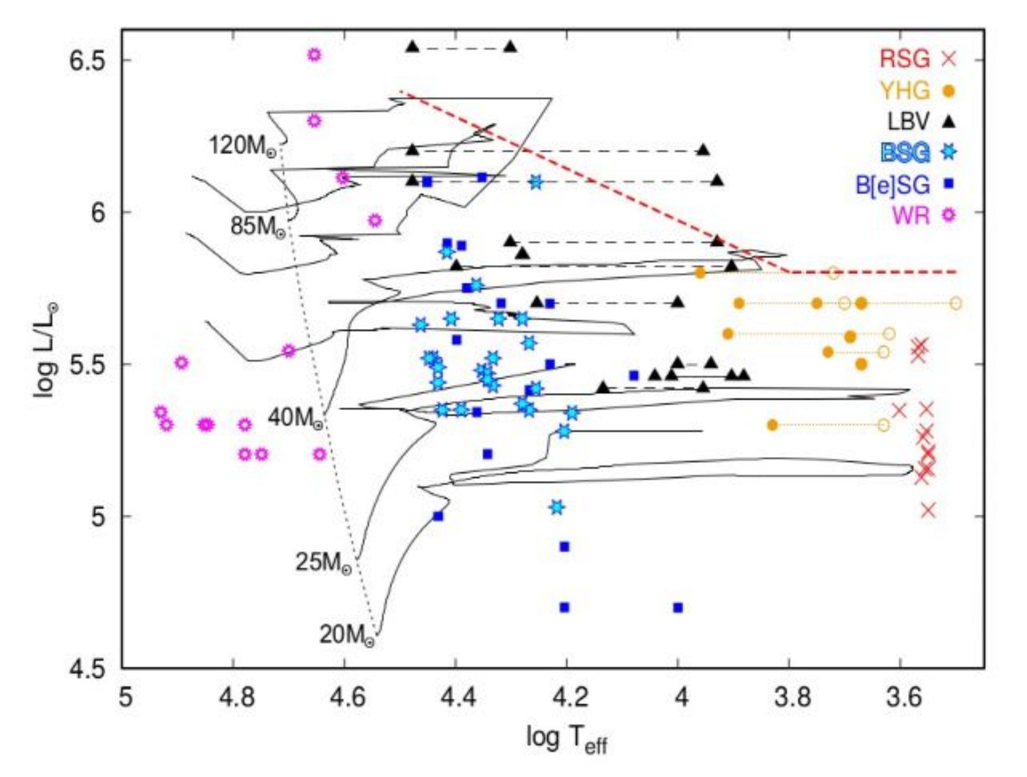
Uncovering the challenges to assess the evolution of B supergiants.

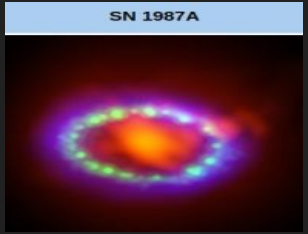
Julieta P. Sanchez Arias

Astronomický ústav AV ČR

POEMS

B supergiant stars



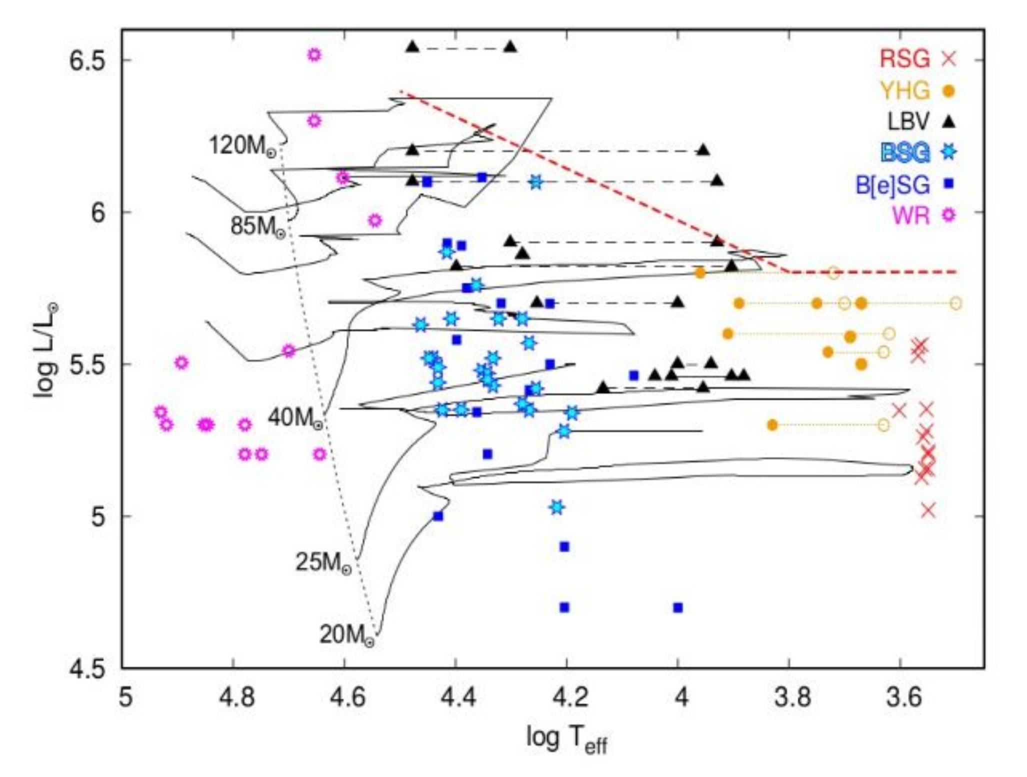


Up to 1987 they thought to be H-shell burning objects on their red-ward evolution.

Two groups:

1. Evolving red-wards after the end of the main sequence
2. Evolving back from the Red Supergiant Stage (RSG)

B supergiant stars

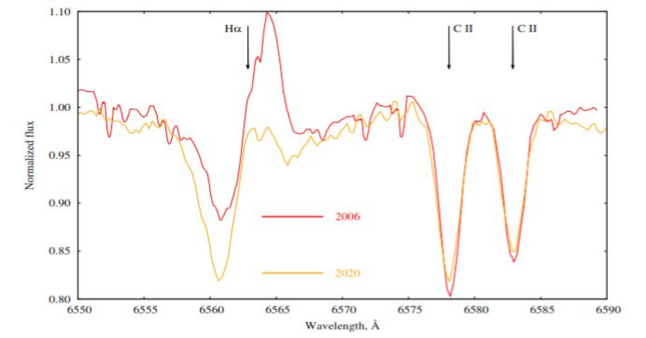


To retrieve information about the evolutionary stage of 3 BSG combining:

1. Frequency analysis
2. Spectroscopy
3. Evolutionary models.

Variations in B Supergiants

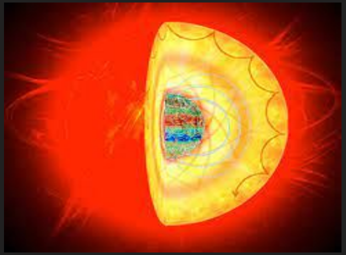
Spectroscopic variations



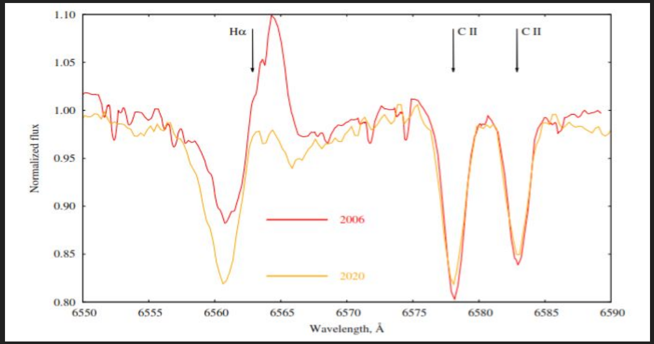
Variations in B Supergiants

Photometric Variations

Self-excited stellar
pulsations.



Spectroscopic variations



Stellar pulsations in B Supergiants

Introduce perturbations in the equations that govern the stellar structure

$$\frac{\delta\rho}{\rho} = -\vec{\nabla}.\delta\vec{r},$$

Mass conservation

$$\frac{\partial^2 \delta\vec{r}}{\partial t^2} = -\vec{\nabla}\psi' - \frac{\vec{\nabla}P'}{\rho} + \frac{\rho'}{\rho}\vec{\nabla}\psi\,,$$

Momentum equation

$$\nabla^2\psi' = 4\pi G\rho'\,,$$

Poisson equation

$$\frac{\delta P}{P} = \Gamma_1 \frac{\delta\rho}{\rho} + \frac{\rho}{P}\left(\Gamma_3 - 1\right) T\delta s$$

Equation of state

$$T\frac{\partial \delta s}{\partial t} = \delta\left(\epsilon - \frac{\mathrm{d}L}{\mathrm{d}m}\right),$$

Energy equation

Stellar pulsations in B Supergiants

Excitation mechanisms

Adiabatic

Non-adiabatic

$$x\frac{\mathrm{d}y_1}{\mathrm{d}x} = \left(\frac{V}{\Gamma_1} - 1 - \ell\right) y_1 + \left(\frac{\ell(\ell+1)}{c_1\omega^2} - \frac{V}{\Gamma_1}\right) y_2 + \frac{\ell(\ell+1)}{c_1\omega^2} y_3 + \upsilon_T y_5,$$

$$x\frac{\mathrm{d}y_2}{\mathrm{d}x} = \left(c_1\omega^2 - A^*\right) y_1 + \left(A^* + 3 - U - \ell\right) y_2 - y_4 + \upsilon_T y_5,$$

$$x\frac{\mathrm{d}y_3}{\mathrm{d}x} = \left(3 - U - \ell\right) y_3 + y_4,$$

$$x\frac{\mathrm{d}y_4}{\mathrm{d}x} = UA^* y_1 + U\frac{V}{\Gamma_1} y_2 + \ell(\ell+1) y_3 + (2 - U - \ell) y_4 - \upsilon_T U y_5,$$

$$x\frac{\mathrm{d}y_5}{\mathrm{d}x} = V\left[\nabla_{\mathrm{ad}}(U - c_1\omega^2) - 4(\nabla_{\mathrm{ad}} - \nabla) + c_{\mathrm{dif}}\right] y_1 + V\left[\frac{\ell(\ell+1)}{c_1\omega^2}(\nabla_{\mathrm{ad}} - \nabla) - c_{\mathrm{dif}}\right] y_2$$
$$+ V\left[\frac{\ell(\ell+1)}{c_1\omega^2}(\nabla_{\mathrm{ad}} - \nabla)\right] y_3 + V\nabla_{\mathrm{ad}} y_4 + \left[V\nabla(4 - \kappa_S) + 2 - \ell\right] y_5 - \frac{V\nabla}{c_{\mathrm{rad}}} y_6,$$

$$x\frac{\mathrm{d}y_6}{\mathrm{d}x} = \left[\ell(\ell+1)c_{\mathrm{rad}}\left(\frac{\nabla_{\mathrm{ad}}}{\nabla} - 1\right) - Vc_{\epsilon,\mathrm{ad}}\right] y_1 + \left[Vc_{\epsilon,\mathrm{ad}} - \ell(\ell+1)c_{\mathrm{rad}}\left(\frac{\nabla_{\mathrm{ad}}}{\nabla} - \frac{3 + \partial c_{\mathrm{rad}}}{c_1\omega^2}\right)\right] y_2$$
$$+ \left[\ell(\ell+1)c_{\mathrm{rad}}\frac{3 + \partial c_{\mathrm{rad}}}{c_1\omega^2}\right] y_3 + \left[c_{\epsilon,S} - \frac{\ell(\ell+1)c_{\mathrm{rad}}}{\nabla V} + \mathrm{i}\omega c_{\mathrm{thm}}\right] y_5 - (\ell+1) y_6.$$

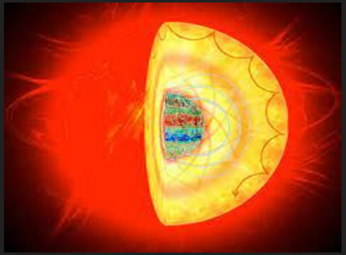
Variations in B Supergiants

Photometric Variations

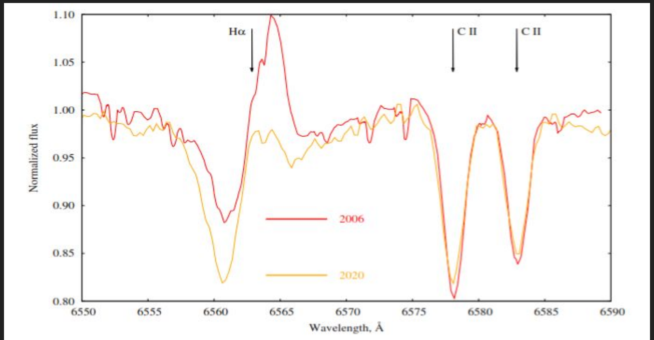
Mean life time between years a Myrs.

Self-excited stellar pulsations.

Among them strange modes → known to facilitate mass loss

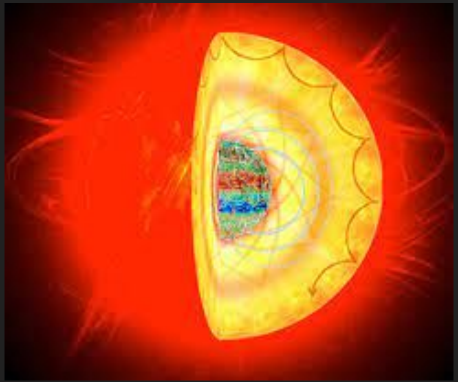


Spectroscopic variations



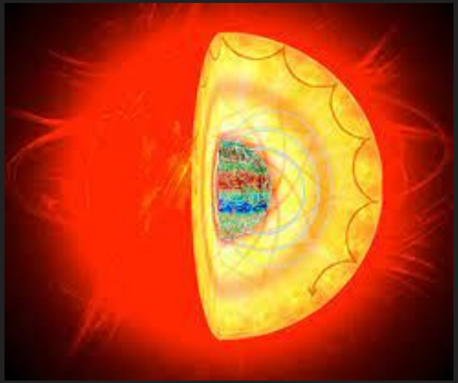
Strange modes

- They are excited by the kappa mechanism.

