Solar Models: an update

PHYSUN II – Gran Sasso 4/10/10

A. Serenelli

Outline

- Solar models with latest abundances
  - helioseismic and neutrino results
- Solar neutrino fluxes from neutrino data: can neutrinos disentangle abundances?
- Updates on nuclear reactions: effect on models
- Solutions? Opacities: an instructive example
- Determining solar abundances from helios. + neutrinos and future work
- Final remarks

Recap on solar abundances

Asplund et al. 2009 latest revision slightly higher abundances than in 2005 (note, particularly, neon and argon: the human factor)

Element	GS98	AGS05	AGSS09	AGSS09ph	CO^5BOLD
C	8.52	8.39	8.43	8.43	8.50
N	7.92	7.78	7.83	7.83	7.86
O	8.83	8.66	8.69	8.69	8.76
Ne	8.08	7.84	7.93	7.93	—
Mg	7.58	7.53	7.53	7.60	—
Si	7.56	7.51	7.51	7.51	—
Ar	6.40	6.18	6.40	6.40	—
Fe	7.50	7.45	7.45	7.50	7.52
Z/X	0.0229	0.0165	0.0178	0.0181	0.0209

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Small differences between photospheric and atmospheric abundances

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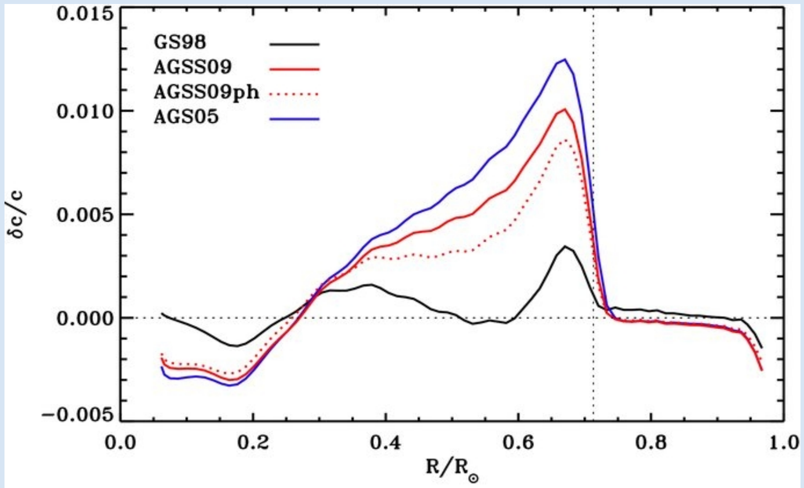
Other group CO5BOLD derives higher abundances (and larger error bars!) although model atmospheres seem to agree very well (comparison of models undergoing)

Some results on helioseismology

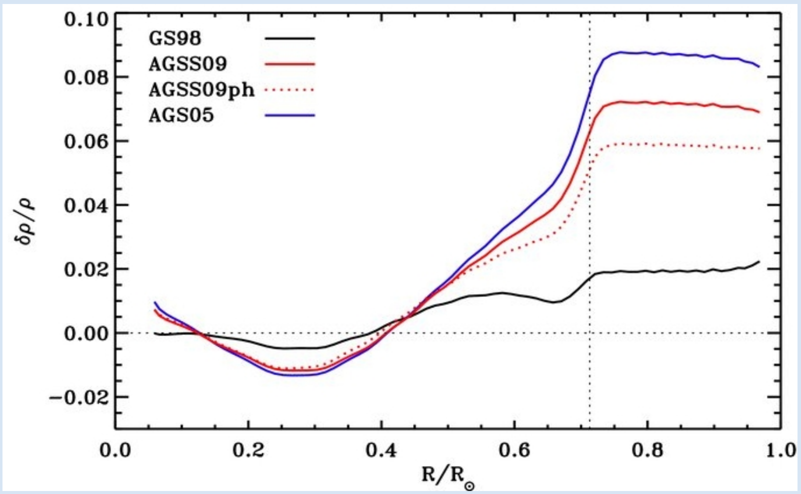
Model	$(Z/X)_S$	Z_S	Z_C	$R_{CZ}/R_\odot$	$\langle\delta c/c\rangle$	$\langle\delta\rho/\rho\rangle$	Y_S	Y_C
GS98	0.0229	0.0170	0.0201	0.713	0.0010	0.011	0.2423	0.6330
AGS05	0.0165	0.0126	0.0149	0.728	0.0049	0.048	0.2292	0.6195
AGSS09	0.0178	0.0134	0.0160	0.724	0.0038	0.040	0.2314	0.6220
AGSS09ph	0.0181	0.0136	0.0161	0.722	0.0031	0.033	0.2349	0.6263
Helios.	—	0.0172	—	0.713	0.0000	0.000	0.2485	—
Helios.	—	±0.002	—	±0.001	0.0000	0.000	±0.0034	—

Peña-Garay & Serenelli (2008) – Serenelli et al. (2009)

Sound speed



Density



Aldo Serenelli – ICE (CSIC-IEEC)

Some results on helioseismology

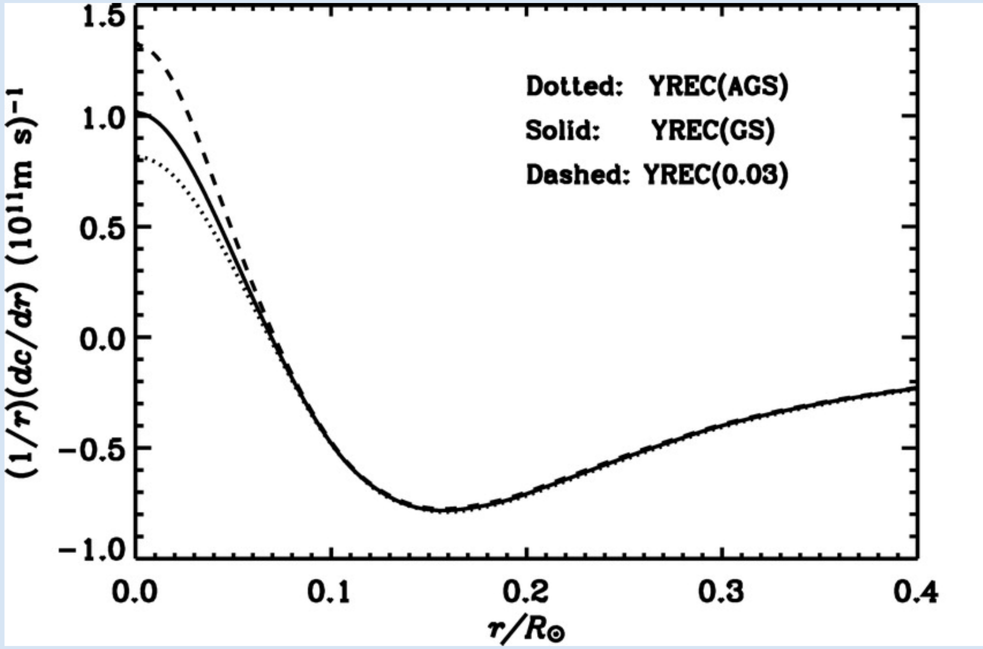
Low degree modes (l=0, 1, 2, 3)

