Solar Models, Neutrinos and Composition

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Instituto Física Teórica, Madrid – February 2016

Outline

* Standard solar models
    * definition
    * observational tests

* Solar composition – impact on solar models
    * helioseismic and solar neutrino tests
    * solar composition problem

* Composition vs. Opacities: what data really tell us

* Breaking the degeneracy with (CN) neutrinos

* Beyond the SSM

Standard Solar Models

SSM assumes

- initially homogeneous – well mixed by convection
- constant mass evolution – 1 $M_\odot$
- evolve up to solar system age 4.57 Gyr

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- Metal to hydrogen surface abundance (Z/X) -- > initial metallicity

$$m_{ij} = \frac{\partial \log c_i}{\partial \log p_j}$$

	$\alpha_{\rm mlt}$	$Y_{\rm ini}$	$Z_{\rm ini}$
$L_\odot$	0.06	2.35	-0.73
$R_\odot$	-0.19	0.56	-0.14
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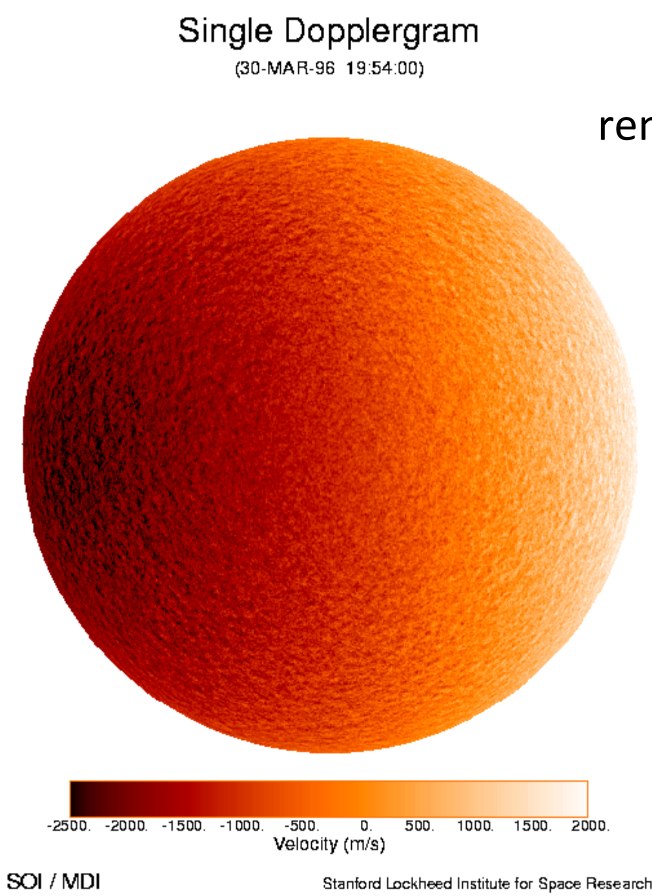
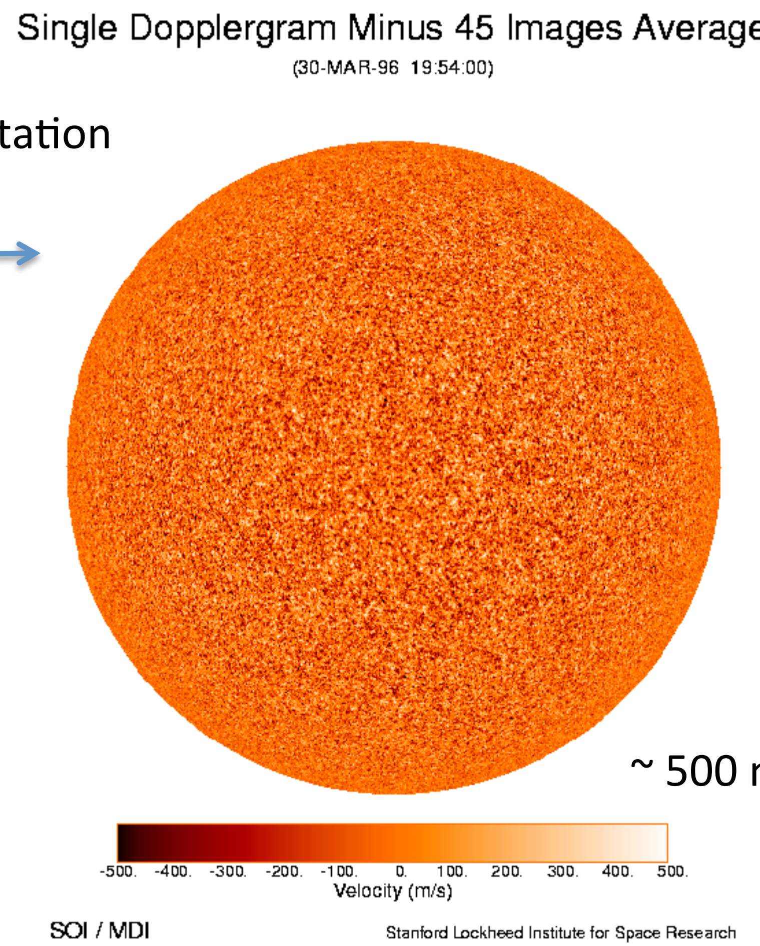
What observables to test models?

Helioseismology – sound speed, surface helium, depth convective zone, etc.
Solar neutrinos – ^{8}B, ^{7}Be … pp, pep

Helioseismology

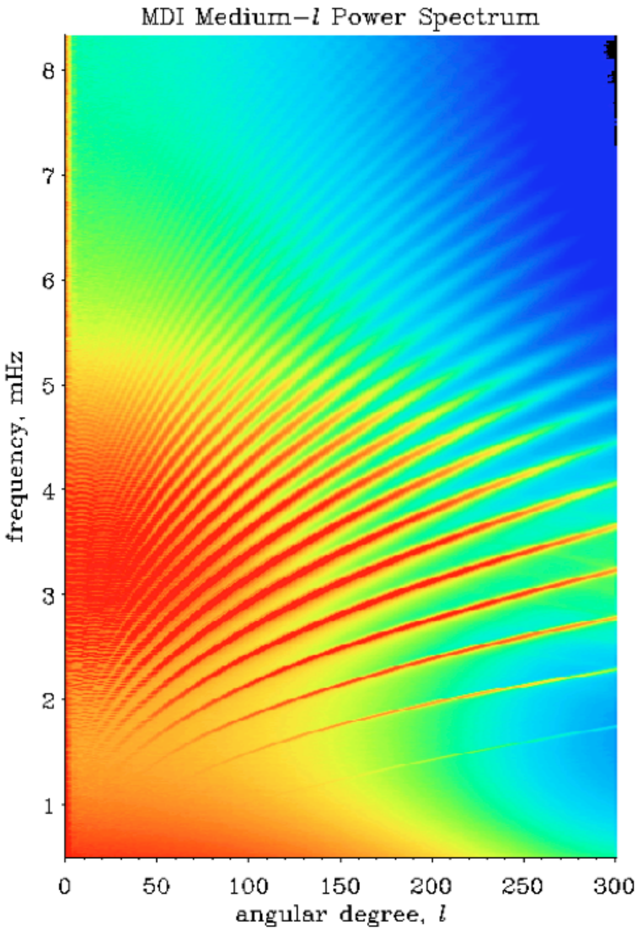


remove solar rotation



~ 500 m/s

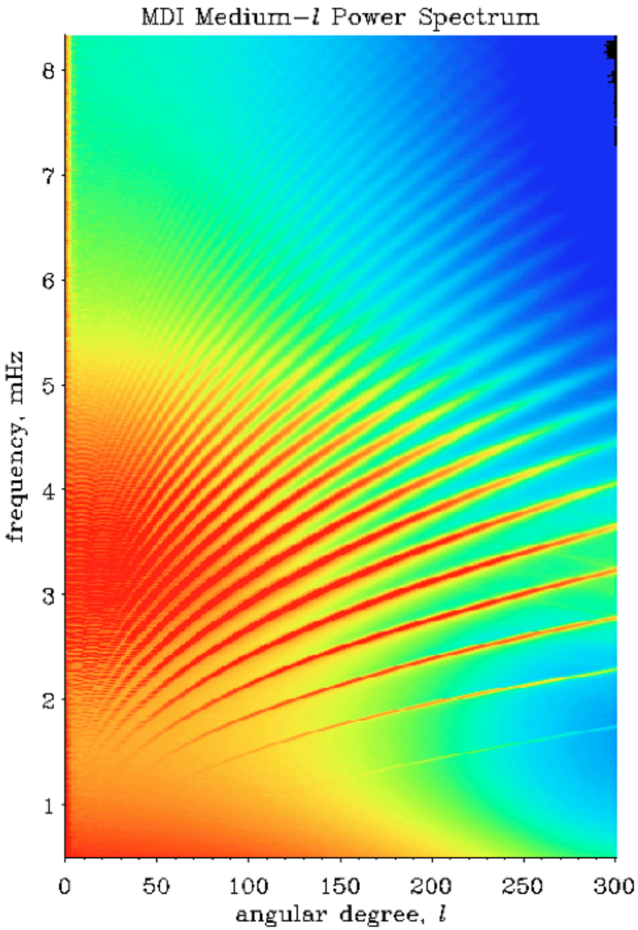
Helioseismology



$$c^2 = \frac{\Gamma_1 p}{\rho}$$

acoustic standing waves (p-modes)
typical period 5 minutes (~ 3 mHz)
amplitudes ~ few cm/s in radial velocity
~ parts per million in brightness

Helioseismology



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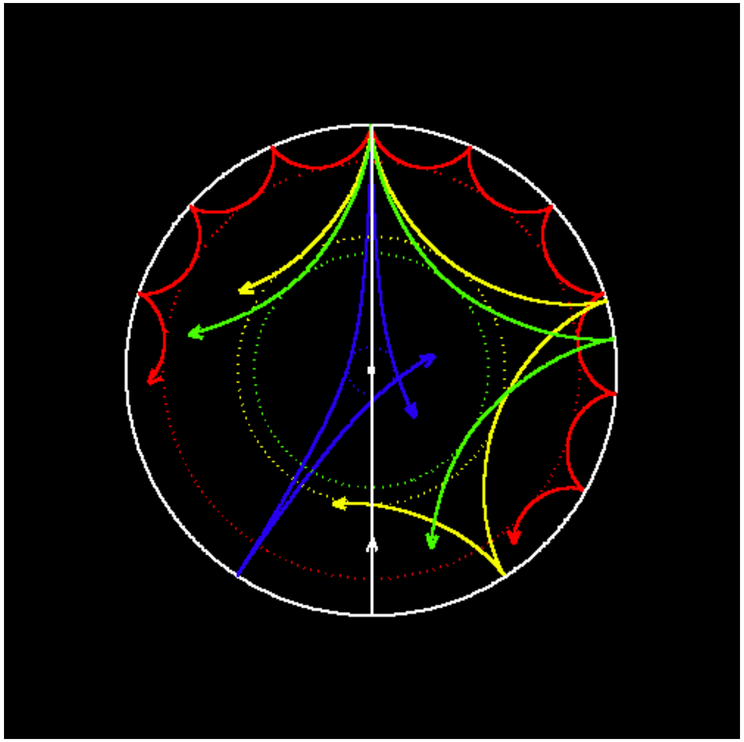


$\ell = 0$
$\ell = 2$
$\ell = 20$
$\ell = 25$
$\ell = 75$

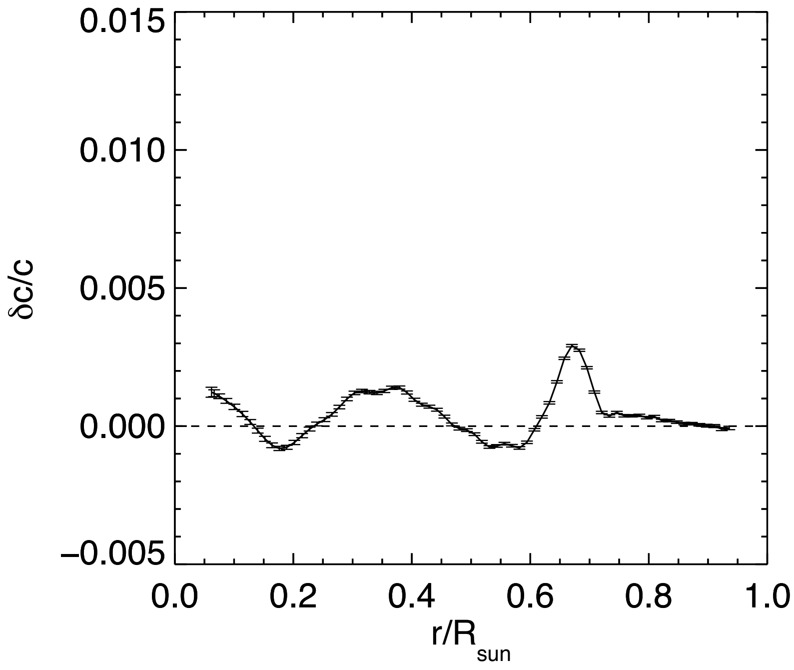
probe different regions of the Sun

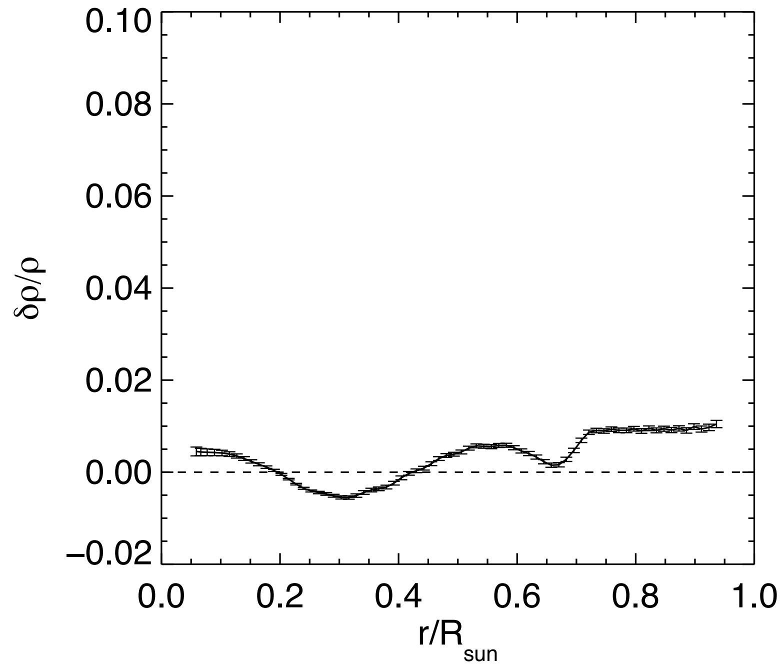
acoustic standing waves (p-modes)
typical period 5 minutes (~ 3 mHz)
amplitudes ~ few cm/s in radial velocity
~ parts per million in brightness

