Validation of selected *TESS* exoplanetary candidates

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SKALNATÉ PLESO

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Selection of targets

m_V < 12.5 mag
$\Delta F \geq 0.0065$ for m_V < 10.5 mag (Mesarč, 2002)
period < 2.2 days
duration < 3 h
Dec > -10 deg

Initially selected TOIs in 2021:

TOI	1518.01	1834.01	2046.01	2109.01	3604.01	3856.01
TESS (mag)	8.75	11.50	11.00	9.79	11.73	11.66
V (mag)	8.95	12.15	11.55	10.22	12.51	12.29
ΔF	9.8	21.1	14.7	6.7	14.9	12.9
Duration (h)	2.35	1.85	2.41	1.80	1.64	2.04
Period (d)	1.90261	1.21681	1.49718	0.67249	1.06669	2.04345

Follow-up observing network

Observation planning by TransitFinder (Jensen, 2013)
https://astro.swarthmore.edu/transits/

Thanks: 33 observers / 14 countries / 2+ years

- Filip Walter (Exoplanet Transit Database)

- ExoClock project (Kokori et al., 2021)

- MuSCAT2 project (Narita et al., 2019)

Follow-up observing network

TESS reduction

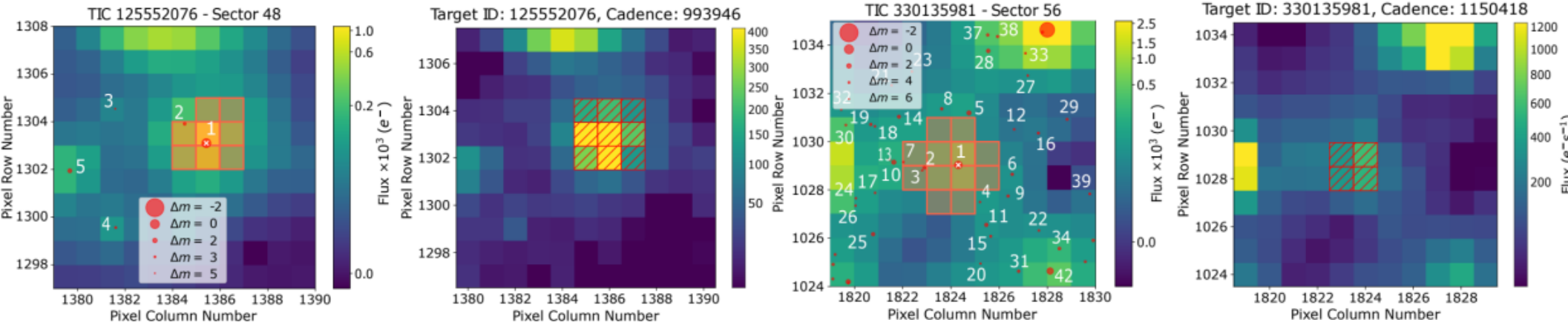
TPF identification – `lightkurve` (Lightkurve collab., 2018)

lightkurve

Custom aperture – `tpfplotter` (Aller et al., 2020)

tpfplotter

Pixel-level-lighcurve plot and FOV inspection



TOI-3856

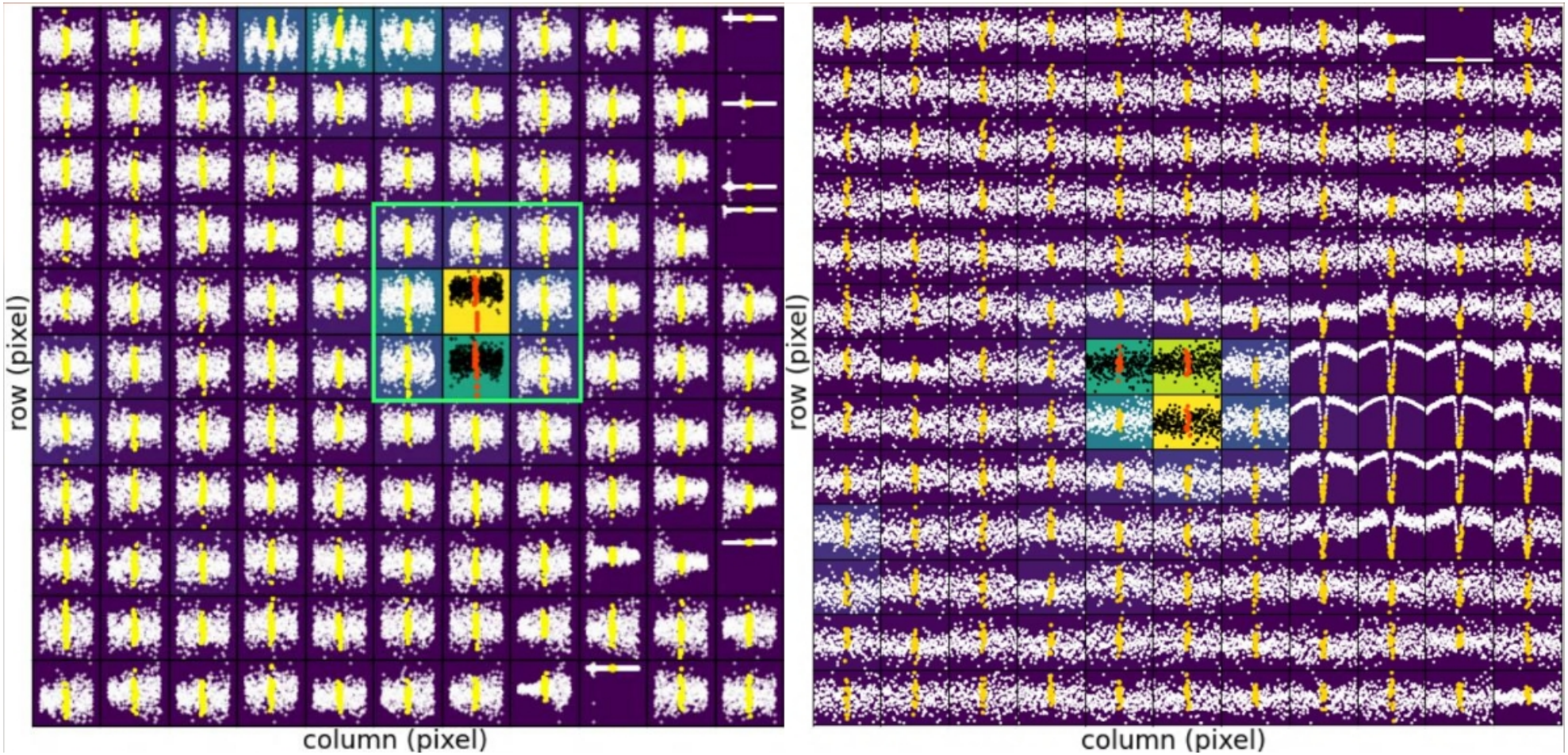
TOI-3604

TESS reduction

Pixel-level-lightcurve plot

constrained

nearby signal source

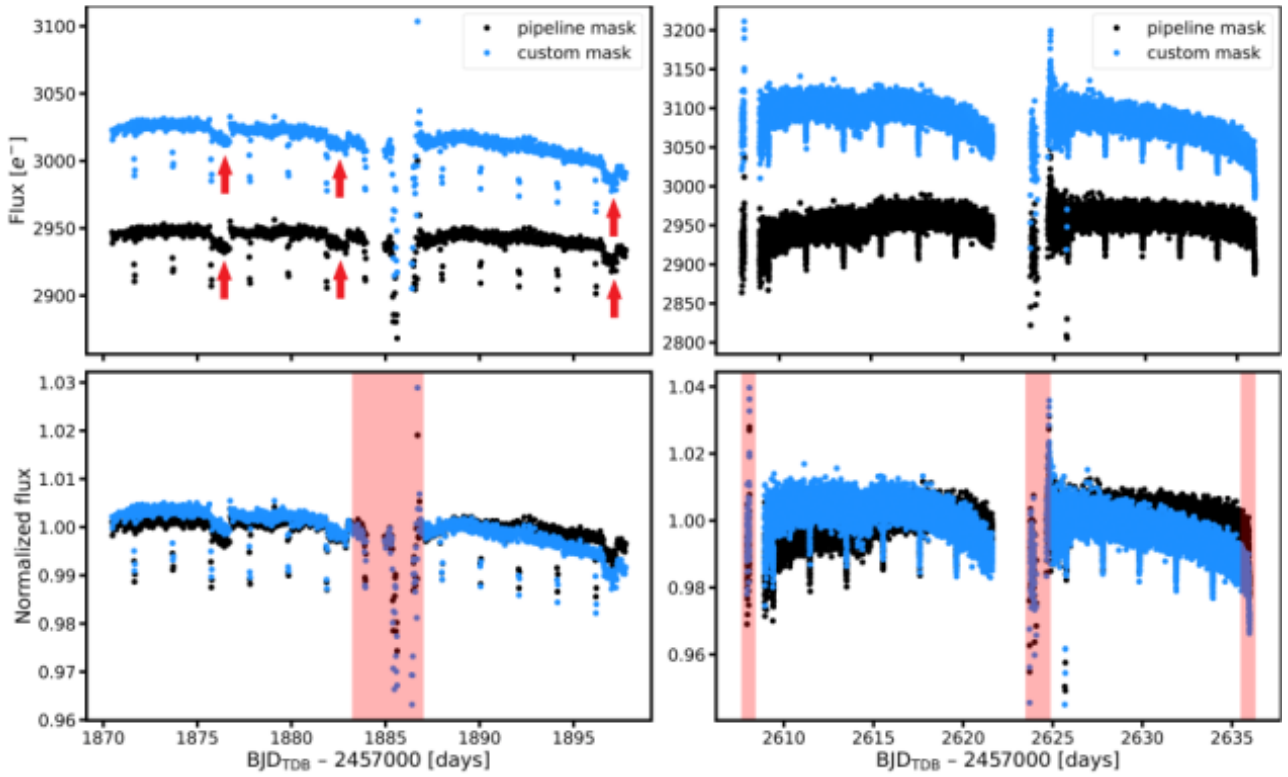


TOI-3856

TIC 142105308

TESS reduction

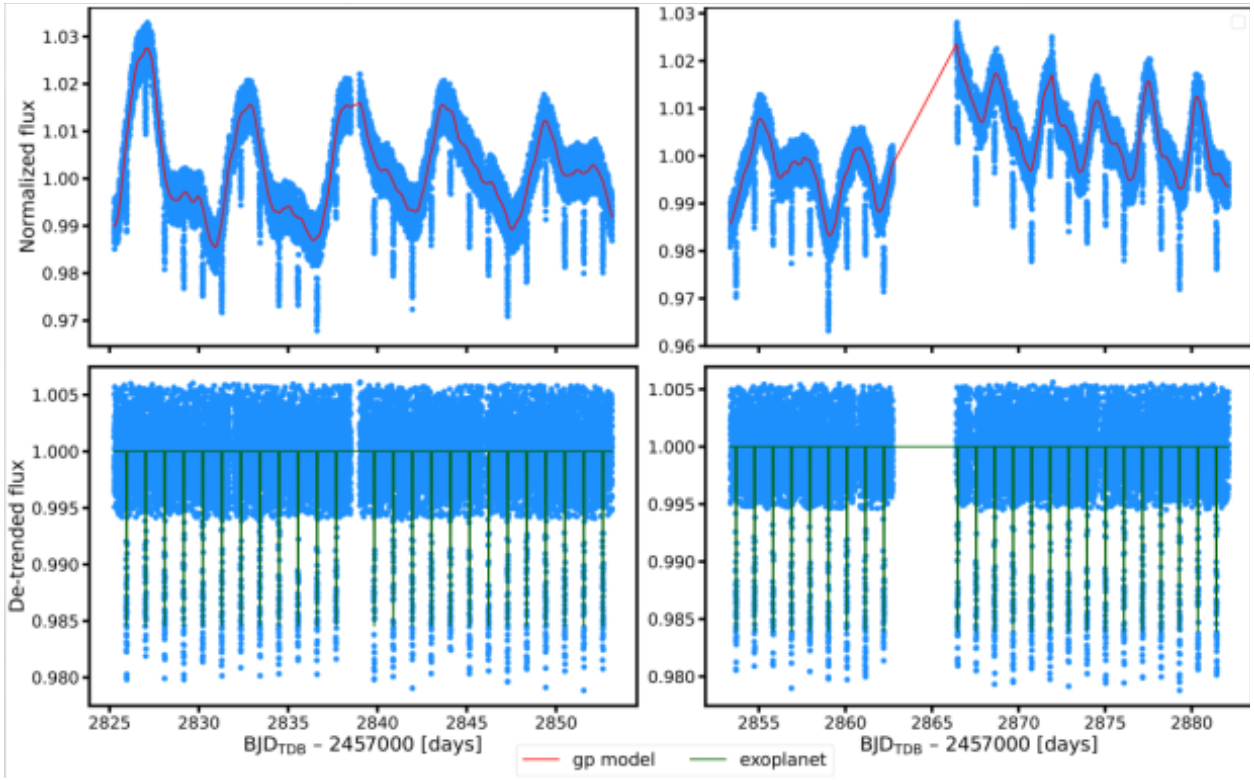
Different sectors: 20 s, 2 min, and 30 min cadence
Removal of momentum dumps, outliers, incomplete transits
https://tess.mit.edu/public/files/Table_of_momentum_dumps.csv



