Status of Standard Solar Models

Aldo Serenelli (ICE/CSIC-IEEC)

Borexino Mini-Workshop

September 5, 2014, Gran Sasso

Observational Constraints to Build Models

At solar age (4.57Gyr)

SSM

- Solar (photon) luminosity (initial helium)
- Solar radius (convection parameter – mixing length)
- Relative metal to hydrogen surface abundance (initial metal abundances)

non-SSM

- surface rotation rate (initial angular momentum)

Theory vs Data

SSM

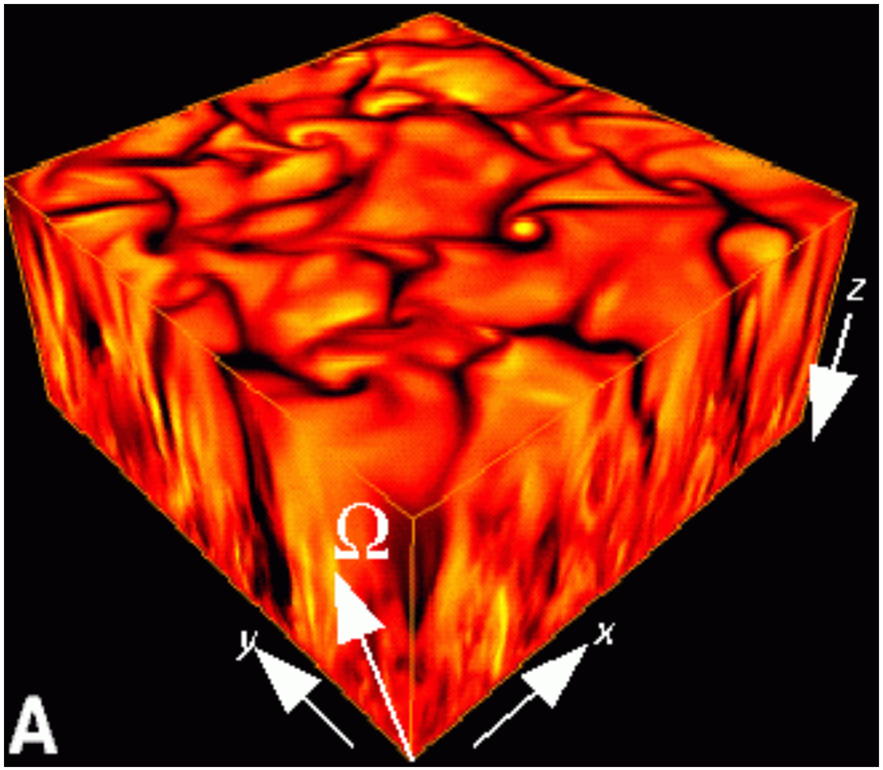
- Depth of convective envelope
- Sound speed & density profiles
- Neutrino fluxes
- Frequency ratios (info on solar core)
- Surface helium abundance
- Surface metal abundance(s)

non-SSM

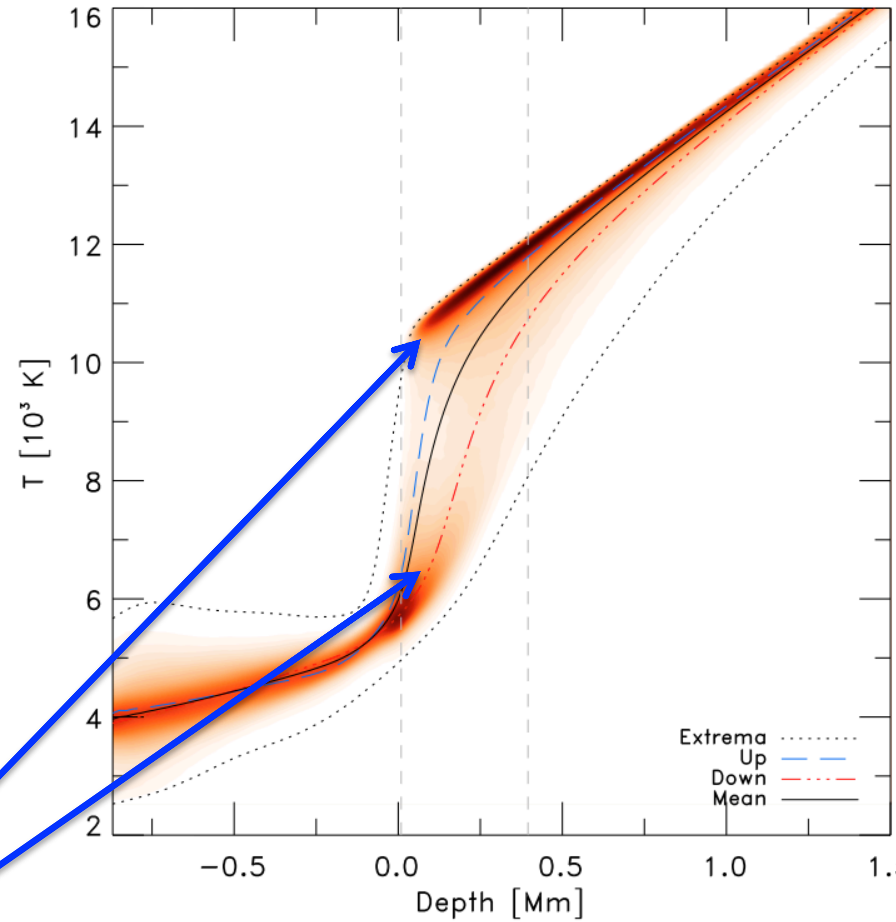
- Surface lithium abundance
- Internal rotation profile

SOLAR ABUNDANCES

Dealing with convection



Credit: N. Brummell



Magic et al. 2014

Hard to mimic with 1D models

Solar Abundances

Element	GS98	AGSS09+met
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

Differences of

CNO(Ne)~30-40%

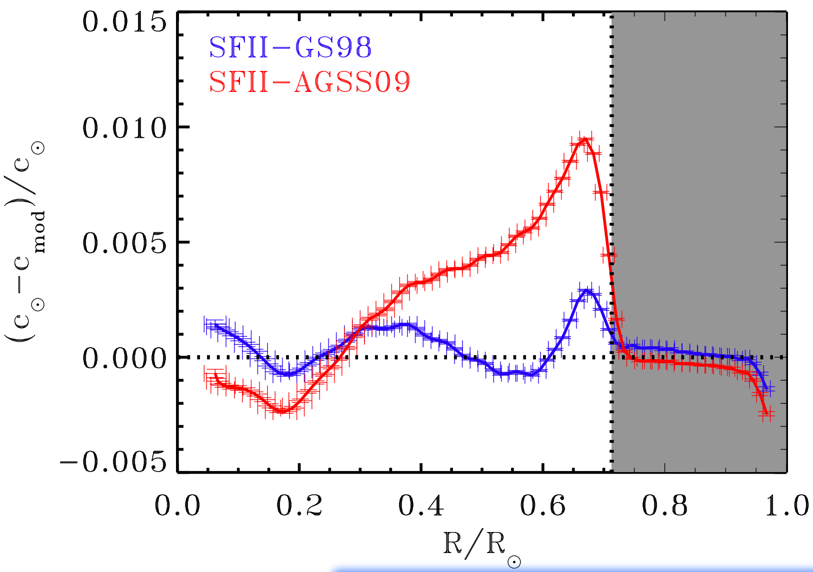
refractories~10%

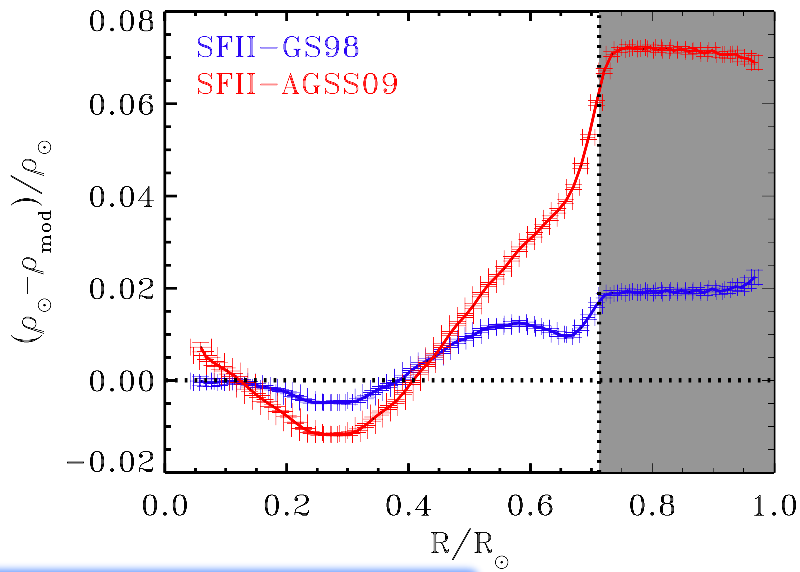
Full revision underway: Scott et al. (2014), Grevesse et al. (2014)

