AARHUS UNIVERSITY
Stellar Astrophysics Centre

Amplitude ratios and phase shifts

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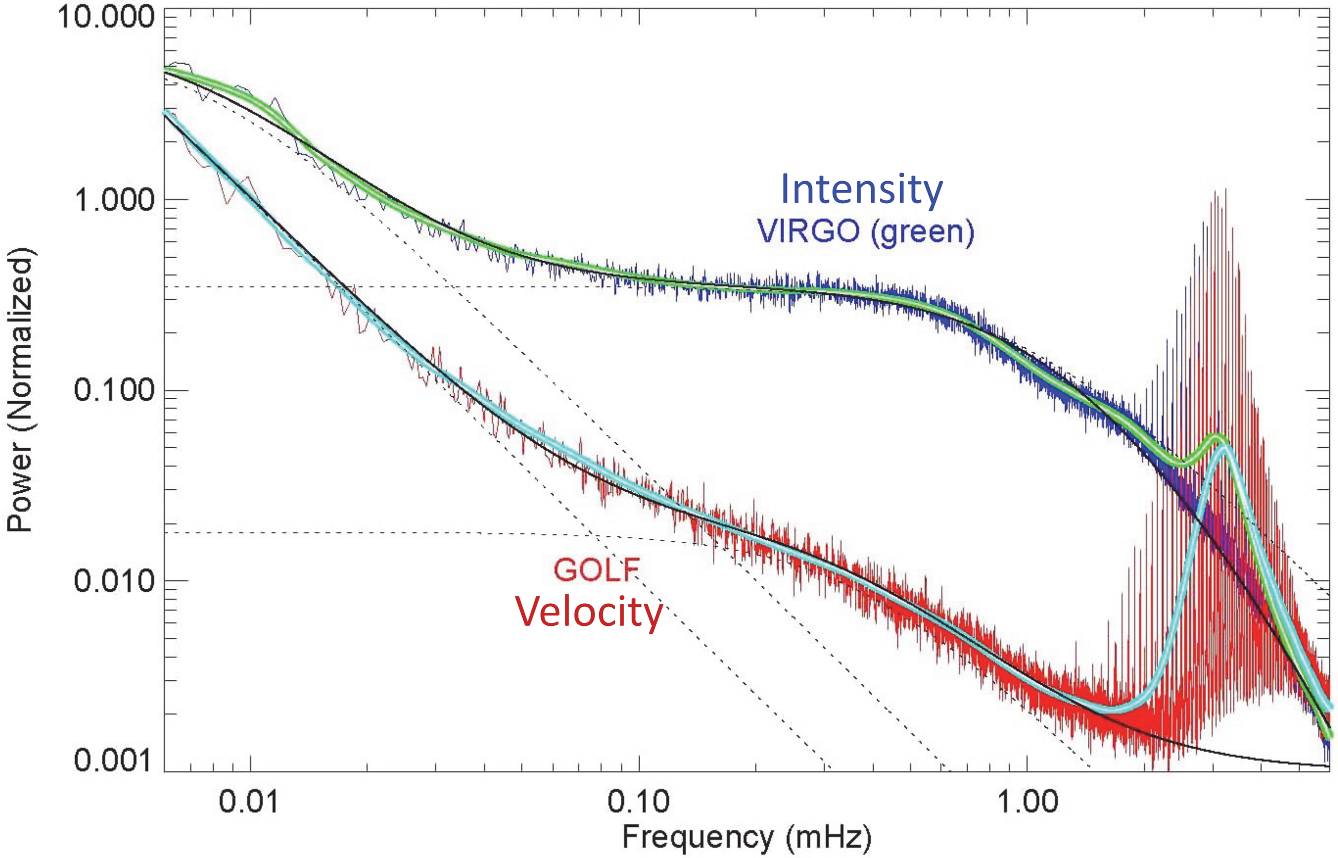
Solar oscillations
(and background noise)