TOI-3856

TESS reduction

De-trending, sigma clipping - `exoplanet` (Foreman-Mackey, 2021)

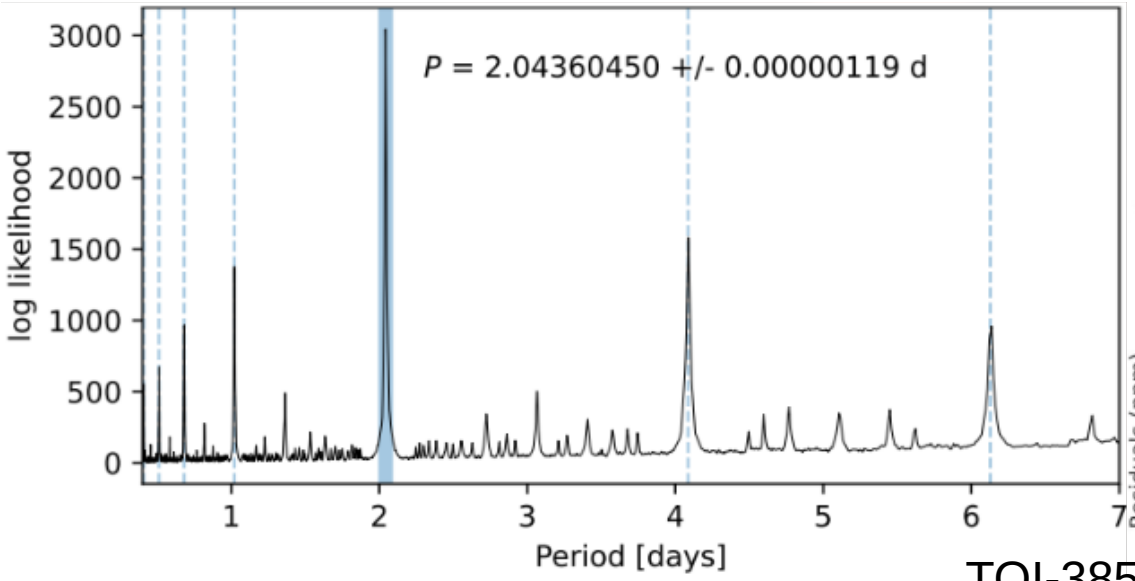


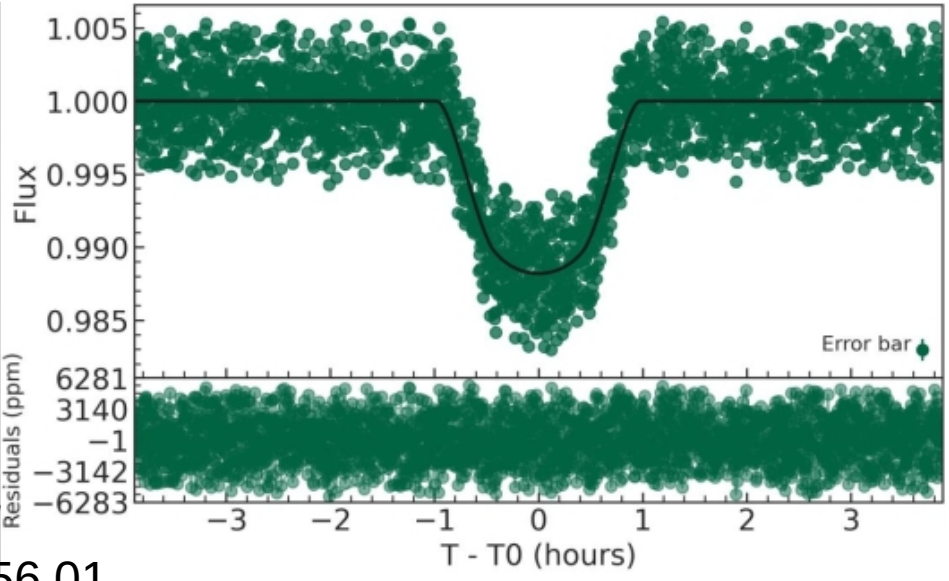
TOI-3604.01

TESS reduction

Box-fitting LS algorithm (Kovacs et al, 2002): P, T_0

Model parameters – `pyaneti` (Barragán et al., 2019)
MCMC: R_P/R_S, a/R_S, i, t_T
+ mean *TESS* transit model – t_T of individual transits for *O-C*
+ individual LD





TOI-3856.01

Ground-based reduction

Reduction of ground-based photometry:
Standard dark+flat, variable aperture photometry
HOPS (Tsiaras, 2019)

Considered detected if difference from *TESS*:
T_{mid} diff < ± 0.01 d
R_P/R_S diff < ± 0.25 x (R_P/R_S)
a/R_S diff < ± 0.33 x (a/R_S)
i diff < ± 5 deg

Ground-based reduction

Modelling and analysing LCs:

`PyLightcurve` (Tsiaras, 2016)

`ExoTETHys` package (Morello et al., 2020)

- non-linear LD coeff. for specific bands
- `PHOENIX` stellar parameters ($T_{\rm eff}$, log g, [M/H])

The non-linear law (Claret, 2000):

$$I(\mu) = I_0[1 - c_1(1 - \mu^{1/2}) - c_2(1 - \mu) - c_3(1 - \mu^{3/2}) - c_4(1 - \mu^2)]$$

