Pulsating stars with the Transiting Exoplanet Survey Satellite (TESS)

Peter De Cat

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Chairs of TASC working groups

Victoria Antoci (Denmark), Thierry Appourchaux (France), Sarbani Basu (USA), Bill Chaplin (UK), Stephane Charpinet (France), Margarida Cunha (Portugal), Gerald Handler (Poland), Saskia Hekker (Germany), JJ Hermes (USA), Daniel Huber (USA), Katrien Kolenberg (Belgium), Victor Silva Aguirre (Denmark), Dennis Stello (Australia), Robert Szabo (Hungary)

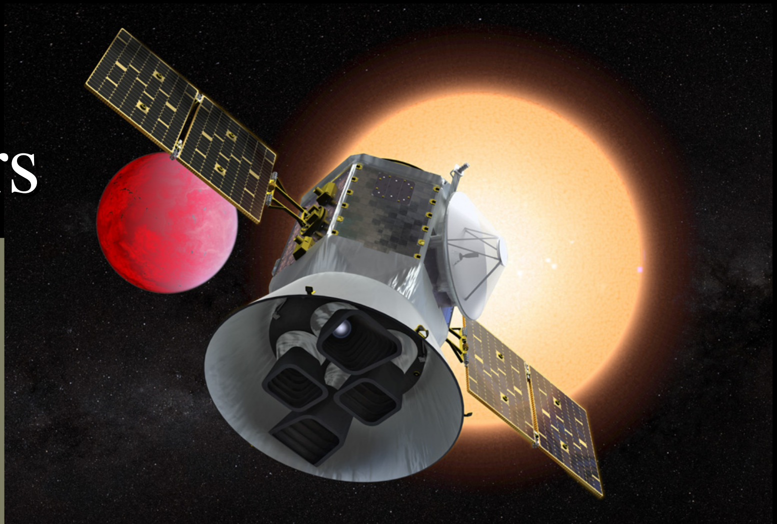
Pulsating stars with TESS

1. TESS as Space Mission
2. TESS and Pulsating stars
3. TESS and First Light Results

Mission objectives

- photometric all-sky survey to search for planets transiting nearby bright stars
  - 85% of sky
  - at least 200,000 main-sequence dwarf stars within 200 parsec
  - planets smaller than Neptune
  - Cousins I-band $I_C \approx 4 - 13$ mag to allow spectroscopic follow-up
    - planet masses
    - atmospheric compositions
- variable stars of all types and flavors

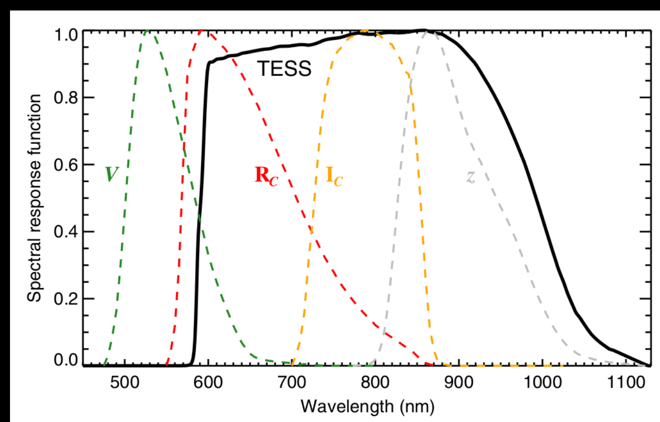
launch: April 18, 2018
orbit: 13.7 day elliptical high-Earth orbit
science operations: July 25, 2018
duration: 2-year prime mission

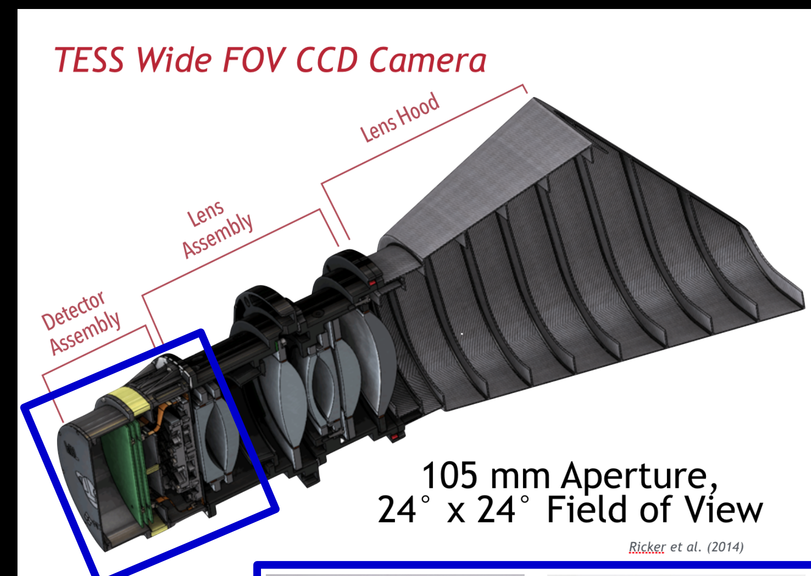


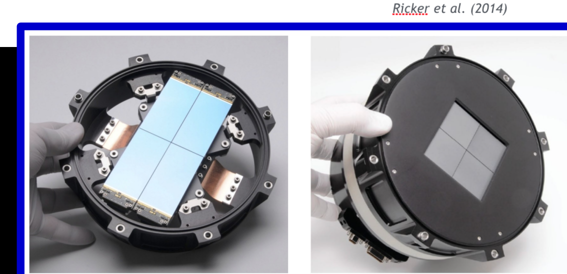
Credit: NASA

Telescope

- four identical wide-field refractive cameras
  - single camera field-of-view: 24° x 24°
  - combined field-of-view: 24° x 96° — sectors
  - entrance pupil diameter: 10.5 cm
  - focal ratio: f/1.4
  - wavelength range: 600-1000 nm



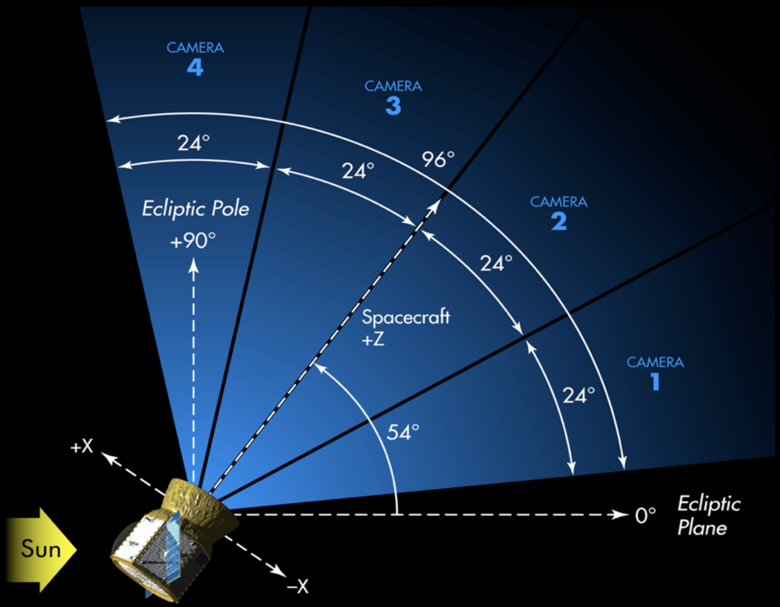


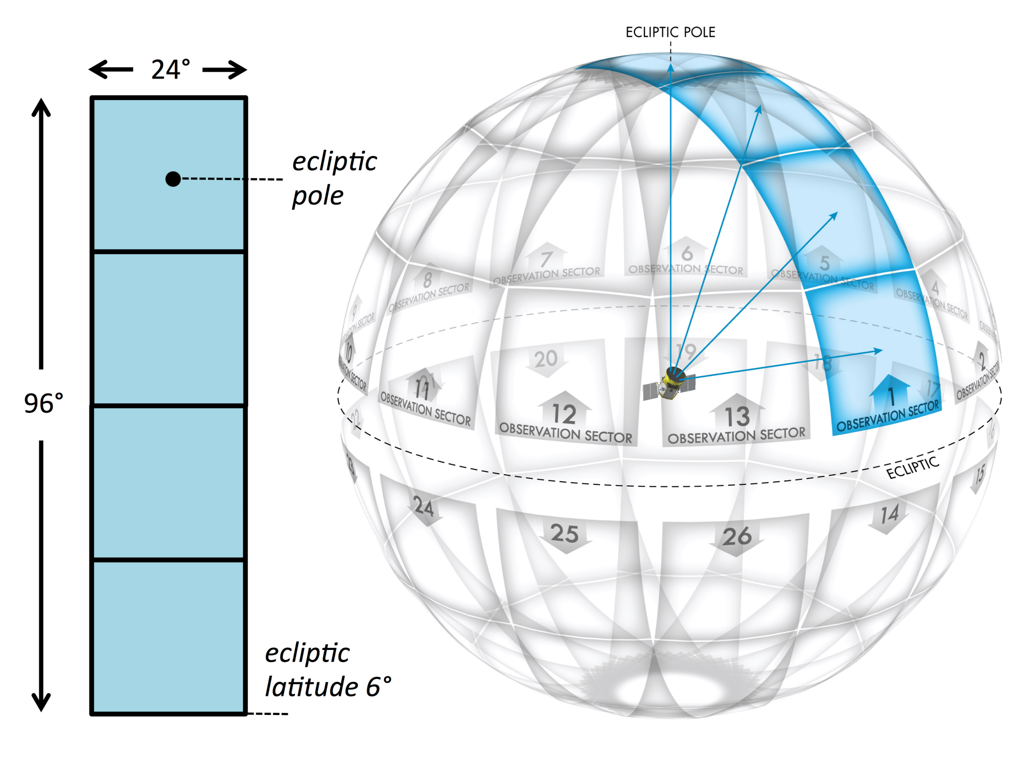


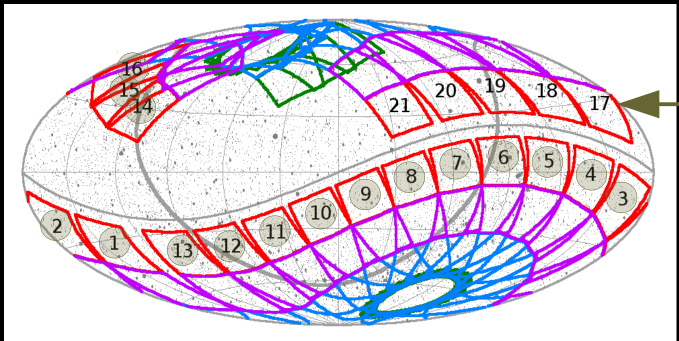
  - pixel size: 21 arcsec or 0.35 arcmin on sky — large pixels

Operations

- field-of-view
  - ➔ 26 observation sectors
    - year 1: 13 southern hemisphere
    - year 2: 13 northern hemisphere
  - ➔ 27 days each