Helioseismology

Inversions used to derive sound speed and density profiles

$$\frac{\delta\omega_i}{\omega_i} = \int K^i_{c^2,\rho}(r)\frac{\delta c^2}{c^2}(r)dr + \int K^i_{\rho,c^2}(r)\frac{\delta\rho}{\rho}(r)dr + F_{surf}(\omega_i)$$



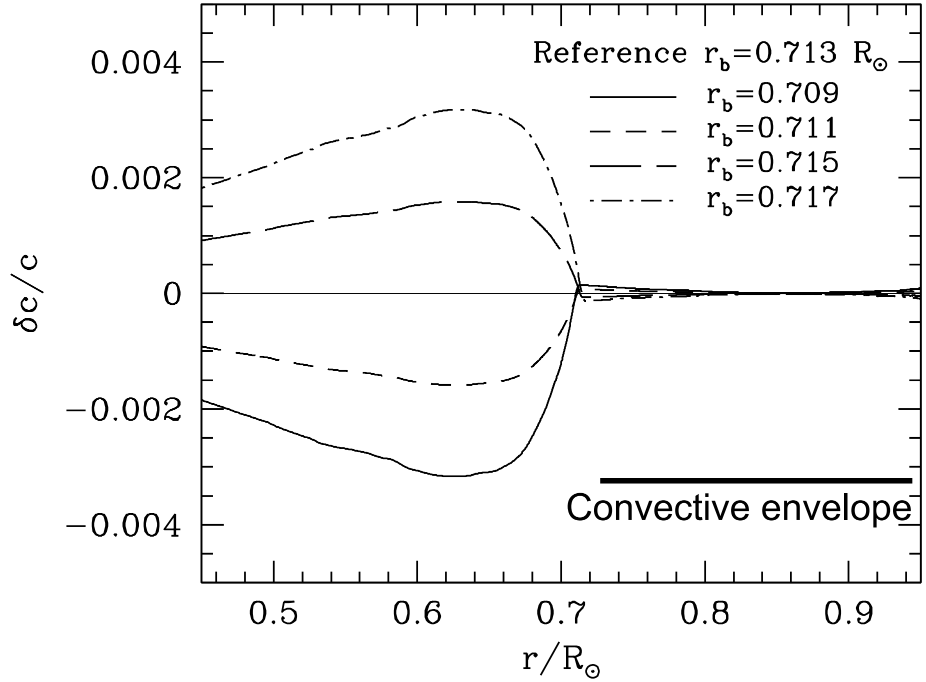


Helioseismology: depth of convective envelope

Sound speed profile sensitive to location of bottom of convective envelope R_{CZ}

R_{CZ}=0.713±0.001 $R_{\odot}$

Basu & Antia 2004 (and many before)



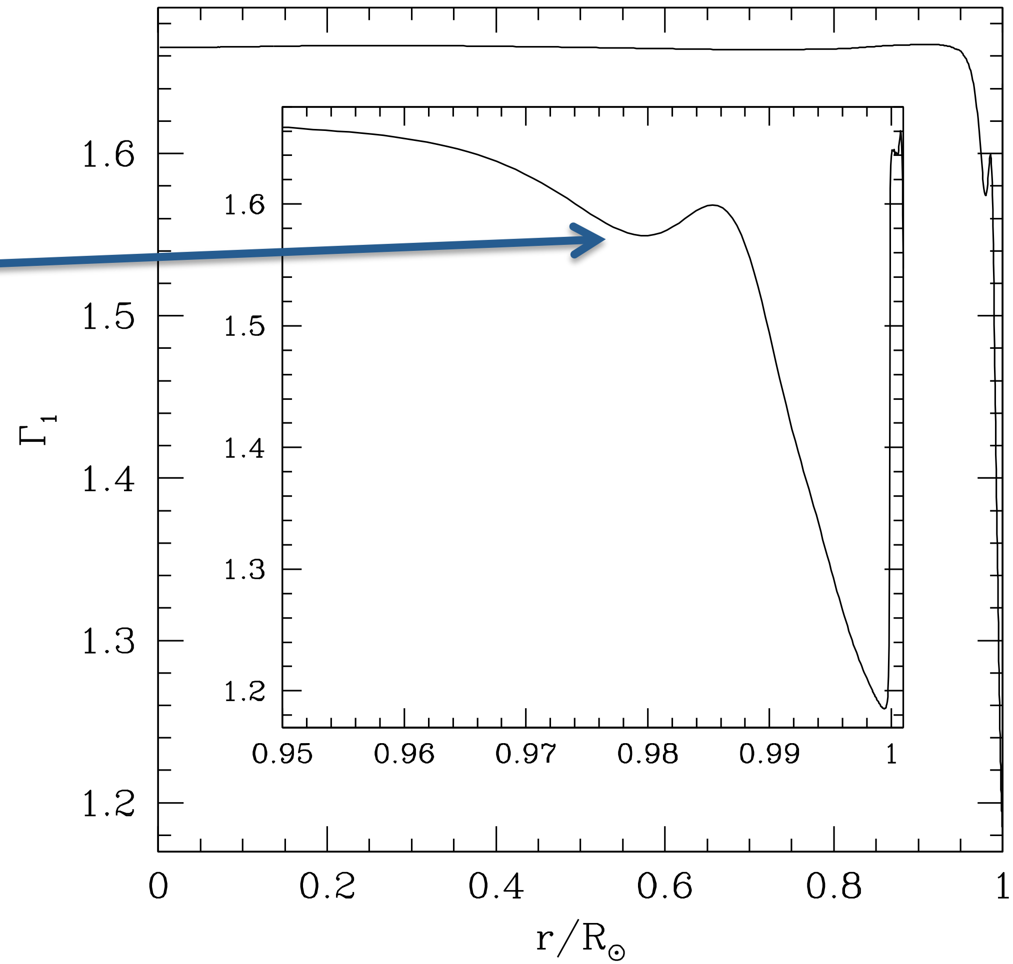
Helioseismology: helium in convective envelope (surface)

Partial ionization zones leave imprints on Γ_1

HeII dip used to determine surface Y
(modulo EOS & other contributions e.g. OIII)

Y_S in the range 0.24-0.25

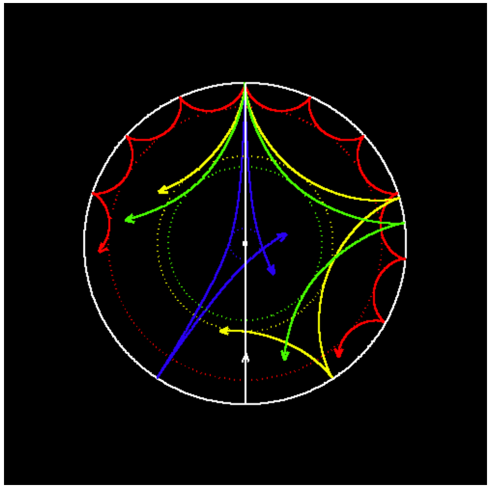
Adopt Y_S=0.2485±0.0034



Helioseismology

Low degree modes; l=0, 1, 2, 3
inner turning point well into the solar core

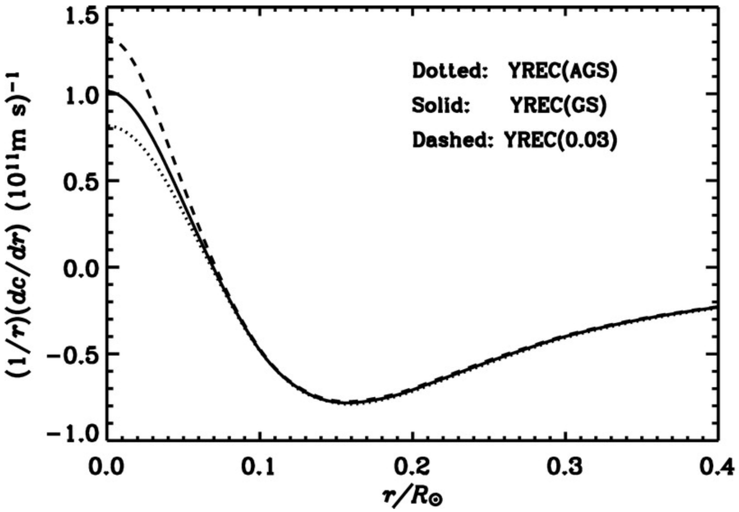
Frequency separation ratios (solar core)



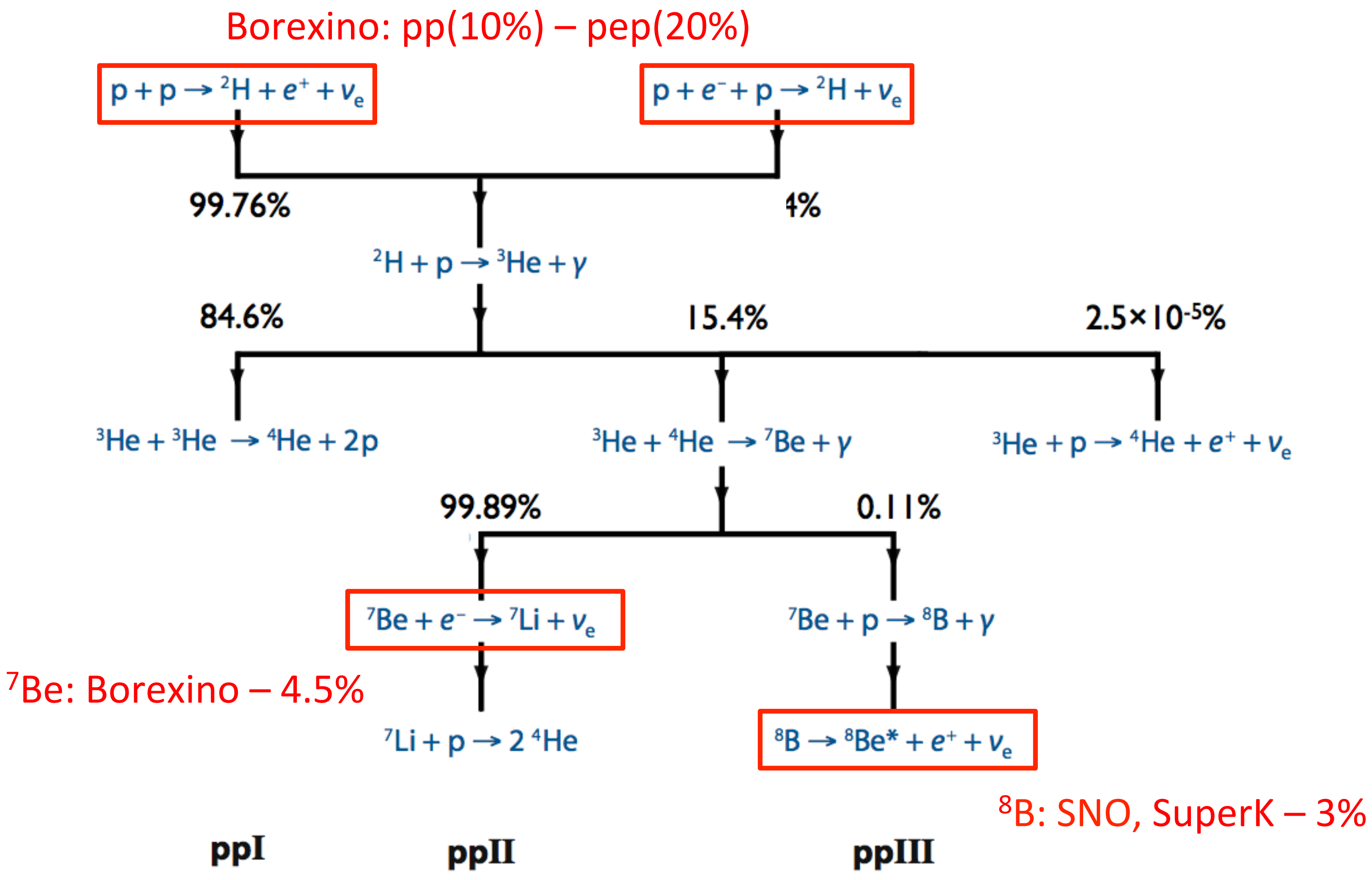
$$r_{02} = \frac{\nu_{n,0} - \nu_{n-1,2}}{\nu_{n,1} - \nu_{n-1,1}}$$

