Surface effects in solar-like oscillators

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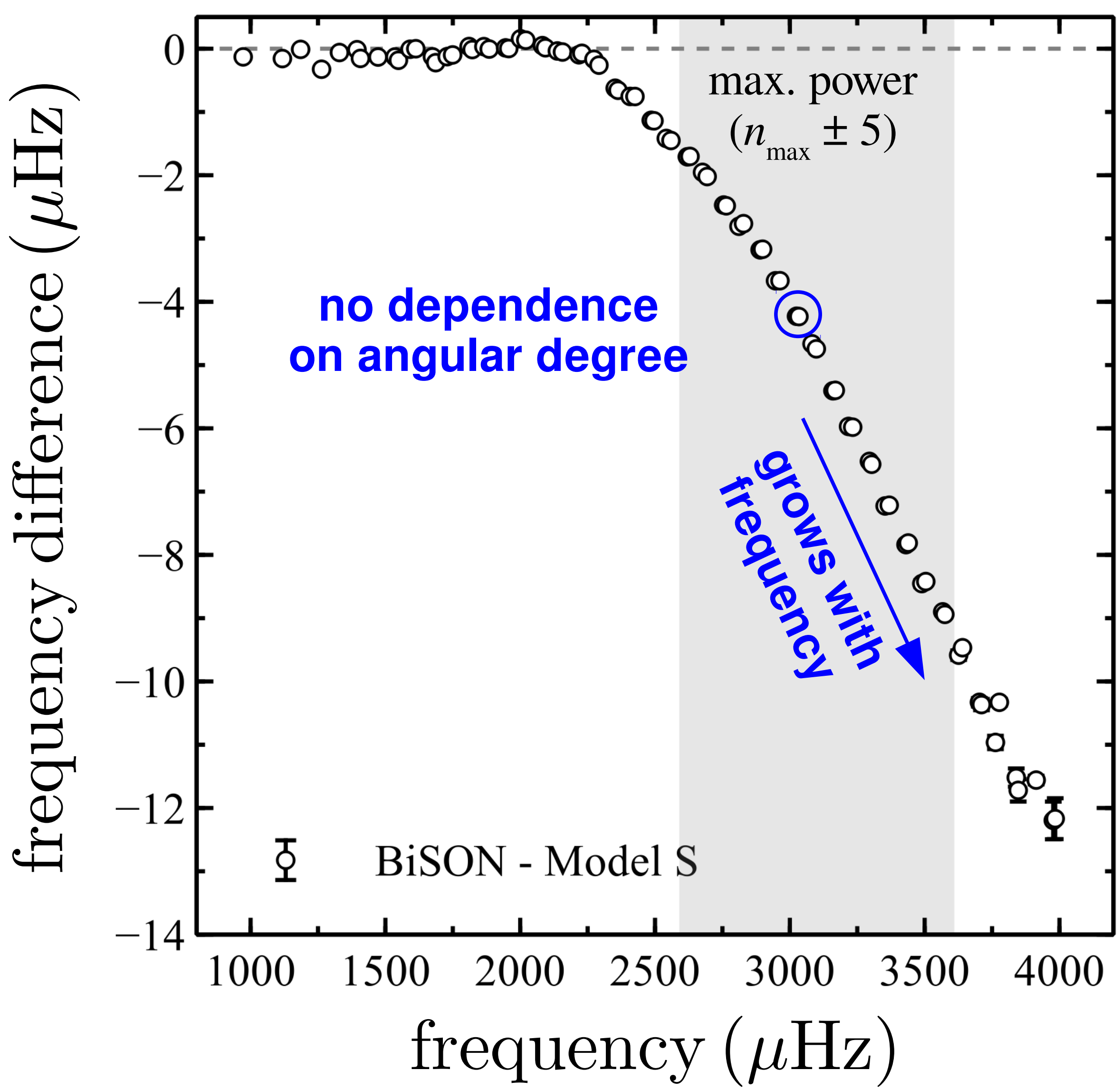
Seismology of the Sun and Distant Stars 2016
12th July 2016

INSTITUT FÜR ASTROPHYSIK GÖTTINGEN

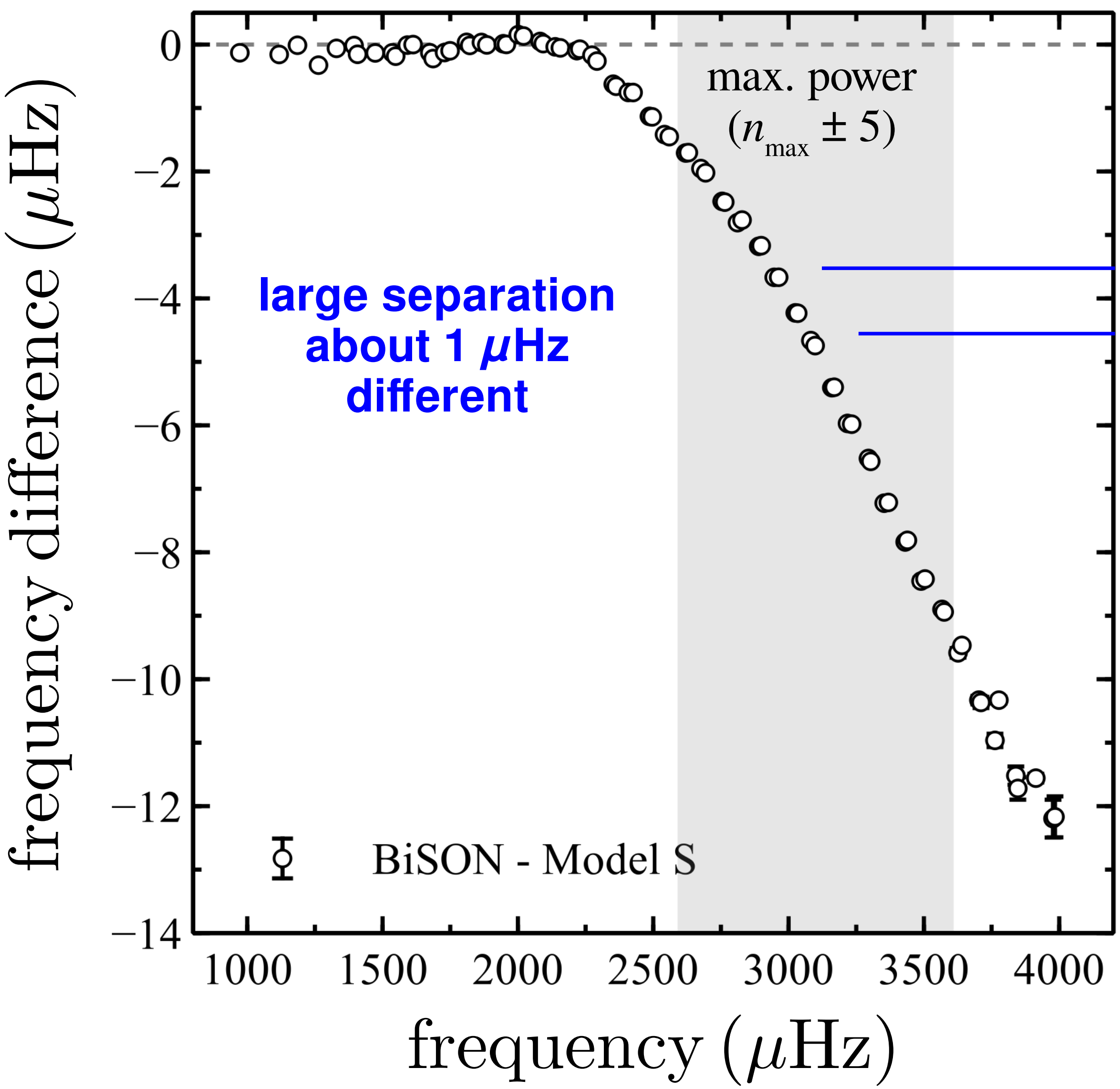
MPS

The problem

What is the surface effect?



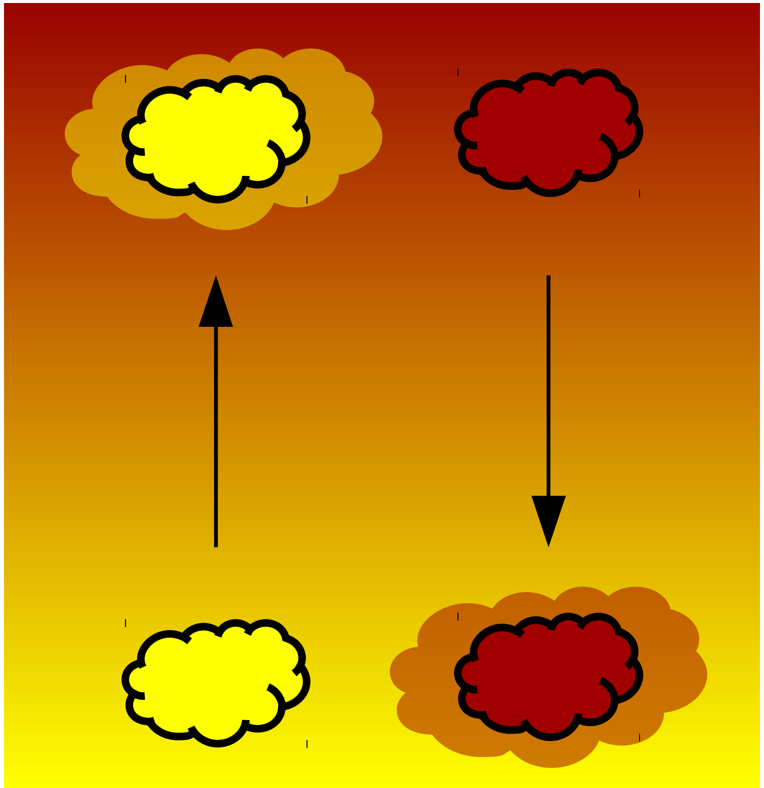
Why is it a problem?



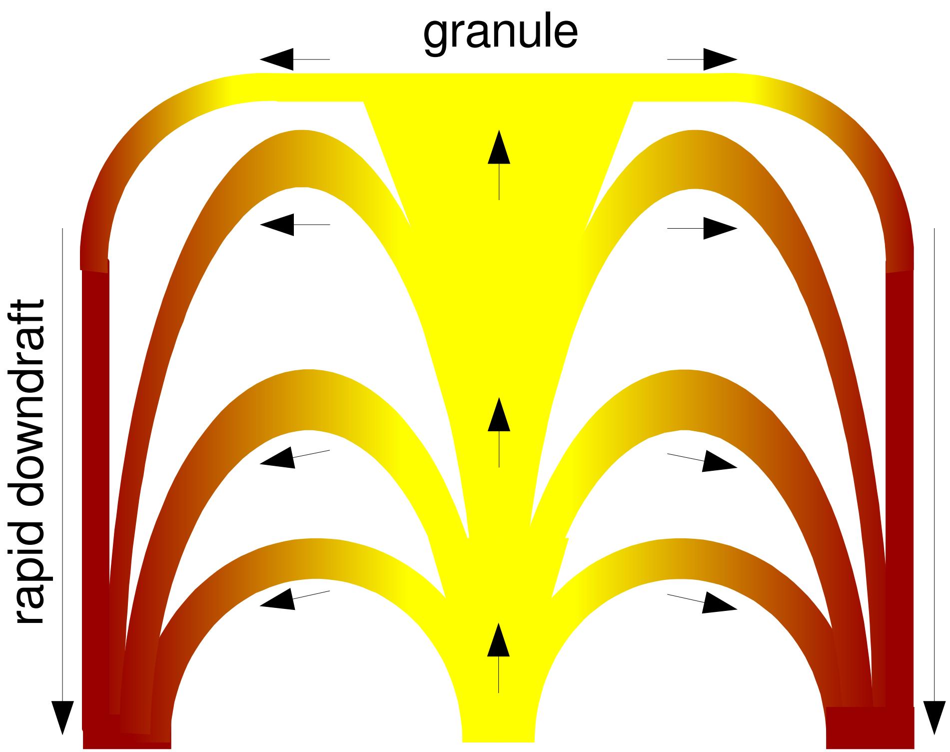
What causes it?

basically, poor modelling of near-surface convection
see Rosenthal (1997)

mixing length theory
(c.f. Böhm-Vitense 1958)



3D RHD simulations
(e.g. review by Nordlund et al. 2009)



What causes it?

Rosenthal (1997)

- “**model**” physics:

  (everything missing from background model)

  - MLT gives inaccurate temperature gradient
  - no turbulent pressure
  - atmospheric structure
  - etc...

- “**modal**” physics:

  (everything missing from oscillation calculation)

  - perturbation to turbulent pressure (Rosenthal et al. 1999)
  - flows modify wave speeds (Brown 1984)
  - non-adiabaticity (Houdek 1996)
  - etc...

Parametrizations

THE ASTROPHYSICAL JOURNAL, 683: L175–L178, 2008 August 20

CORRECTING STELLAR OSCILLATION FREQUENCIES FOR NEAR-SURFACE EFFECTS

HANS KJELDSEN,[1] TIMOTHY R. BEDDING,[2] AND JØRGEN CHRISTENSEN-DALSGAARD[1]
Received 2008 February 4; accepted 2008 July 9; published 2008 July 28

solar-calibrated power law

$$\nu_{\rm obs}(n) - r\nu_{\rm mdl}(n) = a\left[\frac{\nu_{\rm obs}(n)}{\nu_0}\right]^b$$

$$r = (b-1)\left[b\frac{\nu_{\rm mdl}}{\nu_{\rm obs}} - \frac{\Delta\nu_{\rm mdl}}{\Delta\nu_{\rm obs}}\right]^{-1} \approx \left(\frac{\bar{\rho}_{\rm mdl}}{\bar{\rho}_{\rm obs}}\right)^2$$

A&A 568, A123 (2014)
DOI: 10.1051/0004-6361/201424325

Astronomy & Astrophysics

A new correction of stellar oscillation frequencies for near-surface effects

W. H. Ball[1] and L. Gizon[2,1]

from asymptotic behaviour of eigenfunctions near surface
+ sound speed or H_p perturbation

"cubic" term:

$$\nu_{\rm obs} - \nu_{\rm mdl} = a_3 \nu^3 / \mathcal{I}$$

"combined" term:

$$\nu_{\rm obs} - \nu_{\rm mdl} = (a_{-1} \nu^{-1} + a_3 \nu^3) / \mathcal{I}$$

c.f. Gough (1990)

cubic term also in Libbrecht & Woodard (1990) and Goldreich et al. (1991)

A&A 583, A112 (2015)
DOI: 10.1051/0004-6361/201526838

Astronomy & Astrophysics

Surface-effect corrections for solar-like oscillations using 3D hydrodynamical simulations

I. Adiabatic oscillations

T. Sonoi[1], R. Samadi[1], K. Belkacem[1], H.-G. Ludwig[2,3], E. Caffau[3], and B. Mosser[1]

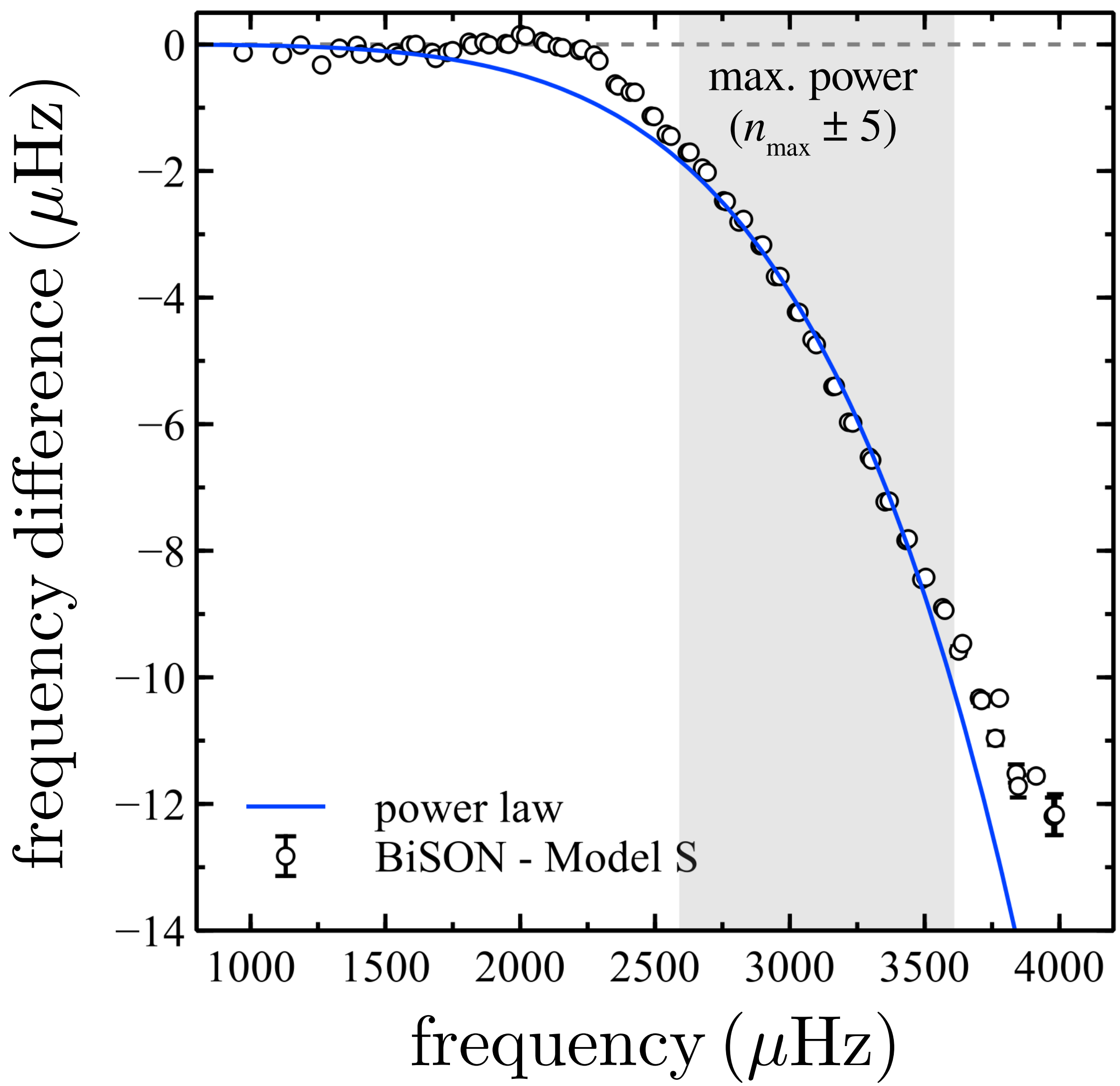
modified Lorentzian:

$$\nu_{\mathrm{obs}} - \nu_{\mathrm{mdl}} = \alpha \nu_{\mathrm{max}} \left[1 - \frac{1}{1 + (\nu_{\mathrm{mdl}}/\nu_{\mathrm{max}})^{\beta}} \right]$$

$$\nu_{\mathrm{max}} = \frac{g}{g_{\odot}} \left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}} \right)^{-\frac{1}{2}} \nu_{\mathrm{max},\odot}$$

