Stochastic Excitation of solar-like acoustic modes, and its impact on mode asymmetry

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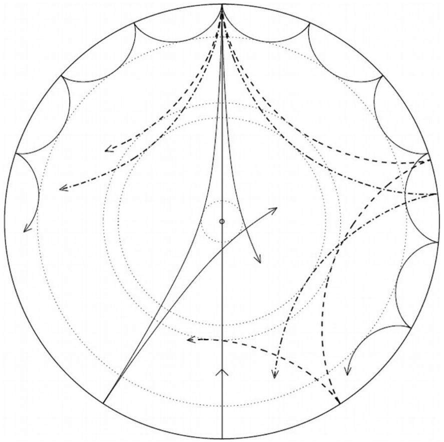
Context

What is asterosismology ?

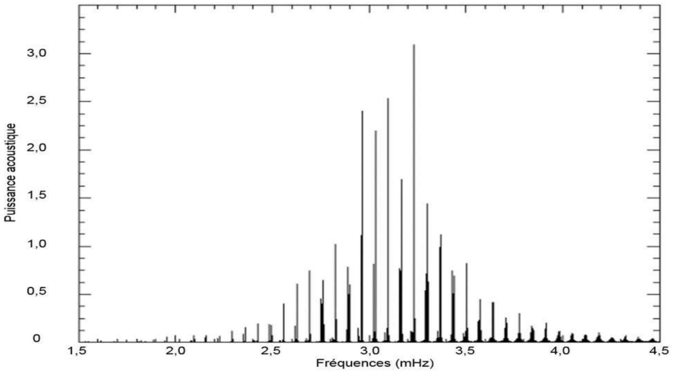
Waves are **reflected** at the surface and **refracted** in the interior



Credits: Cunha et al. (2007)

The star acts as a resonant cavity, within which **resonant modes** develop, which can be either **stable** or **unstable**

- These modes are observed at the surface, by computing the Fourier transform of long time series.
- The stable modes typically have very low amplitudes (a few cm/s for **radial velocity**, a few ppm for **intensity fluctuations**)



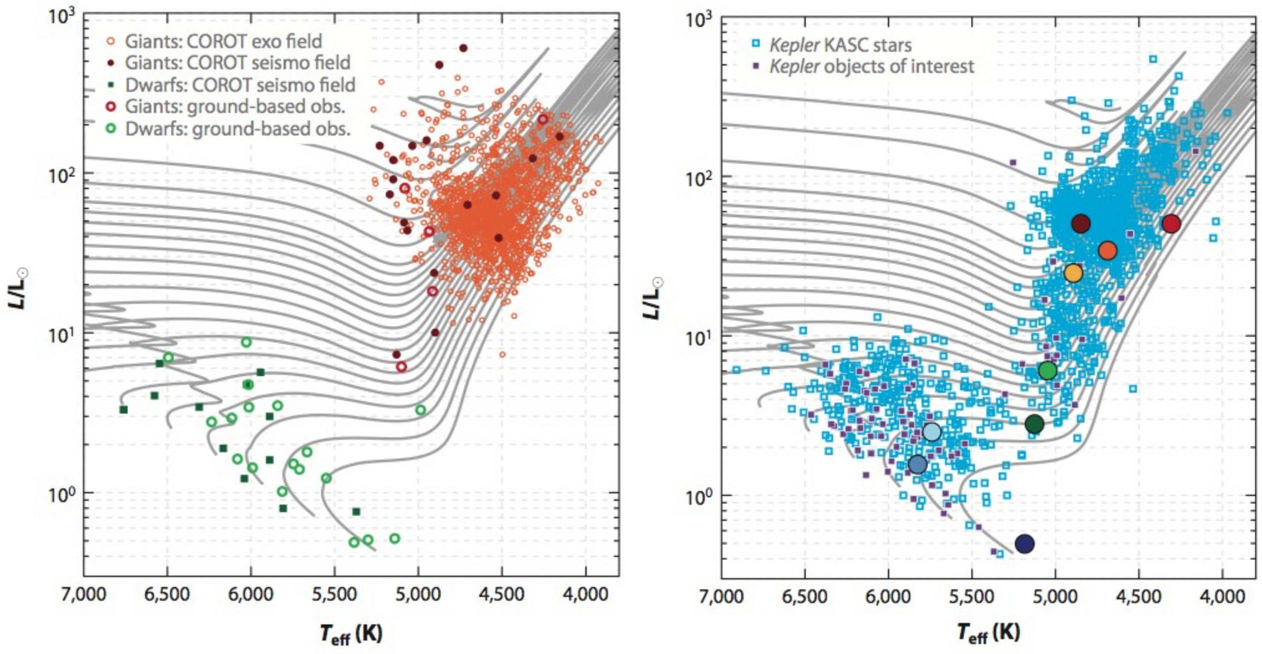
Solar spectrum observed by *GOLF*

Context

Asterosismology: plenty of data

We detect solar-like modes in a **large amount of stars**, at **various evolutionary stages** and **throughout the HR diagram** (CoRoT, Kepler, TESS)

Data will be even more plentiful will PLATO



Credits: Chaplin & Miglio (2013)

Context

Why do we do asterosismology ?

