Neutrino Physics with BOREXINO

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I.N.F.N. at LNGS

International School of Nuclear Physics
32° Course
Particle and Nuclear Astrophysics
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Outline

- BOREXINO: the detector
- Solar neutrinos
- Electron anti-neutrinos
- Neutrinos from core collapse Supernovae
- Conclusions

Borexino Collaboration

Genova

Milano

Perugia

APC Paris

Princeton University

Virginia Tech. University

Dubna JINR (Russia)

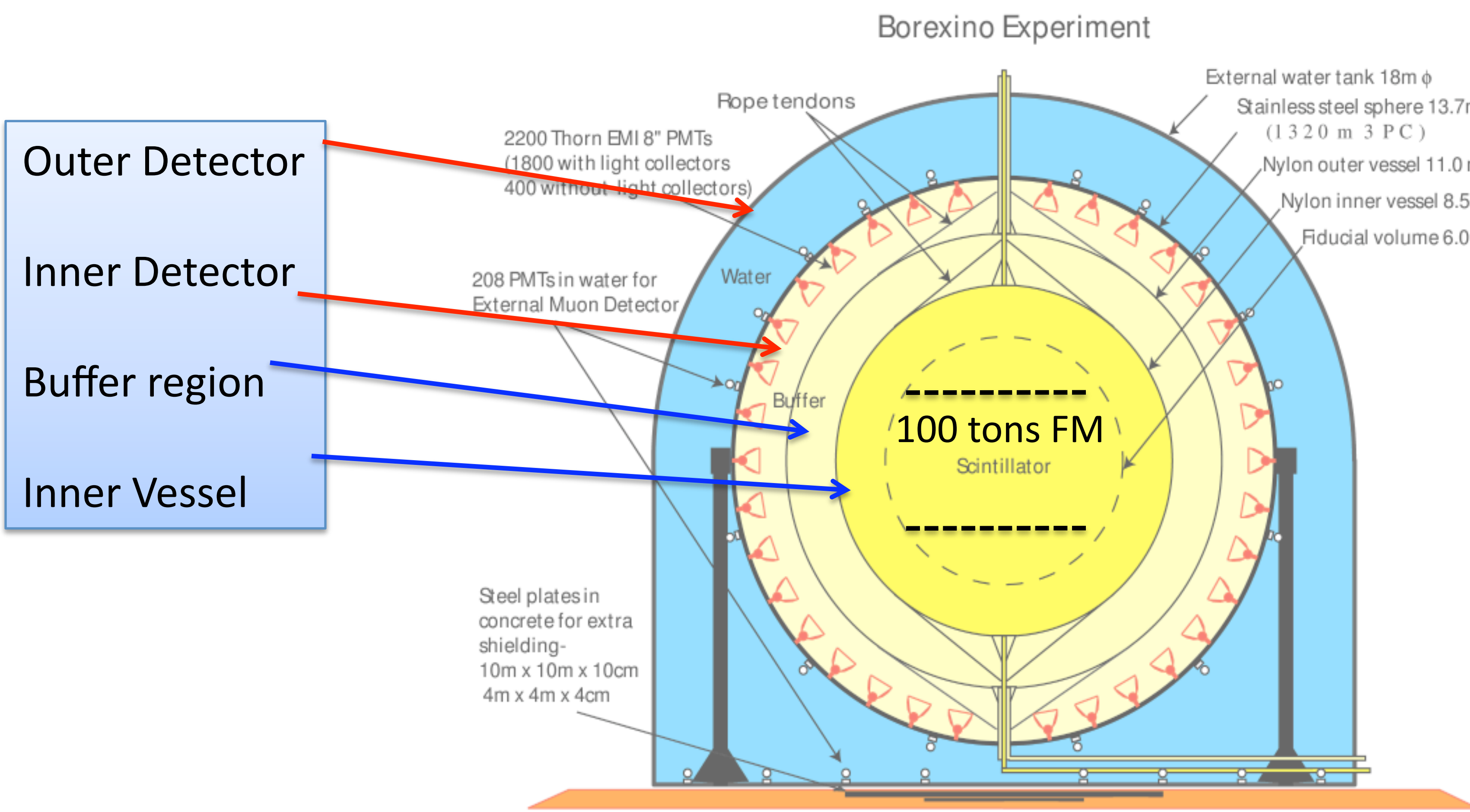
Kurchatov Institute (Russia)

Jagiellonian U. Cracow (Poland)

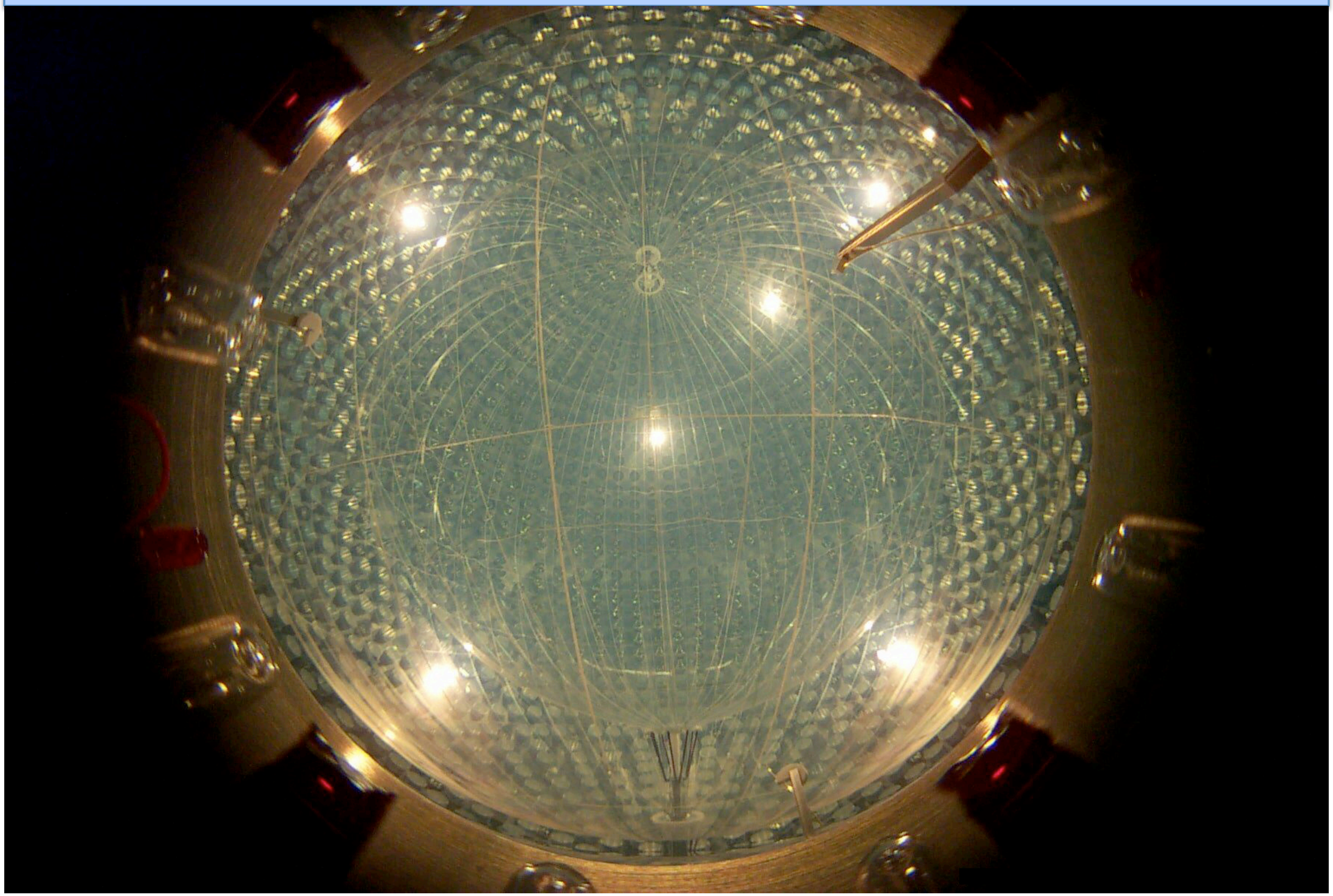
Heidelberg (Germany)

Munich (Germany)

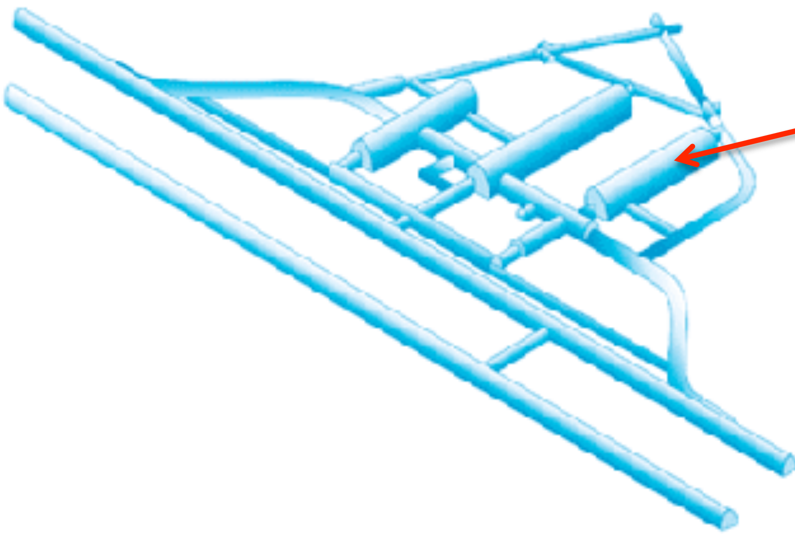
The BOREXINO detector

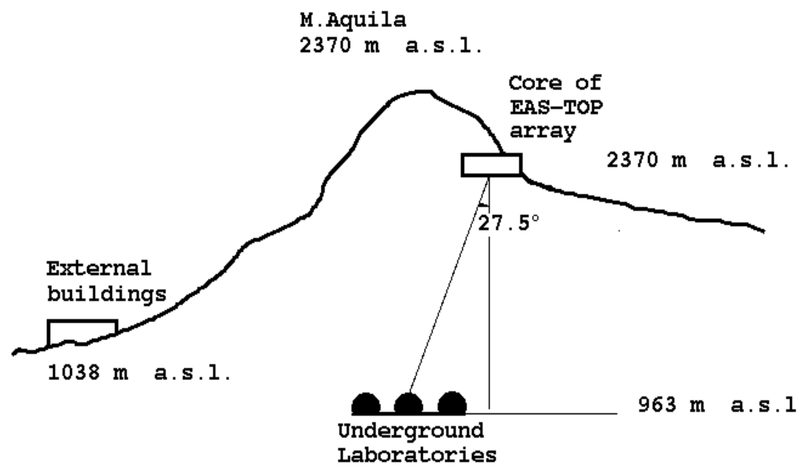


BOREXINO:
view of the Inner Detector



The Gran Sasso Underground Laboratory



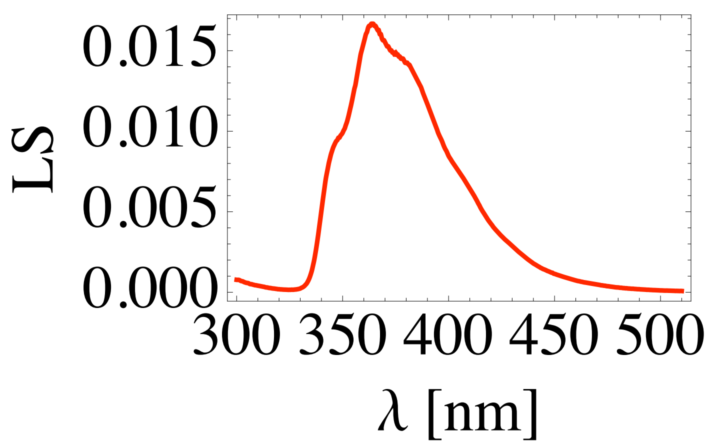


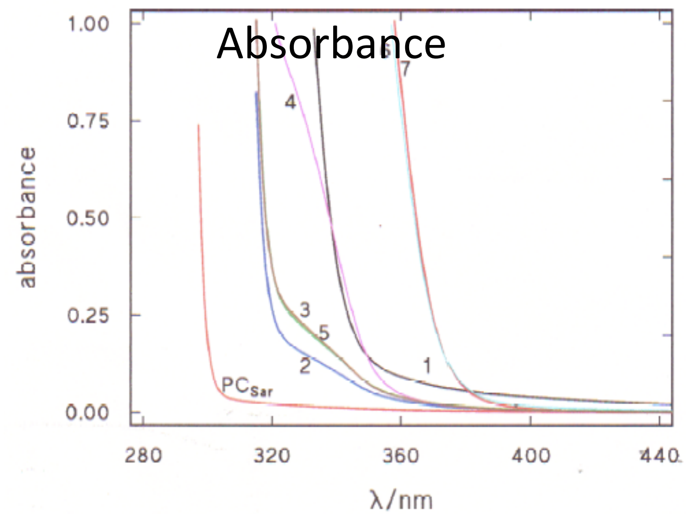
Average depth:
3800 m.w.e.
Minimum depth:
3000 m.w.e.
Cosmic rays flux:
reduced by 10^6

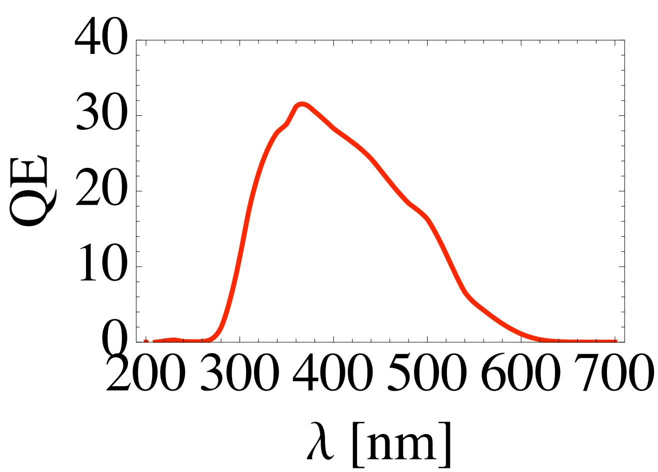
Borexino Liquid Scintillator

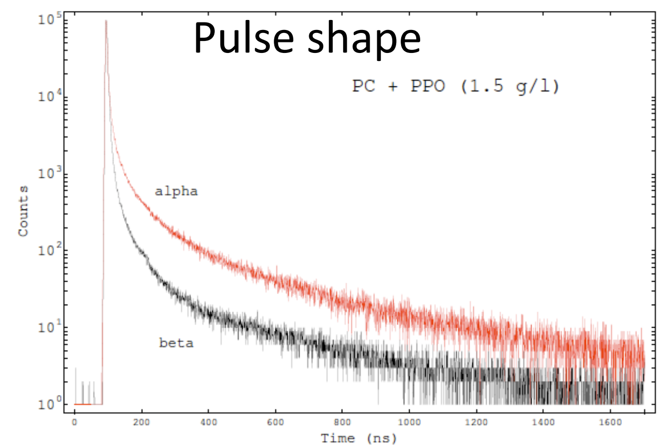
PC [C_9H_{12}] + 1.5g/l of PPO
Decay time ~ 3ns

Emission spectrum ~10^4 ph/MeV



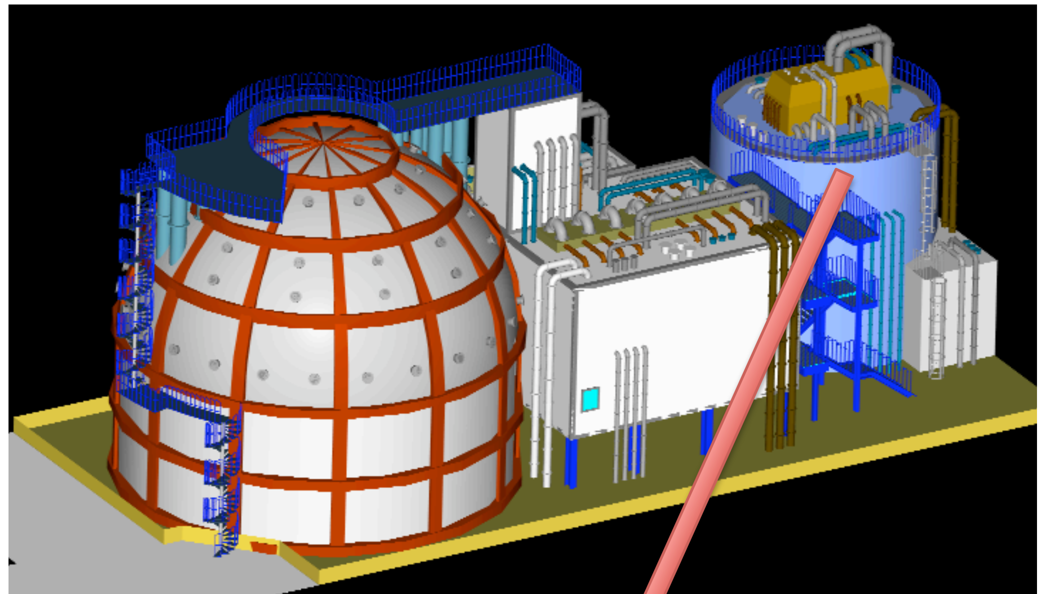


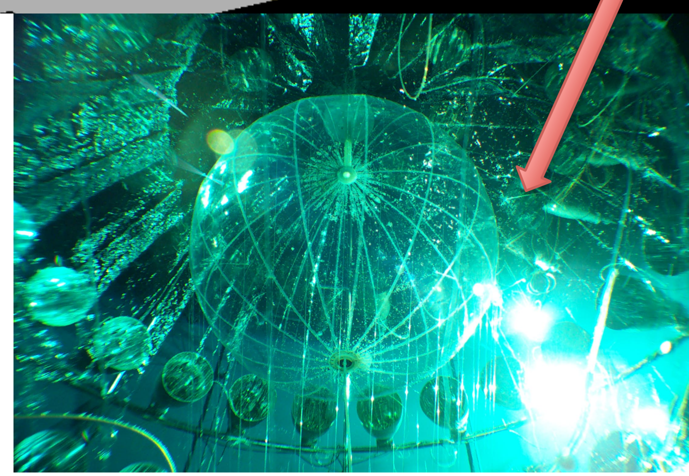




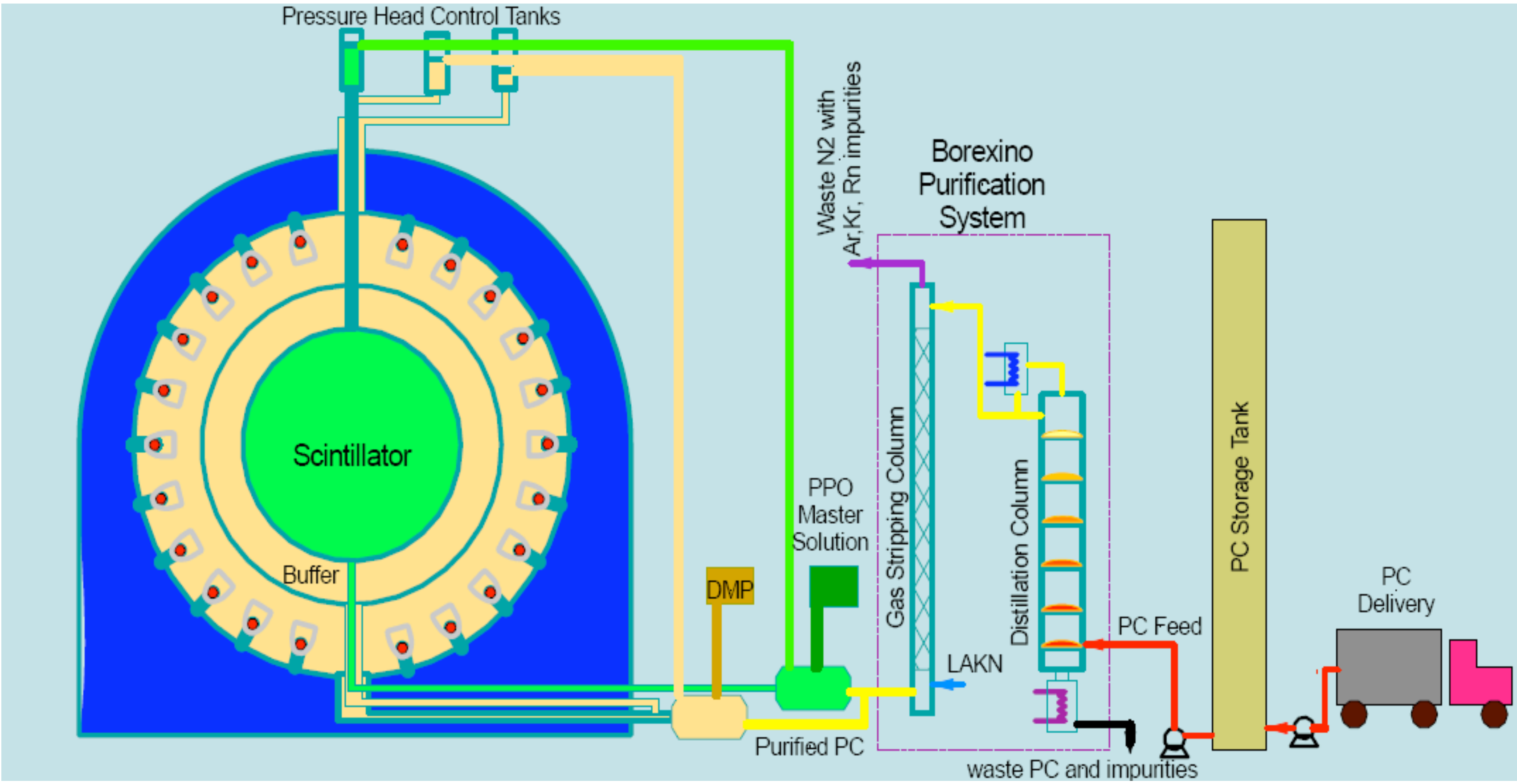
BOREXINO Ancillary Facilities

- **Counting Test Facility**
- **Purification plants** for PC
    - distillation column
    - water extraction column
    - stripping column
- Purification plant for Master Solution
    - Steering water extraction
    - Distillation column
    - Stripping column
- Filling stations
- Loading/Unloading plant





