CHEOPS Timing capabilities: searching for TTVs of warm-Jupiter exoplanets

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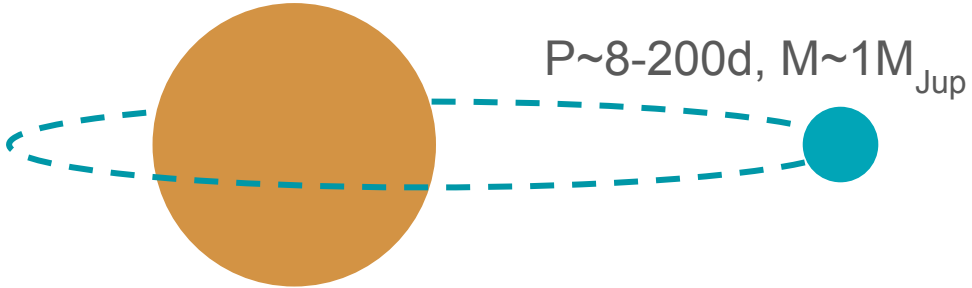
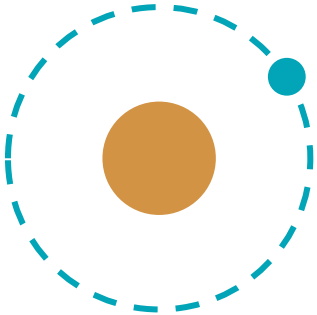
G.Piotto, D. Gandolfi, V.Nascimbeni, G. Lacedelli, F. Marzari & CHEOPS collaboration.

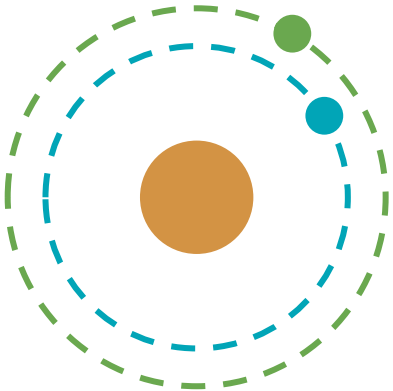
warm-Jupiter planets



hot-Jup in single-planet systems, but the occurrence rate of companions is uncertain and unreliable (Huang, Wu & Triaud 2016)

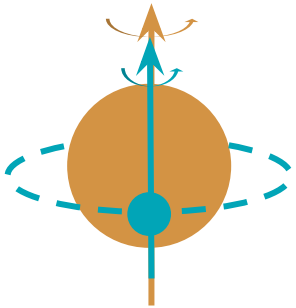


~50% of warm-Jup in the *Kepler* sample are in multi-planet systems (Huang et al., 2016)

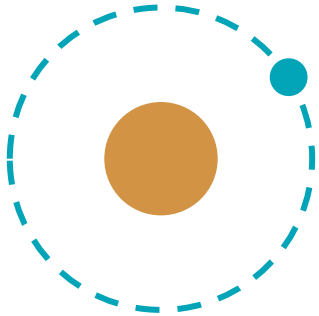


which is the evolution path of warm-Jupiter planets?

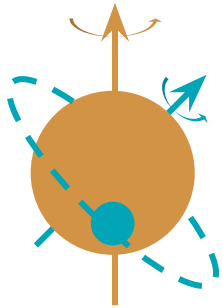
aligned
λ~0°



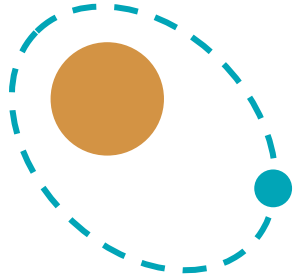
(almost)
circular



misaligned
λ≠0°



eccentric



disk-driven migration?
(Baruteau et al. 2016)

could ∃ lower-mass companion on outer orbit (potentially in MMR)

planet-planet (p-p) scattering?
(Marzari & Nagasawa 2019)

could ∃ outer perturber on possibly eccentric and inclined orbit

which is the evolution path of warm-Jupiter planets?

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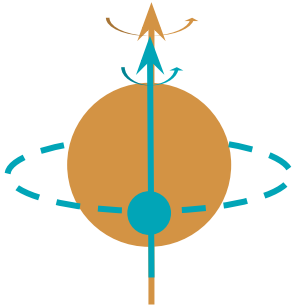
λ~0°



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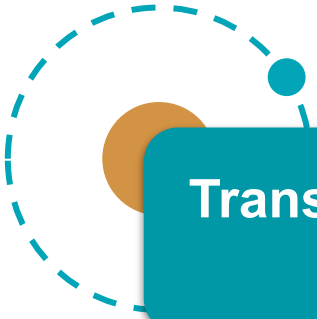