Silicon same as before → refractories (meteoritic) not modified

CNO not yet available – but small changes expected

Standard Solar Models: Helioseismology





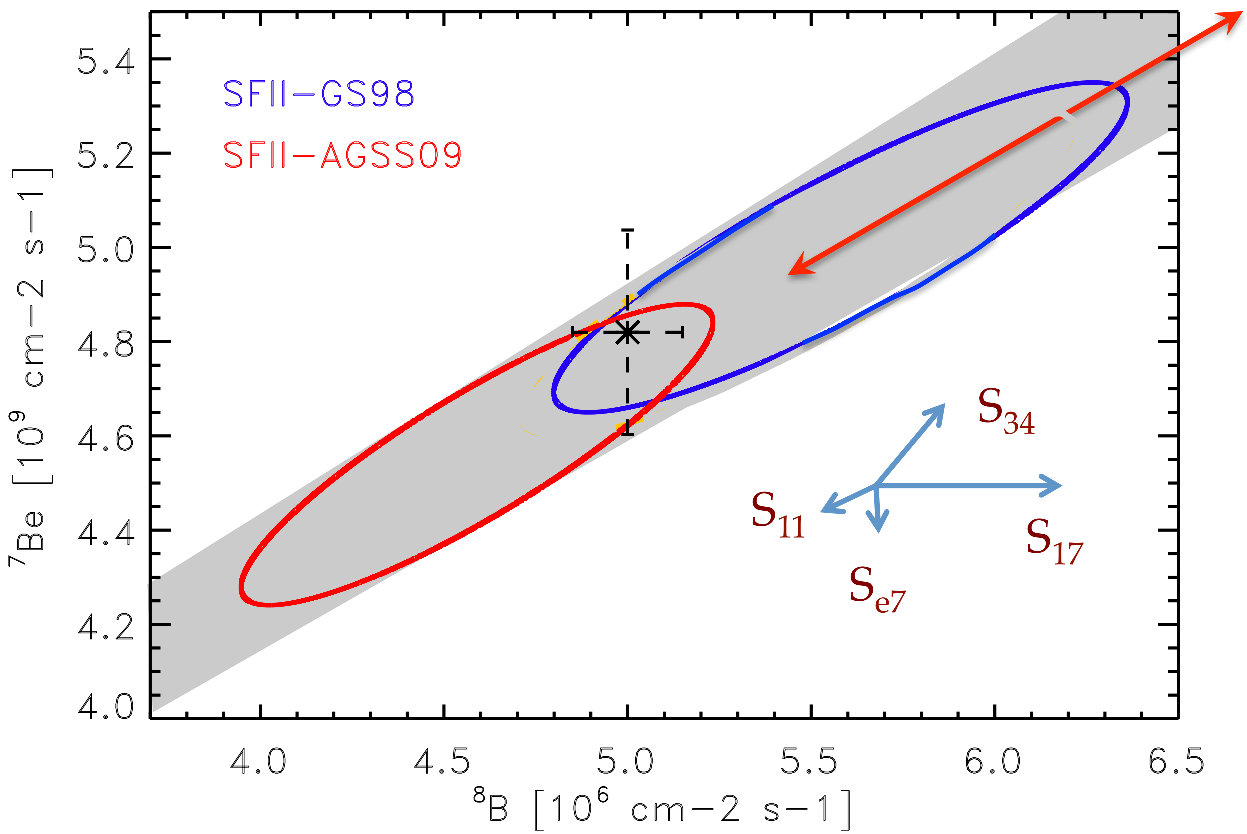
	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001
Y_S	0.2429	0.2319	0.2485 ± 0.0034
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta \rho/\rho \rangle$	0.011	0.040	—

Helioseismology --> high-Z

Standard Solar Models: Neutrinos

Borexino (^{7}Be) – SNO & SuperK (^{8}B)

Core temperature dependence



STANDARD SOLAR MODELS: NEUTRINOS

Flux	SFII-GS98	SFII-AGSS09	Solar
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$
pep	$1.44(1 \pm 0.011)$	$1.47(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	$18(1^{+0.4}_{-0.5})$
^{7}Be	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$
^{8}B	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$
^{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%	—

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

pp and pep are strongly bound by the "luminosity constraint"

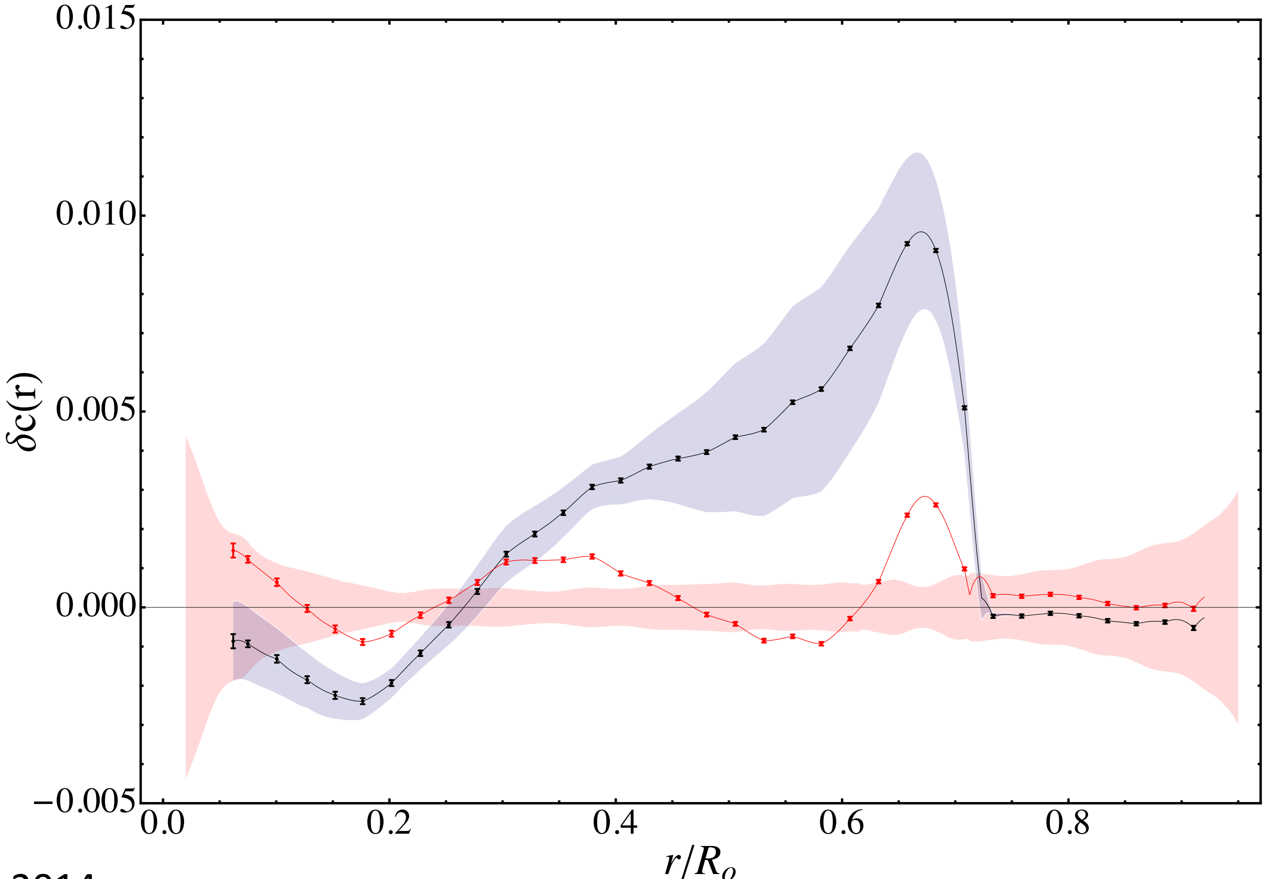
otherwise solar luminosity matched @ 15% (Maltoni et al. 2010)

Direct measurement of pp now to 11% Borexino

Solar Composition: What Data Really Tell Us

Use sound speed radial profile, not just rms

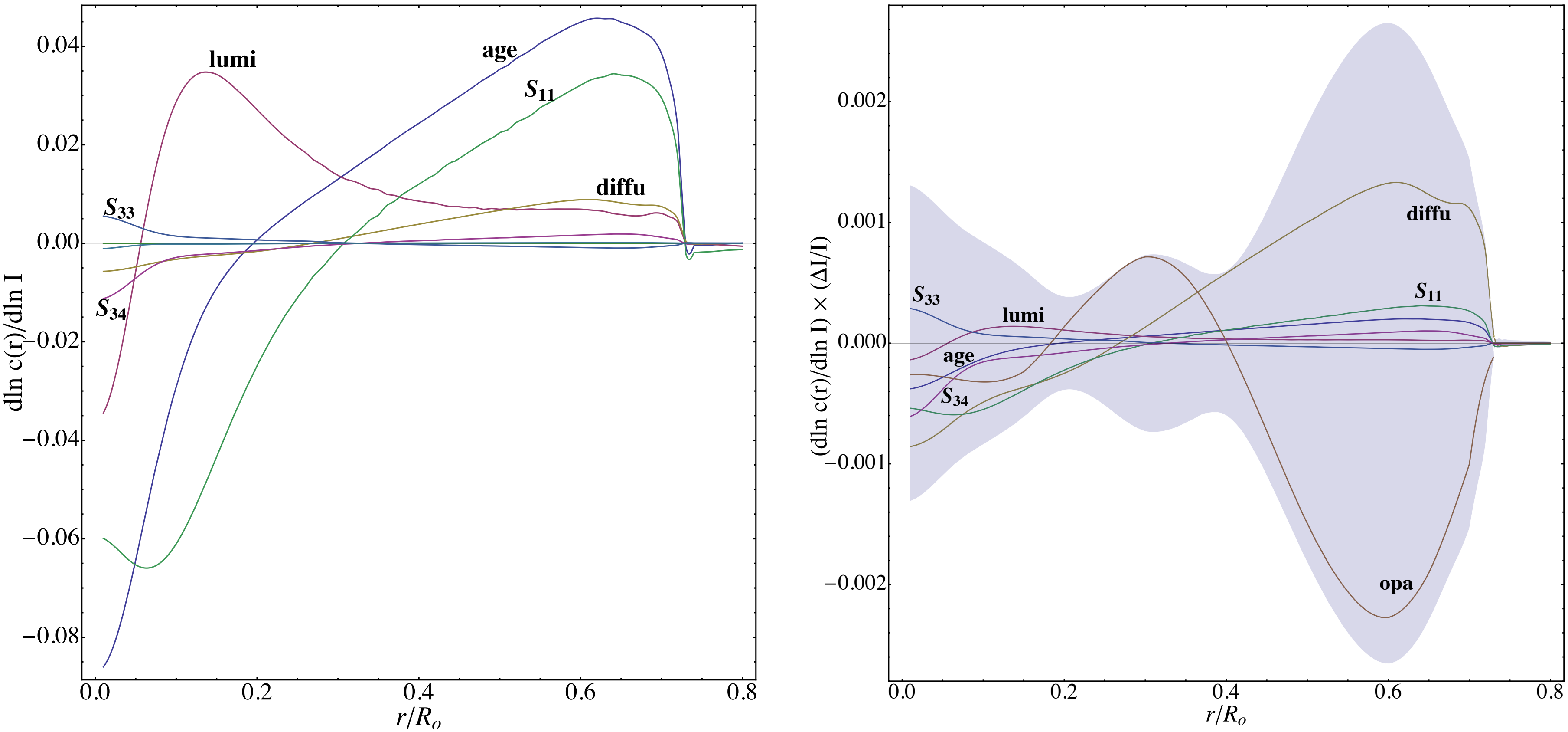
Include (as much as possible) systematic sources of errors



