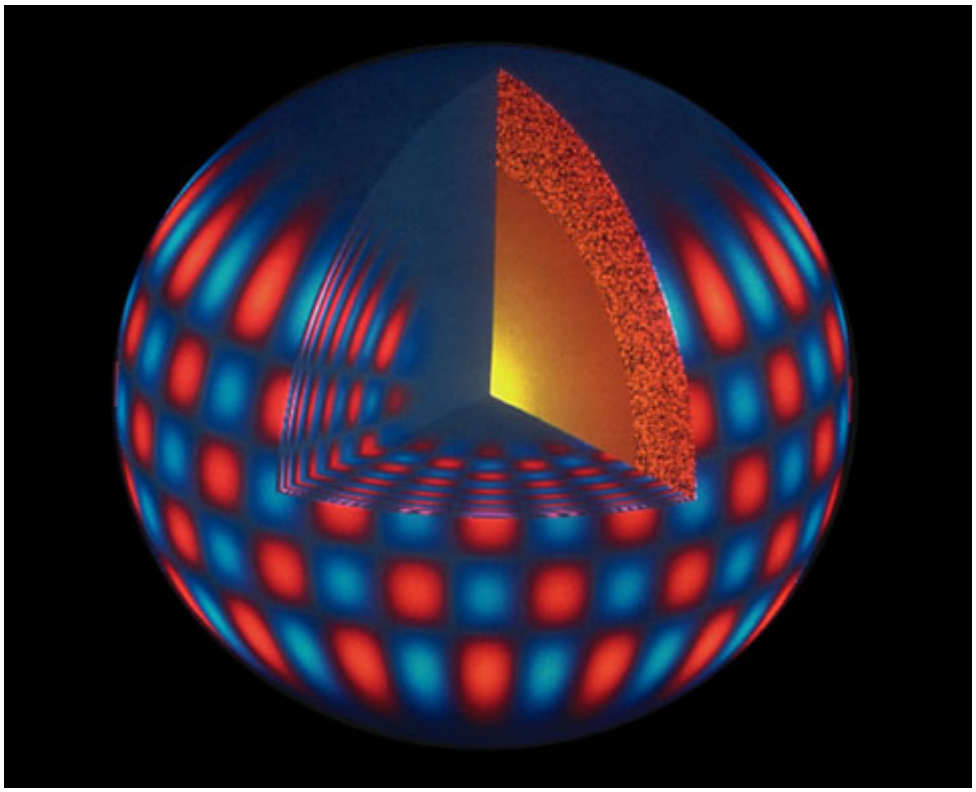
Solar Modeling and Opacities



Joyce Ann Guzik

Los Alamos National Laboratory

Tri-Lab Opacity Workshop
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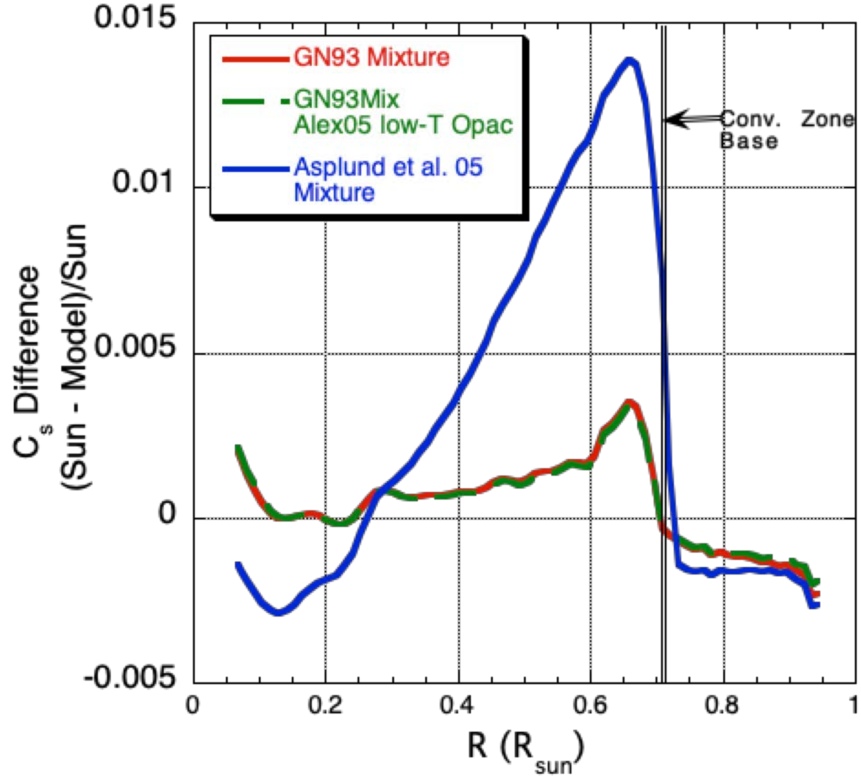
The solar abundance problem

- Until 2004, we thought we knew very well the interior structure of the Sun, and how it reached its present state.
- However, new analyses of the Sun's spectral lines (Asplund et al. 2005) revise *downward* the mass fraction of elements heavier than H and He, particularly the abundances of O, C, and N.
- Models evolved with the new abundances give worse agreement with helioseismic constraints



How can this discrepancy be resolved? Should we adopt the new abundances?

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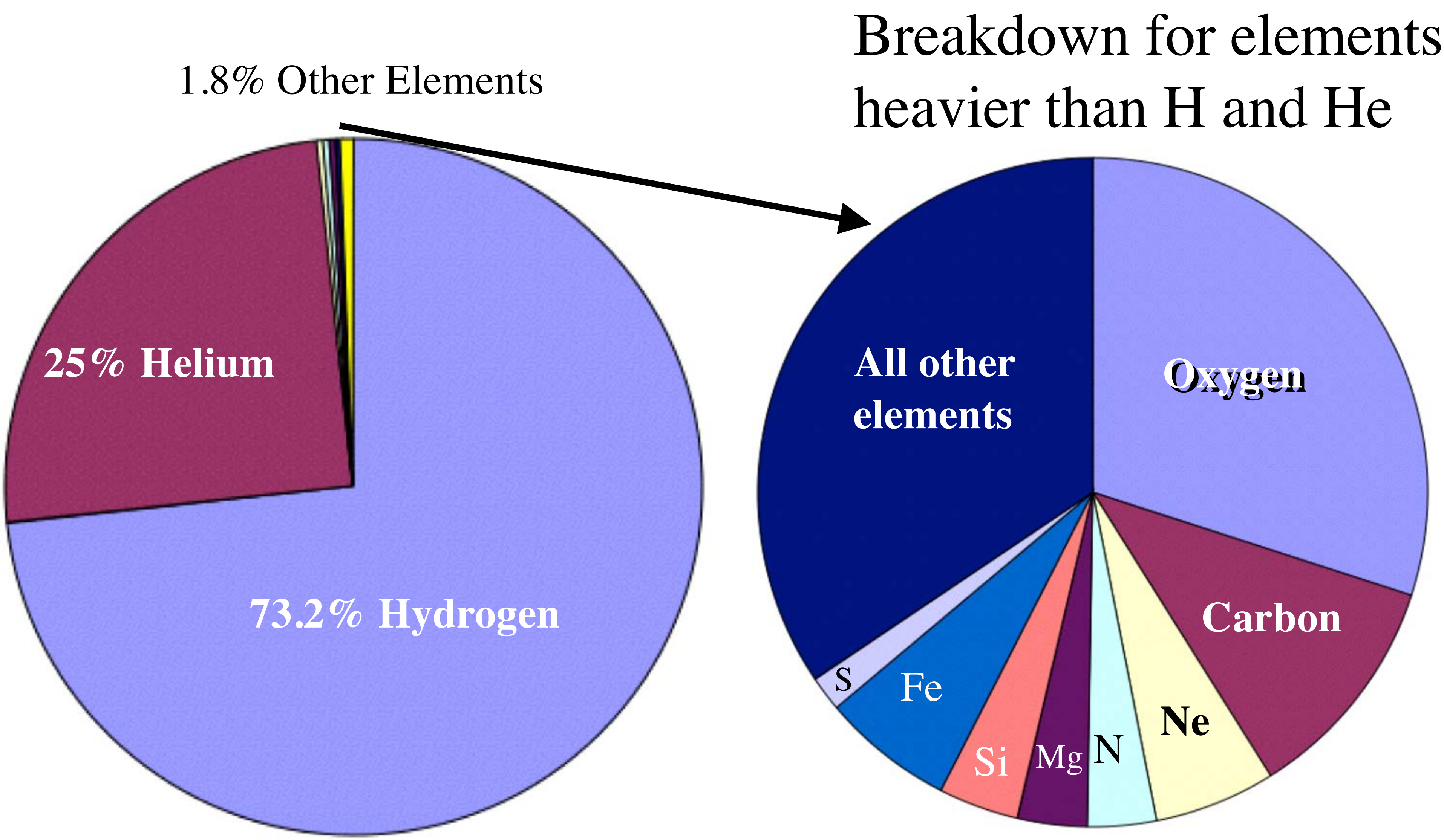
Which is the actual problem?

- The solar *abundance* problem
- The solar *opacity* problem
- The solar *modelling* problem

Outline for talk

- Standard solar model
- Constraints from helioseismology
- Some attempts to reconcile models and observations
- LLNL *OPAL* vs. LANL *OPLIB* opacities

Surface composition of the Sun by mass



Asplund et al. (2005) abundances decreased from previous Grevesse & Sauval (1998) determination

Oxygen	**48% decrease**	8.66±0.05 (*cf* GS98 8.83±0.06)
Carbon	**35% decrease**	8.39 ± 0.05 (*cf* GS98 8.52±0.06)
Nitrogen	**27.5% decrease**	7.78±0.06 (*cf* GS98 7.92±0.06)
Neon	**74% decrease**	7.84 ± 0.06 (*cf* GS98 8.08 ± 0.06)
Argon	**66% decrease**	6.18 ± 0.08 (*cf* GS98 6.40 ± 0.06)

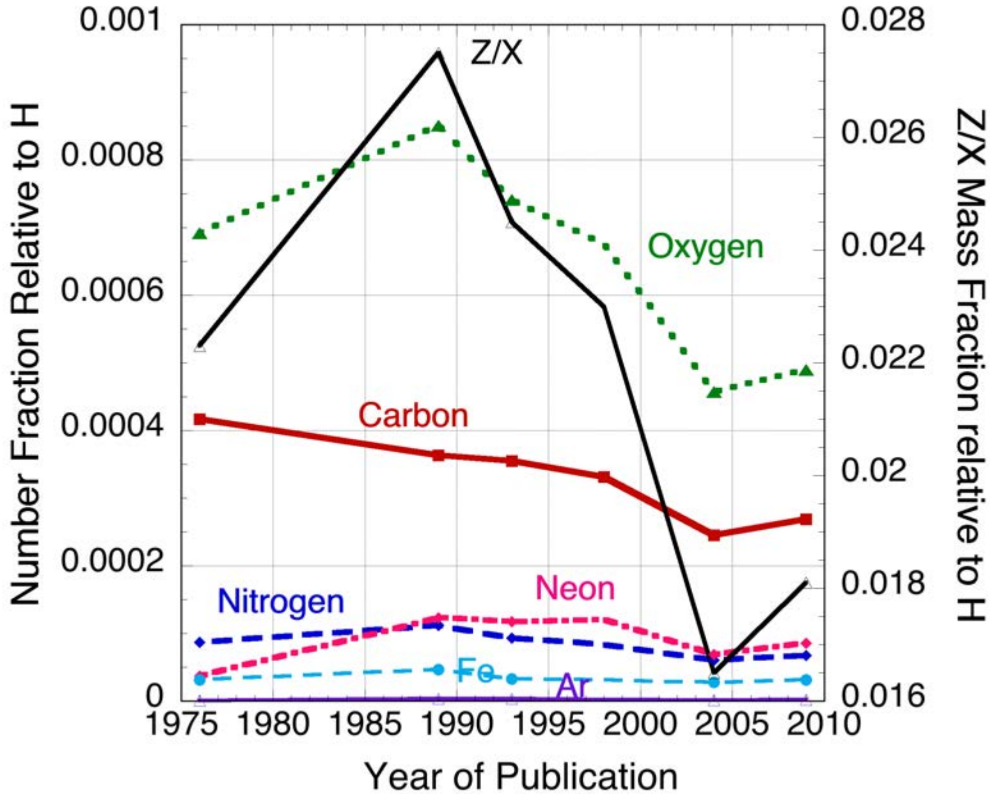
Na to Ca: lower by 0.05 to 0.1 dex (12 to 25%)

Fe: 7.45 ± 0.05 (*cf* GS98 7.50 ± 0.05) **12% decrease**

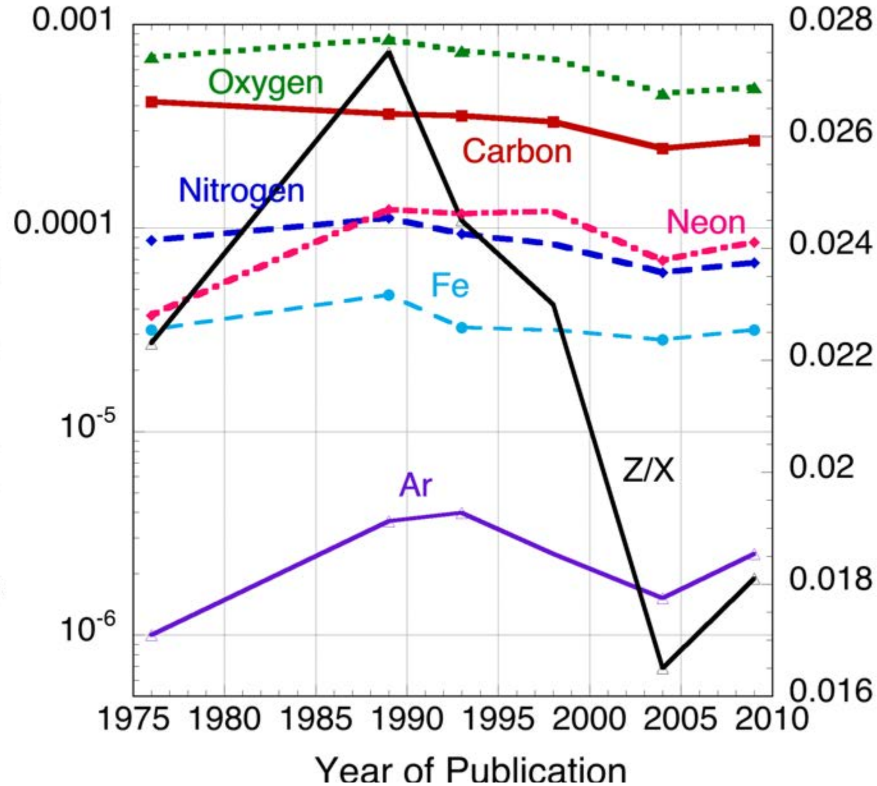
Revised mass fraction of 'metals' at Sun's surface (Z) is only 0.0122 (instead of 0.018)

Published solar abundance determinations have varied since 1976

Linear Scale



Log Scale



Variations over the years are larger than published uncertainties

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What input physics is needed for standard solar interior/evolution modeling?