Groun

Modell

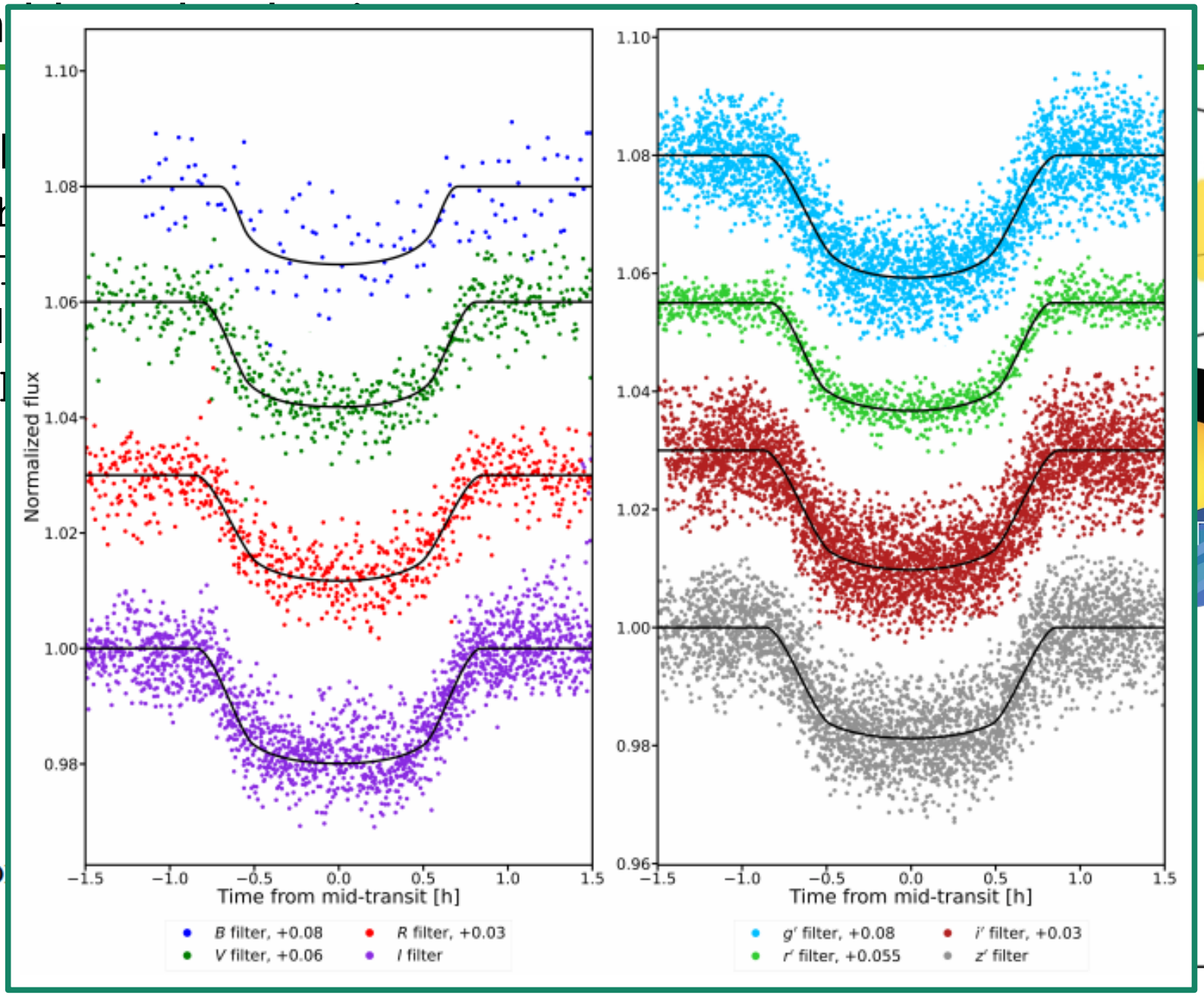
PyLigh

ExoTE

- non-l

- PHOE

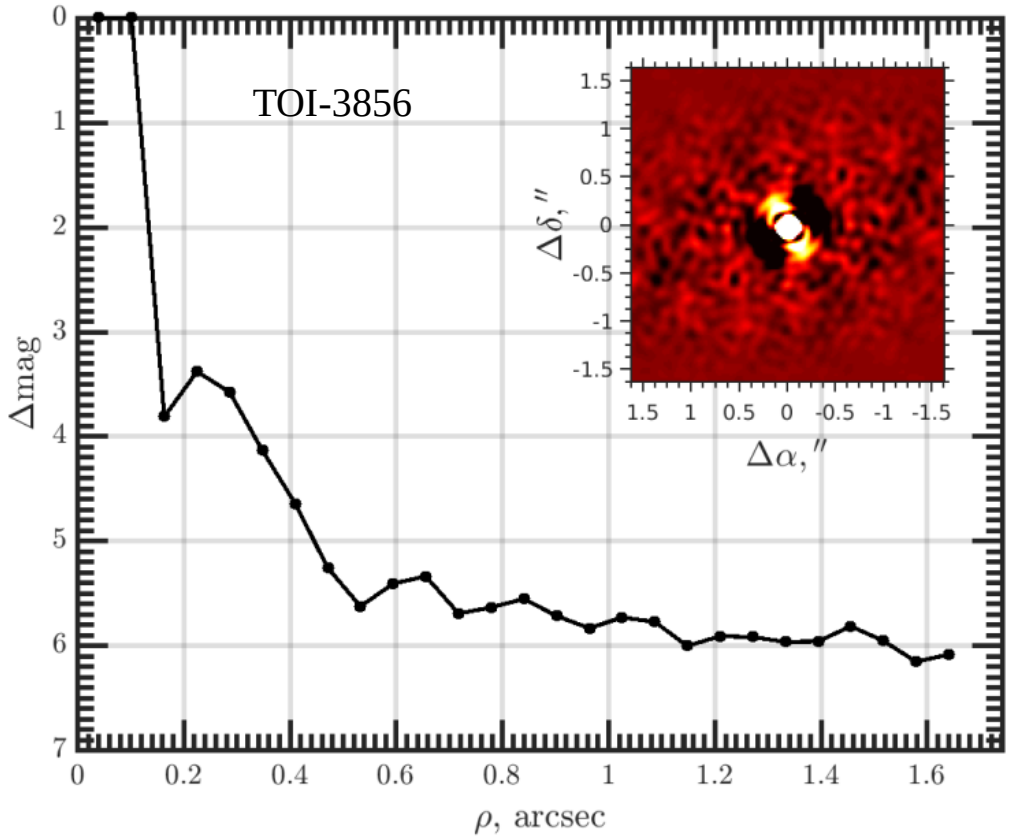
The no



$- \mu^2)]$

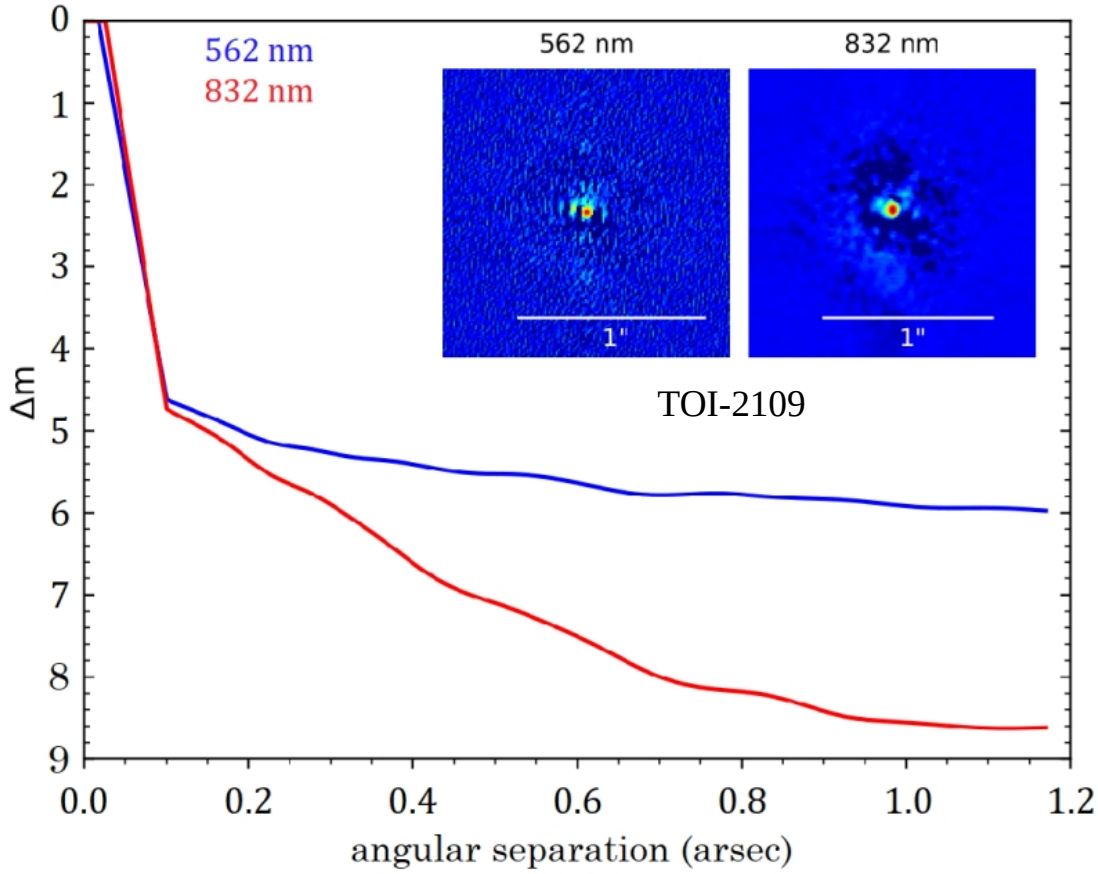
Speckle interferometry

N. Caucassus, SAI 2.5-m telescope λ8800 Å (res~89 mas)
- SPeckle Polarimeter (Safonov et al., 2017)



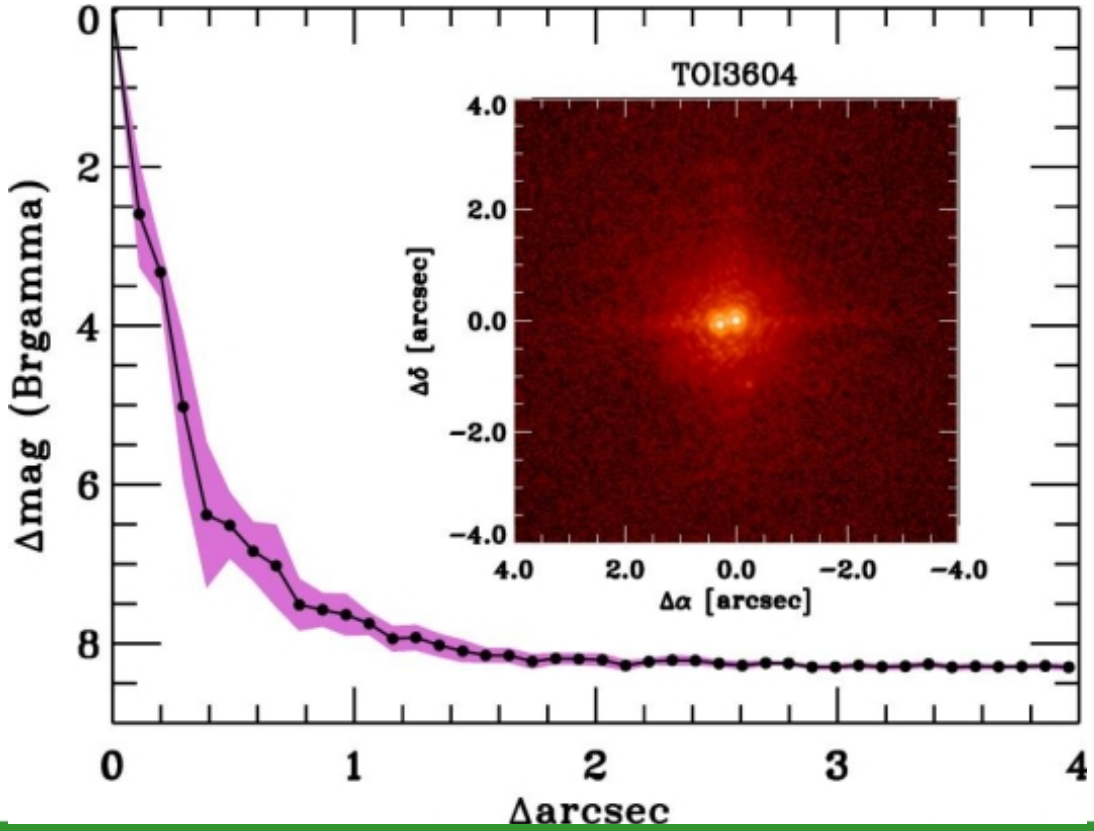
Speckle interferometry

Hawaii, Gemini-N 8-m λ5620 & λ8320 Å (res~20 mas)
- Alopeke Speckle Instrument (Howell et al., 2016; Howell & Furlan, 2022)



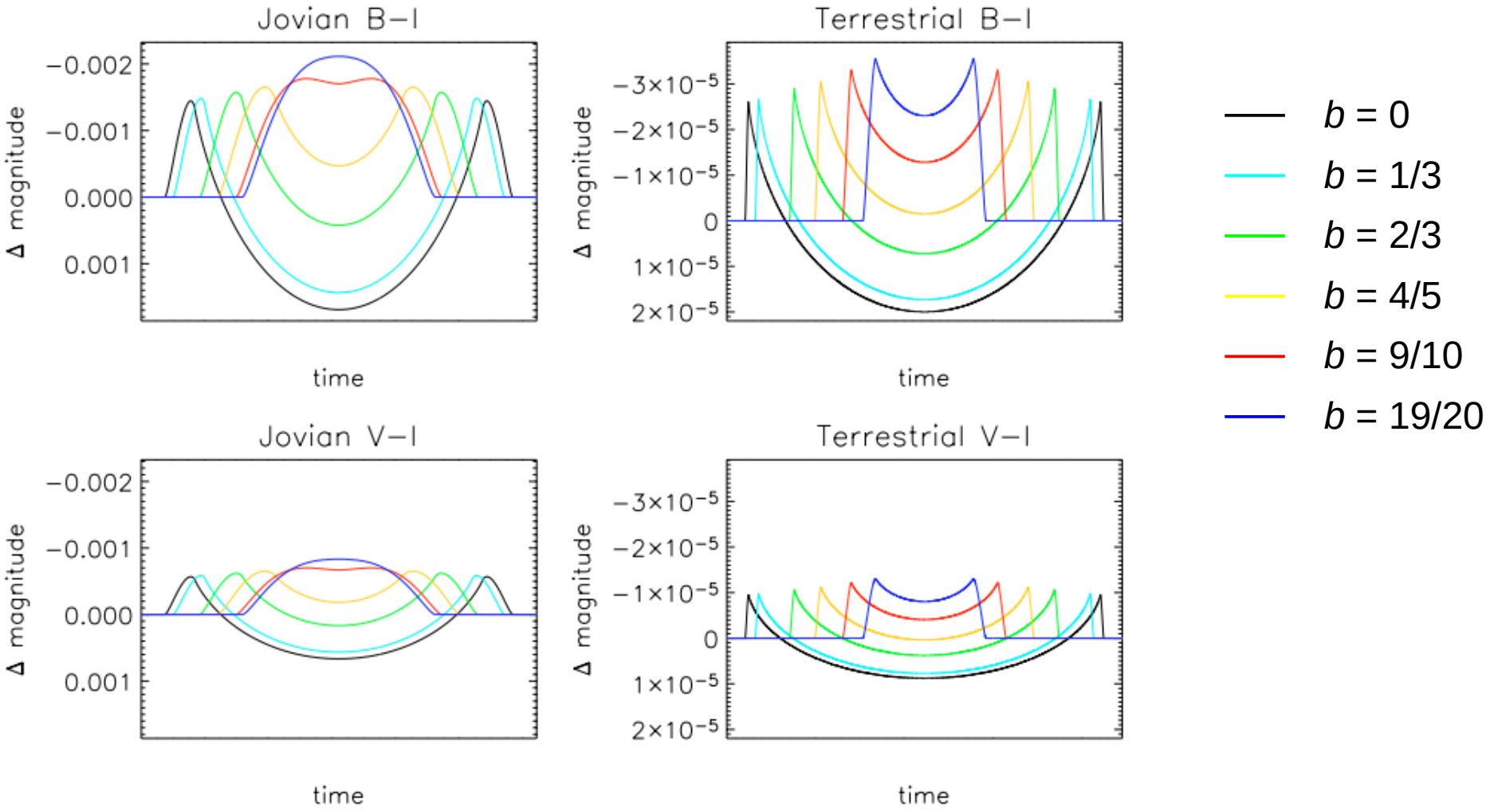
Speckle interferometry

JPL Palomar 5-m λ2.2 & λ1.7 μm (res~89 mas)
- PHARO (Hayward et al., 2001)



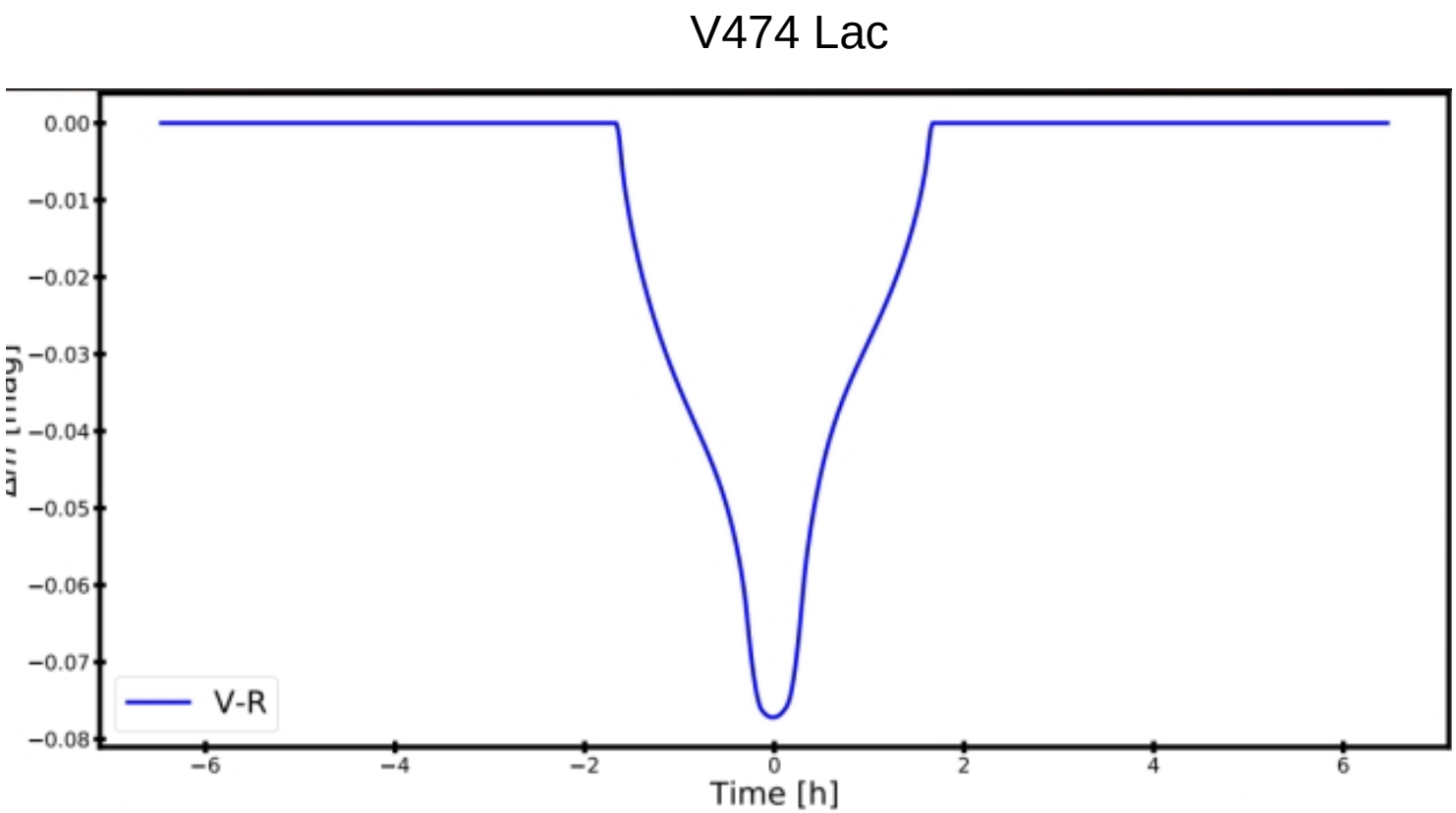
Transit color index

Exoplanet - “double horn” (Tingley, 2004)



