Validating the smallest CoRoT candidates with PASTIS

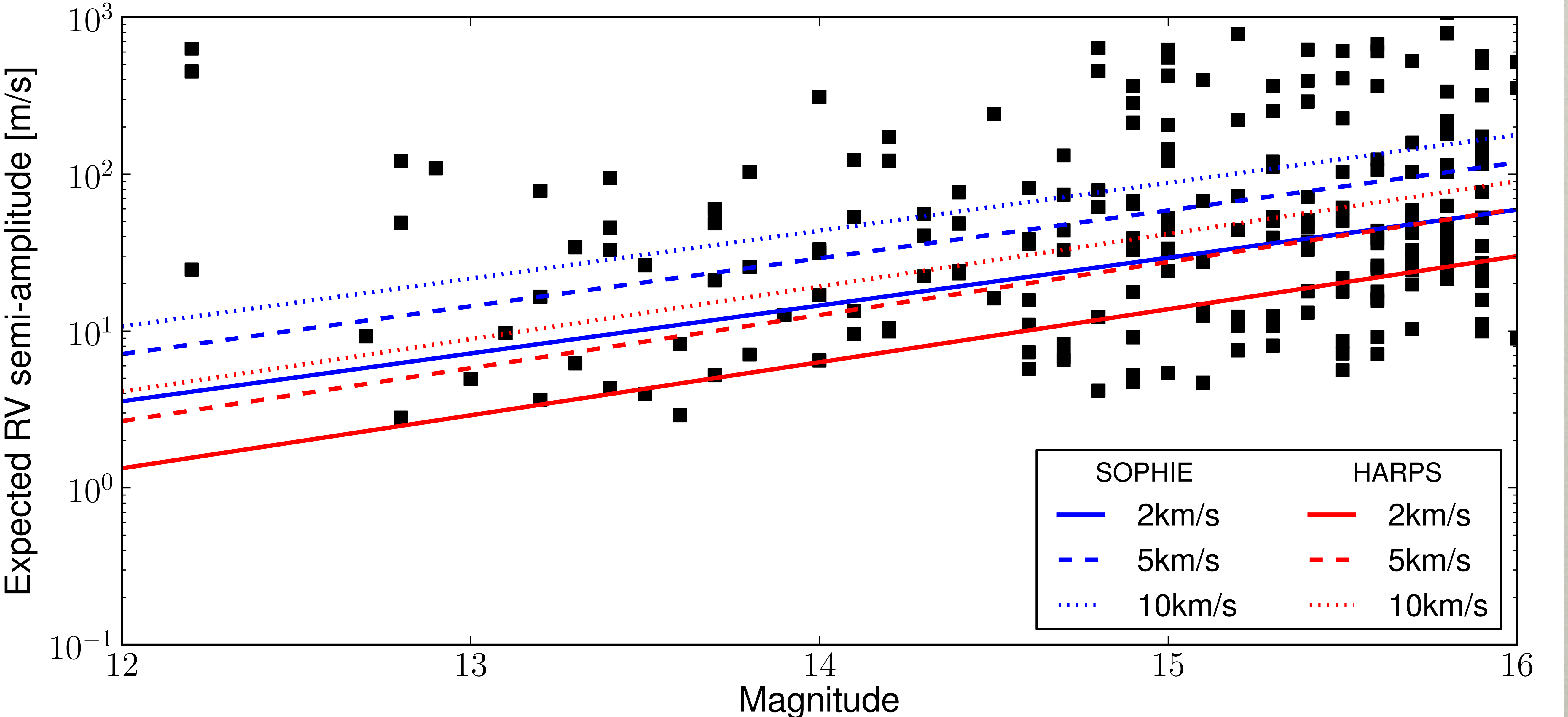
The PASTIS team:
Rodrigo F. Díaz (LAM)
Alexandre Santerne (CAUP/LAM)
José-Manuel Almenara (LAM)

CoRoT Week 11 - Tenerife - March 2013

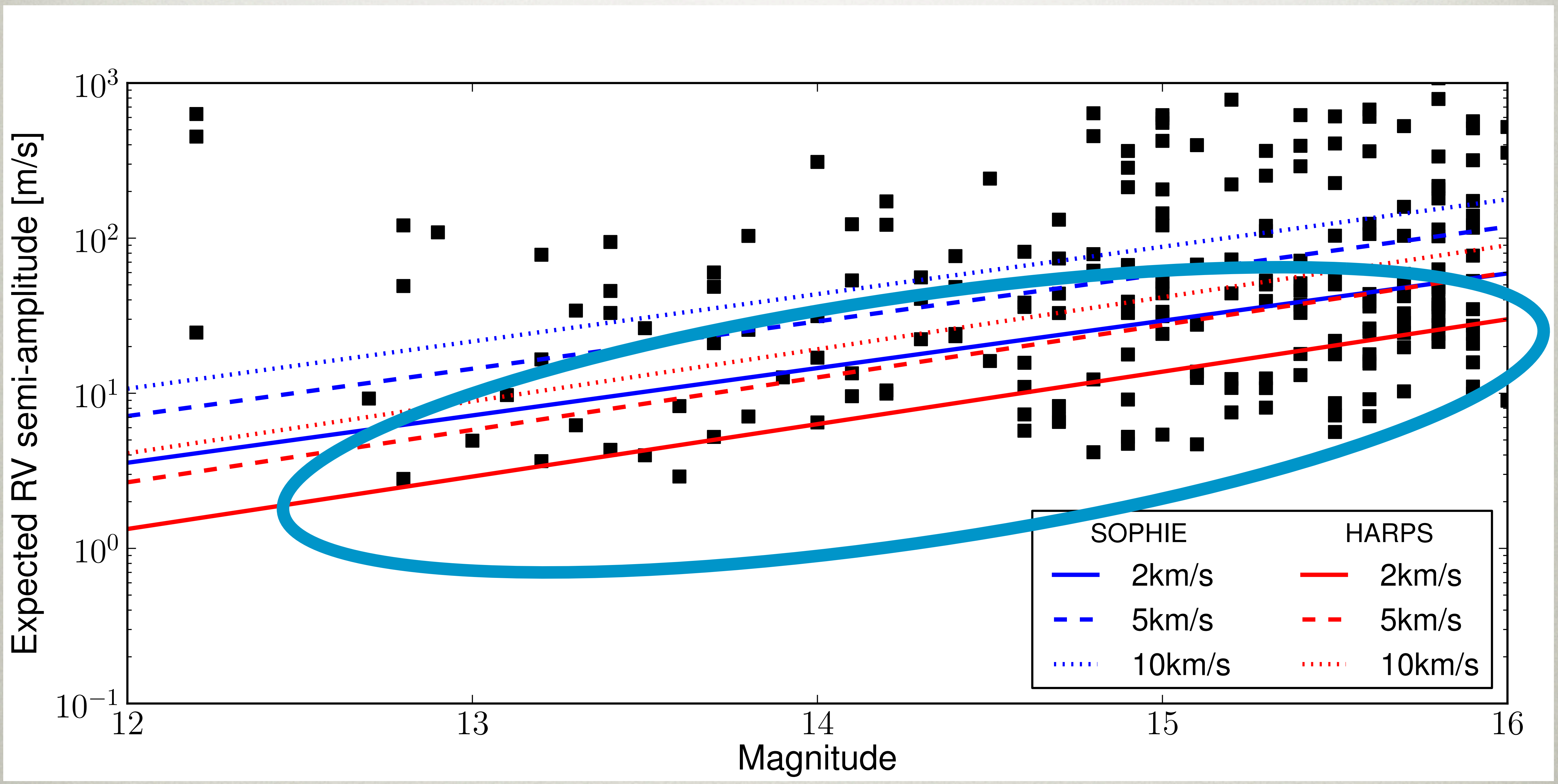
Outline

- The planet validation technique (Rodrigo)
- PASTIS: the method (Rodrigo)
- Constraints from radial velocity (Alexandre)
- Example of CoRoT candidates analyzed with PASTIS (José Manuel)
- Future/on going development (Alexandre)
- Conclusions

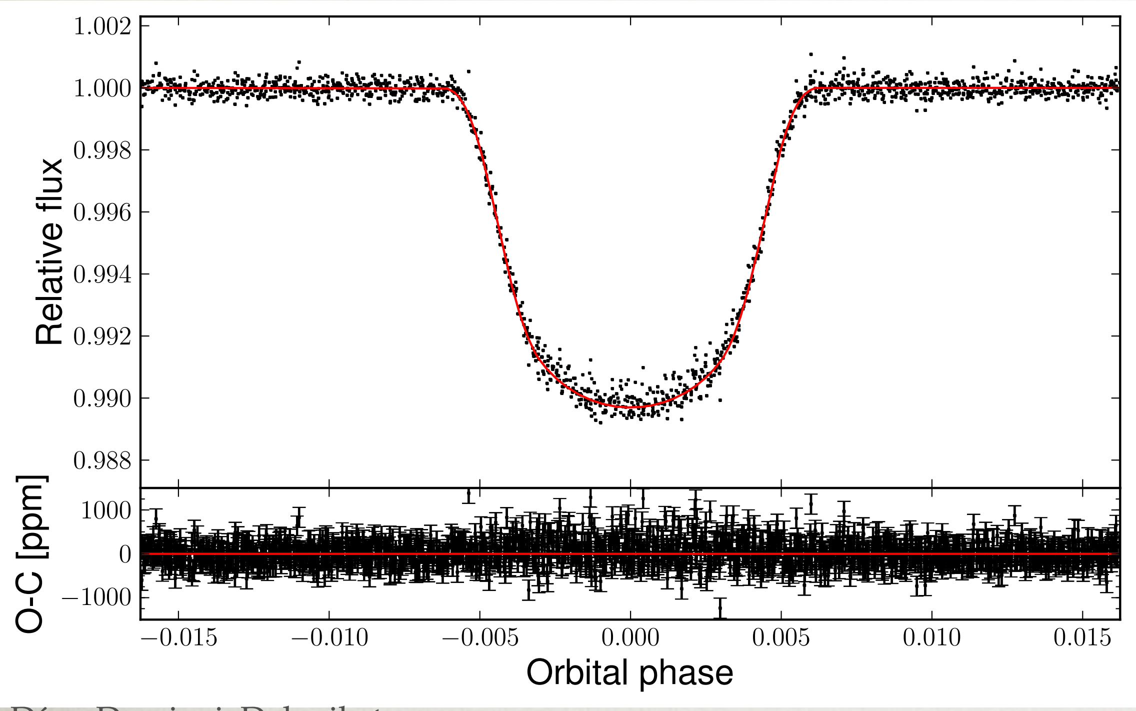
SMALL COROT CANDIDATES NEED PASTIS !



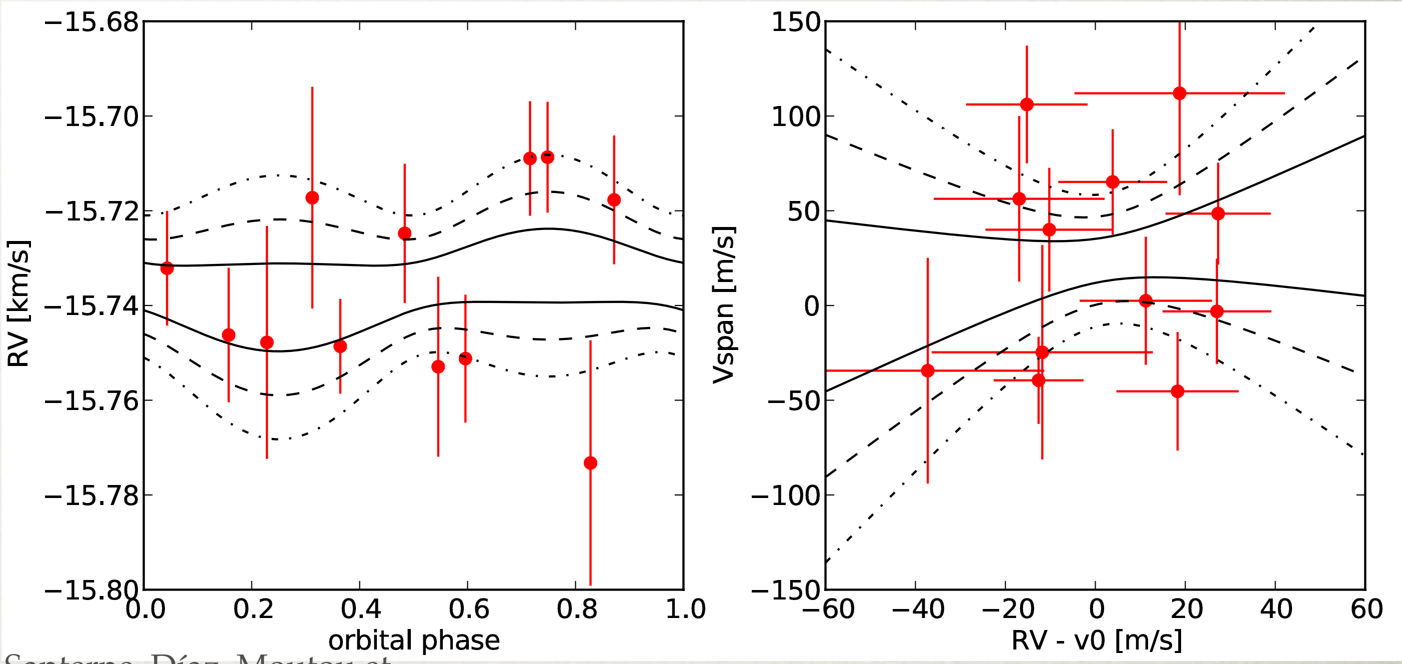
Small CoRoT candidates need PASTIS !



A typical problem



Díaz, Damiani, Deleuil et al. (2013)



Santerne, Díaz, Moutou et al. (2012)

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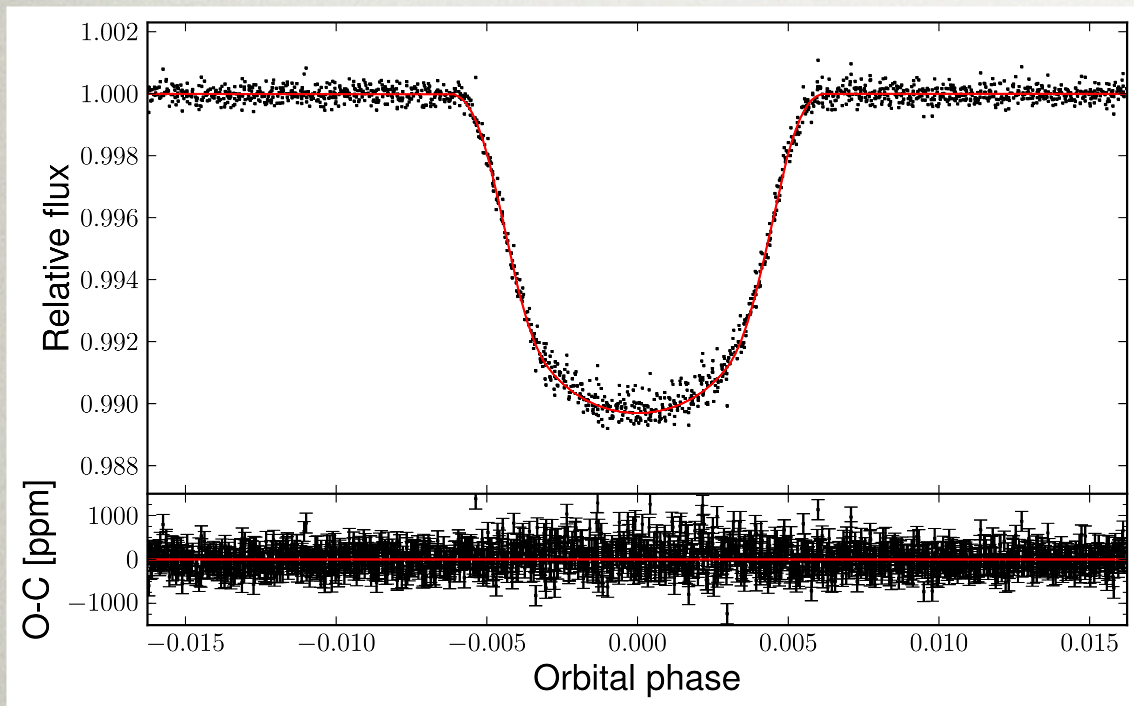

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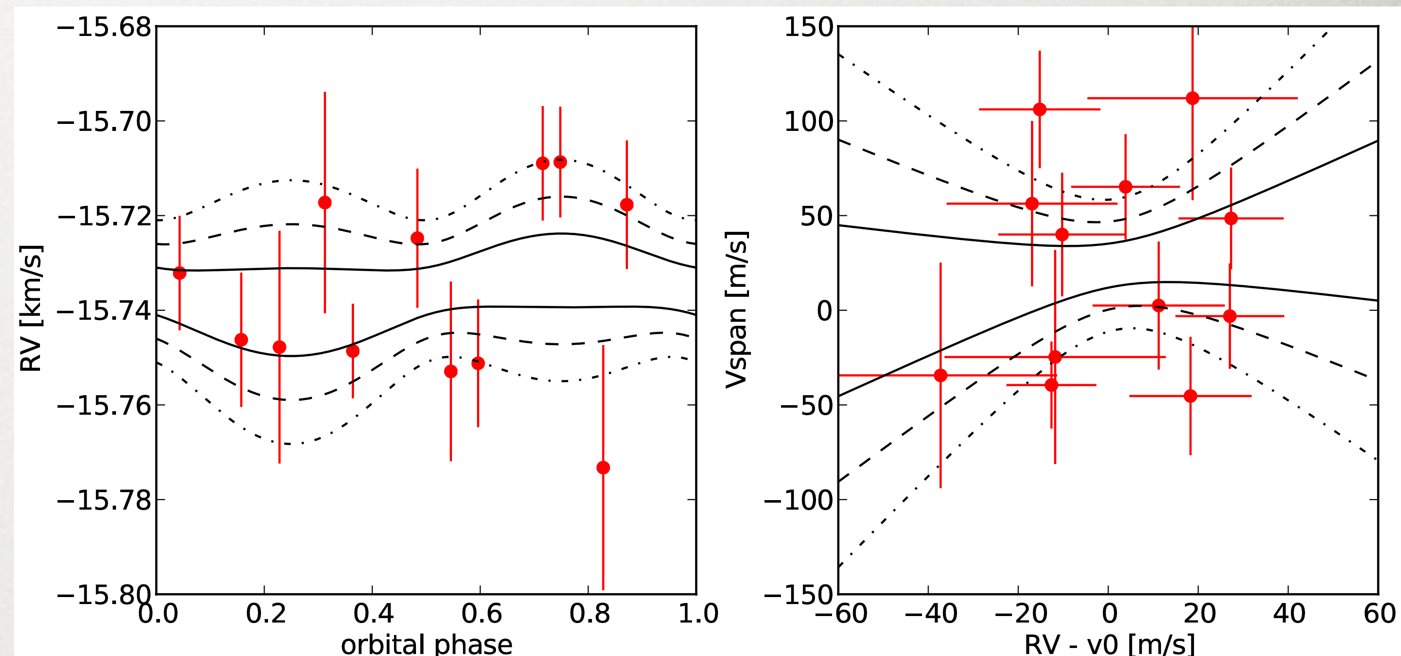
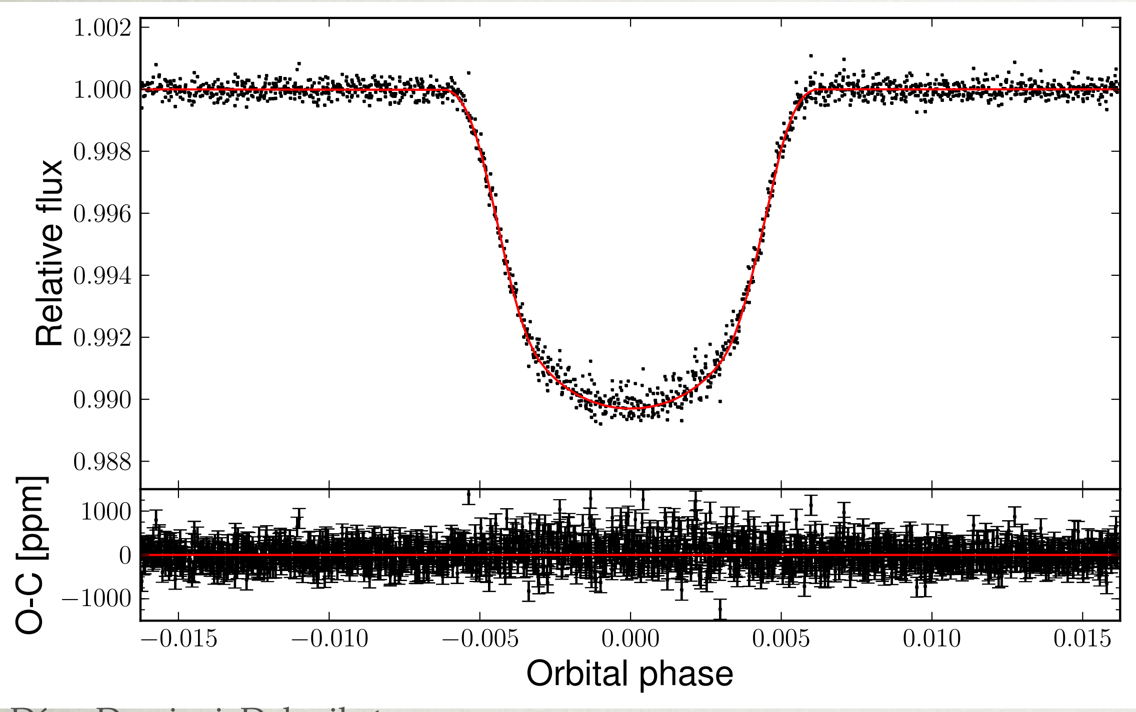


Santerne, Díaz, Moutou et al. (2012)

Is the transit due to a planet or to a diluted binary?

