Asteroseismic probing of low mass solar-like stars throughout their evolution with new techniques

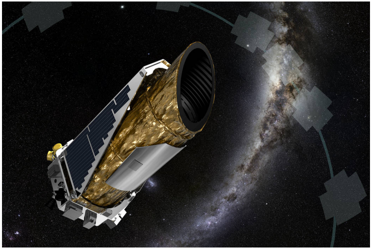
PLATO Mission Conference 2021

Martin Farnir - Université de Liège

12^{th} of October 2021

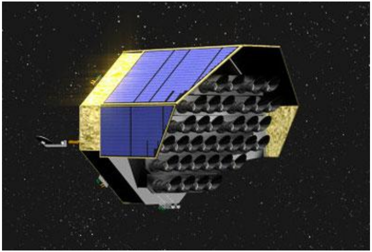
Large amount of data

Kepler (2009-2018)



Credits: NASA

PLATO (2026-. . .)



Credits: CNES

Several hundreds of thousands of pulsating stars!

$\Rightarrow$ Unique opportunity for seismology: precise t, M, and R

Take advantage of the data

Large amount of very precise data!

$\Downarrow$

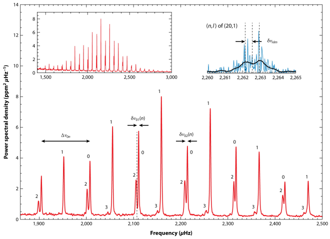
- Need for precise methods
  1. **WhoSGlAd**: Main-sequence stars (Farnir et al. 2019,2020)
  2. **EGGMiMoSA**: Sub- and red giants (Farnir et al. 2021)

Solar-like oscillation spectra

Smooth

$$\nu_{n,l} \simeq \left(n + \frac{l}{2} + \epsilon\right) \Delta\nu$$

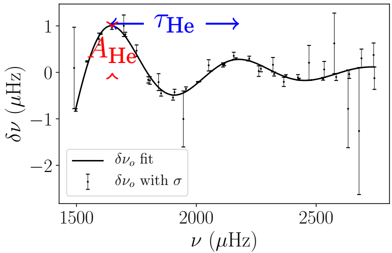
Tassoul (1980), Gough (1986)



Chaplin WJ, Miglio A. 2013. Annu. Rev. Astron. Astrophys. 51:353–92

Glitches

$$\delta\nu = \nu_{\mathrm{obs}} - \nu_{\mathrm{smooth}}$$



WhoSGlAd: Principle

WhoSGlAd - **Whol**e **S**pectrum and **Gl**itches **Ad**justment (Farnir et al. 2019,2020)

Consider the frequencies vector space:

① Build orthonormal basis of functions (Gram-Schmidt);

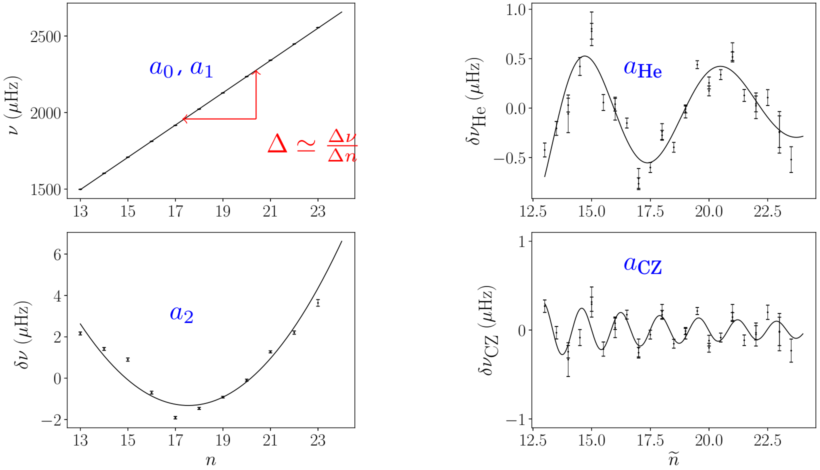
- From regular functions: $\boldsymbol{p}_k$
- Build orthonormal functions: $\boldsymbol{q}_k = \dfrac{\boldsymbol{p}_k - \sum_j^{k-1} \langle \boldsymbol{p}_k | \boldsymbol{q}_j \rangle \boldsymbol{q}_j}{\left\| \boldsymbol{p}_k - \sum_j^{k-1} \langle \boldsymbol{p}_k | \boldsymbol{q}_j \rangle \boldsymbol{q}_j \right\|}$
- With the scalar product: $\langle \boldsymbol{x} | \boldsymbol{y} \rangle = \sum_i^N \frac{x_i y_i}{\sigma_i^2}$

