PLATO Ground-based Follow-up

a) Follow-up science and PIC

b) Information for Follow-up: what shall be in the PIC

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Questions addressed

Main goals of (ground-based) follow-up observations:
- Establish the nature of the transit events and identify/reject false positives
- Characterise the companion mass and eccentricity from Earth to brown-dwarfs.

Vetting

Science

- Science from Follow-up
  - Primary science (e.g. mass), Bonus science, Enlarging science return
  - => requirements for PIC
- Vetting and validation
  - false positives and diagnostics => requirements for PIC
- Ground-based Observation Organisation (PMC+GOP)
  - Inclusion in the consortium overall activities
  - PDC - PIC - Ancillary database - FU specific tool

plato

Scientific Objectives 1-7

S1 - Determine the bulk properties (mass, radius and mean density) of planets in a wide range of systems, including HZ Earth-like planets
S2 - Study how planets and planet systems evolve with age
S3 - Study the typical architectures of planetary systems
S4 - Analyse the correlation of planet properties and their frequencies with stellar parameters (e.g., stellar metallicity, stellar type)
S5 - Analyse the dependence of the frequency of terrestrial planets on the environment in which they formed
S6 - Study the internal structure of stars and how it evolves with age
S7 - Identify good targets for spectroscopic follow-up measurements to investigate planetary atmospheres

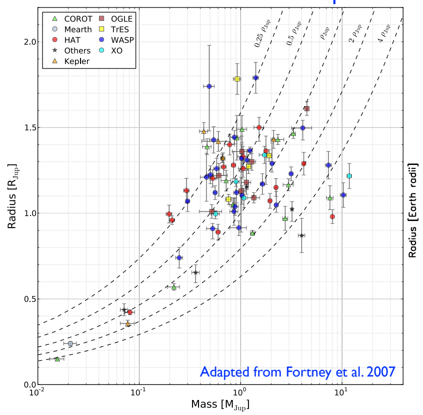
Mass-radius-density relation for planets

