Helioseismology and the solar abundance problem

Katie Mussack

Los Alamos National Laboratory

The solar abundance problem can be attacked on several fronts

- Spectroscopic analysis determines atmospheric abundances
- New spectral measurements can be taken
- Solar models can be adapted to modify interior of model Suns
- Abundances can be inferred through seismology

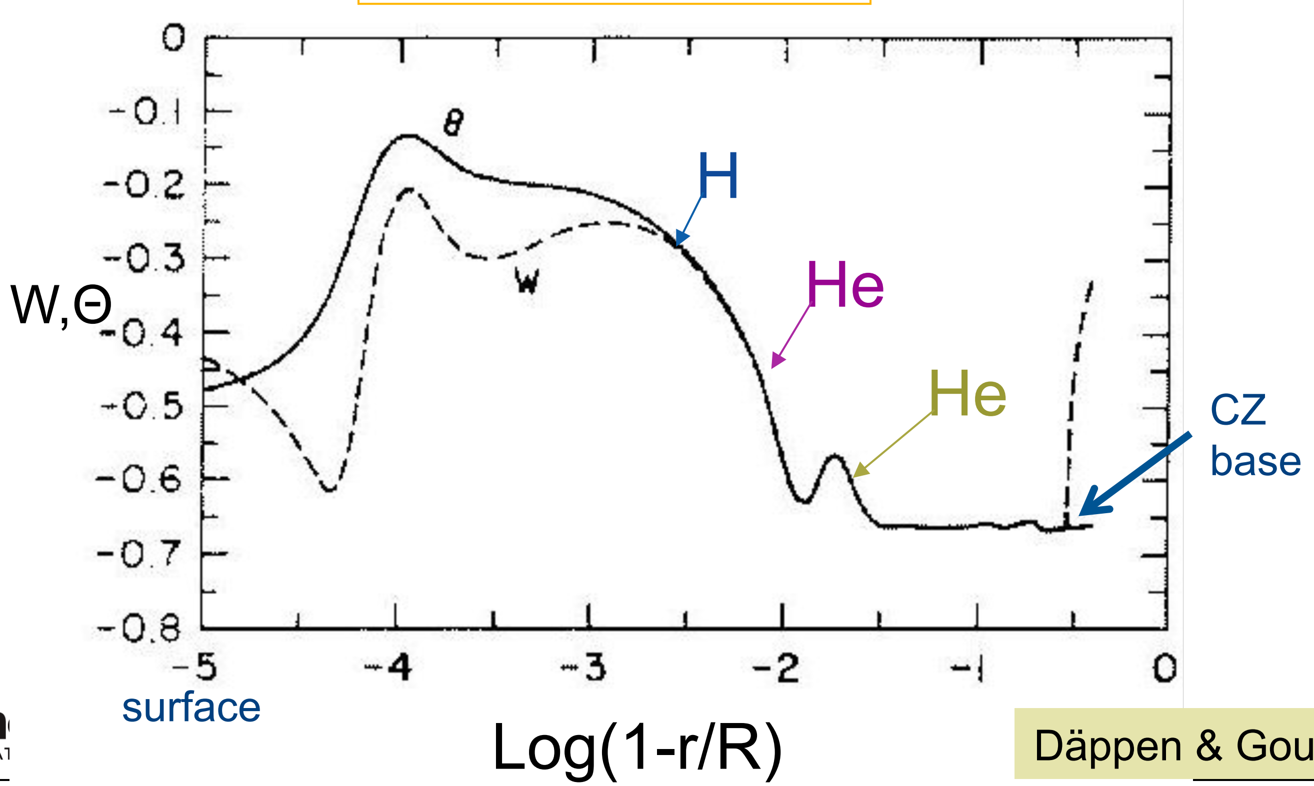
Here:

- Attack on all fronts
- Focus on the role of seismology

Helioseismology was used to determine He abundance in the convection zone

Split up the adiabatic sound speed gradient: $\frac{dc^2}{dr} = \frac{Gm}{r^2}\left\{1-\gamma_1\left[1+\left(\frac{\partial \ln \gamma_1}{\partial \ln p}\right)_S\right]\right\}$

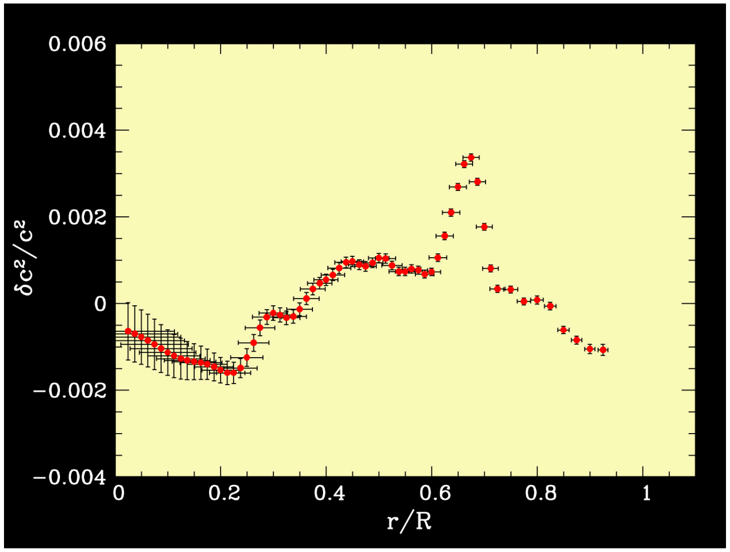
Into: $W = \frac{r^2}{Gm}\frac{dc^2}{dr}$ $\Theta = 1-\gamma_1\left[1+\left(\frac{\partial \ln \gamma_1}{\partial \ln p}\right)_S\right]$



Däppen & Gough, 1984

Simple assumptions were used to model solar interior

- One-dimensional
- Initial homogeneous composition
- Negligible mass loss or accretion
- Neglect rotation and magnetic fields
- Simple surface boundary conditions
- No additional mixing or structural changes
  - convective overshoot
  - shear from differential rotation
  - meridional circulation
  - waves or oscillations



