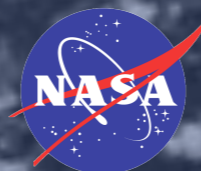


Onward!

Kepler's Exoplanet Census

Kepler



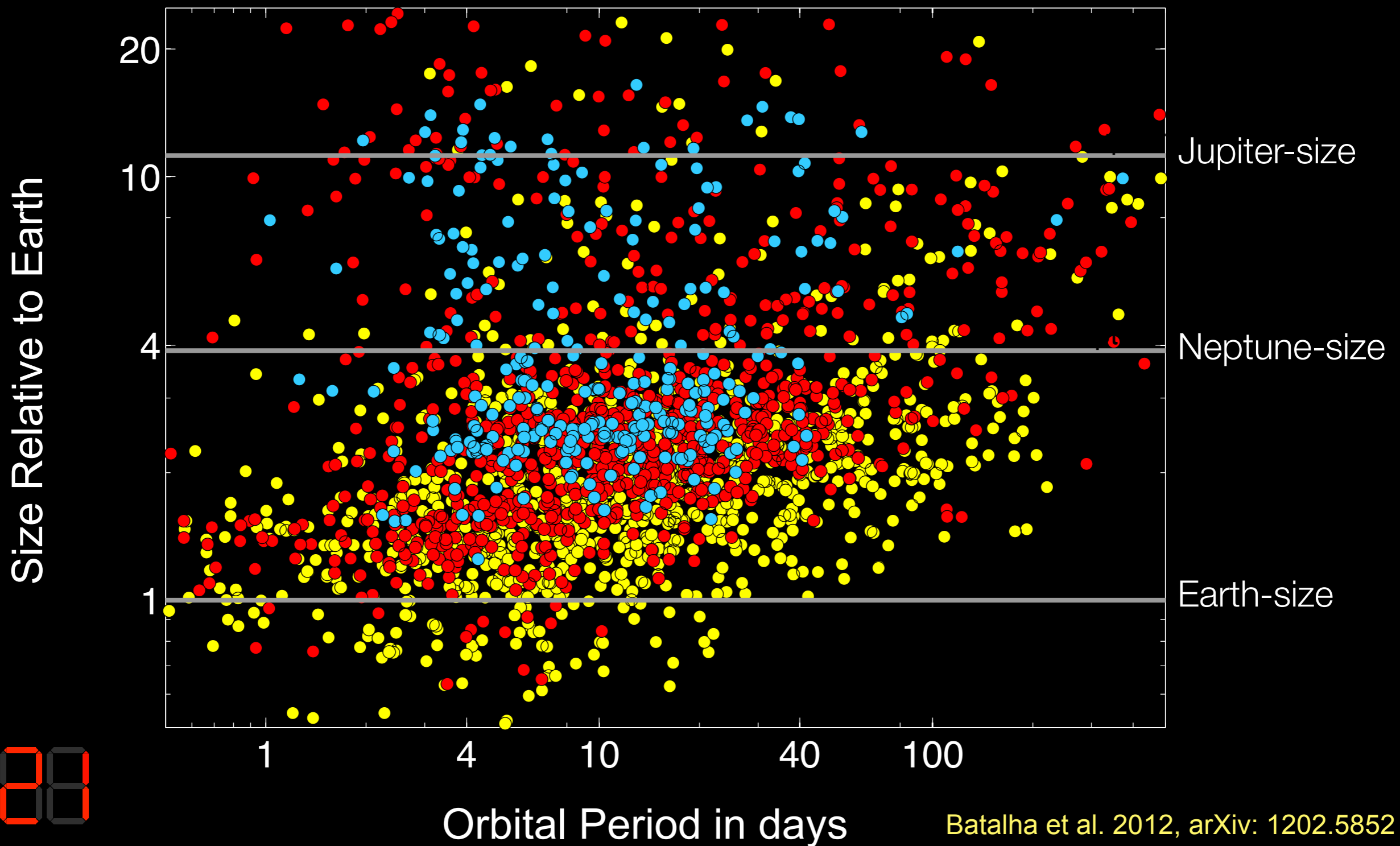
Natalie Batalha
NASA Ames Research Center

Candidates as of Feb 2012

Q0-Q6: May 2009 - Sep 2010

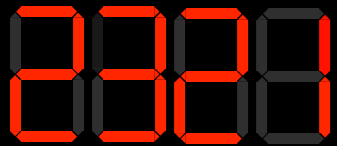
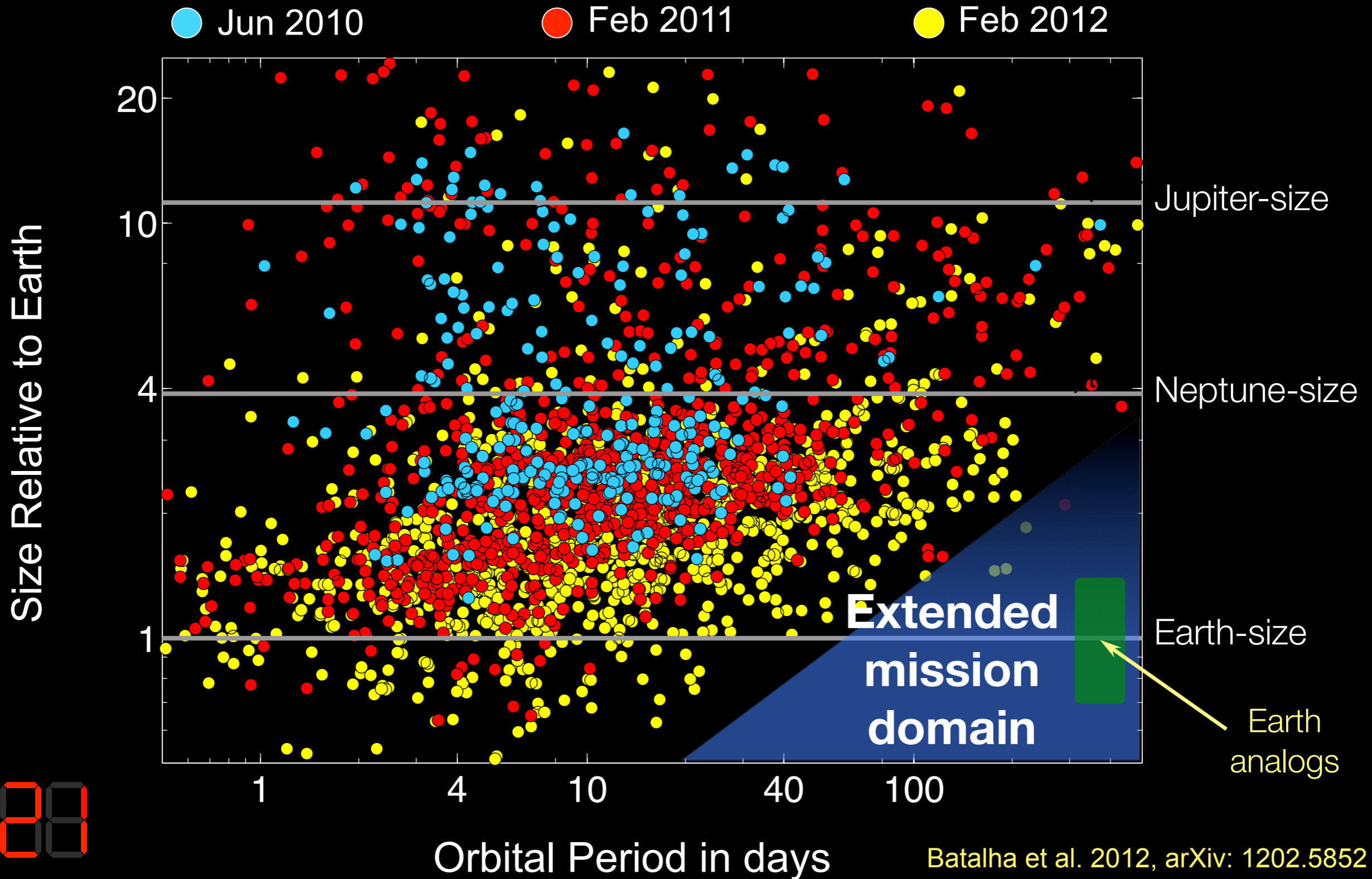
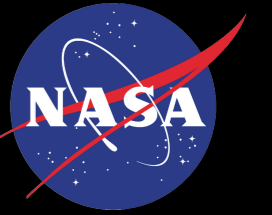


● Jun 2010 ● Feb 2011 ● Feb 2012



Extended Mission

Earth-size planets in the HZ



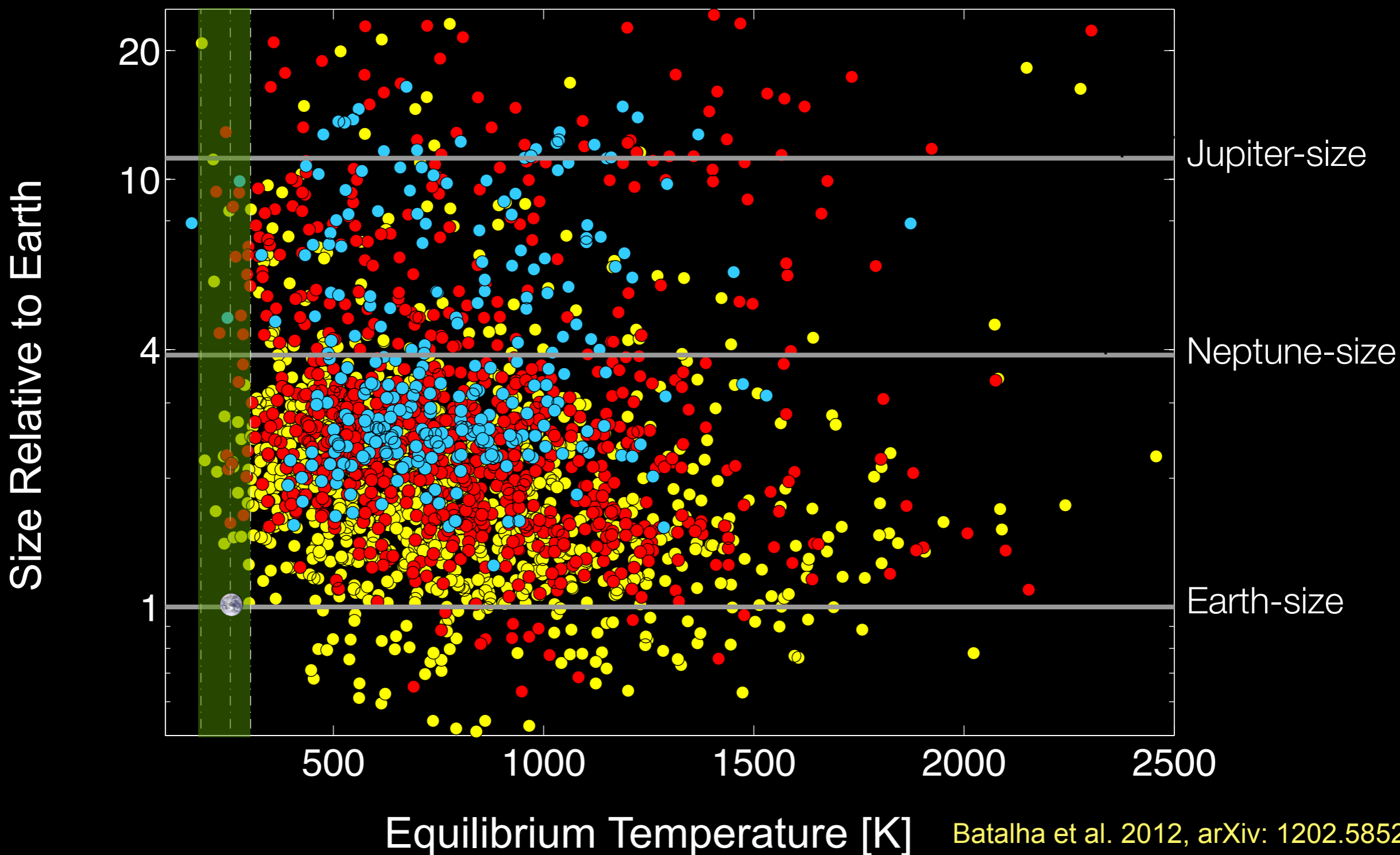
Batalha et al. 2012, arXiv: 1202.5852



HZ Candidates

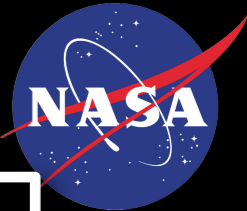
48 with T_{eq} between 185 and 303 K

● Jun 2010 ● Feb 2011 ● Jan 2012



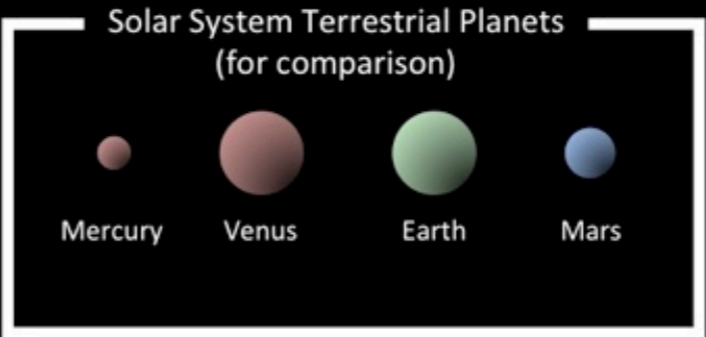
Batalha et al. 2012, arXiv: 1202.5852

HZ Candidates

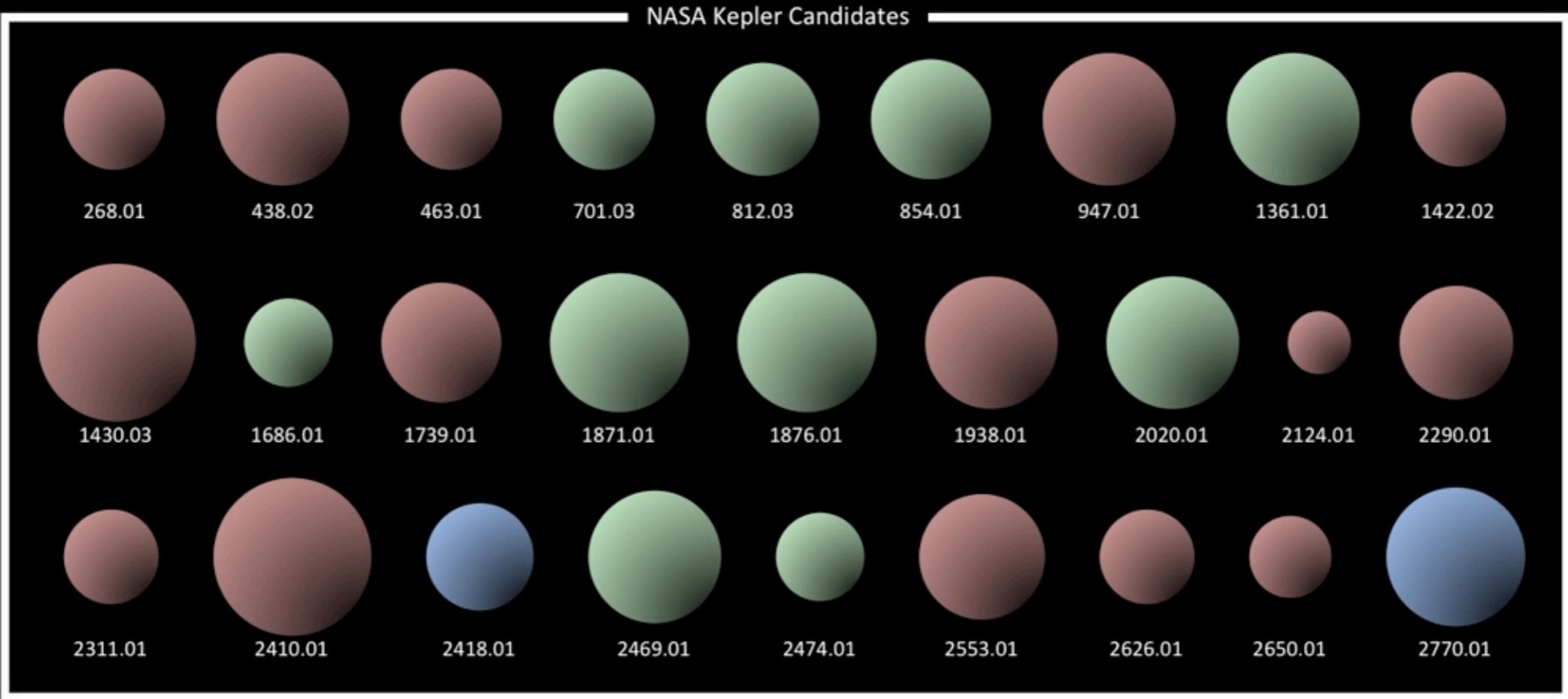


Potential Habitable Exoplanets

(4 confirmed and 27 unconfirmed NASA Kepler Candidates)



Size Relative to Earth



er-size

une-size

n-size

Credit: Planetary Habitability Laboratory, UPR Arecibo (phl.upr.edu) April 2012

Equilibrium Temperature [K]