Understand Planet Formation = Understand Diversity

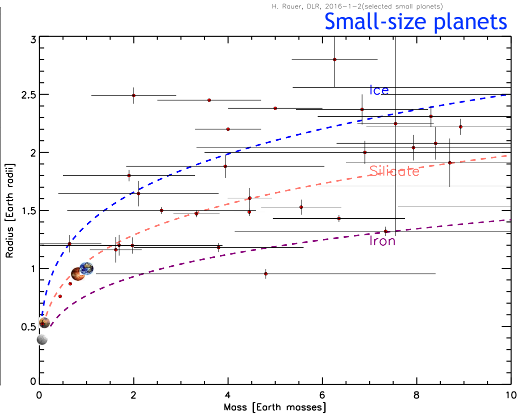
Diversity of composition

=> Importance of data quality

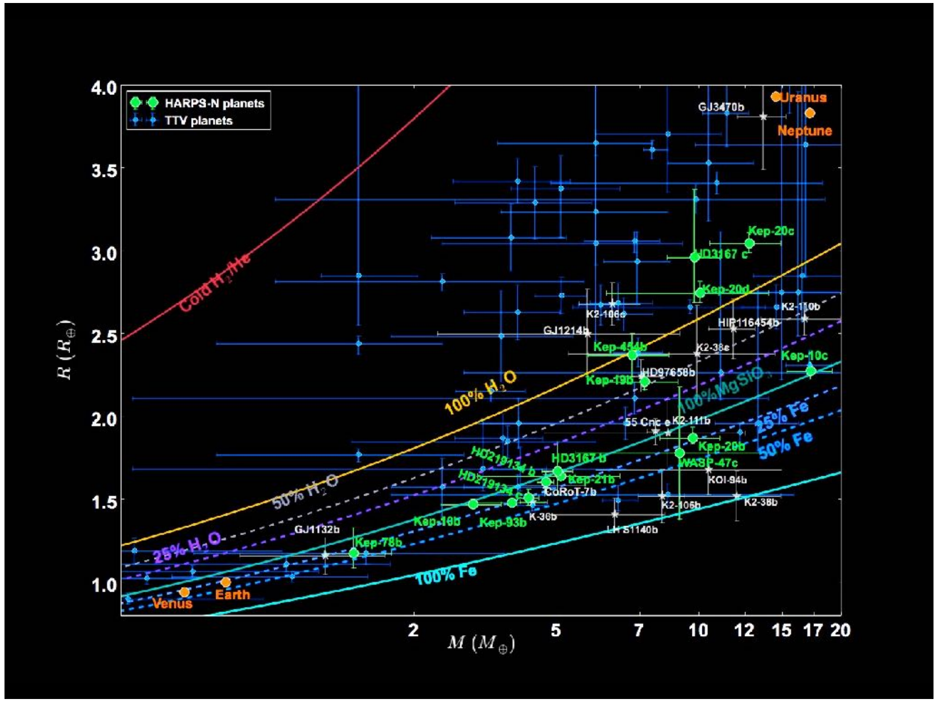
Gaseous planets

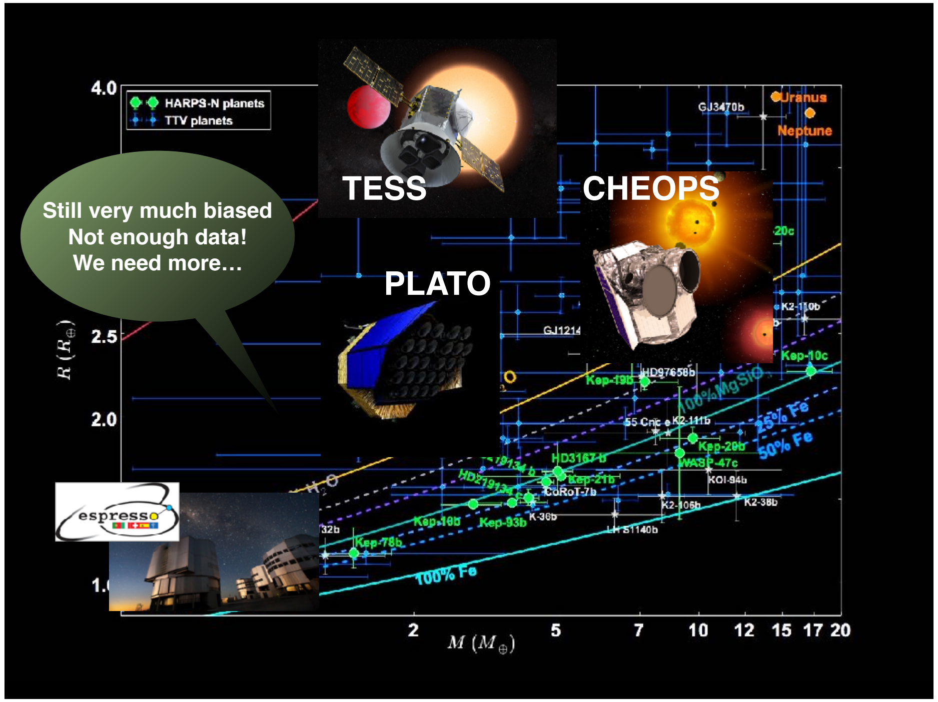


Small-size planets



(Courtesy H. Rauer)





The role of radial velocity observations

1. Detection (census)
2. Mass estimate, a fundamental param
   - to define the nature of the planet (density, composition)
   - for atmospheric characterisation (scale height, gravity)
   - to probe the long term evolution (dynamics)

The next step: characterization!

What is characterizing a planet?

- Host star and Orbit → incident stellar flux
- Mass, Radius → mean densitiy, bulk composition
- Atmosphere → scale height, composition
- Age → evolution (dynamics)
- Biosphere → life

Challenge of characterising small planets

- Multi-planet systems: superposition of signals
  => sample various time scales

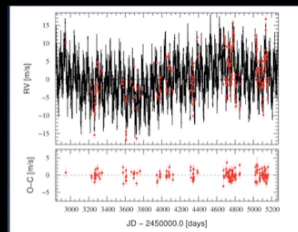
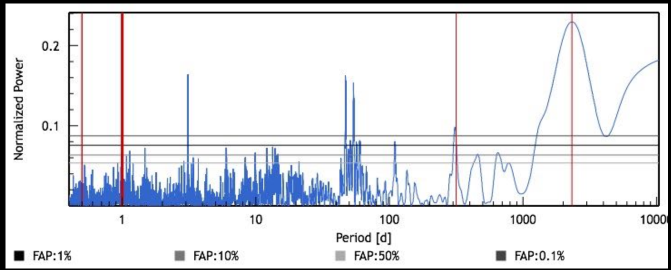


Fig. 5. Radial velocity time series with the 7-Keplerian model overplotted. The lower panel shows the residuals to the model.

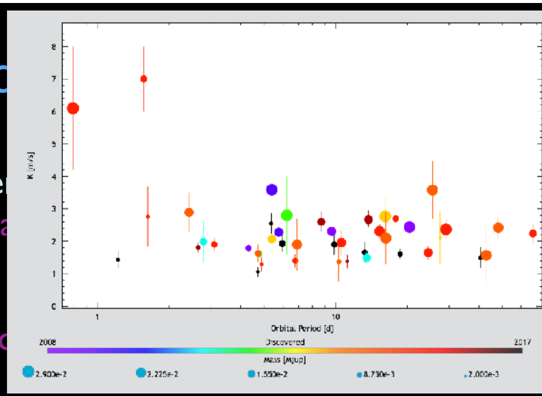
Challenge of characterising small planets

- Multi-planet systems: superposition of signals
  - => sample various time scales
- Sampling effects:
  - => need to cut aliases



Challenge of c… ets

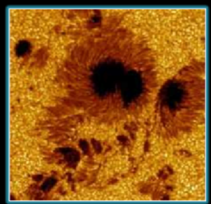
- Multi-planet syste…
  - => sample va…
- Sampling effects:
  - => need to c…



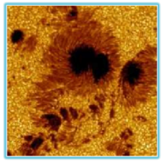
- Data analysis, confidence level
  - => need to increase signal to noise

Challenge of characterising small planets

- Multi-planet systems: superposition of signals
  - => sample various time scales
- Sampling effects:
  - => need to cut aliases



- Data analysis, confidence level
  - => need to increase signal to noise
- Stellar effect
  - => beat down the noise (by brute force averaging?)