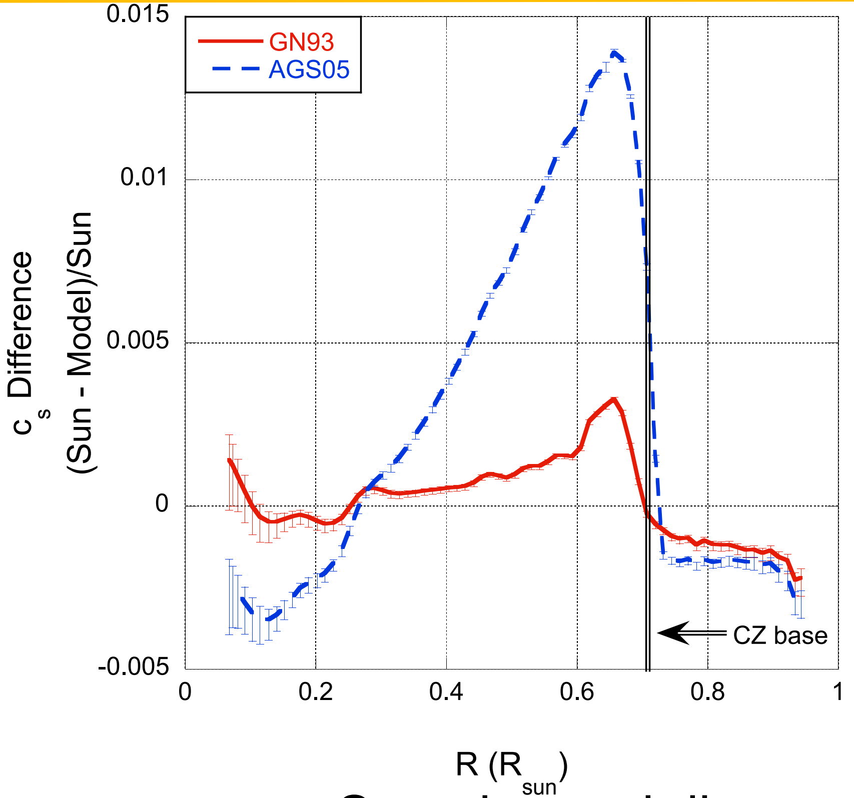
Asplund et al. 2005 lowered abundances

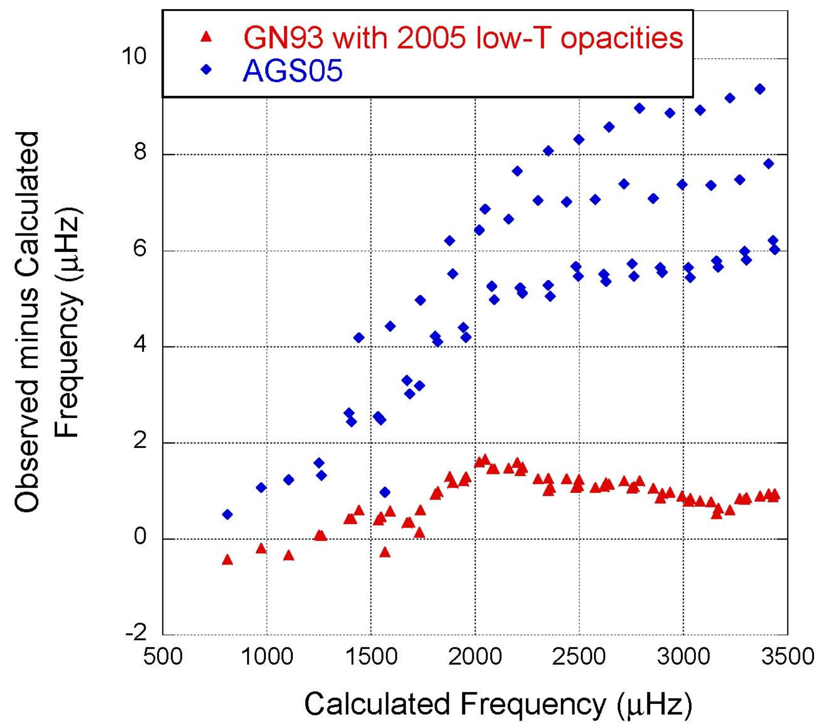
- **Reanalyzed solar optical spectrum**
- **Used updated techniques**
  - improved atomic physics
  - 3D hydrodynamical model atmosphere
- **Confidence in new analysis**
  - Good agreement with observed line profiles and line bisectors
  - Different lines give similar abundances (ie: O)

	AG89	GN93	GS98	AGS05
C	**8.56** ±0.04	**8.55** ±0.05	**8.52** ±0.06	**8.39** ±0.05
N	**8.05** ±0.04	**7.97** ±0.05	**7.92** ±0.06	**7.78** ±0.06
O	**8.93** ±0.04	**8.87** ±0.04	**8.83** ±0.06	**8.66** ±0.05
Ne	**8.09** ±0.10	**8.07** ±0.06	**8.08** ±0.06	**7.84** ±0.06
Z/X	0.0274 ±0.0016	0.0244 ±0.0014	0.0231 ±0.0018	0.0165 ±0.0011

AG89 = Anders & Grevesse (1989)
GN93 = Grevesse & Noels (1993)
GS98 = Grevesse & Sauval (1998)
AGS05 = Asplund, Grevesse, & Sauval (2005)

Lower abundances result in worse agreement with helioseismic constraints





- Sound-speed discrepancy up to 1.4% below CZ
- CZ too shallow
- CZ helium abundance too low

Guzik & Mussack, 2010

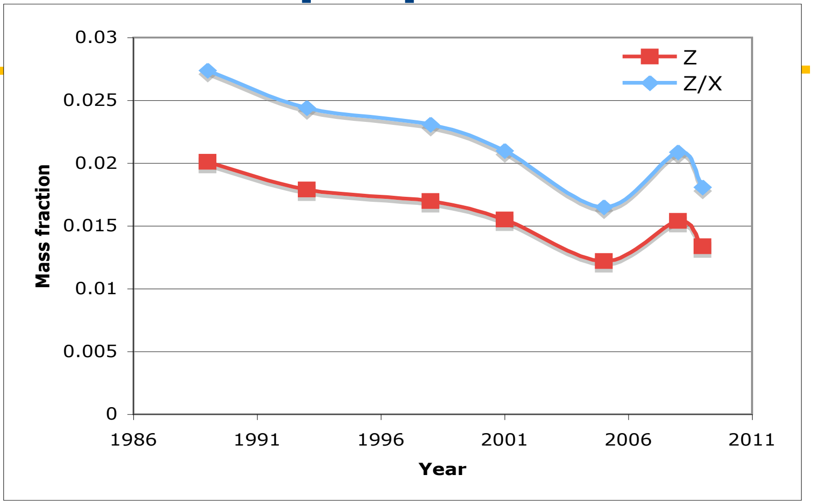
What’s the problem?

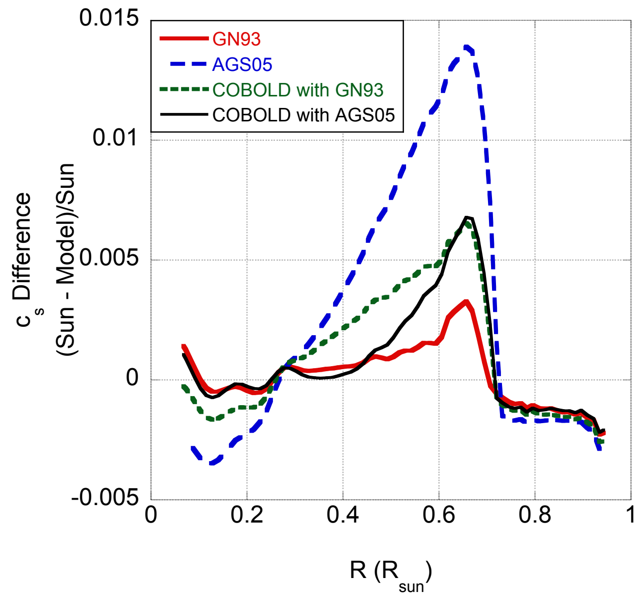
- **“Solar abundance problem”**
  - New abundances inconsistent with helioseismic constraints

- **“Solar model problem”**
  - Agreement with observed line profiles & bisectors
  - Different lines give similar abundances
  - Sun now similar to comparable neighbors
- **Perhaps both models and abundances need to be refined**

2008-2009: Intermediate abundance values proposed

Year	Source	Z	Z/X
1989	Anders & Grevesse	0.0201	0.0274
1993	Grevesse & Noels	0.0179	0.0244
1998	Grevesse & Sauval	0.0170	0.0231
2001, 2004	Holweger (compliled by Turck-Chièze et al. 2004)	0.0155	0.0210
2005	Asplund et al.	0.0122	0.0165
2009	Asplund et al.	0.0134	0.0181
2008, 2009	COBOLD	0.0154	0.0209





Guzik & Mussack, 2010

Coronal X-ray measurements offer a potential solution

- **Measure neon abundance: Ne Kα line**
  - Coronal X-rays near temperature minimum
  - Weak line, but isolated & unblended

- **Measure oxygen abundance: O Kα line**
  - Coronal X-rays just above temperature minimum
  - Essentially uncontaminated & observable

- **Drawback: wait for observations**
  - Sensitive X-ray spectrometer needs to be funded and built

