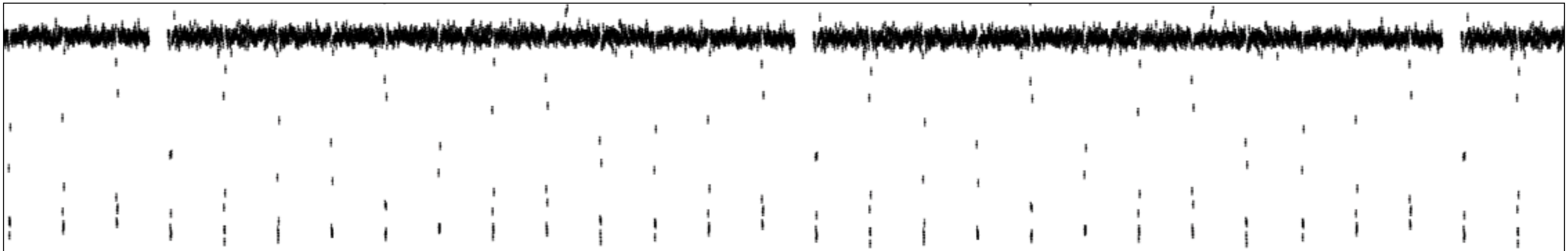


Follow-up of Transit Candidates

Ronan Kerviche, Evan Schneider, Kashmira Tayabaly & Chang You

http://kepler.nasa.gov/Mission/discoveries/kepler8b/

2/23/2012

Project Goals

- Identify false positives
- Measure masses for a large number of transits

Step 1: Don't reinvent the wheel...

Existing Database

Before doing follow-up observations, will search for existed database and evaluate if contamination is possible. Only if there are possible contamination sources will follow-up imaging be carried out.

Using the images from below and simulation of the psf of the image we are given, evaluate possibility of contamination

SDSS, USNO, DENIS survey, 2MASS, Exo-Dat database

Color selection

Slight modification of the detector:

Use a diffraction lens before the camera to get multi-color information simultaneously.

What color helps:

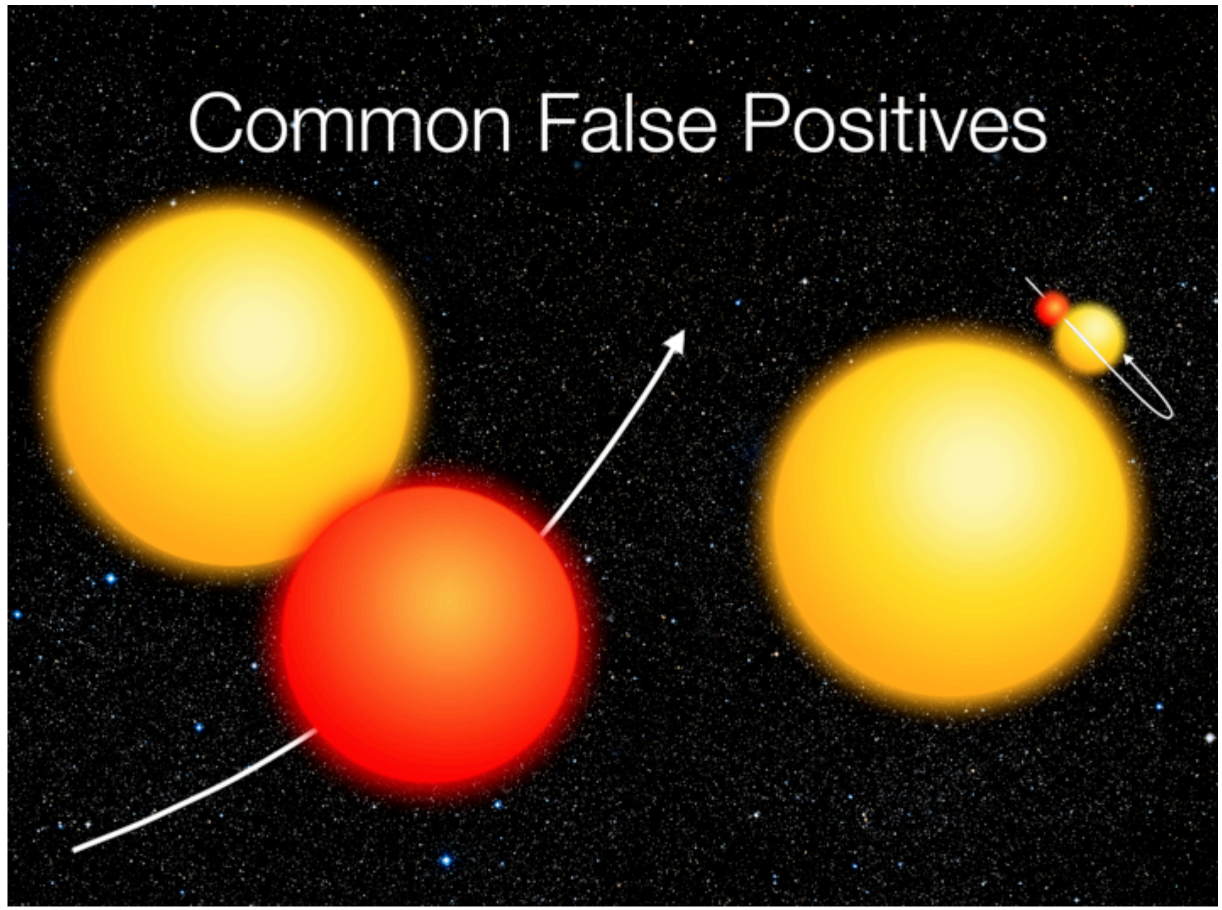
Rule out stellar activities

Rule out Line of Sight Triples or Eclipsing Binaries that changes color during eclipse

