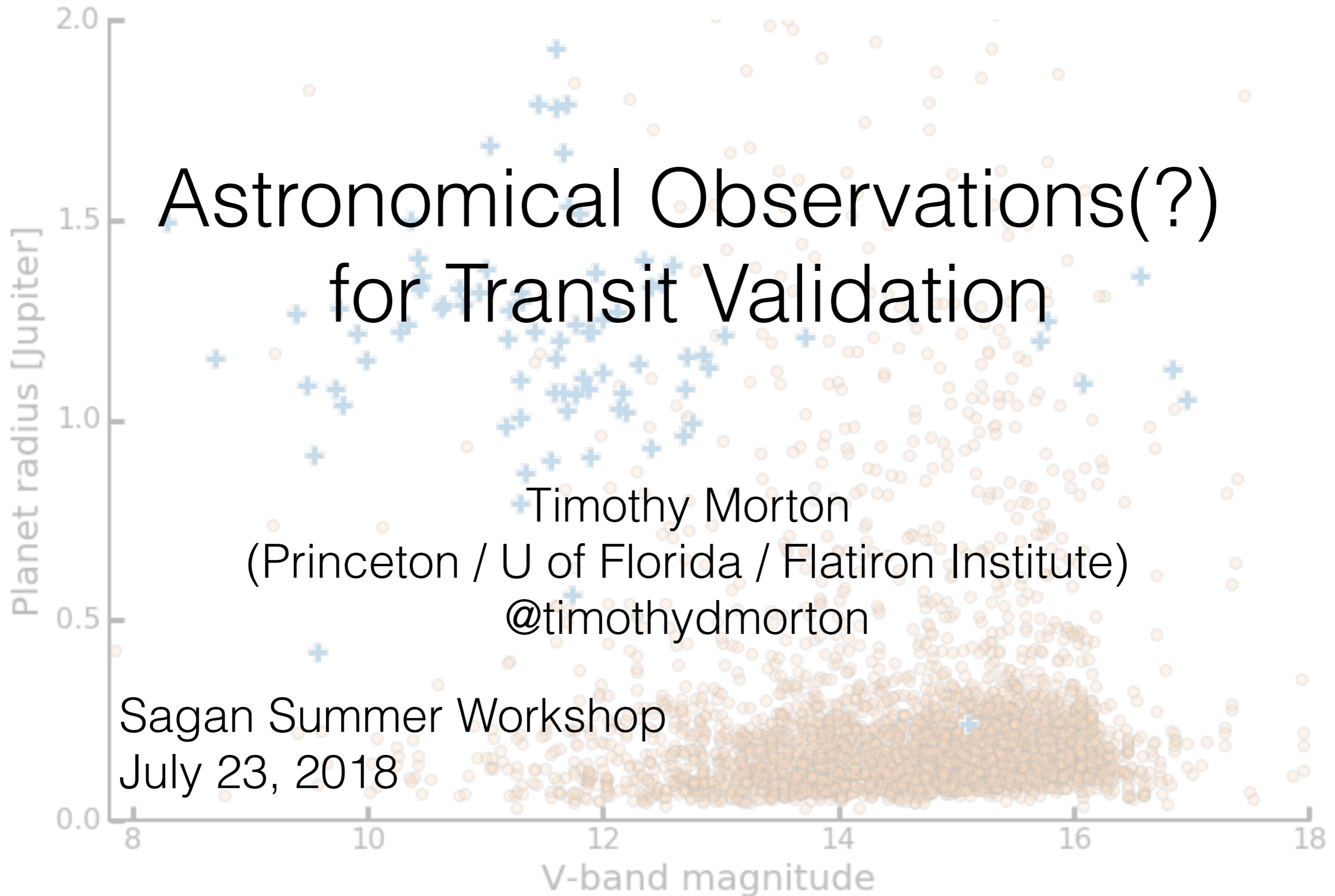


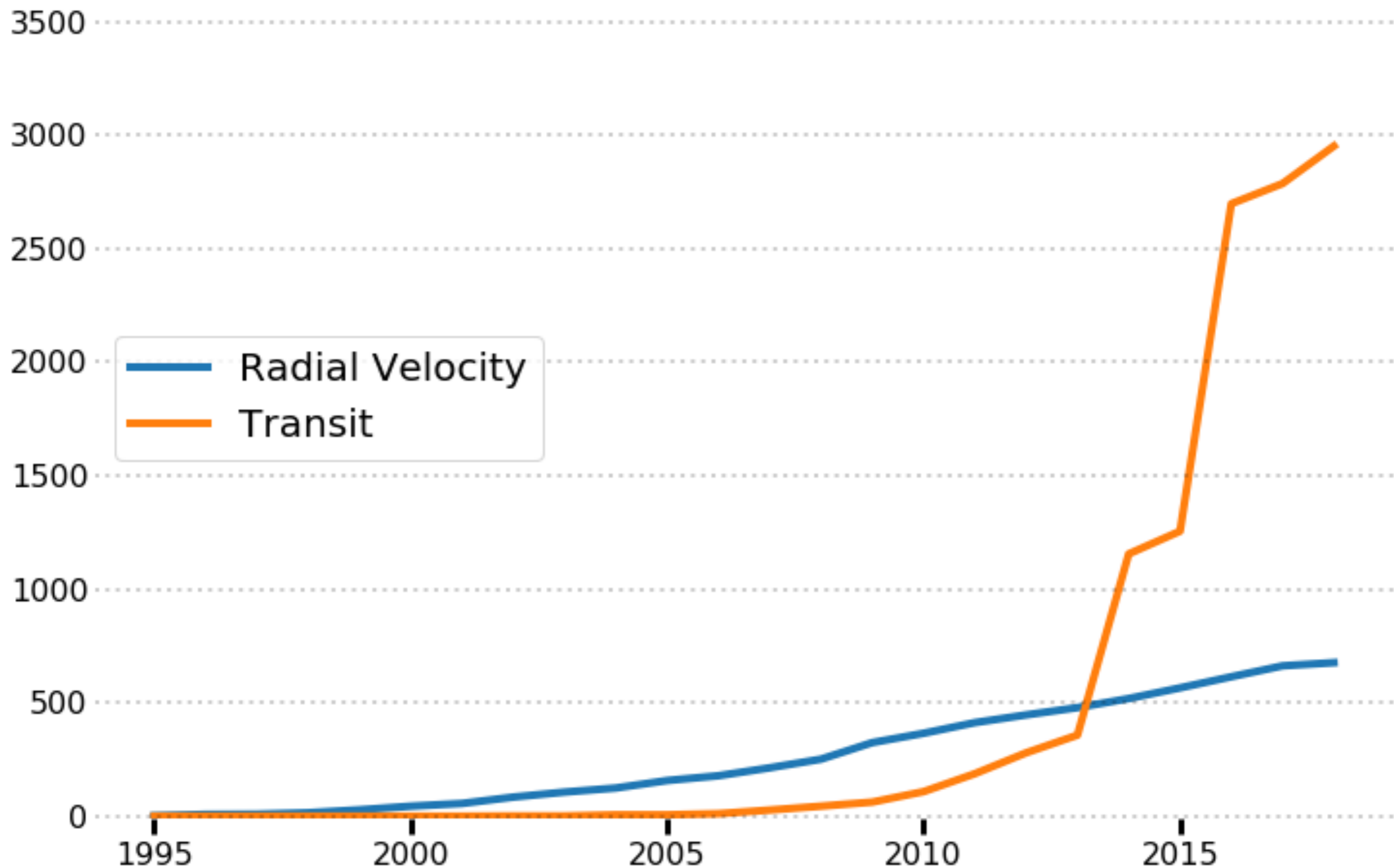
Astronomical Observations(?) for Transit Validation

Timothy Morton
(Princeton / U of Florida / Flatiron Institute)
@timothydmorton

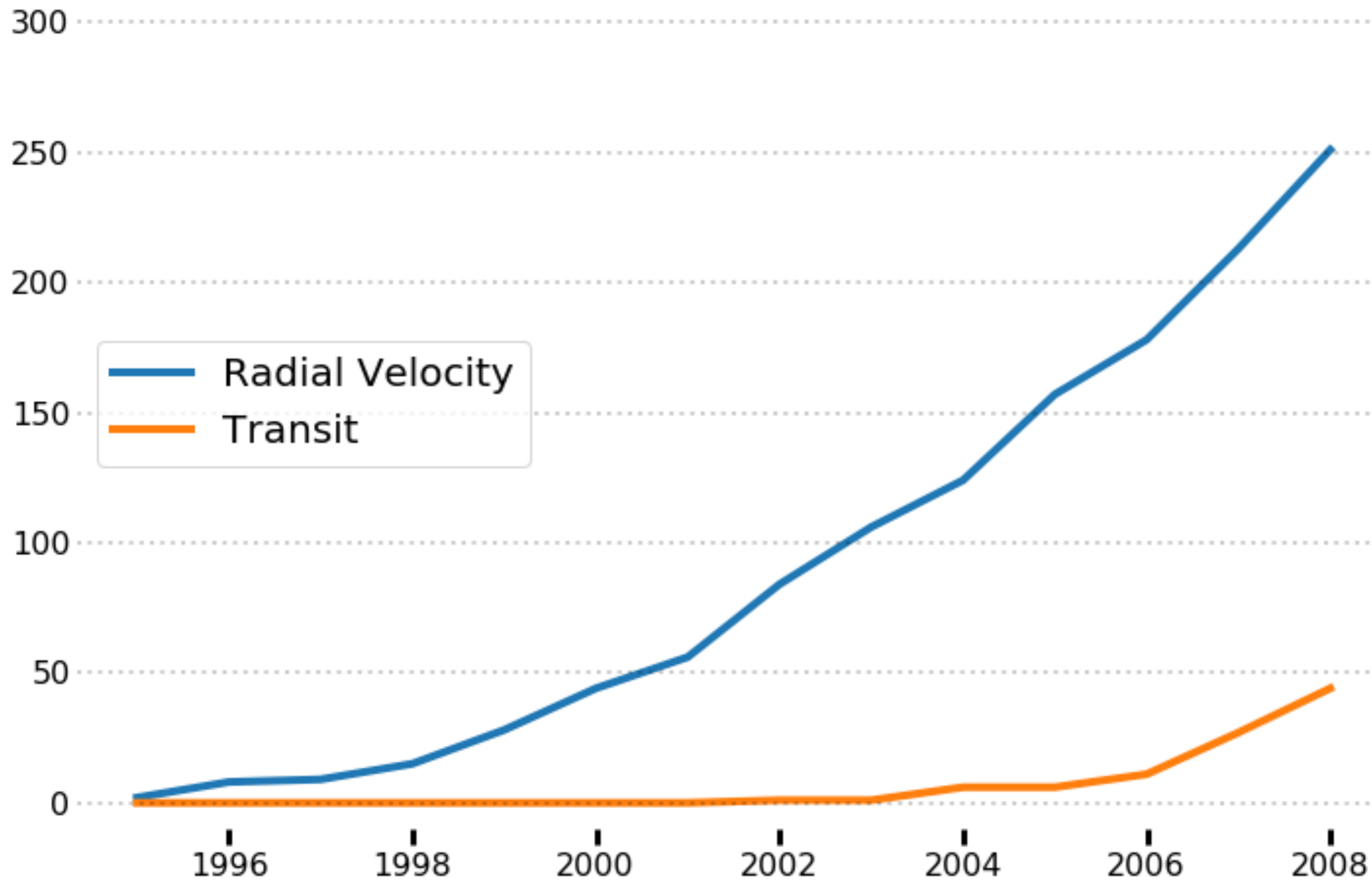
Sagan Summer Workshop
July 23, 2018



Cumulative number of known exoplanets (2018)



Cumulative number of known exoplanets (2008)



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Example Tables and Save... | Orbit Database Kepler Other | Filter: DATE < 2006 and TRANSIT 12/2933 | Export

Name	Msin(i) mjupiter ±	Semi-Major Axis au ±	Orbital Period day ±	Orbital Eccentricity ±	Velocity Semi-amplitude m/s ±	First Reference
OGLE-TR-10 b	0.63	0.0435	3.101290	0	80	Konacki 2005
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GJ 436 b	0.0726	0.02872	2.643850	0.160	18.34	Butler 2004
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Exoplanets Data Explorer | x Tim

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Exoplanets Data Explorer | x Tim

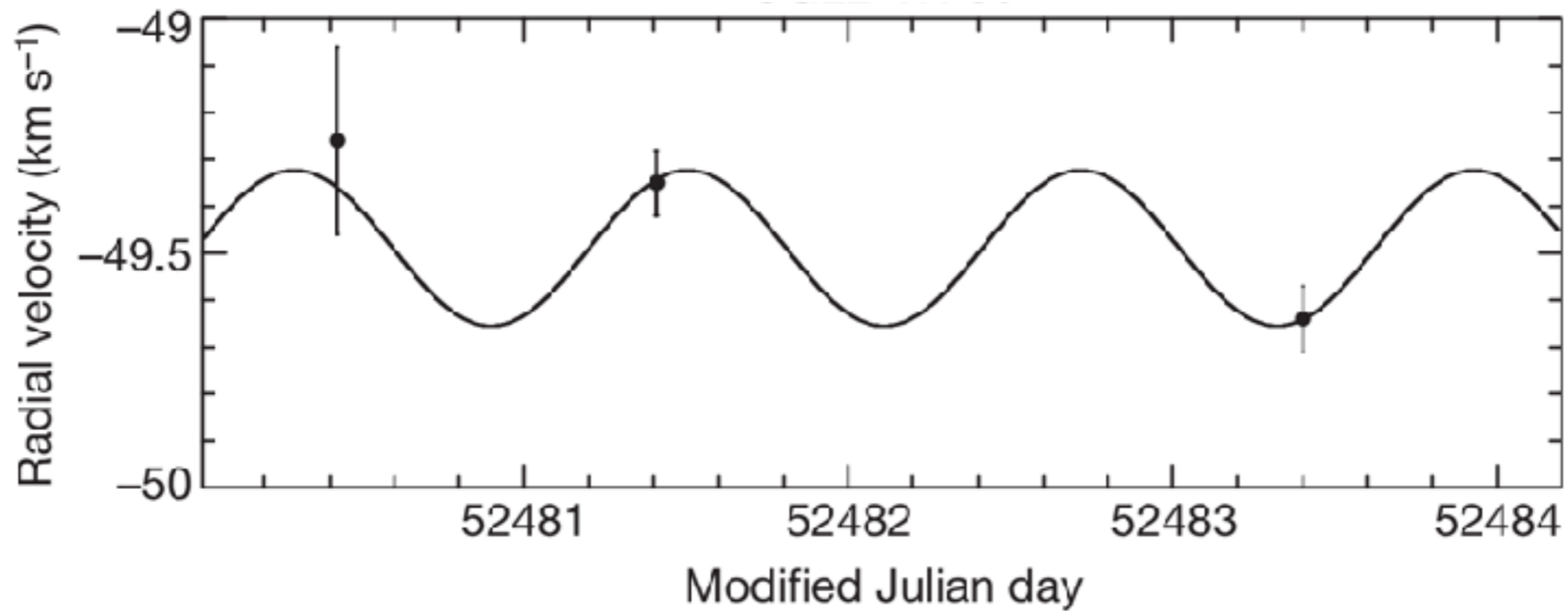
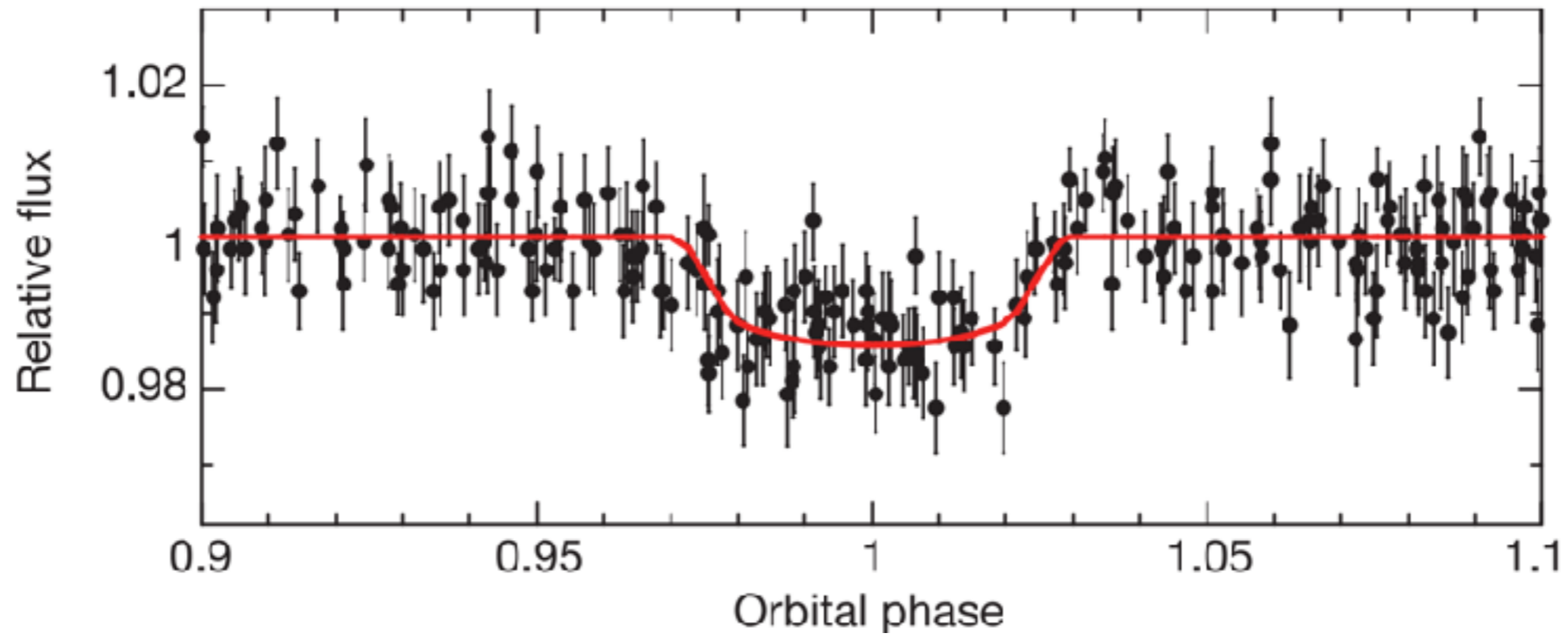
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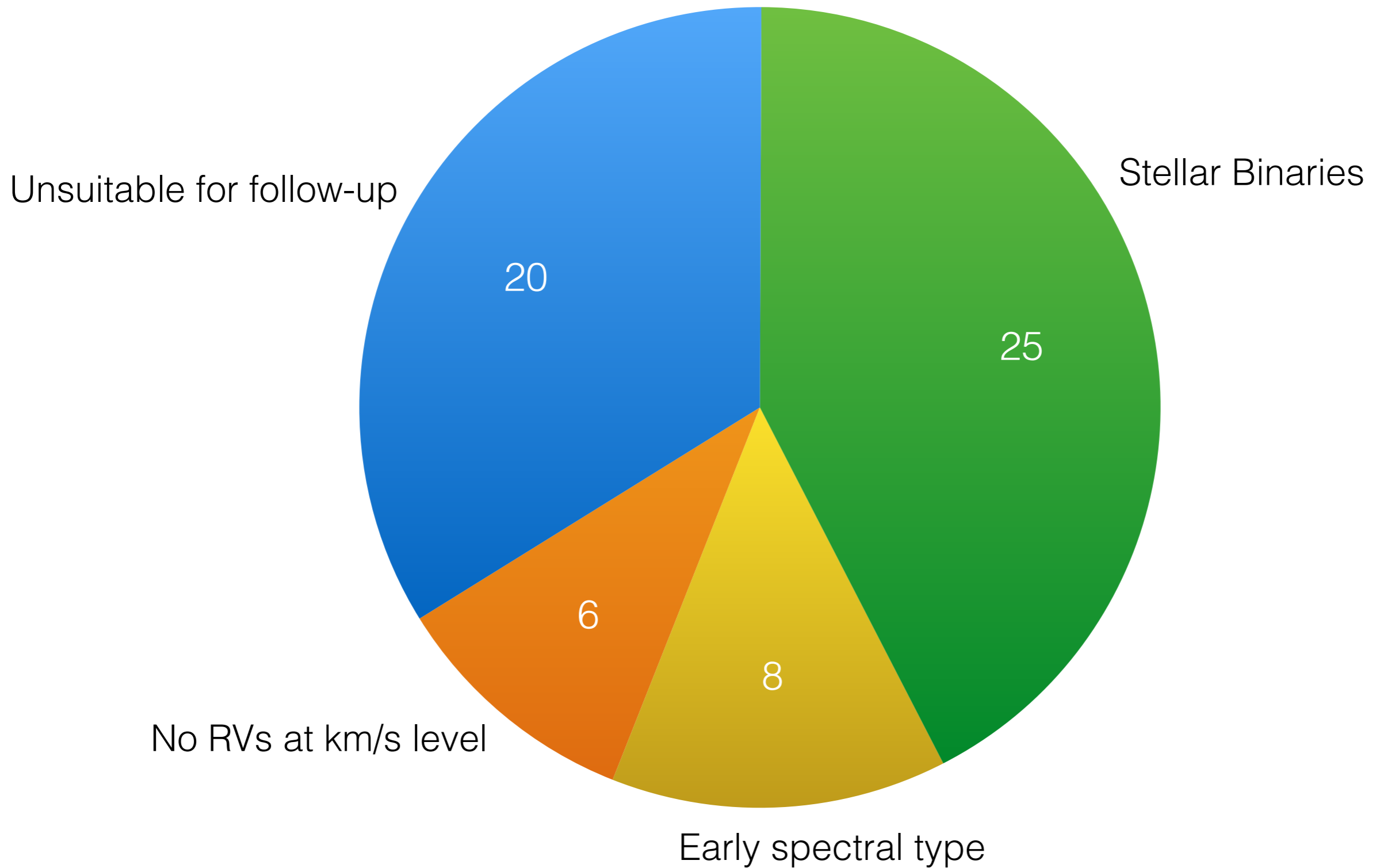
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OGLE-TR-56b



OGLE planet candidates, c.2004



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Exoplanets Data Explorer | x