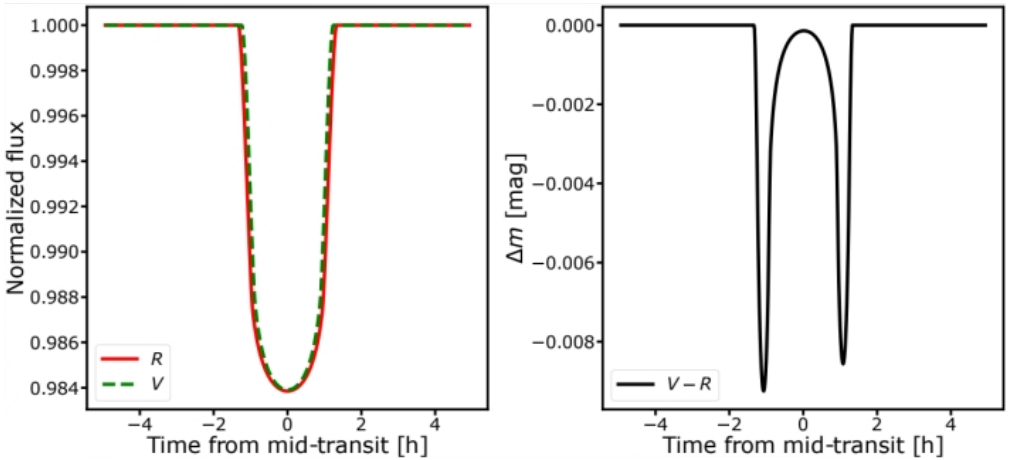
Transit color index

Binary – no “double horn”



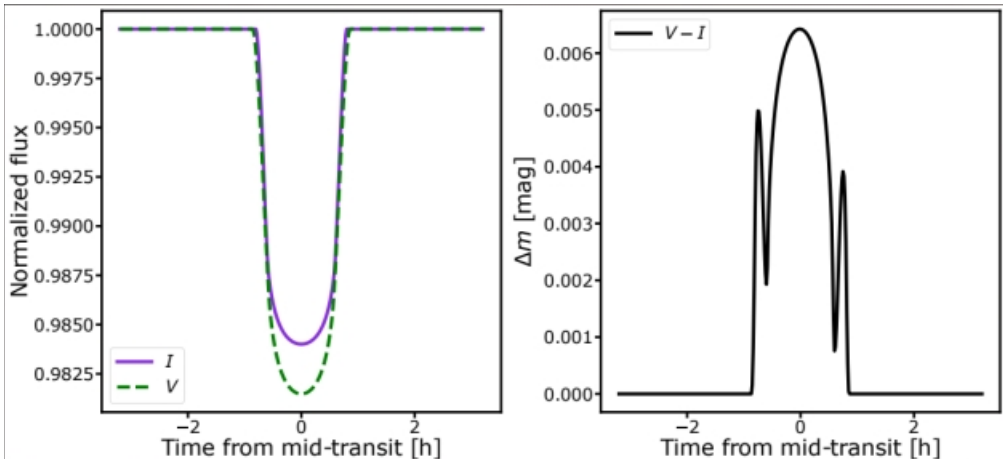
Transit color index

Examples of independent analysis:



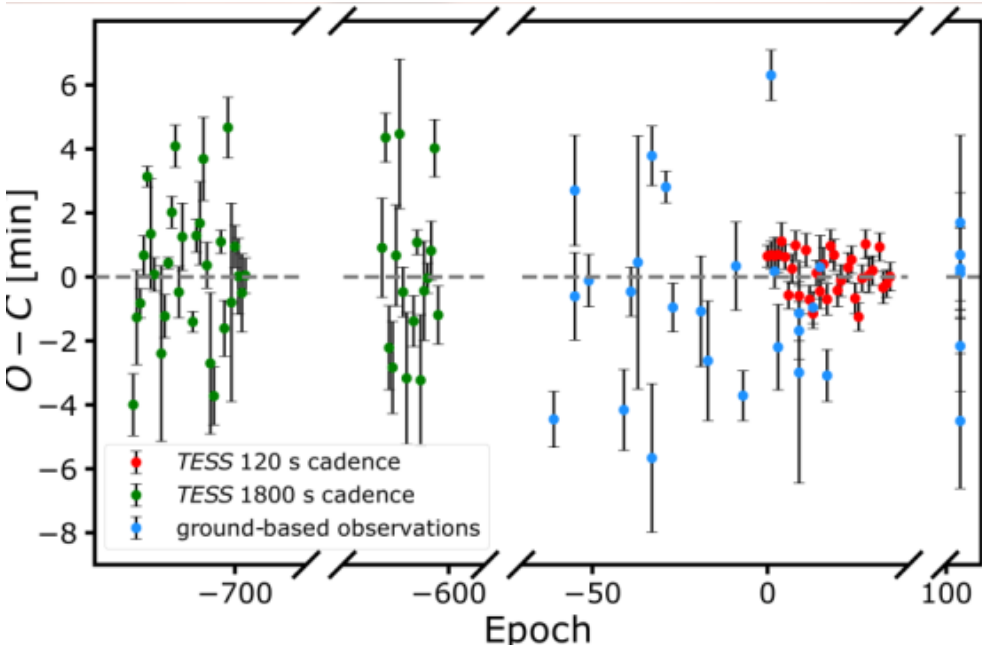
TOI-2046b

TOI-3604.01

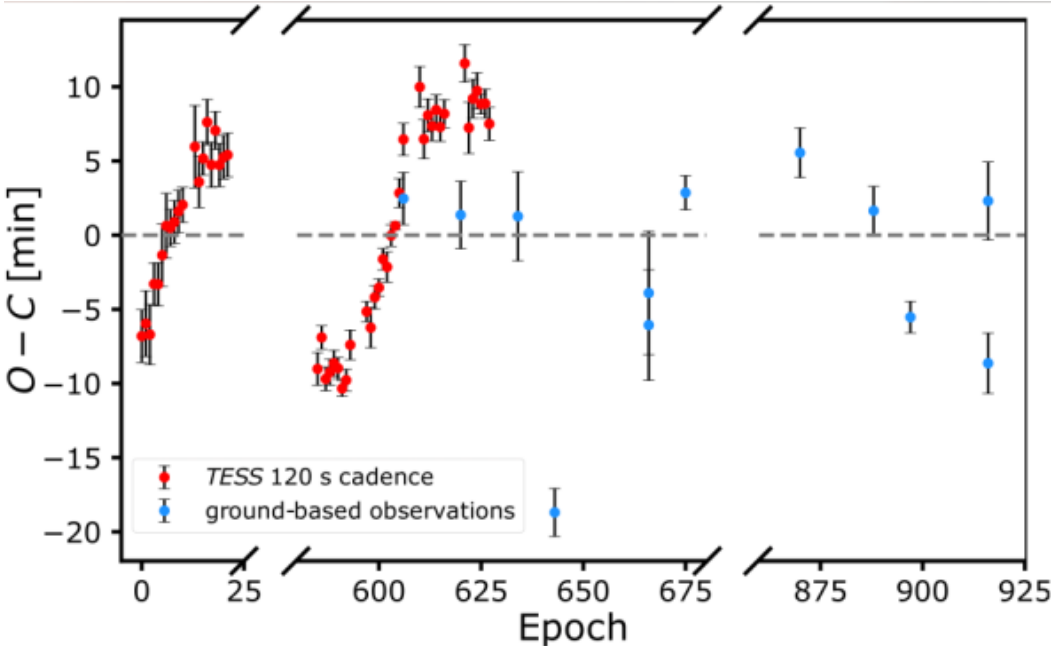


O-C analysis

Only TOI-1834.01 shows a signal



TOI-2046b



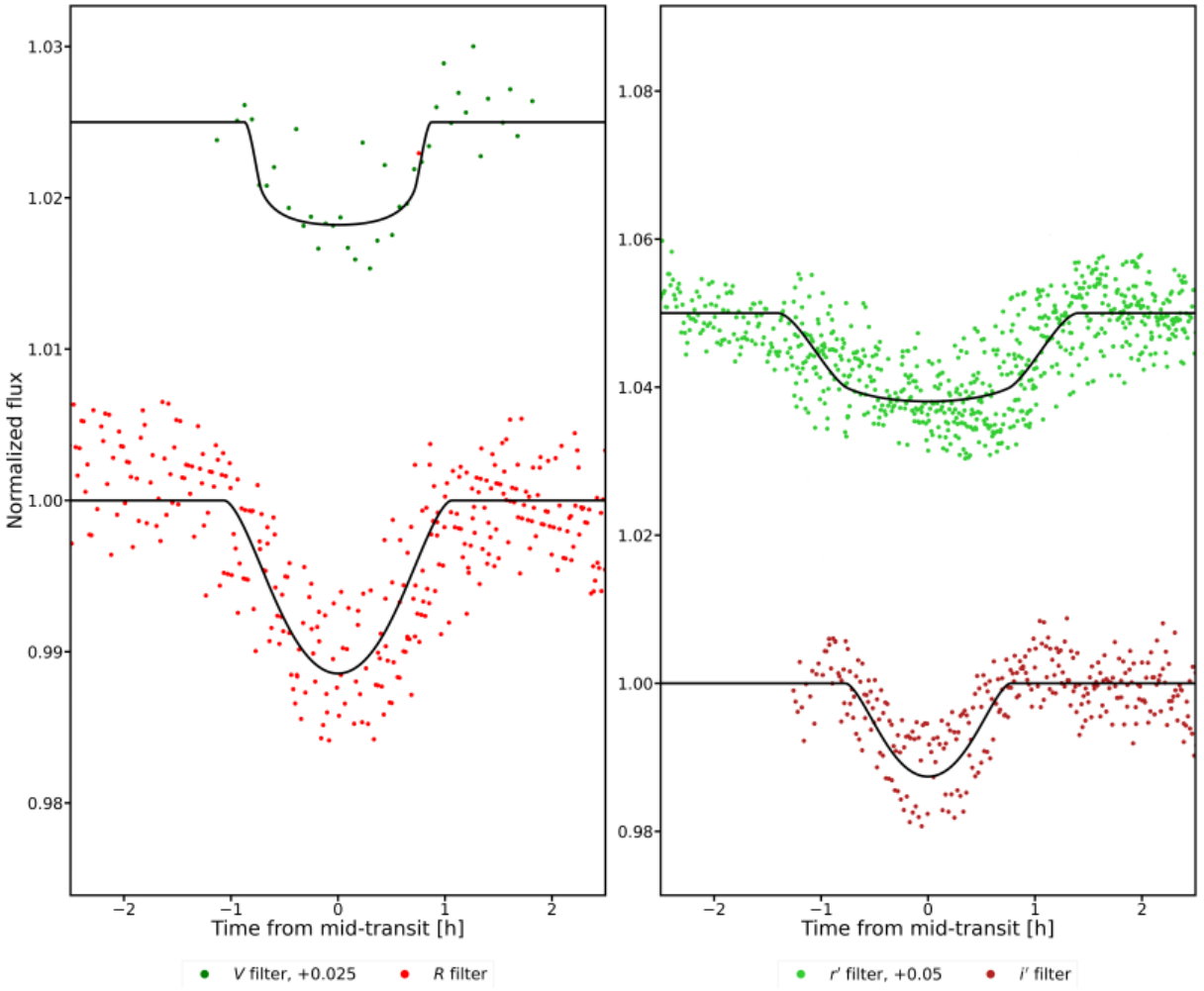
TOI-1834.01

TOI-1834.01

Supposed exoplanet transit model

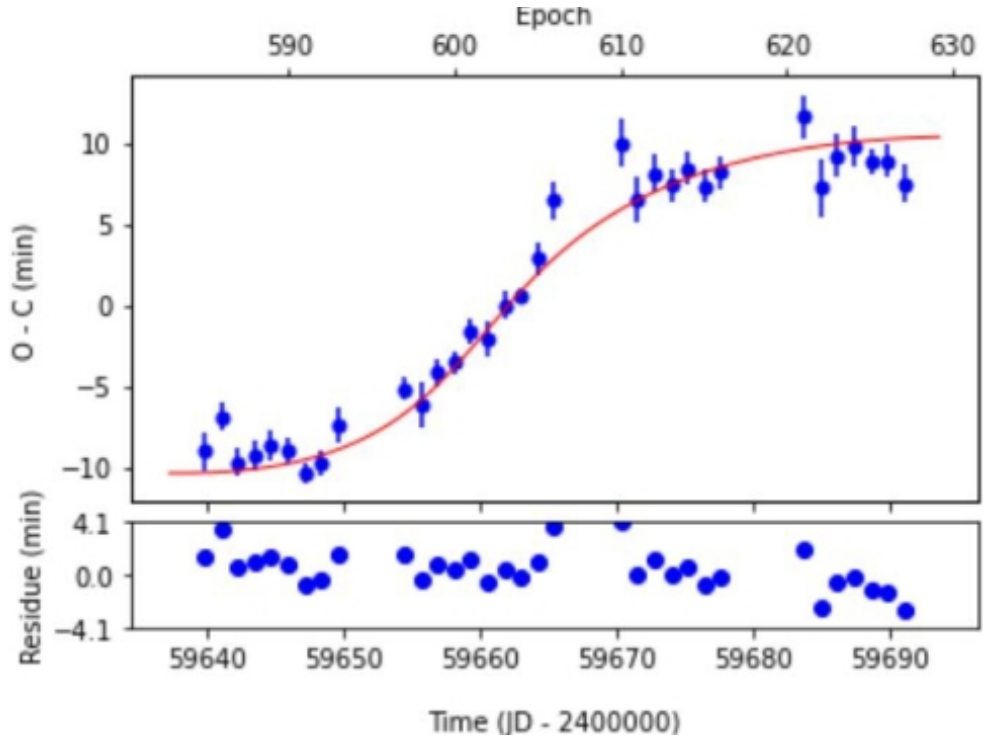
TOI-1834.01

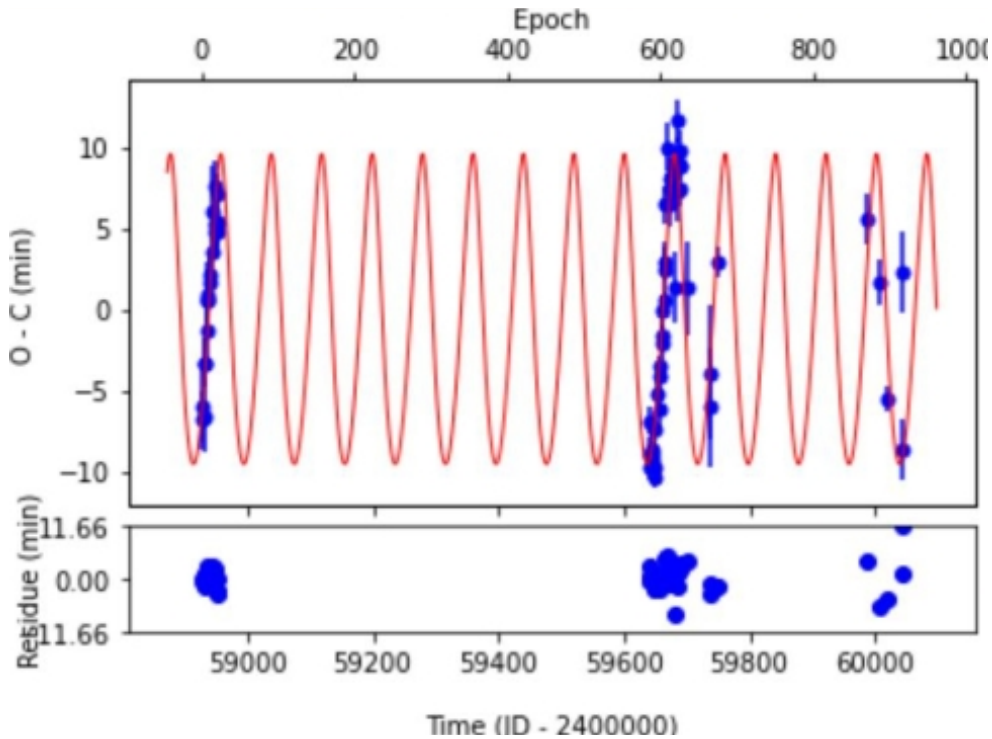
Parameter	pyaneti	ExoFOP
$R_p/R_\star$	$0.14851^{+0.00114}_{-0.00828}$	–
T_0 [BJD_{TDB}]	$2458928.2716370^{+0.0001520}_{-0.0002150}$	$2459689.763585 \pm 0.000236$
P [days]	$1.21644035 \pm 0.00000028$	1.2164402 ± 0.0000007
$a/R_\star$	$3.247^{+0.057}_{-0.041}$	–
b	$0.8906^{+0.0098}_{-0.0080}$	–
i [°]	$74.12^{+0.46}_{-0.41}$	–
t_T [h]	$2.178^{+0.023}_{-0.041}$	1.847 ± 0.065
$\rho_\star$ [g/cm^3]	$1.3316^{+0.1625}_{-0.1620}$	1.3296 ± 0.2850
Depth [ppm]	22056^{+341}_{-390}	15450 ± 177



TOI-1834.01

Third body by `OCFit` (Gajdoš, 2019)





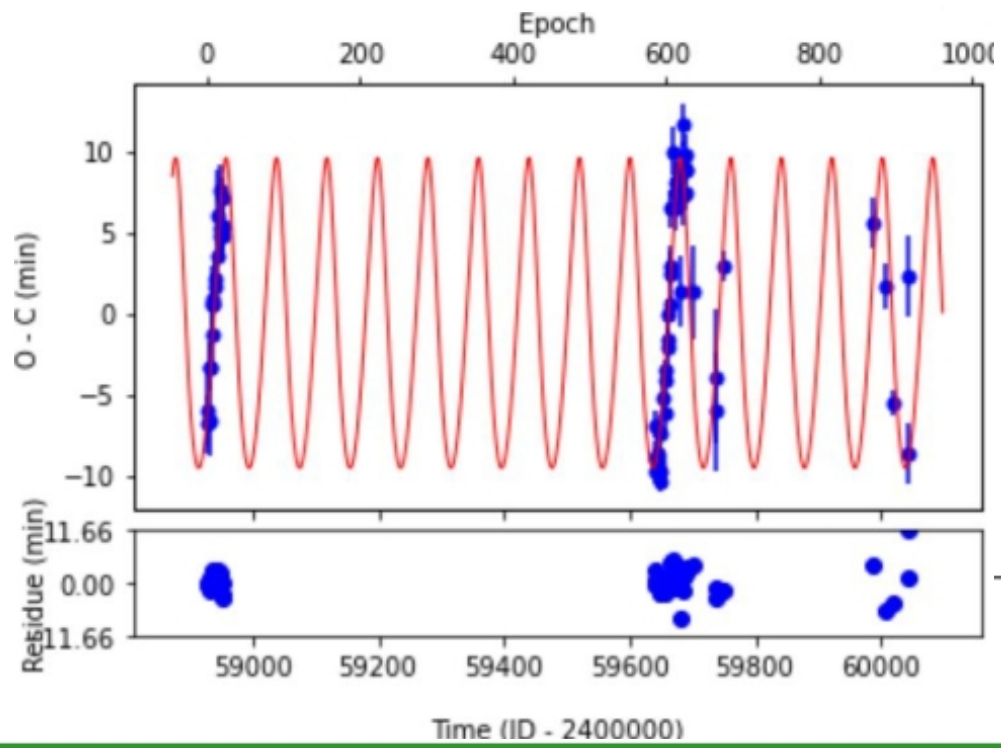
Parameter	Final (MCMC)
P_3 [d]	80.350130 ± 0.314877
$a_3 \sin i_3$ [au]	1.161 ± 0.157
e_3	0.265 ± 0.135
t_{03} [JD]	$59123.765944 \pm 5.239077$
ω_3 [°]	121.53 ± 23.87
$f(m_3)$ [$M_\odot$]	32.33 ± 13.11

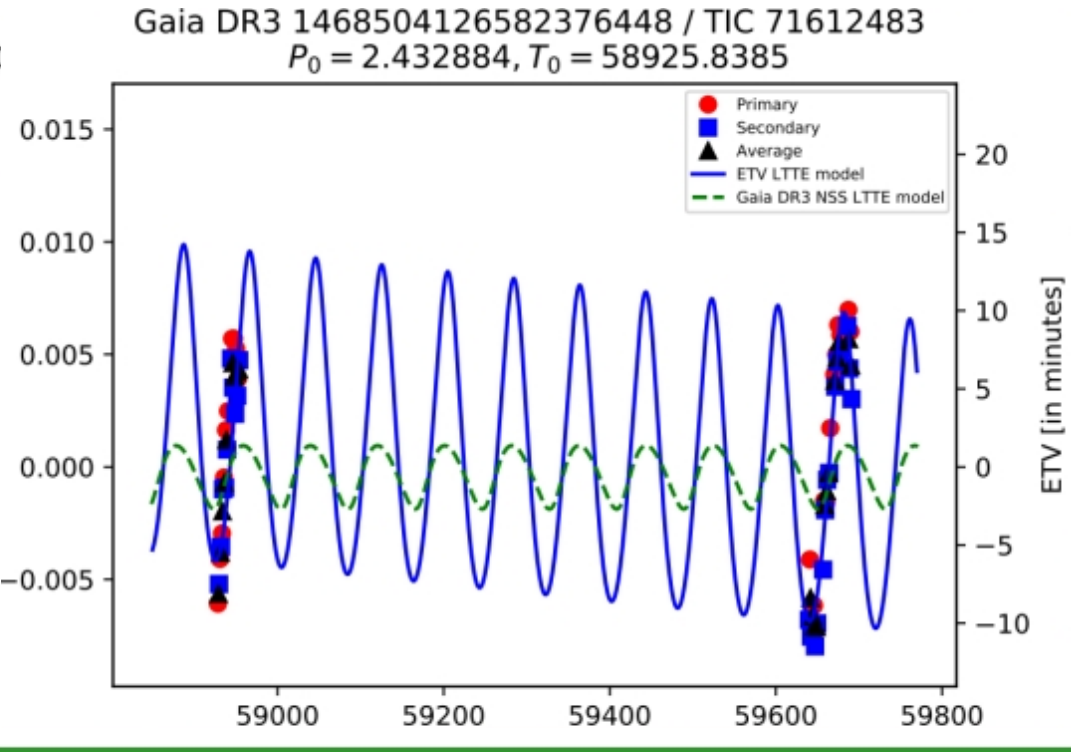
TOI-1834.01

Third body by `OCFit` (Gajdoš, 2019)

This work:
$f(m)$ = 32.33 $M_\odot$
P_3 = 80.35 d
$a_3 \sin i_3$ = 1.161 au

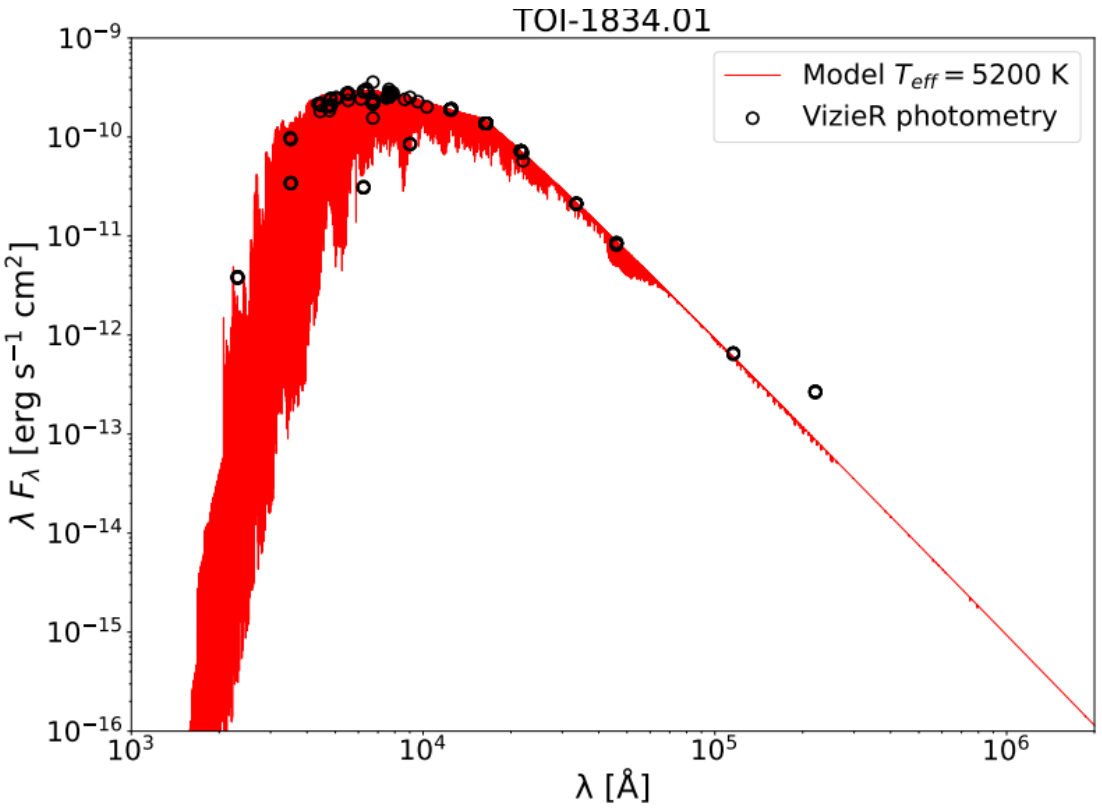
Czavalinga et al. 2023:
$f(m)$ = 20.01 $M_\odot$
P_3 = 79.49 d
$a_3 \sin i_3$ = 259.33 $R_\odot$ = 1.207 au





