Helioseismology, Solar Models, and Stellar Physics

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Helioseismology

- Sensitive diagnostic of internal solar structure
- Complementary to
  - Traditional methods for inferring global solar properties
  - Solar neutrinos

- Examples:
  - Solar Radius

    Transit 6.9599(7)x10^{10} cm

    Seismic 6.9568(3)x10^{10} cm
  - Solar Age

    Meteoritic 4.568(1) Gyr

    Seismic 4.56(4) Gyr
  - Abundances!

Precision Astrophysics Requires Precise Abundances

- Chemical Evolution
- Stellar Ages
- Stellar Physics

- The Sun is a fundamental source of abundances
- Unique meteoritic info
- Powerful diagnostics available in the solar atmosphere and interior

BUT: There is a major controversy about the bulk solar composition!

How Do We Infer the Composition of the Sun?

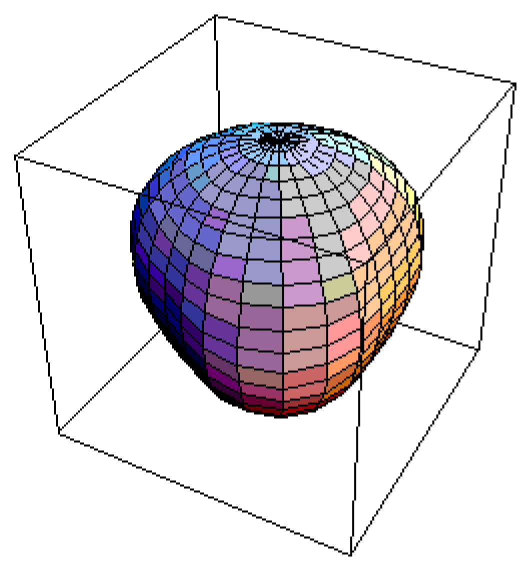
- Meteorites
  - – Can precisely infer relative heavy element abundances ($\sigma \sim 0.01$ dex)
  - – No info on species in gas phase during formation (H, He, Ne) or those with complex chemistry (C, N, O)
- Photosphere and Corona
  - – Model atmospheres used to convert relative (meteoritic) to absolute abundances (Z/X)
  - – CNO abundances from photospheric lines
  - – Ne/O from coronal features
- Helioseismology

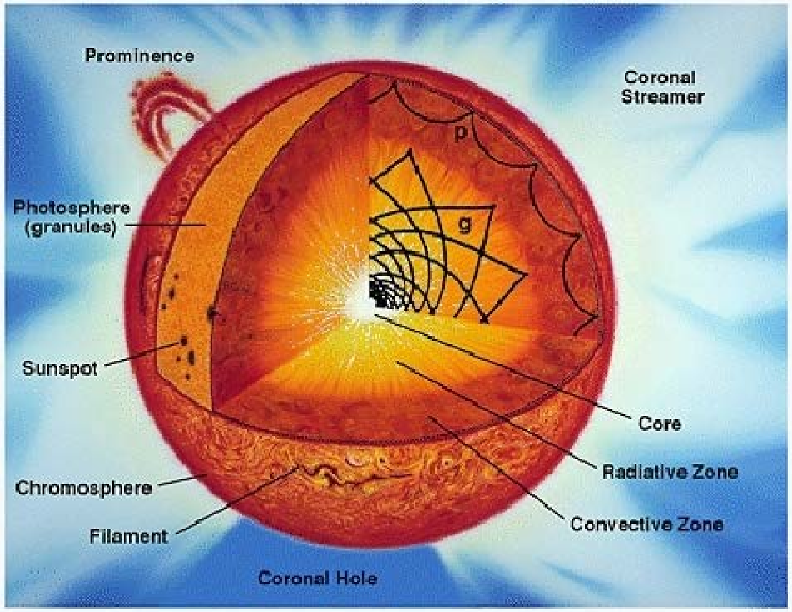
The Solar Abundance Problem

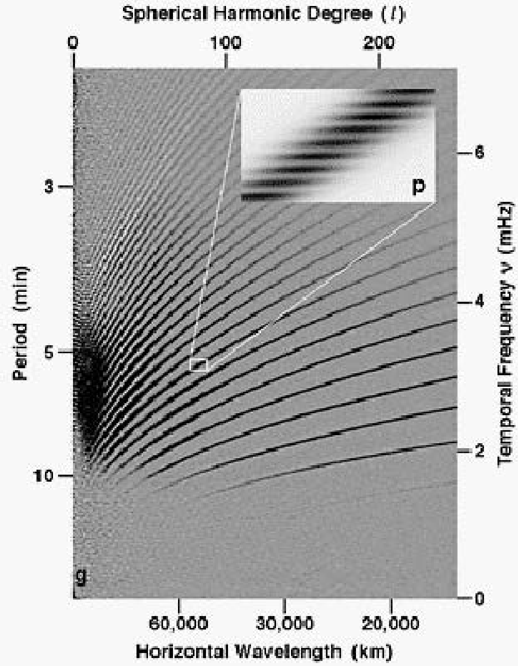
- New 3D atmospheres models test crucial assumptions used in all stellar work
- Heavier elements (Fe, Si, etc.) have numerous diagnostic features
  - good agreement between 3D, 1D results
- C, N, O are challenging to measure
  - 3D models yield large differences (20-40%) from prior 1D results
- MUCH more dramatic changes (10x) claimed for other stars…

Basic Principles of Nonradial Oscillations

- Generated by turbulence
- Discrete modes have positive interference
- g-modes (core) and p-modes (envelope) can be excited; only p modes are seen in the Sun

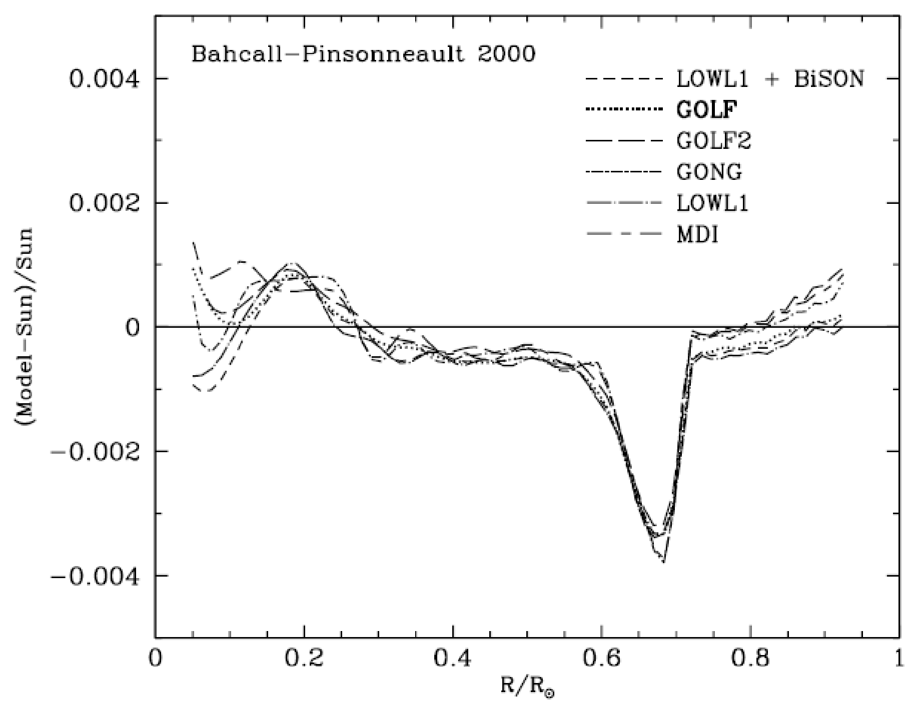






Seismology and Solar Neutrinos

- Longstanding Issue: Measured Solar neutrino fluxes inconsistent with theoretical predictions
- Agreement between theoretical and inferred sound speed profiles was strong evidence against a solar model solution (BP00)



Seismic Tools

- Inversion of the solar thermal structure
  - Sound speed profile
  - Density structure
  - Core mean molecular weight

- Discontinuities in sound speed produce distinctive signals
  - Ionization zones
  - Boundaries of convective regions

Powerful Seismic Constraints

- Convection Zone Depth
  - Discontinuity in Temperature Gradient
  - Sharp Local Feature
- Surface Helium
  - Adiabatic Temperature Gradient reduced in the presence of ionization
  - Degree depends on abundance

Basu & Antia 2008

Sound Speed Gradient

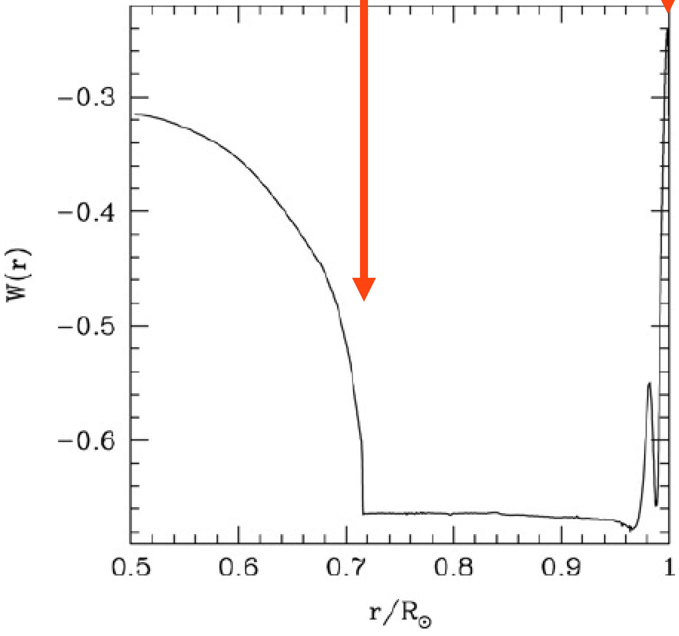
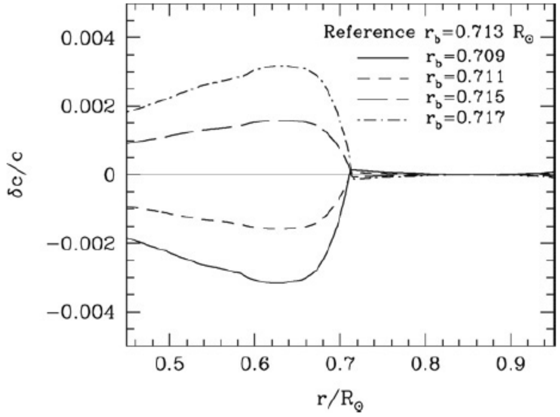


Fig. 6. The dimensionless gradient of sound speed, $W(r)$, of a solar model plotted as a function of radius.



