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# A data-driven outlook for the future of “massive” star research


## Conny Aerts

University of Leuven, Belgium

Radboud University Nijmegen, the Netherlands


MAMSIE

erc 10 years

KITP, 24 March 2017

# Let the data guide the theory: high-precision time-domain astrophysics & back to basics…

## Some questions raised this week (very biased selection!)

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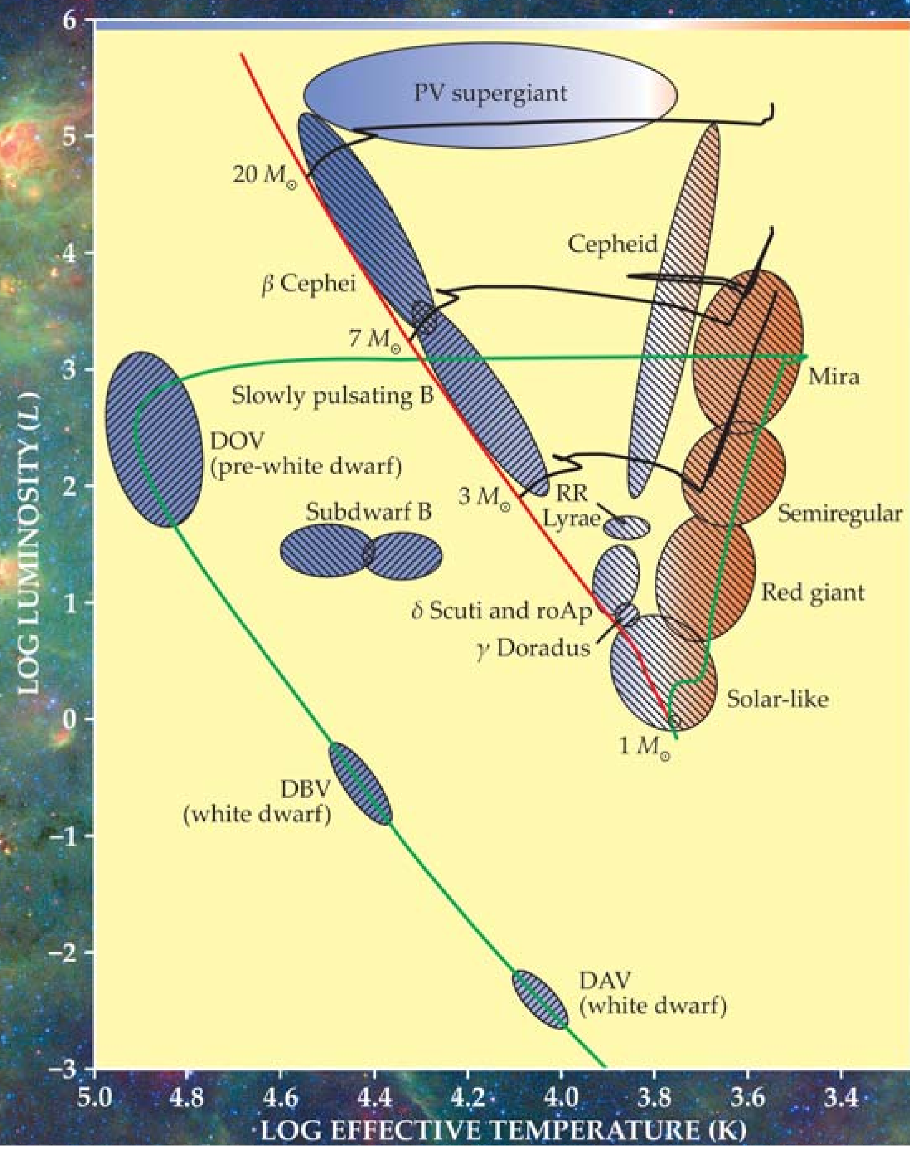
# My favourite HRD…

HRD considers global *surface and wind properties*

Stellar *interior* = probed by *stellar oscillations*

*Variability* in upper HRD is prominent, diverse and has various causes

*Binarity is common* and cannot be ignored




From C. Aerts, Physics Today, 2015

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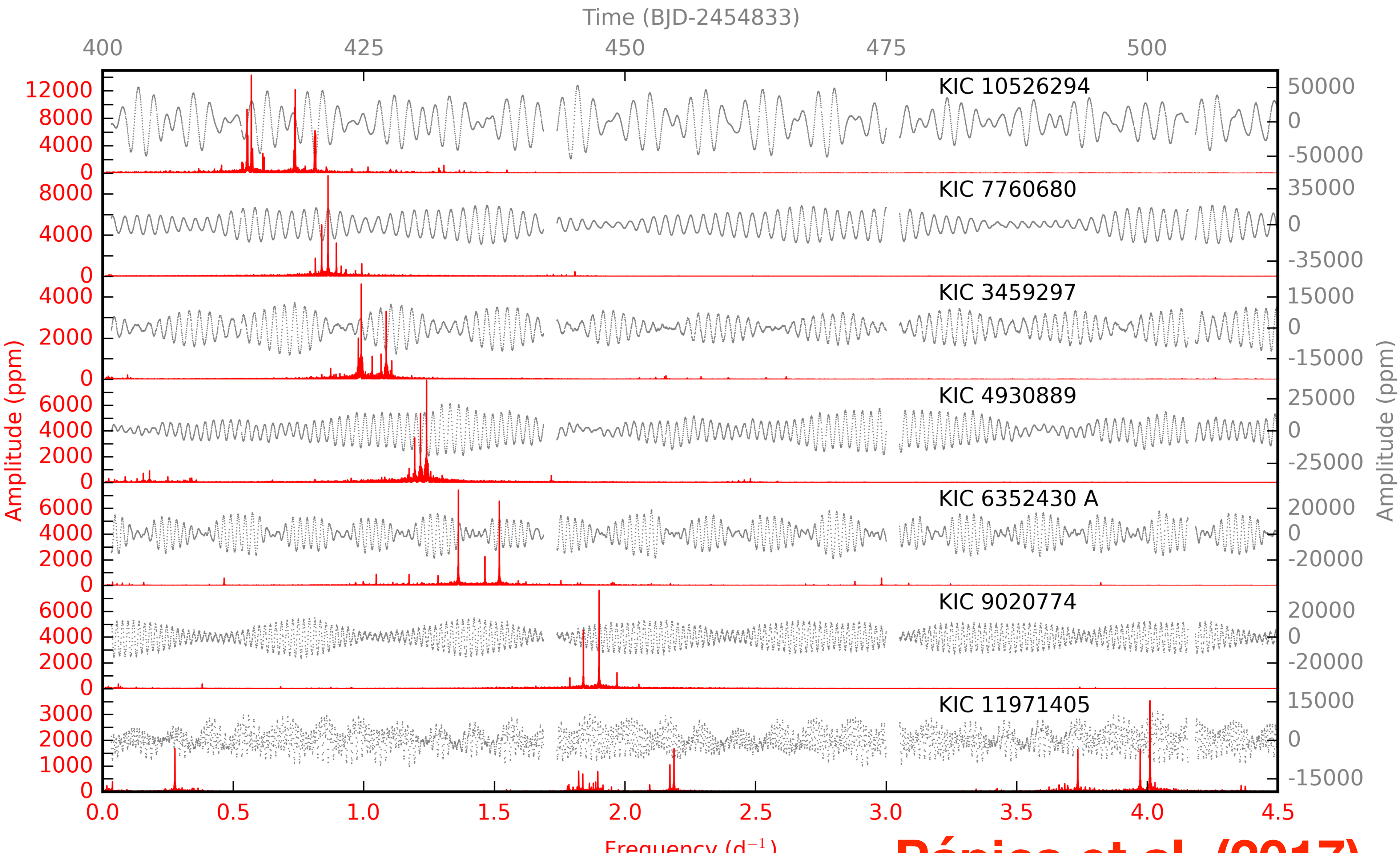
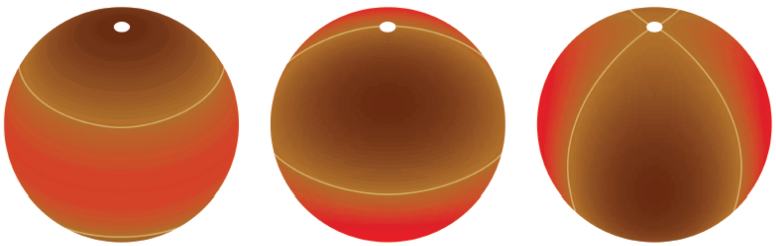
# Detected gravity-mode oscillations in B stars

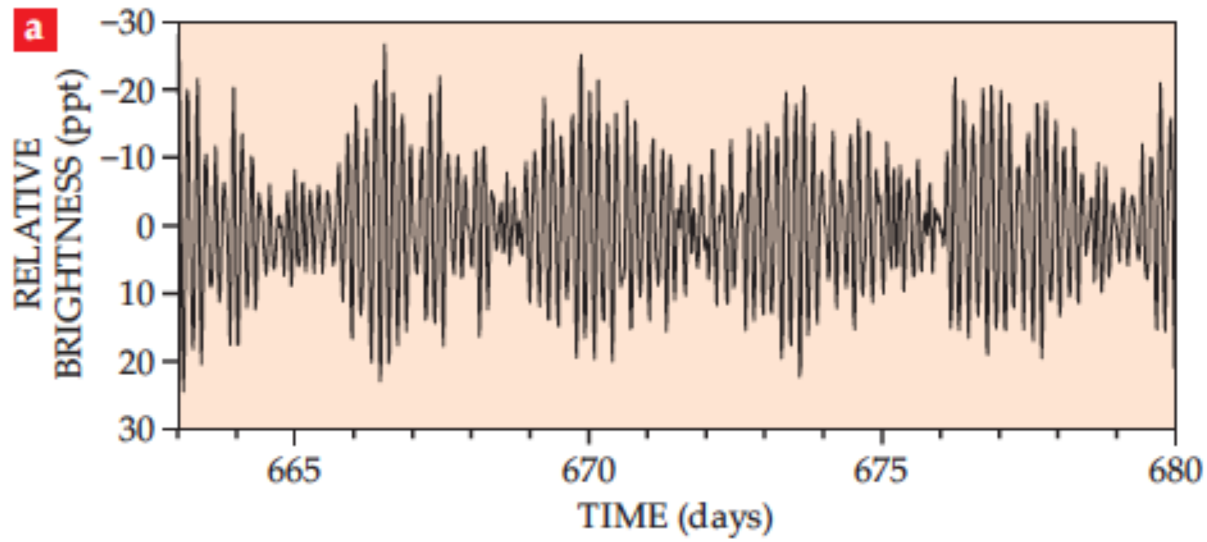


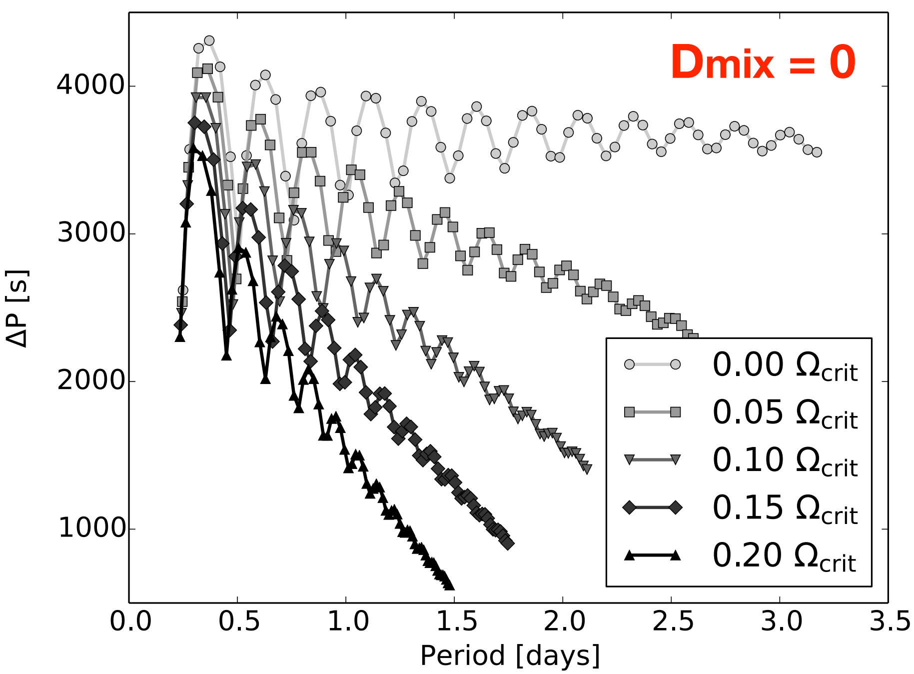

**Pápics et al. (2017)**

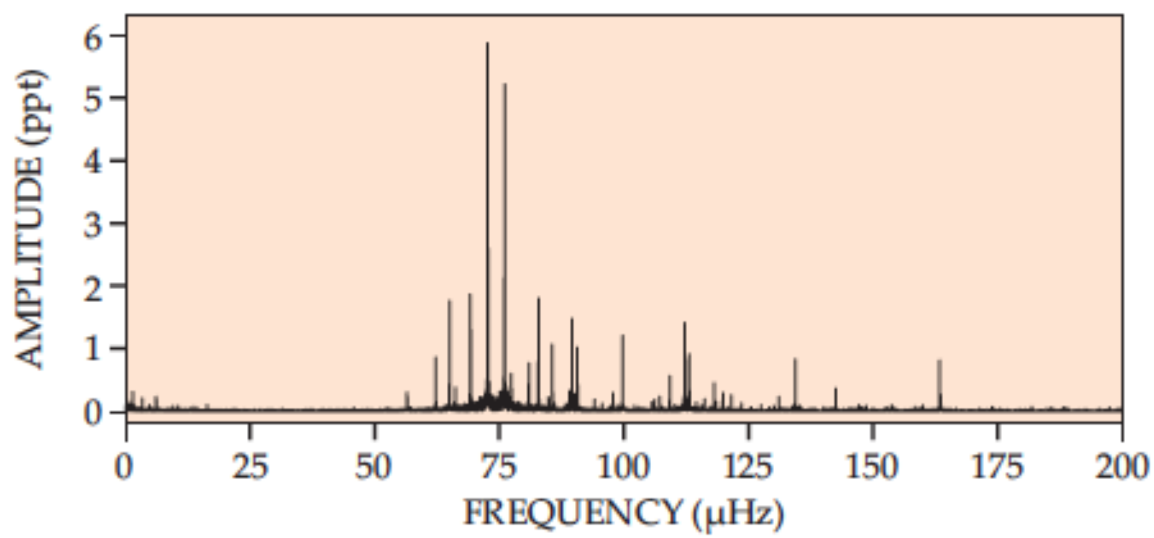
# The boost thanks to space photometry



Detection of 10s of gravity-mode oscillations from **uninterrupted high-precision long-duration (> 1 year) space photometry**