Identifying False Positives

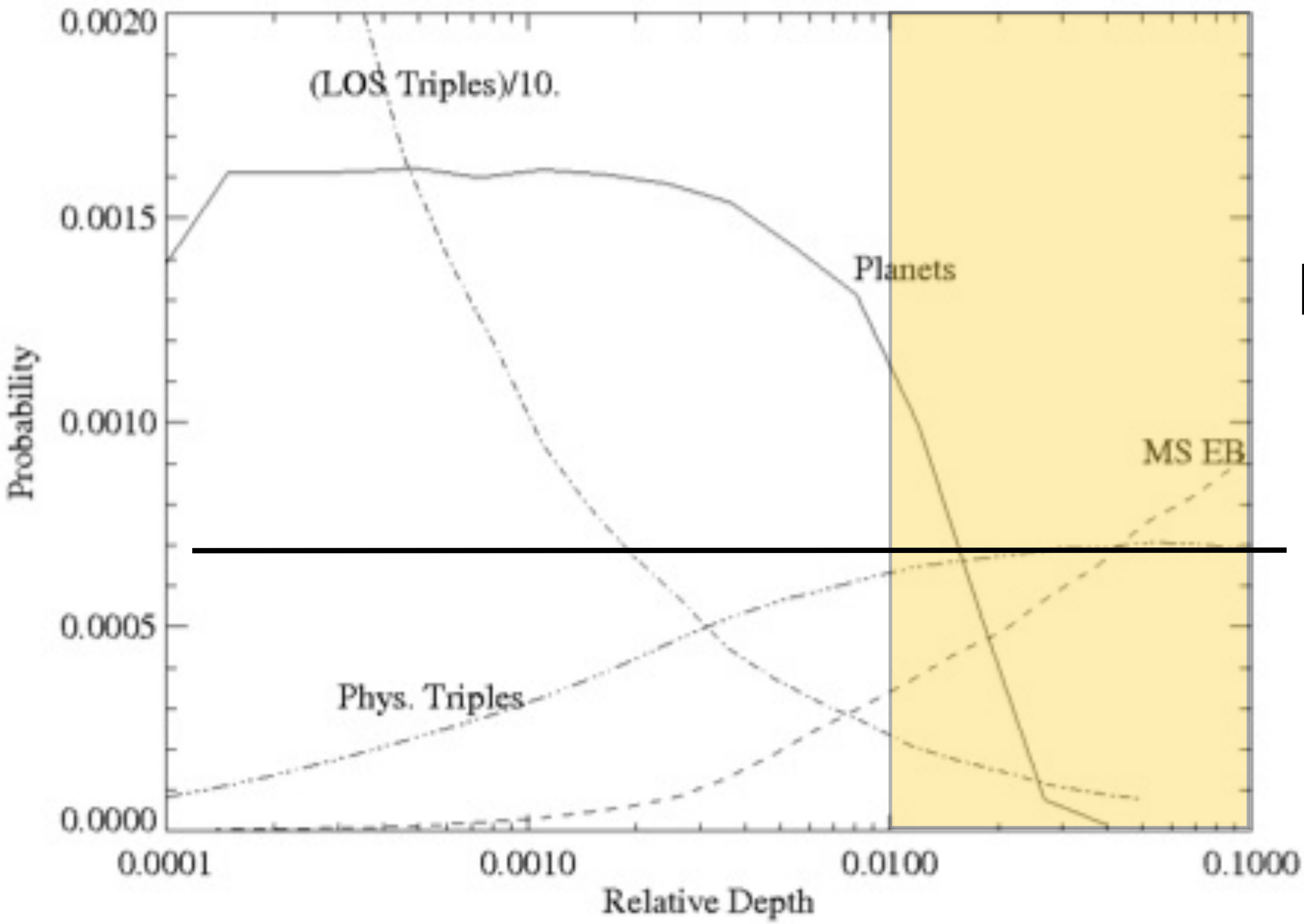
- False positives often outnumber transits

- Grazing Eclipsing Binaries (EBs)
- Line-of-sight Triples
- Physical Triples



http://www.nasa.gov/mission_pages/kepler/multimedia/images/aas_conference.html

Identifying False Positives



LOS triples:
37%
Physical triples:
30%
MS EB:
28%
planets:
5%

Brown & Latham, 2008

Transit curves analysis

Sources of errors

- Noise alone
- Eclipsing binaries:
  - large primary star eclipsed by a small stellar companion
  - grazing eclipsing binary stars
  - diluted systems: LOS triple and physical triples
  - Transiting brown dwarf or M dwarf

Area of interest

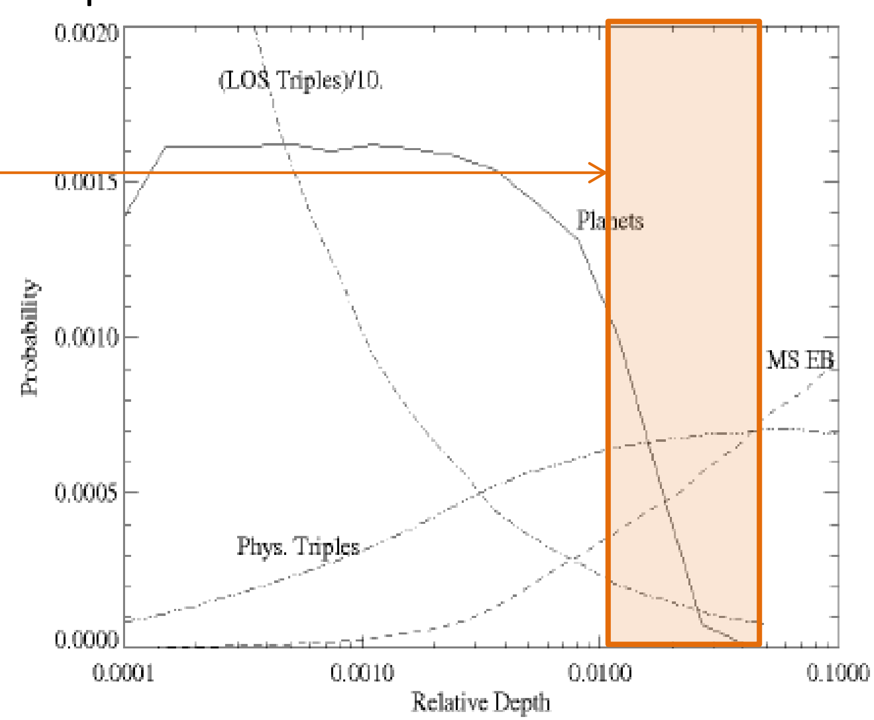


Fig- Probability density (per unit log) for the occurrence of transits with relative depth , for systems in which the transit is caused by a planet, by a grazing eclipse of a main-sequence star in an eclipsing binary, and by eclipses in EB systems that are diluted by light from a third star in a line-of-sight or a gravitationally-bound (physical) triple star system.

Assumptions

1) Light curve of high photometric precision and high sampling.

2) Eclipses have flat bottoms, with a negligible limb darkening: companion fully superimposed on the central star's disk.

3) No secondary eclipses : brightness of the companion planet negligible compared to the host star.

4) Period can be deduced from the light curve: two consecutive eclipses observed.

5) Light coming from a single star.

6) Mass of the planet negligible compared to the host star.

7) Circular orbit.

8) DATA PROCESSED IF AT LEAST 3 TRANSITS ARE OBSERVED

Noise only

- Bootstrap test gives an estimate of the probability of false alarm: detection of a transit without transit.

- *Bootstrap: way to simulate repeated observations from an unknown set using the obtained sample as a basis.*

