Mono-transits and complementary ground-based observations (implications for obs. strategy)

Dr. Paul Strøm

University of Warwick

Why are monotransits important to PLATO?

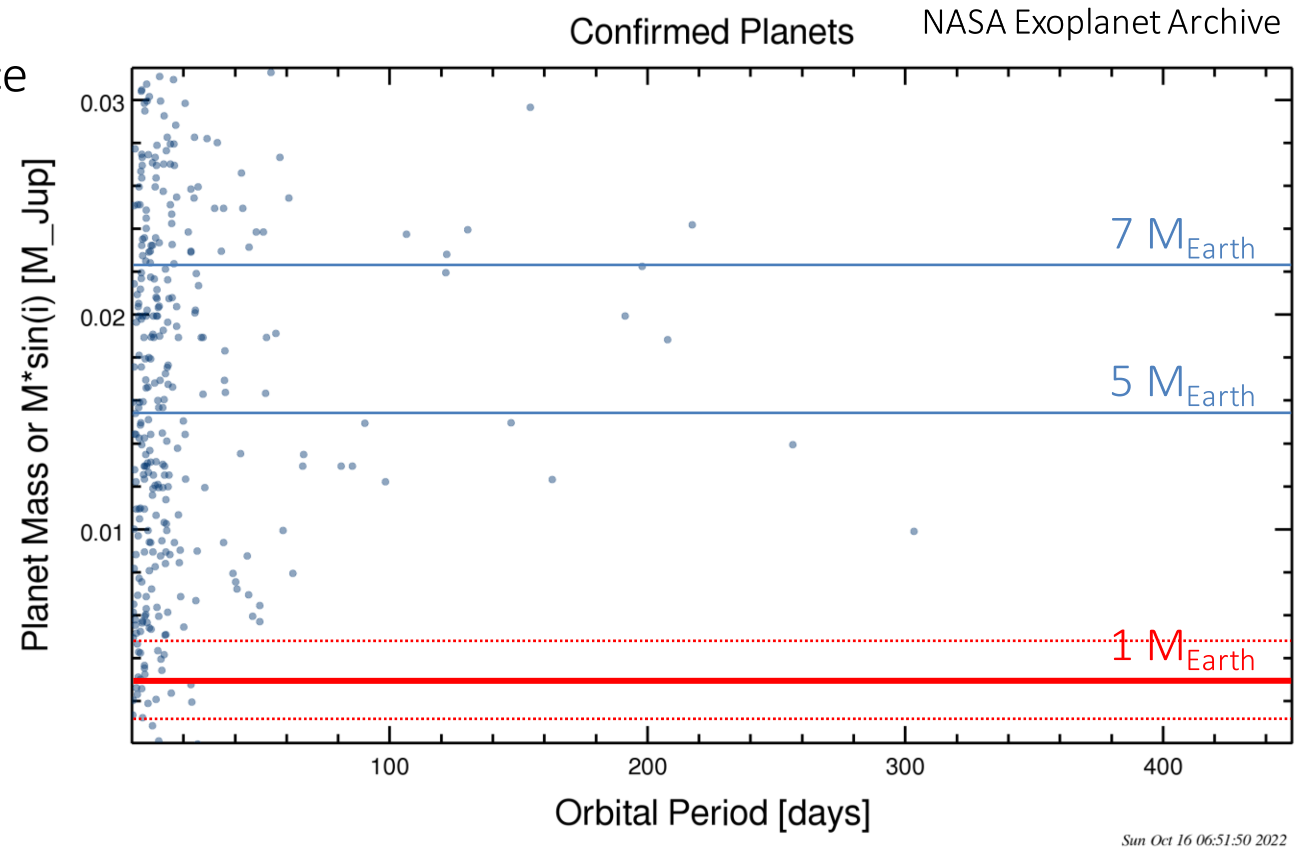
It is critical to successfully achieving one of the key scientific goals:

*"**Detection** of terrestrial exoplanets up to the habitable zone of solar-type stars and **characterisation** of their bulk properties needed to determine their habitability."*

- PLATO Red Book

Why are monotransits important to PLATO?

We are entering a parameter space which has not yet been explored, and which **only PLATO can do**.



Why are monotransits important to PLATO?

