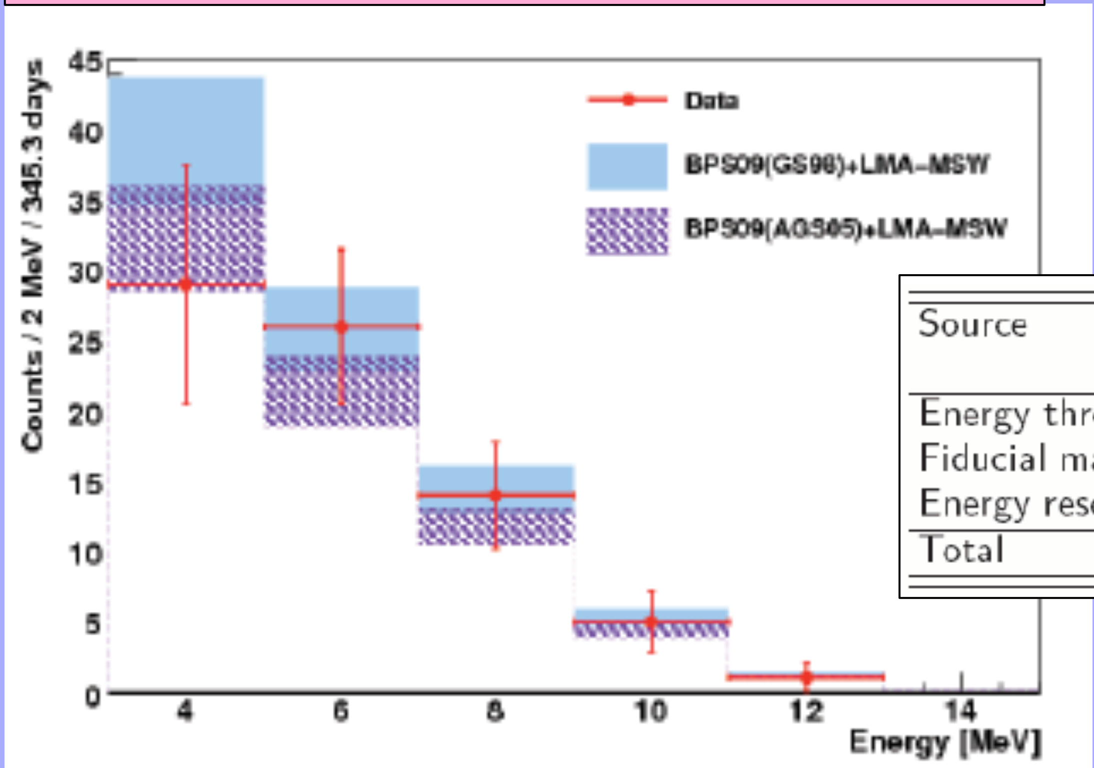
^{7}Be ν_e flux: LMA

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

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. Geoneutrinos
5. Pep first detection
6. 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%

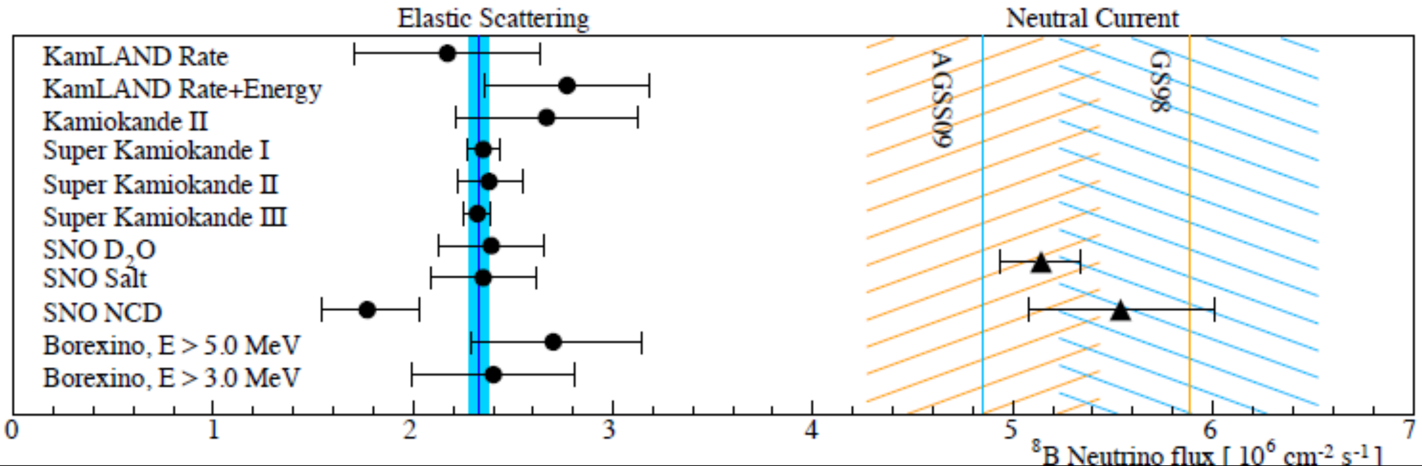
$$R = 0.22 \pm 0.04(stat) \pm 0.01(syst)\ cpd/100t$$