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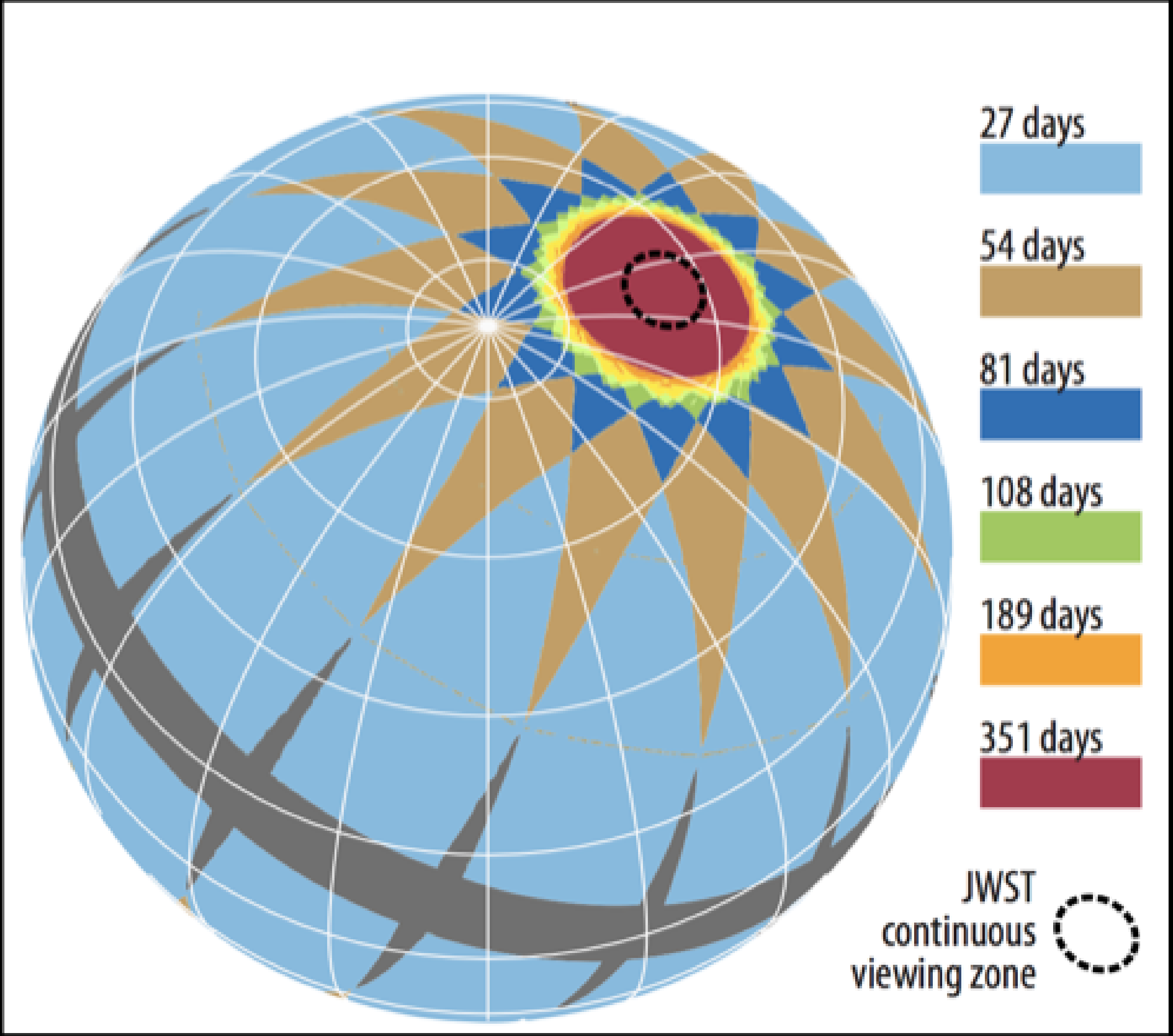
Operations

- field-of-view
- sky coverage
  - min. 27 days
  - max. 351 days
    - contains continuous viewing zone of James Webb Space Telescope (JWST)



Operations

- field-of-view
- sky coverage
- time sampling
  - ➔ continuous full frame integrations of 2 seconds
    - ➢ 30-minute cadence: summed in groups of 900 full frames, all stars
    - ➢ 2-minute cadence: summed in groups of 60 extracted, pre-selected targets

Pulsating stars with TESS

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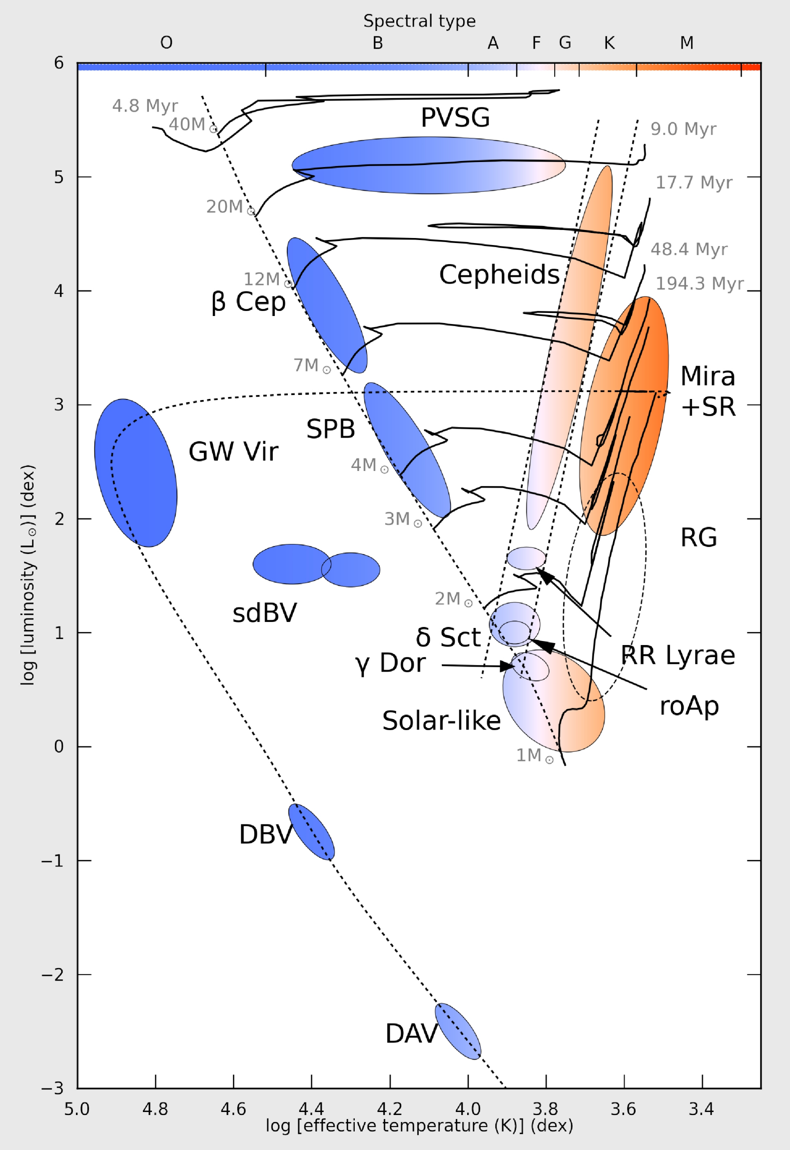
TESS Asteroseismic Science Consortium

- WG-1: Asteroseismology of TESS exoplanet hosts
  - Bill Chaplin & Daniel Huber
- WG-2: Oscillations in solar-type stars
  - Thierry Appourchaux & Bill Chaplin
- WG-3: Oscillating stars in clusters
  - Sarbani Basu & Saskia Hekker
- WG-4: Main Sequence AF "classical" pulsators
  - Victoria Antoci & Margarida Cunha
- WG-5: Main Sequence OB "classical" pulsators
  - Peter De Cat & Gerald Handler
- WG-6: RR Lyrae stars and Cepheids
  - Katrien Kolenberg & Róbert Szabó
- WG-7: Red Giant oscillations
  - Victor Silva Aguirre & Dennis Stello
- WG-8: Compact pulsators
  - Stephane Charpinet & JJ Hermes



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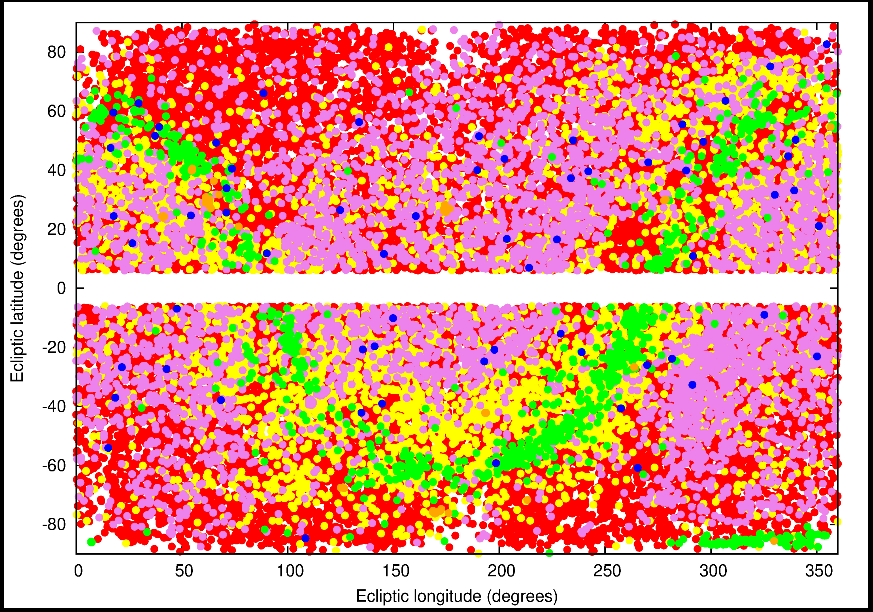

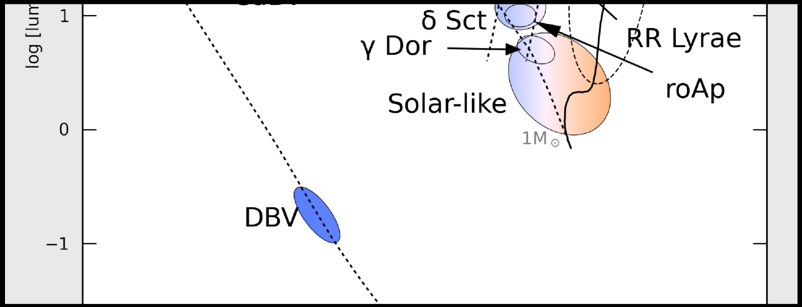

Selection of 2-min cadence targets
Stimulation of collaborations
Coördination of publications

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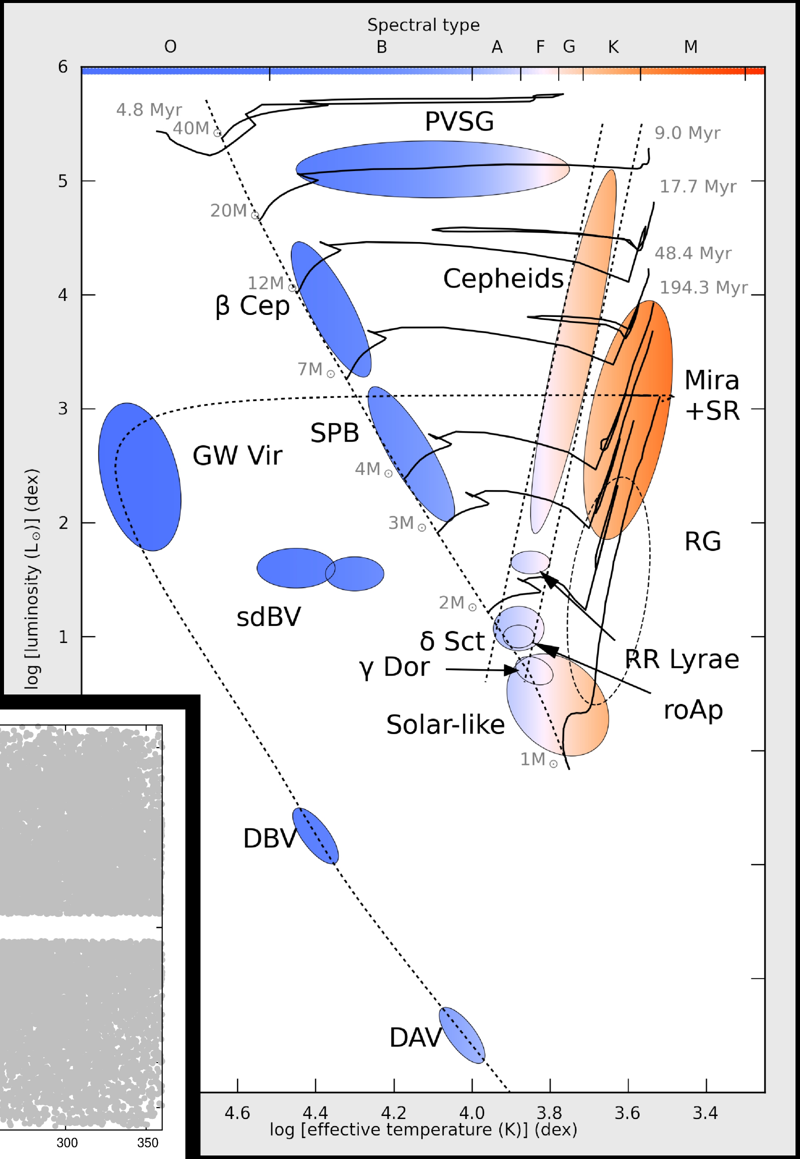
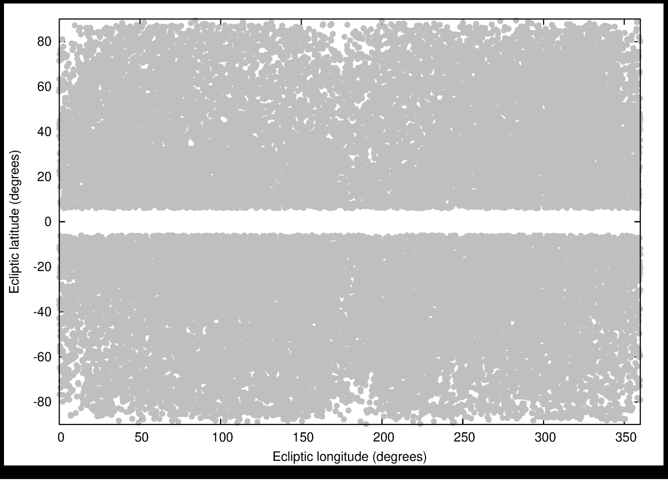
WG-1: Asteroseismology of TESS exoplanet hosts