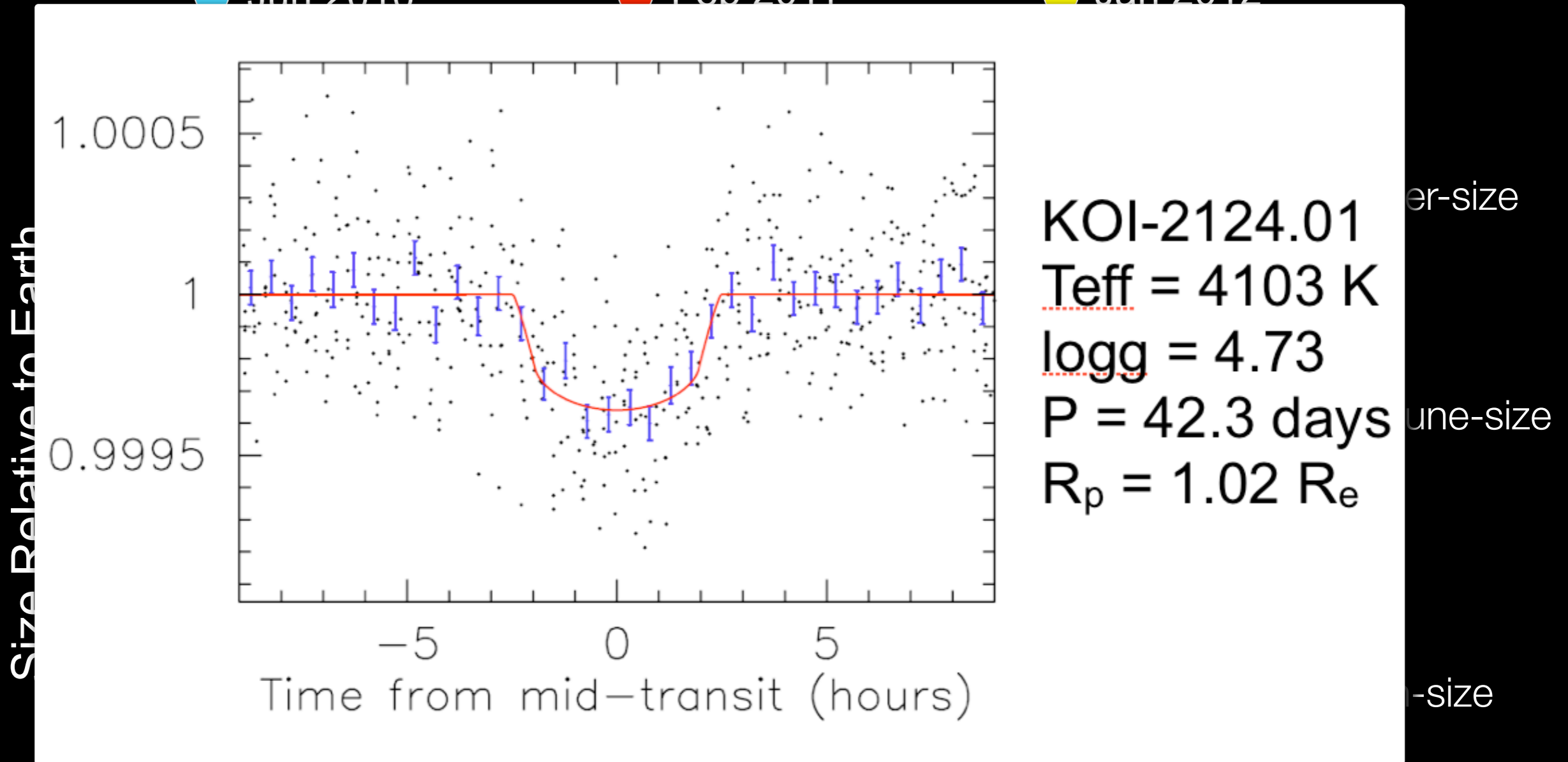
Batalha et al. 2012, arXiv: 1202.5852



HZ Candidates

48 with T_{eq} between 185 and 303 K

● Jun 2010 ● Feb 2011 ● Jan 2012



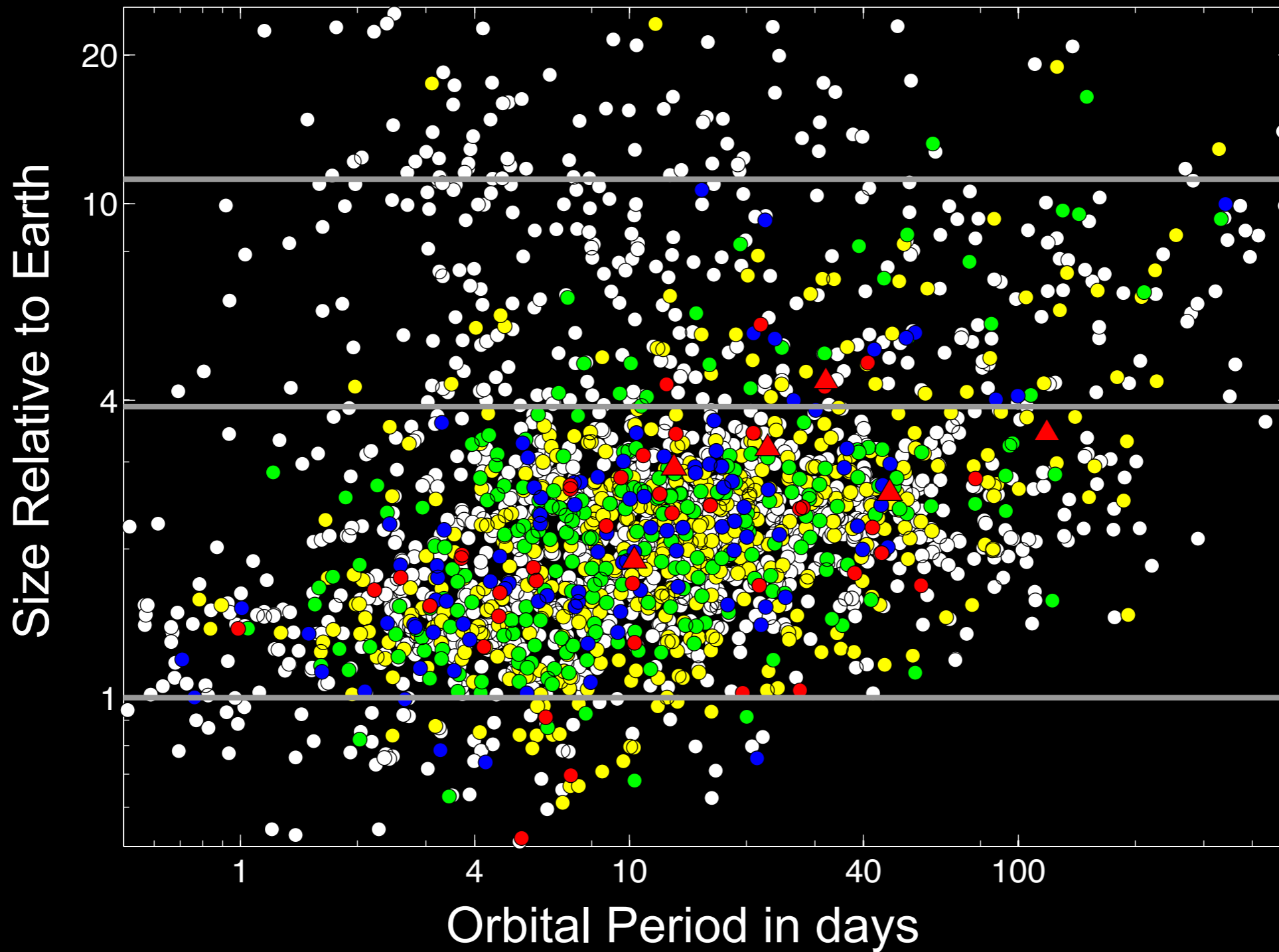
Equilibrium Temperature [K]

Batalha et al. 2012, arXiv: 1202.5852

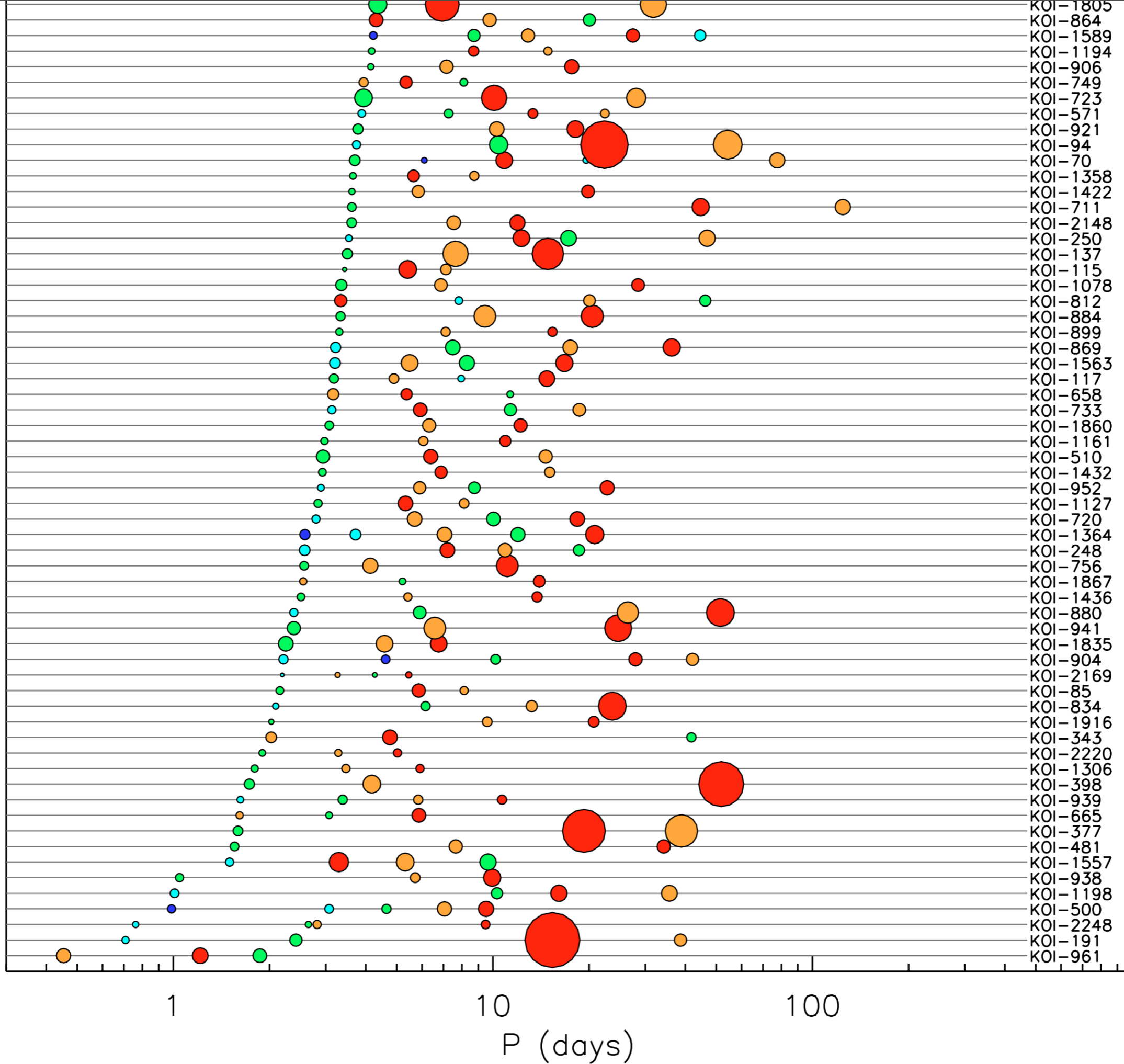
The Multiples

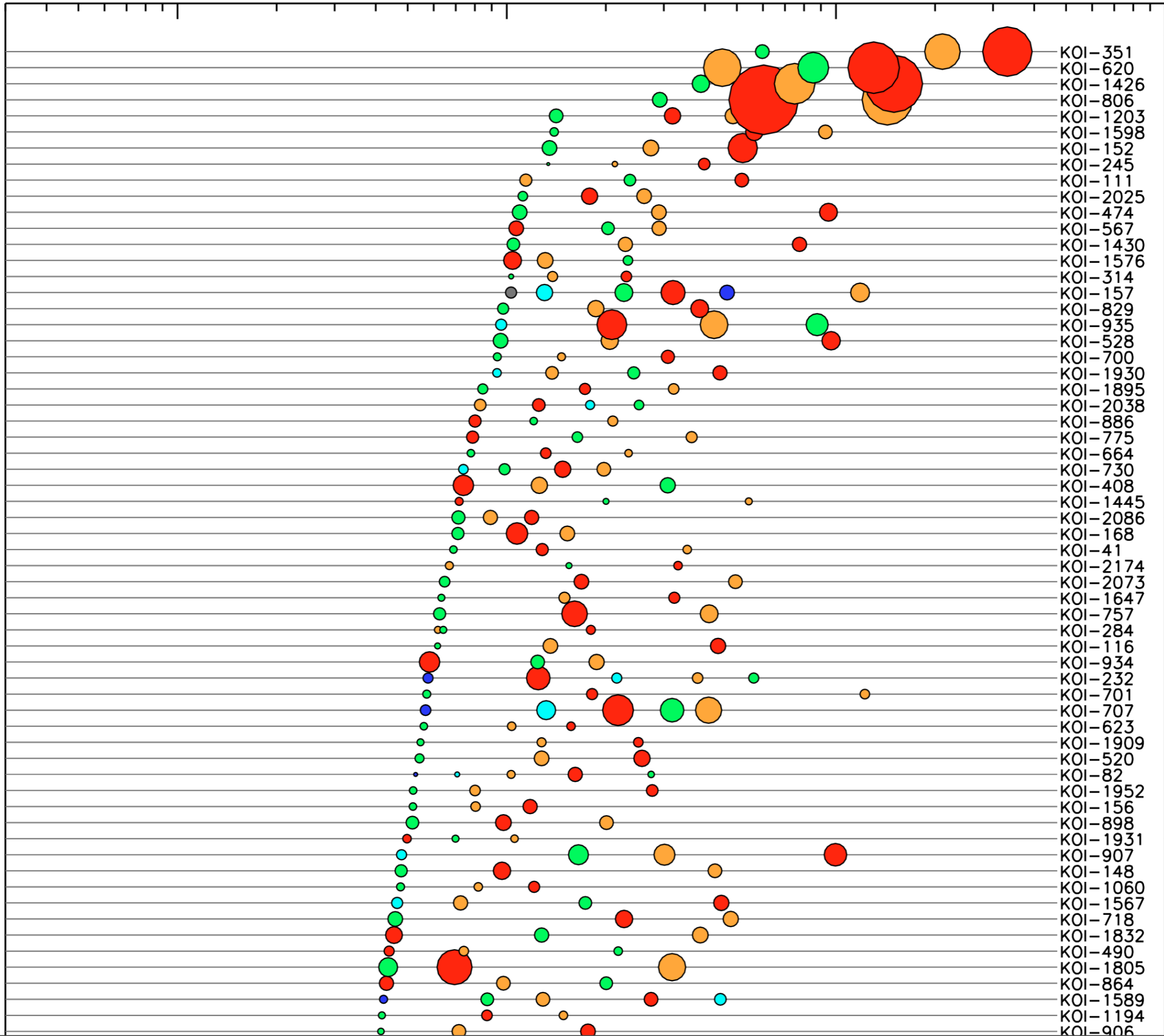


● one - 1425 ● two - 490 ● three - 252 ● four - 108 ● five - 40 ▲ six - 6

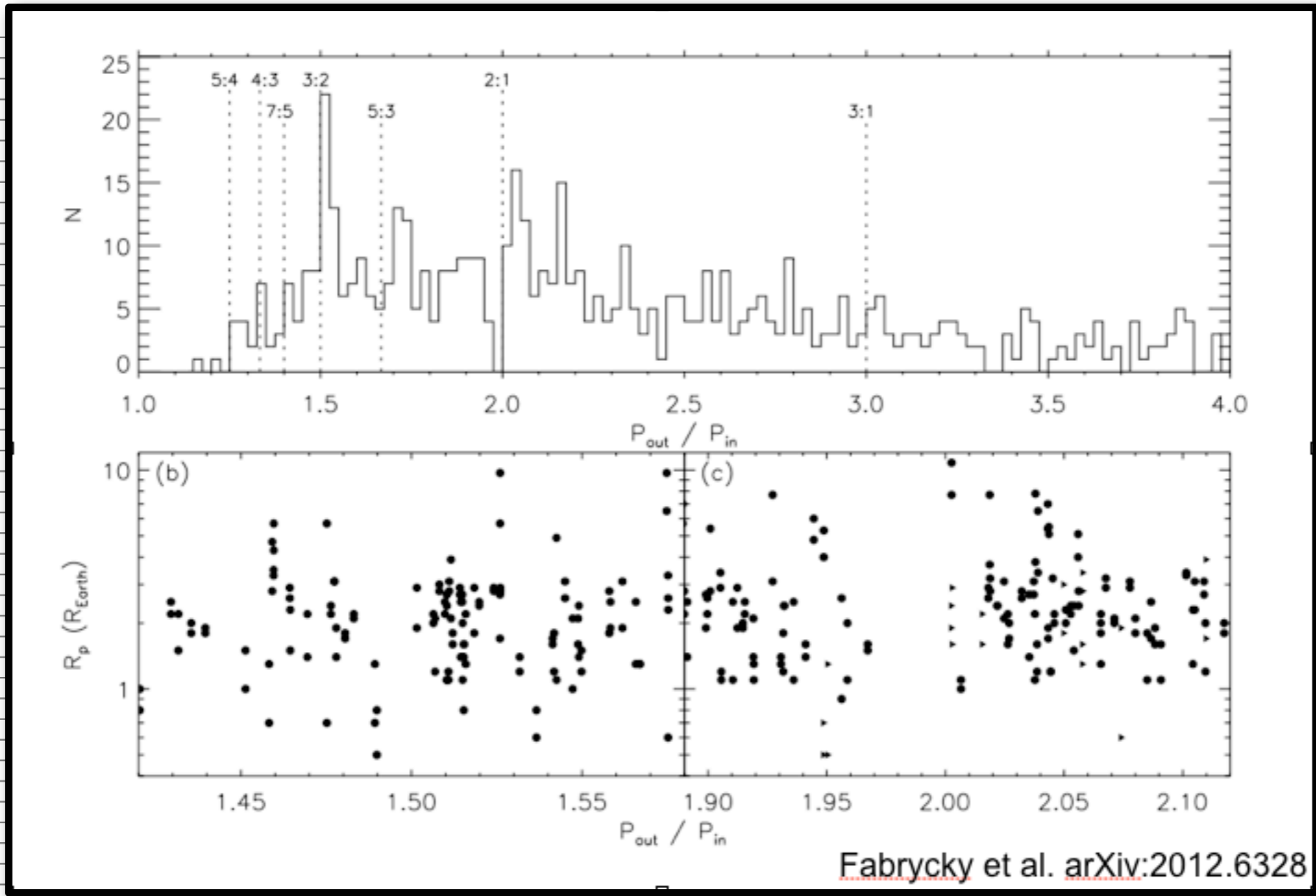


Batalha et al. 2012, arXiv: 1202.5852

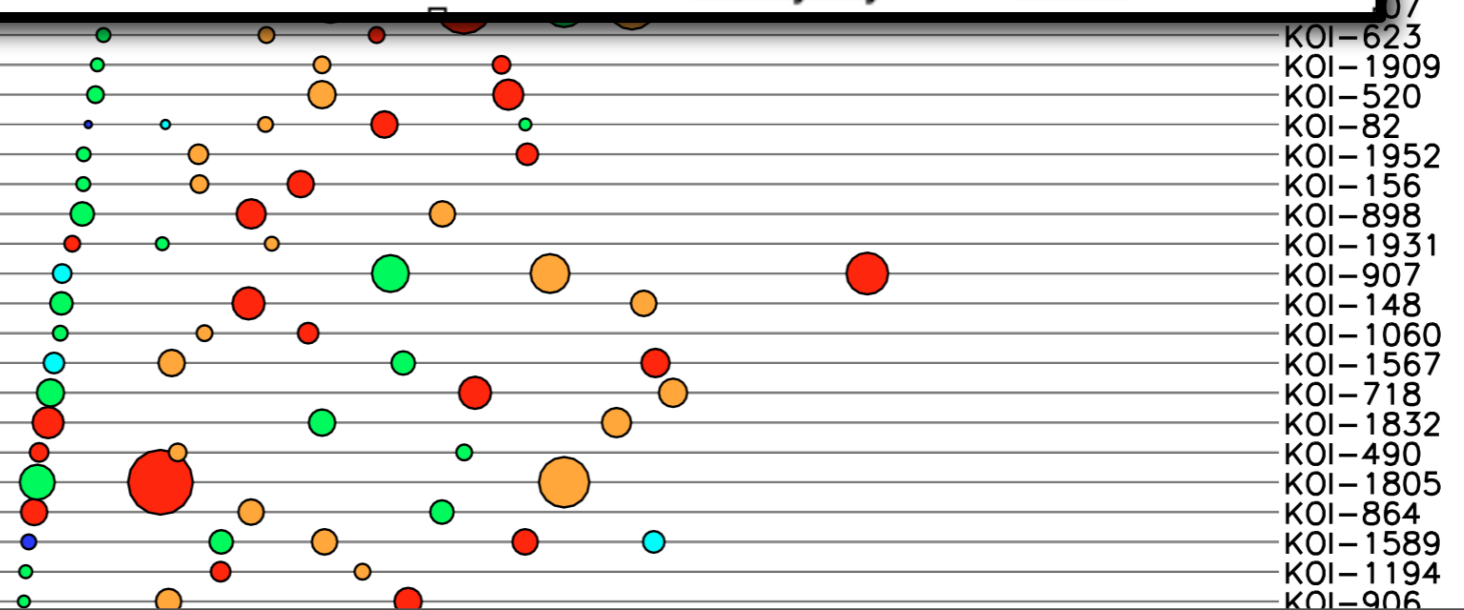




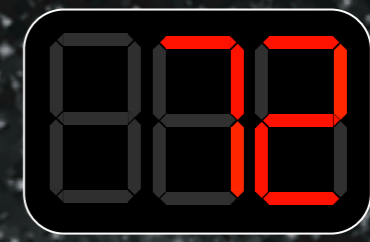
- KOI-351
- KOI-620
- KOI-1426
- KOI-806
- KOI-1203
- KOI-1598
- KOI-152
- KOI-245
- KOI-111
- KOI-2025
- KOI-474
- KOI-567
- KOI-1430
- KOI-1576
- KOI-314
- KOI-157
- KOI-829
- KOI-935
- KOI-528
- KOI-700
- KOI-1930
- KOI-1895
- KOI-2038
- KOI-886
- KOI-775
- KOI-664
- KOI-730
- KOI-408
- KOI-1445
- KOI-2086
- KOI-168
- KOI-41
- KOI-2174
- KOI-2073
- KOI-1647
- KOI-757
- KOI-284
- KOI-116
- KOI-934
- KOI-232
- KOI-701
- KOI-707
- KOI-623
- KOI-1909
- KOI-520
- KOI-82
- KOI-1952
- KOI-156
- KOI-898
- KOI-1931
- KOI-907
- KOI-148
- KOI-1060
- KOI-1567
- KOI-718
- KOI-1832
- KOI-490
- KOI-1805
- KOI-864
- KOI-1589
- KOI-1194
- KOI-906