^{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:



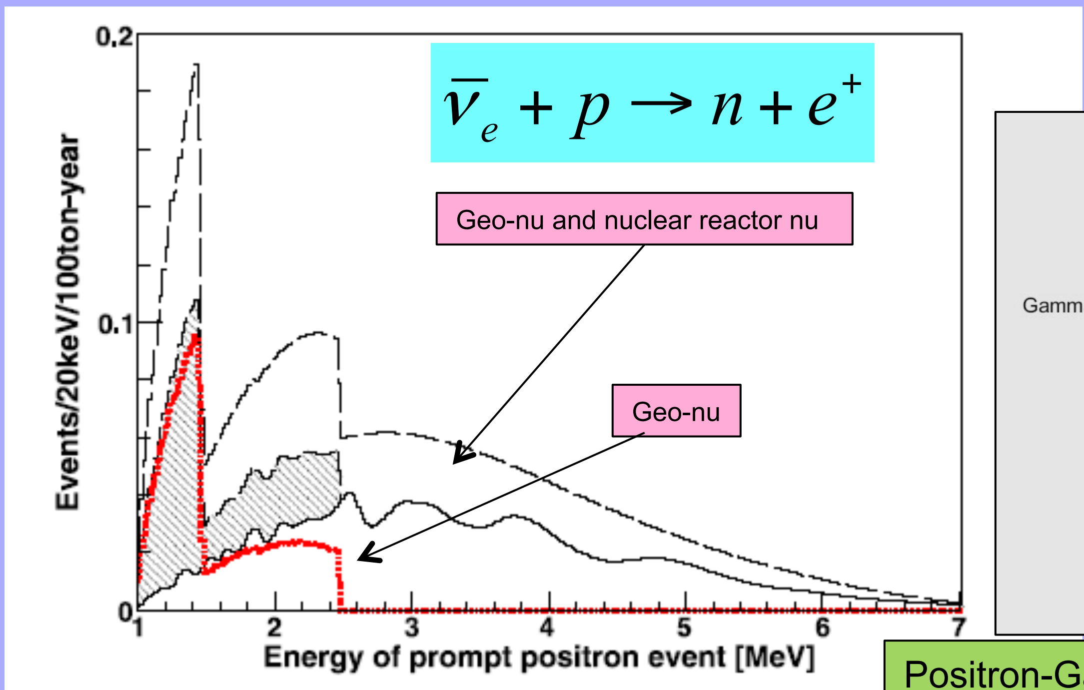
4. Geoneutrinos

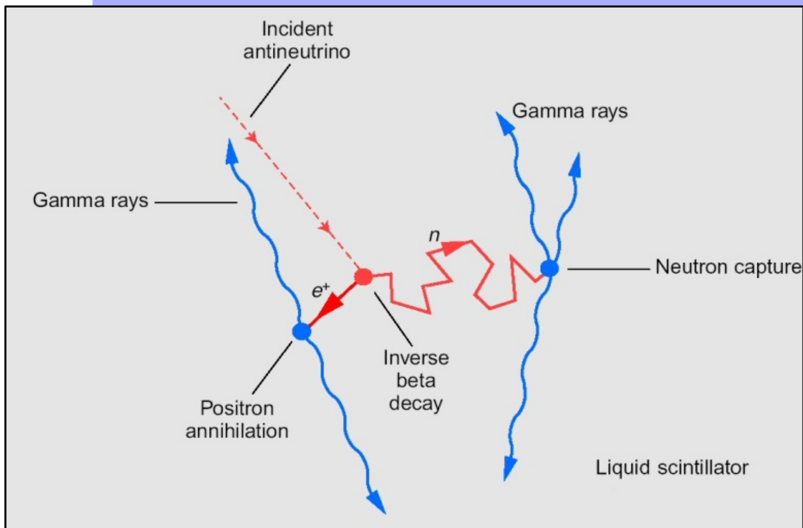
AntiNeutrinos emitted in beta decays of naturally occurreing radioactive isotopes in the Earth's crust and mantle

