Neutrinos from the sun and from radioactive sources

A. Ianni, Borexino collaboration
INFN, LNGS

NOW 2012, Sept 11th

Solar Neutrinos

Solar Neutrinos

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

$<E_\nu>$ ~ 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)

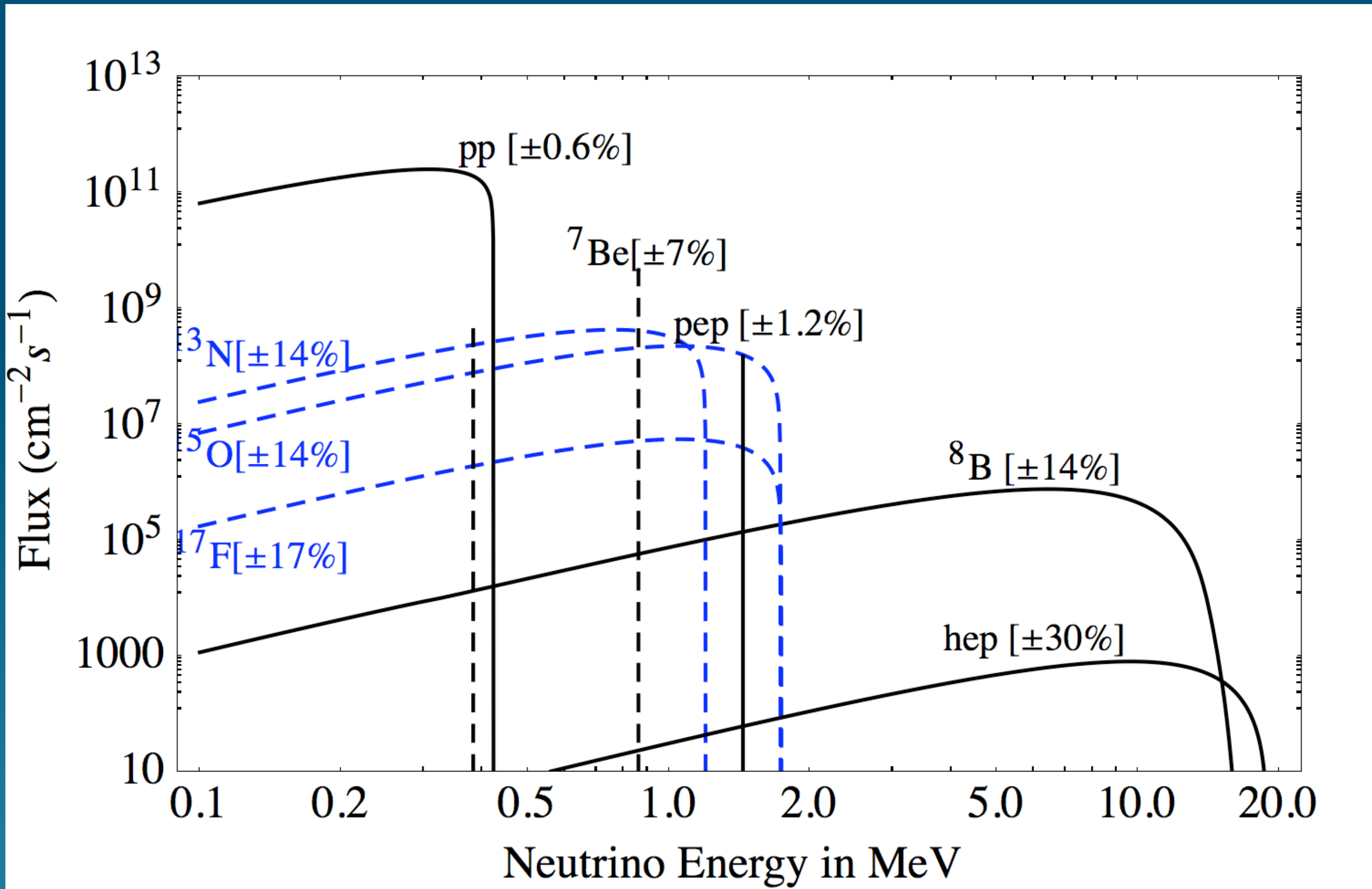
Solar Standard Model

The SSM is the framework from which we make predictions on the production of solar neutrinos
[More on SSM by A. Serenelli this meeting]

Within the SSM solar neutrino fluxes are written as:

$$\begin{aligned}
\phi_{\rm pp} \propto\ & {S_{11}}^{+0.14} \cdot {S_{33}}^{+0.03} \cdot {S_{34}}^{-0.06} \cdot {S_{1,14}}^{-0.02} \cdot {L_\odot}^{+0.73} \cdot {\tau_\odot}^{-0.07} \\
& \cdot {Op_\odot}^{+0.14} \cdot (Z/X)^{-0.08}, \\
\phi_{\rm Be} \propto\ & {S_{11}}^{-0.97} \cdot {S_{33}}^{-0.44} \cdot {S_{34}}^{+0.88} \cdot {L_\odot}^{+3.56} \cdot {\tau_\odot}^{+0.69} \\
& \cdot {Op_\odot}^{-1.49} \cdot (Z/X)^{+0.59}, \\
\phi_{\rm B} \propto\ & {S_{11}}^{-2.59} \cdot {S_{33}}^{-0.40} \cdot {S_{34}}^{+0.81} \cdot {L_\odot}^{+6.76} \cdot {\tau_\odot}^{+1.28} \\
& \cdot {Op_\odot}^{-2.93} \cdot (Z/X)^{+1.36}.
\end{aligned}$$

Solar Neutrino Spectrum at Earth



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

Luminosity Constraint

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

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

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

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

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}

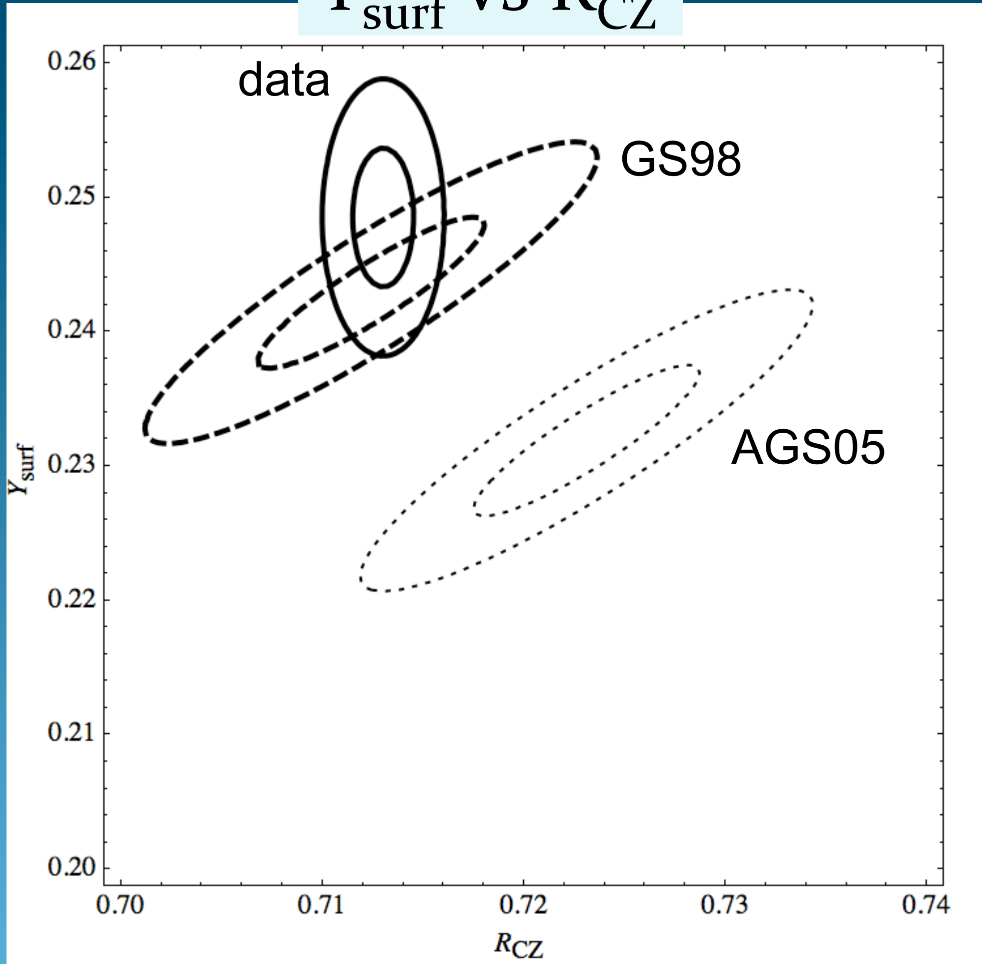
The metallicity problem

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)$\rightarrow$(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

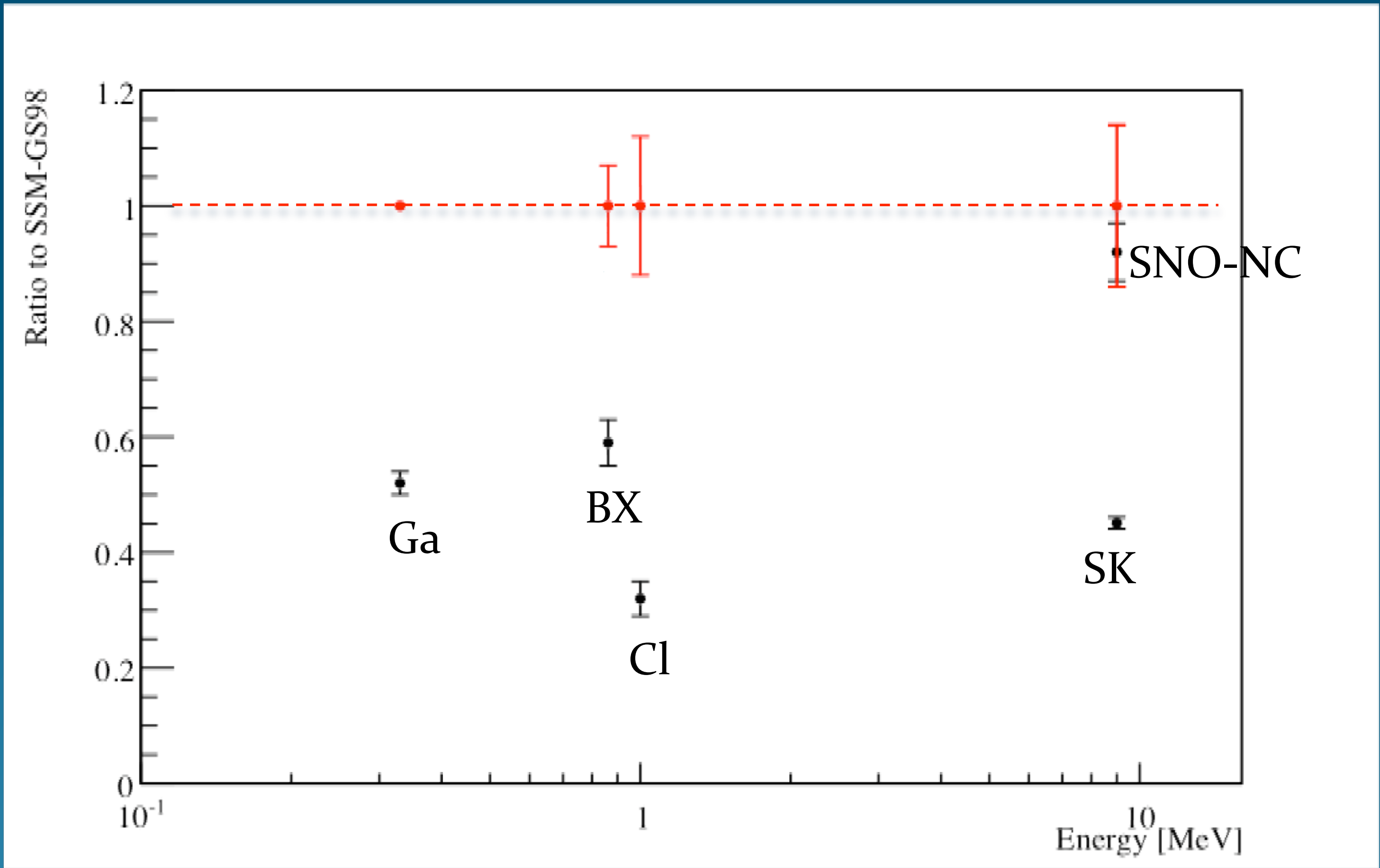
Solar Neutrino Experiments

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 [see H. Sekiya]	22.5ktons	4.5 6.5 4.5 4	1996-2001 2003-2005 2006-2008 **2008-present**
SNO [see N. Barros]	1kton D_2O	5[3.5]	1999-2006
Borexino [see D. Franco]	300ton C_9H_{12}	0.2 MeV	**2007-present**

