# Diffusion and helioseismology

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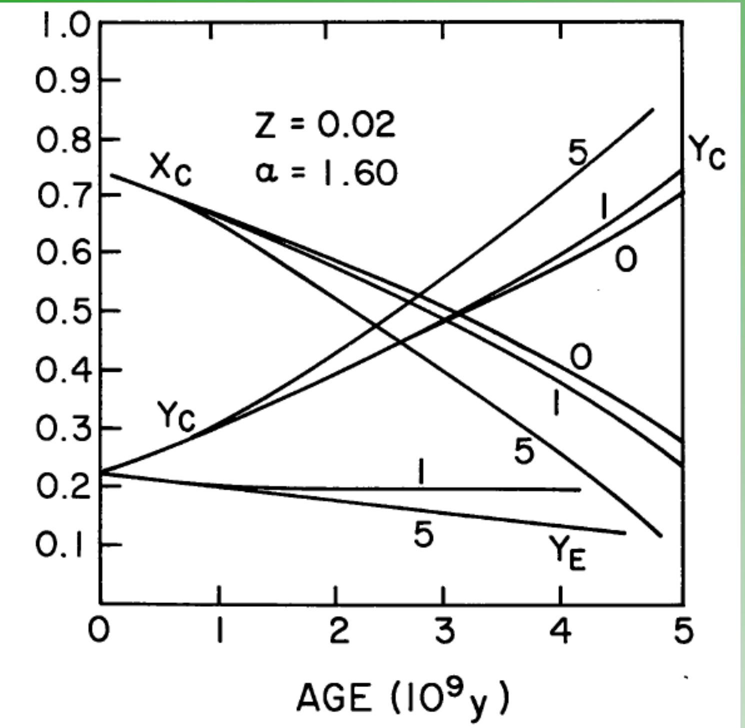
# Eddington (1926): ‘The internal constitution of the stars’

- ‘[T]he heavy elements fall to the centre and the lighter elements rise to the surface’ (p. 275)
- ‘Radiation pressure greatly modifies these results since it has different effects on different ions’ (p. 275)
- ‘It would be difficult to reconcile these results with the observed spectra at the surfaces of the stars .... [is] the approach to this steady state sufficiently rapid to effect appreciable separation in the life-time of a star or to overcome the mixing tendencies which may be retarding it[?]? (p. 276)

# Effects on solar models




Noerdlinger (1977; A&A 57, 407)

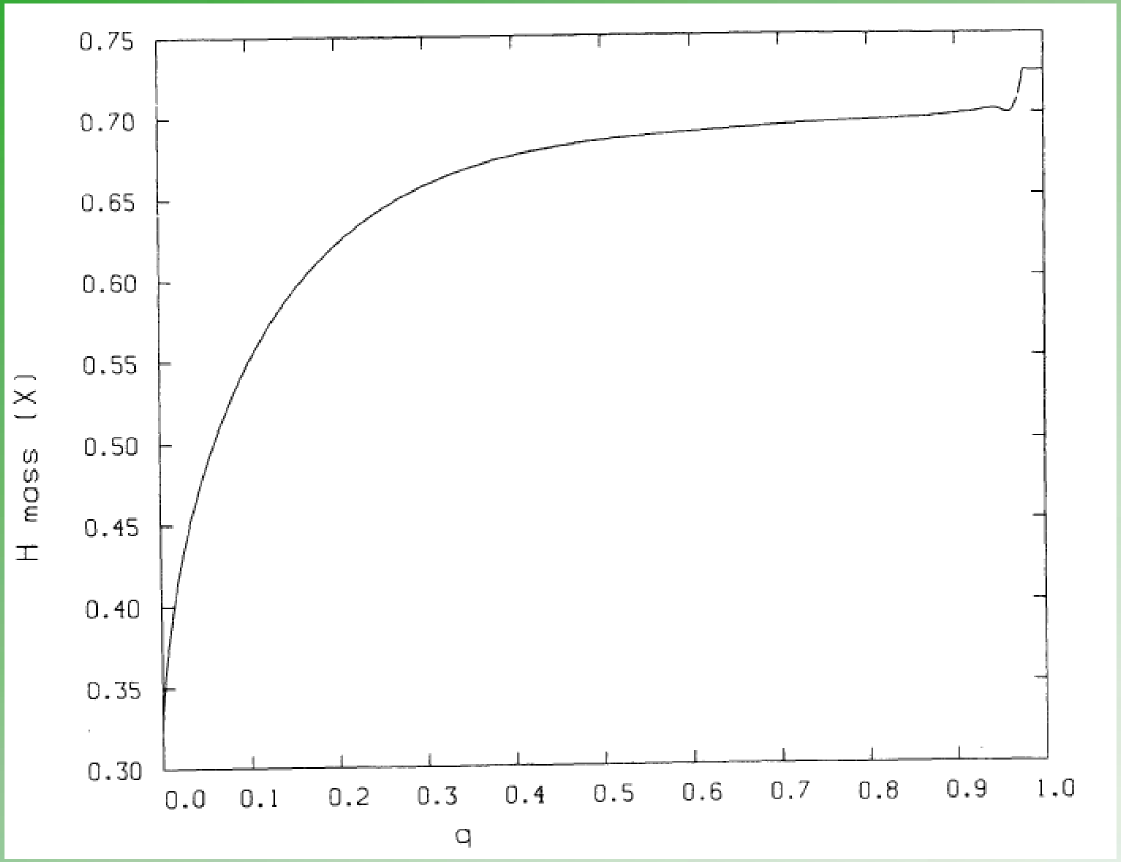
- 0: no diffusion
- 1: normal rate
- 5: 5 times normal

| Model sequence | Diffusion | $\alpha$ | $Y_0$ | $Y_s$ | $Y_c$ | $T_c$ in $10^6$ K |
|---|---|---|---|---|---|---|
| A | 0 | 1.64 | 26.99% | 26.99% | 61.69% | 16.02 |
| B | 1 | 1.75 | 26.79% | 25.63% | 62.65% | 16.12 |
| C | 3 | 1.96 | 26.39% | 23.38% | 65.12% | 16.33 |

- 0: no diffusion
- 1: normal rate
- 3: 3 times normal

Wambsganns (1988; A&A 205, 125)

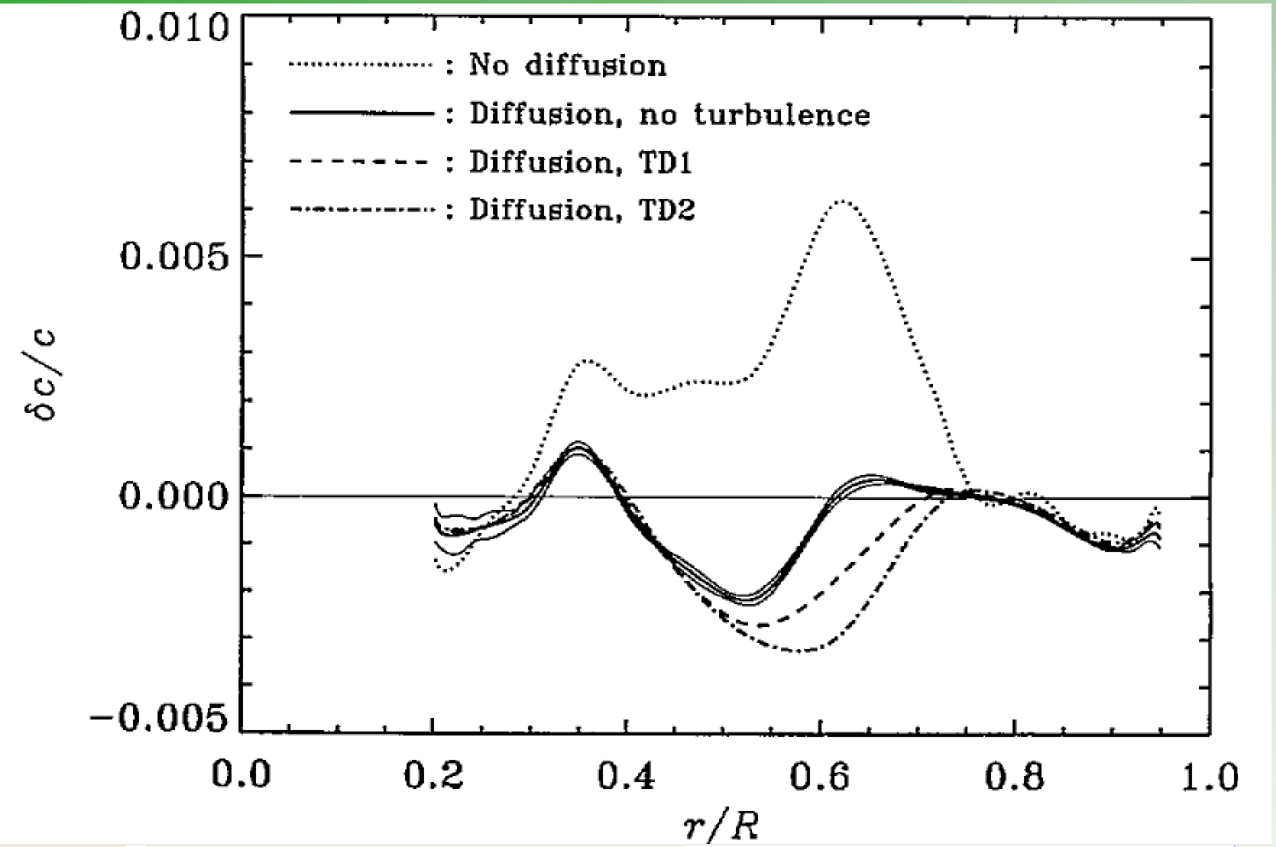
# Detailed effects




Cox et al. (1989; ApJ 342, 1187)

No strong effect on oscillation frequencies

# Helioseismic consequences




- Only He diffusion
- Differential asymptotic inversion

Christensen-Dalsgaard et al. (1993; ApJ 403, L75)

# Treatment of diffusion and settling

$$\frac{\partial X_i}{\partial t} = \mathcal{R}_i + \frac{1}{\rho r^2}\frac{\partial}{\partial r}(r^2 \rho V_i)$$

$$\frac{\partial X_i}{\partial t} = \mathcal{R}_i +$$

$$\frac{1}{\rho r^2}\frac{\partial}{\partial r}\left[r^2 \rho \left(D_i \frac{\partial X_i}{\partial r} + V_i^{(s,1)} X_i + V_i^{(s,2)} V_H X X_i\right)\right] \; .$$

# Michaud & Proffitt approximation

$$V_H = -\frac{B\ T^{5/2}}{\rho \ln\Lambda_{ij}(0.7+0.3X)} \left[\left(\frac{5}{4} + 1.125\nabla\right)(1-X)\frac{d\ln P}{dr} + \frac{(3+X)}{(1+X)(3+5X)} \frac{d\ln X}{dr}\right] \qquad (17)$$

Hydrogen

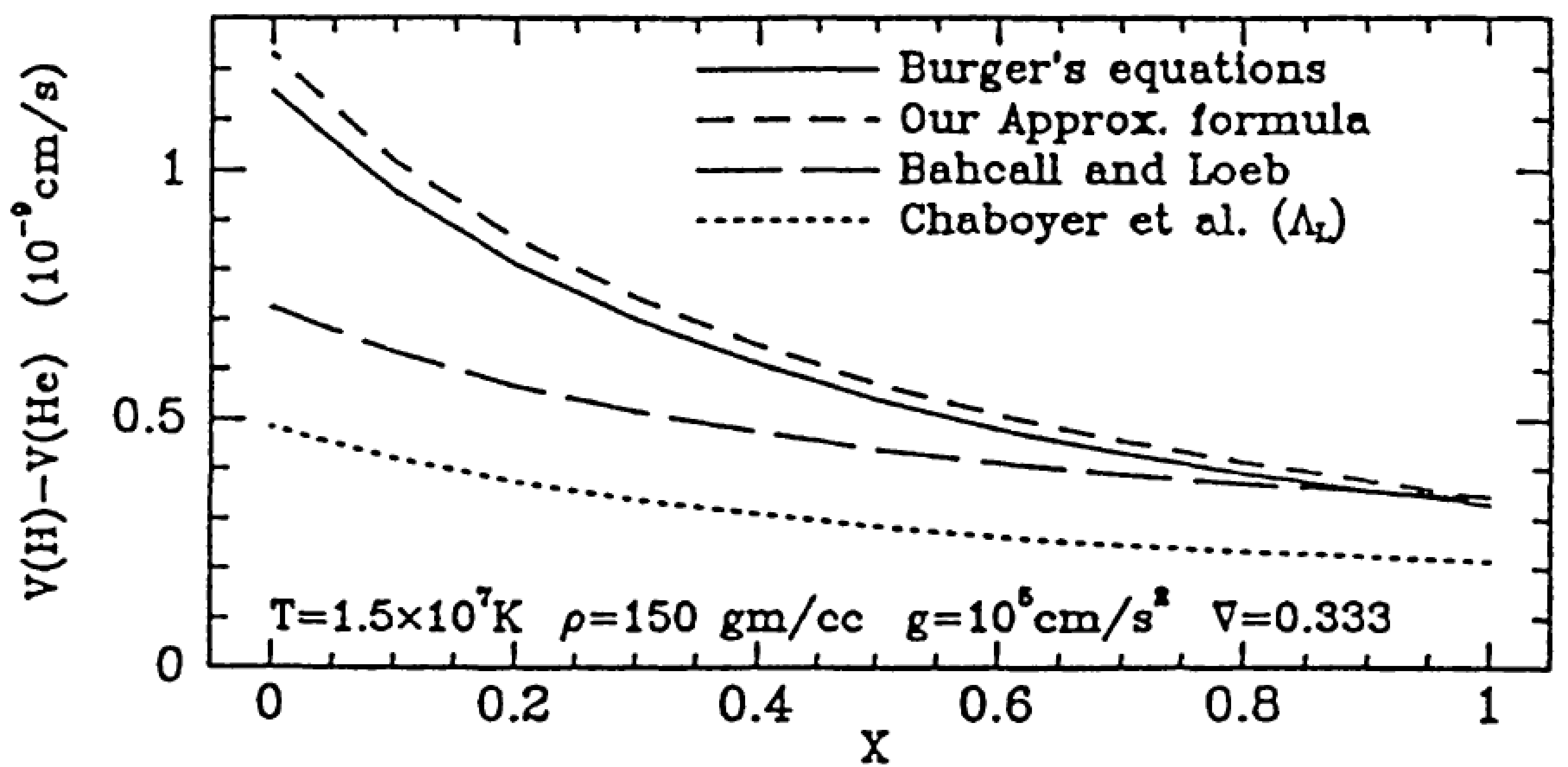
$$V_i = -\frac{2BT^{5/2}}{5^{1/2}\rho Z_i^2} \left[\frac{\frac{d}{dr}\left\{\ln\left[\frac{X_i}{5X+3}\left(\frac{1+X}{5X+3}\right)^{Z_i}\right]\right\} + \left[1+Z_i - A_i\left(\frac{5X+3}{4}\right)\right]\frac{d\ln P}{dr}}{X(A_{ix}^{1/2}C_{ix} - A_{iy}^{1/2}C_{iy}) + A_{iy}^{1/2}C_{iy}}\right]$$

