Neutrinos from the sun and from radioactive sources in Borexino

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INFN, LNGS

Padova 2012, Sept 17th

Solar Neutrinos

Solar Neutrinos

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

$\langle E_\nu \rangle \sim 0.53$ MeV, 2% of total energy produced

$$\phi_\nu = 2 \cdot \frac{2.4 \cdot 10^{39}\ \mathrm{MeV/s}}{26.73 MeV - 0.53 MeV} \cdot \frac{1}{4\pi (A.U.)^2} \approx 6.5 \cdot 10^{10}\ \mathrm{cm}^{-2} s^{-1}$$

Solar neutrinos are a unique tool to probe the physics at the core of the Sun and neutrino propagation in dense matter (100 g/cm^3)

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

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

~0.4%

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

~85%

~15%

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

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

~0.02%

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

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

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

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

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

$$p + {}^{12}C \rightarrow {}^{13}N + \gamma$$

$$ {}^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e + 1.199\ \mathrm{MeV}$$

$$p + {}^{13}N \rightarrow {}^{14}N + \gamma$$

$$p + {}^{14}N \rightarrow {}^{15}O + \gamma$$

$$ {}^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e + 1.732\ \mathrm{MeV}$$

~10^{-2}

$$p + {}^{15}N \rightarrow {}^{16}O + \gamma$$

$$p + {}^{15}N \rightarrow 2\,{}^{4}He + {}^{12}C$$

$$p + {}^{16}O \rightarrow {}^{17}F + \gamma$$

$$ {}^{17}F \rightarrow {}^{17}O + e^{+} + \nu_e + 1.740\ \mathrm{MeV}$$

$$p + {}^{17}O \rightarrow 2\,{}^{4}He + {}^{14}N$$

Solar Standard Model

The SSM is the framework from which we make predictions on the production of solar neutrinos

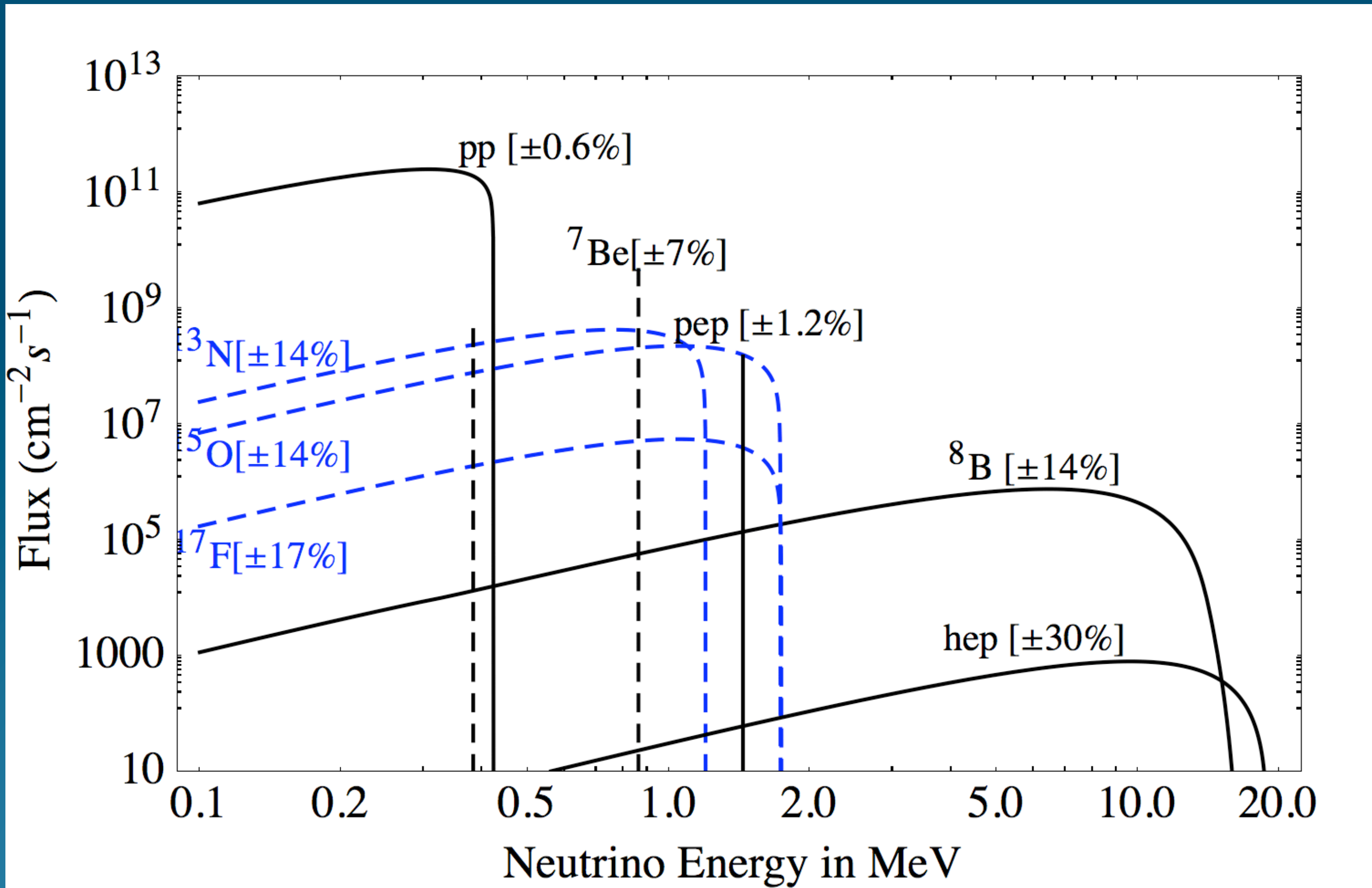
Within the SSM solar neutrino fluxes are written as:

$$\phi_{\rm pp} \propto S_{11}{}^{+0.14} \cdot S_{33}{}^{+0.03} \cdot S_{34}{}^{-0.06} \cdot S_{1,14}{}^{-0.02} \cdot L_{\odot}{}^{+0.73} \cdot \tau_{\odot}{}^{-0.07} \cdot Op_{\odot}{}^{+0.14} \cdot (Z/X)^{-0.08},$$

$$\phi_{\rm Be} \propto S_{11}{}^{-0.97} \cdot S_{33}{}^{-0.44} \cdot S_{34}{}^{+0.88} \cdot L_{\odot}{}^{+3.56} \cdot \tau_{\odot}{}^{+0.69} \cdot Op_{\odot}{}^{-1.49} \cdot (Z/X)^{+0.59},$$

$$\phi_{\rm B} \propto S_{11}{}^{-2.59} \cdot S_{33}{}^{-0.40} \cdot S_{34}{}^{+0.81} \cdot L_{\odot}{}^{+6.76} \cdot \tau_{\odot}{}^{+1.28} \cdot Op_{\odot}{}^{-2.93} \cdot (Z/X)^{+1.36}.$$

Solar Neutrino Spectrum at Earth



A. Serenelli at al., Astrophys. J 7432, 2011

Luminosity Constraint

$$4p \longrightarrow \begin{cases} {}^4He + 2\nu_{pp} + 26.20\ \text{MeV} \\ {}^4He + \nu_{pp} + \nu_{Be} + 25.65\ \text{MeV} \\ {}^4He + \nu_{pp} + \nu_{B} + 19.75\ \text{MeV} \end{cases}$$

$$\frac{\text{L}_{\text{Sun}}}{4\pi(A.U.)^2} = \sum_i a_i \phi_i$$

$$f_i = \frac{\phi_i}{\phi_i^{SSM}}$$

$$f_{pp} = 1.09 - 0.08 f_{Be} - 0.01 f_{CNO}$$

Recent developments of the SSM

Since 2004 a number of improvements in the SSM have taken place which are worth reporting:

- New determination of $^{14}N(p,\gamma)^{15}O$ cross section reduces by a factor ~2 CNO fluxes
- A factor of 2 better accuracy for $^{3}He(^{4}He,\gamma)^{7}Be$ cross section
- New opacities calculations
- New surface abundance calculations based on improved 3D model

	$R_{CZ}/R_{\odot}$	Y_{surf}	$(Z/X)_{surf}$
SSM(GS98)	0.713	0.2423	0.0229
SSM(AGSS09)	0.724	0.2314	0.0178
Helioseismology	0.713 ± 0.001	0.2485 ± 0.0035	

Solar Standard Model neutrino flux predictions

Source	Flux [cm^{-2}s^{-1}] SSM-GS98	Flux [cm^{-2}s^{-1}] SSM-AGSS09	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}

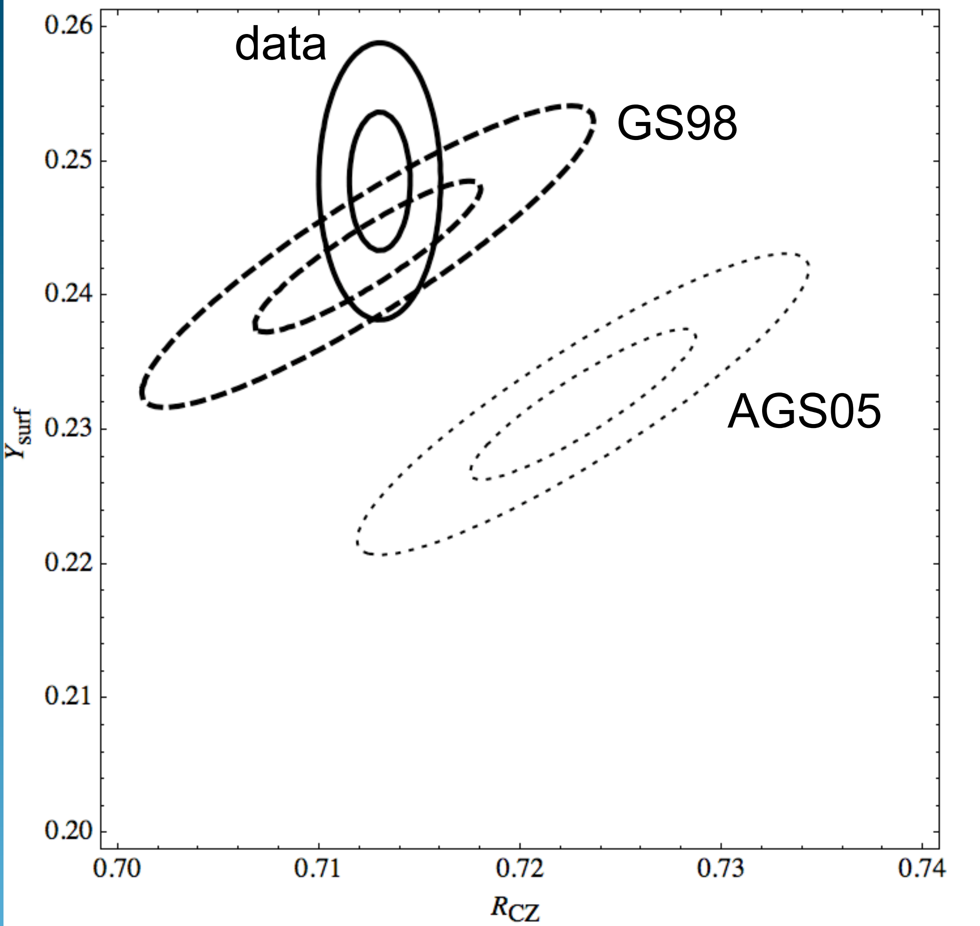
The metallicity problem

Given a number of input parameters …

The SSM determines:
the depth of the convective zone, the helium surface abundance at the present time and ...

Helioseismology provides data for these output quantities

Y_{surf} vs R_{CZ}



Solar Neutrinos Observations

Detecting Solar Neutrinos

- Electron capture: ν_e+(A,Z-1)→(A,Z)+e^- (σ~$10^{-42}cm^2$)
- Elastic Scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$ (σ~$10^{-44}cm^2$)
- $\nu_e + d \rightarrow e^- + p + p$ ($E_\nu \geq 1.44$ MeV) (σ~$10^{-42}cm^2$)
- $\nu_x + d \rightarrow \nu_x + p + n$ ($E_\nu \geq 2.74$ MeV)
  - pure NC interaction

SNO

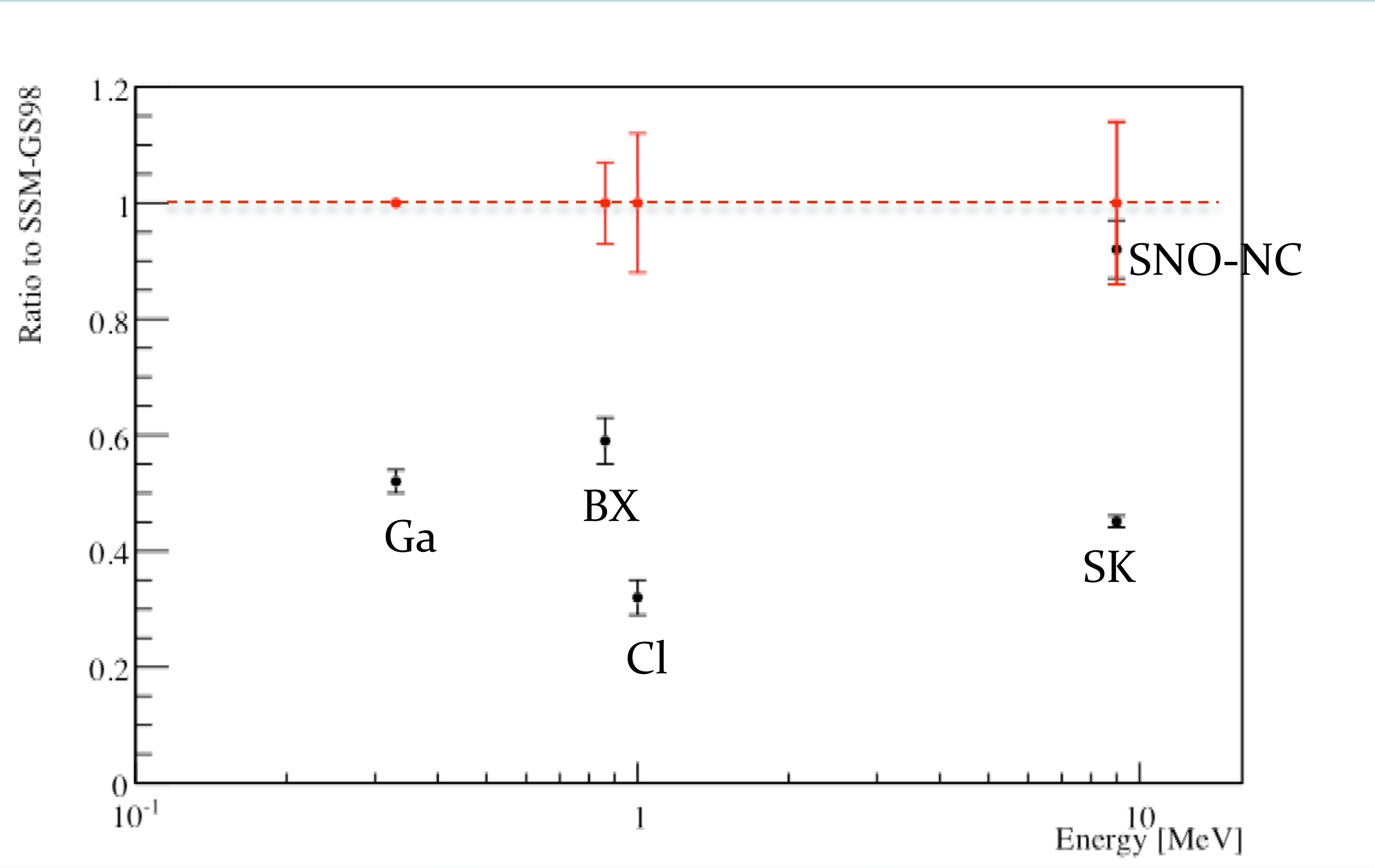
Solar Neutrino Experiments

Detector	Target mass	Threshold [MeV]	Data taking
Homestake	615 tons C_2Cl_4	0.814	1970-1994
Kamiokande	3ktons H_2O	7.5	1983-1990
SAGE	50tons molted metal Ga	0.233	**1989-present**
GALLEX	30.3tons $GaCl_3$-HCl	0.233	1991-1997
GNO	30.3tons $GaCl_3$-HCl	0.233	1998-2003
Super-Kamiokande	22.5ktons	4.5 6.5 4.5 4	1996-2001 2003-2005 2006-2008 **2008-present**
SNO	1kton D_2O	5[3.5]	1999-2006
Borexino	300ton C_9H_{12}	0.2 MeV	**2007-present**