$$r_{13} = \frac{\nu_{n,1} - \nu_{n-1,3}}{\nu_{n+1,0} - \nu_{n,0}}$$

$$\left.\right\} \propto \int_0^R \boxed{\frac{dc}{dr}\frac{dr}{r}}$$



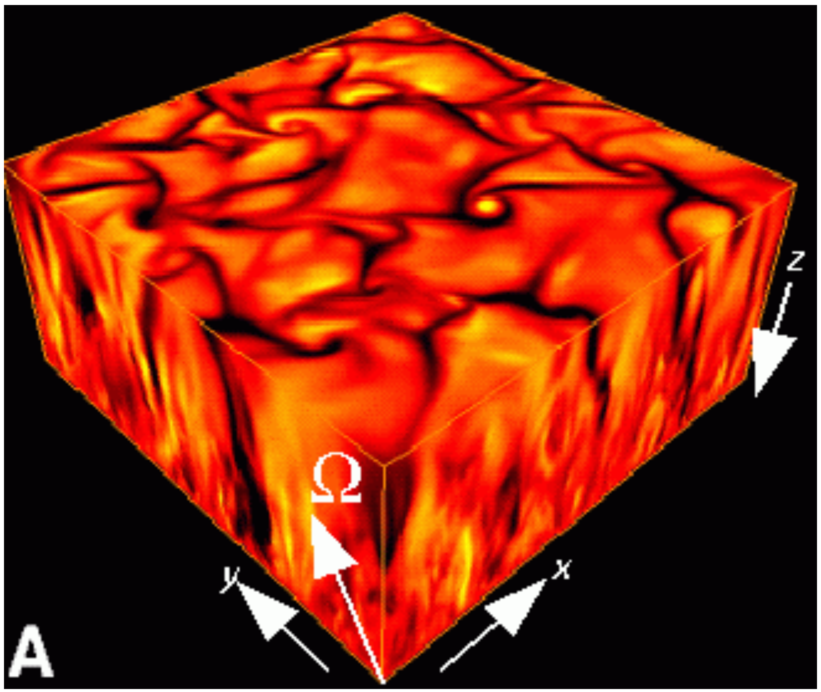
Solar Neutrinos



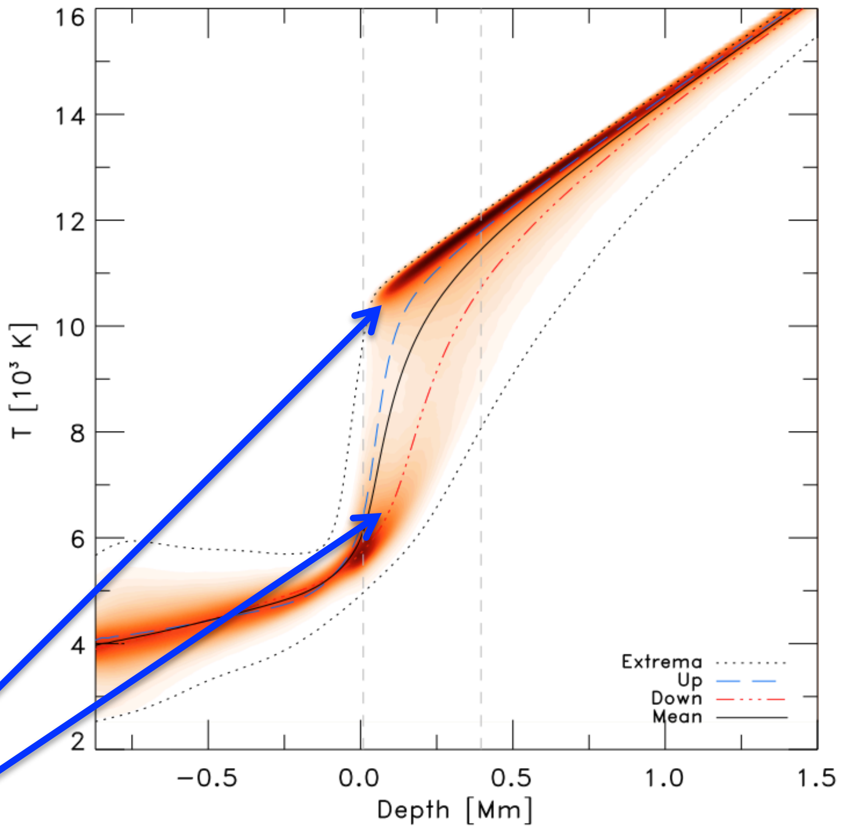
Solar Atmospheres & Abundances

Present day metal to hydrogen surface abundance (Z/X): a key constraint for SSMs

Spectroscopic analysis relies upon solar atmosphere models – 3D models of convection



Credit: N. Brummell



Magic et al. 2014

Hard to mimic with 1D models

Solar Atmospheres & Abundances

Fundamental differences between (old) 1D based and (new) 3D based 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%

Sun has a "sub-solar" metallicity

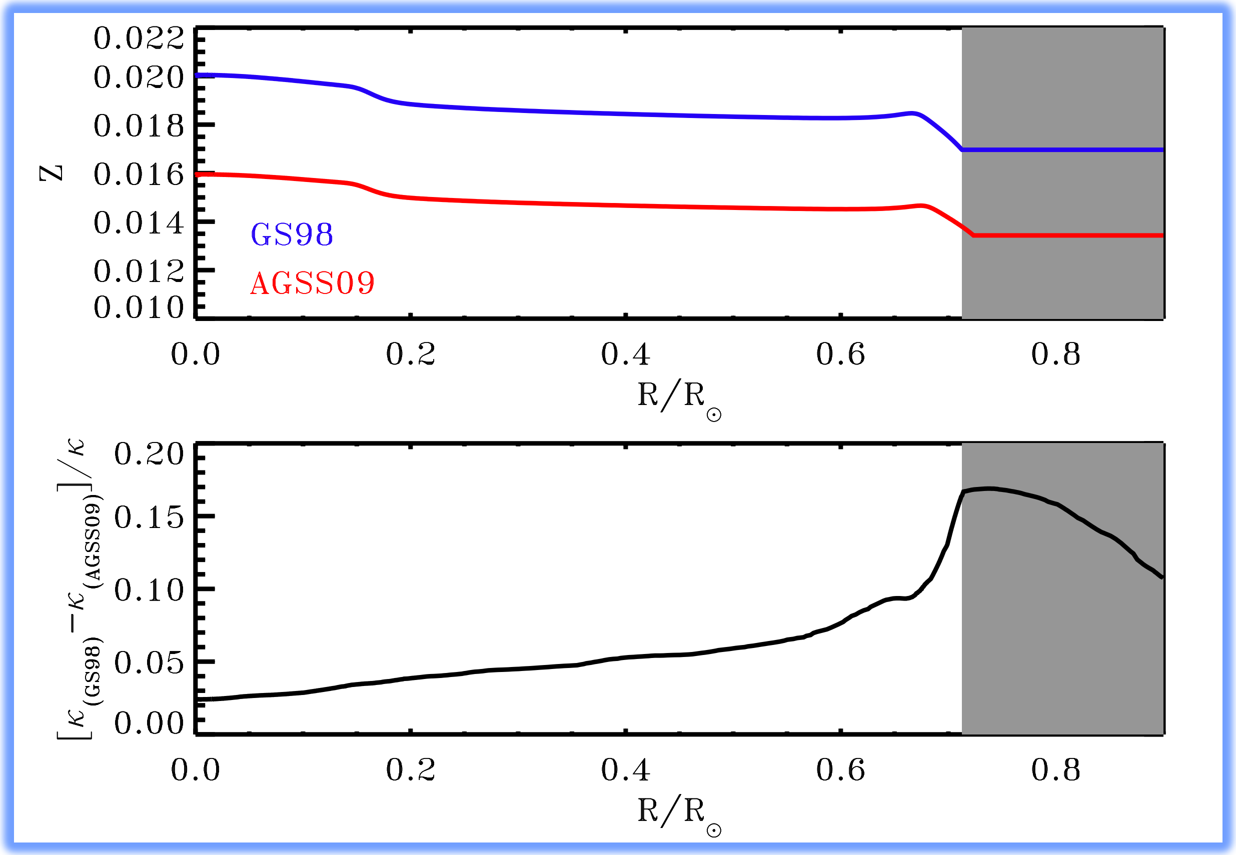
$A(i) = \log(n_i/n_H) + 12$

Changes also stem from selection of spectral lines (blends), improved atomic data, NLTE

Solar Composition: Opacity changes

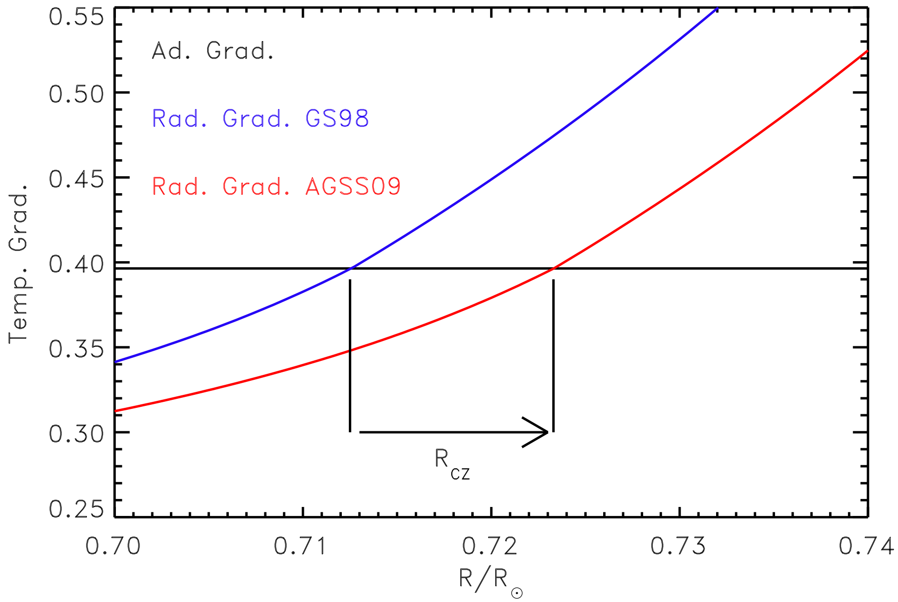
$$\left[\frac{dT^4}{dr}\right]_{\rm rad} \propto \kappa$$

Modifies model structure through the temperature stratification

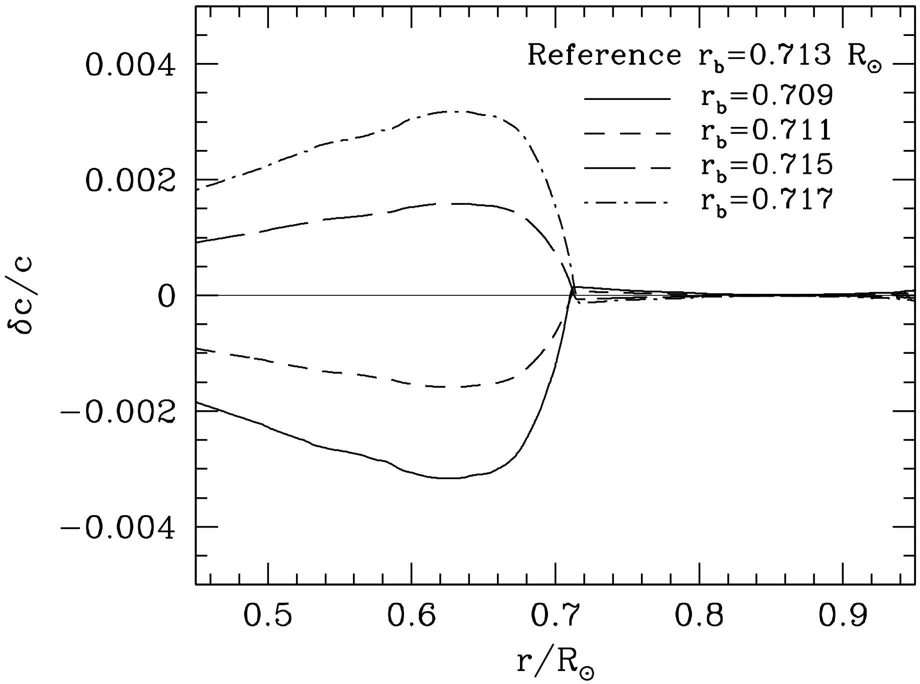


SSM: helioseismology

Temperature gradient displaced by change in opacity -- >
change in location of base of convective envelope



$$\nabla_{\rm rad} = \nabla_{\rm ad}$$



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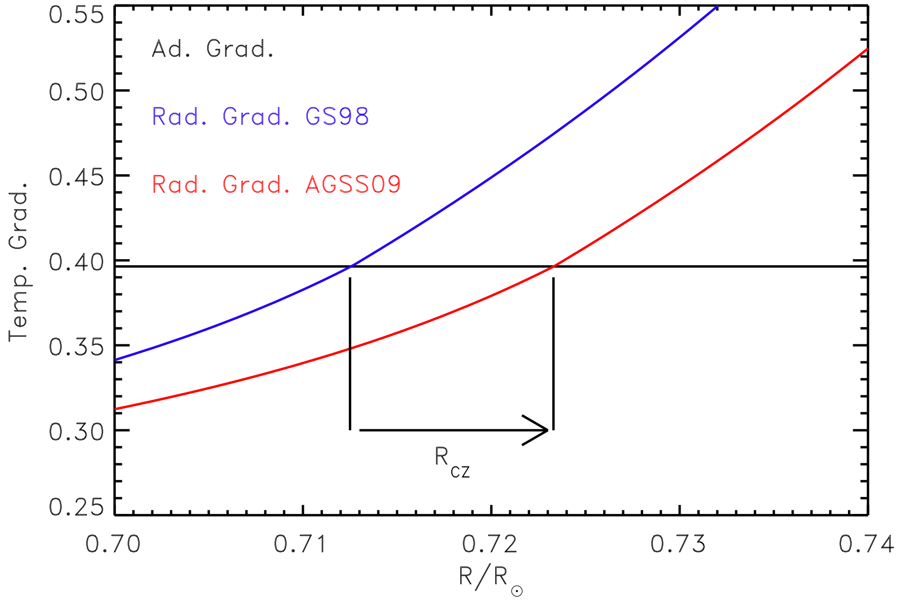

$$\nabla_{\rm rad} = \nabla_{\rm ad}$$

	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{\rm CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001