Drake & Ercolano, 2007 & 2008

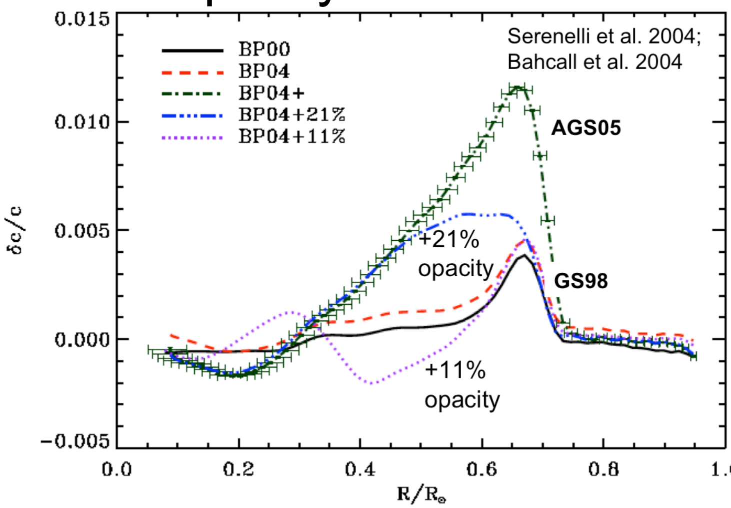
Changes to solar models have been explored

- Opacities – increase below CZ (11-20%)
- Abundances – increase within uncertainty limits
- Ne abundance – increase up to x3
- Diffusive settling – increase at CZ base
- Evolution – early accretion of lower Z material
- Tachocline – mixing
- Various combinations

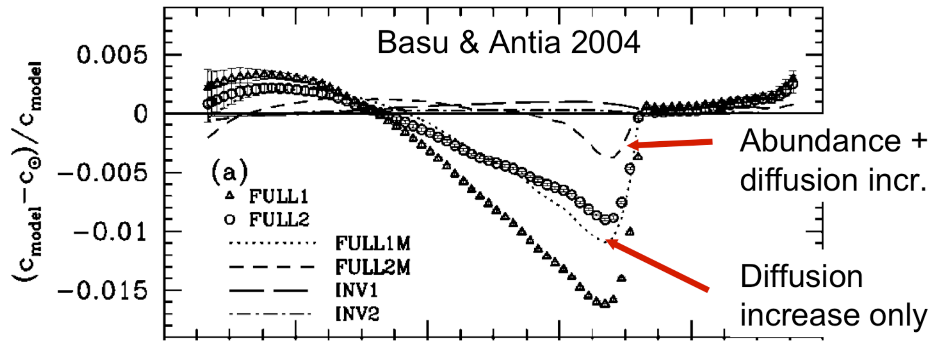
It is difficult to match both the new abundances and the helioseismic constraints for CZ He, CZ depth, and sound-speed profile.

Some modifications improve sound-speed agreement

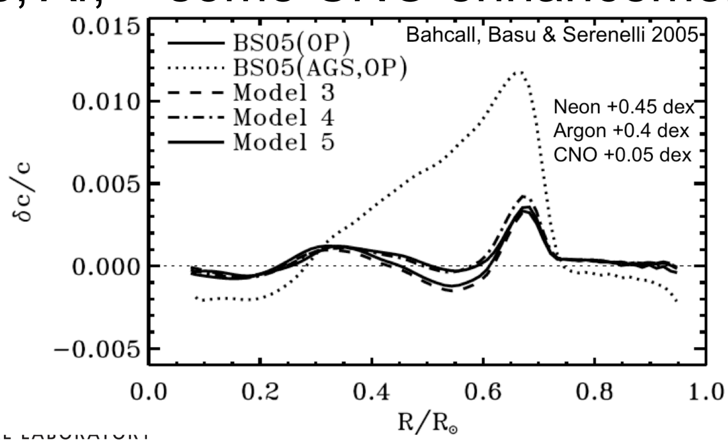
Opacity increases



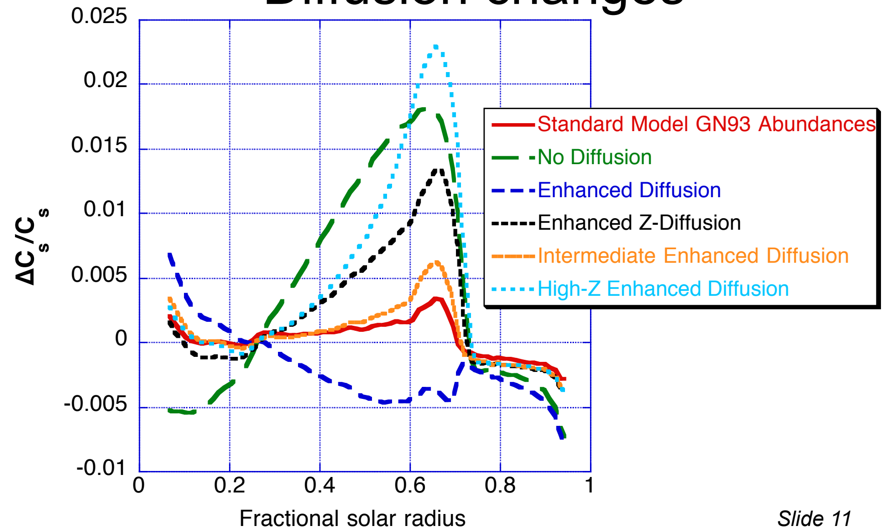
Diffusion and abundance increases



Ne, Ar, + some CNO enhancement

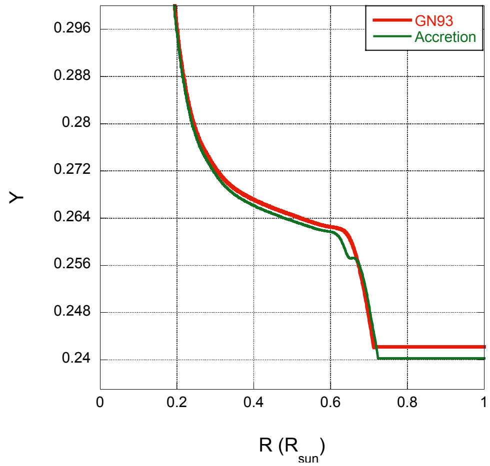


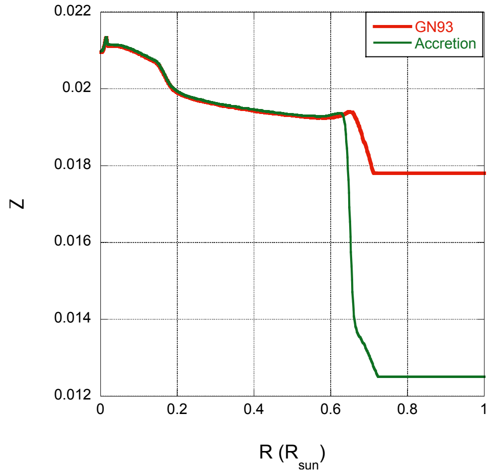
Diffusion changes



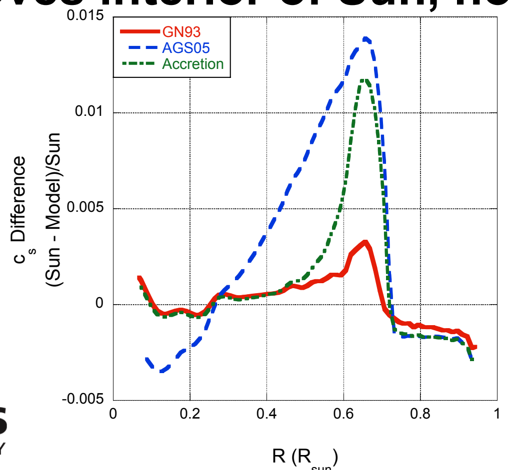
Accretion of low-Z material shows potential

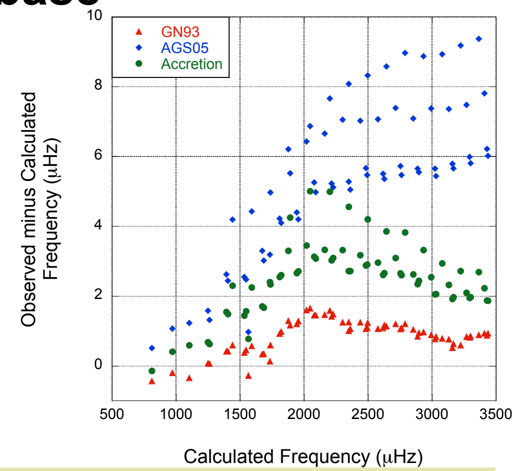
- **Maintain an interior similar to GN93 with lower Z near surface**





