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Helioseismology

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University of Birmingham, UK

The Physics of the Sun and the Solar Neutrinos
Gran-Sasso, Italy, 4 October 2010

The Unseen Interior

Sir Arthur Eddington

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The Unseen Interior

"At first sight it would seem that the deep interior of the sun and stars is less accessible to scientific investigation than any other region of the universe. Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden beneath substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?"

A. S. Eddington, 'The Internal Constitution of the Stars', 1926, Cambridge Uni. Press, p. 1

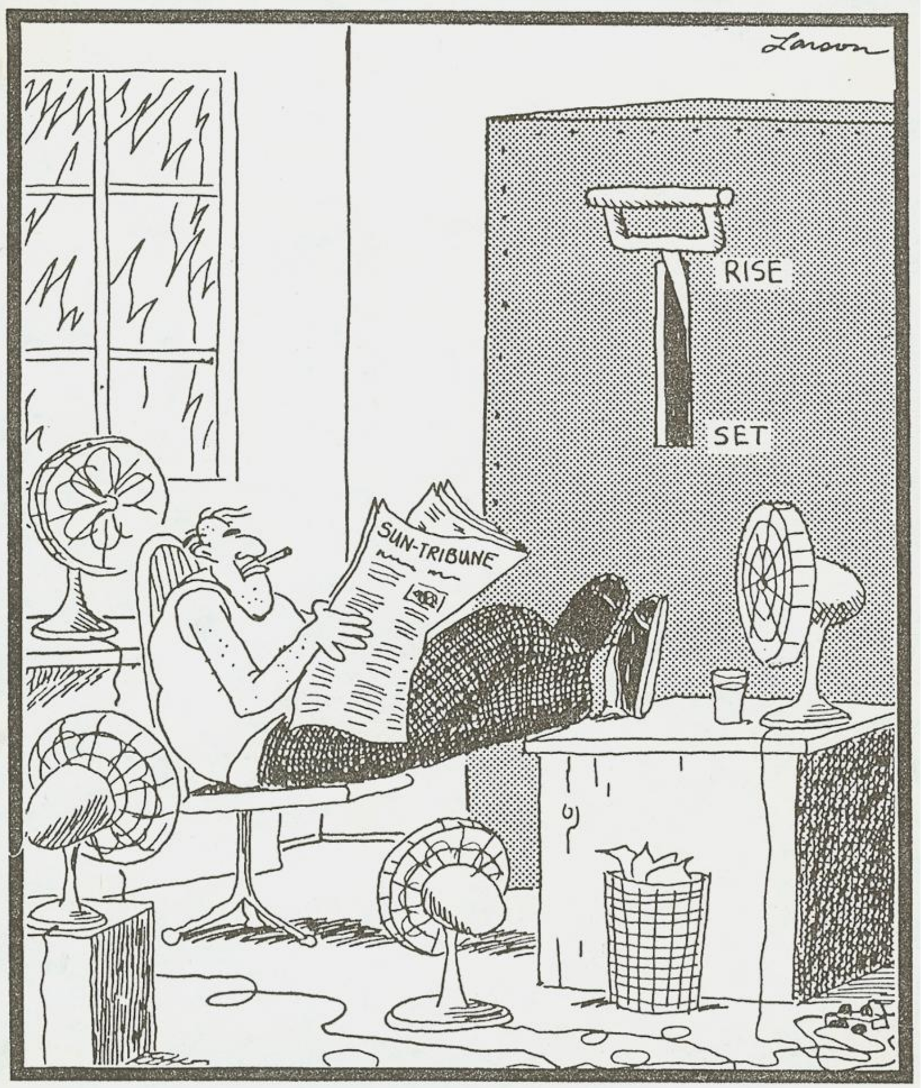
Pulsation opens a window!

"Ordinary stars must be viewed respectfully like objects in glass cases in museums; our fingers are itching to pinch them and test their resilience. Pulsating stars are like those fascinating models in the Science Museum provided with a button which can be pressed to set the machinery in motion. To be able to see the machinery of a star throbbing with activity is most instructive for the development of our knowledge."

A. S. Eddington, 'Stars and Atoms', 1927, Oxford Uni. Press, p. 89

Helioseismology

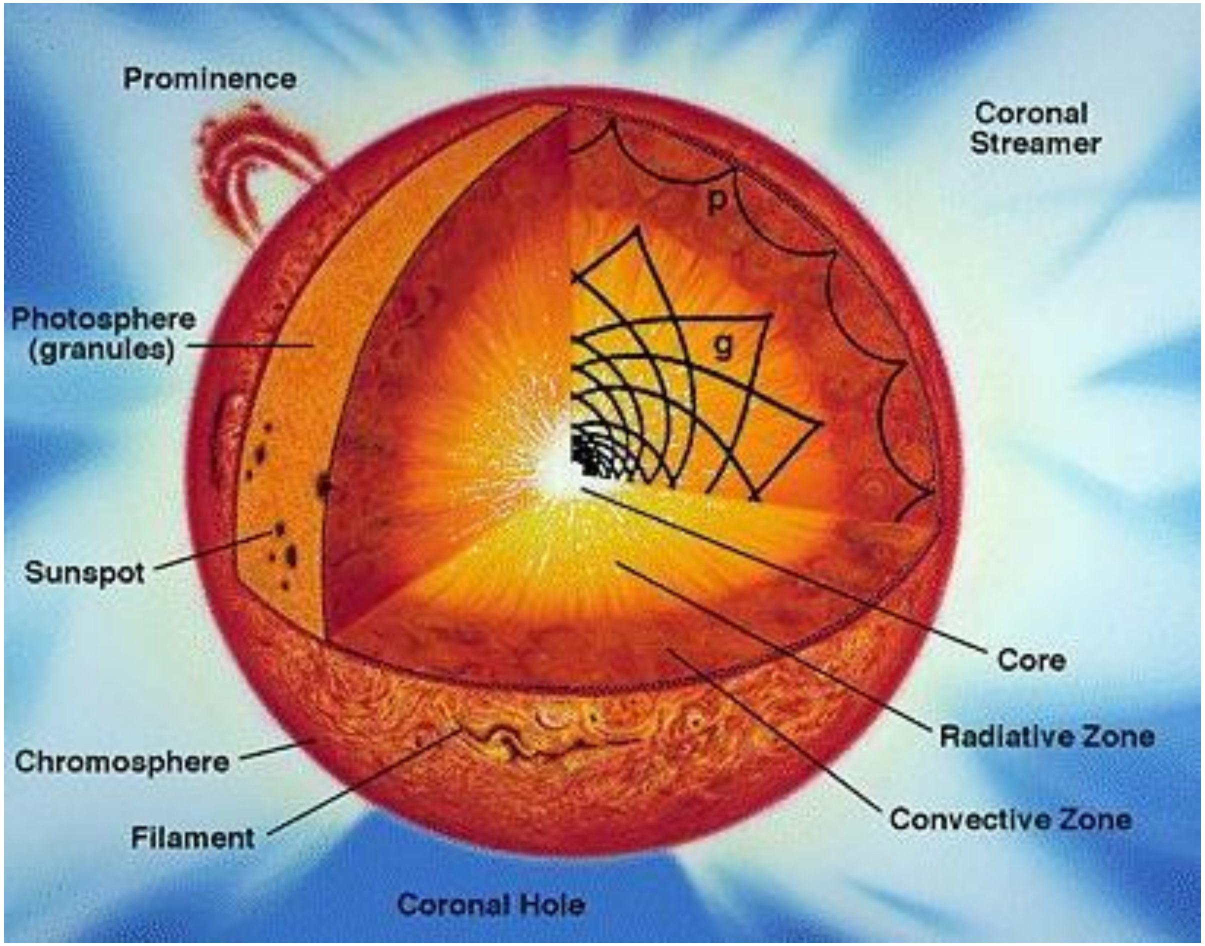
Opening windows on the solar interior



Inside the sun

Gary Larson

The Resonant Sun



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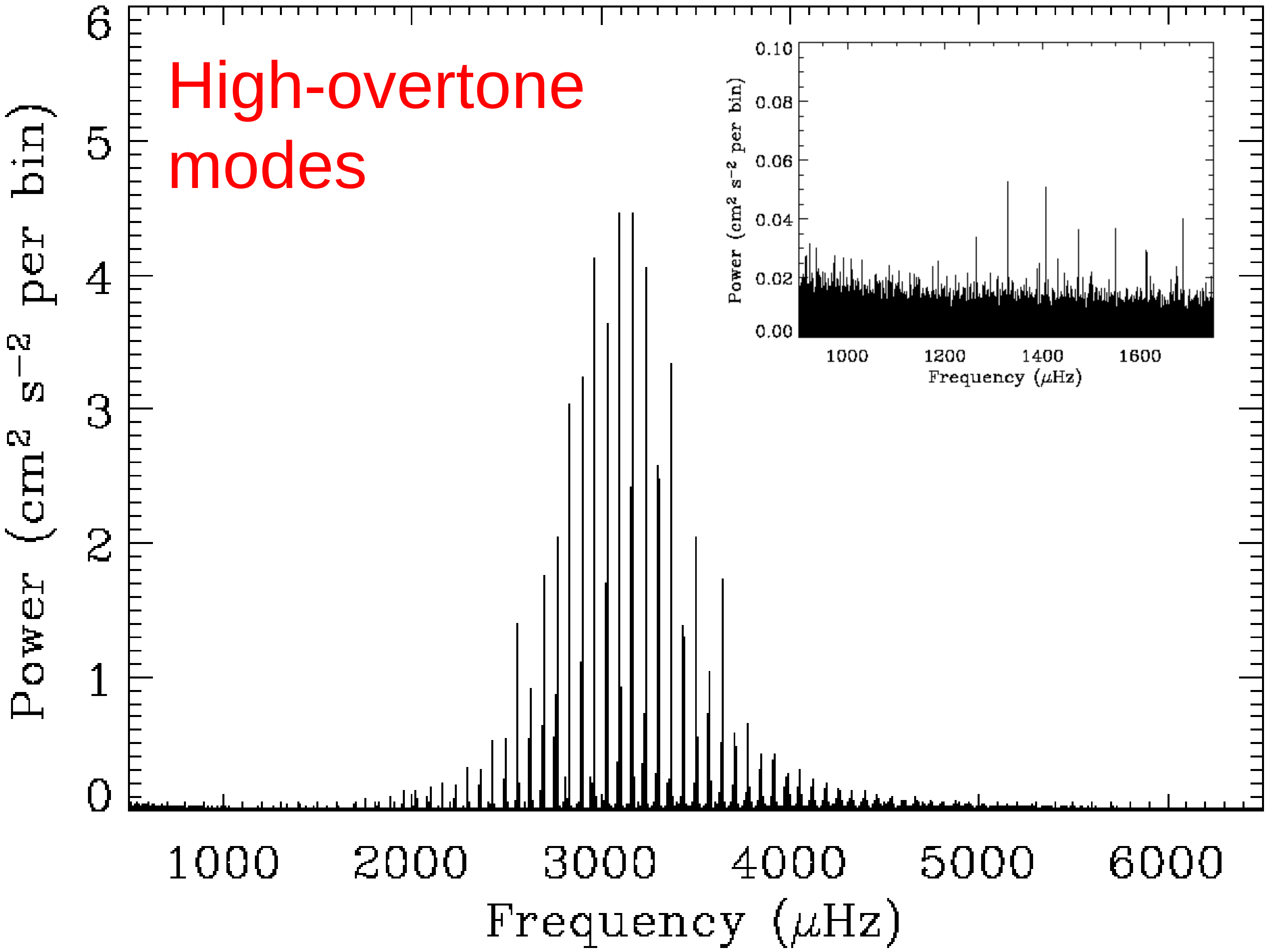
Frequency spectrum of low-degree (low-*l*) modes (contains overtones of $0 \leq l \leq 3$)



