Solar Neutrinos and The Sun

NEUTEL 11 – Venice 15/03/11

A. Serenelli

Outline

- Update on Solar models: abundances and nuclear reaction rates
- Solar neutrino fluxes from neutrino data: can neutrinos disentangle abundances?
- Extracting information from solar neutrino fluxes, an example
- Why CN neutrinos?
- 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
C	8.52	8.39	8.43
N	7.92	7.78	7.83
O	8.83	8.66	8.69
Ne	8.08	[7.84 ± 0.06]	[7.93 ± 0.10]
Mg	7.58	7.53	7.53
Si	7.56	7.51	7.51
Ar	6.40	[6.18 ± 0.08]	[6.40 ± 0.13]
Fe	7.50	7.45	7.45
Z/X	0.0229	0.0165	0.0178

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Not from photosphere

Recap on solar abundances

CO^5BOLD derives higher abundances and (up to 2X) larger error bars although model atmospheres agree very well → diffs in spectral analysis

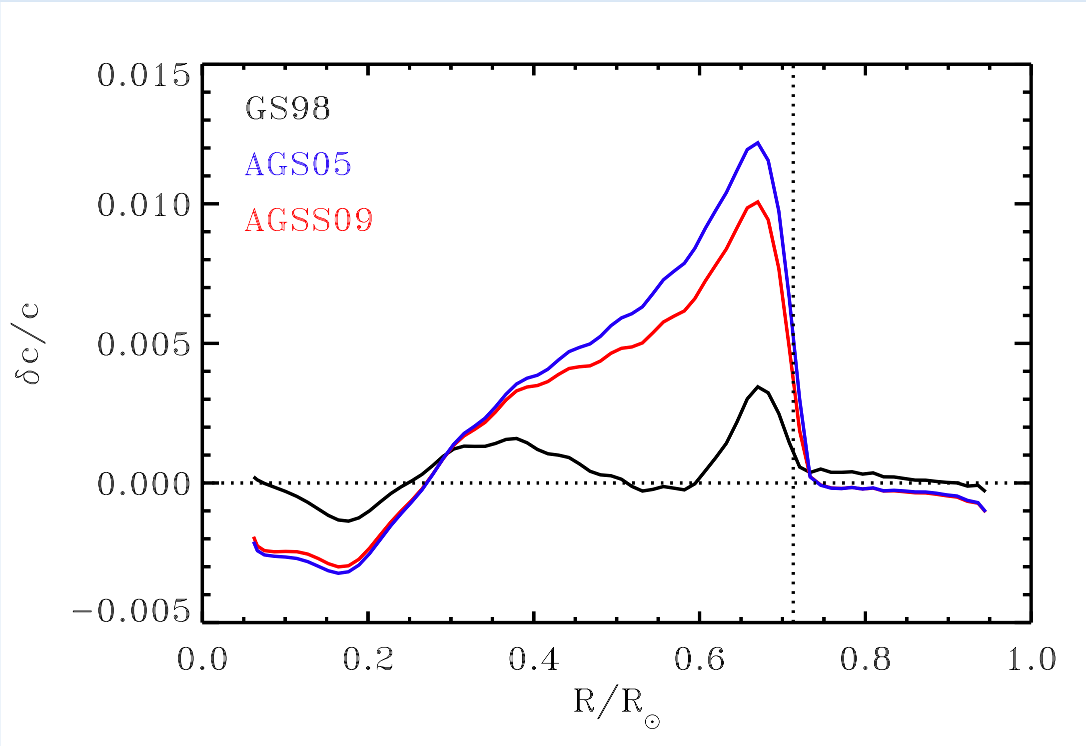
Element	GS98	AGS05	AGSS09	CO^5BOLD
C	8.52	8.39	8.43 ± 0.05	8.50 ± 0.06
N	7.92	7.78	7.83 ± 0.05	7.86 ± 0.12
O	8.83	8.66	8.69 ± 0.05	8.76 ± 0.07
Ne	8.08	7.84	7.93	—
Mg	7.58	7.53	7.53	—
Si	7.56	7.51	7.51	—
Ar	6.40	6.18	6.40	—
Fe	7.50	7.45	7.45	7.52
Z/X	0.0229	0.0165	0.0178	0.0209

Error (mostly) reflect internal dispersion →
determined by selection of lines; human factor?
difficult to estimate model uncertainties (attempt by Asplund et al.)

Helioseismology – The Solar Abundance Problem

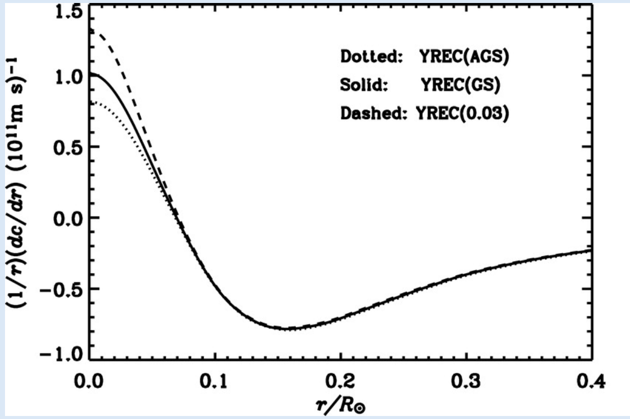
Model	$(Z/X)_S$	Z_S	Z_C	$R_{CZ}/R_\odot$	$\langle \delta c/c \rangle$	$\langle \delta\rho/\rho \rangle$	Y_S	Y_C
GS98	0.0229	0.0170	0.0201	0.713	0.0010	0.011	0.2423	0.6330
AGS05	0.0165	0.0126	0.0149	0.728	0.0049	0.048	0.2292	0.6195
AGSS09	0.0178	0.0134	0.0160	0.724	0.0038	0.040	0.2314	0.6220
Helios.	—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

