WhoSGlAd : A precise characterisation of the Kepler Legacy sample

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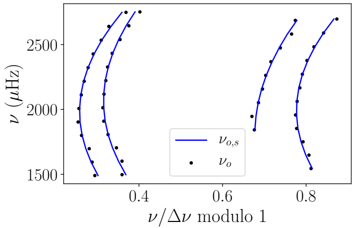
Introduction

- **Aims**:
  - → Constrain solar-like models taking advantage of Kepler data precision:
    - → Ex: Helium - mass degeneracy, extra mixing
- **Outline**:
  - → Solar-like spectrum and glitches
  - → Method
  - → Results: Kepler Legacy Sample, 16 Cyg A

Solar-like spectrum and Acoustic glitches

Solar-like oscillations spectra exhibit:

① regular pattern, smooth



Solar-like spectrum and Acoustic glitches

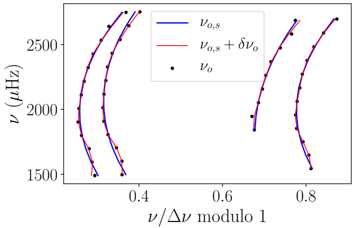
Solar-like oscillations spectra exhibit:

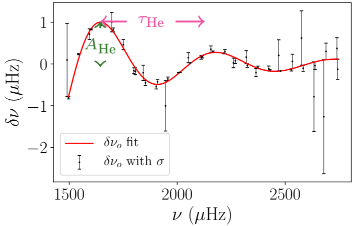
① regular pattern, smooth

② oscillation, glitch, caused by a sharp variation (Γ_1, c), provide localised info:

- $\rightarrow$ Surface helium content, Y_s
- $\rightarrow$ Nature/amount of convective extra mixing

$\rightarrow$ Glitches can help lift model degeneracies





Why improve methods?

Several glitches analysis, for solar-like, have been realised :
Basu et al. 2004, Verma et al. 2014, Monteiro et al. 2014,...
However,

- Separate treatment of glitch and smooth components,
- Use of correlated indicators,
- Seismic and non-seismic constraints not combined in a statistically relevant way.

$\Rightarrow$ Need for a method tackling these issues

WhoSGlAd

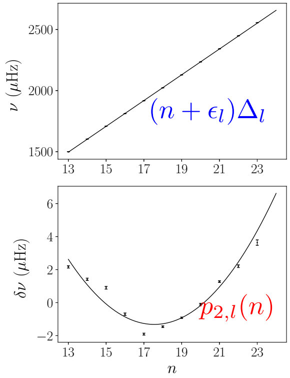
- **Who**le **S**pectrum and **Gl**itches **Ad**justment (Farnir et al. 2019)
  - → Coherent adjustment of both smooth and glitches component of the oscillation spectrum
  - → Proper covariances retrieved

⇒ Precise seismic measurements ⇒ better constraints on stellar modelling

Principle

Represent $\nu_{n,l} \sim {\color{blue}(n+\epsilon_l)\Delta_l} + {\color{red}p_{2,l}(n)} + {\color{orange}\delta\nu_{\rm He}} + {\color{green}\delta\nu_{\rm CZ}}$ as:

2^{nd} order polynomial + oscillatory function



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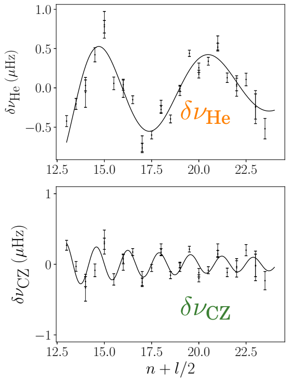


Orthogonalisation $\Rightarrow$ Independent coefficients

Indicators

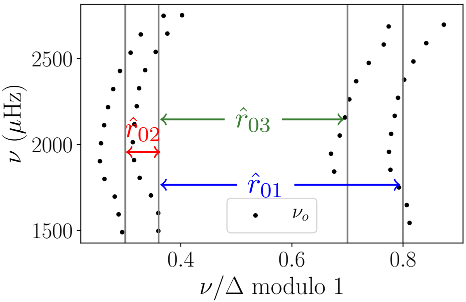
Combine independent coefficients into indicators:
$\hat{r}_{0l}$ ($\sim$ Roxburgh & Vorontsov 2003)