(Chairs: Bill Chaplin & Daniel Huber)

- all types of pulsating stars
  - characterisation of host stars of exoplanets by using asteroseismic techniques





WG-1: Asteroseismology of TESS exoplanet hosts

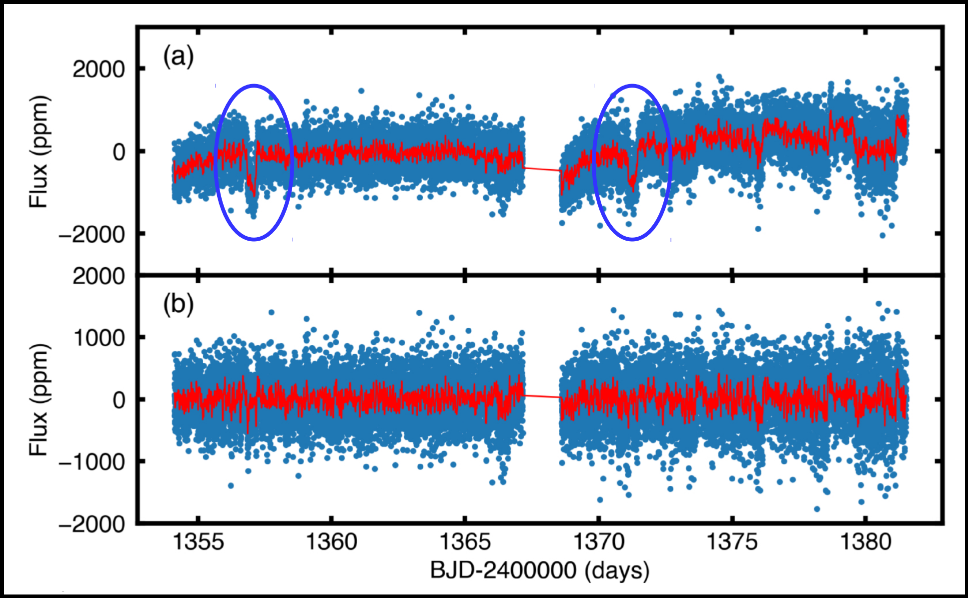
- Huber et al., 2019, AJ, 157, 245: "A Hot Saturn Orbiting an Oscillating Late Subgiant Discovered by TESS"
- Campante et al., 2019, ApJ, accepted: "Tess asteroseismology of the known red-giant host stars HD212771 and HD203949"
- Lund et al., 2019, ApJ, submitted: "Asteroseismology of the multi-planet system K2-93"
- Campante et al., 2019, proceedings of PHOST (Physics of Oscillating Stars): "Synergy between asteroseismology and exoplanet science: an outlook"

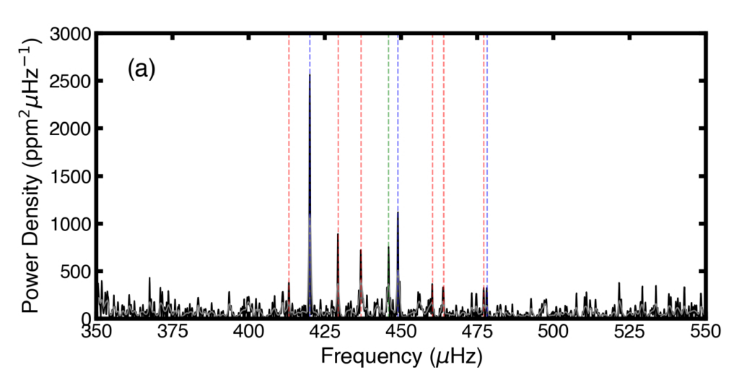
WG-1: *Asteroseismology of TESS exoplanet hosts*

(Huber et al., 2019, AJ, 157, 245)

- Detection of transiting planet orbiting oscillating host star
  - bright star (V = 8.2 mag)
  - clear signature of eclipse and mixed modes
  - oscillation amplitude consistent with *Kepler*
  - asteroseismic modelling host star
    - R_{star} = 2.936(61) R_{sun}
    - M_{star} = 1.198(81) M_{sun}
    - age = 5.04(126) Gyr

    } subgiant





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    - M_{star} = 1.198(81) M_{sun}
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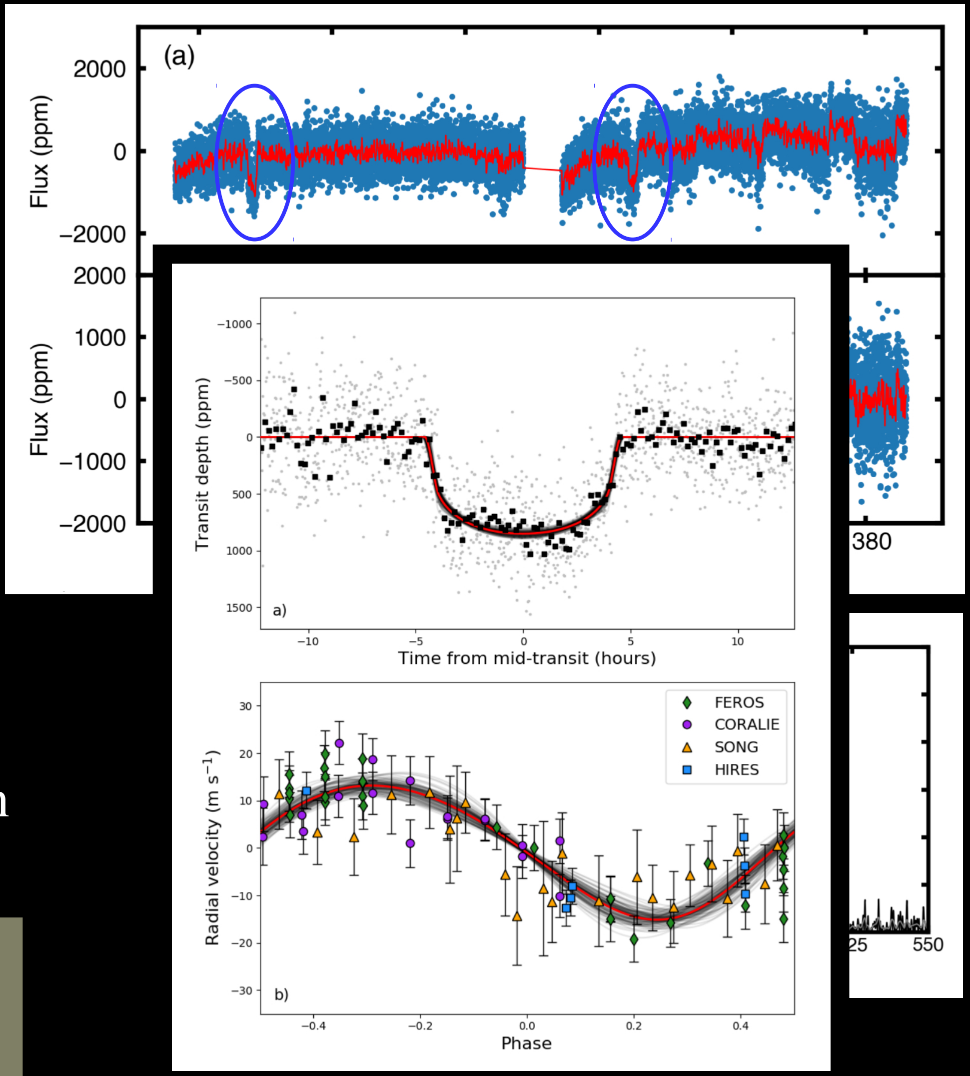
    } subgiant
  - planet characterisation
    - M_{planet} = 0.191(17) $M_{Jupiter}$
    - ρ_{planet} = 0.424(60) gcm^{-3}

    } hot Saturn



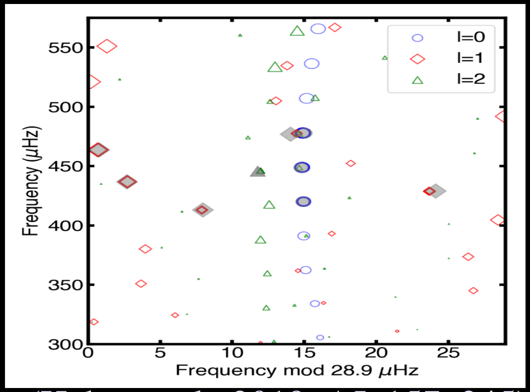
one of the most precisely characterized Saturn-sized planets to date

WG-2: Oscillations in solar-type stars

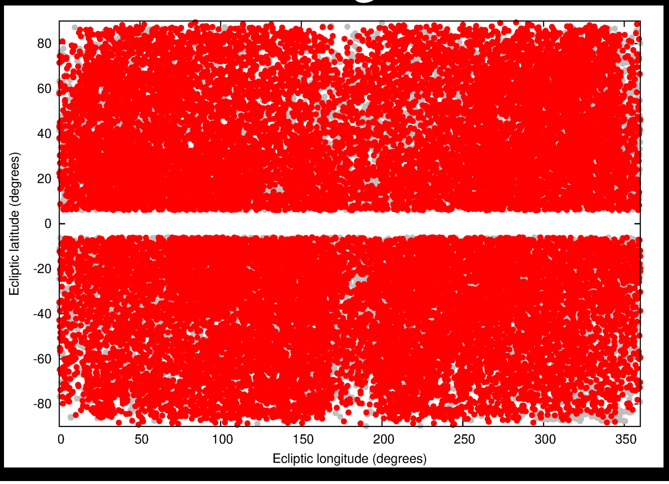
(Chairs: Thierry Appourchaux & Bill Chaplin)