Radial-velocity precision

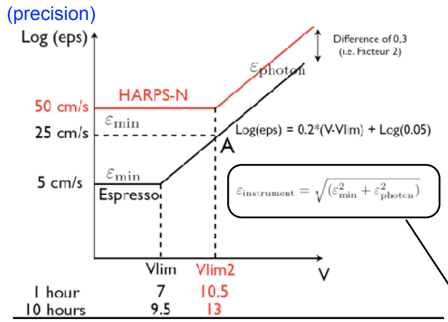
+ activity & granulation effects
(Dumusque et al. 2010a, 2010b)

HARPS-N - 15 minutes [m/s]

activity	1 day	2 days	5 days	10 days
-5.0	1.07	0.75	0.48	0.35
-4.9	1.18	0.87	0.60	0.40
-4.8	1.25	0.97	0.70	0.45
-4.7	3.0			
-4.6	6.0			
-4.5	10.0			
-4.4	15.0			
-4.3	20.0			
-4.2	25.0			
-4.1	30.0			

$\sqrt{N_{\rm binning}}$ decrease

Instrument + photon noise



Neptune	@ 1 AU	: 1.5 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 1 AU	: 45 cm s^{-1}
Earth	@ 1 AU	: 9 cm s^{-1}

ε scales as S/N

Espresso - 45 minutes [m/s]

activity	1 day	2 days	5 days	10 days
-5.0	0.25	0.18	0.11	0.07
-4.9	0.52	0.47	0.37	0.23
-4.8	0.68	0.63	0.50	0.31
-4.7	2.85			
-4.6	5.90			
-4.5	9.90			
-4.4	14.95			
-4.3	20.0			
-4.2	25.0			
-4.1	30.0			

$\sqrt{N_{\rm binning}}$ decrease

$$\varepsilon = \sqrt{(\varepsilon^2_{\rm instrument} + \varepsilon^2_{\rm activity})}$$

<u>The community is very active</u>
(including PLATO FU members)

<u>1) Modelling stellar effects</u>
- Solar telescopes
- Activity indicators
- Activity modelling (GP,…)

<u>2) Telluric contaminations</u>

<u>3) Statistical approaches</u>
- Robustness
- Criteria for trust in detections
- Non-gaussian effects ?

<u>4) Instrumental challenges</u>
- Hardware (light injection, thermo-mechanical stability,…)
- calibration (LFC, FP, lamps …)

<u>5) new instruments</u>
- Visible (ESPRESSO, NEID, EXPRESS, PEPSI, VELOCE,…)
- NIR (CARMENES, SPIRou, NIRPS)

Two examples to illustrate some of the approaches

1. Selected choice of spectrale lines or spectral chunks

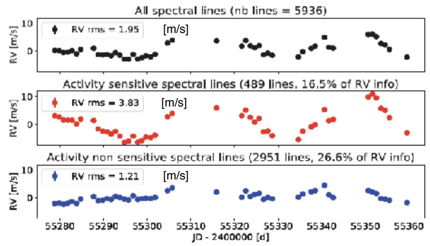
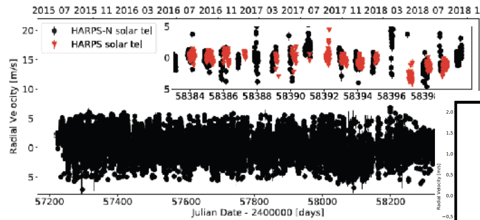


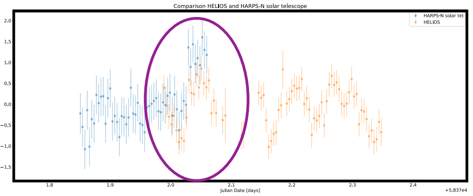
Figure 3: RV data of Alpha Cen B strongly affected by stellar activity. We show here the RV measured using all the spectral line (top) only the very affected ones (middle) and the less affected ones (bottom). By smartly selecting the lines to measure RV, it is possible to mitigate stellar activity by a factor of 1.6 (Dumusque 18).

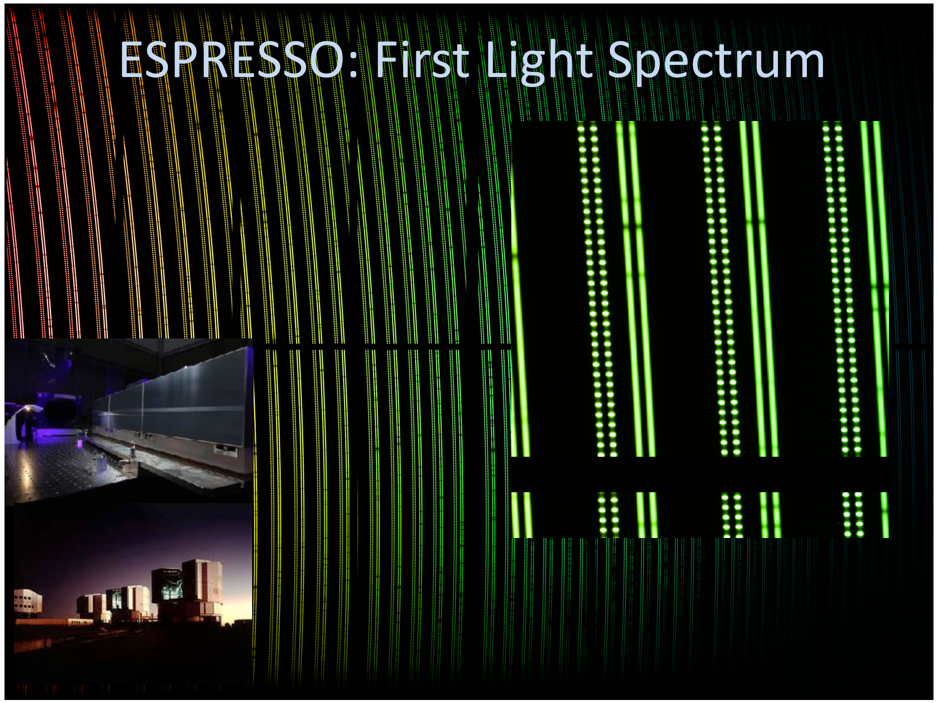
Also Rajpaul, Aigrain, et al. 2019
Blind, machine learning, selection of "non-variable" part of the spectrum