From C. Aerts, Physics Today, 2015

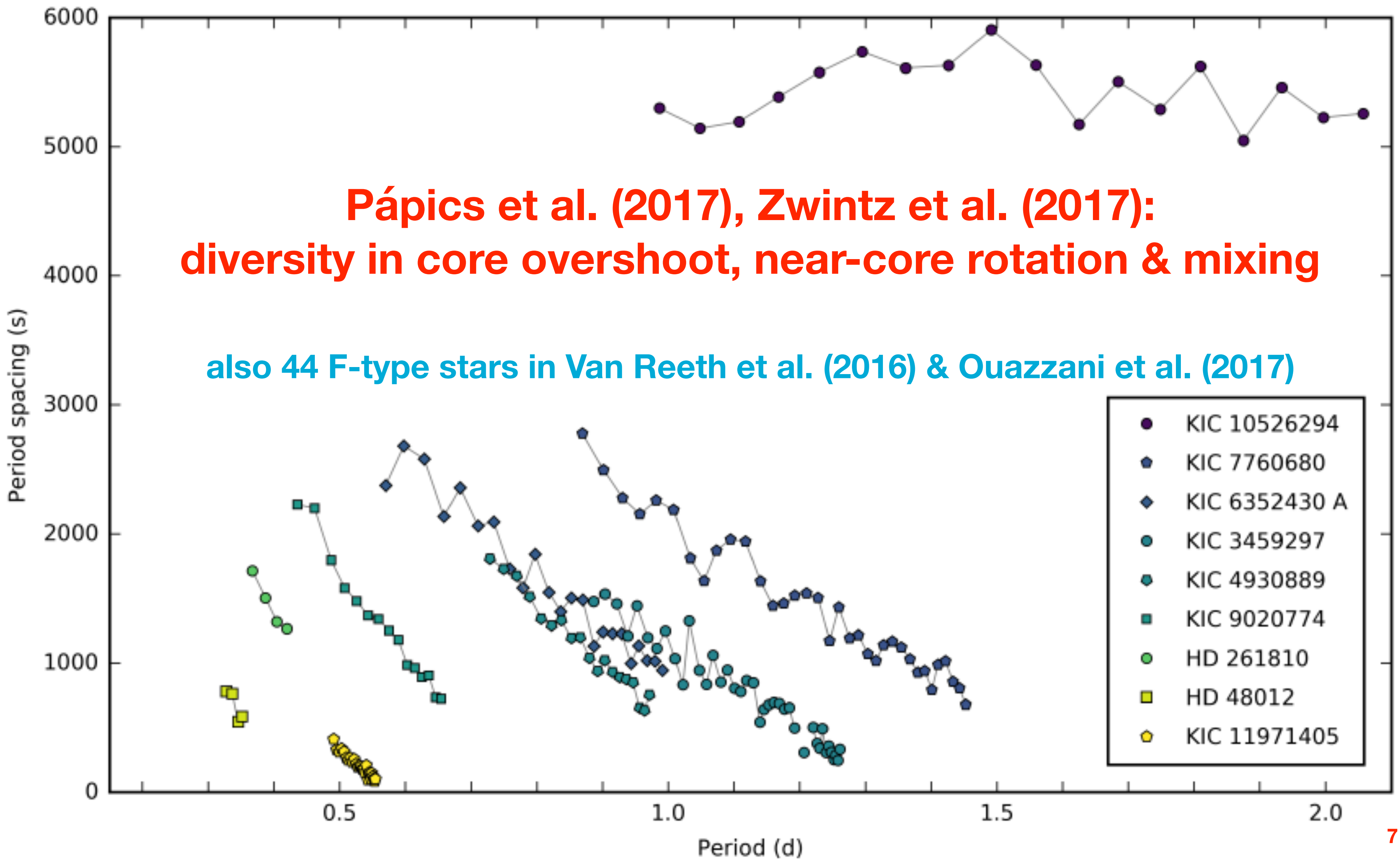
# Let the data guide the theory: high-precision time-domain astrophysics

What is more important: unknowns in macro-physics as of ZAMS versus uncertainties in micro-physics such as nuclear reaction rates in pre-SN?

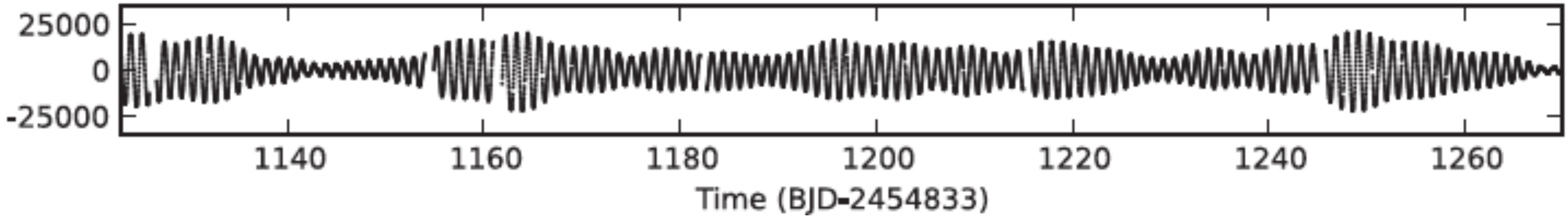
# Gravity-mode period spacings in B stars

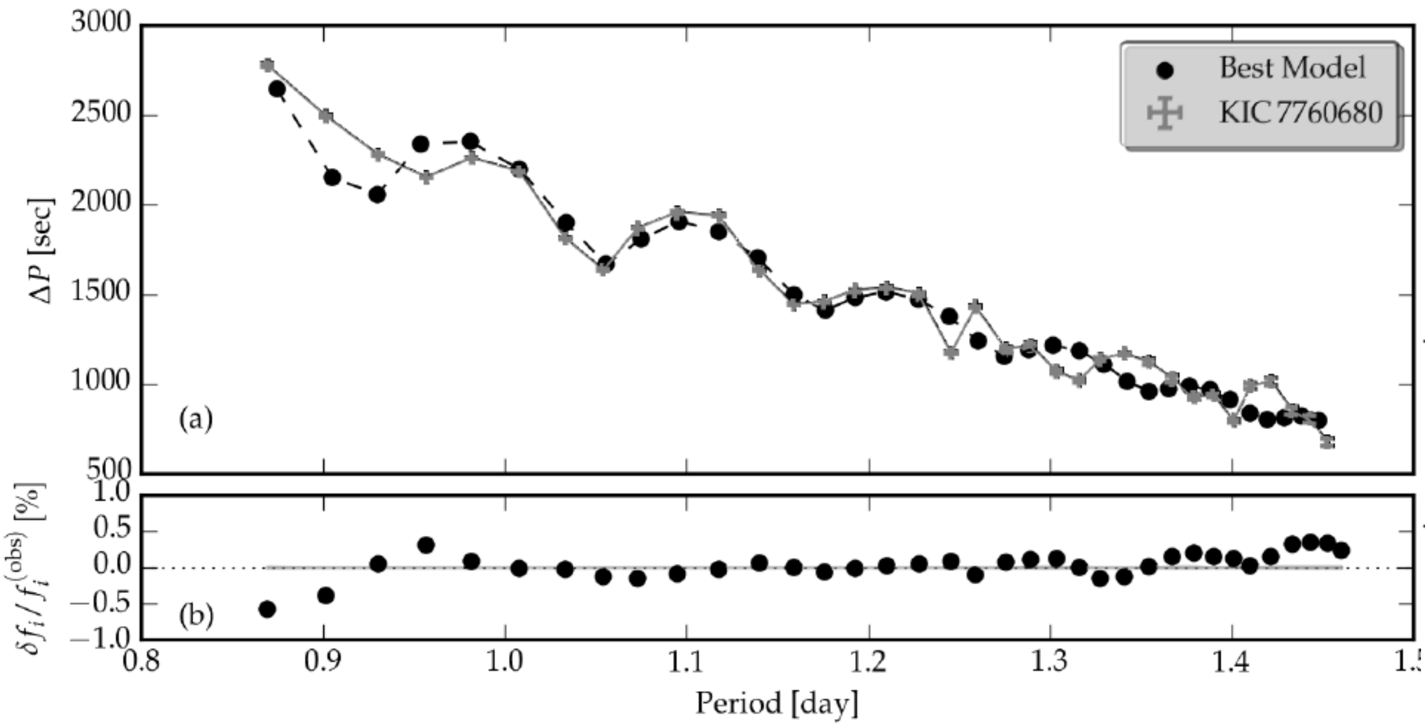
**Pápics et al. (2017), Zwintz et al. (2017): diversity in core overshoot, near-core rotation & mixing**

also 44 F-type stars in Van Reeth et al. (2016) & Ouazzani et al. (2017)



# Level & shape of core overshoot dominate



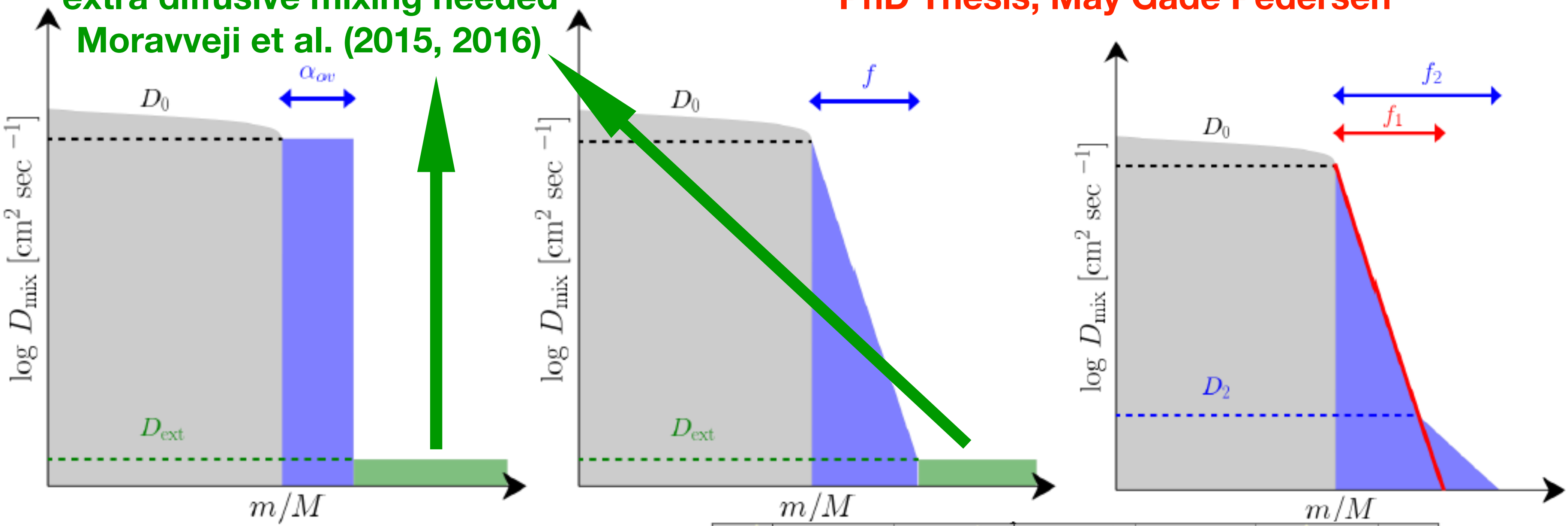

| | |
|---|---|
| $M_{ini}$ [$M_\odot$] | 3.25 (5) |
| $Z_{ini}$ | 0.020 (1) |
| Overshoot | $f_{ov}$=0.024 (1) |
| $\log D_{ext}$ [$cm^2\ sec^{-1}$] | 0.75 (25) |
| $X_c$ | 0.503 (1) |
| $f_{rot}^{(opt)}$ [$day^{-1}$] | 0.4805 |
| $f_{rot}^{(opt)}/f_{crit}$ [%] | 26.4 |
| $M_\star$ [$M_\odot$] | 3.2499 |
| $R_\star$ [$R_\odot$] | 2.7895 |
| $L_\star$ [$L_\odot$] | 110.8 |
| Age [$10^6$ yr] | 202 |
| $m_{cc}$ [$M_\odot$] | 0.6215 |
| $r_{cc}$ [$R_\odot$] | 0.3356 |
| $m_{ov}$ [$M_\odot$] | 0.2642 |
| $r_{ov}$ [$R_\odot$] | 0.0558 |

**vsini=62 km/s; Pápics et al. (2015) & Moravveji et al. (2016)**

# Core overshoot & core mass tuning

Simple overshoot insufficient;
extra diffusive mixing needed
Moravveji et al. (2015, 2016)

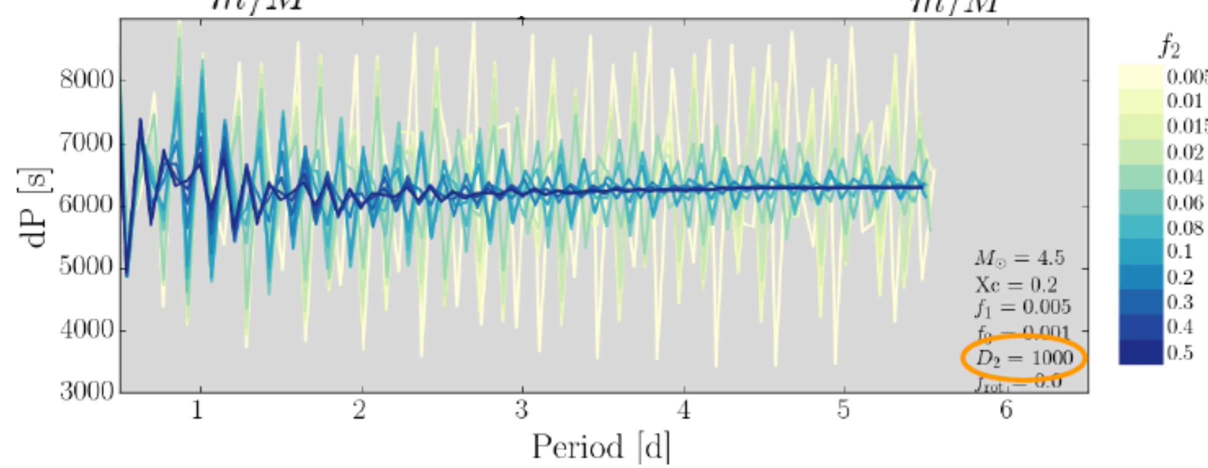
PhD Thesis, May Gade Pedersen




**Kepler, TESS, Gaia:**

**1.2 $M_\odot$ < M < 25 $M_\odot$**

**$Z_{LMC}$<Z<$Z_\odot$**

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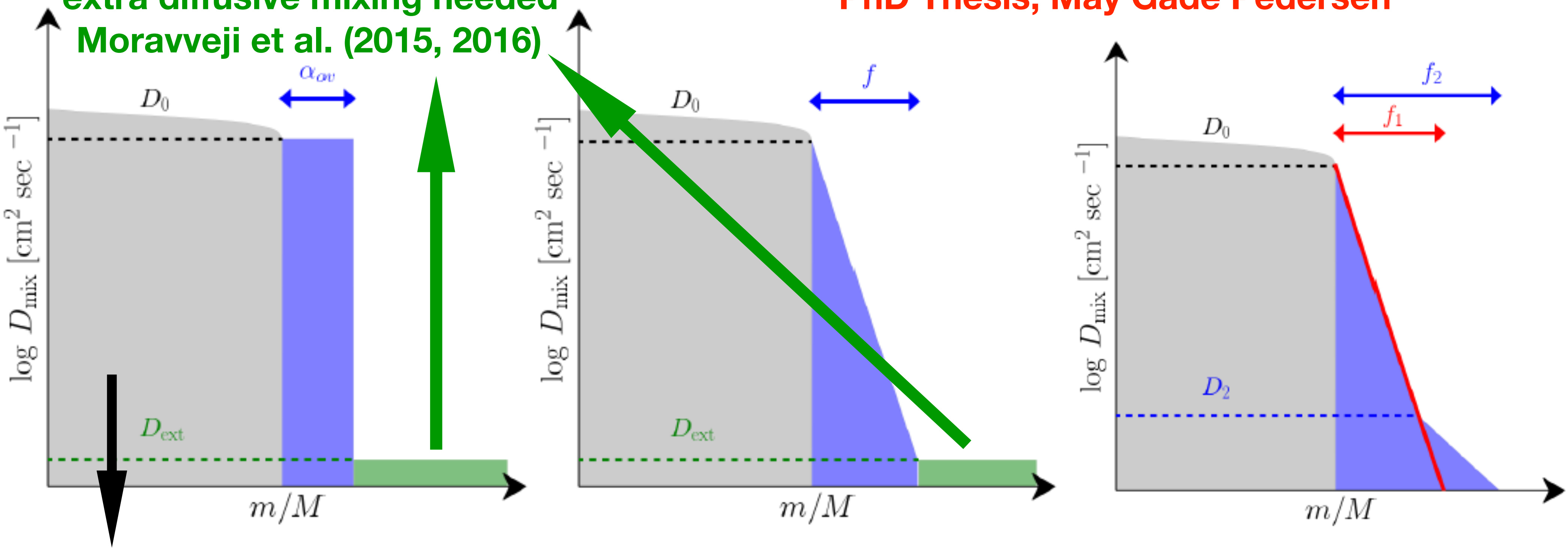