Data courtesy R. García and the GOLF team

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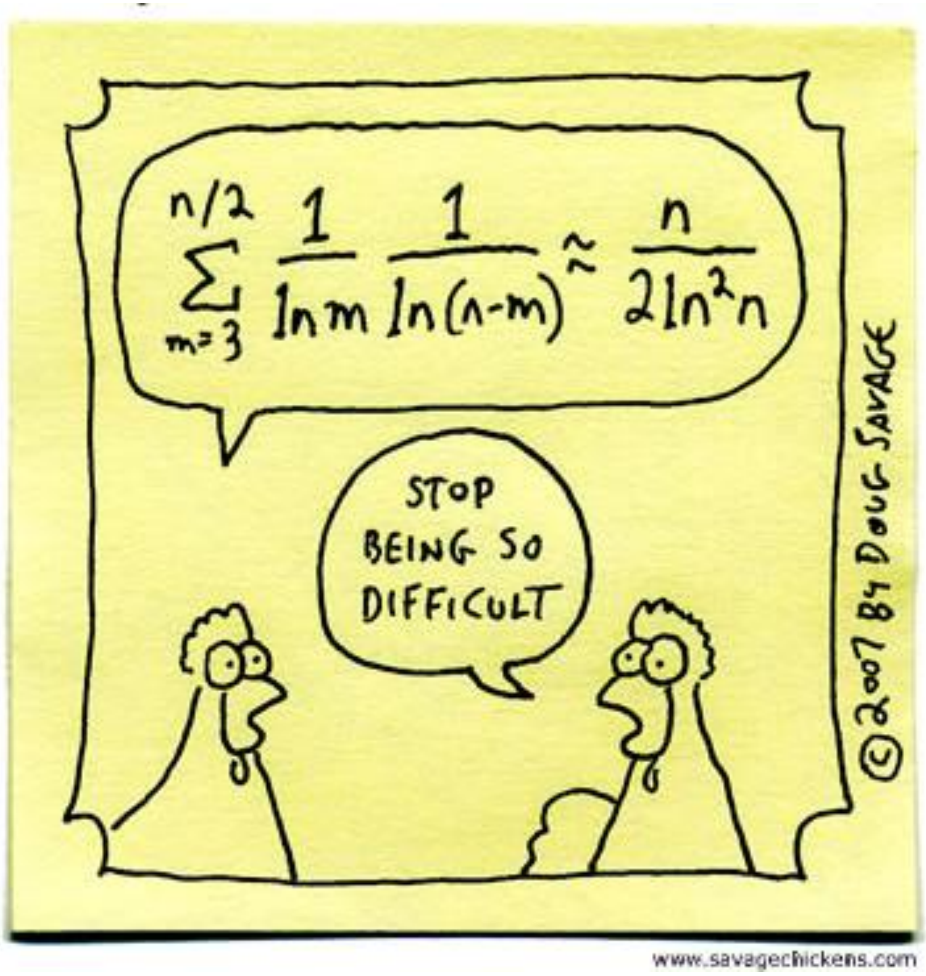
Solar Abundance Problem

- Calculation of capture rate depends crucially on abundances

  [Bahcall 1966; Bahcall & Serenelli 2005]

- Solving the Solar Abundance Problem clearly won’t be easy…

Solar Abundance Problem



www.savagechickens.com

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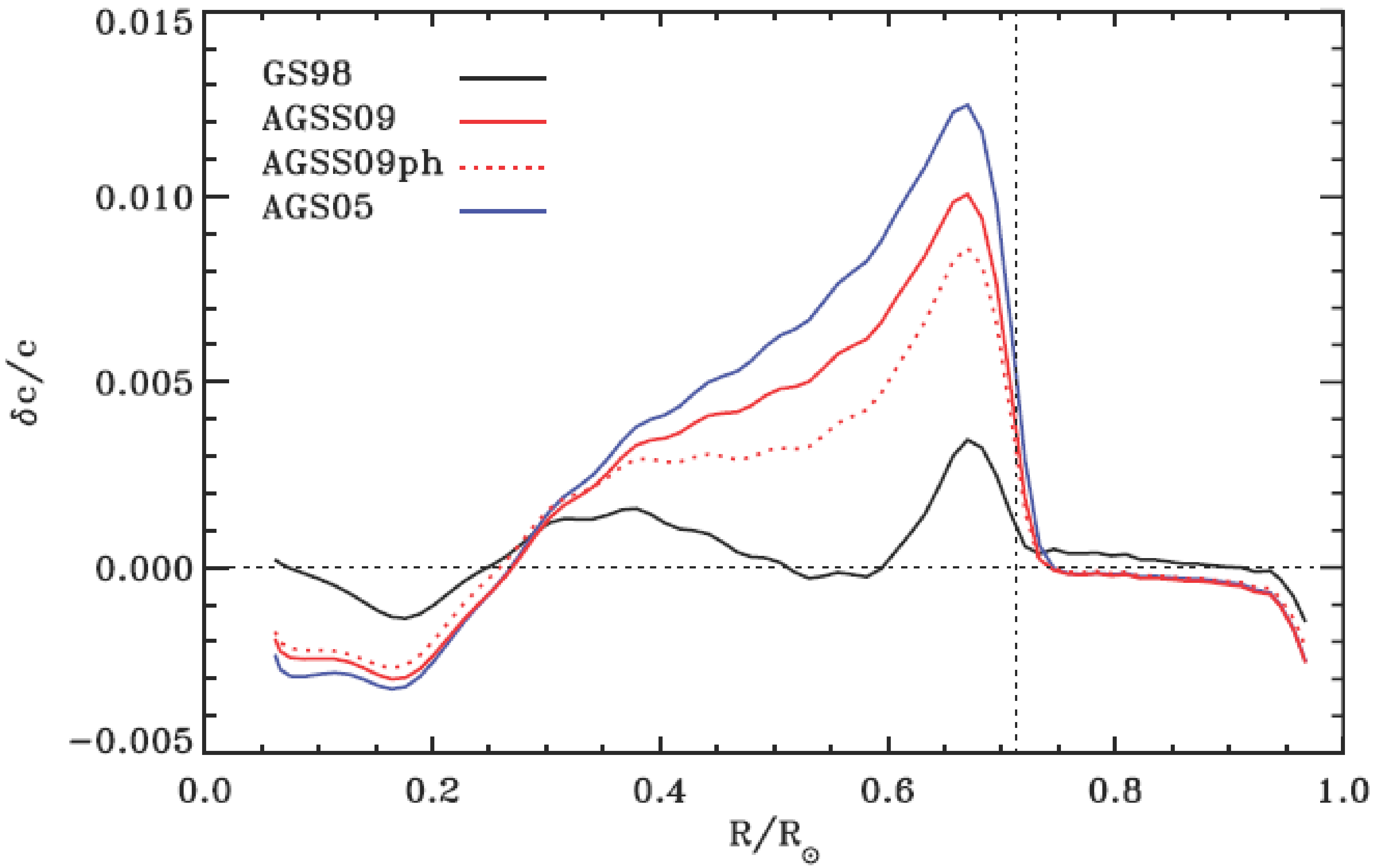
Inversions for solar structure



Serenelli et al. 2009, ApJ, **705**, L123

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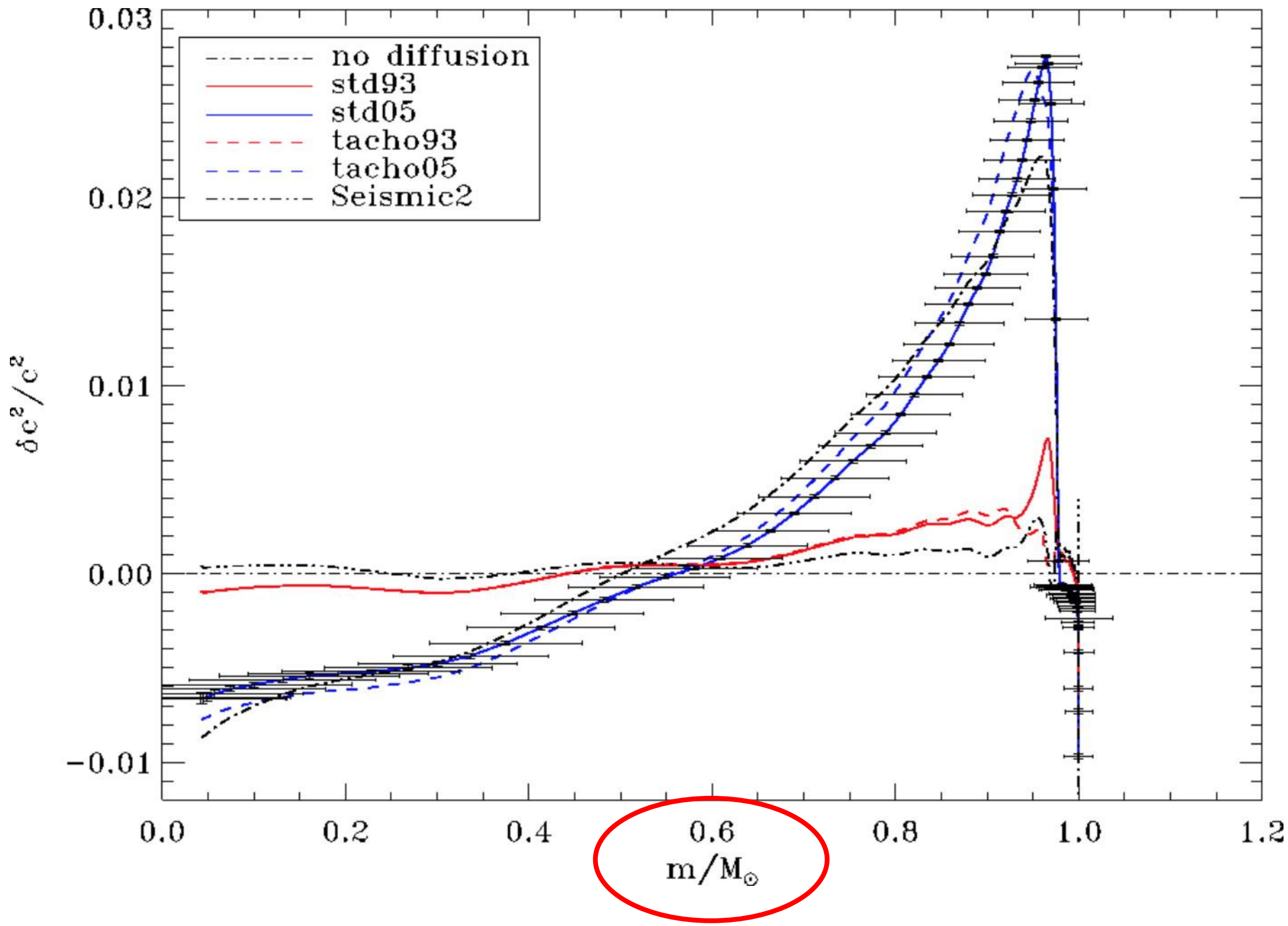
Inversions for solar structure