Large change in R_{CZ}

SSM: helioseismology

	α_{mlt}	Y_{ini}	Z_{ini}
$L_\odot$	0.06	2.35	-0.73
$R_\odot$	-0.19	0.56	-0.14
$(Z/X)_\odot$	0.06	0.08	1.11

$L_\odot$ well known -- > $0 \approx 2.35\,\delta Y_{\rm ini} - 0.73\,\delta Z_{\rm ini}$

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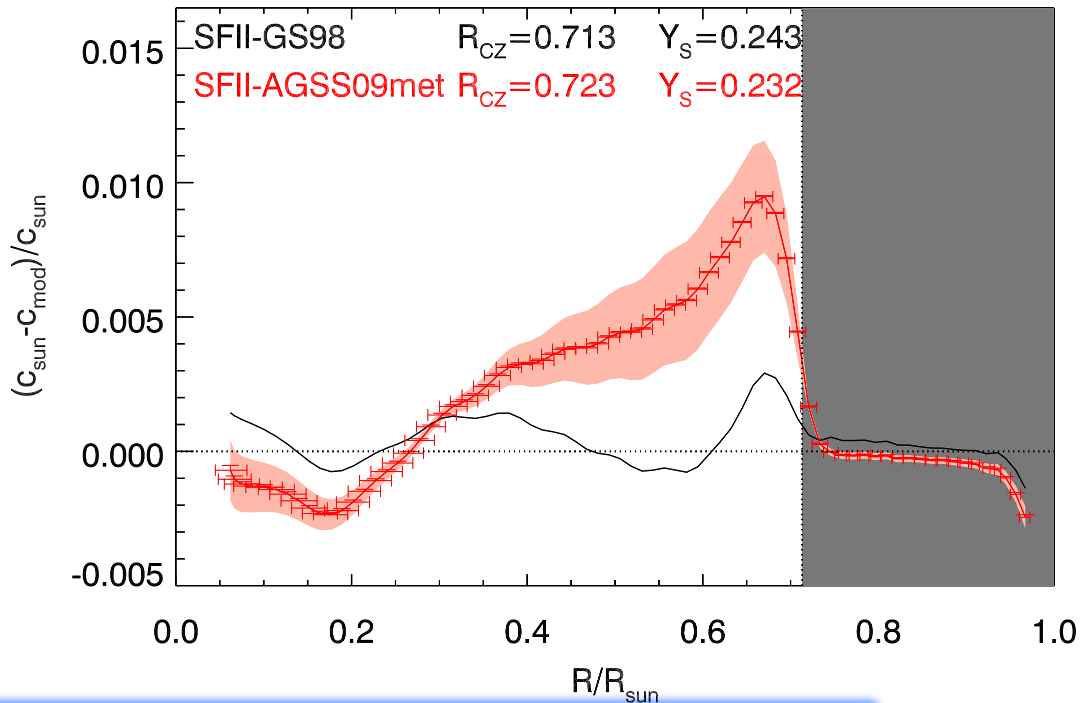
Decrease in initial Helium

SSM: helioseismology



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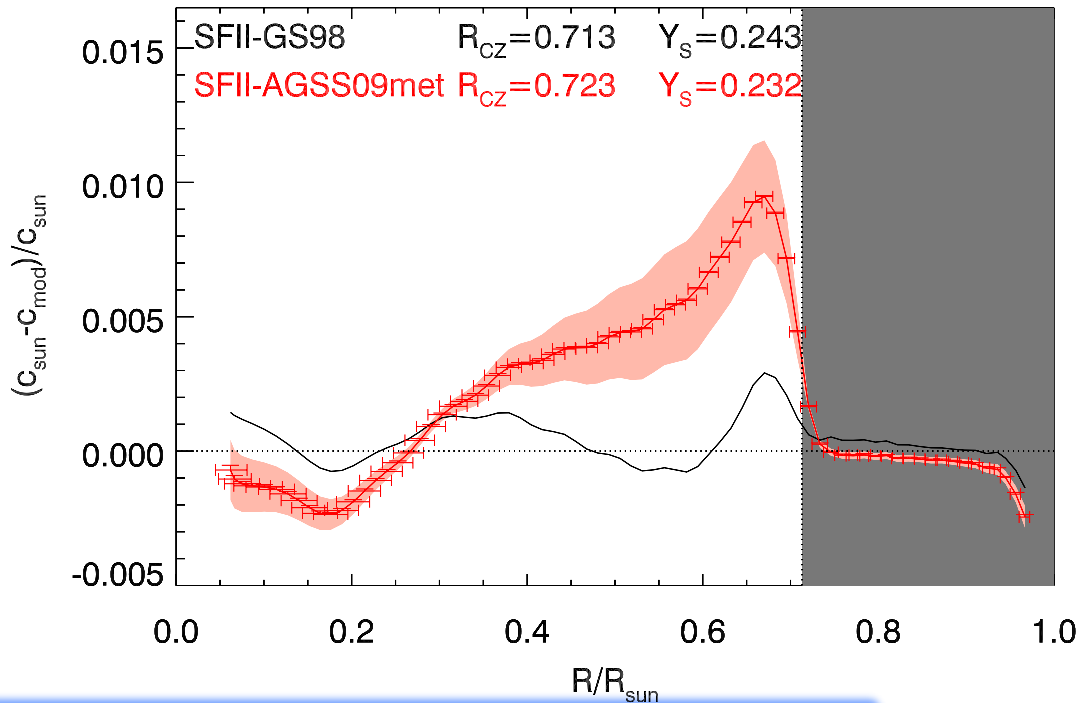
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta \rho/\rho \rangle$	0.011	0.040	—

Sound speed & Density

SSM: helioseismology



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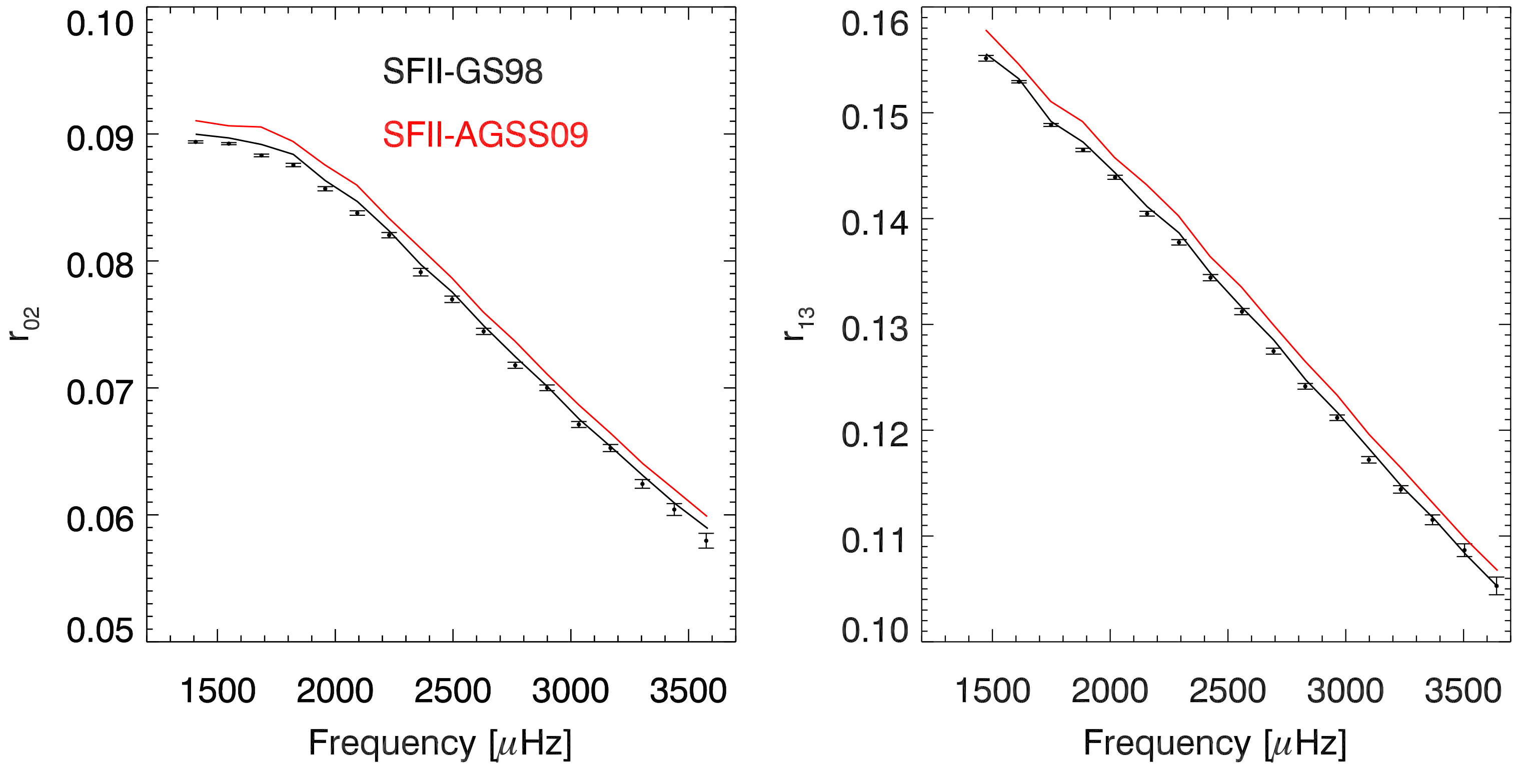
High-Z models are preferred

SSM: helioseismology

Frequency separation ratios – peeking into the solar core



Helioseismic predictions of SSM --> high-Z
Solar atmospheres & spectroscopy -- > low-Z

Solar Abundance Problem

SSM: neutrinos

Flux	SFII-GS98	SFII-AGSS09	Solar
pp	$5.98(1 \pm 0.006)$	6.03	$5.97(1 \pm 0.006)$
pep	$1.44(1 \pm 0.011)$	1.47	$1.45(1 \pm 0.009)$
hep	$8.04(1 \pm 0.30)$	8.31	$1.9(1 \pm 0.55)$
^{7}Be	$5.00(1 \pm 0.07)$	4.56	$4.80(1 \pm 0.048)$
^{8}B	$5.58(1 \pm 0.14)$	4.59	$5.16(1 \pm 0.02)$
^{13}N	$2.96(1 \pm 0.14)$	2.17	≤ 13.7
^{15}O	$2.23(1 \pm 0.15)$	1.56	≤ 2.8
^{17}F	$5.52(1 \pm 0.17)$	3.40	≤ 85

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

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Bergstrom et al. 2016 using all ν-experimental data
& luminosity constraint