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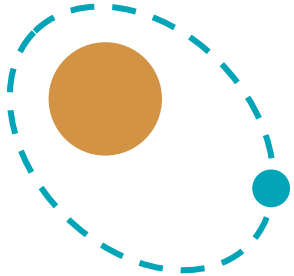


Transit Timing Variations (TTVs)

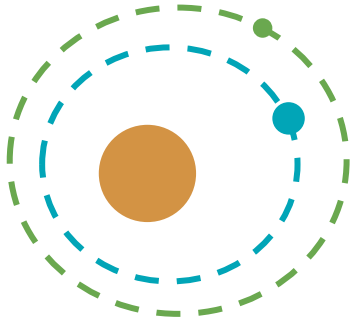
disk-driven migration?
(Baruteau et al. 2016)

planet-planet (p-p) scattering?
(Marzari & Nagasawa 2019)

could ∃ lower-mass companion on outer orbit (potentially in MMR)

could ∃ outer perturber on possibly eccentric and inclined orbit

what is a TTV? what is it useful for?



Agol et al., 2005; Holman & Murray 2005

P ≠ const
mutual interaction
among planets

Transit Timing Variation (TTV)
w.r.t
Linear Ephemeris
$T_{0,lin} = T_{0,ref} + P \times N$

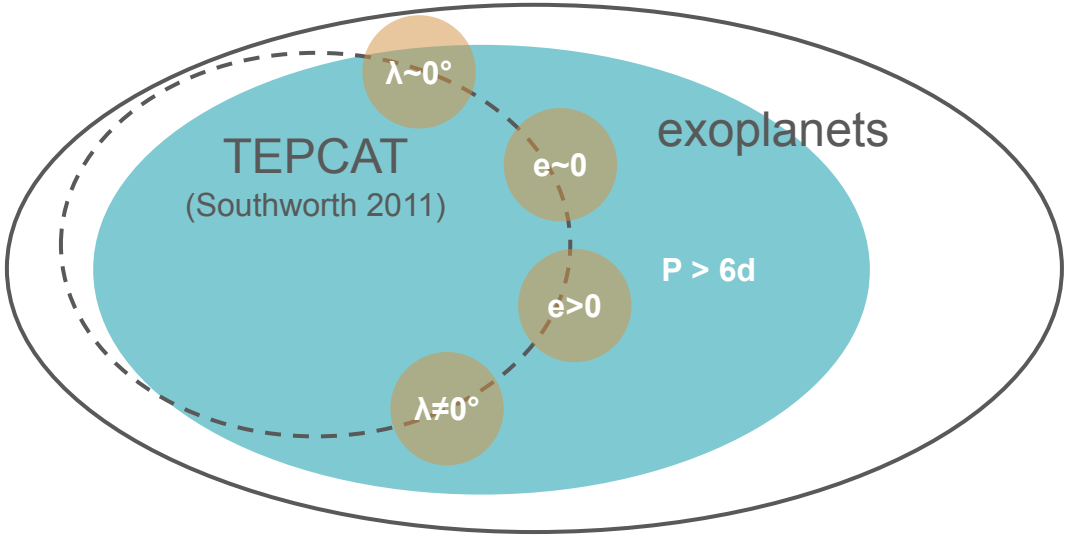
Establish **planetary nature** of transiting planets
Detect unknown planets (also non-transiting)

multi-planet system characterisation
mass of the perturber (perturbers if more than one planets)
orbital **parameter determination** and degeneracy breaking

architecture characterisation: ~MMR, formation and evolution processes

complementary to RV for mass determination

how do we select our sample?



visible with CHEOPS?

↓

Feasibility Checker (FC)

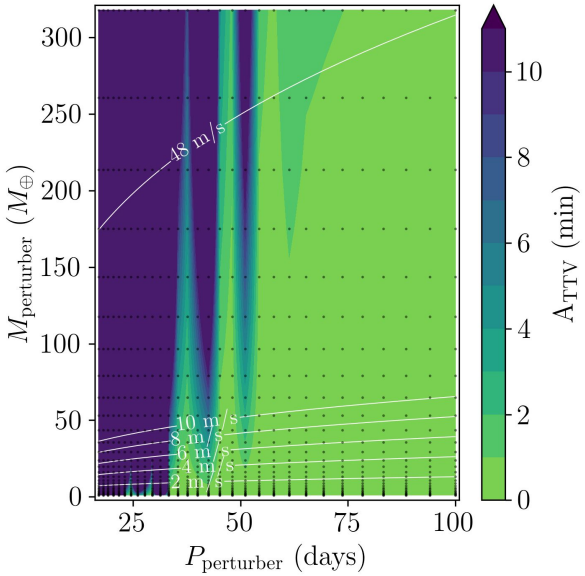
created **TTV maps** with TRADES (Borsato et al., 2014, Borsato et al., 2021)

pertuber:
30 log-spaced P_{per} (<100d)
30 log-space M_{per} ($1M_{\oplus}$-$1M_{Jup}$)
2 ecc_{per} (0, 0.1)
2 Δinc_{per} (0°, 60°)