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. **Geoneutrinos**
5. Pep first detection
6. Future





Positron-Gamma (2.2 MeV) delayed coincidence

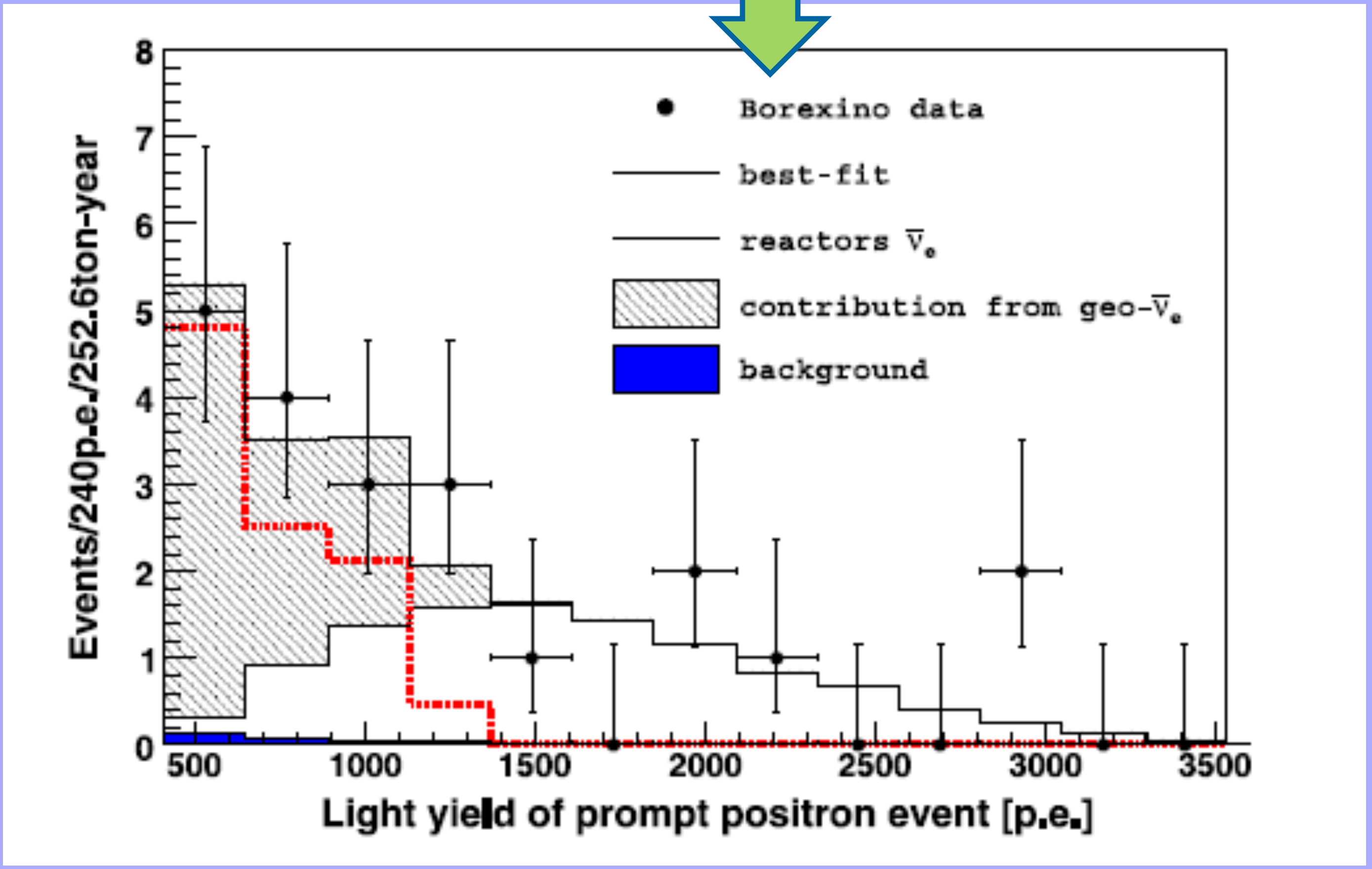
Search for delayed coincidences in the Borexino detector
Main background sources:

• Li-9, He-8, untagged muons, accidentals……………

$$3.9\ ^{+1.6}_{-1.3}\left(^{+5.8}_{-3.2}\right)\ ev/(100 tons \cdot yr)$$

68.3 %CL

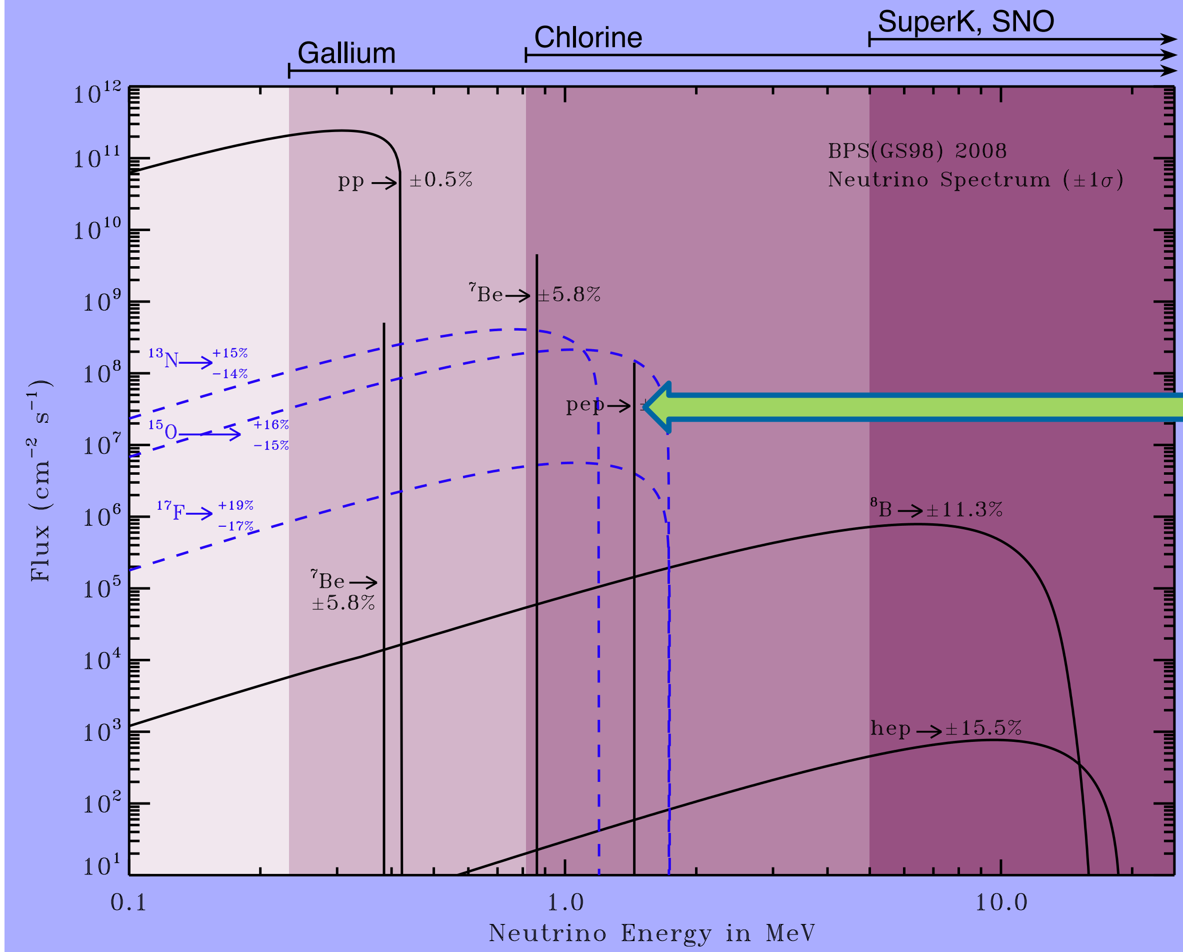
99.73 %CL



5. Pep first detection

Pep reaction

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



1. BOREXINO
2. Be-7 flux measurement
3. B-8 measurement
4. Geoneutrinos
5. **Pep first detection**
6. Future

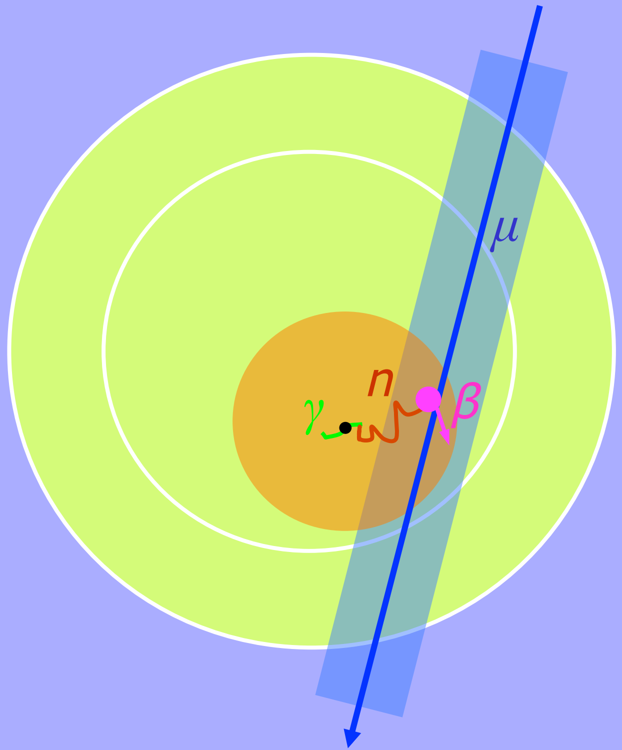
Monoenergetic 1.44 MeV neutrinos

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.