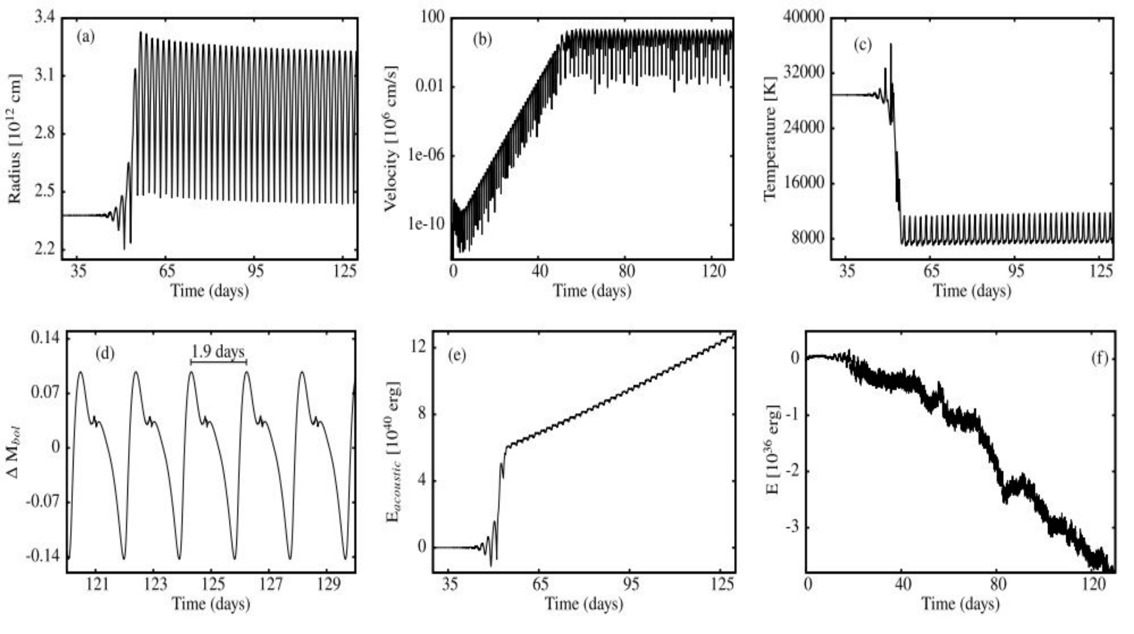


Strange modes

- They are excited by the kappa mechanism.
- They are known to facilitate the mass loss



Strange modes

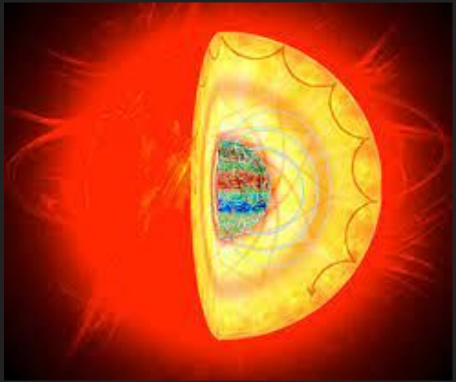


Non linear stability analysis are required to determine if the mode can facilitate mass loss by **comparing the mode velocities in the outer layers with the escape velocity.**

Parida et al. (2023)

Strange modes

- They are excited by the kappa mechanism.
- They are known to facilitate the mass loss
- They appear at highly non-adiabatic environments



Linearized form of the energy conservation for stellar envelope

$$T\frac{\partial \delta S}{\partial t} = -\frac{L}{M}\frac{\partial}{\partial q}\left(\frac{\delta L}{L}\right)$$

post-RSG are excellent targets for strange modes occur

Variations in B Supergiants

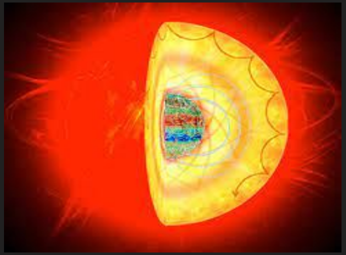
Photometric Variations

Spectroscopic variations

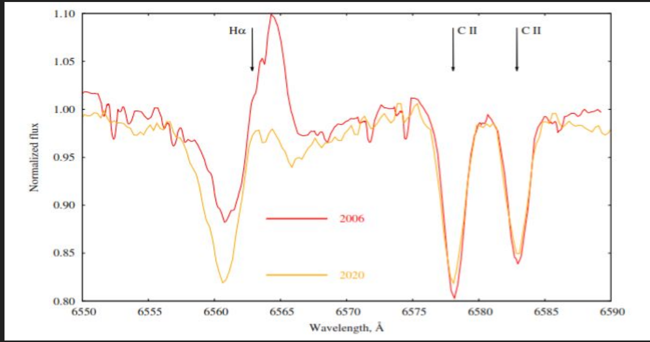
Mean life time between years a Myrs.

Self-excited stellar pulsations.

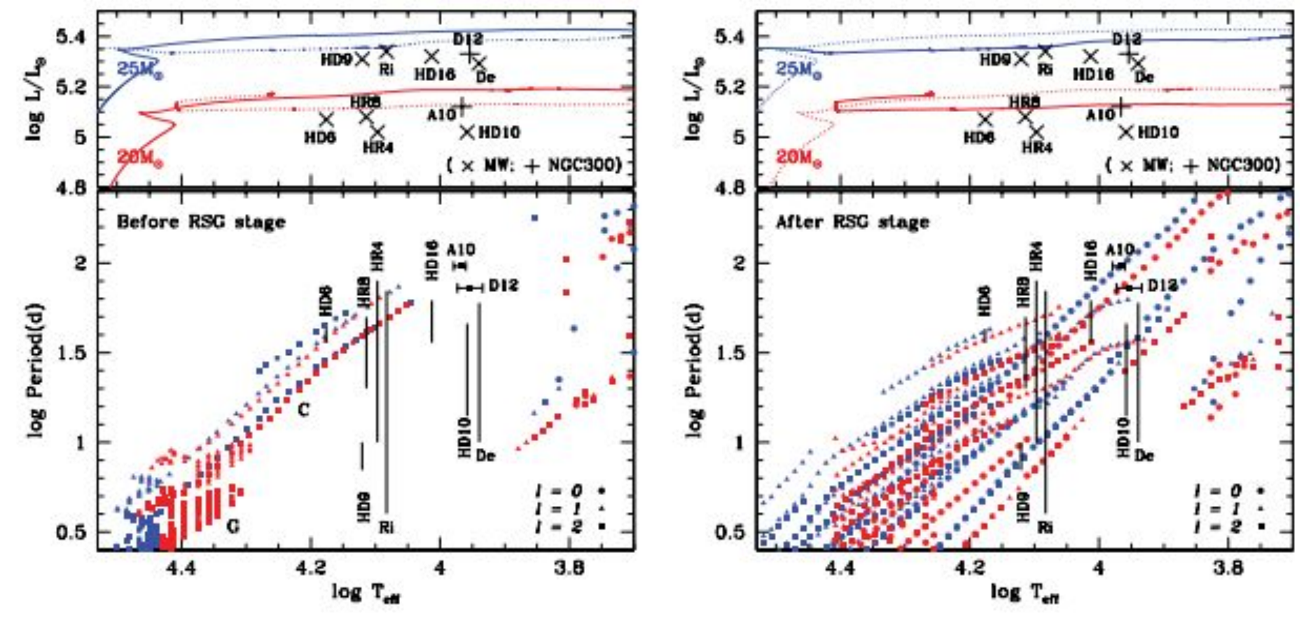
Among them strange modes → known to facilitate mass loss



No studies about their mean life time



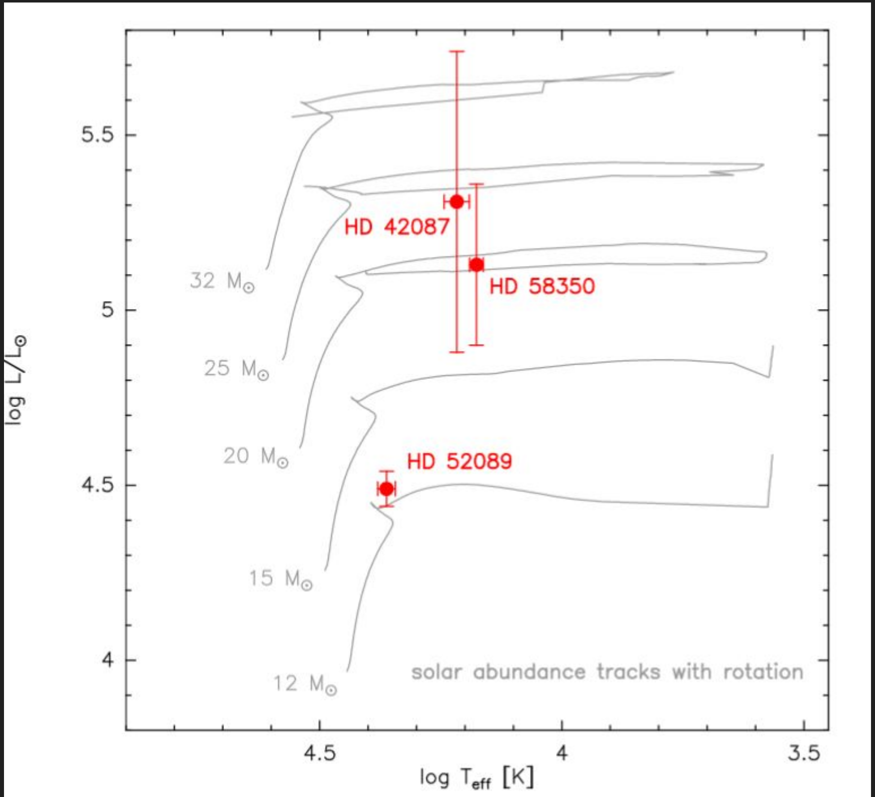
Stellar pulsations in B Supergiants

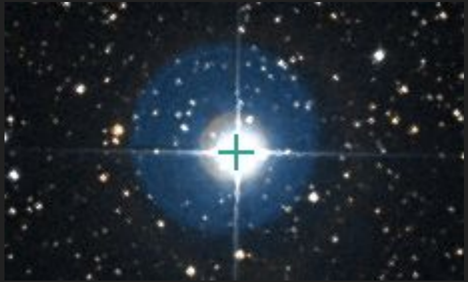


Post-RSGs excite significantly more pulsation modes (including strange modes) than their counterpart at the pre-RSG.

Saio et al. (2013)

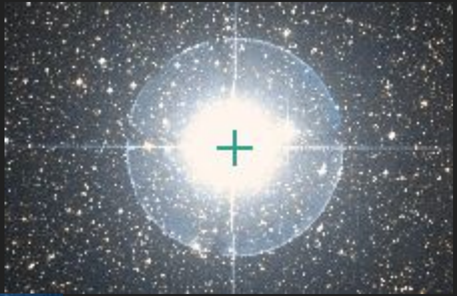
Target selection





HD 58350

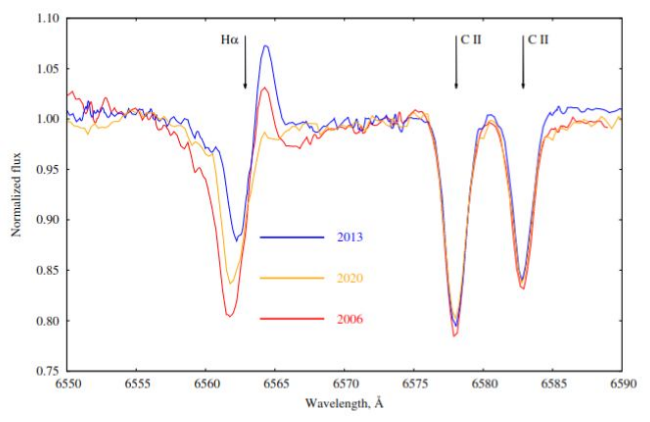
HD 52089



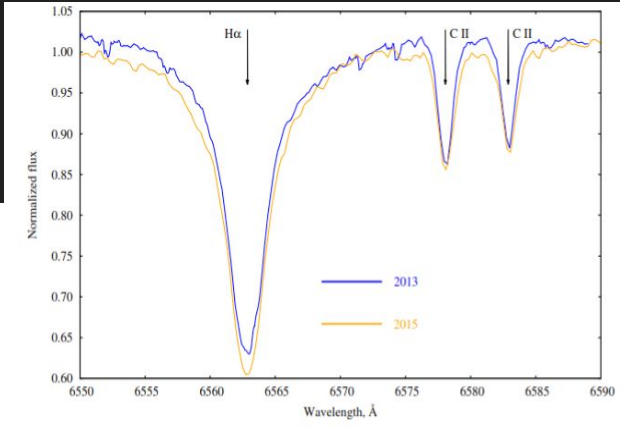
HD 42087

Observations: Spectra

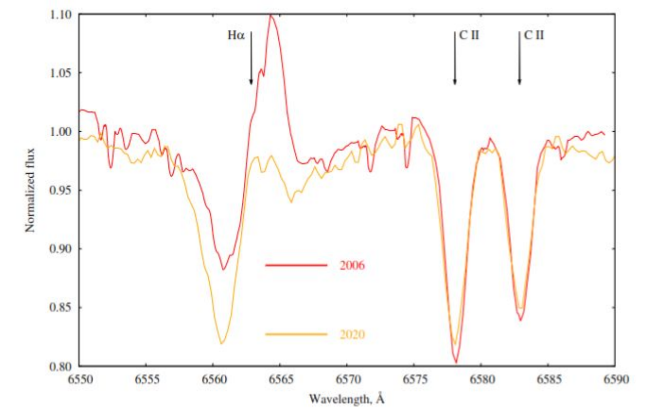
We used the REOSC spectrograph attached to the Jorge Sahade 2.15 m telescope at the Complejo Astronómico El Leoncito (CASLEO), San Juan, Argentina. Covering a range: [4275, 6800] A and R=12600 and R=13900 at 4500 and 6500 A, respectively.



