Solar Neutrinos and the Solar Model

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Outline

- Solar Neutrinos and Standard Solar Model
- Observations of Solar Neutrinos
- What we have learned today from solar neutrinos
- What next? (from my point of view)

Solar Neutrinos

The source of energy in the sun (and in H-burning stars) makes neutrinos:

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

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

Hydrogen burning works through:
- pp-chain reactions
- CNO bi-cycle

pp-chain H burning

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

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

~0.4%

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

~85%

~15%

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

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

~0.02%

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

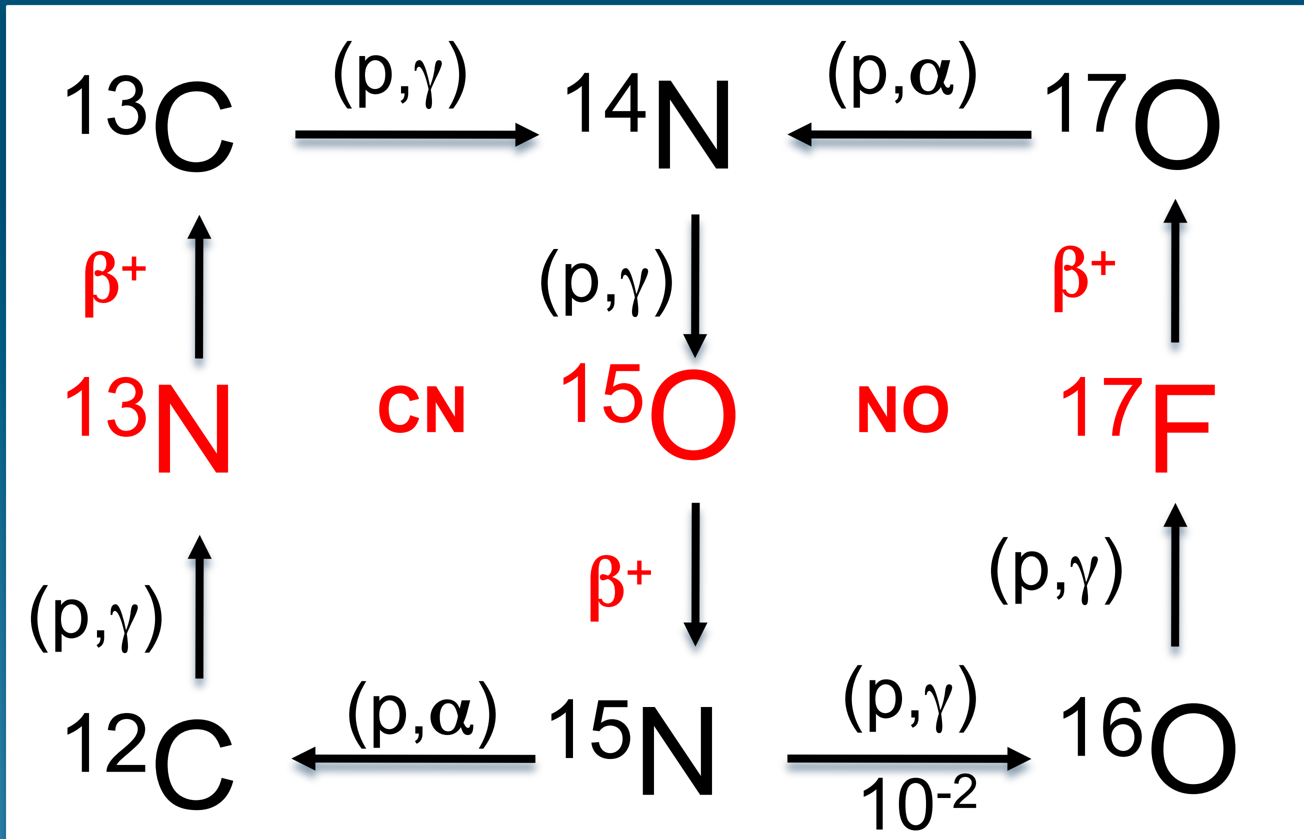
$${}^7Be + p \rightarrow {}^8B + \gamma + 0.137 \text{ MeV}$$

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

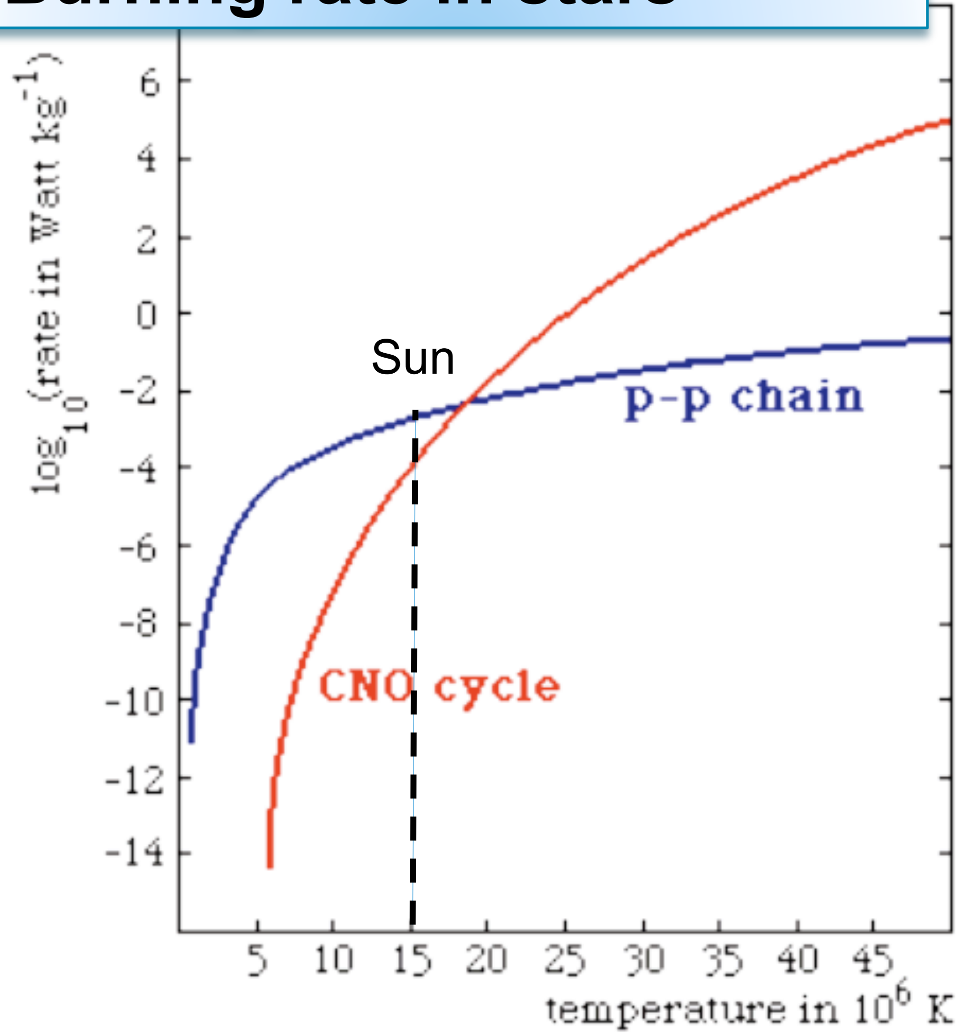
$${}^8B \rightarrow {}^8Be^{*} + e^{+} + \nu_e + 15.04 \text{ MeV}$$

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

CNO bi-cycle H burning



Burning rate in stars



Motivations for Solar Neutrino detection

- Solar neutrinos are a **unique probe** for understanding the interior of the sun and its energy source

- The sun can be used to calibrate stellar models

- Probing neutrino propagation (physics) in a high density medium (~100 g/cm^3)

Standard Solar Model

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

- **Assumptions of the SSM**
  - Hydrostatic equilibrium
  - Spherical symmetry, no rotation, no magnetic field
  - Energy generation by H burning
  - **Homogeneous zero-age Sun**:
    - initial metallicity approximately equal to present surface metallicity, corrected for the effect of diffusion

Standard Solar Model

- Solar mass, solar age: fixed

Construct $1M_{sun}$ and match L_{sun}, R_{sun}, $(Z/X)_{surf}$ better than $1/10^5$

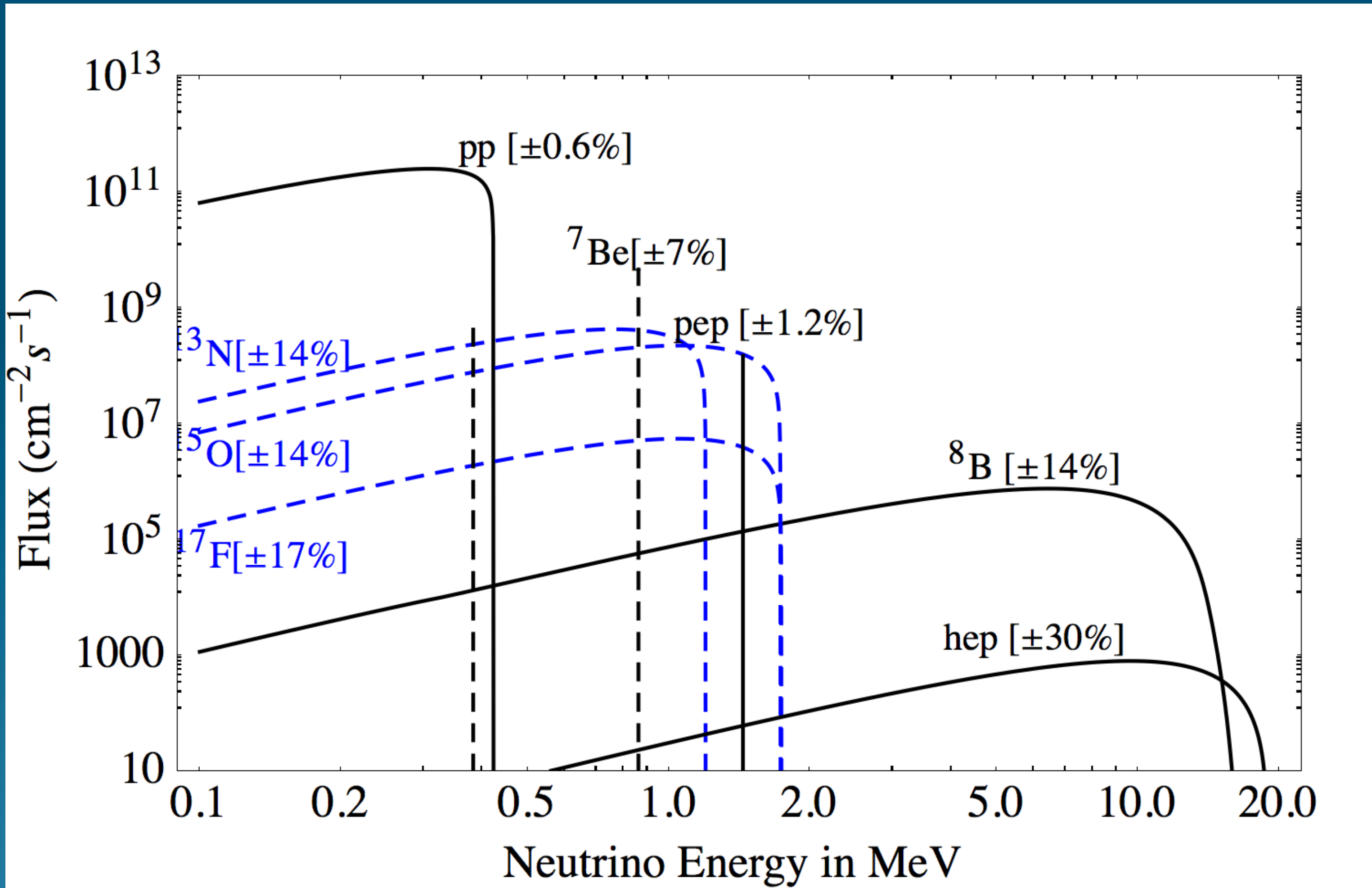
Free parameters:

- initial relative mass abundances:
  - X_{in} (Hydrogen), Y_{in}(Helium), Z_{in}(metals)$=1-X_{in} - Y_{in}$
- Mixing Length Theory parameter for convection

Output of SSM

- Neutrino production region, neutrino fluxes
- Depth of convection zone, $\mathbf{R_{CZ}}$
- Surface helium abundance, $\mathbf{Y_{surf}}$
- Profile of X(r), Y(r) and Z(r)
- density and sound speed profiles
- …

Solar Neutrino Spectrum at Earth



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

Solar Surface Composition

- Inferred from photospheric and meteoritic abundances (see F. Villante)

- Needed radiative transfer model for solar atmosphere to describe observed spectrum

- Convection has been traditionally described with 1-D semi-empirical photospheric model

- A 3D, time-dependent, radiative-hydrodynamical simulation of the outer layers of the convection zone, including the photosphere, has been developed [Asplund et al., 2005]

- **Derived elemental abundances, using the 3D model and a demanding selection of spectral lines, are smaller by about a factor of two wrt previous calculations**

Solar Chemical Compositions: GS98 vs AGSS09

Element	GS98 $\log(N_i/N_H) + 12$	AGSS09 $\log(N_i/N_H) + 12$	GS98/AGSS09 - 1
C	8.52	8.43	0.23
N	7.92	7.83	0.23
O	8.83	8.69	0.38
Ne	8.08	7.93	0.41
Mg	7.58	7.53	0.12
Si	7.56	7.51	0.12
S	7.20	7.15	0.12
Fe	7.50	7.45	0.12

Grevesse and Sauval, Space Sci. Rev., 1998
Asplund et al., Ann. Rev. Astrom Astrophys, 2009

1D vs 3D

Test	1D	3D
• Obs. spectrum vs λ	Yes	Yes
• Granulation	No	Yes
• Widths of lines	Yes*	Yes
• Shifts of lines	No	Yes
• Asymmetries	No	Yes

* With ad-hoc micro- and macro-turbulance

Standard Solar Model neutrino flux predictions

Source	Flux $[cm^{-2}s^{-1}]$ SSM-GS98*	Flux $[cm^{-2}s^{-1}]$ SSM-AGSS09	Difference (wrt to GS98)
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	1%
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	2%
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	9%
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	18%
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$2.17(1\pm0.15)\times10^{8}$	27%
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	30%
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	38%