Typically used
in EB isochrone
fitting
(Claret & Torres 2016)
$1.2\ M_\odot < M < 4.4\ M_\odot$

# Let the data guide the theory: high-precision time-domain astrophysics

## Can we use a more realistic mixing profile?

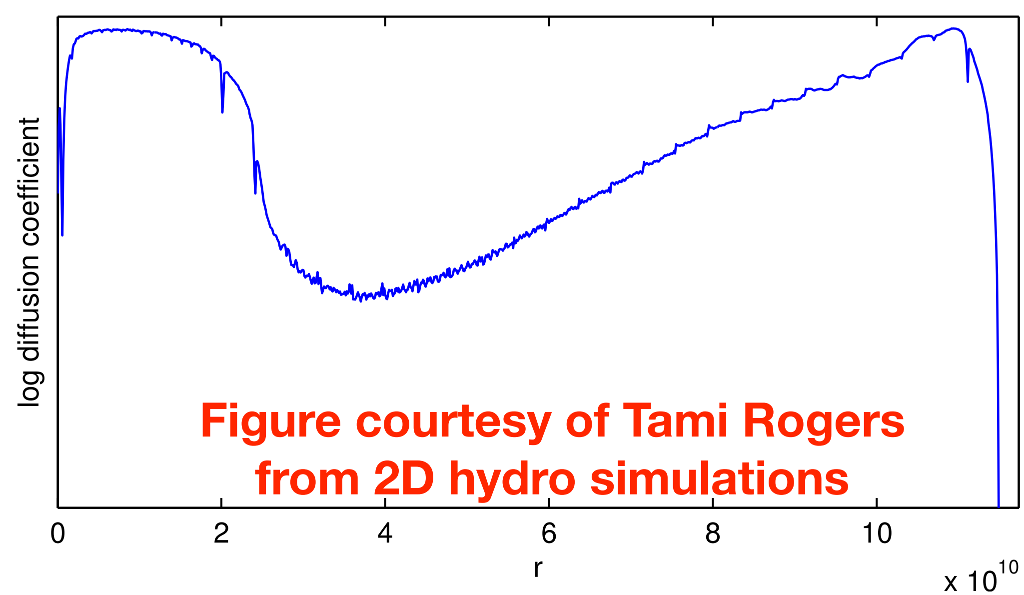
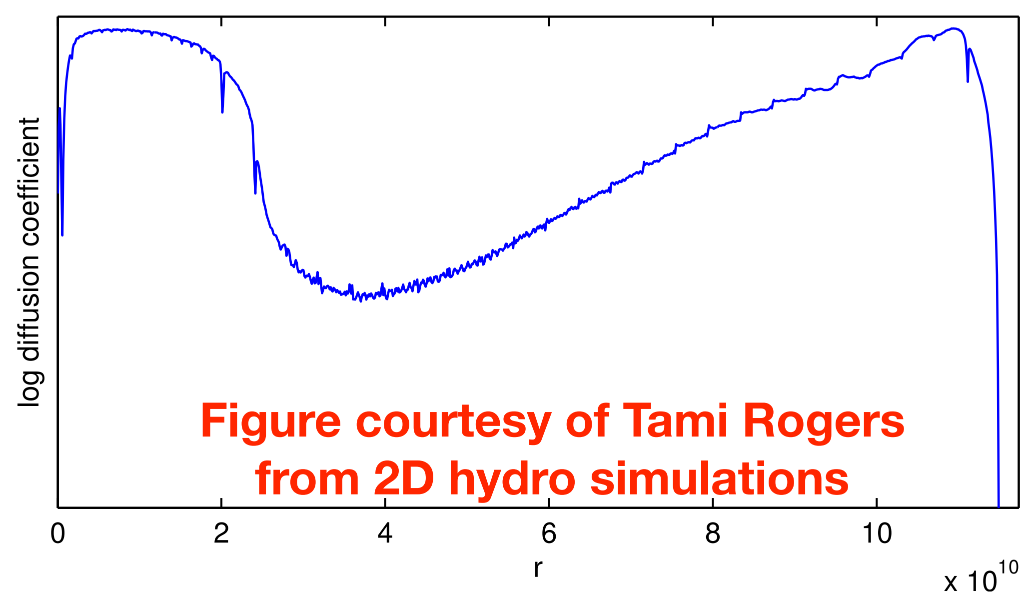



Figure courtesy of Tami Rogers from 2D hydro simulations

# Let the data guide the theory: high-precision time-domain astrophysics

## Can we use a more realistic mixing profile?

**What is the scale on the y-axis?**



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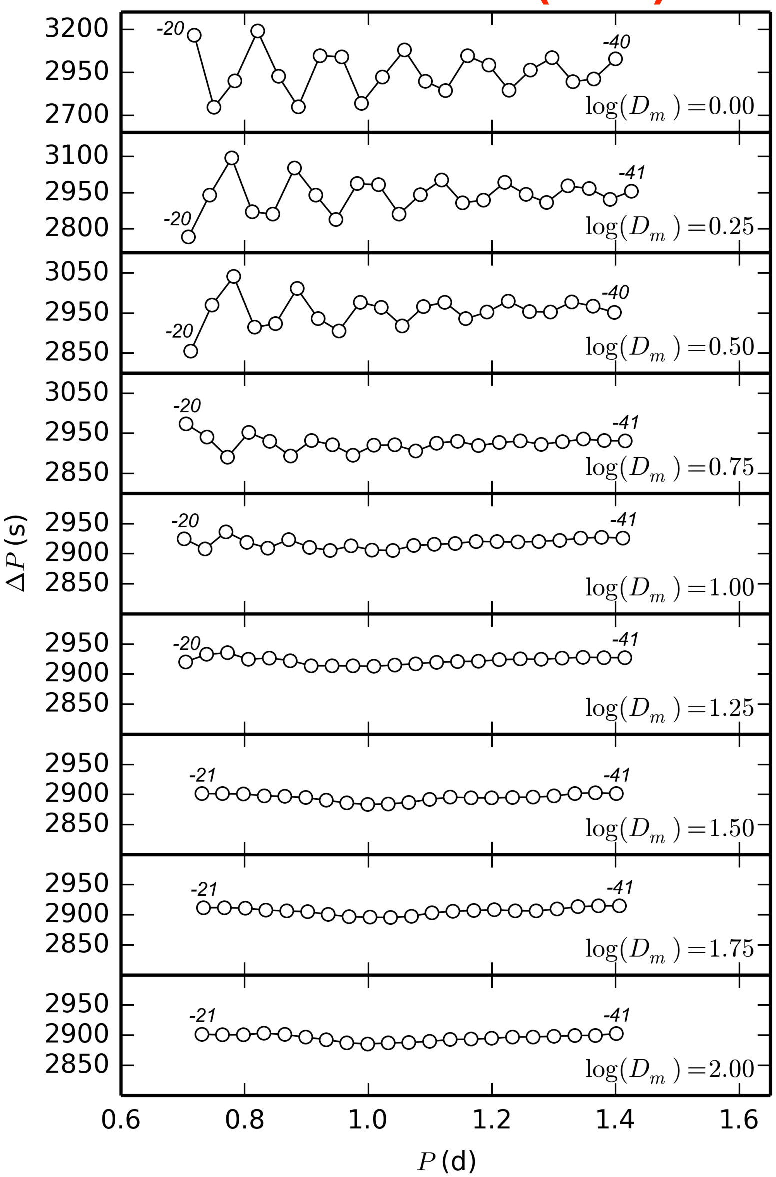
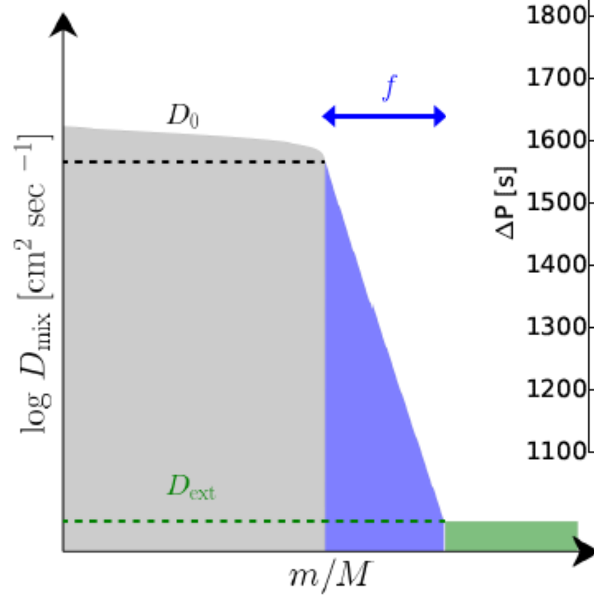
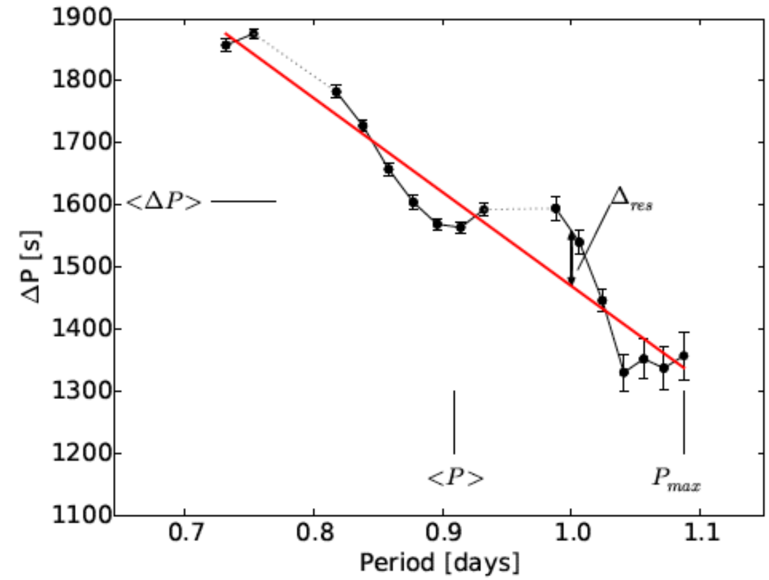
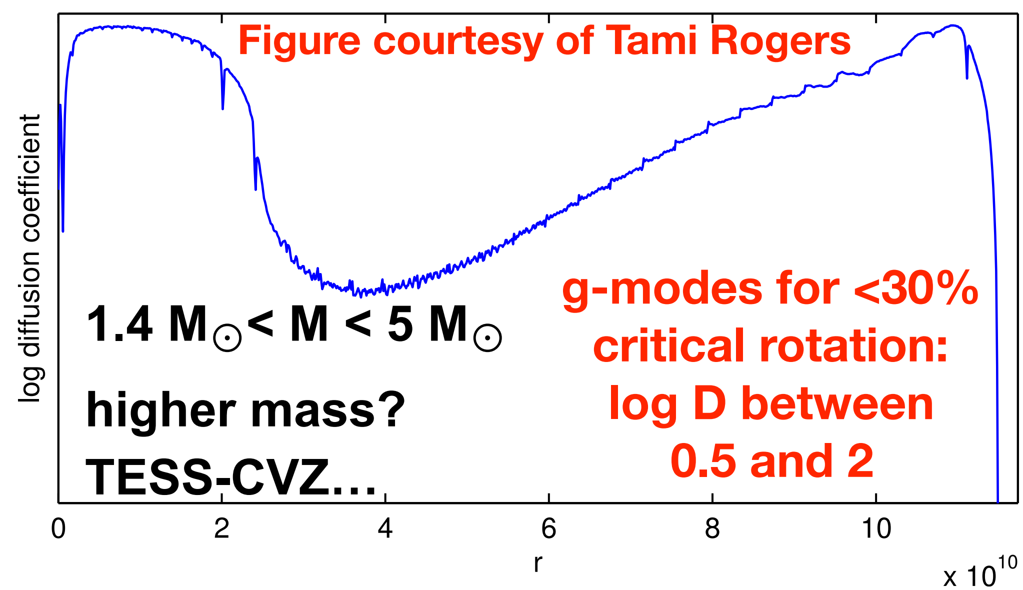
# Dips in ΔP give level of chemical mixing

