Asteroseismology of OB stars

From birth to adulthood

Peter De Cat

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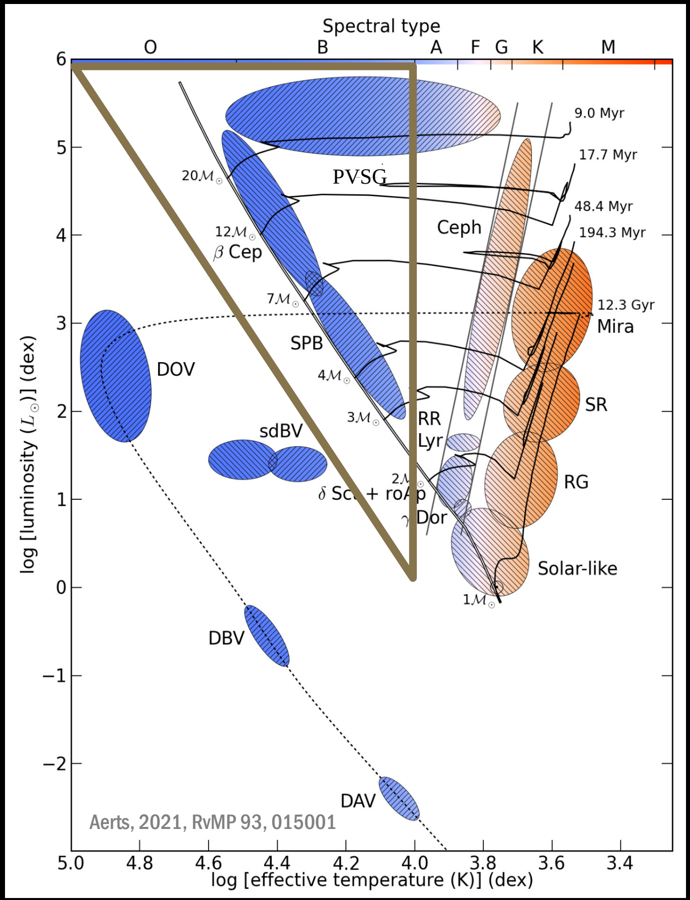
... a very incomplete point of view

OB-type stars

Convective core
Radiative envelope



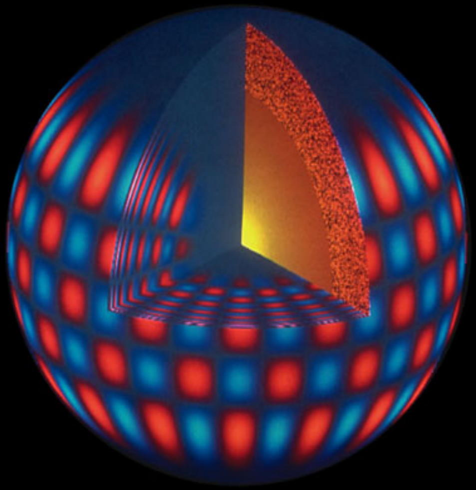
- → **β Cephei stars** (βCep)
  - ➢ Low order p and g modes with periods of few hours
- → **Slowly Pulsating B stars** (SPB)
  - ➢ High order g modes with periods of several hours to few days
- → **Periodic Variable Supergiants** (PVSG)
  - ➢ g modes with periods of order of 10 to 100 days

Hybrids?

- → **Be stars** (Be)
  - ➢ Rotational modulation and/or Pulsations?
- → **Maia variables**

Excitation mechanisms at play

- ➢ Opacity mechanism operating in Z bump



Period p or Frequency f
Order n → # nodesurfaces in interior
Degree ℓ → # nodelines on surface
Azimuthal number m → # nodelines on surface ⊥ equator

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Asteroseismic requirements and tools

→ Time series

→ Observed pulsation modes

- Frequency f ⟶ Frequency analysis
- Degree ℓ
- Azimuthal number m

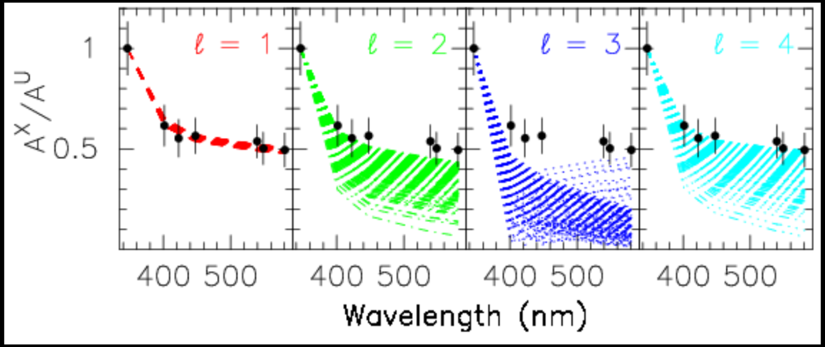
} ⟶ Mode identification

mmag precision

* Multicolour photometry: method of photometric amplitude ratios and frequency shifts (Dupret et al., 2003, A&A 398, 677)

* High-resolution spectroscopy

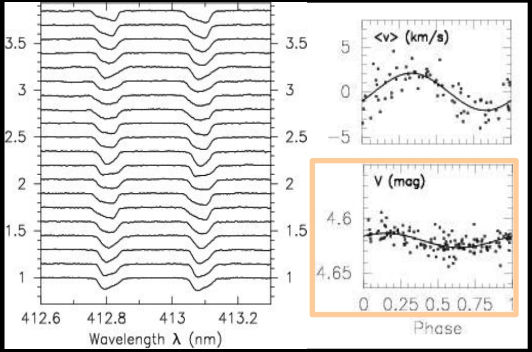
HD24587 = 33 Eridani
#137 Geneva phometry
#65 CAT spectra
f_1 = 1.1569 d^{-1}



observed ampltiude ratios relative to the bluest filter
(given with dots and error bars in black)

⇓

compare with calculated ampltiude ratios for modes with different ℓ values
(given with coloured lines)



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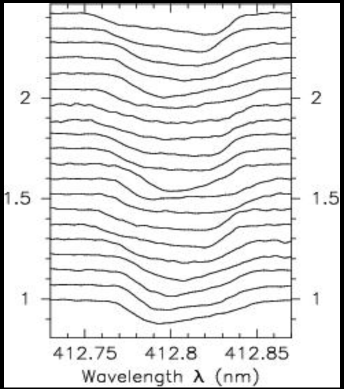

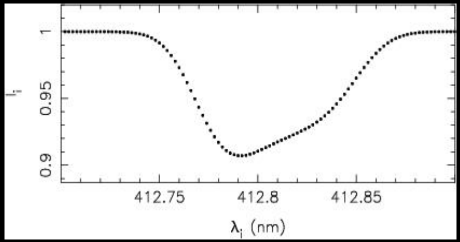

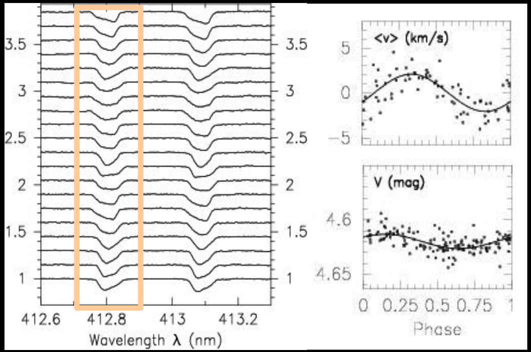

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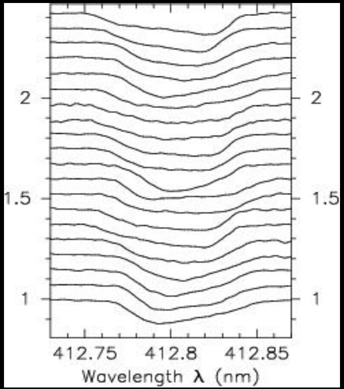

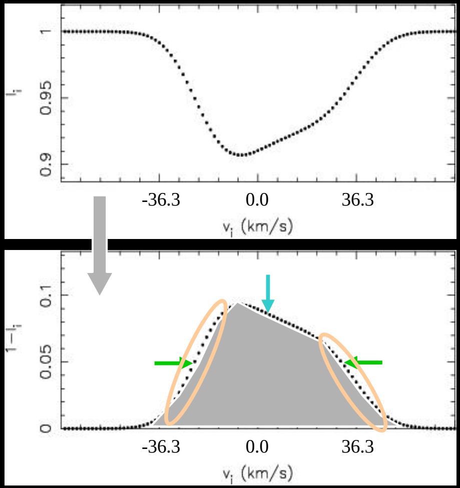

$$\langle v^n \rangle = \frac{\Sigma_i \, (1-I_i) \, v_i^n \, (v_i - v_{i-1})}{\Sigma_i \, (1-I_i) \, (v_i - v_{i-1})}$$

denominator = equivalent width

$\langle v^1 \rangle$ ~ radial velocity

$\langle v^2 \rangle$ ~ width

$\langle v^3 \rangle$ ~ skewness

⇓

compare with velocity moments calculated for modes with different (ℓ, m)

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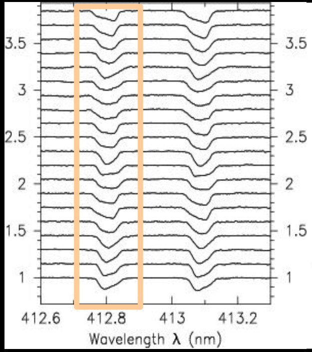

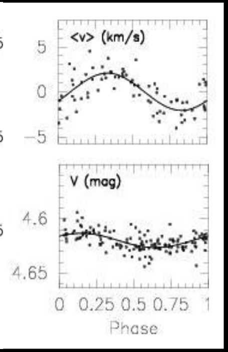

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Group meeting at BNU (25/09/2024, Beijing, China)

KSB - ORB

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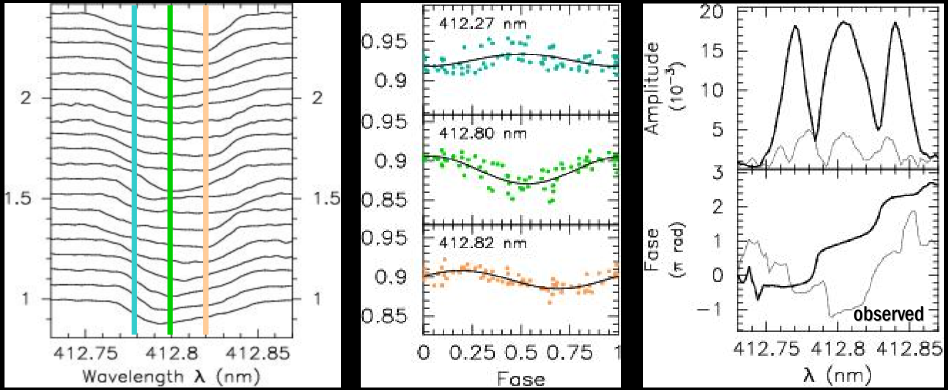

