Standard Solar Model

NOW 2012

Aldo Serenelli – ICE (CSIC-IEEC)

Outline

- Solar abundances and impact on solar modeling: helioseismic and solar neutrino results

- Solar abundances from helioseismology & neutrinos?
  Degeneracy with opacity

- Breaking the degeneracy or "Why do we need CNO fluxes?"

- Solar νs and planet formation: a possible connection?

SOLAR ABUNDANCES

Solar "direct" abundances

Two paradigmatic sets

Element	GS98	AGSS09
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.53
Si	7.56	7.51
Ar	6.40	6.40
Fe	7.50	7.45
Z/X	0.0229	0.0178

$\log \varepsilon_X = \log (N_X/N_H) + 12$

GS98: Grevesse & Sauval (1998)
AGSS09: Asplund et al. (2009)

Differences

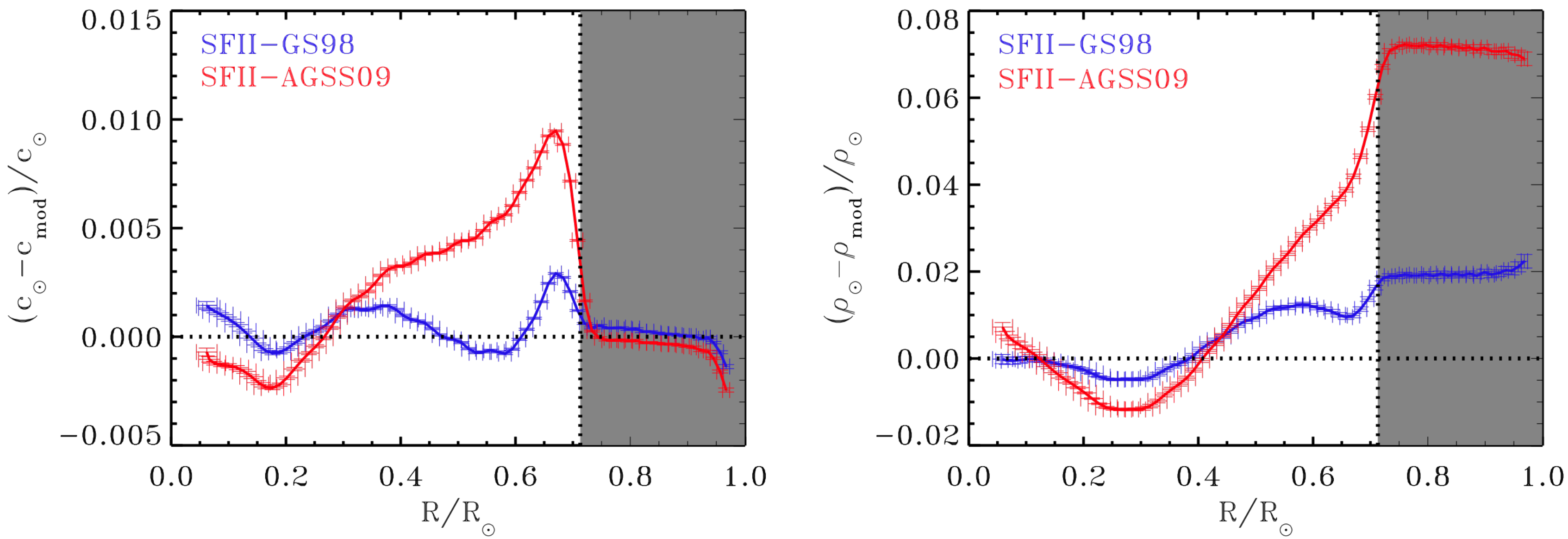
- New 3-D hydrodynamic models of solar atmosphere
- NLTE treatment of some elements
- Refined selection of lines (e.g. identification of blends)

Reduction of CNO(Ne) ~ 30-40%

Condition IMPOSED on solar models

Solar Abundances

Sound speed and density profiles



Solar abundance problem

	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001
Y_S	0.2429	0.2319	0.2485 ± 0.0034
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta\rho/\rho \rangle$	0.011	0.040	—

Solar Neutrinos

Solar neutrinos vs Solar abundances

Flux	SFII-GS98	SFII-AGSS09	Solar
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$\boxed{6.05(1 \pm 0.006)}$
pep	$1.44(1 \pm 0.011)$	$1.47(1 \pm 0.012)$	$\boxed{1.46(1 \pm 0.012)}$
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	$18(1 \pm 0.45)$
^{7}Be	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$\boxed{4.82(1 \pm 0.045)}$
^{8}B	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$\boxed{5.00(1 \pm 0.03)}$
^{13}N	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7
^{15}O	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2
^{17}F	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	≤ 59
$\chi^2/P^{\rm agr}$	3.5 / 90%	3.4 / 90%	—

Nuclear reaction rates from Solar Fusion II (Adelberger et al. 2011)

^{8}B @ 3% (SNO & SK) and now ^{7}Be @ 4.5% (Borexino)

pp and pep are strongly bound by the “luminosity constraint”