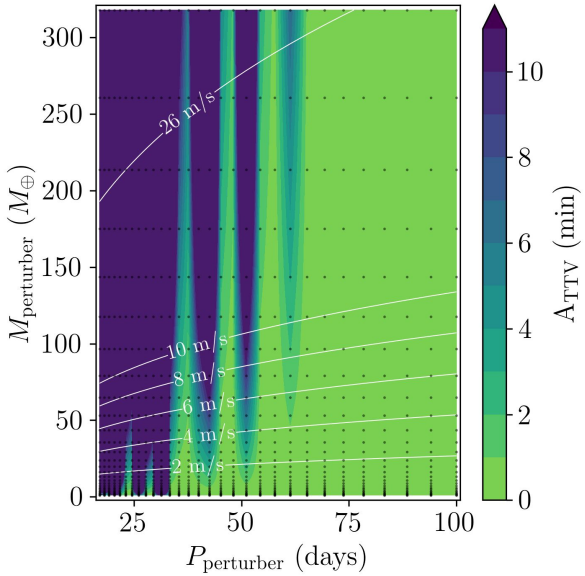
- selected 15 random transits in 3.5 years
- computed A_{TTV} (semi-amplitude of O-C)
- repeated 100 times
- taken the median

example of TTV maps for HAT-P-17 + perturber

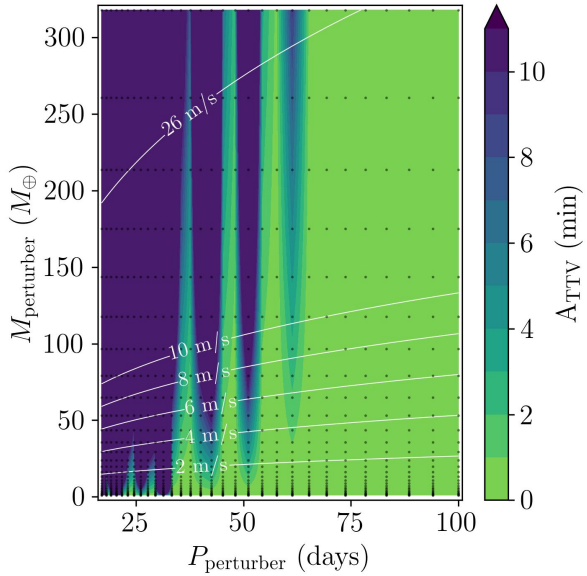
ecc_{per}=0 , Δinc_{per}=0°



ecc_{per}=0 , Δinc_{per}=60°



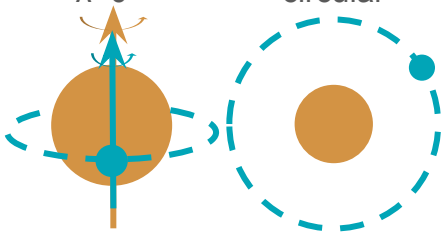
ecc_{per}=0.1 , Δinc_{per}=60°



which are the targets in this work?

aligned
λ~0°

(almost)
circular

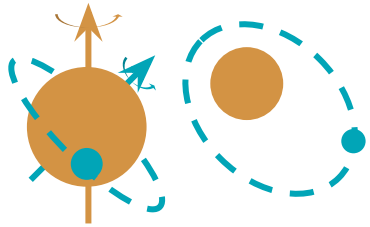


WASP-38 b (4)

misaligned
λ≠0°

eccentric

WASP-8 b (2)



WASP-130 b (3)

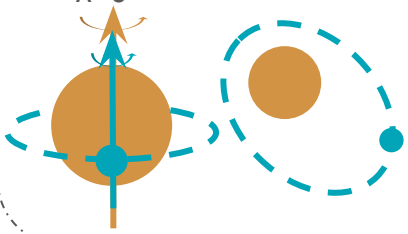
WASP-106 b (1)

K2-287 b (3)

17 visits in total

aligned
λ~0°

eccentric

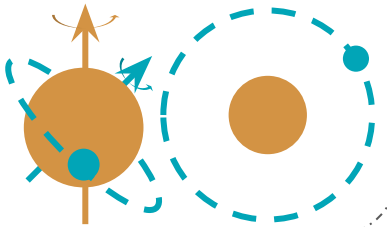


HAT-P-17 b (3)