Max. amp. ratio: ~ 0.24 ppm/cm s^{-1}

Max. amplitude

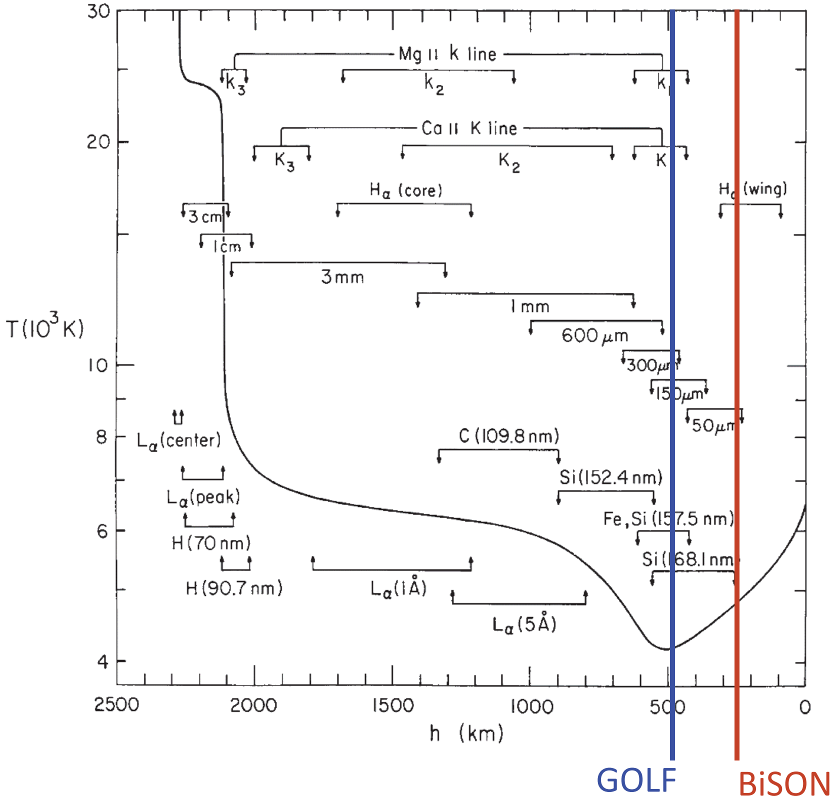
- ~ 4.8 parts per million
- ~ 20 cm/sec



Courtesy of JCD

Amplitude ratios

Spectral line formation is the solar atmosphere

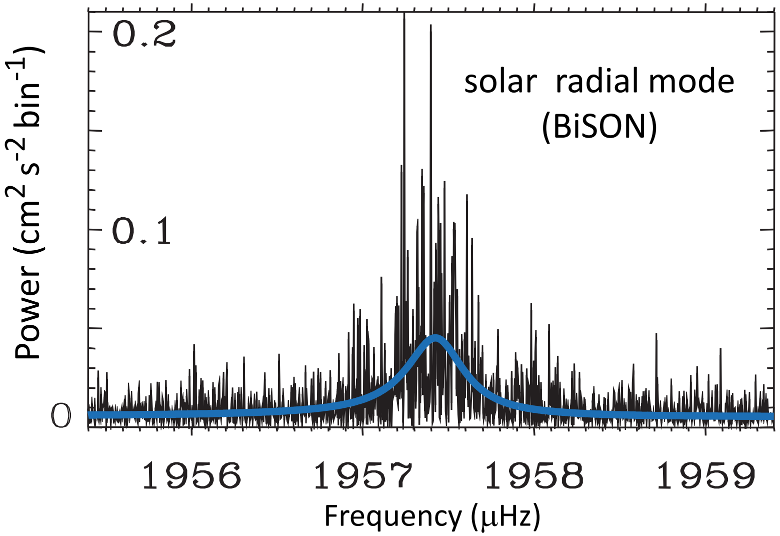


Vernazza, Avrett, Loeser (1981); (VAL-C)

Instrument	line	λ (Å)	τ_{5000}	height (km)
BBSO	Ca	6439	0.05	~129
BiSON	K	7699	0.013	~260
MDI	Ni I	6708	9×10^{-3}	~213
GOLF	Na D1/D2	5690	5×10^{-4}	~480

see also:
Christensen-Dalsgaard & Gough (1982)
Houdek et al. (1995)
Baudin et al. (2005)
Jimenez-Reyes et al (2007)

Stochastic Excitation (solar-like oscillations)



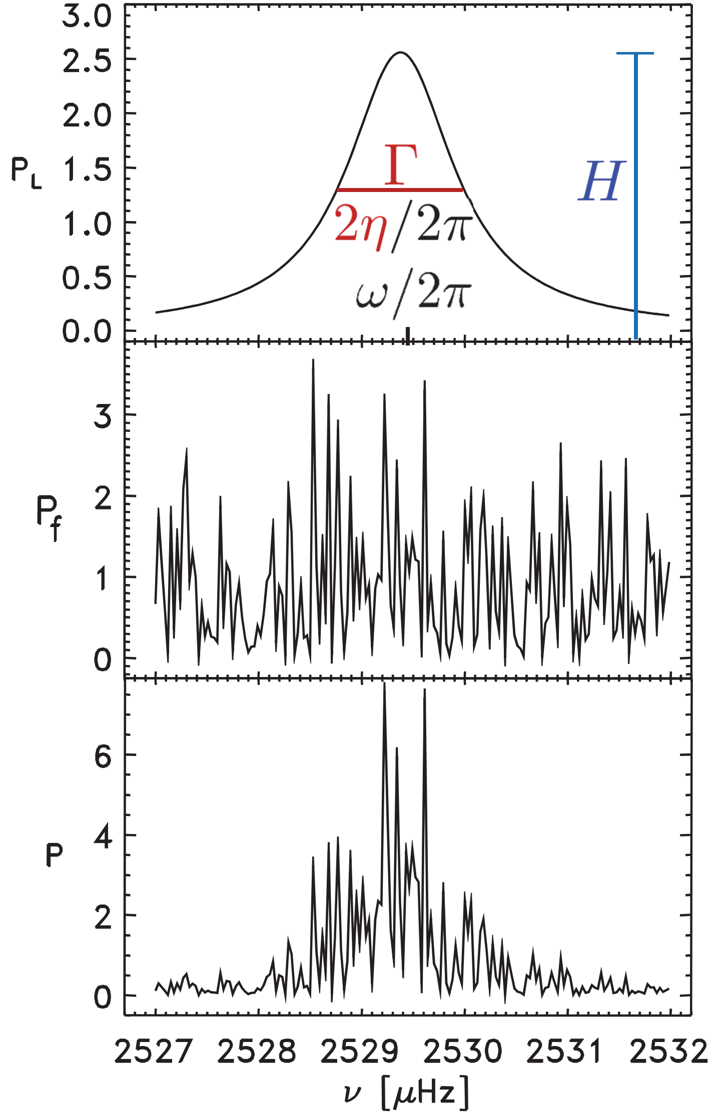
- Damped, harmonic oscillator:

$$E\left(\ddot{\xi} + 2\eta\dot{\xi} + \omega^2\xi\right) = f(t)$$

- Power (spectral density): $P \propto P_{\mathrm{L}}\, P_{\mathrm{f}}$

- Mean square velocity:

$$V^2 \propto \frac{P_{\mathrm{f}}(\omega)}{E} \propto \eta H$$



Solar-type pulsator: excitation model

(Goldreich & Keeley 1977; Balmforth 1992; Samadi et al. 2001; Chaplin, Houdek et al. 2005)

