# *Pulsating stars with the Transiting Exoplanet Survey Satellite (TESS)*

**Peter De Cat**

Royal Observatory of Belgium, Ringlaan 3, 1180 Brussels, Belgium

## 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)

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1. *TESS as Space Mission*
2. *TESS and Pulsating stars*
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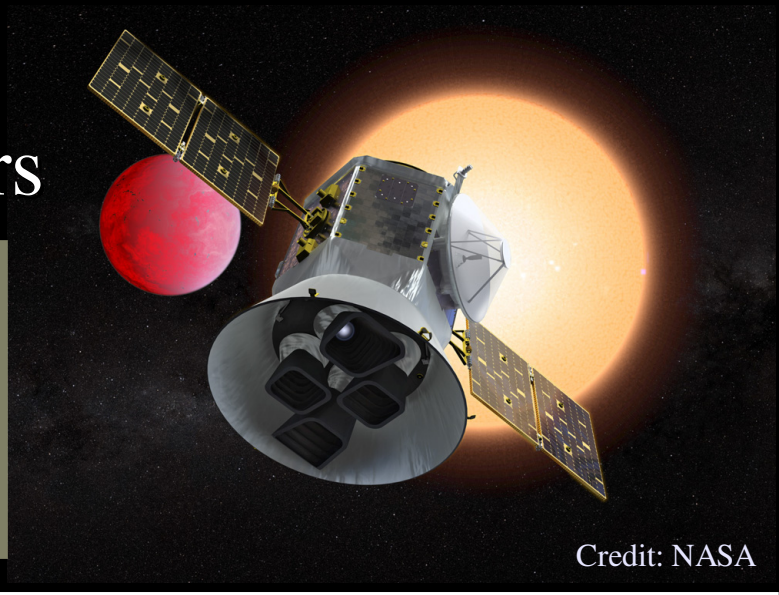
# Mission objectives

- 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

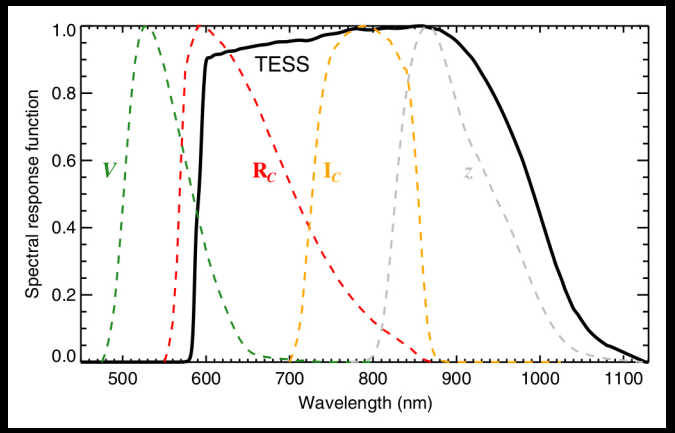


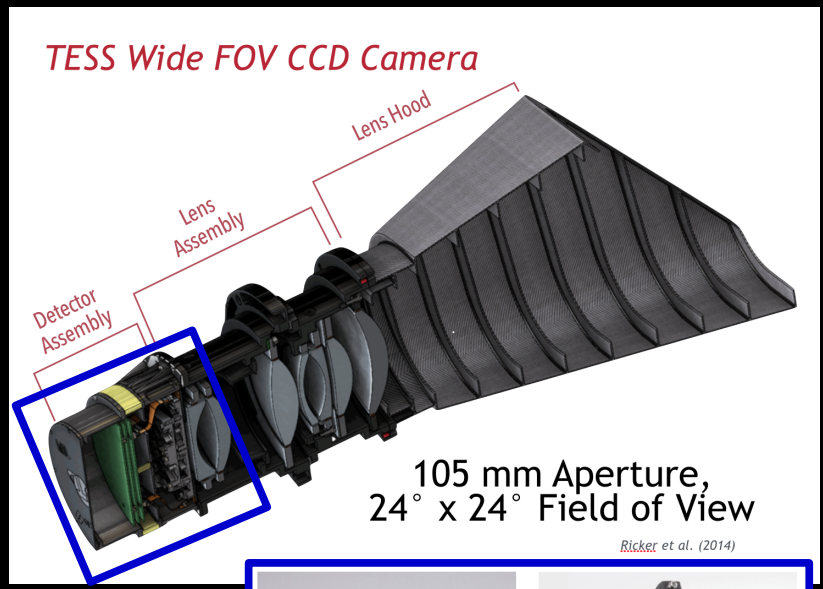
Credit: NASA

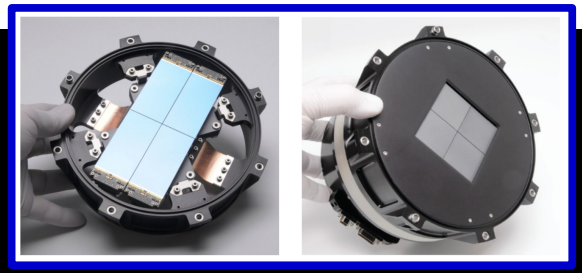
# Telescope

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

sectors



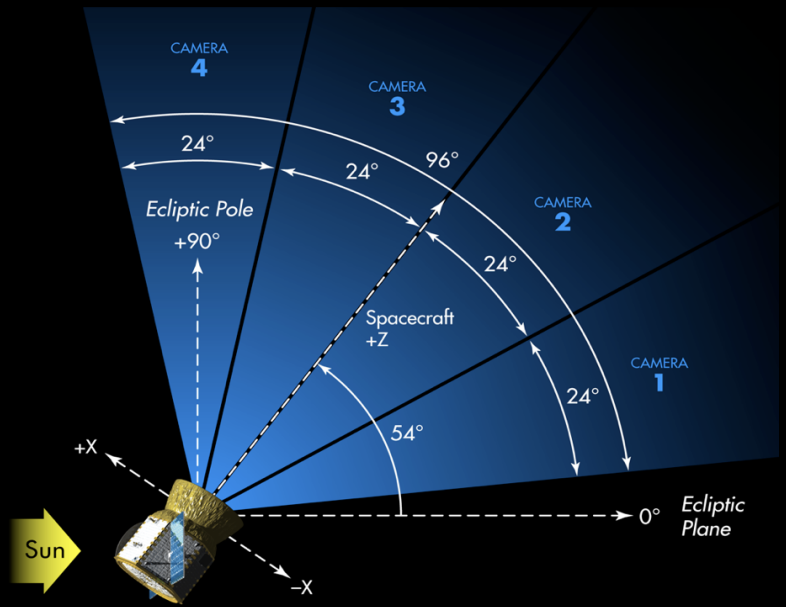



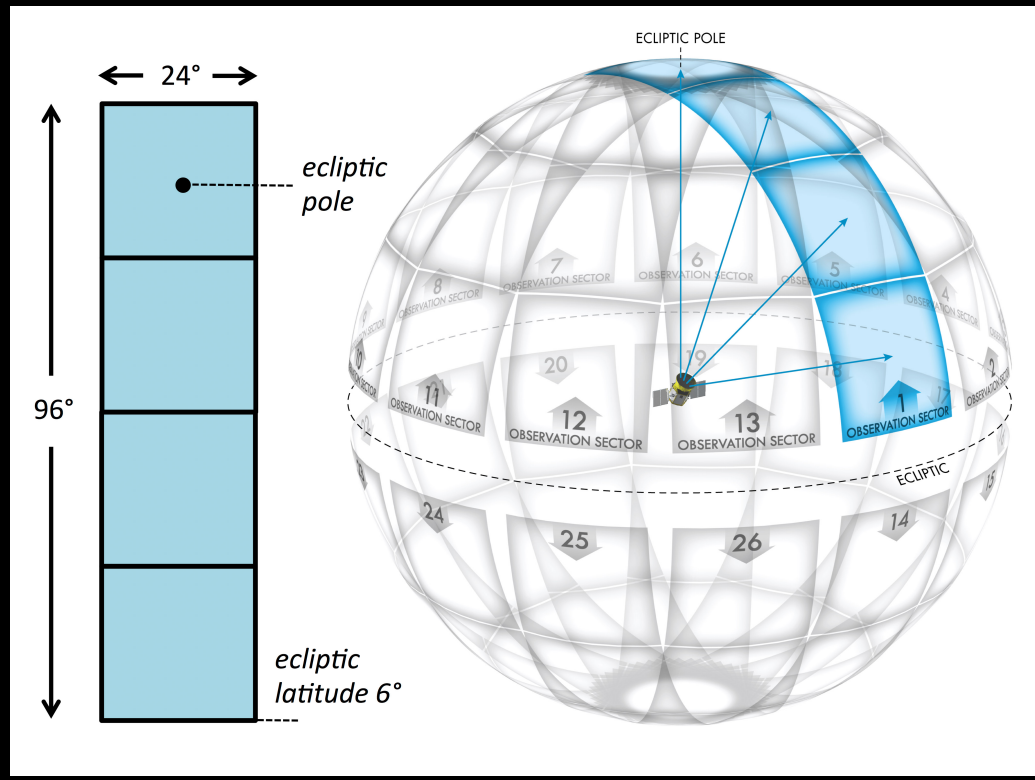
- pixel size: 21 arcsec or 0.35 arcmin on sky