SOLAR NEUTRINOS

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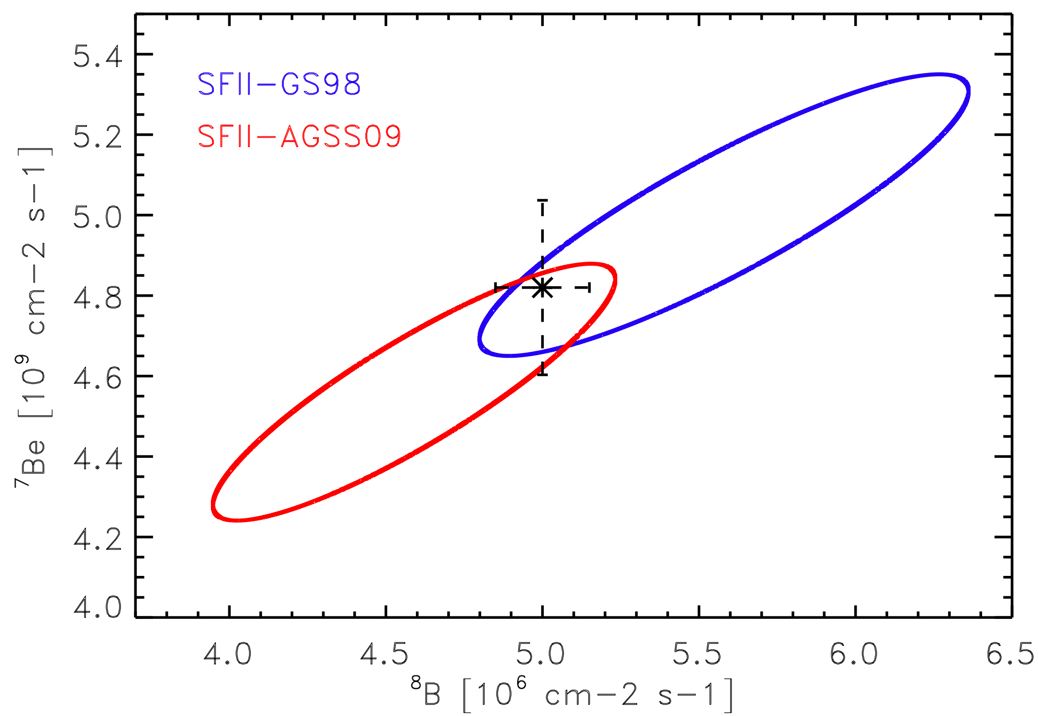


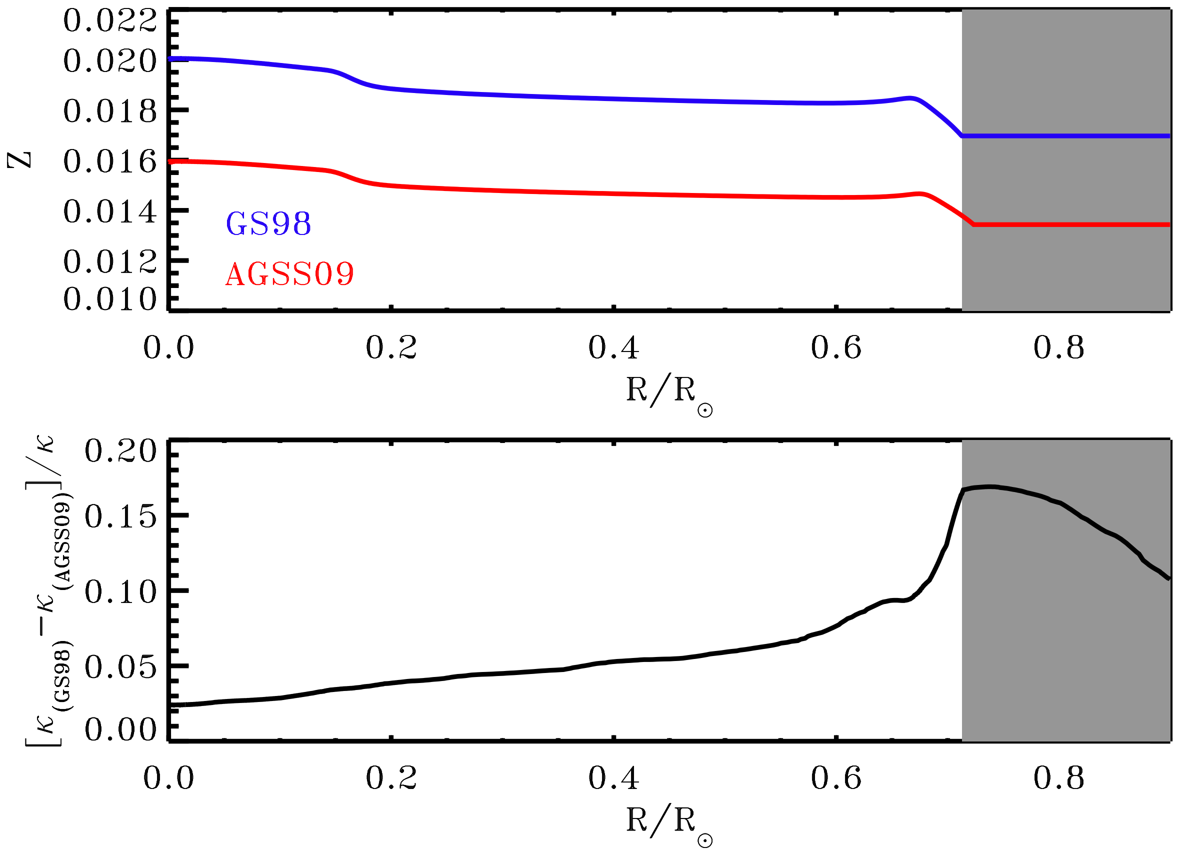
However... experimental results do not discriminate compositions

