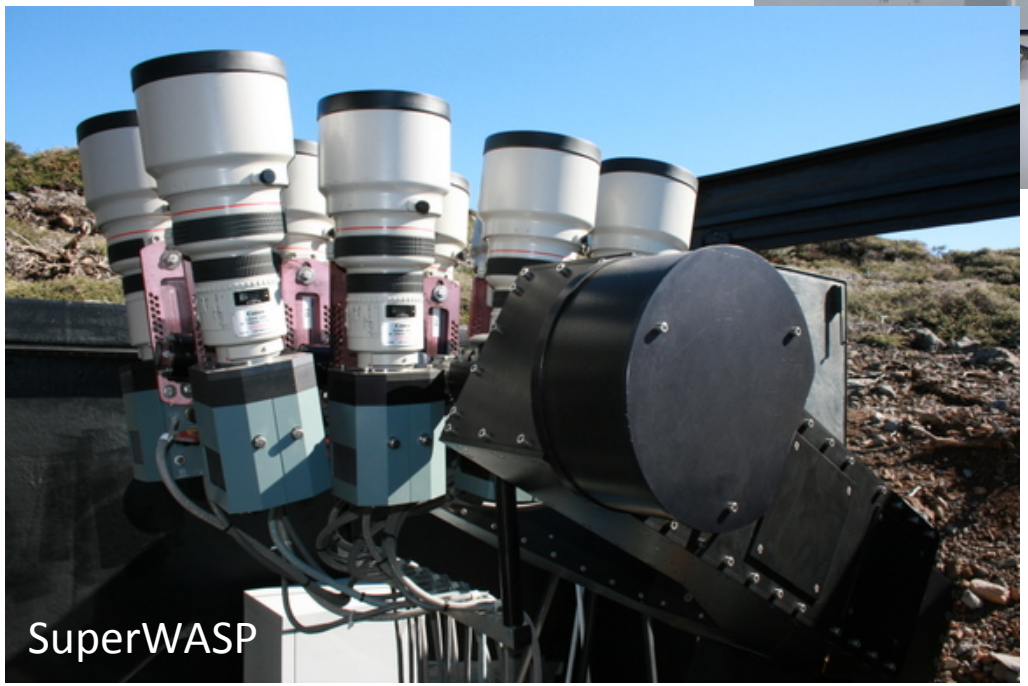
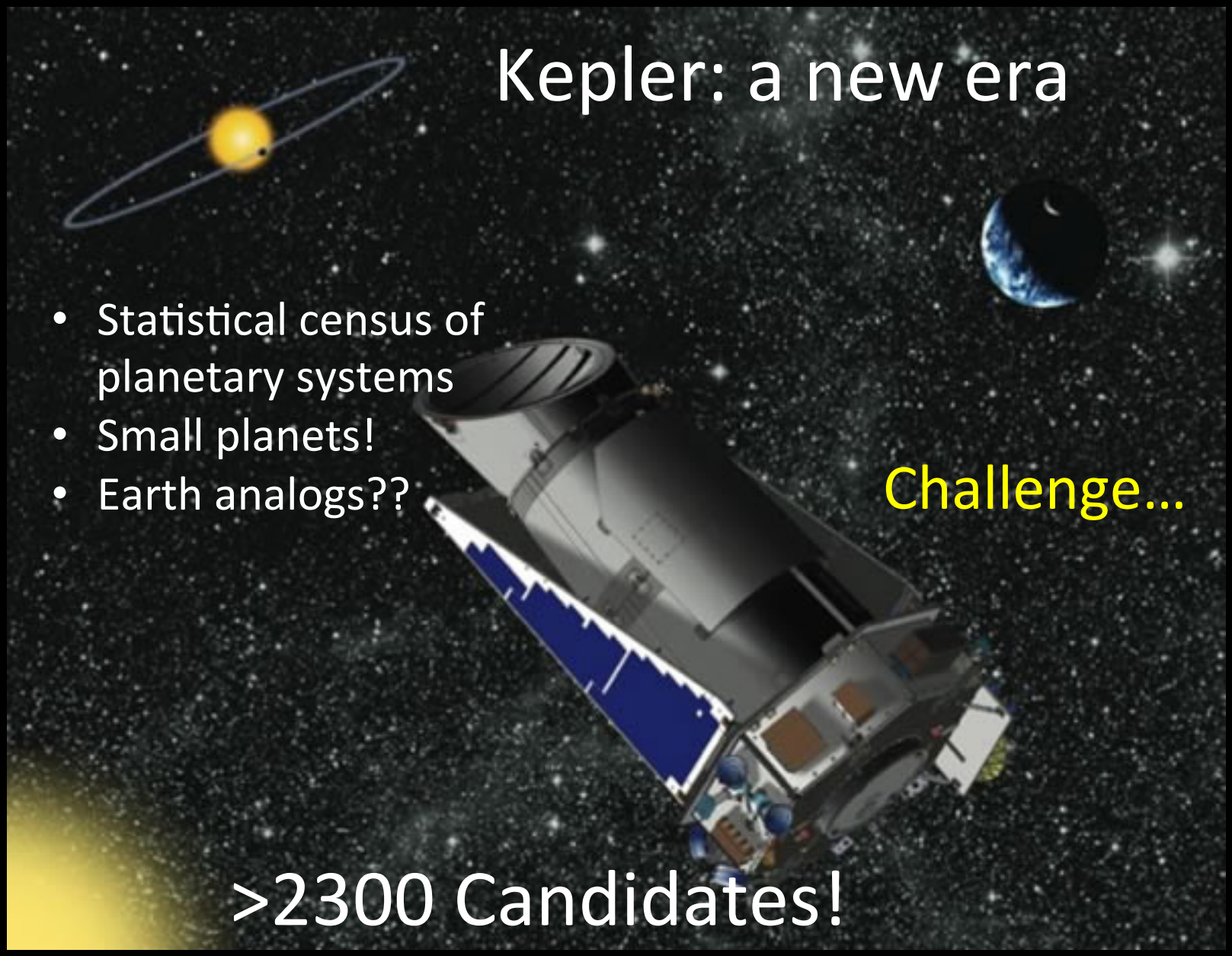
Ground-based Transit Surveys

~100 planets discovered
(6 years since HAT-P-1b)



Limited by follow-up resources!

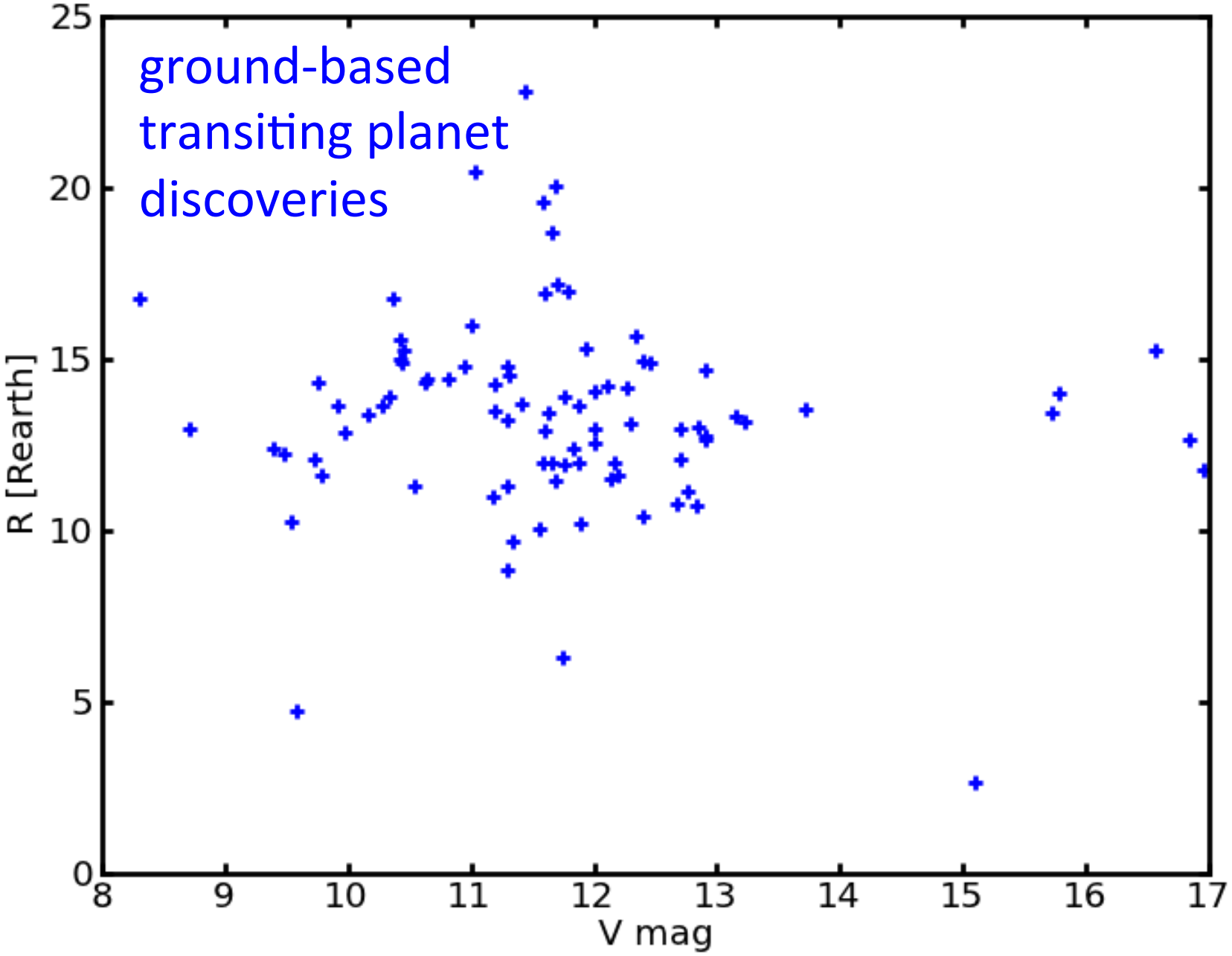
Kepler: a new era

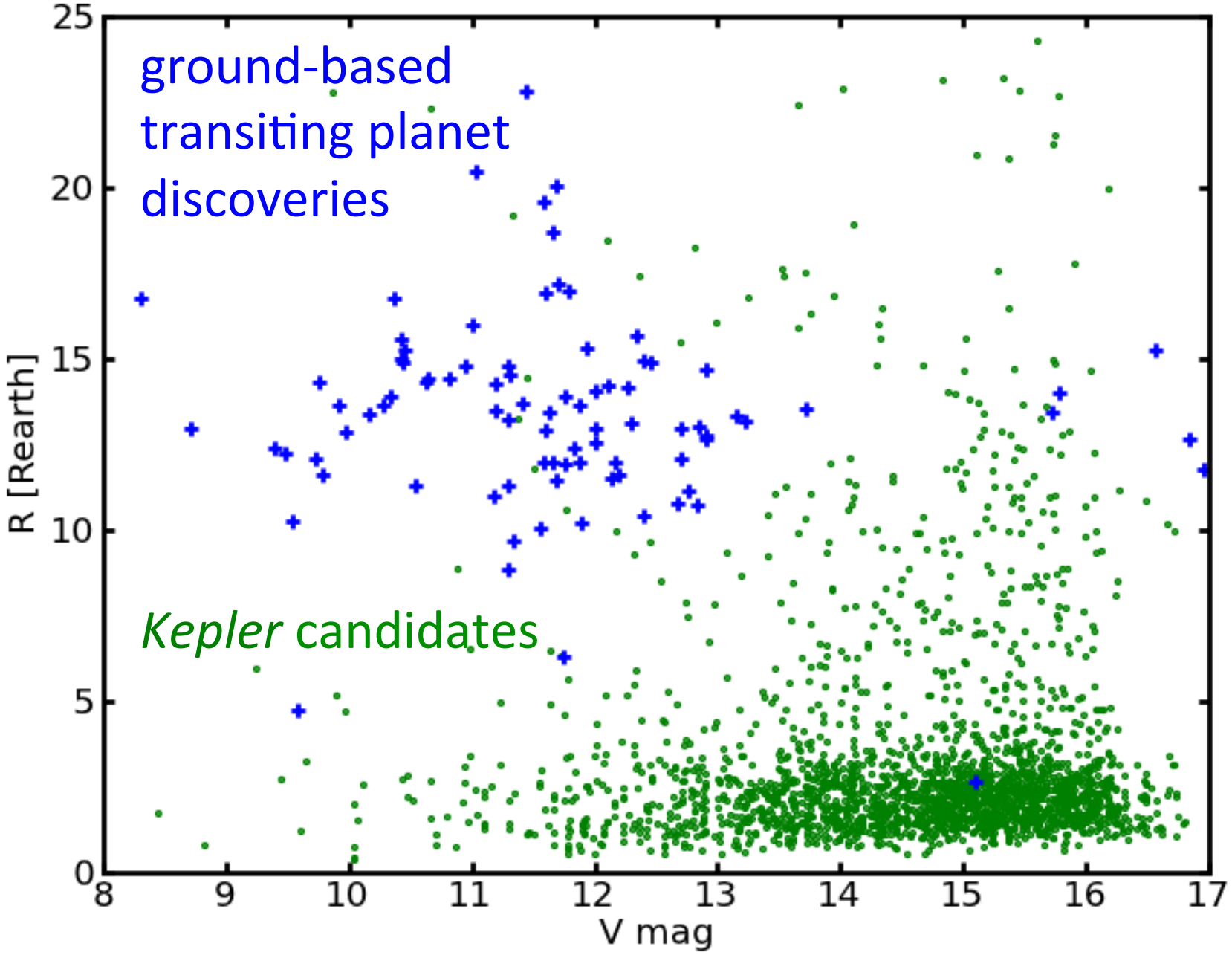


- Statistical census of planetary systems
- Small planets!
- Earth analogs??

