Solar Model & Neutrinos

PHYSUN 3rd – Gran Sasso

Aldo Serenelli – ICE (CSIC-IEEC)

Outline

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

- Solar abundances from neutrinos? Degeneracy with temperature & opacity

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

- Beyond the solar abundance problem. Testing mixing processes with solar νs: the homegeneous Sun and planets formation: a possible connection?

Solar Composition

Element	GS98	AGSS09	CO^5BOLD
C	8.52	8.43	8.50
N	7.92	7.83	7.86
O	8.83	8.69	8.76
Ne	8.08	7.93	(8.05)
Mg	7.58	7.53	(7.54)
Si	7.56	7.51	(7.52)
Ar	6.40	6.40	(6.50)
Fe	7.50	7.45	(7.46)
Z/X	0.0229	0.0178	0.0205

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%

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CO^5BOLD closer to older abds.

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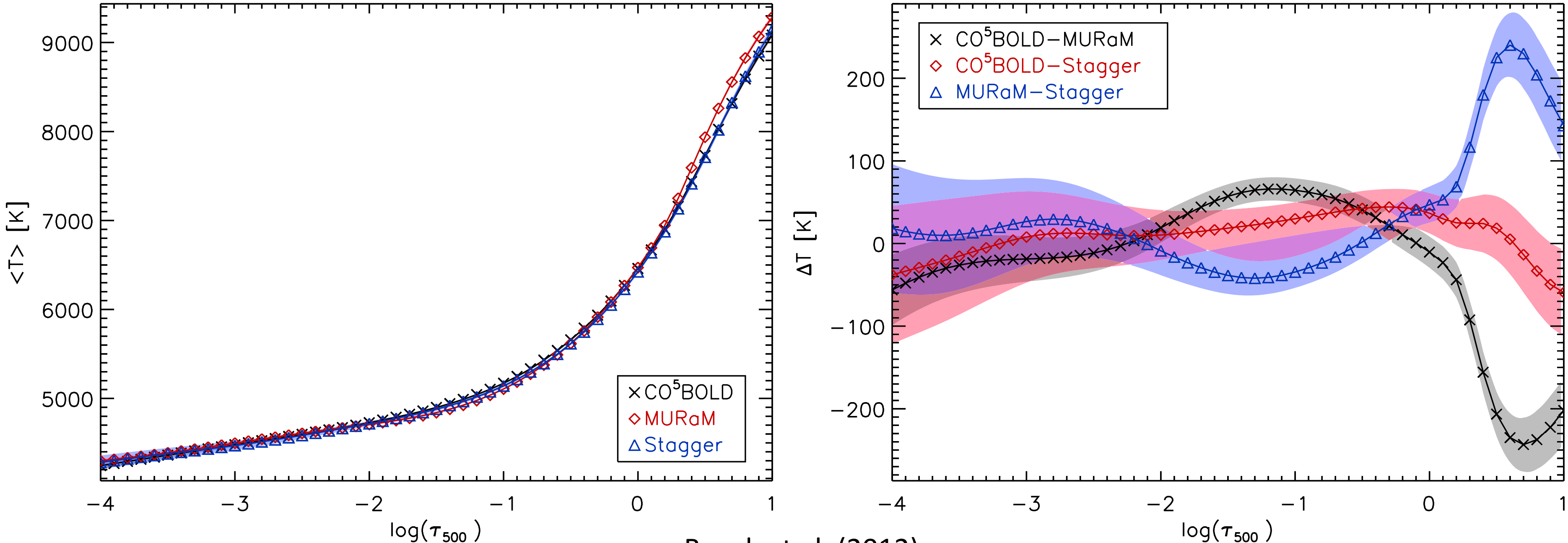
Solar Atmosphere Models

Structure of solar atmosphere consistent from different calculations



Beeck et al. (2012)

Differences in radiative transfer (line formation)? Selection of lines?