HD 58350



HD 52089



HD 42087

Observations: Photometry

We used the 2 min TESS cadence light curves (~27d)

Selection criteria:

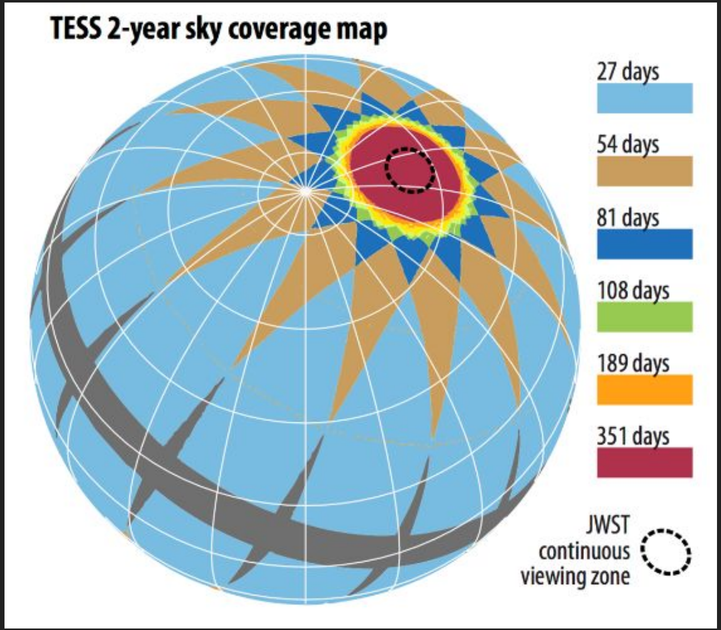
-We searched for period between [0,50] c/d and worked on the residuals after deriving each frequency.

-We dismissed those frequencies below 0.1 c/d for single sectors.

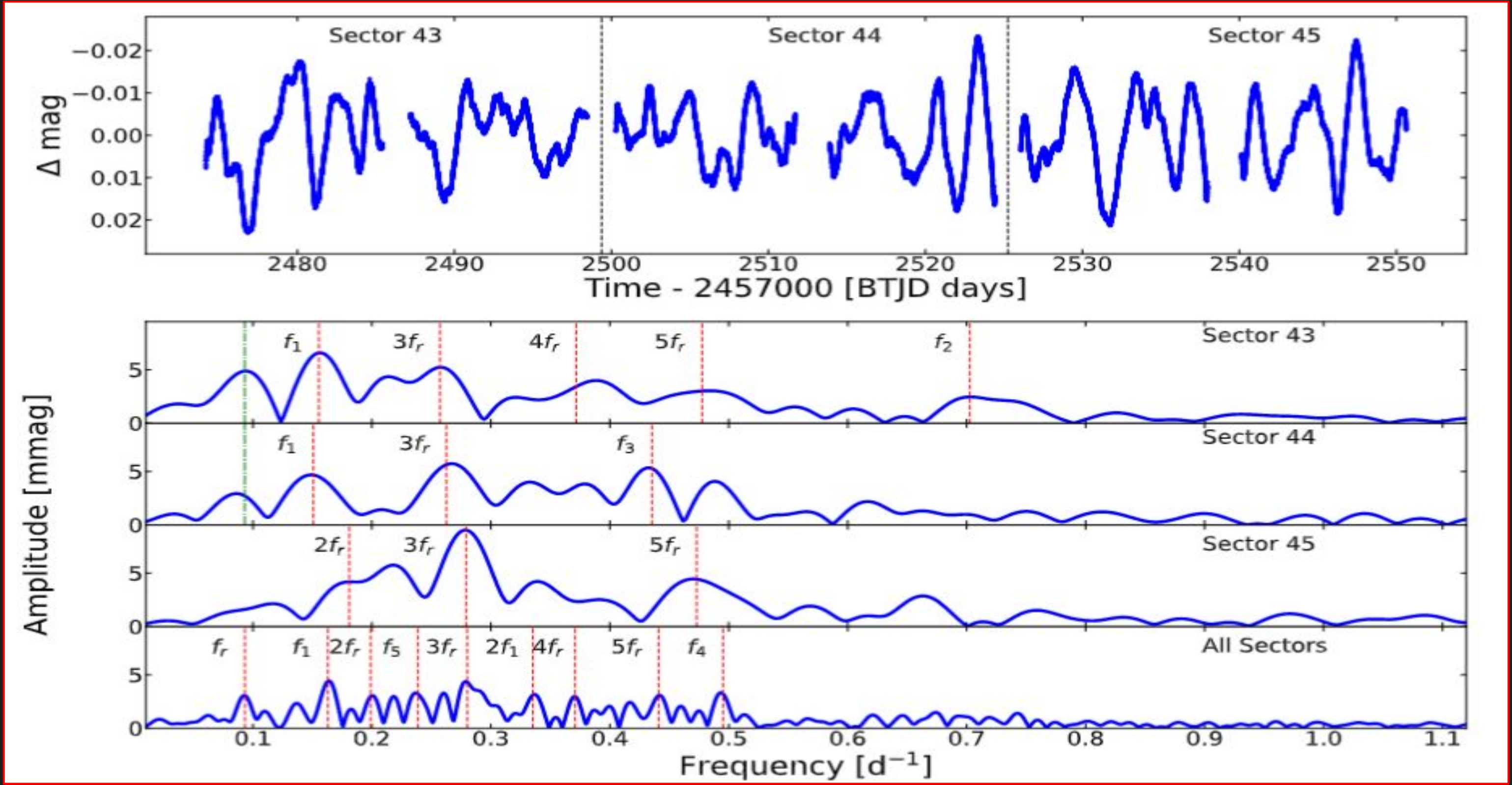
-We discard those frequencies with a separation less than 2/T.

-We used the recommend values from Baran & Koen (2021) for the S/N

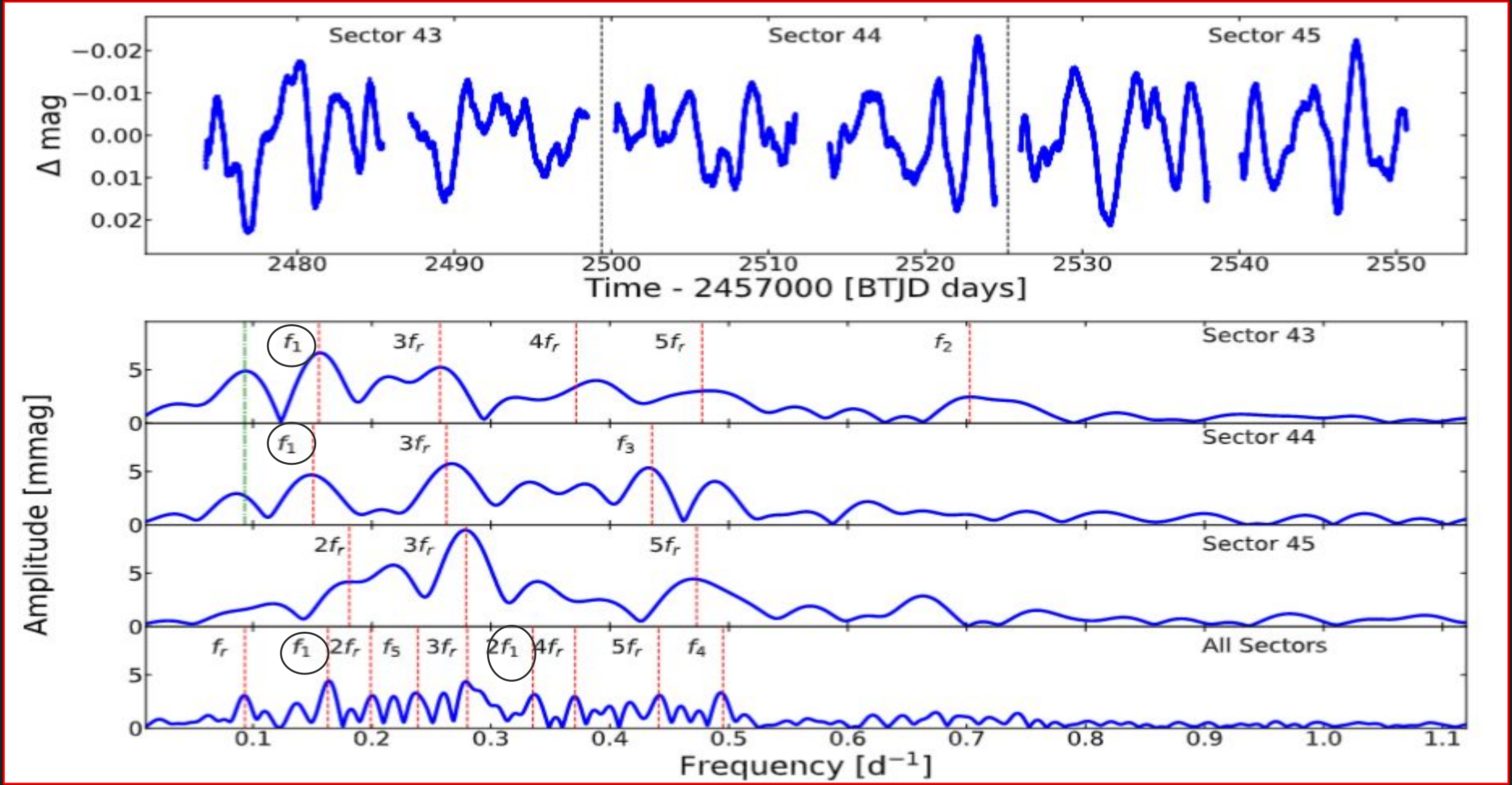
$$S/N = 5.2902(48) + 0.1351(26) \cdot \ln N_s \quad \text{for} \quad \Delta t = 20\,\text{s}$$
$$S/N = 5.0355(38) + 0.1417(20) \cdot \ln N_s \quad \text{for} \quad \Delta t = 120\,\text{s}$$
$$S/N = 4.6200(29) + 0.1559(15) \cdot \ln N_s \quad \text{for} \quad \Delta t = 1800\,\text{s}$$