BOREXINO Filling Strategy



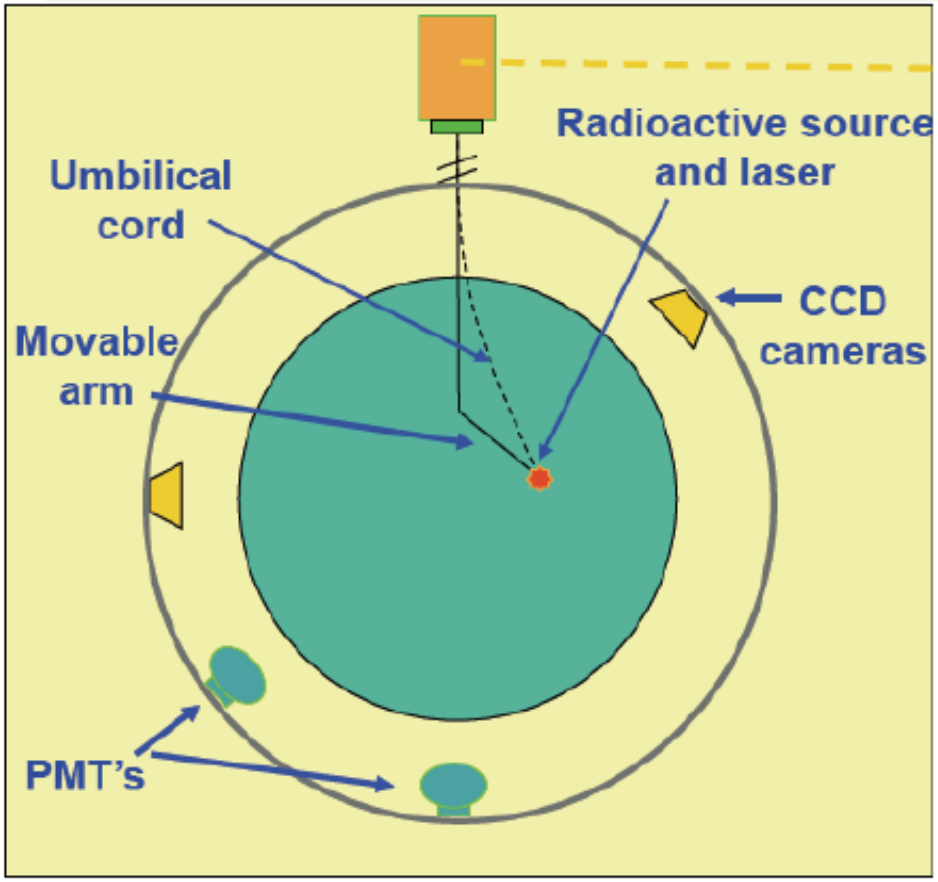
What do we measure?

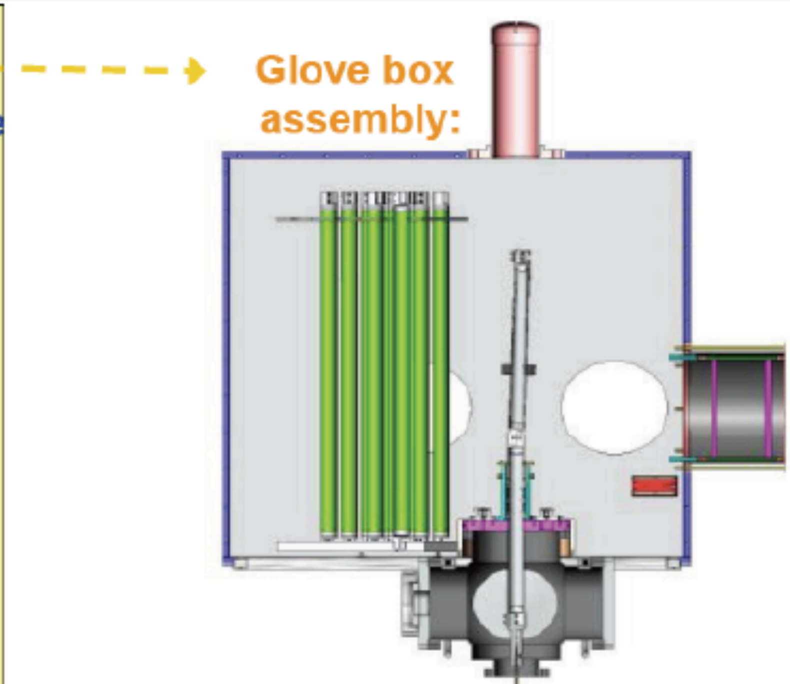
- **Timing**: time distribution of hit PMTs
  - This define the vertex position of scintillation signals
- **Energy**: calorimetric measurement of energy released by neutrinos or backgrounds

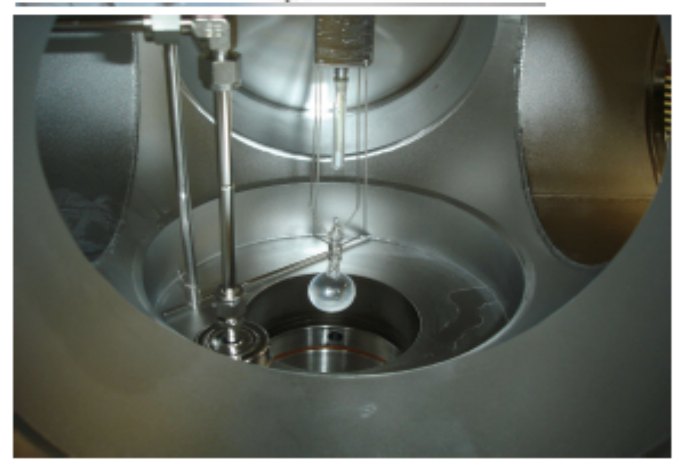
Muons detection

- Muons are identified by
  - the outer (Cherenkov light) 99.5% eff.
  - the inner detector (pulse shape analysis) ≥99.9% eff
- Muons can produce neutrons and cosmogenic radioactive isotopes on ^{12}C
- Muon rate in BOREXINO: ~0.05μ/s

Calibration system







Calibration measurements

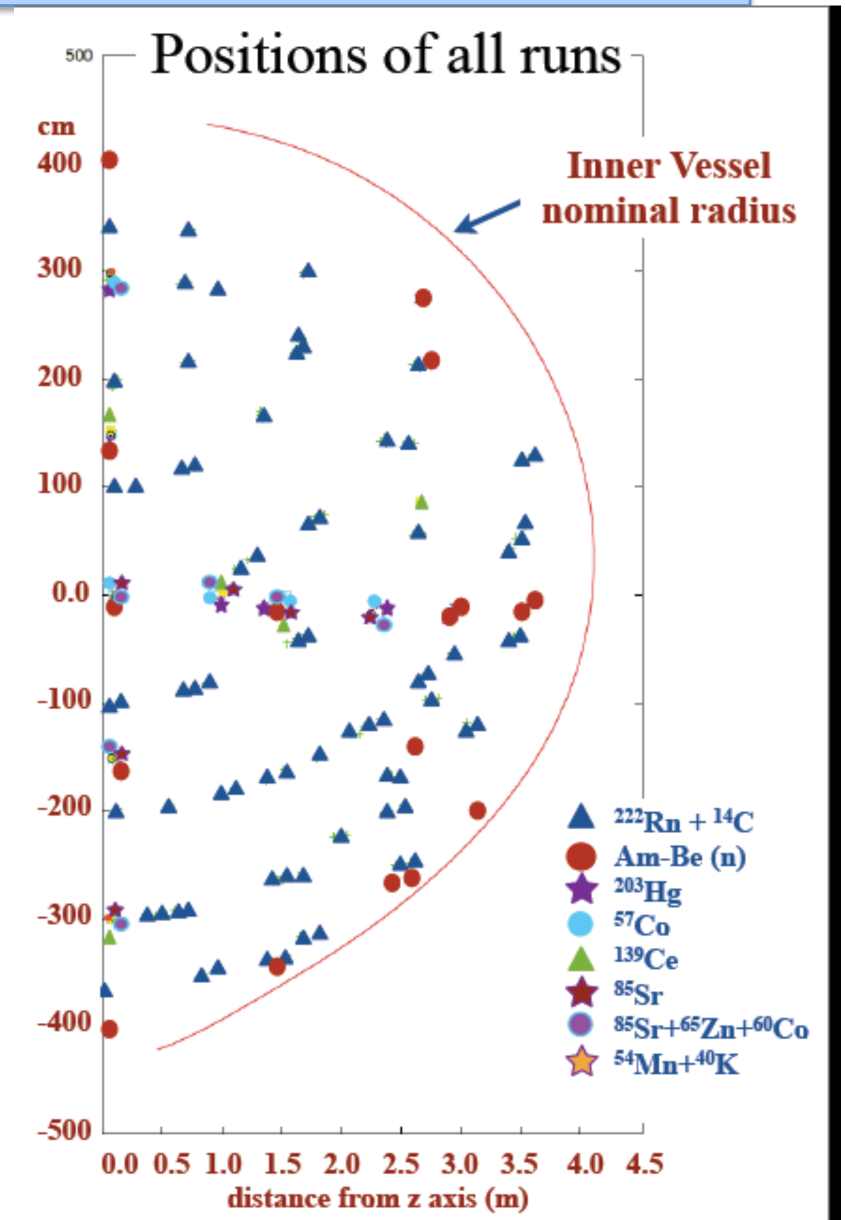
Three calibration campaigns with

- α, β,γ and n sources
- One external ^{208}Tl source

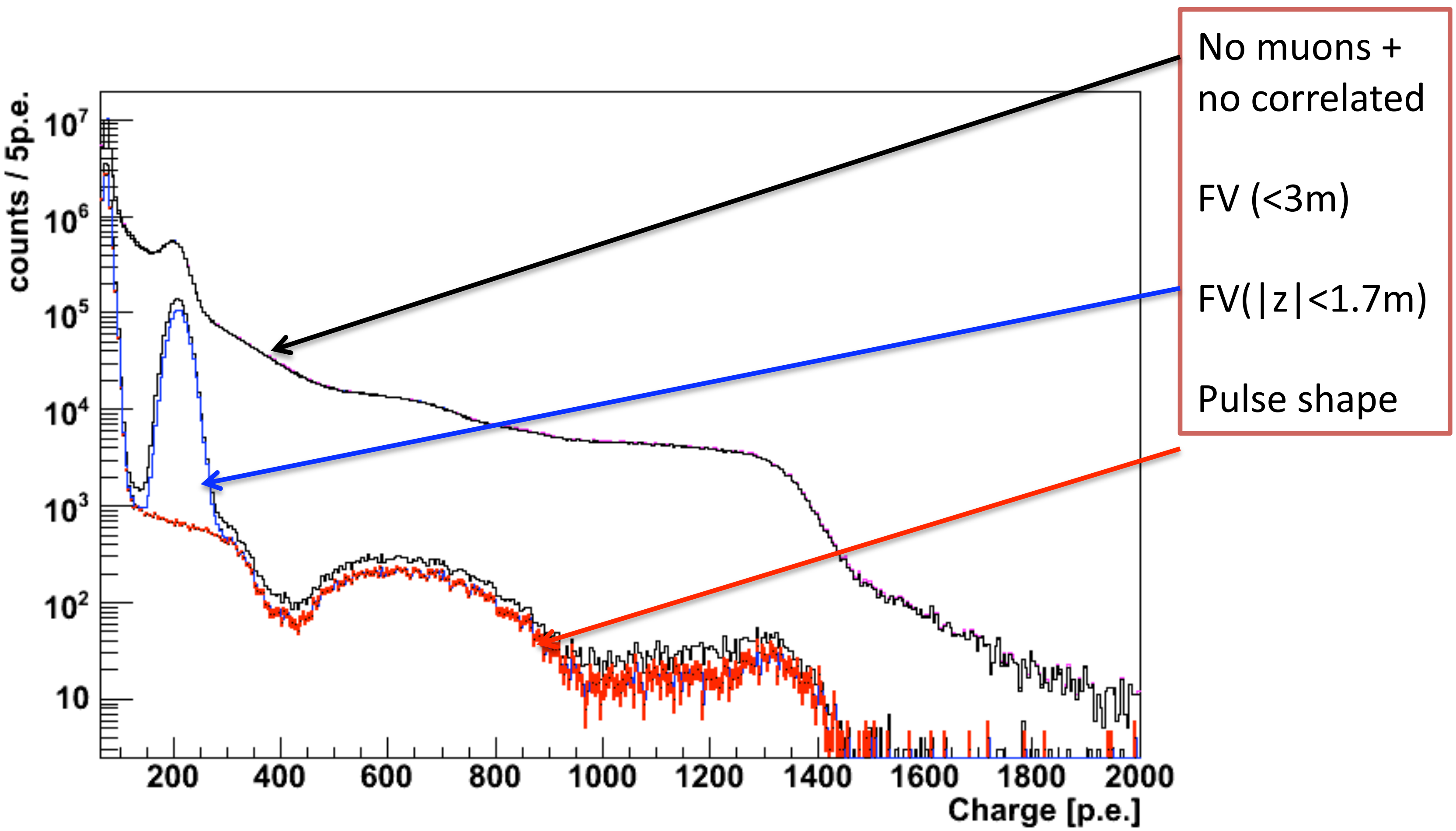
Source deployed on-axis and off-axis

Careful study of:

- Scintillator light response
- Energy scale 2-3% in FV
- Position reconstruction algorithm 2% in FV



Data reduction



Solar Neutrinos

Looking at the Sun through neutrinos

- The Sun shines by burning H fuel

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + (24.69 + 2\cdot 1.022)\,MeV$$

- Electroweak processes in the core of the Sun produce **electron neutrinos**

- Neutrinos time scale ~ 500

- Photons time scale takes ~10^4-10^5 yr to reach the surface

Solar Neutrinos Sources: pp chain

$$p + p \rightarrow d + e^{+} + \nu_e + 0.42\ \text{MeV}$$

$$p + e^{-} + p \rightarrow d + \nu_e + 1.442\ \text{MeV}$$

~0.4%

$$p + d \rightarrow {}^{3}He + \gamma + 5.494\ \text{MeV}$$

~85%

S_{33}

$$ {}^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p + 12.860\ \text{MeV}$$

~15%

S_{34}

$$ {}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma + 1.586\ \text{MeV}$$

$$ {}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e + 0.862\ \text{MeV}$$

$$ {}^{7}Li + p \rightarrow 2\,{}^{4}He + 17.347\ \text{MeV}$$

~0.02%

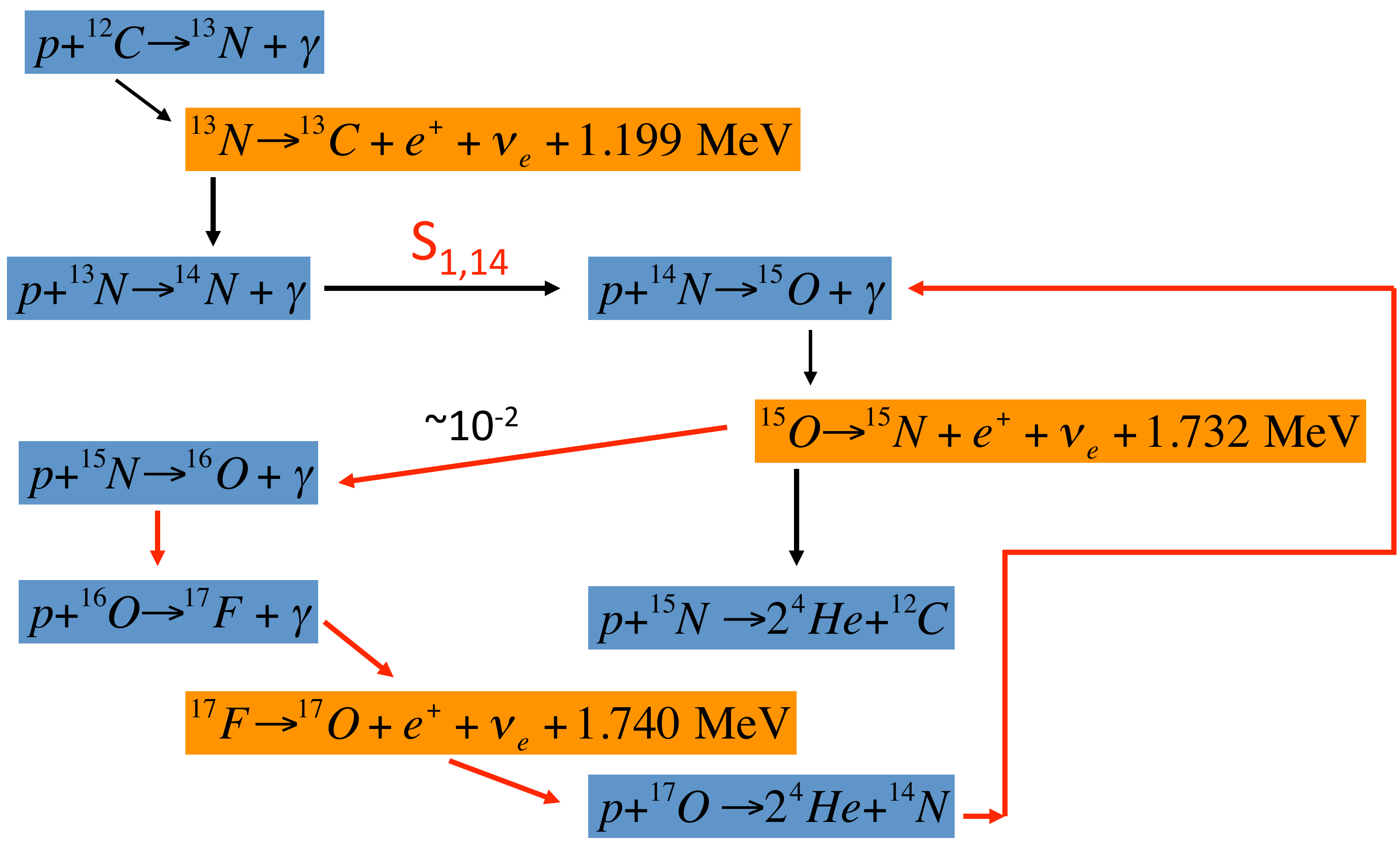
$$ {}^{7}Be + p \rightarrow {}^{8}B + \gamma + 0.137\ \text{MeV}$$

$$ {}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e + 15.04\ \text{MeV}$$

$$ {}^{8}Be^{*} \rightarrow 2\,{}^{4}He + 3.03\ \text{MeV}$$

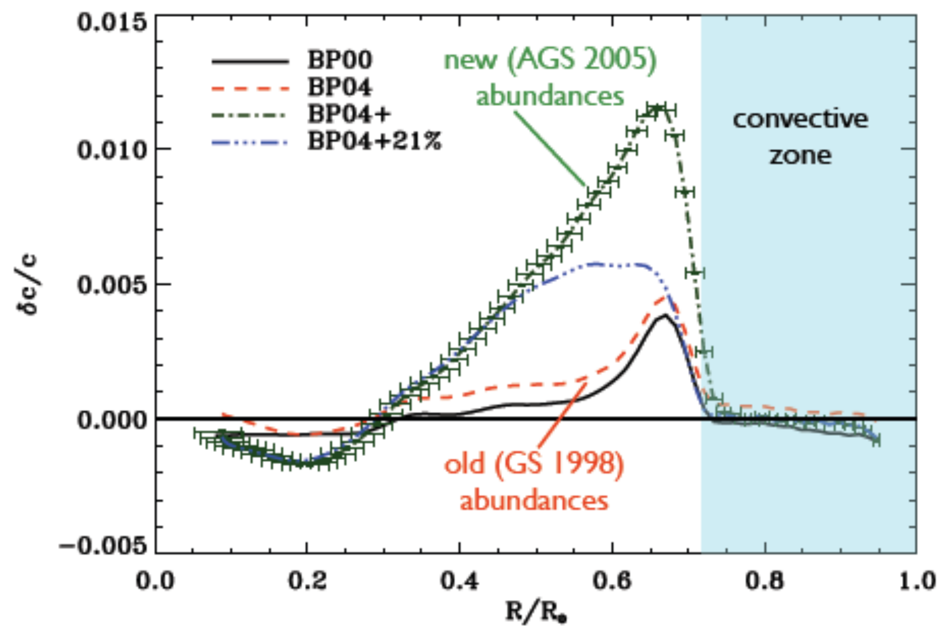
See C. Broggini at this meeting for details on astrophysical factors measurements in LUNA