Talks later today by Grevesse & Caffau

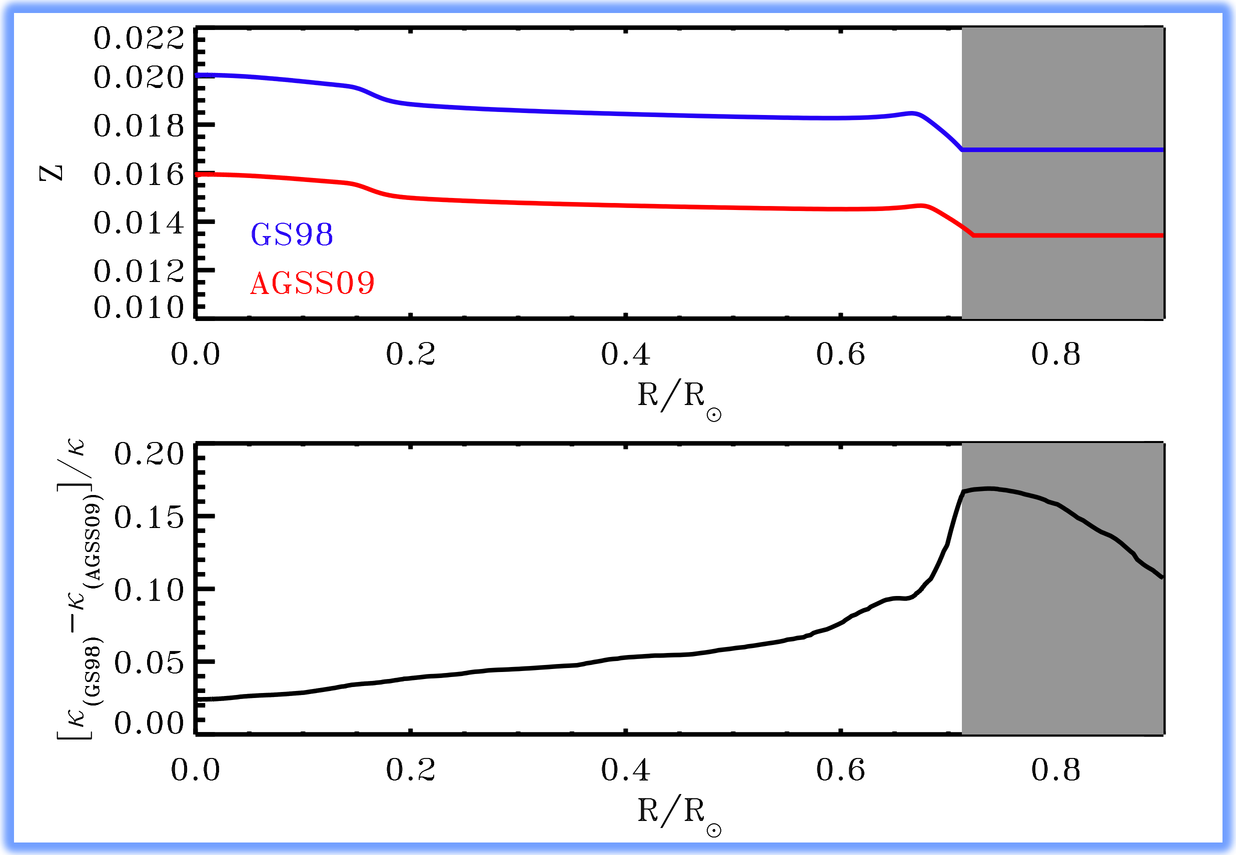
Composition vs Opacity

Opacity changes

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

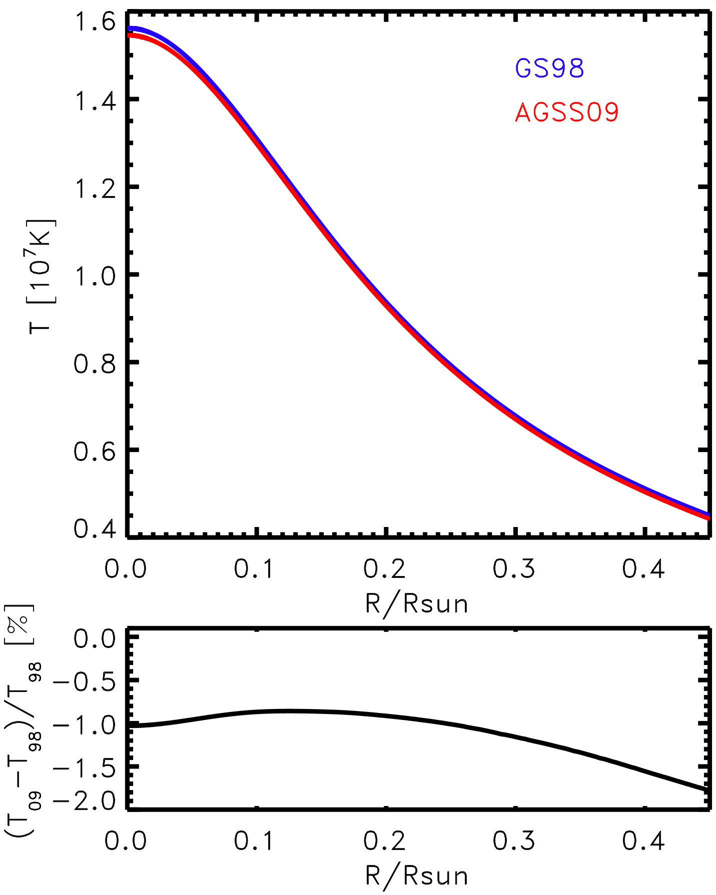
Modifies model structure – mostly temperature stratification

Helioseismic probes strongly affected (talk by MP)



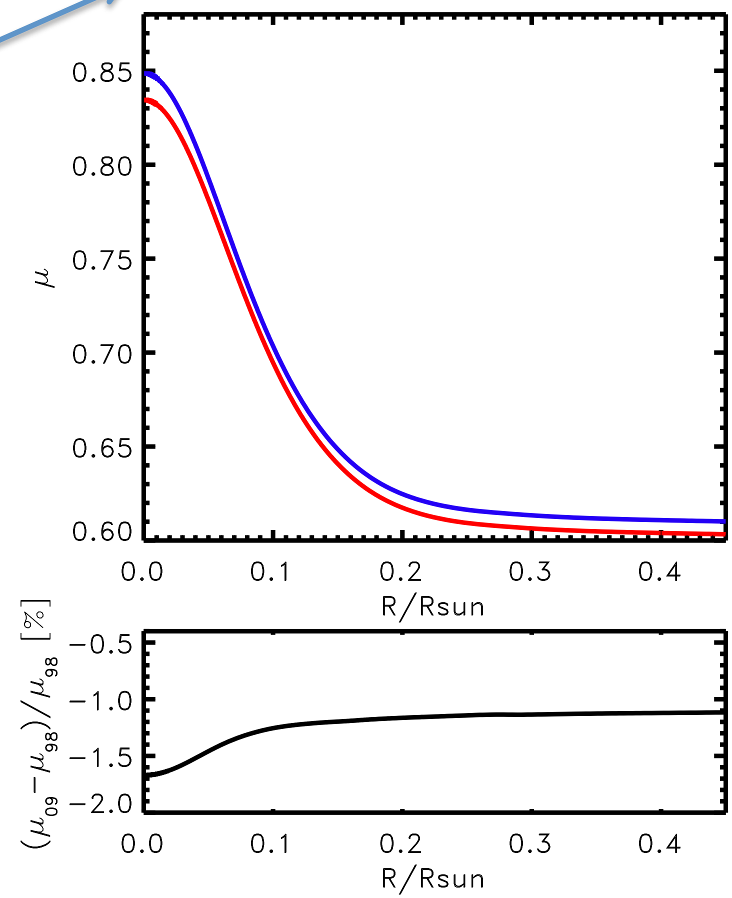
Solar Fluxes

Lower T in solar core



more H to sustain $L_\odot$

Lower μ in solar core



$c^2 \propto T/\mu$ Solar abundance problem

Solar Fluxes

Flux	GS98	AGSS09	CO^{5}BOLD	Solar
pp	$5.98(1 \pm 0.006)$	6.03	6.01	$6.05(1 \pm 0.006)$
pep	$1.44(1 \pm 0.011)$	1.47	1.46	$1.46(1 \pm 0.012)$
hep	$8.04(1 \pm 0.30)$	8.31	8.19	$18(1 \pm 0.45)$
^{7}Be	$5.00(1 \pm 0.07)$	4.56	4.74	$4.82(1 \pm 0.045)$
^{8}B	$5.58(1 \pm 0.14)$	4.59	4.98	$5.00(1 \pm 0.03)$
^{13}N	$2.96(1 \pm 0.14)$	2.17	2.62	≤ 6.7
^{15}O	$2.23(1 \pm 0.15)$	1.56	1.92	≤ 3.2
^{17}F	$5.52(1 \pm 0.17)$	3.40	4.27	≤ 59
χ^2/P^{agr}	3.5 / 90%	3.4 / 90%	3.2 / 92%	—

Serenelli et al. (2011)

Fluxes using available data in April 2011, incl. 740 days of Borexino

For the 1st time ALL fluxes from pp-chains very well constrained experimentally (~~hep~~)

