Fundamental effective temperature from EBs

Nikki Miller

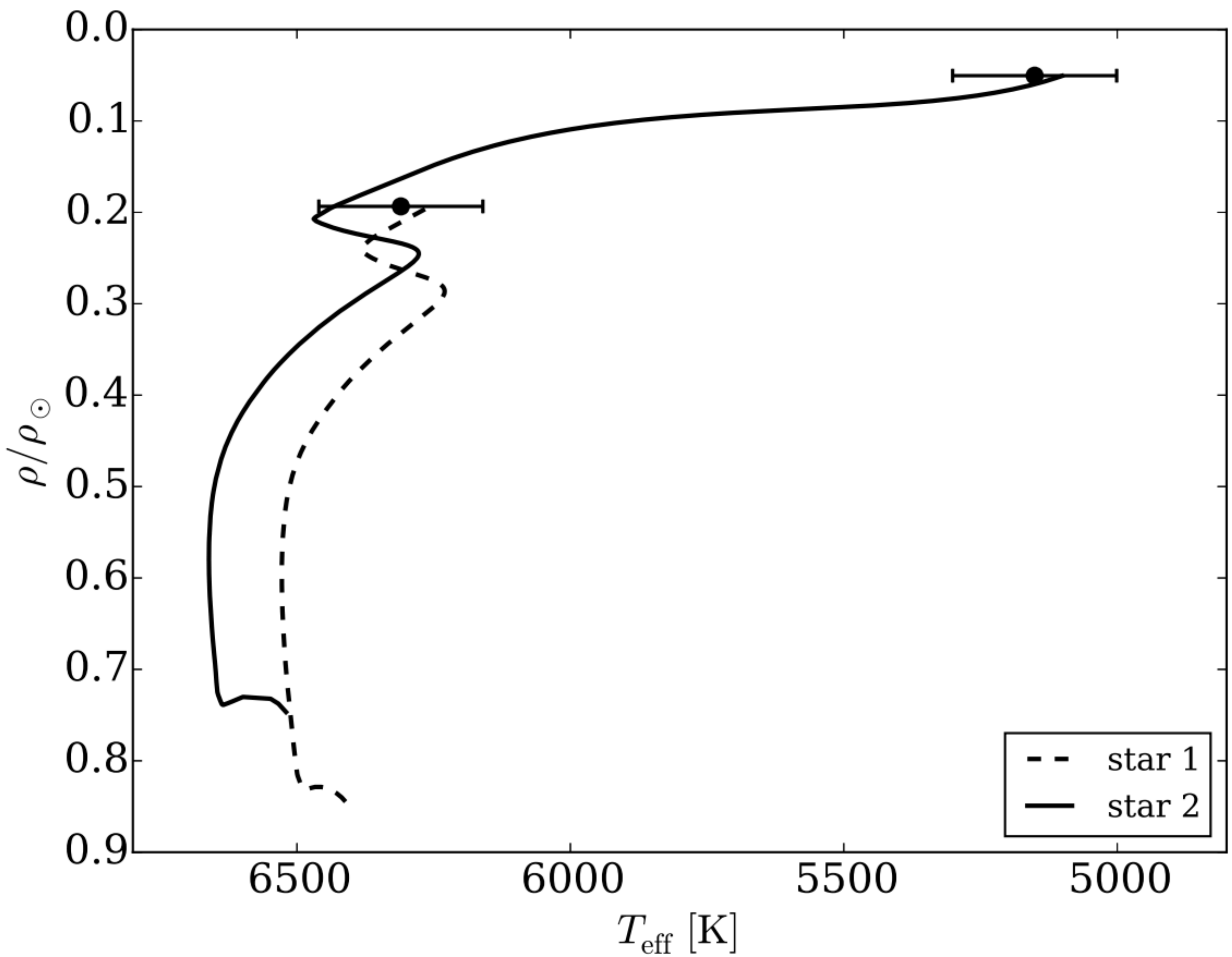
Keele University, Staffordshire, UK
Supervisor: Dr. Pierre Maxted

“Assuming typical observational uncertainties, for MS the **most important error source in the reconstructed age is the effective temperature of the star.**

