Direct effective temperature measurements from eclipsing binaries

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Accuracy of T_{eff} for FGK dwarfs

Petigura et al. (2017) California-Kepler Survey

“we encourage adding 100 K systematic uncertainty”

Berger et al. (2020) Gaia–Kepler Stellar Properties Catalog

“there are systematic errors in interferometric angular diameters which, in turn, set the fundamental limit on T_{eff} errors: ≈ 2%.”

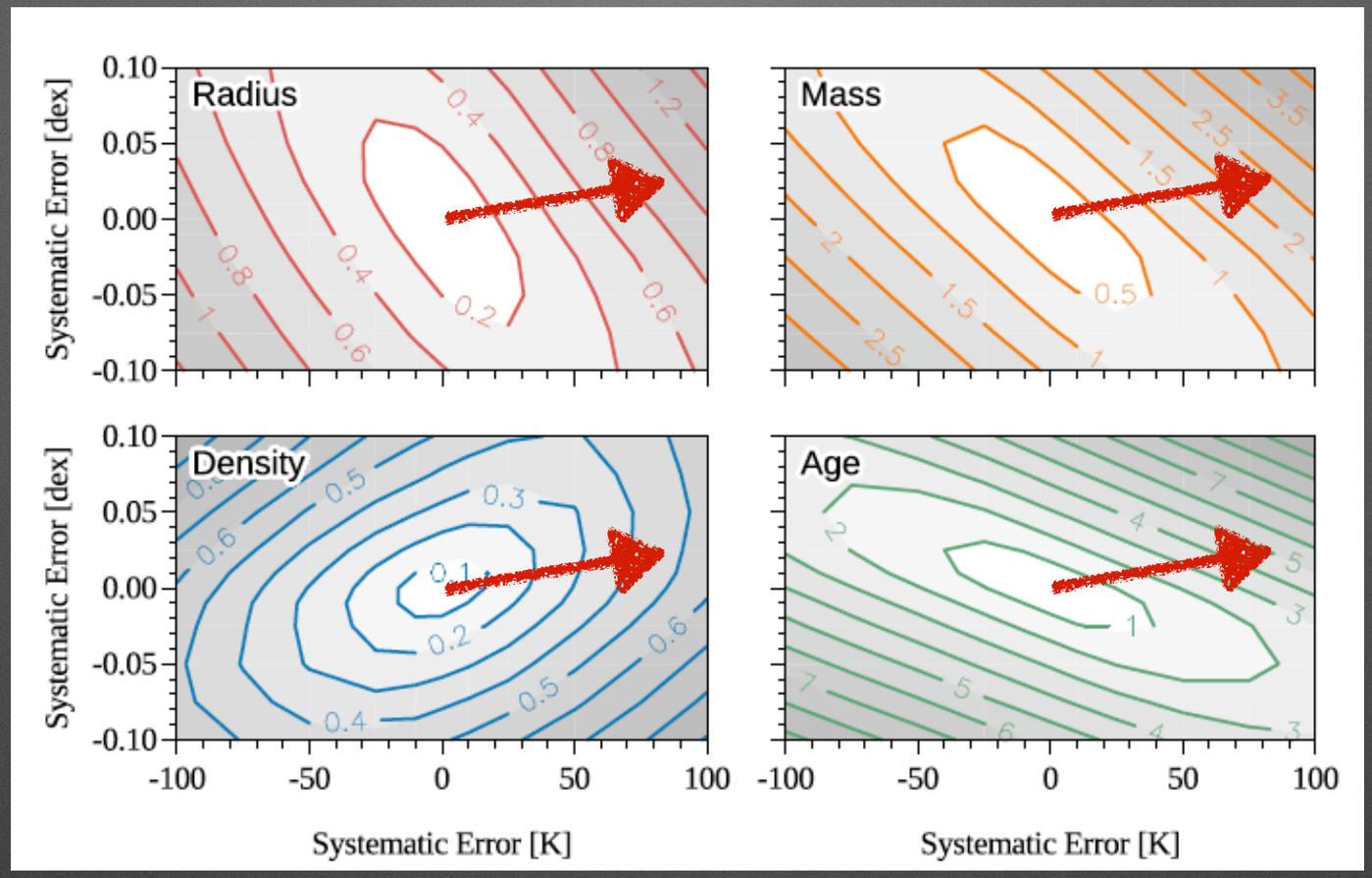
Ryabchikova et al. (2016) Spectroscopy Made Easy (sme)

“The uncertainty in the effective temperature is 50–70 K for the S/N = 200 spectra of the MS F-, G-, K-type stars.”

Doyle et al. (2013) Accurate spectroscopic parameters of WASP planet host stars

“ limit to the accuracy … using high S/N spectra, and the average uncertainty in T_{eff} … is 83 K,”

Impact of T_{eff} errors



Bellinger et al. 2020A&A...635C...2B — Kepler + SPI

Doyle et al. 2013MNRAS.428.3164D : ΔT_{eff} = +83 K ⇒ Δ[Fe/H] = +0.02 — +0.03

- ✦Also impacts accuracy of planet parameters
- ✦Expect bigger impact for stars where we have less information, e.g., M dwarfs
- ✦Limiting factor for calibrating stellar models using eclipsing binaries.
- ✦These are *systematic errors* ⇒ spurious trends for large samples