TOI-1834.01

VizieR photometry + SED with PHOENIX model spectrum (Husser et al., 2013)

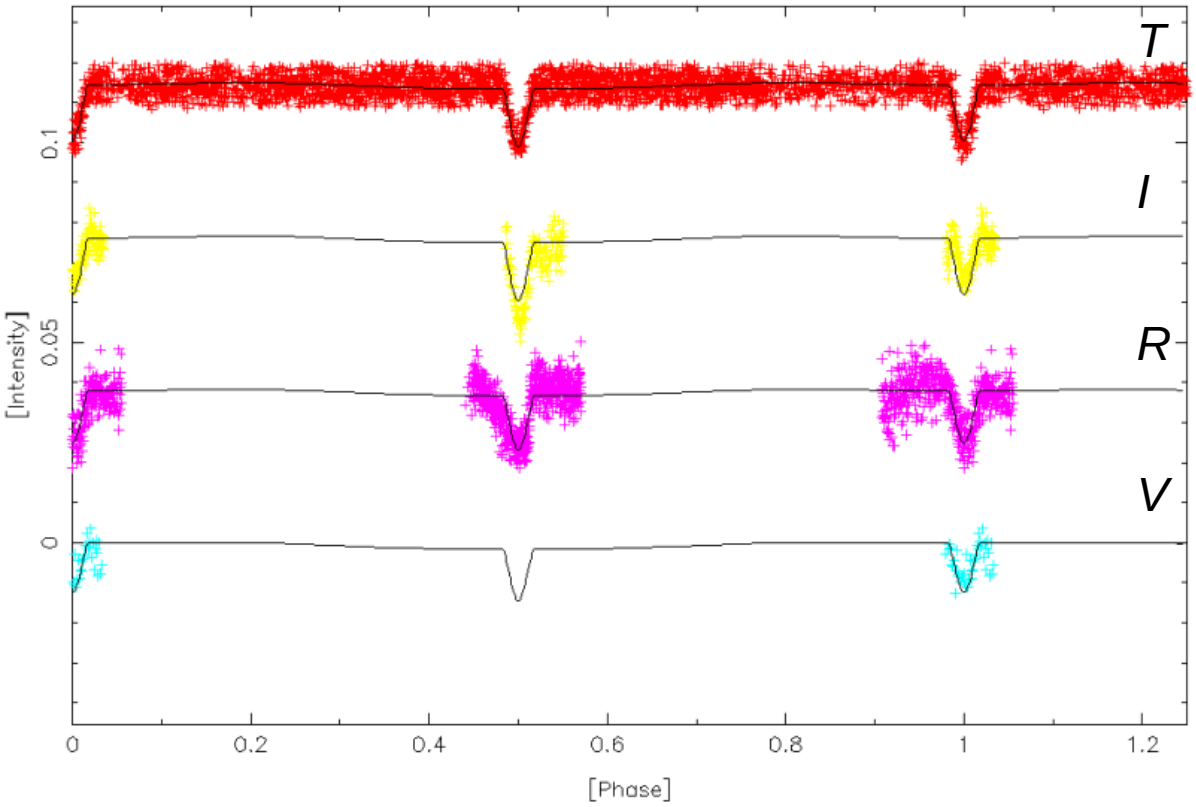


Binary:
Sp. type: K0
M ~ 0.79 $M_\odot$
R ~ 0.85 $R_\odot$
(Cox et al., 2000)

Parameter	Initial	Final
P [JD]	58925.834984	(fixed)
t_0 [d]	2.432884	(fixed)
i[°]	80	76.74 ± 1.19
R_1/a	0.0963	0.1279 ± 0.0126
R_2/R_1	1.0	0.9871 ± 0.0500
e	0.0	(fixed)
T_1 [K]	5200	(fixed)
T_2 [K]	5200	5307 ± 187
A_1, A_2	0.56	(fixed)

TOI-1834.01

Grazing binary (i ~ 80 deg) with shallow eclipse?
Roche-geometry binary model `RMF` code (Garai et al., 2020)



Binary:
Sp. type: K0
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Parameter	Initial	Final
P [JD]	58925.834984	(fixed)
t_0 [d]	2.432884	(fixed)
i[°]	80	76.74 ± 1.19
R_1/a	0.0963	0.1279 ± 0.0126
R_2/R_1	1.0	0.9871 ± 0.0500
e	0.0	(fixed)
T_1 [K]	5200	(fixed)
T_2 [K]	5200	5307 ± 187
A_1, A_2	0.56	(fixed)

TOI-1834.01

Amplitudes of LTTE and dynamical effects (Borkovits et al., 2016):

$$\mathcal{A}_{LTTE} = 1.1 \times 10^{-4} f(m)^{1/3} P_3^{2/3} \sqrt{(1 - e_3^2 \cos^2 \omega_3)},$$

$$\mathcal{A}_{dyn} = \frac{1}{2\pi} \frac{M_3}{M_1 + M_2 + M_3} \frac{P_{12}^2}{P_3} (1 - e_3^2)^{3/2}$$

Suppose M_1=M_2=M_3

$\mathcal{A}_{LTTE}$ = 78.65 s

$\mathcal{A}_{dyn}$ = 567.38 s

$\mathcal{A}_{total}$ = 646.03 s

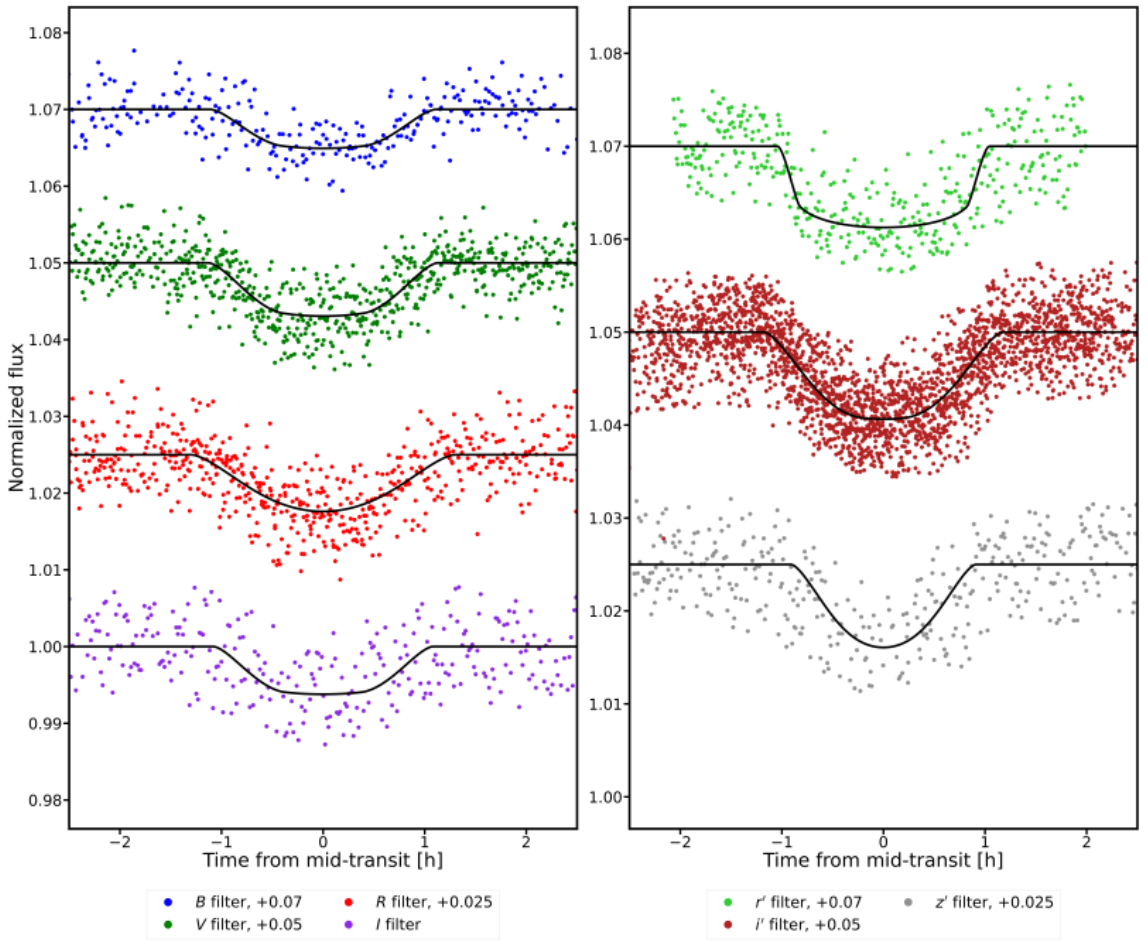
$\mathcal{A}_{obs}$ = 617.5 s

TOI-1518b – Independent analysis

Supposed exoplanet transit model

TOI-1518b

Parameter	pyaneti	article (Wong et al., 2021)
$R_p/R_\star$	$0.08185^{+0.00073}_{-0.00042}$	0.08155 ± 0.00022
T_0 [BJD_{TDB}]	$2459718.730971^{+0.000082}_{-0.000075}$	$2459378.459370 \pm 0.000059$
P [days]	$0.67247386 \pm 0.00000017$	$0.67247414 \pm 0.00000028$
$a/R_\star$	$2.139^{+0.008}_{-0.007}$	2.268 ± 0.021
b	$0.7853^{+0.0053}_{-0.0070}$	0.7481 ± 0.0073
i [°]	$68.87^{+0.36}_{-0.22}$	70.74 ± 0.37
t_T [h]	$2.070^{+0.012}_{-0.011}$	1.801 ± 0.125
$\rho_\star$ [g/cm^3]	$0.4171^{+0.0527}_{-0.0457}$	0.4170 ± 0.0545
Depth [ppm]	6670^{+50}_{-61}	6651 ± 36

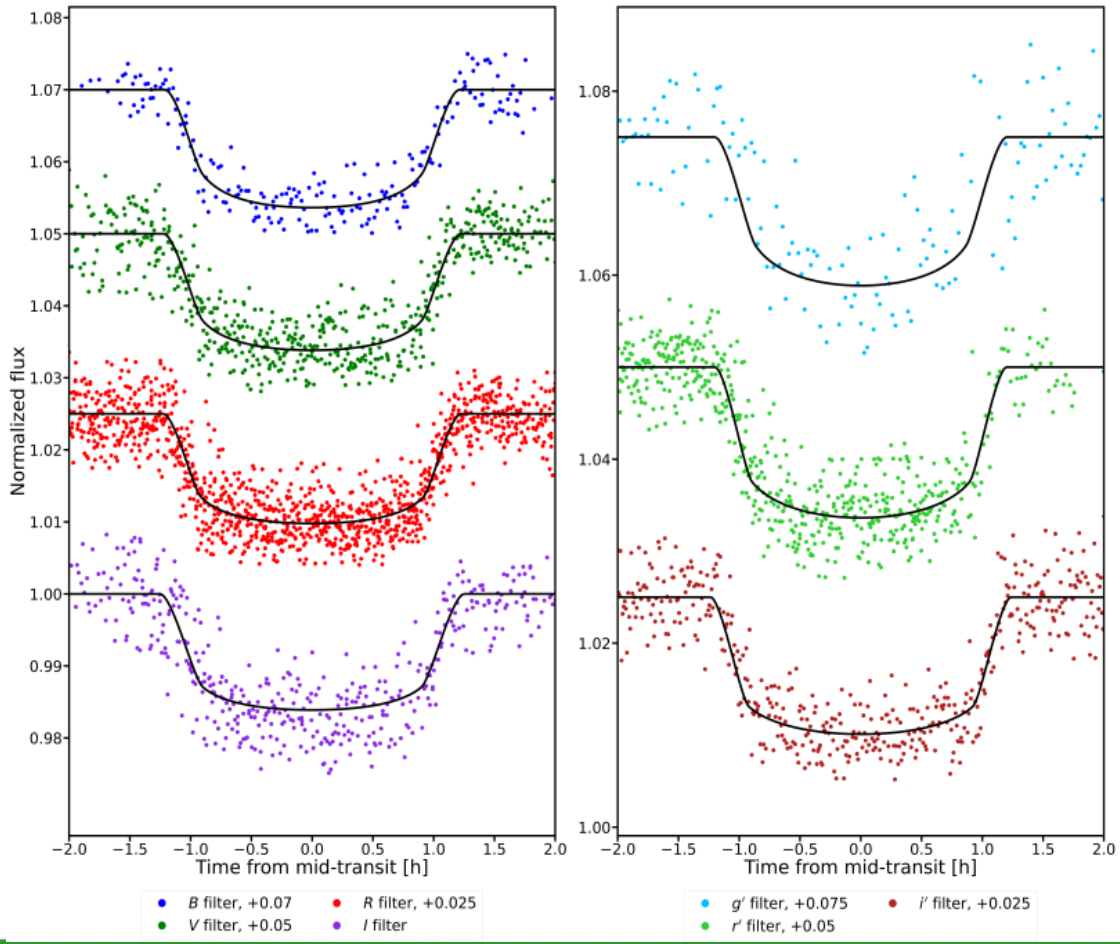


TOI-2046b - Independent analysis

Supposed exoplanet transit model

TOI-2046b

Parameter	pyaneti	article (Kabáth et al., 2022)
$R_p/R_\star$	$0.1173^{+0.0008}_{-0.0007}$	$0.1213^{+0.0017}_{-0.0021}$
T_0 [BJD_{TDB}]	$2459883.844897^{+0.000058}_{-0.000059}$	$2457792.844897^{+0.0024}_{-0.0022}$
P [days]	$1.49718679 \pm 0.00000015$	$1.4971842^{+0.0000031}_{-0.0000033}$
$a/R_\star$	$4.53^{+0.05}_{-0.05}$	$4.75^{+0.18}_{-0.17}$
b	$0.60^{+0.02}_{-0.02}$	$0.51^{+0.06}_{-0.07}$
i [°]	$81.8^{+0.3}_{-0.3}$	83.6 ± 0.9
t_T [h]	$2.591^{+0.010}_{-0.0103}$	$2.410^{+0.032}_{-0.030}$
$\rho_\star$ [g/cm^3]	$0.859^{+0.106}_{-0.096}$	0.890 ± 0.098
Depth [ppm]	14757^{+186}_{-180}	16266 ± 85

