A review of TTV techniques, and their application to PLATO

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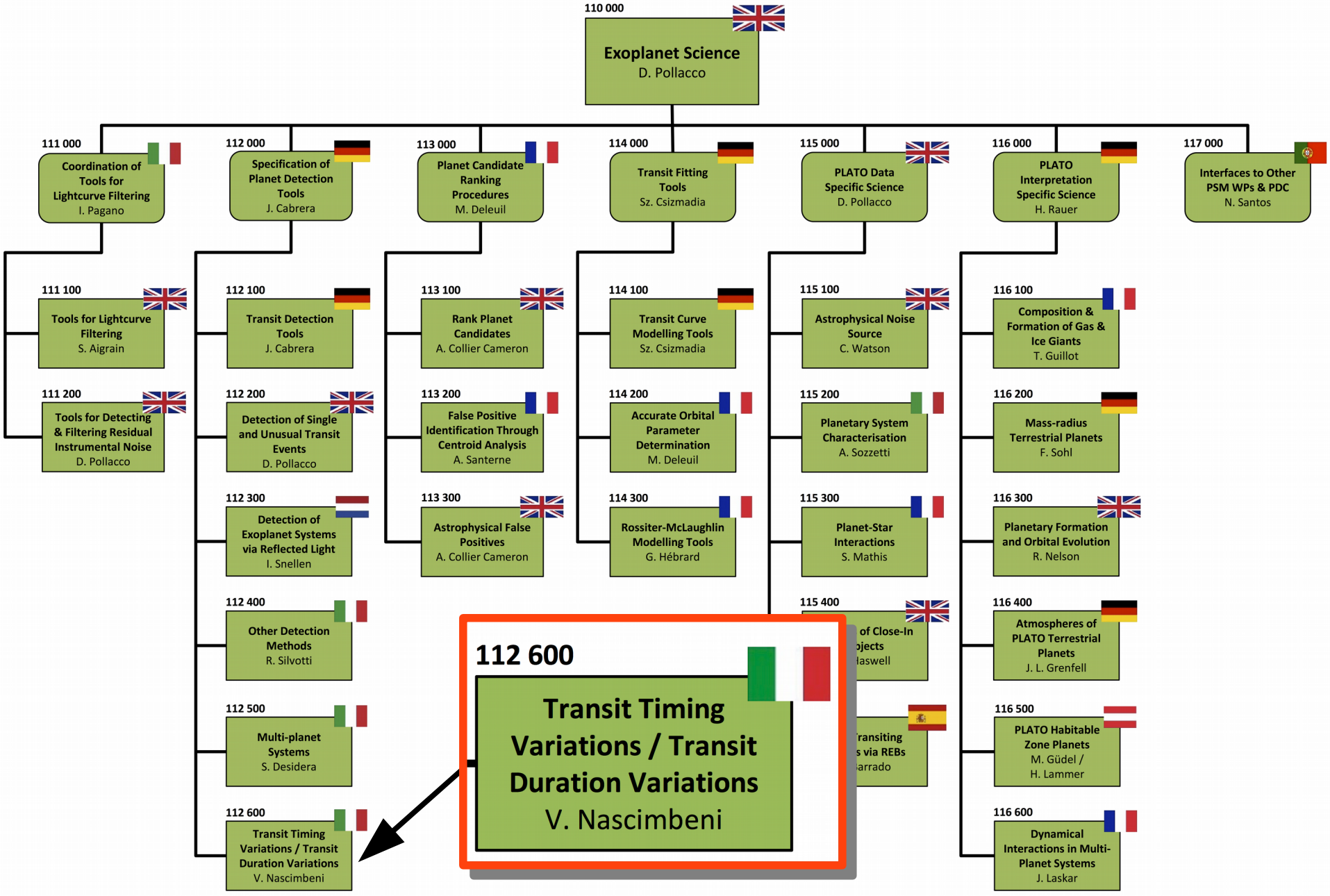
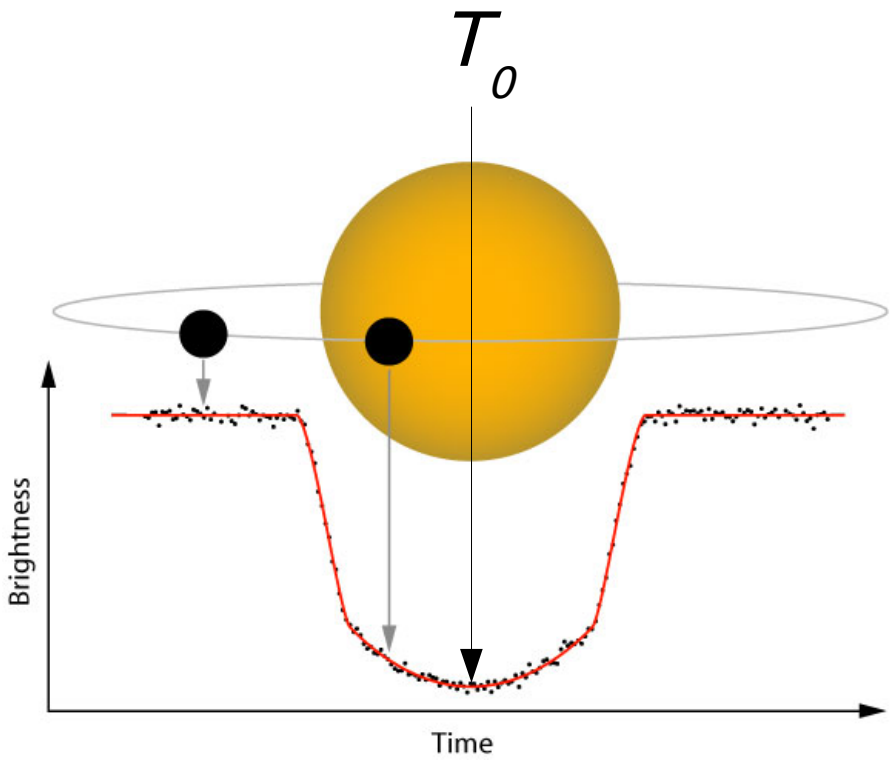
The WP 112600 (PSM)



What a TTV is

Transiting planets allow us to measure the transit center (T_0) and hence the orbital period *P* very precisely.