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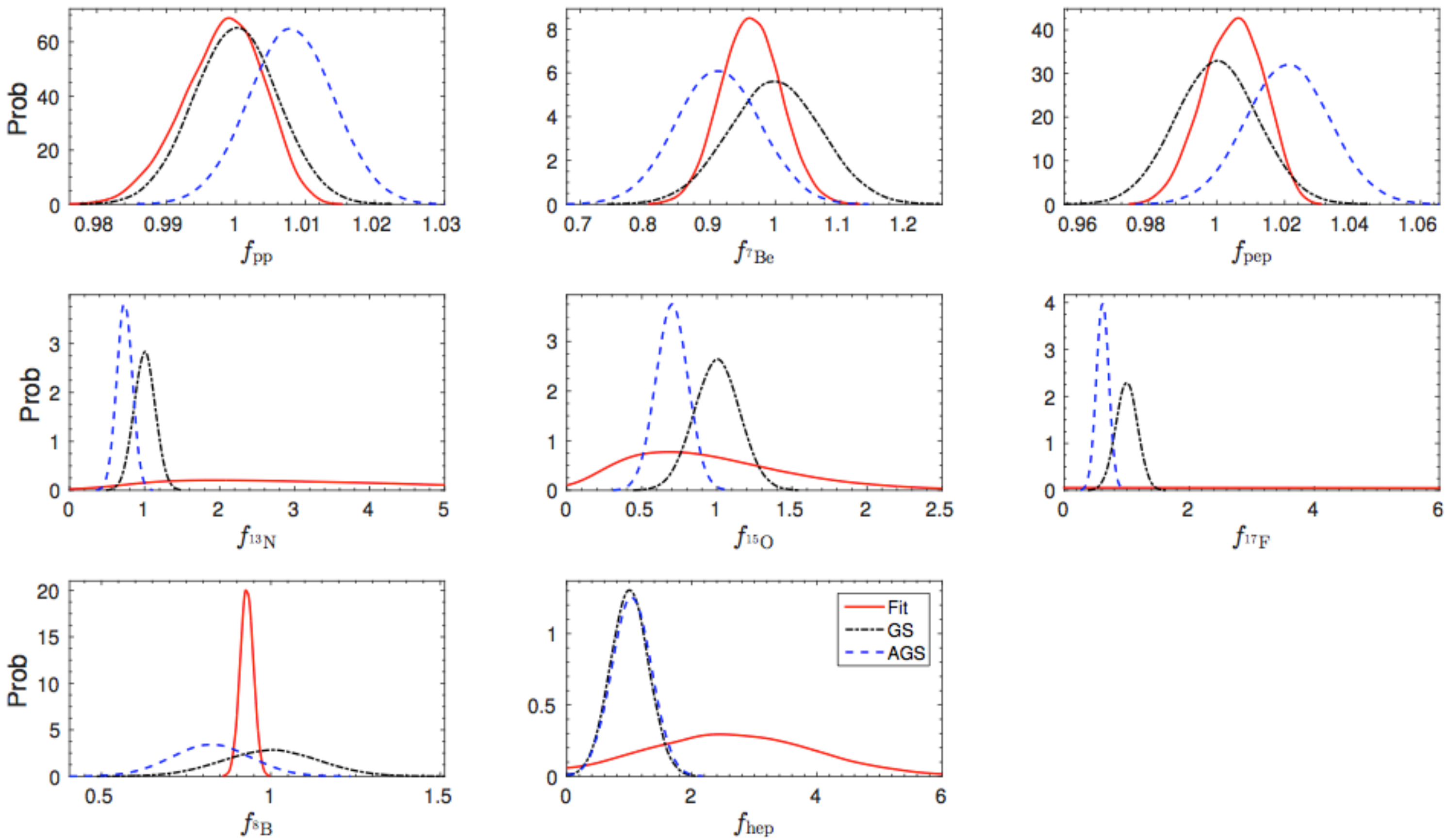
Solar luminosity determined from solar neutrinos

$$\frac{L_{\rm pp}}{L_\odot} = 0.991 \pm 0.005 \qquad \frac{L_{\rm CNO}}{L_\odot} = 0.009 \pm 0.005$$ with luminosity constraint

$$\frac{L_{\rm pp}}{L_\odot} = 1.03 \pm 0.07 \qquad \frac{L_{\rm CNO}}{L_\odot} = 0.008 \pm 0.005$$ without luminosity constraint

SSM: neutrinos

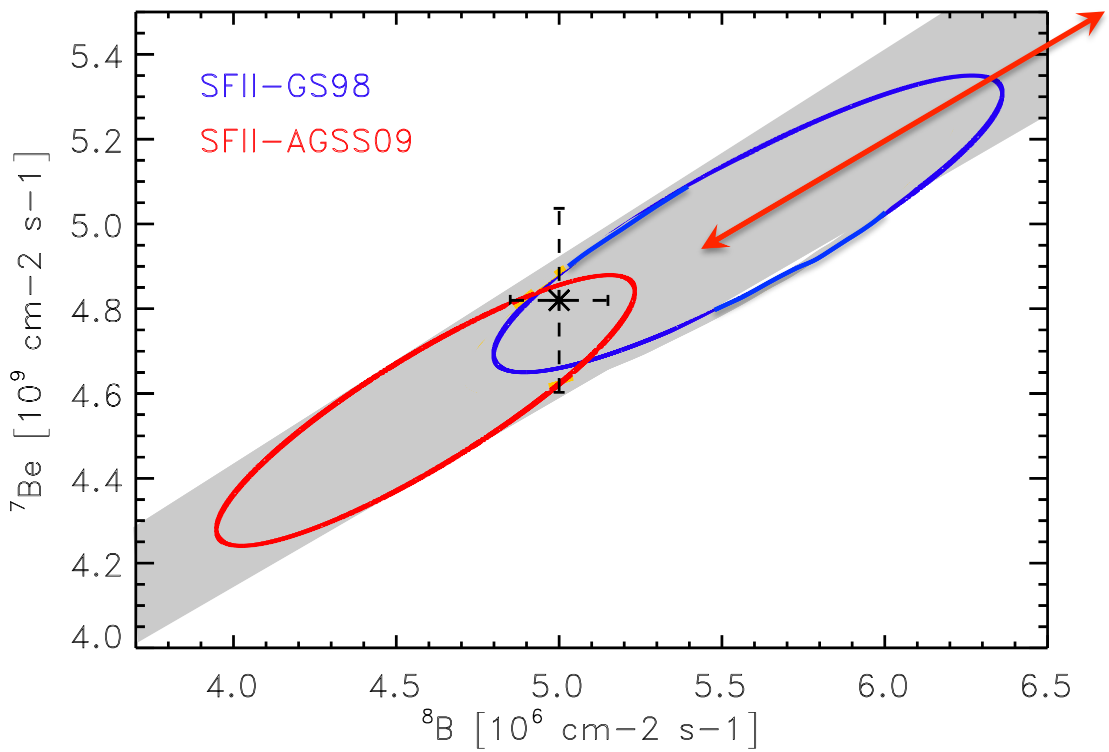


Current solar ν-data has no preference over any composition

SSM: neutrinos

Differences in pp-chain neutrinos results from temperature differences

Dependence on core temperature



pp-chain νs excellent to learn conditions in the core – but not directly composition

Composition – radiative opacity degeneracy

* all robust helioseismic probes
* pp-chain neutrinos

→ depend on T stratification, i.e. energy transport not directly on composition

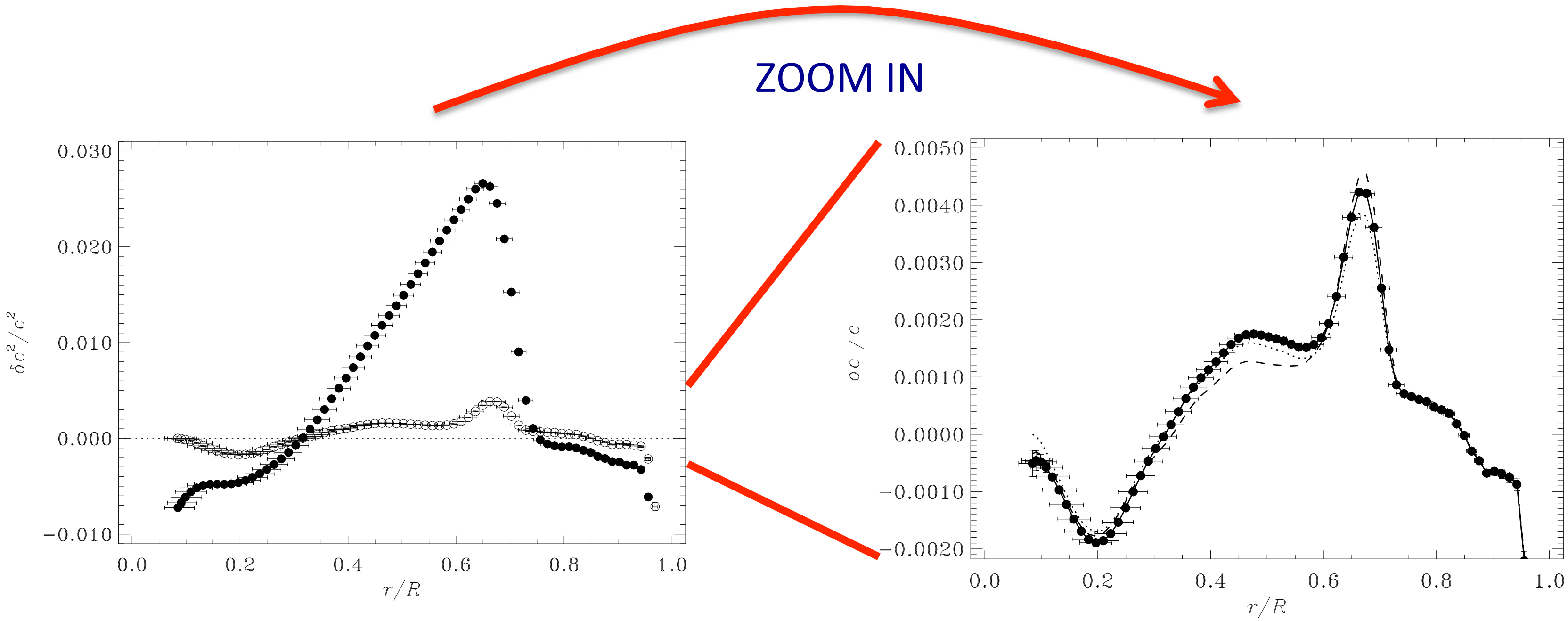
in solar interior T grad. scales with radiative opacity κ

degeneracy between κ and composition

Seismic data and pp-chain neutrinos constrain radiative gradient / opacity profile

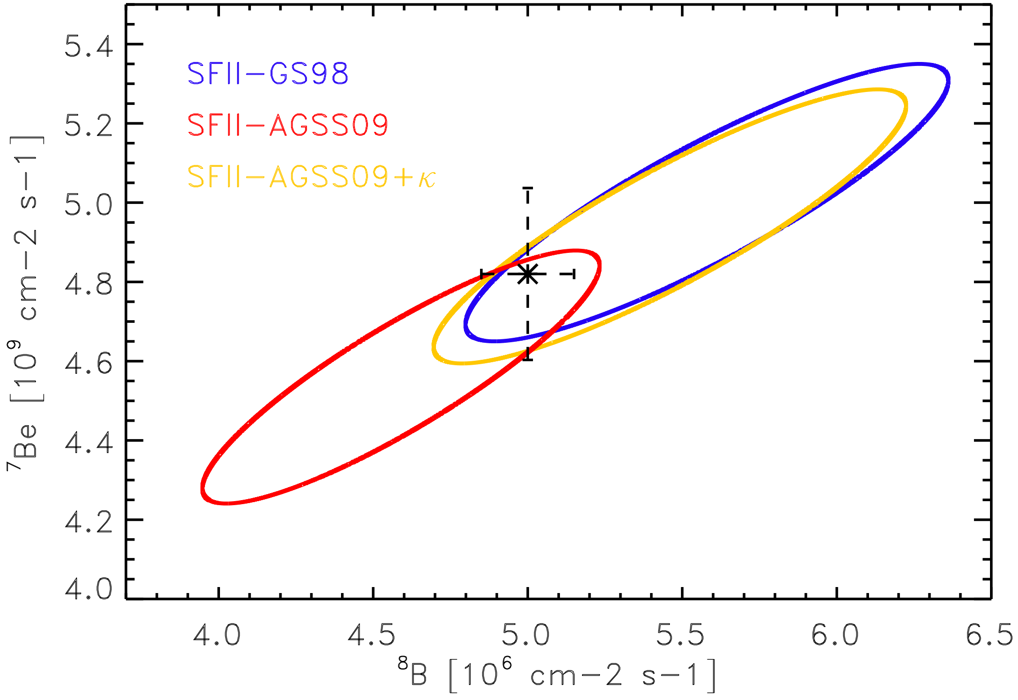
Composition – radiative opacity degeneracy