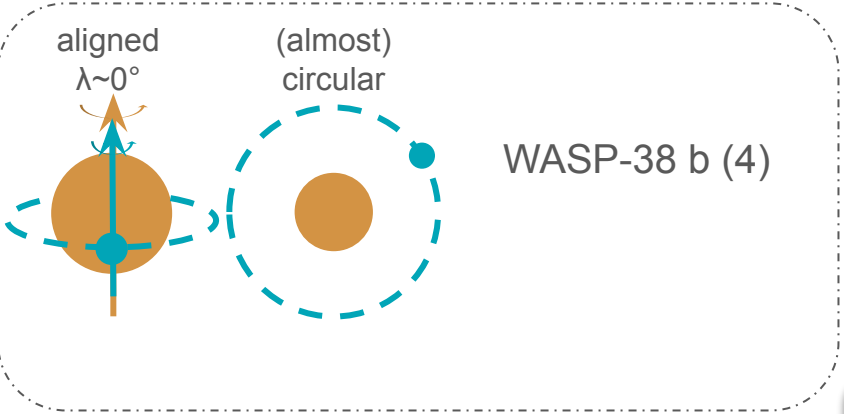
misaligned
λ≠0°

(almost)
circular

KELT-6 b (1)



which are the targets in this work?



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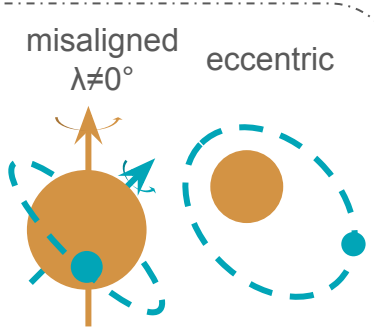
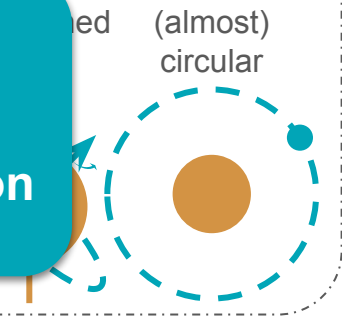
17 visits in total

WASP-8 b (2)



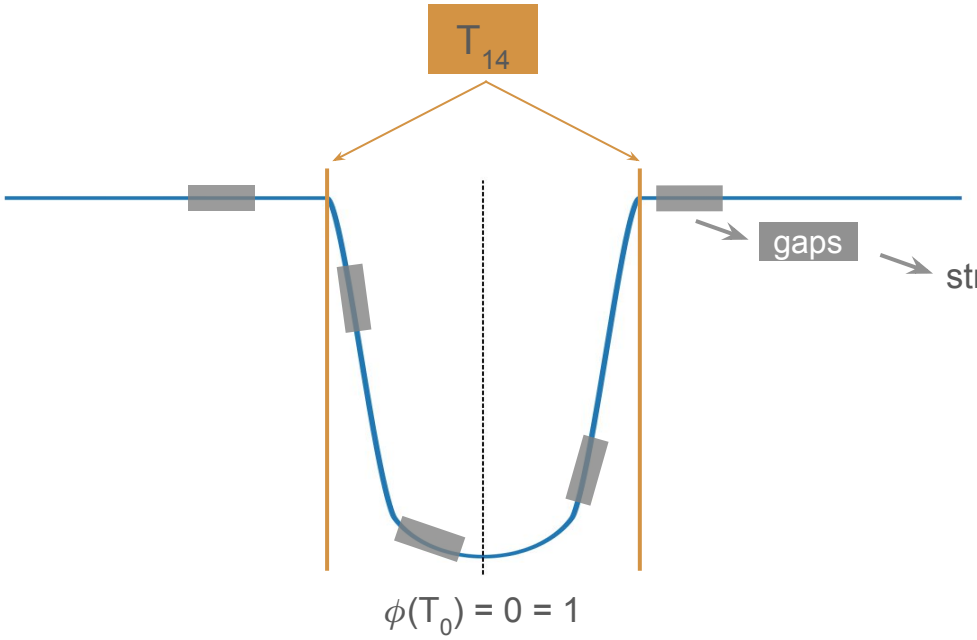


At least: 5 visits / target / year ⇒ detect TTV

Goal: 15 visits / target / 3.5 years ⇒ full characterization

how do we set a CHEOPS observation for this program?

visit duration $\mathbf{dur_{vis}}$ **= transit + out-of-transit = maximum(**$\mathbf{T_{14}}$ **+ lag +** $\mathbf{n_{cheops\_orbit}}$ **,** $\mathbf{2 \times T_{14}}$ **+ lag)**



