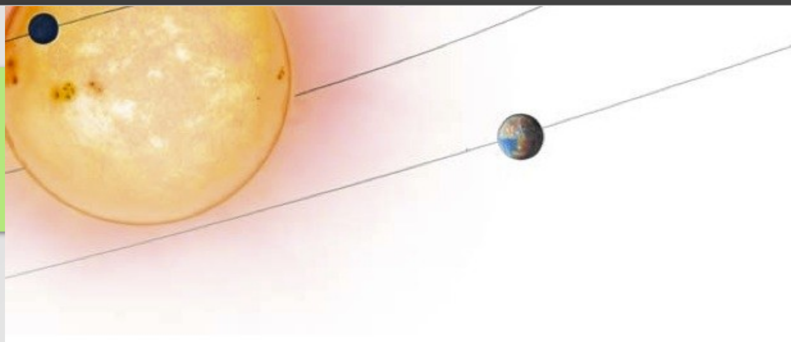
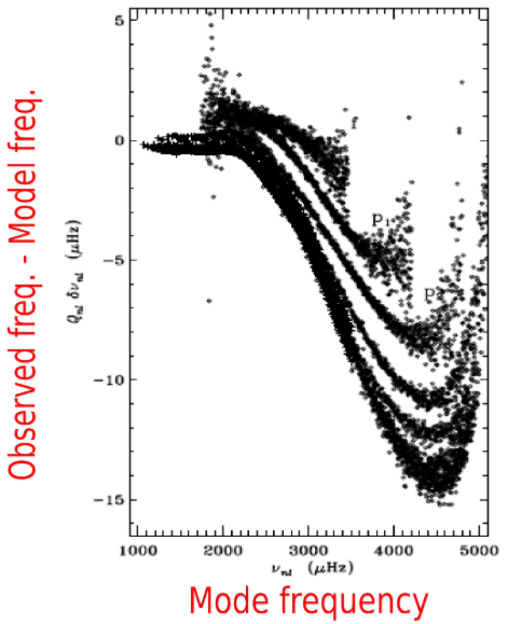


Mode near surface effects

PLATO- PSM - WP 126 100

R. Samadi

Introduction



Rosenthal et al (1999)

Systematic difference between observed and theoretical mode frequencies → the signature of poor descriptions of both surface layers *and* mode physics

Several possible origins:

* structural effects:
  - contribution of turbulent pressure to stratification
  - convective 'back-warming' (e.g. Trampedach et al. 2013);
* modal effects:
  - coupling with turbulent pressure (Houdek+2010, Houdek+2017, Sonoi et al 2017)
  - non-adiabatic effects (e.g. Houdek+2010, Grigahcène+2012, Houdek+2017)
  - wave propagation through an inhomogneous flow = Mode scattering, advection, Reynolds stress (e.g. Brown 1984, Bohmer & Rudiger 1999, Zhugzhda & Stix 2004, Bhattacharya+2015)

Adiabatic pulsations

$$\frac{\delta p_{\rm tot}}{p_{\rm tot}} = \frac{p_{\rm th}}{p_{\rm tot}} \frac{\delta p_{\rm th}}{p_{\rm th}} = \Gamma_1^{\rm r} \frac{\delta \rho}{\rho} \cdot$$

"Reduced $\Gamma 1$"
RGM

Rosenthal+ 1995:

$$\delta P_t = 0$$

$$\frac{\delta p_{\rm turb}}{p_{\rm turb}} \simeq \frac{\delta p_{\rm tot}}{p_{\rm tot}} \simeq \frac{\delta p_{\rm th}}{p_{\rm th}} = \Gamma_1 \frac{\delta \rho}{\rho},$$

"Gas $\Gamma 1$"
GGM

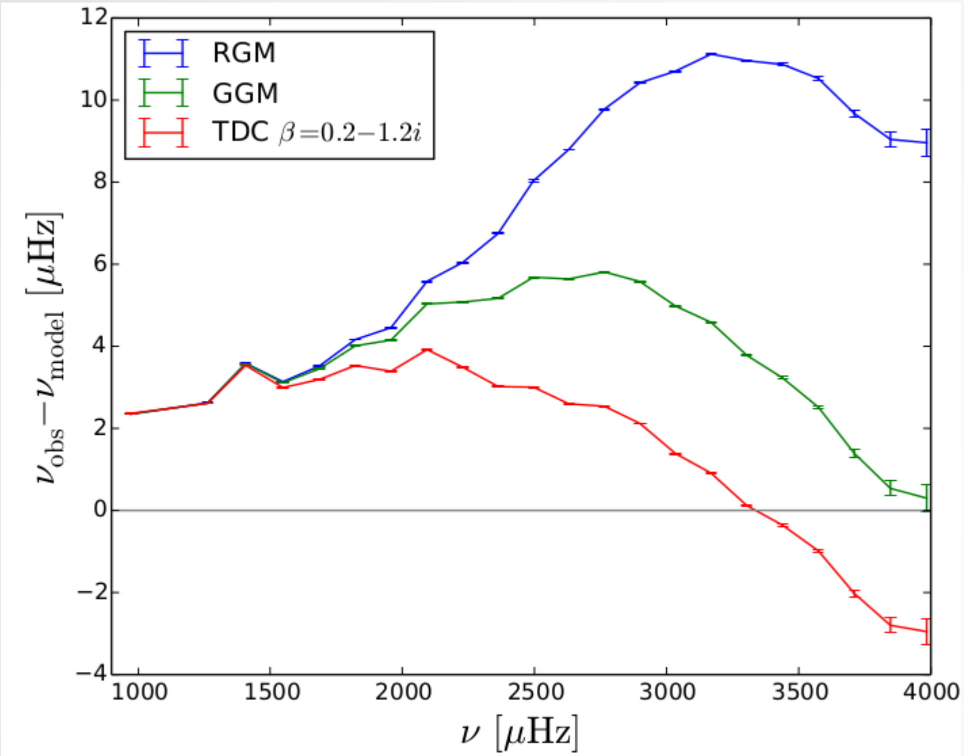
Rosenthal+ 1999:
Perturb. of turbulent pressure scales a the gas pressure → lack of physical justification

$$\frac{\delta p_{\rm turb,l}}{p_{\rm tot}} = \Pi \frac{\delta p_{\rm th}}{p_{\rm tot}} + \Xi \frac{\xi}{R}$$

Theoretical modeling of the perturbation of the turbulent pressure in the adiabatic limit: Sonoi+ 2017

Based on Grabriel's time-dependent convection (**TDC**) formalism (Gabriel et al 1975, Grigahcene et al 2005)
Includes non-local description of convection, controlled by two parameters (*a* and *b*) adjusted from a solar 3D hydro model

Adiabatic pulsations

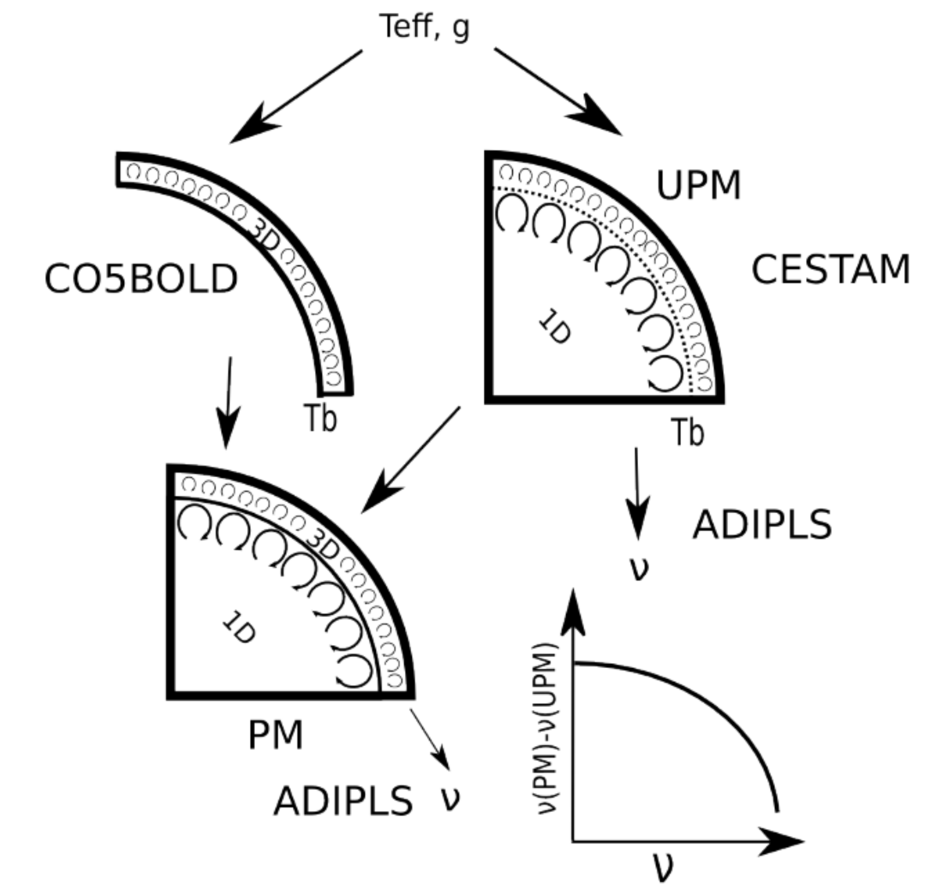


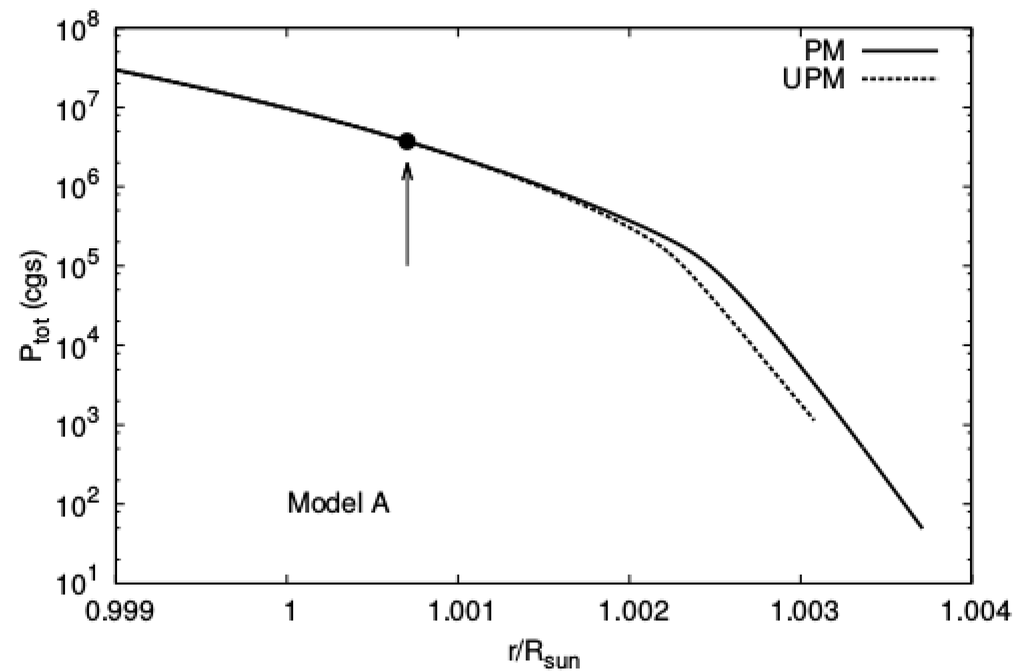
Three adiabatic treatments:
RGM - “Reduced Γ1”
GGM - “Gas Γ1”
TDC – adiabatic limit (Sonoi+ 2017)

$$\frac{\delta p_{\rm turb,l}}{p_{\rm tot}} = \Pi \frac{\delta p_{\rm th}}{p_{\rm tot}} + \Xi \frac{\xi}{R}$$

→ The first term dominates, this justifies the relation between δP_t and δPg (GGM) but with a coefficient different to one and varying spatially.