Composition vs Opacity

Opacity changes

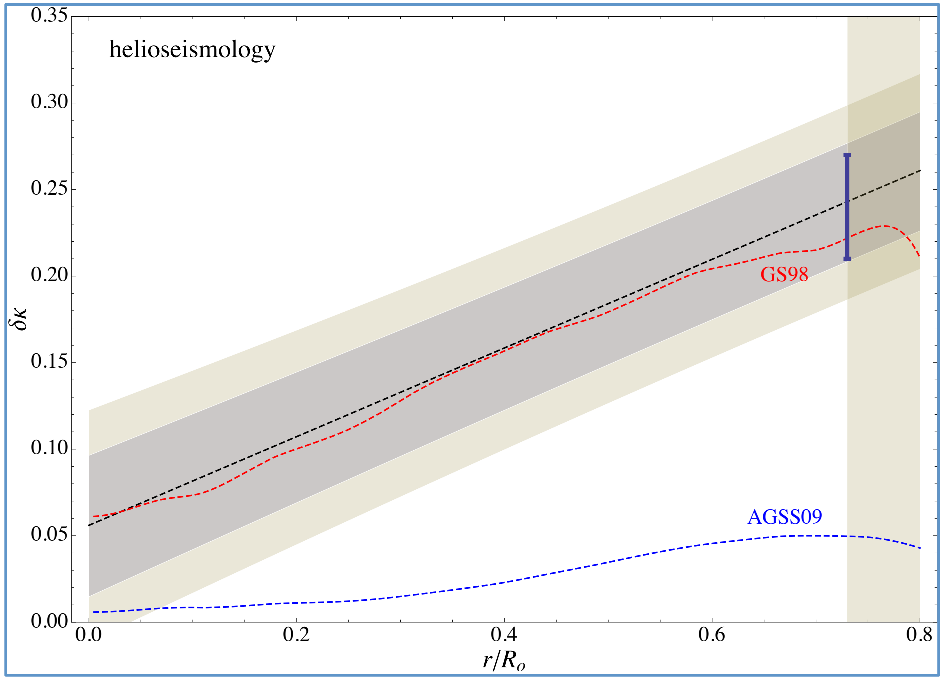
$$\left[\frac{dT^4}{dr}\right]_{\rm rad} \propto \kappa$$

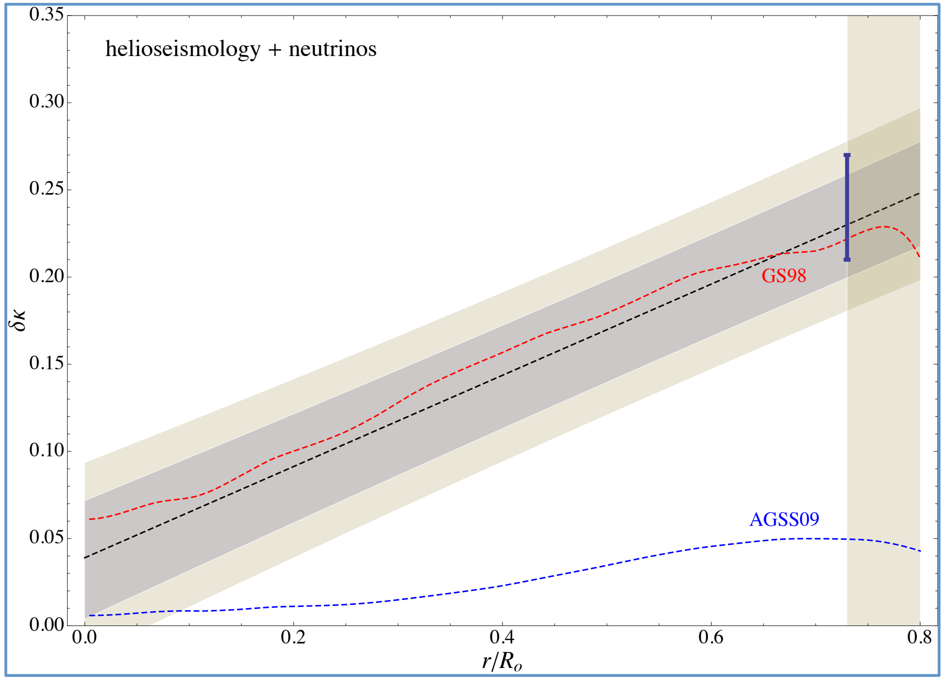
Modifies model structure - sensitivity of helioseismic observables