- Element abundances
- Opacities (radiative, conductive, low-temp.)
- Equation of state
- Nuclear reaction rates
- Convection treatment
- Diffusive settling/radiative levitation
- Surface boundary condition/model atmosphere

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Some physics is usually omitted in standard solar interior/evolution modeling

- Rotation and rotation-induced mixing
- Magnetic fields
- Mass loss
- Convective overshoot
- Mixing and momentum and energy transport due to acoustic or gravity waves
- Turbulence driven by instabilities, turbulent pressure and energy

These requires multi-dimensional modeling, or occur on timescales significantly shorter than the evolution timescale

In some cases, a parametrized treatment has been implemented in 1D evolution models, based on 2D and 3D localized models

For the old abundances, the simplest 'spherical sun' assumptions resulted in good agreement with helioseismic tests

- One-dimensional
- Initial homogeneous composition
- Negligible mass loss or accretion
- No effects of rotation or magnetic fields
- No additional mixing or structure changes from
  - convective overshoot
  - shear from differential rotation
  - meridional circulation
  - waves or pulsations
- Simple surface boundary conditions

For the old abundances, the latest physical data produced models in agreement with helioseismic tests

Input physics for calibrated solar models

- **Opacities**
  - LLNL OPAL (Iglesias & Rogers 1996)
- **Low-temperature Opacities**
  - Alexander & Ferguson 1995; Ferguson et al. 2004
- **Equation of State**
  - SIREFF in-line (Guzik & Swenson 1997)
- **Nuclear Reaction Rates**
  - NACRE (Angulo et al. 1999)
- **Convection Treatment**
  - Bohm-Vitense (1958) mixing-length theory
- **Diffusive Element Settling Treatment**
  - Burgers 1969; Cox, Guzik & Kidman 1988; includes thermal, gravitational, and chemical diffusion of H, He, C, N, O, Ne, Mg, electrons

Stellar Structure Equations (1)

1) $$\frac{dr}{dM} = \frac{1}{4\pi r^2 \rho}$$

Mass conservation

2) $$\frac{dP}{dM} = -\frac{GM_r}{4\pi r^4}$$

Hydrostatic equilibrium

3) $$\frac{dL}{dM} = \varepsilon - \frac{TdS}{dt}$$

Thermal equilibrium
(note time derivative)

$$\boxed{dQ = TdS = dU + PdV}$$

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Stellar Structure Equations (2)

4) Temperature gradient

$$\frac{dT}{dM} = -\frac{3}{4ac}\frac{\kappa_g}{T^3}\frac{L_r}{16\pi^2 r^4}$$

radiative diffusion

or, if $\boxed{\nabla_{rad} > \nabla_{ad}}$

$$\frac{\Gamma_2 - 1}{\Gamma_2} = \left(\frac{\partial \ln T}{\partial \ln P}\right)_S = \nabla_{ad}$$

$$\frac{dT}{dM} = \frac{\Gamma_2 - 1}{\Gamma_2}\frac{T}{P}\frac{dP}{dM}$$

convection

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Standard solar model evolution

- Divide Sun's mass in into several hundred radial zones

- Run model forward for several hundred timesteps from the time the Sun starts to burn H in core to the present time (4.52 billion years later)

- Compare model properties to observations of the present Sun: *radius, luminosity, mass, surface composition (Z/X)*

- If the result disagrees, adjust initial helium abundance, Z abundance, and mixing length parameter, and rerun

Solar model calibration

Radius	**6.9599 x 10^{10} cm** (Allen 1973)
Luminosity	**3.846 ± 0.005 x 10^{33} erg/s** (Willson et al. 1986)
Mass	**1.9891 ± 0.0004 x 10^{33} g** (Cohen & Taylor 1986)
Age	**4.52 ± 0.04 Gyr** (Guenther et al. 1992)

Photospheric element mixture and surface Z/X (elements/hydrogen)

0.0245 ± 0.0015 (Grevesse & Noels 1993, GN93)
0.0230 ± 0.0023 (Grevesse & Sauval 1998, GS98)
0.0165 ± 0.0017 (Asplund et al. 2004, 2005, AGS05)
0.0177 (Lodders 2003)
0.0181 (Asplund et al. 2009, AGSS09)

Solar model calibration

Helium abundance, initial Z, Y and mixing length (α) are adjusted to match solar L, R, and Z/X at present solar age

	Grevesse & Noels 1993 Mixture	**Asplund, Grevesse & Sauval 2005 Mixture**	*Helioseismic inference (Basu & Antia 2004)*
$\mathbf{Y_o}$	0.2703	0.2570	
$\mathbf{Z_o}$	0.0197	0.0135	
α	1.7698	1.9948	
$\mathbf{Y_{surface}}$	0.2418	0.2273	0.248 ± 0.003
$\mathbf{R_{czb}\ (R_{sun})}$	0.7133	0.7306	0.713 ± 0.001

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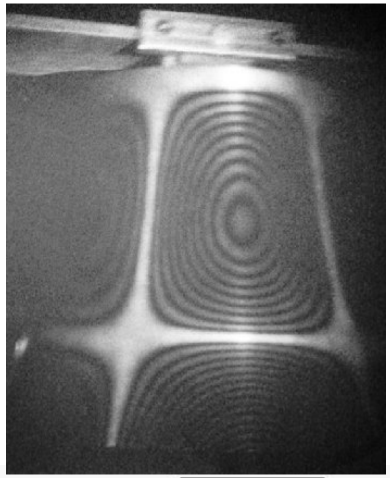
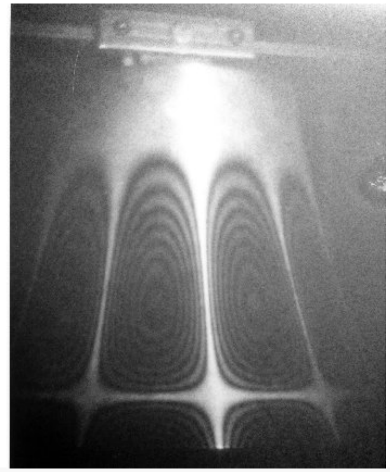
The Sun oscillates in thousands of acoustic modes, in a similar way to this bell

