Solar models, solar neutrinos and helioseismology

F. L. Villante – Università dell’Aquila and LNGS-INFN

Outline

- The present situation
- The solar composition problem
- The role of CNO neutrinos
- Summary and conclusions

Hydrogen Burning: PP chain and CNO cycle

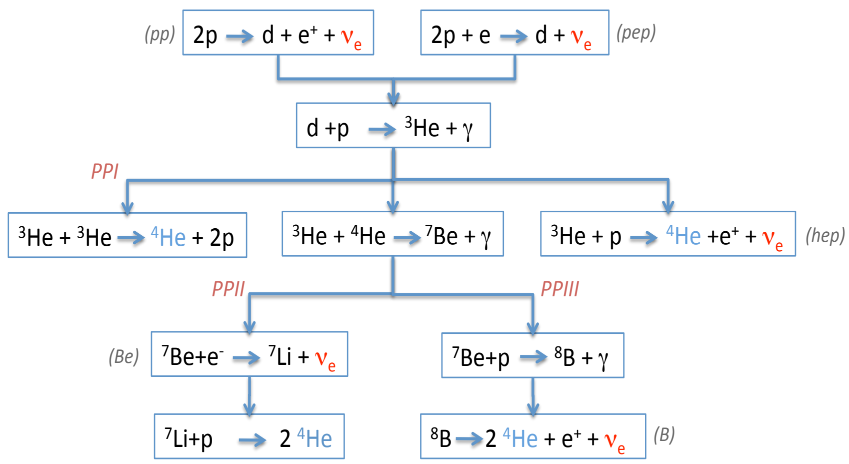
The Sun is powered by nuclear reactions that transform H into ^{4}He:

$$4H + 2e^- \rightarrow {}^4He + 2\nu_e + \text{energy}$$

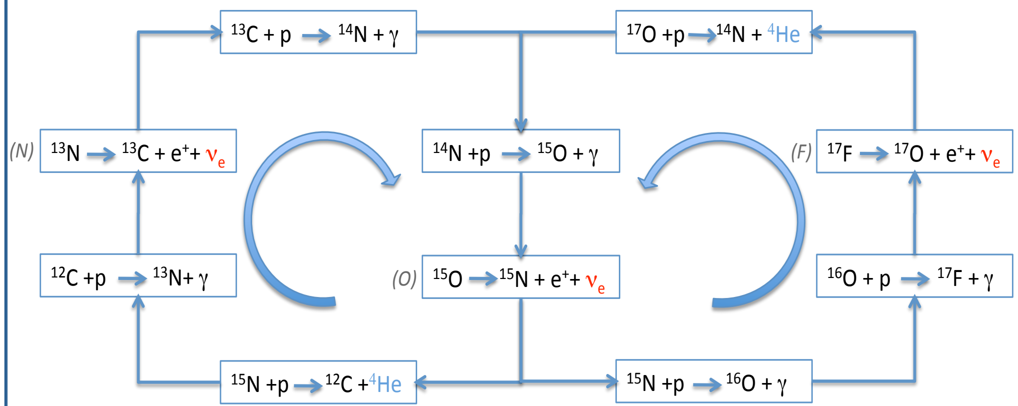
Q = 26,7 MeV (globally)

Free stream – 8 minutes to reach the earth
Direct information on the energy producing region.

The PP-chain



The CN-NO bi-cycle

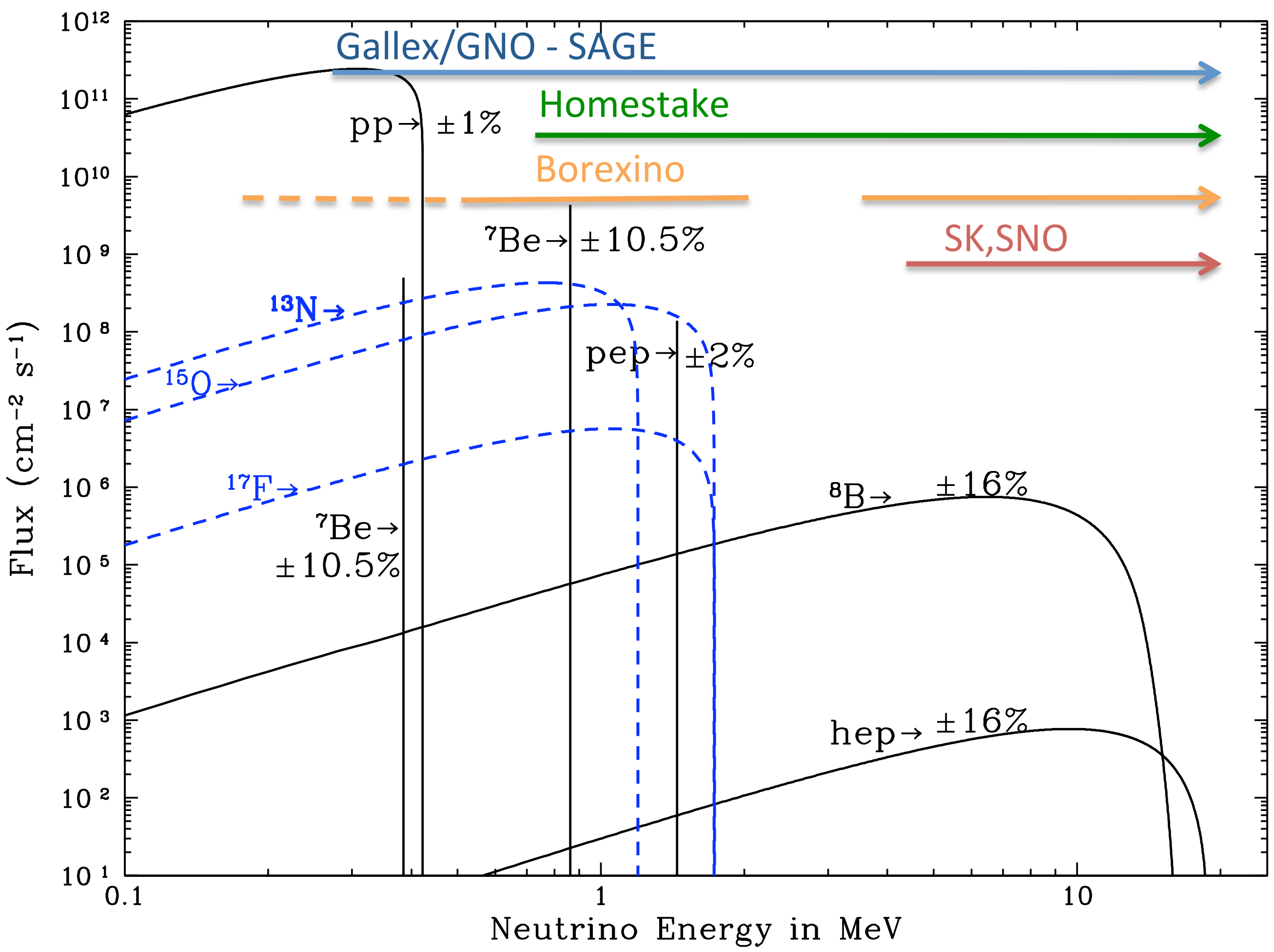


The pp chain is responsible for about 99% of the total energy (and neutrino) production.

C, N and O nuclei are used as catalysts for hydrogen fusion.

CNO cycle is responsible for about 1% of the total neutrino (and energy) budget. Important for more advanced evolutionary stages

The solar neutrino spectrum



The present situation

Experimental results agree with Standard Solar Models (SSM) + ν flavor oscillations:

Serenelli, Haxton, Pena-Garay, ApJ 2011

ν flux	AGSS09	GS98	Solar
$\Phi_{\rm pp}$	$6.03\,(1 \pm 0.006)$	$5.98\,(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$
$\Phi_{\rm pep}$	$1.47\,(1 \pm 0.012)$	$1.44\,(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$
$\Phi_{\rm Be}$	$4.56\,(1 \pm 0.07)$	$5.00\,(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$
$\Phi_{\rm B}$	$4.59\,(1 \pm 0.14)$	$5.58\,(1 \pm 0.14)$	$5.00(1 \pm 0.03)$
$\Phi_{\rm hep}$	$8.31\,(1 \pm 0.30)$	$8.04\,(1 \pm 0.30)$	$18(1^{+0.4}_{-0.5})$
$\Phi_{\rm N}$	$2.17\,(1 \pm 0.14)$	$2.96\,(1 \pm 0.14)$	≤ 6.7
$\Phi_{\rm O}$	$1.56\,(1 \pm 0.15)$	$2.23\,(1 \pm 0.15)$	≤ 3.2
$\Phi_{\rm F}$	$3.40\,(1 \pm 0.16)$	$5.52\,(1 \pm 0.16)$	≤ 59

Units:
pp: 10^{10} cm ^{2} s^{-1};
Be: 10^{9} cm ^{2} s^{-1};
pep, N, O: 10^{8} cm ^{2} s^{-1};
B, F: 10^{6} cm ^{2} s^{-1};
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Real time detection (SK,SNO,Borexino)

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Note that:

$$\delta\Phi_{\rm B} \simeq 20\ \delta T_{\rm c}$$

Solar thermometer!

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CNO neutrinos

- No direct detection
- Loose upper bounds obtained by combining the different expt results

Note that:

$$\delta\Phi_{\rm B} \simeq 20\ \delta T_{\rm c}$$

Solar thermometer!