Modify opacity profile -- > agreement with helioseismology



Christensen Dalsgaard et al 2009

SSM: neutrinos



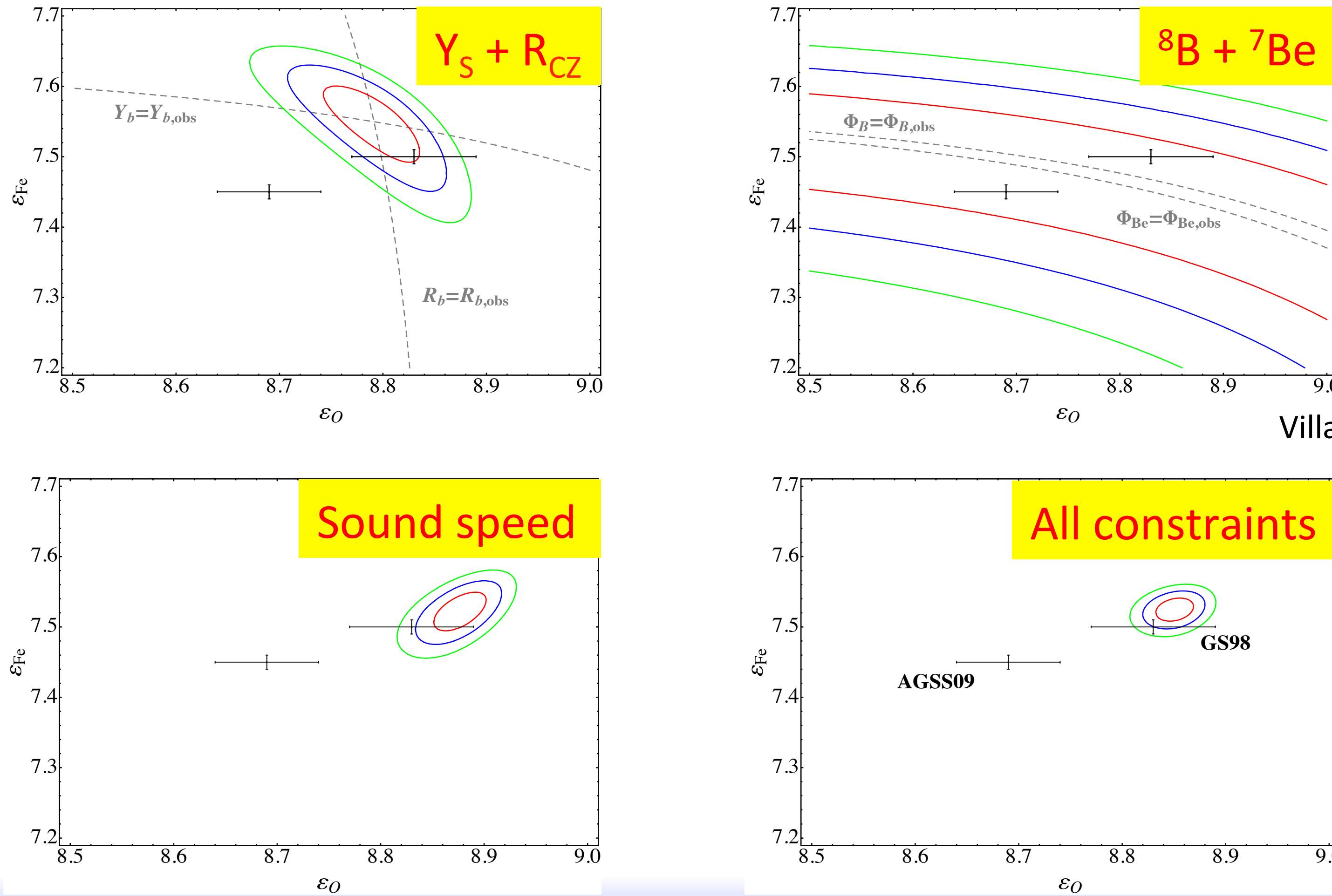
In terms of solar composition, ^{7}Be and ^{8}B fluxes are degenerate with core temperature

Difficult to extract information on abundances –

Example: degeneracy between opacity and composition

Solar composition – a 2-parameter analysis w/helioseismology

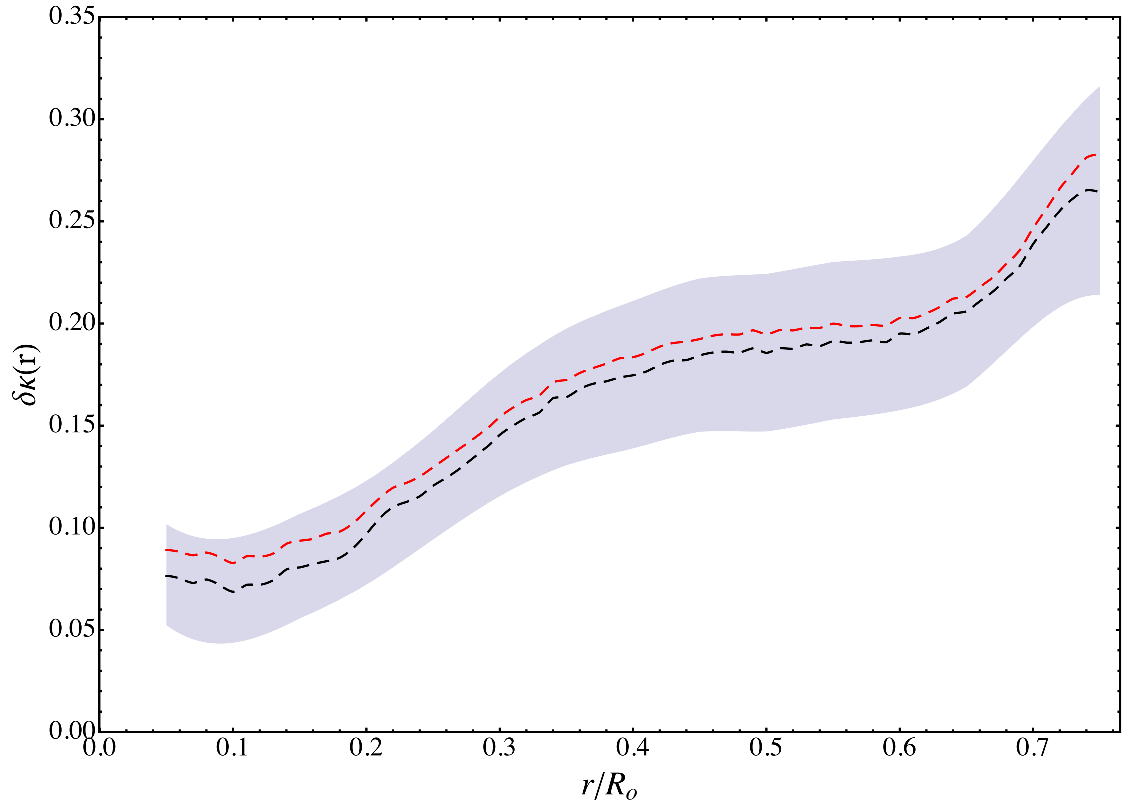
Based on linearized solar models
Volatiles (C, N, O, Ne) & Refractories (S, Si, Fe, etc.)



Villante et al. 2014

Composition – radiative opacity degeneracy

Using helioseismic data and solar neutrinos – obtain solar opacity profile

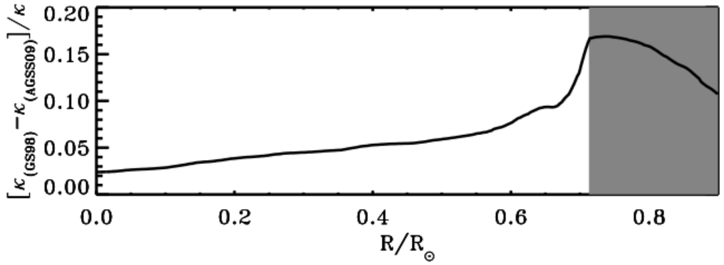


Villante et al. 2014

Fractional opacity difference wrt AGSS09 solar model

few % center to 20% at convective boundary

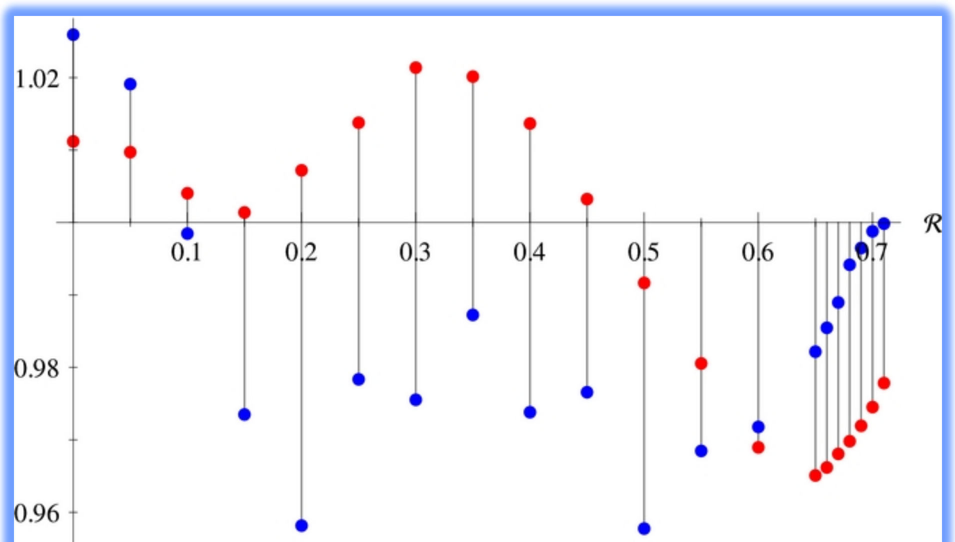
Opacity: 3 different theoretical calculations



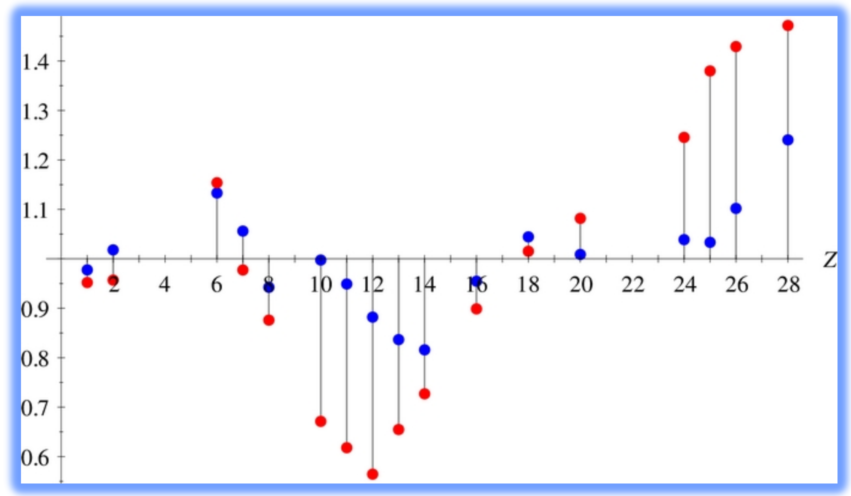
"Loss" of opacity ~15-20% at base of CZ

3-4% center

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



Rosseland mean in solar interior – smallish differences < 4%

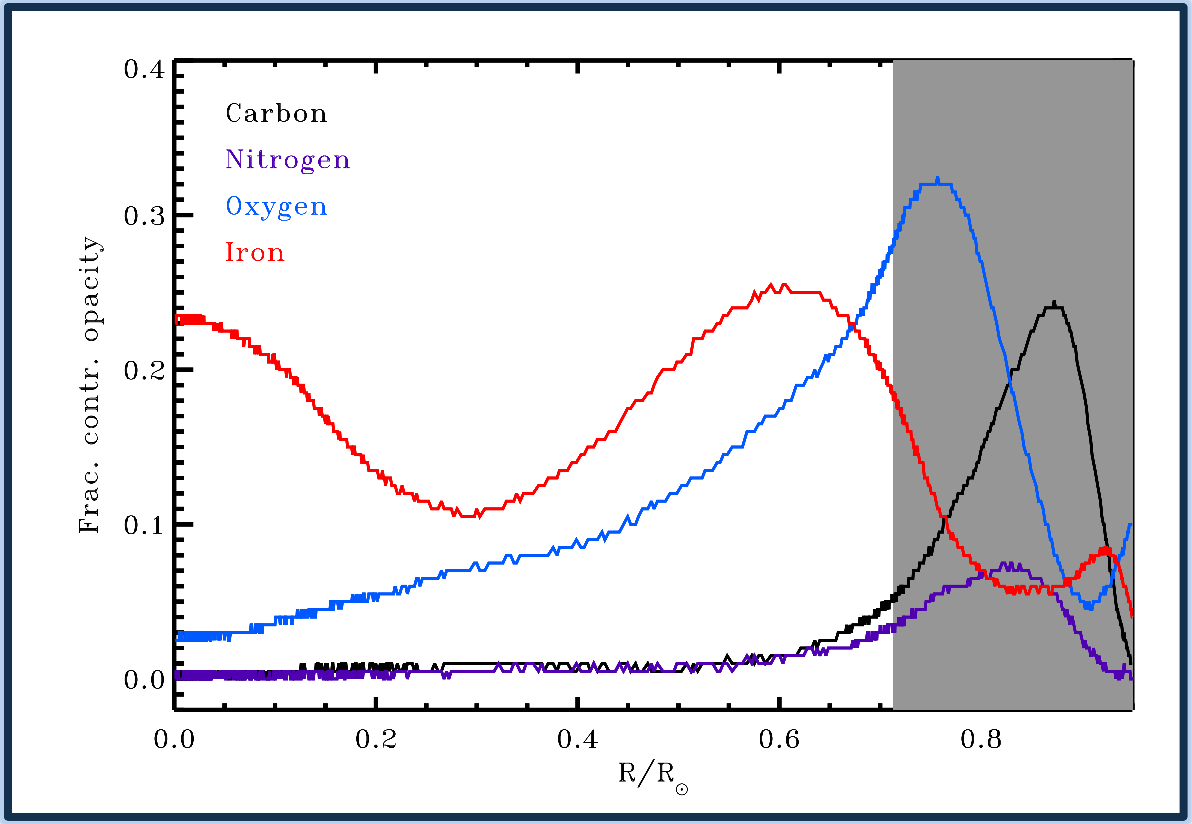


Element contribution at base of CZ much larger differences

Blancard et al. (2012)