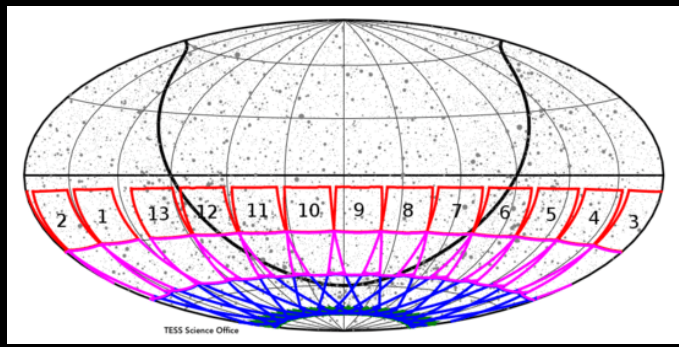
large pixels

# Operations

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



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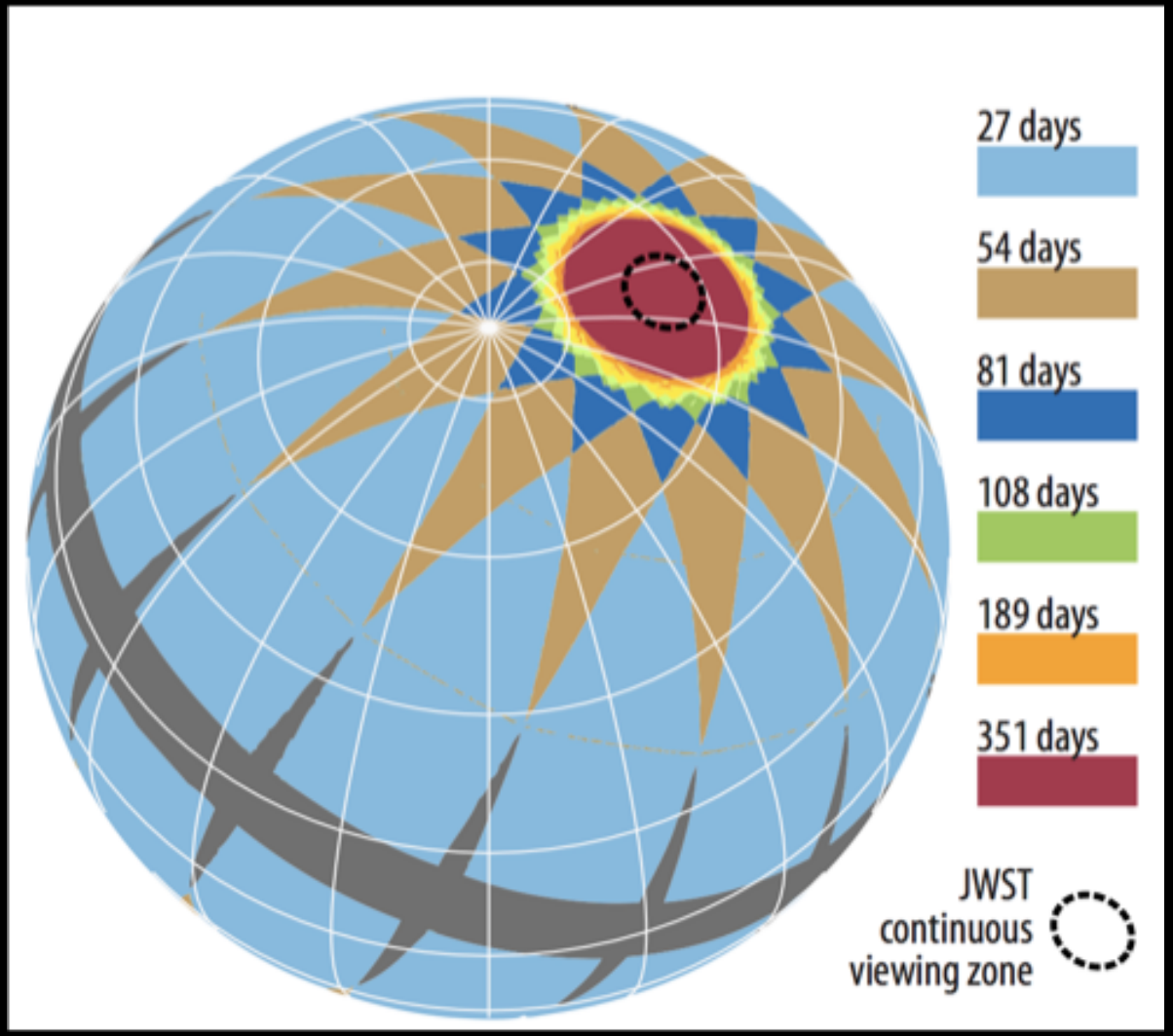
# Operations

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



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# 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

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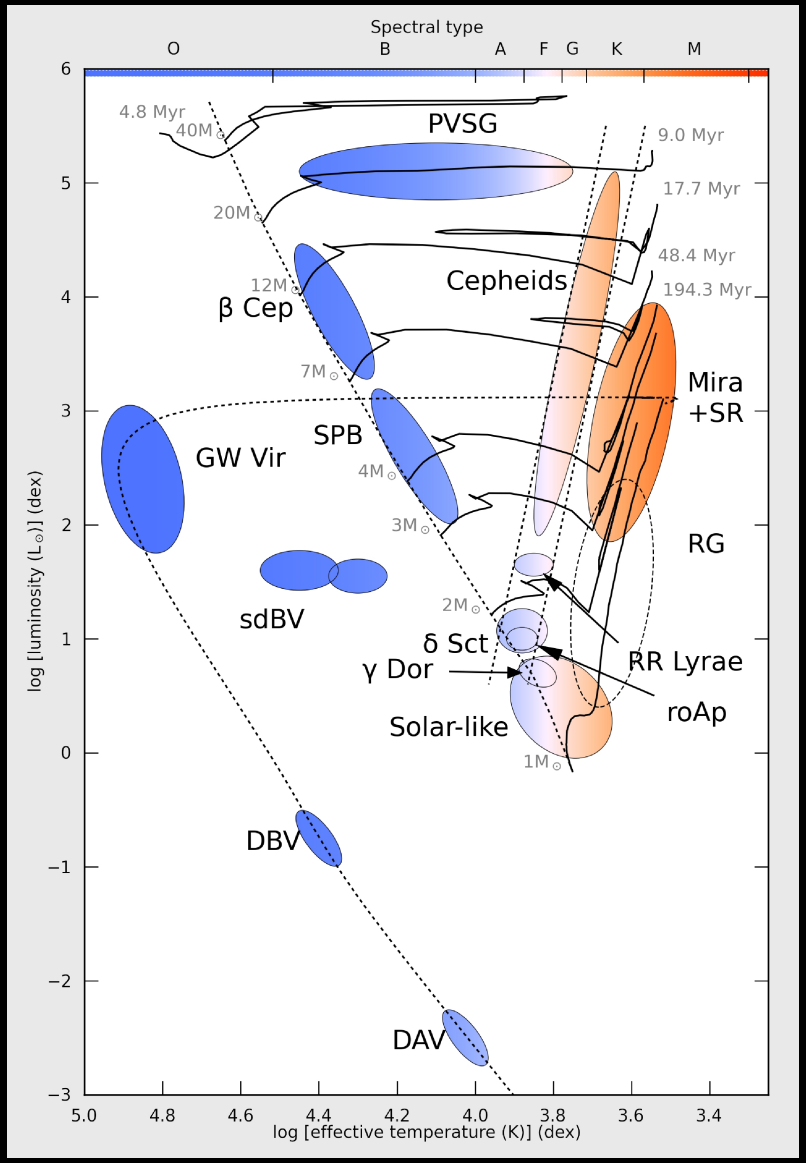
# TESS Asteroseismic Science Consortium

- 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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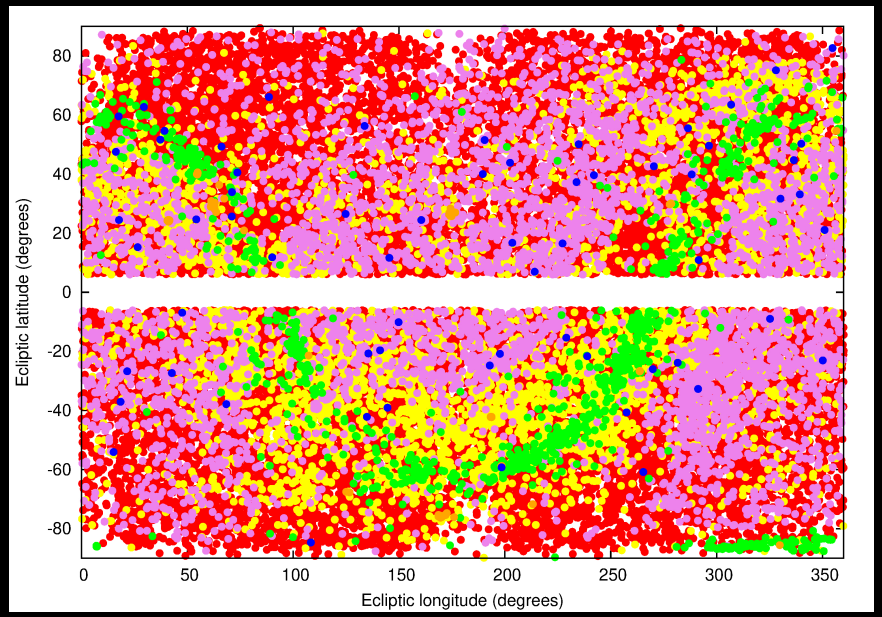


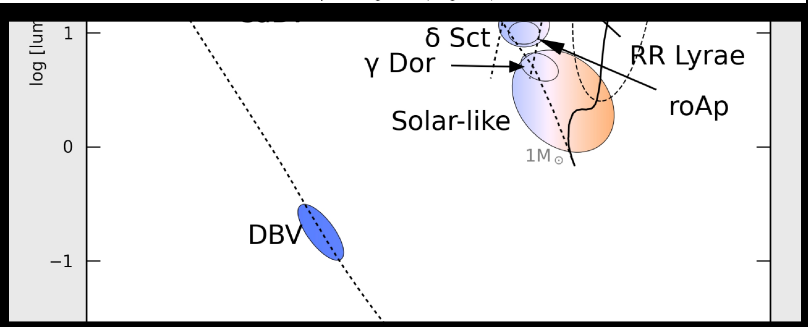


Selection of 2-min cadence targets
Stimulation of collaborations
Coördination of publications