A typical problem



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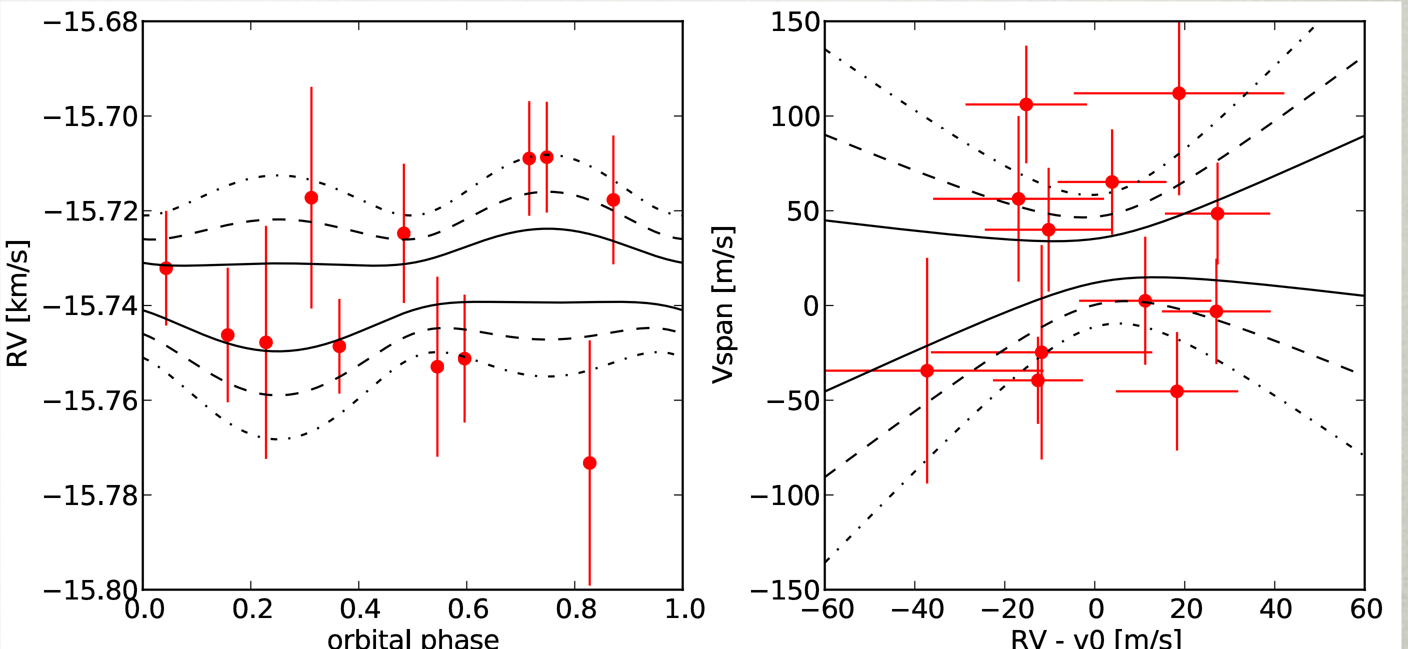
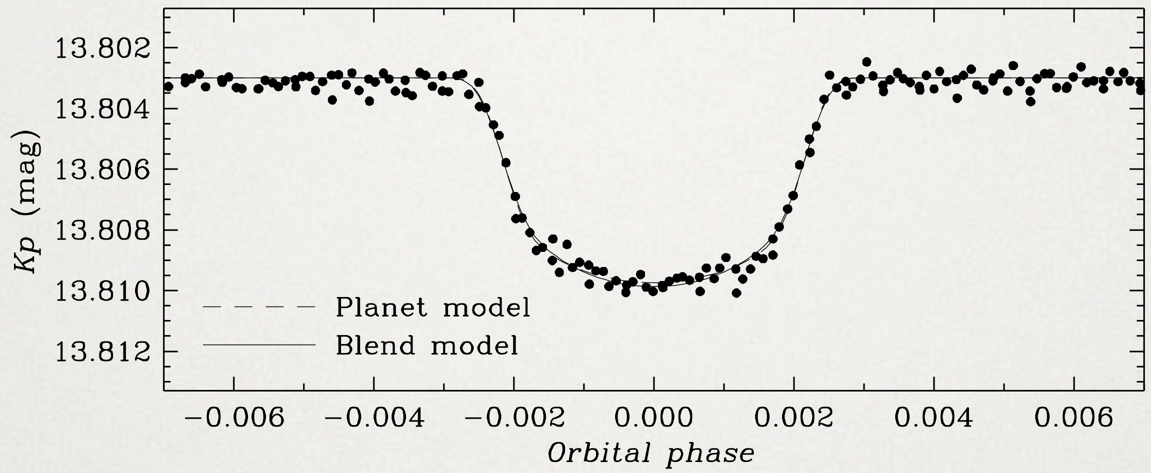


Santerne, Díaz, Moutou et al. (2012)

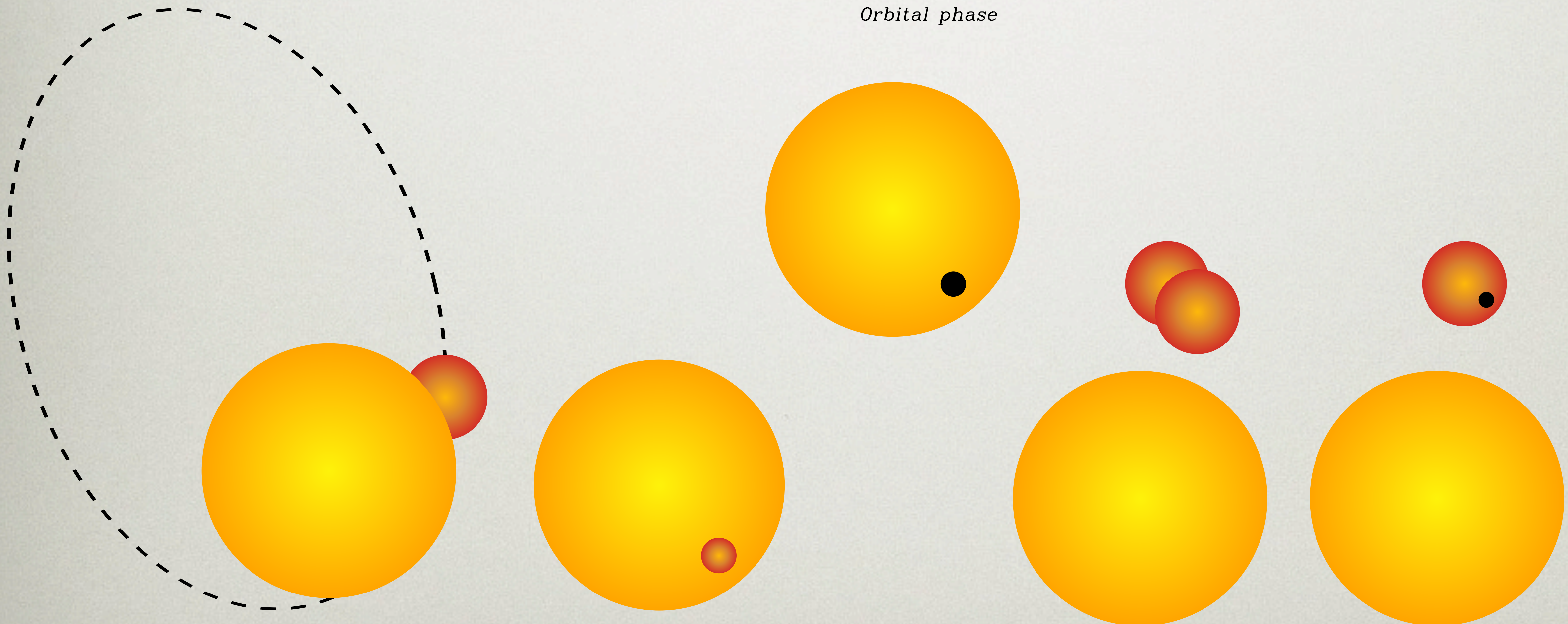
Is the transit due to a planet or to a diluted binary?

Compare model M_{pla} (planet) with M_{BEB} (bkg eclipsing binary).

False Positives



Kepler-9d
(Torres et al., 2010)



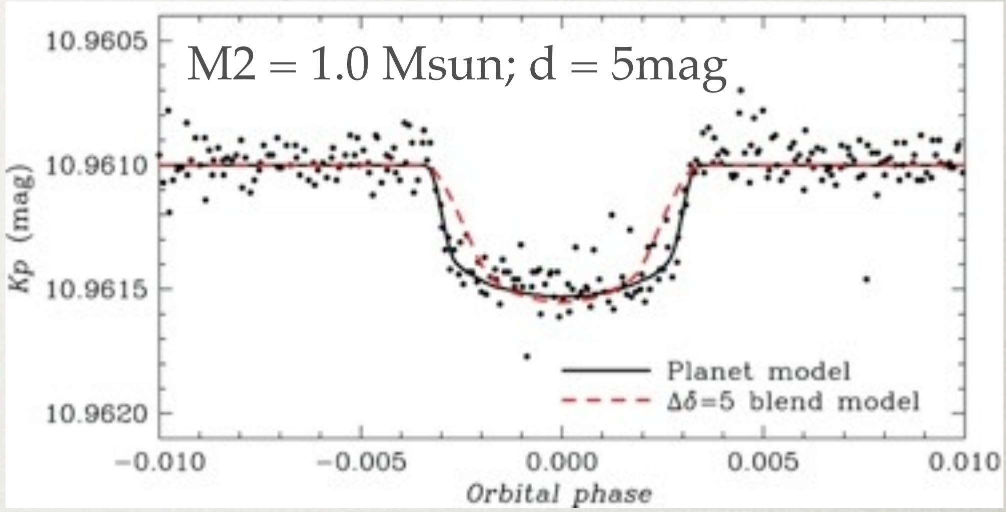
Undiluted scenarios

Diluted scenarios

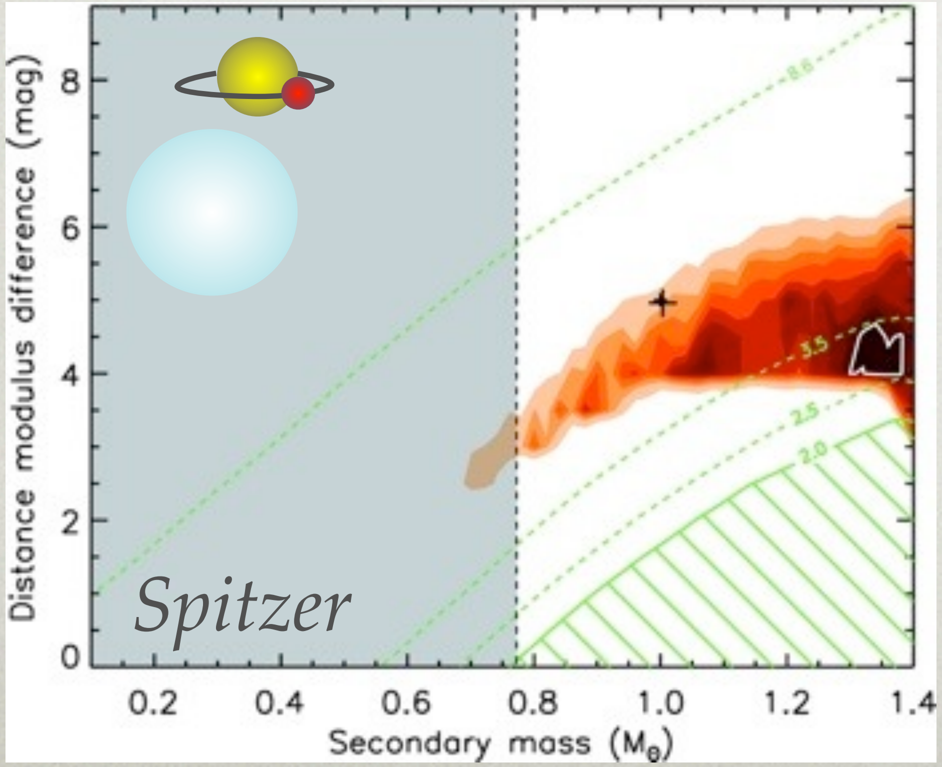
Planet Validation (to the rescue)

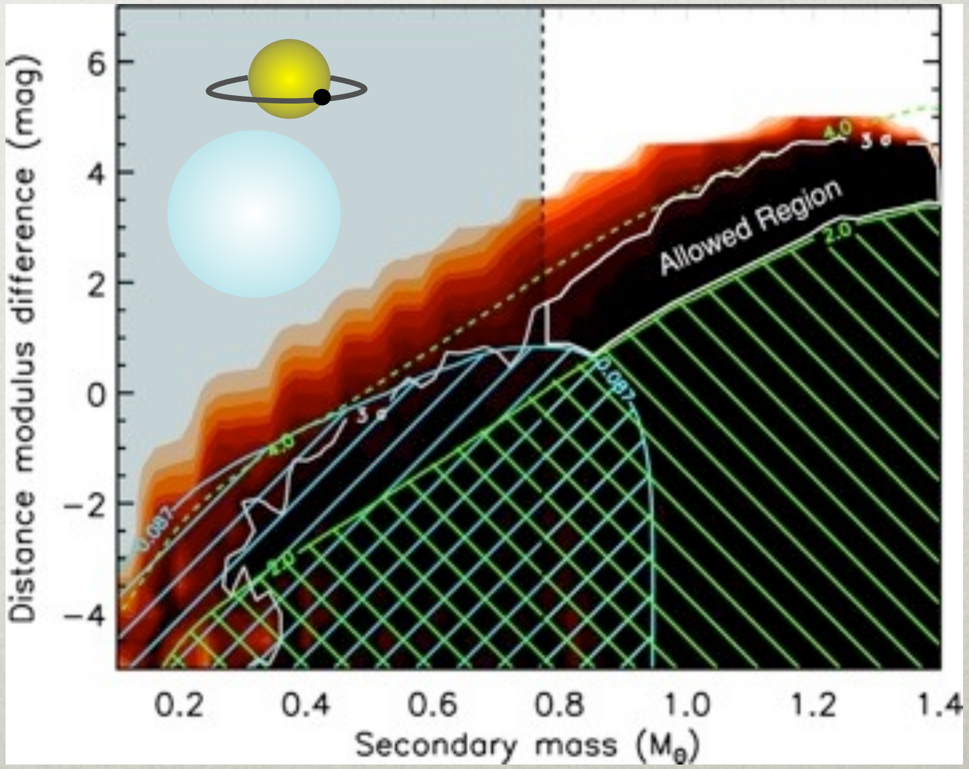
- Use all the information in the transit LC to constrain possible false positives (FPs).
- Add additional constrains from other datasets: RV, AO, multi-band photometry, ...

Kepler-10 c

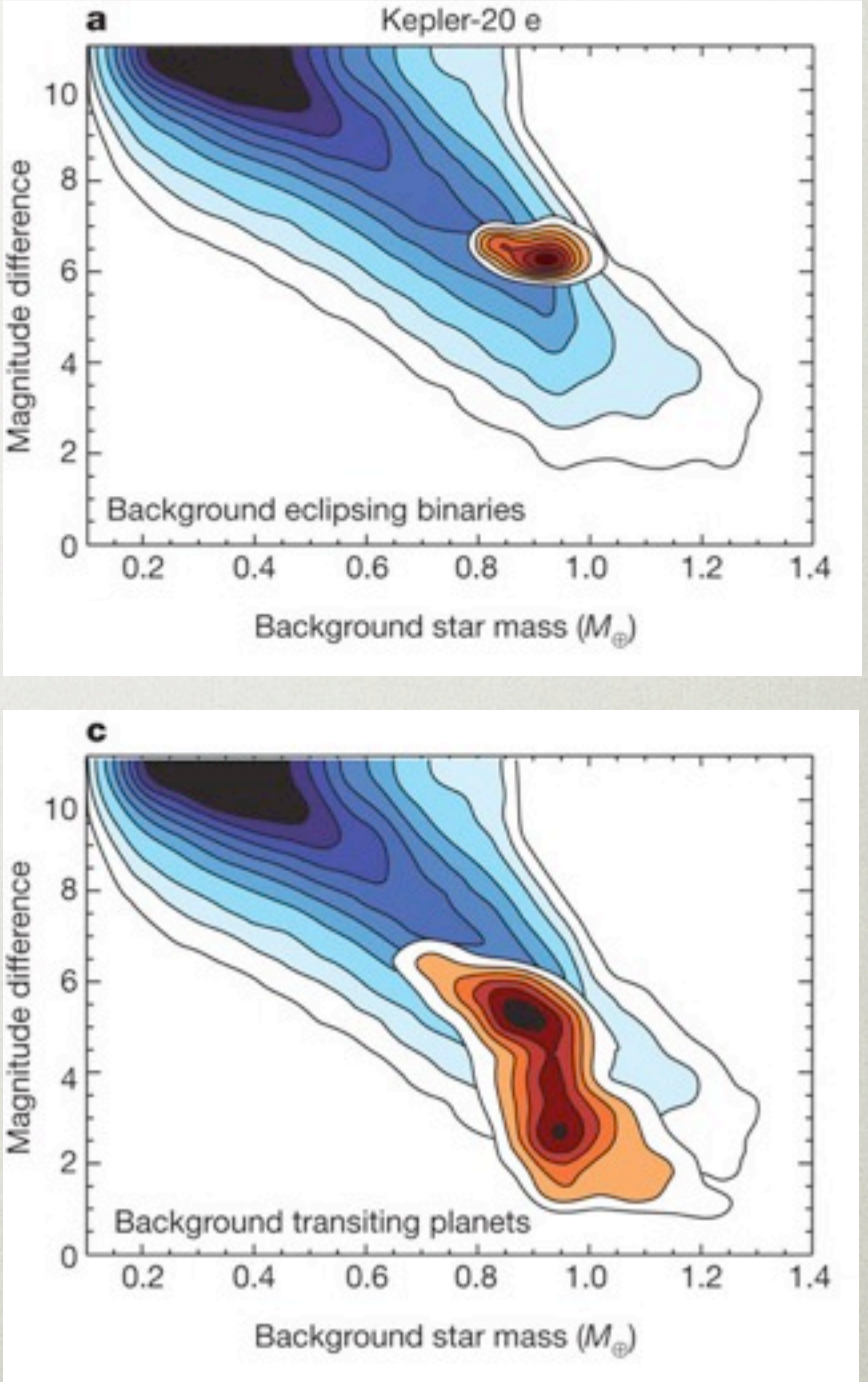


Fressin et al. (2011)





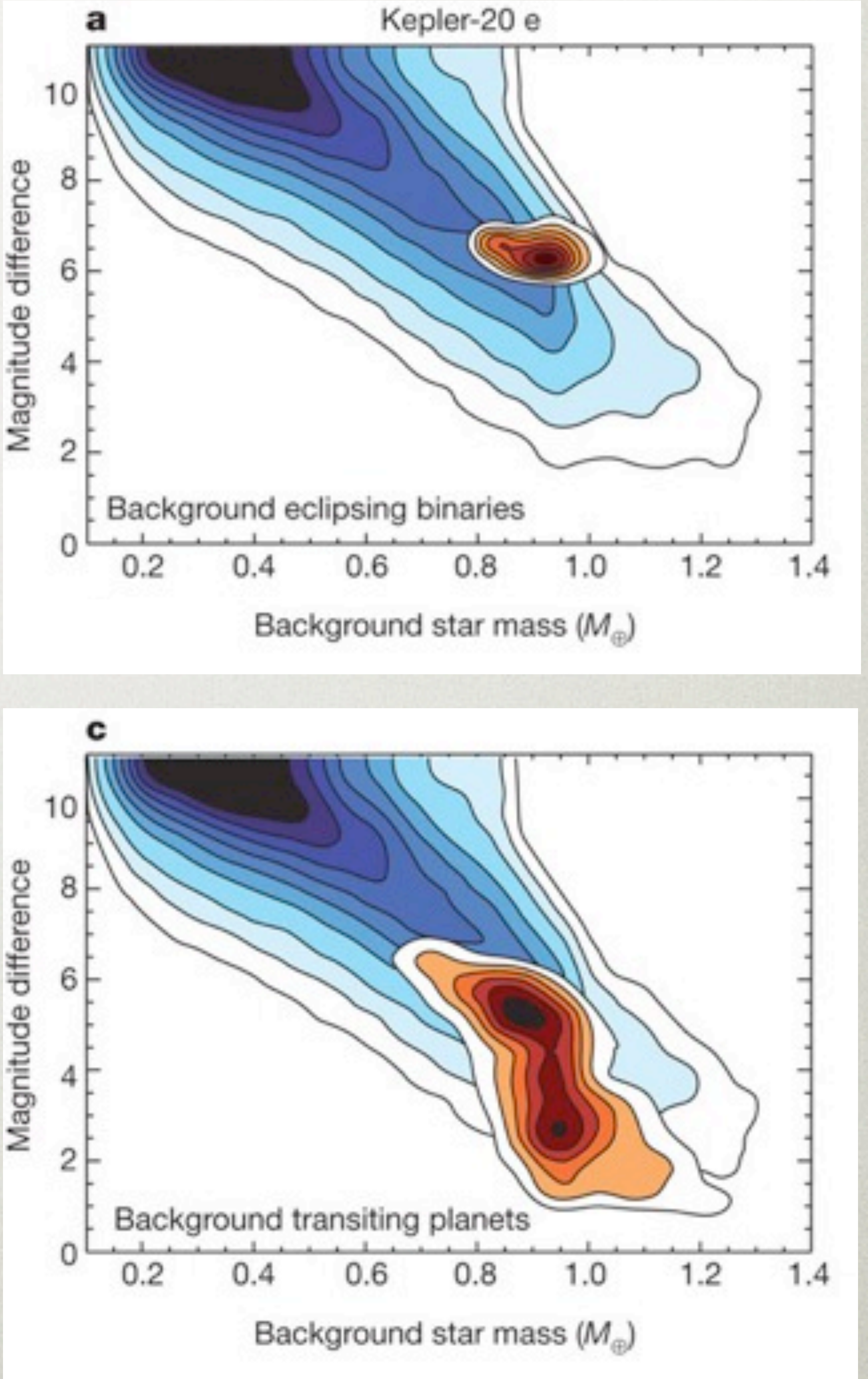
Planet Validation (to the rescue)



Fressin et al. (2012)

Planet Validation (to the rescue)

- Evaluate relative occurrence of planets to surviving blends.
  - use Galactic structure models or catalogs.
  - prior knowledge on planet occurrence rate.



Fressin et al. (2012)

Planet Validation (to the rescue)

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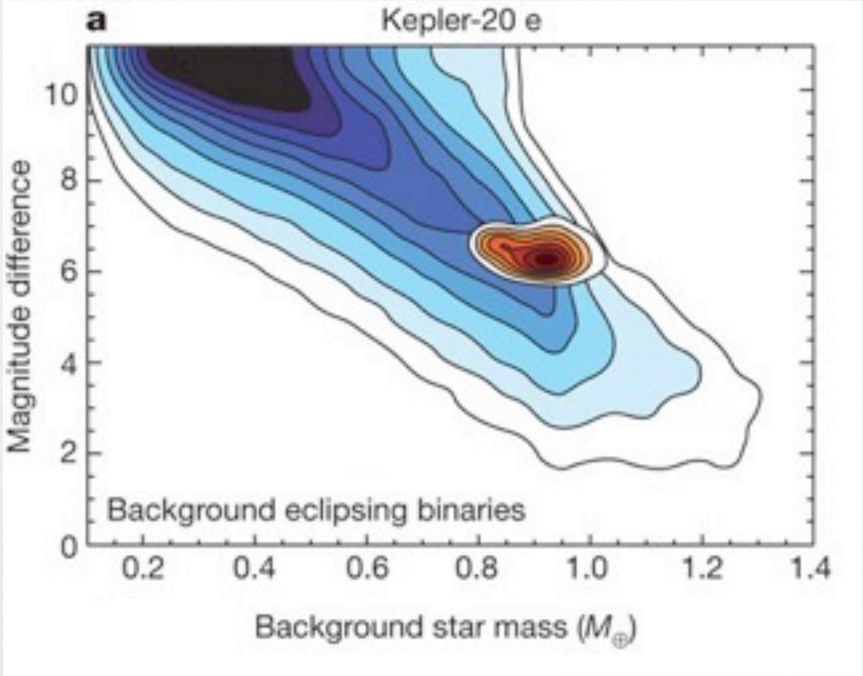
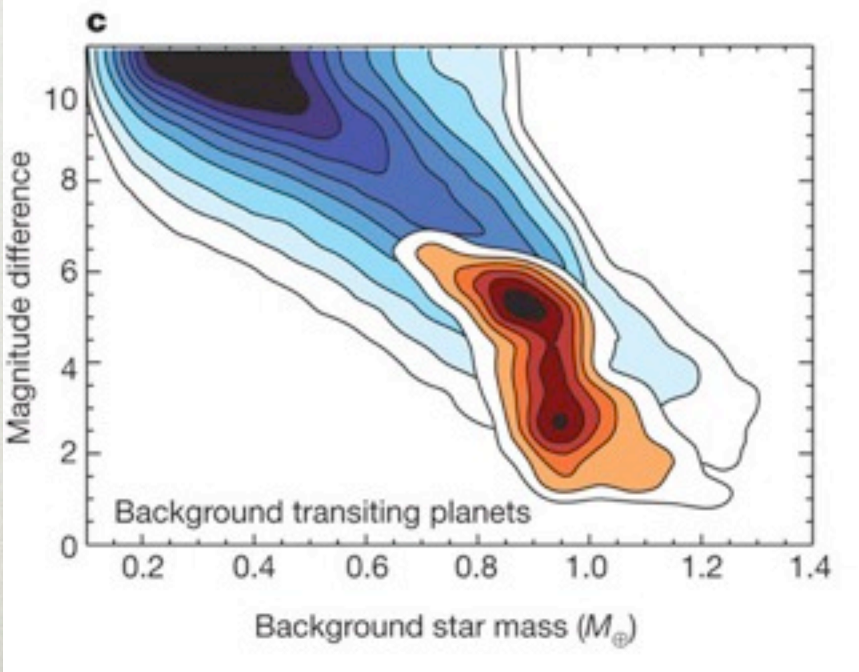
- Validate planet if

  P(planet) >> P(FP)





Fressin et al. (2012)

Planet Validation (to the rescue)