$$+ XV_H \frac{(A_{ix}^{1/2}C_{ix} - A_{iy}^{1/2}C_{iy})}{X(A_{ix}^{1/2}C_{ix} - A_{iy}^{1/2}C_{iy}) + A_{iy}^{1/2}C_{iy}} \ . \qquad (18)$$

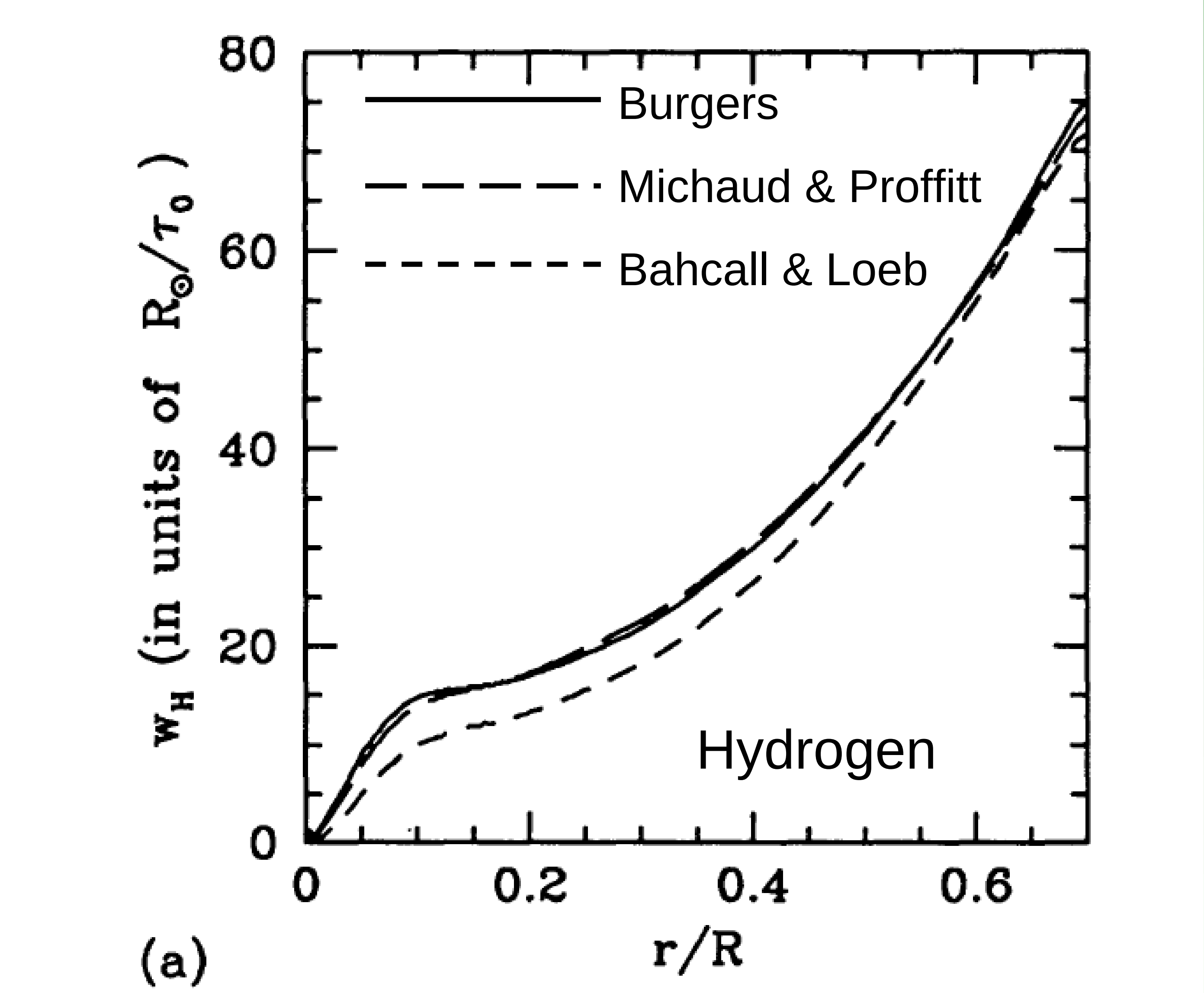
Trace element

1993: ASP Conf. Ser. 40, p. 246

# Comparison with Burgers (1969)

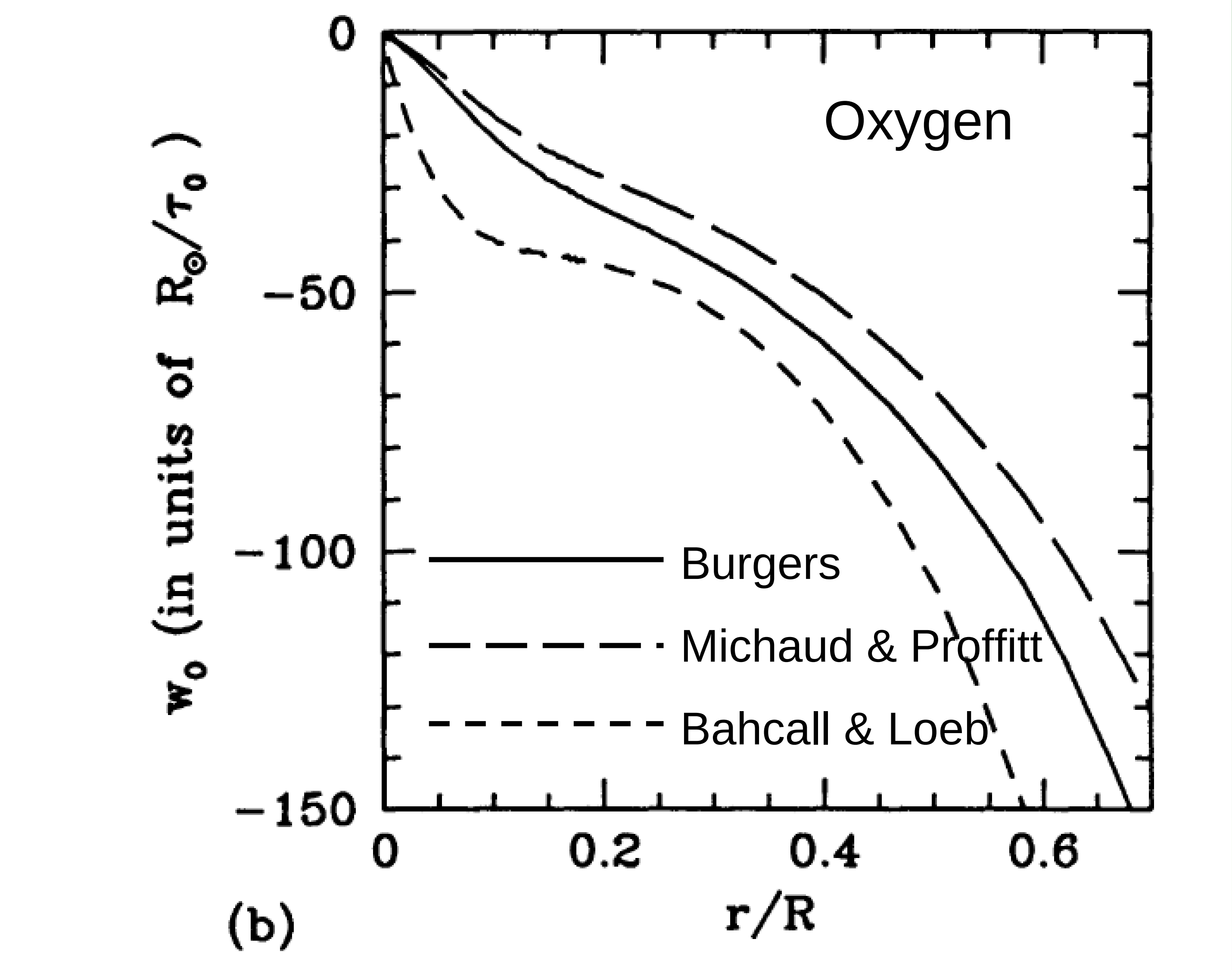


# Comparison with Burgers (1969)




Thoul et al. (1994; ApJ 421, 828)

# Comparison with Burgers (1969)




Thoul et al. (1994; ApJ 421, 828)

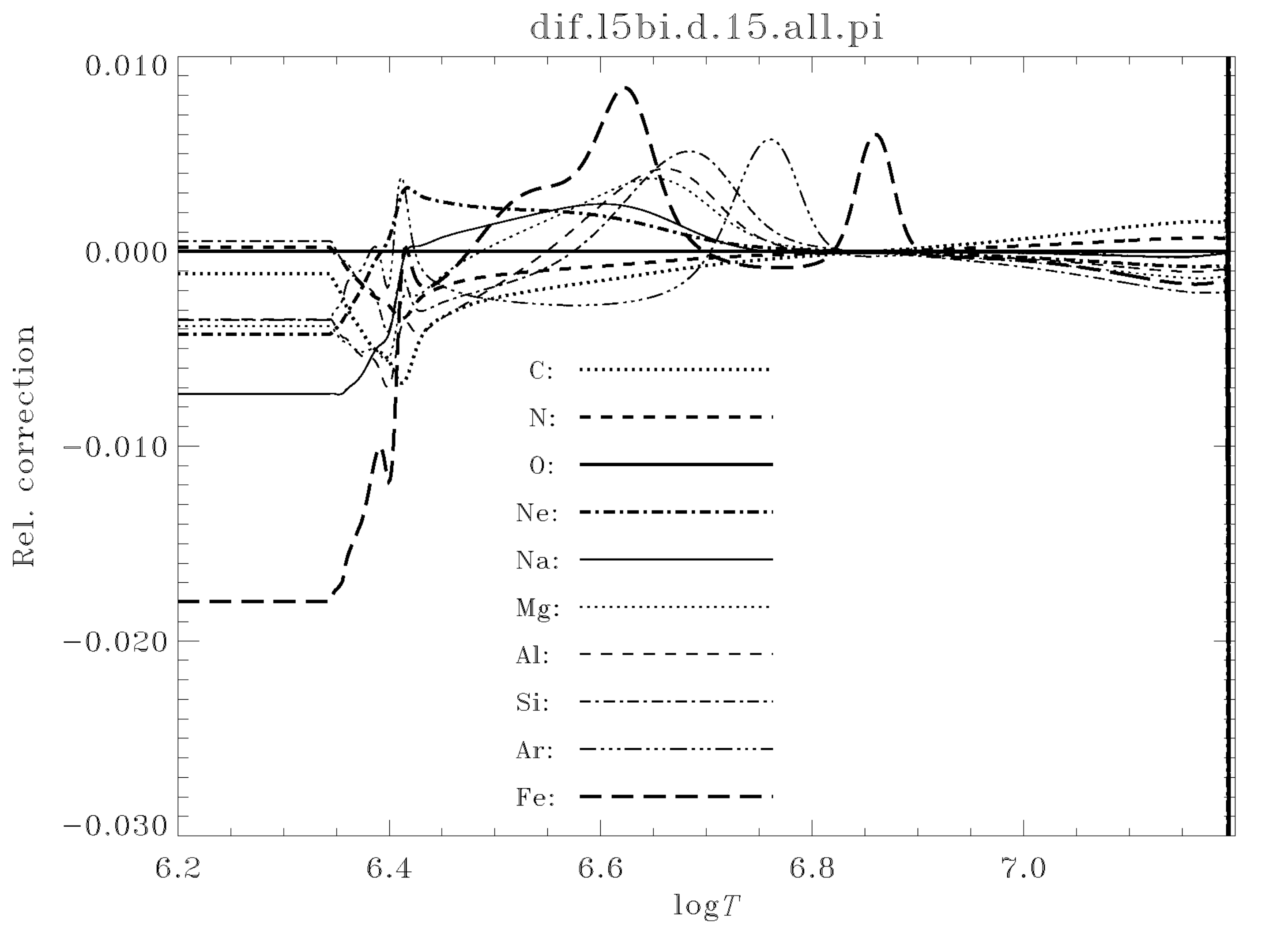
# Further issues in diffusion computation