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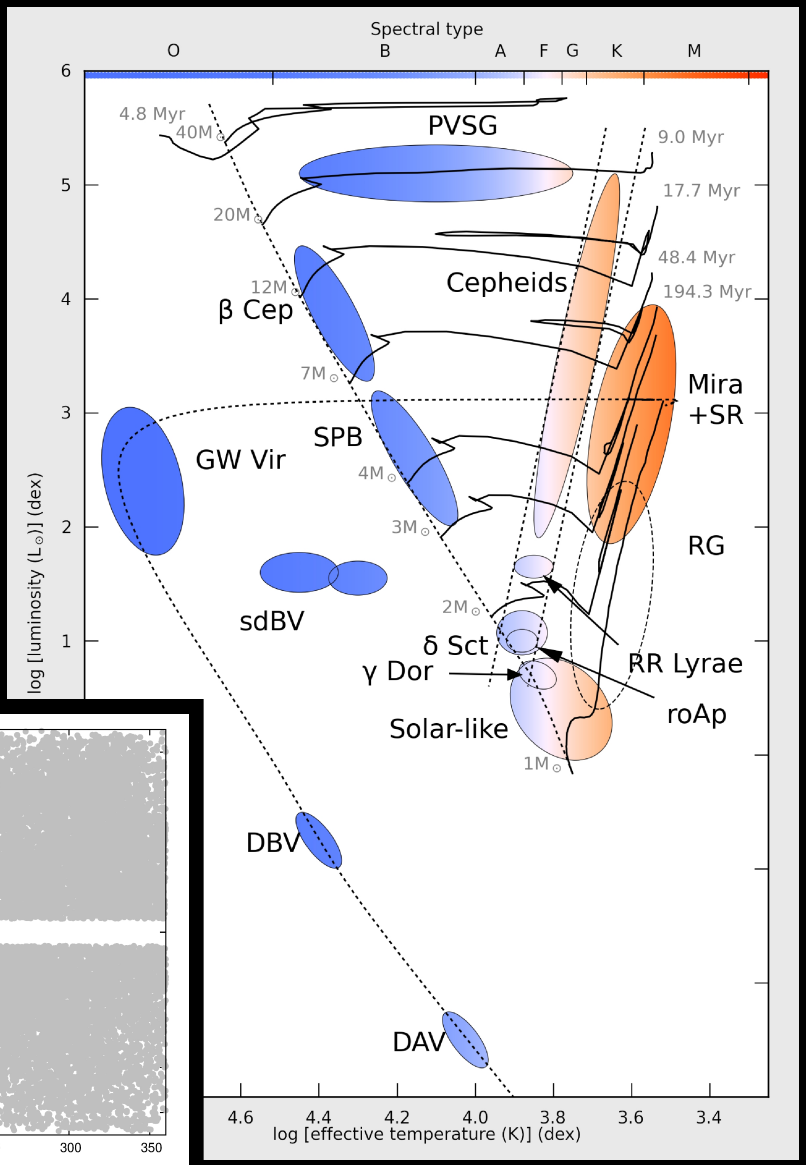
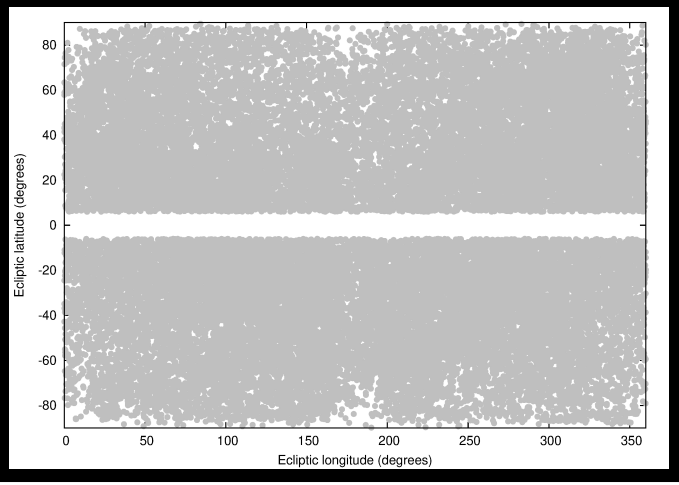
# WG-1: Asteroseismology of TESS exoplanet hosts

(Chairs: Bill Chaplin & Daniel Huber)

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



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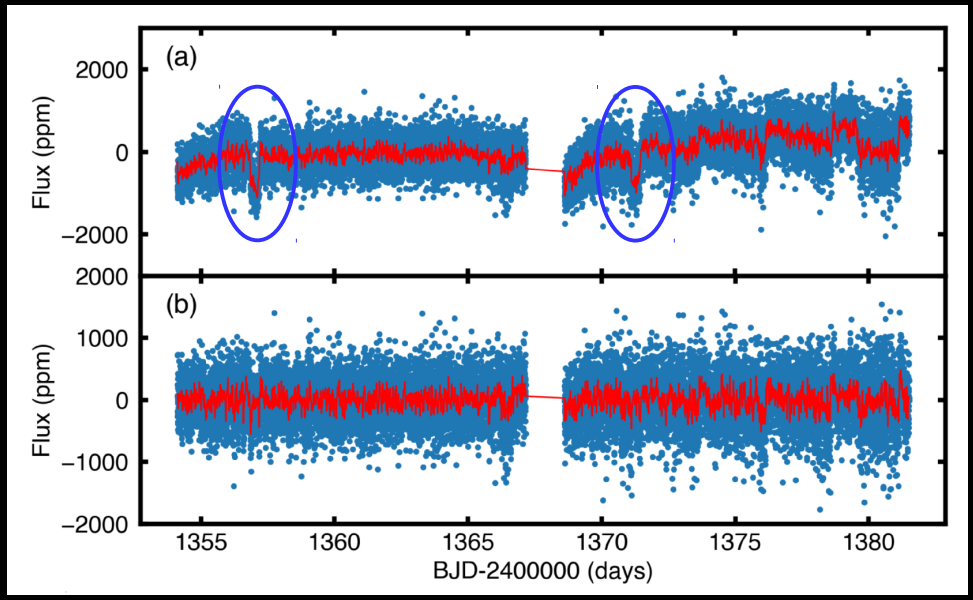
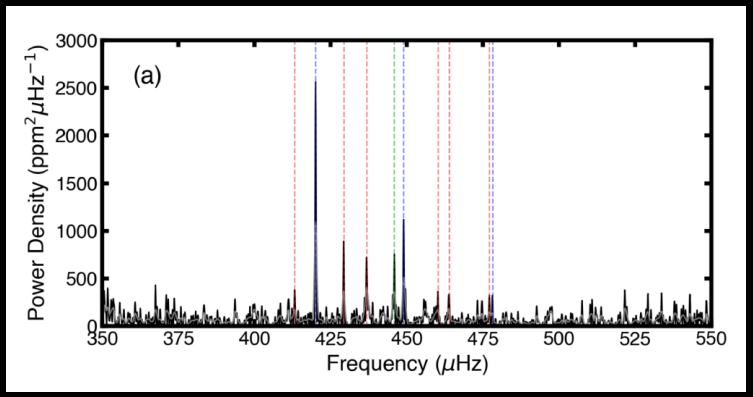
# WG-1: Asteroseismology of TESS exoplanet hosts

(Huber et al., 2019, AJ, in press)

- Detection of transiting planet orbiting oscillating host star
  - bright star (V = 8.2 mag)
  - clear signature of eclipse and mixed modes



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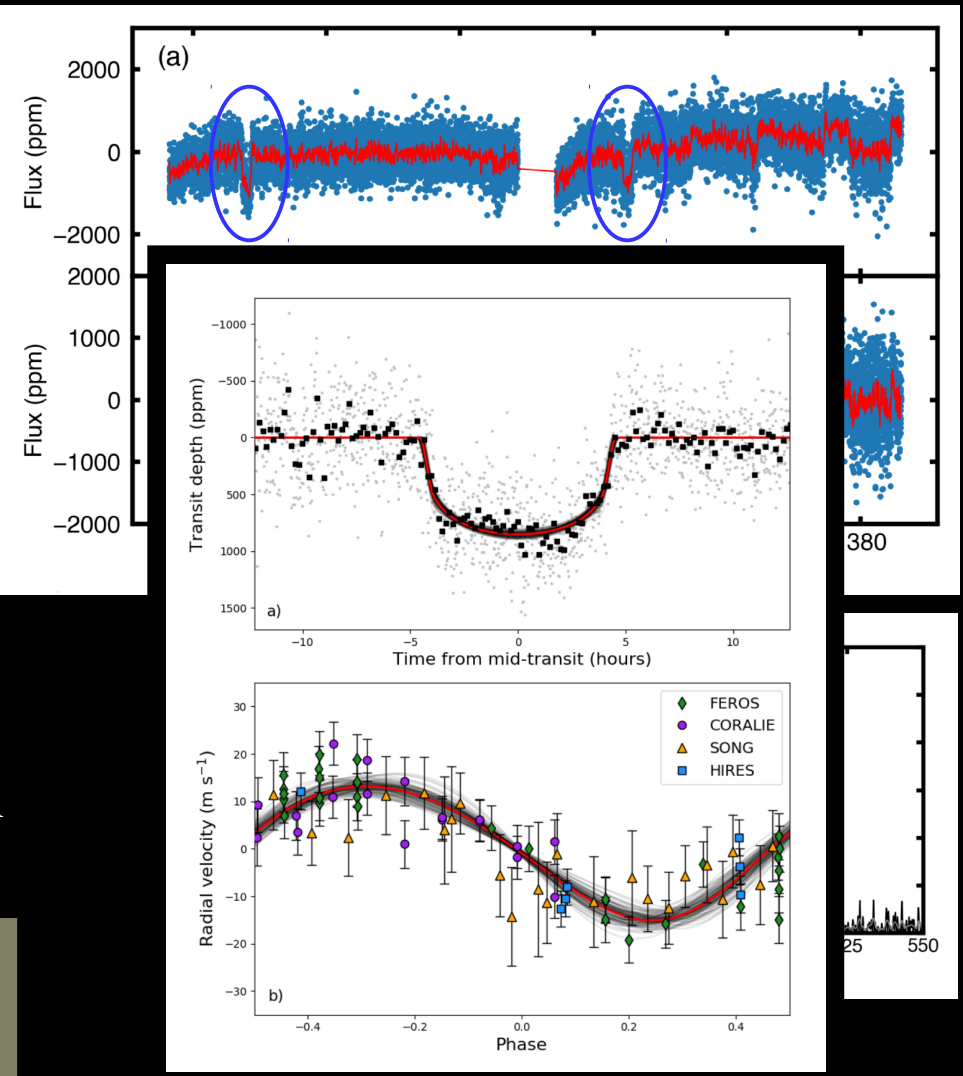
(Huber et al., 2019, AJ, in press)

- 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
  - planet characterisation
    - $M_{planet} = 0.191(17)\ M_{Jupiter}$
    - $\rho_{planet} = 0.424(60)$ gcm$^{-3}$