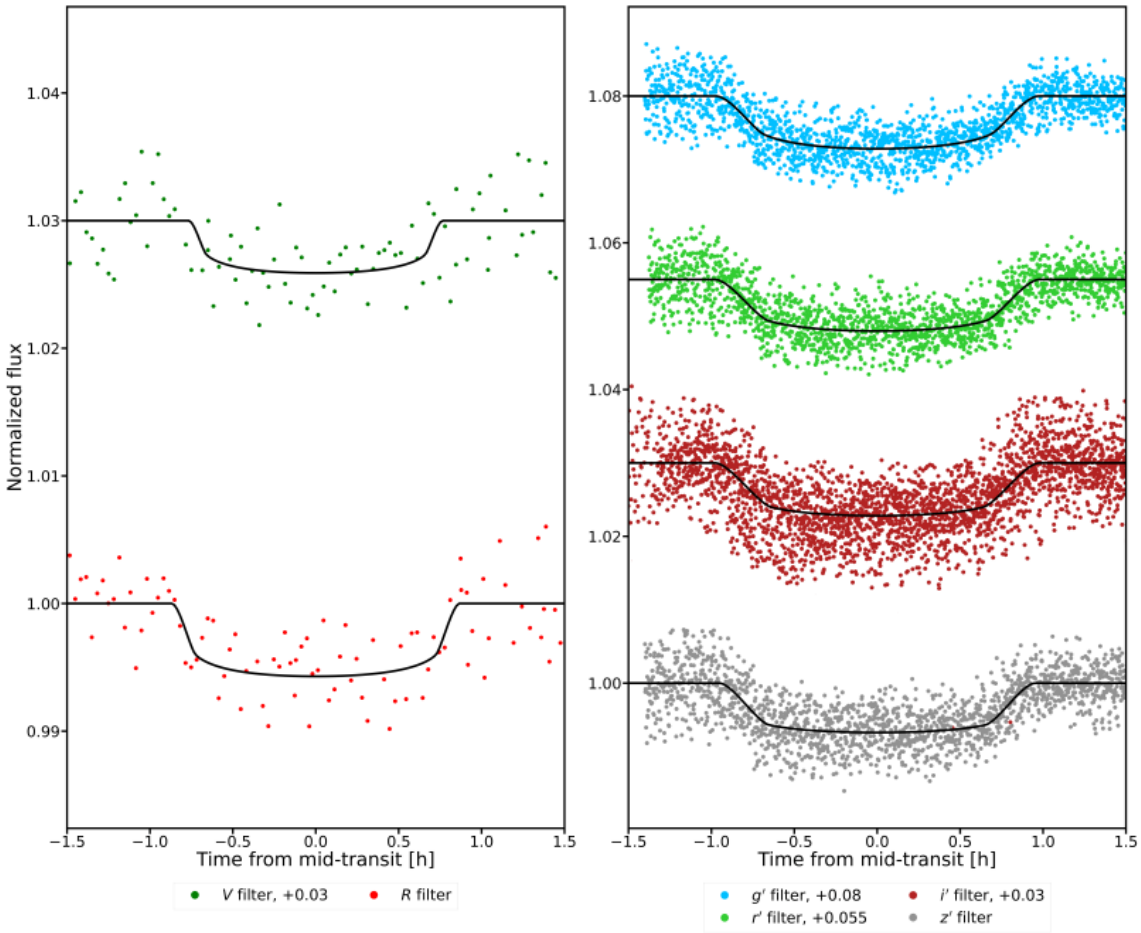


TOI-2109b - Independent analysis

Supposed exoplanet transit model

TOI-2109b

Parameter	pyaneti	article (Cabot et al., 2021)
$R_p/R_\star$	$0.1022^{+0.0019}_{-0.0021}$	$0.0988^{+0.0015}_{-0.0012}$
T_0 [BJD_{TDB}]	$2459854.414430^{+0.000040}_{-0.000042}$	$2458787.049255 \pm 0.000094$
P [days]	$1.90261125 \pm 0.00000009$	1.902603 ± 0.000011
$a/R_\star$	$4.133^{+0.056}_{-0.048}$	$4.291^{+0.057}_{-0.061}$
b	$0.8813^{+0.0048}_{-0.0066}$	$0.9036^{+0.0061}_{-0.0053}$
i [°]	$77.70^{+0.22}_{-0.21}$	$77.84^{+0.23}_{-0.26}$
t_T [h]	$2.395^{+0.018}_{-0.017}$	2.347 ± 0.008
$\rho_\star$ [g/cm^3]	$0.341^{+0.057}_{-0.054}$	–
Depth [ppm]	10443.56^{+197}_{-131}	9761 ± 77

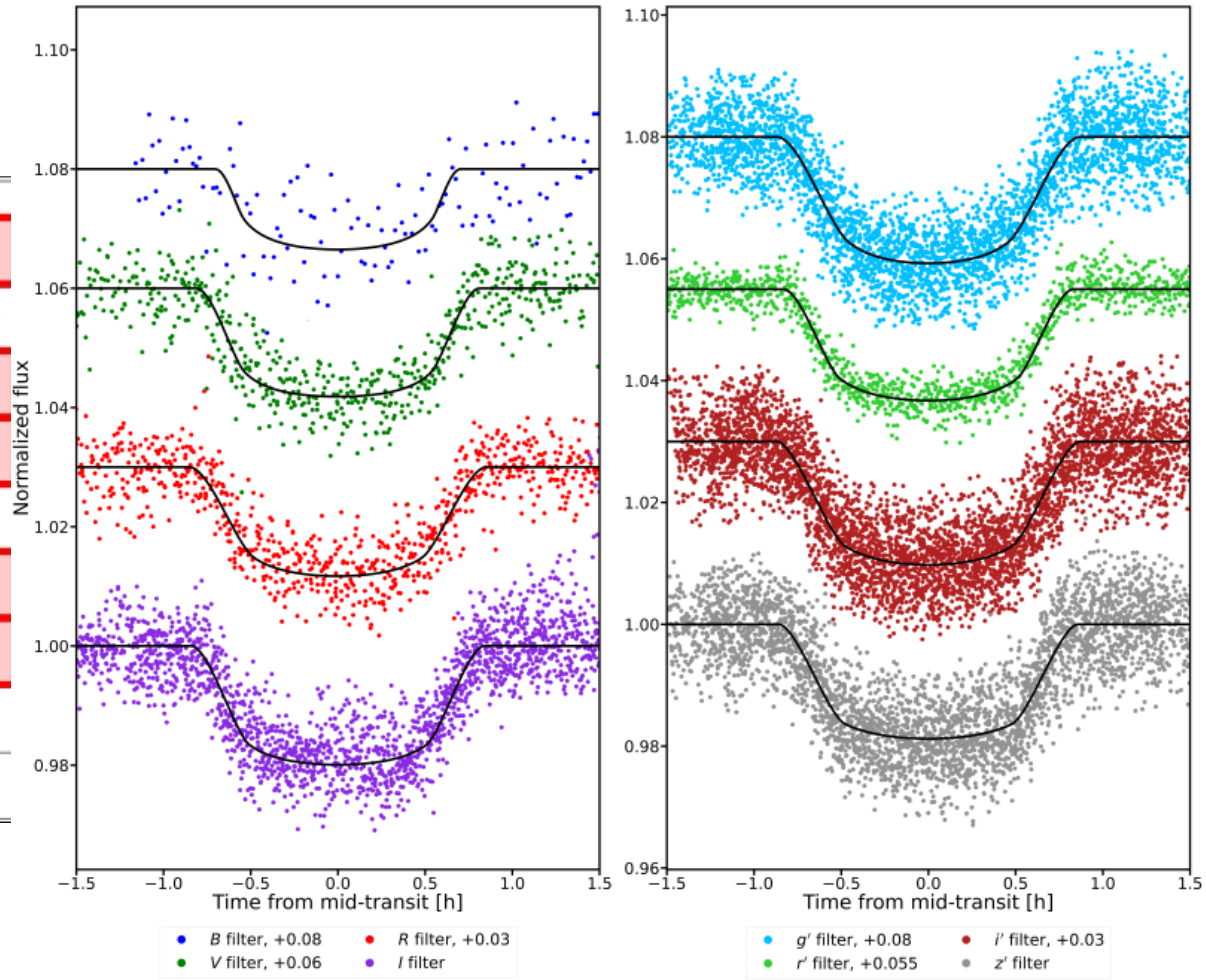


TOI-3604.01

Supposed exoplanet transit model

TOI-3604.01

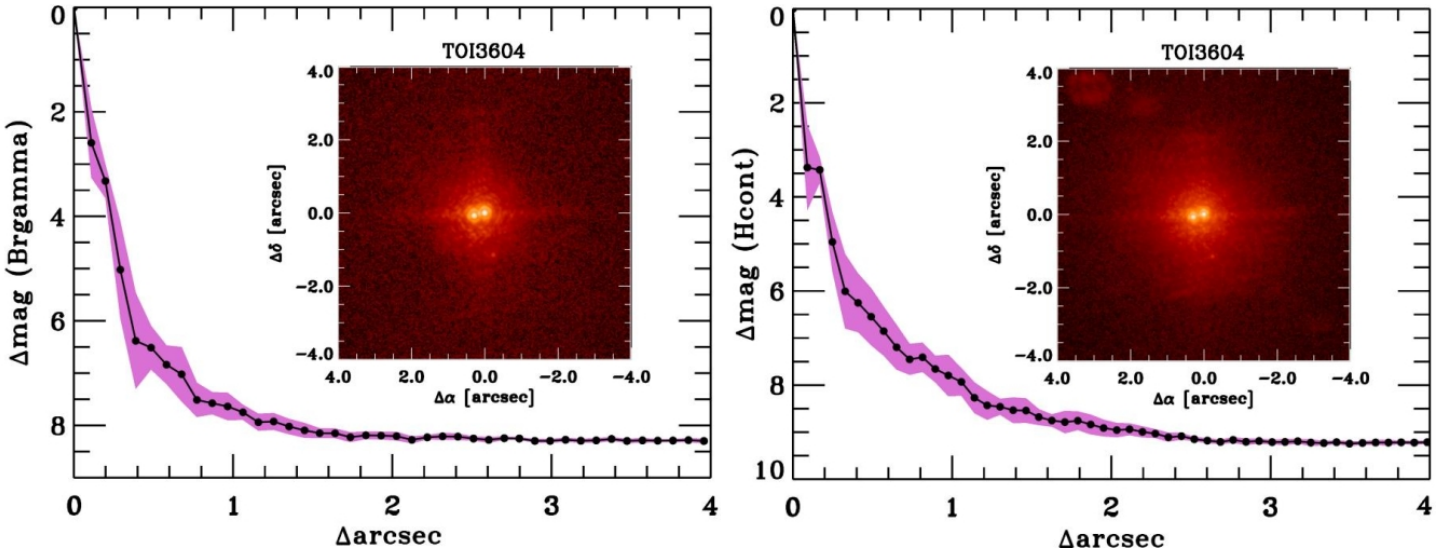
Parameter	Companion is present	ExoFOP
$R_p/R_\star$	$0.12187^{+0.00202}_{-0.00204}$	–
T_0 [BJD_{TDB}]	$2459825.953340^{+0.000840}_{-0.000850}$	$2459853.68732 \pm 0.0002436$
P [days]	1.0666837 ± 0.00000427	1.06666975 ± 0.0000159
$a/R_\star$	$4.381^{+0.087}_{-0.081}$	–
b	$0.6837^{+0.0213}_{-0.0269}$	–
i [°]	$81.02^{+0.51}_{-0.45}$	–
t_T [h]	$1.689^{+0.015}_{-0.014}$	1.641 ± 0.018
$\rho_\star$ [g/cm^3]	$1.4067^{+0.3513}_{-0.3697}$	–
Depth [ppm]	15851^{+396}_{-394}	18768 ± 169