Solar Neutrinos Sources: CNO chain

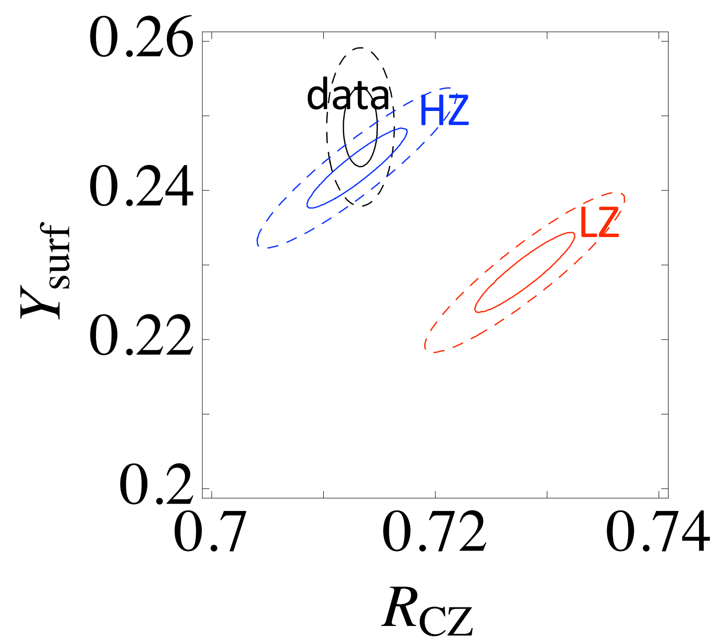


Solar Standard Model conflict with helioseismology

Neutrino predictions come from the SSM. However, recently a large disagreement With some observations has been found

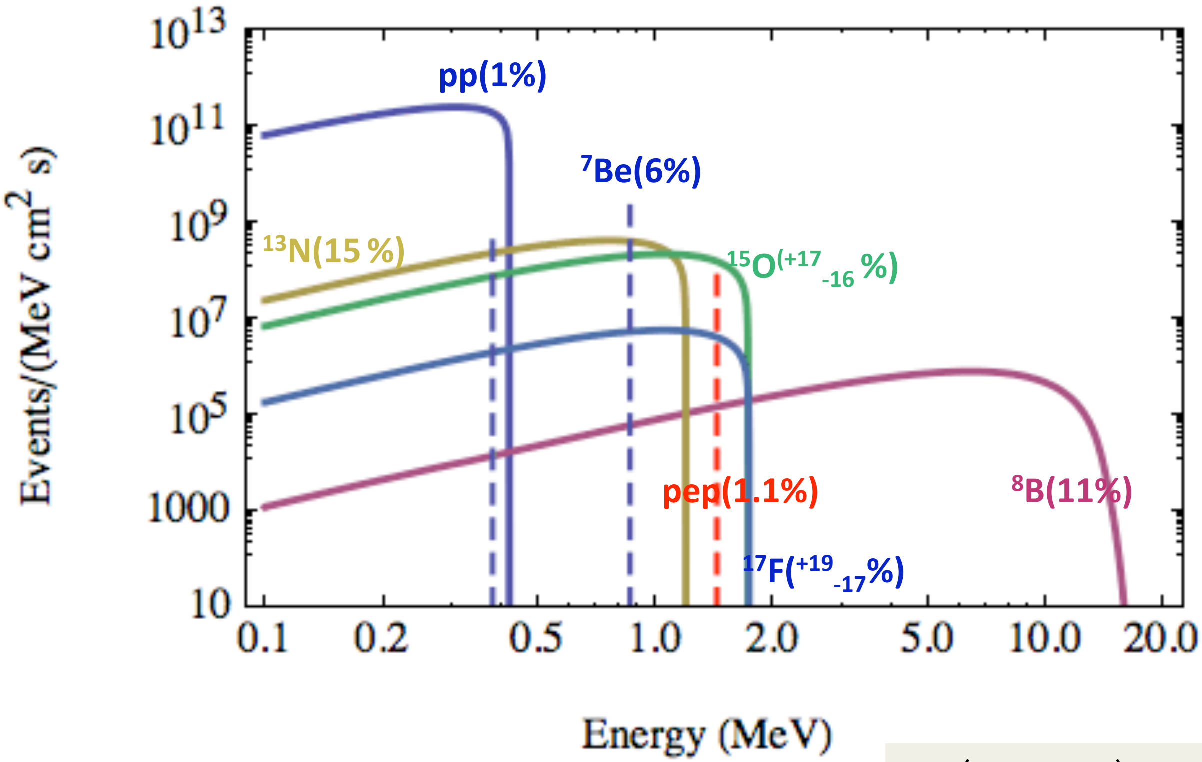


Taken from W. Haxton and A. Serenelli, arXiV:0902.0036



Conflict might be due to some wrong basic assumption in the SSM

Solar Neutrino Spectrum - BPS08(HZ)



$$\phi_{Be} \propto S_{33}^{-0.43} S_{34}^{+0.86} (Z/X)^{+0.62} Op^{-1.49} diff^{+0.69} L^{+3.40}$$

$$\phi_{B} \propto S_{33}^{-0.40} S_{34}^{+0.81} S_{17}^{+1.0} (Z/X)^{+1.36} Op^{-2.93} diff^{-2.20} L^{+6.76}$$

$$\phi_{pp} \propto S_{33}^{+0.03} S_{34}^{-0.06} (Z/X)^{-0.08} Op^{+0.14} diff^{+0.13} L^{+0.73}$$

$$\ln\left(\frac{\phi_i}{\phi_i^{SSM}}\right) = \sum_{j=1}^{k} \alpha_{ij} \ln\left(\frac{x_j}{x_j^0}\right)$$

k unknown parameters out of n>k

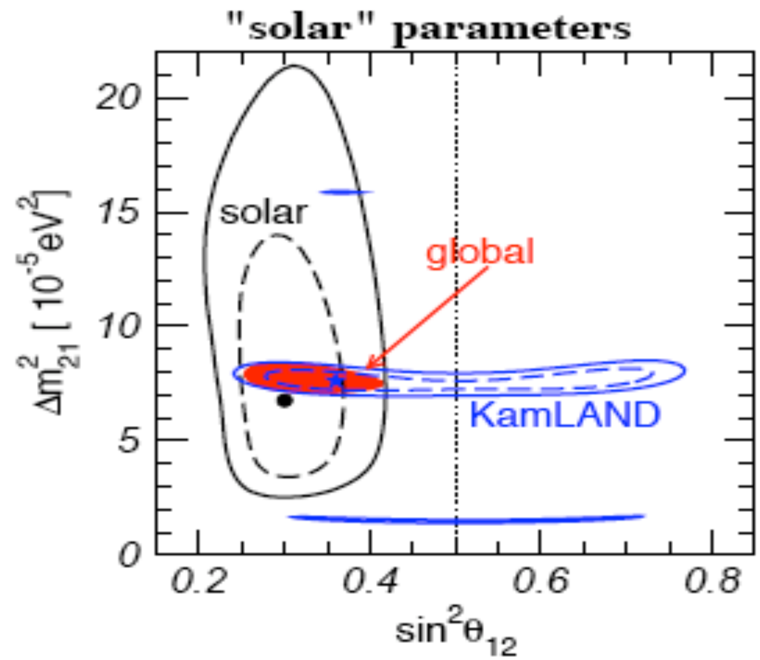
Solar Neutrino Measurements

Experiment	Sources contributing to rate	R_{exp} / R_{Th} [R_{exp}]
Homestake E_{th}=0.814 keV	^{7}Be(13.1%)+pep(2.7%)+ CNO(2.4%)+^{8}B(81.8%)	**0.31±0.03** CC [2.56±0.23 SNU*]
GALLEX/GNO/SAGE E_{th}=0.233 keV	pp(55%)+^{7}Be(28.3%)+ pep(2.3%)+ CNO(3.4%)+^{8}B(11%)	**0.53±0.05** CC [67.6±5.12 SNU]
Super-Kamiokande E_{th}=5 MeV	^{8}B(100%)	**0.451±0.017** ES
SNO E_{th}=5 keV	^{8}B(100%)	**0.28±0.01** CC 0.88±0.05 NC
BOREXINO E_{th}=0.2 keV	^{7}Be(100%)	**0.65±0.07** ES [49±5 cpd/100ton]

* 1SNU = 10^{-36} s^{-1}

Solar Neutrinos + Reactor Neutrinos global fit

Oscil. parameters	Best-fit [10^{-5} eV^2]	3σ
δm_{12}^2	7.6	7.1-8.3
$\sin^2\theta_{12}$	0.32	0.26-0.4



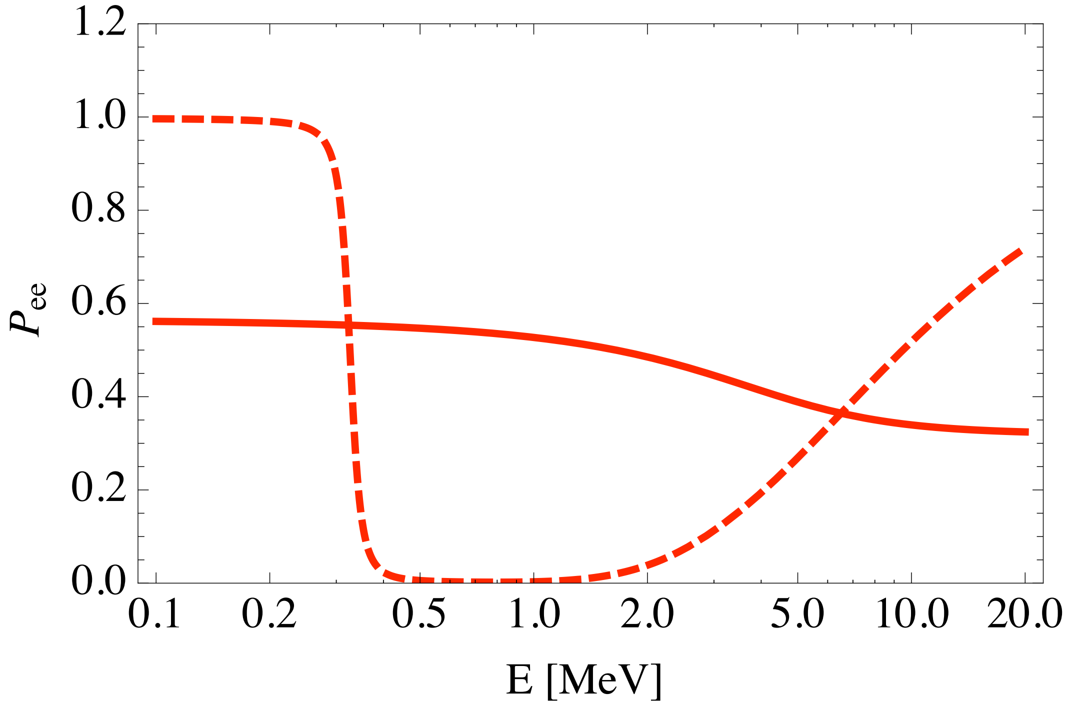
Why do we study solar neutrinos today?

- Probe neutrino propagation properties through high density matter
- Probe the physics of stars
  - – Neutrinos vs photons luminosity
  - – pp vs CNO contribution to solar energy
    - SSM CNO predicts <1%
  - – Metallicity, opacity and other properties

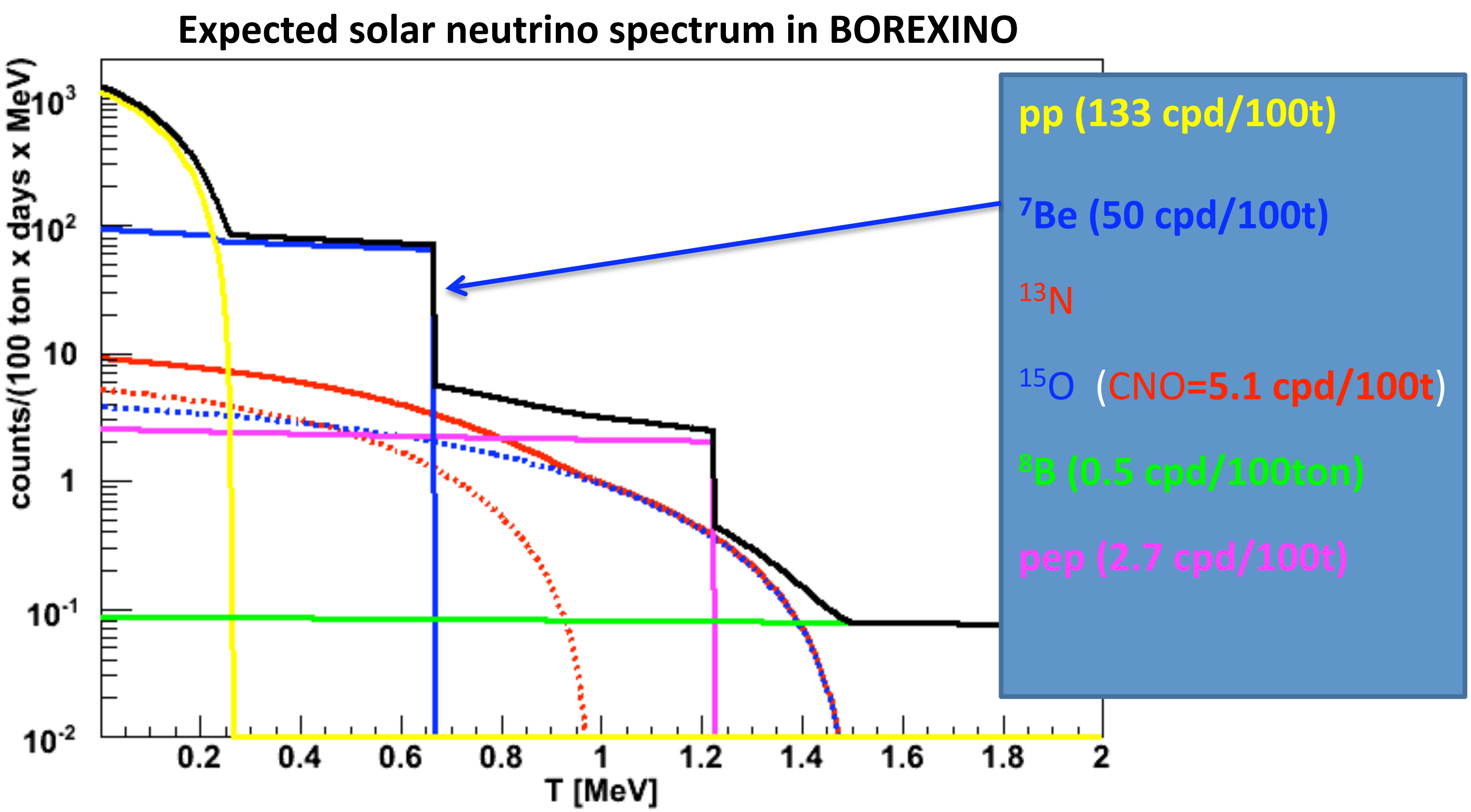
Survival probability for solar neutrinos inside the Sun

Solid line: $\sin^2 2\theta = 0.87$ and $\Delta m^2 = 7\times10^{-5}$ eV^2

Dashed line: $\sin^2 2\theta = 0.005$ and $\Delta m^2 = 5\times10^{-6}$ eV^2



Solar neutrino signal in BOREXINO



It is a matter of background

- **^{7}Be rate ~50 cpd/100ton**

- 1ppt ^{232}Th = 4.06×10^{-6} Bq/kg
- 1ppt ^{238}U = 12.4×10^{-6} Bq/kg

- Assuming 100% eff. for α/β discrimination and for removing correlated decays (Bi-Po fast $\beta-\alpha$ decays), one needs contaminations at the level of 10^{-16} g/g to have ~ 50 cpd/100ton from U and Th

- **S/B≈1 with a purity of ~10^{-4} μBq/kg**

Moreover,

- ^{85}Kr (Q_β=0.687MeV), ^{39}Ar(Q_β=0.565MeV), ^{210}Bi(Q_β=1.162MeV) at 1cpd/100tons will give 1.5 cpd/100tons in [0.25,0.8] MeV

Irreducible Background Sources

- ^{14}**C** (Q_β=0.156 MeV) : ≈7 Hz [0.1,0.2]MeV
- **Cosmogenic** [see *T. Hagner et al. Astrop. Phys. 14 (2000) 33*]

Radioactive isotopes which are produced by muons and their secondary shower particles when passing through a scintillator (^{12}C) target[a]

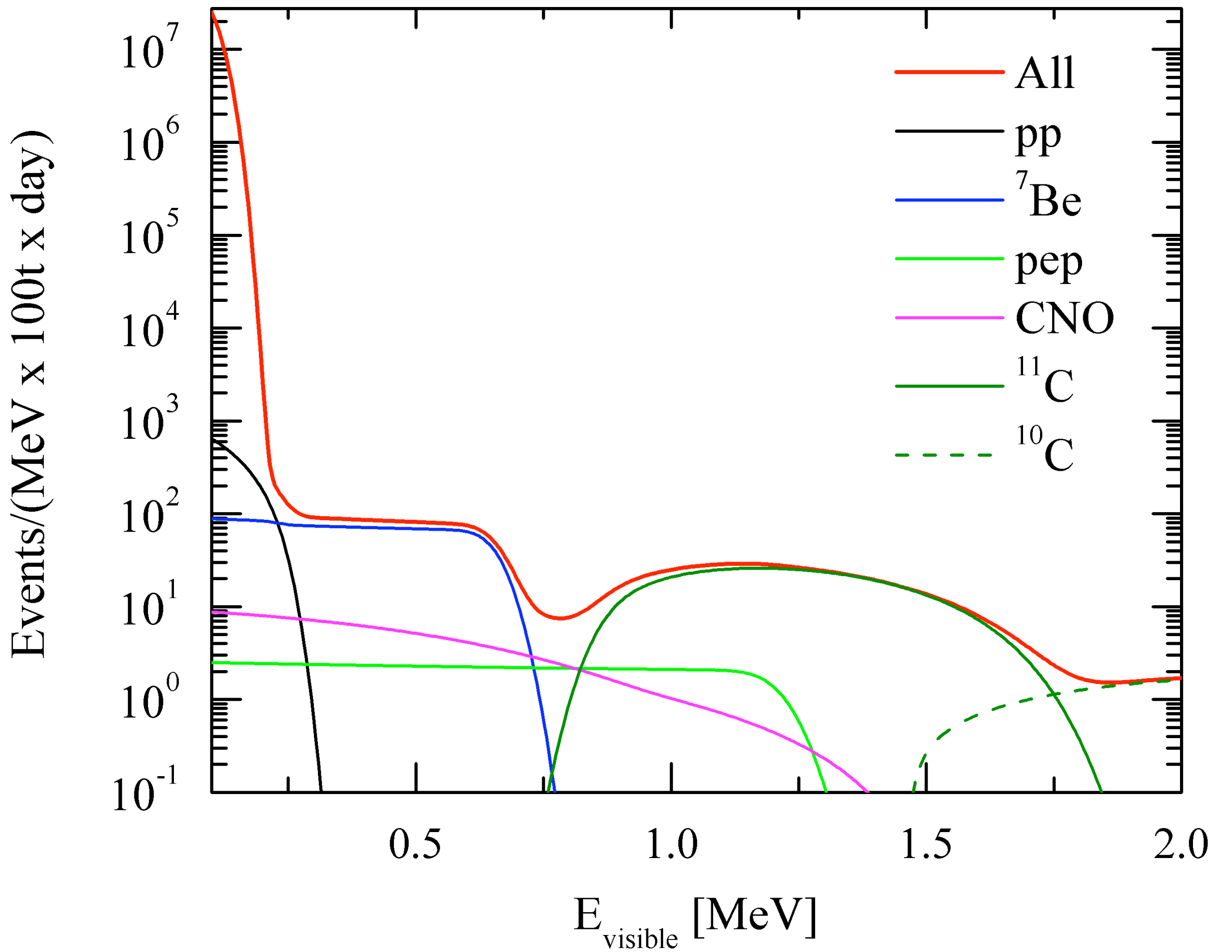
	Isotopes	$T_{1/2}$	E_{max} (MeV)
β^-	^{12}B	0.02 s	13.4 (β^-)
	^{11}Be	13.80 s	11.5 (β^-)
	^{11}Li	0.09 s	20.8 (β^-)
	^{9}Li	0.18 s	13.6 (β^-)
	^{8}Li	0.84 s	16.0 (β^-)
	^{8}He	0.12 s	10.6 (β^-)
	^{6}He	0.81 s	3.5 (β^-)
β^+, EC	^{11}C	20.38 min	0.96 (β^+)
	^{10}C	19.30 s	1.9 (β^+) (+0.72 MeV γ, 98.53%)
	^{9}C	0.13 s	16.0 (β^+)
	^{8}B	0.77 s	13.7 (β^+)
	^{7}Be	53.3 d	0.478 (γ, 10%)

[a] Of particular relevance for BOREXINO are the isotopes ^{7}Be, ^{11}C, ^{10}C and ^{11}Be. Radio unstable isotopes which emit β-neutron cascades as ^{8}He, ^{9}Li and ^{11}Li are important for anti-neutrino spectroscopy.