2. Solar telescopes on HARPS-N and HARPS (Helios)



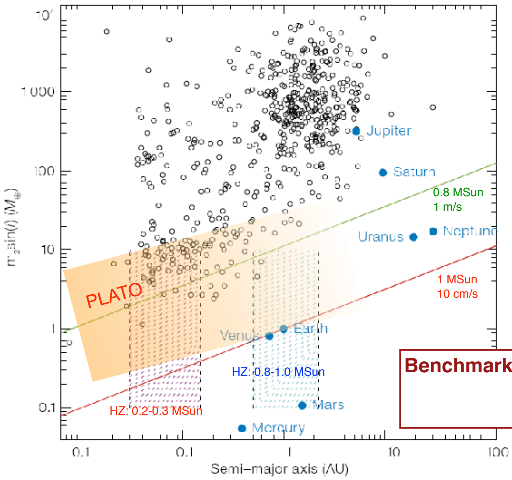
Real stellar effect?





PLATO and ESPRESSO on the VLT

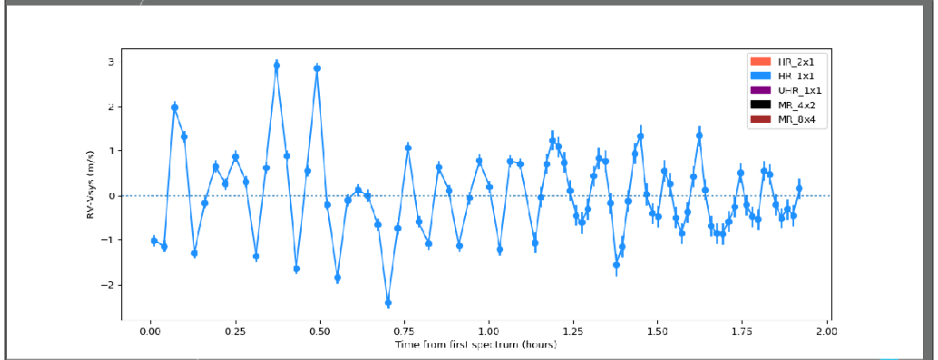
Performance and scientific relevance for PLATO



Benchmarks: Mv=7.65, Texp = 5 min. -> 25 cm/s
Mv=10, Texp = 10 min. -> 50 cm/s
Mv=12, Texp = 60 min. -> 50 cm/s

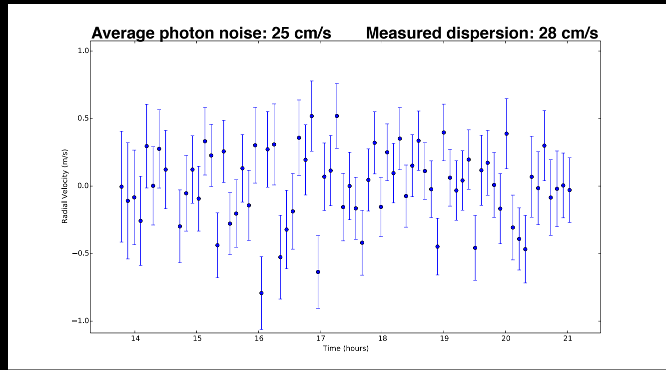
Short-term precision

HD 190248
V=3.6, G8IV



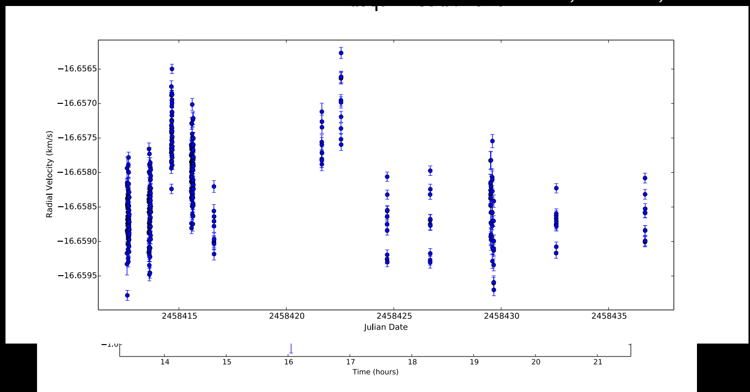
Rocky planets in HZ with ESPRESSO

HD85512



Rocky planets in HZ with ESPRESSO

Tau Ceti, 1 month, 62 cm/s



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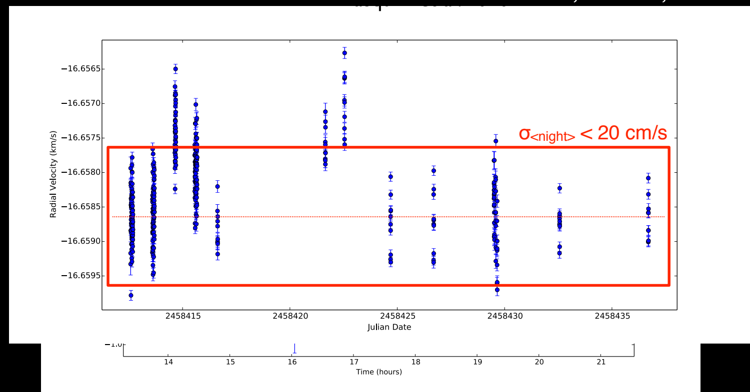