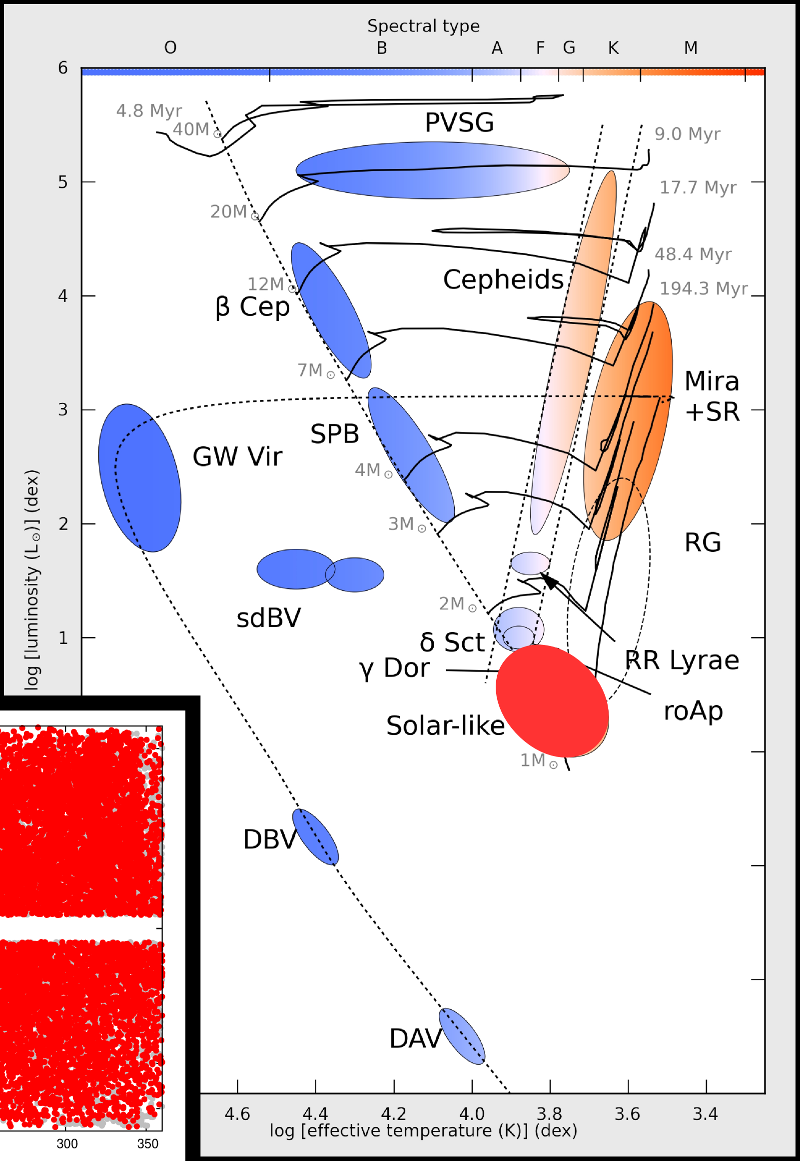
- solar-like oscillations (Solar-like)
  - order of minutes (p/mixed-modes)
  - short-lived (bell-shaped frequency distribution)
  - scaling relations
    - $\Delta\nu \sim \mathrm{sqrt}(M/R^3)$ (large frequency spacing)
    - $\nu_{max} \sim g/\mathrm{sqrt}(T_{eff})$ (frequency of maximum power)

      → mass and radius
  - fitting of individual frequencies in échelle diagram



(Huber et al., 2019, AJ, 157, 245)





WG-2: Oscillations in solar-type stars

- Bugnet et al., 2019, AA, 624, A79: "FliPer_Class: In search of solar-like pulsators among TESS targets"
- Schofield et al., 2019, ApJS, 241, 12: "The Asteroseismic Target List for Solar-like Oscillators Observed in 2 minute Cadence with the Transiting Exoplanet Survey Satellite"
- Chaplin et al., 2019, submitted: "Age dating of an early Milky Way merger via asteroseismology of the naked-eye star ν Indi"

TESS: progress from
* combination with ground-based follow-up data
* statistical studies
  - detection of solar-like oscillations
  - understanding of evolved systems with planets

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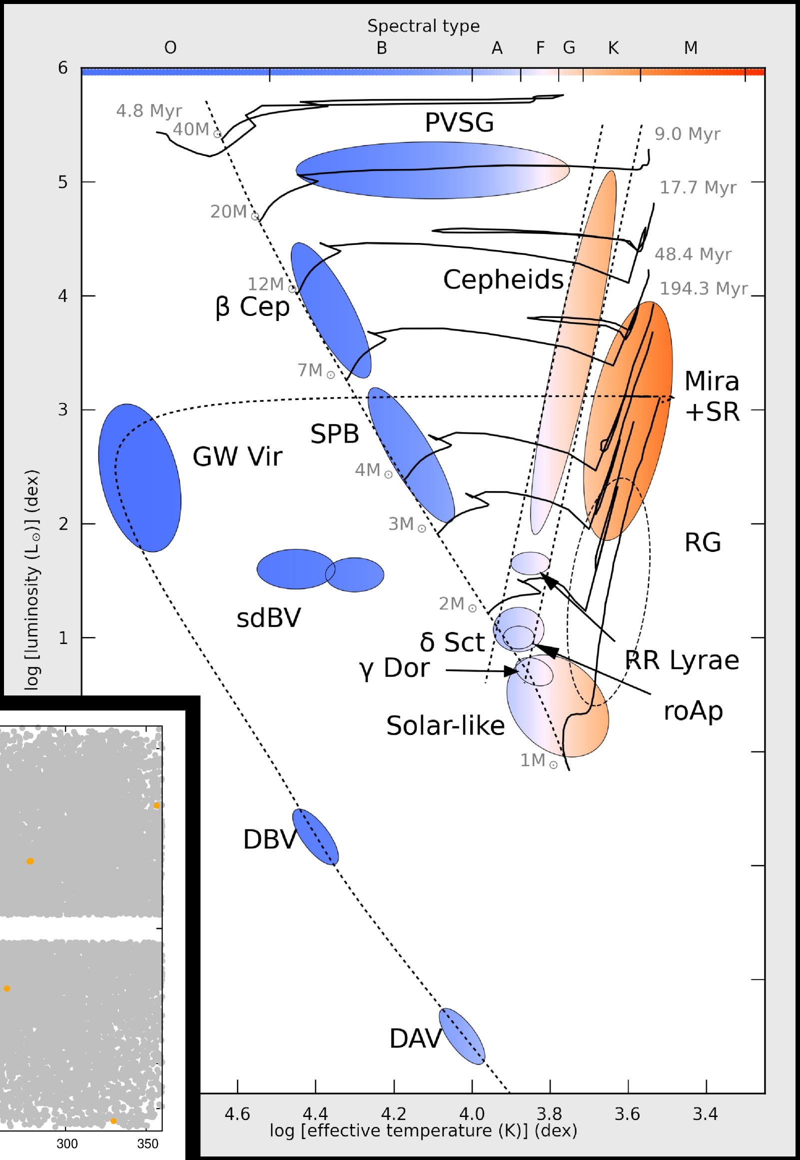
WG-3: *Oscillating stars in clusters*

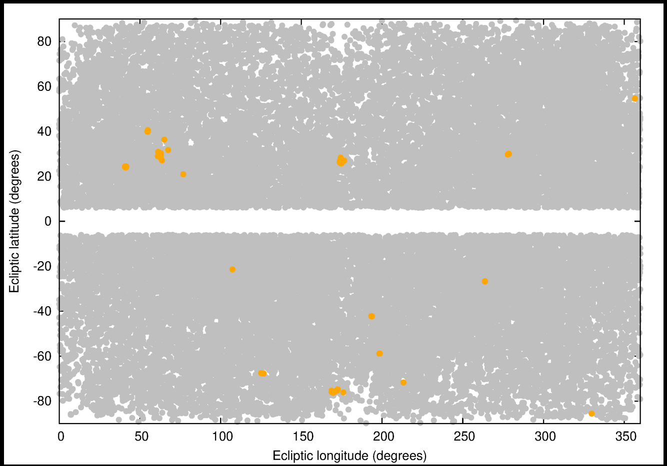
(Chairs: Sarbani Basu & Saskia Hekker)

➔ all types of pulsating stars

TESS not ideal for this type of research:

* large pixel size (contamination)
* main-sequence stars in clusters are faint
* lack of clusters in fields with long time-base

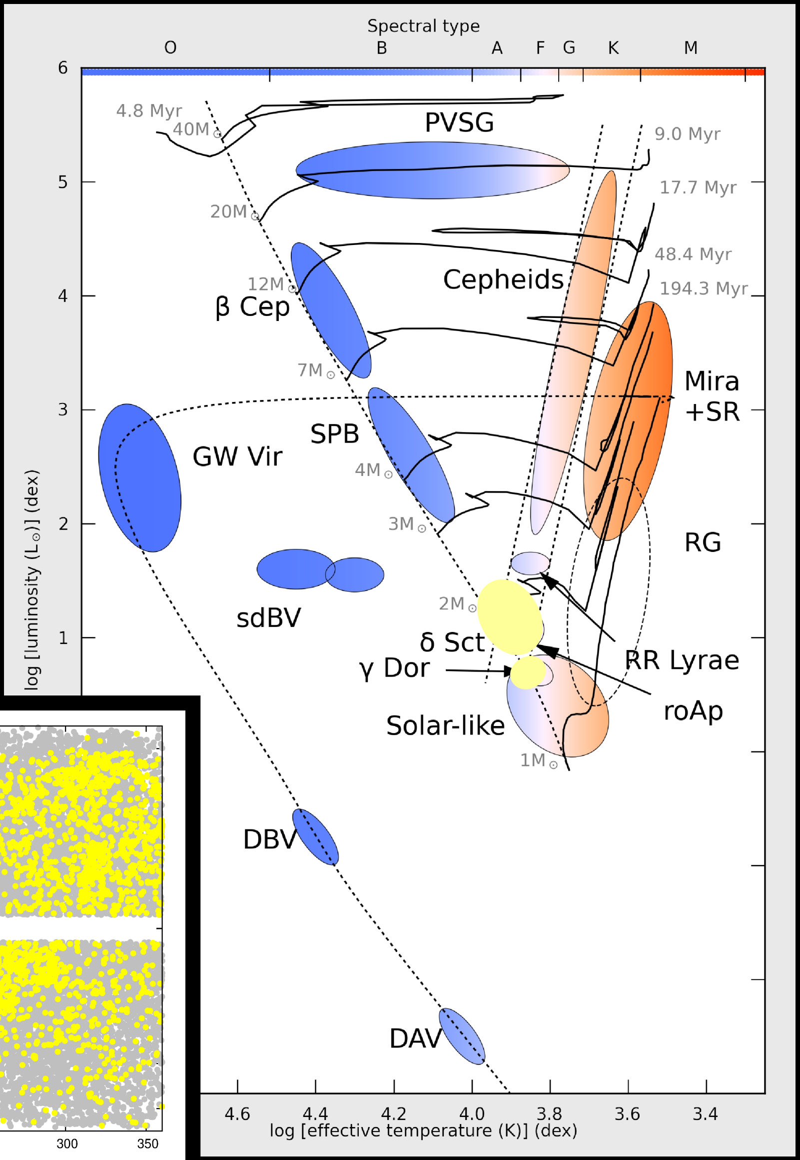


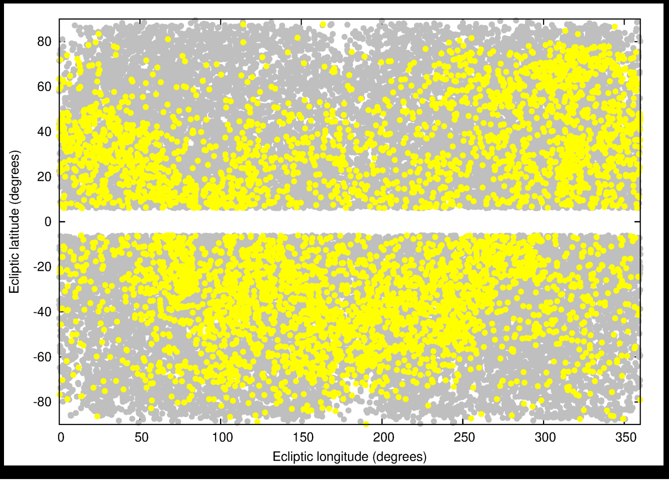


WG-4: Main sequence AF “classical” pulsators

(Chairs: Victoria Antoci & Margarida Cunha)

- δ Scuti stars (δSct)
  - 1 - 5 hours (p-modes)
- γ Doradus stars (γDor)
  - 0.3 – 3 days (g-modes)
- rapidly oscillating Ap stars (roAp)
  - 5 – 25 minutes (p-modes)
  - chemically peculiar
  - magnetic field
- magnetic A-type stars
- pre-main sequence