Patched models



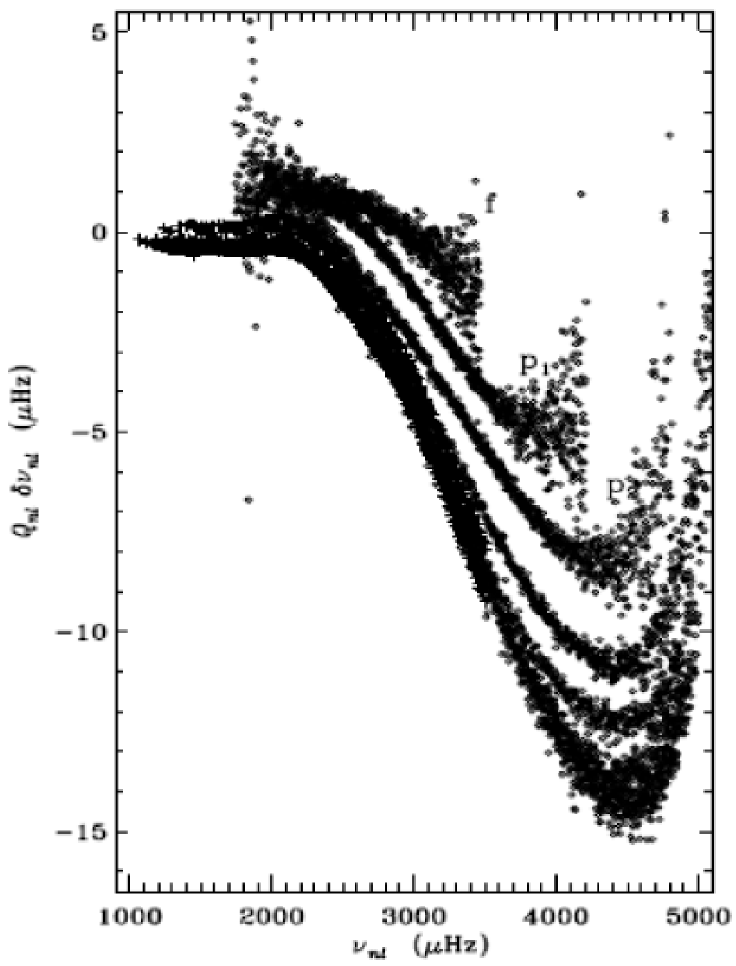


PM has larger radius due to the additional support by turbulent pressure (e.g. Rosenthal+ 1999) and back-warming (Trampedach+ 2013) This effect becomes larger with increasing Teff or decreasing gravity g (e.g. Sonoi+ 2015)

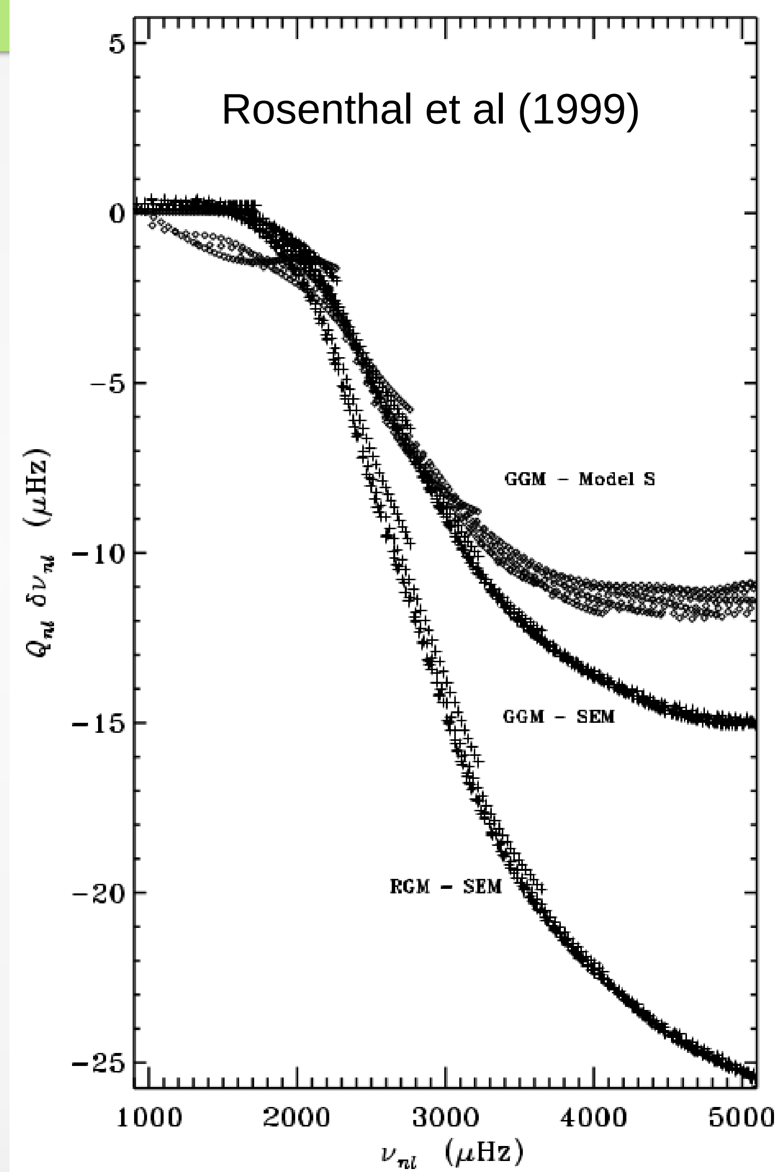
Matching procedure (Jørgensen+ 2018):
- Must be done at sufficient depth
- Choice of the variable (r,T,G1,..) has non-negligible impact

Case of the the Sun

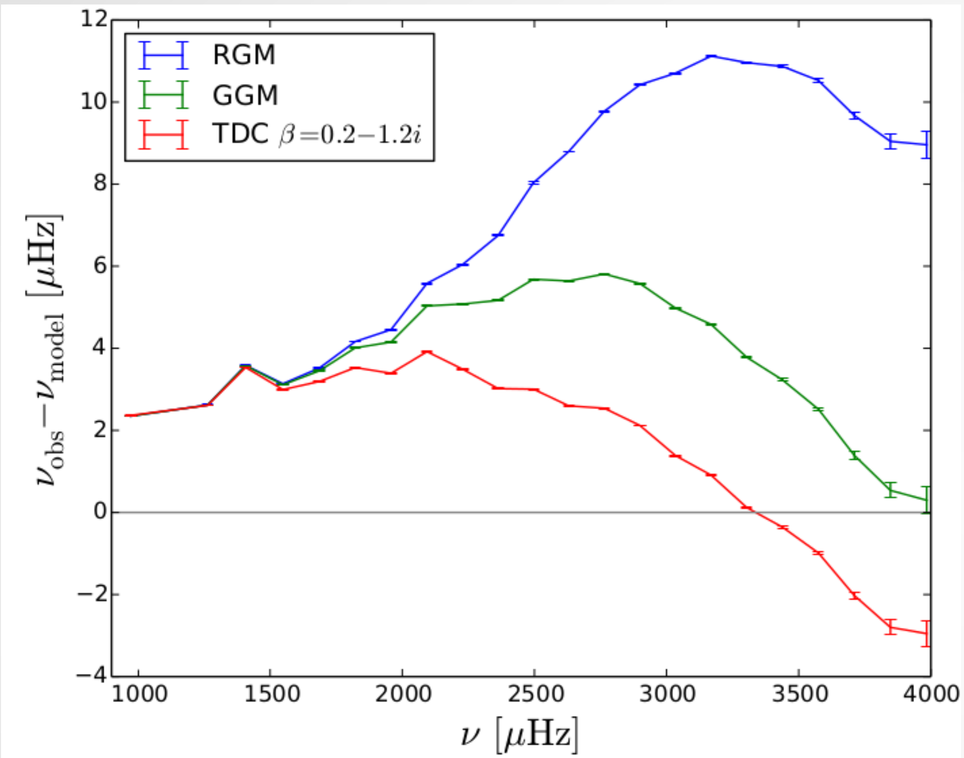
Observed freq. - Model freq.



Mode frequency



Adiabatic pulsations



Three adiabatic treatments:

- RGM - “Reduced Γ1”
- GGM - “Gas Γ1”

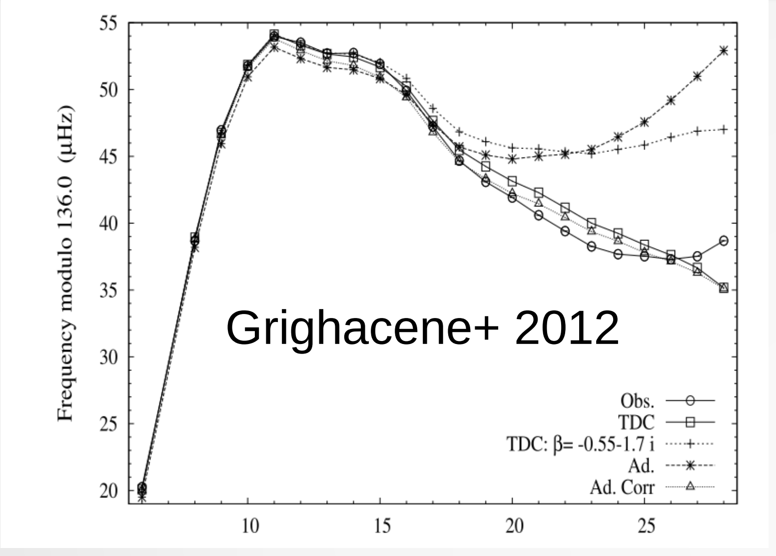
$$\frac{\delta p_{\rm turb}}{p_{\rm turb}} \simeq \frac{\delta p_{\rm tot}}{p_{\rm tot}} \simeq \frac{\delta p_{\rm th}}{p_{\rm th}} = \Gamma_1 \frac{\delta \rho}{\rho},$$

- **TDC – adiabatic limit** (Sonoi+ 2017)

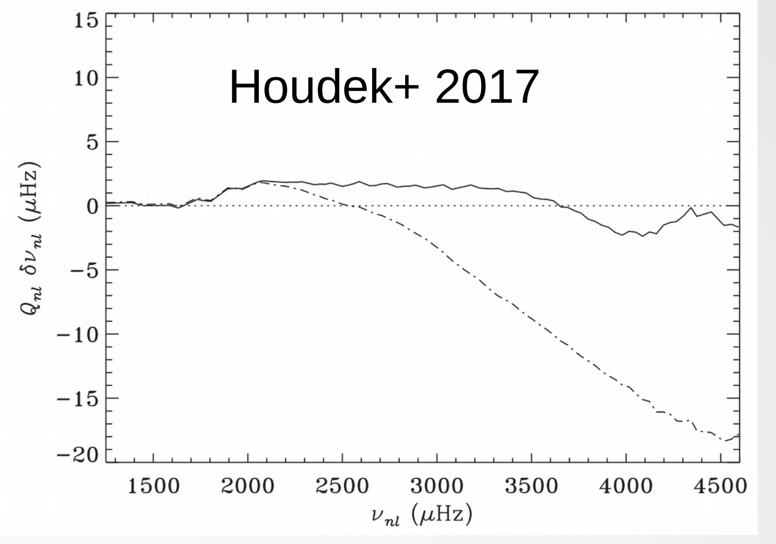
$$\frac{\delta p_{\rm turb,l}}{p_{\rm tot}} = \Pi \frac{\delta p_{\rm th}}{p_{\rm tot}} + \Xi \frac{\xi}{R}$$

→ The first term dominates, this justifies the relation between δP_t and δPg (GGM) but with a coefficient different to one and varying spatially.

Non-adiabatic pulsations



Gabriel's TDC formalism (MAD code)



Gough' s TDC formalism (Gough 1977, Balmforth 1992, Houdek+ 1999):

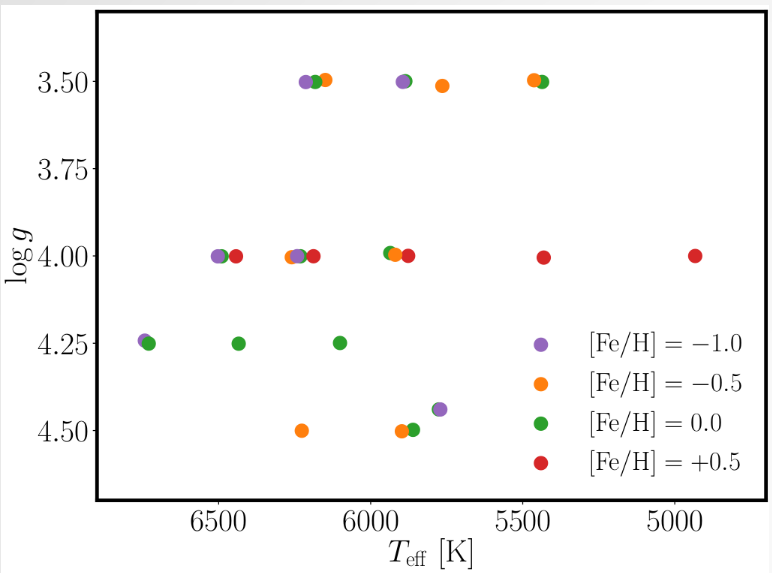
Both calculation include both perturb. of turbulent pressure (δP_t) and non-adiabatic effects

TDC models involve several free parameters:

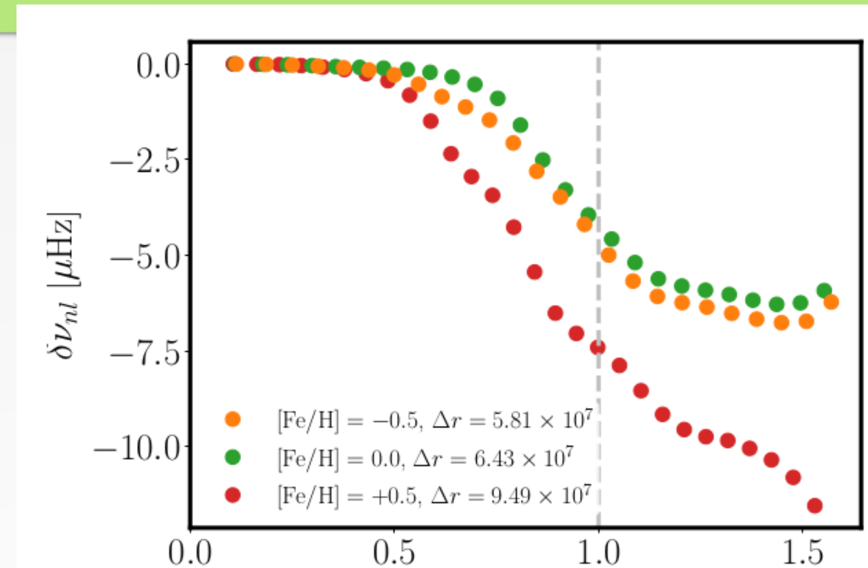
- Anisotropy factor (Φ)
- non-local parameters (*a* and *b*)
- Complex parameter in the entropy pertubation (→ MAD code)

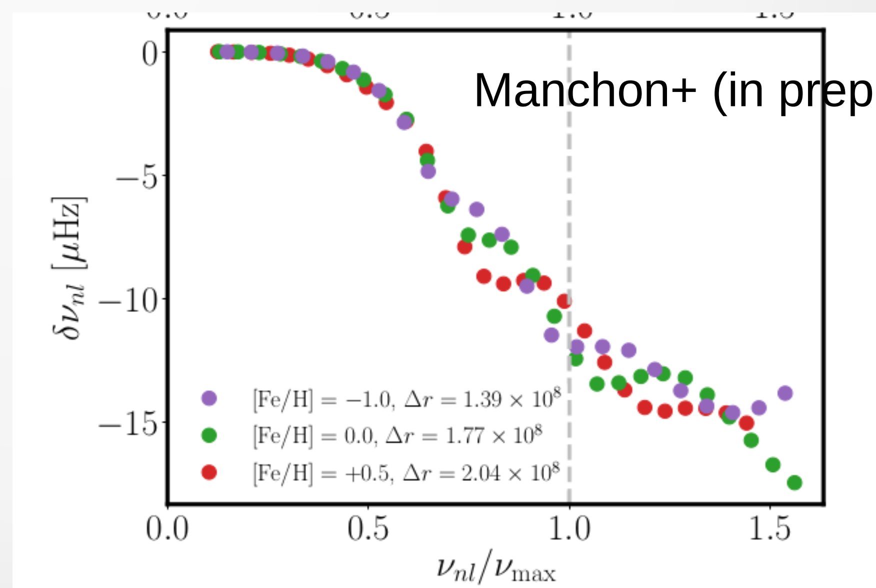
See the review by Houdek & Dupret (2015)

Surface elevation and metal abundance



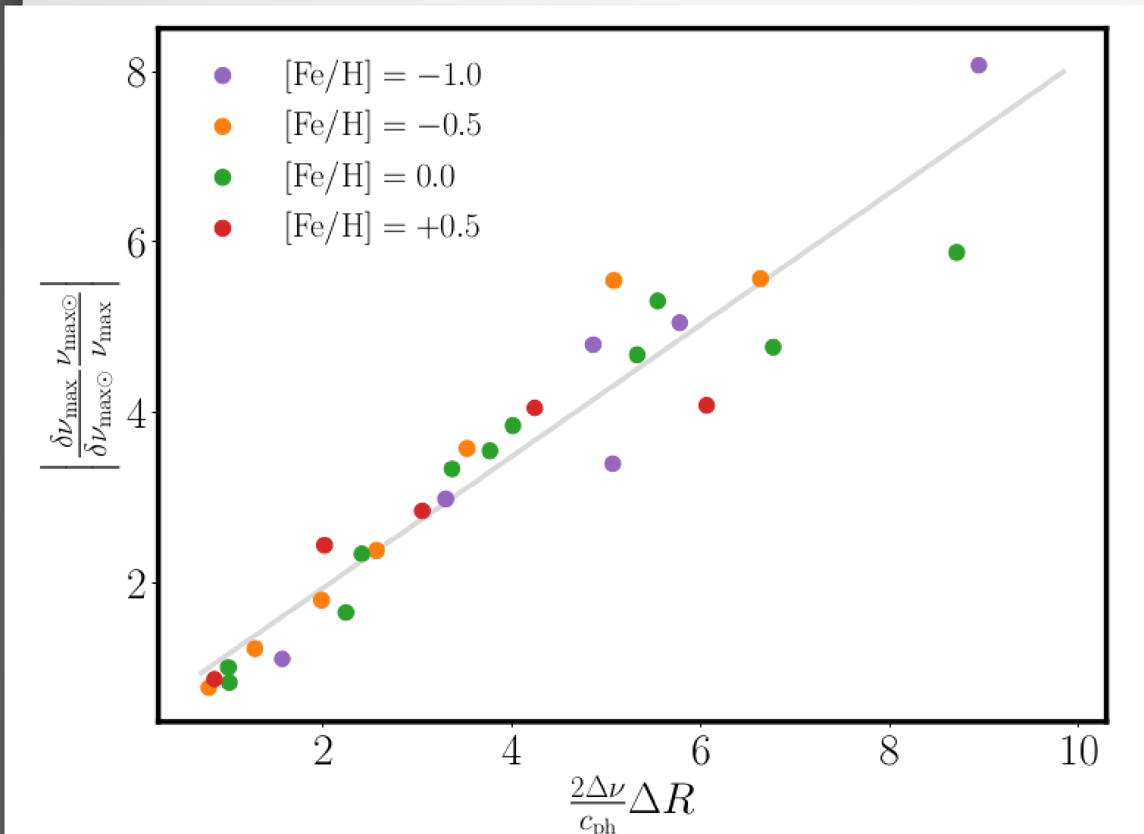
CIFIST grid of hydri. 3D models computed with the CO5BOLD code (Caffau et al, GEPI)





Manchon+ (in prep.)

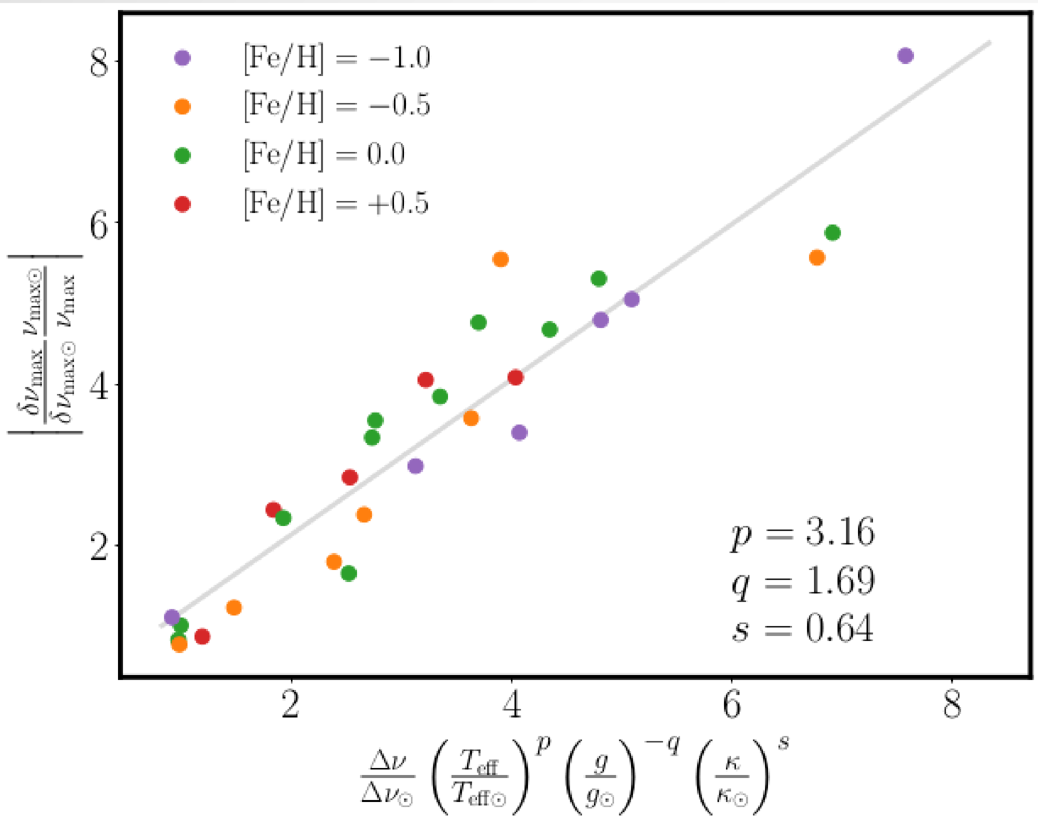
Surface elevation and metal abundance



Rosenthal+ 1999 – following Christensen-Dalsgaard & Thompson (1997) derived:

$$\frac{\delta\nu}{\nu} \simeq \frac{\Delta\nu\Delta r}{c_{\rm ph}}$$

Surface elevation and metal abundance



Rosenthal+ 1999:

$$\frac{\delta\nu}{\nu} \simeq \frac{\Delta\nu\Delta r}{c_{\rm ph}}$$

Manchon+ (in prep.)

$$\Delta r \simeq H_p^{\rm PM} \frac{p_{\rm turb}}{p_{\rm tot}}$$

$$v_{\rm conv}^2 \propto \frac{T_{\rm eff}^{8/3}}{\rho^{2/3}}$$

Theoretical scaling relation for the elevation:

$$\Delta r \propto \left(\frac{T_{\rm eff}}{T_{\rm eff\odot}}\right)^{10/3} \left(\frac{g}{g_\odot}\right)^{-5/3} \left(\frac{\kappa}{\kappa_\odot}\right)^{2/3}$$

Empirical functionals

$$\frac{\delta\nu}{\nu_{\max}} = a\left[\frac{\nu_{\rm PM}(n)}{\nu_{\max}}\right]^b$$

Kjeldsen+ 2008
Power law
Purely empirical

$$\frac{\delta\nu}{\nu_{\max}} = \frac{a_{3,\rm BG3}}{E}\left(\frac{\nu}{\nu_{\max}}\right)^3$$

Ball & Gizon 2014
“Cubic correction”
(BG3)

Induced by near surface variations of the sound speed (Gough 1990 ; Goldreich+ 1991)

$$\frac{\delta\nu}{\nu_{\max}} = \frac{1}{E}\left(a_{-1,\rm BG4}\left(\frac{\nu}{\nu_{\max}}\right)^{-1} + a_{3,\rm BG4}\left(\frac{\nu}{\nu_{\max}}\right)^3\right)$$

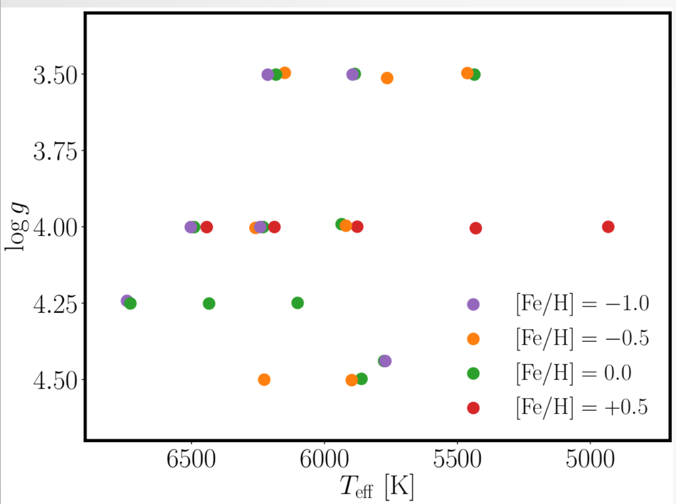
Ball & Gizon 2014
‘Inverse cubic’ correction (BG4)
Induced by near surface variations of the pressure scale-height (→ “surface elevation)