Long period planets may have experienced a different evolution and migration path compared to compact multiplanet systems.

They are not highly irradiated, and thus have cooler atmospheres, which will make them interesting objects for atmospheric characterisation and habitabiliby studies.

The importance of starting follow-up early

For most single transit events, the ground based component of PLATO will be essential.

To mitigate stellar activity and obtain periods it is important to start follow-up right after the first transit.

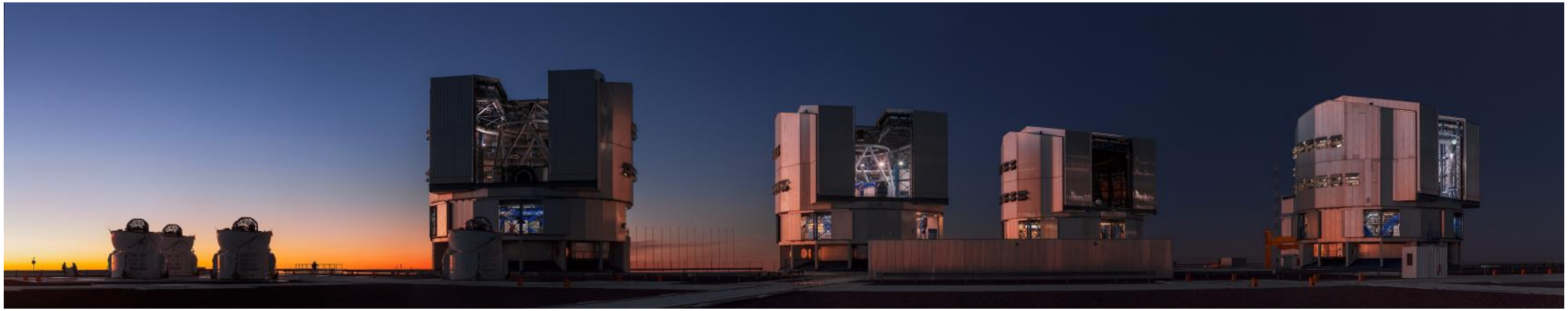
Early observations help rule out false positives, and can provide period estimates which reduce follow-up time.

Credit: ESO/C.Madsen

Importance of starting follow-up early

If big telescope time is 'wasted' on astrophysical false positives, then this will impact our chances of getting observing time in the future.

Planetary systems which cannot be sufficiently characterised (such as a grazing transit) are not of interest PLATO. Can't get radii, can't get density.



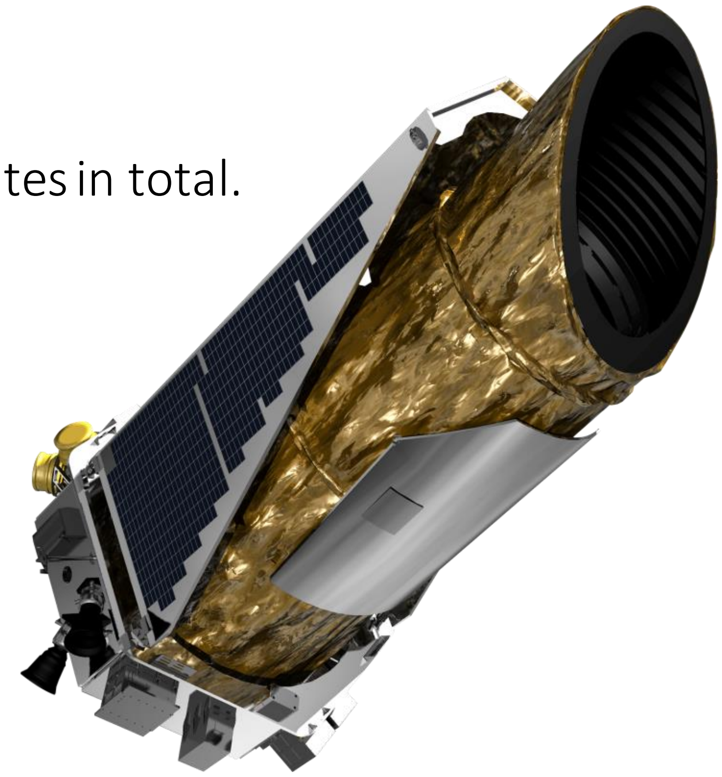
Credit: ESO/B. Tafreshi

Single transit work with Kepler and K2

Kepler helped discover over 200 mono transit candidates in total.