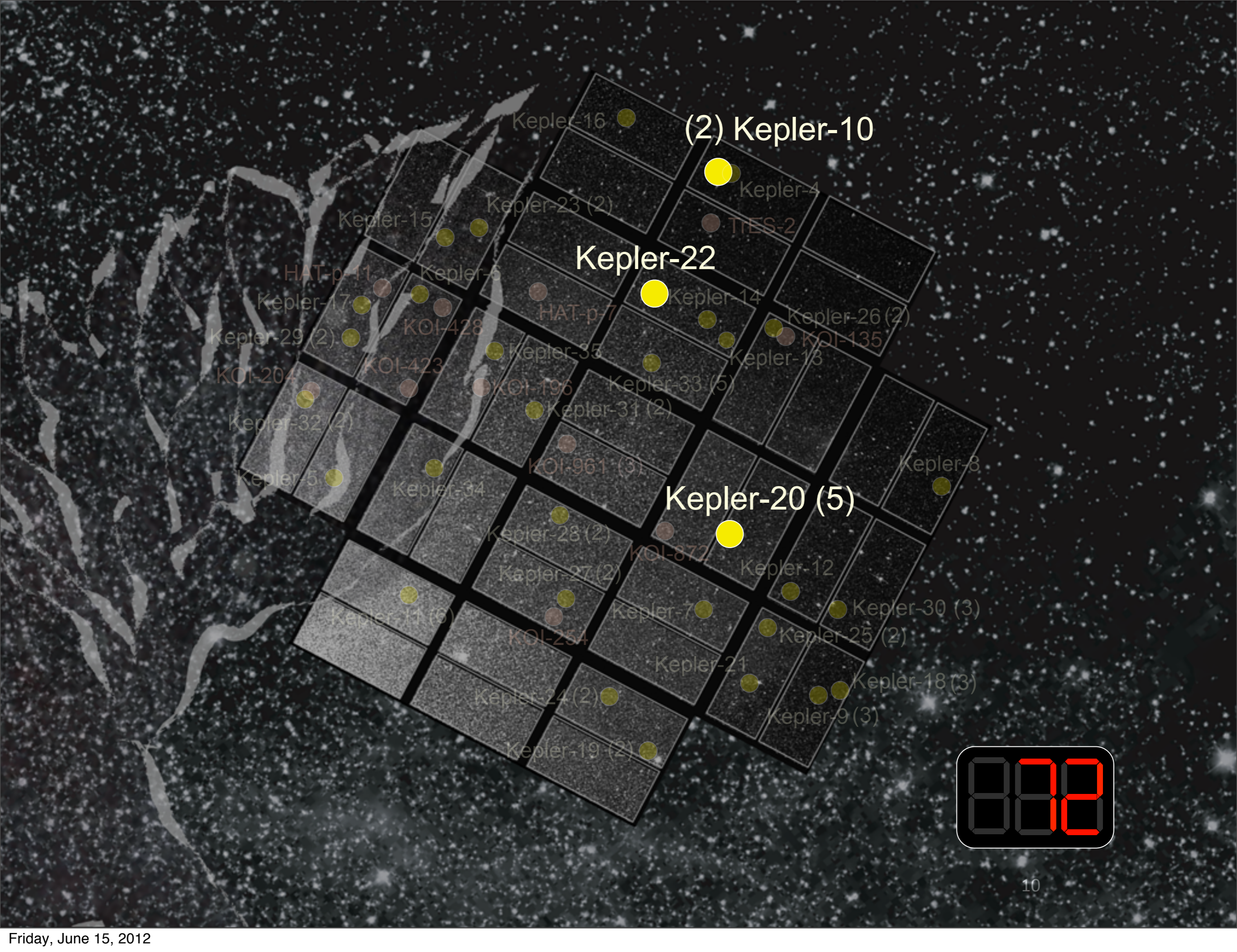


Fabrycky et al. arXiv:2012.6328



51
20
426
06
203
598
52
45
11
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74
67
430
576
14
57
29
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KOI-623
KOI-1909
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KOI-1952
KOI-156
KOI-898
KOI-1931
KOI-907
KOI-148
KOI-1060
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KOI-1194
KOI-906

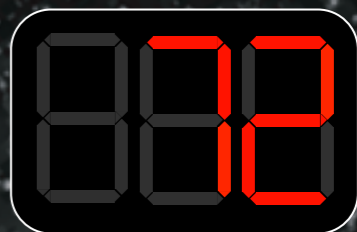




(2) Kepler-10

Kepler-22

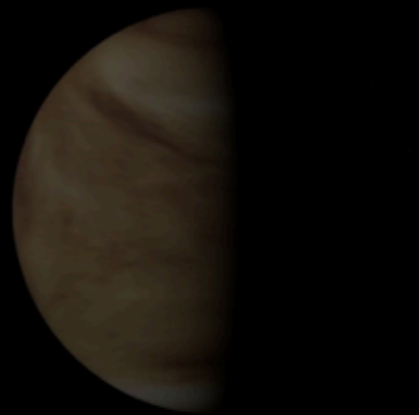
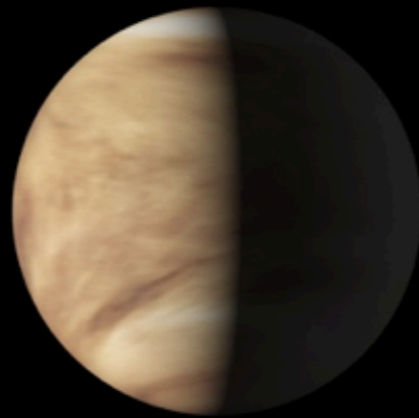
Kepler-20 (5)



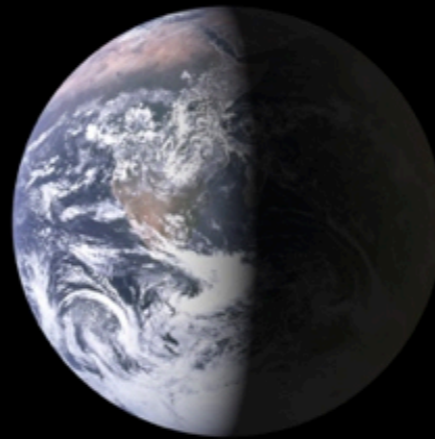
Kepler-20e



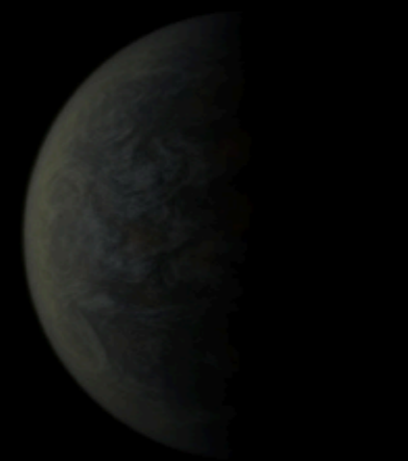
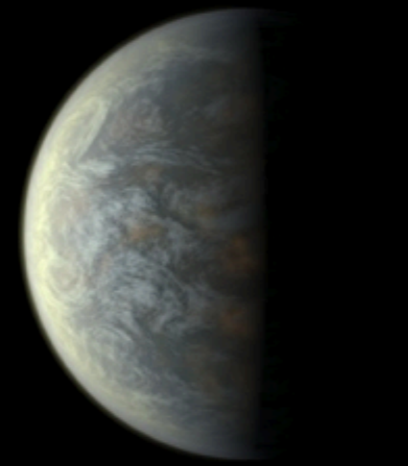
Venus



Earth



Kepler-20f



Fressin et al. 2012

Kepler-22b

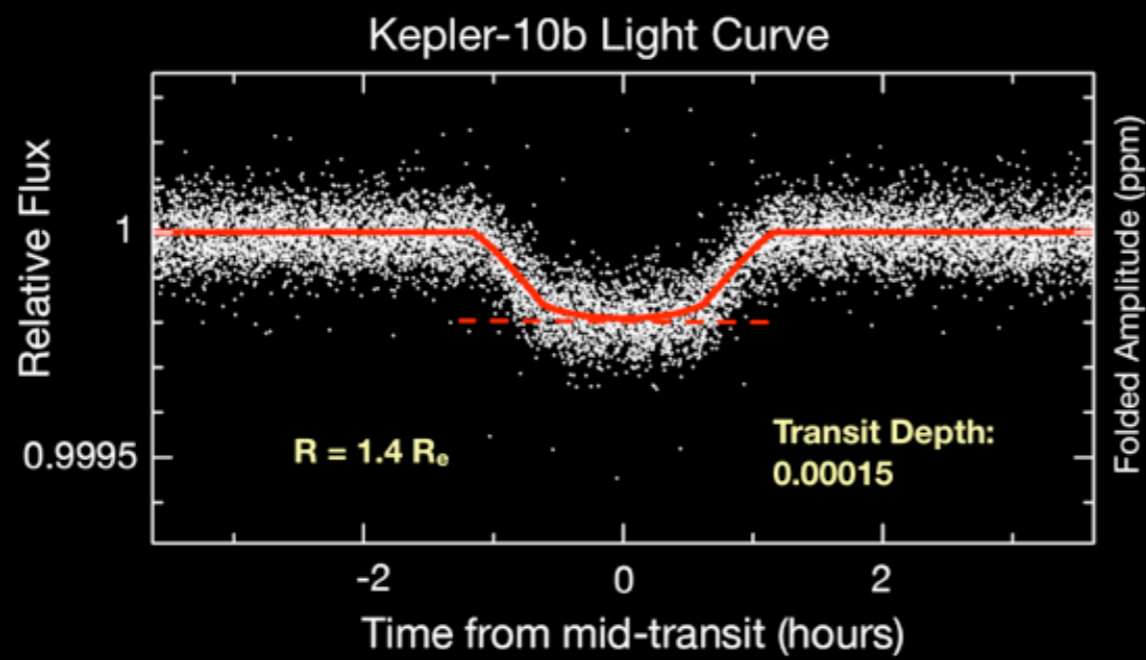
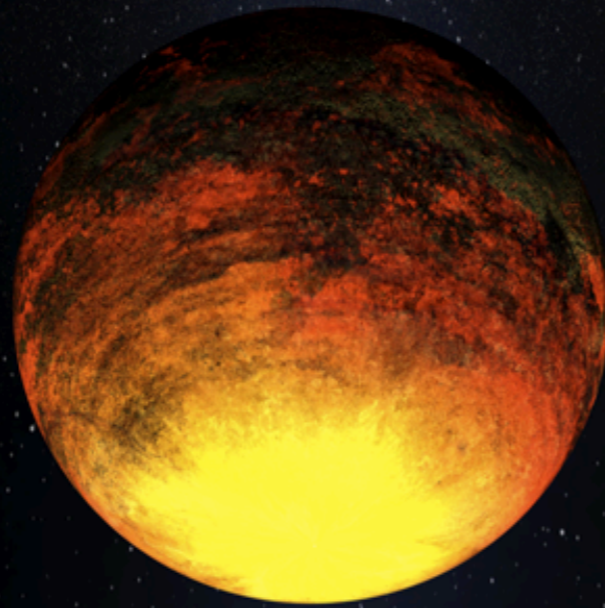
$P=289.8623$ days

$R_p=2.38\pm 0.13 R_{\oplus}$

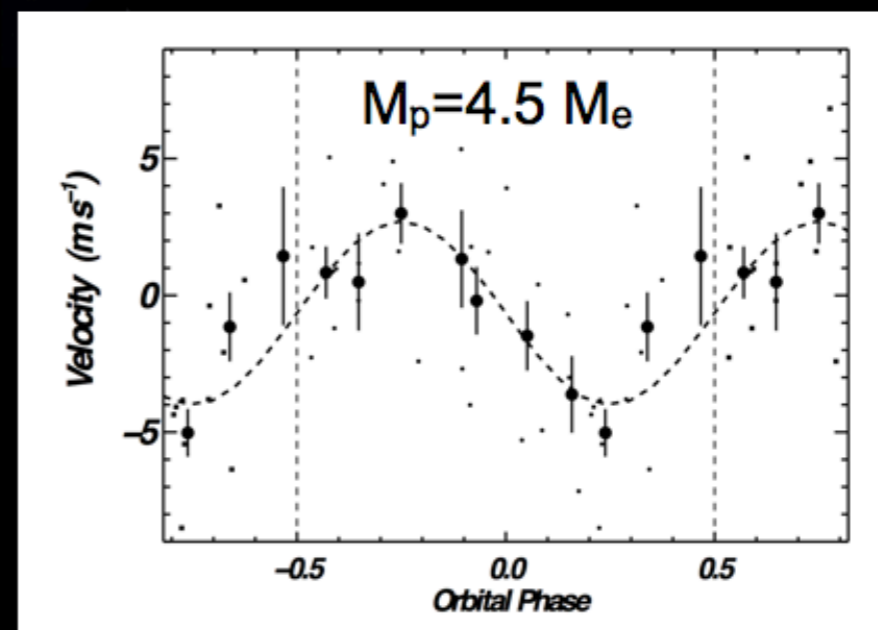
$T_{eq}=262$ K



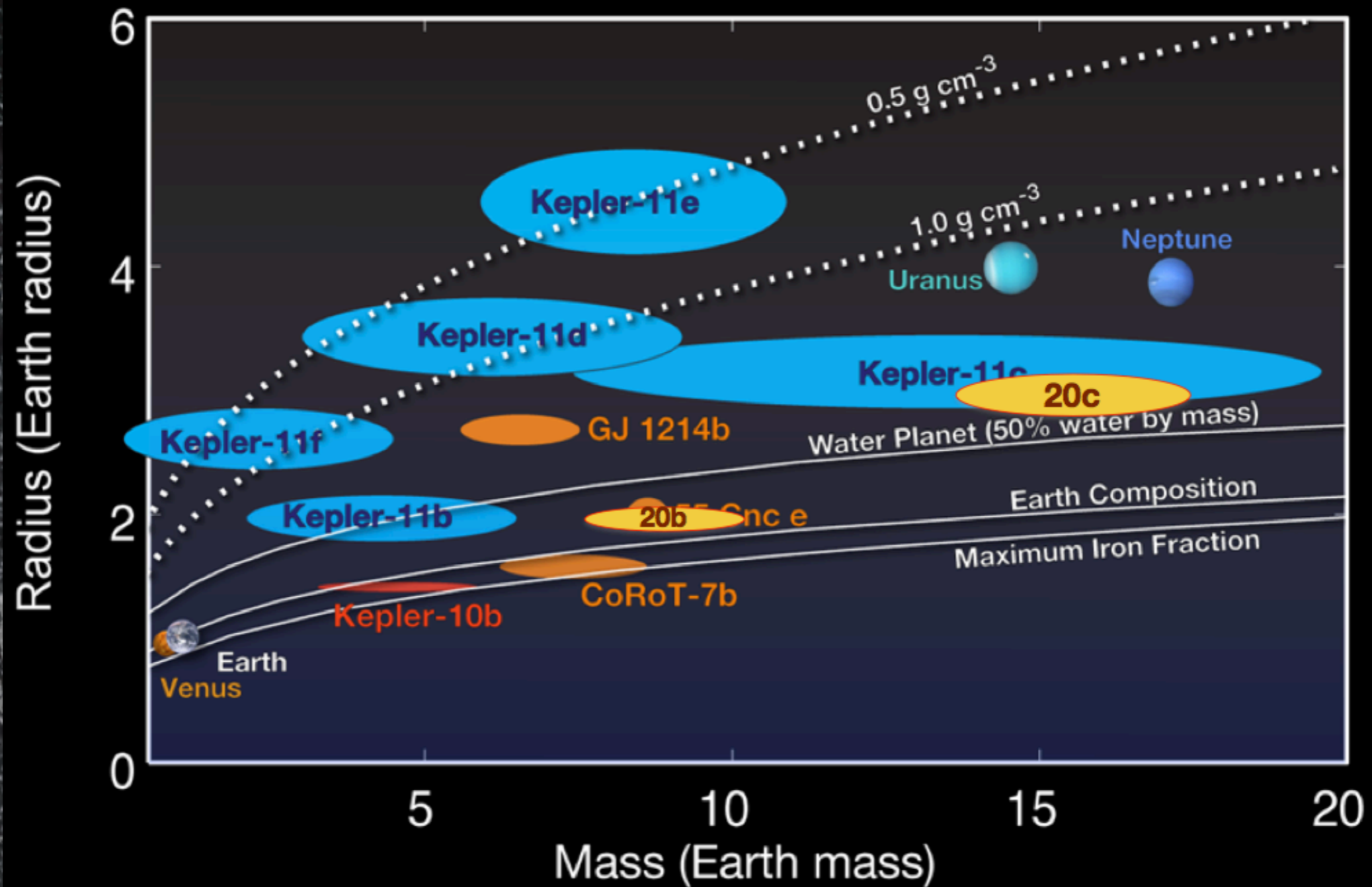
Borucki et al. 2012, ApJ, 745, 120

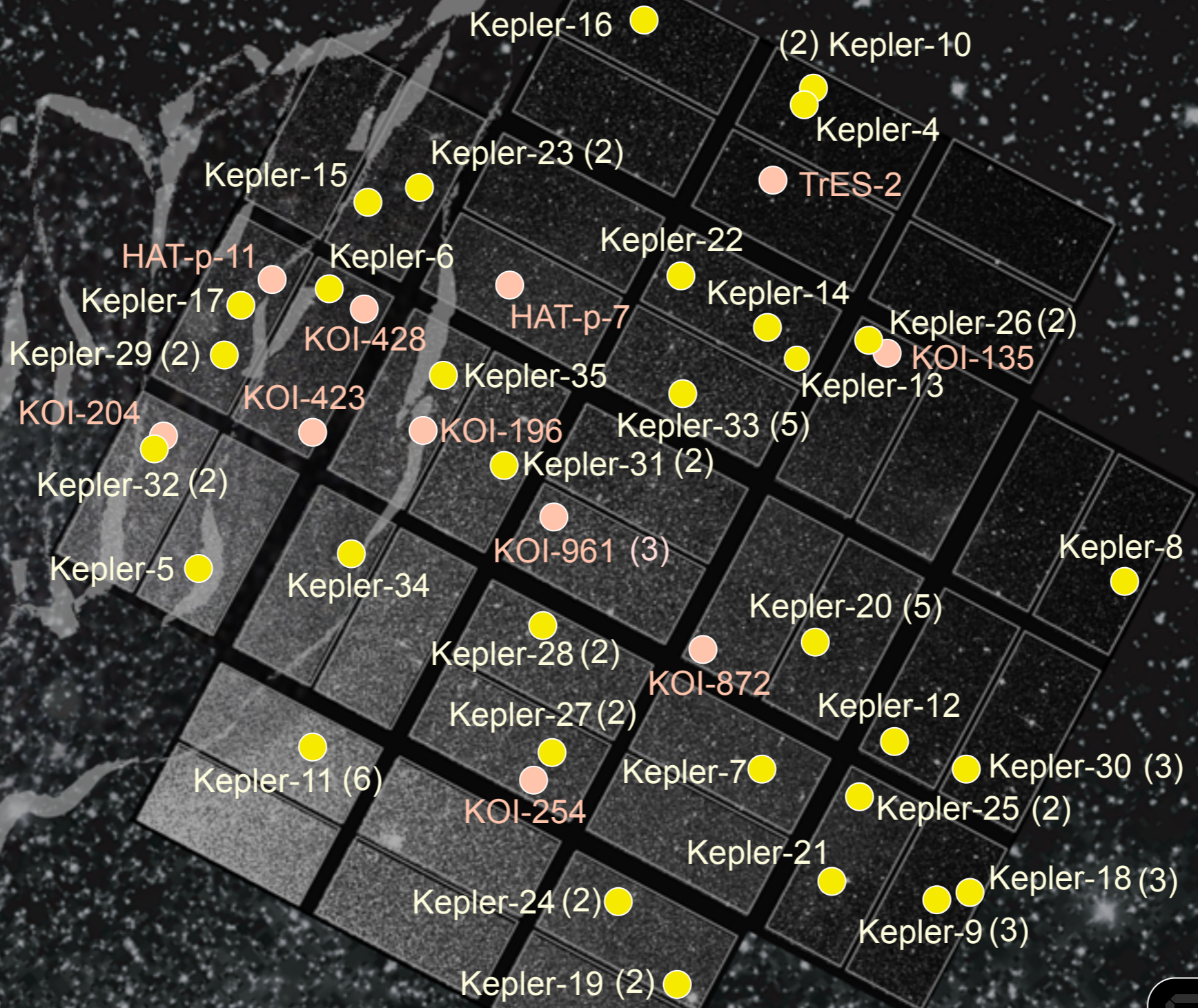


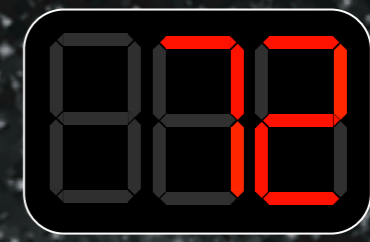
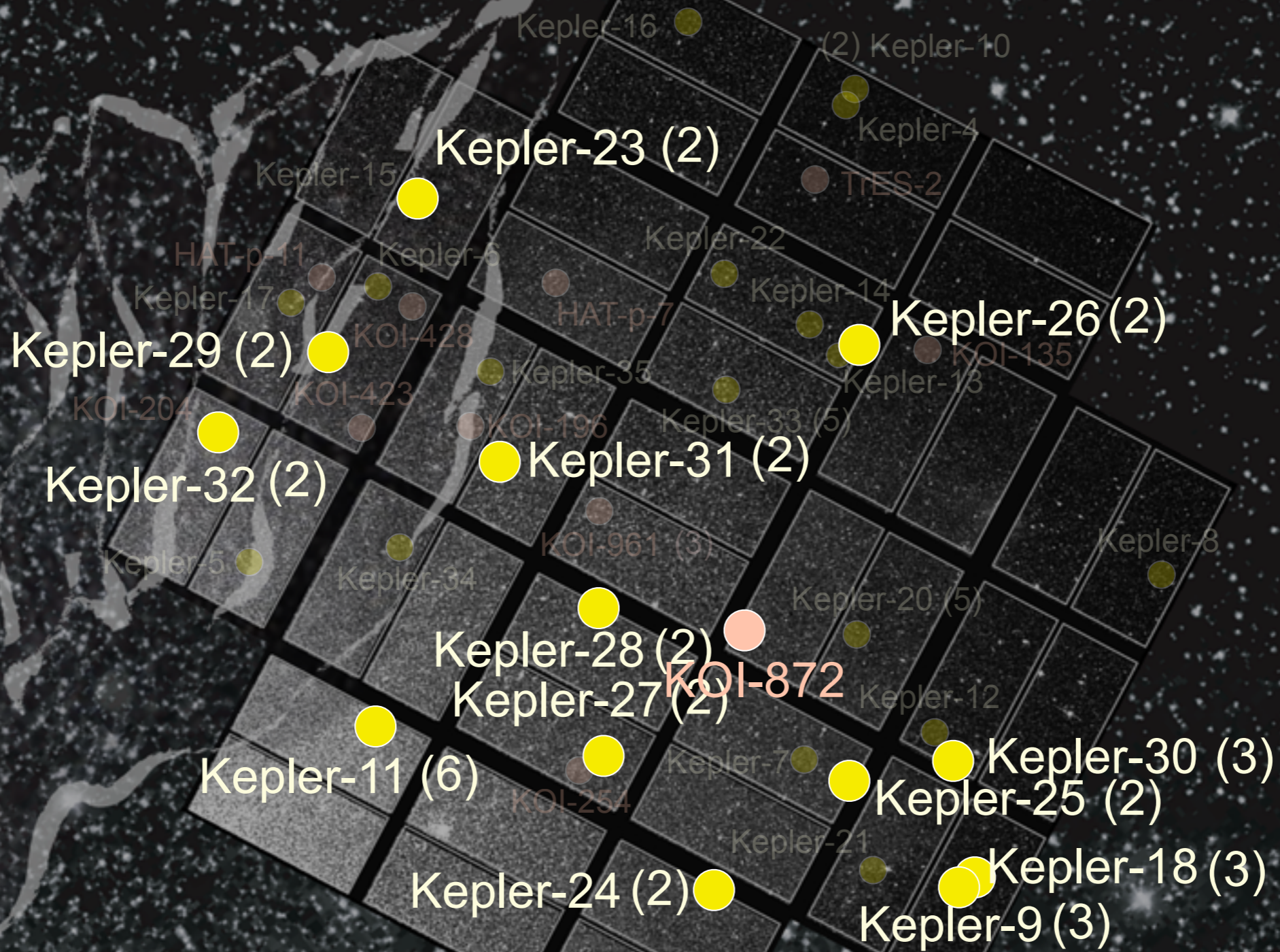
Total SNR > 140 (22 months of data)