Mathur et al., 2007, ApJ, **668**, 594

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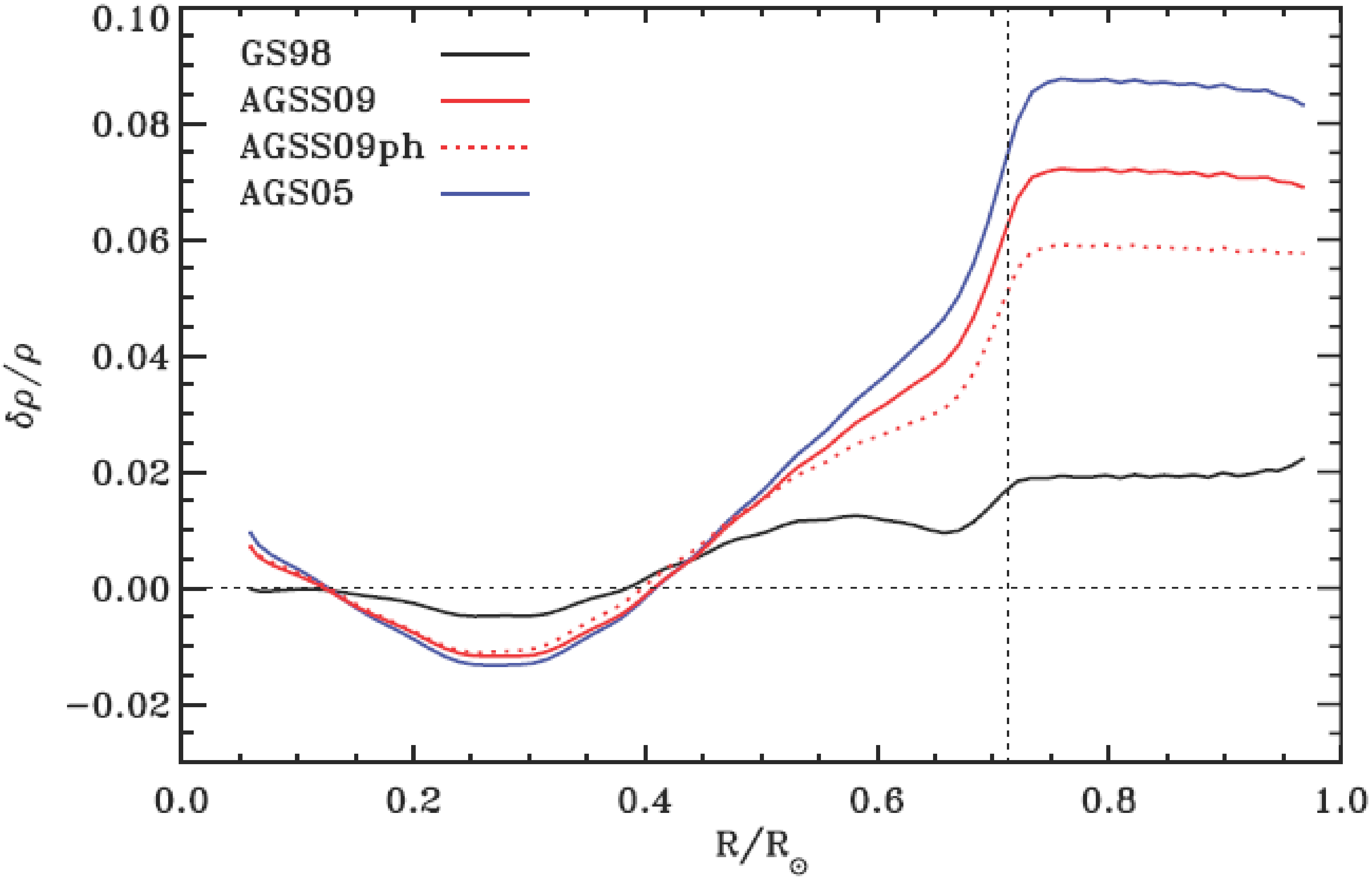
Inversions for solar structure



Serenelli et al. 2009, ApJ, **705**, L123

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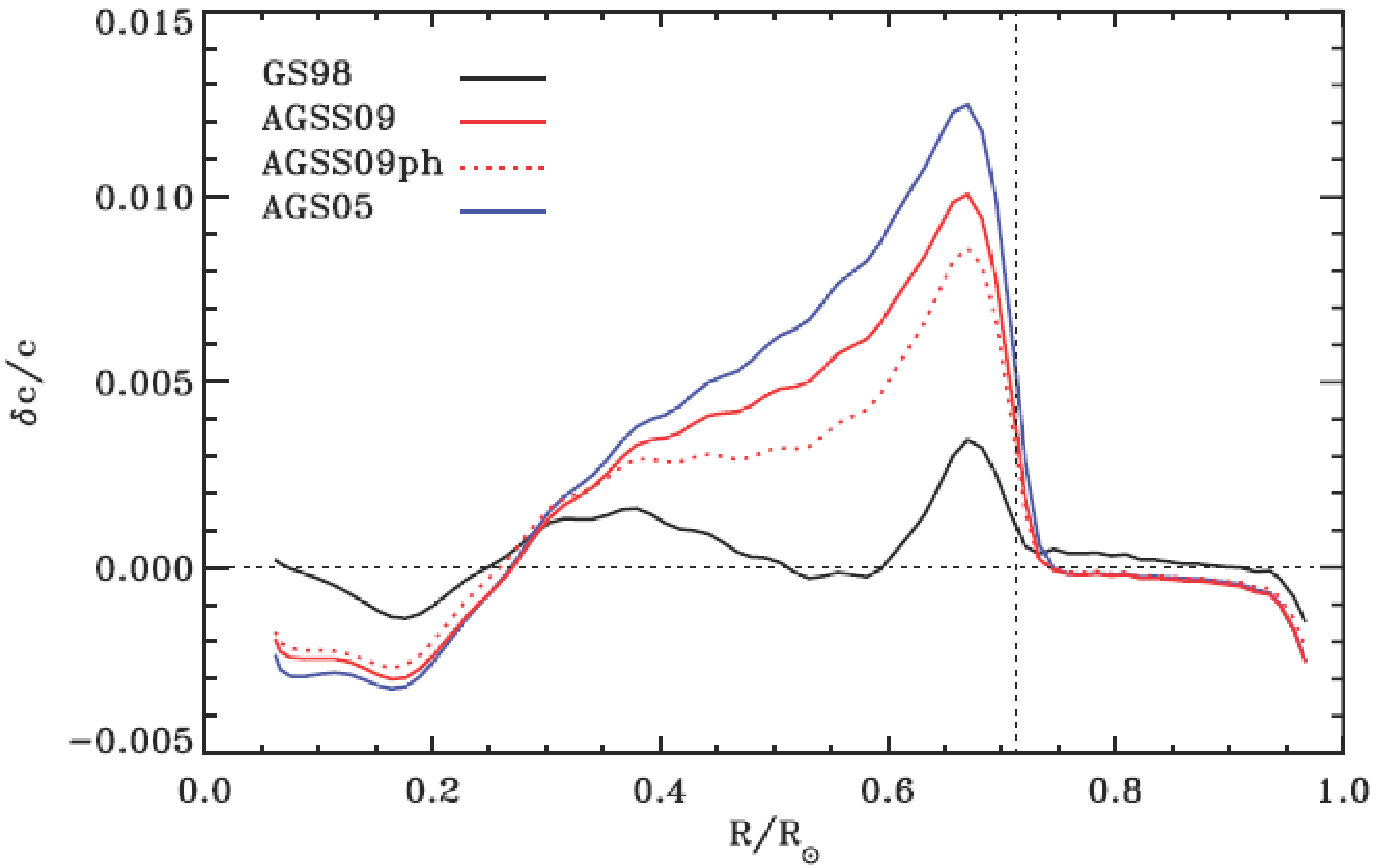
Inversions for solar structure