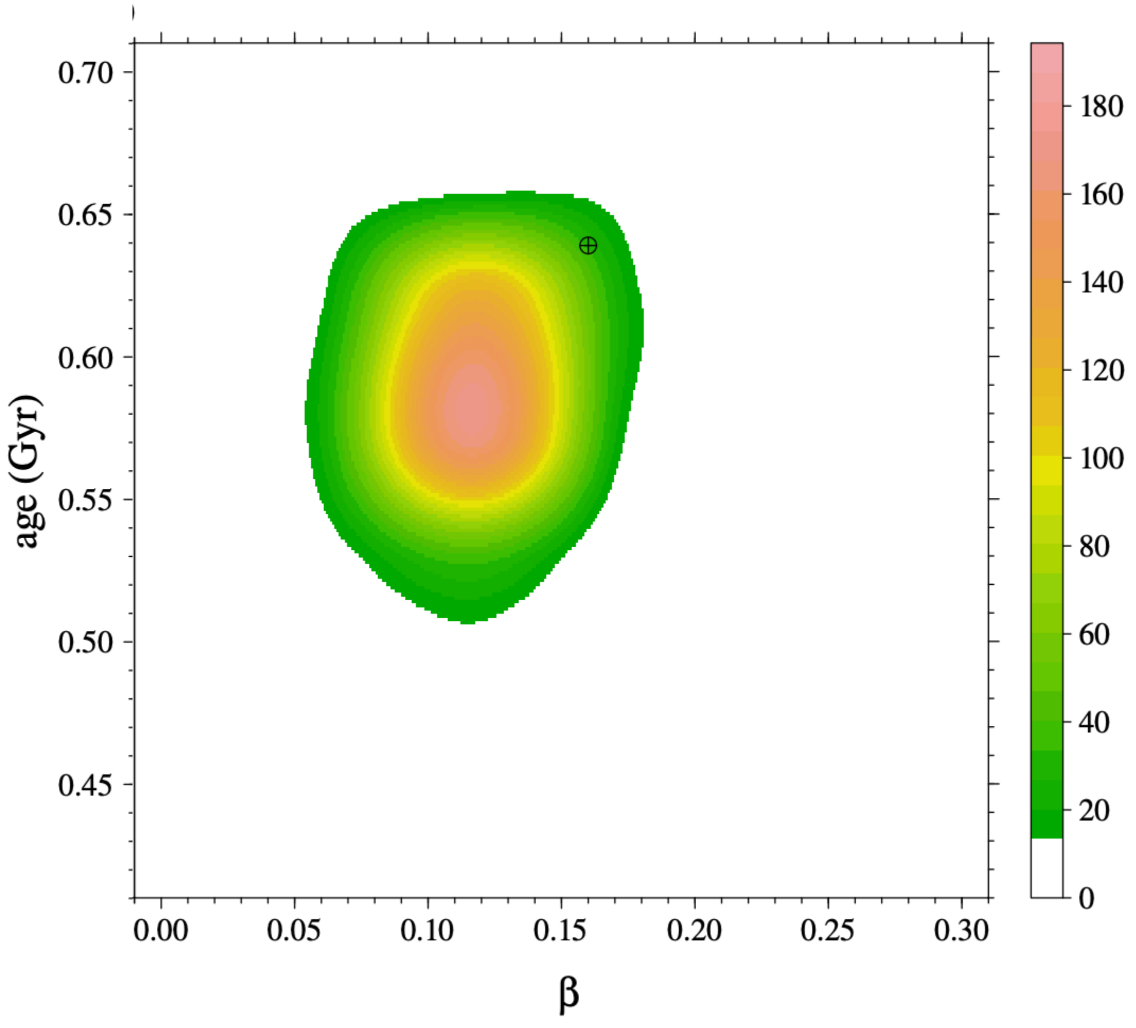
An offset of 75 K accounts for an underestimation of the stellar age from 0.4 to 0.6 Gyr for initial and terminal MS.”

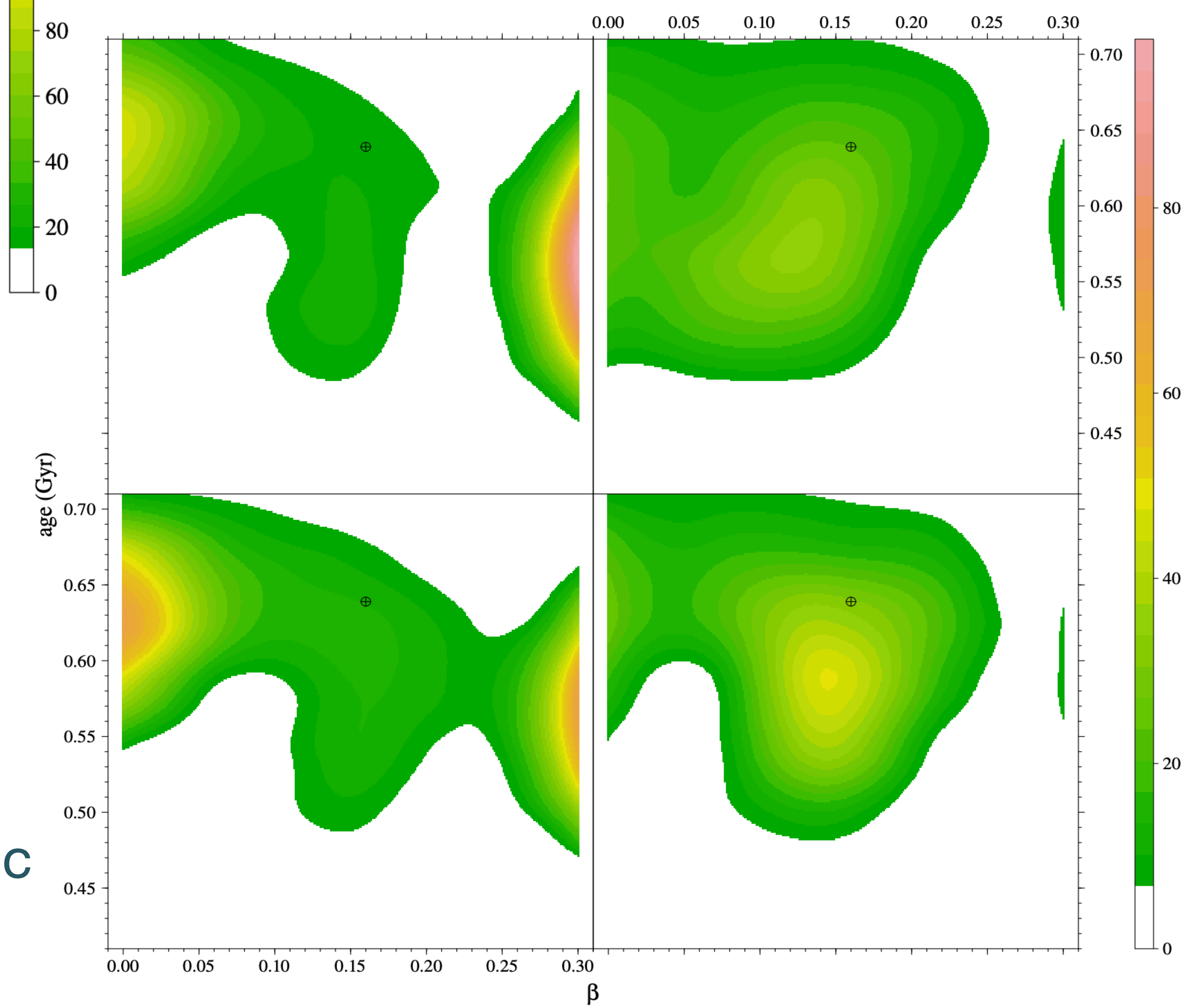
Valle, G. et al., A&A **620** (2018)