Future goals

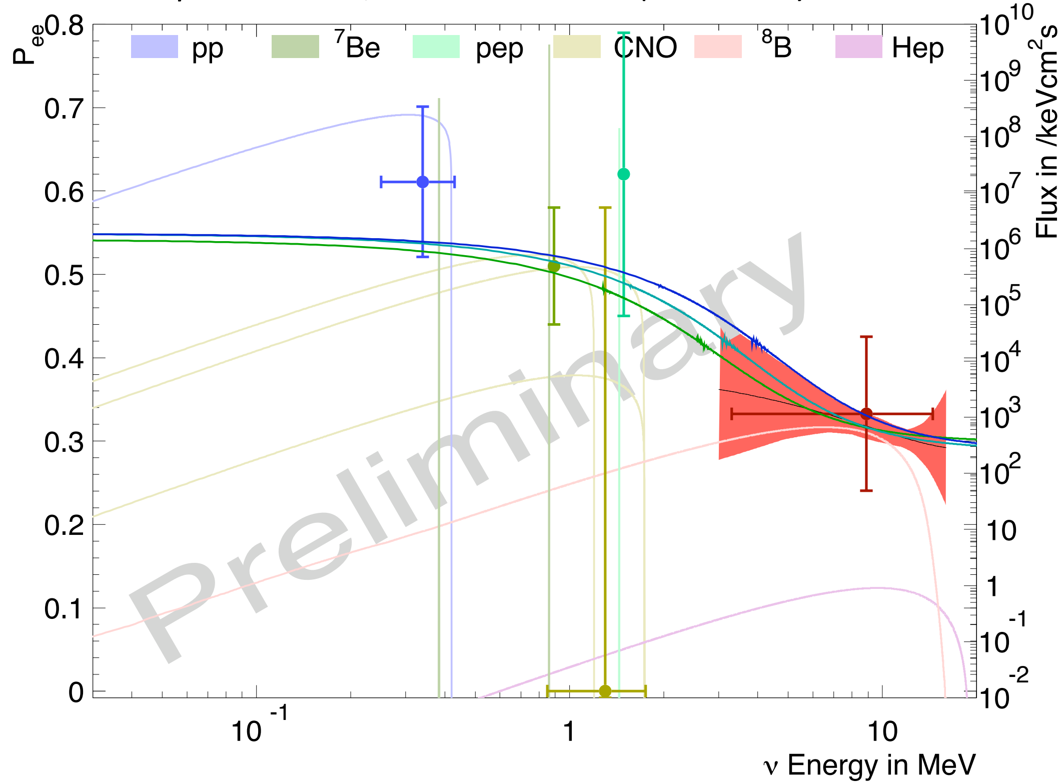
- Final confirmation of MSW transition (or looking for new physics):

The ν_e survival probability at E_ν~ 1-3MeV probes transition between vacuum and matter dominated regimes

Sensitive to new physics effects (mass varying neutrinos, sterile neutrinos, NSI, etc.)

Combined analysis of SK I-IV PRL 112 (2014) 091805 Provide a 2.7σ observation of day-night effect;

Super-K collab., arXiv 1403.4575 (Mar 2014)



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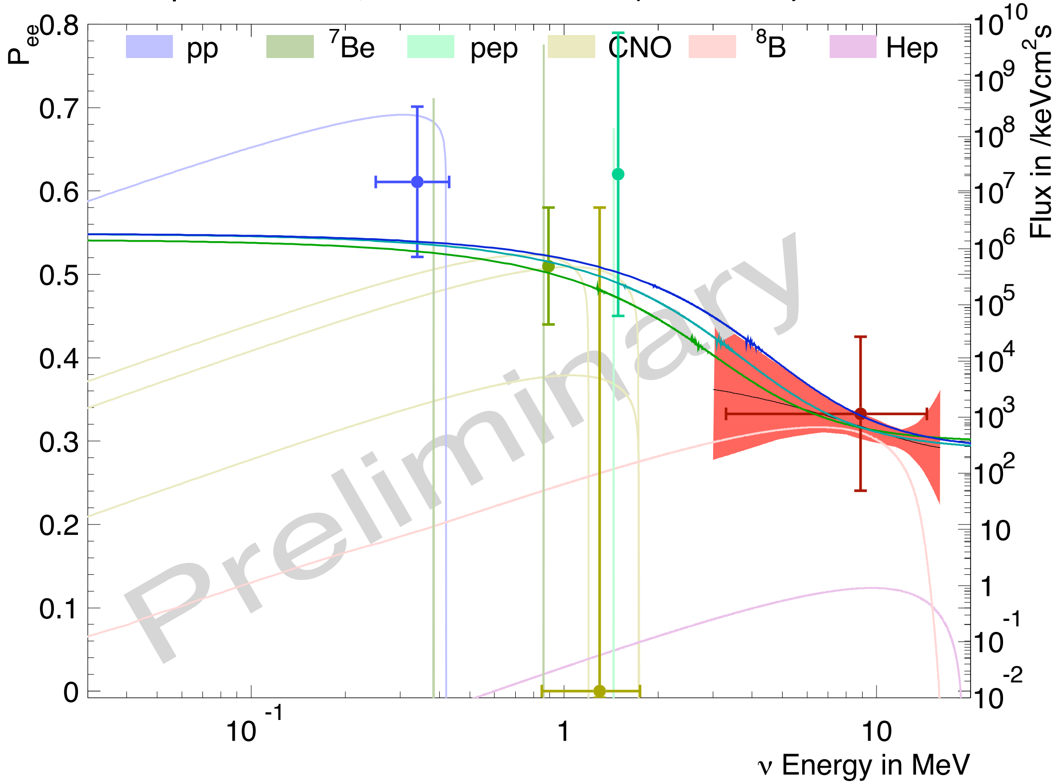


• Seeing all the solar ν branches
→ solving the solar composition problem

Helioseismology

The Sun is a non radial oscillator. The observed oscillation frequencies can be used to determine the properties of the Sun. Linearizing around a known solar model:

$$\frac{\delta\nu_{nl}}{\nu_{nl}} = \int_0^R dr\; K^{nl}_{u,Y}(r)\,\frac{\delta u}{u}(r) + \int_0^R dr\; K^{nl}_{Y,u}(r)\,\delta Y + \frac{F(\nu_{nl})}{\nu_{nl}}$$

surface helium abundance

squared isothermal sound speed

See Basu & Antia 07 for a review

Impressive agreement with SSM predictions …

Surface helium abundance

$Y_\mathrm{b} = 0.2485 \pm 0.0035$

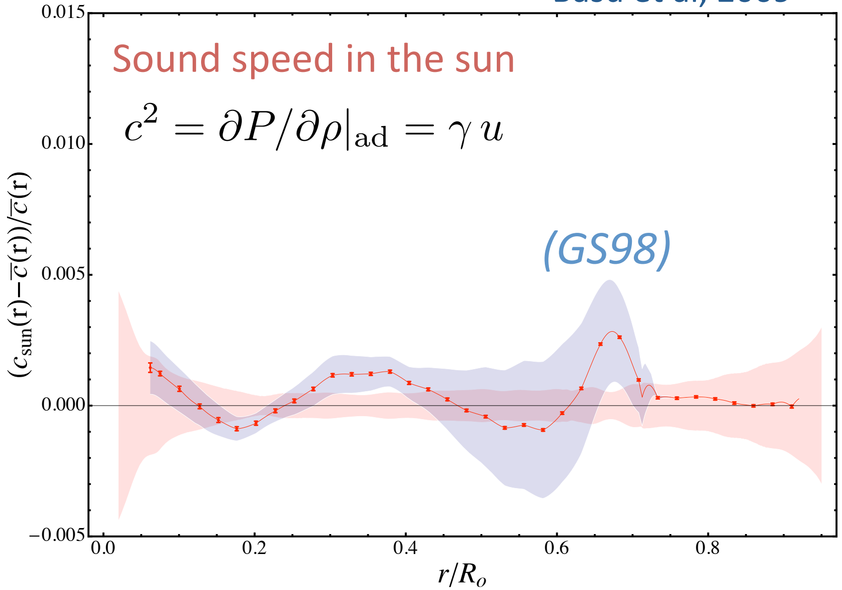
$Y_\mathrm{b} = 0.243$ *(GS98)*

Inner radius of the solar convective envelope

$R_\mathrm{b}/R_\odot = 0.713 \pm 0.001$

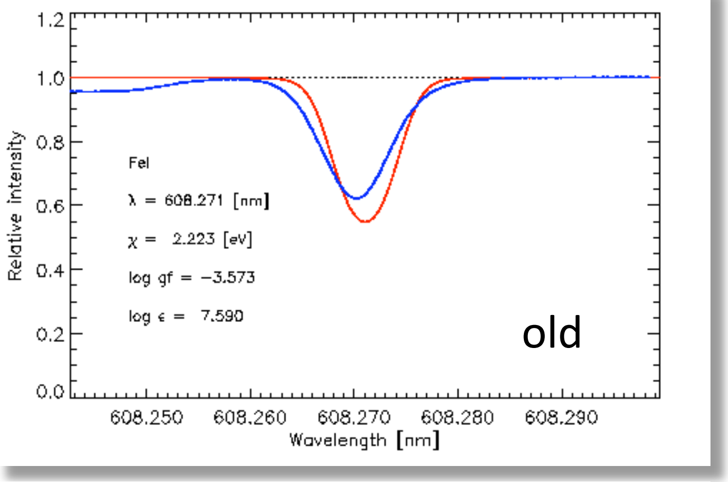
$R_\mathrm{b}/R_\odot = 0.712$ *(GS98)*

Basu et al, 2009



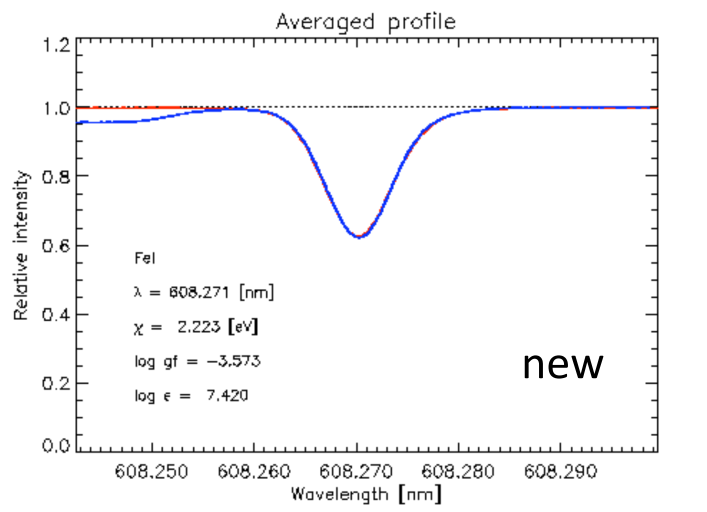
… till few years ago

Asplund et al. 05 (AGS05); Asplund et al. 09 (AGSS09)
Re-determination of the photospheric abundances of nearly all available elements **(inputs for SSM calculations)**