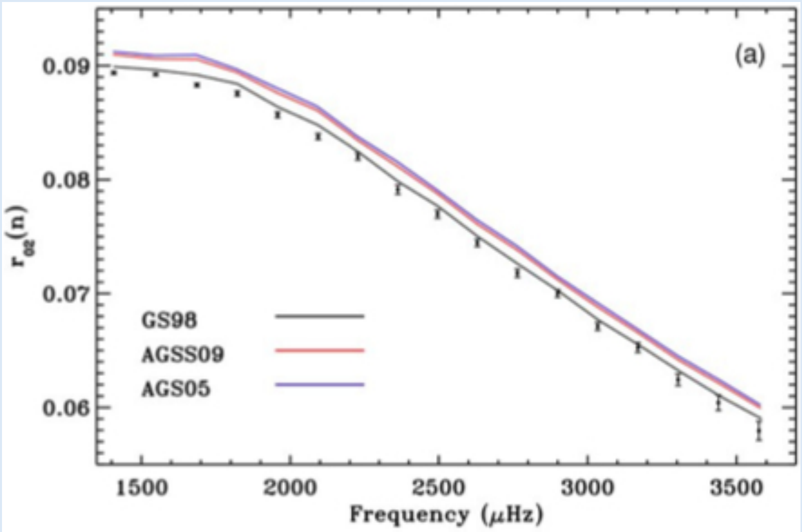
Serenelli et al. (2009)

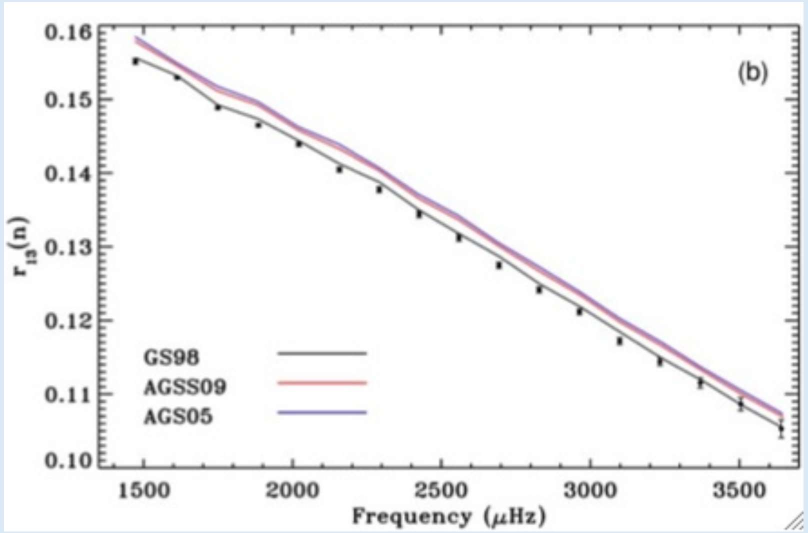


Helioseismology – Small separation ratios: ℓ = 0, 1, 2, 3

$$\left.\begin{aligned} r_{02}(n) &= \frac{\nu_{n,0}-\nu_{n-1,2}}{\nu_{n,1}-\nu_{n-1,1}} \\ r_{13}(n) &= \frac{\nu_{n,1}-\nu_{n-1,3}}{\nu_{n+1,0}-\nu_{n,0}} \end{aligned}\right\} \propto \int_0^R \frac{dc}{dr}\frac{dr}{r}$$







r_{02} & r_{13} → core mean molecular weight – warning for non-SSM

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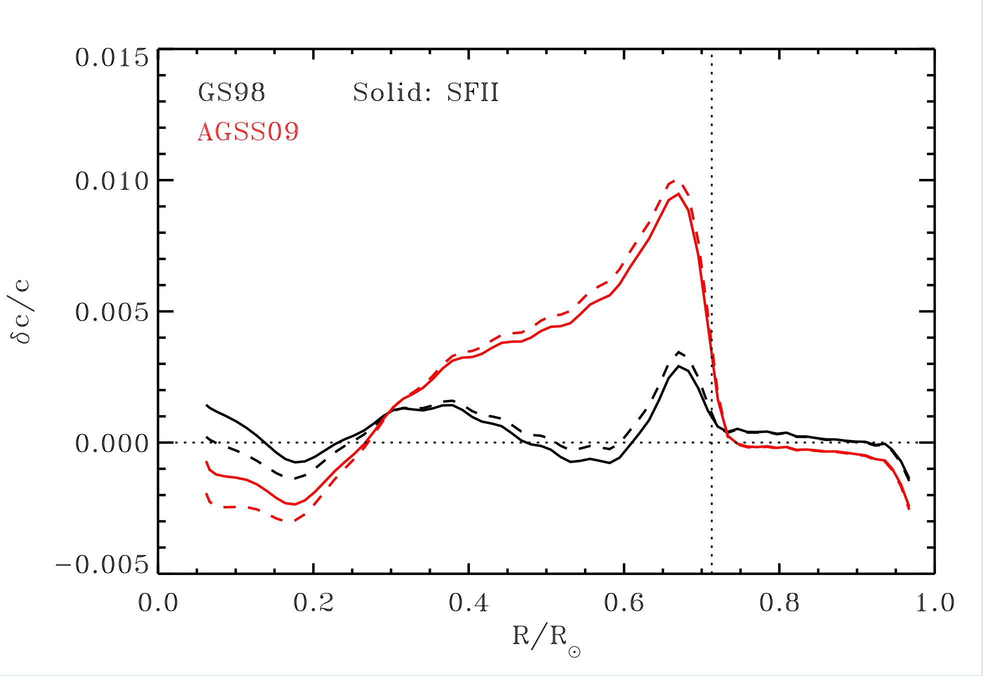
Revised nuc. cross sections: Solar Fusion II

(Adelberger et al. - arxiv:1004.2318)

Reaction	SFII (keV-b)	Previous (keV-b)	Δ
S_{11}	$4.01 \times 10^{-22}(1 \pm 0.010)$	$3.94 \times 10^{-22}(1 \pm 0.004)$	+1.8%
S_{33}	$5.21 \times 10^{3}(1 \pm 0.052)$	$5.4 \times 10^{3}(1 \pm 0.06)$	-3.5%
S_{34}	$0.56(1 \pm 0.054)$	$0.567(1 \pm 0.03)$	-1.2%
S_{17}	$2.08 \times 10^{-2}(1 \pm 0.077)$	$2.14 \times 10^{-2}(1 \pm 0.038)$	-2.8%
$S_{1,14}$	$1.66(1 \pm 0.072)$	$1.57(1 \pm 0.08)$	+5.7%
R(pep)/R(pp)	↑ 2.5%	—	