Transit Time Variation (TTV) is a dynamical technique to:



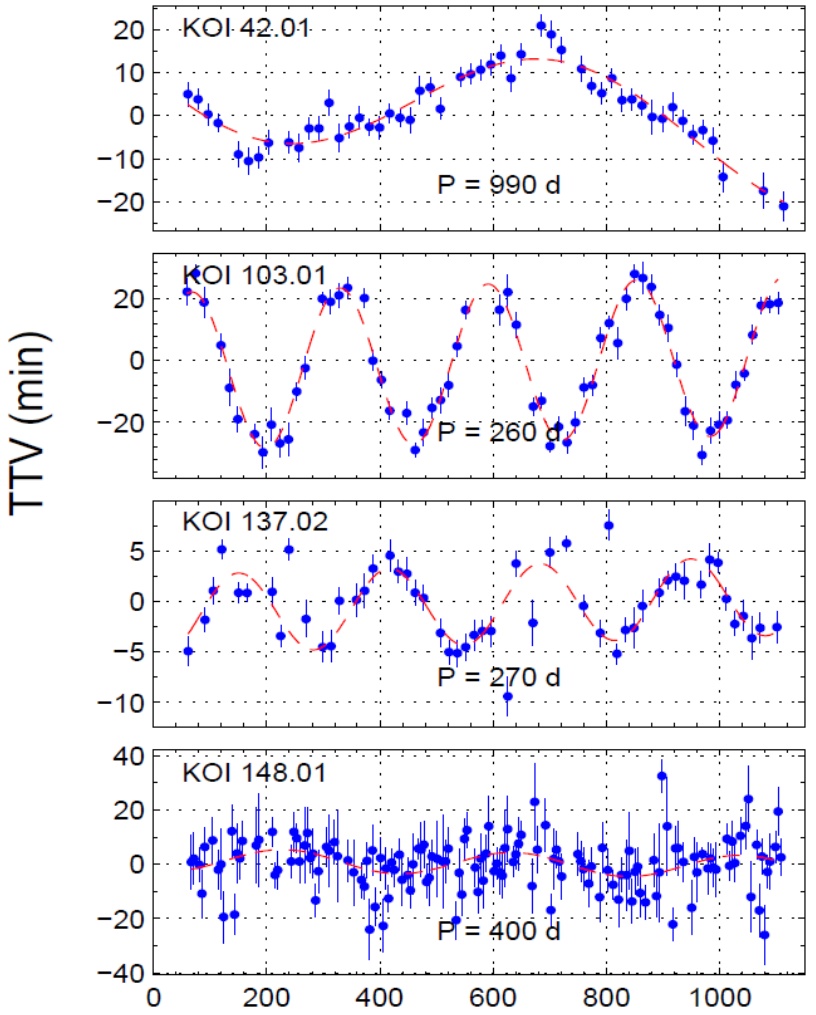
1) **measure the masses** of multiple planetary systems without need of (on in synergy with) radial velocities (RV);

2) **discover new planets** (not necessarly transiting) which are perturbing the known ones

The O-C diagram

The “Observed – Calculated” **O–C diagram** is the basic tool of TTV analysis.

First the best **linear ephemeris** $T_0 = kP + T_{ref}$ is found which best explains the data; then this quantity is subtracted to each measured T_0.



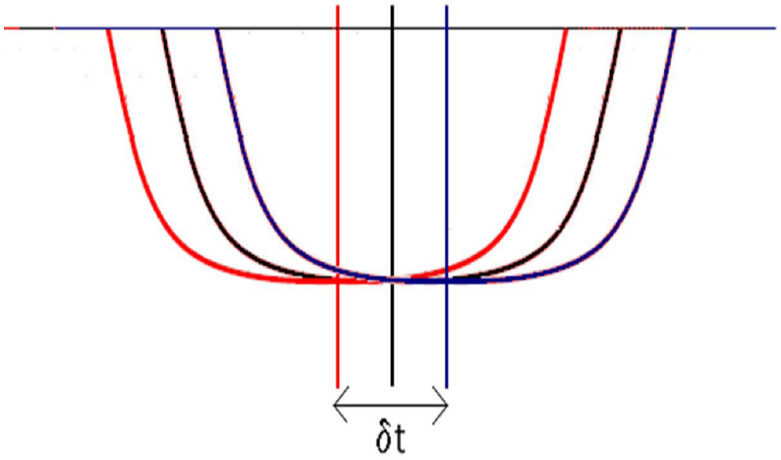
Mazeh+ 2013

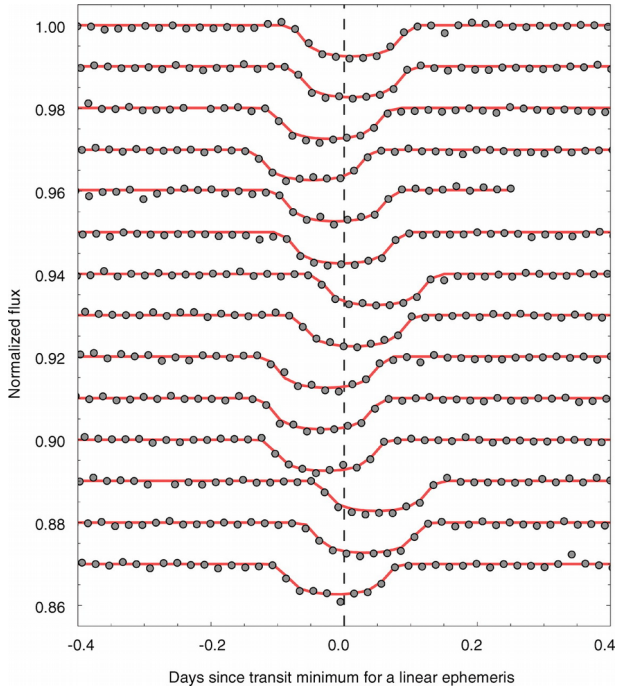
How the TTV technique works

Simple 2-body system (star + planet): strictly constant *P* → linear ephemeris, flat *O*-*C* diagram

Multiple planetary system: mutual perturbations, *P* changes → **TTV!** In principle we can infer the perturber parameters (including mass) from the *O*-*C* shape

Outside particular cases, TTV is a **small** effect (ΔT_0 ~ seconds → $\Delta T_0/P \sim 10^{-6}$)