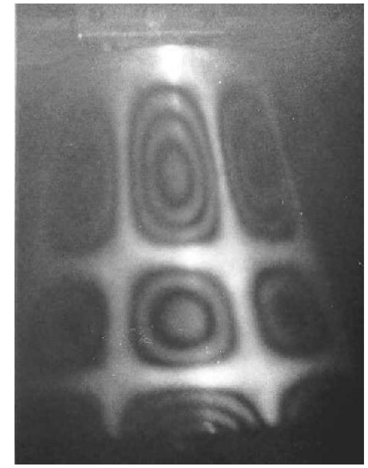
1342.3 Hz

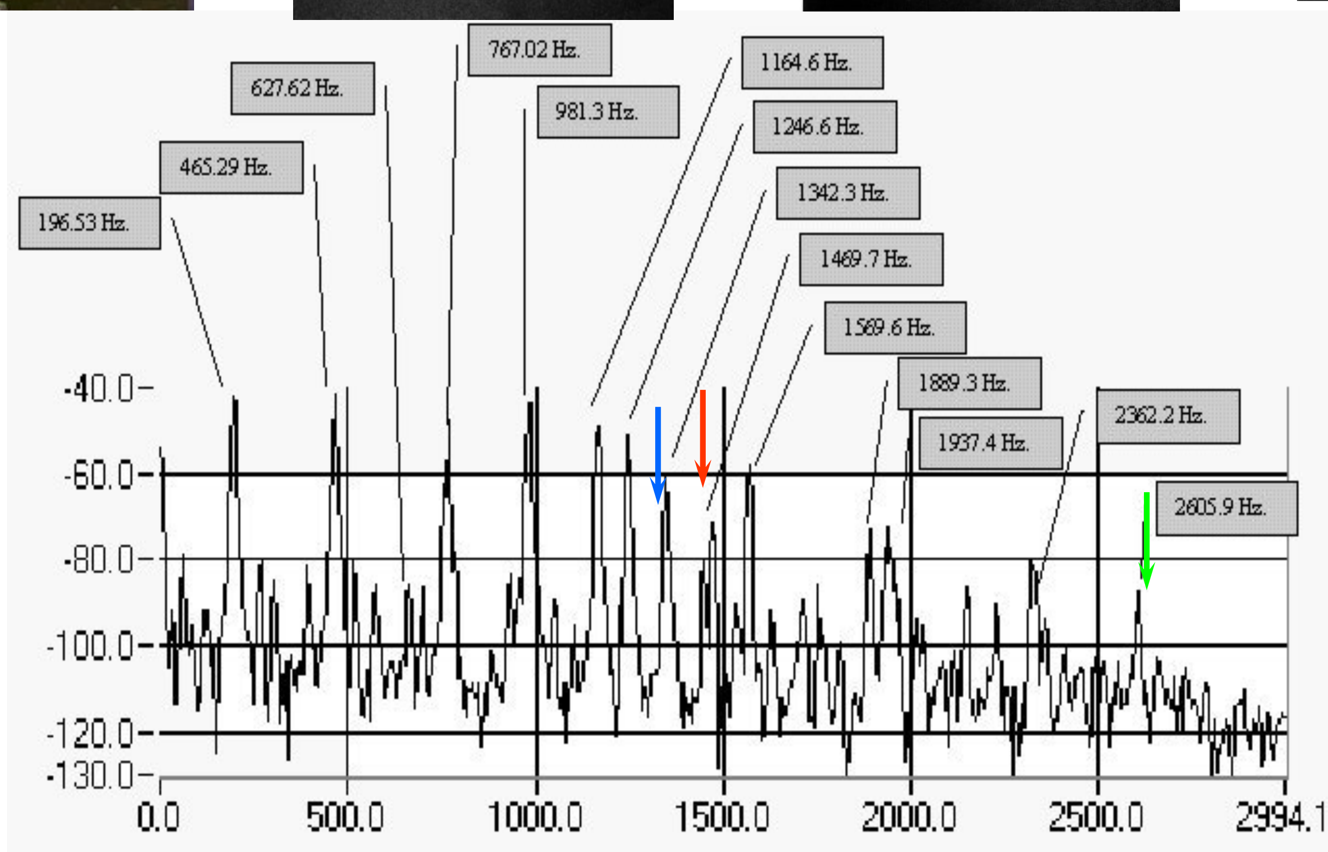


1469.7 Hz

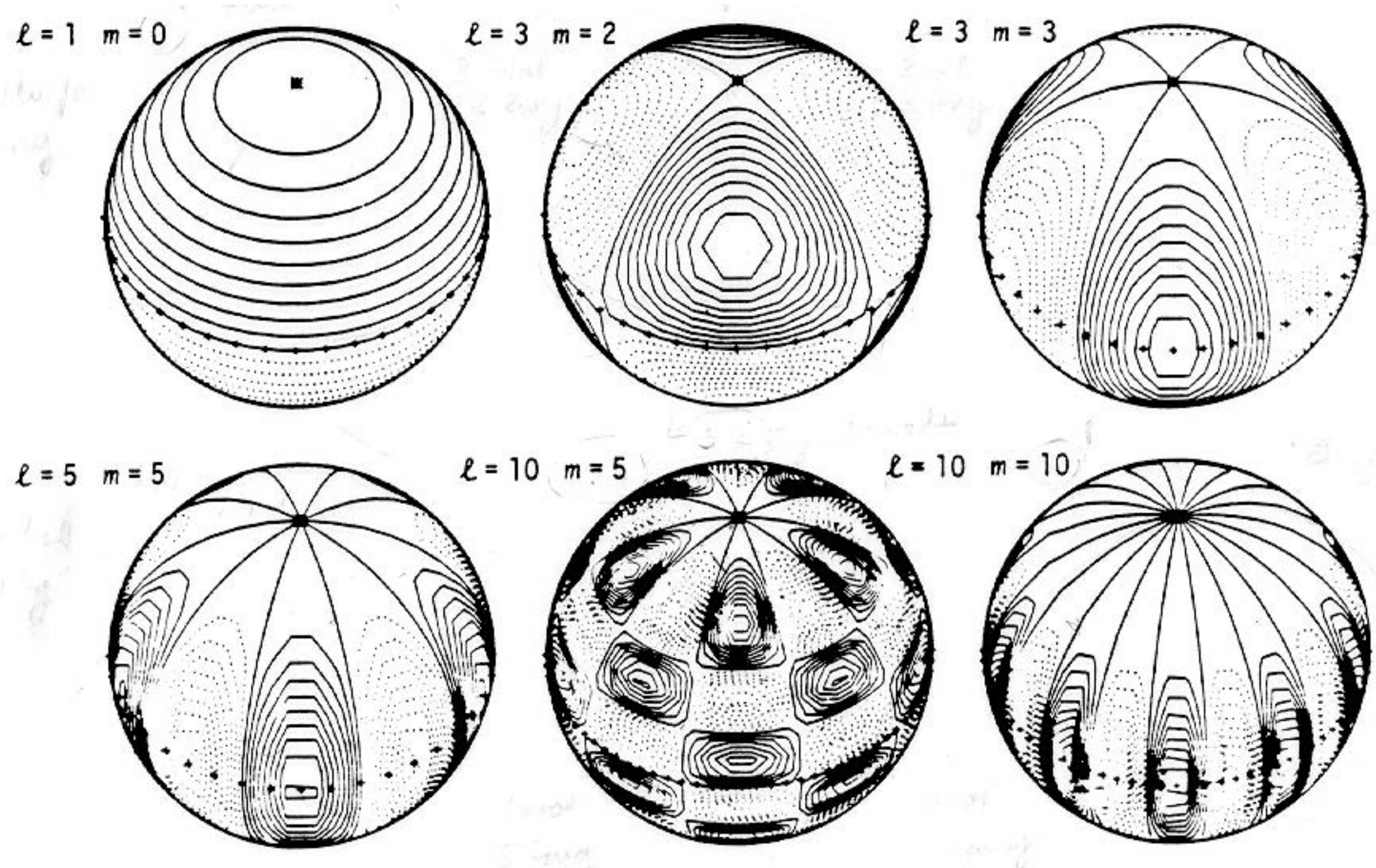


2605.9 Hz

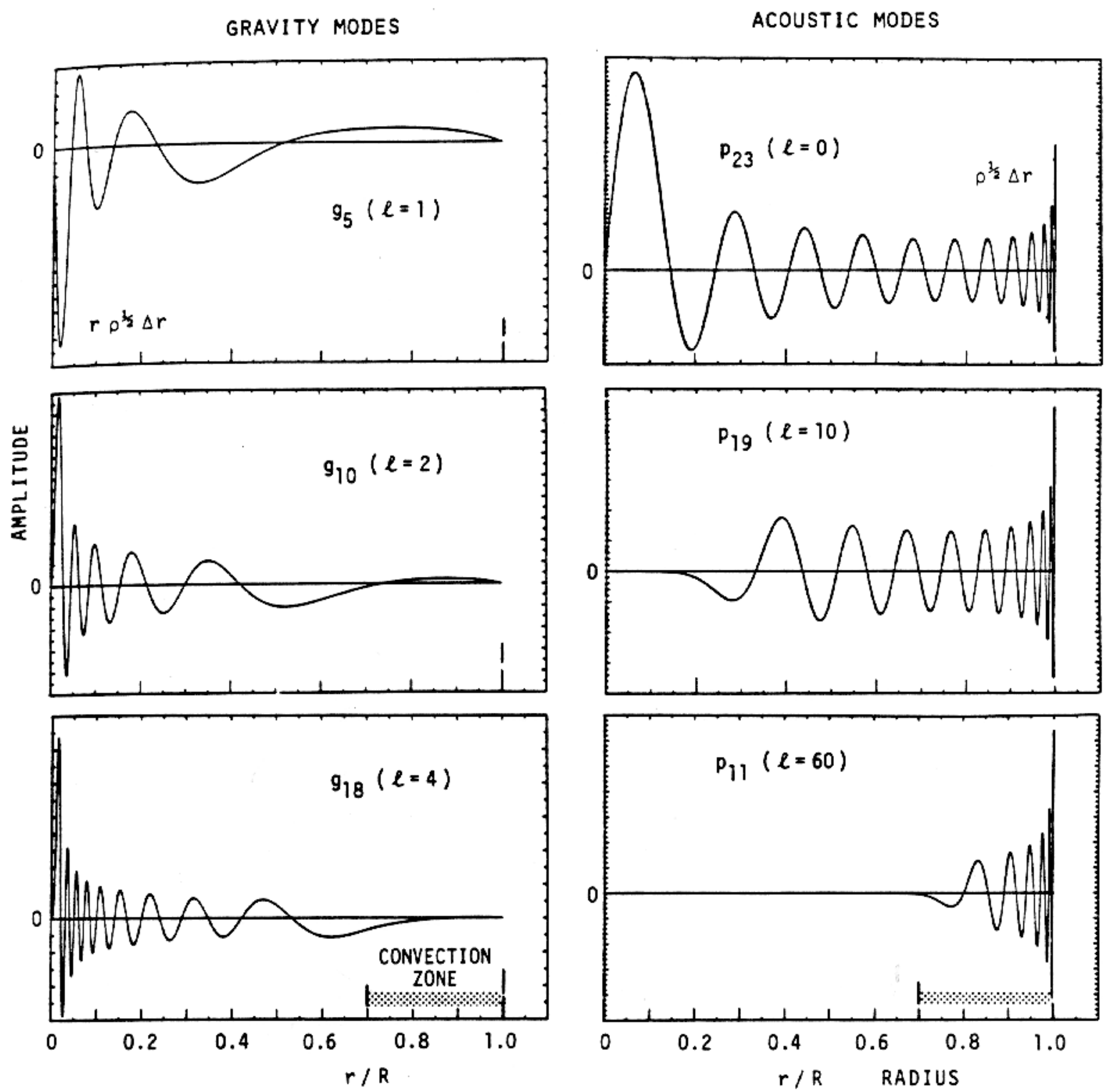




The angular dependence of modes is described by spherical harmonics

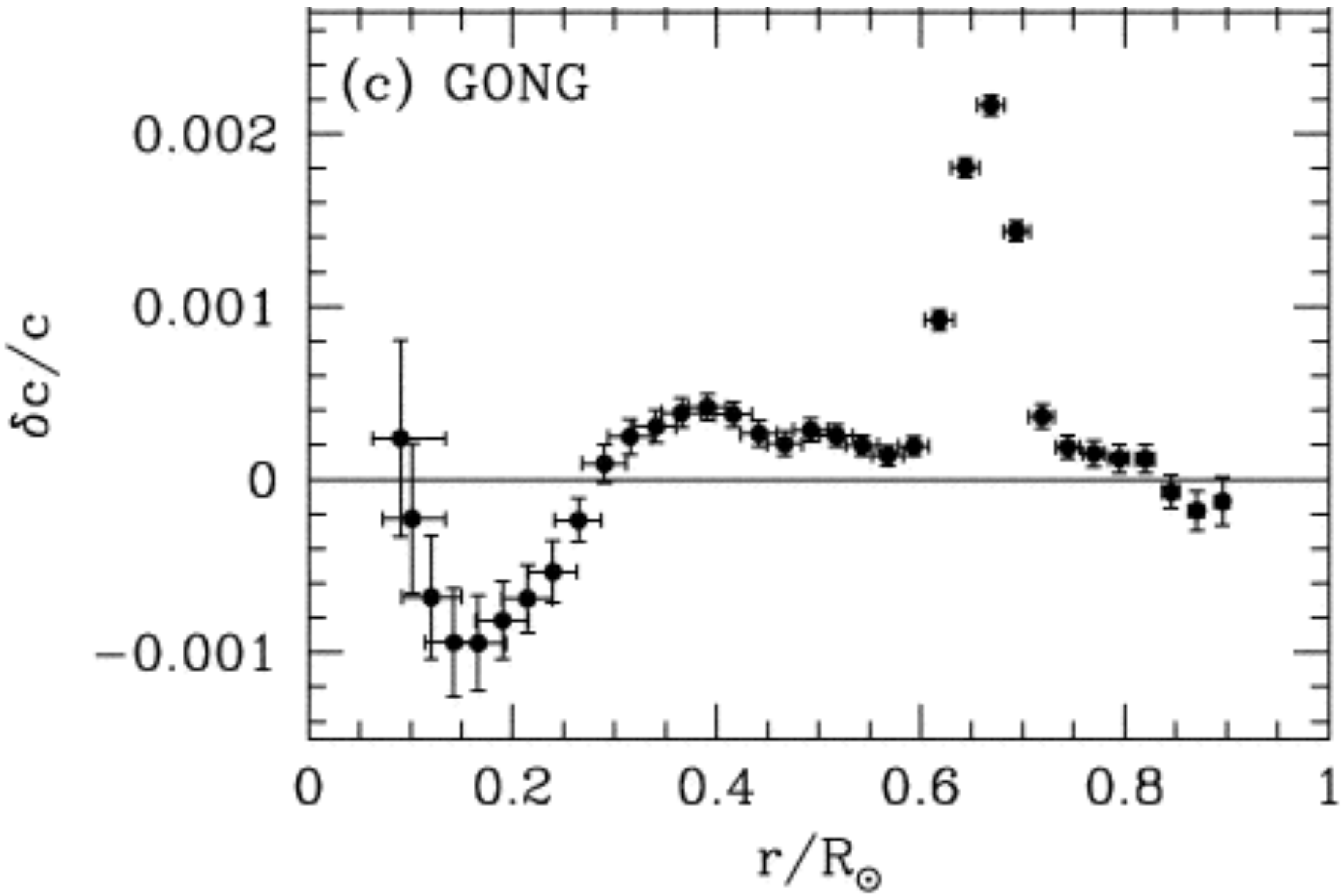


Solar acoustic and gravity mode eigenfunctions show that the modes are sensitive to the entire interior structure