## Schmid & Aerts (2016)




**1.4 $M_\odot$ < M < 5 $M_\odot$**

**higher mass?**

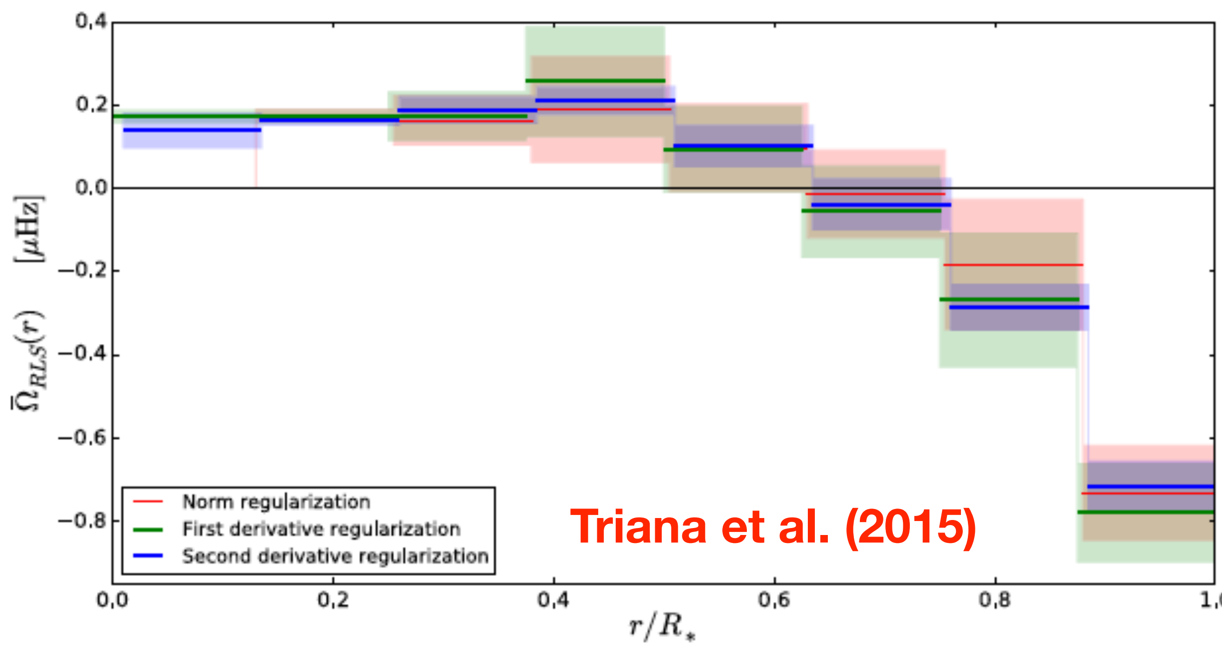
**TESS-CVZ…**

**g-modes for <30% critical rotation: log D between 0.5 and 2**

# Let the data guide the theory: high-precision time-domain astrophysics

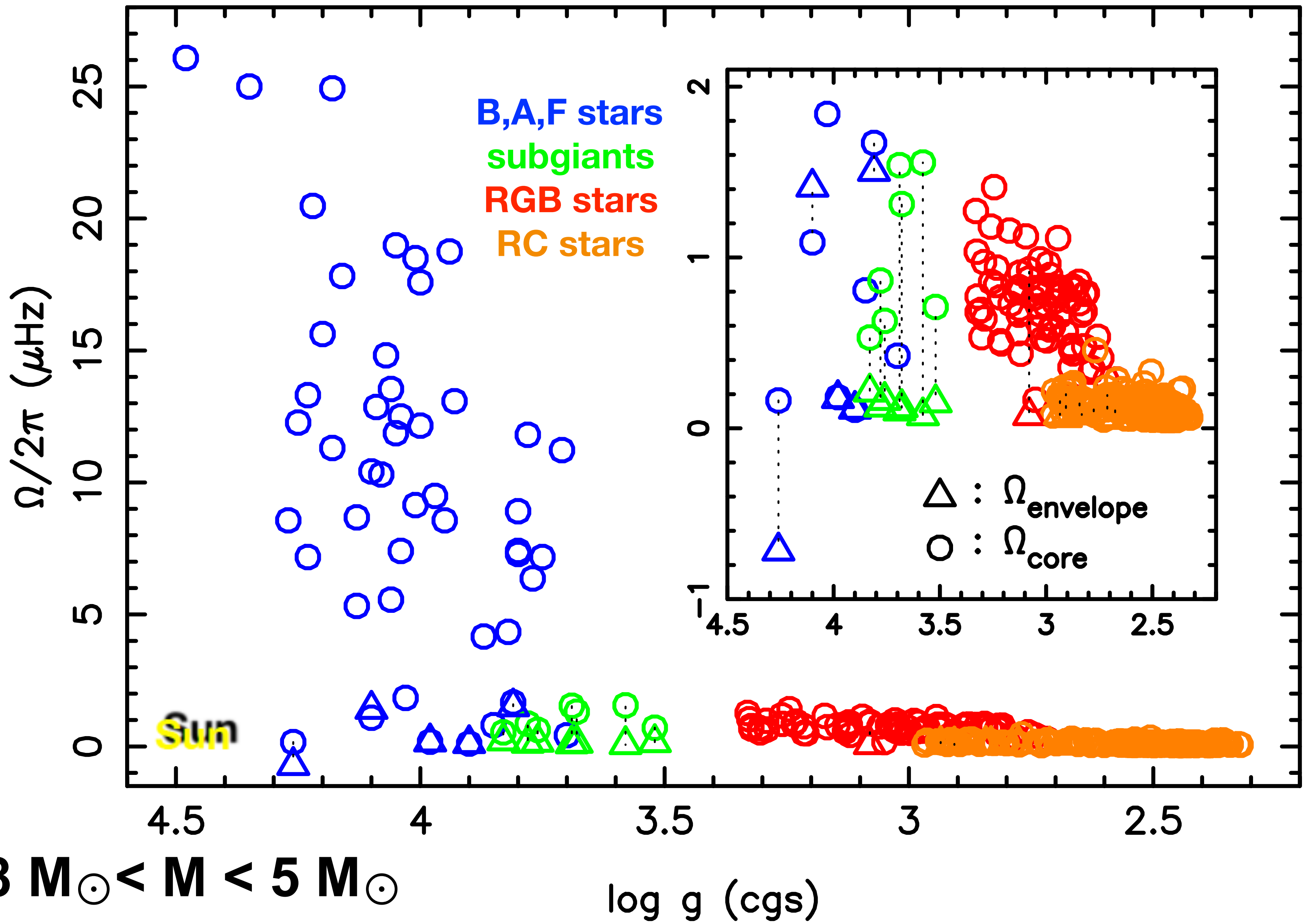
What is the core to envelope rotation for the more “usual” cases in the massive star context?

(not only ultra-slow rotators…)



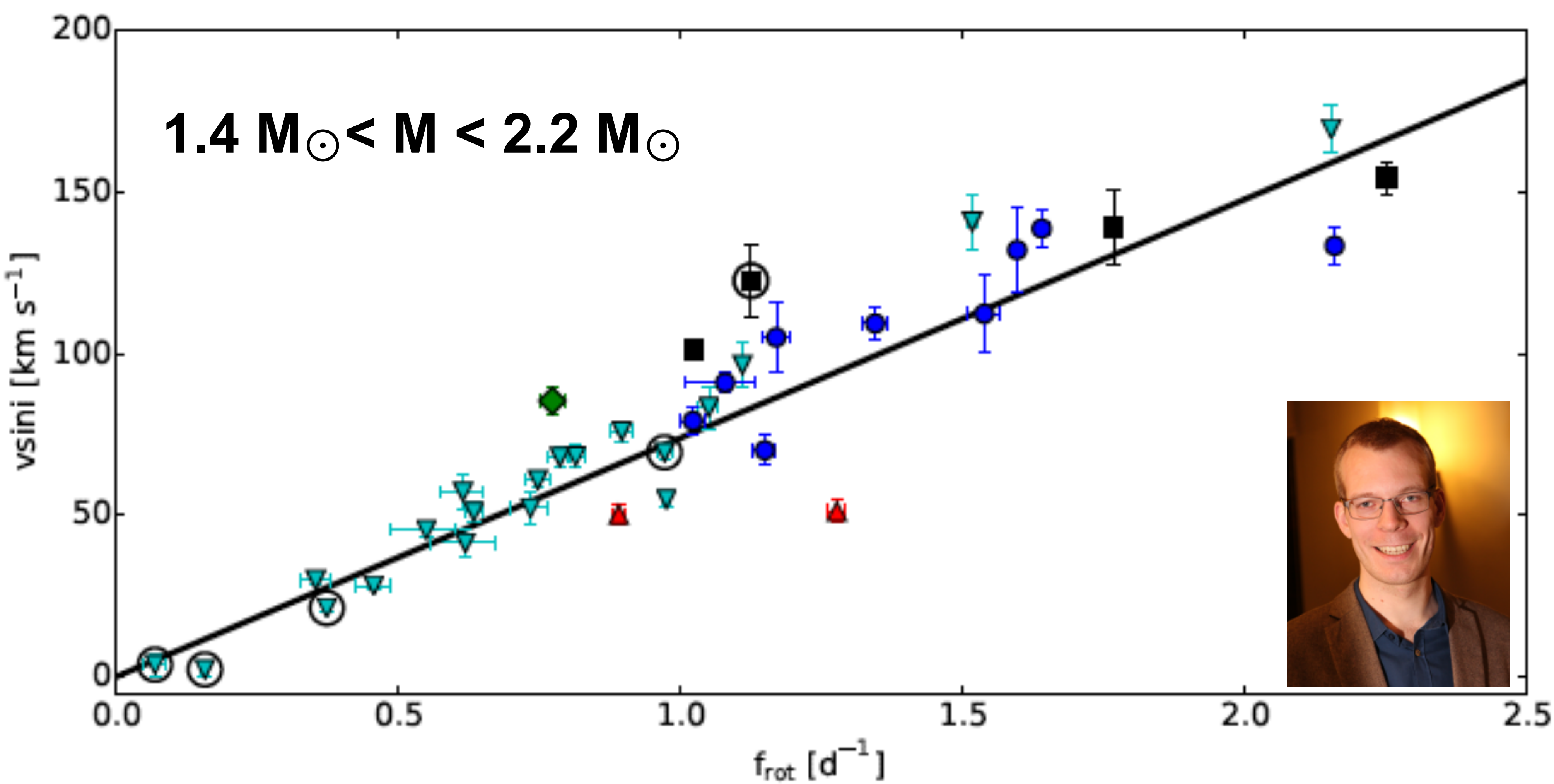

Triana et al. (2015)