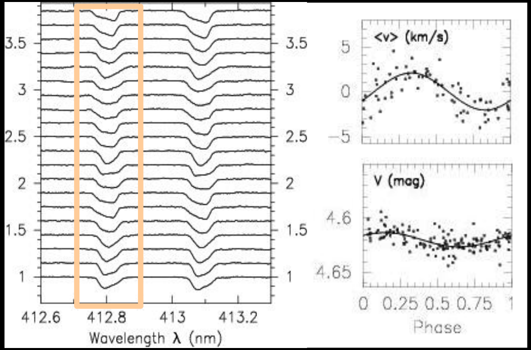

change of amplitude and phase within observed line profiles ⟹ compare with those calculated for modes with different (ℓ,m)

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Asteroseismic requirements and tools

→ Time series

→ Observed pulsation modes

- Frequency f ⟶ Frequency analysis
- Degree ℓ
- Azimuthal number m

} ⟶ Mode identification (mmag precision)

⇓

Modelling

* Multicolour photometry: method of photometric amplitude ratios and frequency shifts (Dupret et al., 2003, A&A 398, 677)

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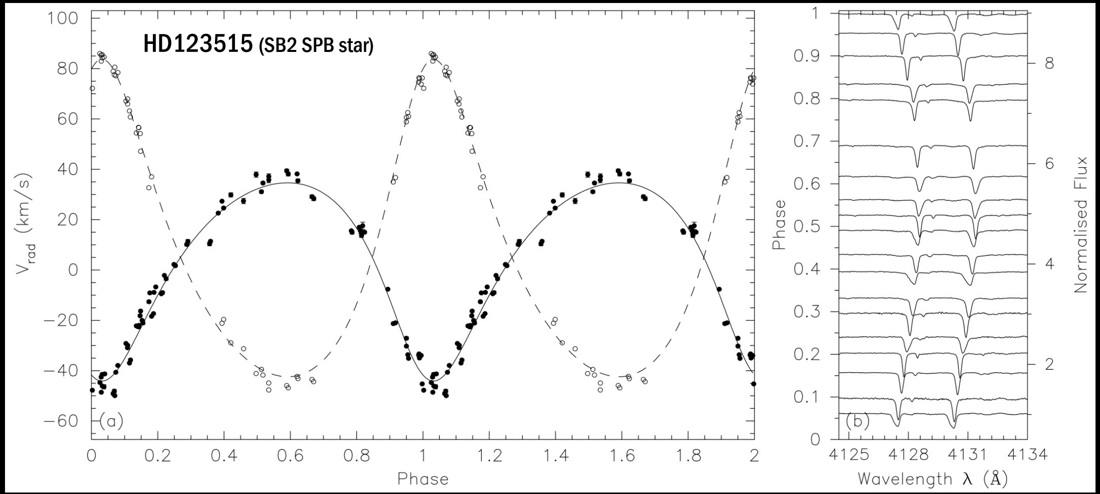
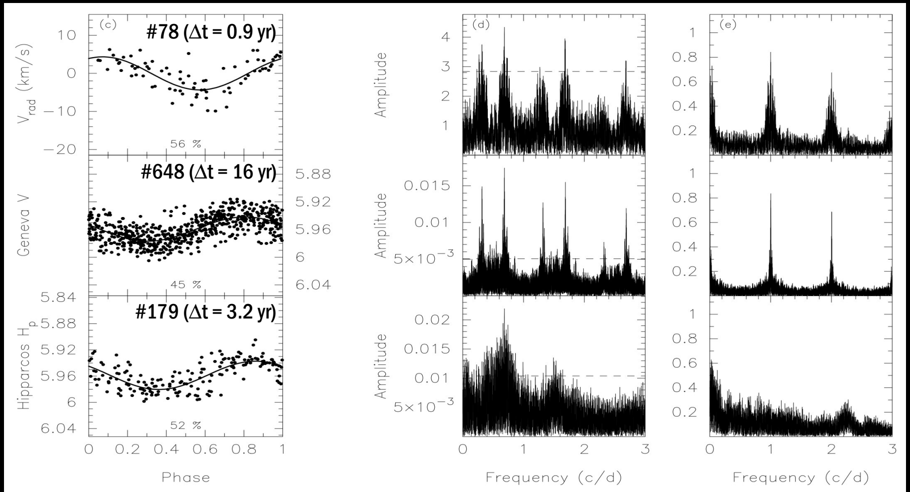


De Cat et al., 2000, A&A 355, 1015



KSB - ORB

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Asteroseismic requirements and tools

→ Time series

→ Observed pulsation modes

- Frequency f → Frequency analysis
- Degree ℓ
- Azimuthal number m

Degree ℓ and Azimuthal number m → Mode identification

⇓

Modelling

Mode identification

µmag precision

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2003-2019 MOST

2009-2018 Kepler and K2

2018-now TESS

2006-2014 CoRoT

2013-now BRITE

2013-now Gaia

Asteroseismic requirements and tools

→ Time series

→ Observed pulsation modes

- ➢ Frequency f ⟶ Frequency analysis
- ➢ Degree ℓ
- ➢ Azimuthal number m

(Degree and azimuthal number) ⟶ Mode identification

⇓

Modelling

µmag precision

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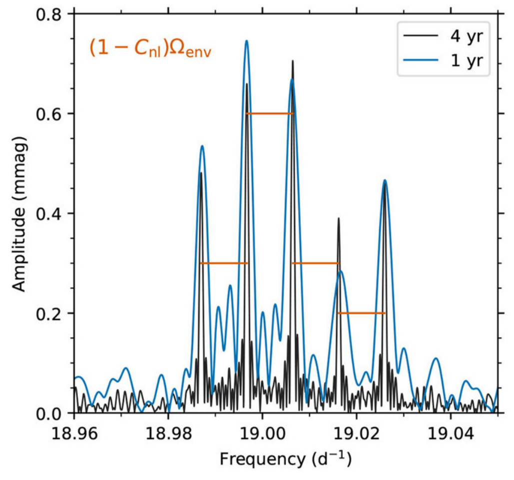
→ Present day asteroseismic diagnostics

- ➢ Rotational multiplets
- ➢ g mode period spacing patterns (asymptotic regime)

Bowman, 2020, FrASS 7, 70



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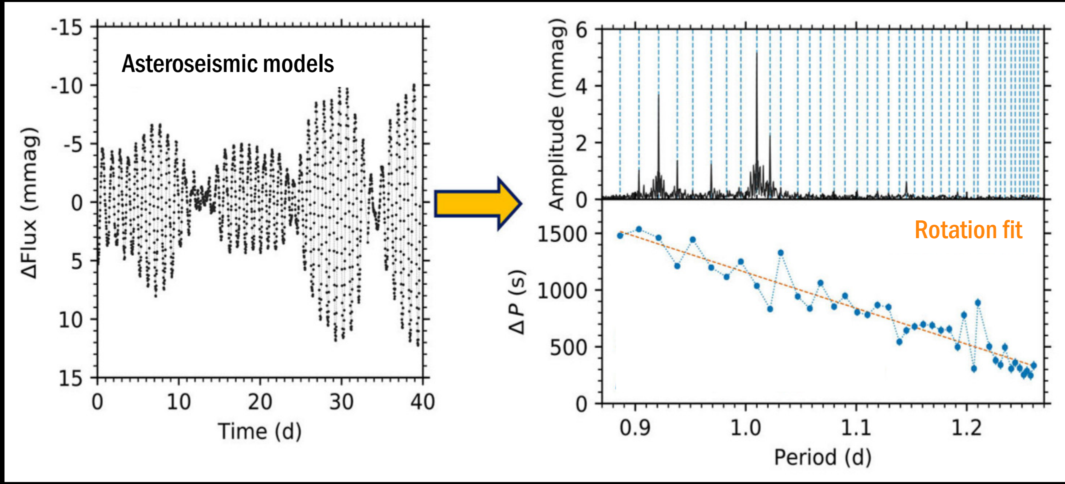

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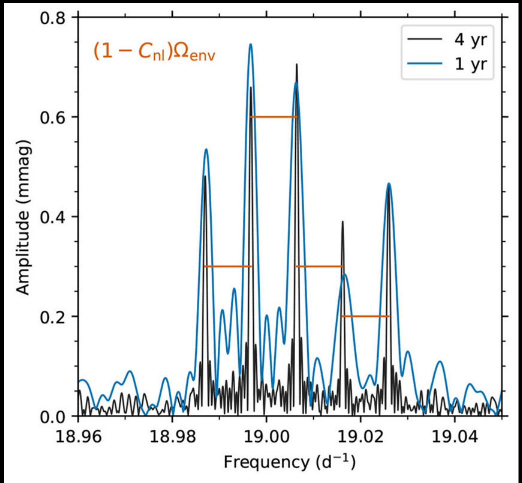

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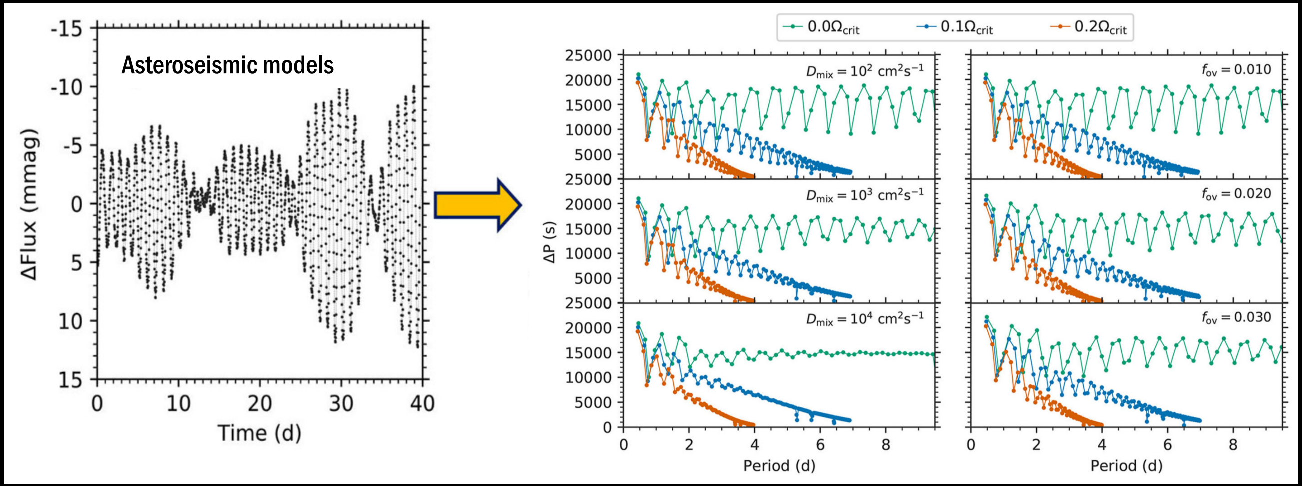