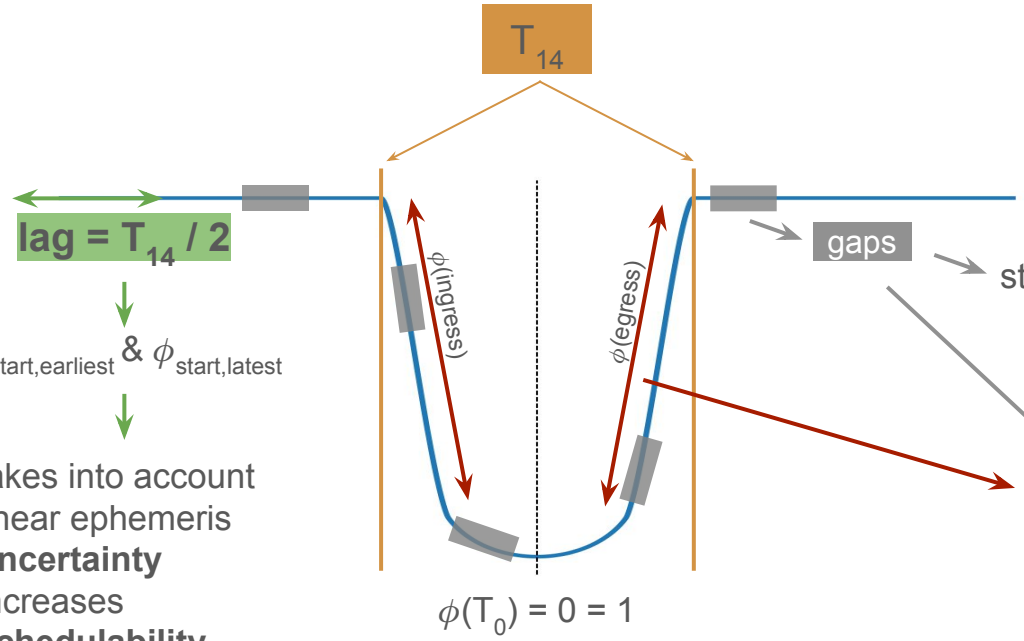
out-of-transit
(n_{cheops_orbit} = 3 x cheops orbits)

decorrelation of systematics

strongly impact the Global Efficiency
G_{EFF}

how do we set a CHEOPS observation for this program?

visit duration **dur_{vis} = transit + out-of-transit = maximum(T_{14} + lag + n_{cheops_orbit} , 2 x T_{14} + lag)**



$\phi_{start,earliest}$ & $\phi_{start,latest}$

- takes into account linear ephemeris **uncertainty**
- increases **schedulability**

out-of-transit
(n_{cheops_orbit} = 3 x cheops orbits)

decorrelation of systematics

strongly impact the Global Efficiency **G_{EFF}**

critical phase ranges (cpr) of ϕ(ingress) & ϕ(egress)

efficiencies **cpr_{EFF}** strongly impact on the **σ_{T0}**

how do we set a CHEOPS observation for this program?

visit duration **dur_{vis} = transit + out-of-transit = maximum(T_{14} + lag + n_{cheops_orbit} , 2 x T_{14} + lag)**

IMPORTANT!

T_{14}

out-of-transit
(n_{cheops_orbit} = 3 x cheops orbits)

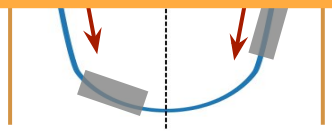
decorrelation of systematics

lag = T_{14} / 2

FC → **≠** → strongly impact the Global Efficiency **G_{EFF}**

$\phi_{start,earliest}$ & $\phi_{start,latest}$

- takes into account linear ephemeris **uncertainty**
- increases **schedulability**



$\phi(T_0) = 0 = 1$

critical phase ranges (cpr) of
ϕ(ingress) & ϕ(egress)

efficiencies **cpr_{EFF}** strongly impact on the **σ_{T0}**

how do we set a CHEOPS observation for this program?

visit duration **dur_{vis} = transit + out-of-transit = maximum(T_{14} + lag + n_{cheops_orbit} , 2 x T_{14} + lag)**

IMPORTANT!

T_{14}

out-of-transit
(n_{cheops_orbit} = 3 x cheops orbits)

↓

decorrelation of systematics

lag = T_{14} / 2

gaps

$\phi_{start,earliest}$ & $\phi_{start,latest}$

FC

critical phase ranges (cpr) of
ϕ(ingress) & ϕ(egress)

↓

efficiencies **cpr_{EFF}** strongly impact
on the **σ_{T0}**

how did we analyse our data?