Ruling out grazing binaries

- Short duration transit
- Particular V-Shape curve

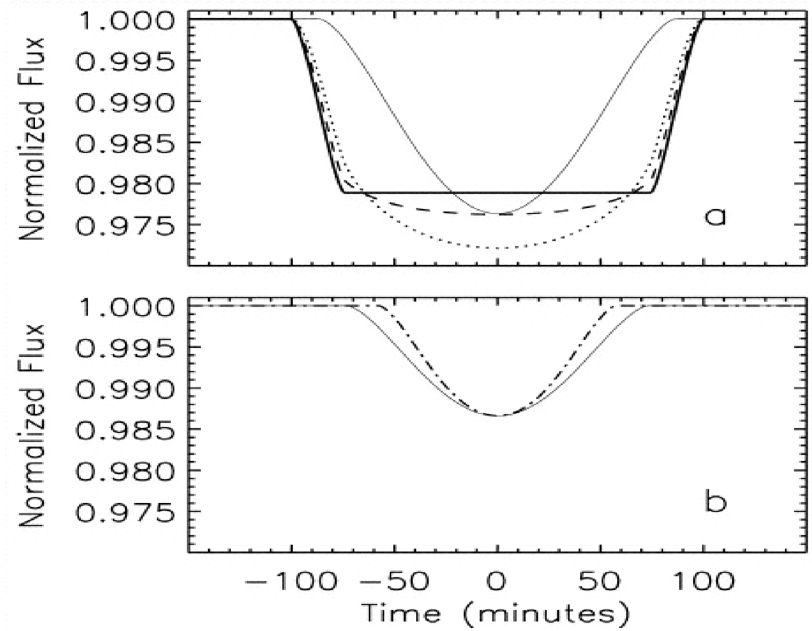


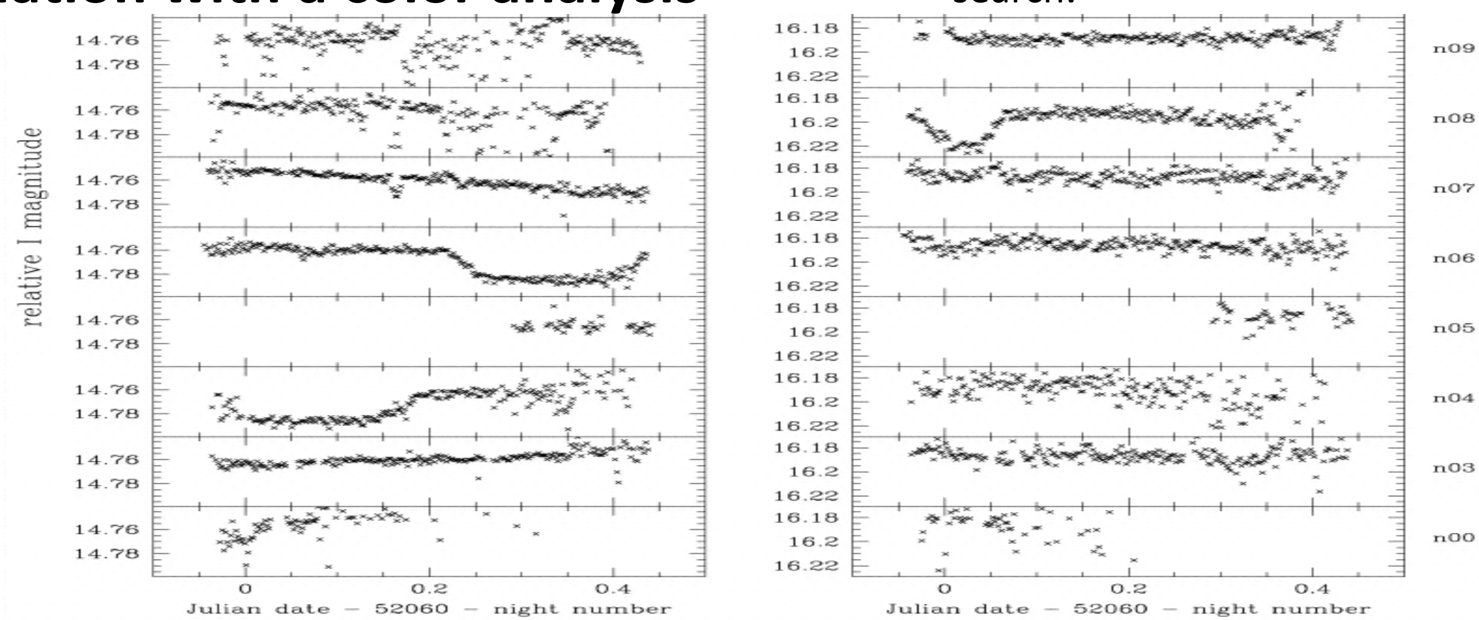
Fig- Comparison of a planet transit light curve and a grazing, eclipsing binary star light curve.

- Under a certain range of inclination -> possibly a planet
- LIMITATIONS:
  - Requires high time sampling and high precision photometry
  - Better in a bandpass not affected by limb darkening.

Ruling out EBs with a large primary star

- For a same period orbit, duration of eclipse is much larger (0.2 to more than 5 days), peak usually deeper (25%)
- Elliptical period
- Presence of a secondary eclipse
- **Confirmation with a color analysis**

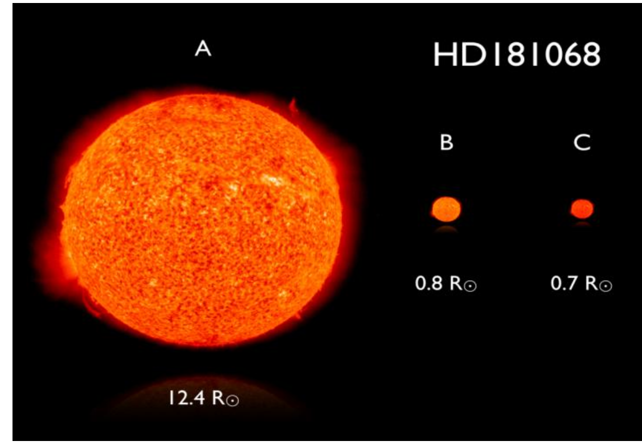
Fig- Two eclipsing binary star systems from the EXPLORE I search.



Diluted systems

A) Line of sight triple

- 4 times more common than planetary transits.
- Centroid shift test.



B) Physical triple

- Most difficult to rule out.
- But V-shape with too long duration of ingress and egress to be a planet.

Necessary to follow up with HR spectroscopy and HR imaging.