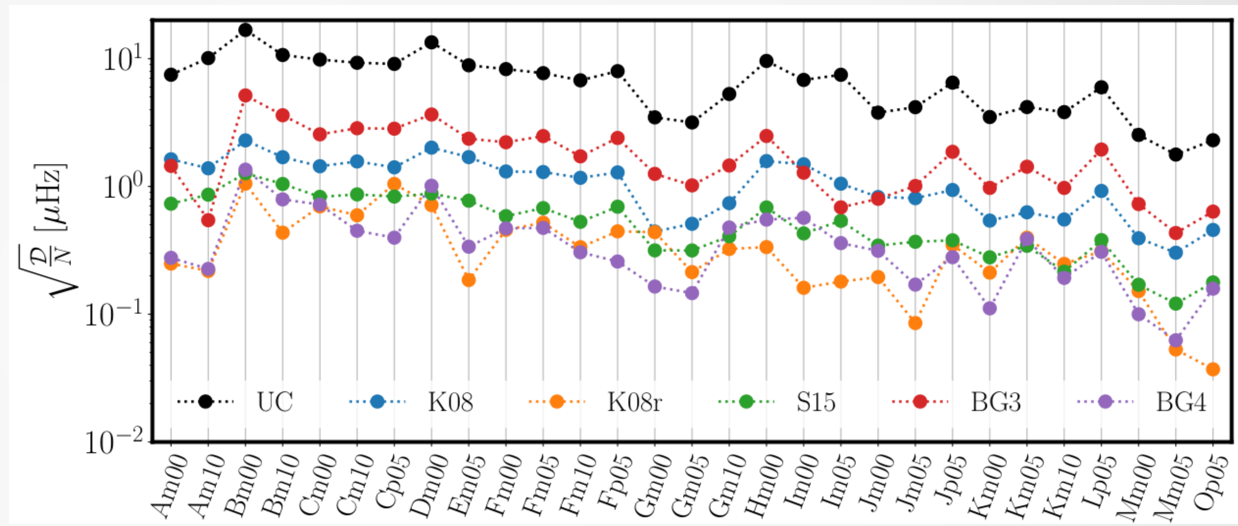
$$\frac{\delta\nu}{\nu_{\max}} = \alpha\left[1 - \frac{1}{1 + \left(\frac{\nu_{\rm PM}}{\nu_{\max}}\right)^\beta}\right]$$

Sonoi+ 2015
Modified lorentzian
Purely empirical
At low freq. tends toward Kjeldsen+ 2018 power-law

Empirical functionals: tested against 3D models

Manchon+ (in prep.): overall, BG4 empirical functionals performed better in particular for sub-giants stars because of the presence of mixed mode: agreement with Ball+ 17



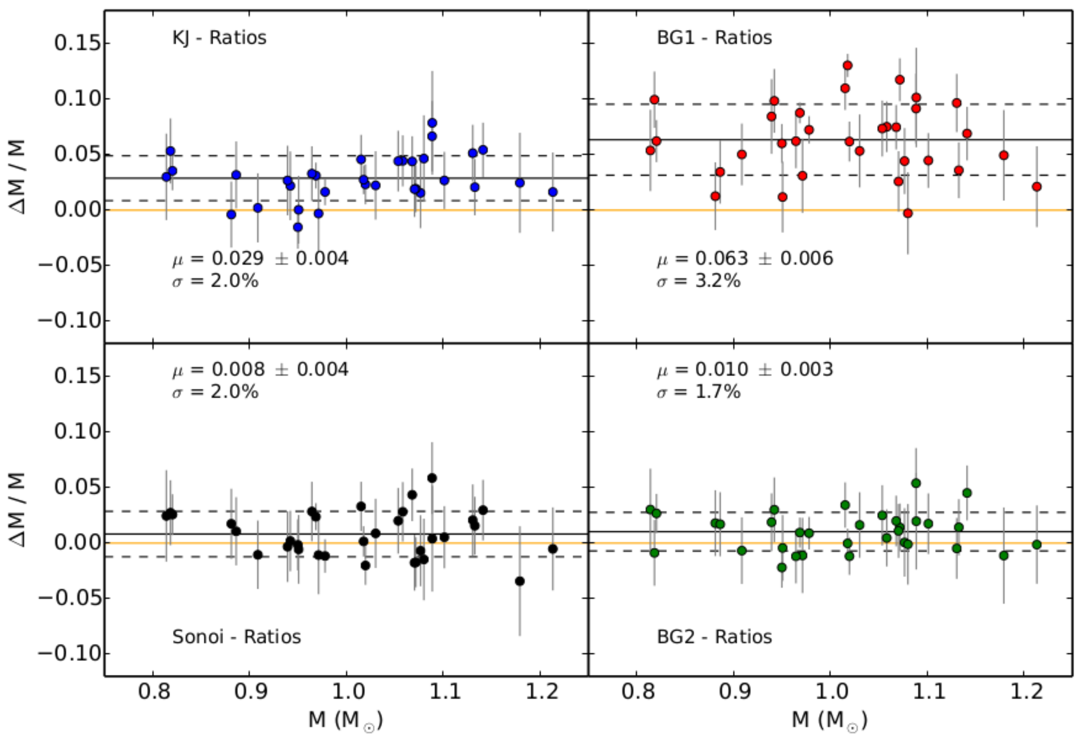


Manchon+ (in prep.) derived scaling laws for each empirical functionals, which depend on the opacity at the photopshere (can easly be derived from grid of 1D stellar models)

$$\log|\alpha| = 1.01 \log \Delta\nu + 3.18 \log T_{\rm eff} - 1.7 \log g + 0.639 \log \kappa - 17.2$$

$$\log \beta = -0.481 \log \Delta\nu - 1.52 \log T_{\rm eff} + 0.814 \log g - 0.306 \log \kappa + 7.89$$

Empirical functionals: tested against stellar seismic constraints



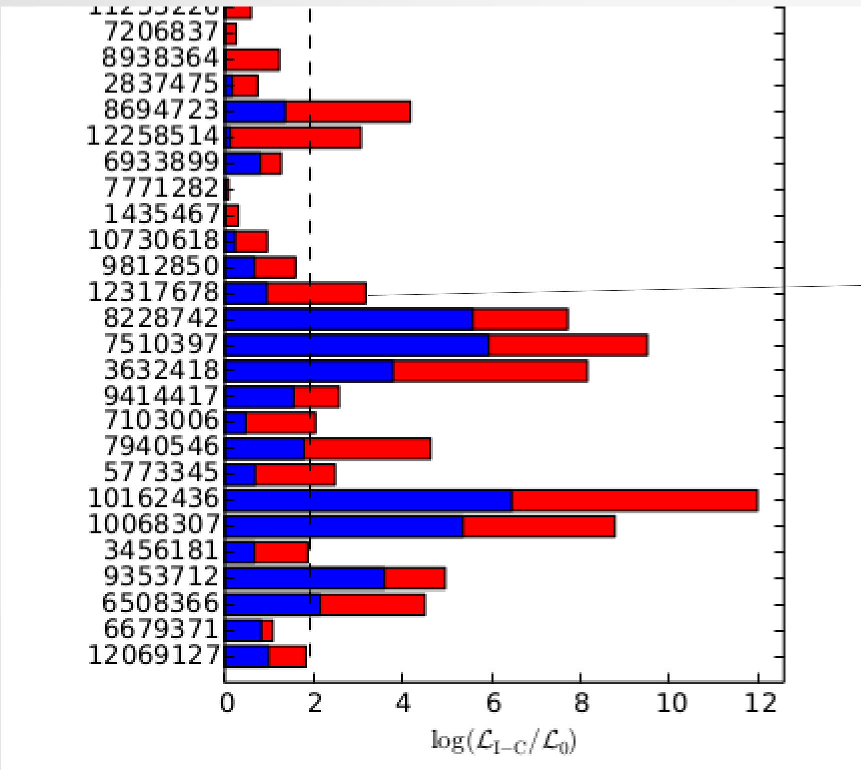
Nsamba+ 2018:
34 solar-like pulsators observed with Kepler

Optimization made with the AIMS code together with MESA grids of stellar models

→ Corrections by Sonoi+ 2015 (modified lorentzian) and BG4 (inverse-cubic) yield the least internal systematics:

- Radius: 0.9% and 0.8%
- Mass: 2.0% and 1.7%
- Age: 8.2% and 7.3%

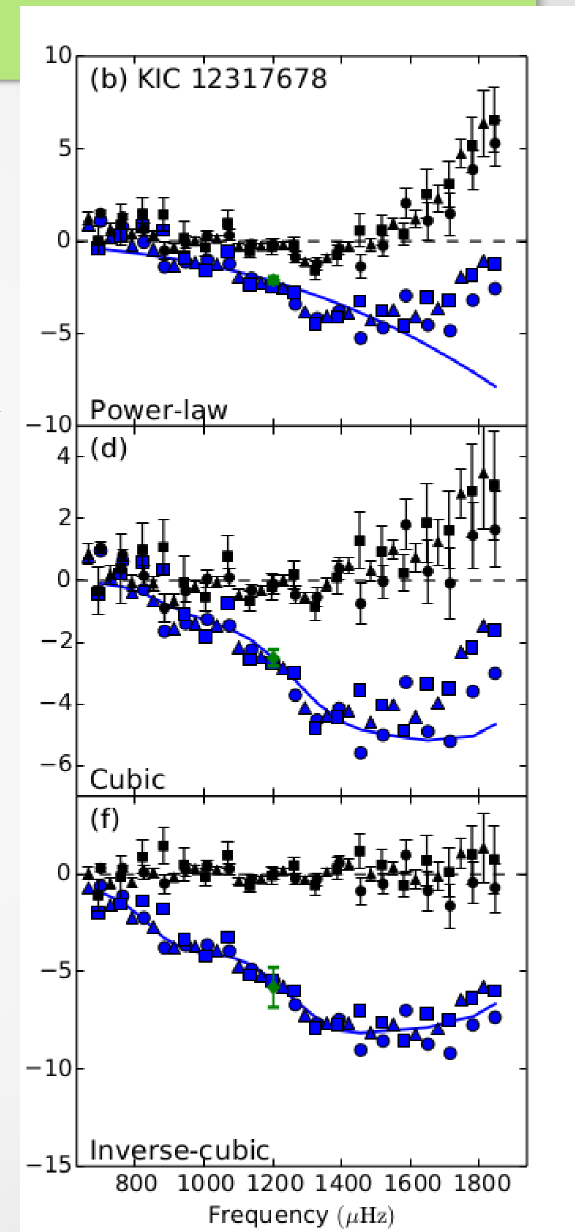
Empirical functionals: tested against stellar seismic constraints



Compton+ 2018 (submitted)

67 solar-type pulsators observed with Kepler + Sun

MESA grids

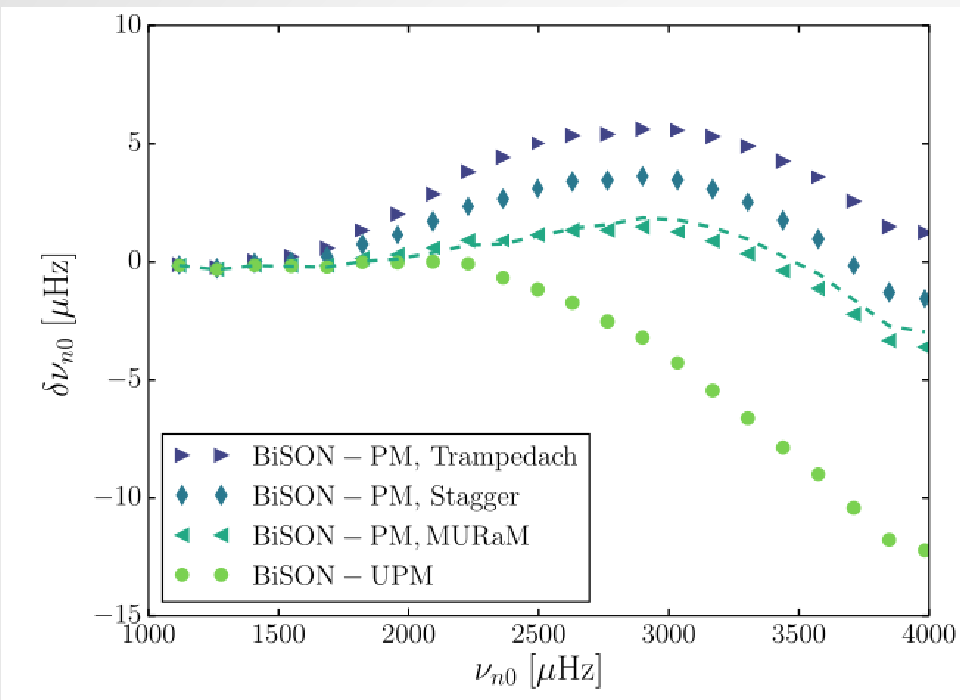


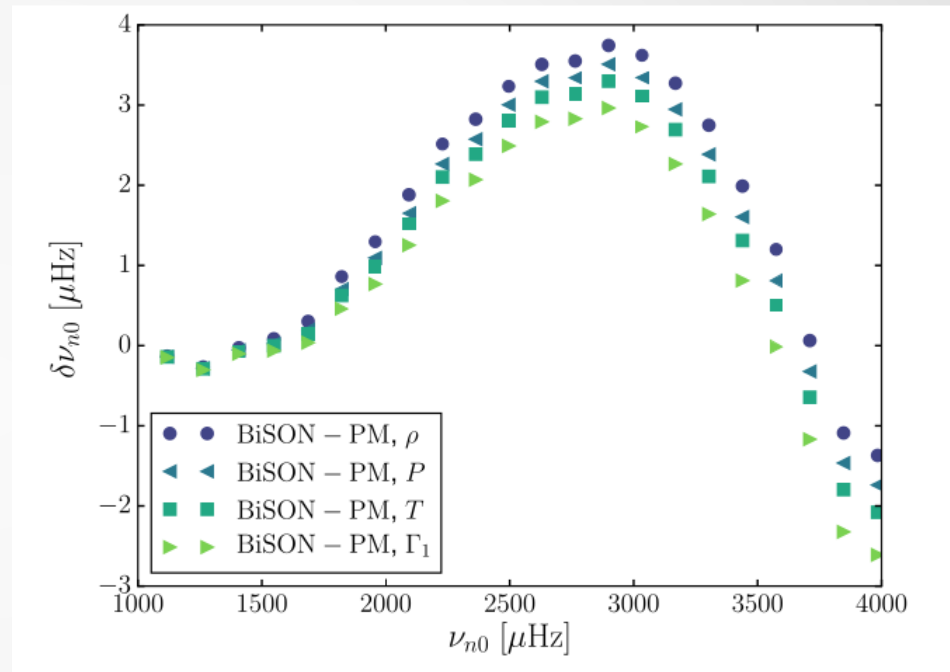
Logarithmic likelihood ratio between inverse-cubic and the power-law (red) or cubic (blue) functionnals