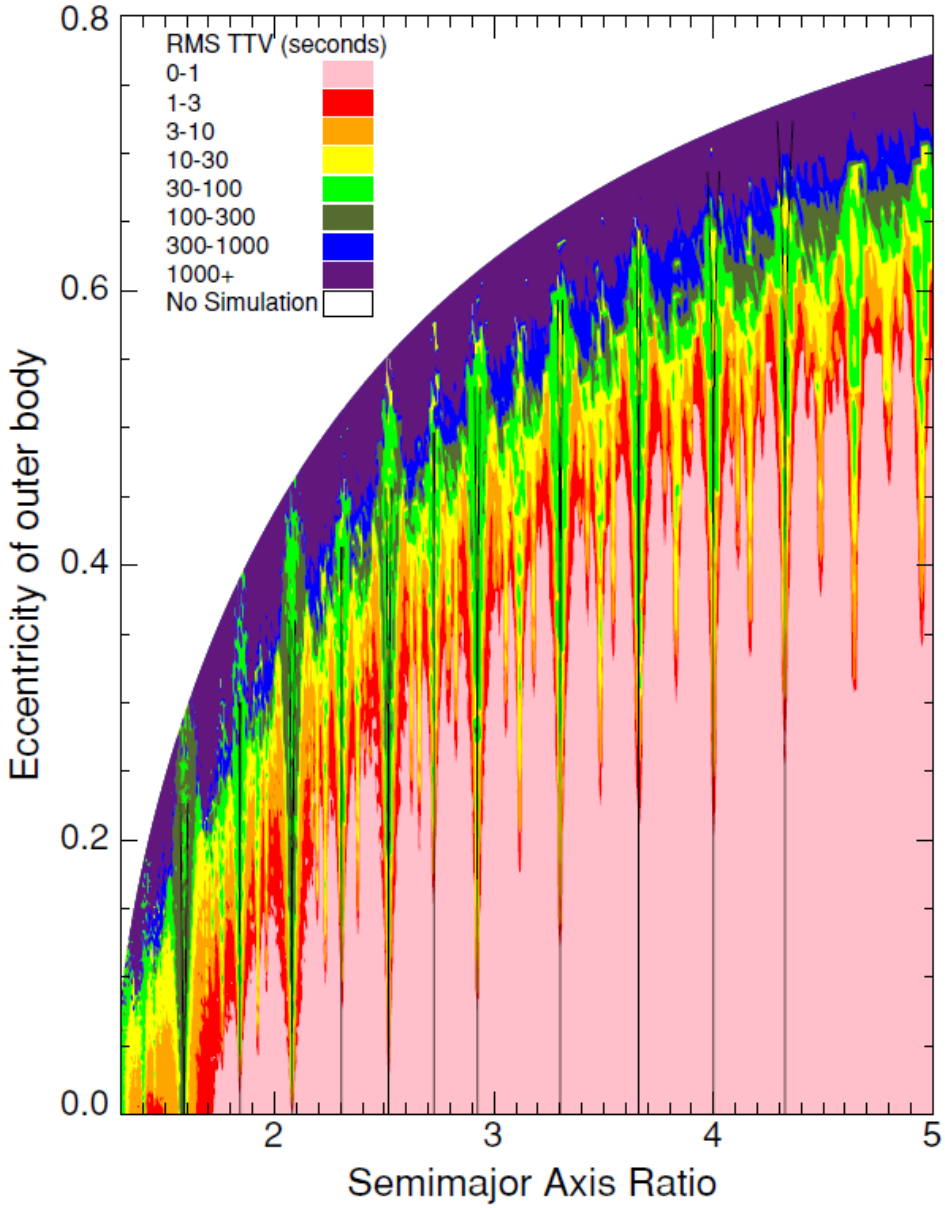


TTV in resonances

TTV are strongly boosted by low-order mean-motion **resonances!** (MMR: P_2/P_1 = 2:1, 3:2 etc)

(and to a lower extent, by eccentricity and mutual inclination: Veras+ 2011)

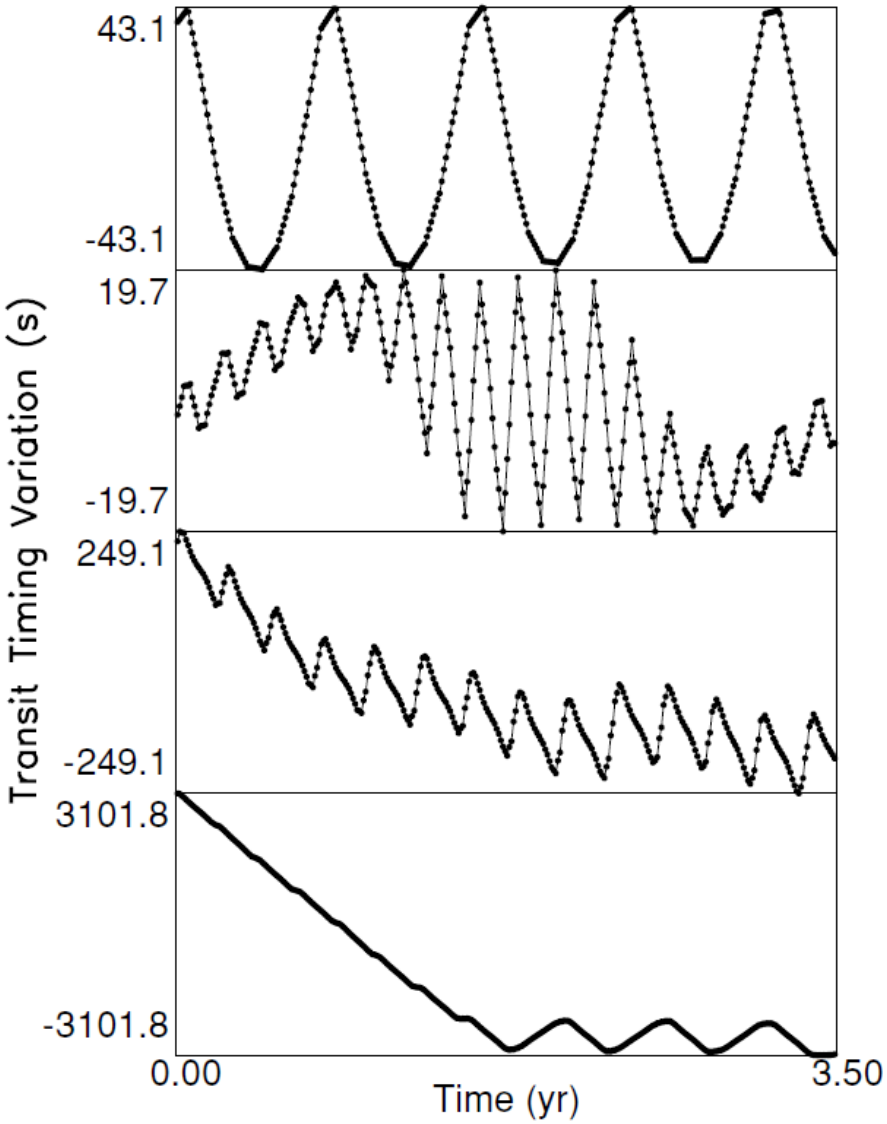
Resonant systems are **common** among Kepler multiple systems (7%+18% on 3:2 and 1:2, Wang+ 2014)



The TTV signal

O–C diagrams are not necessarily **flat** or **periodic**, due to multiple perturbers, mutual perturbations, chaotic configurations, chopping, etc.

