Benchmark stars for PLATO

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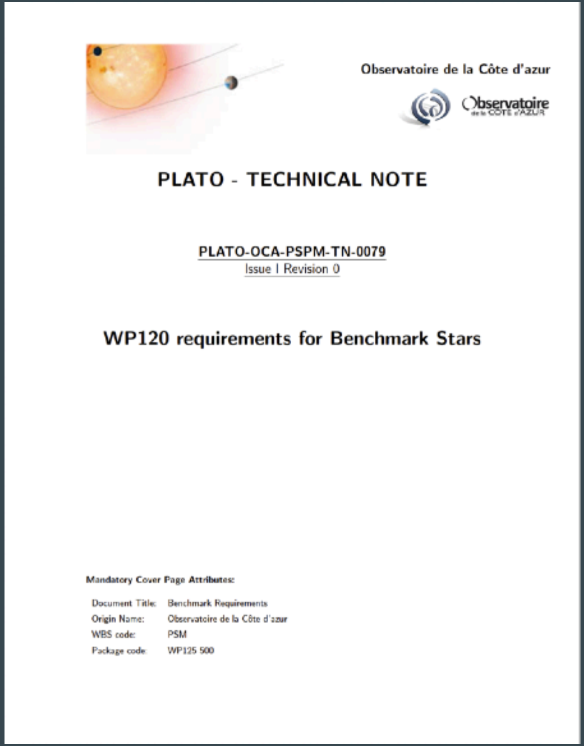
Benchmark stars for PLATO

- WP125500 Benchmark stars work package
- Example of successful benchmarking — limb-darkening
- Benchmark database
- State-of-the-art for detached eclipsing binary stars
- New eclipsing binaries in the LOP fields
- Resolved white dwarfs + FGK star binaries

WP125500 Benchmark stars

- “A benchmark star is a star for which reliable measurements of the star's properties[1] are known.”
- “… used to test and prepare the pipelines in the development phase prior to launch (DEV phase) …”
- “validating the products that are produced during the mission (OPS phase).”

[1]physical quantities, unambiguously defined, and independent of the observer


Observatoire de la Côte d'azur

PLATO - TECHNICAL NOTE

PLATO-OCA-PSPM-TN-0079
Issue I Revision 0

WP120 requirements for Benchmark Stars

Mandatory Cover Page Attributes:

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WBS code:	PSM
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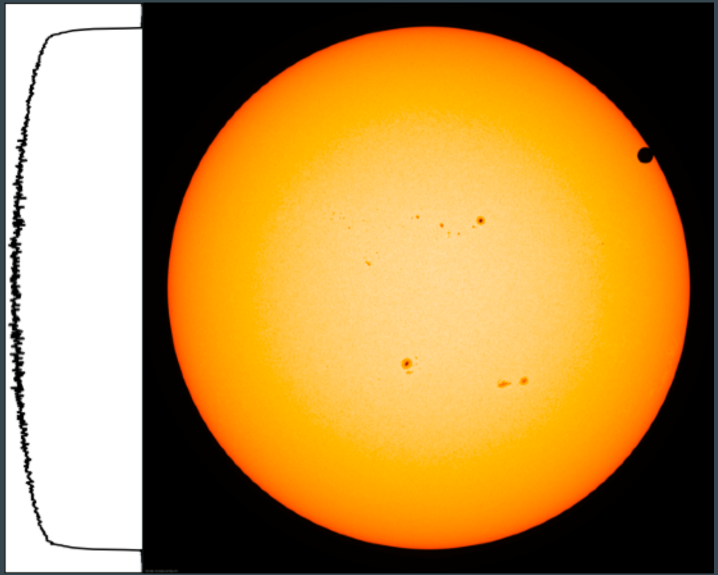
Limb-darkening

$r = 1, \ \mu = 0$ →

$$\mu = \sqrt{1 - r^2}$$

$r = 0, \ \mu = 1$ →



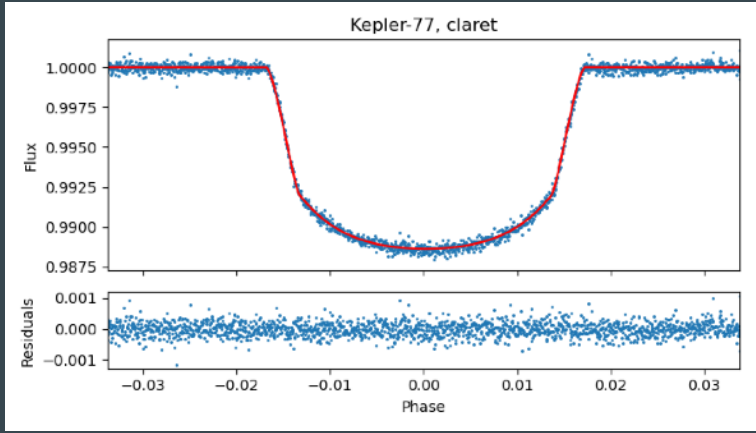
2012 Transit of Venus, Solar Dynamics Observatory

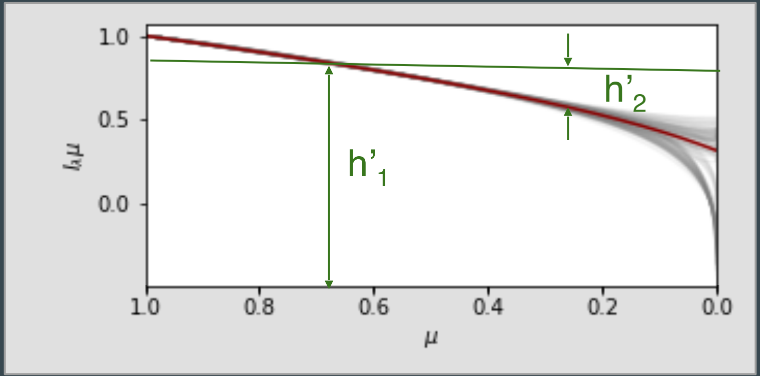
"When one fixes the limb darkening values according to some theoretical predictions, the inconsistencies of the tables do not allow us to reach accuracy in the planetary radius of better than 1-10%"
Csizmadia et al. 2013