Small changes in helioseismic properties



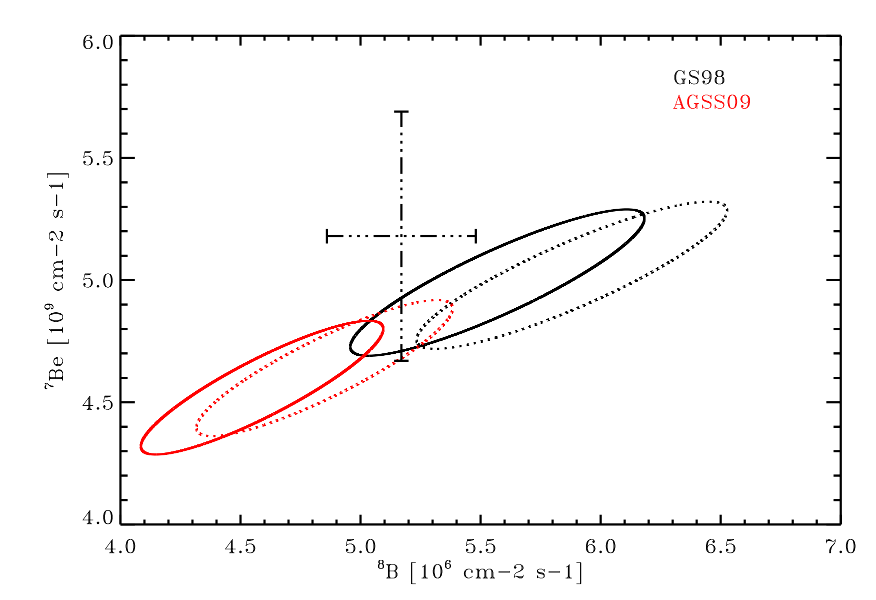
Solar Neutrinos

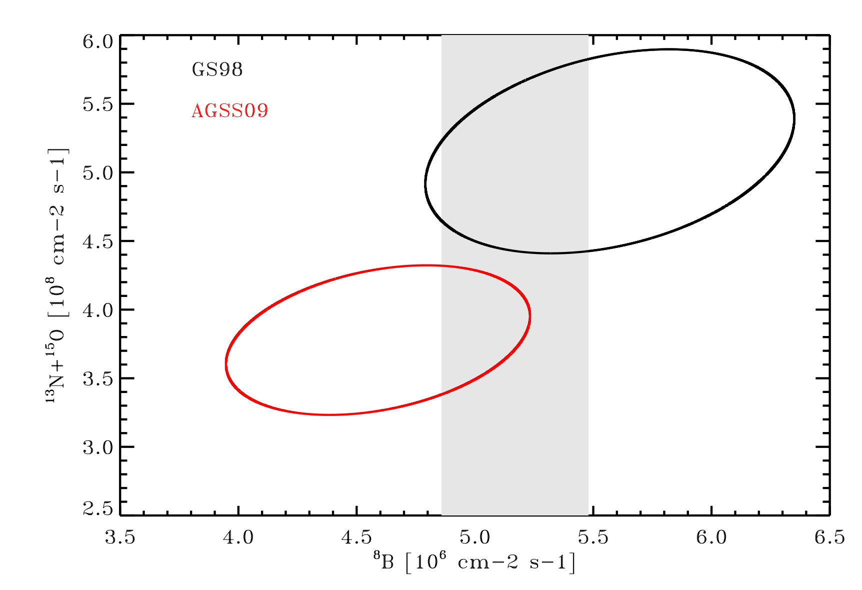
ν fluxes with Solar Fusion II – Serenelli et al. (2011)

Flux	SFII-GS98	SFII-AGSS09	Δ
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	+0.1%
pep	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	+2%
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	+1.6%
^{7}Be	$4.99(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	-1.7%
^{8}B	$5.57(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	-5%
^{13}N	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	+5%
^{15}O	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	+5-6%
^{17}F	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	+2%

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

Small increase in uncertainties





Neutrino fluxes

Gonzalez-Garcia et al. (2010)

Global analysis of solar & terrestrial ν data

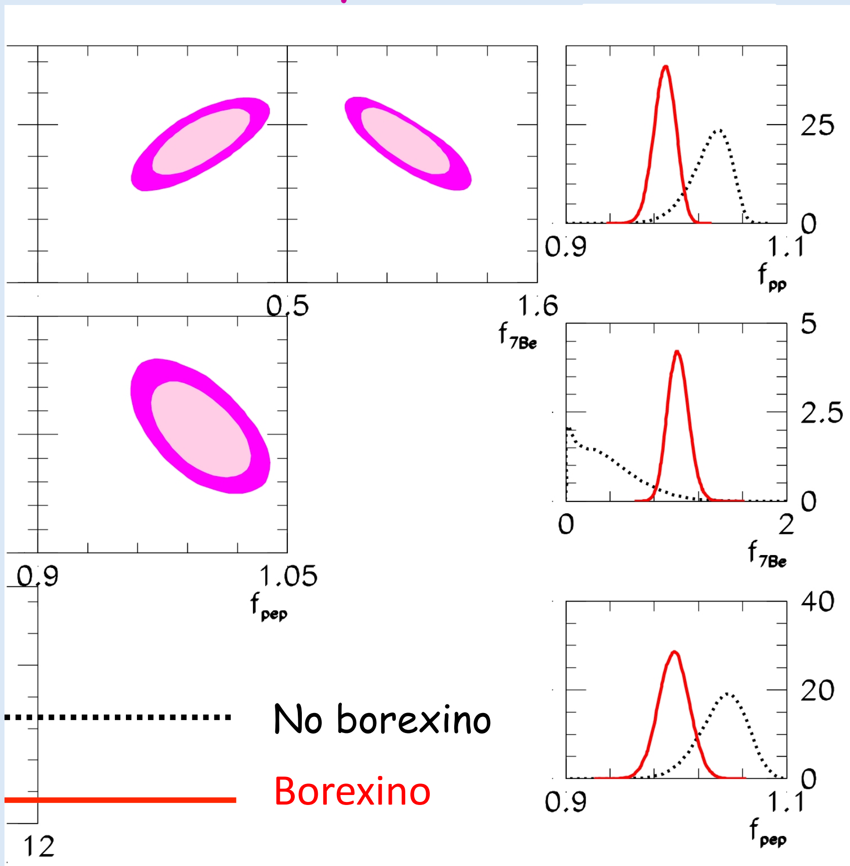
3 flavor-mixing framework

Basic constraints from pp-chains and CNO cycles

Luminosity constraint (optional)