***) Remark: GS98 abundances are thought to be wrong**

Antonelli, Miramonti, Pena-Garay, Serenelli, arXiv:1208.1356

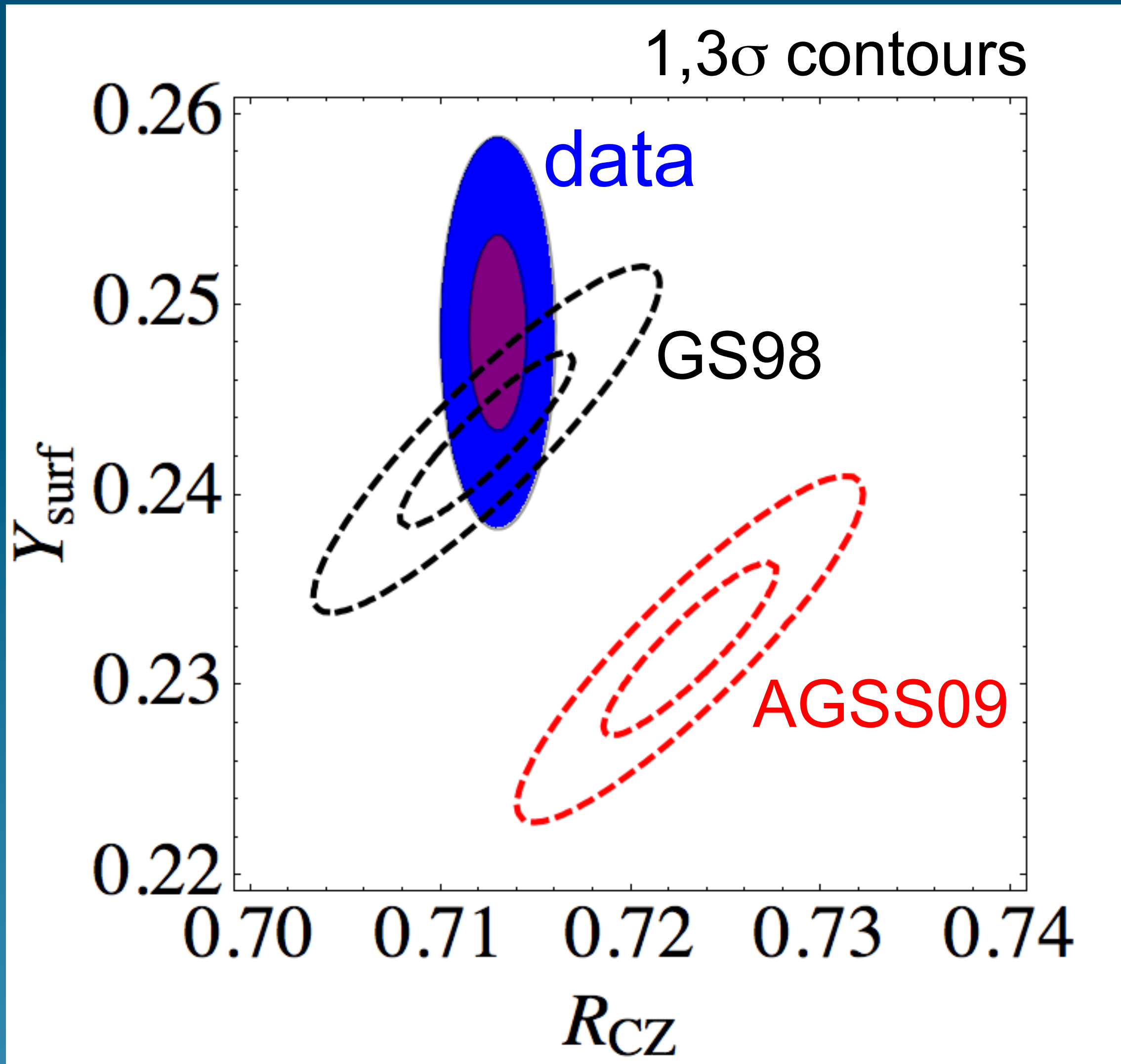
Helioseismology

Solar oscillations, stochastically excited by near-surface convection, provide unique information on solar convection and solar interior.

Helioseismology vs SSM

	BSP11-GS98	BSP11-AGSS09	Helioseismology
Z/X	0.0229	0.0178	-
Y_S	0.2429	0.2319	0.2485 ± 0.0034
R_{CZ} / R_{sun}	0.7124	0.7231	0.713 ± 0.001

The Solar Abundance Problem



Observations of Solar Neutrinos

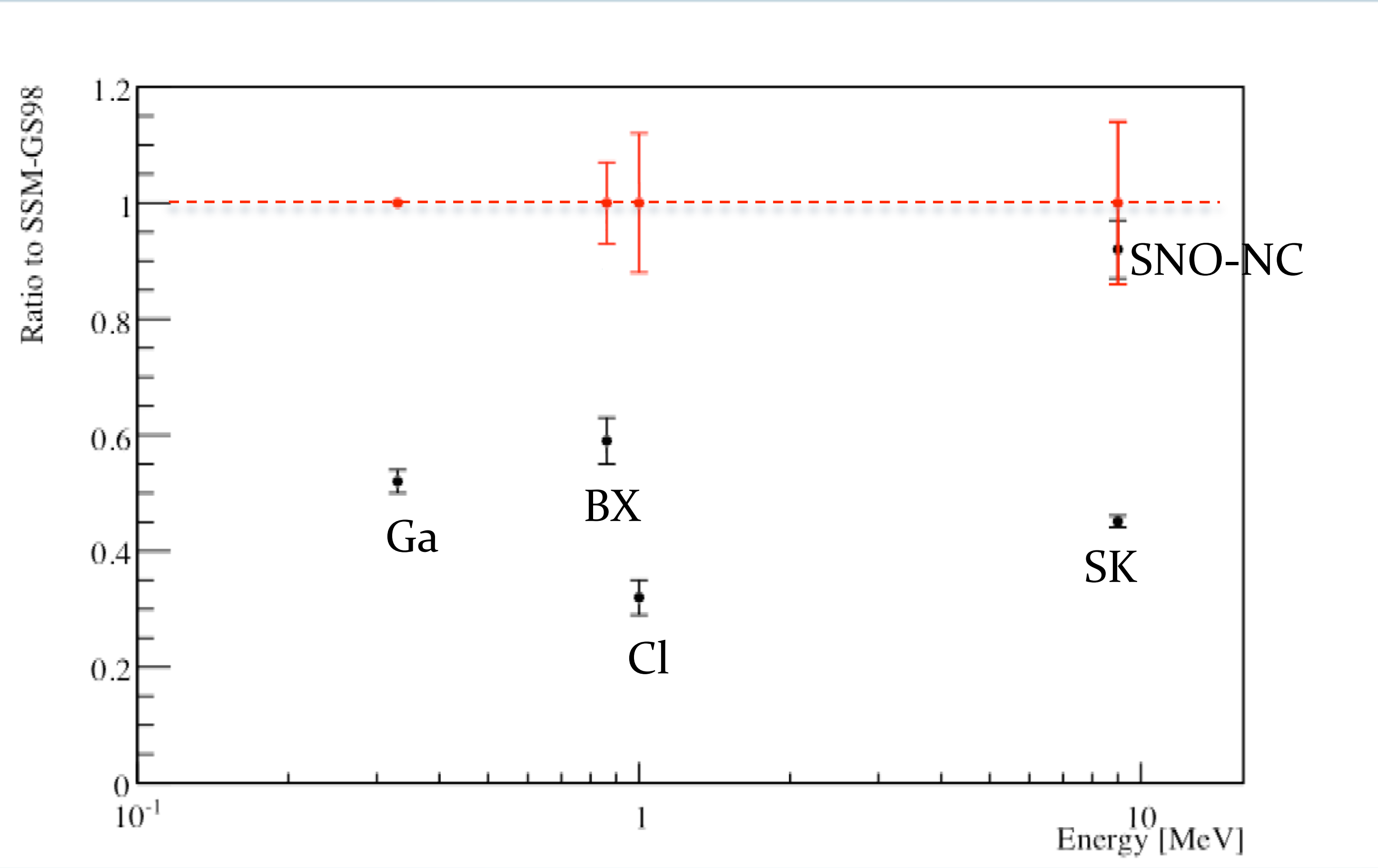
Solar Neutrino Experiments

Detector	Target mass	Threshold [MeV]	Data taking
Homestake	615 tons C_2Cl_4	0.814	1970-1994
Kamiokande II/III	3ktons H_2O	7.5 / 7.0	1983-1995
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 A. Renshaw]	22.5ktons	5 7 4.5 3.5	1996-2001 2003-2005 2006-2008 **2008-present**
SNO	1kton D_2O	3.5	1999-2006
Borexino [see F. Calaprice/O. Smirnov]	300ton C_9H_{12}	0.2 MeV	**2007-present**

Solar Neutrino Measurements

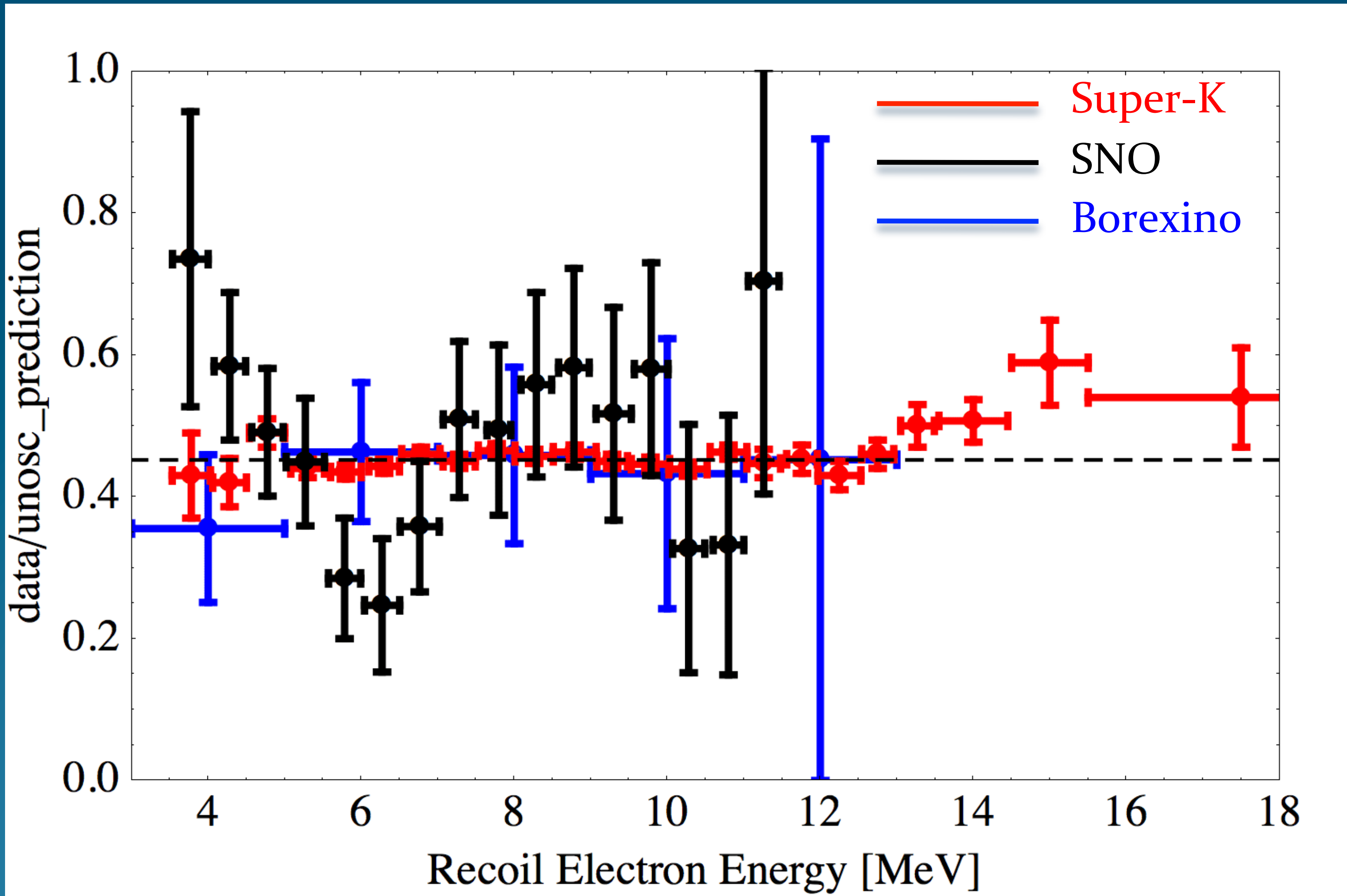
Experiment	Sources contributing to data	**Data**
Homestake	^{7}Be(13.1%)+pep(2.7%)+ CNO(2.4%)+^{8}B(81.8%)	2.56±0.16±0.16 SNU
GALLEX/GNO/SAGE	pp(55%)+^{7}Be(28.3%)+ pep(2.3%)+ CNO(3.4%)+^{8}B(11%)	66.1±3.1 SNU
Kamiokande II/III Super-Kamiokande (I, II, III, IV)	^{8}B	$\Phi_{\nu e} = (2.80\pm0.38)\times10^6\ cm^{-2}s^{-1}$ $\Phi_{\nu e} = (2.35\pm0.08)\times10^6\ cm^{-2}s^{-1}$ $\Phi_{\nu e} = (2.38\pm0.16)\times10^6\ cm^{-2}s^{-1}$ $\Phi_{\nu e} = (2.39\pm0.06)\times10^6\ cm^{-2}s^{-1}$ $\Phi_{\nu e} = (2.34\pm0.05)\times10^6\ cm^{-2}s^{-1}$
SNO	^{8}B [$\times10^6\ cm^{-2}s^{-1}$]	$\phi_B = 5.25\pm0.16^{+0.11}_{-0.13}$ $\phi_{NC} = 5.14\pm0.16^{+0.13}_{-0.12}$
BOREXINO	^{7}Be(0.862MeV) pep ^{8}B(>3MeV)	46±1.5±1.6 cpd/100tons 3.1±0.6±0.3 cpd/100tons 0.22±0.04±0.01 cpd/100tons