Batalha et al. 2011, ApJ, 729, 27







Kepler-16

(2) Kepler-10

Kepler-11

Kepler-9

Kepler-8

Kepler-7

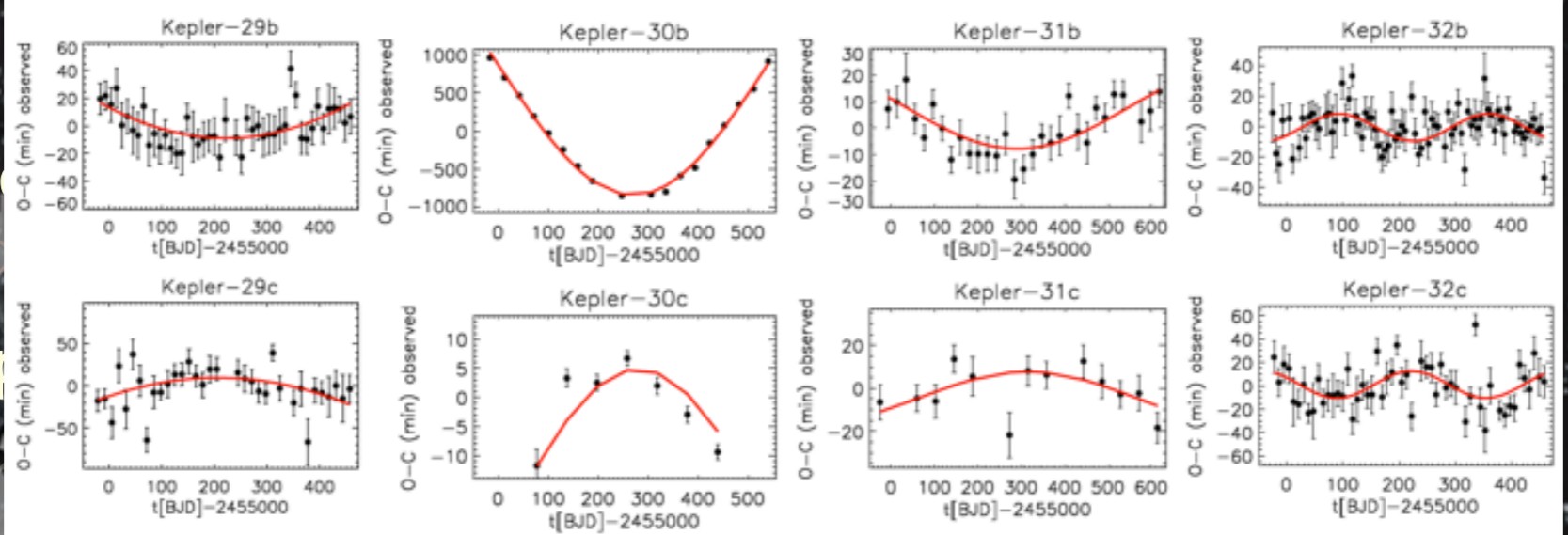
Kepler-19 (2)



Kepler-16 (2) Kepler-10

Other Systems: A TTV-Confirmation Catalog

Kepler
Kepler

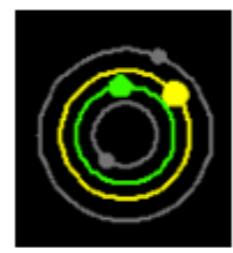
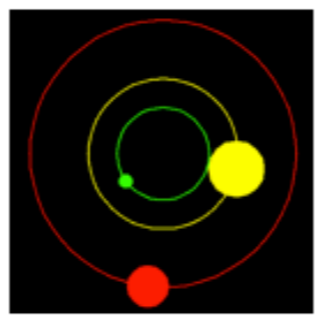
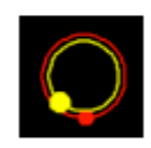


9:7 resonance

near 2:1

near 2:1

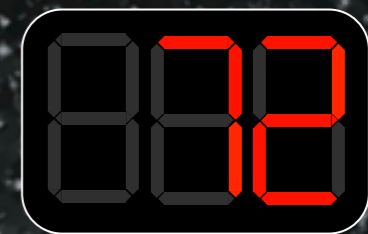
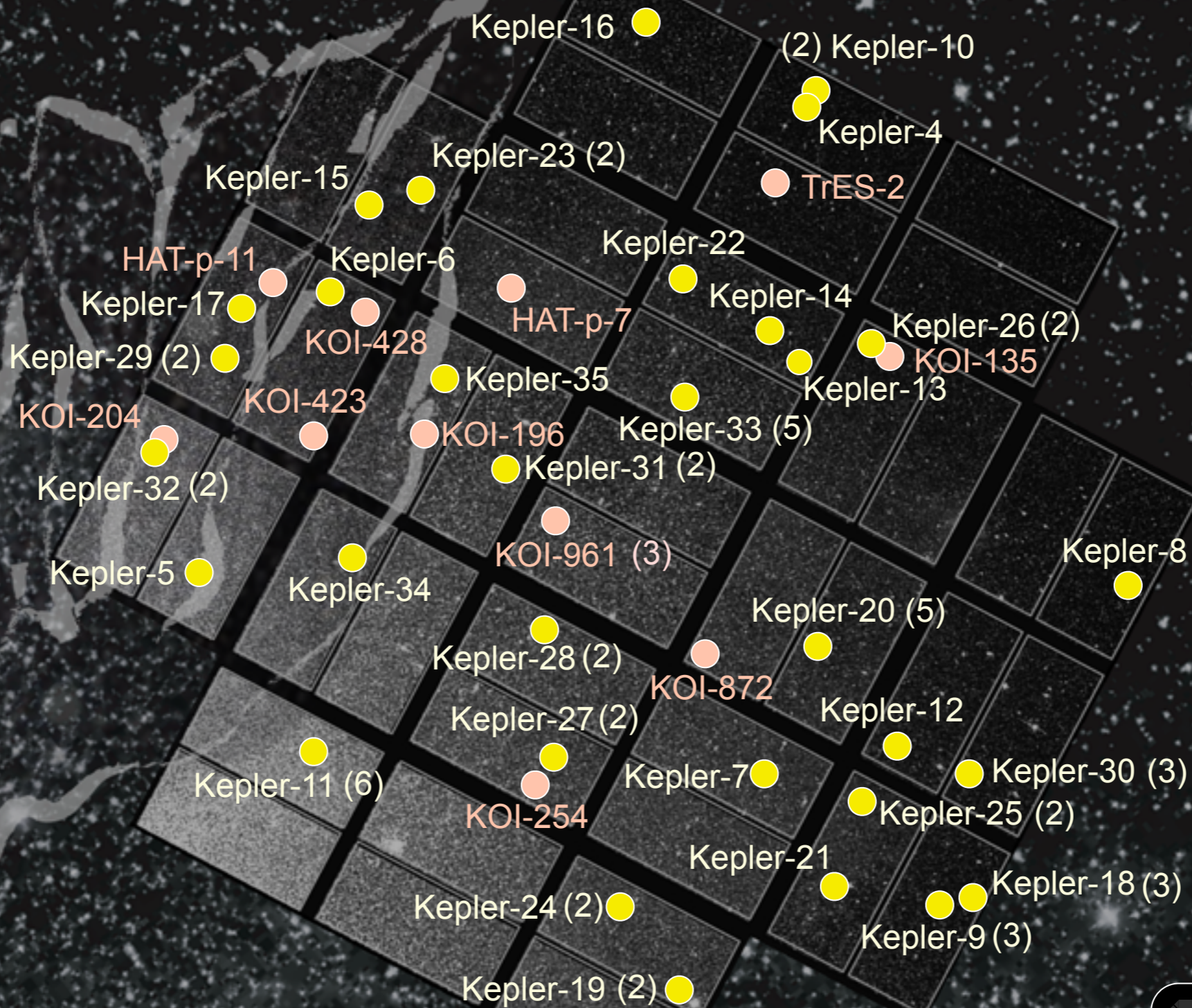
near 3:2



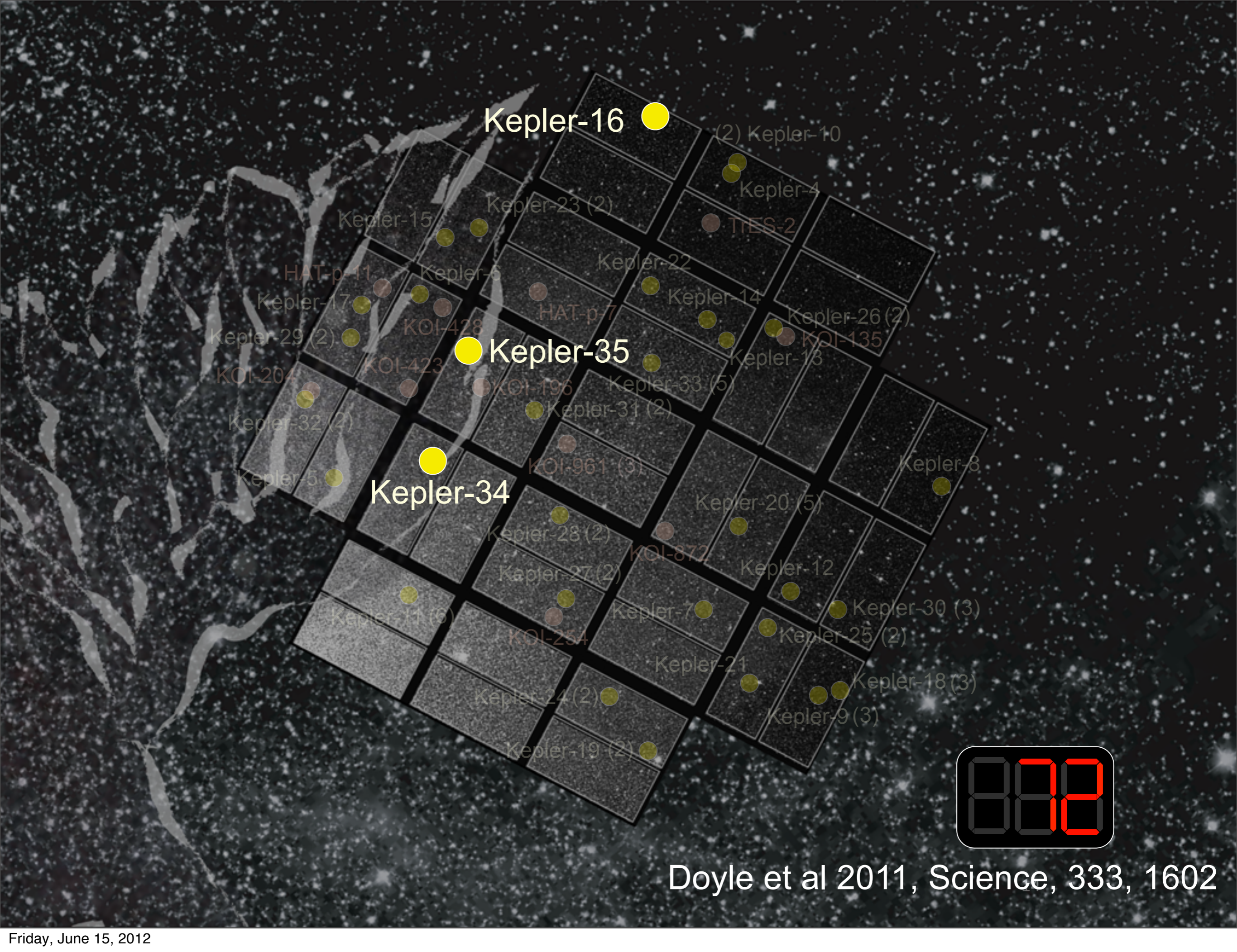
Ford et al. 2012, Steffen et al. 2012, Fabrycky et al. 2012

3)
3)





Doyle et al 2011, Science, 333, 1602



Kepler-16



(2) Kepler-10

Kepler-4

TrES-2

Kepler-15

Kepler-23 (2)

Kepler-22

HAT-p-11

Kepler-6

Kepler-14

Kepler-17

HAT-p-7

Kepler-26 (2)

Kepler-29 (2)

KOI-428

Kepler-35

KOI-135

KOI-204

KOI-423

KOI-196

Kepler-33 (5)

Kepler-13

Kepler-32 (2)

Kepler-31 (2)

Kepler-5

KOI-961 (3)

Kepler-34

Kepler-20 (5)

Kepler-8

Kepler-28 (2)

KOI-872

Kepler-12

Kepler-27 (2)

Kepler-7

Kepler-30 (3)

Kepler-11 (6)

KOI-254

Kepler-25 (2)

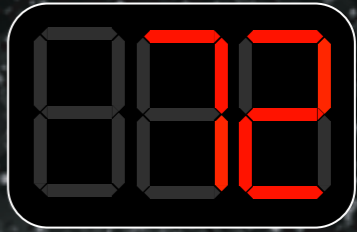
Kepler-21

Kepler-18 (3)

Kepler-24 (2)

Kepler-9 (3)

Kepler-19 (2)



Doyle et al 2011, Science, 333, 1602

Kepler-16 ●

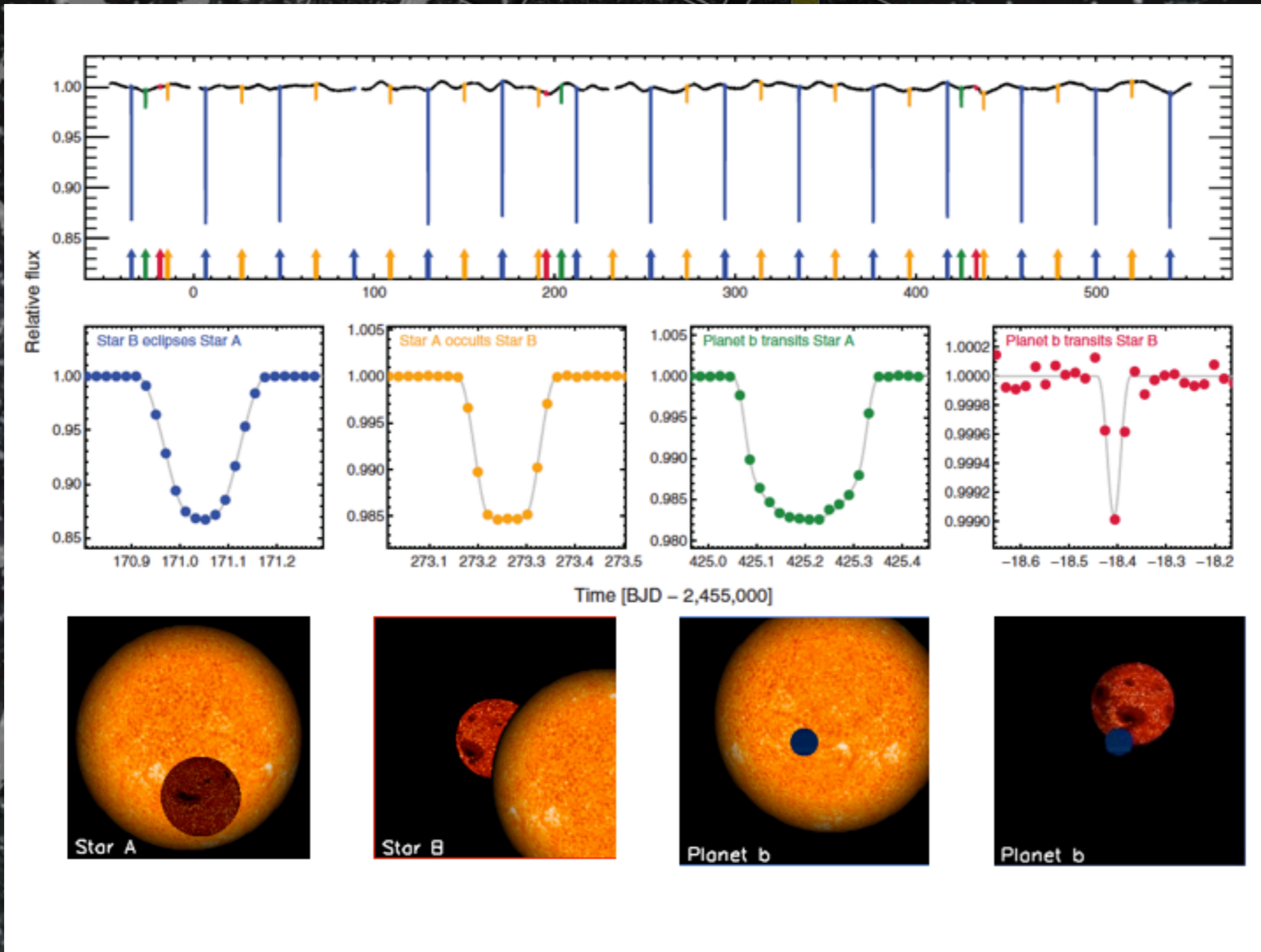
(2) Kepler-10 ●●



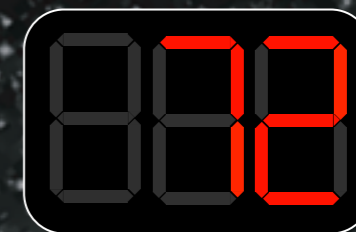
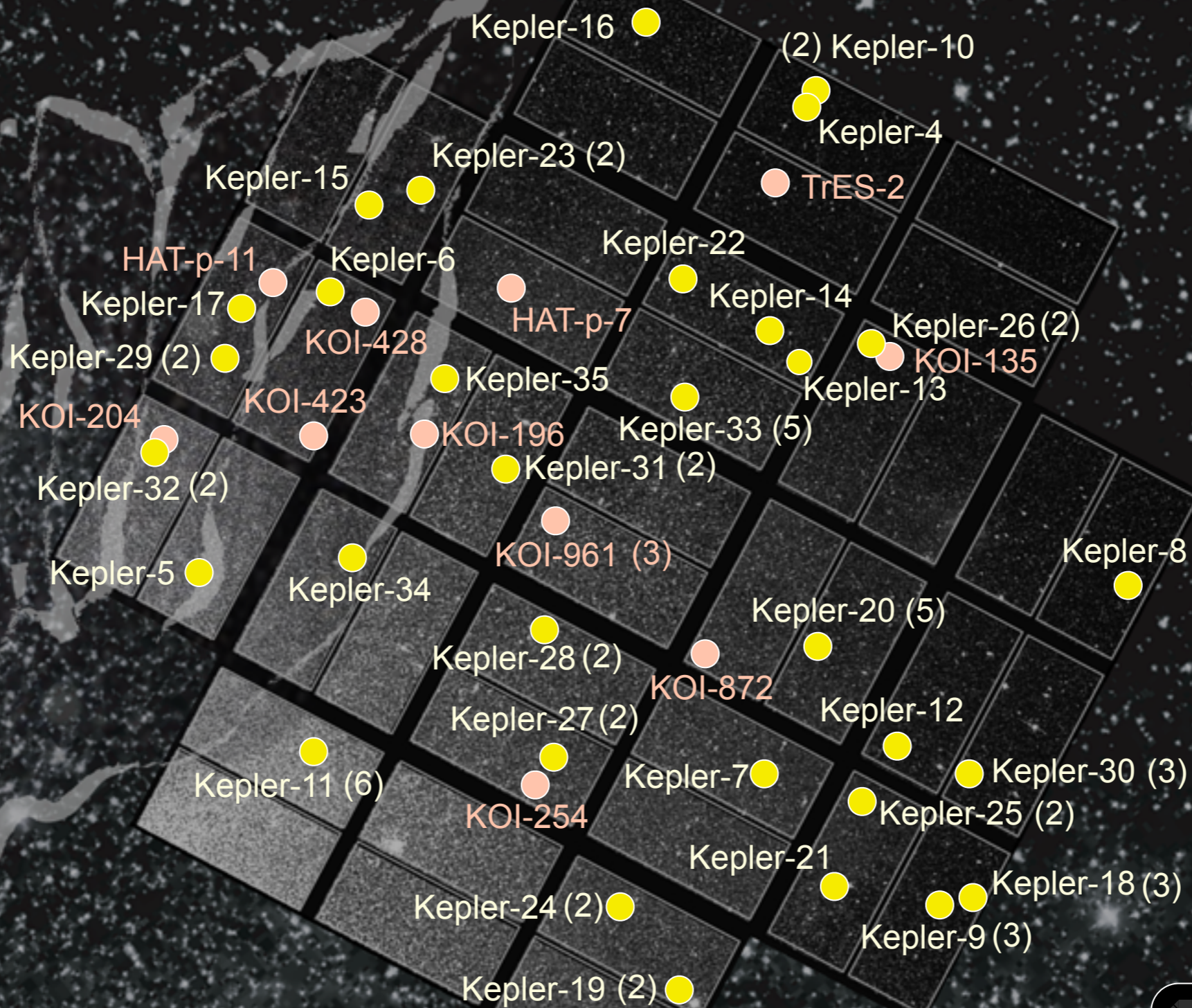
Doyle et al 2011, Science, 333, 1602