Serenelli et al. 2009, ApJ, **705**, L123

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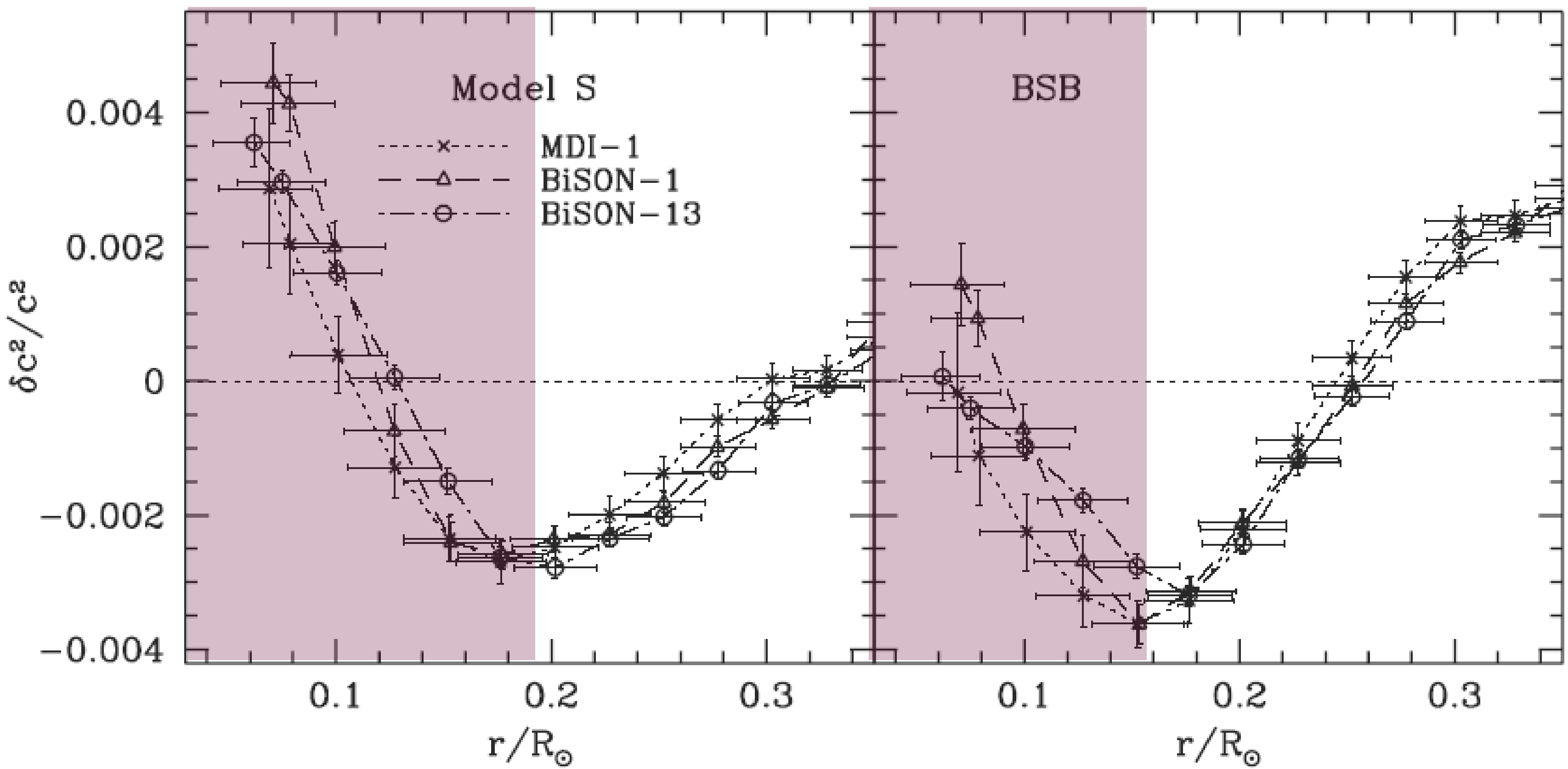
Impact in the core: change of reference solar model



Basu et al. 2009, ApJ, **699**, 1403

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Seismic estimates of Z

- Two broad categories:

1. Use seismic signatures from radiative interior
2. Use seismic signatures from CZ

Seismic estimates of Z

1. Signatures from radiative interior:
   - Results depend upon opacities
   - Use seismic signatures from base of CZ on down…
     - Depth of convection zone (determined by opacity at that location)
     - Frequency separations
     - Mean molecular weight in core

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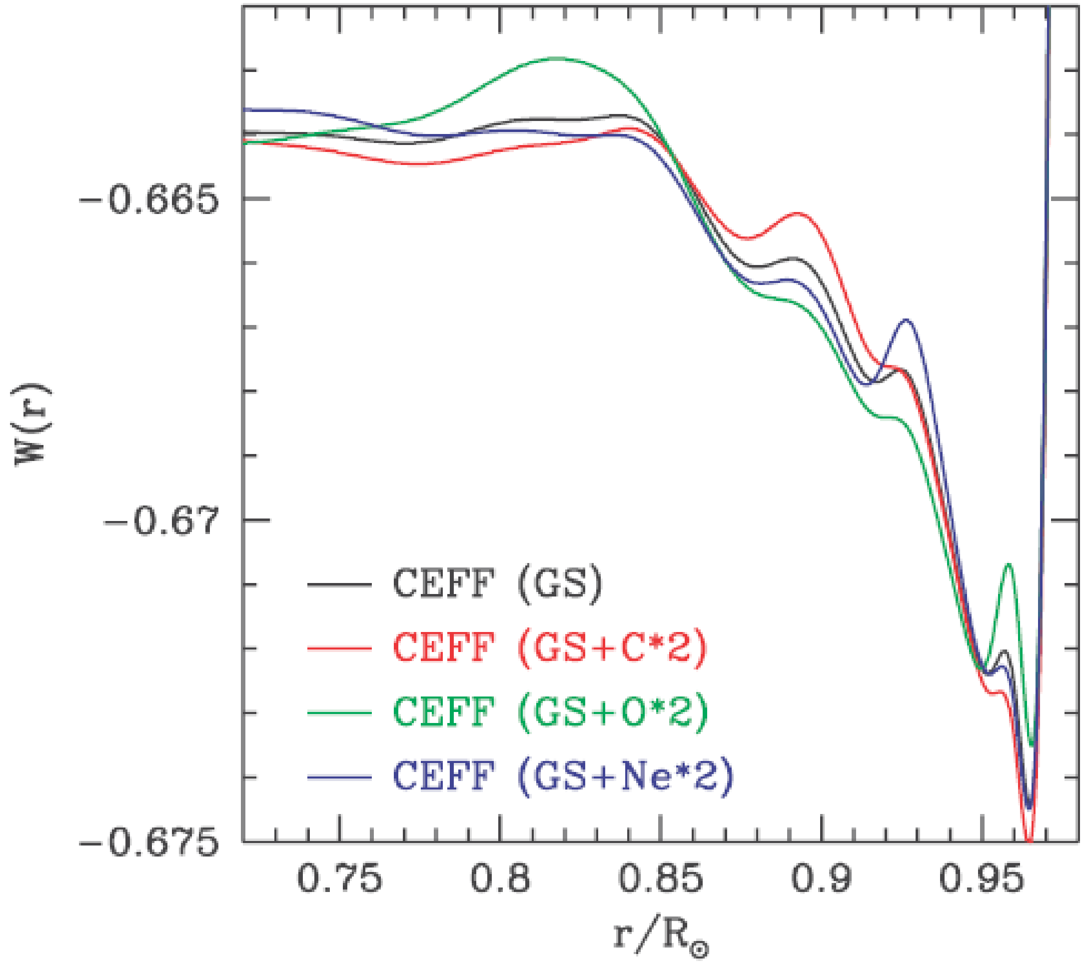
Seismic estimates of Z

2. Signatures from CZ:
   - Ionization of elements leaves signature on adiabatic exponent, gradient of sound speed
   - EOS dependence

Signatures from CZ

- Effect hard to see: but data on modes that probe CZ are extremely precise
- Can attempt to measure effect on Γ_1 (e.g., Lin et al., 2007)
- Or: Measure impact on (dimensionless) sound-speed gradient $W(r) = g^{-1} dc^2 / dr$

Signatures from CZ



Antia & Basu 2006, ApJ, **644**, 1292

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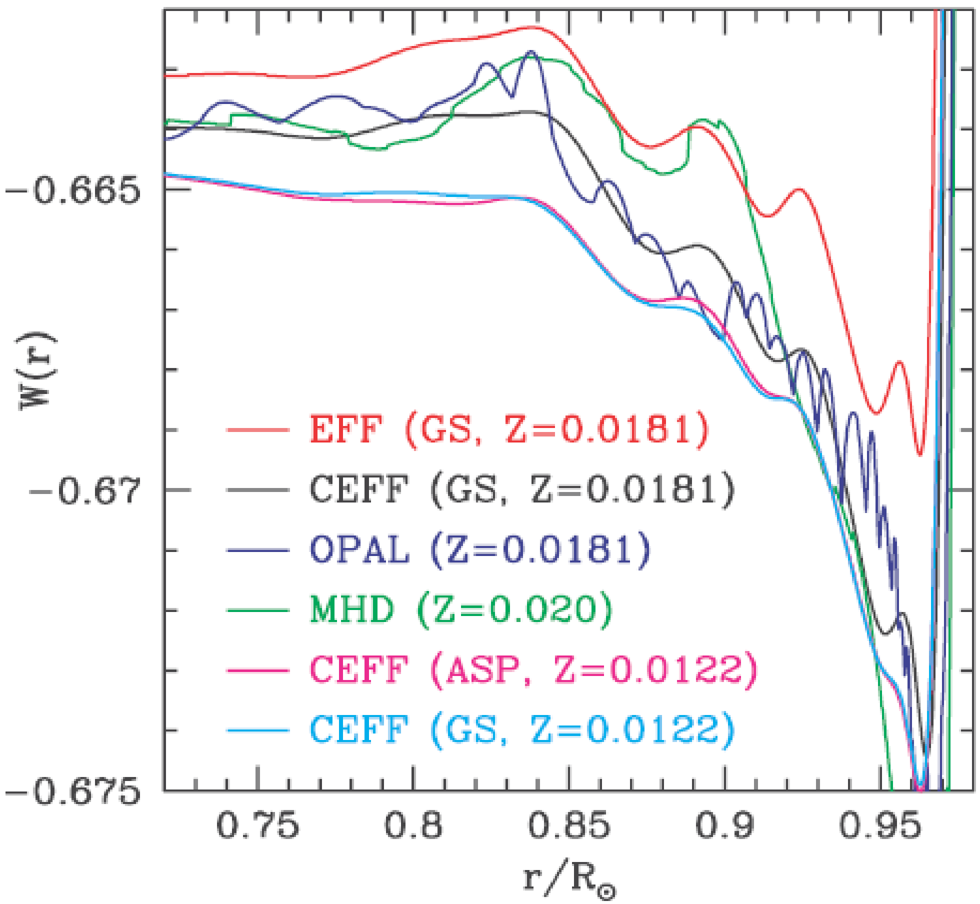
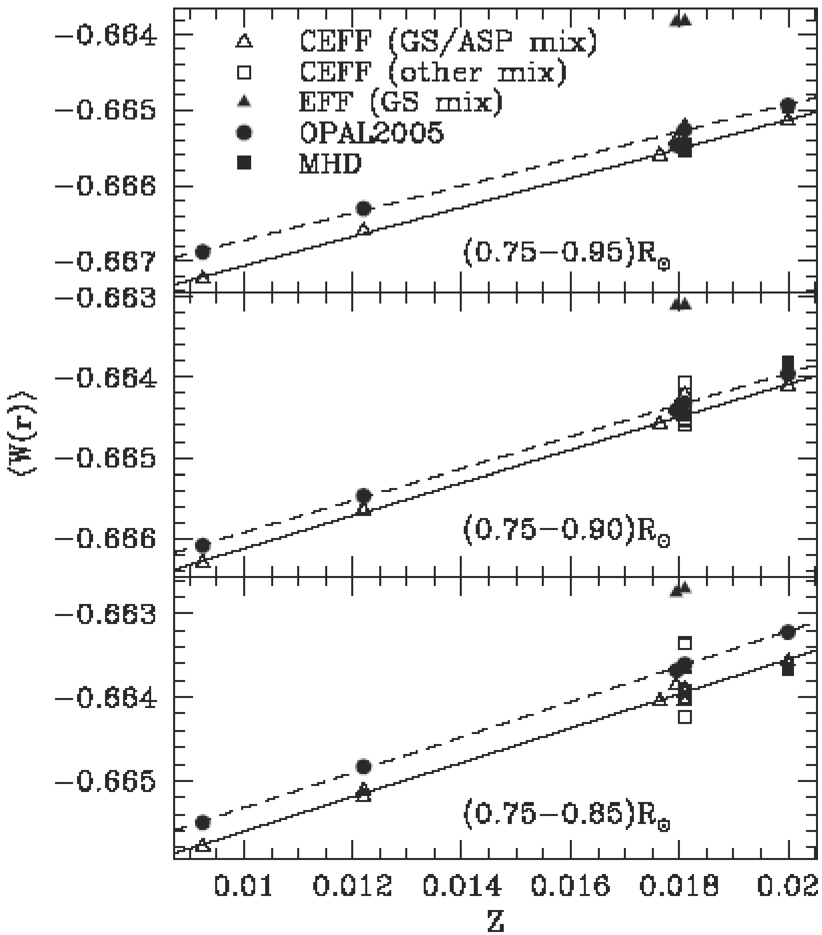
Signatures from CZ