Mean distance between 2 ridges

$\rightarrow$ Info about:

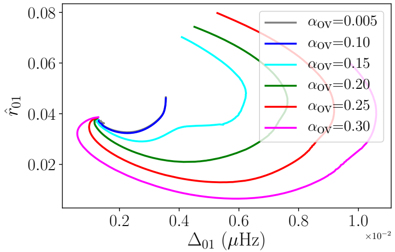
- $\hat{r}_{01}$: Composition
- $\hat{r}_{02}$: Evolution

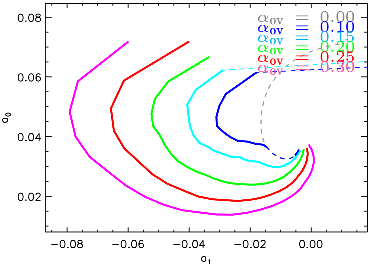
σ 4 times smaller than usual indicators



$\hat{r}_{01}$ - Δ_{01} diagram

Evolution on MS of models of given mass and composition:





Credits: Farnir et al. 2019

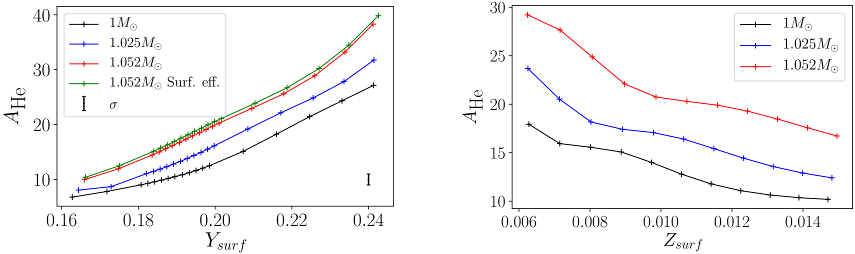
Credits: Deheuvels et al. 2016

Relative slope differences: $\Delta_{0l} = \frac{\Delta_l}{\Delta_0} - 1$

$\rightarrow$ Δ_{01}: central extra mixing

Helium glitch amplitude

Models at fixed Δ:



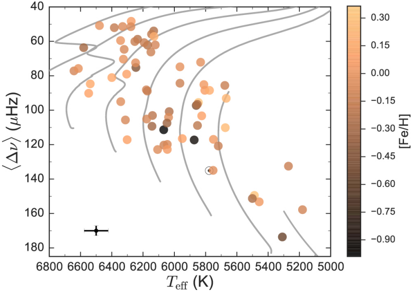
Credits: Farnir et al. 2019

→ Very good indicator of Y_s

→ But $Y_s - Z_s$ degeneracy (see also Basu et al. 2004)

WhoSGIAd and Kepler Legacy Sample

66 solar-like stars $\rightarrow$ best quality data



Credits: Silva Aguirre et al. 2016

Application:

- Free parameters:
  $\rightarrow$ $M, t, \alpha_{ov}, (Z/X)_0, Y_0$
- Constraints:
  $\rightarrow$ $\Delta, \hat{r}_{01}, \hat{r}_{02}, \Delta_{01}, A_{\mathbf{He}}, [Fe/H]$

WhoSGIAd and Kepler Legacy Sample

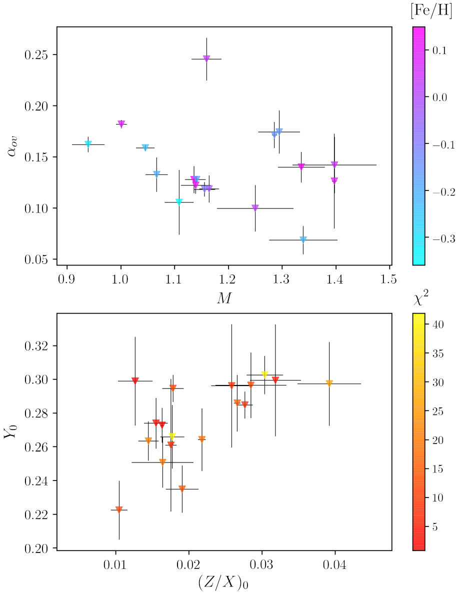
- No $\alpha_{\mathbf{ov}}$ and M correlation observed (to be confirmed)
- Y_0 and $(Z/X)_0$ correlated $\Rightarrow$ Galactic enrichment?