- Different elements move at different rates
- Effects of partial ionization
- **Radiative effects**

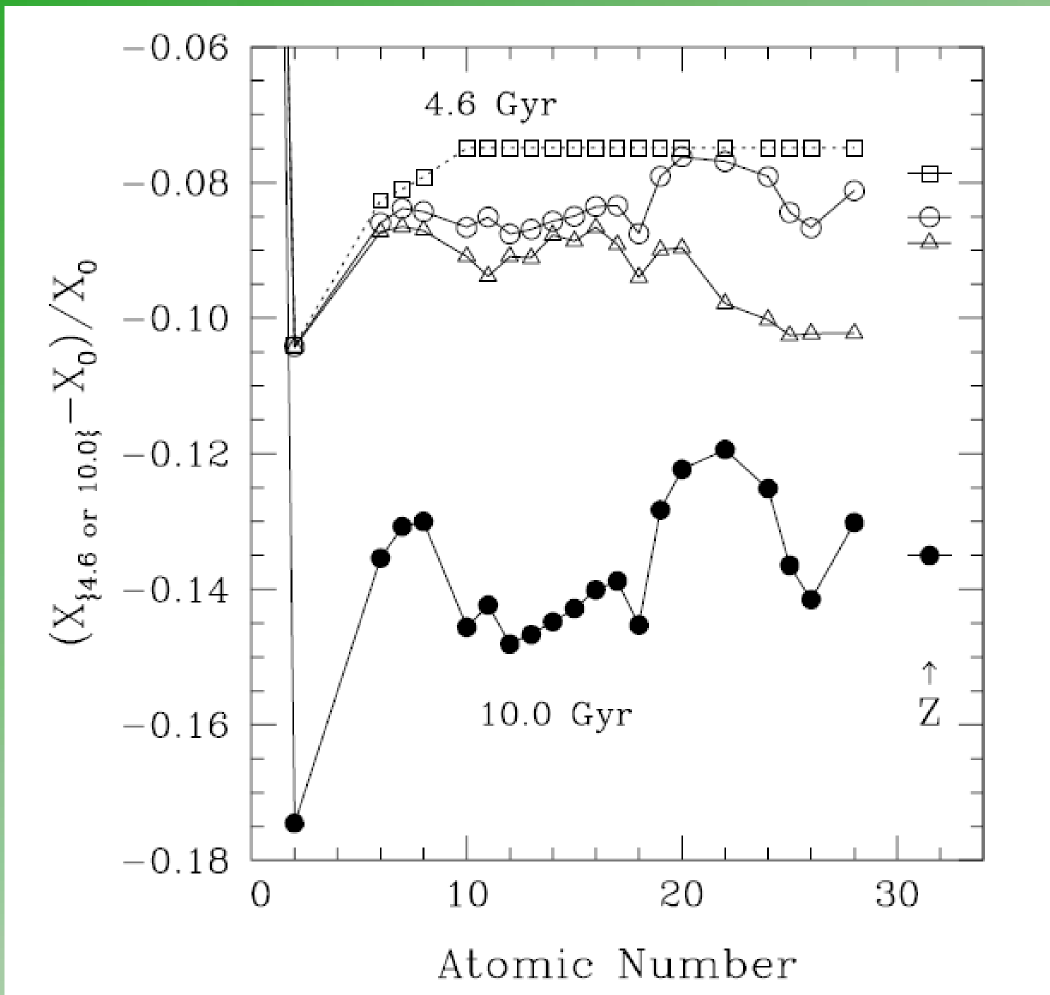
**Note that change in relative composition of heavy elements should in principle be taken into account in the opacity calculation**

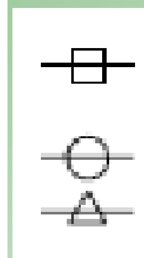
# Difference between elements

Relative to oxygen



# Radiative effects on surface abundance



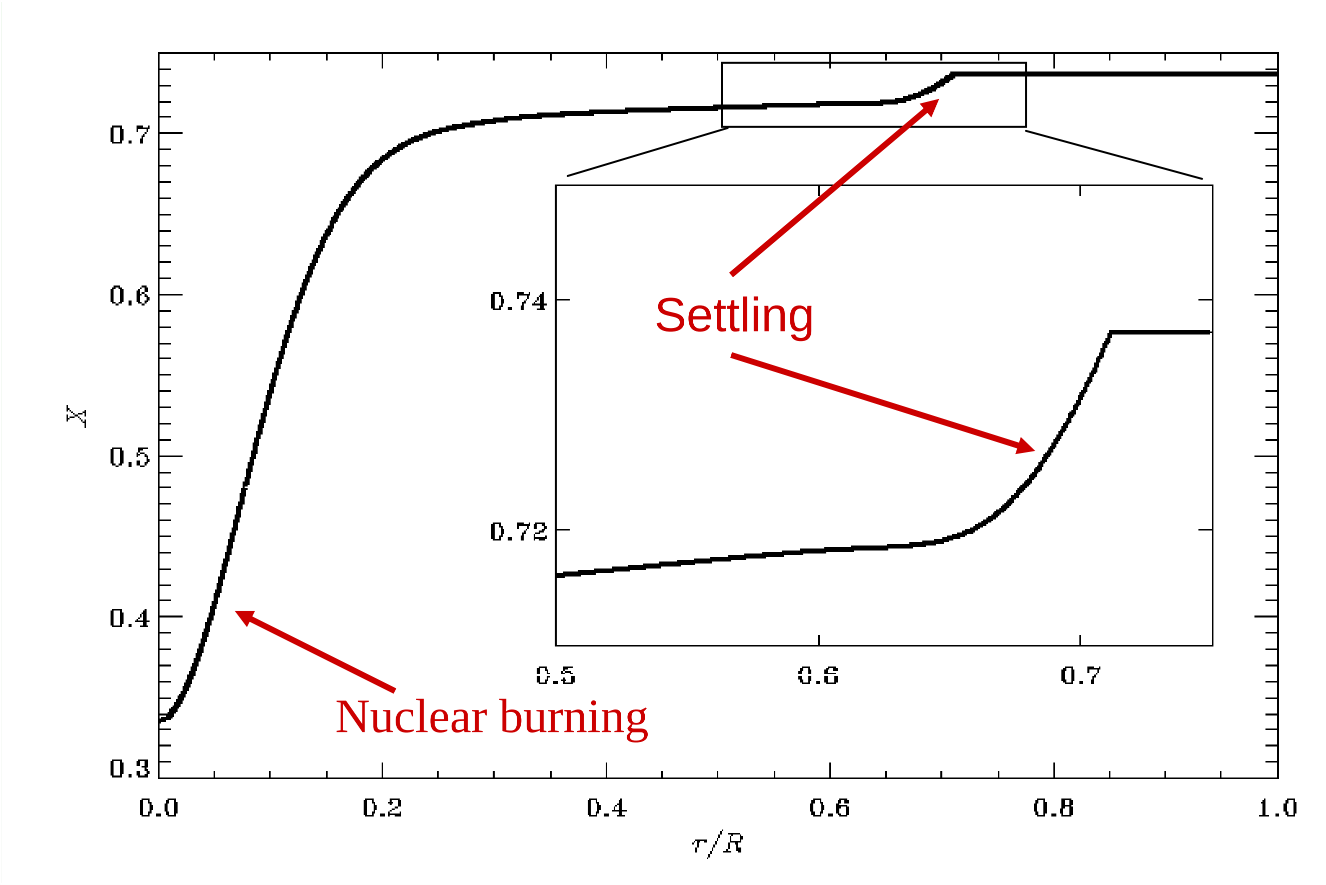
No radiation, as fully ion. Fe

Radiation, part. ion.

No radiation, part. ion.

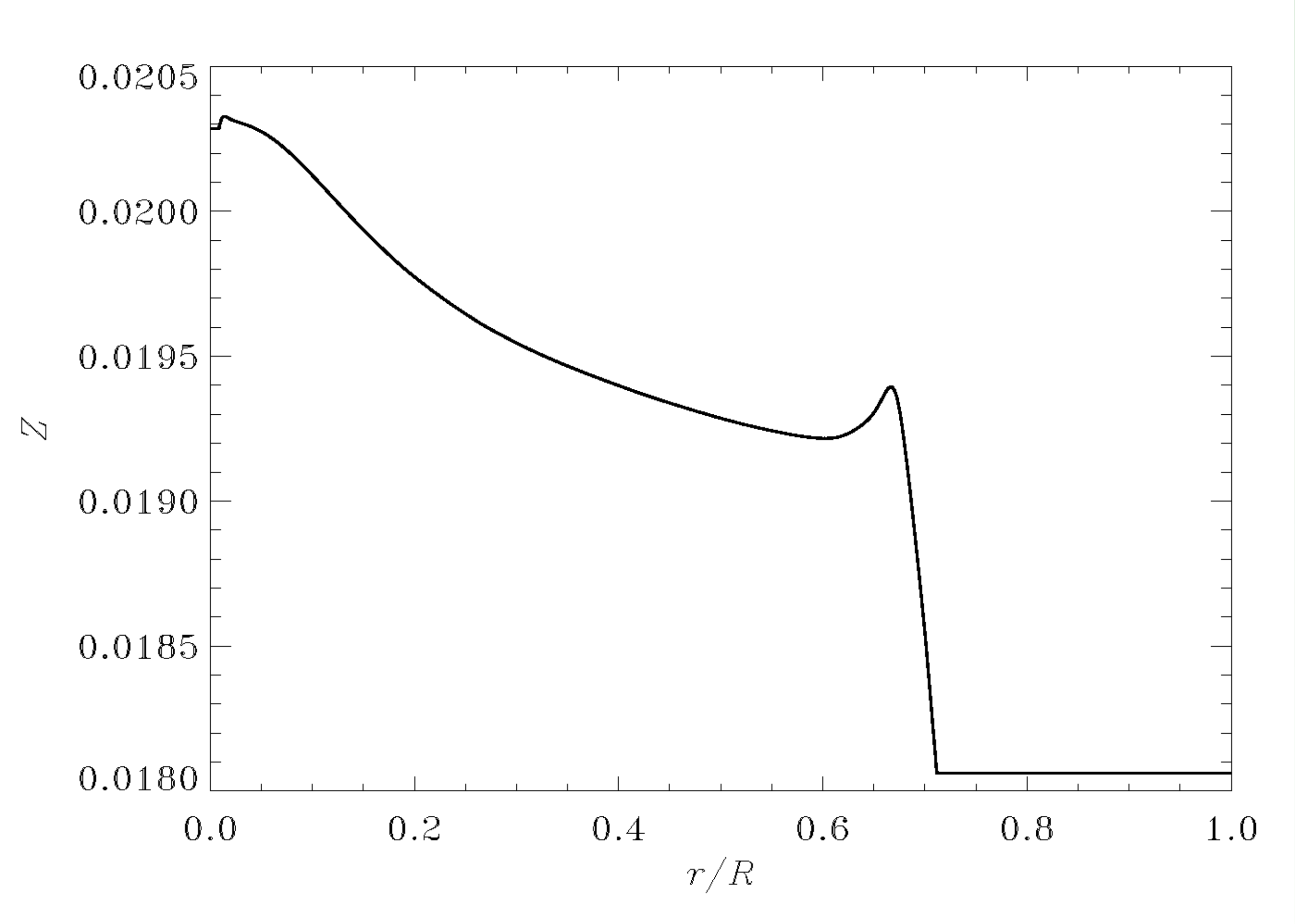
Turcotte et al. (1998; ApJ 504, 539)