- **Improves interior of Sun, not near CZ base**

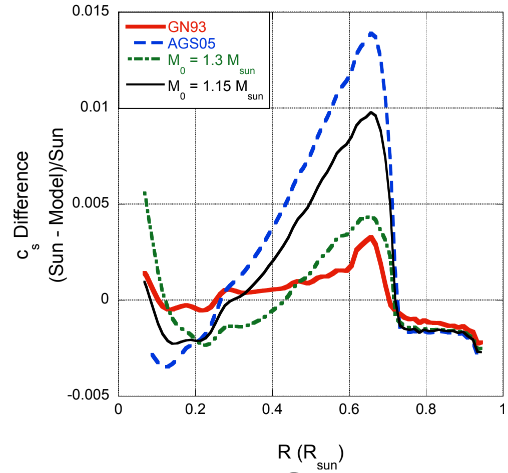


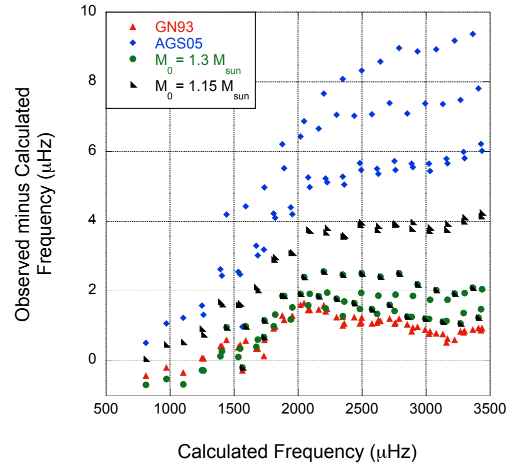


Guzik & Mussack, 2010

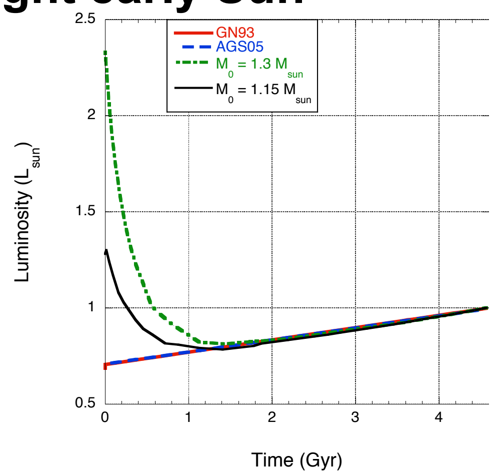
Including mass loss in solar models can improve the agreement

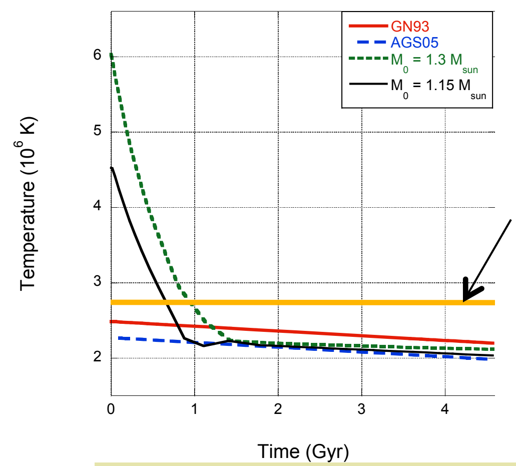
- **Mass loss can improve sound-speed agreement and O-C frequencies**





- **Hot, bright early Sun**

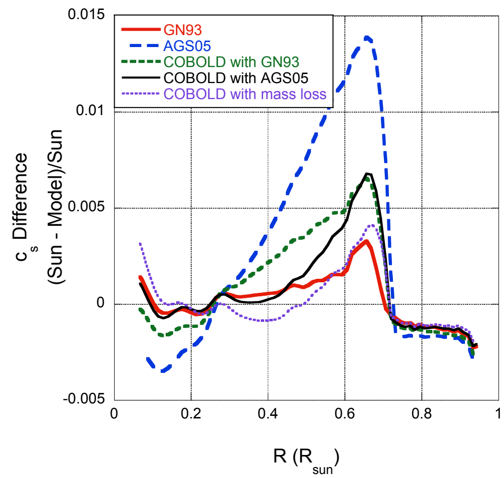


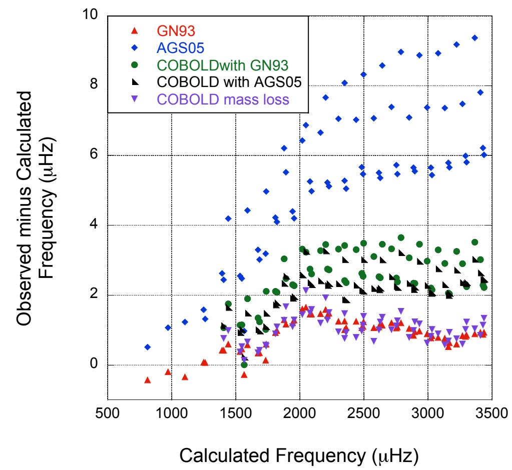


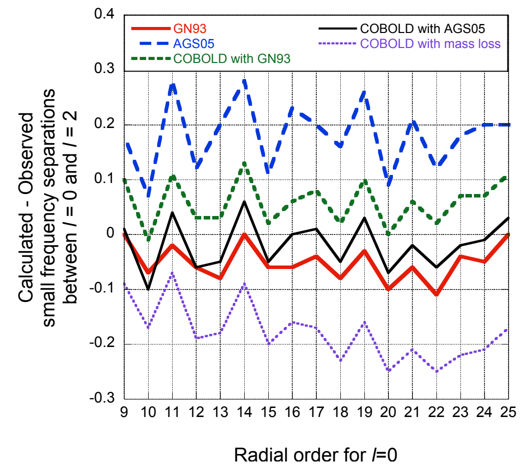
Li destroyed at $T=2.8 \times 10^6$ K

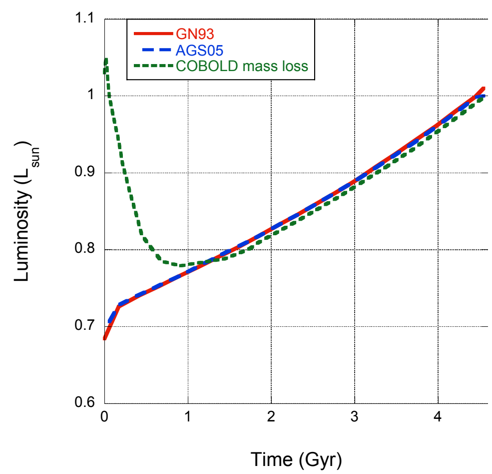
Guzik & Mussack, 2010

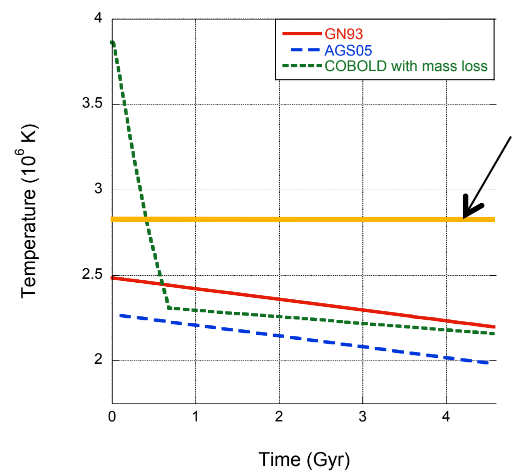
Mass-loss + intermediate abundances is even better