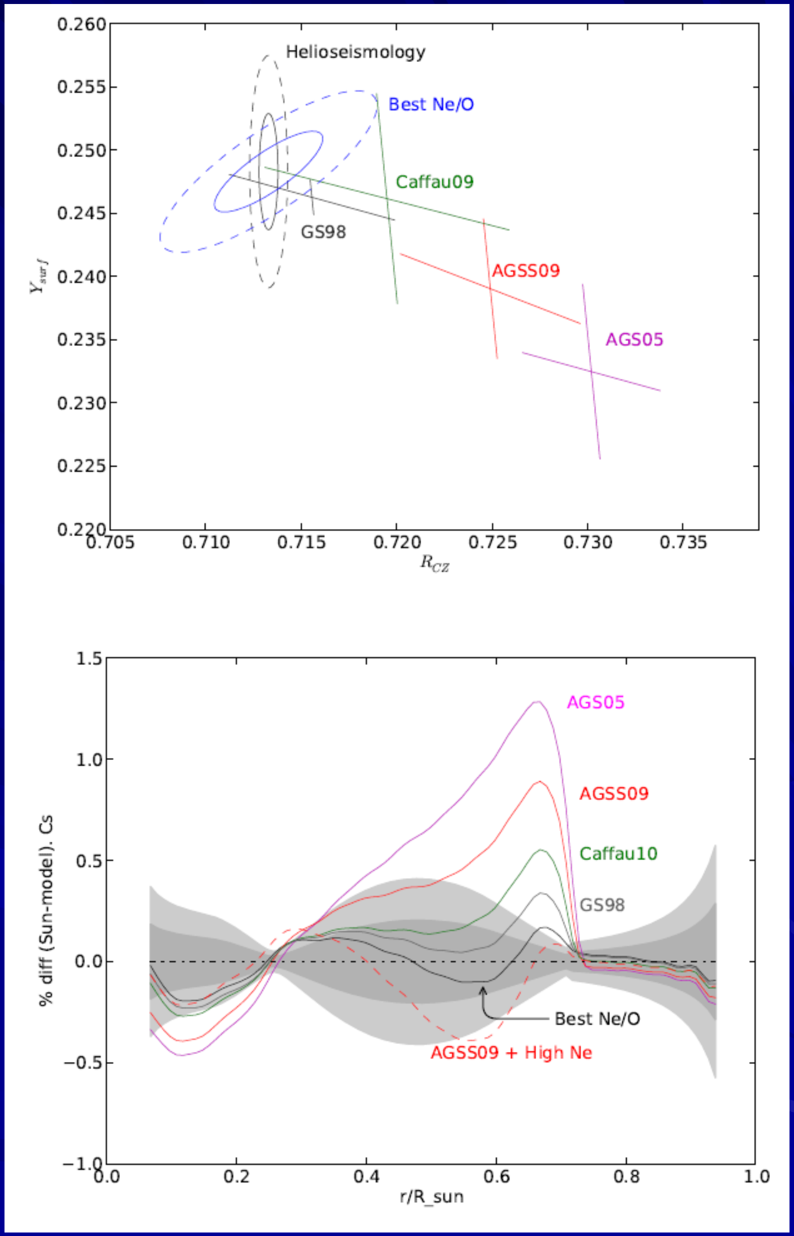
Precise Localization of the CZ depth is possible

The Solar Abundance Problem

- GS98 [O/Fe] = 8.83
- AGS05, 09 [O/Fe] = 8.66, 8.69
- Lower solar abundances degrade agreement with all seismic observables:
  - Surface Y
  - CZ depth
  - Sound Speed

Surface Helium

Sound Speed Difference



Fractional Radius

Can We Turn the Problem Around?

OPACITY

- Sound Speed measurements constrain the temperature gradient
- dT/dr related to κ
- κ related to abundance

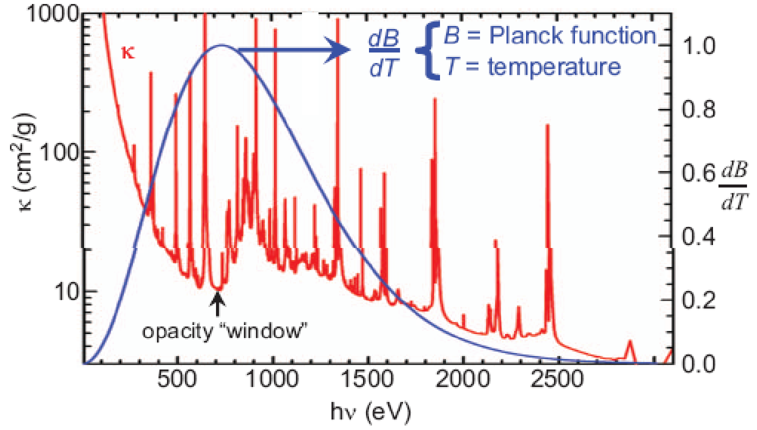


FIG. 2. (Color) Frequency dependent opacity (Refs. 13 and 14) for a 17 element solar composition (Ref. 6) near the base of the solar convection zone compared to dB/dT. The electron temperature and density were 193 eV and 1×10^{23} cm^{-3}, respectively.

Bailey et al. 2008

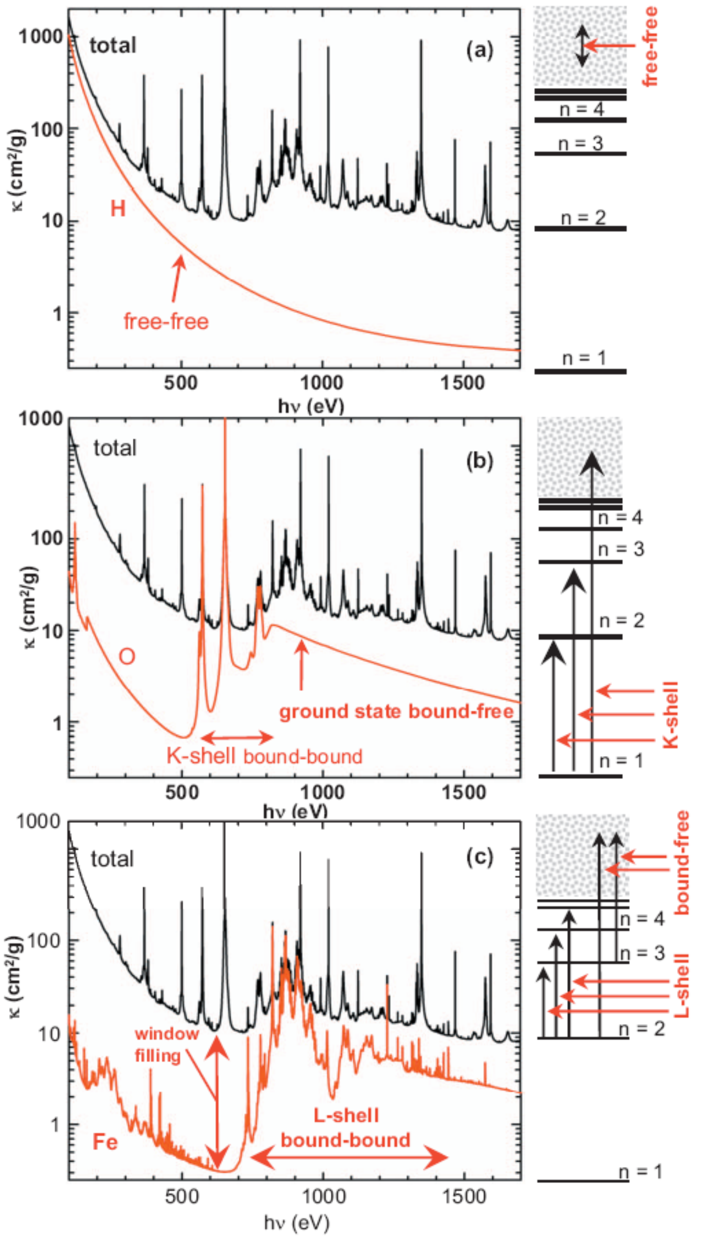
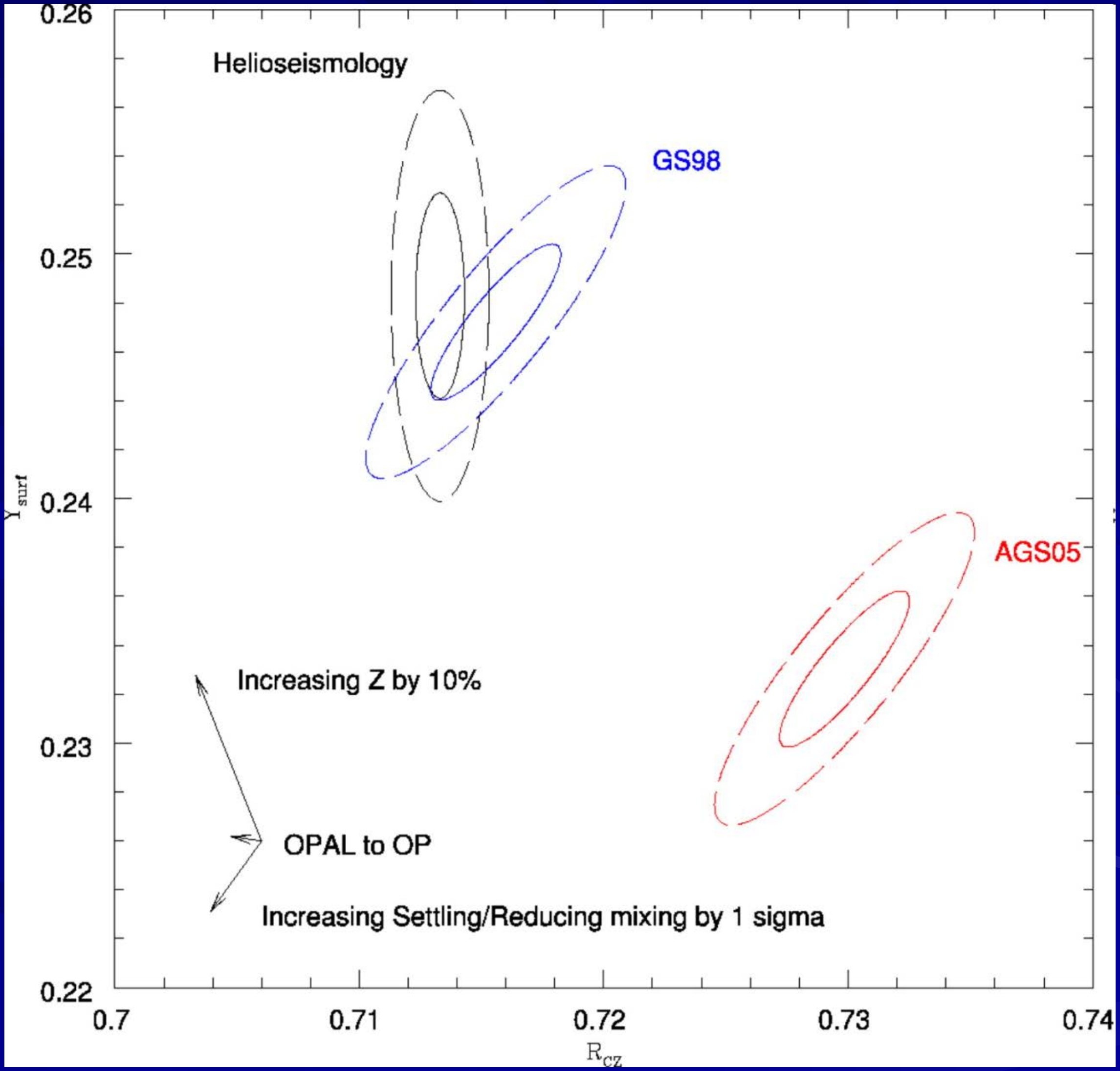