Sometimes they can be very complicated, aperiodic and highly dependent on initial conditions! (Veras+ 2011)



TTV: observational challenges

Measuring TTV at best requires:

1) **high-precision photometry** (especially when monitoring low-mass planets, which are the best candidate to being hosted in multiple systems; Rowe+ 2014);

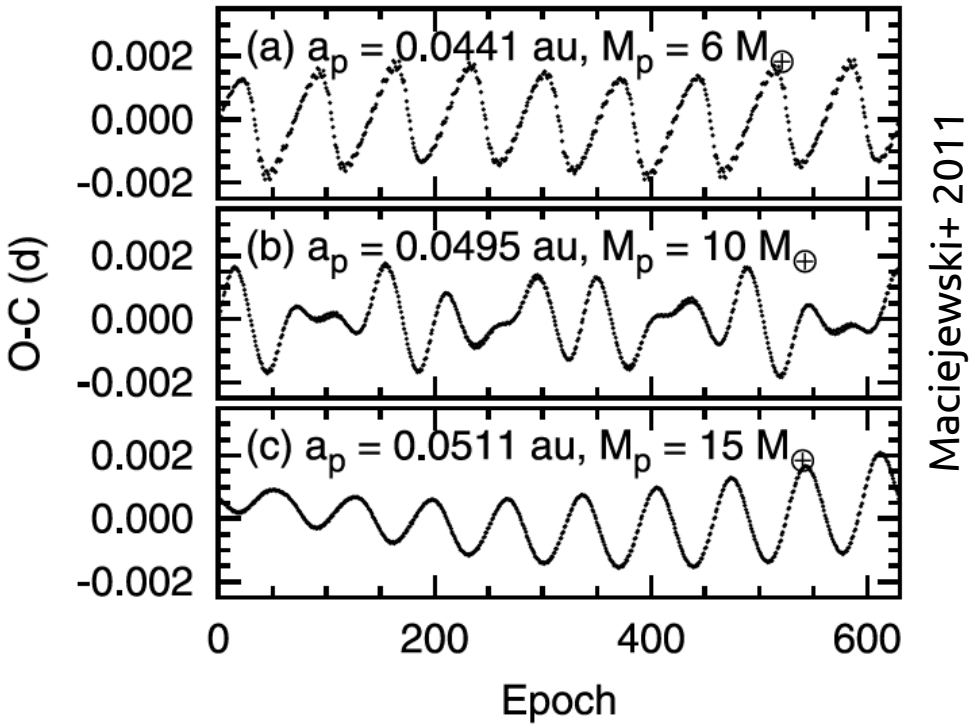
2) **fast-cadence sampling** (at least to optimally sample T_{12} and T_{34}; i.e. <a few minutes);

3) keeping **correlated ("red") noise** at minimum.

→ **PLATO** will deliver <34 ppm/h photon-limited photometry of ~15,000 bright dwarfs at 50-s cadence for >2 yr!

TTV: the inverse problem

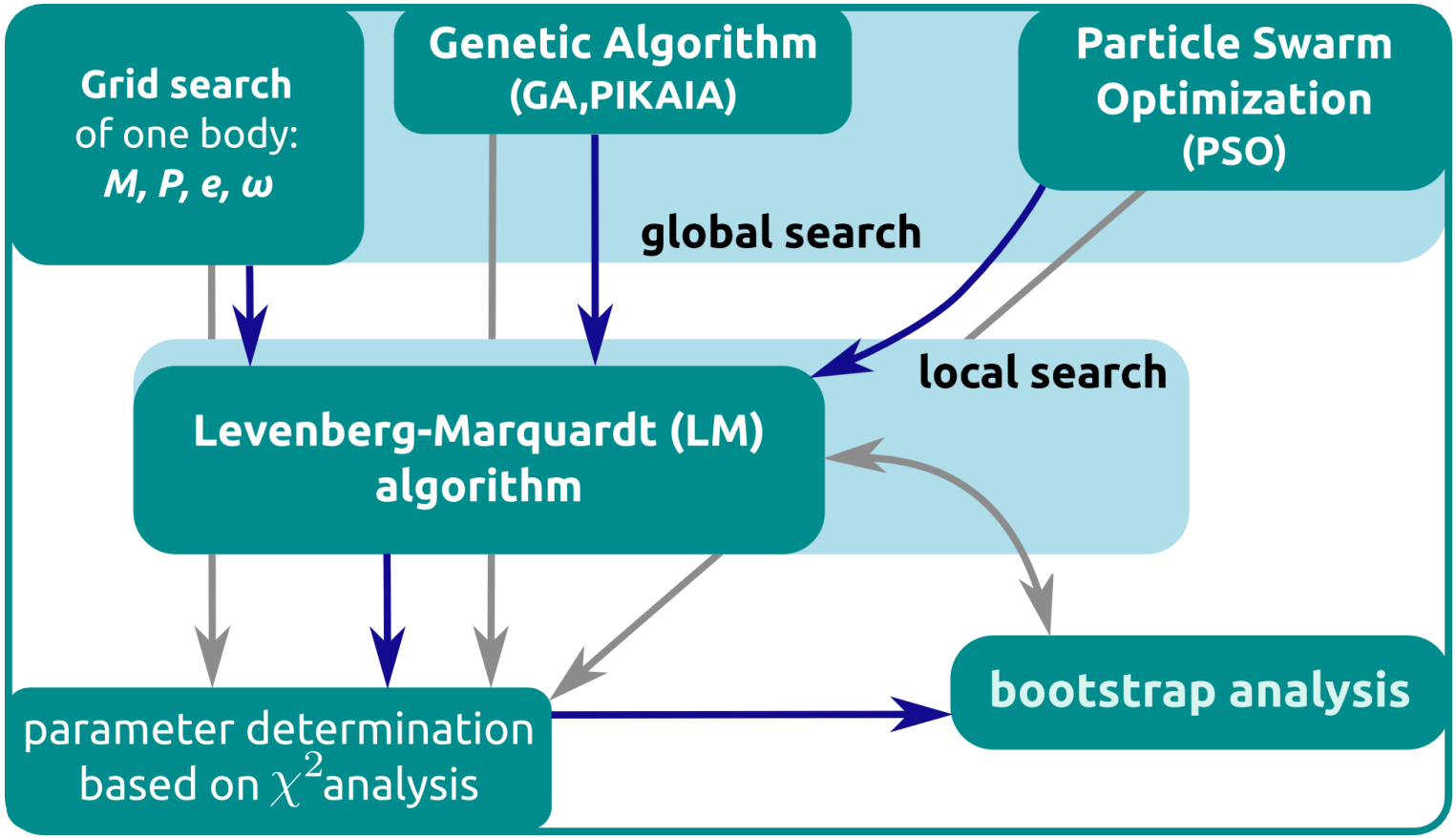
In principle TTV analysis require **N-body dynamical integration** and is numerically challenging (many free parameters, forrests of local minima, long integration times, multiple degeneracies, stability checks)... in particular, the solution could not be unique!