Magnetic fields

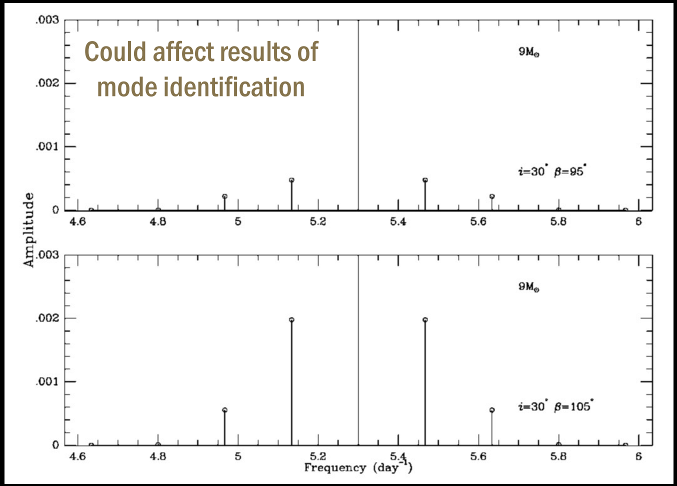
Fossil field

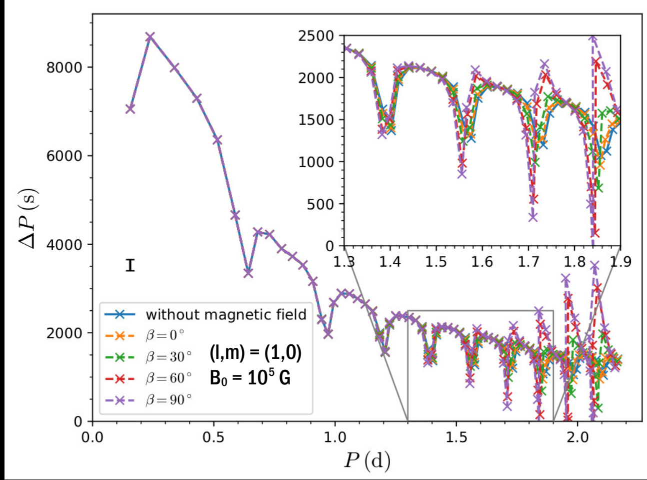
→ Effects of magnetic field on asteroseismic diagnostics of pulsating stars

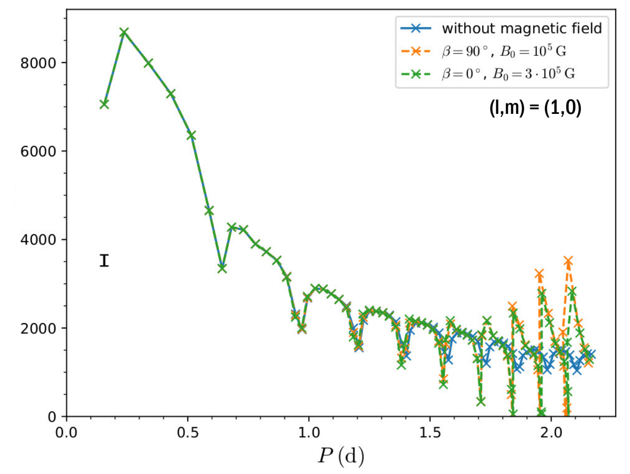
➢ Magnetic multiplets
(Shibahashi & Aerts, 2000, ApJ 531, L143)

➢ Period spacings
(Prat et al., 2020, A&A 636, A100)

➢ Inhibition of mixing ⇒ no overshooting
(Briquet et al., 2016, A&A 587, A126)







Magneto-asteroseismology

✔ Ground-based	β Cep	(Shibahashi & Aerts, 2000, ApJ 531, L143)
	ζ Cas	(Briquet et al., 2016, A&A 587, A126)
	V2052 Oph	(Briquet et al., 2012, MNRAS 427, 483)
✔ CoRoT	HD43317	(Buysschaert et al., 2018, A&A 616, A148)
✔ K2	ι Lib	(Buysschaert et al., 2018, SF2A Conf., 369)

Magnetic fields

→ Overview of surveys to (1) discover new magnetic massive stars with spectropolarimetric observations
(2) improve the models of magnetic stars

- BOB — B Fields in OB Stars (Morel et al., 2014, Messenger 157, 27)
  - ✔ Southern OB stars
- BritePol — BRITE spectropolarimetric survey (Neiner et al., 2014, SF2A Conf, 505)
  - ✔ ~600 stars with V ≤ 4
- BinaMIcs — Binarity and Magnetic Interactions in various classes of stars (Alecian et al., 2015, IAUS 307, 330)
  - ✔ ~200 hot binary stars
- MiMeS — Magnetism in Massive Stars (Wade et al., 2016, MNRAS 456, 2)
  - ✔ ~550 massive stars
- LIFE — Large Impact of magnetic Fields on the Evolution of hot stars (Martin et al., 2018, MNRAS 475, 1521)
  - ✔ ~60 evolved hot stars
- MOBSTER — Magnetic OB[A] Stars with TESS: probing their Evolutionary and Rotational properties (David-Uraz et al., 2019, MNRAS 487, 304)
  - ✔ confirmed and candidate magnetic OBA stars that are observed with TESS

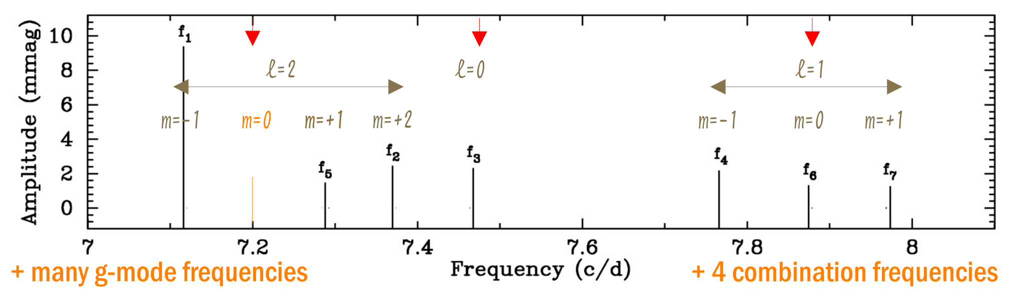
Detected for ~10% of B stars

Opacities

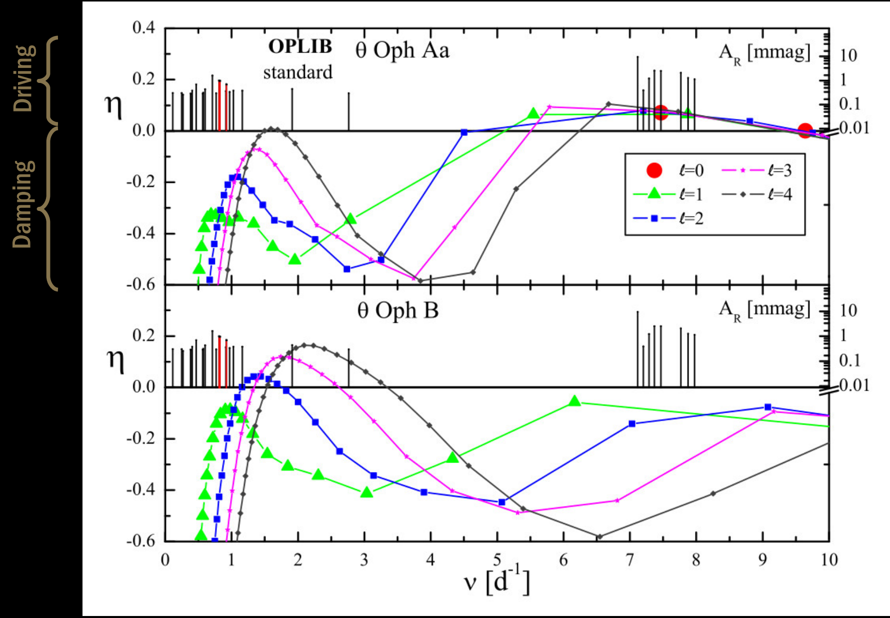
→ θ Ophiuchi (Walczak et al., 2019, MNRAS 485, 3544)

- Known βCep pulsator with 7 pulsation frequencies — Hybrid pulsator
- Triple system:
  - ✔ θ Oph Aa: massive B2IV star
  - ✔ θ Oph Ab: low-mass star (M < 1 $M_{\odot}$)
  - ✔ θ Oph B: massive B5 star

(Aa + Ab: 56.71 days; with B: ~ 14 years)



BRITE photometry (2014 UBr; 2016+2017 UBr, BHr, BAb, BLb)
SMEI photometry (2003-2010)



- Complex asteroseismology
  - ✔ Fitting centroid frequencies
  - ✔ Getting the mode instability in the observed frequency range
  - ✔ Reproduce the emperical value of *f* (ratio of the relative bolometric flux to the relative radial displacement)

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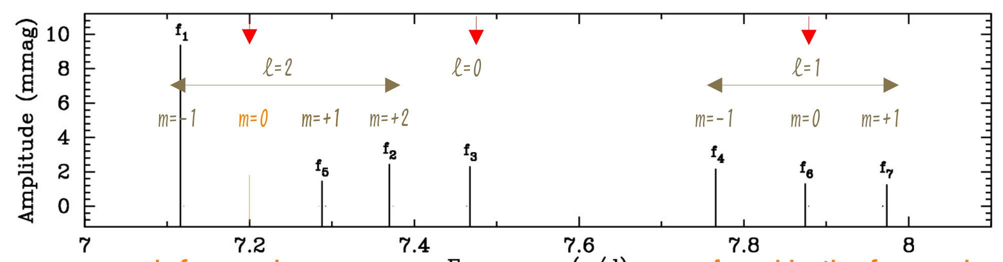

+ many g-mode frequencies

+ 4 combination frequencies

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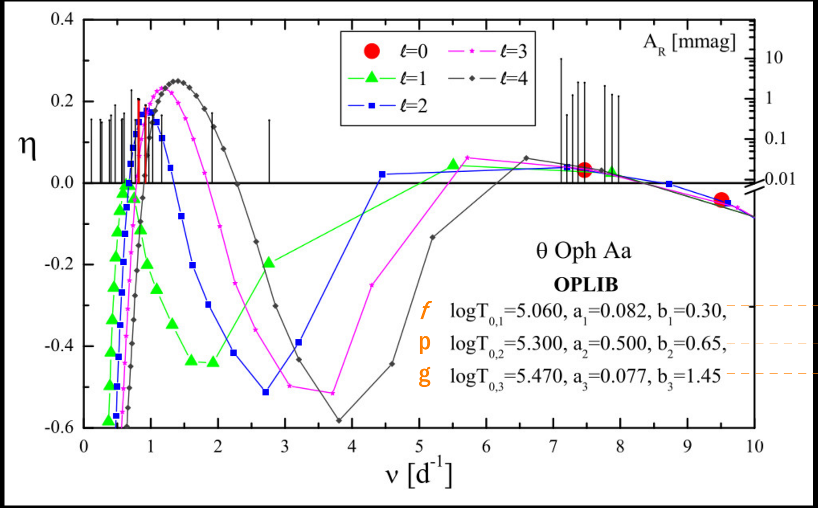
SMEI photometry (2003-2010)