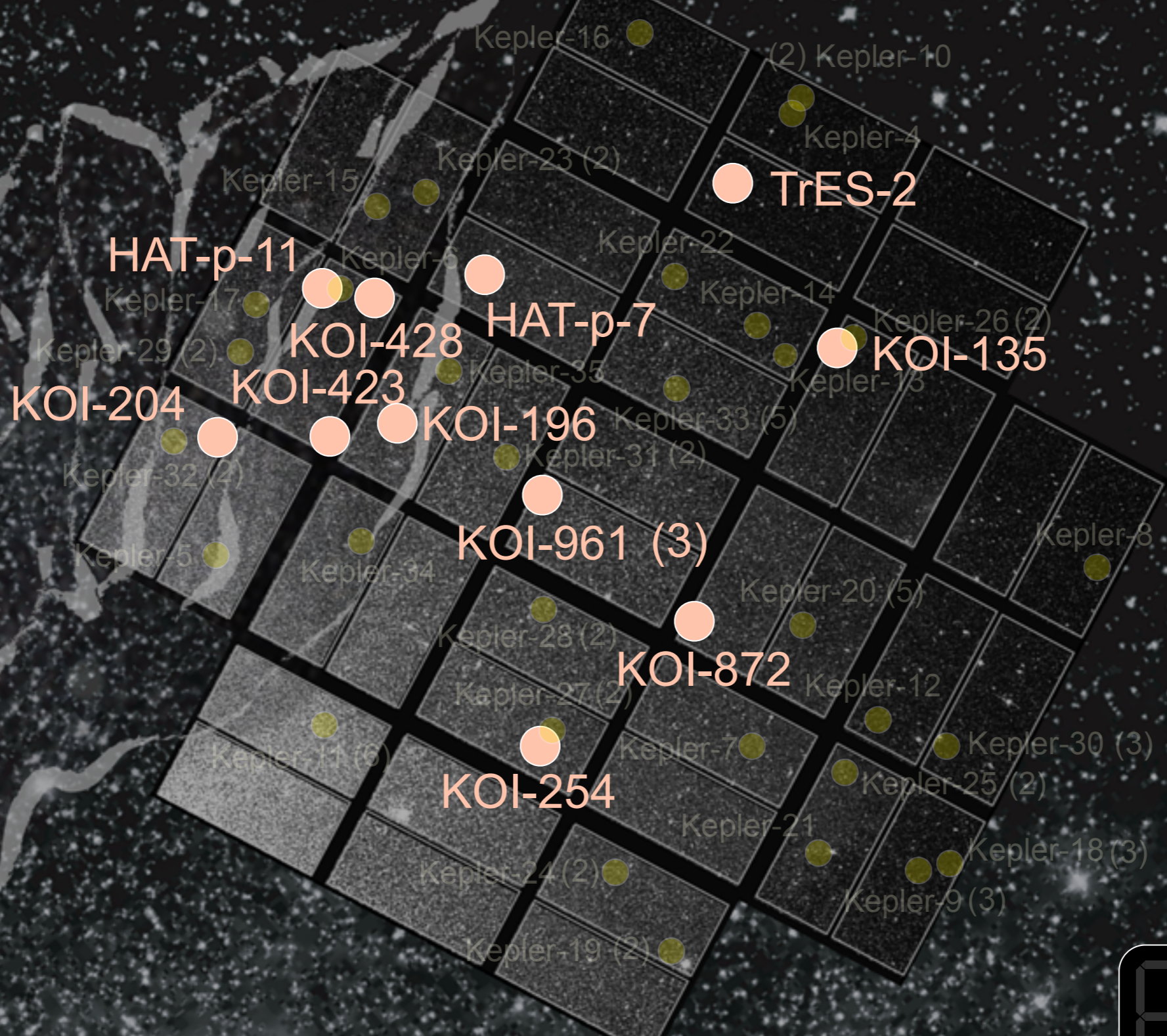
Kepler-16

(2) Kepler-10



Doyle et al 2011, Science, 333, 1602





● TrES-2

HAT-p-11

KOI-428

HAT-p-7

KOI-135

KOI-204

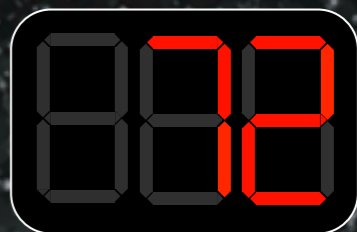
KOI-423

KOI-196

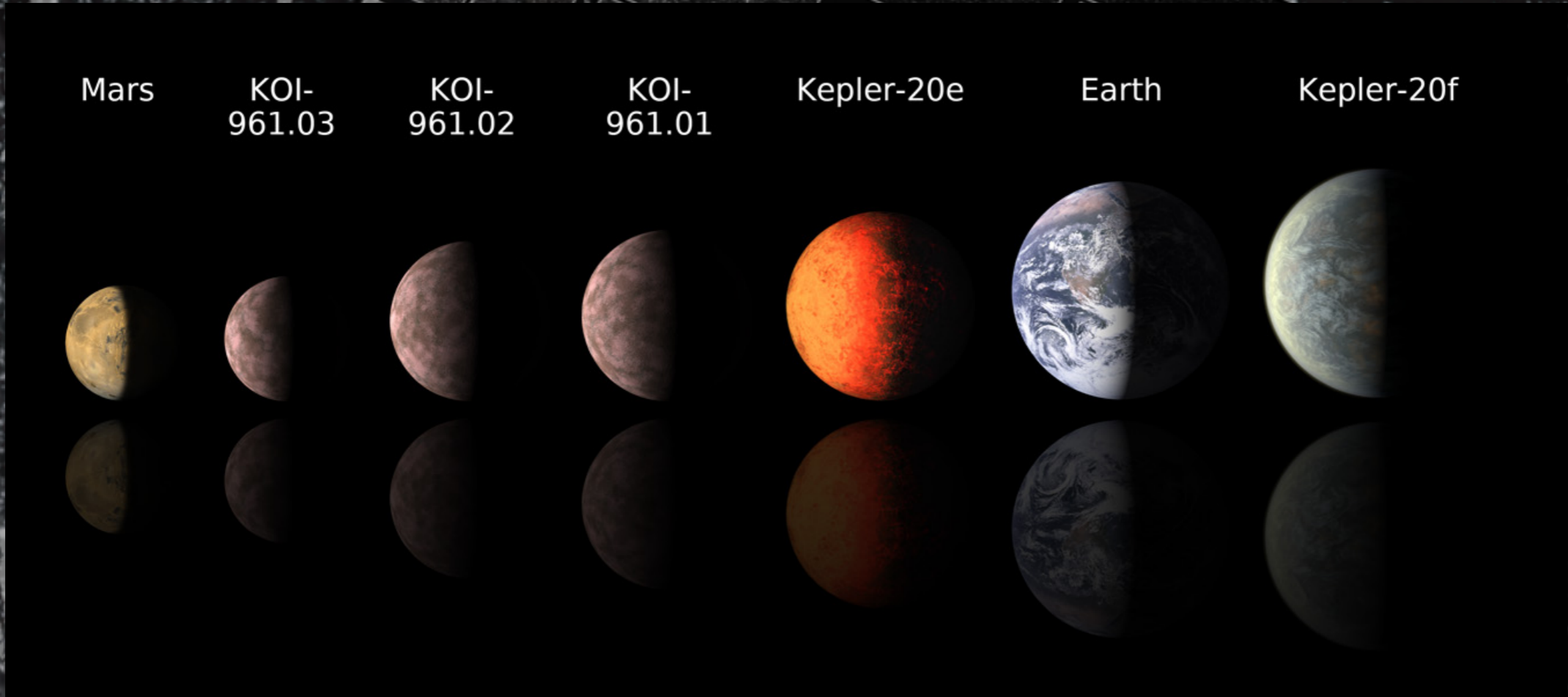
KOI-961 (3)

KOI-872

KOI-254



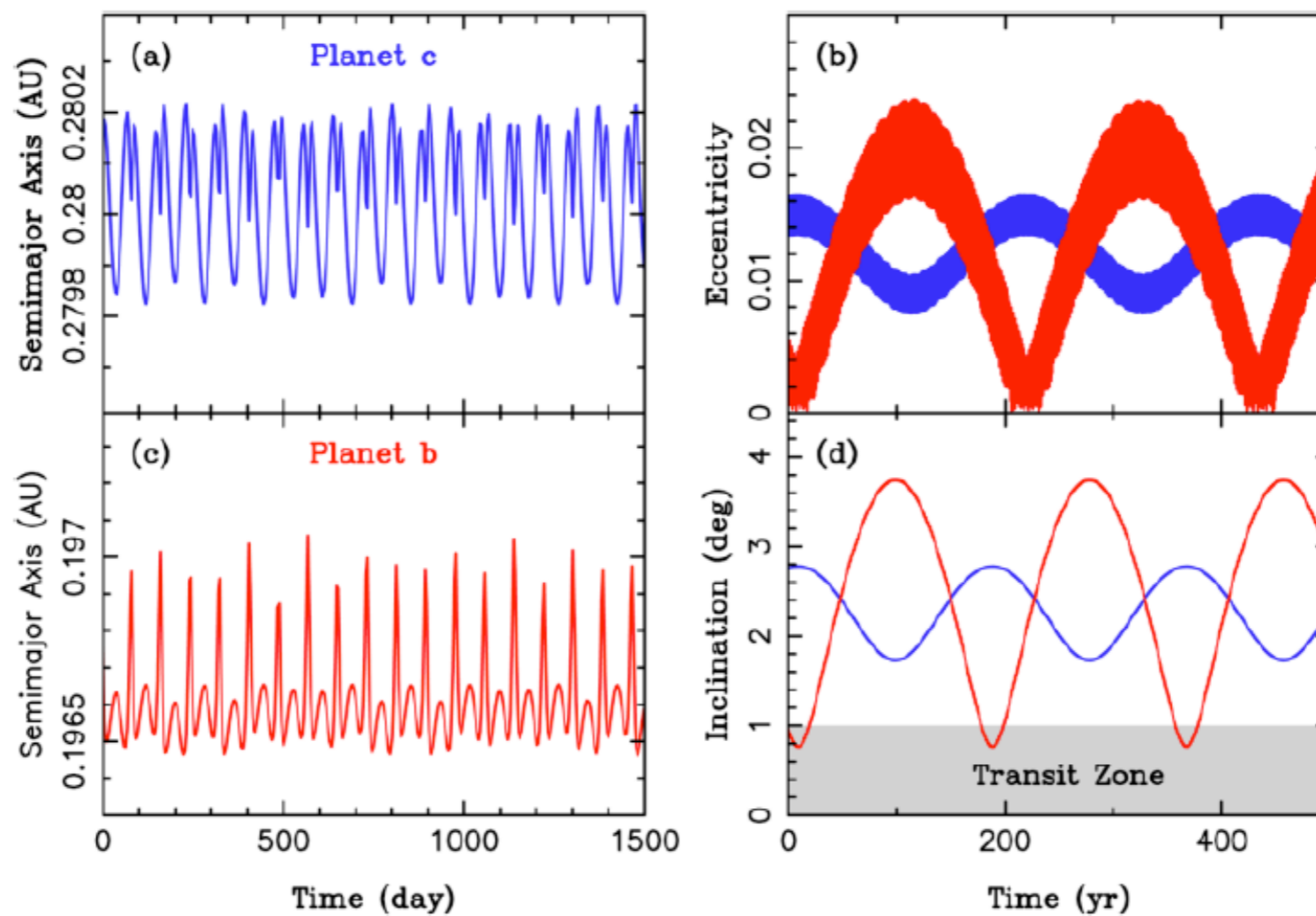
Kepler-16 ●
 (2) Kepler-10 ●●
 Kepler-4 ●
 TrES-2 ●
 Kepler-23 (2) ●●
 Kepler-15 ●●



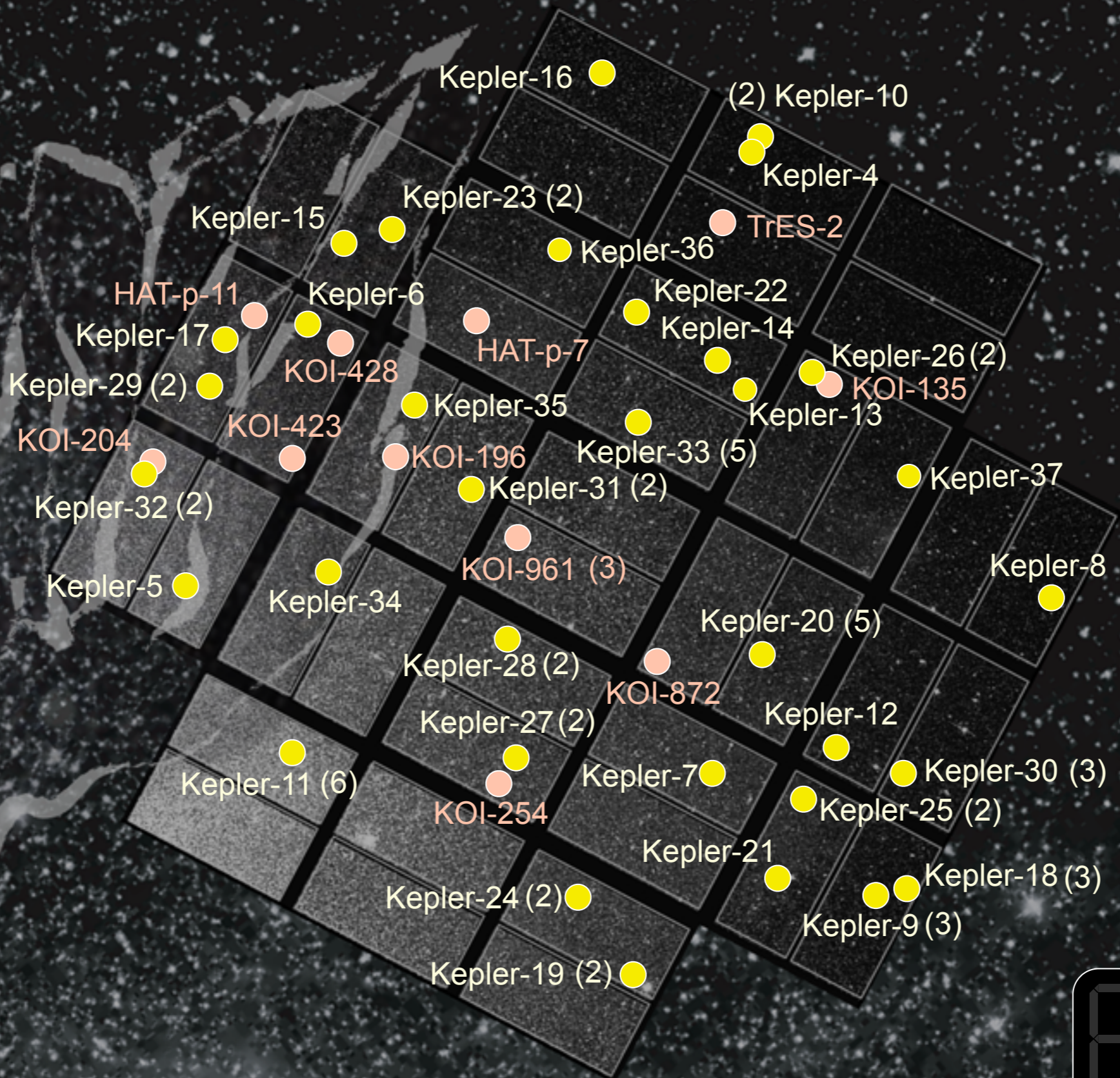
Kepler-24 (2) ●●
 Kepler-19 (2) ●●
 Kepler-9 (3) ●●●
 Kepler-10 (3) ●●●