# Interior rotation from Kepler: summary



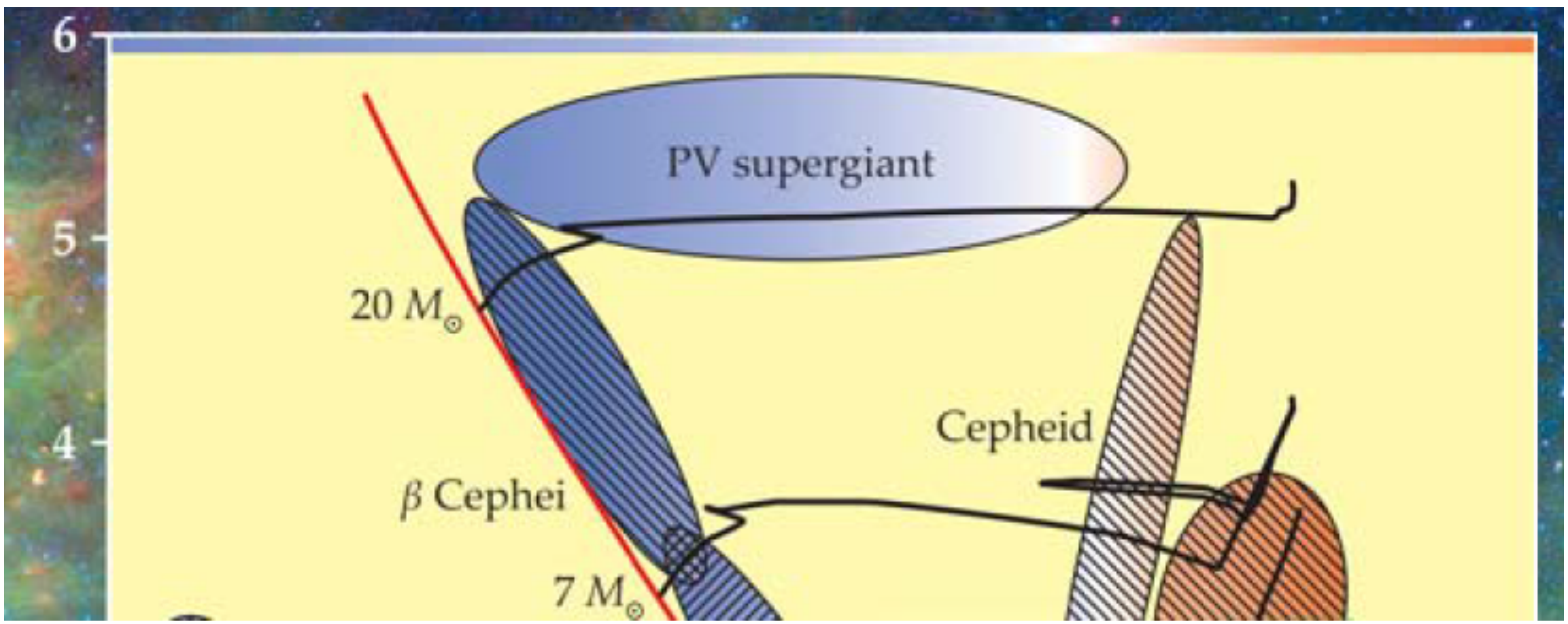

$0.8 \, M_\odot < M < 5 \, M_\odot$

# Interior versus surface rotation F stars



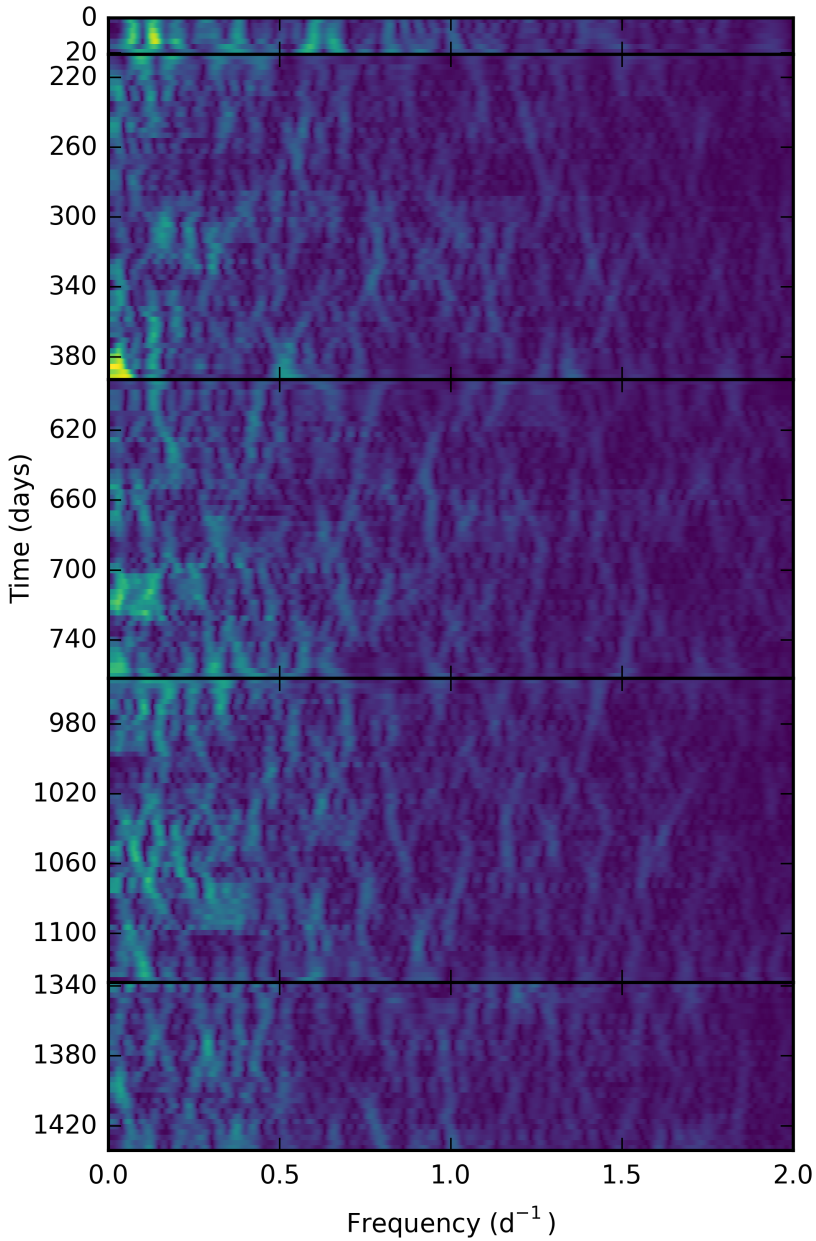

**PhD Thesis of Timothy Van Reeth (2017): consistent with quasi-rigid, but unknown sini…**

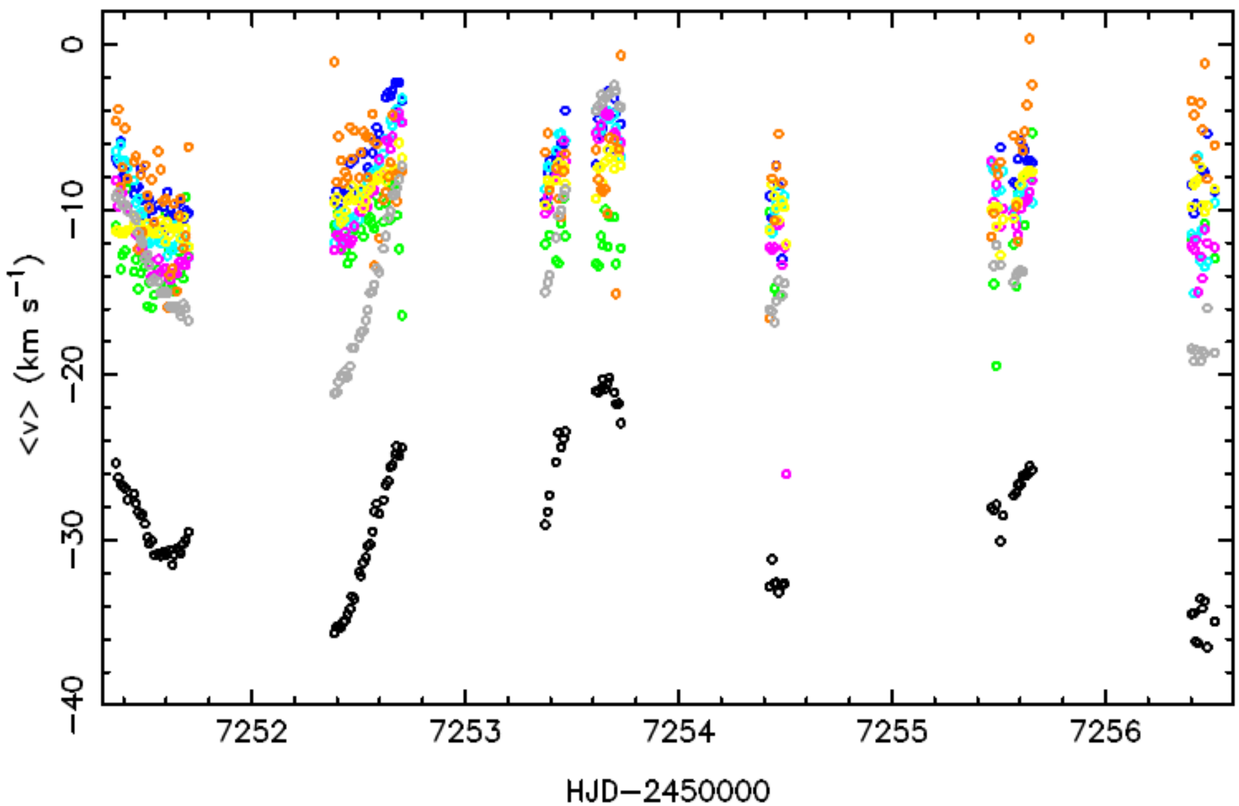
# Let the data guide the theory: how about time-domain astrophysics for supergiants?




Variability all over the place…

# Gravity waves in O9Iab supergiant HD 188209



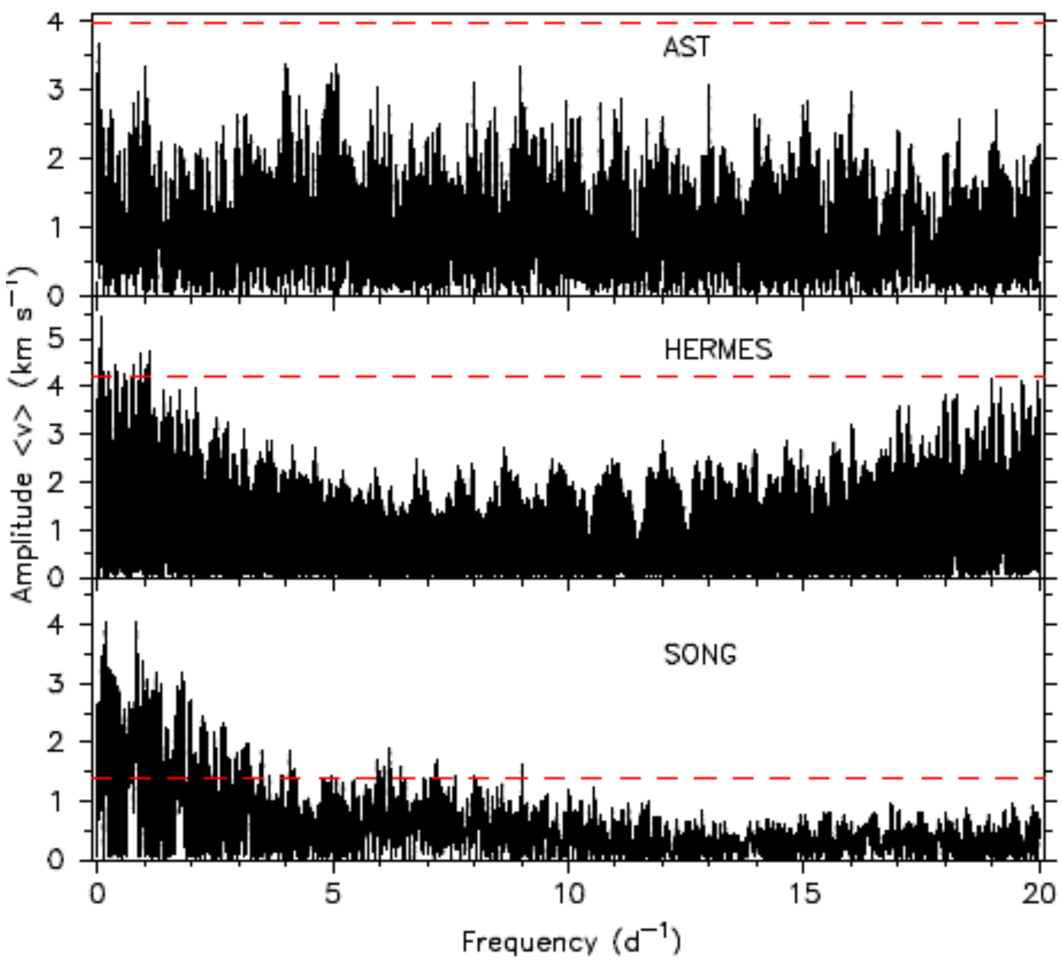



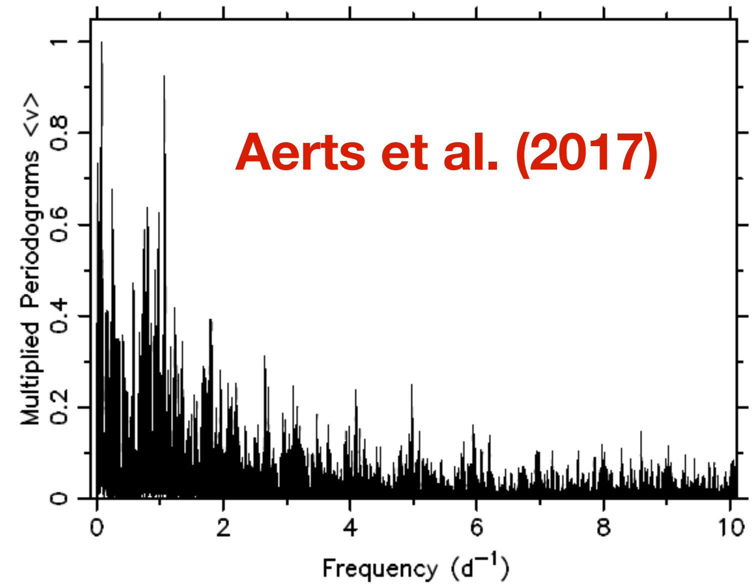

| | | |
|---|---|---|
| Hβ | 4861.325 | black |
| Si III | 4567.841 | purple |
| He I | 4922.931 | cyan |
| He I | 5875.599 | grey |
| He I | 5015.678 | pink |
| He I | 4713.139 | dark blue |
| He II | 5410.53 | yellow |
| He II | 4541.591 | green |
| C IV | 5811.97 | orange |

**spectroscopy (1800d)**

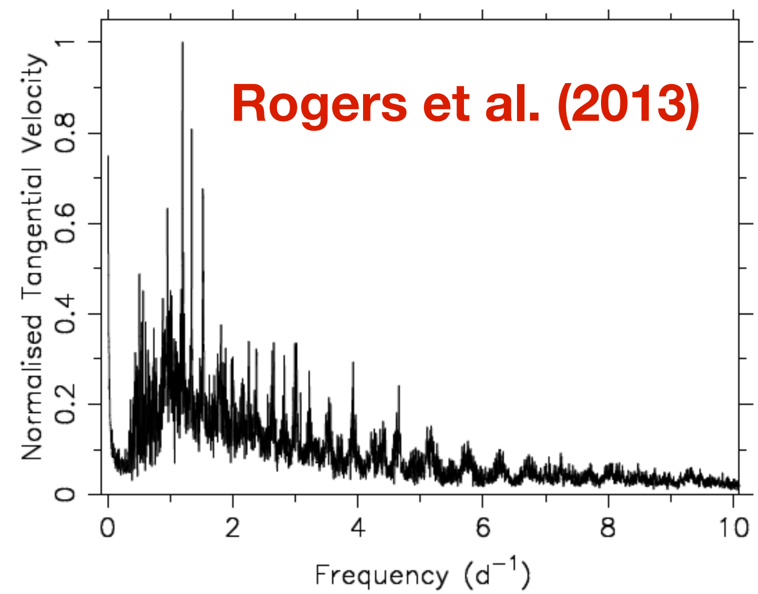
**Aerts et al. (2017)**

# Gravity waves in O9Iab supergiant HD 188209



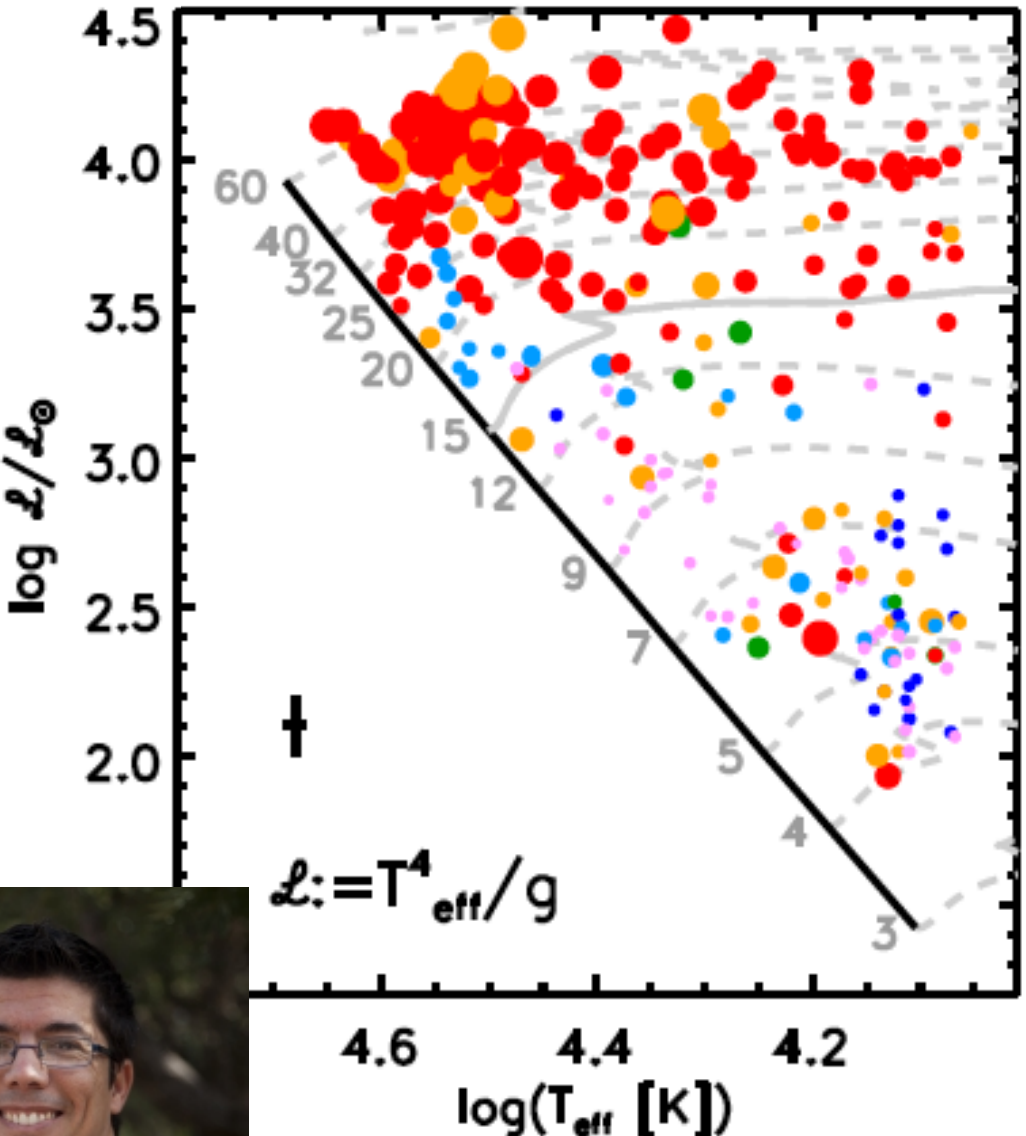

Aerts et al. (2017)




Rogers et al. (2013)

**Note that RT macroturbulence = 65 km/s: some 10x amplitude <v> as expected for multiple waves….**

# Line-profile variability in upper HRD



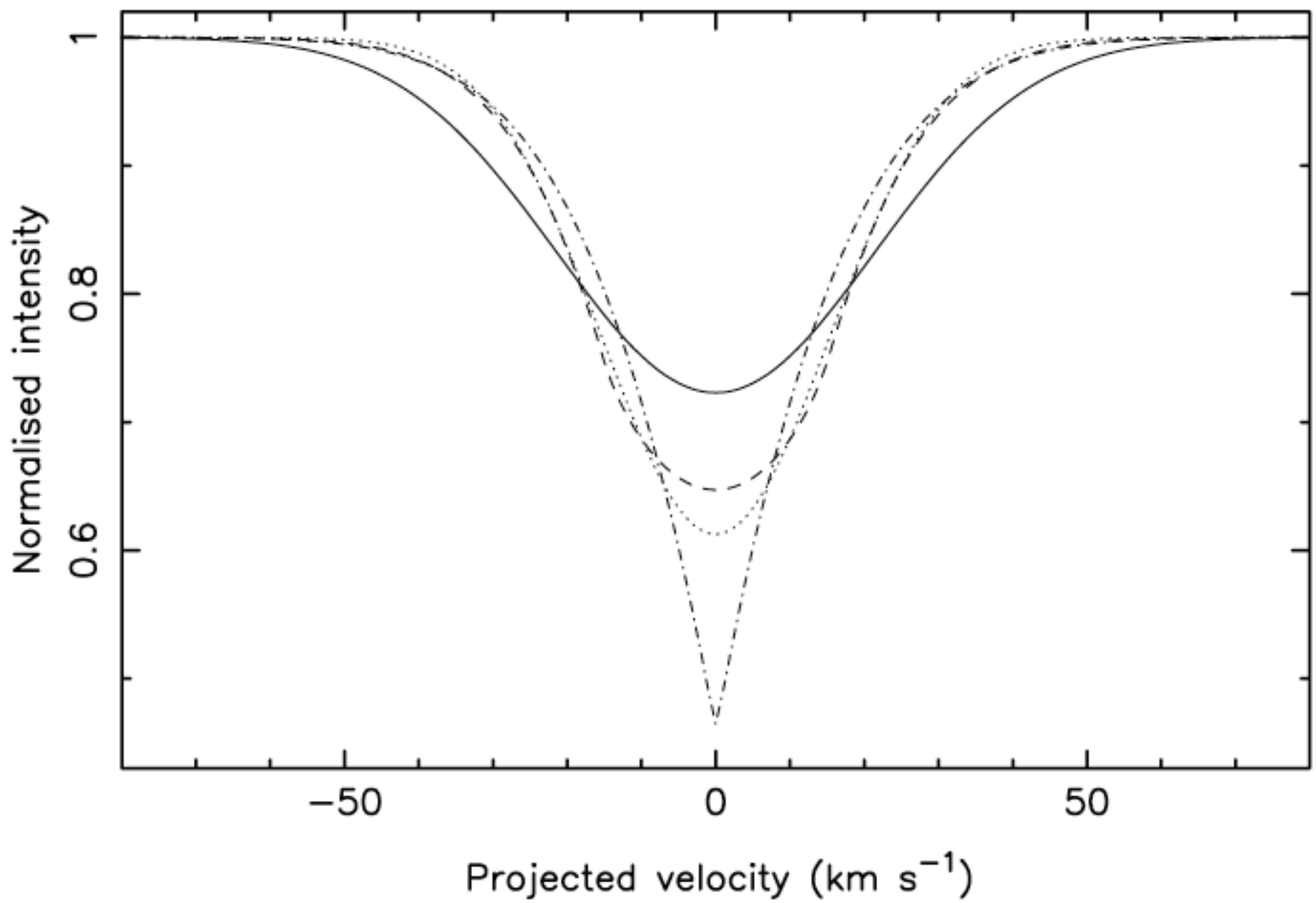

Heroic efforts by Símon Díaz et al. (2016): years of spectroscopic monitoring of 100s of OB stars shows large diversity