WhoSGlAd: Principle

② Independent ν projections: $a_k = \langle \boldsymbol{\nu}_{\mathrm{obs}} | \boldsymbol{q}_k \rangle$

$$\Rightarrow \boldsymbol{\nu}_{\mathrm{fit}} = \sum_k^K a_k \boldsymbol{q}_k \ ;$$

Smooth **Glitches**



WhoSGlAd: Principle

③ Combine independent a_k into indicators as uncorrelated as possible;

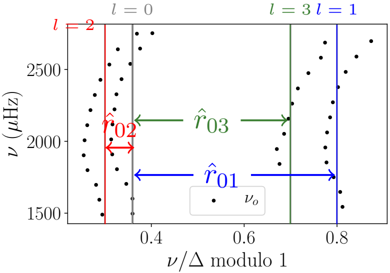
- $\Delta_l = a_{l,1} R^{-1}_{l,1,1}$,
- $\hat{r}_{0l} = \frac{a_{0,0} R^{-1}_{0,0,0} - a_{l,0} R^{-1}_{l,0,0}}{a_{0,1} R^{-1}_{0,1,1}} + \overline{\boldsymbol{n}_l} - \overline{\boldsymbol{n}_0} + \frac{l}{2}$,
- $\Delta_{0l} = \frac{a_{l,1} R^{-1}_{l,1,1}}{a_{0,1} R^{-1}_{0,1,1}} - 1$,
- $A_{\mathbf{He}} = \|\boldsymbol{\delta\nu}_{\mathbf{He}}\| = \sqrt{\sum a^2_{\mathbf{He}}}$,
- $\ldots$

with $R^{-1}_{l,k,j}$ the transformation matrix: $\boldsymbol{q}_{l,k} = \sum_{j \leq k} R^{-1}_{l,k,j} \boldsymbol{p}_{l,j}$

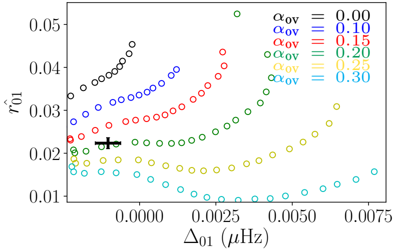
Seismic indicators

Smooth:

- $\hat{r}_{0l}$ → Composition and evolution (∼ Roxburgh & Vorontsov 2003)
- Δ_{0l} → Overshooting (See also Deheuvels et al. 2016)



Farnir et al. (2019)



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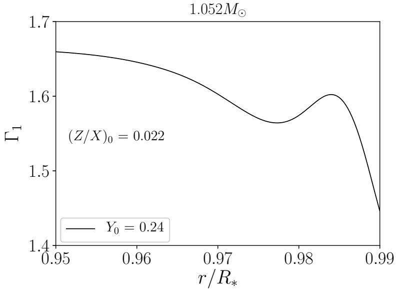
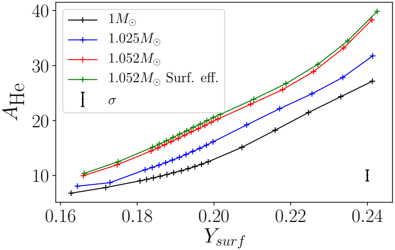
Glitch indicators

Glitch:

- $A_{\mathrm{He}} \rightarrow$ Helium content





Farnir et al. (2019)

Independent of smooth indicators

Glitch indicators

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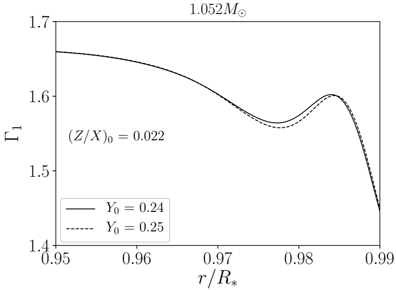

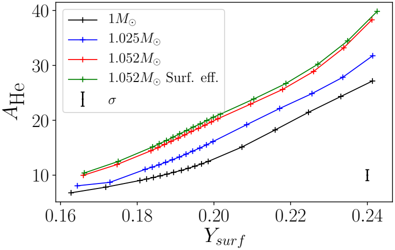

Farnir et al. (2019)

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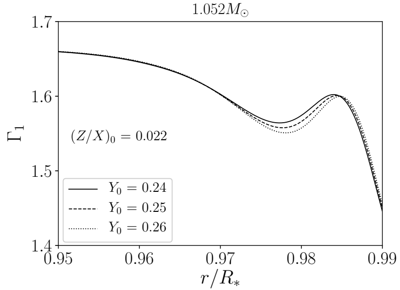

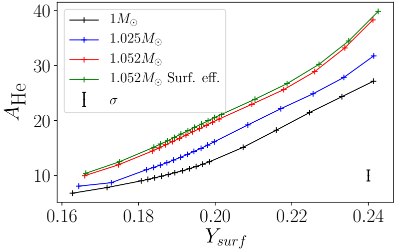

Farnir et al. (2019)

Independent of smooth indicators

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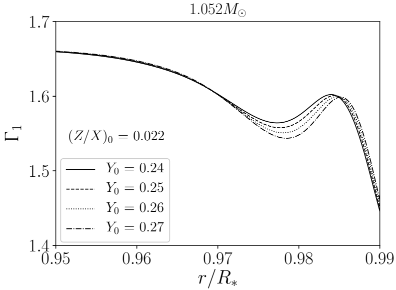
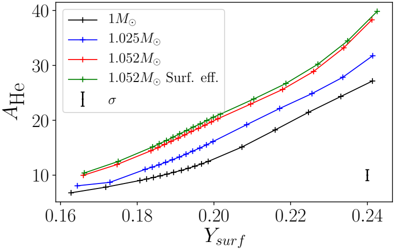




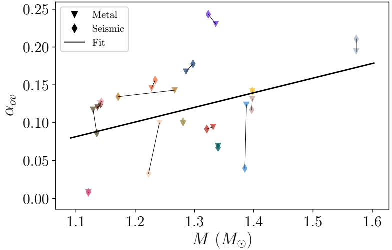
Farnir et al. (2019)

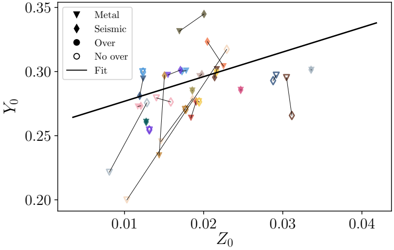
Independent of smooth indicators

Application to the Kepler LEGACY sample

- Overshooting
  $\Delta\alpha_{\mathbf{ov}}/\Delta M = 0.2 \pm 0.1$,
  $\alpha_{\mathbf{ov},0} = -0.1 \pm 0.2$

- Galactic enrichment
  $\Delta Y/\Delta Z = 1.92 \pm 0.79$,
  $Y_p = 0.26 \pm 0.01$