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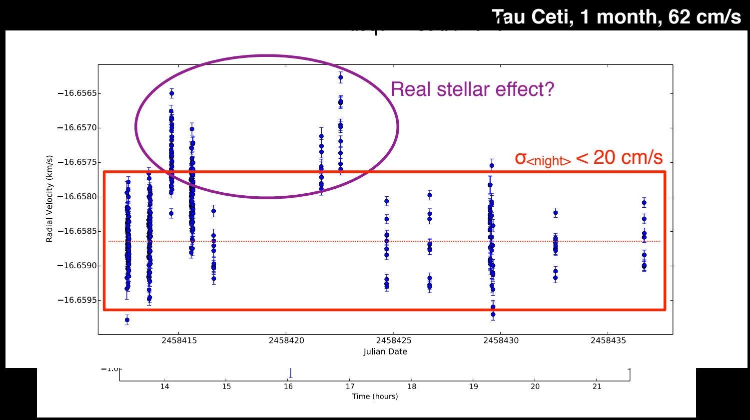
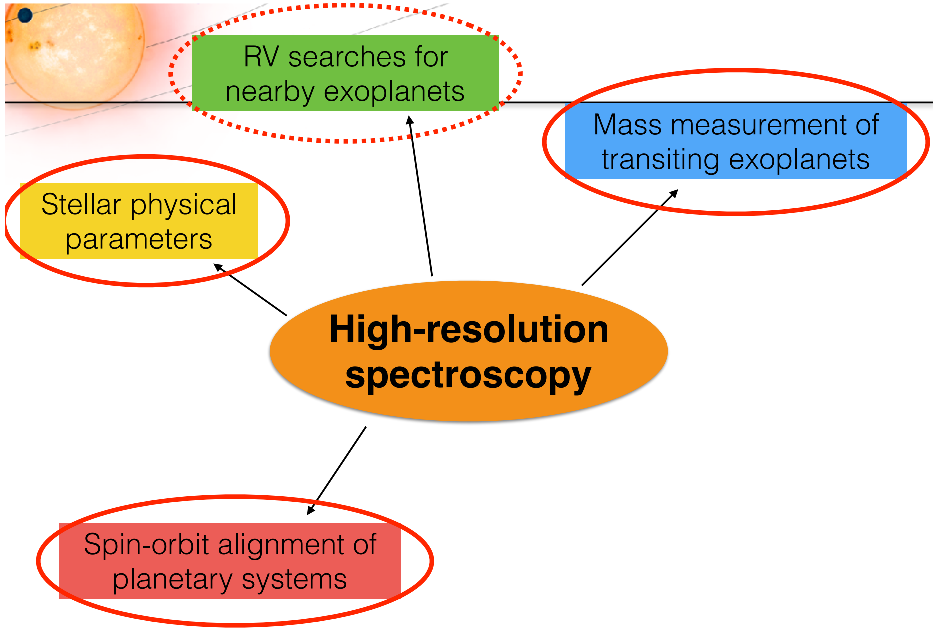
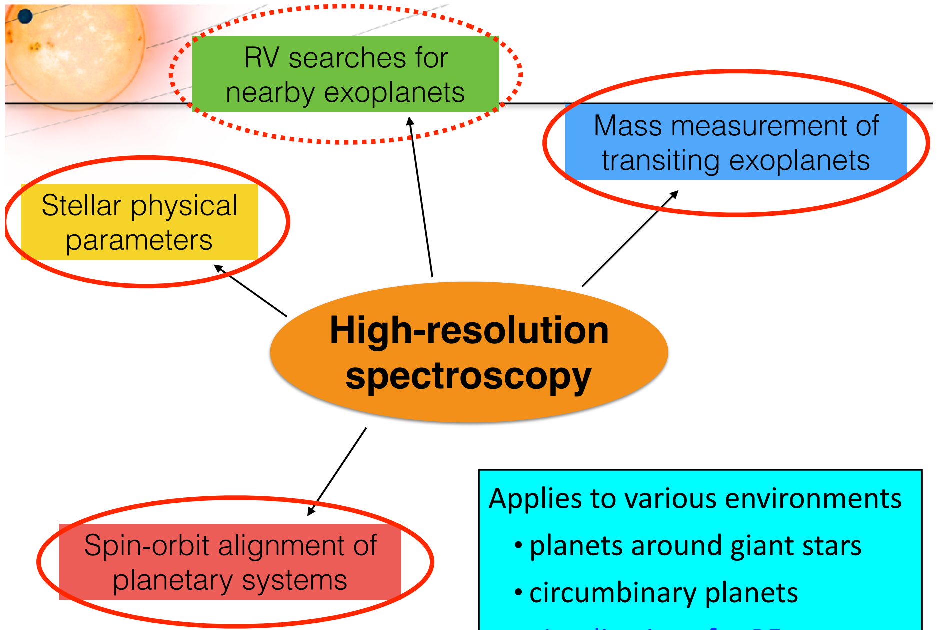