Typical precision:

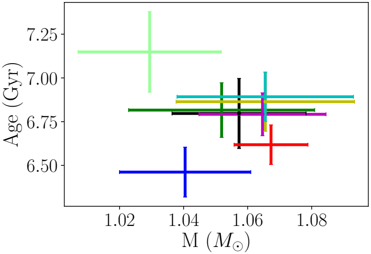
- $\sigma(M) \in [0.02, 0.05] M_\odot$
- $\sigma(t) \in [0.1, 0.5]$ Gyrs
- $\sigma(Y) \in [0.01, 0.05]$
- $\sigma(\alpha_{\mathbf{ov}}) \in [0.01, 0.05]$

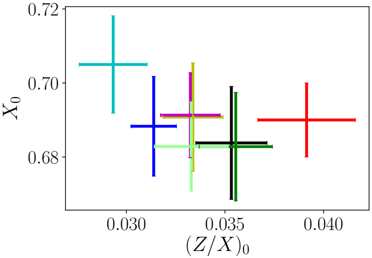
Only one set of input physics tested

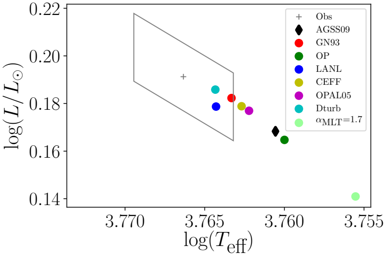
$\Rightarrow \sigma$ relative to the method



In depth modelling: 16 Cygni A







Physics tested:

- Solar ref.
- Opacity
- EOS
- α_{MLT}
- Diffusion

Conclusion

- **Method**:
  - $\rightarrow$ σ 4 times lower $\Rightarrow$ better models
- **16 Cyg A**: (Farnir et al. 2019b in prep.)
  - $\rightarrow$ Possibility to discriminate choices of physics
- **Kepler Legacy**: (Farnir et al. 2019c in prep.)
  - $\rightarrow$ Both [Fe/H] and A_{He} necessary
  - $\rightarrow$ Correlation between Y_0 and $(Z/X)_0$
    $\Rightarrow$ Galactic enrichment?
  - $\rightarrow$ No correlation between α_{ov} and M observed
- **Future perspectives**:
  - $\rightarrow$ Adaptation to subgiants and mixed modes

Principle

Observed spectrum $\boldsymbol{\nu_{obs}}$ —— Projection over basis $a_j = \langle \boldsymbol{\nu_{obs}} | \boldsymbol{q_j} \rangle$ ——→ Independent coefficients $\boldsymbol{\nu_f} = \sum_j a_j \boldsymbol{q_j}$

- Gram-Schmidt → discrete orthonormal basis functions
  → glitch completely independent of smooth part
- Combine coefficients a_j → seismic indicators as uncorrelated as possible
  → tighter constraints

Gram-Schmidt

Construction of orthonormal basis elements

1. Subtract from current element its projection on the previous orthonormal elements,
2. Normalise it.

$$\boldsymbol{u}_{j_0} = \boldsymbol{p}_{j_0} - \sum_{j=1}^{j_0-1} \left\langle \boldsymbol{p}_{j_0} | \boldsymbol{q}_j \right\rangle \boldsymbol{q}_j, \tag{1}$$