WARNING for misconception of macroturbulence: multiple gravity waves are time-dependent & tangential

↓

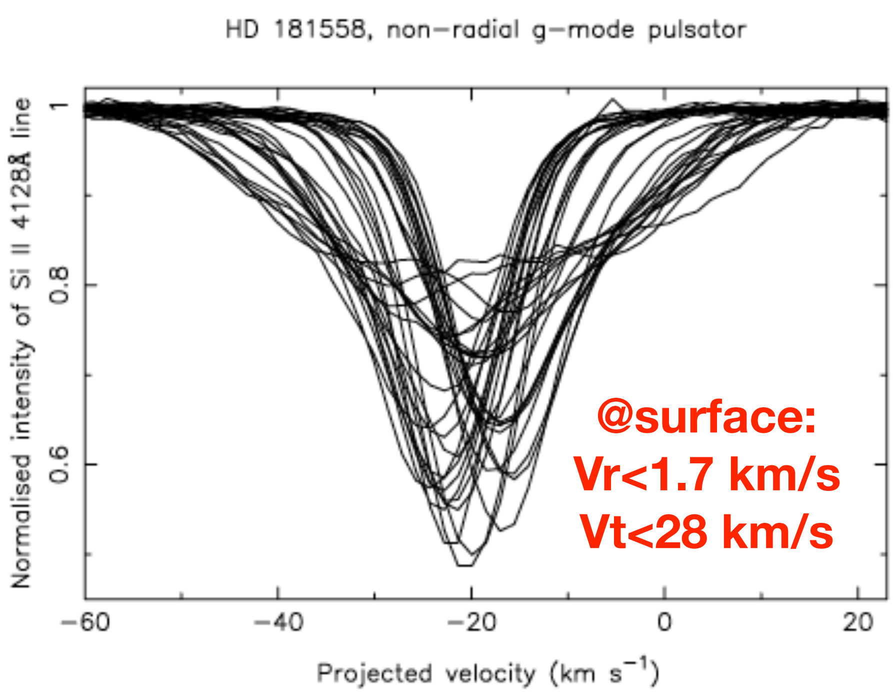
don't fit with constant isotropic or RT Gaussian!

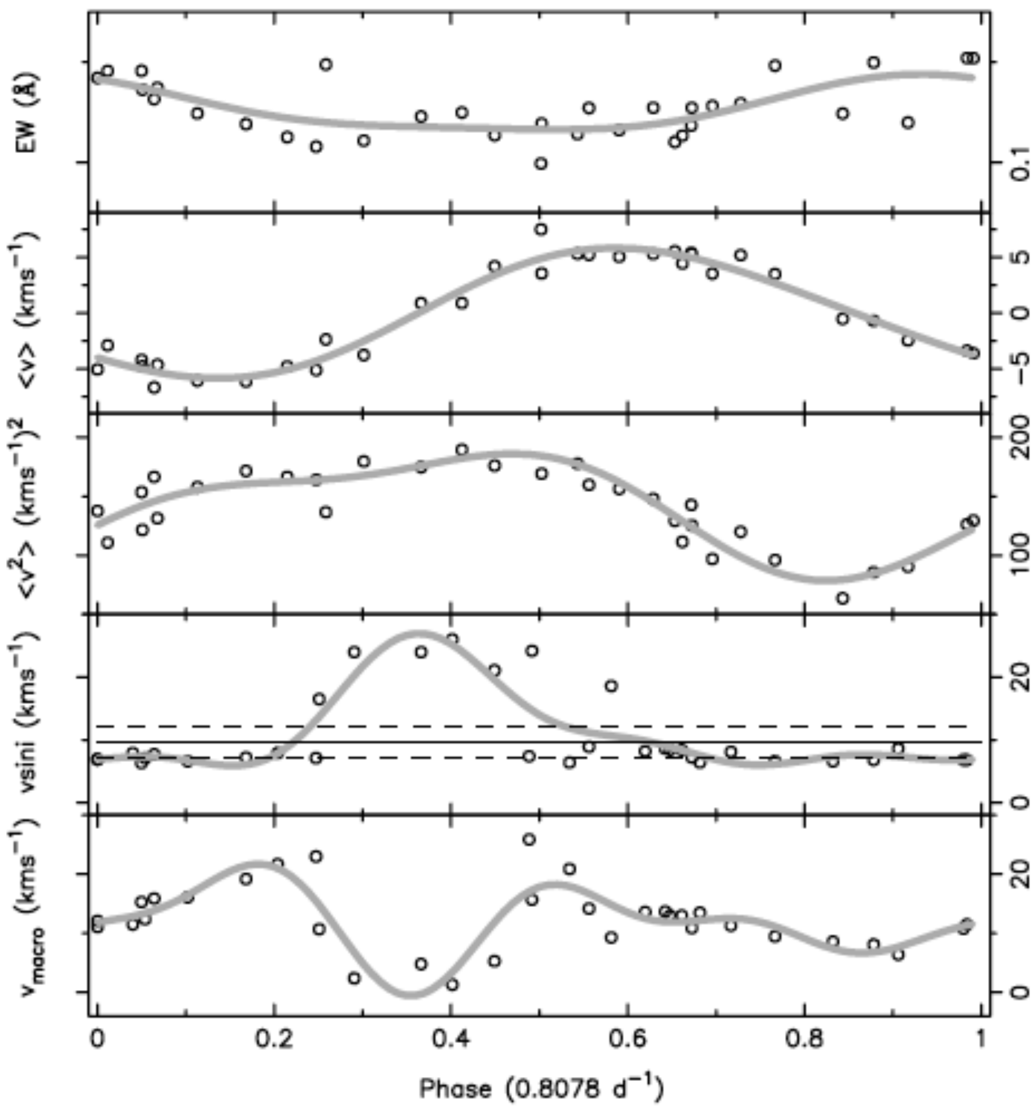
# Line profile broadening is not Gaussian…




**Aerts et al. (2014): warning about isotropic, radial, tangential, RT spectral-line broadening in addition to rotational broadening & limb darkening, all constant in time ≠ reality**