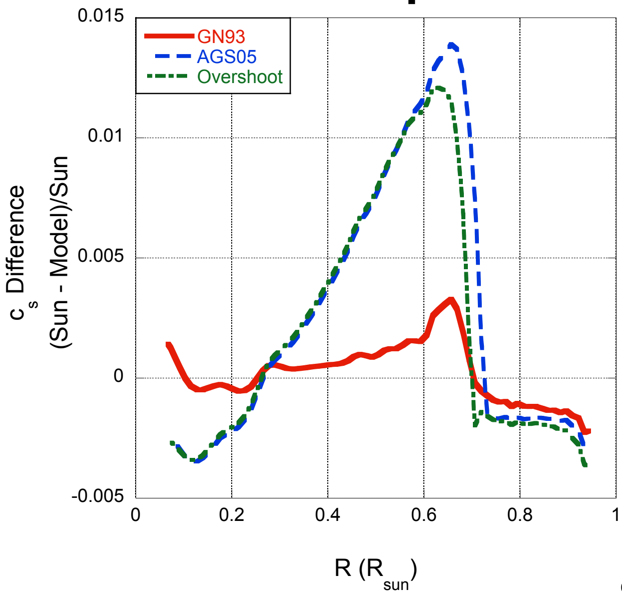


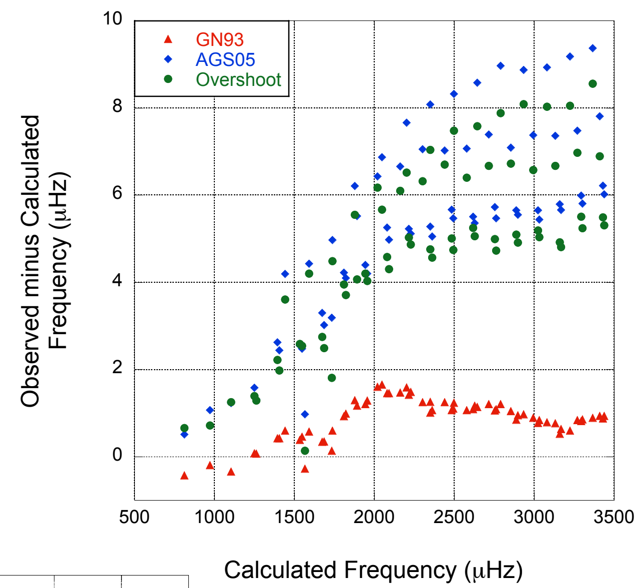
Li destroyed at $T=2.8\times10^{6}$ K

Guzik & Mussack, 2010

Convective overshoot was proposed as a way to improve agreement

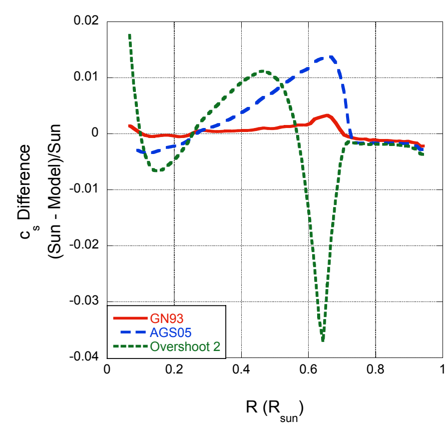
- **Overshoot did not provide much improvement**





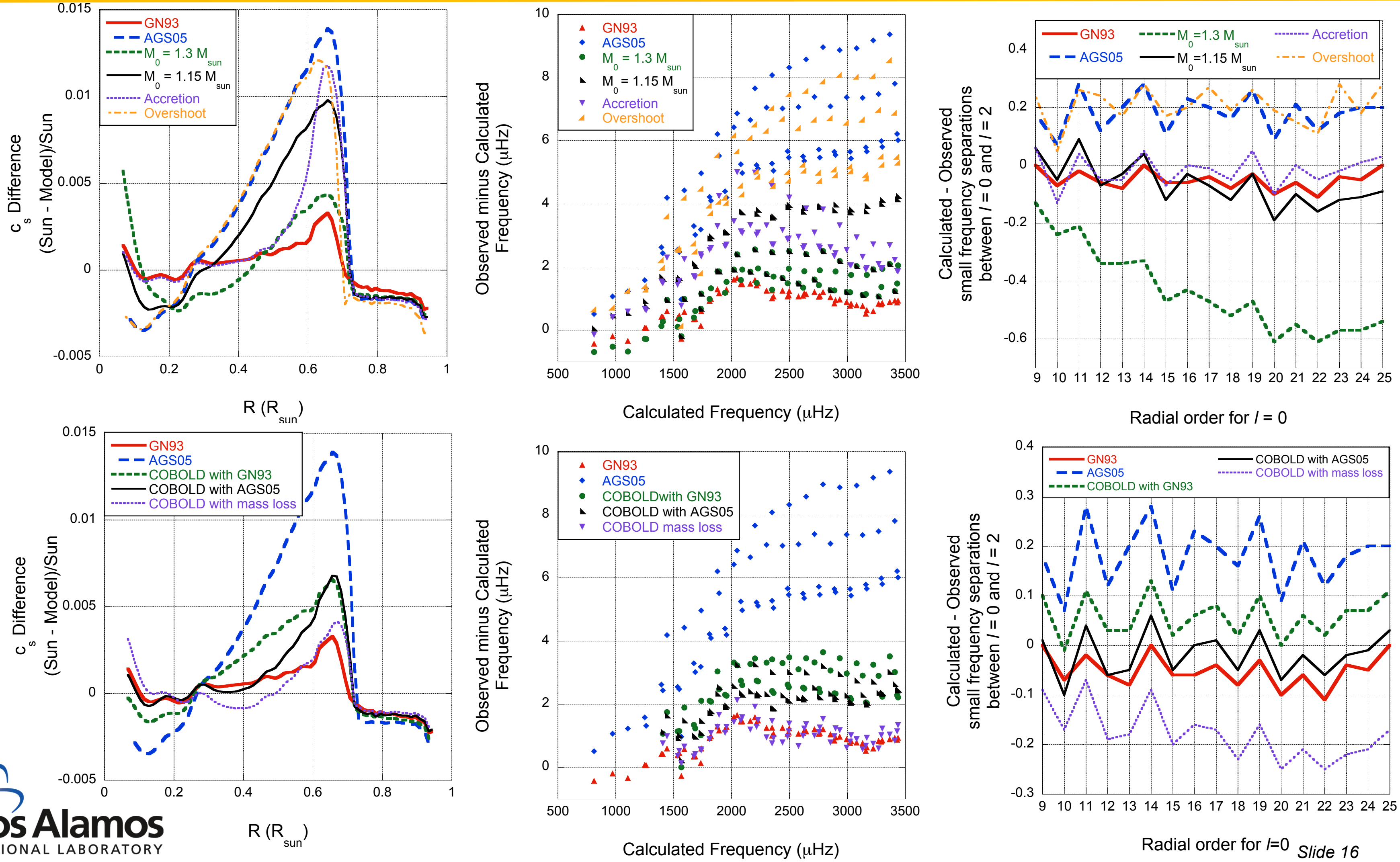
- **Extra overshoot**

made the problem worse



Guzik & Mussack, 2010

Model changes can be evaluated using sound-speed differences, O-C frequencies, and small separations



Slide 16

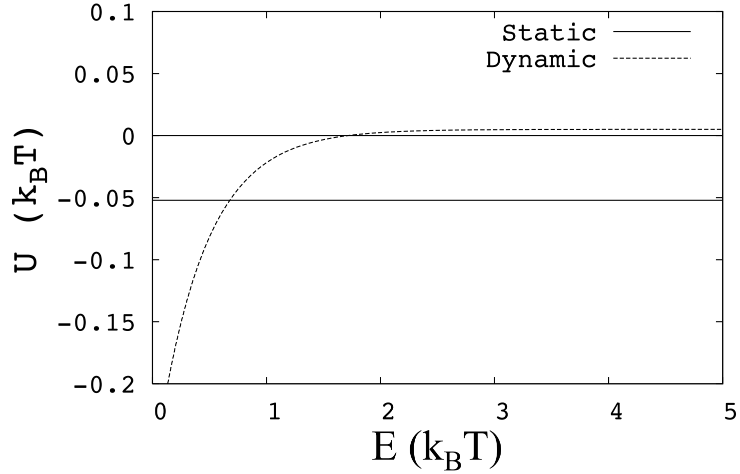
Los Alamos NATIONAL LABORATORY EST.1943

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

Guzik & Mussack, 2010

NNSA

Dynamic screening introduces a correction to p-p reaction rates in the solar core