Challenge…

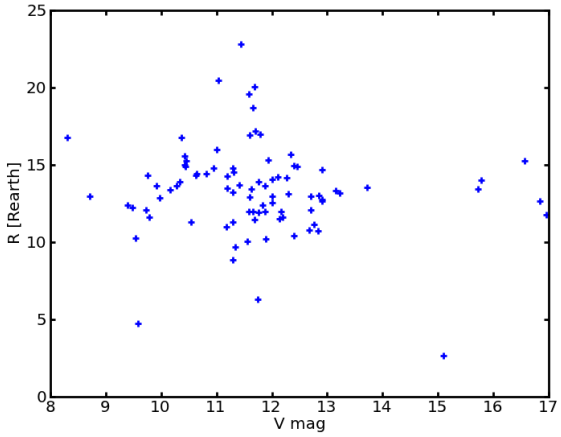
>2300 Candidates!


ground-based
transiting planet
discoveries
R [Rearth]
V mag
0
5
10
15
20
25
8
9
10
11
12
13
14
15
16
17


ground-based
transiting planet
discoveries
Kepler candidates
R [Rearth]
V mag
0
5
10
15
20
25
8
9
10
11
12
13
14
15
16
17

Candidates

Follow-up observations



Precision RVs

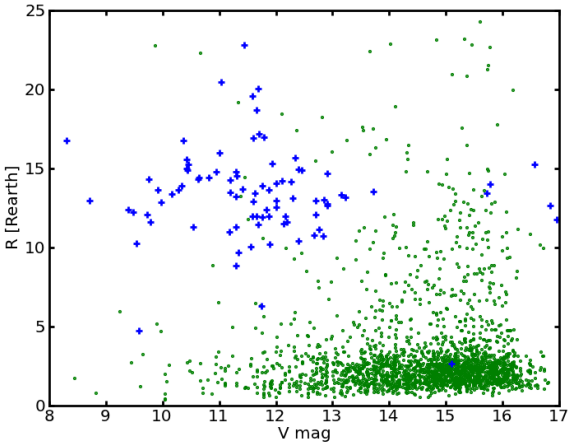
Confirmed planets

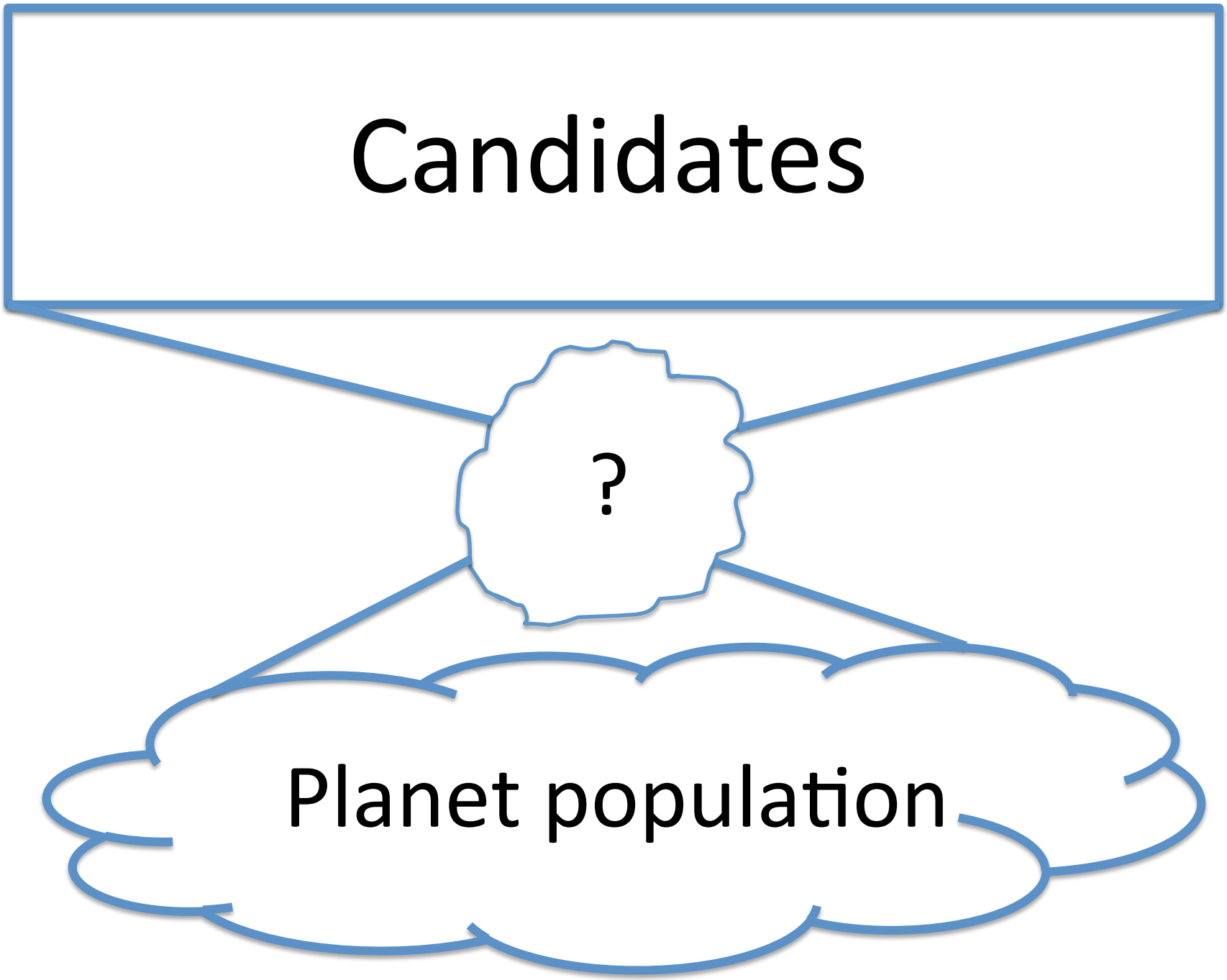
Candidates

Follow-up observations

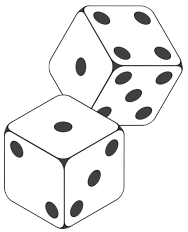
Precision RVs

Confirmed planets




Candidates
?
Planet population

Candidates



Planet population

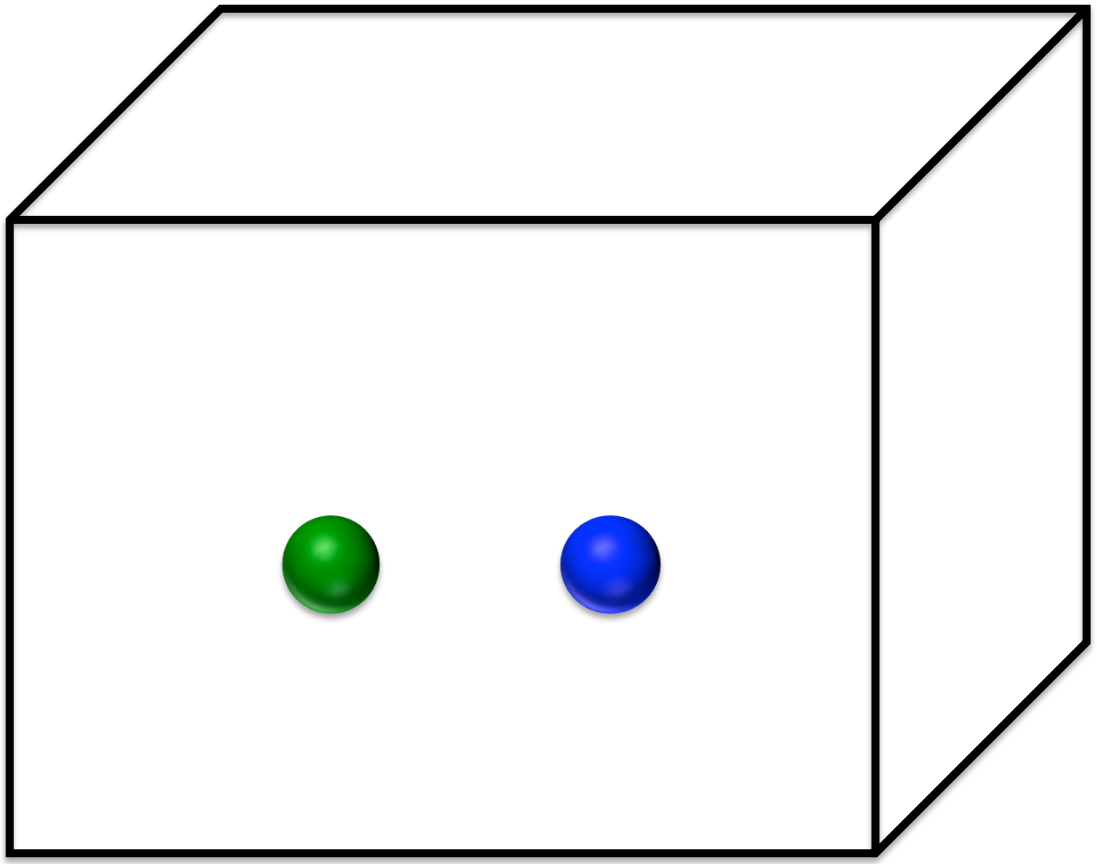
Philosophy: Posterior Probability

What is the probability
that a transit-like signal is a true planet,
given
a priori assumptions
and
observed data?

Planet candidates are marbles.

What do we know?