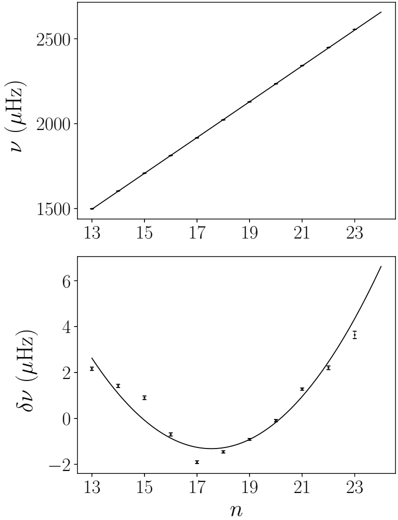
$$\boldsymbol{q}_{j_0} = \frac{\boldsymbol{u}_{j_0}}{\|\boldsymbol{u}_{j_0}\|}. \tag{2}$$

An Illustrative Example : Smooth

At a given degree, projection of the frequencies on the successive basis elements.

- $\rightarrow$ 0 order : mean value;
- $\rightarrow$ 1st order : straight line approximation;
- $\rightarrow$ 2nd order : parabola approximation.

Follow the proper ordering to define seismic indicators

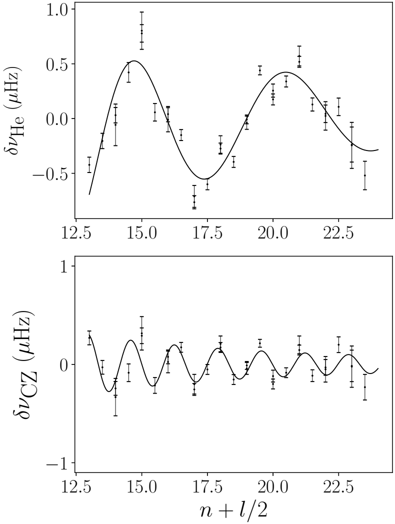


An Illustrative Example : Glitch

Simultaneous projection of the frequencies for every spherical degree on the successive basis elements.

→ First for the helium;

→ Then for the convection zone.



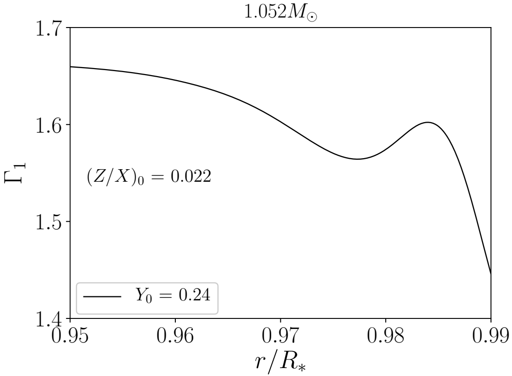
Formulation

$$f(n,l) = \overbrace{\sum_{k=0}^{2} a_{k,l} n^k}^{\text{Smooth}} \quad + \overbrace{\sum_{k=5}^{4} \left[s_{k,\mathrm{He}} \sin(4\pi T_{He}\widetilde{n}) \right.}^{\text{He Glitch}}$$
$$\left. + c_{k,\mathrm{He}} \cos(4\pi T_{He}\widetilde{n}) \right] \widetilde{n}^{-k} \qquad (3)$$

Degeneracy

- Correlated with Y_{surf};
- Anti-correlated with Z_{surf};

→ Γ_1 toy model provides an explanation.



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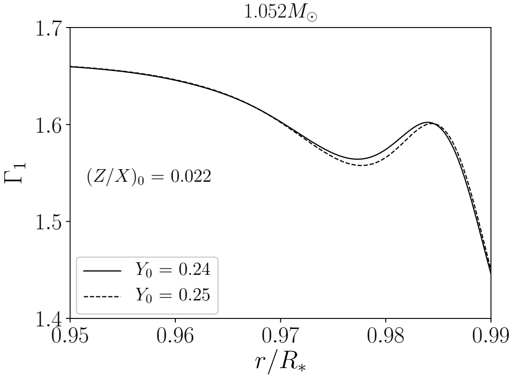