Imaging

I. Motivation – Why do imaging

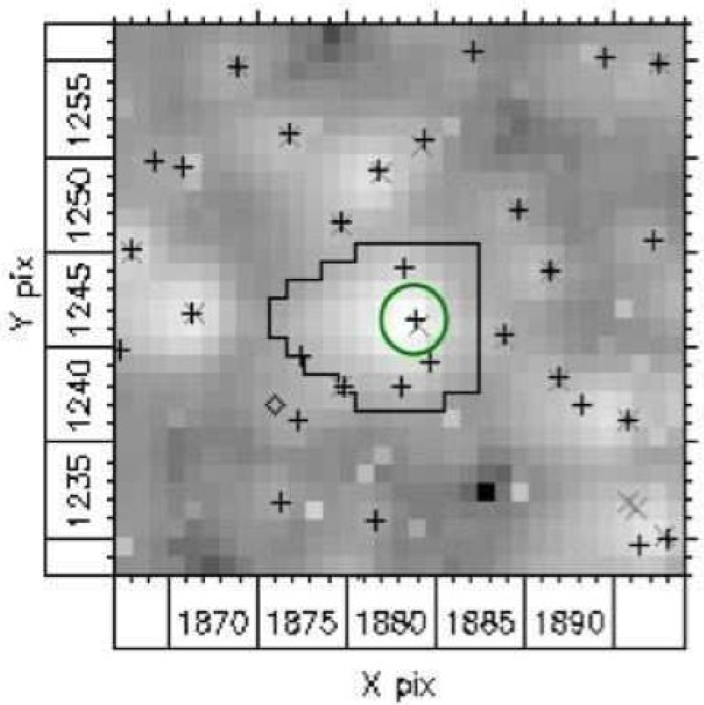
II. How Imaging Works

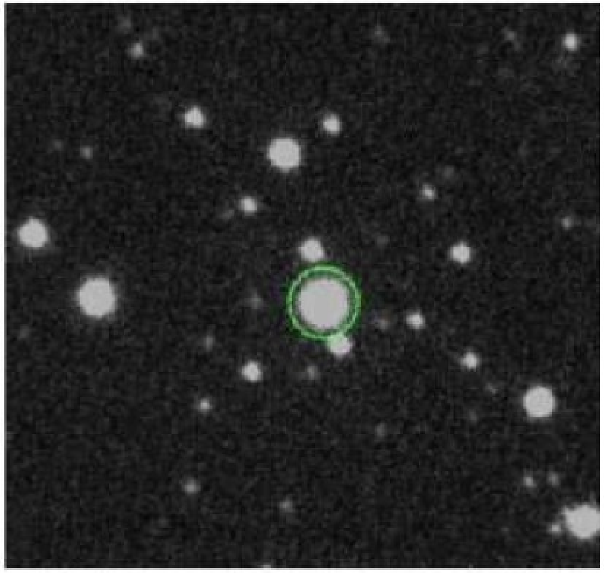
III. An Example

Motivation

Large **PSF** from original survey data allows for contamination

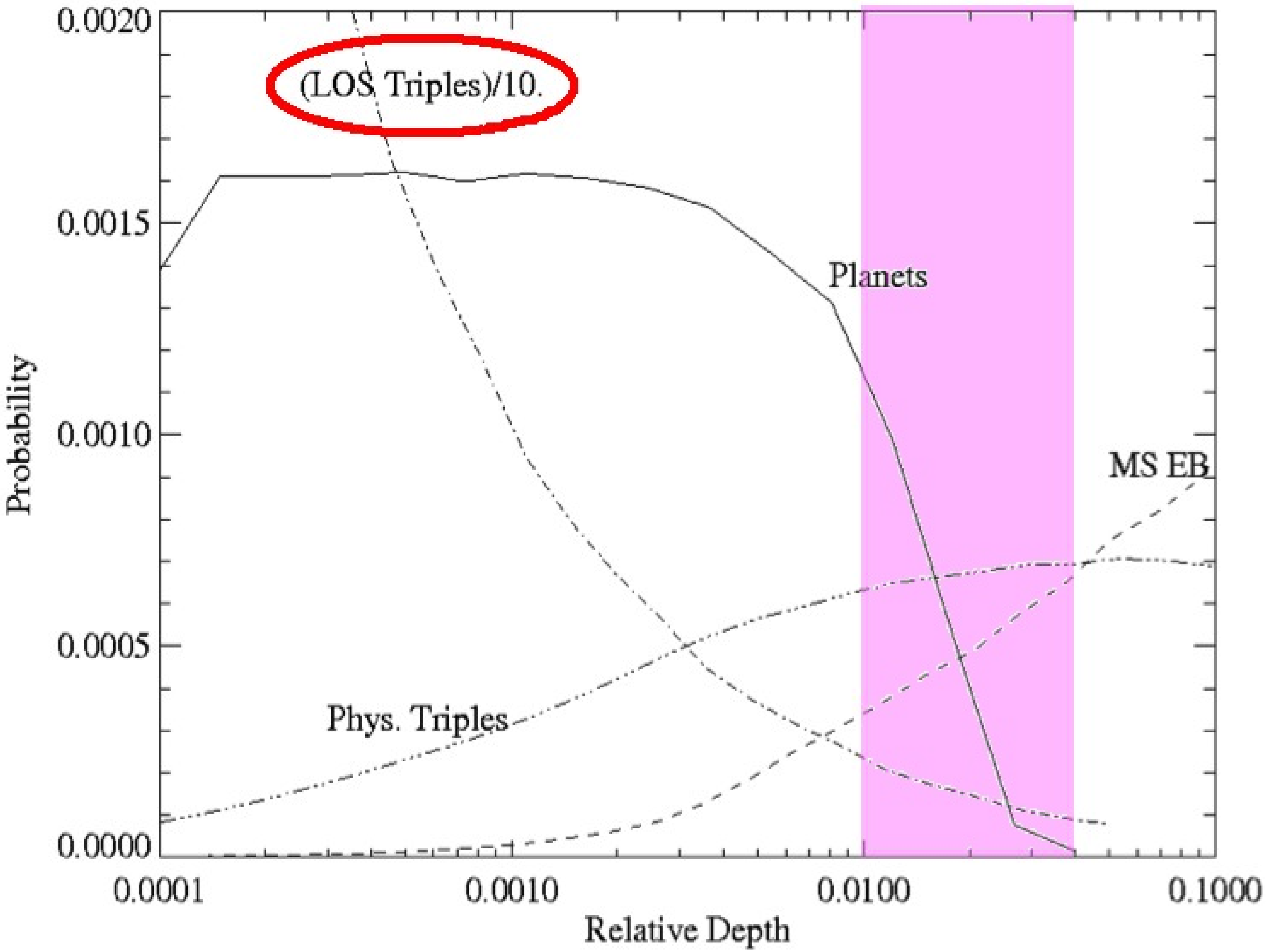
e.g. Team 2 estimates their psf size to be:
10 arcsec * 10 arcsec





Motivation

Imaging will help get rid of **Line of Sight Triples**, which is dominant source of contamination



How Imaging Works: step 1

Resolving contaminating sources

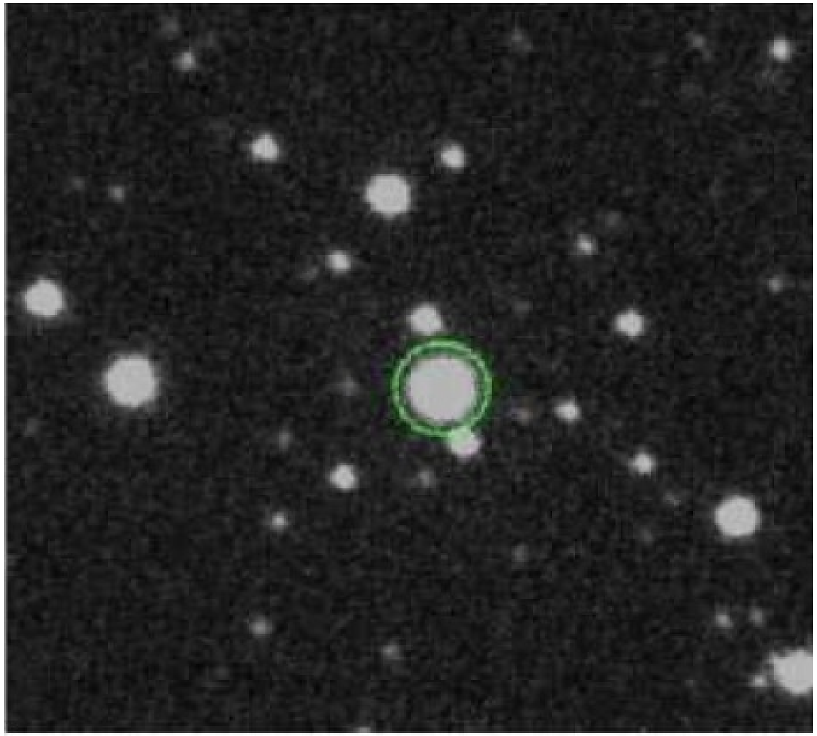
The probability of resolving the contaminating source:(For Line of Sight Triples)
$P_{detc} = 1 – A_{psf,hi} / A_{psf,lo}$

Assume we have PSF with diameter 1.2 “, we can resolve 98.5% of the contaminating sources