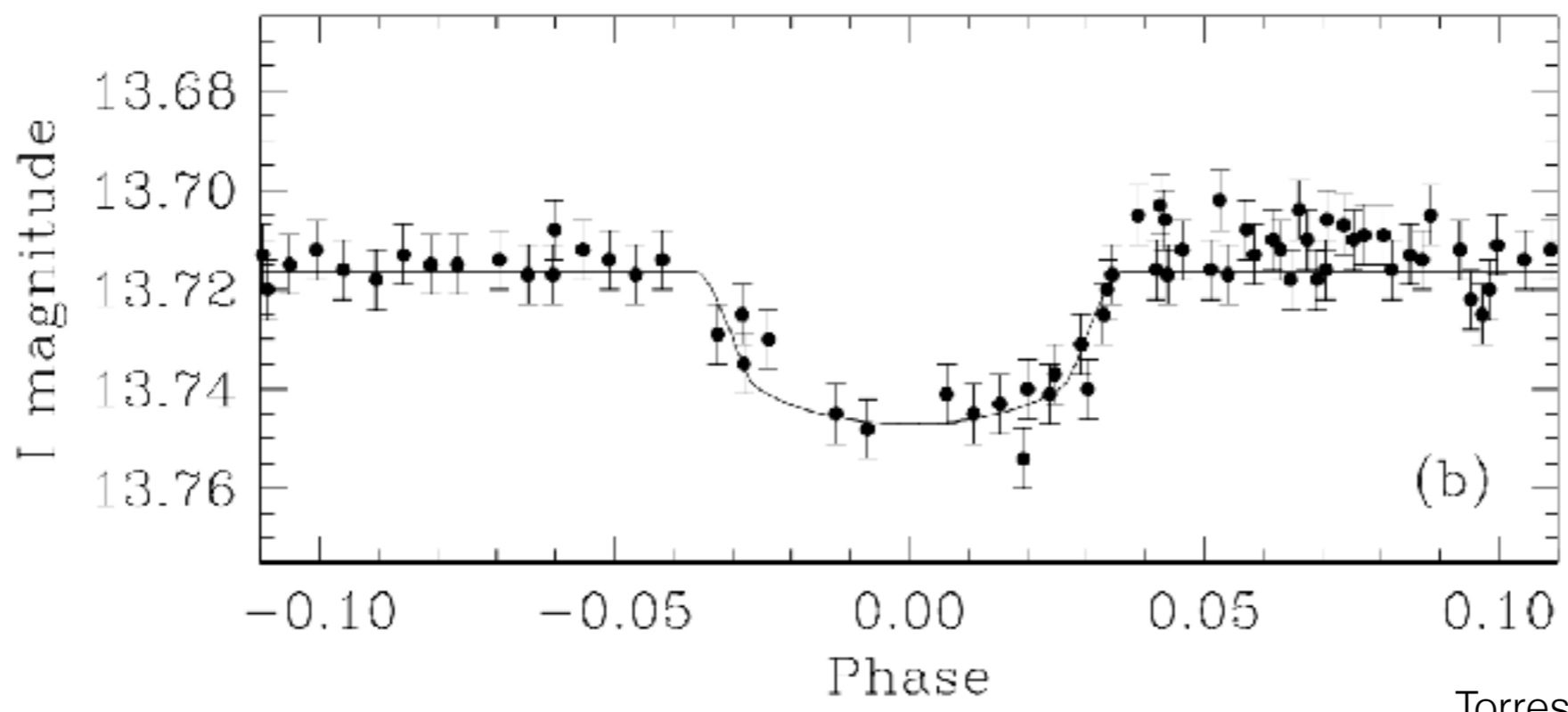
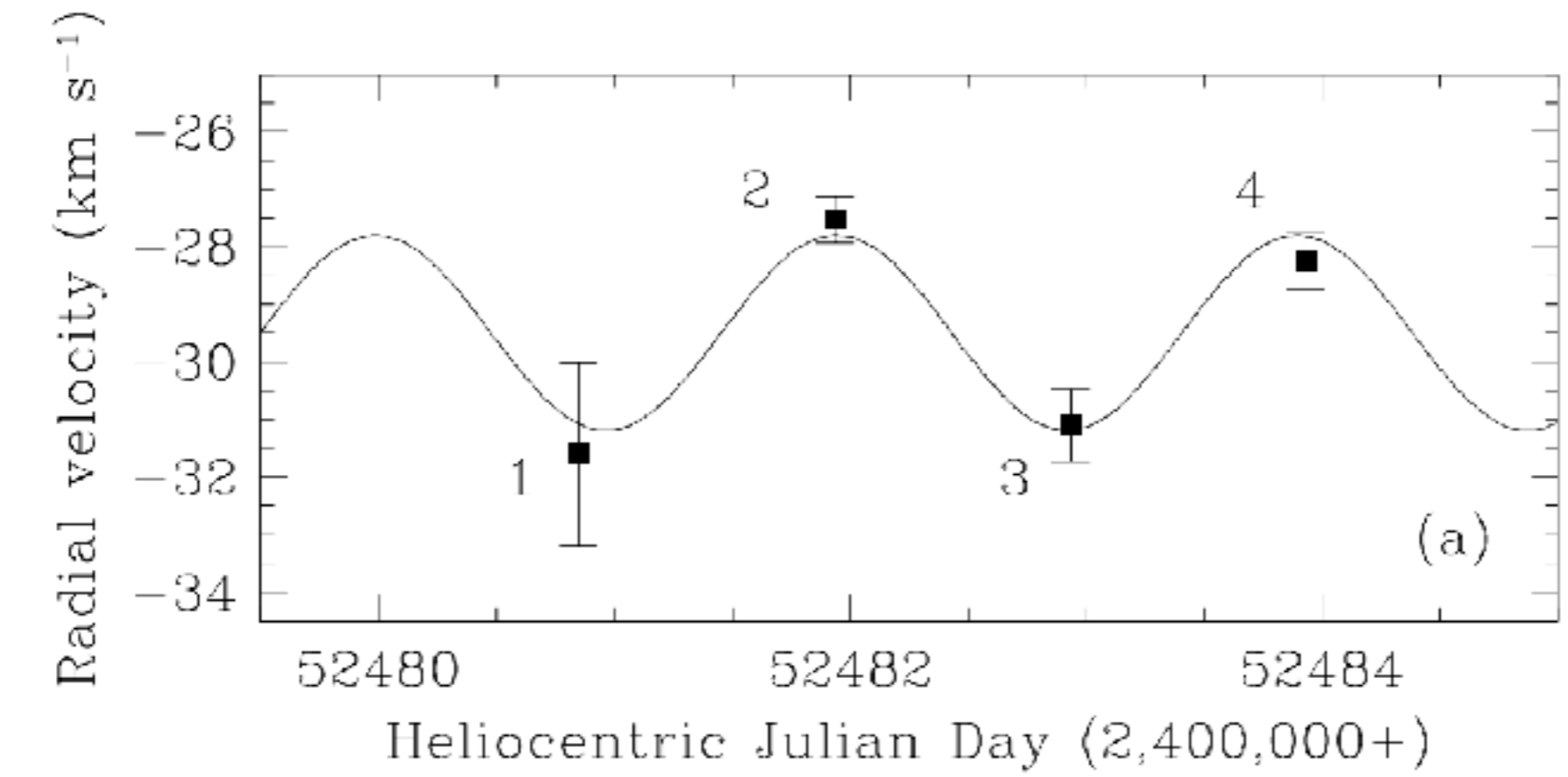
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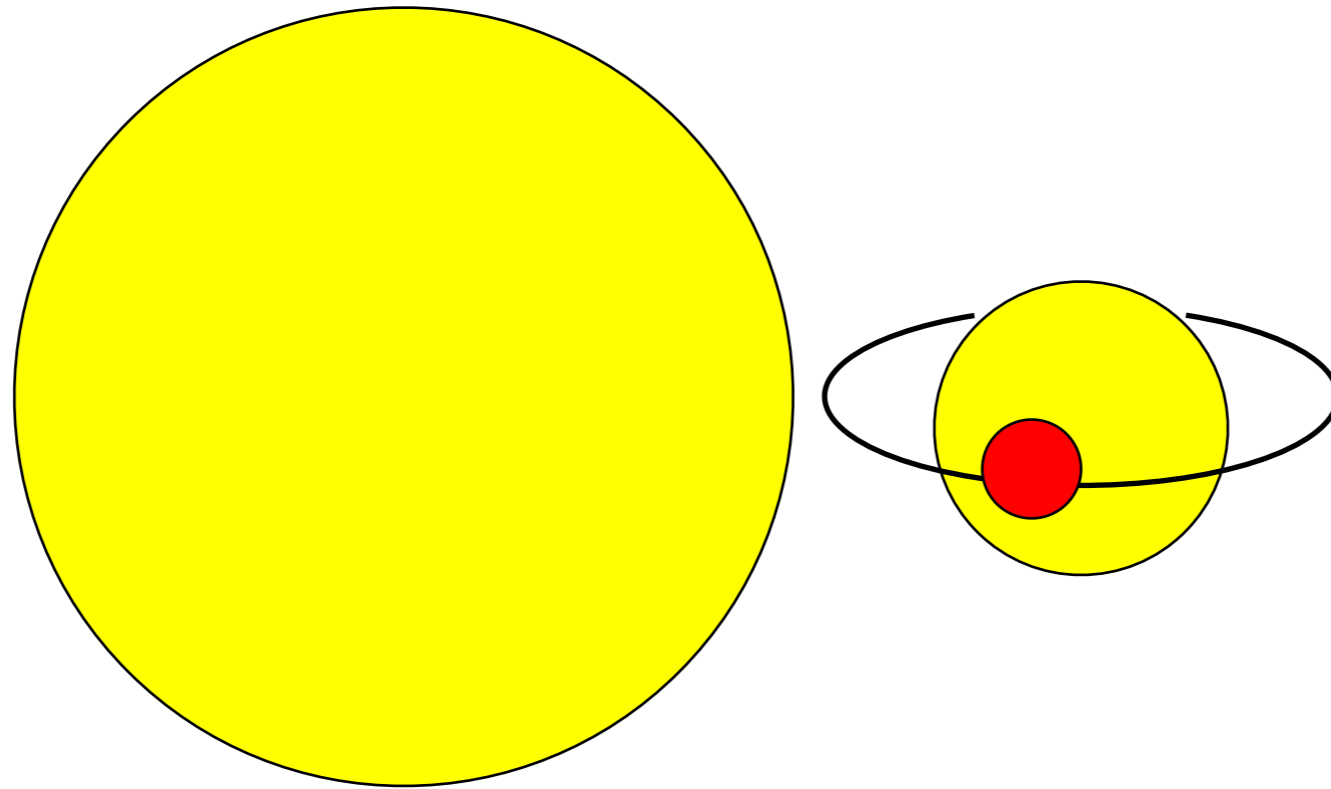
Exoplanets Data Explorer Table Plots Send data reports to: datamaster@exoplanets.org and bug reports to: webmaster@exoplanets.org Help

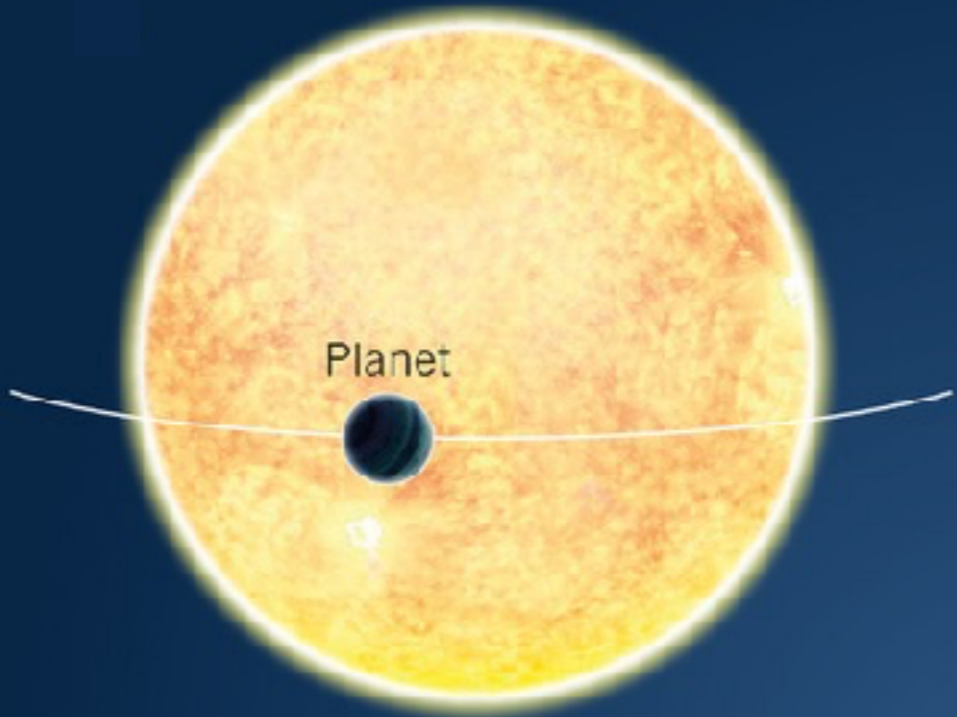
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OGLE-TR-33						Torres 2004

OGLE-TR-33

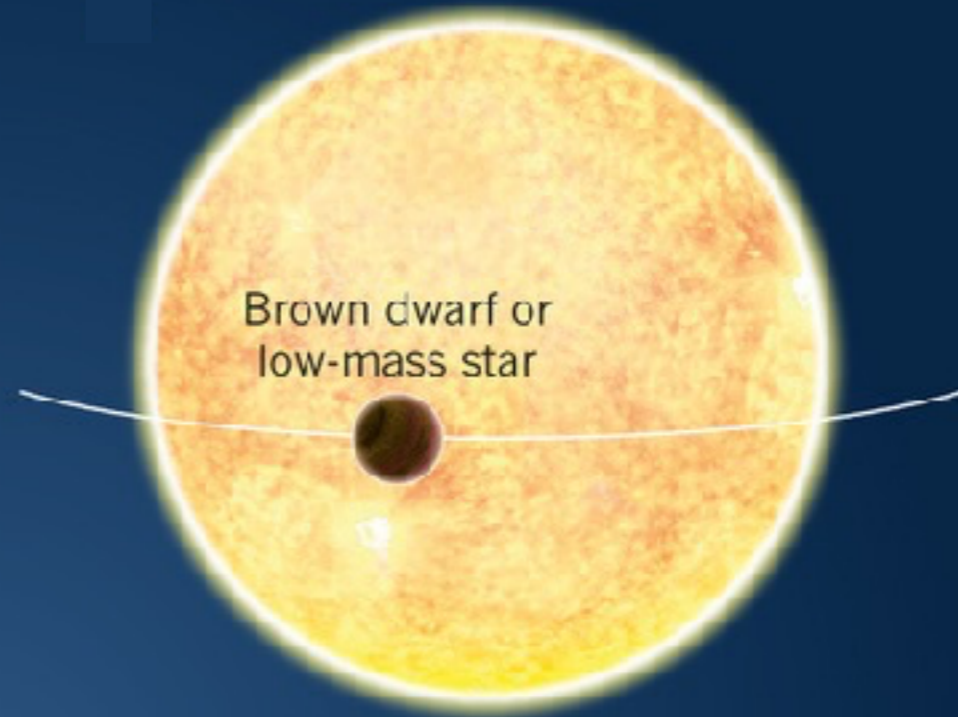




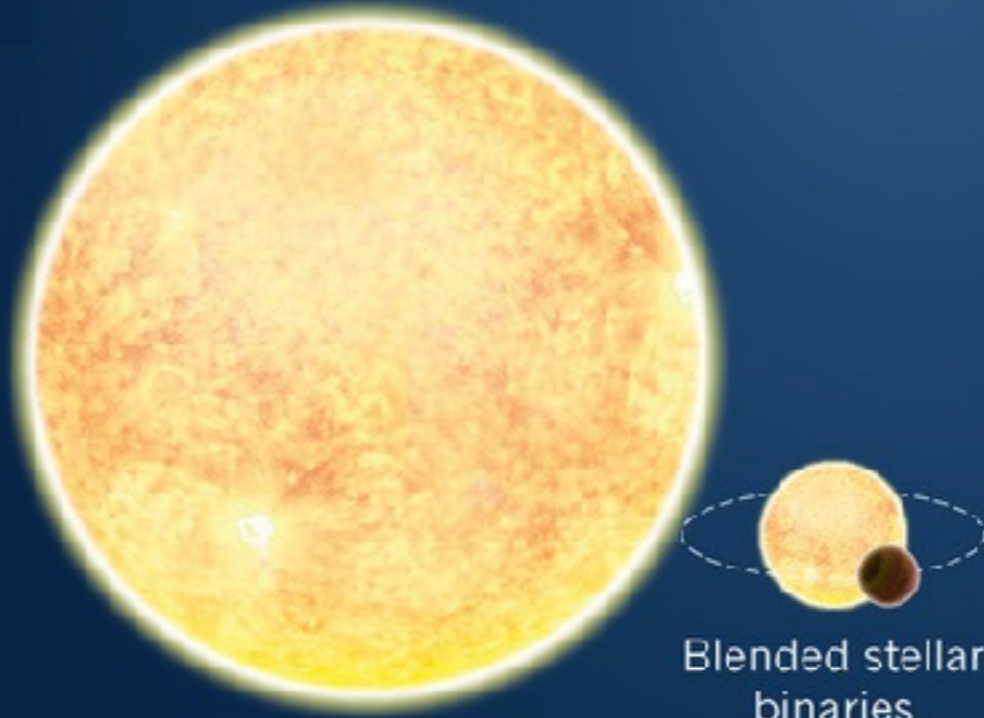


Planet

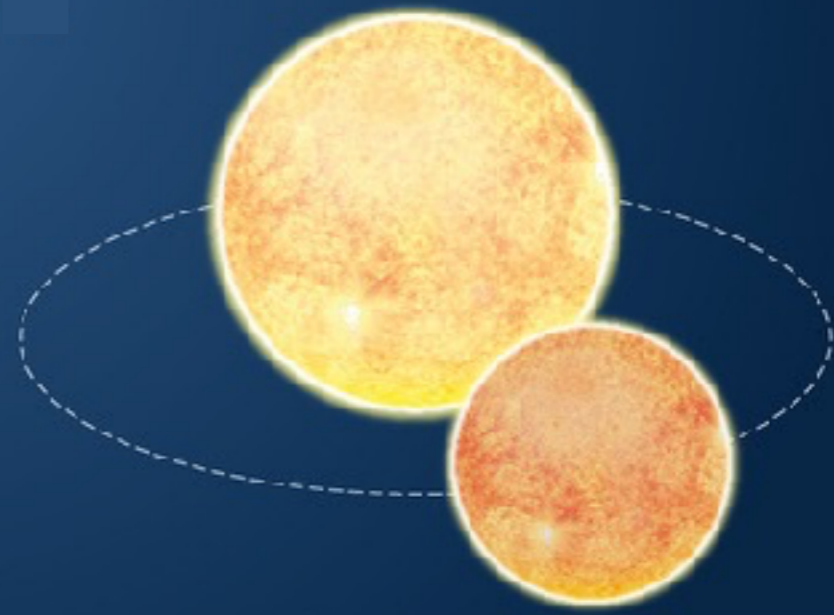
Star



Brown dwarf or
low-mass star

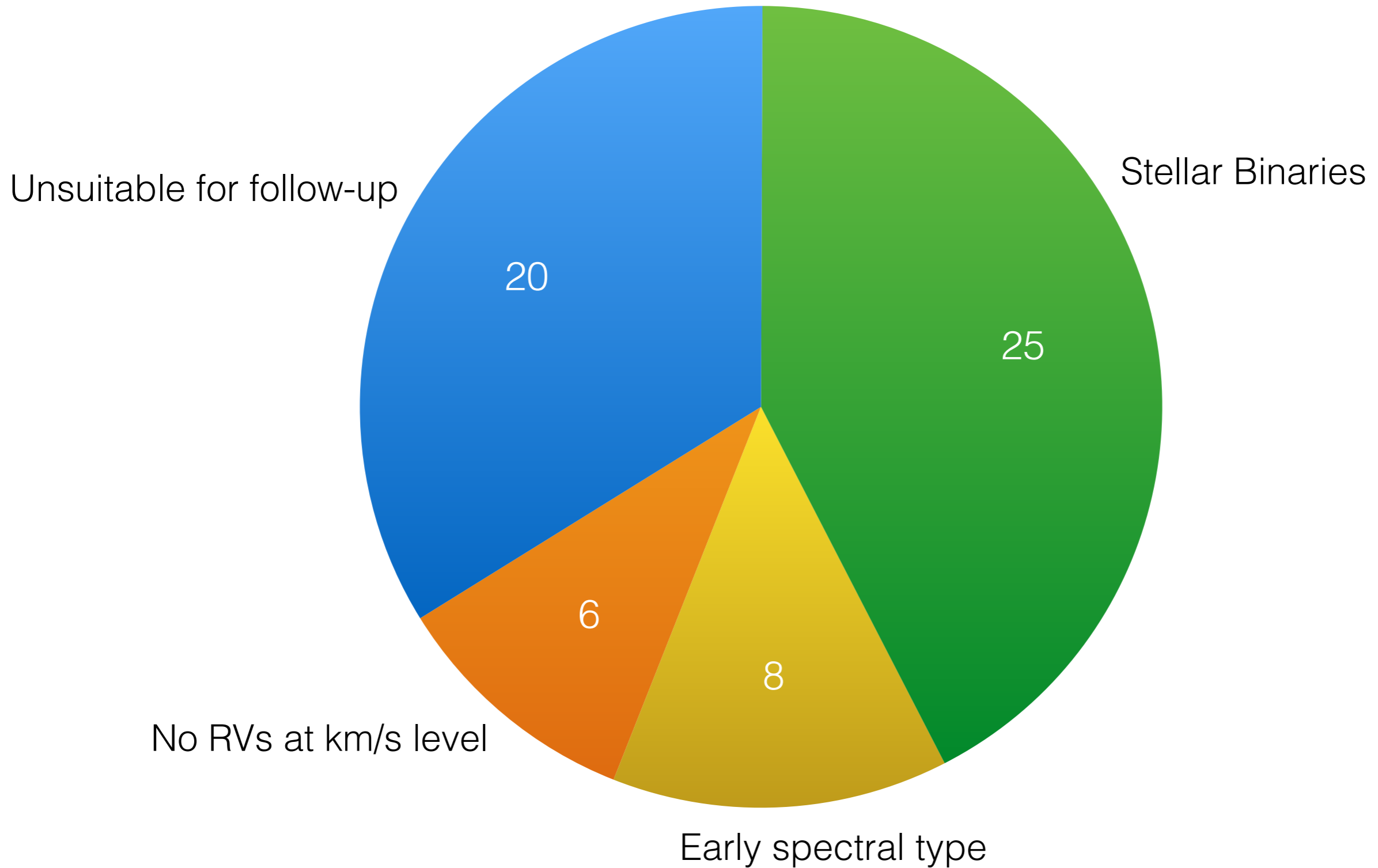


Blended stellar
binaries





Grazing stellar
binaries

OGLE planet candidates, c.2004



Follow-up observations for transit follow-up & confirmation

- Follow-up photometry, possibly in multiple filters
 - Is depth color-dependent?
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OGLE-TR-33						Torres 2004

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Example Tables and Save... | Orbit Database Kepler Other | Filter: 12/2933 | Export