Composition vs Opacity

Constraints on opacity (composition) using available information



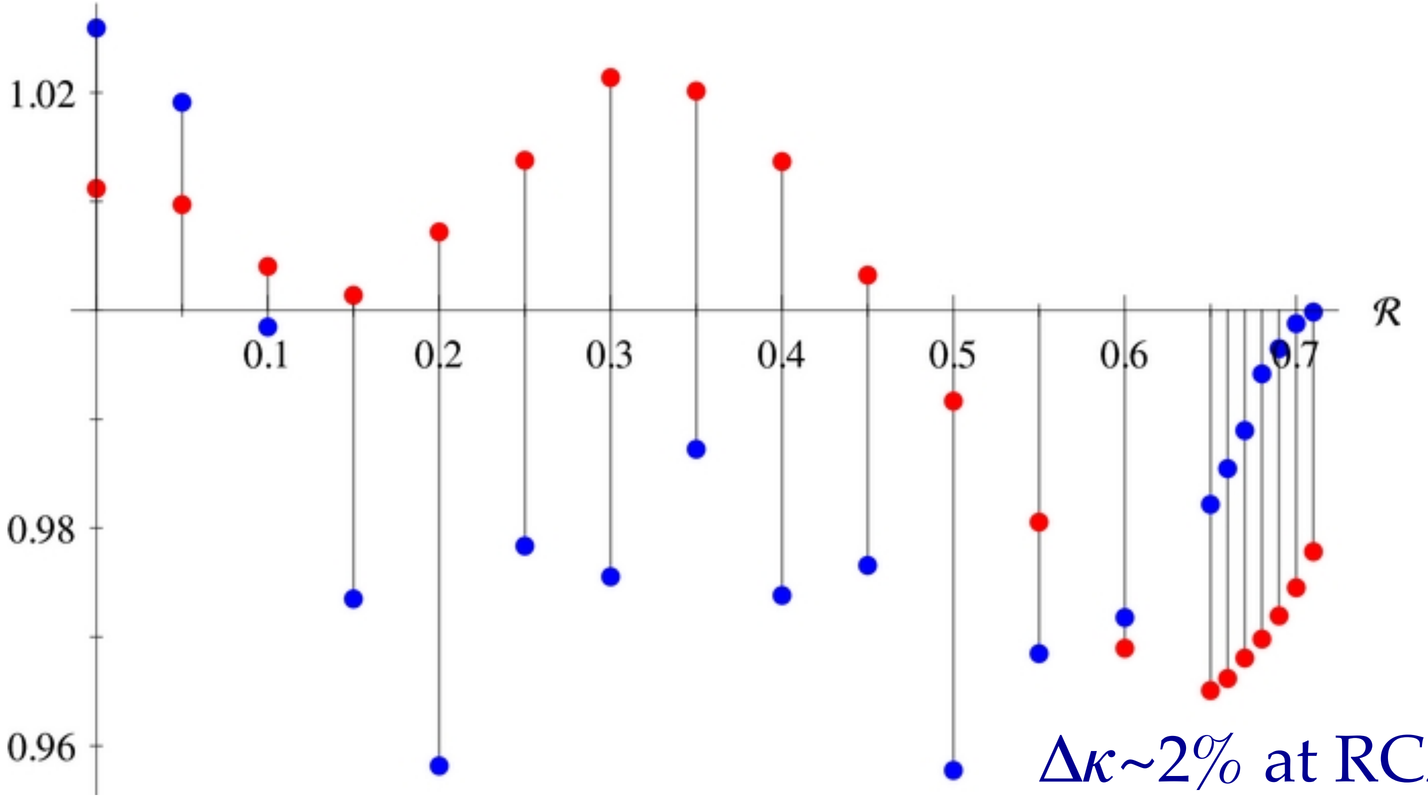


Villante 2010

Needed: $\Delta\kappa$~15-20% at RCZ
$\Delta\kappa$~4% at core

Opacity: State of the Art

OPAS vs OP (blue) - OPAL vs OP (red)



Blancard et al. 2012

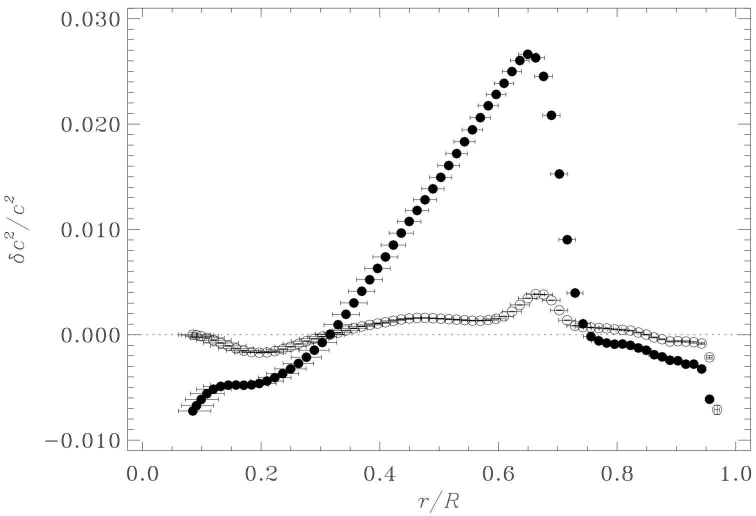
$\Delta\kappa$~2% at RCZ
$\Delta\kappa$<4% at any radii