How Imaging Works: step 2

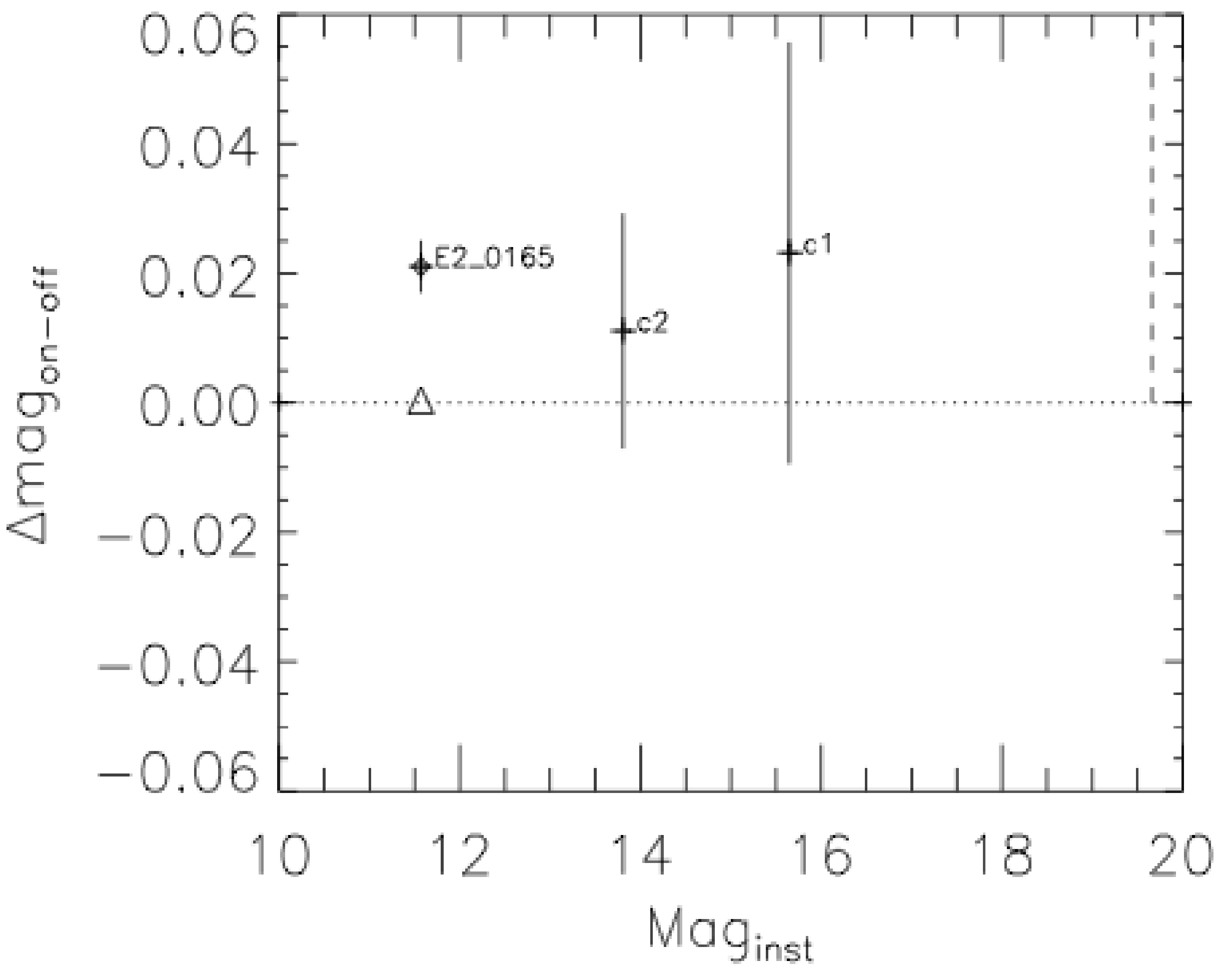
Identify possible contaminating variable source