The corresponding planets are all substantially larger than Earth (Wang et al. 2013, 2015), LaCourse & Jacobs 2018).

See talks by Daniel Fabrycky, Alexandre Santerne and Nolan Grieves



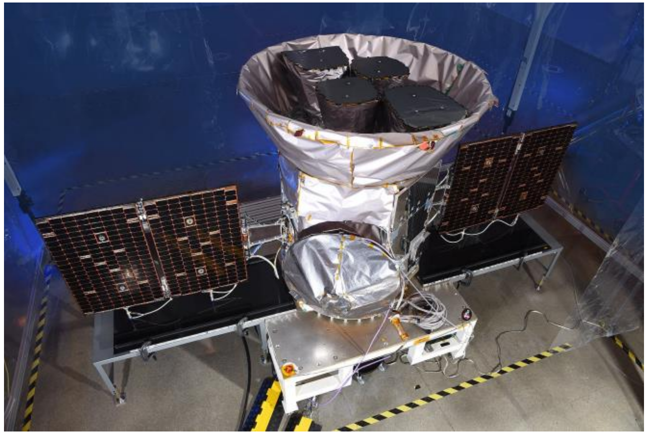
Credit: NASA

Single transits from TESS

TESS was initially biased towards short period planets, due to most stars being observed for 27 days.

With 4 years of TESS planets are being detected with periods ranging from tens to hundreds of days.

The advantage of TESS over Kepler is the much larger number of stars observed and their brightness (which enable mass determinations, detailed orbit and atmospheric characterisation.

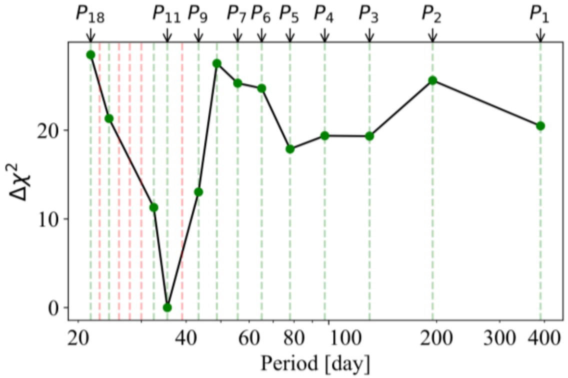


Credit: Orbital ATK / NASA

Single transits from TESS

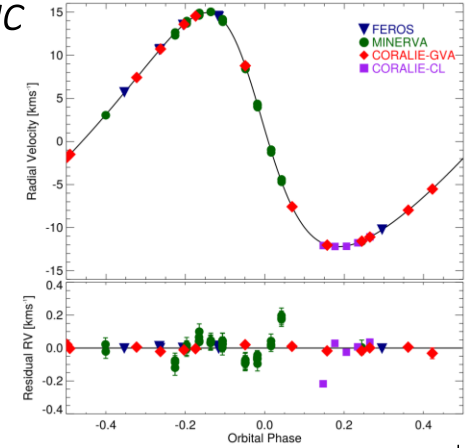
NGTS-11 b (single TESS transit "Saturn-like" planet, with 79 nights of NGTS monitoring which resulted P~35 days, T_{eq}~ 435 K) - Gill et al. (2020)

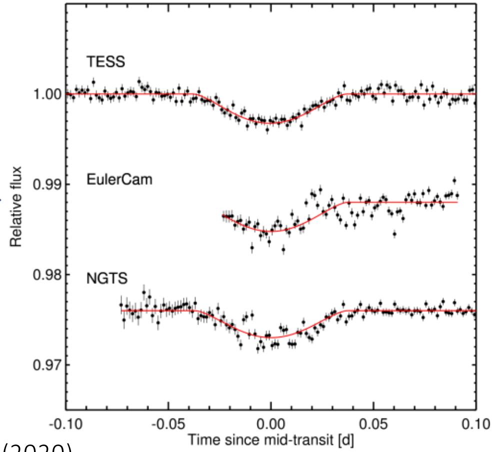
Gill et al. (2020)