Separation ratios

$$r_{02}(n)=\frac{\nu_{n,0}-\nu_{n-1,2}}{\nu_{n,1}-\nu_{n-1,1}}$$

$$r_{13}(n)=\frac{\nu_{n,1}-\nu_{n-1,3}}{\nu_{n+1,0}-\nu_{n,0}}$$

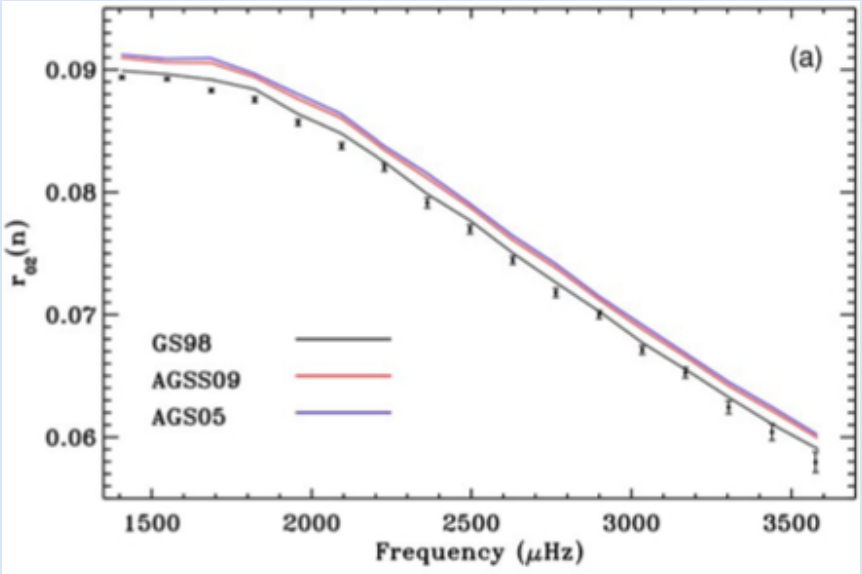
$$\propto\int_0^R\frac{dc}{dr}\frac{dr}{r}$$