A few **codes** have been developed specifically to solve the TTV problem: **TTVFast** (Deck+ 2014) and **TRADES** (Borsato+ 2014). Particular configurations may allow an analytic or semi-analytic approaches (e.g. Lithwick+ 2012)

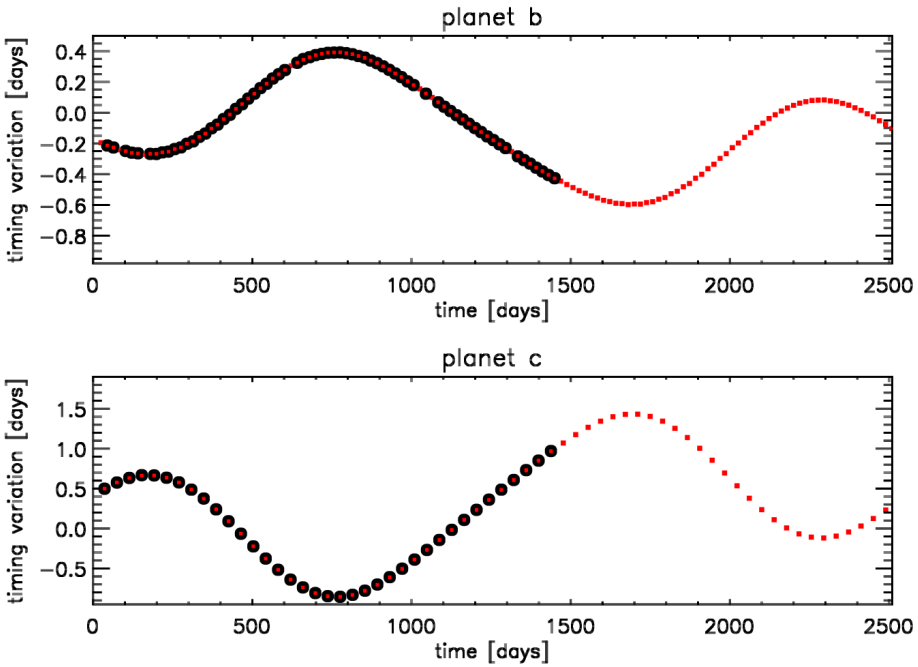
The TRADES code

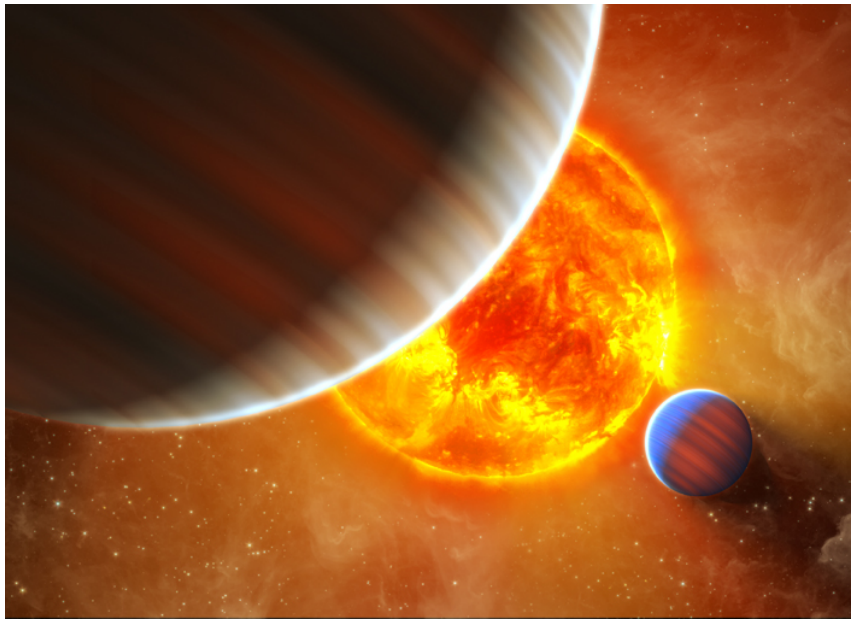
TRADES: *Transits and Dynamics of Exoplanetary Systems*
(Borsato+ 2014, A&A 571, 38)



The Kepler results: Kepler-9

Kepler-9 (Holman+ 2010) is a pair of transiting hot Saturns around a faint (V~14) G2 dwarf. RV confirmation unfeasible or expensive!





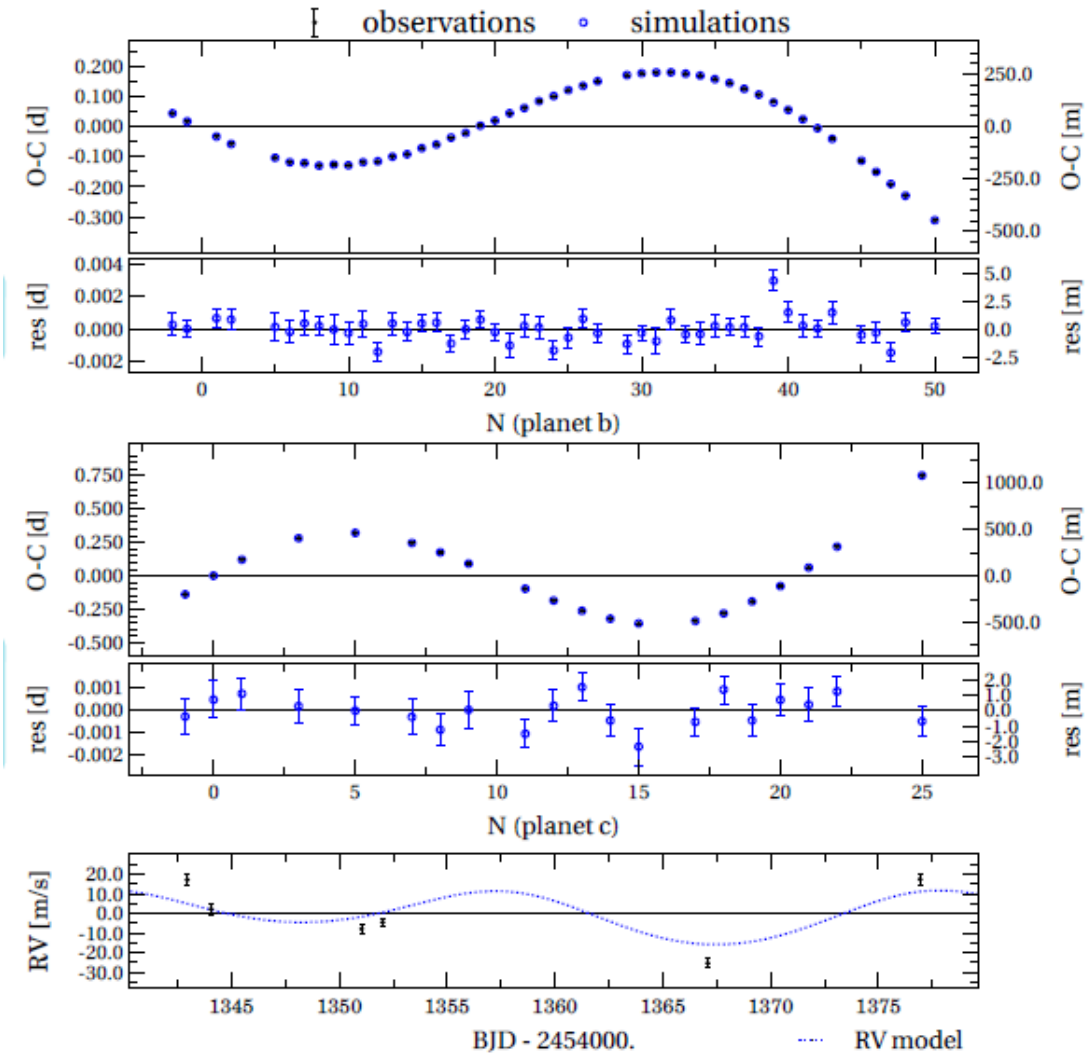
The planets are locked close to a 2:1 resonance at P~19, ~39 d and show impressive (~hours), anti-correlated TTVs → dynamical modeling → planetary masses!