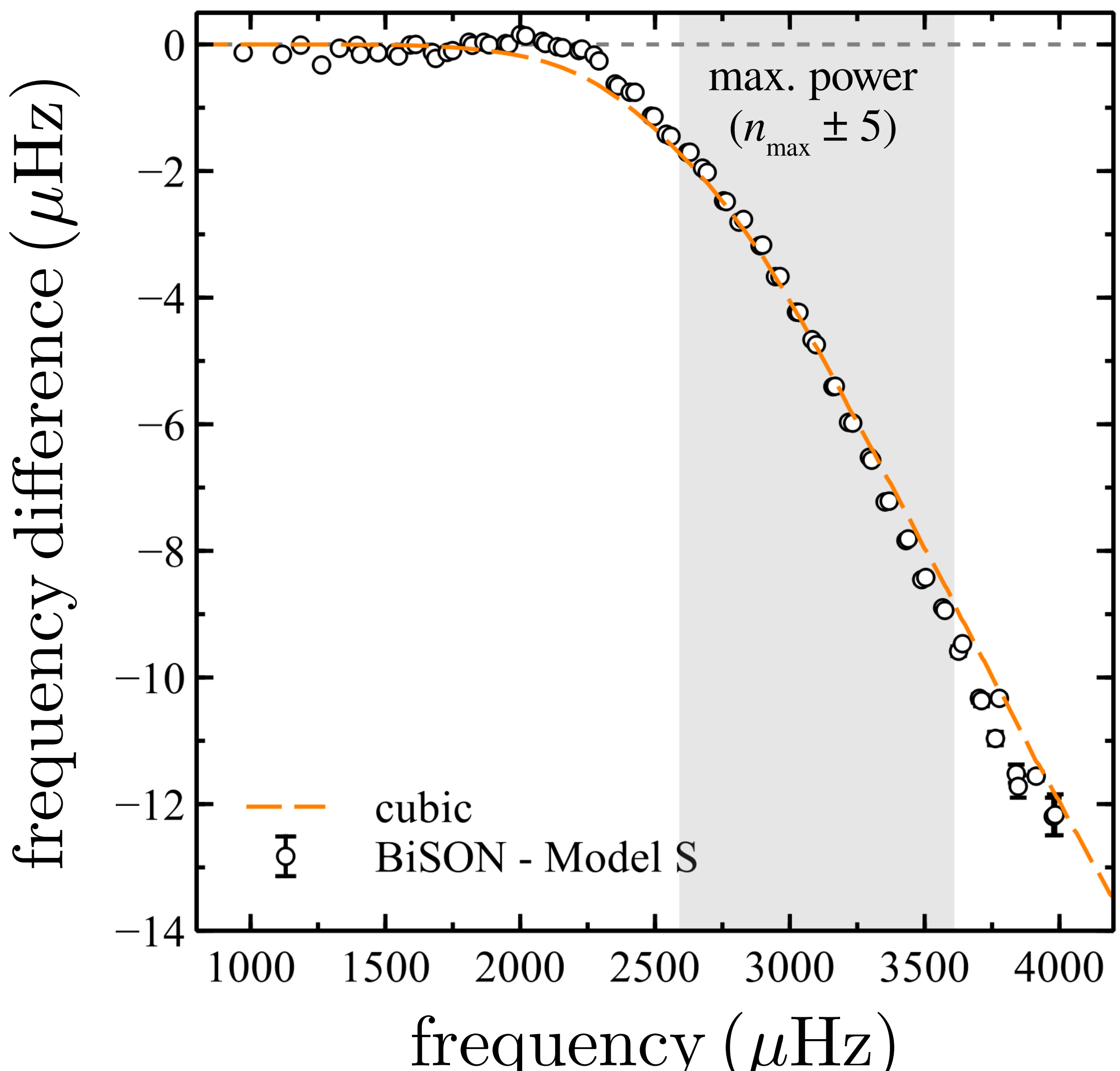
Power law correction

Kjeldsen et al. (2008)



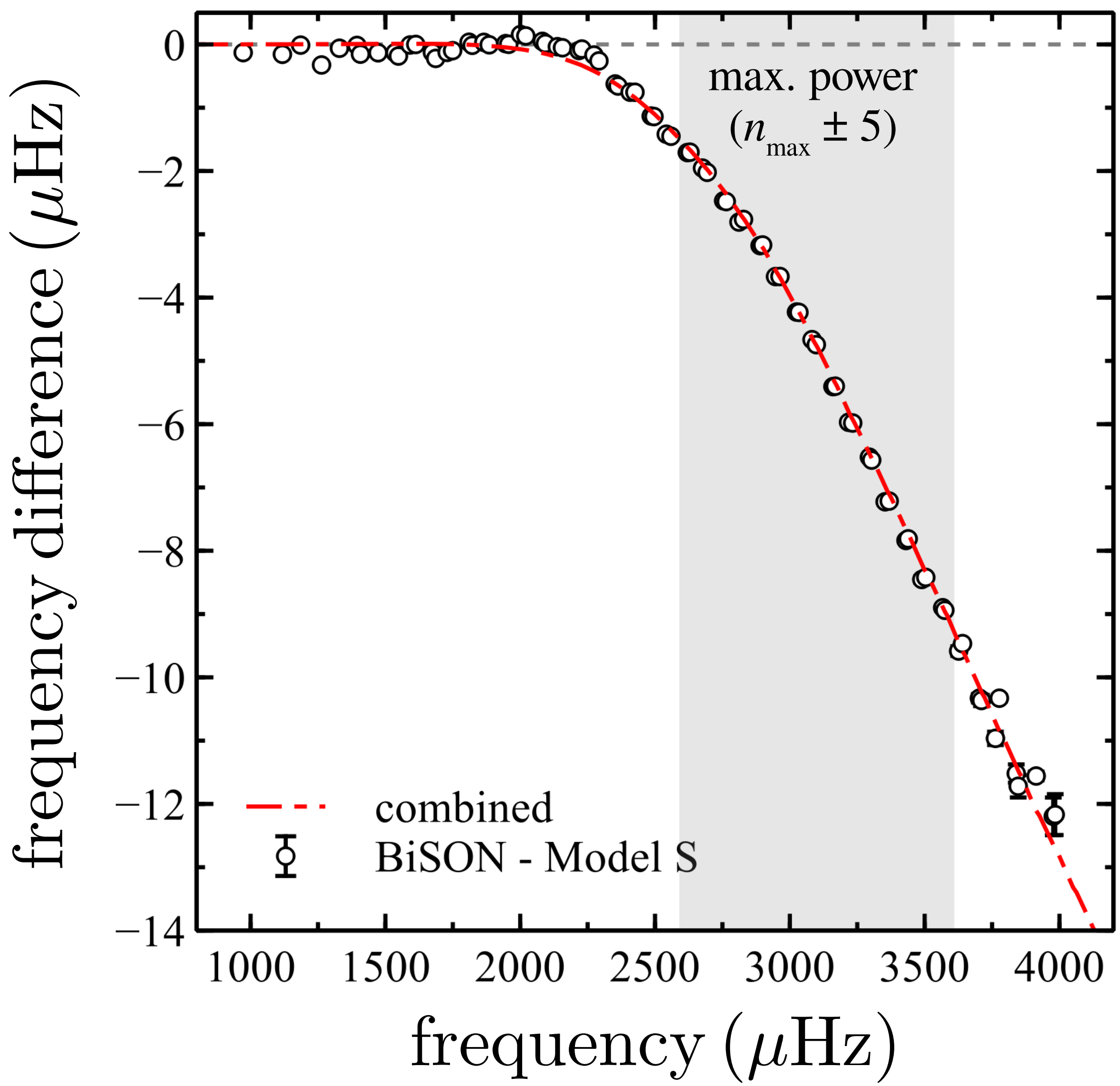
Cubic correction

Ball & Gizon (2014)



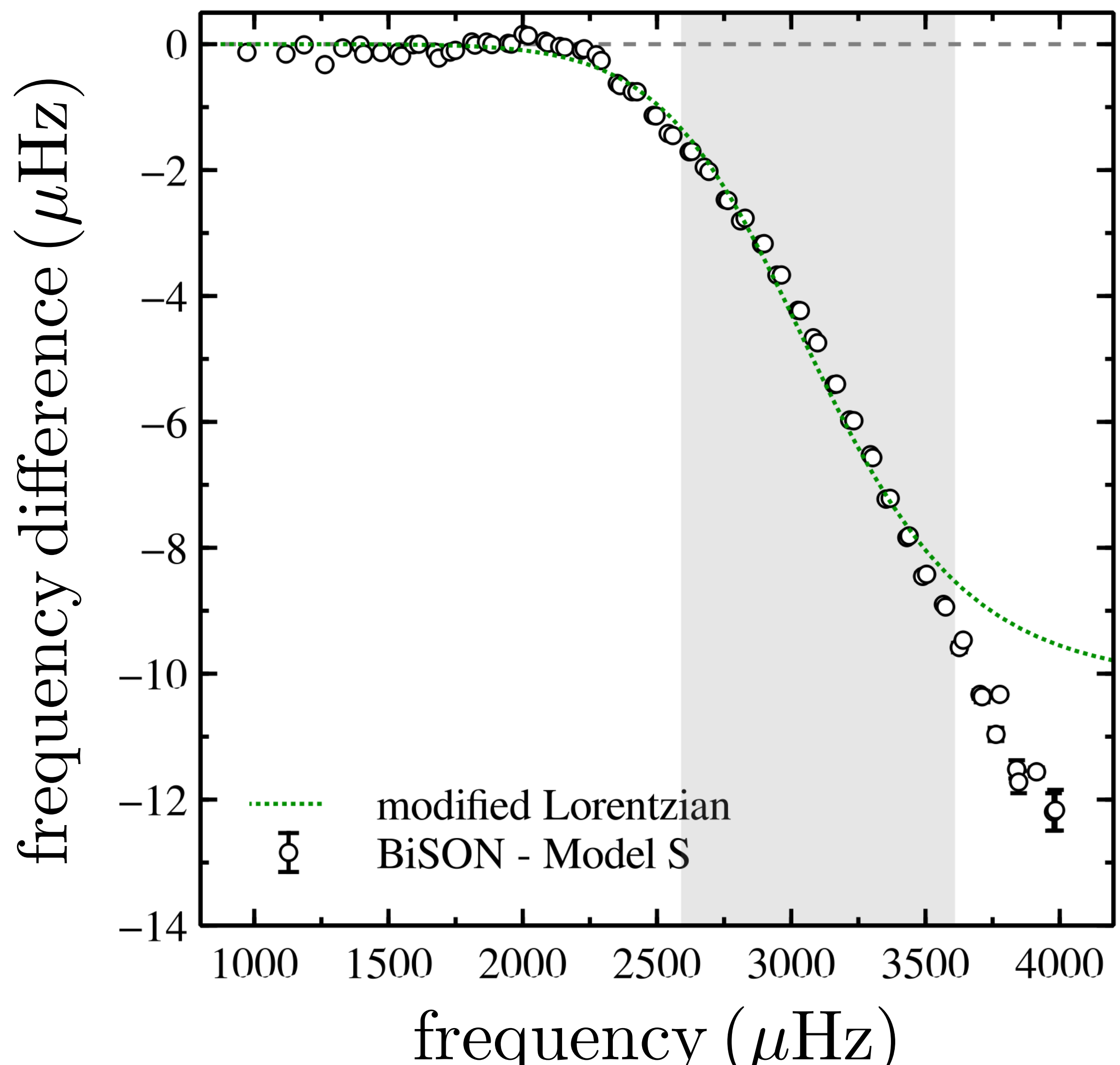
Combined correction

Ball & Gizon (2014)



Modified Lorentzian correction

Sonoi et al. (2015)



A&A 411, 215–220 (2003)
DOI: 10.1051/0004-6361:20031318

Astronomy & Astrophysics

The ratio of small to large separations of acoustic oscillations as a diagnostic of the interior of solar-like stars

I. W. Roxburgh[1,2] and S. V. Vorontsov[1,3]

$$r_{02}(n) = \frac{\nu_{n,0} - \nu_{n-1,2}}{\nu_{n,1} - \nu_{n-1,1}}$$

$$r_{13}(n) = \frac{\nu_{n,1} - \nu_{n-1,3}}{\nu_{n+1,0} - \nu_{n,0}}$$

$$r_{01}(n) = \frac{1}{8}\frac{\nu_{n-1,0} - 4\nu_{n-1,1} + 6\nu_{n,0} - 4\nu_{n,1} + \nu_{n+1,0}}{\nu_{n,1} - \nu_{n-1,1}}$$

$$r_{10}(n) = -\frac{1}{8}\frac{\nu_{n-1,1} - 4\nu_{n,0} + 6\nu_{n,1} - 4\nu_{n+1,0} + \nu_{n+1,1}}{\nu_{n+1,0} - \nu_{n,0}}$$

A&A 411, 215–220 (2003)
DOI: 10.1051/0004-6361:20031318

Astronomy & Astrophysics

The ratio of small to large separations of acoustic oscillations as a diagnostic of the interior of solar-like stars

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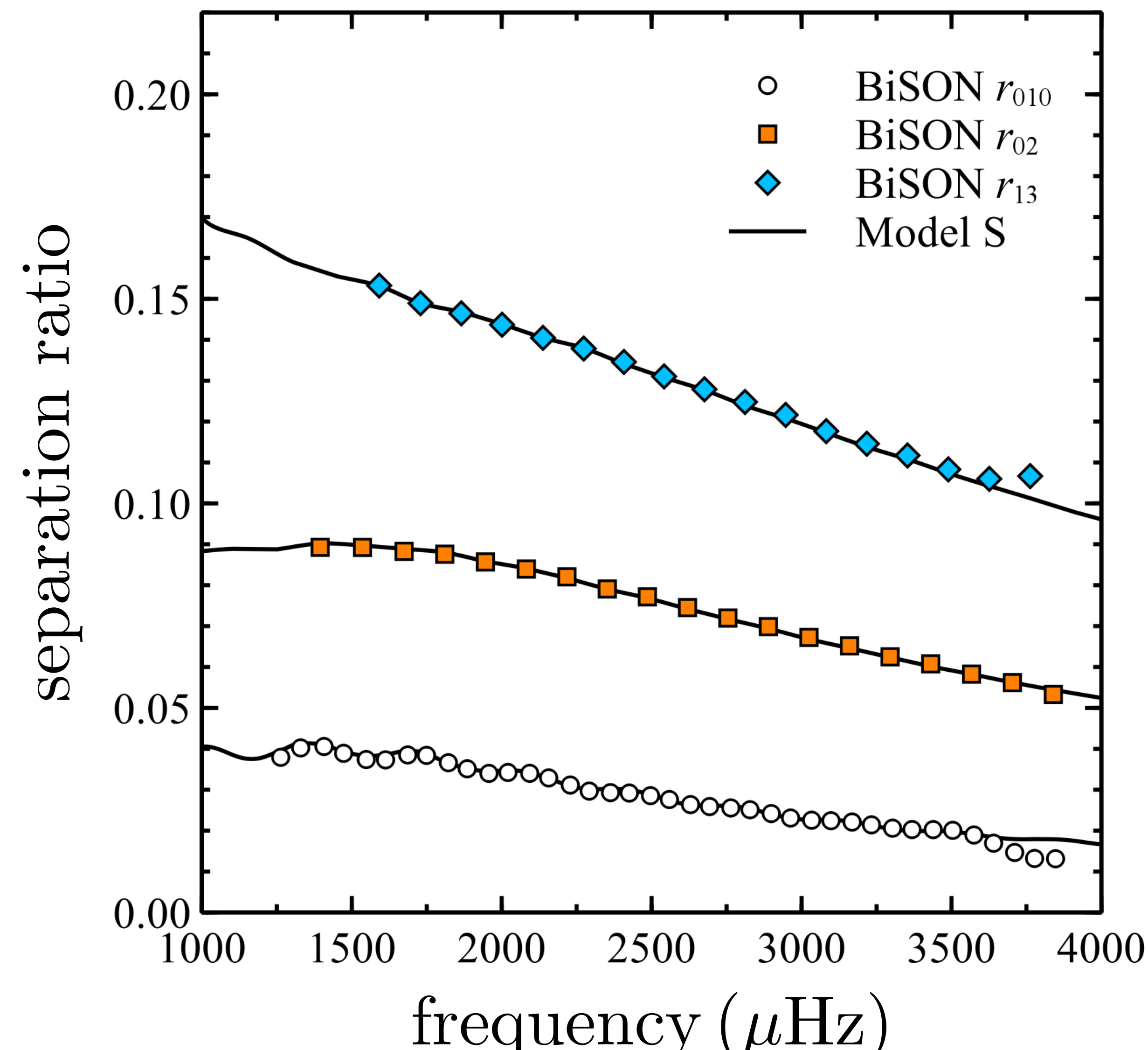
$$\left.\begin{array}{l} r_{02}(n) = \\[2em] r_{13}(n) = \end{array}\right\} \frac{\text{small separation}}{\text{large separation}}$$

$$\left.\begin{array}{l} r_{01}(n) = \\[2em] r_{10}(n) = \end{array}\right\} \frac{\text{five-point difference}}{\text{large separation}}$$

(also visit Roxburgh's poster comparing his various methods)

Separation ratios

Roxburgh & Vorontsov (2003)



State of the art

- Parametrizations
  - ratios widely used and presumably reliable
  - “combined” term appears the best formula
  - Sun is still the only real test

Schmitt & Basu (2015)

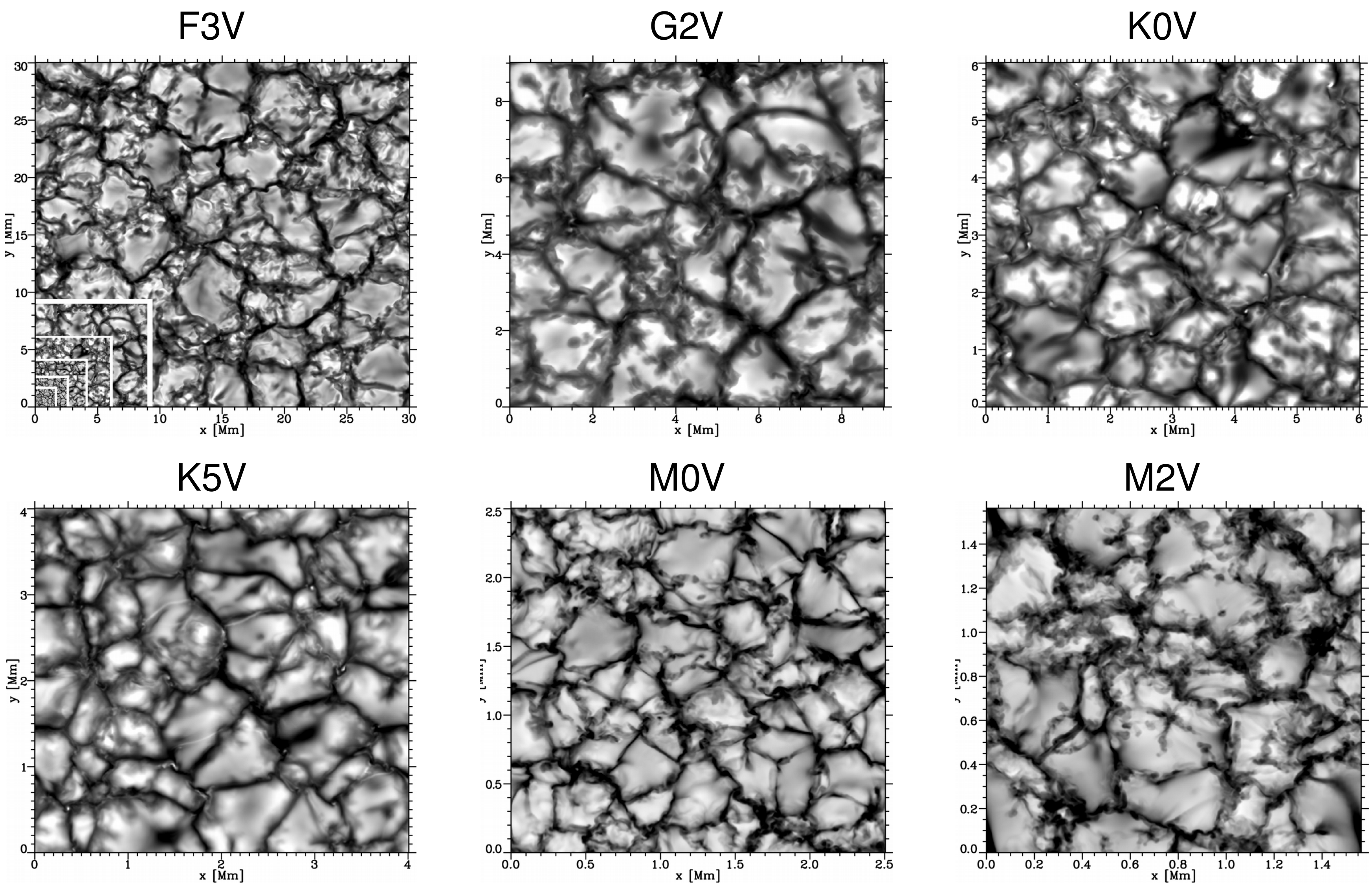
Three-dimensional radiation hydrodynamics