# Effects on solar composition



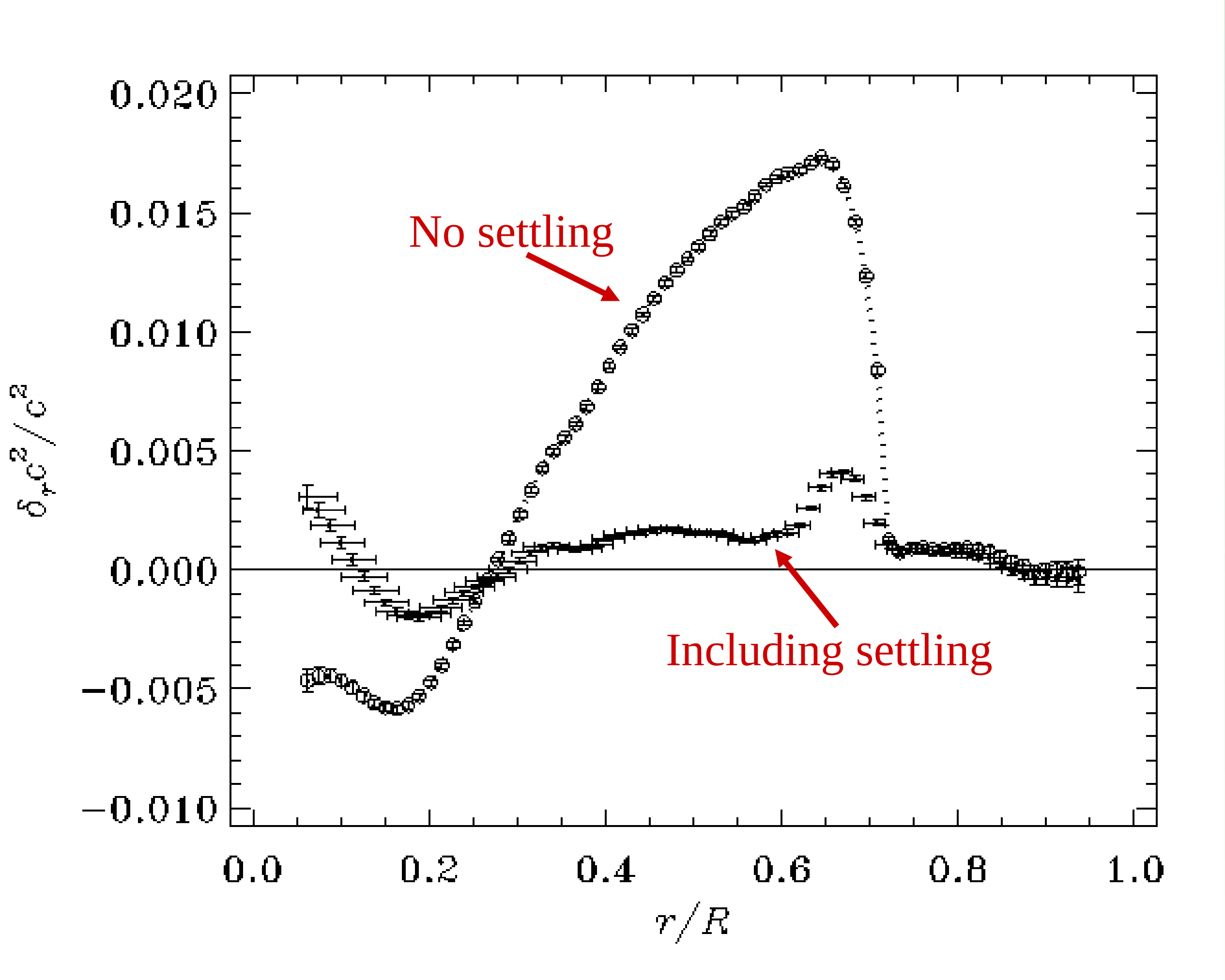

ASTEC calculation, all heavy elements behave as fully ionized $^{18}O$

# Effects on solar composition




ASTEC calculation, all heavy elements behave as fully ionized $^{18}O$

# Comparison with helioseismic sound speed



# Revision of solar abundances

Nicolas Grevesse

Asplund et al. (2004; A&A 417, 751. 2005; astro-ph/0410214 v2):

$$N(\mathrm{O})/N(\mathrm{H})|_{\mathrm{old}} = 8.5\times10^{-4}\,, \qquad Z_{\mathrm{old}} = 0.0193$$

$$N(\mathrm{O})/N(\mathrm{H})|_{\mathrm{new}} = 4.6\times10^{-4}\,, \qquad Z_{\mathrm{new}} = 0.0122$$

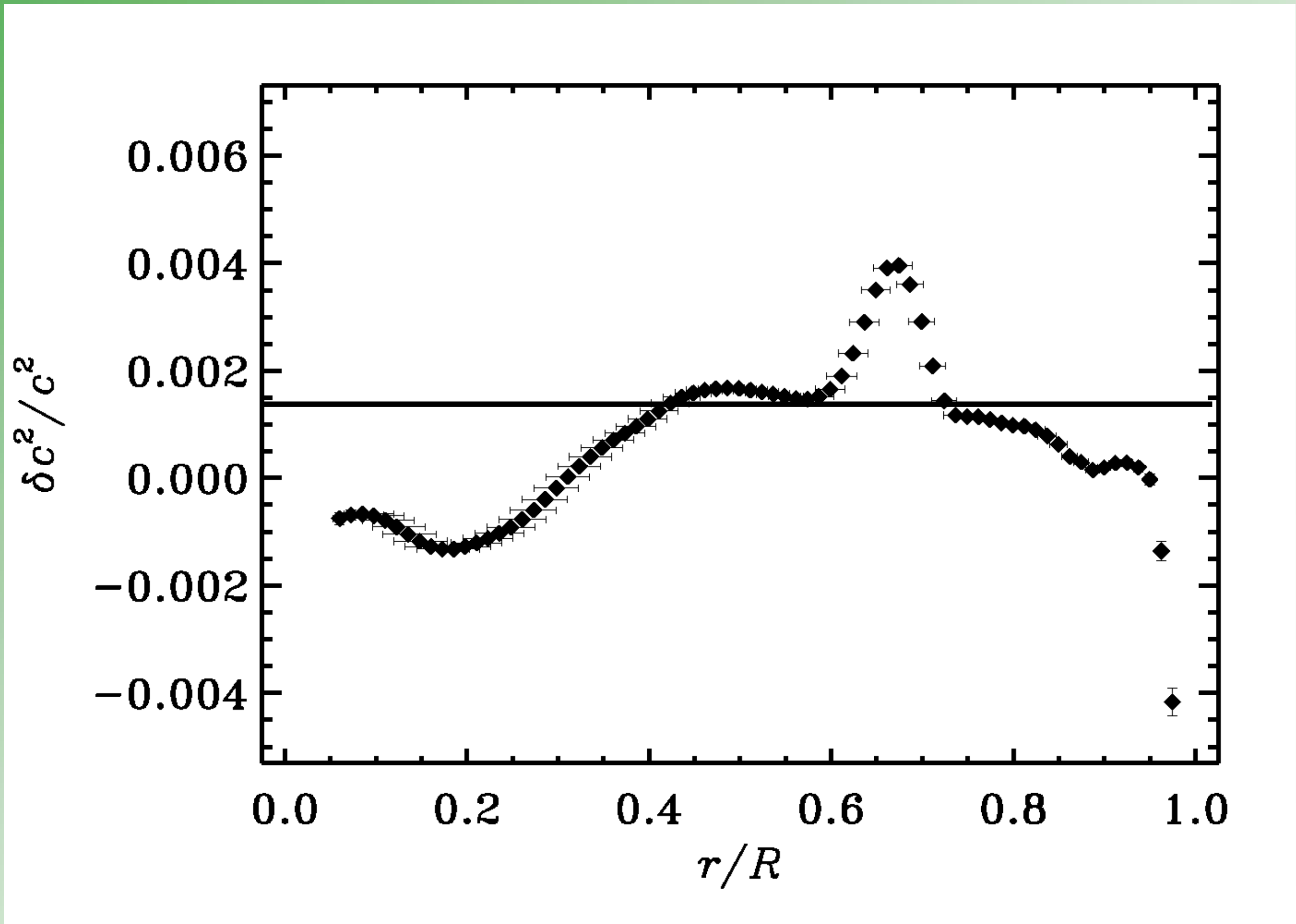
Improvements:

- Non-LTE analysis
- 3D atmosphere models
- **Consistent abundance determinations for a variety of indicators**

# Effect on helioseismology: a grain of sand or a rock?

Grevesse (Sheffield, 2006)

Sun - Model S



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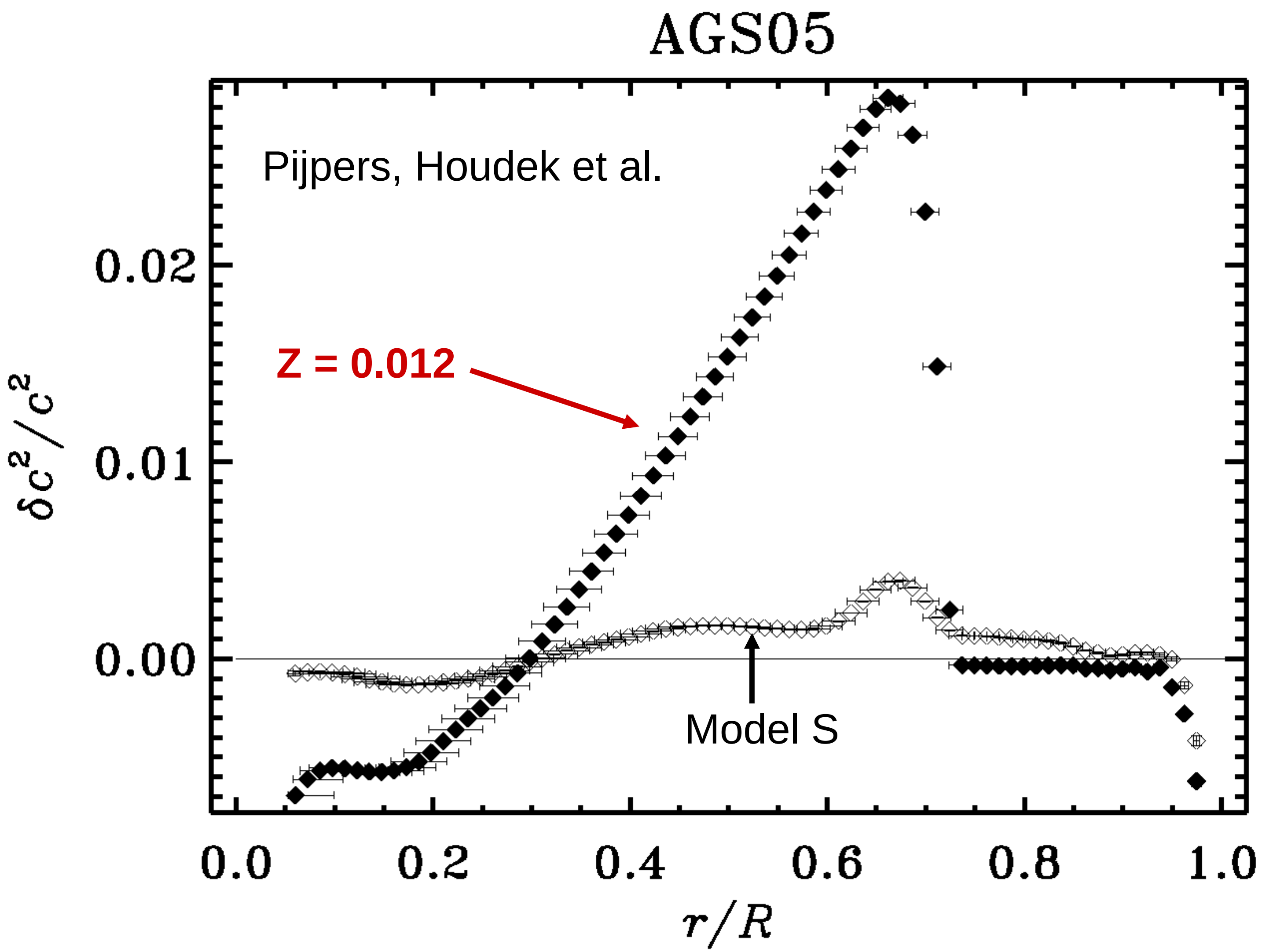


# Possible solutions

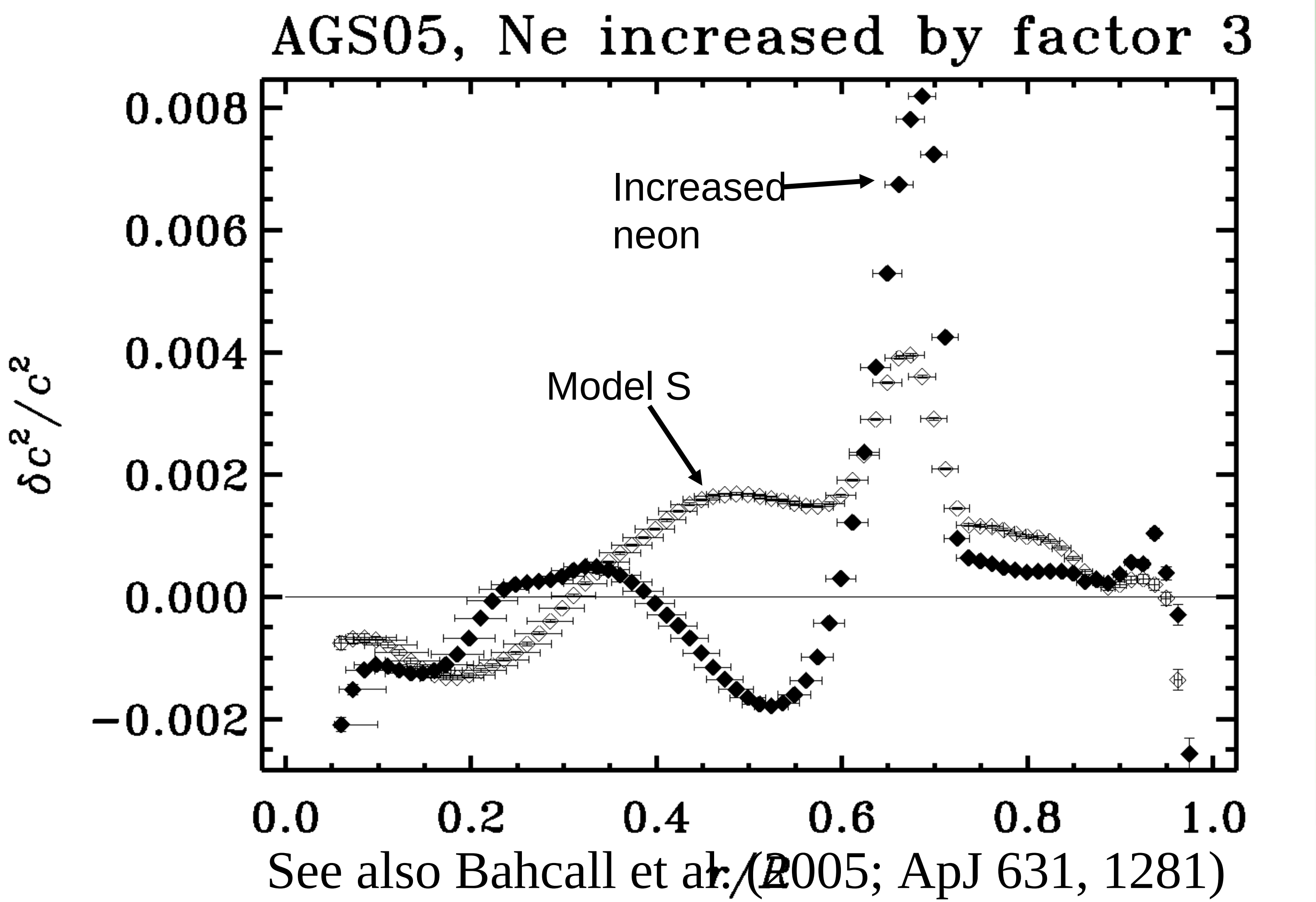
Joyce Guzik

- Can neon and argon help?
- The neon abundance cannot be determined in the photosphere
- Neon has a substantial effect on the opacity