# Line profiles due to waves are not Gaussian



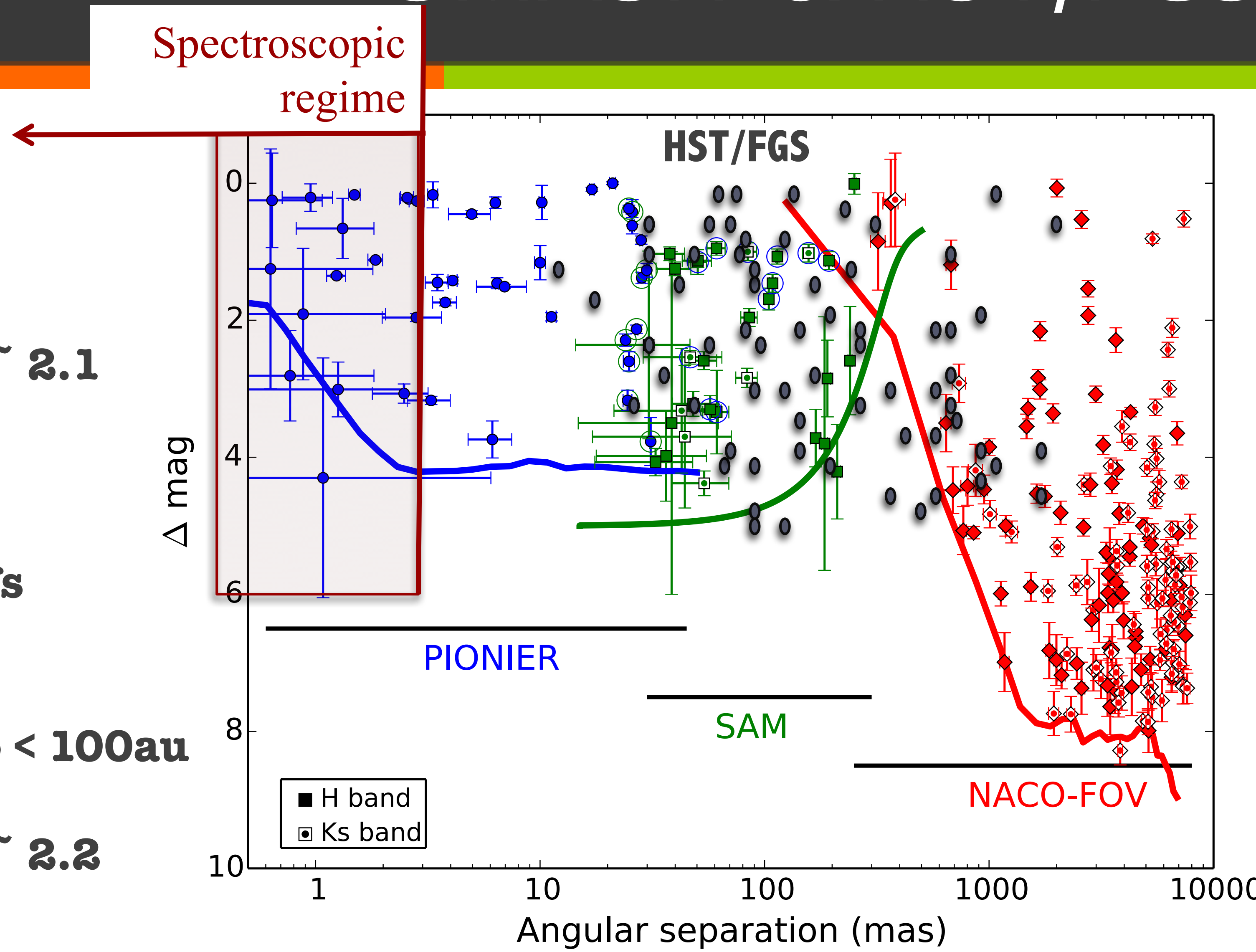




**Fitted with vsini & RT vmacro instead of dipole pulsation mode: vmacro up to 25 km/s**

**Aerts et al. (2014)**

**When multiperiodic: collective effect of all waves by single vmacro not appropriate!**

# SMASH & HST/FGS




F_mult > 0.80

< N_companion> ~ 2.1

For dwarfs

F_mult = 1.00

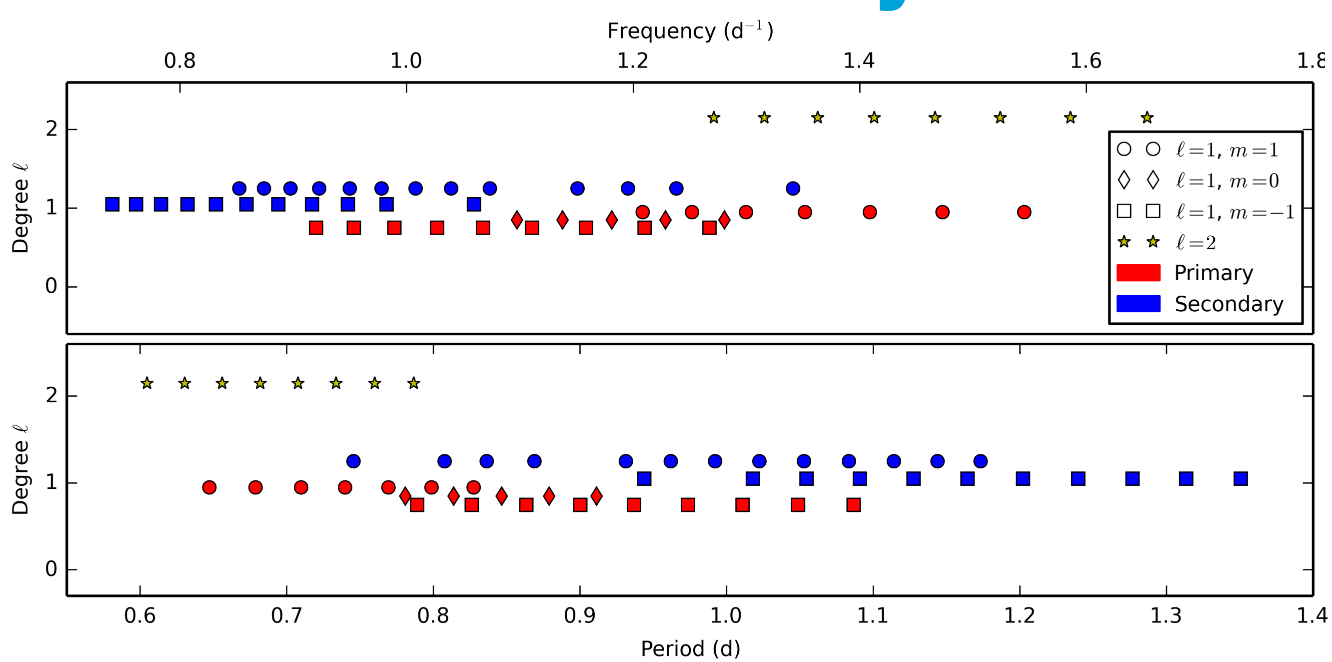
@ ρ < 100au

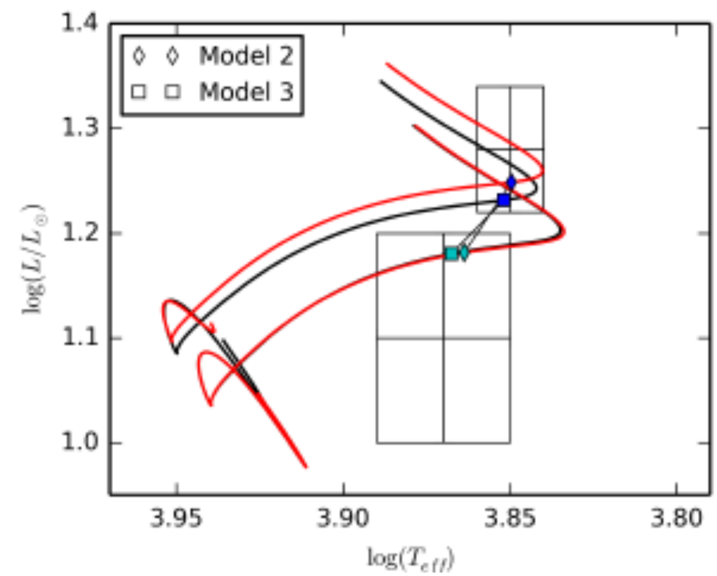
< N_companion> ~ 2.2

**Slide courtesy of Hugues Sana (Dec., 2016)**

# Let the data guide the theory: high-precision time-domain astrophysics of binaries

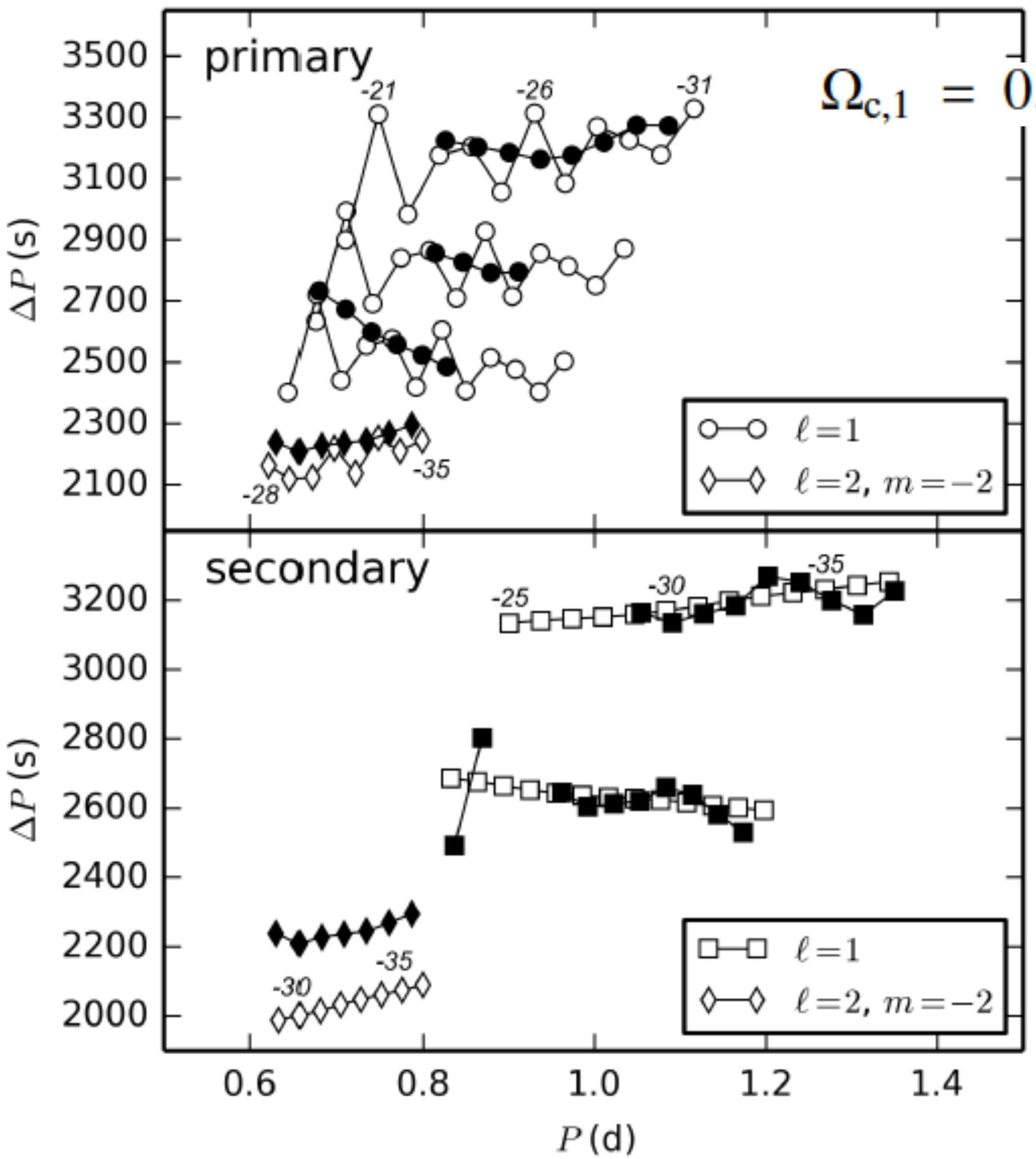
## How about binarity and asteroseismology?




Schmid & Aerts (2016)

# Asteroseismology of free modes in EBs




$\Omega_{c,1} = 0.13963\ d^{-1}$ and $\Omega_{c,2} = 0.09034\ d^{-1}$

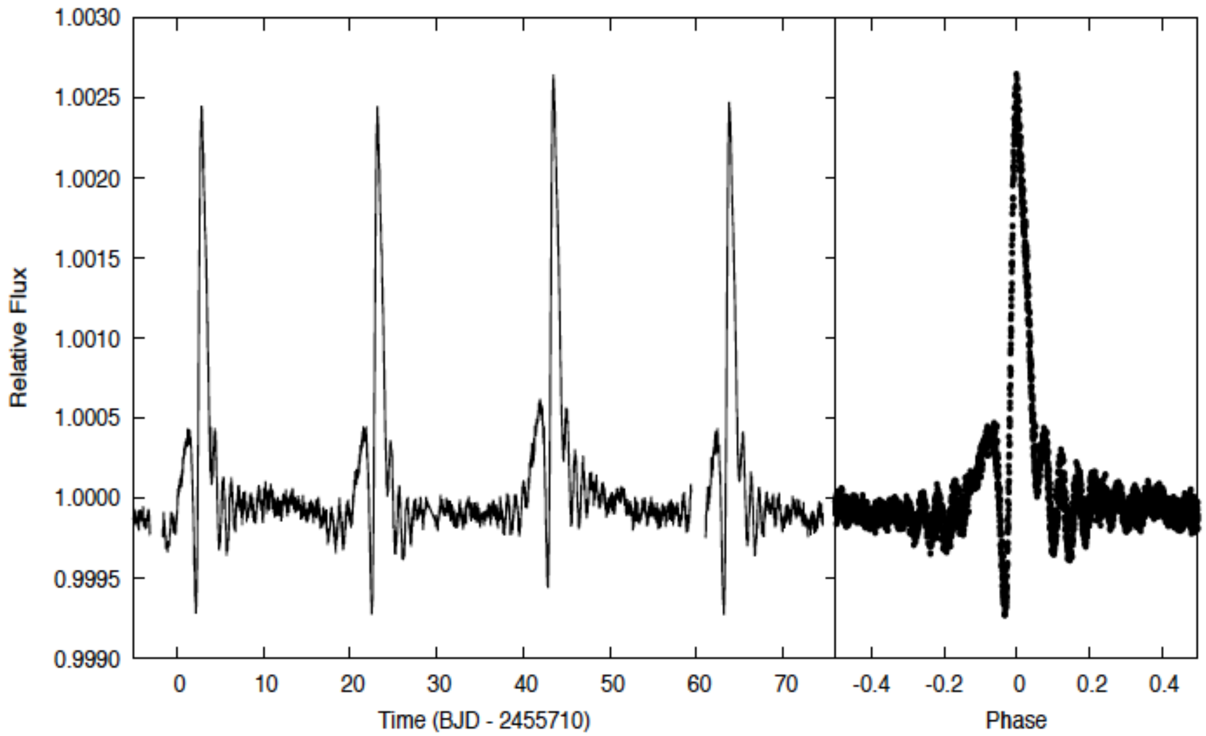
$\Omega_{e,1}/\Omega_{c,1} = 0.94 \pm 0.2$

$\Omega_{e,2}/\Omega_{c,2} = 1.35$

| | |
|---|---|
| $f_{orb}$ ($d^{-1}$) | $0.06520 \pm 0.00004$ |
| $M_1$ ($M_\odot$) | 1.82 |
| $M_2$ ($M_\odot$) | 1.76 |
| $Z$ | 0.0125 |
| $f_{ov,1}$ or $\alpha_{ov,1}$ | 0.008 |
| $f_{ov,2}$ or $\alpha_{ov,2}$ | 0.005 |
| $\log(D_{mix,1})$ | 0.25 |
| $\log(D_{mix,2})$ | 1.5 |

Schmid & Aerts (2016)

# Tidal asteroseismology: only starting now




| Parameter | Number of pulsations 0 | 7 |
|---|---|---|
| **Fitted** | | |
| Orbital inclination (degrees) | 60.2(1) | 62(1) |
| Argument of periastron (rad) | 2.14(2) | 2.15(4) |
| Eccentricity | 0.633(3) | 0.659(6) |
| Primary gravity brightening | 0.95(3) | 0.95(3) |
| Secondary gravity brightening | 0.29(2) | 0.52(6) |
| Primary polar radius ($R_\odot$) | 1.9(1) | 1.98(4) |
| Secondary polar radius ($R_\odot$) | 1.1(1) | 1.20(4) |
| Mass ratio | 0.73(1) | 0.739(9) |
| Phase shift | -0.110(3) | -0.109(5) |
| Gamma velocity (km $s^{-1}$) | -14(2) | -15(1) |
| Semi-major axis ($R_\odot$) | 43(1) | 45.7(7) |
| **Calculated** | | |
| Primary mass ( $M_\odot$) | 1.5(1) | 1.78(6) |
| Secondary mass ( $M_\odot$) | 1.1(1) | 1.32(4) |
| Primary fractional luminosity | 0.85(4) | 0.82(2) |
| Primary rotation rate | 7.1(3) | 7.1(2) |
| Secondary rotation rate | 4.0(1) | 4.0(1) |

**Hambleton et al. (2017):**
**7 tidally excited modes;**
**apsidal advance after**
**4 years requires 3rd body**

**Numerous additional cases**
**from Kepler mission,**
**all intermediate-mass stars**

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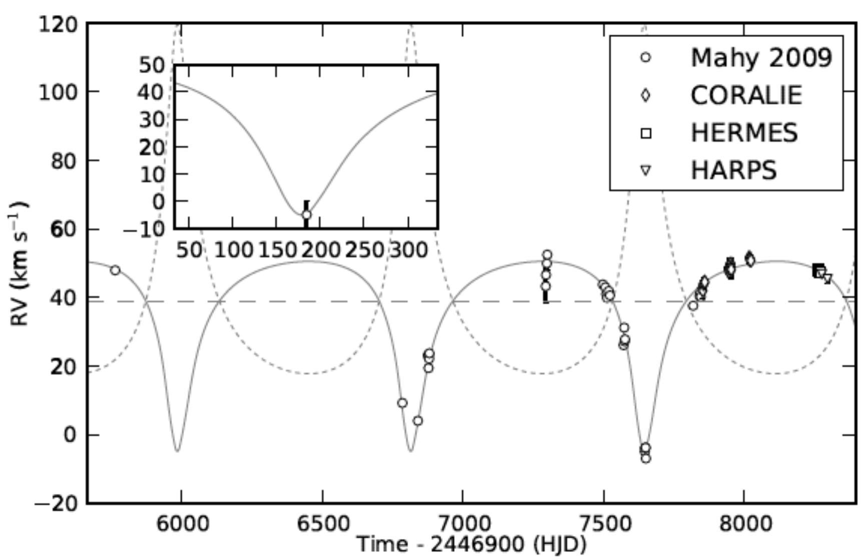
# Let the data guide the theory: high-precision time-domain astrophysics

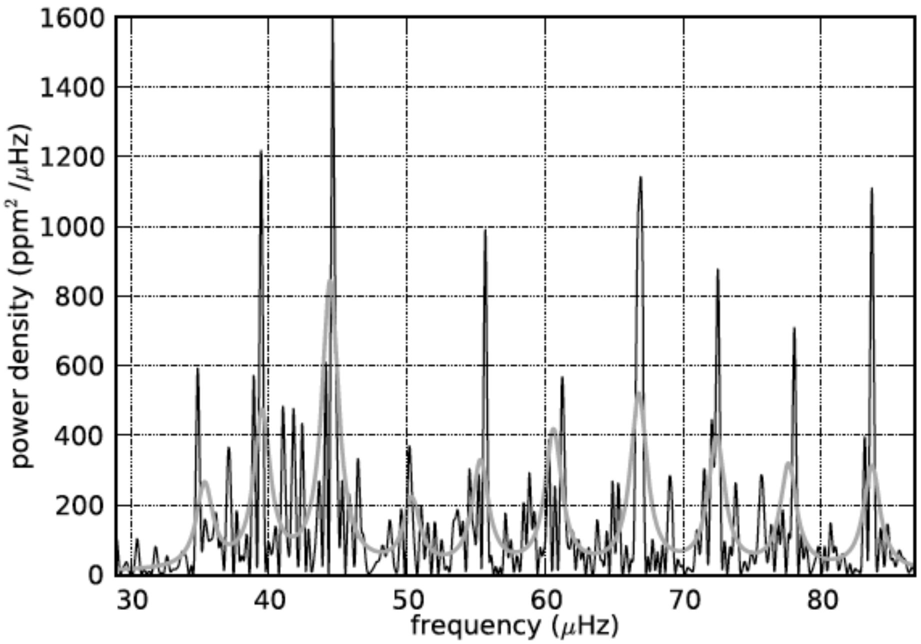
## How about massive binary asteroseismology?