Direct $T_{\rm eff}$ measurements

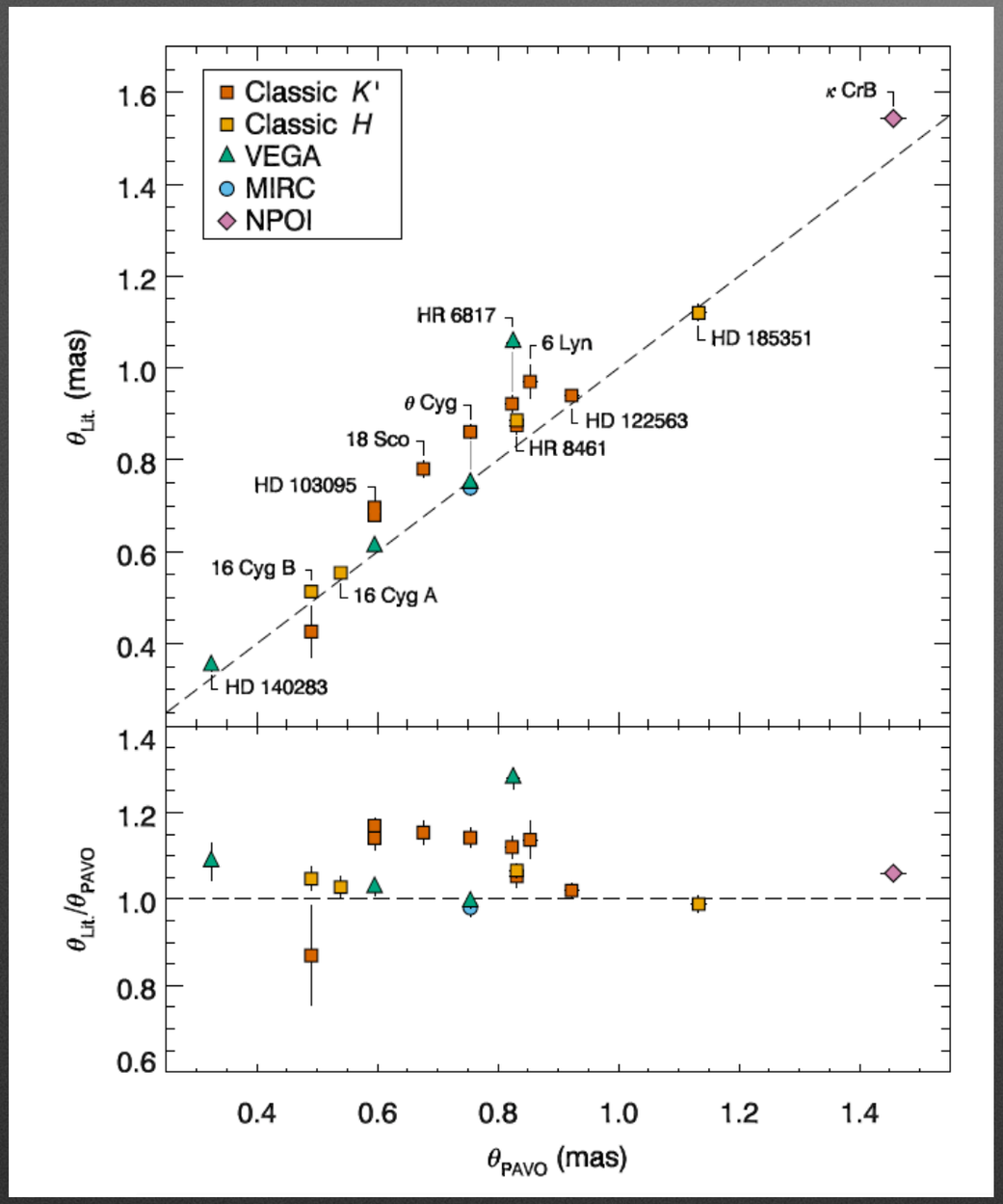
$$L = 4\pi R^2 \sigma T_{\rm eff}^4$$

$$T_{\rm eff} = \left(\frac{4 F_{\rm bol}}{\sigma \theta^2} \right)^{1/4}$$

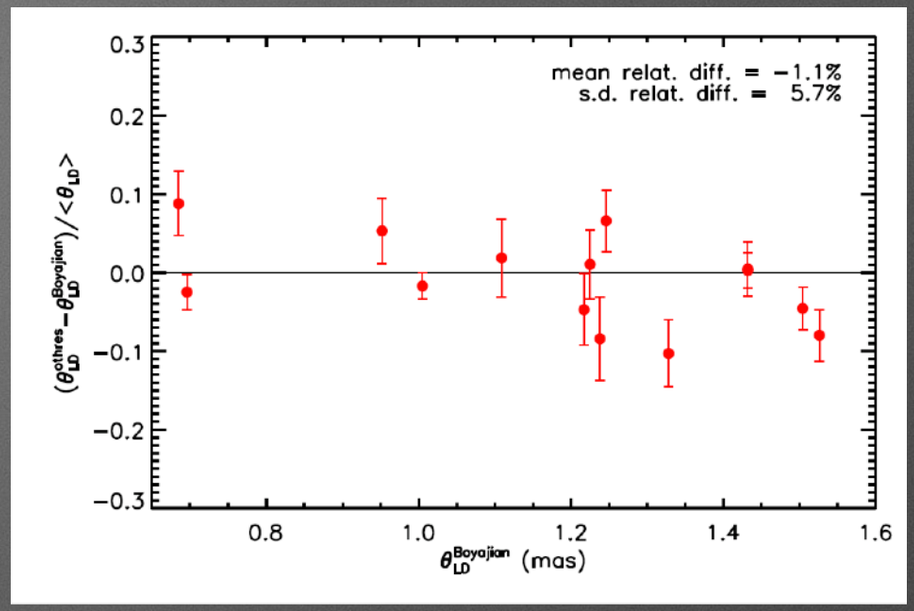
- $\theta = 2R/d$, angular diameter
  - $\theta = 9.30\,{\rm mas} \times (R/R_\odot)/(d/{\rm pc})$
- $F_{\rm bol} = L/4\pi d^2$, bolometric flux (ignoring reddening)
- $\Rightarrow T_{\rm eff}$ ± ~2% for $1 R_\odot$ @ 10 pc if θ from interferometry
- Eclipsing binaries:
  - R ± 0.5% or better
  - d ± 1% @ 250 pc (Gaia DR2), ± 0.25% (Gaia DR4)