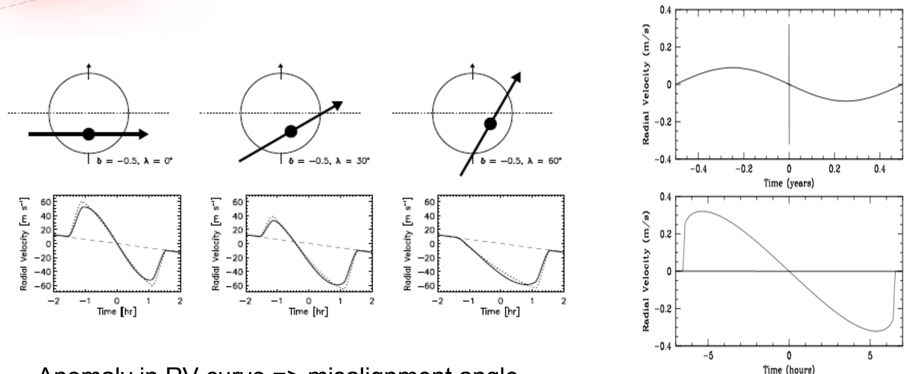


Applies to various environments

- planets around giant stars
- circumbinary planets

=> Implications for P5

Rossiter-McLaughlin effect

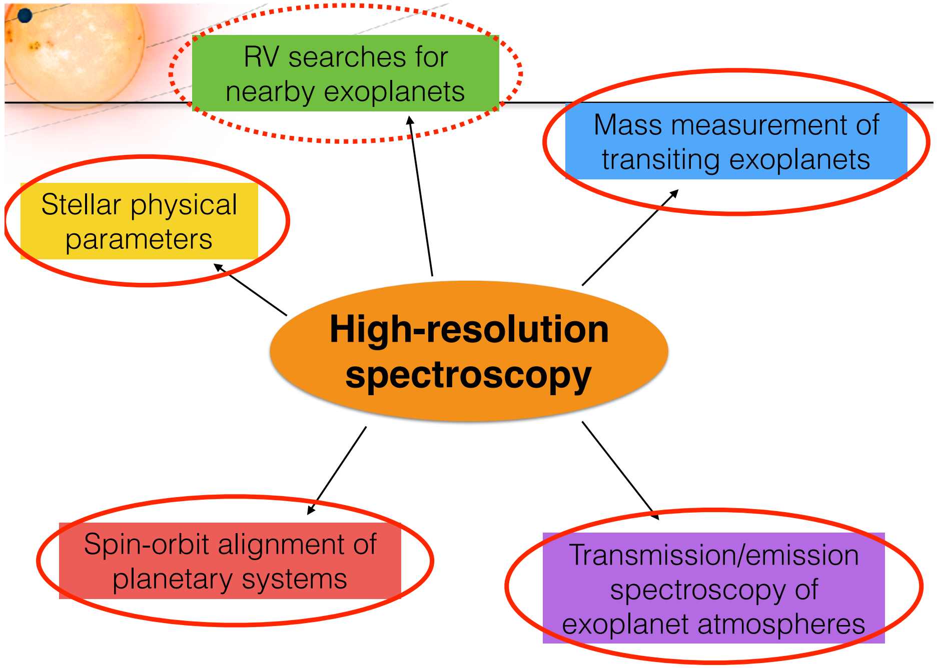


Anomaly in RV curve => misalignment angle
=> system geometry

An Earth around a Sun star

- K amplitude ~10 cm/s
- RM effect amplitude ~20 cm/s

=> "quick" planet validation when possible



FU-science needs from PIC

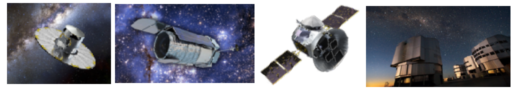
1. Basic stellar parameters
   - coordinates, magnitudes, spectral type,…
   - specific for the reduction pipeline: star RV
   - … others ?
2. System properties: environment
   - binarity, known planets and their parameters
   - contaminants
3. Best radial-velocity measurements
   - vsini, activity level (RV precision, choice of instrument)
   - … others ?

} => in PIC

4. Time series from previous surveys (with uncertainties)
   - RVs: known or long-P planets
   - Activity proxy: star-planet disentangling

=> in ancillary database

=> use existing archive data



(From surveys: Gaia, TESS, RVs, etc)

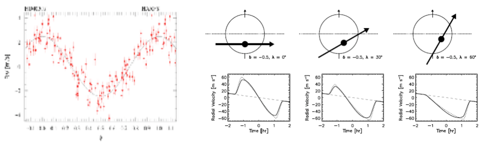
Rem: FU will provide
- Time series with BJD, RV, Sig_RV, CCF bisector, activity index,
- + 1 combined spectra: v*sini*, Fe/H, Teff, mean activity level (various indexes)

Importance of the follow-up

Goals - Necessity - Organisation

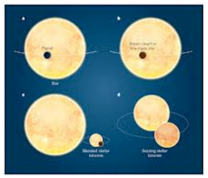
1) Planet parameters

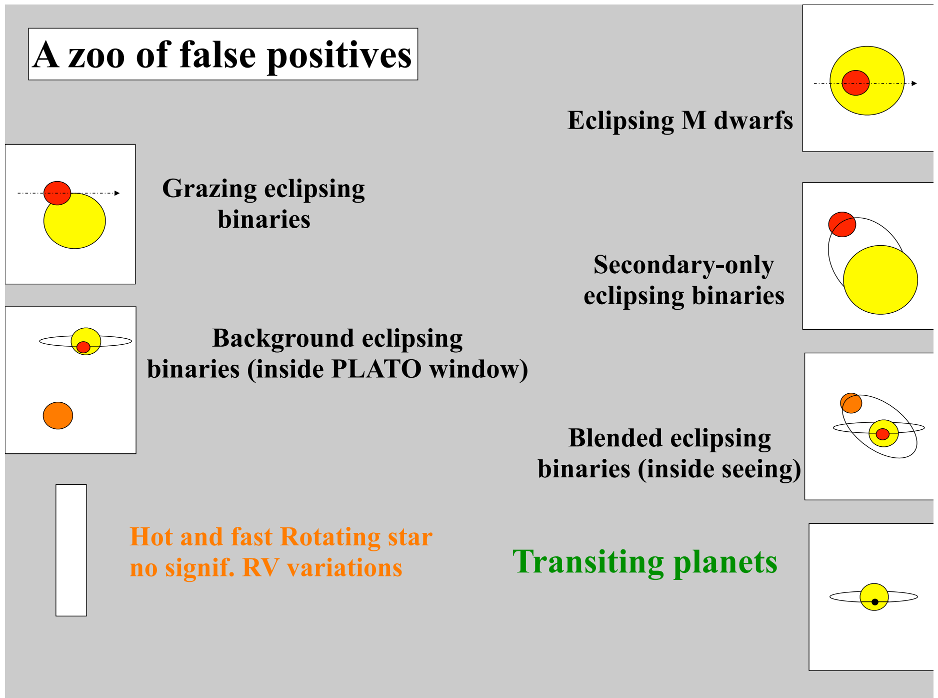
Not obtained from the light curves
- mass, density
- temperature, geometry
- others