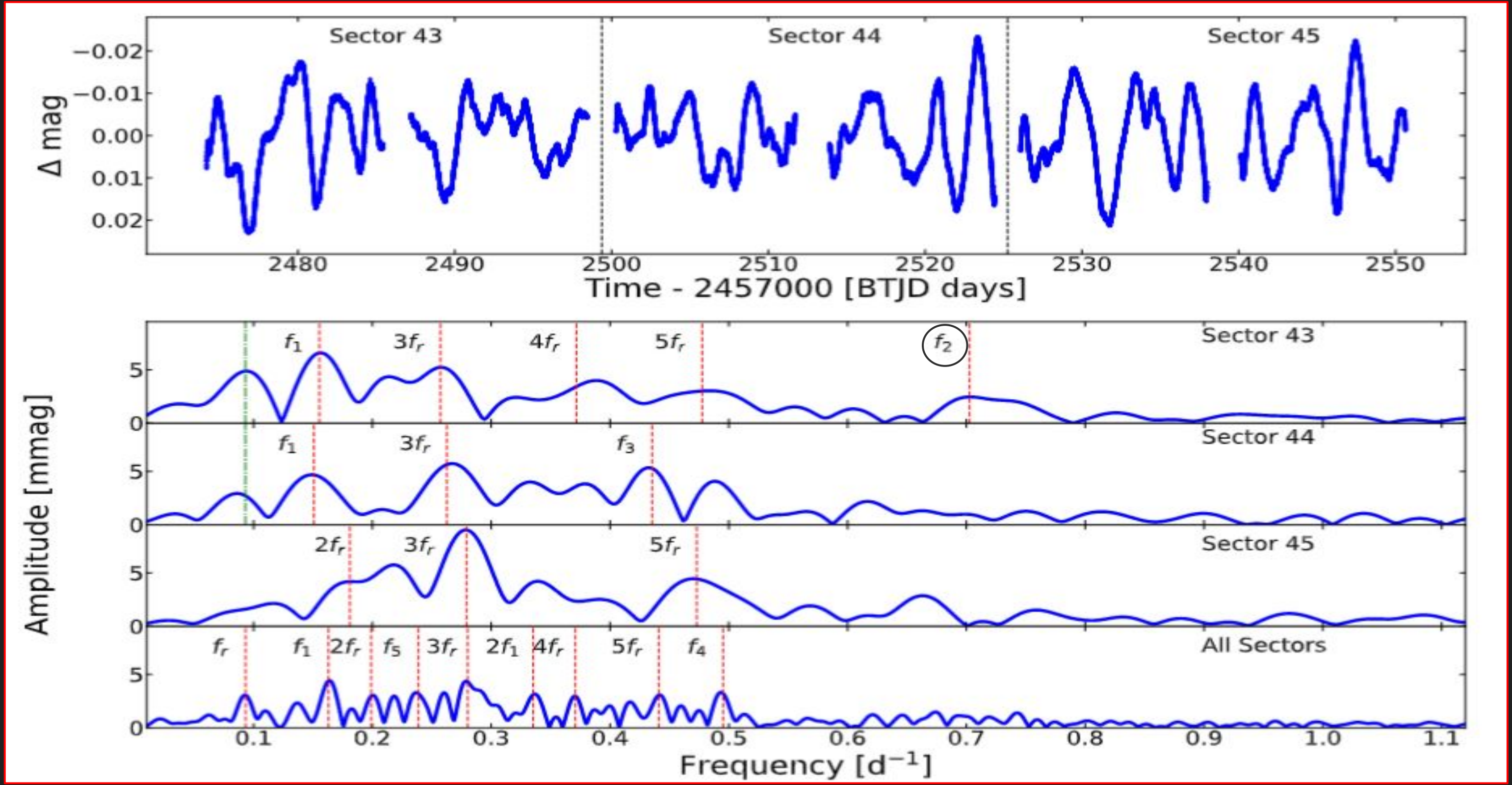
Frequency Analysis: HD 42087



Frequency Analysis: HD 42087



Frequency Analysis: HD 42087



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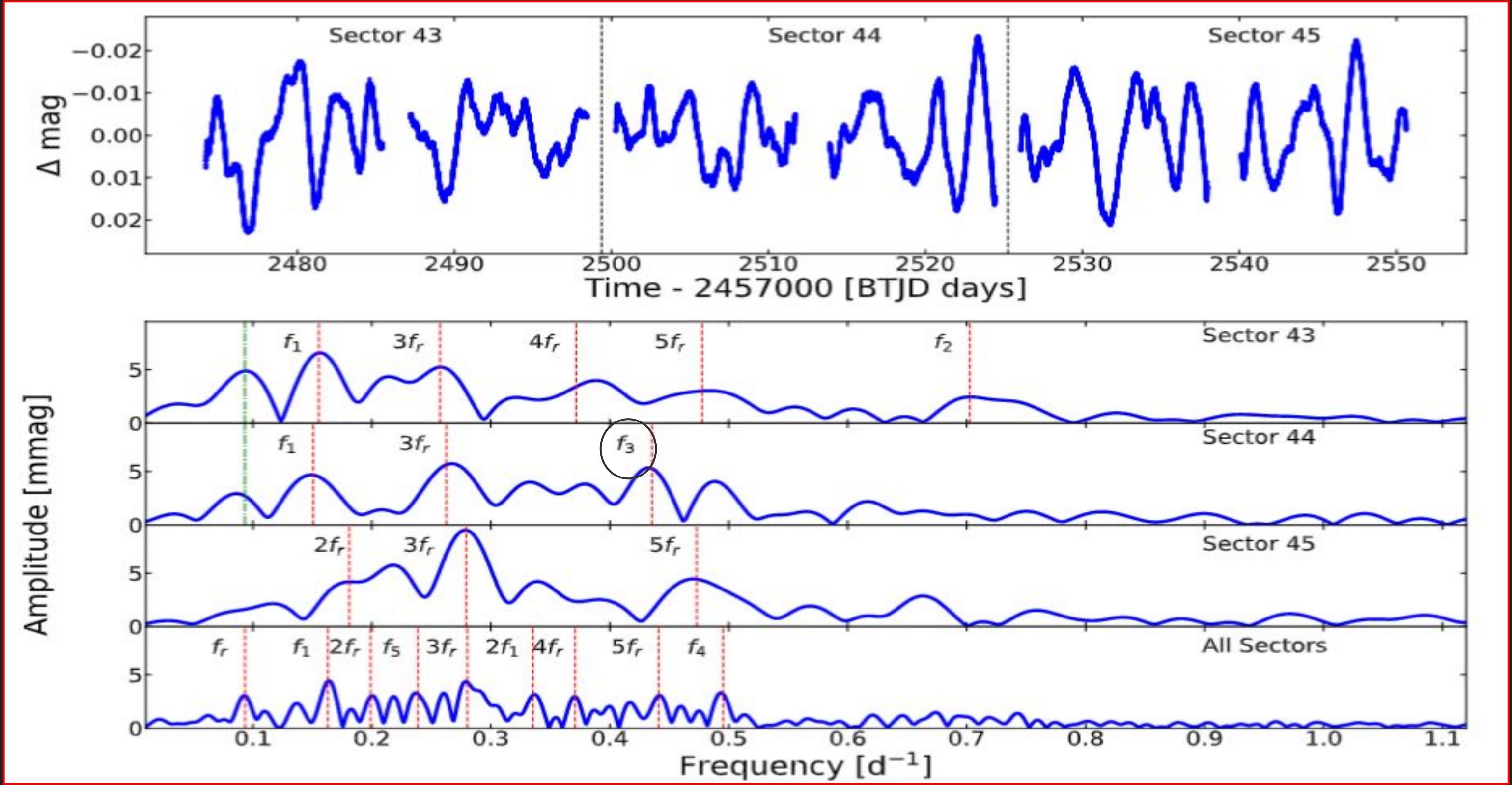
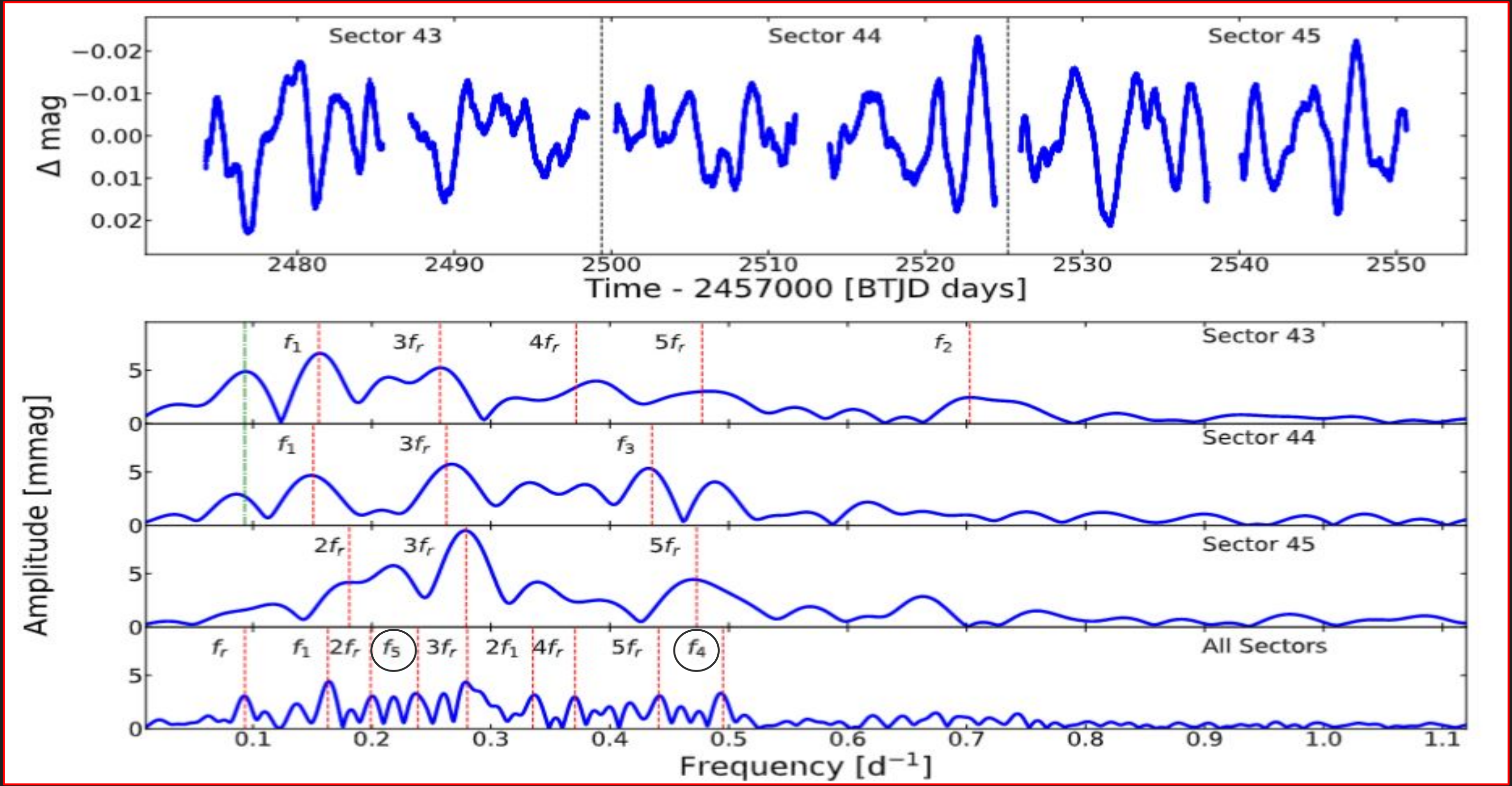
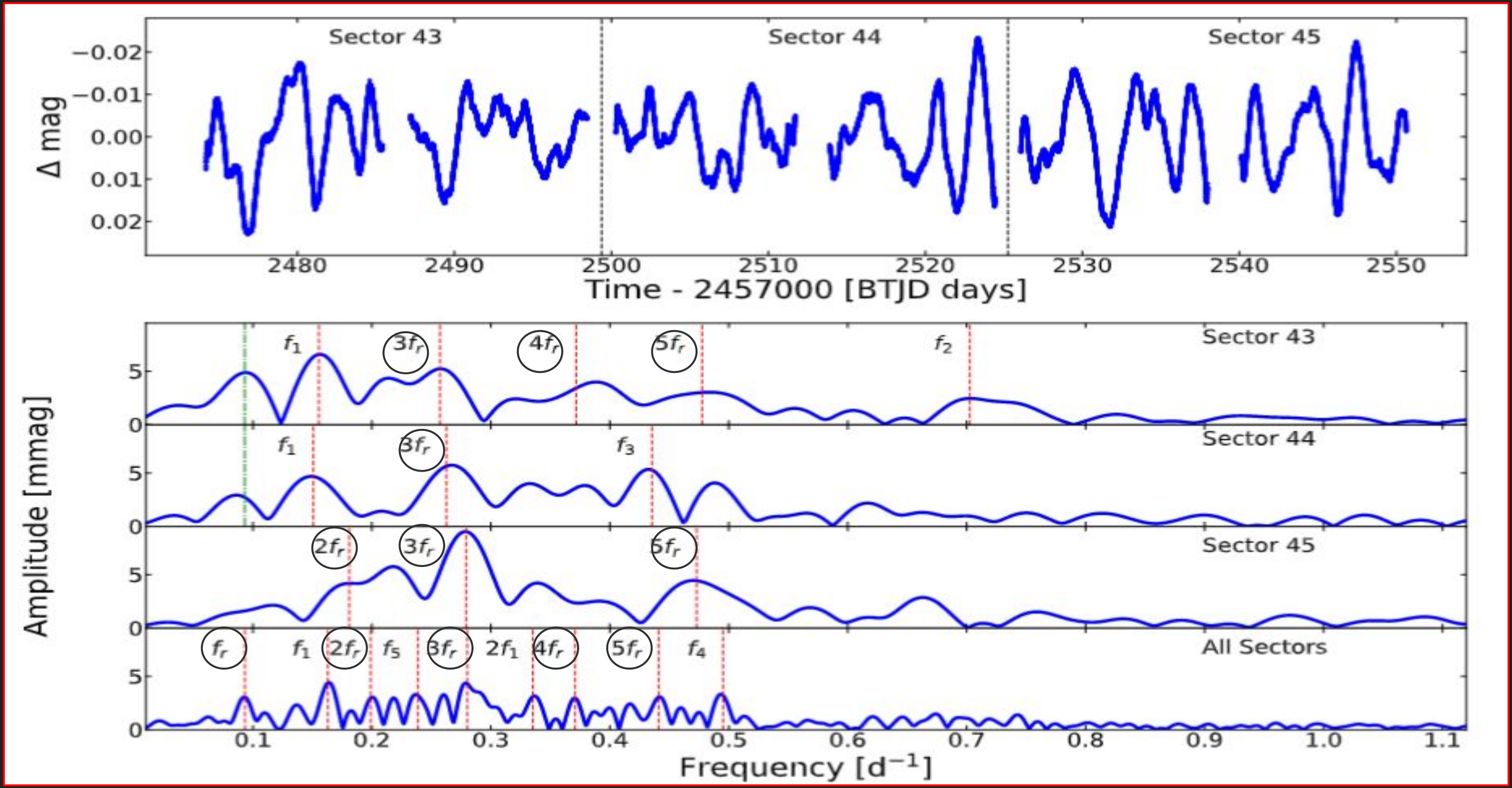