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

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

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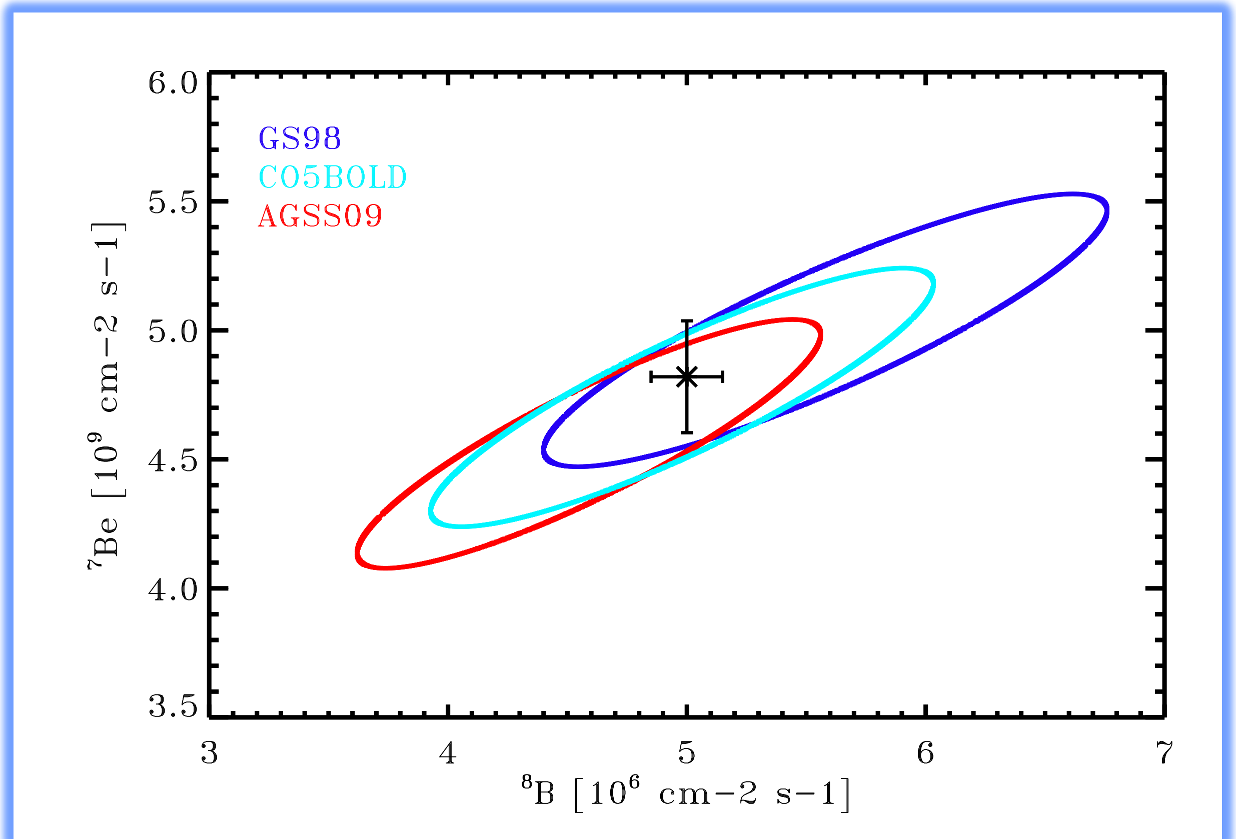
^{7}Be & ^{8}B change 10% and 20% due to composition

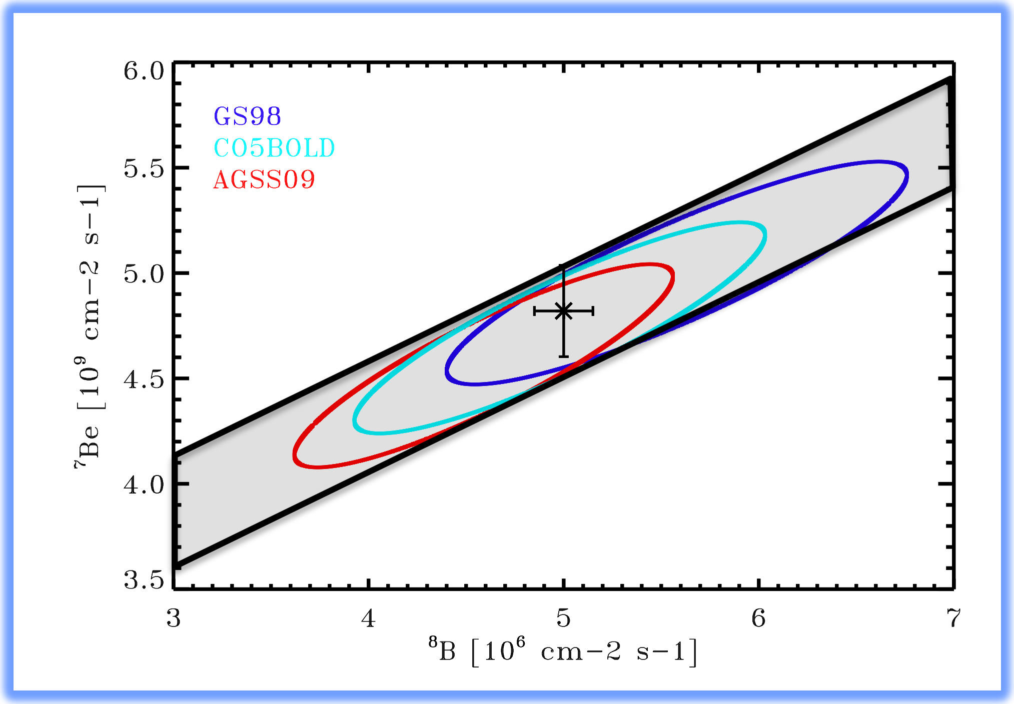
Overall agreement with experimental data very good

Solar Fluxes



Experimental results for pp-chain fluxes do not discriminate compositions… Could they ever?