Kurucz bump

Z-bump

Ni

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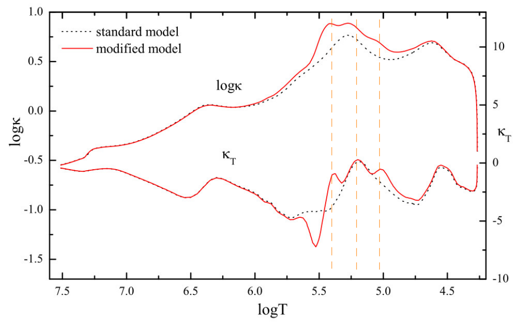

Opacity increase needed to excite g-modes

(θ Oph Aa)

Opacities

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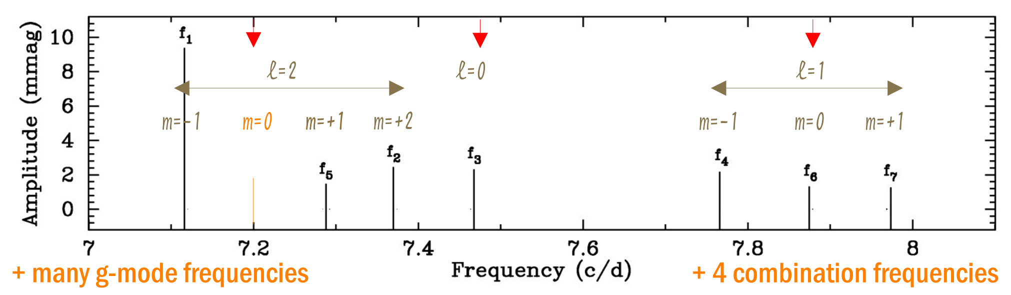

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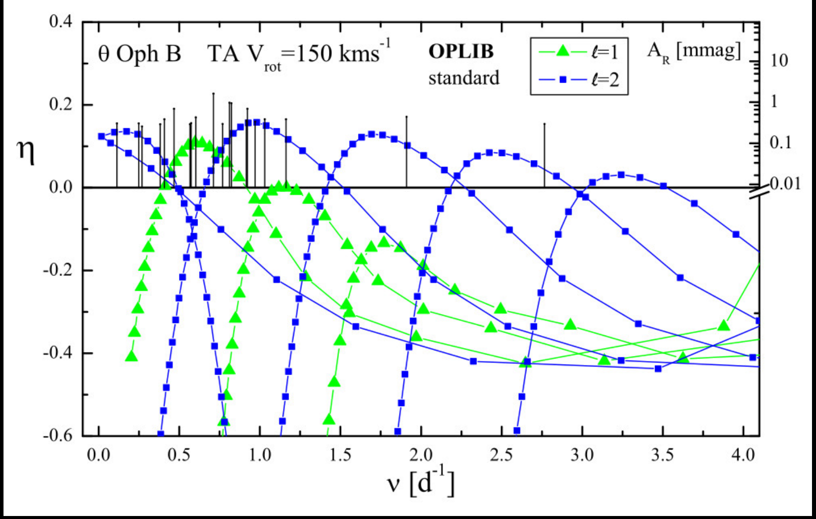

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Fast rotation needed to excite g-modes
(θ Oph B)

Opacity increase needed to excite g-modes
(θ Oph Aa)

Opacities

- → θ Ophiuchi (Walczak et al., 2019, MNRAS 485, 3544)
- → β Centauri (Pigulski et al., 2016, A&A 588, A55)
  - ➢ Triple system:
    - ✔ β Cen Aa: early B-type star (M = 12.02(13) $M_\odot$), faster rotator (v_{rot} = 200-250 km s^{-1})
    - ✔ β Cen Ab: early B-type star (M = 10.58(18) $M_\odot$), slower rotator (v_{rot} = 70-120 km s^{-1}), magnetic
    - ✔ β Cen B: distant, mid B-type star
  - ➢ 8 g-modes, 9 p-modes, and 2 combination frequencies

Aa–Ab: 357 days, e=0.81, resolved; with B: 125-220 years

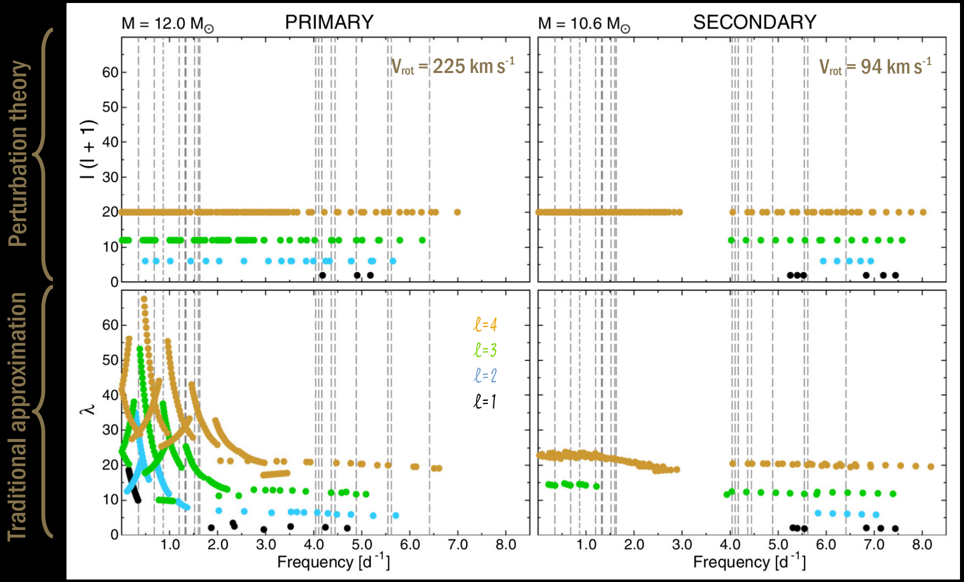
BRITE photometry (2014, 146d, UBr, BTr, BAb, BLb)
BRITE photometry (2014, 27d, BLb)
BRITE photometry (2014, 6d, BTr)

Ideal to study influence of
Rotation
Magnetic field

Light time effect: attribution to Aa and Ab component inconclusive for most frequencies

If effects rotation taken into account, no need for
Increase opacity
Increase metallicity
Change chemical composition

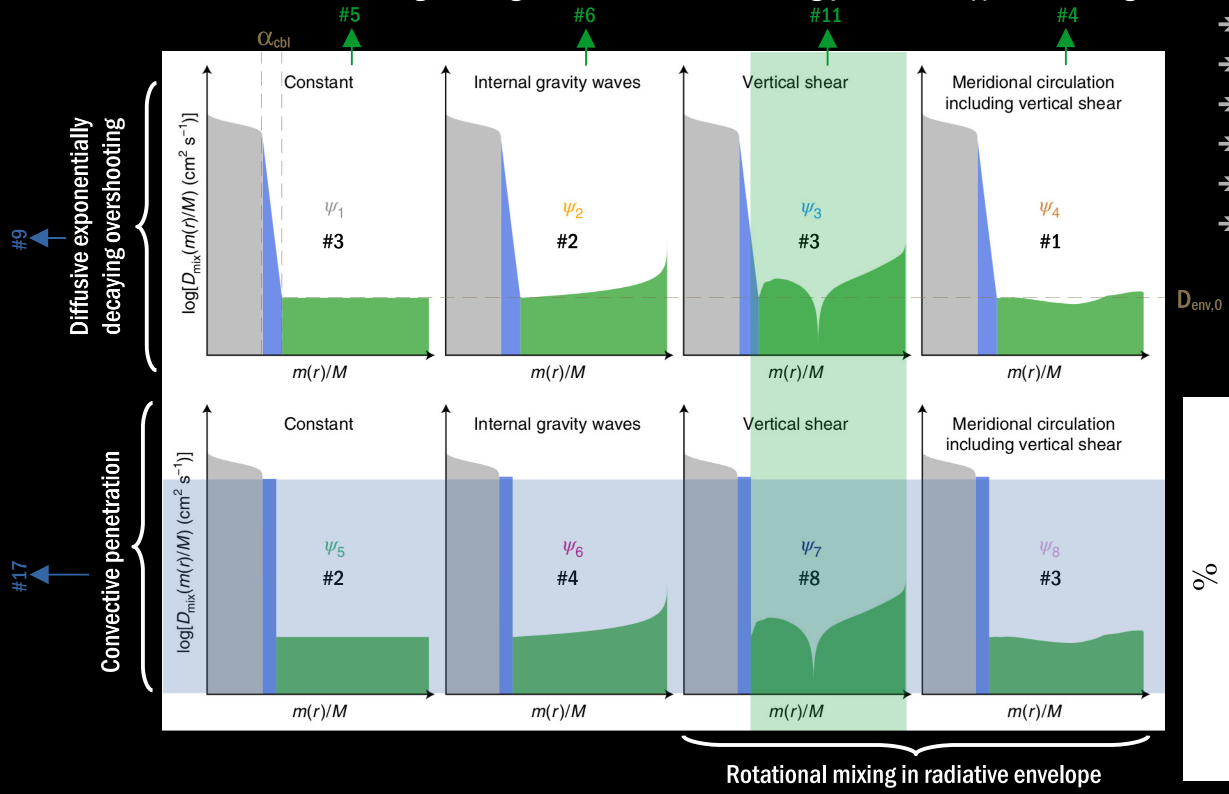
Coeval models



Interior mixing profile

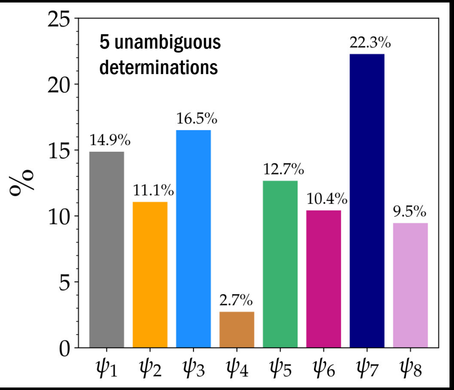
→ Pedersen et al., 2021, NatAs 5, 715

- ➢ Sample of 26 SPB stars showing period spacings patterns from dipole g-modes (~4% of all B stars in the nominal Kepler field of view)
- ➢ Asteroseismic modelling with eight different interior mixing profiles $D_{mix}(r)$ each having three regions (convective core $D_{conv}(r)$, core boundary layer $D_{cbl}(r)$, radiative envelope $D_{env}(r)$)



- ➔ M_{ini} initial mass
- ➔ Z metal mass fraction
- ➔ X_c/X_{ini} hydrogen mass fraction in fully mixed convective core/inital hydrogen mass fraction
- ➔ Ω_{rot} interior rotation frequency
- ➔ α_{cbl} length scale connected with the size of the core boundary layer
- ➔ $D_{env,0}$ level of mixing at bottom of radiative envelope