Motivation



Kirkby-Kent, J. et al., A&A **591**, A124 (2016)





Introducing a systematic T_{eff} error of ±150 K …

Valle, G. et al., A&A **615**, A62 (2018)

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

$$f_{\oplus} = \frac{L}{4\pi d^2} = \frac{\sigma}{4} \theta^2 T_{eff}^4$$

Theory

Observed flux from binary:

$$f_{\oplus,b} = f_{\oplus,1} + f_{\oplus,2} = \frac{\sigma_{SB}}{4}[T_{eff,1}^4\theta_1^2 + T_{eff,2}^4\theta_2^2]$$

- Angular diameter $\theta = 2R\varpi$
- Radius, R, for stars in eclipsing binaries to ±0.5% or better
- Parallax ϖ from Gaia DR2 ±40 μas or better.
  - End-of-mission will be ± 5-16 μas
- Important error source is accurate optical/UV flux scale
  - Currently 1-2% for CALSPEC
  - ACCESS will improve this to <1% (needed for dark energy survey)
- Reddening ignored here but included in our analysis

Spectral energy distribution (SED)

- SED used to calculate synthetic photometry
  - binary star magnitudes (e.g.,Gaia G, BP, RP, etc.)
  - flux ratio $f_{\lambda,2} / f_{\lambda,1}$
- Assume True SED = Model SED × Distortion, i.e.,

$$\mathcal{F}_{\lambda,\mathrm{true}} = \mathcal{F}_{\lambda,\mathrm{model}} \times [1 + \Sigma c_\ell P_\ell(x)]$$

- $P_\ell(x)$ = Legendre polynomials

$$x = \frac{(\lambda - \lambda_{\mathrm{min}})}{(\lambda_{\mathrm{max}} - \lambda_{\mathrm{min}})}$$

- Models fluxes are BT-Settl
- $\mathcal{F}_\lambda$ is normalised, i.e. $\int \mathcal{F}_\lambda \mathrm{d}\lambda = 1$
  - $\Rightarrow f_{\lambda,\oplus} = \sigma_{SB}\, T_{\mathit{eff},1}^4 \theta_1^2 \mathcal{F}_\lambda$
- Normalisation + distortion ⇒ this method is *not* SED fitting

Bayesian analysis

Model parameters, $\boldsymbol{M}$

- $T_{eff,1}$; $T_{eff,2}$
- θ_1; θ_2
- Reddening E(B-V)
- σ_{ext} = extra error on magnitudes
- σ_{L} = extra error on flux ratios
- $c_{\ell,1}$; $c_{\ell,2}$ - SED distortion coefficients

Data, $\boldsymbol{D}$

- $\theta_1 \pm \sigma_{\theta,1}$; $\theta_2 \pm \sigma_{\theta,2}$
- Magnitudes, $m_{X,i} \pm \sigma_{X,i}$
- Flux ratios, $L_{\lambda,i} \pm \sigma_{L,i}$

Meta-data/assumptions, A

- Response functions, $R_X(\lambda)$
- Zero-points, $ZP_X \pm \sigma_{ZP,X}$
- $\mathscr{F}_{\lambda,model,1}$; $\mathscr{F}_{\lambda,model,2}$