The Kepler results: Kepler-9

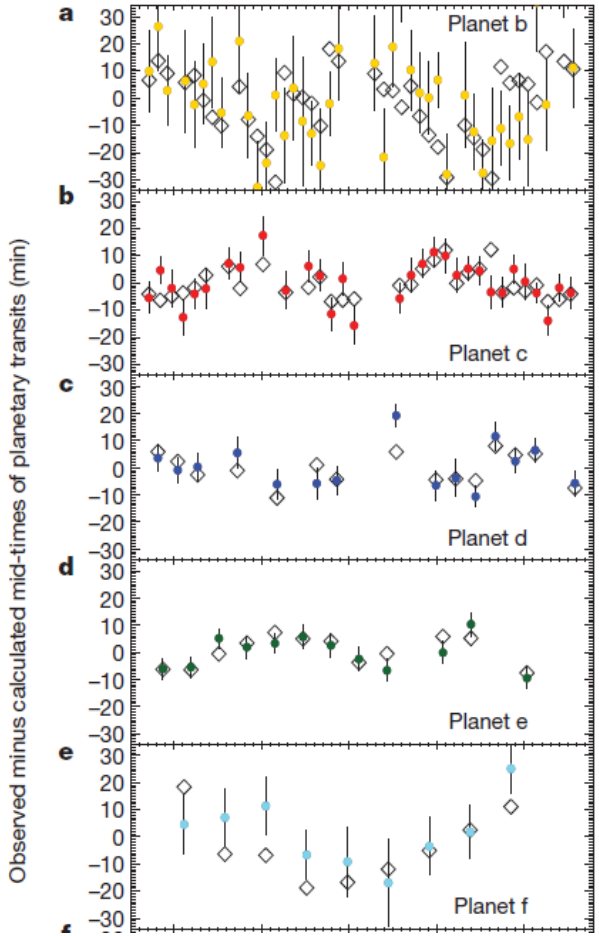
Full TRADES dynamical analysis (Borsato+ 2014):

1) different simulations and algorithms lead to consistent mass estimates: a **global minimum** is found

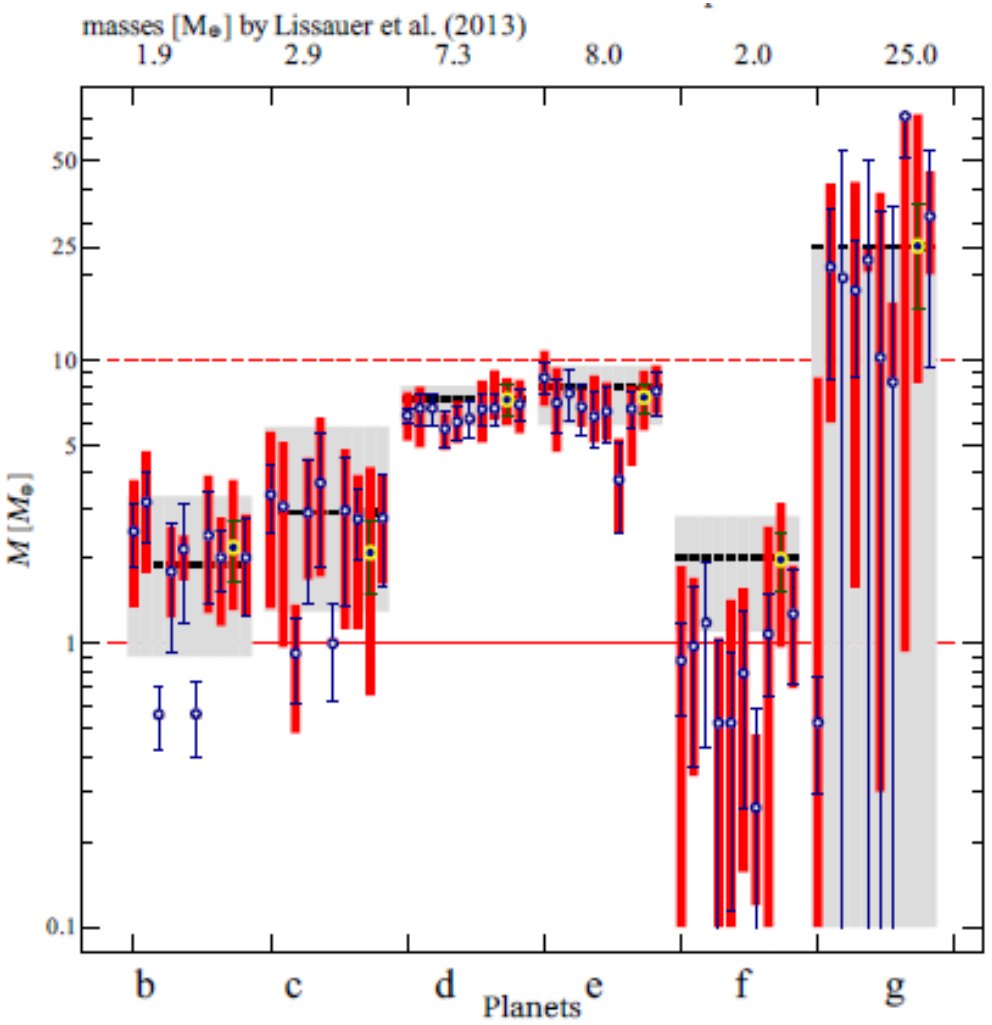
2) adding RVs into the fit greatly improves and constrain the final solution: **RV + TTV complementarity**



The Kepler results: Kepler-11



Lissauer et al. (2011)