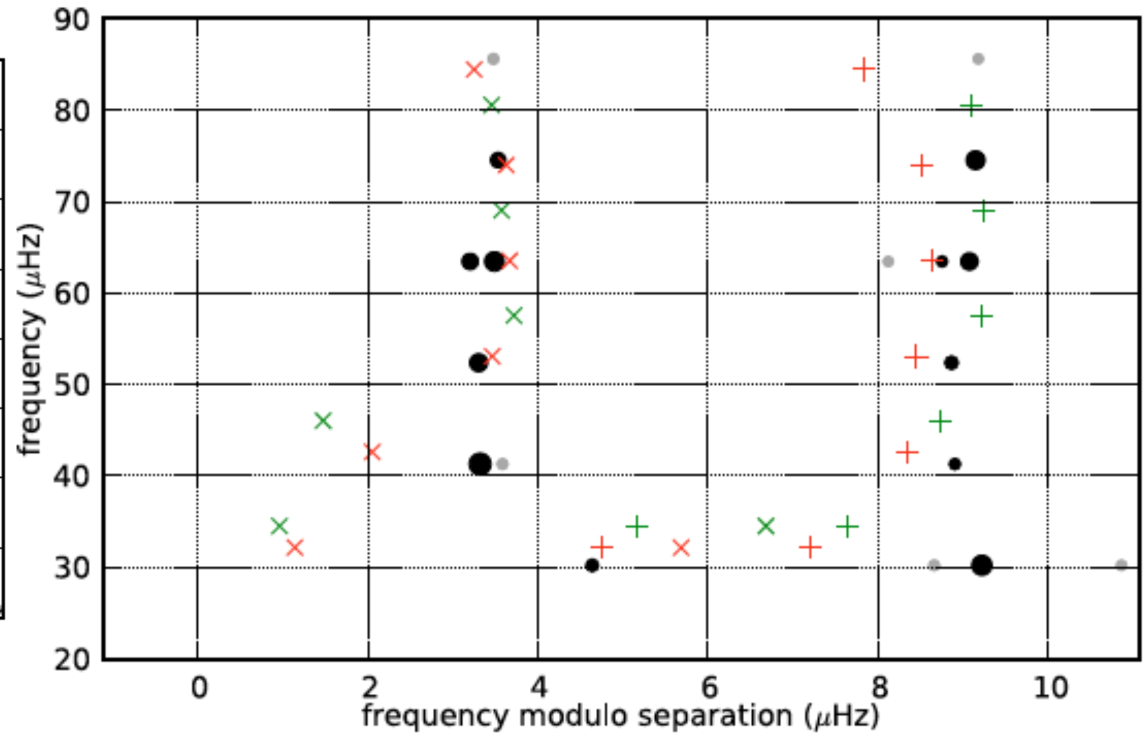



Degroote et al. (2010)

| Parameter | Value | Uncertainty |
|---|---|---|
| From spectroscopy | | |
| $P$ (d) | 829 | 4 |
| $K_1$ (km s$^{-1}$) | 27.7 | 0.4 |
| $e$ | 0.59 | 0.02 |
| $\Omega$ (°) | 172.1 | 1.5 |
| $\gamma$ (km s$^{-1}$) | 39.0 | 0.3 |
| $T_0$ (HJD) | 2 454 538 | 5 |
| $T_{\rm eff,1}$ (K) | 36 000 | 1000 |
| $T_{\rm eff,2}$ (K) | 33 000 | 1500 |
| $\log_{10} g_1$ (cgs) | 3.7 | 0.1 |
| $\log_{10} g_2$ (cgs) | 4.0 | 0.15 |
| $v_{\rm eq,1} \sin i$ (km s$^{-1}$) | 30 | 10 |
| $L_1/L_{\rm tot}$ | 0.75 | – |

# CoRoT pulsating O8V primary HD 46149




| $M/M_\odot$ | $\log T_{\rm eff}$ | $\log g$ | $R/R_\odot$ | $\log L/L_\odot$ | Age (Myr) |
|---|---|---|---|---|---|
| 30 | 4.512 | 3.575 | 14.80 | 5.341 | 5.0 |
| 34 | 4.539 | 3.643 | 14.56 | 5.436 | 4.2 |

**Degroote et al. (2010): detection of solar-like oscillations need better spectroscopic orbital coverage**

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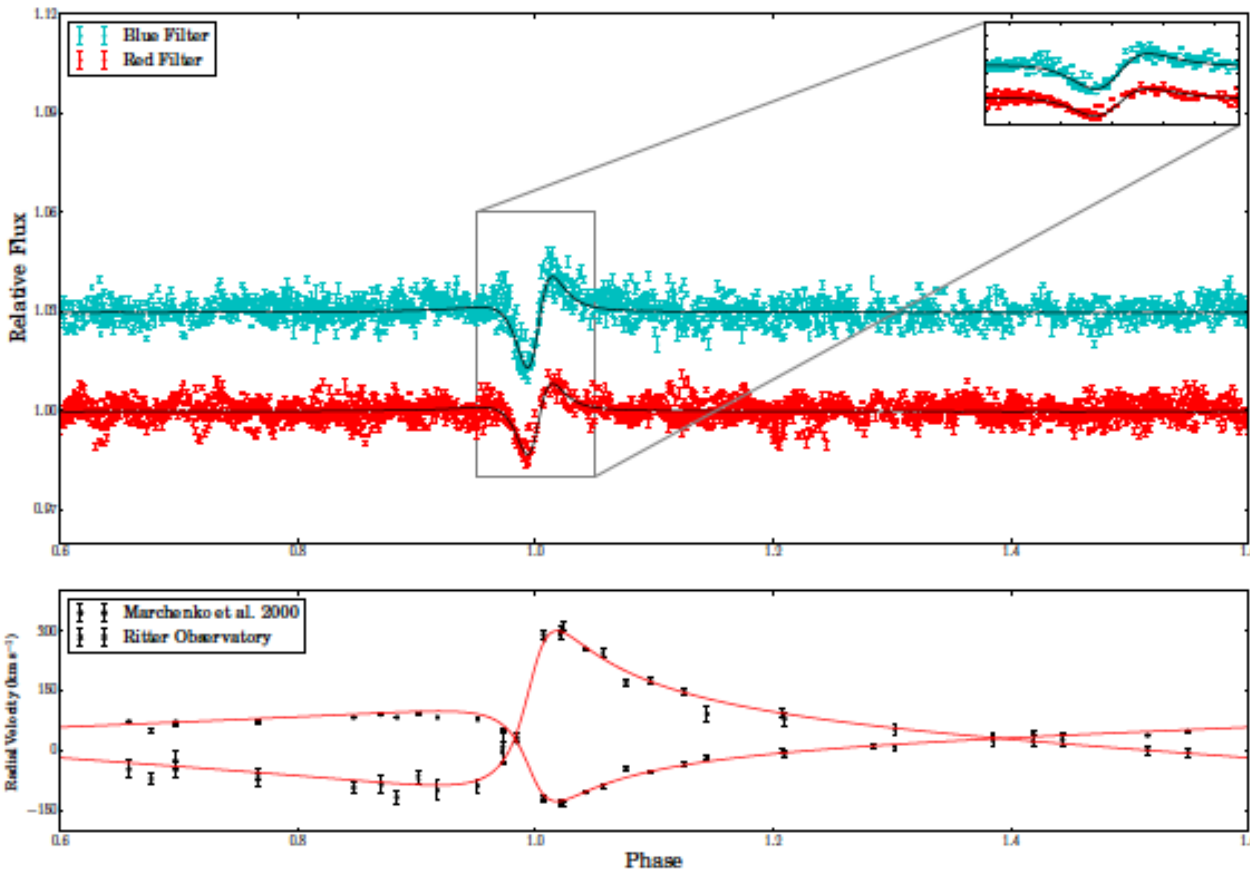
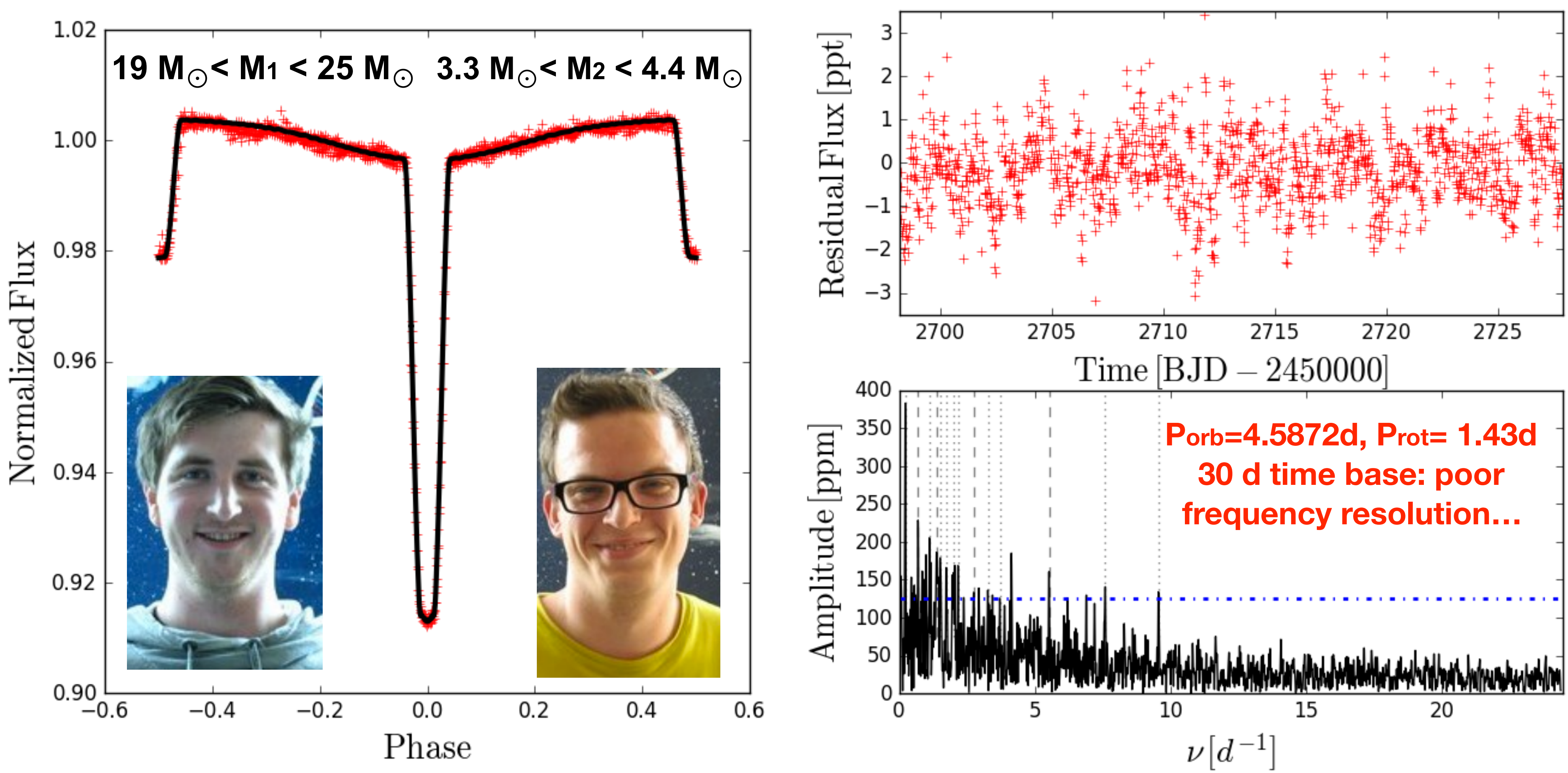
# BRITE: pulsating O star in iota Ori




| Parameter | Primary | Secondary |
|---|---|---|
| $P_{\rm orb}(d)$ | 29.13376 (fixed) | |
| $T_0$(HJD – 2450000) | 1121.658 (fixed) | |
| $i$ (°) | $62.86^{+0.17}_{-0.14}$ | |
| $\omega$ (°) | $122.15^{+0.11}_{-0.11}$ | |
| $e$ | $0.7452^{+0.0010}_{-0.0014}$ | |
| $q$ | $0.5798^{+0.0077}_{-0.0084}$ | |
| $a$ ($R_\odot$) | $132.32^{+1.01}_{-0.96}$ | |
| $v_\gamma$ ($kms^{-1}$) | $32.02^{+0.30}_{-0.32}$ | |
| $T_{\rm eff}$ ($K$) | 31000 (fixed) | $18319^{+531}_{-758}$ |
| $R$ ($R_\odot$) | $9.10^{+0.12}_{-0.10} R_\odot$ | $4.94^{+0.16}_{-0.23}$ |
| $f$ | $14.86^{0.34}_{-0.23}$ | $28.14^{+2.78}_{-2.017}$ |
| $M$ ($M_\odot$) | $23.18^{+0.57}_{-0.53} M_\odot$ | $13.44^{+0.30}_{-0.30}$ |

**Pablo et al. (2017): 7 significant frequencies, some tidally excited quadrupole modes**

# K2: pulsating O+B EB HD165246




**Johnston et al. (2017): 25 frequencies, 10 are multiples of orbital frequency; follow-up in spectroscopy to unravel cause**

# Let the data guide the theory: high-precision time-domain astrophysics

Great opportunities coming up:
how high can we go in mass for
high-precision binary & seismic modelling
of core overshoot, mixing, interior rotation?

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# Near future: TESS-CVZ + Gaia + AS4

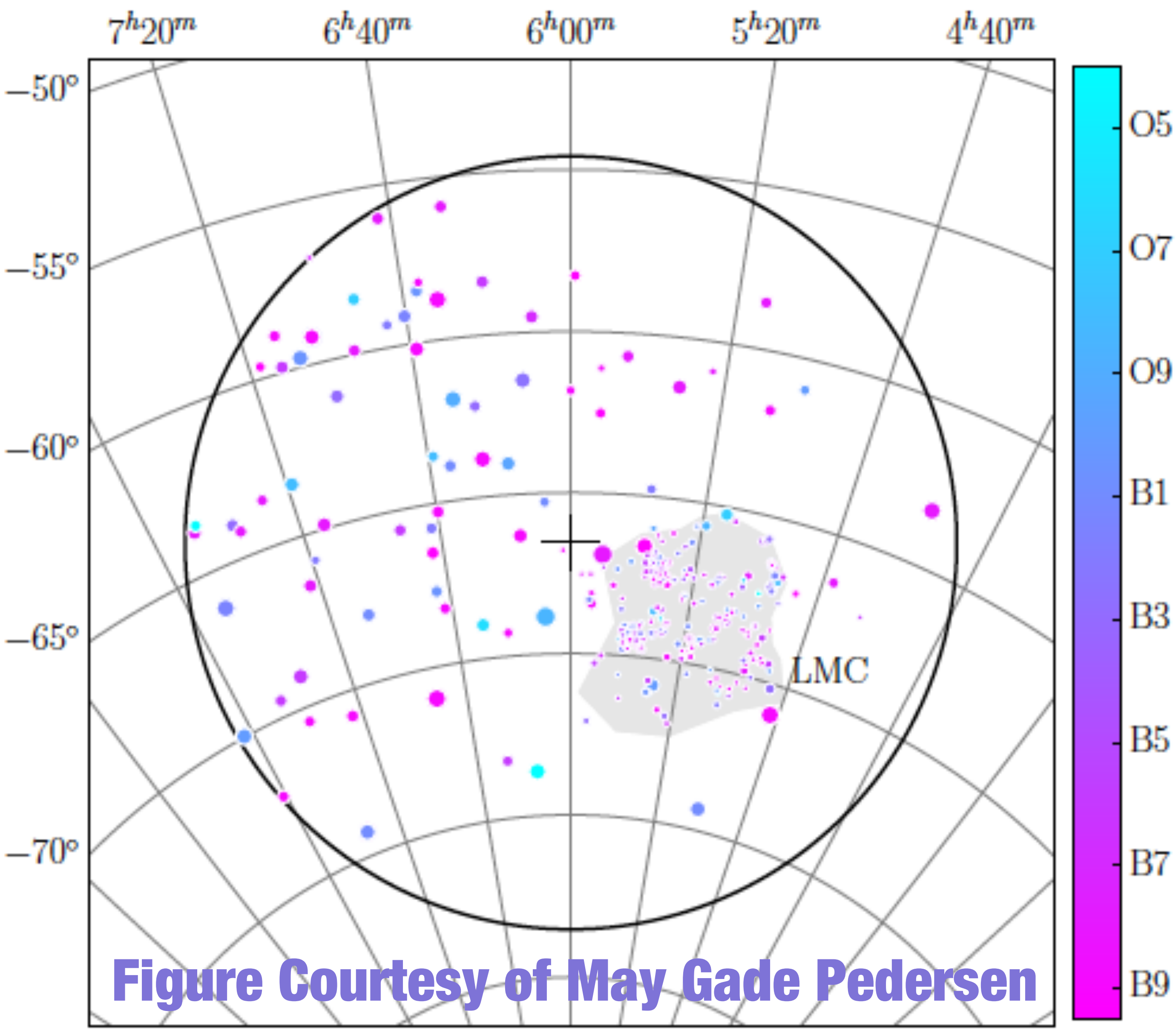


Figure Courtesy of May Gade Pedersen

341 OB stars (V = 4 - 13) in TESS-CVZ, to be monitored for 351 d, including LMC stars (≈105@V<10) + Gaia + AS4 spectroscopy

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# Farther future potential: PLATO mission

## Beyond 2025:
## PLATO main mission & PLATO-CS with targets of choice
## https://fys.kuleuven.be/ster/Projects/plato-cs/