Observations vs Predictions: The Solar Neutrino Problem



^{8}B Solar Neutrino Spectrum

Detection by neutrino-electron ES

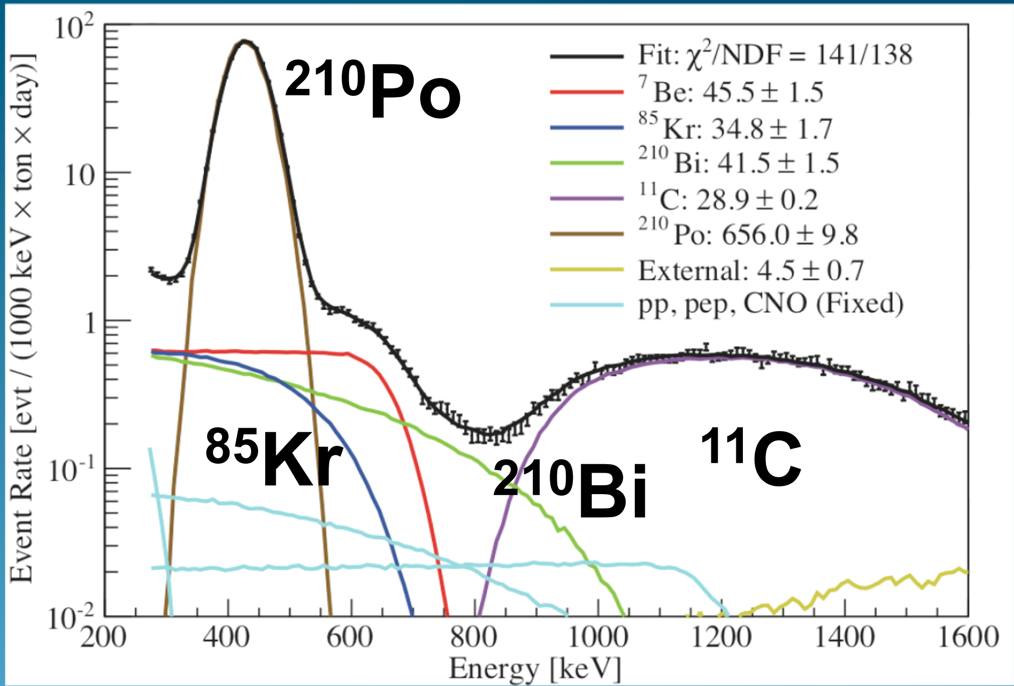


^{7}Be Solar Neutrino Measurement in Borexino

Rate($Be_{0.862}$) = 46.0 ± 1.5(sta)$^{+1.6}_{-1.5}$(sys) cpd/100tons

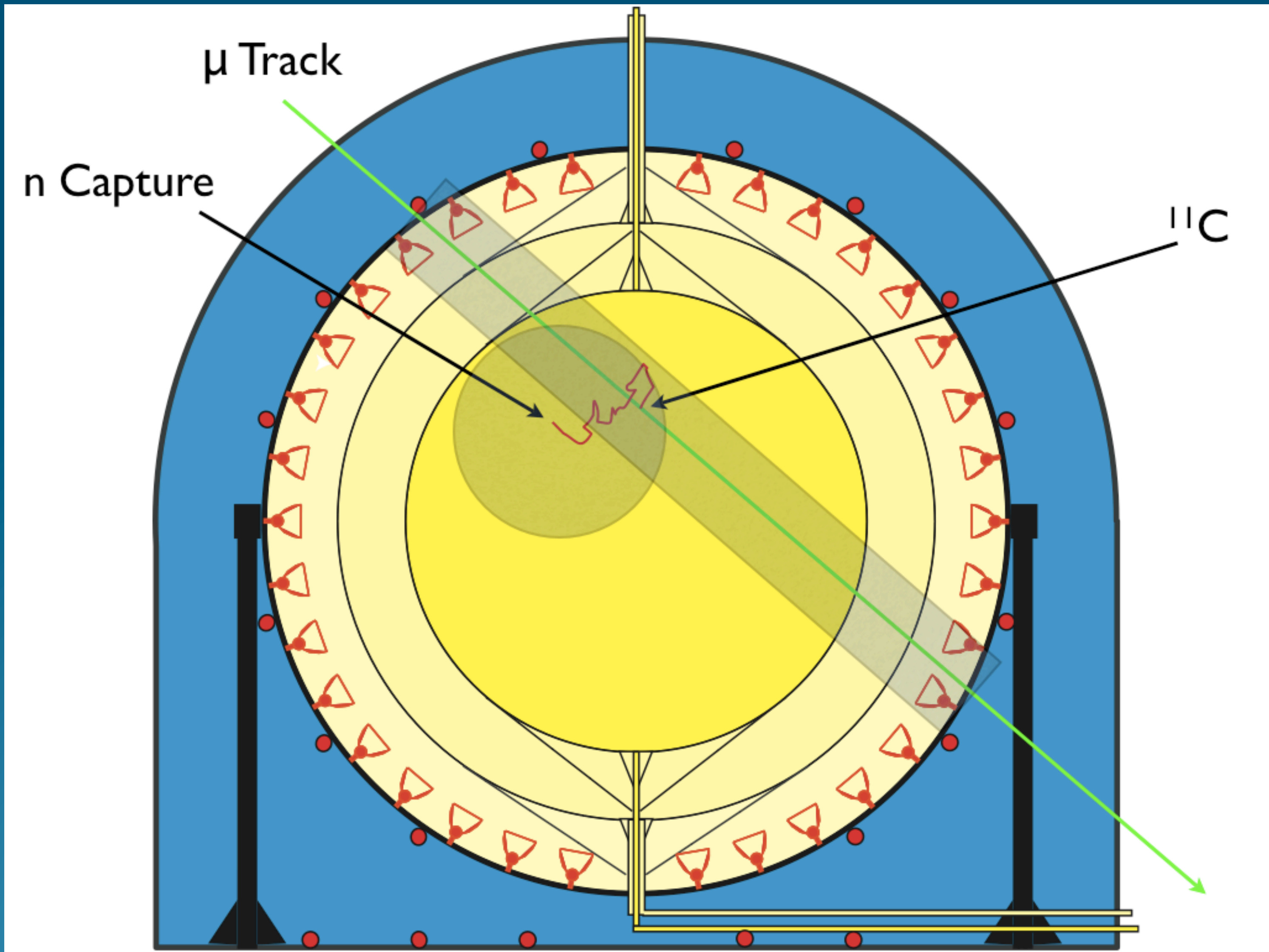
[Borexino coll., PRL 107, 2010]

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



see F. Calarice / O. Smirnov this meeting

Tagging and removing ^{11}C cosmogenic background

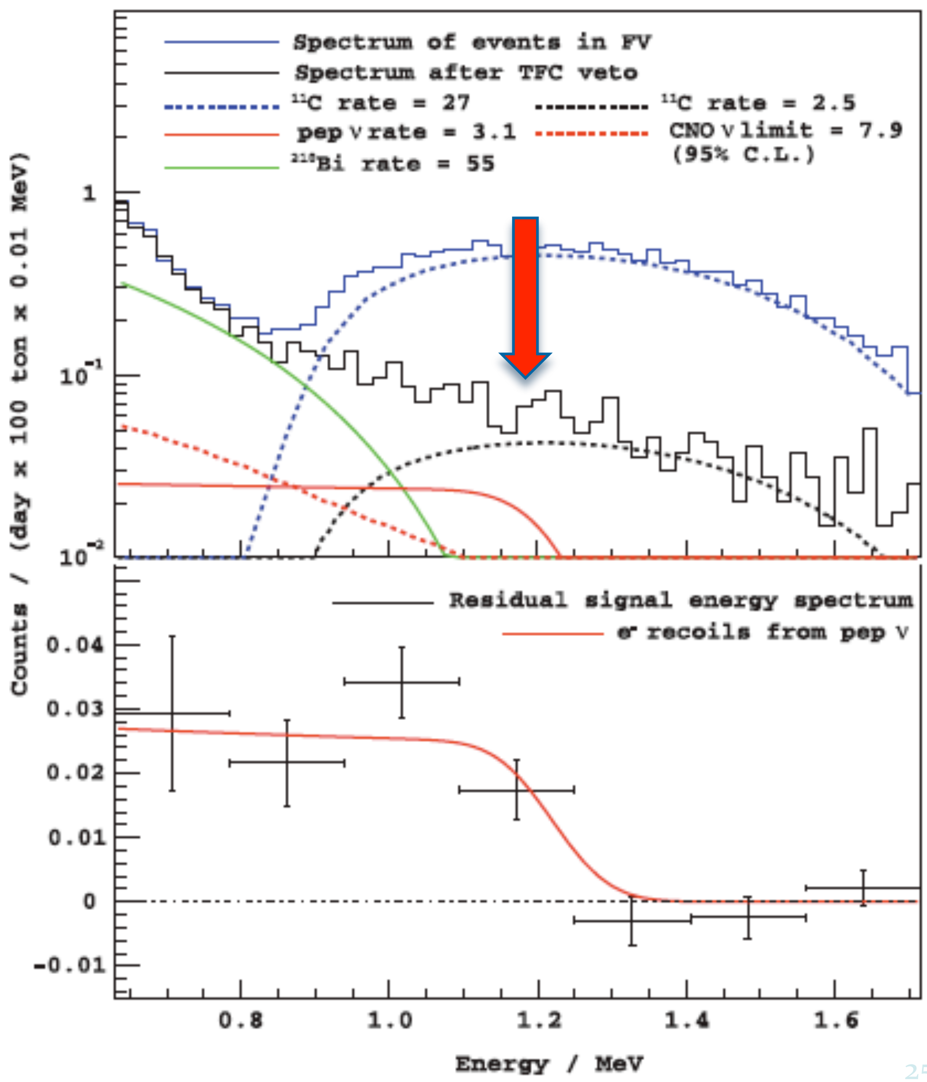


pep Solar Neutrino Measurement in Borexino

Rate(pep) = 3.1 ± 0.6(sta) ± 0.3(sys) cpd/100tons

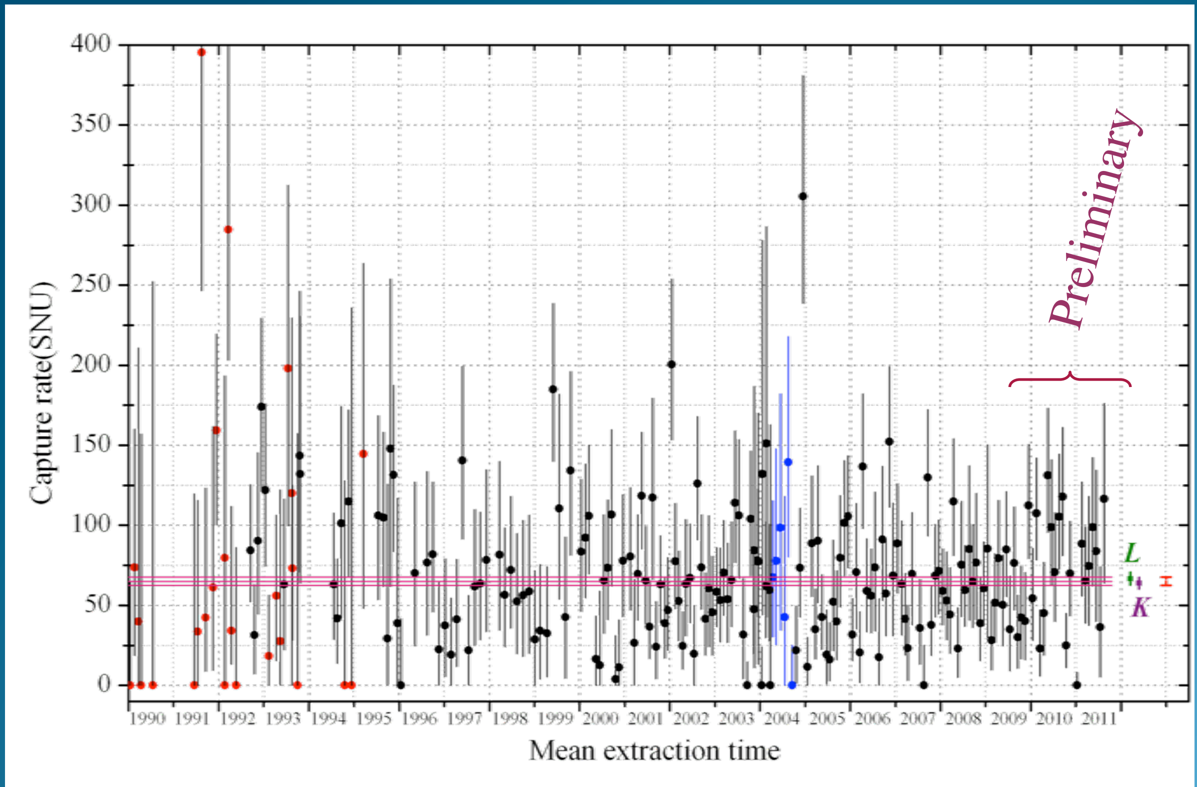
[Borexino coll., PRL 108, 2012]

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



SAGE

SAGE continues to perform regular solar neutrino extractions every four weeks with ~50 t of Ga