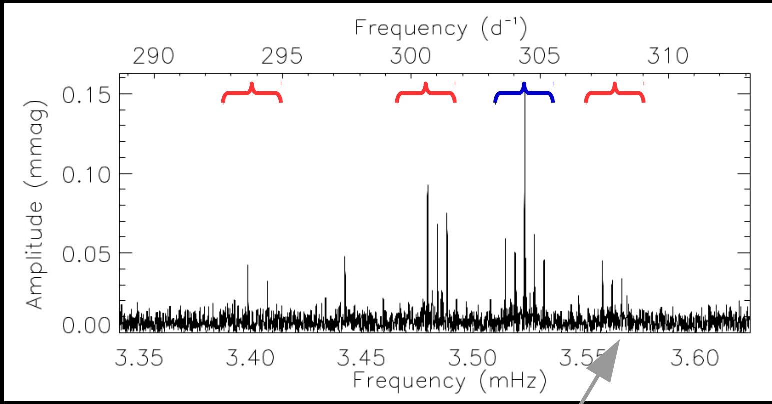
WG-4: Main sequence AF "classical" pulsators

- Cunha et al., 2019, MNRAS, 487, 3523: "Rotation and pulsation in Ap stars: first light results from TESS sectors 1 and 2"
- David-Uraz et al., 2019, MNRAS, 487, 304: "Magnetic OB[A] Stars with TESS: probing their Evolutionary and Rotational properties (MOBSTER) – I. First-light observations of known magnetic B and A stars"
- Balona, 2019, MNRAS, 487, 2117: "High frequencies in TESS A–F main-sequence stars"
- Sikora et al., 2019, MNRAS, 487, 4695: "MOBSTER – II. Identification of rotationally variable A stars observed with TESS in sectors 1–4"
- Holdsworth et al., 2019, MNRAS, 489, 4063: "HD42659: the only known roAp star in a spectroscopic binary observed with B photometry, TESS, and SALT"
- Antoci et al., 2019, MNRAS, accepted: "The first view of δ Scuti and γ Doradus stars with the TESS mission"
- Khalack, 2019, MNRAS, accepted: "Rotational and pulsational variability in the TESS light curve of HD27463"
- Bowman et al., 2019, ApJL, accepted: "Discovery of tidally-perturbed pulsations in the eclipsing binary U Gru: a pioneering system for tidal asteroseismology"
- Bedding et al., 2019, submitted: "Regular sequences of pulsation overtones in young intermediate-mass stars"

WG-4: Main sequence AF "classical" pulsators

- Rotation and pulsation in Ap stars: first light results from TESS sectors 1 and 2

(Cunha et al., 2019, MNRAS, 487, 3523)



  - analysis of 2-min cadence data of 83 stars
  - detection of
    - 5 new roAp stars (4 multiperiodic + 4 rotational mode splitting)
    - shortest pulsation period roAp star known to date (4.68 min; frequency 3.563 mHz)
    - additional oscillation modes in some stars
    - true pulsation modes from aliases in ground-based data
    - rotation periods for 27 rotational variables (10 improved values; shortest rotation period roAp star known to date: 5.855 days)
  - constraints on *i* and magnetic obliquity for 4 stars (application oblique pulsator model)
  - confirmation of absence of pulsations down to 6/13 µmag for 2 known noAp stars
  - amplitudes in TESS filter factor 6 smaller than amplitudes in *B* filter from ground

confirmation of potential of TESS for study of roAp stars

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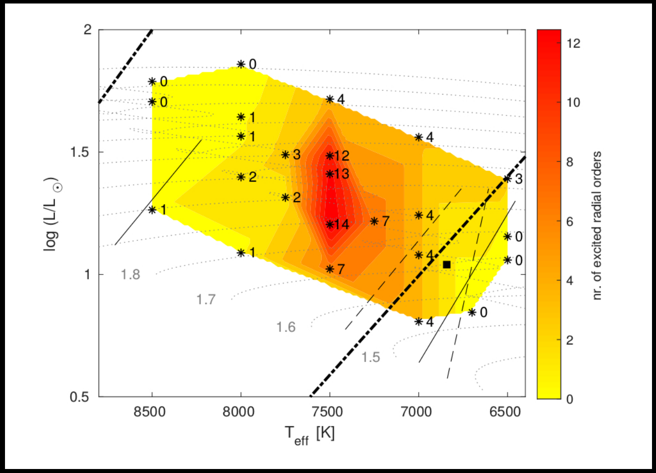
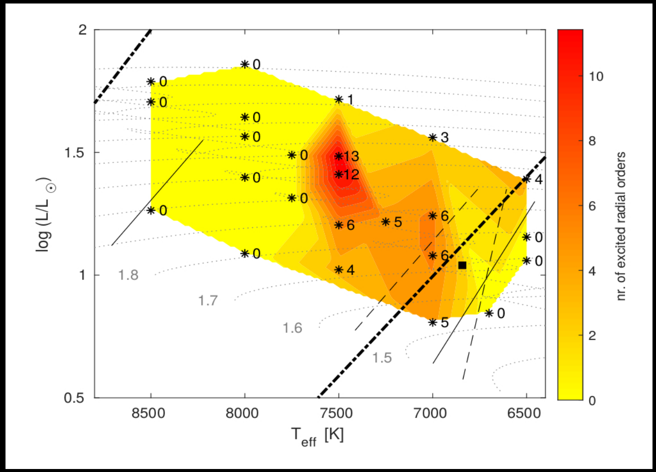
WG-4: Main sequence AF "classical" pulsators

(Antoci et al., 2019, MNRAS, accepted)

➔ First view of δSct and γDor stars with TESS

- 2-min cadence data of 117 stars, incl.
  - γ Doradus
  - SX Phoenicis
- confrontation theoretical models of pulsation driving
  - time-dependent non-local convection treatment
  - mimicking He depletion in outer envelope





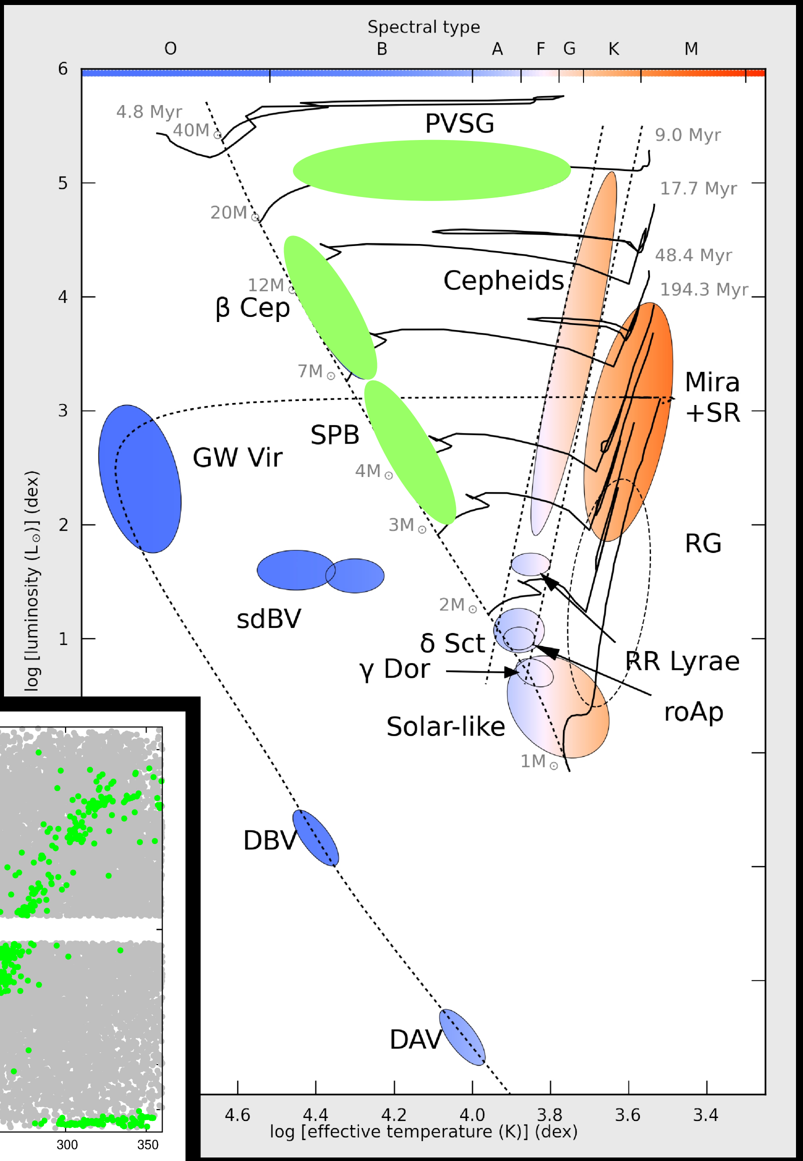
> turbulent pressure plays important role
> explanation for driving in Am stars
> strongest driving in center of classical instability strip (~7500K)

- ratio of amplitude in TESS to Kepler about 74%

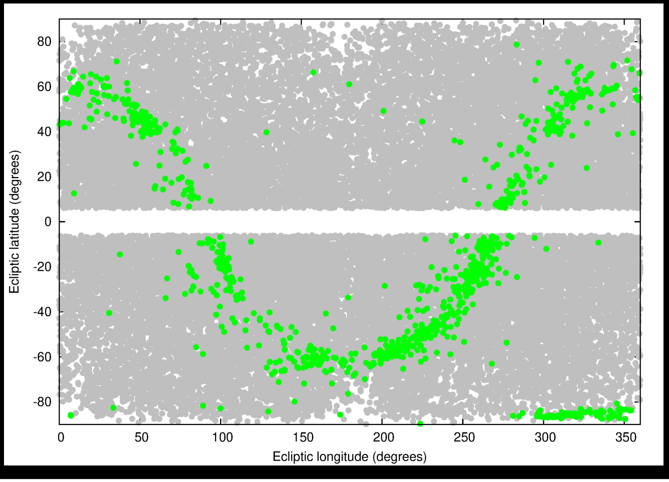
WG-5: Main sequence OB "classical" pulsators

(Chairs: Peter De Cat & Gerald Handler)

- β Cephei stars (βCep)
  - 2 – 7 hours (p/g-modes)
- Slowly Pulsating B stars (SPB)
  - 0.3 – 3 days (g-modes)
- Periodically Variable Supergiants (PVSG)
  - 10 – 100 days (internal gravity waves)
- Be stars (rapid rotation, episodes of Hα emission)
- magnetic OB-type stars
- pre-main sequence



lack of space-based studies for OB-type stars



WG-5: Main sequence OB "classical" pulsators

- Pedersen et al., 2019, ApJL, 872, L9: "Diverse Variability of O and B Stars Revealed from 2-minute Cadence Light Curves in Sectors 1 and 2 of the TESS Mission: Selection of an Asteroseismic Sample"
- Handler et al., 2019, ApJL, 873, L4: "Asteroseismology of Massive Stars with the TESS Mission: The Runaway β Cep Pulsator PHL 346 = HN Aqr"
- Balona et al., 2019, MNRAS, 485, 3457: "Rotational modulation in TESS B stars"
- David-Uraz et al., 2019, MNRAS, 487, 304: "Magnetic OB[A] Stars with TESS: probing their Evolutionary and Rotational properties (MOBSTER) – I. First-light observations of known magnetic B and A stars"
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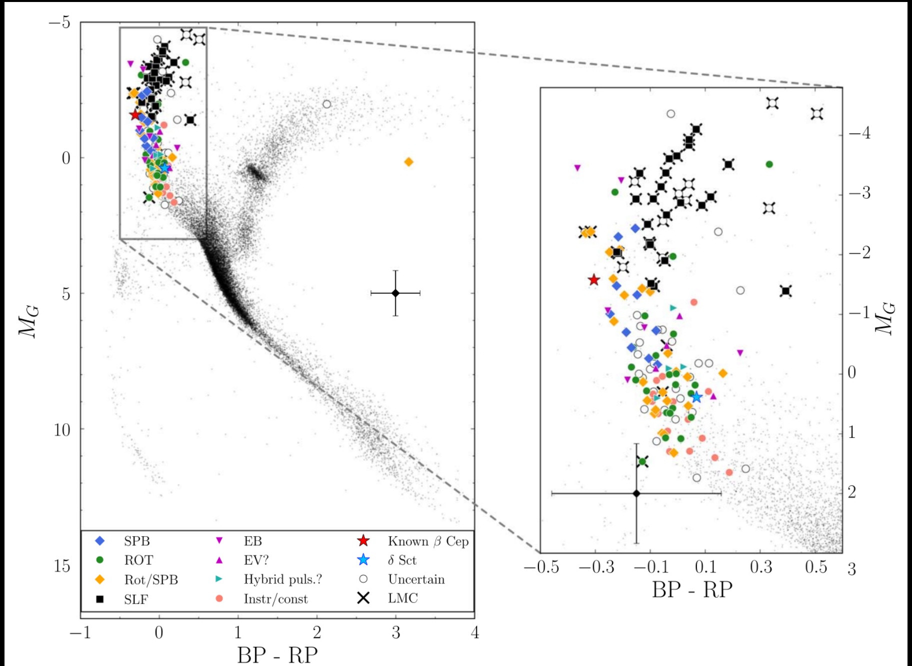
- Wade et al., 2019, MNRAS, submitted: "Evolving pulsation of the slowly rotating magnetic β Cep star ξ^1 CMa"