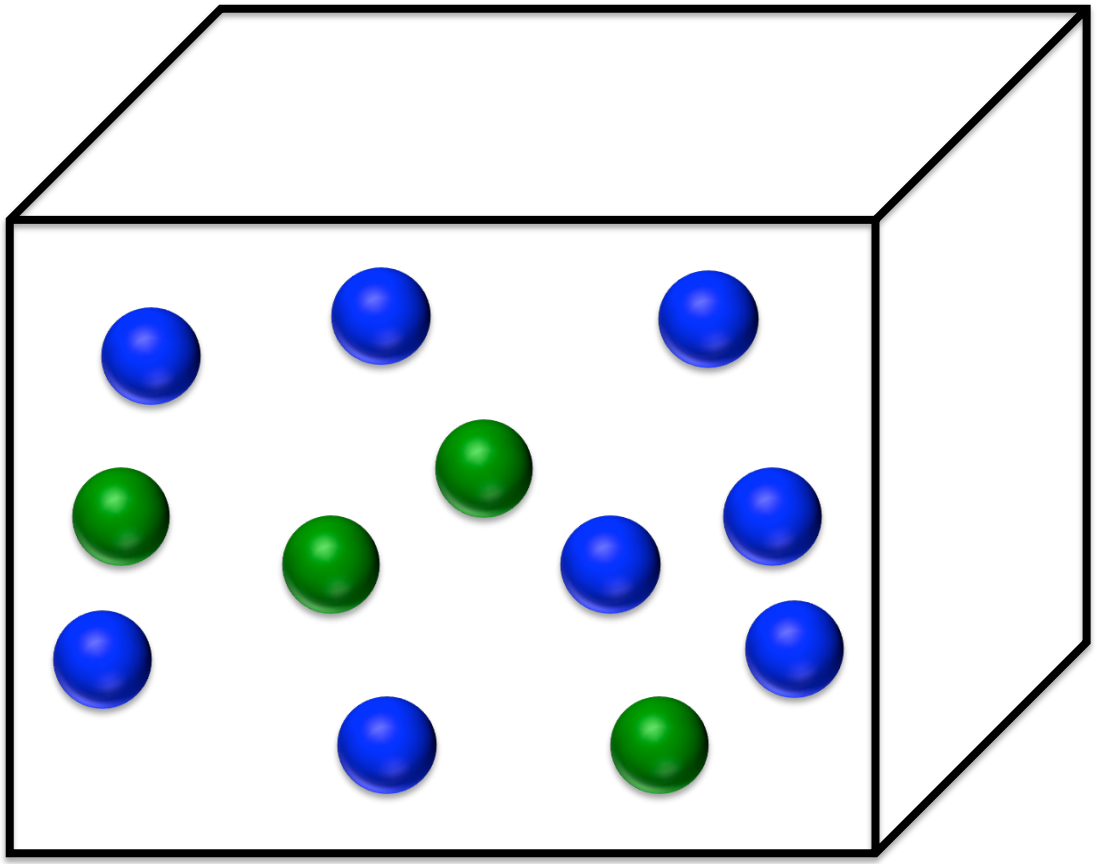
- What colors exist



Planet candidates are marbles.

What do we know?

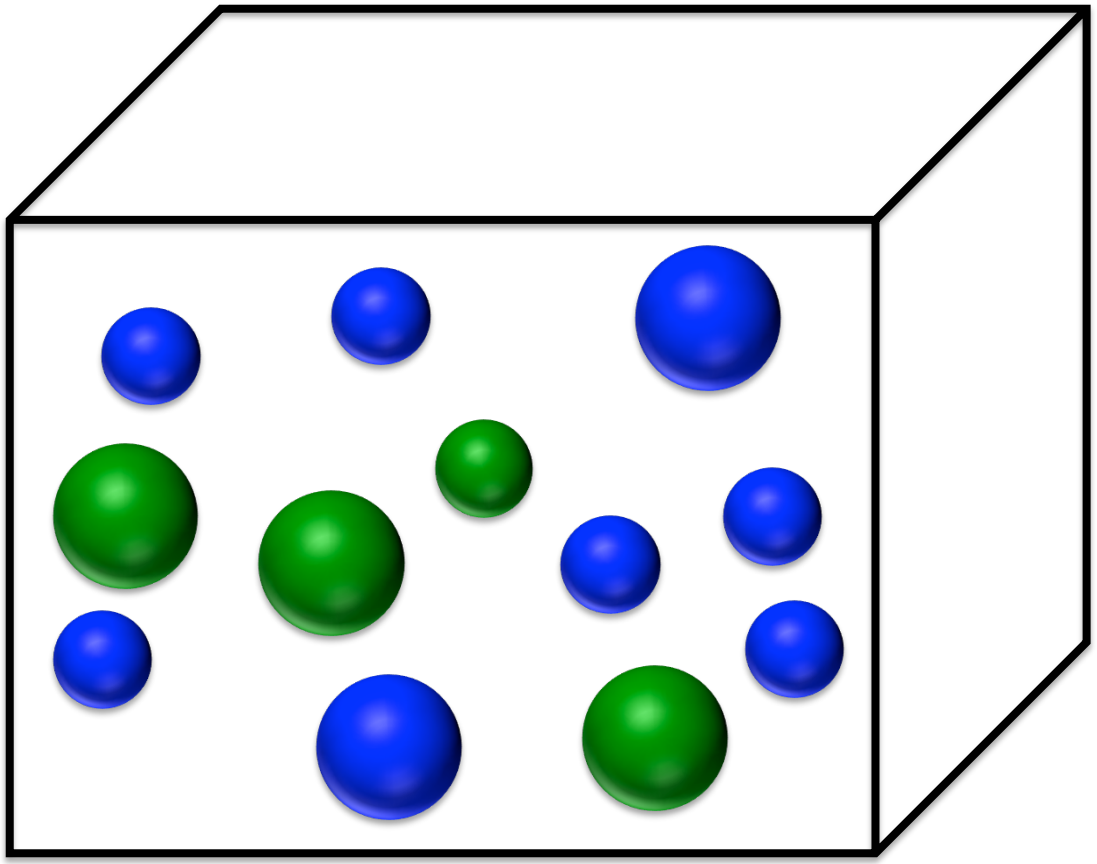
- What colors exist
- How many of each color there are



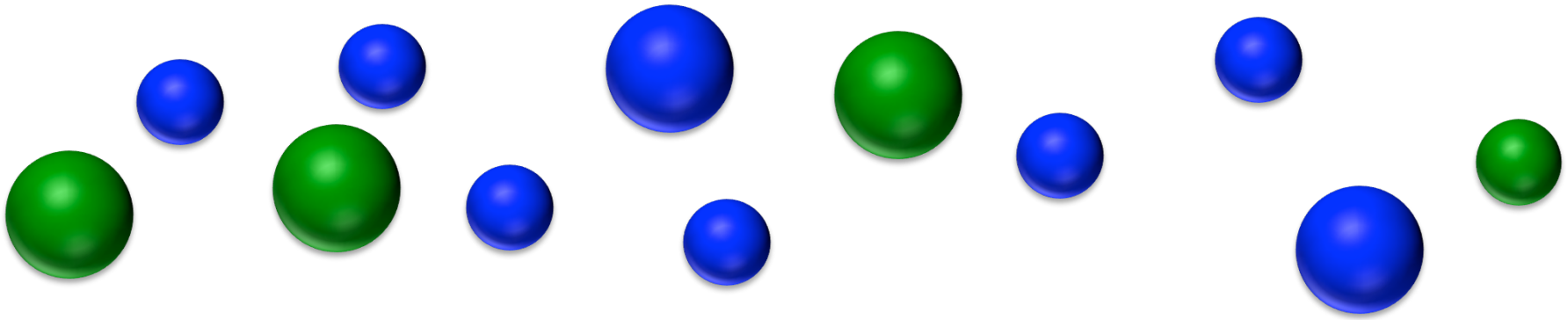
Planet candidates are marbles.

What do we know?

- What colors exist
- How many of each color there are
- The size distribution of the different colors



More a priori *knowledge enables more accurate assessment of the probabilities!*



$$\Pr(\text{planet} \mid \text{signal}) = \frac{(3/4) \cdot 4}{(3/4)\ 4 \qquad + (1/4)\ 8}$$

$\mathcal{L}$ = likelihood = "probability of data given model"
= e.g. 3/4 or 1/4 if a large marble is observed

π = prior = "probability of model" = e.g. 4 or 8

= 3/5


Recipe
How to…
Calculate an *a priori* false positive probability…

$$M = \{\text{Planet}, \text{FP}\} \qquad \text{FP} = \{\ldots\}$$

For each M_i in M, calculate:

π_i

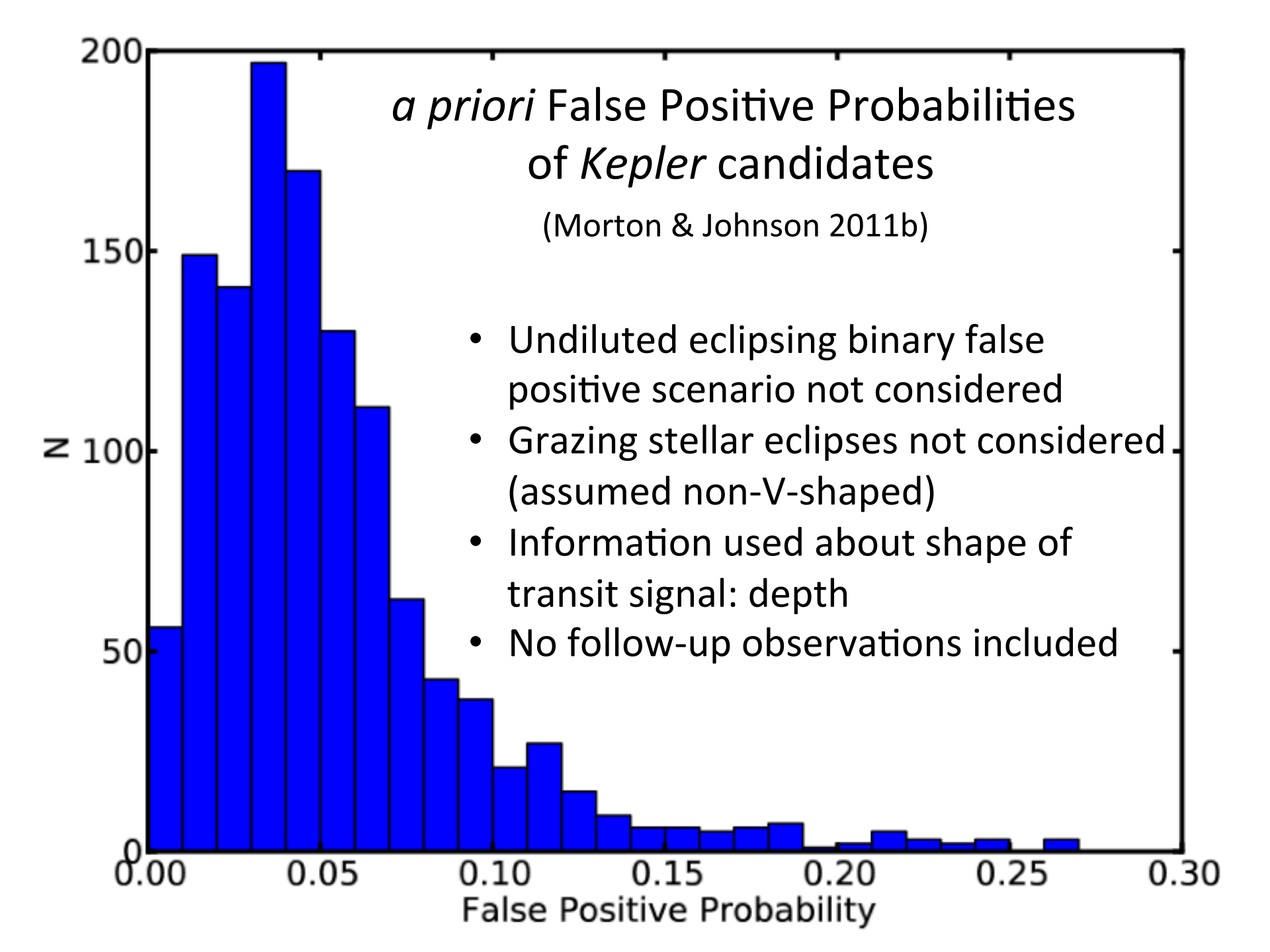
"How common do we believe scenario M_i is?"