See also Bahcall et al. (2005; ApJ 631, 1281)

# Possible solutions

Joyce Guzik

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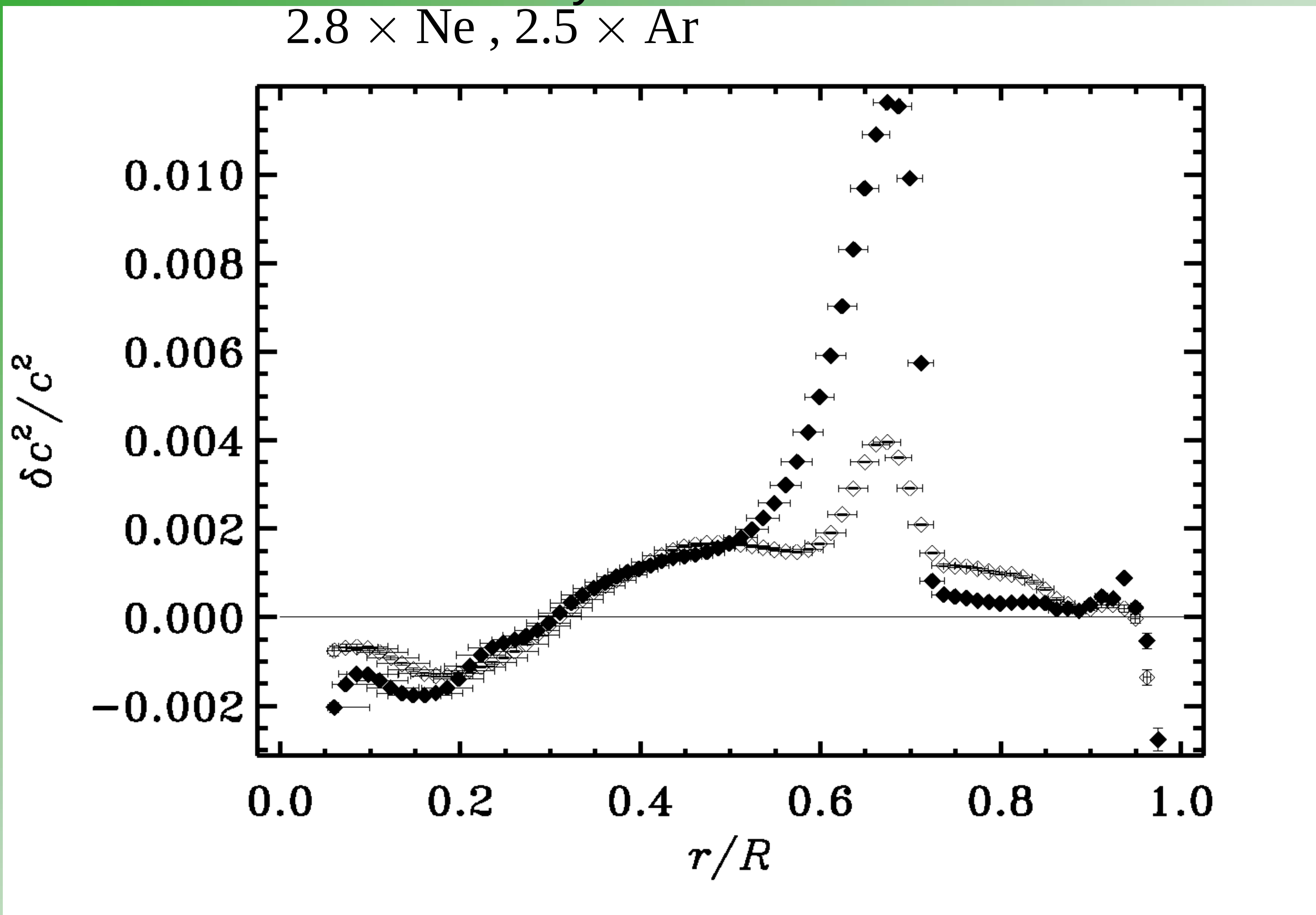
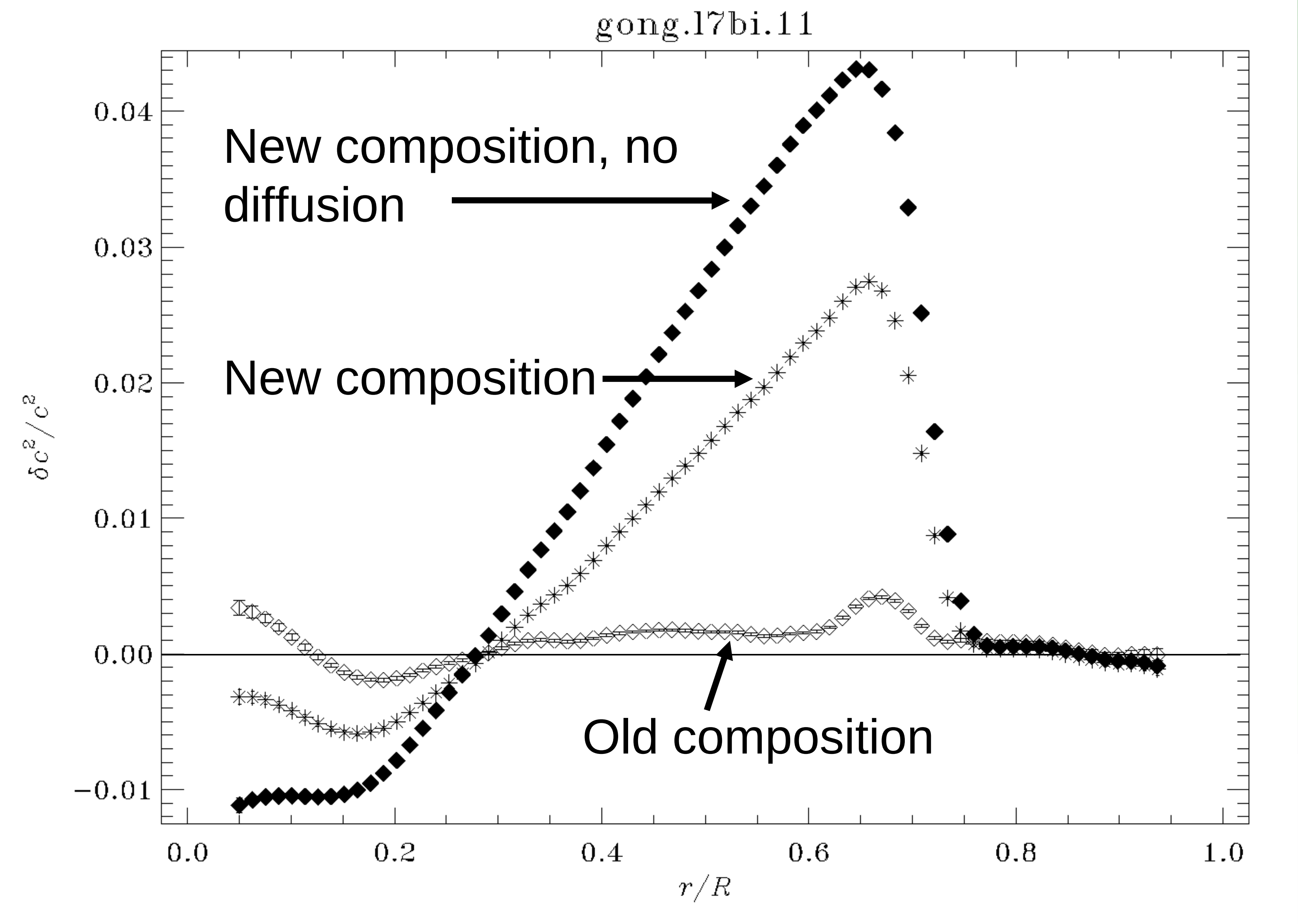


# Diffusion still helps!

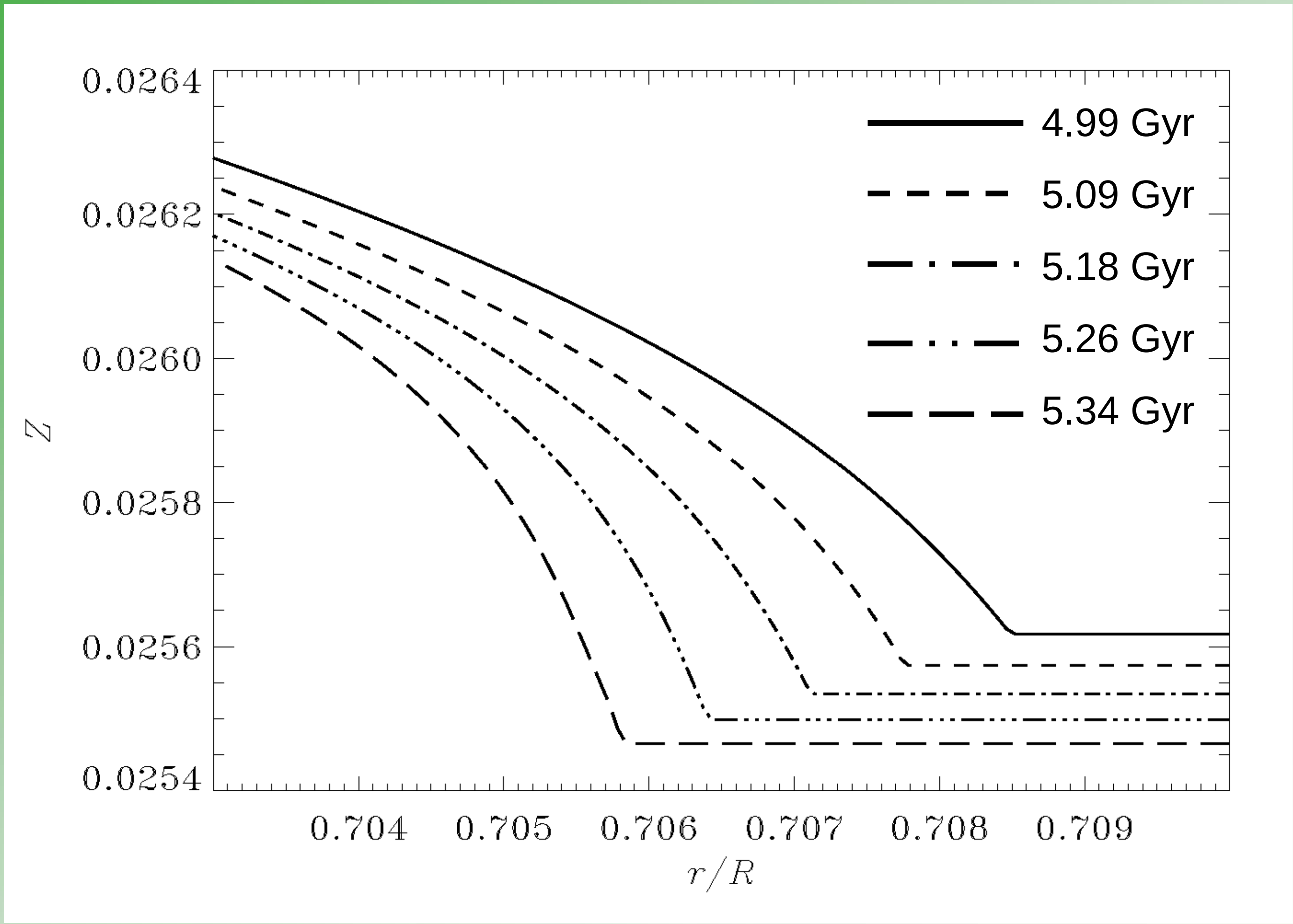


# Semiconvection at the base of the convective envelope

Noted by Bahcall et al. (2001; ApJ 555,990)