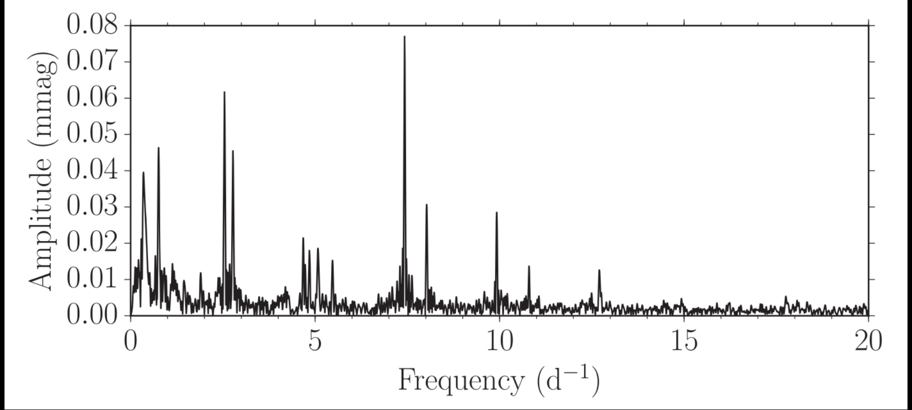
WG-5: *Main sequence OB "classical" pulsators*

➔ Diverse variability of O and B stars

(Pedersen et al., 2019, ApJL 872, 9)

- analysis of 2-min cadence data of 154 OB-type stars
- detection of variability in 90% of objects:
  - 23 multiperiodic pulsators
  - 6 eclipsing binaries
  - 21 rotational variables
  - 25 stars with stochastic low-frequency variability
  - variables with overlap in categories
  - hybrid pulsators





selection of sample of OB-type stars with high potential for asteroseismic + spectroscopic modelling of interior structure with unprecedented precision

Beijing Normal University (Beijing, China)
October 10, 2019

Peter De Cat
Royal Observatory of Belgium

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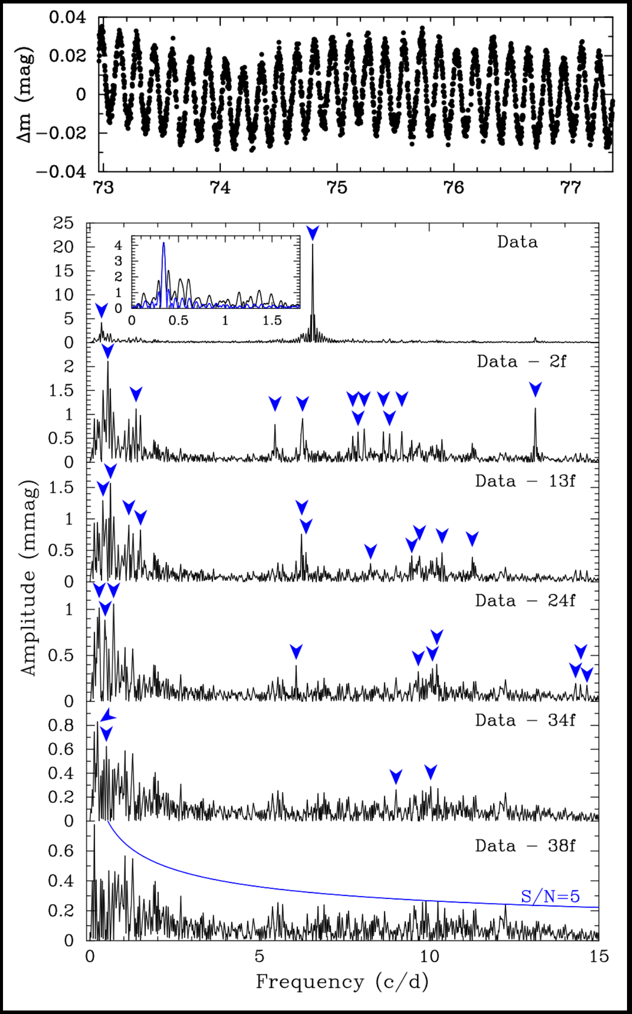
WG-5: *Main sequence OB "classical" pulsators*

- Runaway βCep pulsator PHL346 = HN Aqr
  - previously known as single-periodic pulsator
  - detection of
    - at least 34 oscillation modes (12 g-mode, 22 p-modes)
    - amplitude & frequency variability of dominant mode
    - long-term radial velocity variations
    - age constraint of 23(1) Myr (kinematic analysis)
      - → not compatible with first attempts of asteroseismic modelling

(Handler et al., 2019, ApJL 873, 4)

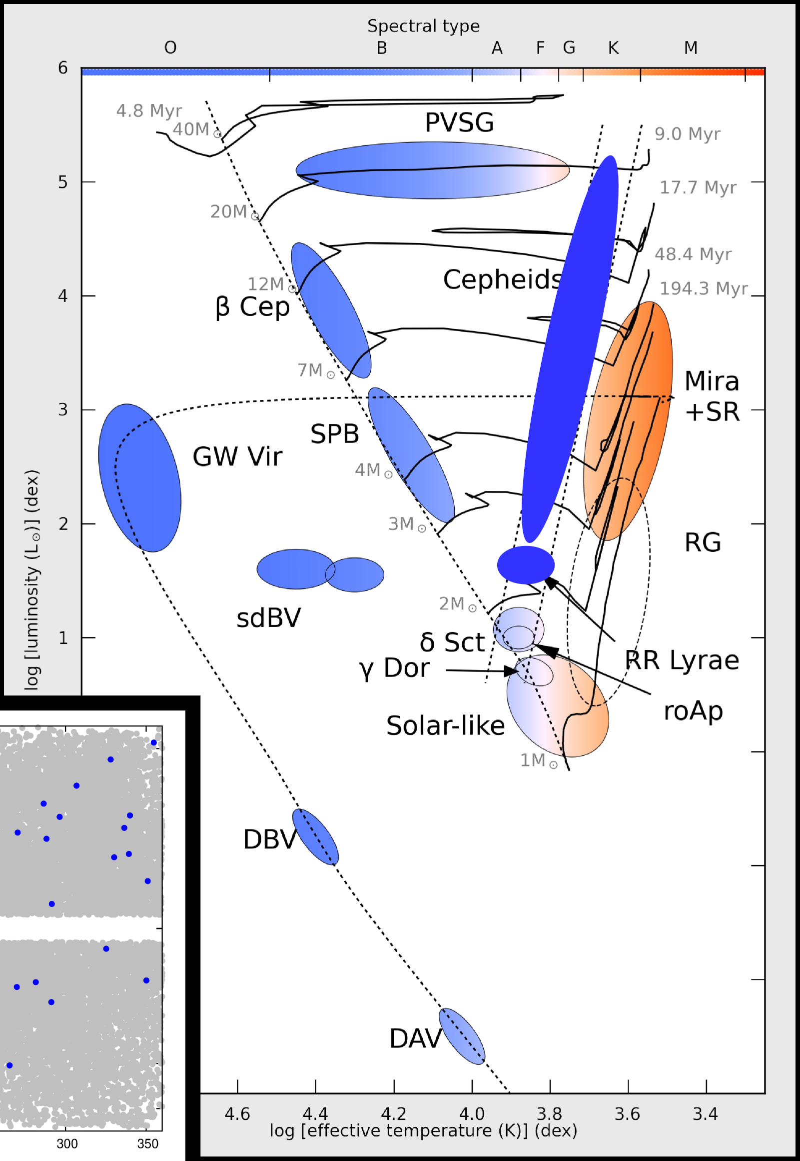


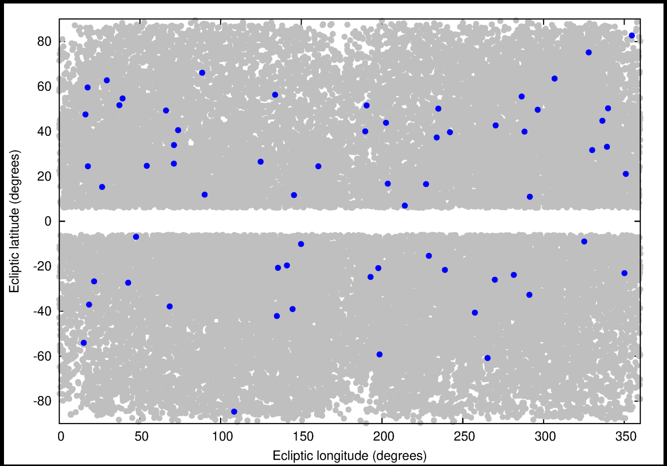
accurate age determination of runaway pulsators can become vital in tracing the evolutionary history of these objects

WG-6: RR Lyrae stars and Cepeids

(Chairs: Katrien Kolenberg & Róbert Szabó)

- ➔ **RR Lyrae stars** (RR Lyrae)
  - ➢ RRab variables: 0.3 – 1 days (fundamental F)
  - ➢ RRc variables: 0.2 – 0.5 days (first-overtone 1O)
  - ➢ RRd variables: 0.2 – 1 days (F+1O)
- ➔ **Cepheids**
  - ➢ classical Cepheids
    - ✗ F: 1 – 200 days
    - ✗ 1O: 0.24 – 8 days
  - ➢ Type II Cepheids
    - ✗ BL Her: 1 – 5 days
    - ✗ W Vir: 4 – 20 days
    - ✗ RV Tau: 40 – 100 days
  - ➢ anomalous Cepheids
    - ✗ F: 0.1 – 2 days
    - ✗ 1O: 0.3 – 1 days