The resonant frequencies give information on the **internal structure** of the star:

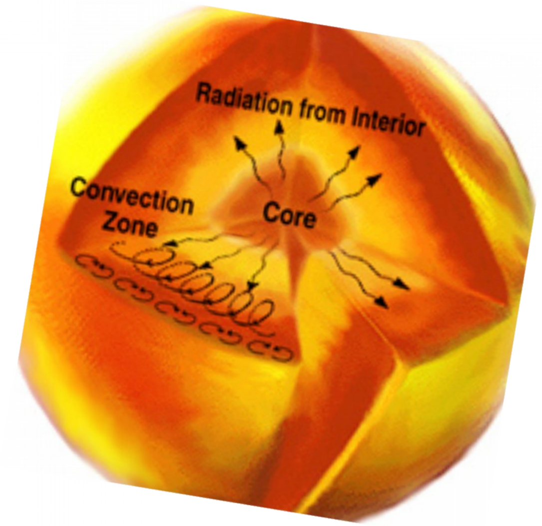
$$\nu_{n,l} = \Delta\nu \left(n + \frac{l}{2} + \widetilde{\alpha} \right) + \epsilon_{n,l}$$

with

$$\Delta\nu = \left(2 \int_0^R \frac{dr}{c(r)} \right)^{-1} \propto \; \overline{\rho}^{1/2}$$

For solar-like oscillators, the amplitudes and linewidths give information on the **turbulent convection**:

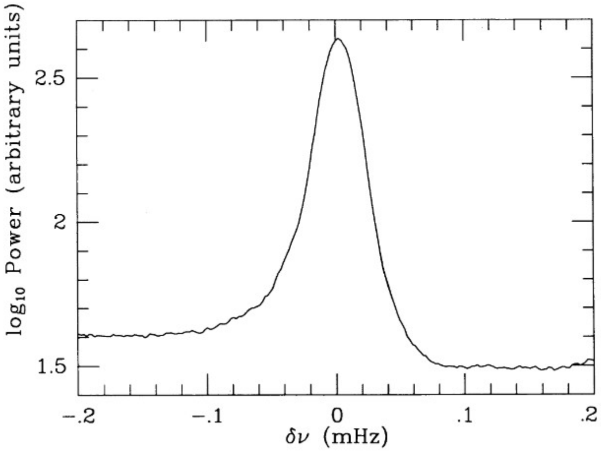
- Sub-surface convection is very turbulent ($\mathrm{Re} \sim 10^{14}$) → stochastic processes
- Mode amplitude is the result of a balance between **stochastic excitation** and **damping**
- Mode linewidth is related to the rate at which the mode is **stochastically damped**



Mode asymmetry

What is it ?

The line profile of the modes in the Fourier spectrum are **asymmetric**



Credits: Duvall et al. (1993)

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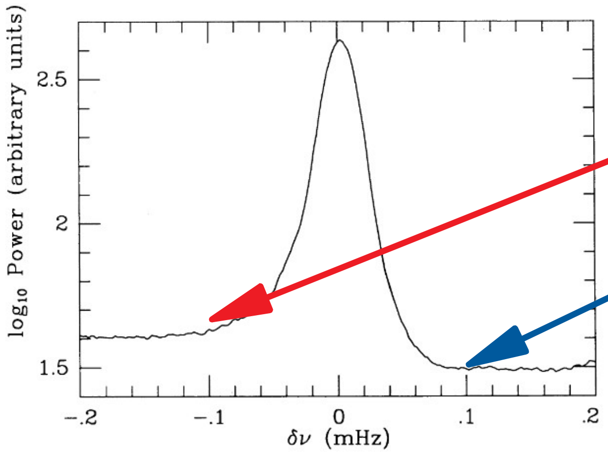

Credits: Duvall et al. (1993)

- The first contribution to mode asymmetry is the **localisation of the source** (Duvall et al. 1993)

  The two waves propagating from the source in opposite directions interfere more constructively **here** than **here**