Limb-darkening benchmark stars

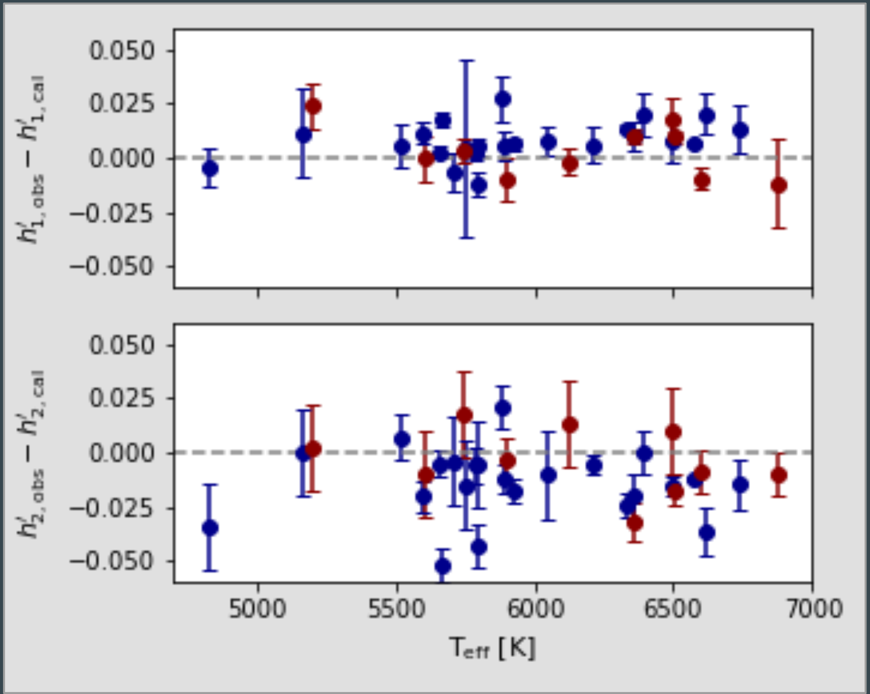
New limb-darkening measurements for 43 FGK stars in Maxted, 2023MNRAS.519.3723M

- From analysis of hot-Jupiter transits
- Fit with Claret 4-parameter law
- Compare to model using
    - $h'_1 = I_\lambda(\mu=2/3)$ [r≈75%]
    - $h'_2 = h'_1 - I_\lambda(\mu=1/3)$ [r≈94%]
- 33 Kepler, 10 TESS