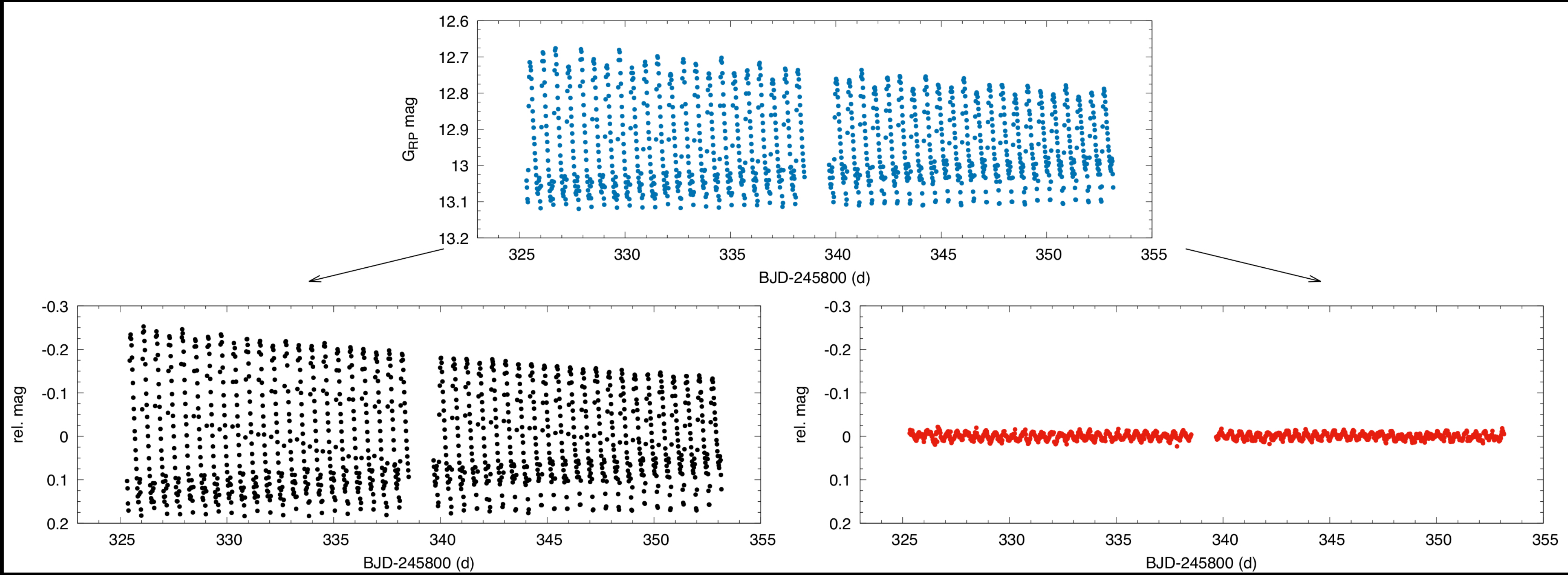
WG-6: RR Lyrae stars and Cepeids

- Light curves of handful Cepheid and ~hundred RR Lyrae stars

(Plachy, Molnár et al., 2019, in preparation)

  - RRa variable (fundamental mode) with unusually strong additional mode
    - first radial overtone outside the classical double-mode regime?
    - non-radial mode with a similar period?

→ suitable for mode identification from southern telescopes



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  - RRa variable (fundamental mode) with unusually strong additional mode
    - ✗ first radial overtone outside the classical double-mode regime?
    - ✗ non-radial mode with a similar period?

      → suitable for mode identification from southern telescopes
  - difference of distribution for additional modes in RRc variables (first-overtone) between
    - ✗ region near Sun observed by TESS
    - ✗ region in Galactic bulge observed by OGLE

      → due to differences in composition between field and bulge RR Lyrae stars? selection bias in TESS sample?

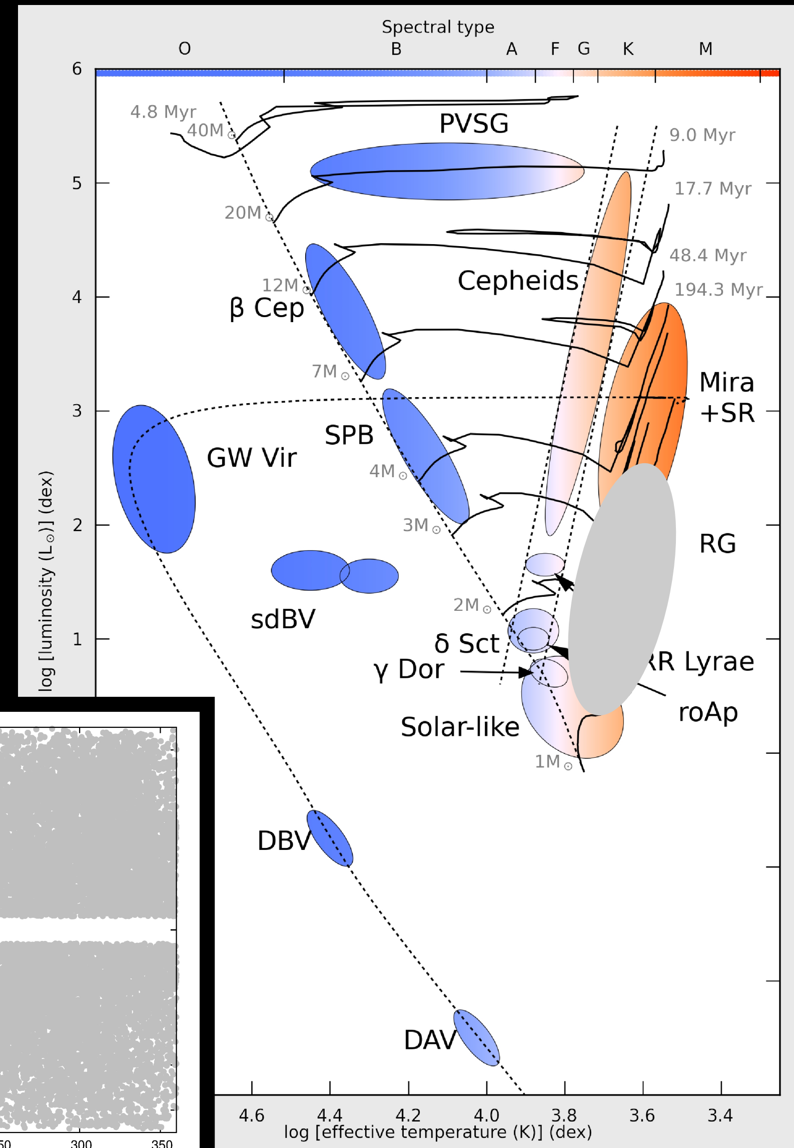
TESS expected to have large impact on serveral topics, e.g.
* proper classification of subtypes for short period Cepheids and RR Lyrae stars
* statistical study of occurrence of additional modes (understanding of mode selection), nonlinear effects, light curve stability, etc.
* clarification of evolutionary stages of anomalous Cepheids

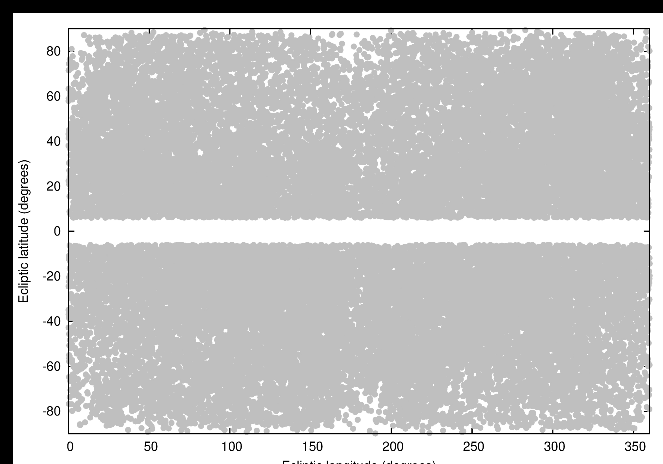
WG-7: Red giant oscillators

(Chairs: Victor Silva Aguirre & Dennis Stello)

- red giant stars (RG)
  - 1 hour – 4 days (solar-like, mixed-modes)
  - distinguish red giants burning helium in cores from those still only burning hydrogen in a shell

(Bedding et al., 2011, Nature 471, 608)



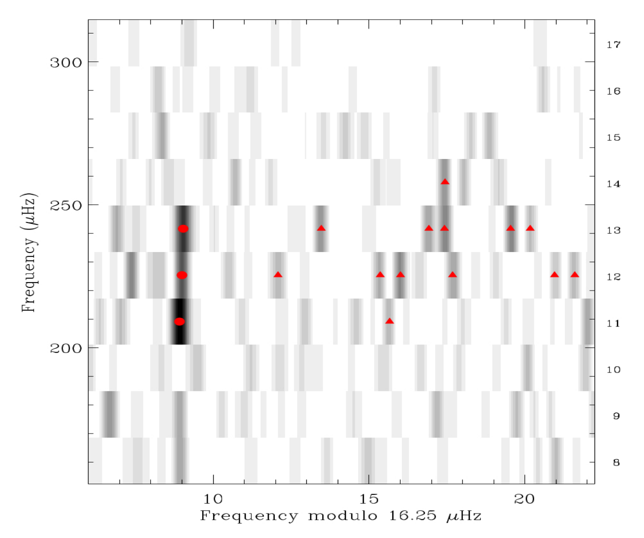


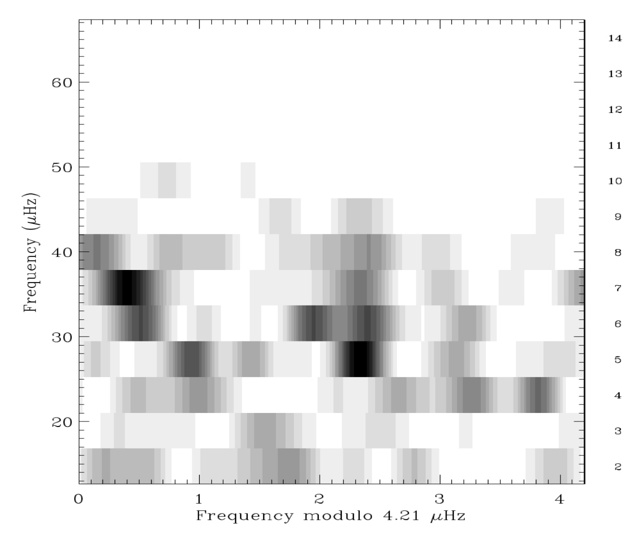
WG-7: Red giant oscillators

- Campante et al., 2019, ApJ, accepted: "Tess asteroseismology of the known red-giant host stars HD212771 and HD203949"
- Pereira et al., 2019, MNRAS, accepted: "Gaussian Process modelling of granulation and oscillations in red-giant stars"

WG-7: Red giant oscillators

- TESS asteroseismology of known host stars (Campante et al., 2019, ApJ, submitted)
  - HD212771 (G8IV; T=6.75)
    - Juvian planet ($M_P sini = 2.3(4)\ M_J$)
    - orbit of 373.3 days
  - HD203949 (K2III; T=4.75)
    - massive planet ($M_P sini = 8.2(2)\ M_J$)
    - orbit of 184.2 days
  - stellar parameters (T_{eff}, [Fe/H]) and abundances from high-resolution spectroscopy
  - constraints on stellar radii and luminosity (L_*) from spectral energy distribution fitting (broadband photometry)
  - first detection of oscillations with TESS for red-giant planet host stars ($\Delta\nu$, ν_{max})





WG-7: *Red giant oscillators*

➔ TESS asteroseismology of known host stars

(Campante et al., 2019, ApJ, submitted)