Reynolds stress contribution

eigenfunction ξ

Energy supply rate: $$P \propto I^{-1} \int_0^R \ell^3 \left(r \frac{\partial \xi_{i_r}}{\partial r} p_{\rm t} \right)^2 \mathcal{S}\, {\rm d}r$$

$$H \ := \ P/\eta^2 I = 2V^2/\eta$$

Amplitude ratio is independent of excitation model: $$\Delta L/\Delta V =: \frac{\delta L/L}{\omega_{\rm r} r \ \delta r/r} \qquad ; \ \delta r \equiv \xi_r$$

Nonlocal, time-dependent convection model (Gough 1977)

$$\mathcal{F}_\mathrm{c}(r) \simeq \frac{a}{\ell}\int_{-\infty}^{\infty} F_\mathrm{c}(r_0)\exp(-a|r_0 - r|/\ell)/2\,\mathrm{d}r_0 \quad \hat{=} \quad \frac{\mathrm{d}^2\mathcal{F}_\mathrm{c}}{\mathrm{d}\ln p^2} = \frac{a^2}{\alpha^2}(\mathcal{F}_\mathrm{c} - F_\mathrm{c})$$

5 convection parameters (need calibration):

(1) Mixing-length parameter: calibrated to convection-zone depth of (ASTEC) stellar models

(2) Nonlocal parameter for turbulent pressure p_t: calibrated to max(p_t) of 3D simulations

(3) Nonlocal parameter for convective heat flux: calibrated to fit Legacy linewidths

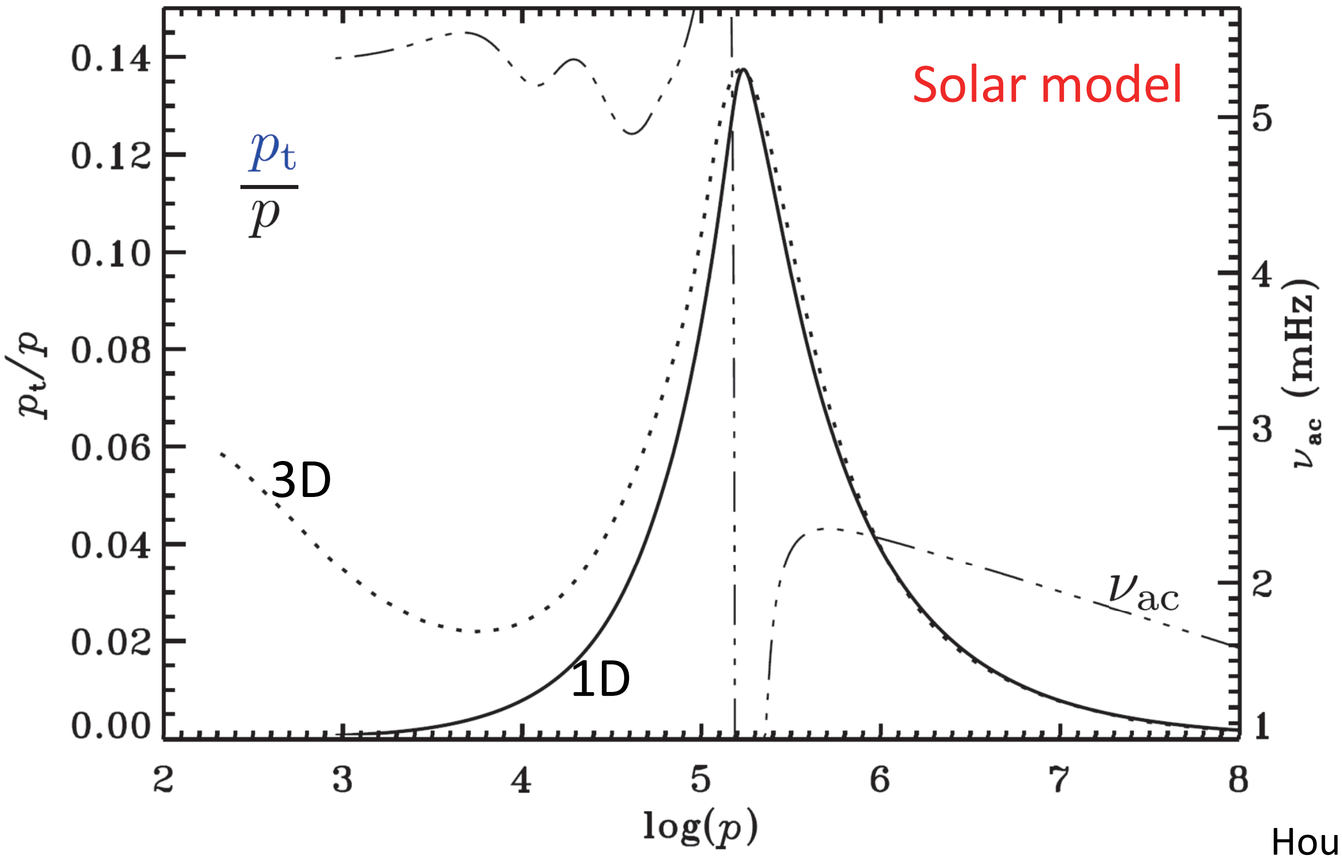
(4,5) Anisotropy Φ of convective velocity field: calibrated to fit Legacy linewidths with guidance from 3D simulations