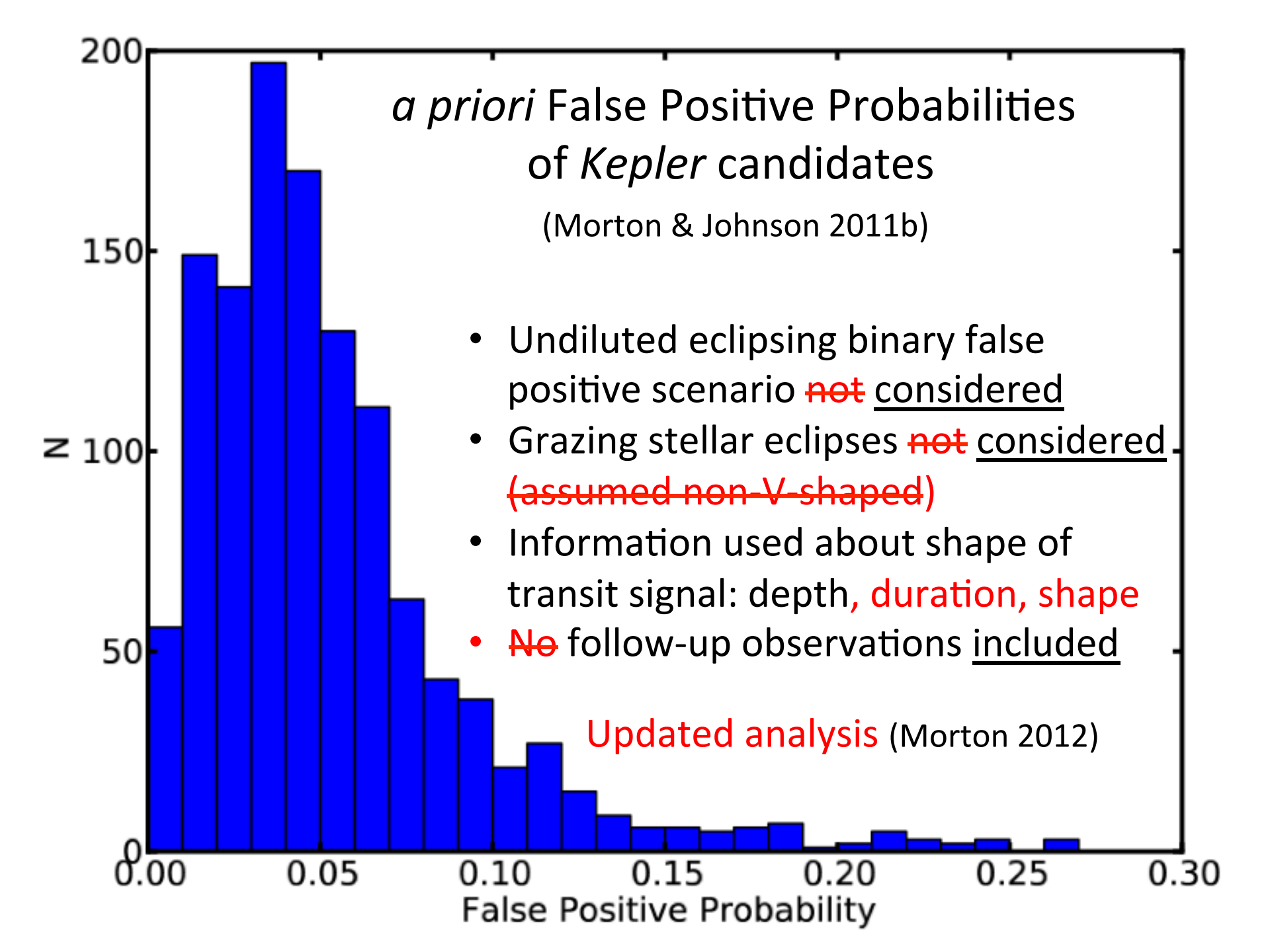
- Galactic population models
- Stellar multiplicity statistics
- Stellar models
- Orbital distributions of multiple systems (*P*,*e*)
- Planet occurrence rate

$\mathcal{L}_i$

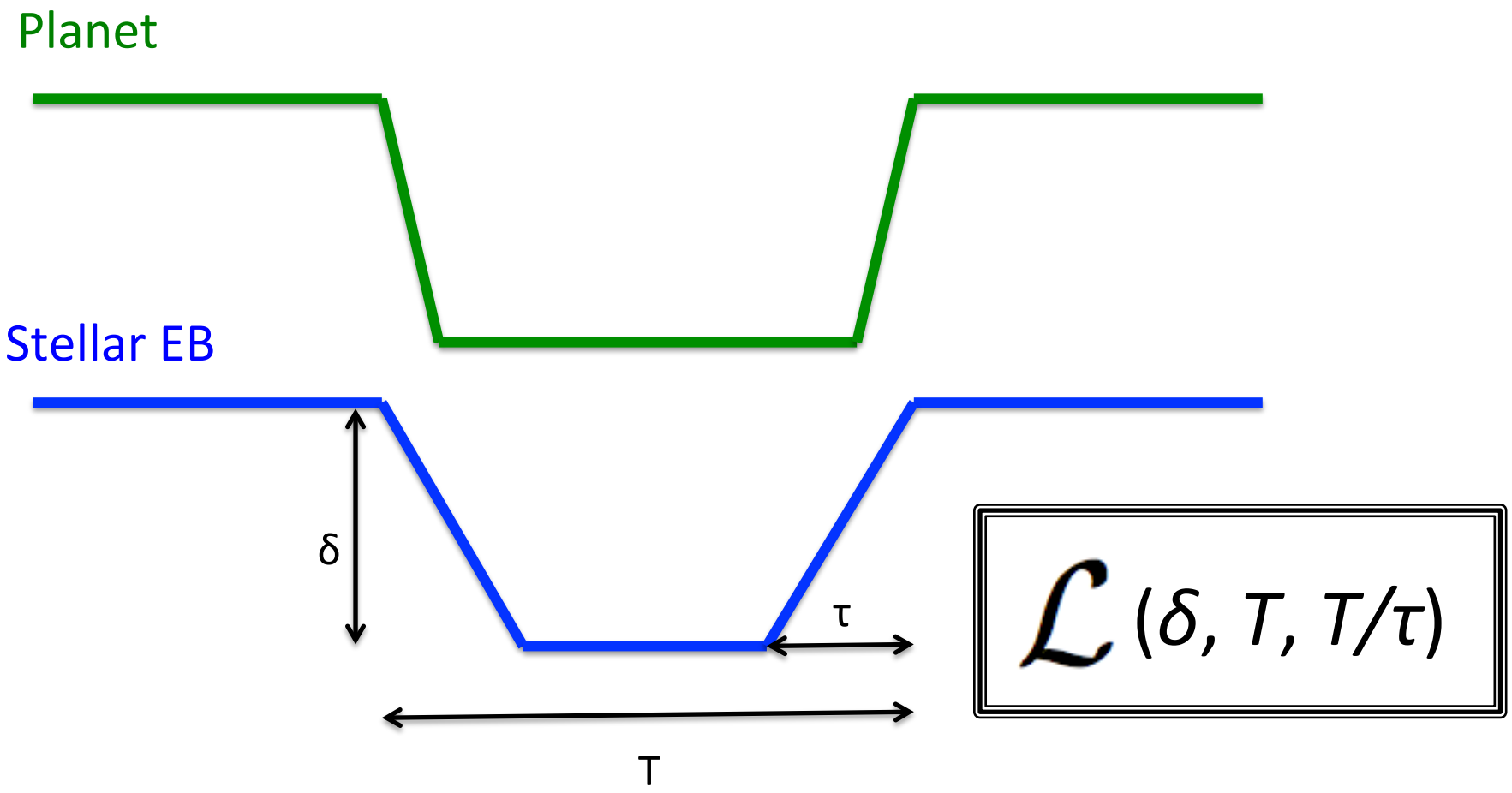
"How much does the observed signal look like scenario M_i?"

- Description of scenario light curves
- Description of data light curve
- Other follow-up observations/ constraints


a priori False Positive Probabilities of *Kepler* candidates
(Morton & Johnson 2011b)
• Undiluted eclipsing binary false positive scenario not considered
• Grazing stellar eclipses not considered (assumed non-V-shaped)
• Information used about shape of transit signal: depth
• No follow-up observations included
N
False Positive Probability
0
50
100
150
200
0.00
0.05
0.10
0.15
0.20
0.25
0.30

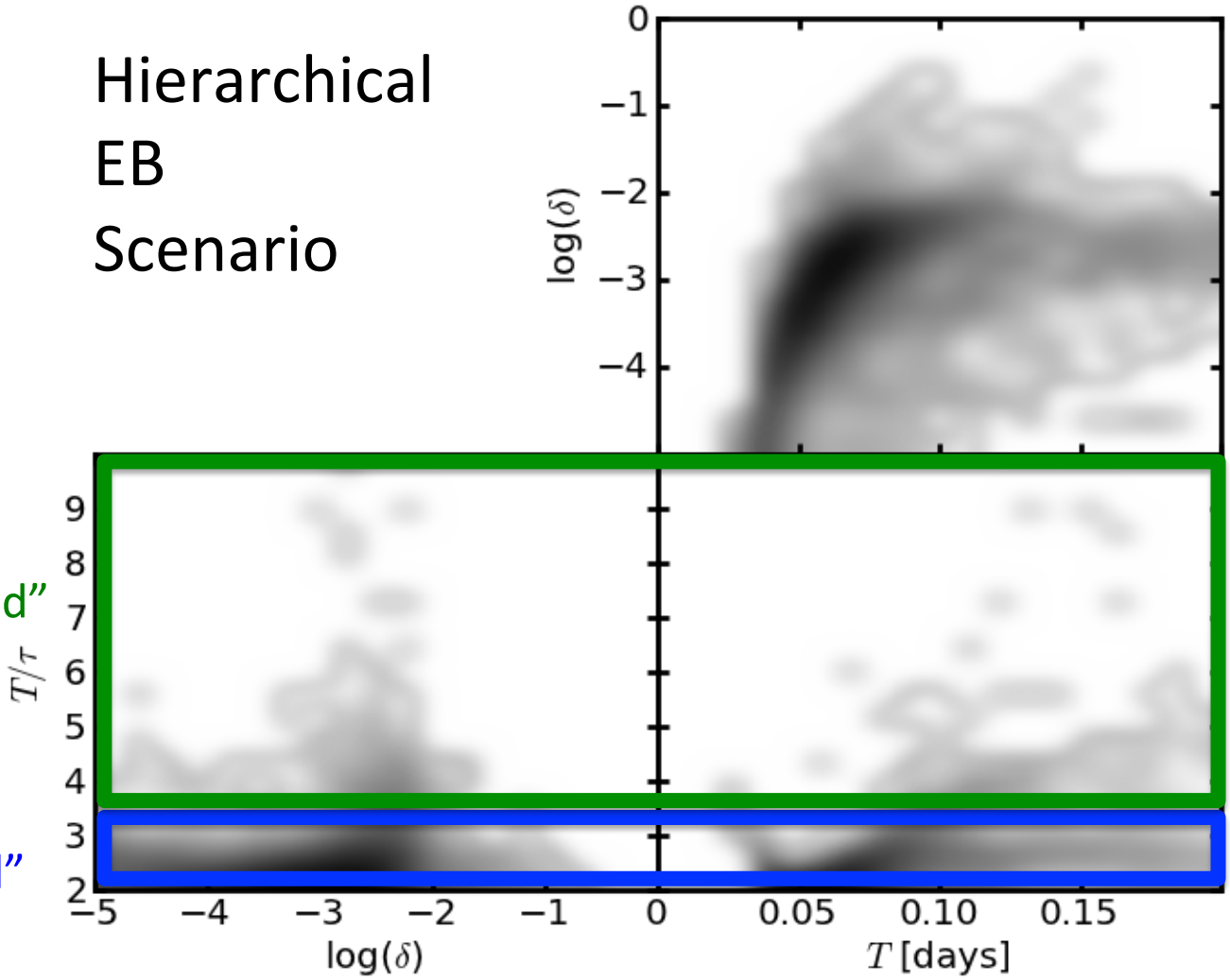

a priori False Positive Probabilities of *Kepler* candidates
(Morton & Johnson 2011b)
• Undiluted eclipsing binary false positive scenario ~~not~~ considered
• Grazing stellar eclipses ~~not~~ considered ~~(assumed non-V-shaped)~~
• Information used about shape of transit signal: depth, duration, shape
• ~~No~~ follow-up observations included
Updated analysis (Morton 2012)
N
False Positive Probability
0
50
100
150
200
0.00
0.05
0.10
0.15
0.20
0.25
0.30