FIG. 4. (Color) Physical processes responsible for the contribution to opacity by different elements. The calculated (Refs. 13 and 14) total opacity of the solar mixture at the base of the convection zone is compared with the contribution from hydrogen, oxygen, and iron in (a), (b), and (c), respectively.

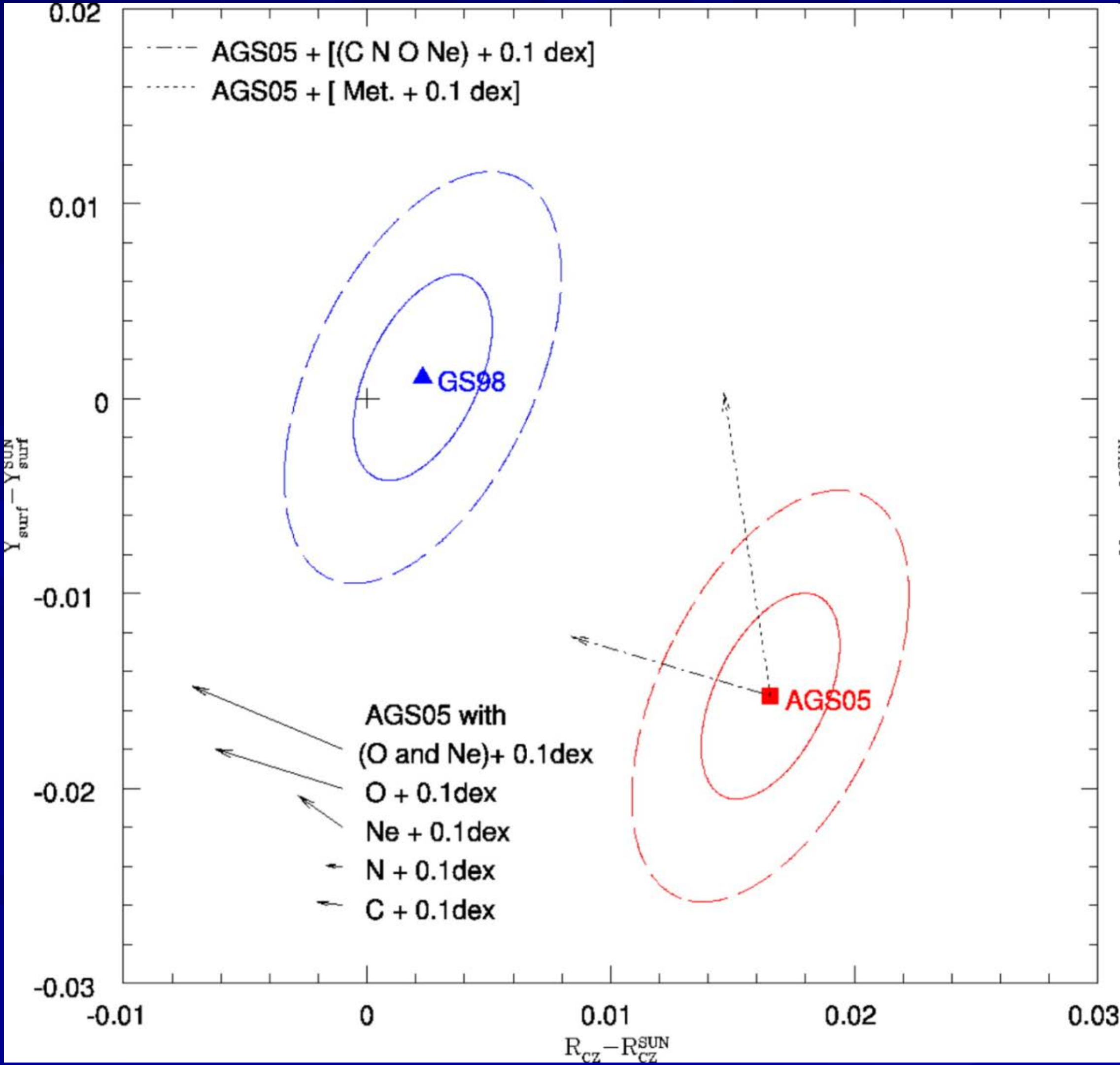
Establishing Theoretical Errors

- Compute impact of uncertainties in input physics on Ysurf, Rcz
- Implies a theoretical error along with measurement uncertainties



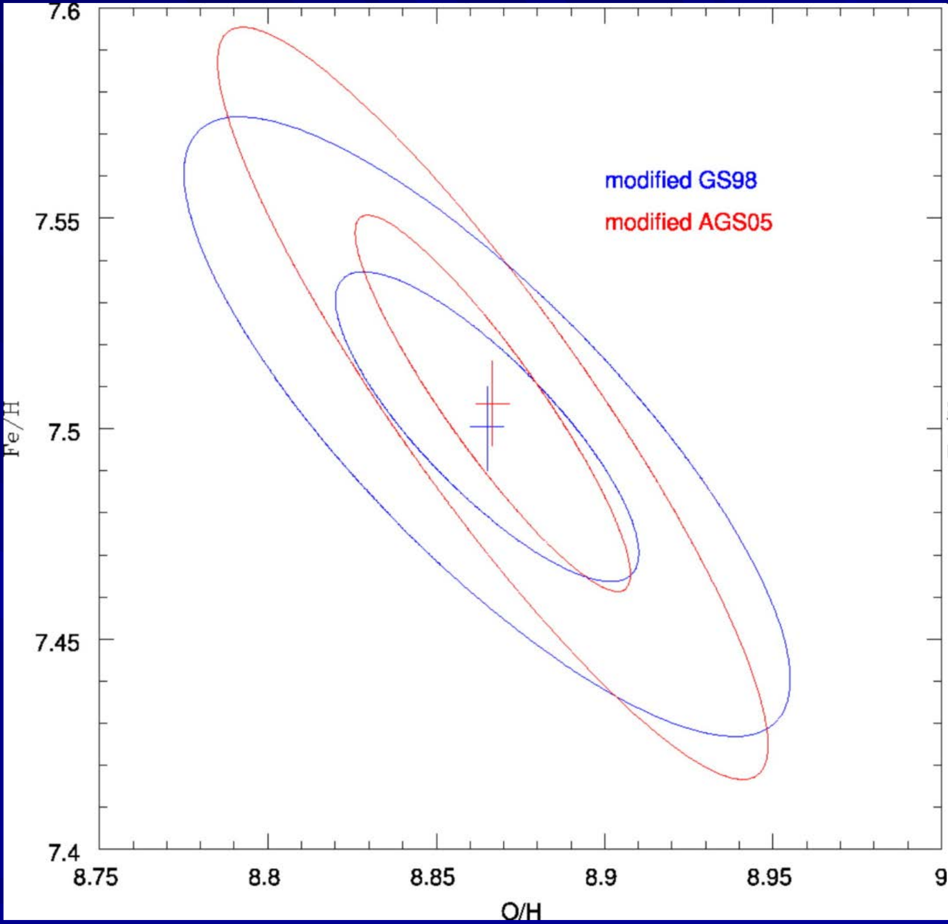
Absolute Abundances

- Delahaye & Pinsonneault 2006 approach:
- Surface Helium constrains core L (Fe) and diffusion
- Surface Convection Zone depth constrains envelope opacity (CNONe)