Improvements with respect to previous analysis[*]:

- 3D model instead of the classical 1D model of the lower solar atmosphere
- Careful and very demanding selection of the spectral lines… AVOID blends!!! NOT TRIVIAL!!!
- Careful choice of the atomic and molecular data NOT TRIVIAL!!!!
- NLTE instead of the classical LTE hypothesis… WHEN POSSIBLE !!!
- Use of ALL indicators (atoms as well as molecules,CNO)



[*]N. Grevesse talk at PHYSUN10

The solar composition problem

AGS05 and AGSS09

Downward revision of heavy elements photospheric abundances …

Element	GS98	AGSS09	δz_i
C	8.52 ± 0.06	8.43 ± 0.05	0.23
N	7.92 ± 0.06	7.83 ± 0.05	0.23
O	8.83 ± 0.06	8.69 ± 0.05	0.38
Ne	8.08 ± 0.06	7.93 ± 0.10	0.41
Mg	7.58 ± 0.01	7.53 ± 0.01	0.12
Si	7.56 ± 0.01	7.51 ± 0.01	0.12
S	7.20 ± 0.06	7.15 ± 0.02	0.12
Fe	7.50 ± 0.01	7.45 ± 0.01	0.12
Z/X	0.0229	0.0178	0.29

$$[I/H] \equiv \log\left(N_I/N_H\right) + 12$$

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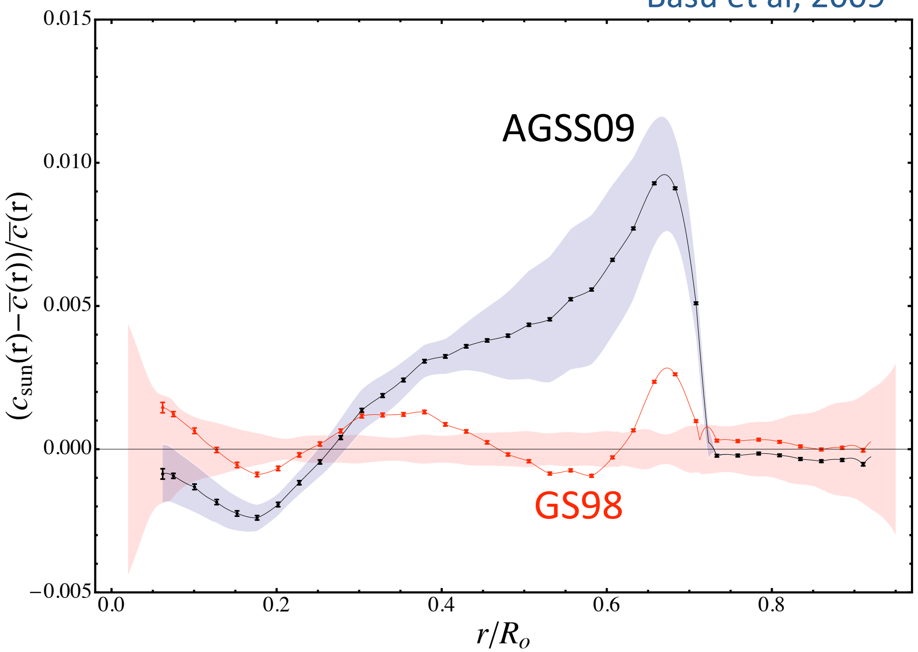

… leads to SSMs which do not correctly reproduce helioseismic observables

	AGSS09	GS98	Obs.
$Y_{\rm b}$	$0.2319\,(1 \pm 0.013)$	$0.2429\,(1 \pm 0.013)$	0.2485 ± 0.0035
$R_{\rm b}/R_\odot$	$0.7231\,(1 \pm 0.0033)$	$0.7124\,(1 \pm 0.0033)$	0.713 ± 0.001
$\Phi_{\rm pp}$	$6.03\,(1 \pm 0.005)$	$5.98\,(1 \pm 0.005)$	$6.05(1^{+0.003}_{-0.011})$
$\Phi_{\rm Be}$	$4.56\,(1 \pm 0.06)$	$5.00\,(1 \pm 0.06)$	$4.82(1^{+0.05}_{-0.04})$
$\Phi_{\rm B}$	$4.59\,(1 \pm 0.11)$	$5.58\,(1 \pm 0.11)$	$5.00(1 \pm 0.03)$
$\Phi_{\rm N}$	$2.17\,(1 \pm 0.08)$	$2.96\,(1 \pm 0.08)$	$\lesssim 6.7$
$\Phi_{\rm O}$	$1.56\,(1 \pm 0.10)$	$2.23\,(1 \pm 0.10)$	$\lesssim 3.2$

(≈ 4σ discrepancies)

So what …

Is there something **wrong** or **unaccounted** in solar models?

Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?

Are properties of the solar matter (e.g. **opacity**) correctly described?

Is this discrepancy pointing at **new physics** (e.g. WIMPs in the solar core?)

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Note that:

It is not just the problem of deciding between AGSS09 (new) and GS98 (old and presumably wrong) abundances
→ Theory of stellar interiors confronts with stellar atmosphere models

The Sun provide the ***benchmark*** *for stellar evolution. If there is something wrong in solar models, then this is wrong for all the stars ...*

A quantitative analysis of the solar composition problem

To combine observational infos, we need an estimator that is **non-biased** and that can be used as a **figure-of-merit** for solar models with different composition:

$$\chi^2 = \min_{\{\xi_I\}} \left[\sum_Q \left(\frac{\delta Q - \sum_I \xi_I \, C_{Q,I}}{U_Q} \right)^2 + \sum_I \xi_I^2 \right] .$$

Fogli et al. 2002

$$\delta Q = \frac{Q_{\rm obs} - Q}{Q}$$

where:

$$\{\delta Q\} = \{\delta\Phi_{\rm B},\, \delta\Phi_{\rm Be},\, \delta Y_{\rm b},\, \delta R_{\rm b};\, \delta c_1,\, \delta c_2,\, \ldots,\, \delta c_{30}\}$$

^{7}Be and ^{8}B neutrino fluxes

Surface helium and convective radius

Sound speed data points (from Basu et al, 2009)

and:

- U_Q — Uncorrelated (observational) errors
- $C_{Q,I}$ — Correlated (systematical) uncertainties

We consider 18 input parameters:

$$\{I\} = \{\text{opa},\ \text{age},\ \text{diffu},\ \text{lum},\ S_{11},\ S_{33},\ S_{34},\ S_{17},\ S_{e7},\ S_{1,14},\ S_{\rm hep},\ \text{C},\ \text{N},\ \text{O},\ \text{Ne},\ \text{Mg},\ \text{Si},\ \text{S},\ \text{Fe}\}$$

Enviromental

Nuclear

Composition

The status of the AGSS09 standard solar model

The SSM implementing the AGSS09 composition provides a poor fit of the observational data (**χ^2/ d.o.f. = 72.5/34;** χ^2_{obs}= 42.9 ; χ^2_{syst}= 29.6)

$$\chi^2 \equiv \chi^2_{\rm obs} + \chi^2_{\rm syst} = \sum_Q \tilde{X}_Q^2 + \sum_I \tilde{\xi}_I^2$$

$\bar{\xi}_I \equiv$ *Pulls of systematic*

$$\tilde{X}_Q \equiv \frac{\delta Q_{\rm obs} - \sum_I \tilde{\xi}_I \, C_{Q,I}}{U_Q}$$