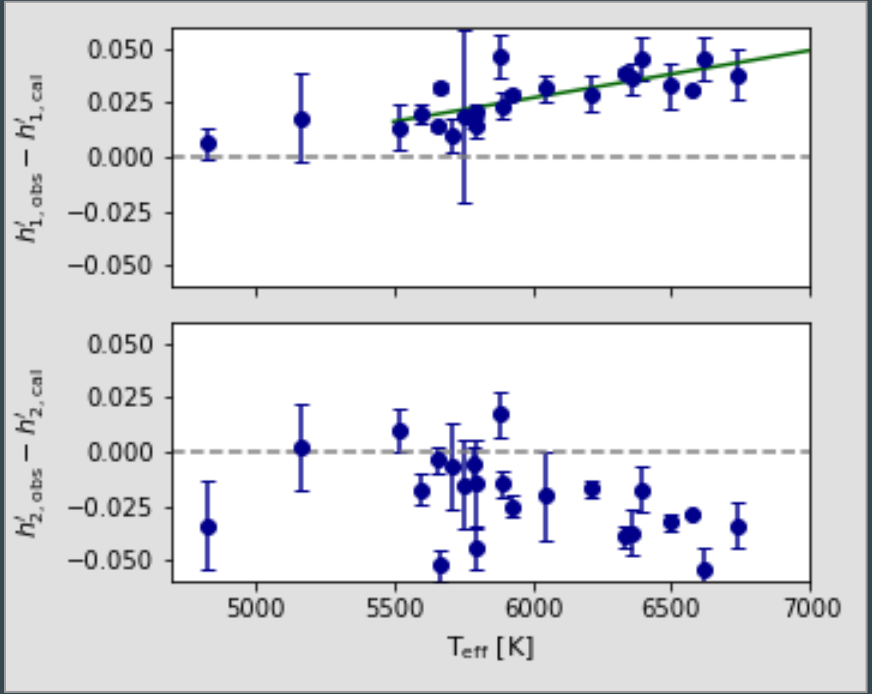




Limb-darkening – comparison to models

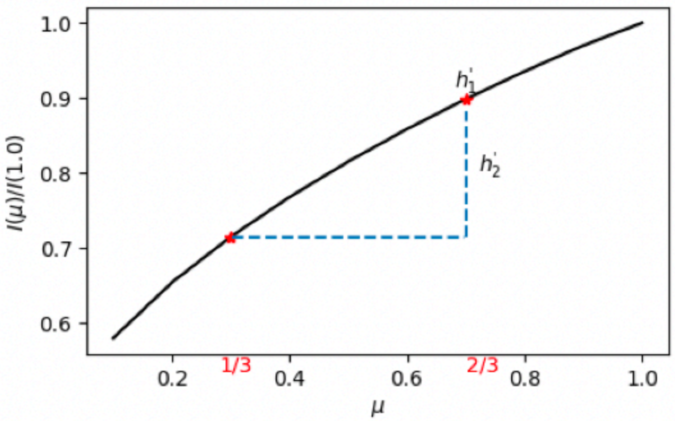


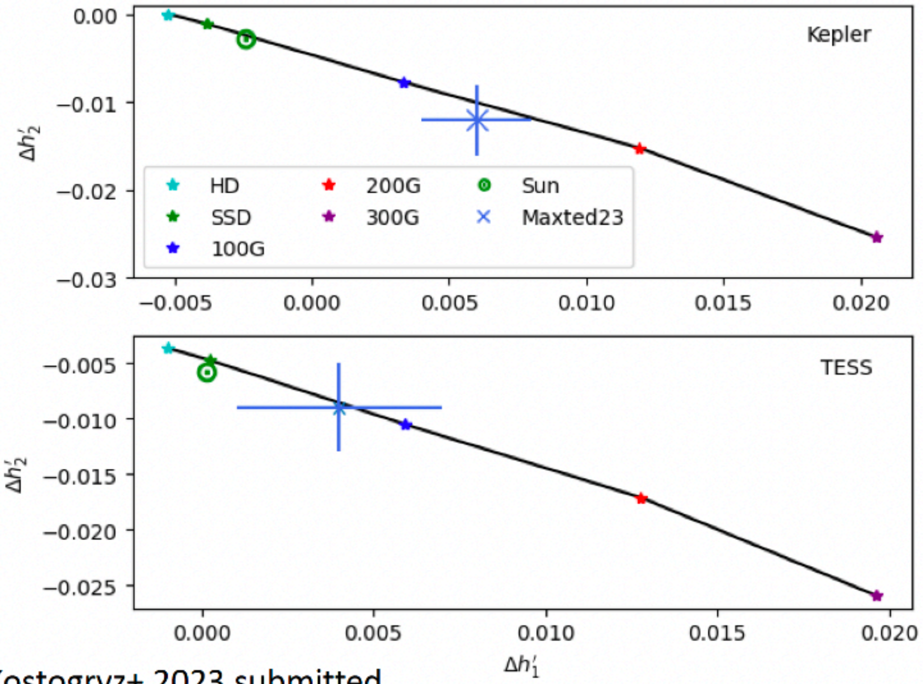
Kostogryz et al. 2023RNAAS...7...39K (MPS-ATLAS)



Morello et al. 2022RNAAS...6..248M (MARCS) https://zenodo.org/record/8117867

Stellar Limb Darkening





$$\Delta h'_{1,2} = h'_{3DMagn} - h'_{REFLD}$$

3DMagn: 3D MURaM (HD, SSD, 100G, 200G, 300G)
REFLD: MPS-ATLAS set1 (Kostogryz + 2022)

Sun in Kepler and TESS: from Neckel & Labs 1994

Stellar LD in Kepler and TESS: from Maxted 2023

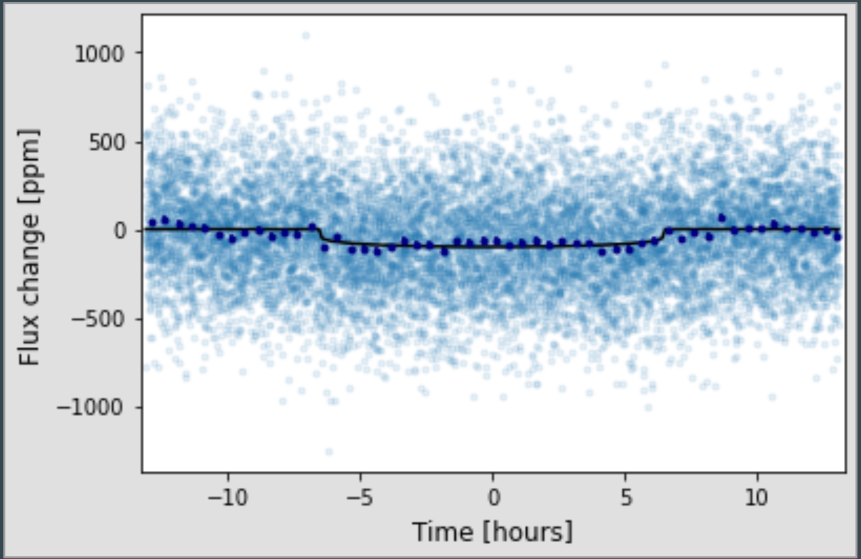
Kostogryz+ 2023 submitted

- The offset in LD modelling can be explained by considering magnetic field.
- We can measure magnetic field from limb darkening

Limb-darkening – implications for PLATO

Earth - Sun transit simulation

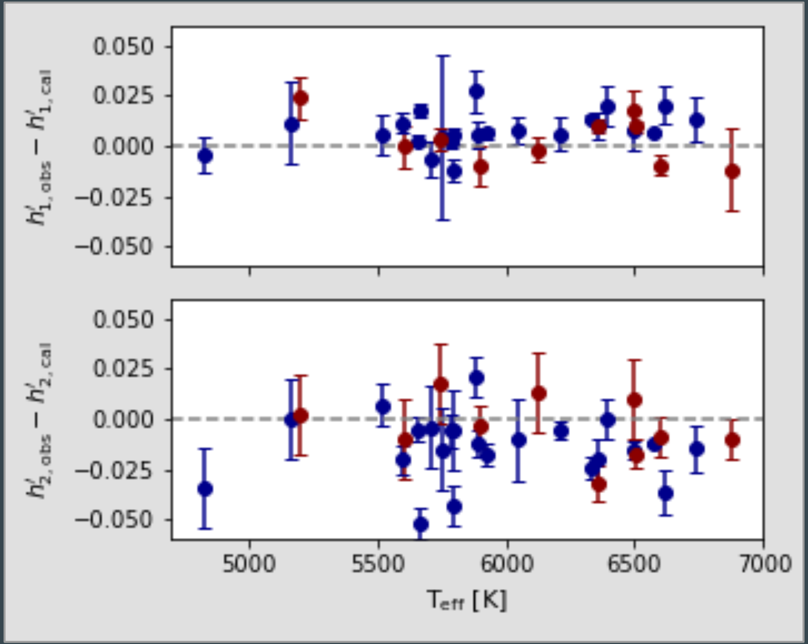
- Noise from PSLS, V=10, 24 cameras
- 3 transits, P = 1 year, b = 0
- Fit with power-2 law limb-darkening
- Gaussian priors on limb-darkening
    - $h'_1 = 0.85 \pm 0.01$
    - $h'_2 = 0.19 \pm 0.01$
- Prior on stellar density ±1%
- Excess variance from l.d. = $(0.3\%)^2$