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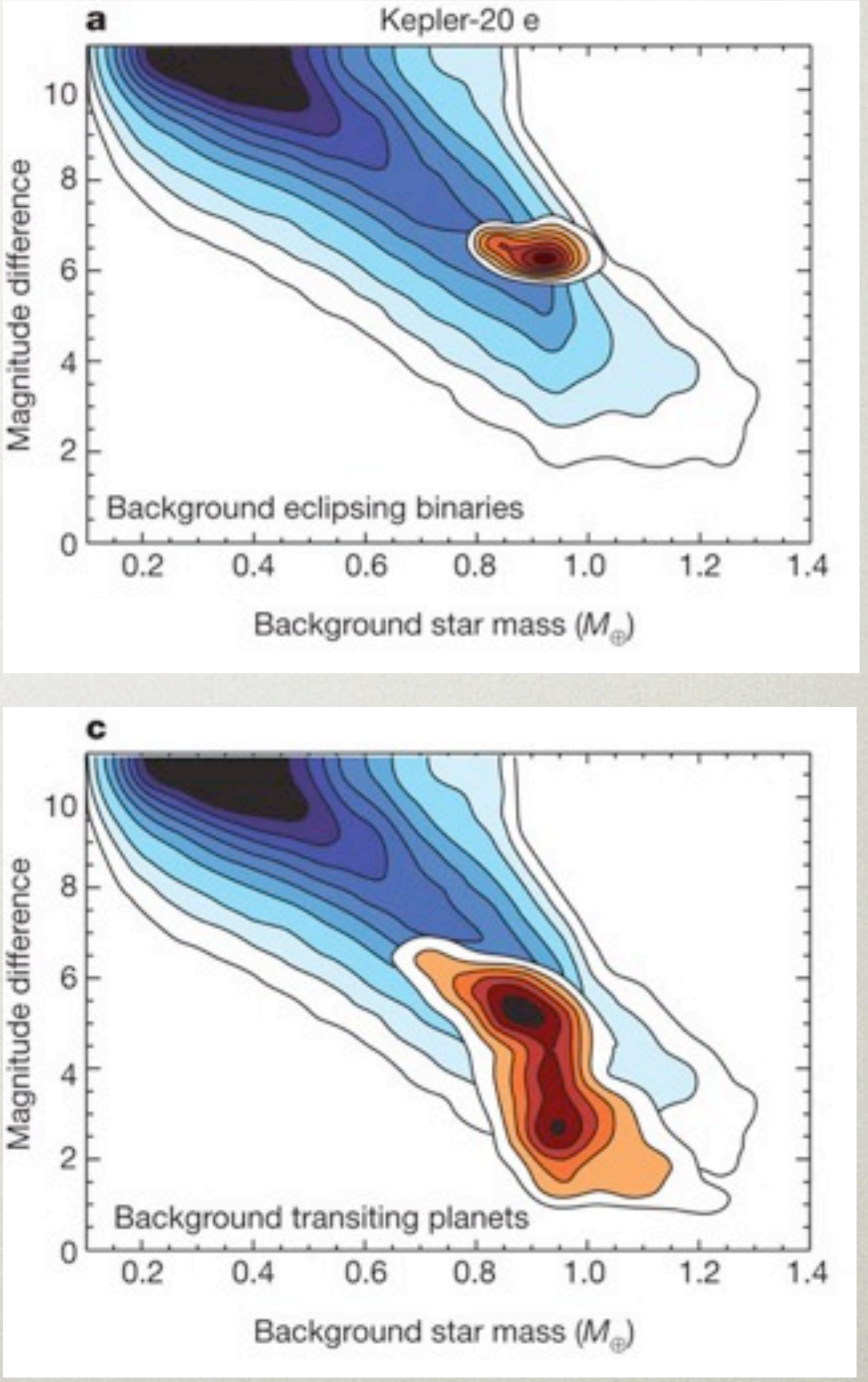
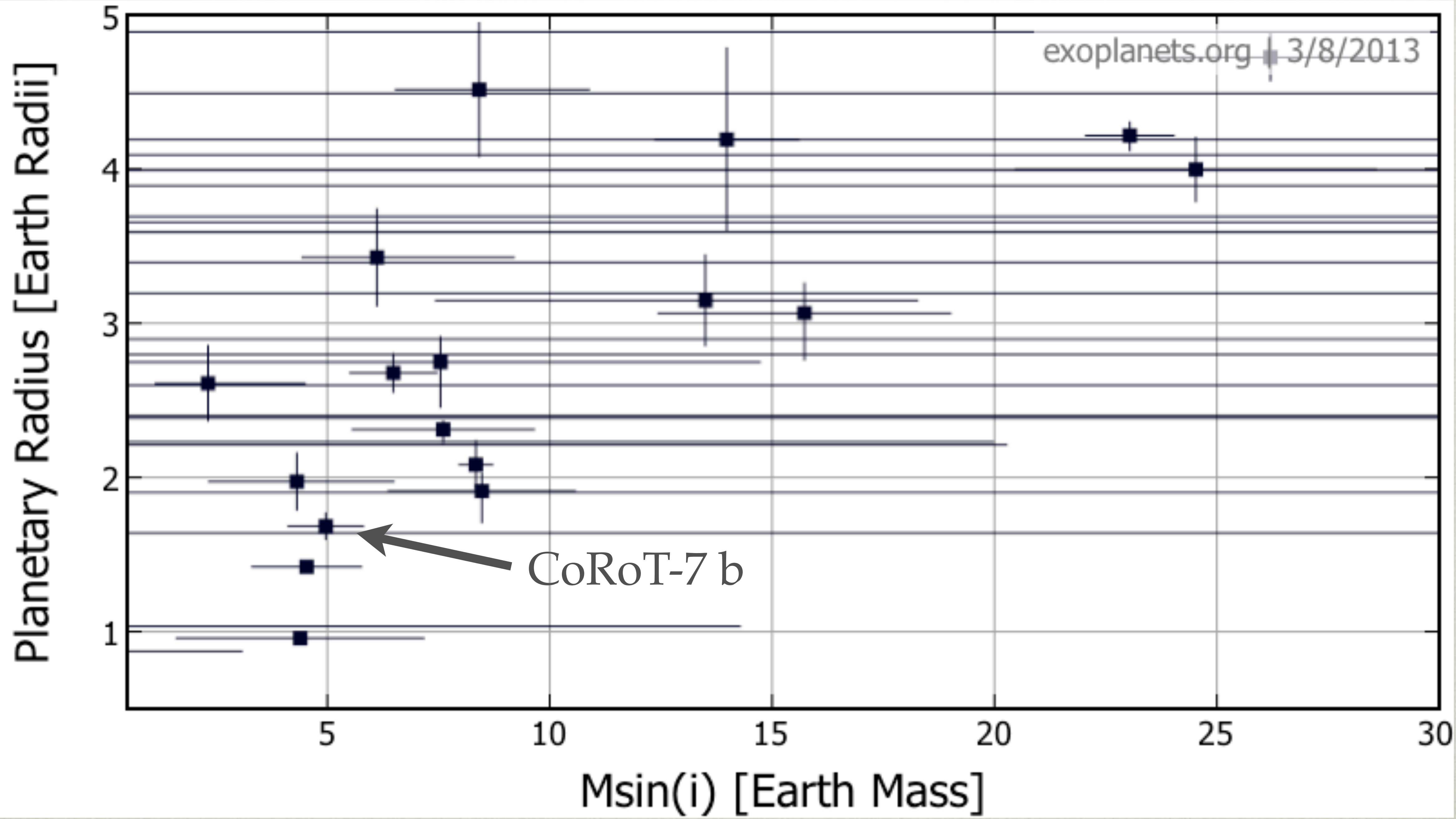
- Result: new planet (but no mass measurement).



Fressin et al. (2012)

Planets without mass



BLENDER: room for improvement

BLENDER: the *Kepler* solution to planet validation

— External constraints not considered rigorously (no self-consistent fit).

— Use of “home-made” statistics. Might work but not yet proven. Mix of frequentist and bayesian approach.

— Grid evaluation of likelihood

- — Limited number of parameters.
- — Impractical for large samples.

Our solution...

PASTIS

Planet Analysis & Small Transit Investigation Software

More, better, faster, ... and independently

Bayesian Basics

Model comparison is done based on the **odds ratio**

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D},\mathrm{I})}{p(\mathrm{H_j}|\mathrm{D},\mathrm{I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i},\mathrm{I})}{p(\mathrm{D}|\mathrm{H_j},\mathrm{I})}$$

Model prior ratio

Bayes' factor

Hypothesis must be described by a model M

$$p(D|M) = \int d\theta \; p(\theta|M)p(D|\theta, M) = \mathcal{L}(M).$$

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- $\mathrm{H_i}$ can also be thought of as a model with a certain *value* of a given parameter. In that case, $\{\mathrm{H_i}\}$ is an infinite, continuous set.
- Methods exist to take samples from the posterior when the computation cannot be done analytically. MCMC is one of these methods.

Planet Analysis and Small Transit Investigation Software

Light curves
(*Kepler*, *CoRoT*, *Spitzer*, ...)

Radial velocities
RV, Bisector, FWHM
(HARPS, SOPHIE)

Spectral Energy Distribution
(SDSS, 2MASS, WISE, ...)

Model prior
(Binaries prop., planets prop., ...)

PASTIS

MCMC / PCA

Parameters for scenario:
- planet
- binary
- triple
-...

Stellar evolution tracks, SAM
(Dartmouth, Geneva, ...)

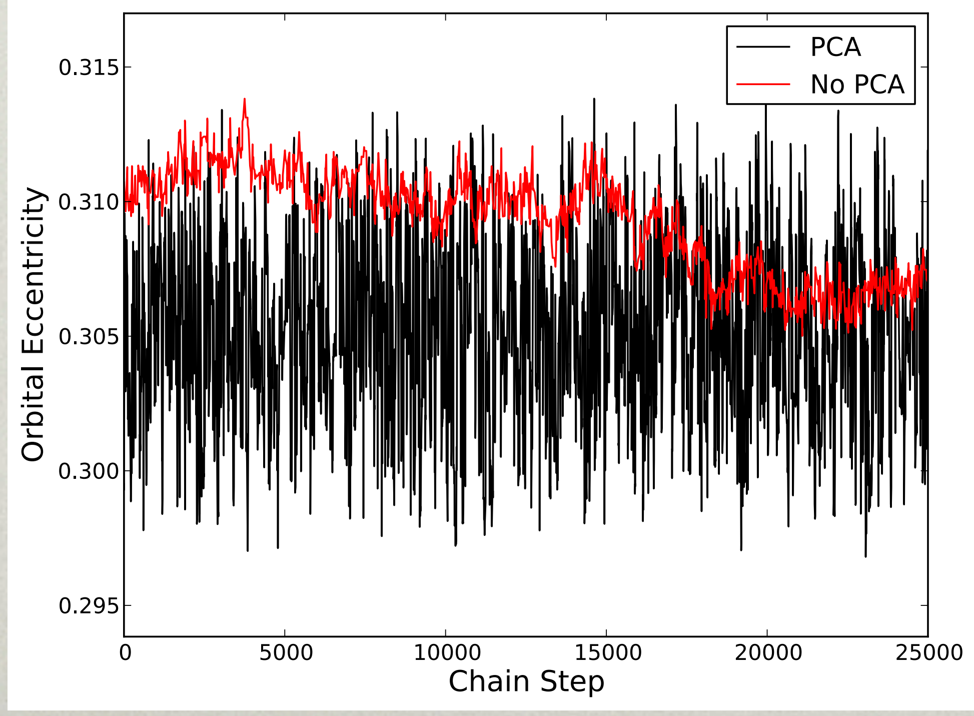
$$\frac{\mathcal{P}(H_i|D,I)}{\mathcal{P}(H_j|D,I)} = \frac{\mathcal{P}(H_i|I)}{\mathcal{P}(H_j|I)} \cdot \frac{\mathcal{P}(D|H_i,I)}{\mathcal{P}(D|H_j,I)}$$

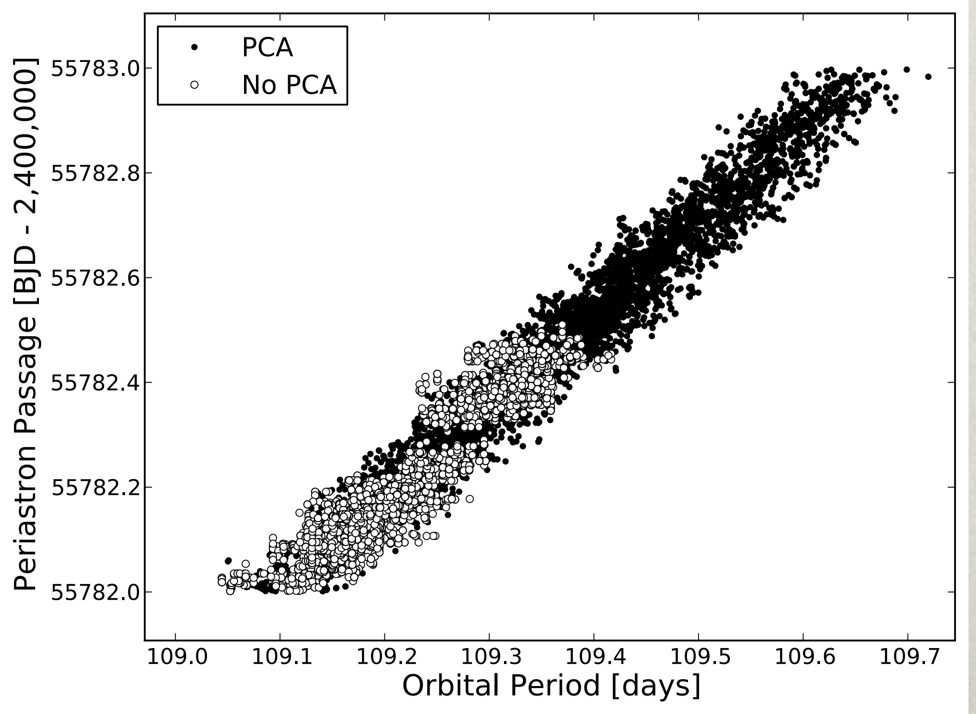
Díaz et al. (in prep.), Santerne et al. (in prep.)

developped par J.-M. Almenara, R. Díaz & A. Santerne

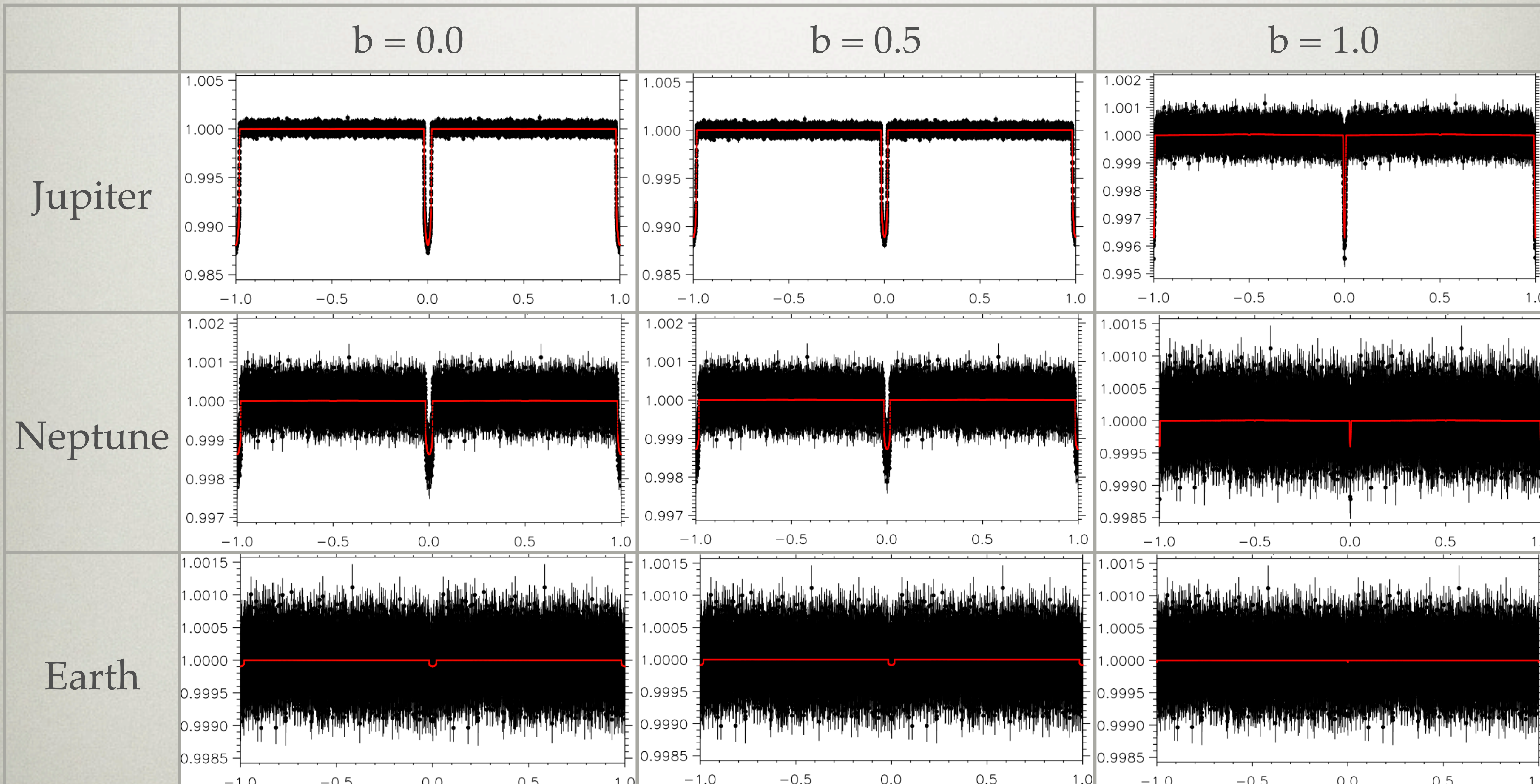
Planet Analysis and Small Transit Investigation Software

- Markov Chain Monte Carlo.
  - Efficient sampling of the parameter posterior. No time wasted on regions of poor fit.
  - Practically unlimited number of parameters (current record: 68 for CoRoT-7; see Susana's talk on Thursday).
  - Caveats (convergence, multiple minima, correlations) dealt with.

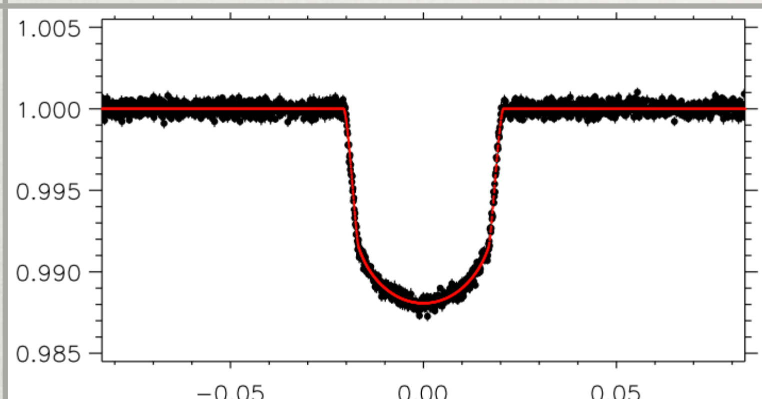
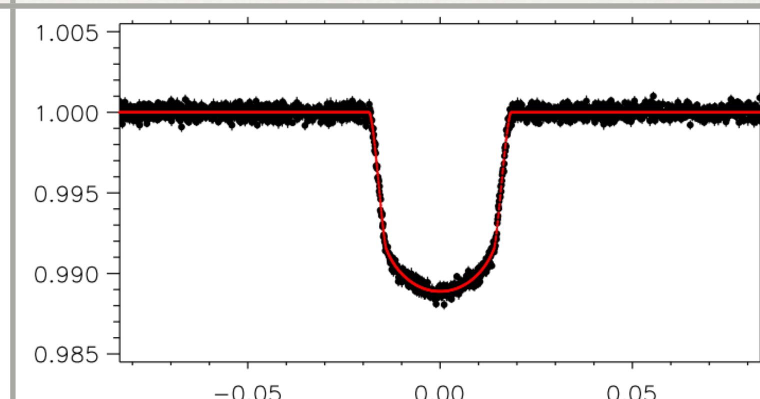
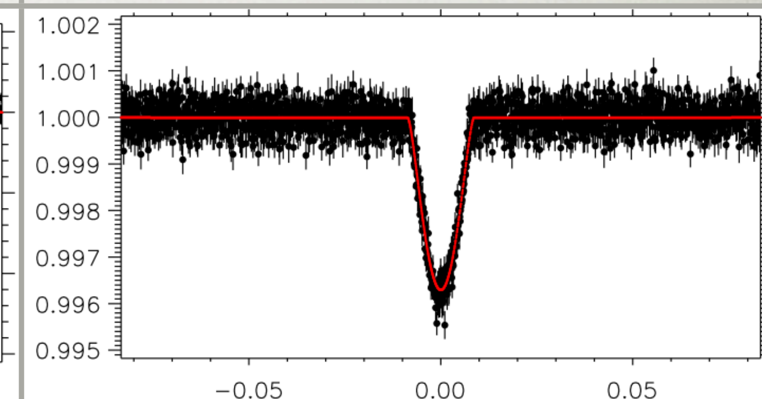
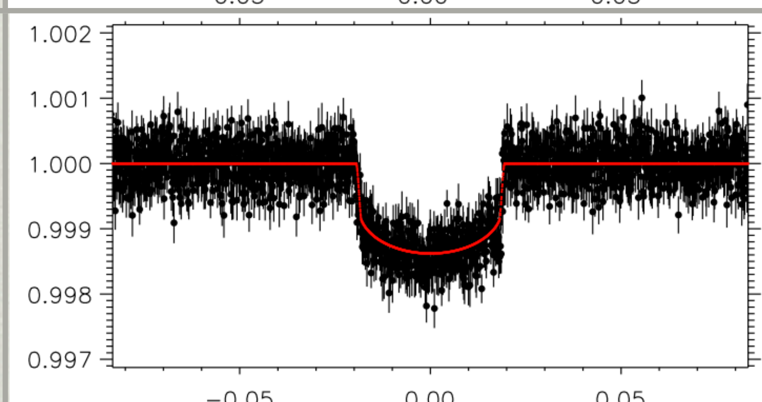
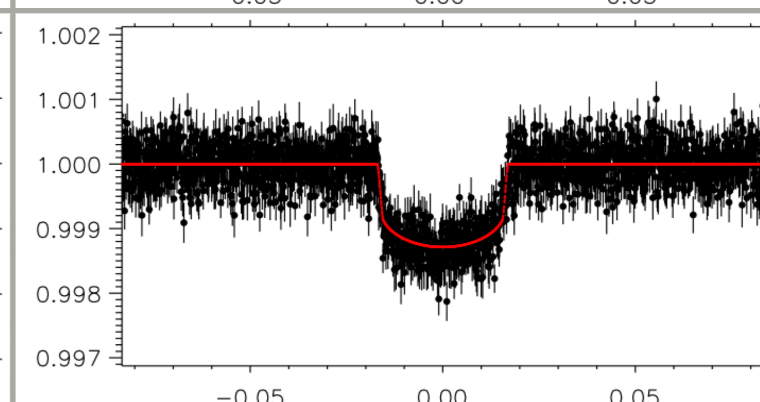
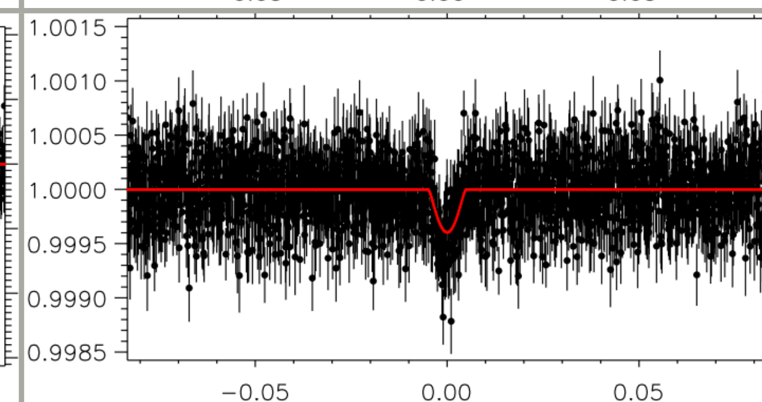
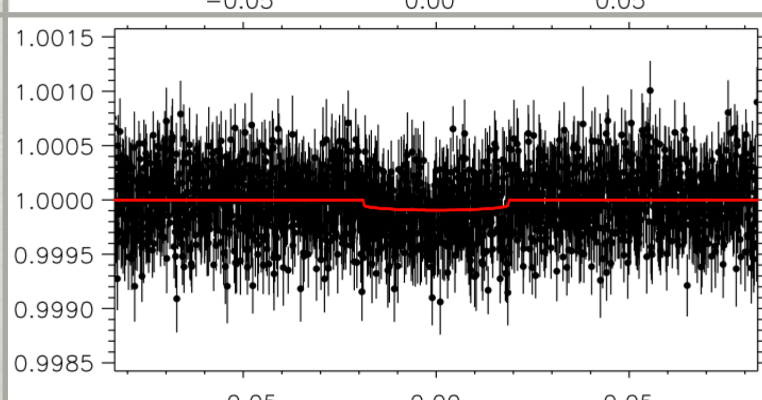
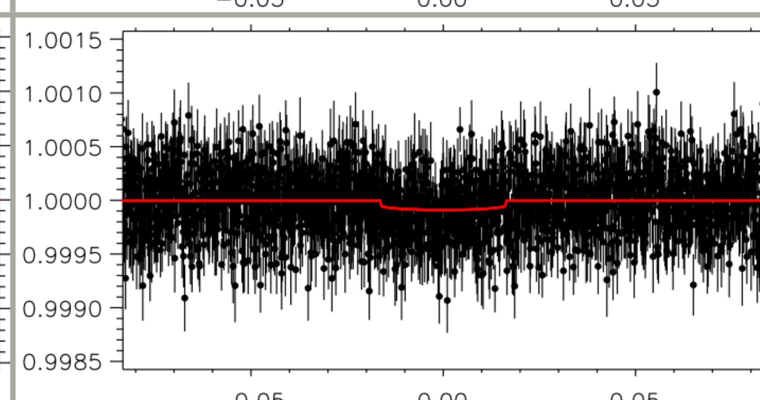
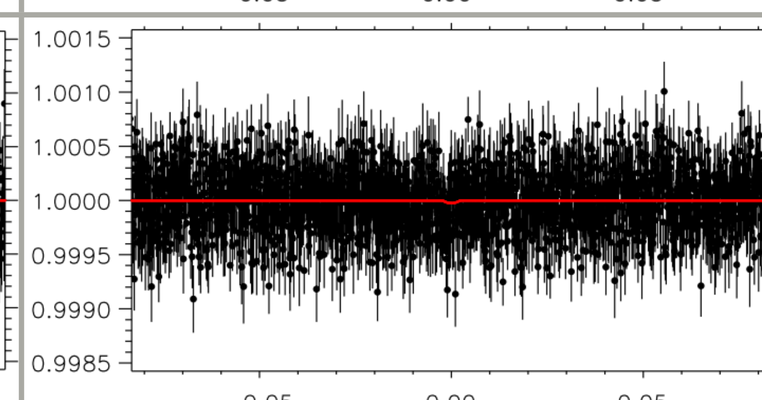