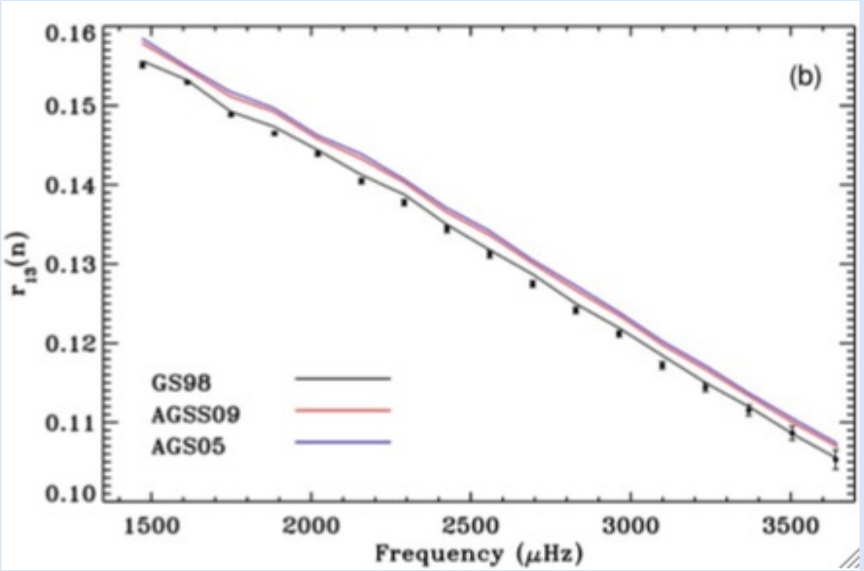


Enhance effects in the core

Some results on helioseismology

Using individual separation ratios



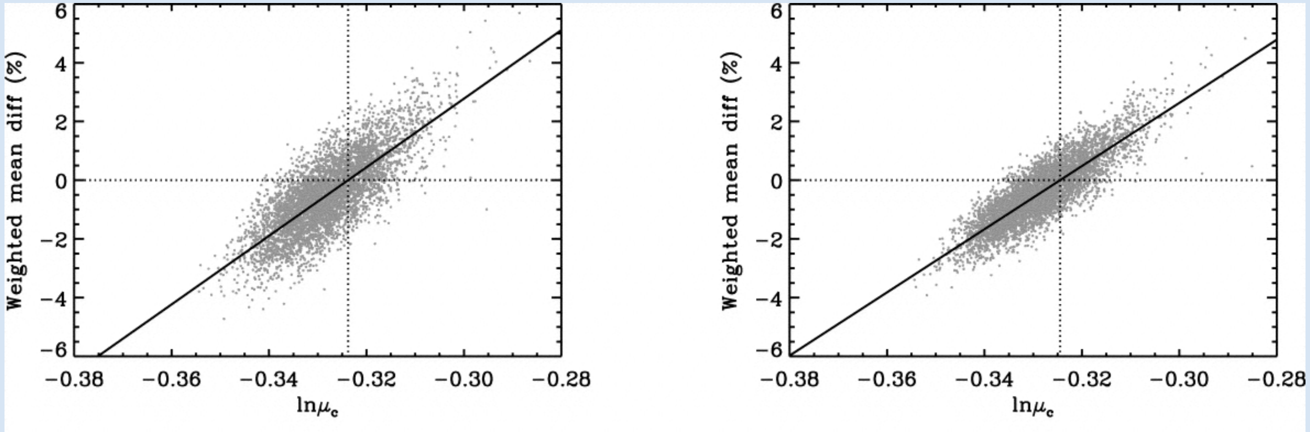


Some results on helioseismology

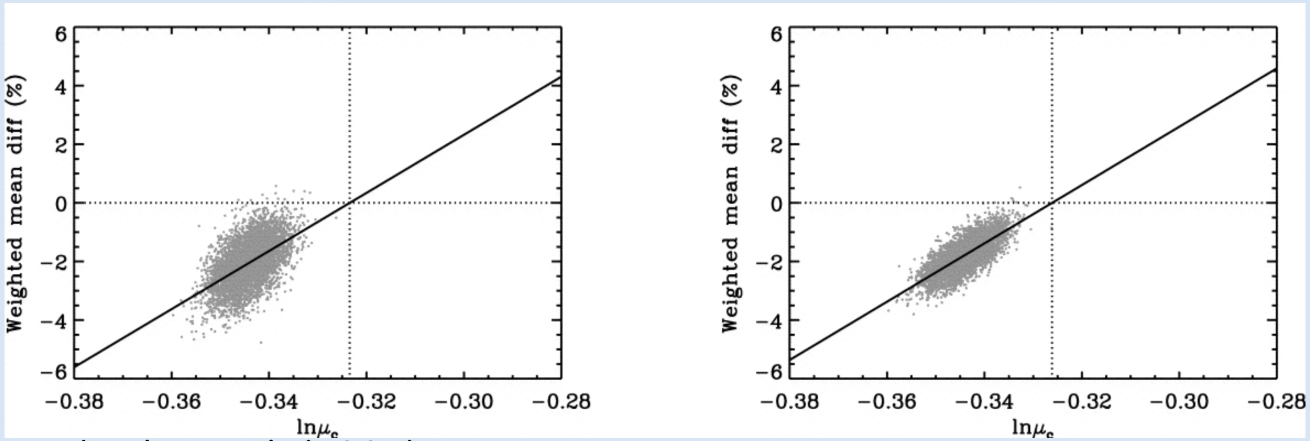
Using separation ratios

μ_e averaged
over $R < 0.2R_\odot$

GS98



AGS05



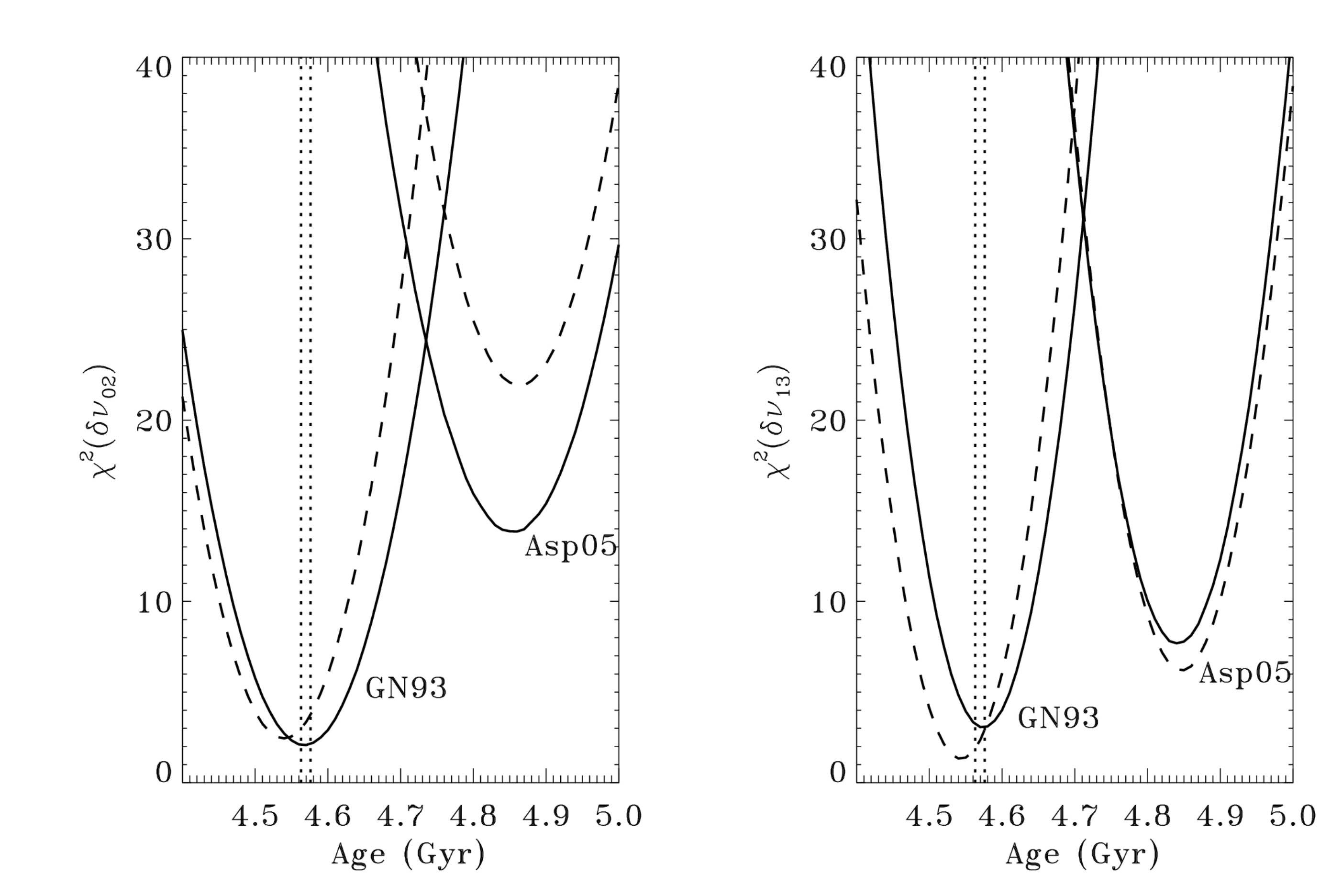
Both compositions
$\mu_e = 0.723 \pm 0.003$

Chaplin et al. (2007)

Some results on helioseismology

Is the low-Z Sun too young?

Christensen-Dalsgaard (2009)

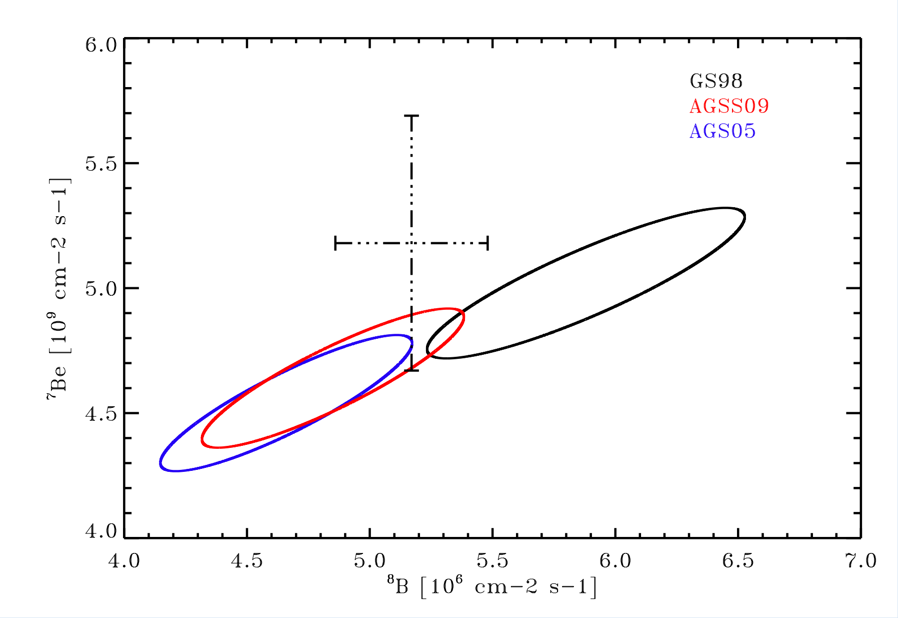


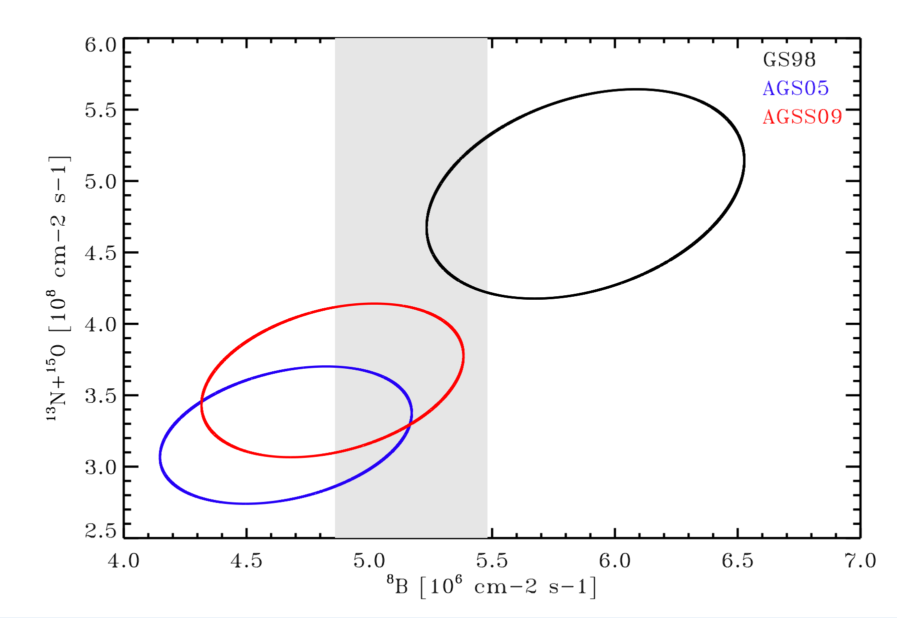
Neutrino fluxes

Model	pp	pep	hep	^{7}Be	^{8}B	^{13}N	^{15}O	^{17}F
GS98	5.97	1.41	7.91	5.08	5.88	2.82	2.09	5.65
AGS05	6.04	1.44	8.24	4.54	4.66	1.85	1.29	3.14
AGSS09	6.03	1.44	8.18	4.64	4.85	2.07	1.47	3.48

Peña-Garay & Serenelli (2008) – Serenelli et al. (2009)

Direct measurements of ^{7}Be and ^{8}B from Borexino and SNO





Neutrino fluxes

Gonzalez-Garcia et al. (2010)