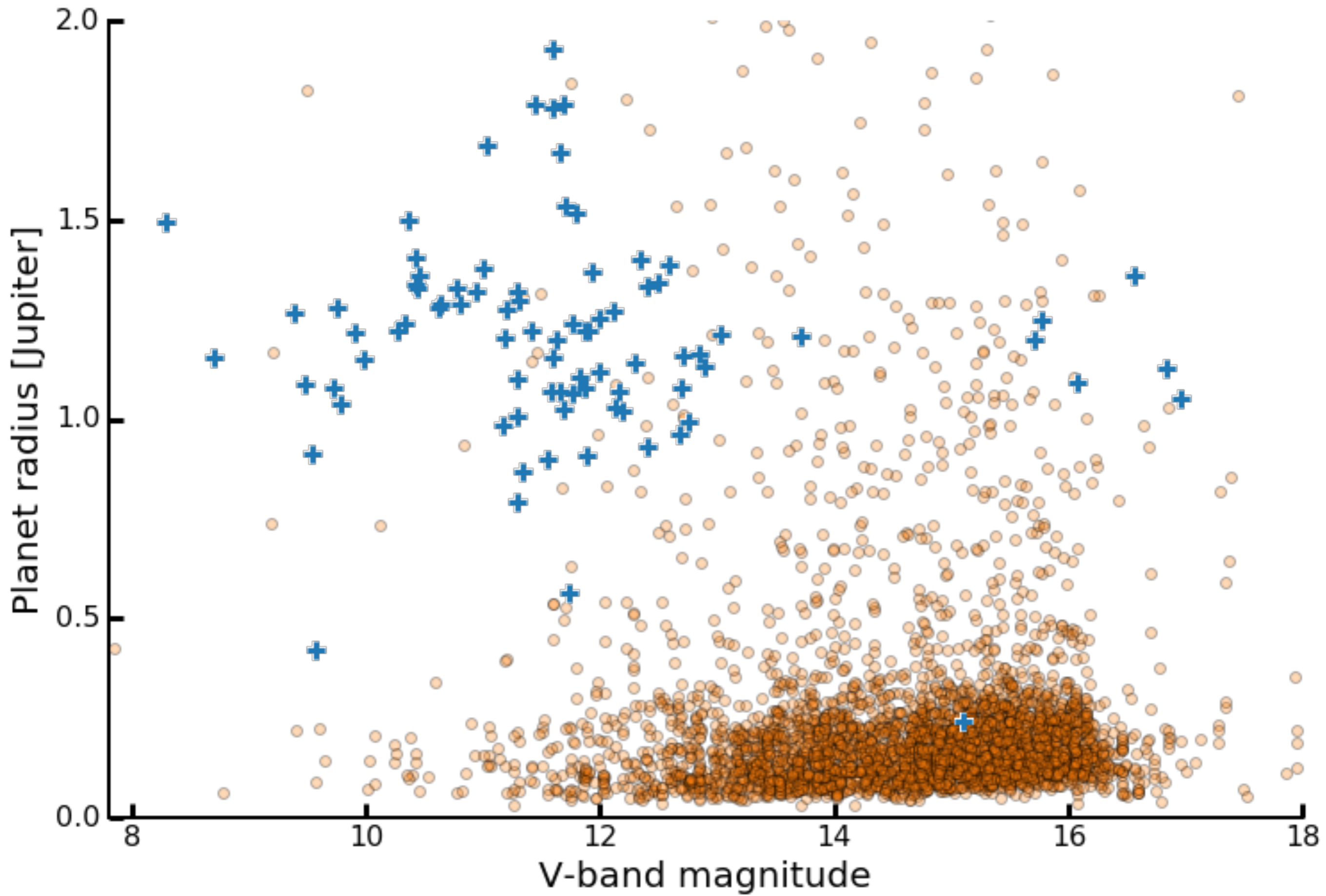
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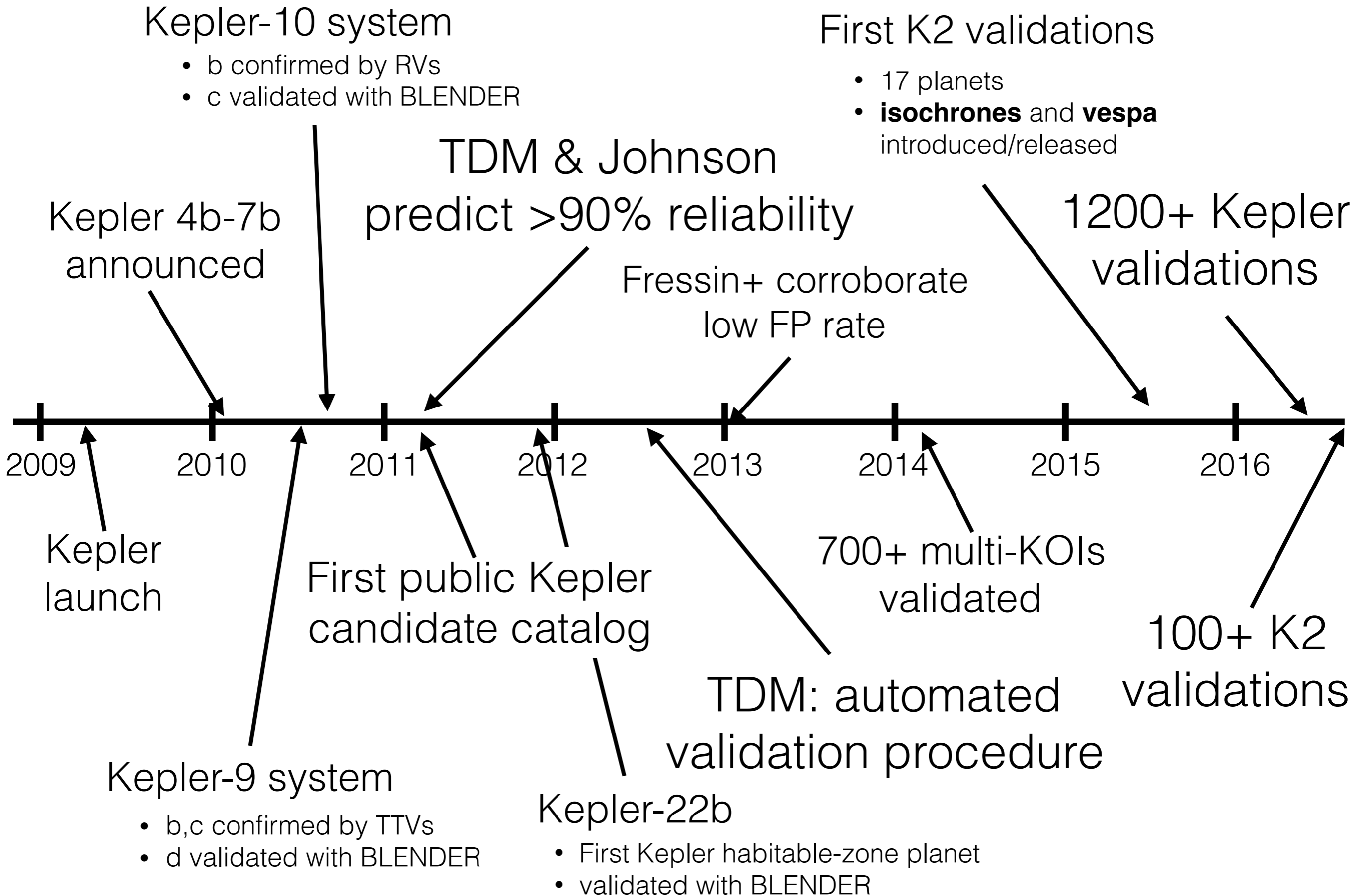
TRES-1 b

Alonso+ (2004)

- $V = 11.4$
- Follow-up observations:
 - H- and K- band AO imaging
 - Medium-resolution spectroscopy (7 epochs)
 - Multi-color transit photometry (3 facilities, 7 filters)
 - Keck/HIRES RV spectroscopy (8 epochs)
- **80% false positive rate** for this survey







Kepler-10 system

- b confirmed by RVs
- c validated with BLENDER

First K2 validations

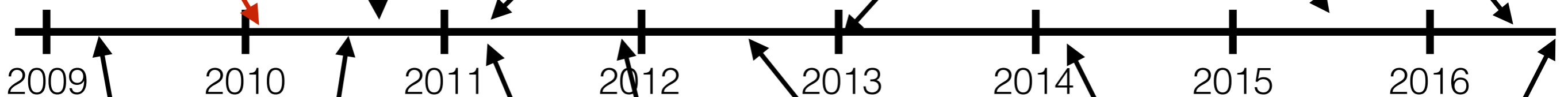
- 17 planets
- **isochrones** and **vespa** introduced/released

TDM & Johnson
predict >90% reliability

Kepler 4b-7b
announced

Fressin+ corroborate
low FP rate

1200+ Kepler
validations



Kepler
launch

First public Kepler
candidate catalog

700+ multi-KOIs
validated

100+ K2
validations

Kepler-9 system

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Kepler-22b

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TDM: automated
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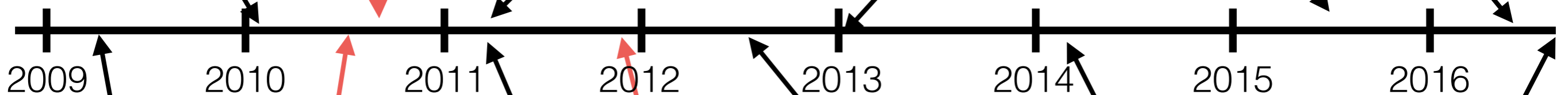
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Kepler
launch

2009

2010

2011

2012

2013

2014

2015

2016



Kepler-22b

Borucki et al. (2011):

- Imaging from 3 different facilities (seeing-limited, speckle, AO)
- Keck/HIRES spectroscopy at 17 epochs
- 17 hours of *Warm Spitzer* observation to measure transit color dependence
- BLENDER analysis



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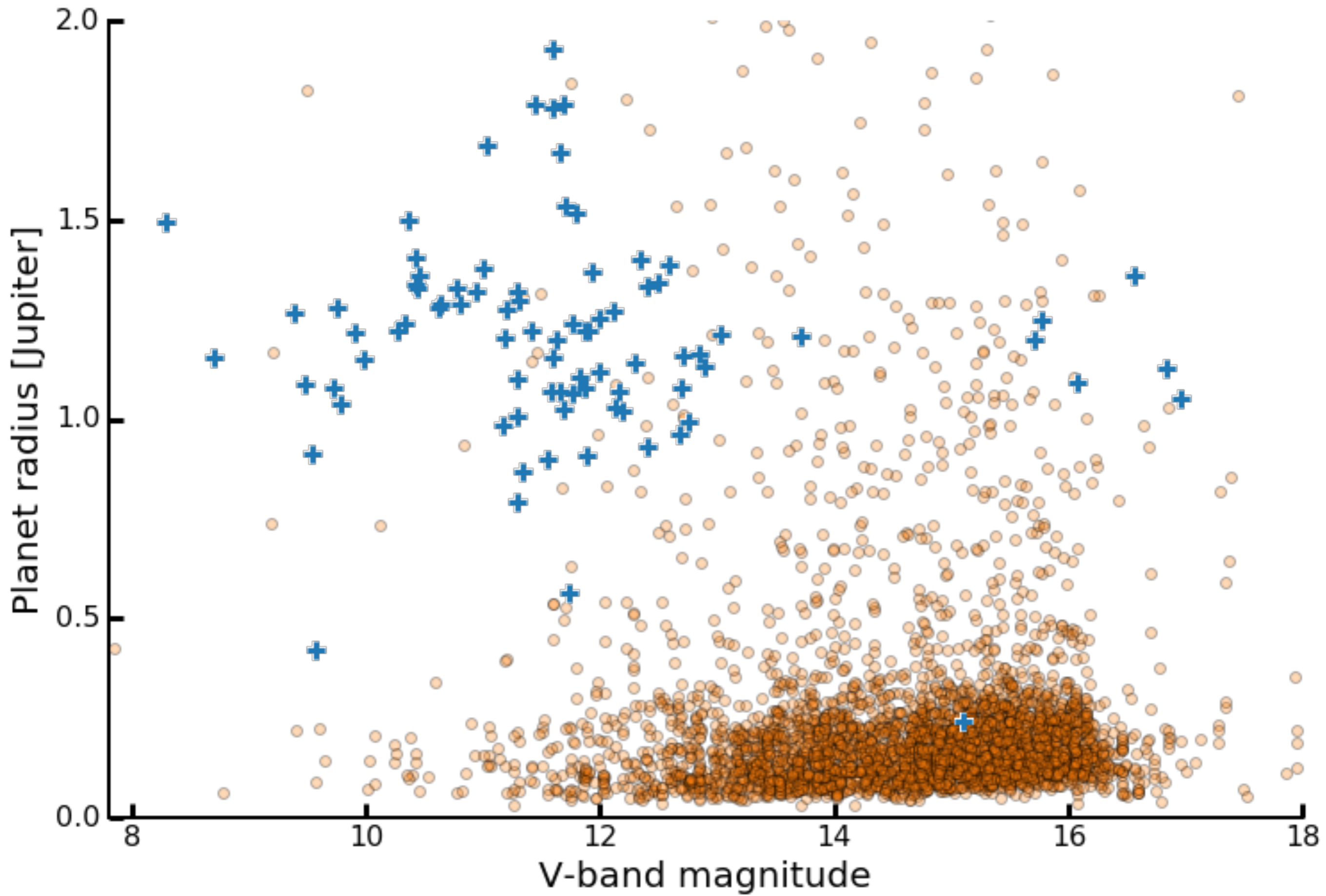
Vetting

- Measure the mass of the planet?

Probabilistic arguments



Confirmation!
Validation!



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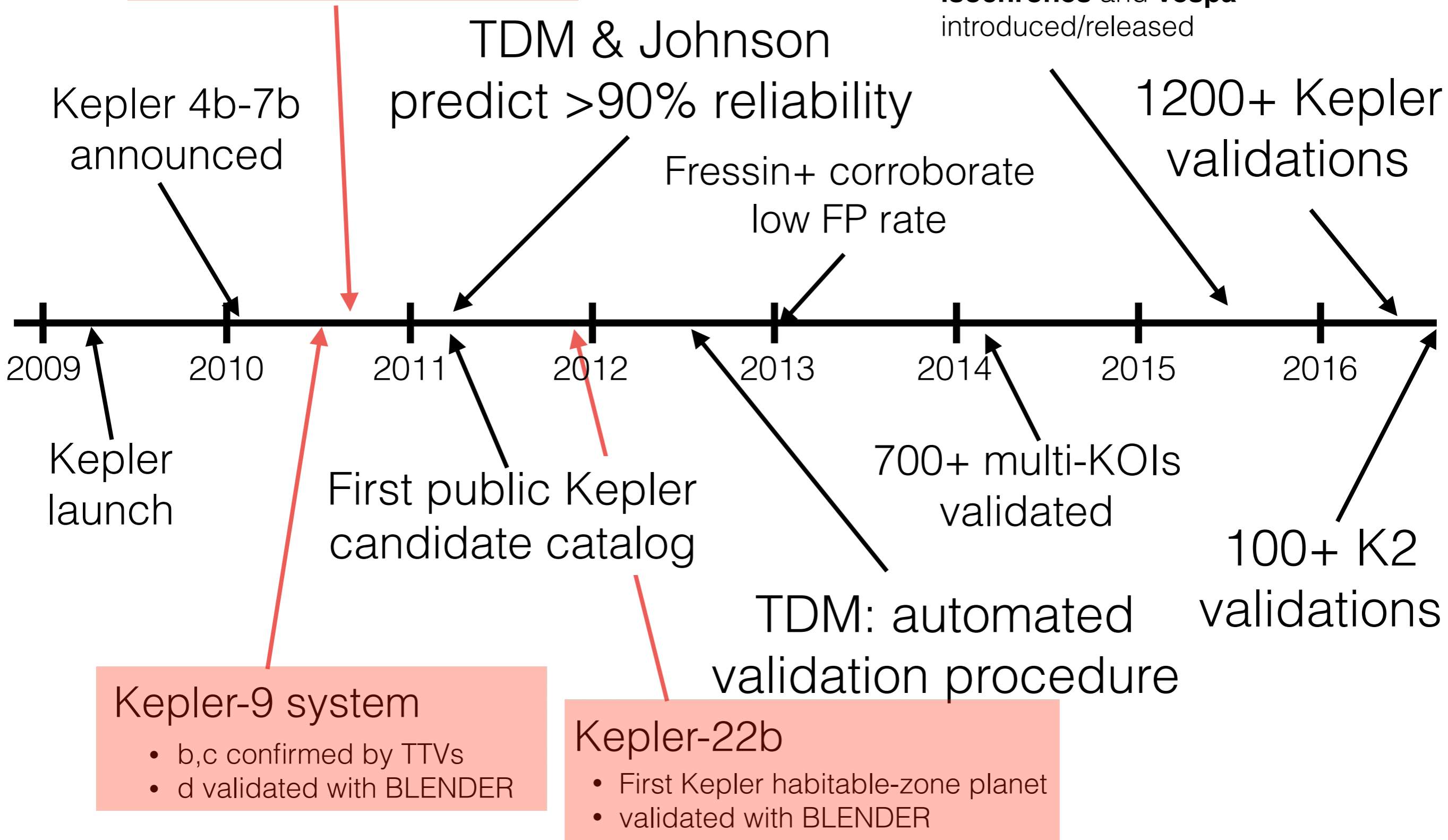
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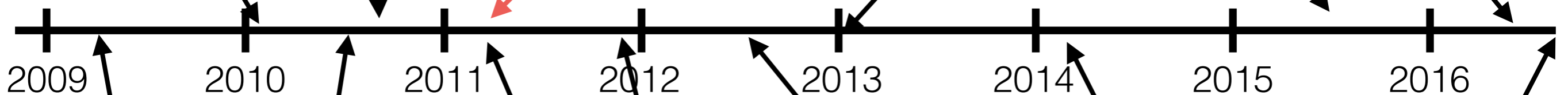
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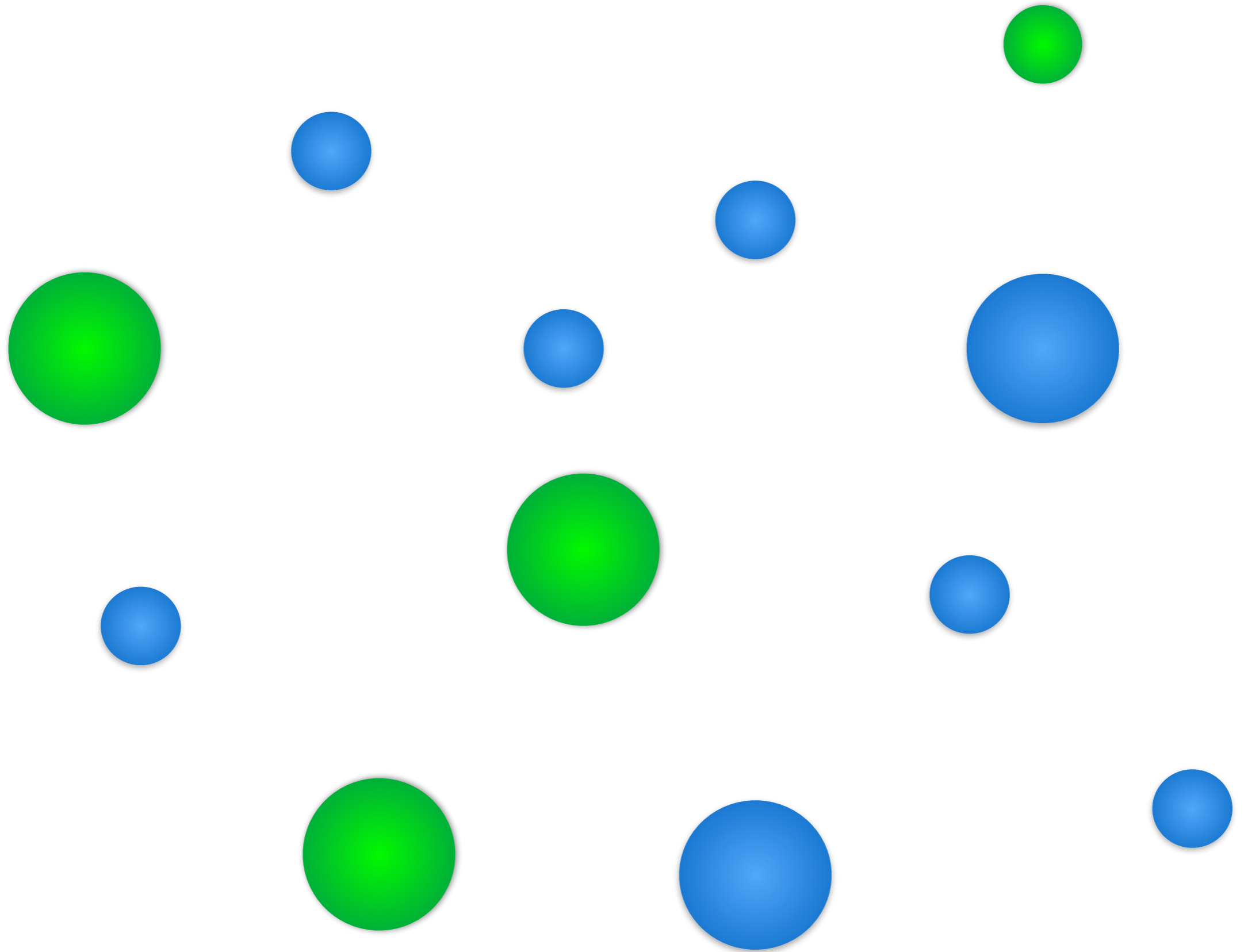
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$$\{H_i\} = \{\text{planet}, \text{FP}_1, \text{FP}_2, \dots\}$$

$$p(H_i | \text{data}) = \frac{\mathcal{L}_i(\text{data} | H_i)\pi(H_i)}{\sum_j \mathcal{L}_j(\text{data} | H_j)\pi(H_j)}$$

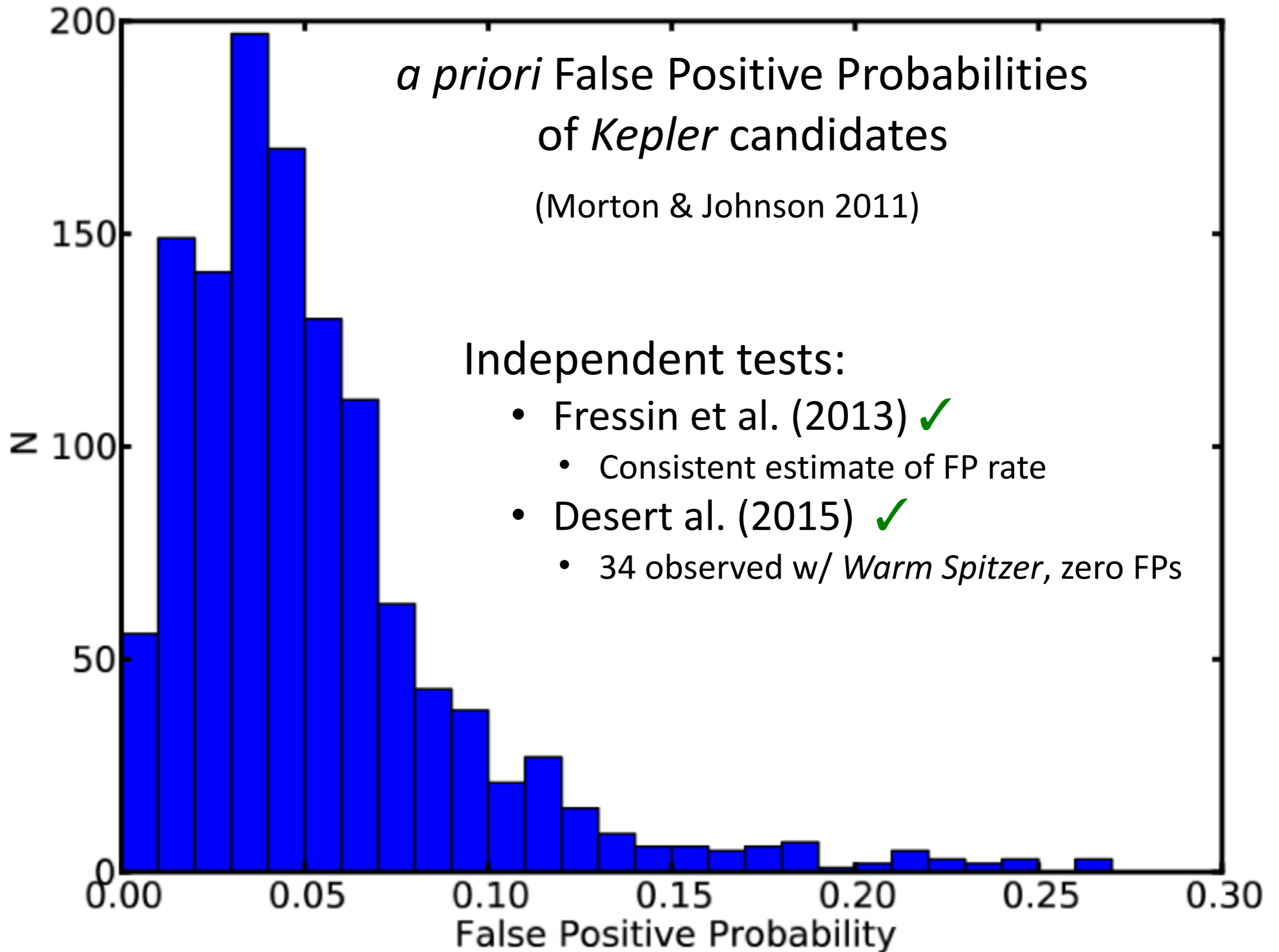
$$\mathcal{L}_i \quad \pi(H_i)$$

a priori False Positive Probabilities
of *Kepler* candidates

(Morton & Johnson 2011)