Solar Neutrino Measurements

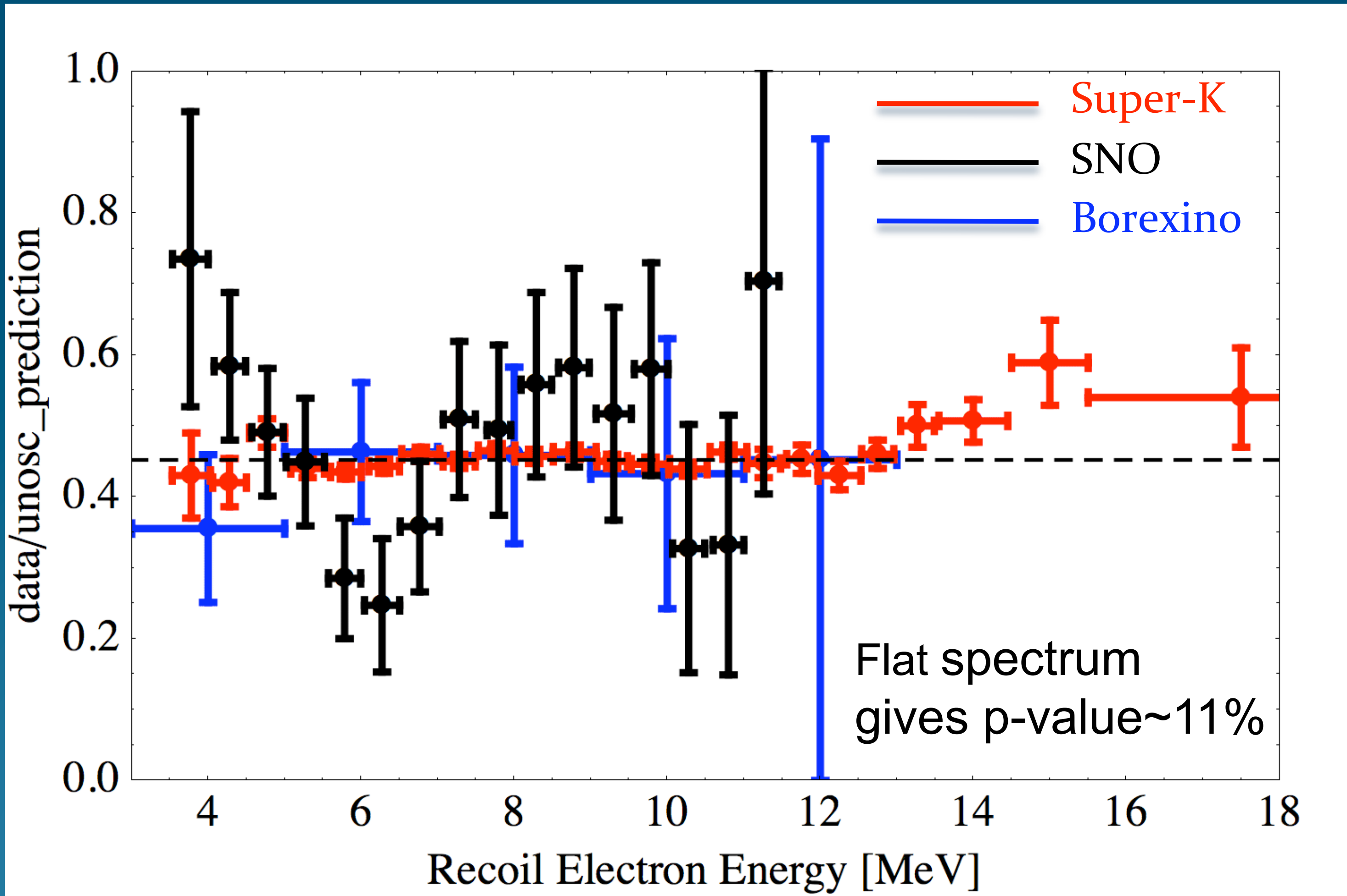
Experiment	Sources contributing to data	**Data**
Homestake	^{7}Be(13.1%)+pep(2.7%)+ CNO(2.4%)+^{8}B(81.8%)	2.56±0.16±0.16 SNU
GALLEX/GNO/SAGE	pp(55%)+^{7}Be(28.3%)+ pep(2.3%)+ CNO(3.4%)+^{8}B(11%)	66.2±3.2 SNU
Super-Kamiokande (I, II, II)	^{8}B	$\Phi_{\nu e} = (2.38 \pm 0.08) \times 10^6$ cm^{-2}s^{-1} $\Phi_{\nu e} = (2.41 \pm 0.16) \times 10^6$ cm^{-2}s^{-1} $\Phi_{\nu e} = (2.39 \pm 0.07) \times 10^6$ cm^{-2}s^{-1}[~3%}
SNO	^{8}B	$\phi_B = 5.25 \pm 0.16^{+0.11}_{-0.13}$ [~4%] CC/NC=0.301±0.033
BOREXINO	^{7}Be(0.862MeV) pep ^{8}B(>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

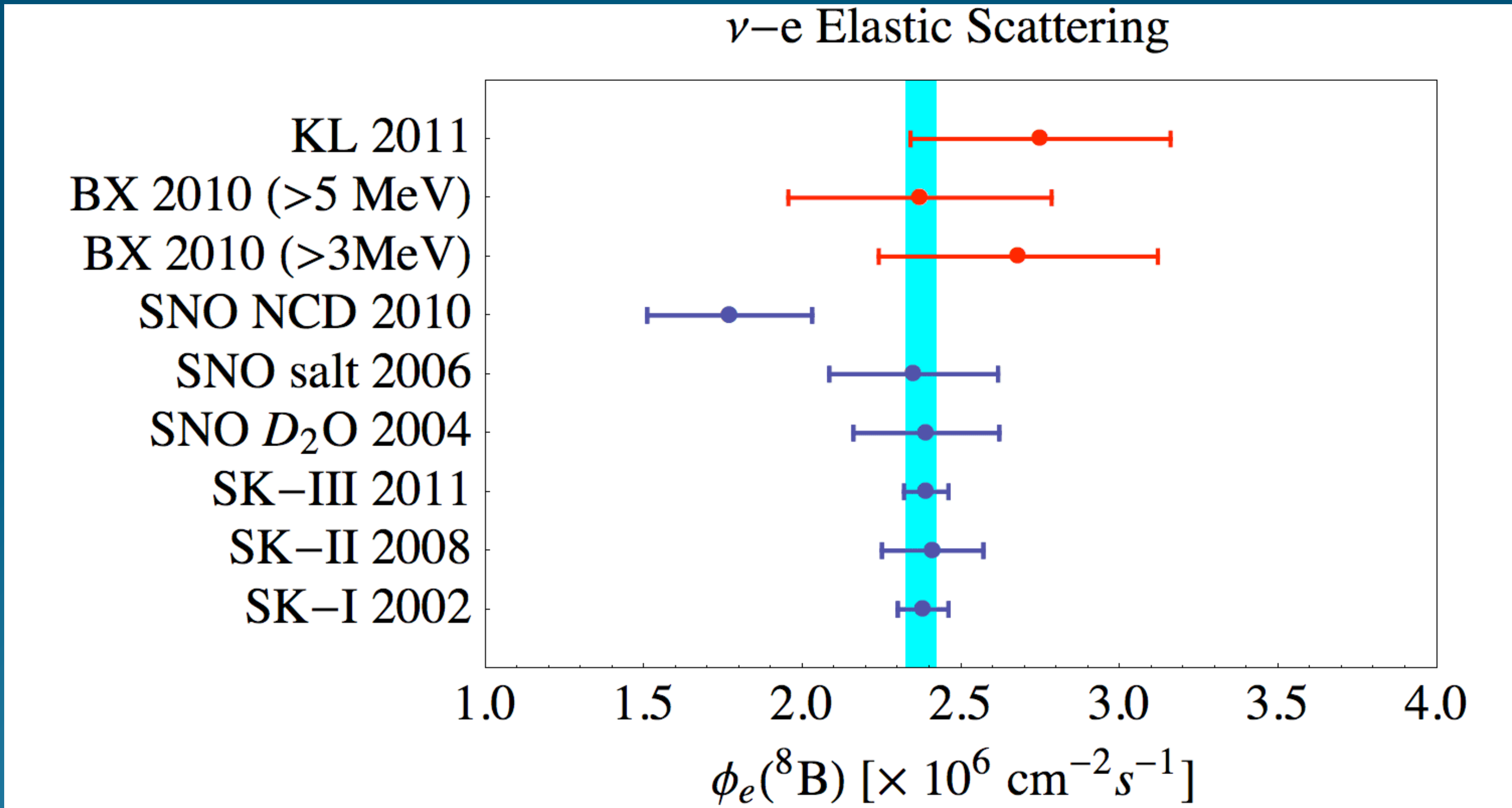


^{8}B Solar Neutrino Spectrum

Detection by neutrino-electron ES

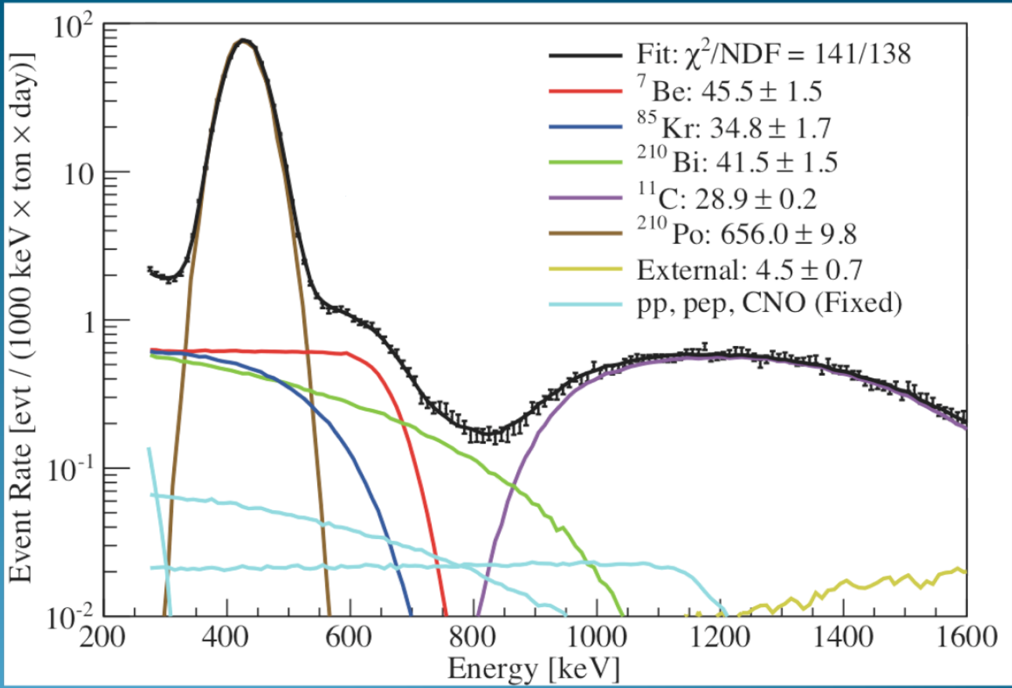


ν_e-equivalent flux for ^{8}B neutrinos



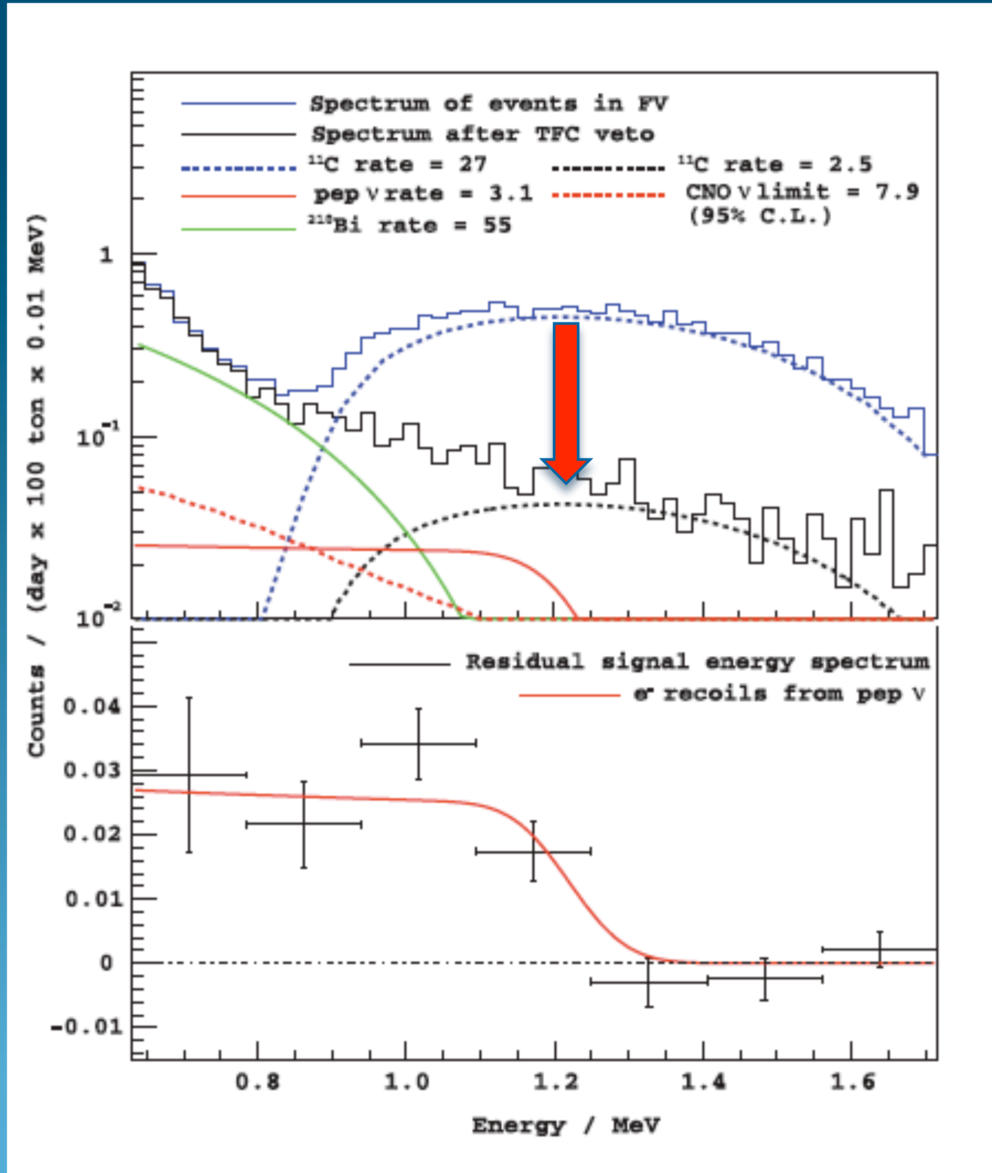
^{7}Be Solar Neutrino Measurement in Borexino