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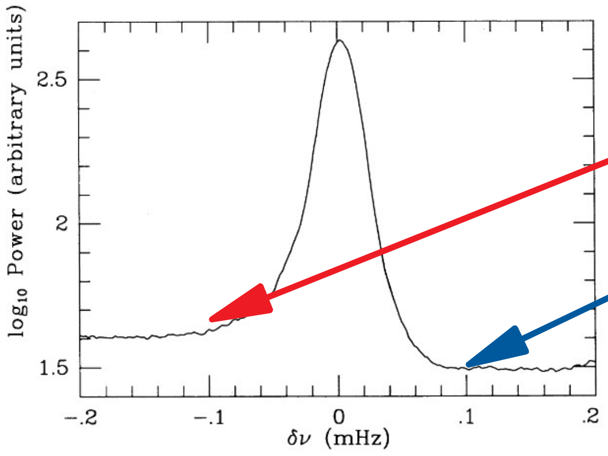

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- The first contribution to mode asymmetry is the **localisation of the source** (Duvall et al. 1993) The two waves propagating from the source in opposite directions interfere more constructively **here** than **here**
- The **correlated background** affects this interference pattern: it is the second contribution to mode asymmetry (Nigam & Kosovichev, 1998)

Mode asymmetry

Why is it important ?

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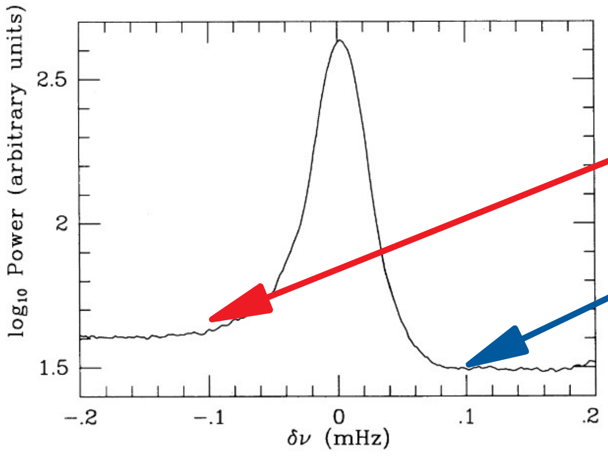

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- Prior studies had simplified models (point-like source), very parametrised, and they fit each mode individually (Nigam et al. 1998, Kumar & Basu 1999, Severino et al. 2001, Toutain et al. 2006). Goal: **mainly to infer the position of the source**

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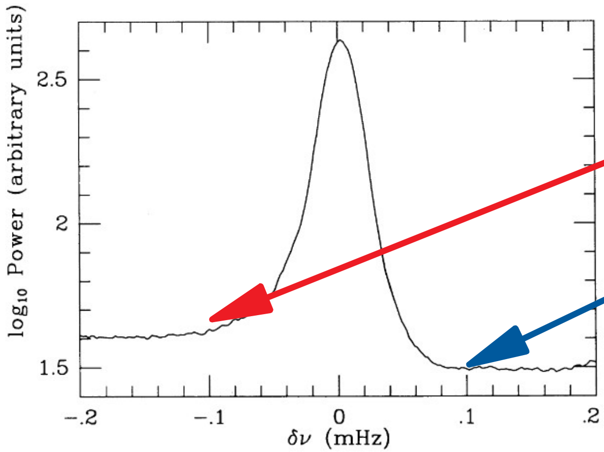