Majority for convective penetration (55%)
vertical shear (39%)



Pedersen, 2022, AJ 930, 94

➔ Expected helium core masses at end of main-sequence evolution:
* underestimated without mixing
* increase with initial stellar mass
* heavily influenced by amount of envelope mixing

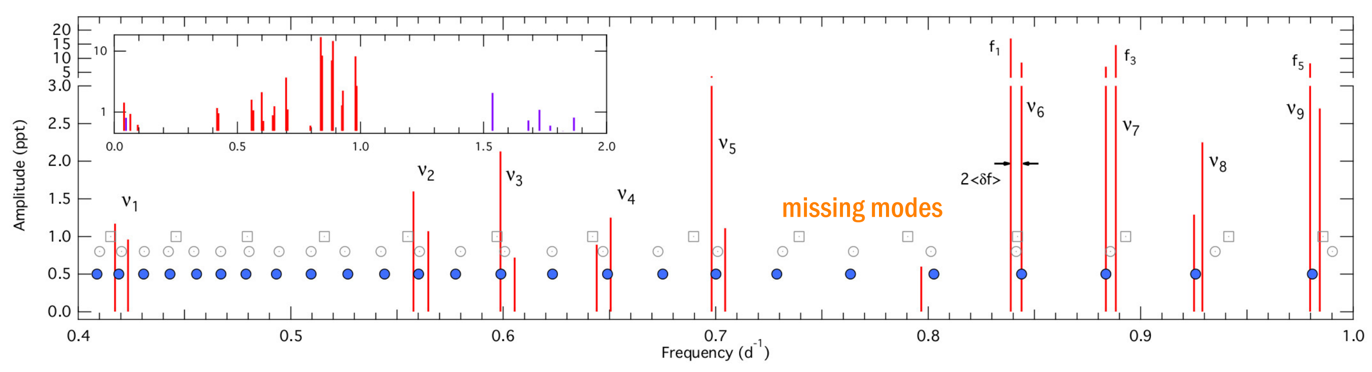
cf. Kaiser et al, 2020, MNRAS 496, 1967
Johnston, 2021, A&A 655, A29

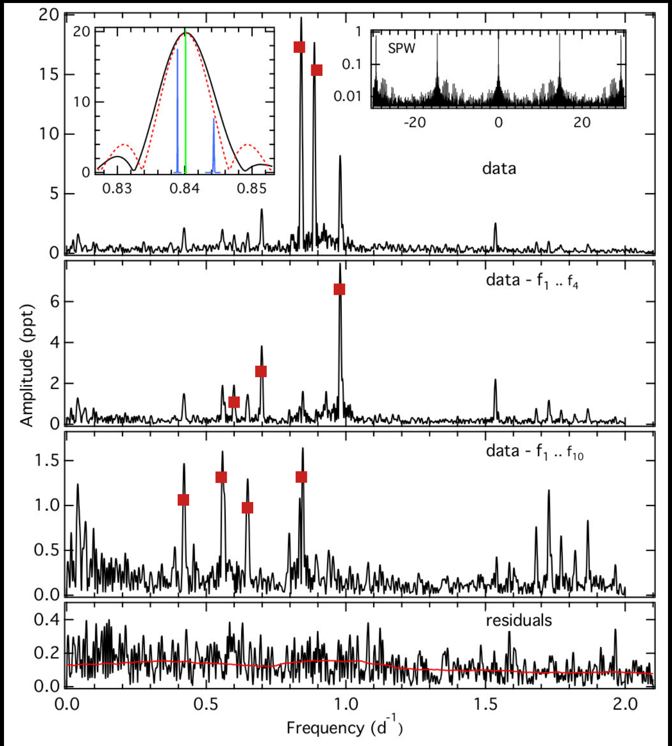
Interior rotation profile

→ HD201433 (Kallinger et al., 2017, A&A 603, A13)

BRITE photometry (6 seasons in 2013-2019; 156 days; BTr, BIb; cadence 0.338 min)
SMEI photometry (8 years; 101.6 min)
Radial velocites (96 years)

- Single-lined spectroscopic triple system:
  - ✔ B9V star (suspected SPB star; close to the cool border of instability strip) with two low mass companions
  - ✔ 3.3 days
  - ✔ 154 days
- Frequency analysis BTr data
  - ✔ 9 statisticaly significant closely separated doublets (ℓ=1 modes with m=±1) (red squares)
  - ✔ 4 additional independent frequencies
  - ✔ 7 combination frequencies





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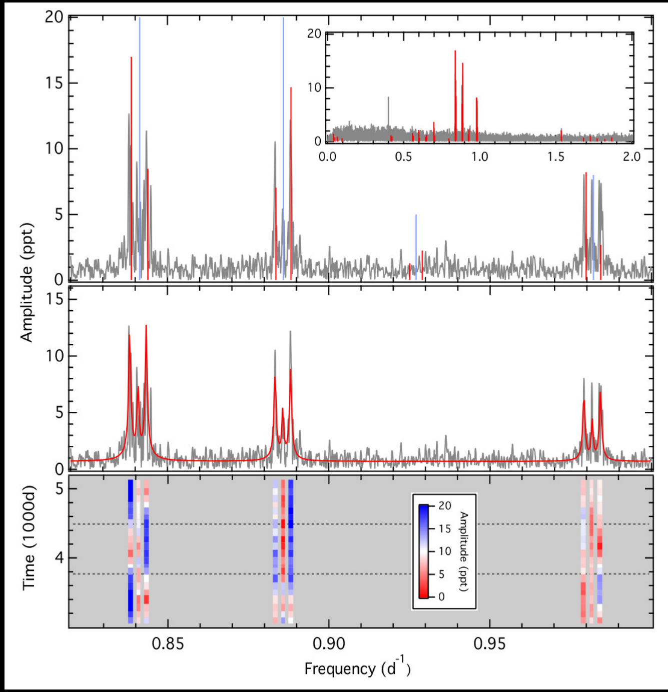
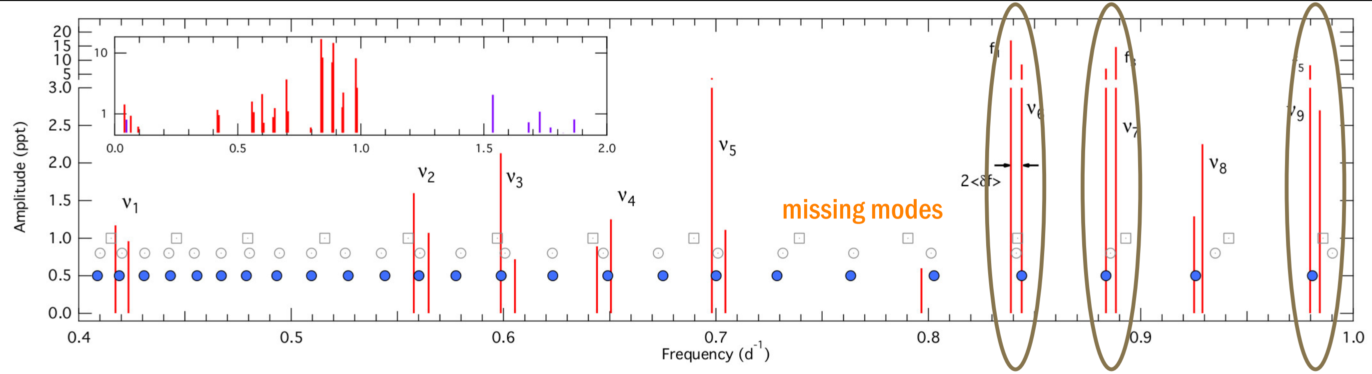
- ➢ Single-lined spectroscopic triple system:
  - ✔ B9V star (suspected SPB star; close to the cool border of instability strip) with two low mass companions
  - ✔ 3.3 days
  - ✔ 154 days
- ➢ Frequency analysis BTr data
- ➢ Frequency analysis SMEI data
  - ✔ Confirmation 3 closely separated triplets of ℓ=1 modes
  - ✔ Evidence for amplitude changes (mode lifetime of 680(110) days)



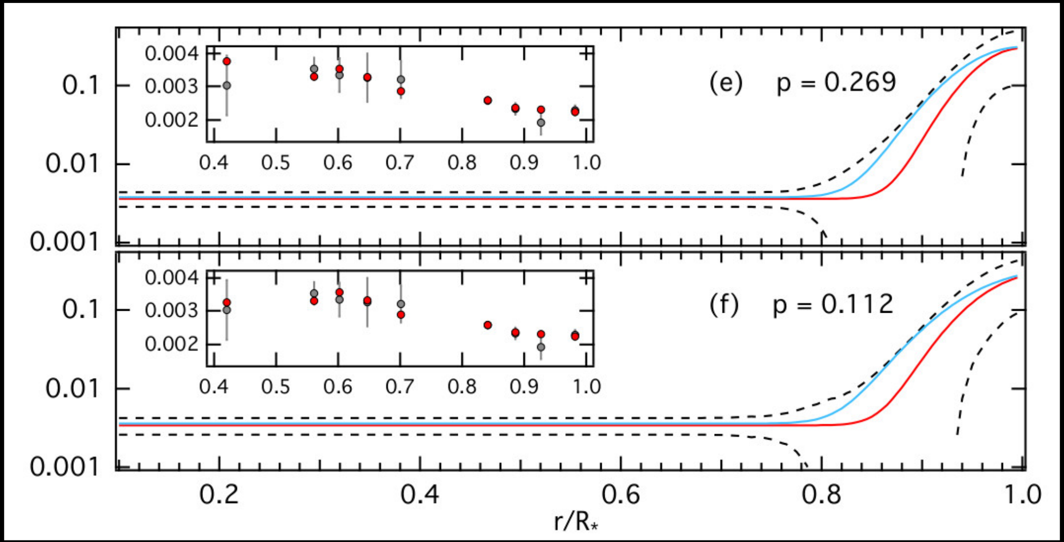


Interior rotation profile

→ HD201433 (Kallinger et al., 2017, A&A 603, A13)

BRITE photometry (6 seasons in 2013-2019; 156 days; BTr, Blb; cadence 0.338 min)
SMEI photometry (8 years; 101.6 min)
Radial velocites (96 years)

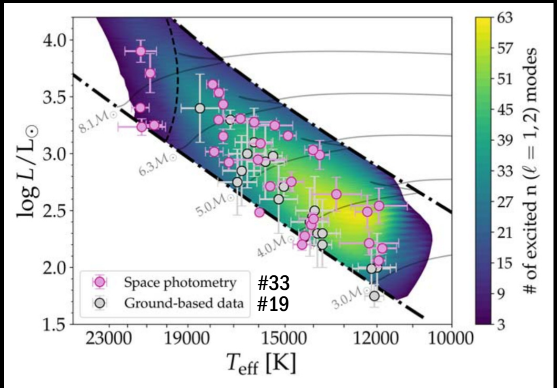
- Single-lined spectroscopic triple system:
  - B9V star (suspected SPB star; close to the cool border of instability strip) with two low mass companions
  - 3.3 days
  - 154 days
- Frequency analysis BTr data
- Frequency analysis SMEI data
- Interior rotation profile radiative envelope
  - Slowly and ridigly rotating envelope
  - Thin and significantly more rapidly rotating surface layer
    - Compatible with orbital period of innermost companion