Mapping Thermal Structure Onto Abundances

- Modest absolute errors
- Degeneracy between changes in C, N, O, Ne
- Consistent with GS98, Caffau 2008
- Inconsistent with A04, A09

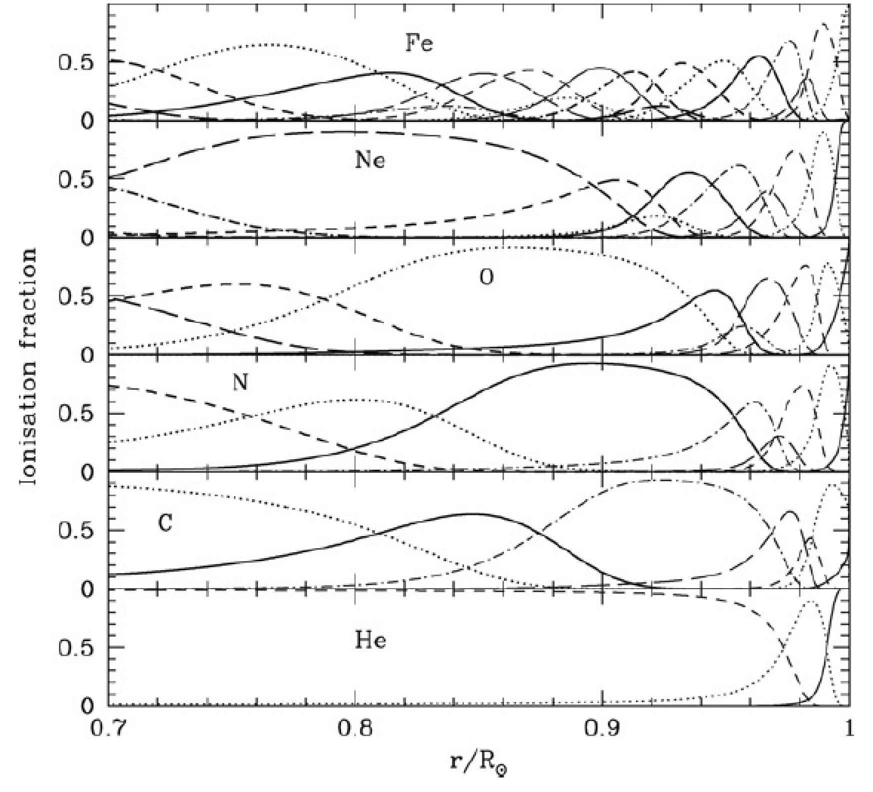


$$O/H = 8.86 \pm 0.041 - 0.198\, d(\mathrm{C}) - 0.135\, d(\mathrm{N}) - 0.351\, d(\mathrm{Ne}),$$

$$Fe/H = 7.50 \pm 0.045 + 0.038\, d(\mathrm{C}) + 0.014\, d(\mathrm{N}) - 0.038\, d(\mathrm{Ne}),$$

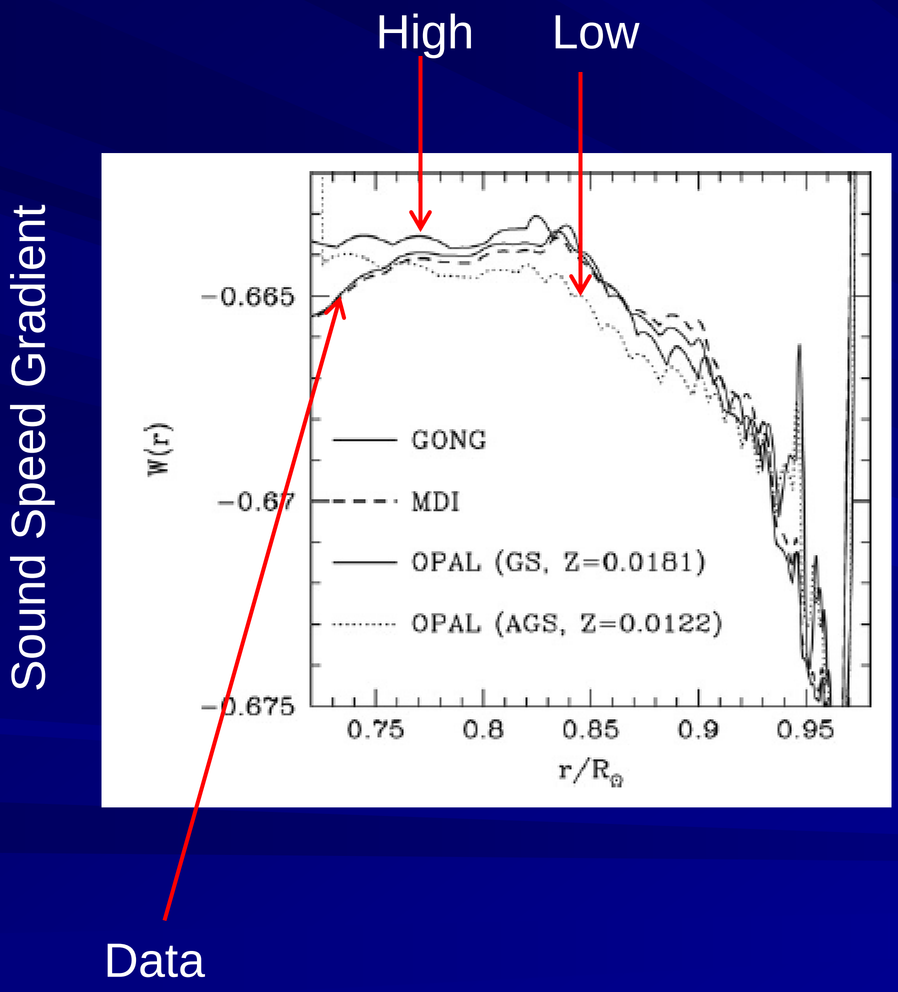
Independent Confirmation: Equation of State Test

- Ionization lowers the adiabatic temperature gradient
- Strength of the effect proportional to abundance



This will appear as an overall lowering of Del in the CZ, especially sensitive to the most abundant species (O)

Metal Ionization Detected in the Solar Surface CZ

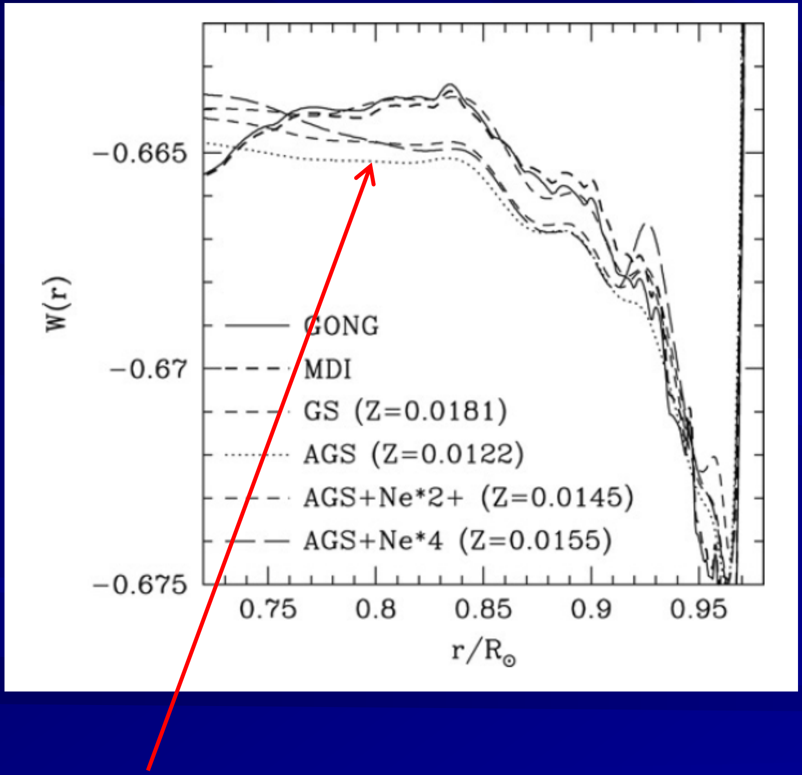


EQUATION OF STATE

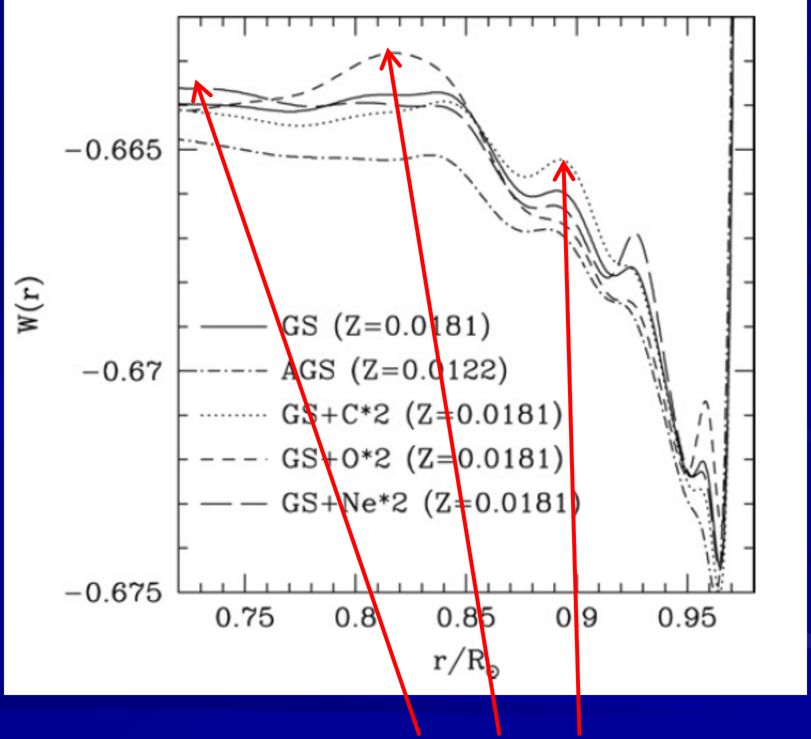
- Metal ionization seen (Basu & Antia 2006, 2008)
- Zcz = 0.017 +/- 0.002
- Consistent with the high abundance scale
- Tests EoS, not opacity…different systematics