PASTIS: Testing performance



PASTIS: Testing performance

	b = 0.0	b = 0.5	b = 1.0
Jupiter			
Neptune			
Earth			

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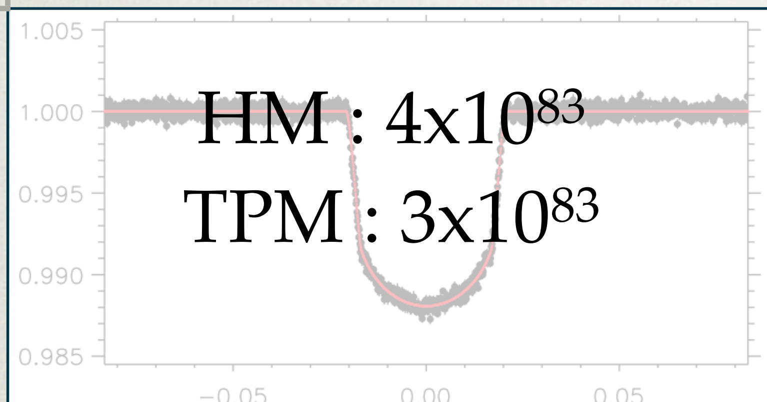
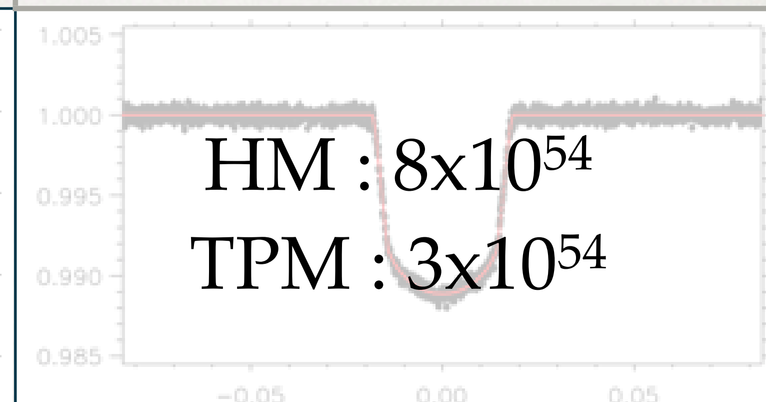
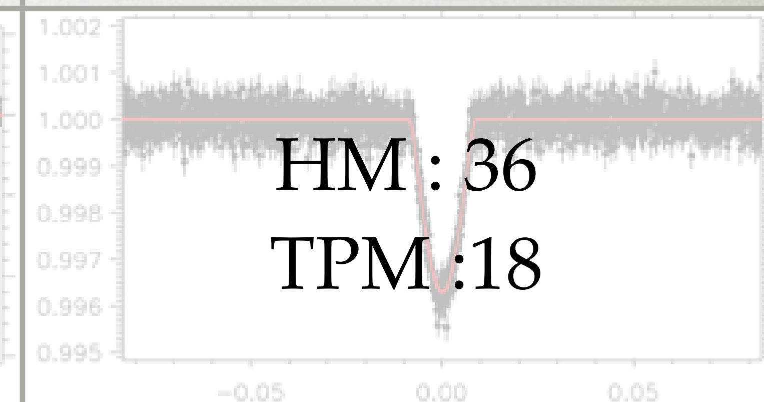
Jupiter	 HM : $4x10^{83}$ TPM : $3x10^{83}$	 HM : $8x10^{54}$ TPM : $3x10^{54}$	 HM : 36 TPM :18

PASTIS: Testing performance

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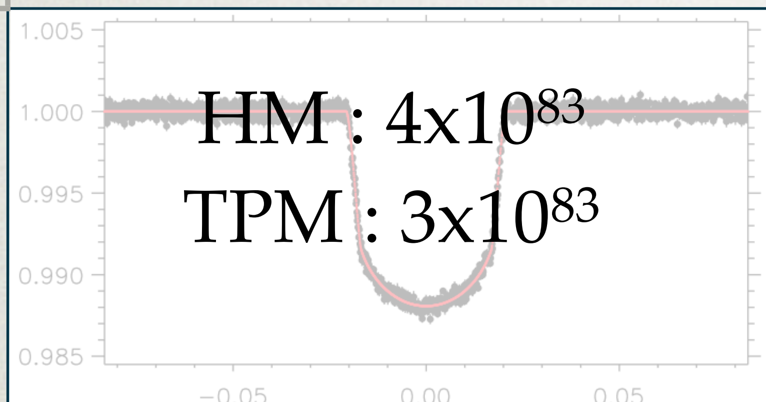
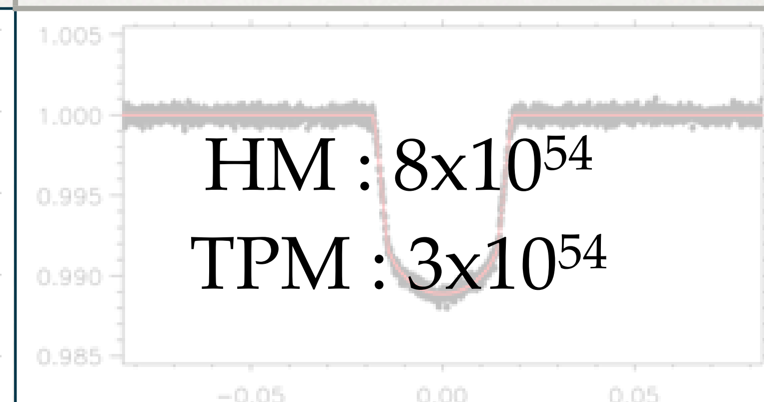
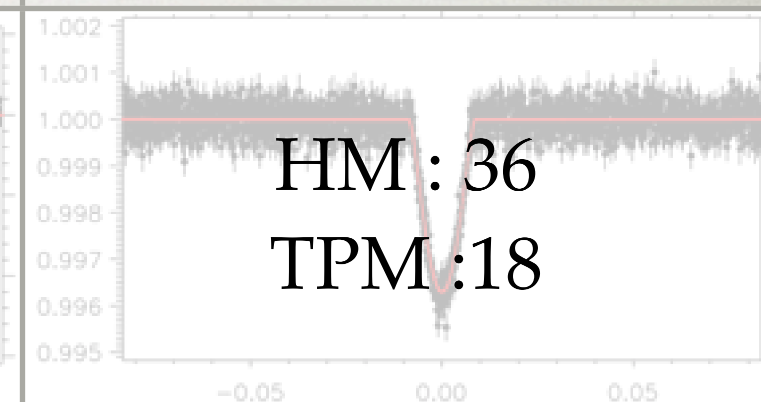
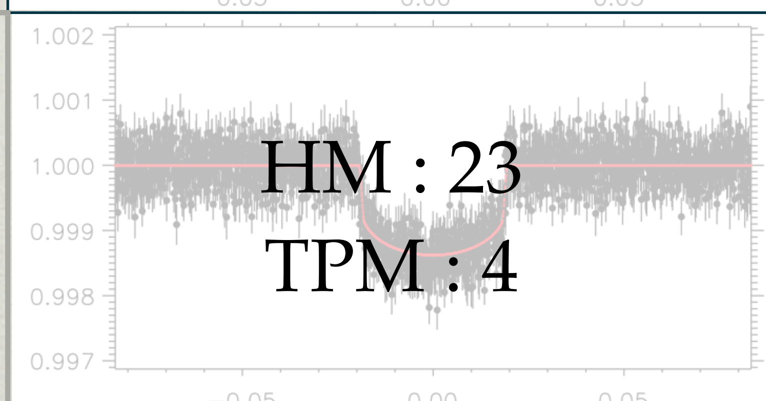
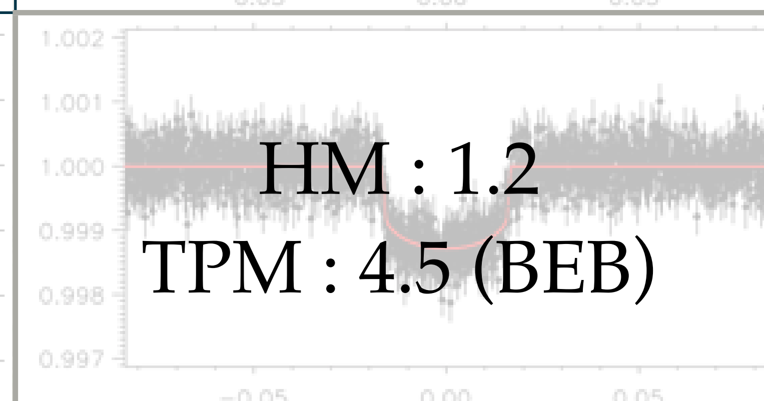
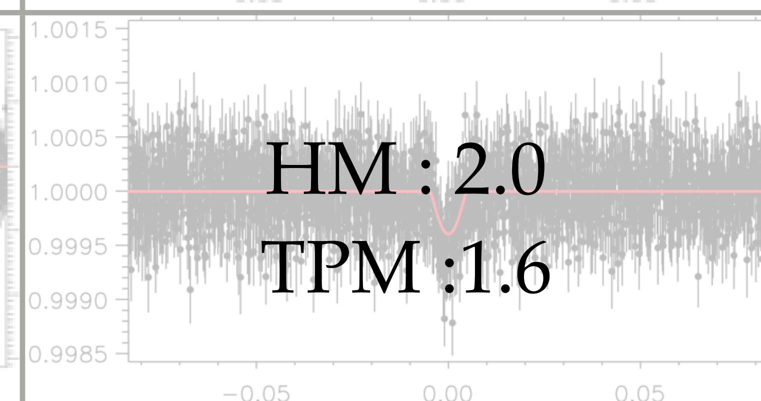
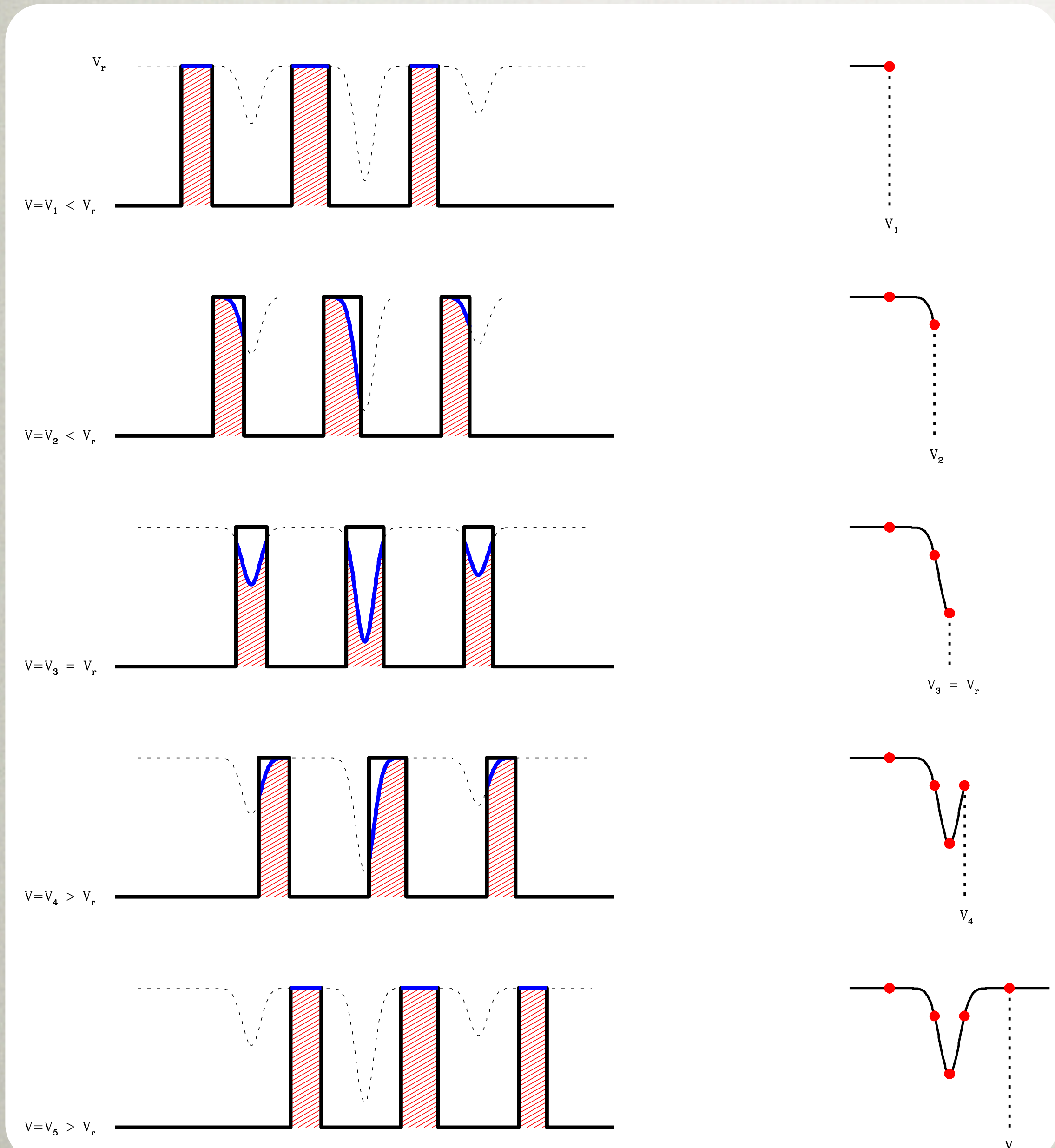
Jupiter	 HM : $4\text{x}10^{83}$ TPM : $3\text{x}10^{83}$	 HM : $8\text{x}10^{54}$ TPM : $3\text{x}10^{54}$	 HM : 36 TPM :18
Neptune	 HM : 23 TPM : 4	 HM : 1.2 TPM : 4.5 (BEB)	 HM : 2.0 TPM :1.6

PASTIS: Testing performance

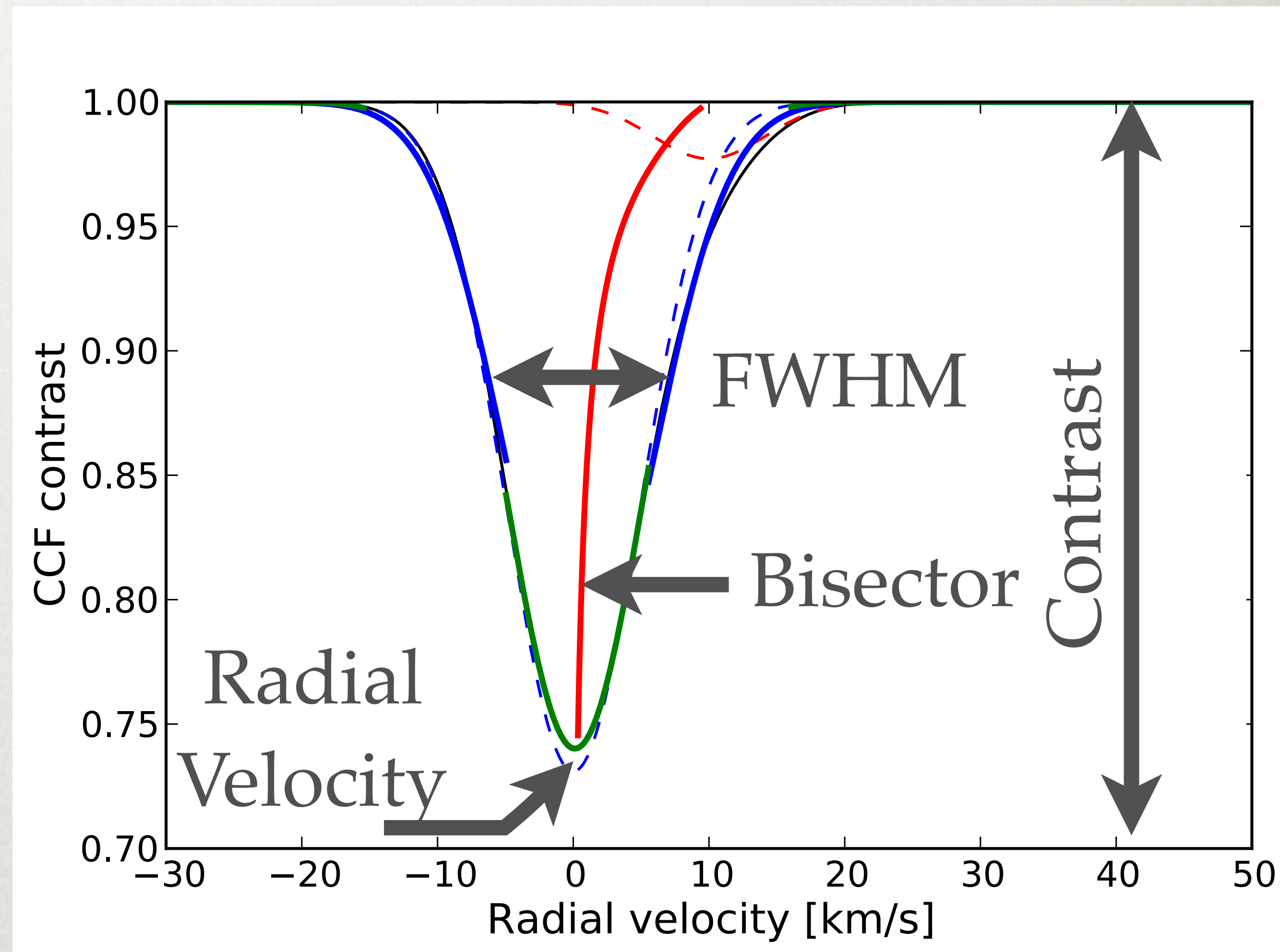
	b = 0.0	b = 0.5	b = 1.0
Jupiter	HM : 4×10^{83} TPM : 3×10^{83}	HM : 8×10^{54} TPM : 3×10^{54}	HM : 36 TPM :18
Neptune	HM : 23 TPM : 4	HM : 1.2 TPM : 4.5 (BEB)	HM : 2.0 TPM :1.6
Earth	HM : 30 (BEB) TPM : 16 (BEB)	HM : 11 (BEB) TPM : 35 (BEB)	HM : 2.6 (BEB) TPM : 1.4 (BEB)

Radial Velocity CCF



Melo (2001)

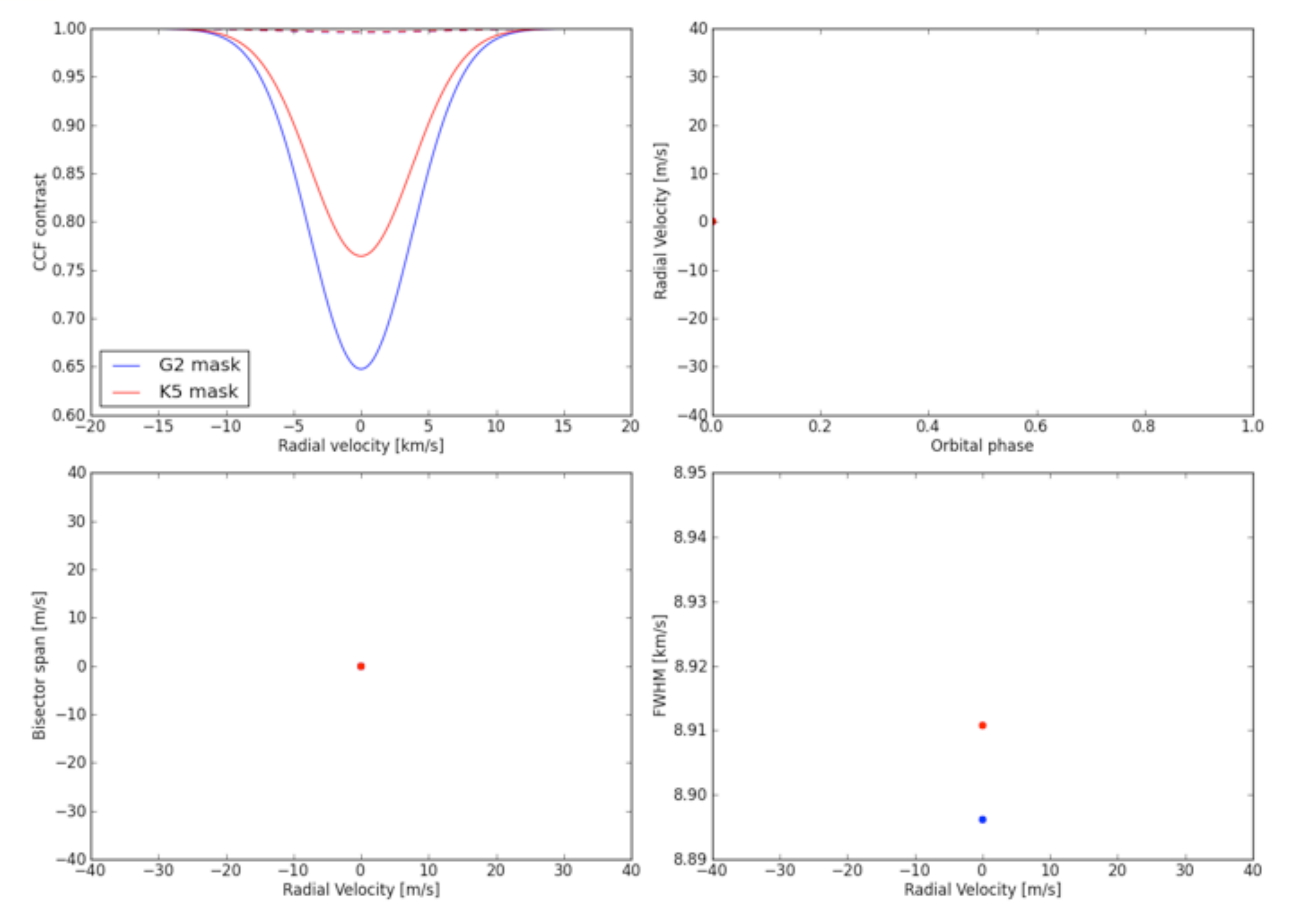
Mask: F0, G2, K0, K5, M5, ...



Radial Velocity constraints

Santerne et al. (in prep.)

Radial Velocity constraints



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Constraining possible blend scenarios