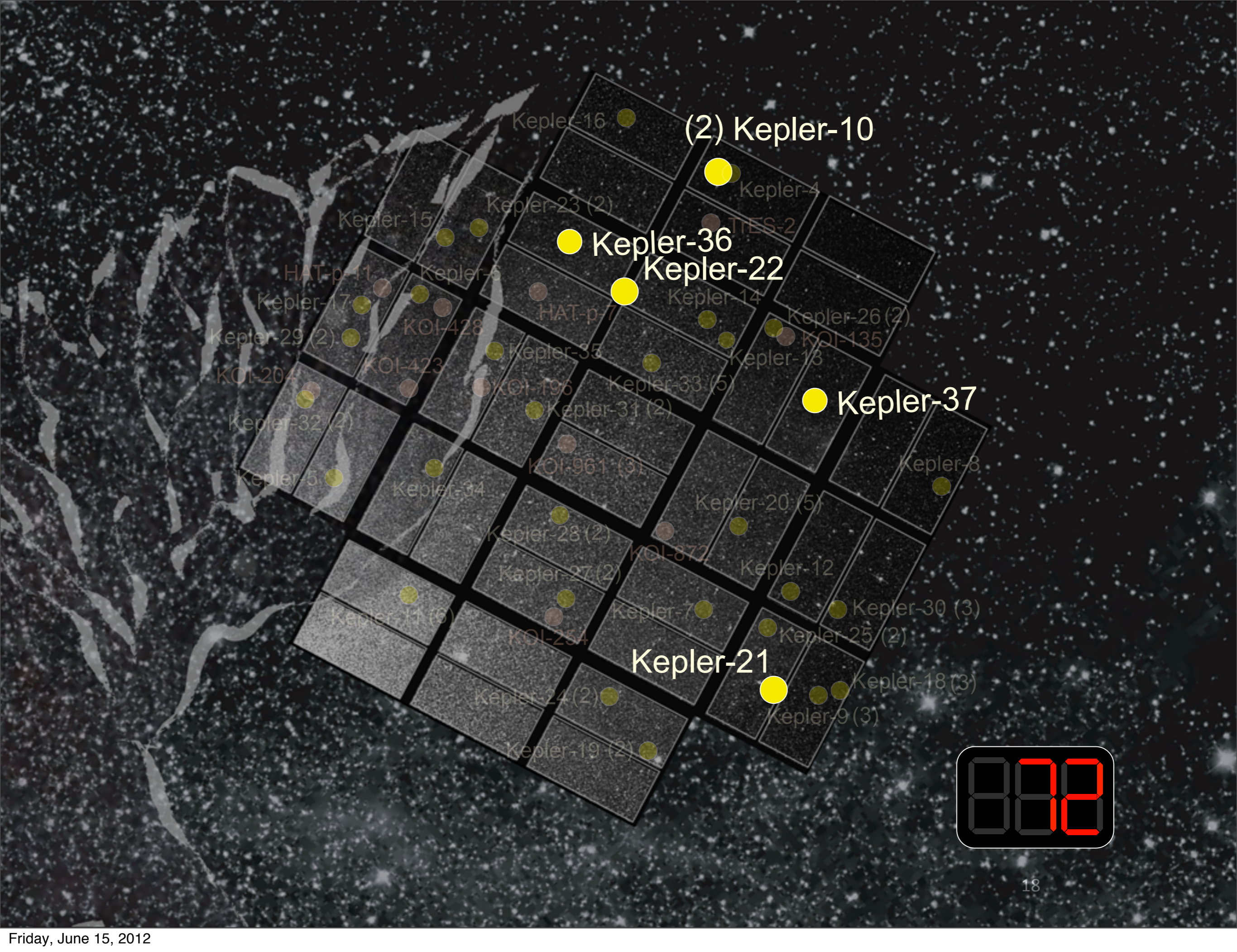


KOI-872 b & c



Nesvorny et al., ScienceExpress, 12 May 10





(2) Kepler-10

Kepler-36

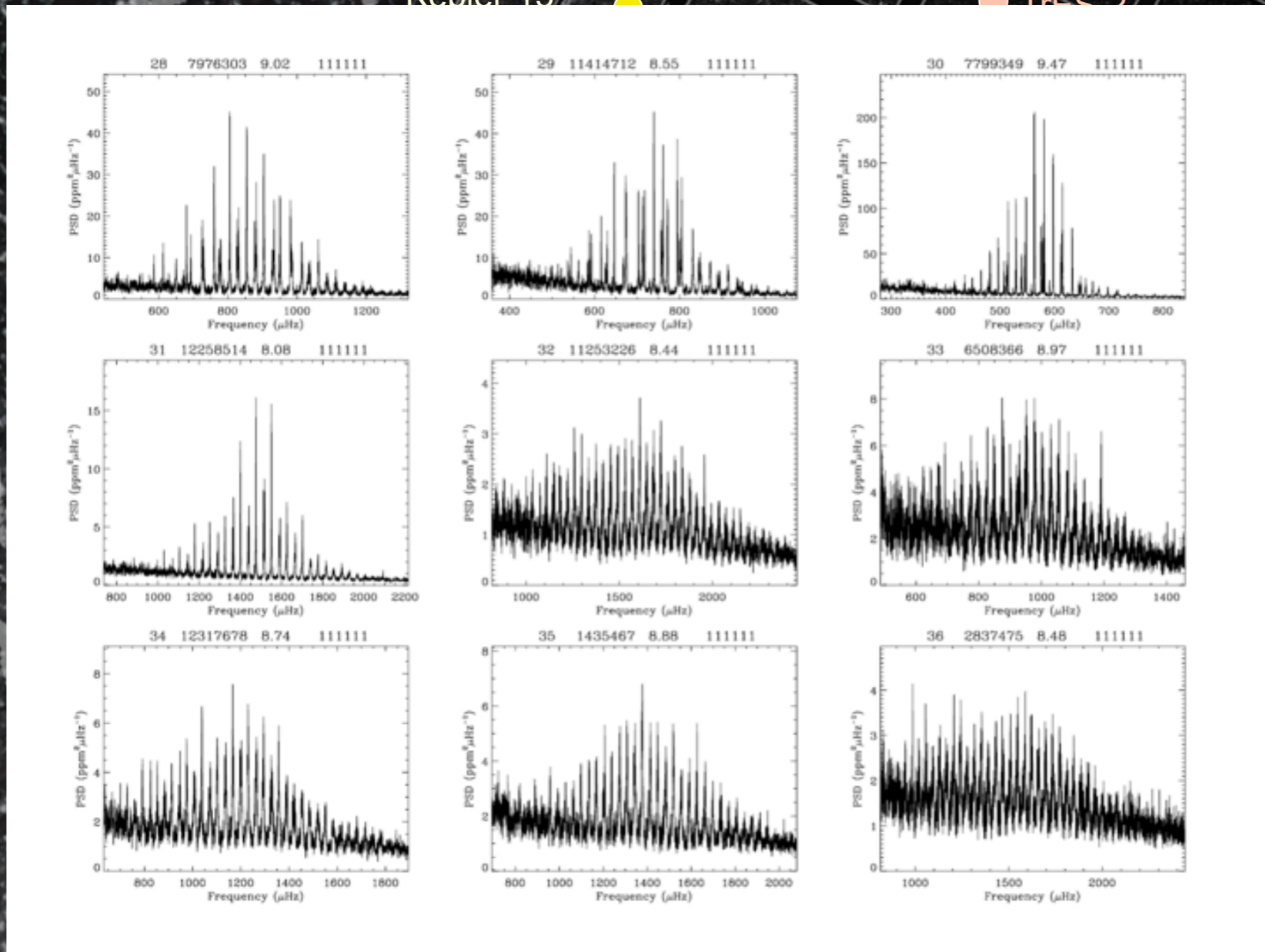
Kepler-22

Kepler-37

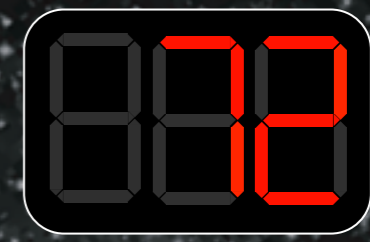
Kepler-21



Kepler-16 ●
 (2) Kepler-10 ●●
 Kepler-4 ●
 Kepler-15 ●
 Kepler-23 (2) ●●
 TrES-2 ●

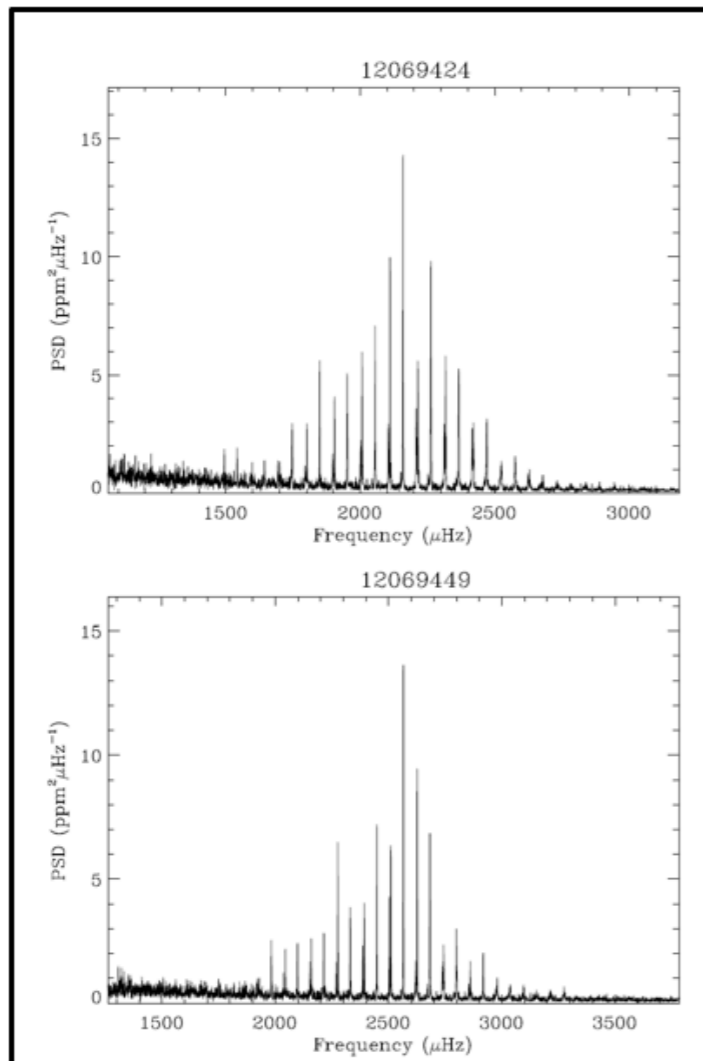


(2)
 Kepler-37
 Kepler-8 ●
 Kepler-30 (3)
 (2)
 Kepler-18 (3)

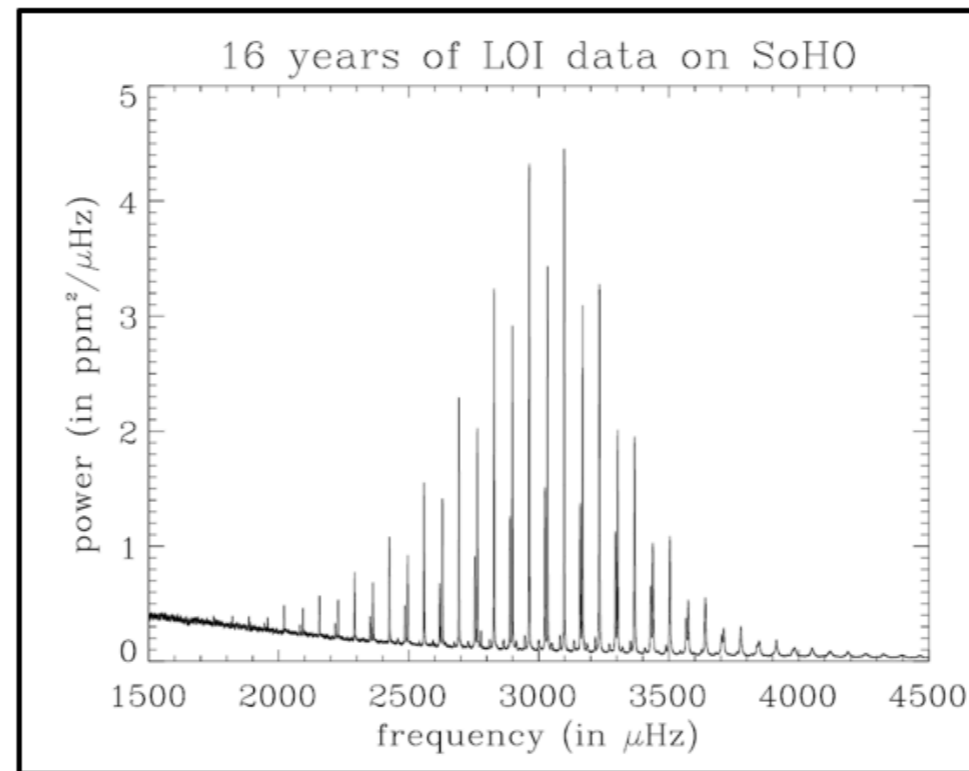


(2) Kepler-10

Kepler

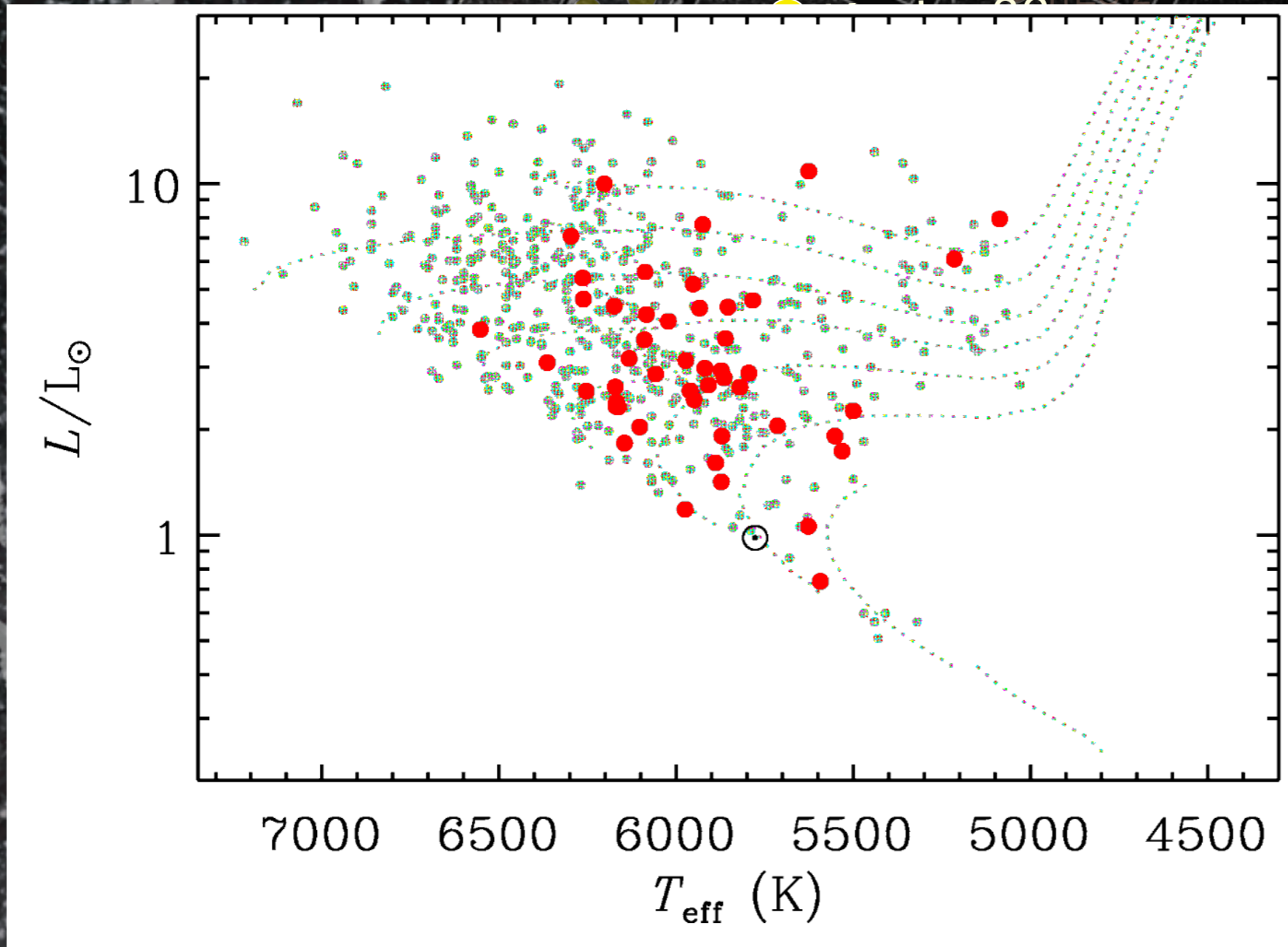


SOHO

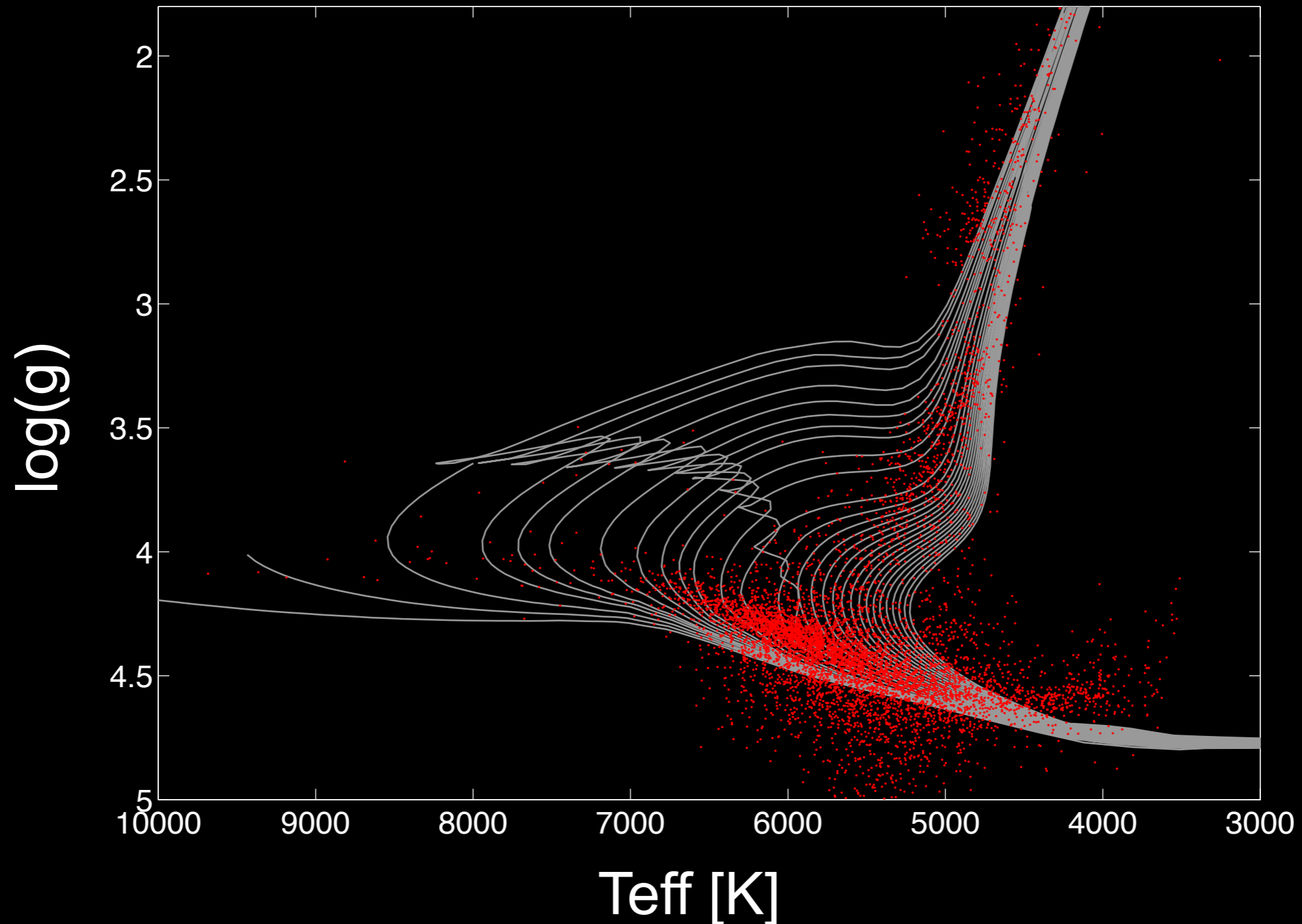


From Thierry Appourchaux...