Villante et al. 2014

Solar Composition: What Data Really Tell Us

Sound speed sensitivity and errors



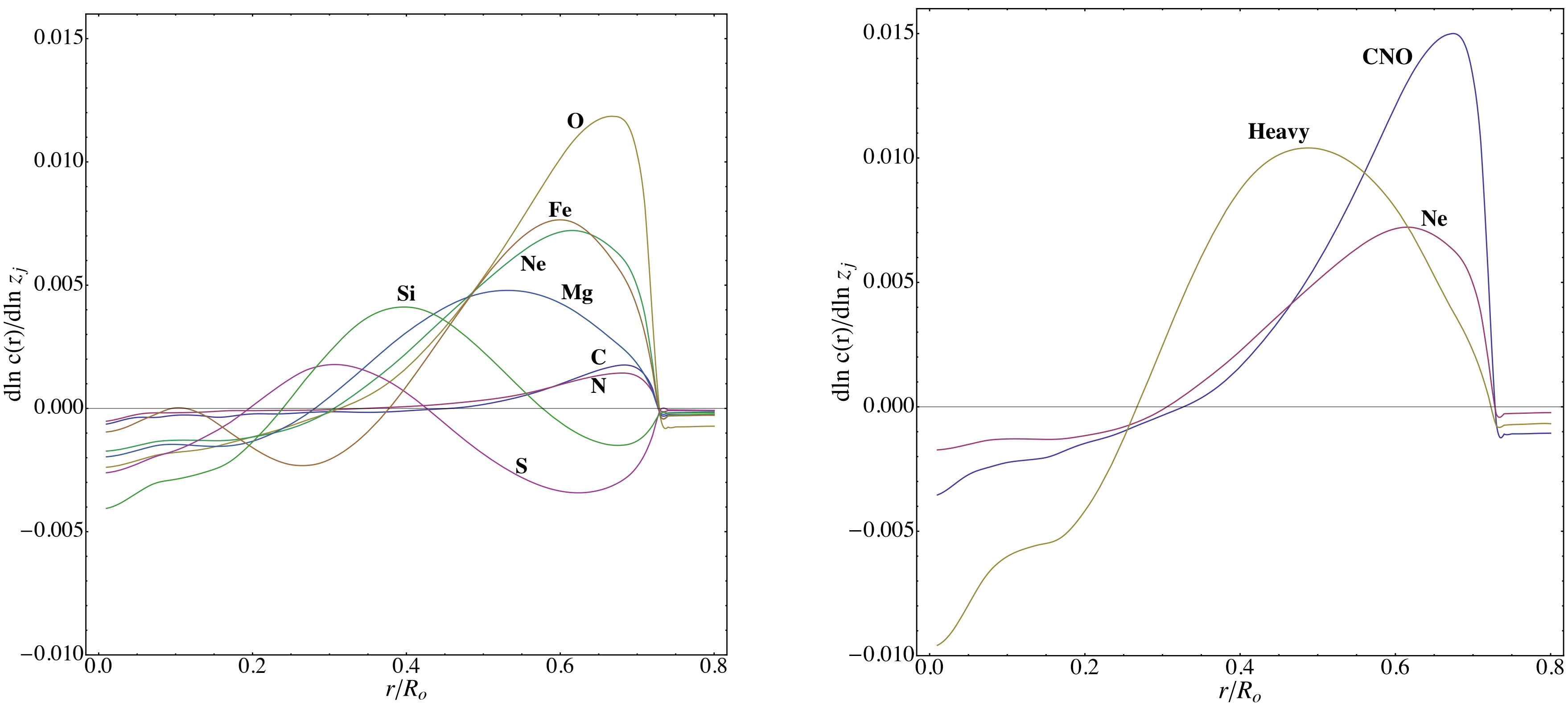
Villante et al. 2014

Solar Composition: What Data Really Tell Us

Sound speed sensitivity to composition

Lowering expectations: 2 parameters (volatile – refractories)

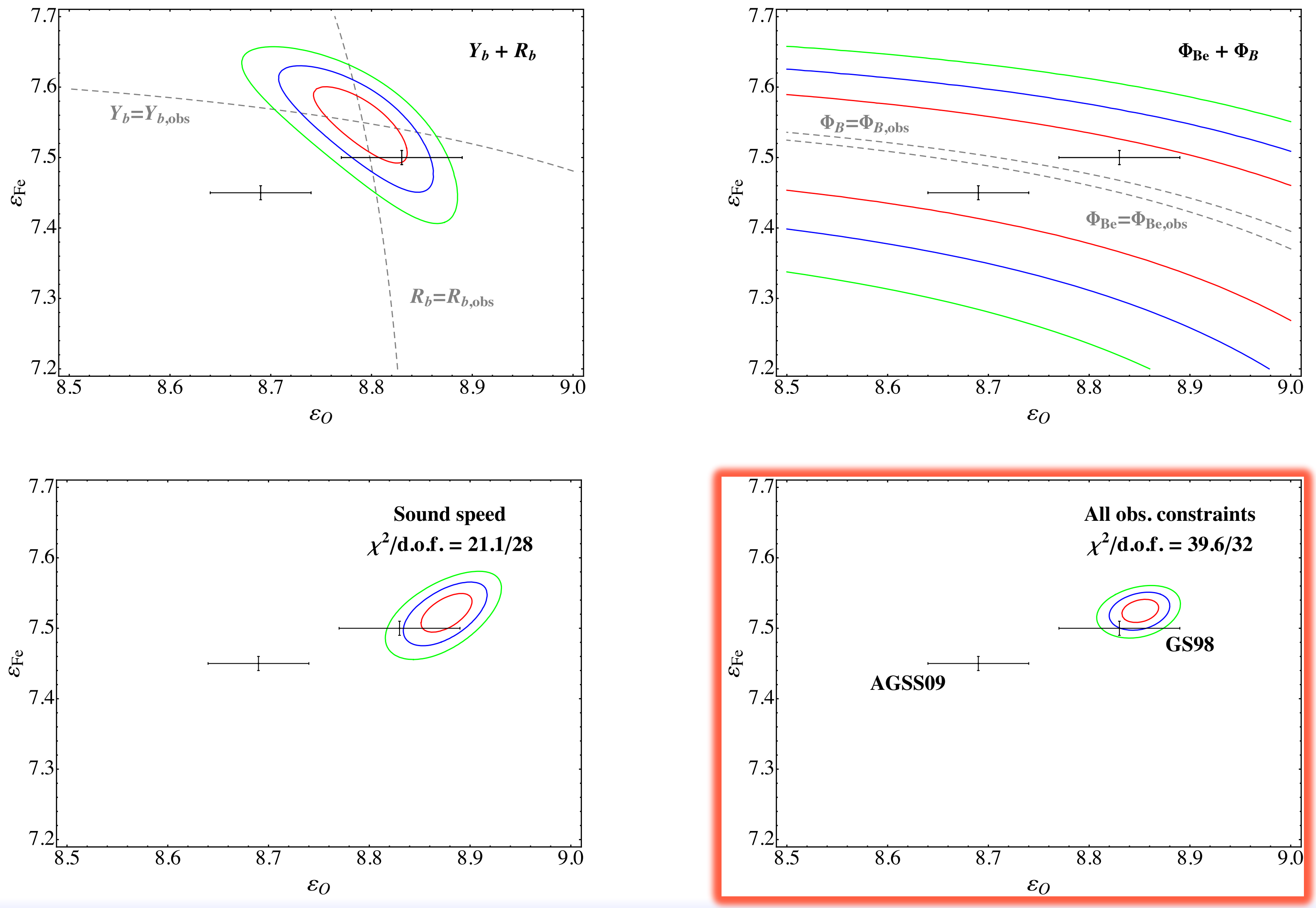
3 parameters (CNO – Ne – refractories)