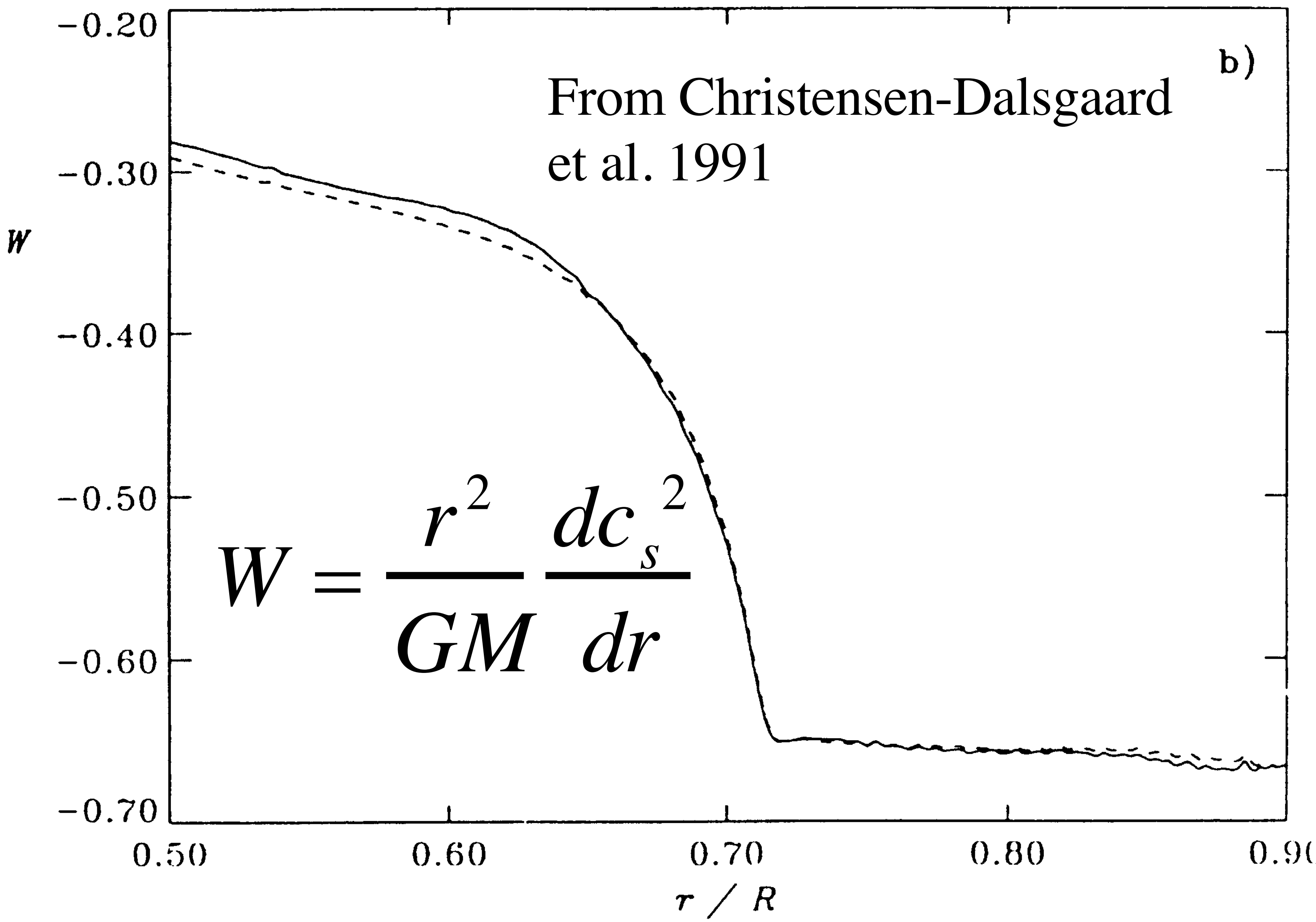
From Toomre 1984

Inferred sound speed from oscillation frequencies compared to reference model



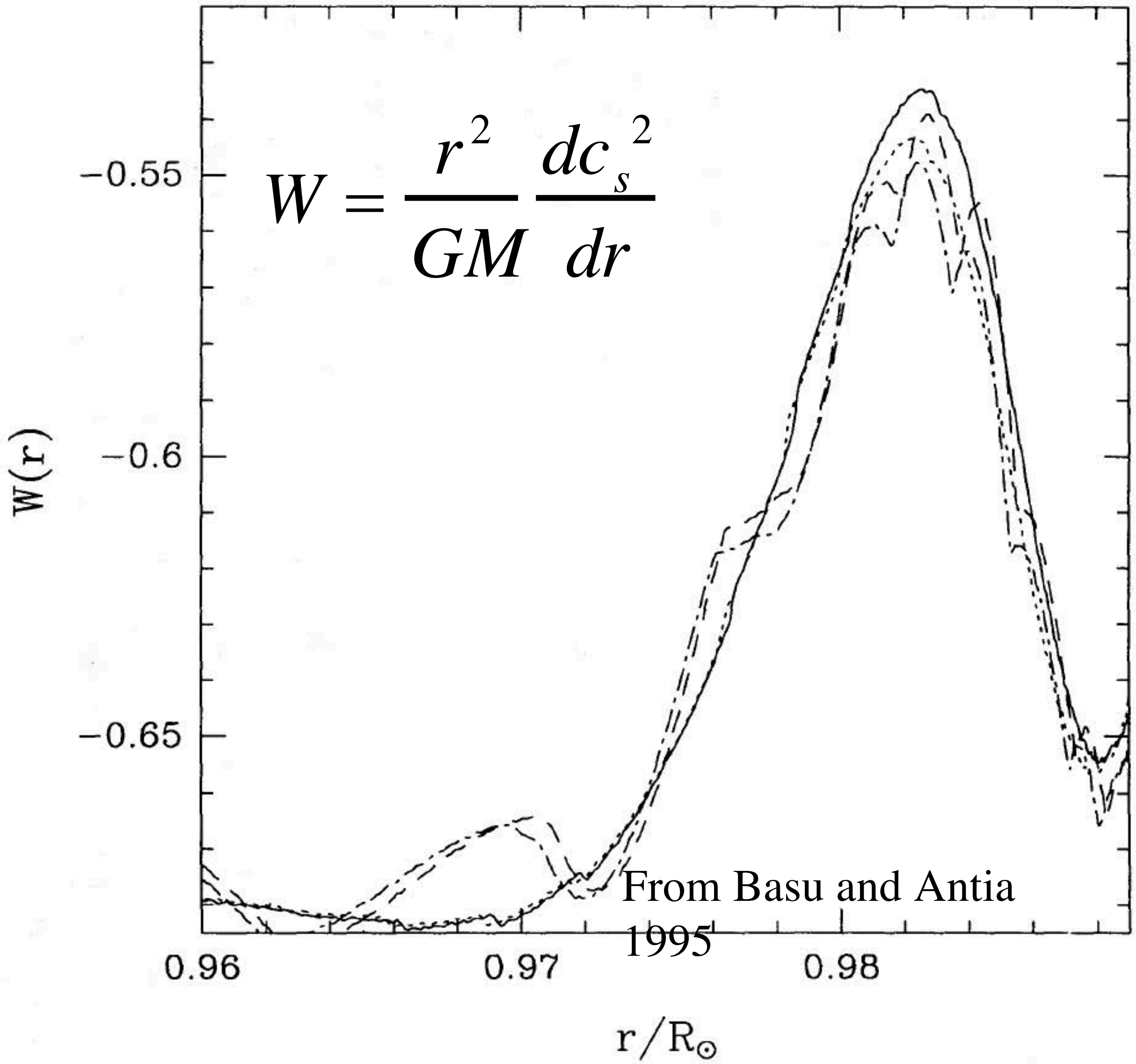
From Basu et al. 2000

Change in inferred sound speed gradient locates convection zone base



$$W = \frac{r^2}{GM}\frac{dc_s^{\,2}}{dr}$$

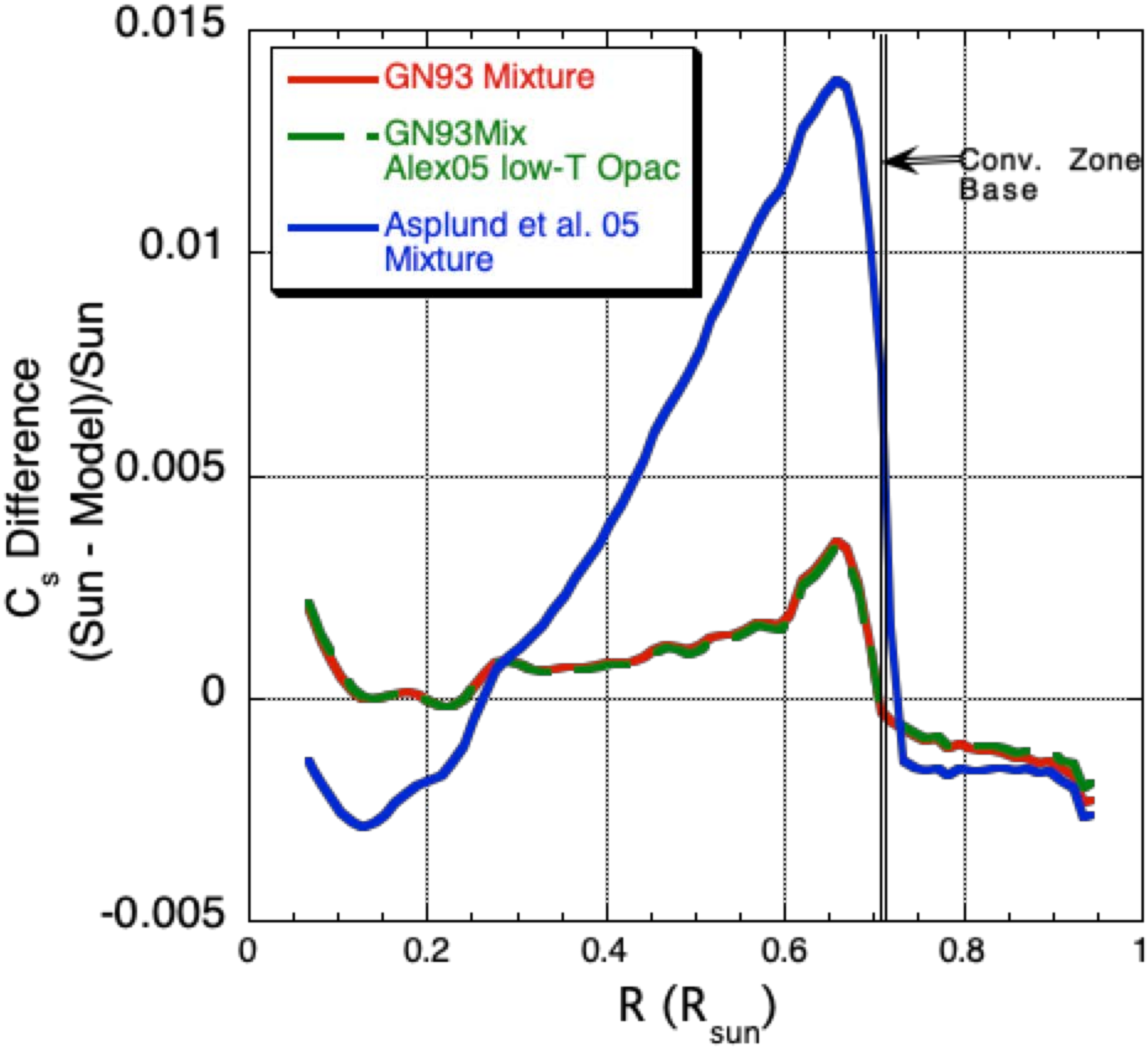
The sound speed gradient bump in the He ionization region can be used to determine the envelope He abundance



$$W = \frac{r^2}{GM}\frac{dc_s^{\,2}}{dr}$$

From Basu and Antia 1995

Sound speed profile agrees better with inferences for old higher abundances



Asplund, Grevesse, & Sauval 2005 mixture:

$R_{czb} = 0.7306$; $Y=0.227$, $Z=0.0124$

Grevesse & Noels 1993 mixture:

$R_{czb} = 0.7133$; $Y=0.242$, $Z=0.0181$

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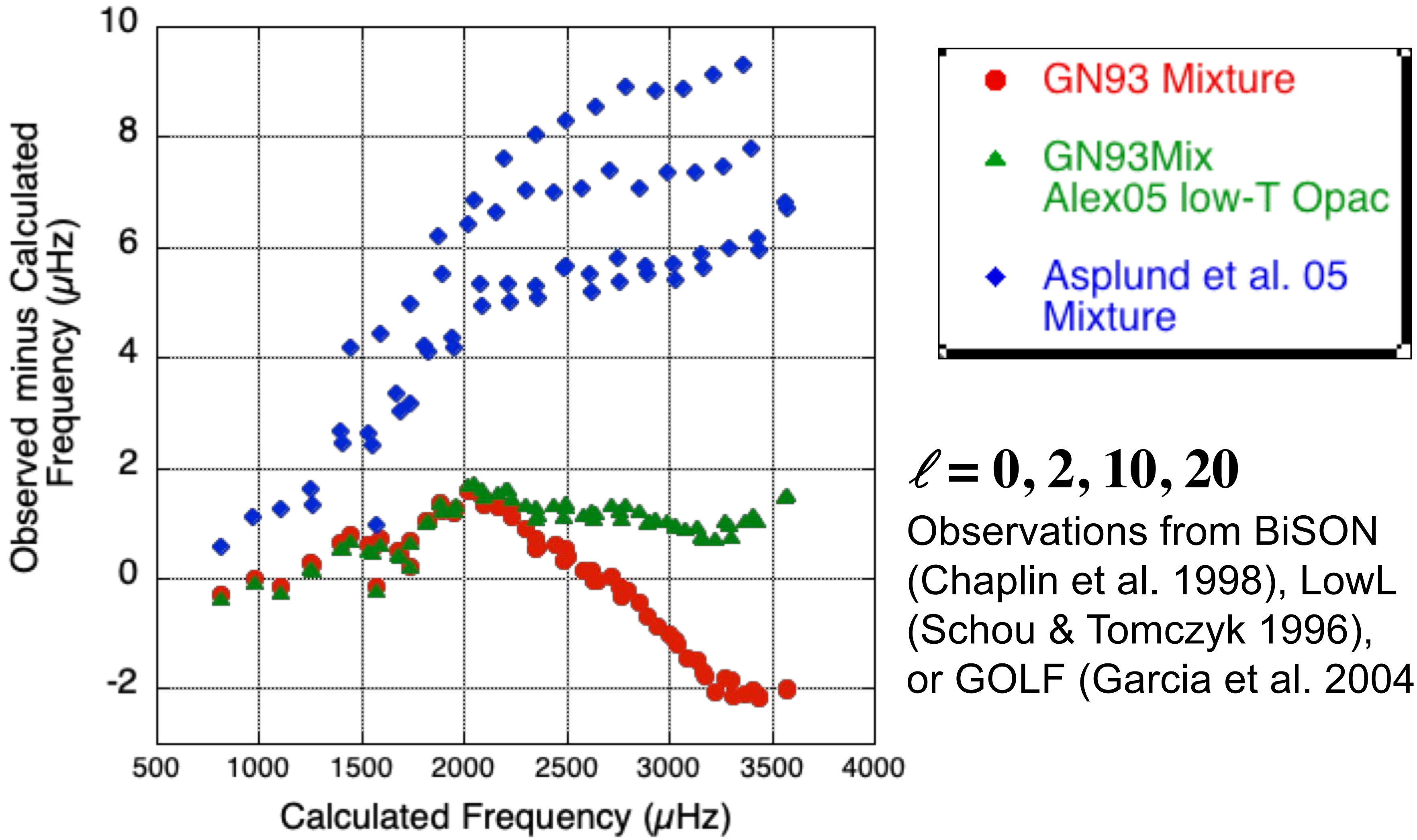
Observed - calculated frequency differences are smaller for old abundances



$\ell = 0, 2, 10, 20$

Observations from BiSON (Chaplin et al. 1998), LowL (Schou & Tomczyk 1996), or GOLF (Garcia et al. 2004)

Examples of attempts to restore agreement

- Enhanced thermal diffusion, different rates for elements and helium (Y)
- Accretion of low-Z material
- Convective overshoot
- Early mass loss
- New opacities

For lower abundances, it is difficult to simultaneously match helioseismic constraints:

sound-speed profile, envelope helium abundance, and convection zone depth

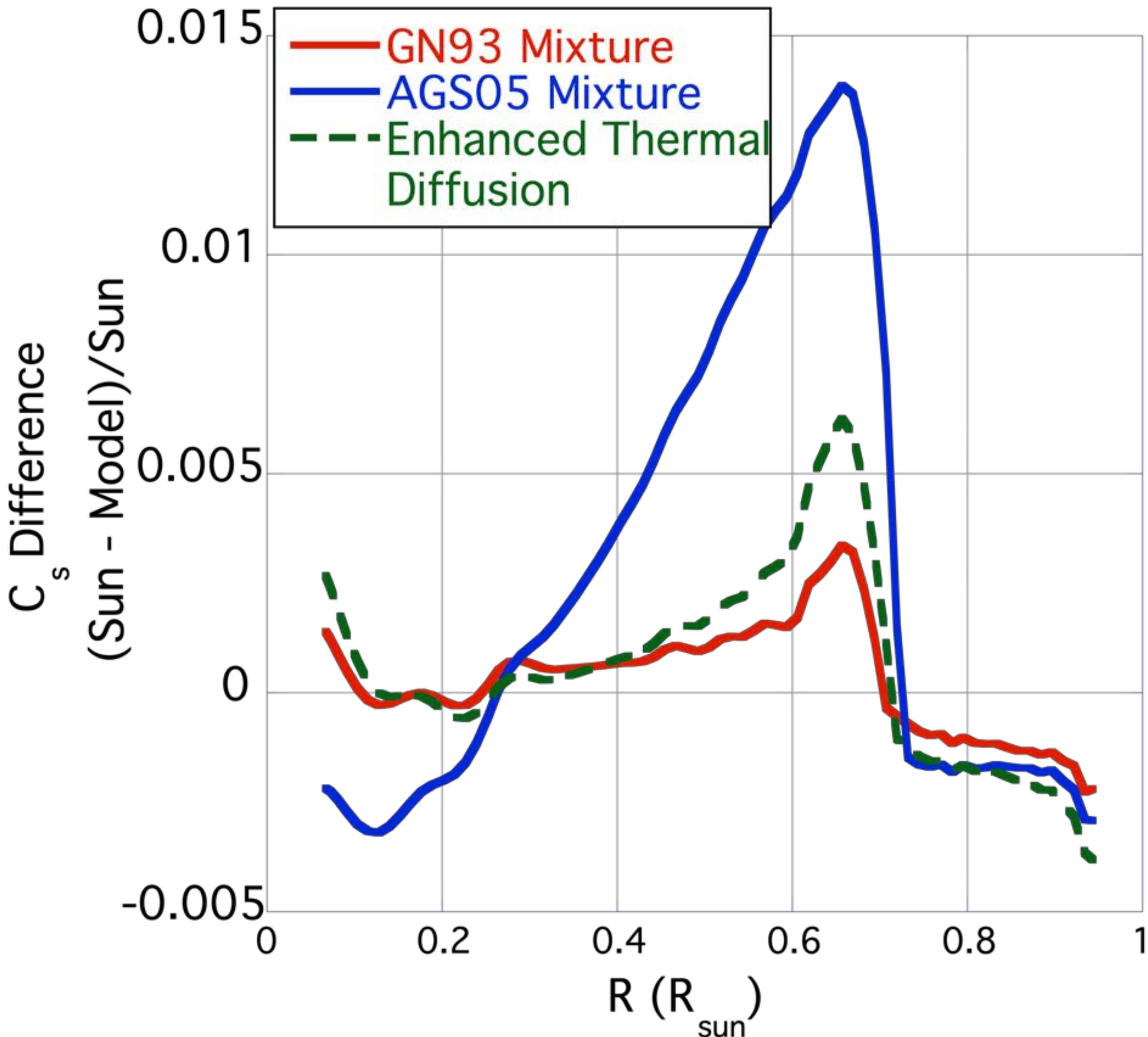
Enhanced Thermal Diffusion

Lowered binary thermal resistance coefficients x 1/4 for C, N, O, Ne, Mg and x 2/3 for He

- Can retain higher Z in core, and use diffusion to produce observed lower photospheric abundances
- Not changing gravitational diffusion--physically more plausible than a straight diffusion multiplier?
- Different diffusion rate for Y and Z to avoid diffusing too much helium

Guzik, Watson, and Cox ApJ 2005

Enhanced diffusion improves sound speed agreement



CZ base at $0.718\ R_{sun}$

$Y_{cz} = 0.227$

Accretion of low-Z material

- Initial ~98% of Sun's mass accumulated could have had higher Z with a mixture similar to GN93 or GS98 abundances.
- Last ~2% of mass accreted would need to be lower Z, and collected after Sun begins core hydrogen burning and is no longer fully convective.
- Retains higher Z below envelope convection zone.
- Implemented by allowing accretion of matter progressively depleted in Z in six increments during ~36 million years after onset of core H burning.