TOI-3604.01

At least two sources in *TESS* pixel

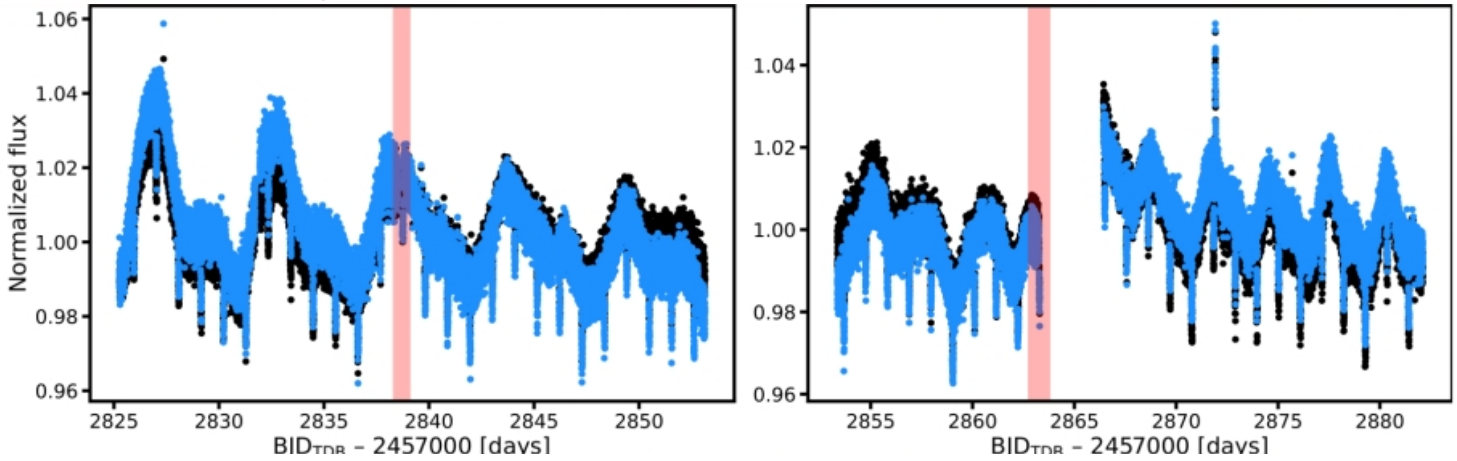
Suppose:
$L_1 = L_2$



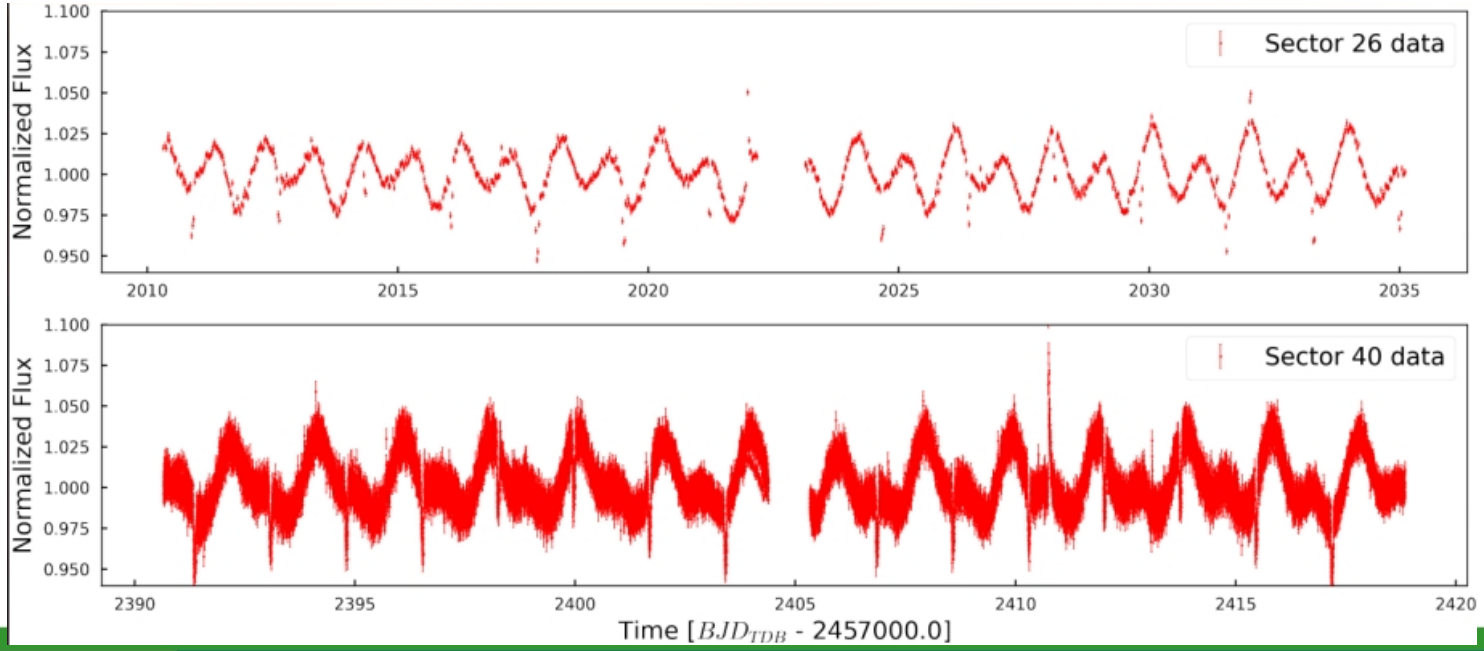
Parameter	Companion is present	Companion is excluded	ExoFOP
$R_p/R_\star$	$0.12187^{+0.00202}_{-0.00204}$	$0.15987^{+0.00071}_{-0.00057}$	–
T_0 [BJD_{TDB}]	$2459825.953340^{+0.000840}_{-0.000850}$	$2459825.953340^{+0.000840}_{-0.000850}$	$2459853.68732 \pm 0.0002436$
P [days]	1.0666837 ± 0.00000427	1.0666837 ± 0.00000427	1.06666975 ± 0.0000159
$a/R_\star$	$4.381^{+0.087}_{-0.081}$	$5.504^{+0.024}_{-0.038}$	–
b	$0.6837^{+0.0213}_{-0.0269}$	$0.7237^{+0.0513}_{-0.0469}$	–
i [°]	$81.02^{+0.51}_{-0.45}$	$86.51^{+0.87}_{-0.85}$	–
t_T [h]	$1.689^{+0.015}_{-0.014}$	$1.715^{+0.009}_{-0.008}$	1.641 ± 0.018
$\rho_\star$ [g/cm^3]	$1.4067^{+0.3513}_{-0.3697}$	$1.4067^{+0.3513}_{-0.3697}$	–
Depth [ppm]	15851^{+396}_{-394}	25557^{+285}_{-274}	18768 ± 169

TOI-3604.01

Similar system



TOI-3604
R_P/R_S ~ 0.16
P ~ 1.07 d
T_{eff} ~ 4900 K
M_S ???



TOI-5375
R_P/R_S ~ 0.17
P ~ 1.7 d
T_{eff} ~ 4000 K
M_S ~ 0.62 $M_\odot$
M_P ~ 83.8 ± 2.1 M_J

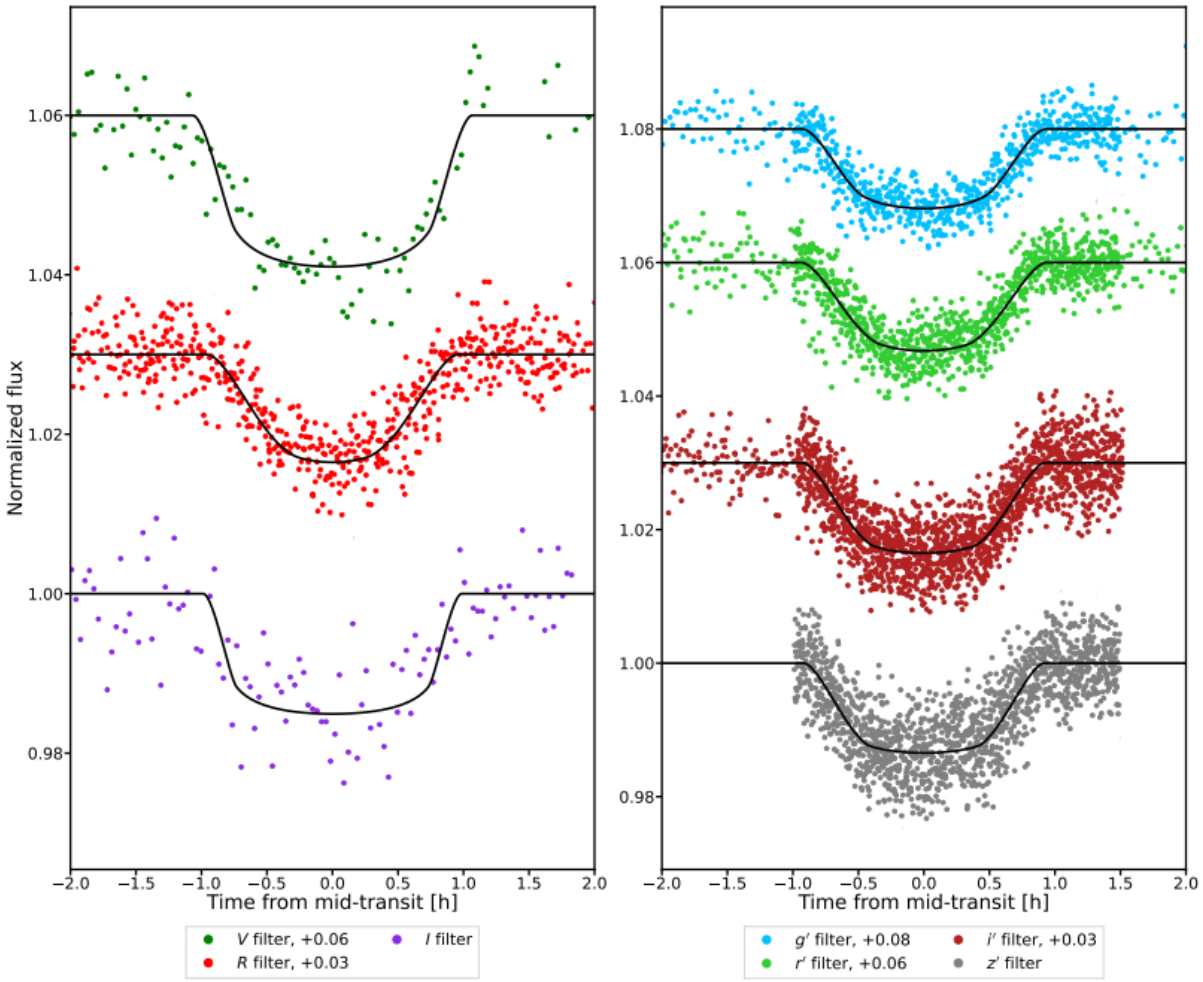
(Lambert et al, 2023)

TOI-3856.01

Supposed exoplanet transit model

TOI-3856.01

Parameter	pyaneti	ExoFOP
$R_p/R_\star$	$0.1135^{+0.0024}_{-0.0023}$	–
T_0 [BJD_{TDB}]	$2459609.405178^{+0.0002180}_{-0.0002170}$	$2459631.884549 \pm 0.000340$
P [days]	$2.04360450 \pm 0.00000119$	2.0436029 ± 0.0000013
$a/R_\star$	$6.129^{+0.260}_{-0.228}$	–
b	$0.8179^{+0.0257}_{-0.0269}$	–
i [°]	$82.33^{+0.54}_{-0.52}$	–
t_T [h]	$1.942^{+0.038}_{-0.042}$	1.513 ± 0.077
$\rho_\star$ [g/cm^3]	$0.9568^{+0.2200}_{-0.1816}$	$0.9611 \pm 0.0.2240$
Depth [ppm]	12891^{+130}_{-120}	12980 ± 4



Conclusions

- 316 individual transits from *TESS* data (*O-C* points)
- 163 ground-based transits
- Independent analysis:
  - TOI-1518b (Cabot et al., 2021)
  - TOI-2046b (Kabáth et al., 2022)
  - TOI-2109b (Wong et al., 2021)
- Triple system found:
  - TOI-1834.01 (Czavalinga et al., 2023)
- New:
  - TOI-3604.01 – low mass star orbiting an M dwarf?
  - TOI-3856.01 – still undecided exoplanetary candidate

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Validation of selected *TESS* exoplanetary candidates

Thank you !

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