1D models including **turbulent pressure** $p_{\rm t}$

$$\frac{\partial}{\partial m}(p_{\rm g} + p_{\rm t}) = -\frac{1}{4\pi r^2}\left(\frac{Gm}{r^2}\right)$$

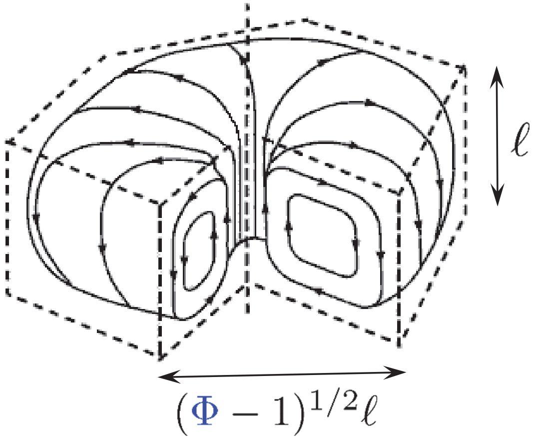
$$p_{\rm t} := \overline{\rho\, ww}$$

$$\boldsymbol{u} = (u, v, w)$$



Houdek et al. (2017)

Anisotropy of the turbulent velocity field

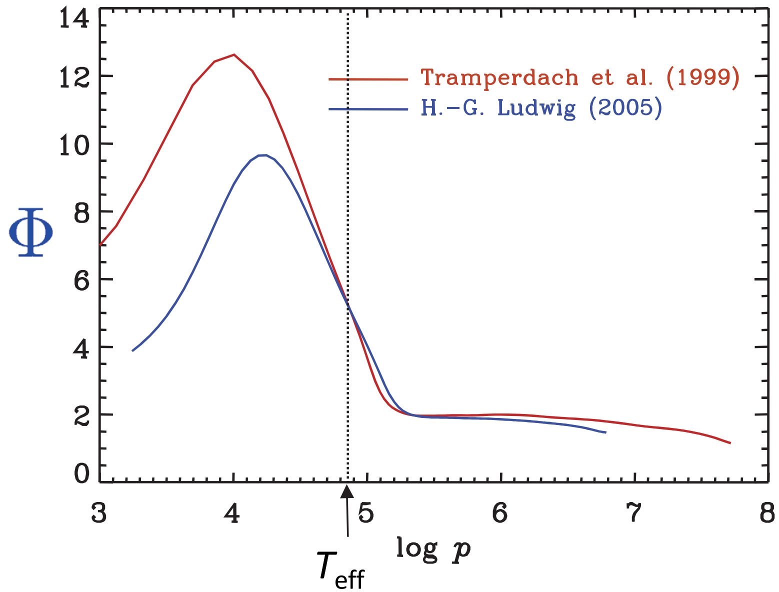


Anisotropy factor:

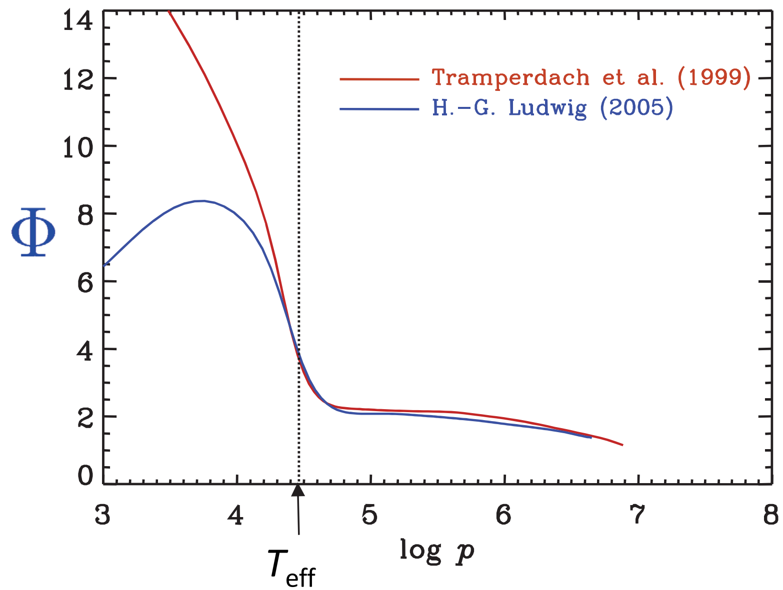
$$\Phi = \frac{\langle u^2 \rangle + \langle v^2 \rangle + \langle w^2 \rangle}{\langle w^2 \rangle}$$