Global analysis of solar & terrestrial ν data

3 flavor-mixing framework

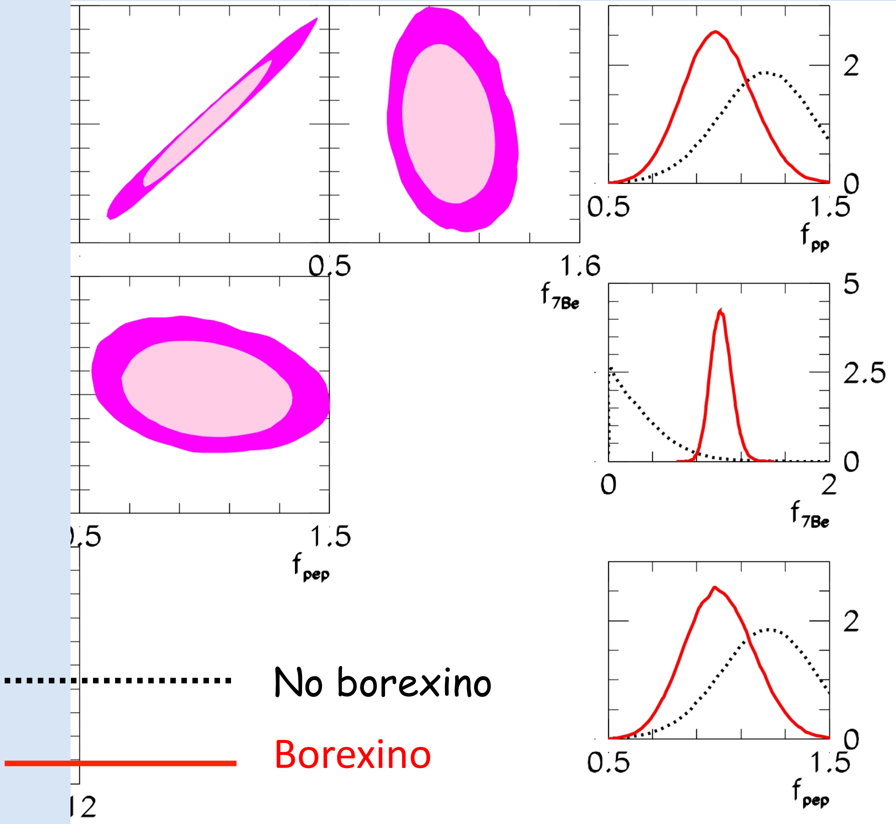
Basic constraints from pp-chains and CNO cicles

Luminosity constraint (optional)

Exhaustive discussion of importance of Borexino

Neutrino fluxes

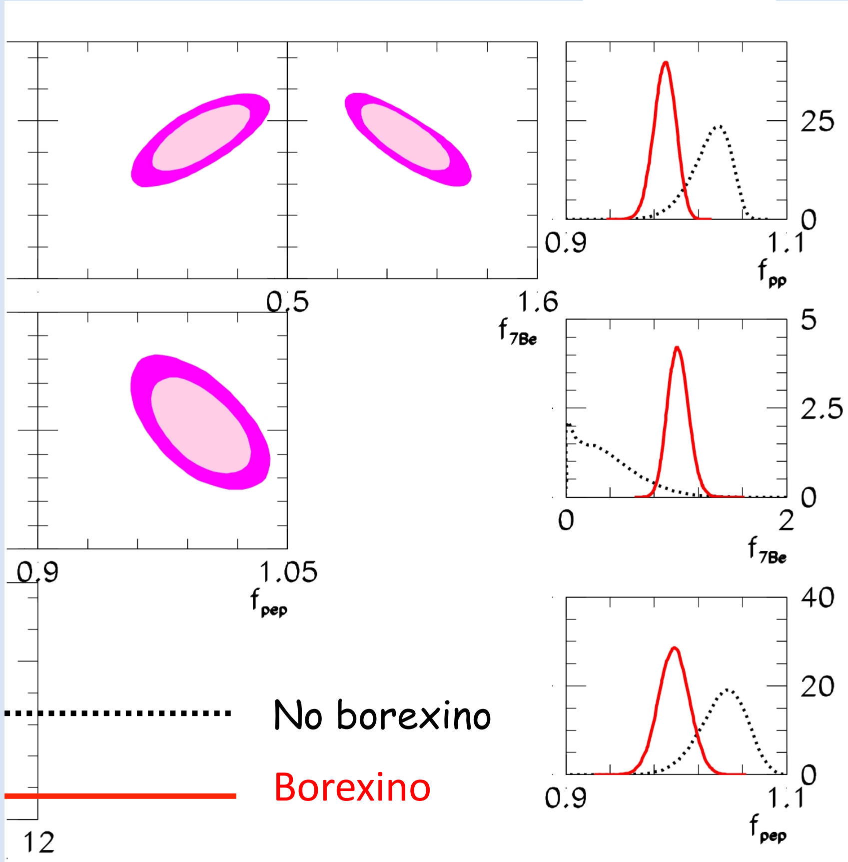
No luminosity constraint



$$L_{\rm pp} = 0.98^{+0.15}_{-0.14}$$

$$L_{\rm CNO} = 0.015^{+0.005}_{-0.007}$$

Luminosity constraint



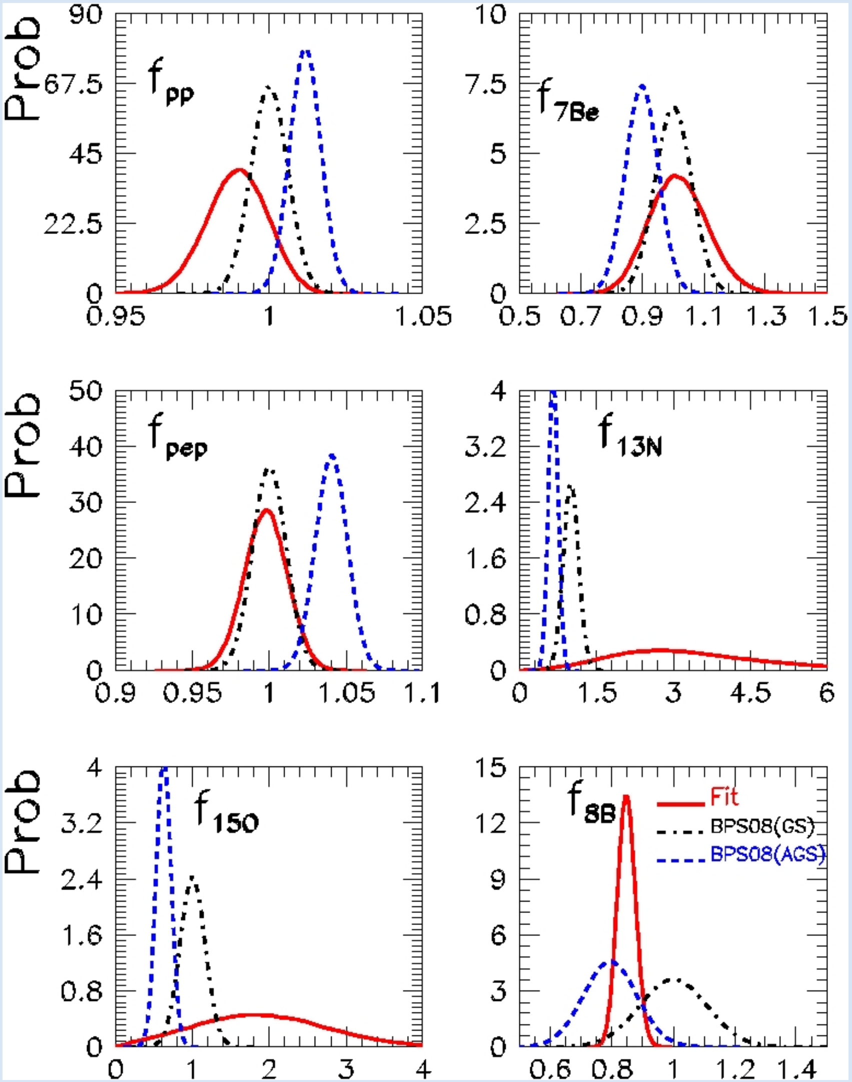
$$L_{\rm pp} = 0.986^{+0.005}_{-0.006}$$