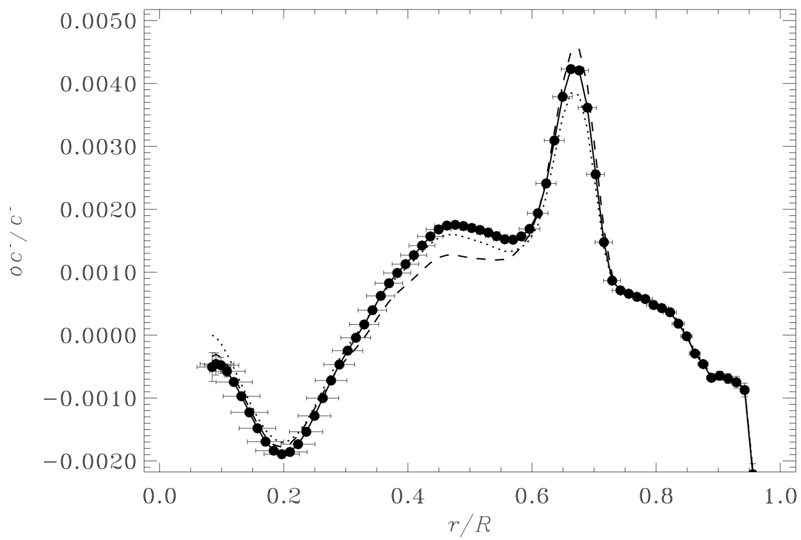
Composition vs Opacity

Seismic results are degenerate with stellar opacities

Low-Z model + increased κ

Christensen Dalsgaard et al 2009

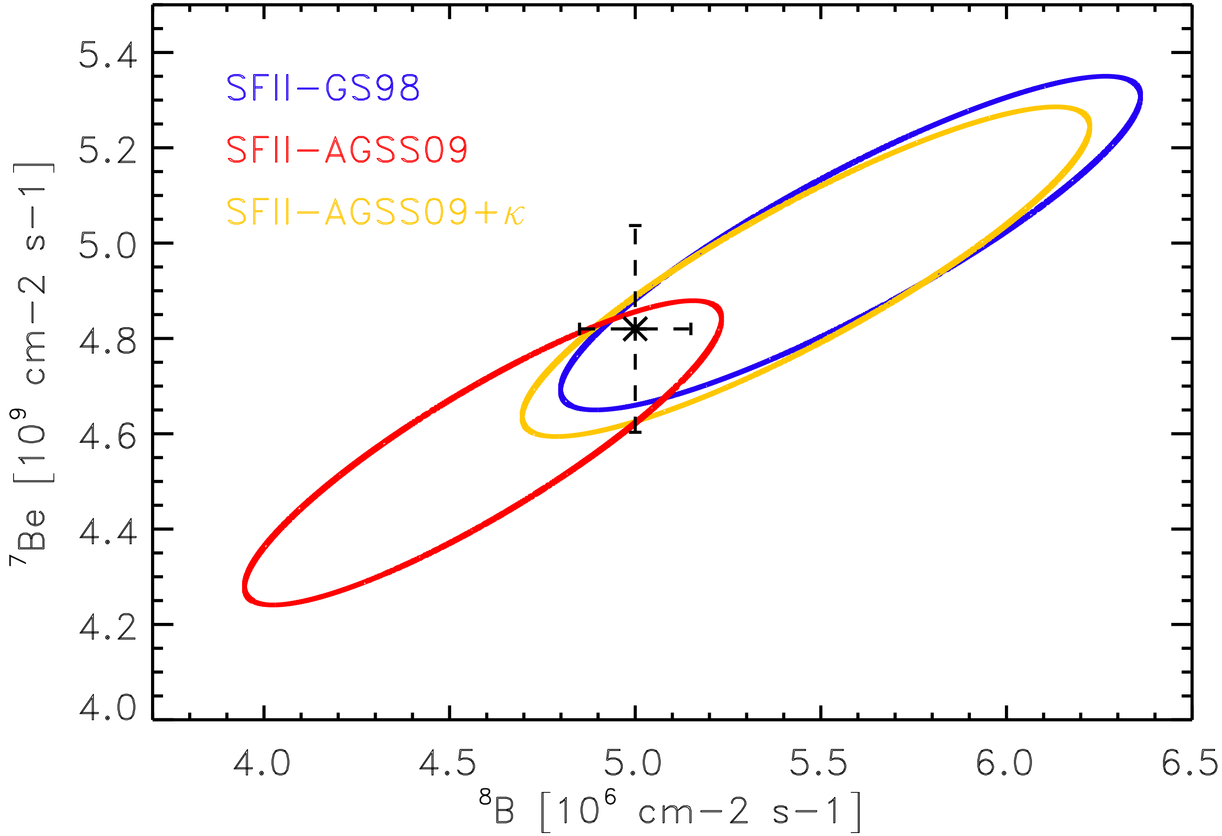




All helioseismic probes discussed before are recovered if opacity is increased
Intrinsic degeneracy between opacity and metal abundance