$\boldsymbol{u} = (u, v, w)$ ...turbulent velocity field

Solar model

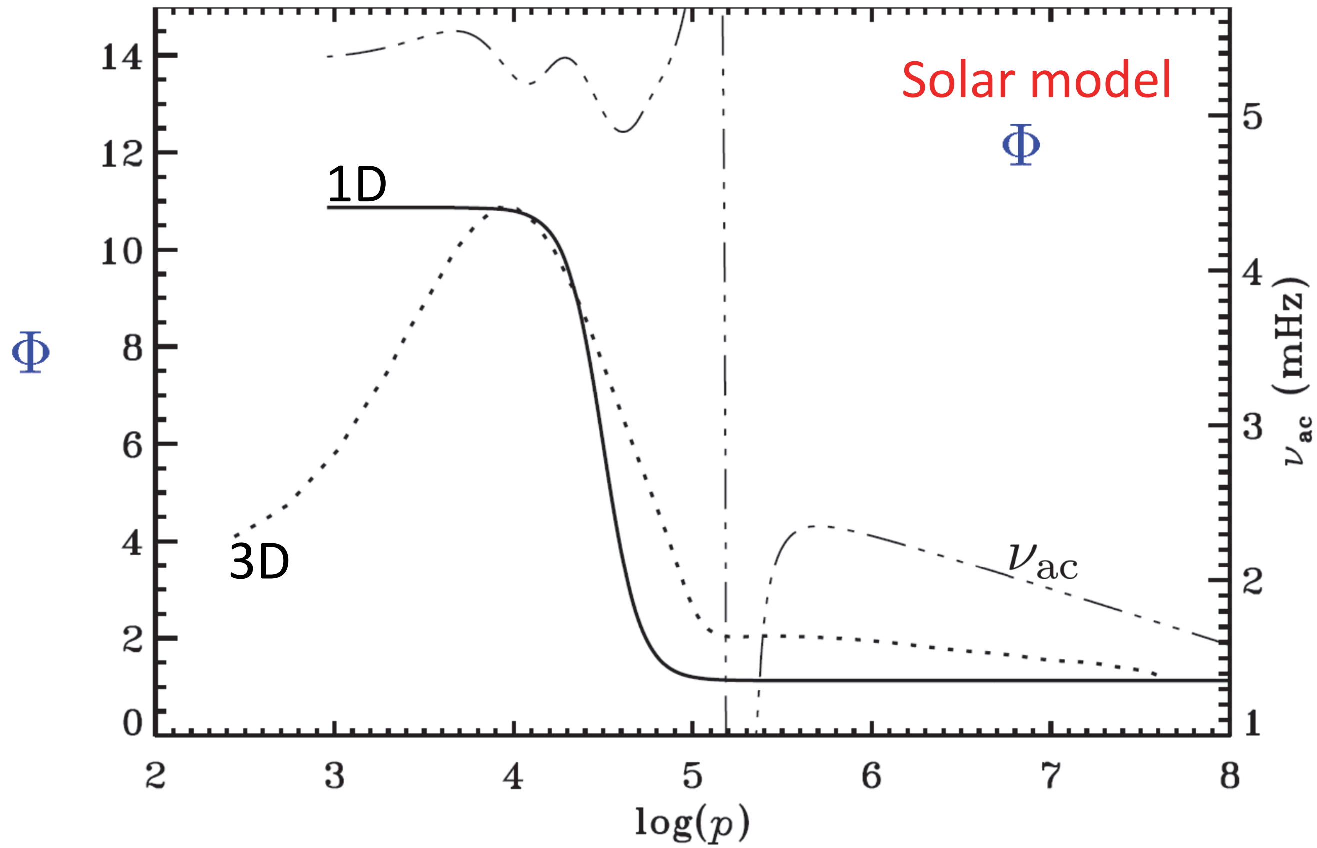


Model of Procyon A



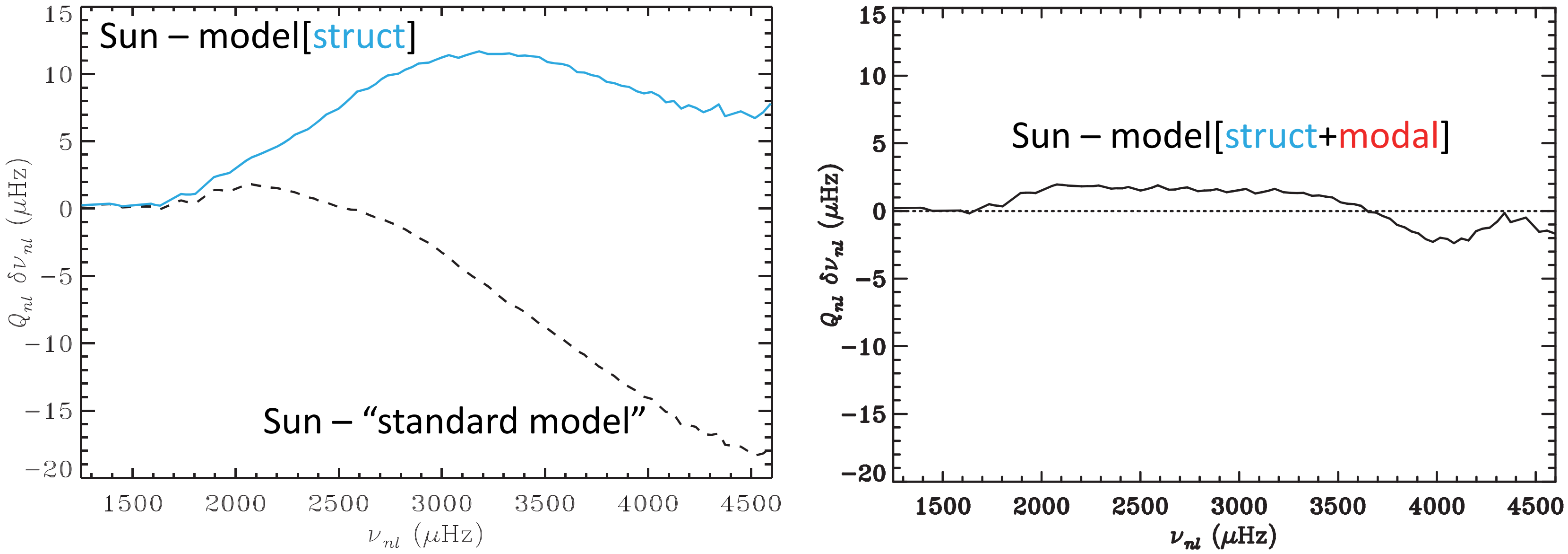
Anisotropy of the turbulent velocity field