Solar Fluxes



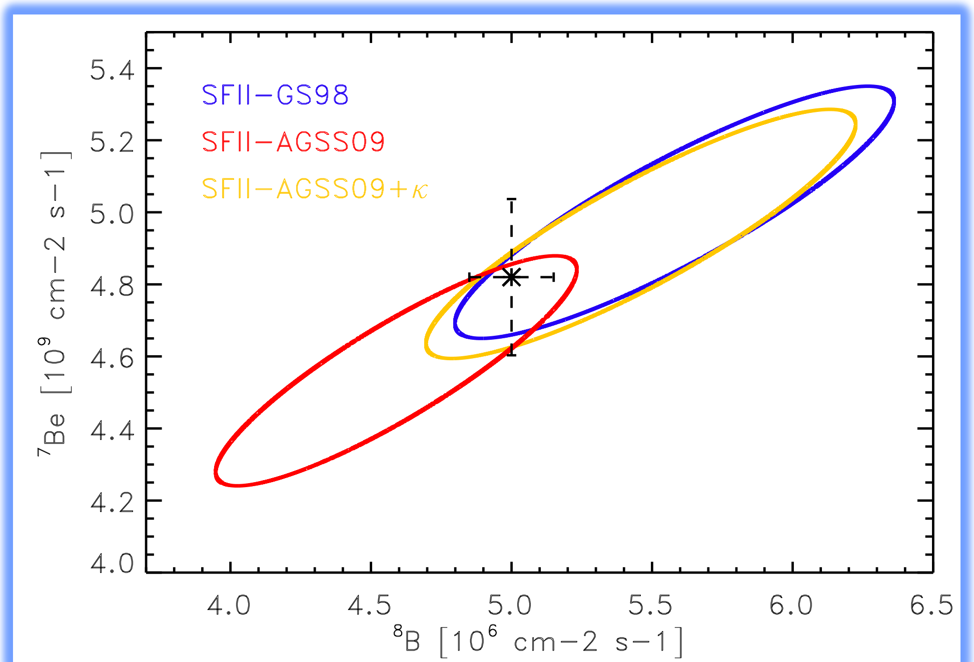
^{7}Be & ^{8}B fluxes shift along the band as a function of temperature

Present-day SSM "band" runs across experimental results → good check for S_{17}, S_{34} and S_{33}

"Fixing" the solar abundance problem implies getting T/μ profile right

No matter how you do it has to mimick results from GS98 model

Solar Fluxes

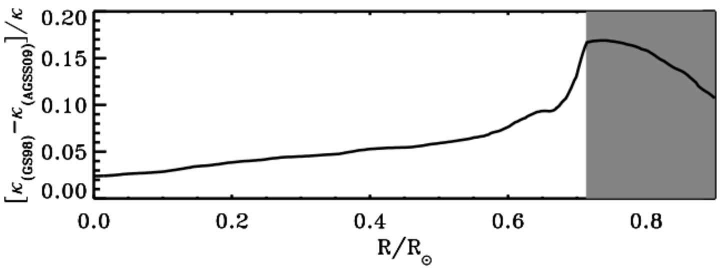


In terms of solar composition, 7Be and 8B fluxes are degenerate with core temperature

Difficult to extract information on abundances –

Example: degenerary between opacity and composition

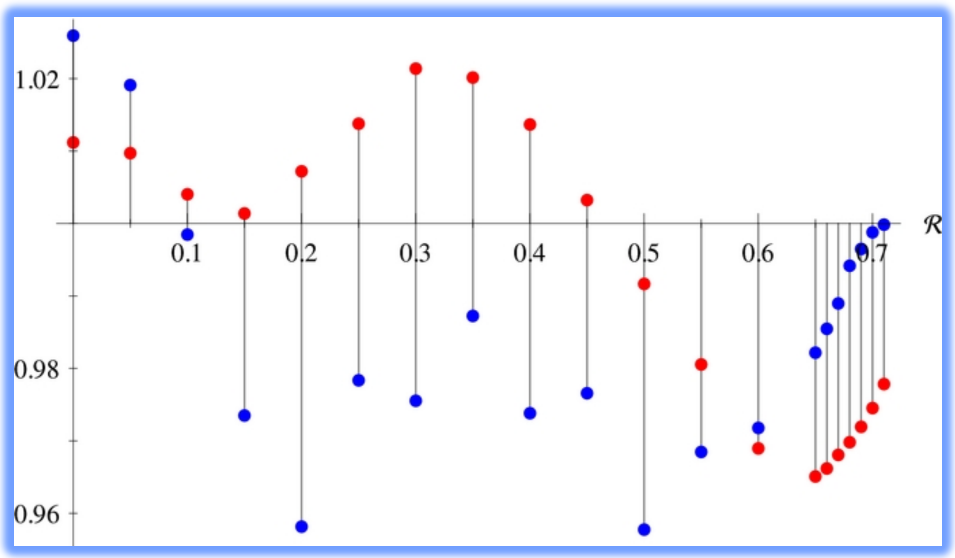
Opacities from Theory Calc.