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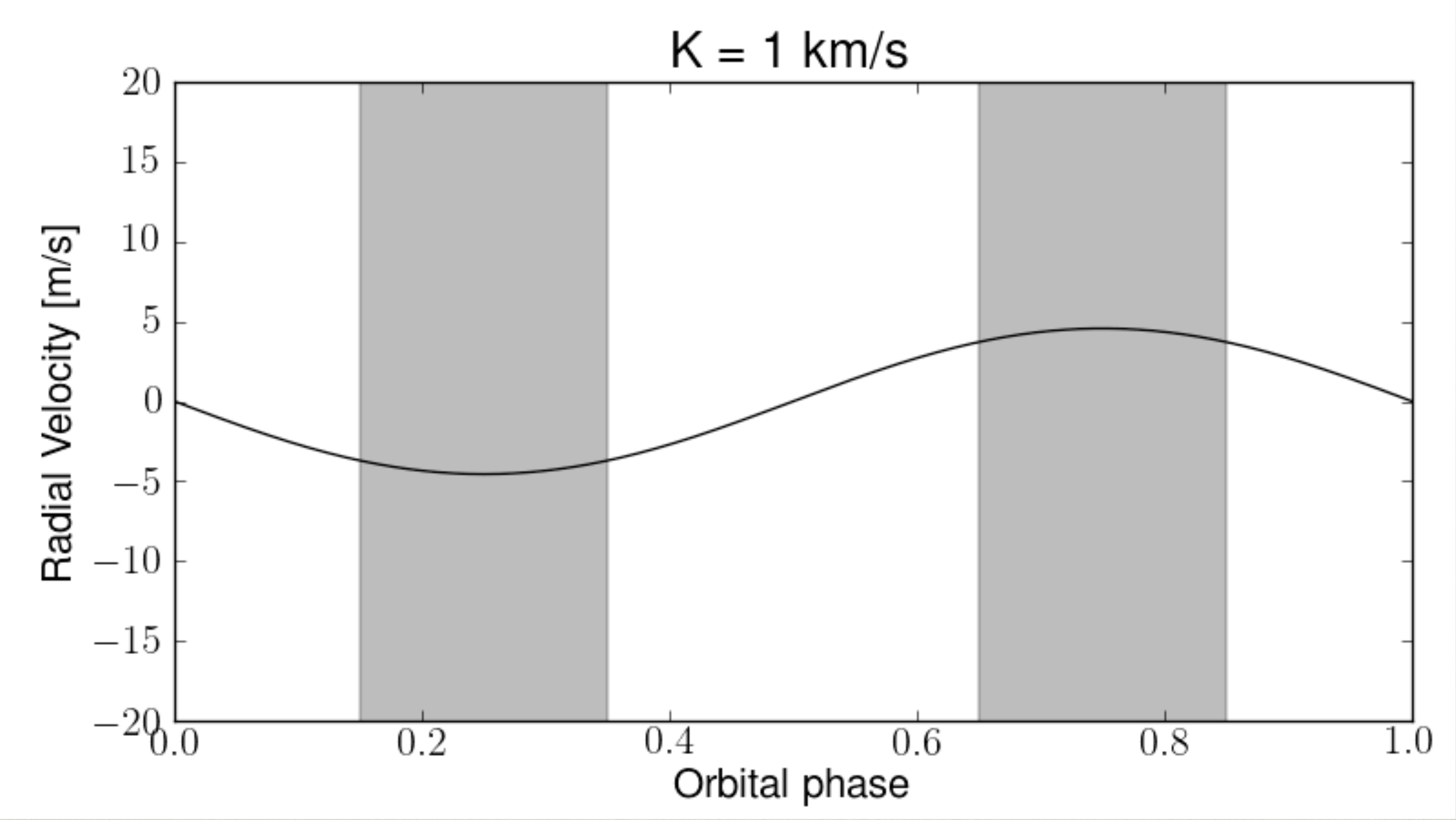
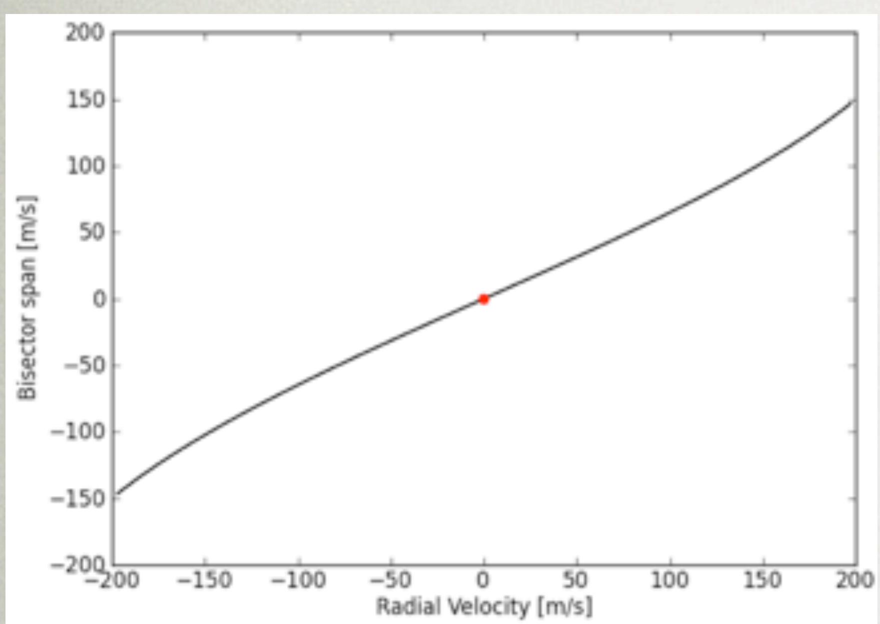
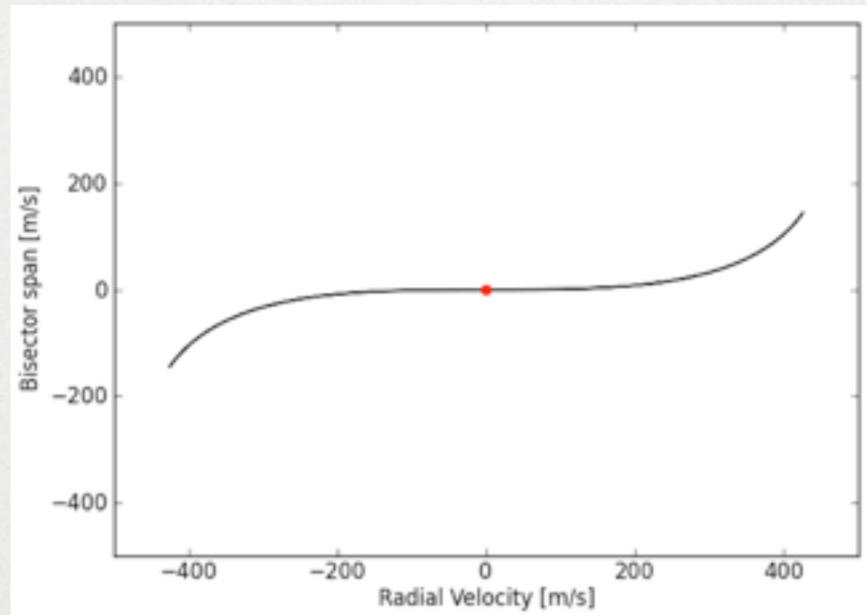
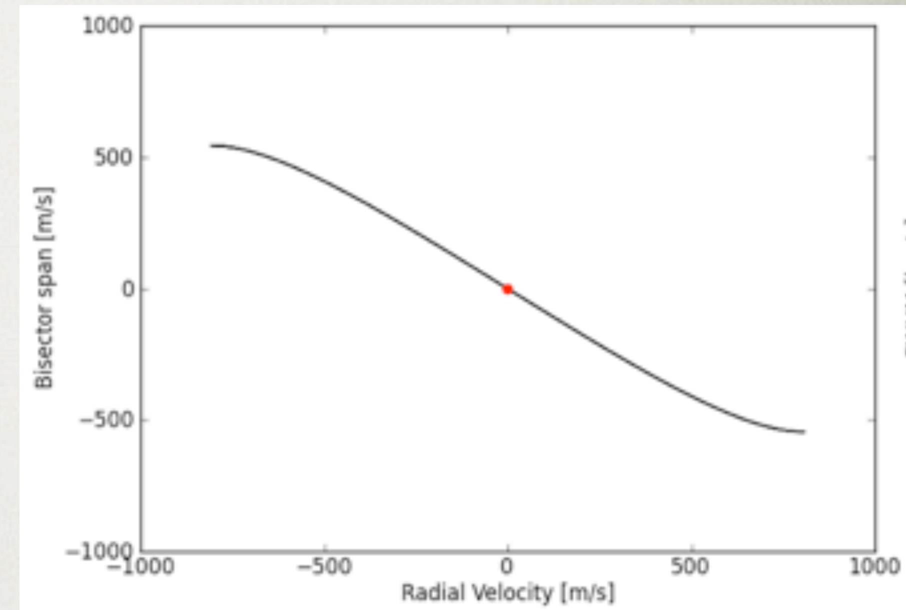


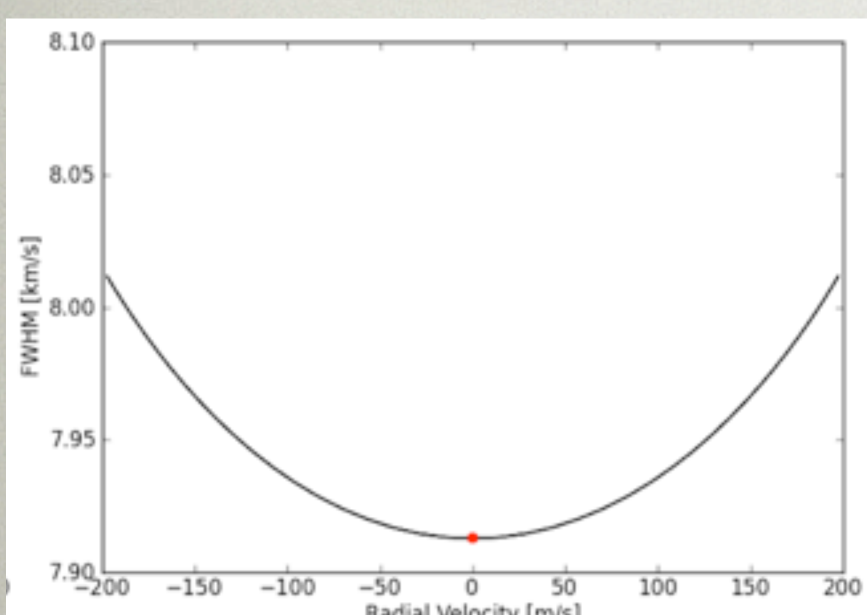
Influence of vsini on CCF diagnosis

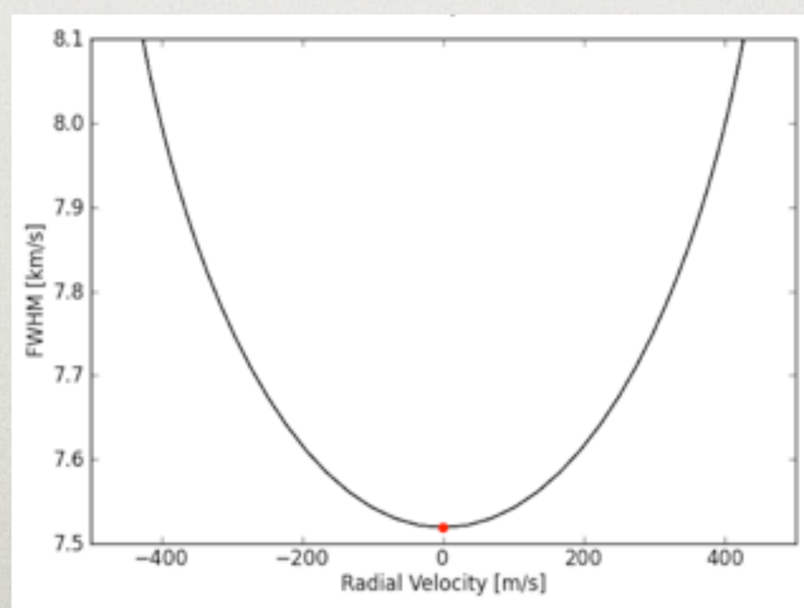


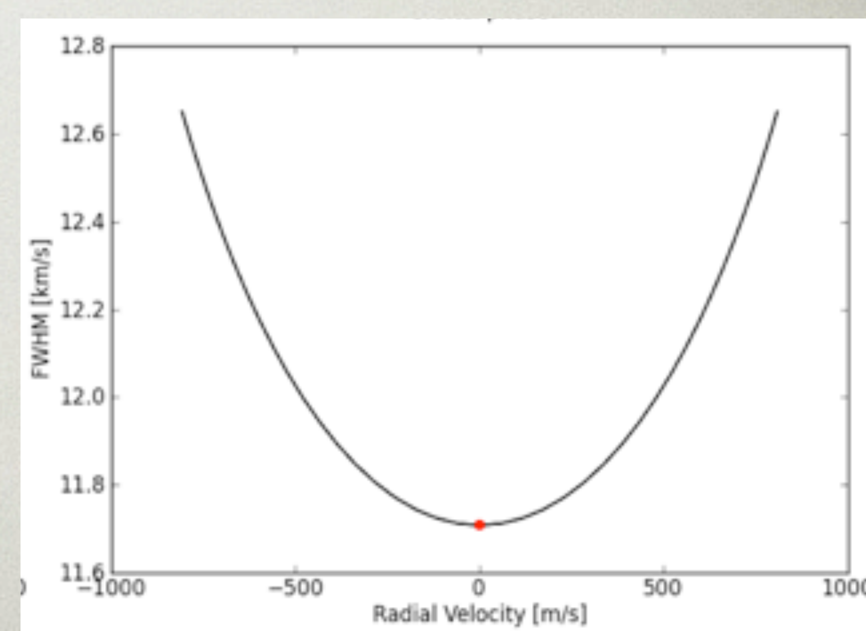




$(v \sin i)_1 < (v \sin i)_2$ $(v \sin i)_1 = (v \sin i)_2$ $(v \sin i)_1 > (v \sin i)_2$

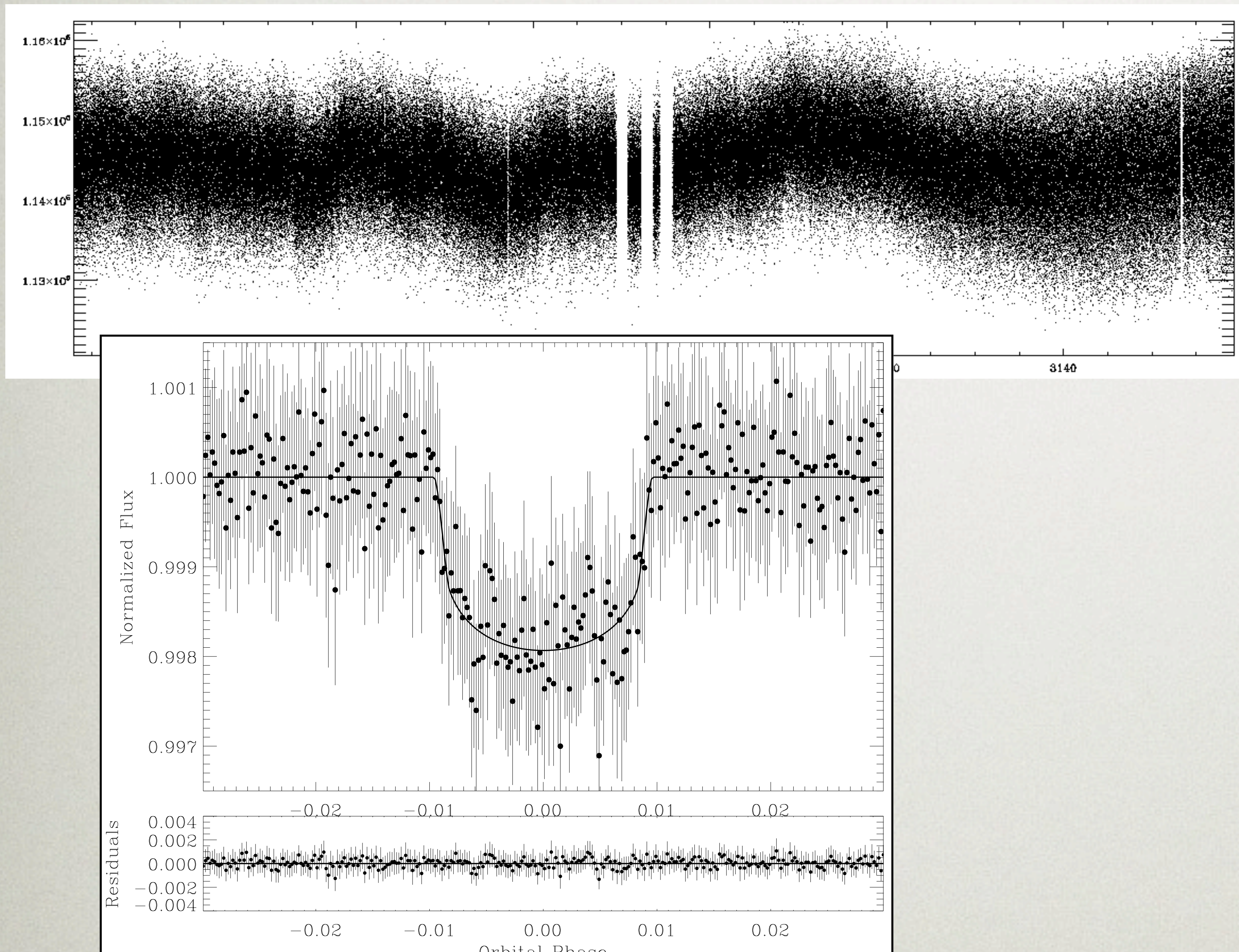






Santerne et al. (in prep.)

CoRoT-22



Moutou, Almenara, Alonso et al.

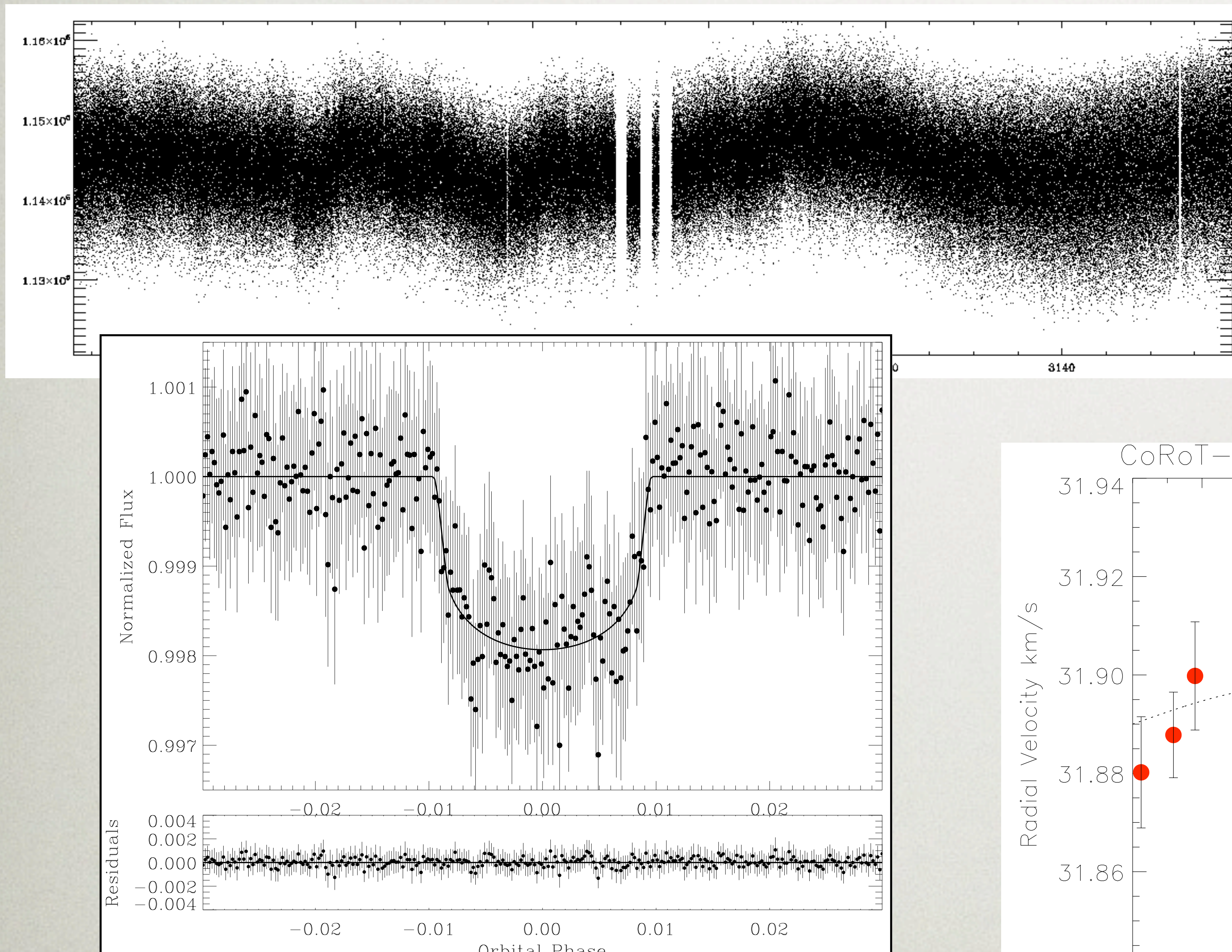
LRc02_E1_0591

P = 9.76 d

depth = 0.2 %

V = 13.9 (color LC)

CoRoT-22



Moutou, Almenara, Alonso et al.

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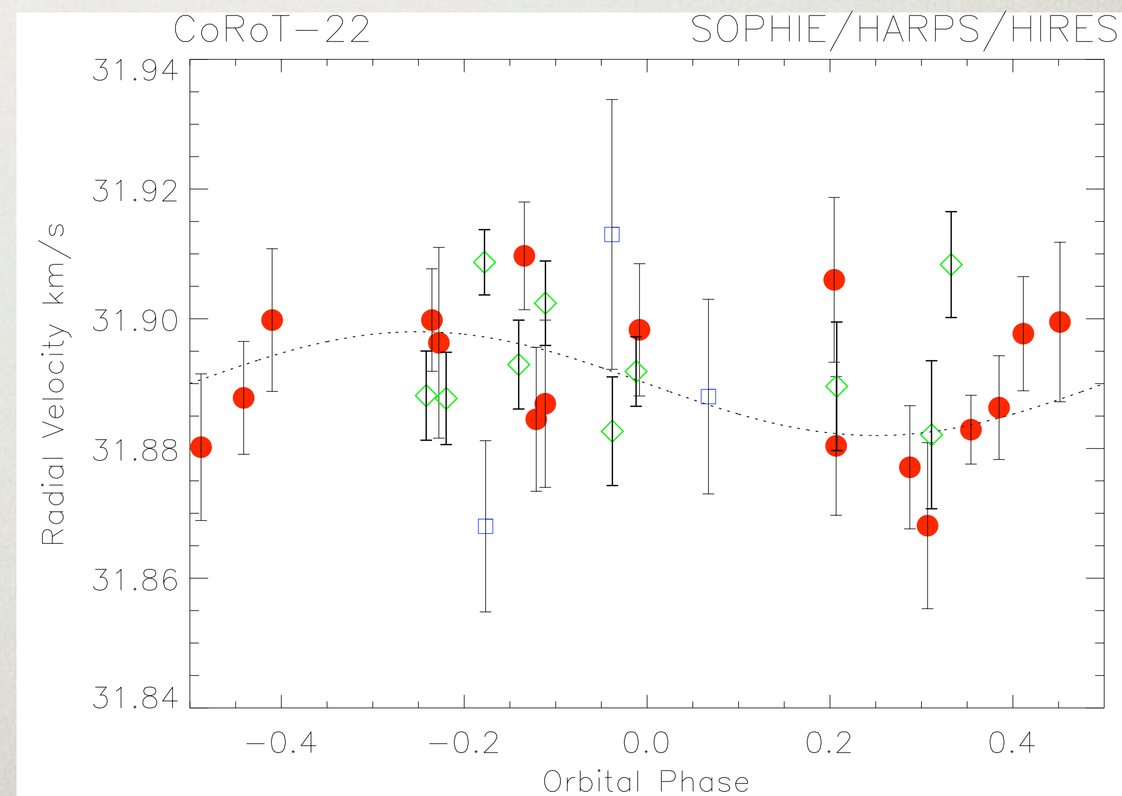
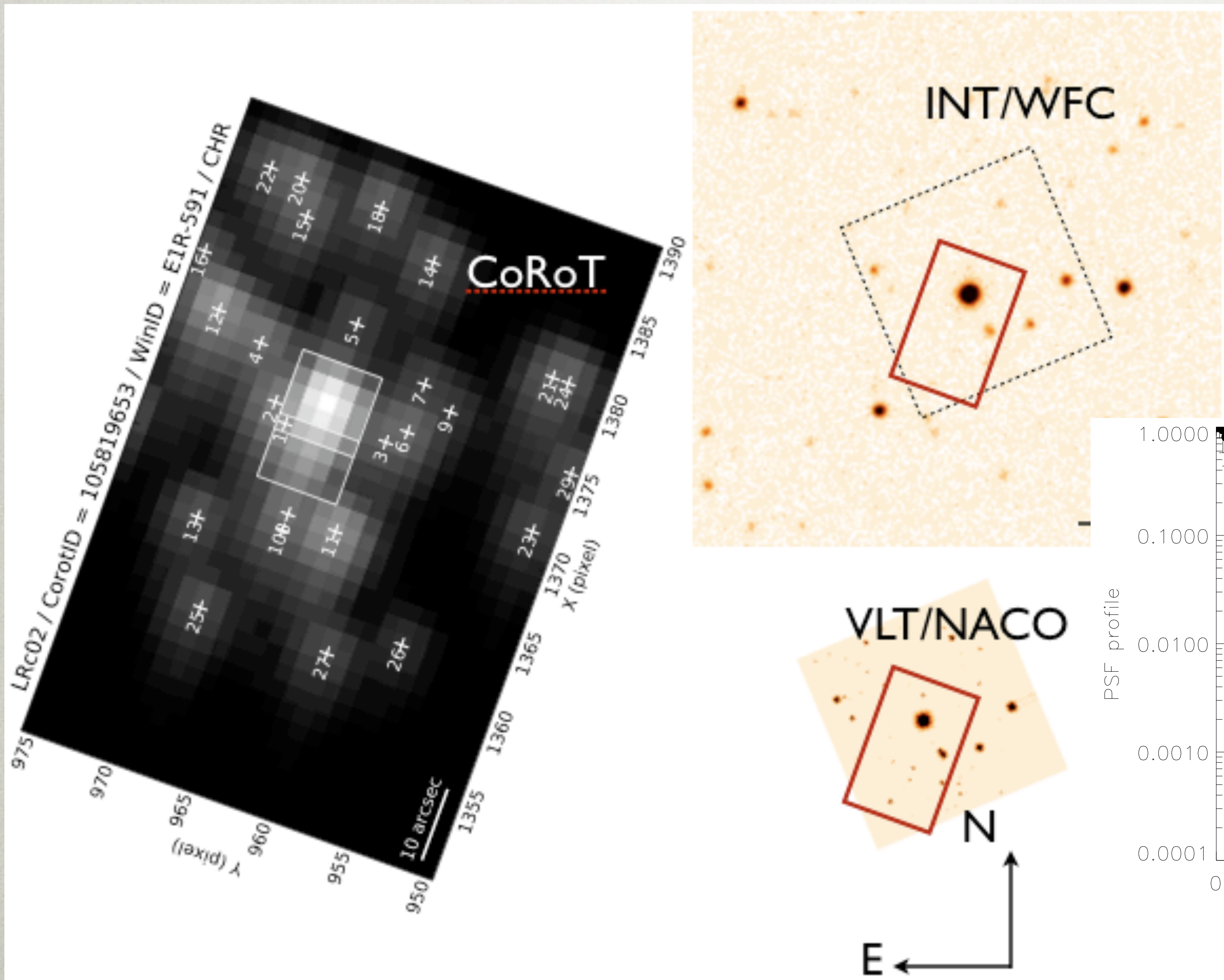
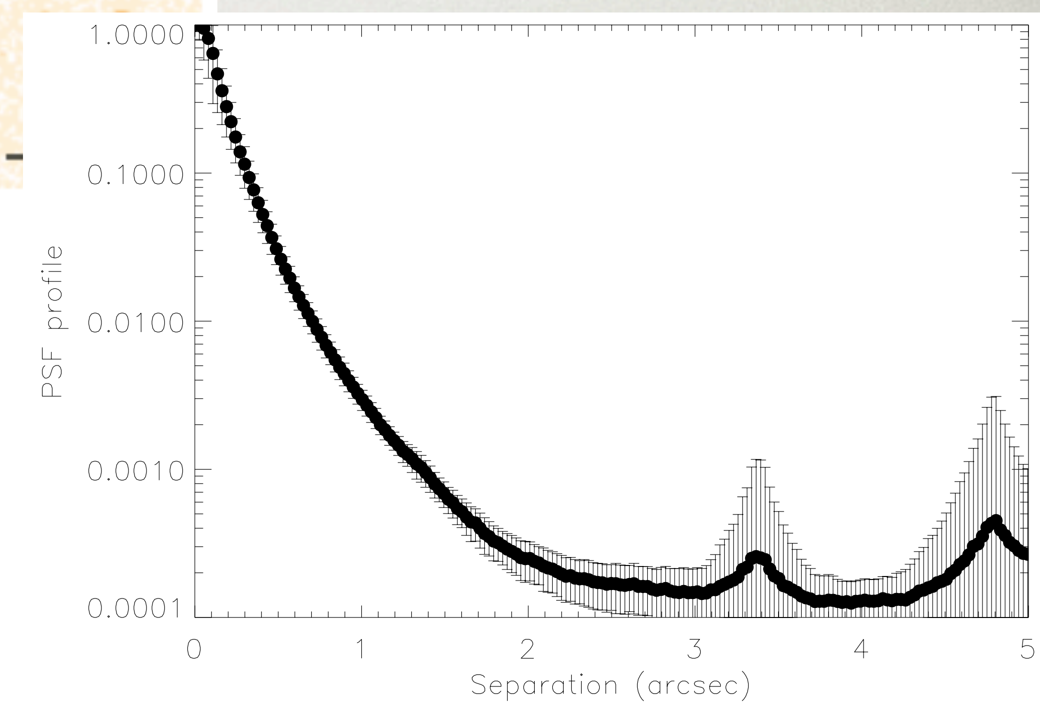


CoRoT-22 - AO



On-Off

AO excludes possible contaminants farther than 0.9″ from the star.