$$\Phi = \frac{\langle u^2\rangle + \langle v^2\rangle + \langle w^2\rangle}{\langle w^2\rangle}$$



Solar model: “surface effects”

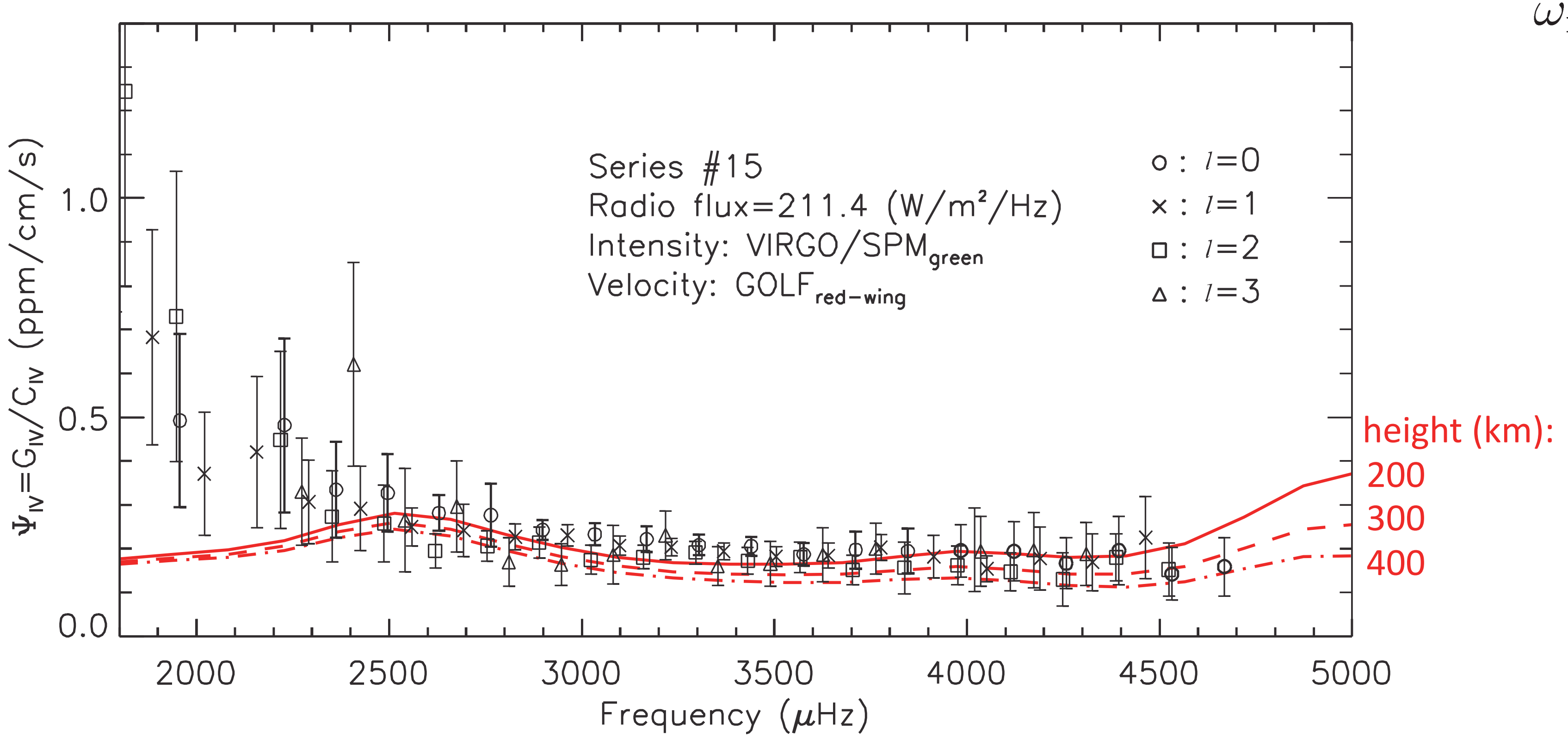
Houdek, Trampedach et al. (2017)



Sun: Virgo and GOLF (data: Jimenez et al 2002)