Antia & Basu 2006, ApJ, **644**, 1292

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Signatures from CZ

- Seismic estimate from $W(r)$:

$$Z = 0.0172 \pm 0.002$$

GS98: 0.0170

AGS05: 0.0126

AGSS09: 0.0134

Antia & Basu 2006, ApJ, **644**, 1292

Signatures from radiative interior

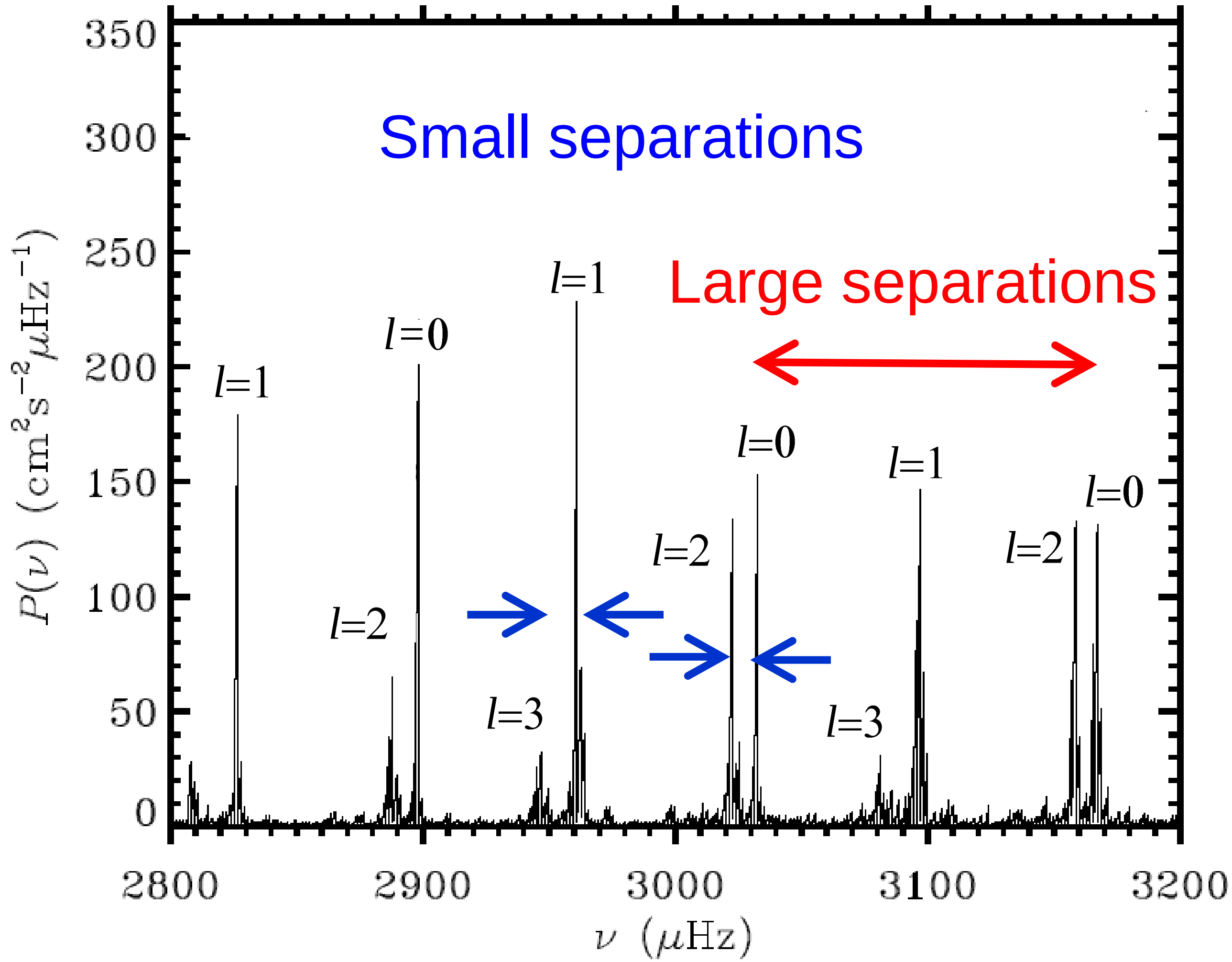
- Use low-degree (low-*l*) core-penetrating modes
- Place constraints on mean molecular weight, μ, in core
- Then infer Z in CZ, which is related (higher Z results in higher μ)

Chaplin et al. 2007, ApJ, **670**, 872

Signatures from radiative interior

- Small spacings and separation ratios (Basu et al. 2007; Chaplin et al. 2007; Zaatri et al. 2007)

Important frequency separations



BiSON data

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Signatures from radiative interior

- Small separations and separation ratios (Basu et al. 2007; Chaplin et al. 2007; Zaatri et al. 2007)
  - Ratios = small separations ÷ large separations
  - Suppresses contributions to frequencies from near-surface layers

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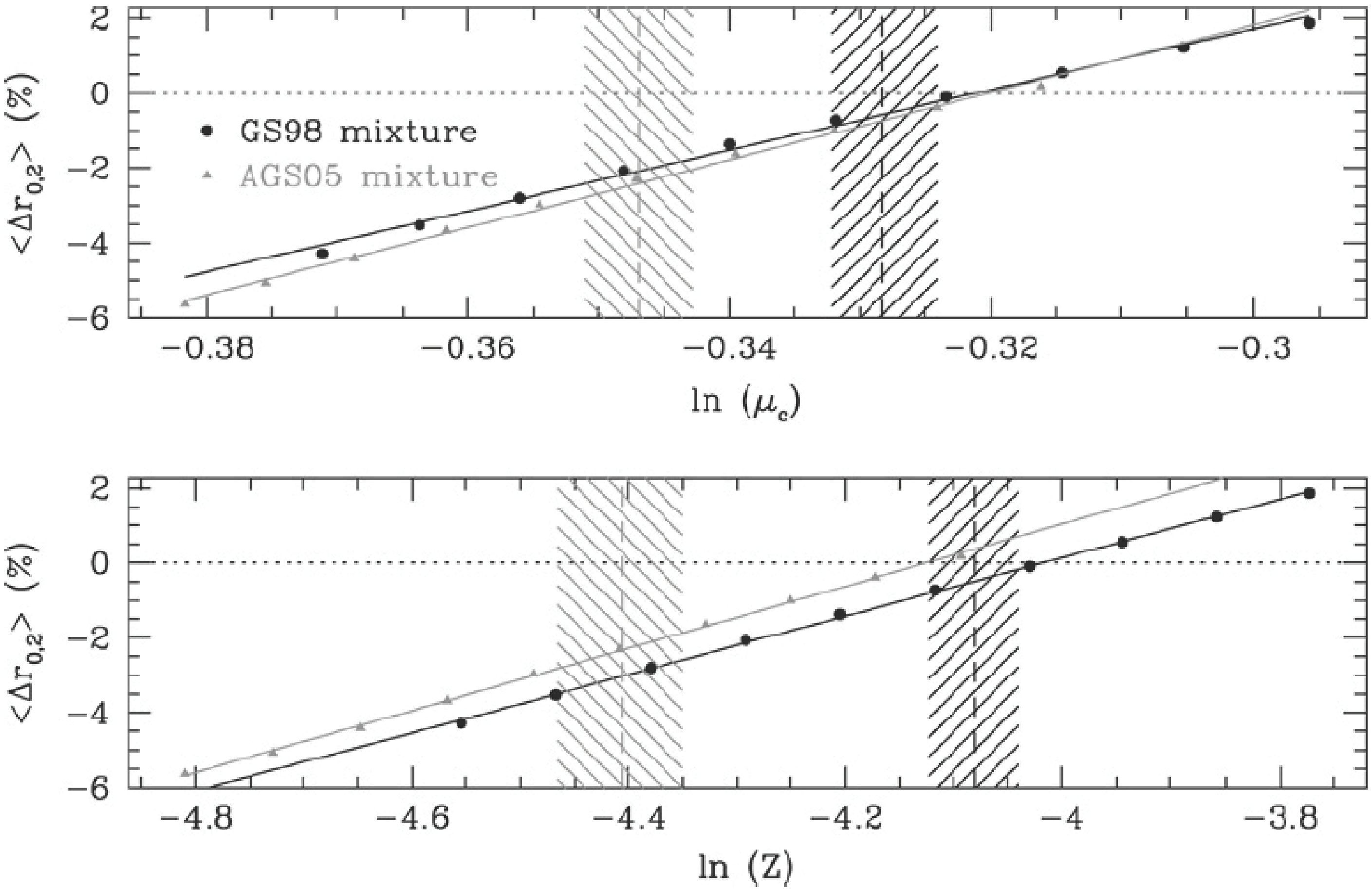
Signatures from radiative interior

Average differences in separation ratios (obs – model)



Chaplin et al. 2007, ApJ, **670**, 872

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Signatures from radiative interior

- Use Monte-Carlo sequences of models to estimate uncertainties:

  μ = 0.7209 – 0.7231 (errors 0.5%)

  [GS98: within 1σ AGS05: Lower by 3-4σ]

  Z = 0.0187 to 0.0239 (errors 12 – 19%)

  [GS98: 0.0170   AGS05: 0.0126   AGSS09: 0.0134]

Chaplin et al. 2007, ApJ, **670**, 872

Signatures from radiative interior

- Use Monte-Carlo sequences of models to estimate uncertainties:
  - Problem is not just one of “outer” layers
  - Mismatches *extend to the core*

Chaplin et al. 2007, ApJ, **670**, 872

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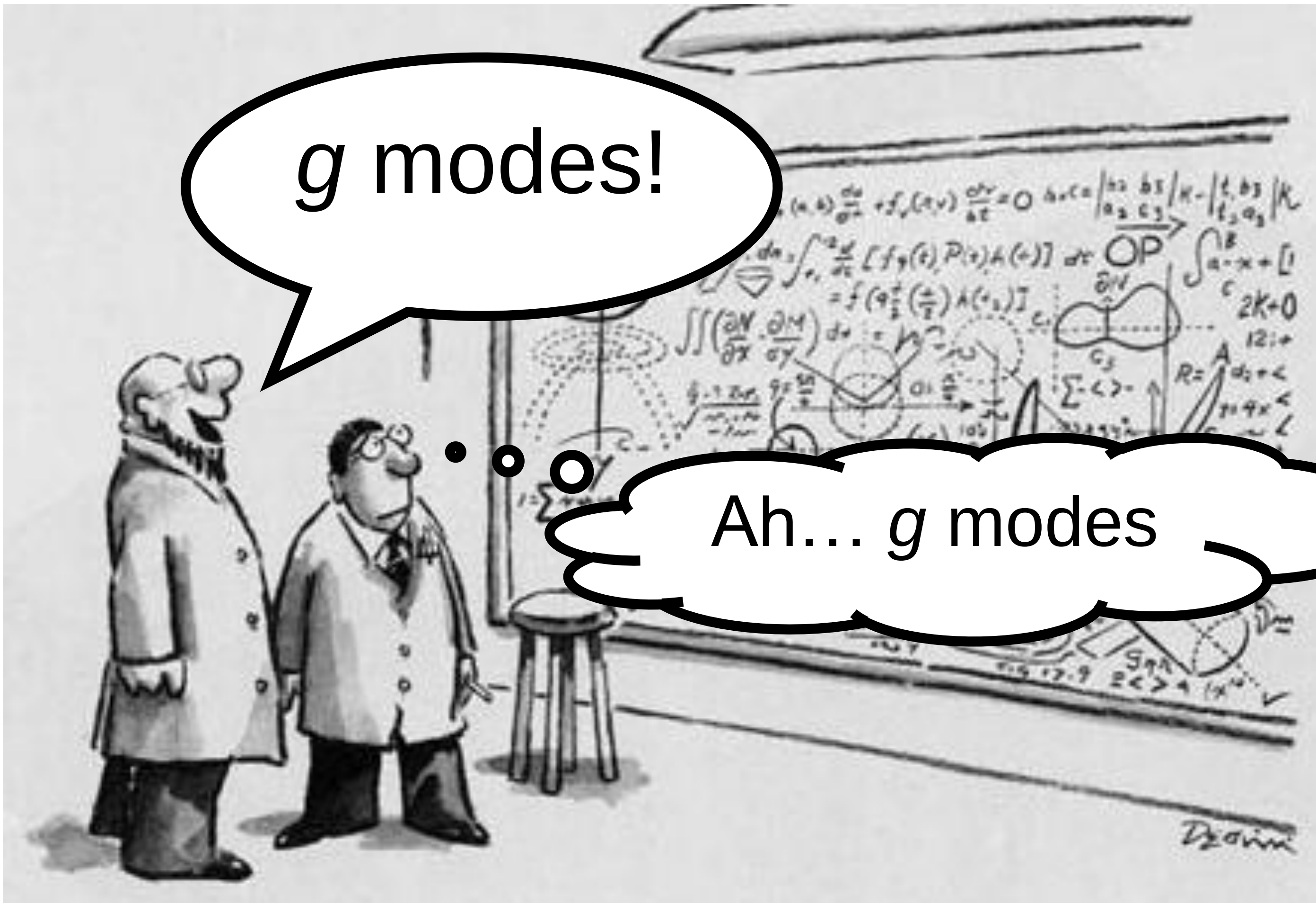
The observer's Holy Grail



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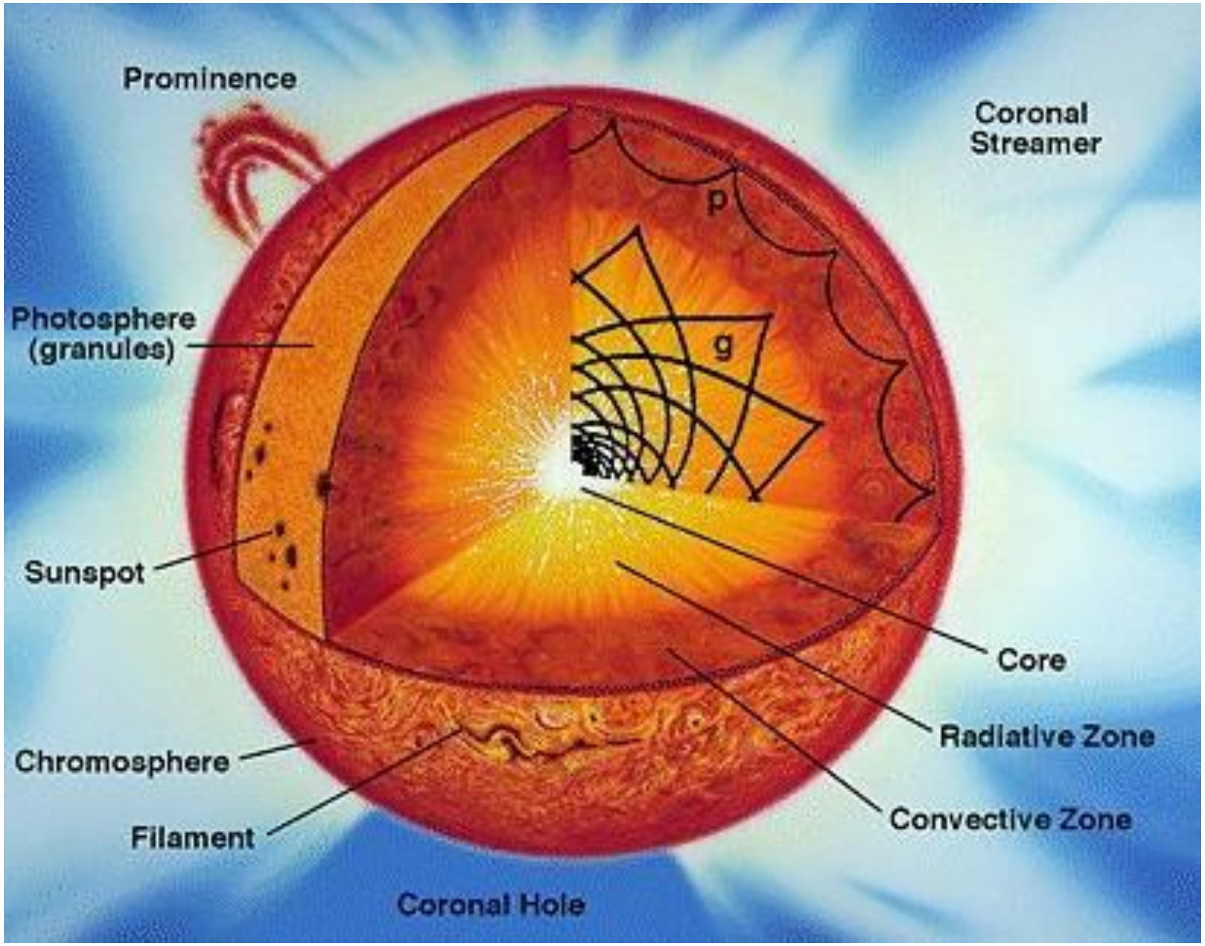
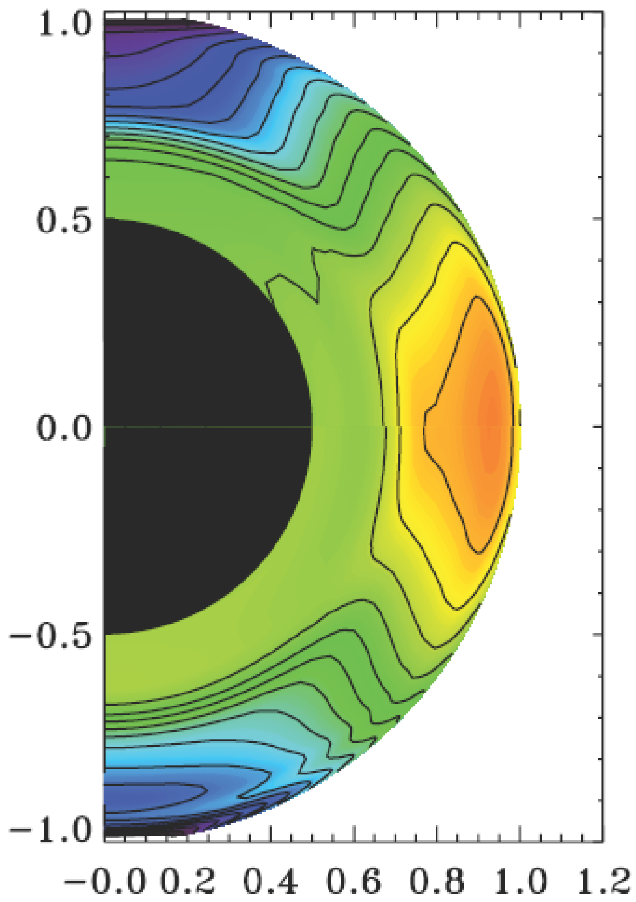
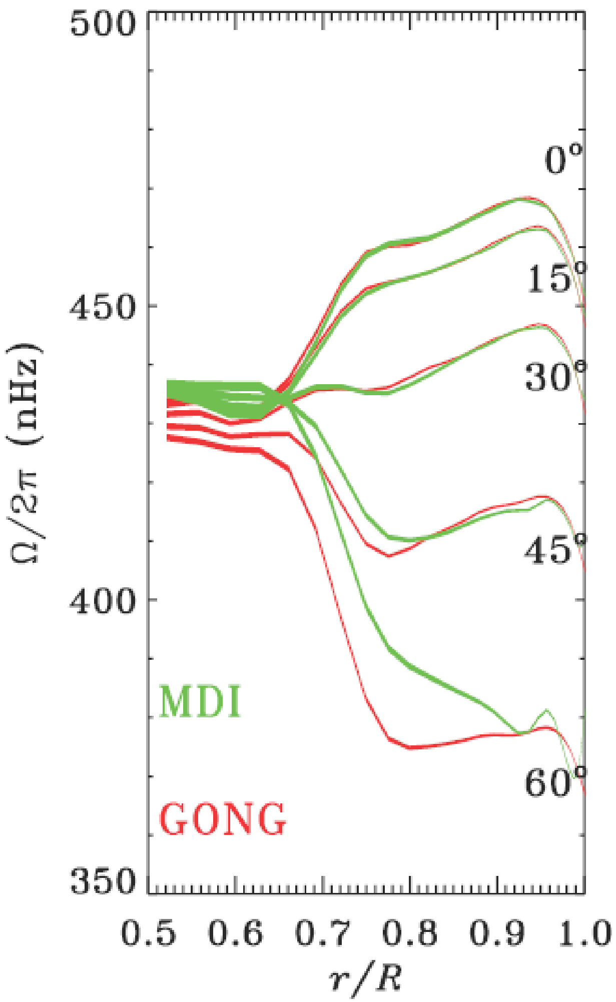
The Resonant Sun