Villante et al. 2014

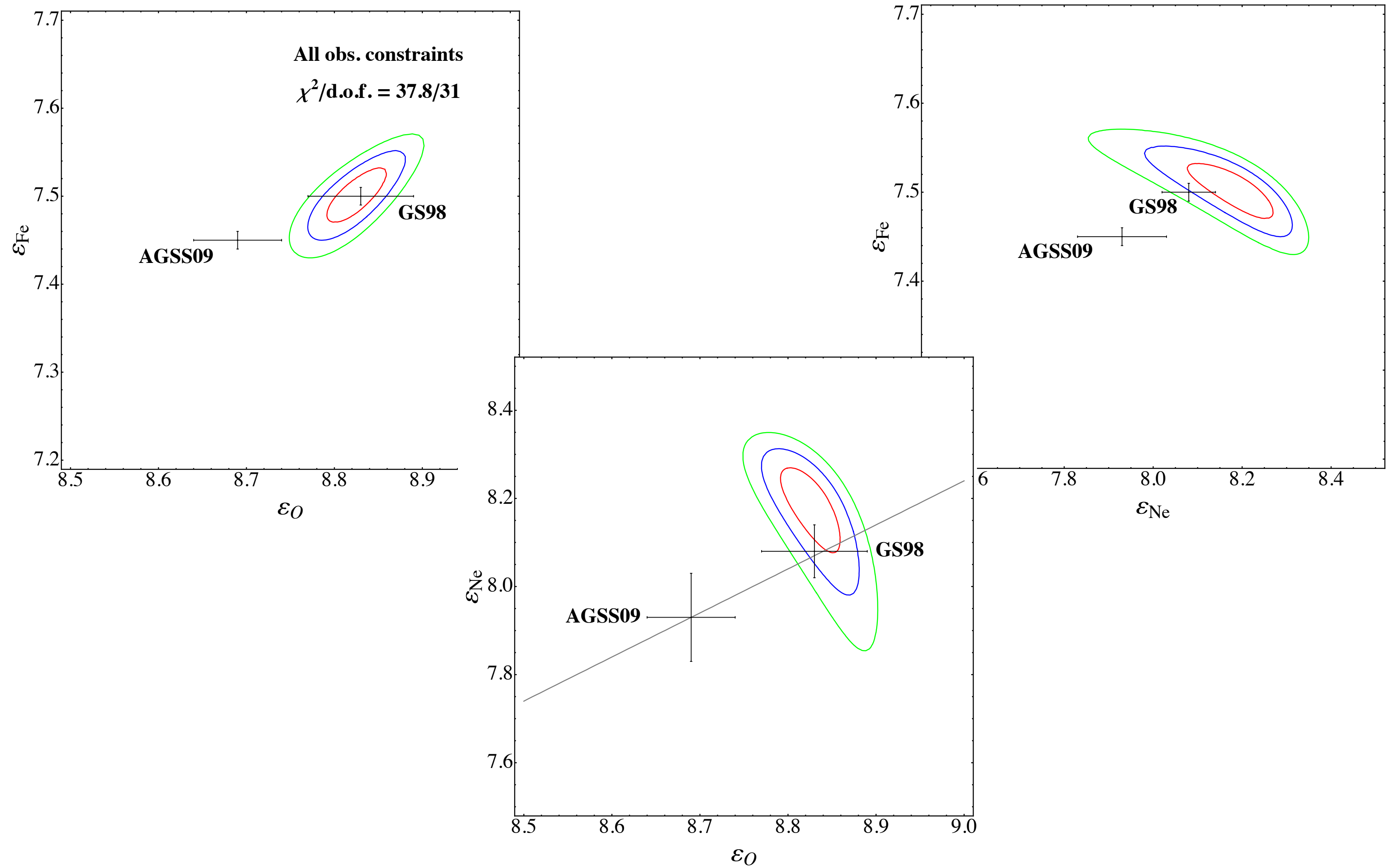
Solar Composition: 2-Parameter Analysis

Volatiles (CNONe) & Refractories



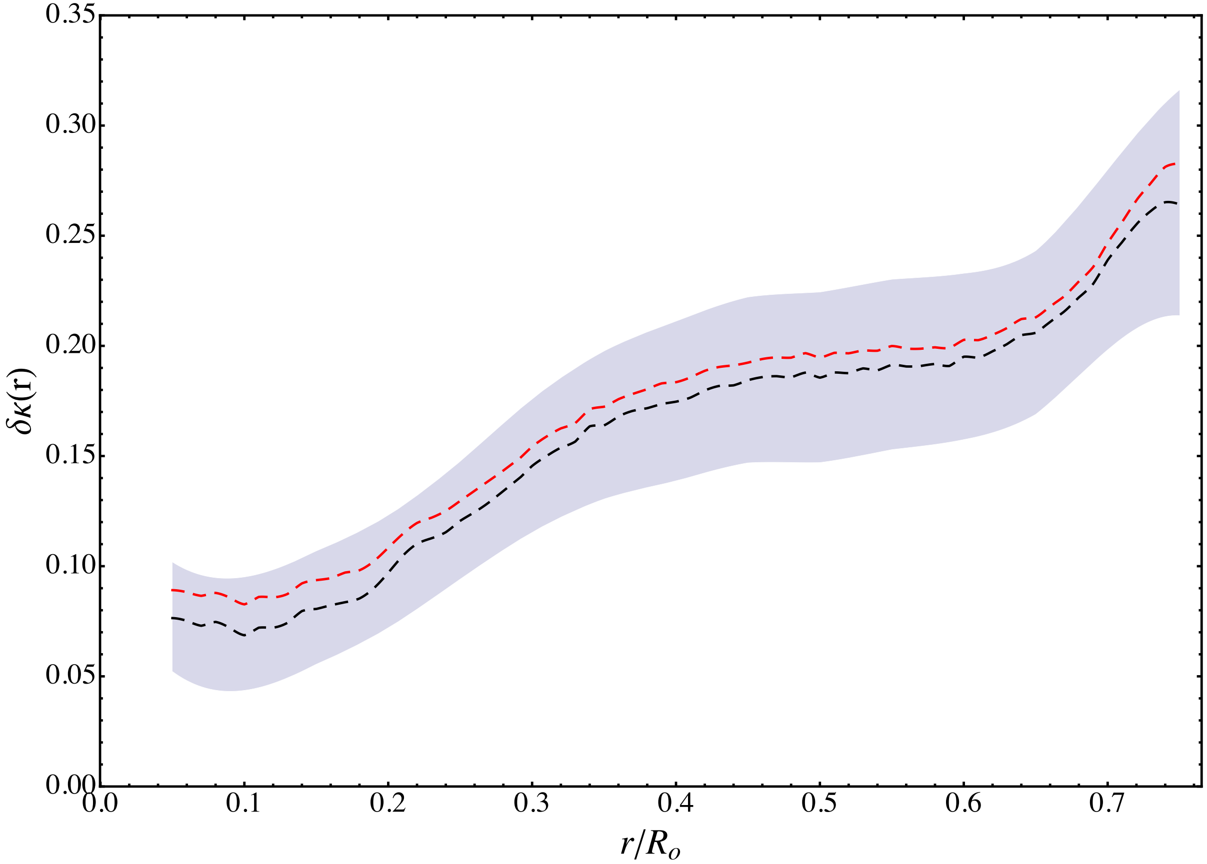
Solar Composition: 3-Parameter Analysis

Volatiles (CNO), Ne & Refractories



Learning on Solar Opacity – Not Composition

Current data constrains radiative opacity profile

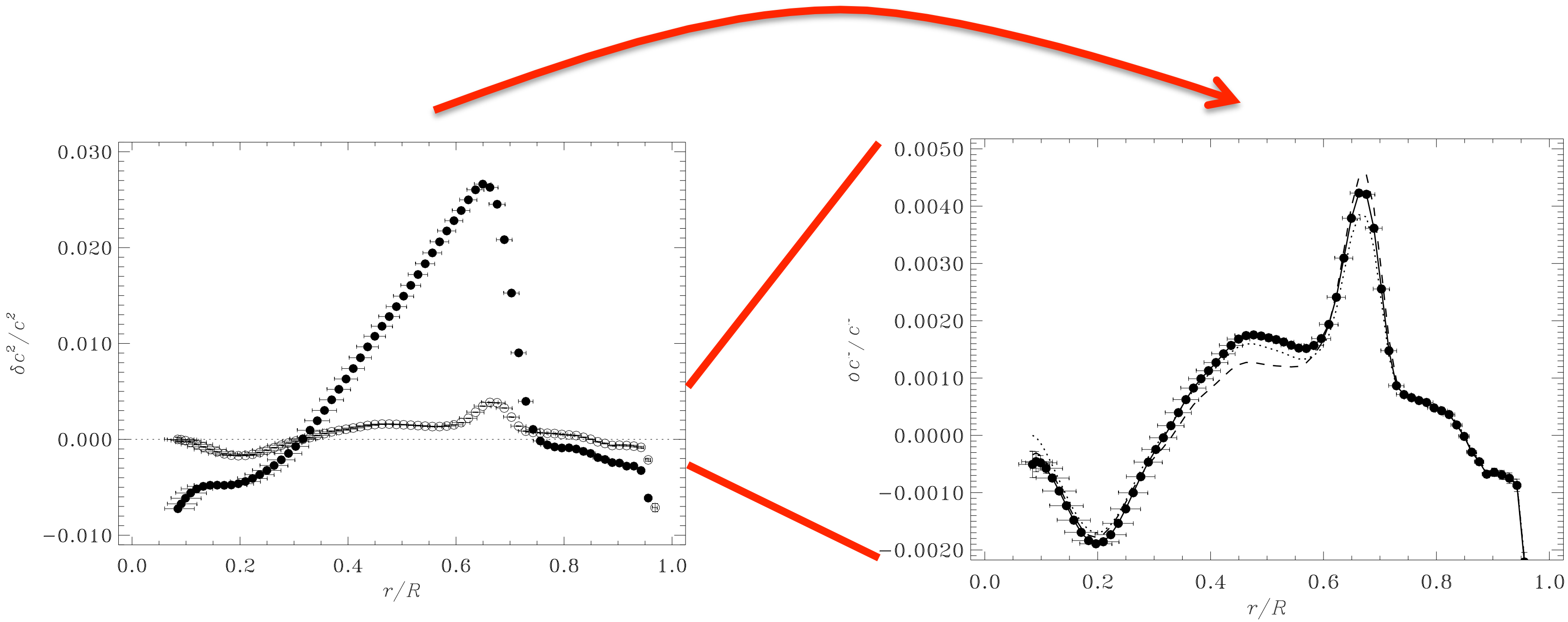


Fractional opacity difference wrt AGSS09 solar model

few % center to 20% at convective boundary

Learning on Solar Opacity – Not Composition

AGSS09 model + increased κ

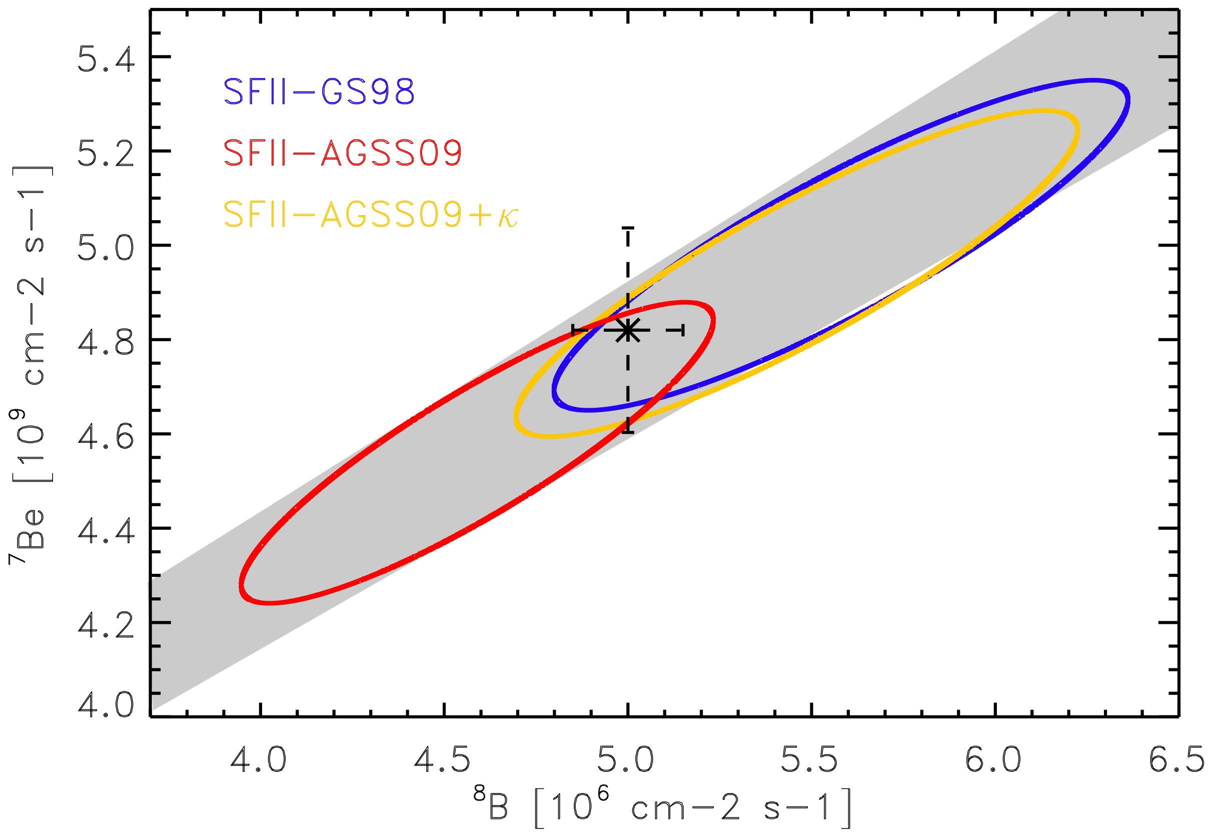


Christensen Dalsgaard et al 2009

Degeneracy between metals & opacity for helioseismic probes

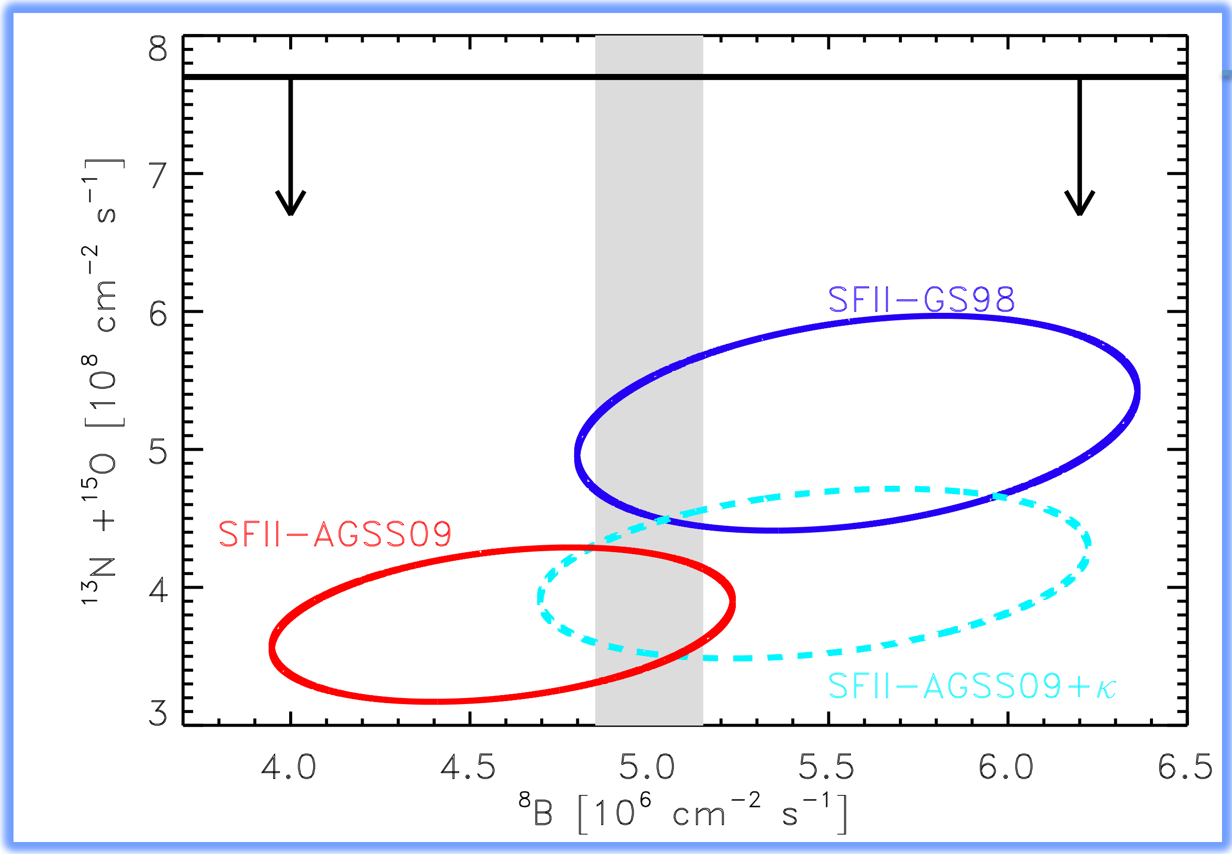
pp-chain Neutrinos Sensitive to Opacity

Fluxes linked to pp-chains not so sensitive to composition – indirect dependence through opacity



Breaking the Degeneracy

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



Upper limit by Borexino

Standard Solar Models: Neutrinos

Relate CN and ^{8}B fluxes

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.785} = x_C^{0.794} x_N^{0.212} D^{0.172}$$

$$\times \left[L_\odot^{0.515} O^{-0.016} A^{0.308}\right]$$ → Temp. dep.

$$\times \left[\mathrm{S}_{11}^{-0.831}\ \mathrm{S}_{33}^{0.342}\ \mathrm{S}_{34}^{-0.685}\ \mathrm{S}_{17}^{-0.785}\ \mathrm{S}_{e7}^{0.785}\ \mathrm{S}_{114}^{0.995}\right]$$ → Nuclear rates

$$\times \left[x_{\mathrm{O}}^{0.003} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.003} x_{\mathrm{Si}}^{-0.001} x_{\mathrm{S}}^{-0.001} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.003}\right]$$ → Temp. dep.