A&A 558, A48 (2013)
DOI: 10.1051/0004-6361/201321343

Astronomy & Astrophysics

Three-dimensional simulations of near-surface convection in main-sequence stars★

B. Beeck[1,2], R. H. Cameron[1], A. Reiners[2], and M. Schüssler[1]

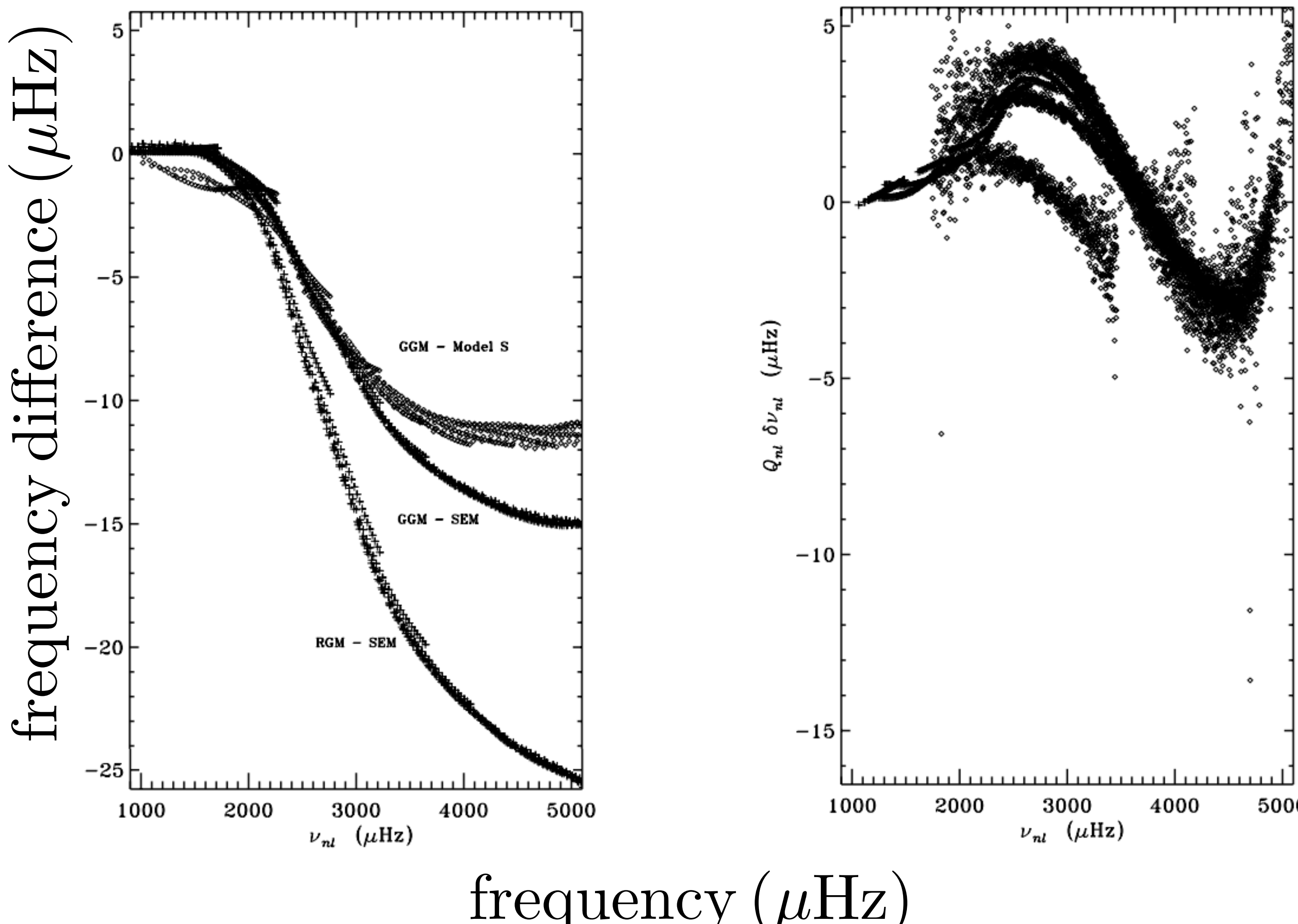


Astron. Astrophys. 351, 689–700 (1999)

ASTRONOMY AND ASTROPHYSICS

Convective contributions to the frequencies of solar oscillations

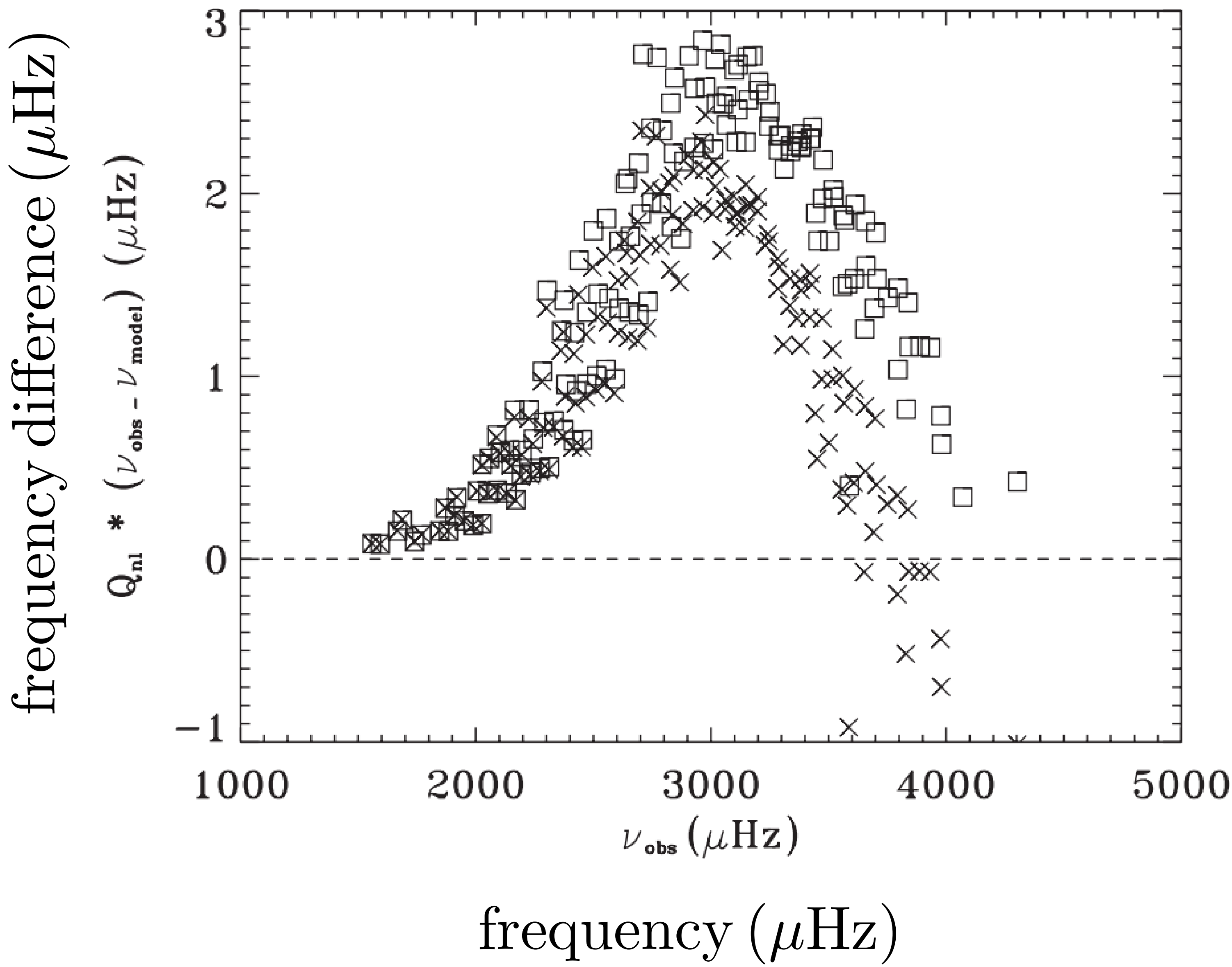
C.S. Rosenthal[1,⋆], J. Christensen-Dalsgaard[1,2], Å. Nordlund[3,4], R.F. Stein[5], and R. Trampedach[1,2]



MNRAS **437,** 164–175 (2014)
Advance Access publication 2013 October 28
doi:10.1093/mnras/stt1866

Models of solar surface dynamics: impact on eigenfrequencies and radius

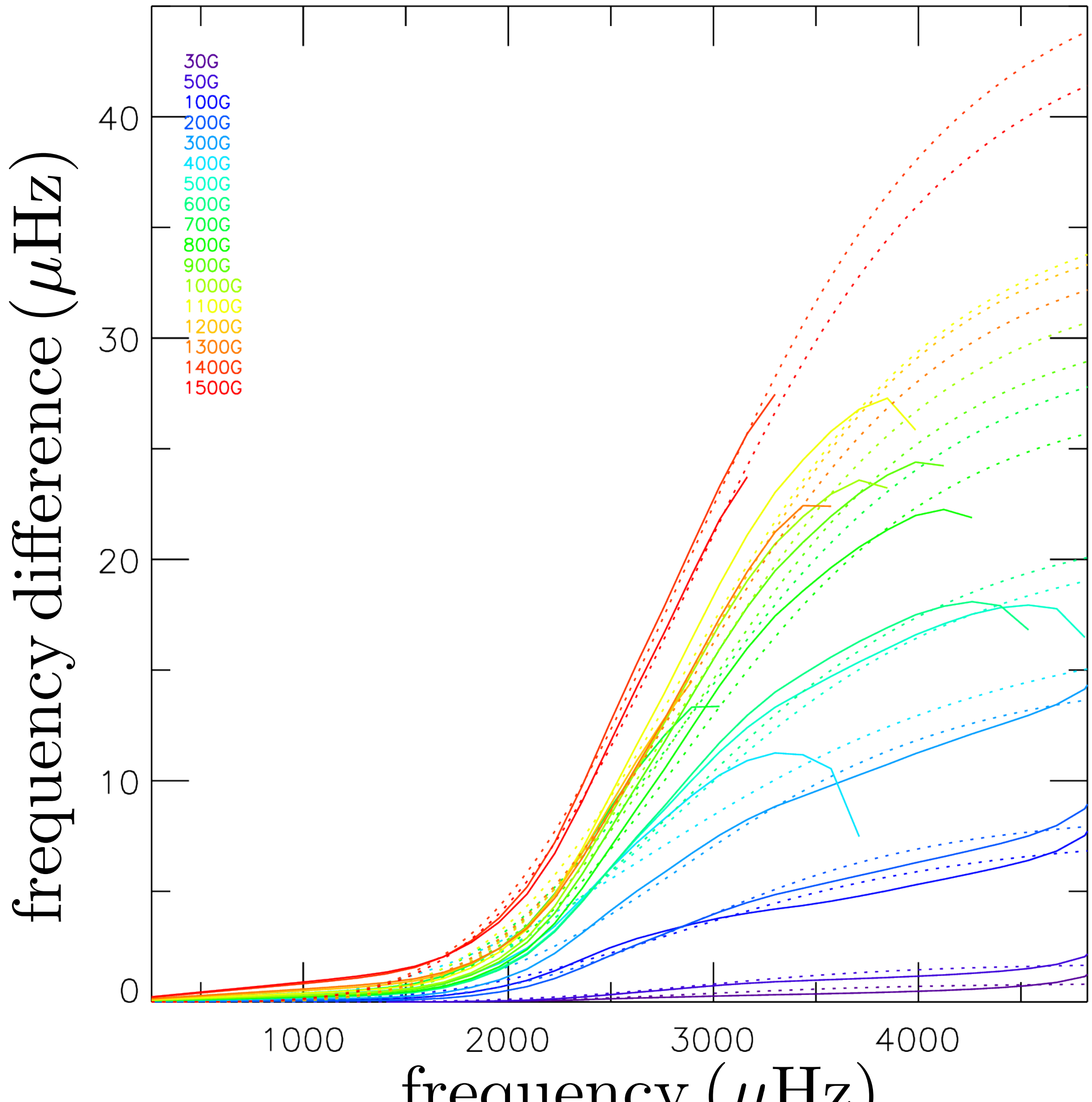
L. Piau,[1★] R. Collet,[2] R. F. Stein,[3] R. Trampedach,[4] P. Morel[5] and S. Turck-Chièze[6]



Surface-effect corrections for the solar model

Z. Magic[1,2] and A. Weiss[3]

(A&A accepted, arXiv:1606.01030)



A&A 583, A112 (2015)
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Astronomy & Astrophysics

Surface-effect corrections for solar-like oscillations using 3D hydrodynamical simulations

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CESTAM + CO^{5}BOLD

MESA meets MURaM

Surface effects in main-sequence solar-like oscillators computed using three-dimensional radiation hydrodynamics simulations

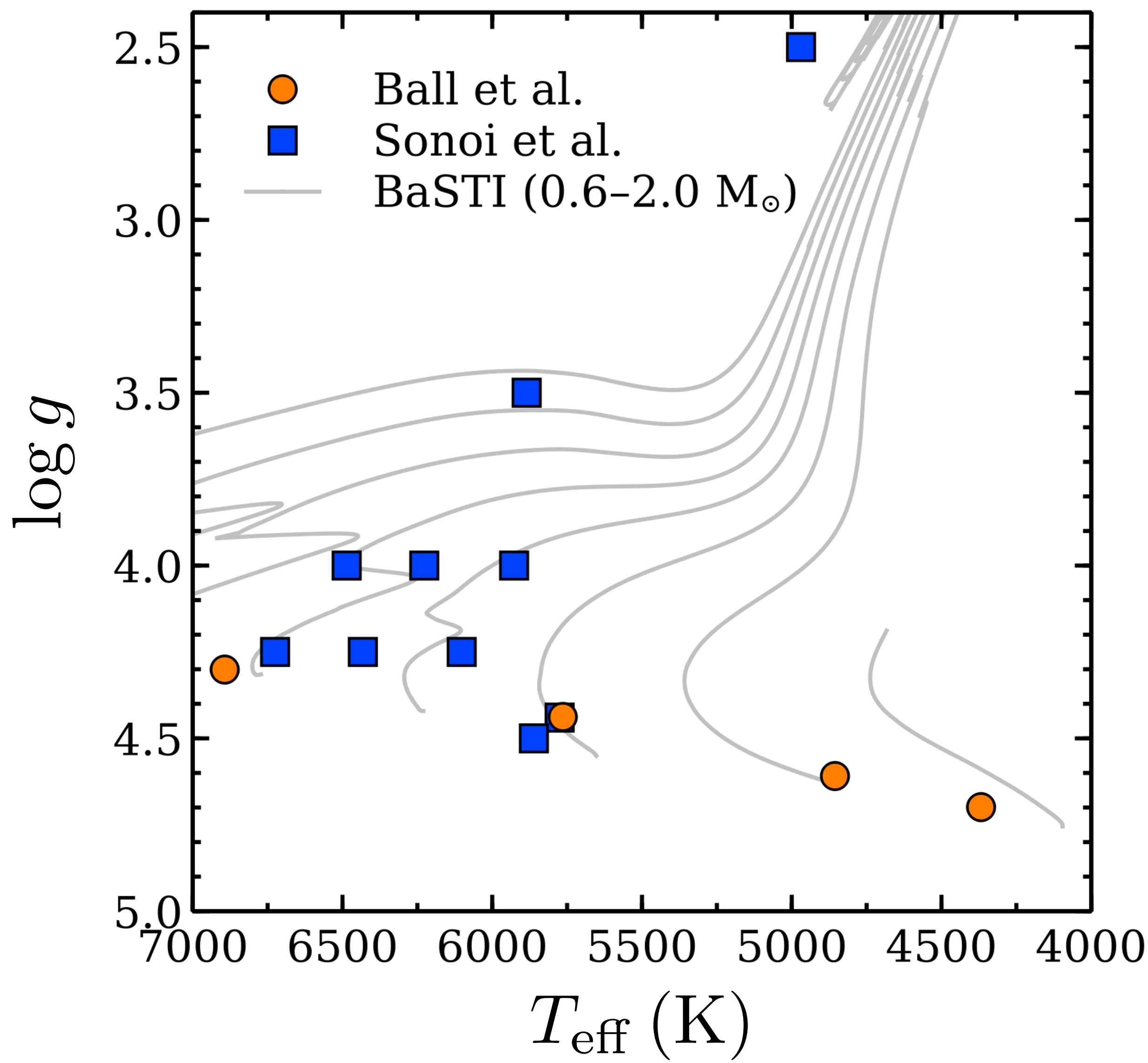
W. H. Ball[1,2], B. Beeck[2], R. H. Cameron[2], and L. Gizon[2,1]

(A&A accepted, arXiv:1606.02713)