    } hot Saturn

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



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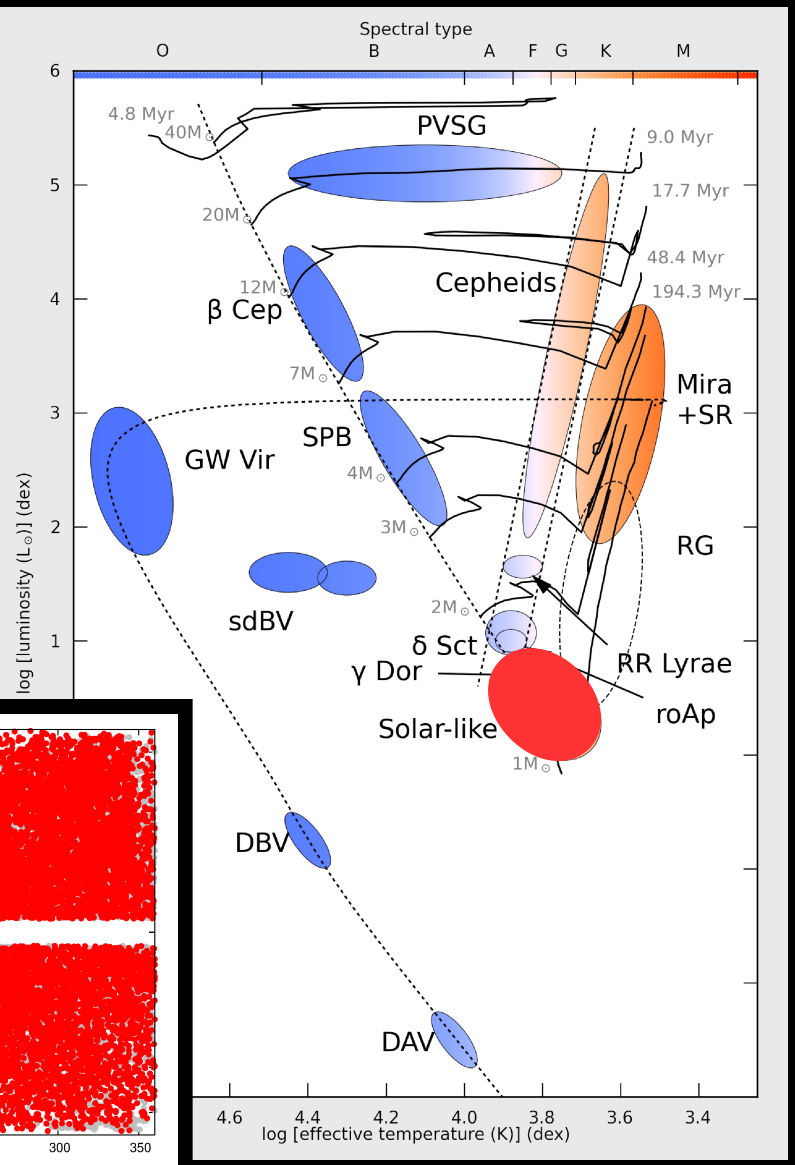
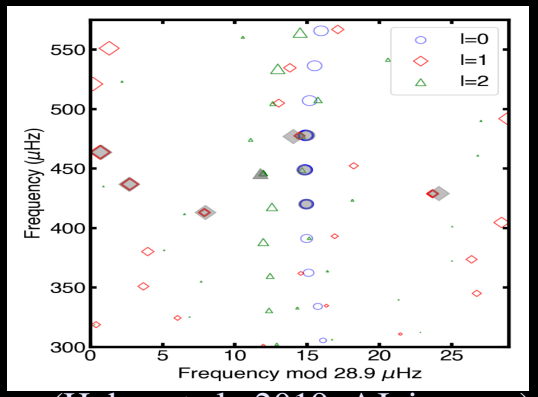
# WG-2: Oscillations in solar-type stars

(Chairs: Thierry Appourchaux & Bill Chaplin)

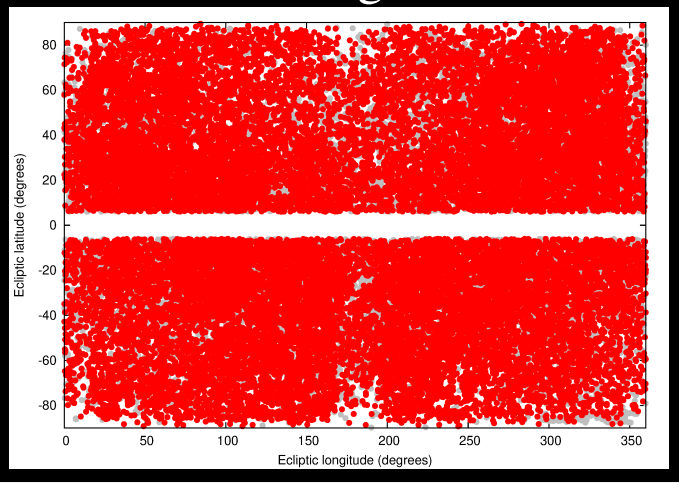
- solar-like oscillations (Solar-like)
  - order of minutes (p/mixed-modes)
  - short-lived (bell-shaped frequency distribution)
  - scaling relations
    - ✗ $\Delta\nu \sim \mathrm{sqrt}(M/R^3)$ (large frequency spacing)
    - ✗ $\nu_{max} \sim g/\mathrm{sqrt}(T_{eff})$ (frequency of maximum power)

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




(Huber et al., 2019, AJ, in press)



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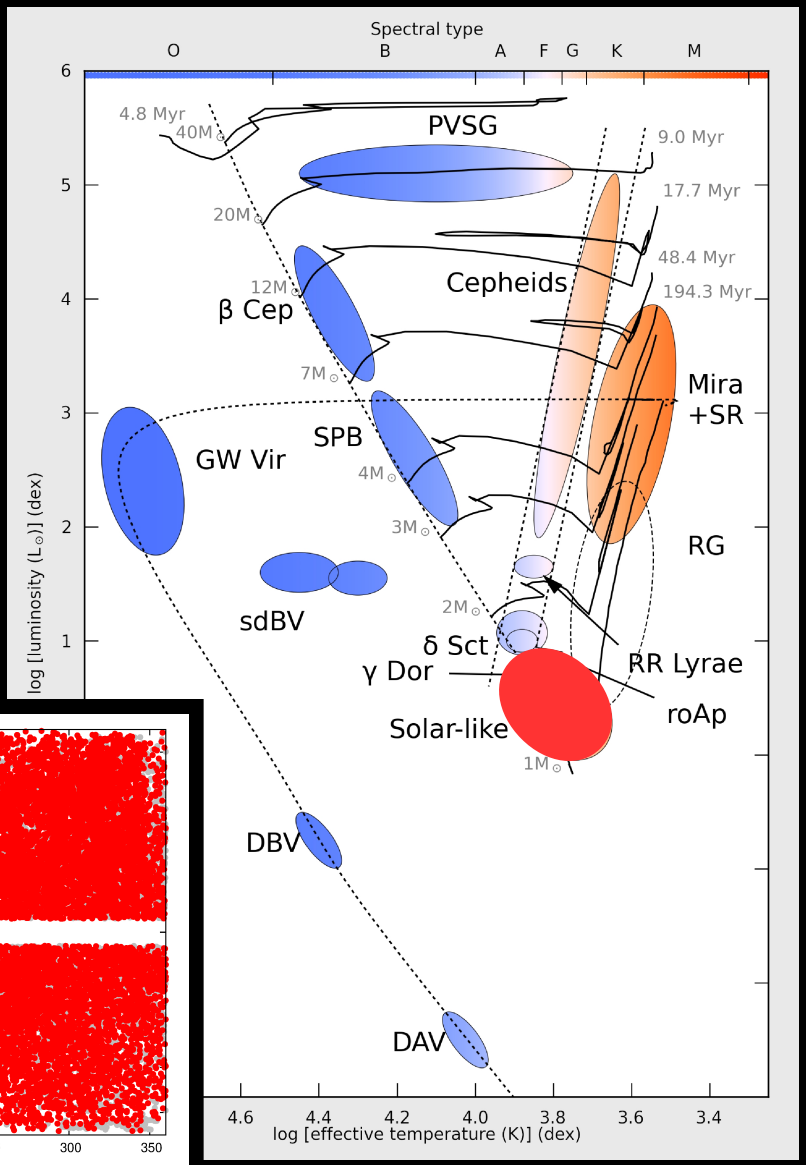


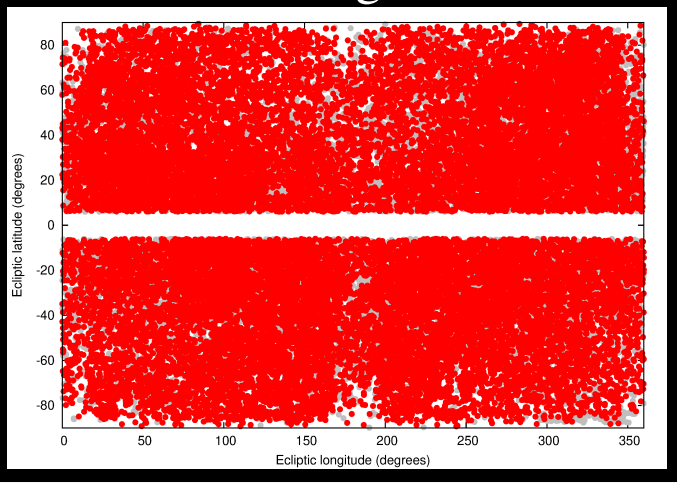


## TESS: progress from

* combination with ground-based follow-up data

* statistical studies

- detection of solar-like oscillations
- understanding of evolved systems with planets