Time-averaged internal rotation profile





GONG data; courtesy R. Howe

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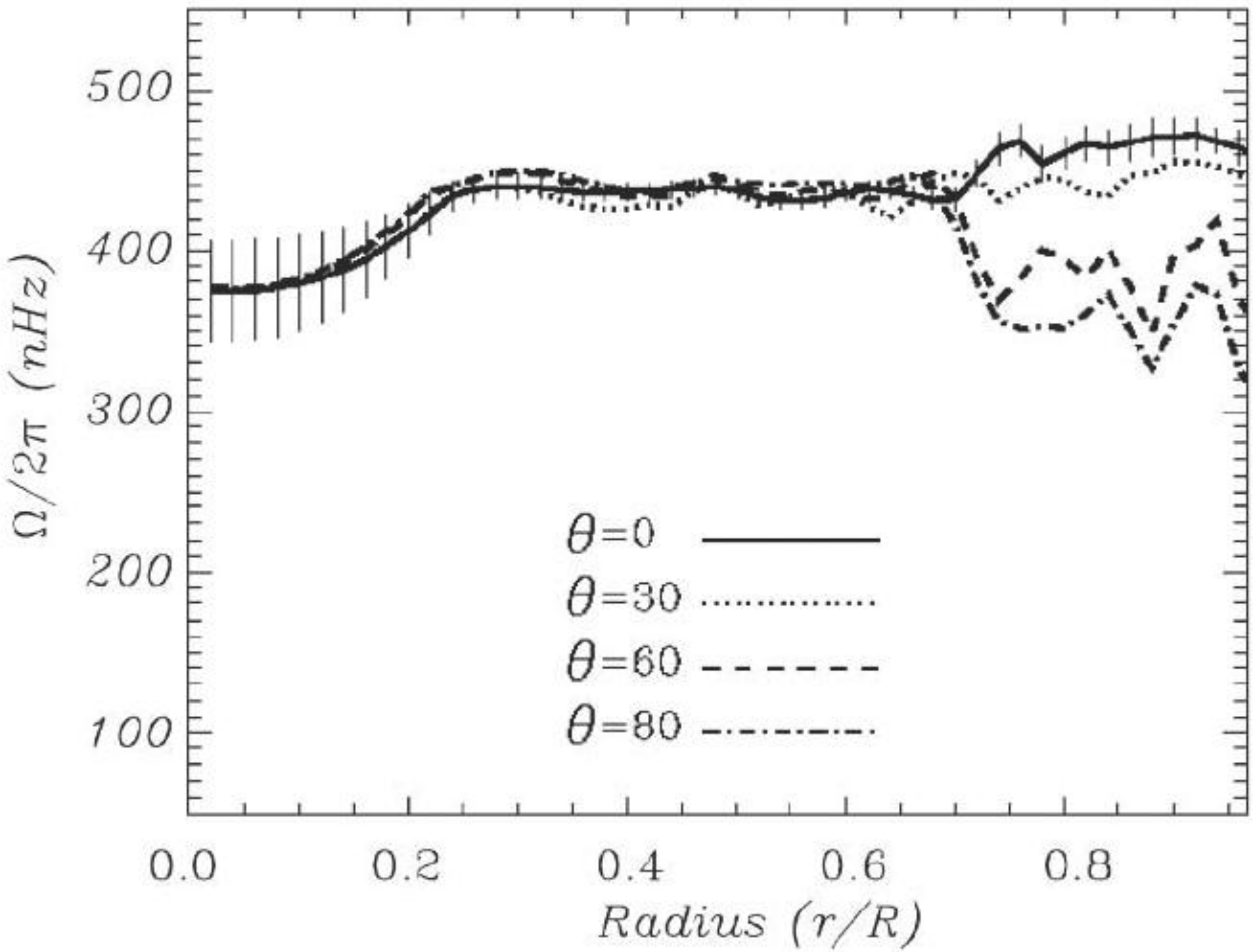
Rotation of the deep solar interior



Eff-Darwich et al. 2008, ApJ, **679**, 1636

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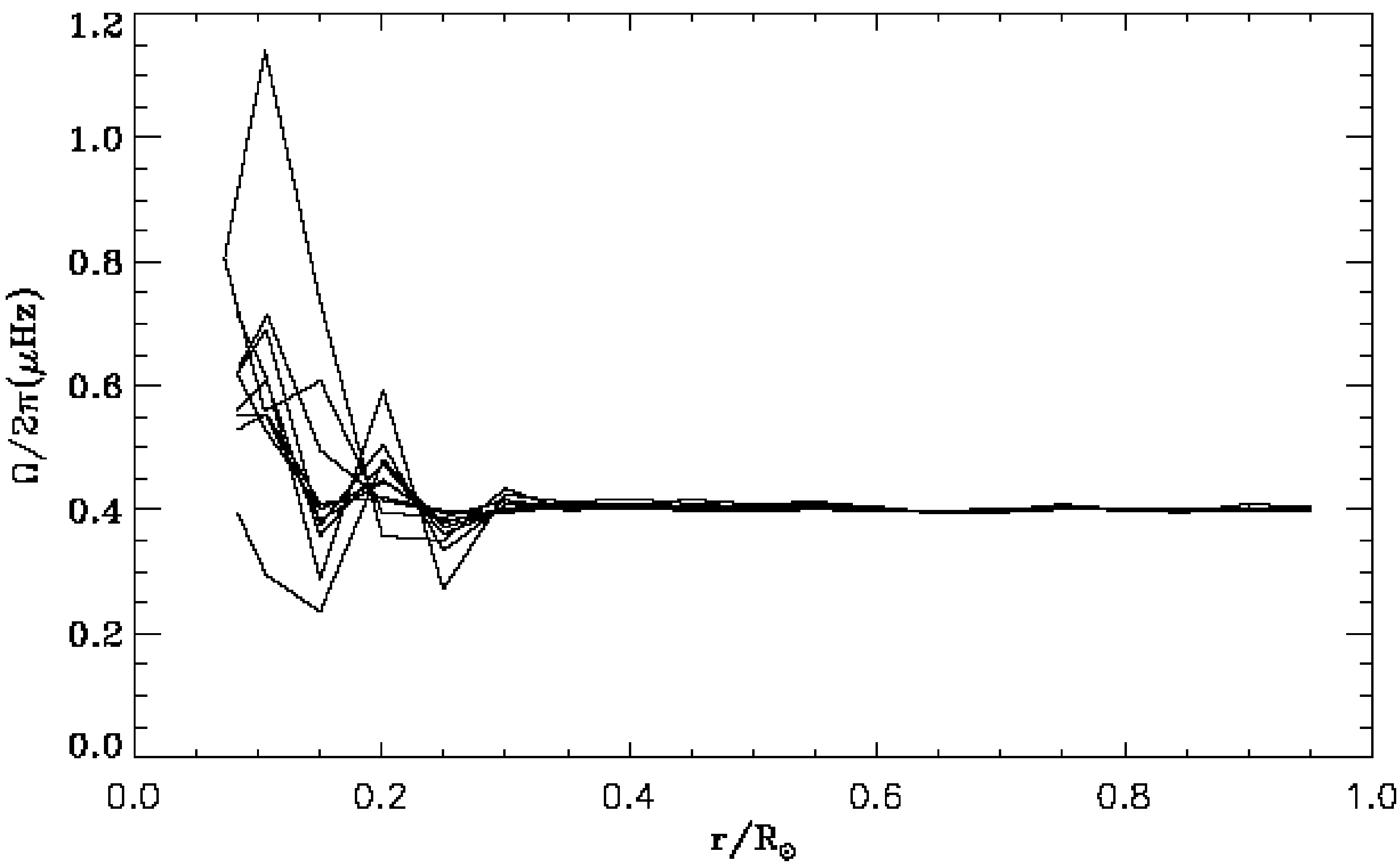
SolarFLAG hare-and-hounds exercise
Inversion of artificial frequency splittings