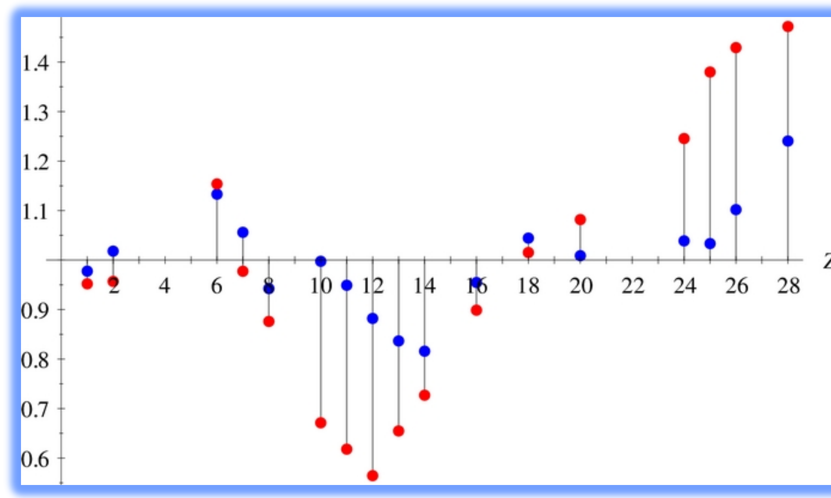
"Loss" of opacity ~15% at base of CZ

3-4% center

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



Rosseland mean in solar interior – smallish differences < 4%

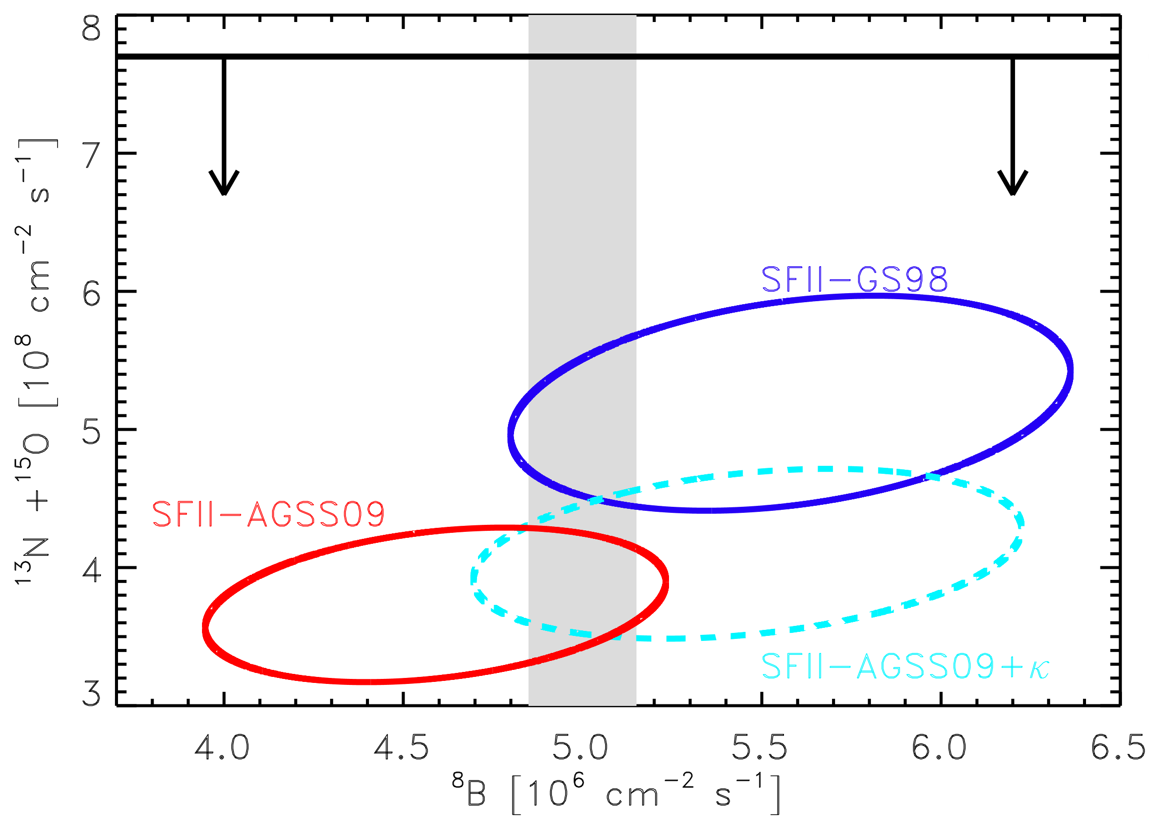


Element contribution at base of CZ much larger differences

Blancard et al. (2012)

Breaking the Degeneracy: CN νs

CN fluxes carry extra linear dependence on C+N abundance not associated with temperature



New limit from Borexino

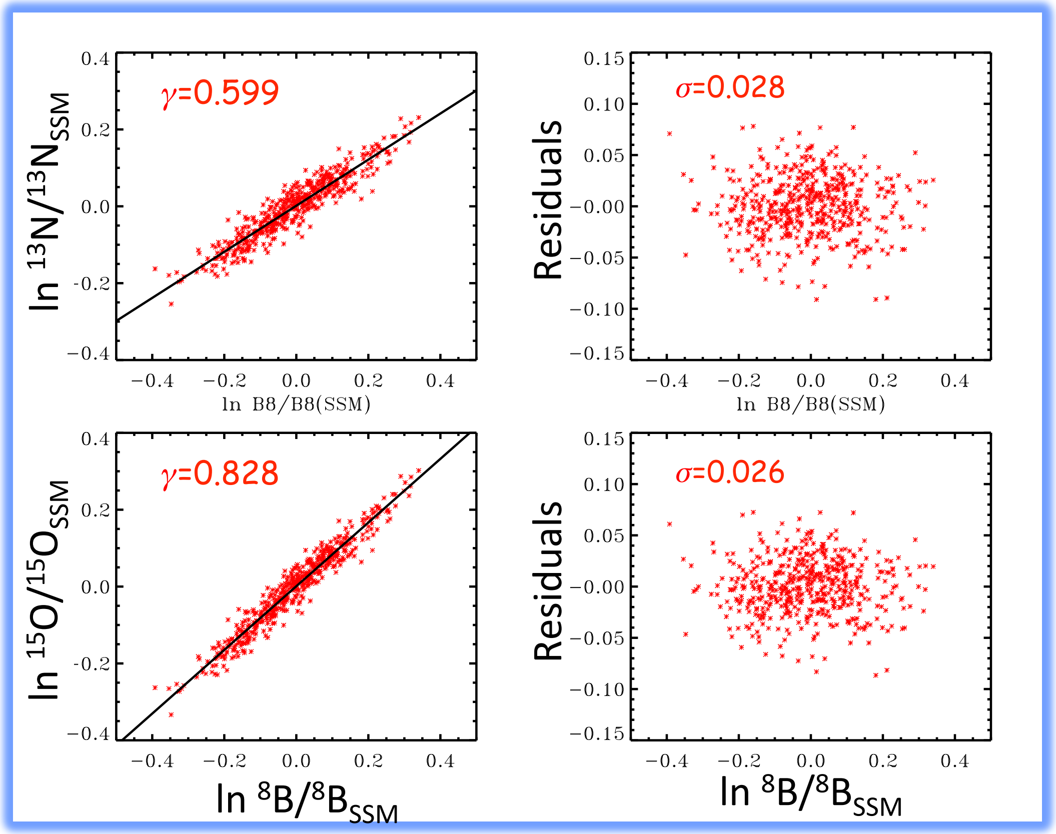
Composition from ν-fluxes

Correlations between ^{8}B and CN-cycle fluxes (only environmental)

Small dispersion <3%

Remaining contributions:

- nuclear
- C&N abundances



Haxton & Serenelli (2008)

$$\frac{\Phi(^{15}O)}{\Phi^{\rm SSM}(^{15}O)} = \left[\frac{\Phi(^{8}B)}{\Phi^{\rm SSM}(^{8}B)}\right]^{0.828} [1 \pm 2.8\%({\rm env}) \pm 10.5\%({\rm nucl})]$$

$$\times \left[\frac{X(C)}{X(C)_{\rm SSM}}\right]^{0.805} \left[\frac{X(N)}{X(N)_{\rm SSM}}\right]^{0.199}$$

CN Abundance from Neutrinos

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

Combining expressions for ^{13}N and ^{15}O, including experimental sensitivity & neutrino oscillations

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

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

- 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 $\Phi(^{13}N+^{15}O)$: $X(C+N)_{\rm Borexino} < 0.0076$

$X(C+N)_{\rm GS98} = 0.0048$ -- $X(C+N)_{\rm AGSS09} = 0.0039$

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Pre –LUNA (S_{114}) determination would have been X(C+N)<0.0039