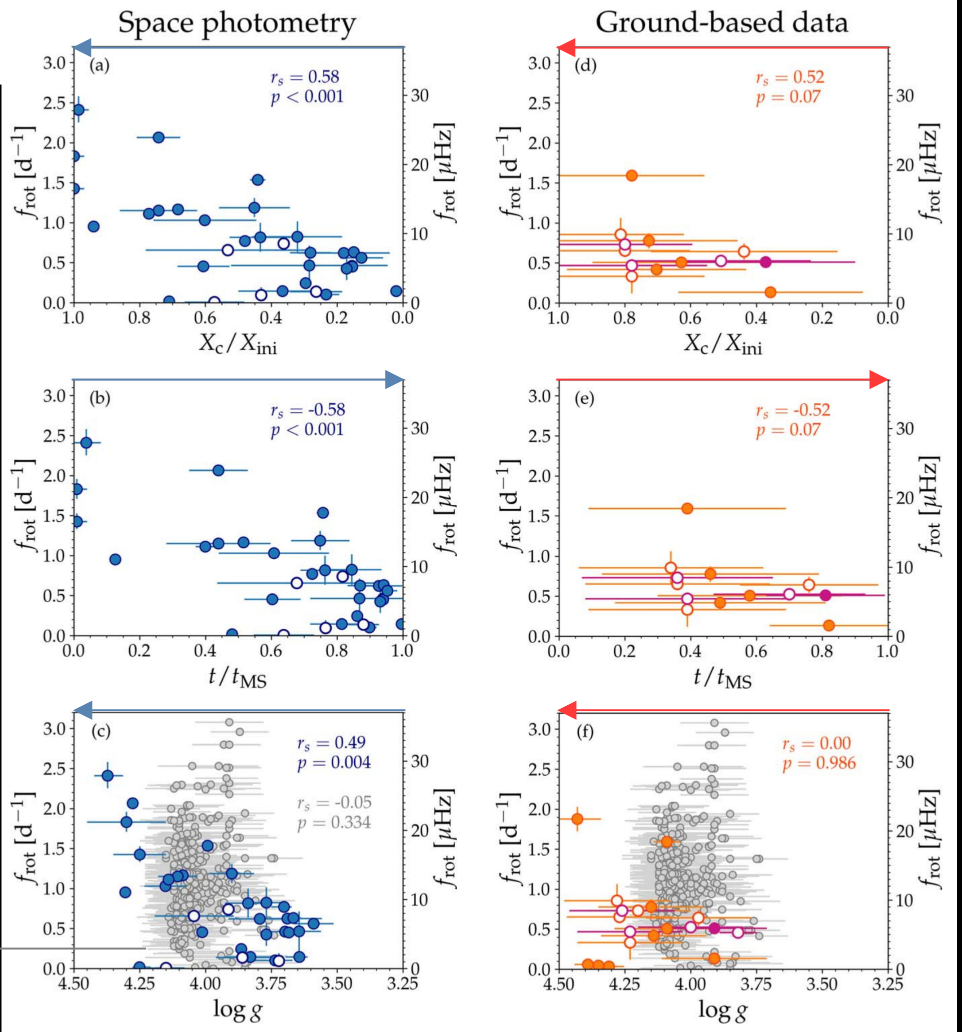
Interior rotation profile

→ Pedersen, 2022, ApJ 940, 49

- 52 SPB stars for which
  - ✔ Internal rotation frequencies derived using g-mode oscillations
  - ✔ Unambiguous mode identification for at least one g-mode
  - ✔ Ages from X_c/X_{ini}, t/t_{MS} and/or log g



Core rotation decreases with age



300 γDor stars
(Li et al., 2020, MNRAS 491, 3586)

KSB - ORB

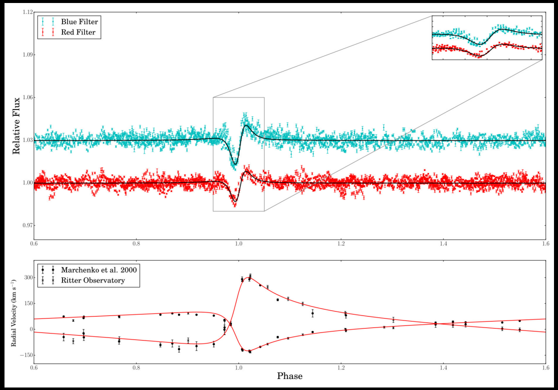
Peter De Cat (Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussels, Belgium)

Tidal forces

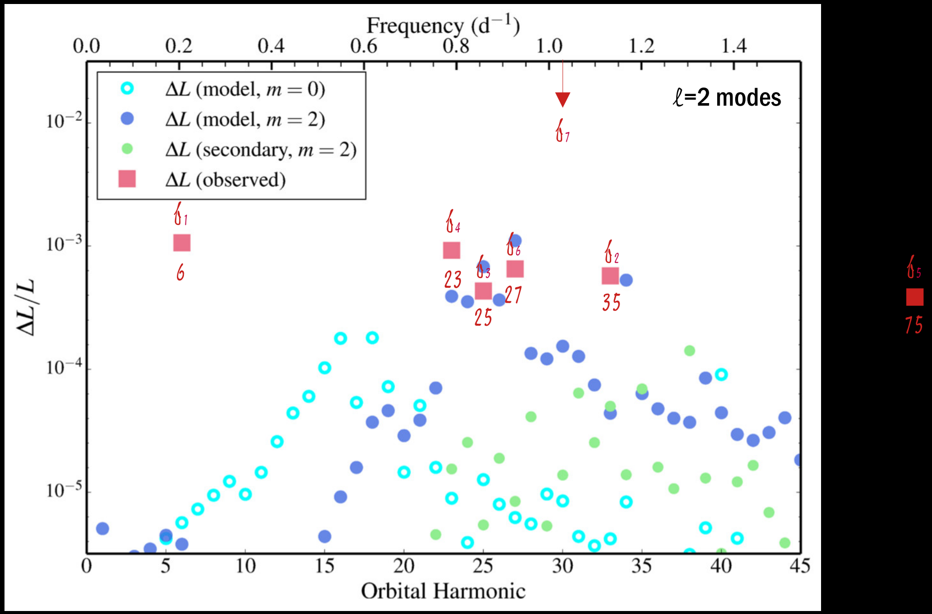
→ ι Orionis (Pablo et al., 2017, MNRAS 467, 2494)

- Massive binary
  - ✔ O9 III + B1 III/IV
  - ✔ P_{orb} = 29.13376 days
  - ✔ e = 0.764
- Frequency analysis
  - ✔ 7 frequencies

BRITE photometry (2013 & 2015; 9 months; UBr, BTr, BHr, BAb, BIb)
High-resolution spectra (2025-2016; #11; 1.06-m Ritter Observatory)
Archival radial velocities (Marchenko et al., 2000)



(heartbeat signal at periastron)



Tidally excited oscillations discovered in O stars

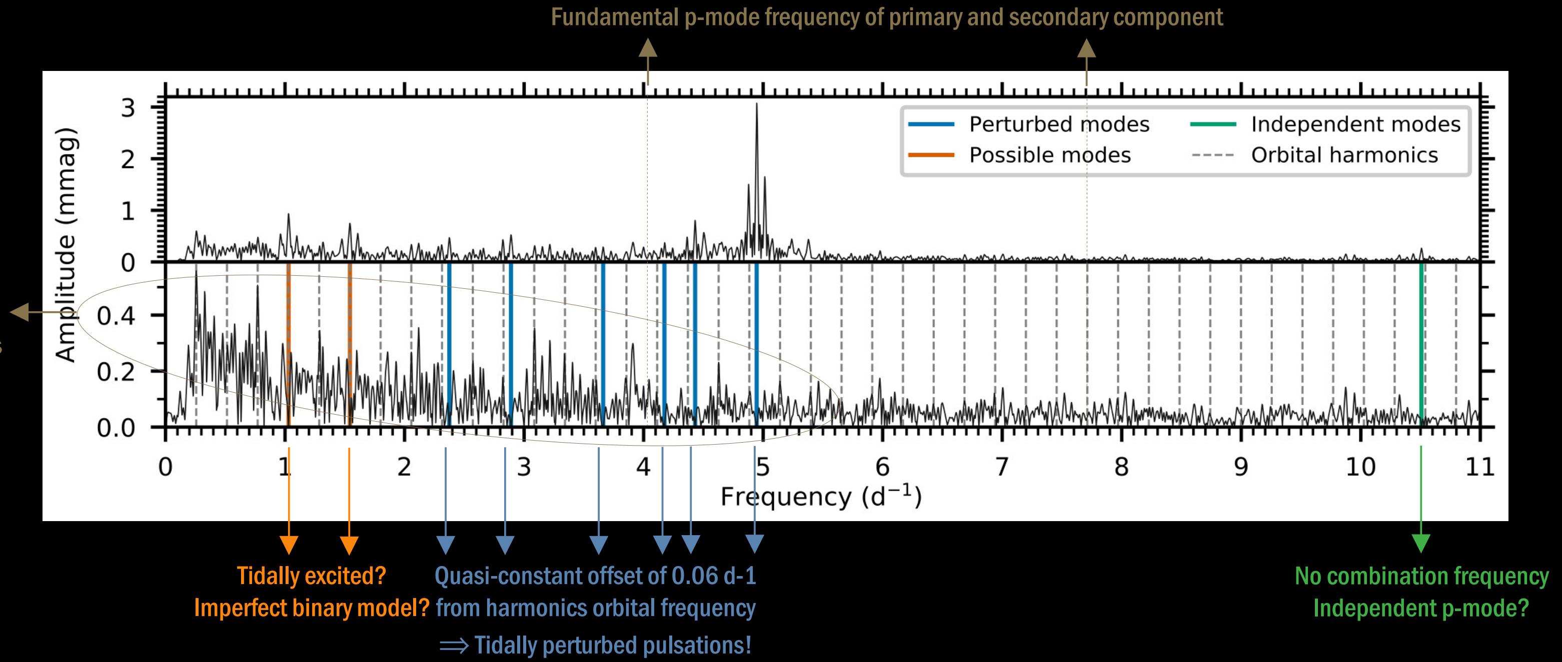
→ η Carina (Richardson et al., 2018, MNRAS 475, 5417)

→ ε Lupi (Pablo et al., 2019, MNRAS 488, 64)

Tidal forces

→ **V453 Cygni** (Southworth et al., 2020, MNRAS 497, L19)