→ w.r.t the power law, inverse cubic functional (BG4 improves fit of individual freq. but in some cases leads to over fitting problem

Patched models: tested against solar seismic constraints

Jørgensen+ 2017

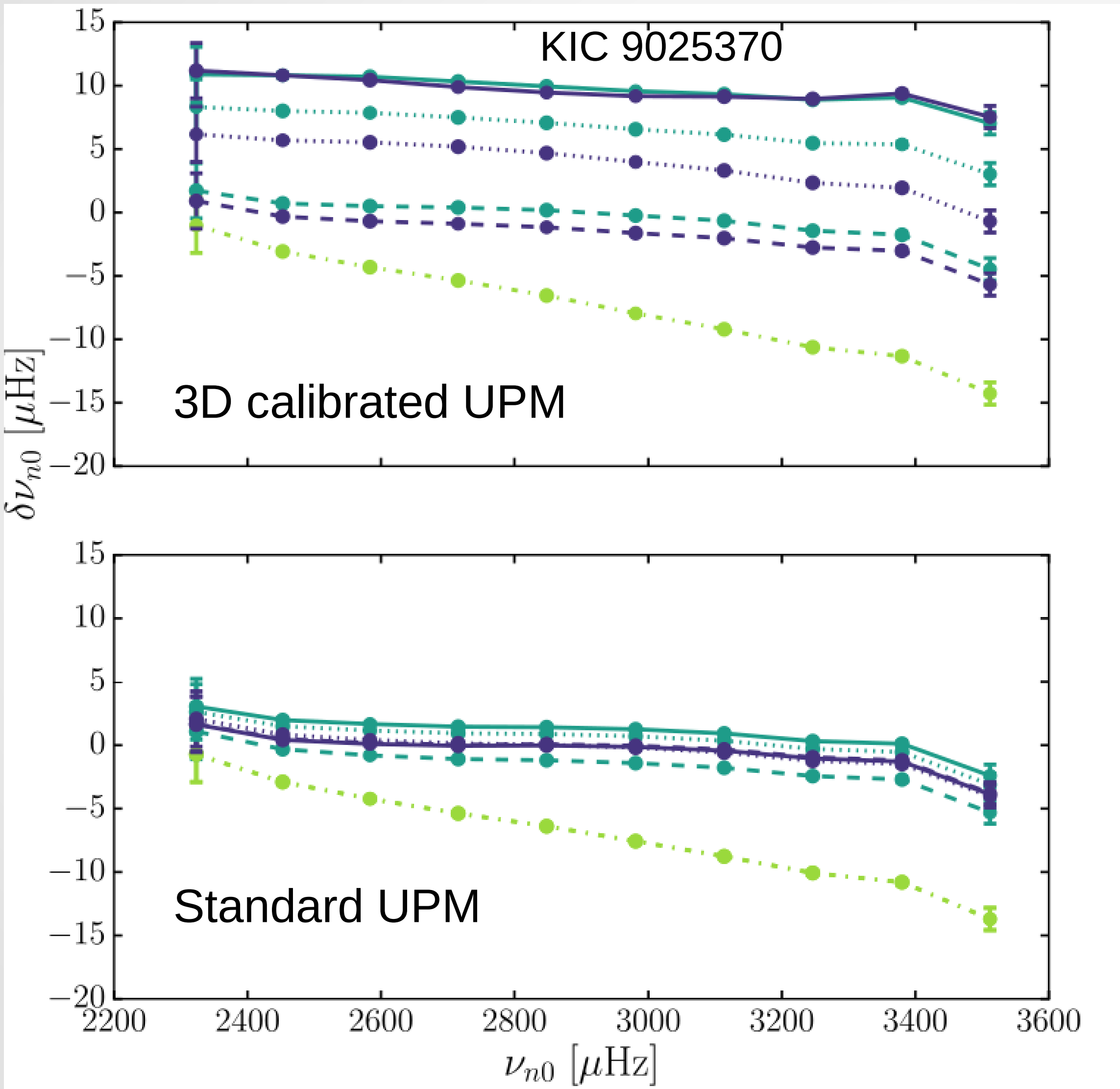




Differences of few µHz between the various 3D hydro models

Choice of the matching quantity has some impact (but less than 1 µHz)

Patched models: tested against stellar seismic constraints

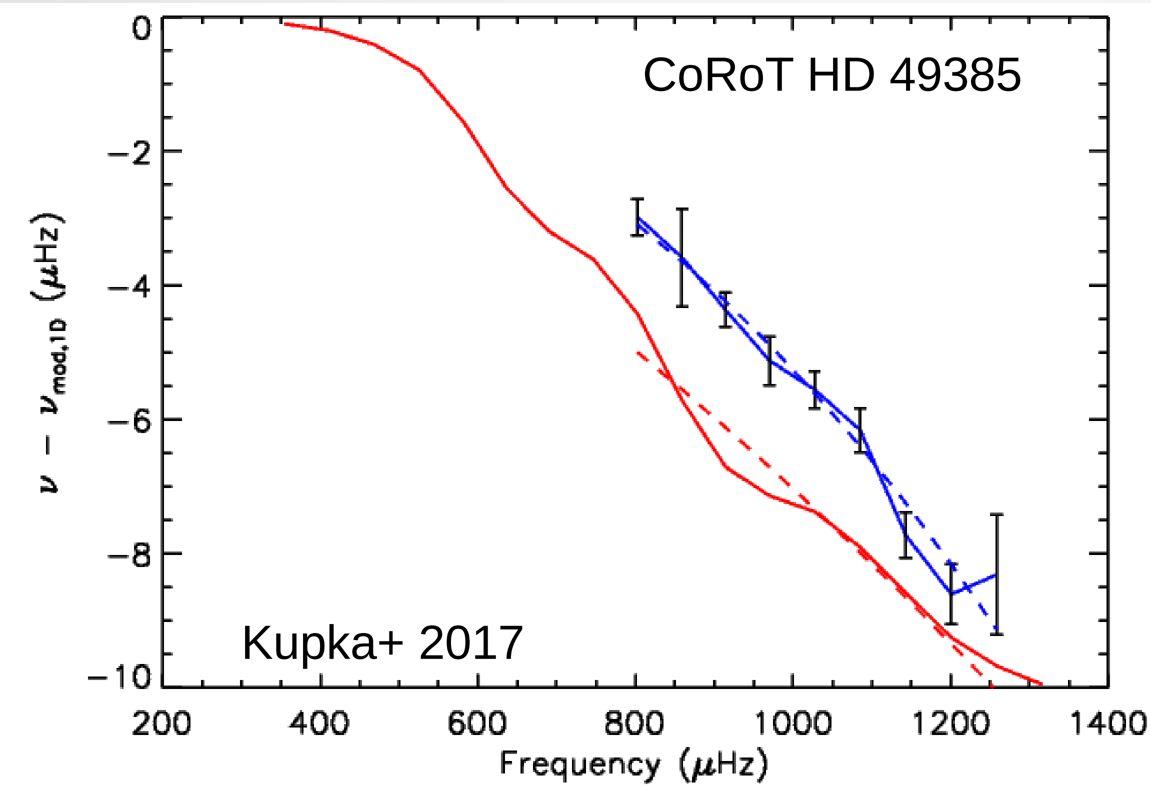


Jørgensen+ 2017:
4 dwarf stars with solar-like pulsations (LEGACY target)

- "3D calibrated UPM": based on a grid of 1D models computed with a T-τ law derived from 3D hydro. models (Mosumgaard+ 2016)
- Standard UPM: based on a grid of standard 1D models (Eddington grey atmosphere)

→ As for the sun, patching 3D atmospheres reduces frequencies shift
→ Important discrepancy between "3D calibrated UPM" and standard 1D model

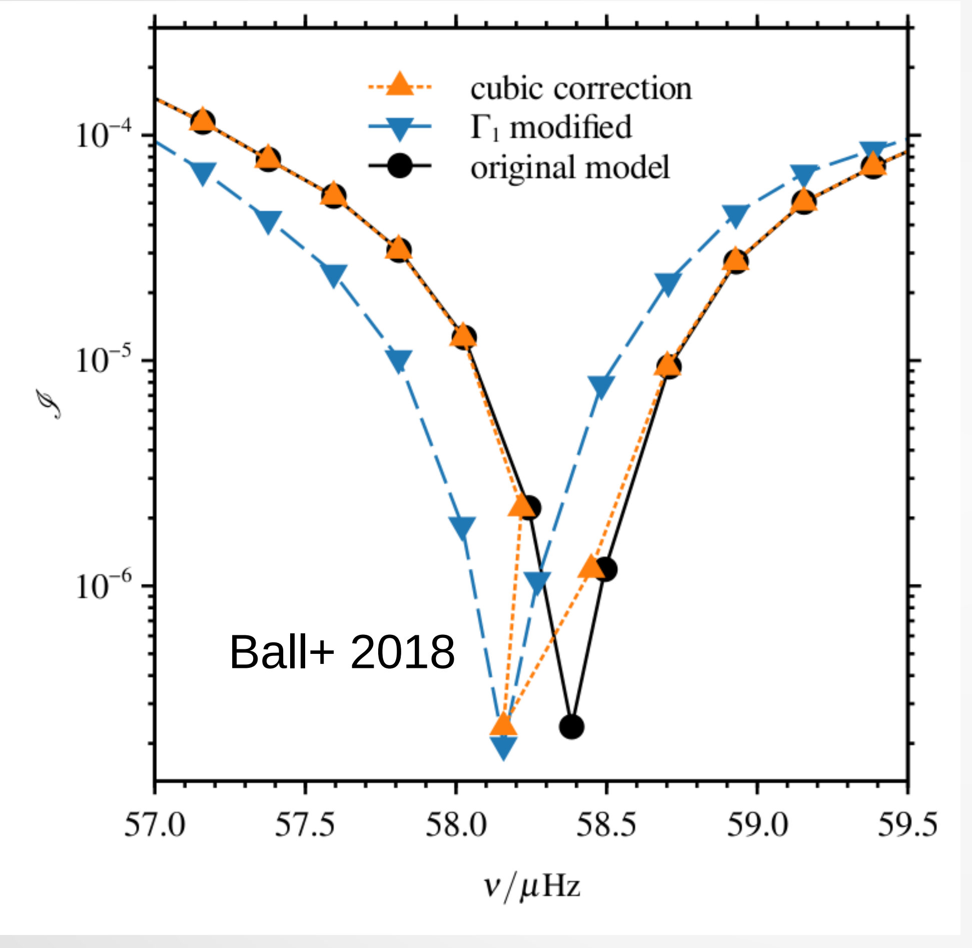
Patched models: tested against stellar seismic constraints



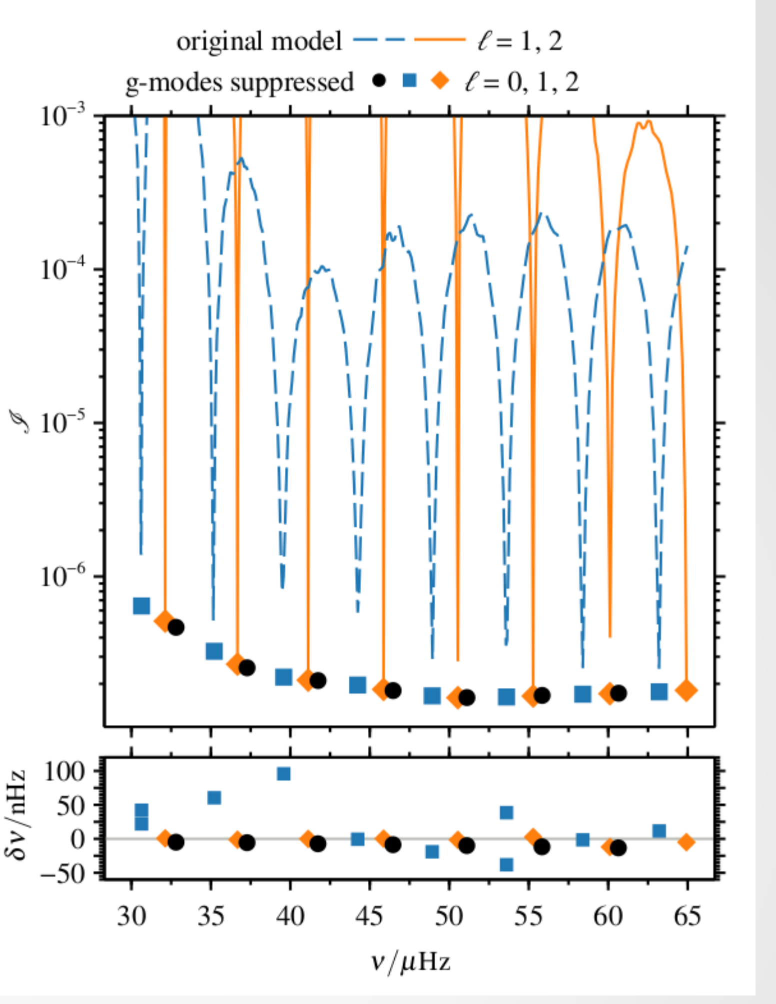
Standard UPM: computed with CESAM code using standard 1D stellar physics (Eddington grey atmosphere) ; matches optimally the bottom of the 3D model **and** CoRoT seismic constraints weakly sensitive to surface effects: 5-point small separations d_{01} and d_{10} (Roxburgh & Vorontsov 2003)