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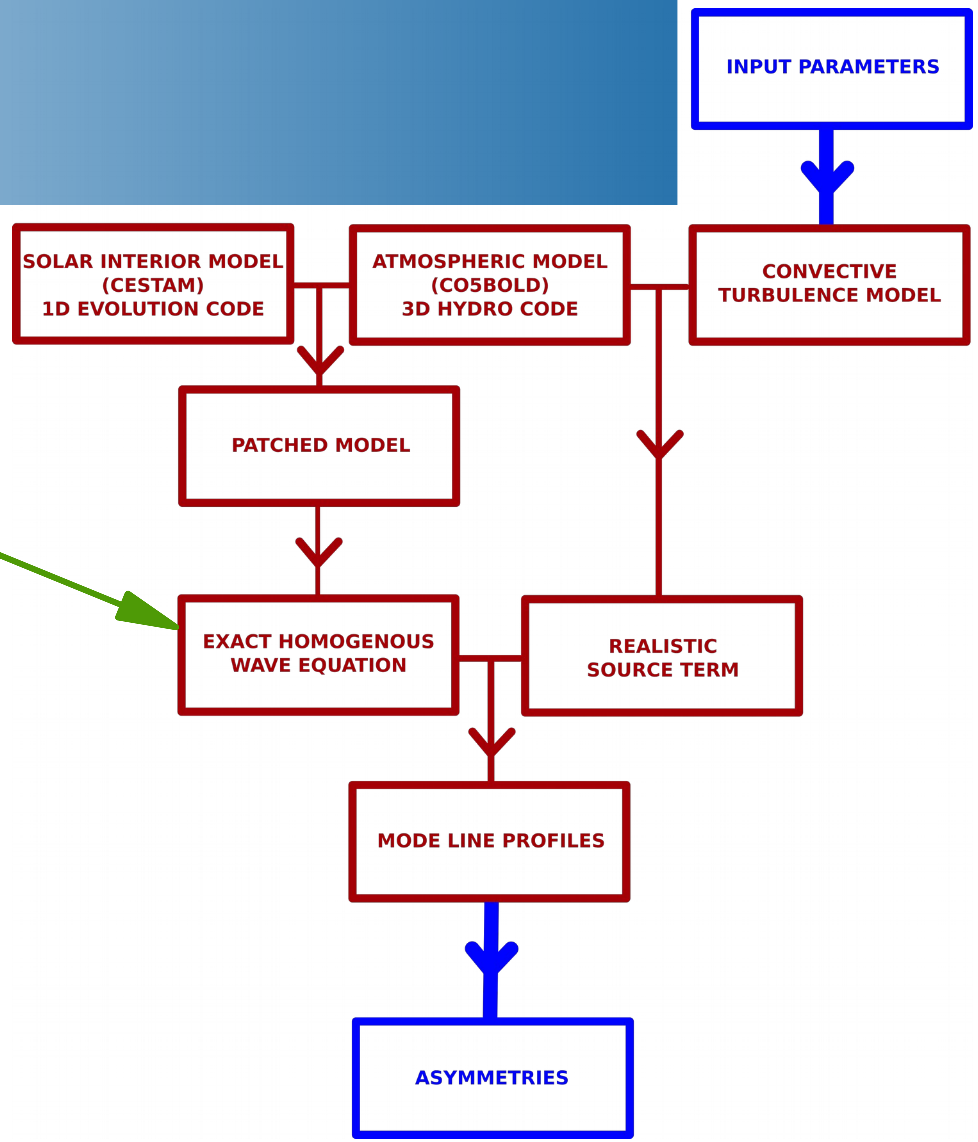
We need a more realistic model for the source, with very few parameters, to compare the results with observations. Goal: **to make quantitative predictions applicable to stars other than the Sun**

Mode asymmetry

Our modelling approach

$$\frac{d^2\Psi}{dr^2} + \left(\frac{\omega^2 + j\omega\Gamma}{c^2} - V(r) \right) \Psi = 0$$