Solar Neutrino Measurements

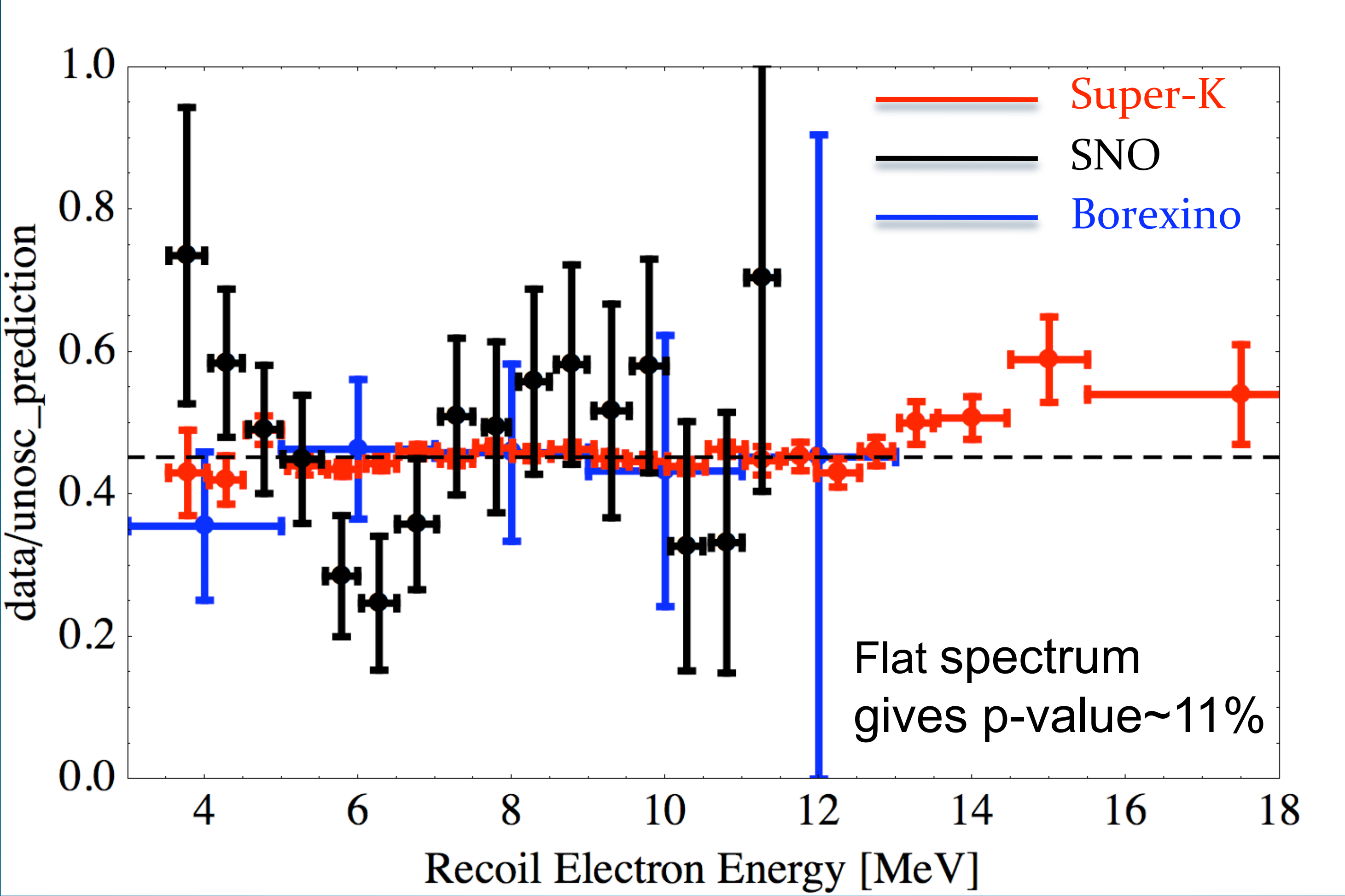
Experiment	Sources contributing to data	**Data**
Homestake	^7Be(13.1%)+pep(2.7%)+ CNO(2.4%)+^8B(81.8%)	2.56±0.16±0.16 SNU
GALLEX/GNO/SAGE	pp(55%)+^7Be(28.3%)+ pep(2.3%)+ CNO(3.4%)+^8B(11%)	66.2±3.2 SNU
Super-Kamiokande (I, II, II)	^8B	$\Phi_{\nu e} = (2.38\pm0.08)\times10^6\ cm^{-2}s^{-1}$ $\Phi_{\nu e} = (2.41\pm0.16)\times10^6\ cm^{-2}s^{-1}$ $\Phi_{\nu e} = (2.39\pm0.07)\times10^6\ cm^{-2}s^{-1}$[~3%}
SNO	^8B	$\phi_B = 5.25\pm0.16^{+0.11}_{-0.13}$ [~4%] CC/NC=0.301±0.033
BOREXINO	^7Be(0.862MeV) pep ^8B(>3MeV)	46±1.5±1.6 cpd/100tons [~5%] 3.1±0.6±0.3 cpd/100tons 0.22±0.04±0.01 cpd/100tons

Observations vs Predictions

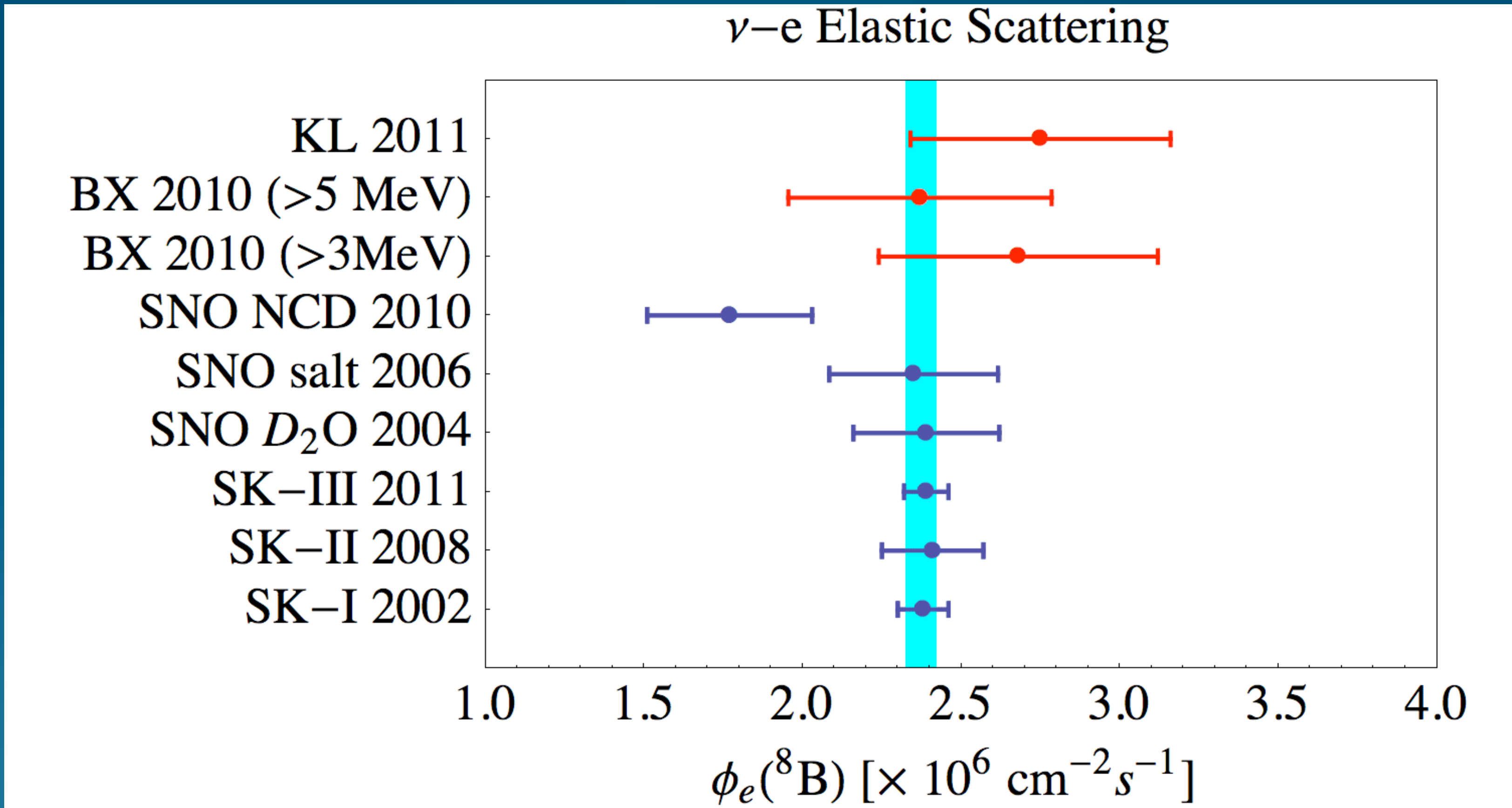


^{8}B Solar Neutrino Spectrum

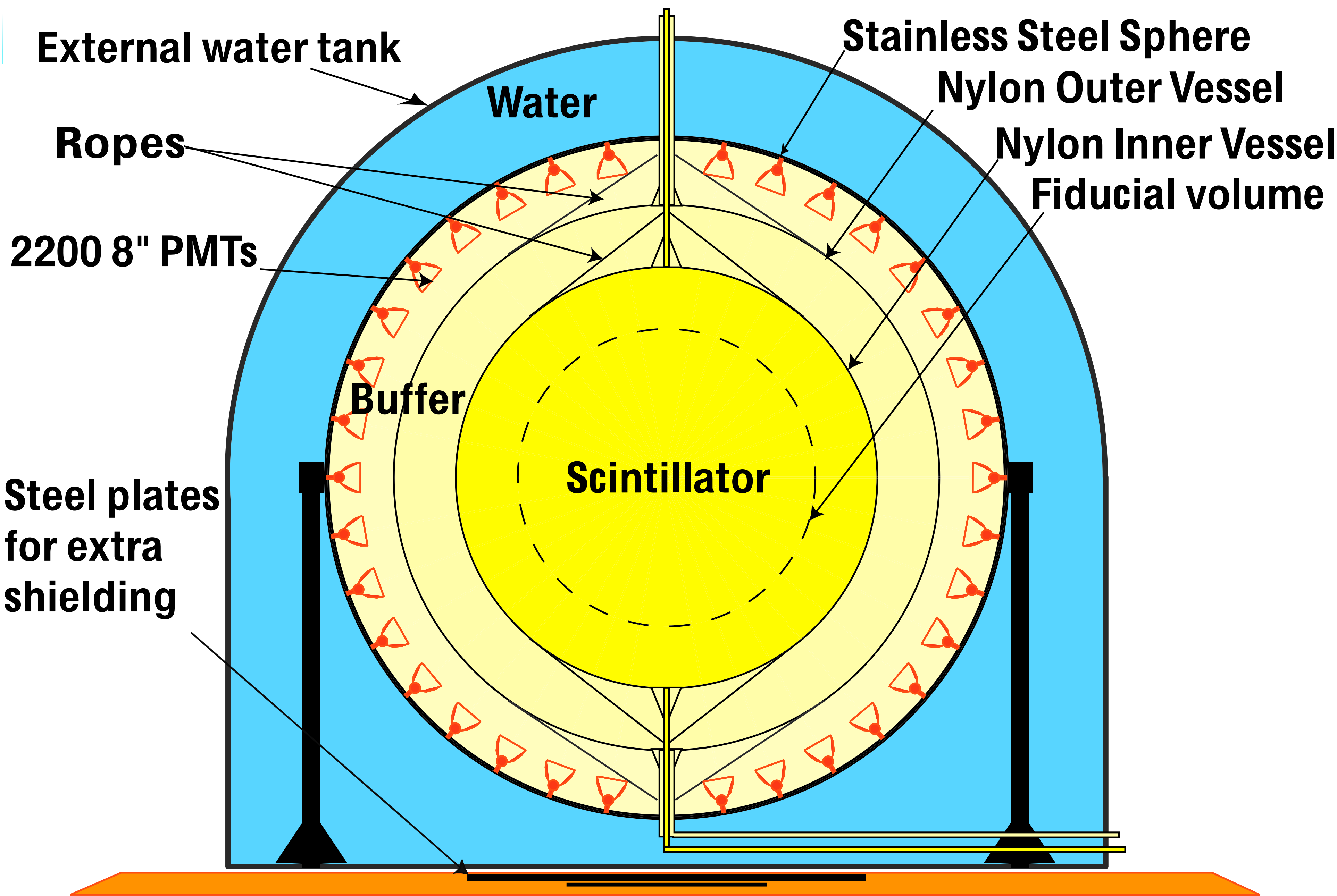
Detection by neutrino-electron ES



ν_e-equivalent flux for ^{8}B neutrinos

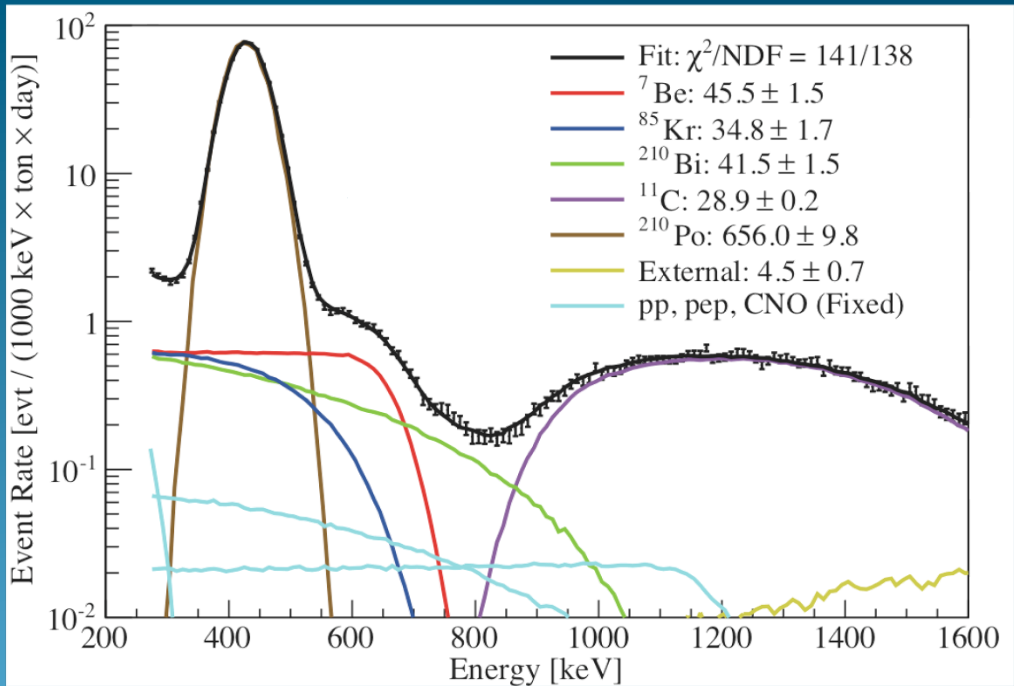


Borexino Experiment



^{7}Be Solar Neutrino Measurement in Borexino

MAIN sources of systematic uncertainties	%
Fiducial Volume	$^{+0.5}_{-1.3}$
Energy response	2.7
Fit methods	2.0