Consistency of θ from interferometry

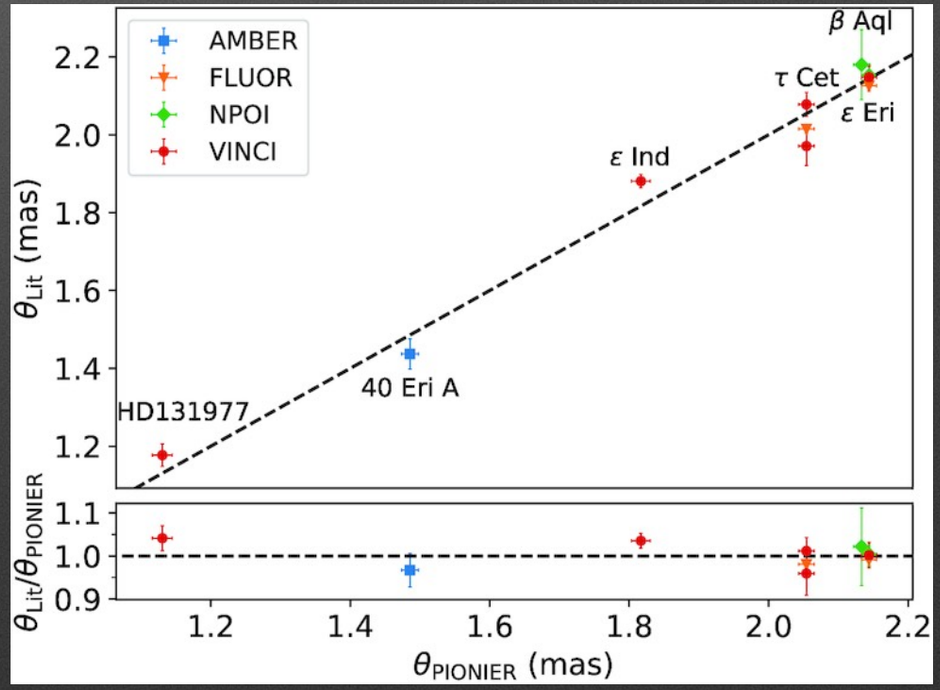
Systematic errors ≈ 0.05 mas



White et al. 2018MNRAS.477.4403W

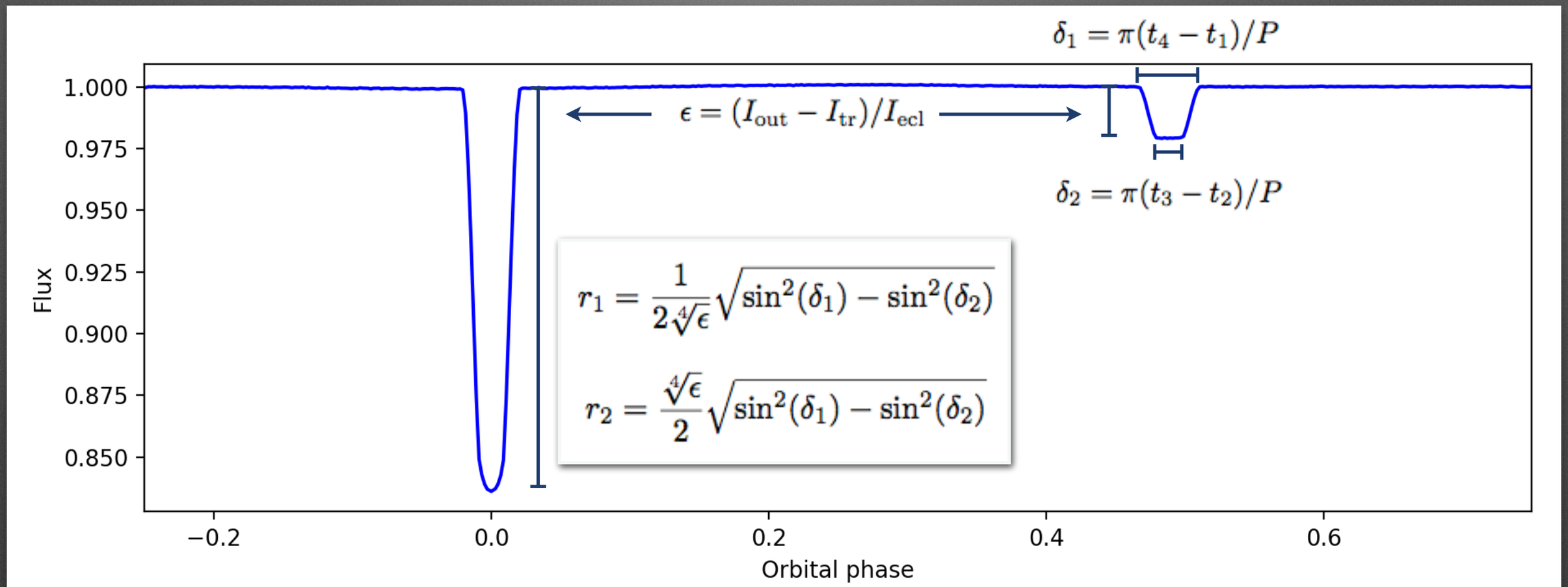


Huang et al. 2015MNRAS.454.2863H



Raines et al. 2020MNRAS.493.2377R