single-visit analysis

DRP → DEFAULT aperture

pycheops → lmfit → emcee → min BIC detrending model selection → MLE

Maxted et al., 2021

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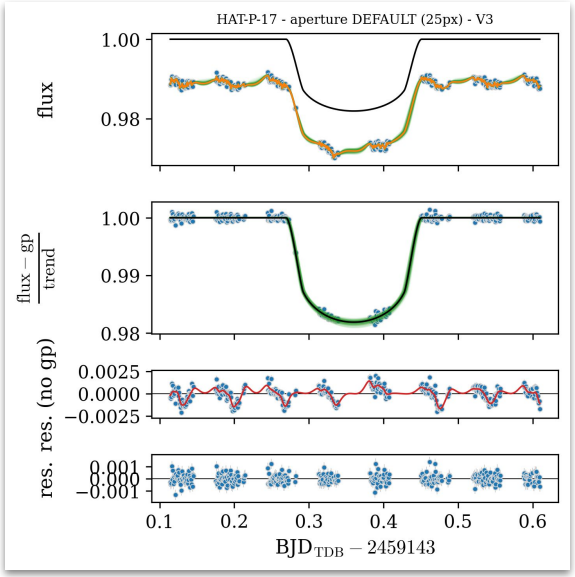

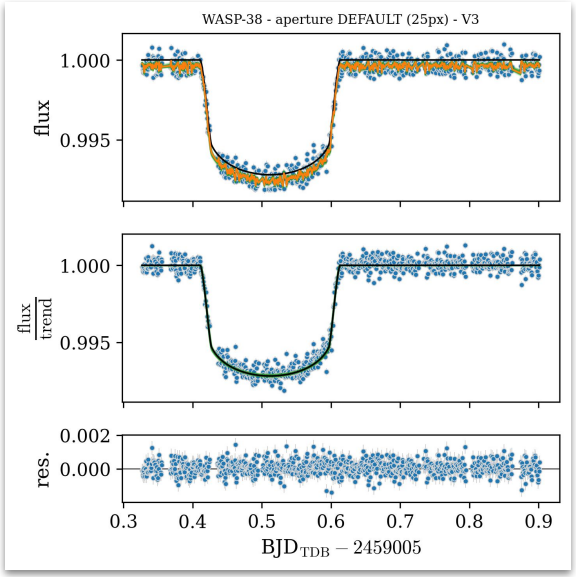

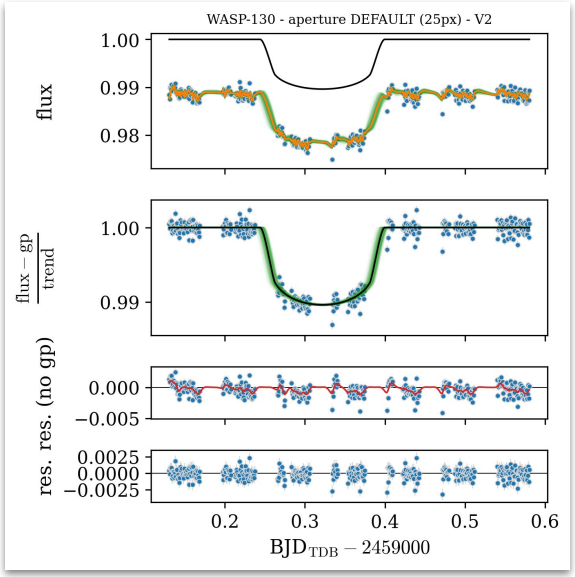

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DRP → DEFAULT aperture

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Maxted et al., 2021

WASP-38 b V2	**best**	**σ_{T0} = 13 seconds**	100% ingress & egress
WASP-130 b V2	**worst**	**σ_{T0} = 251 seconds**	0% ingress & egress

how did we analyse our data?

multi-visit analysis

single-visits MLE

pycheops → emcee → fit linear ephemeris → fix linear ephemeris + fit O-C

Maxted et al., 2021

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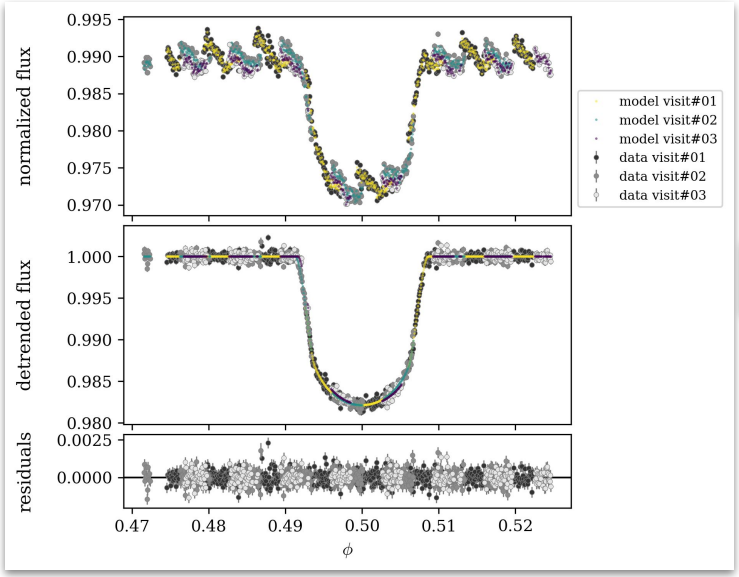
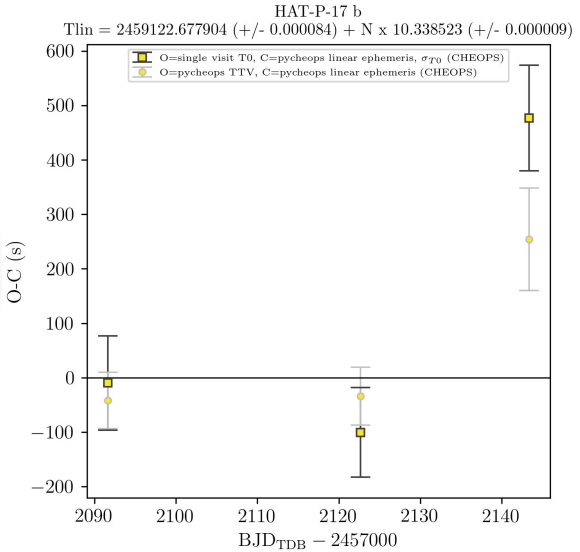