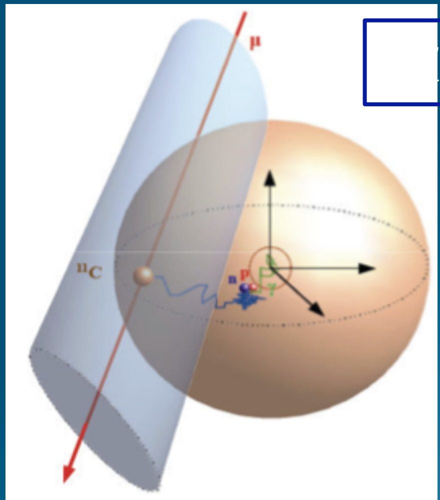
First observation of pep neutrinos

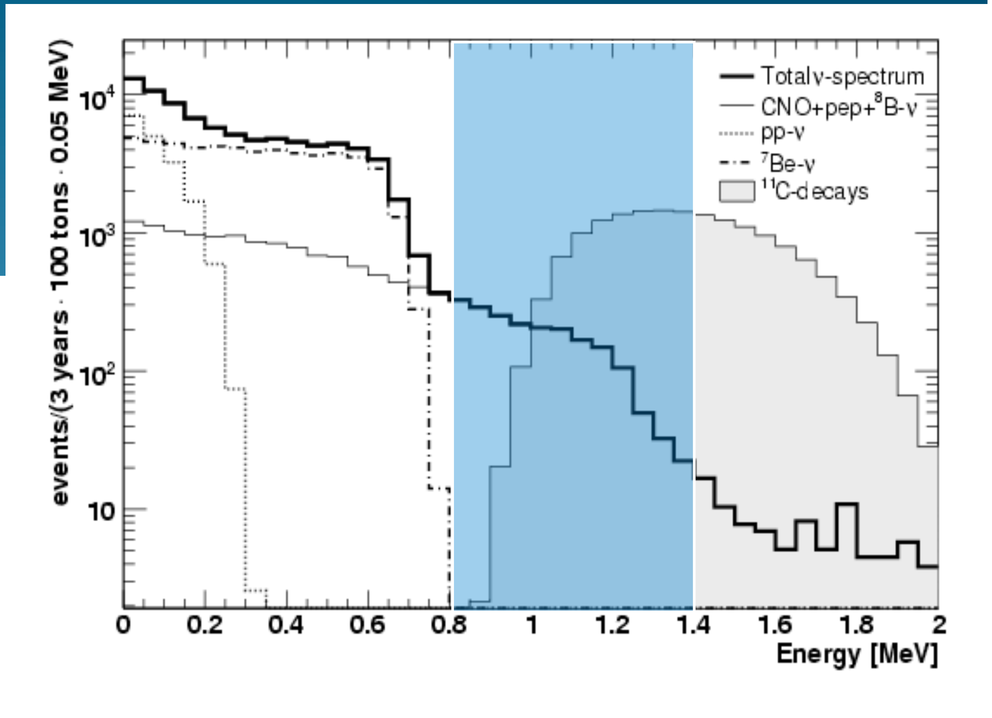
$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$$

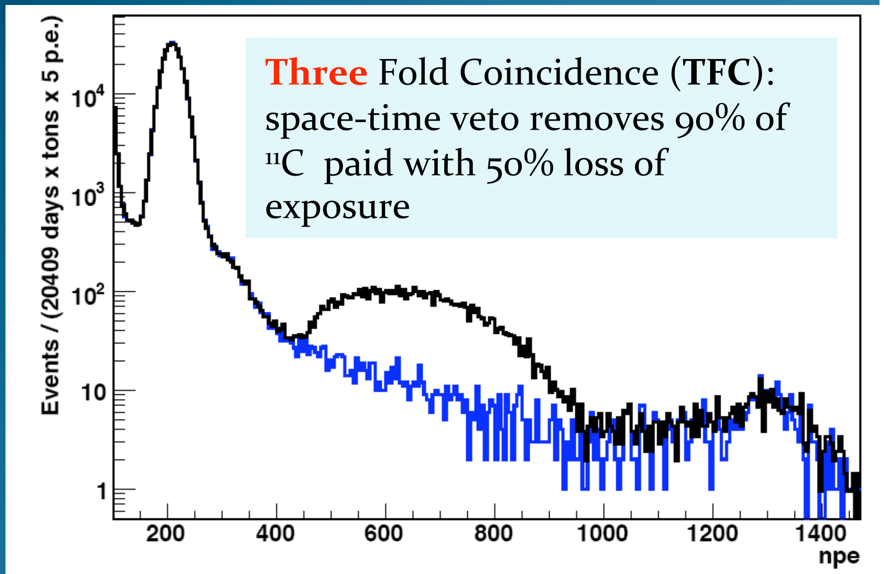
$$+ p \rightarrow d + \gamma$$

$\tau \sim 30$ min

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



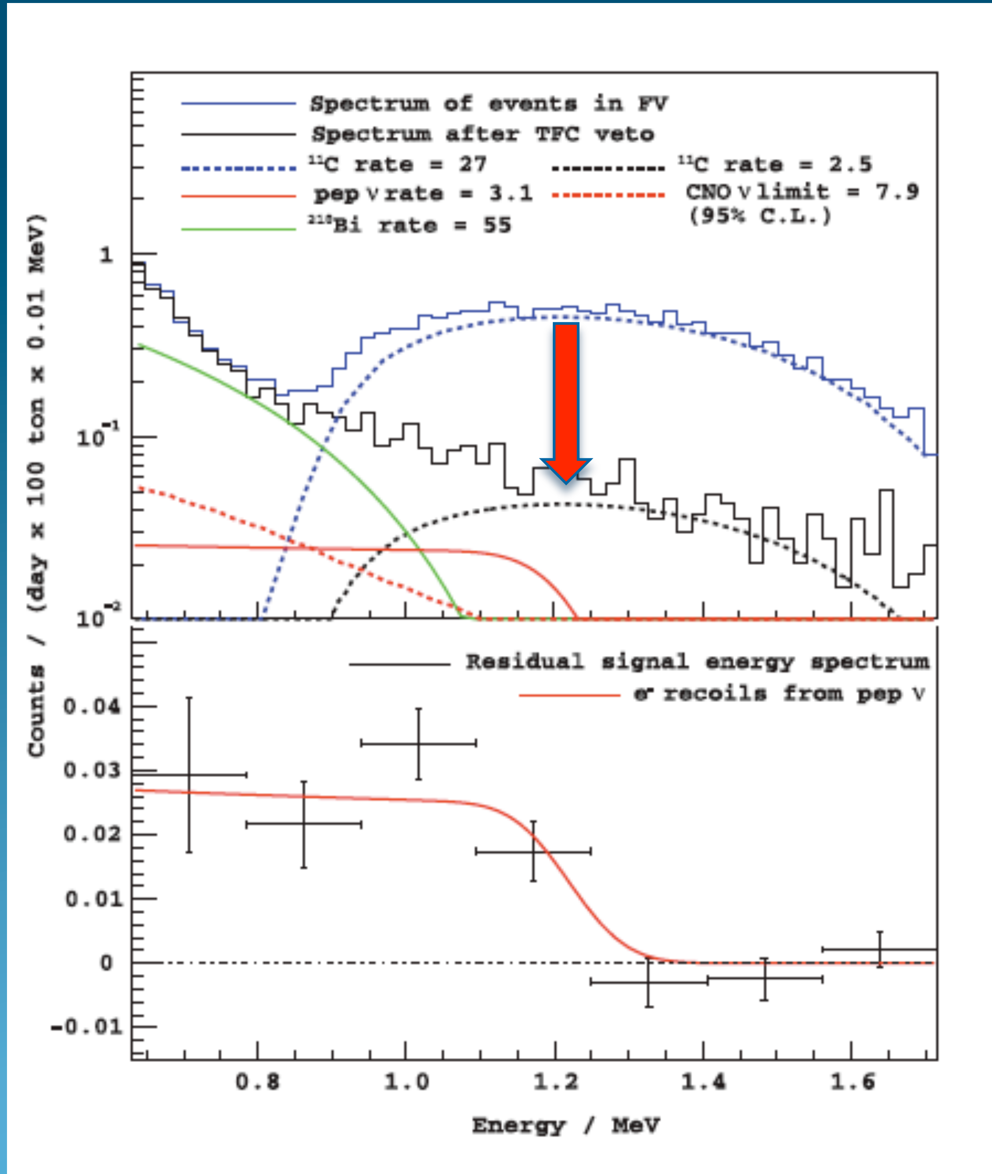




Three Fold Coincidence (**TFC**): space-time veto removes 90% of ^{11}C paid with 50% loss of exposure

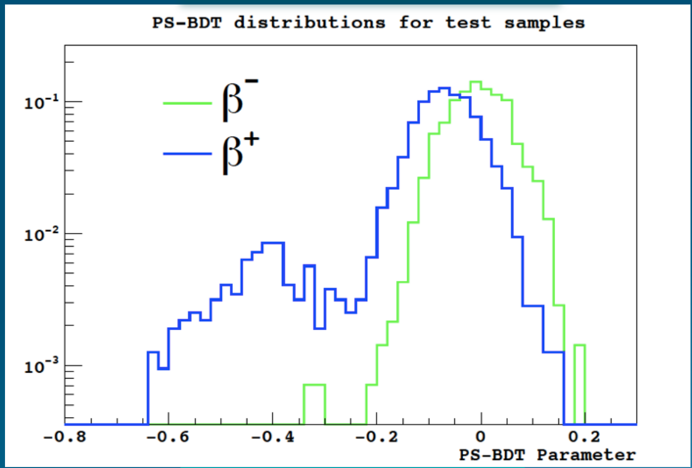
pep Solar Neutrino Measurement in Borexino

MAIN sources of systematic uncertainties	%
Fiducial Volume	$^{+0.6}_{-1.1}$
Energy response	4.1
Fit methods	5.7
PSD	5
^{210}Bi shape	$^{+1}_{-5}$

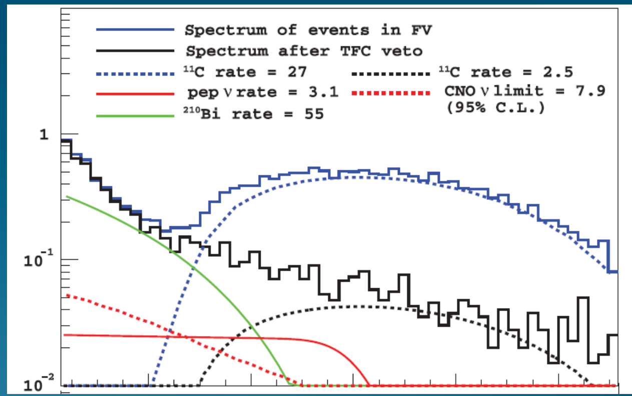


Multivariate maximum likelihood fit

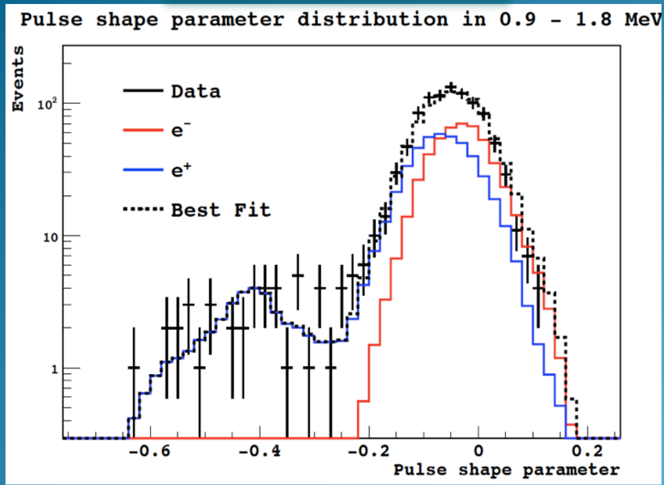
Pulse shape test



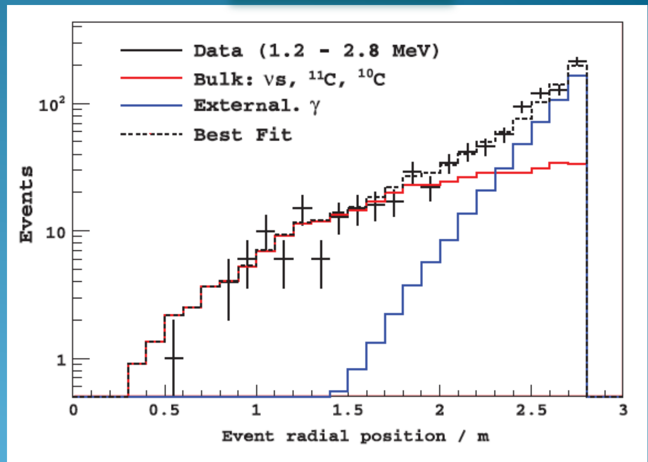
Energy spectral fit



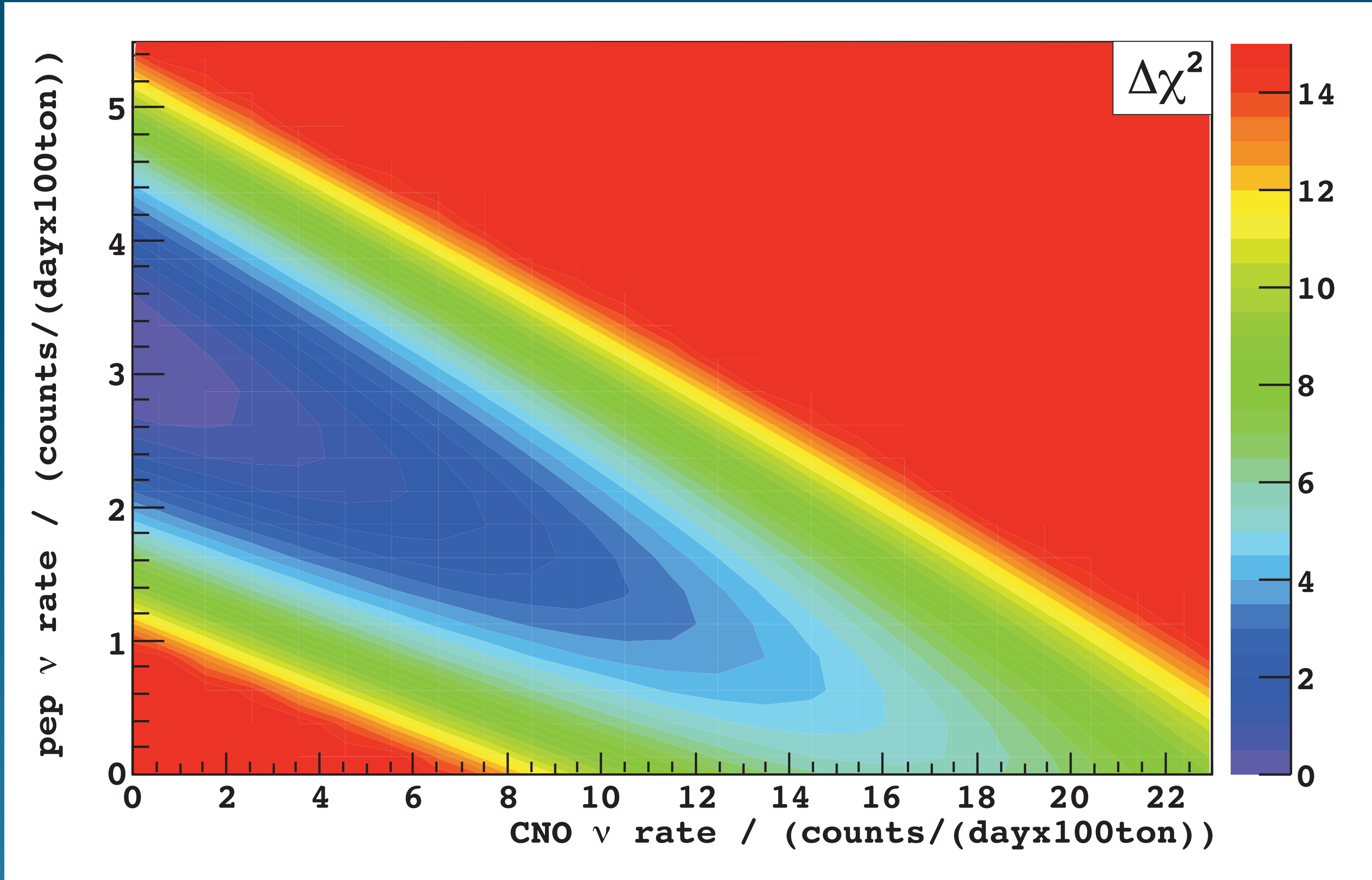
Pulse shape fit



Radial fit



pep vs CNO rates in Borexino



Global Analysis of Solar Neutrino Data

In the framework of neutrino oscillations one defines:

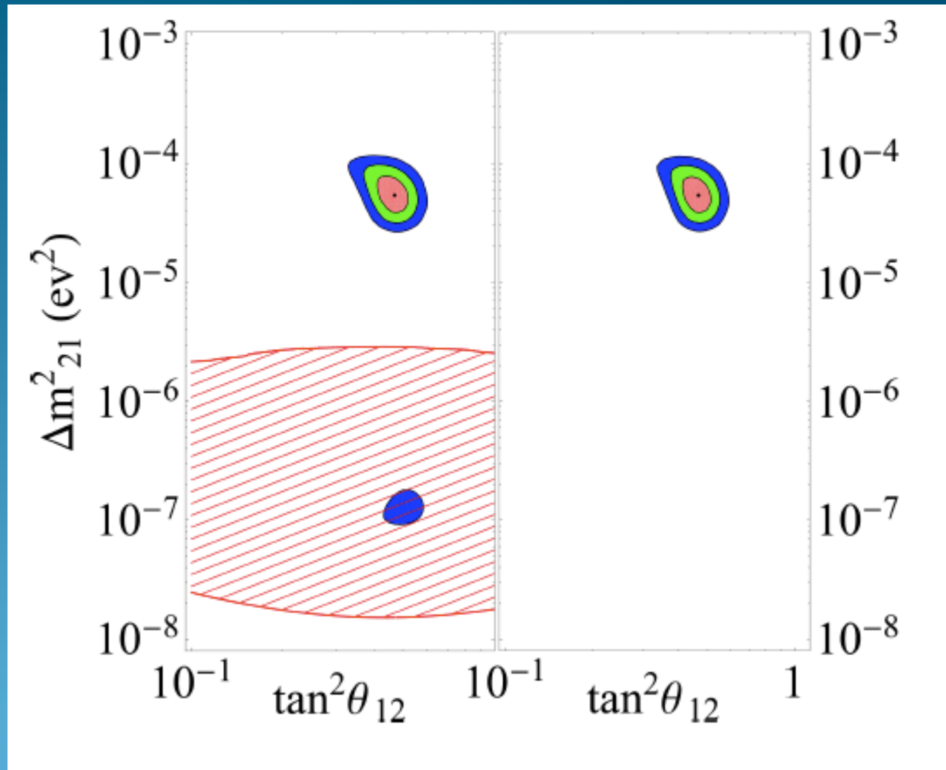
$$\chi^2_{\text{solar+KL}} = \chi^2_{\text{solar}}(\Delta m^2_{21},\, \tan^2\theta_{12},\, \sin^2\theta_{13}) + \chi^2_{\text{KL}}(\Delta m^2_{21},\, \tan^2\theta_{12},\, \sin^2\theta_{13})$$

$$\Delta m^2_{21} = 7.50^{+0.18}_{-0.21} \times 10^{-5}\ \text{eV}^2$$

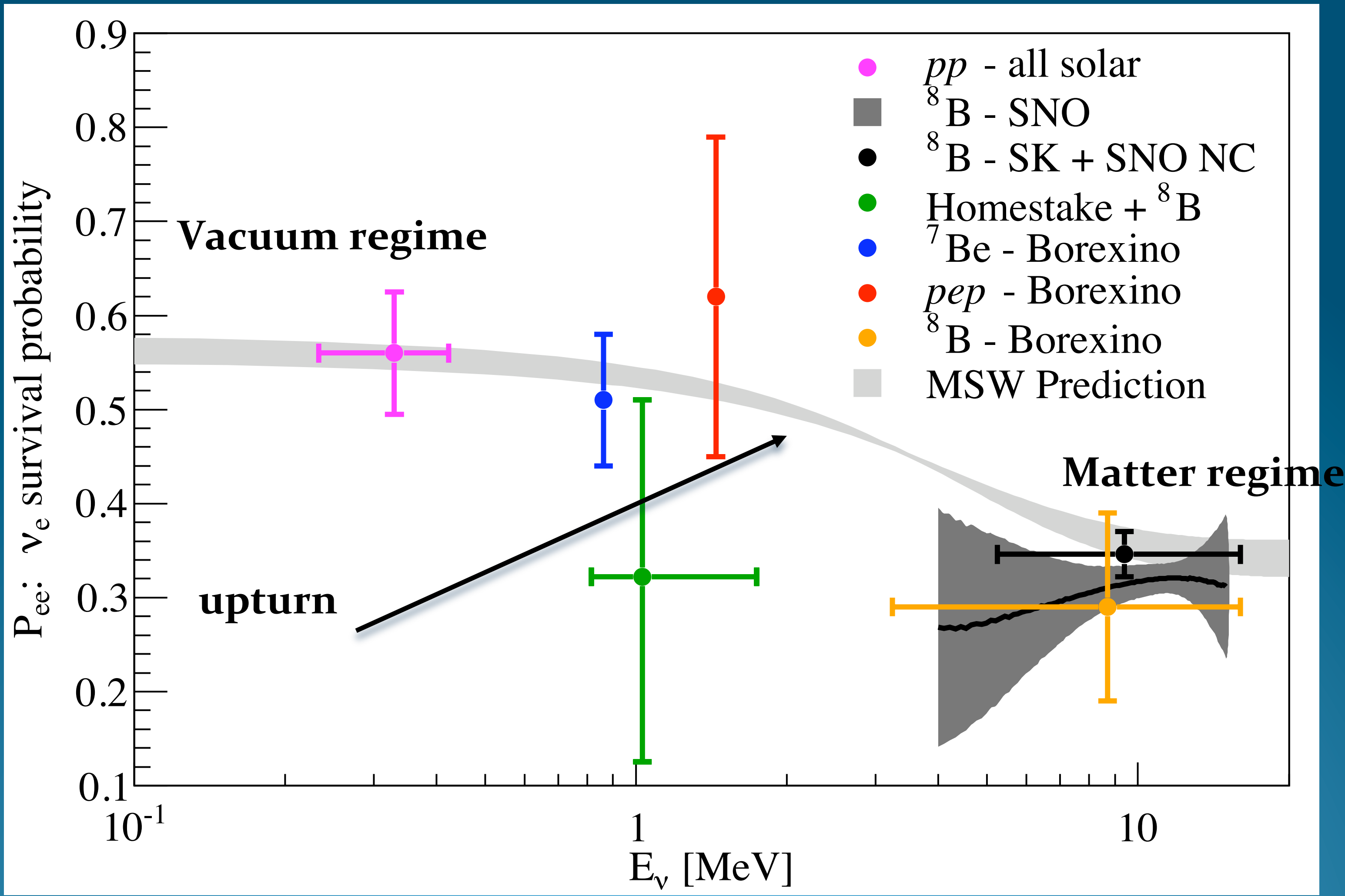
$$\tan^2\theta_{12} = 0.457^{+0.038}_{-0.025}\ \left[0.462^{+0.032}_{-0.033}\right]$$

$$\sin^2\theta_{13} = 0.023^{-0.014}_{-0.018}\ \left[0.025^{-0.003}_{-0.004}\right]$$

Daya Bay and RENO included

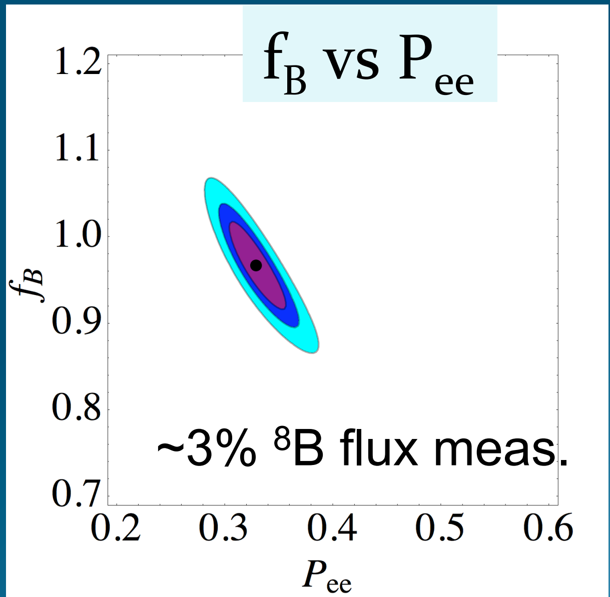


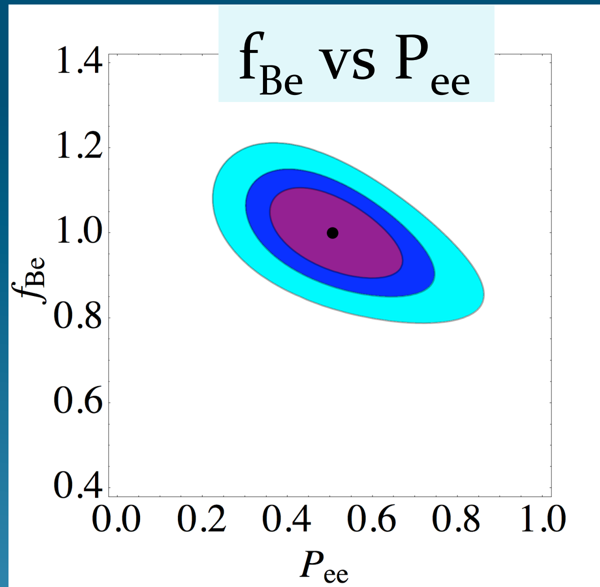
Solar Neutrinos Survival Probability



Determine neutrino fluxes and probe the SSM with neutrinos

^{8}B and ^{7}Be Solar Neutrino Flux from data





Super-K + SNO + Borexino + KamLAND:

$\Phi(^8B) = (5.40\pm0.17)\times10^6$ cm^{-2}s^{-1}

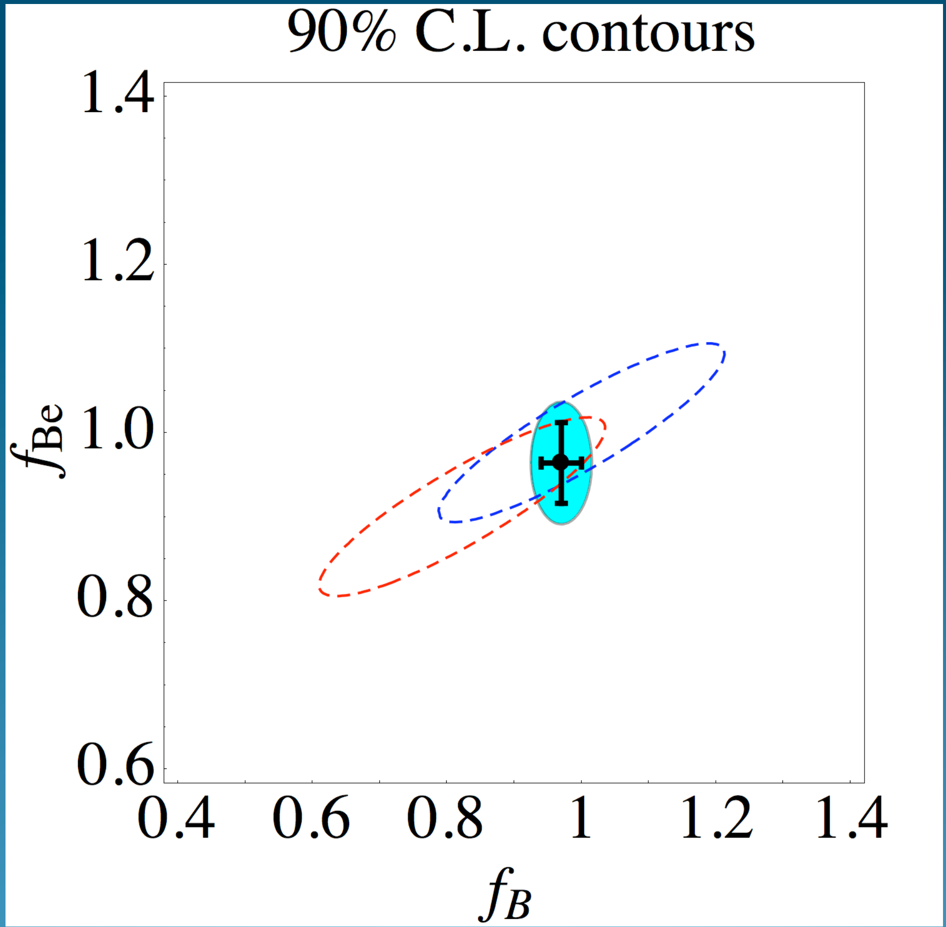
SNO results combined:

$\Phi(^8B) = (5.25\pm0.20)\times10^6$ cm^{-2}s^{-1}

Borexino:

$\Phi(^7Be) = 4.84(1\pm0.05)\times10^9$ cm^{-2}s^{-1}

High-Z and Low-Z SSM vs Data



Solar Neutrino fluxes: observations vs predictions

Source	Flux $[cm^{-2}s^{-1}]$ SSM-GS98	Flux $[cm^{-2}s^{-1}]$ SSM-AGSS09	Flux $[cm^{-2}s^{-1}]$ Data
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	$6.06(1^{+0.003}_{-0.01})\times10^{10}$
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	$1.60(1\pm0.19)\times10^{8}$
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	$4.84(1\pm0.05)\times10^{9}$
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	$5.40(1\pm0.031)\times10^{6}$
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$3.76(1\pm0.15)\times10^{8}$	$<6.7\times10^{8}$
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	$<3.2\times10^{8}$
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	$<59\times10^{6}$
CNO	5.24×10^{8}	3.76×10^{8}	**$<7.7\times10^{8}$ (2σ)**

Without the luminosity constraint:
ϕ_{pp} determined with 15% uncertainty

upper limit smaller than 2004 prediction!

What Next with Solar Neutrinos?