20.6 year period (1990 – 11.2011):
214 runs,
396 separate counting sets

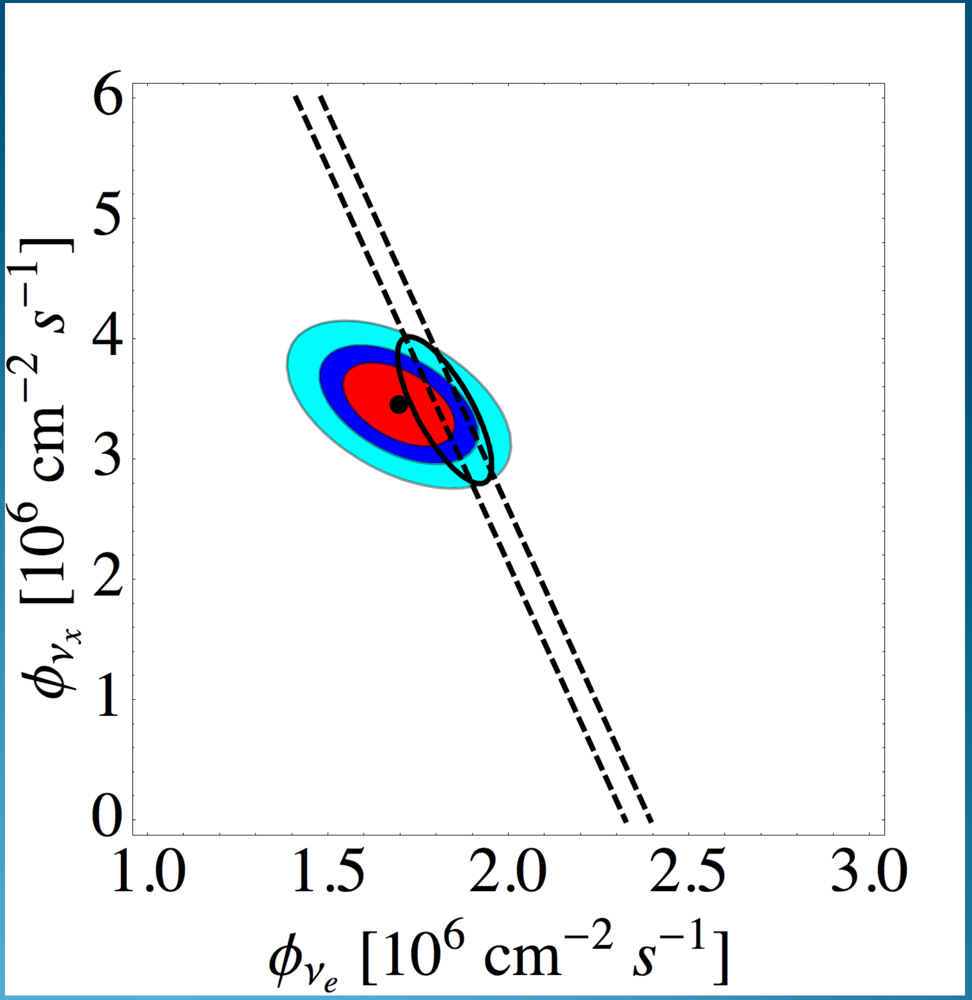
What we have learned today from solar neutrinos

Flavor change determined by SNO and SK

1,2,3σ contour from SNO CC, ES and NC

1σ band from SuperK

3σ contour combined



Using ^{8}B solar neutrino measurements

Model independent determination of ϕ_B and <P_{ee}> after equalization of SK and SNO response functions

[F. Villante et al., PRD 59, 1999. Fogli et al., PRD 63, 2001]

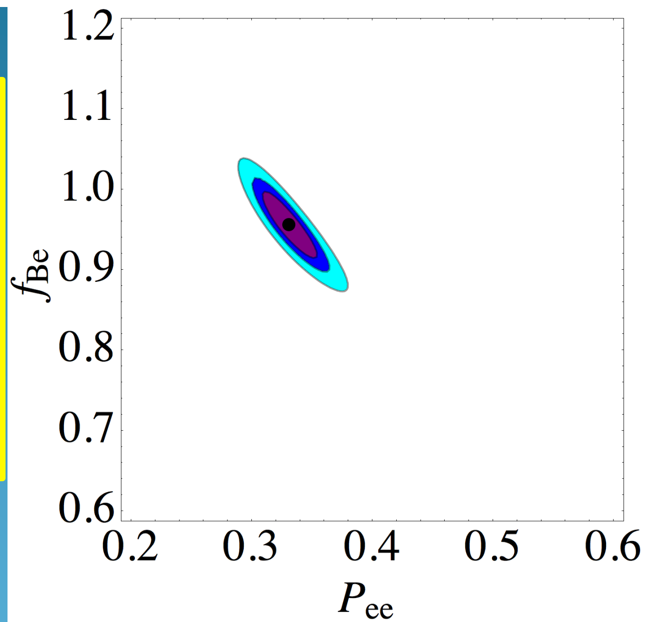
$$\phi_{ES}^{SK} = \phi_B\left[\langle P_{ee}\rangle + \rho\left(1-\langle P_{ee}\rangle\right)\right] = (2.36 \pm 0.03)\cdot 10^6\ \mathrm{cm^{-2}s^{-1}}$$

$$\phi_{CC}^{SNO} = \phi_B\langle P_{ee}\rangle = (1.67 \pm 0.07)\cdot 10^6\ \mathrm{cm^{-2}s^{-1}}$$

$$\phi_{CC}^{SNO} = \phi_B = \left(5.25 \pm 0.16^{+0.11}_{-0.13}\right)\cdot 10^6\ \mathrm{cm^{-2}s^{-1}}$$

$$P_{ee}^{B} = 0.329^{+0.018}_{-0.017} \approx \sin^2\theta_{12}$$

$$\phi_B = (5.39 \pm 0.18)\times 10^6\ \mathrm{cm^{-2}s^{-1}}$$



SNO and SuperKamiokande

SNO and SuperKamiokande provide:

1. ~ 3% measurement of ^{8}B solar neutrinos which can be used as a solar thermometer

2. ~ 6% determination of survival probability (< 1/2) at about 10 MeV

3. Precise determination of the mixing angle θ_{12}

4. Determination of Day-Night effect in SK at 2.7σ
[see A. Renshaw this meeting]

^{7}Be solar neutrino measurement

Rate measured in Borexino:

$R(Be_{0.862}) = 46.0 \pm 1.5(stat)\ ^{+1.6}_{-1.5}(sys)$ cpd/100tons

[Borexino coll., PRL 107, 2010]

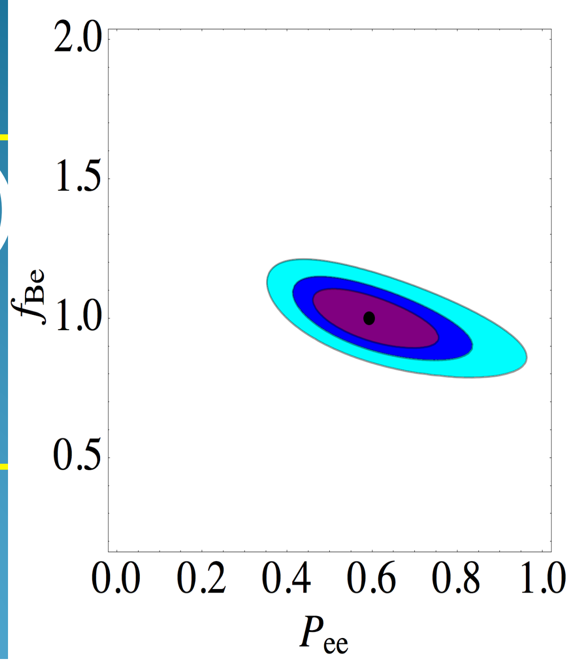
$$\frac{R^{BX}_{0.862}}{R^{SSM}_{0.862}} = f_{Be} \cdot P^{Be}_{ee} + \frac{\langle \sigma_{\nu_\mu} \rangle}{\langle \sigma_{\nu_e} \rangle} f_{Be} \cdot \left(1 - P^{Be}_{ee}\right)$$

$R_{0.862}^{SSM} = 74 \pm 5$ cpd/100tons

$R_{0.862}^{SSM-osc} = 42 \pm 3$ cpd/100tons

$P_{ee}^{Be\_0.862} = 0.59^{+0.08}_{-0.07}$ (AGSS09)

$\phi_{Be} = (4.99 \pm 0.24)\times 10^9\ cm^{-2}s^{-1}$



pep solar neutrino measurement

Rate measured in Borexino:

R(pep) = 3.1 ± 0.6(stat) ± 0.3(sys) cpd/100tons

[Borexino coll., PRL 108, 2012]

$$\frac{R_{pep}^{BX}}{R_{pep}^{SSM}} = f_{pep} \cdot P_{ee}^{pep} + \frac{\langle \sigma_{\nu_\mu} \rangle}{\langle \sigma_{\nu_e} \rangle} f_{pep} \cdot \left(1 - P_{ee}^{pep}\right)$$

$R_{pep}^{SSM} = 4.46 \pm 0.05$ cpd/100tons

$R_{pep}^{SSM-osc} = 2.73 \pm 0.05$ cpd/100tons

$$\boxed{\mathbf{P_{ee}^{pep} = 0.60 \pm 0.18\ (AGSS09)}}$$

$$\boxed{\mathbf{\phi_{Be} = (1.63 \pm 0.35)\times 10^{8}\ cm^{-2}s^{-1}}}$$

Luminosity Constraint

$$\frac{L_{sun}}{4\pi(A.U.)^2} = \sum_i a_i \phi_i$$

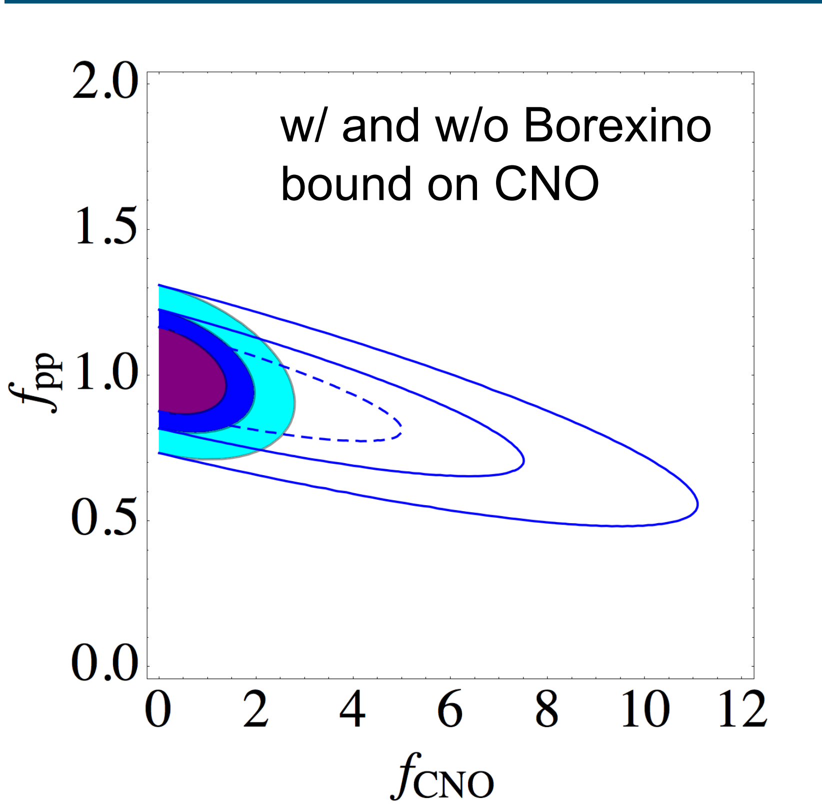
$$1 = \sum_i \left(\frac{a_i}{10\ \mathrm{MeV}}\right) \frac{\phi_i}{8.5243 \cdot 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}}$$

BPS2011-AGSS09:

$1 = 0.927\, f_{pp} + 0.067\, f_{Be} + 0.005\, f_{CNO} + 0.002 f_{pep} + \ldots$

$f_{pp} = 1.08 - 0.07\, f_{Be} - 0.008\, f_{CNO} + \ldots$

Luminosity from neutrino fluxes



No luminosity constraint

$\phi_{pp} = (6.14 \pm 0.61)\times 10^{10}\ \mathrm{cm^{-2}s^{-1}}$

$\phi_{CNO} < 6.8\times 10^{8}\ \mathrm{cm^{-2}s^{-1}}$ (95%CL)

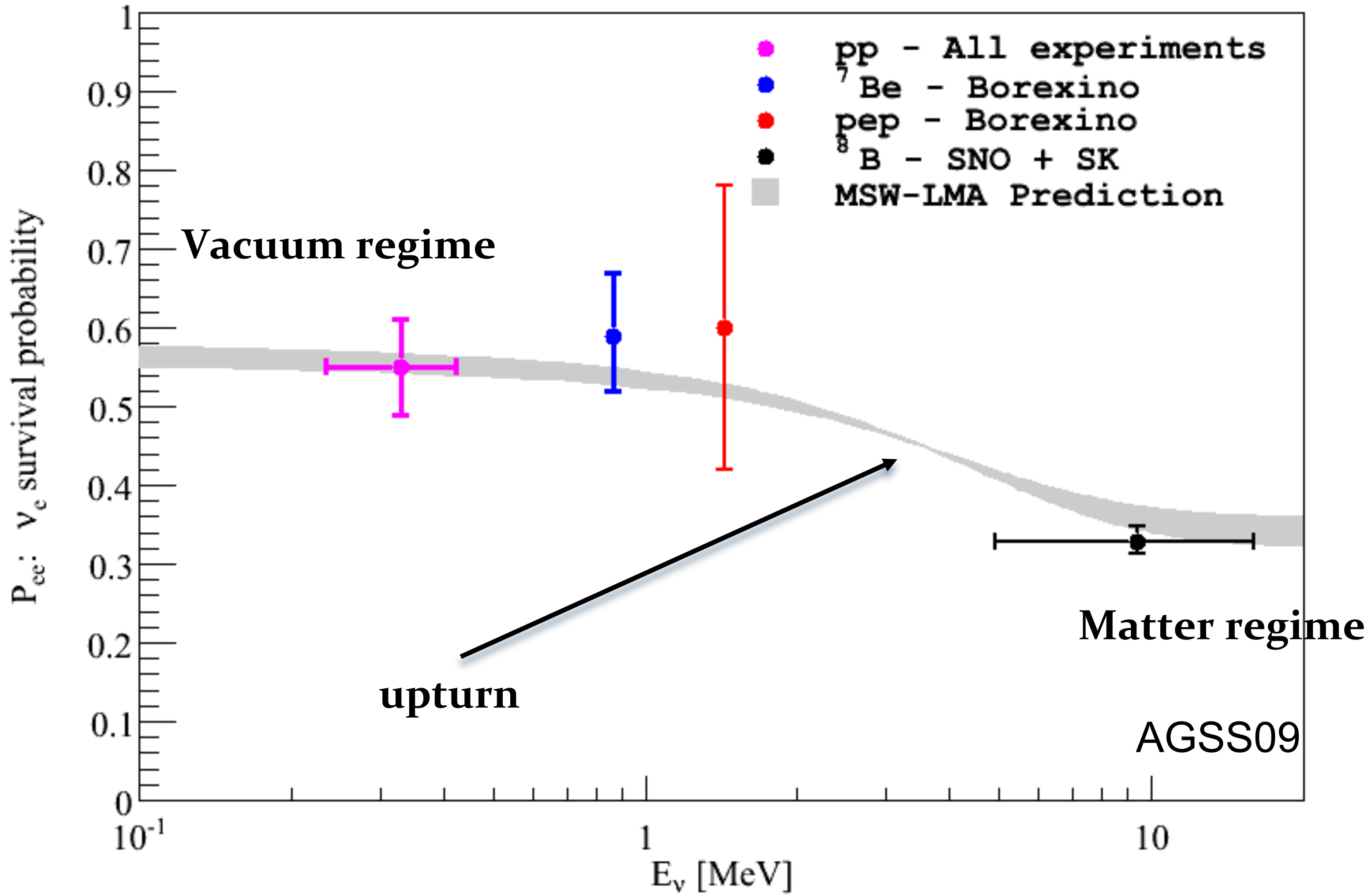
$$\mathbf{L_\nu / L_{sun} \approx 1.00 \pm 0.10}$$

Gonzalez-Garcia et al, JHEP 1005:072,2010: $L_\nu / L_{sun} = 0.98^{+0.15}_{-0.14}$
Bahcall et al., JHEP 0408 (2004) 016 : $L_\nu / L_{sun} = 1.4^{+0.2}_{-0.3}$

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	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	$6.02(1^{+0.002}_{-0.01})\times10^{10}$
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	$1.63(1\pm0.21)\times10^{8}$
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	$4.99(1\pm0.05)\times10^{9}$
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	$5.33(1\pm0.026)\times10^{6}$
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$2.17(1\pm0.15)\times10^{8}$	$<6.7\times10^{8}$
^{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}	**$<6.8\times10^{8}$ (2σ)** **$<7.7\times10^{8}$ (2σ) [BX]**
p-value Be,B,pep	0.91	0.77	

Solar Neutrinos Survival Probability



What next?