$$\nabla_{\mathsf{rad}} \propto \kappa \propto Z(1+X)$$

# Semiconvection at the base of the convective envelope




α Cen A models

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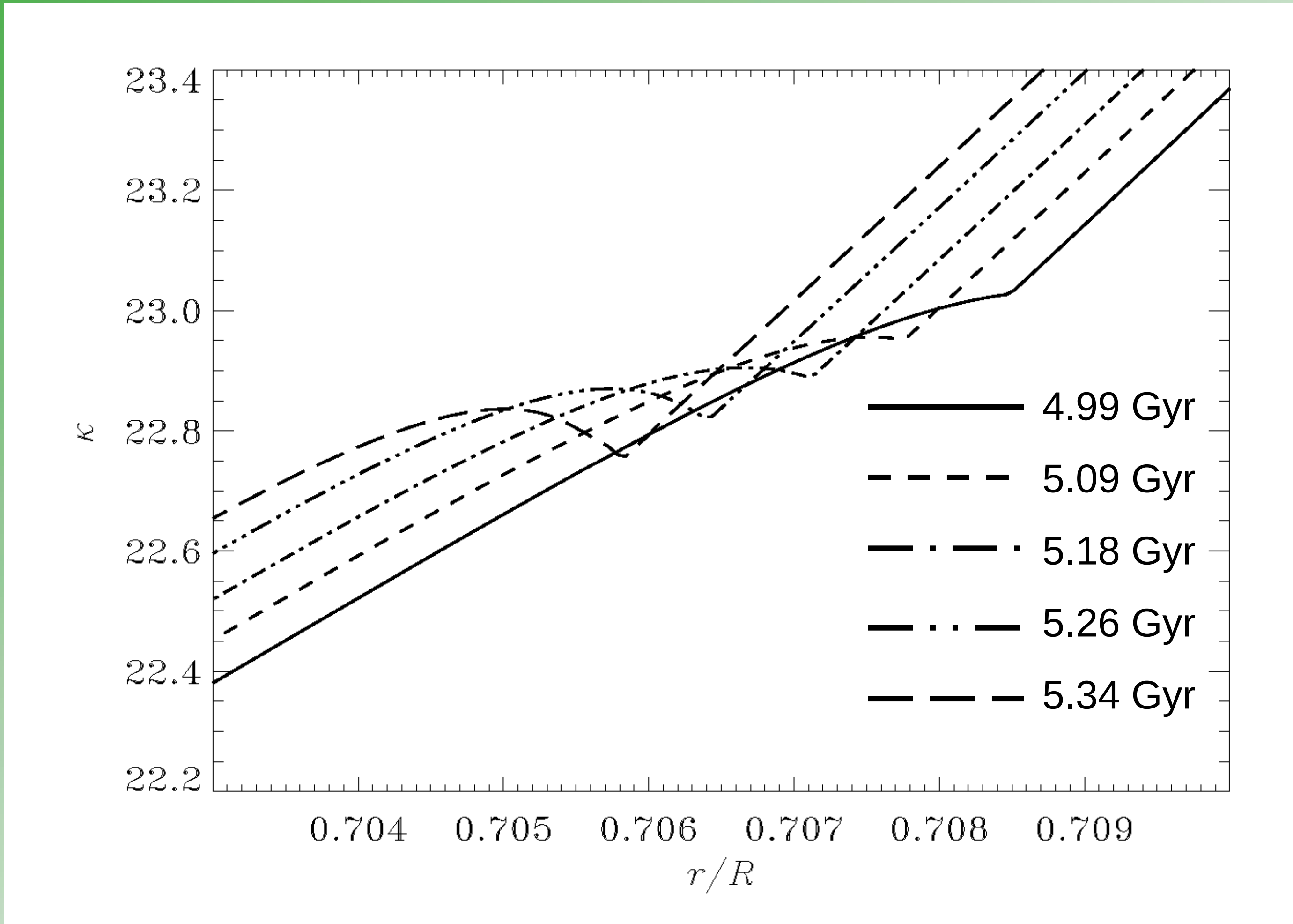


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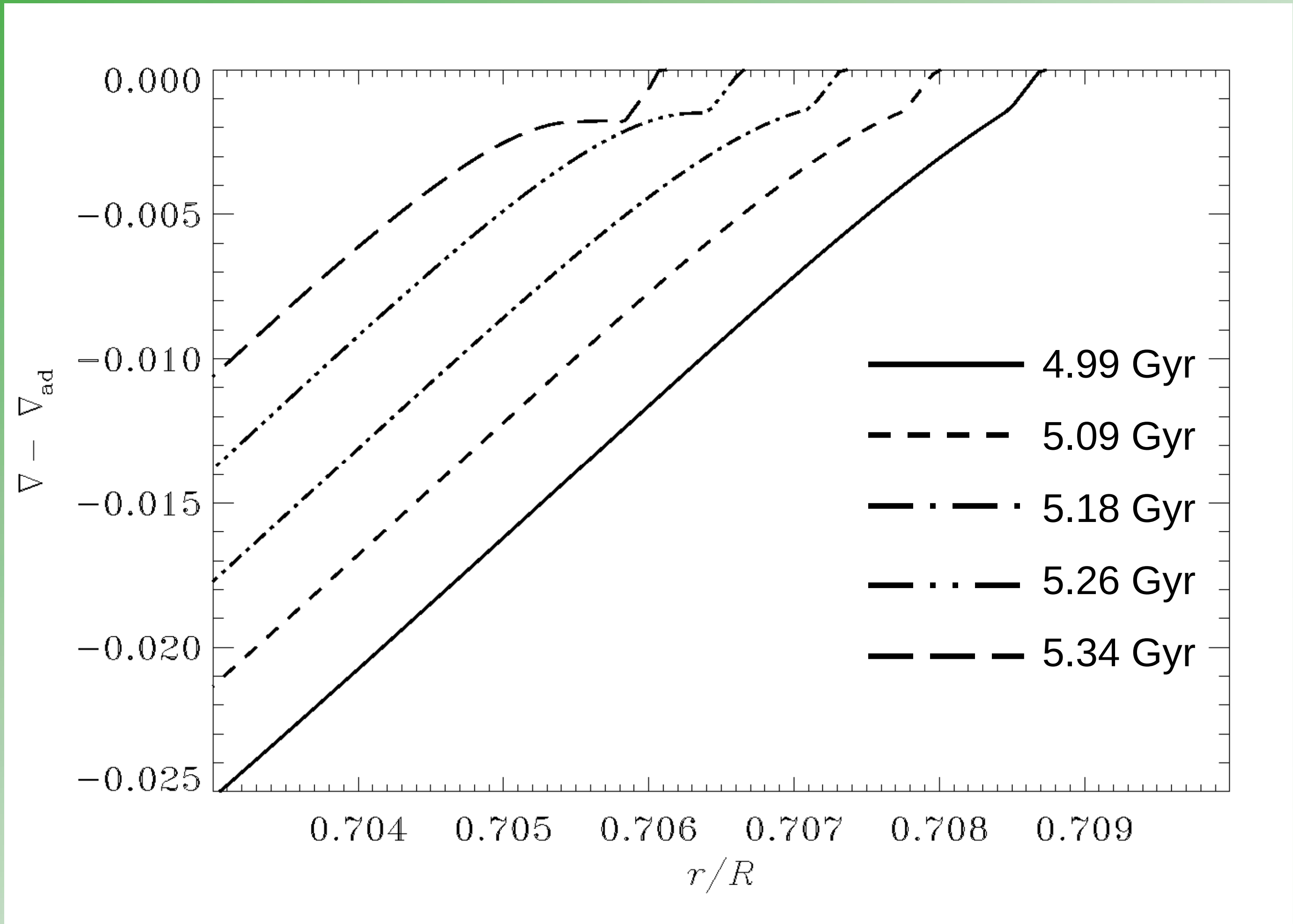


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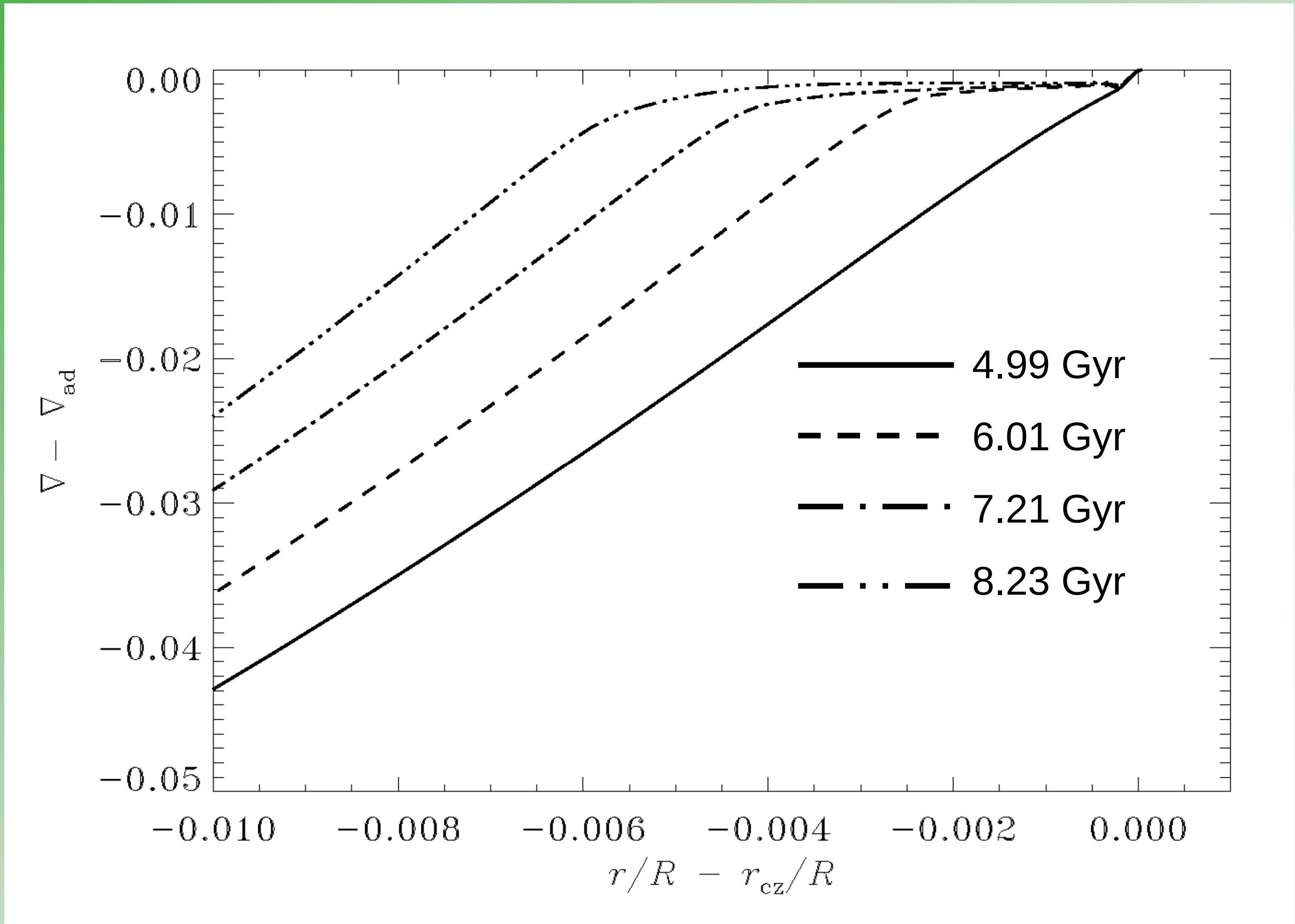


$\alpha$ Cen A models

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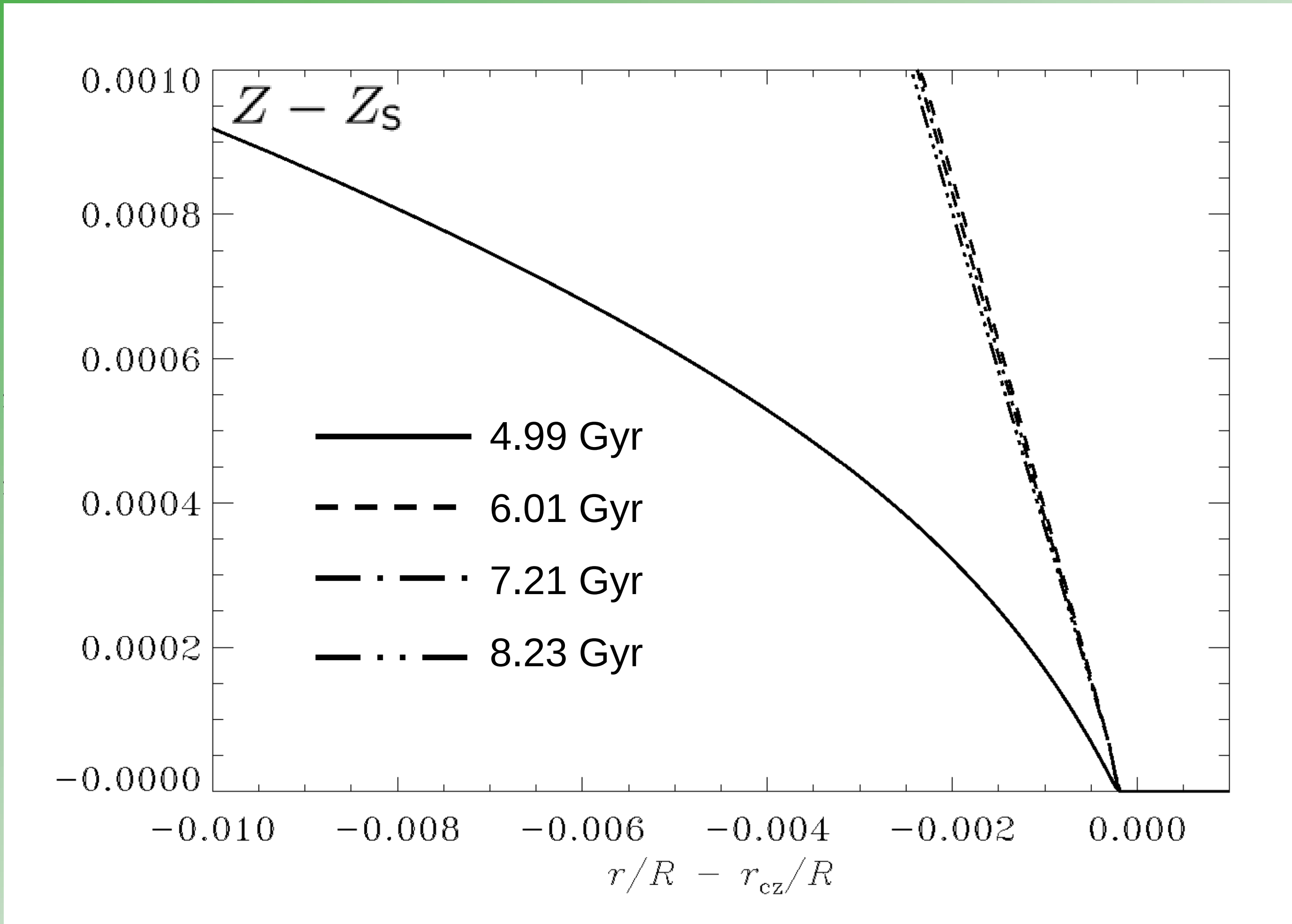