light curve shape



Simulate representative populations

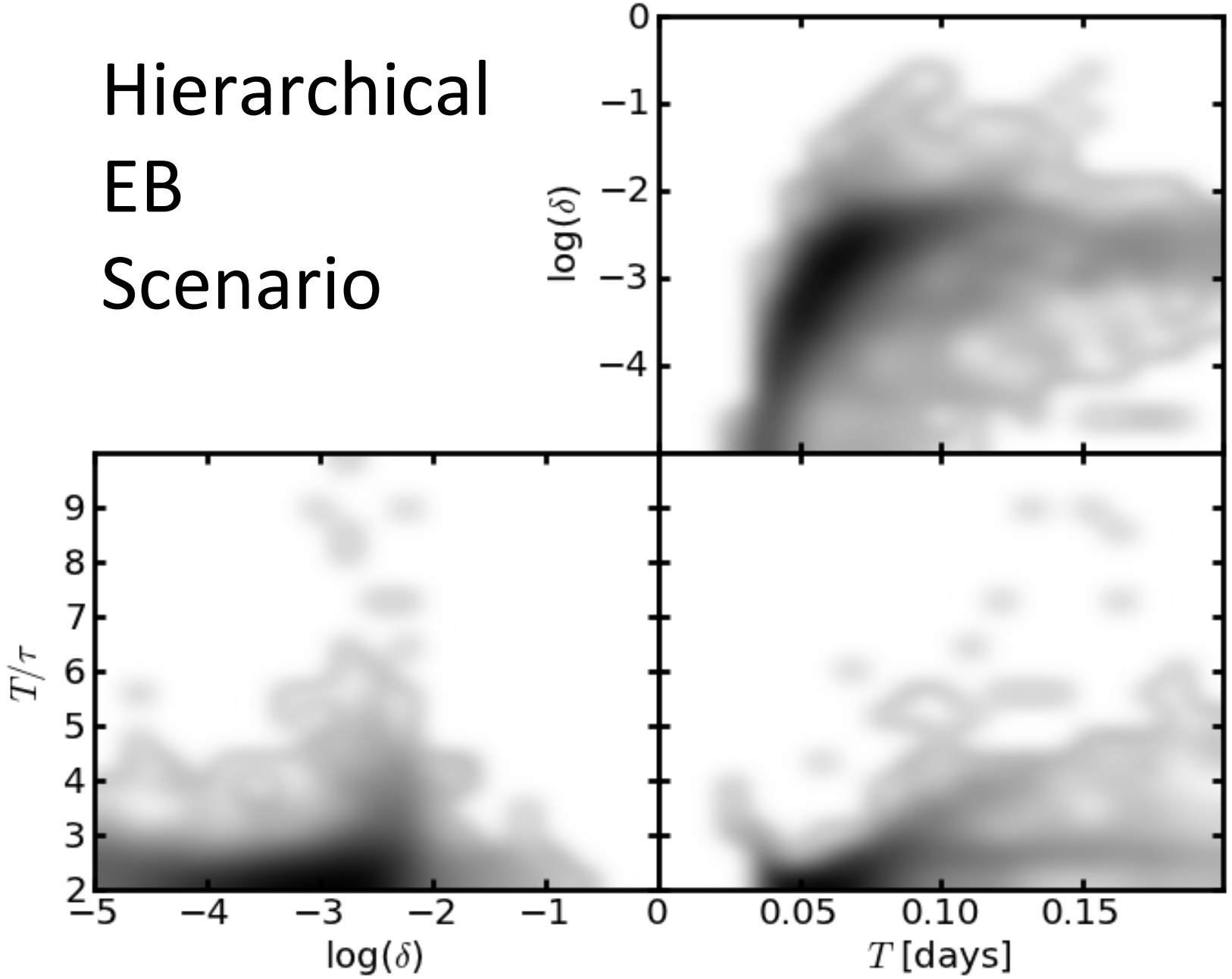
Hierarchical
EB
Scenario



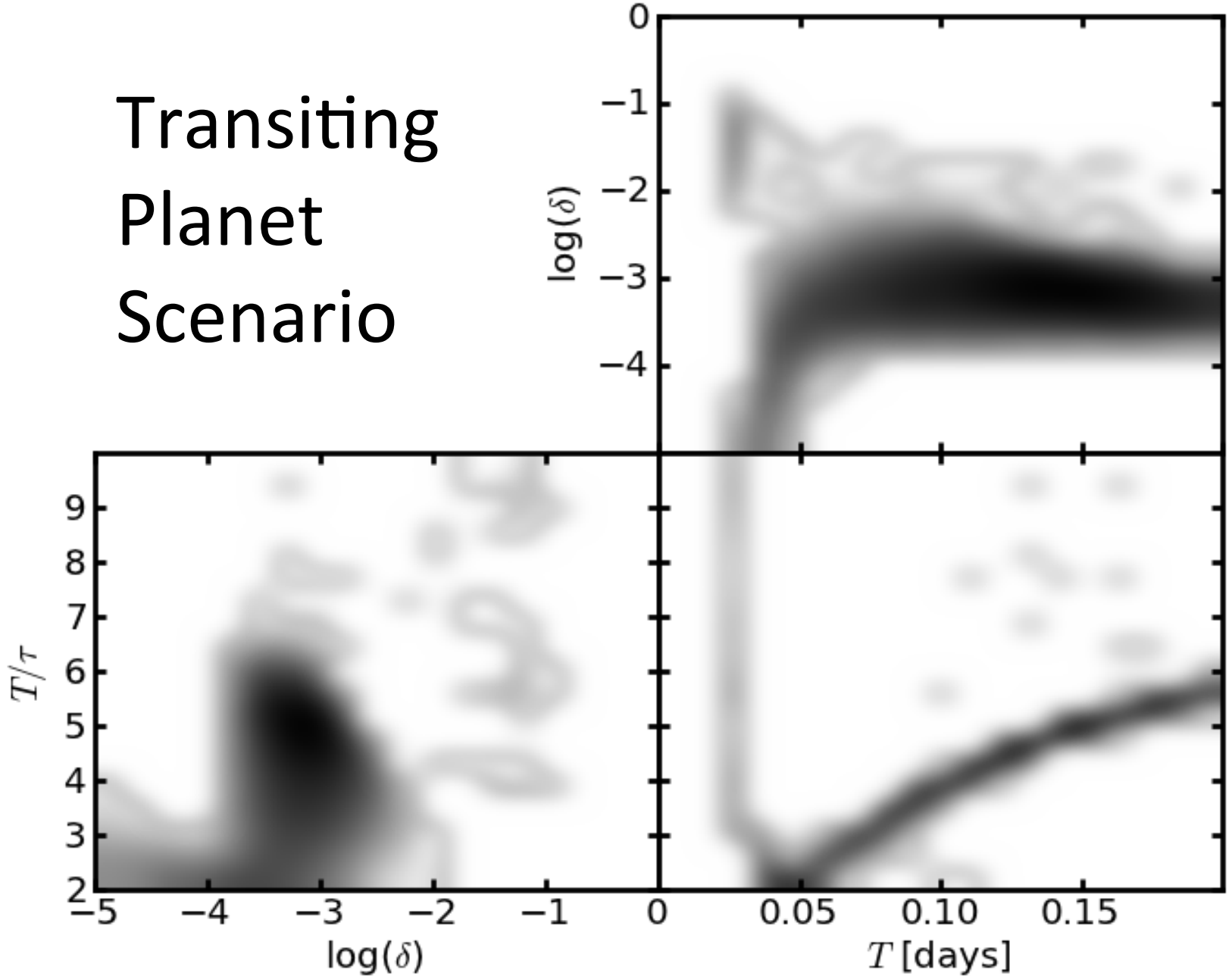
“box-shaped”

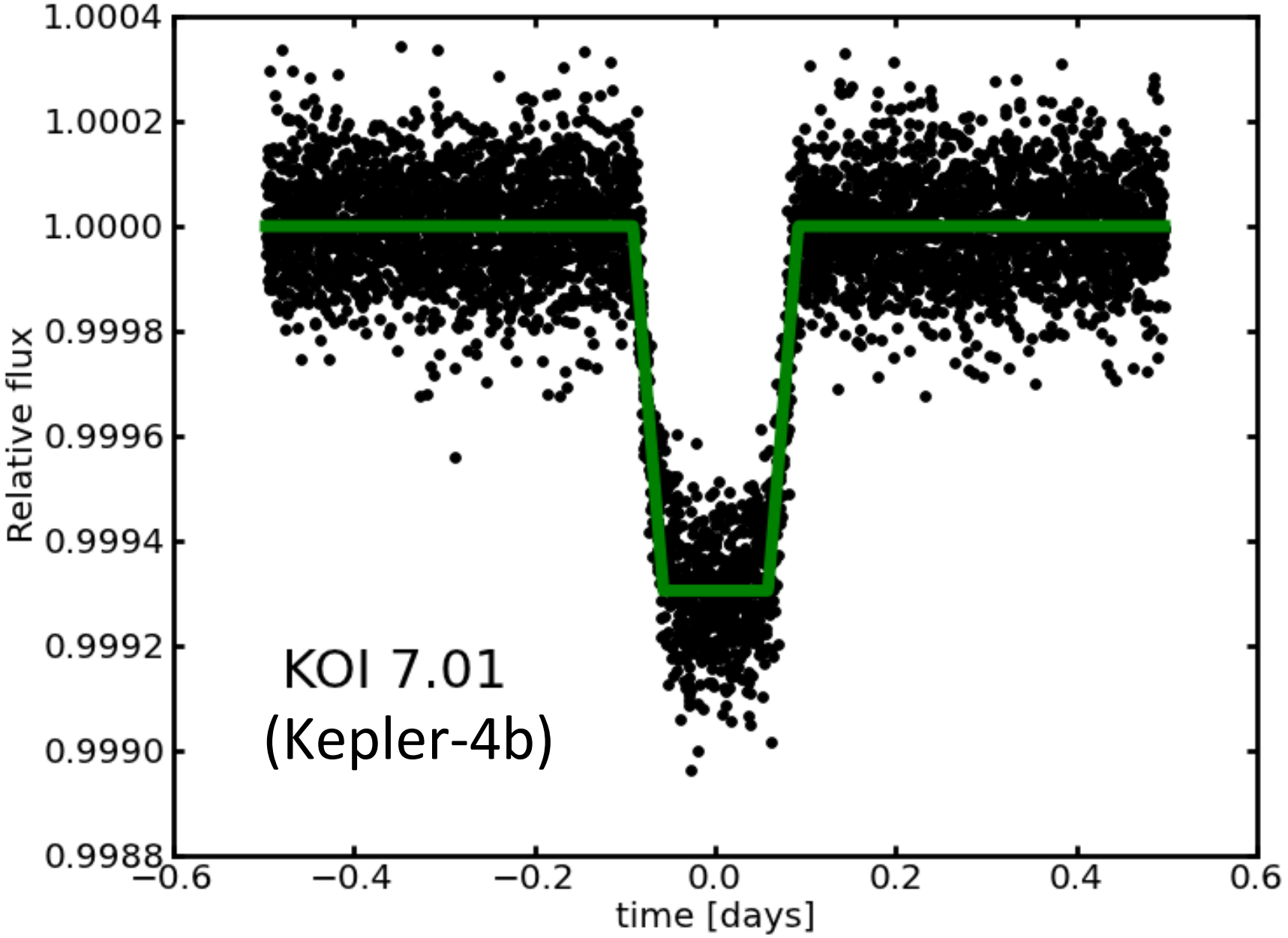
“V-shaped”