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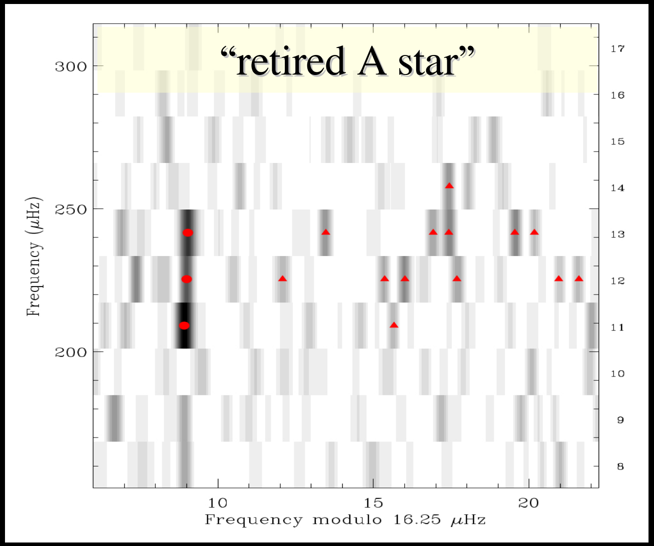
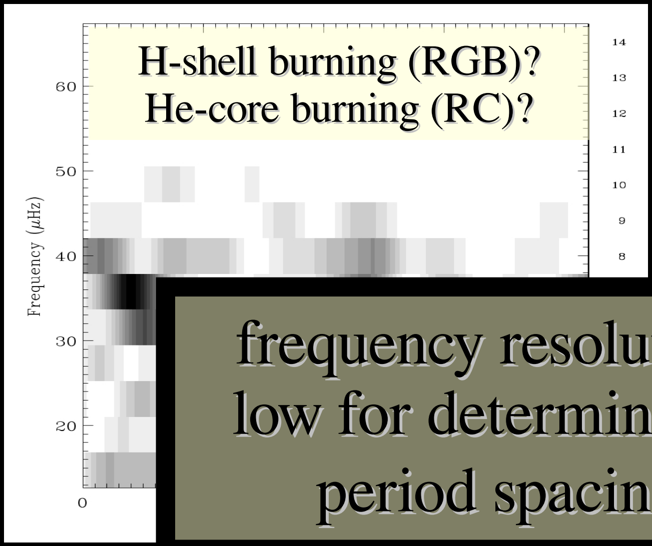


grid-based modelling approach

ν, ν_{max}, [Fe/H], T_{eff}, L_*

⇓

M_*, R_*, ρ_*, logg, age



frequency resolution too low for determination of period spacing Π_1

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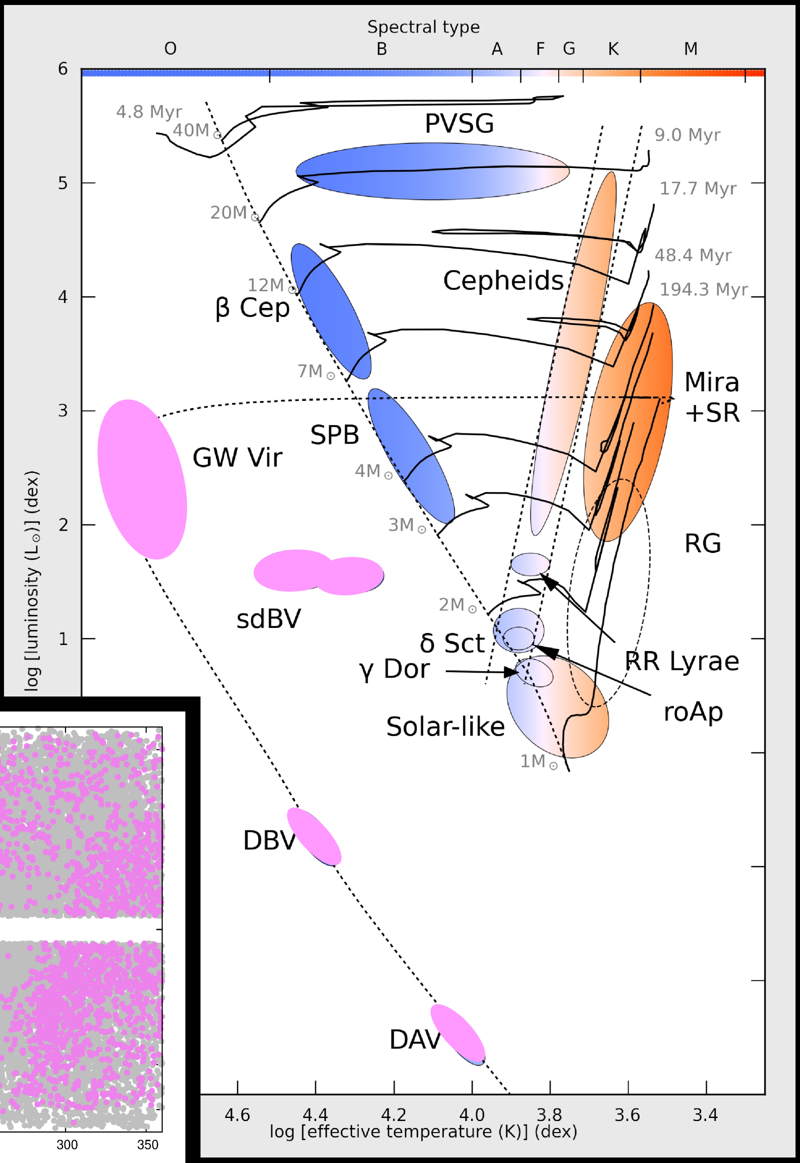
  - first detection of oscillations with TESS for red-giant planet host stars ($\Delta\nu$, ν_{max})
  - ratio of amplitude TESS to K2: 75(14)%

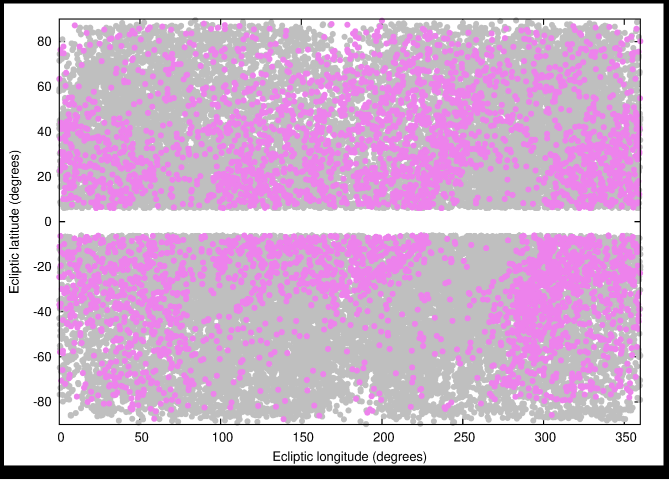
TESS: revision of properties of stellar population surrounding Sun
* asteroseismology of red giants
* in unbiased way
* to a much larger volume than before (~3000 parsec)

WG-8: Compact pulsators

(Chairs: Stéphane Charpinet & JJ Hermes)

- sub-dwarf B variables (sdBV)
  - $sdBV_r$: 90 - 600 sec (p-modes)
  - $sdBV_s$: 1 - 4 hours (g-modes)
  - $sdBV_{rs}$: both regimes
- pulsating pre-white dwarfs
  - GW Virginis stars (GW Vir): 5 – 85 min (g-modes)
- pulsating white dwarfs
  - DBV stars:
    200 – 1000 sec (g-modes)
  - DAV stars:
    100 –1500 sec (g-modes)



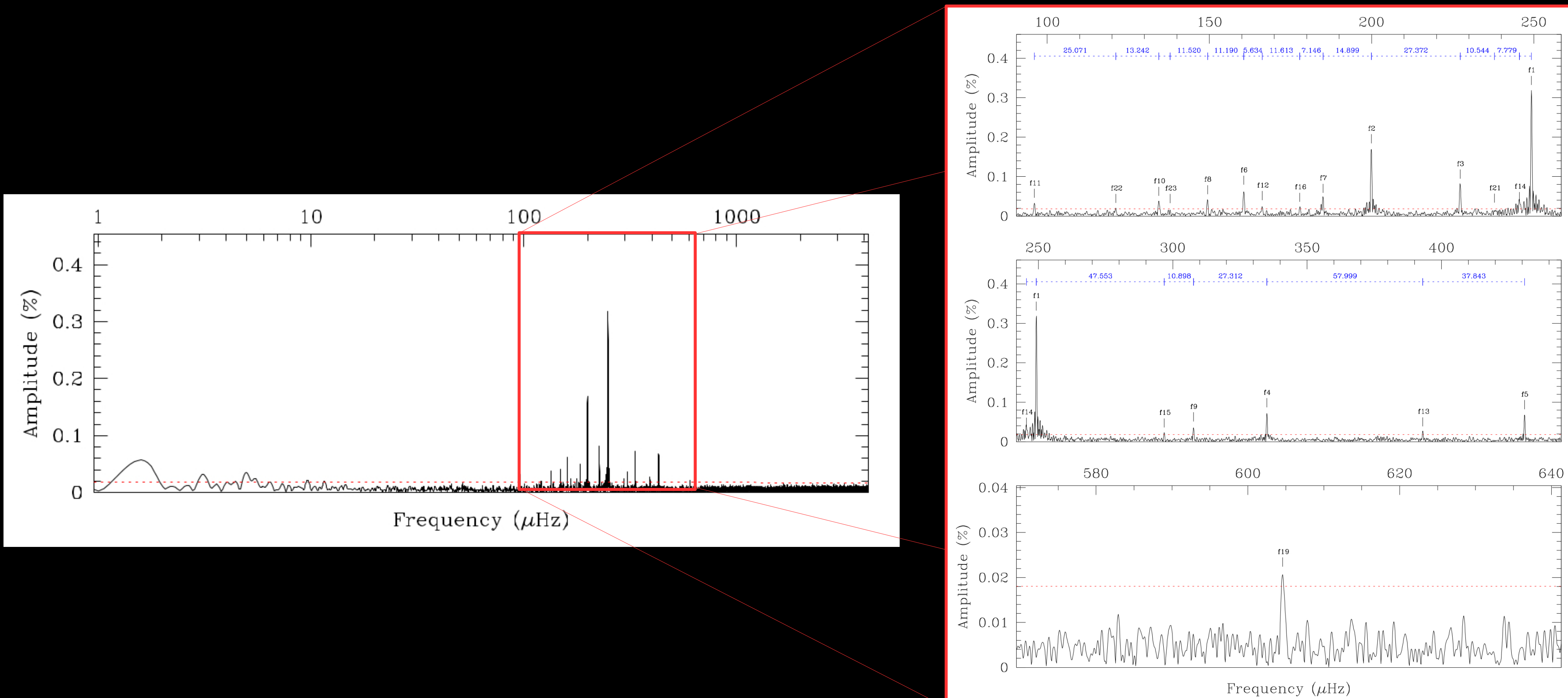


WG-8: Compact pulsators

- Charpinet et al., 2019, A&A, submitted: "TESS first look at evolved compact pulsators: Discovery and asteroseismic probing of the g-mode hot B subdwarf pulsator TIC278659026"
- Bell et al., 2019, RNAAS, 3, 81: "A Hot Subdwarf B Star Eclipsed by a Low-mass White Dwarf in TESS Data"
- Bell et al., 2019, A&A, submitted: "TESS first look at evolved compact pulsators: "Asteroseismology of the pulsating helium-atmosphere white dwarf TIC257459955"
- Althaus et al., 2019, A&A, submitted: "On the existence of warm H-rich pulsating white dwarfs"
- Reed et al., 2019, MNRAS, TASC review: "TESS observations of the interesting pulsating subdwarf B star CDS-28 1974"

WG-8: Compact pulsators

- Discovery and asteroseismic probing of g-mode hot B subdwarf pulsator (based on analysis of 2-min data in sector 1) (Charpinet et al. 2019, A&A, submitted)
  - rich frequency spectrum between 96 – 605 μHz (27 – 174 min; incl. 20 independent g-modes)



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  - asteroseismic modelling in agreement with frequencies, atmospheric parameters, and astrometry
    - ✗ $M = 0.391(9)\ M_{sun}$ (low) → progenitor red giant, not undergone He-core flash?
    - ✗ He-rich envelope mass = $0.0037(10)\ M_{sun}$
    - ✗ $R = 0.1694(81)\ R_{sun}$
    - ✗ $L = 8.2(11)\ L_{sun}$
    - ✗ internal chemical stratification: double-layered He/H composite profile
      → ongoing gravitational settling of He at bottom of thick H-rich envelope
    - ✗ core: → 43% in mass of central He burnt
      → $M_{core} = 0.198(10)\ M_{sun}$ (relatively large mixed core)
      → $X(O)_{core} = 0.16(+13/-5)$ in mass produced by He-burning core

constraints for studies of $^{12}C(\alpha,\gamma)^{16}O$ nuclear reaction rate

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TESS will have an enormous impact on the field of compact pulsators given the large number of stars ultimately monitored

on rate

Conclusions and future prospects

- Advantages of TESS for many classes of pulsating stars
  - accurate photometry with either 30 min or 2 min cadence
  - for many targets given that 85% of the sky will be observed
  - including bright objects allowing ground-based follow-up for characterization
- Disadvantages of TESS for some classes of pulsating stars
  - contamination problems due to large pixel size
  - sectors observed for 27 days
- Importance of ground-based data
  - extension of time-base of observations
  - characterisation of the stars

Best prospects for
* statistical studies
* variables with short enough periods

TASOC webpage: https://tasoc.dk/

Thank you!

Peter De Cat
Royal Observatory of Belgium