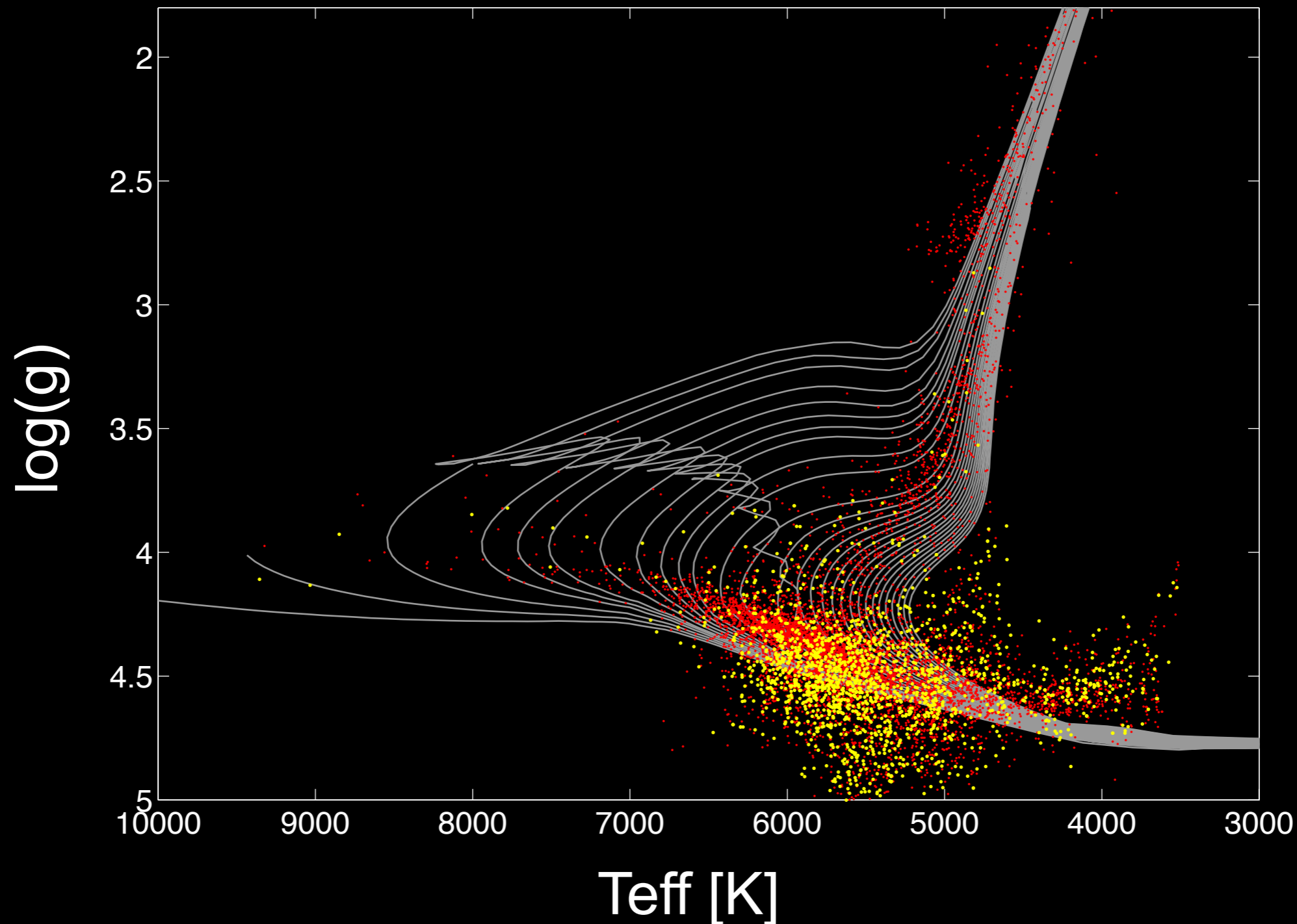


The Stellar Sample



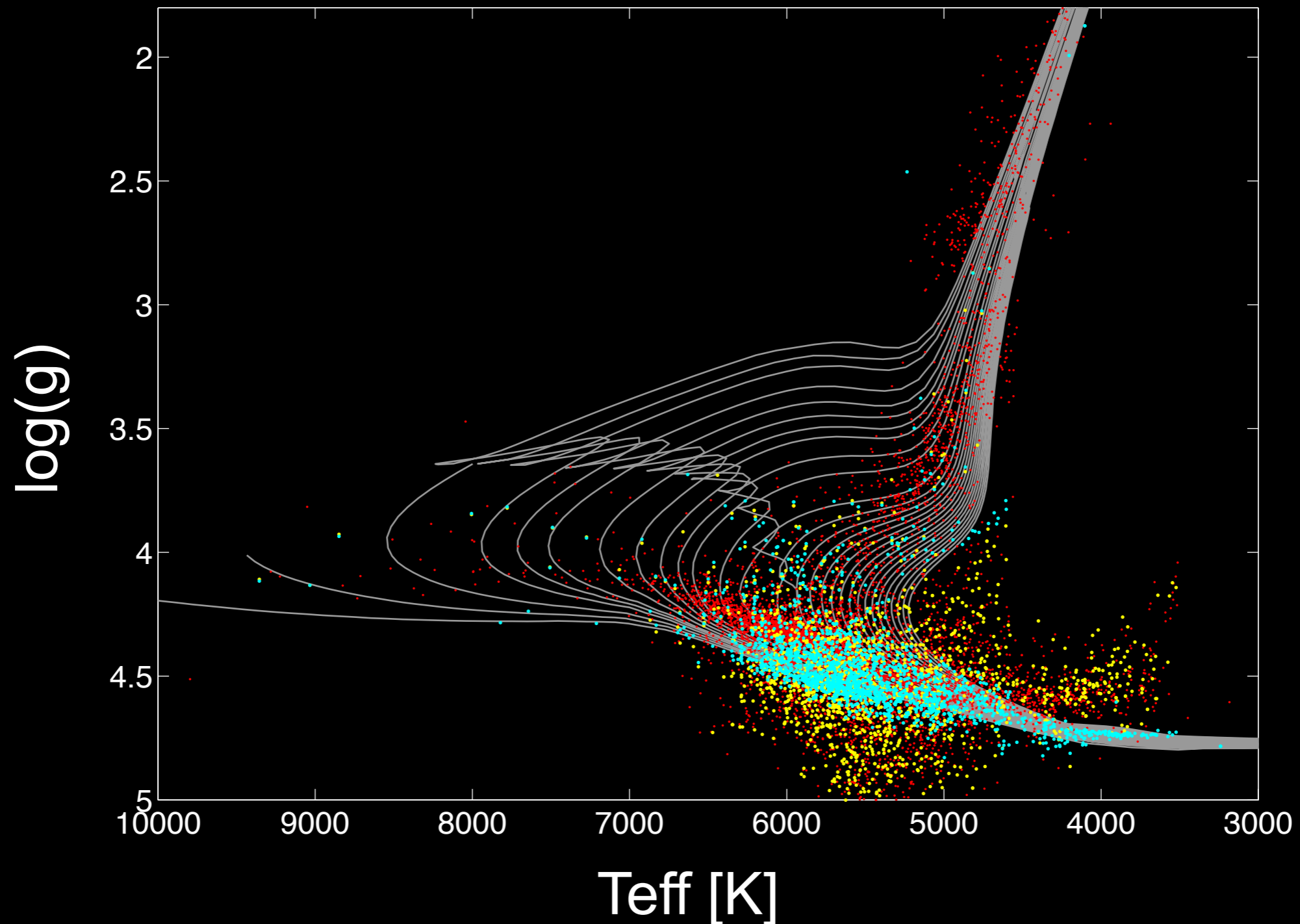
Pinsonneault et al 2012: recalibration of KIC photometry; systematic T_{eff} error
Muirhead et al 2011: IR spectra of 84 cool stars; factor of 2 smaller stellar radii
Mann et al. 2012: systematic errors in parent sample affect exoplanet statistics

The Stellar Sample



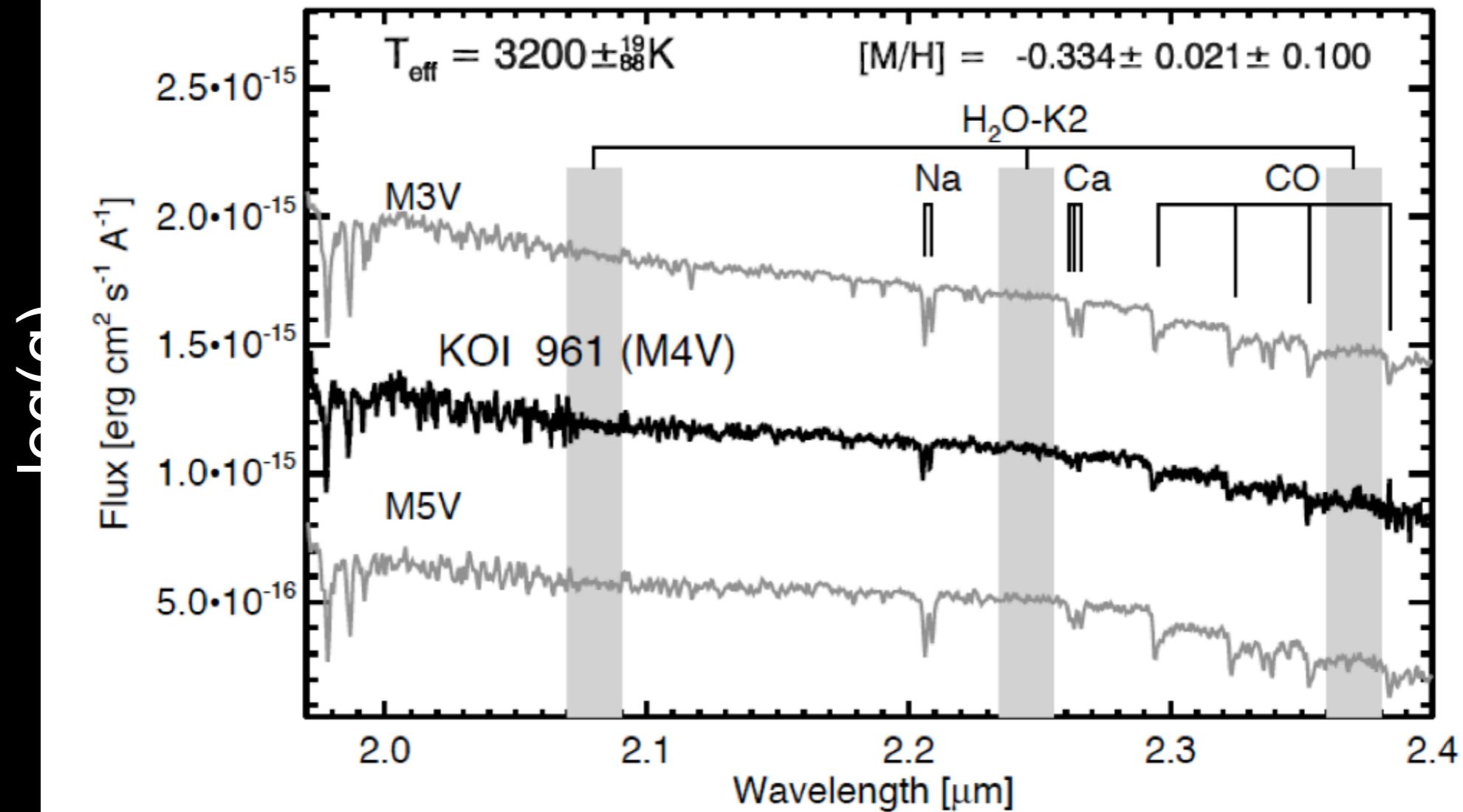
Pinsonneault et al 2012: recalibration of KIC photometry; systematic T_{eff} error
Muirhead et al 2011: IR spectra of 84 cool stars; factor of 2 smaller stellar radii
Mann et al. 2012: systematic errors in parent sample affect exoplanet statistics

The Stellar Sample



Pinsonneault et al 2012: recalibration of KIC photometry; systematic T_{eff} error
Muirhead et al 2011: IR spectra of 84 cool stars; factor of 2 smaller stellar radii
Mann et al. 2012: systematic errors in parent sample affect exoplanet statistics

The Stellar Sample



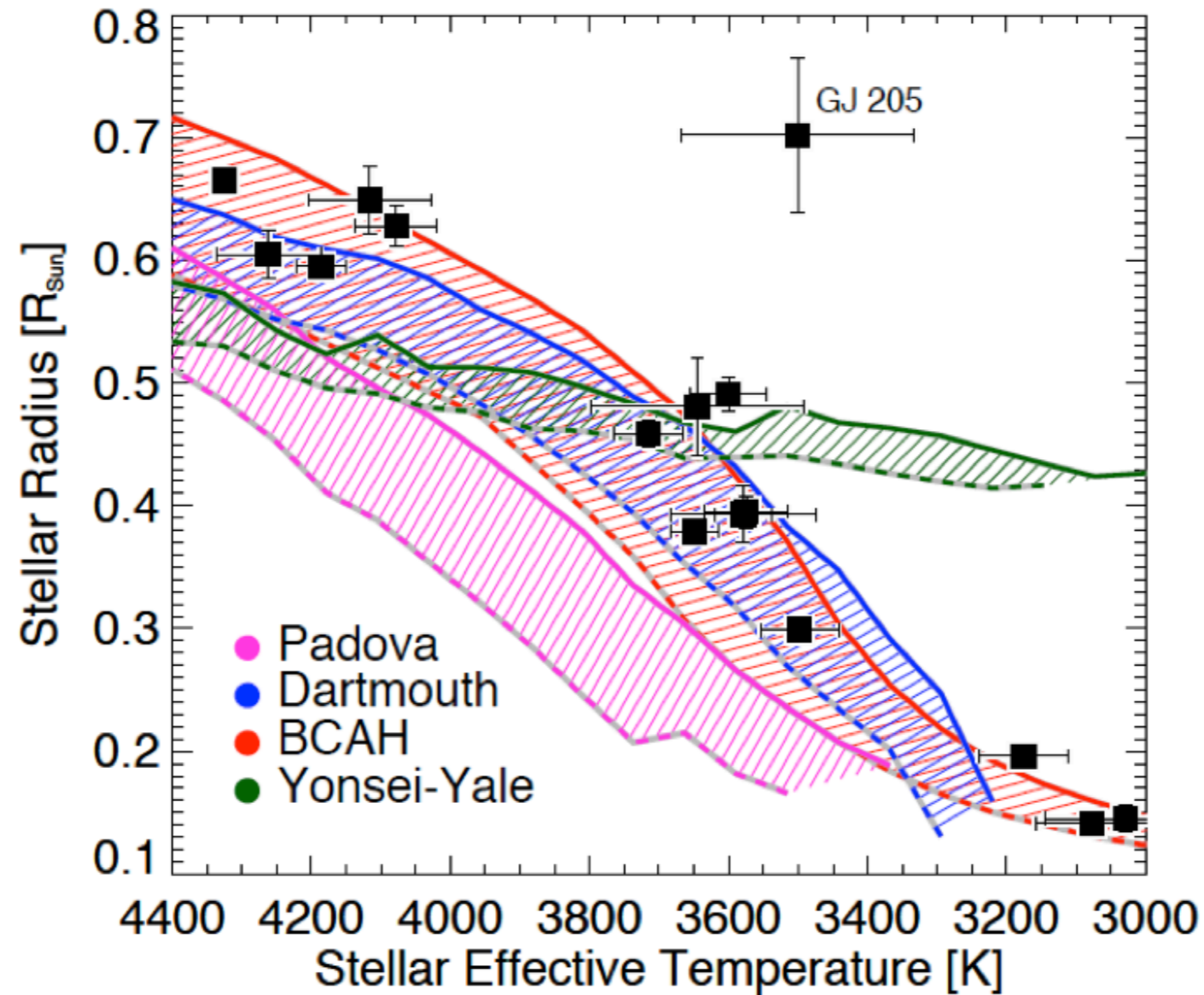
Muirhead et al 2012, ApJ, 747, 144

- Pinsonneault et al 2012: recalibration of KIC photometry; systematic T_{eff} error
- Muirhead et al 2011: IR spectra of 84 cool stars; factor of 2 smaller stellar radii
- Mann et al. 2012: systematic errors in parent sample affect exoplanet statistics

The Stellar Sample



100(a)



Muirhead et al. 2012 arXiv:1109.1819v2

Pinsonneault et al 2012: recalibration of KIC photometry; systematic T_{eff} error
Muirhead et al 2011: IR spectra of 84 cool stars; factor of 2 smaller stellar radii
Mann et al. 2012: systematic errors in parent sample affect exoplanet statistics

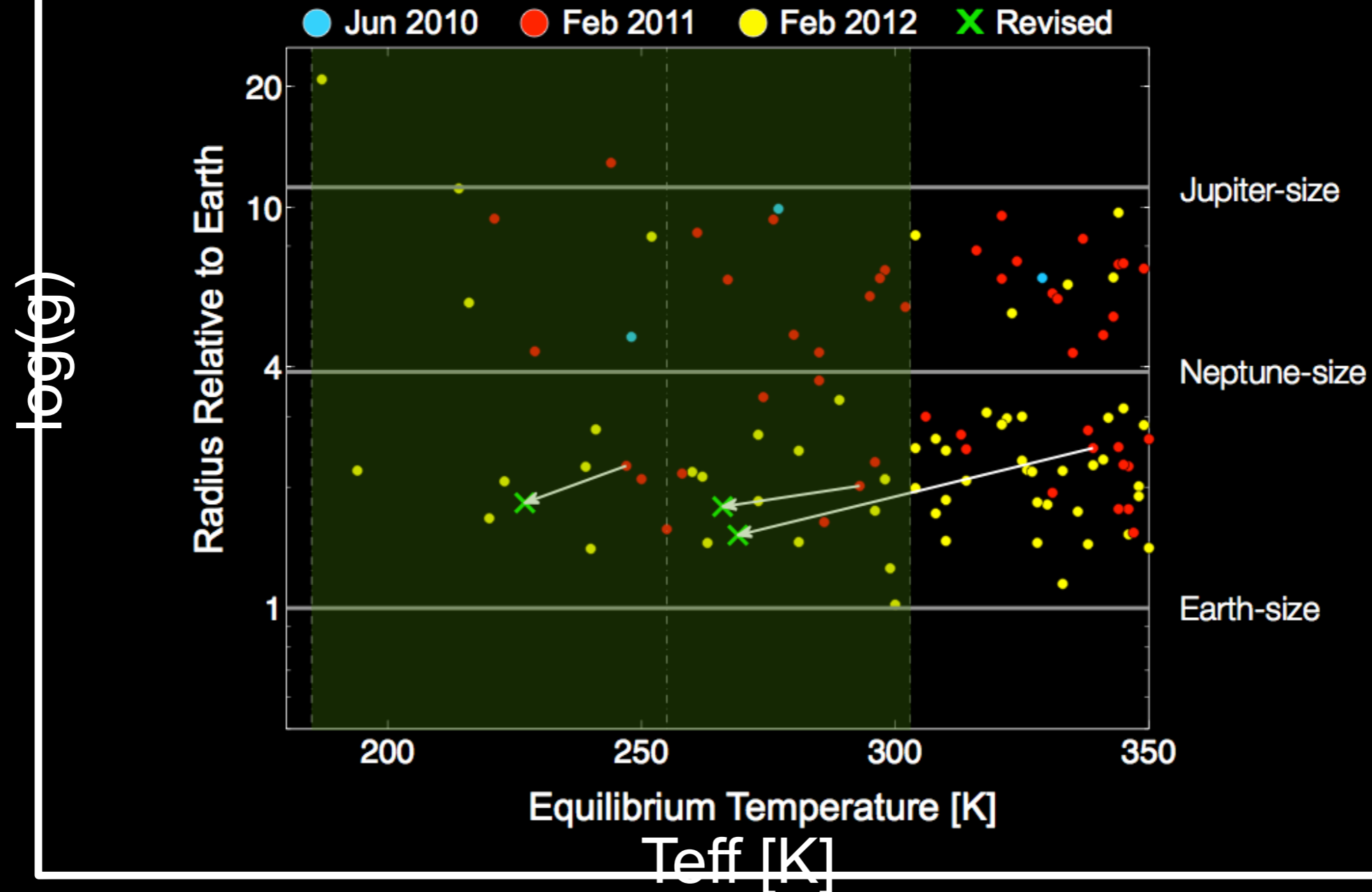
The Stellar Sample



Kepler

Candidates in the Habitable Zone

Revisions from Muirhead et al. 2012, ApJ, 750, 37



Pinsonneault et al 2012: recalibration of KIC photometry; systematic Teff error
Muirhead et al 2011: IR spectra of 84 cool stars; factor of 2 smaller stellar radii
Mann et al. 2012: systematic errors in parent sample affect exoplanet statistics

Exoplanet Science in the Extended Mission

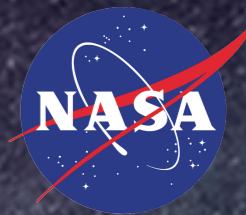


- KOI Review Team (michael.r.haas@nasa.gov)
- Stellar Characterization (your name here)
- Small Planet Completeness (jessie.l.christiansen@nasa.gov)
- Asteroseismology (gillil@stsci.edu)
- Transit Timing Variations (eford@astro.ufl.edu)
- Eclipsing Binaries (aprsa@villanova.edu)
- False Positive Tracking (Steve.Bryson@nasa.gov)
- Follow-up Observation Program (ciardi@ipac.caltech.edu)
- Other (Giant Planets, Circumbinary Planets)



Summary

- 72 Confirmed and/or characterized planets
 - rocky, earth-size, HZ, circumbinary, multiples
- 2,321 planet candidates, 1091 of which are new this year
- 16 months of data has been search for transits
- 250 earth-size candidates, one of which (KOI-2124.01) is in/near the HZ
- Power-law increase toward small planets down to $2 R_e$
- Pipeline completeness still improving
- 20% of stars observed to harbor >1 candidate
- Paucity of short-period giants in flat systems
- Small pile-up just outside of low-order resonances
- Stellar classification is high priority for reliable planet radii
- Stellar Variability (6.5-hour) is 50% higher than predicted
- Extending mission from 3.5 to 7.5 years recovers baseline performance.
- Extending mission allows for determinations of eta-Earth-size **in the HZ.**

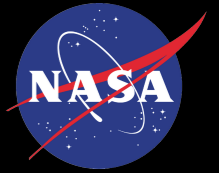


Onward!