1. Timescale: < 10 years

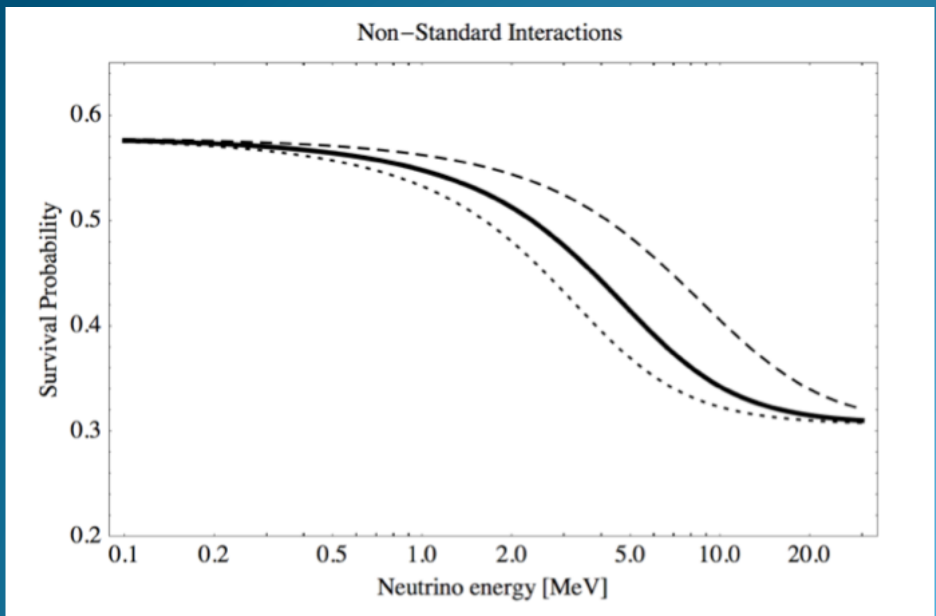
2. Running detectors:
   SuperKamiokande, Borexino, SAGE

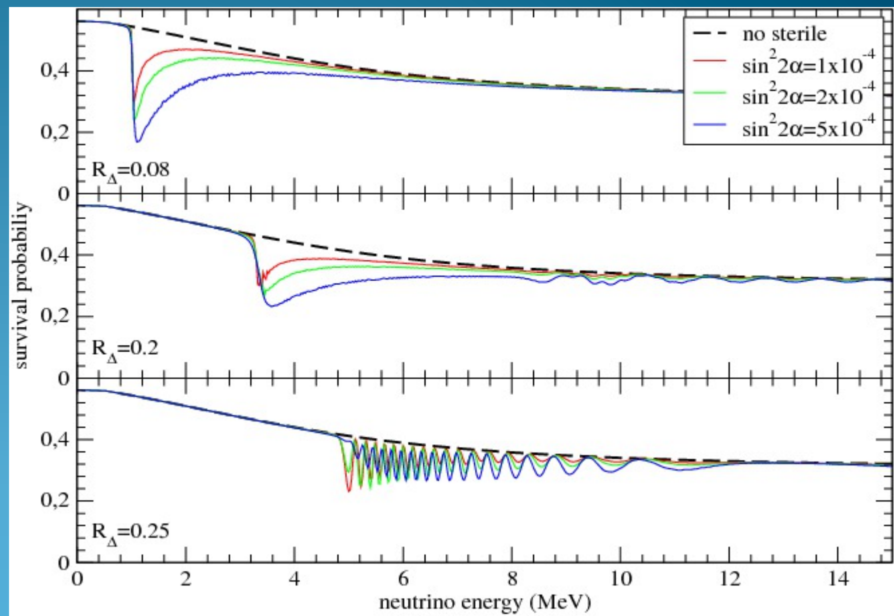
3. Upcoming: SNO+ (see J. Kaspar this meeting)
   - Filling 2014
   - Present planning: solar neutrino physics delayed after double beta decay search
     - **Main goals**: CNO + low energy ^{8}B (even during double beta decay search)

New Physics at up-turn

- Non Standard Interaction can change significantly the shape of the survival probability at the upturn [Y. Minakata and C. Pena-Garay,2010]

- Light sterile neutrinos, $\Delta m^2 \sim 10^{-5}$ eV^2, $\sin^2 2\theta \sim 10^{-3}$ [P. de Holanda and Y. Smirnov, PRD 83, 2011]]





CN-cycle neutrino measurement: Motivations

1. Independent test of solar metallicity, wrt photospheric determinations

2. Probe a **main assumption of SSM**: take primordial core metal abundances from today's surface metal abundances

3. Test nuclear physics governing massive main-sequence stars

4. Constraints metal accretion during a pre-main-sequence solar phase [$M_{acc} \sim 0.01 M_{sun}$]

W. Haxton and A. Serenelli, Ap. J., 2008

A. Serenelli, W. Haxton, C. Pena-Garay, Ap. J, 2011

CN-cycle ν fluxes to probe C+N

$$\frac{\phi\left({}^{15}O\right)}{\phi\left({}^{15}O\right)^{SSM}} \Big/ \left[\frac{\phi\left({}^{8}B\right)}{\phi\left({}^{8}B\right)^{SSM}}\right]^{0.785} = x_C^{0.794} x_N^{0.212} \times \left[L_{sun}^{0.515} Op^{-0.016} A^{0.308} D^{0.172}\right]$$

$$\times\left[S_{11}^{-0.831} S_{33}^{0.342} S_{34}^{-0.685} S_{17}^{-0.785} S_{e7}^{0.785} S_{1,14}^{0.995}\right]$$

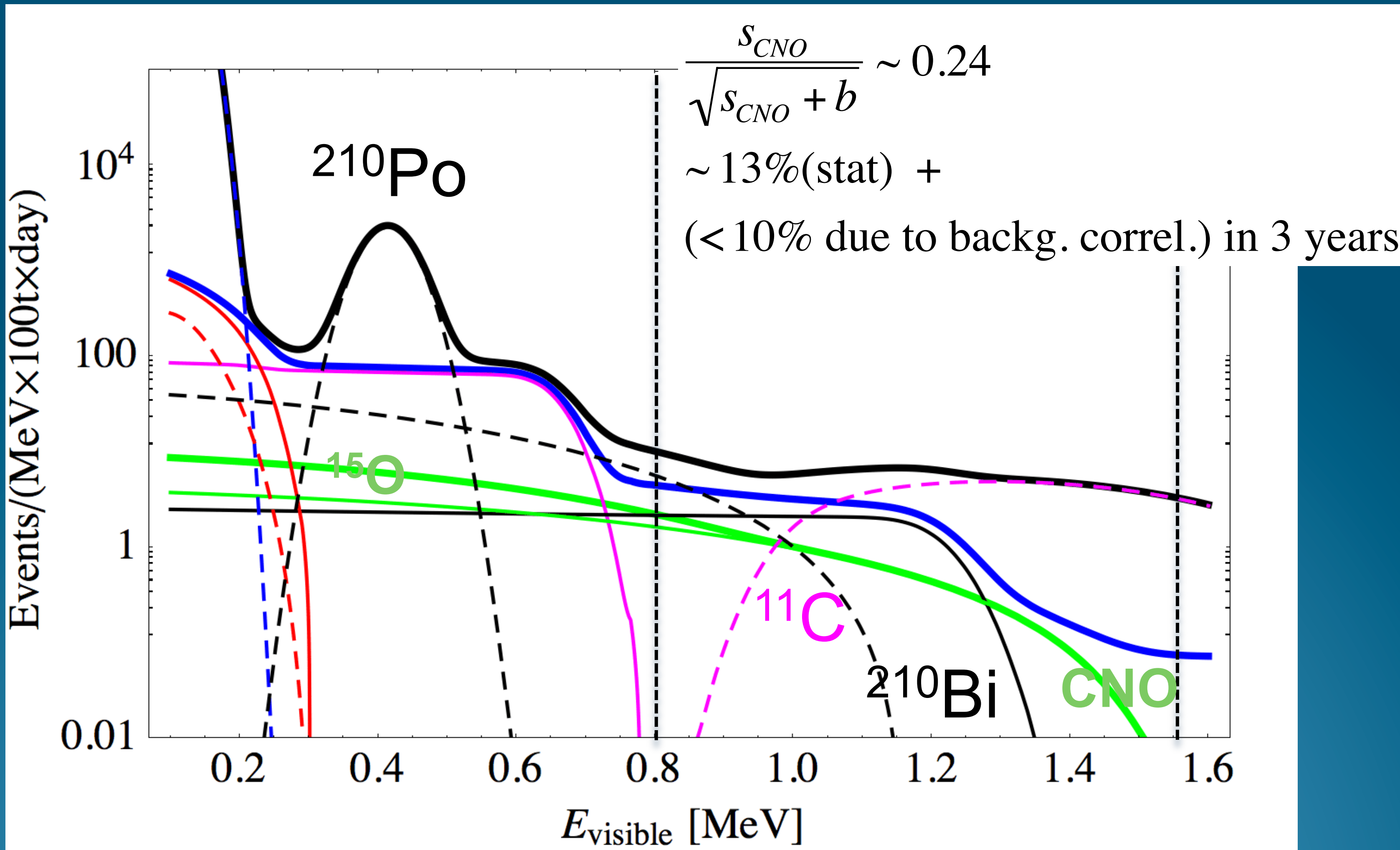
$$\times\left[x_O^{0.003} x_{Ne}^{-0.005} x_{Mg}^{-0.003} x_{Si}^{-0.001} x_S^{-0.001} x_{Ar}^{0.001} x_{Fe}^{0.003}\right]$$

✓~ 3% uncertainty from "environmental" parameters but C+N

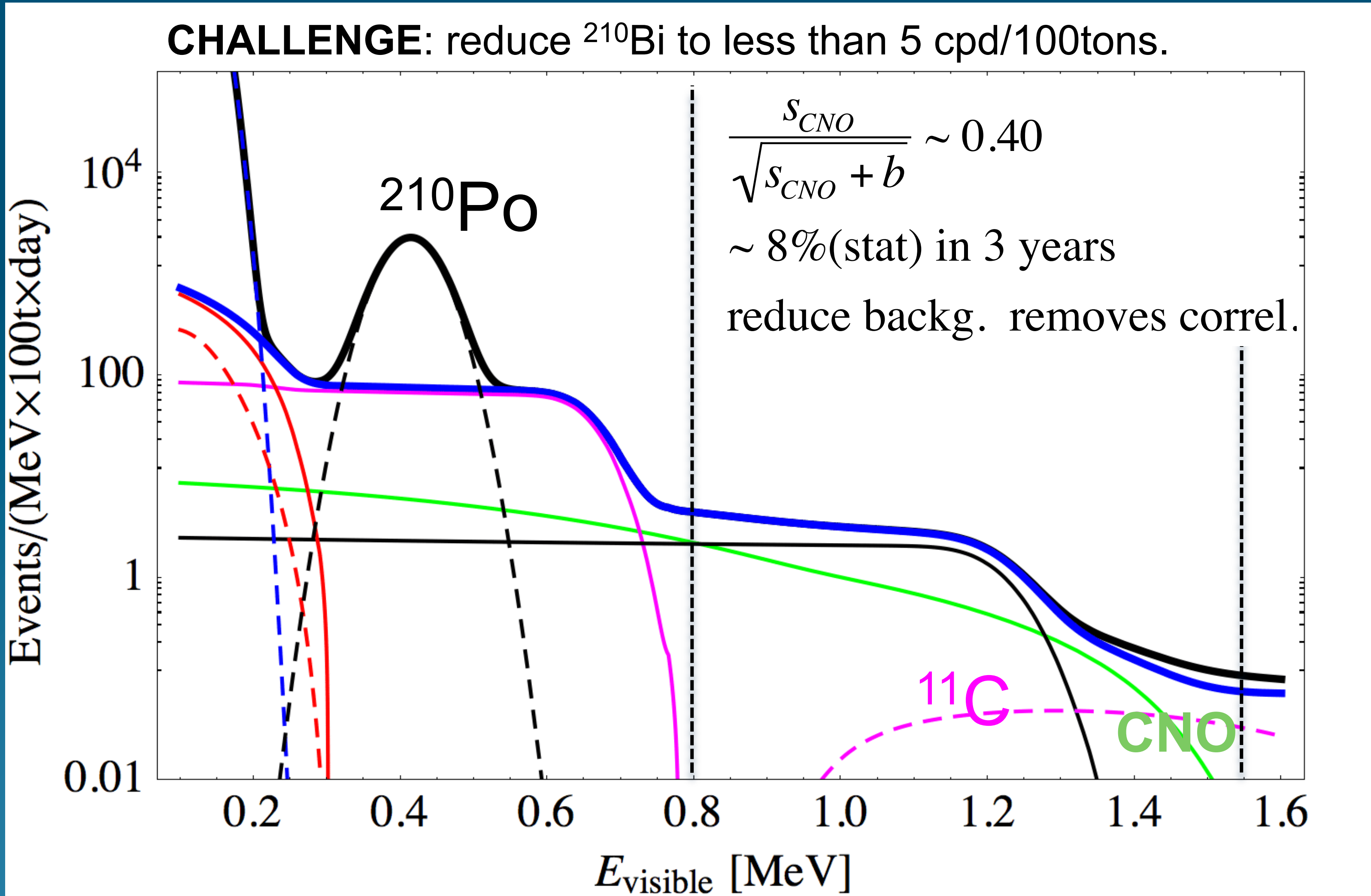
✓ ~ 10% from S-factors

A 10%(7%) ^{15}O neutrino measurement determines C+N abundance at ~15%(10%) level

Search for CNO neutrinos with a BX-like detector



Improving S/B in a BX-like detector @ SNOlab depth



Determine SSM parameters

Neutrino fluxes sensitive to nuclear S-factors and core temperature

- Explore SSM parameters using solar neutrino measurements
  - Bandyopadhyay, Choubey, Goswami and Petcov, PRD 75, 2007
  - Serenelli, Haxton and Pena-Garay, arXiv:1211.6740
- Most unknown parameters:
  - Diffusion (15%), S_{34} (5.2%), S_{17} (7.7%)
- Example:
  - S_{17} at 12% with present measurement
  - S_{17} at ~8% with ^{7}Be and S_{34} at 3%

Lesson from Solar Neutrinos

About half a century ago, first solar neutrinos were detected, which led us to the "**Solar Neutrino Problem**".