Exhaustive discussion of importance of Borexino

Luminosity constraint

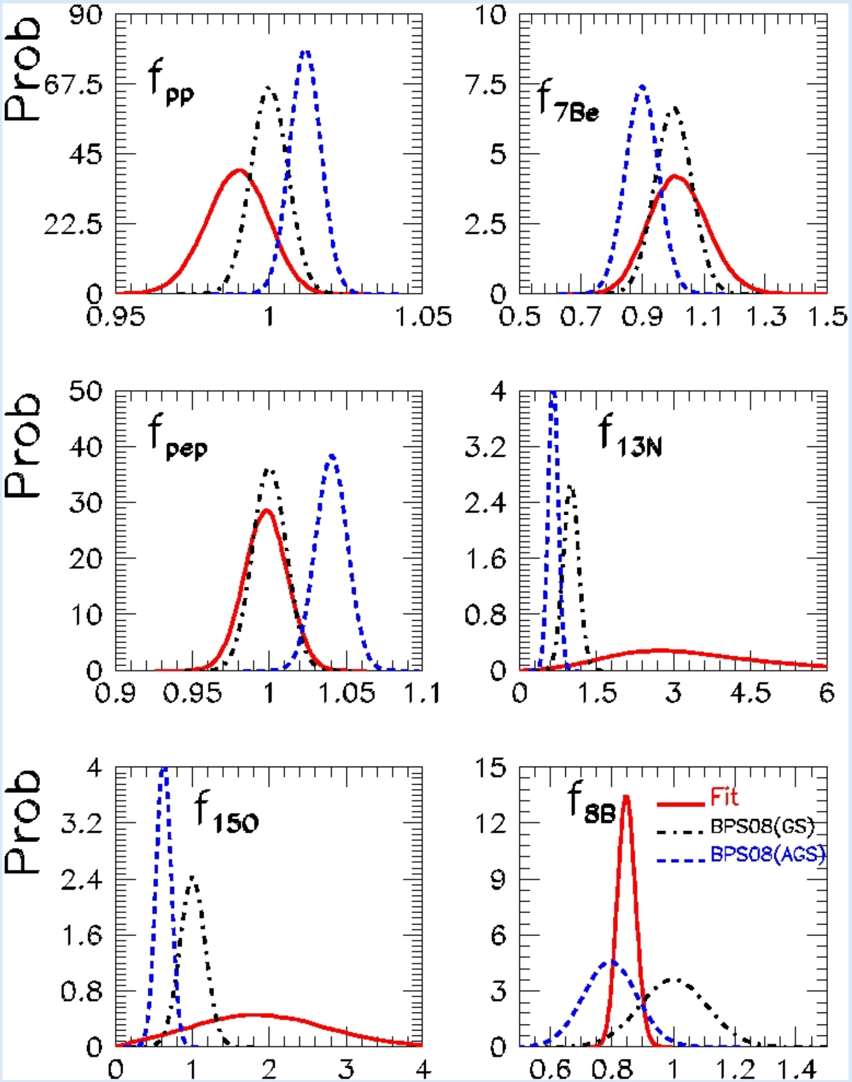


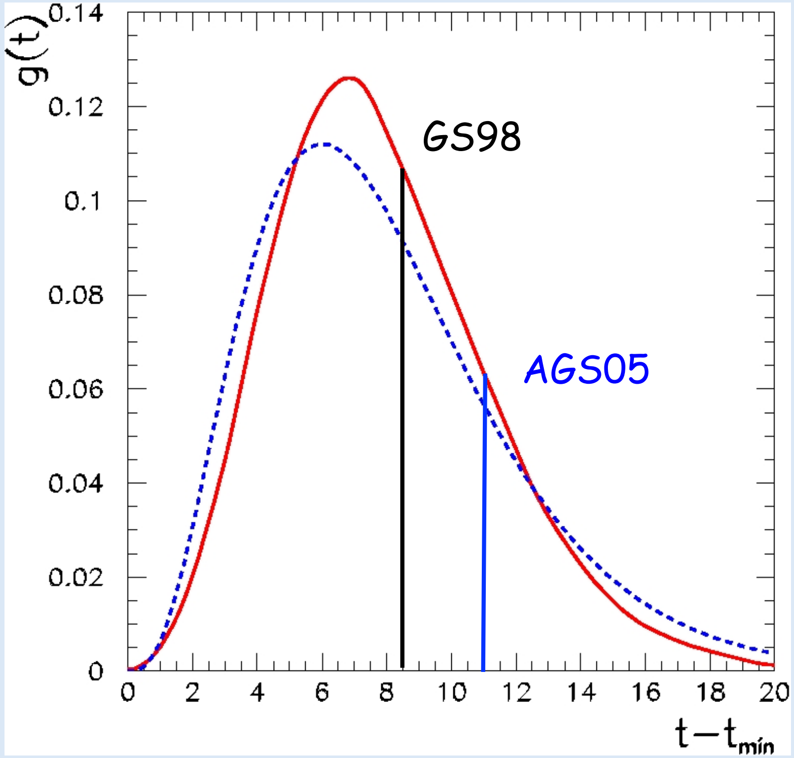
$$L_{\rm pp} = 0.986^{+0.005}_{-0.006}$$