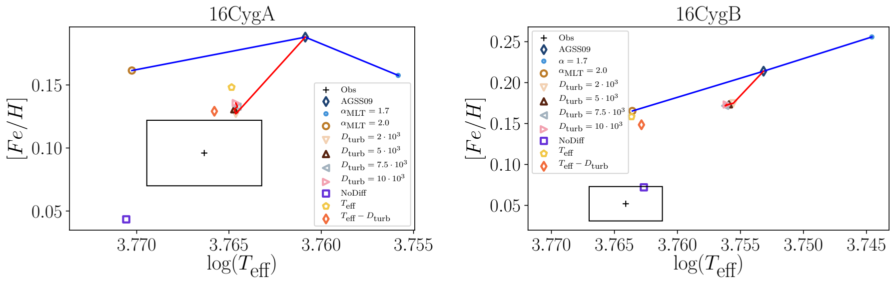
Free param.: t, M, X_0, $(Z/X)_0$, and $\alpha_{\mathbf{ov}}$;

Seismic: Models with only Δ, $\hat{r}_{01}$, $\hat{r}_{02}$, Δ_{01}, and A_{He};

Metal: Models with only Δ, $\hat{r}_{01}$, $\hat{r}_{02}$, Δ_{01}, and [Fe/H].

Application to 16 Cygni

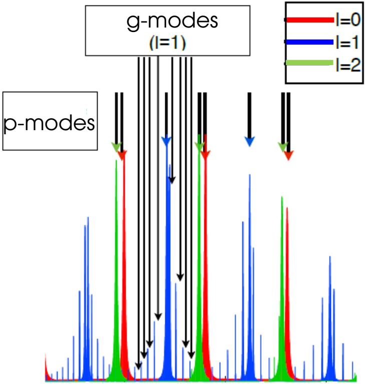
Fitting only Δ, $\hat{r}_{01}$, $\hat{r}_{02}$, and $A_{\mathbf{He}}$:



Seismology alone cannot discriminate models
(Farnir et al. 2020)
See also Bulden et al. (2021 in prep.)

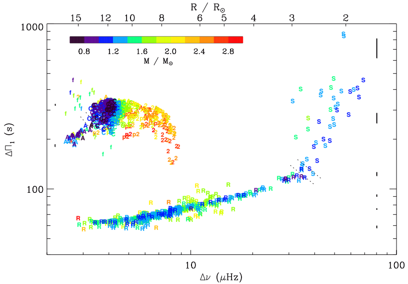
Sub- and red giants: Mixed-Modes

Pressure and **gravity** character
$\Rightarrow$ Probe the **whole** structure!



Credits: Grosjean (Thesis, 2015)

H-shell vs. **core-He** burning
(Montalbàn et al. 2010, Bedding et al. 2011)



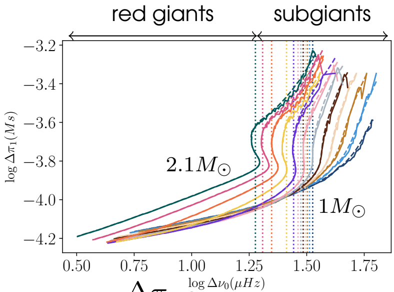
Credits: Mosser et al. 2014

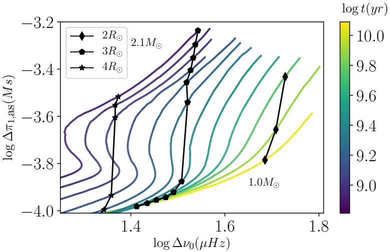
$\Delta\pi_1$: Period spacing

EGGMiMoSA

EGGMiMoSA:
Extracting **G**uesses about **G**iants via **Mi**xed-**Mo**des **S**pectrum **A**djustment (Farnir et al. 2021)

Info on **mass**, **radius**, and **age**





—— $\Delta\pi_{1,\mathrm{fit}}$

$$- - - \ \Delta\pi_{1,\mathrm{asy}} = 2\pi^2\left(\int_g \frac{N}{r}dr\right)^{-1}$$

Farnir et al. (2021)

Conclusions

- Two methods to probe most of the evolution of solar-like pulsators;
- Fast ($< 1s$ per star) and automated;
- Robust indicators for stellar modelling;
- Well suited candidates for the analysis of the PLATO data.