$$m_{diff} \leq -2.5\log\left((\Delta F/F)_s\, k^{-1}\right) - 0.55$$

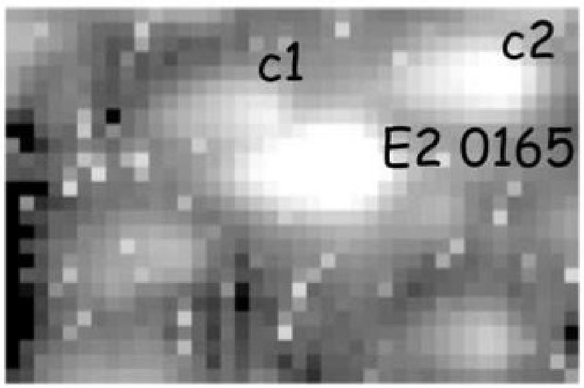


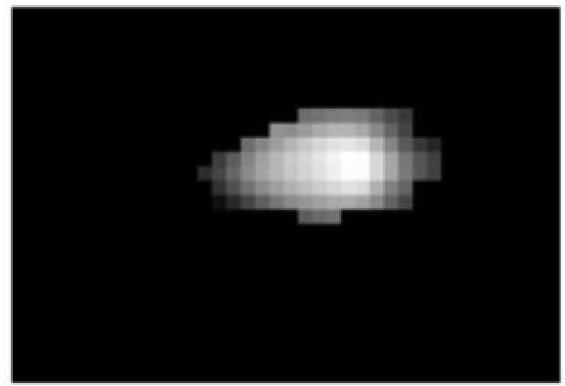
How Imaging works: Step 3

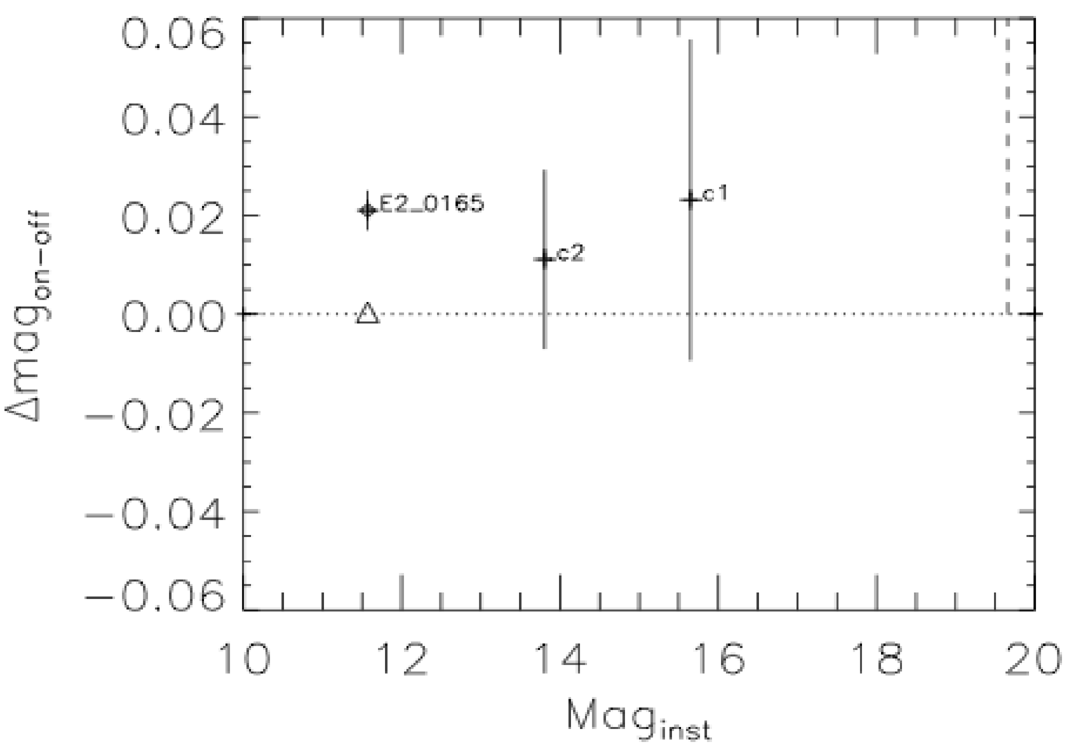
Compare on and off transit brightness

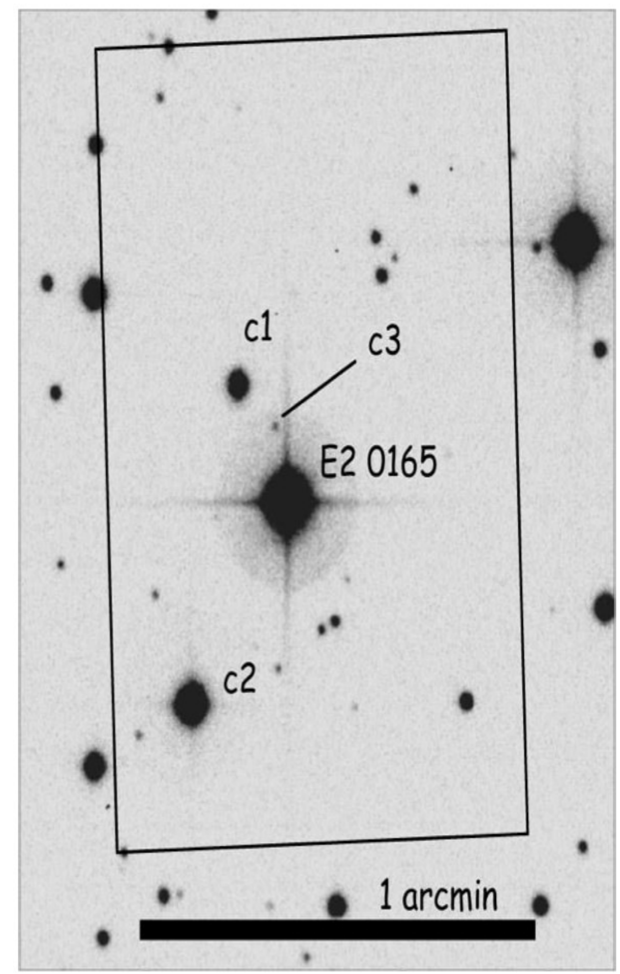


One example from CoRoT: CoRoT-7



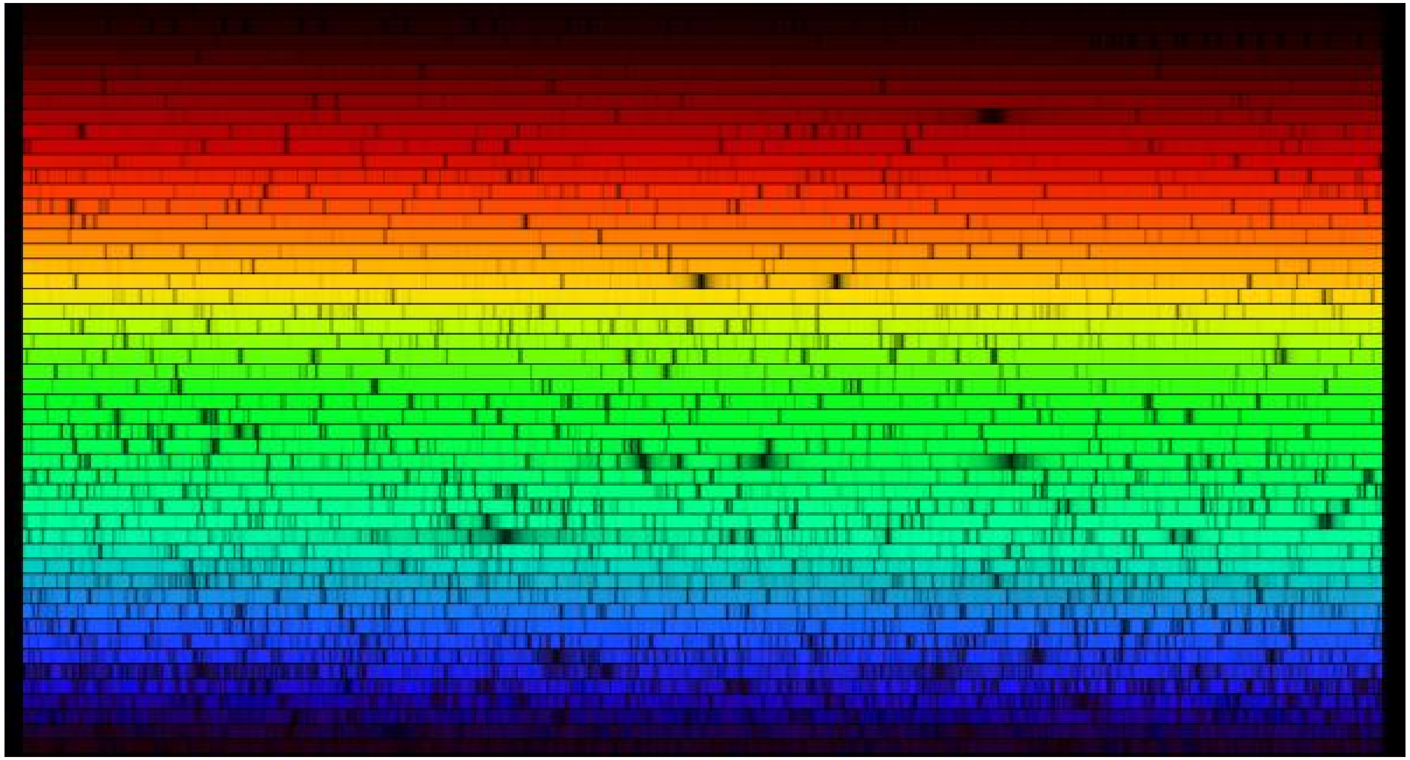






High Precision Spectrography for Radial Velocity Measurement

Measuring the mass of a stellar companion or an exoplanet



Doppler Effect on the frequencies and observation

$$f = (1 - {}^{v}/_{c})\, f_0 \Rightarrow D_f = {}^{v}/_{c}\, f_0$$

Radial Velocity : What is measured?

$$V_{star,meas.} = V_{planet}\, {}^{Mp}/_{Ms} \sin(i)$$

Typical values for the solar system (for i=90°) :

Sun	1.99E+30		
Object	Mass (Kg)	Vplanet (m.s^-1)	Induced Vstar (m.s^-1)
Earth	5.97E+24	29780	0.09
Jupiter	1.90E+27	13070	12.48
Saturn	5.68E+26	9690	2.77

Kepler's third law

$$R^3 = P^2\, G\, M_s / (4\, pi^2)$$

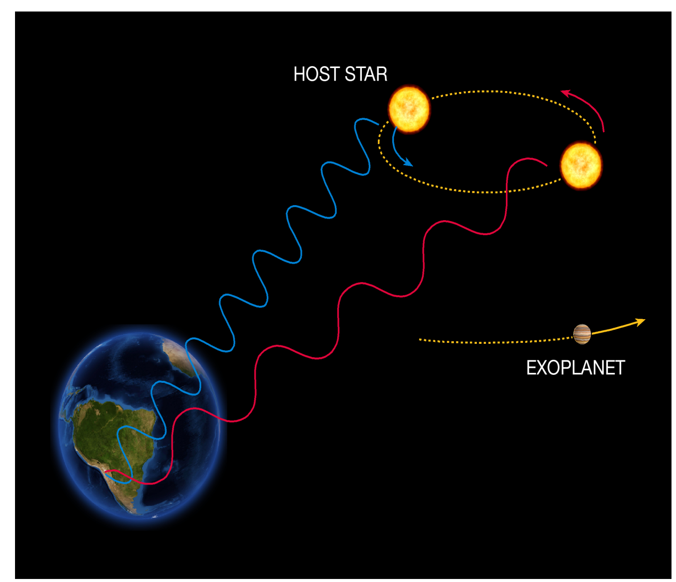
<u>*During the observation...*</u>

We measure P, the periodicity and using Kepler's 3rd law **we have the semi-major axis R.**

Knowing R, we can compute using **P**, the planet speed $\mathbf{V_{pl}=2pi\ {}^{R}/_{P}}$.