MESA + MURaM

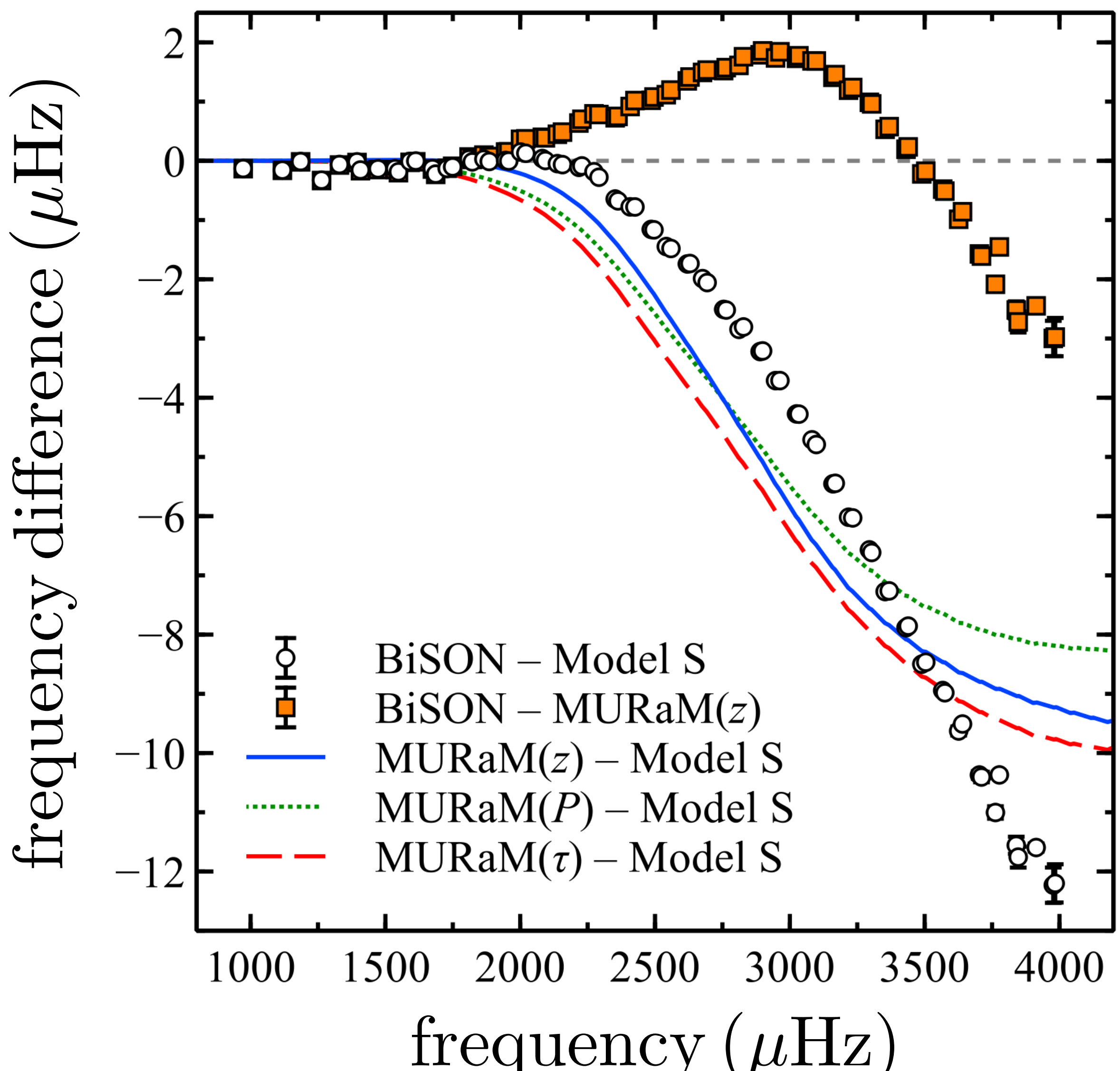
Simulation parameters

Sonoi et al. (2015), Ball et al. (2016)



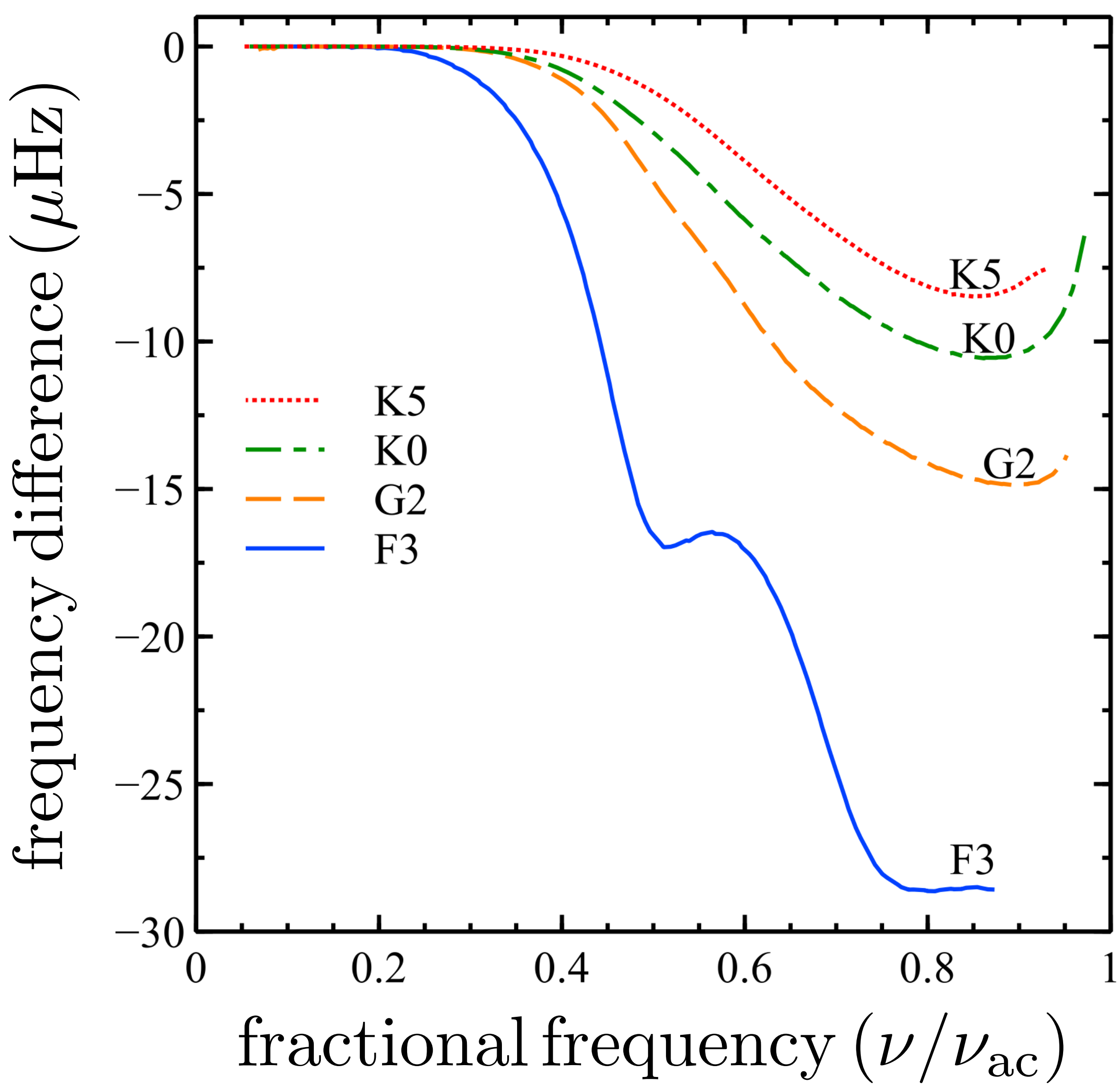
Solar-calibrated model (Model S)

Ball et al. (2016)



All four models

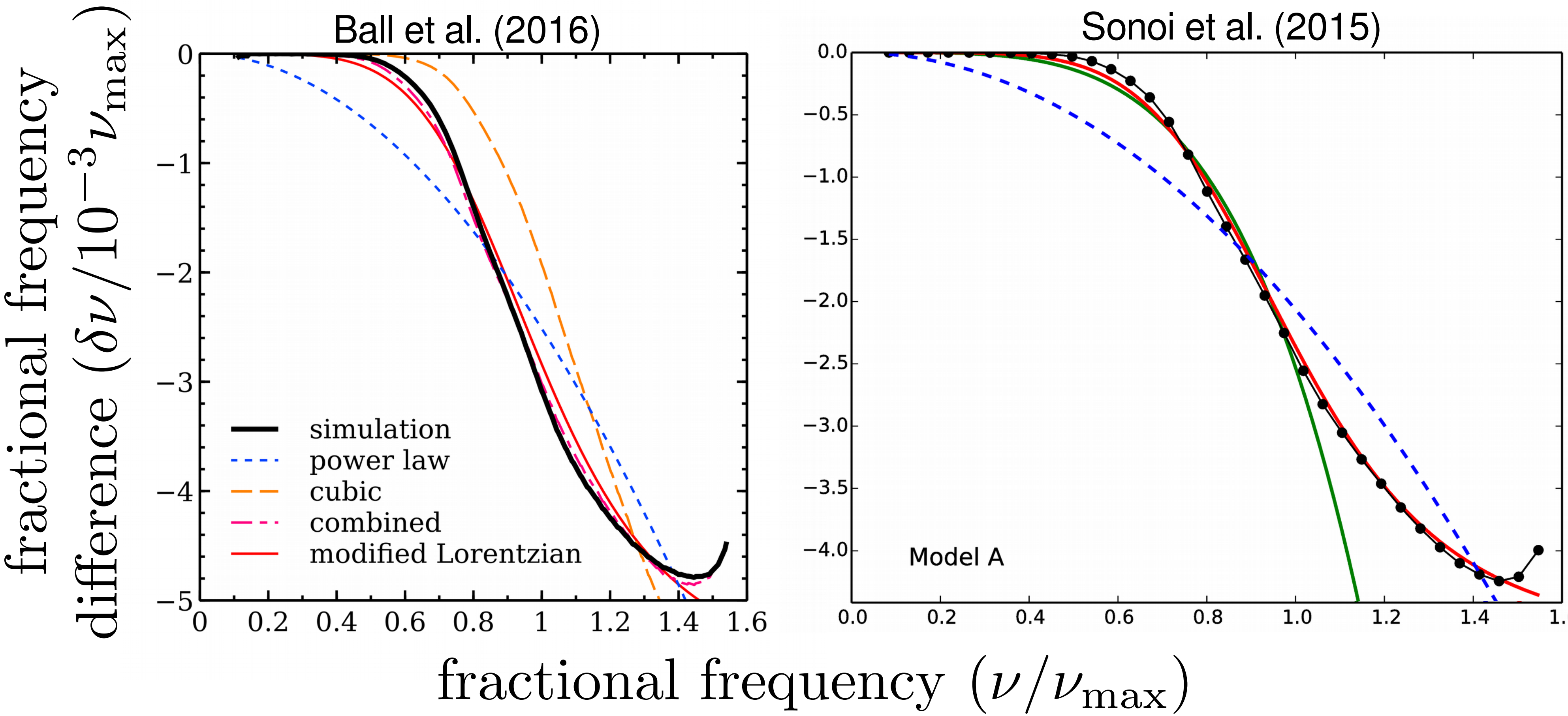
Ball et al. (2016)



G2 and Model A

$T_{\text{eff}} = 5764\,\mathrm{K}$ $\quad$ $T_{\text{eff}} = 5775\,\mathrm{K}$

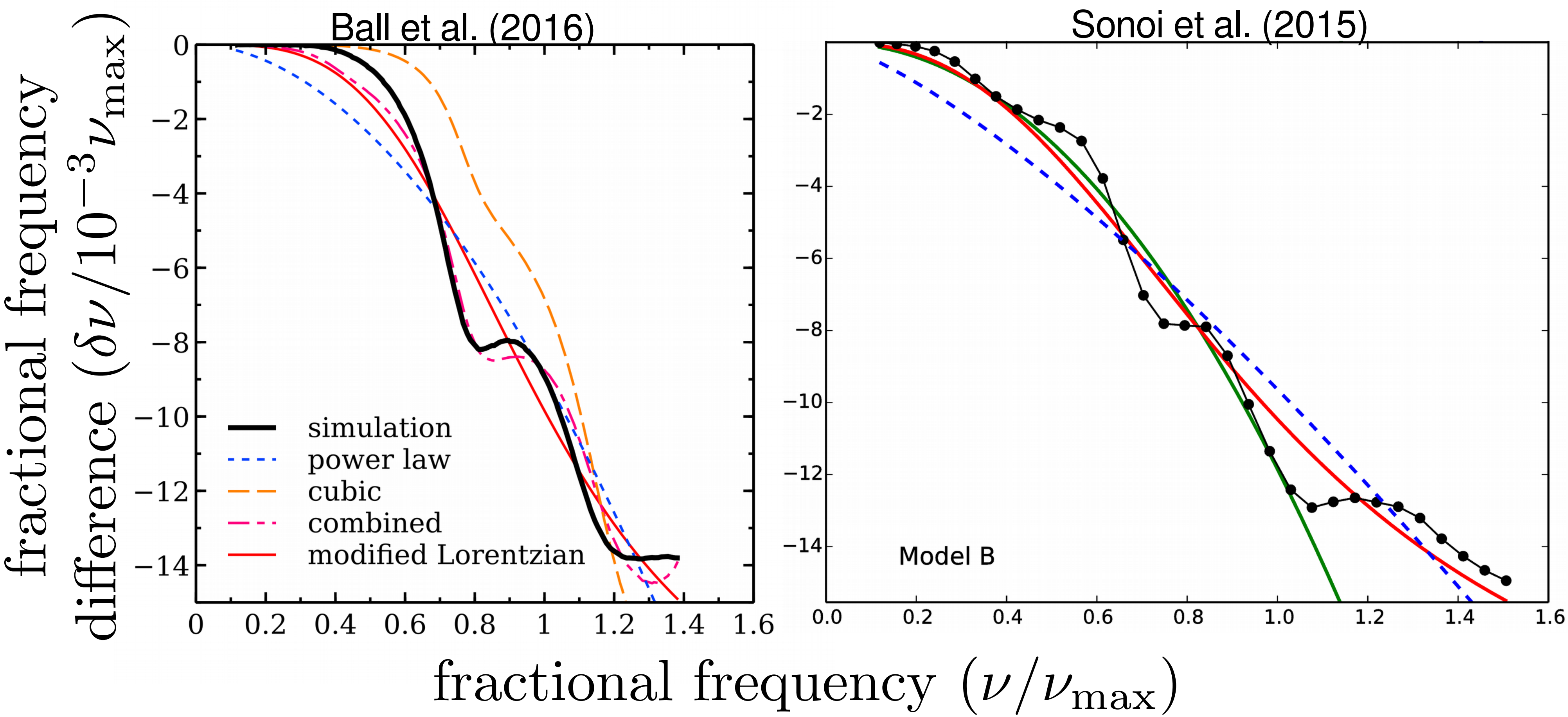
$\log g = 4.44$ $\quad$ $\log g = 4.44$



F3 and Model B

$T_{\mathrm{eff}} = 6893\,\mathrm{K}$ $T_{\mathrm{eff}} = 6725\,\mathrm{K}$

$\log g = 4.30$ $\log g = 4.25$



State of the art

- Parametrizations
  - ratios widely used; phase-matching very new
  - “combined” term appears the best formula
  - Sun is still the only real test
- 3D RHD simulations
  - “patching” models seems reliable
  - results are robust
  - currently limited to structural effects

The future

The future

- Make more of the 3D RHD simulations
  - "modal" physics: flows, non-adiabaticity, etc.
  - calibrating mixing length parameter helps too

The future

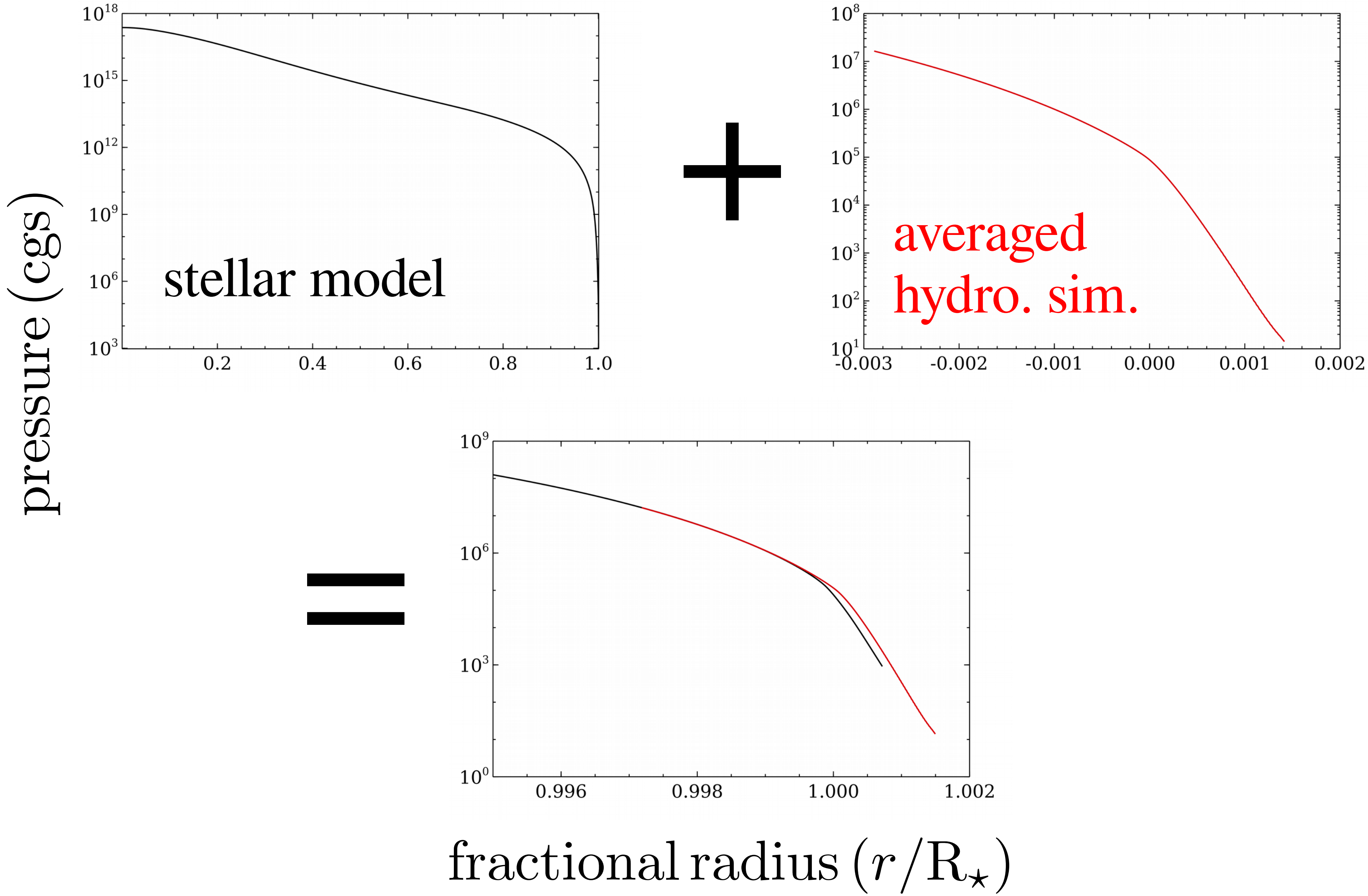
- Make more of the 3D RHD simulations
  - “modal” physics: flows, non-adiabaticity, etc.
  - calibrating mixing length parameter helps too

- Push observations to lower radial order
  - best nominal *Kepler* data almost there
  - velocity data from SONG