Moutou, Almenara, Alonso et al.

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D}, \mathrm{I})}{p(\mathrm{H_j}|\mathrm{D}, \mathrm{I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i}, \mathrm{I})}{p(\mathrm{D}|\mathrm{H_j}, \mathrm{I})}$$

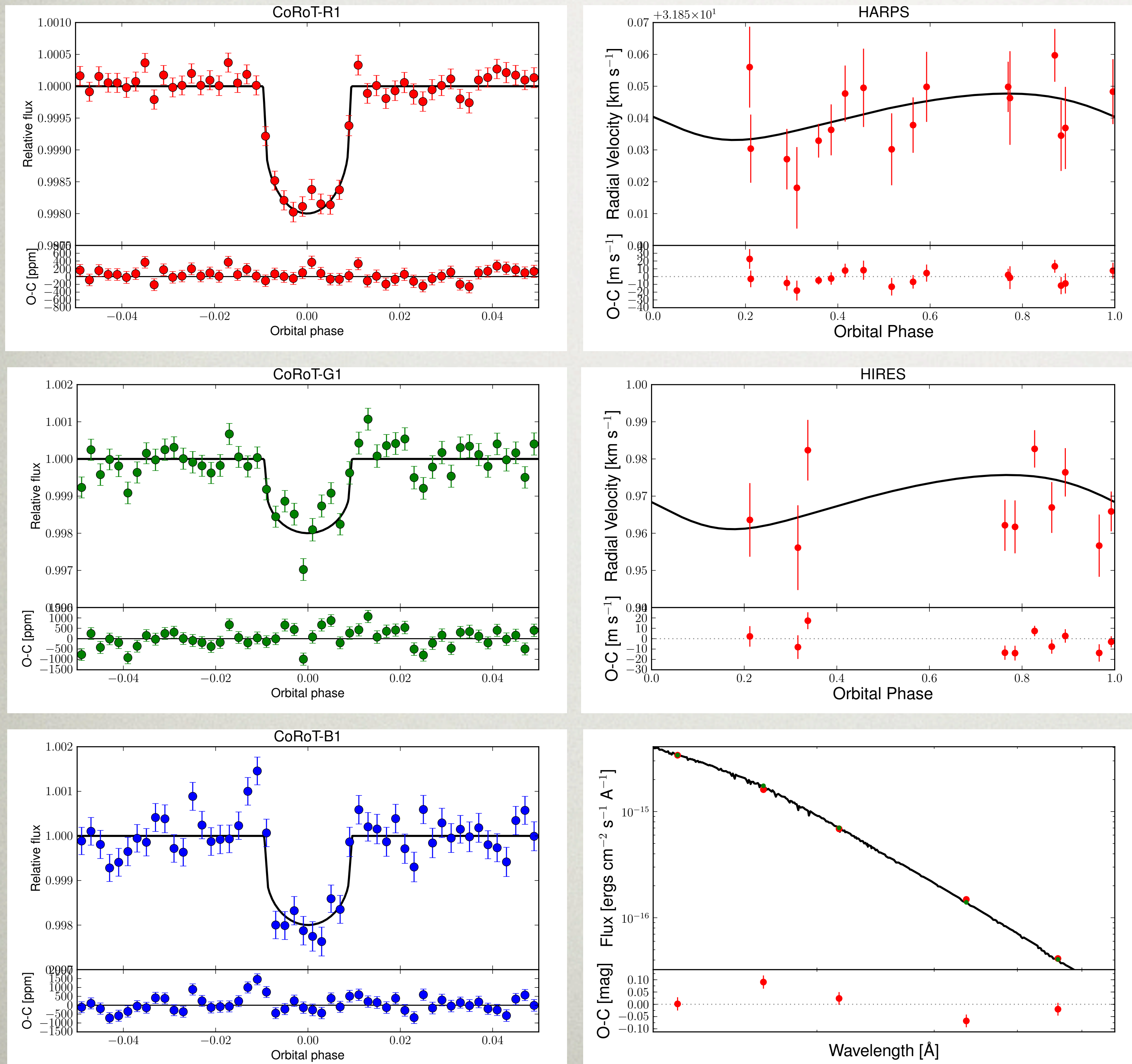
Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D, I})}{p(\mathrm{H_j}|\mathrm{D, I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i, I})}{p(\mathrm{D}|\mathrm{H_j, I})}$$

H_1 = “The transits observed in CoRoT-22 are produced by an extrasolar planet in orbit.”

H_2 = “The transits observed in CoRoT-22 are produced by an unresolved background eclipsing binary.”

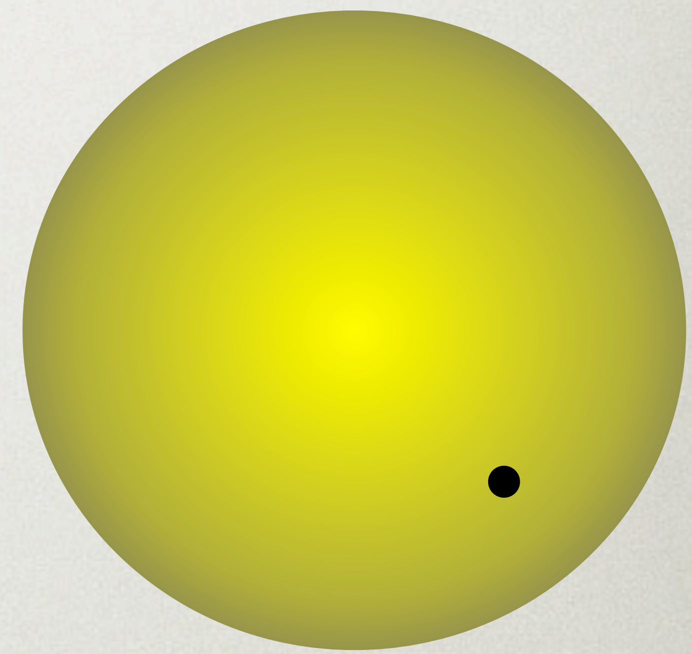
Planet scenario



$M_\star = 1.14 \pm 0.08\ M_\odot$

$R_\star = 1.44 \pm 0.17\ R_\odot$

Distance $= 760 \pm 90$ pc



$K < 15.6$ m/s (99%)

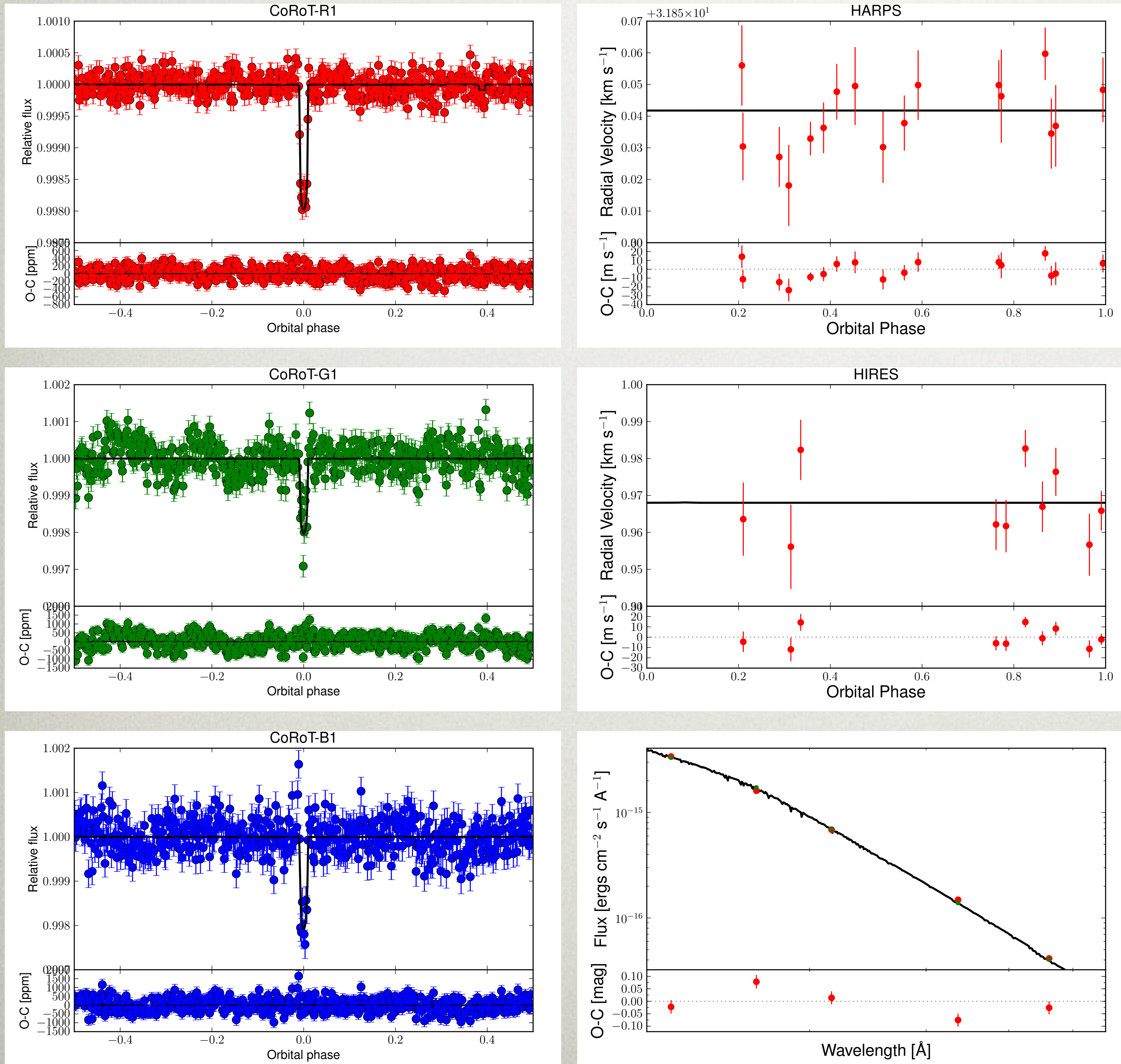
$e < 0.76$ (99%)

$M_p < 0.17\ M_{Jup}$ (99%)

$R_p = 0.57 \pm 0.07\ R_{Jup}$

$b = 0.27 \pm 0.22$

BEB scenario



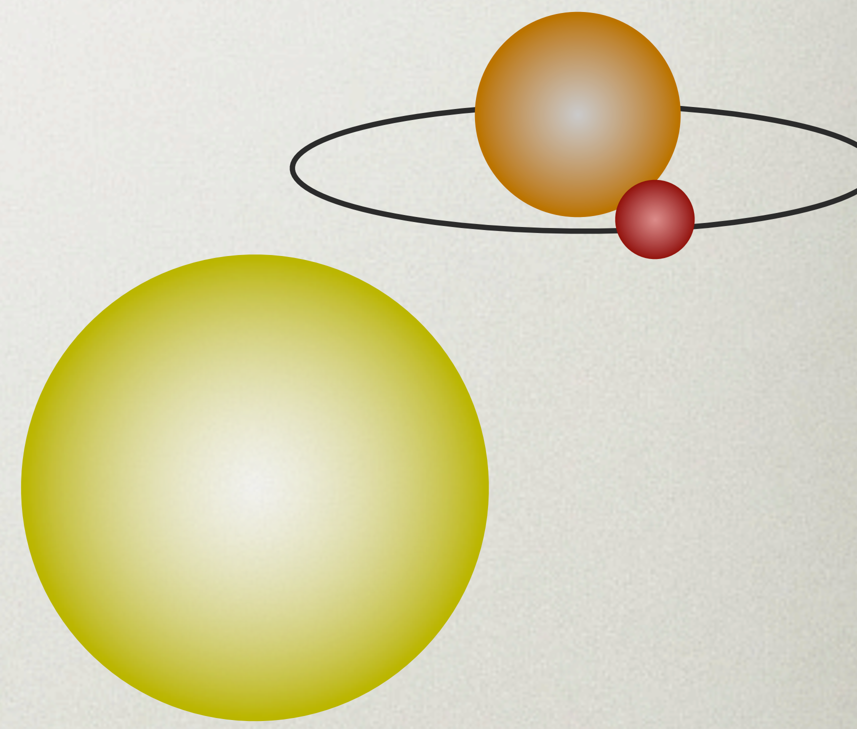
$M_1 = 0.99 \pm 0.05\ M_\odot$

$M_2 = 0.11 \pm 0.02\ M_\odot$

Distance = 1600 ± 200 pc

$e < 0.78$ (99%)

$b = 0.49 \pm 0.34$

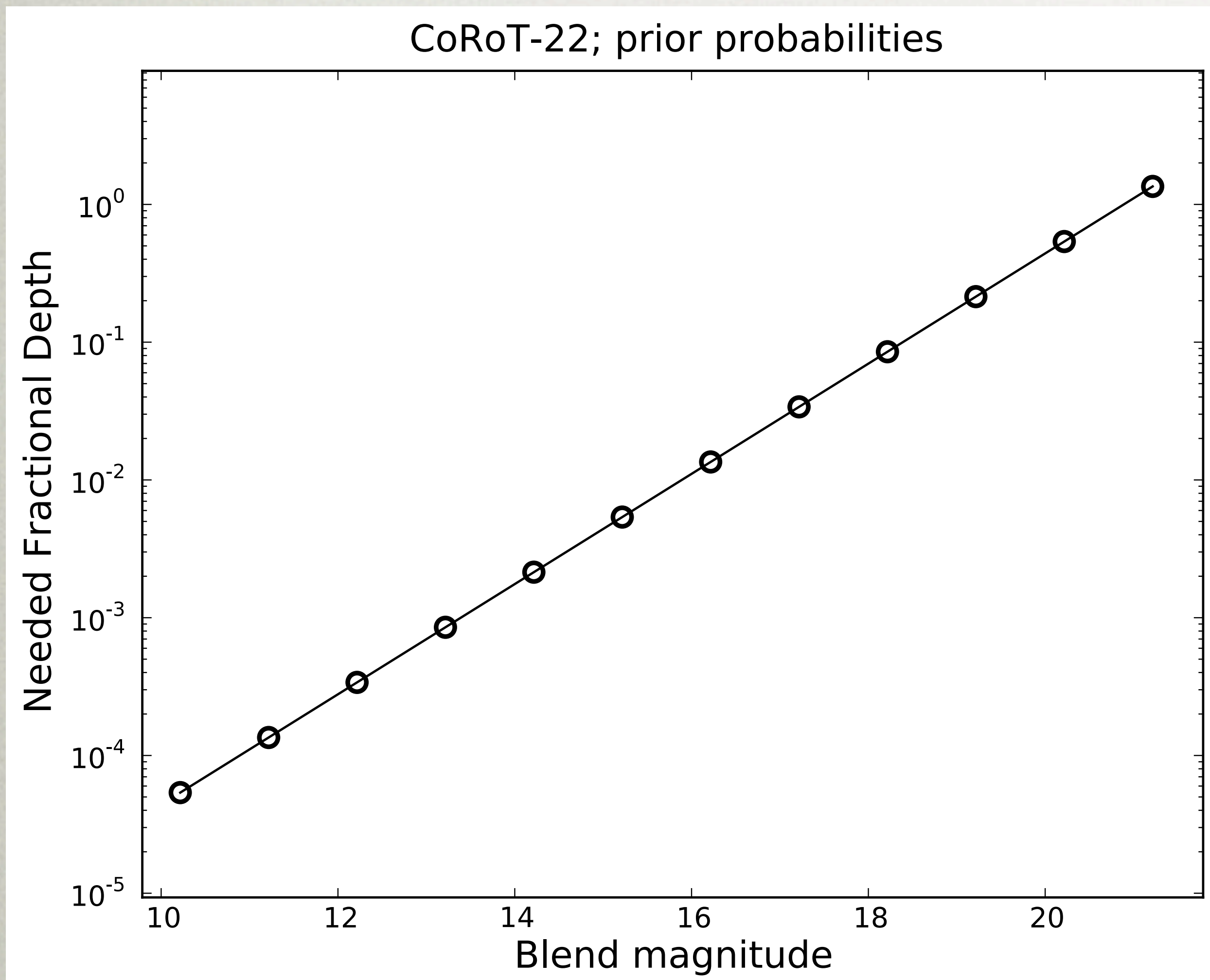


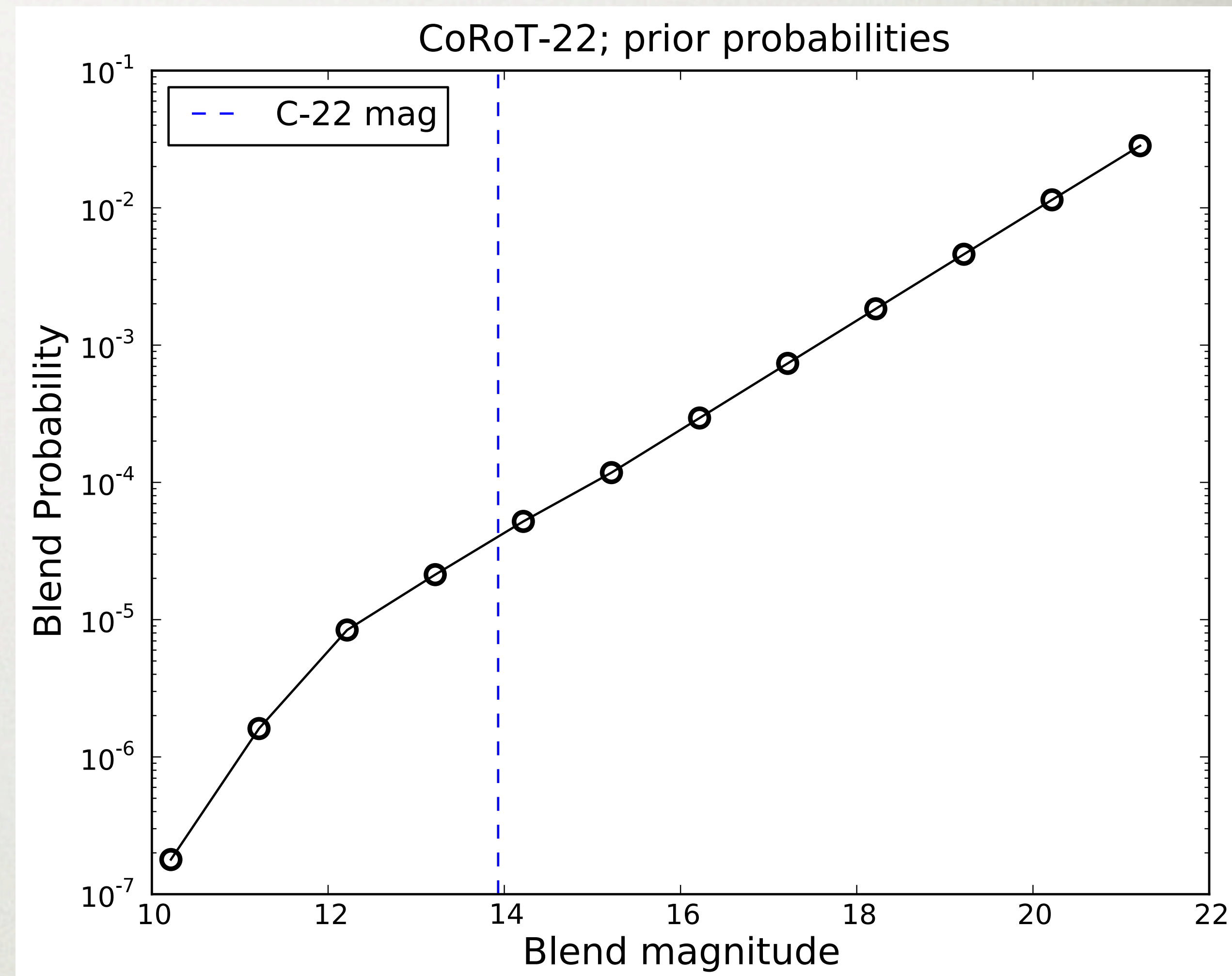
$M_\star = 1.14 \pm 0.08\ M_\odot$

$R_\star = 1.40 \pm 0.13\ R_\odot$

Distance = 780 ± 80 pc

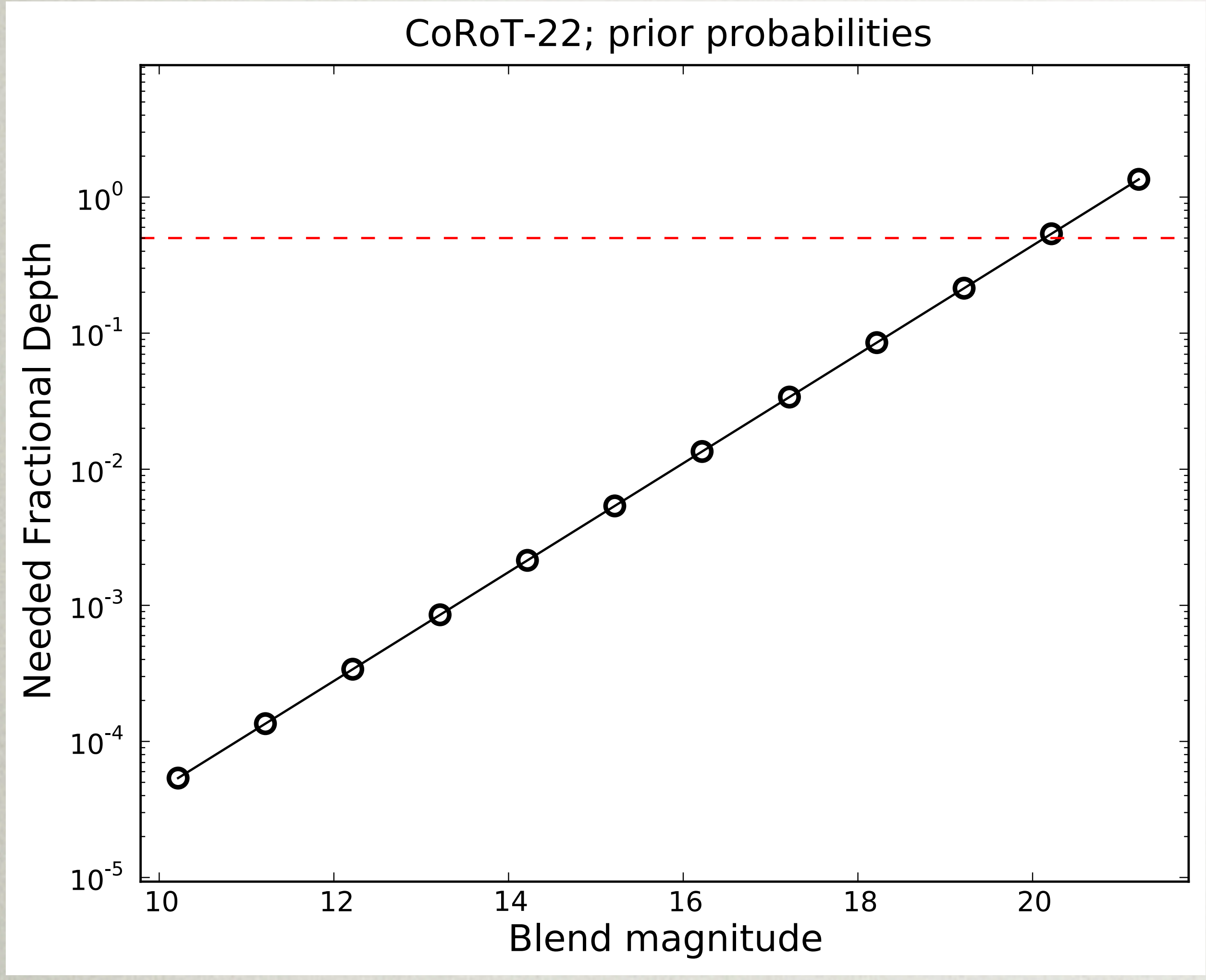
Hypothesis priors

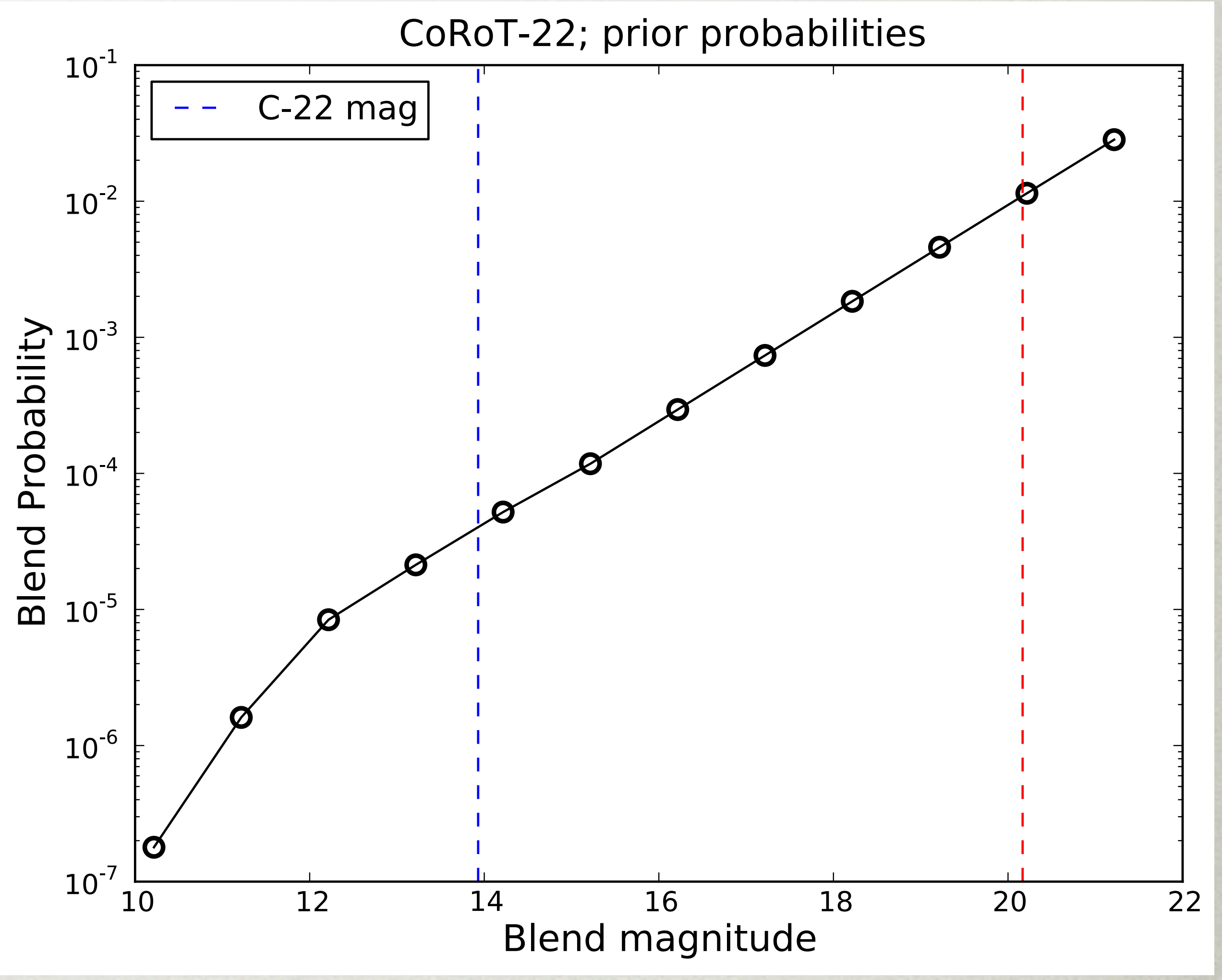




Probability of finding a blending star in a 0.9″ radius (given by AO)