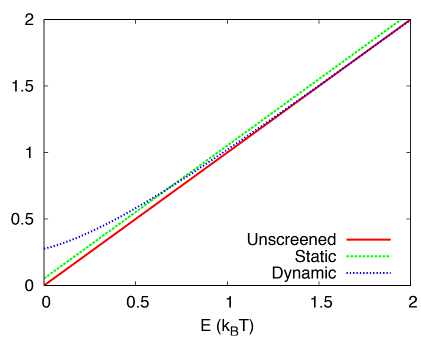


Static reaction rate calculation:

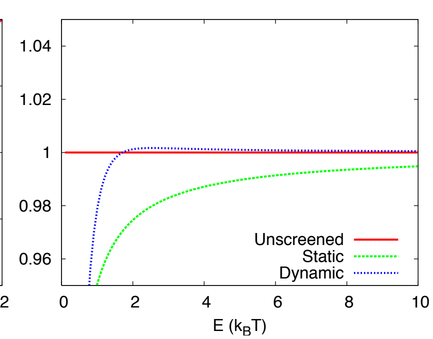
$$\langle \sigma v \rangle_{\alpha\beta} \propto \int_0^\infty \exp\left(-\frac{E}{kT} - \frac{b}{\sqrt{E}}\right) dE$$

With energy dependent screening:

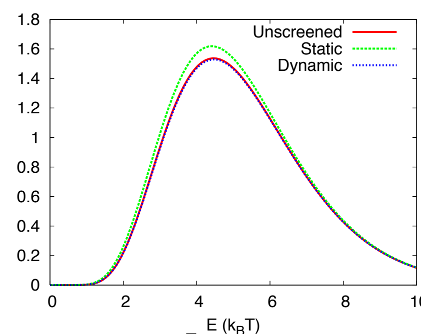
$$\langle \sigma v \rangle_{\alpha\beta} \propto \int_0^\infty \frac{E}{E - U_o(E)} \exp\left(-\frac{E}{kT} - \frac{b}{\sqrt{E - U_o(E)}}\right) dE$$



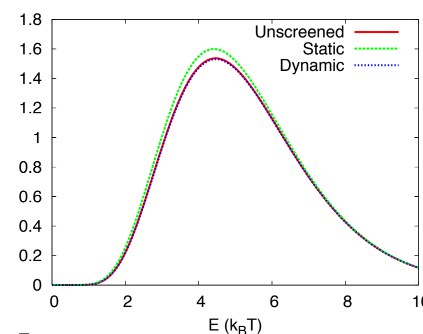
$$G(E) = E - U$$



$$H(E) = \frac{E}{G(E)}$$



$$J(E) = \exp\left[-\frac{E}{kT} - \frac{b}{\sqrt{G(E)}}\right]$$

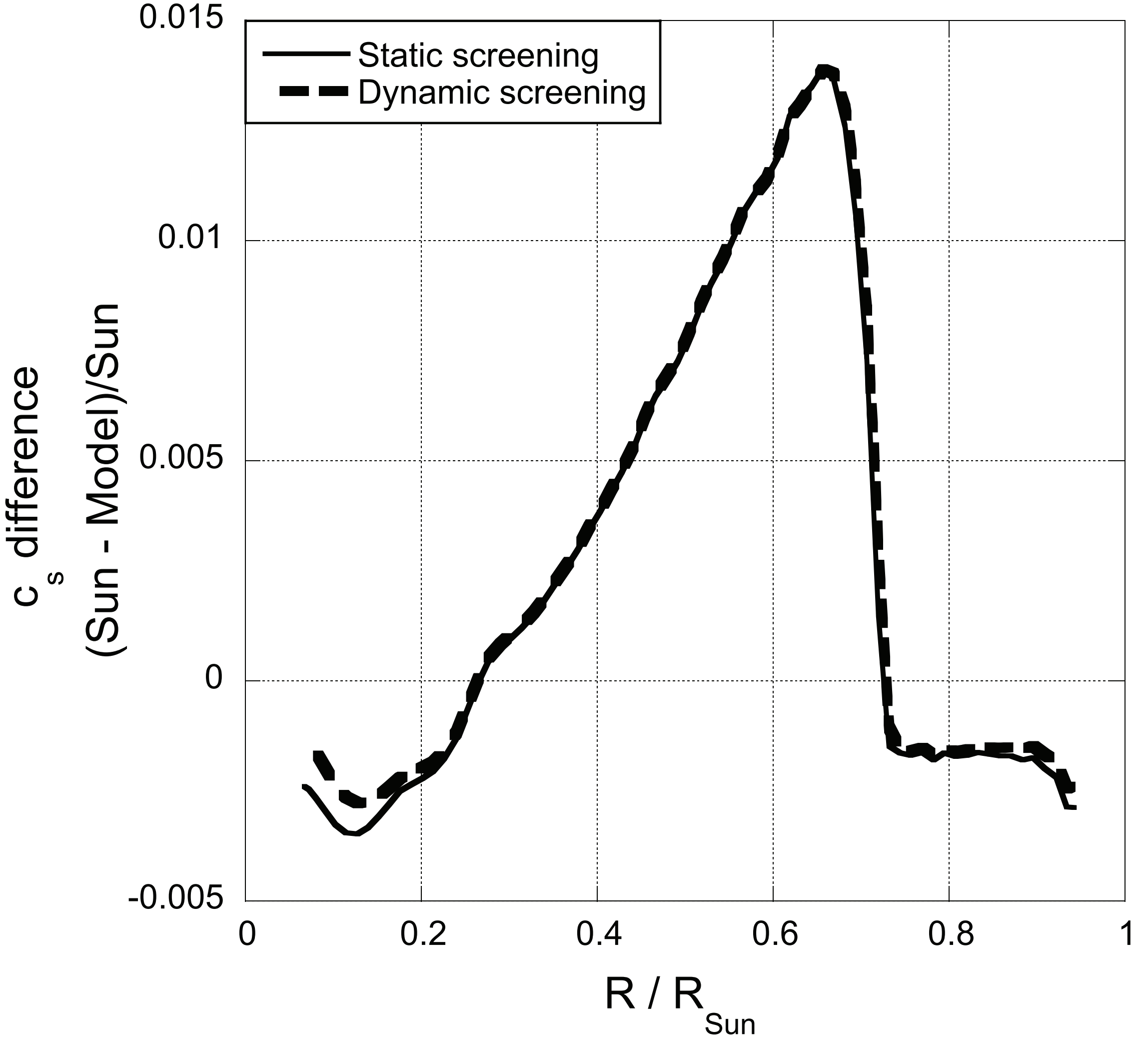


$$F(E) = H(E)J(E)$$

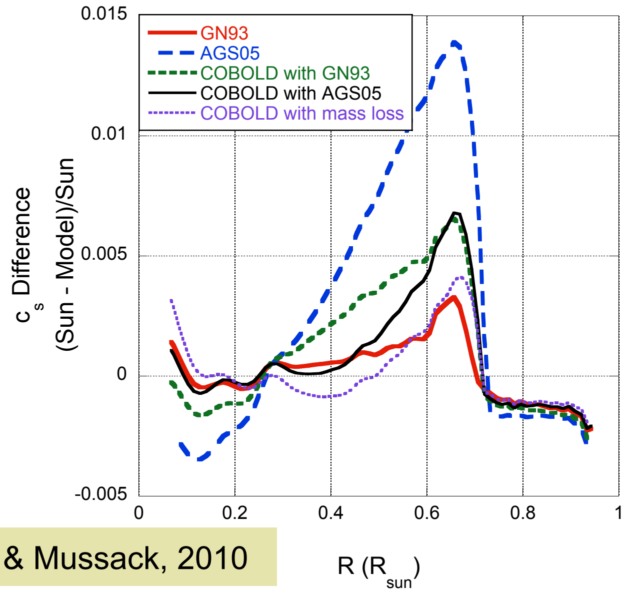
Energy dependence reduces the screening correction to ~1