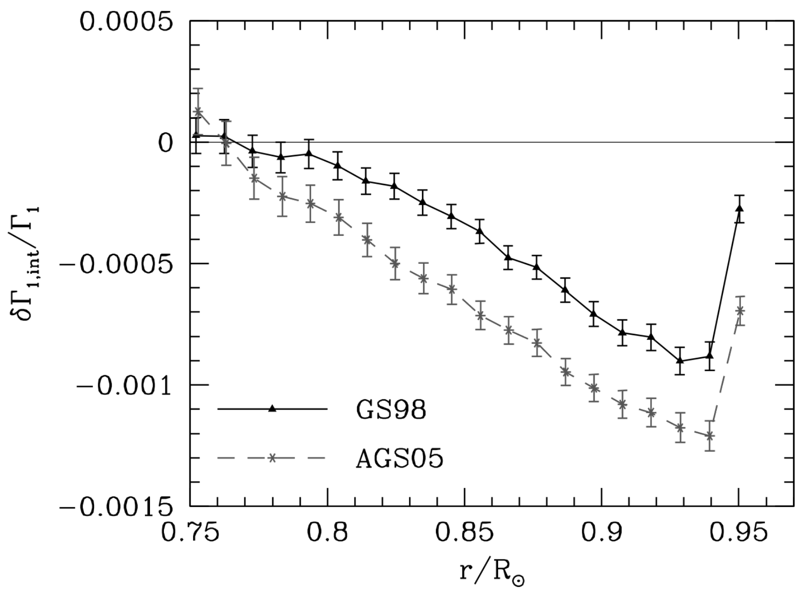
With old S_{114} GS98 ruled out & AGSS09 marginally compatible

Using Borexino upper limit for $\Phi(^{13}N+^{15}O)$: $X(C+N)_{\rm Borexino} < 0.0076$

$X(C+N)_{\rm GS98} = 0.0048$ -- $X(C+N)_{\rm AGSS09} = 0.0039$

Beyond the Abundance Problem

Assume CN(O) abundances are finally, somehow, well determined in solar outer layers – e.g. photospheric results from different groups robust, helioseismic determination of metals from partial ionization signal in Γ_1



Basu & Antia 2008

Then CN abundance from neutrinos will directly tell us by how much core composition has changed on the course of solar evolution.

No need to even get solar structure exactly right if combined with ^{8}B and ^{7}Be measurements

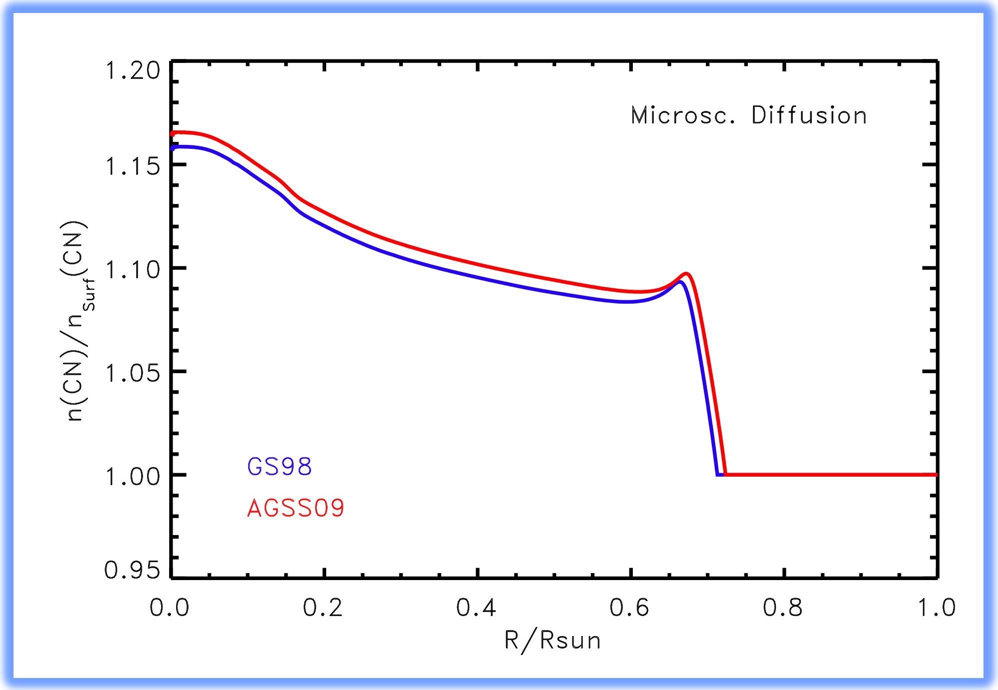
Beyond the Abundance Problem

Some possibilities leading to a composition gradient in the Sun

Gravitational settling –

~15% in SSM
down to ~10% with turbulent mixing

relatively well constrained from helioseismology (indirectly) but can be accounted for up to 5% in n(CN)

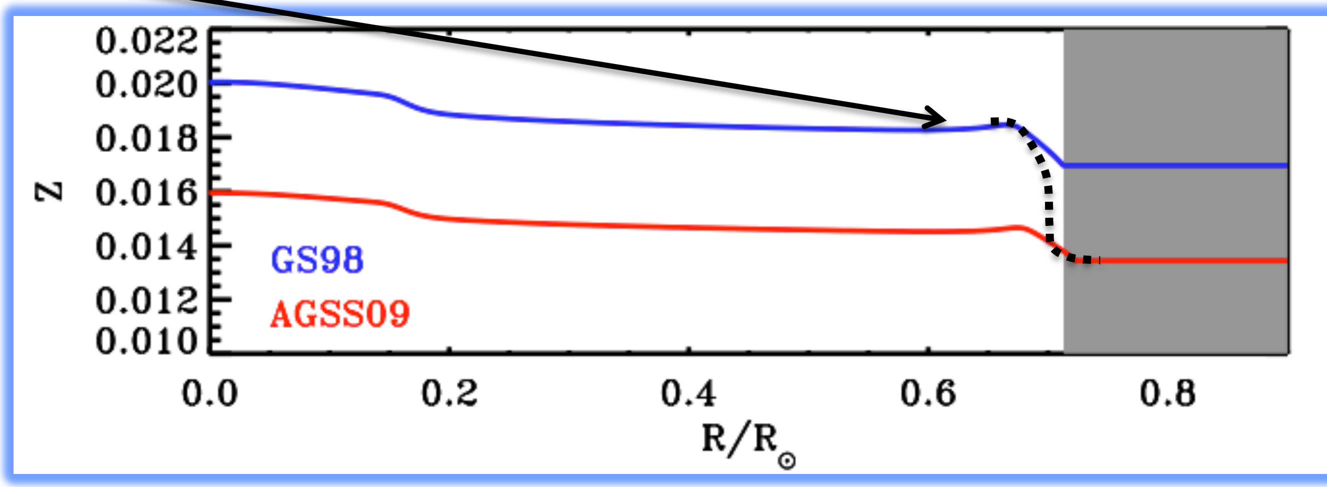


Beyond the Abundance Problem

Was the Sun initially homogeneous?