Frequency Analysis: HD 42087

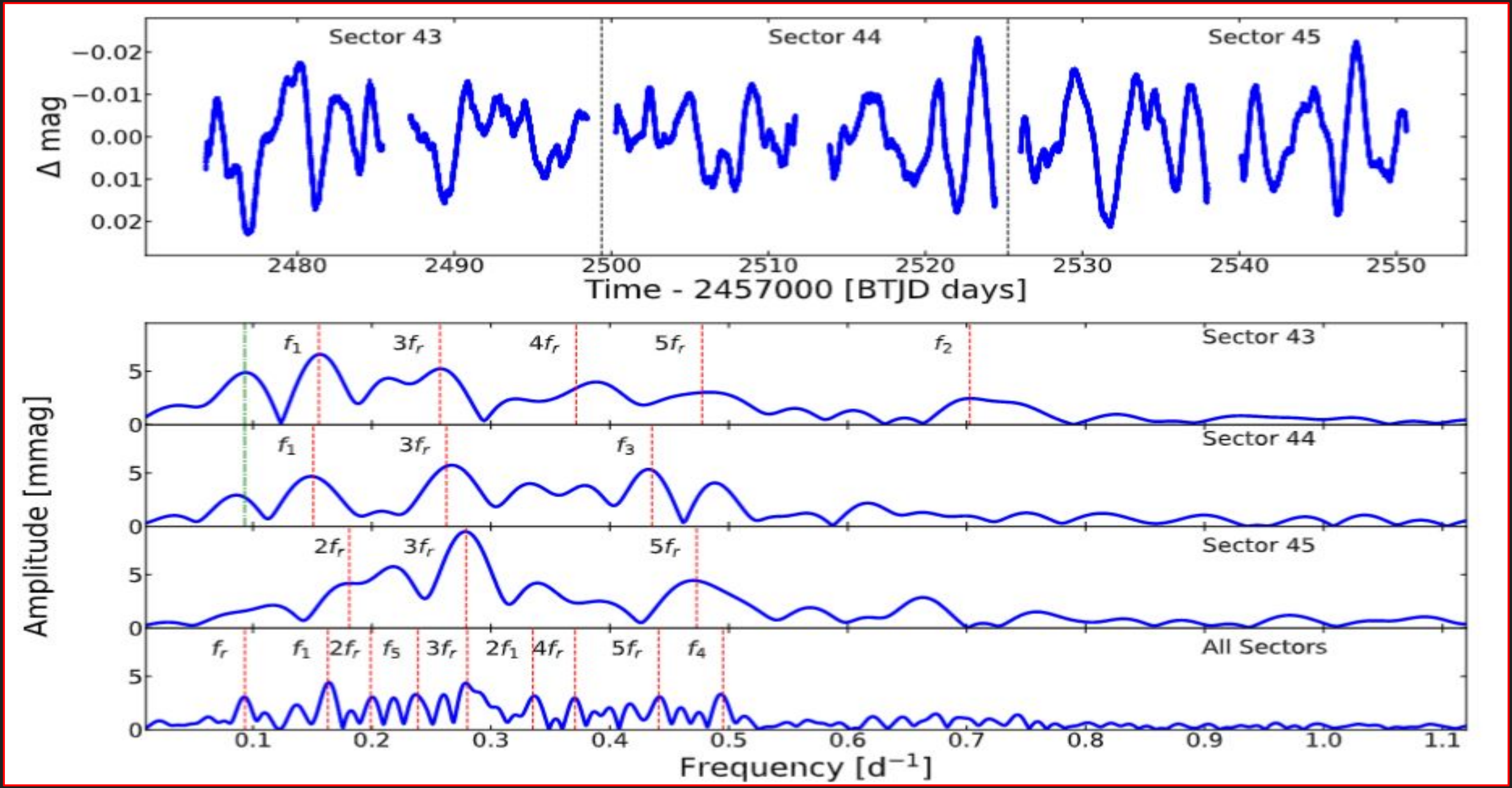


Frequency Analysis: HD 42087

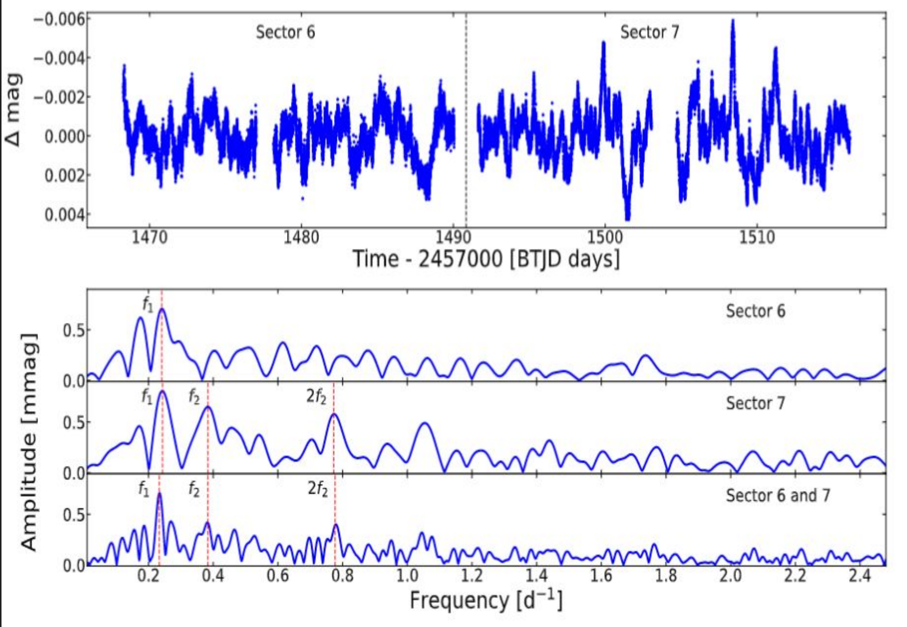


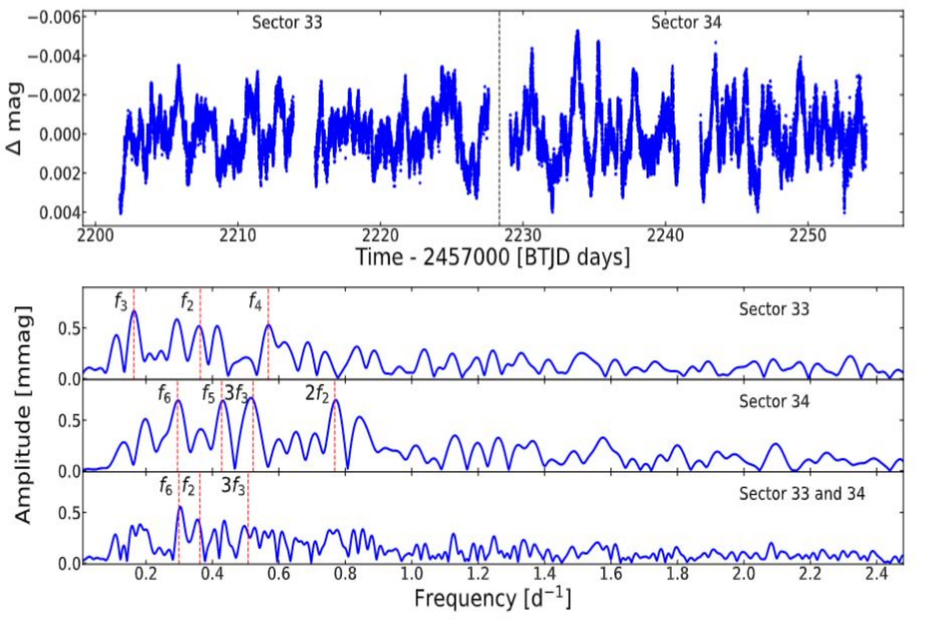
Frequency Analysis: HD 42087

Pre-RSG

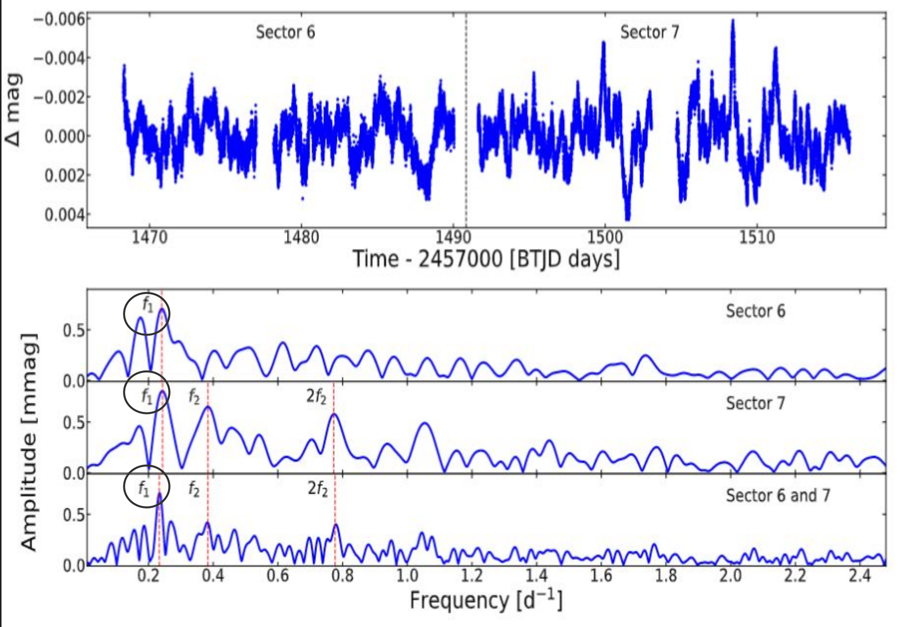


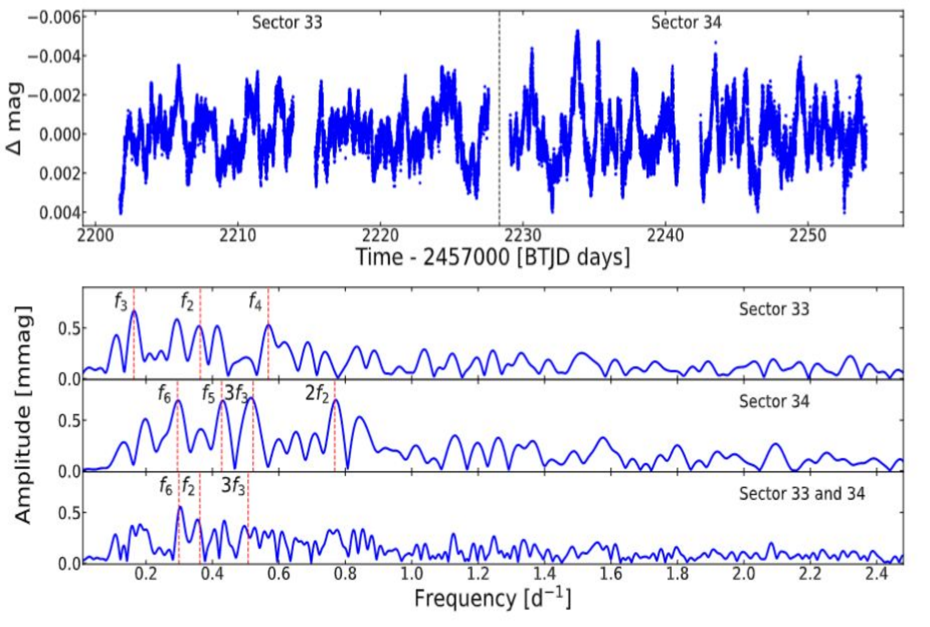
Frequency Analysis: HD 52089



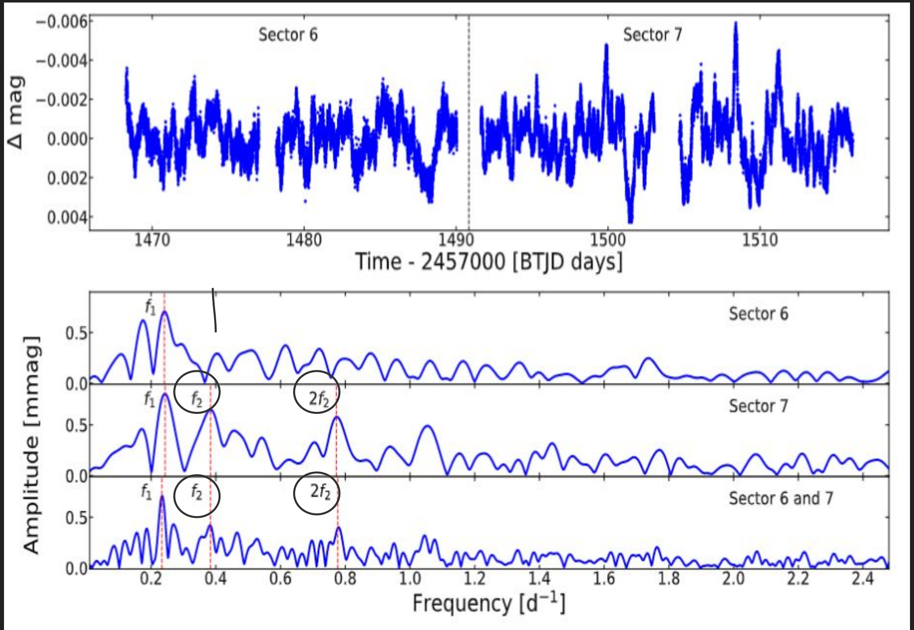


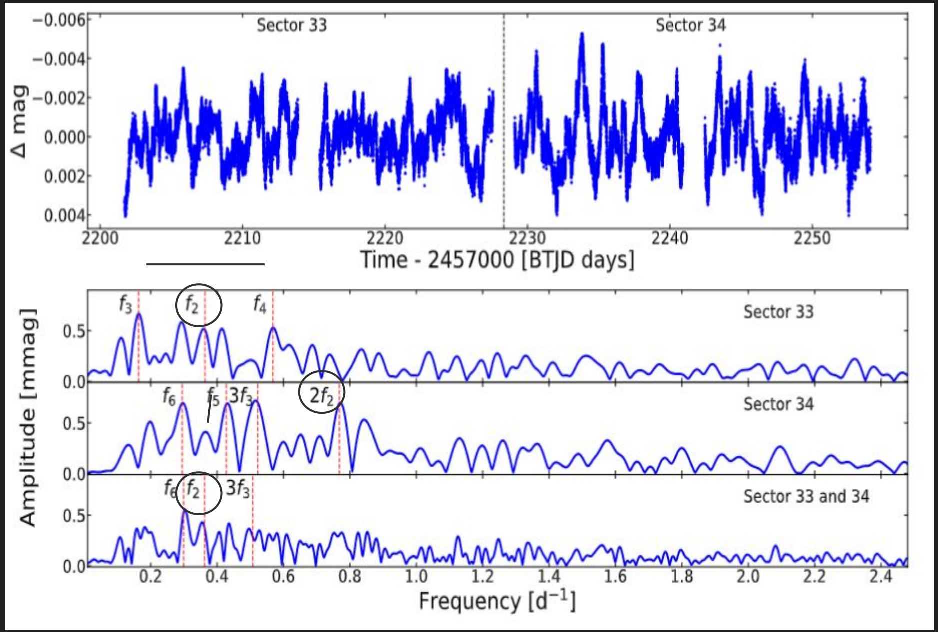
Frequency Analysis: HD 52089





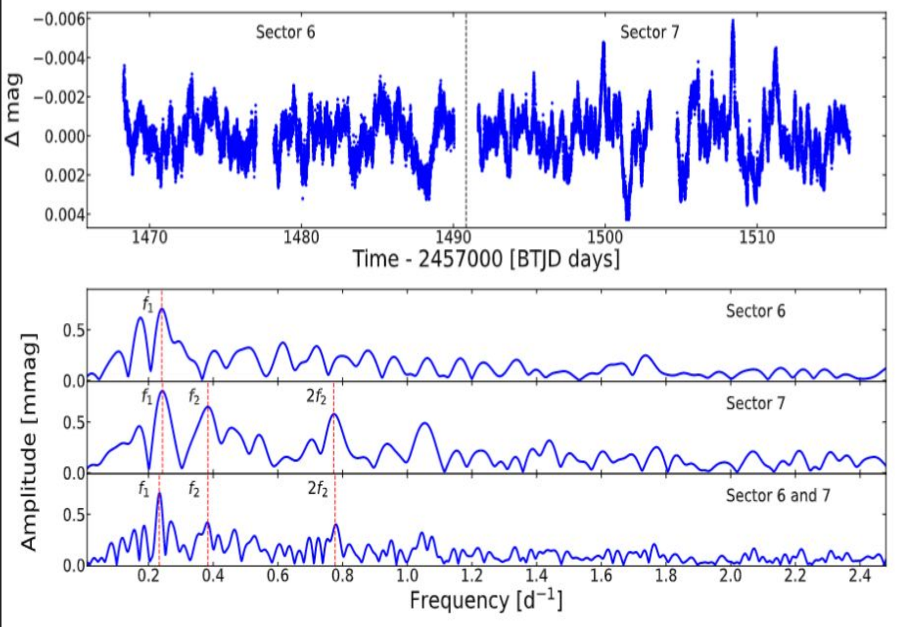
Frequency Analysis: HD 52089

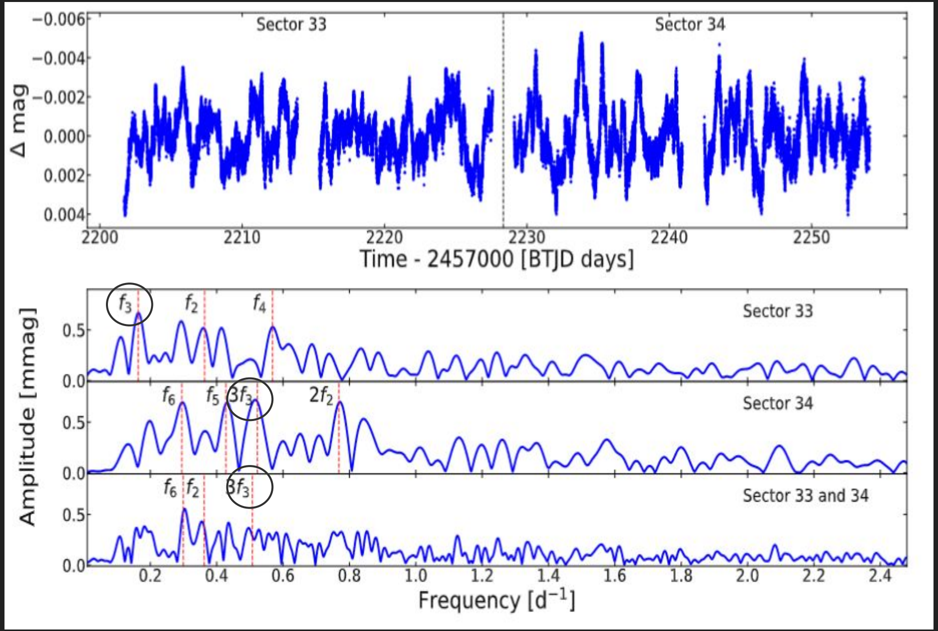