Knowing $\mathbf{V_{pl}}$ **and after measuring** $\mathbf{V_{star,meas}}$, we can compute :

$$M_p \sin(i) = M_s\, V_{star,meas.} / V_{planet}$$

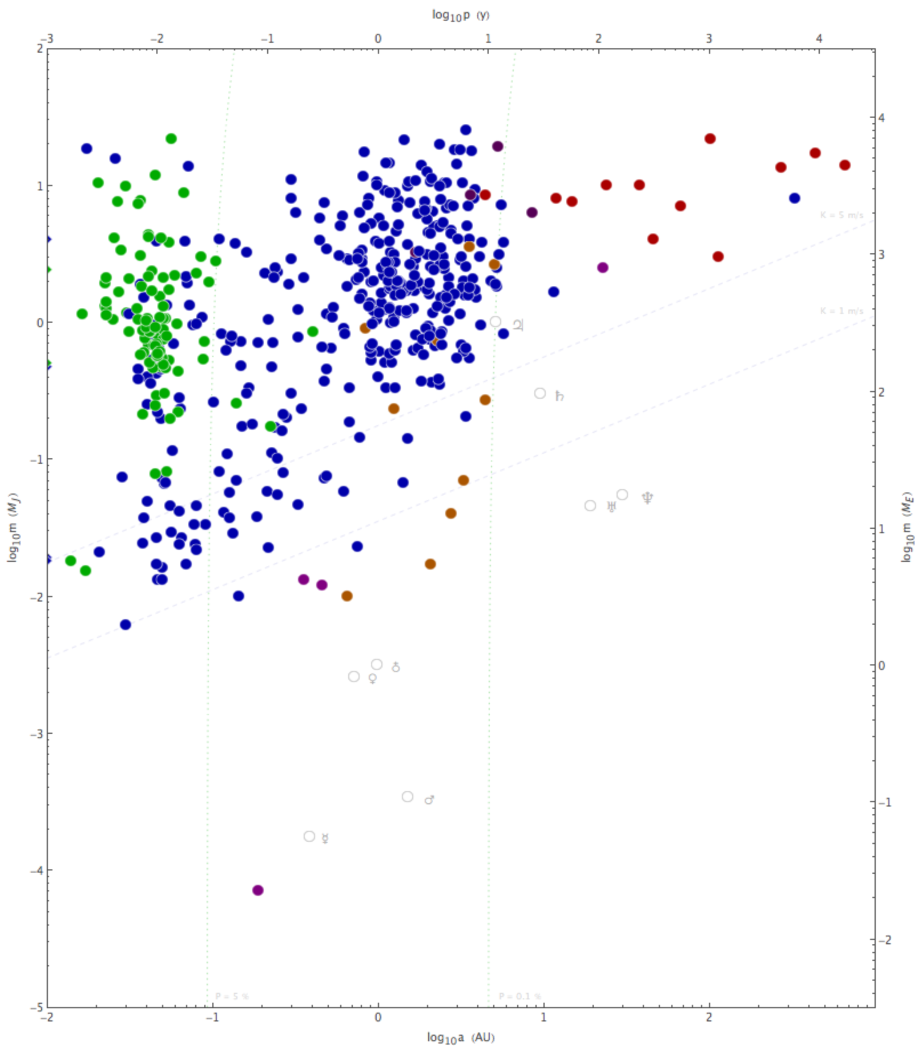


The Radial Velocity Method

ESO Press Photo 22e/07 (25 April 2007)

Main characteristics of the exoplanets

In order to rule out stellar-mass companion



For a sun-mass star :

Distance : 4 AU

Periodicity : 1 year

Velocity : 119 $Km.s^{-1}$

For comparison : HARPS sensitivity is estimated to about 80$cm.s^{-1}$

$^{Df}/_{f} = 4\ 10^{-4} = {}^{Dl}/_{l}$

=> 1.6 Angstrom at 400nm

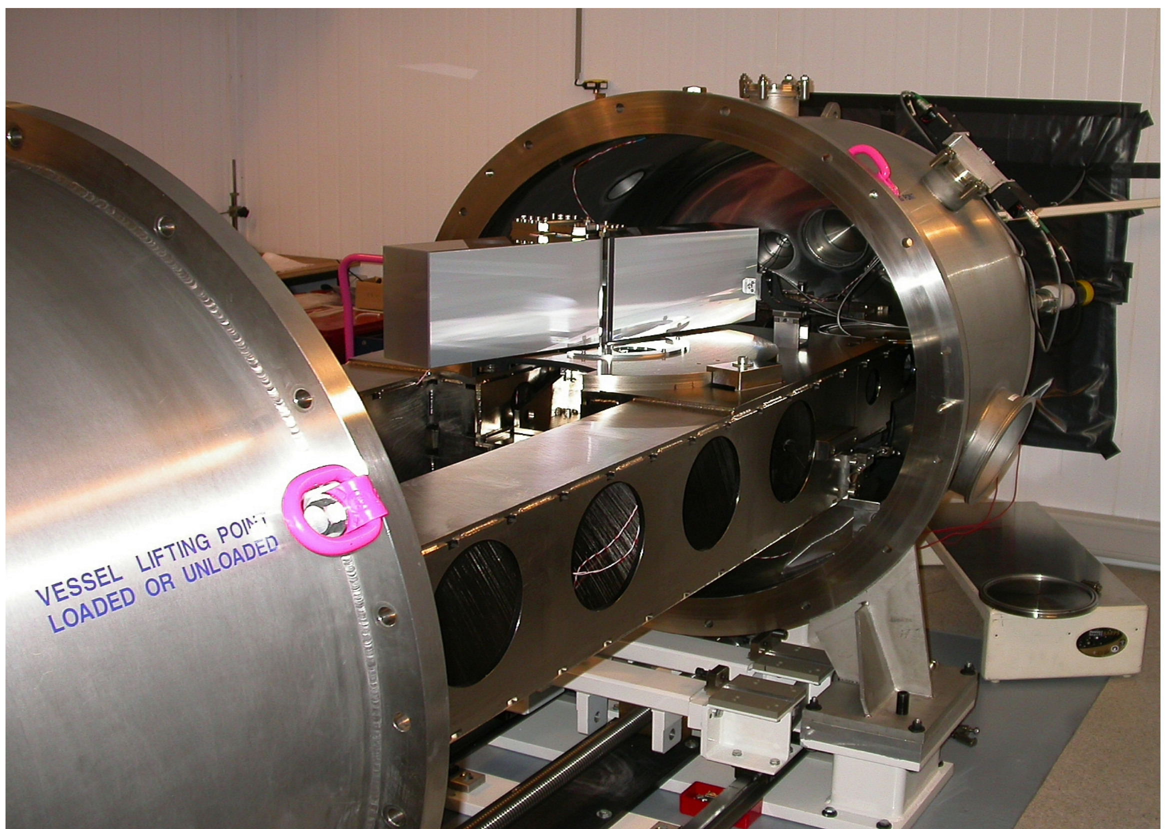
For comparison : HARPS wavelength accuracy is about 0.05 Angstrom

Measuring the mass of an exoplanet

Lower-bound for the mass given previous condition : 10 M_{Earth}

Ratio 10 M_{Earth} / M_{star} = 10^{-5} , precision at 1/10th

$V_{star,meas.}$ = 10^{-6} V_{planet} = **12 cm.s^{-1}** (for V_{planet} = 119Km/s)



Reconstruction of the data

NOAO Software Package : *The IRAF Radial Velocity Analysis Package (1) (2)*.