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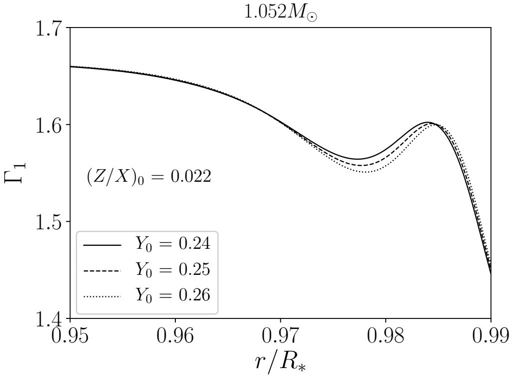

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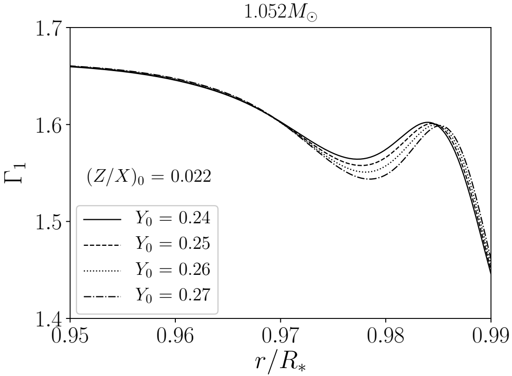

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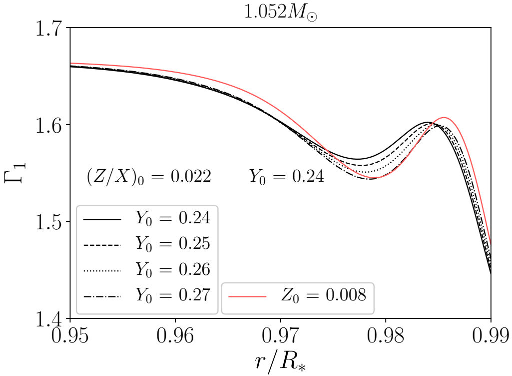

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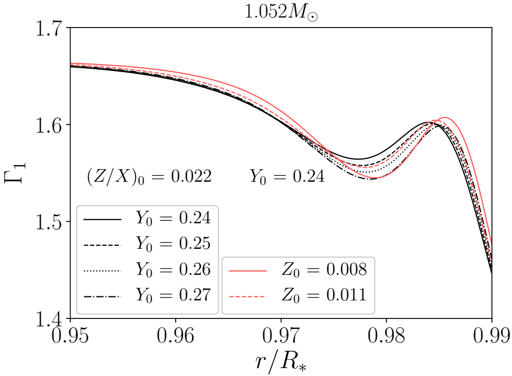

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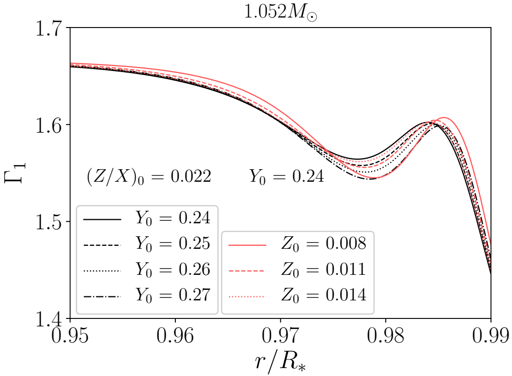

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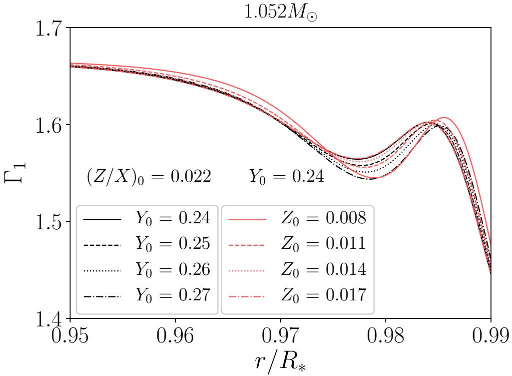

Γ_1 Toy Model