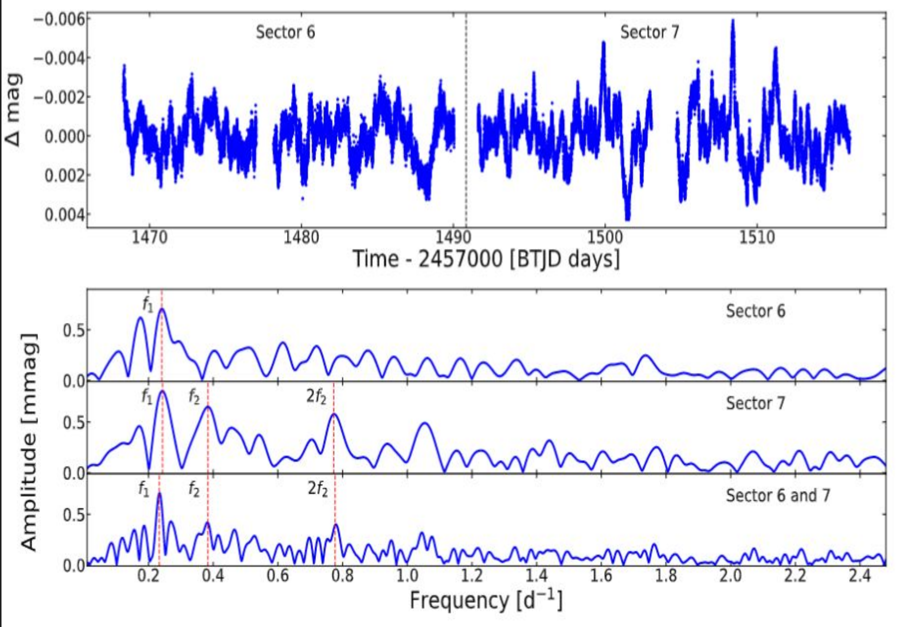
$$\nu_{nlm} = \nu_{nl} + m(1 - C_{nl})\frac{\Omega}{2\pi},$$

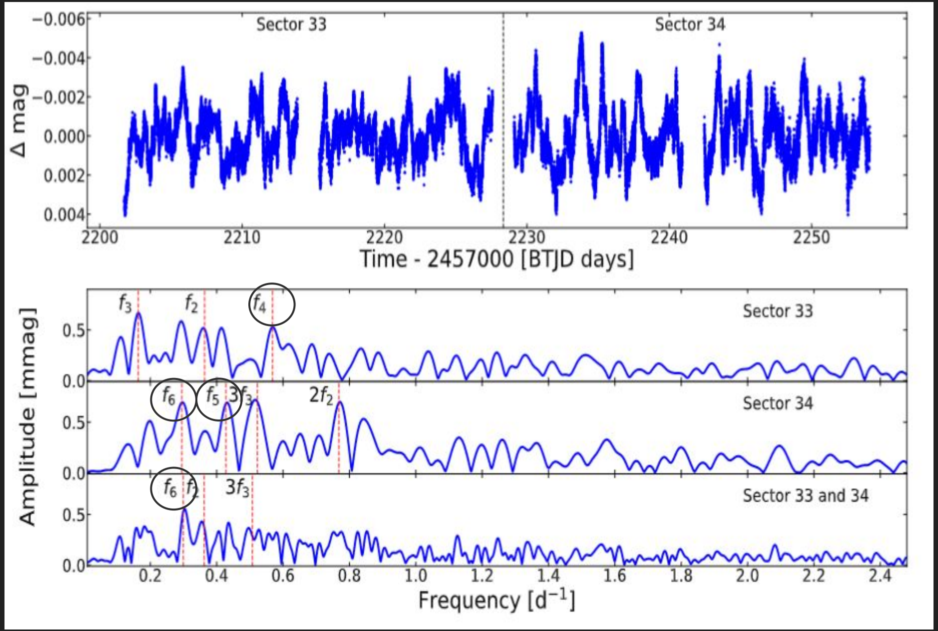
Frequency Analysis: HD 52089





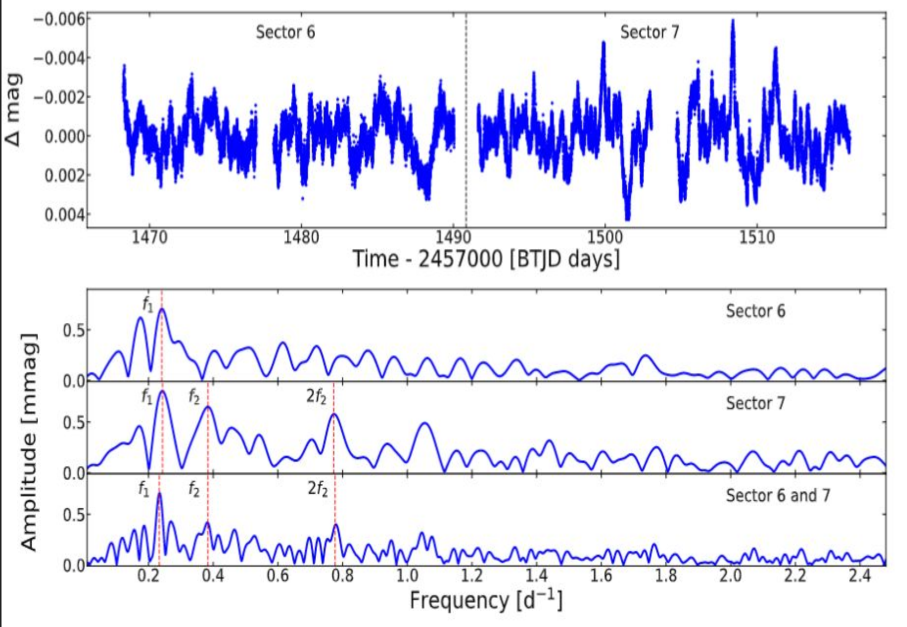
Frequency Analysis: HD 52089

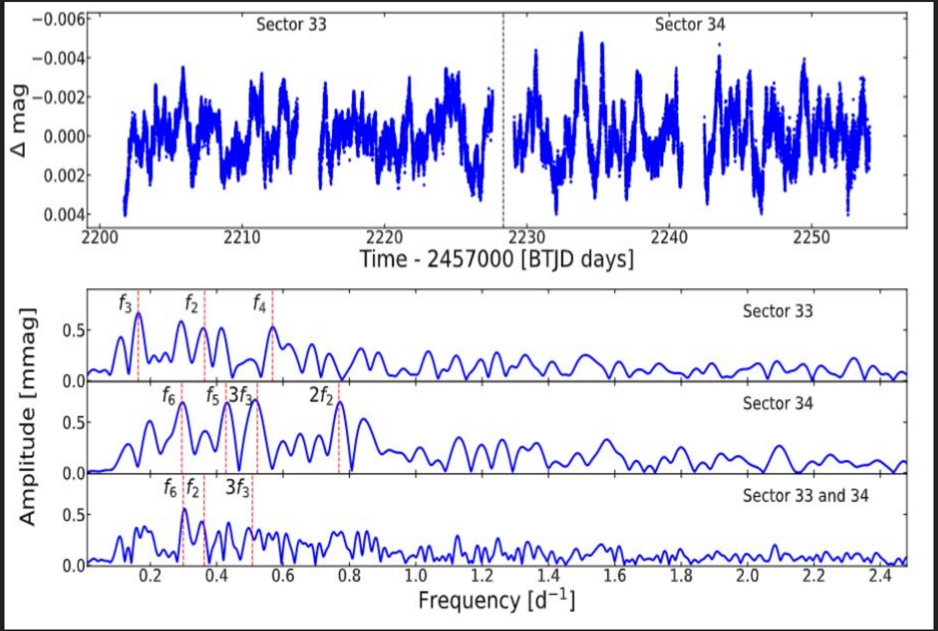




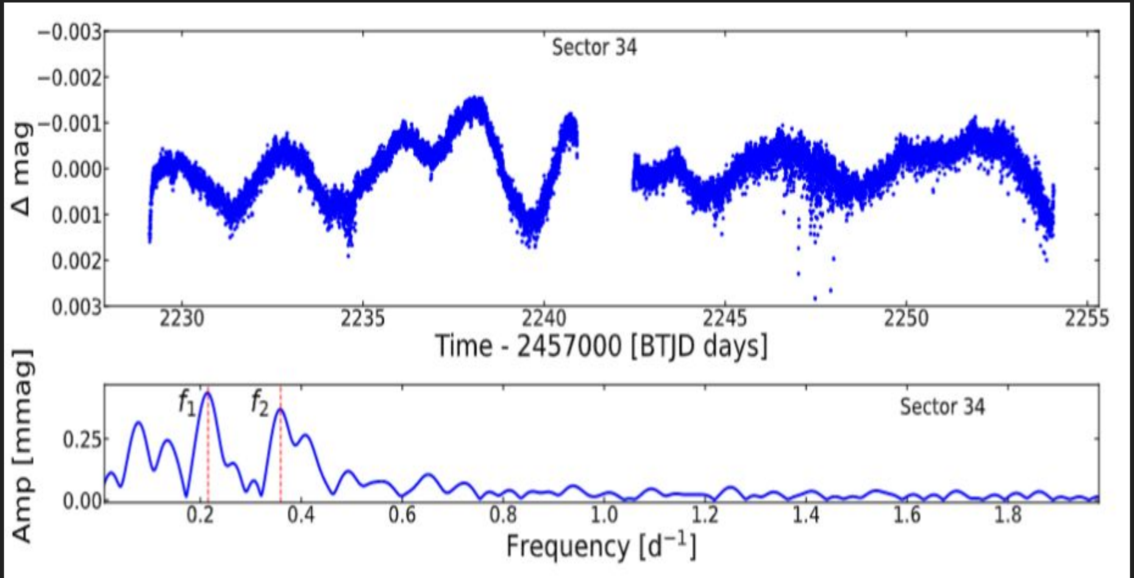
Frequency Analysis: HD 52089

Pre-RSG



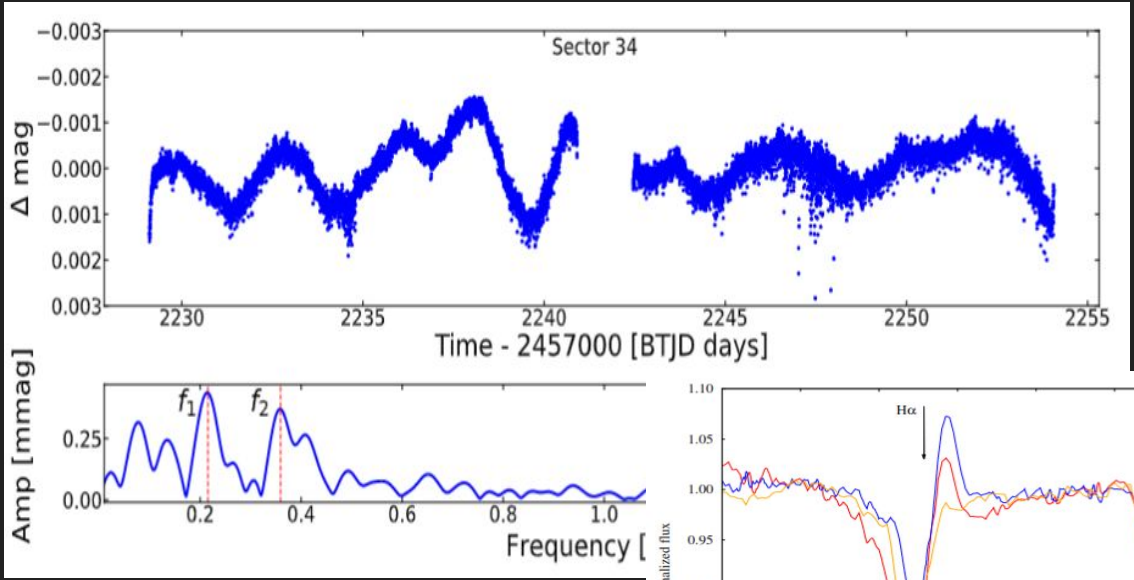


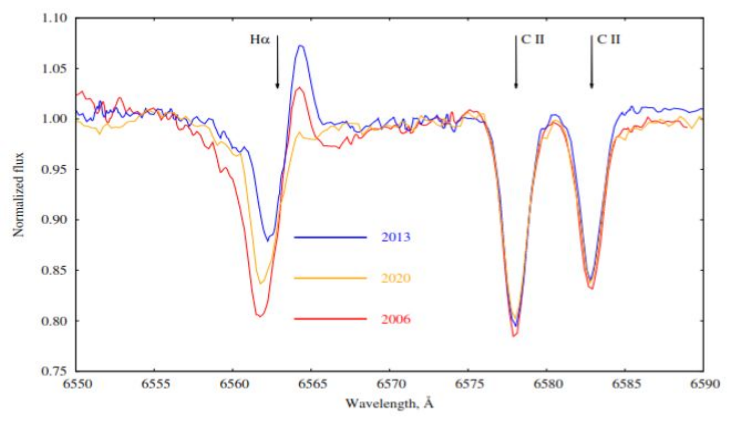
Frequency Analysis: HD 58350



Frequency Analysis: HD 58350

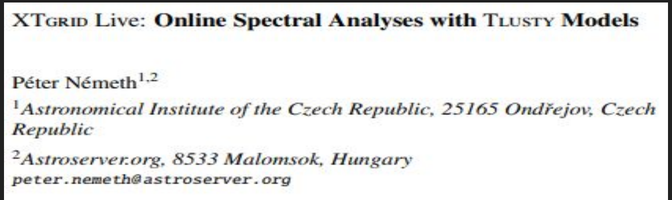
Pre-RSG?