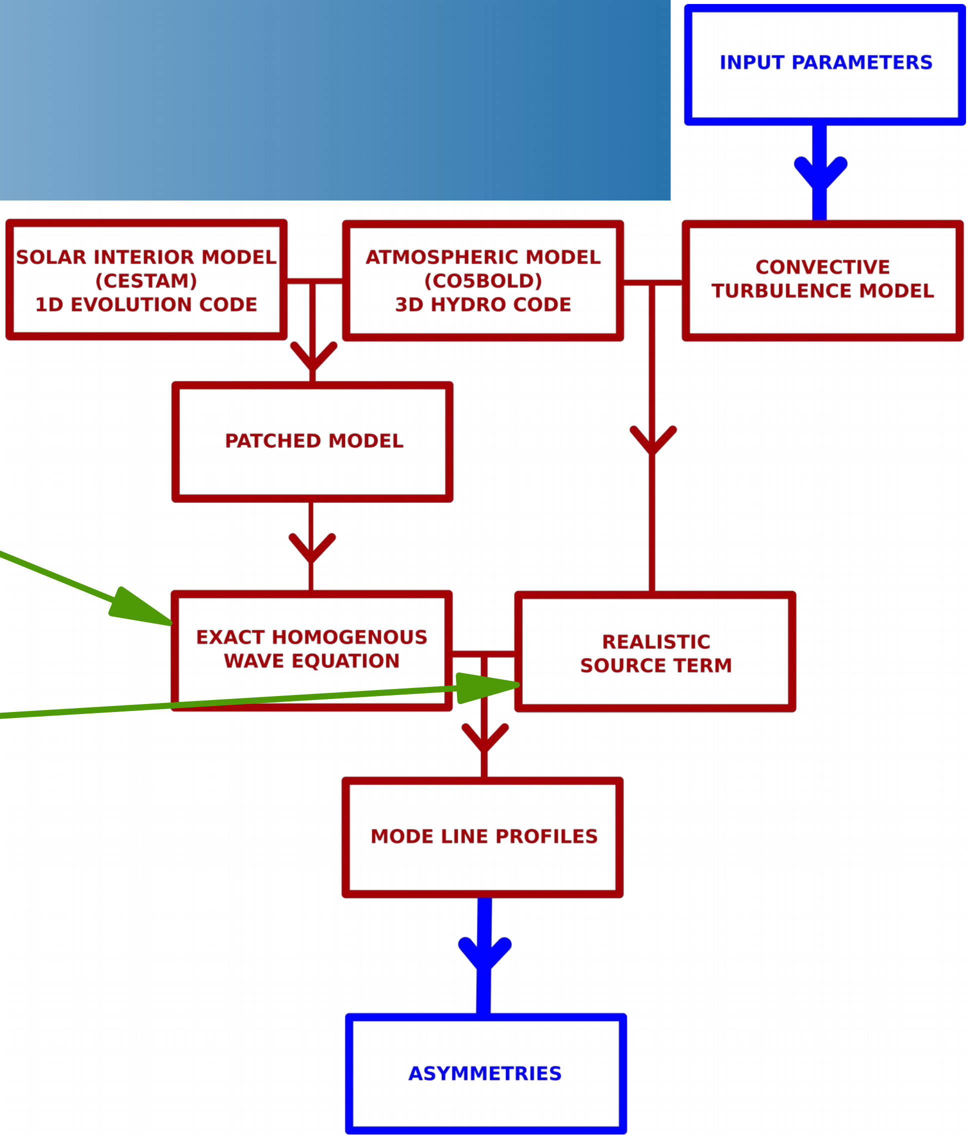
Mode asymmetry

Our modelling approach

$$\frac{d^2\Psi}{dr^2} + \left(\frac{\omega^2 + j\omega\Gamma}{c^2} - V(r)\right)\Psi = S(r)$$

combined with

$$S(r) = \boldsymbol{\nabla} : \rho\boldsymbol{u}\boldsymbol{u} - \boldsymbol{\nabla} : \overline{\rho\boldsymbol{u}\boldsymbol{u}}$$



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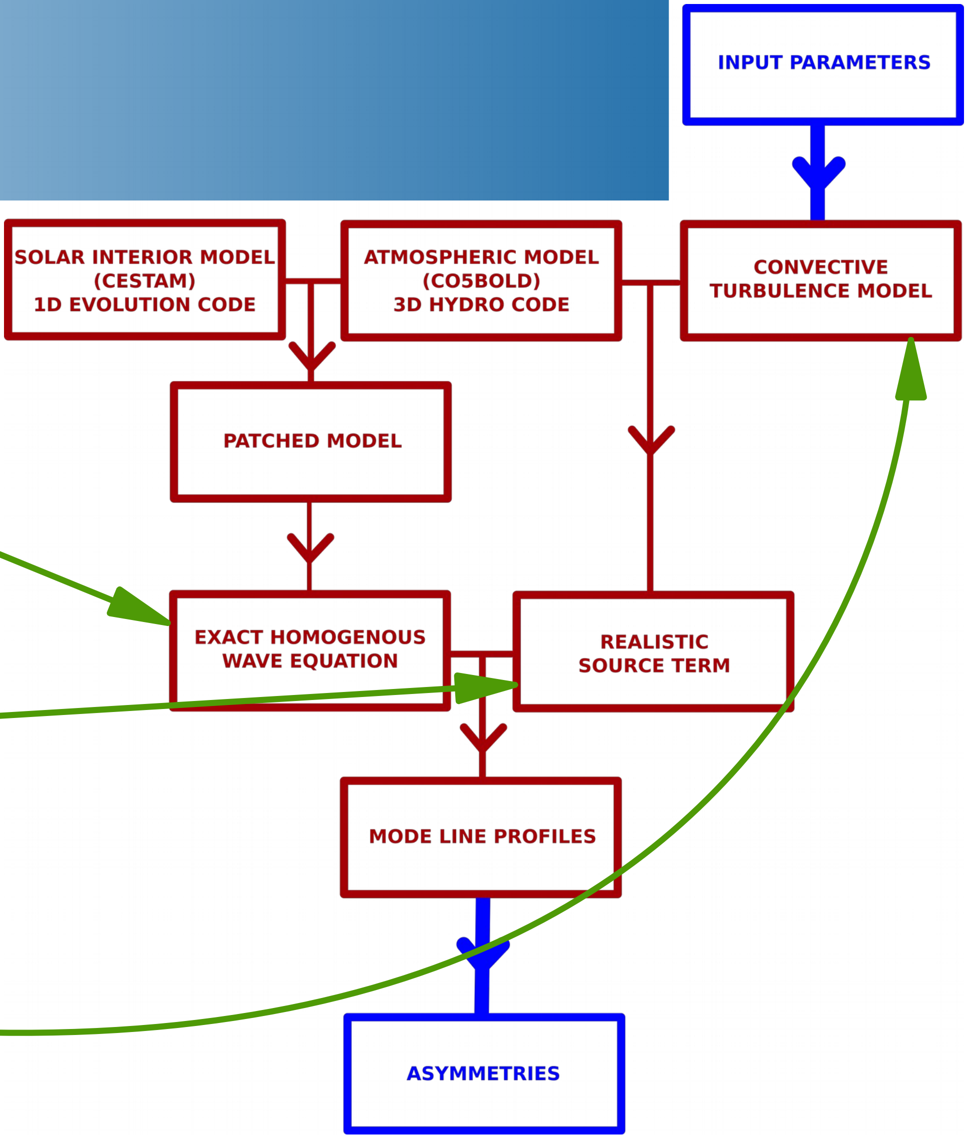
gives the value of the spectrum for a given frequency