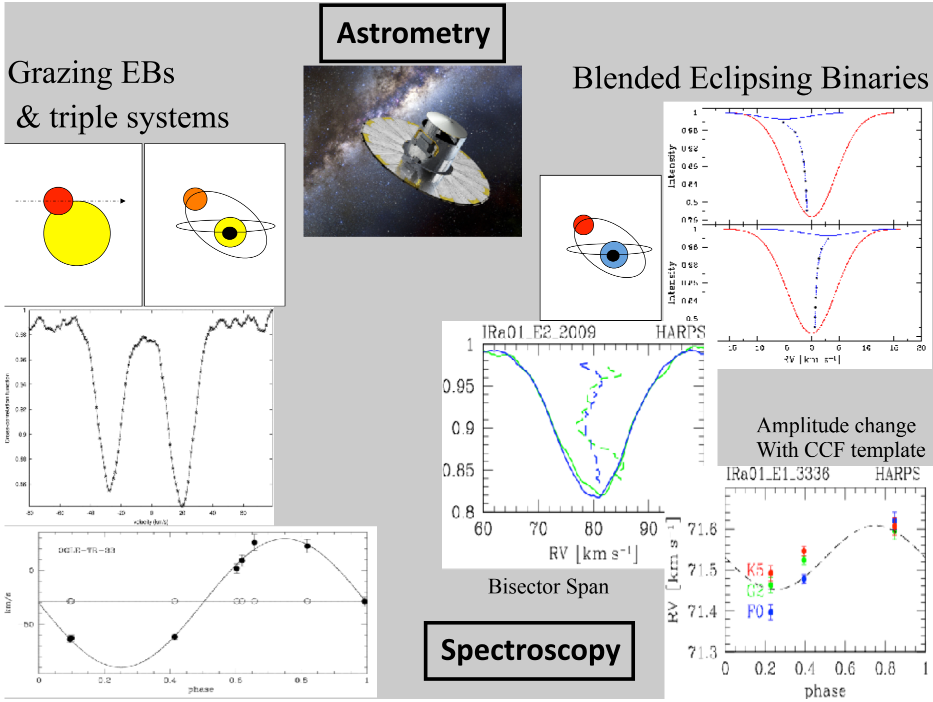


2) False positives

Experience gained from
- ground-based => giant planets
- space => small planets

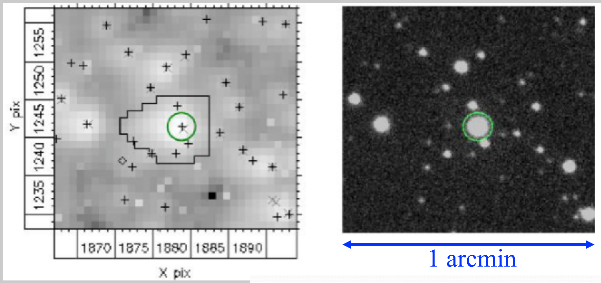






Ground-based photometric & imaging follow-up

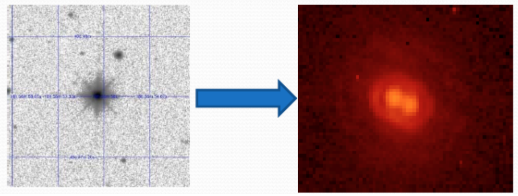
- To estimate dilution factor within photometric mask
- To exclude diluted eclipsing binaries with ON-OFF photometry
- To identify close contaminant at high angular resolution



CoRoT example

KOI 1422 is binary: R = 1.5 Re → R = 2.1 Re

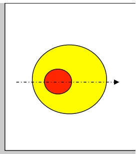
Kepler example



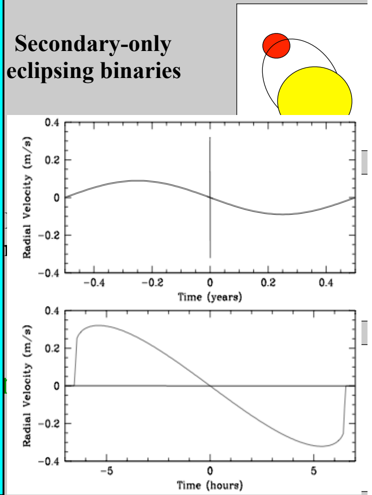
A zoo of false positives

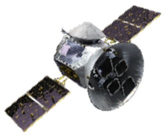
- Small-size planets
  - => add false-positive due to diluted transits by giant planets on secondaries
  - => standard diagnostics applicable
    - Consistency checks (duration, etc)
    - Light curve shape (V, ellipsoidal, etc)
    - Astrometry, RVs, line bisector
    - Imaging (dilution), on-off photometry
- 10% - 30% false positives (from Kepler)
  small - giant planets
- statistical approach (BLENDER/PASTIS)
  => Validation, ranking
- Validation of Earths via Rossiter-McLaughlin

Eclipsing M dwarfs



Secondary-only eclipsing binaries





TESS Follow-Up: where we are

What we have already learned that will be useful for PLATO:

- Follow-up vetting is critical but not all aspects at the same level

5 TFOP Working-groups:

- Seeing limited Photometry (Karen A. Collins) → Lots of participating facilities
- Recon spectroscopy (Samuel N. Quinn) → Less required than expected => HARPS
  - Advantages? Needed?
- High Resolution Imaging (David Ciardi) → Not much used yet
- Precise RV (David W. Latham) → The most important one
- Space-based photometry (Diana Dragomir) → Mission critical - precision? ARIEL?