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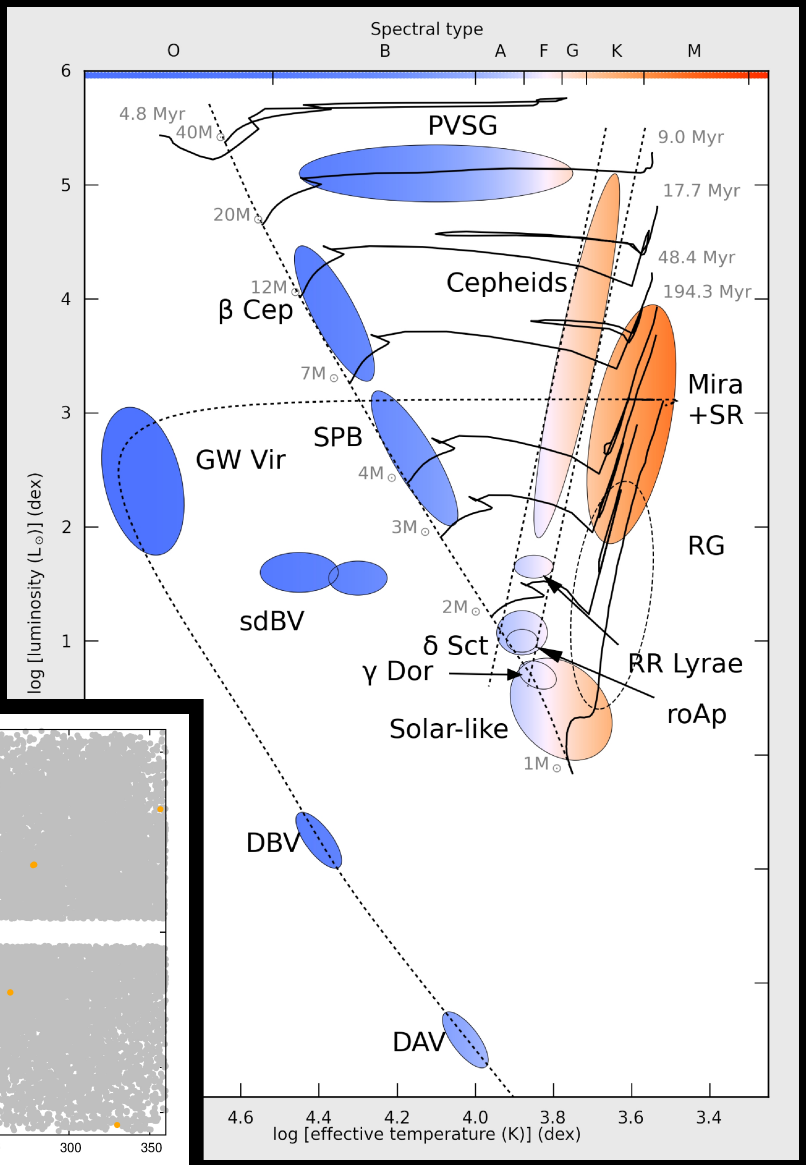
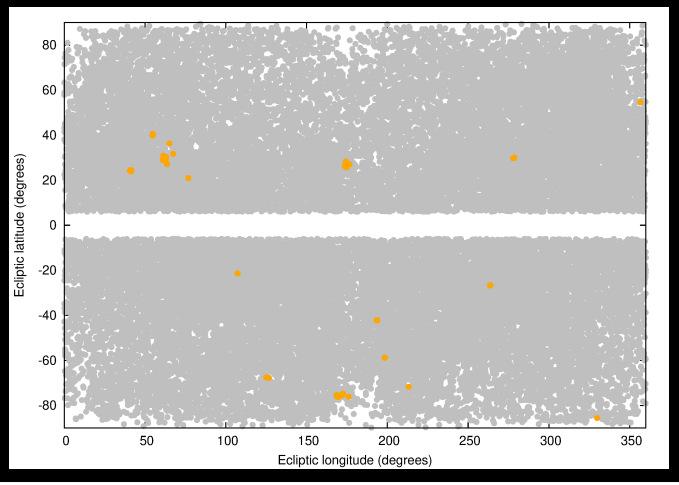
# WG-3: Oscillating stars in clusters

(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



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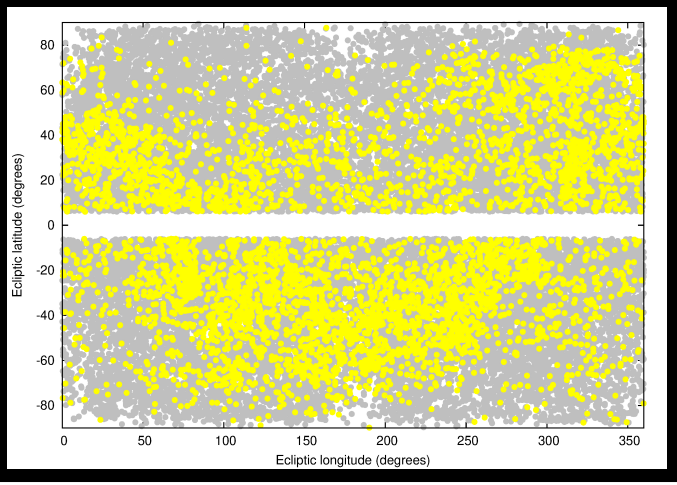
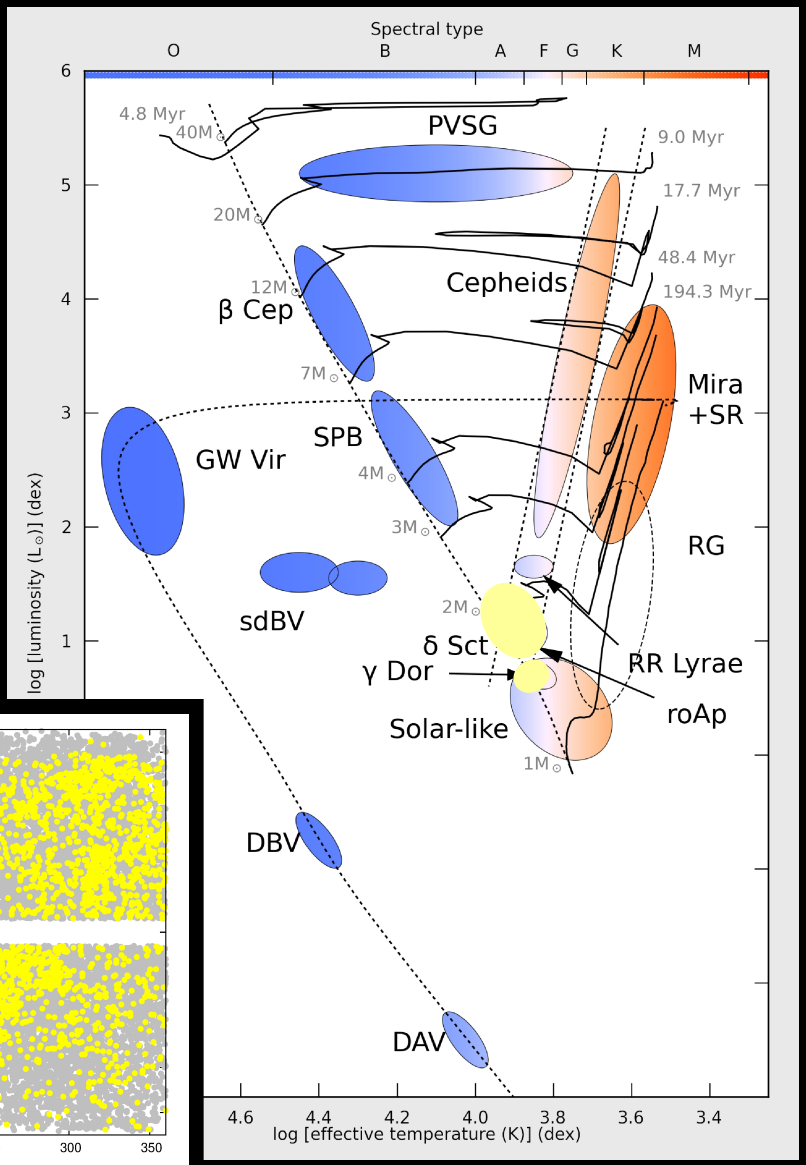
# WG-4: Main sequence AF "classical" pulsators

(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



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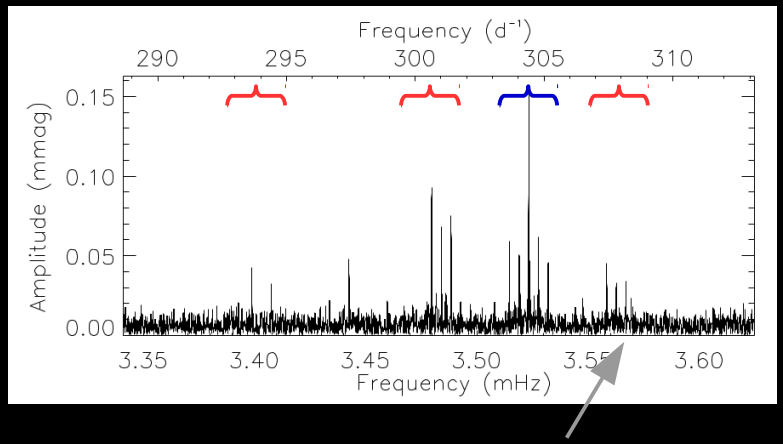
# WG-4: Main sequence AF "classical" pulsators

(Cunha et al., 2019, MNRAS, submitted)