$$P(\omega) = f\left(\left\langle u^2(t,\boldsymbol{R})u^2(t+\tau,\boldsymbol{R}+\boldsymbol{r})\right\rangle, \left\langle u^2(t,\boldsymbol{R})u(t+\tau,\boldsymbol{R}+\boldsymbol{r})\right\rangle\right)$$



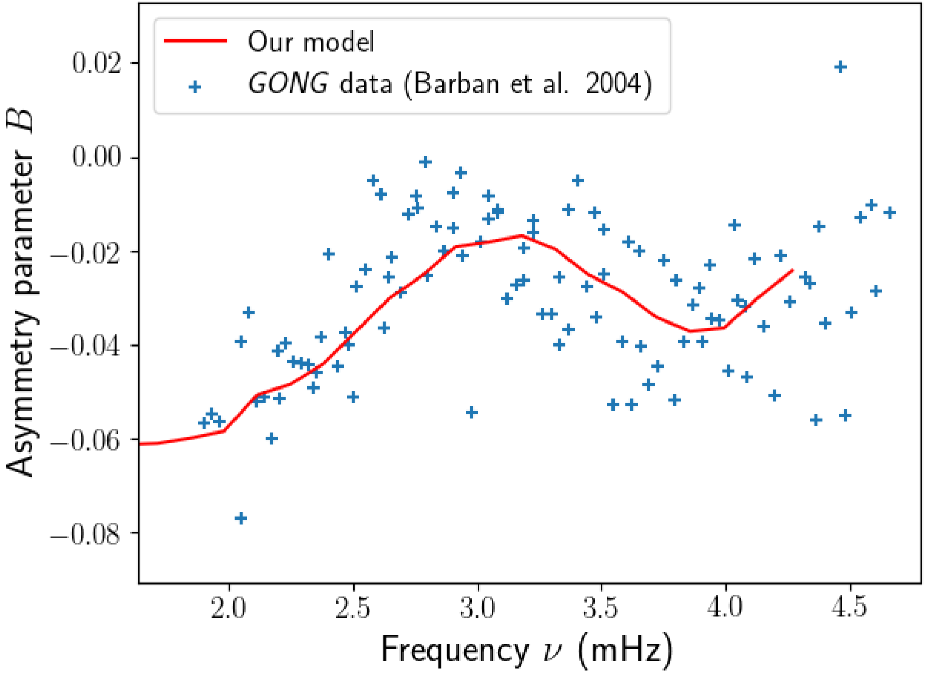
Mode asymmetry

Main results

- The predictions of the model are in **agreement with observations** → model validated

- The **spatial extent of the source** is crucial (sensitivity to how the properties of turbulence change above and below the photosphere)

- The contribution of the **correlated background is negligible**

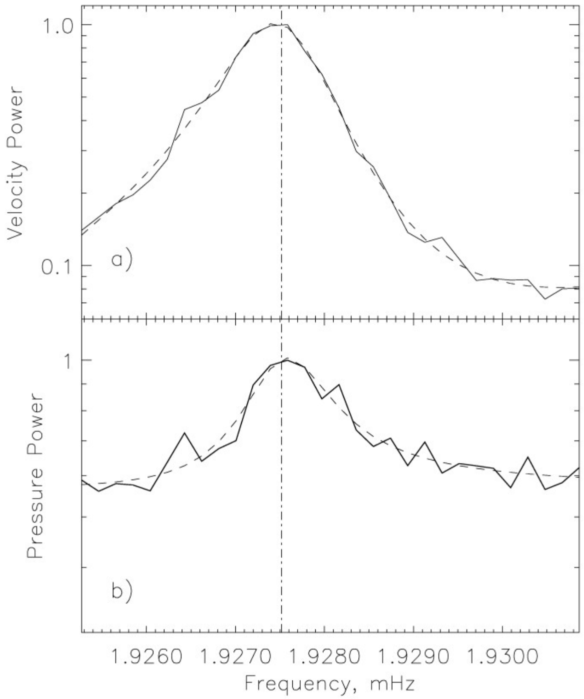


Credits: Philidet et al. (submitted to A&A)

Asymmetry reversal

What is it ?