Mussack & Dappen, 2011

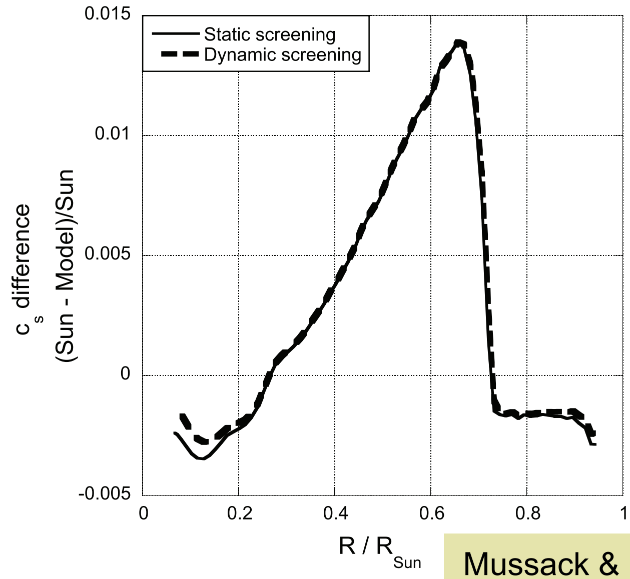
Dynamic correction to screening improves sound-speed agreement in the solar core



Mass loss + dynamic screening may help



Guzik & Mussack, 2010

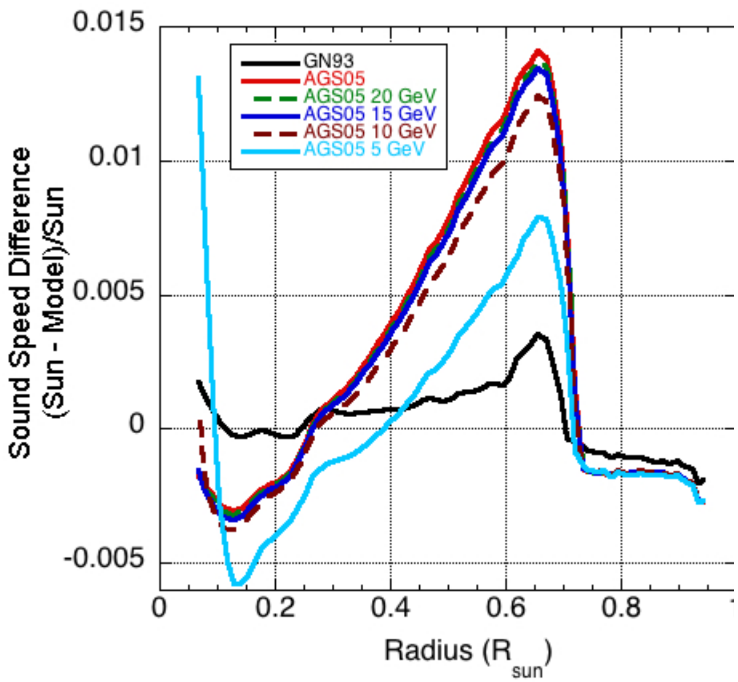


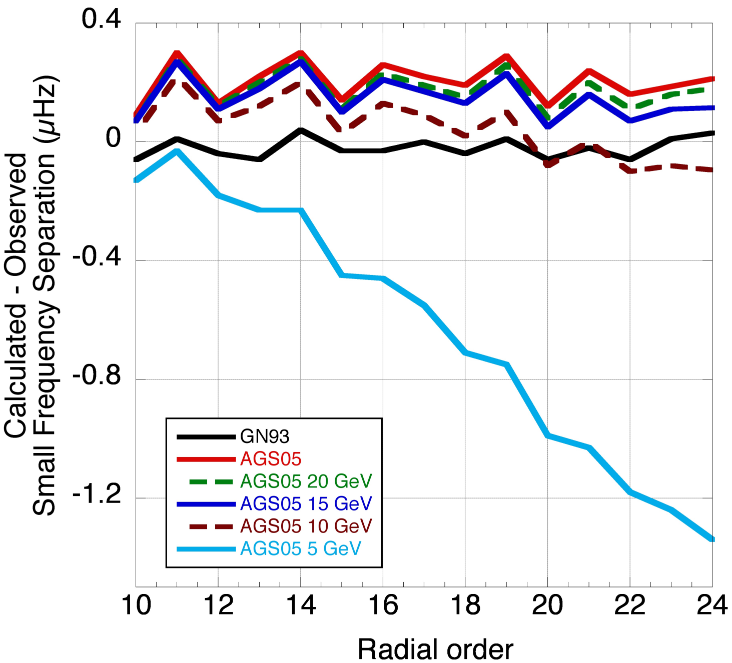
Mussack & Dappen, 2011

- **Mass loss improves model below the base of the convection zone**
- **Dynamic screening correction improves model in the core**
- **Work in progress: combine mass loss and dynamic screening correction in a solar model (Suzannah Wood)**

Dark matter may also improve agreement in the core

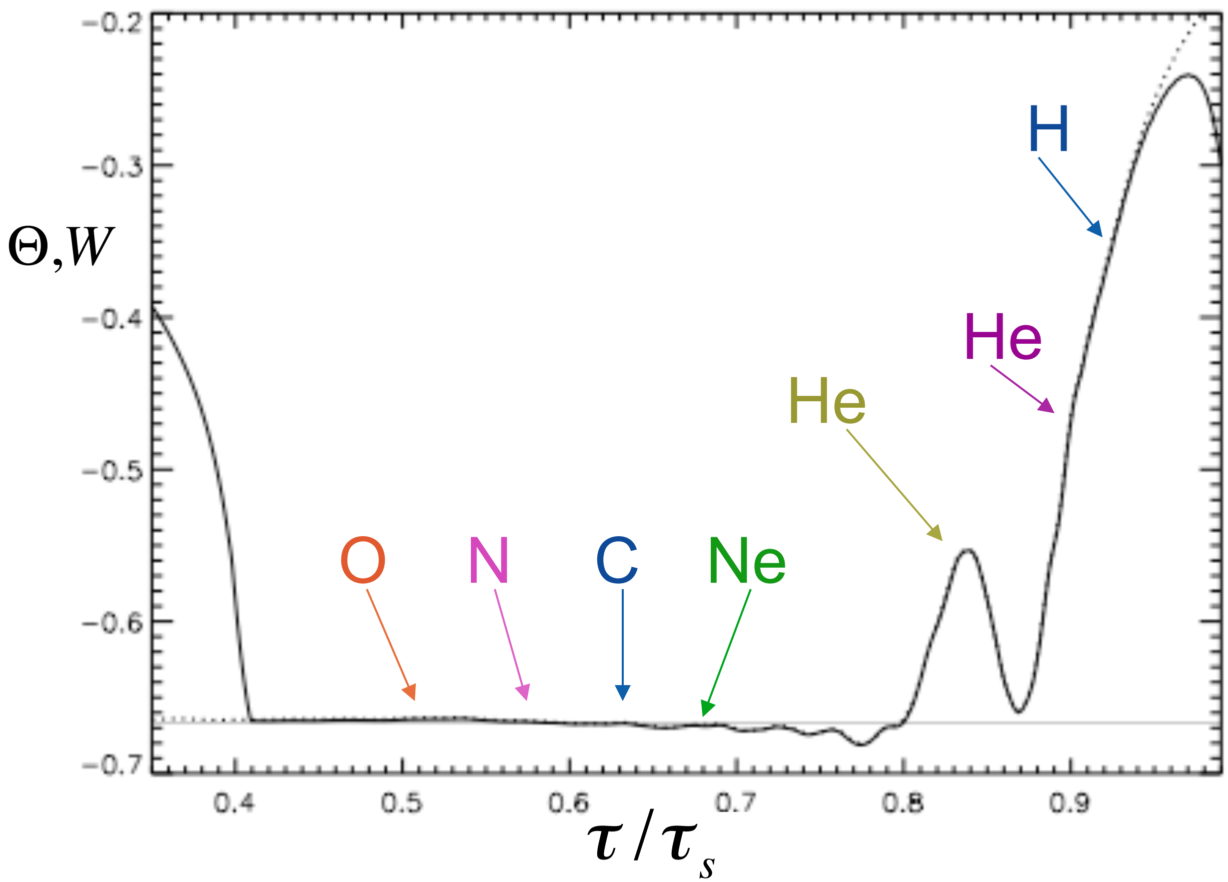
- **Explored solar models with WIMP masses low enough and cross sections high enough to influence solar structure**
- **Included WIMPs in solar model by modifying the opacity**
- **Models rule out WIMP masses <10 GeV**