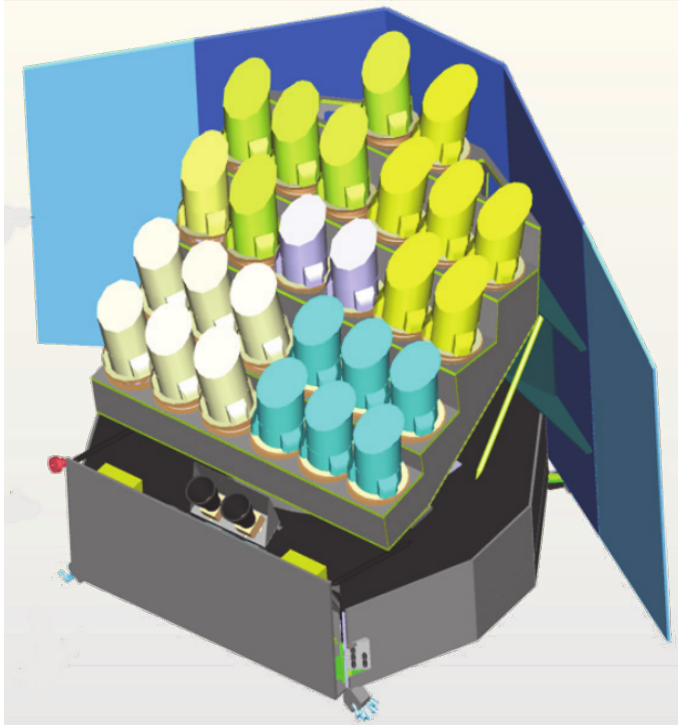
Borsato et al. (2014)

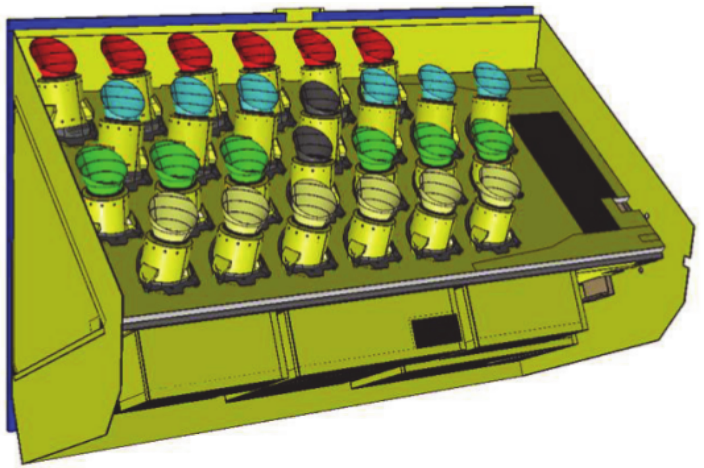
Again, mass estimates are consistent with each other and confirm the five most inner planets (here without any help from RVs)

The TTV opportunity for PLATO

PLATO will deliver hundreds of telluric and neptunian planetary candidates around P1 (V<11) stars**; ~30% of them will be in multiple systems** (Lissauer+ 2011).

Basing on the Kepler experience (Ford+2012), **≥15% of them will show detectable TTVs** → “easy” & cheap validation/confirmation from PLATO photometry alone