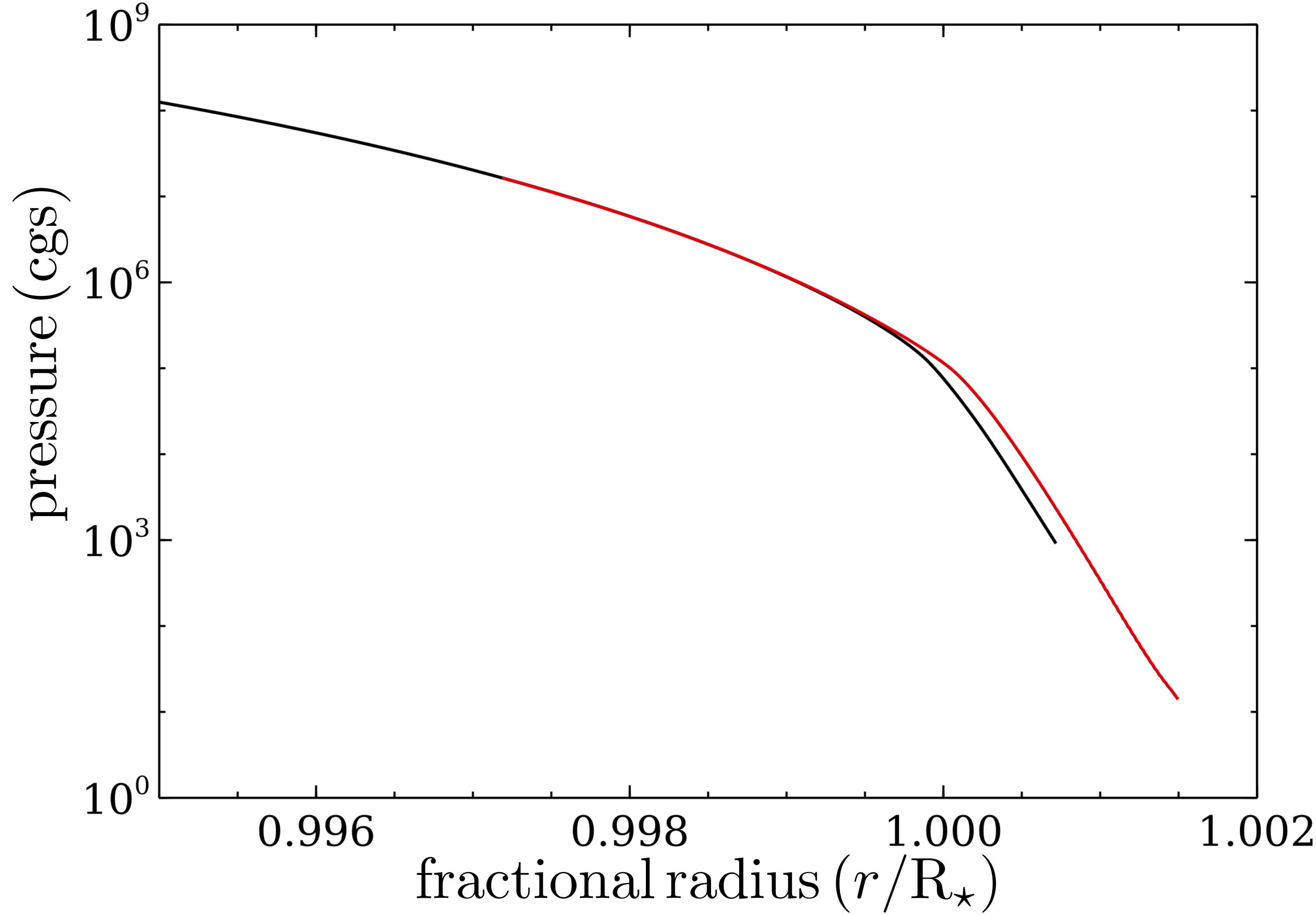
A

Additional slides

Combining models



Combining models

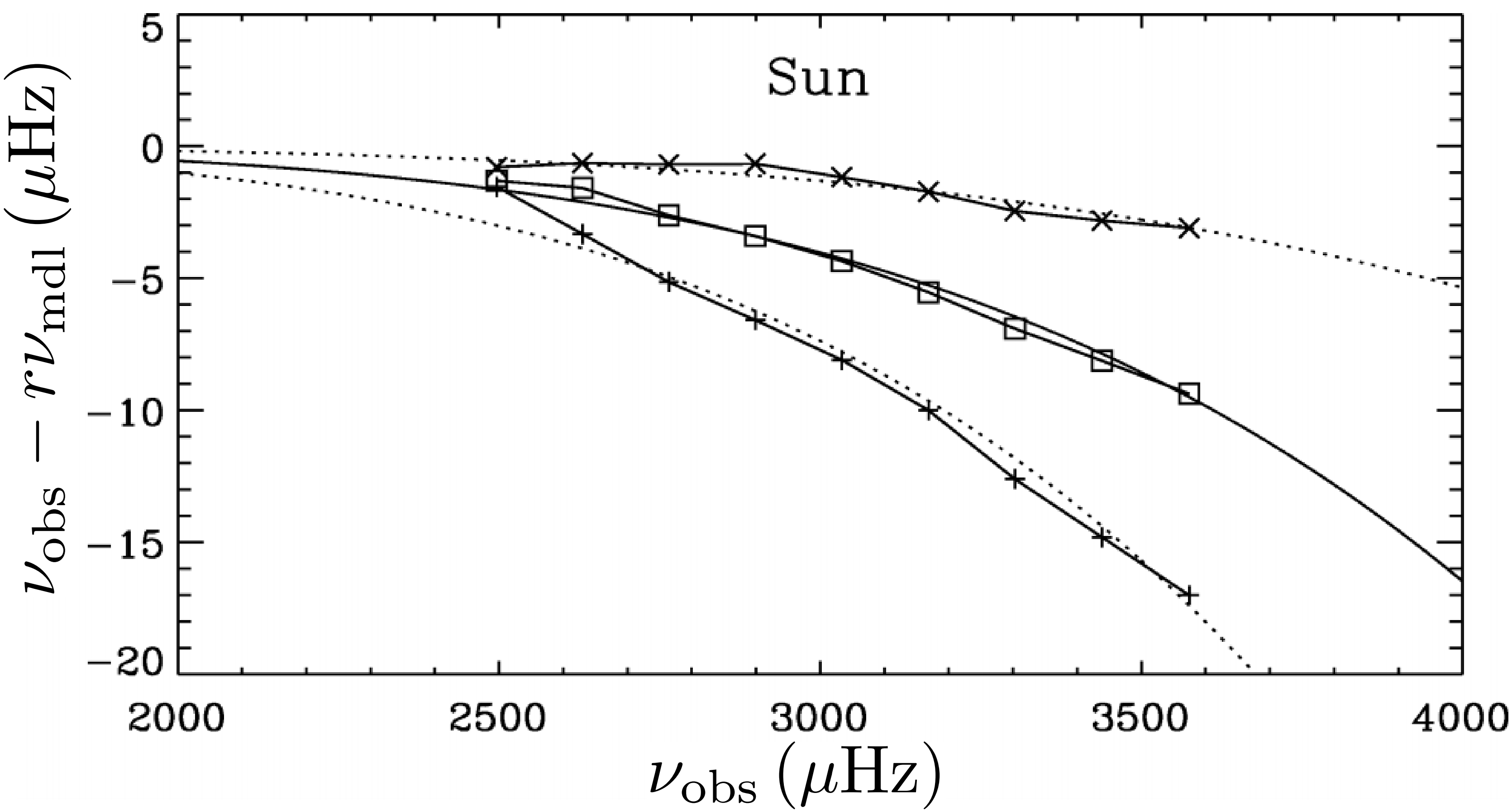


The Astrophysical Journal, 683: L175–L178, 2008 August 20

CORRECTING STELLAR OSCILLATION FREQUENCIES FOR NEAR-SURFACE EFFECTS

Hans Kjeldsen,[1] Timothy R. Bedding,[2] and Jørgen Christensen-Dalsgaard[1]
Received 2008 February 4; accepted 2008 July 9; published 2008 July 28

$$\nu_{\rm obs}(n) - r\nu_{\rm mdl}(n) = a\left[\frac{\nu_{\rm obs}(n)}{\nu_0}\right]^b$$



A&A 585, A63 (2016)
DOI: 10.1051/0004-6361/201526593

Astronomy & Astrophysics

Asteroseismic model fitting by comparing $\epsilon_{n\ell}$ values

Ian W. Roxburgh

$$\epsilon_\ell^{\rm obs}(\nu) = \nu/\Delta\nu^{\rm obs} - n - \ell/2$$

$$\epsilon_\ell^{\rm mdl}(\nu) = \nu/\Delta\nu^{\rm mdl} - n - \ell/2$$

$$\mathcal{E}(\ell,\nu) = \epsilon_\ell^{\rm mdl}(\nu) - \epsilon_\ell^{\rm obs}(\nu)$$

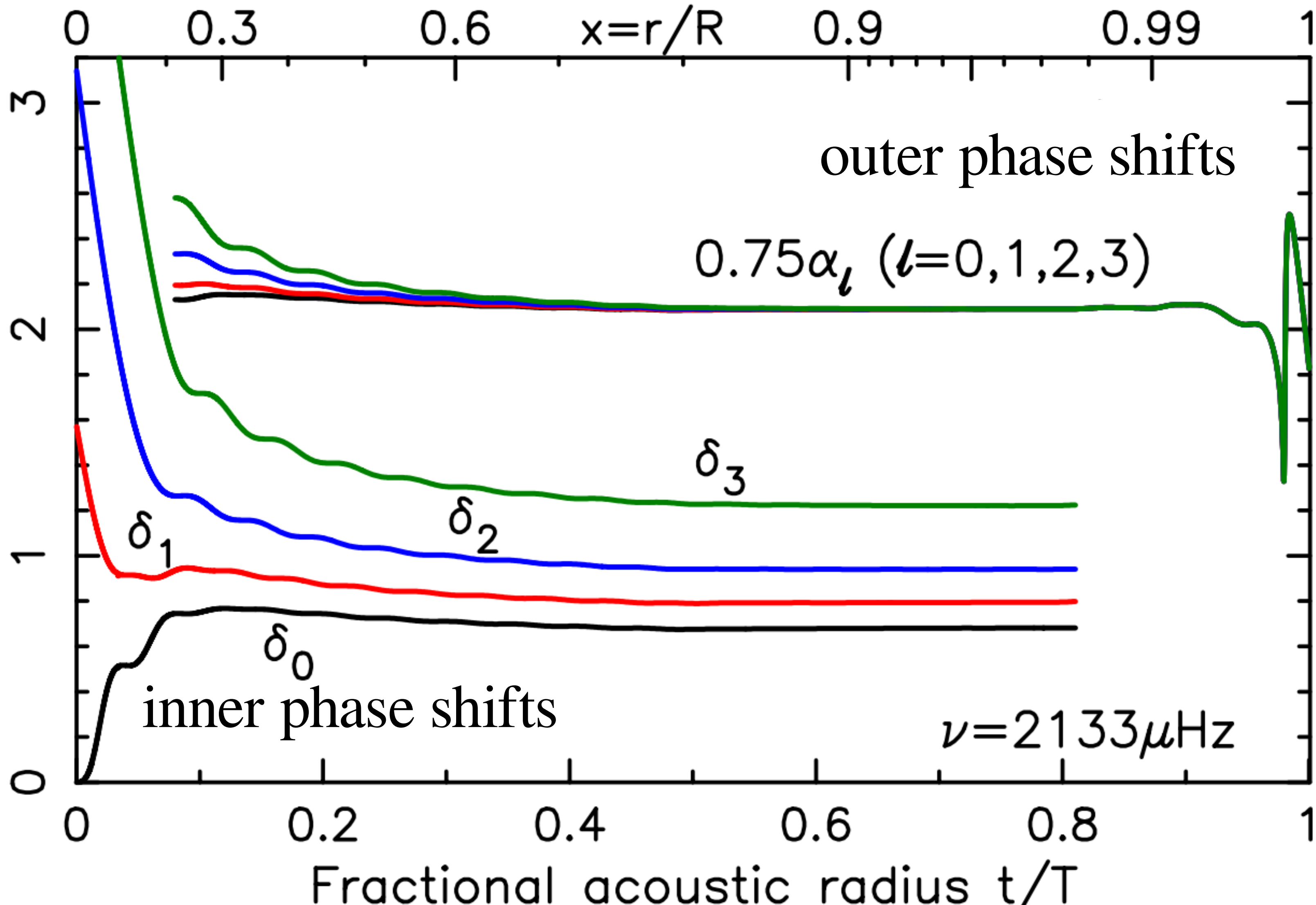
$$\chi^2 = \frac{1}{N_{\rm obs}-M}\sum^{N_{\rm obs}}\left(\frac{\mathcal{E}(\ell,\nu_{n\ell}{}_{n\ell}^{\rm obs}) - \mathcal{F}(\nu_{n\ell}^{\rm obs})}{\sigma_{n\ell}/\Delta\nu}\right)^2$$

$\mathcal{F}(\nu)$ is an M-degree polynomial

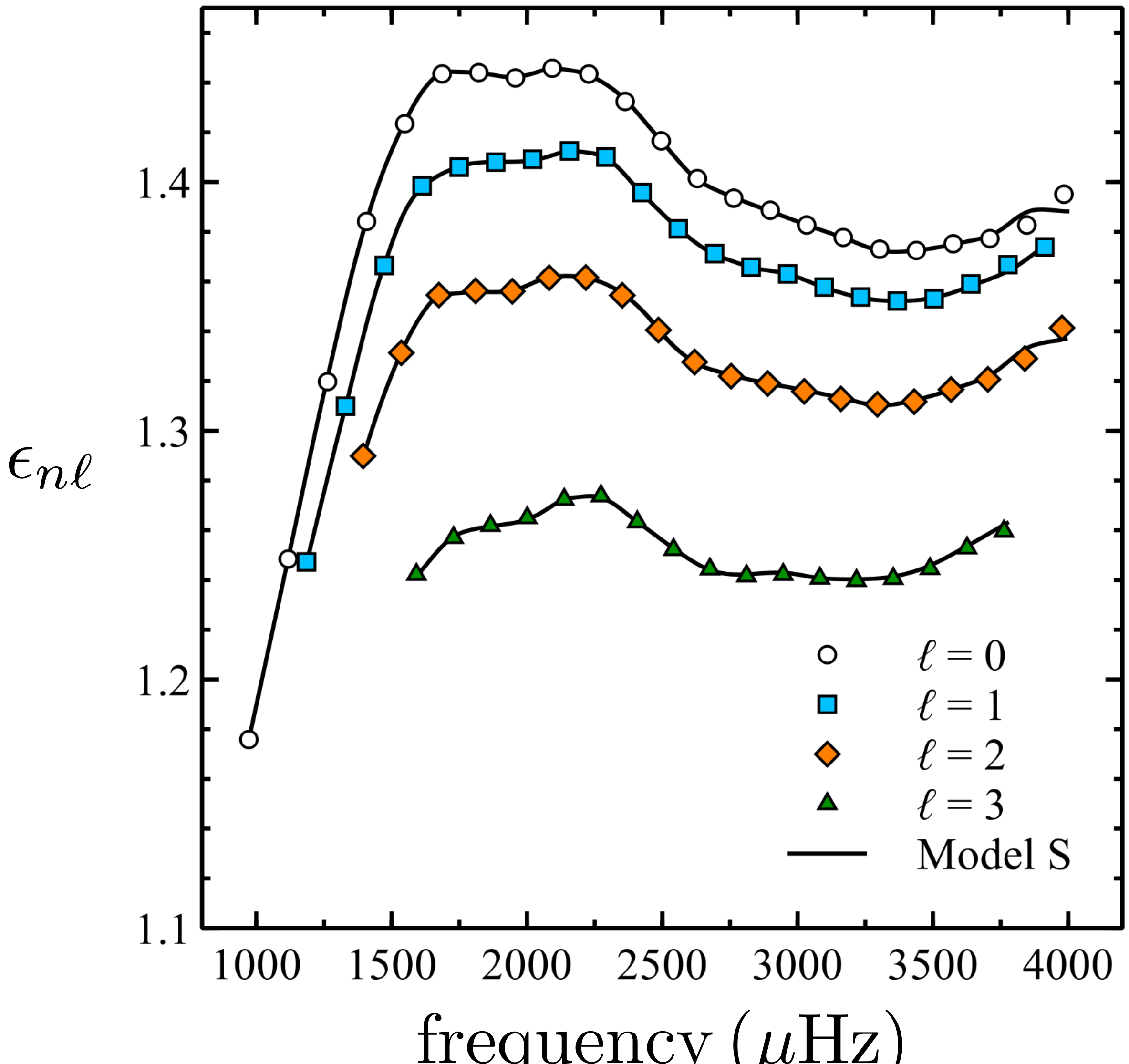
see also Roxburgh (2015; A&A 574, A45)

Basis of Roxburgh's methods

combine frequencies to cancel outer phase shifts



Epsilon matching



Epsilon matching

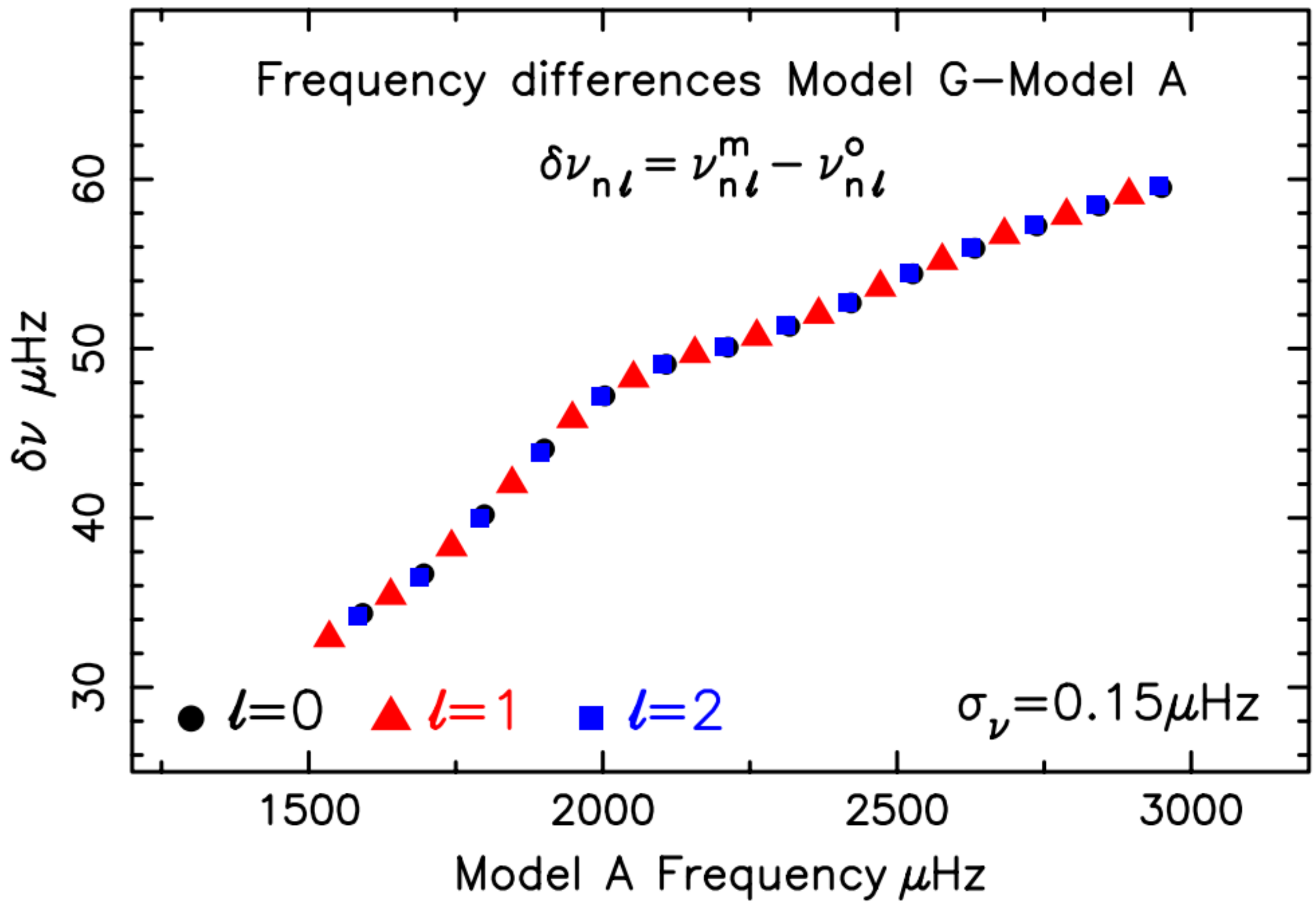


Fig. 3. Superposed curves for the outer phase shifts $\alpha_\ell(\nu, t)$ of Model A at 3 frequencies. The values of α_ℓ are independent of ℓ until deep inside the star.