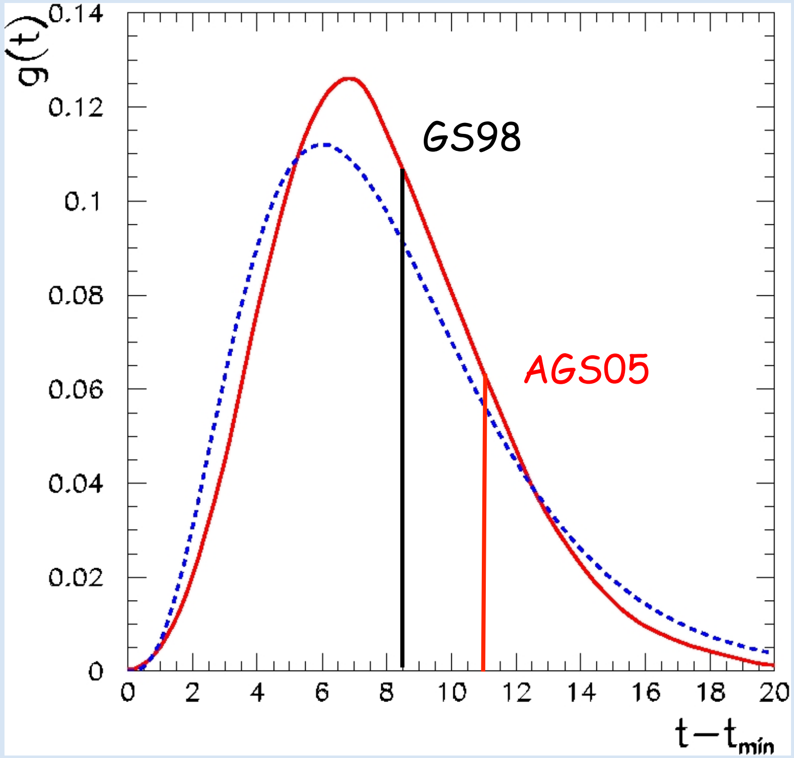
$$L_{\rm CNO} = 0.014^{+0.006}_{-0.005}$$

Aldo Serenelli - ICE (CSIC-IEEC)

Neutrino fluxes

Gonzalez-Garcia et al. 2010

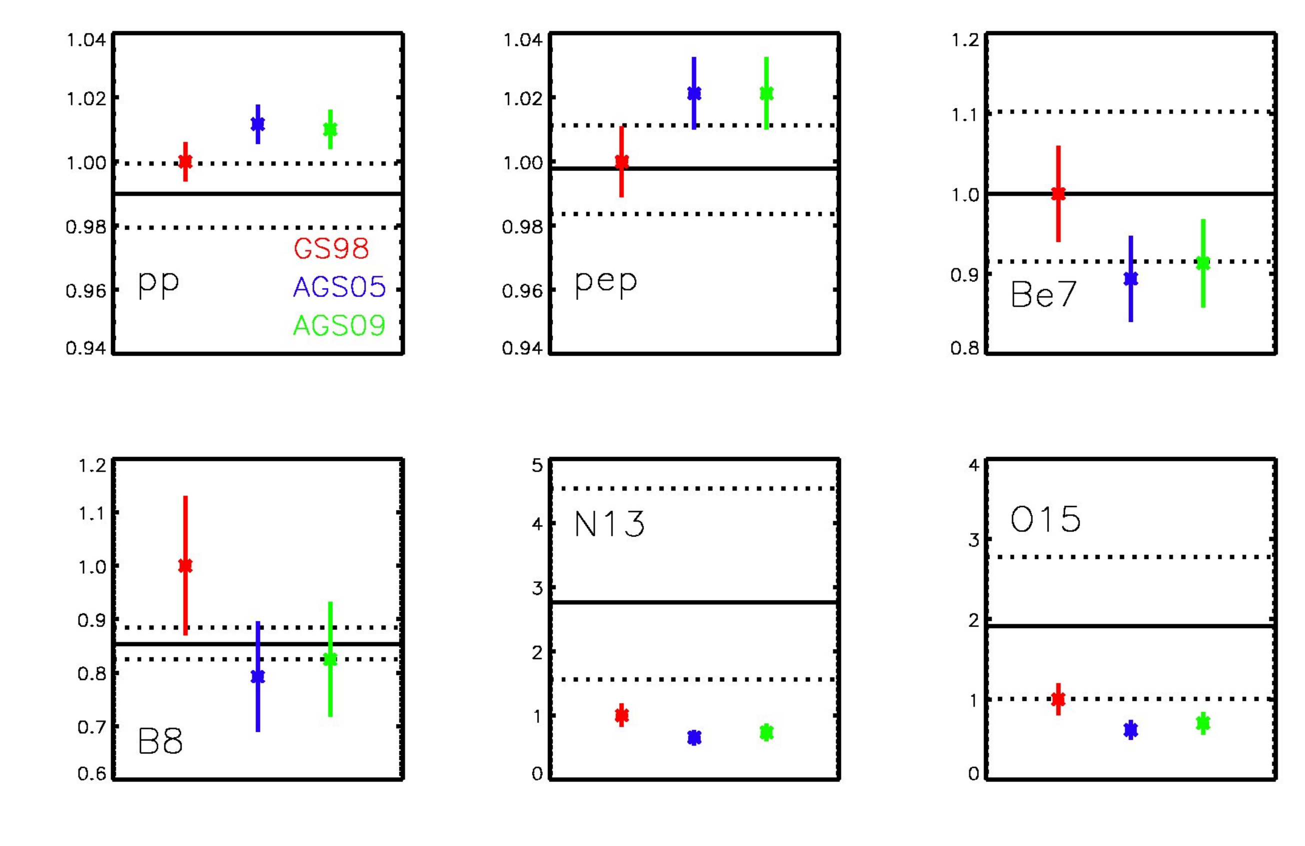




P(GS98) = 43%

P(AGS05)= 20%

Neutrino fluxes



	GS98	AGS05	AGS09
χ^2 =	5.2 (74%)	5.7 (68%)	5.05 (76%)

However: Is the comparison fair?

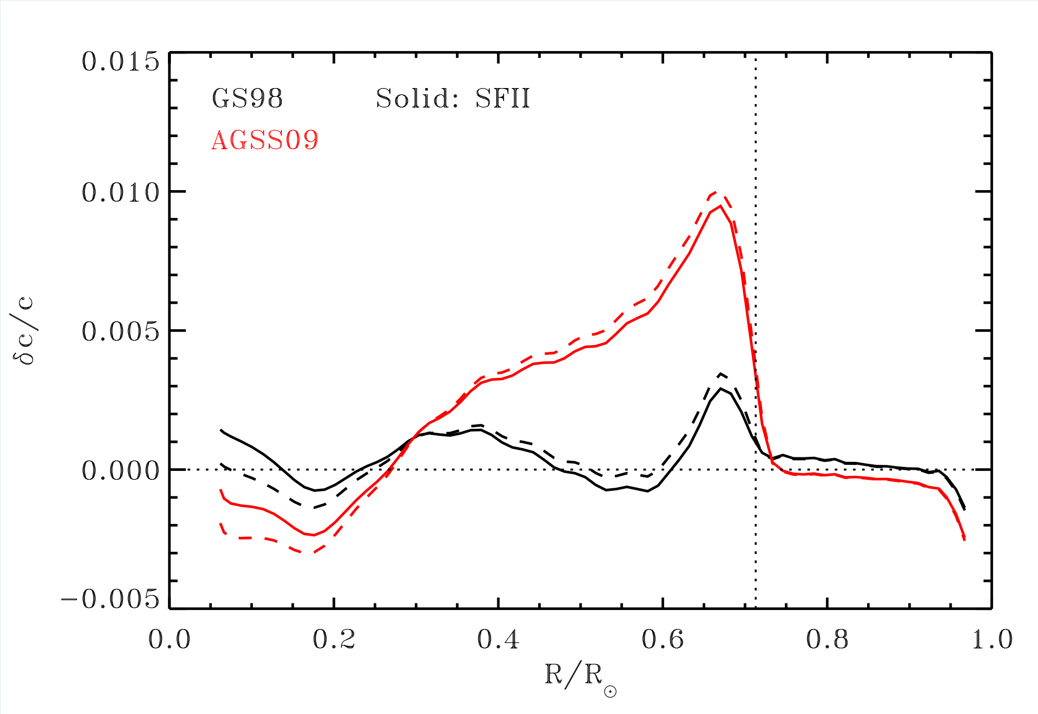
Revised nuc. cross sections: Solar Fusion II (arxiv:1004.2318)