Oxygen Ionization is Most Important

- **The detection of a high bulk metallicity is *not* consistent with a high Ne/low O solution**

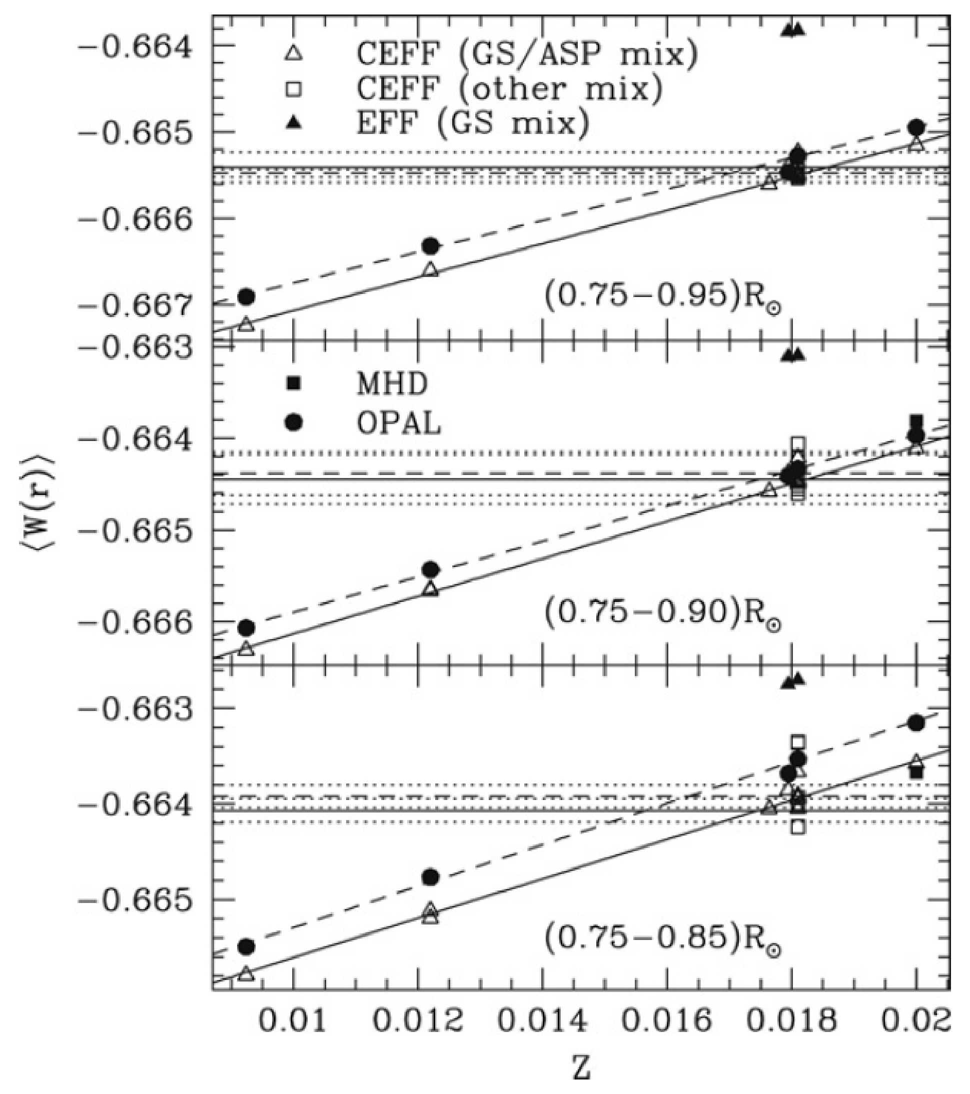


Effect of varying Ne with low O

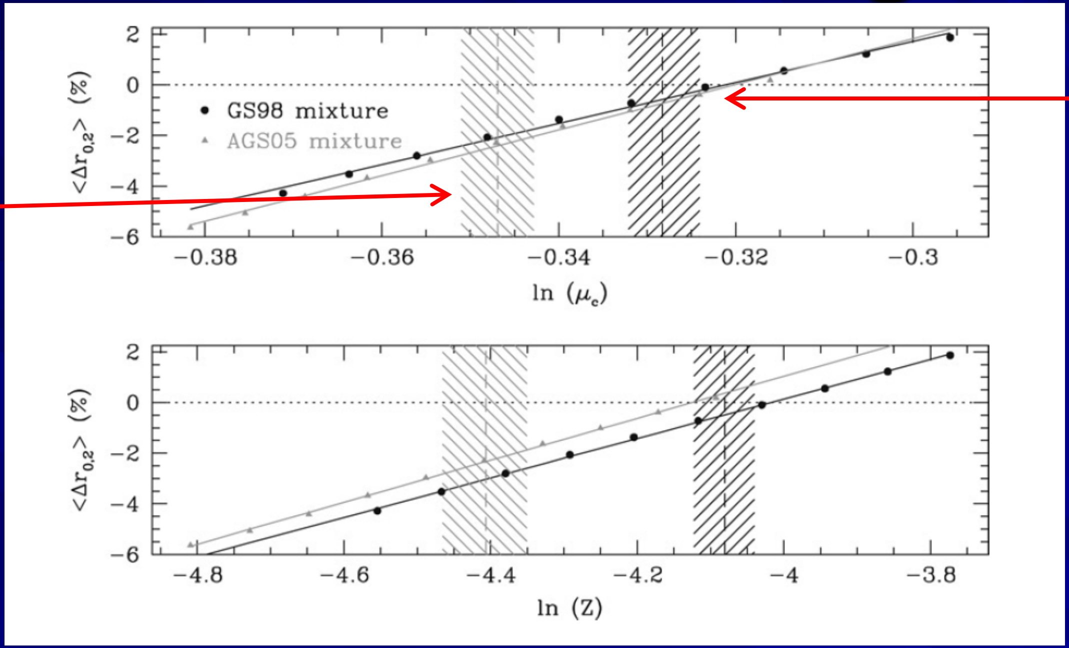


Effect of varying Ne, O, C

High Metallicity Favored By Ionization Signature



Third Test: Core Mean Molecular Weight



GS98 mix

AGS05 mix

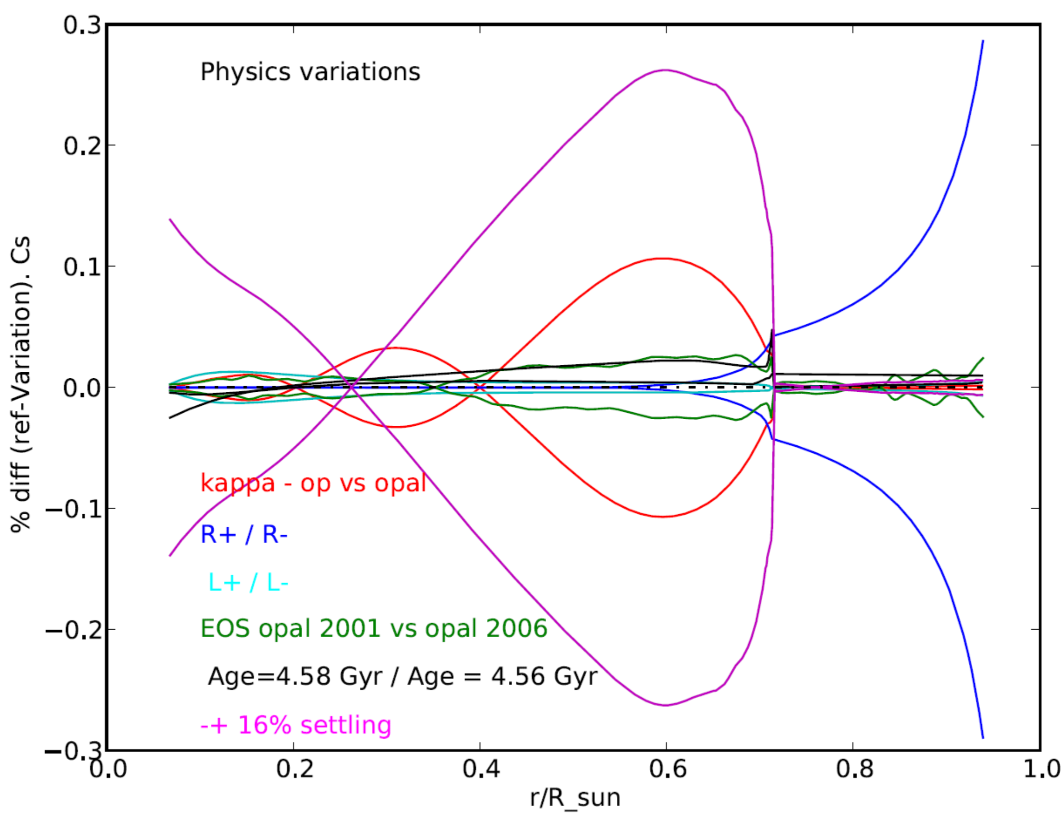
- Chaplin et al. 2007: Core μ measured to high precision; modeling of solar He production during lifetime yields interesting bounds on the bulk solar Z

Can We Learn More from the Sound Speed Profile?