THE ASTROPHYSICAL JOURNAL, **342**: L95–L98, 1989 July 15

TOPOLOGY OF CONVECTION BENEATH THE SOLAR SURFACE

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Department of Physics and Astronomy, Michigan State University

AND

Å. NORDLUND
Copenhagen University Observatory

Received 1989 March 9; accepted 1989 April 14

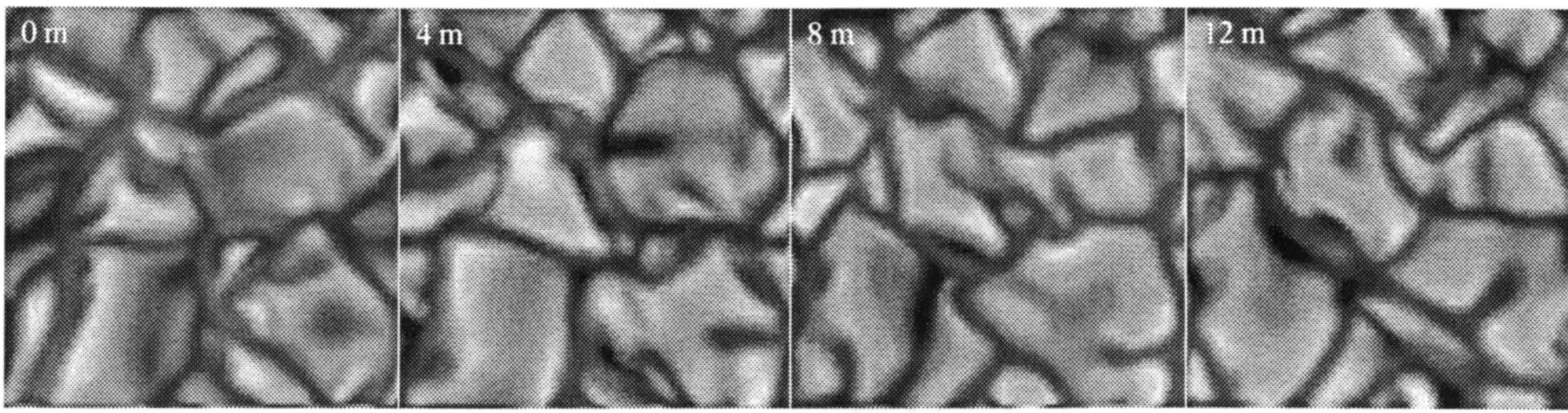
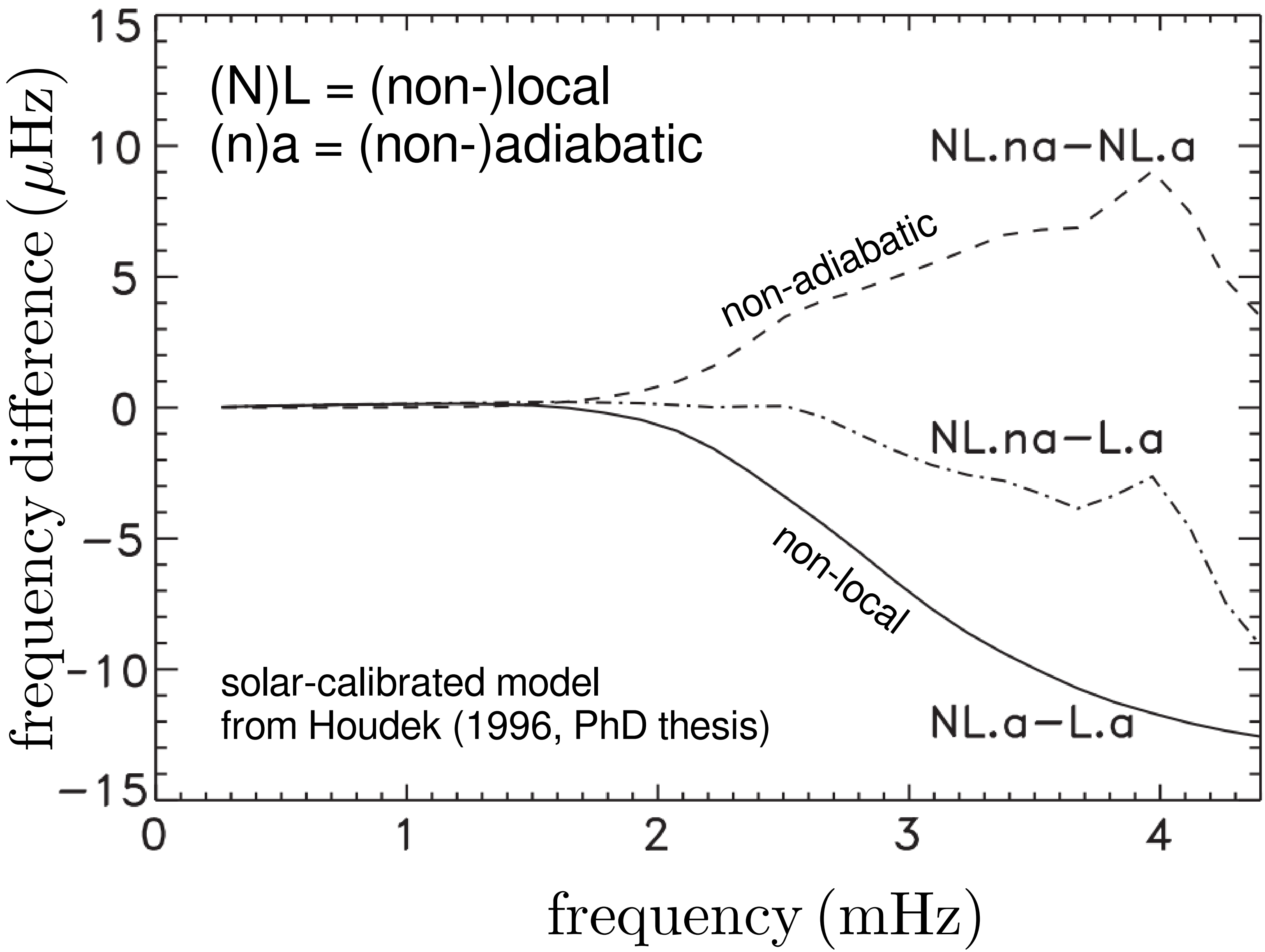
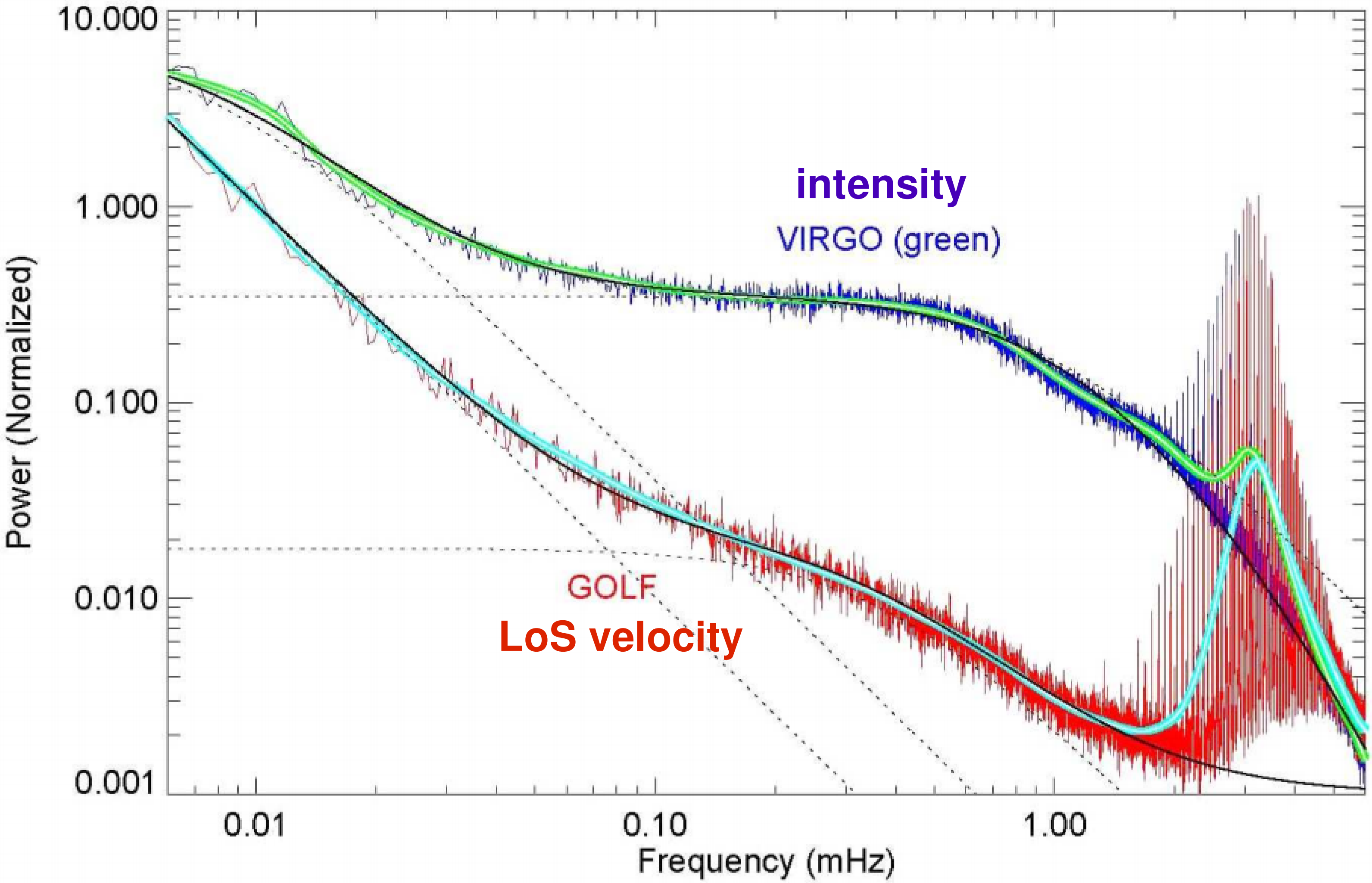


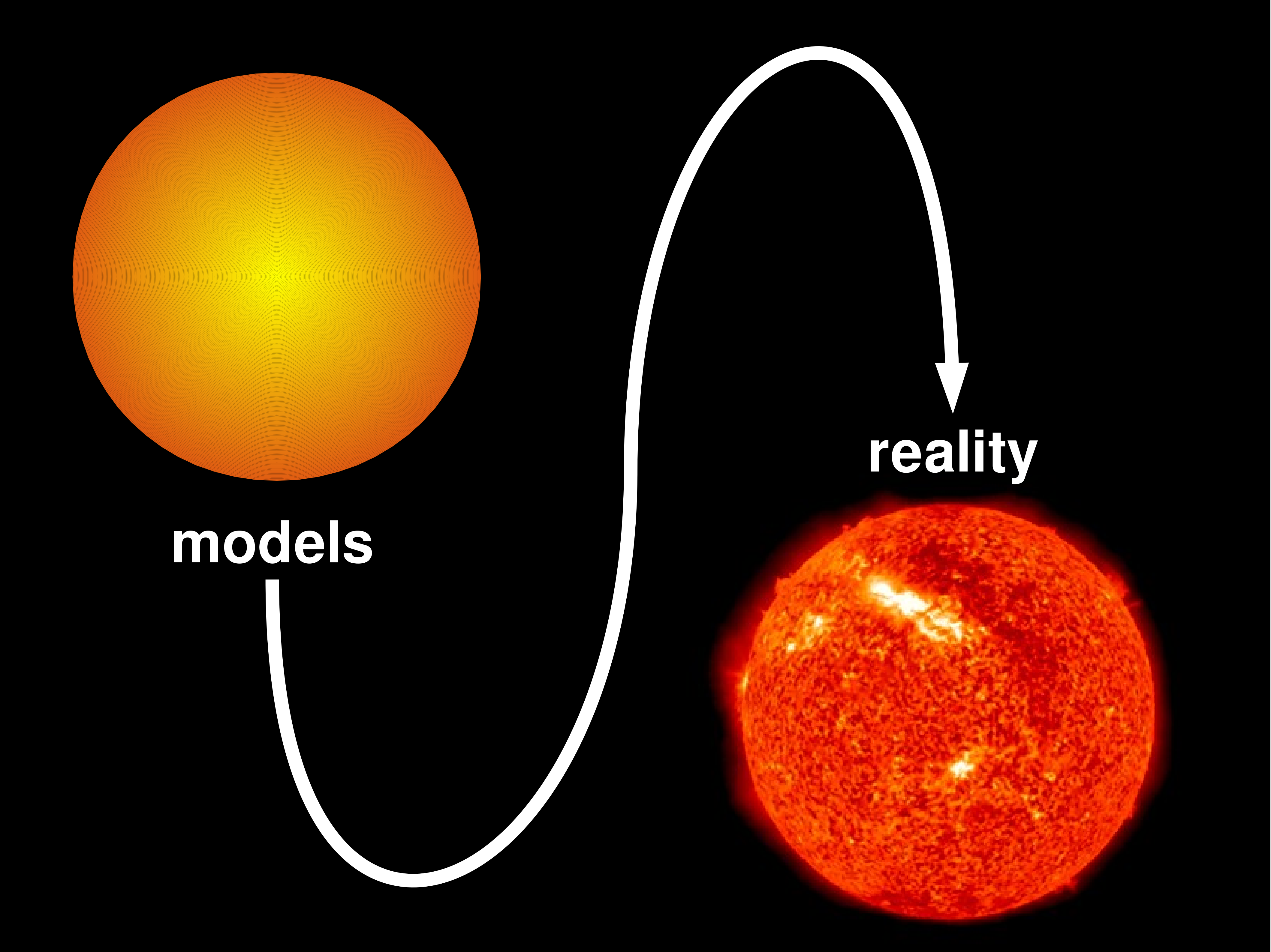
FIG. 1.—Simulated snapshots of integrated radiation surface intensity. These approximate monochromatic continuum intensity snapshots. Each snapshot is 6 × 6 Mm (8″ × 8″). The sequence, spanning 12 minutes, approximates a 6 × 24 Mm image of the Sun.

Non-local convection and non-adiabaticity

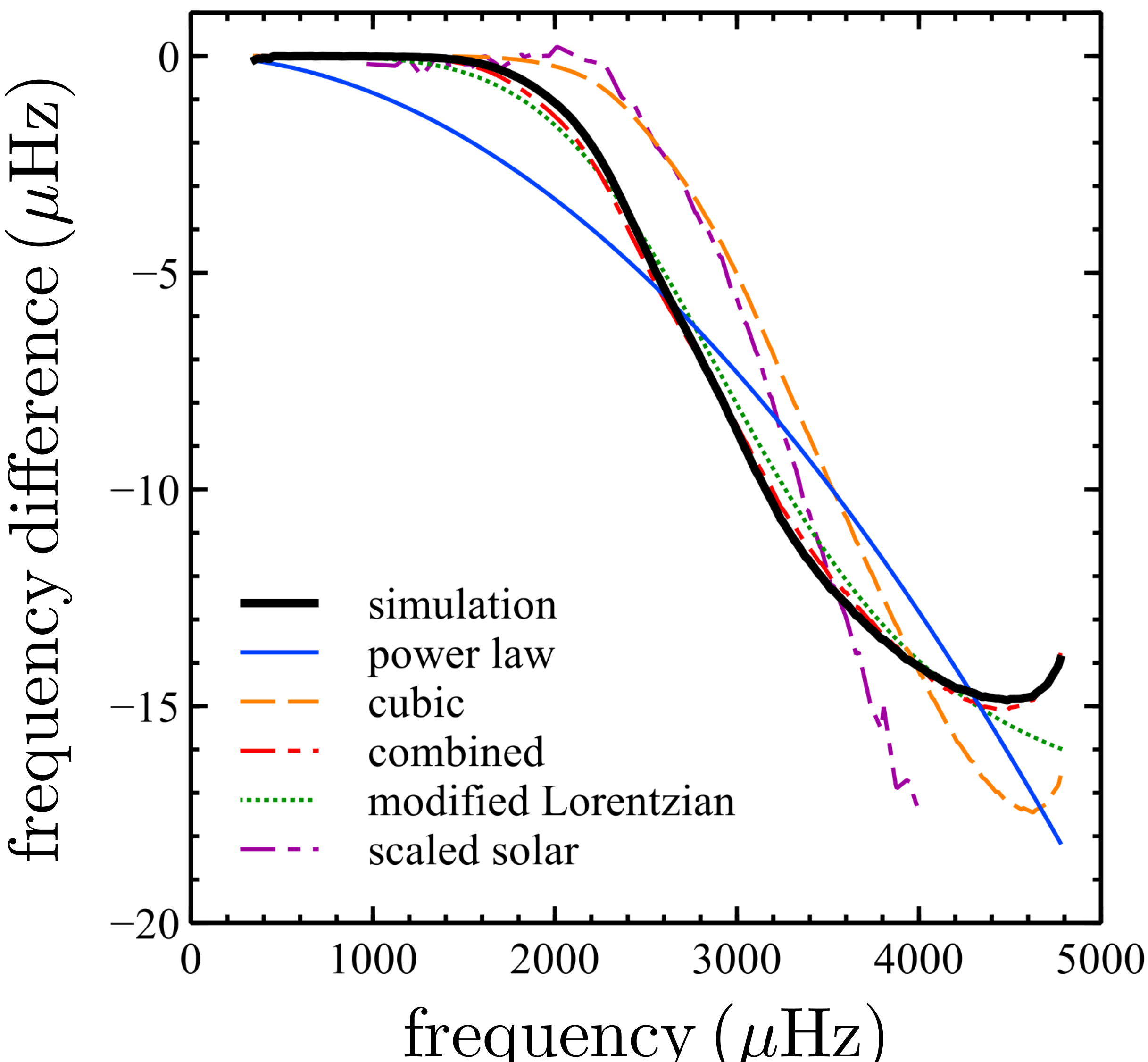


Lower radial order with SONG?