Reaction	SFII (keV-b)	Previous (keV-b)
S_{11}	$4.01 \times 10^{-22}(1 \pm 0.010)$	$3.94 \times 10^{-22}(1 \pm 0.004)$
S_{33}	$5.21 \times 10^{3}(1 \pm 0.052)$	$5.4 \times 10^{3}(1 \pm 0.06)$
S_{34}	$0.56(1 \pm 0.054)$	$0.567(1 \pm 0.03)$
S_{17}	$2.08 \times 10^{-2}(1 \pm 0.077)$	$2.14 \times 10^{-2}(1 \pm 0.038)$
$S_{1,14}$	$1.66(1 \pm 0.072)$	$1.57(1 \pm 0.08)$
R(pep)/R(pp)	$\uparrow$ 2.5%	—

Talk by A. Formicola

Some changes in S(0) and errors more conservative

Small changes in helioseismic properties



Revised nuc. cross sections: Solar Fusion II (Adelberger et al. arxiv:1004.2318)

Flux	SFII-GS98	SFII-AGSS09
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$
pep	$1.44(1 \pm 0.011)$	$1.47(1 \pm 0.012)$
hep	$8.04(1 \pm 0.15)$	$8.31(1 \pm 0.15)$
^{7}Be	$4.99(1 \pm 0.07)$	$4.56(1 \pm 0.07)$
^{8}B	$5.57(1 \pm 0.14)$	$4.59(1 \pm 0.14)$
^{13}N	$2.96(1 \pm 0.16)$	$2.17(1 \pm 0.14)$
^{15}O	$2.23(1 \pm 0.17)$	$1.56(1 \pm 0.16)$
^{17}F	$5.52(1 \pm 0.19)$	$3.40(1 \pm 0.17)$

Slight increase of pp → small decrease of ^{7}Be and ^{8}B

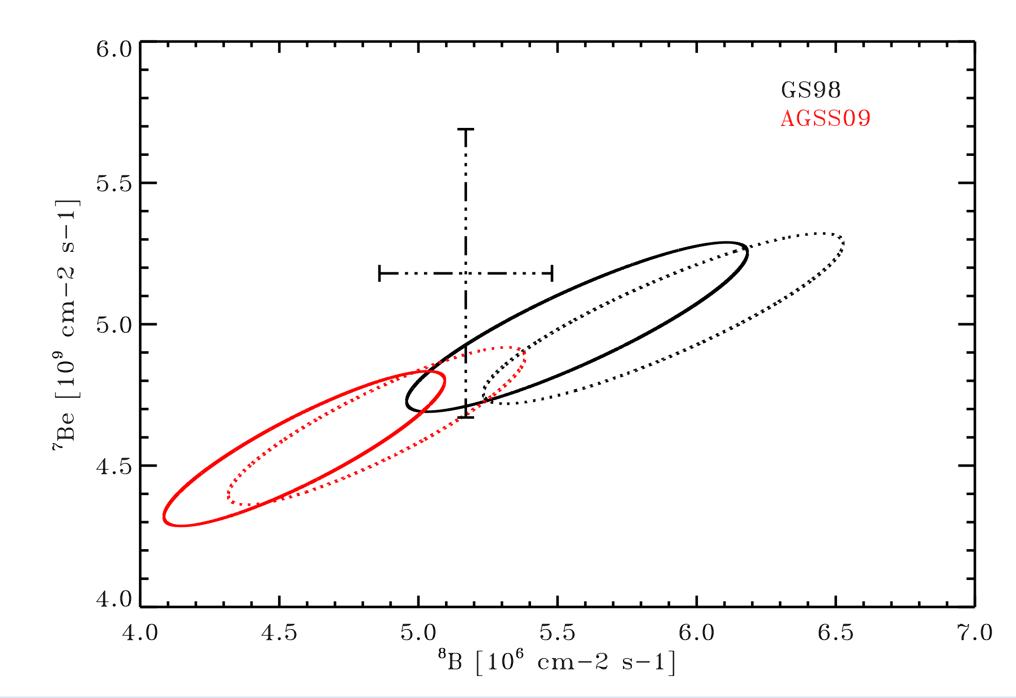
Increase in uncertainties

Using results from Gonzalez-Garcia et al. (2010)

χ^2(SFII-GS98)=4.6 (80%)

χ^2(SFII-AGSS09)=7.1 (52%)

Neutrinos do not show clear preference for Z



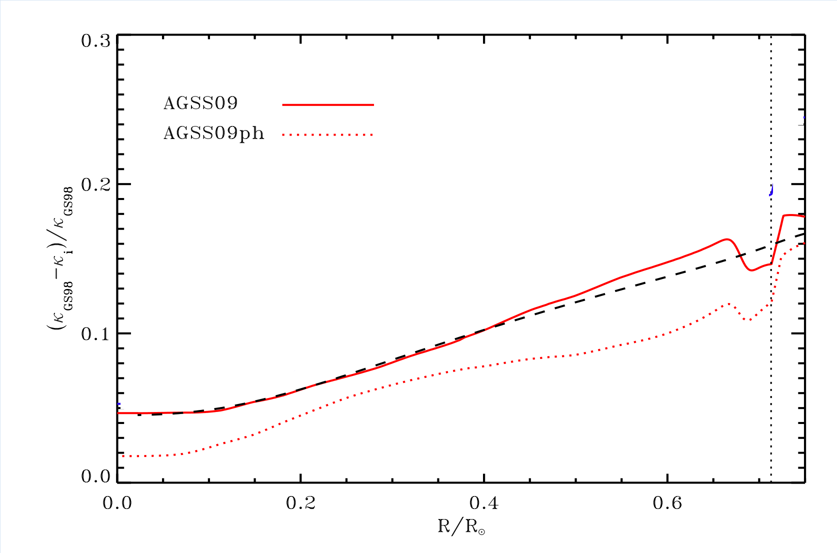
Solutions?

- Is there a problem at all?
  - abundances too low?
  - uncertainties too optimistic?
- Missing physics in SSM: of course
  - extra mixing
  - rotation, gravity waves
  - diffusion, etc.

    but… which? Do they help at all?