TODAY:

1. Precise measurement of θ_{12}
2. Oscillations of ν_e and matter-vacuum effect
3. pp-chain hydrogen burning evidence
4. Neutrino fluxes: ^{8}B, ^{7}Be and pep, pp
5. Bound on CNO neutrinos
6. L_ν / L_{sun} @ 10% level

7. Solar Abundance Problem

Goals for present and upcoming detectors

1. Study Matter-Vacuum transition and day-night effect to test LMA-MSW and probe possible new physics
2. Improve bound on CNO in BX
3. Improve precision on ^{8}B flux in SK
4. pp direct measurement in BX
5. pp measurement in SAGE (more than 20 years!)
   Take into account new results from D. Frekers et al., PL B 706, 2011 on capture cross section
6. Face detection of CNO neutrinos and solve "**Solar Abundance Problem**".
   Feasibility will very much depend on the BACKGROUND ISSUE (see F. Calaprice this meeting)

Solar Neutrino Search has more to give

Acknowledgements

To TAUP organizers for inviting me

To Y. Suzuki for information on SuperKamiokande

To V. Gavrin for information on SAGE

To M. Chen for information on SNO+

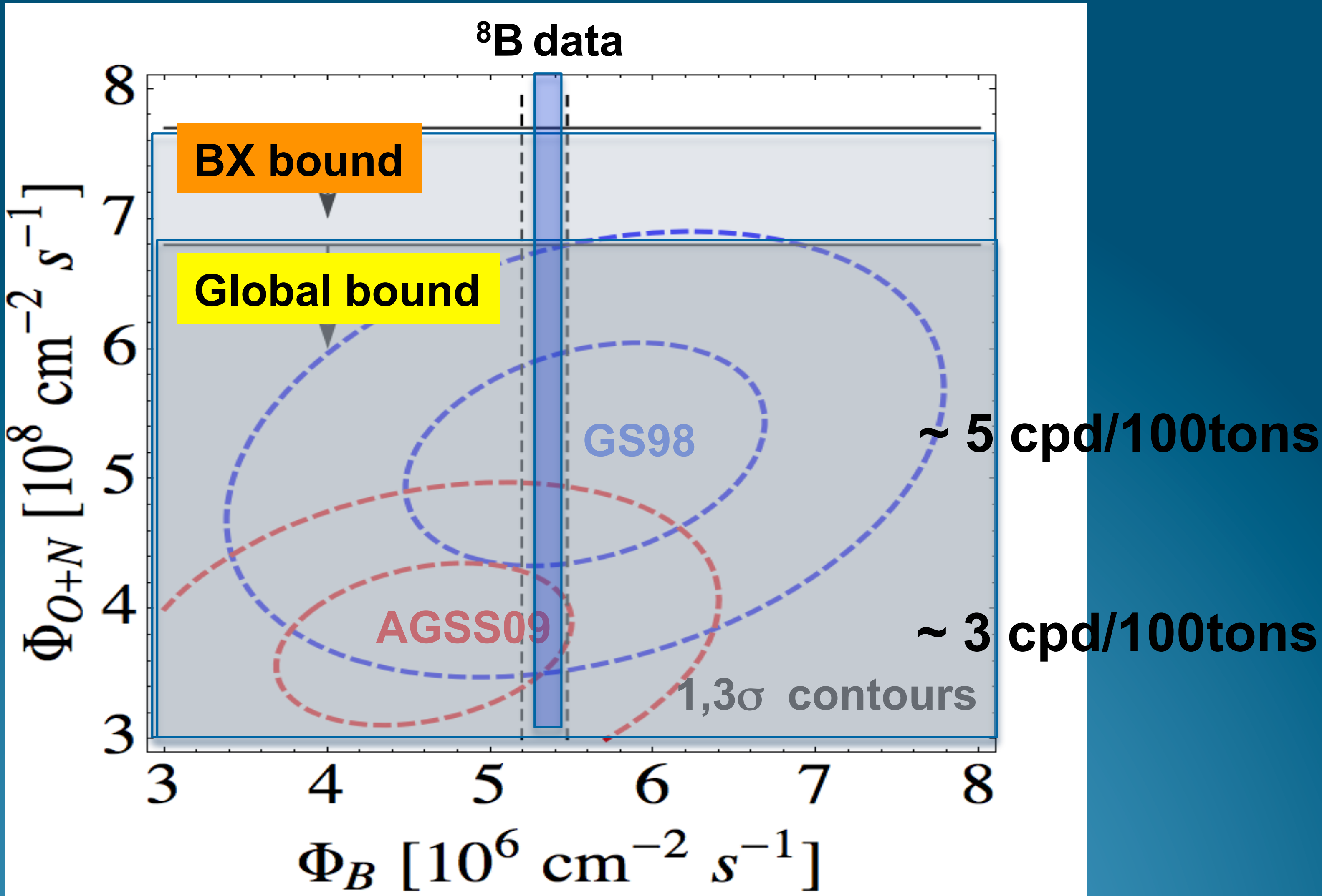
To A. Serenelli, C. Pena-Garay, F. Villante, F. Vissani for comments and suggetions

To Nicolas Grevesse for discussions on solar metal abundances

To All my Colleagues in Borexino

To the speakers of parallel session on low energy neutrinos reporting on Borexino, SuperK, SNO+ and SSM

N+O vs ^{8}B



^{8}B data
BX bound
Global bound
GS98
AGSS09
1,3σ contours
~ 5 cpd/100tons
~ 3 cpd/100tons
Φ_{O+N} [10^8 cm^{-2} s^{-1}]
Φ_B [10^6 cm^{-2} s^{-1}]
3
4
5
6
7
8

Spares

Detecting Solar Neutrinos

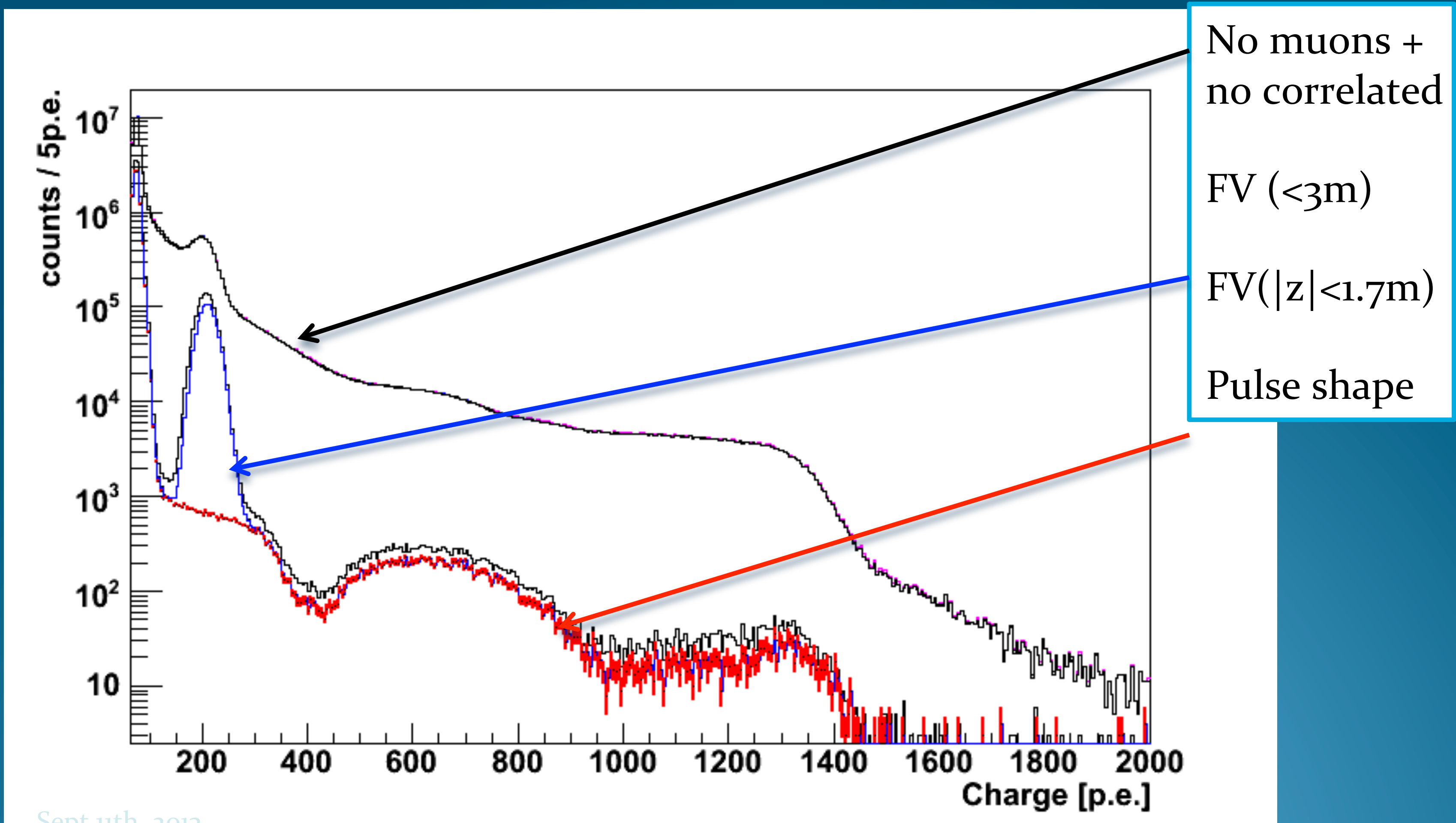
- Electron capture: ν_e+(A,Z-1)→(A,Z)+e^- (σ~$10^{-42}cm^2$)

- Elastic Scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$ (σ~$10^{-44}cm^2$)

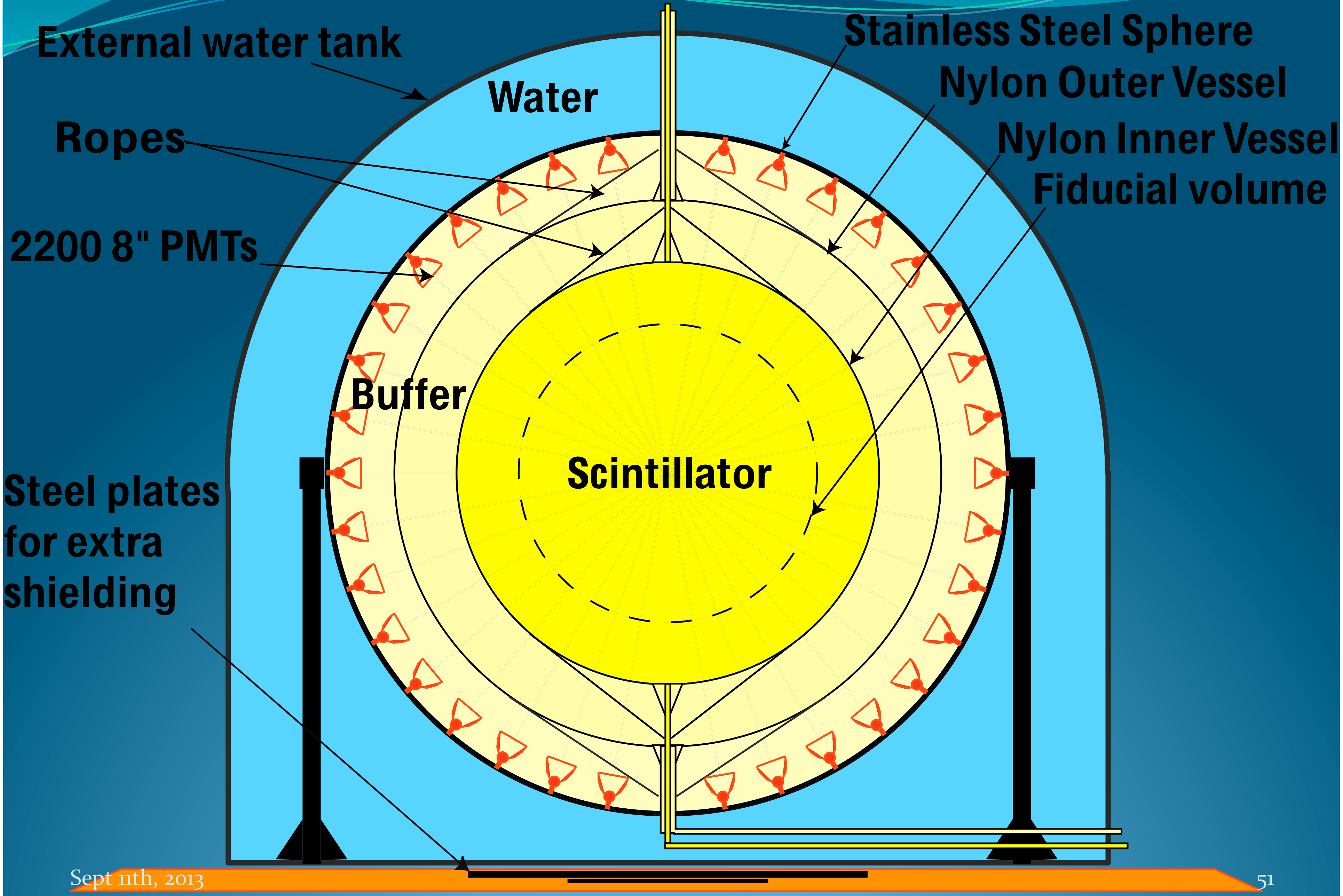
- $\nu_e + d \rightarrow e^- + p + p$ ($E_\nu \geq 1.44$ MeV) (σ~$10^{-42}cm^2$)
- $\nu_x + d \rightarrow \nu_x + p + n$ ($E_\nu \geq 2.74$ MeV)
  - pure NC interaction