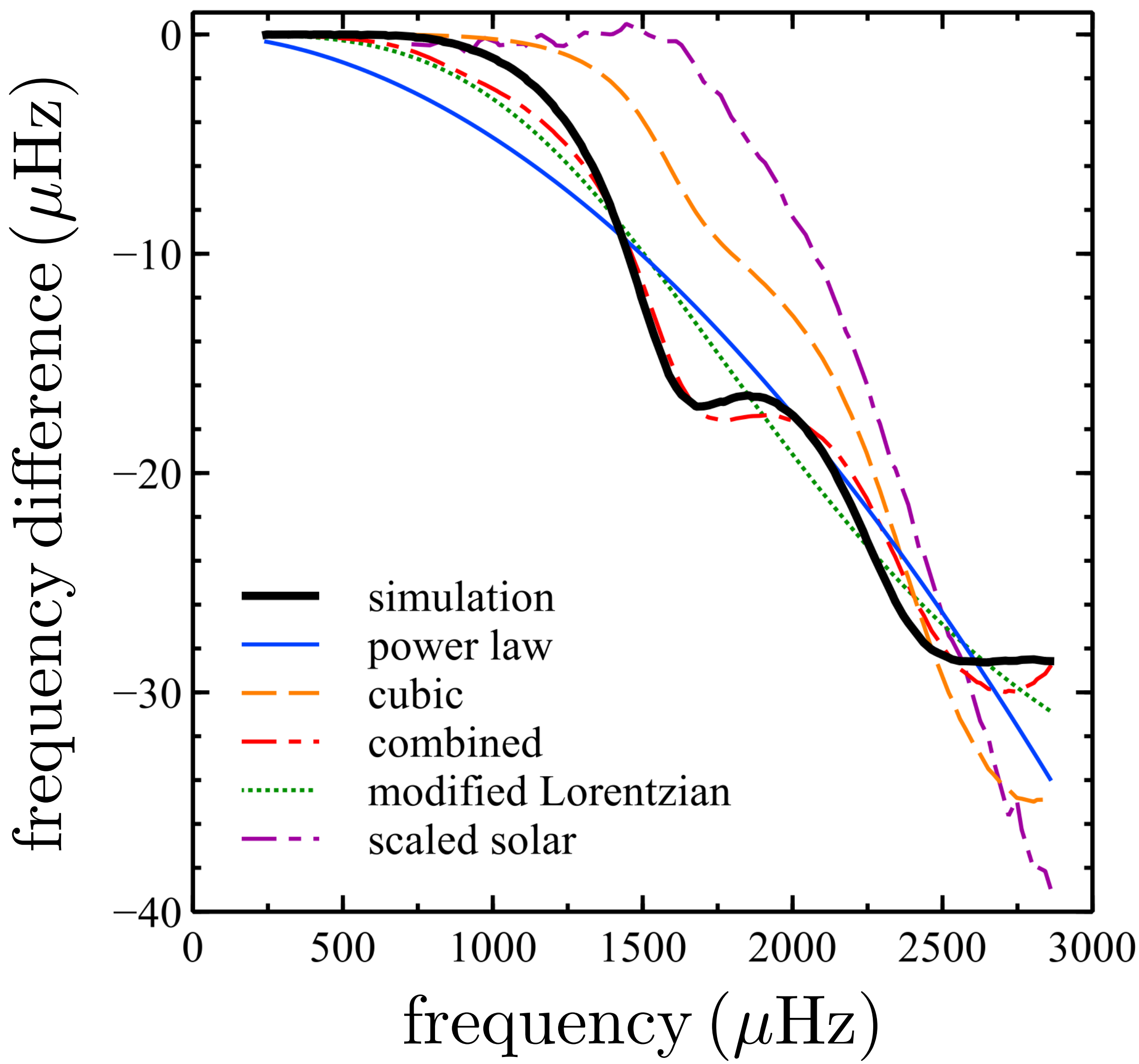



reality
models

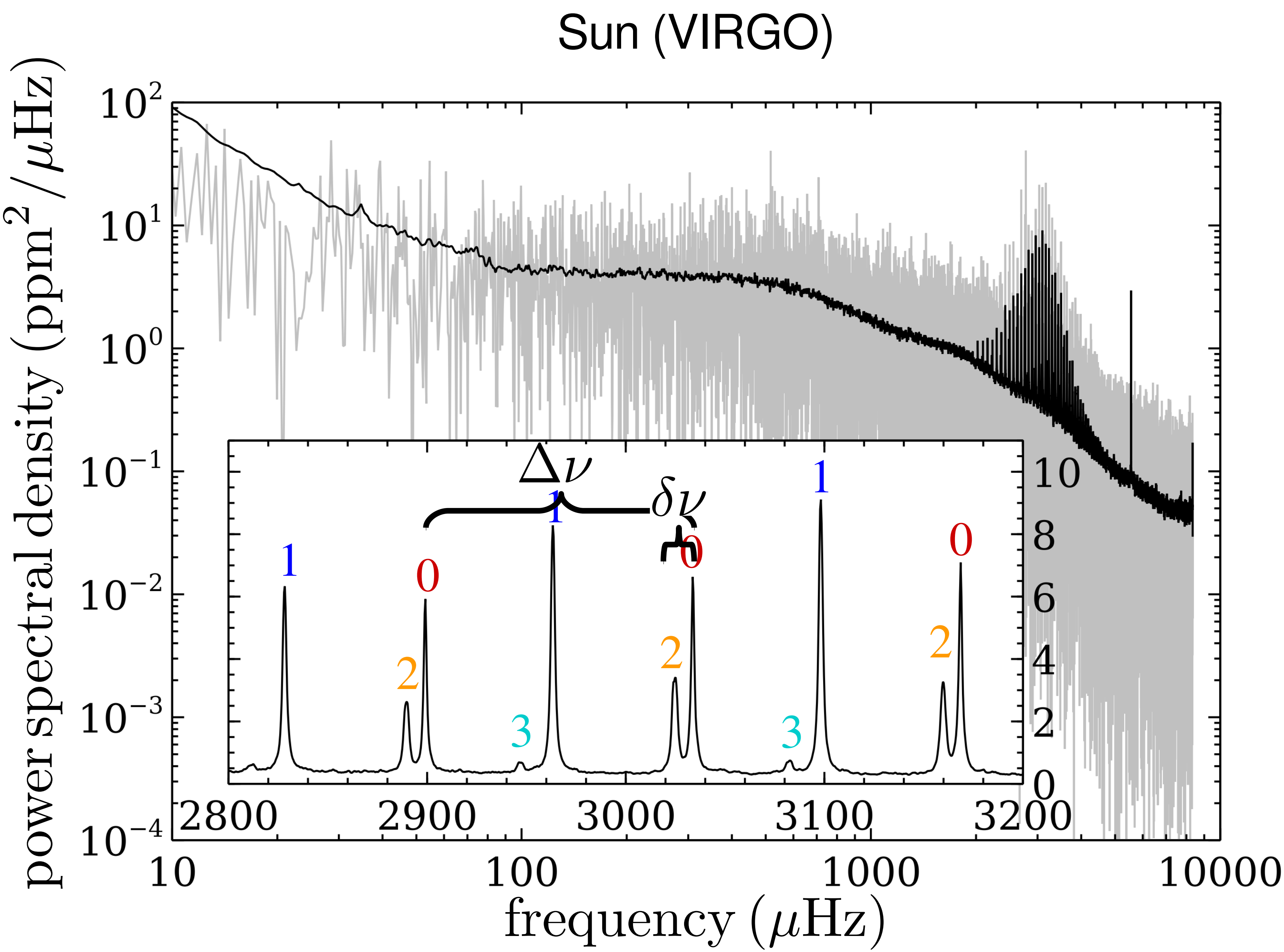
Comparing parametrizations: G2



Comparing parametrizations: F3

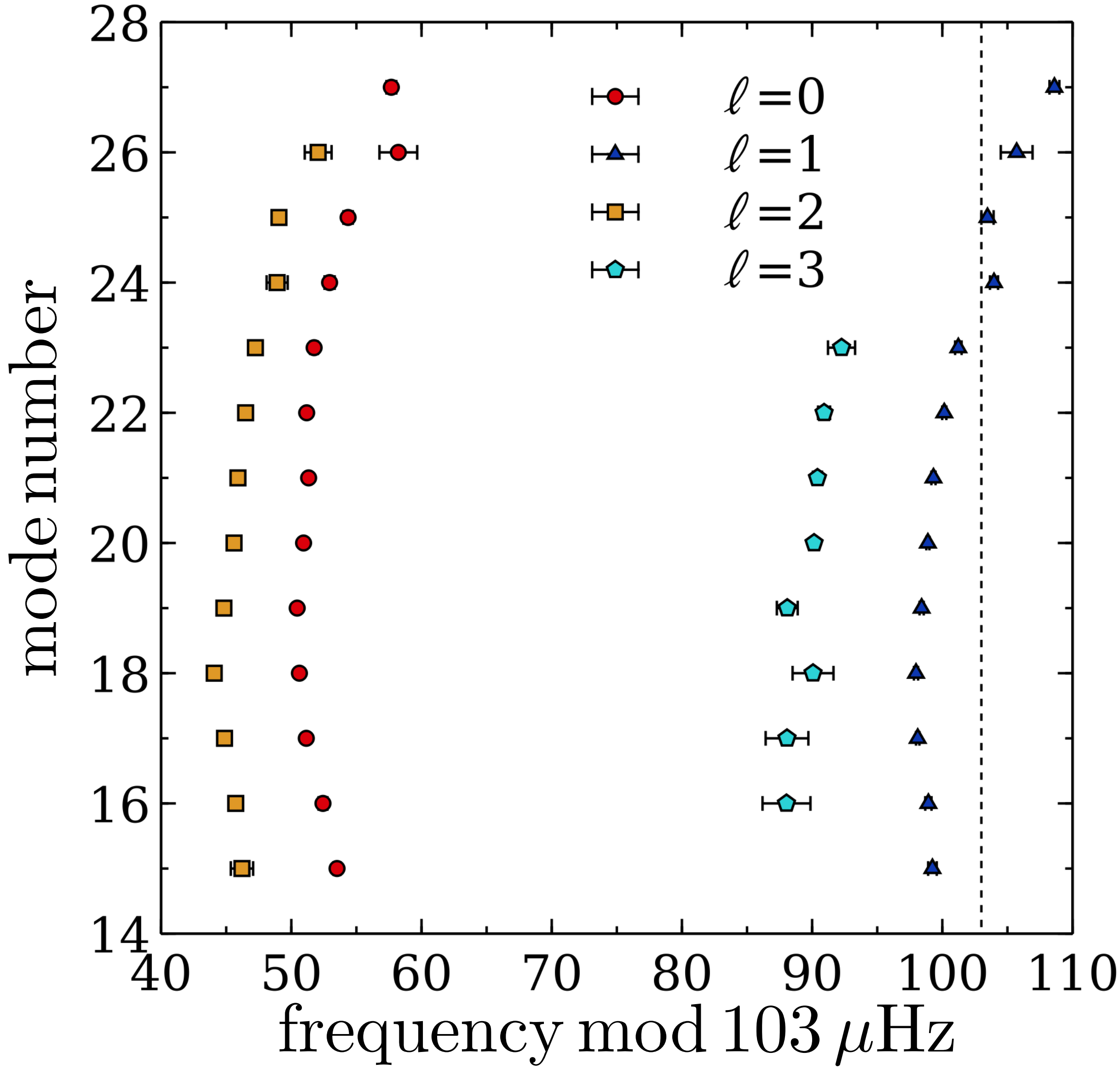


Solar oscillations

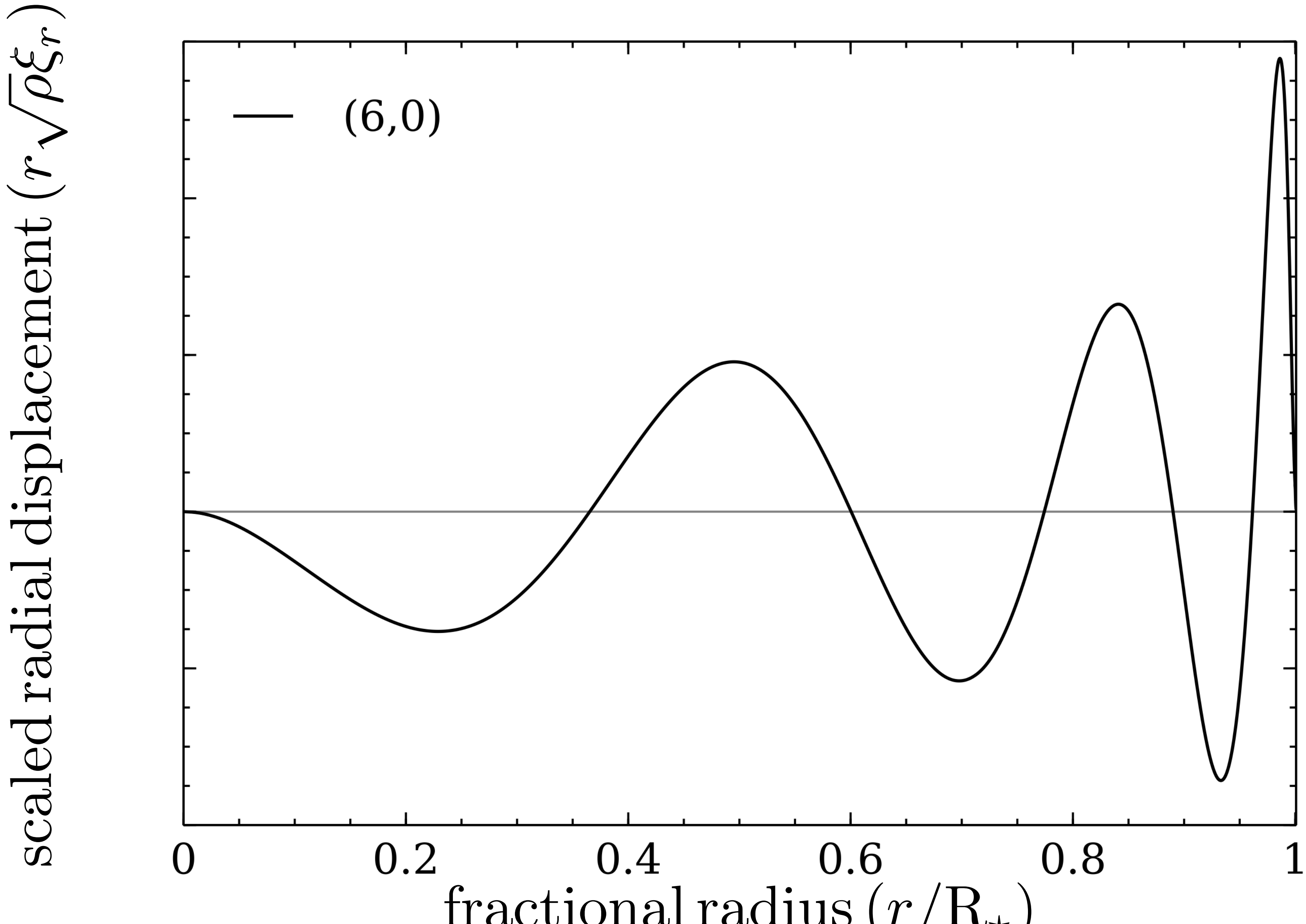


Echelle diagram

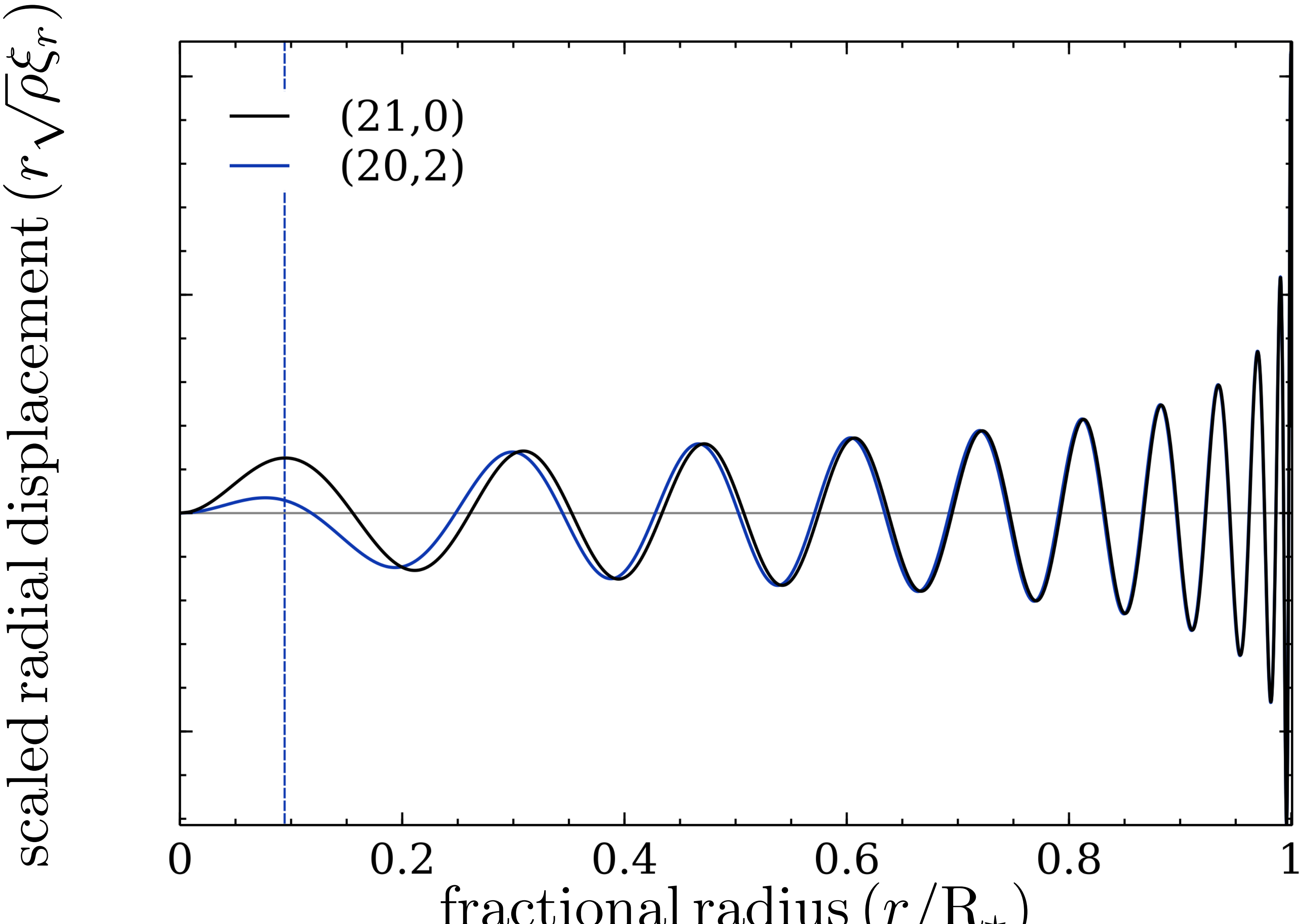
16 Cyg A (*Kepler*)



Displacement eigenfunctions



Displacement eigenfunctions



KIC 12508433

Deheuvels et al. (2014)