Independent tests:

- Fressin et al. (2013) ✓
 - Consistent estimate of FP rate
- Desert et al. (2015) ✓
 - 34 observed w/ *Warm Spitzer*, zero FPs



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First K2 validations

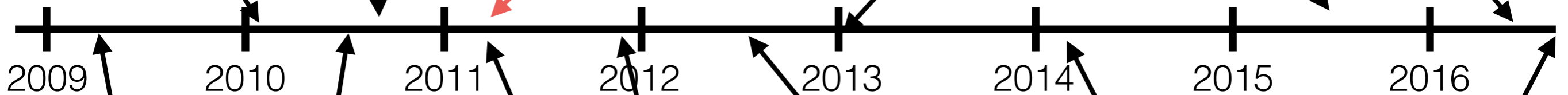
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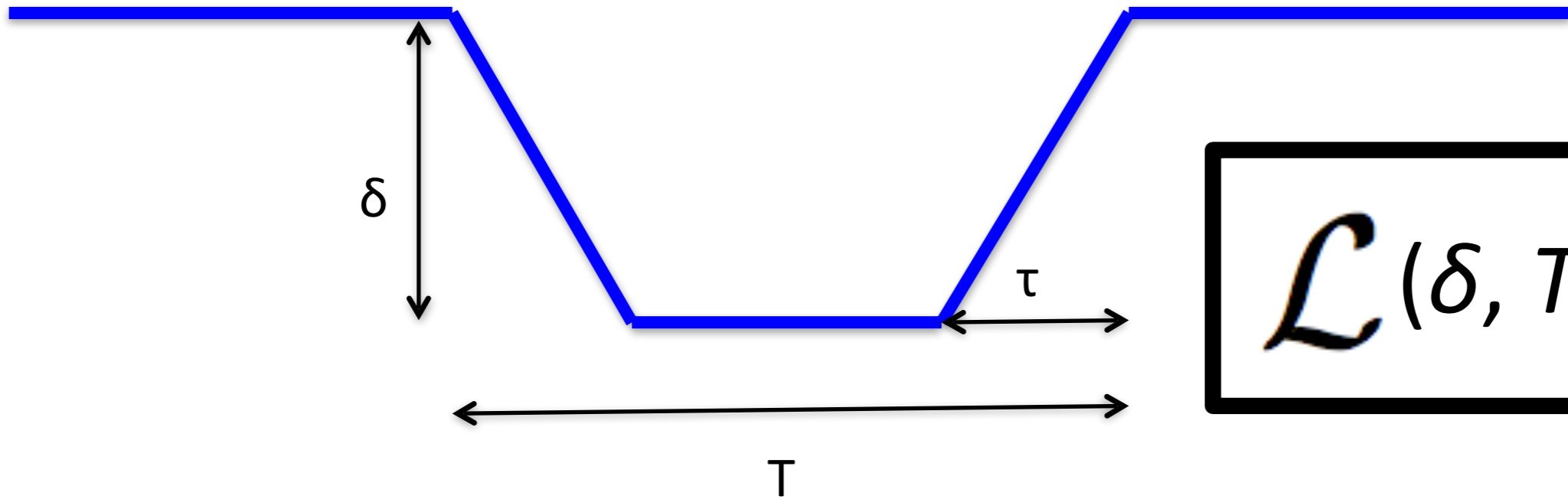
TDM: automated
validation procedure