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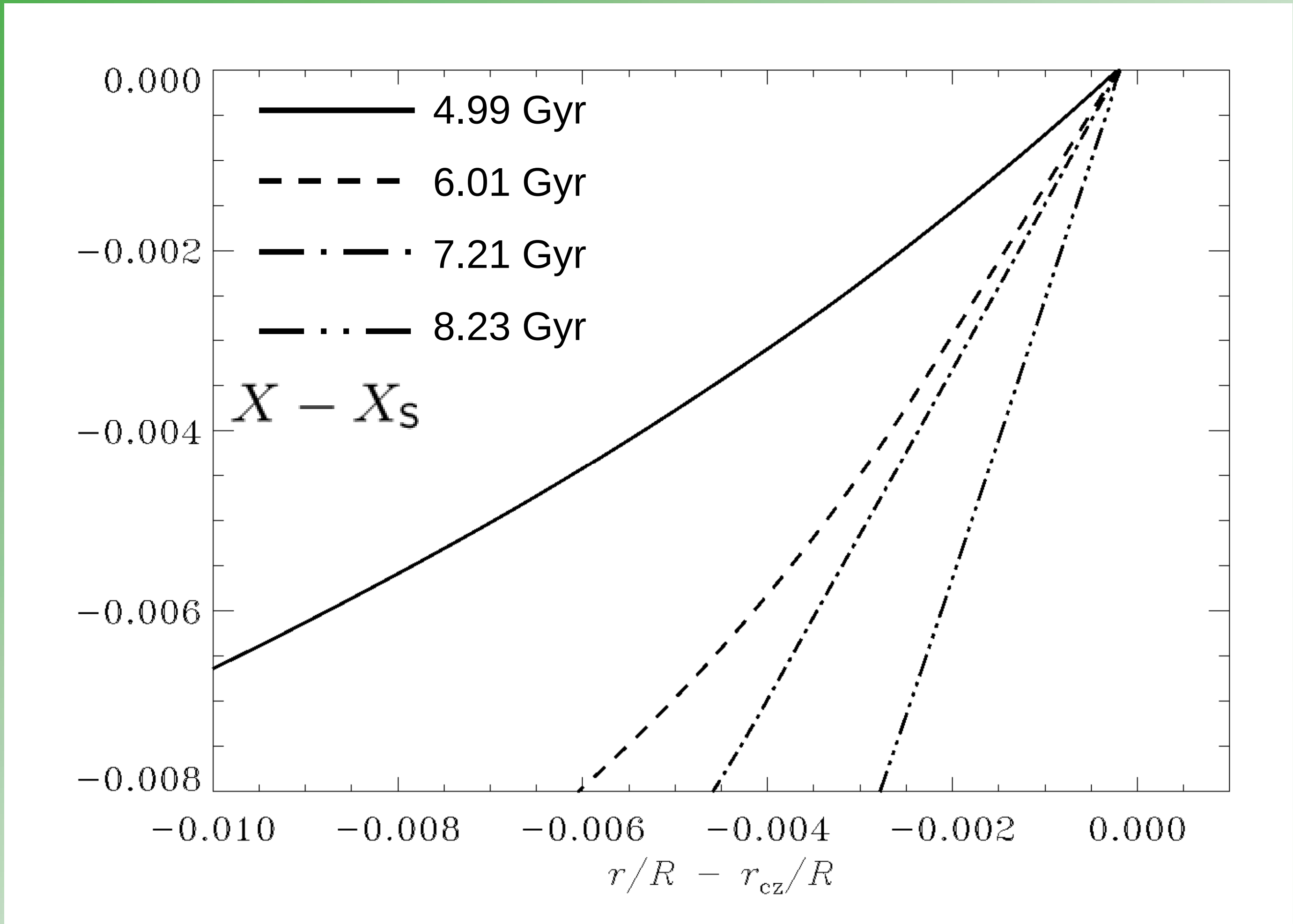
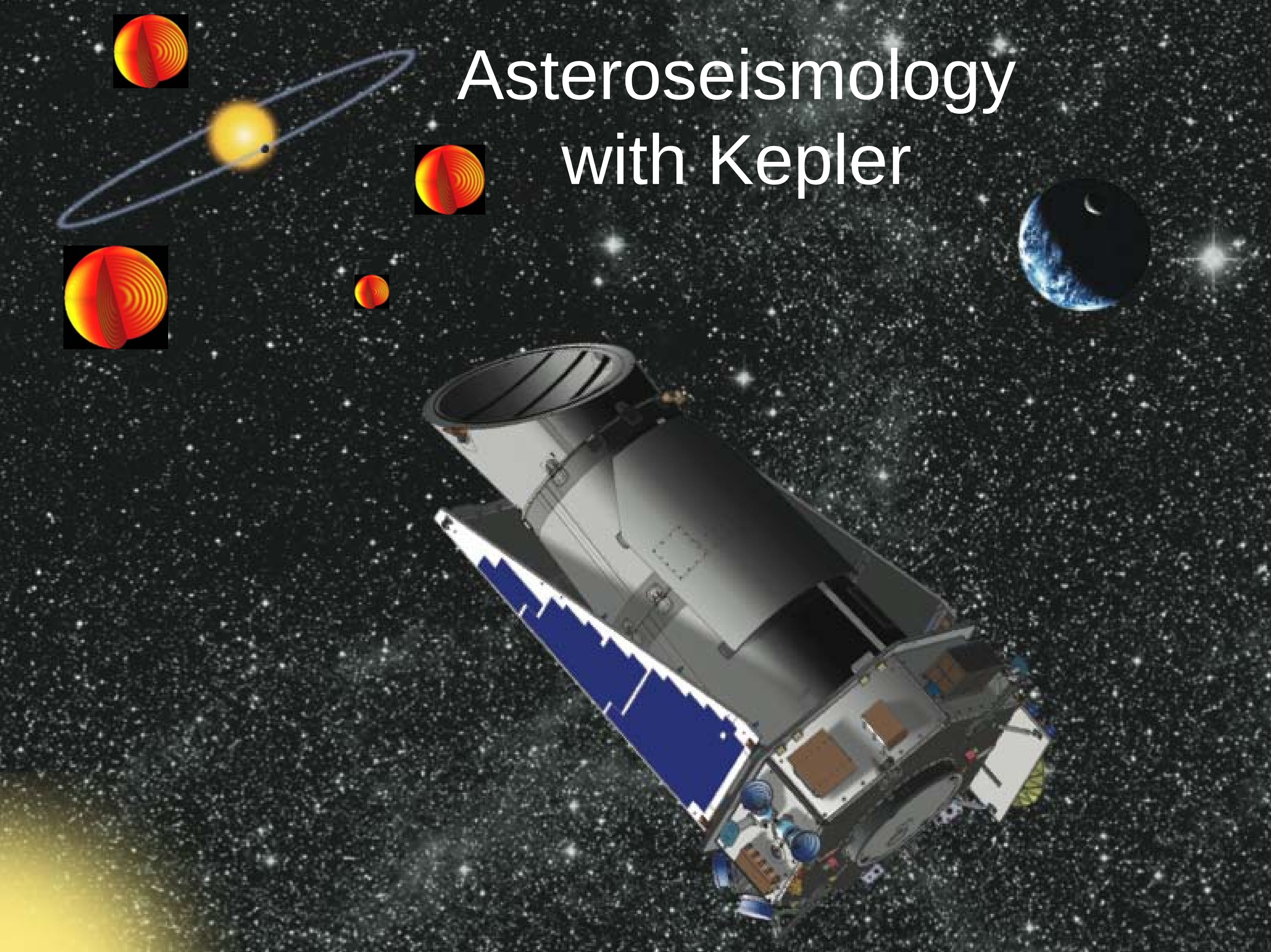



α Cen A models

# And now these messages

# Asteroseismology with Kepler

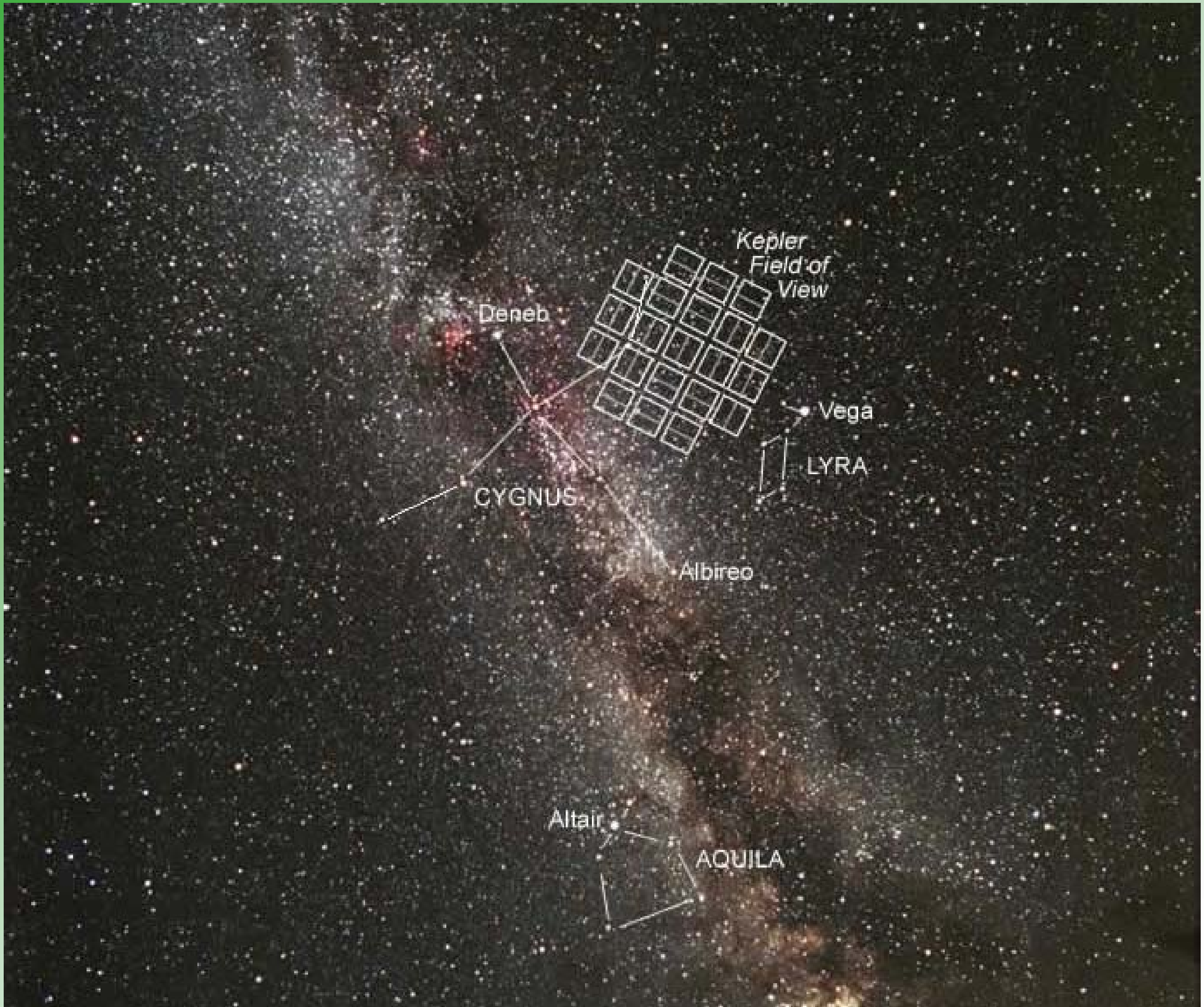


# *Kepler* MISSION CONCEPT

*Kepler*

- Is NASA's first mission capable of finding Earth-size and smaller planets.
- Is a photometric space based mission designed specifically for finding habitable planets ( **0.5 to 10 $M_e$** ) in and near the habitable zone of solar-like stars.
- Uses a one-meter Schmidt telescope with a FOV **>100 $deg^2$** using an array of 42 CCD.
- Will be launched into a heliocentric orbit for continuous viewing.
- Launch expected in November 2008.