Basic theory — light curves



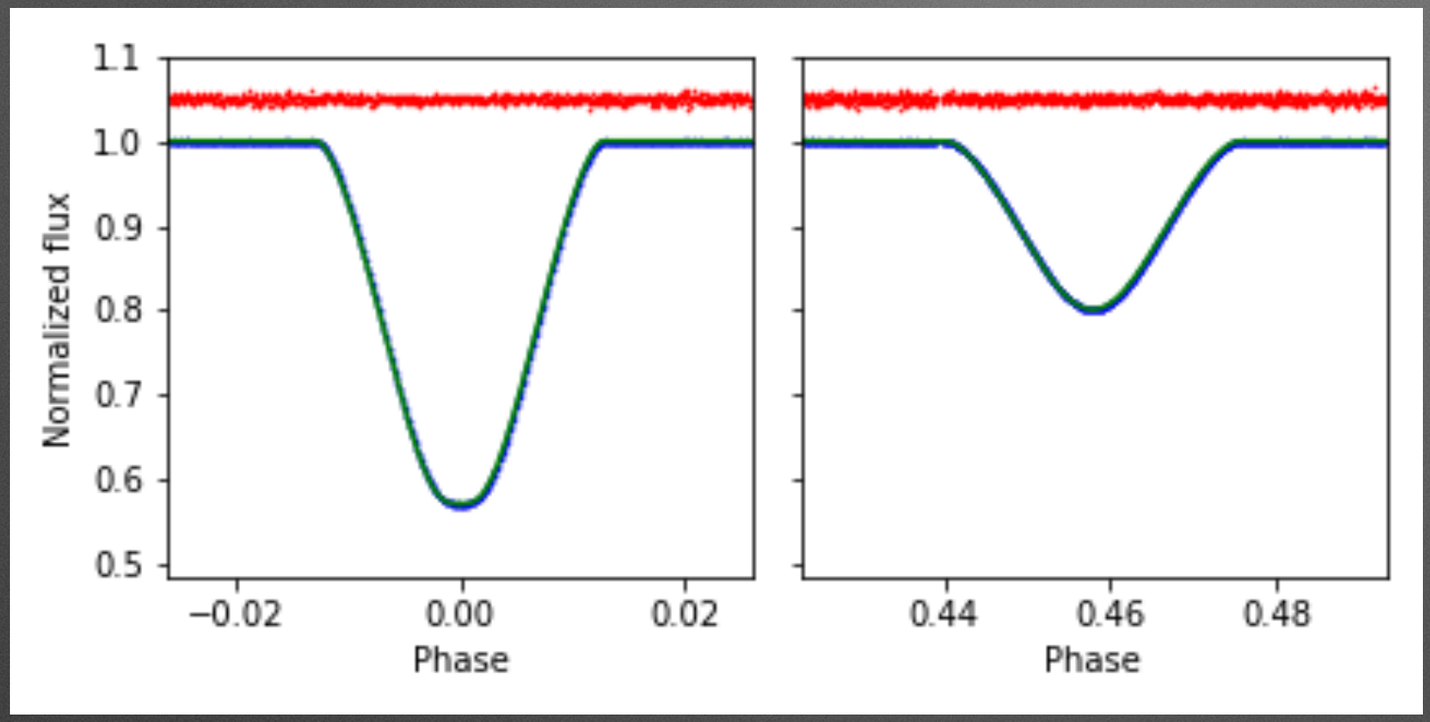
4 observables

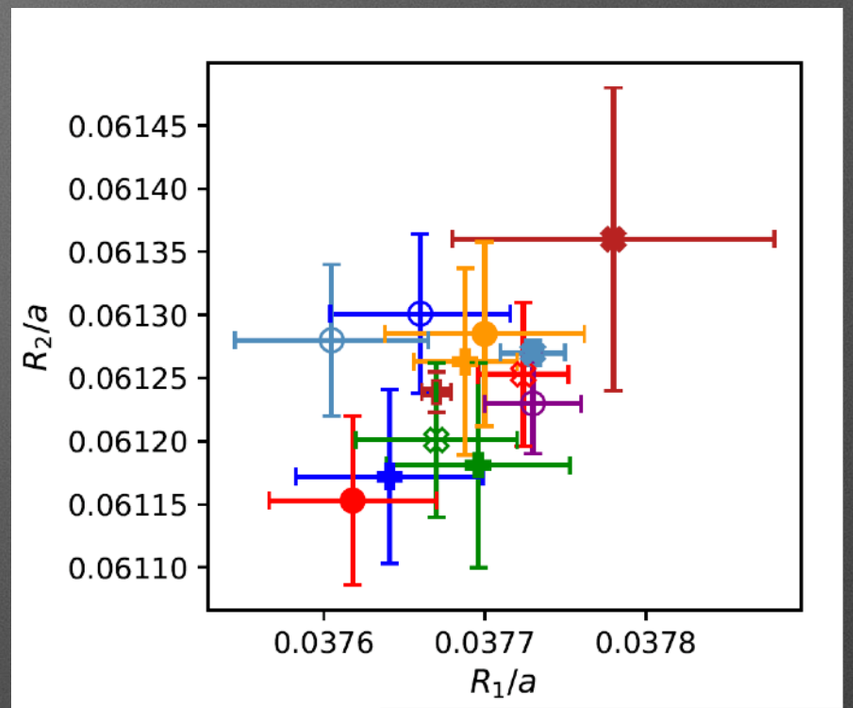
- Depth of primary eclipse
- Depth of secondary eclipse
- Duration of eclipse (1st-4th contact)
- Duration of totality (2nd-3rd contact)