light curve shape

Planet



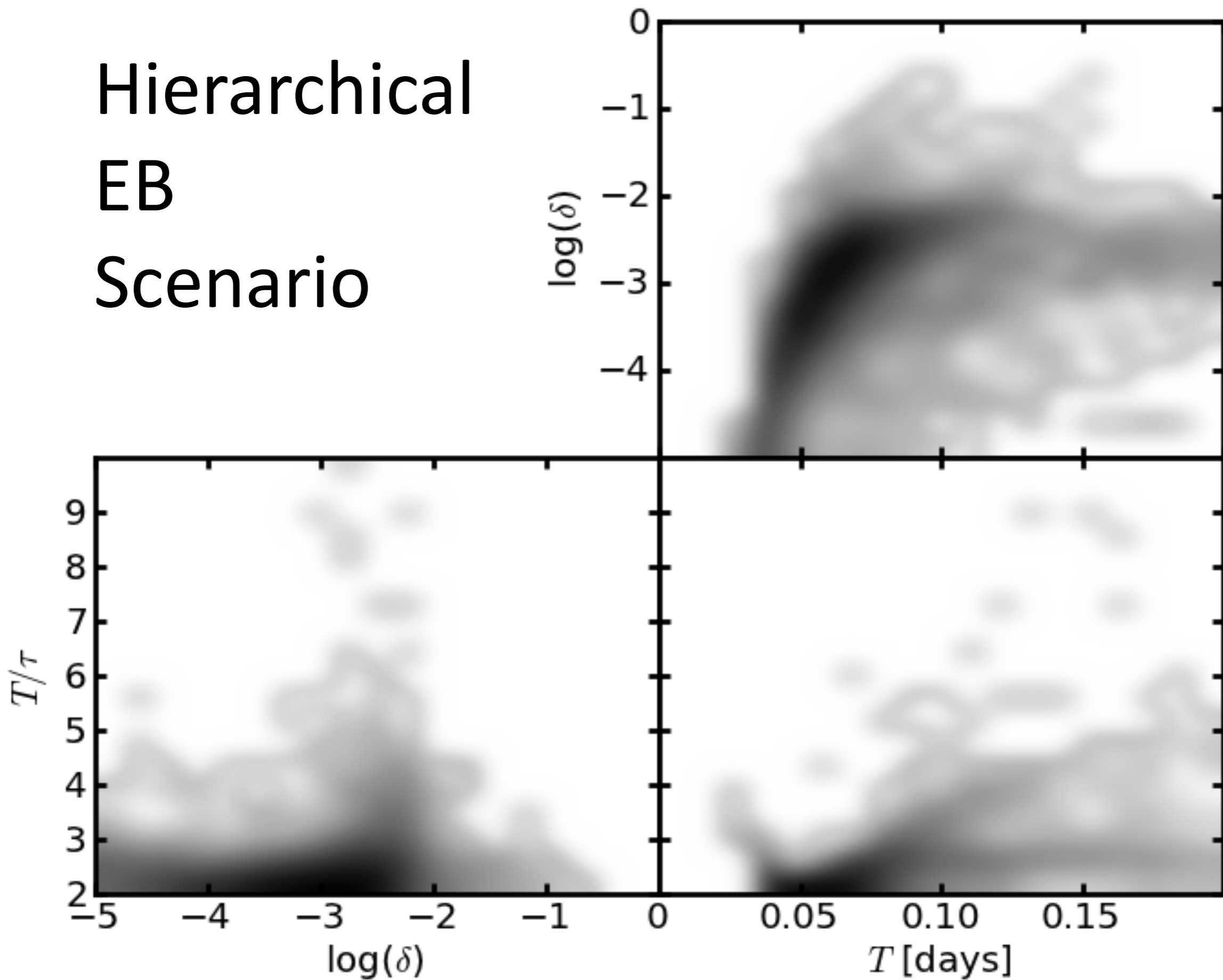
Stellar EB



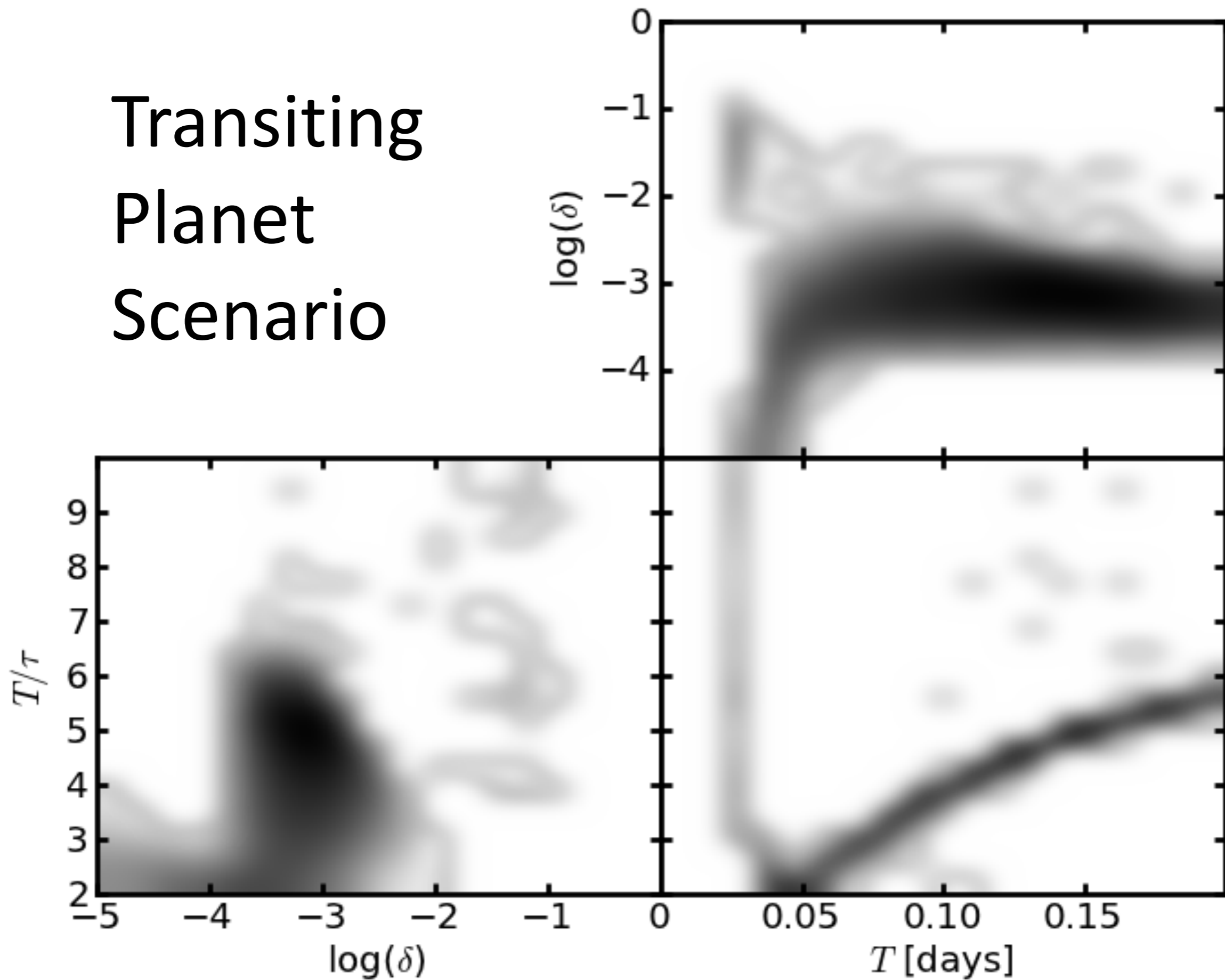
$$\mathcal{L}(\delta, T, T/\tau)$$

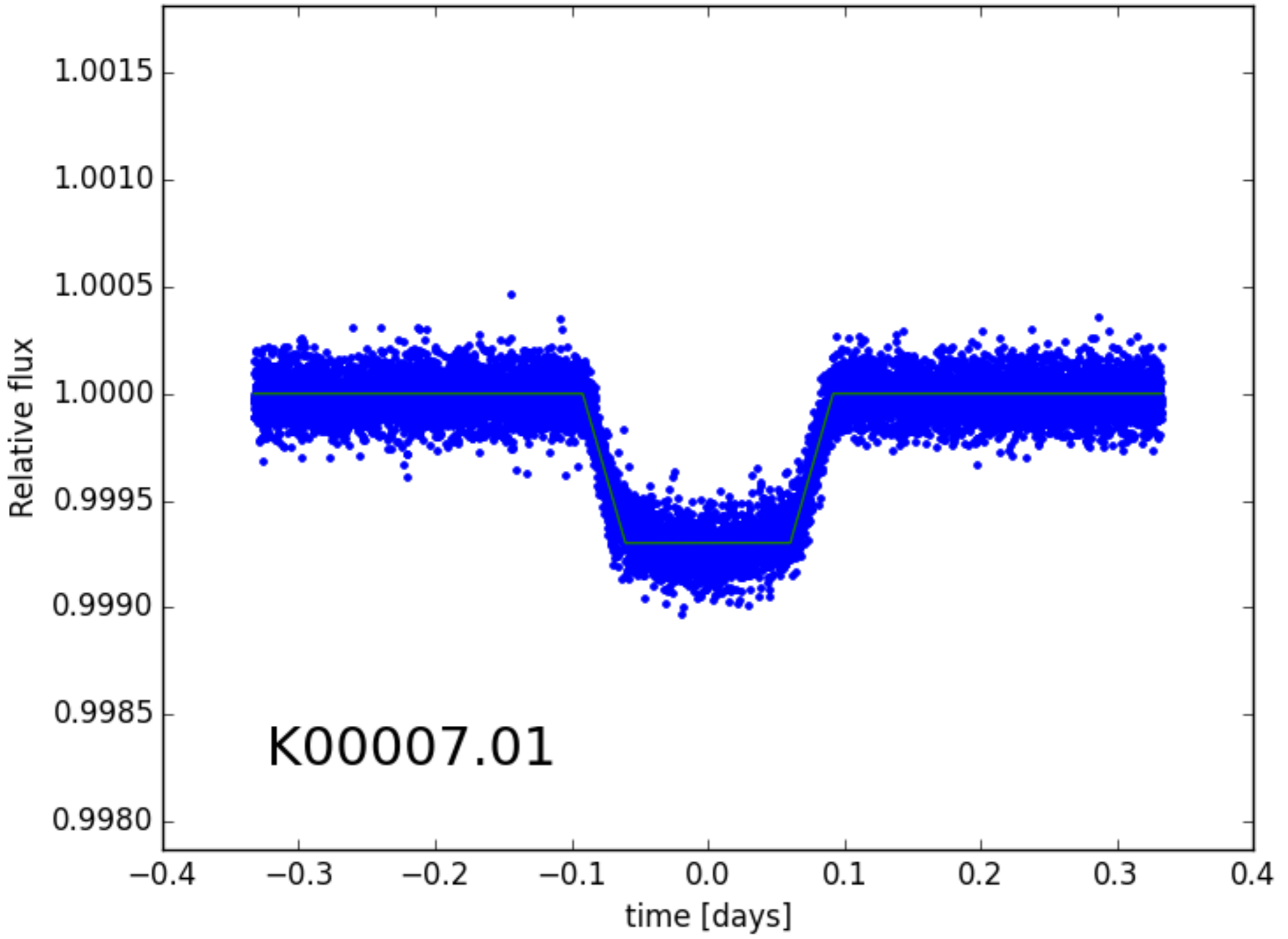
Simulate representative populations

Hierarchical EB Scenario



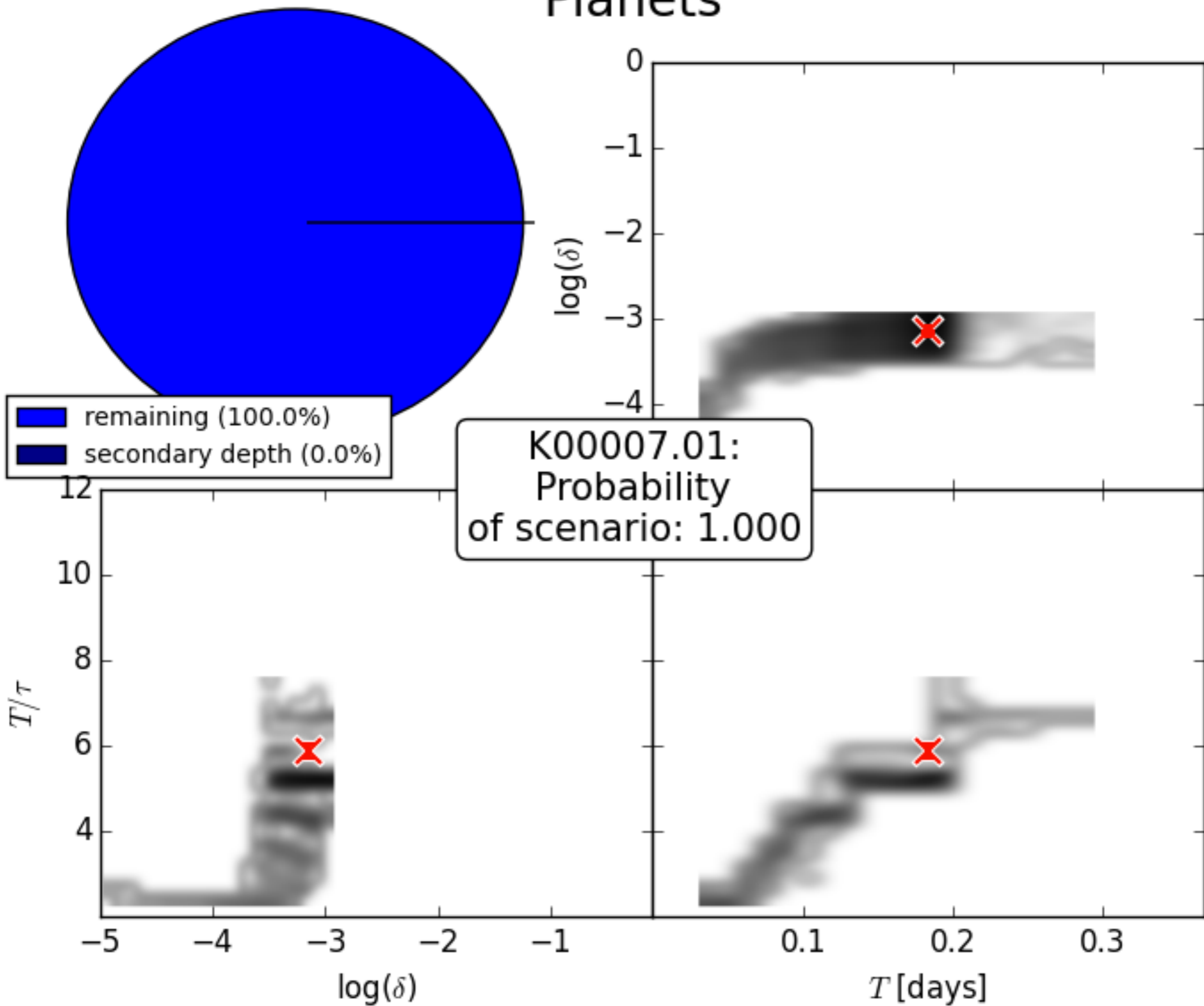
Transiting Planet Scenario



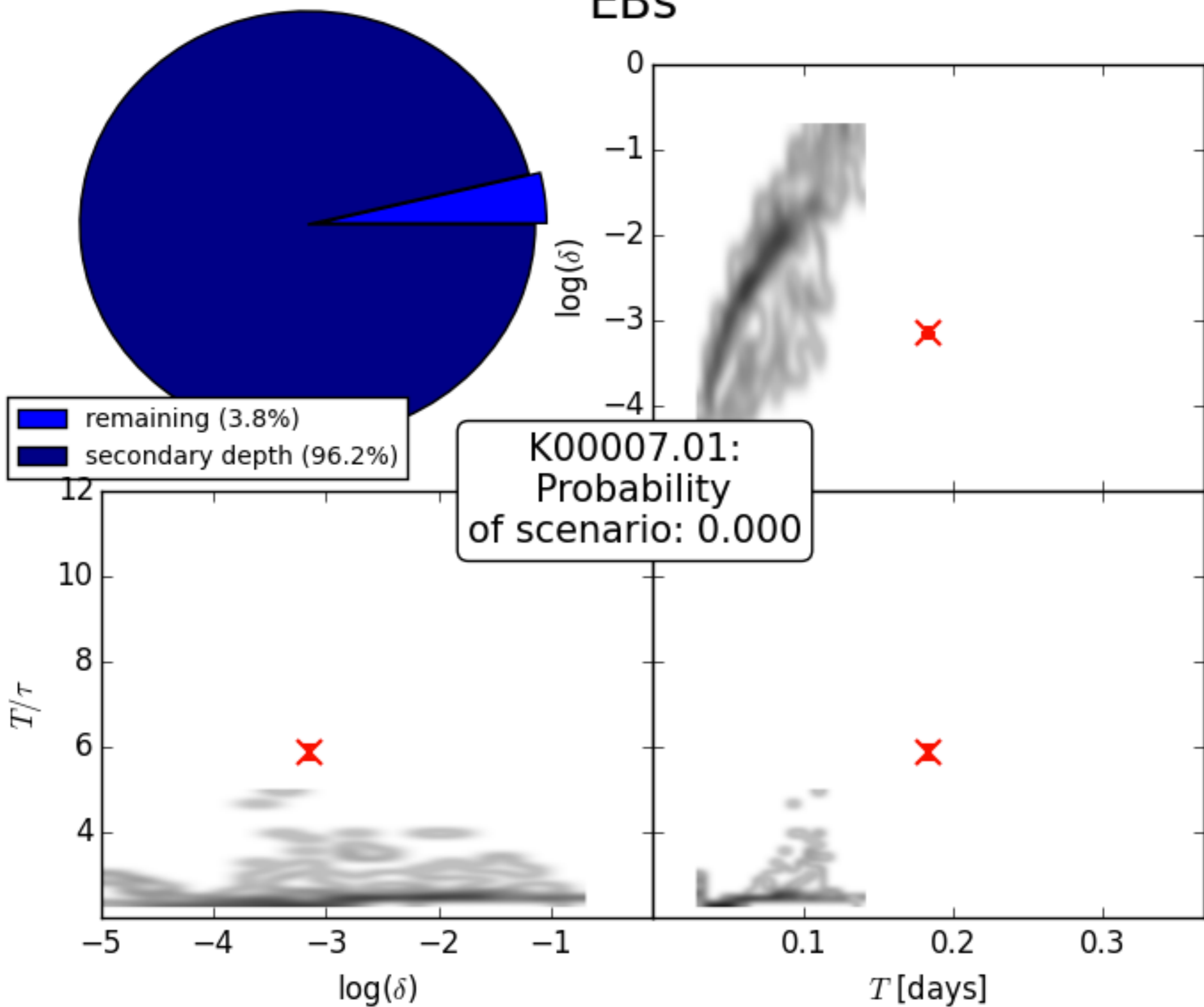


K00007.01

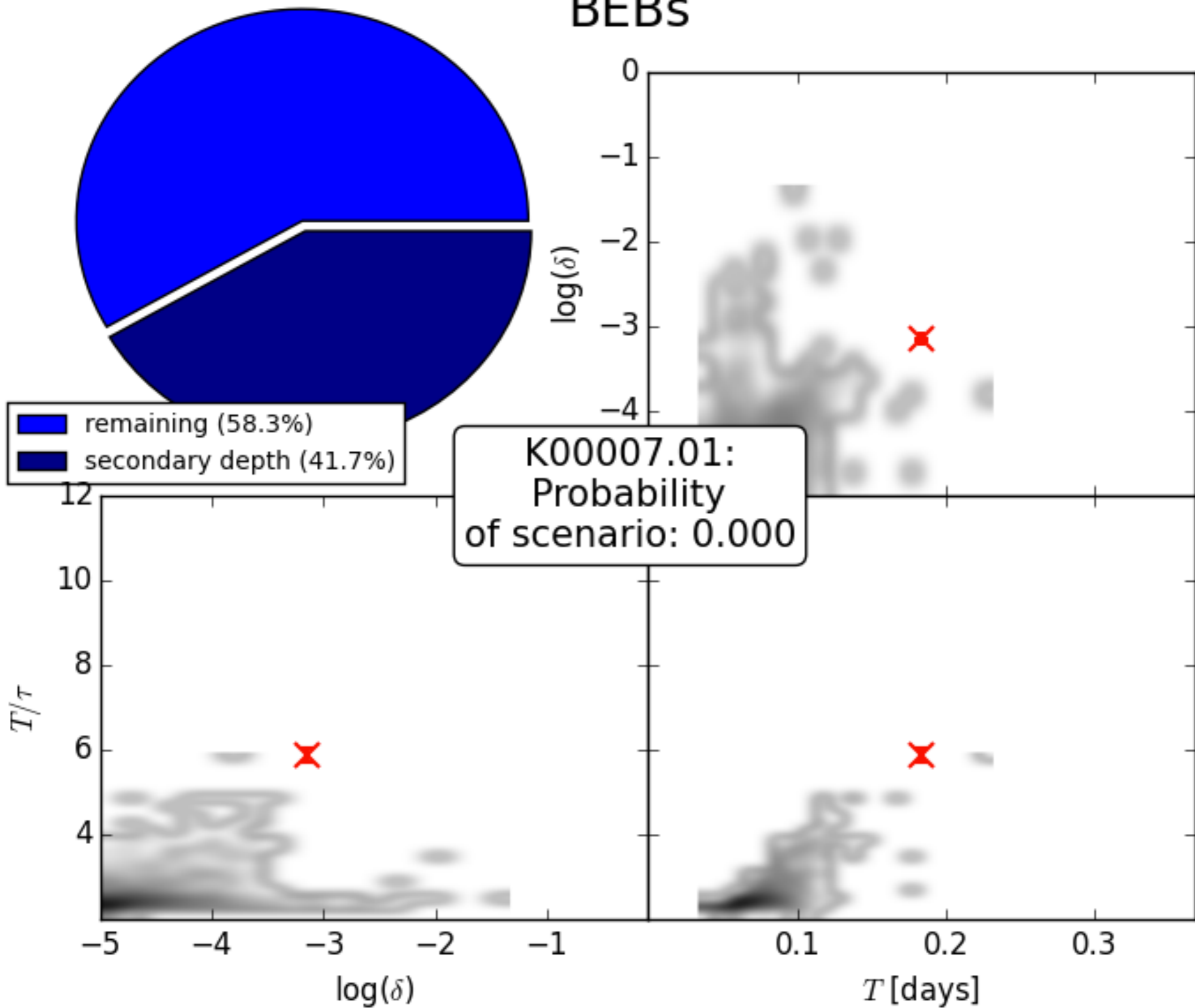
Planets



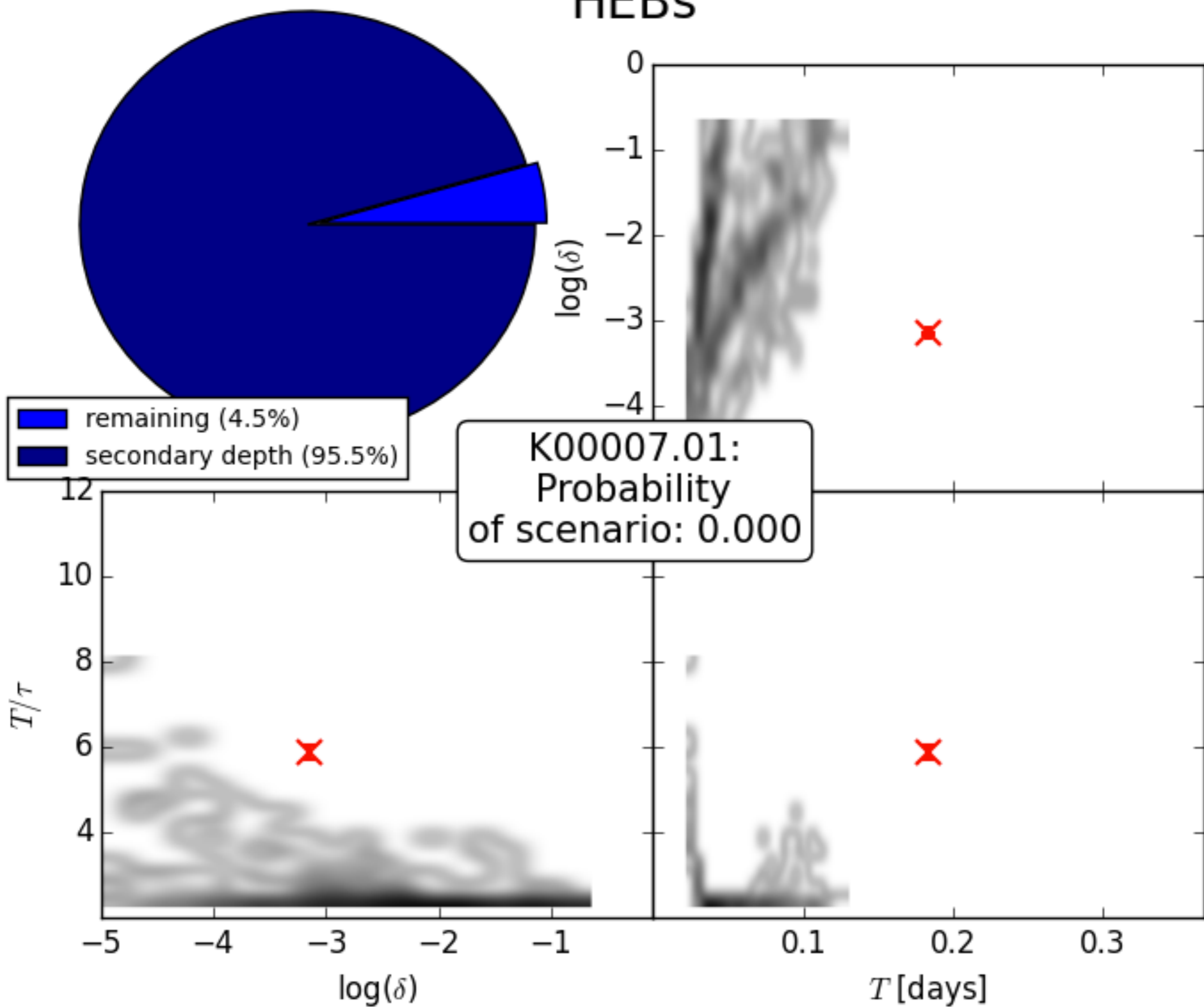
EBs



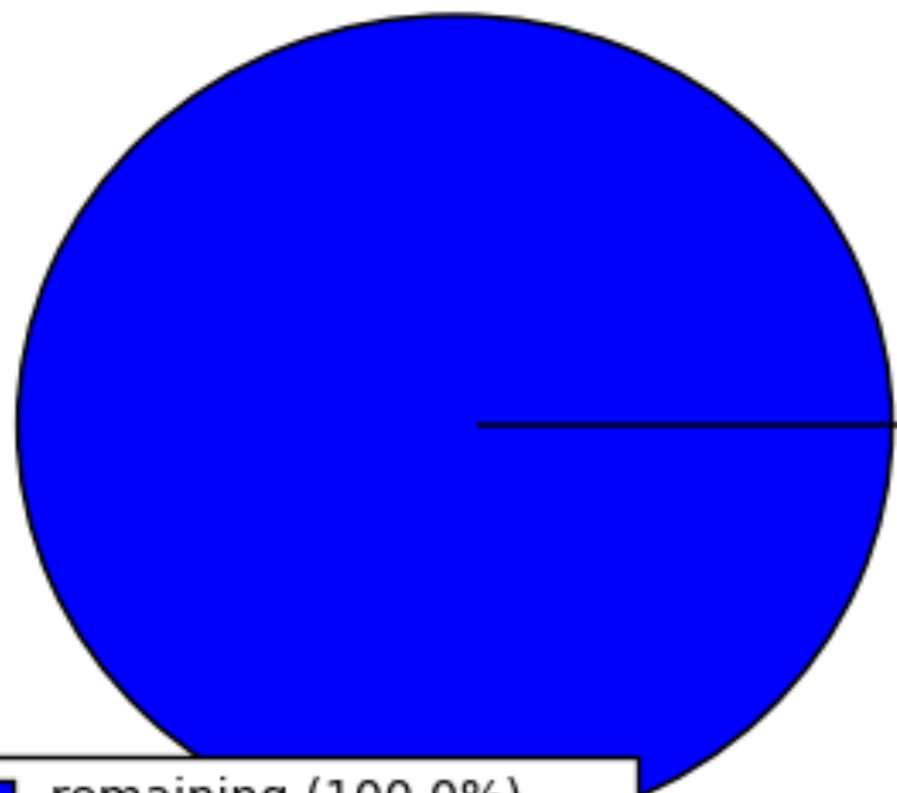
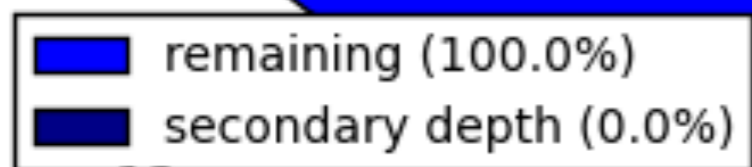
BEBs



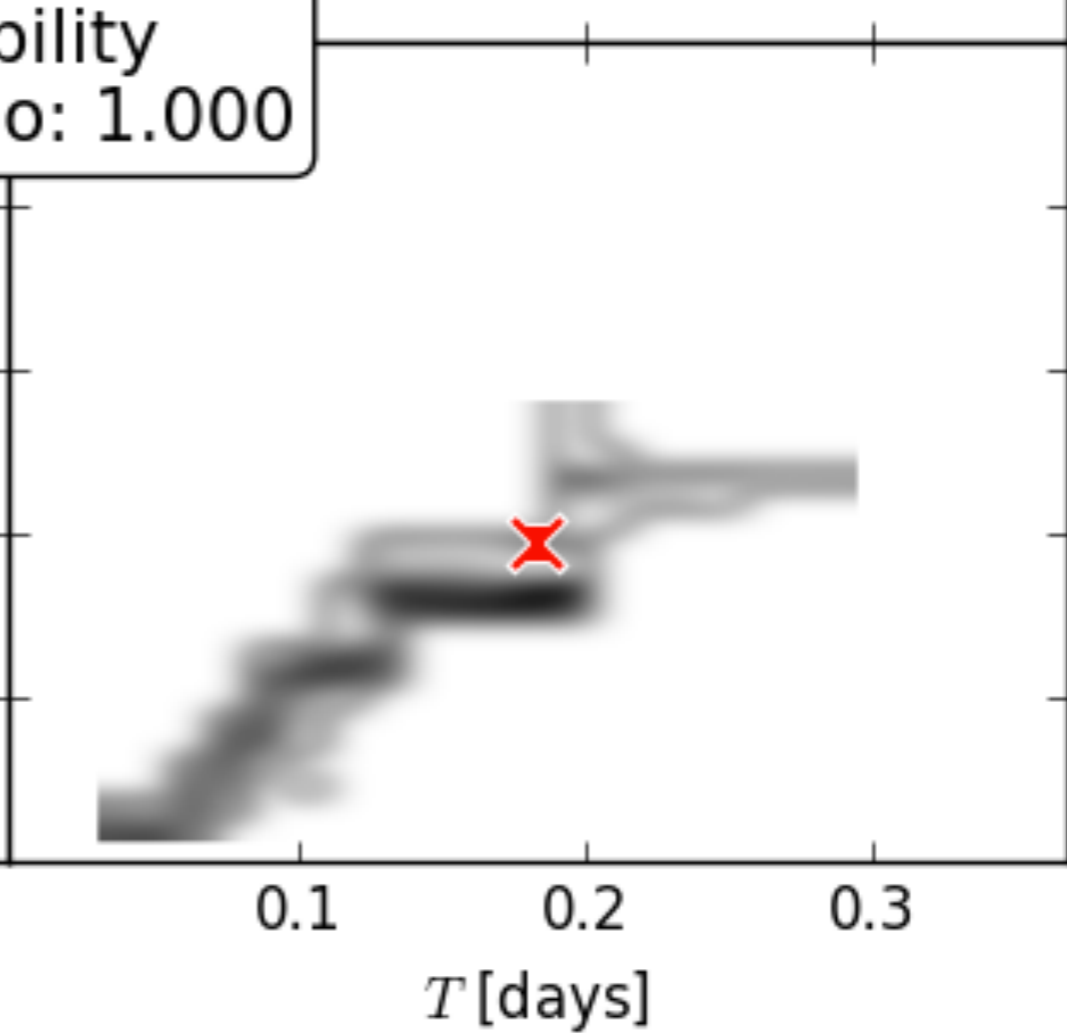
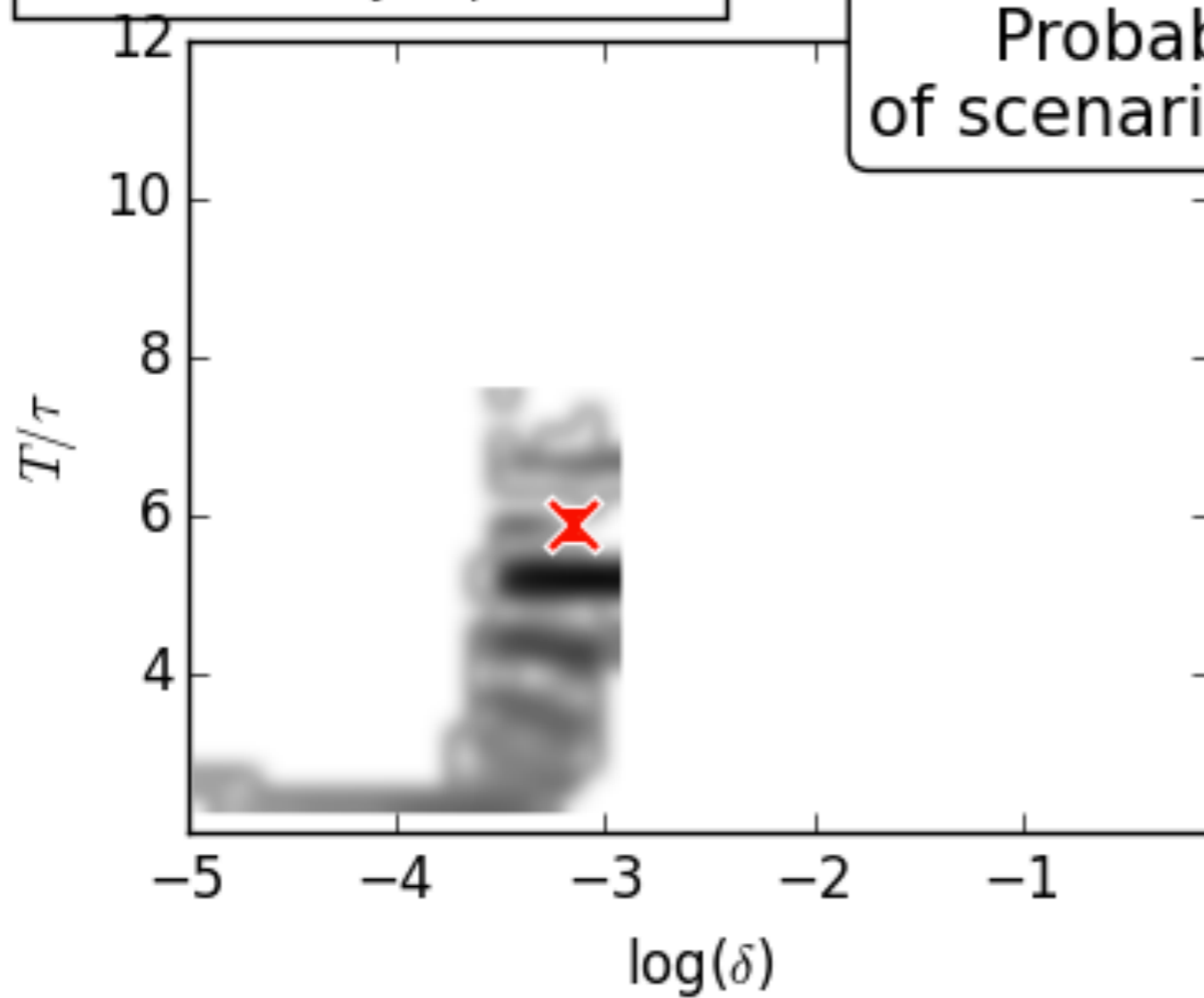
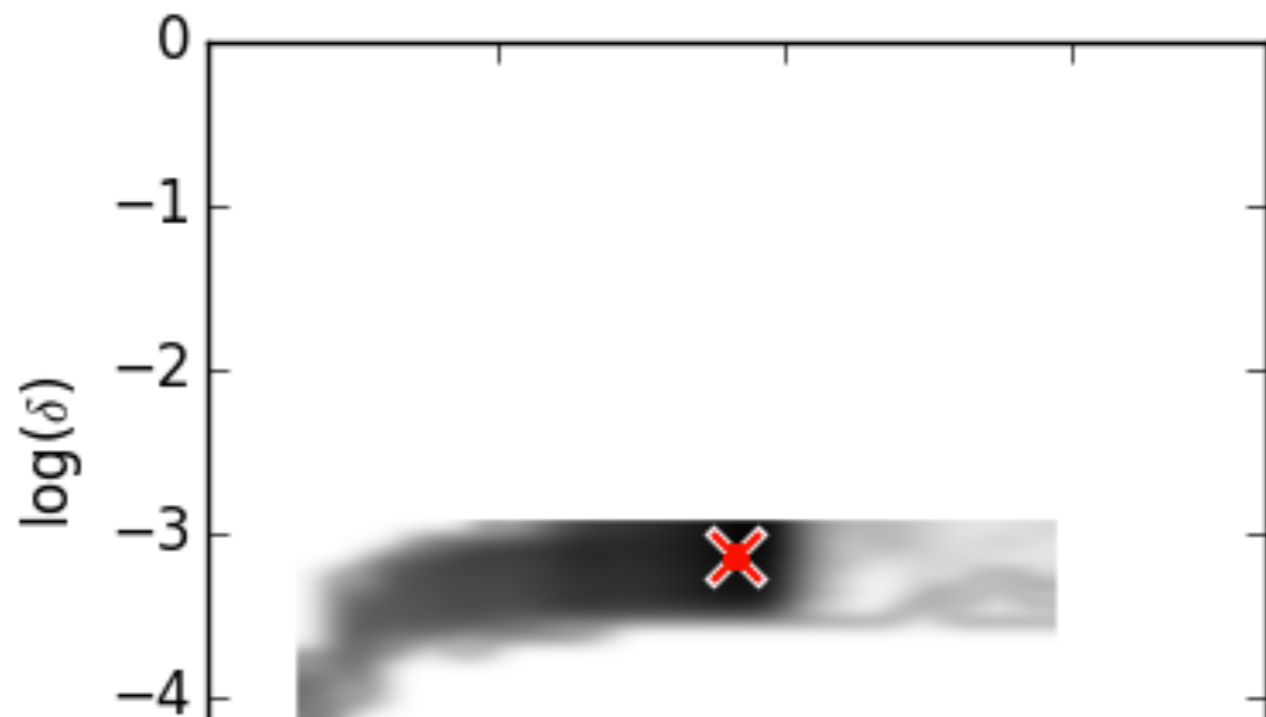
HEBs