Freq. of patched model are systematically *smaller* than ~ 2 µHz wrt to the measurements

Red giants



→ Two neighbouring mixed modes
are shifted by very different amounts which does
not scales as the ratio of their inertia



Calculation of pure dipolar p-modes
→ g-mode suppression method
Gives unbiaised freq for the p-dominated dipolar modes

Conclusion & perspectives

- No consensus about the modal effects so far…
- Among the empirical/semi-empirical functionals: the inverse cubic correction seams to provide the best results (Ball & Gizon 2014)
- Surface metal abundance has important impacts (through opacity) but can be handled by most of the empirical functionals
- Detailed comparison with observations (other than the Sun) is just starting: differences btw freq. of patched and observations remains within few μHz ; they need to be explained

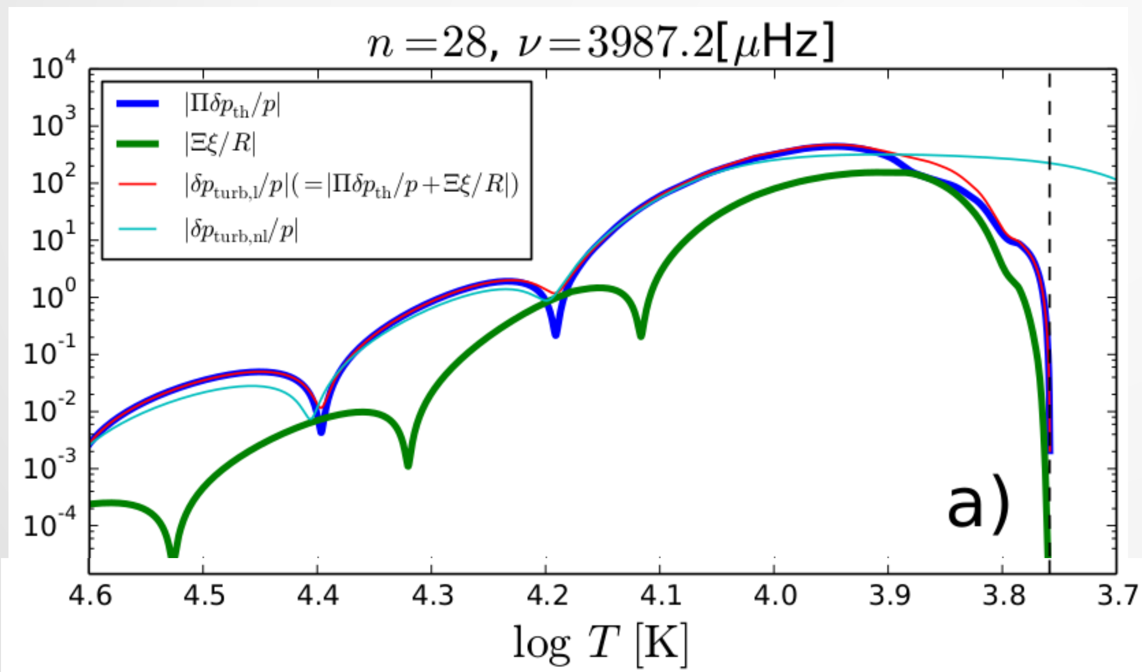
Additional slides

Adiabatic pulsations

Sonoi+ 2017

$$\frac{\delta p_{\mathrm{turb,l}}}{p_{\mathrm{tot}}} = \Pi \frac{\delta p_{\mathrm{th}}}{p_{\mathrm{tot}}} + \Xi \frac{\xi}{R}$$

→ δP_t does varies proportionally with δPgas

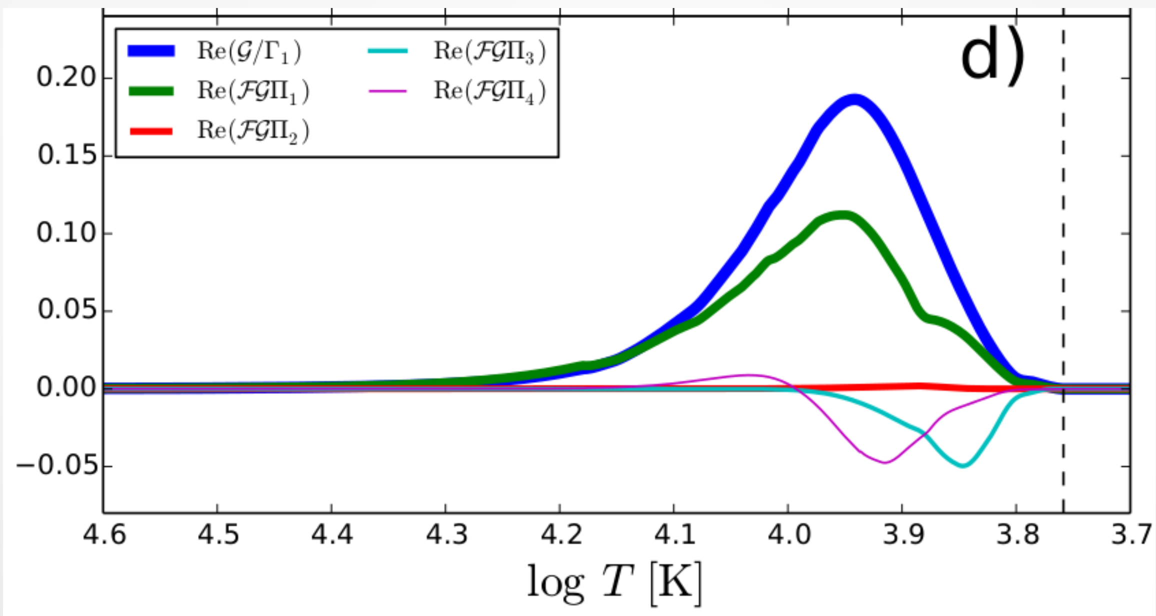


Adiabatic pulsations

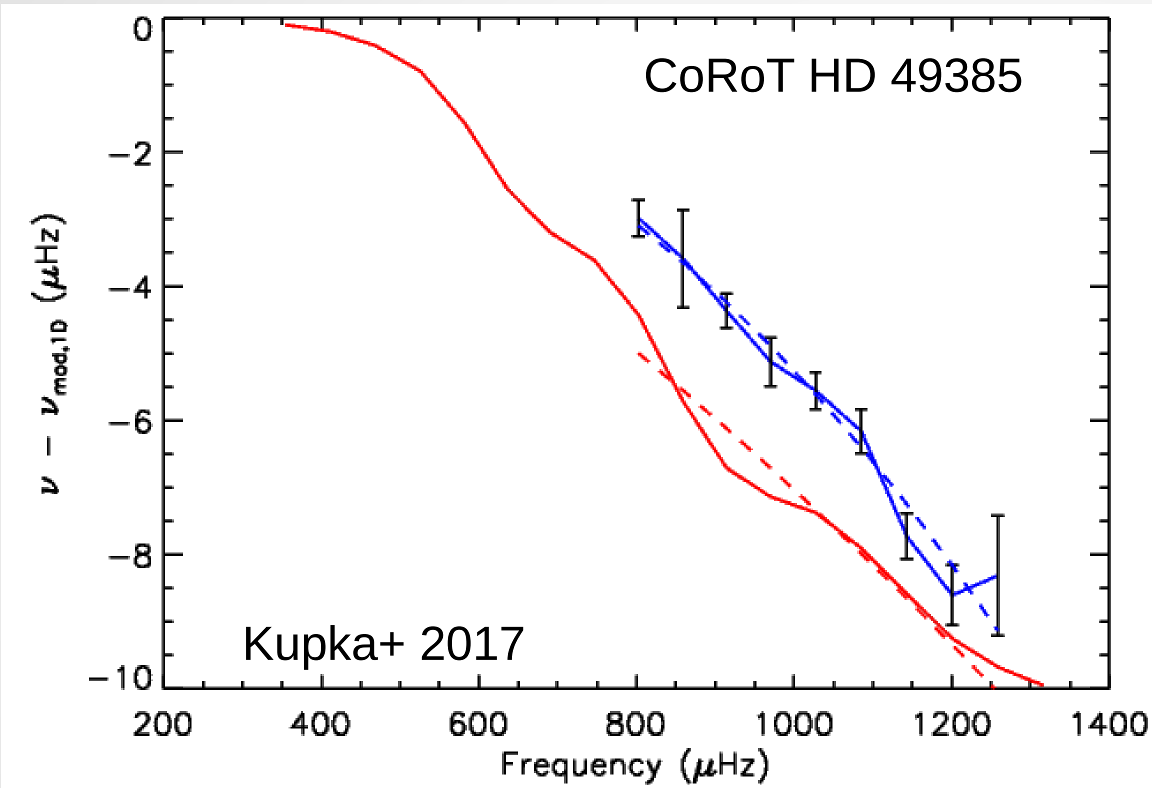
Sonoi+ 2017

$$\frac{\delta p_{\mathrm{turb,l}}}{p_{\mathrm{tot}}} = \Pi \frac{\delta p_{\mathrm{th}}}{p_{\mathrm{tot}}} + \Xi \frac{\xi}{R}$$