Spectral Analysis

We employed XTgrid with CMFGEN code to model the atmospheres


XTGRID Live: **Online Spectral Analyses with TLUSTY Models**

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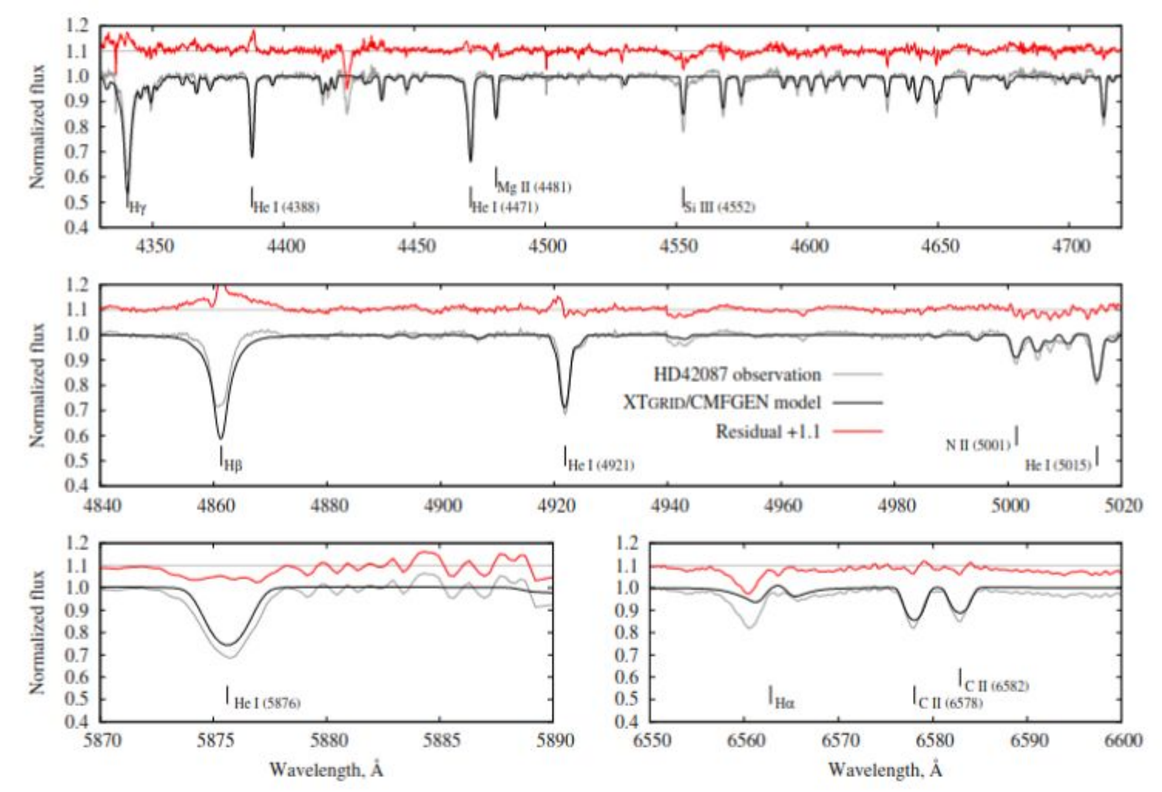
Model limitations:

We kept fixed the radii, turbulent velocity, microturbulence, beta, terminal velocity , as in Haucke et al. (2018).

All elements, except CNO were kept fixed to solar abundances & He/H=0.2 as in Searle et al. (2008) .

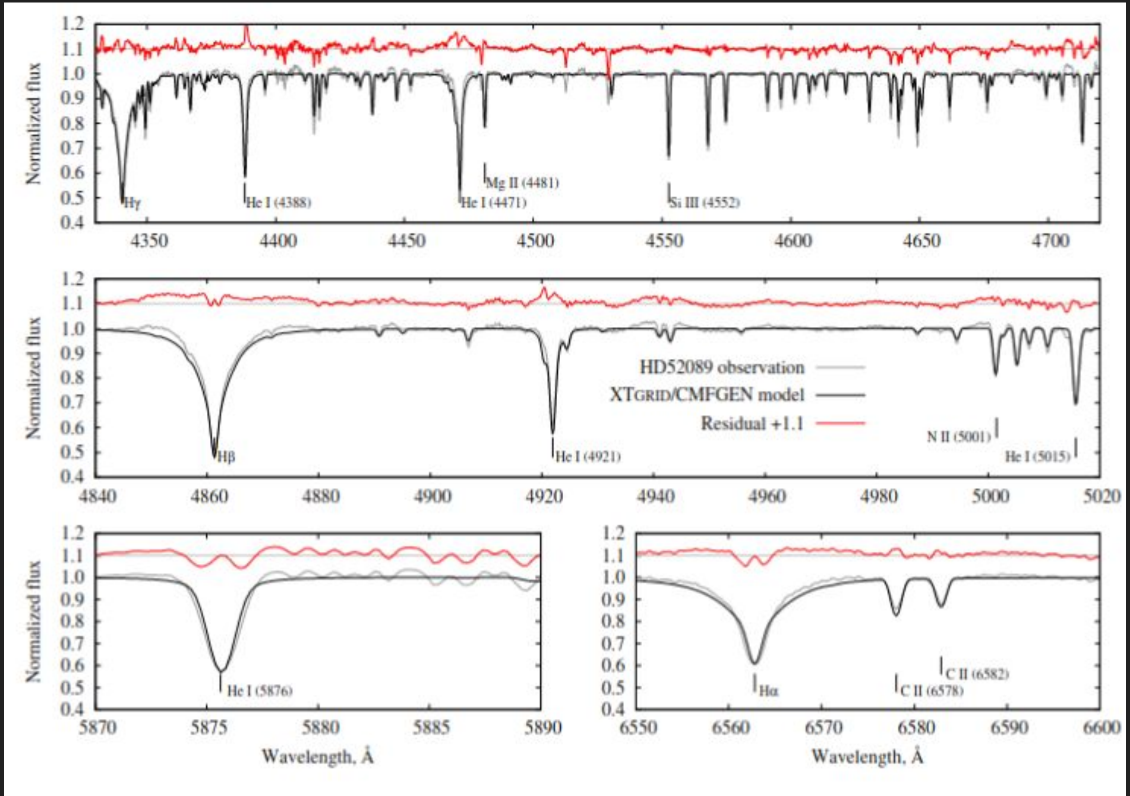
And we changed mass loss rates.

Spectral Analysis: HD 42087



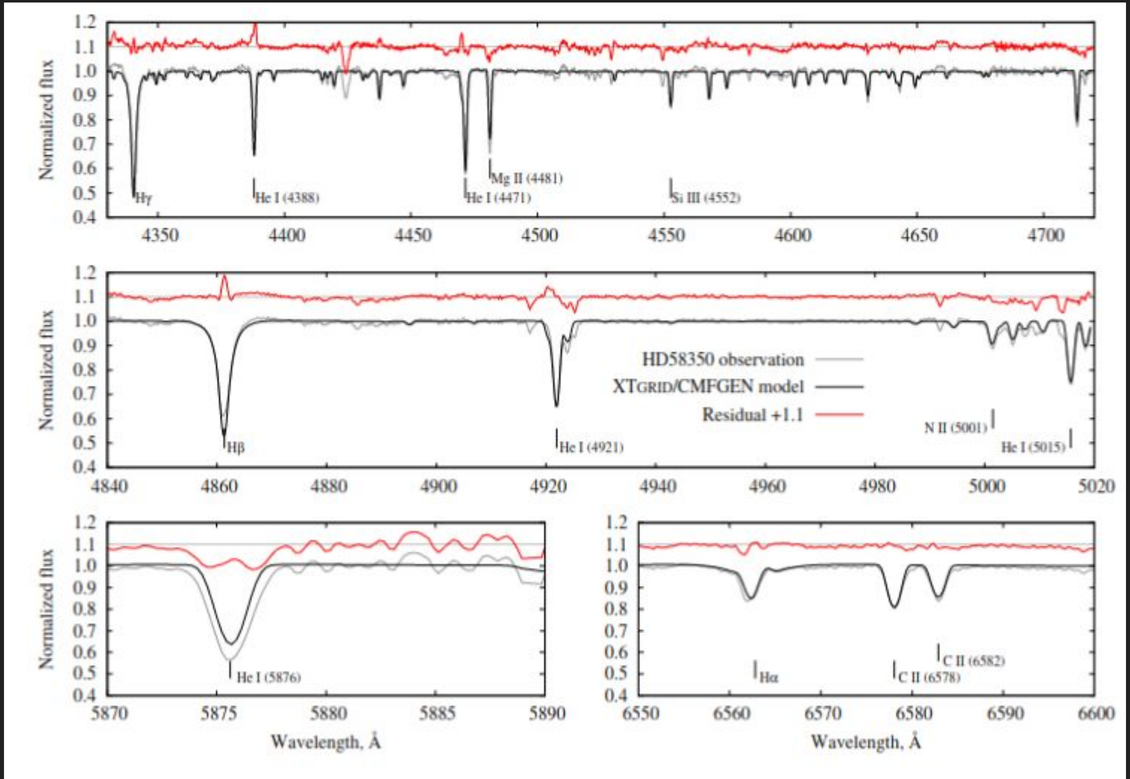
Parameter	HD 42087	
$T_{\rm eff}$ (K)	18400^{+1000}_{-200}	
$\log g$ (cm s^{-2})	$2.34^{+0.01}_{-0.17}$	
$v \sin i$ (km s^{-1})	73.4 ± 8.0	
$v_{\rm turb}$ (km s^{-1})	x10	
$\dot{M}$ ($M_\odot$ yr^{-1})	$(2.3 \pm 1.0) \times 10^{-7}$	
v_∞ (km s^{-1})	x700	
β	x2	
$L_\star$ ($L_\odot$)	**312700^{+74000}_{-13000}**	
$M_\star$ ($M_\odot$)	24.3	
$R_\star$ ($R_\odot$)	x55	
$\log L_\star / M_\star$	4.1	
Mean atomic mass (a.m.u.)	1.4490	
Distance (pc)	2470^{+420}_{-290}	
E($B-V$) (mag)	0.4	
Element	**ϵ**	**mass fr.**
Hydrogen	12	5.89×10^{-1}
Helium	x11.23±0.10	4.01×10^{-1}
Carbon	8.31±0.08	1.37×10^{-3}
Nitrogen	8.12±0.06	1.09×10^{-3}
Oxygen	8.60±0.08	3.75×10^{-3}
	[N/C]	[N/O]
Abundance ratios	0.41	0.38

Spectral Analysis: HD 52089



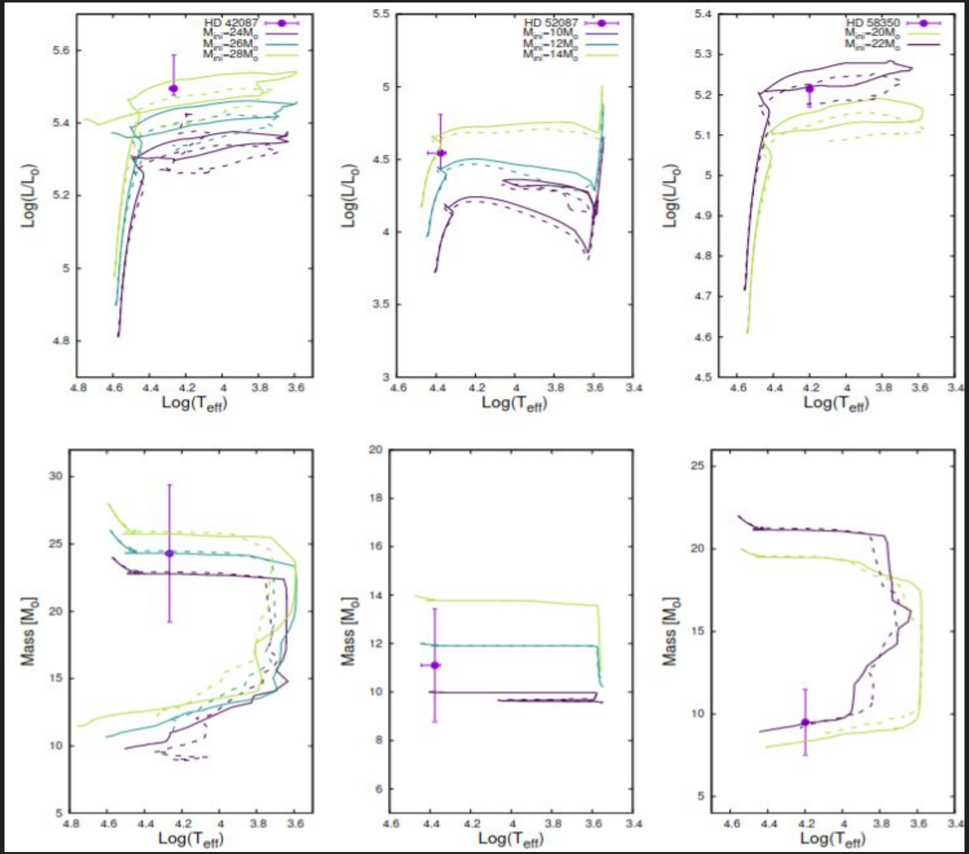
Parameter	HD 52089	
$T_{\rm eff}$ (K)	23800^{+3900}_{-1400}	
$\log g$ (cm s^{-2})	$3.40^{+0.01}_{-0.60}$	
$v \sin i$ (km s^{-1})	38.4 ± 5.0	
$v_{\rm turb}$ (km s^{-1})	x10	
$\dot{M}$ ($M_\odot$ yr^{-1})	$(1.9 \pm 0.2) \times 10^{-8}$	
v_∞ (km s^{-1})	x900	
β	x1	
$L_\star$ ($L_\odot$)	35000^{+29200}_{-7500}	
$M_\star$ ($M_\odot$)	11.1	
$R_\star$ ($R_\odot$)	x11	
$\log L_\star / M_\star$	3.5	
Mean atomic mass (a.m.u.)	1.5097	
Distance (*pc*)	124±2	
E($B-V$) (*mag*)	0.005	
Element	ϵ	**mass fr.**
Hydrogen	12	5.52×10^{-1}
Helium	x11.30±0.17	4.41×10^{-1}
Carbon	8.19±0.15	1.04×10^{-3}
Nitrogen	7.97±0.06	7.25×10^{-4}
Oxygen	8.30±0.13	1.78×10^{-3}
	[N/C]	[N/O]
Abundance ratio	0.38	0.53