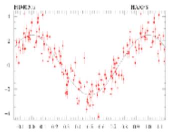
Lessons learned:

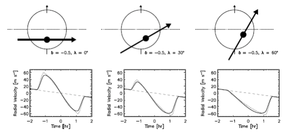
- There are good stars => improvement from HARPS to ESPRESSO
- Warning: not all stars are good.
  - activity the only sufficient criterium?
  - Sampling is important => Observing strategy
  - Statistics is a key aspects => large number of observations required
    When "star-limited": sampling/number of obs more important than precision

Importance of the follow-up

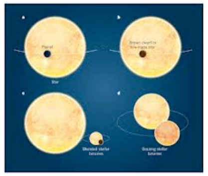
Goals - Necessity - Organization

1) Goal: planet parameters
Not obtained from the light curves
- mass, density
- temperature, geometry
- others



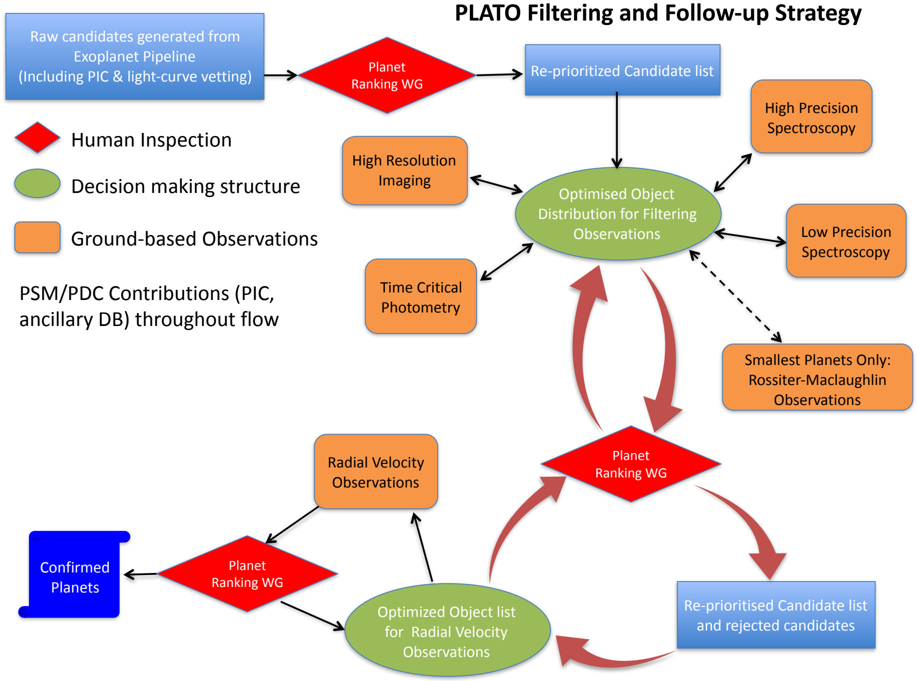


2) Necessity: false positives
- experience gained from ground and space surveys
- after diagnostics on light curves



3) Organization: optimisation
Enhanced science return
- strategy, organisation
- Synergies

PLATO Filtering and Follow-up Strategy



Follow-up organization of the work

- Large number of expected transit candidates
  => systematic observation of all transits with large telescopes unfeasible
  => an optimised follow-up scheme has to be organised
- Same level of precision cannot be reached for all stars (spectral type, luminosity class, activity, brightness)
- Same is true for the RVs and high-contrast imaging
- Strategy for the follow-up: efficient approach
  => matching targets and adequate facilities
  => minimum number of used facilities per target

In practice => a multi-step approach from moderate to high-precision (filtering)
=> a "guided" approach

=> need to design and develop tools:
- automatic distribution of targets in boxes according to their needs
- optimum match between participating facilities and target needs (boxes)
- efficient interface between observers and target information (PIC, ancillary DB)

Expected from the input catalog
=> information needed in PIC to run and optimise the Follow UP

FU science+vetting needs from PIC

1. Basic stellar parameters
   - coordinates, magnitudes, spectral type, etc.
   - system properties: binarity, known planets
   - … others ?
2. Best radial-velocity measurements
   - basic parameters, for the reduction pipeline, star RV
   - activity level, vsini
   - … others ?

=> in PIC

3. Optimised photometric measurements and follow-up
   - knowledge of the star environment, contaminants (resolution needed for on-off)
   => Sources: Existing catalogs (Gaia, TESS, 2MASS, etc)
   - … others ?
4. Efficient high-angular resolution screening
   - similar type reference stars nearby ?
   - … others ?

=> in ancillary database

5. Need for FU programming optimisation?
   - activity, vsini, star RV + local observational constraints (location, Moon, etc)
   - knowledge about the expected planet => no more PIC but living data base?
   - information about already performed FU observations => FU data base

FU works on diff. time scales than satellite/PDC => dedicated FU tool