Lessons learned …

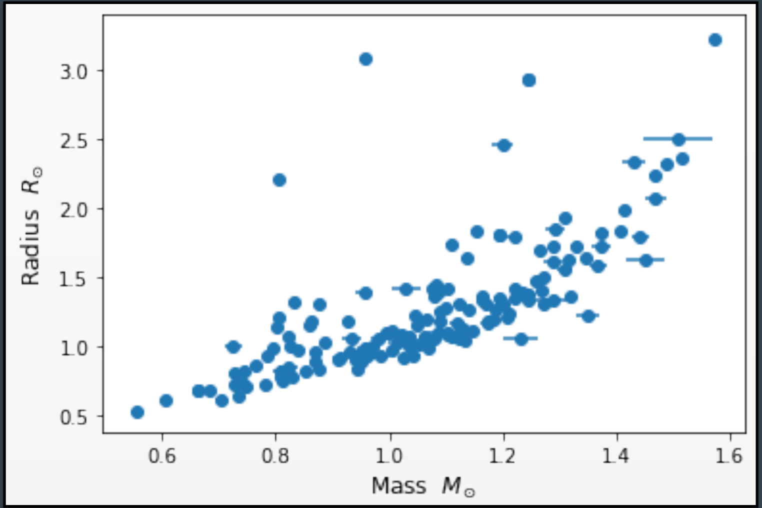
Benchmarking exercise for limb-darkening …

- … enables PLATO to achieve required accuracy on $R_p/R_\star$ of ±3%;
- … enables us to set accurate priors on limb-darkening for light curve analysis;
- … identifies an issue with PLATO MARCS models used for PLATO data analysis;
- … enables new science to be done with PLATO light curves.



WP125500 Benchmark database

- Seismic stars (OLC)
  - Kepler legacy, etc.
- Detached eclipsing binary stars (PM)
  - 151 P1-like stars in 90 binaries from DEBCat
- M-dwarfs (UH)
  - K7—M4 stars with measured angular diameters
- Wide binaries (TM)
  - Age / [Fe/H] consistency check
- etc…



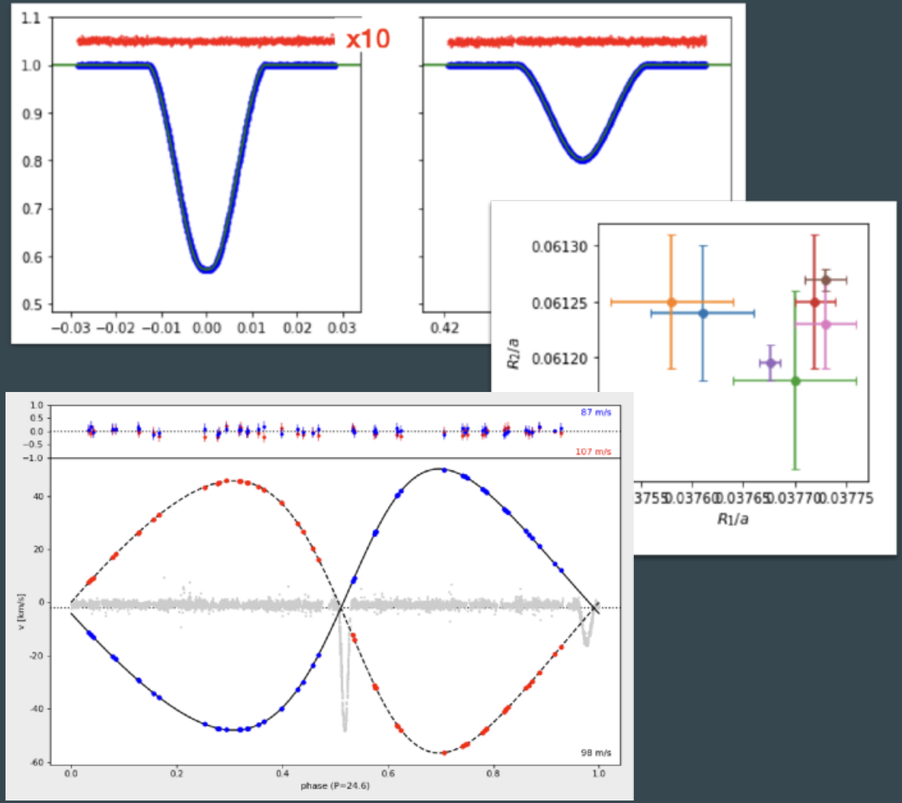
P1-like stars from DEBCat

State-of-the-~~art~~ science for detached eclipsing binaries (DEBs)

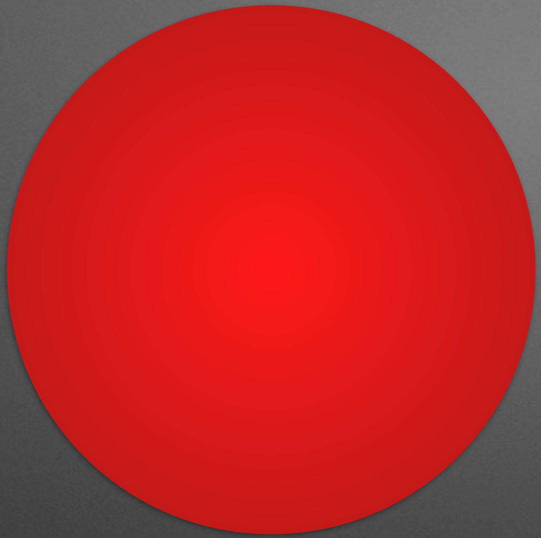
AI Phe (Maxted et al. 2020MNRAS.498..332M)