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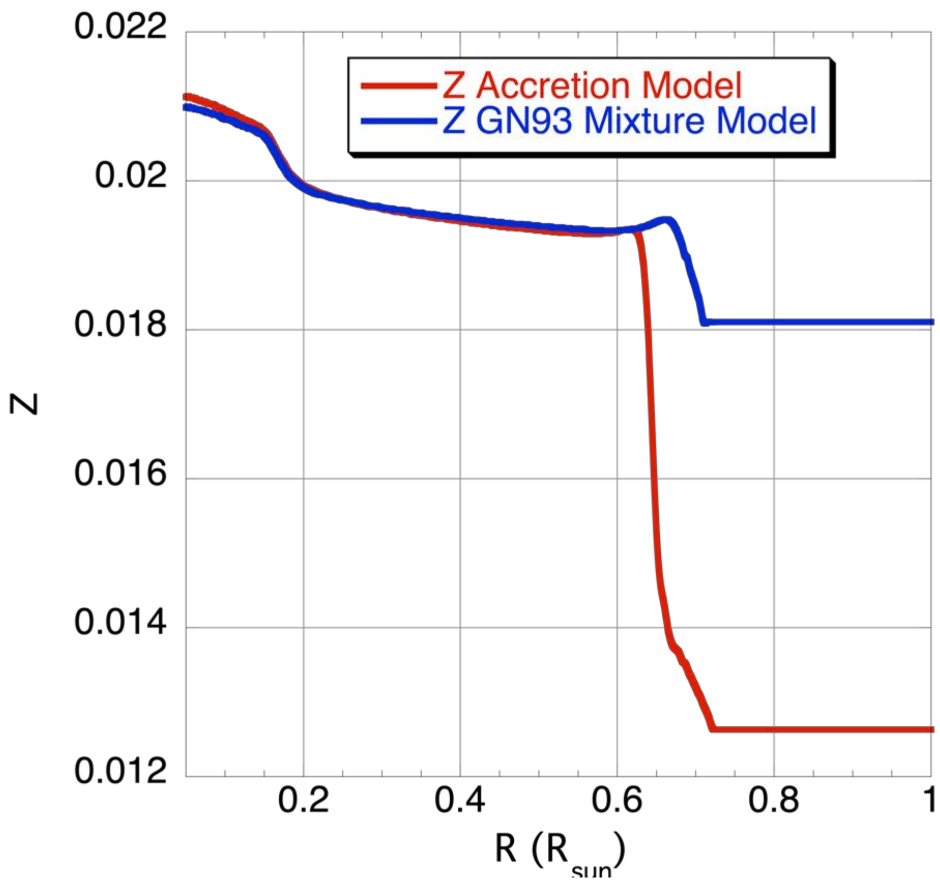
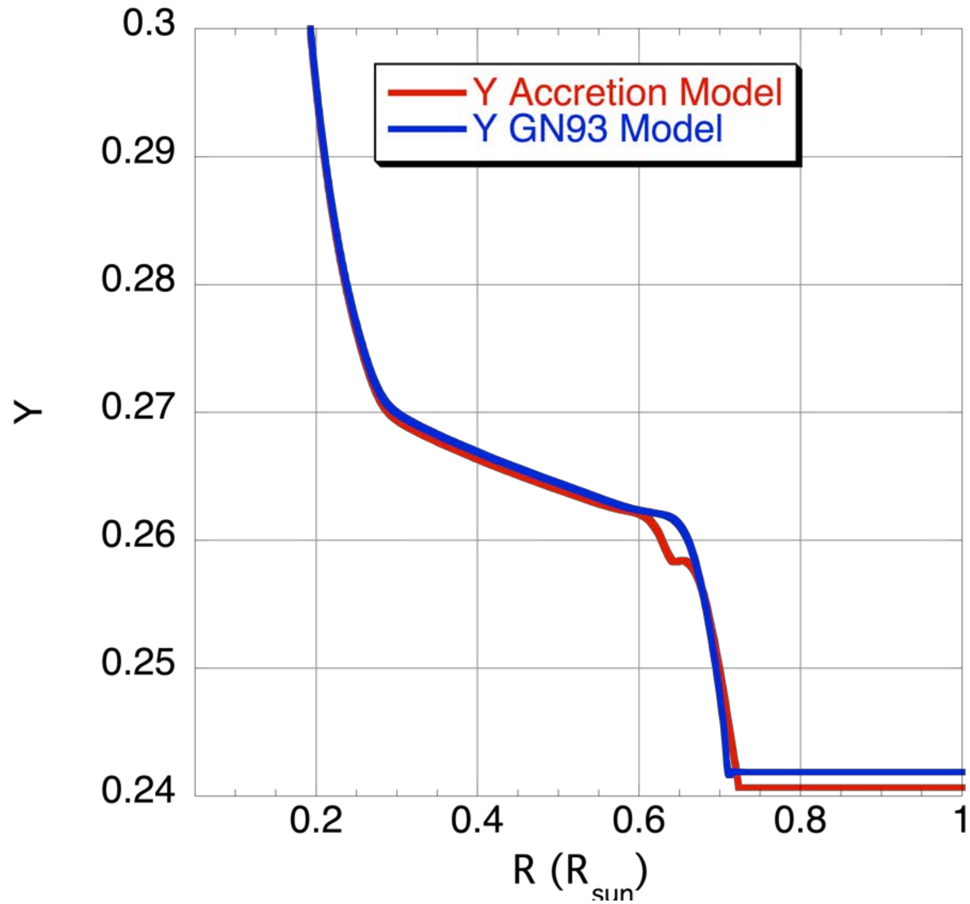
Accretion model has lower Z in and just below convection zone





CZ Y abundance only slightly lower for accretion model

Guzik and Mussack ApJ 2010

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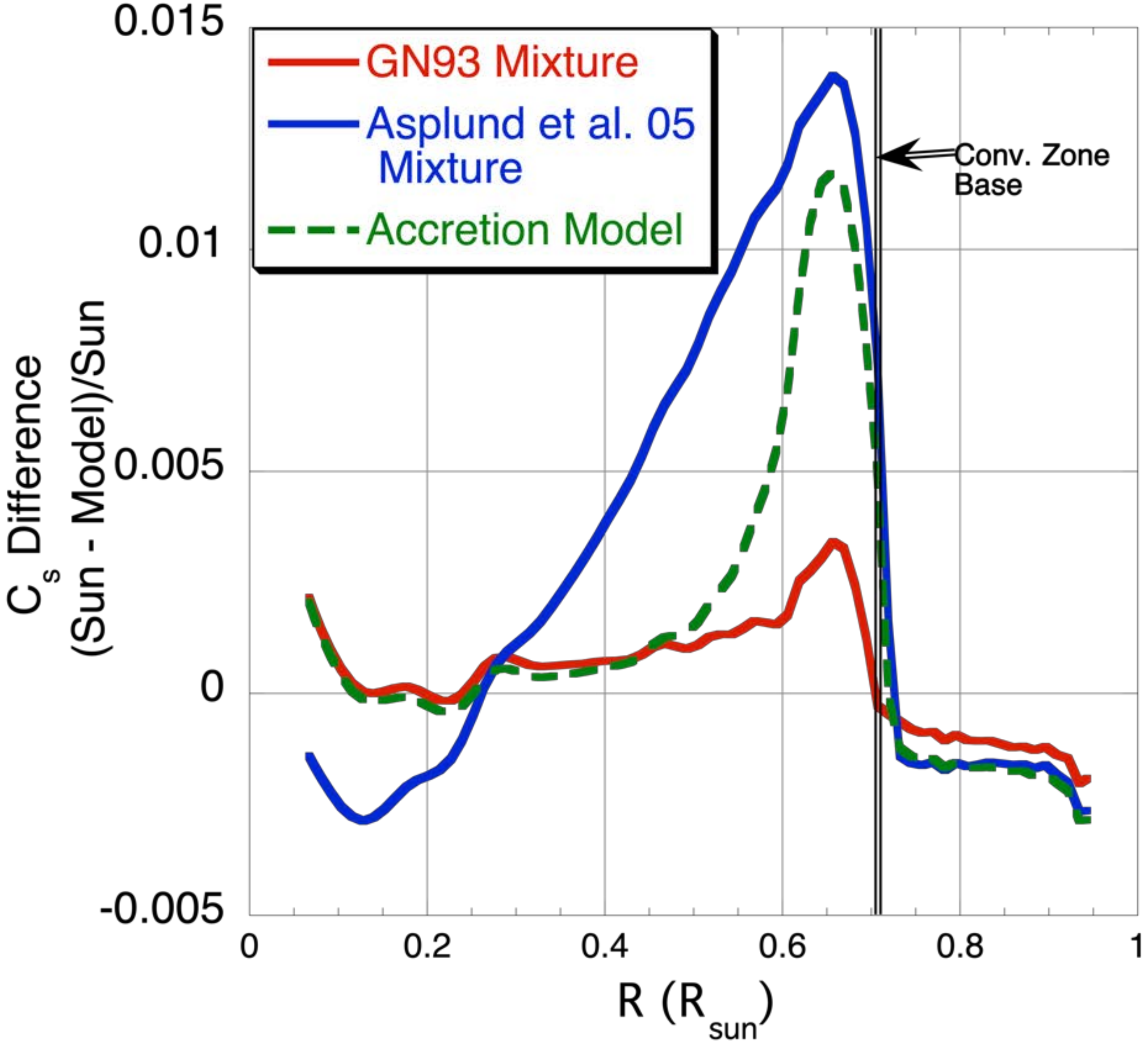
Accretion model improves sound-speed agreement



Guzik and Mussack ApJ 2010

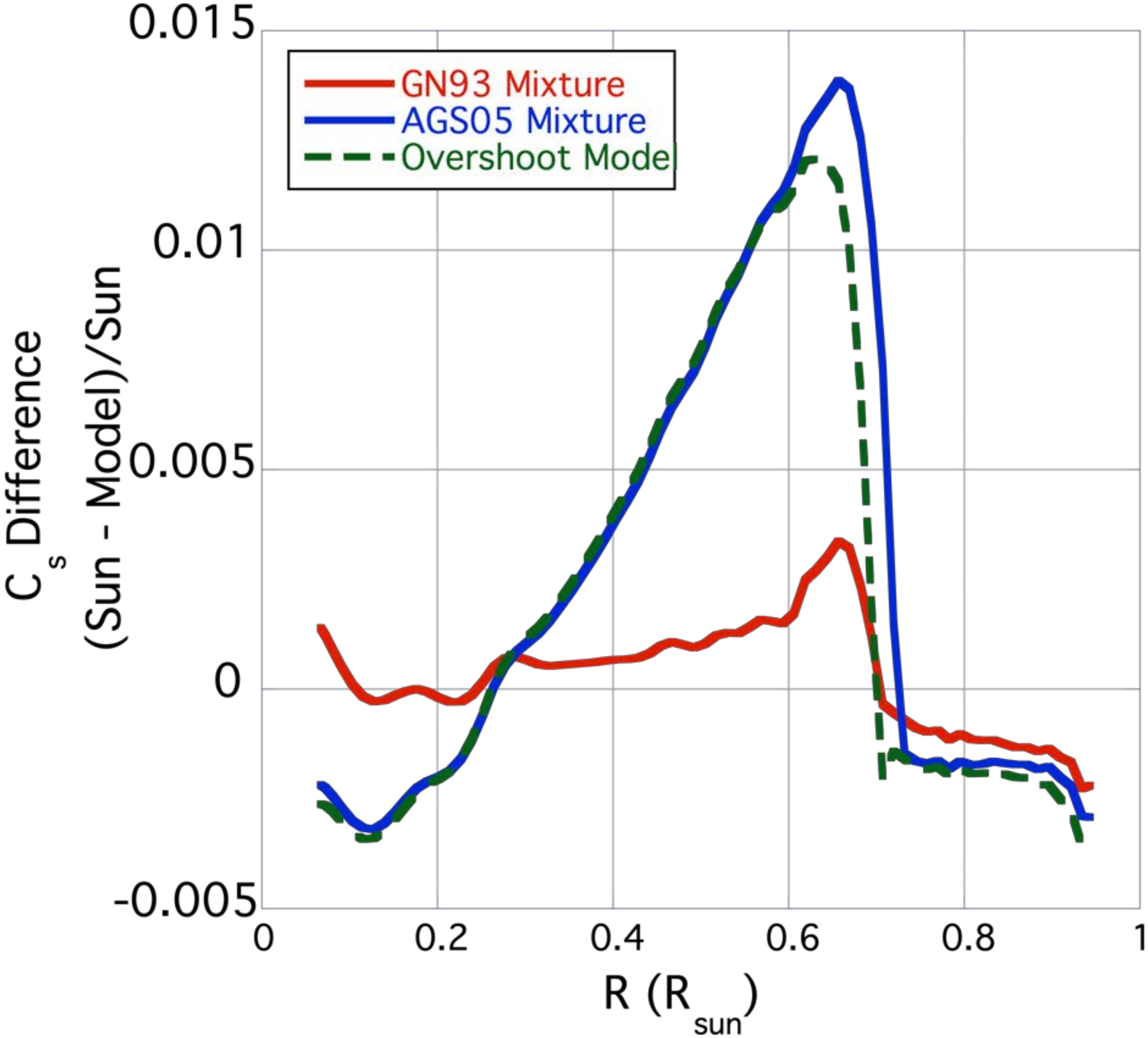
CZ base at 0.723 R_{sun}

$Y_{cz} = 0.241$

Convective overshoot

- Evolve Sun with AGS05 abundances, but extend the convection zone that follows the adiabatic gradient to optimize agreement with sound speed inversions.
- Deeper convection zone might inhibit diffusion and keep Y abundance higher.