- Three experiments in data taking at present:
  - Super-K: running w/ lower threshold, improved DAQ
  - Borexino: running w/ lower background w/ the possibility to improve it further
  - SAGE: ~21 years regularly in operation

- SNO+ approaching (>2013):
  - main goal double beta decay
  - check radiopurity for solar neutrinos
  - see talk by S. Peeters

- Long term projects: LENS, CLEAN, XMASS, LENA, MOON …

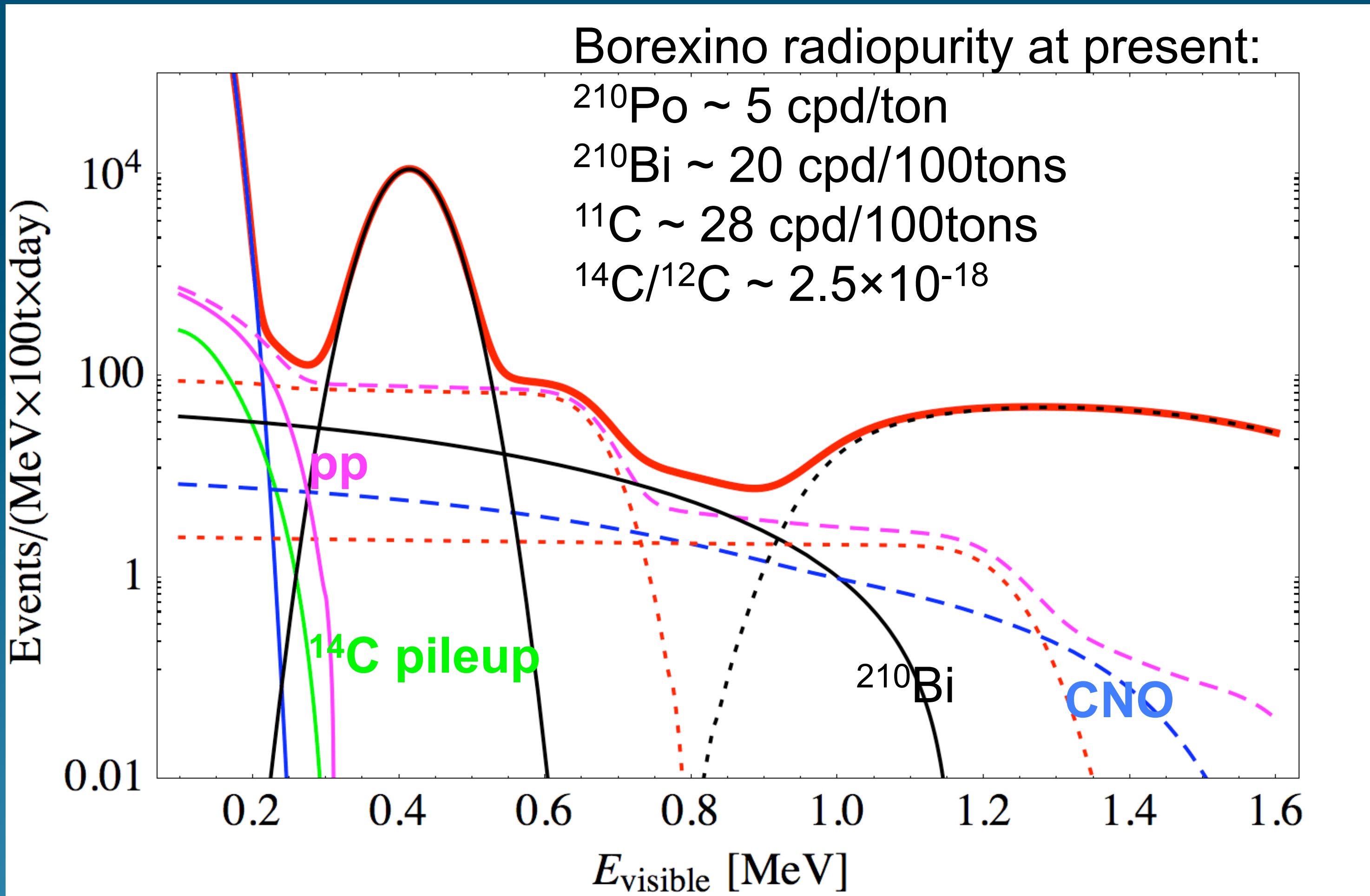
Goals for next steps

- Upturn of survival probability and NSI
  - Need to measure 1 MeV range -> NOT easy!

- Observation and/or measurement of pp neutrinos
  - Discussion next slides
  - Improved ^{7}Be measurement to 3% for a 3% pp neutrino measurement in LENS

- **MAIN goal**: CNO neutrinos observation
  - Need very low background and ^{11}C suppression
  - Observation in Borexino possible but VERY difficult, comments later
  - SNO+ could offer an opportunity in the coming years

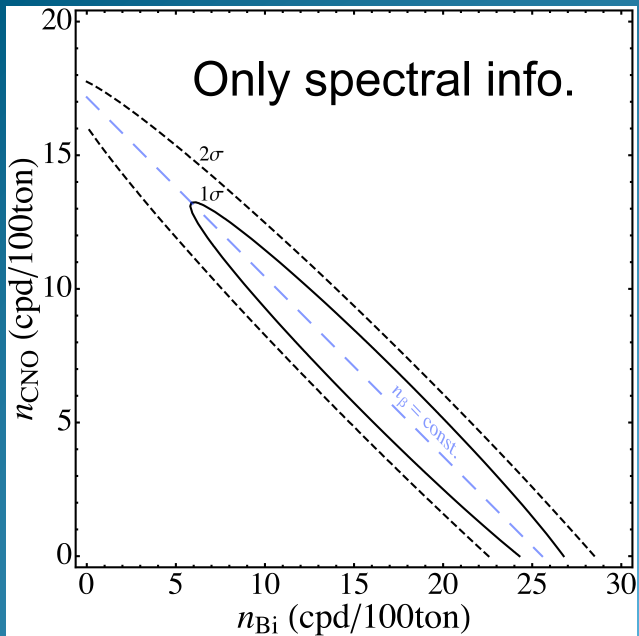
Toward a CNO observation: step 1

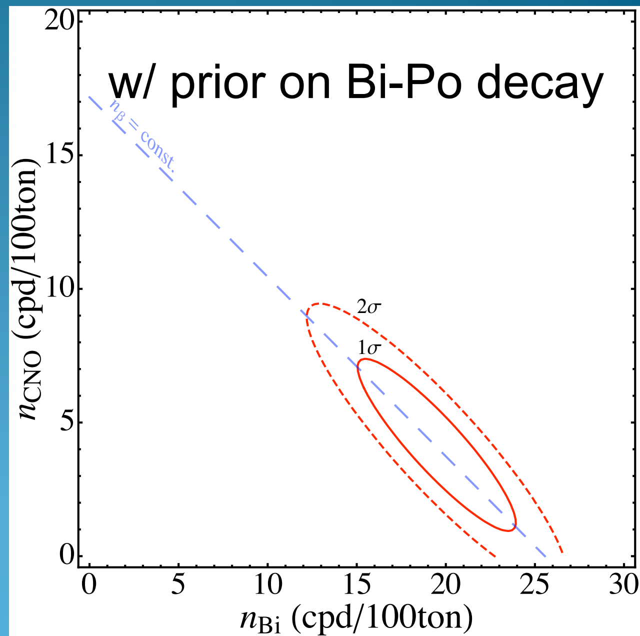


CNO neutrino measurements

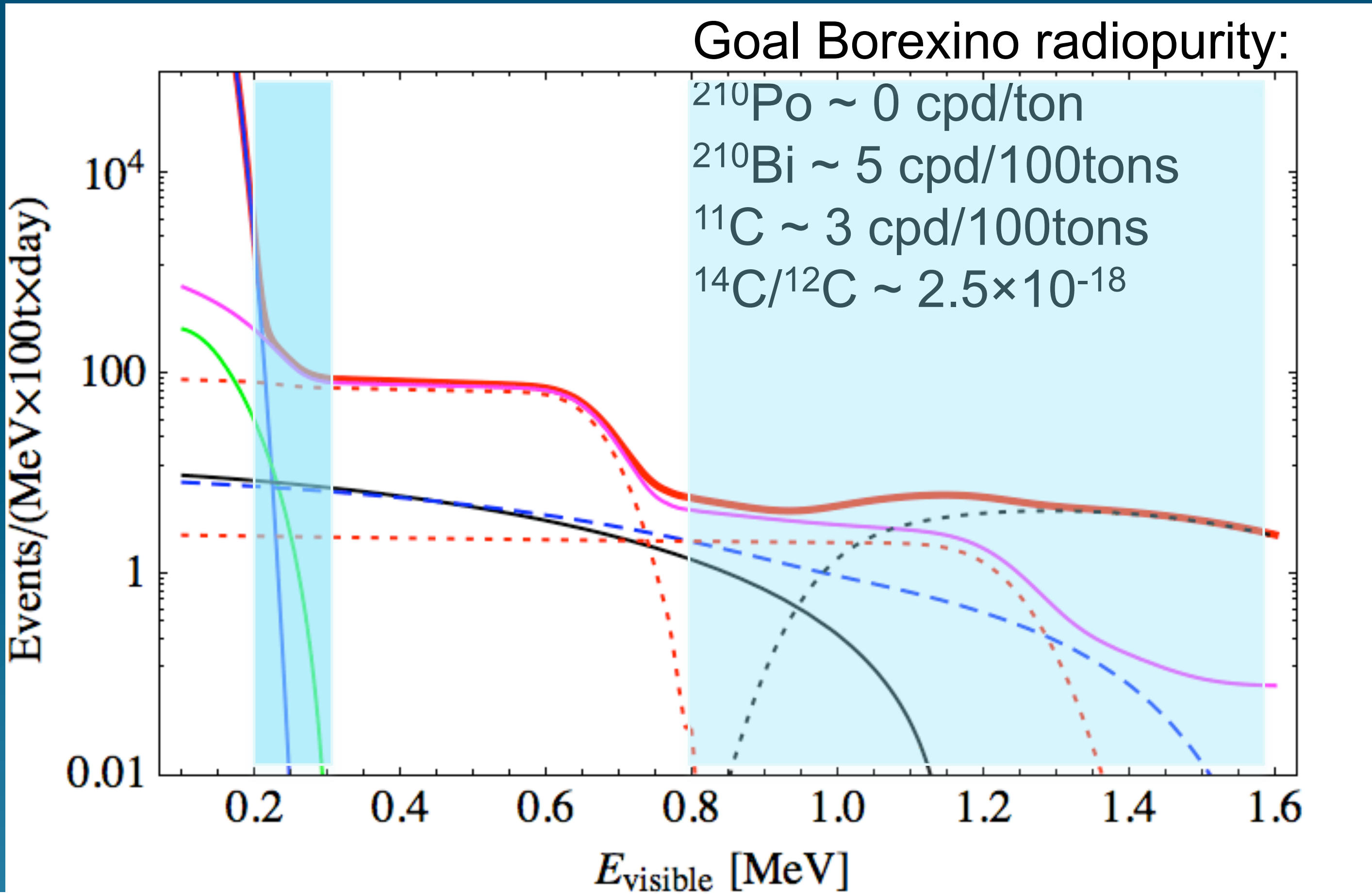
Degeneragy in the energy spectrum between ^{210}Bi and CNO with the addition of ^{11}C background makes this measurement very challenging

One possibility is offered by trying to constrain ^{210}Bi rate using the ^{210}Po tagging (Villante et al. , Phys. Lett. B 701, 2011).



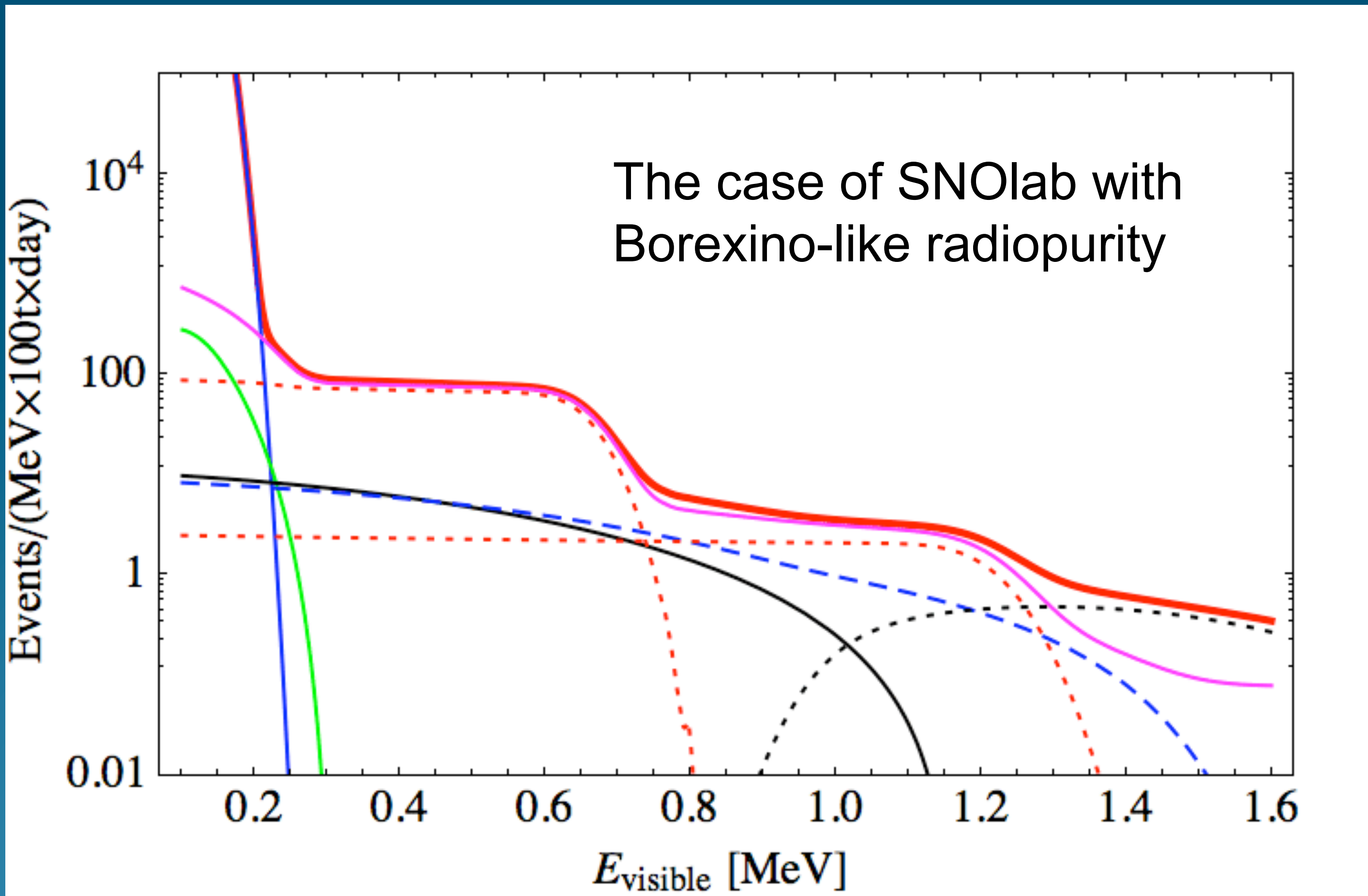


Toward CNO observation: step 2



$$\frac{s_{CNO}}{\sqrt{s_{CNO}+b}} \sim 0.23$$

Toward CNO observation: step 3



... at the end of the solar neutrino phase
… before turning to a “new” detector or stopping
A neutrino radioactive source project seems a good opportunity to make use of present performances and equipments …