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



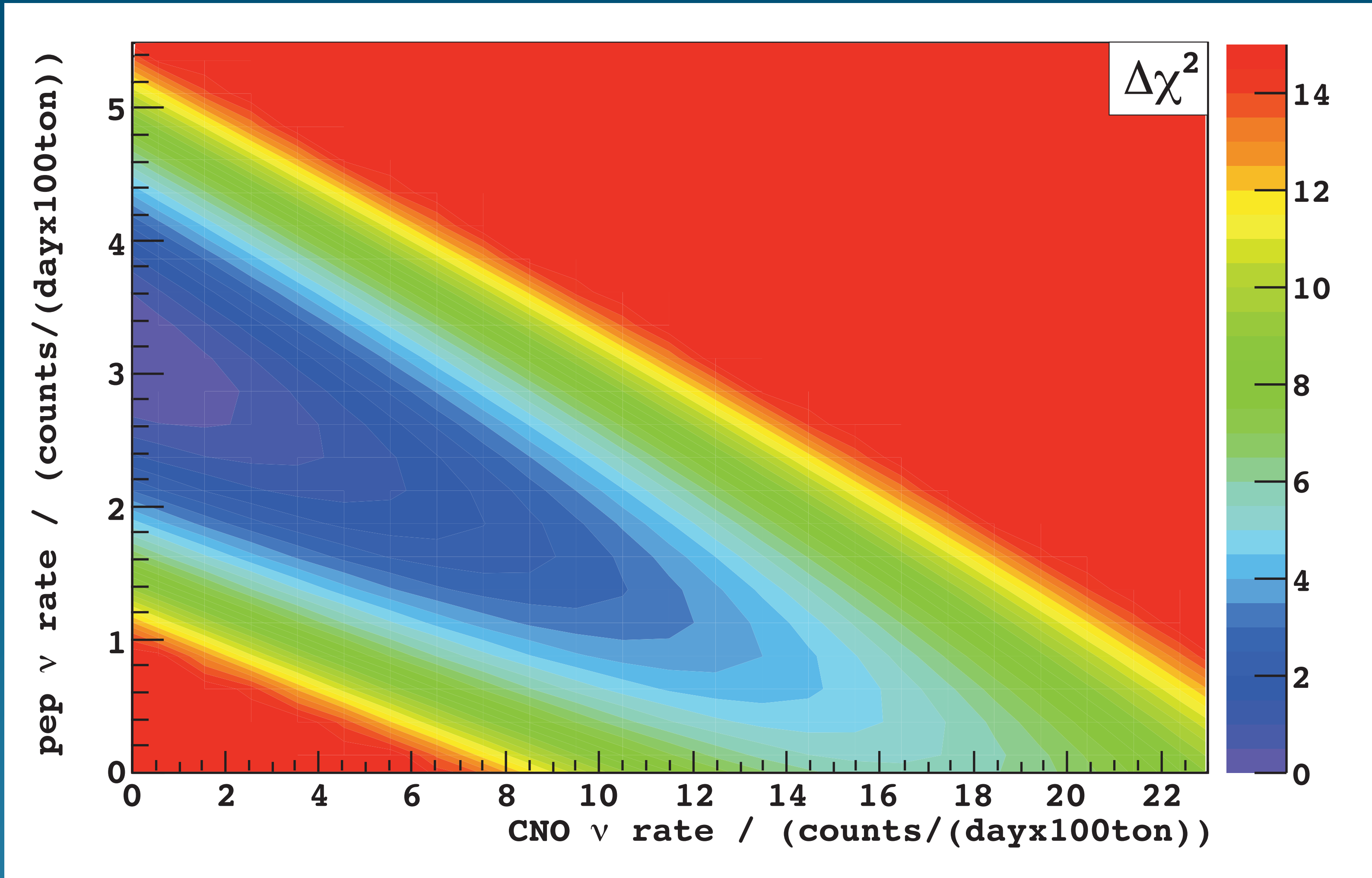
pep Solar Neutrino Measurement in Borexino

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



More details on the pep analysis by D. Franco

pep vs CNO rates in Borexino



Global Analysis of Solar Neutrino Data

In the framework of neutrino oscillations one defines:

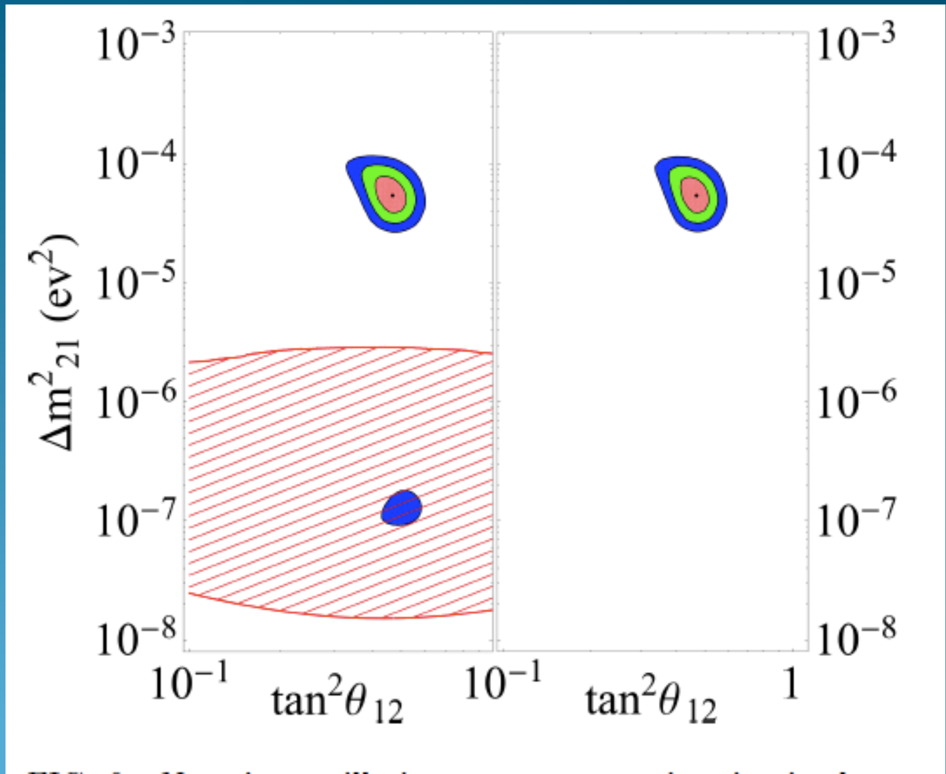
$$\chi^2_{\text{solar+KL}} = \chi^2_{\text{solar}}(\Delta m^2_{21},\ \tan^2\theta_{12},\ \sin^2\theta_{13}) + \chi^2_{\text{KL}}(\Delta m^2_{21},\ \tan^2\theta_{12},\ \sin^2\theta_{13})$$

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

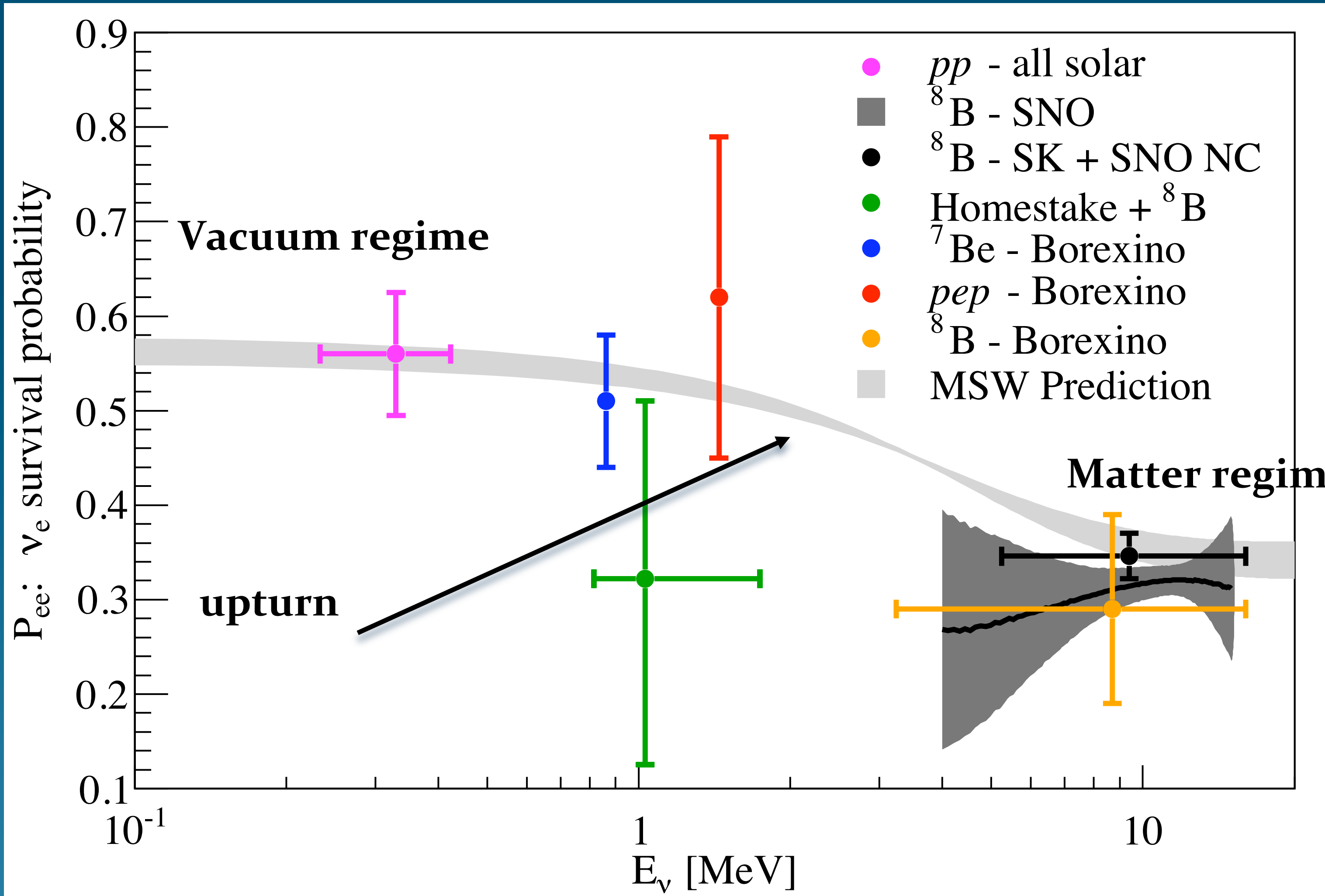
$$\tan^2\theta_{12} = 0.457^{+0.038}_{-0.025}\ \left[0.462^{+0.032}_{-0.033}\right]$$