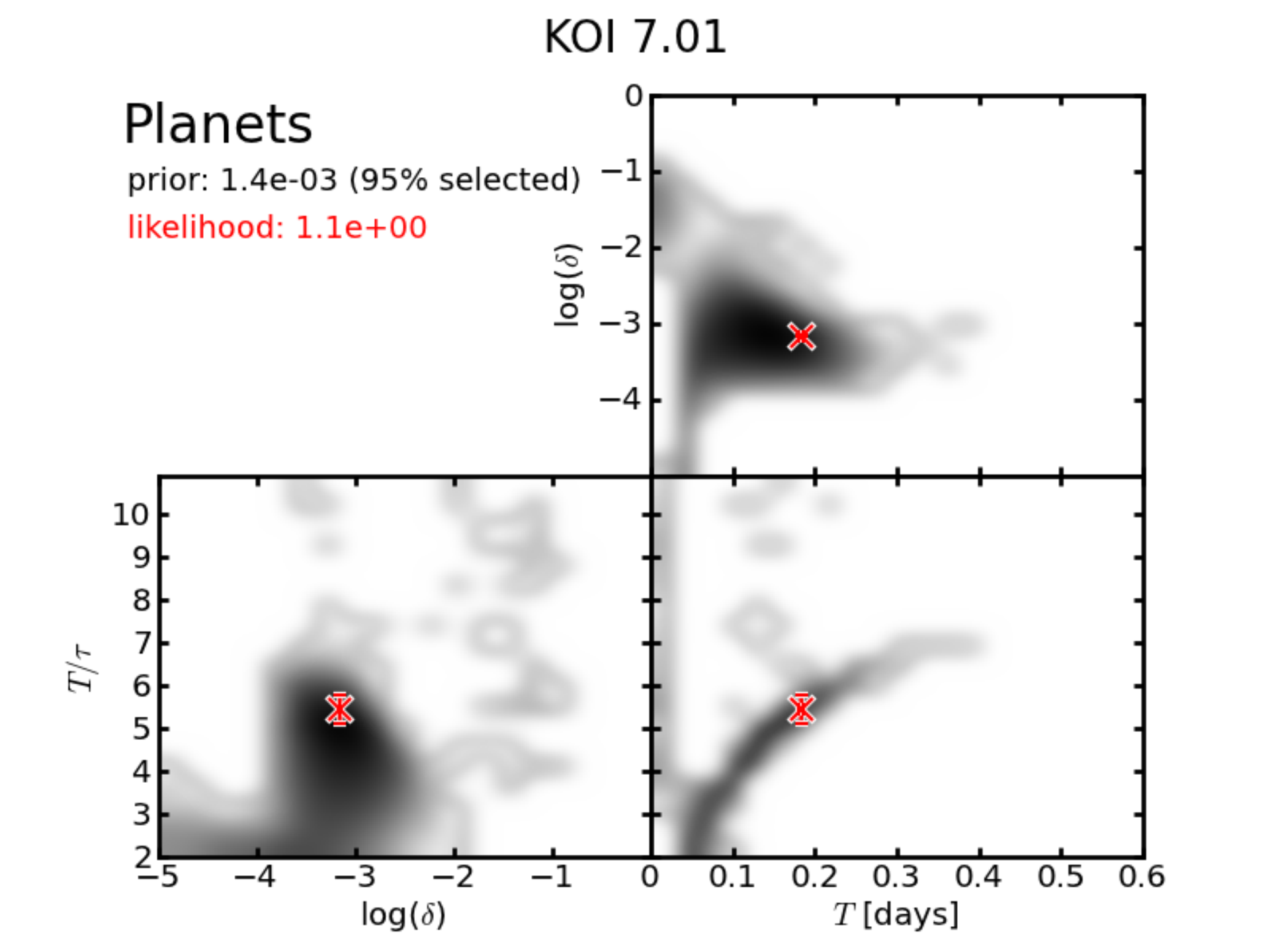
Hierarchical EB Scenario

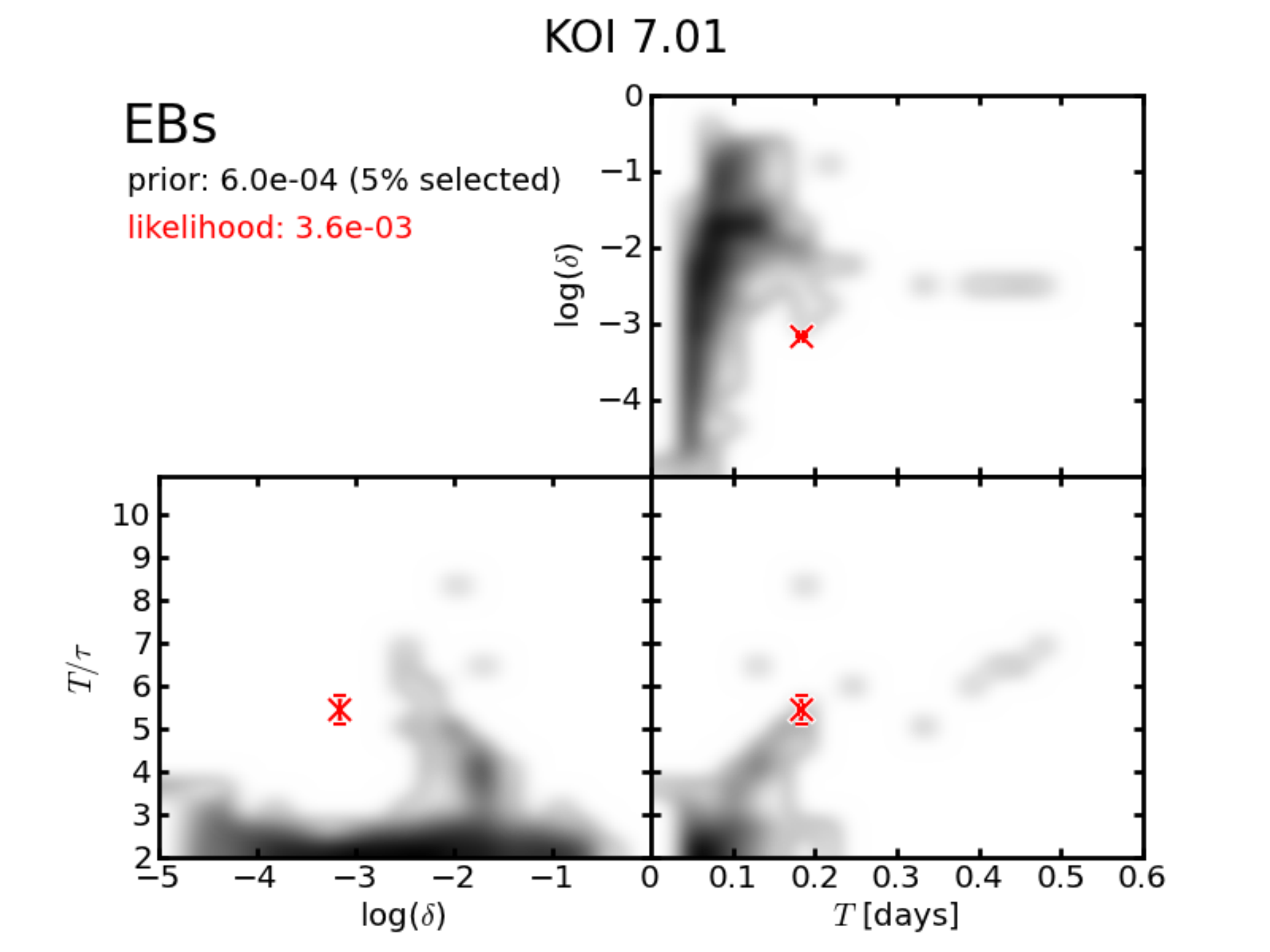


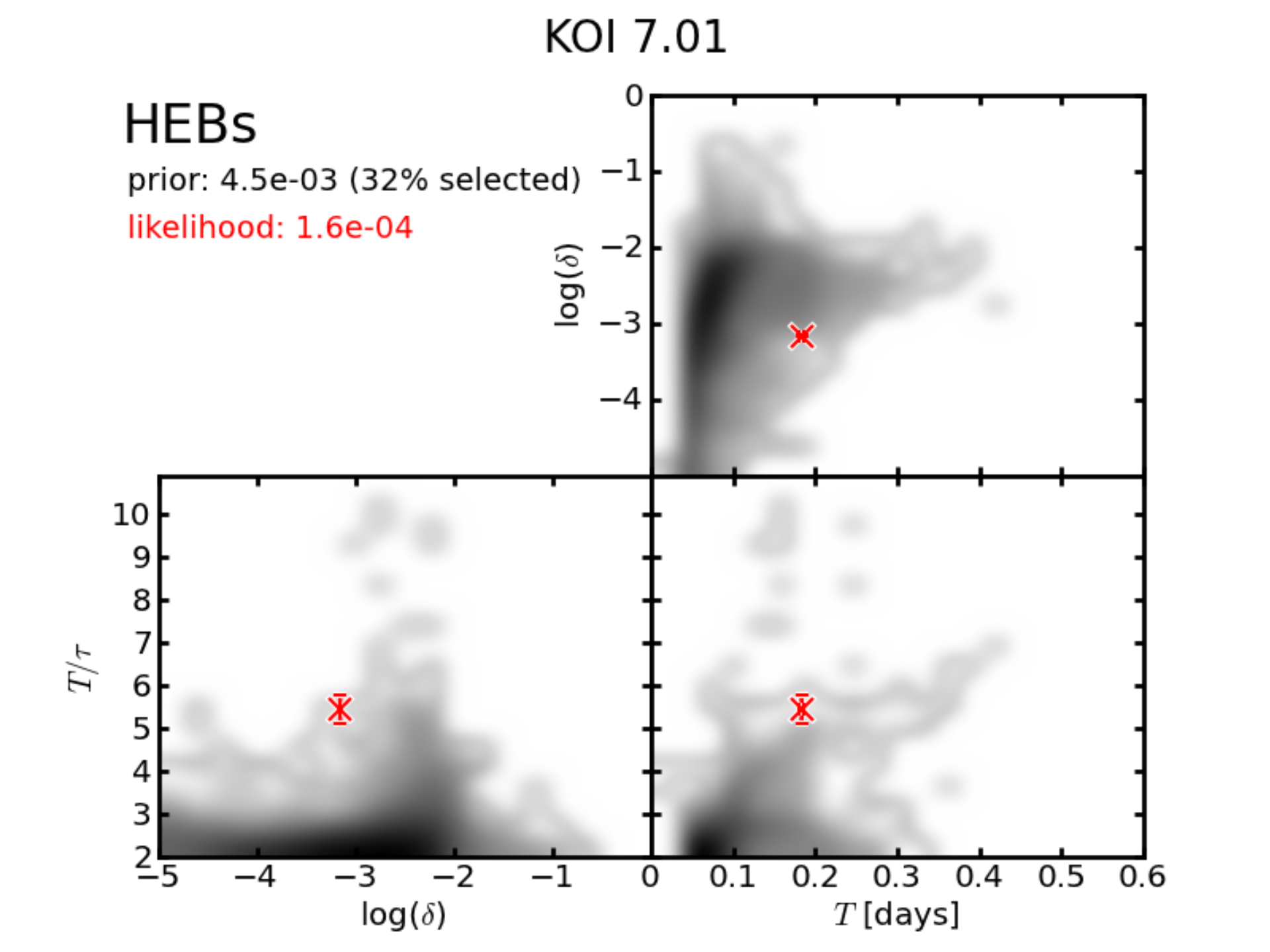
Transiting Planet Scenario

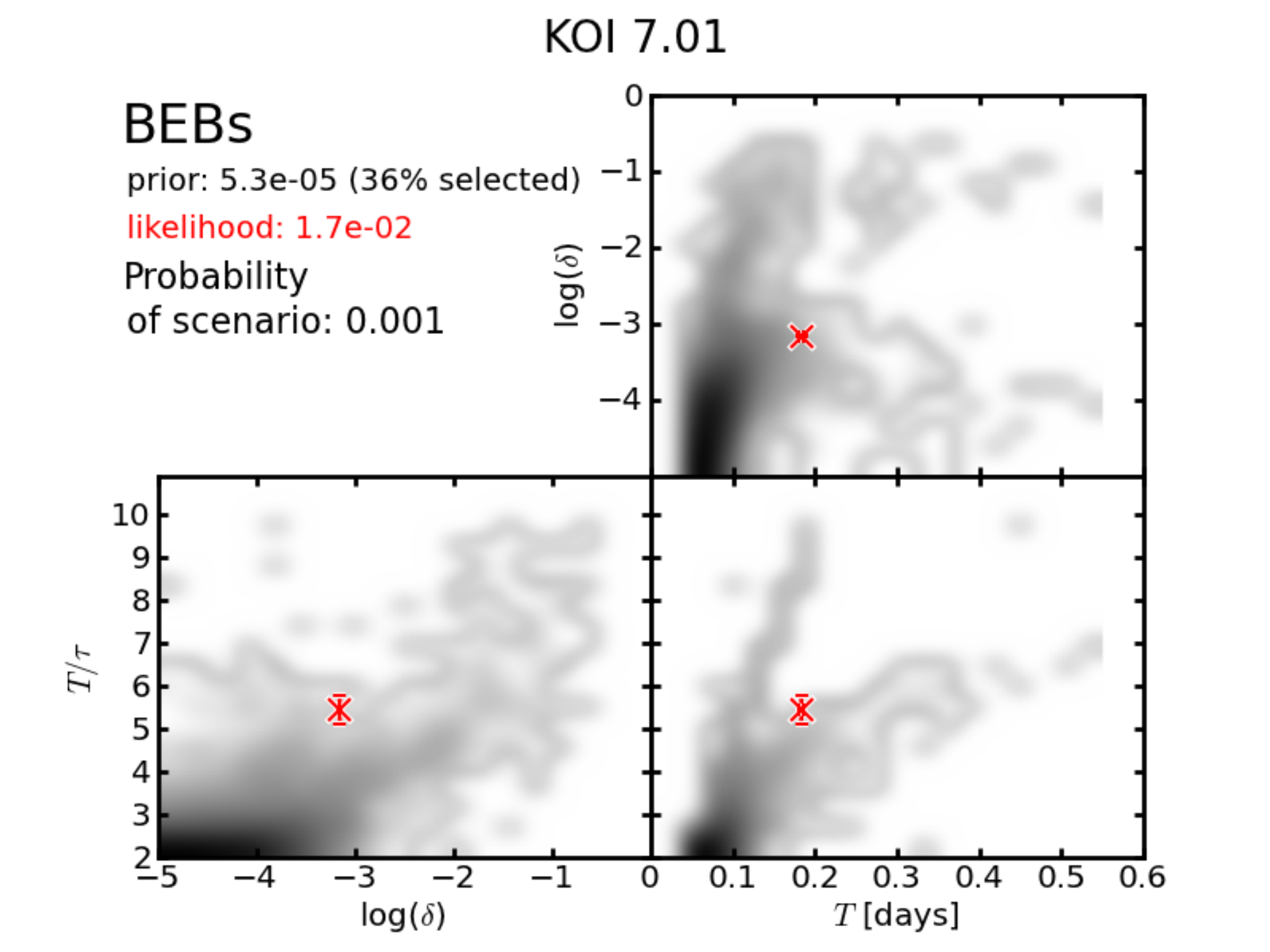


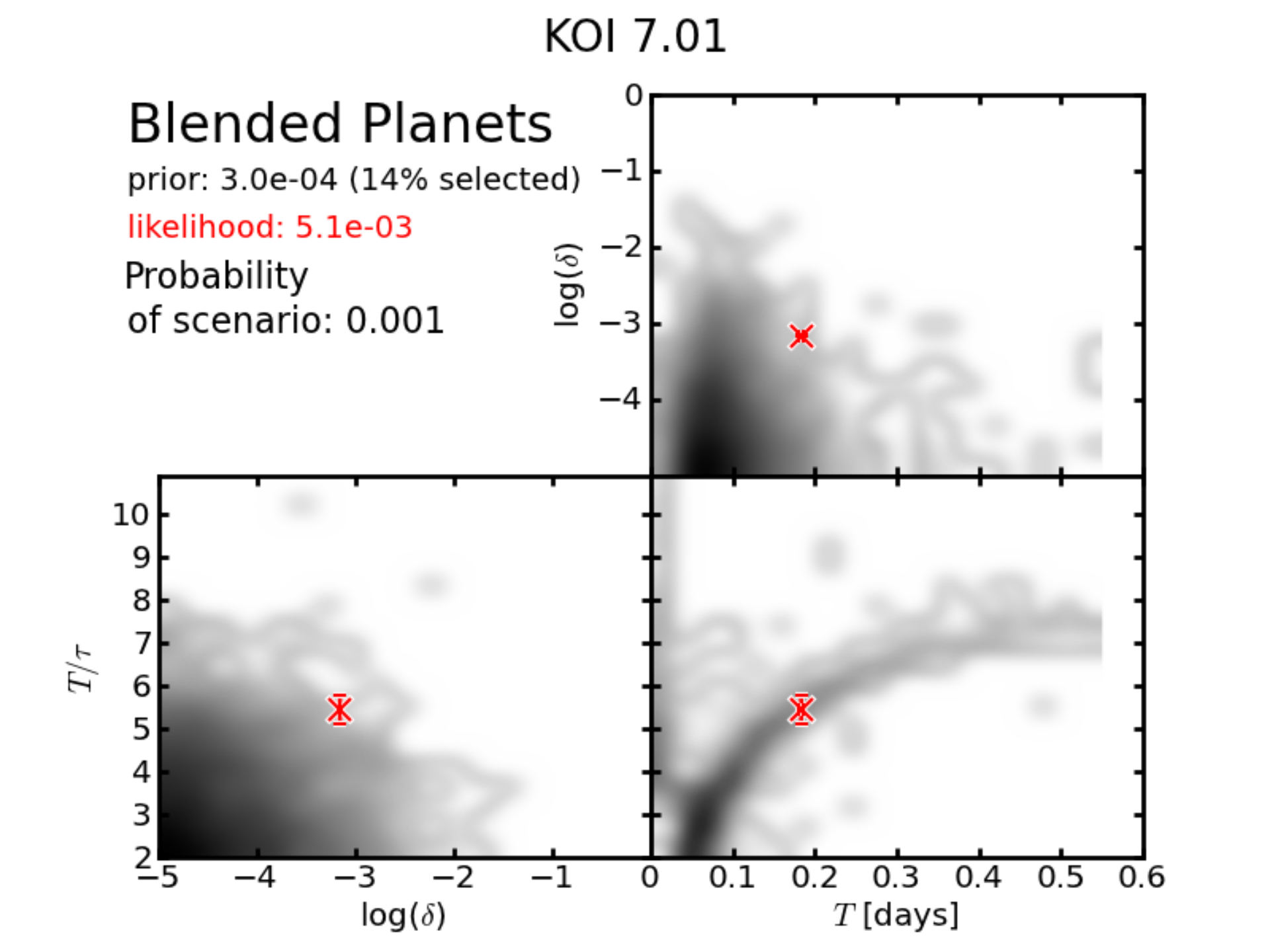

1.0004
1.0002
1.0000
0.9998
0.9996
0.9994
0.9992
0.9990
0.9988
Relative flux