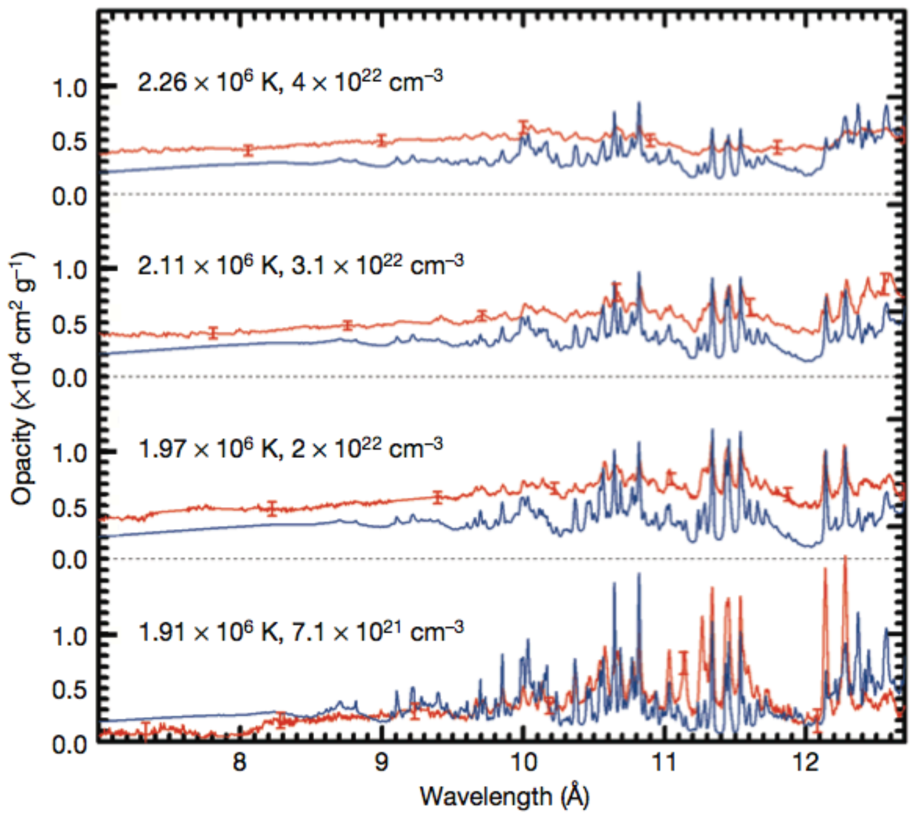
Opacity: recent experiment on Fe

Iron is important for opacity

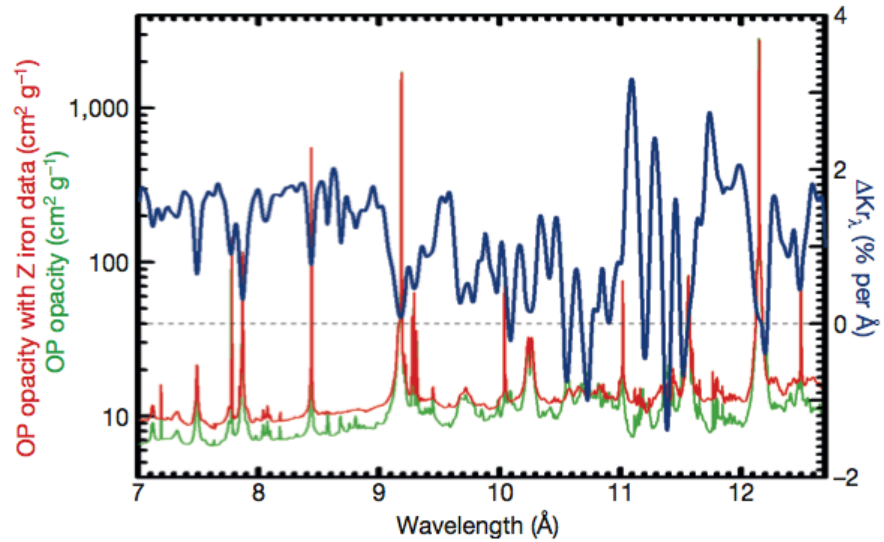


Opacity: recent experiment on Fe

@Sandia lab – Z-facility – conditions close to solar (factor 4 too low in density)



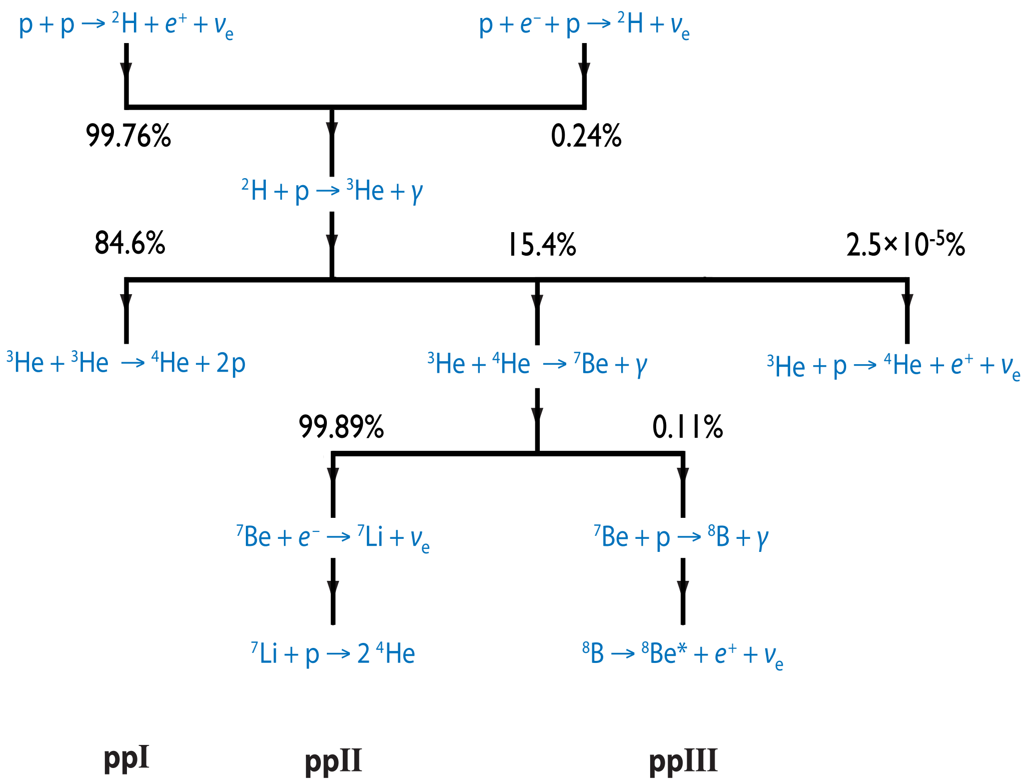
Bailey et al. 2015



When included in Rosseland mean
-- > 7% increase (15-20% needed)

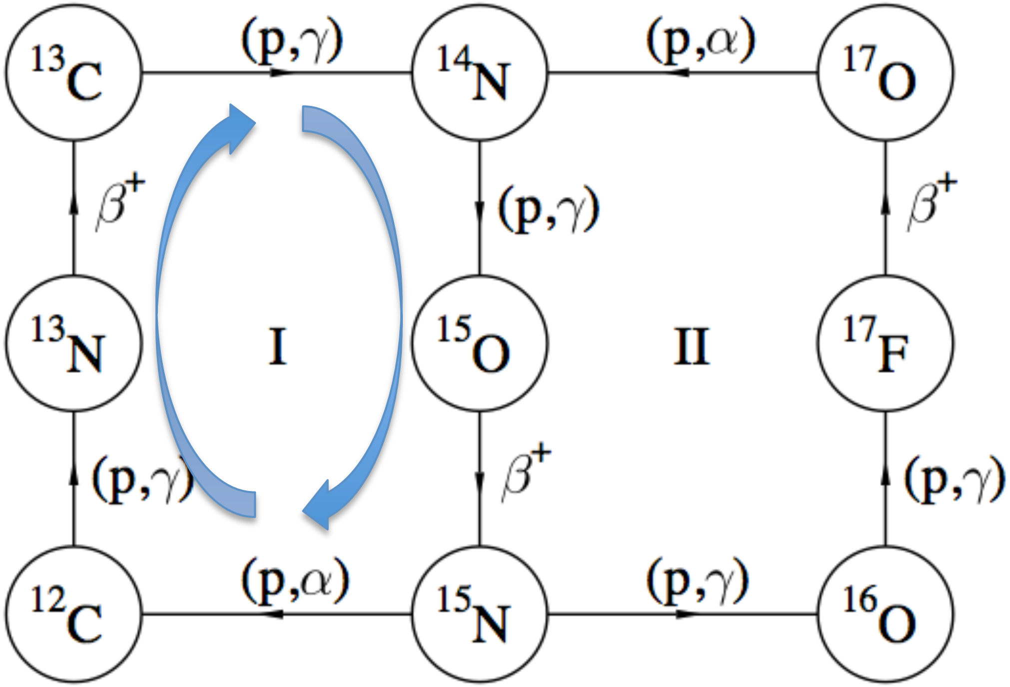
Opacity – Composition: breaking the degeneracy

No direct information on composition in pp-chains –
but determine conditions in the core (pp flux, mainly)



Opacity – Composition: breaking the degeneracy

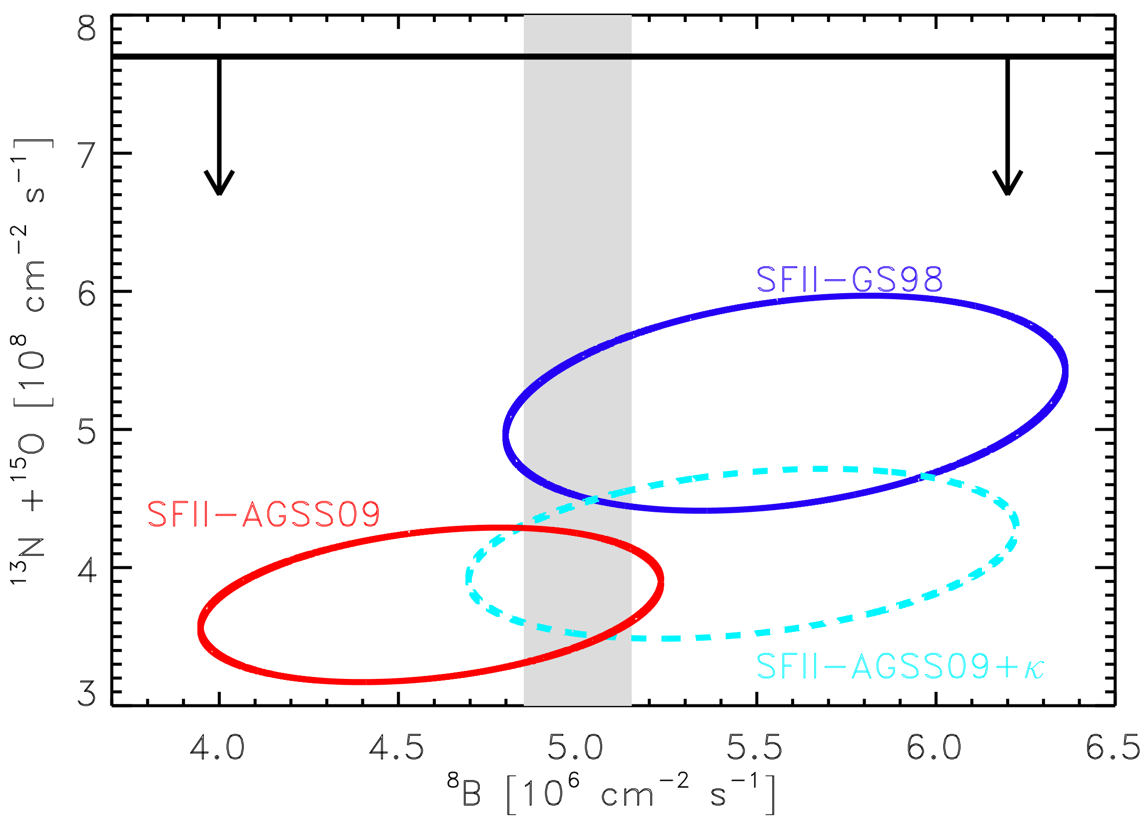
CNO-bicycle – secondary process
CNO abundances catalyze the cycles – in practice only care about CN-cycle



Energetically marginal < 1% -- > very sensitive to changes in conditions (like ^{8}B)
C+N abundances determine total rate of CN cycle

Opacity – Composition: breaking the degeneracy

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



Upper limit by Borexino

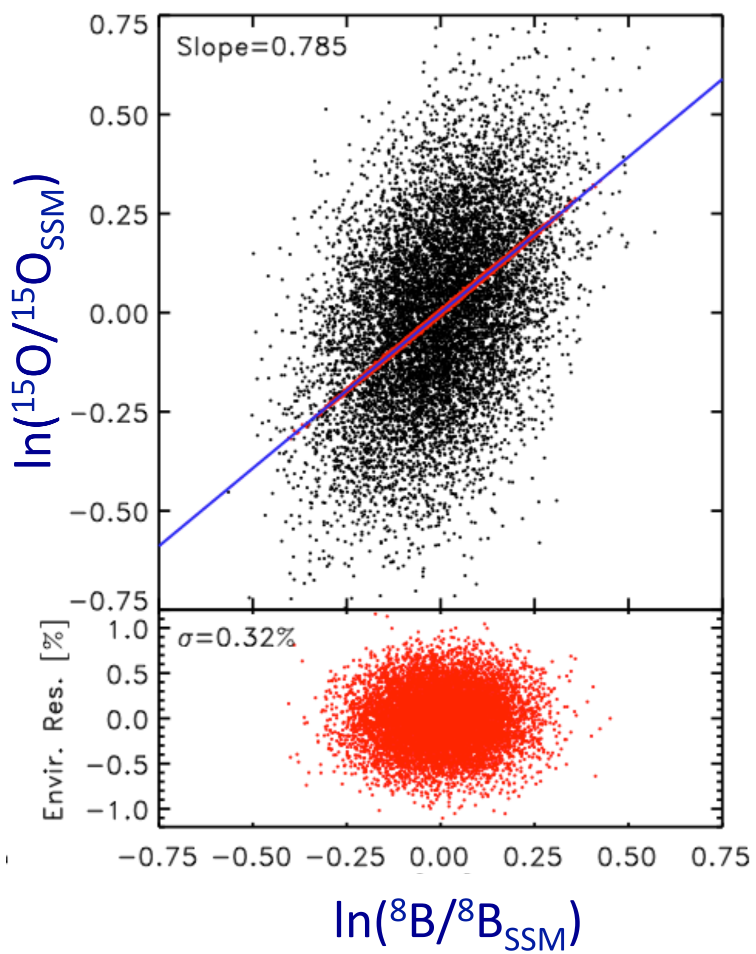
^8B as a Thermometer

Environmental parameters: determine temperature of solar core
Nuclear rates: affect individual reactions
C+N: catalyze CN-cycle

^8B very sensitive to temperature
-- > good thermometer

Relate to CN fluxes (here ^{15}O)

Residuals from environmental quantities ~ 0.3 % -- > fixing ^8B (measurement) reduces uncertainty from envir.