- F7V + K0IV
- V = 8.6
- P = 24.6 d
- $M_A = 1.1938 \pm 0.0008\ M_\odot$
- $R_A = 1.8050 \pm 0.0022\ R_\odot$
- $M_B = 1.2438 \pm 0.0008\ M_\odot$
- $R_B = 2.9332 \pm 0.0023\ R_\odot$

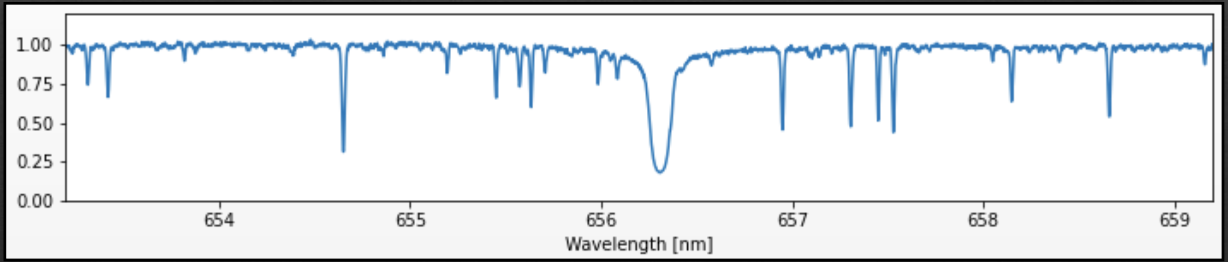
<u>Accurate mass and radius measurements ±0.1% are possible in favourable cases.</u>



Primary eclipse



Secondary eclipse



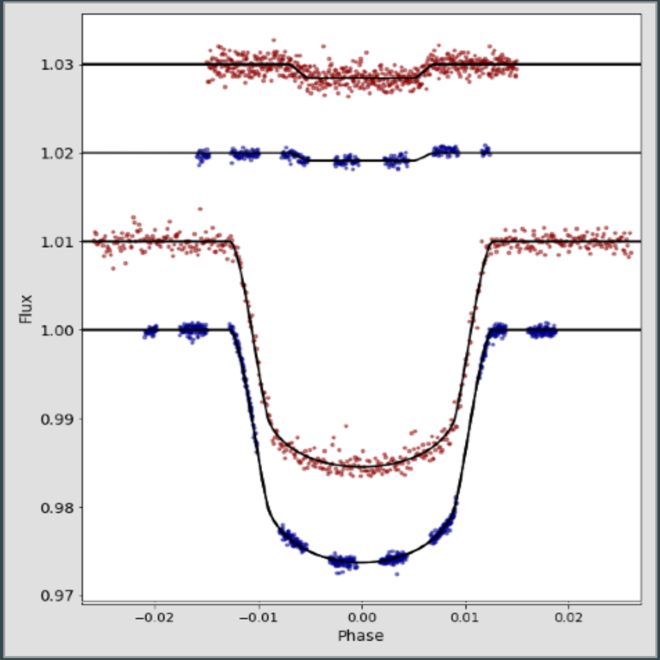
UVES spectrum of K0IV star, T_{exp}=530s

State-of-the-~~art~~ science for detached eclipsing binaries (DEBs)

EBLM J0113+31

- G0V + M4V
- V = 10.1
- P = 14.3 d
- 4-σ detection of M4V star by stacking CCFs from 22 SPIRou spectra
- $M_A = 1.029 \pm 0.025\ M_\odot$
- $R_A = 1.417 \pm 0.014\ R_\odot$
- $M_B = 0.197 \pm 0.003\ M_\odot$
- $R_B = 0.215 \pm 0.002\ R_\odot$

<u>Masses can be measured for DEBs with optical flux ratios ≳0.1%.</u>

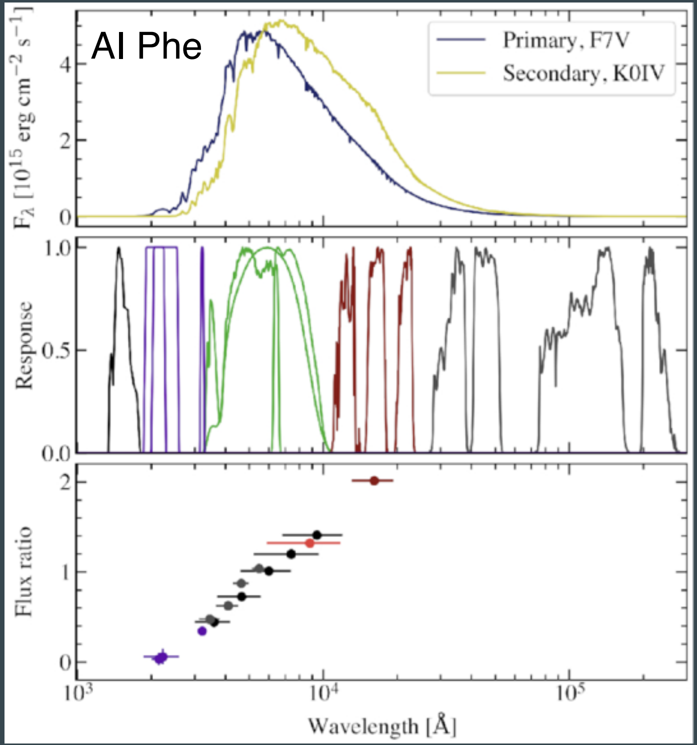


Maxted et al. 2022MNRAS.513.6042M

Fundamental T_{eff} measurements for DEBs

$$T_{\rm eff} = \left(\frac{4\mathscr{F}_{\rm bol}}{\theta^2}\right)^{\frac{1}{4}}$$