→ The Π coefficient varies *spatially* in contrast with the GGM assumption



Patched models: tested against stellar seismic constraints



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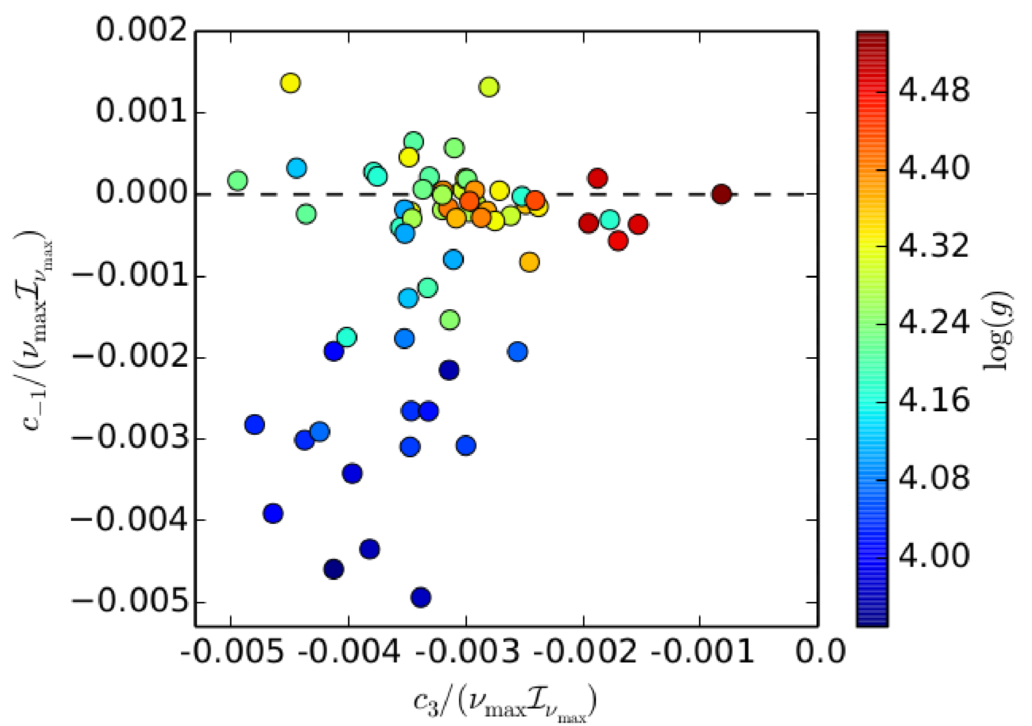
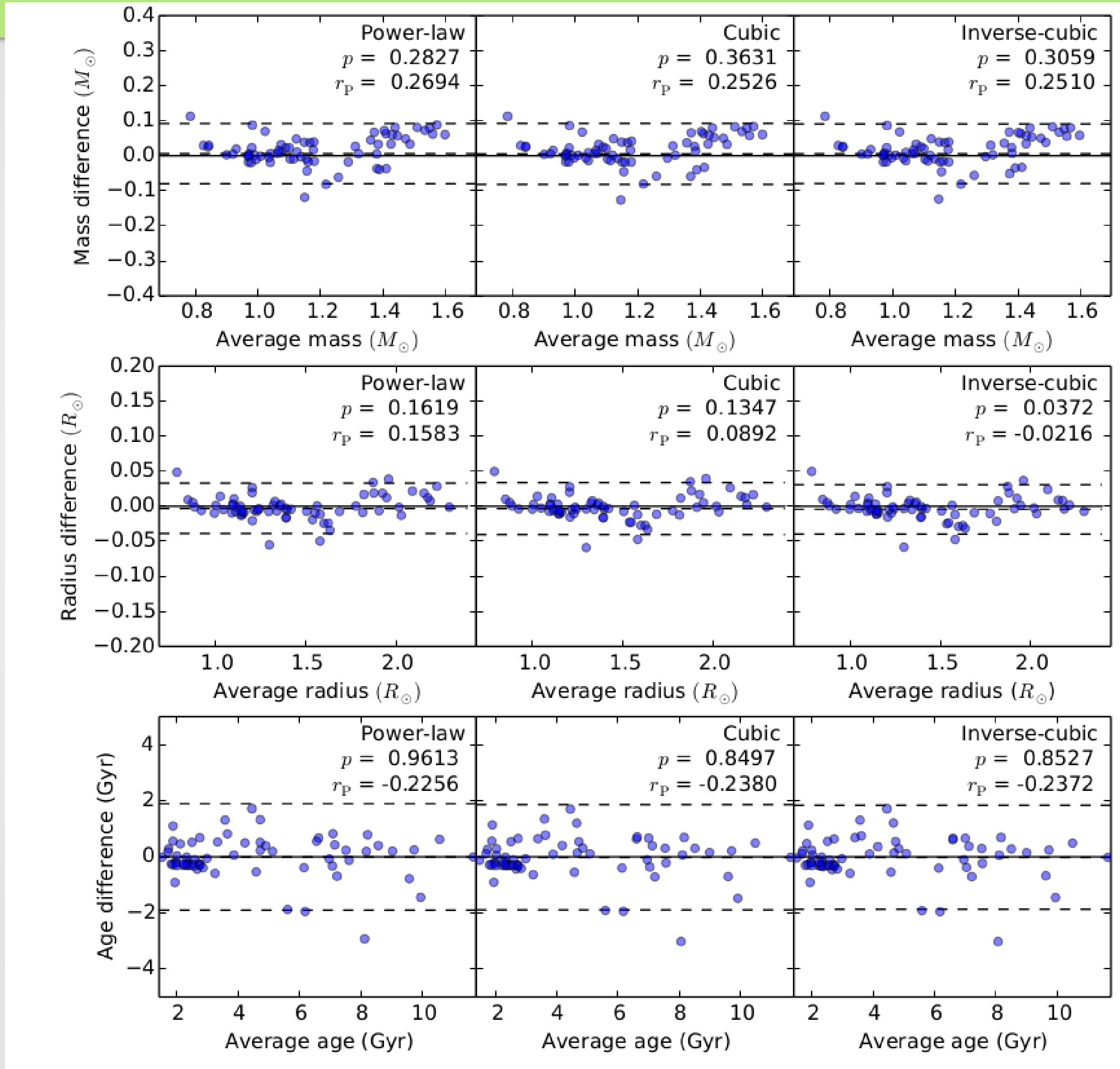
Freq. of patched model are systematically *smaller* than ~ 2 μHz wrt to the measurements



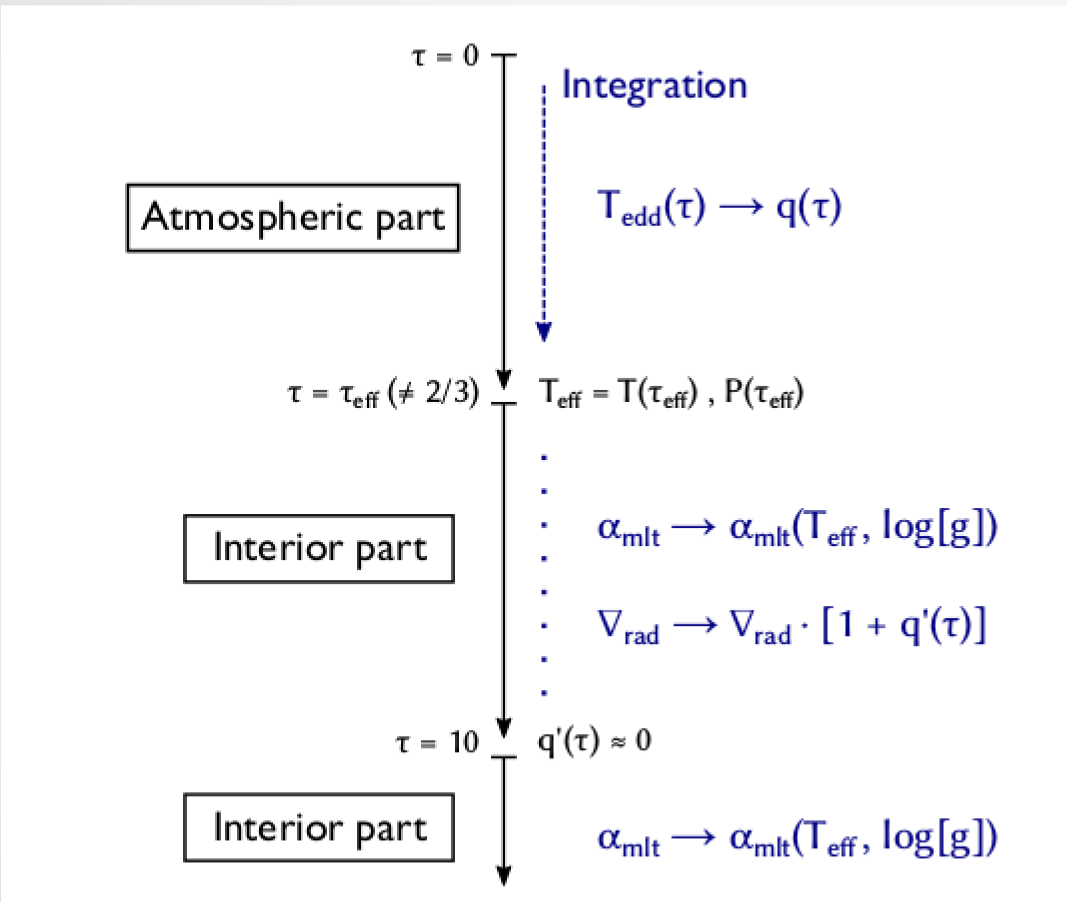
Compton+ 2018

the contribution of the inverse coefficient term is most noticeable in stars with lower surface gravity