TOI-2067 transiting three-planet system of sub-Neptunes, discovered by utilising *space-based and ground-based photometric follow-up* - Osborn et al. (2022)

TOI-222, 34-day eclipsing binary. Single transit detected in TESS data - Lendl et al. (2020)





Lendl et al. (2020)

The importance of S/N

The detectability of mono-transits **depends on the S/N** which is governed by:

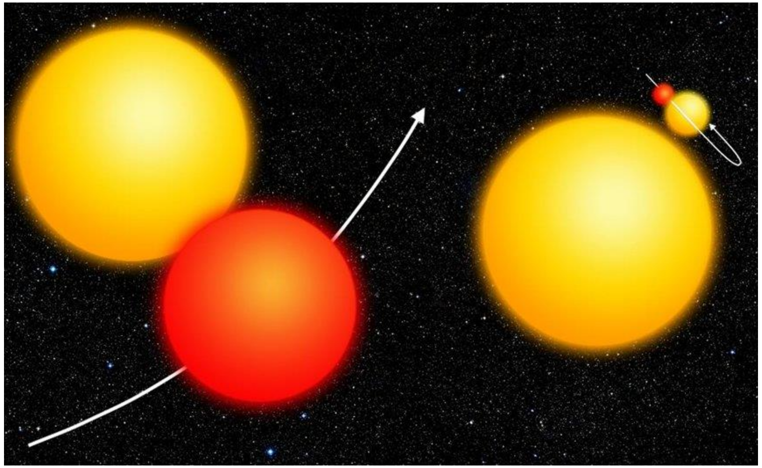
- transit depth
- stellar contamination
- instrument noise
- the number of points in transit

It is perhaps no surprise then that most of the mono-transits followed up to date have been big (large and massive) and around more quiet stars.

Astrophysical false positives

Various configurations of Eclipsing Binary (EB) stars can mimic the signal of a transiting planet

- Grazing stellar binary system
- Blended EB (the EB comprises only a small fraction of the total light in the photometric aperture)



Line of sight larger planet transiting

Different planets in the same system

Astrophysical false positives

What can we do?

--> Check period

--> Look for both primary and secondary eclipses

--> The transit: Duration, depth, shape, change between transits

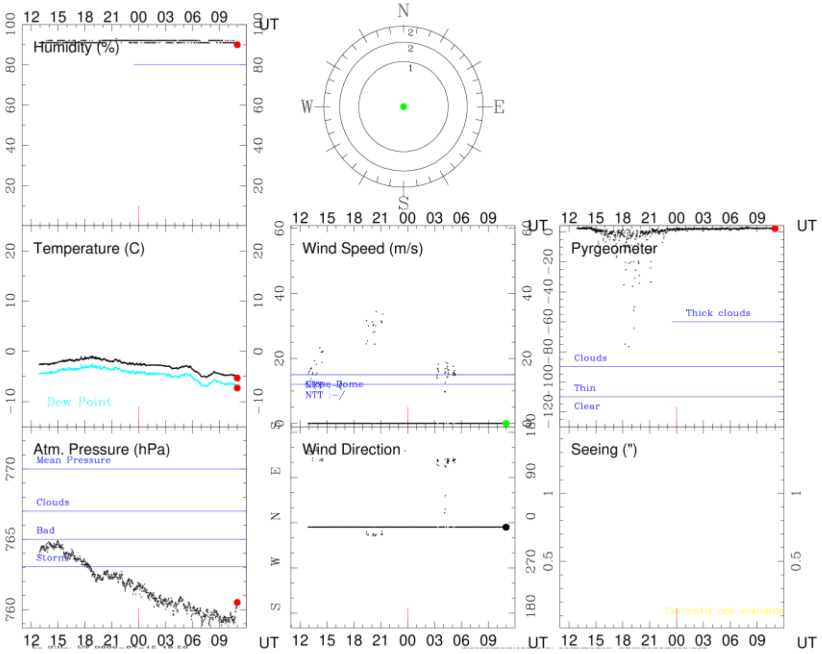
--> Duration / period constraints

Periods and aliases

Non continuous observations are a problem as they result in **missed transit observations**.

From the ground the problem is the day/night cycle, weather (and long transit durations).

If the period is long enough, this also becomes a problem for space based observations (change of observing field, downlink time, ...)