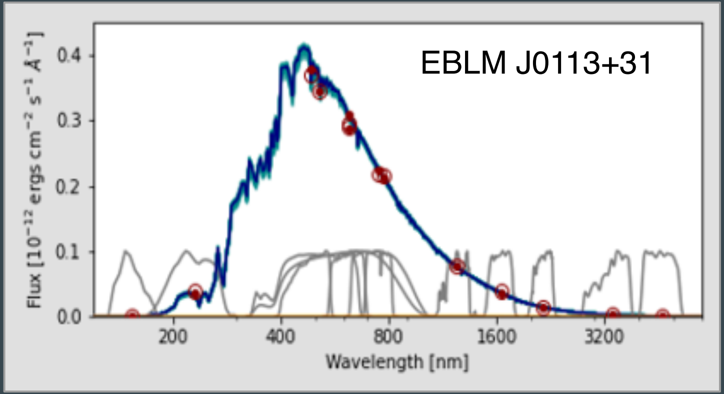
- $\theta = 2R/d$ (angular diameter)
- Distances, *d*, to DEBs from Gaia
- Bolometric flux, $\mathscr{F}_{\rm bol}$, from GALEX + GAIA + 2MASS + …
- For DEBs,
    - $\mathscr{F}_{\rm bol} = \mathscr{F}_{\rm bol,1} + \mathscr{F}_{\rm bol,2}$
    - $\mathscr{F}_{\rm bol,2}/\mathscr{F}_{\rm bol,1}$ from light curves + empirical colour — T_{eff} relations.
- Full method described in Miller et al. 2020MNRAS.497.2899M
- This is <u>not</u> SED fitting

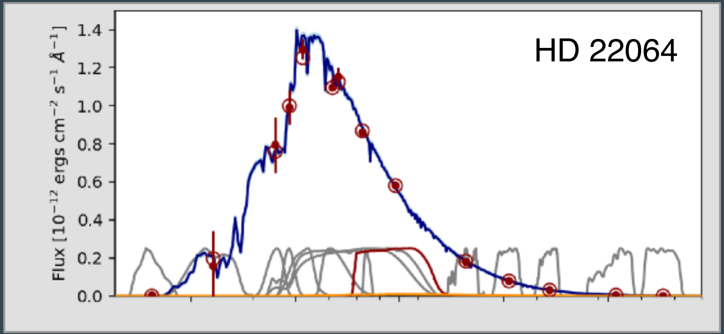


Miller et al. 2020MNRAS.497.2899M

Fundamental T_{eff} measurements for DEBs

- **AI Phe**: $T_{eff,A}$ = 6199 ± 22 K, $T_{eff,B}$ = 5094 ± 16 K
  - Miller et al. 2020MNRAS.497.2899M
- **CPD-54 810**: $T_{eff,A}$ = 6462 ± 43 K, $T_{eff,B}$ = 6331 ± 43 K
  - Miller et al. 2022MNRAS.517.5129M
- **EBLM J0113+31**: $T_{eff,A}$ = 6124 ± 40 K
  - Maxted et al. 2022MNRAS.513.6042M
- **HD 22064**: $T_{eff,A}$ = 6763 ± 39 K
  - Maxted 2023MNRAS.522.2683M

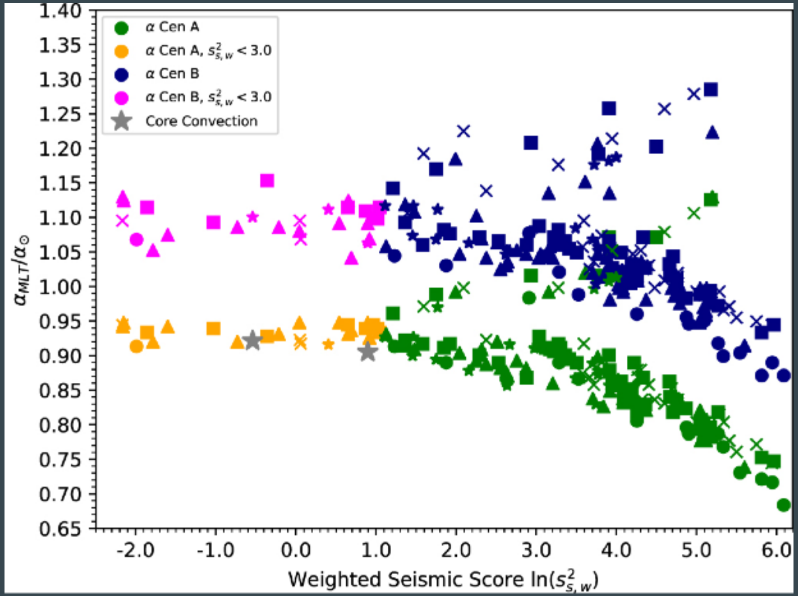




α Cen A & B – a taste of things to come

- Errors on mass & radius ≈ ±0.4%
    - Similar to typical recent results for DEBs
- Random errors on $T_{\rm eff}$ ≈ 20K
    - cf. ~100K for most EBs
    - 1% error on absolute flux scale ⇒ ±10K

- A: r_{02} = 0.055 ± 0.001 (44 modes)
- B: r_{02} = 0.066 ± 0.004 (37 modes)
- ⇒ ΔY/ΔZ = 0.90 ± 0.12



Joyce & Chaboyer 2018ApJ...864...99J

Previously-studied eclipsing binaries in LOPN1/LOPS2

Select from DEBCat (M,R ±2% or better)