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

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



τ (n capture): ~250 μs

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

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

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

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

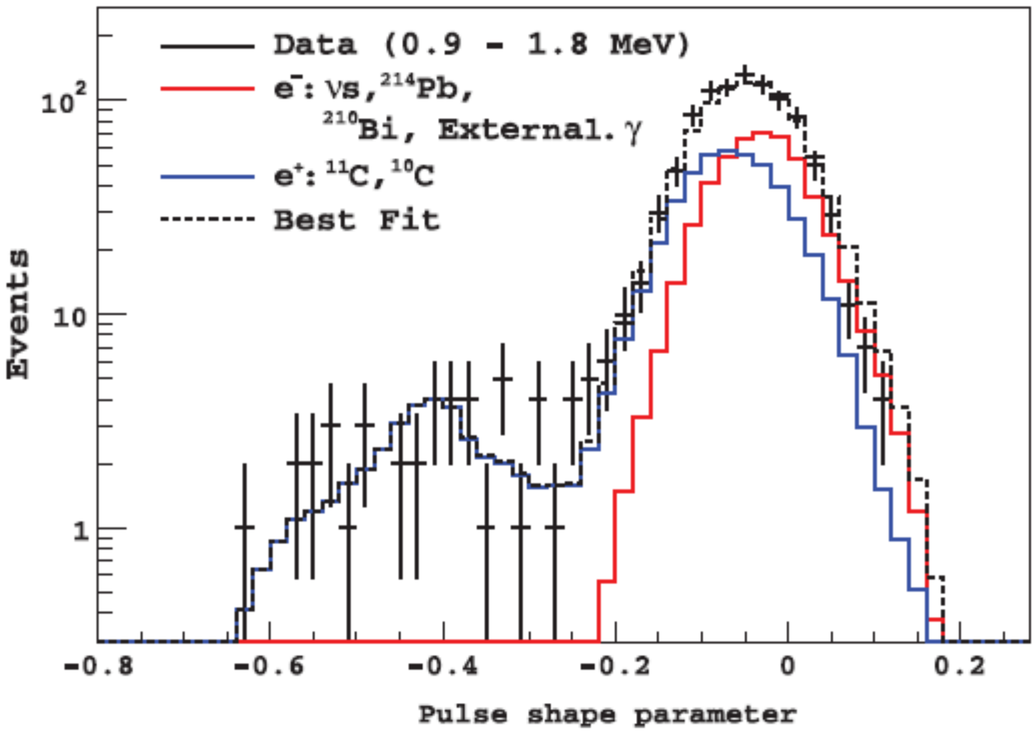
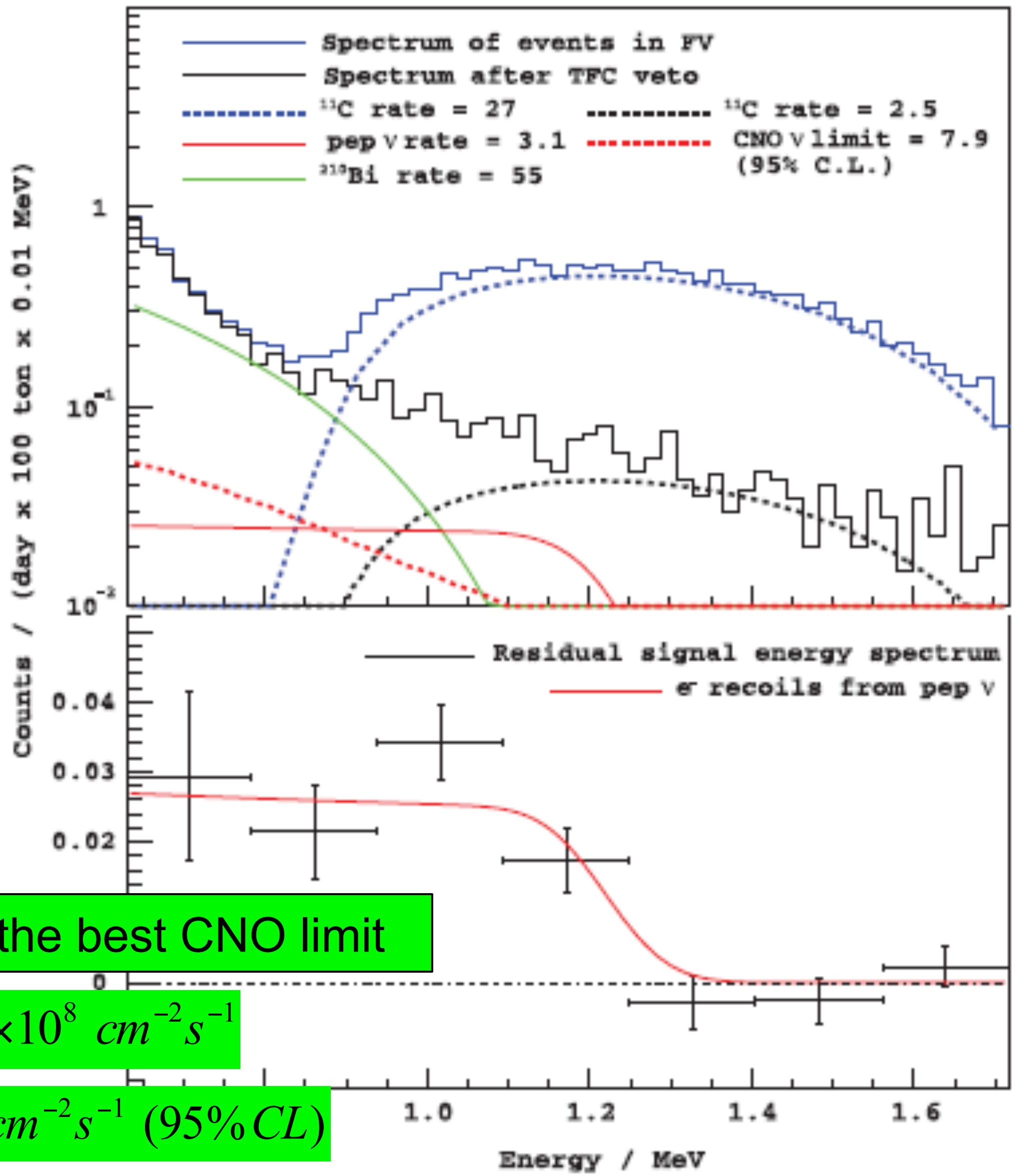


FIG. 2 (color). Experimental distribution of the pulse-shape parameter (black data points). The best-fit distribution (dashed black line) and the corresponding e^- (solid red line) and e^+ (solid blue line) contributions are also shown.