4 observables

- $r_1 = R_1/a$
- $r_2 = R_2/a$
- orbital inclination
- Flux ratio

AI Phe - radius & parallax

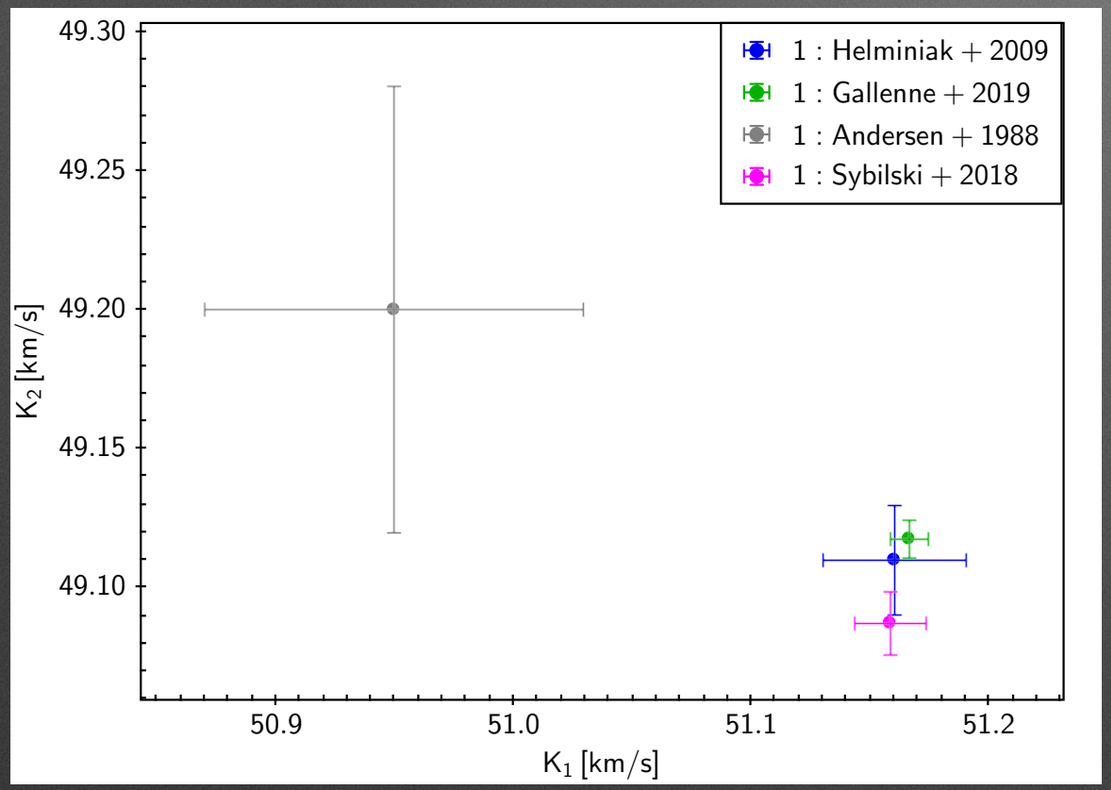




PARALLAX (MAS)	SOURCE	NOTE
5.834 ± 0.026	GAIA DR2	Including zero-point correction –0.031
5.905 ± 0.024	GALLENE ET AL.	Astrometric (VLTI + HARPS)