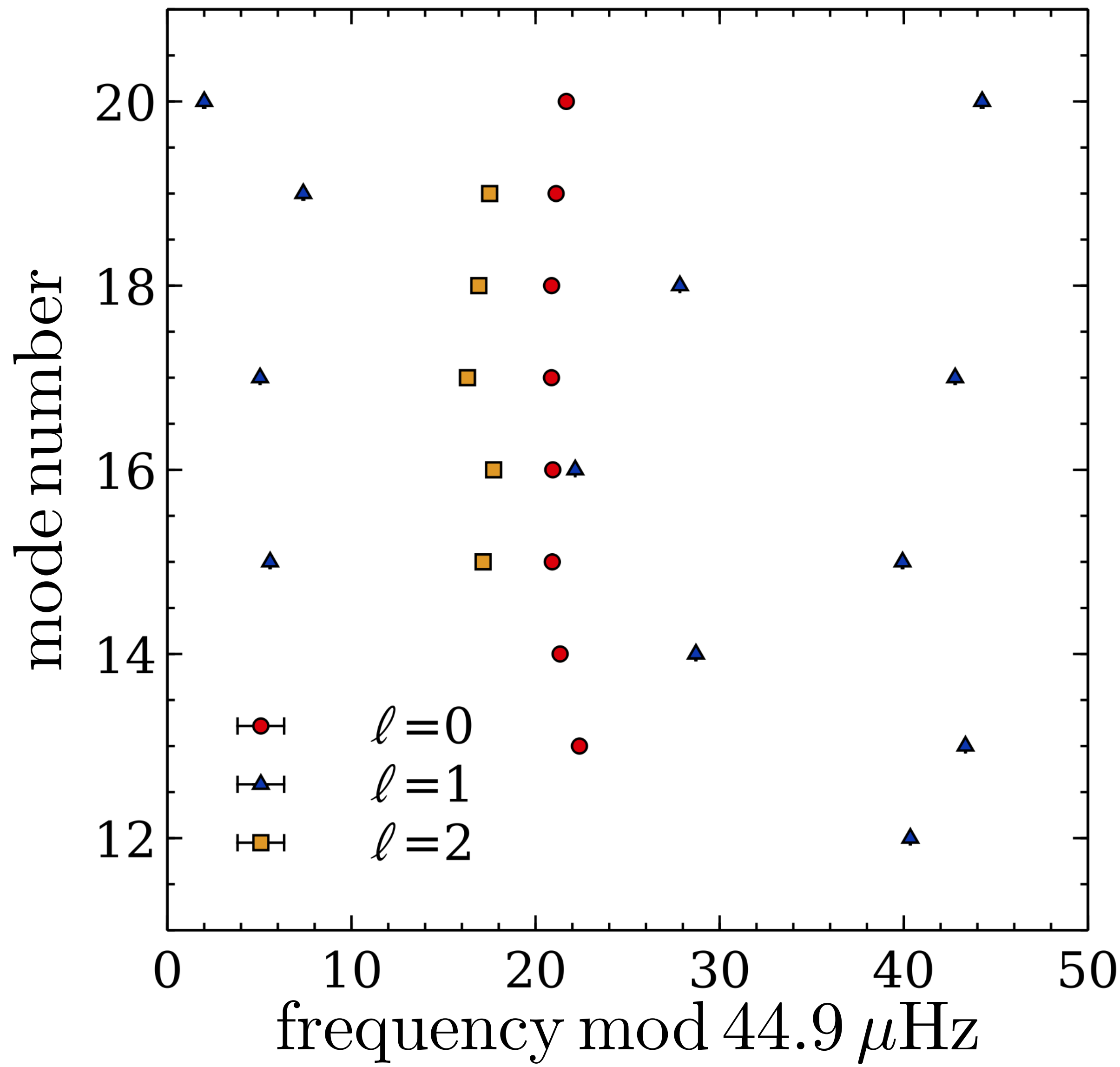
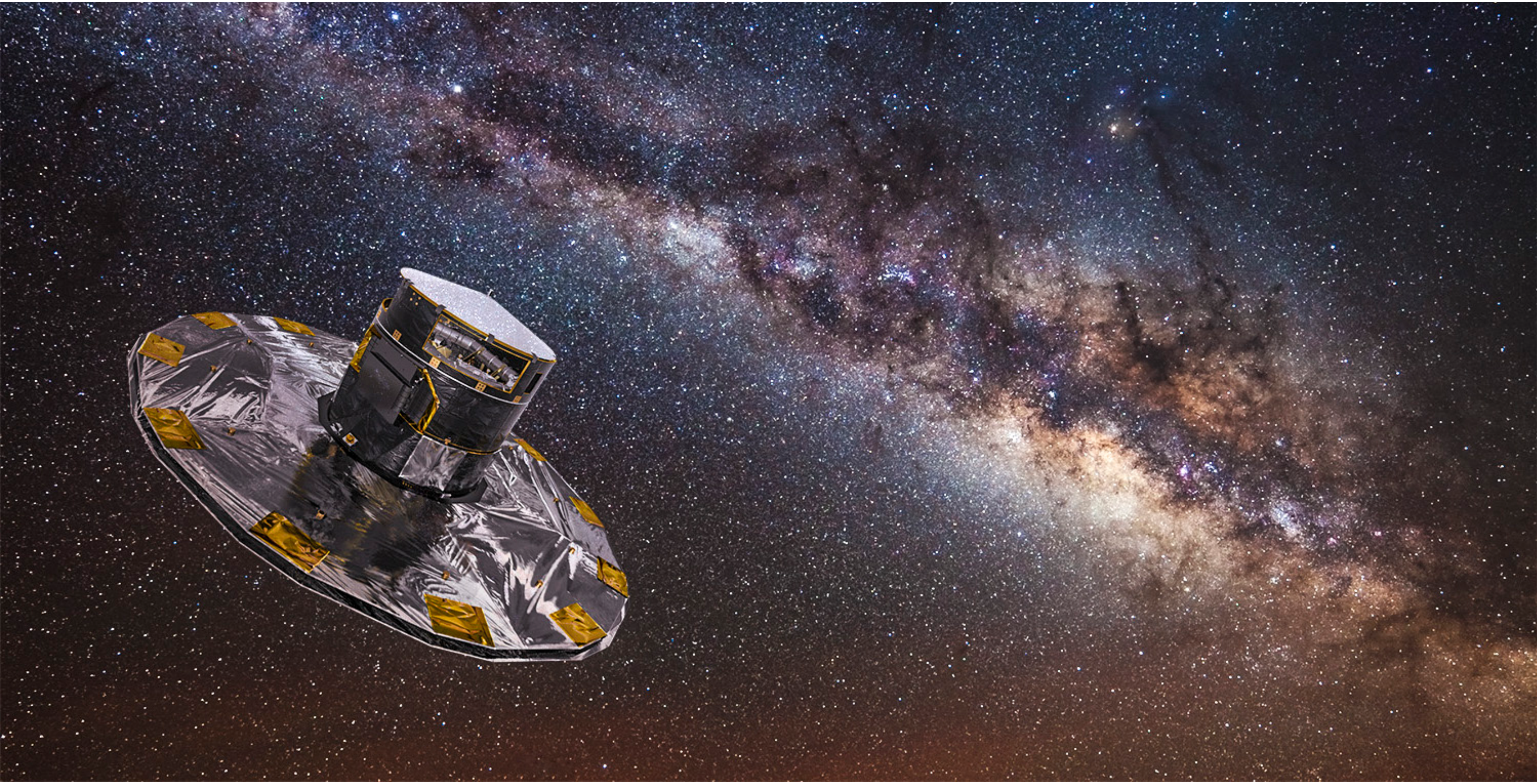


Table 2. Box sizes and grid resolutions.

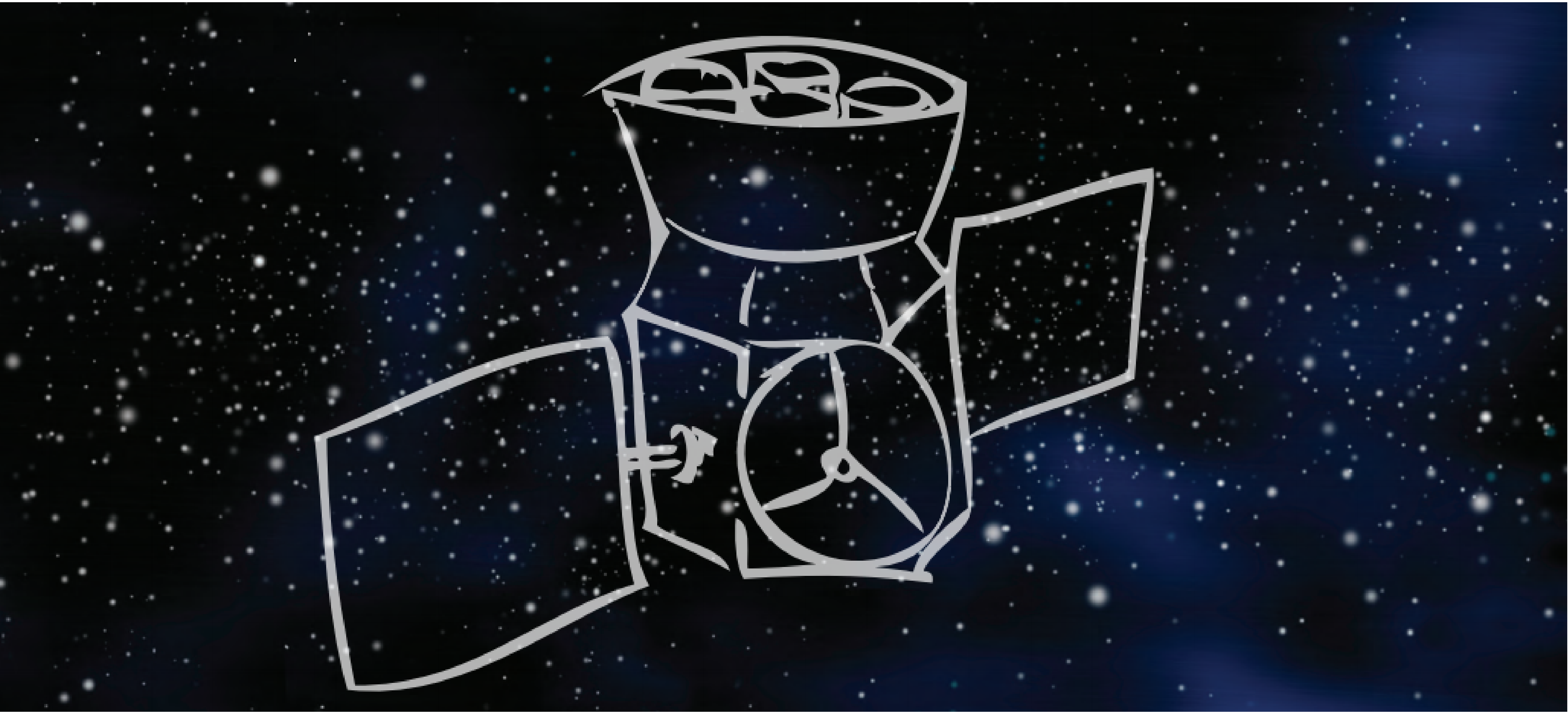
Simulation	F3V	G2V	K0V	K5V	M0V	M2V
Box height [Mm]	9	3	1.8	1.5	0.9	0.8
above z_0[a]	1.57	0.95	0.48	0.41	0.25	0.21
below z_0	7.43	2.05	1.32	1.09	0.65	0.59
# of pressure scale heights	13.1	14.0	13.2	15.3	14.8	14.5
above z_0	6.9	8.6	7.1	9.1	8.4	7.8
below z_0	6.2	5.4	6.2	6.4	6.4	6.8
H_p at z_0 [km]	500	200	90	65	38	35
Δz^b [km]	11.25	10	6	5	4	3.2
$\min(H_\mathrm{p})/\Delta z$	18.1	10.0	9.57	7.87	6.53	7.19
Horizontal box size [Mm]	30	9	6	4	2.5	1.56
$\Delta x, \Delta y^c$ [km]	58.6	17.6	11.7	7.81	4.88	3.05
$\Delta x/\Delta z$	5.21	1.76	1.95	1.56	1.22	0.953

Notes. [(a)] $z_0 = \langle z(\tau_\mathrm{R} = 1)\rangle$; [(b)] Δz is the vertical grid resolution; [(c)] Δx and Δy are the horizontal grid resolution; in all simulations considered here, $\Delta x = \Delta y$ was chosen.

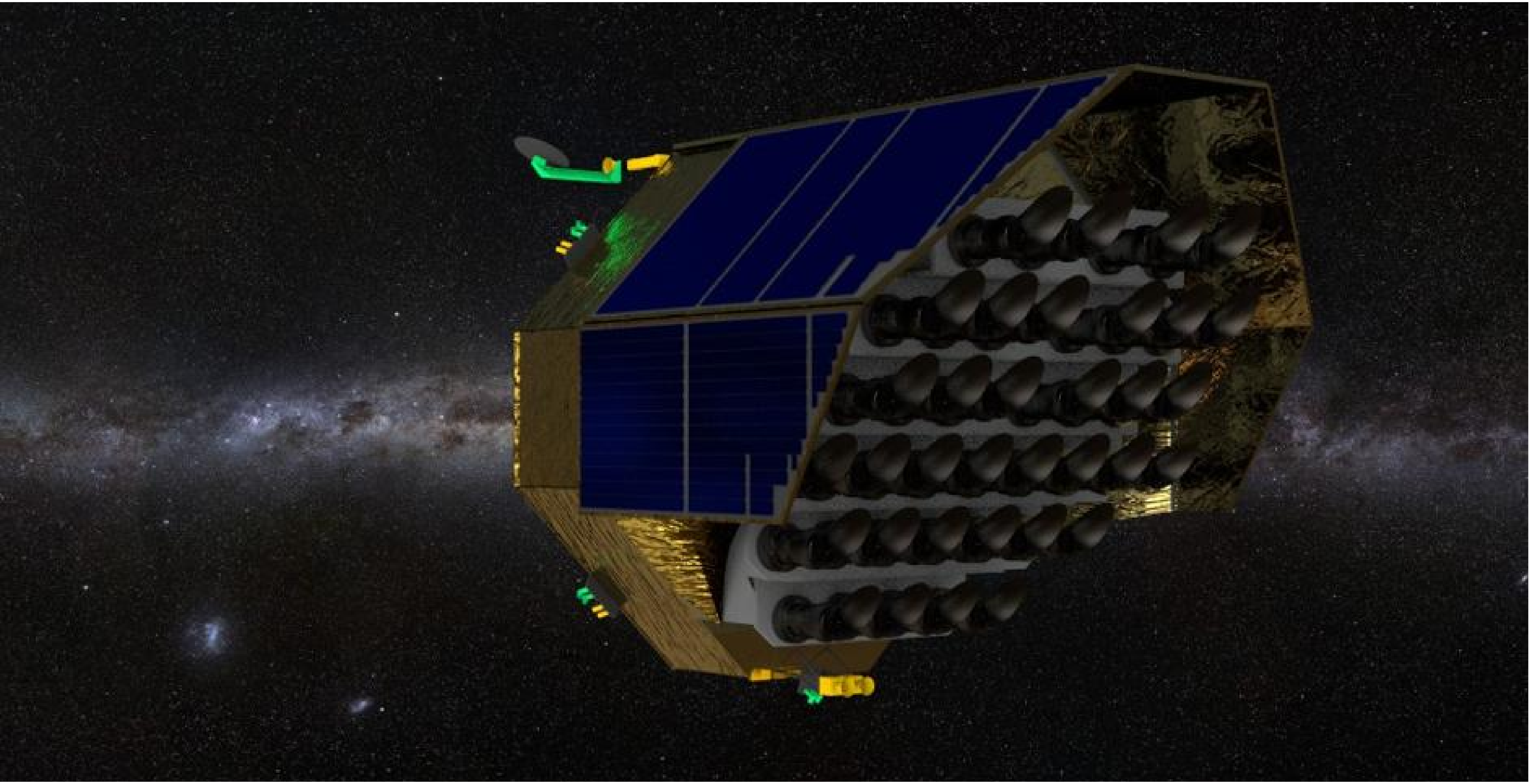
GAIA



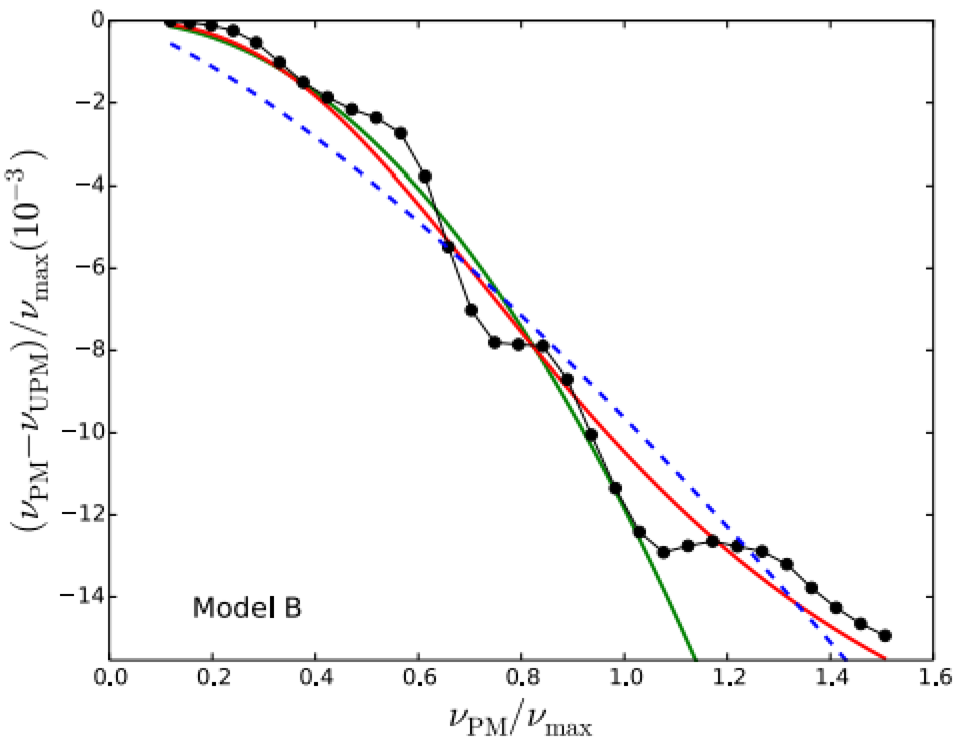
TESS

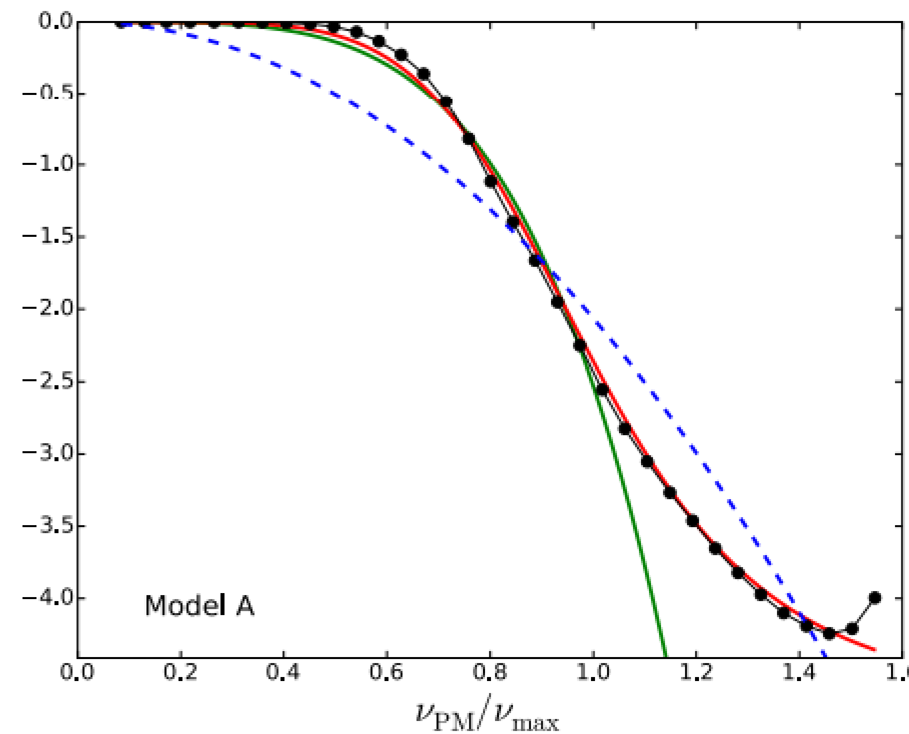


PLATO



Solar Oscillations Network Group





$$T_{\rm eff} = 6725\,{\rm K}$$

$$\log g = 4.25$$

$$T_{\rm eff} = 5775\,{\rm K}$$

$$\log g = 4.44$$