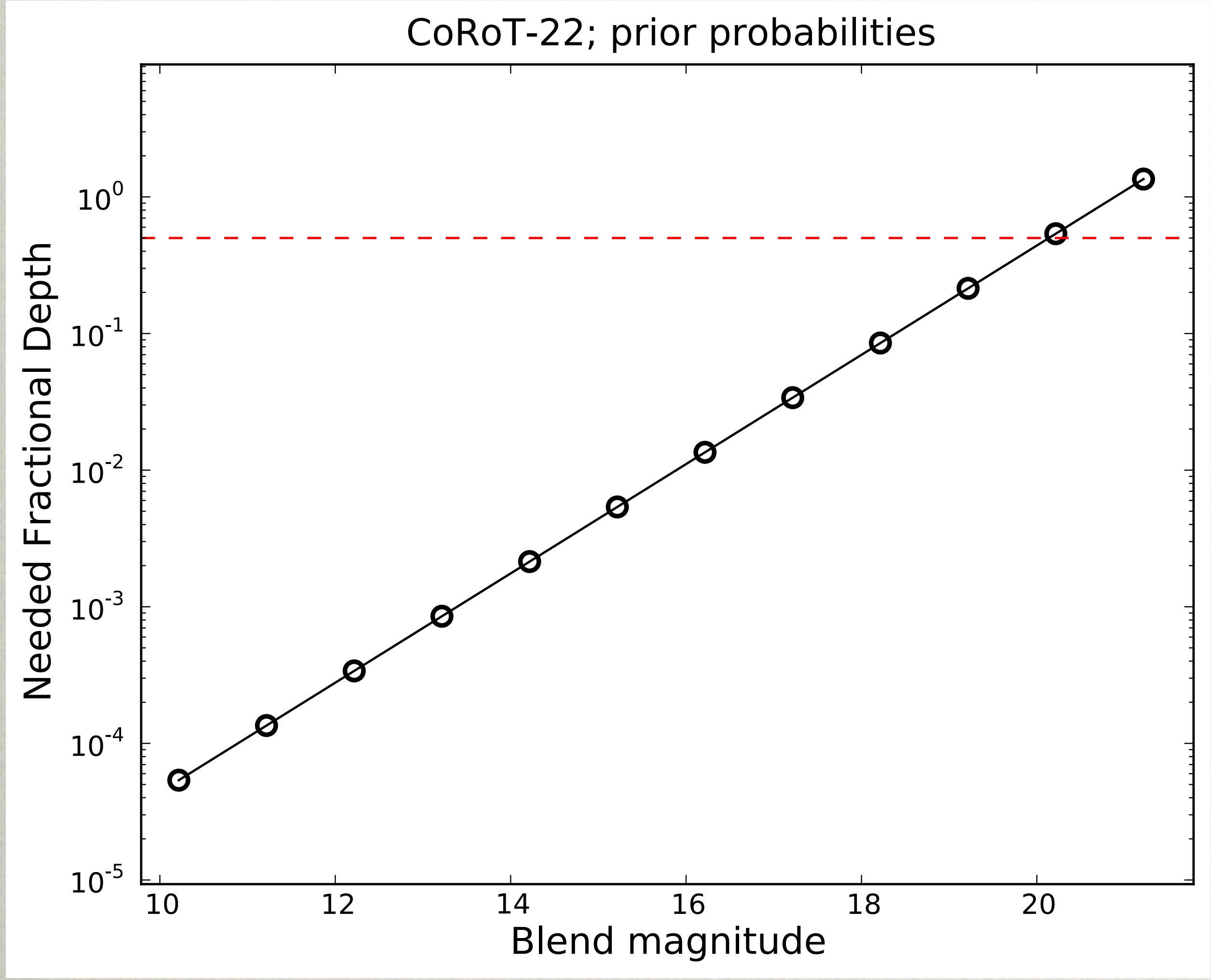
Hypothesis priors

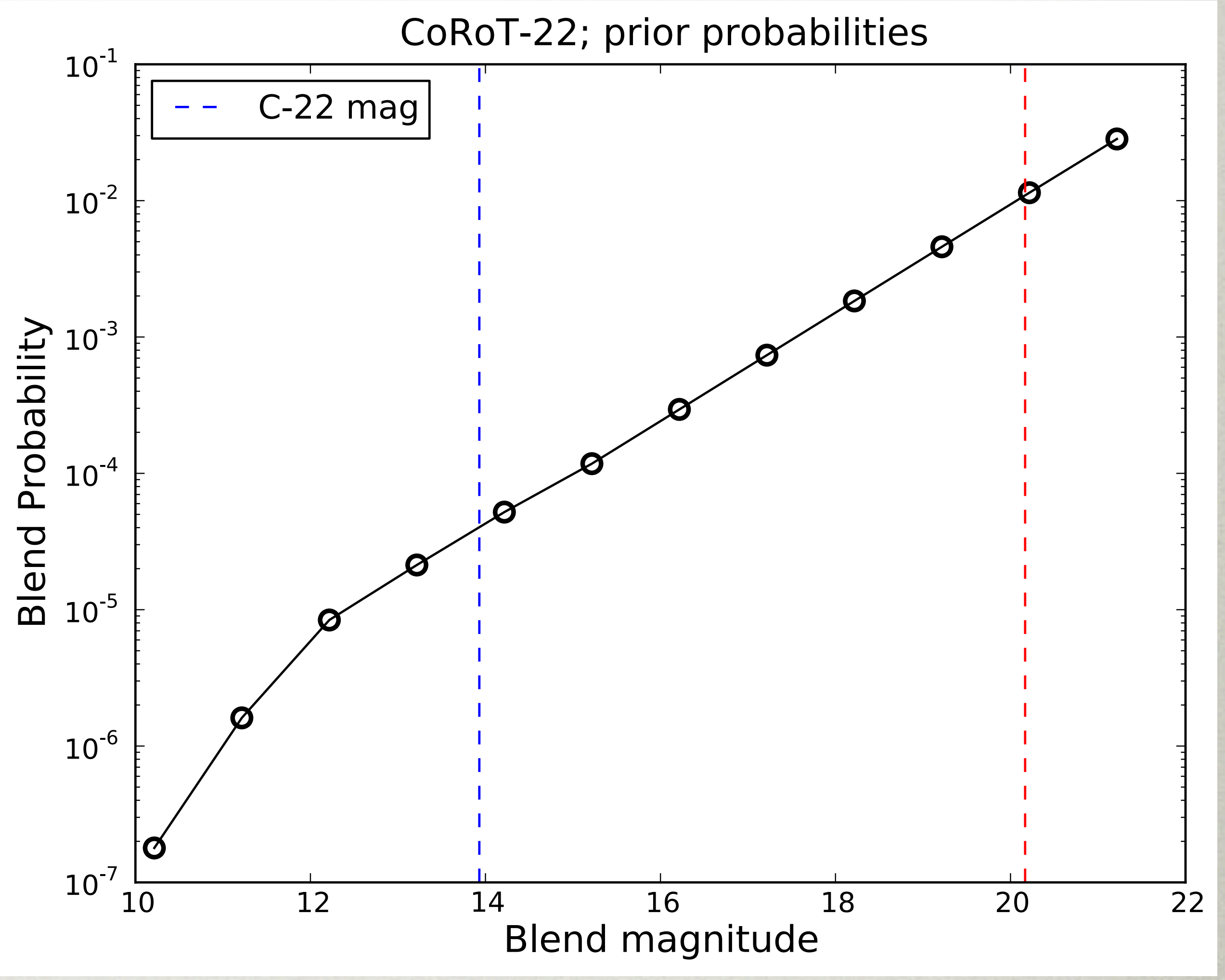




Probability of finding a blending star in a 0.9″ radius (given by AO)

Hypothesis priors





Probability of finding a blending star in a 0.9″ radius (given by AO)

$$p(M_{\mathrm{BEB}}|\mathrm{I}) = 0.0134 \times 0.5 = 6.7 \times 10^{-3}$$

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D}, \mathrm{I})}{p(\mathrm{H_j}|\mathrm{D}, \mathrm{I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i}, \mathrm{I})}{p(\mathrm{D}|\mathrm{H_j}, \mathrm{I})}$$

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D,I})}{p(\mathrm{H_j}|\mathrm{D,I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i,I})}{p(\mathrm{D}|\mathrm{H_j,I})}$$

$p(M_{\mathrm{BEB}}|\mathrm{I}) = 0.0134 \times 0.5 = 6.7 \times 10^{-3}$

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D,I})}{p(\mathrm{H_j}|\mathrm{D,I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i,I})}{p(\mathrm{D}|\mathrm{H_j,I})}$$

$$p(M_{\mathrm{BEB}}|\mathrm{I}) = 0.0134 \times 0.5 = 6.7 \times 10^{-3}$$

$$p(M_{\mathrm{pla}}|\mathrm{I}) = 0.2$$

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D, I})}{p(\mathrm{H_j}|\mathrm{D, I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i, I})}{p(\mathrm{D}|\mathrm{H_j, I})}$$

$$p(M_{\mathrm{BEB}}|\mathrm{I}) = 0.0134 \text{ x } 0.5 = 6.7 \text{ x } 10^{-3}$$

$$p(M_{\mathrm{pla}}|\mathrm{I}) = 0.2$$

$$p(D|M_{\mathrm{BEB}})/p(D|M_{\mathrm{pla}}) = 1.16$$

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D, I})}{p(\mathrm{H_j}|\mathrm{D, I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i, I})}{p(\mathrm{D}|\mathrm{H_j, I})}$$

$$p(M_{\mathrm{BEB}}|\mathrm{I}) = 0.0134 \text{ x } 0.5 = 6.7 \text{ x } 10^{-3}$$

$$p(M_{\mathrm{pla}}|\mathrm{I}) = 0.2$$

$$p(D|M_{\mathrm{BEB}})/p(D|M_{\mathrm{pla}}) = 1.16$$

$$O_{\mathrm{BEB;pla}} = p(\mathrm{pla})/p(\mathrm{BEB}) = 26$$

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D}, \mathrm{I})}{p(\mathrm{H_j}|\mathrm{D}, \mathrm{I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i}, \mathrm{I})}{p(\mathrm{D}|\mathrm{H_j}, \mathrm{I})}$$

$$p(M_{\mathrm{BEB}}|\mathrm{I}) = 0.0134 \text{ x } 0.5 = 6.7 \text{ x } 10^{-3}$$

$$p(M_{\mathrm{pla}}|\mathrm{I}) = 0.2$$

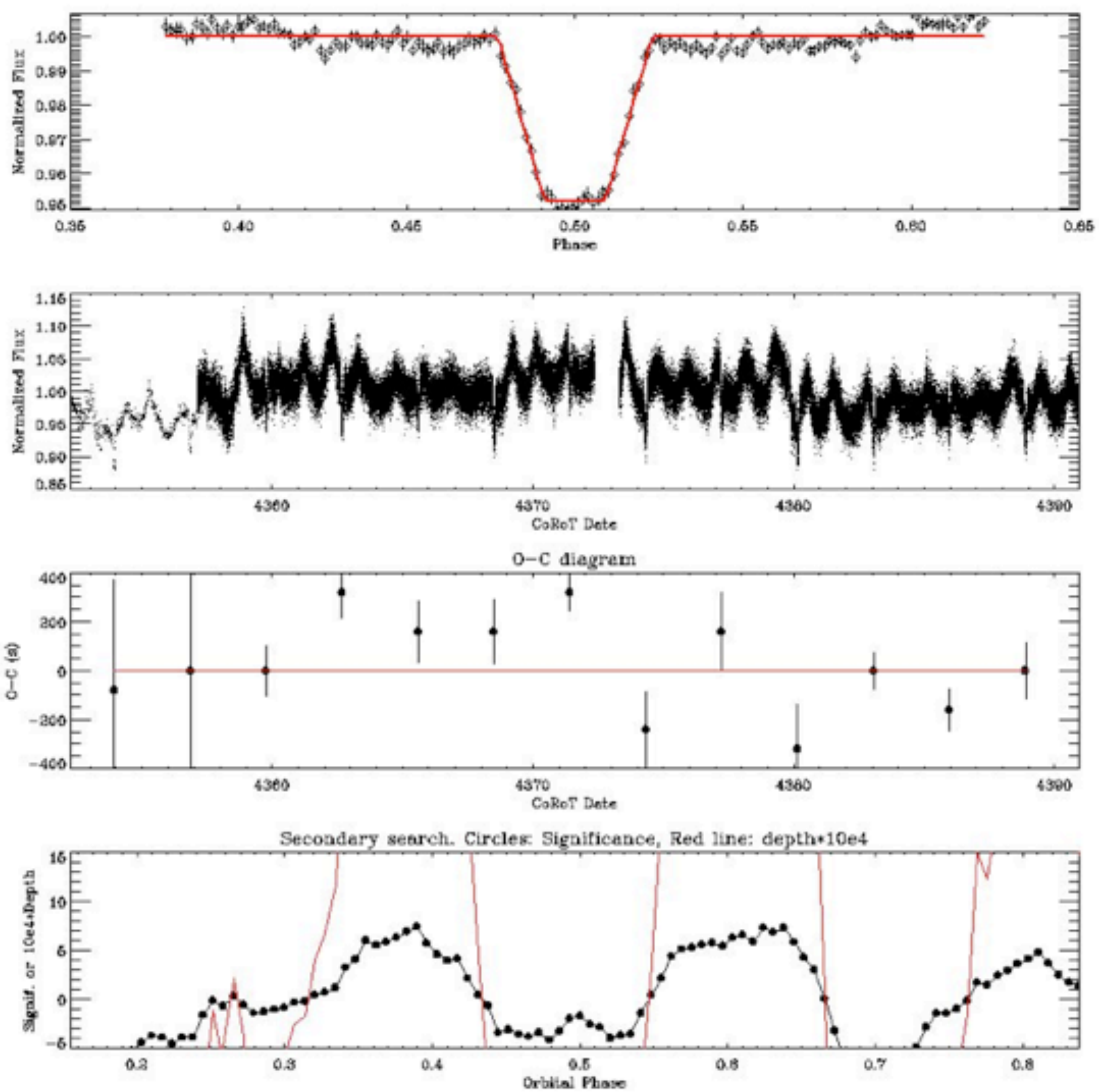
$$p(D|M_{\mathrm{BEB}})/p(D|M_{\mathrm{pla}}) = 1.16$$

$$O_{\mathrm{BEB;pla}} = p(\mathrm{pla})/p(\mathrm{BEB}) = 26$$

Usually required > 150 for strong evidence against one scenario

SRa05_E2_4016

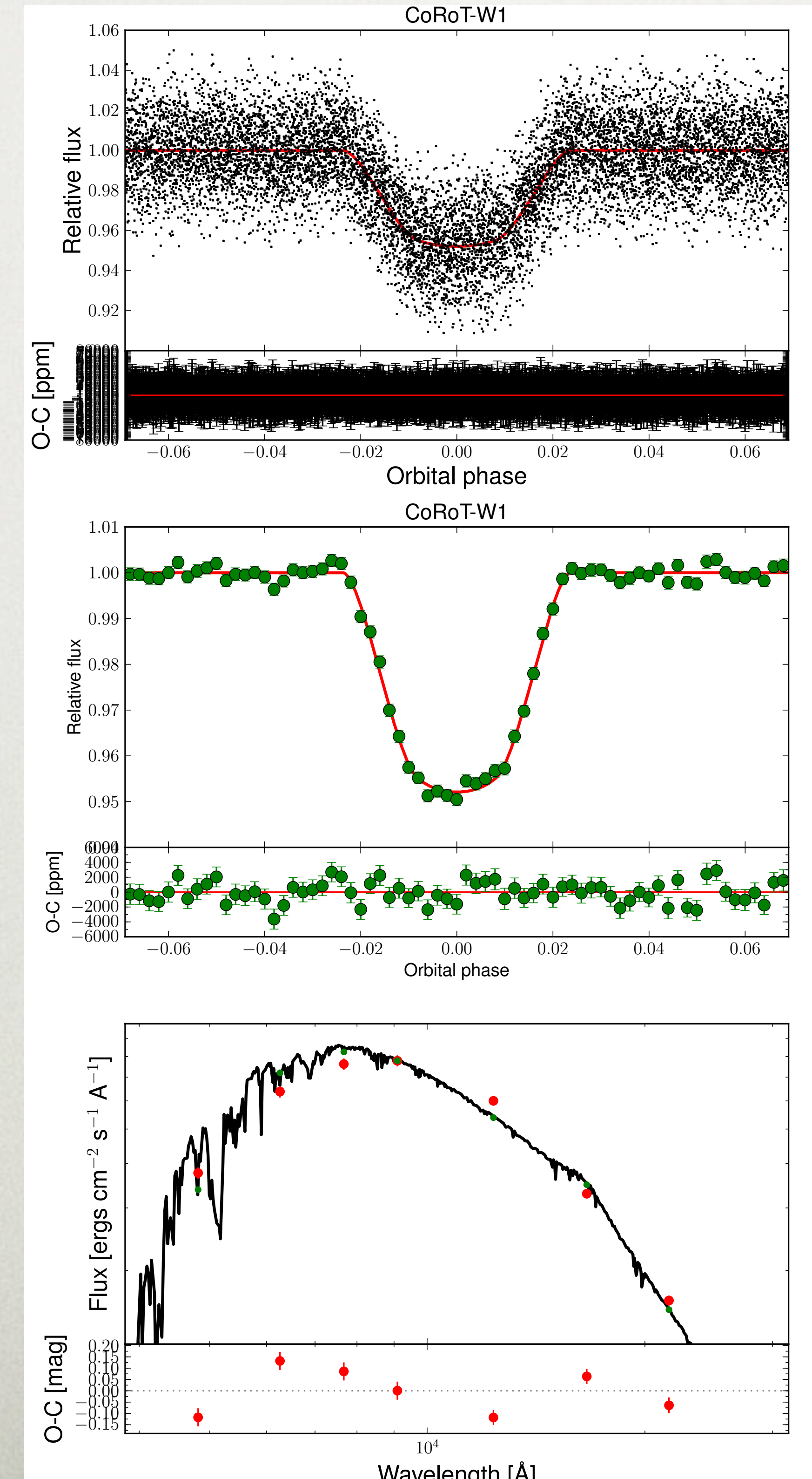
CANDIDATE SRa05_E2_4016 MARKS – Sec: 9/10 TF: –2/10 Rad: 7/10



Period (d)	2.9115587+/–0.00010629342	
Epoch (HJD – 2450000.0)	5898.9488+/–0.00083114435	
Total duration (hours)	3.2127987	
Flat part duration (hours)	1.2526894	
Depth (flux)	0.048073406	
Impact parameter	0.67173386	
Stellar density (fit)	5.5862275	* Solar
Stellar density (J–K)	1.87739	* Solar
Stellar radius (J–K)	0.704154	
Planetary radius (R_j)	1.5037628	
Significance of sec eclipse	1.64829	Sigmas
Phase of sec eclipse	0.389600	
Depth of sec eclipse	0.00719058	
R.A.	Empty	
Declination	Empty	
J – K color (2MASS)	0.755000	
V mag	16.7520	
B – V color	Empty	