Extending the convection zone only slightly improves sound-speed agreement

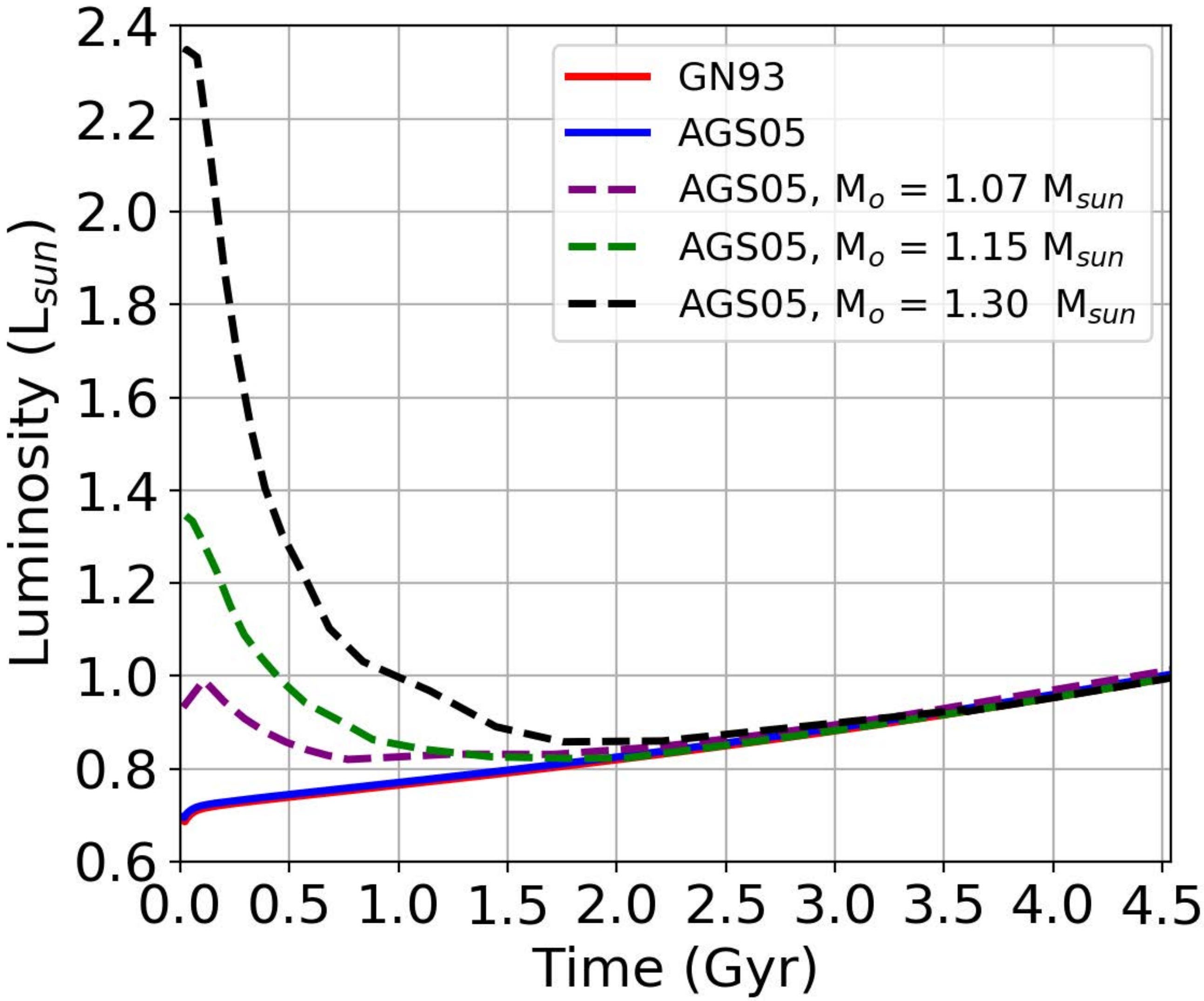


CZ base at 0.704 R_{sun}
$Y_{cz} = 0.229$

Overshoot does not significantly inhibit Y diffusion

Guzik and Mussack ApJ 2010

Mass-losing models evolved with initial mass 1.3, 1.15, and 1.07 M_{sun}

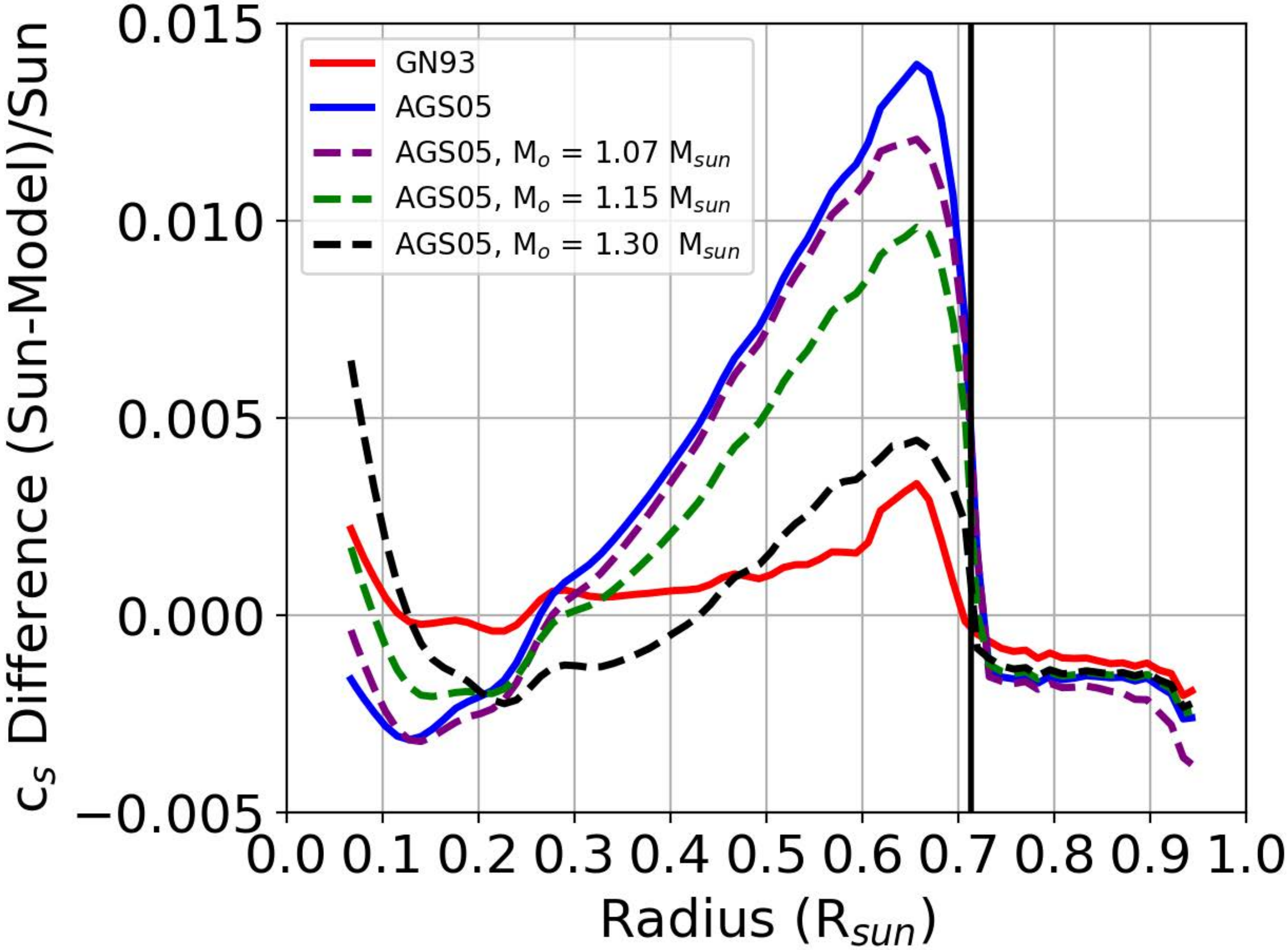


Mass-loss rate exponentially-decaying with e-folding time 0.45 Gyr.

Initial Mass Loss rates 6.55, 3.38, and 1.55 x 10^{-10} M_{sun}/yr.

Luminosities higher for the first 1-2 Gyr than for standard models.

Early mass loss improves sound-speed agreement



AGS05 Mixture model:

$R_{czb} = 0.7306$

$Y_{cz} = 0.227$

Most extreme mass loss model:

$R_{czb} = 0.7195$

$Y_{cz} = 0.233$

Wood, Mussack, and Guzik Solar Physics 2018

About the Los Alamos OPLIB opacities generated with the ATOMIC code

Los Alamos OPLIB tables have been generated for the first 30 elements of the periodic table and are available online[1]

This new OPLIB release includes a number of improvements such as a more accurate equation-of-state treatment, refined temperature grid, and significant fine-structure detail in the atomic physics calculations. For details, see Colgan et al. (2013, 2015, 2016)

The opacities used in this work were obtained by mixing the pure-element OPLIB tables under the assumption of electron-temperature and electron-degeneracy equilibrium with the TOPS code

[1] http://aphysics2.lanl.gov/opacity/lanl

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Solar model parameters using AGSS09 abundances

	OPAL opacities	OPLIB opacities	
Y_o	0.2641	0.2570	
Z_o	0.0150	0.0151	
α	2.0118	2.0637	*Helioseismic inference (Basu & Antia 2004)*
$Y_{surface}$	0.2345	0.2283	0.248 ± 0.003
$Z_{surface}$	0.0135	0.0136	
R_{czb} (R_{sun})	0.7264	0.7251	0.713 ± 0.001

The AGSS09 element abundances are slightly higher than those of AGS05. The opacity derivative for the OPLIB opacities is steeper at the CZ base than that of the OPAL opacities, resulting in a deeper convection zone.

Guzik et al. 2015), Colgan et al. (2016)

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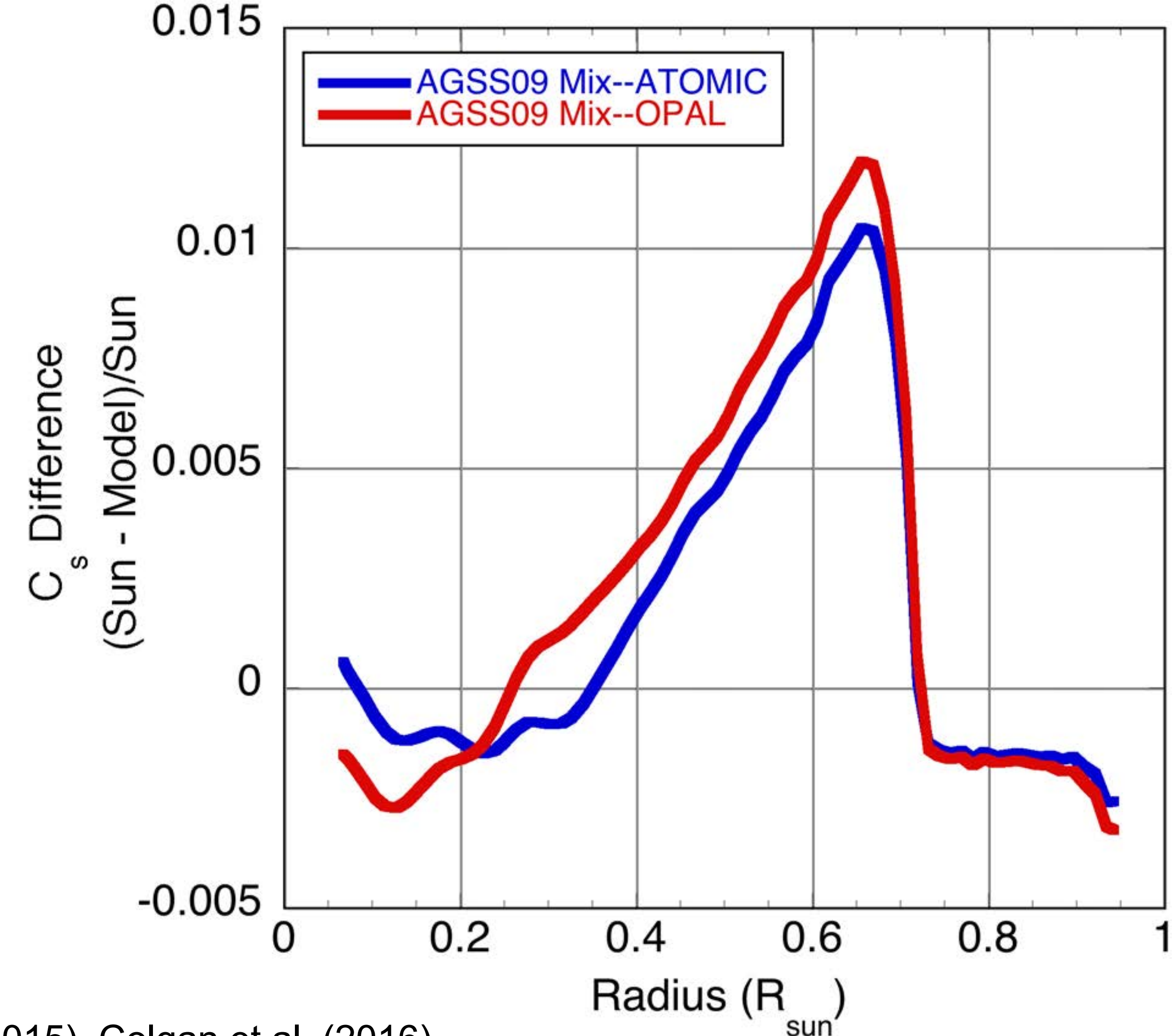
The calculated – inferred sound speed difference is smaller using the OPLIB opacities vs. the OPAL opacities



Guzik et al. (2015), Colgan et al. (2016)

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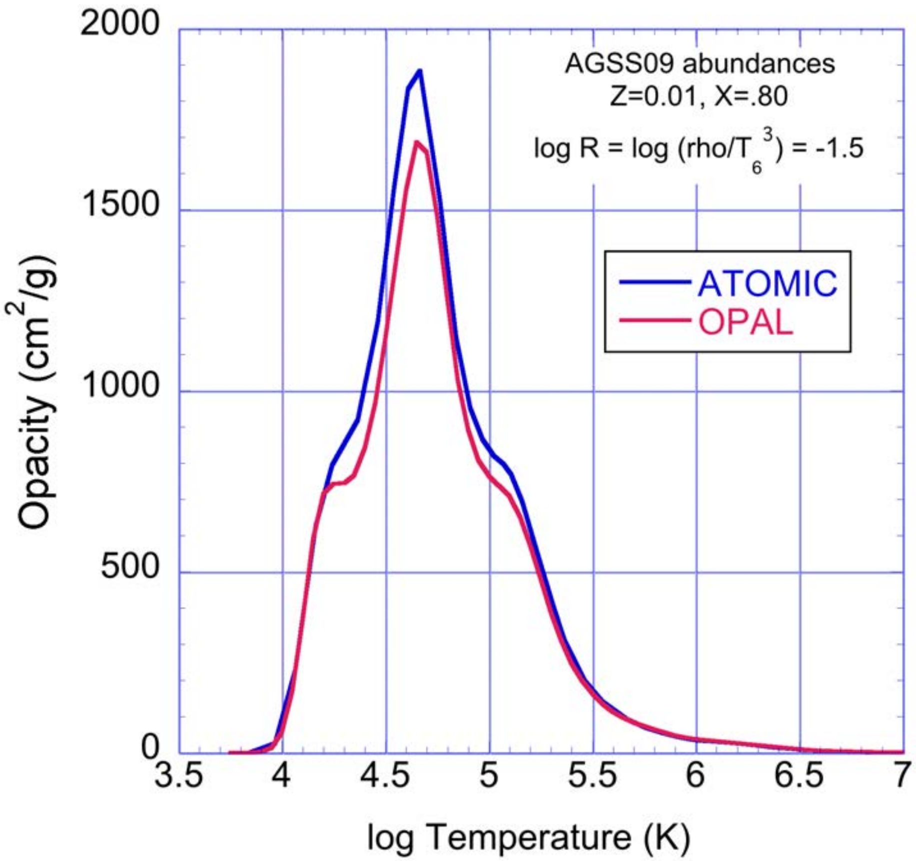
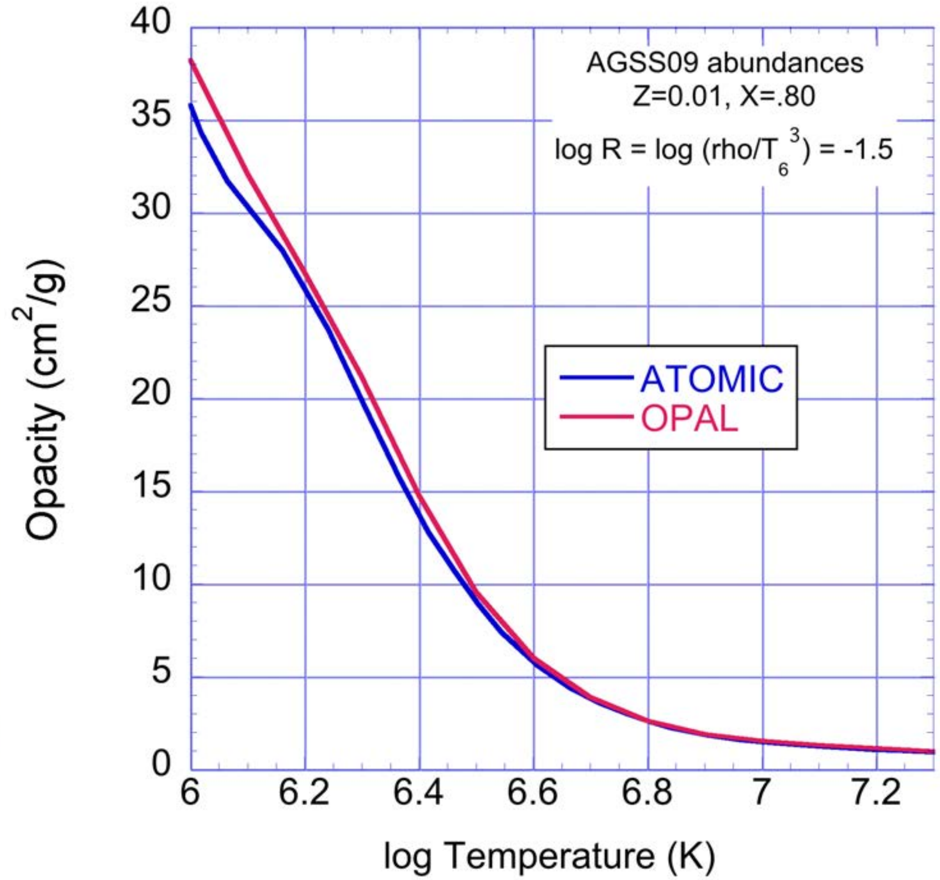
OPLIB opacities are higher than OPAL for solar convective envelope temperatures, but lower in the radiative interior