- FGK: 4050 K < T_{eff} < 6510 K
- IV/V: $R_\star < 3.5\ R_\odot$
- $R_\star/a < 0.15$ (to avoid tidal spin-up ⇒ magnetic activity ⇒ suppression of modes)
- An estimate for [Fe/H]

Six stars in 5 binaries in the LOPN1/LOPS2 with V < 11

- ASAS_J065134-2211.5, P = 8.2 d, 1.0 $M_\odot$
- KIC 6525196 P = 3.4 d (triple), 1.0 $M_\odot$
- WASP 0639-32, P = 11.7 d, 1.2 $M_\odot$
- FL Lyr, P = 2.2 d, 1.0+1.2 $M_\odot$
- CPD-54 810, P = 26.1 d, 1.3 $M_\odot$

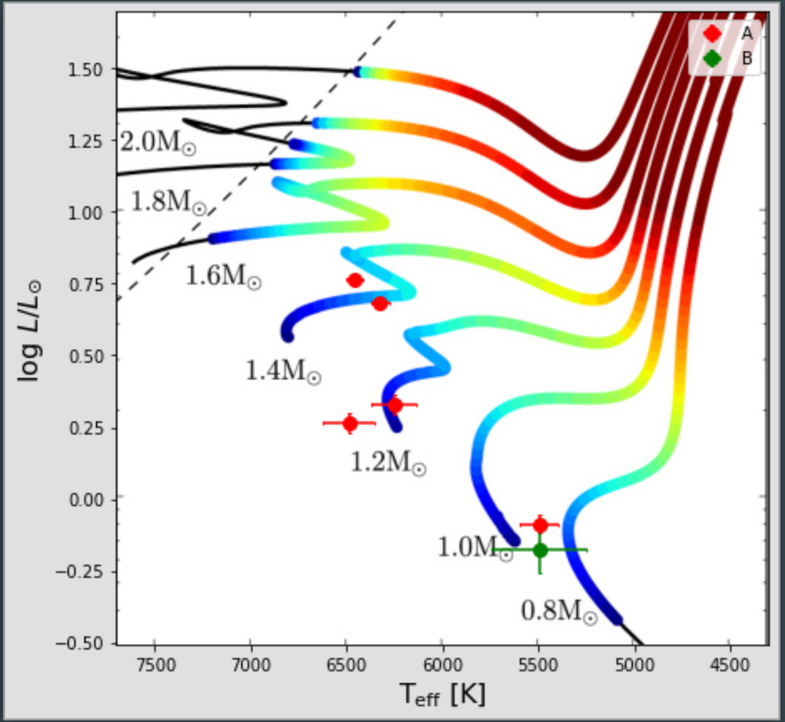
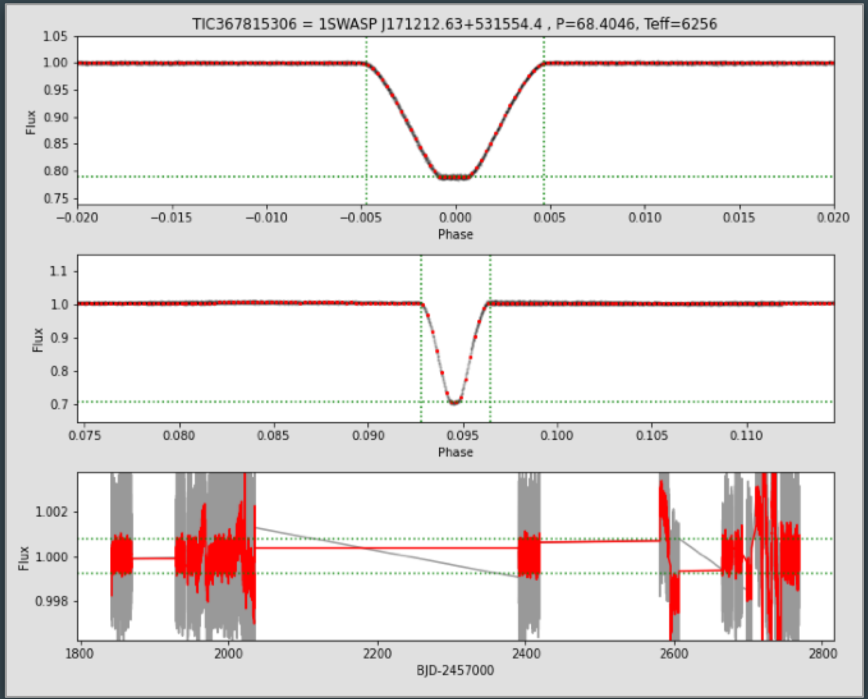
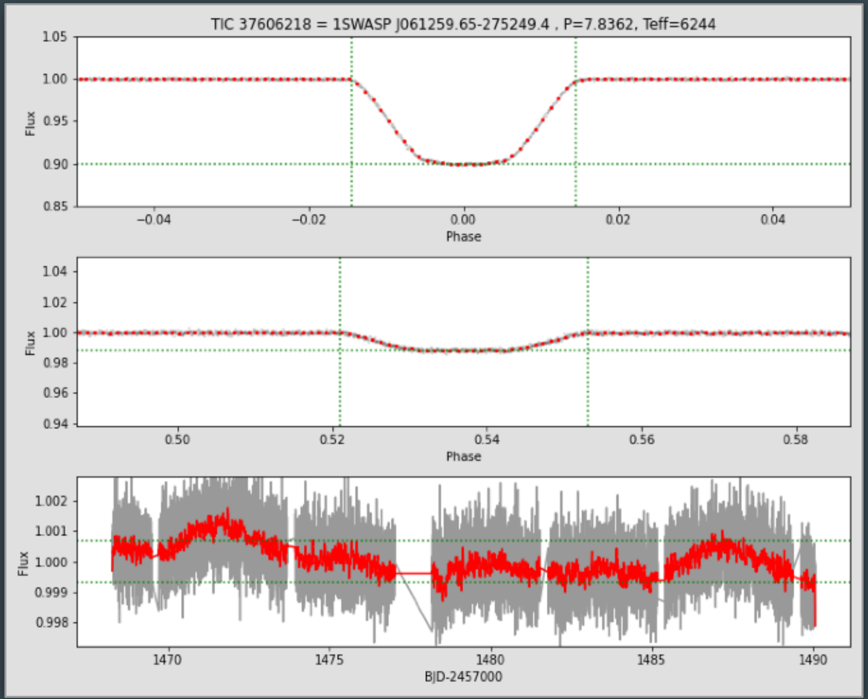