Planets

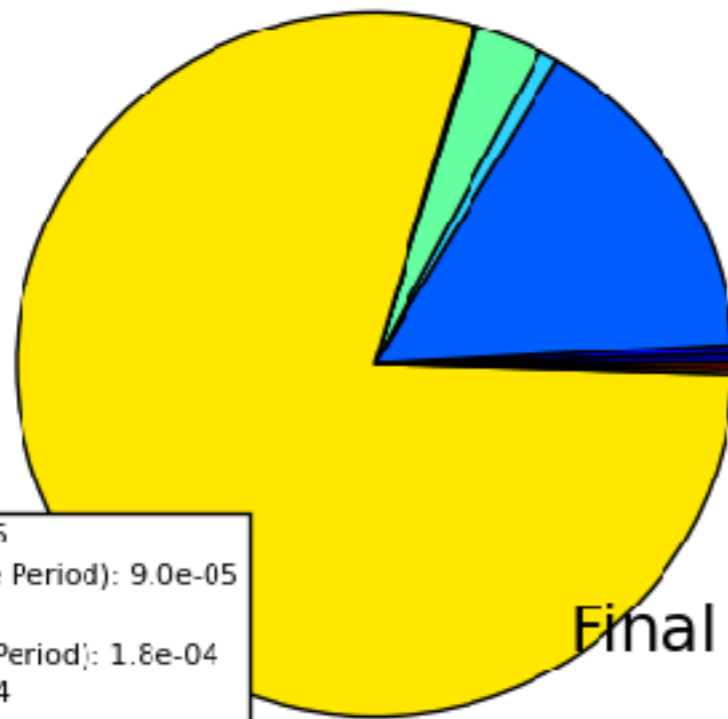


K00007.01:
Probability
of scenario: 1.000



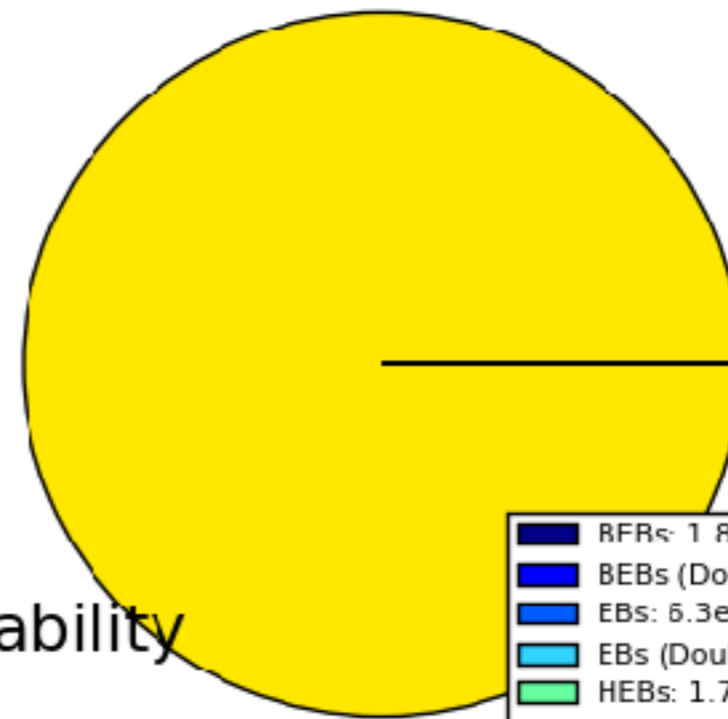
K00007.01

Priors



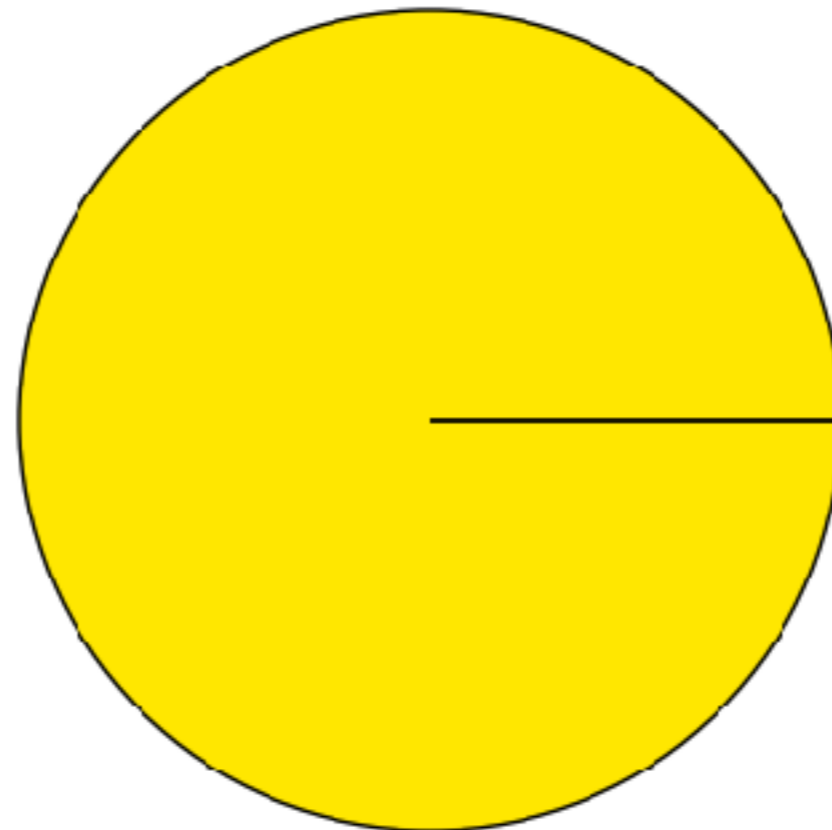
RFRs	: 9.6e-05
BEBs (Double Period)	: 9.0e-05
EBs	: 3.3e-03
EBs (Double Period)	: 1.8e-04
HEBs	: 6.3e-04
HEBs (Double Period)	: 3.2e-05
Planets	: 1.7e-02
boxy	: 5.0e-05
long	: 5.0e-05

Likelihoods



RFRs	: 1.8e-75
BEBs (Double Period)	: 5.1e-47
EBs	: 6.3e-12
EBs (Double Period)	: 7.5e-12
HEBs	: 1.7e-11
HEBs (Double Period)	: 1.4e-08
Planets	: 1.0e-02
boxy	: 0.0e+00
long	: 0.0e+00

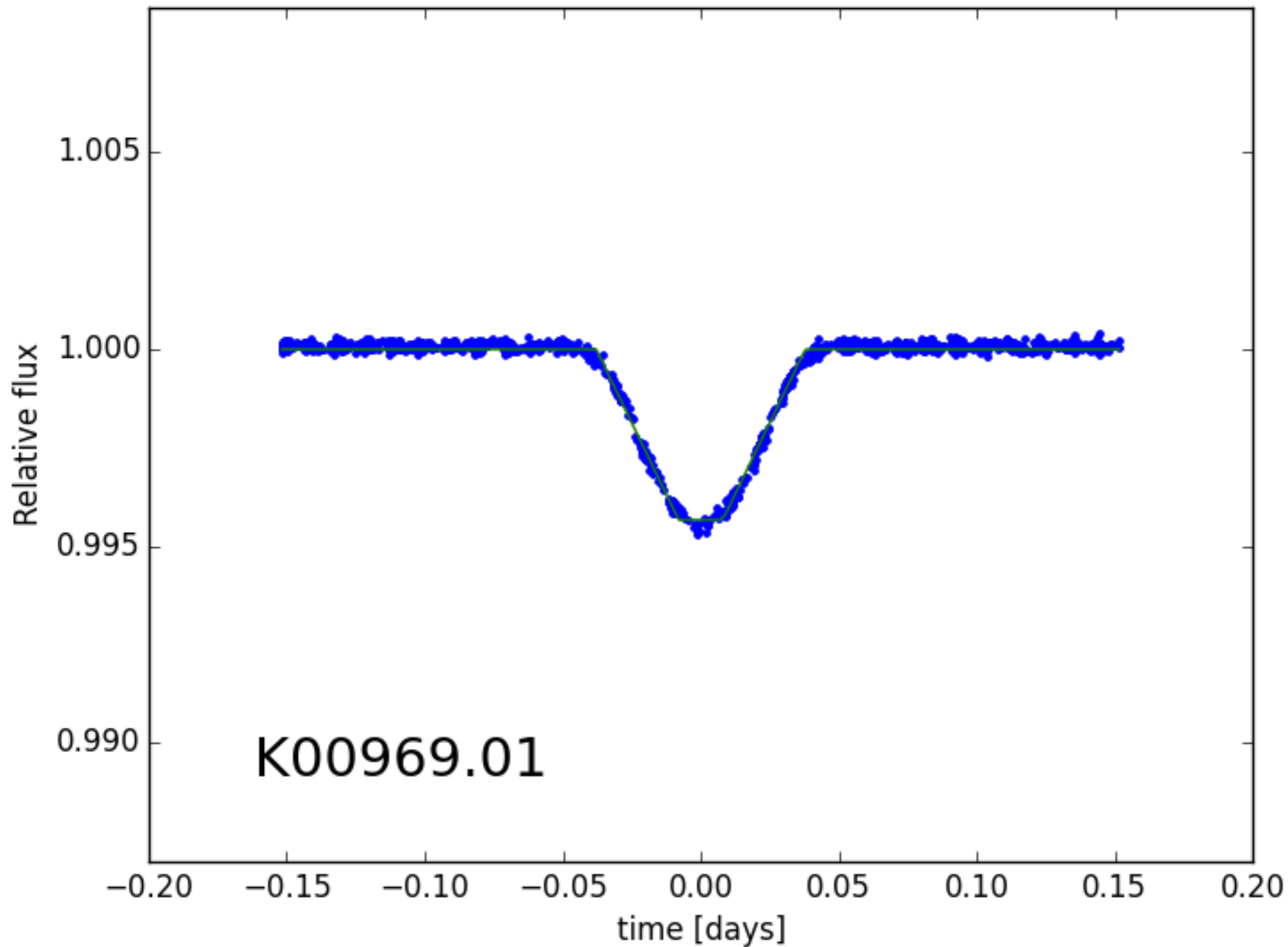
Final Probability



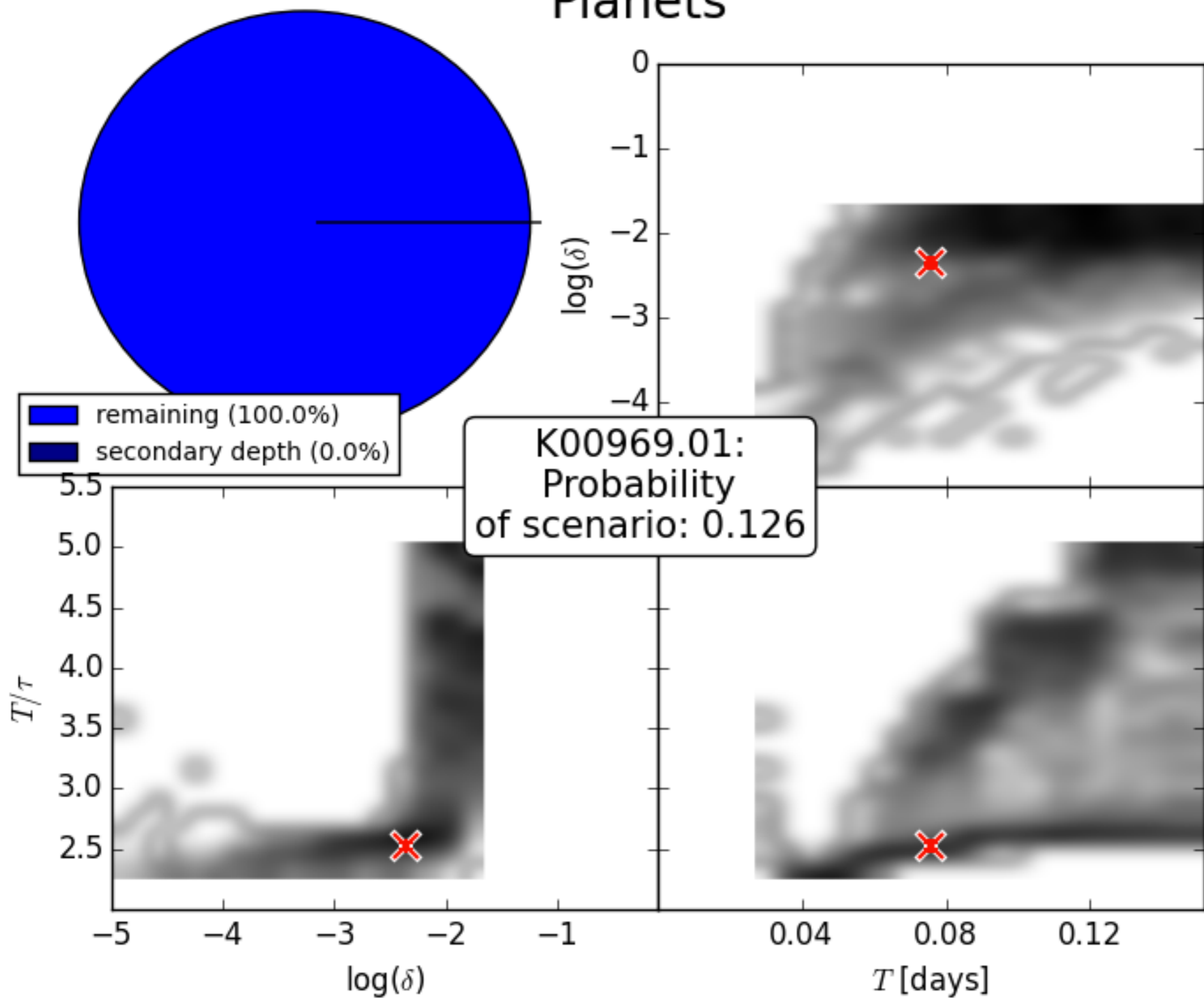
BEBs	: 0.000
BEBs (Double Period)	: 0.000
EBs	: 0.000
EBs (Double Period)	: 0.000
HEBs	: 0.000
HEBs (Double Period)	: 0.000
Planets	: 1.000
boxy	: 0.000
long	: 0.000

Constraints:
secondary depth < 1.24e-05
odd-even < 1.11e-05

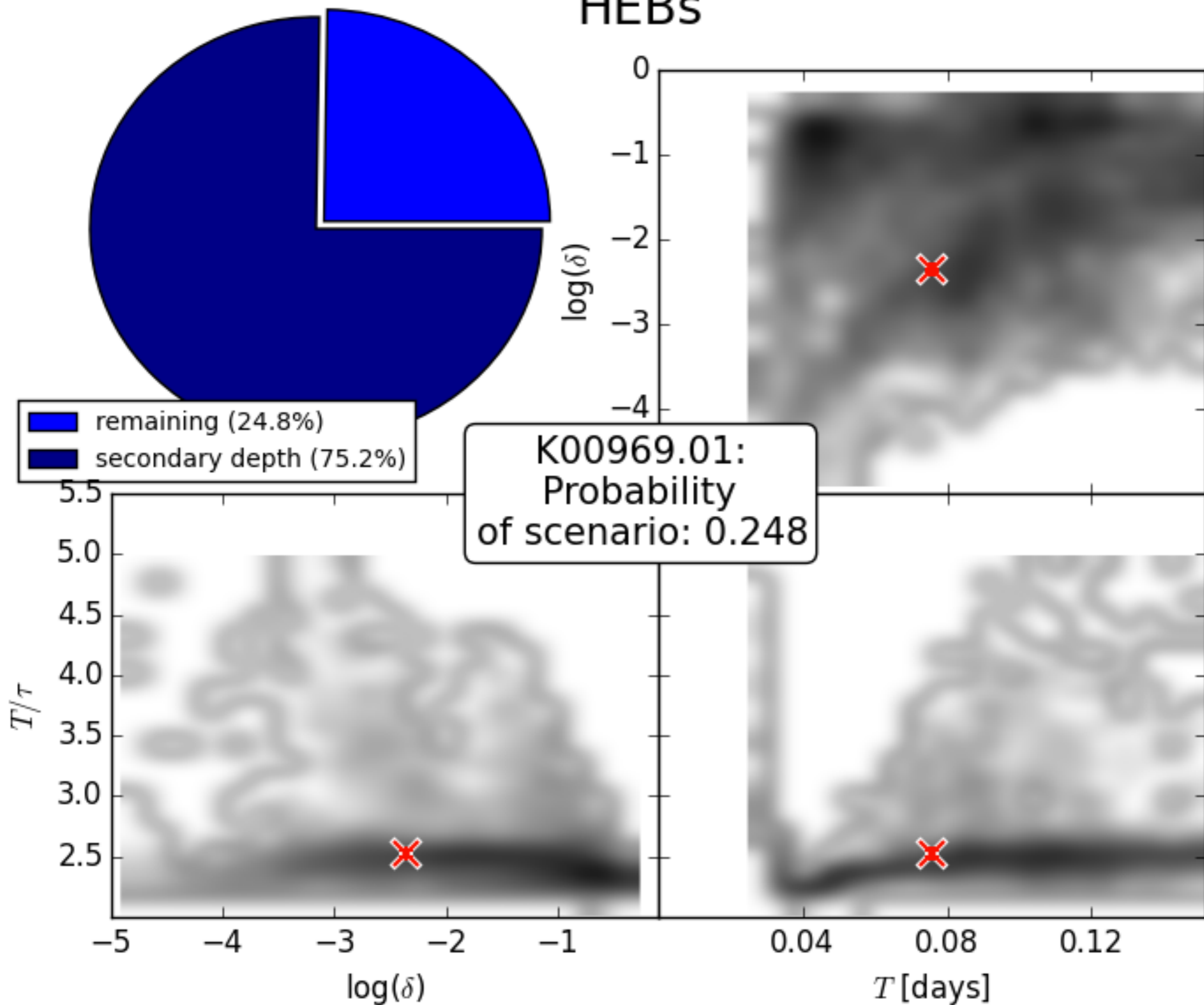
$f_{pl,V} = 0.000$
FPP: < 1 in 1e6



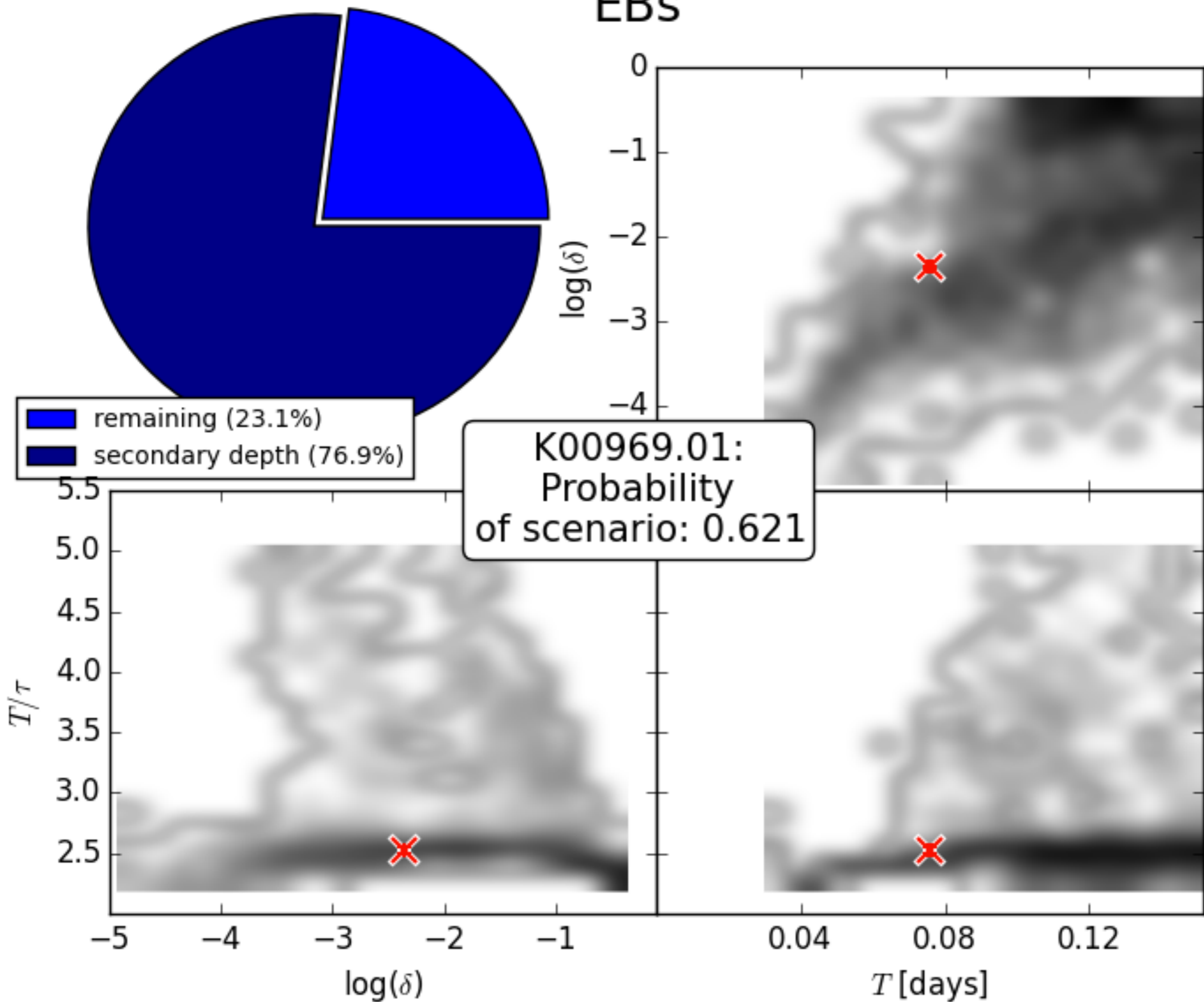
Planets



HEBs

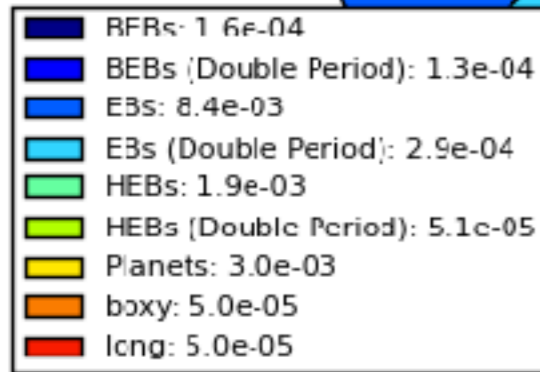
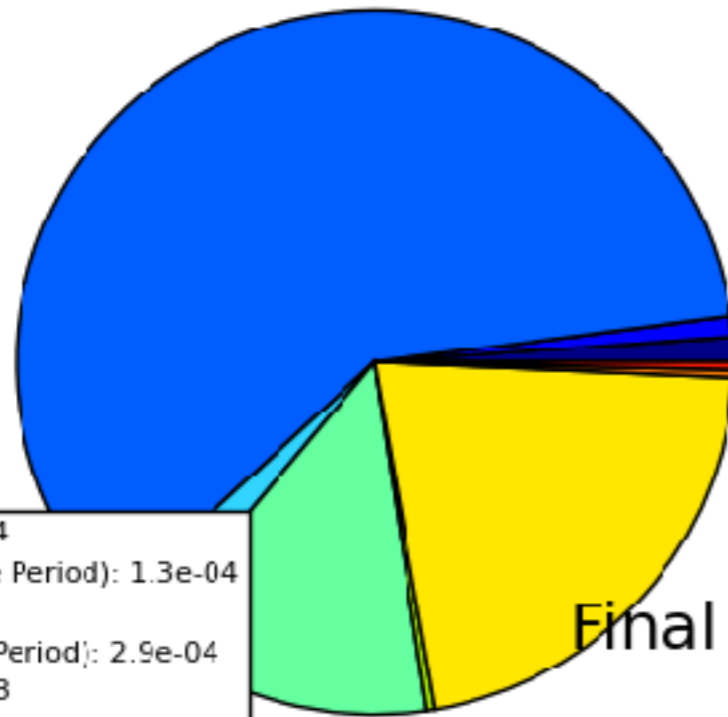


EBs

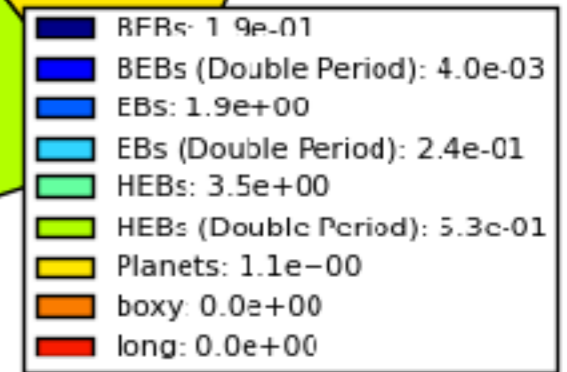
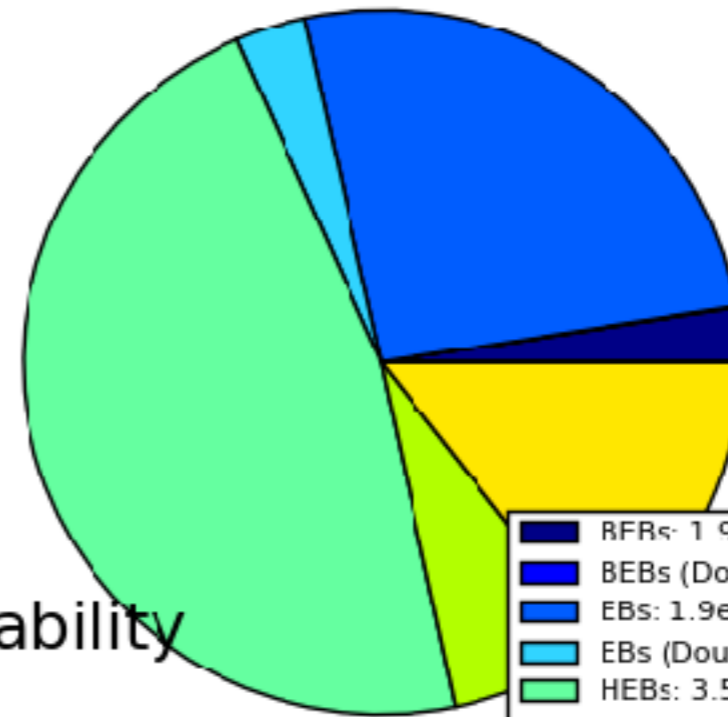