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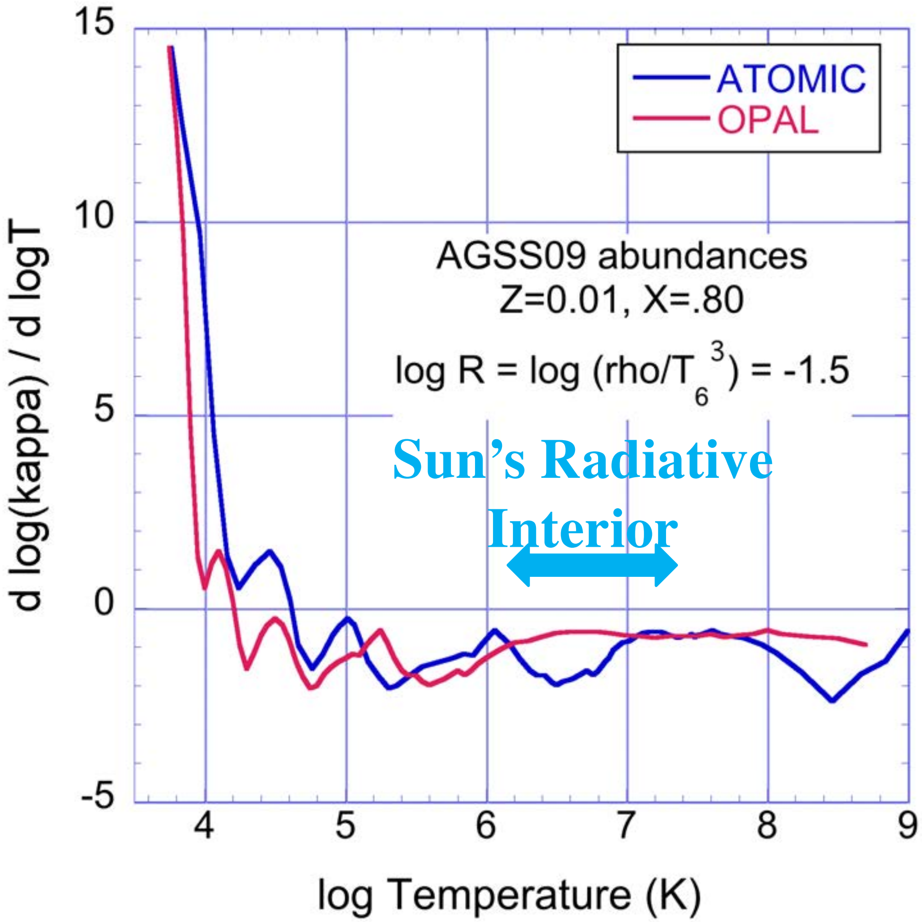
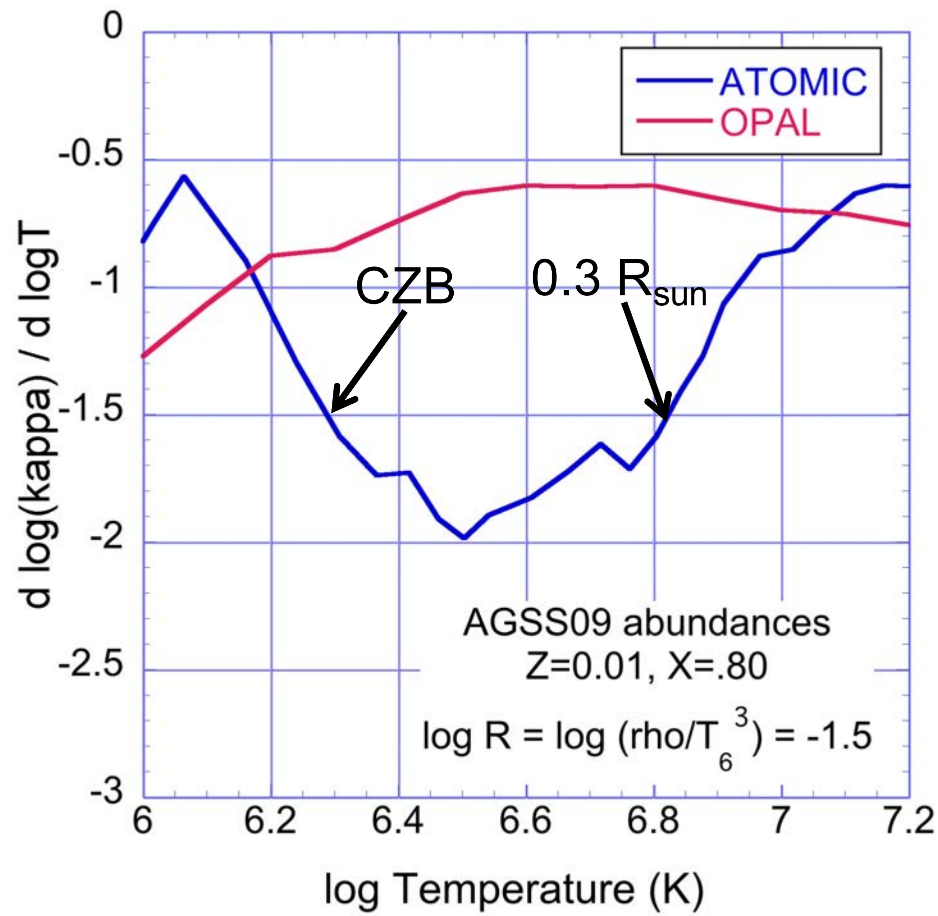
OPLIB opacity derivatives are steeper at log T = 6.3 (CZ base) and 6.8 (0.3 R_{sun}) where sound-speed differences between solar models using OPAL and OPLIB are largest





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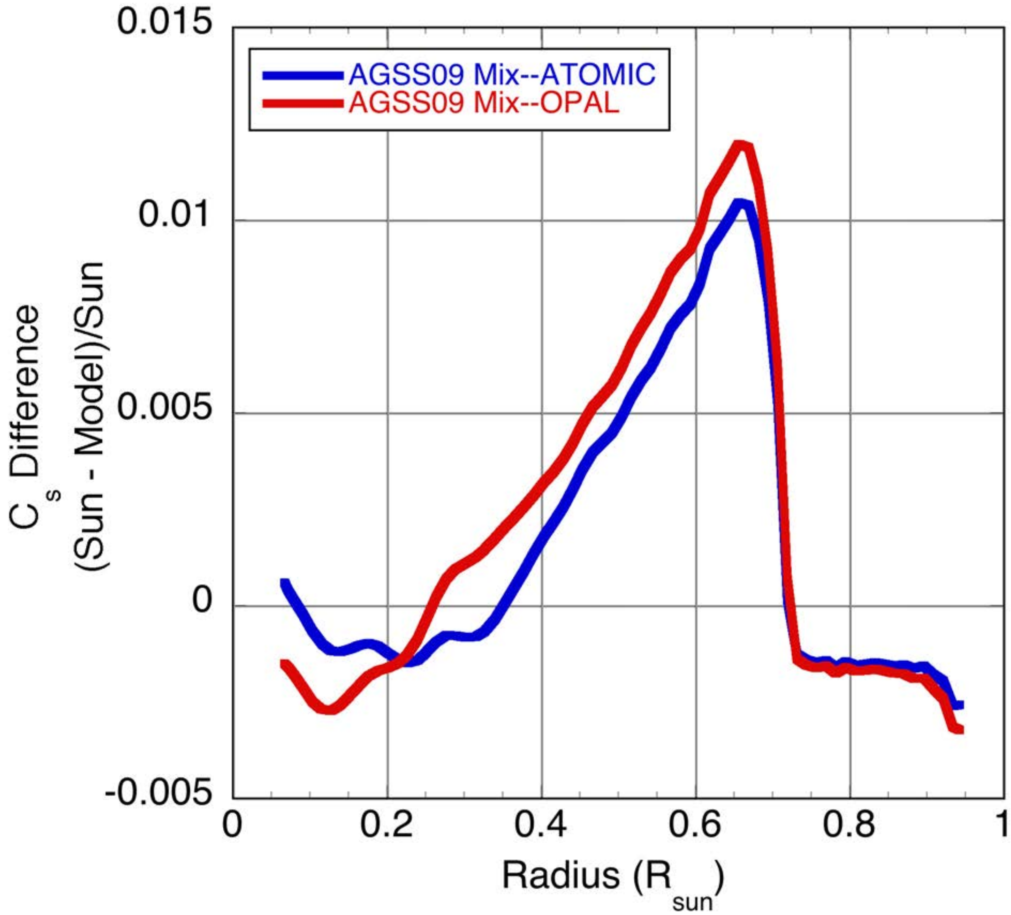