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

Neutrino fluxes

Gonzalez-Garcia et al. 2010



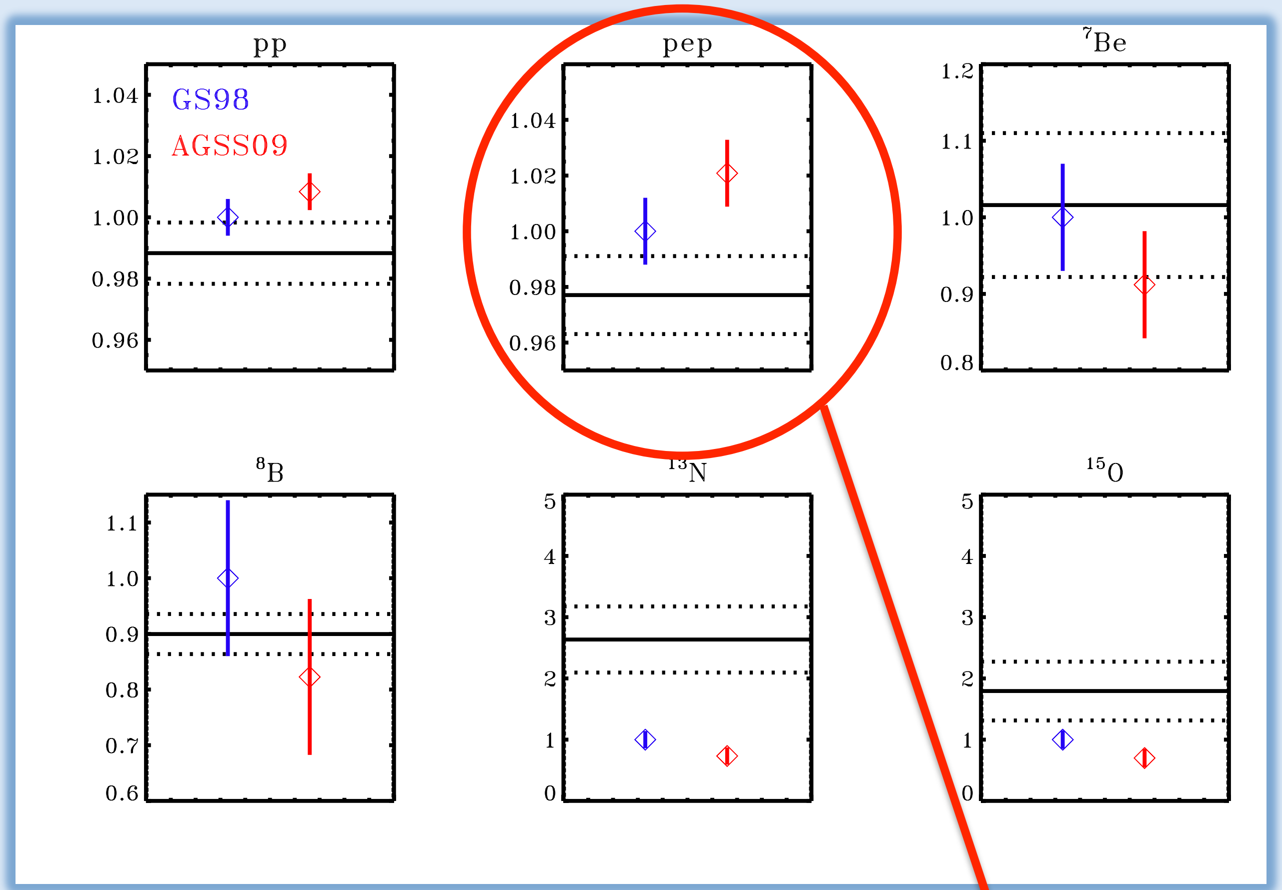


P(GS98) = 43%

P(AGS05)= 20%

AGSS09 + SFII + new data?

Neutrino fluxes



Results after AGSS09 & SFII

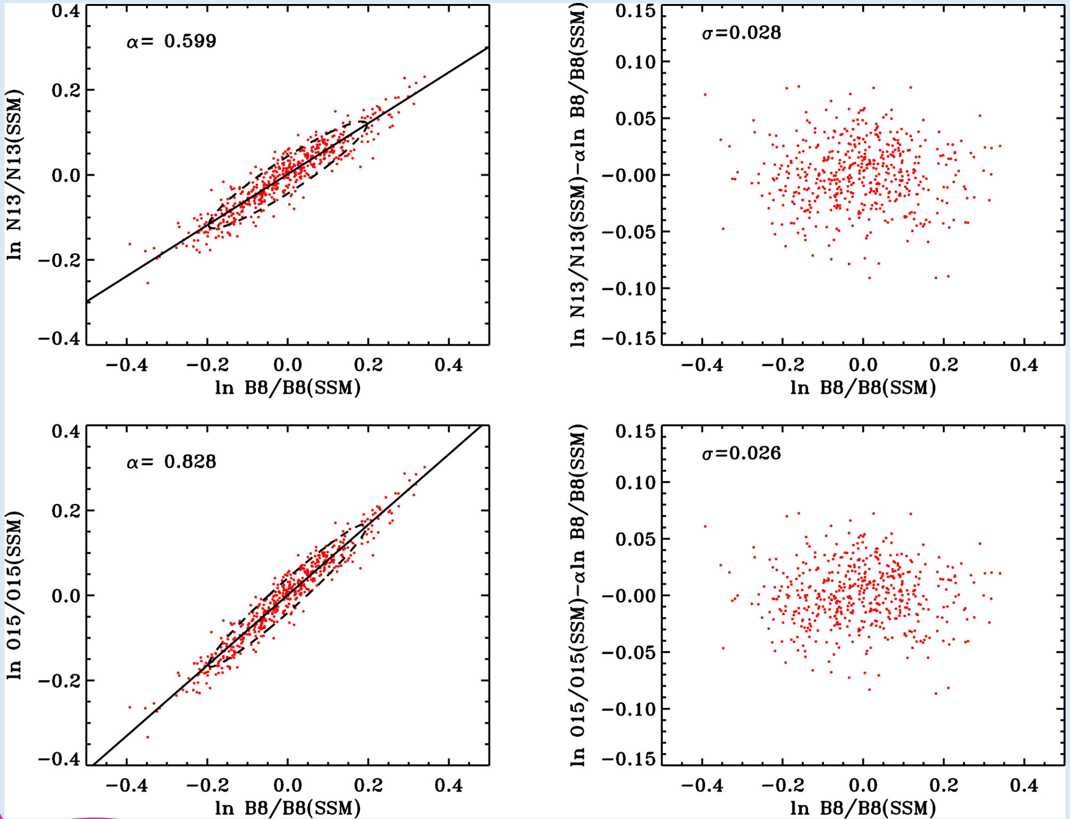
χ^2(GS98)= 4.2 - 83%
χ^2(AGSS09)= 6.7 - 57%

Solar pep flux would need revision due to R(pp)/R(pep) change in SFII

Neutrino fluxes

Extracting information from ν fluxes – C + N

"environmental factors" can be (partially) cancelled out by taking appropriate ratios



Flux	$L_\odot$	Age	Diff	C	N	Si	Fe
^{8}B	7.130	1.380	0.280	0.025	0.007	0.211	0.510
^{13}N	4.400	0.855	0.340	0.861	0.148	0.109	0.262
^{15}O	6.005	1.338	0.394	0.810	0.207	0.158	0.386