Can a switch to high metallicity in the interior solve the solar abundance problem?

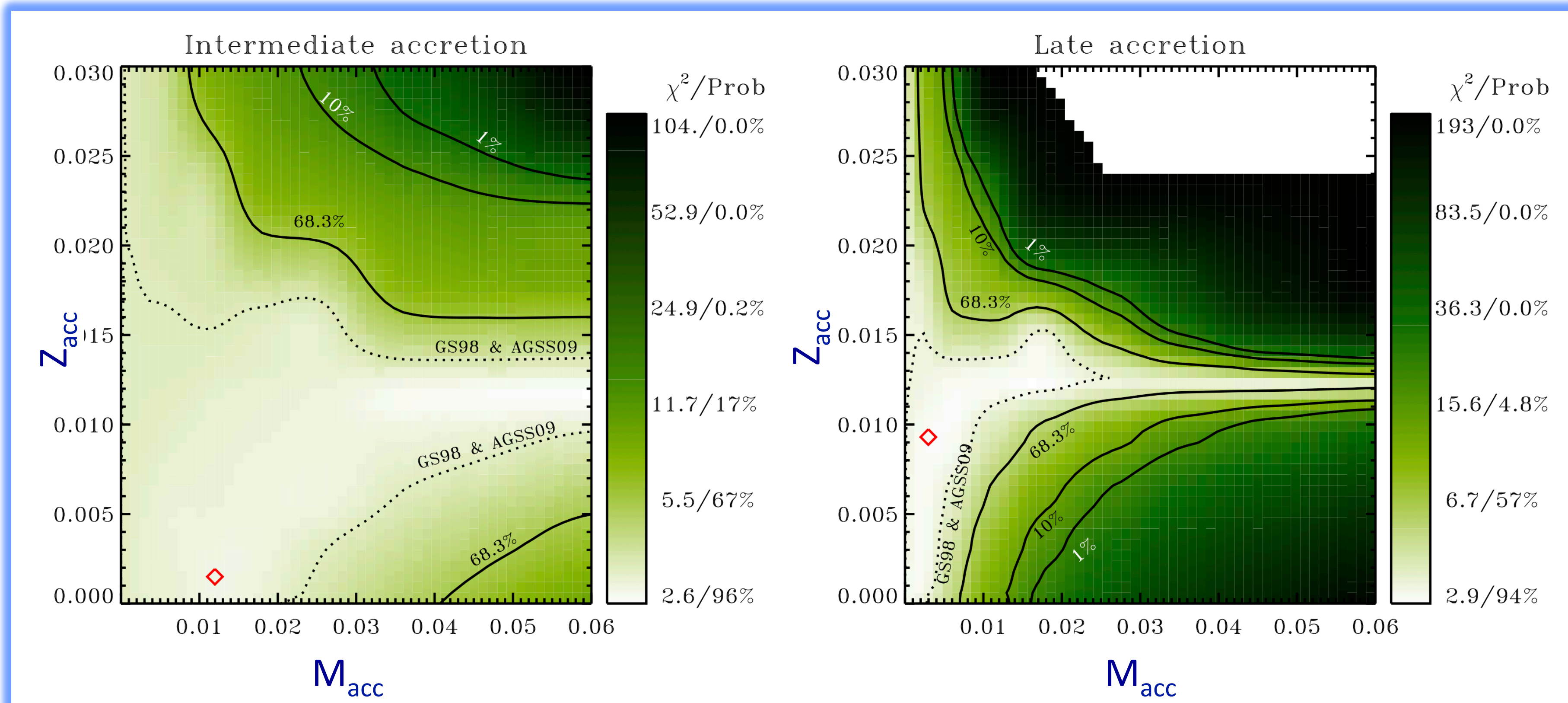
Contrast in CN abd. up to ~50% between surface and core



Beyond the Abundance Problem

Some tests of different accretion scenarios

Models with AGSS09 surface composition after accretion



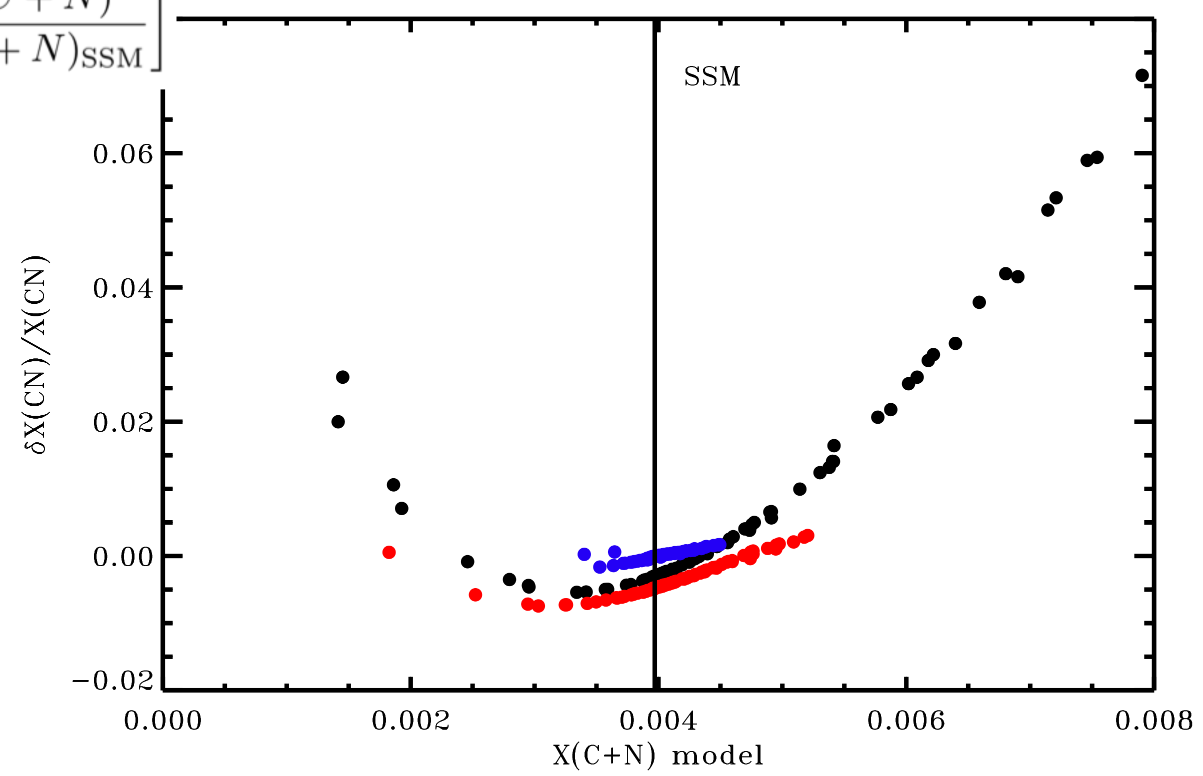
Beyond the Abundance Problem

Can the core CN abundance be recovered from ν fluxes alone even for non-SSM with accretion?