Artificial Neutrino Sources with a low threshold Solar Neutrino detector

The idea: make use of a neutrino source in a Borexino-like detector

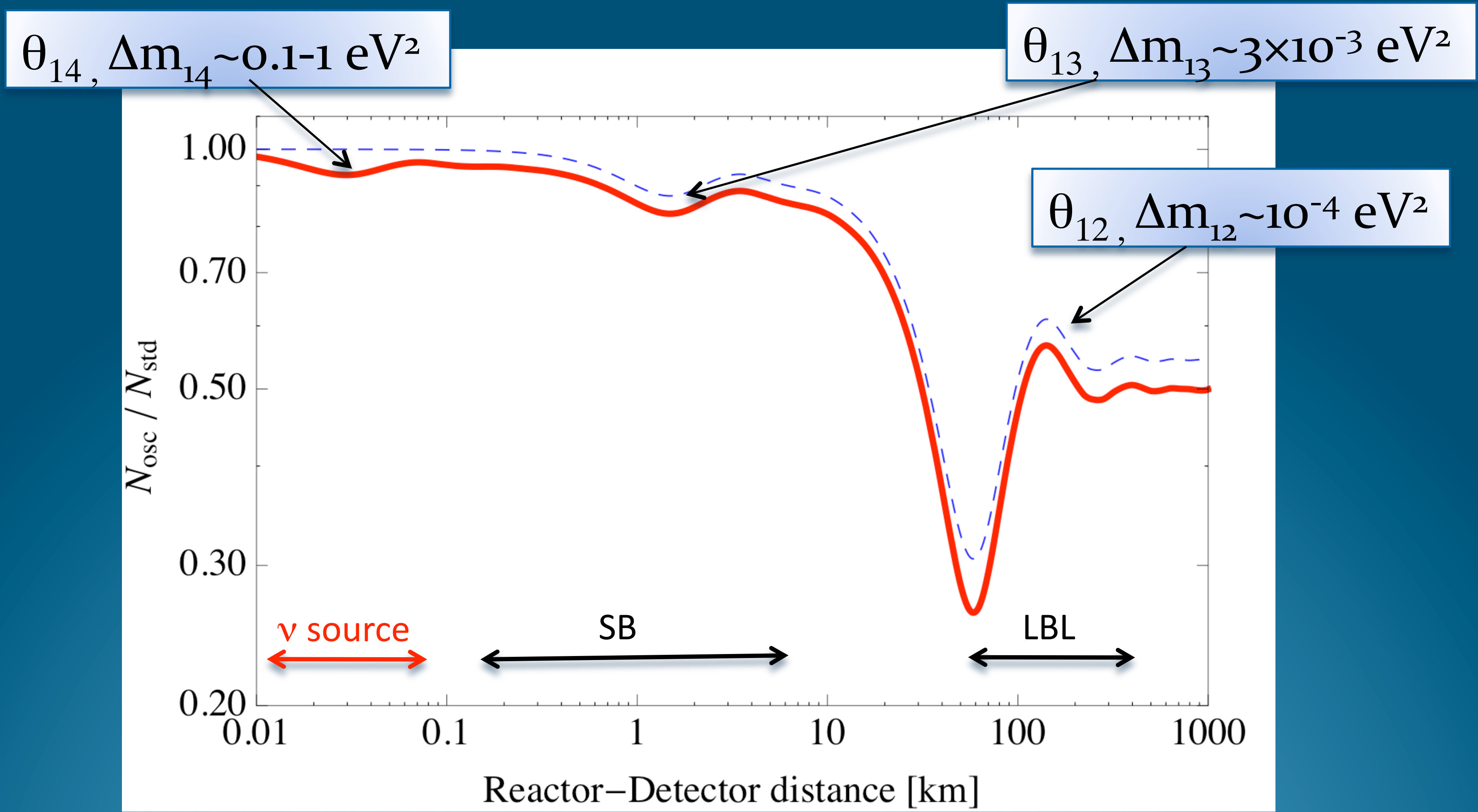
- N.G.Basov,V.B.Rozanov, JETP 42 (1985)
- Borexino proposal, 1991
- J.N.Bahcall,P.I.Krastev,E.Lisi, Phys.Lett.B348:121-123,1995
- N.Ferrari,G.Fiorentini,B.Ricci, Phys. Lett B 387, 1996
- I.R.Barabanov et al., Astrop. Phys. 8 (1997
- Gallex coll. PL B 420 (1998) 114
- A.Ianni,D.Montanino, Astrop. Phys. 10
- A.Ianni,D.Montanino,G.Scioscia, Eur. Phys. J C8, 1999
- SAGE coll. PRC 59 (1999) 2246
- SAGE coll. PRC 73 (2006) 045805
- C.Grieb,J.Link,R.S.Raghavan, Phys.Rev.D75:093006,2007
- V.N.Gravrin et al., arXiv: nucl-ex:1006.2103
- C.Giunti,M.Laveder, Phys.Rev.D82:113009,2010
- C.Giunti,M.Laveder, arXiv:1012.4356
- White paper, arXiv:1204.5376

Sterile Neutrino Case and Source Experiment

Recently the Gallium and reactor anomaly gave a boost to the interest in a new possible physics at very short baselines.

Low threshold detector such as Borexino, KamLAND, SAGE and in the near future SNO+ might offer a possibility to perform a <10m baseline oscillation search

The case of reactor anti-neutrinos



Source Experiment: Physics Case

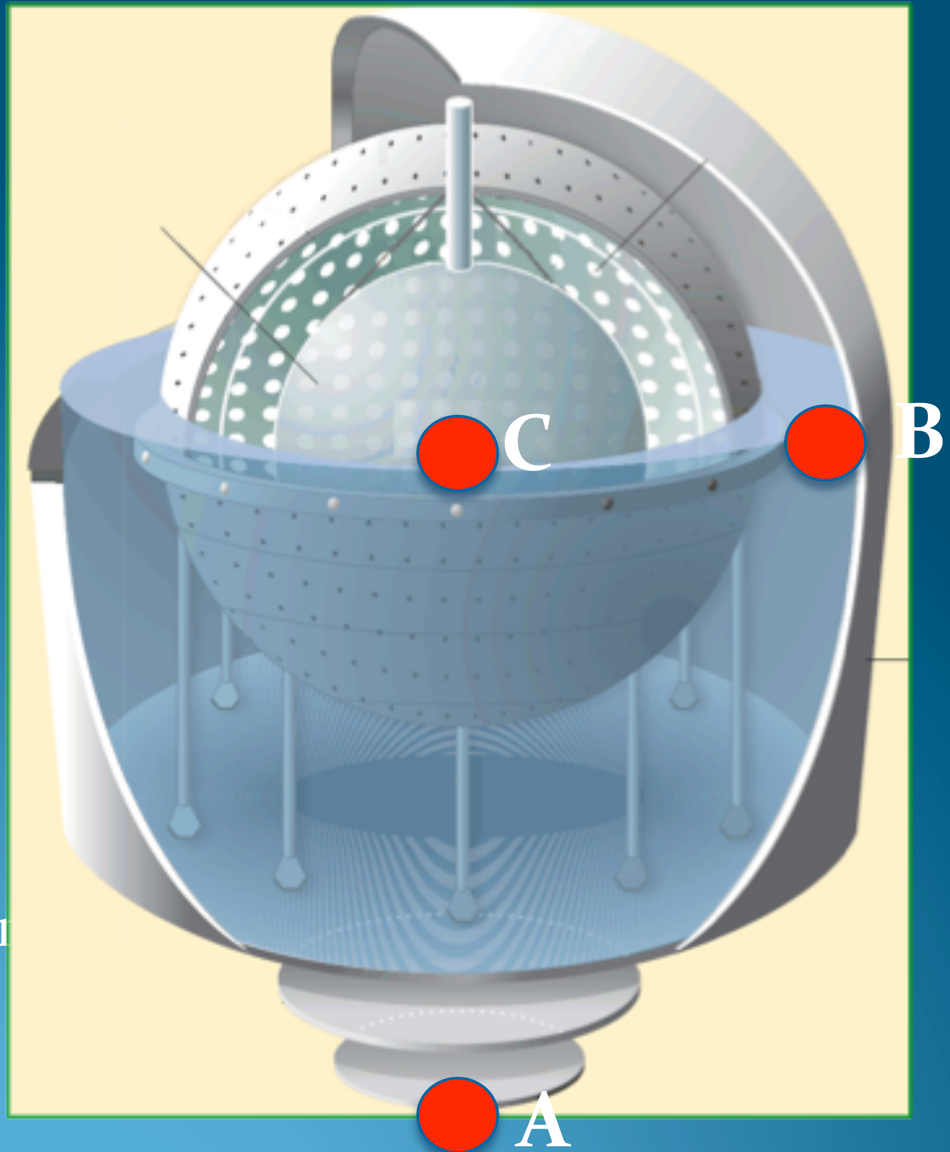
- Probing Short Baseline Flavor Oscillations in disappearance
- Search for Neutrino Magnetic moment
- Probe neutrino-electron scattering at 1 MeV scale
  - Weinberg’s angle
  - g_V and g_A coupling

Radioactive Sources

Source	decay	τ [days]	Energy [MeV]	Kg/MCi	W/kCi
^{51}Cr	e-capture (E_γ=0.32 MeV 10%)	40	0.746 81%	0.011	0.19
^{90}Sr-^{90}Y	Fission product β^-	15160	<2.28 MeV 100%	7.25	6.7
^{144}Ce-^{144}Pr	Fission product β^-	411	<2.9975 MeV 97.9%	0.314	7.6

Source location in Borexino (SOX project)

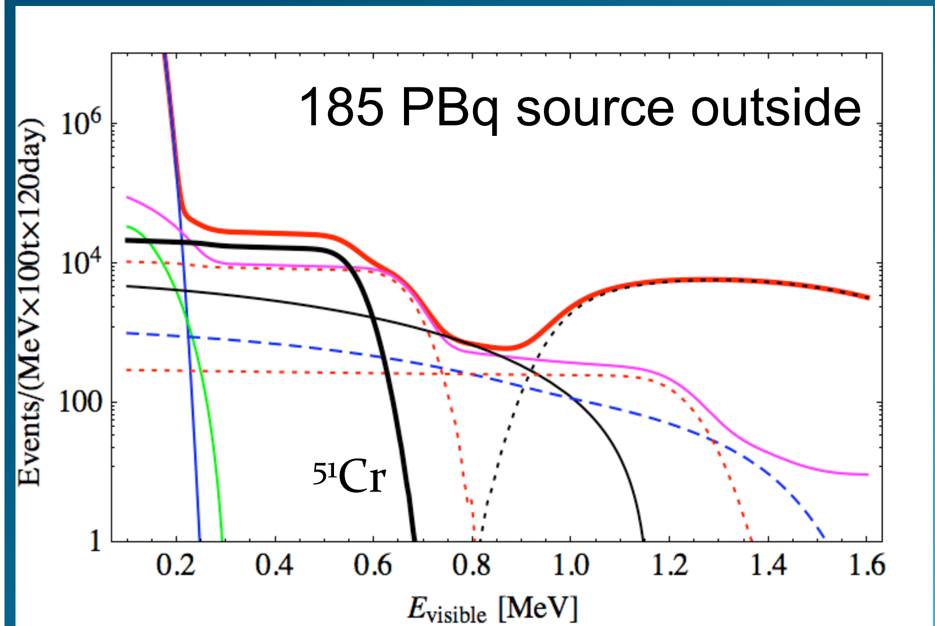
- A: underneath WT
  - D=825 cm
  - No change to present configuration
- B: inside WT
  - D = 700 cm
  - Need to remove shielding water
- C: center
  - Major change
  - Remove inner vessels
  - To be done at the end of solar neutrino physics



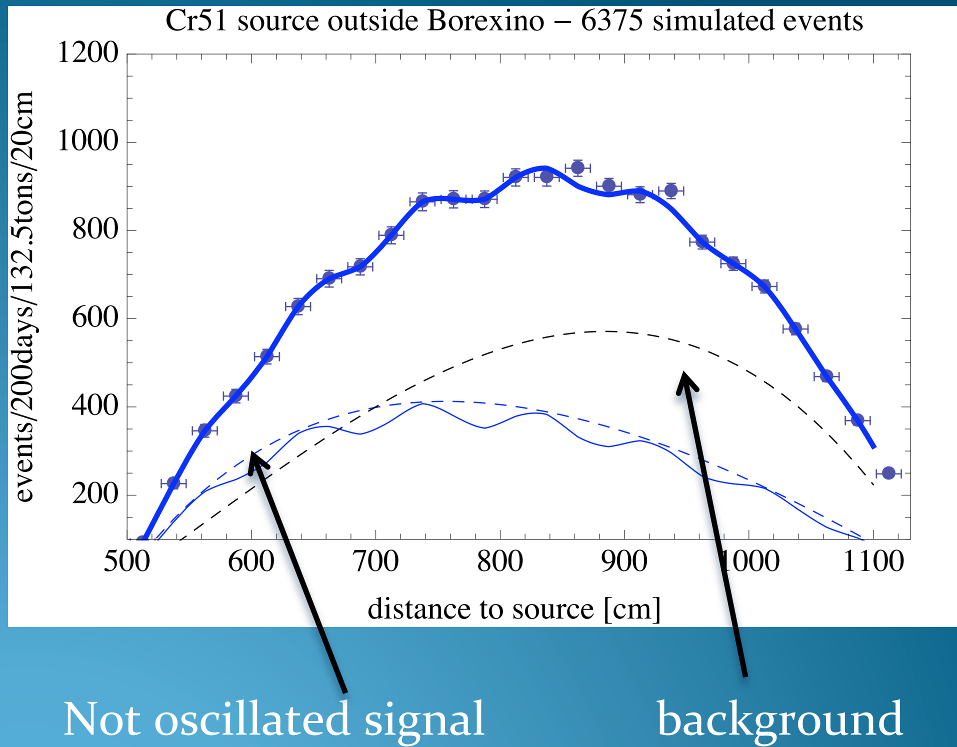
Source position A

^{51}Cr in a Borexino

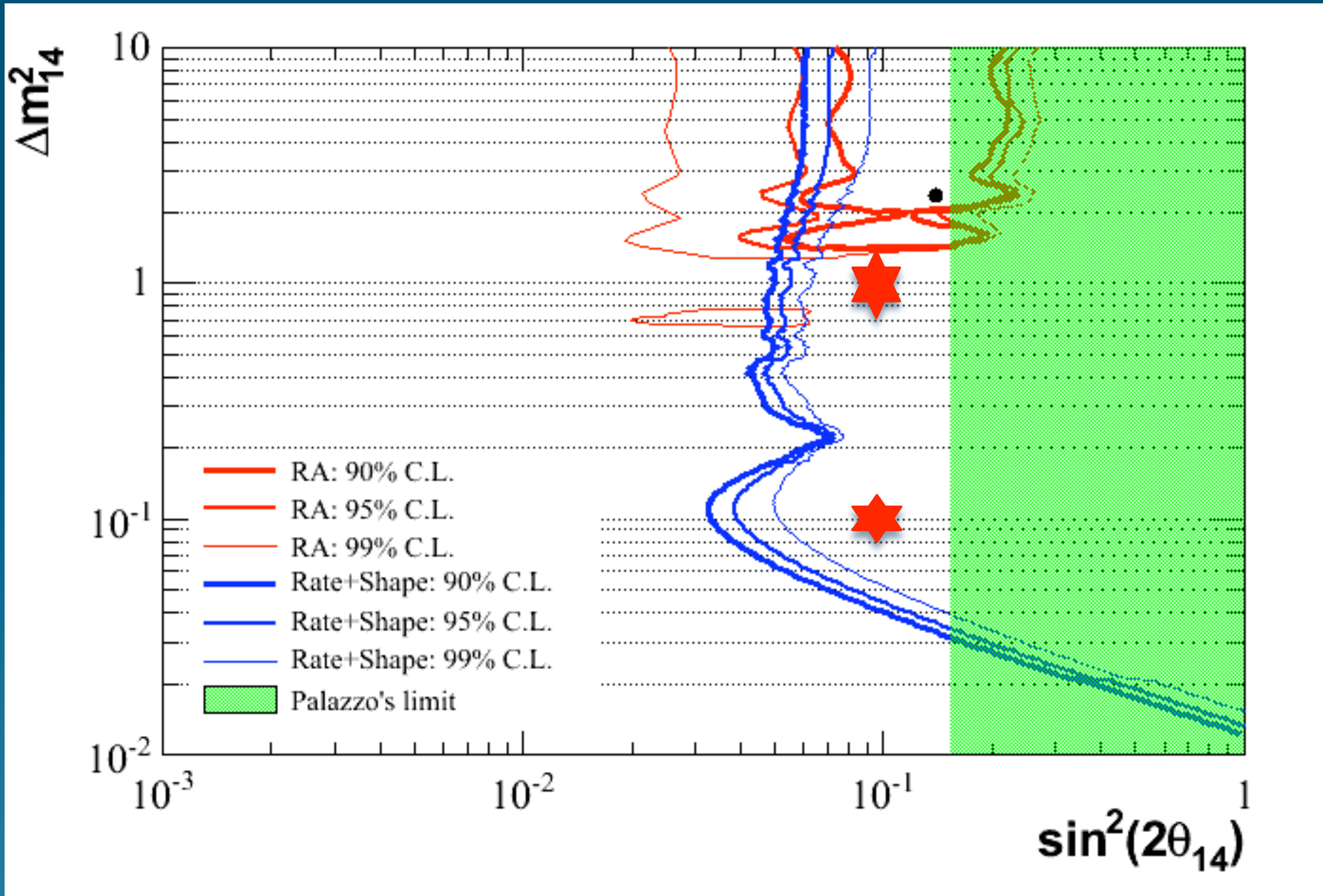
Features for an electron neutrino source outside Borexino