Mode asymmetry have **opposite sign in velocity and in intensity**



Credits: Nigam et al. 1998

Asymmetry reversal

Why is it important ?

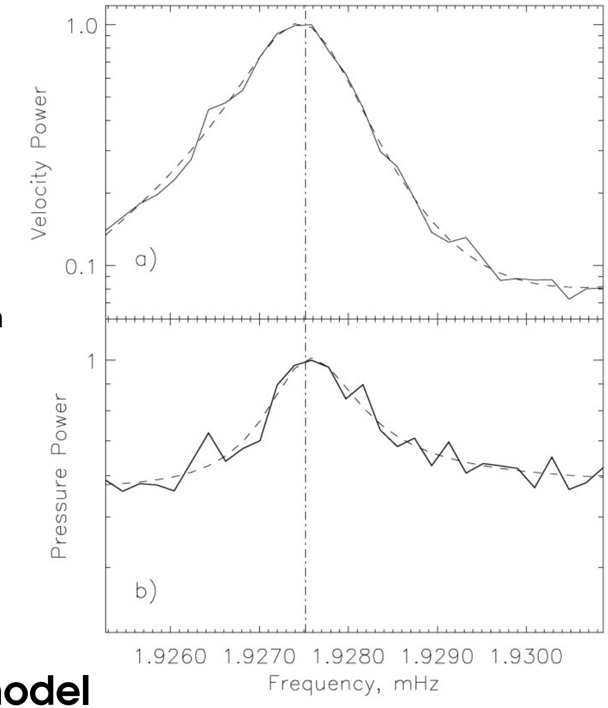
Mode asymmetry have
opposite sign in velocity and in intensity

There is no consensus on the explanation:

- correlated background higher than in velocity (Nigam & Kosovichev 1998)
- radiative effects (Georgobiani et al. 2001)
- non-adiabatic effects (Duvall et al. 1993)

→ **still an unsolved problem**

→ **up to now, no predictive model**



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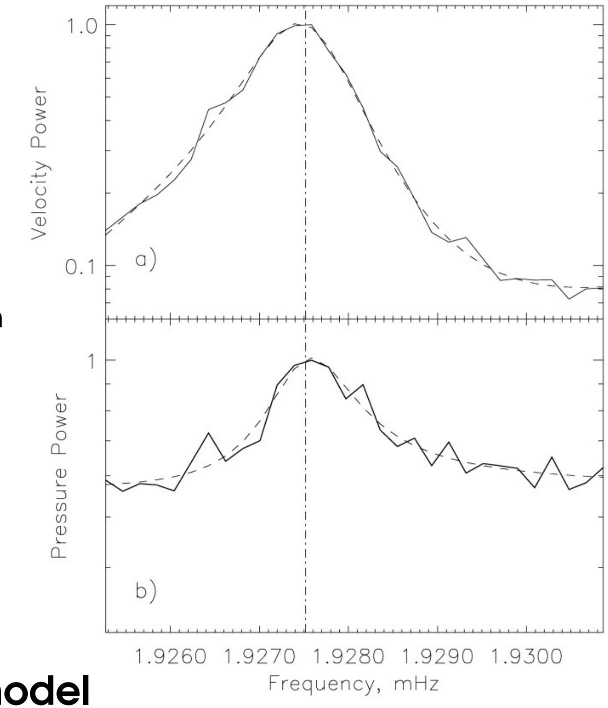
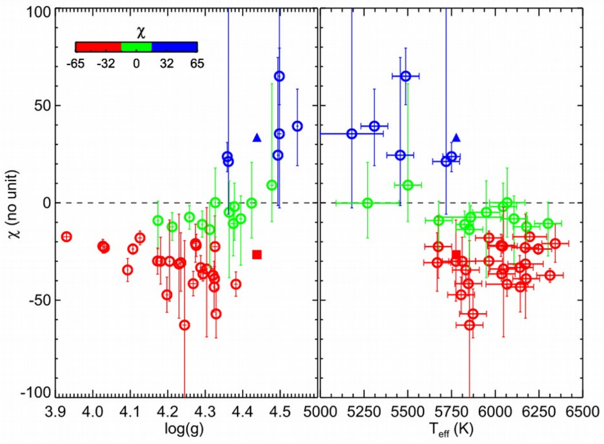