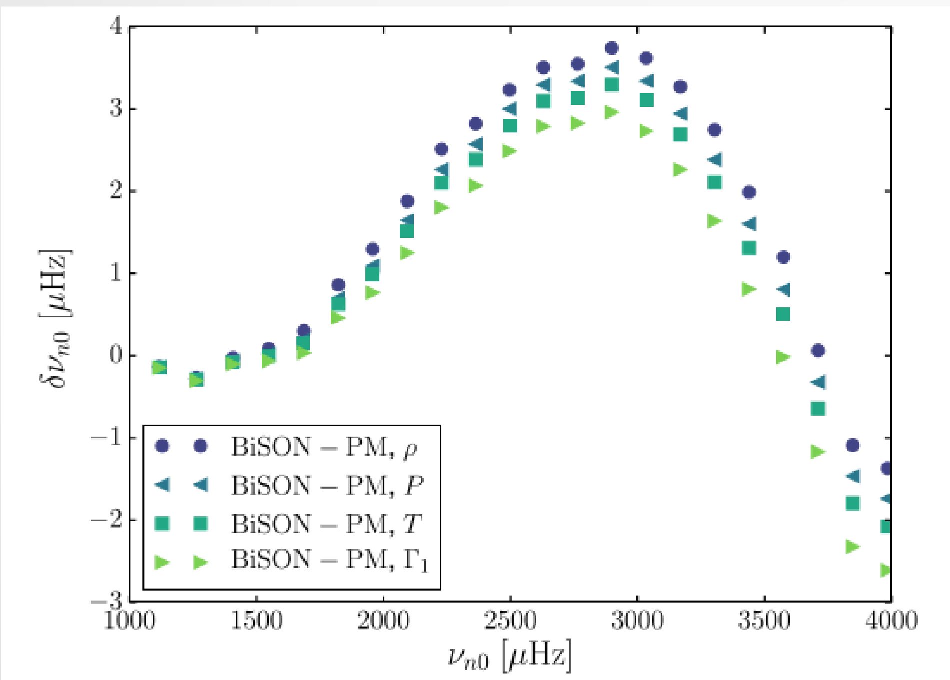
Compton+ 2018

Improving 1D Stellar Models with 3D Atmospheres

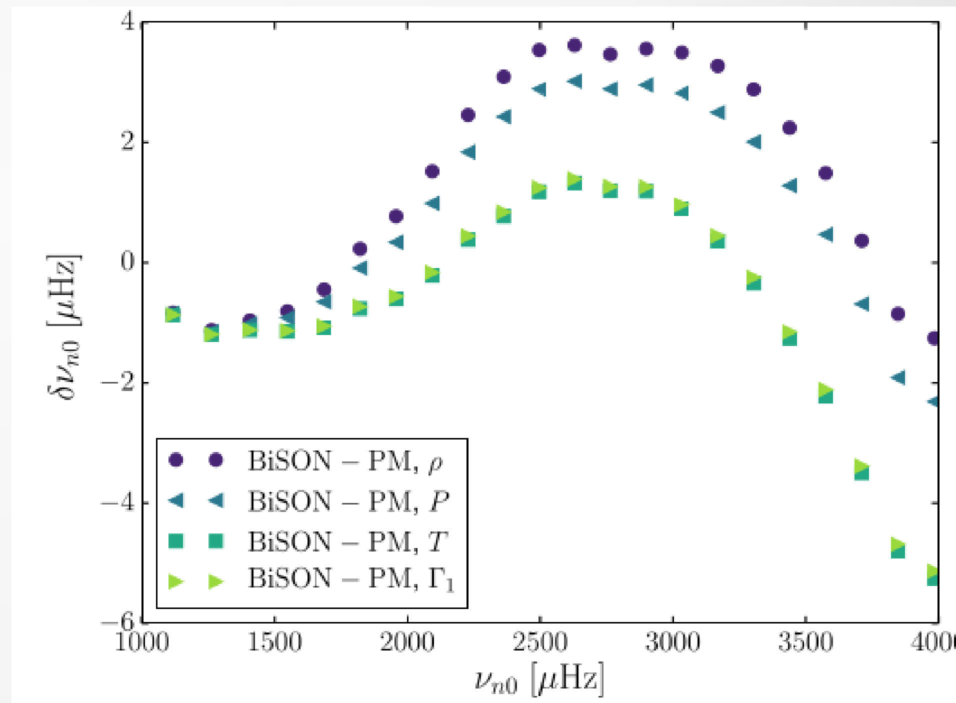


Mosumgaard+ 17

Jorgensen+ 2017



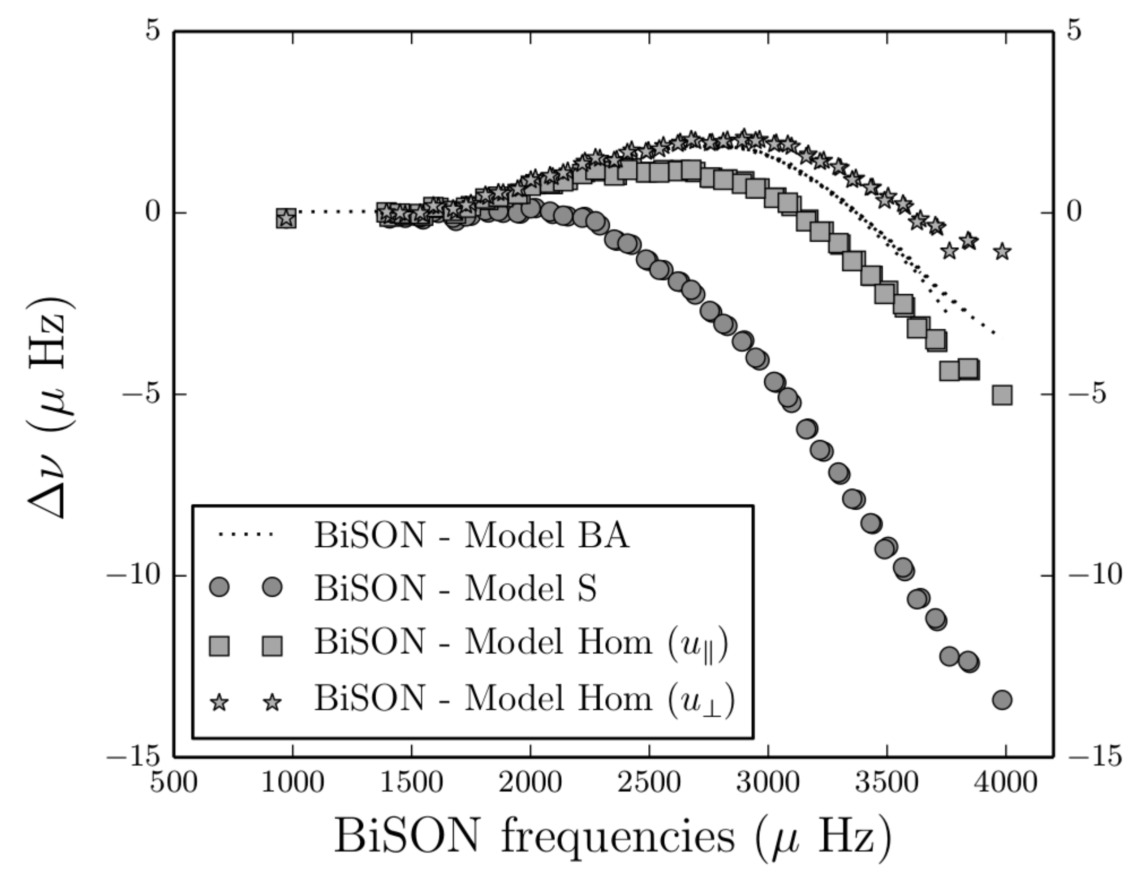
Standard 3D UPM



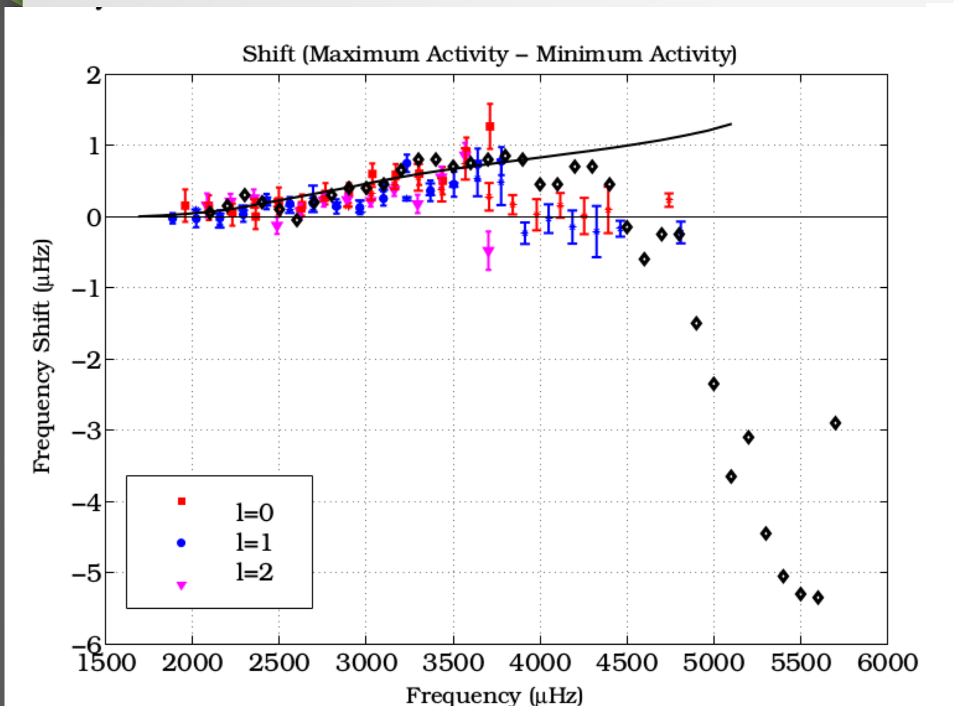
3D calibrated UPM

$$\partial_t^2 \boldsymbol{\xi}_0 - \boldsymbol{\nabla}_{\mathbf{x}} \cdot \left[\langle \tilde{\mathrm{C}} \rangle : \boldsymbol{\nabla}_{\mathbf{x}} \boldsymbol{\xi}_0 \right] = \mathbf{0}$$

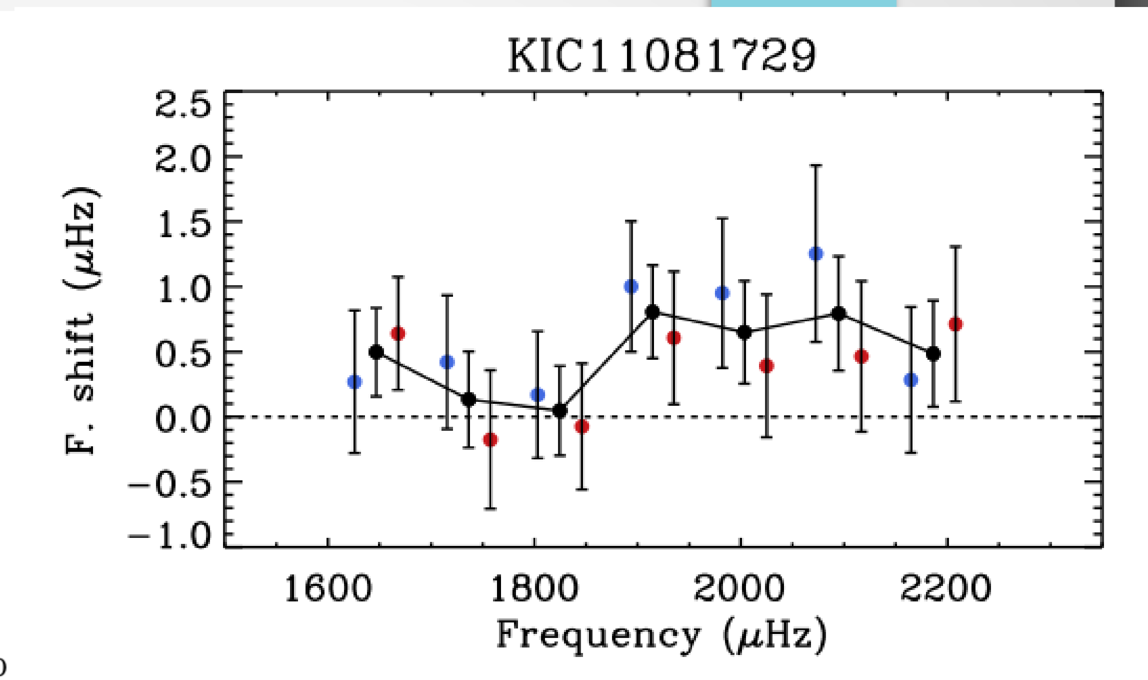
Bhattacharya +2015 focused only on sound-speed variations induced by flows



$$\tilde{\mathrm{C}} = c^2 \mathbf{II} - \mathbf{uu} \cdot \tilde{\mathrm{I}}_4.$$



Salabert+ 2004

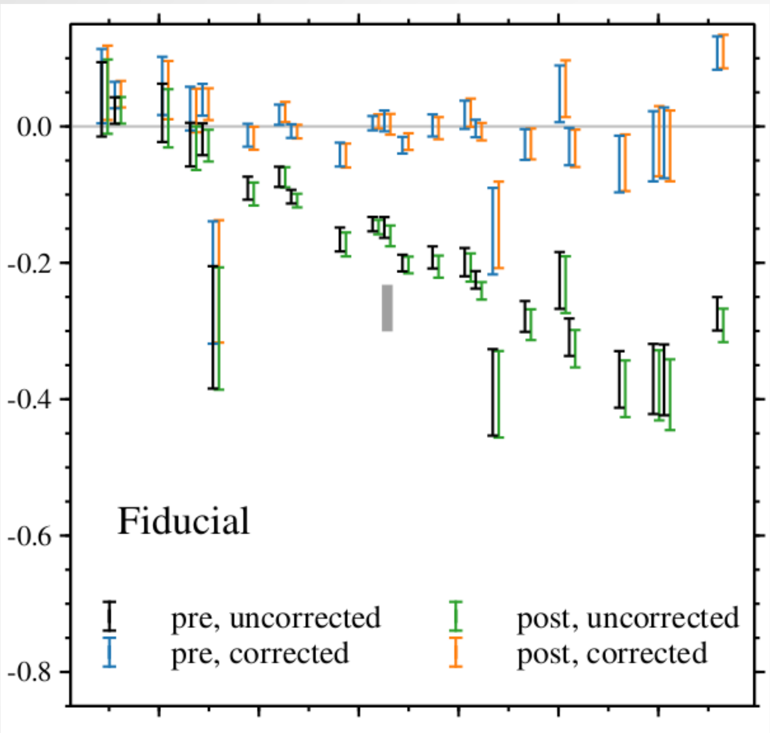


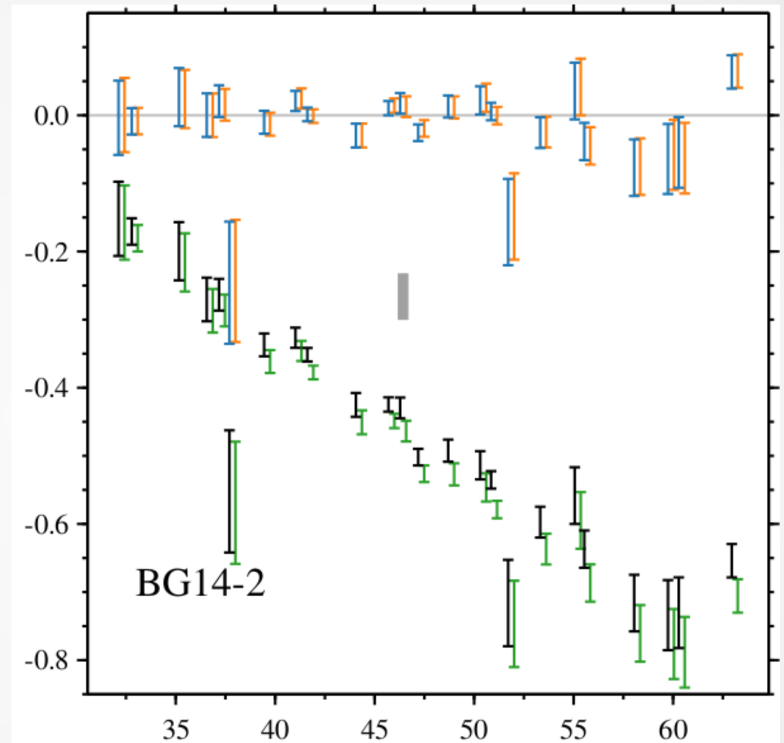
Salabert+2018

Red giants

Ball+ 2018

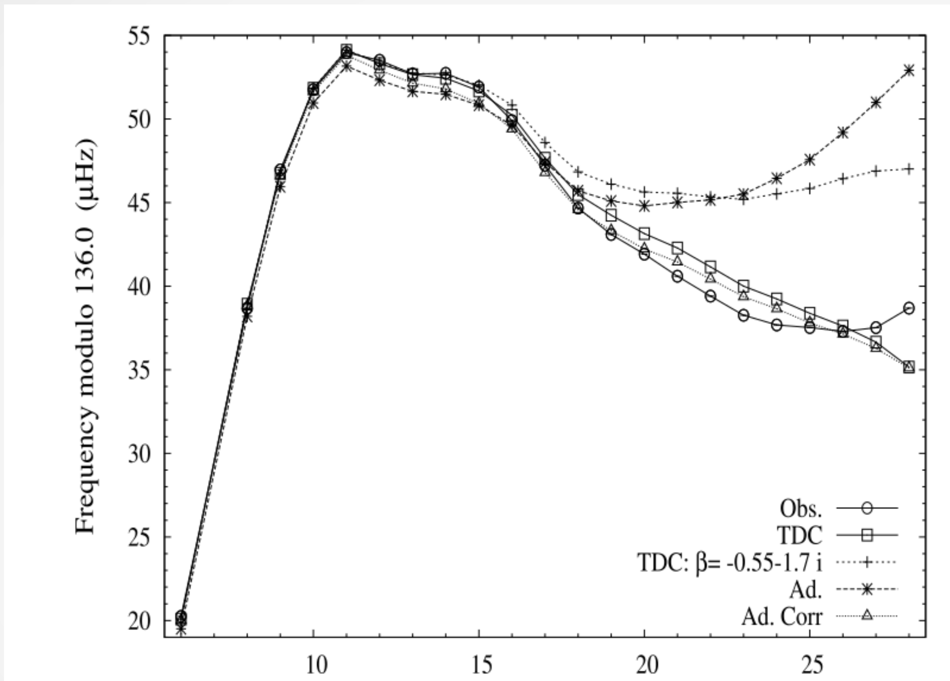
KIC 8410637





Cubic correction (BG3)
→ Same level of correction as predicted by Sonoi+ 2015

Inverse cubic (BG4)
→ larger correction



Grigahcène+ 2012