C-11 reduction strategy:

- Threefold coincidence (muon,neutron,C11)
- Pulse shape discrimination electron/ gamma/positron (Ps formation)



First pep measurement and the best CNO limit

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

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

6. Future (summary)

1. BOREXINO

2. Be-7 flux measurement

3. B-8 measurement

4. Geoneutrinos

5. Pep first detection

6. Future

Solar Neutrinos:

- Early motivation → study of the Sun
- Unexpected finding → neutrino oscillations

Solar Neutrinos today:

Study of the P(ee) oscillation pattern as a function of energy

Study of the interior of the Sun

Neutrino Oscillations

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

atmospheric $s_{ij} = \sin\theta_{ij}$ $c_{ij} = \cos\theta_{ij}$ 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} θ_{13}, δ θ_{sol}

PMNS neutrino mixing matrix, analogous to CKM matrix for quarks

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

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

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

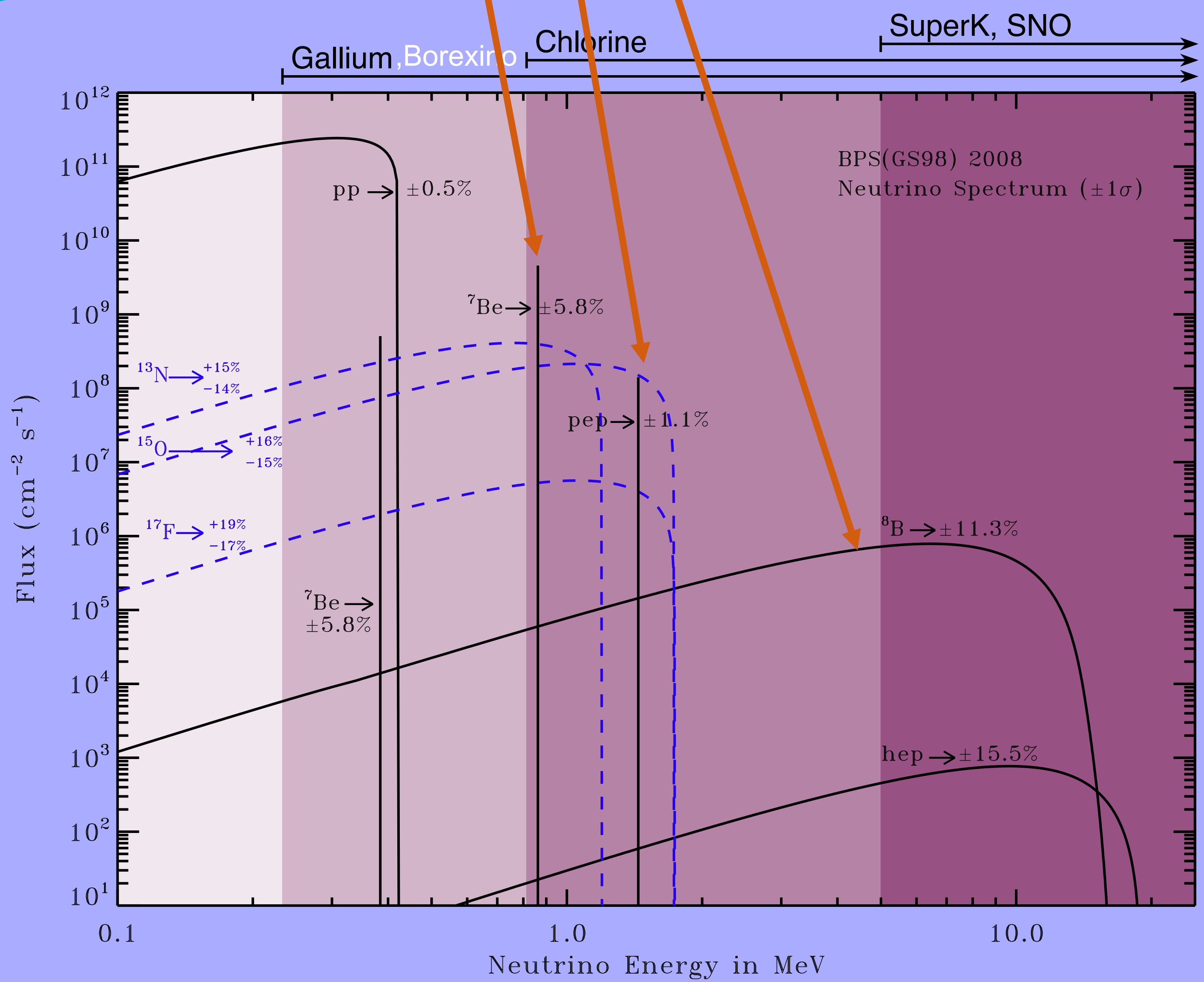
$\Delta m^2_{32} = (2.43 \pm 0.13) \times 10^{-3}\ \mathrm{eV}^2$