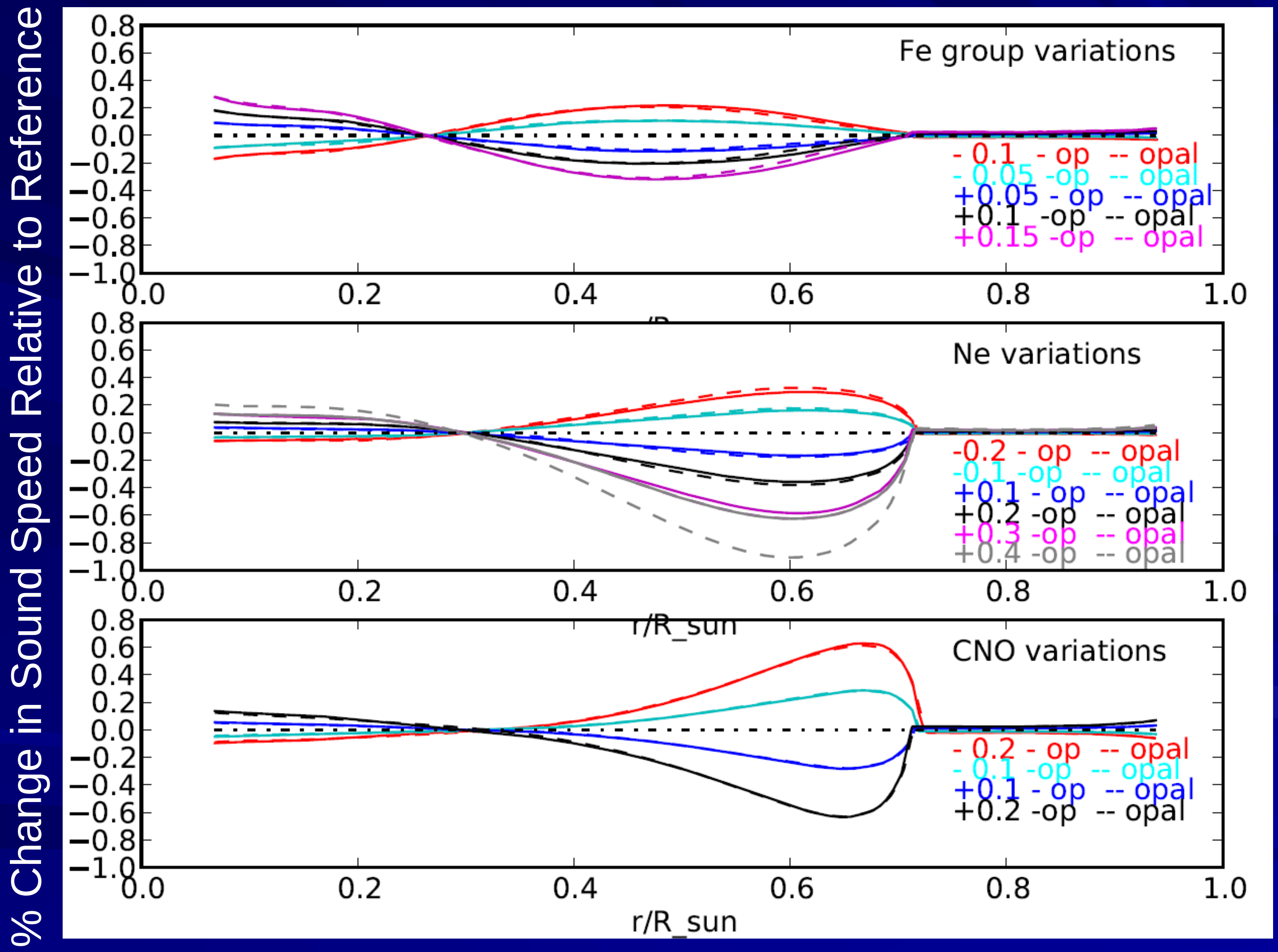
- Need to establish errors arising from
  - Background physics
  - Observational uncertainties in the solar sound speed, Rcz, Ysurf
- Then look at signatures of different elements