Amplitude ratios ΔL/ΔV (ppm cm^{-1} s)

$$\Delta L/\Delta V =: \frac{\delta L/L}{\omega_{\rm r} r\ \delta r/r}$$

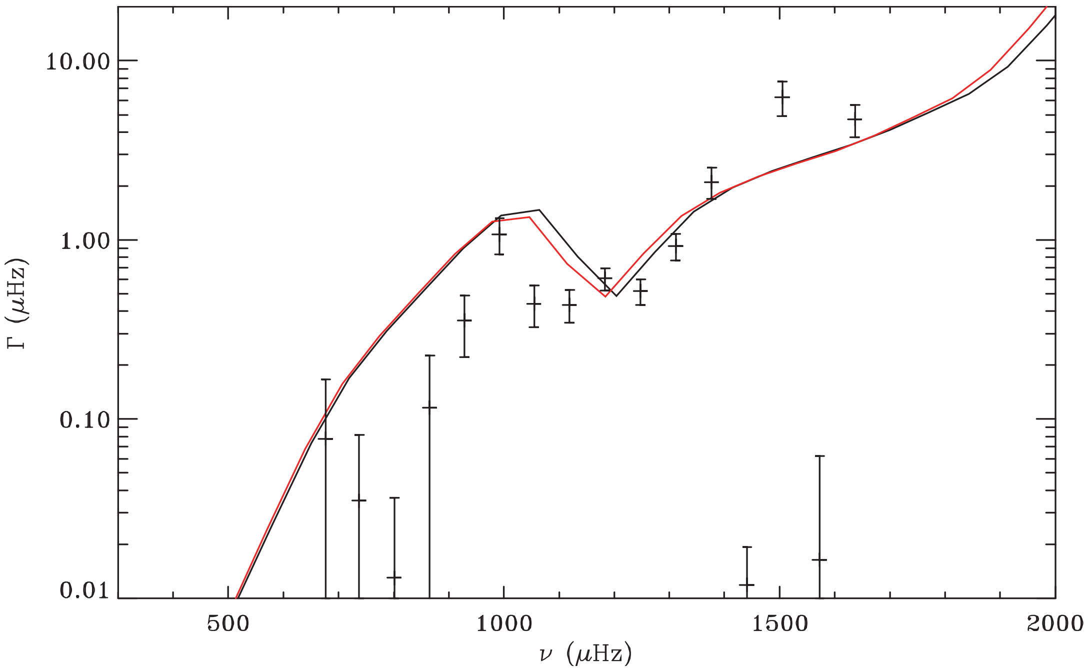


Sub giants

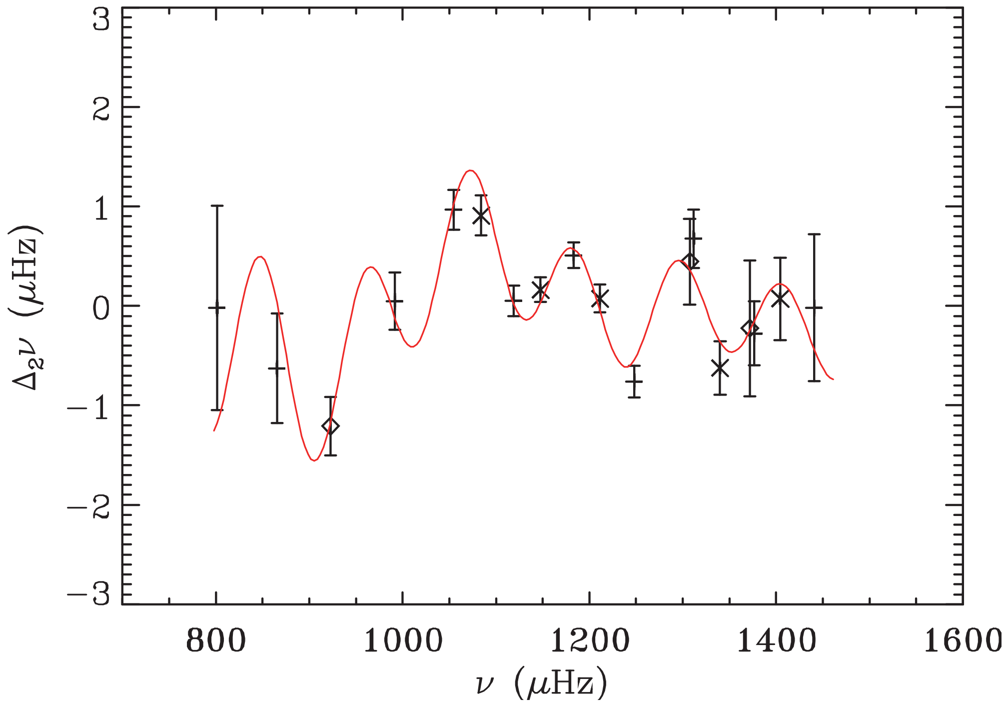
μ Herculis: $T_{\rm eff}$ = 5649 K ; log g = 4.029

(Grundahl et al. 2017)

Linewidths / damping rates



Acoustic glitches (2nd ν-differences)