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

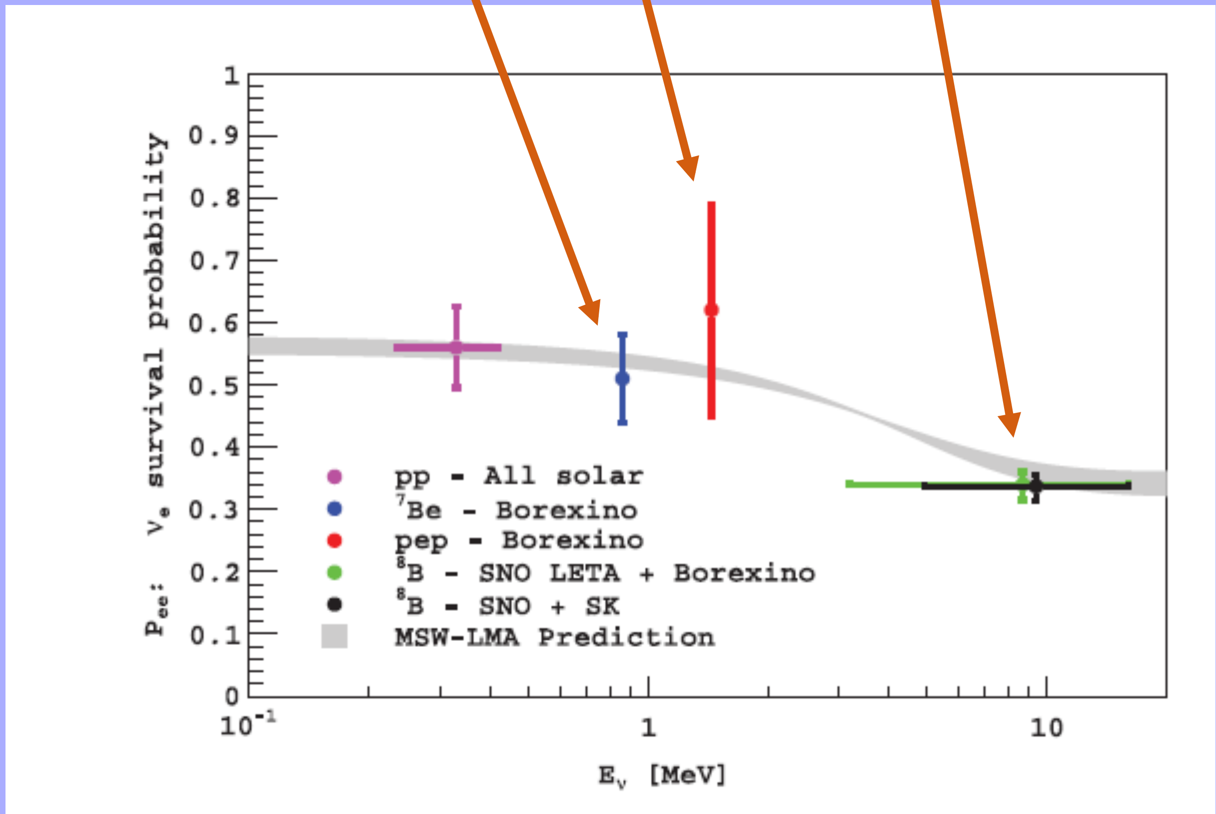
Solution of the Solar Neutrino Problem is neutrino oscillation with matter (MSW) effect at Large Mixing Angle (LMA)

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

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

Futures perspectives

Detector still fully operational after almost five years of running

Purification capability to be improved

Deal with residual backgrounds

- Measurement of the CNO solar component
- Measurement of short baseline neutrino oscillations with a radioactive source
- Neutrino magnetic moment
- Supernova alert system (SNEWS)
- Measurement of neutrino speed (CNGS beam)

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 — Geo ν

- G. Bellini et al., Phys. Rev. Lett 108 (2012) 051302 — pep