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

Daya Bay and RENO included

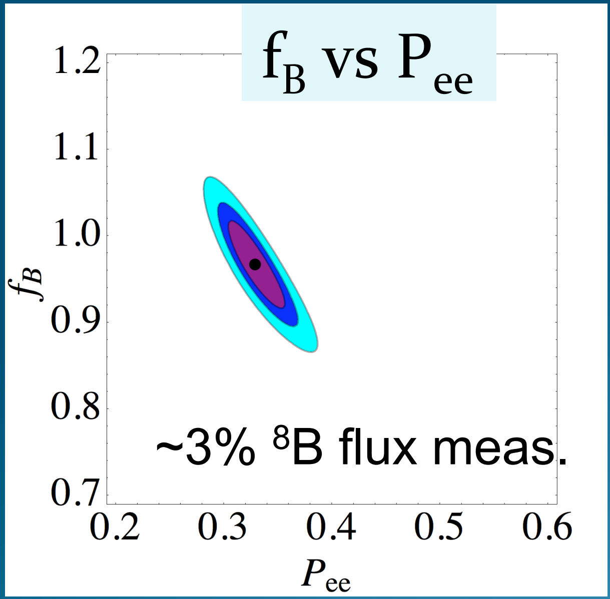


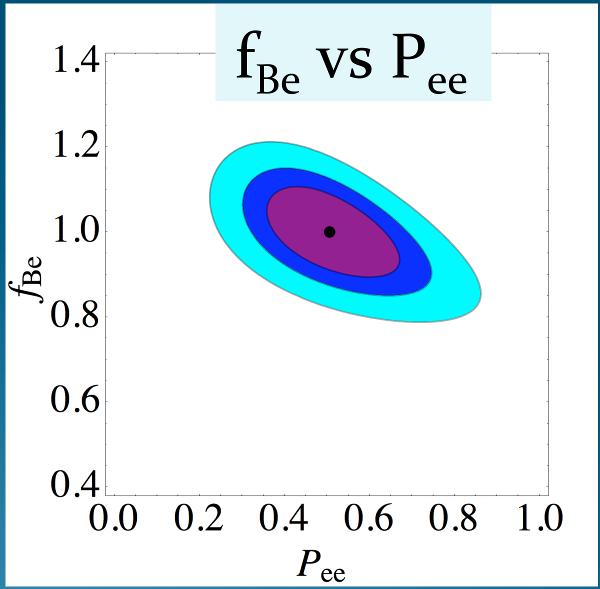
Solar Neutrinos Survival Probability



Determine neutrino fluxes and probe the SSM with neutrinos

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





Super-K + SNO + Borexino + KamLAND:

$\Phi(^8B) = (5.40 \pm 0.17) \times 10^6$ cm^{-2}s^{-1}

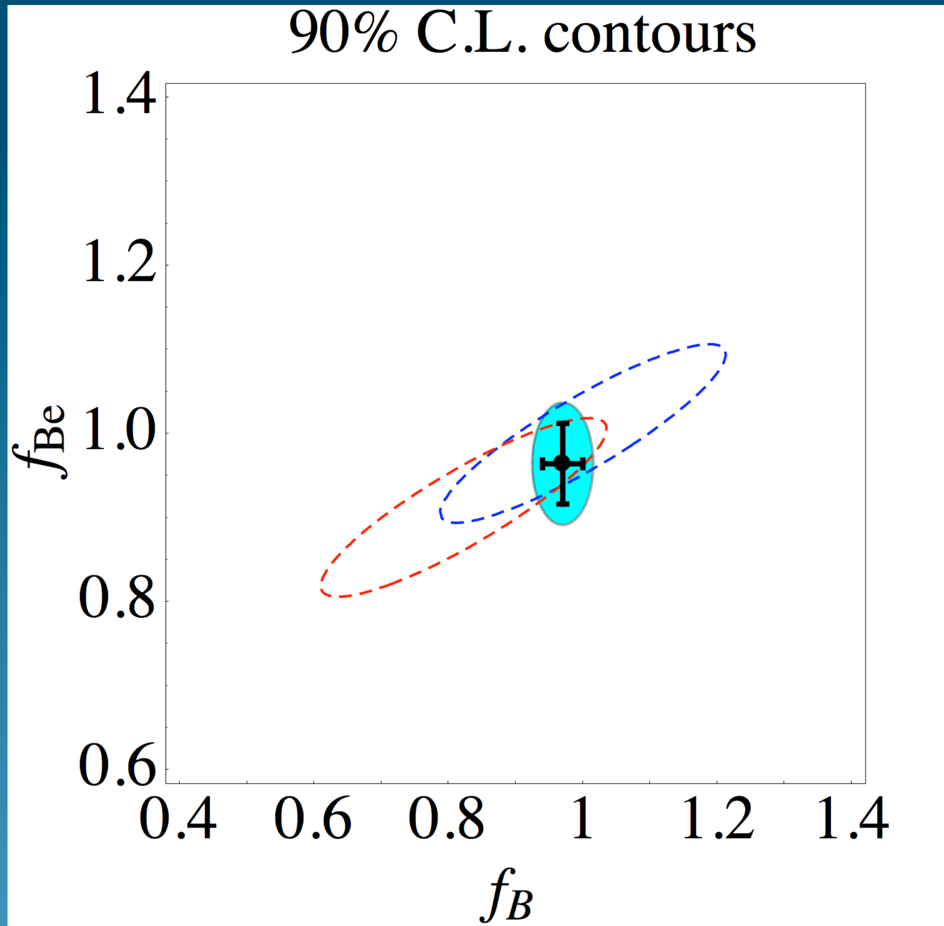
SNO results combined:

$\Phi(^8B) = (5.25 \pm 0.20) \times 10^6$ cm^{-2}s^{-1}

Borexino:

$\Phi(^7Be) = 4.84(1 \pm 0.05) \times 10^9$ cm^{-2}s^{-1}

High-Z and Low-Z SSM vs Data



More from A. Serenelli

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 …

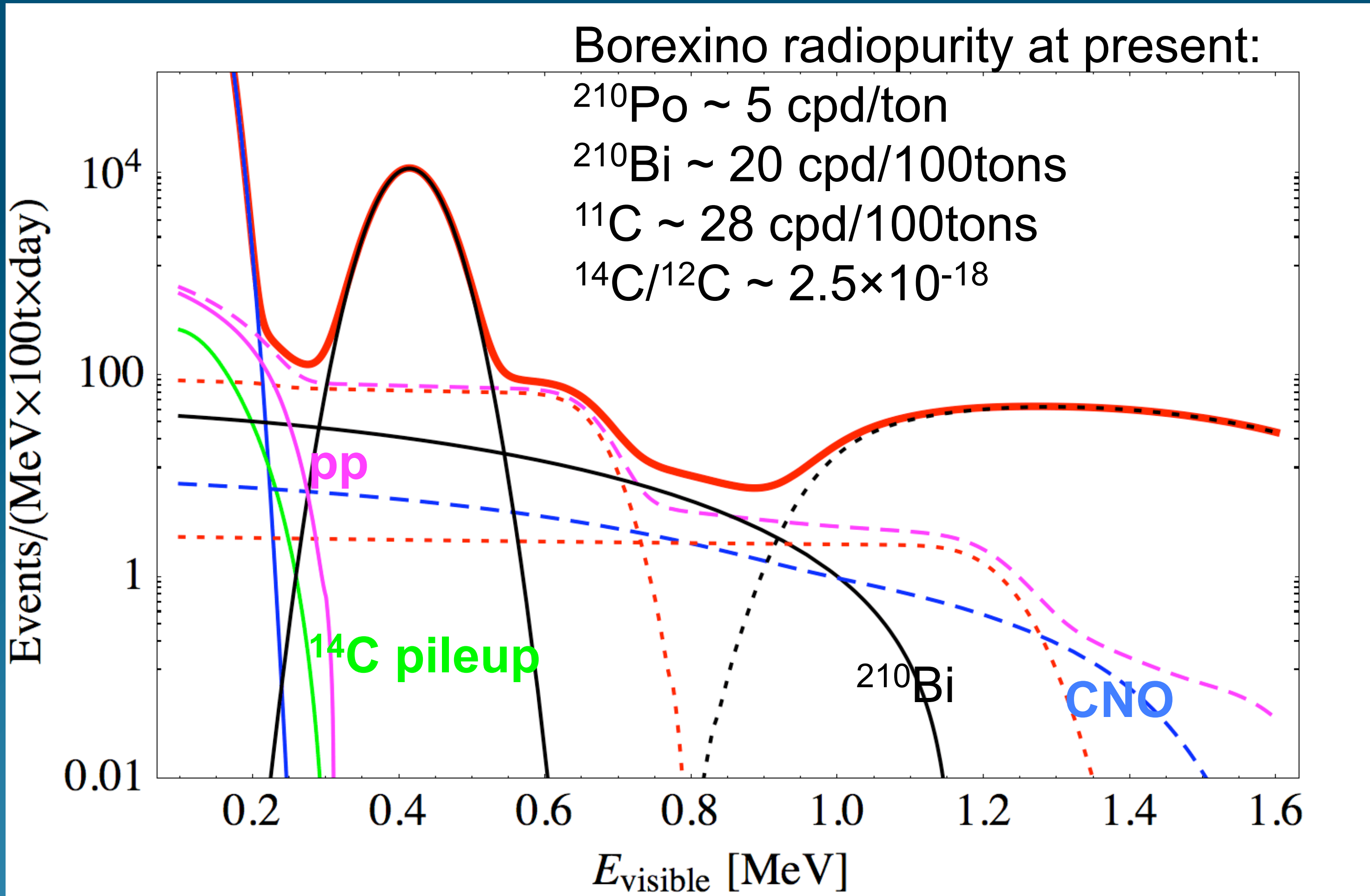
Goals for next steps

- 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

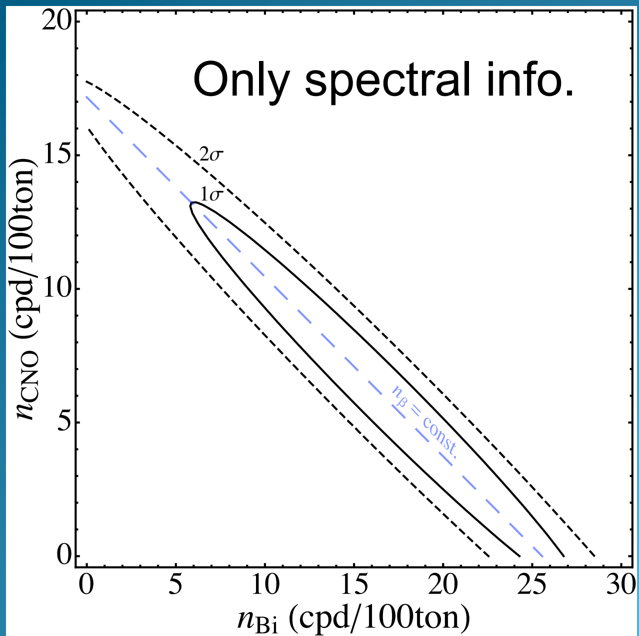
Toward a CNO observation: step 1

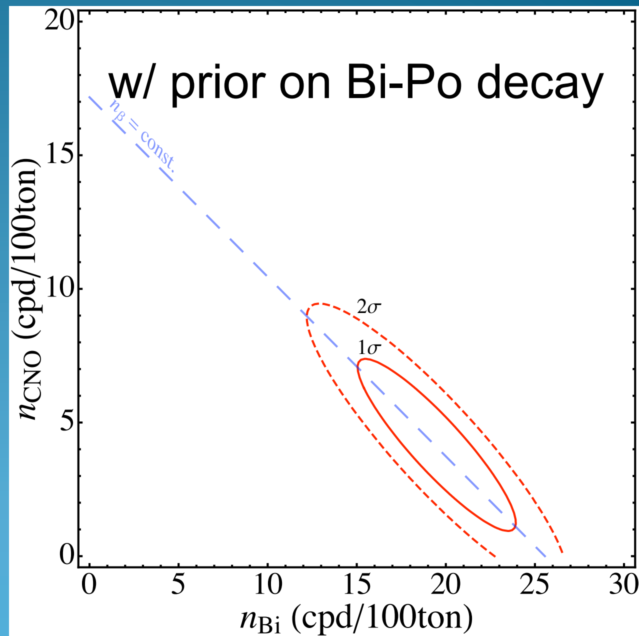


CNO neutrino measurements

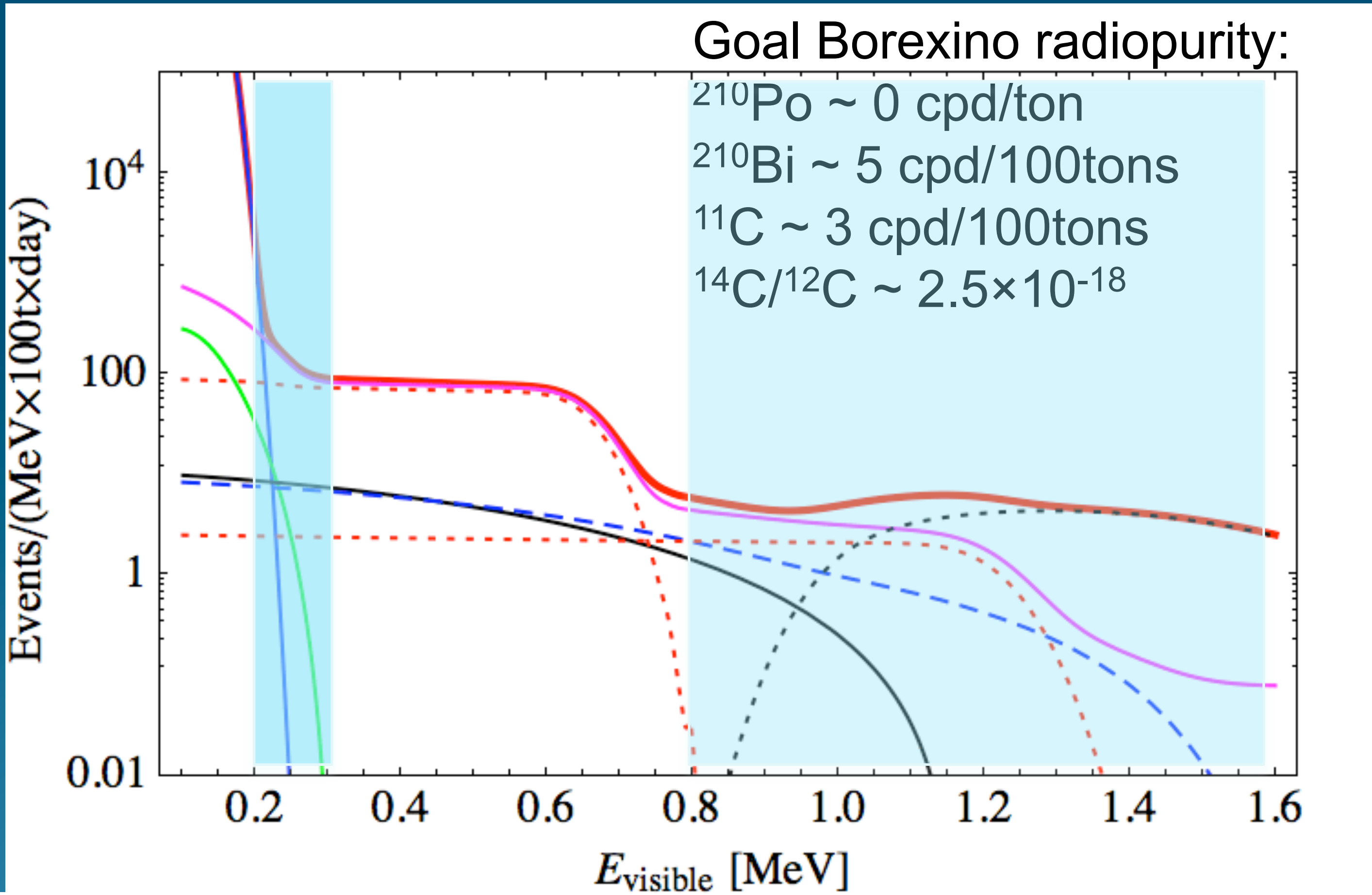
Degeneragy in the energy spectrum between ^{210}Bi and CNO with the addition of ^{11}C background makes this measurement very challenging

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



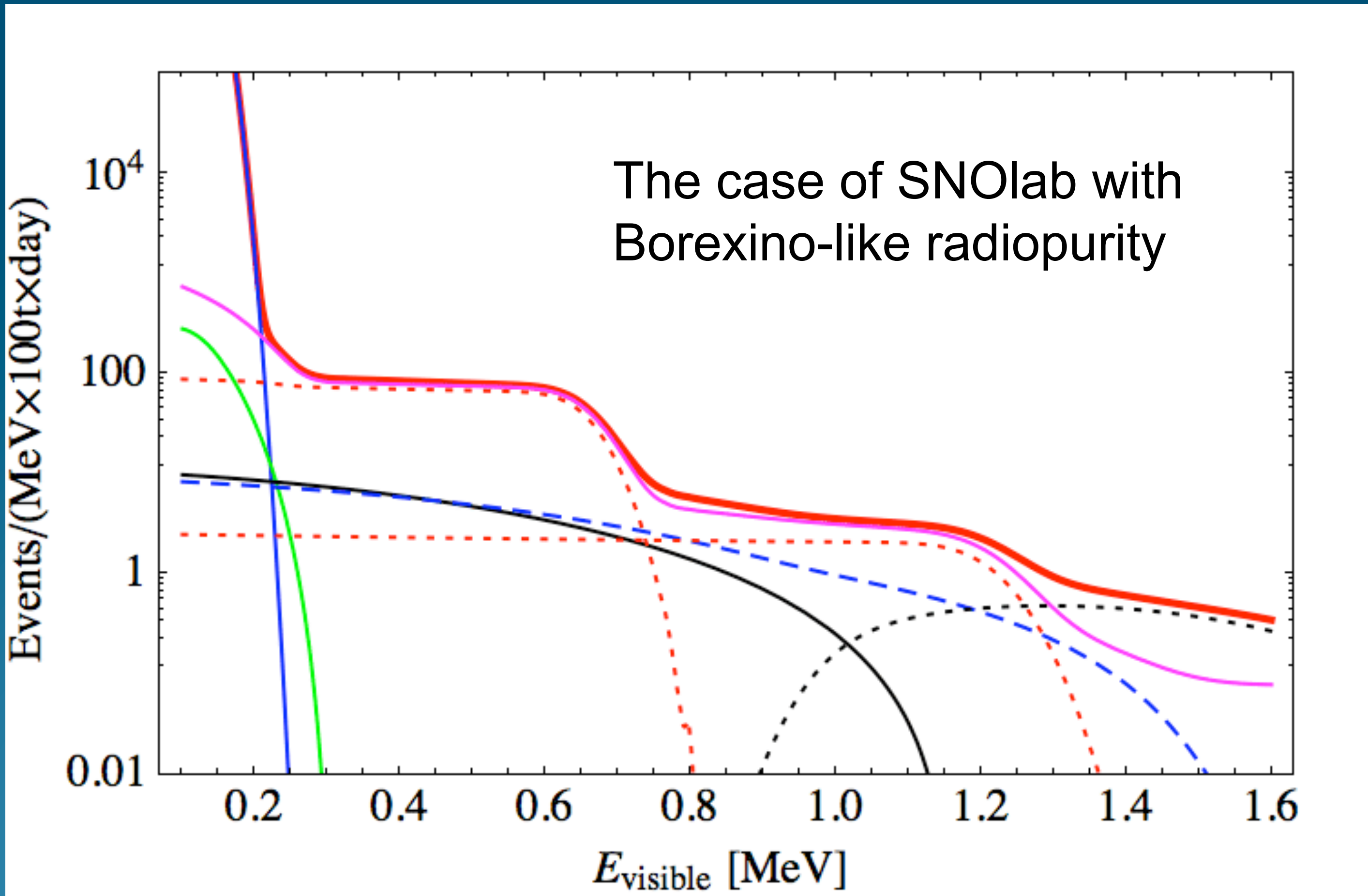


Toward CNO observation: step 2



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

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

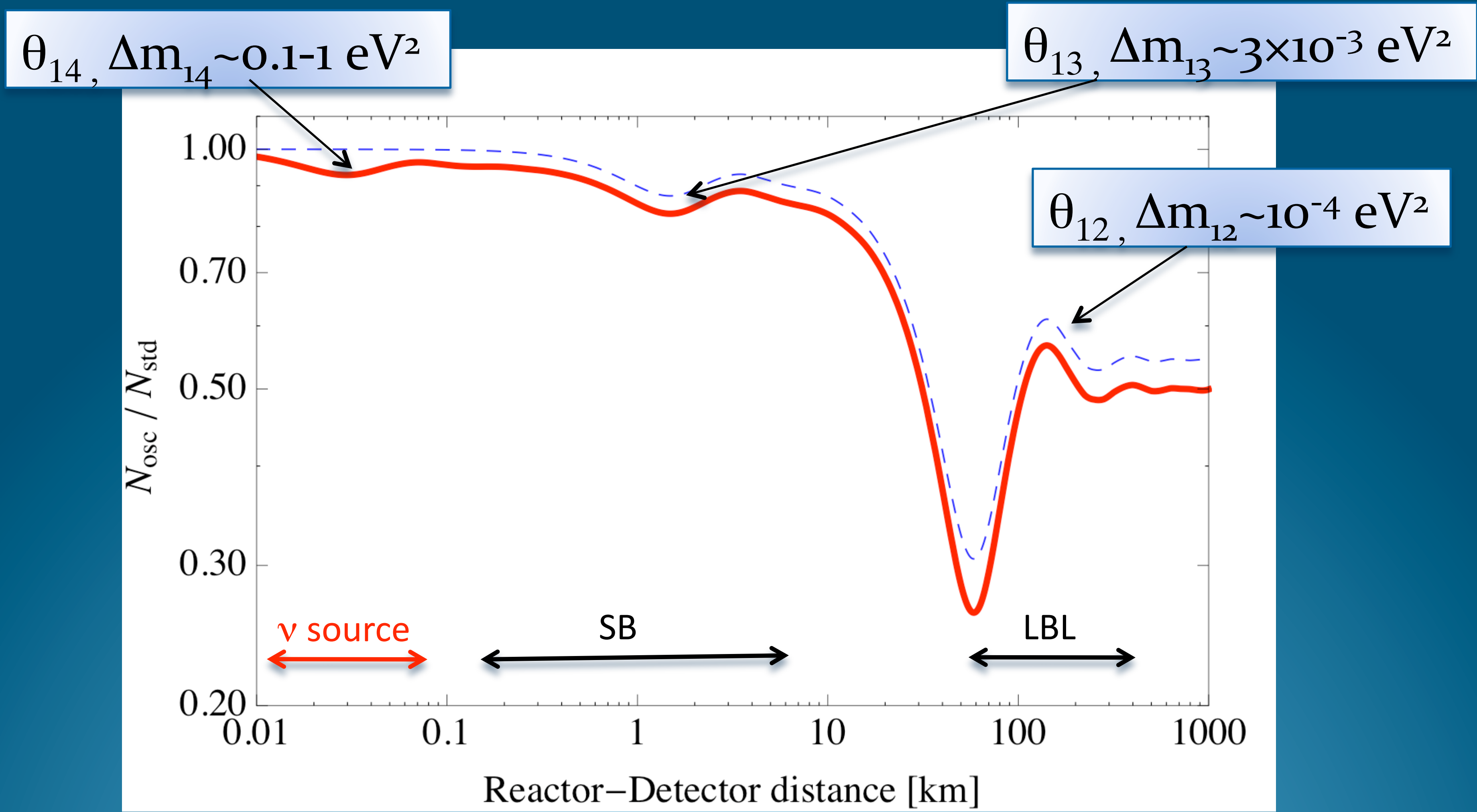
- N.G.Basov,V.B.Rozanov, JETP 42 (1985)
- Borexino proposal, 1991
- J.N.Bahcall,P.I.Krastev,E.Lisi, Phys.Lett.B348:121-123,1995
- N.Ferrari,G.Fiorentini,B.Ricci, Phys. Lett B 387, 1996
- I.R.Barabanov et al., Astrop. Phys. 8 (1997
- Gallex coll. PL B 420 (1998) 114
- A.Ianni,D.Montanino, Astrop. Phys. 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.
See at this meeting: C. Giunti and J. Link

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

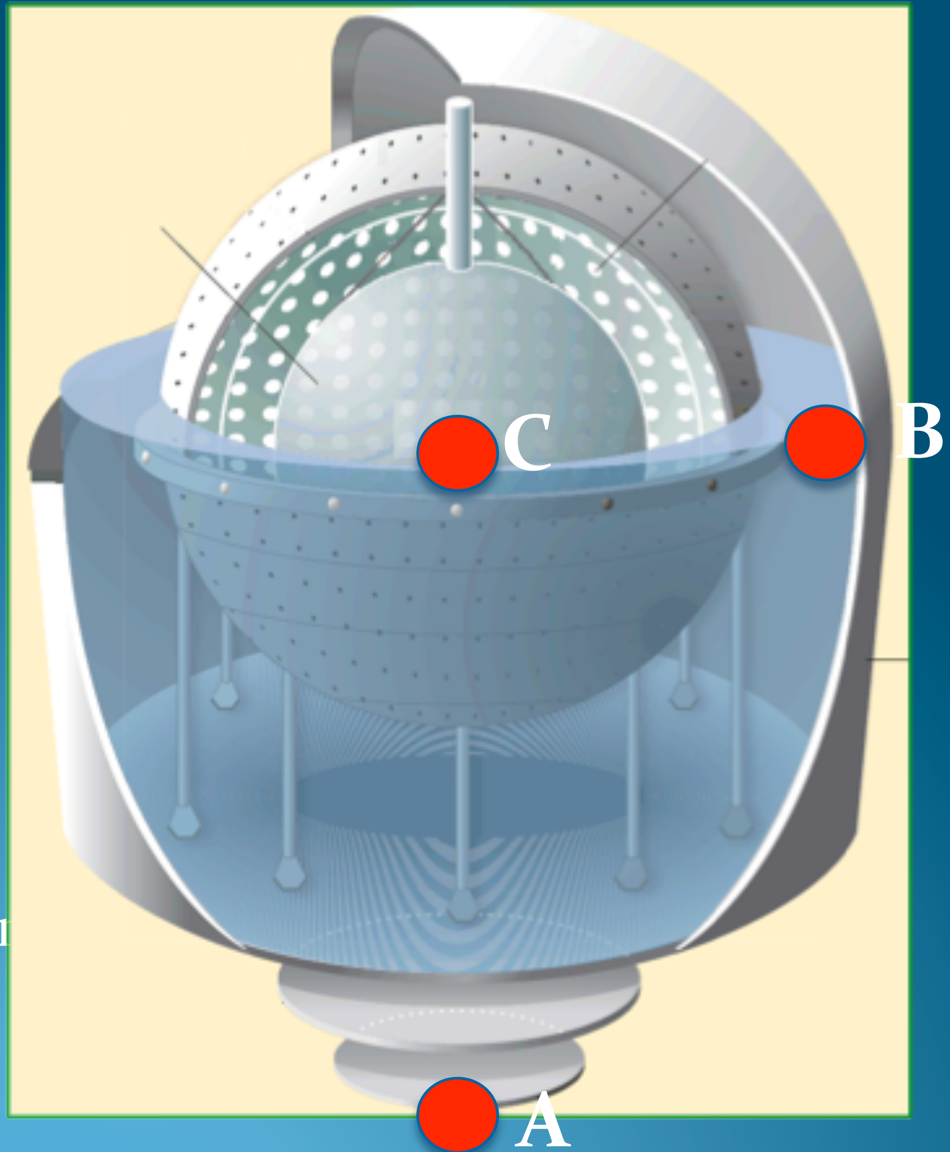
- Probing Short Baseline Flavor Oscillations in disappearance
- Search for Neutrino Magnetic moment
- Probe neutrino-electron scattering at 1 MeV scale
  - Weinberg's angle
  - g_V and g_A coupling