Credits: Nigam et al. 1998

Asymmetries in other stars are measured in intensity → adapting our model to intensity spectrum is a key step to **apply the model to stars other than the Sun**



Credits: Benomar et al. 2018

Asymmetry reversal

Adaptation to intensity spectrum

$$\frac{\mathrm{d}^2\Psi_\omega}{\mathrm{d}r^2} + \left(\frac{\omega^2 + j\omega\Gamma}{c^2} - V(r)\right)\Psi_\omega = S(r)$$

+

$$\frac{\delta L}{L} = \frac{L_R}{L}\Bigg(\underbrace{\left[(4+3\kappa_\rho)A_\xi + (4-\kappa_T)A_T + r\kappa_\rho\frac{\mathrm{d}A_\xi}{\mathrm{d}r} - H_T\frac{\mathrm{d}A_T}{\mathrm{d}r}\right]}_{\equiv A_L}\Psi_\omega$$

$$+\underbrace{\left[(4-\kappa_T)B_T + r\kappa_\rho A_\xi - H_T\left(A_T + \frac{\mathrm{d}B_T}{\mathrm{d}r}\right)\right]}_{\equiv B_L}\frac{\mathrm{d}\Psi_\omega}{\mathrm{d}r}\underbrace{-H_T B_T}_{\equiv C_L}\frac{\mathrm{d}^2\Psi_\omega}{\mathrm{d}r^2}\Bigg)$$

The intensity eigenfunction do not depend only on Ψ_ω, but also on its radial derivatives

↓

The nodes in velocity and intensity are different

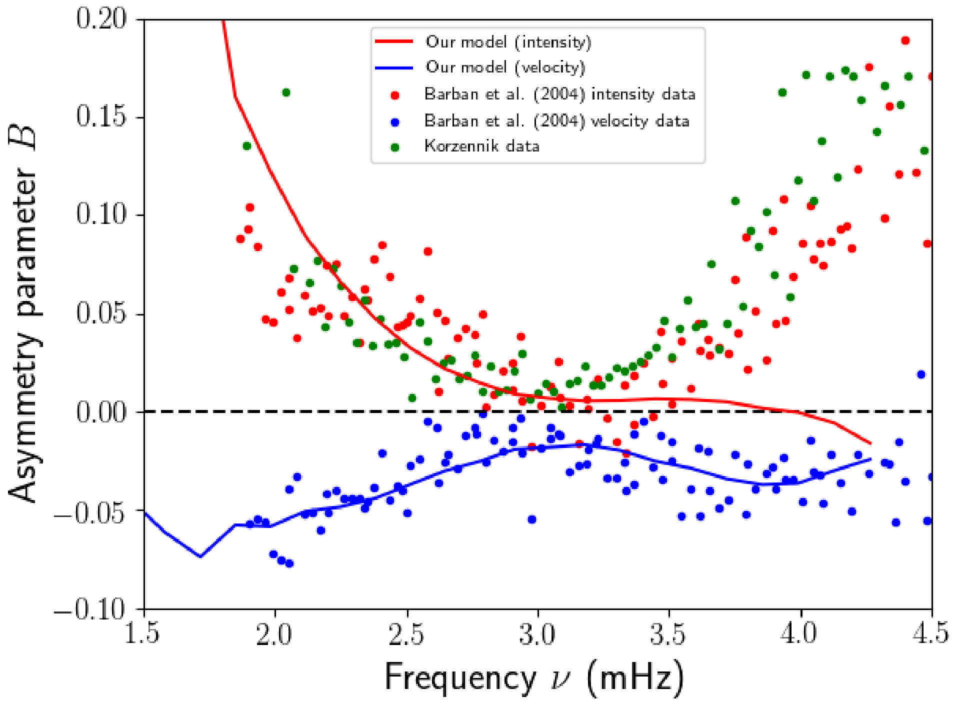
↓

The asymmetries are different too

Asymmetry reversal

Main results

- We find agreement with observations with the **same model and same parameter values** as in velocity → no additional mechanism needed
- **Radiative effects** reduce the amplitude of the mode in intensity, but **do not affect asymmetry**
- Discrepancies at high frequency in intensity:
  – Non-adiabaticity ?
  – Correlated background ?
  – Contribution of convective flux ?



Credits: Philidet et al. (in prep)

Thank you for your attention !