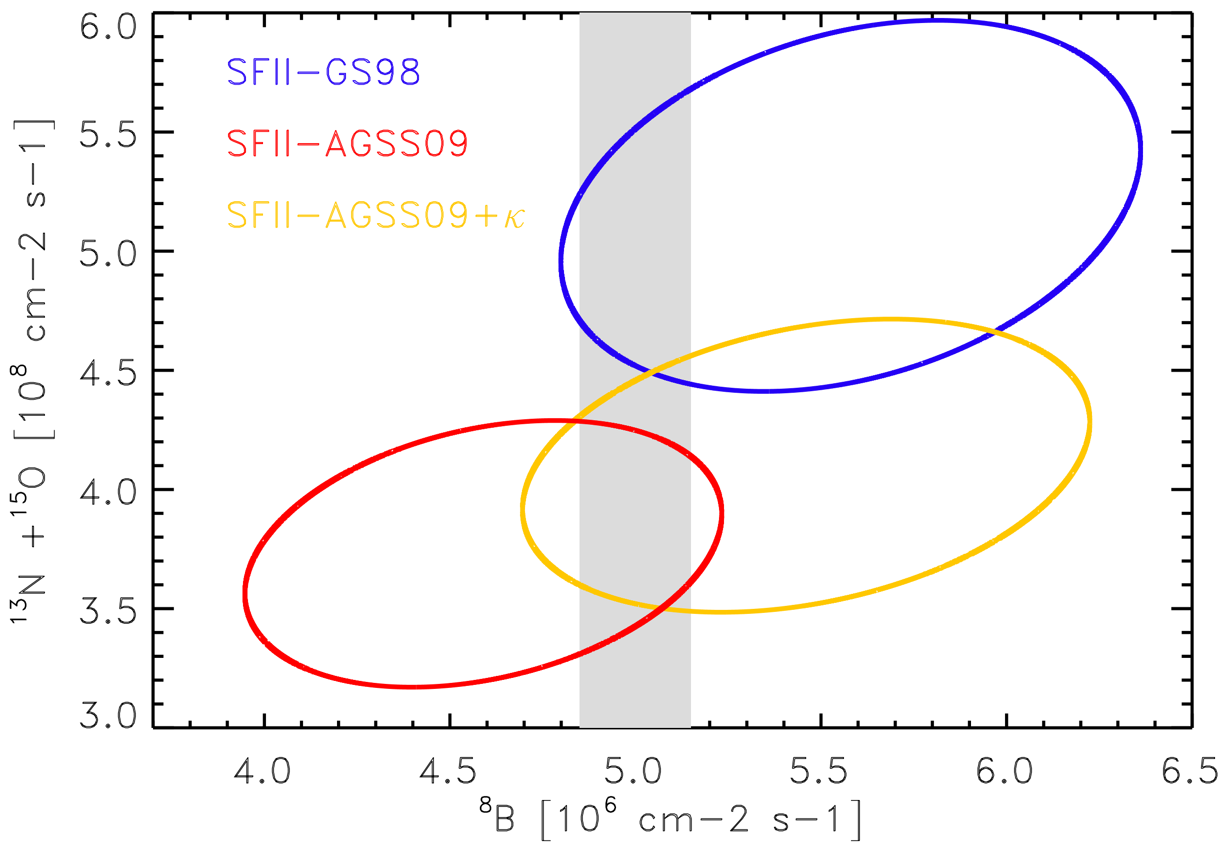
Composition vs Opacity

^{7}Be and ^{8}B fluxes also show degeneracy – composition only through T-dependence of fluxes



Breaking the Degeneracy: CN νs

CN fluxes carry extra linear dependence on C+N abundance



CN Abundance from Neutrinos

^{8}B precisely determined 3% - used as a thermometer

Combining expressions for ^{13}N and ^{15}O, including experimental sensitivity & neutrino oscillations (Haxton & Serenelli 2008)

$$\frac{\Phi^{\exp}(CN)}{\Phi^{\mathrm{SSM}}(CN)} = \left[\frac{\Phi^{\mathrm{SK}}(^{8}B)}{\Phi^{\mathrm{SSM}}(^{8}B)}\right]^{0.828} \left[\frac{X(C+N)}{X(C+N)_{\mathrm{SSM}}}\right]$$

$$\times\, [1 \pm 0.03(\mathrm{SK}) \pm 0.028(\mathrm{env}) \pm 0.03(\mathrm{LMA}) \pm 0.105(\mathrm{nucl})]$$

- SSM only used as a reference point (and exponents)
- Exponents 'robust' to variations in solar model inputs
- Uncertainty dominated by experimental (S_{17} & $S_{1\,14}$) contributions

"Perfect" CN measurement gives central C+N to about 12%

Using Borexino upper limit for $\Phi(^{13}\mathrm{N}+^{15}\mathrm{O})$: $X(C+N)_{\mathrm{Borexino}} < 0.076$

$X(C+N)_{\mathrm{GS98}} = 0.048$ -- $X(C+N)_{\mathrm{AGSS09}} = 0.039$

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Pre –LUNA (S_{114}) determination would have been X(C+N)<0.039!!!

With old S_{114} GS98 ruled out & AGSS09 marginally compatible !!!