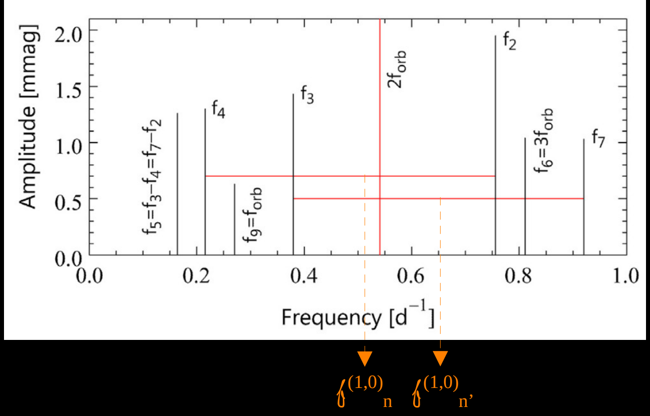
- Eclipsing binary consisting of B0.4IV and B0.7IV components (orbital period 3.89 days, slightly eccentric ~0.025, apsidal motion with period of 72 years)
- TESS (two sectors; 2-min cadence): 9 significant frequencies ⟹ at least one component with βCep pulsations



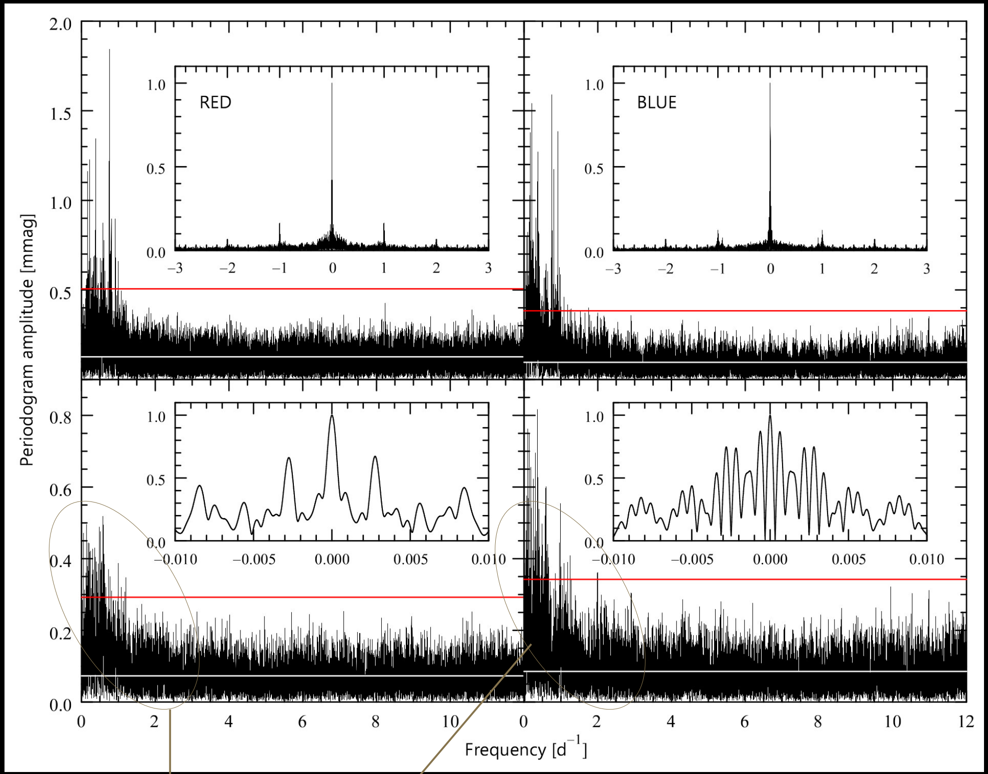
Tidal forces

→ π^5 Orionis (Jerzykiewicz et al., 2020, MNRAS 496, 2391)

- SB1 system and ellipsoidal variable
  - ✔ Two early B-type stars
  - ✔ P_{orb} = 3.70 days
  - ✔ Circularized orbit
  - ✔ Synchronized rotation
- Frequency analysis
  - ✔ 9 frequencies



BRITE photometry (6 seasons in 2013-2019; UBr, BTr, BHr, BAb, BLb)



Self excited (ℓ,m)=(1,0) g-modes in primary that are distored by equilibrium tide

(if axis of pulsating component is tilted)

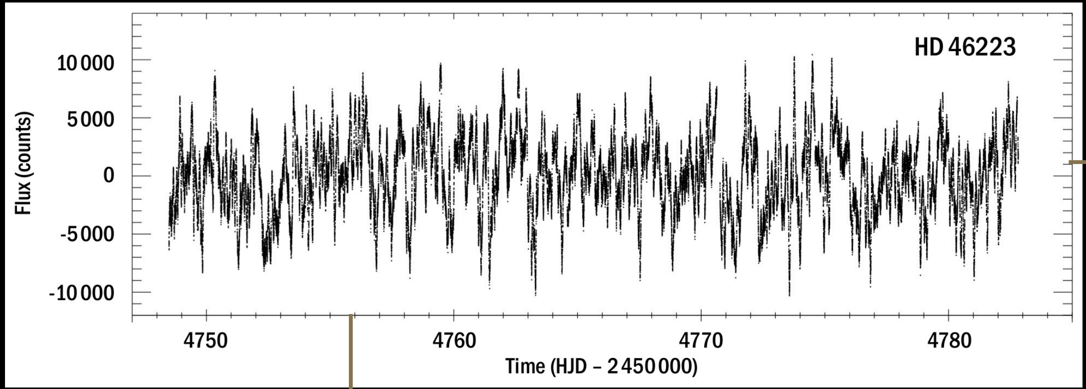
Red noise excess at low frequencies

Stochastic Low-Frequency Variability (SLFV)

→ Observations of SLFV (red noise excess at low frequencies)

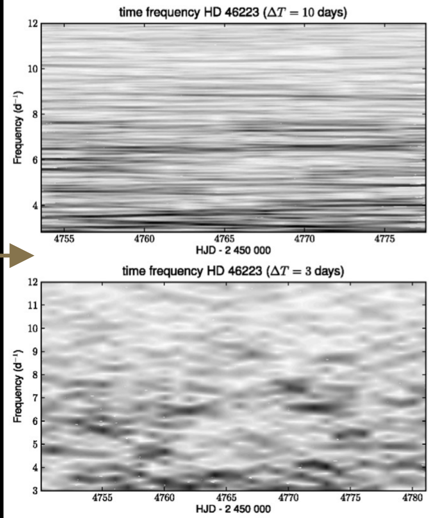
✔ Blomme et al., 2011, A&A 533, A4 → HD46223, HD46150 & HD4696 (O stars)

CoRoT



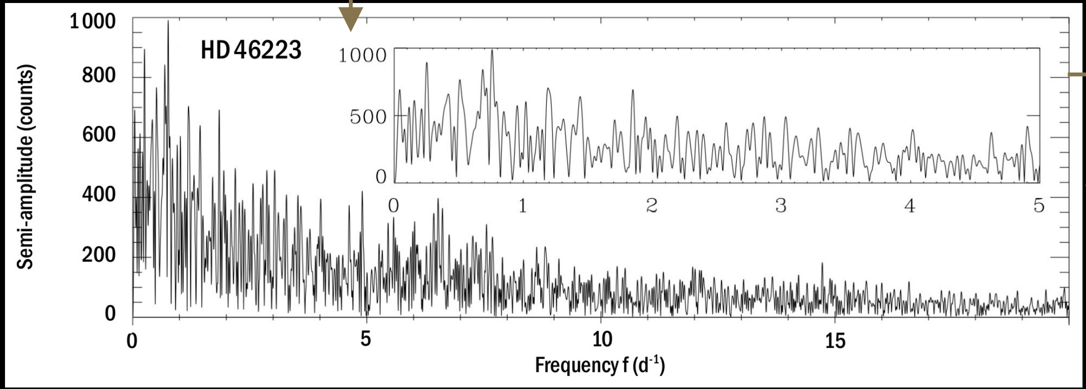
Time-dependent frequency analysis (sliding window)

Short-lived variability



Stochastic excitation?

Lomb-Scargle periodogram

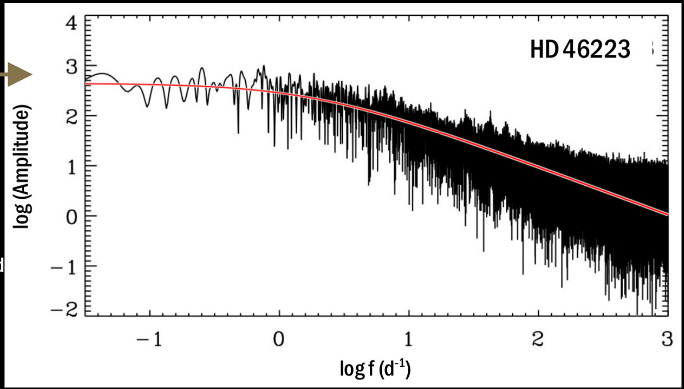


Semi-Lorentzian function

$$\alpha(f) = \frac{\alpha_0}{1 + (2\pi\tau_{char} f)^{\gamma}}$$

with

- α_0 amplitude as f → 0
- τ_{char} characteristic timescale on which red noise is correlated
- γ steepness of amplitude spectrum



Stochastic Low-Frequency Variability (SLFV)

→ Observations of SLFV (red noise excess at low frequencies)

✔	Blomme et al., 2011, A&A 533, A4	→ HD46223, HD46150 & HD4696 (O stars)	CoRoT
✔	Tkachenko et al., 2014, MNRAS 438, 3093	→ primary of massive binary V380 Cyg (B star)	Kepler + spectra
✔	Aerts et al., 2017, A&A 602, A32	→ HD188209 (O9.5 Iab blue supergiant)	Kepler + spectra
✔	Simón-Díaz et al., 2018, A&A 612, A40	→ HD2905 (early-B supergiant)	spectra
✔	Bowman et al., 2019, A&A 621, A135	→ 35 OBAF stars	CoRoT
✔	Bowman et al., 2019, NatAs 3, 760	→ 114 ecliptic OB stars & 53 LMC OB stars	K2 + TESS
✔	Dorn-Wallenstein et al., 2019, AJ 878, 155	→ 6 LMC yellow supergiants & 2 LMC luminous blue variables	TESS
✔	Bowman et al., 2020, A&A 640, A36	→ 70 OB stars	TESS + spectra
✔	Dorn-Wallenstein et al., 2020, AJ 902, 24	→ 28 LMC yellow supergiants & 48 Galactic red supergiants	TESS
✔	Rauw et al., 2019, A&A 621, A15	→ HD149404 (massive post-Roche Lobe overflow system)	BRITE
✔	Nasé et al., 2021, MNRAS 502, 5038	→ 26 Wolf-Rayet stars & 8 luninous blue variables	TESS
✔	Lenoir-Craig et al., 2022, AJ 925, 79	→ 50 Galactic Wolf-Rayet stars	BRITE
✔	Elliot et al., 2022, MNRAS 509, 4246	→ P Cygni (luminous blue variable)	BRITE
✔	Bowman et al., 2022, A&A 668, A134	→ 30 OB stars	CoRoT
✔	Kołaczek-Szymański et al., A&A 659, A47	→ MACHO 80.7443.1718 (blue supergiant + late O-type dwarf)	TESS
✔	Dorn-Wallenstein et al., 2022, AJ 940, 27	→ 101 LMC and 25 SMC cool supergiants	TESS

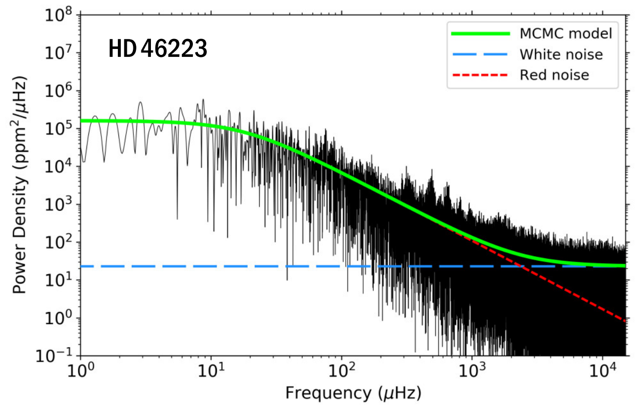
Feature observed for many different types of massive stars!