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)

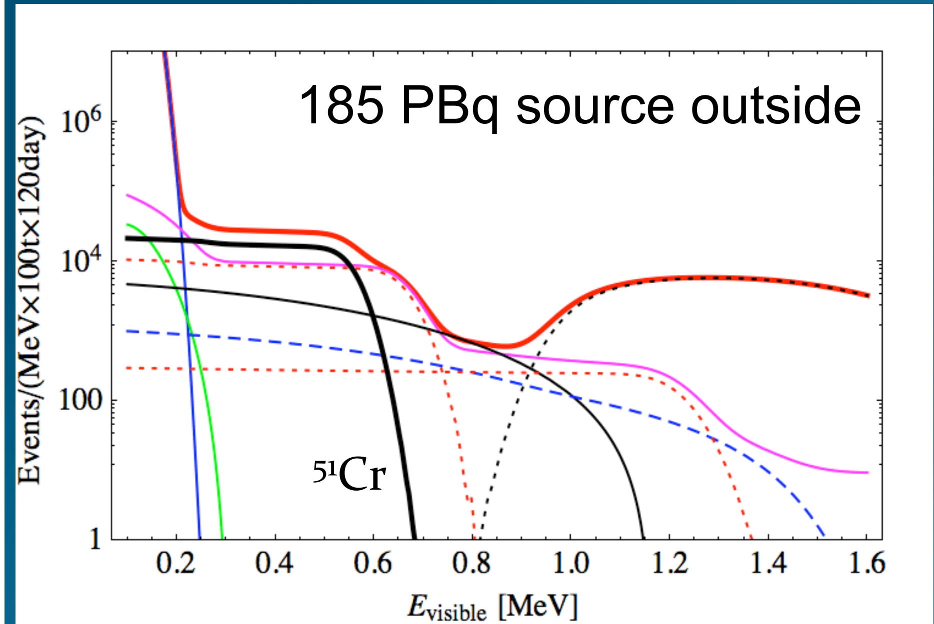
- A: underneath WT
  - D=825 cm
  - No change to present configuration
- B: inside WT
  - D = 700 cm
  - Need to remove shielding water
- C: center
  - Major change
  - Remove inner vessels
  - To be done at the end of solar neutrino physics

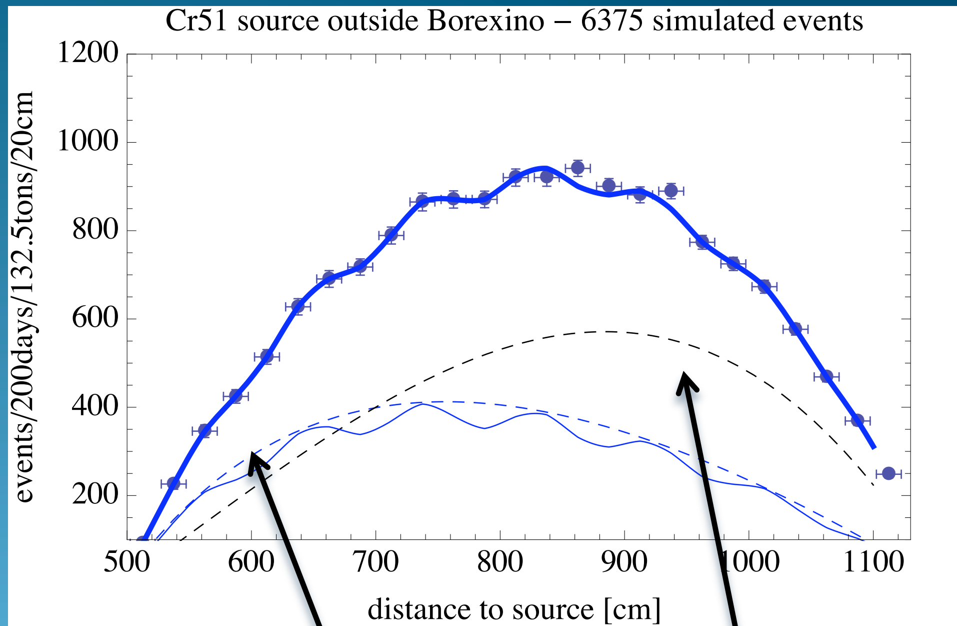


^{51}Cr in a Borexino

Features for an electron neutrino source outside Borexino

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

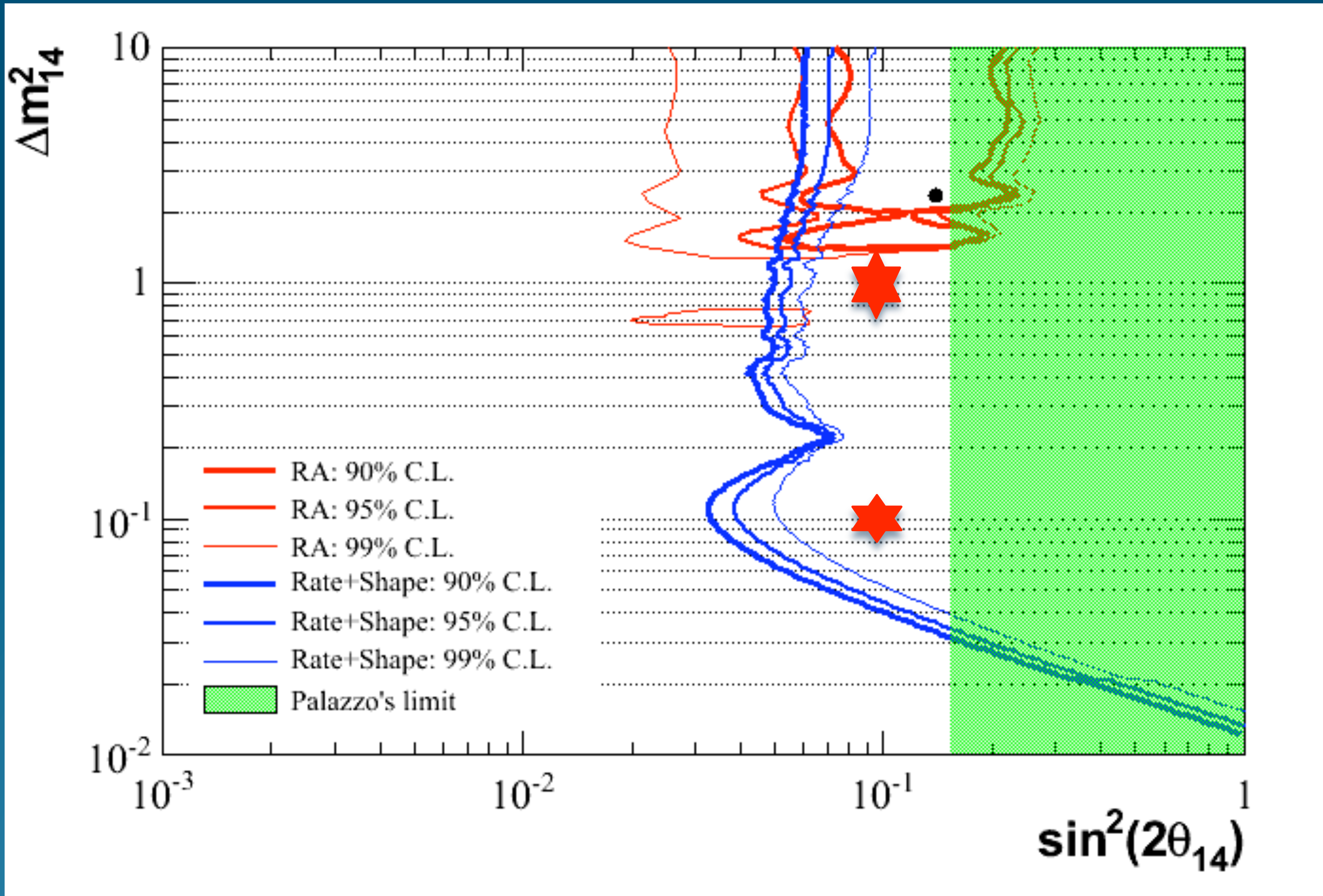




Not oscillated signal

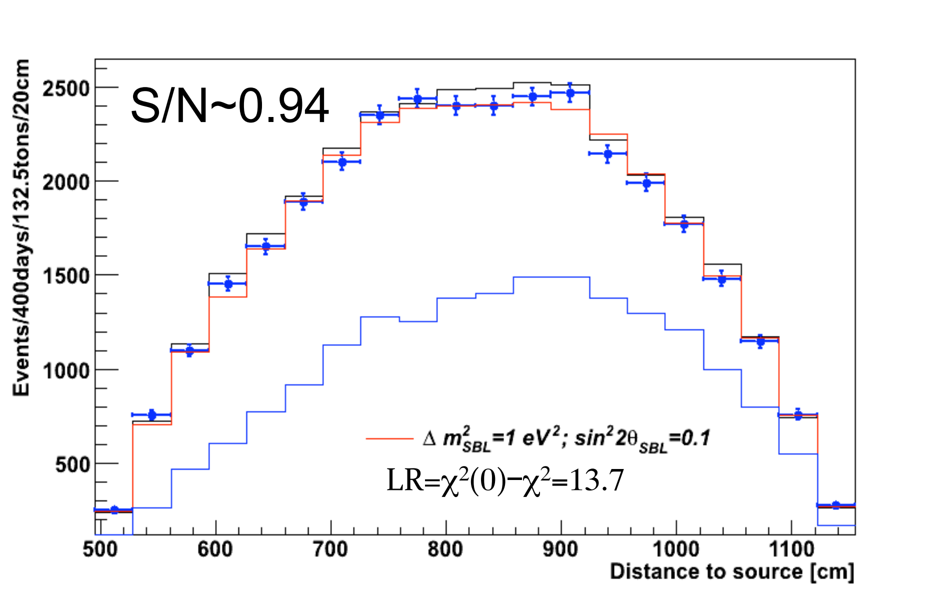
background

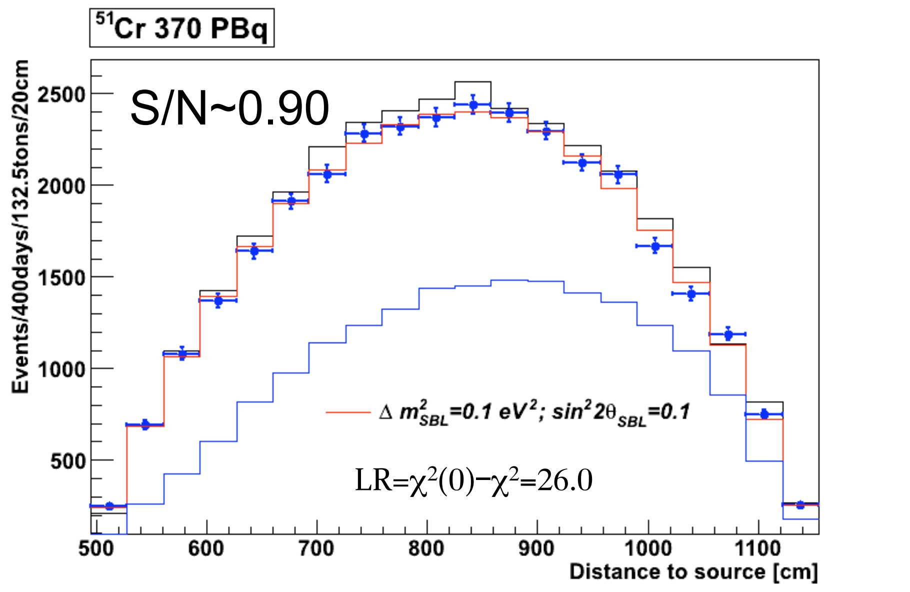
Sensitivity of a ^{51}Cr source in Borexino