SNO

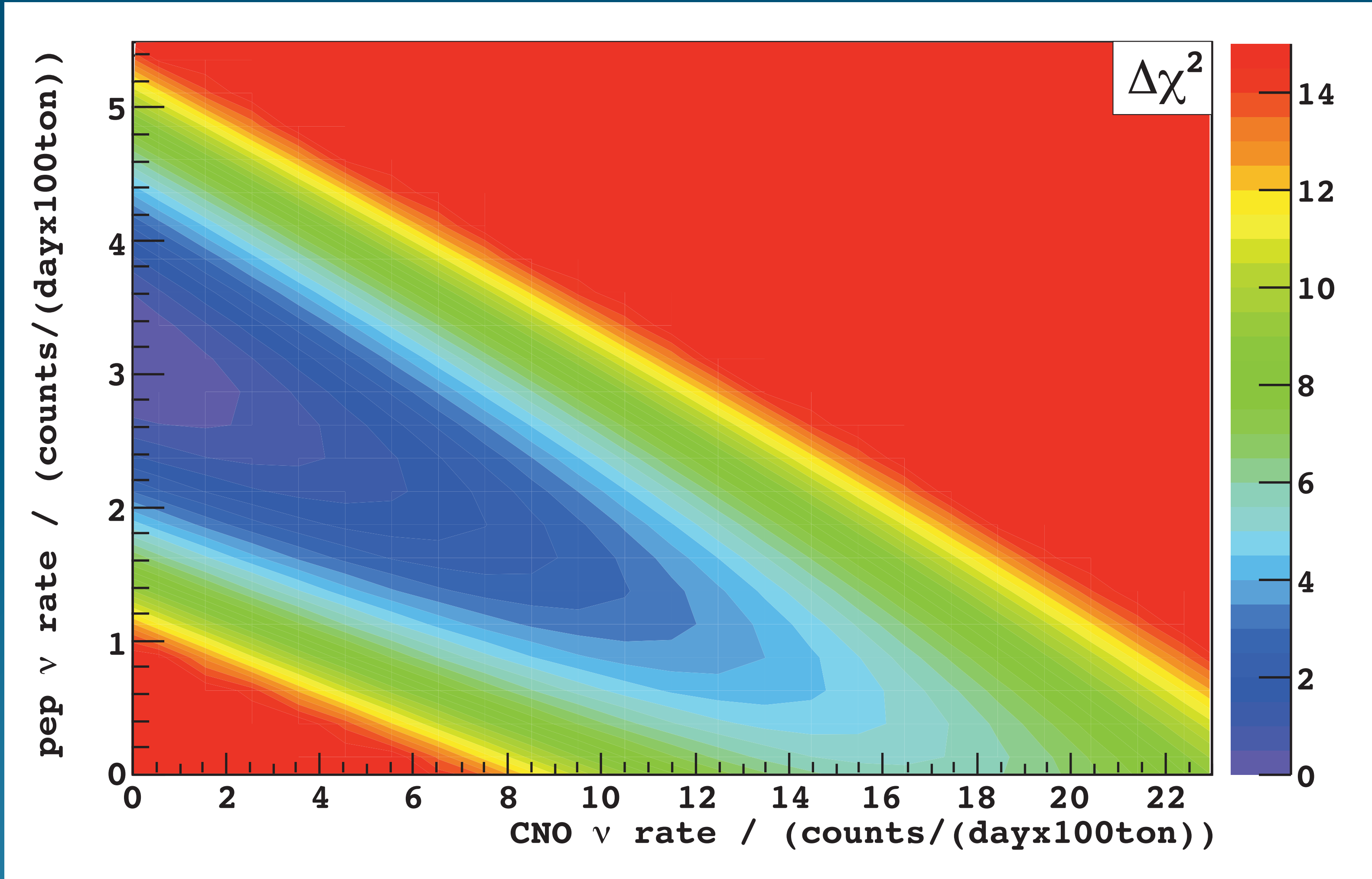
Data reduction in Borexino



Borexino Experiment



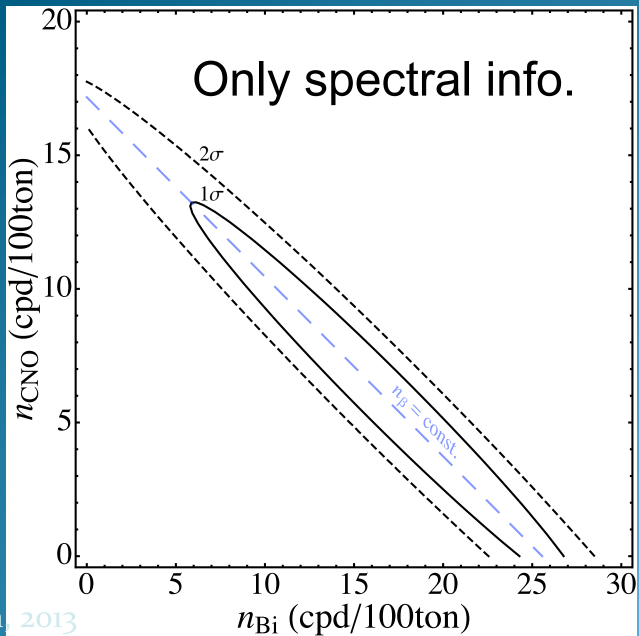
pep vs CNO rates in Borexino

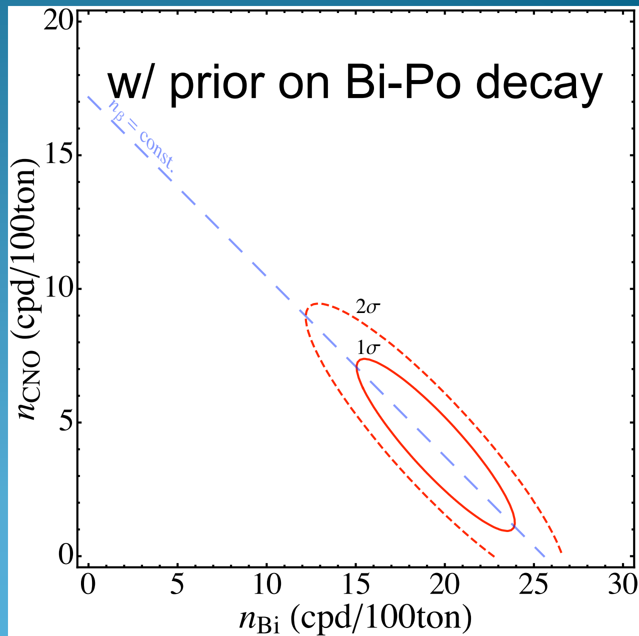


CNO neutrino measurements

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).





Background in Borexino

$^{214}Bi^{214}Po$	$^{212}Bi^{212}Po$	^{210}Po	^{210}Bi	^{85}Kr
$(5.4\pm1.1)\times 10^{-19}$ g/g **$(1.6\pm0.6)\times 10^{-19}$ g/g***	$<1.2\times10^{-18}$ g/g (95% CL)	~200 cpd/ 100tons	20±5 cpd/ 100tons	~ 0 cpd/ 100tons

*** not including a temperature fluctuation event**

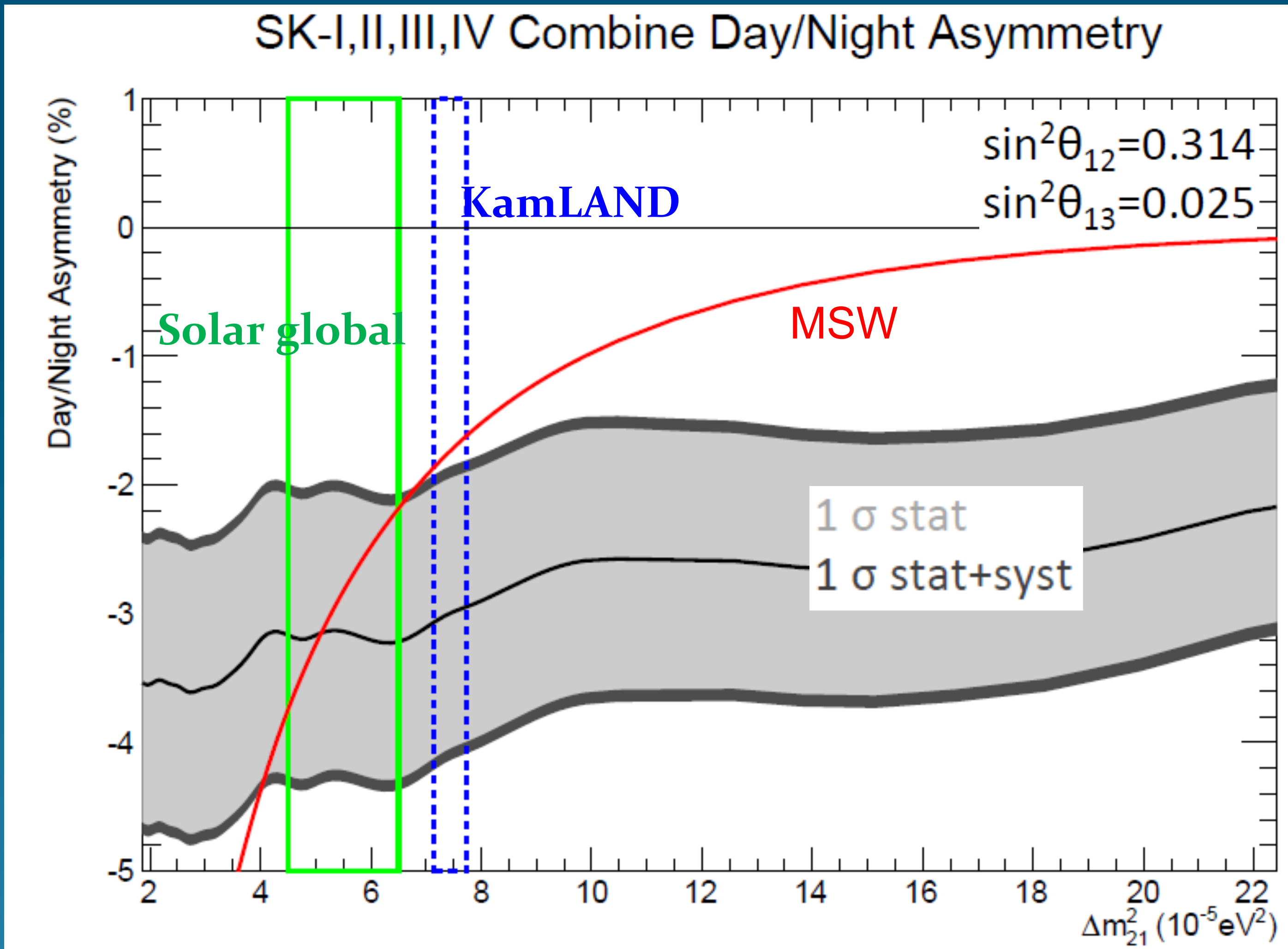
Study ^{15}O flux to determine C+N abundance

$$\phi\left({}^{15}O\right) = \phi\left({}^{15}O\right)^{SSM}\left[L_{sun}^{5.942} Op^{2.034} A^{1.364} D^{0.382}\right] \times \left[S_{11}^{-2.912} S_{33}^{0.024} S_{34}^{-0.052} S_{1,14}^{1.0}\right]$$
$$\times\left[x_C^{0.815} x_N^{0.217} x_O^{0.112} x_{Ne}^{0.081} x_{Mg}^{0.069} x_{Si}^{0.150} x_S^{0.109} x_{Ar}^{0.028} x_{Fe}^{0.397}\right]$$

- ✓ ~ 20% uncertainty from C+N abundances
- ✓ ~ 11% uncertainty from other "environmental" parameters
- ✓ ~ 8% from S-factors

Strategy from Serenelli, Pena-Garay, Haxton, 2012: use well-measured ^{8}B flux to remove environmental parameters dependence

Day-Night effect: dependence of asymmetry on Δm^2_{21}



Direct evidence of matter effects. In SK evidence at 2.6σ

Global Analysis of Solar Neutrino Data

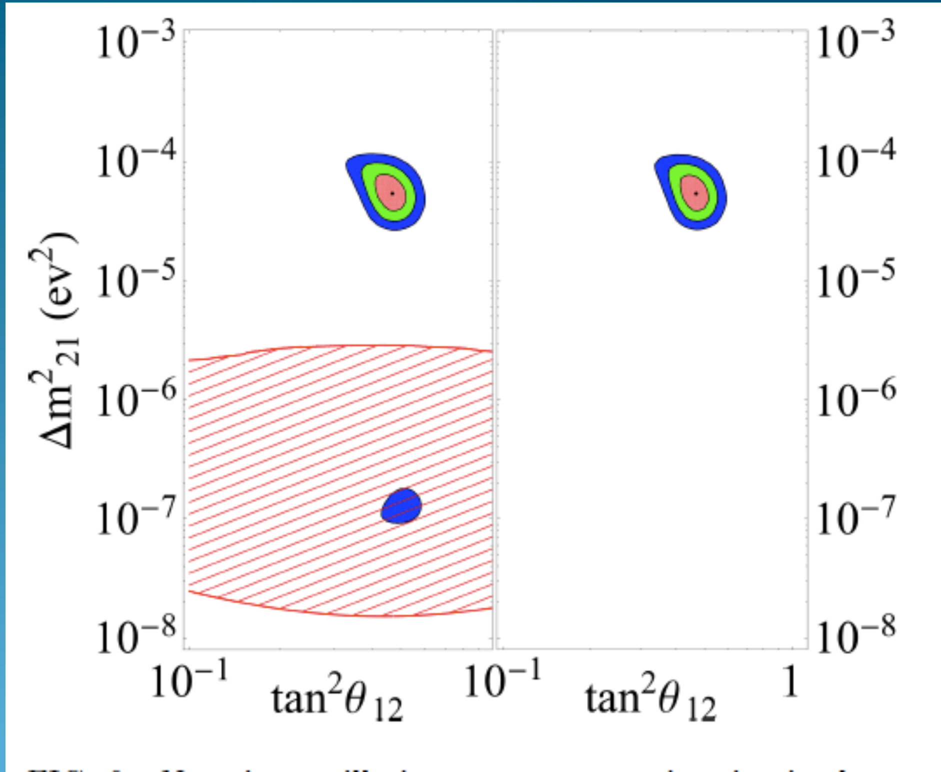
In the framework of neutrino oscillations one defines:

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

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

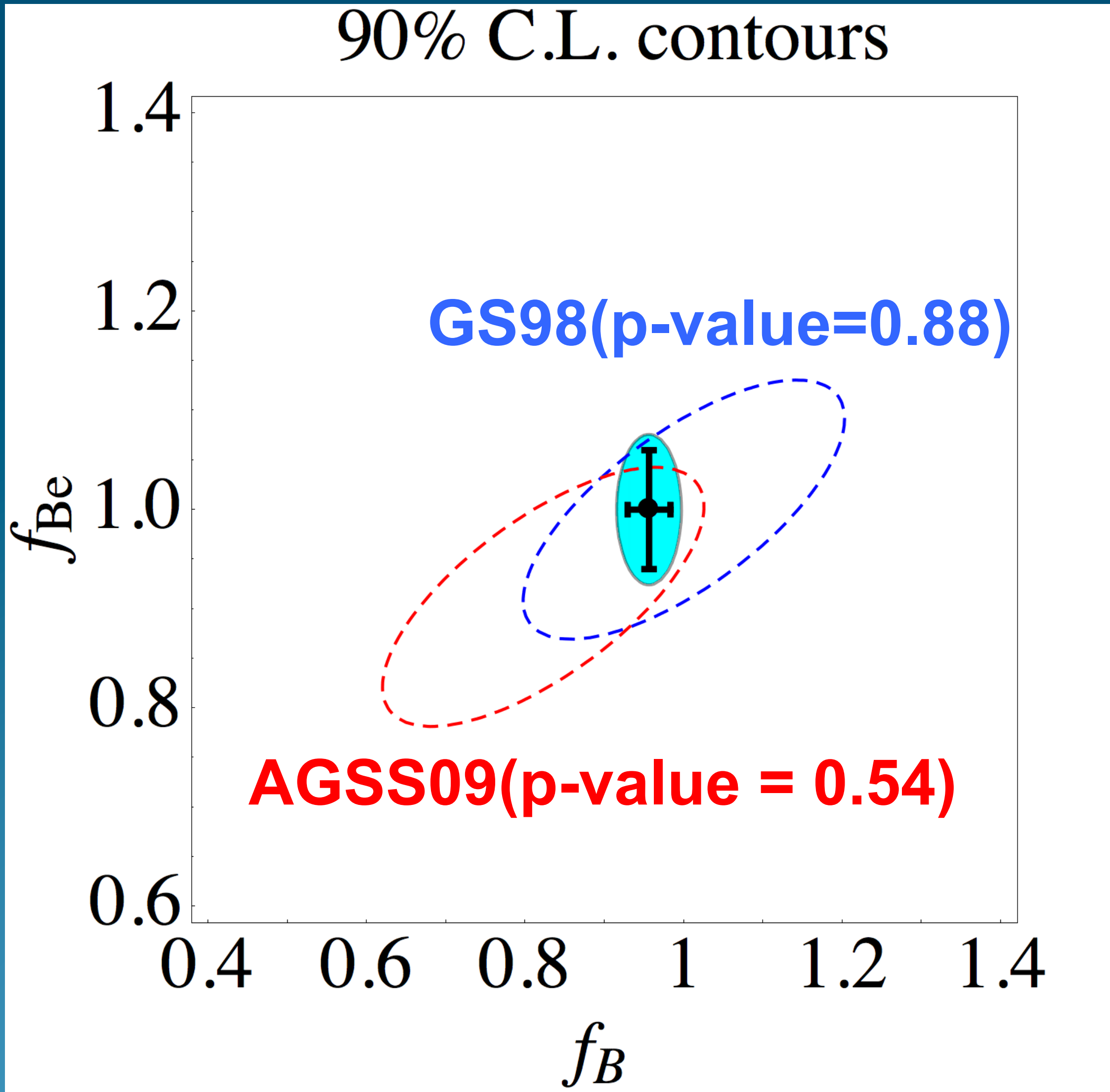
$$\tan^2\theta_{12} = 0.457^{+0.038}_{-0.025}\ \left[0.462^{+0.032}_{-0.033}\right]$$

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



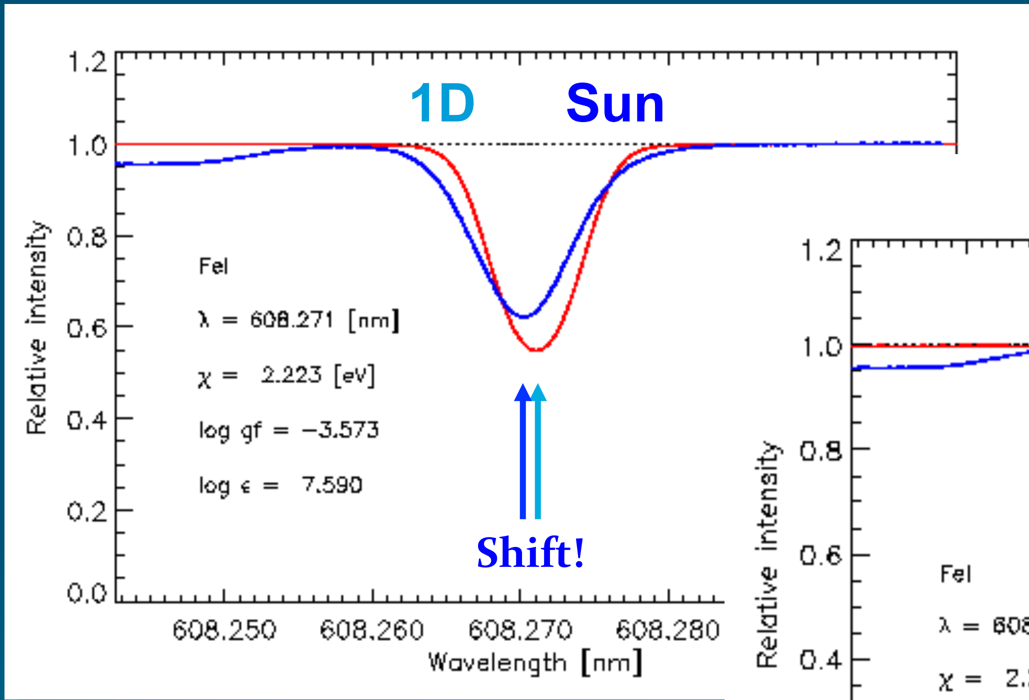
Borexino coll., PL B 707, 2012

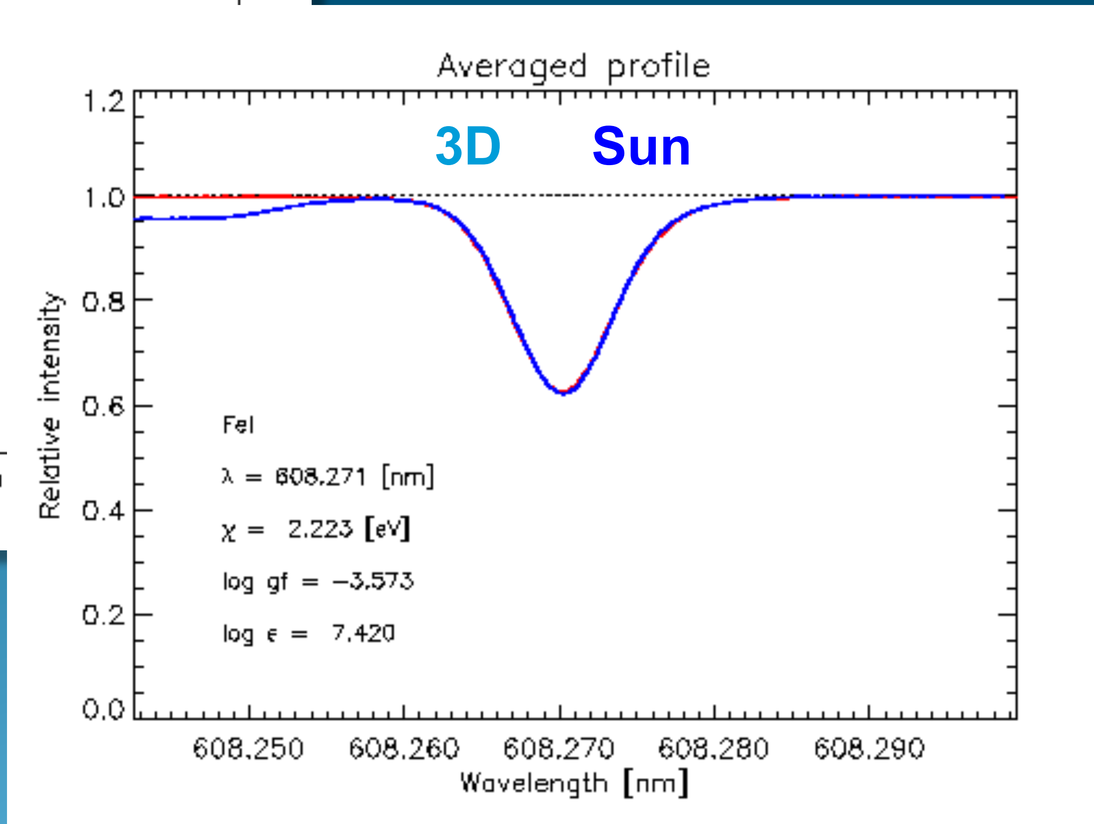
^{8}B vs ^{7}Be



90% C.L. contours
1.4
1.2
1.0
0.8
0.6
f_{Be}
0.4
0.6
0.8
1
1.2
1.4
f_B
GS98(p-value=0.88)
AGSS09(p-value = 0.54)

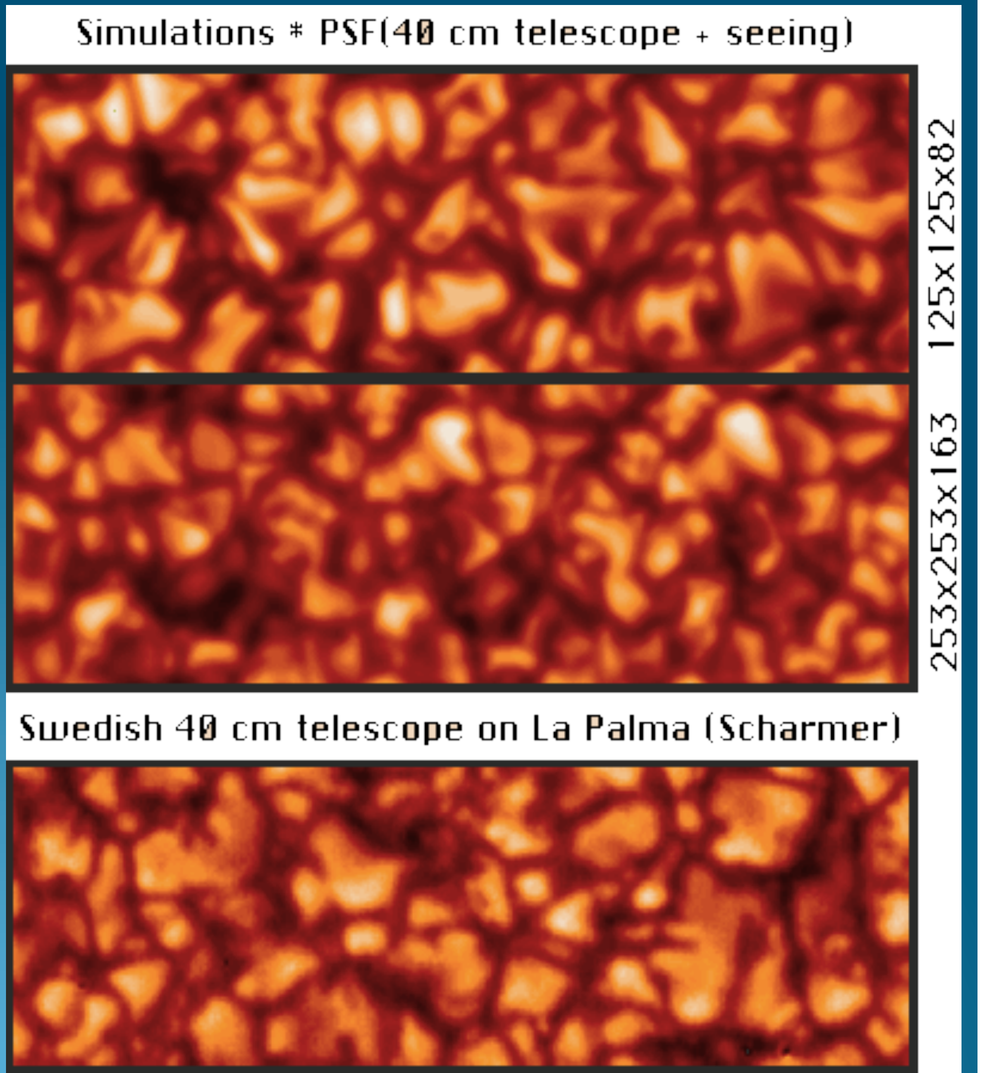
1D vs 3D: Averaged line profiles





3D model success

- **Topology and convective motions**



CN-cycle neutrino measurement: Strategy

Study feasibility of a CN-neutrino measurement on the basis of recent solar neutrino searches

1. W. Haxton, A. Serenelli, Astrop. J, 687, 2008
2. A. Serenelli, C. Pena-Garay, W: Haxton, arXiv: 1211.6740