Sound Speed Profile is Insensitive to Errors in Most Ingredients

- However, changes are spatially correlated



Sound Speed Profile Is Composition Sensitive

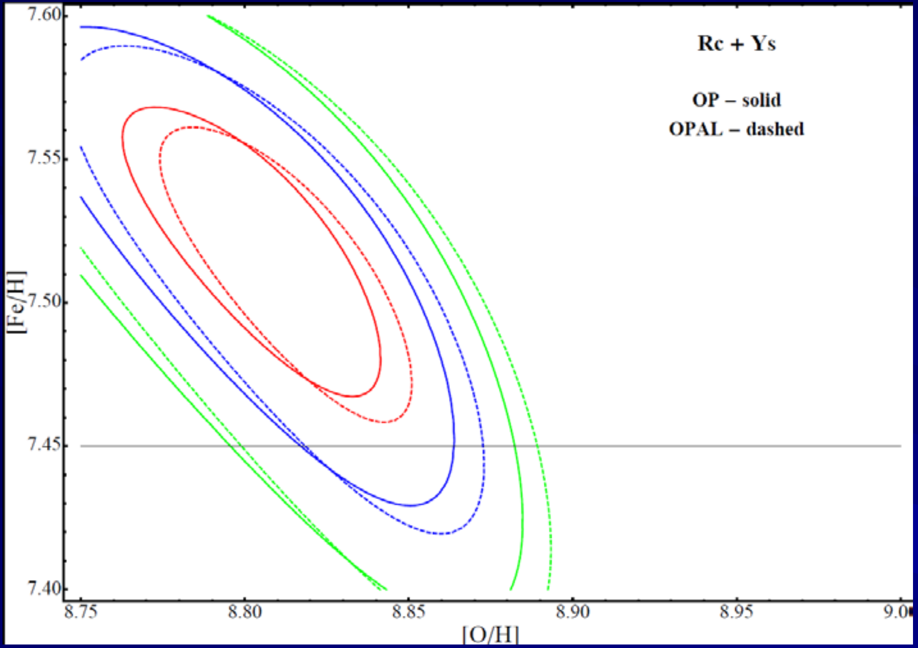


Different Species Ionize at Different Temperatures

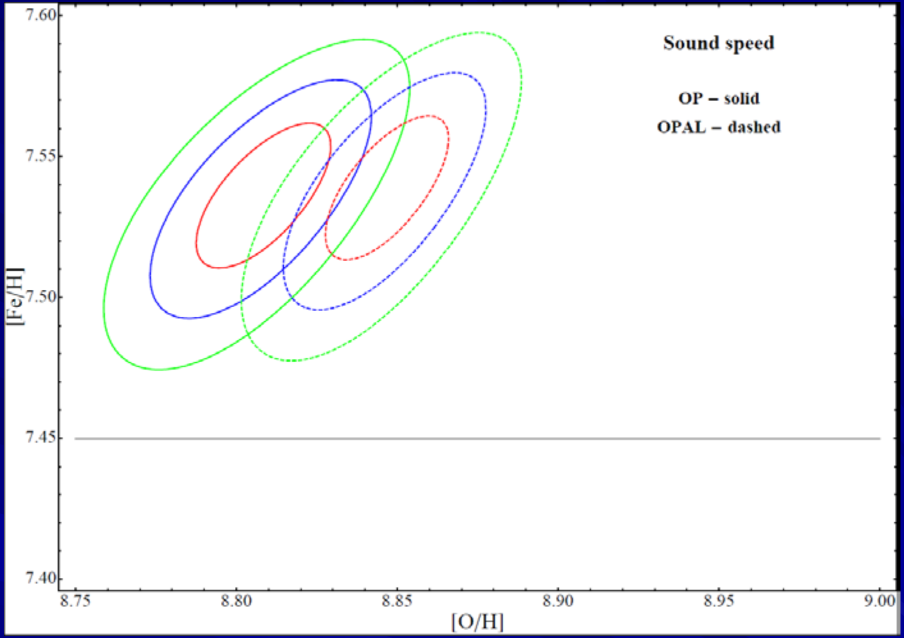
Fe Deep
Ne Intermediate
CNO Shallow

⇒Even at fixed Rcz, Ysurf there is still a way to distinguish Ne and CNO

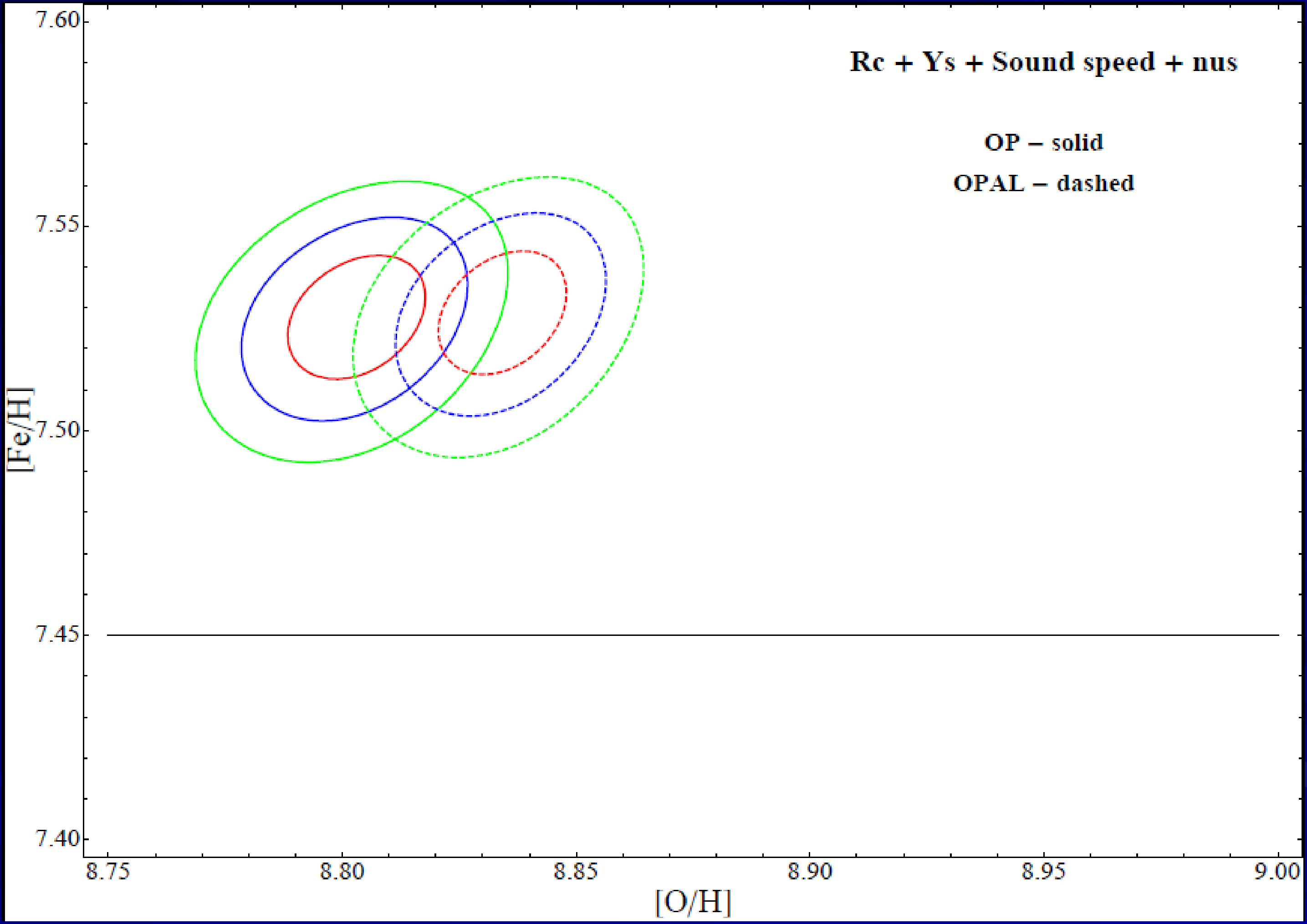
Scalars + Neutrinos

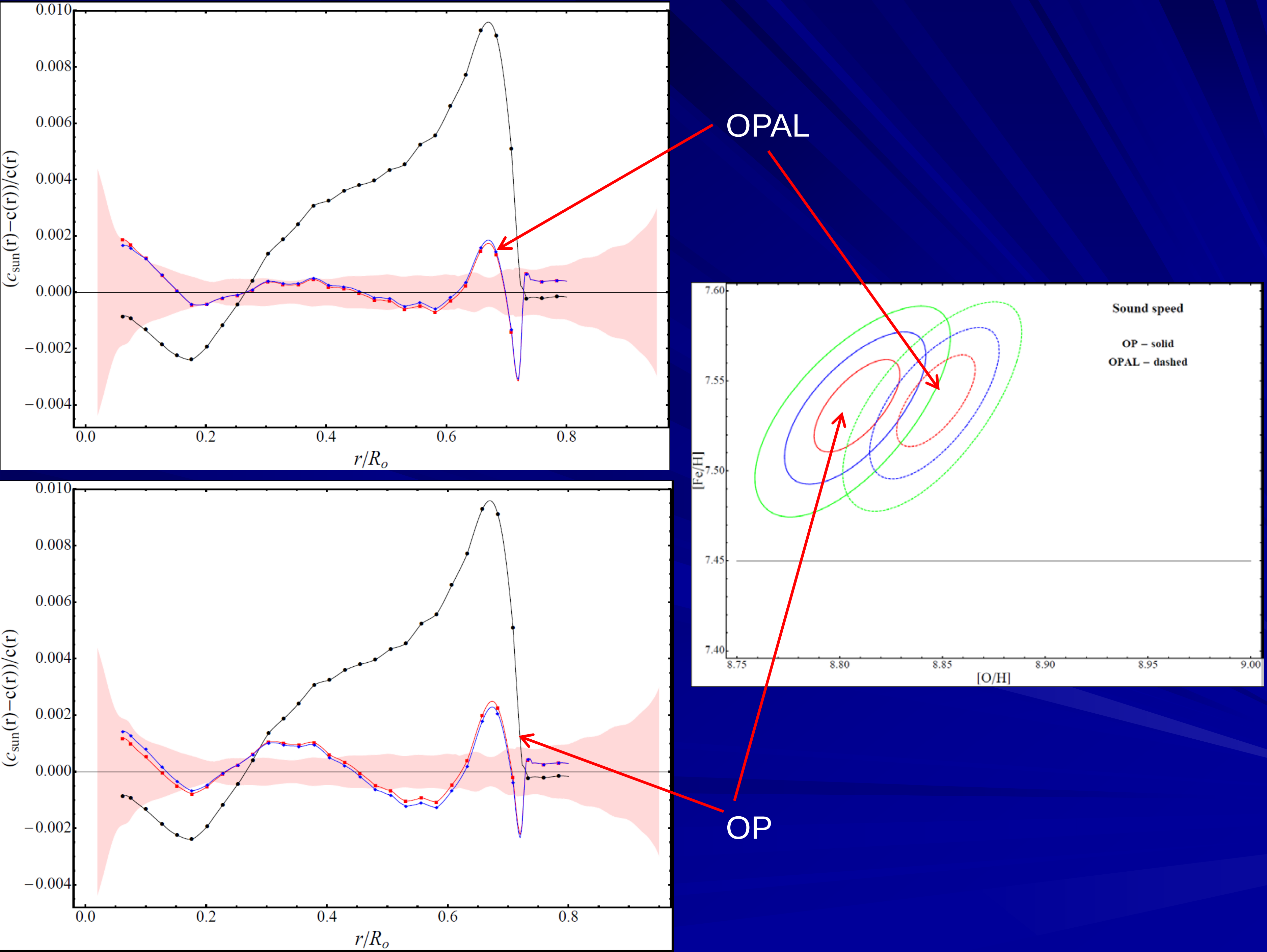


Sound Speed



Joint Constraint




0.010
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
$(c_{\rm sun}(r)-c(r))/c(r)$
0.0
0.2
0.4
0.6
0.8
r/R_o
Sound speed
OP – solid
OPAL – dashed
7.60
7.55
7.50
7.45
7.40
[Fe/H]
8.75
8.80
8.85
8.90
8.95
9.00
[O/H]

OPAL

OP

Experimentally Based Opacities

- It is now possible to measure opacities for stellar interiors conditions in the lab
- Fe measurements ongoing; Ne + O planned
- Good agreement in Rosseland mean so far

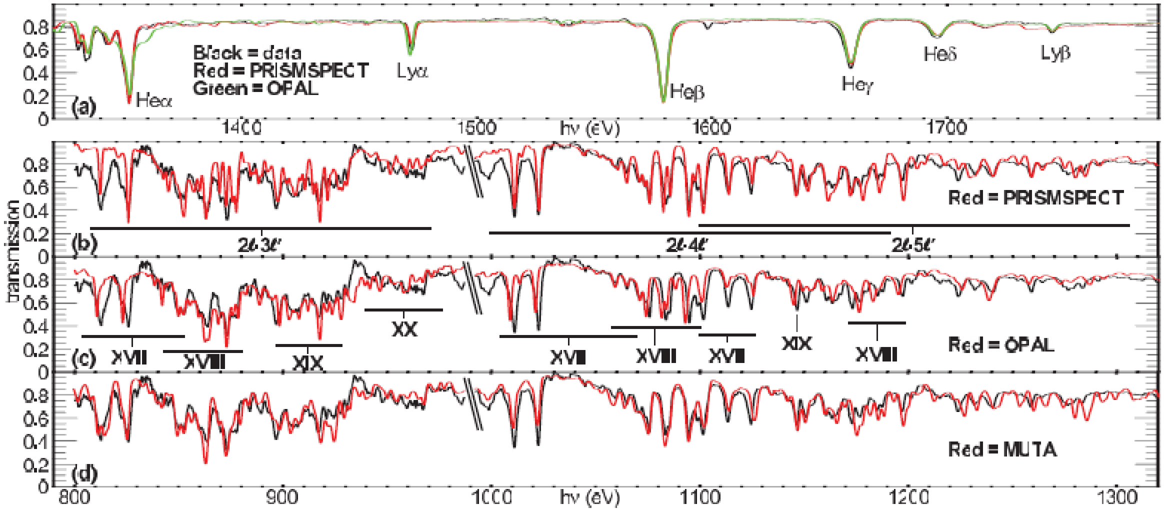


FIG. 3 (color). Average experimental transmission from the thick samples (black line, $h\nu > 990$ eV) and the thin samples (black line, $h\nu < 990$ eV). The spectral range including the Fe b-f and Mg K shell (a) is compared with PRISMSPECT (red) and OPAL (green). Comparisons in the Fe L shell spectral energy range are shown for PRISMSPECT (b), OPAL (c), and MUTA (d) (models in red). The charge states and configurations responsible for many of the strong absorption features are indicated, although millions of b-b transitions are present.