- Rotation and pulsation in Ap stars: first light results from TESS sectors 1 and 2
  - 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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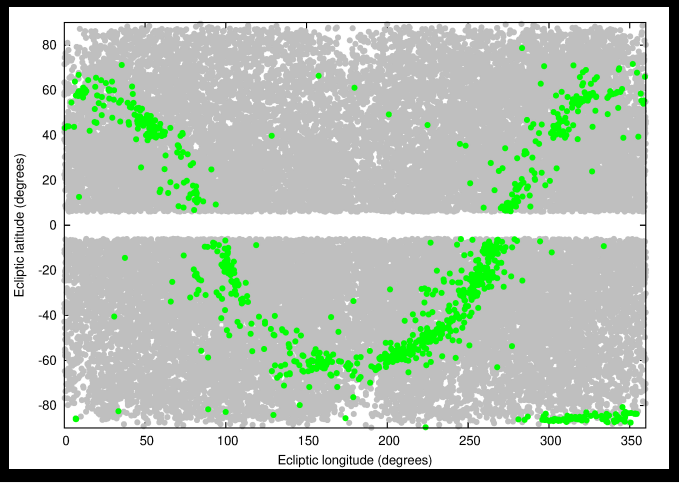
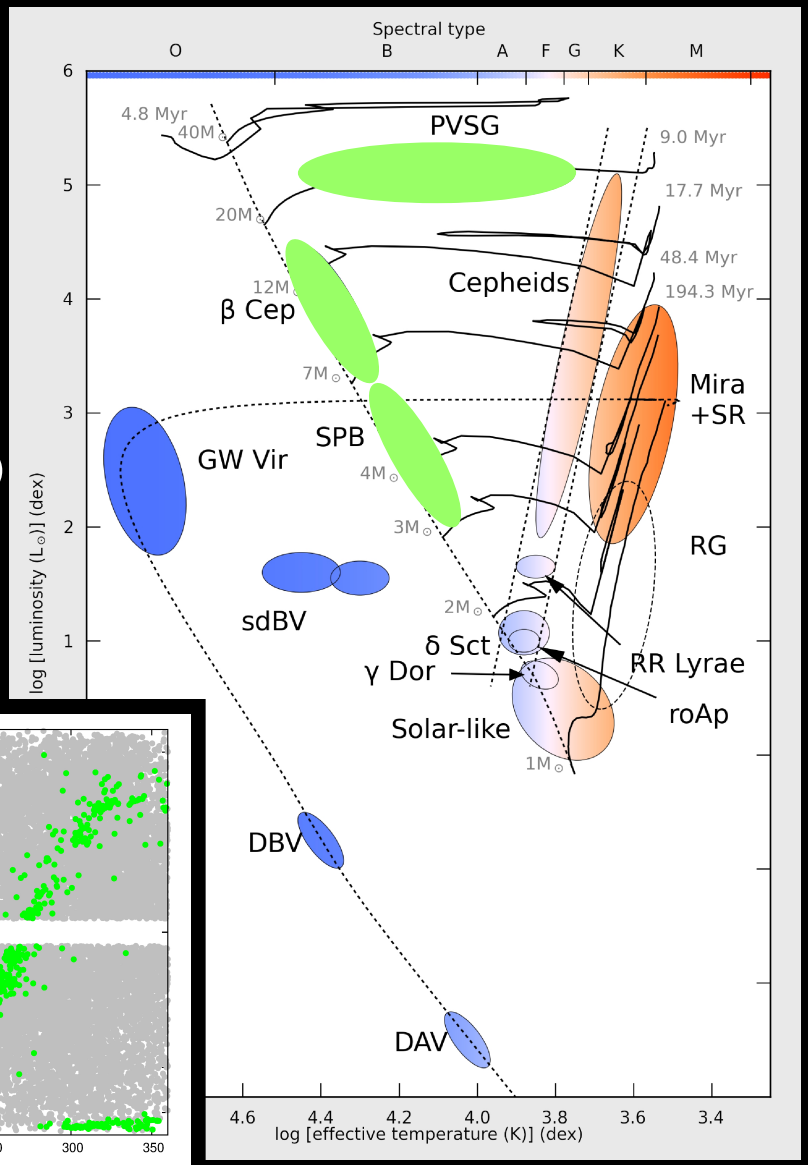
# WG-5: Main sequence OB "classical" pulsators

(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



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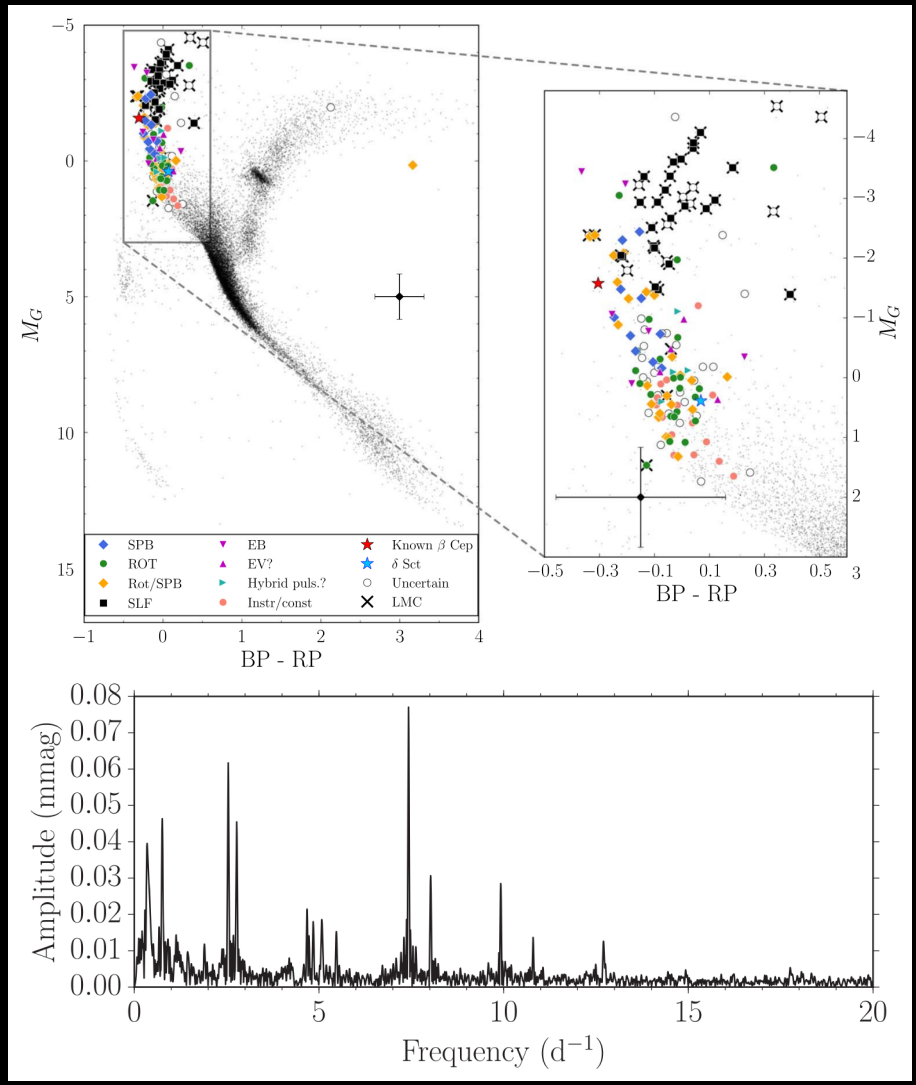
# WG-5: Main sequence OB "classical" pulsators

- 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



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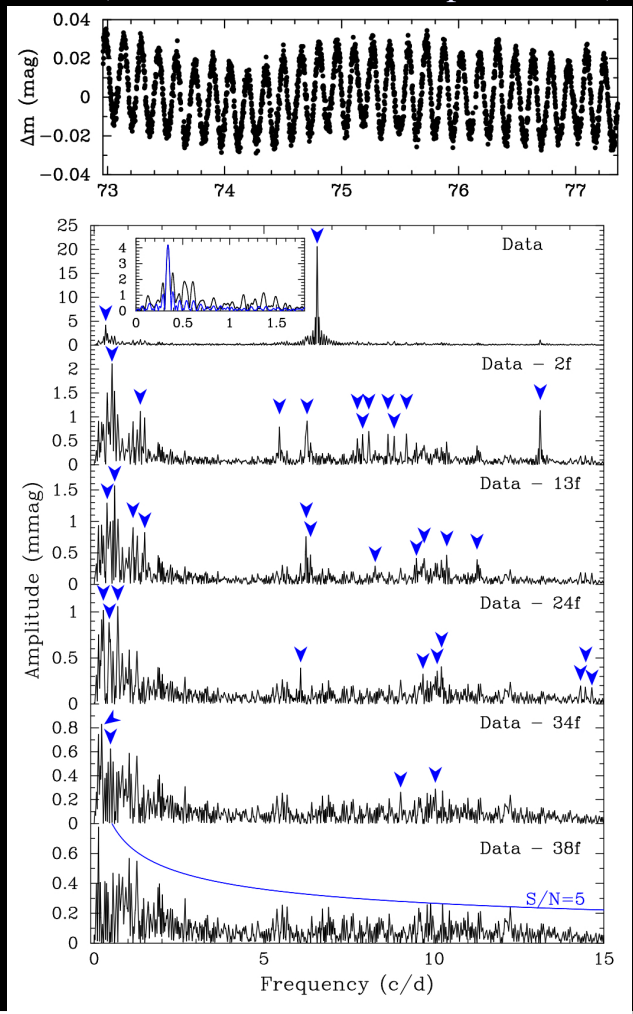
# WG-5: Main sequence OB "classical" pulsators

- Diverse variability of O and B stars (Pedersen et al., 2019, ApJL 872, 9)
- Runaway βCep pulsator PHL346 = HN Aqr (Handler et al., 2019, ApJL 873, 4)
  - 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




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



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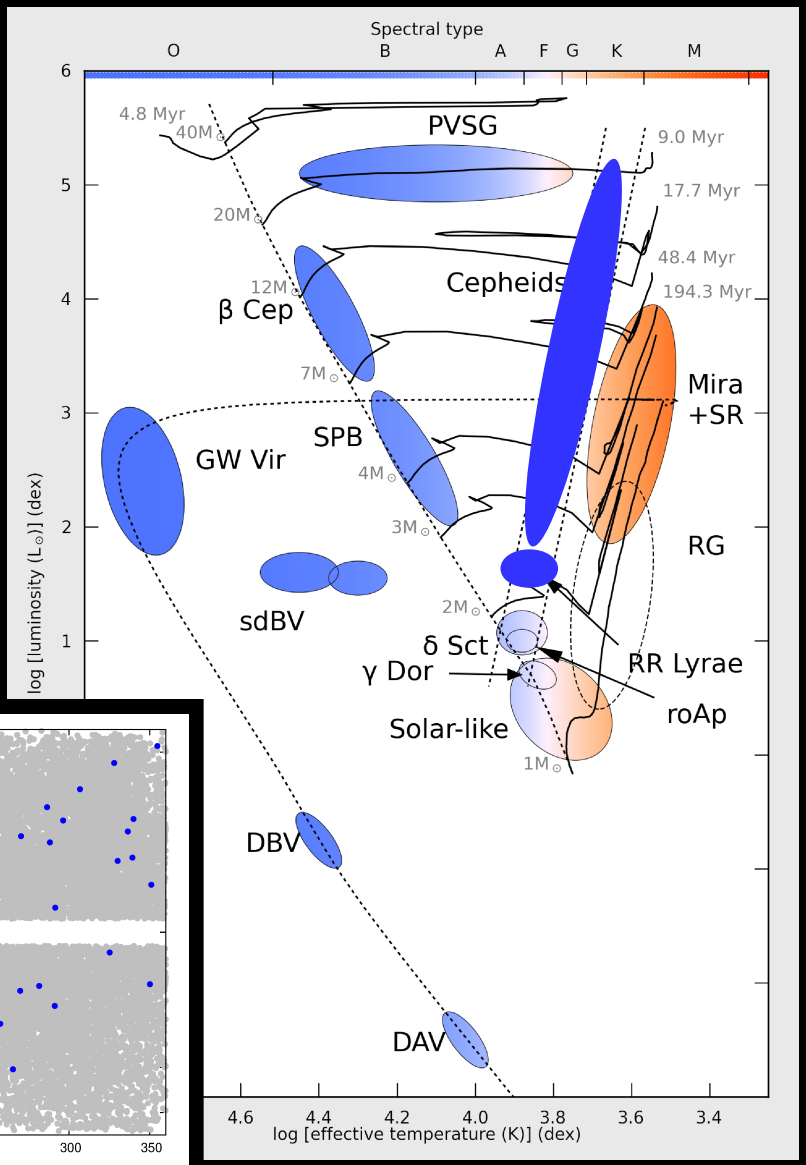
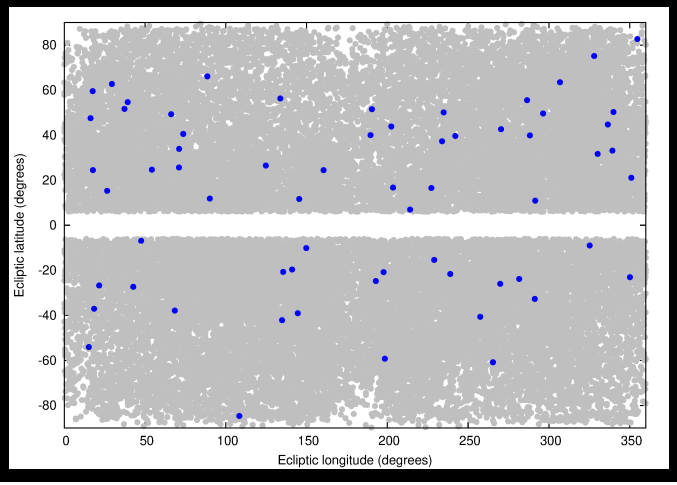
- Diverse variability of O and B stars (Pedersen et al., 2019, ApJL 872, 9)
- Runaway βCep pulsator PHL346 = HN Aqr (Handler et al., 2019, ApJL 873, 4)
- Rotational modulation in TESS B stars (Balona et al., 2019, MNRAS, submitted)
  - classification
  - determination of radii and equatorial rotational velocities
- Magnetic OB[A] Stars with TESS: probing their Evolutionary and Rotational properties (MOBSTER) (David-Uraz et al., 2019, MNRAS, submitted)
  - determination of rotation periods
  - discussion of overall photometric phenomenology
  - proposition of observational strategy