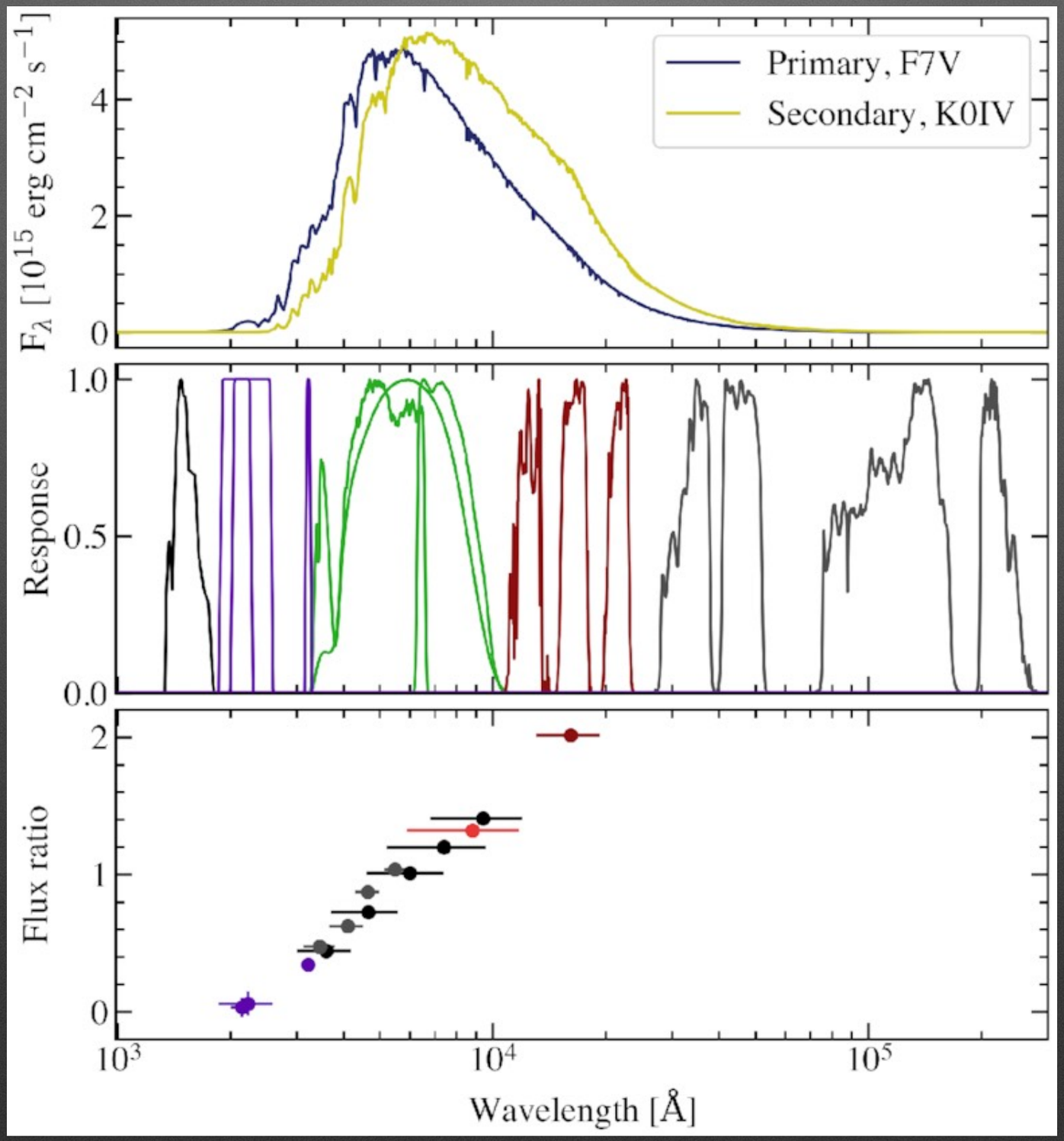
Al Phe — masses and radii

Maxted et al., 2020MNRAS.tmp.1795M



Parameter	Value	
$M_1/\mathcal{M}_\odot^{\mathrm{N}}$	1.1938 ± 0.0008	[0.07%]
$M_2/\mathcal{M}_\odot^{\mathrm{N}}$	1.2438 ± 0.0008	[0.06%]
$R_1/\mathcal{R}_\odot^{\mathrm{N}}$	1.8050 ± 0.0022	[0.12%]
$R_2/\mathcal{R}_\odot^{\mathrm{N}}$	2.9332 ± 0.0023	[0.08%]
$\rho_1/\rho_\odot^{\mathrm{N}}$	0.20299 ± 0.00076	[0.38%]
$\rho_2/\rho_\odot^{\mathrm{N}}$	0.04928 ± 0.00014	[0.29%]
$\log g_1$	4.0020 ± 0.0011	[0.03%]
$\log g_2$	3.5981 ± 0.0009	[0.03%]