It can fits Data, from 1D and 2D spectrograph measurement. It can also **remove the Earth motion which is corrupting the measurement** (sidereal and orbital motion) given the measurement date.

(1) http://iraf.noao.edu/projects/rv/rv.html
(2) http://stsdas.stsci.edu/cgi-bin/gethelp.cgi?fxcor

Time Needed for Follow-up

Observation	Planets	EB	LOS Triple	Physical Triple	# of Targets	Observing Time
Examine Light Curves	1000	5600	7400	6000	20000	-
Seeing-limited Imaging	1000	1680	740	1836	5256	2628h 0.5-1m
Single Spectrum	1000	1680	74	1836	4590	689h 1-2m
Radial Velocity Spectra (km/s)	1000	1427	44	1101	3572	1786h 1-2m
High-Quality Light Curve	1000	72	15	396	1483	7415h 0.5-1m
High-Quality RV Spectra	1000	29	6	159	1194	2388h 2-4m

Thus, we would need to use an existing 1 m facility full-time for several years to do follow-up → probably worth constructing.

Detection of Rocky Planets

- Scientific motivation : it is among those rocky planets that we will probably find extraterrestrial life.
- Assumption: planet orbiting about a Sun-like planet:

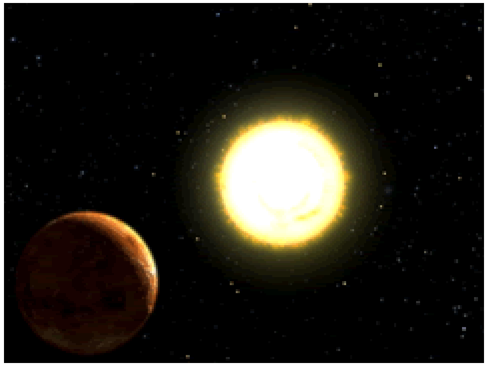
$$TD = \left(\frac{R_{planet}}{R_{star}}\right)^2$$

$$R_{star} \cong 696\,000\ km$$
$$R_{rocky\ planets} \in [5000\ \ 13800]km$$

$$TD \in [0.005\ \ 0.04]\ \%$$

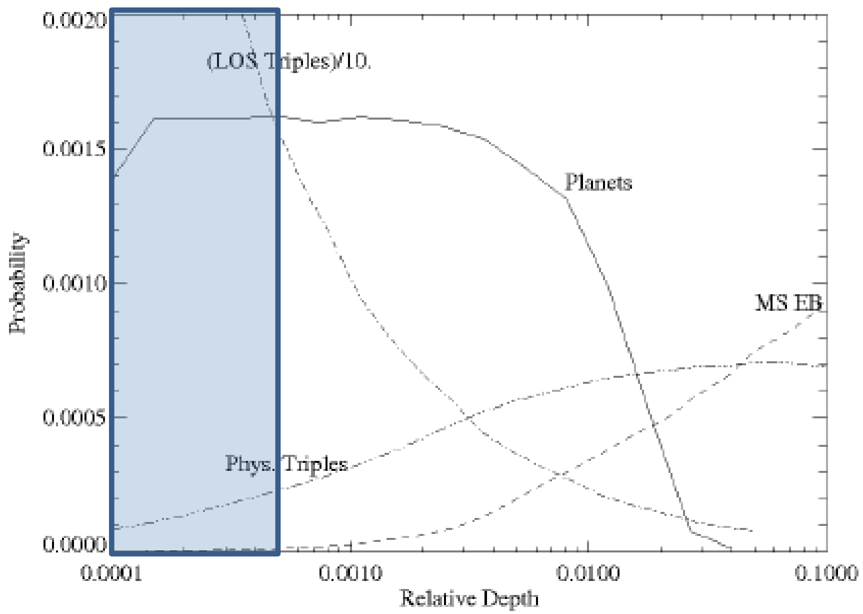
→ **Scientific challenge**

- Previously in our transit curve analysis, we were interested in 1% depth transit and more. We considered that below, SNR was too low for a good detection (SNR<< 8)



Detection of Rocky Planets

- Shifting the region of interest:



- Principal source of error here: LOS triples + noise.

- Follow up strategy:

$$P_{planet\ if\ TD<1\%} \approx 0.0016.$$

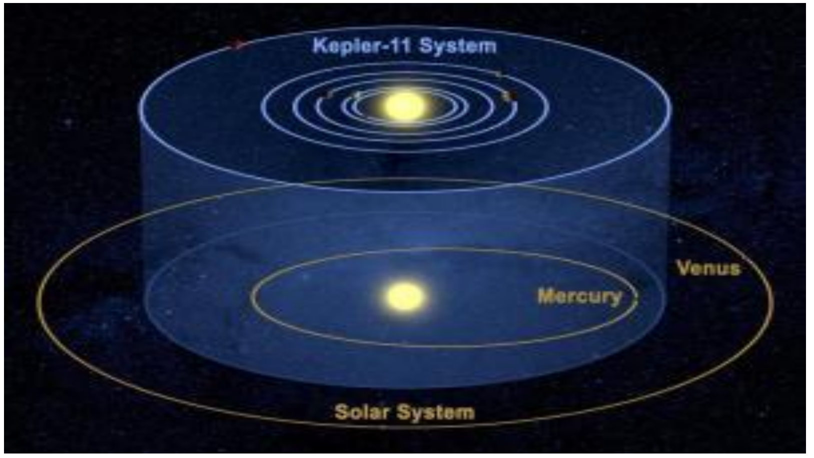
TD	# targets	# planets	# other
> 1%	20 000	< 22	19 988
< 1%	180 000	288	179712

- Random selection of Sr, a set of 280 targets among the less than 1% transit depth candidates.
- Follow up of these data with:
  1. Improved spatial resolution transit curve
  2. Direct imaging to rule out LOS triples: large eclipsing binaries can easily be spatially resolved.
  3. Worse cases: adaptive optic and high resolution imaging can be considered.

Detection of Rocky Planets

- **Expectations:**
  - Requires more accurate and costly measurements, mainly because adaptive optics (AO) and high resolution imagery are likely to be necessary (resolving physical triples requires AO too)
  - But it would give us an estimate of the proportion of rocky planets we could expect to observe with more advanced technologies.

Next challenge is to increase the discovery of rocky planets in the habitable zones of a star…



This artist's conception shows the Kepler-11 planetary system and our solar system from a tilted perspective to demonstrate that the orbits of each lie on similar planes. (Credit: NASA/Tim Pyle)

References

1) Expected planet & false positive detection rates for the transiting exoplanet survey satellite. Timothy M.Brown and David W Latham, 2008. eprint arXiv:0812.1305

2) Rate and nature of false positives in the CoRoT exoplanet search. J.M. Almenara et al. A&A 506: 337-341, 2009.

3) Kepler Data Processing Handbook. KSCI-19081-001 April 2011

4) The EXPLORE Project I.A Deep Search for Transiting Extrasolar Planets. G.Malén-Oreas et al. Astrophysical Journal 582: 1123-1140, 2003 January 10.

5) Ground-based photometry of space-based transit detections: Photometric follow-up of the CoRoT mission. H.J. Deeg et al 2009 A&A 506: 343D.

6) EXPECTED DETECTION AND FALSE ALARM RATES FOR TRANSITING JOVIAN PLANETS by Timothy M. Brown 2003 *ApJ* 593 L125

7) http://smsc.cnes.fr/COROT/

8) http://kepler.nasa.gov/