# 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



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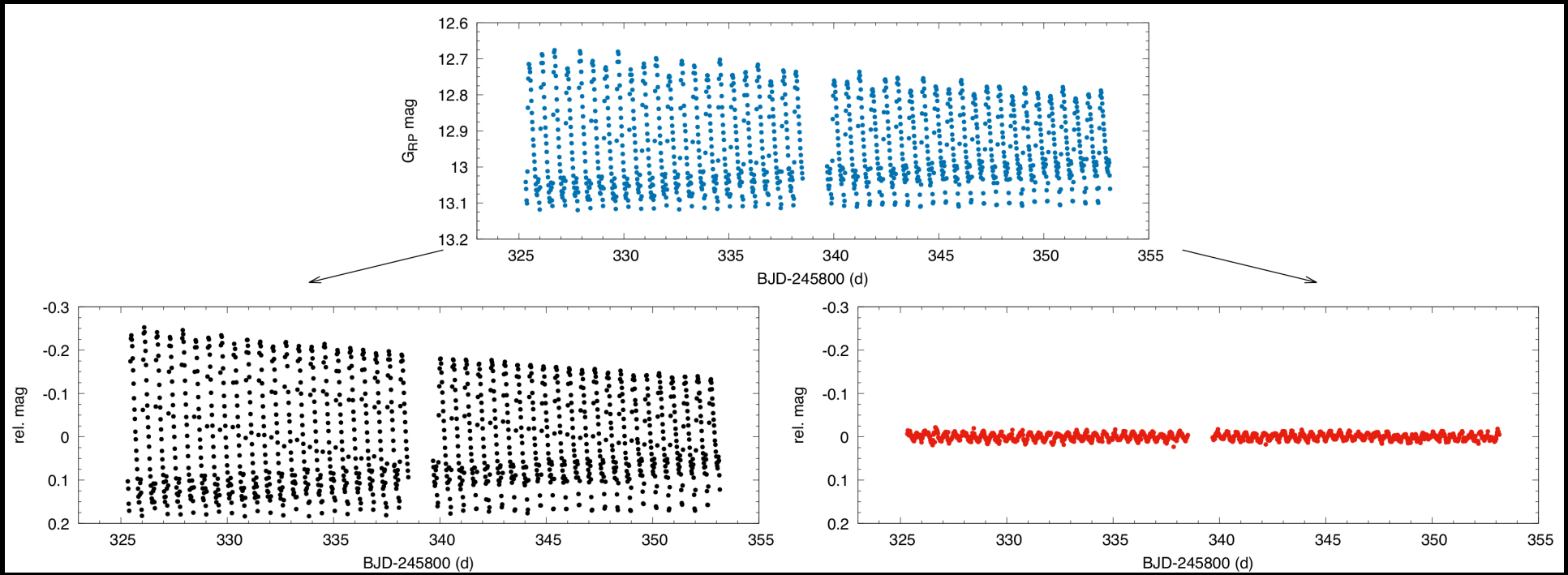
# WG-6: RR Lyrae stars and Cepeids

- 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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    - ✗ 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?

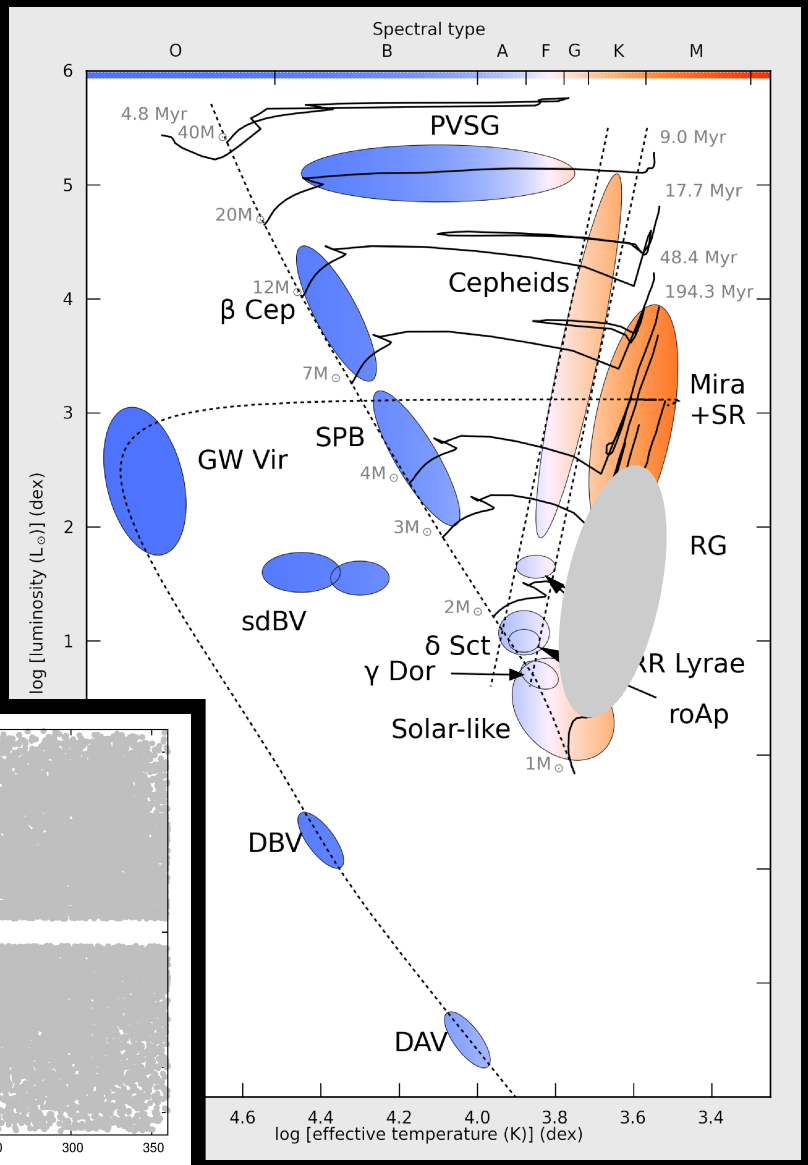
TESS expected to have large impact on serveral topics, e.g.
* proper classification of subtypes for short period Cepheids and RR Lyrae stars
* statistical study of occurrence of additional modes (understanding of mode selection), nonlinear effects, light curve stability, etc.
* clarification of evolutionary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

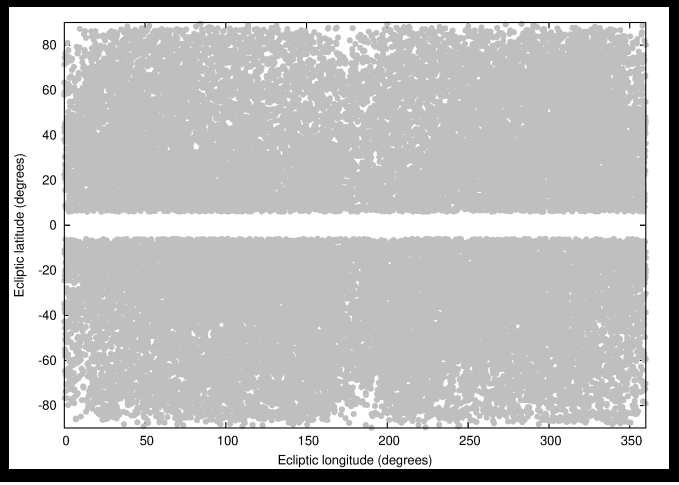
# WG-7: Red giant oscillators

(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)