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
time [days]
KOI 7.01
(Kepler-4b)

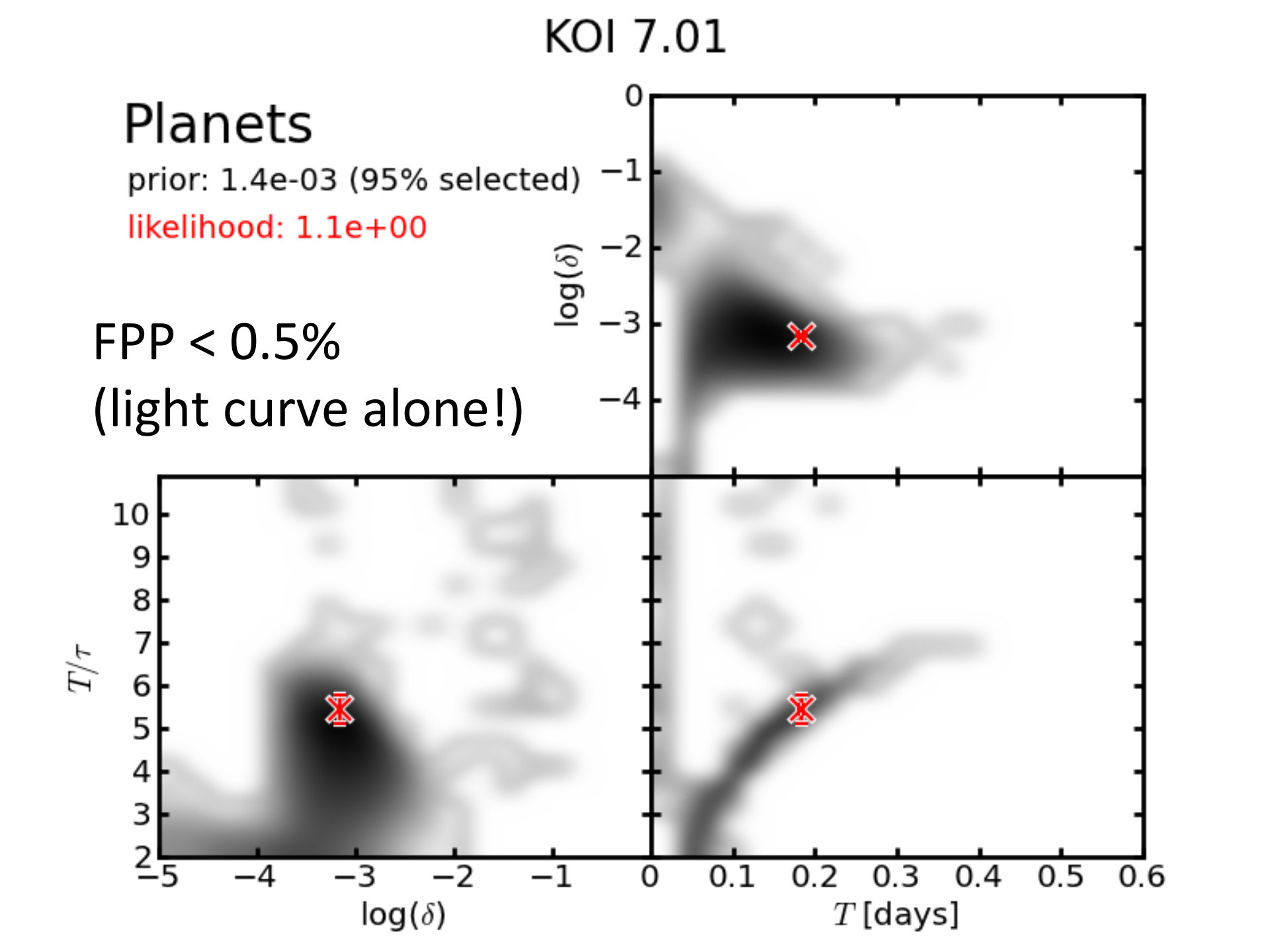

KOI 7.01
Planets
prior: 1.4e-03 (95% selected)
likelihood: 1.1e+00
log(δ)
T/τ
log(δ)
T [days]

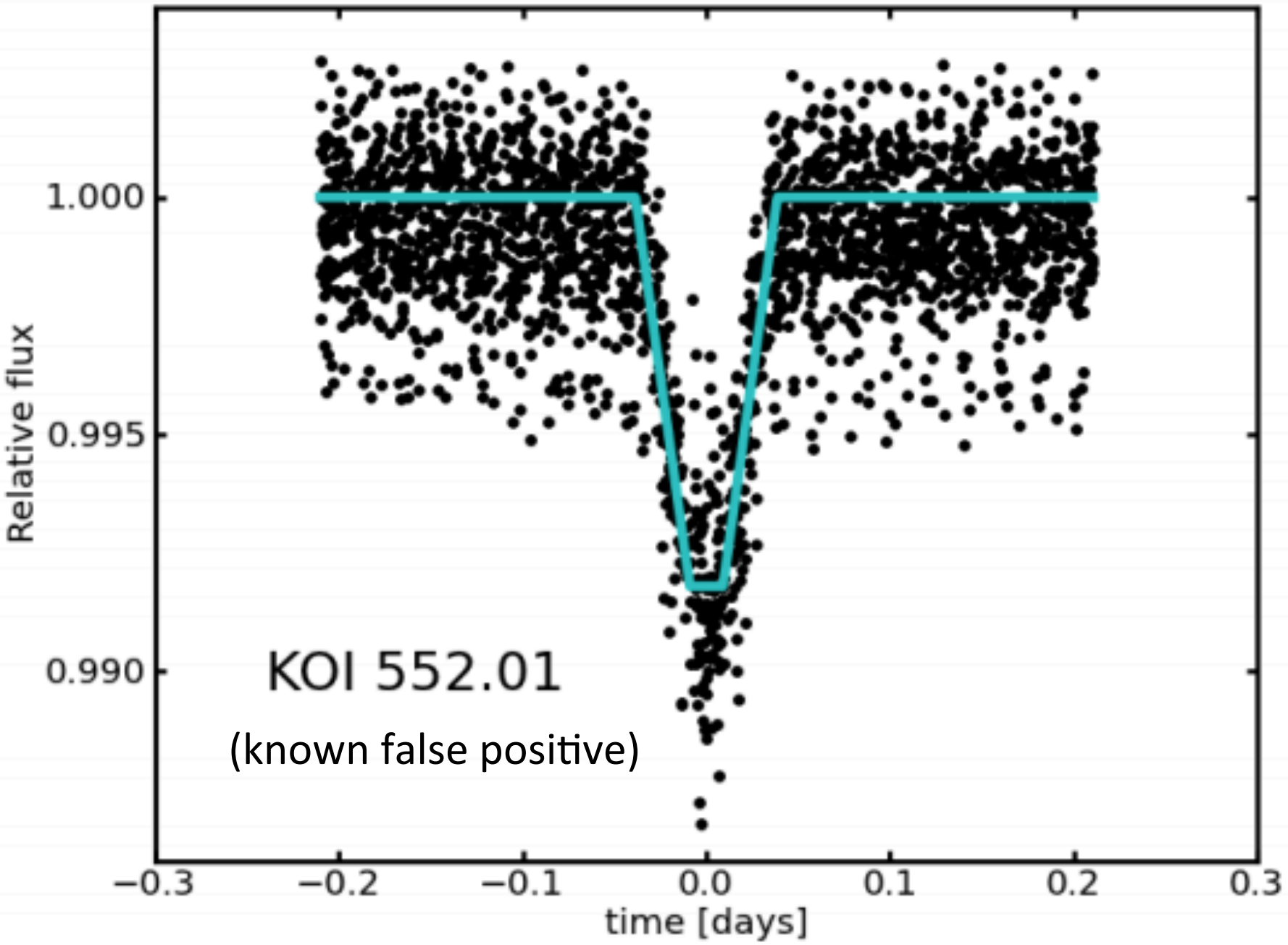

KOI 7.01
EBs
prior: 6.0e-04 (5% selected)
likelihood: 3.6e-03
log(δ)
T/τ
log(δ)
T [days]