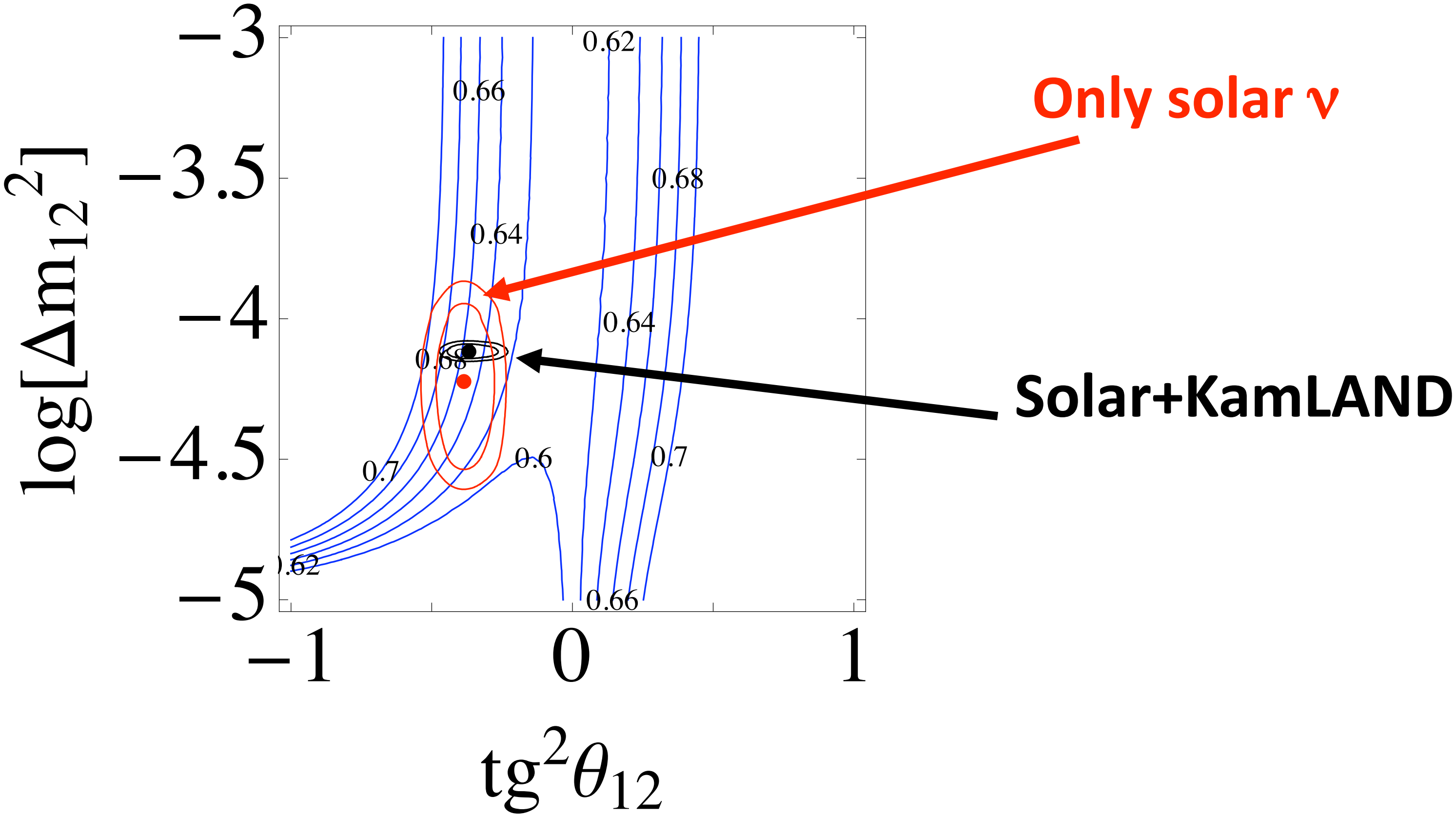
Isotopes	σ in μbarn for E_μ (GeV)
	100
^{11}C	576 ± 45
^{7}Be	127 ± 13
^{11}Be	<1.22 (68% CL)
^{10}C	77.4 ± 4.9
^{8}Li	2.93 ± 0.80
^{6}He	10.15 ± 1.0
^{8}B	4.16 ± 0.81
^{9}C	
$^{9}Li + {}^{8}He$	

Borexino Expected Solar ν Spectrum

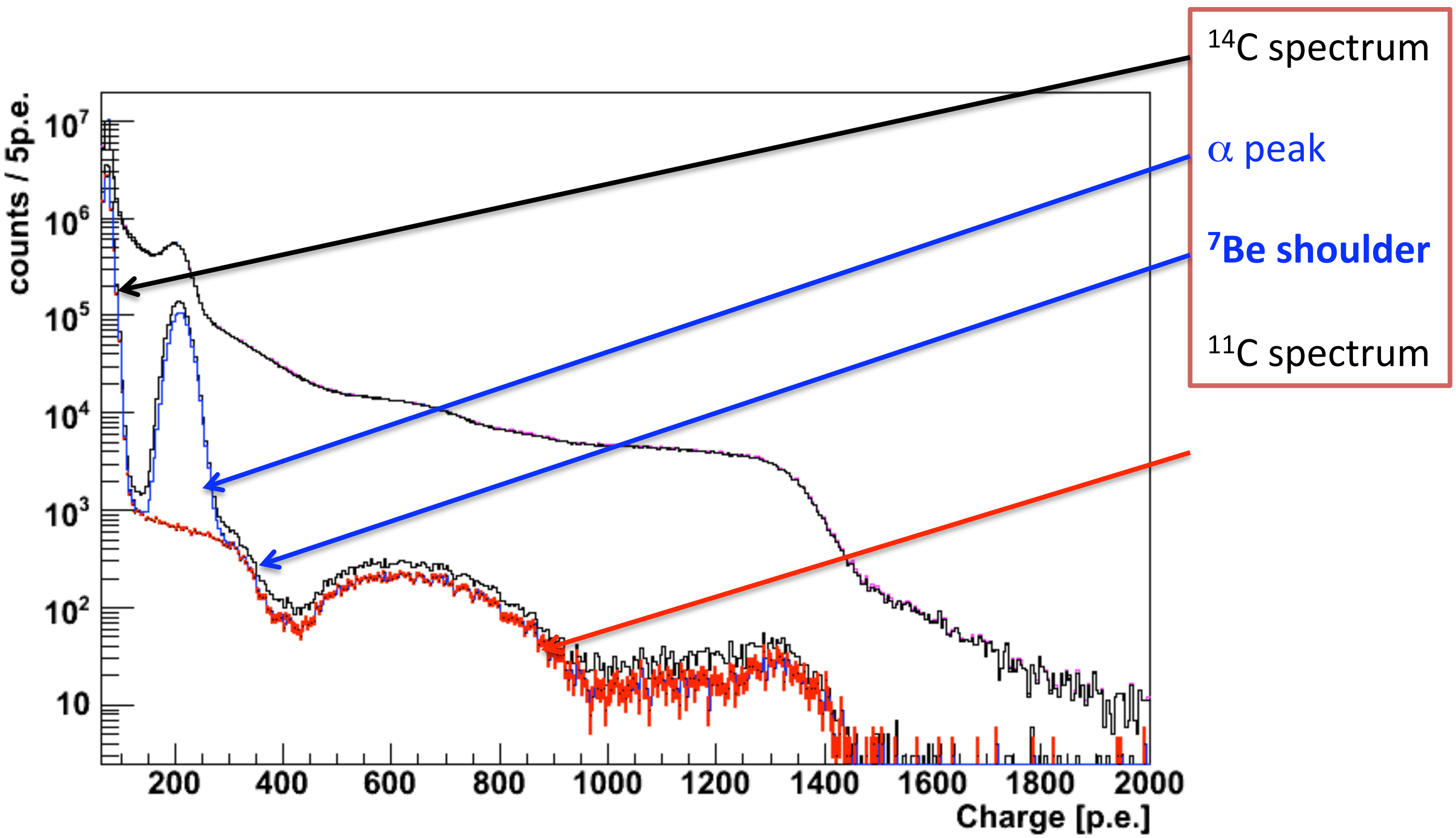
Spectrum with irreducible backgrounds



$R_{7Be}(\Delta m_{12}^2, \theta_{12}) / R_{7Be}^{SSM}$

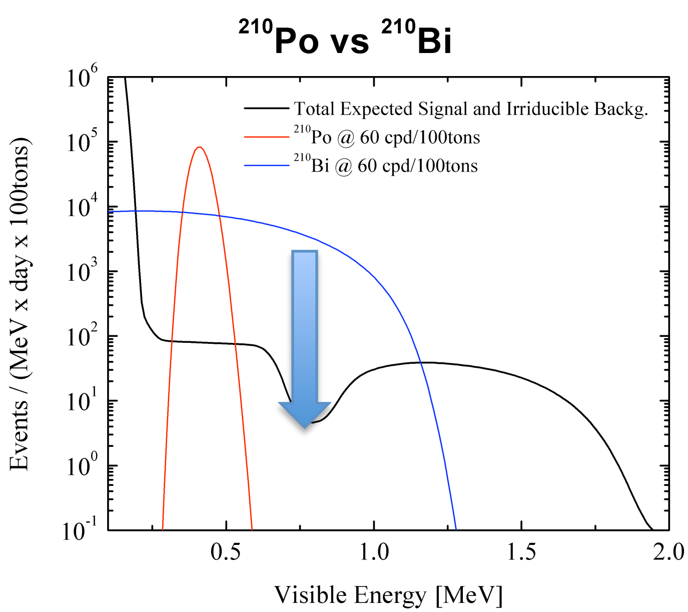


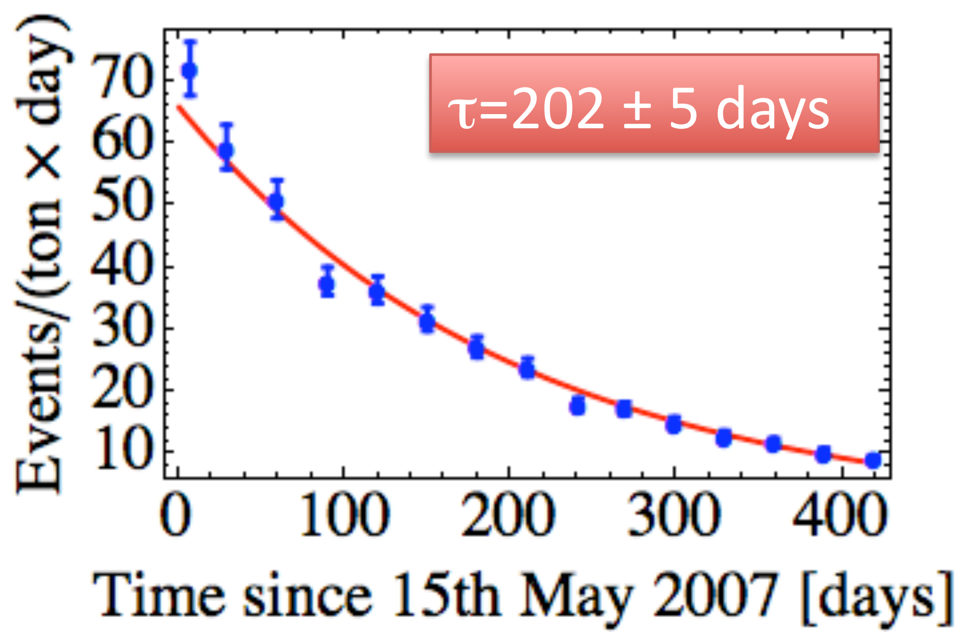
Some features of the observed spectrum



^{210}Po in Borexino

- Chain: ^{210}Pb(β;τ=32yr) ->^{210}Po(α;τ=199.6days)->^{210}Bi
- ^{210}Po not in equilibrium
- not clear origin (PPO, particulate etc)





Measurement of ^{7}Be solar neutrinos

Free parameters:
LY, ^{7}Be, ^{11}C, ^{85}Kr, CNO+^{210}Bi, ^{210}Po

^{7}Be : 49 ± 3_{stat} ± 4_{sys} cpd/100tons

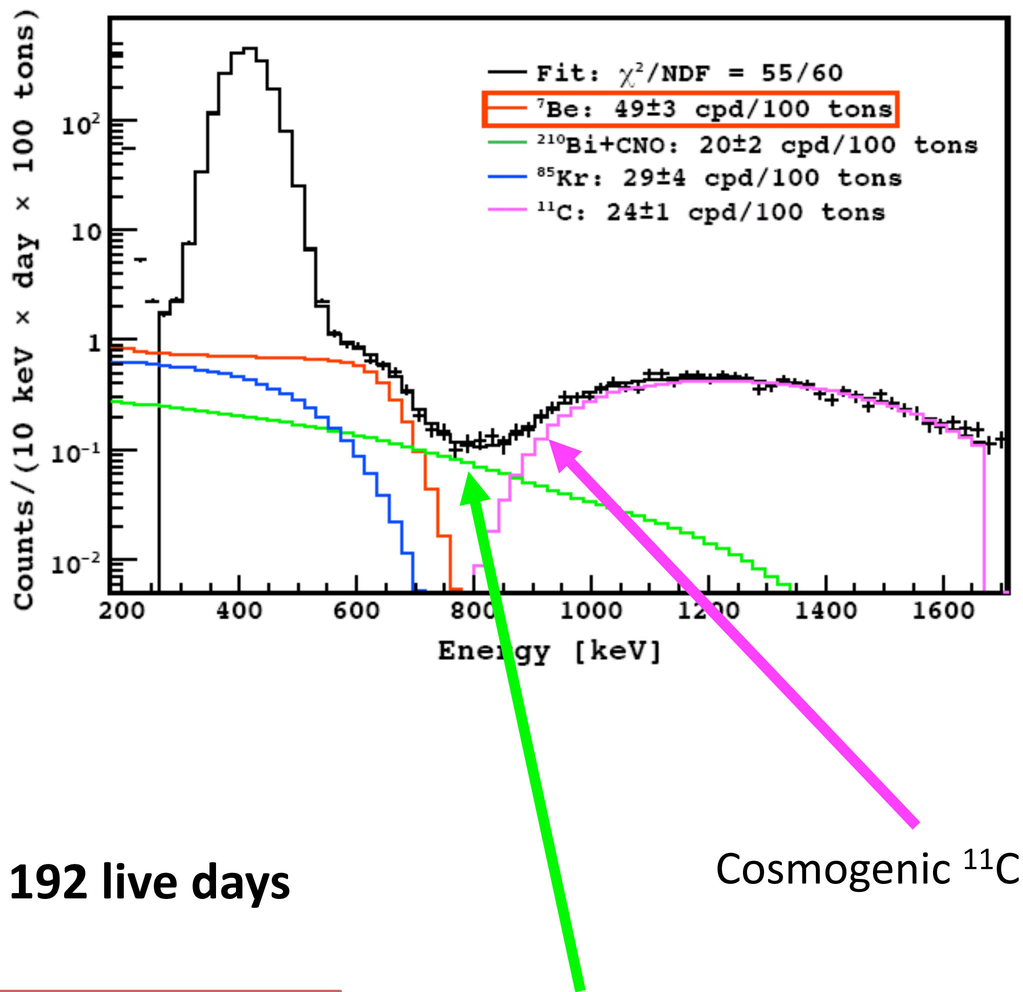
Systematics: 6% energy scale, 6% Fiducial Volume

No oscillation hypothesis rejected at 4σ

^{11}C : measured/expected ≈ 1.6

^{85}Kr : consistent with delayed coincidences meas.