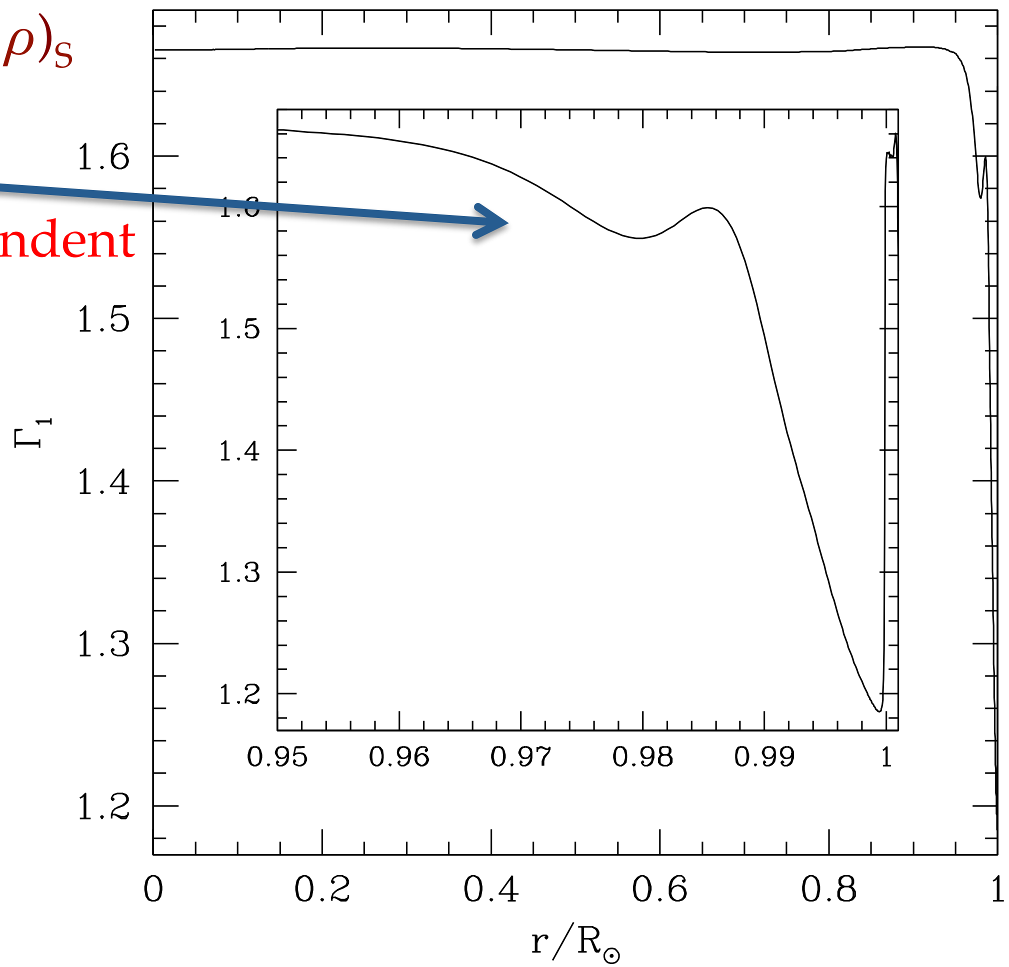
$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.785} = \left[\frac{C+N}{C^{\mathrm{SSM}}+N^{\mathrm{SSM}}}\right]\left(1 \pm 0.4\%\,(\mathrm{env}) \pm 2.6\%\,(\mathrm{D}) \pm 10\%\,(\mathrm{nucl})\right)$$

Nuclear uncertainty: S_{11} & S_{17} (~7% each)

Update on Microphysics: EOS

Partial ionization zones
leave imprints on $\Gamma_1 = (d\ln P / d\ln \rho)_S$

HeII dip used to determine surface Y (modulo EOS – independent of opacities)

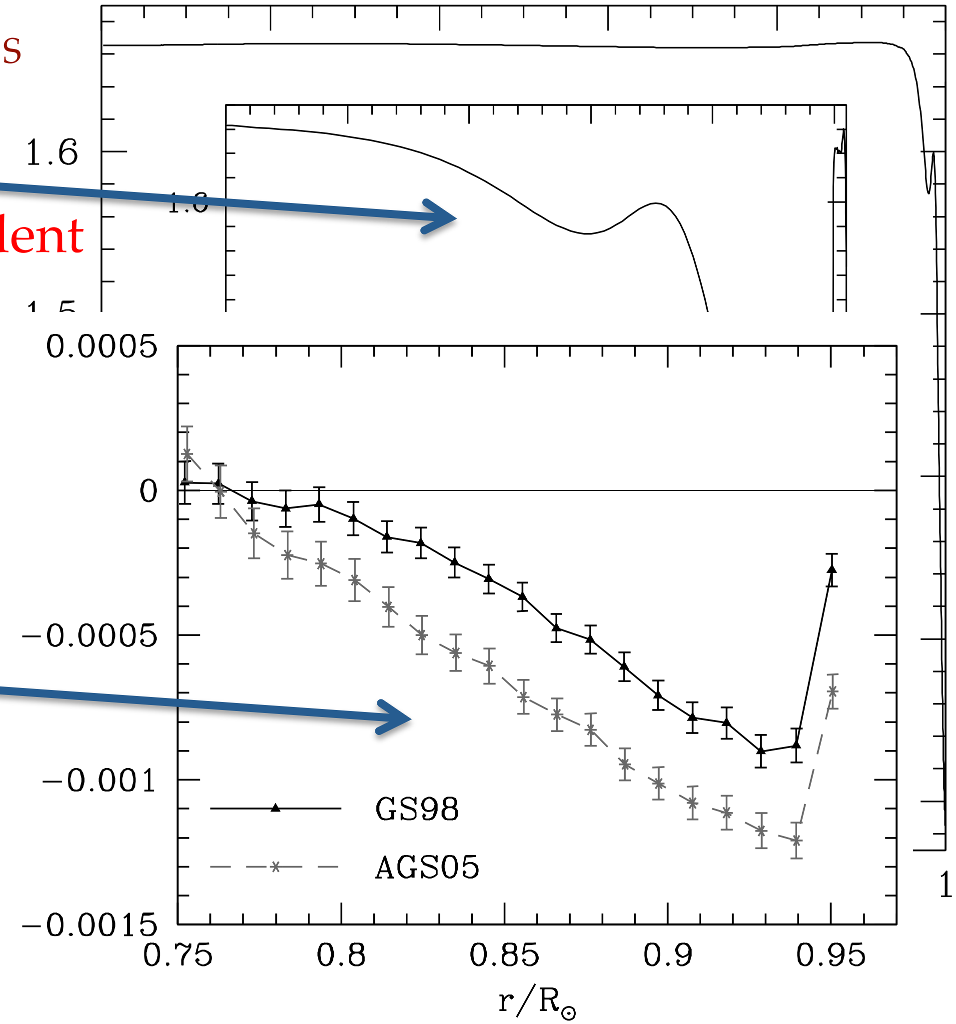


Update on Microphysics: EOS

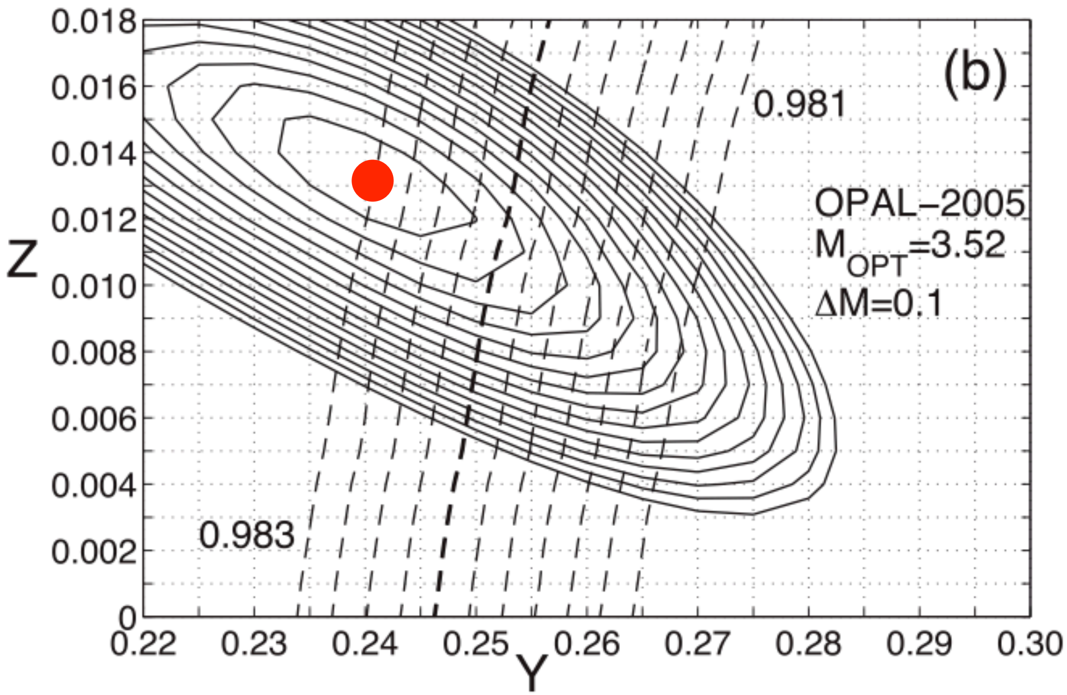
Partial ionization zones leave imprints on $\Gamma_1 = (d\ln P/d\ln \rho)_S$

HeII dip used to determine surface Y (modulo EOS – independent of opacities)