Stochastic Low-Frequency Variability (SLFV)

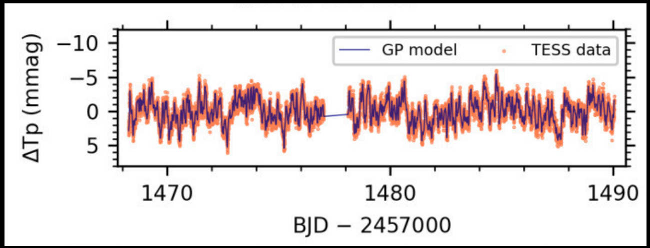
→ **Characterisation of SLFV** (red noise excess at low frequencies)

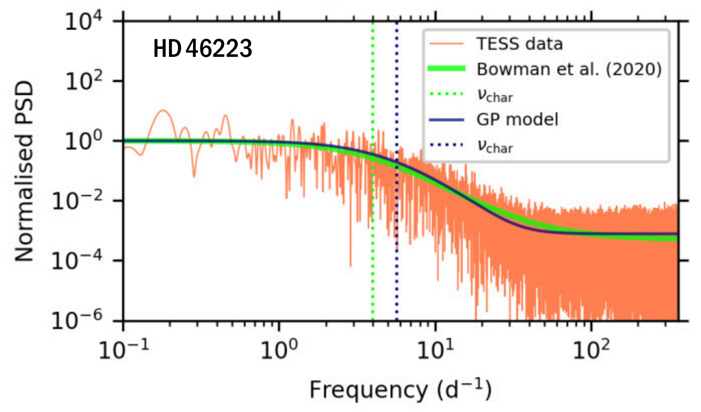
- Amplitude spectrum fitting (frequency domain)
  - ✔ Semi-Lorentzian function
    - ➔ α_0 — characteristic amplitude as frequency ⟶ 0
    - ➔ $\tau_{char} = 1/\nu_{char}$ — characteristic timescale on which red noise is correlated
    - ➔ γ — steepness of amplitude spectrum
    - ➔ α_w — frequency independent noise term (white noise)

- Gaussian process regression (time domain)
  - ✔ Damped simple harmonic oscillator
    - ➔ σ_A — characteristic amplitude
    - ➔ $\rho_{char} = 2\pi/\omega_0$ — characteristic variability timescale
    - ➔ τ_{damp} — characteristic damping timescale
    - ➔ C_{jitter} — jitter term to emulate uncorrelated noise in the observations
    - ➔ Q — quality factor (more damping if low value)



Bowman et al., 2019, A&A 621, A135





Bowman et al., 2022, A&A 668, A134

Peter De Cat (Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussels, Belgium)
Group meeting at BNU (25/09/2024, Beijing, China)

Stochastic Low-Frequency Variability (SLFV)

→ **Characterisation of SLFV** (red noise excess at low frequencies)

- Amplitude spectrum fitting (frequency domain)
  - ✔ Semi-Lorentzian function
    - ➔ α_0 — characteristic amplitude as frequency ⟶ 0
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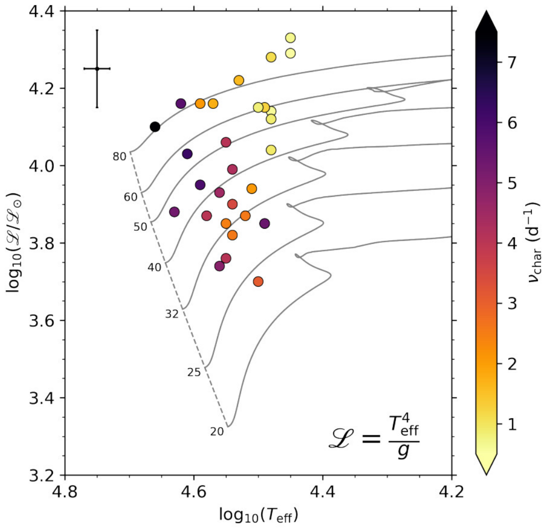
    - ➔ C_{jitter} — jitter term to emulate uncorrelated noise in the observations
    - ➔ Q — quality factor (more damping if low value)

"yellow subgroup":
- Low ν_{char} + high α_0/σ_A + low ν_{damp}
- Higher mass
- More evolved (closer to TAMS)
- Less stochastic (high Q value)

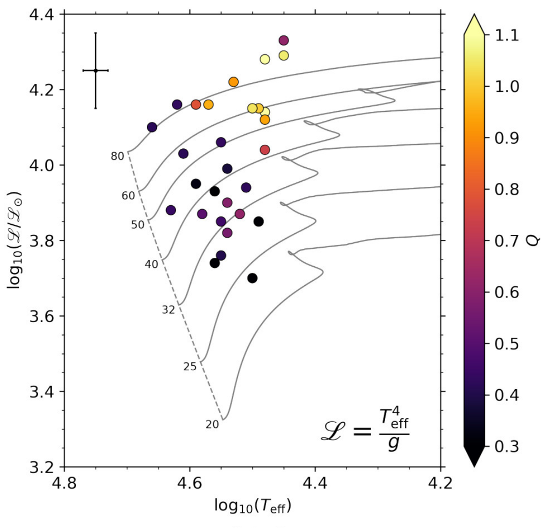
"blue subgroup":
- High ν_{char} + low α_0/σ_A + high ν_{damp}
- Less evolved (closer to ZAMS)
- More stochastic (low Q values)

ν_{char} probes mass, age and degree of coherency

Bowman et al., 2022, A&A 668, A134



Bowman et al., 2022, A&A 668, A134



Stochastic Low-Frequency Variability (SLFV)

→ Interpretation of SLFV

- Surface granulations (cf. red giant stars)
- Internal Gravity Waves (IGWs)
  - ✔ Travelling waves that are stochastically excited at the interface of a convective region and a stably stratified zone
    - ➔ turbulent core convection
    - ➔ turbulent pressure fluctuations in subsurface convective zones in outer envelope (Fe-opacity peak converction zone)
  - ✔ Propagate and dissipate within radiative regions
- Wind-driven processes
  - ✔ Clumpy, aspherical, and inhomogeous stellar wind (line deshadowing instability)

Stochastic Low-Frequency Variability (SLFV)

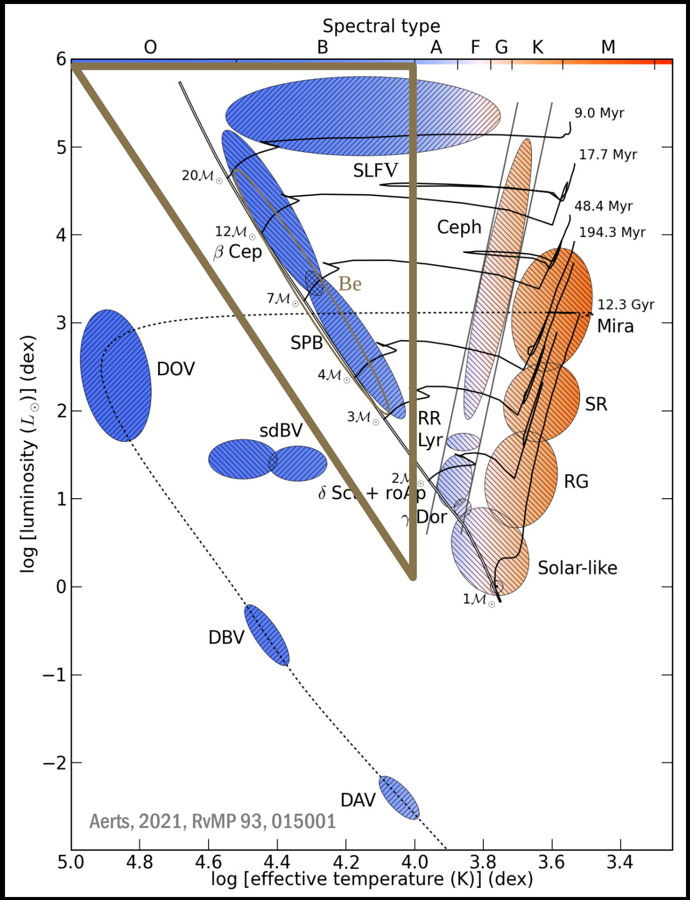
→ Interpretation of SLFV

- Surface granulations (cf. red giant stars) but ν_{char} order of magnitude smaller than predicted ν_{gran} for majority of stars (Bowman et al., 2019, A&A 621, A135)
- Internal Gravity Waves (IGWs)
  - ✔ Travelling waves that are stochastically excited at the interface of a convective region and a stably stratified zone
    - ➔ turbulent core convection
    - ➔ turbulent pressure fluctuations in subsurface convective zones in outer envelope (Fe-opacity peak converction zone)
  - ✔ Propagate and dissipate within radiative regions
- Wind-driven processes
  - ✔ Clumpy, aspherical, and inhomogeous stellar wind (line deshadowing instability)

No consensus yet...

OB-type stars

Convective core
Radiative envelope



- → **β Cephei stars** (βCep)
  - ➢ Low order p and g modes with periods of few hours
- → **Slowly Pulsating B stars** (SPB)
  - ➢ High order g modes with periods of several hours to few days

} Hybrids!

- → **Stochastic low-frequency variability** (SLFV)
  - ➢ α Cygny stars
  - ➢ Fast Yellow Pulsating Supergiants (?)
- → **Be stars** (Be)
  - ➢ Pulsations
- → **Maia variables (?)**

Excitation mechanisms at play

- ➢ Opacity mechanism operating in Z bump
- ➢ Stochastic excitation
- ➢ Non-linear mode excitation
- ➢ Rotation
- ➢ Tidal excitation

Influencing factors

- ➢ Opacities
- ➢ Interior mixing profile
- ➢ Interior rotation profile
- ➢ Interior temperature profile
- ➢ Tidal forces
- ➢ Magnetic fields
- ➢ Mass loss
- ➢ Stellar wind