Credit: Olivier Hainaut

Periods and aliases

Two transit events are not enough to constrain a period. You cannot be certain it is the same planet. There is a reason for BLS/TLS needing 3 transits!

The separation of transit times tells you

--> an upper period limit

--> that the true period must equal this separation divided by an integer

Ruling out the aliases requires continued observations

Photometric follow-up

Successful follow-up of mono-transits have mostly been photometrically led.

Photometric follow-up is generally ‘cheaper’ as a small dedecated telescope can be used. But in certain cases it can be very 'expensive' (e.g. Ariel, CHEOPS).

Credit: ESO/R. West

RV follow-up

Credit: ESO

For an object with a mass smaller than that of Neptune, things become tricky as we enter the <1m/s (only period folding can solve it).

The bottleneck becomes stellar variability, more than instrument capability (see Francesco Pepe's talk)

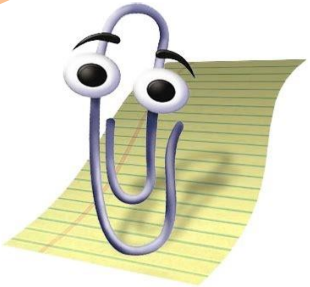
In general, without a period estimate, confirming mono-transits are hard.

RV follow-up

Nevertheless, RV follow-up ought to start as soon as possible for promising objects.

For both radial velocity and astrometry, there is **information** about the orbiting planets in measurements **made at all times**—not just during transit

Did you know?
RV observations can be scheduled without a well constrained orbital period



The combination of the two

Combining RV and photometric observations results in more periods being found than either method by themselves (see Cooke et al. 2020)

Photometric and spectroscopic data provide complimentary information.

		Transits	Radial Velocities
Basic facts:	• Planet number		✓
	• Masses		✓
	• Radii	✓	
	• Periods (& ratios)	✓✓	✓
Dynamical properties:	• Eccentricities		✓
	• Mutual Inclinations		

Talk by Daniel Fabrycky

The greatest challenge: Earth-analogues

Credit: Towtow10 (deviant art)

The greatest challenge: Earth-analogues

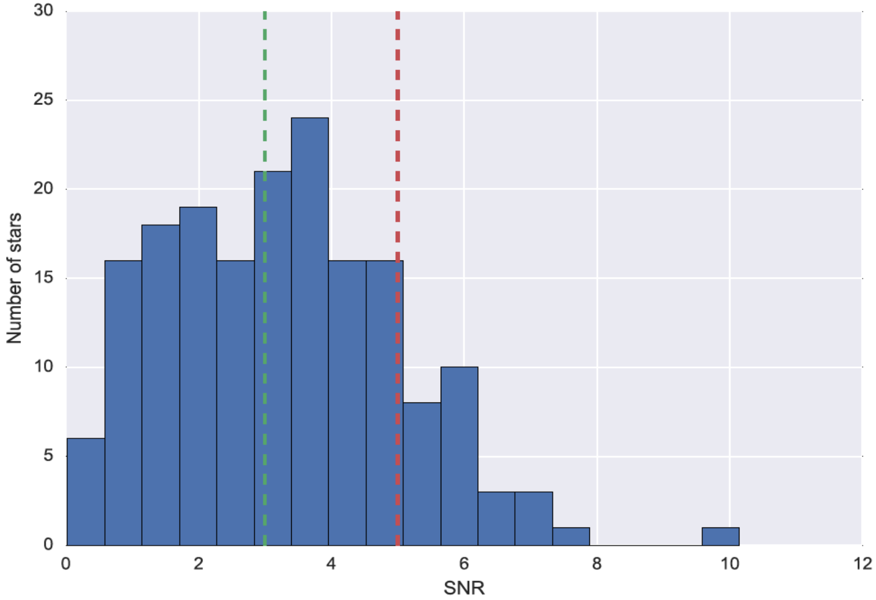
If it were only a matter of S/N, then PLATO should be able to detect Earth-analogues.

The 2x2yr PLATO stares requires detection of Earth analogs from 2 transits – is this even possible?