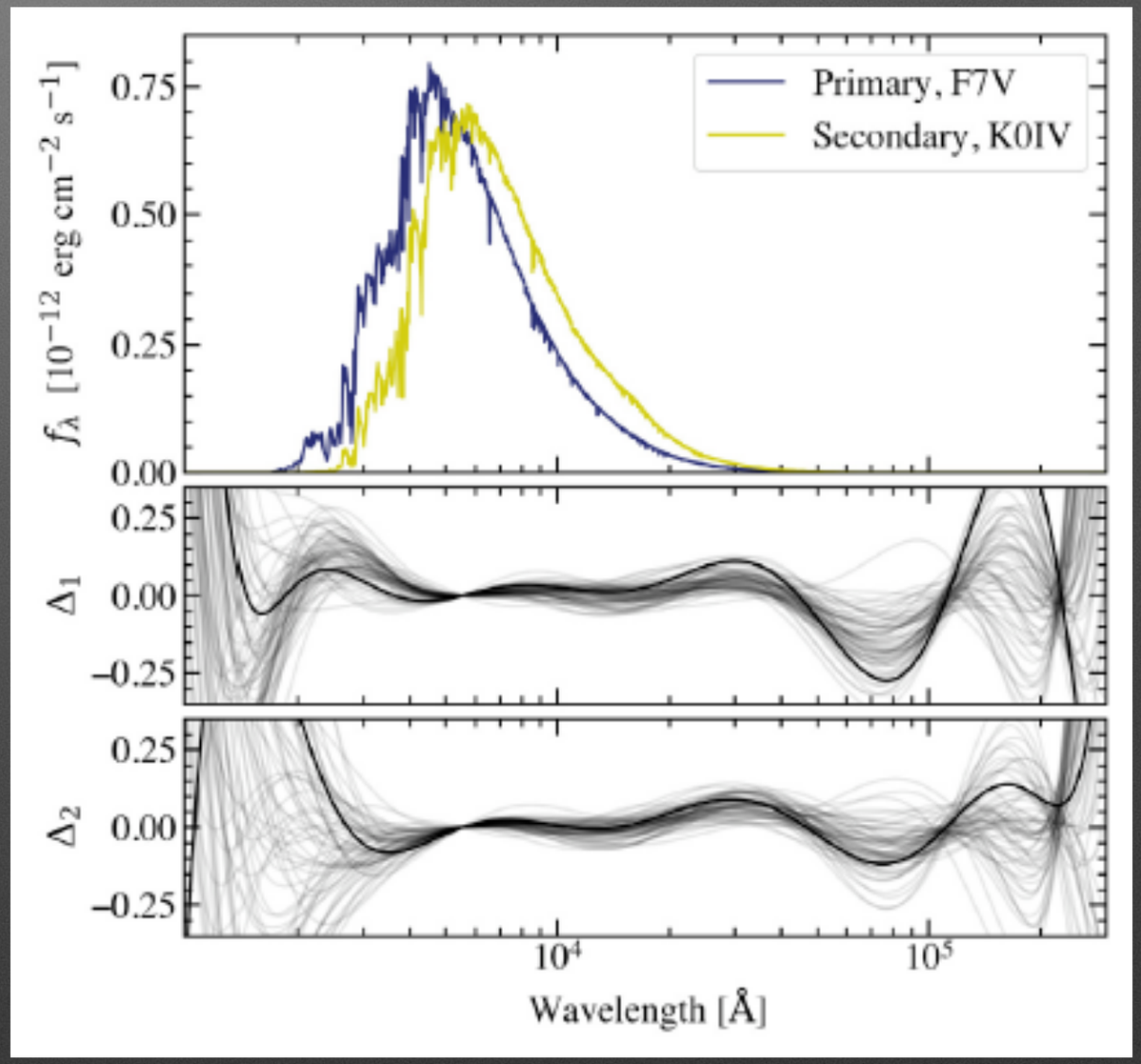
Al Phe - fluxes and flux ratios



Synthetic photometry

$$\tilde{f}_{\lambda,i} = f^m_{\lambda,i} \times \Delta_i(x) = f^m_{\lambda,i} \times \left(d_{0,i} + \sum_{j=1}^{N_\Delta} d_{j,i}\, P_j(x) \right)$$

SED = Model × Distortion

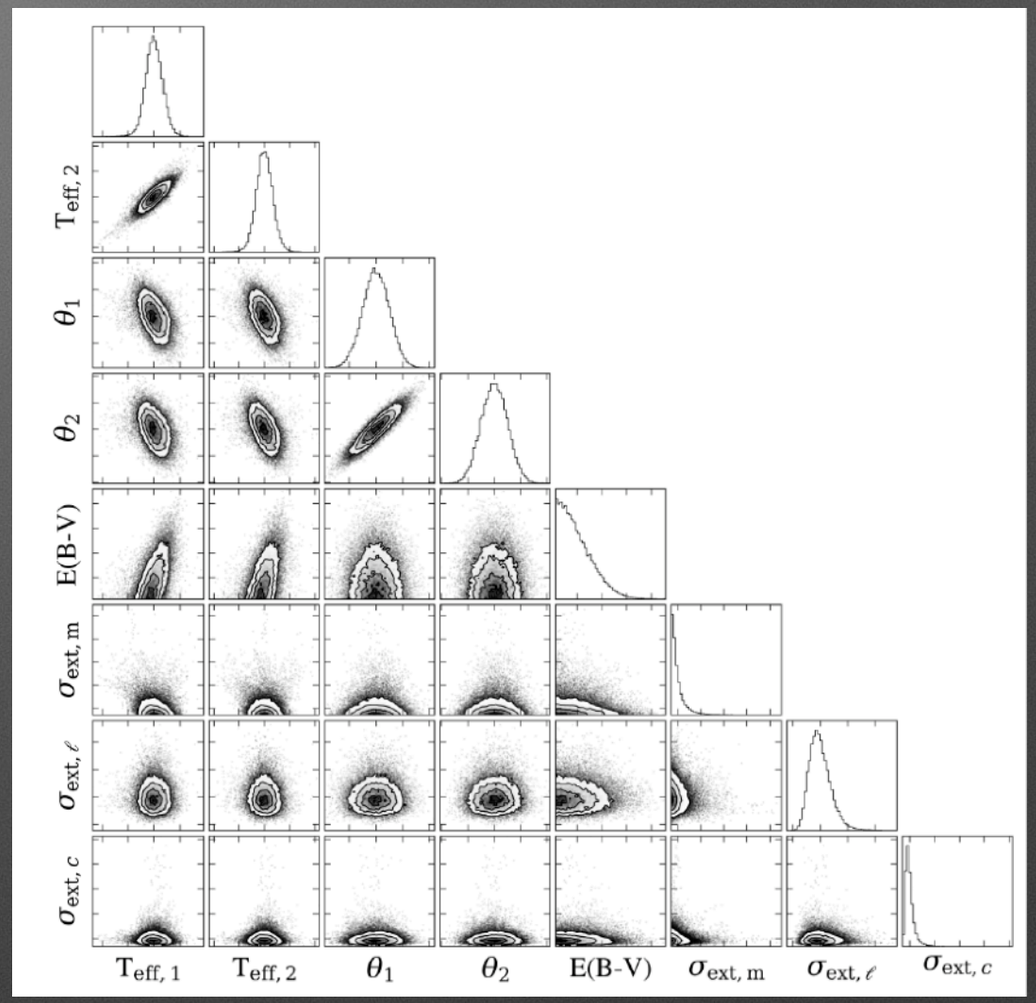


Distortion coefficients $d_{j,i}$ from fit to fluxes and flux ratios

Results for AI Phe

Miller, Maxted & Smalley
2020MNRAS.497.2899M

- 6199 ± 22 K
- 5094 ± 16 K
- ± 11K systemic error



ToDo:

- Compare to T_{eff} from fit to spectra
- Compare M, R, T_{eff} to stellar models
- Apply to more binaries …

Number of suitable DEBS

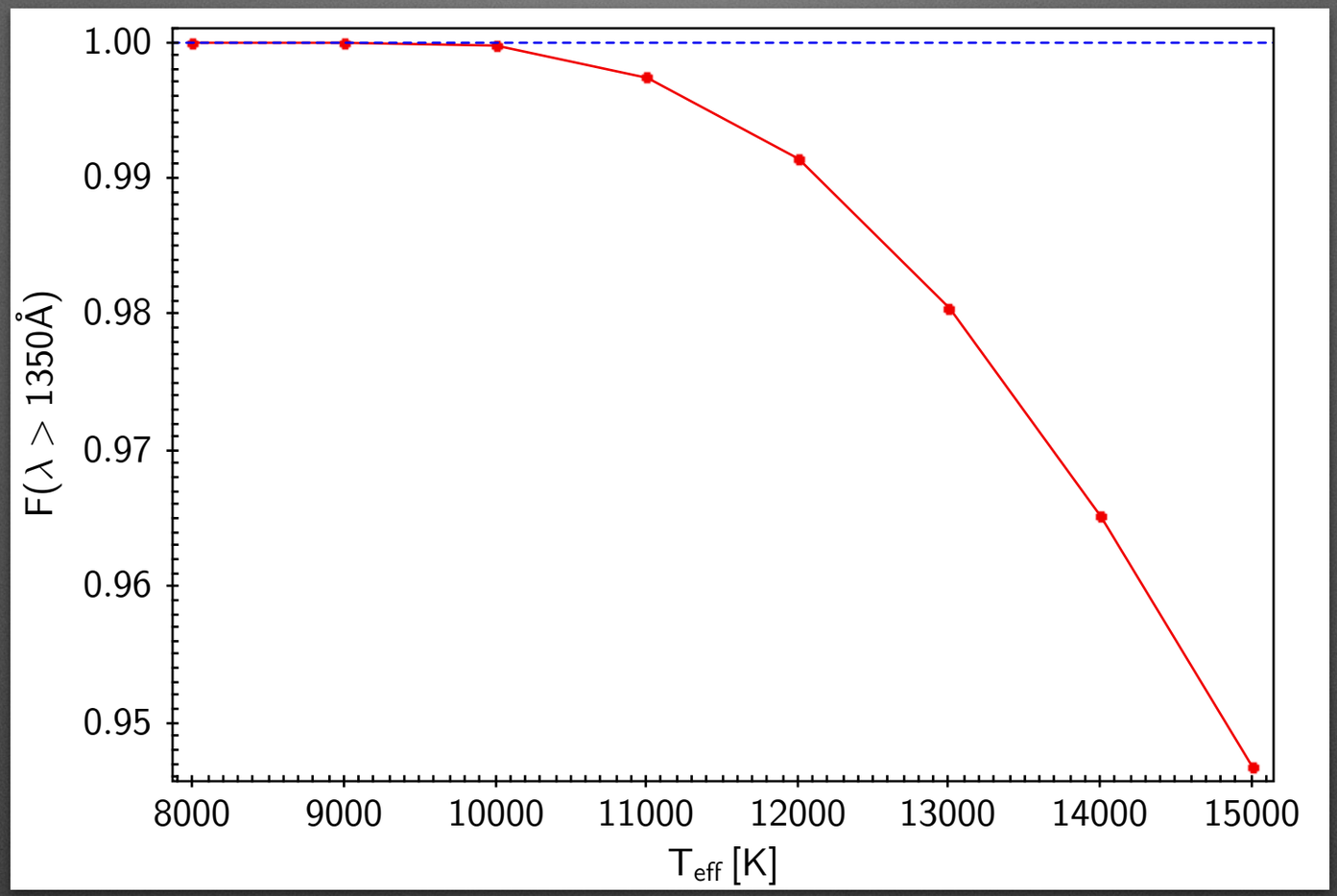
Eclipsing binaries with total eclipses

EPIC	K_P	P/day	d/pc	$T_{eff,1}$ [K]	$T_{eff,2}$ [K]
201408204	11.9	8.5	446	5845	5830
201648133	10.1	35.0	172	6010	5250
203728604	10.6	36.1	636	6050	5840
204822807	11.8	67.5	707	5625	4620
204870619	13.2	34.1	737	5435	4800
206109641	12.4	62.6	613	5905	5805
206212261	12.7	31.0	613	5385	4010
206288770	12.5	24.8	449	6290	3870
206433263	12.0	21.2	549	6000	5525

Maxted & Hutcheon 2018A&A...616A..38M

- 9 targets in 3 K2 fields ⇒ ~1400 targets on the sky
- … or more if short period binaries included
- … but reddening may become a significant source of error

Applicability — upper T_{eff} limit



- ✦ Upper Teff limit set by requirement to measure UV flux
- ✦ 1350Å is blue edge of GALEX FUV band
  - ✦ other UV instruments are available, e.g., SWIFT/UVOT, ASTROSAT/UVIT
- ✦ A-stars no problem, B-stars may be possible