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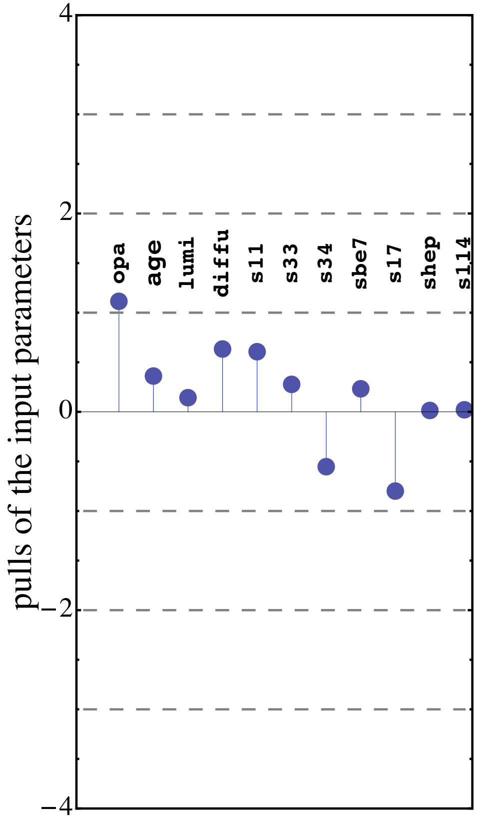
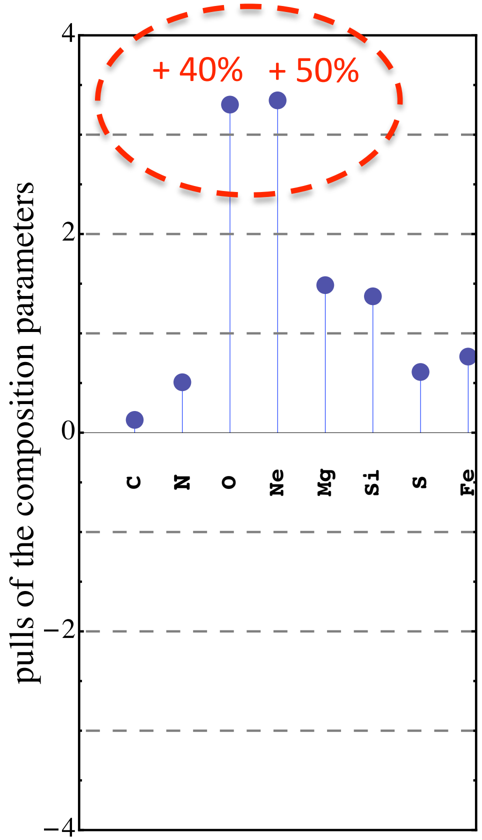
The distribution of the pulls of systematics highlight tensions in the model:





Obs. data requires an increase of the metal abundance of the sun, in particular for light elements (O, Ne).

Inferring the solar composition …

We take the **surface abundances** (with respect to hydrogen) as free parameters:

$$z_{\rm j} \equiv Z_{\rm j,b}/X_{\rm b}$$

We group metals according to the method by which they are determined

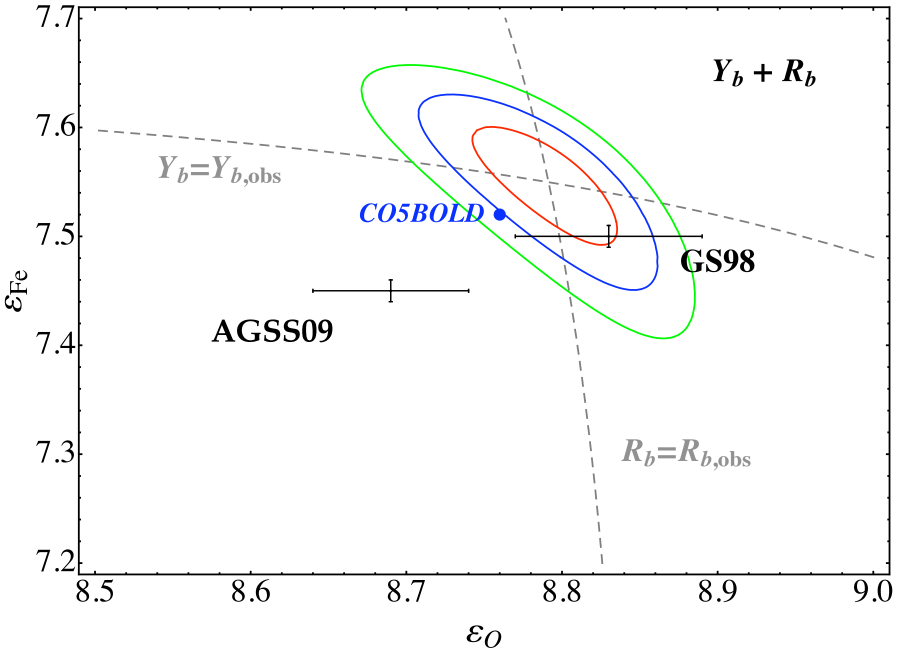
$$1 + \delta z_{\rm CNO} \equiv \frac{z_{\rm C}}{\overline{z}_{\rm C}} \equiv \frac{z_{\rm N}}{\overline{z}_{\rm N}} \equiv \frac{z_{\rm O}}{\overline{z}_{\rm O}} \qquad \textit{(photosphere)}$$

$$1 + \delta z_{\rm Ne} \equiv \frac{z_{\rm Ne}}{\overline{z}_{\rm Ne}} \qquad \textit{(chromosphere and corona)}$$

$$1 + \delta z_{\rm Heavy} \equiv \frac{z_{\rm Mg}}{\overline{z}_{\rm Mg}} \equiv \frac{z_{\rm Si}}{\overline{z}_{\rm Si}} \equiv \frac{z_{\rm S}}{\overline{z}_{\rm S}} \equiv \frac{z_{\rm Fe}}{\overline{z}_{\rm Fe}} \qquad \textit{(meteorites)}$$

We infer the **best-fit composition** by minimizing the χ^2

Two parameter analysis ($\delta Z_{CNO} = \delta Z_{Ne}$; δZ_{Heavy})



- Results are presented by using the astronomical scale for logarithmic abundances ε_j in order to facilitate comparison with obs. data.
- The coloured lines are obtained by cutting at 1, 2, 3 σ confidence levels.
- The data points show the obs. values (and 1σ errors) for oxygen and iron abundances in the AGSS09, GS98 and CO5BOLD compilations.

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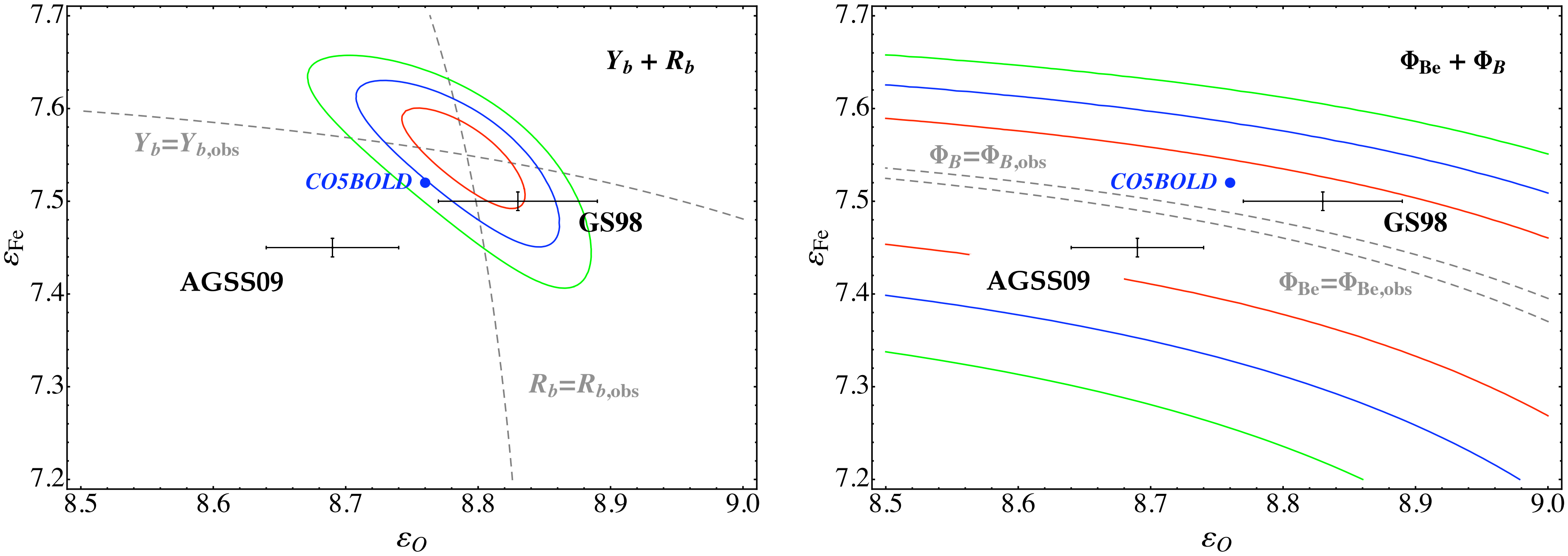
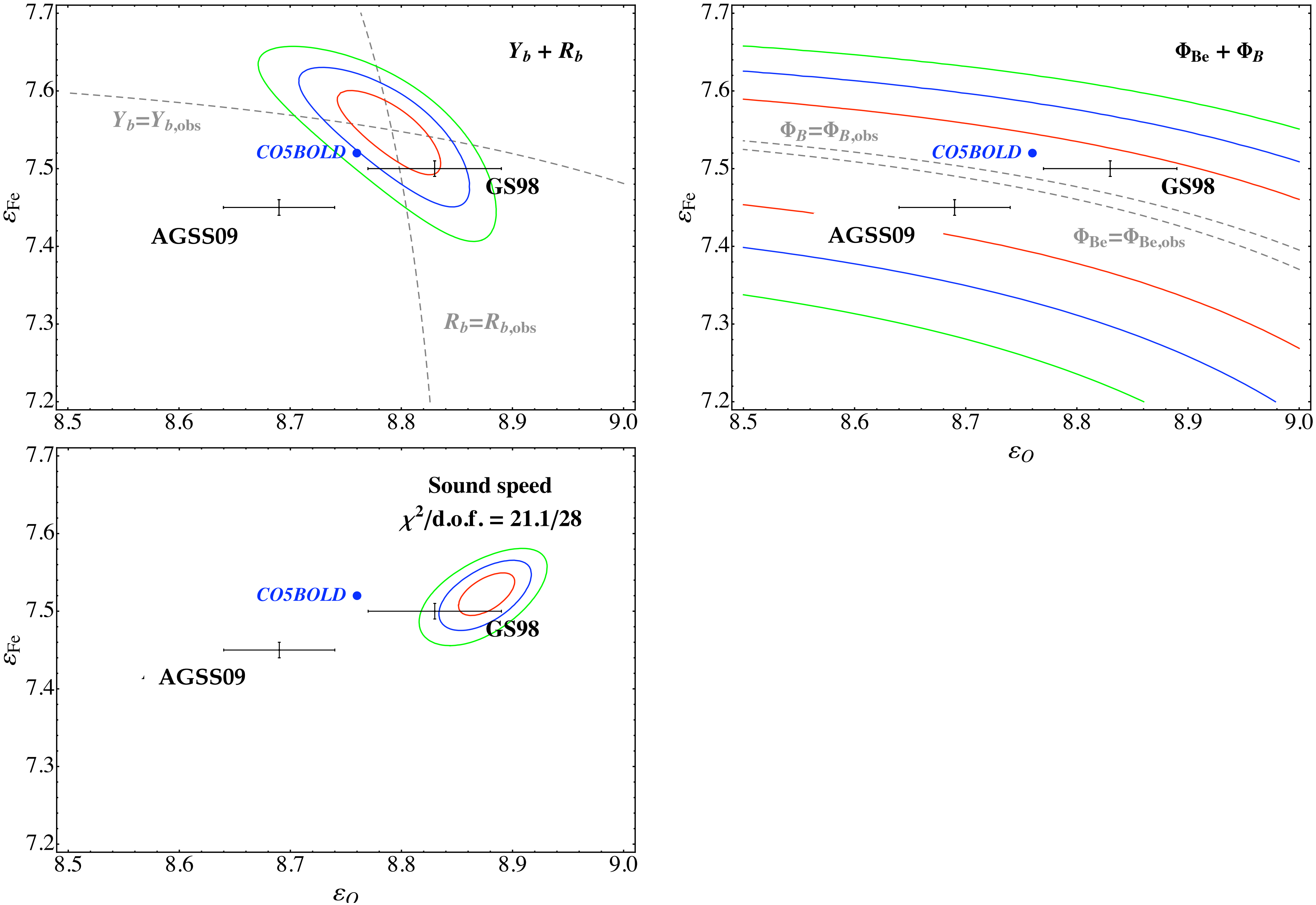