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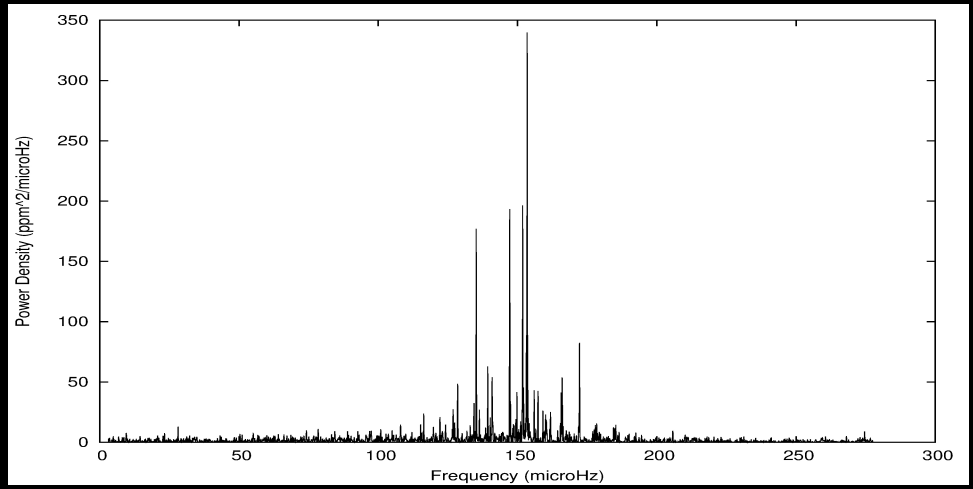
# WG-7: Red giant oscillators

- Analysis of 25 red giants (Silva Aguirre et al. in preparation)
  - potential of TESS for asteroseismology of red giants and Galactic archeology




- Long term goal

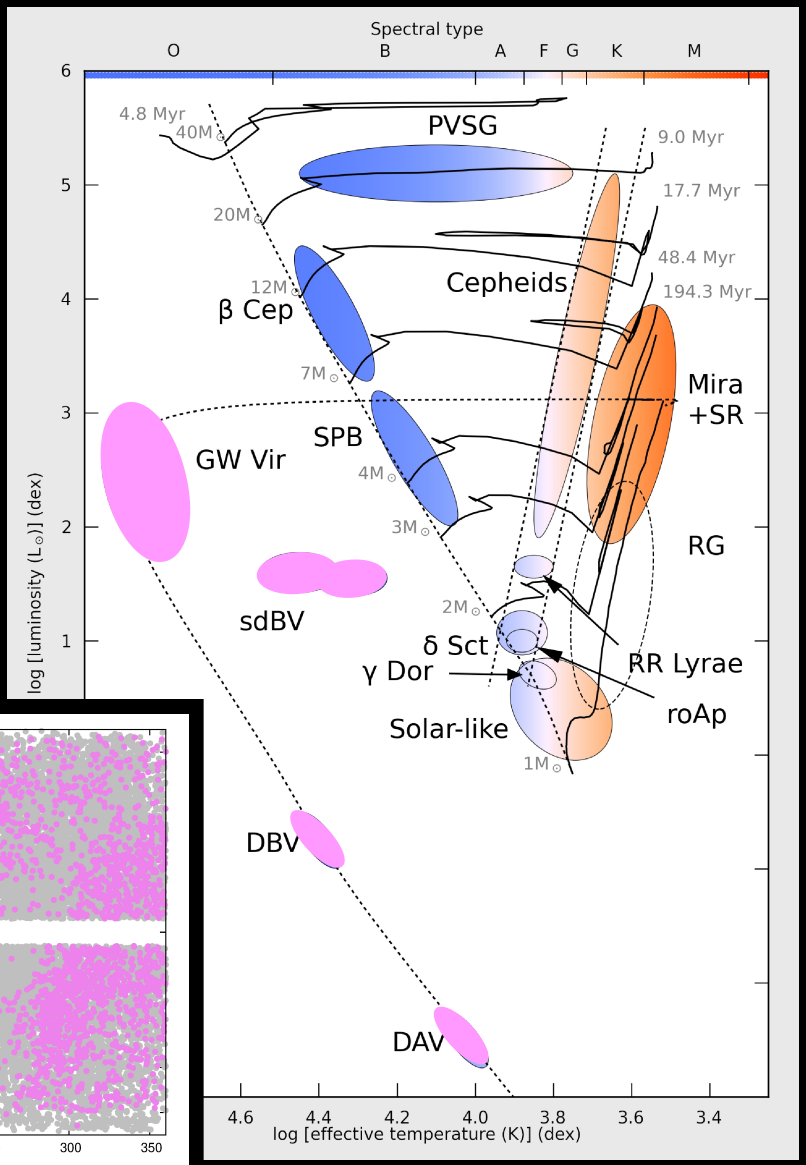
TESS: revision of properties of stellar population surrounding Sun
* asteroseismology of red giants
* in unbiased way
* to a much larger volume than before (~3000 parsec)

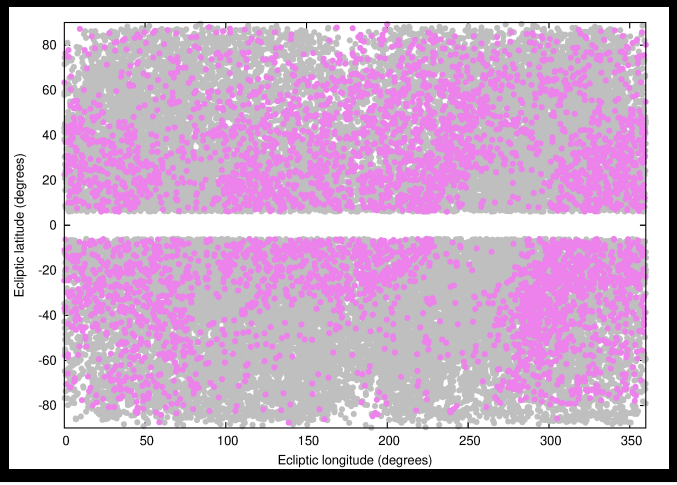
  - new and much stronger constraints to models of Milky Way evolution
  - information about formation of Galactic disk

# 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)



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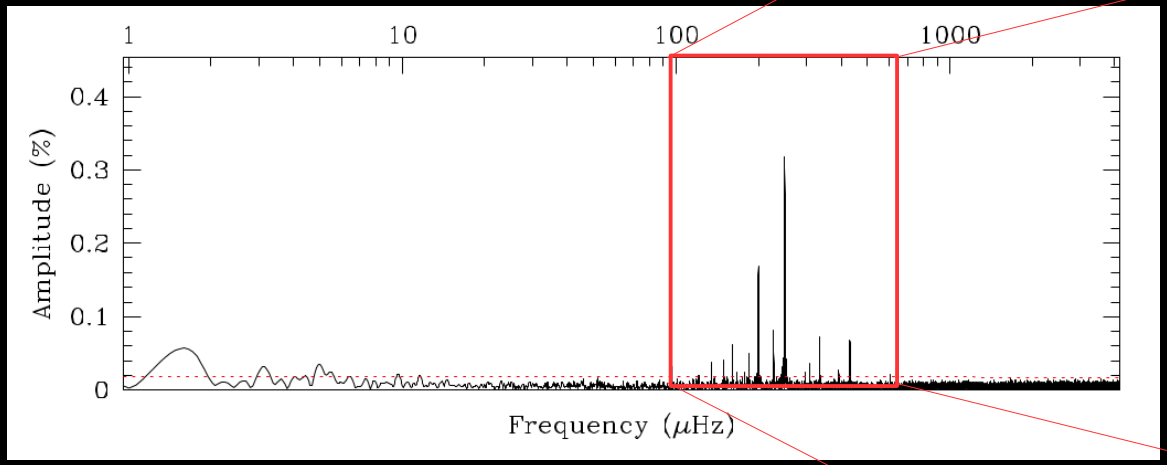
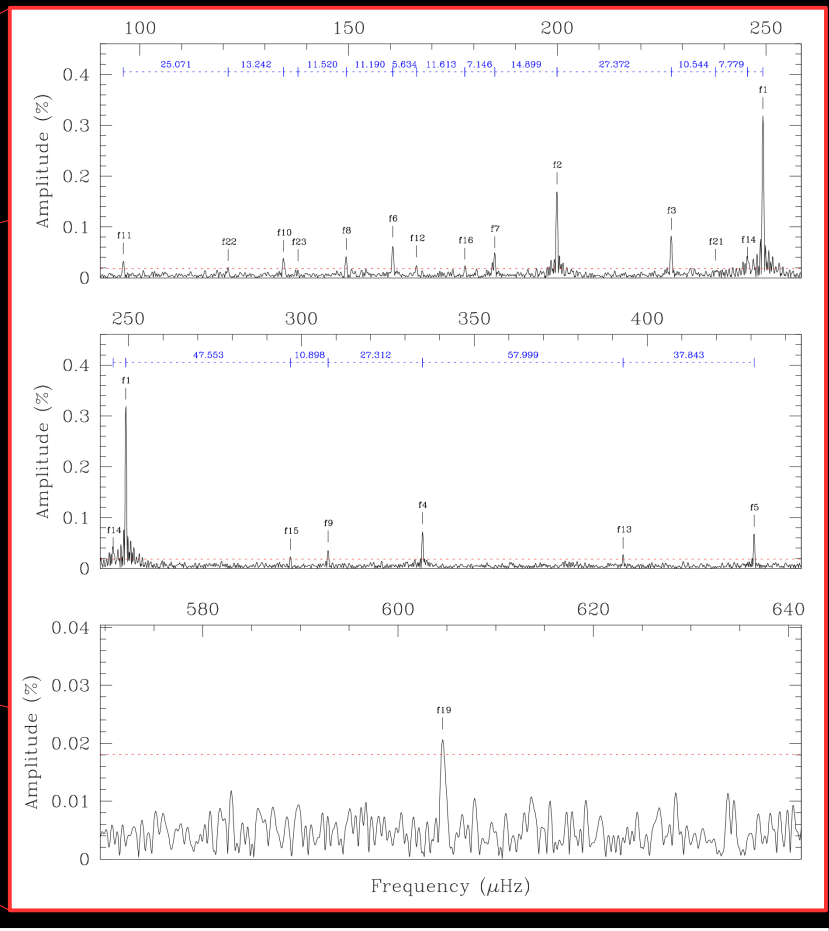
# WG-8: Compact pulsators

- 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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# WG-8: Compact pulsators

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  - rich frequency spectrum between 96 – 605 μHz (27 – 174 min; incl. 20 independent g-modes)
  - 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

# 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)
- Ongoing studies
  - hot pulsating pre-white dwarf NGC246
    - ✗ first GW Virginis star to be monitored from space
  - discovery of an interesting DBV white dwarf
  - plenty of binaries including several eclipsing systems

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

# 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

So far first light results based on data of sectors 1 & 2 only, but a lot of TESS data and papers are yet to come!

Thank you!



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