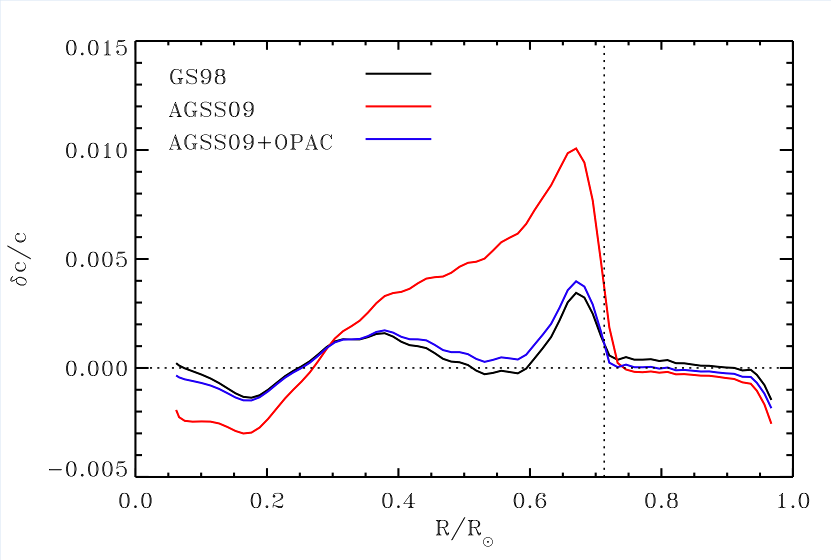
  Can be modeled without ad-hoc assumptions?
- Trivial answer: opacities. Several ongoing experimental efforts

Illustrative case: opacities



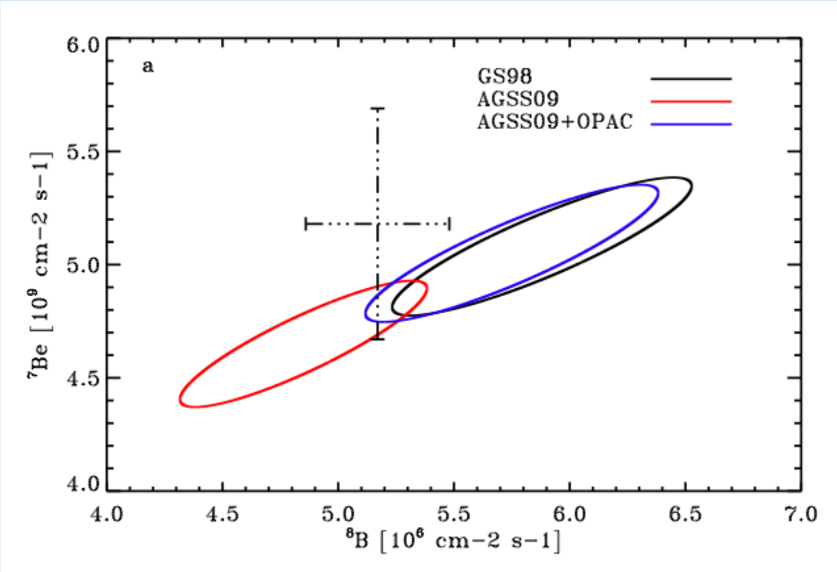
After Christensen-Dalsgaard et al. (2009)

Opacity increase compensates low-Z perfectly well



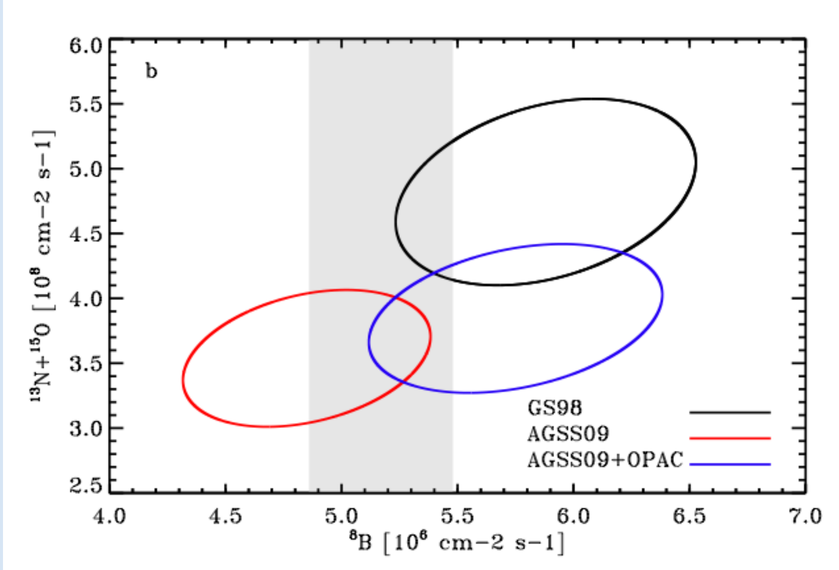
All seismic quantities fall into place (except Γ_1?)

Illustrative case: opacities



But CN neutrinos could tell between increase in opac and high Z (CN)

Even if a model can be "constructed" that satisfies helioseismic quantities, it does not imply robust predictions for neutrino fluxes



Solar composition derived from helios.+neutrinos?

YES… but

BAD - metal abundance is usually degenerate with opacity
(exceptions: CNO neutrinos and Γ_1)

GOOD - different metals contribute in different
regions and to different quantities

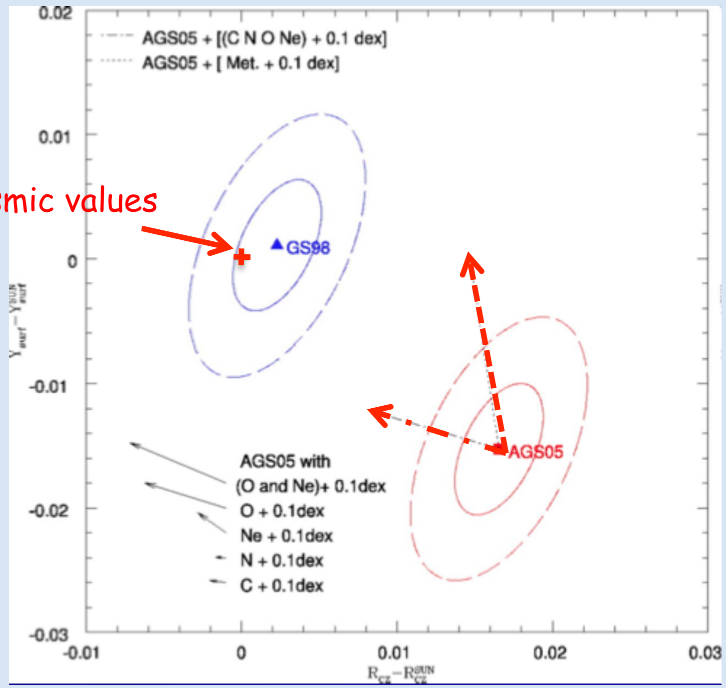
Control on opacity uncertainties is necessary (but unavailable)

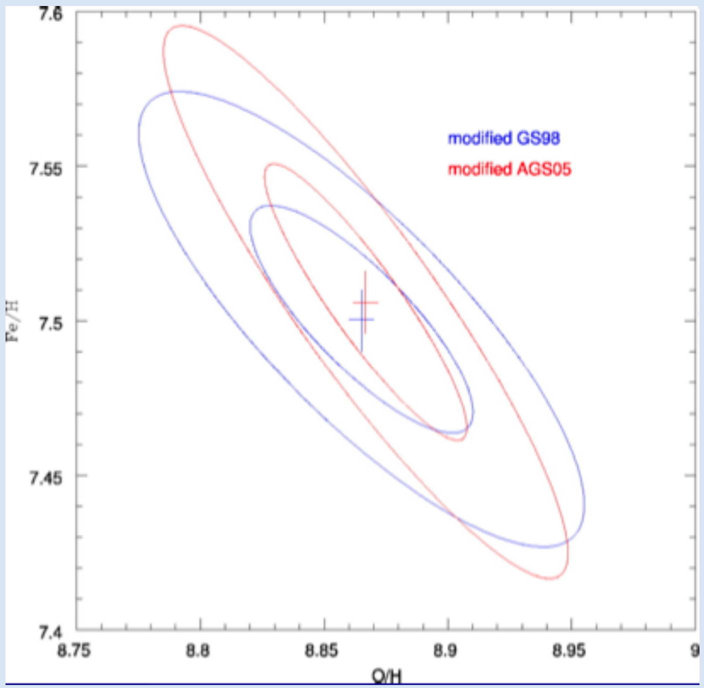
Discussion on effect of opacities by Villante later today

Solar composition derived from helios.+neutrinos?