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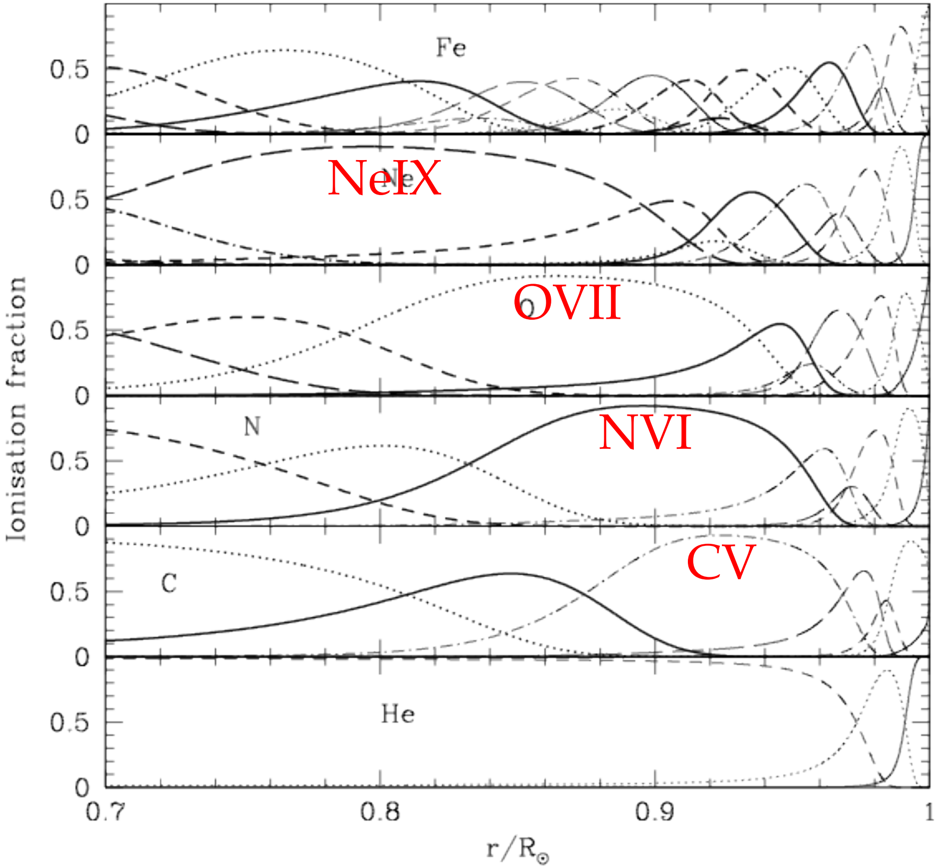
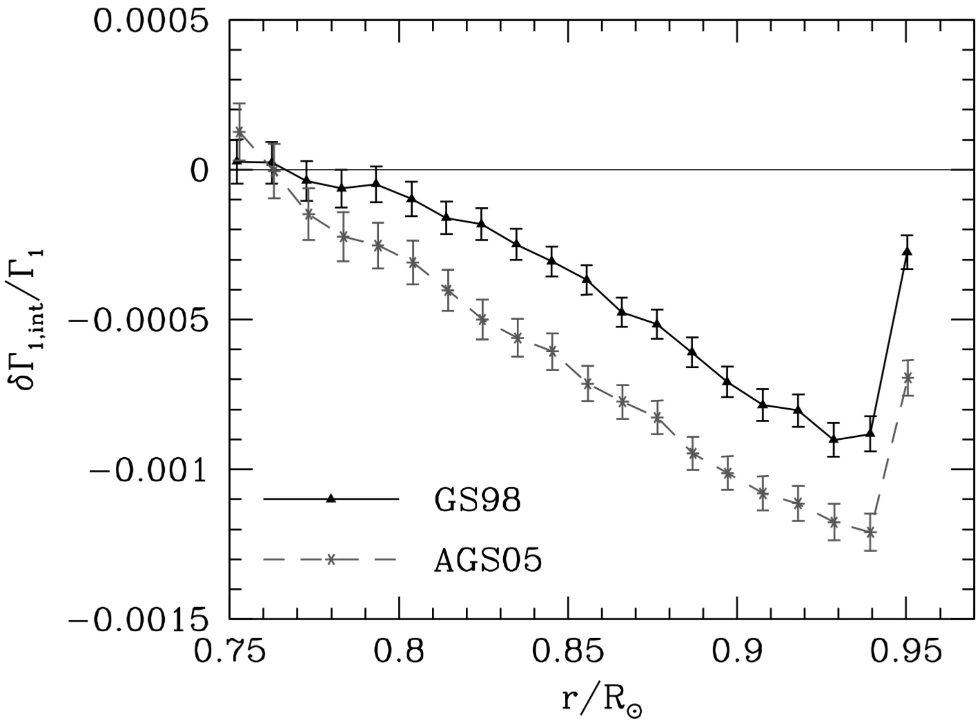
Beyond the Abundance Problem

If CNO determined from helioseismology

Partial ionization of metals at $R < 0.98R_{\odot}$





Basu & Antia 2008

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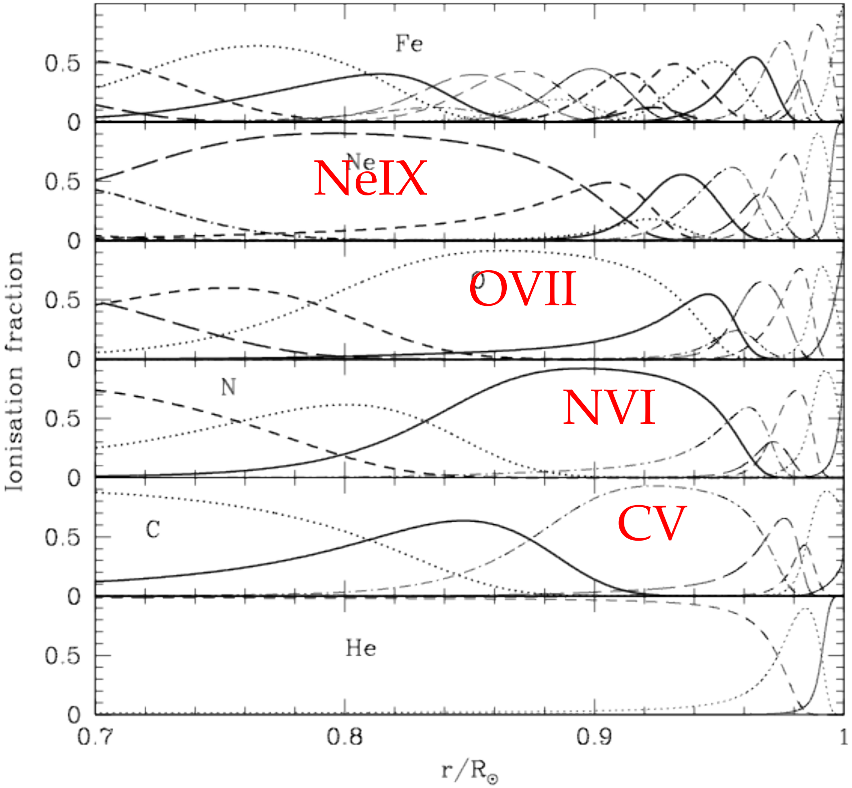
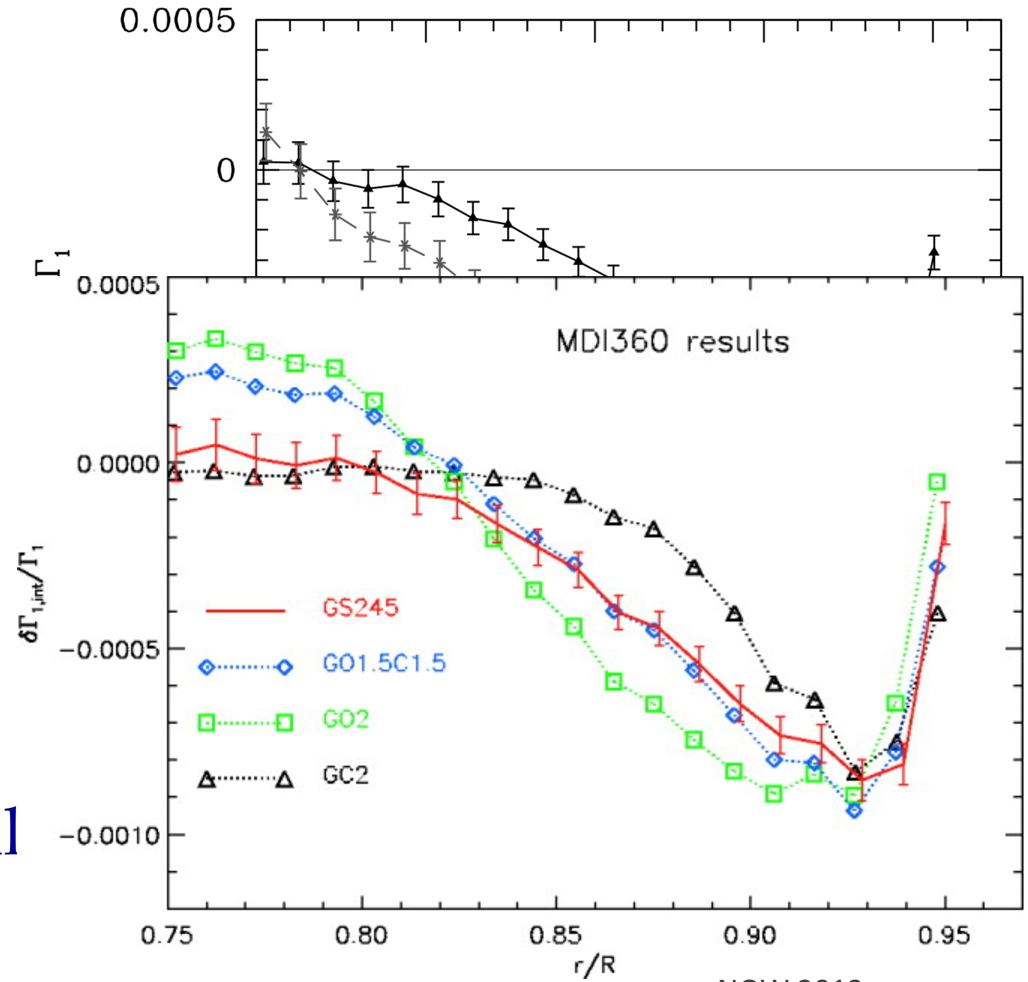