Note that: the error budget for ^{8}B and ^{7}Be neutrinos is dominated by systematical uncertainties

	Age	Diffu	Lum	S_{11}	S_{33}	S_{34}	S_{17}	S_{e7}	$S_{1,14}$	Opa
Y_b	-0.001	-0.012	0.002	0.001	0	0.001	0	0	0.	0.0036
R_b	-0.0004	-0.0029	-0.0001	-0.0006	0.0001	-0.0002	0	0	0	0.0014
Φ_{pp}	0	-0.002	0.003	0.001	0.002	-0.003	0	0	0	-0.0008
Φ_{Be}	0.003	0.022	0.014	-0.010	-0.023	0.047	0	0	0	0.009
Φ_B	0.006	0.044	0.029	-0.025	-0.022	0.046	0.075	-0.02	0	0.020
Φ_N	0.004	0.054	0.018	-0.019	0.001	-0.003	0	0	0.051	0.013
Φ_O	0.006	0.062	0.024	-0.027	0.001	-0.002	0	0	0.072	0.018

Table 1: *The contributions $C_{Q,I}$ to uncertainties in theoretical predictions for helio-seismic observables and solar neutrino fluxes.*

Two parameter analysis ($\delta Z_{CNO} = \delta Z_{Ne}$; δZ_{Heavy})



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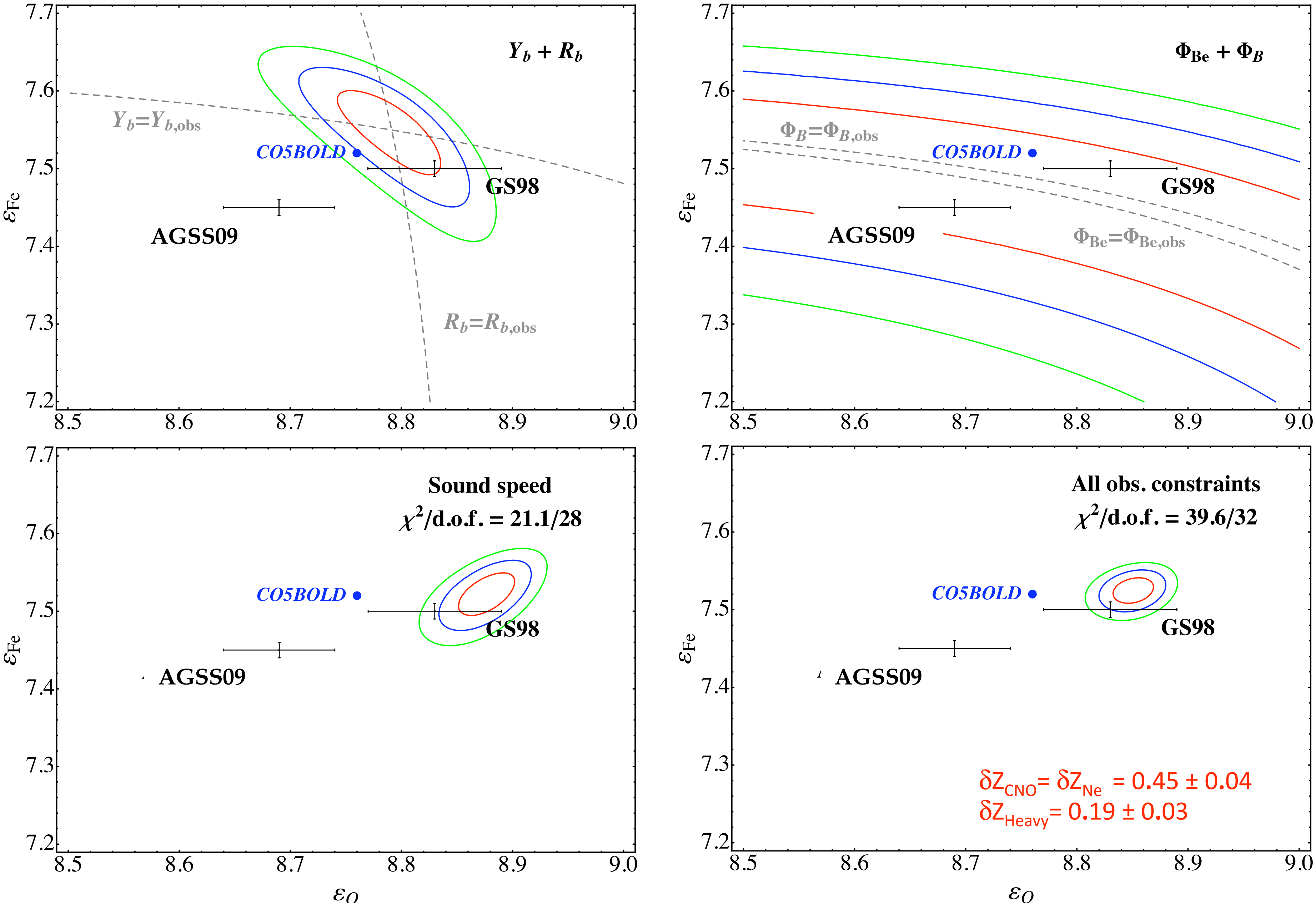


$\delta Z_{CNO} = \delta Z_{Ne} = 0.45 \pm 0.04$
$\delta Z_{Heavy} = 0.19 \pm 0.03$

Two parameter analysis ($\delta Z_{CNO} = \delta Z_{Ne}$; δZ_{Heavy})

✧ The AGSS09 composition is **excluded** at an high confidence level being
χ^2**/ d.o.f. = 176.7/32.**

✧ Substantial agreement between the infos provided by the various observational constraints. The quality of the fit is quite good being
χ^2**/ d.o.f. = 39.6/32**.

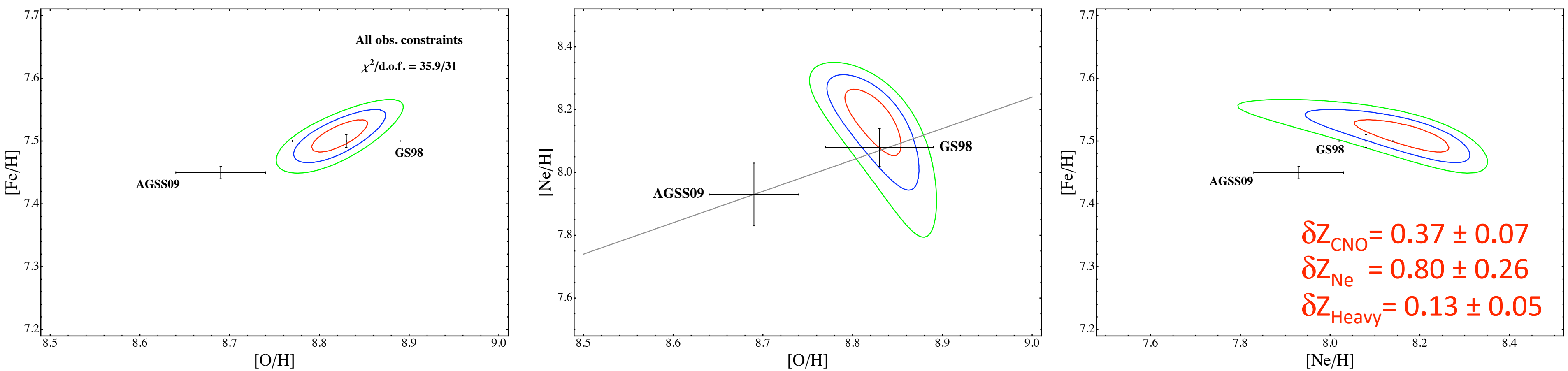
✧ The best-fit abundances are **consistent** at 1 sigma with **GS98**.