Image from Campante et al. 2016ApJ...830..138C

Search for new eclipsing binaries in LOPN1/LOPS2

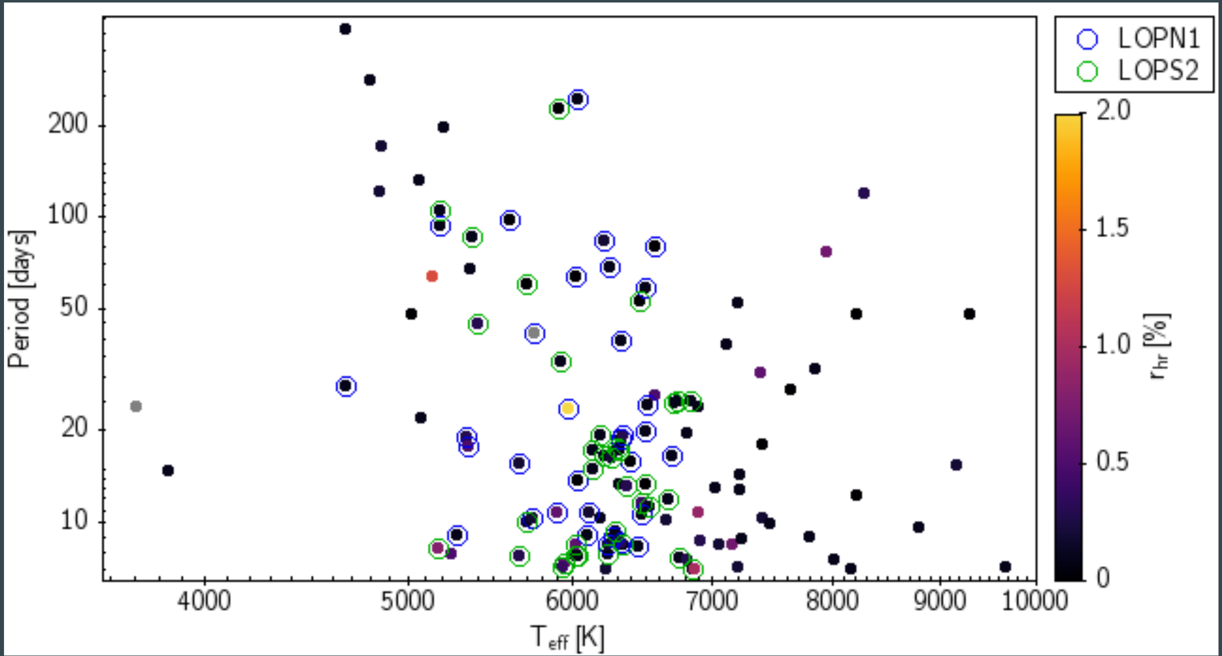


J171212.63+531554.4, T=9.96, T_{eff} = 6256 K, P = 68.40 d



J061259.65-275249.4, T=9.26, T_{eff}=6244 K, P = 7.84 d

Search for new eclipsing binaries in LOPN1/LOPS2

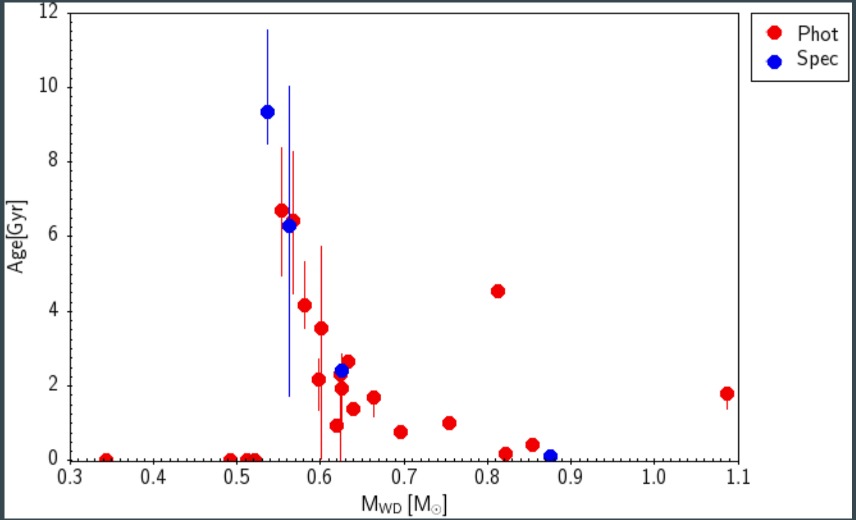


36 binaries in pLOPS2PICtarget2.0.0.1-t

32 binaries in pLOPN1PICtarget2.0.0.1-t

Resolved white dwarfs + FGK star binaries

- Age of system from WD cooling age + main-sequence lifetime
- Does not work if $M_{WD} \lesssim 0.5\ M_\odot$
- Best ages from massive white dwarfs
  - Typical $M_{WD} \approx 0.6 M_\odot$ may be useful
- 11 stars in pLOPN1PICtarget2.0.0.1-t with
  - $V < 11$
  - $M_{WD} > 0.55\ M_\odot$
- To do:
  - Systematic search with Gaia DR3
  - Get spectra for all WD companions



Rebassa-Mansergas et al.2021MNRAS.505.3165R

Thanks for your attention

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