# Kepler field



# PHOTOMETRIC CHARACTERISTICS

- **Differential photometric precision of 6.6 ppm for 6.5 hour** integration
  (Includes instrument noise, stray light, background stars, etc.)
  (**Photon shot noise** in 6.5 hours for R=12 star is an additional **16 ppm**)

- **Continuously observe a single FOV for 4-6 years**, except for ≤1 day every month
  Need to body point monthly to download data
  Need to rotate the spacecraft 90 deg every 3 months to keep the Sun on the solar arrays and the CCD radiator pointed to deep space

- **Simultaneously observe >100 000** main-sequence stars
  Start with 170 000 stars and downselect to 100 000 after about 3 years
- **Time resolution**
  **30 minutes** for most stars
  **1 minute** time resolution for subset 512 objects

- **Bandpass 430 to 890 nm** (50%) to avoid Ca II H& K and fringing in red

- Point spread function FWHM about 6 arc sec (one pixel is 3.98 arc sec)

# Goals of Kepler asteroseismology

- to provide support for the studies of extrasolar planetary systems by characterizing the central stars of the systems
- to perform in-depth asteroseismic investigations of a large number of stars, predominantly but not exclusively those showing solar-like oscillations.

# Asteroseismology with Kepler

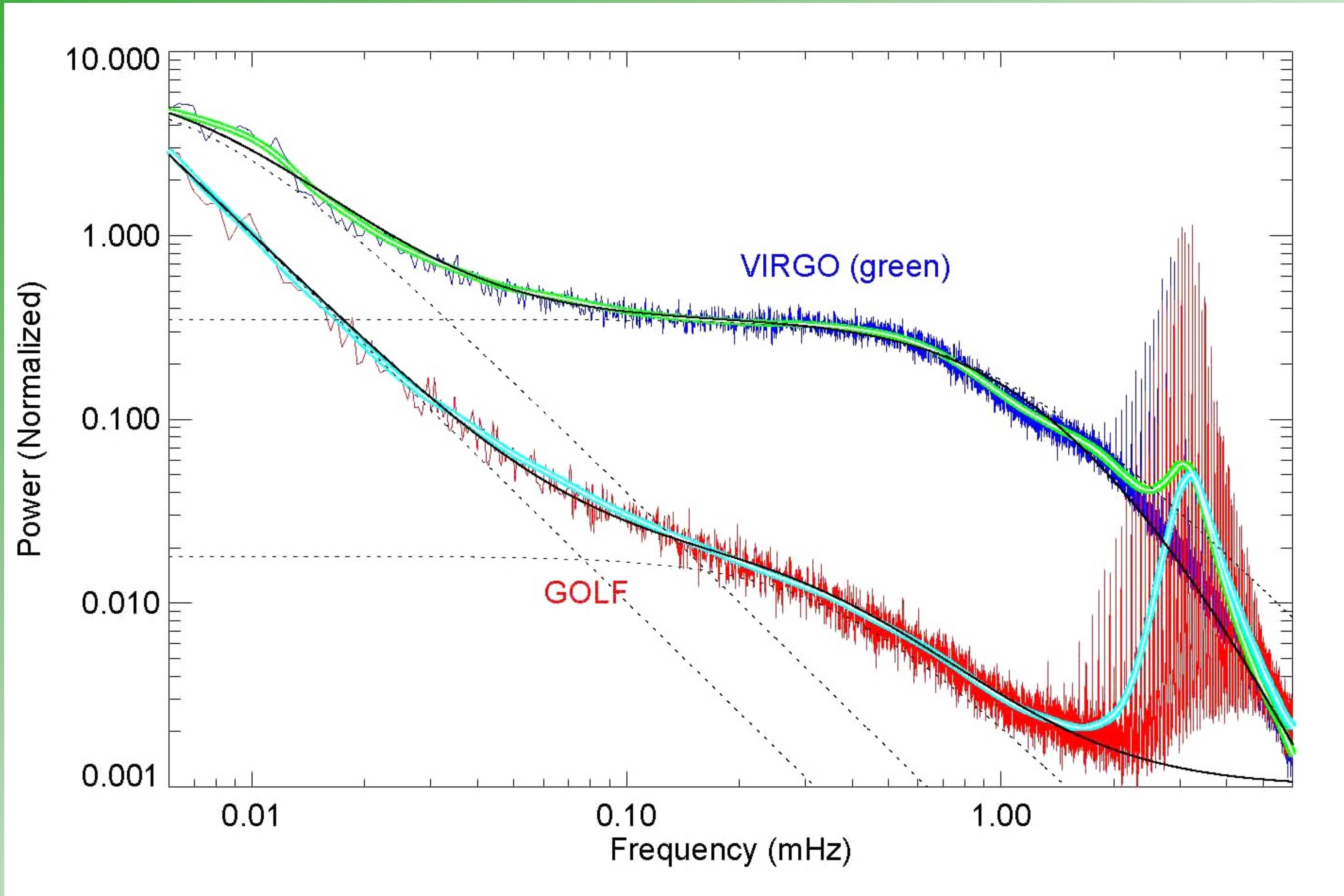
- 512 star at any given time with 1-min cadence (can change selection every three months, if desirable)
- Fixed 105 sq. degree field in Cygnus, 4 – 6+ year mission
- Excellent asteroseismic data at magnitude 9 – 11. Some information (radius, evolutionary state) for fainter stars
- 100 000 stars with 30 min cadence. Excellent for giant pulsators, some main-sequence heat-engine pulsators.

# Required activities

- Selection of asteroseismic targets
- Characterization of asteroseismic targets
- Development and verification of data analysis pipeline
- Development and verification of data interpretation pipeline
- Developing stellar modelling techniques

# But this is not all

# Stellar noise vs. oscillations



# SONG: the Stellar Oscillations Network Group

http://astro.phys.au.dk/SONG

Coming soon: first newsletter, registration for Science Consortium

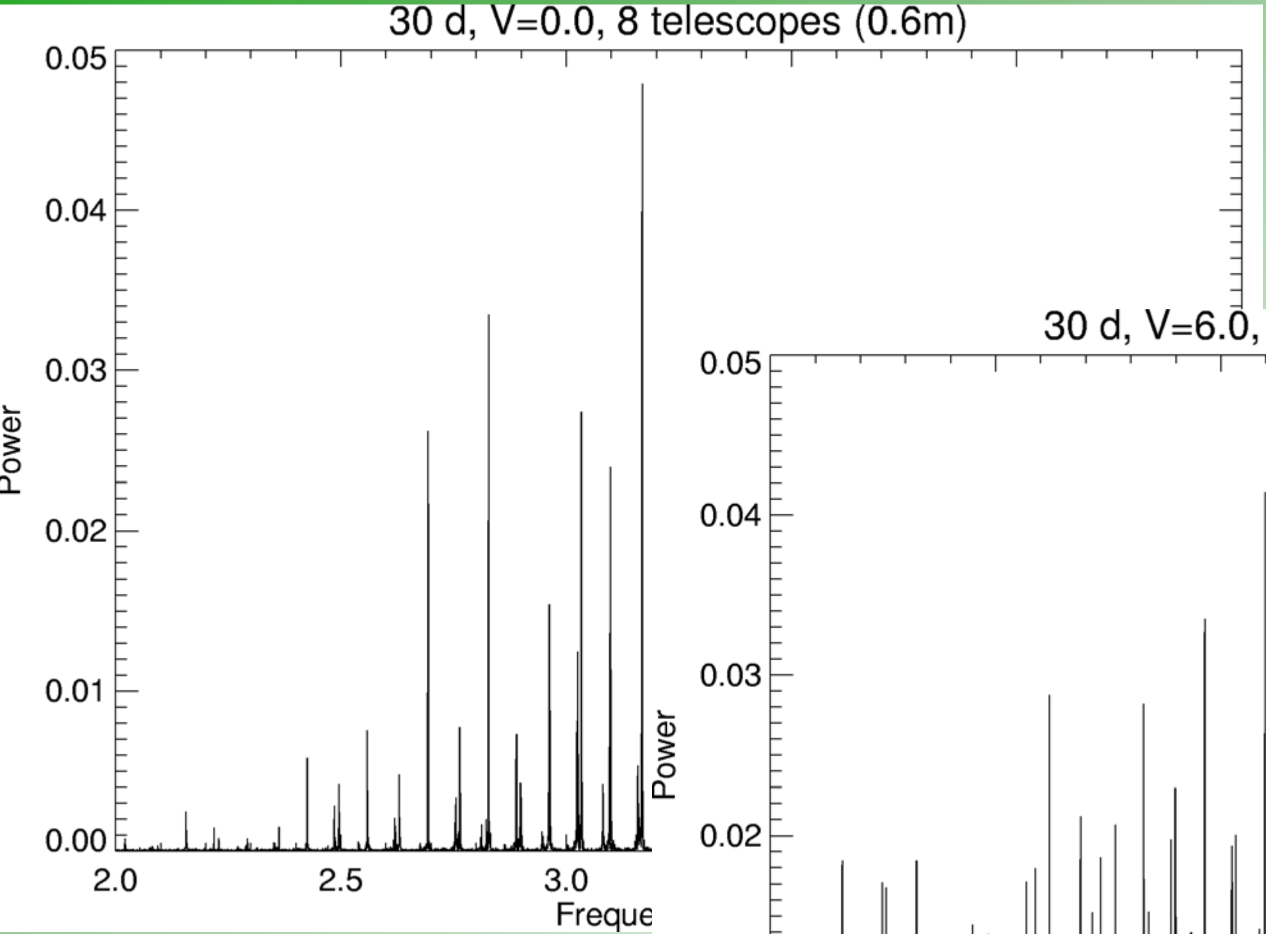
# Concept

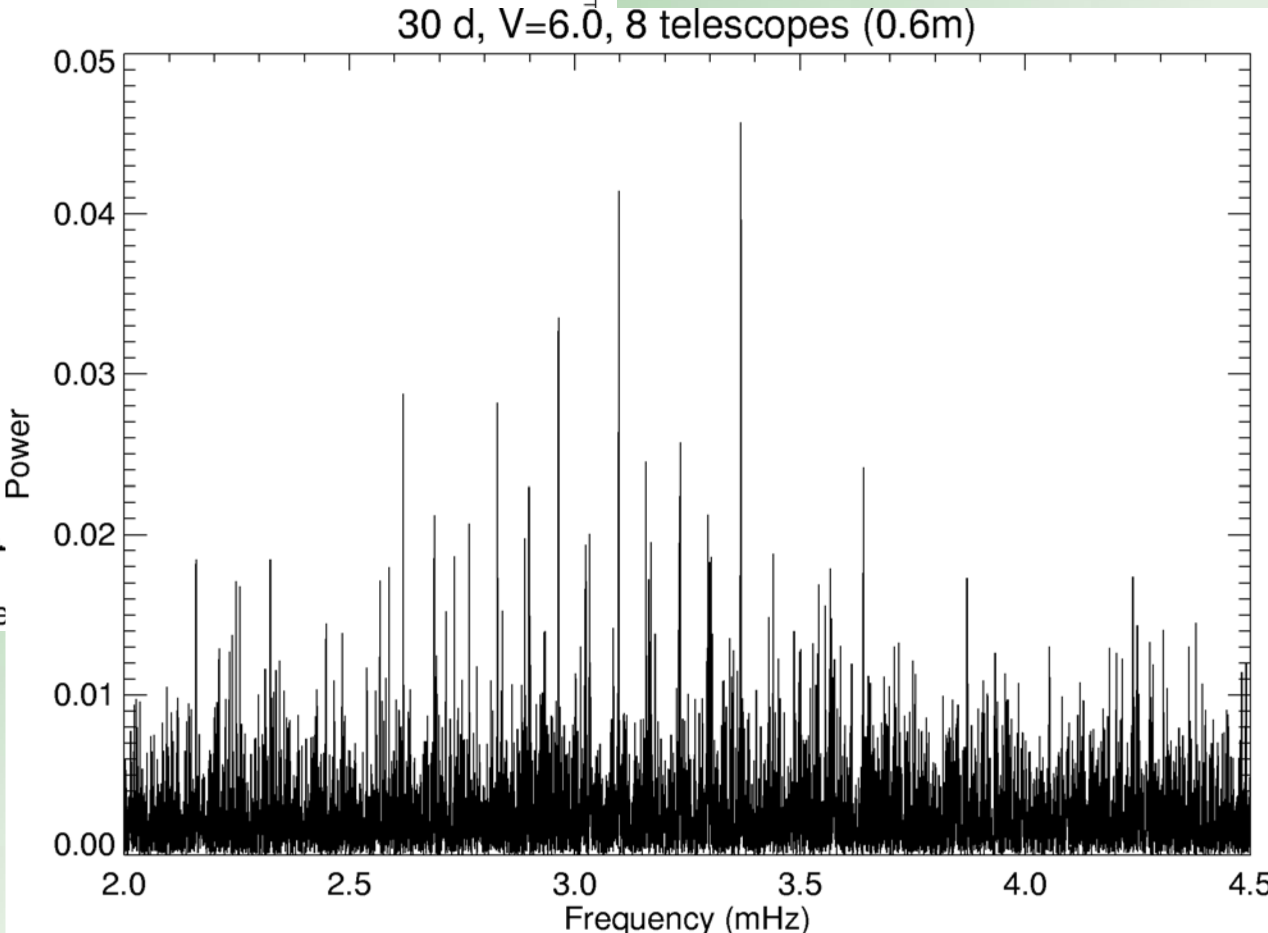
- Around 1 m telescopes
- Very stable spectrograph, iodine cell
- 6 – 8 stations with suitable geographical distribution
- Fully automatic operation
- Using existing observatory sites with required infrastructure

# Possible site layout

# Possible distribution of sites

# Predicted performance



# Gains with SONG: mode selection