Yes, using

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

generally better than 4%

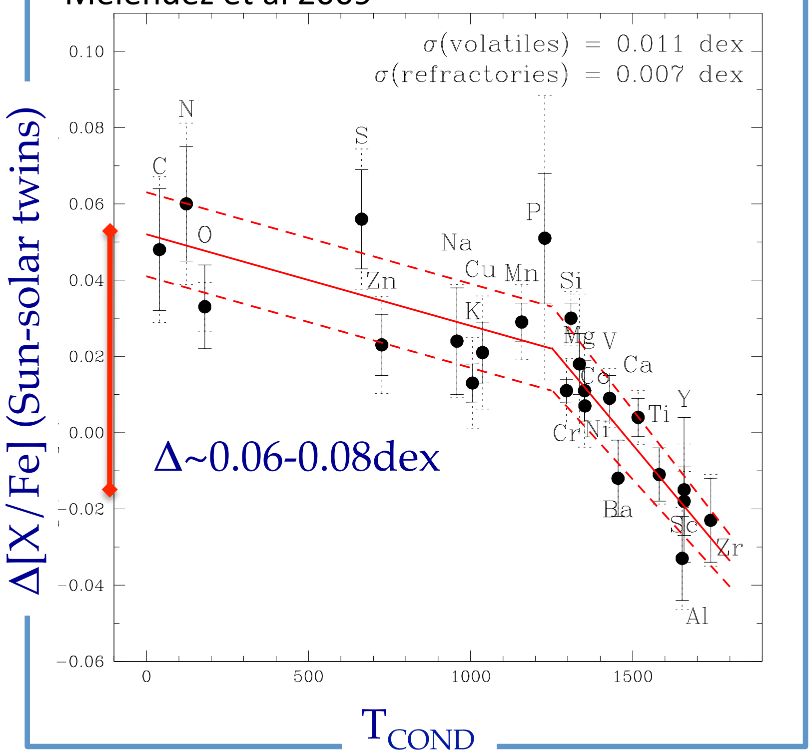


Beyond the Abundance Problem

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, CN in the core
initially 15-20% lower than surface!!

Comparable to microscopic diffusion
so present-day so
central CN ~equal to surface value

Summary

Solar abundances impact solar structure through opacity: degeneracy between temperature and composition changes affects interpretation of current neutrino data

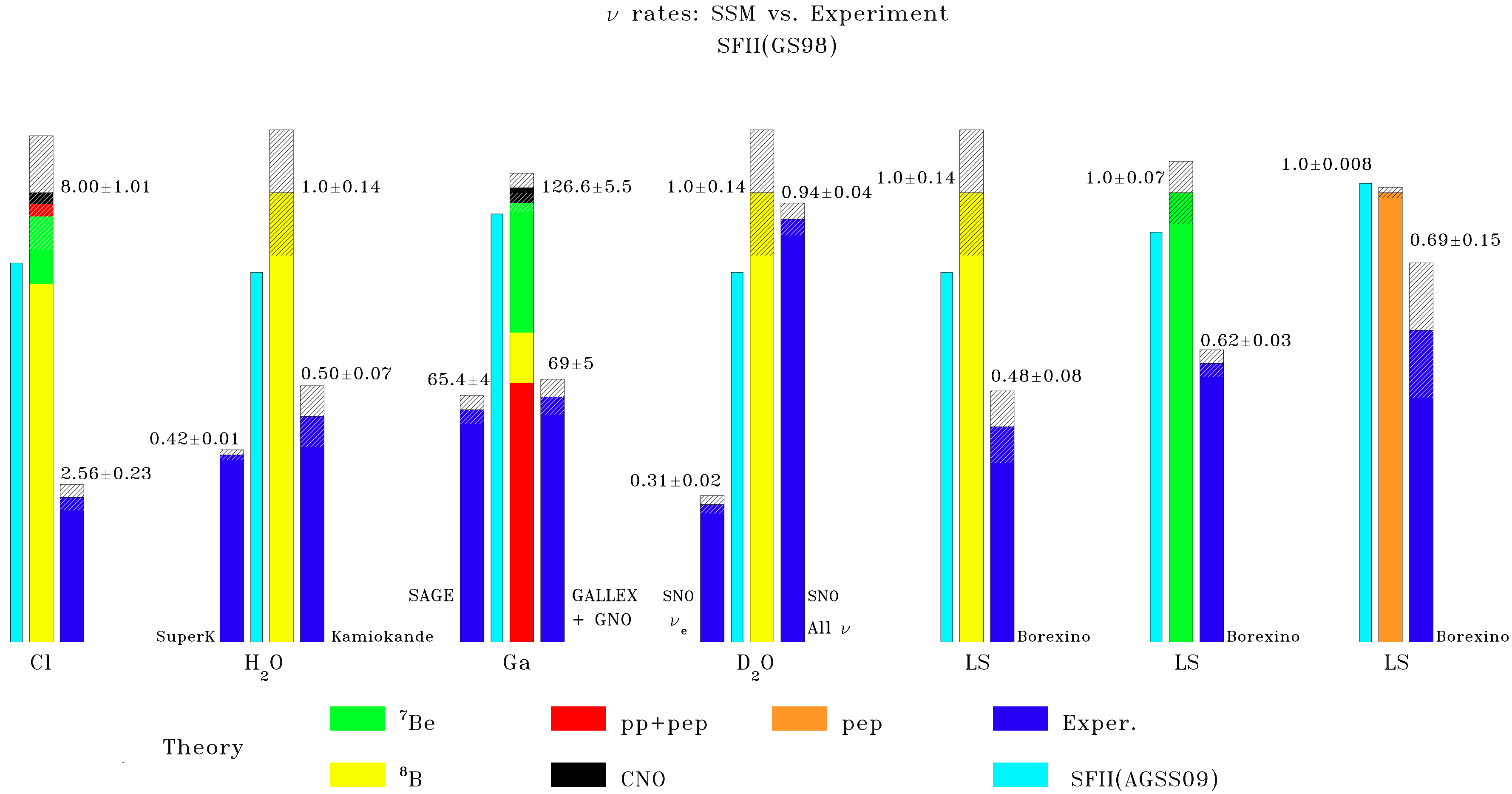
CN fluxes offer alternative

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

Not touched upon: non-SSM (Turck-Chièze) – Sun & DM (Taoso)

SOLAR νS: MODEL VS EXPERIMENTS



Experimental talks in tomorrow's session