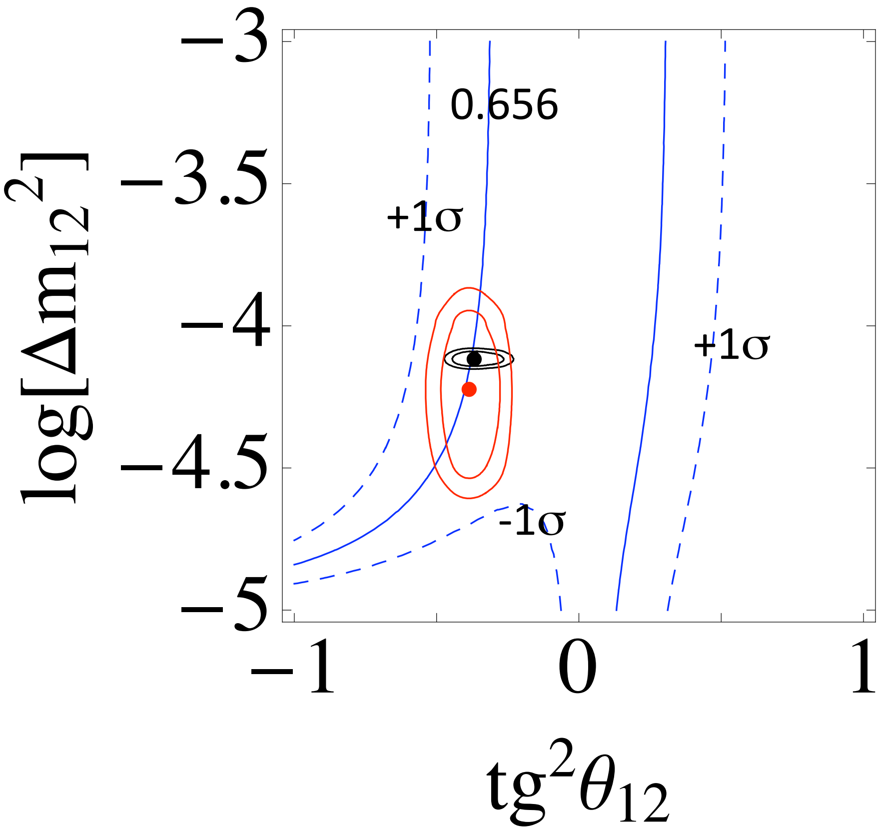
^{210}Bi+CNO/CNO ≈ 4



192 live days

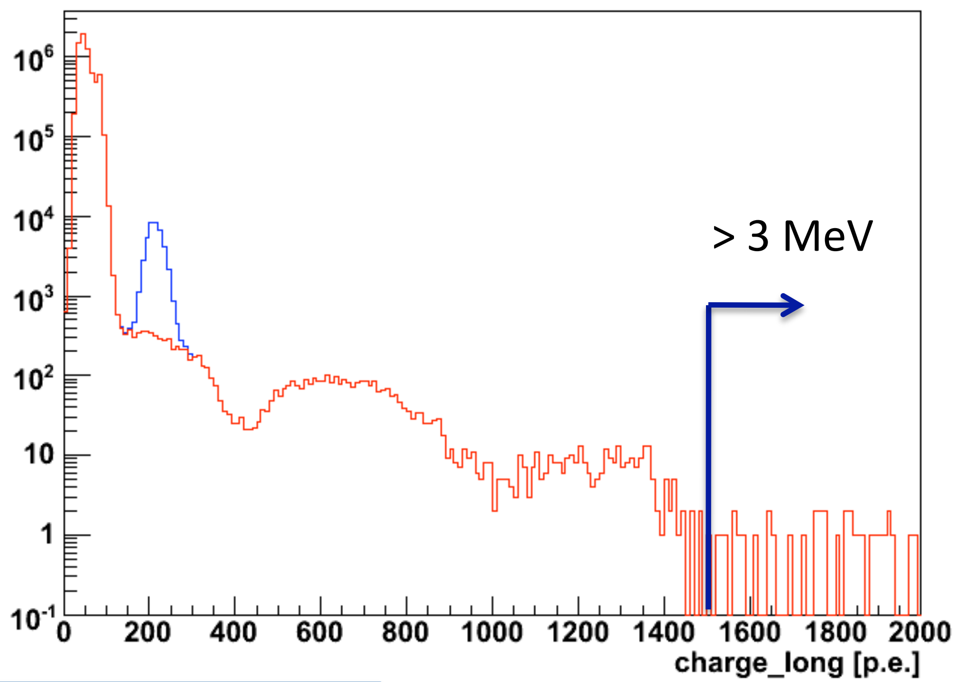
$$\Phi(^{7}Be) = (5.18 \pm 0.51) \times 10^{9}\ cm^{-2}\ s^{-1}$$

$R_{7Be}^{Borexino}/R_{7Be}^{SSM}$



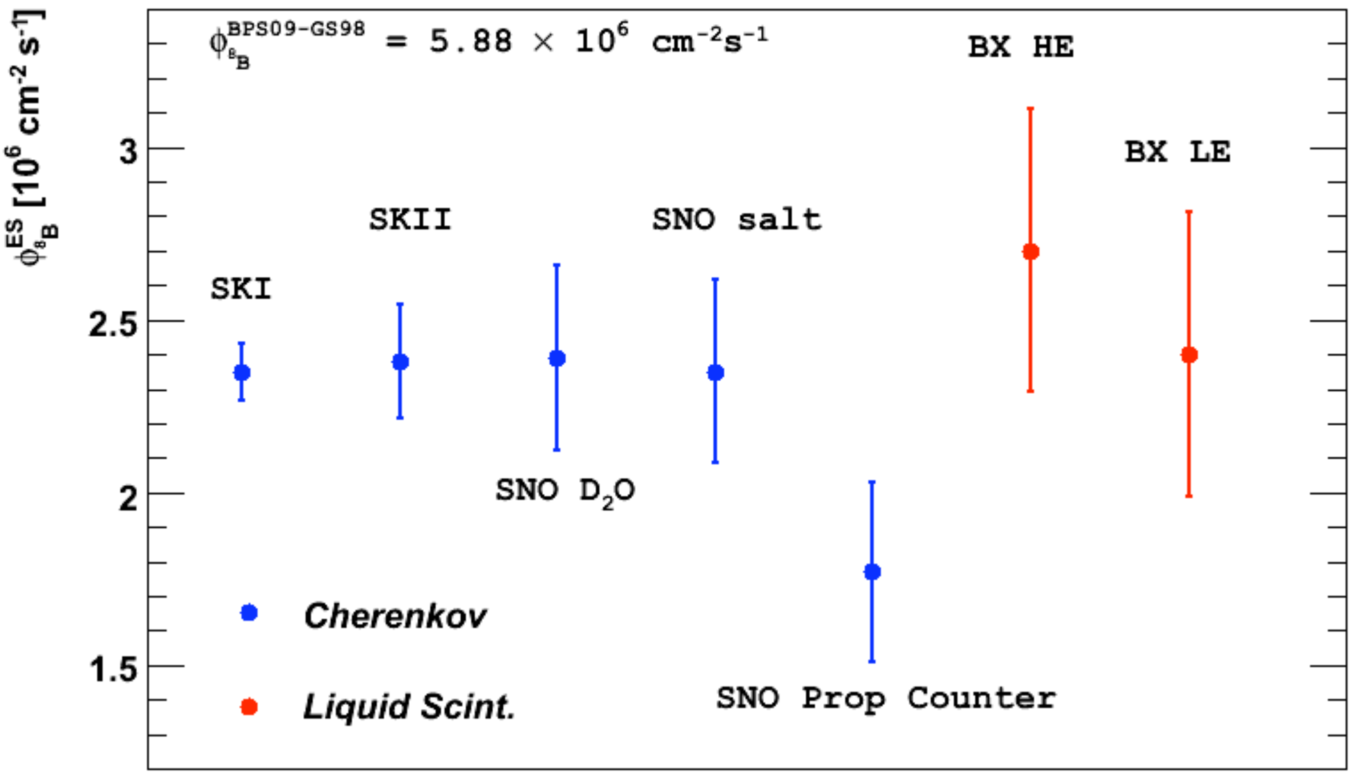
^{8}B neutrinos in Borexino

- Measure ^{8}B neutrino spectrum on ES interactions in 100 tons FM above 3 MeV

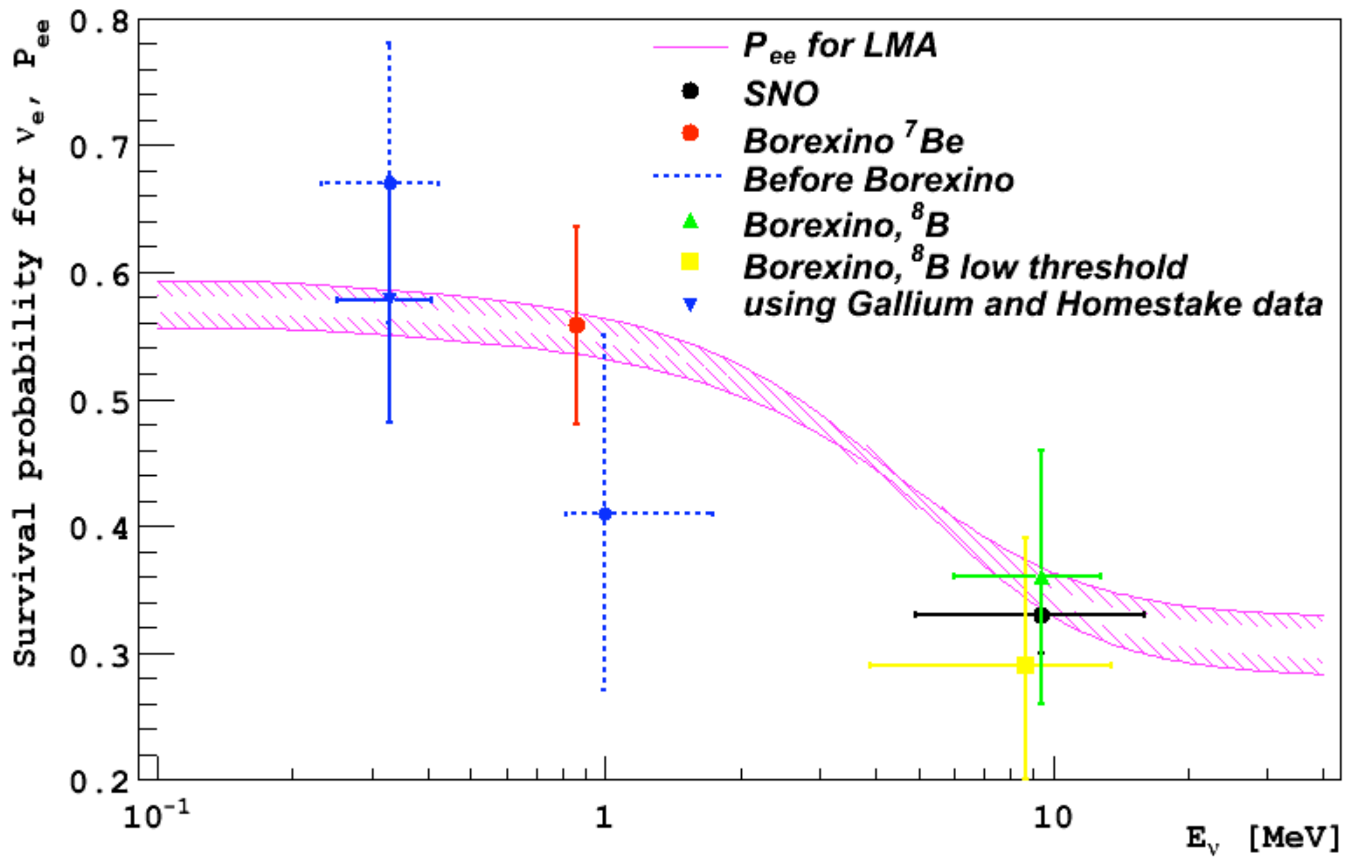


For details see M. Buizza at this meeting

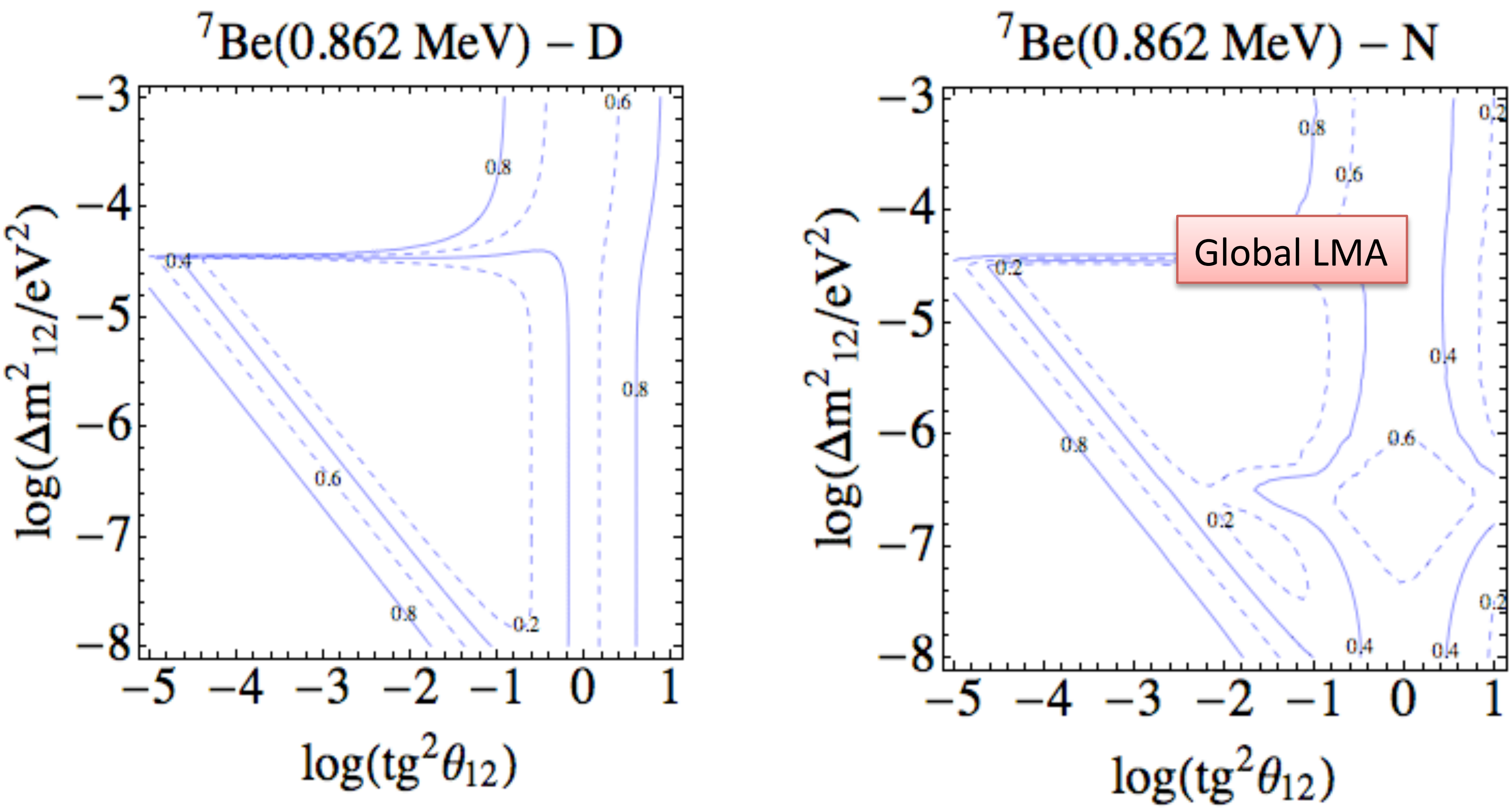
^{8}B solar neutrino measurements



Measurement of the Electron Neutrino Survival probability

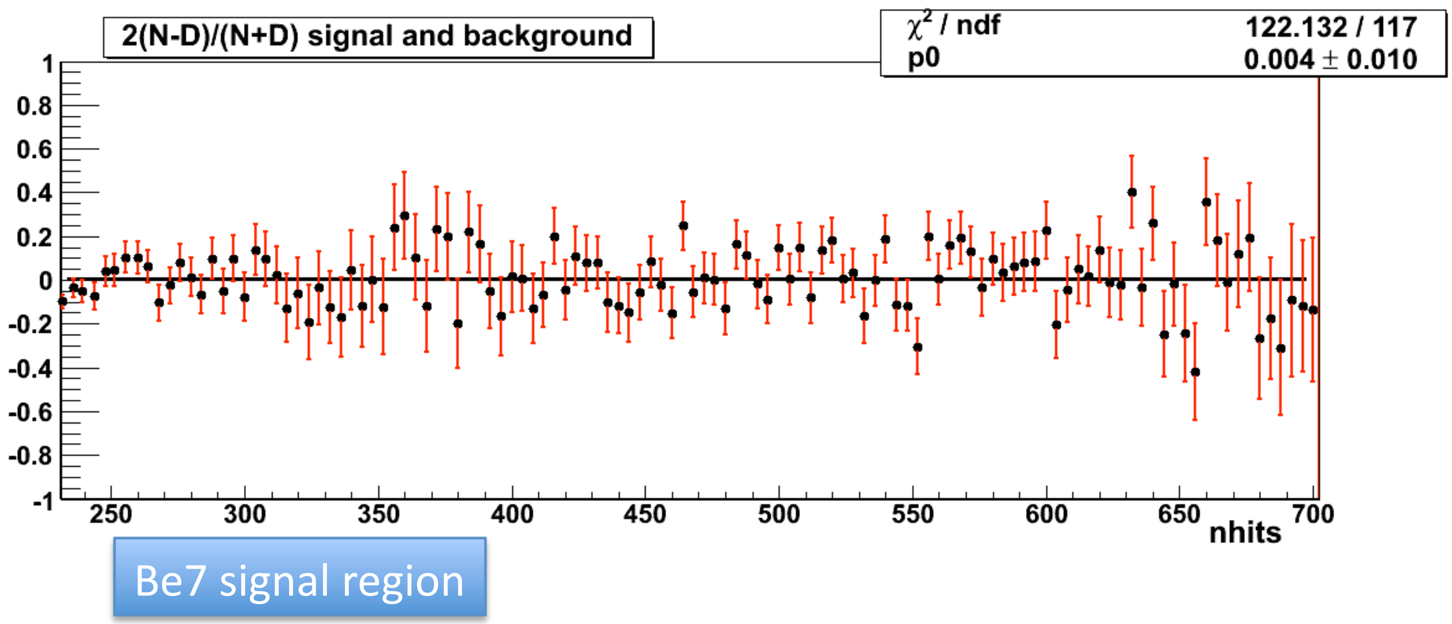


Day-Night regeneration



Day-Night asymmetry for ^{7}Be rate

$$ADN = \frac{N - D}{(N + D)/2} = 0.007 \pm 0.073\,(stat)$$



For more details see M. Buizza at this meeting

Probing the energy generation: SSM w/o the luminosity constraint

- **Before Borexino**:
  - $f_{pp}=1.34^{+0.25}_{-0.38}$
  - $f_{Be}=0.28^{+0.74}_{-0.28}$ w/ CNO fixed
  - $f_{Be}=0.18^{+1.0}_{-0.18}$
  - $L_{\nu}/L_{sun}=1.3\pm0.3$
- **After Borexino**:
  - $f_{Be}=1.02\pm0.10$
  - $f_{pp}=1.04^{+0.16}_{-0.19}$
  - $L_{CNO} < 8\%$ (3σ)
  - $L_{\nu}/L_{sun}=1.0\pm0.2$

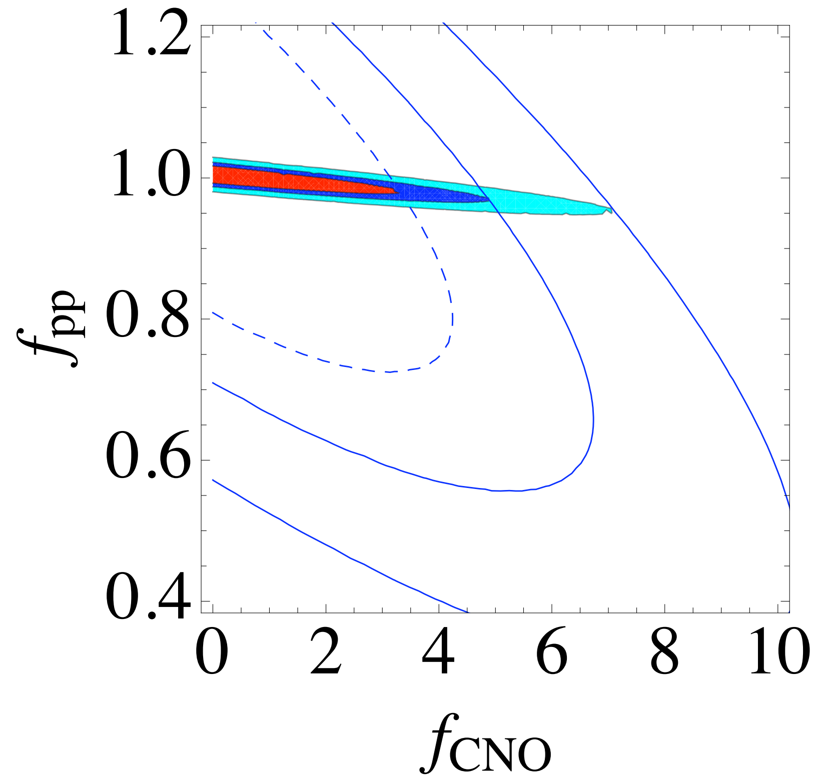
f_{Be} poorly determined

Probing the SSM w/ the luminosity constraint

After Borexino:

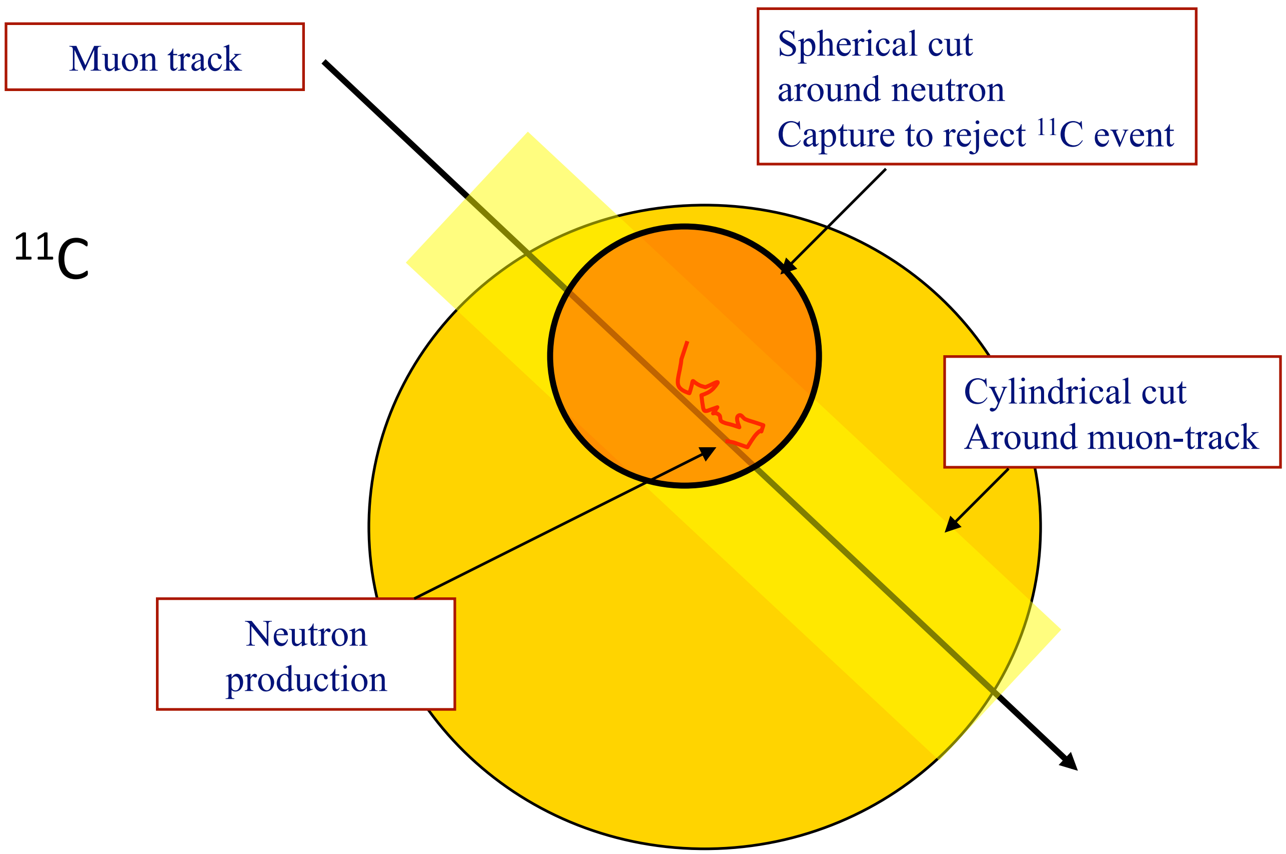
$f_{pp}=1.005^{+0.008}_{-0.017}$

$L_{CNO} < 6\% \ (3\sigma)$



Tagging pep/CNO neutrinos

Need to reduce ^{11}C background



Borexino coll: CNO and pep neutrino spectroscopy in Borexino: measurement of the deep-underground production of cosmogenic ^{11}C in an organic liquid scintillator,
Phys. Rev. C 74, 045805 (2006).

Electron anti-neutrinos

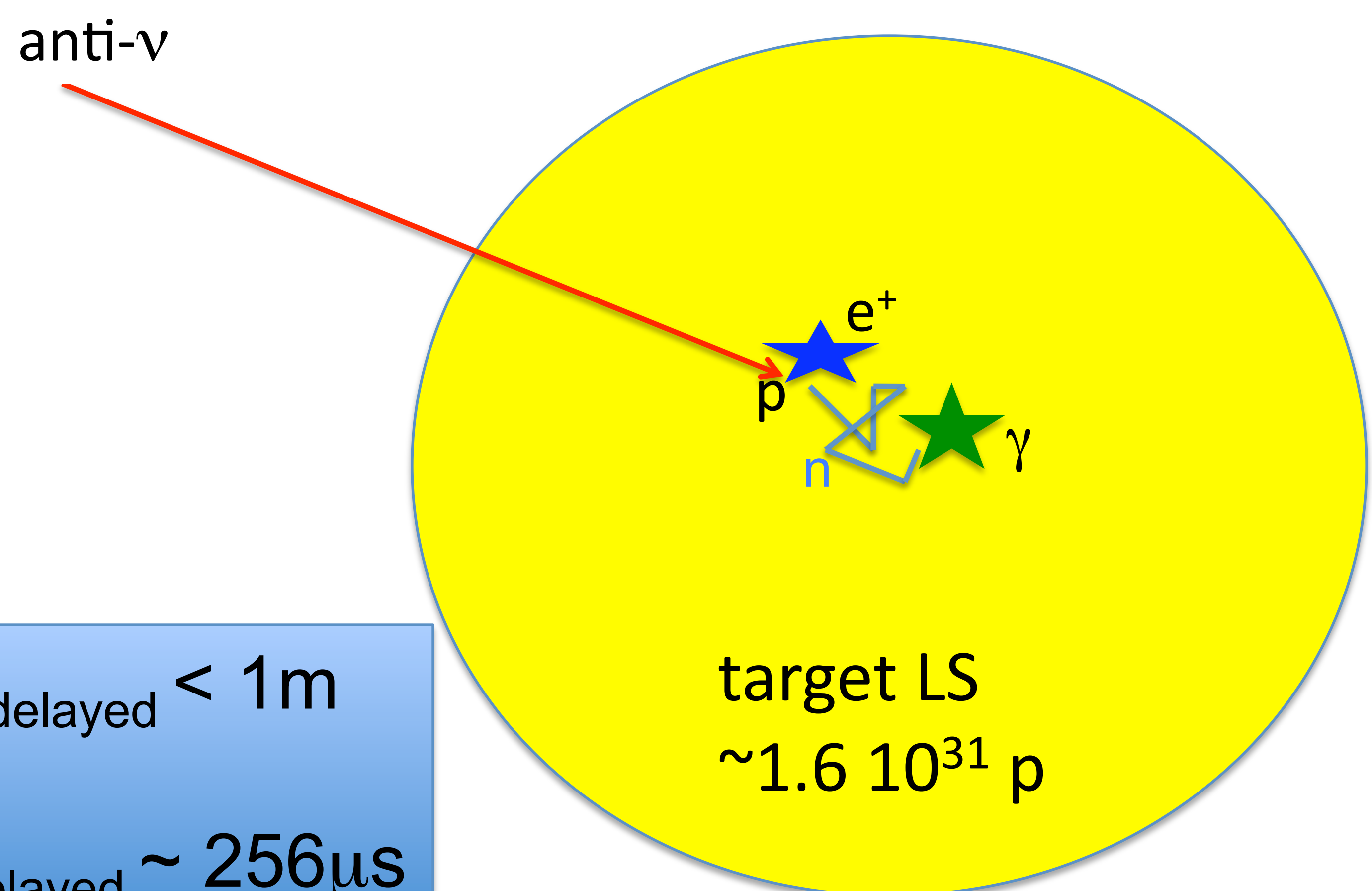
The Earth shines in electron anti-neutrinos (geo-ν)

Decay	E_{max} [MeV]	Q [MeV]	Q - $\langle E_\nu \rangle$ [MeV]	$kg^{-1}\ s^{-1}$	$W\ kg^{-1}$
$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 6e^- + \mathbf{6\bar{\nu}_e}$	**3.25**	51.7	47.7	7.41×10^{7}	0.94×10^{-4}
$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + \mathbf{4\bar{\nu}_e}$	**2.25**	42.7	40.4	1.62×10^{7}	0.26×10^{-4}
$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e$ (89%)	1.311	1.311	0.59	2.30×10^{8}	0.22×10^{-4}
$^{40}K + e \rightarrow {}^{40}Ar + e^- + \nu_e$ (11%)	0.044	1.505	1.461	0.28×10^{8}	0.67×10^{-5}

How many geo-ν?

We need to know how much U, Th and K on Earth

Topology of the anti-ν event



$\Delta R_{prompt\text{-}delayed} < 1m$

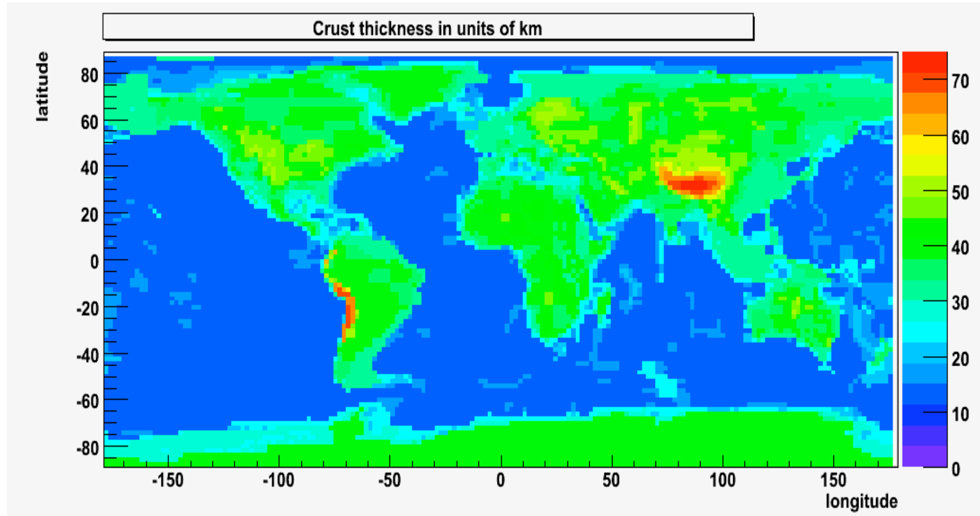
$\Delta t_{prompt\text{-}delayed} \sim 256\mu s$

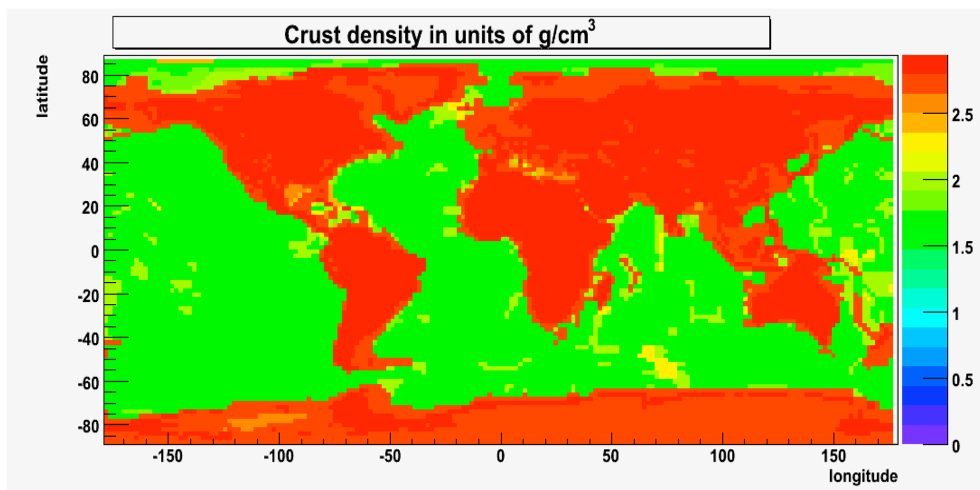
The Earth's Crust

- We know for a fact that the Crust contains **Heat Producing Elements (HPE)**
- Empirical determination of HPE abundances in the crust
- We use a 2°×2° mesh model with different layers (UC, MC, LC) CRUST 2.0 model

200 km scale

- $m_C(U) \sim 0.3\times10^{17}$ kg
- $L_\nu(U) \sim 2\times10^{24}$ s^{-1}
- $H_\nu(U) \sim 3$ TW





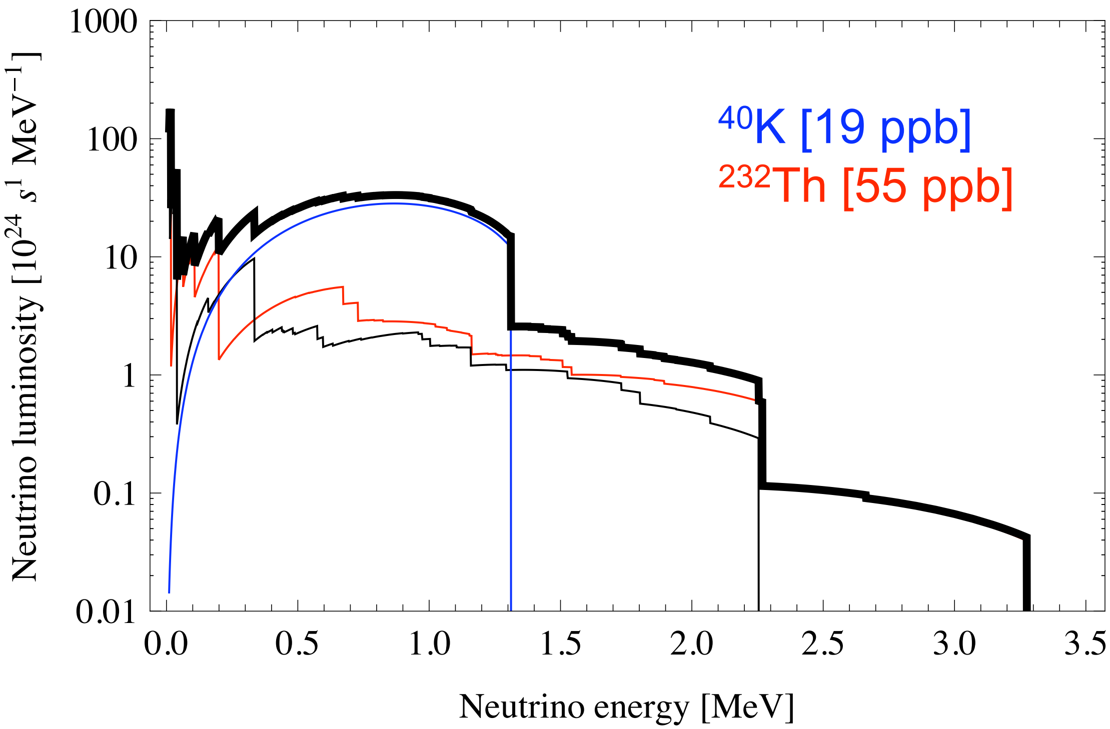
A reference model: the Bulk Silicate Earth

- Earth global composition from chondritic meteorites
- Use geochemical arguments to account for loss and fractioning during planet formation
- Obtain composition of primitive mantle before crust formation
- BSE gives total m(U) and **a(Th):a(U)**:a(K)~**4:1**:12000
- $m_{BSE}(U) \sim 0.8\times10^{17}$ kg; $m_{Mantle}(U) \sim m_{BSE}(U) - m_{Crust}(U)$

Geo-ν luminosity and flux

^{40}K : 26×10^{24} s^{-1}
^{232}Th : 5.3×10^{24} s^{-1}
^{238}U : 6.8×10^{24} s^{-1}

L(geo-ν) ~ 38×10^{24} s^{-1}



For comparison

L_ν(Sun) ~ 1.8×10^{38} s^{-1}

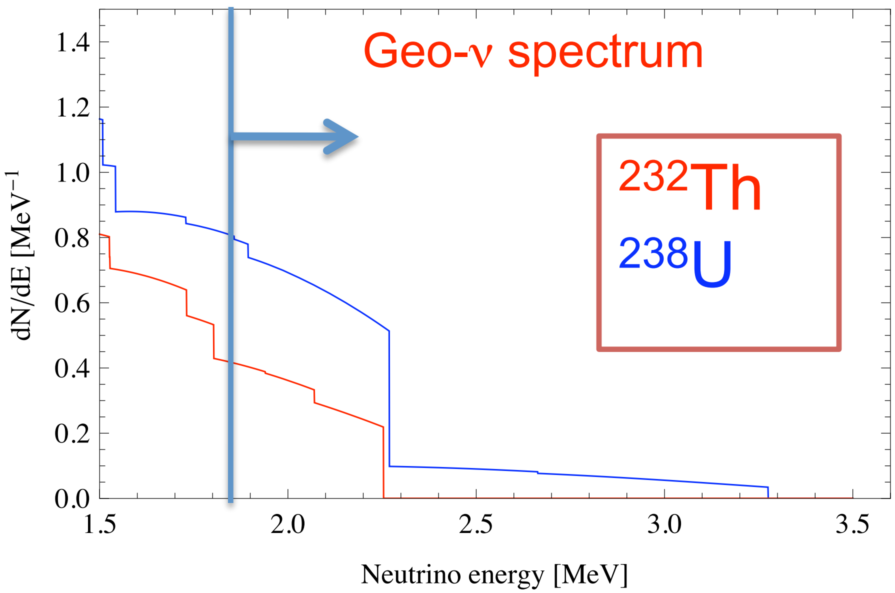
L_ν($SN_{\text{electron anti-}\nu}$) ~ 3×10^{57} s^{-1}

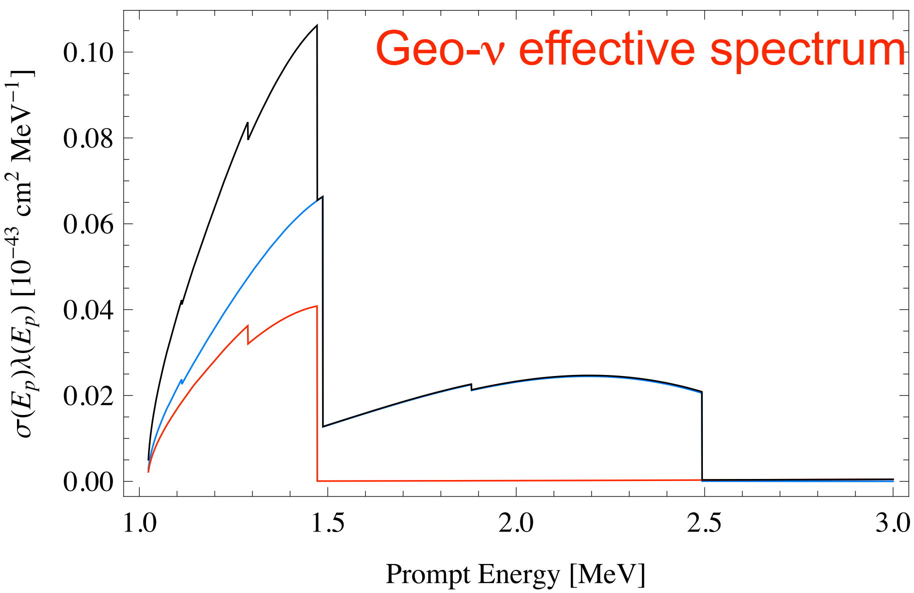
$$\phi^{eff}_{geo-\nu} \sim \langle P_{ee} \rangle \frac{L_{geo-\nu}}{4\pi R_\oplus^2} \sim 4\times10^6\ \mathrm{cm}^{-2} s^{-1}$$

Detection of geo-ν

- **Golden channel: inverse-beta decay**
  - Strong tagging in massive Liquid Scintillators with prompt and delayed signals
  - Threshold: 1.806 MeV
  - **Only U and Th geo-ν can be detected**
- **Running experiments**
  - KamLAND(since 2005) and Borexino(since 2010)

Spectroscopy of geo-ν signal





Geo-ν as a probe of the Earth's interior

Goals of geo-ν observations

- What is the fraction of radiogenic heat on Earth
  - Total heat from the Earth ~ 46 TW
  - BSE predicts about ~40% from HPE
- What is the abundance of the Heat Producing Elements
- How much U and Th is in the mantle
- Any contribution from the Core?