HAT-P-17 b



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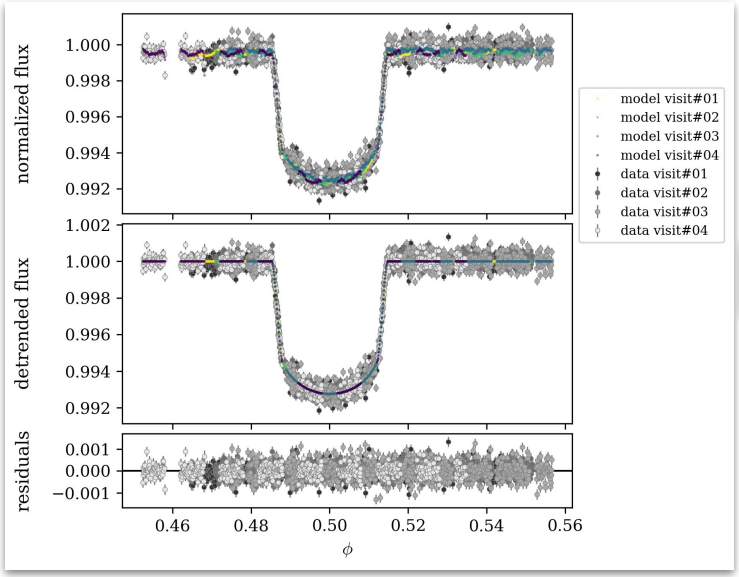
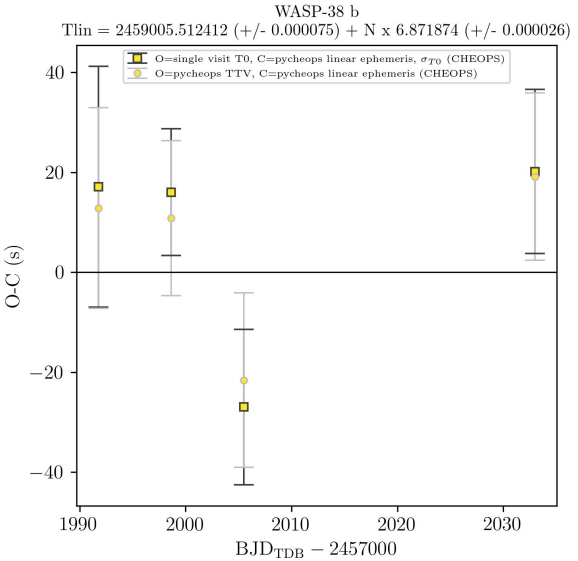