✧ The **errors** on the inferred abundances **are smaller** than what is obtained by observational determinations.

✧ The **CNO neutrino fluxes** are expected to be ~50% larger than predicted by AGSS09 (this result, however, depends on the assumed heavy element grouping).

Three parameter analysis (δZ_{CNO}; δZ_{Ne} ; δZ_{Heavy})

Prior: Neon-to-oxygen ratio forced at the AGSS09 value with 30% accuracy



GS98 still favored by observational data but:

- errors in the inferred abundances larger than before;
- degeneracies appear among the various δZ_i ;
- obs.data do not effectively constrain the Ne/O ratio (we recover the prior).

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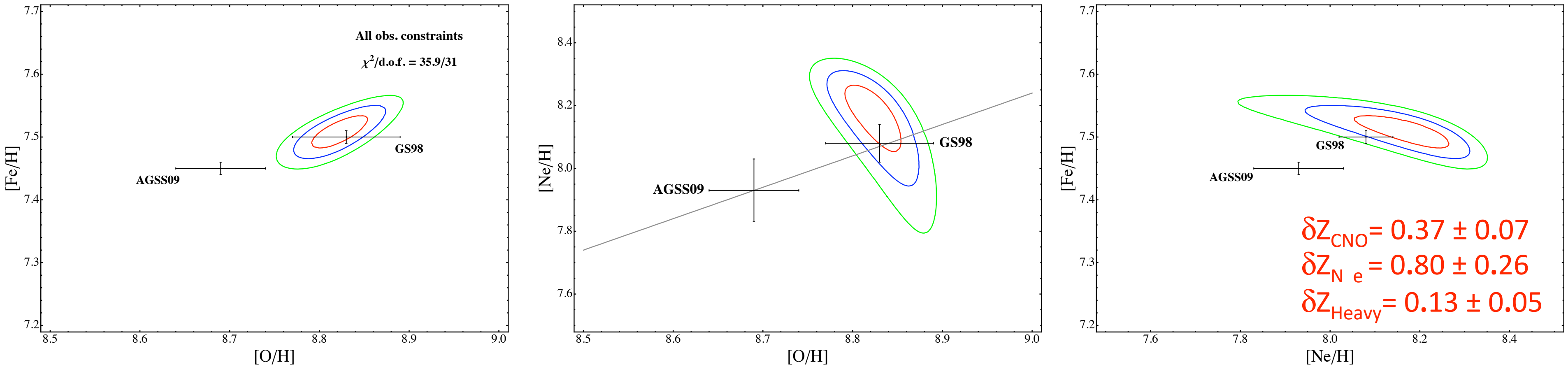

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What data are really saying us? …

Metals in the Sun

- Metals give a **substantial** contribution to **opacity**:

Energy producing region ($R < 0.3\ R_o$)

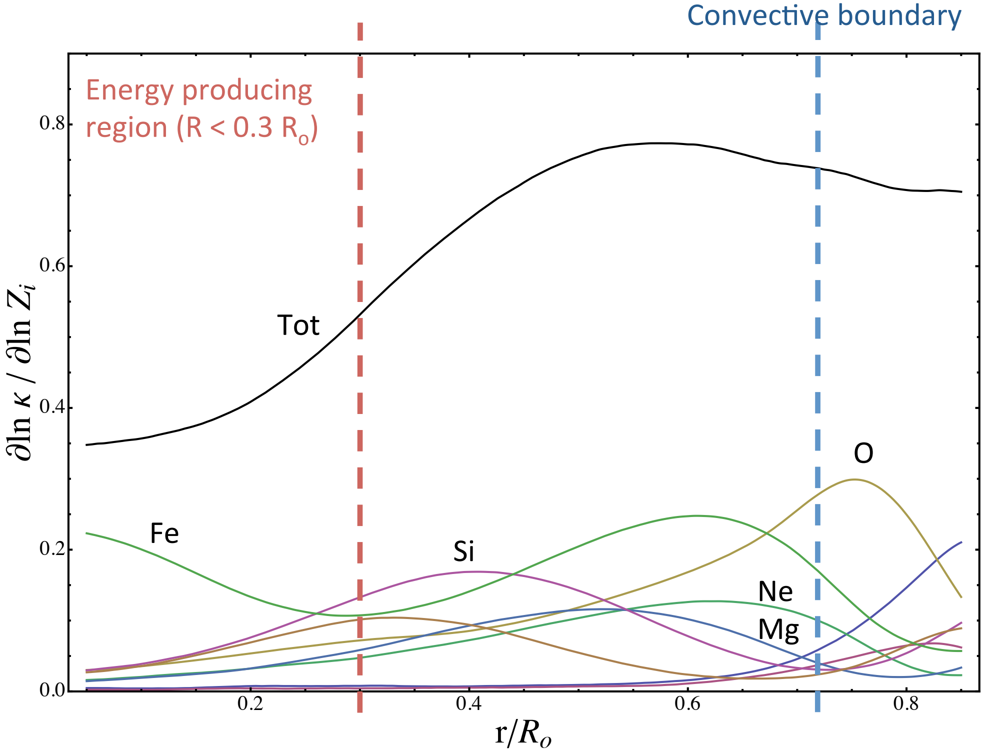
$$\kappa_Z \approx \frac{1}{2}\kappa_{tot}$$

Fe gives the largest contribution.

Outer radiative region ($0.3 < R < 0.73\ R_o$)

$$\kappa_Z \sim 0.8\ \kappa_{tot}$$

Relevant contributions from several diff. elements (O,Fe,Si,Ne,…)



Composition opacity change:

$$\delta\kappa_Z(r) \simeq \sum_j \frac{\partial \ln \kappa(r)}{\partial \ln Z_j}\, \delta z_j$$

What we know about the opacity profile of the present sun?

F.L. Villante and B. Ricci - ***Astrophys.J.714:944-959,2010***
F.L. Villante – **Astrophys.J.724:98-110,2010**

Composition opacity change

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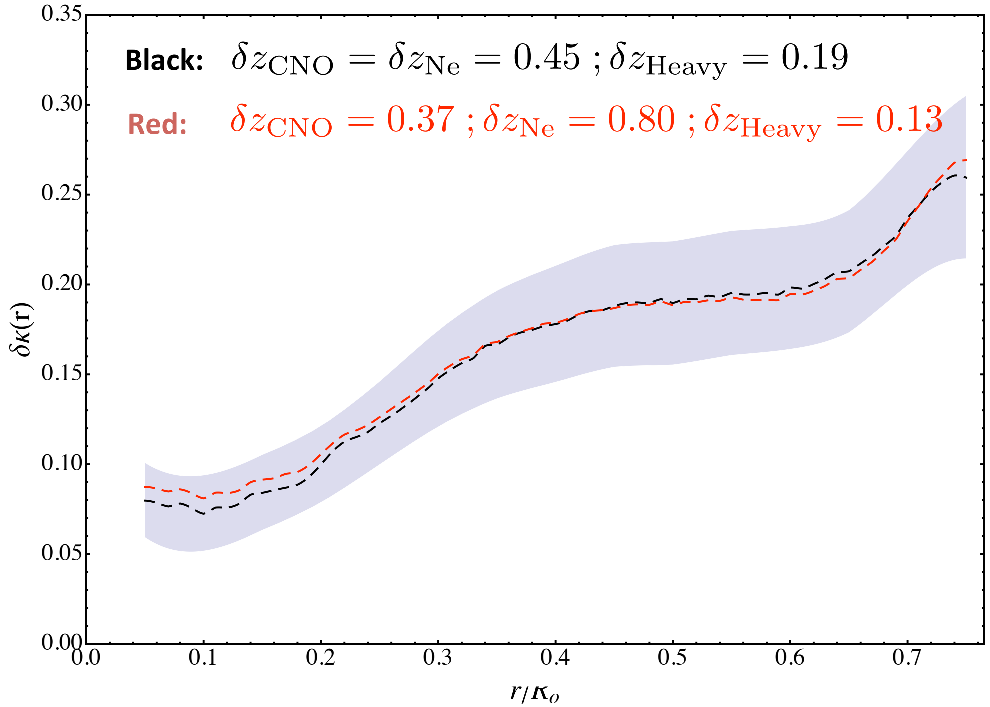

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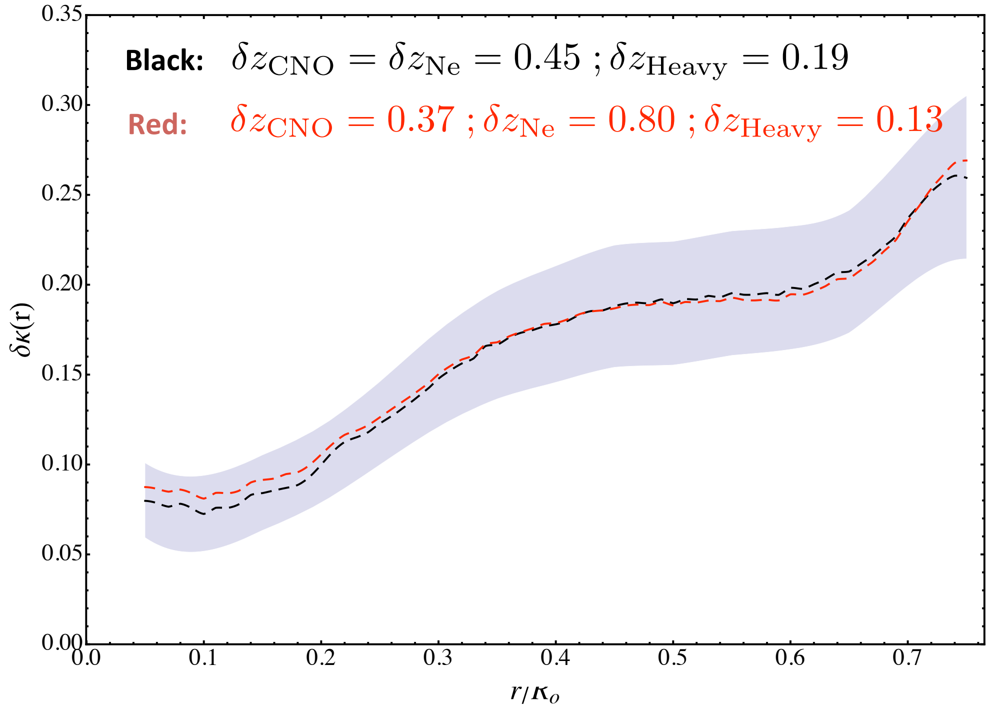

Are there other effects that can provide the required opacity change?