Backgrounds

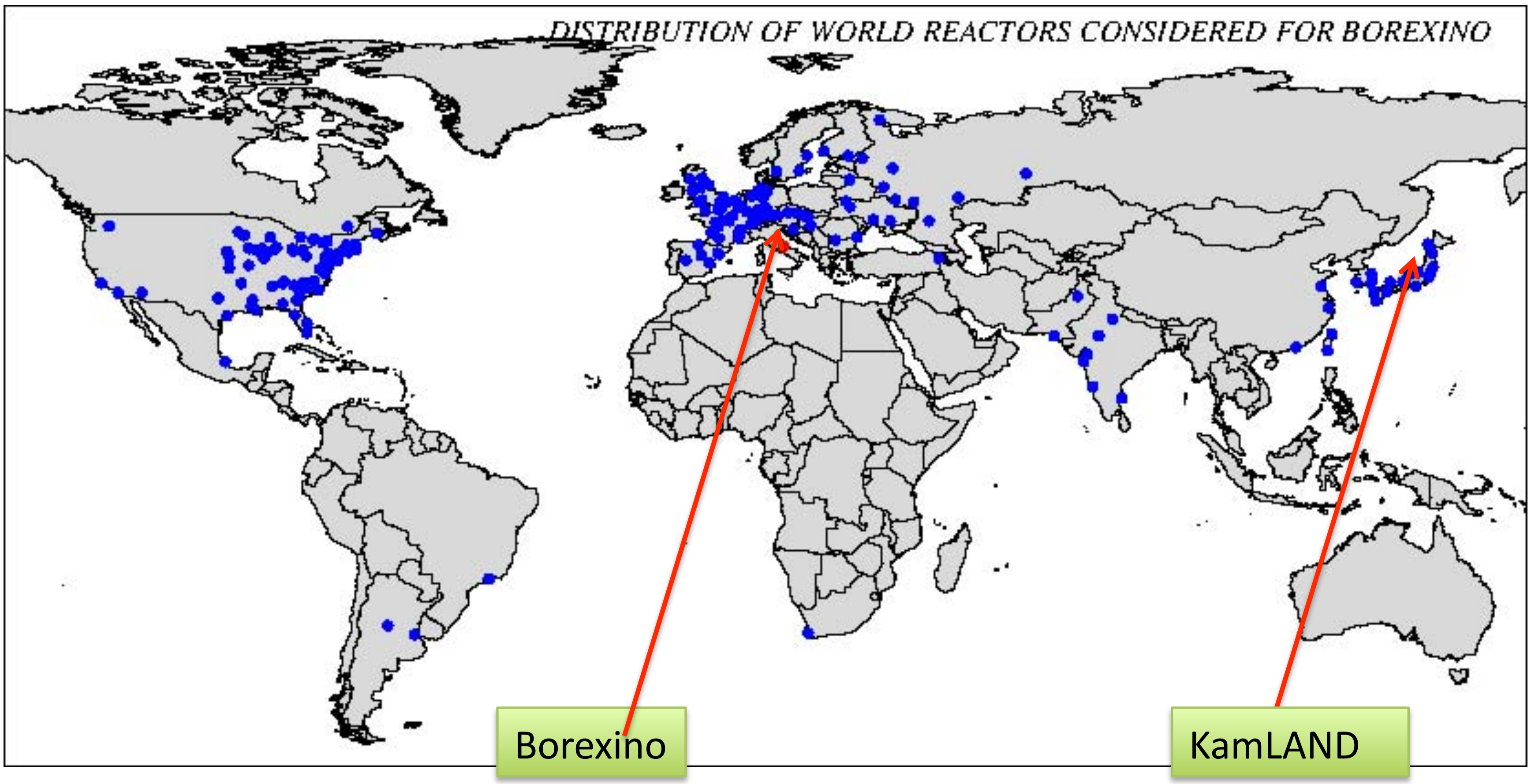
1. **Anti-neutrinos from reactors**

2. **Possible sources of *fake* anti-ν events**

(prompt + delayed):

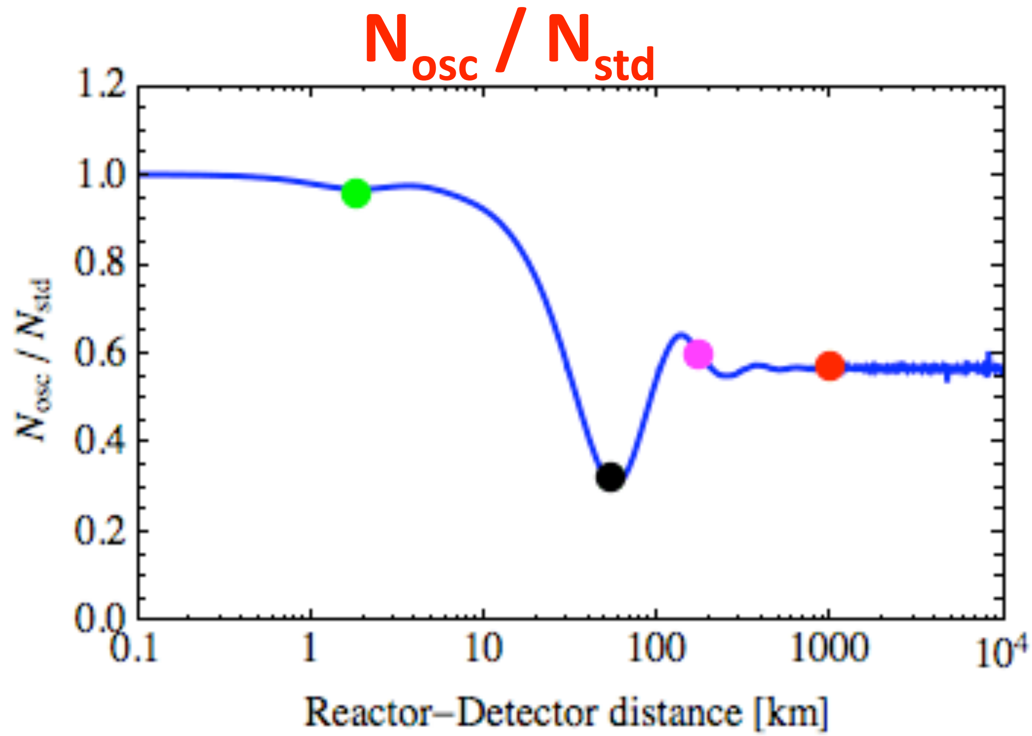
- ✓ **Background induced from (α,n) and (γ,n) interactions**
  - ✓ Mainly from $^{13}C(\alpha,n)^{16}O$
- ✓ **Muons**
  - ✓ β−n emitters such as ^{9}Li and ^{8}He
  - ✓ High energy neutrons
- ✓ **Accidental coincidences**
  - ✓ Need high radiopurity

Reactors in the World

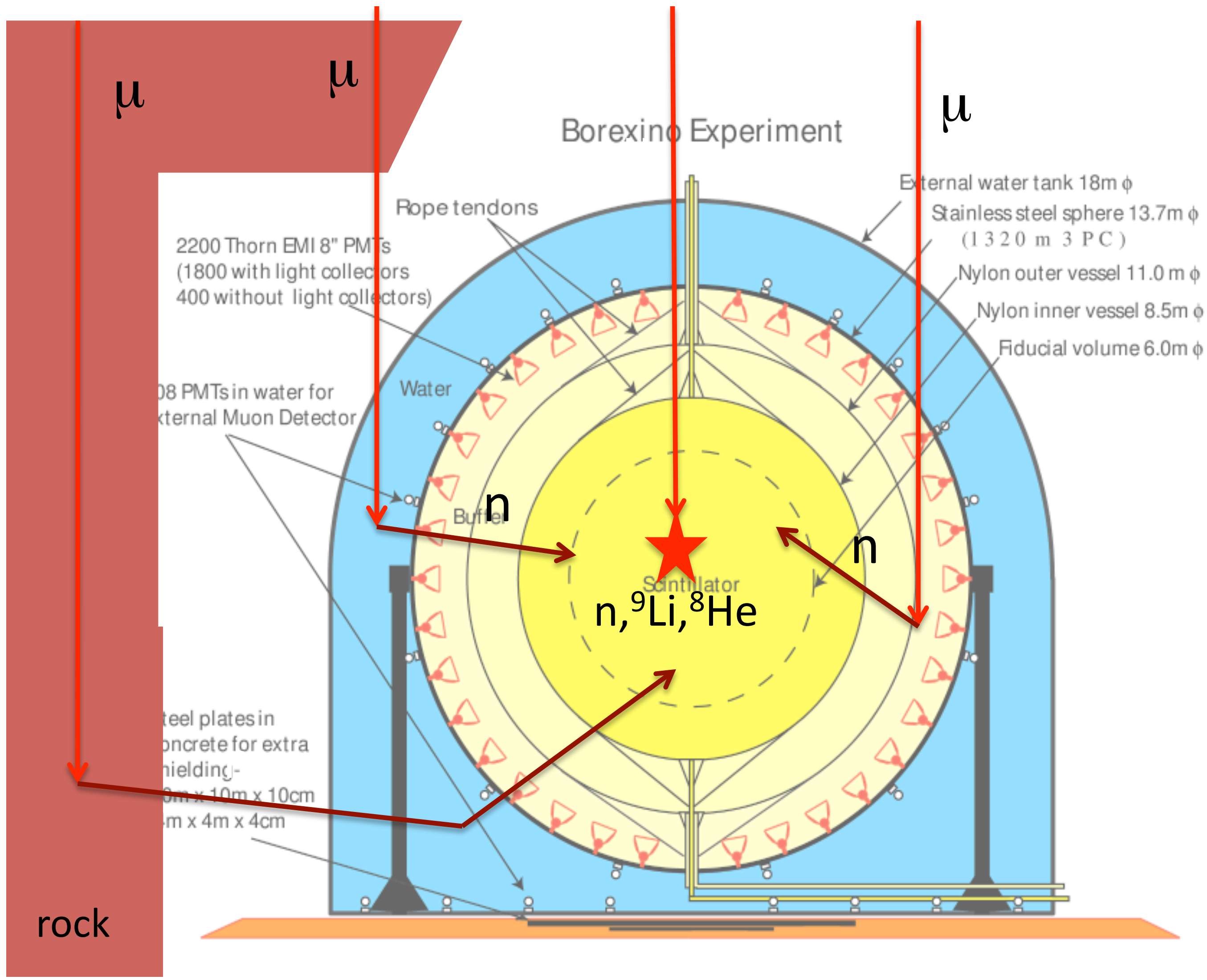


Reactor anti-ν's with Borexino

CHOOZ
KamLAND
BOREXINO
Future proposal



Muon-induced Backgrounds



Summary of Backgrounds for the case of Borexino

Exposure:
252.6 ton-year

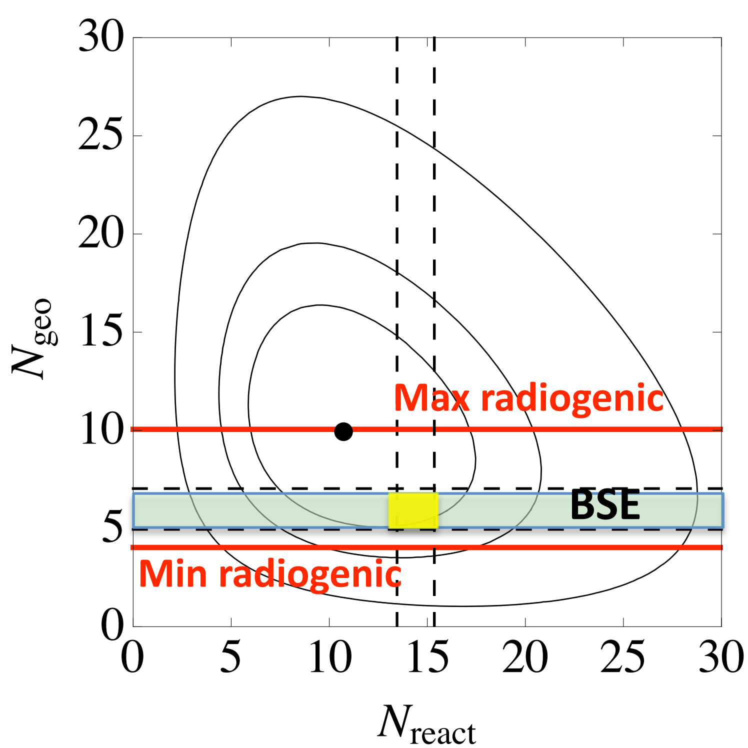
10% deadtime included comes from 2s veto to remove cosmogenic background

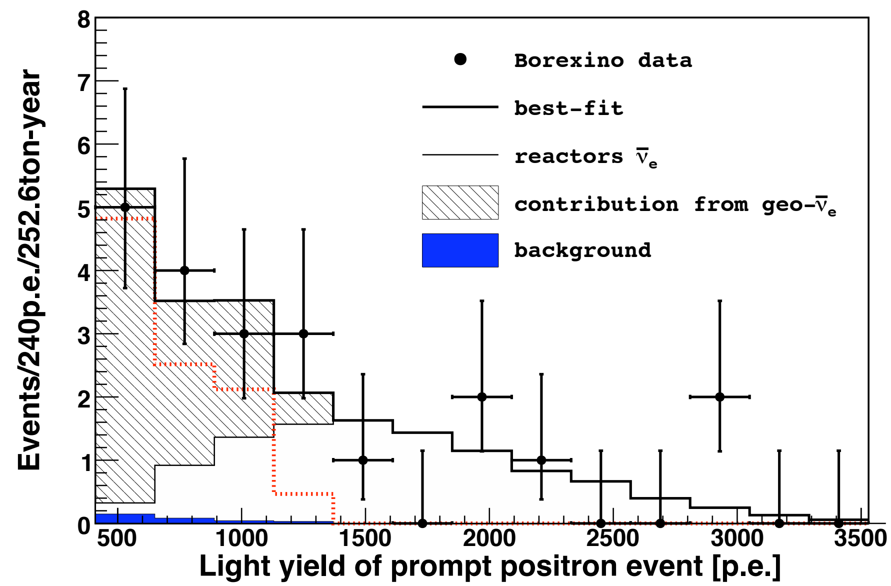
Detected 21 anti-ν events

Source	Background [events/(100 ton·yr)]
^{9}Li–^{8}He	0.03±0.02
Fast n's (μ's in WT)	<0.01
Fast n's (μ's in rock)	<0.04
Untagged muons	0.011±0.001
Accidental coincidences	0.080±0.001
Time corr. background	<0.026
(γ,n)	<0.003
Spontaneous fission in PMTs	0.0030±0.0003
(α,n) in scintillator	0.014±0.001
(α,n) in the buffer	<0.061
Total	0.14±0.02

Expect: $2.5^{+0.3}_{-0.5}$ geo-ν/(100ton-year)

Best-fit parameters from likelihood analysis





1σ(3σ)

$$\phi_U = 7.1^{+2.9}_{-2.4}\left(^{+10.6}_{-5.8}\right)\times 10^{6}\ \mathrm{cm}^{-2}s^{-1}$$

Summary of geo-neutrino measurements

Experime nt	Reference	Geoneutrino events	Geoneutrino flux for U [10^6 cm^{-2} s^{-1}]	Predicted flux for U [10^6 cm^{-2} s^{-1}]
KamLAND (2005)	Nature 436, 499	25^{+19}_{-18}	$5.6^{+4.3}_{-4.0}$	$3.7^{+2}_{-1.6}$
KamLAND (2008)	PRL 100, 221803	73±27	4.2±1.6	$3.7^{+2}_{-1.6}$
Borexino (2010)	PLB 687, 299	$9.9^{+4.1(+14.6)}_{-3.4(-8.2)}$	$7.1^{+2.9(+10.6)}_{-2.4(-5.8)}$	$4.2^{+2.1}_{-1.9}$
KamLAND (2010)	Neutrino 2010	106^{+29}_{-28}	4.3±1.2	$3.7^{+2}_{-1.6}$

Combined analysis of geoneutrino observations: KamLAND2008 + Borexino2010

- **The time of multi-experiment geo-ν observations and global analysis has come**
  (see Fogli, Lisi, Palazzo, Rotunno, arXiv: 1006.1113)

- Free parameters:
  oscill. pars + {$R_{BX}(U)$, $R_{BX}(Th)$, $R_{KL}(U)$, $R_{KL}(Th)$}

- Marginalize oscill. pars
  - ✓ 4 d.o.f.
  - ✓ Use $R_{BX}(Th)/R_{BX}(U) = R_{KL}(Th)/R_{KL}(U)$: 3 d.o.f

1σ regions

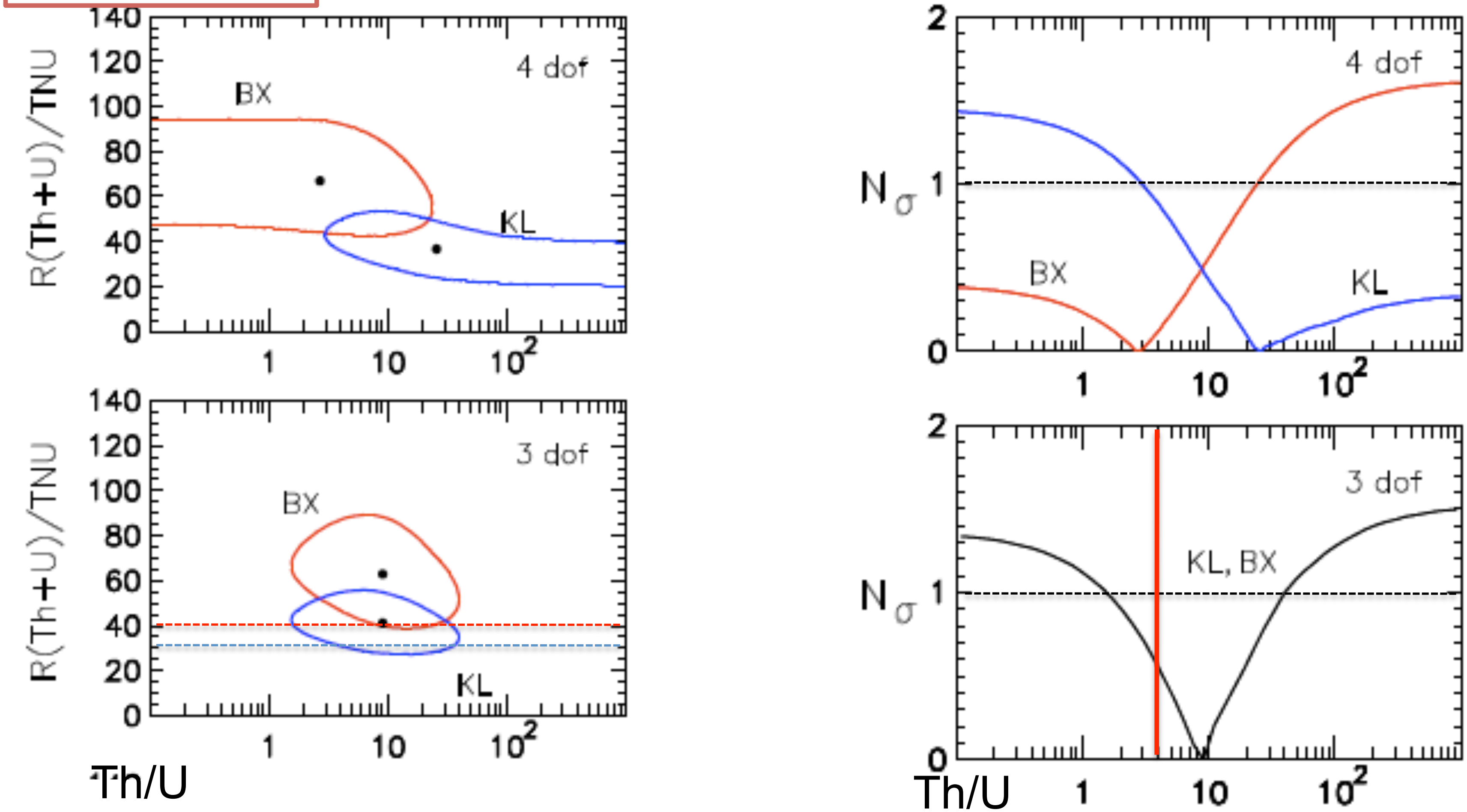


TABLE II: Best fits and 1σ ranges from the data analysis with degrees of freedom $N_D \leq 4$. Event rates R are expressed in TNU. Derived or fixed numbers are given in brackets.