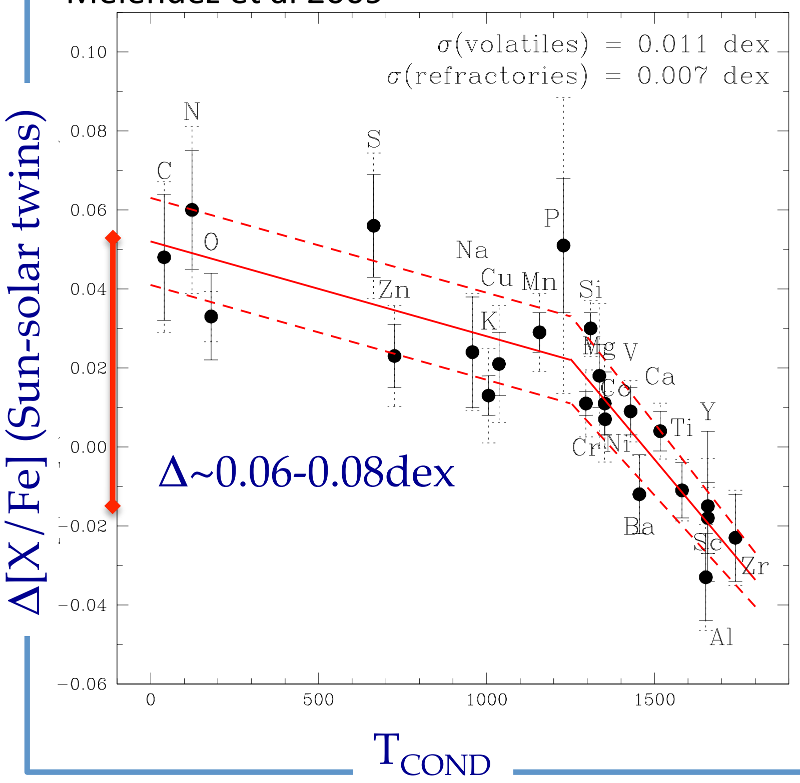
Some sensitivity on individual elements, e.g. C & O in CZ

Beyond the Abundance Problem

CN abundances from νs to check homogeneous young Sun
e.g. accretion during formation of planetary system

Signature of terrestrial planet formation?

Melendez et al 2009



Differential analysis of solar twins – no planets known

If interpretation true, contrast in CNO between solar surface and core ~15-20% - compensates diffusion effects :

central CNO ~equal to surface value

Summary

Status of solar abundance problem

Solar abundances impact solar structure through opacity: degeneracy affects helioseismic and current neutrino data

CN fluxes offer alternative

C+N abundance using ^{8}B flux as thermometer: first limits from Borexino

CN beyond solar abundance problem: unique probe of core composition. Homogeneous Sun? Application: planetary system formation

Beyond the Abundance Problem

Candidate for terrestrial planet search?

Melendez et al 2012