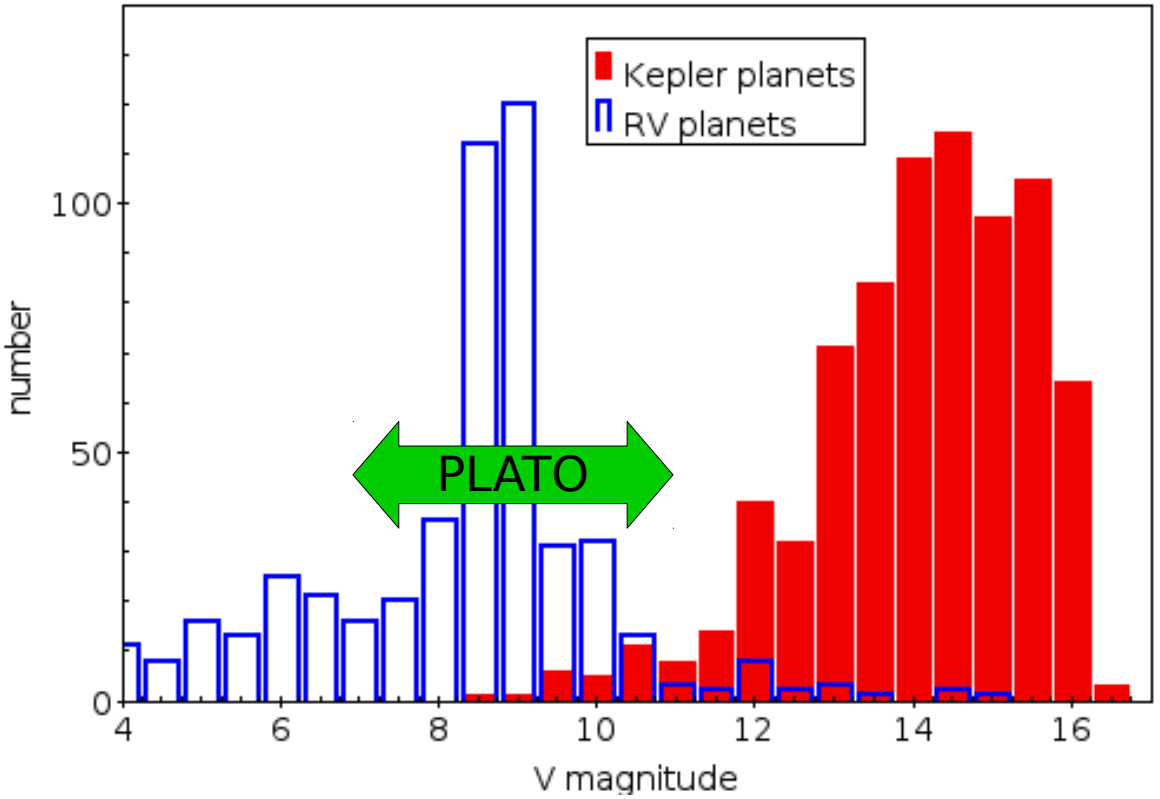




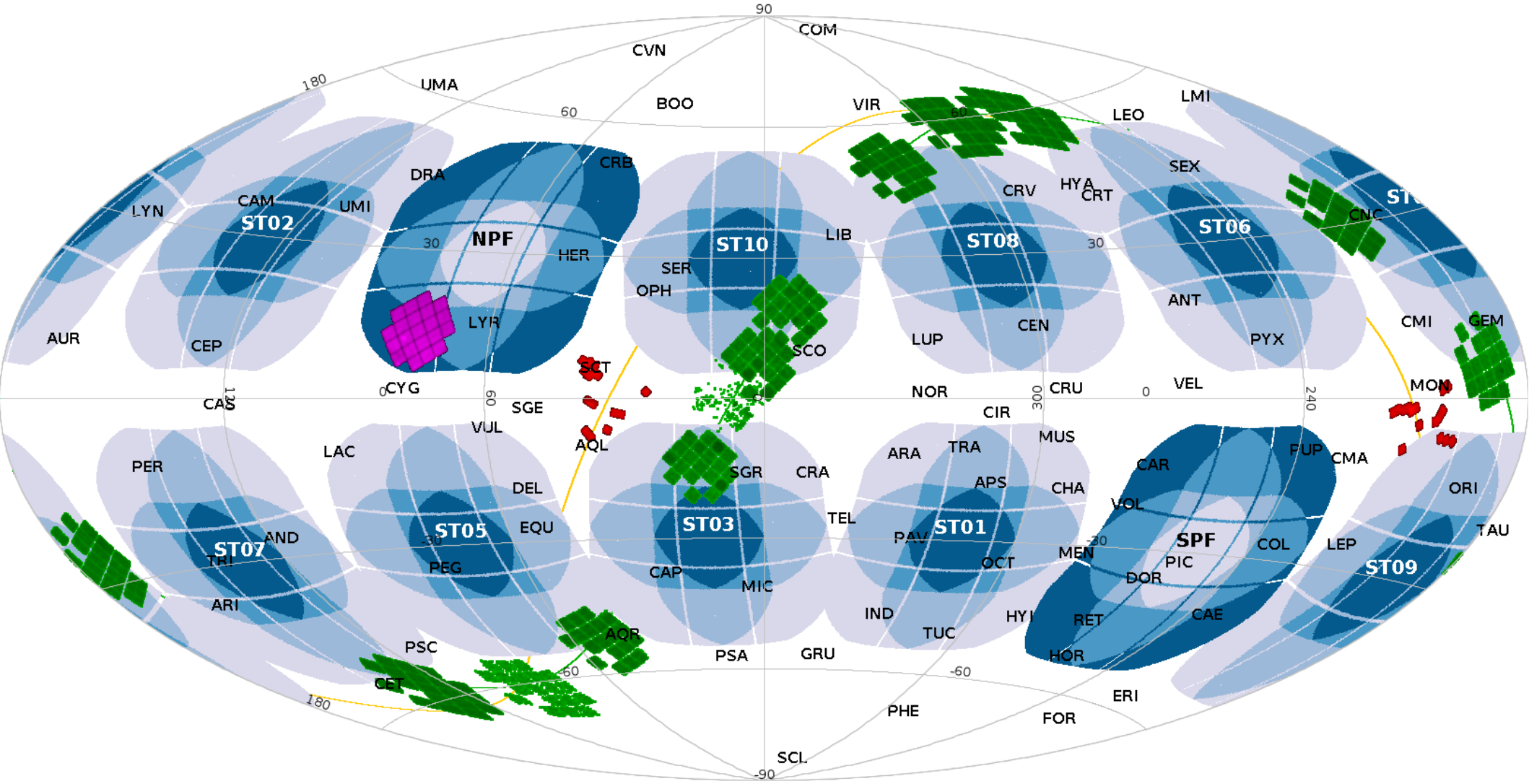
The TTV opportunity for PLATO

Unlike Kepler, PLATO is focused on discovering planets hosted by **bright stars** (V<11) for which an RV follow-up is feasible through a reasonable effort

Exploiting the **RV+TTV complementarity** → solving degeneracies, full characterization of the system (mutual inclinations, true masses, etc.)



PLATO as a follow-up TTV machine



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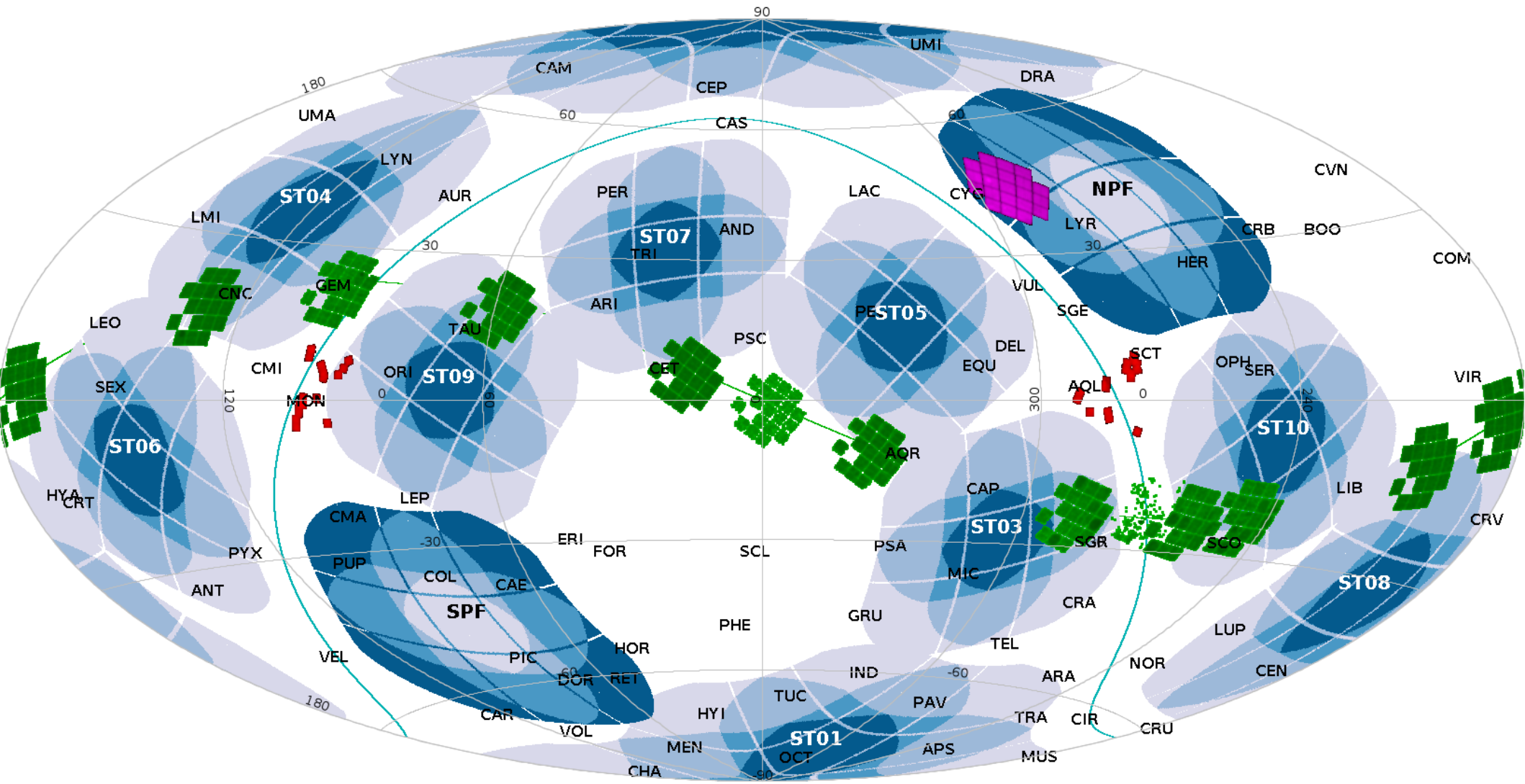

PLATO as a follow-up TTV machine