K00969.01

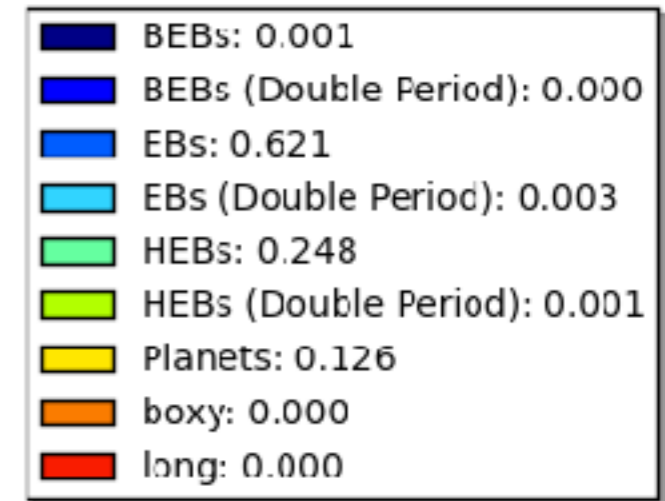
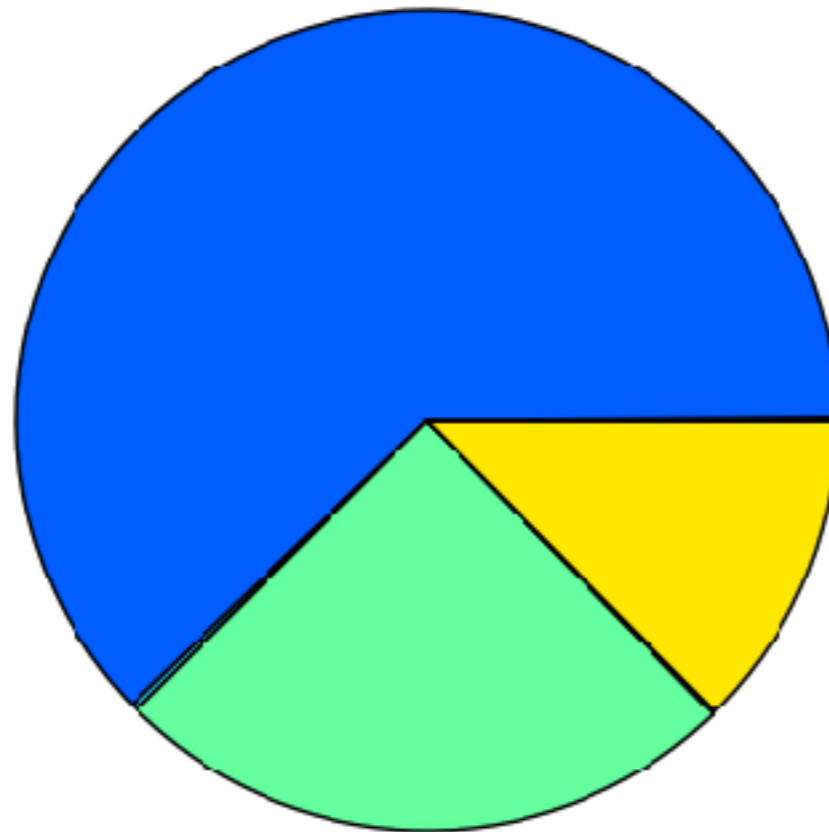
Priors



Likelihoods



Final Probability



Constraints:
 secondary depth < 5.44e-05
 odd-even < 0.000127

$f_{pl,V} = 48.681$
 FPP: 1 in 1

Kepler-10 system

- b confirmed by RVs
- c validated with BLENDER

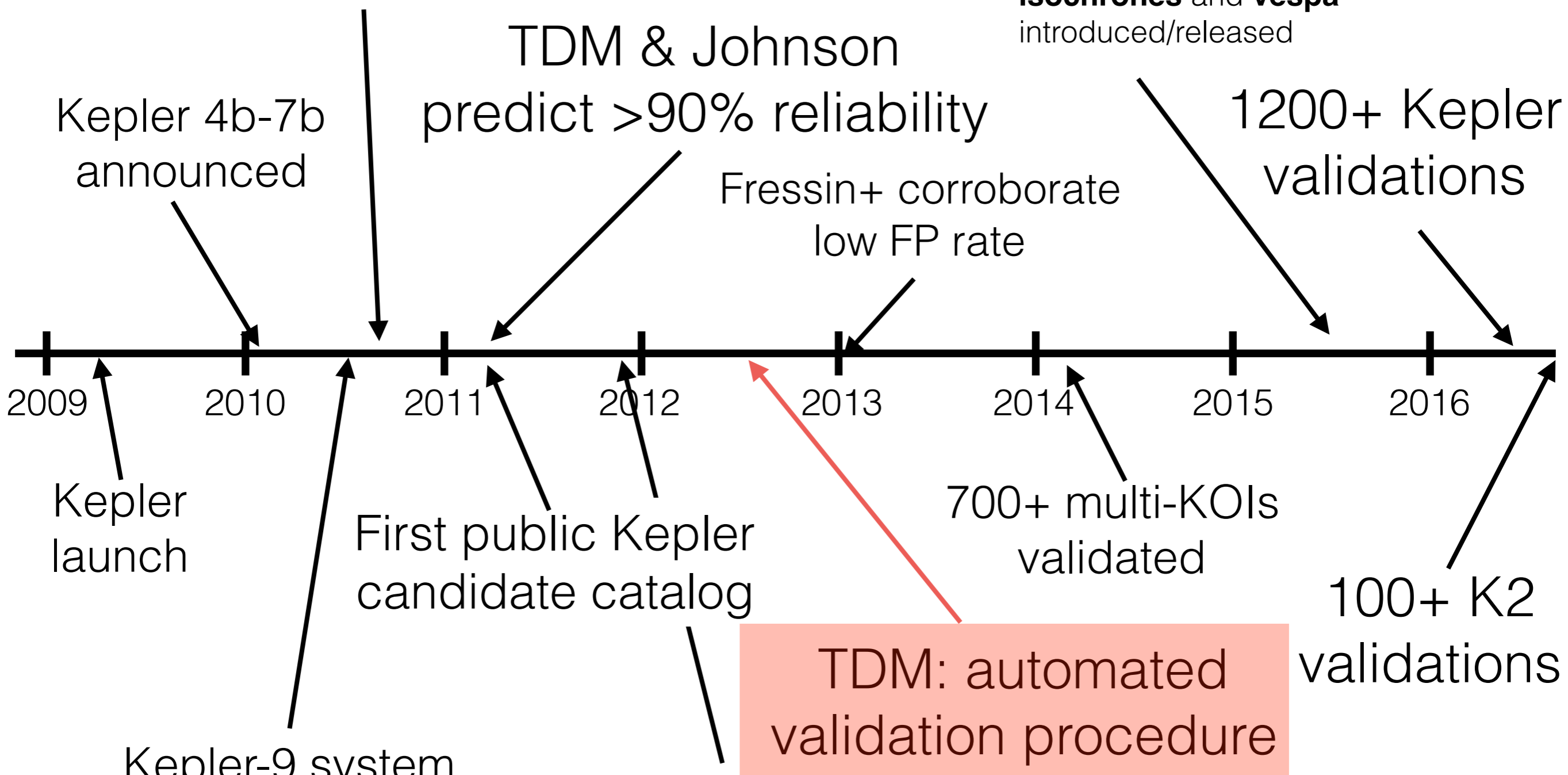
First K2 validations

- 17 planets
- **isochrones** and **vespa** introduced/released

TDM & Johnson
predict >90% reliability

Fressin+ corroborate
low FP rate

1200+ Kepler
validations



Kepler 4b-7b
announced

2009

2010

2011

2012

2013

2014

2015

2016

Kepler
launch

First public Kepler
candidate catalog

TDM: automated
validation procedure

700+ multi-KOIs
validated

100+ K2
validations

Kepler-9 system

- b,c confirmed by TTVs
- d validated with BLENDER

Kepler-22b

- First Kepler habitable-zone planet
- validated with BLENDER

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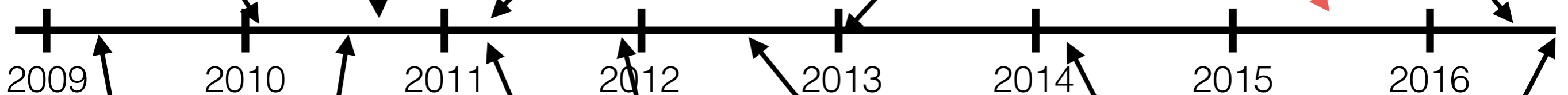
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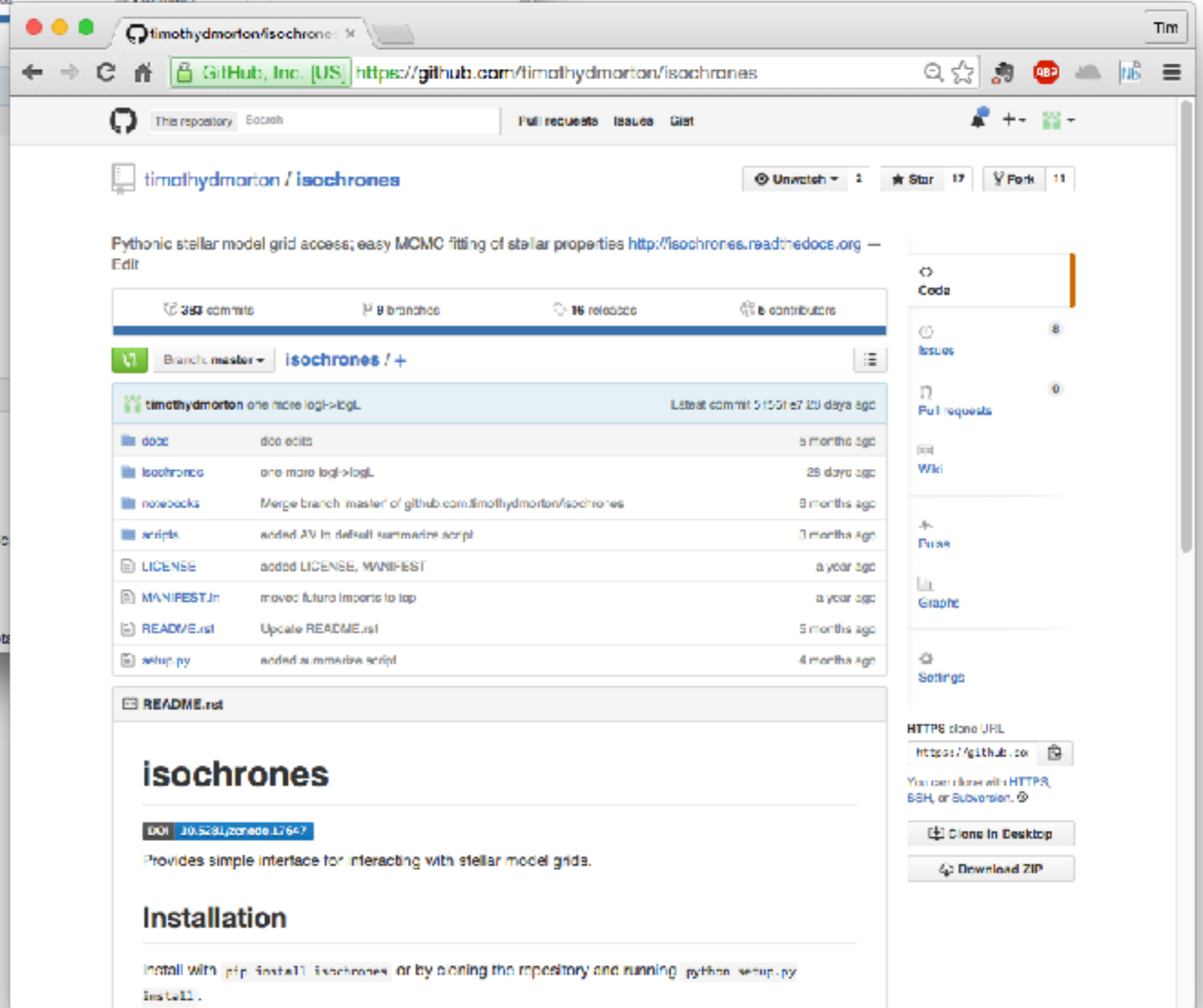
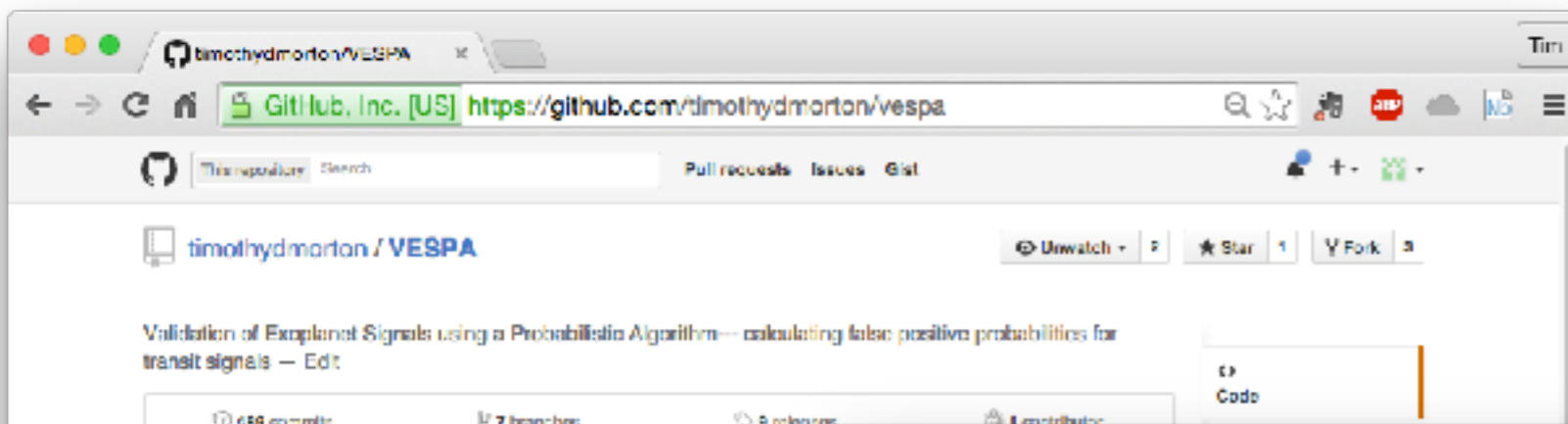
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github.com/timothydmorton

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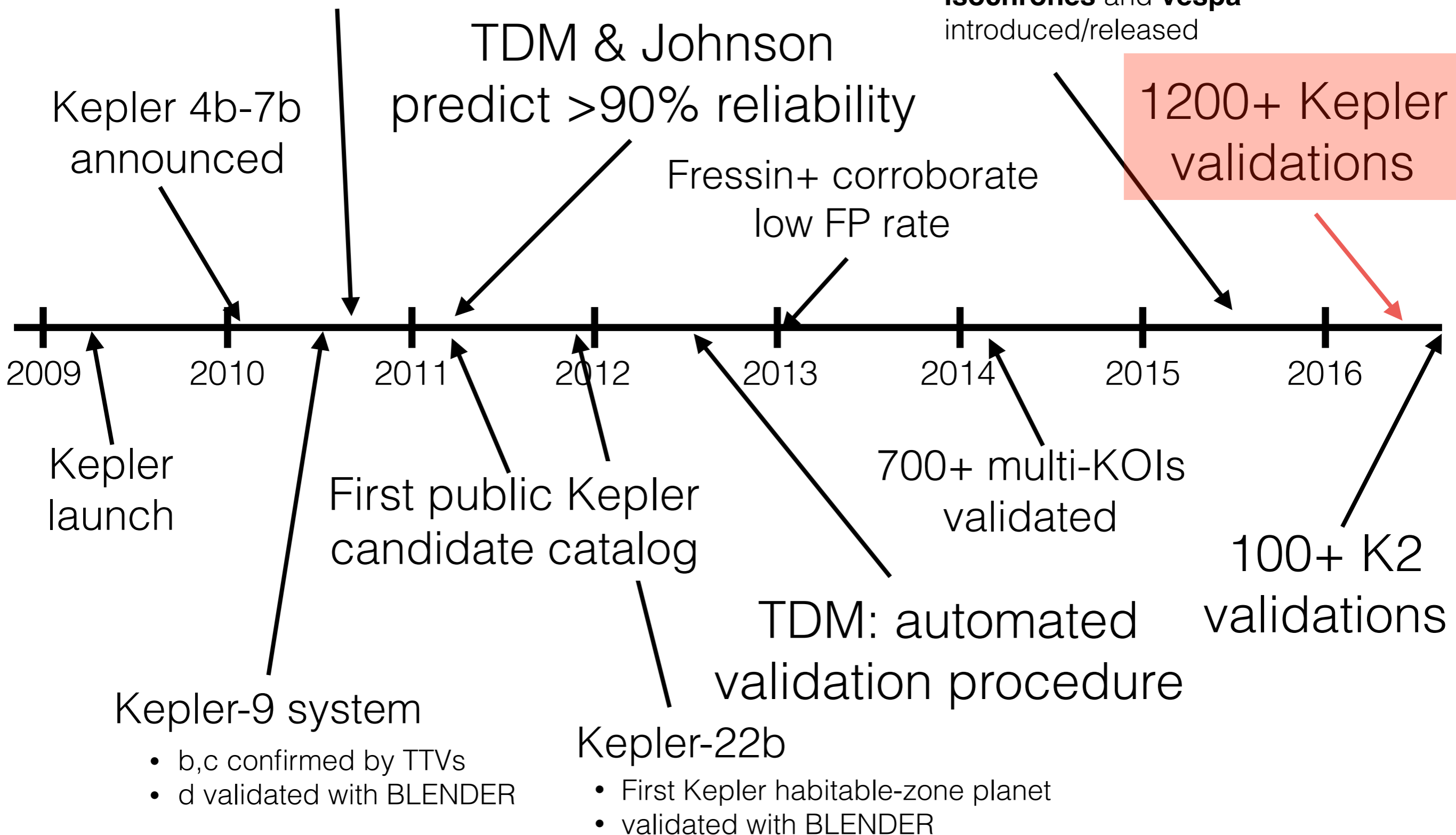
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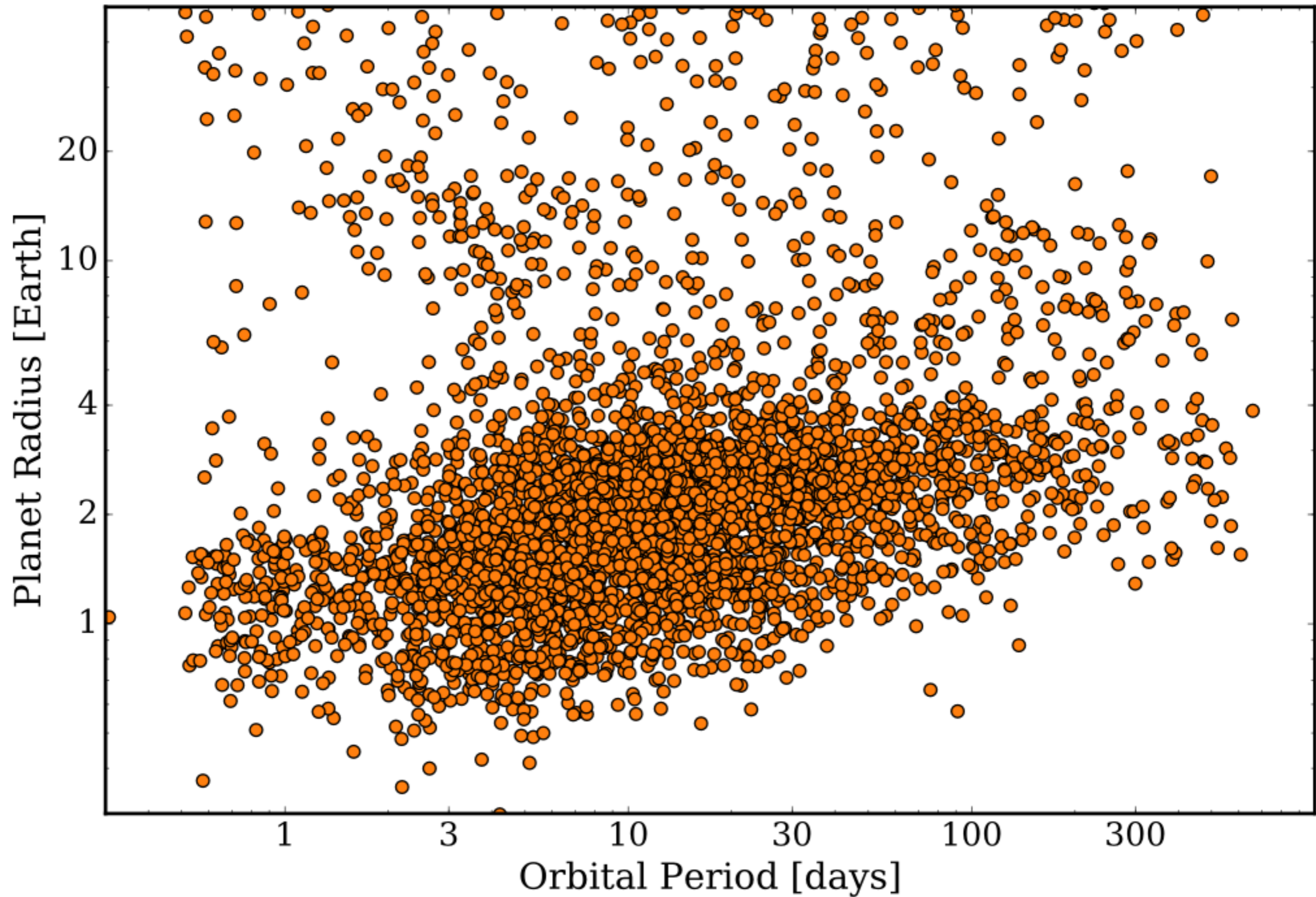
Kepler-9 system