By subtracting He-contribution metals can be detected



Update on Microphysics: EOS



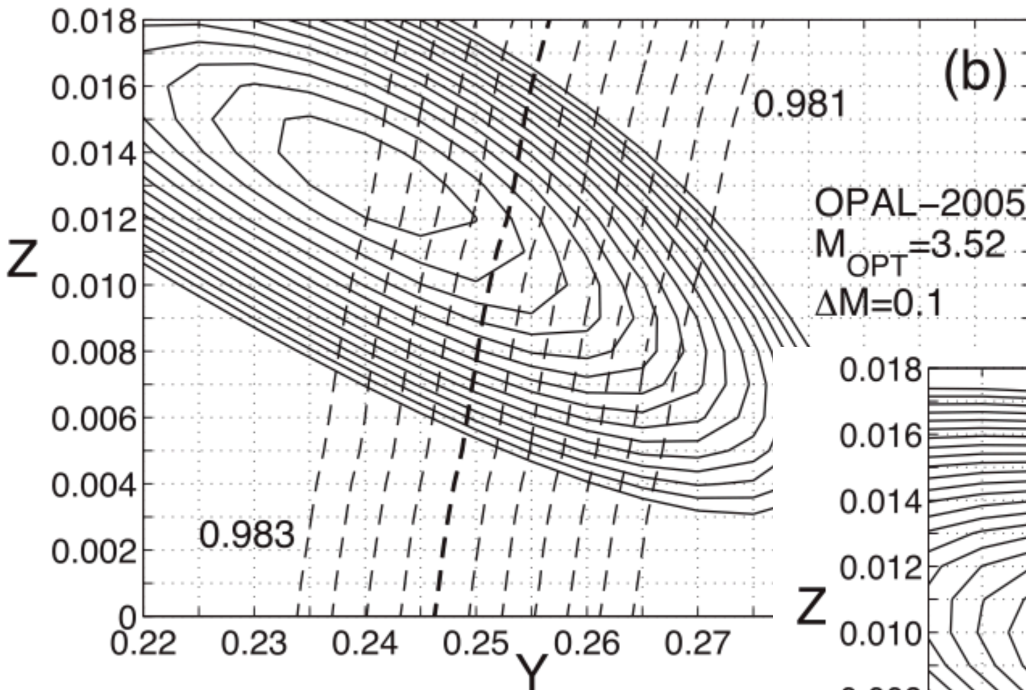
OPAL-EOS

Y (and Z) sensitive to EoS

Vorontsov et al 2013

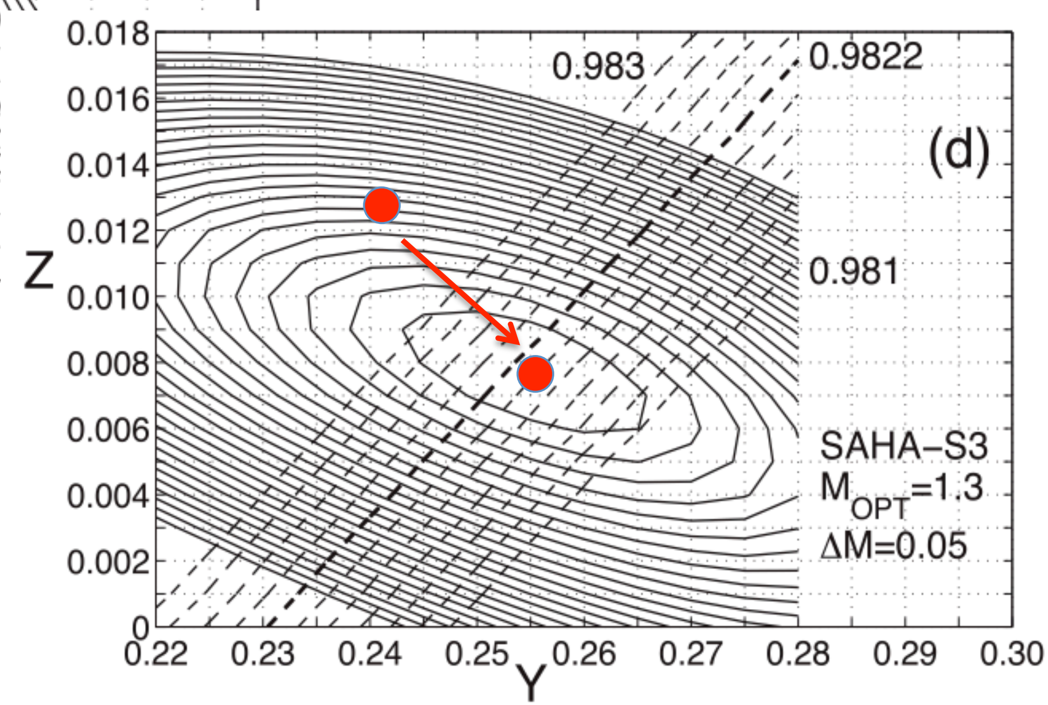
Similar technique, same EOS, lower Y and Z values

Update on Microphysics: EOS



OPAL-EOS

SAHA-S3



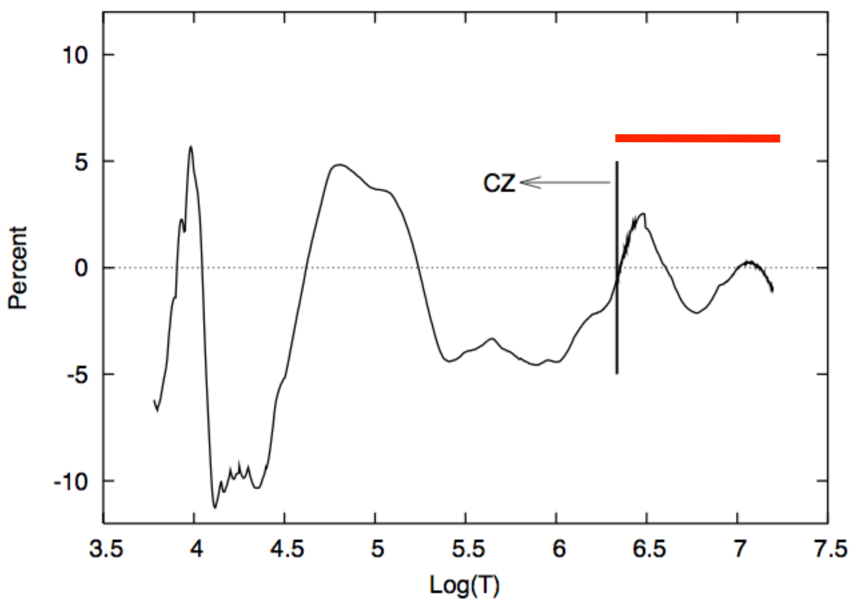
Y (and Z) sensitive to EoS

Much lower Z values with new EOS

Vorontsov et al 2013

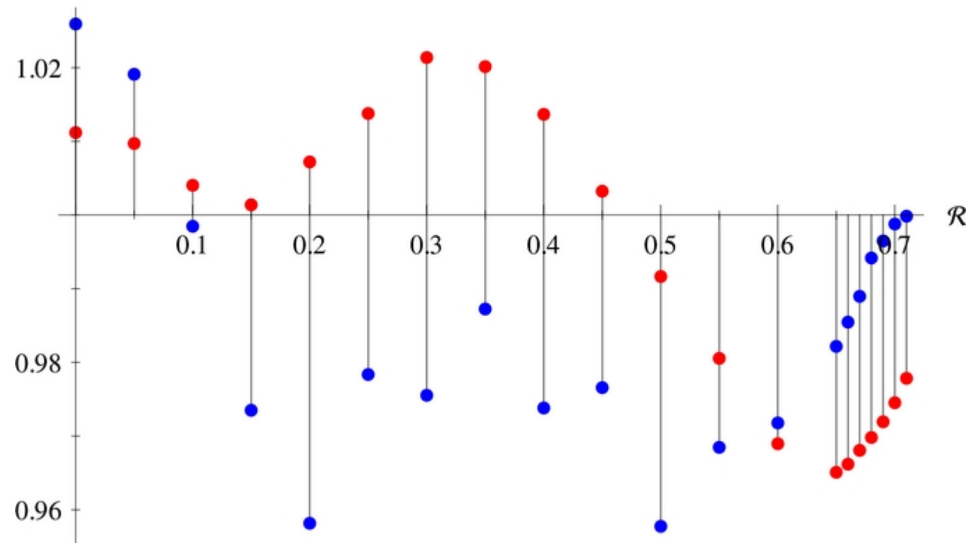
Update on Microphysics: Opacity

OP vs OPAL



Badnell et al. 2005

OPAS vs OP (blue)



Blancard et al. 2012

Just few percent in solar interiors

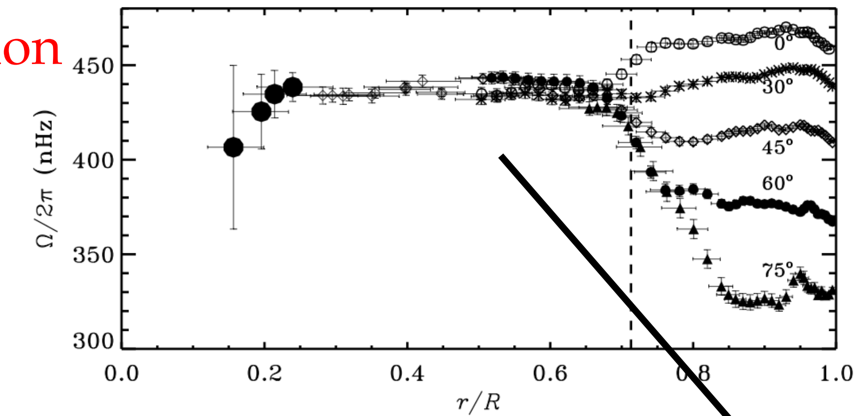
Multielectronic resonant recombination quite important (Beilmann et al. 2013)
- effect not yet quantified for Rosseland mean

Rare elements contribution to opacity neglected (e.g. Ba – Pinsonneault priv.comm.)