$(\Delta m^2, \sin^2 2\theta_{SBL}) = (2eV^2, 0.15)$



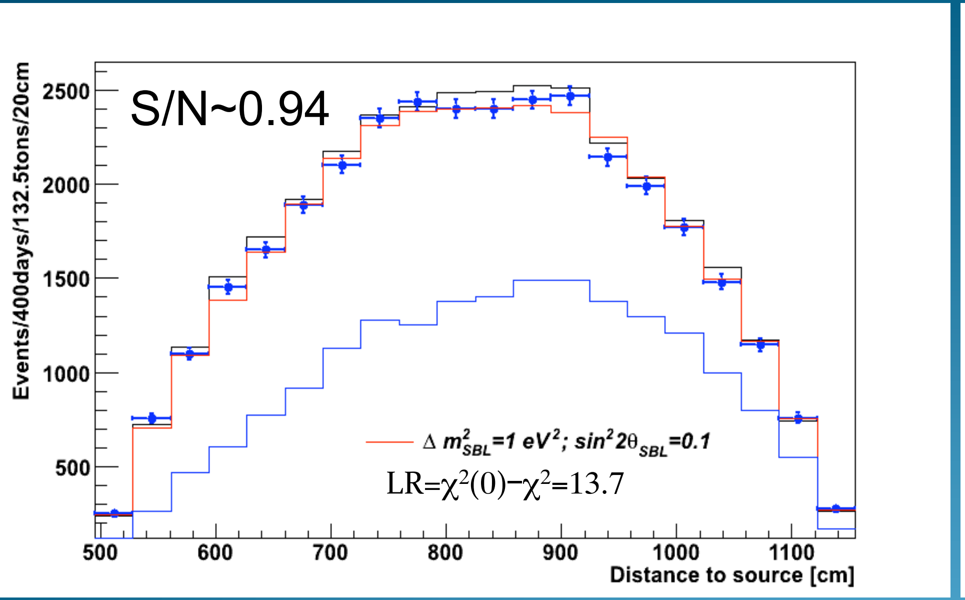
Sensitivity of a ^{51}Cr source in Borexino