Use `emcee` to sample

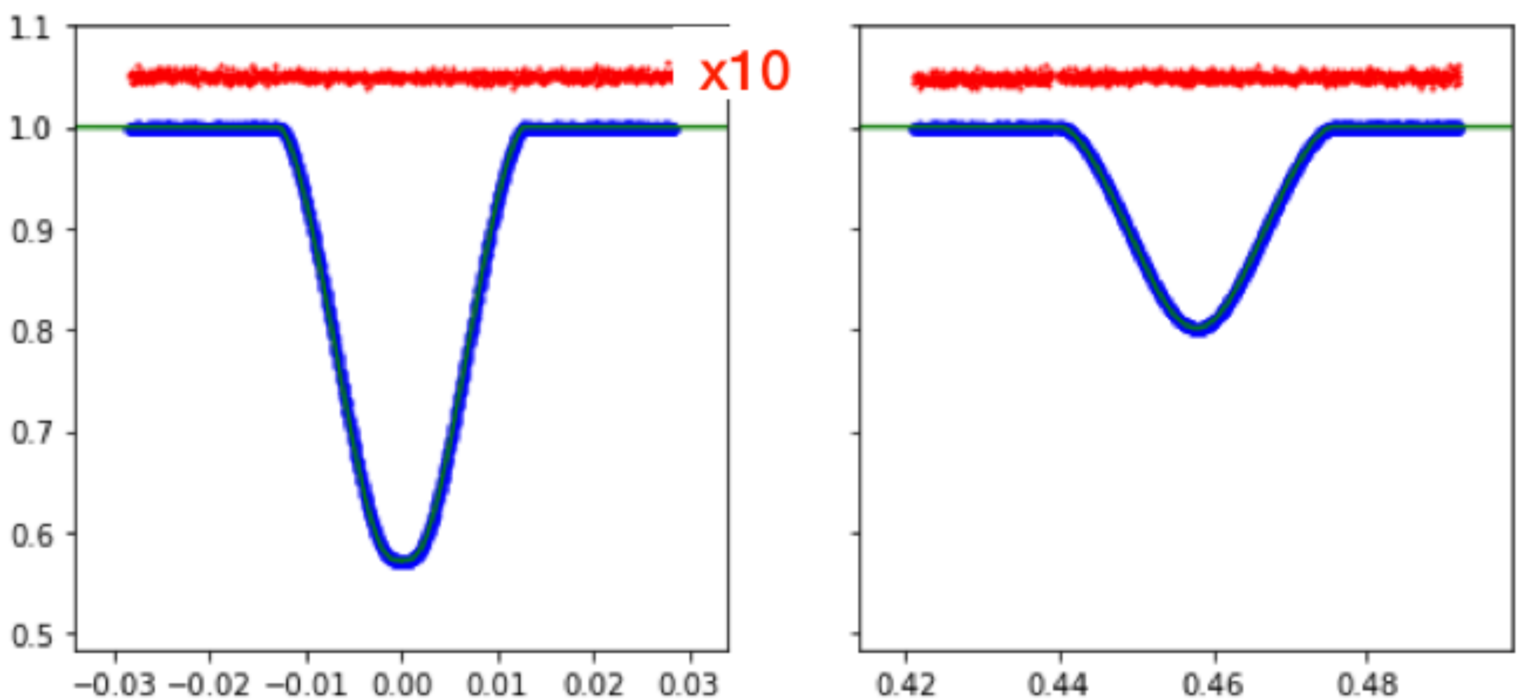
$$P(\boldsymbol{M} \mid \boldsymbol{D}, A) = P(\boldsymbol{D} \mid \boldsymbol{M}, A)\, P(\boldsymbol{M})$$

AI Phoenecis (AI Phe)

- Detached EB (total eclipses)
- K0IV + F7V
- Orbital period 24.6 days
- V mag 8.6
- Plenty of data

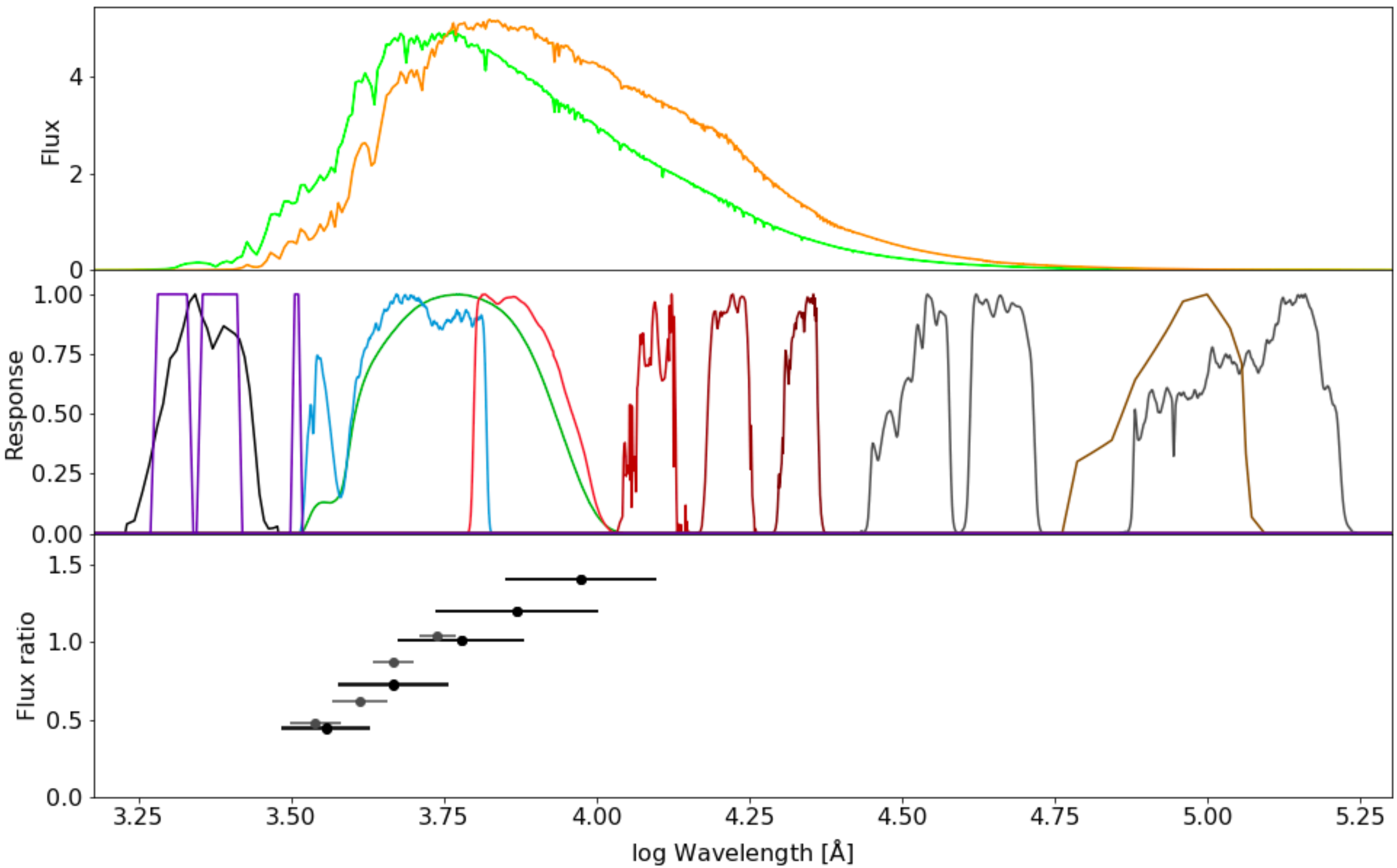
Parameter	This work	Hełminak et al. (2009)	Andersen et al. (1988)
P (days)	24.592483	24.59241	24.592325
Error in P	(17)	(8)	(8)
K_1 (km s^{-1})	51.16(3)		50.90(8)
K_2 (km s^{-1})	49.11(2)		49.24(7)
q	1.0417(7)	1.0418(8)	1.034(2)
$M_1 \sin^3 i$ ($M_\odot$)	1.1961(37)	1.1922(30)*	1.194(4)
$M_2 \sin^3 i$ ($M_\odot$)	1.2460(39)	1.2421(32)*	1.234(5)
e	0.1821(51)	0.187(4)	0.188(2)
ω(°)	110.73(78)	110.1(9)	109.9(6)
i (°)	88.502(39)	84.4(5)	88.45(5)
M_1 ($M_\odot$)	1.1973(37)	1.2095(44)*	1.1954(41)
M_2 ($M_\odot$)	1.2473(39)	1.2600(46)*	1.2357(45)
R_1 ($R_\odot$)	1.835(14)	1.82(5)	1.816(24)
R_2 ($R_\odot$)	2.912(14)	2.81(7)	2.930(48)