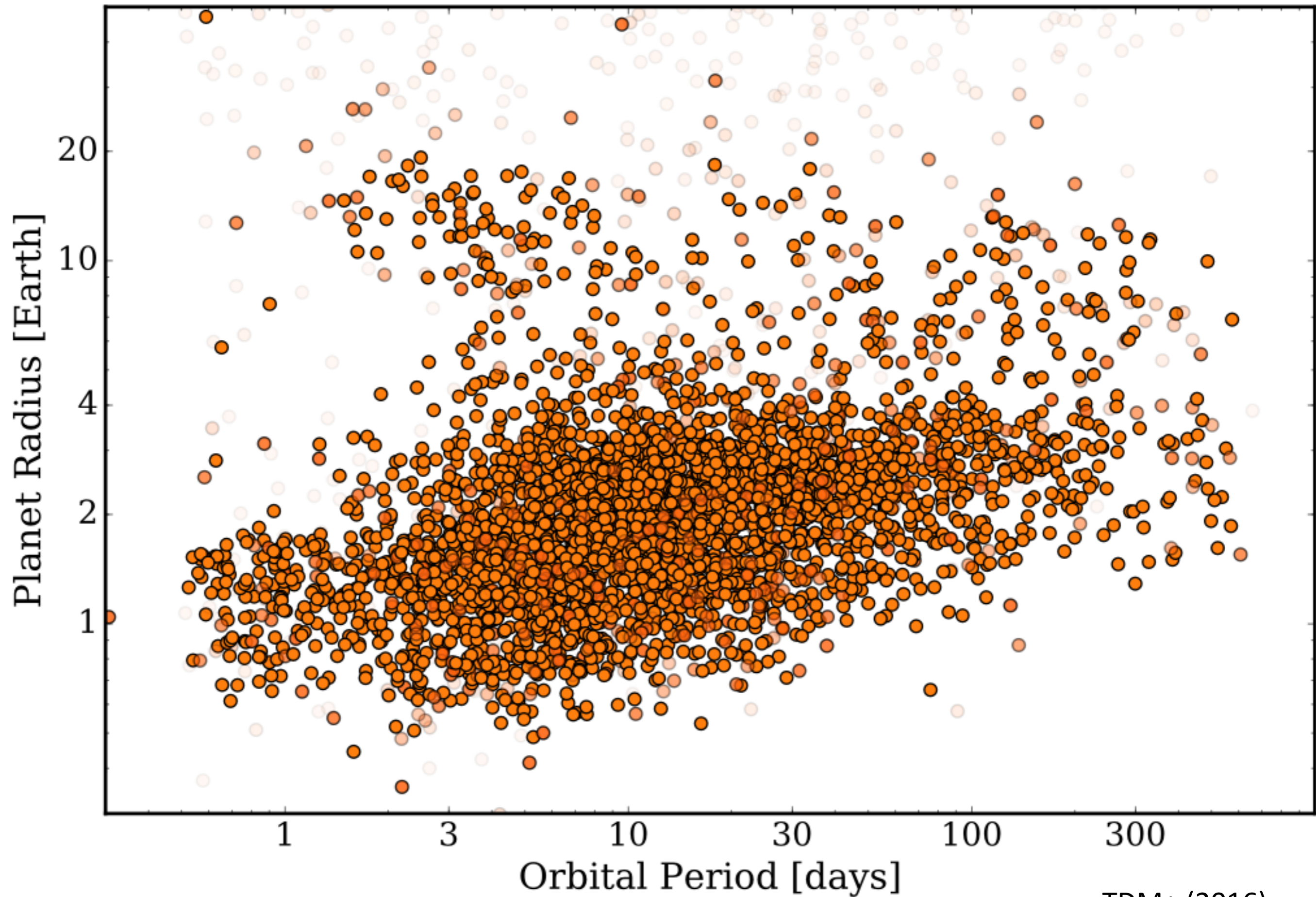
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Kepler-22b

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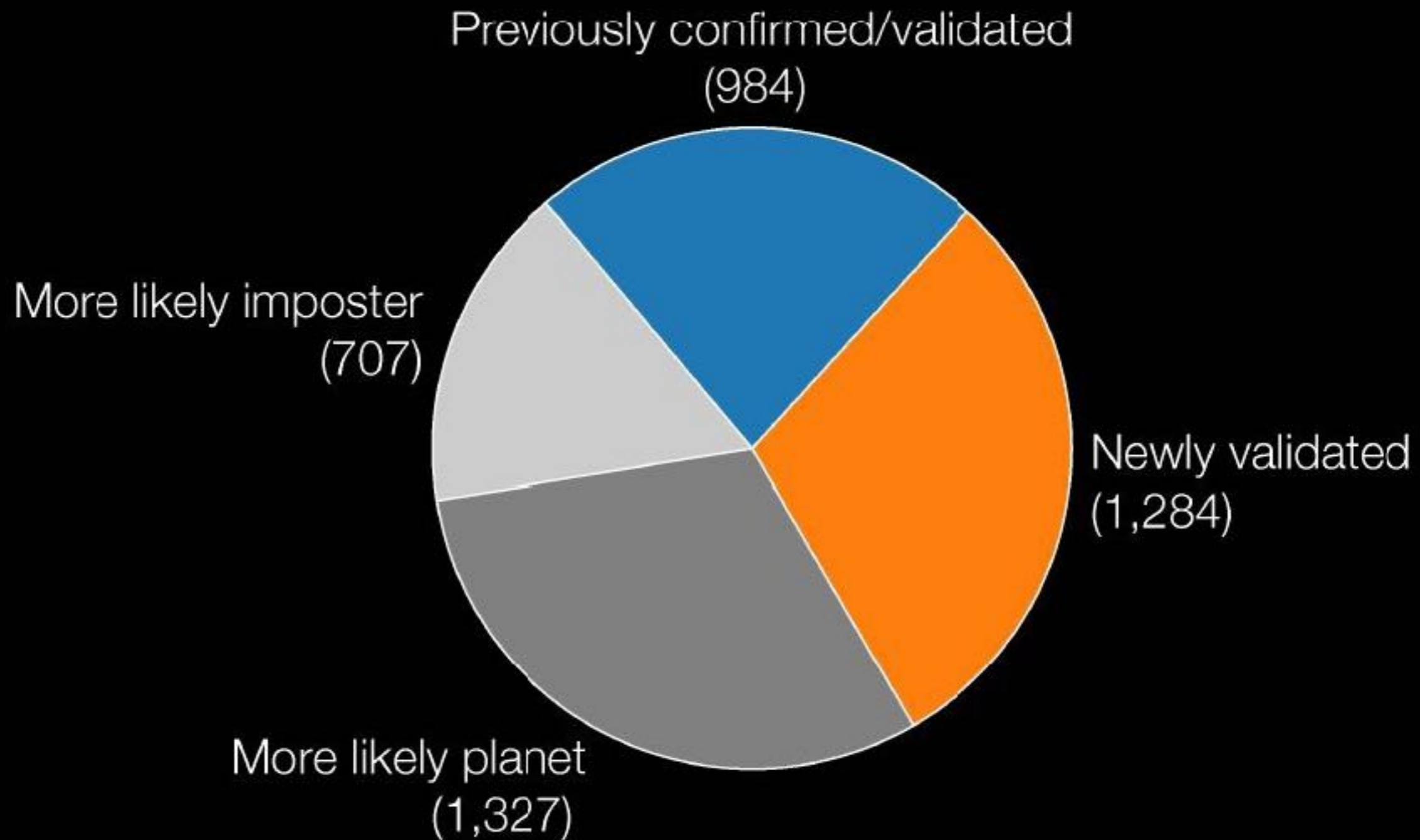






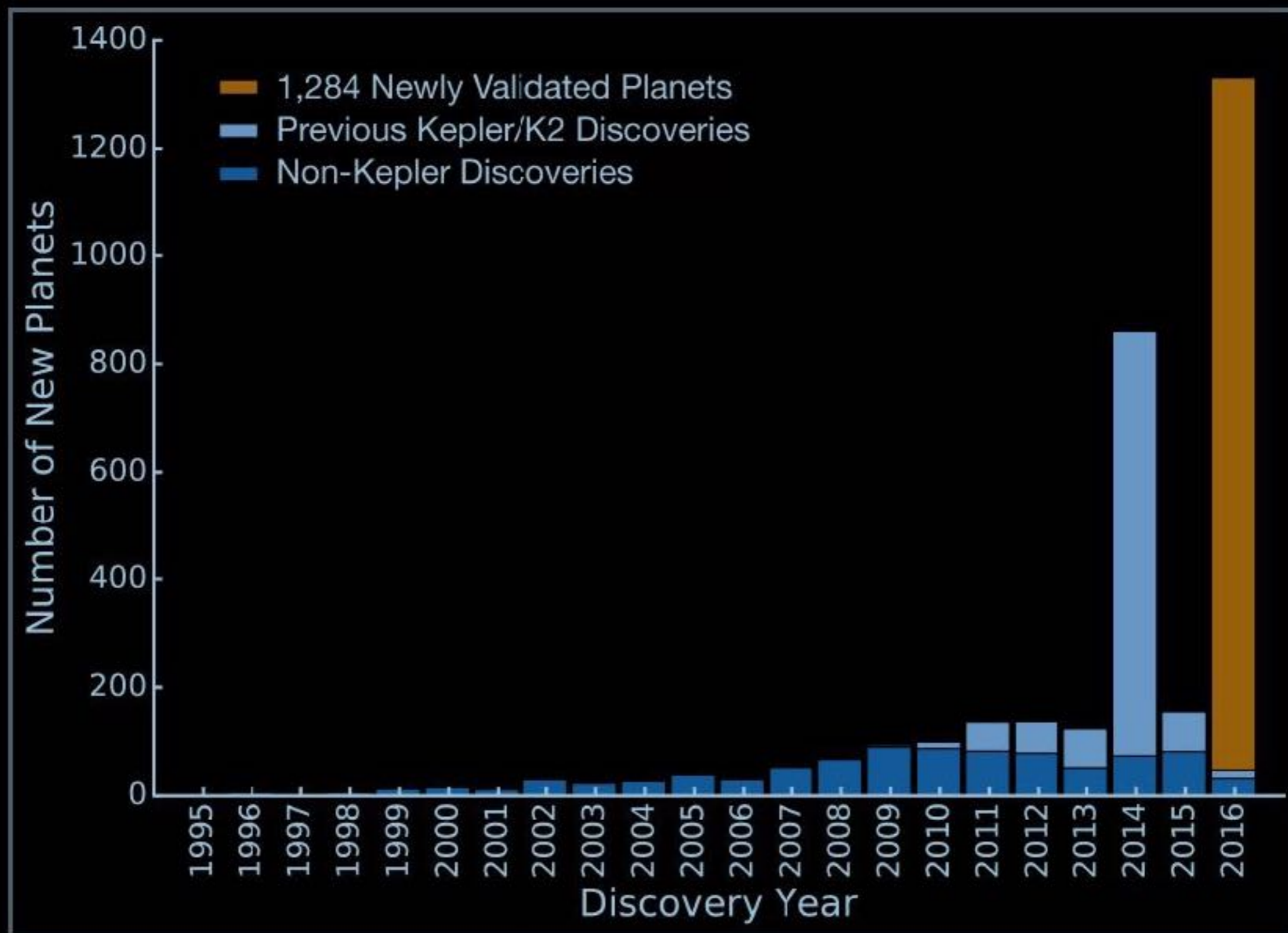
Kepler Candidates

From the DR24 Catalog (2015)



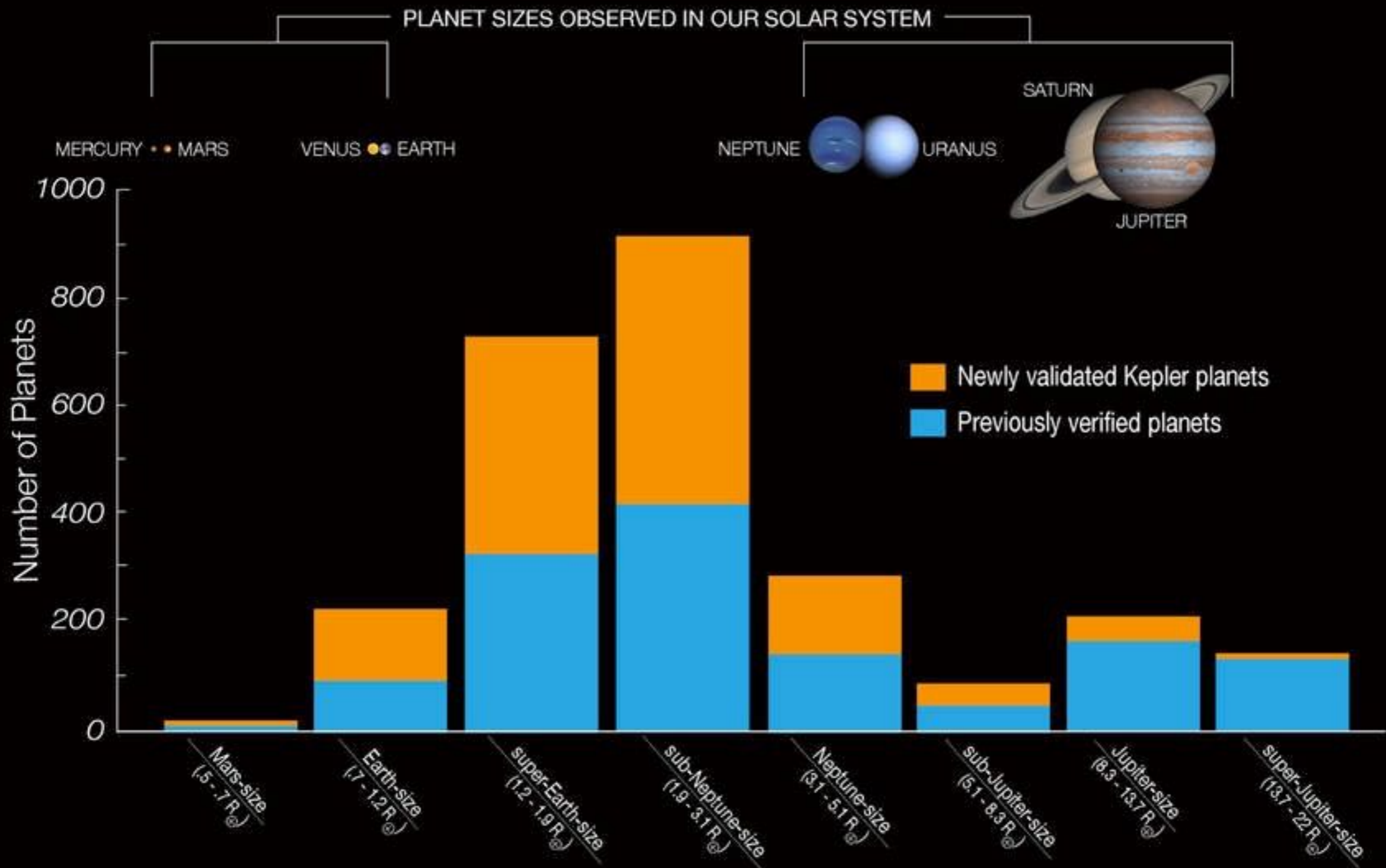
Exoplanet Discoveries Through the Years

As of May 10, 2016



Known Transiting Planets by Size

As of May 10, 2016



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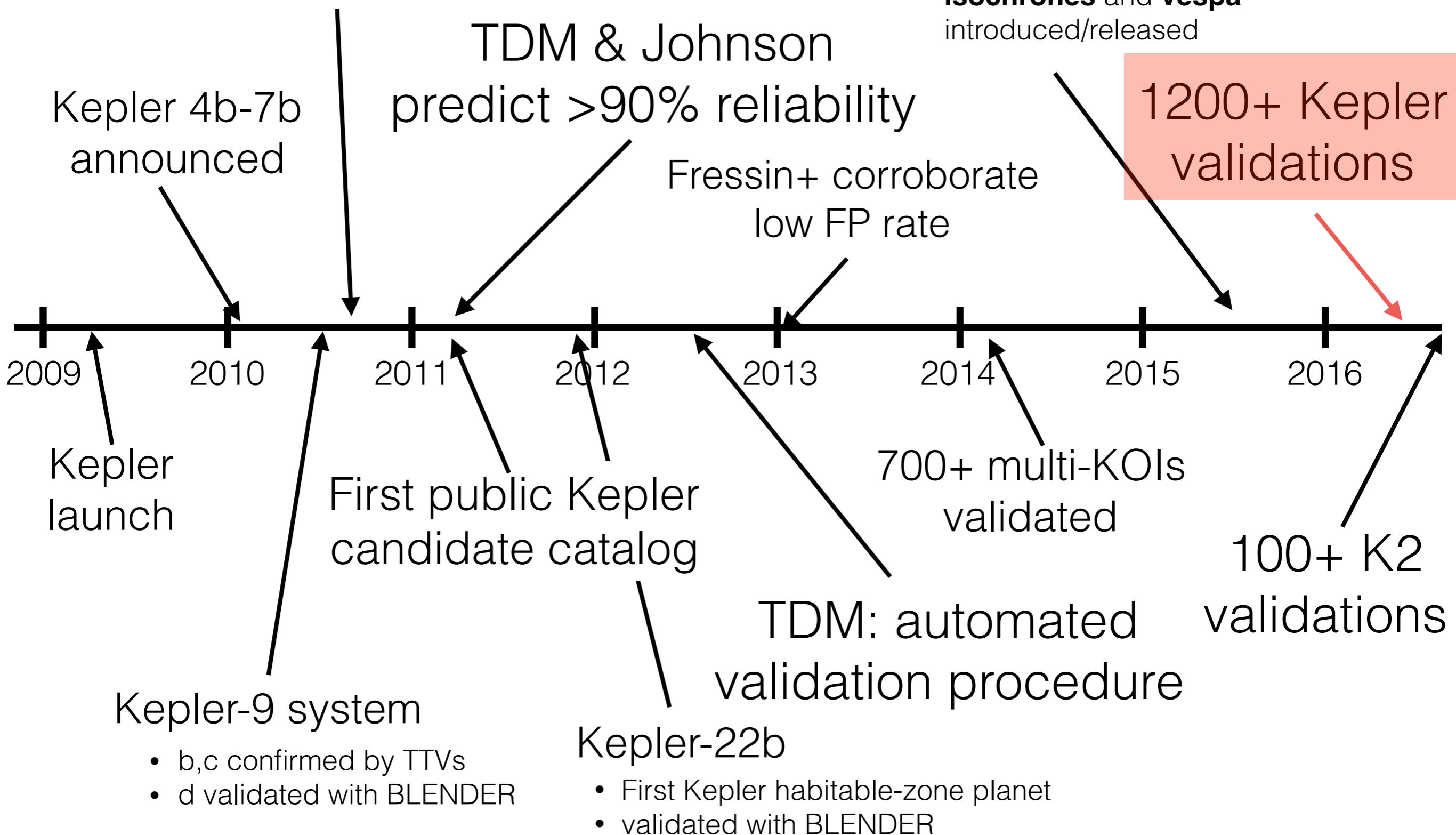
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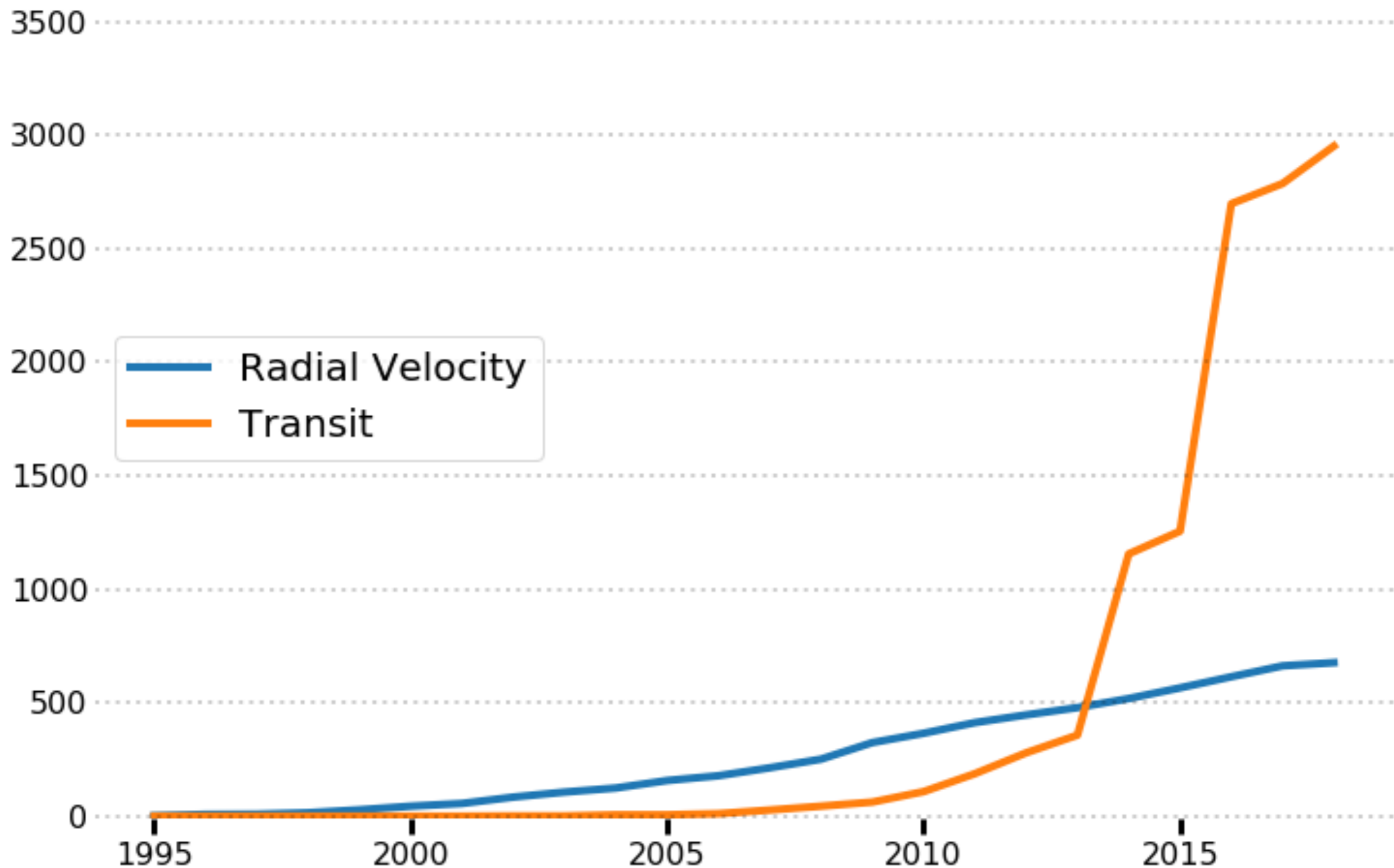
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Cumulative number of known exoplanets (2018)



Follow-up observations for transit follow-up & validation

- Follow-up photometry, possibly in multiple filters
 - Is depth color-dependent?
- Reconnaissance spectroscopy to characterize host star
 - Is it a giant? Rapid rotator?
- Medium-precision (\sim km/s) RVs observations
 - Is it an eclipsing binary? Brown dwarf?
- High-resolution imaging
 - Is there another star (or stars) in the aperture?
- ~~High-precision radial velocity~~

Vetting

- Measure the mass of the planet?

Probabilistic arguments



Confirmation!
Validation!

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