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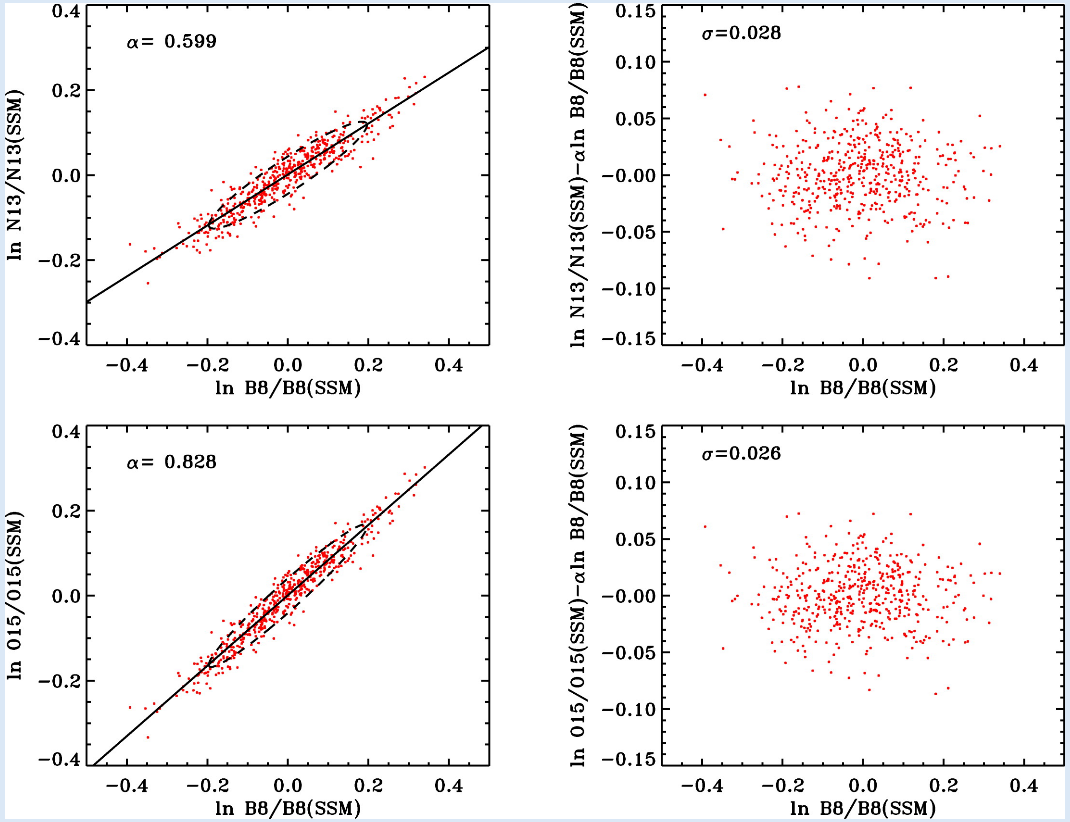

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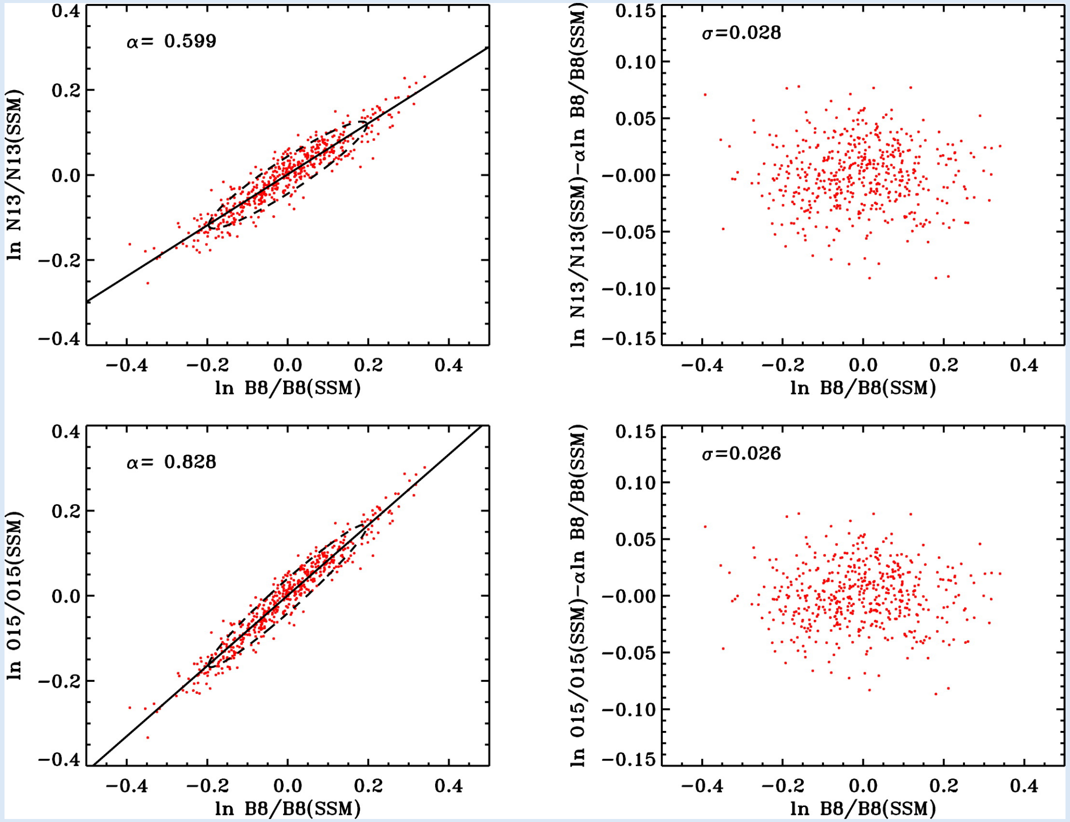
C+N to 10% and remaining uncert. experimental