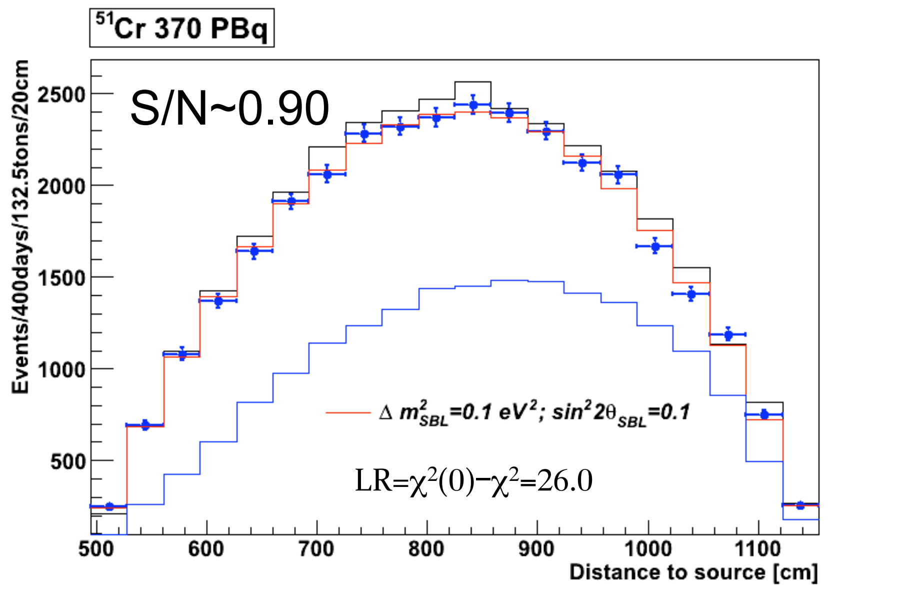


^{51}Cr source outside Borexino

Baseline < 7m

~14500 events predicted w/o oscillations



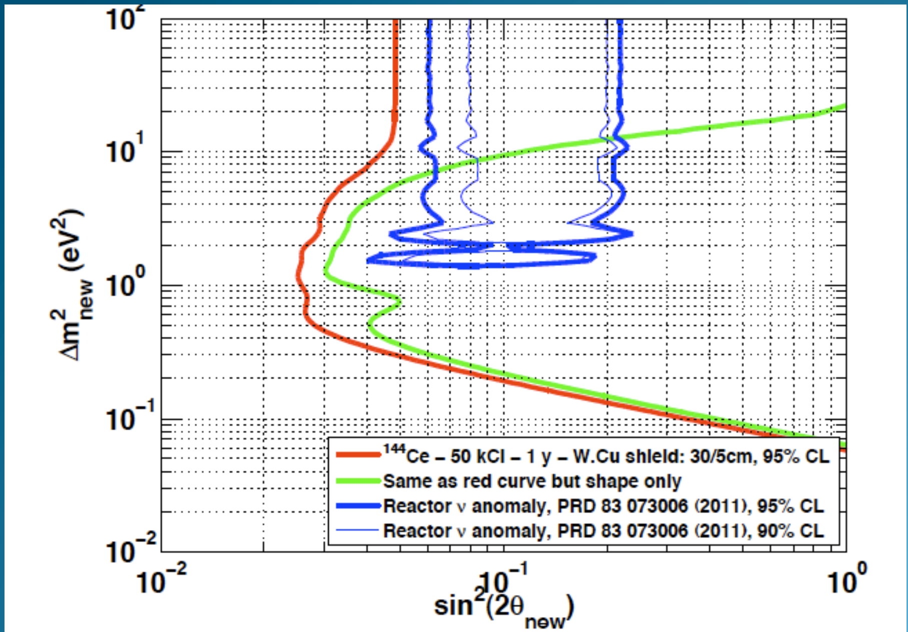


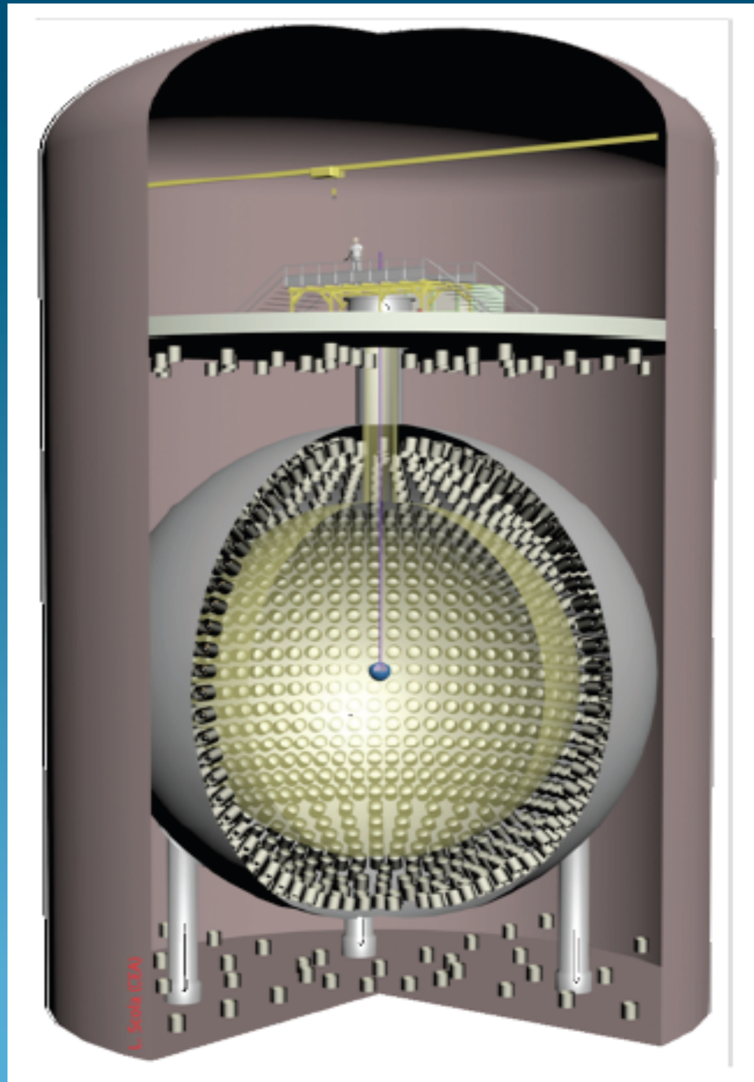
Source location in KamLAND

- **CeLAND** proposal

PRL 107, 201801, 2011

- 1.85 PBq Ce-Pr source

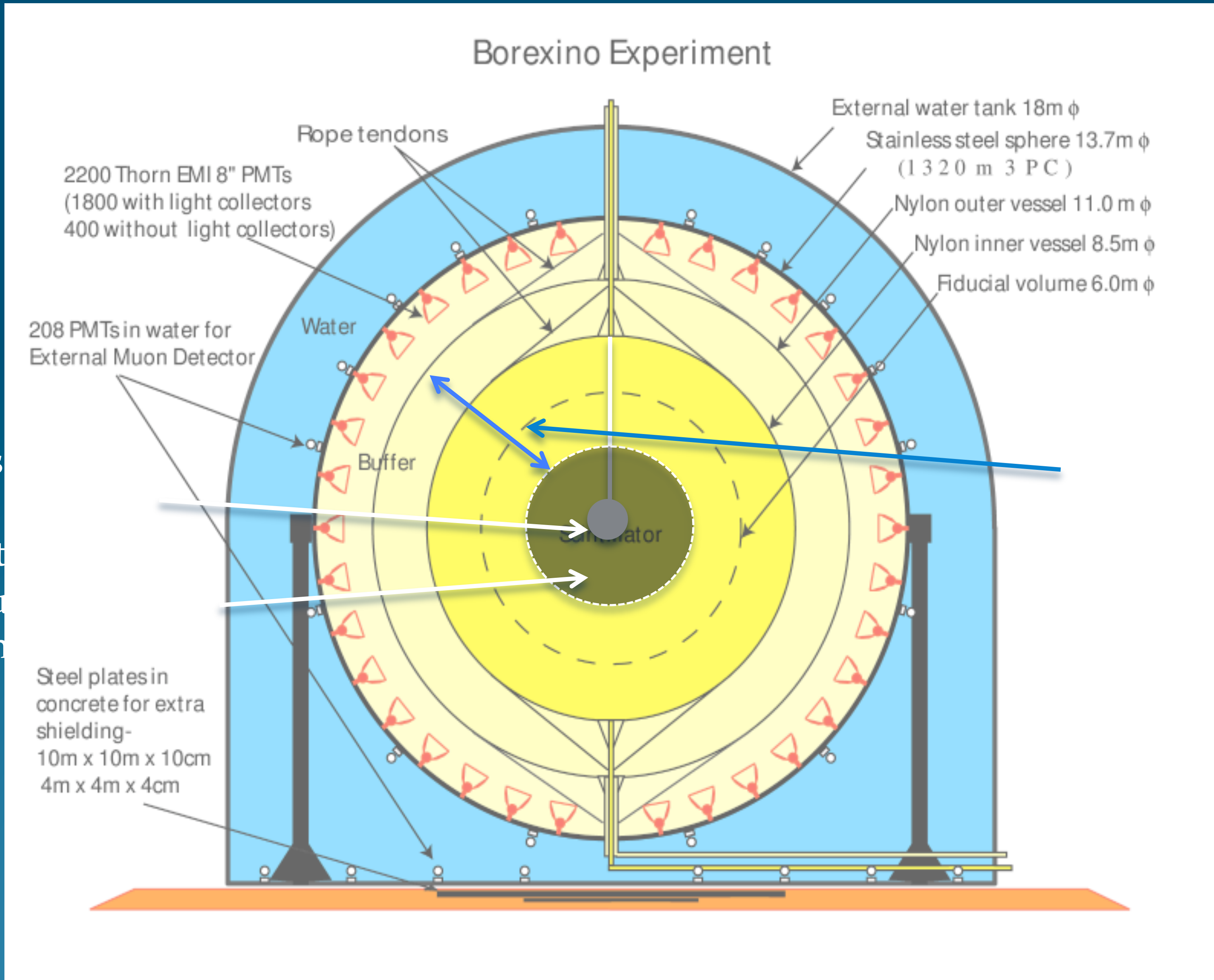




Borexino with source @ center

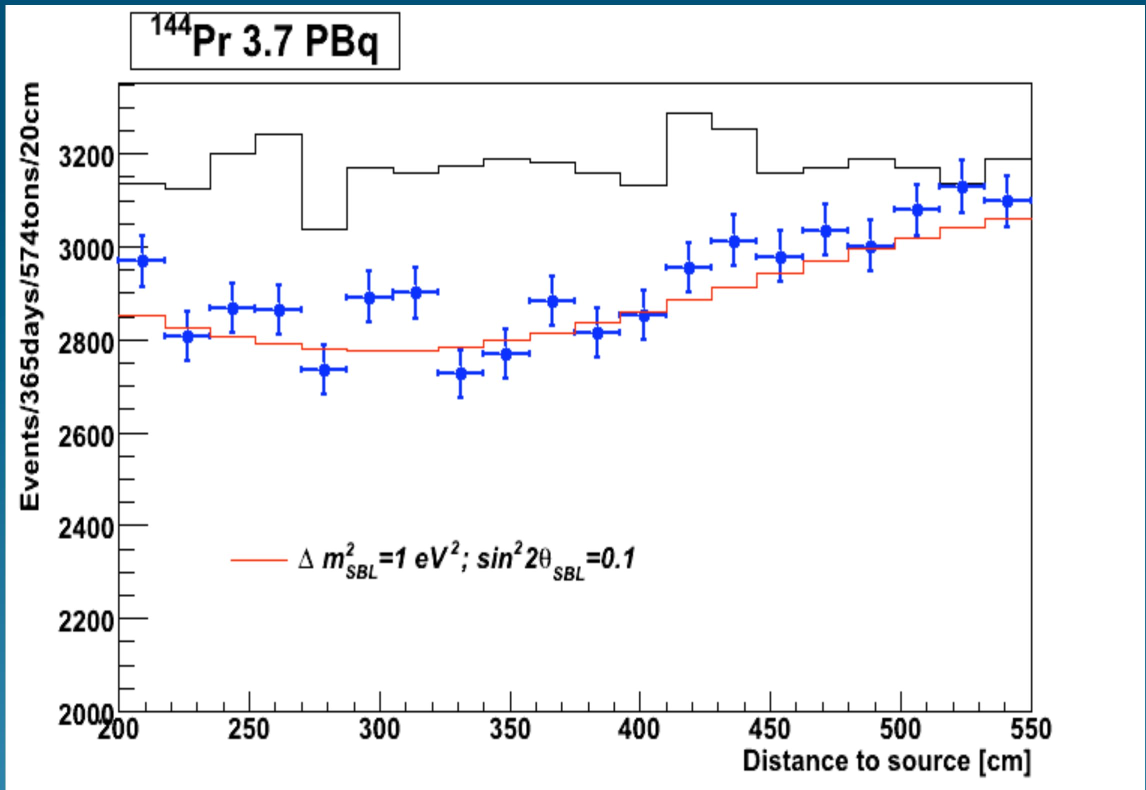
Source+s

Volume t
backgrou
source sh



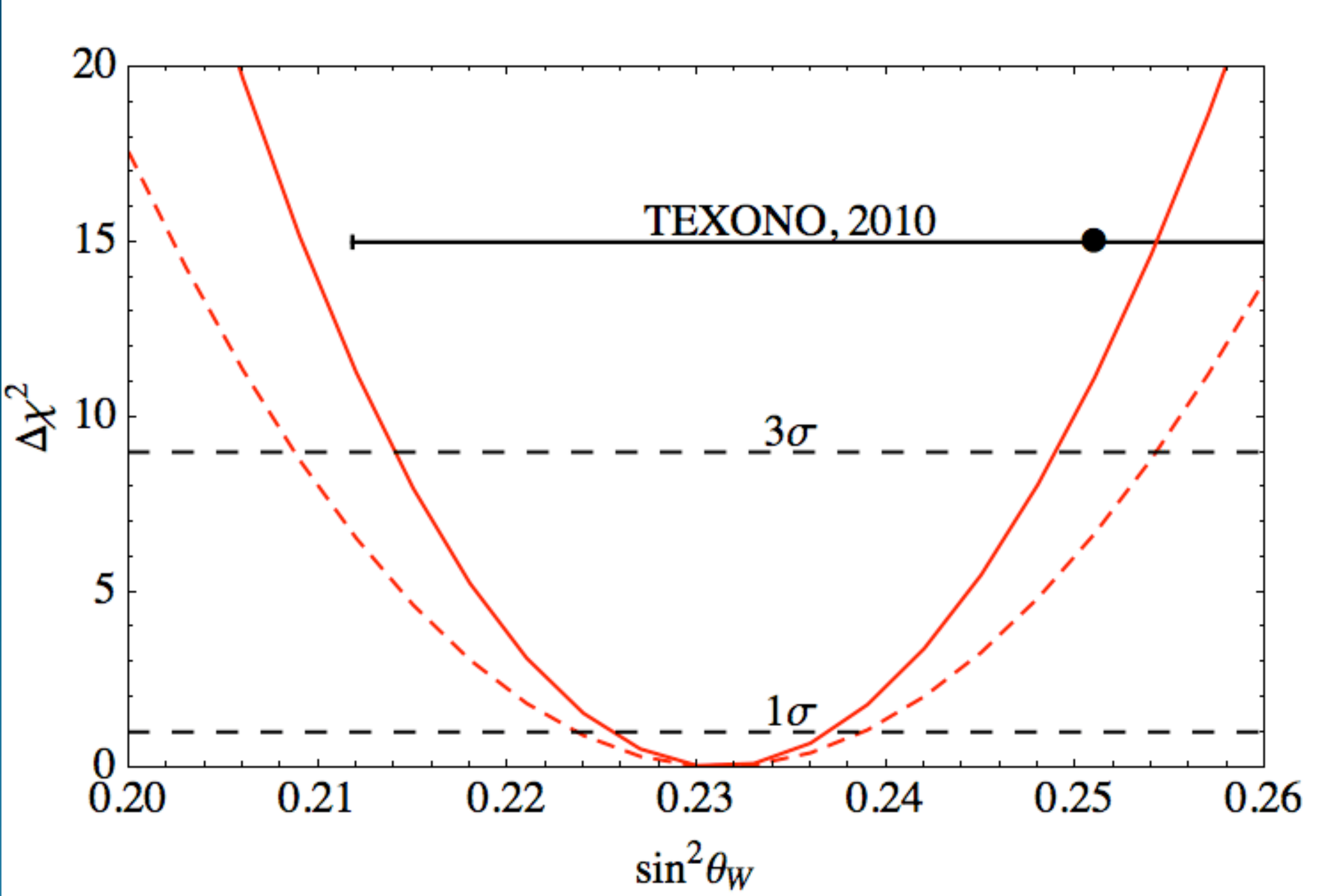
olume

^{144}Ce-^{144}Pr source @ center of Borexino



$\Delta m_{SBL}{}^2$ = 1 eV^2, $\sin^2 2\theta_{SBL}$ = 0.1, $N_{predicted}$ ($\Delta m_{SBL}{}^2$, $\sin^2 2\theta_{SBL}$)=59294 with an exposure = 0.584 kton-y

Weinberg's Angle @ 1 MeV

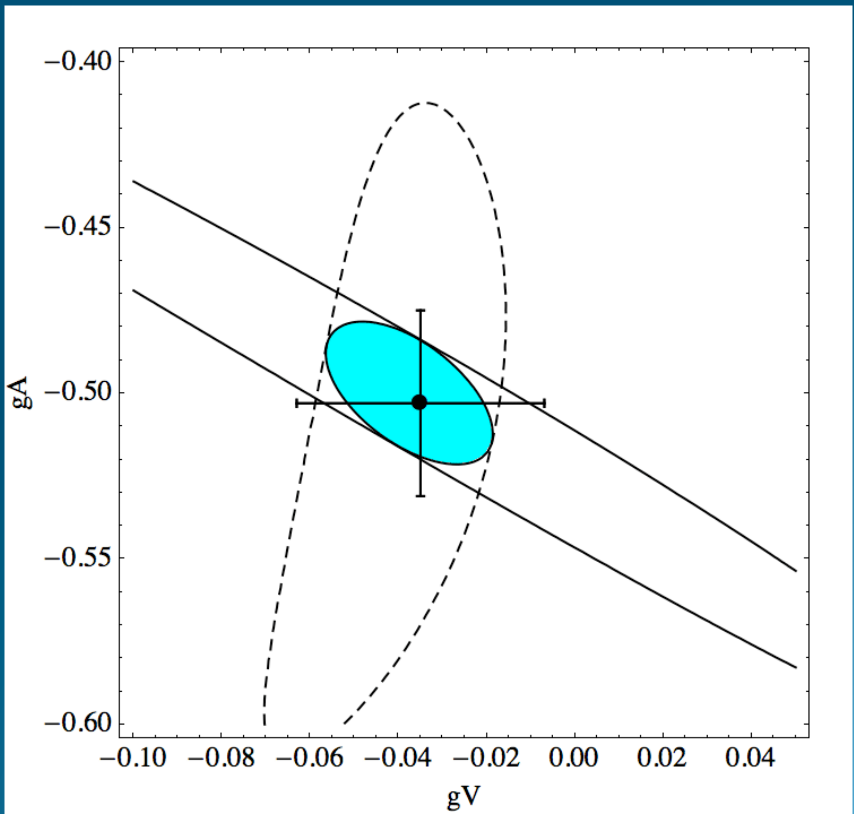


10 MCi source

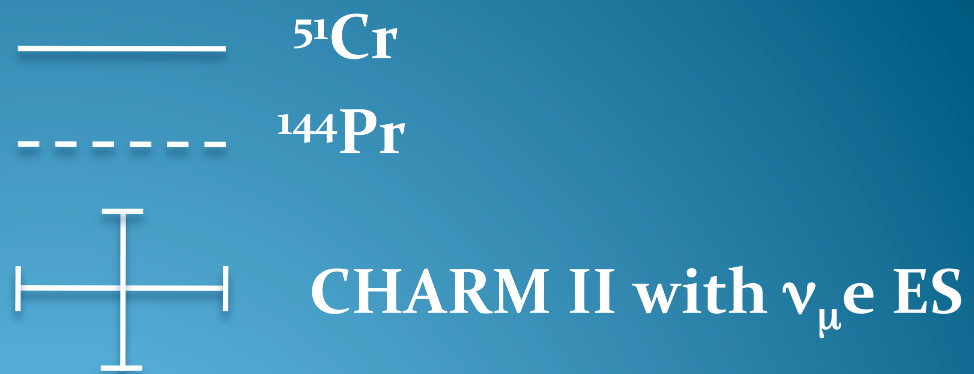
5 MCi source

$\delta(\sin^2\theta_W) = 2.6\%$

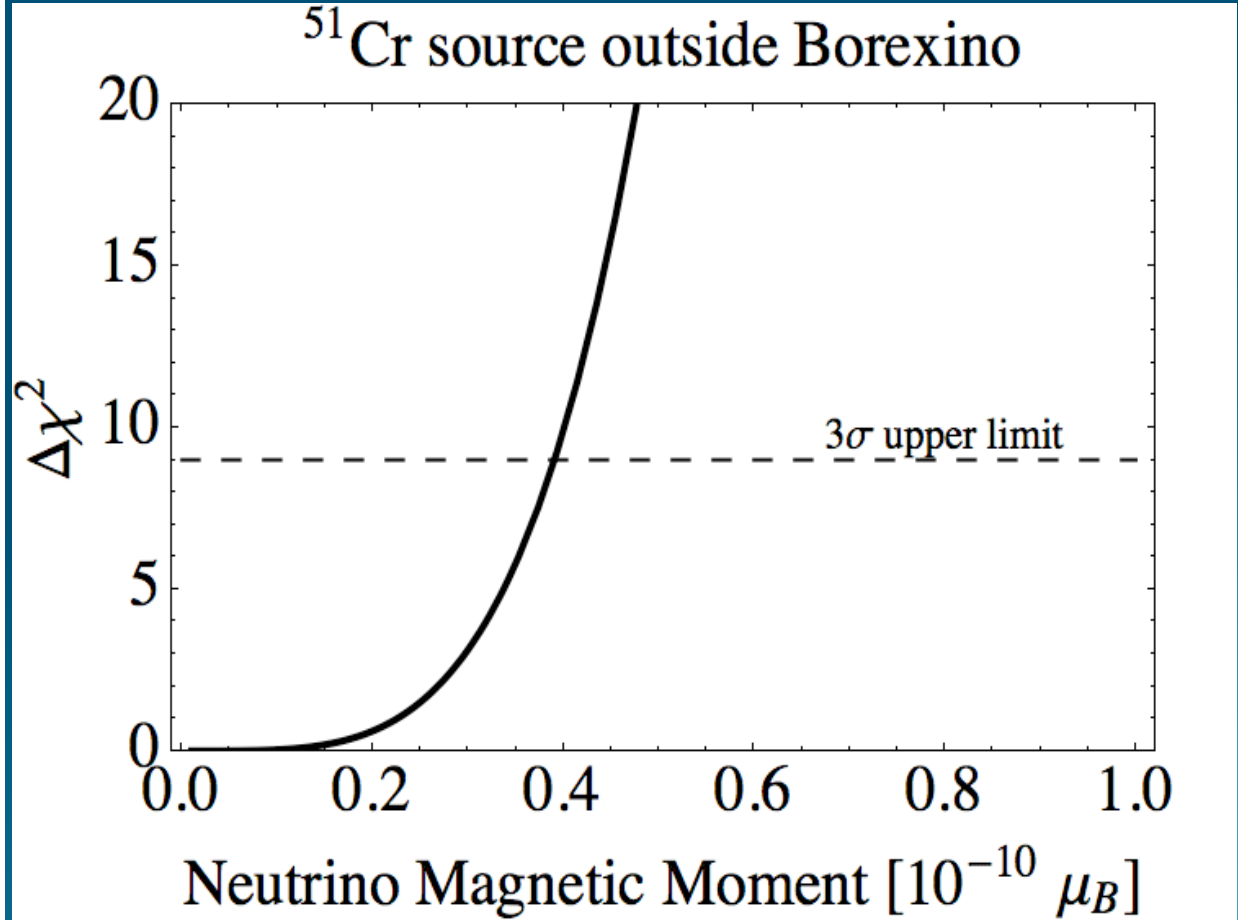
EW couplings



- Standard Model
  - $g_V = -1/2+2\sin^2 q_W = -0.038$
  - $g_A = -0.5$
- Use three-level cross-section
- Use ^{51}Cr and ^{144}Ce source



Neutrino Magnetic Moment



Reactor anti-neutrinos: ~6×10^{-11} μ_B (90% CL)

From Borexino: ~5×10^{-11} μ_B (90% CL)

Conlusions

- Direct real time solar neutrino fluxes (pep, ^{7}Be and ^{8}B) measured
- ^{7}Be and ^{8}B measured at <5% level
- At present three experiments in data taking (Super-K, SAGE and Borexino)

- Next goals for present and near future experiments: pp and CNO

- With some R&D, based on previous experience (GALLEX/SAGE), low threshold solar neutrino detectors could be used to probe oscillations at <10m scale and physics for neutrino-electron interactions at 1 MeV with neutrino radioactive sources [an alternative to IsoDAR-like projects]
  - SOX in Borexino
  - CeLAND in KamLAND

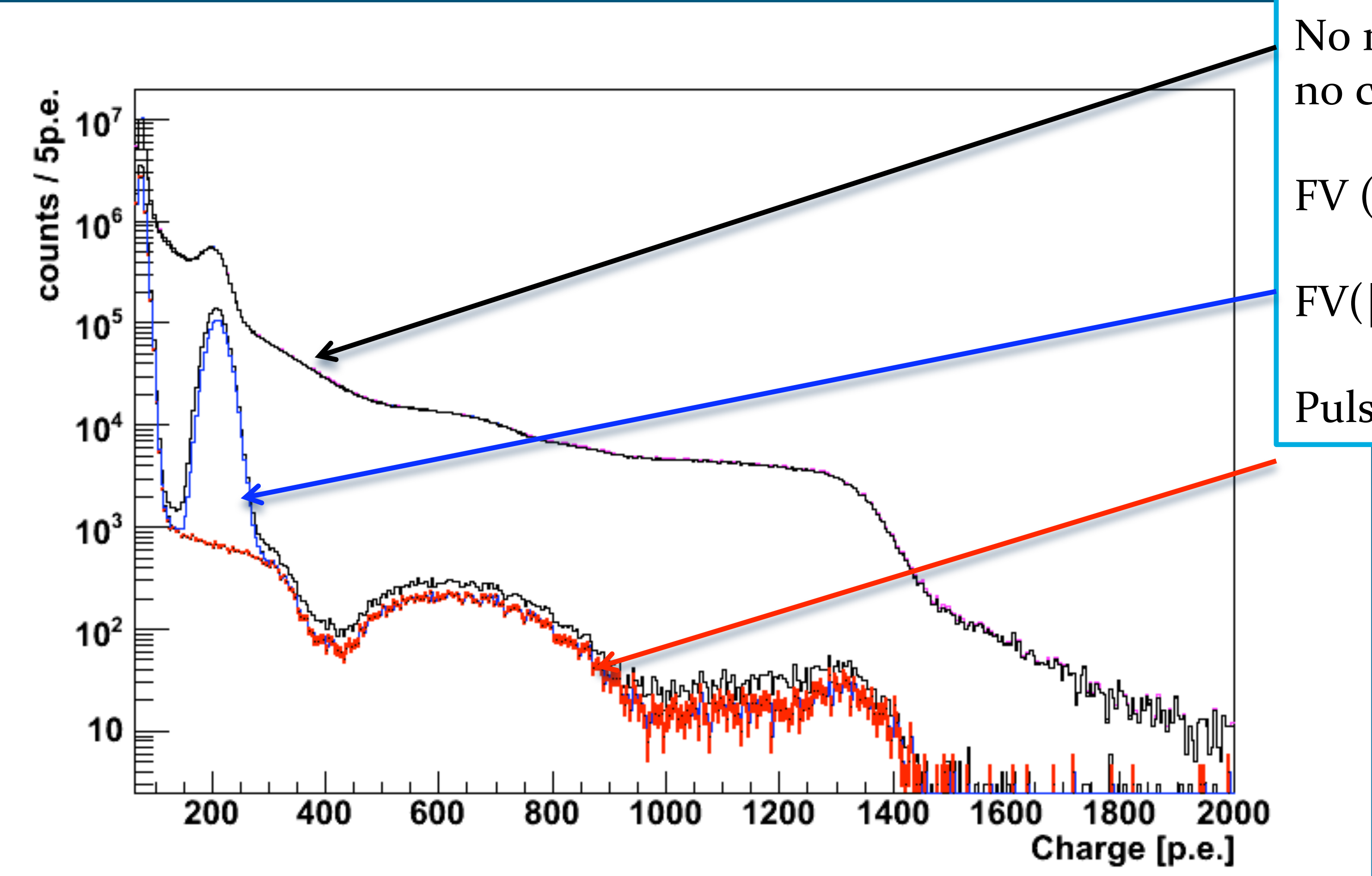
Spares

Weinberg's Angle @ 1 MeV

- ^{51}Cr source outside Borexino
- Expected statistics:
  - ~ 12650 events from source
  - ~4300 from background
- Recent determination from reactor anti-ν:

$\sin^2\theta_W = 0.251 \pm 0.031 \pm 0.024$

Data reduction in Borexino



No muons +
no correlated

FV (<3m)

FV(|z|<1.7m)

Pulse shape

Detector Calibration

Detector response vs position:

✓100 Hz ^{14}C+^{222}Rn in scintillator in >100 positions

Quenching and energy scale:

✓Beta: ^{14}C, ^{222}Rn in scintillator

✓Alpha: ^{222}Rn in scintillator

✓Gamma: ^{139}Ce, ^{57}Co, ^{60}Co, ^{203}Hg, ^{65}Zn, ^{40}K, ^{85}Sr, ^{54}Mn

✓Neutron: AmBe