SRa05_E2_4016

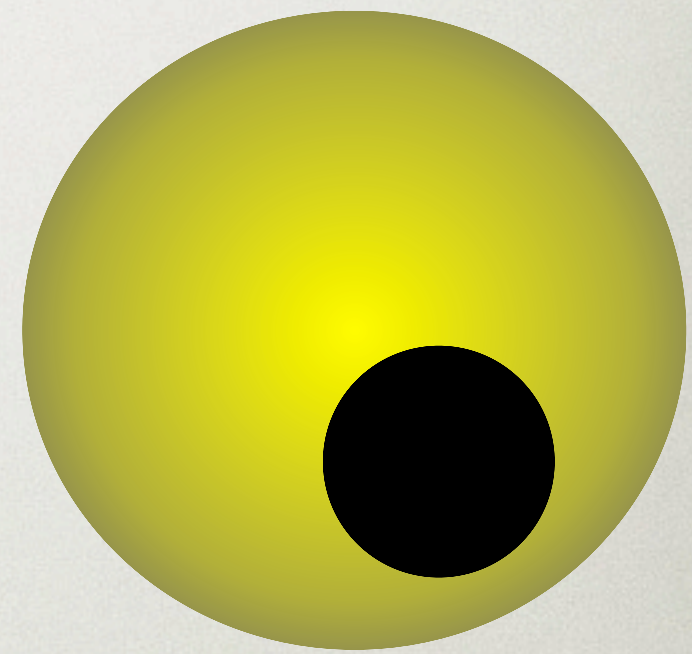
Planet



$M_\star = 0.48 \pm 0.04\ M_\odot$

$R_\star = 0.46 \pm 0.04\ R_\odot$

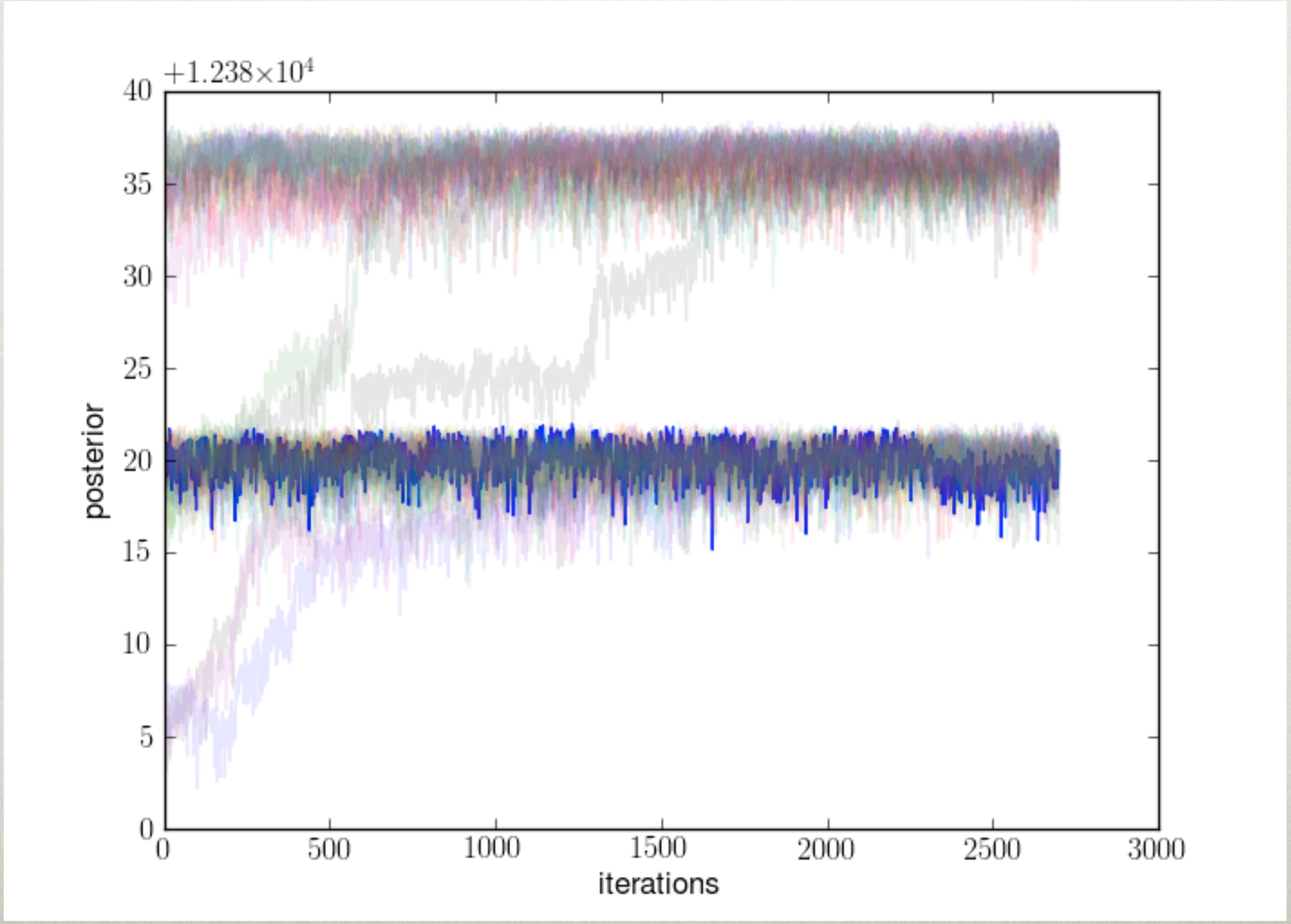
Distance = 380 ± 40 pc



$R_p = 0.97 \pm 0.09\ R_{Jup}$

SRa05_E2_4016

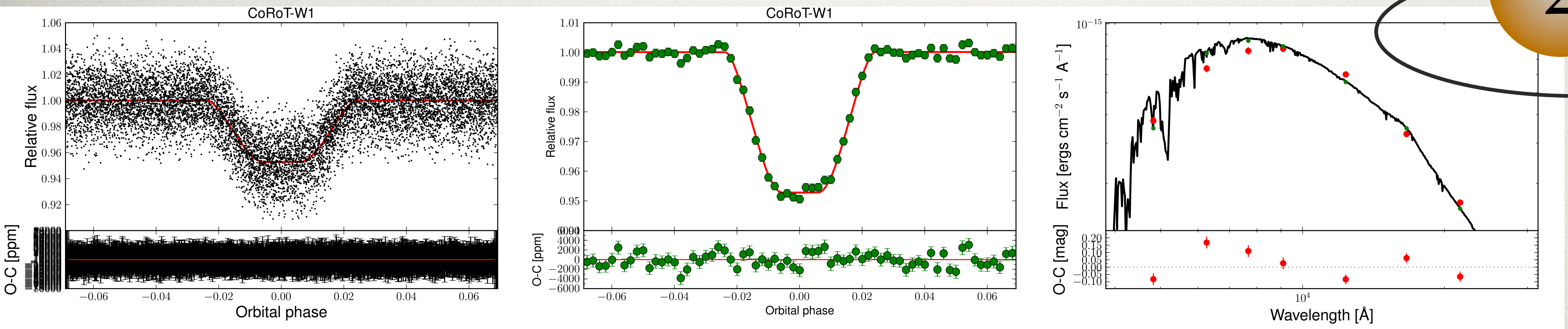
Binary

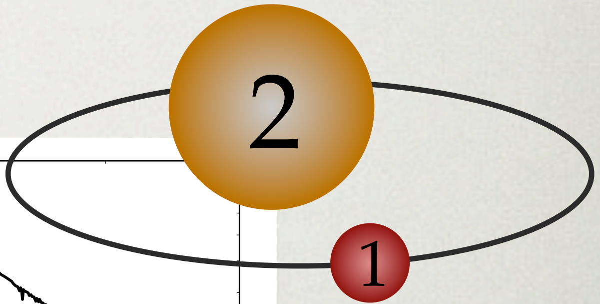


SRa05_E2_4016

Binary

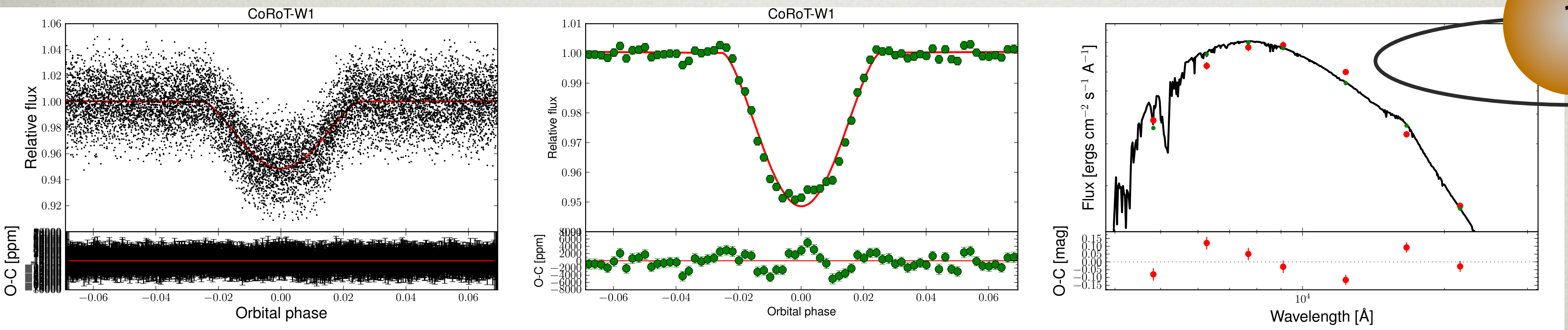
Secondary

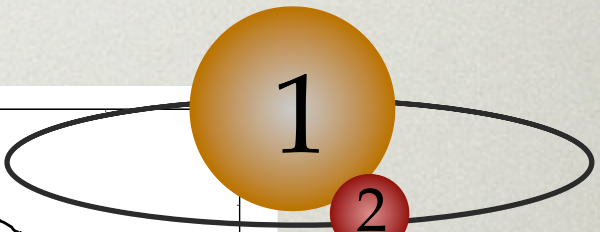




$M_1 = 0.12 \pm 0.02\ M_\odot$
$M_2 = 0.39 \pm 0.05\ M_\odot$
Distance = 320 ± 50 pc

Primary





$M_1 = 0.24 \pm 0.04\ M_\odot$
$M_2 = 0.11 \pm 0.01\ M_\odot$
Distance = 870 ± 50 pc

SRa05_E2_4016

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D},\mathrm{I})}{p(\mathrm{H_j}|\mathrm{D},\mathrm{I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i},\mathrm{I})}{p(\mathrm{D}|\mathrm{H_j},\mathrm{I})}$$

SRa05_E2_4016

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D},\mathrm{I})}{p(\mathrm{H_j}|\mathrm{D},\mathrm{I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i},\mathrm{I})}{p(\mathrm{D}|\mathrm{H_j},\mathrm{I})}$$

$$p(M_{\mathrm{bin}}|\mathrm{I}) = 0.5$$

SRa05_E2_4016

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D},\mathrm{I})}{p(\mathrm{H_j}|\mathrm{D},\mathrm{I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i},\mathrm{I})}{p(\mathrm{D}|\mathrm{H_j},\mathrm{I})}$$

$$p(M_{\mathrm{bin}}|\mathrm{I}) = 0.5$$

$$p(M_{\mathrm{pla}}|\mathrm{I}) = 0.2$$

SRa05_E2_4016

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D}, \mathrm{I})}{p(\mathrm{H_j}|\mathrm{D}, \mathrm{I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i}, \mathrm{I})}{p(\mathrm{D}|\mathrm{H_j}, \mathrm{I})}$$

$$p(M_{\mathrm{bin}}|\mathrm{I}) = 0.5$$

$$p(M_{\mathrm{pla}}|\mathrm{I}) = 0.2$$

$$p(D|M_{\mathrm{pla}})/p(D|M_{\mathrm{bin}}) = 3$$

SRa05_E2_4016

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D},\mathrm{I})}{p(\mathrm{H_j}|\mathrm{D},\mathrm{I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i},\mathrm{I})}{p(\mathrm{D}|\mathrm{H_j},\mathrm{I})}$$

$$p(M_{\mathrm{bin}}|\mathrm{I}) = 0.5$$

$$p(M_{\mathrm{pla}}|\mathrm{I}) = 0.2$$

$$p(D|M_{\mathrm{pla}})/p(D|M_{\mathrm{bin}}) = 3$$

$$\boxed{O_{\mathrm{pla;bin}} = p(\mathrm{pla})/p(\mathrm{bin}) = 1.2}$$

SRa05_E2_4016

Odds ratio

$$O_{ij} = \frac{p(\mathrm{H_i}|\mathrm{D}, \mathrm{I})}{p(\mathrm{H_j}|\mathrm{D}, \mathrm{I})} = \frac{p(\mathrm{H_i}|\mathrm{I})}{p(\mathrm{H_j}|\mathrm{I})} \cdot \frac{p(\mathrm{D}|\mathrm{H_i}, \mathrm{I})}{p(\mathrm{D}|\mathrm{H_j}, \mathrm{I})}$$

$$p(M_{\mathrm{bin}}|\mathrm{I}) = 0.5$$

$$p(M_{\mathrm{pla}}|\mathrm{I}) = 0.2$$

$$p(D|M_{\mathrm{pla}})/p(D|M_{\mathrm{bin}}) = 3$$

$$\boxed{O_{\mathrm{pla;bin}} = p(\mathrm{pla})/p(\mathrm{bin}) = 1.2}$$

Need RVs, but V ~ 16.8!

PASTIS: Future / On Going developments

Light curves
(*Kepler*, *CoRoT*, *Spitzer*, ...)

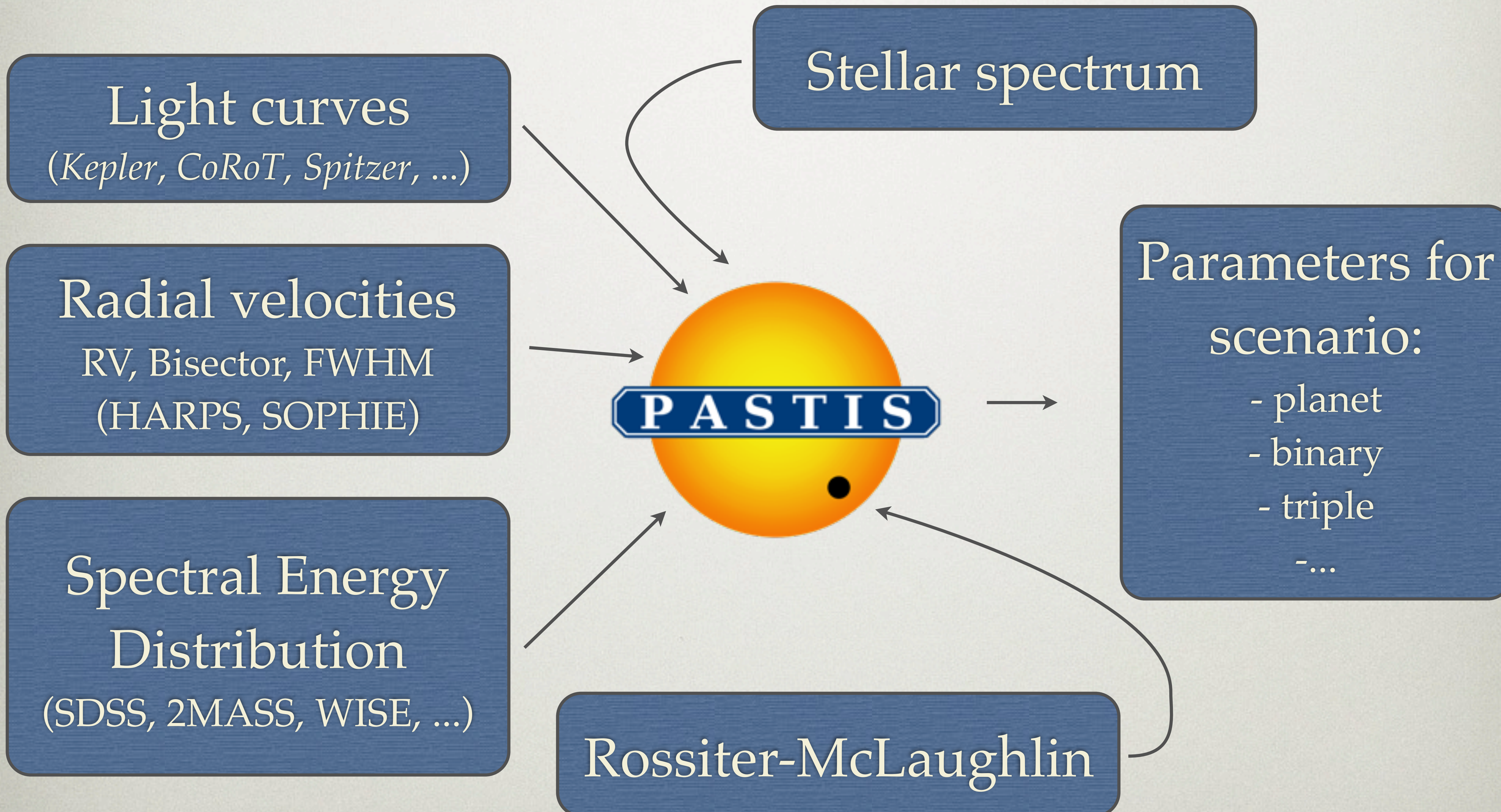
Radial velocities
RV, Bisector, FWHM
(HARPS, SOPHIE)

Spectral Energy Distribution
(SDSS, 2MASS, WISE, ...)

→ PASTIS →

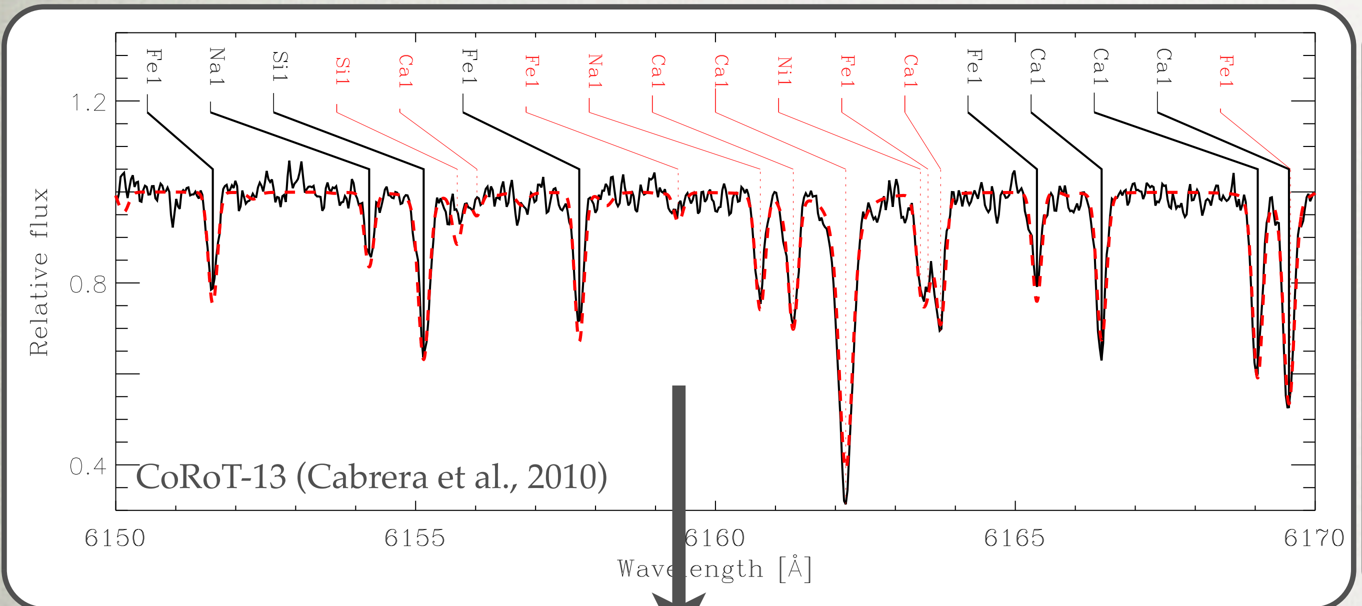
Parameters for scenario:
- planet
- binary
- triple
-...

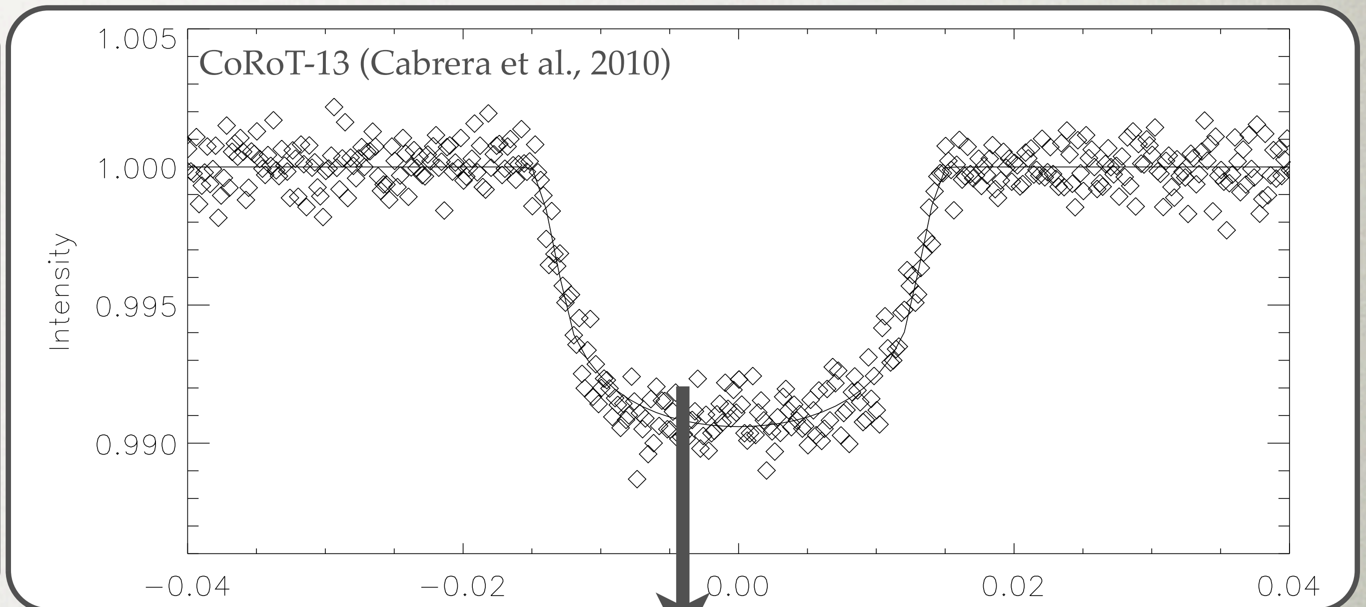
PASTIS: Future / On Going developments



Centro de Astrofísica da Universidade do Porto

On-going developments: Stellar spectrum constraints ?





Constraints on Teff, logg, [Fe/H] + Constraints on stellar density

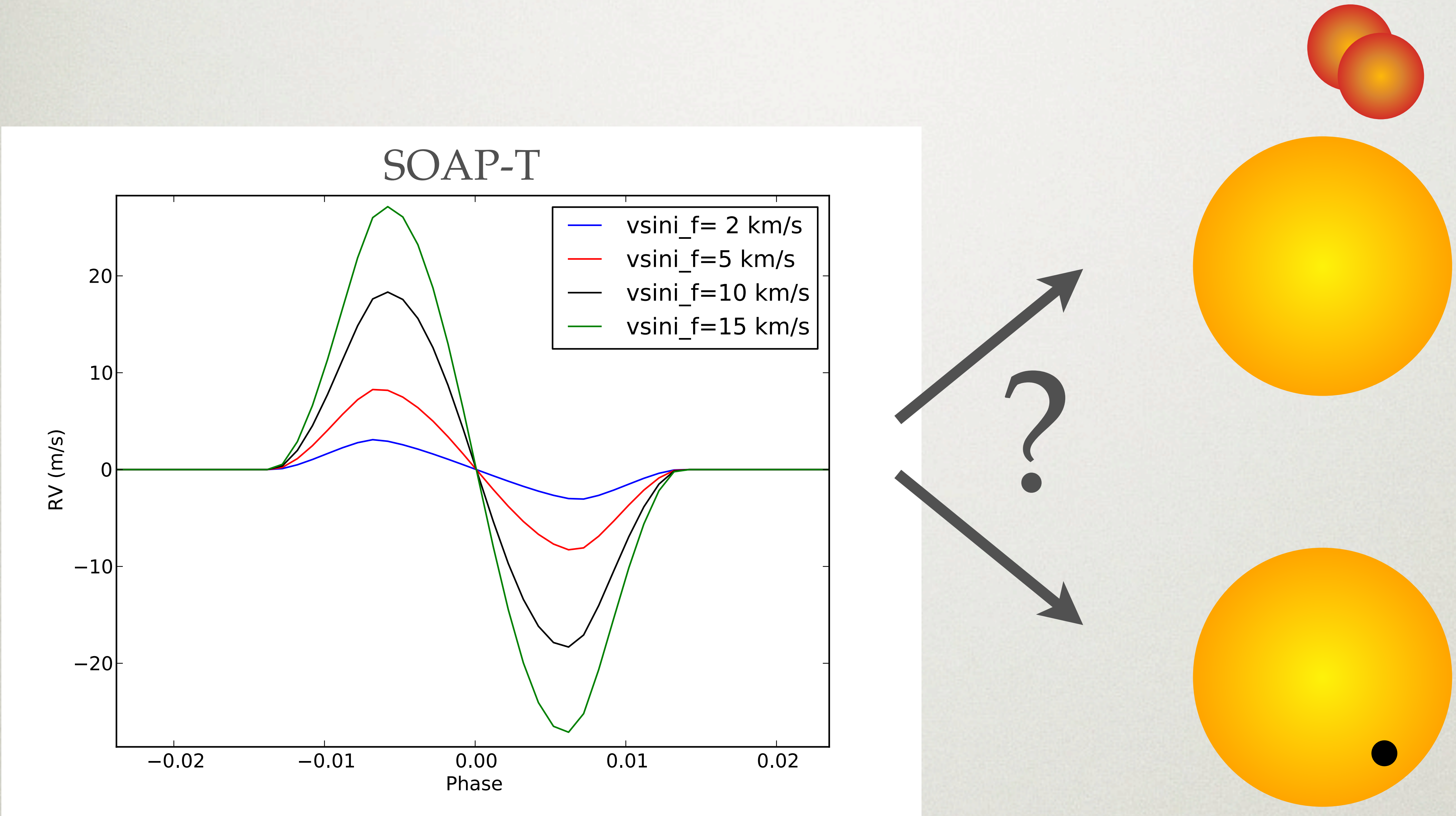
= ?

- Better constraints on planetary system
- Constraints on contaminant SpT and flux

On going development in CAUP (w. Santos, Sousa...)

Also useful in the context of the CHEOPS mission

On-going developments: Simulation of blended RM-effect



On going development in CAUP using SOAP-T (Oshagh et al., 2013)

Conclusions & Perspectives

- False positives, a classic nuisance in transit surveys.
- At present, planet validation is the only way to establish the nature of the smallest transit candidates discovered.
- A self-consistent analysis of all available data backed by rigorous statistics is needed.
- PASTIS provides an efficient way to validate planet candidates.
- First tests show power of bayesian approach. Test with more realistic error distributions under way.
- Prior dependence not fully considered by estimation methods. Use thermodynamic integration. Ongoing study.

Conclusions & Perspectives

- PASTIS: new types of data to be included in the future: centroid, imaging, RM effect (**ongoing**), Spectral analysis (**ongoing**), etc.
- Validate a large number of CoRoT and Kepler small-size candidates to:
  - Obtain a measurement of the False Positive Ratio (useful for statistical studies based on candidates alone, see Howard et al. 2012; cf. Santerne et al. 2012).
  - Identify promising candidates for the next generation of instruments (ESPRESSO).
- Planet validation will provide support for future missions as **PLATO**.


Planet Validation Workshop
Marseille, 13 - 15 May 2013
www.lam.fr
Registration before 1st April
Invited speakers:
Bordé, P. (IAS)
Cassan, A. (IAP)
Chauvin, G. (IPAG)
Diaz, R. (LAM)
Girardi, L. (INAF)
Leconte, J. (LMD)
Mordasini, C. (MPIA)
Sozzetti, A. (INAF)
Torres, W. (CfA)
★ Observations and data modeling
★ Fit method and model comparison
★ Stellar multiplicity
★ Planetary systems
★ Galactic structure