WASP-38 b



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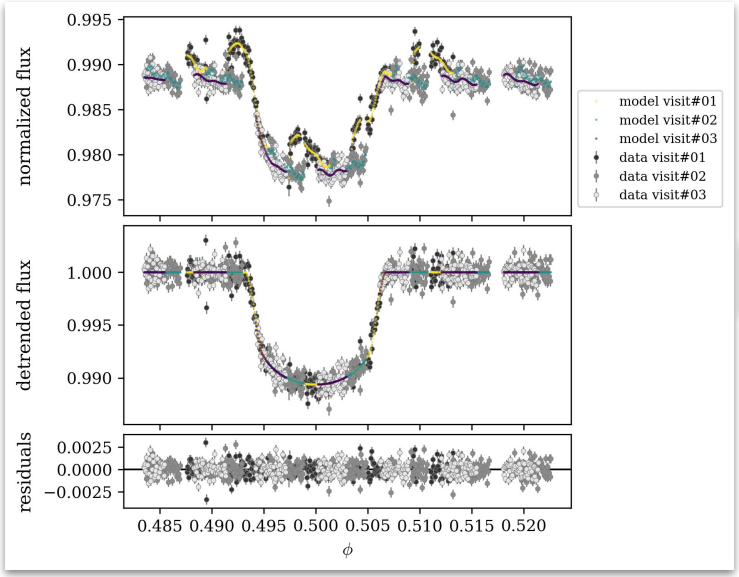
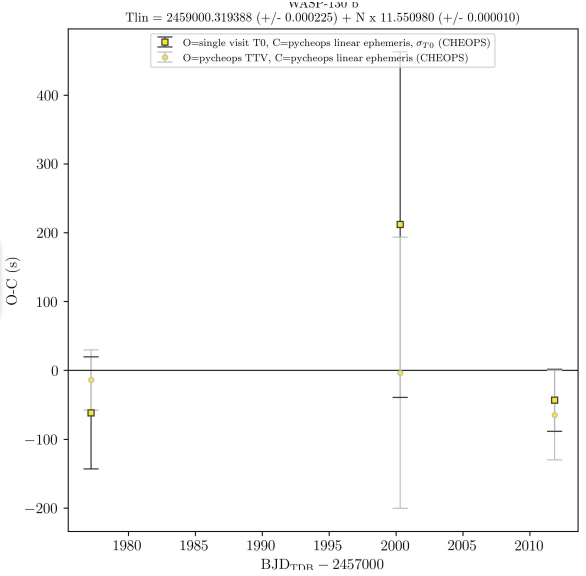


WASP-130 b



how did we analyse our data?

multi-visit analysis

single-visits MLE

pycheops → emcee → fit linear ephemeris → fix linear ephemeris + fit O-C

Maxted et al., 2021

		single-visit	**multi-visit**
WASP-38 b V2	best	σ_{T0} = 13 seconds	→ σ_{T0} = 16 seconds
WASP-130 b V2	worst	σ_{T0} = 251 seconds	→ σ_{T0} = 197 seconds

a summary of this work

collected
17 transit light-curves
of 7 warm-Jupiters

single-visit & multi-visit analysis

σ_{T0} for TTV analysis: ~13s to ~3m

reaching at least
5 transit times (goal 15) per target
will be possible to do TTV
characterization

evolution path

improved
planetary parameters
&
linear ephemeris

a summary of this work

collected
17 transit light-curves
of 7 warm-Jupiters

single-visit & multi-visit analysis

σ_{T0} for TTV analysis: ~13s to ~3m

We can further improve it!

reaching at least
5 transit times (goal 15) per target
will be possible to do TTV

improved
planetary parameters

pycheops @ https://github.com/pmaxted/pycheops

cheope @ https://github.com/tiziano1590/cheops_analysis-package
doc @ https://tiziano1590.github.io/cheops_analysis-package/index.html

my take-home message: find your trade-off!

visit duration

leave some freedom to the start of the visit → lag ⇒ ≠ ϕ_{start}

longer out-of-transit for **decorrelation** and to takes into account uncertainties

shorter out-of-transit for higher **chance to be scheduled**

G_{EFF}

higher G_{EFF} better for **decorrelation**

lower G_{EFF} higher **number of feasible visits**

≠ with ≠ ϕ_{start} ⇒ FC

cpr_{EFF}

= with ≠ ϕ_{start} ⇒ FC

lower cpr_{EFF} higher **chance to be scheduled**

improve **science outcome**

my take-home message: find your trade-off!

visit duration

longer out-of-transit for **decorrelation** and to takes into account uncertainties

leave some freedom to the start of the visit → lag ⇒ $\neq \phi_{start}$

shorter out-of-transit for higher

G_{EFF}

high

cprEFF ~30%-50%

↓

multi-visit analysis improves σ_{T0}

cpr_{EFF}

= with $\neq \phi_{start}$ ⇒ FC

lower cpr_{EFF} higher **chance to be scheduled**

improve **science outcome**

my take-home message: find your trade-off!

visit duration

longer out-of-transit for **decorrelation** and to takes into account uncertainties

leave some freedom to the start o

WARNING
Feasibility Checker (FC) is very helpful but not exact!

G_{EFF}

be

cpr_{EFF}

= with ≠ ϕ_{start} ⇒ FC

lower cpr_{EFF} higher **chance to be scheduled**

improve **science outcome**

Thank you!

uncertainties on transit times σ_{T0}

target	σ_{T_0} (seconds) V1	V2	V3	V4
HAT-P-17 b	52 (87)	53 (82)	94 (97)	
KELT-6 b	114			
WASP-8 b	50 (53)	28 (31)		
WASP-38 b	20 (24)	16 (13)	17 (16)	17 (16)
WASP-106 b	60			
WASP-130 b	44 (81)	197 (251)	65 (45)	
K2-287 b	80 (85)	128 (226)	103 (71)	

if multi-visit analysis: $\sigma_{T0,multi}$ ($\sigma_{T0,single}$)