See talk by Hans Deeg for the PLATO transit sample

The greatest challenge: Earth-analogues

In a study of the PLATO planet yield (Don and others) did an analysis of bright (<11 mag) Kepler main sequence stars (178 objects available) across a range of activity levels – *how many are quiet enough for single transit detection?*



98 have (>3 sigma detection, marginal)
29 have (>5 sigma, easily to detect)

~25% of transits could be detected

Matches well the numbers of targets needed for follow up to realise science aims

It is possible. Single transits are detectable.

The greatest challenge: Earth-analogues

It will be a great challenge to predict their period as we will be **working at the limit of what is possible**.

This is an exciting prospect! But how do we do it?

What if only one transit is observed?

By fitting the transit we can calculate the impact parameter from the ingress / egress duration (and estimated Rp/Rs from the transit depth)

We get the velocity from the chord length and transit duration

Period from the velocity

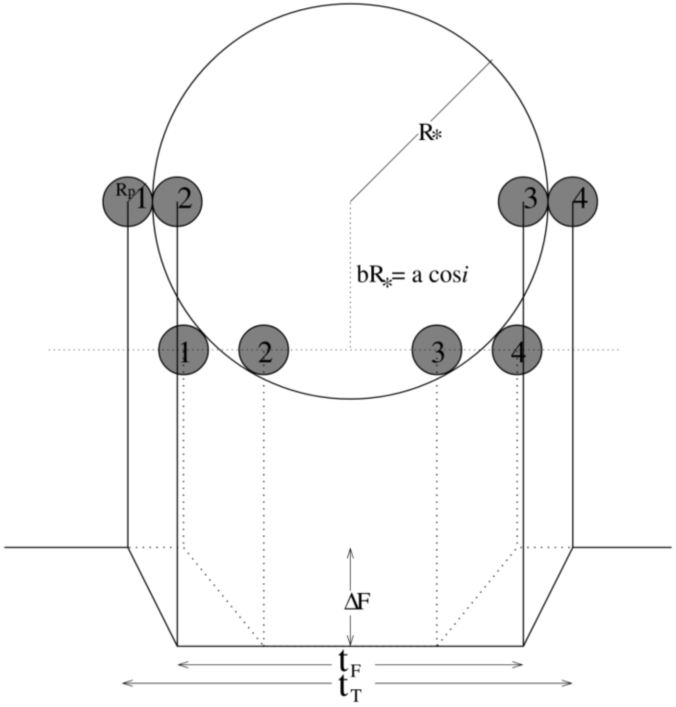
This assumes a circular orbit. For eccentric orbits the uncertainty increases by ~30%

What if only one transit is observed?

Assuming a *circular orbit* and that m_p << M* and the **stellar density** is known, then the planet's period can be estimated from the photometry of a single transit (Seager & Mallén-Ornelas 2003)

$$P = \frac{M_*}{R_*^3} \frac{G\pi}{32} \frac{\left(t_T^2 - t_F^2\right)^{3/2}}{\Delta F^{3/4}}$$

$$P \le \frac{G\pi}{32} \frac{M_*}{R_*^3} \frac{t_T^2}{\Delta F^{3/4}}$$



Suggestions / discussion points

As soon as a long period is found, **check archival data** and start RV follow-up as **soon as possible**

This will rule out any false positives and help **combat stellar activity** (which is the main challenge)

We should model the transit to **estimate a period**. **Fold the RV** data on the estimated period. If possible, **combine RV data with photometry** (ideally simultaneously**)** to rule out aliases.

For Earth-like planets there are no ground based follow-up possibilities. Time on ARIEL, HST and JWST would be too expensive. This means a **longer duration pointing** (still possible) or a **field revisit** through a mission extension.