Cumberbatch et al., 2010

Abundance can also be inferred using seismology

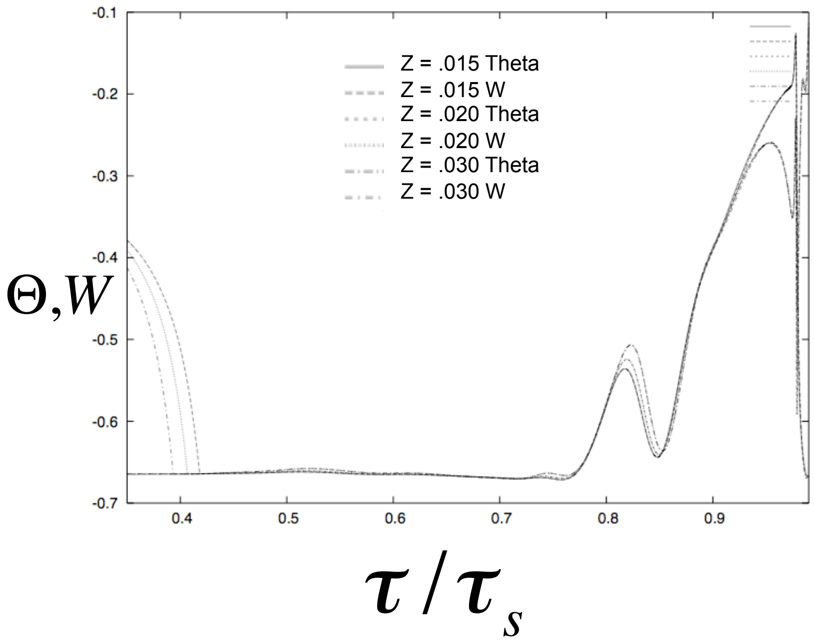


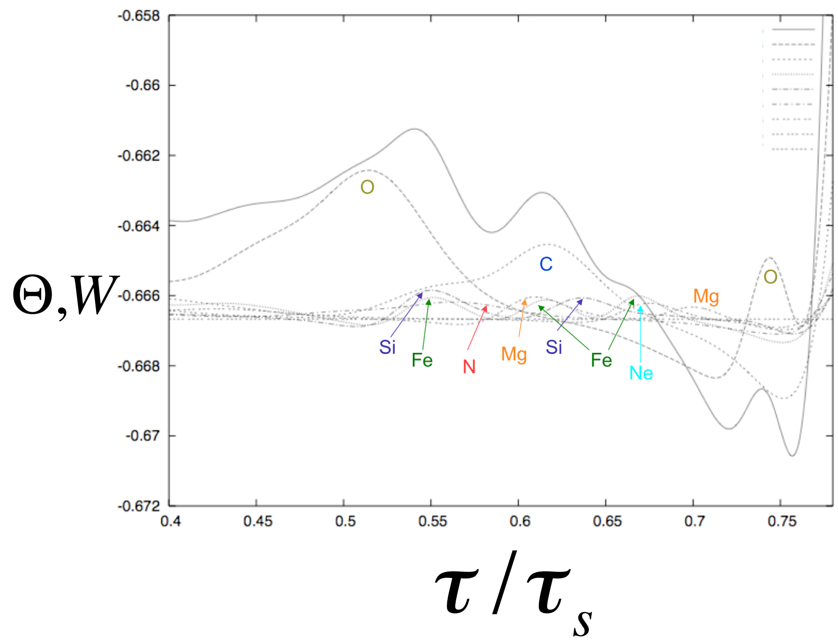
Acoustic radius: $\tau = \int c^{-1} \mathrm{d}r$

Gough, 2006

Total Z and individual abundances can be evaluated through the ionization bumps in W and Θ

EFF Models at 4.6Gy





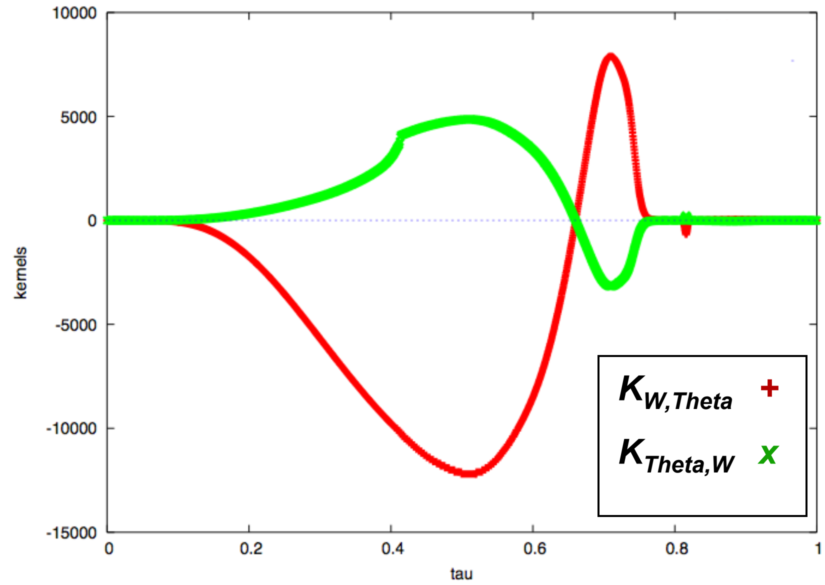
Acoustic radius: $\tau = \int c^{-1} \mathrm{d}r$

Standard Mix:		
O =.4987	C =.2254	
Fe = .0795	Si =.0565	N =.0549
Mg = .0436	Ne =.0335	
Al =.00403	Na =.00197	Ar =.00180

Seismic inversion can be used to evaluate models with different abundances

- **Use W and Θ kernels to find δ*W***

$$\frac{\delta\omega^2}{\omega^2} = \int_0^R \left(K_{W,\Theta} + K_{\Theta,W}\right)\delta W \, \mathrm{d}r$$



- **Calibrate abundances in models to match solar *W***

Where are we now?

- **Intermediate abundance values are more agreeable**
  - COBOLD, 2008-2009: Z = 0.0154
  - AGSS, 2009: Z = 0.0134
- **Modifications of solar models make some improvement in agreement**
  - Mass loss
  - Accretion
- **Further investigation is needed**
  - Seismic determination of abundances in the CZ
  - Models with mass loss + dynamic screening or dark matter
  - Other adjustments to models
  - Data from solar atmosphere

Douglas continues to influence seismic investigations of abundances

- "Sources of uncertainty in direct seismological measurements of the solar helium abundance", Kosovichev, Christensen-Dalsgaard, Däppen, Dziembowski, Gough, Thompson, 1992
- "On the influence of treatment of heavy elements in the equation of state on the resulting values of the adiabatic exponent", Däppen, Gough, Kosovichev, Rhodes, 1993
- "On the composition of the solar interior", Gough, 1998
- "The Sun is not severely deficient in Heavy Elements", Christensen-Dalsgaard & Gough, 2004
- "Effect of He ionization on stellar eigenfrequencies", Houdek & Gough, 2004
- "Asteroseismic signature of He ionization", Houdek & Gough, 2007

Thank you

Katie Mussack

Los Alamos National Laboratory, XTD-2

mussack@lanl.gov