C+N abundance from CN measurement

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.

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

Nuclear uncertainty: S_{11} & S_{17} (~7% each) + experimental uncertainty in CN fluxes

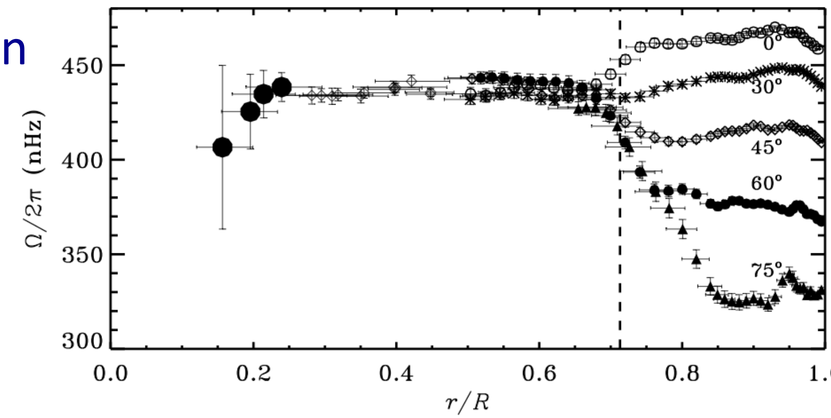
Comparable precision to spectroscopic measurements

Beyond solar composition problem: test for mixing processes in the Sun

Is this the limit for SSM framework?

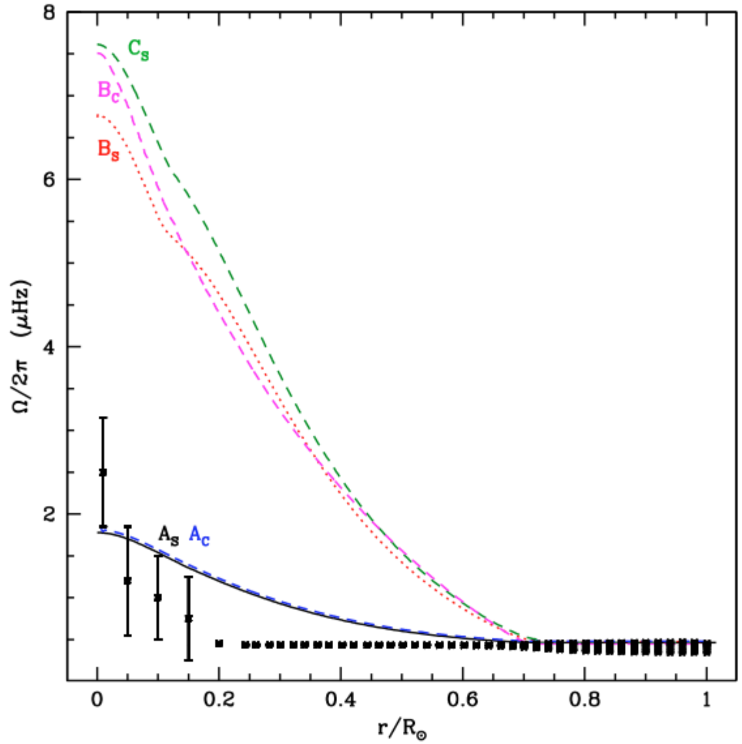
SSM does not account for: rotation, magnetic fields, internal (g) waves, etc.

Solar rotation



Thompson et al. 2003

Solar models w/rotation

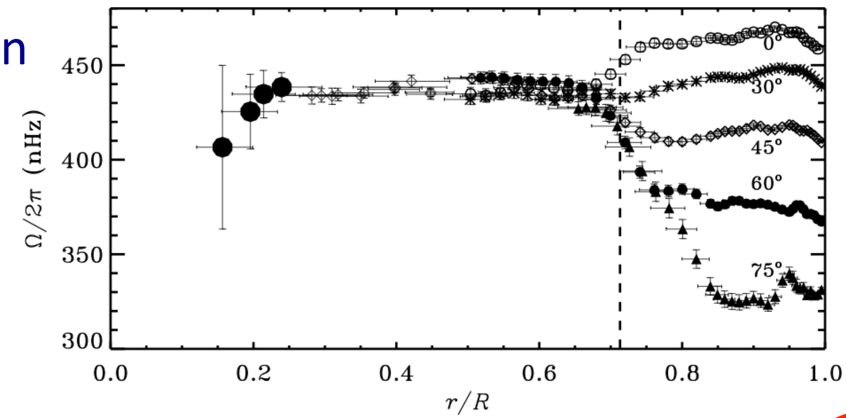


Turck-Chieze et al. 2010

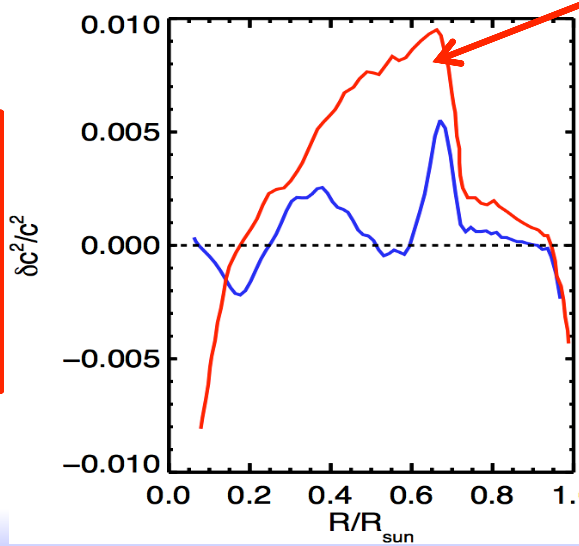
Beyond the SSM

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

Solar rotation

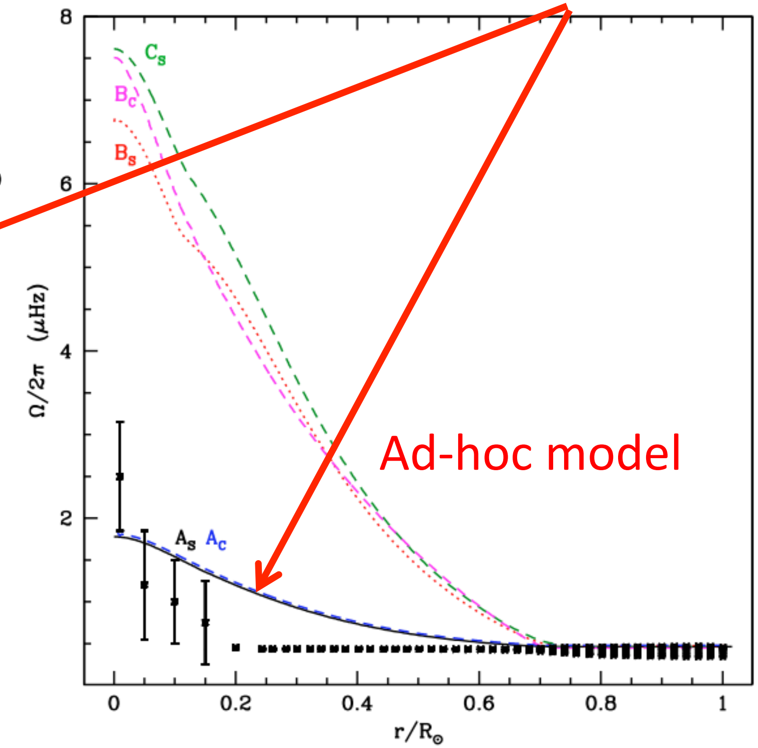


Thompson et al. 2003



Transport of angular momentum not understood

Solar models w/rotation



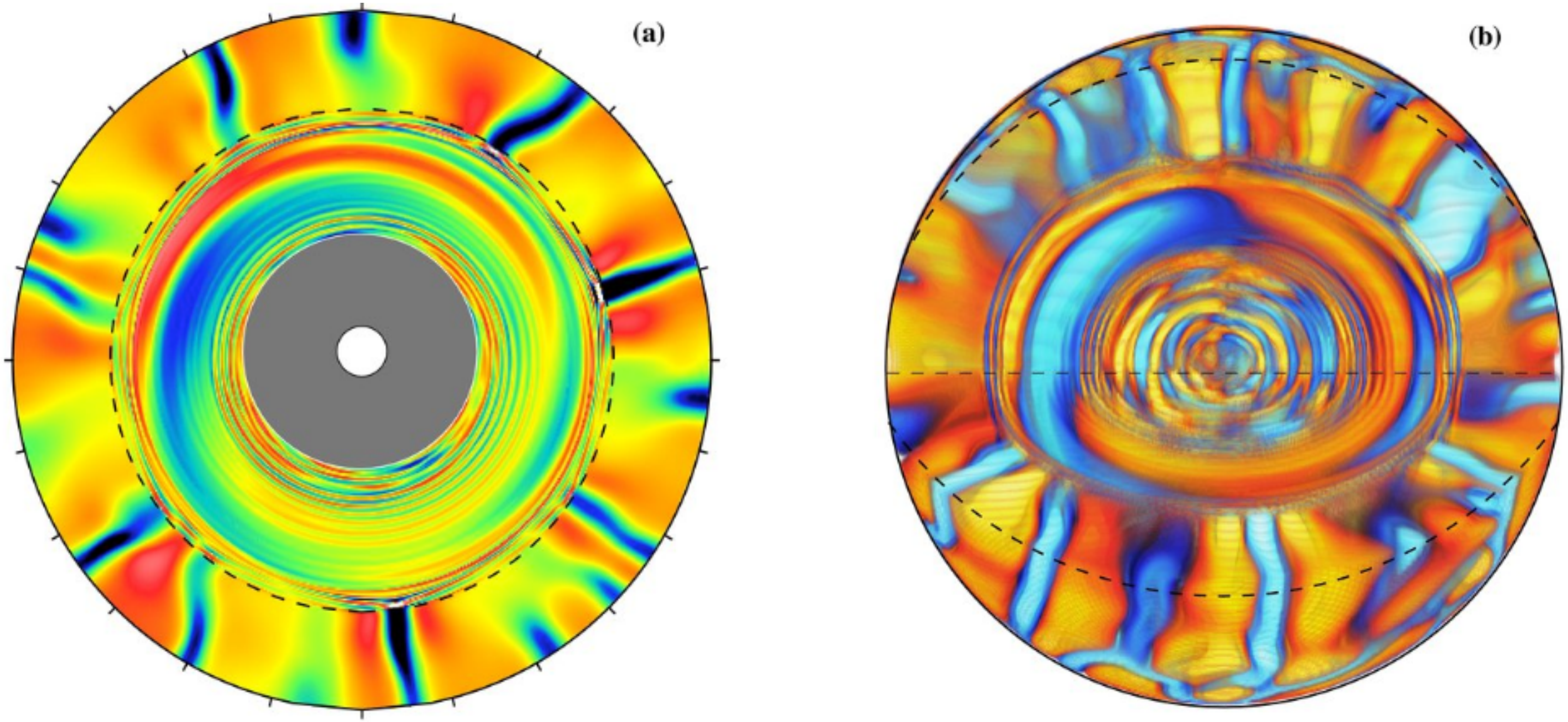
Ad-hoc model

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

Solar abundance problem -
- discrepancy in helioseismic properties of model
- no preference from current neutrino data
  - actually probes of opacity (temperature) solar profile
  - degeneracy between composition & opacities

Intrinsic limitation of framework standard solar (stellar) models?

Or "simply" inadequate microscopic physics (atomic opacities)?

CN neutrinos most direct probe of C+N composition in solar core
- big step forward in breaking the degeneracy
- beyond abundance problem: test of mixing processes in the Sun

SSM has intrinsic limitations because: no rotation, no magnetic fields
- current understanding from 1D models very poor