Additional slides

Number of Earth-sized planets in the HZ

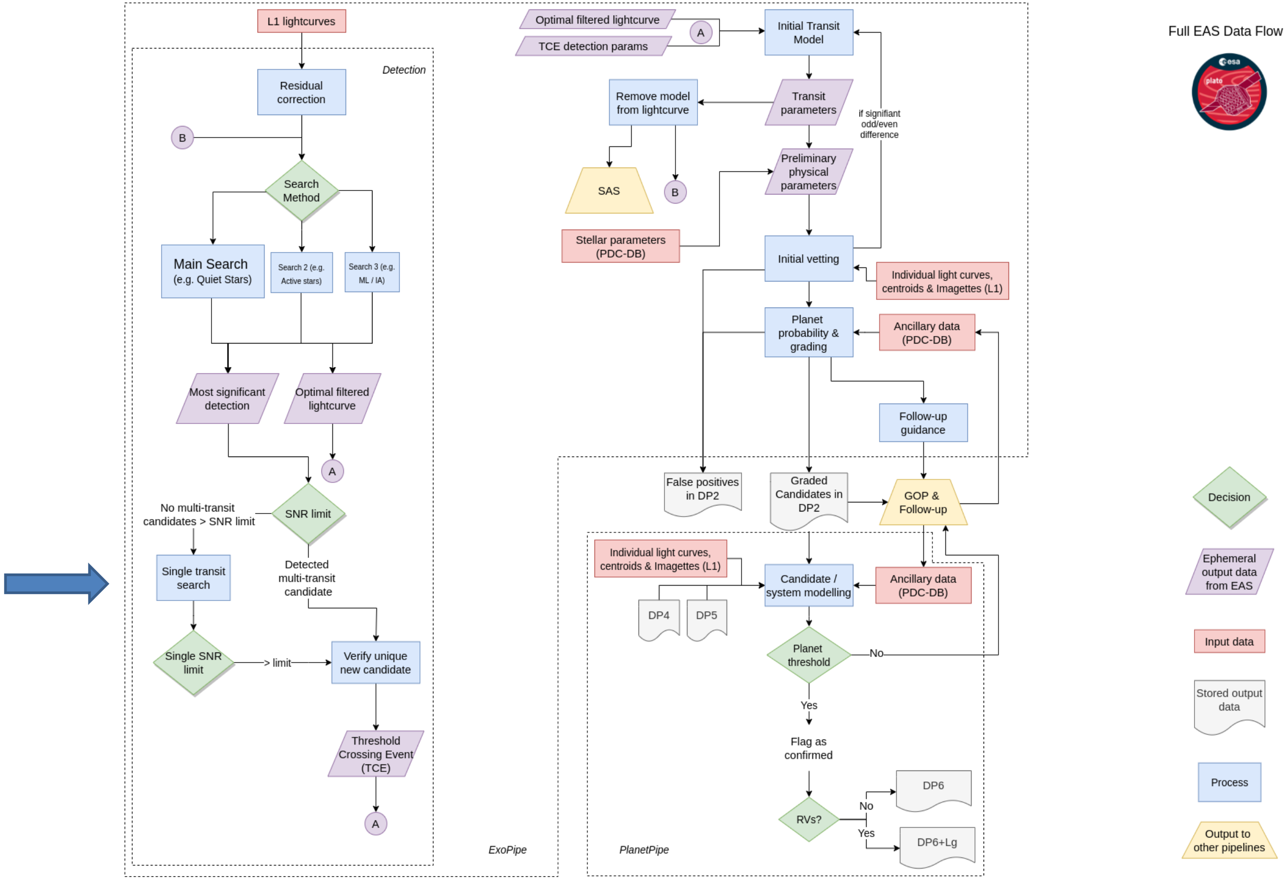
The geometric transit probability $P_{geo} \sim R_s/a$

R_s /1 AU ~ 0.5%

P1 sample * occurance rate * probability = # of po (15,000 to 20,000) x (37 to 88)% x 0.5% = 28 to 88

PLATO ought to be able to detect a dozen Earth-sized planets in the HZs around solar-type stars

How does transit pipe discover single transits?



The harsh reality

We need three transits. Single transits are feasible, but very difficult.

For low mass, long period planets (such as the coveted earth-analogues) the only option for follow-up is going to be space based and will require a lot of follow-up time

Since the period of the orbit is poorly constrained and transits are sparse, any prediction of a subsequent transit time will be too uncertain to schedule targeted photometric follow-up (Beichman et al. 2016; Dalba & Muirhead 2016).

Transit Time Variations (TTVs)

Long-term monitoring of transits in multi-planet systems can also help constrain planetary masses, number of planets, eccentricities through TTV measurements.

Wang et al. (2015) found that half of the 10 long-period exoplanets (periods between 430 and 670 days) discovered by Kepler show transit timing variations (TTVs) ranging from $\sim$2 to 40 hr.