Wrong **opacity** calculations? → the required variations seems large wrt uncertainties

Different **distribution of metals** in the Sun? → According to the standard assumption, metals are nearly omogeneous in the sun (elemental diffusion is responsible for a slight increase at the solar center). Is this an oversimplified picture of chemical evolution?

Is this discrepancy pointing at **new physics** (e.g. WIMPs in the solar core?)

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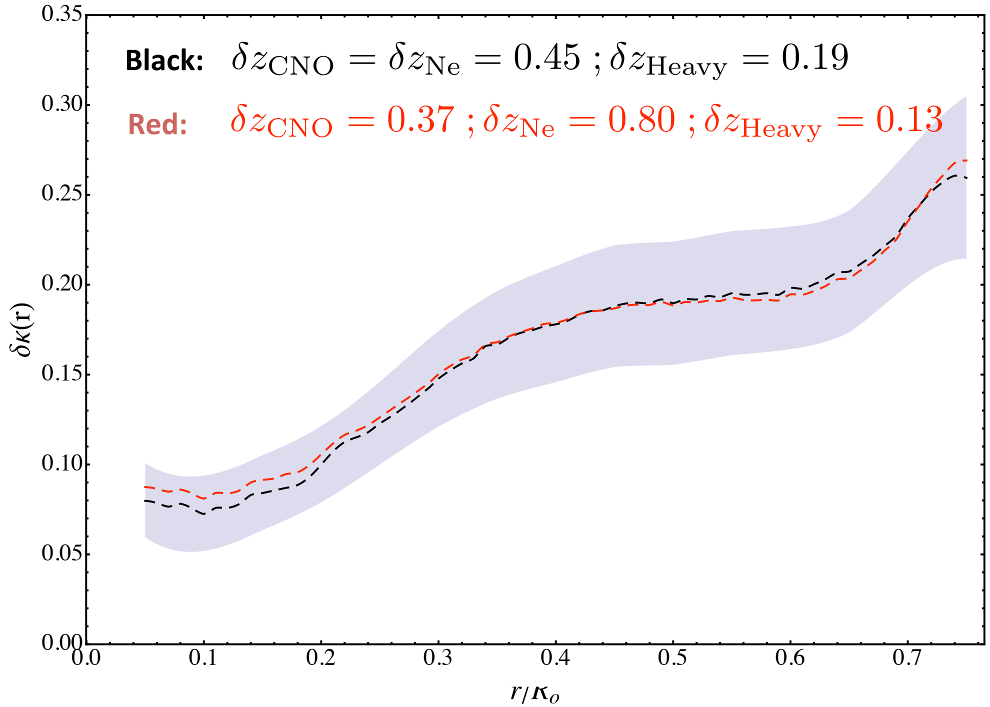

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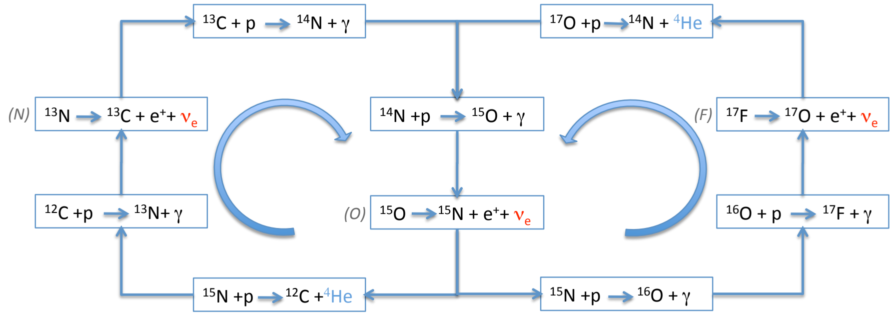
… Not just a problem of AGSS09.vs.GS98

CNO neutrinos



CNO neutrinos break the degeneracy between opacity and metals:

$$1 + \delta\Phi_\nu = (1 + \delta X_{\rm CN}) \left[1 + \int dr\, K_\nu(r)\, \delta\kappa(r)\right]$$

$$X_{\rm CN} \equiv X_{\rm C}/12 + X_{\rm N}/14$$

Total number of catalysts for CN-cycle

Determines the central temperature

At present, we only have a loose upper limit on CNO neutrino fluxes:

ν flux	GS98	AGSS09	Solar
^{13}N $(10^8\,{\rm cm}^{-2}\,{\rm s}^{-1})$	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7
^{15}O $(10^8\,{\rm cm}^{-2}\,{\rm s}^{-1})$	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.3
^{17}F $(10^6\,{\rm cm}^{-2}\,{\rm s}^{-1})$	$5.52(1 \pm 0.17)$	$3.04(1 \pm 0.16)$	≤ 59

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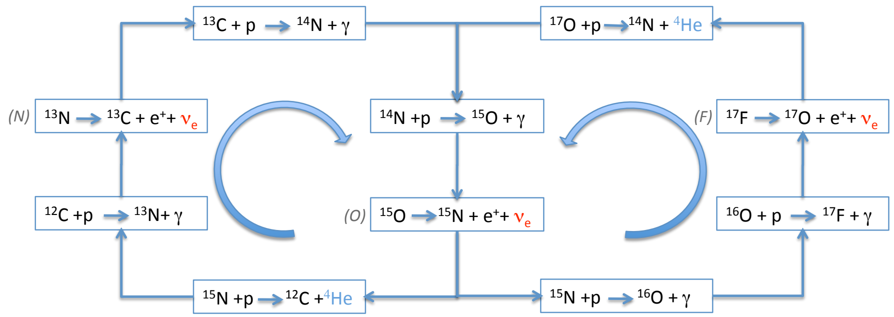

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Will it be possible to detect CNO neutrino?

Very difficult, in practice. Not impossible, in principle .....

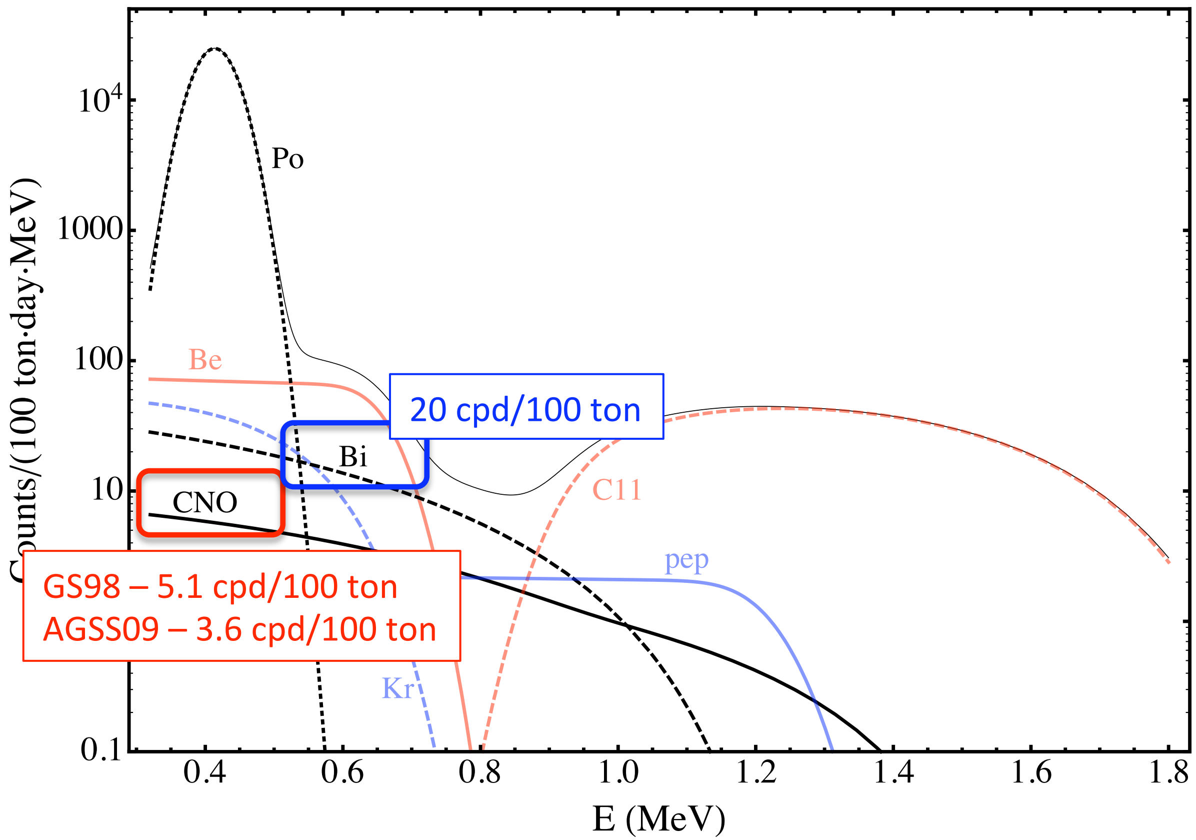
F.L. Villante et al. – Phys.Lett. B701 (2011) 336

Is it possible to observe CNO neutrinos in LS?