Beyond the SSM

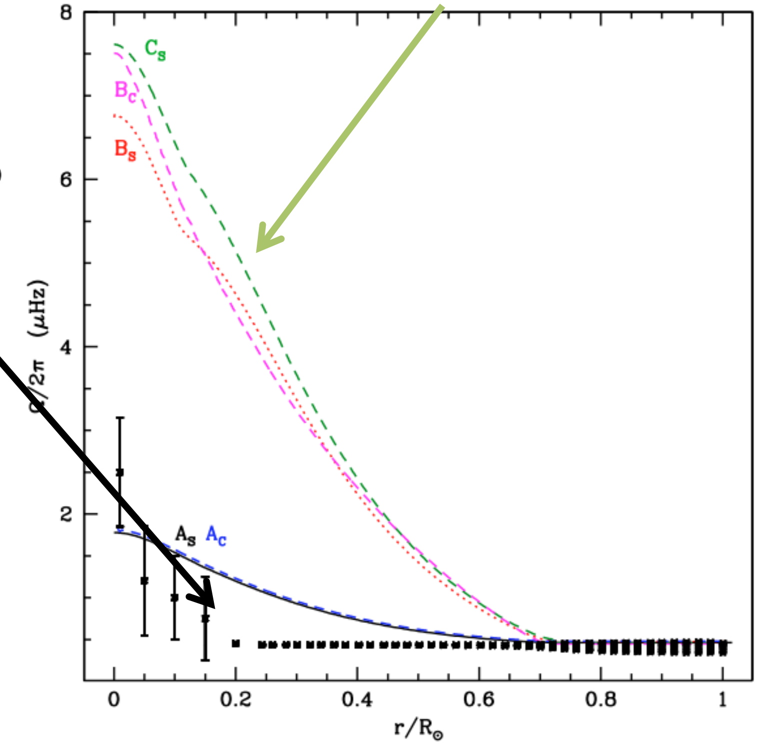
SSM does not account for: rotation, magnetic fields, internal (g) waves, etc.

Solar rotation



Thompson et al. 2003

Solar models w/ rotation

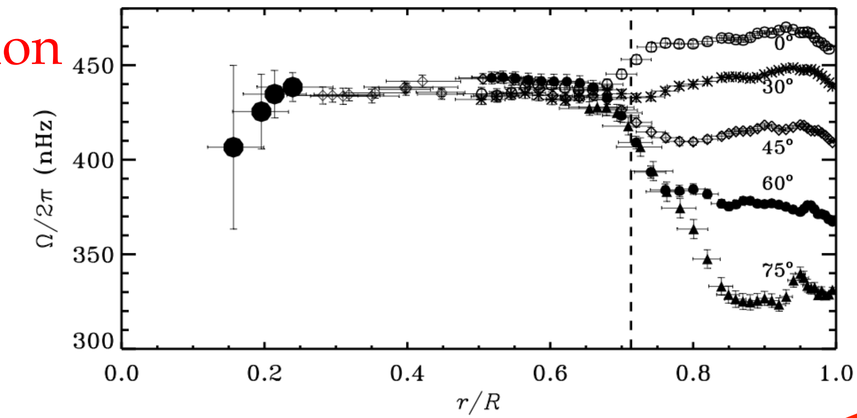


Turck-Chieze et al. 2010

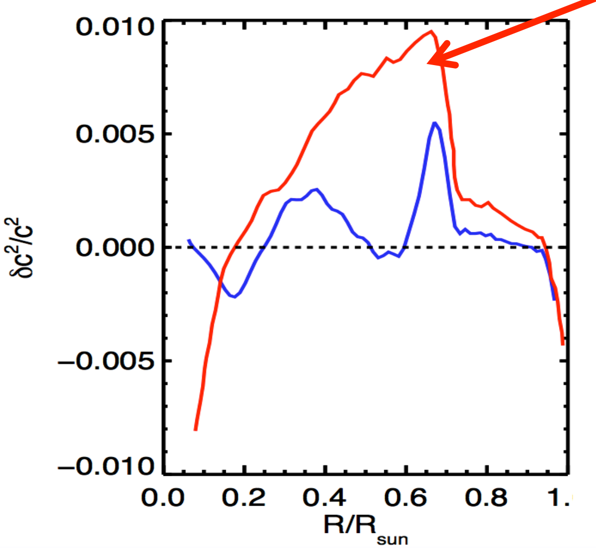
Beyond the SSM

SSM does not account for: rotation, magnetic fields, internal (g) waves, etc.

Solar rotation

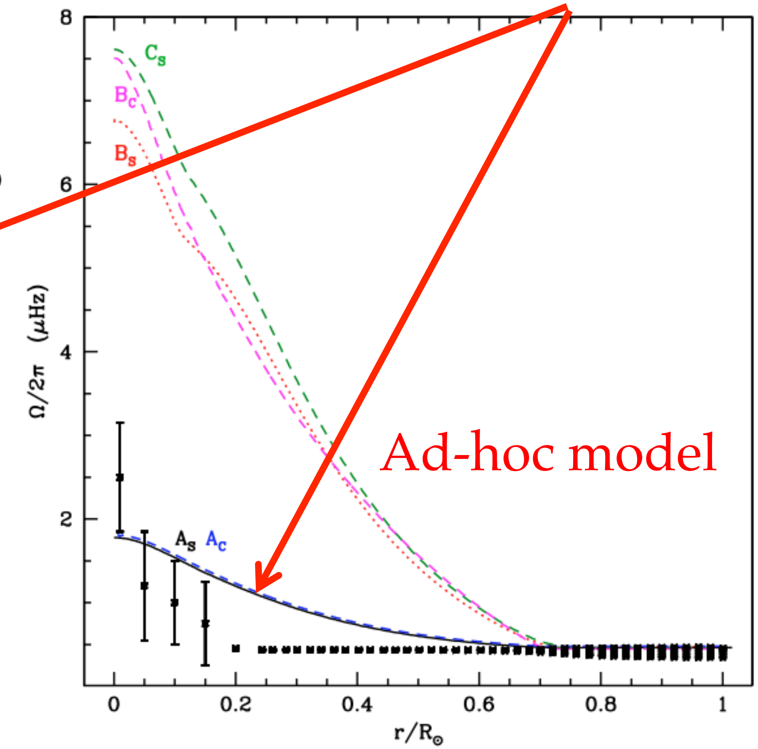


Thompson et al. 2003



Transport of angular momentum not understood

Solar models w/ rotation

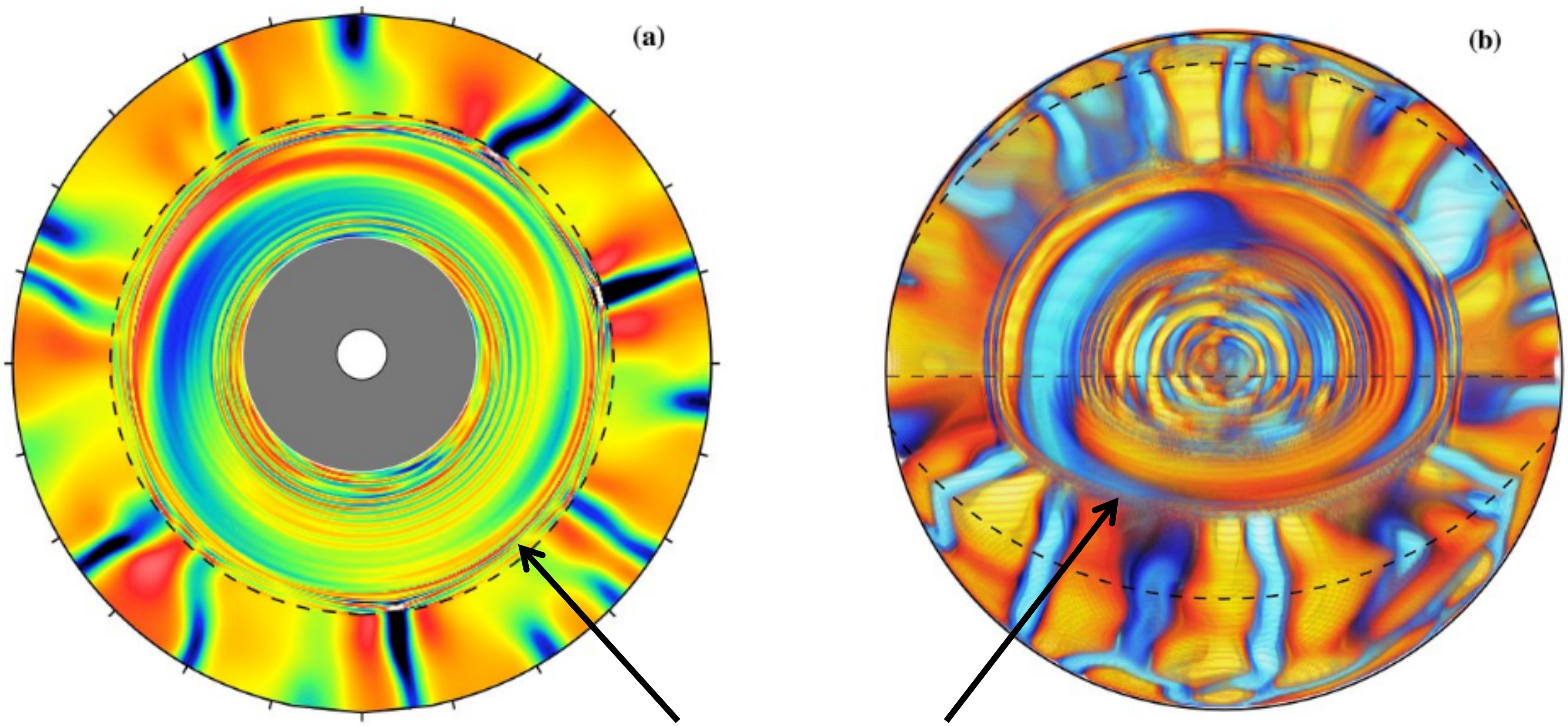


Ad-hoc model

Turck-Chieze et al. 2010

Beyond the SSM

3D-Hydro simulations for deriving realistic 1D models of physical processes
Example: internal gravity waves (Brun et al. 2011)



Radial velocity in radiative (stable) zone apparent in both plots

SUMMARY

Most complete analysis of solar data to date favors high
metallicity/opacity

Sensitivity limited by type of data (degenerate with opacity)

CN fluxes can break the degeneracy

Update on microphysics

EOS needs more checks

Development in opacity calcualtions/models

Beyond SSM

3D models needed to understand angular momentum transp.

TODAY, ONLY THIS MATTERS…