Notes. (*) These errors have been recalculated using JKTABSDIM as the quoted errors have been under-estimated.



Kirkby-Kent, J. et al., A&A **591**, A124 (2016)

Data



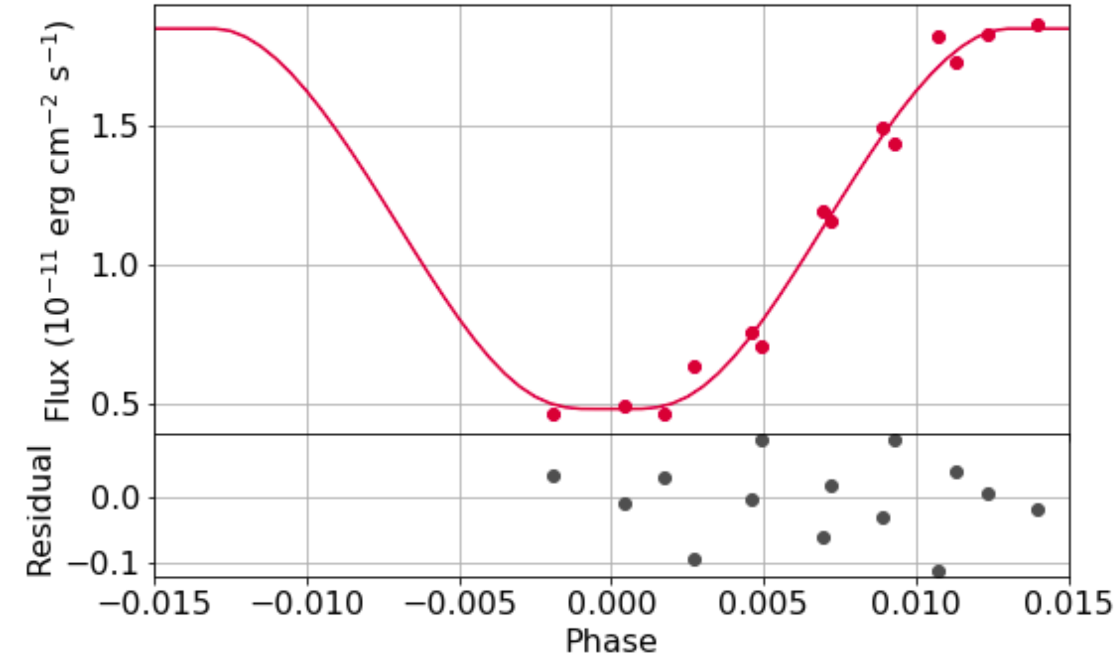
Flux
4
2
0
Response
1.00
0.75
0.50
0.25
0.00
Flux ratio
1.5
1.0
0.5
0.0
3.25
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
log Wavelength [Å]