The detection of CNO neutrinos is very difficult:

- Low energy neutrinos → endpoint at about 1.5 MeV
- Continuos spectra → do not produce recognizable features in the data.
- Limited by the background produced by beta decay of ^{210}Bi.

Event spectrum in ultrapure liquid scintillators (Borexino-like)



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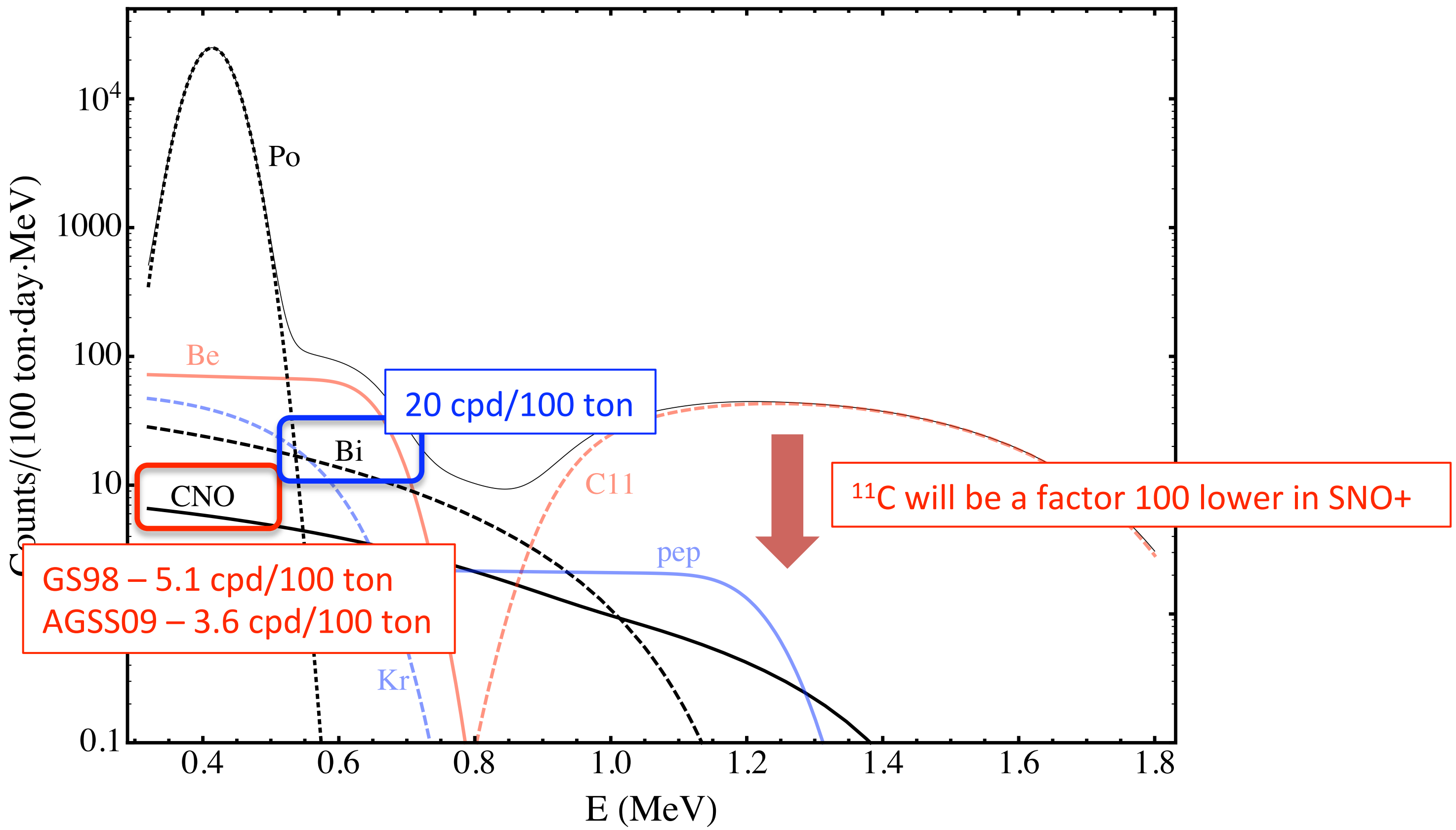

Summary and conclusions

✦ Solar neutrino physics in still interesting

✦The solar composition problem is open and is potentially pointing at inadequacy in standard solar model paradigm.

✦Hopefully, all the components of the solar neutrino flux measurements (pp, CNO) will be directly determined the future.

✦CNO neutrino detection requires careful bkgd evaluation in existing or next future LS detectors and/or new experimental approaches.

(see Orebi-Gann@Neutrino2014 for a discussion of future expt. tecniques)

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- Application: what we know about opacity and metals in the sun

F.L. Villante – **Astrophys.J.724:98-110,2010**

- A step toward CNO neutrino detection

F.L. Villante et al. - **Phys.Lett. B701 (2011) 336-341**

Determining ^{210}Bi with the help of ^{210}Po?

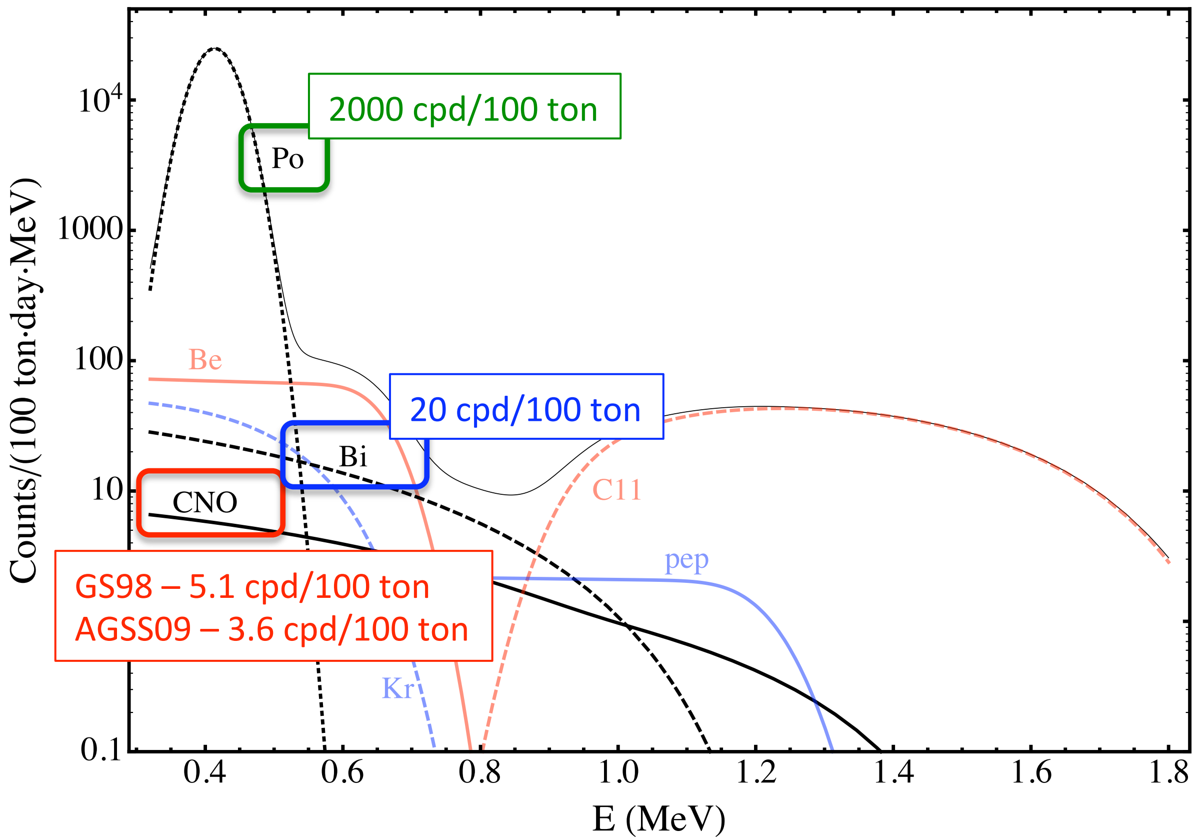
$$^{210}\mathrm{Bi} \rightarrow {}^{210}\mathrm{Po} + e^- + \overline{\nu}_e$$

t_{Bi} = 7.232 d

$$^{210}\mathrm{Po} \rightarrow {}^{206}\mathrm{Pb} + \alpha$$

t_{Po} = 199.634 d

Event spectrum in ultrapure liquid scintillators



Deviations from the exponential decay law of Po210 can be used to determine Bi210:

$$n_{\rm Po}(t) = [n_{\rm Po,0} - n_{\rm Bi}]\ \exp(-t/\tau_{\rm Po}) + n_{\rm Bi}$$

Expected accuracy:

$$\Delta n_{\rm Bi} \simeq \sqrt{\frac{n_{\rm Po,0}}{\tau_{\rm Po}\, M}}\ f(\Delta t)$$

$$f(\Delta t) = \left(\frac{2\,\tau_{\rm Po}}{\Delta t}\right)\ e^{-\frac{\Delta t}{4\tau_{\rm Po}}}\ \sqrt{\frac{1+e^{-\frac{\Delta t}{2\tau_{\rm Po}}}}{1-e^{-\frac{\Delta t}{2\tau_{\rm Po}}}}}$$