Delahaye & Pinsonneault (2006) : CNONe (Phot.) & MgSiSFe (Met.)

Helioseismic values





$$R - R_{\rm helio} = \Delta{\rm Phot}\frac{\delta R_{\rm CZ}}{\delta{\rm Phot}} + \Delta{\rm Met}\frac{\delta R_{\rm CZ}}{\delta{\rm Met}}$$

$$Y - Y_{\rm helio} = \Delta{\rm Phot}\frac{\delta Y_{\rm surf}}{\delta{\rm Phot}} + \Delta{\rm Met}\frac{\delta Y_{\rm surf}}{\delta{\rm Met}}$$

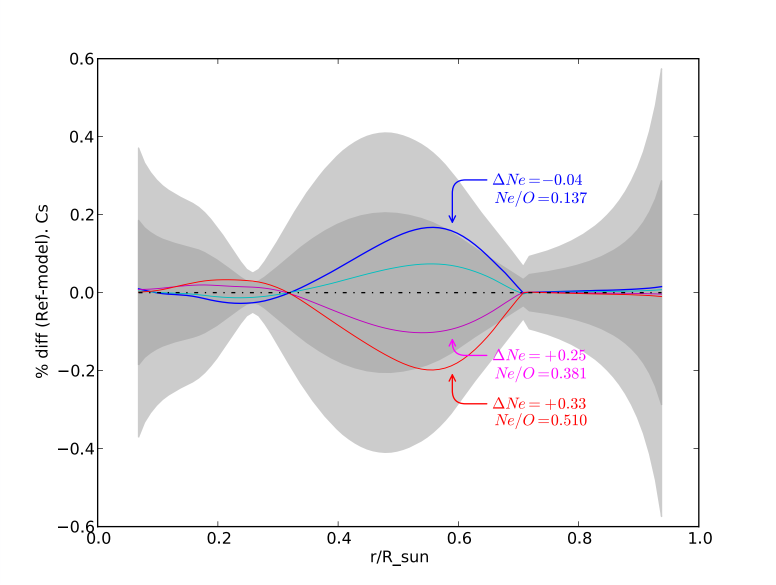
[O/H]= 8.86/8.87 ± 0.04

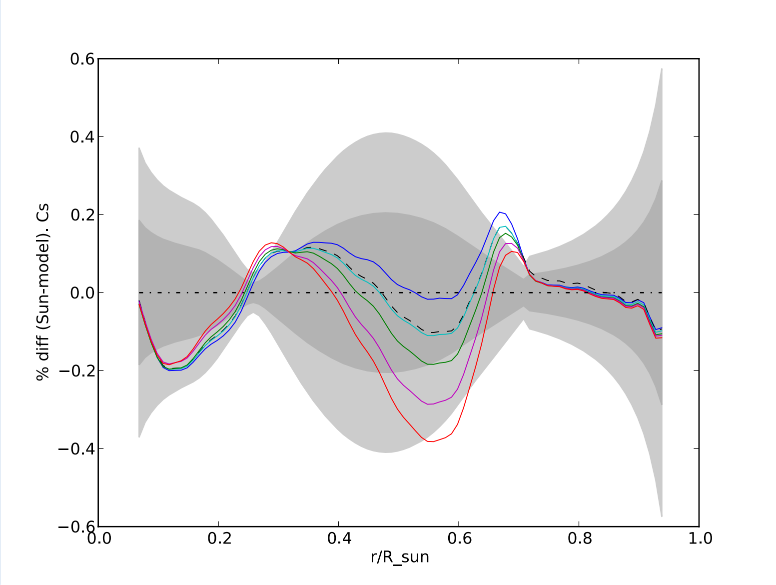
[Fe/H]= 7.50/7.51 ± 0.05

Consistent with high Z

Solar composition derived from helios.+neutrinos?

Delahaye et al. (2010): sound speed used to extract Ne

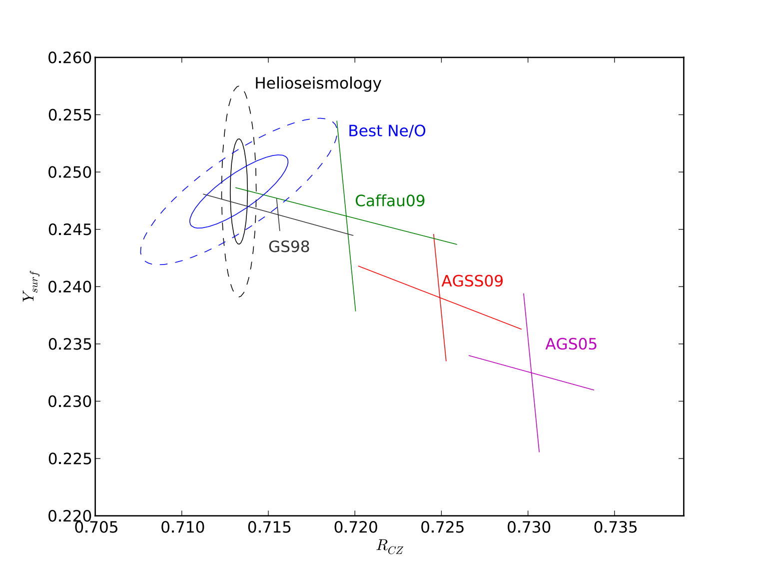


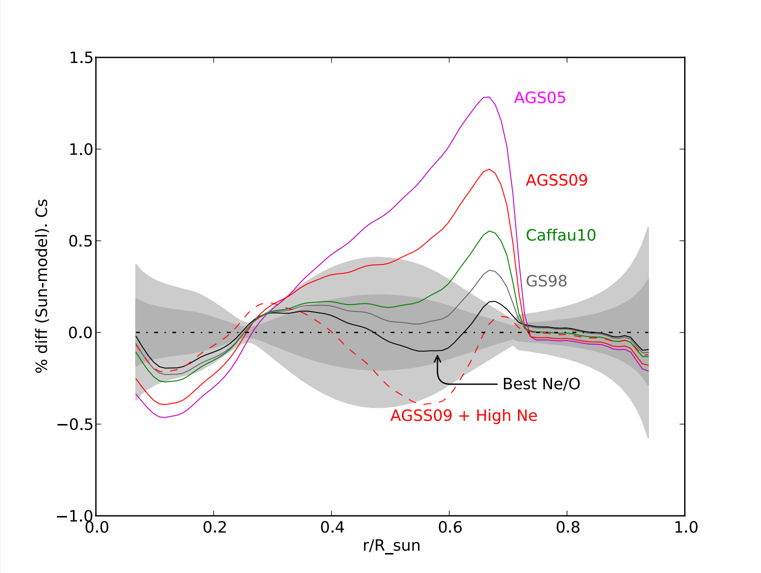


Same Y_S and R_{CZ} but different Ne/O ratio show sound speed variations → Ne can be separated from other phot. elements

Solar composition derived from helios.+neutrinos?

Delahaye et al. (2010): sound speed used to extract Ne





A(O)= 8.86 ± 0.04 - A(Ne)= 8.15 ± 0.17 - A(Fe)= 7.50 ± 0.05
Consistent with previous 1-D abundances and, marginally, with CO5BOLD (Caffau et al)

Radiative interior not very sensitive to C and N → CN fluxes

Conclusions

- Model with latest abundance revision (AGSS09) do not agree with helioseismology

- Model atmospheres from different groups agree very well (T strat.); abundances do not. Human element (MP)? Uncertainties too optimistic?

- Solar neutrinos cannot separate models (yet). CN flux measurements needed.

- Updates in nuclear cross sections have small effects

- Helioseismic and neutrino data can be used to extract solar composition. Different indicators sensitive to different elements. Stay tuned!
- Interesting test for non-SSM

The end