Spectral Analysis: HD 58350



Parameter	HD 58350	
$T_{\rm eff}$ (K)	15800^{+100}_{-400}	
$\log g$ (cm s^{-2})	$1.95^{+0.02}_{-0.03}$	
$v \sin i$ (km s^{-1})	51.5 ± 5.0	
$v_{\rm turb}$ (km s^{-1})	x12	
$\dot{M}$ ($M_\odot$ yr^{-1})	$(6.2 \pm 2.0) \times 10^{-8}$	
v_∞ (km s^{-1})	x230	
β	x3	
$L_\star$ ($L_\odot$)	163800^{+4200}_{-15900}	
$M_\star$ ($M_\odot$)	9.5	
$R_\star$ ($R_\odot$)	x54	
$\log L_\star / M_\star$	4.2	
Mean atomic mass (a.m.u.)	1.5095	
Distance (pc)	608^{+148}_{-148}	
E($B-V$) (mag)	0.03	
Element	ϵ	**mass fr.**
Hydrogen	12	5.52×10^{-1}
Helium	x11.31±0.12	4.41×10^{-1}
Carbon	8.07±0.08	7.75×10^{-4}
Nitrogen	8.21±0.12	1.25×10^{-3}
Oxygen	8.19±0.09	1.38×10^{-3}
	[N/C]	[N/O]
Abundance ratio:	0.74	0.88

Comparison with evolutionary models

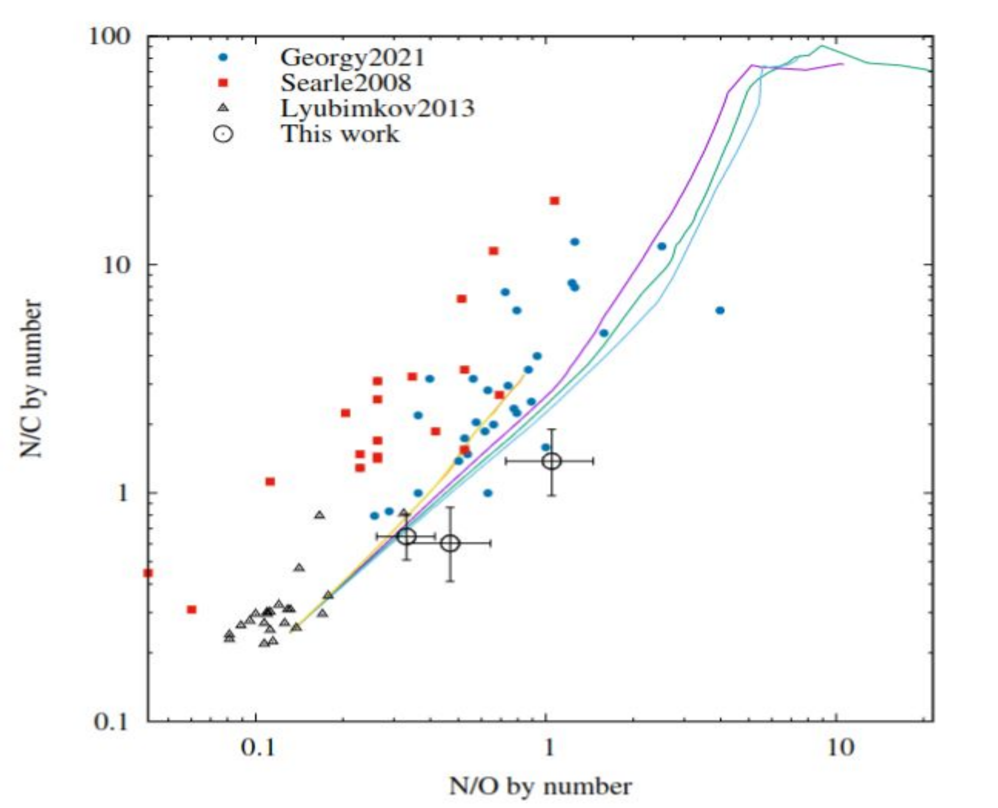


With the new values for the Teff, log L and the M, the evolutionary tracks from Ekstrom et al. (2012) indicate

HD 42087→ Pre-RSG
HD 52089→ Pre-RSG
HD 58350→ Post-RSG

Z=0.014
Vink mass loss recipe

What about surface abundances?



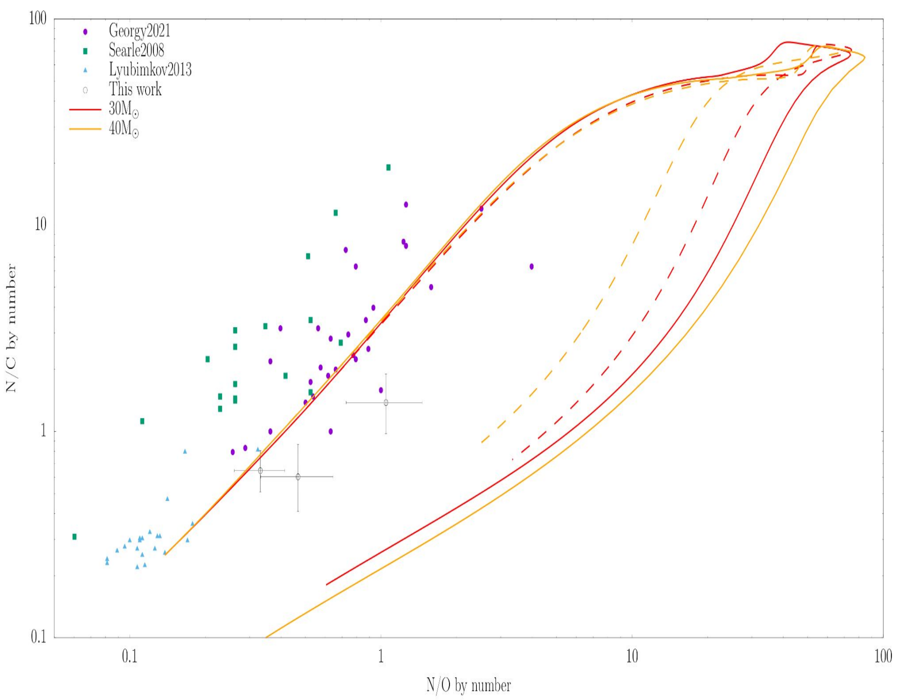
Our stars have C overestimation and and O underestimation compared with he evolutionary models and other samples.

Tracks: Ekstrom et al. 2012. Z=0.014 , Vink mass loss recipe , M=22, 26, 28, 10 Msun

What about surface abundances?

Can our stars be at the post-RSG?

Why these samples do not match the predictive CNO abundances?



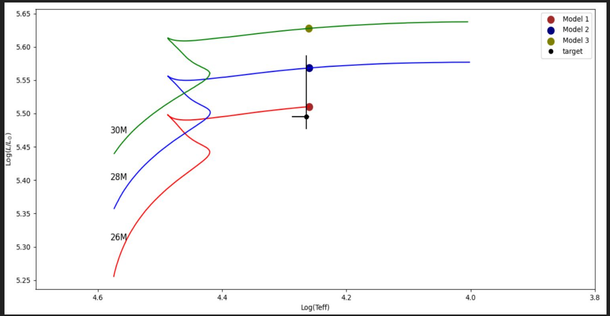
Tracks: MESA, Z=0.014 , Vink mass loss recipe for different mass loss efficiencies with O=0.5Ocrit

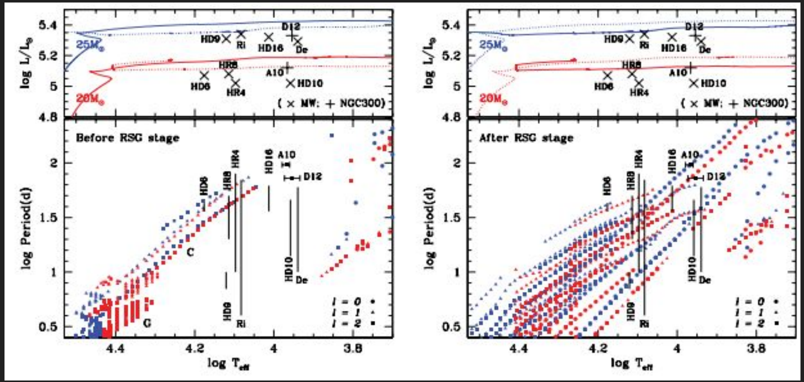
Takeaway

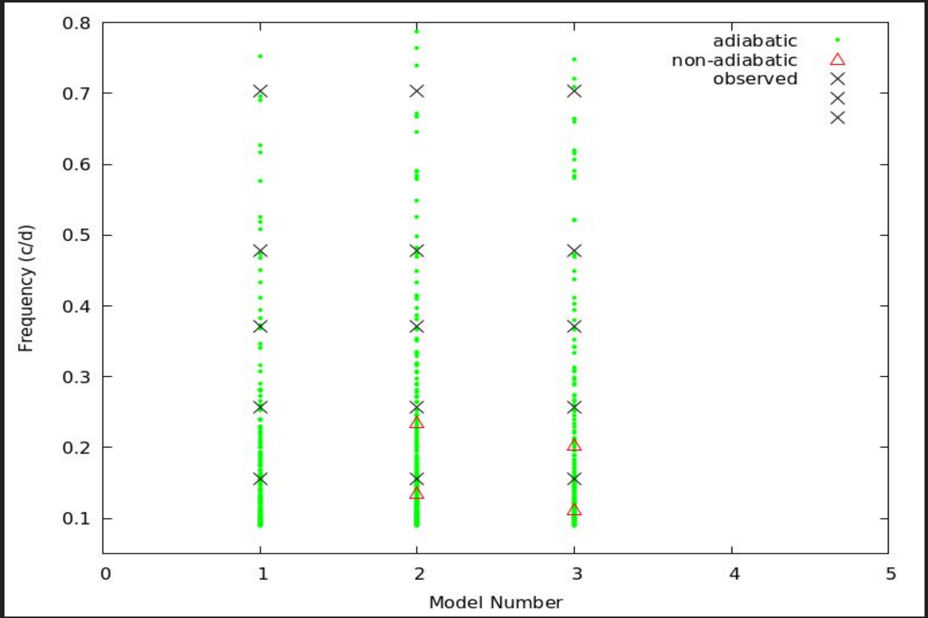
- We need to combine asteroseismology, spectroscopic analysis and evolutionary models to overcome the difficulties in B supergiant models.
- We need to study homogeneously a large sample of BSG to analyze the systematic offsets of CNO abundances.
- We need multi-epoch observations to set constraints and study R and Teff variations due to oscillations.
- To consider stellar oscillations as a mechanism which might facilitate the mass loss and affect the surface abundances.
- We need long term photometric observations to retrieve the usually short frequencies of strange modes.
- To study the effect of different mass loss recipes at advanced evolutionary stages.
- To improve numerical solutions for highly non adiabatic computations.

Pusation models: HD 58350

Stelar pulsations?

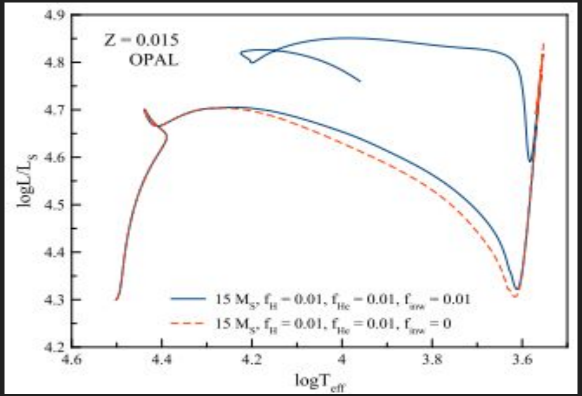


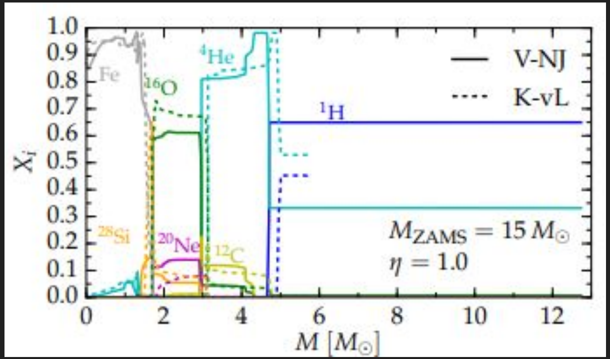




Peculiarities

- They can be in the pre- or post-RSG stage
- The physical properties of massive stars change considerably within each stage of their life.
- Their evolutionary tracks depends on many physical parameters (mass loss rates, rotation, chemical mixing..)
- Parameters are far from being firmly established.
- Small changes in their input parameters result in significant different evolution





Renzo et al. (2017)