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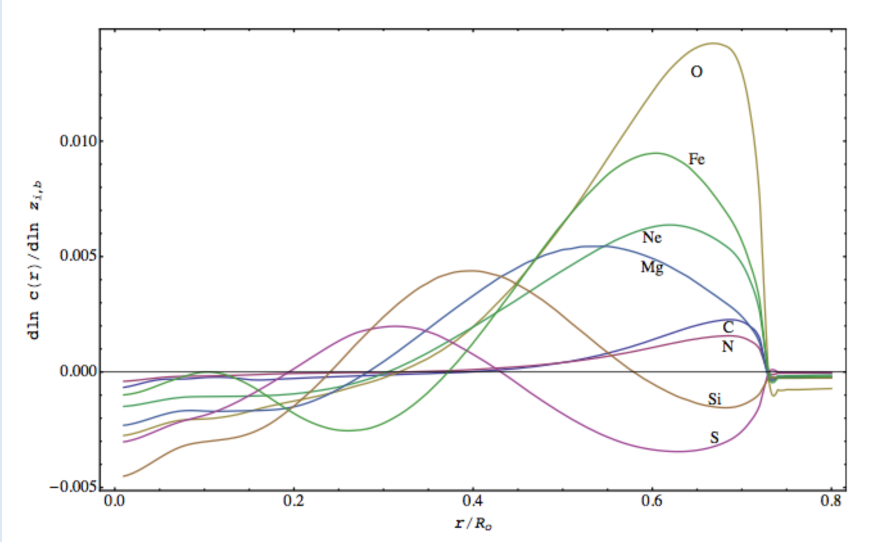
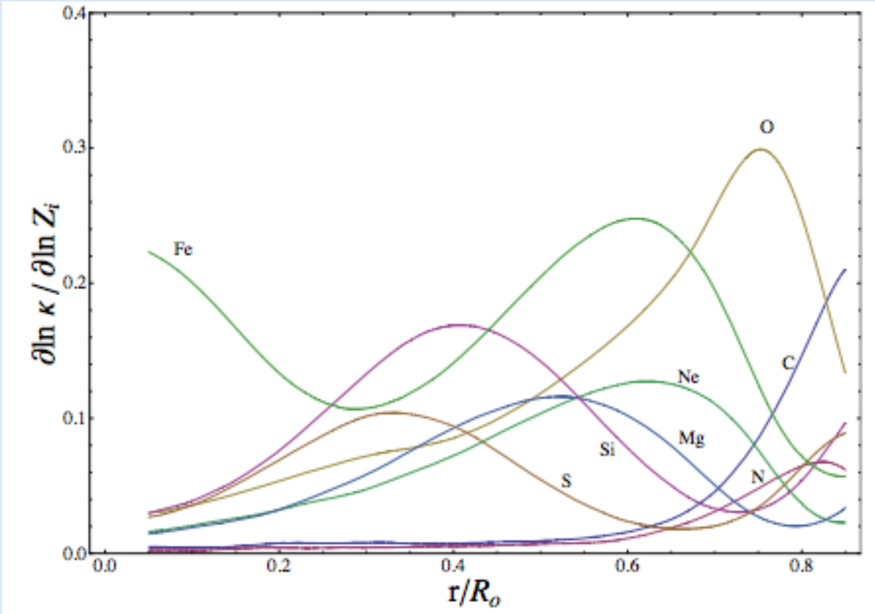
$$\frac{R(CN)}{R^{SSM}(CN)} = \frac{X(C+N)}{X^{SSM}(C+N)}\left[\frac{R^{SK}(^8B)}{R^{SSM}(^8B)}\right]^{0.828} \times [1 \pm 0.03(\mathrm{SK}) \pm 0.026(\mathrm{res\ env}) \pm 0.049(\mathrm{LMA}) \pm 0.071(\mathrm{nucl})]$$