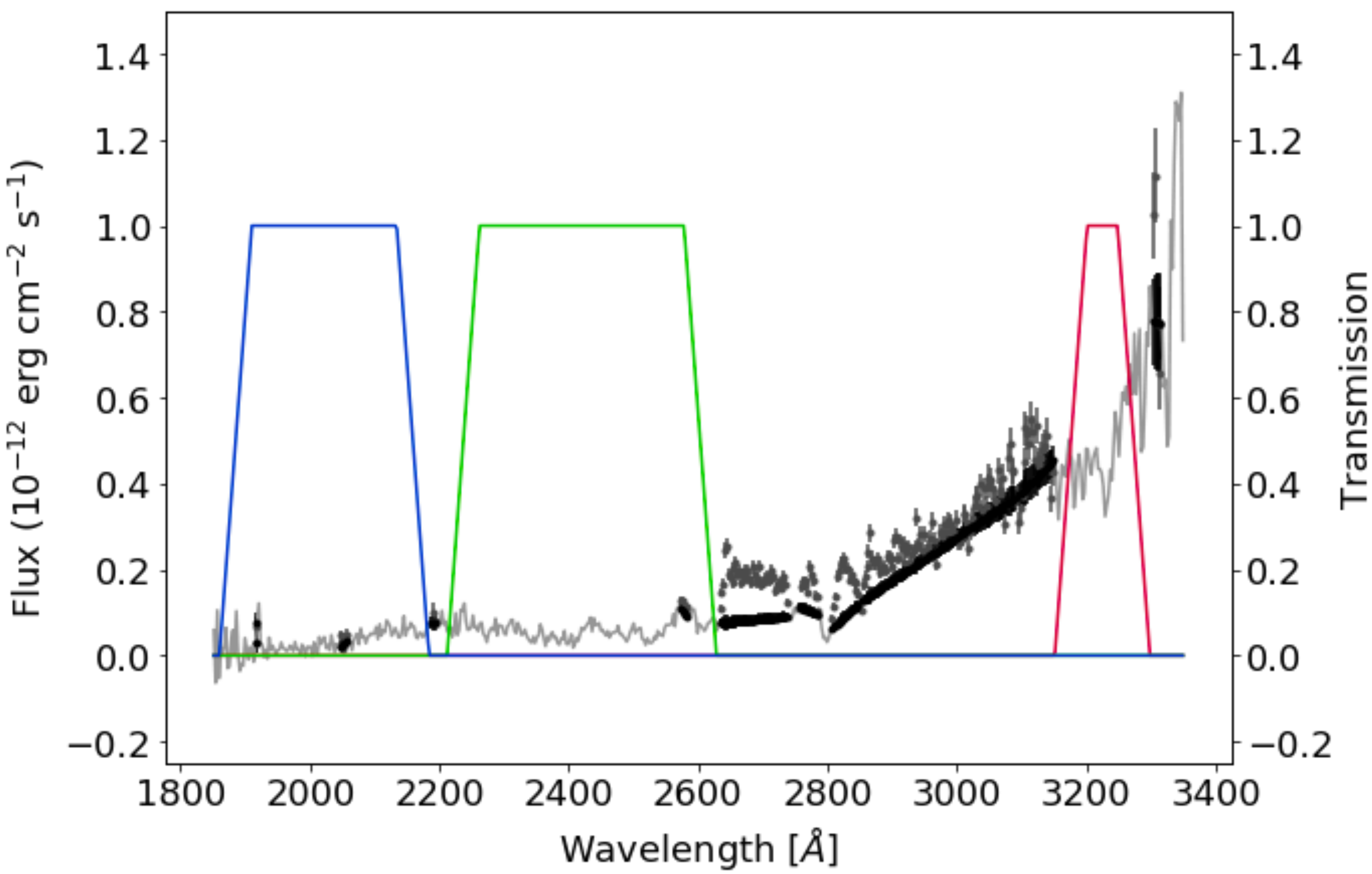
IUE spectra

Pinning down the UV end of the spectrum

IUE spectra available covering primary eclipse

- Flux out of eclipse (⇒ magnitude)
- Flux ratio





Preliminary results

$T_{eff,1}$ = 6144 K ± 33 K (rnd.) ± 10 K (sys.)

$T_{eff,2}$ = 5154 K ± 23 K (rnd.) ± 10 K (sys.)

- Systematic error from CALSPEC zero point error
- θ_1, θ_2 is the main source of error
- E(B-V) < 0.016 as expected
- σ_{ext} = 0.008 ± 0.009 mag
- T_{eff} insensitive to distortion coefficients $c_{\ell,1}$; $c_{\ell,2}$ (up to n_c = 5)

Future direction

Testing, testing, testing…

- Adding flux ratios from IUE spectra
- Effect of changing e.g. reference spectra, binning, distortion coefficients
- Correlation of $\theta_1; \theta_2$
- Third light correction: ~5 K impact

Goals:

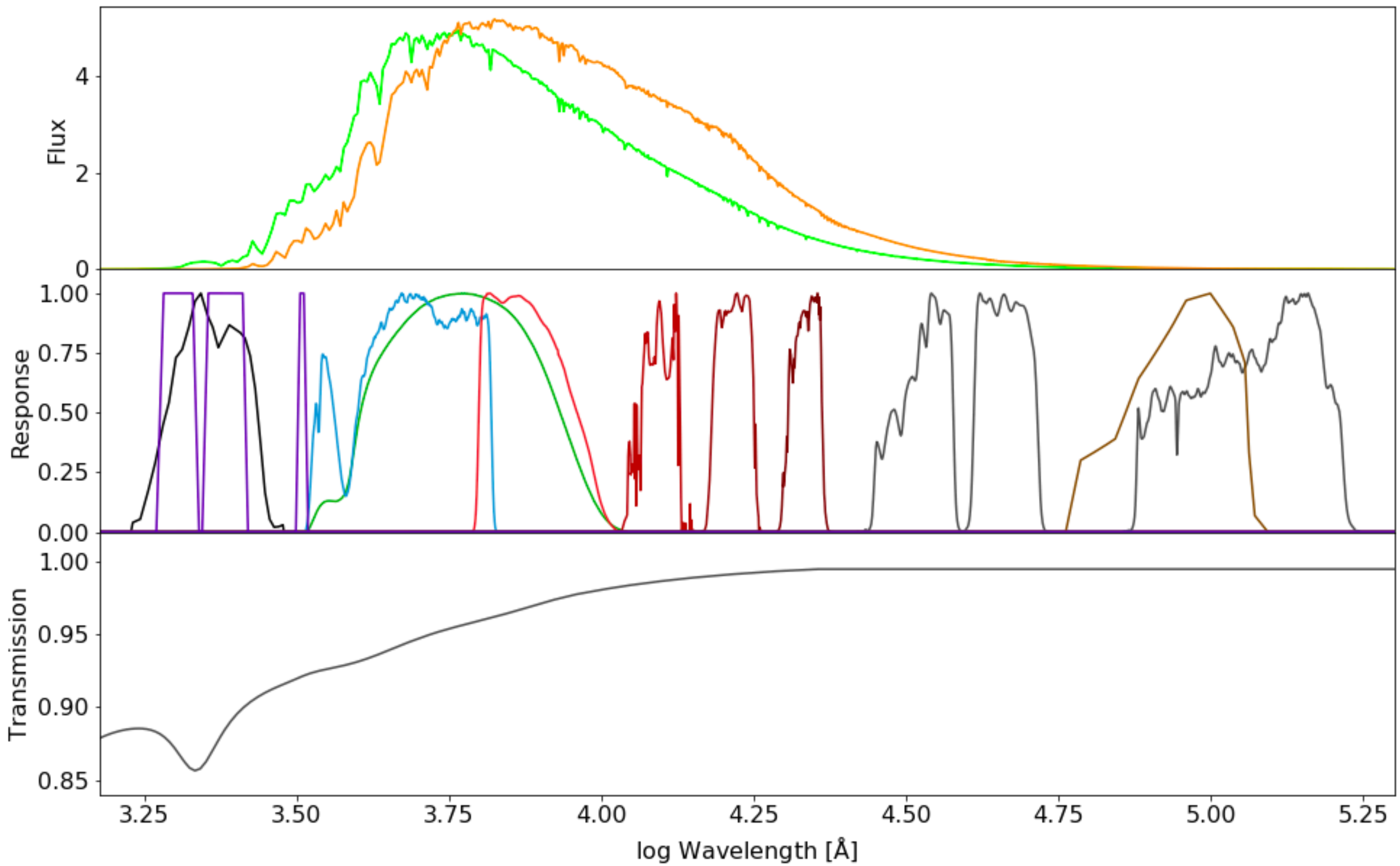
Short term - Publish AI Phe results

Medium term - Apply method to other well-known EBs

Long term - Develop a set of benchmark systems for PLATO

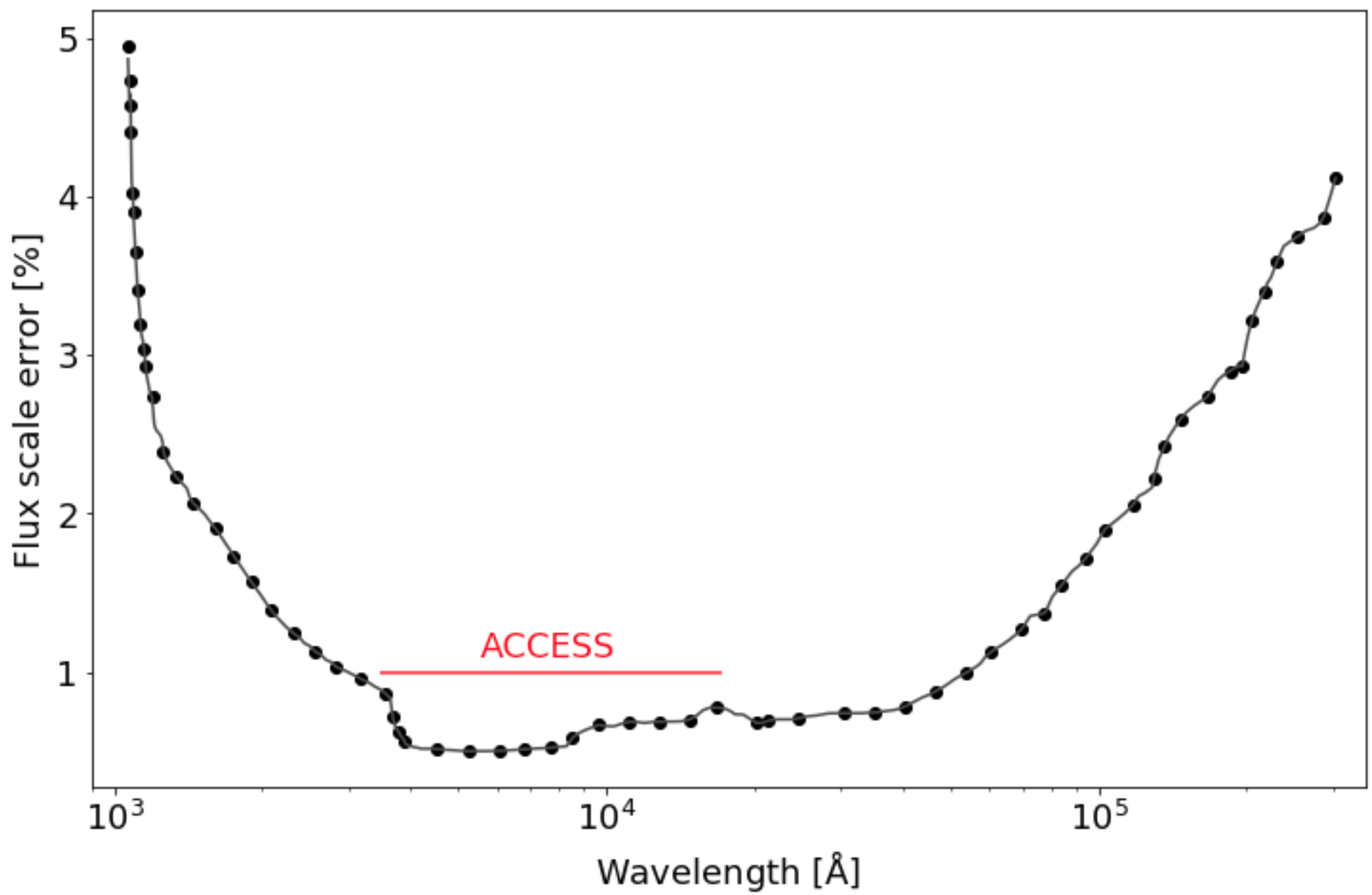
Reddening

Milky Way Diffuse, R(V)=3.1



Cardelli, J. A. et al., ApJ **345**, 245 (1989)