- Experimental Opacity Measurements for Solar Conditions (Bailey et al. 2007, 2008)

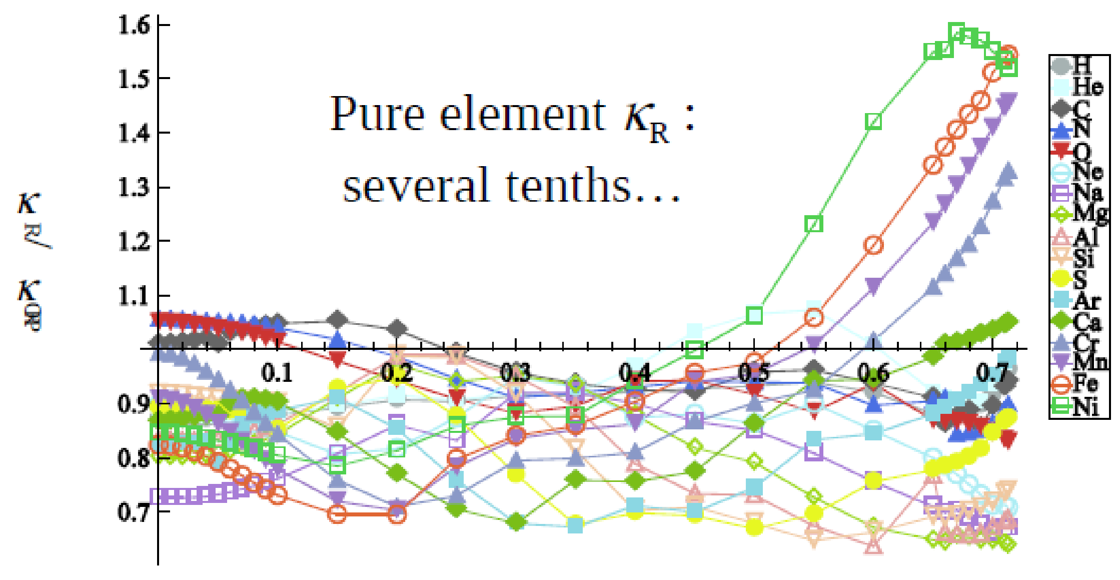
OP vs. OPAS

Large differences in specific computed elemental opacities…

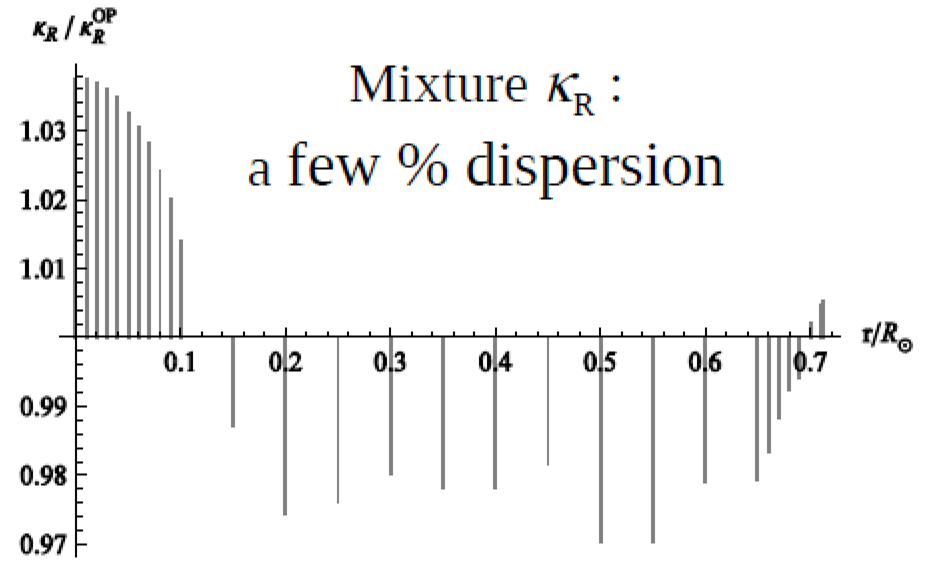
- OPAS agrees better with experimental data, but predicts a similar Rosseland mean opacity

Turck-Chieze et al. 2011

…Imply a small change in mean opacity



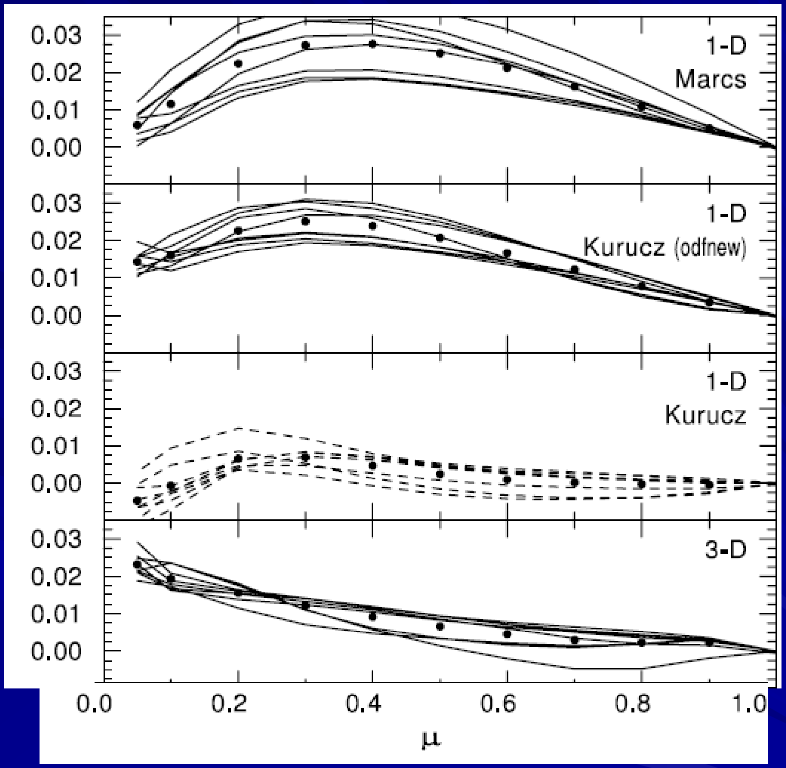
Pure element κ_R : several tenths…



Mixture κ_R : a few % dispersion

What Could Be the Issue with Atmospheres?

- Theoretical thermal structure from Asplund et al. 2004 was too cool compared with solar limb-darkening data
- New models have improved thermal structure, but abundances are still below seismic estimates ([O/H] = 8.69 +/- 0.05; AGS09)



Koesterke et al. 2008 Theoretical Models vs. Limb-Darkening Data

Independent 3D Atmospheres Code: Different Oxygen

- Caffau et al. (2008) found higher abundances with a independent 3D atmosphere
- Solar [O/H] = 8.76+/-0.07, compatible with interiors

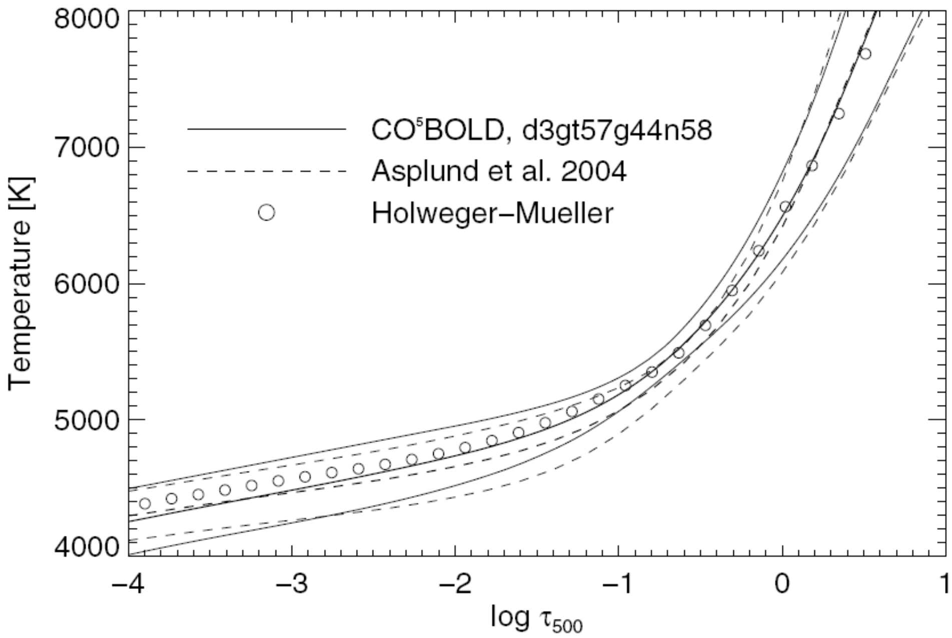


Fig. 1. Comparison of the temperature structures of the CO^{5}BOLD model used in this work, the 3D model of A04, and the Holweger-Müller model. For the 3D models the RMS fluctuations (thin lines) around the mean (thick lines) are indicated.

BUT: atmospheres are actually similar to Asplund et al. 2009. Why is the abundance answer so different?

The Human Element

- All oxygen abundance indicators are unhappy in their own special way
- Series of judgment calls required
  - Continuum level
  - Treatment of blended features
  - Which indicators to use
  - Which data set to use
- Multiple problematic indicators don’t reduce global errors

Neutrinos and Abundances

Neutrinos	**Solar**	**AGS09**	**GS98**
Be^7 (10^9/cm^2)	4.82 +0.24/ -0.19	4.56 +/- 0.32	5.00 +/-0.35
B^8 (10^6 / cm^2)	5.00 +/- 0.15	4.59 +/- 0.64	5.58 +/- 0.78

Haxton et al. 2012

- Direct fluxes weakly constrain
- However, CN fluxes for well-measured Be7+B8 are a powerful and independent diagnostic

Summary

- Seismology and interiors models can be used to predict absolute solar and stellar abundances
- Seismic diagnostics favor a higher O and tightly constrain Fe and other heavies
- Experimental tests of opacities underway
- Important role for CNO neutrino detection