Neutrinos & Helioseismology: towards a complete analysis

Sound speed sensitivity



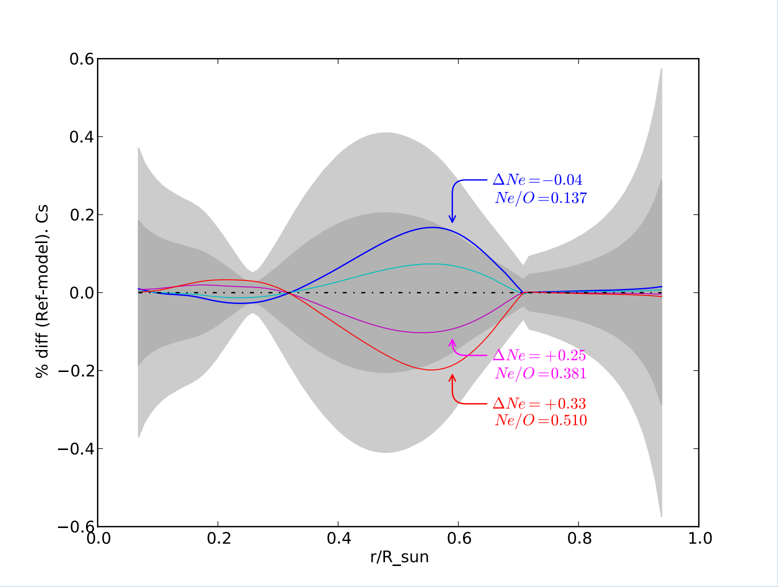
Opacity sensitivity

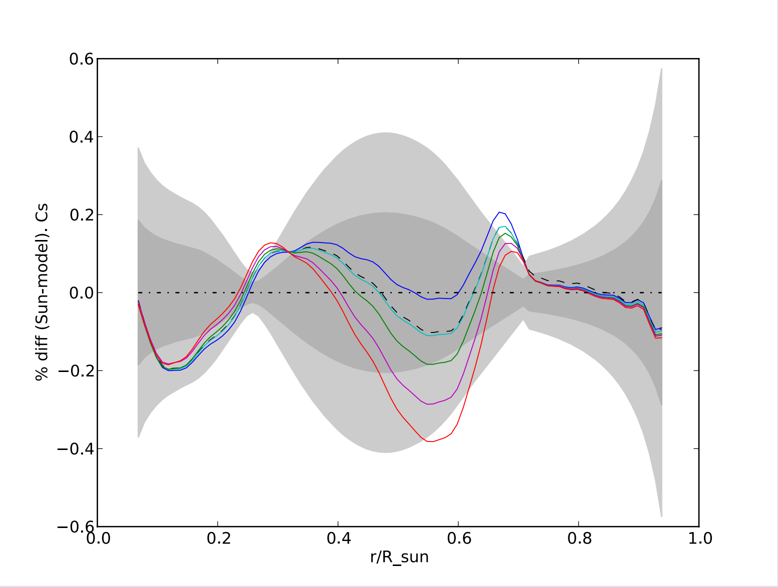


Both insensitive to C and N

Neutrinos & Helioseismology: towards a complete analysis

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

Additional motivations for CN neutrinos

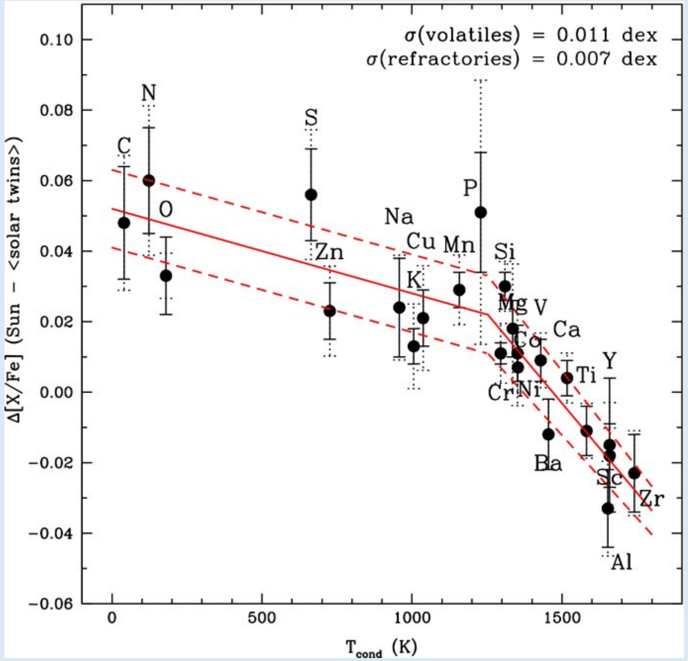
Experimental detection of CNO-cycles

Test of non-abundance "solutions to solar abundance problem", e.g. opacities

Solar abundances

Solar abundance problem (Sun initially homogeneous?)

Suggestions of Sun different from solar twins



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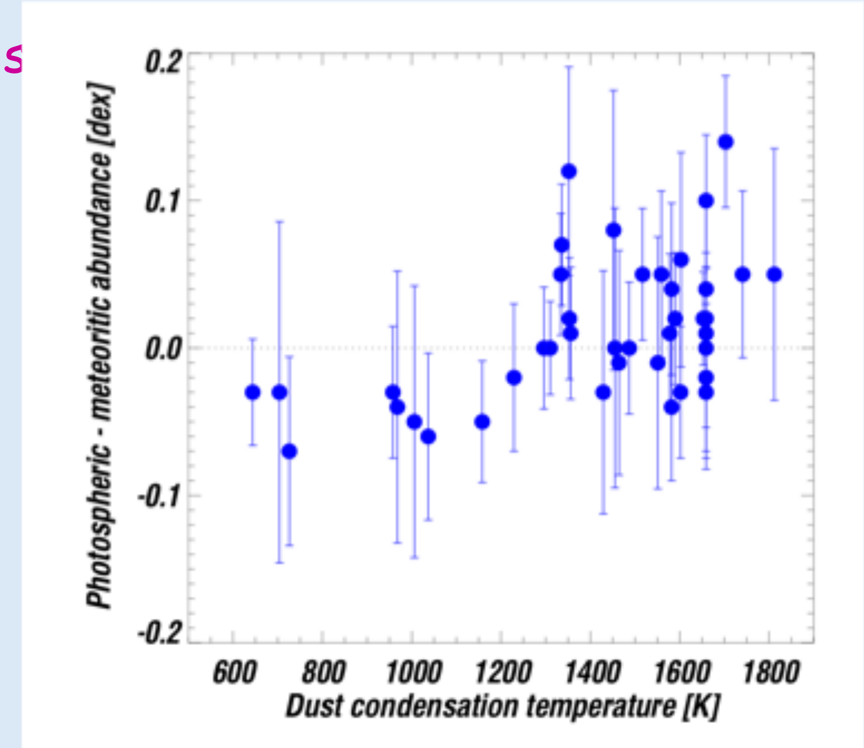

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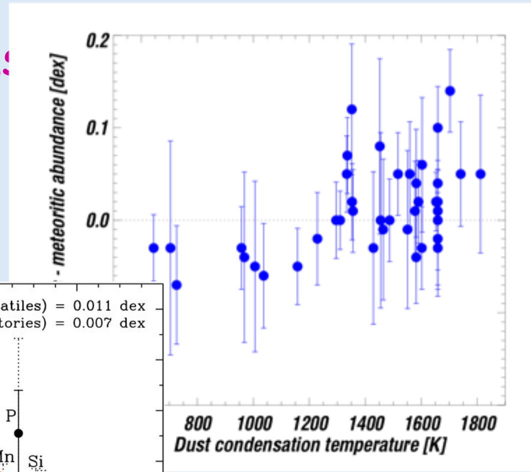
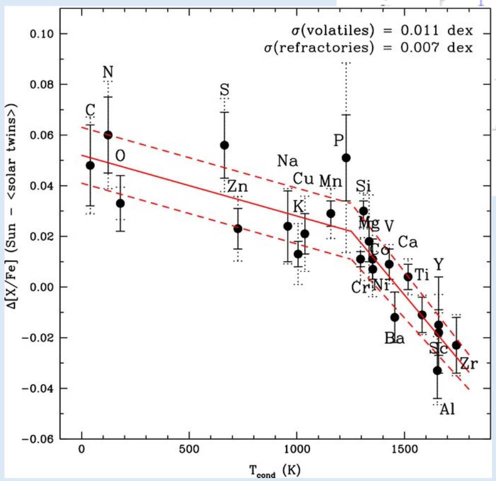
All would produce CN contrast between envelope and core





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Final Remarks

- Updated solar models with latest abundance revision
  - AGSS09 – solar abundance problem (helioseismology)
  - Solar Fusion II rates: changes in ^{8}B (-5%), ^{13}N-^{15}O(+6%)
  - ν uncertainties slightly larger (^{8}B)

- Solar neutrino data cannot separate models (yet); CN flux needed

- Solar neutrinos used to extract physical information about the Sun: example C+N core abundance, other S_{17}

- Solar core C+N abundance (direct from CN neutrino) & difference with surface value: accretion processes, diffusion rates, opacity changes

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