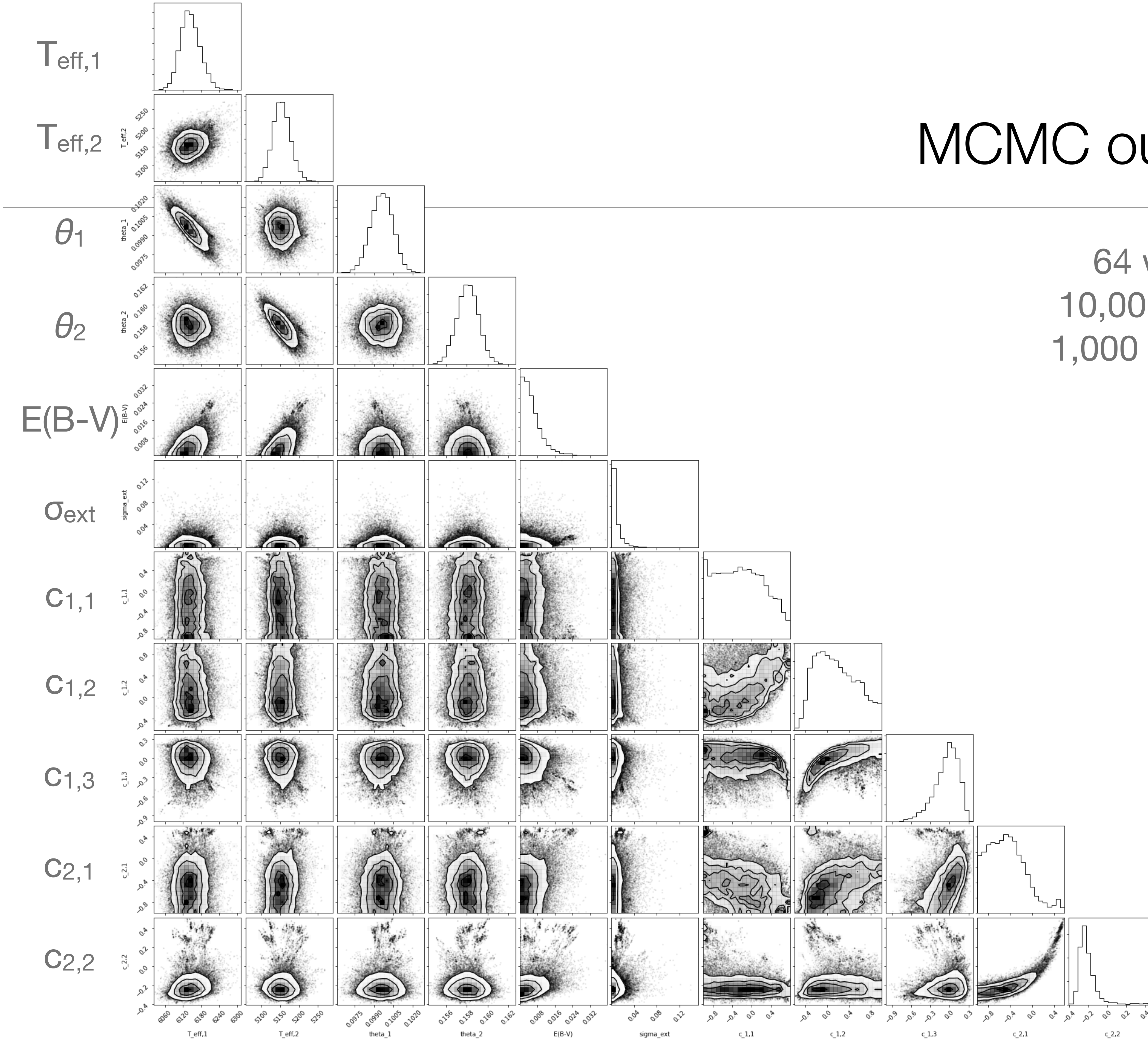
Flux scale zero-point error



Bohlin, R. et al., PASP **126**, 711-732 (2014)

MCMC output

64 walkers
10,000 steps
1,000 burn-in



AI Phe primary eclipses

- For Paranal …
  - 2020 Jun 26, 0754 UT
  - 2020 Sep 8, 0229 UT
  - 2020 Oct 27, 0656 UT
  - 2021 Jan 9, 0142 UT
  - … ± 8 minutes
- Spectrum of K0 IV star only
- Use spectral disentangling to …
  - … boost S/N for K0IV star
  - … get spectrum of F7V star
  - HARPS data exist to do this
- Eclipse is 28 minutes long
- New eclipse time would help
- Espresso S/N/pxl in 1200s …
  - 250 @ 700nm
  - 240 @ 600nm
  - 160 @ 500nm
  - 26 @ 400nm

Extras

- Uncertainty on Gaia zero point ~0.03 mas, ~1 sigma
- Third light ~0.7% in TESS band
  - M dwarf / WD?
- ACCESS will calibrate stellar standards to an accuracy of 1% in wavelength range 0.35 - 1.7 μm