Chaplin et al. 2006, ESA-SP **624**, p. 82

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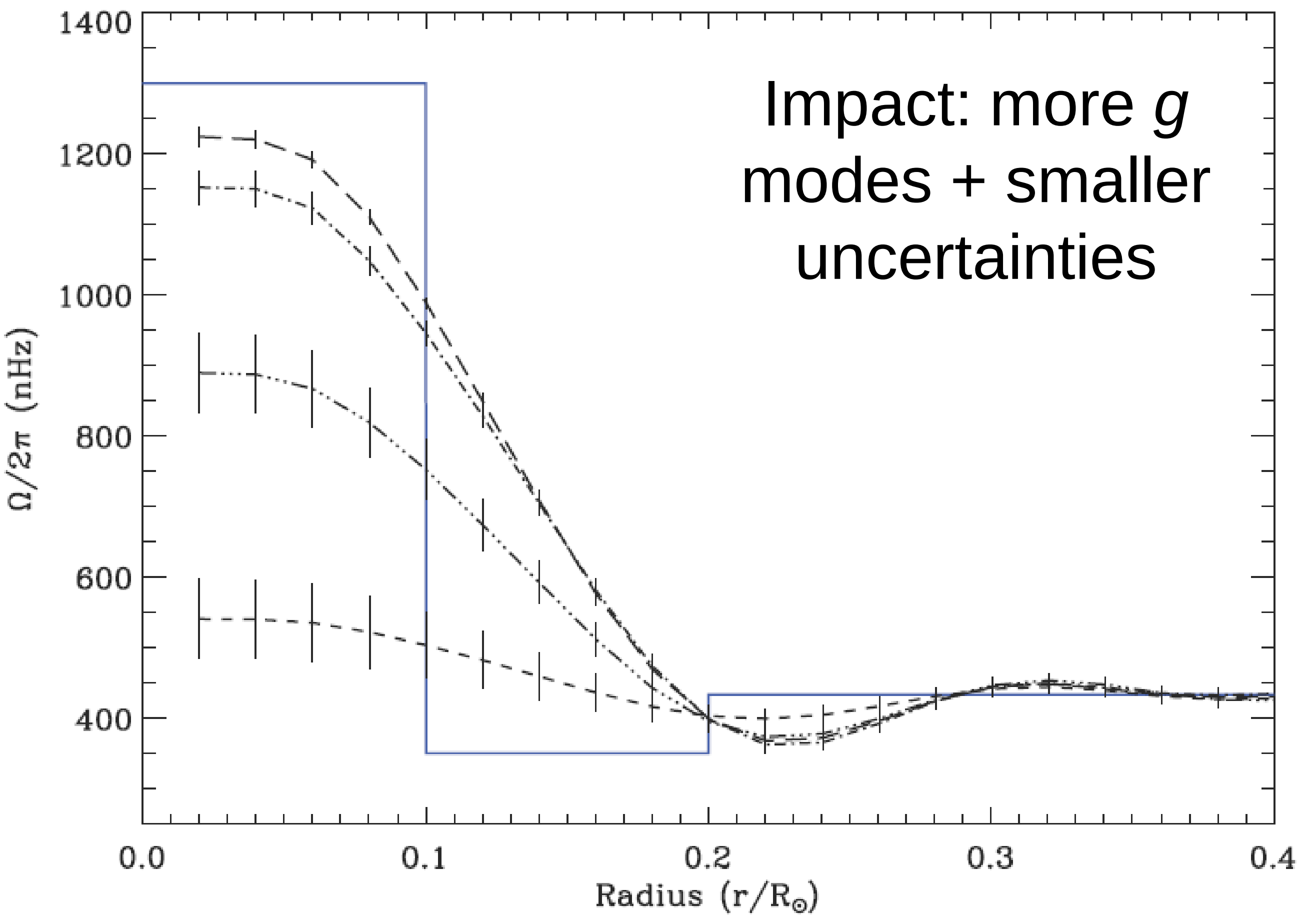
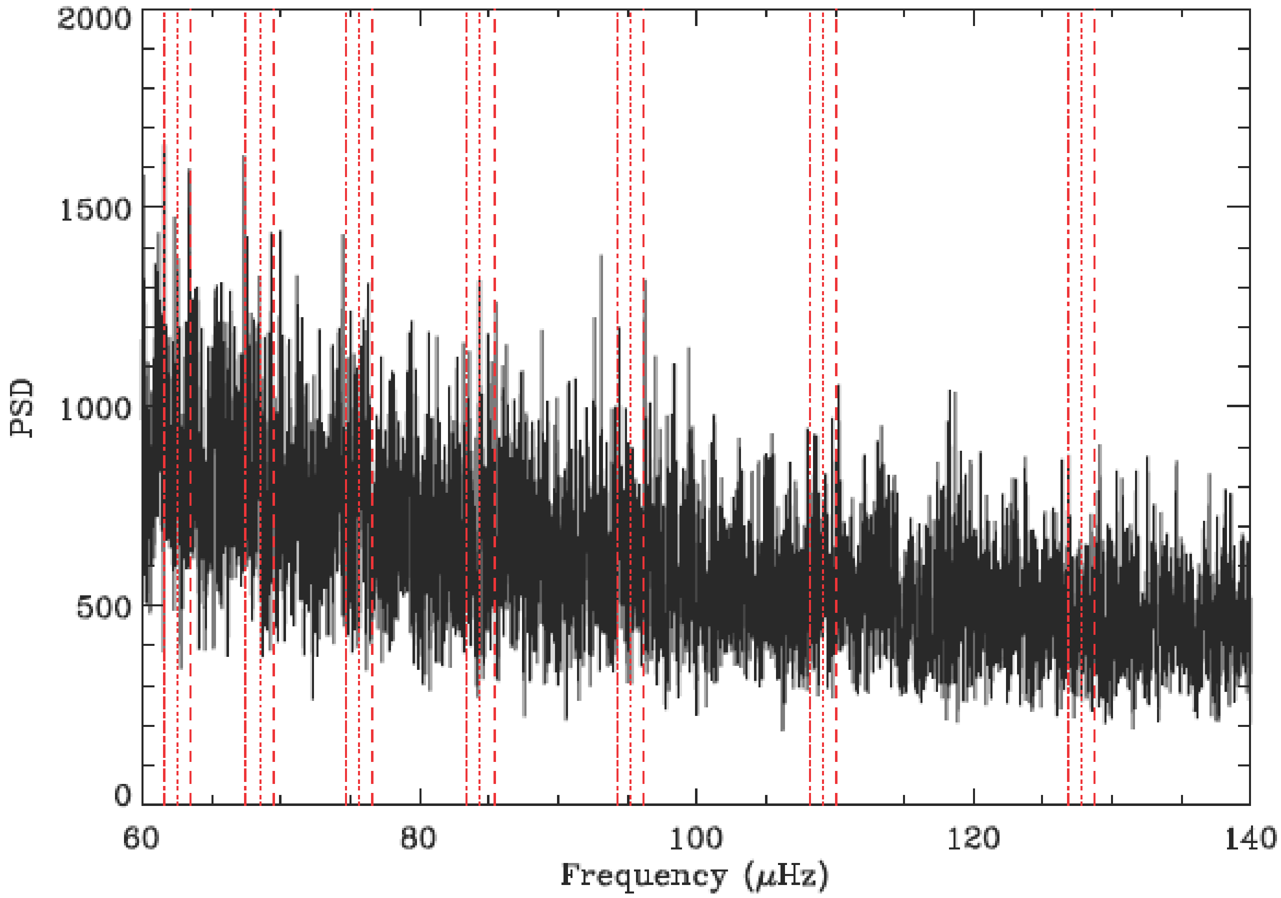
Impact of *g* modes on core inference: tests with artificial data



Mathur et al. 2008, A&A, **484**, 517

Needles in Haystacks

Is a spike noise or a mode?



Garcia et al. 2010, AN, in the press

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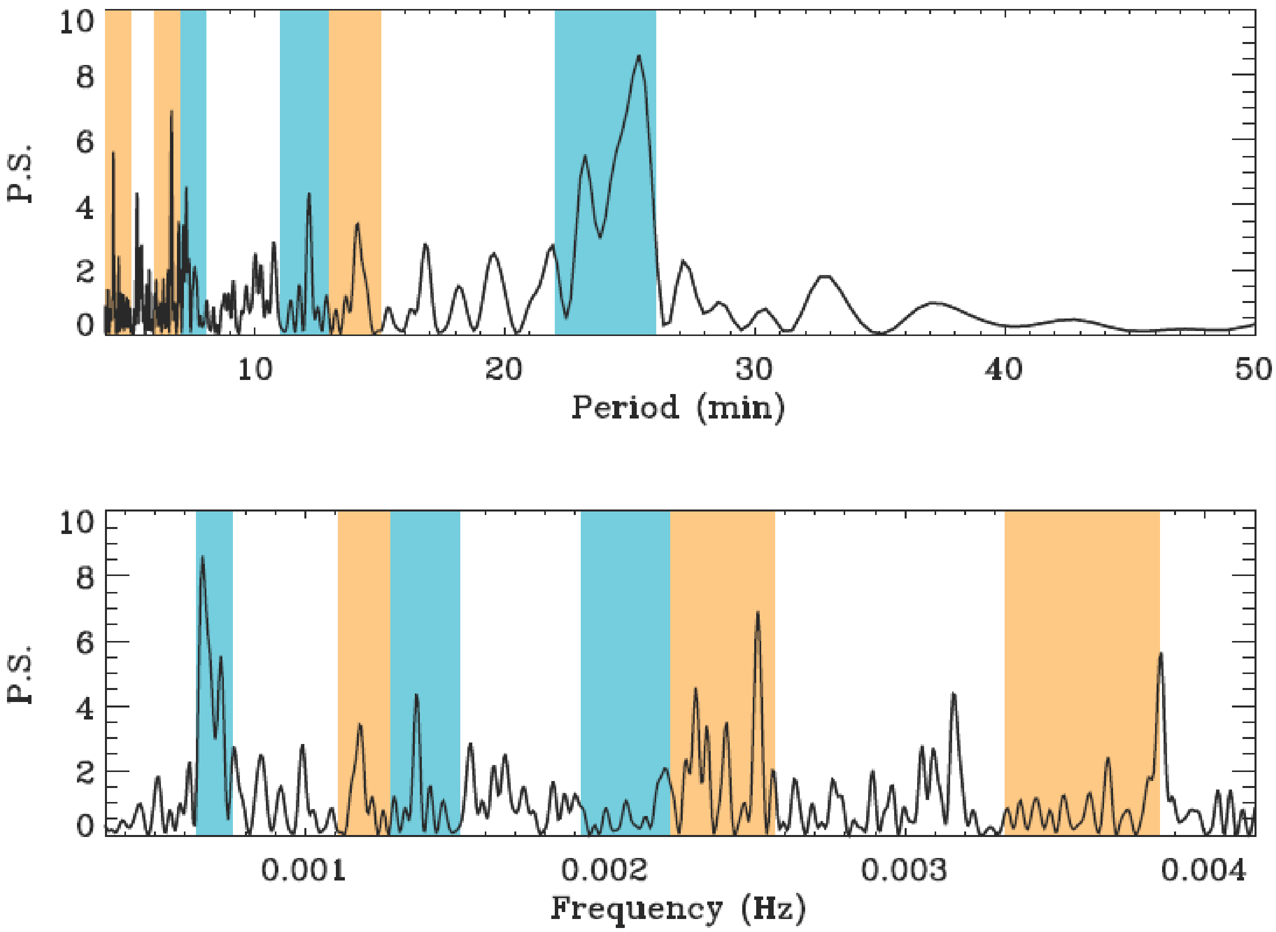
Detection of ensemble signature of *g* modes?



See: Garcia et al. 2007, Science, **316**, 1591

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Needles in Haystacks
Is a spike noise or a mode?

- Noise properties of data are key
- Statistical inference:
  – Frequentist (“false alarm”)
  – Bayesian (“odds ratios”)
- Tests for presence of individual modes inconclusive (e.g., Broomhall et al., 2010)
- Cf. theoretical predictions of amplitudes (e.g., Appourchaux et al. 2010)