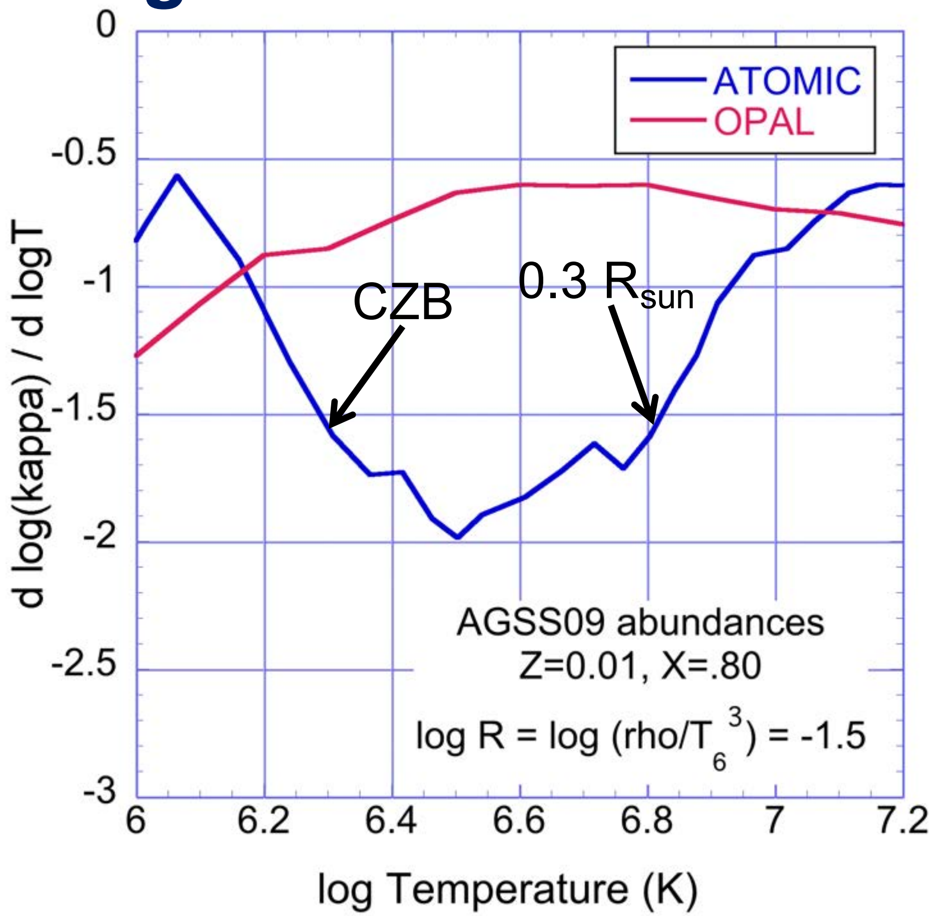

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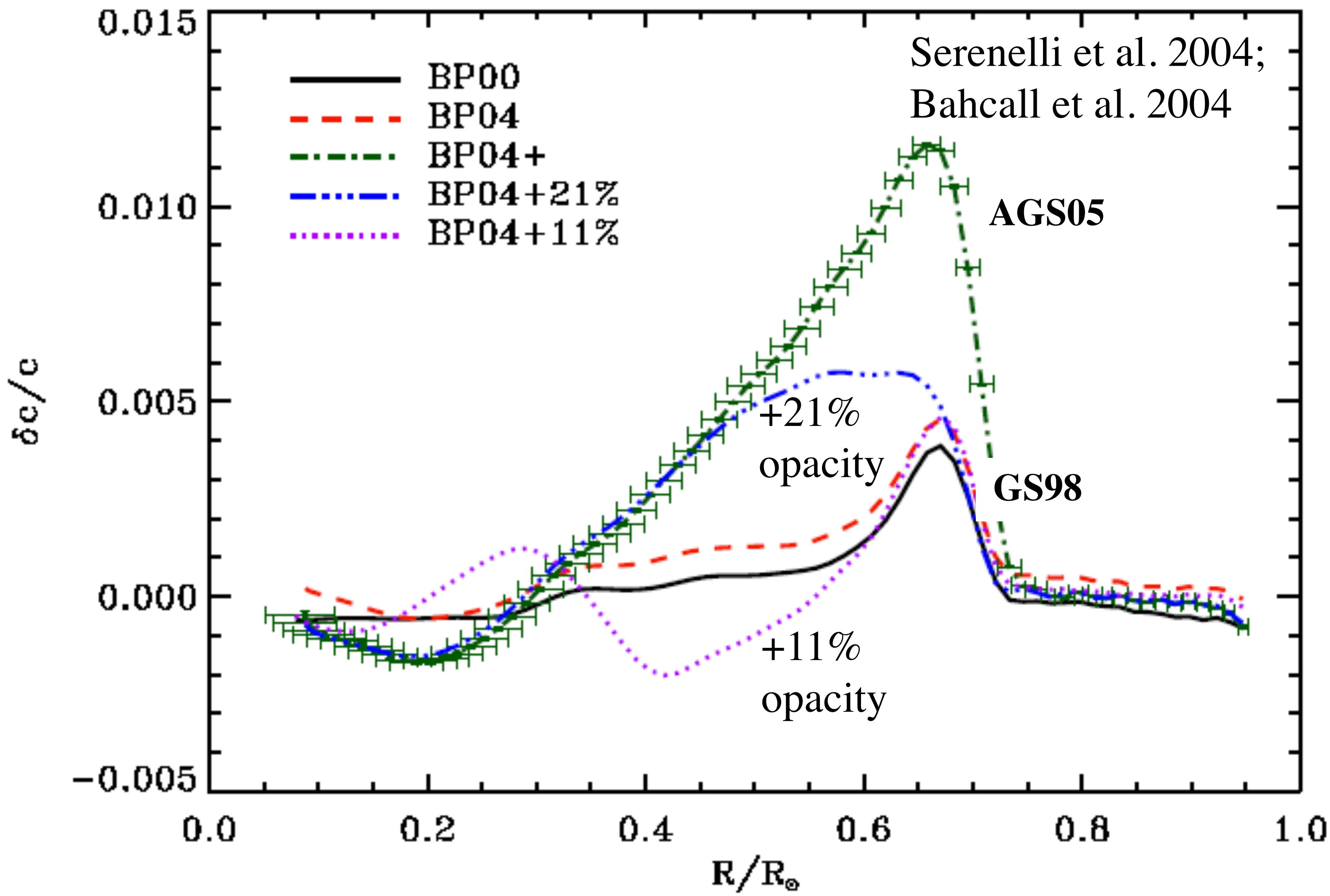
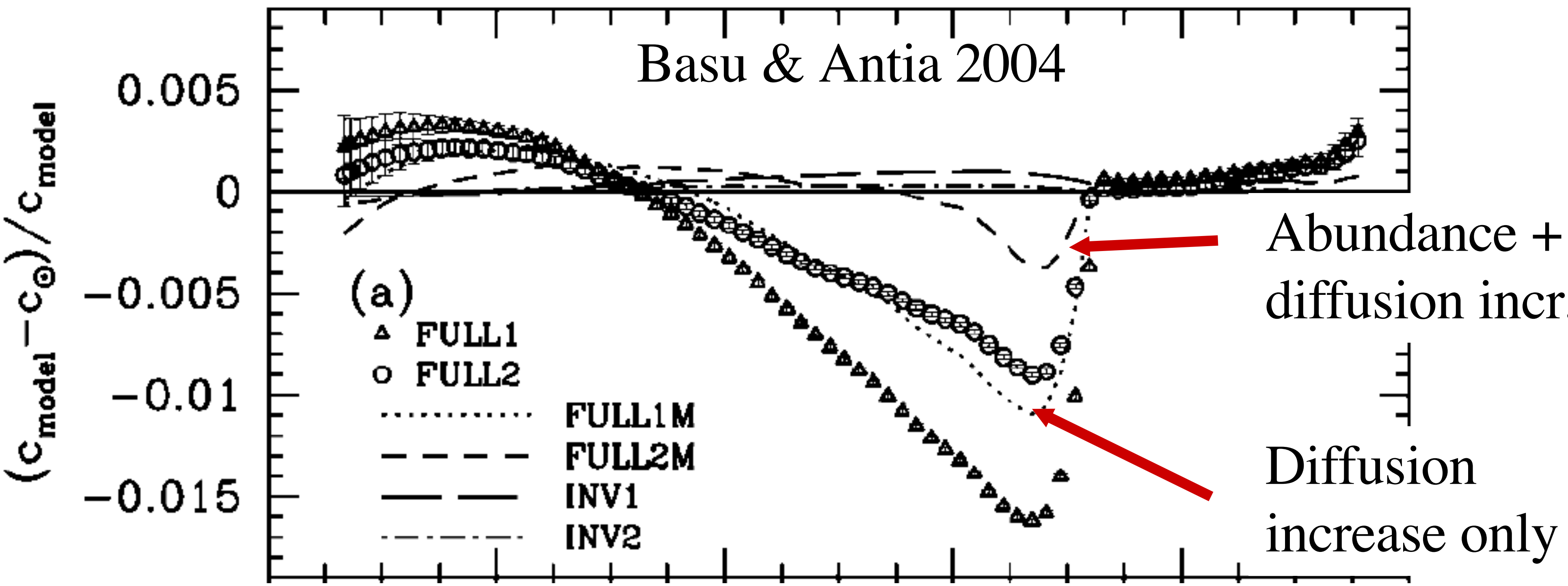
Opacity increases improve agreement



Diffusion (x 1.65) and abundance increases improve agreement

(R_{czb}= 0.7283, Y_{cz}= 0.2339, Z/X = 0.0206 for FULL2M)



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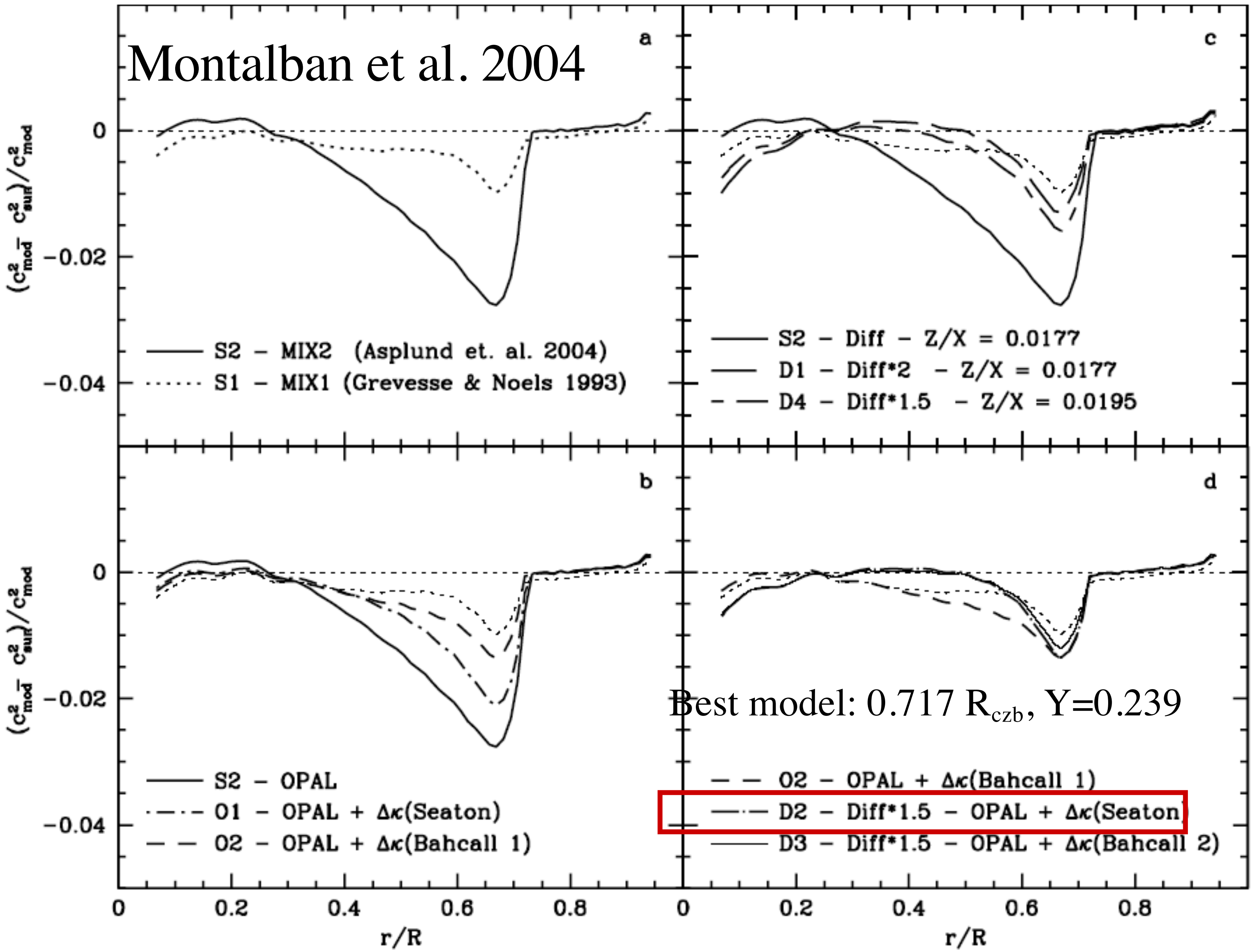
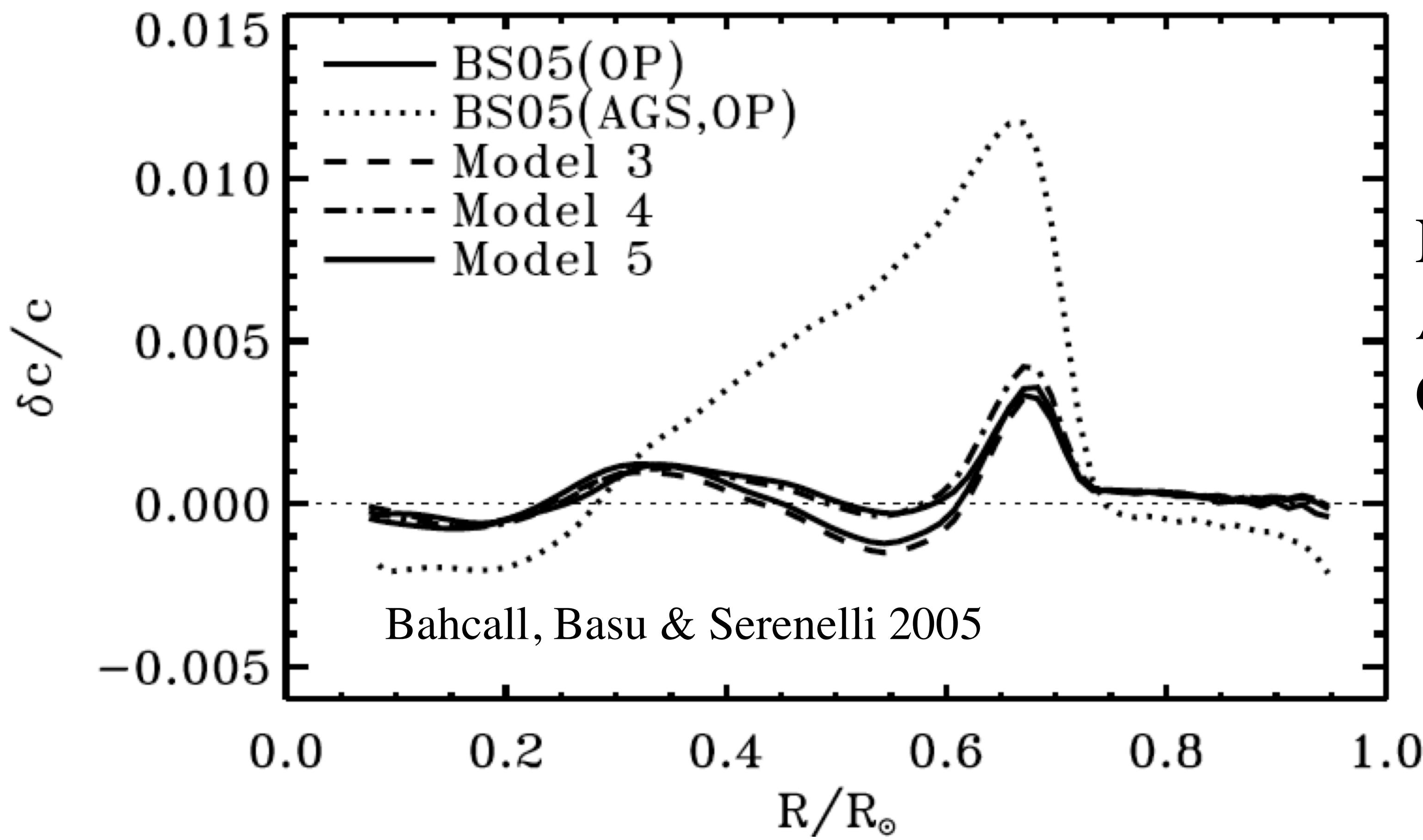
Combinations of opacity, diffusion, and abundance increases improve agreement



Neon, argon, + smaller CNO enhancements restore agreement



Neon +0.45 dex
Argon +0.4 dex
CNO +0.05 dex

Conclusions

- New solar photospheric element abundances give worse agreement with helioseismology.
- Simple single changes in input physics or assumptions for solar models (abundances, opacities, diffusion, convective overshoot, early mass loss or accretion) do not restore agreement or are not physically justified.
- Combinations of effects are more physically possible but are contrived and do not completely restore agreement.
- The LANL OPLIB opacities only slightly improve agreement, not because they are higher, but because they have steeper derivatives in the solar radiative interior

We do not have an obvious solution to the solar abundance problem

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- Thanks to Carlos Iglesias for pointing out the new solar abundances to me in 2004.

Recom-mended Review: Buldgen et al. 2019

Frontiers in Astronomy and Space Sciences

Progress in Global Helioseismology: A New Light on the Solar Modeling Problem and Its Implications for Solar-Like Stars

Gaël Buldgen[1,2,3], Sébastien Salmon[3] and Arlette Noels[3]*

[1] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom, [2] Observatoire de Genève, Université de Genève, Geneva, Switzerland, [3] STAR Institute, Université de Liège, Liège, Belgium

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Joergen Christensen-Dalsgaard,
Aarhus University, Denmark

***Correspondence:**
Gaël Buldgen
Gael.Buldgen@unige.ch

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Since the first observations of solar oscillations in 1960, helioseismology has probably been one of the most successful fields of astrophysics. Data of unprecedented quality were obtained through the implementation of networks of ground-based observatories such as the GONG project or the BiSON network, coupled with space-based telescopes such as SOHO and SDO missions and more data is expected from the Solar Orbiter mission. Besides the improvement of observational data, solar seismologists developed sophisticated techniques to infer the internal structure of the Sun from its eigenfrequencies. These methods, then already extensively used in the field of Geophysics, are called inversion techniques. They allowed to precisely determine the position of the solar convective envelope, the helium abundance in this region and the internal radial profiles of given thermodynamic quantities. Back in 1990s these comparisons showed a very high agreement between solar models and the Sun. However, the downward revision of the CNO surface abundances in the Sun in 2005, confirmed in 2009, induced a drastic reduction of this agreement leading to the so-called solar modeling problem. More than 10 years later, in the era of the space-based photometry missions which have established asteroseismology of solar-like stars as a standard approach to obtain their masses, radii and ages, the solar modeling problem still awaits a solution. In this paper, we will present the results of new helioseismic inversions, discuss the current uncertainties of solar models as well as some possible solutions to the solar modeling problem. We will show how helioseismology can help us grasp what is amiss in our solar models. We will also show that, far from being an argument about details of solar models, the solar problem has significant implications for seismology of solar-like stars, on the main sequence and beyond, impacting asteroseismology as a whole as well as the fields requiring precise and accurate knowledge of stellar masses, radii and ages, such as Galactic archaeology and exoplanetology.

Keywords: the Sun, helioseismology, asteroseismology, solar abundances, stellar structure and evolution, solar-like stars

Which is the actual problem?

- The solar *abundance* problem
- The solar *opacity* problem
- The solar *modelling* problem

Abstract

In 2004, improved analyses of solar spectra resulted in a downward revision of the abundances of elements heavier than hydrogen and helium, in particular, the elements C, N, and O. Solar models evolved using these lower abundances showed discrepancies with inferences from solar oscillation observations (helioseismology). This problem has not been solved satisfactorily in the intervening 16 years. How serious/important is this problem?

This talk will give an overview of how standard solar models are calculated and of the constraints from helioseismology. The talk will also present results of some attempts to change input physics or assumptions in the standard solar model, including opacity modifications, to try to resolve the discrepancies. I would like to have a discussion with the participants after the talk about which directions appear most promising to resolve the problem.