KOI 7.01
HEBs
prior: 4.5e-03 (32% selected)
likelihood: 1.6e-04
log(δ)
T/τ
log(δ)
T [days]


KOI 7.01
BEBs
prior: 5.3e-05 (36% selected)
likelihood: 1.7e-02
Probability
of scenario: 0.001
log(δ)
T/τ
log(δ)
T [days]

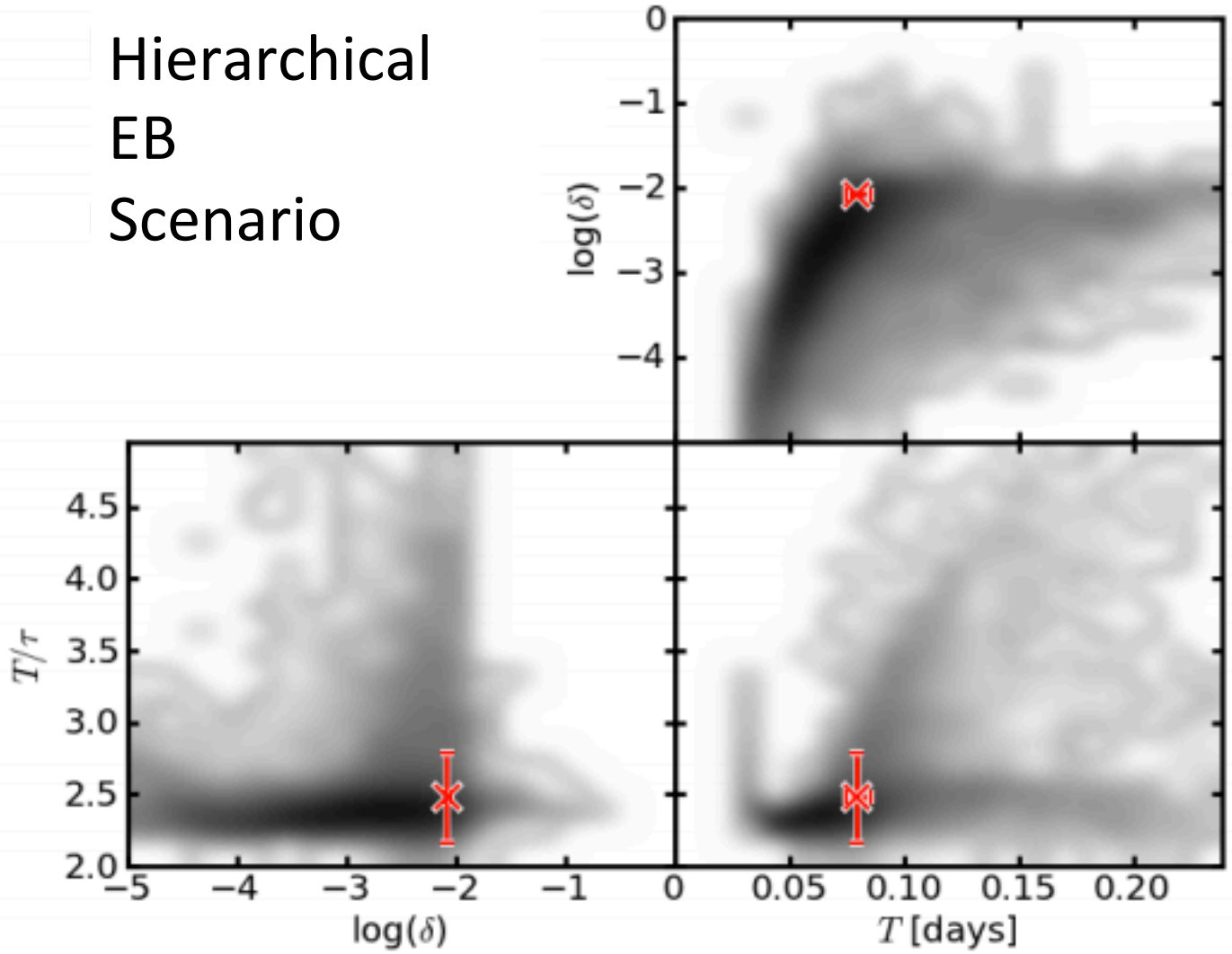

KOI 7.01
Blended Planets
prior: 3.0e-04 (14% selected)
likelihood: 5.1e-03
Probability
of scenario: 0.001
log(δ)
T/τ
log(δ)
T [days]


KOI 7.01
Planets
prior: 1.4e-03 (95% selected)
likelihood: 1.1e+00
FPP < 0.5%
(light curve alone!)
log(δ)
T/τ
log(δ)
T [days]


1.000
0.995
0.990
Relative flux
KOI 552.01
(known false positive)
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
time [days]

KOI-552 (known false positive)

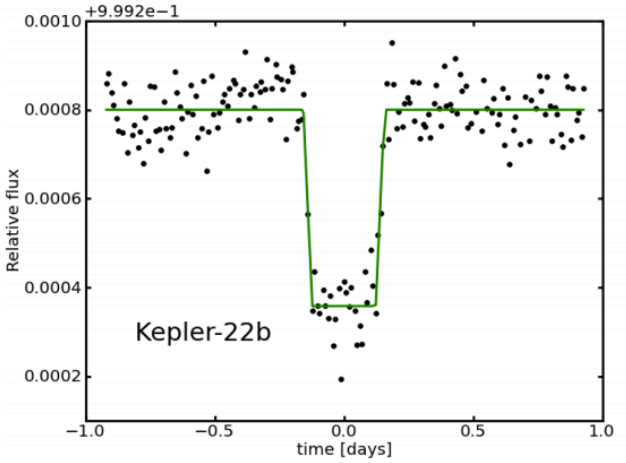
Hierarchical
EB
Scenario



FPP = 0.90!

Control tests

Morton (2012)

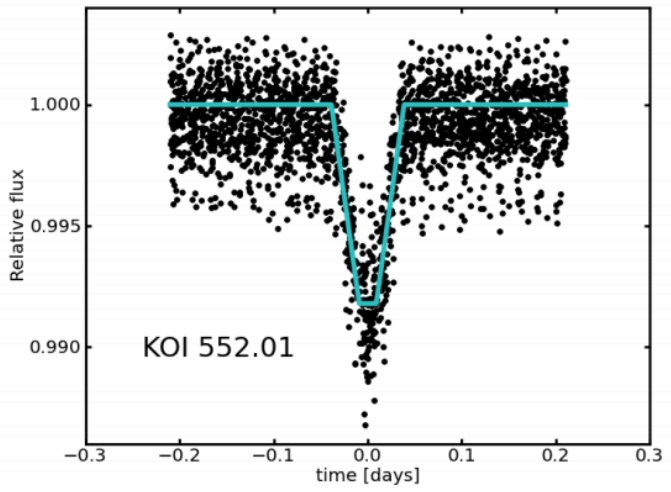


18 known Kepler planets:

- 4 could be validated with just photometry
- 9 with just stellar characterization
- 7 with just AO observations
- 14 with both stellar characterization and AO (remaining 4 are all giant planets)

11 known KOI false positives:

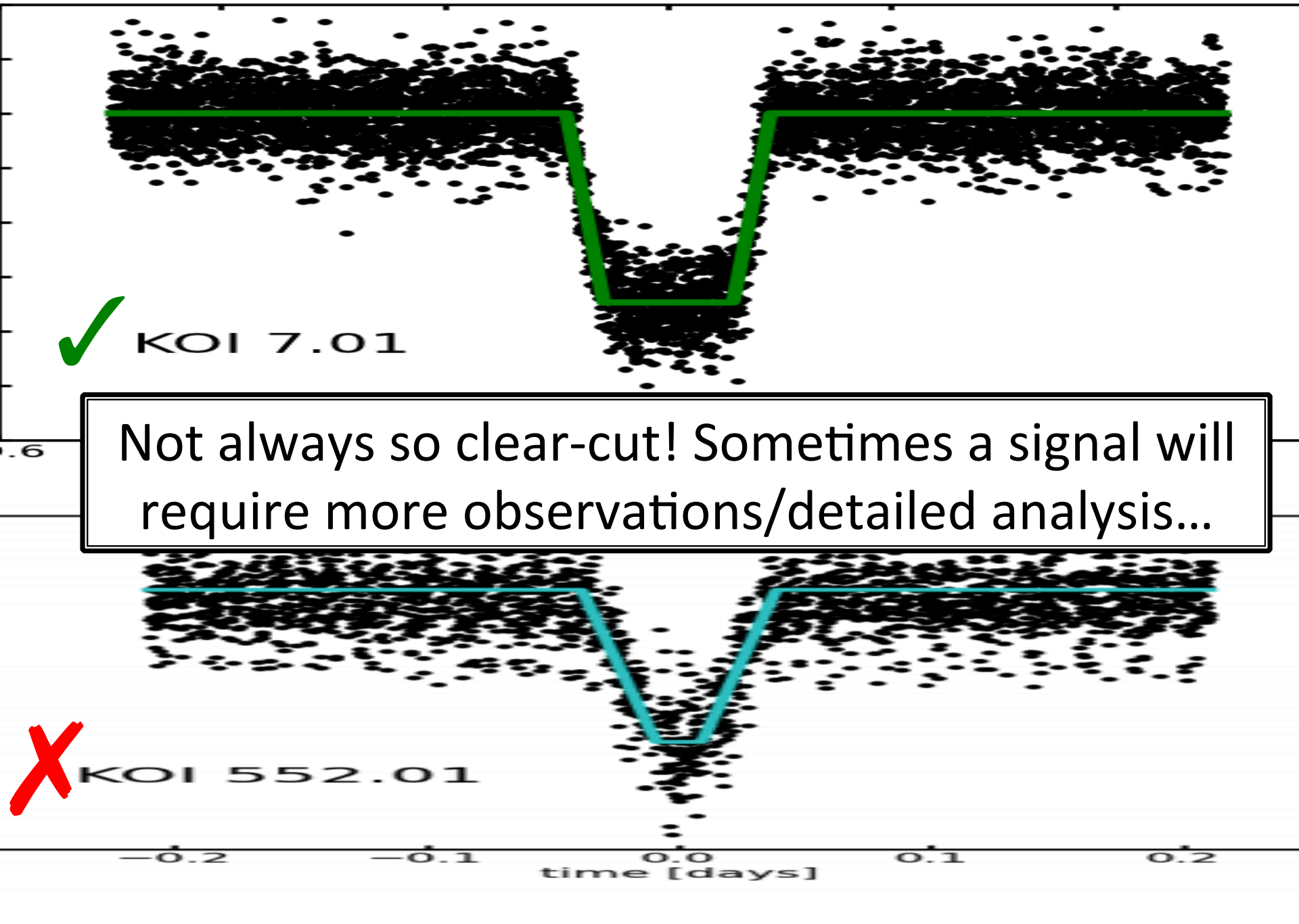
- All but 2 have FPP > 0.40
- 5 have FPP > 0.90



It works!

a priori FPPs, redux

- Identify a set of false positive scenarios to test the planet hypothesis against
- Use knowledge about stellar populations to determine how common each false positive scenario should be
- Generate populations of each scenario (false positives and planets) to generate distributions of light curve shapes, and compare to the observed light curve.
- Sometimes, this is all you need to either validate a signal or identify a likely false positive!



Not always so clear-cut! Sometimes a signal will require more observations/detailed analysis…