N_D	$R(\mathrm{Th+U})_{\mathrm{KL}}$	$(\mathrm{Th/U})_{\mathrm{KL}}$	$R(\mathrm{Th+U})_{\mathrm{BX}}$	$(\mathrm{Th/U})_{\mathrm{BX}}$
4	$36.8^{+16.2}_{-16.1}$	$25.9^{+\infty}_{-22.9}$	$66.9^{+27.3}_{-23.8}$	$2.7^{+20.2}_{-2.7}$
3	$41.3^{+14.0}_{-12.6}$	$9.1^{+23.5}_{-7.4}$	$63.0^{+26.0}_{-24.0}$	$[9.1^{+23.5}_{-7.4}]$
2	$45.1^{+11.8}_{-11.2}$	$9.6^{+33.7}_{-7.6}$	$[51.7^{+13.6}_{-12.9}]$	$[9.6^{+33.7}_{-7.6}]$
1	$47.7^{+11.2}_{-11.2}$	[3.9]	$[54.9^{+12.9}_{-12.9}]$	[3.9]

Neutrinos from SN in BOREXINO

Stellar collapse and ν emission

4 phases:

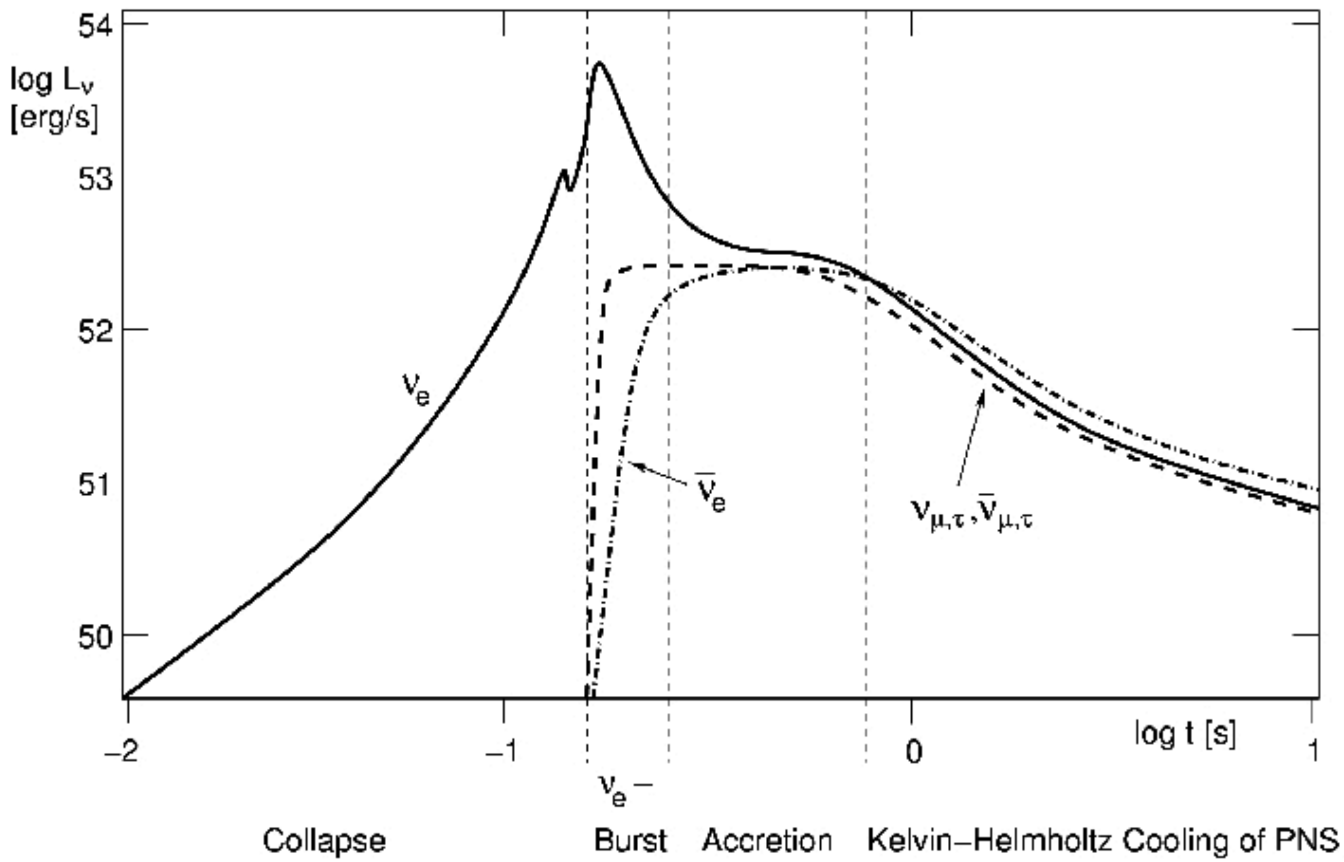
- **Infall**: free-fall time scale: $(3\pi/32G\rho)^{1/2}$ ~ 100ms
- **Falling material on inner stiff core and bounce**
  - Shock wave in outer core
  - Early emission of ν_e: $e^- p \rightarrow n \nu_e$

PROMPT EMISSION

- **Accretion and delayed shock revival** ~ 500ms
  - $e^+ + n \rightarrow p +$ anti-ν_e
  - $e^+ + e^- \rightarrow \nu_i +$ anti-ν_i
- **Cooling ~**10s
  - $e^+ + n \rightarrow p +$ anti-ν_e and $e^- + p \rightarrow n + \nu_e$
  - $e^+ + e^- \rightarrow \nu_i +$ anti-ν_i

LATE THERMAL EMISSION

Neutrino Luminosities



SN Neutrino Oscillations

$$F_e^0 \rightarrow F_e = P_{ee} F_e^0 + P_{\mu e} F_\mu^0 + P_{\tau e} F_\tau^0$$

$$F_e = P_{ee} F_e^0 + (1 - P_{ee}) F_x^0 \quad \text{with } \mathrm{F}_x^0 = F_\mu^0 = F_\tau^0$$

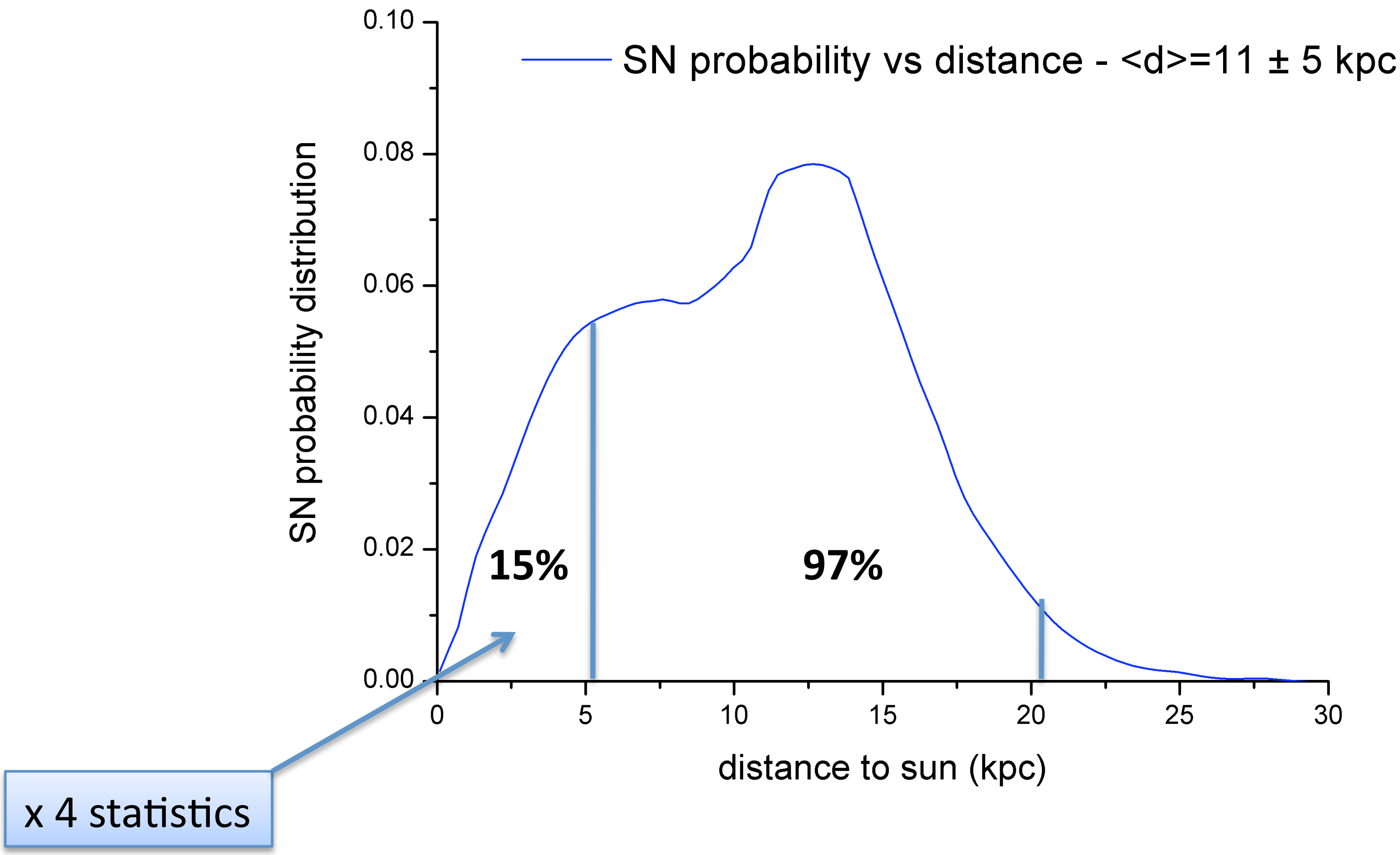
$$2F_x + F_e = 2\mathrm{F}_x^0 + F_e^0$$

For normal hierarchy with $\theta_{13} > 1^\circ$

$$F_{\bar{e}} = \cos^2\theta_{12} F_{\bar{e}}^0 + \sin^2\theta_{12} F_{\bar{x}}^0 \approx 0.7 F_{\bar{e}}^0 + 0.3 F_{\bar{x}}^0$$

$$F_e = \sin^2\theta_{13} F_e^0 + \cos^2\theta_{13} F_x^0 \approx F_x^0$$

Galactic SN vs distance to the Sun

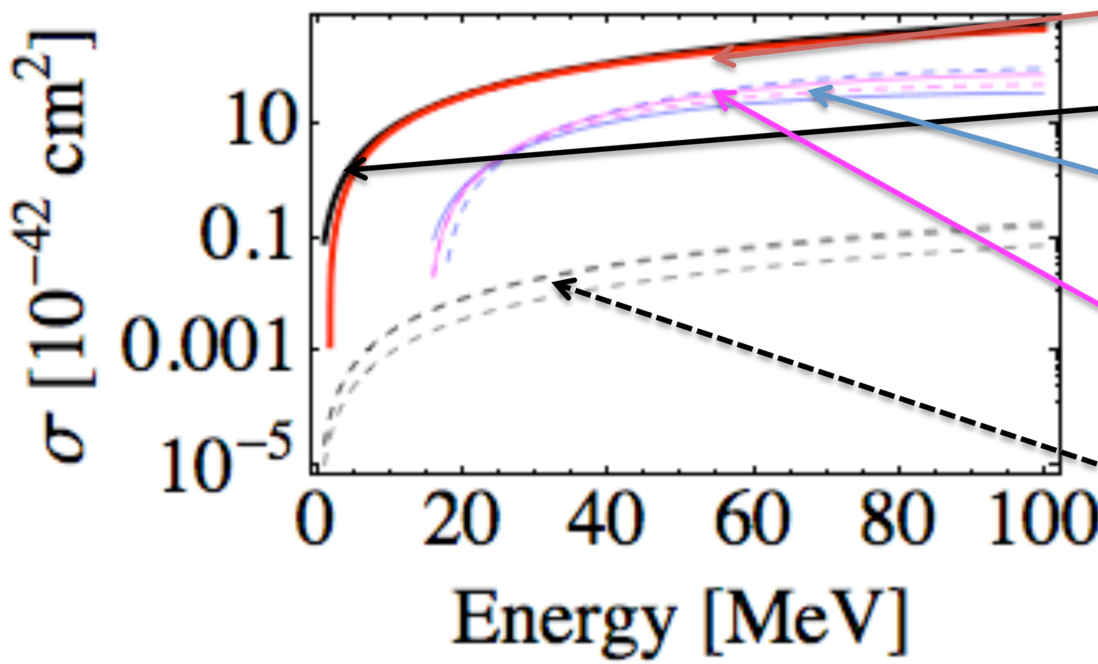


Plot adapted from Mirizzi, Raffelt and Serpico, JCAP 0605,012(2006)

Detection channels

CC	NC	ES
$\nu_e + n \rightarrow e^- + p$	$\nu + p \rightarrow \nu + p$	$\nu_x + e^- \rightarrow \nu_x + e^-$
$\bar{\nu}_e + p \rightarrow e^+ + n$	$\nu + (A,Z) \rightarrow \nu + (A,Z)^*$	
$\bar{\nu}_e + (A,Z) \rightarrow e^+ + (A,Z-1)$	$\bar{\nu} + (A,Z) \rightarrow \bar{\nu} + (A,Z)^*$	
$\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)$	$\nu + (A,Z) \rightarrow \nu + (A,Z)$	

Cross-sections for a LS detector



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

$$\nu + p \rightarrow \nu + p$$

$$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$$

$$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$$

$$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$$

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

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

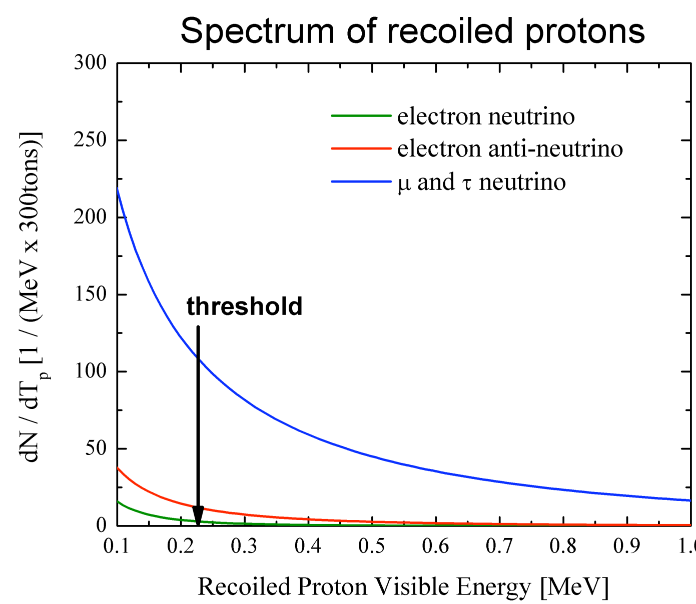
Expected events in Borexino

	No oscillations	Oscillations NH	Oscillations IH
Golden ch.	67	78	101
<E> for golden ch. [MeV]	25	30.5	39
CC on $^{12}C \rightarrow ^{12}B$ CC on $^{12}C \rightarrow ^{12}N$	2 0.5	3 9	6 6
ES	5	5	5
NC on ^{12}C	9 + 8(anti-ν)		
νp	64		

The ν+p channel: measurement of T_x

- The golden ch. gives the temperature of anti-ν_e
- This NC ch. can give the temperature of ν_x
- Due to quenching only the contribution from ν_x can be measured

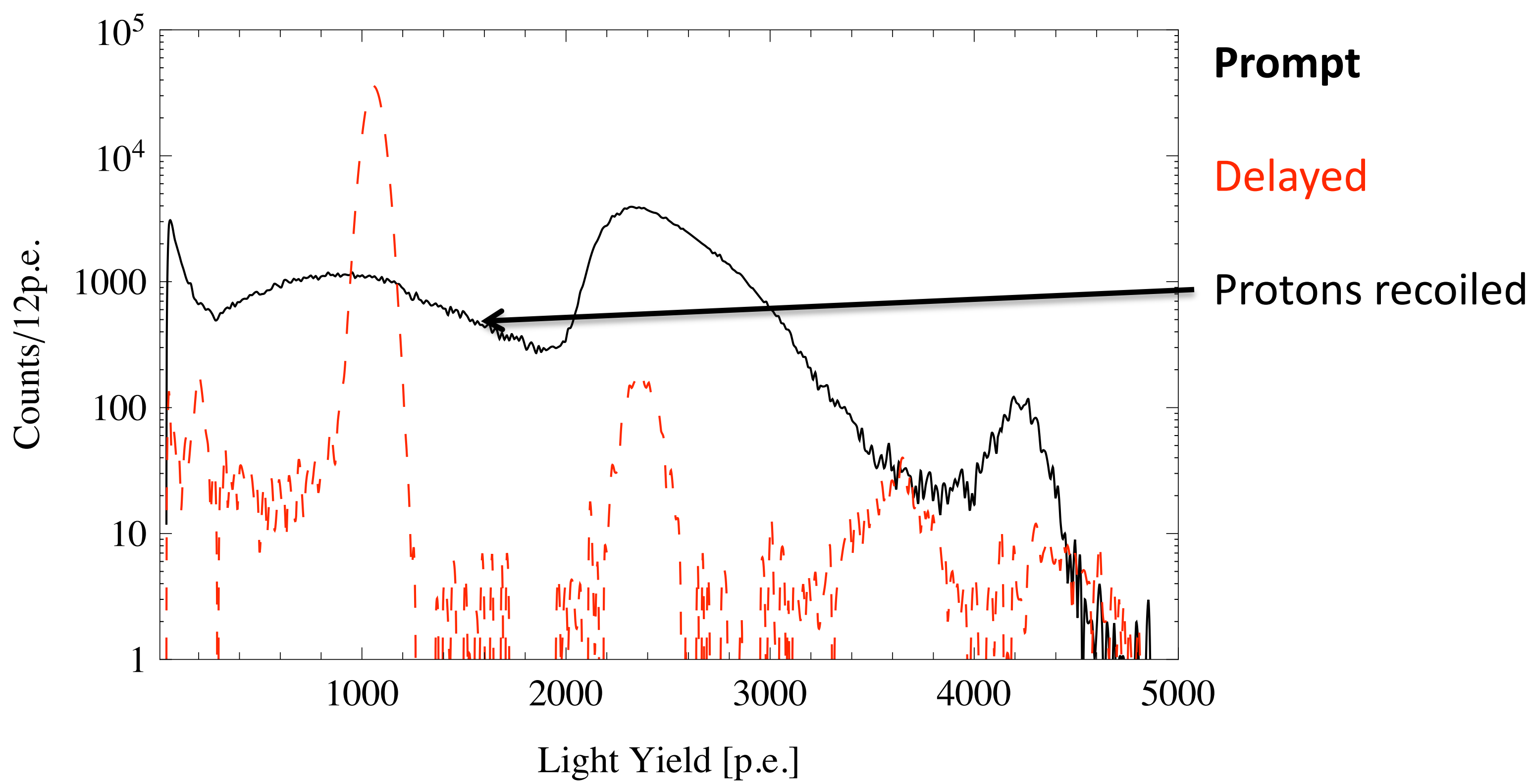
$$\text{Events} \propto \left(4\frac{E_B}{6}\right)\frac{\langle\sigma\rangle}{T_x}$$



First proposed by J. Beacom et al., PRD66:033001, 2002

Proton quenching in the neutrino-proton interaction

- Measure proton quenching in the LS
- Make use of AmBe source calibrations



Conclusions

Conclusions on solar neutrinos

- **First measurement of ^{7}Be solar neutrino** flux performed at 10% level
- **First ^{8}B solar ν detection in liquid scint.** (16% at present)
- P_{ee} measured at low and high energy : 2σ effect at present

- Coming next :
  - Reduced systematic error at 5%
  - tagging of cosmogenic background to aim to detect pep/CNO neutrinos even with a large uncertainty
- Use future measurement to solve conflict between SSM and helioseismology
  - Use correlations
  - Solve inverse problem

Conclusions from geo-ν observations

1. **First observation of geo-neutrinos in Borexino (4.2σ)**
   1. Large signal-to-noise ratio
   2. Results limited ONLY by present statistics

2. **First measurement of electron anti-neutrino disappearance on a base line of ~1000km (2.9σ) from Borexino**

3. **Combined analysis (KamLAND2008+Borexino2010) at present gives**
   1. **5σ evidence**
   2. At 1σ hint for a mantle contribution
   3. Th/U ratio in broad agreement with chondritic expectation

Conclusions on SN neutrinos in BOREXINO

- Together with LVD and ICARUS offers a third possibility to detect SN neutrinos at the same underground site
- Due to the high radiopurity is the only detector at present which can probe the neutrino-proton ES and determine both T_x and L_x. Limited by statistics.