^{51}Cr source outside Borexino

Baseline < 7m
~14500 events predicted w/o oscillations



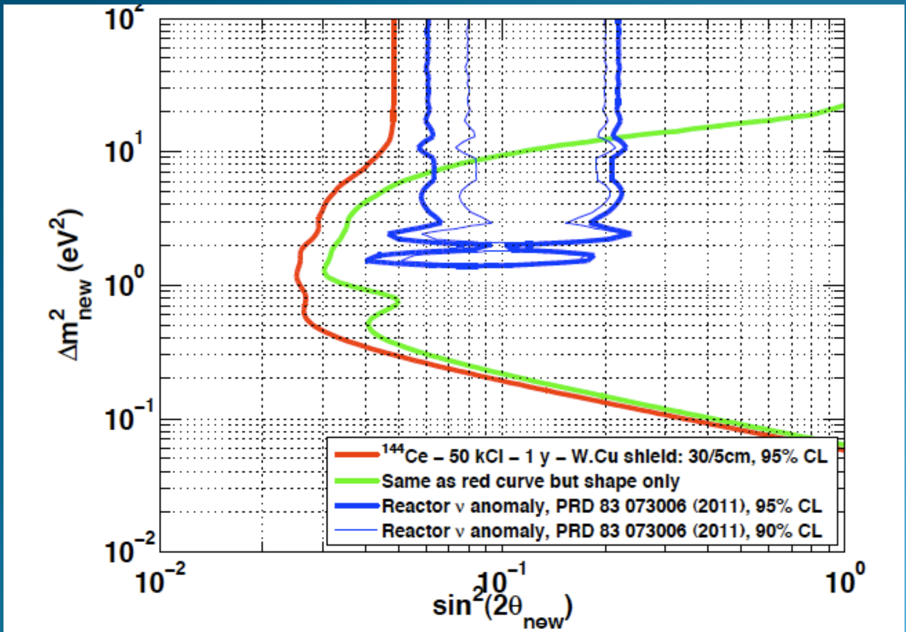


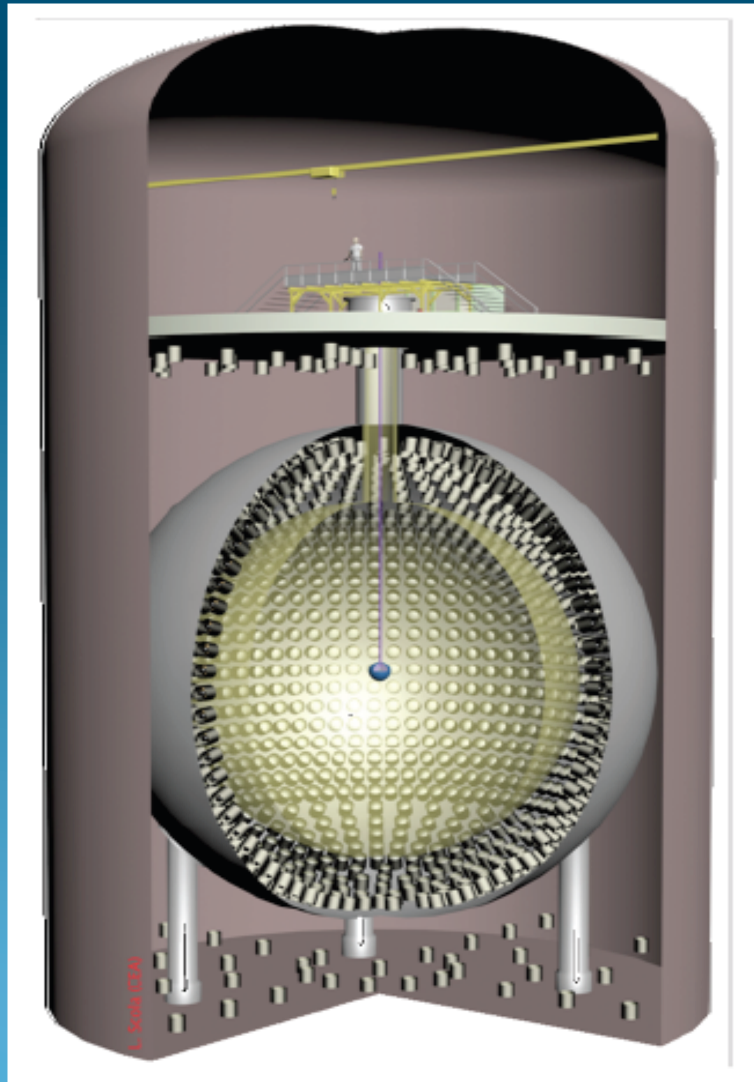
Source location in KamLAND

- **CeLAND** proposal

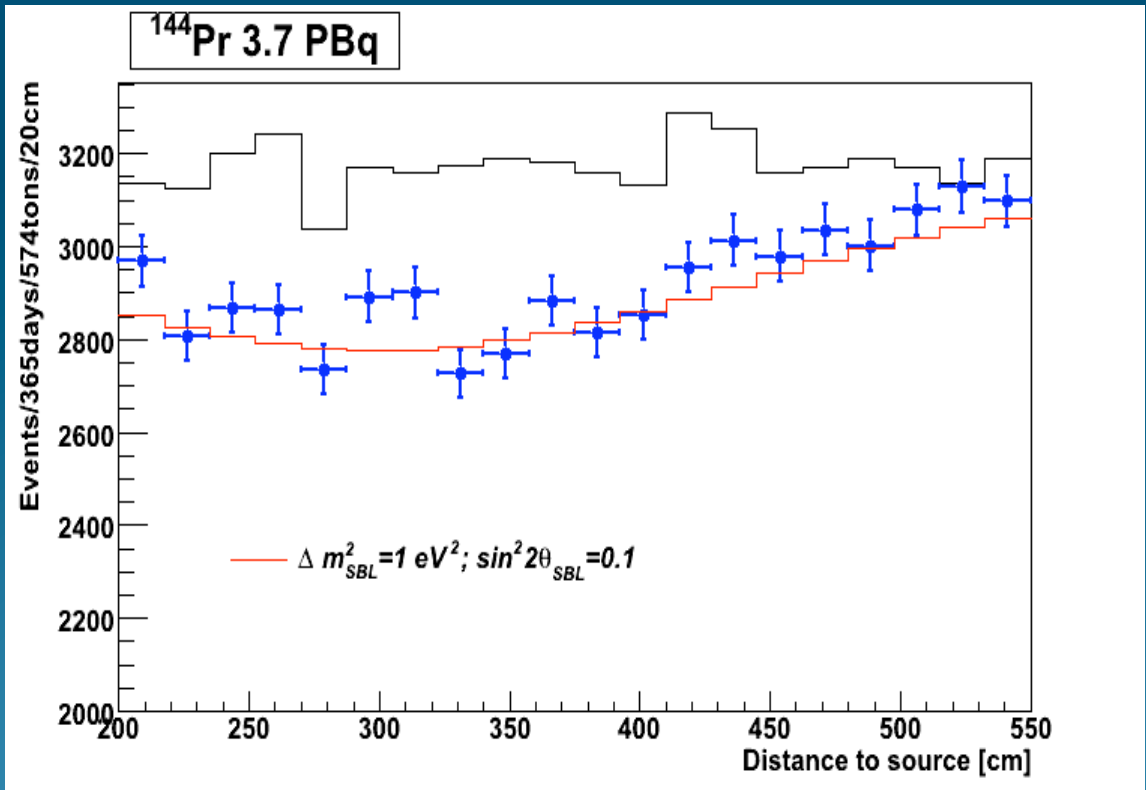
PRL 107, 201801, 2011

- 1.85 PBq Ce-Pr source



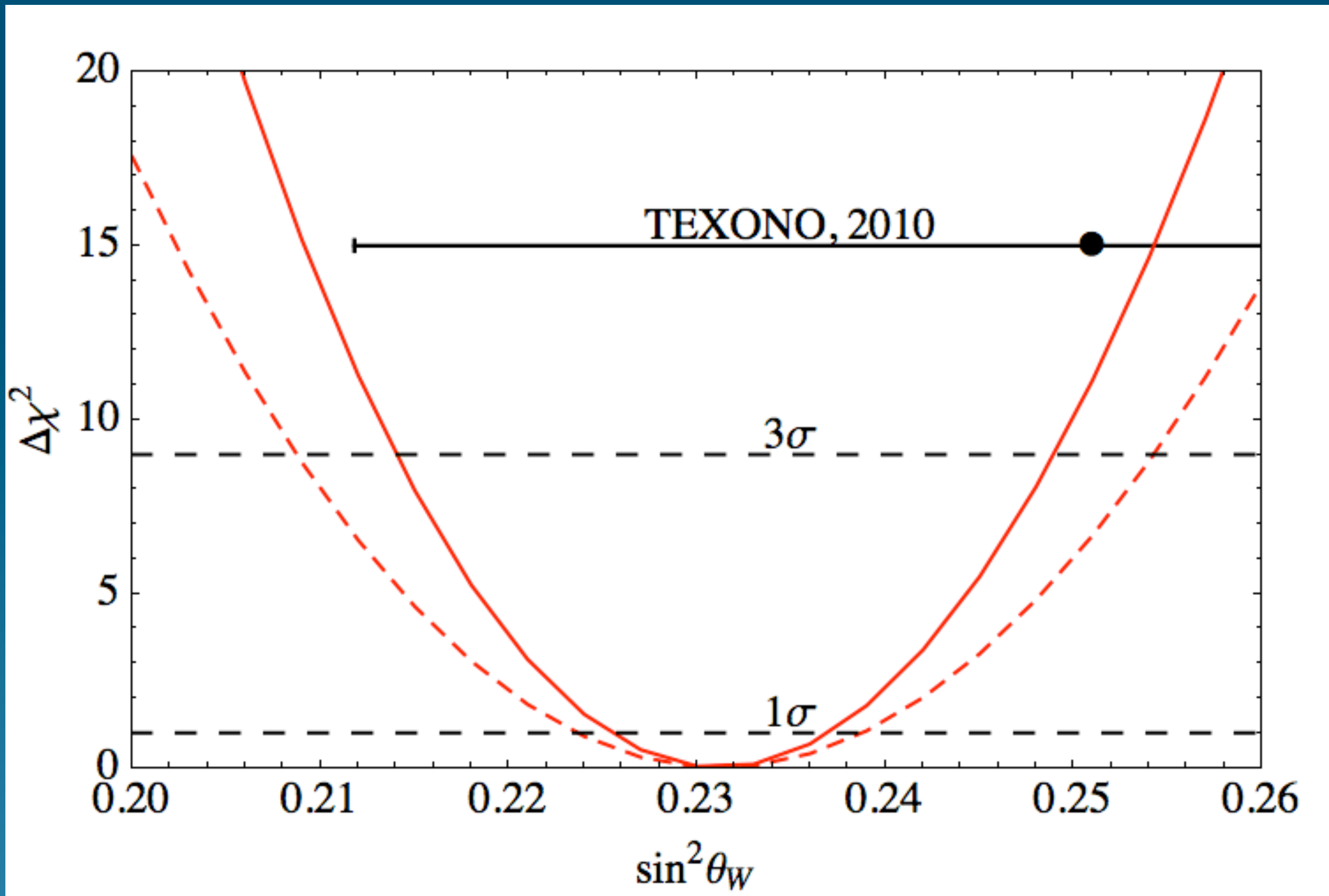


^{144}Ce-^{144}Pr source @ center of Borexino



$\Delta m_{SBL}{}^2$ = 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

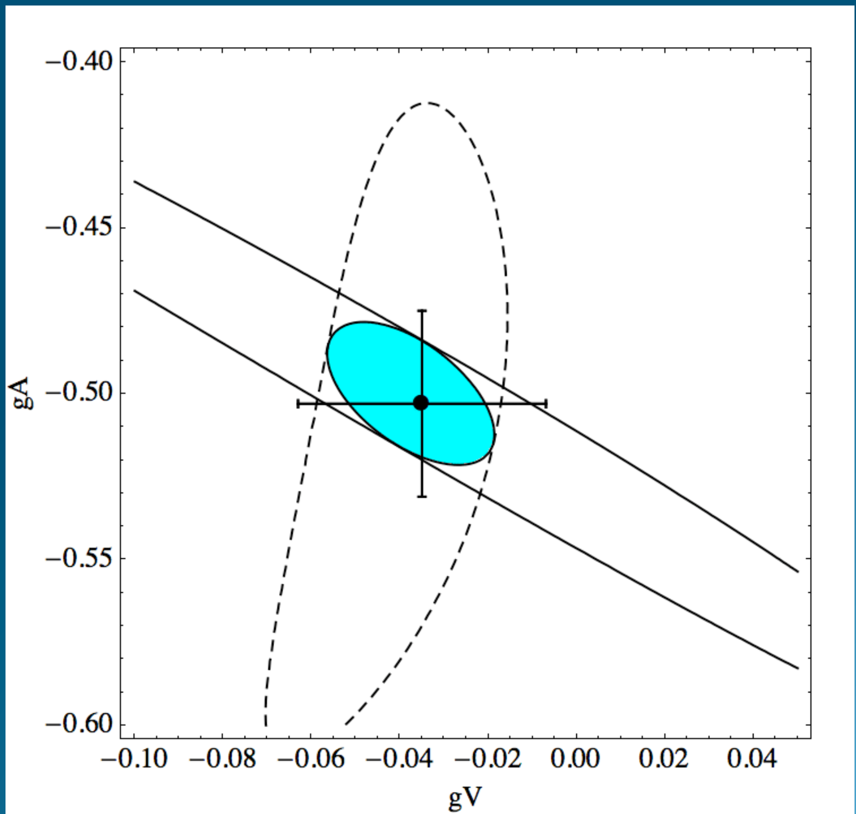


10 MCi source

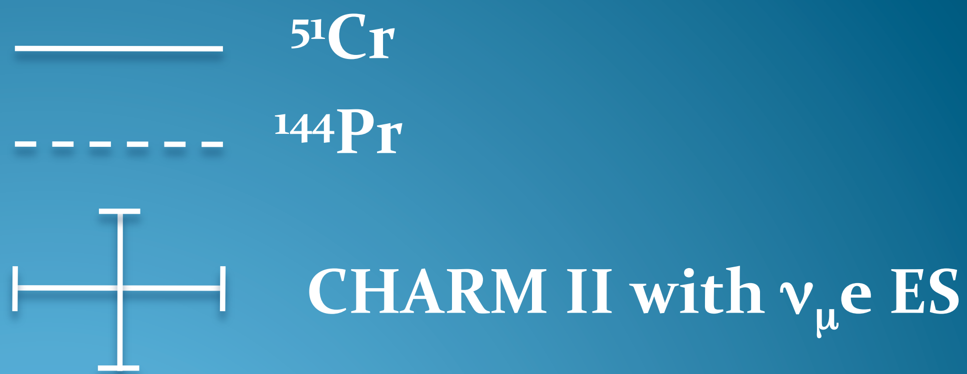
5 MCi source

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

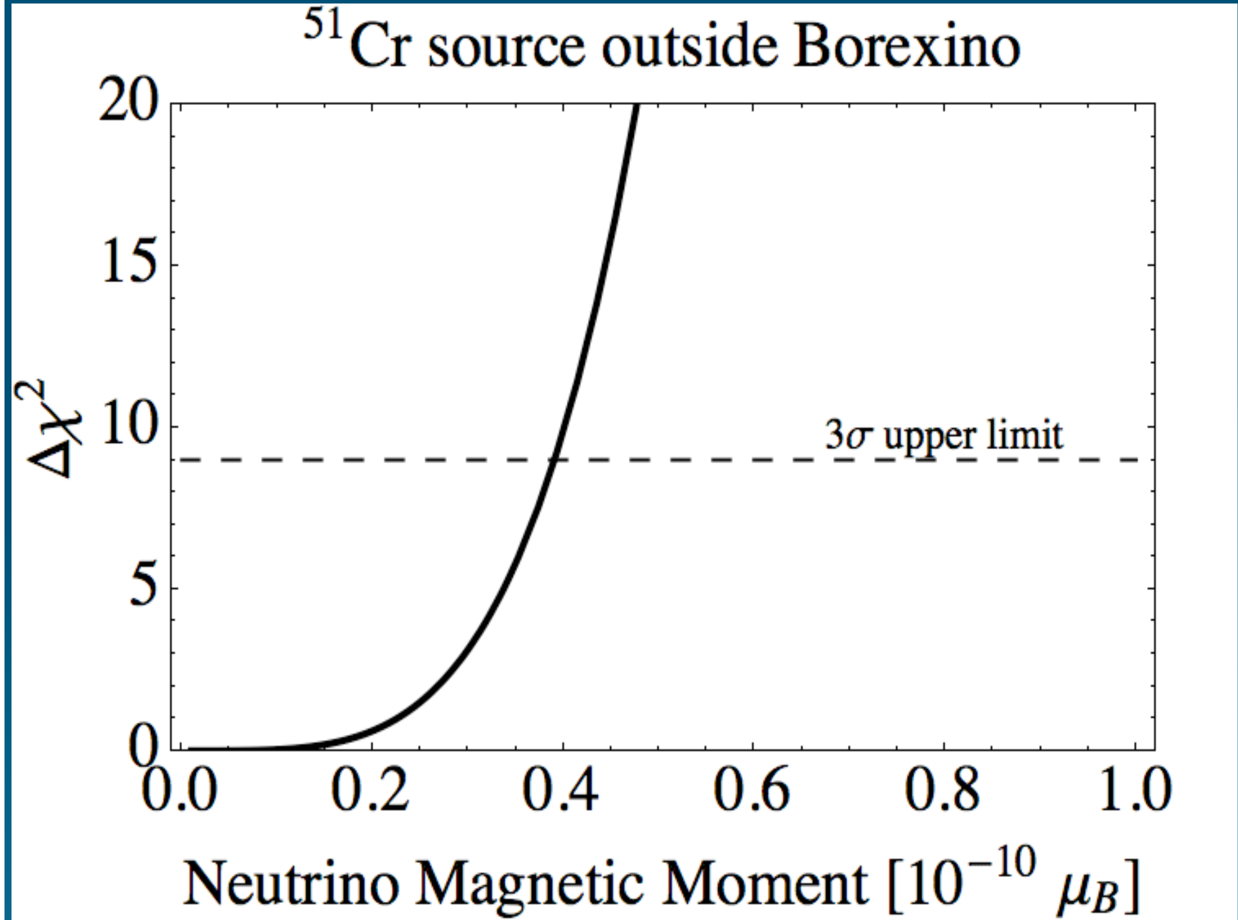
EW couplings



- Standard Model
  - g_V = -1/2+2sin^{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

Acnowledgements

I would like to thank my colleagues from the Borexino Collaboration

Michael Smy for information on Super-Kamiokande

Vladimir Gavrin for information on SAGE

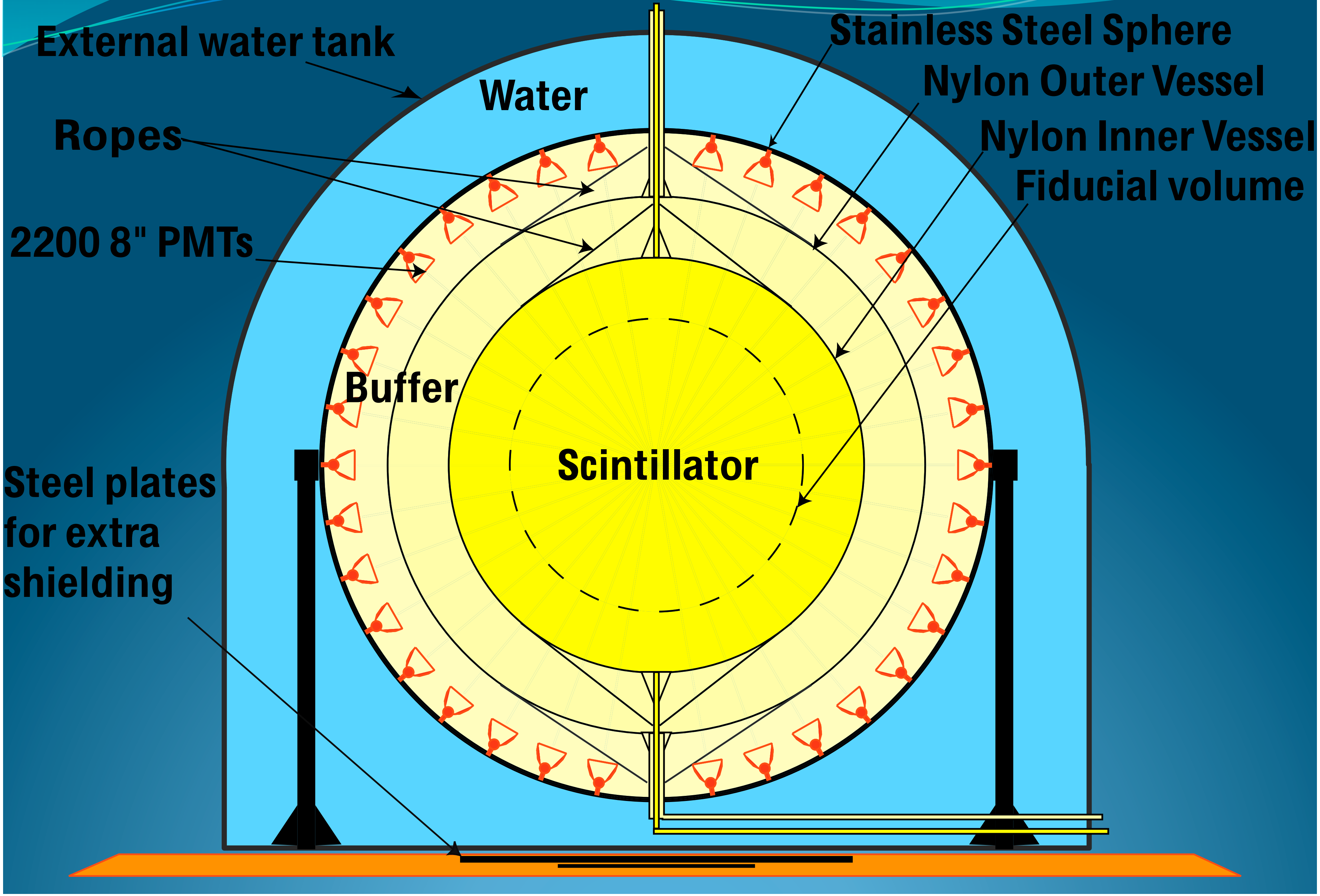
Francesco Villante for discussions

All of you for listening

Spares

Source position A

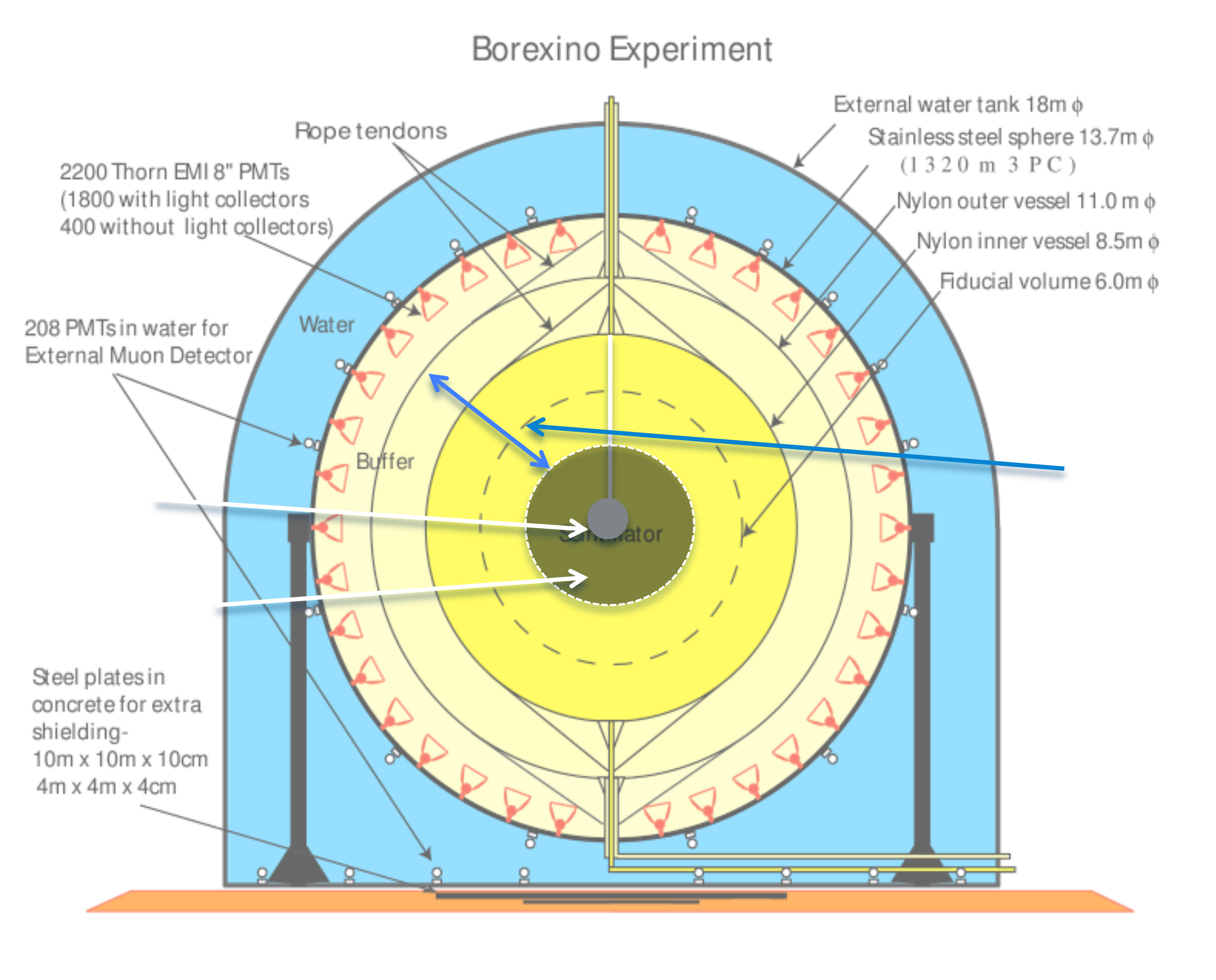
Borexino Experiment



Borexino with source @ center

Source+s

Volume t
backgrou
source sh



olume

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

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

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

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

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

~10^{-2}

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

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

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

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

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

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

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

~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%

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

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

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

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

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

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