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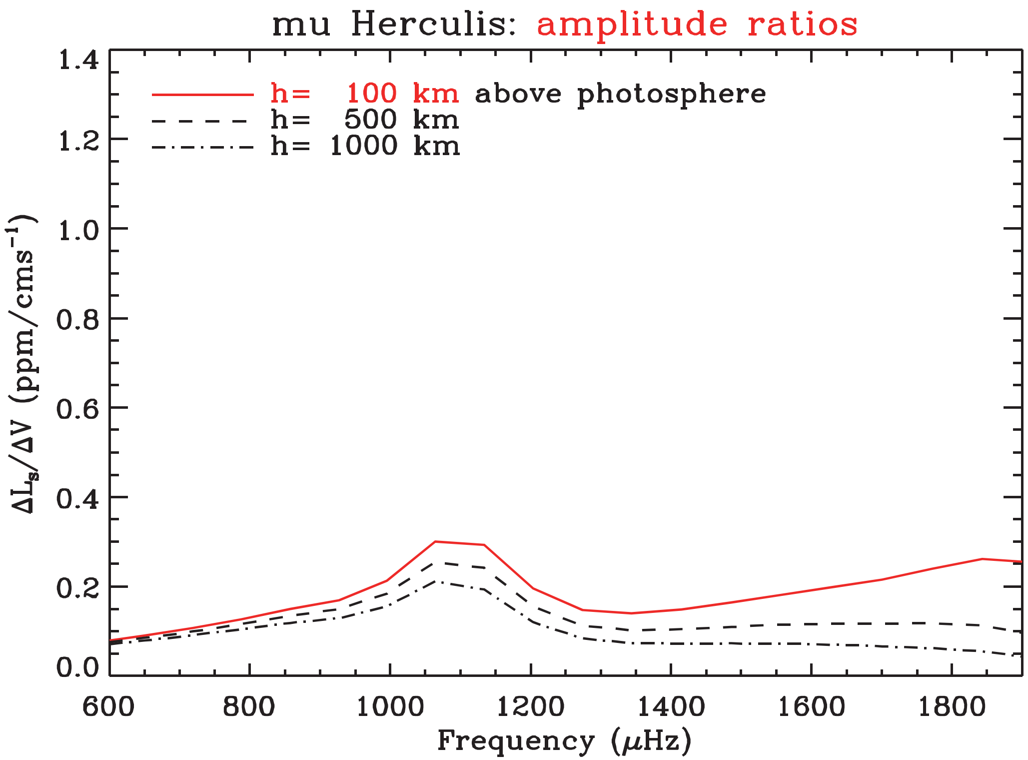

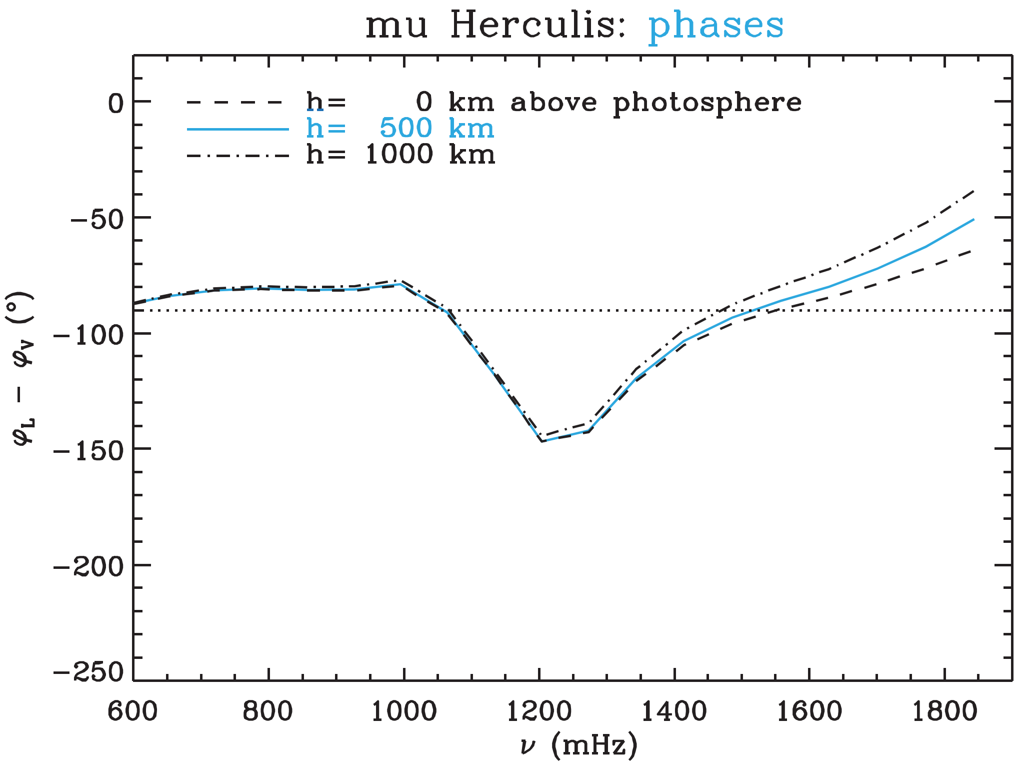

Summary / Conclusion

- Amplitude ratios and pulsation phases provide valuable information on the shape of the pulsation eigenfunctions and consequently also on the stellar stratification, without the need of a model for stochastic mode excitation.

- This (observational) information constrains the physical processes in the still ill-understood surface layers.

- Convection dynamics and nonadiabaticity crucially modify the oscillation properties in the surface layers: the use of (improved) time-dependent convection models is essential to reproduce the observations.

- **TESS**/**PLATO** will observe stars bright enough for contemporaneous ground-based observations in spectroscopy (SONG !!!).