natalie.batalha@nasa.gov

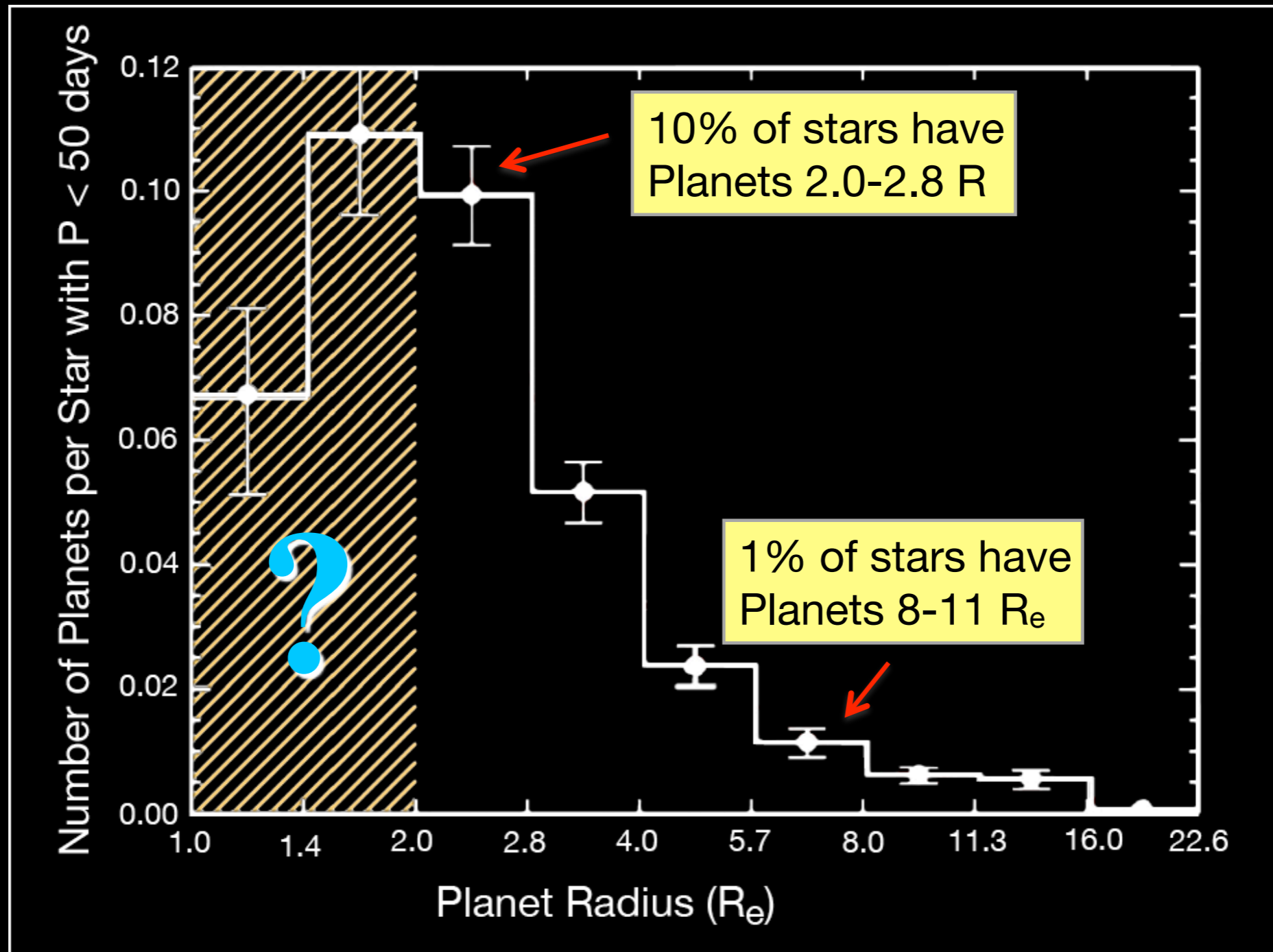


Supplemental Slides



Distribution of Planet Diameters

For Orbital Periods < 50 Days



Howard et al. 2011, arXiv: 1103.2541



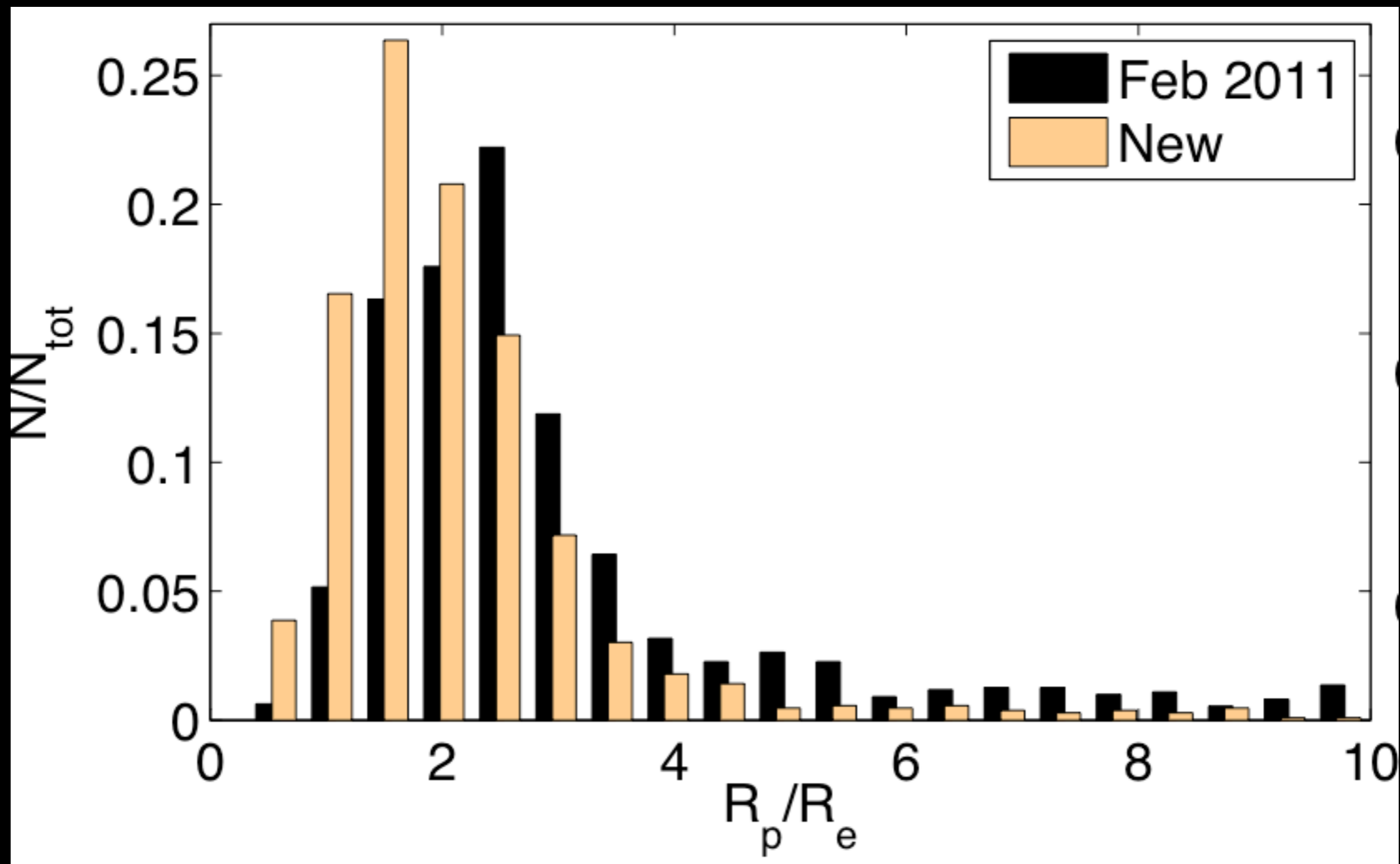
N(Q6)/N(Q5)

	1.25 Re < Rp < 2 Re		2.5 Re < Rp < 6 Rp
	5 < P < 50	50 < P < 150	10 < P < 125
Modeled	1.1	1.4	1.0
Observed	2.8	7.2	1.6

Gains cannot be explained solely by longer data collection.



Fractional Gains



$R_p < 2 R_e$: 197%

$R_p > 2 R_e$: 52%

$P > 50$ days : 123%

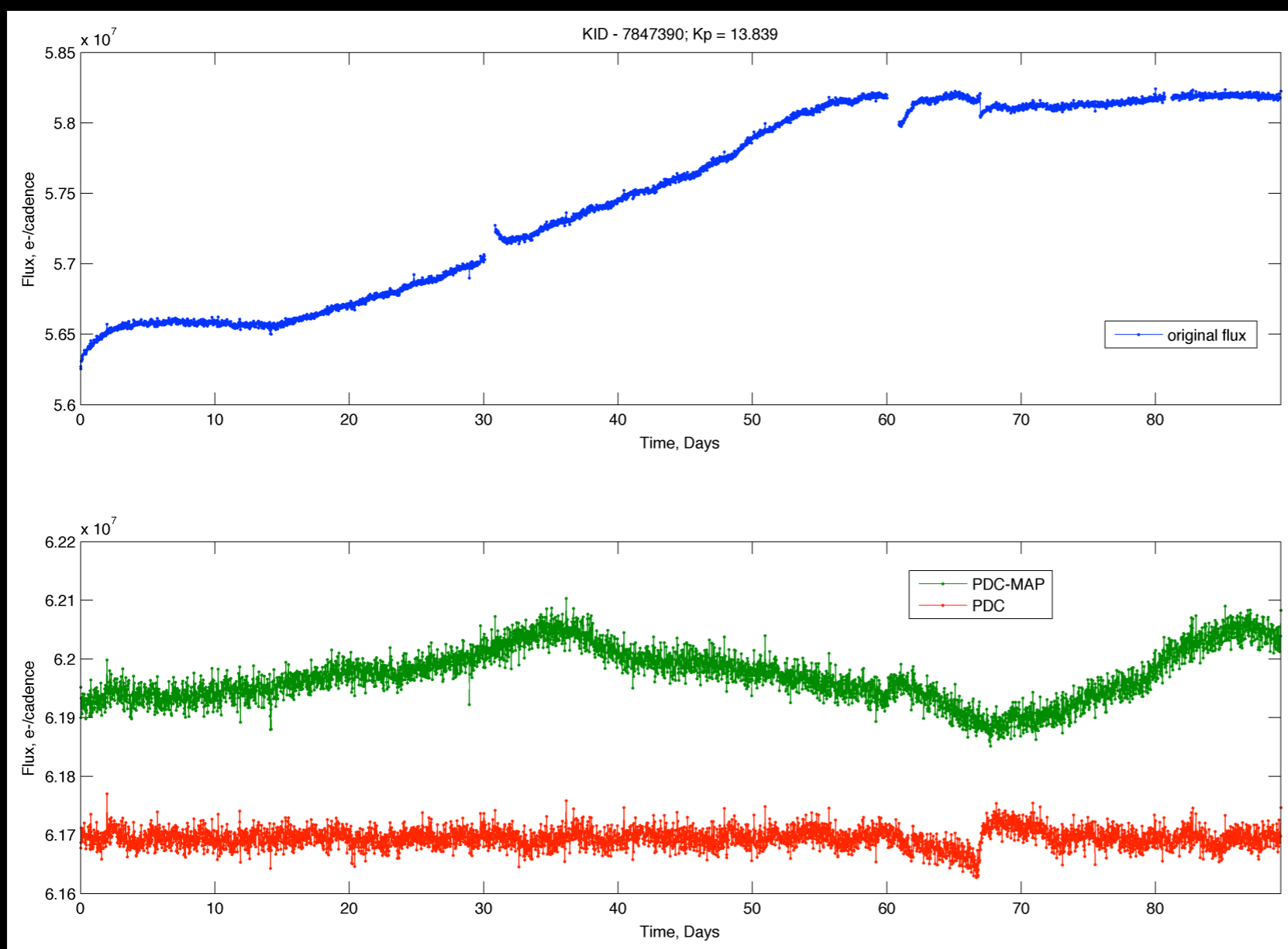
$P < 50$ days : 85%



Factors Affecting Completeness

Sudden Pixel Sensitivity Dropouts:

Transit detection analysis keys off on anomalous event instead of real transits. This, also, is treated in PDC-MAP.



Original flux

PDC

PDC-MAP

arXiv:1203.1383

Impact of Measured Noise



Mission design based on a peak at 20 ppm

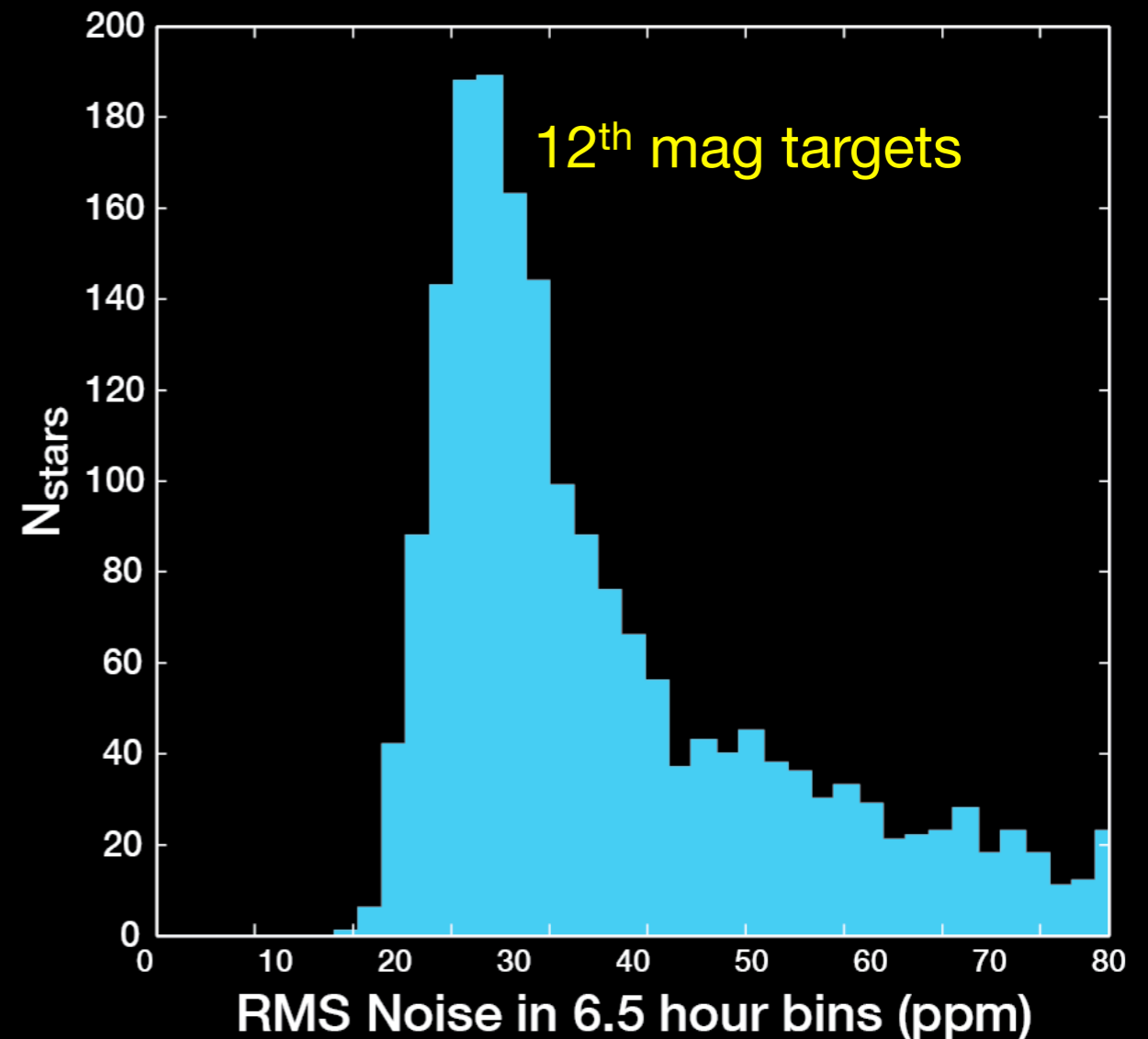
Histogram peaks at 30 ppm

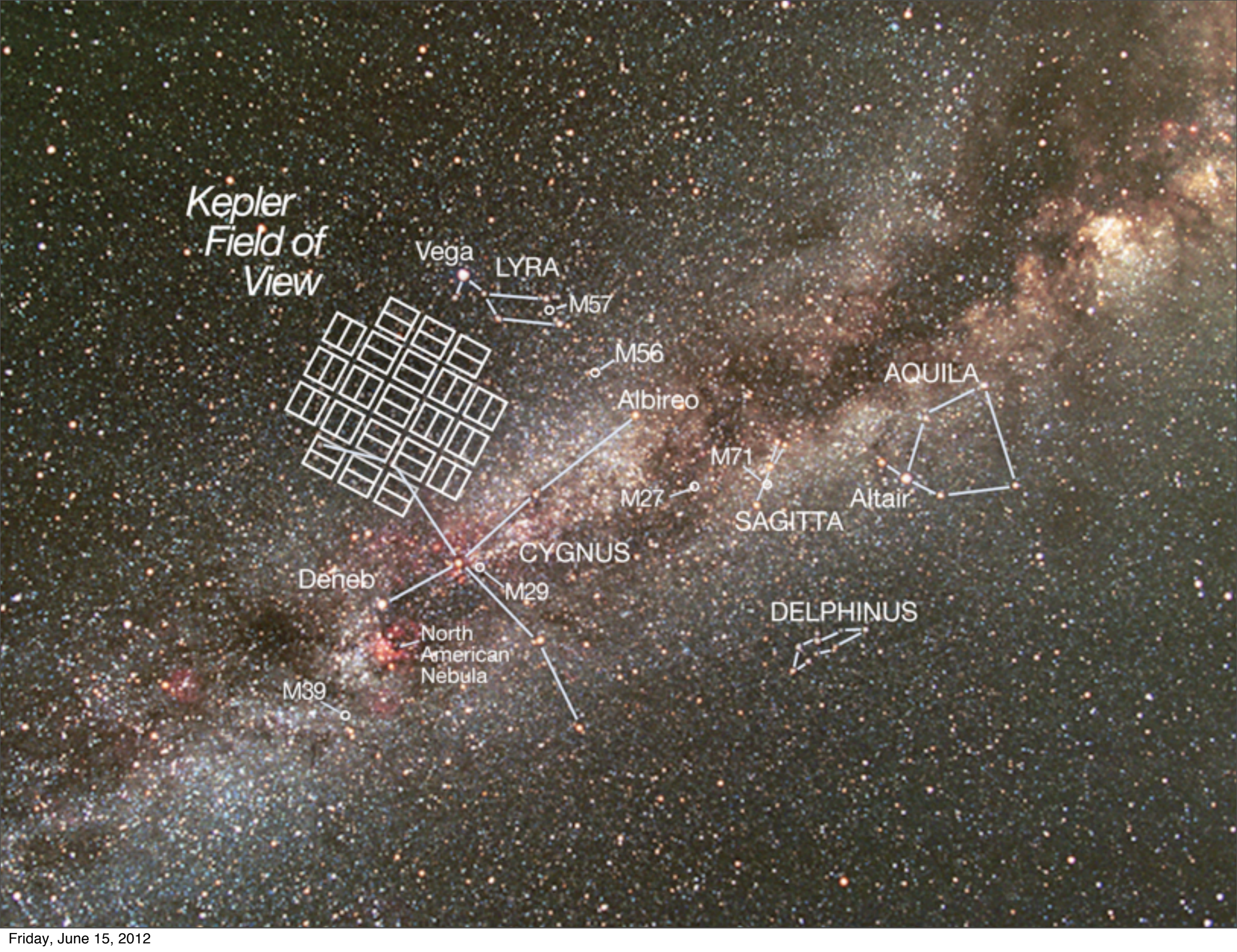
- Yields only 2% completeness for Earth analogs in baseline mission

Sensitivity improves as \sqrt{t}

- Noise is uncorrelated in successive transits
- Yields ~50% completeness for Earth analogs with 7.5 year mission

Noise Histogram





*Kepler
Field of
View*

Vega

LYRA

M57

M56

Albireo

M71

SAGITTA

AQUILA

Altair

CYGNUS

Deneb

M29

North
American
Nebula

DELPHINUS

M39

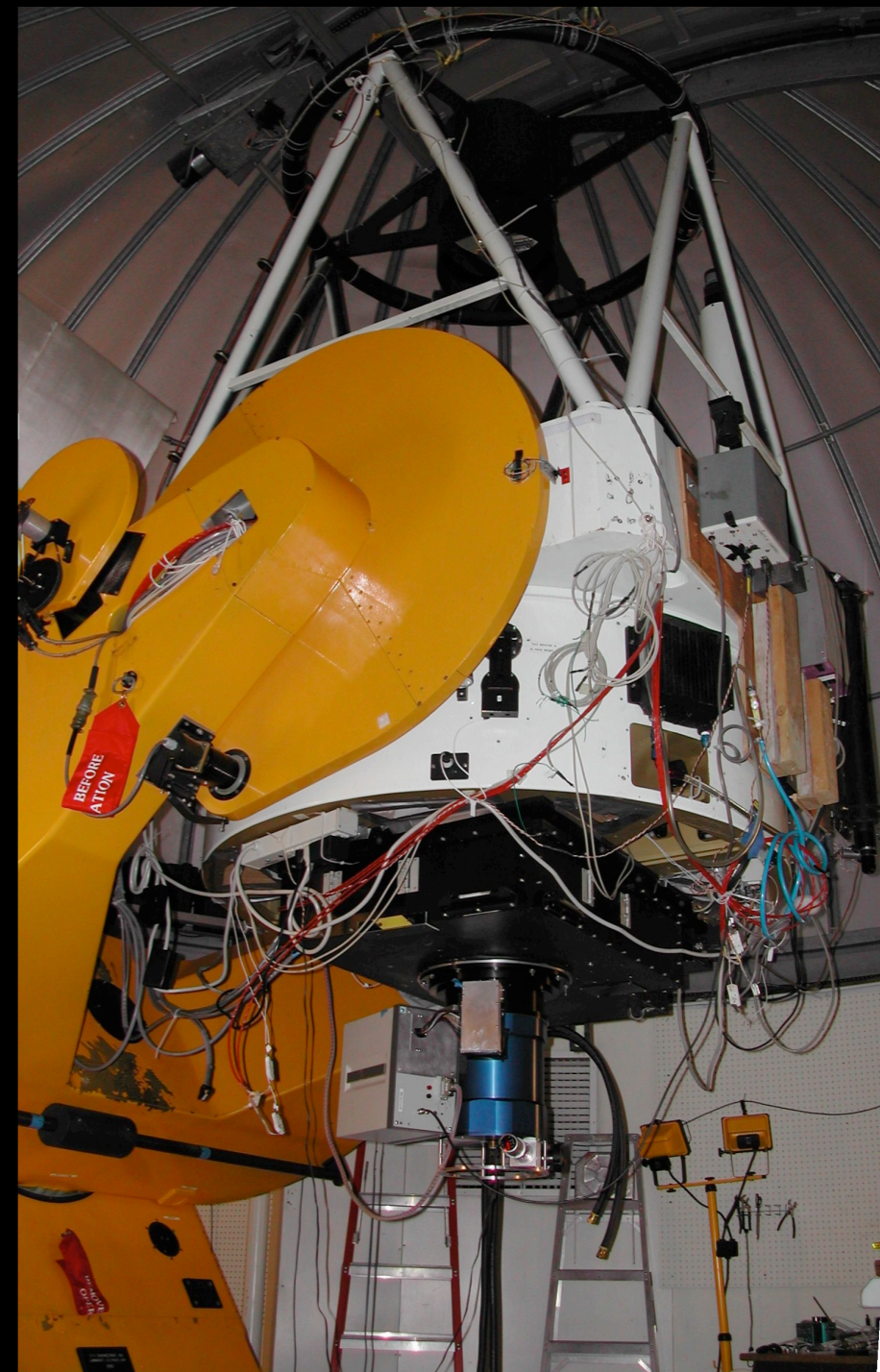


Kepler Input Catalog

- KeplerCam, 1.2-m, Mt. Hopkins
 - SDSS g, r, i, z + D51
- Archive data
 - 2MASS JHK, USNO-B
- Yields Stellar Parameters:
 - T_{eff} , $\log(g)$, $\log(Z)$, A_V , $E(B-V)$
 - Kp (kepler magnitude)
 - Radius

<http://archive.mast.edu/kepler>

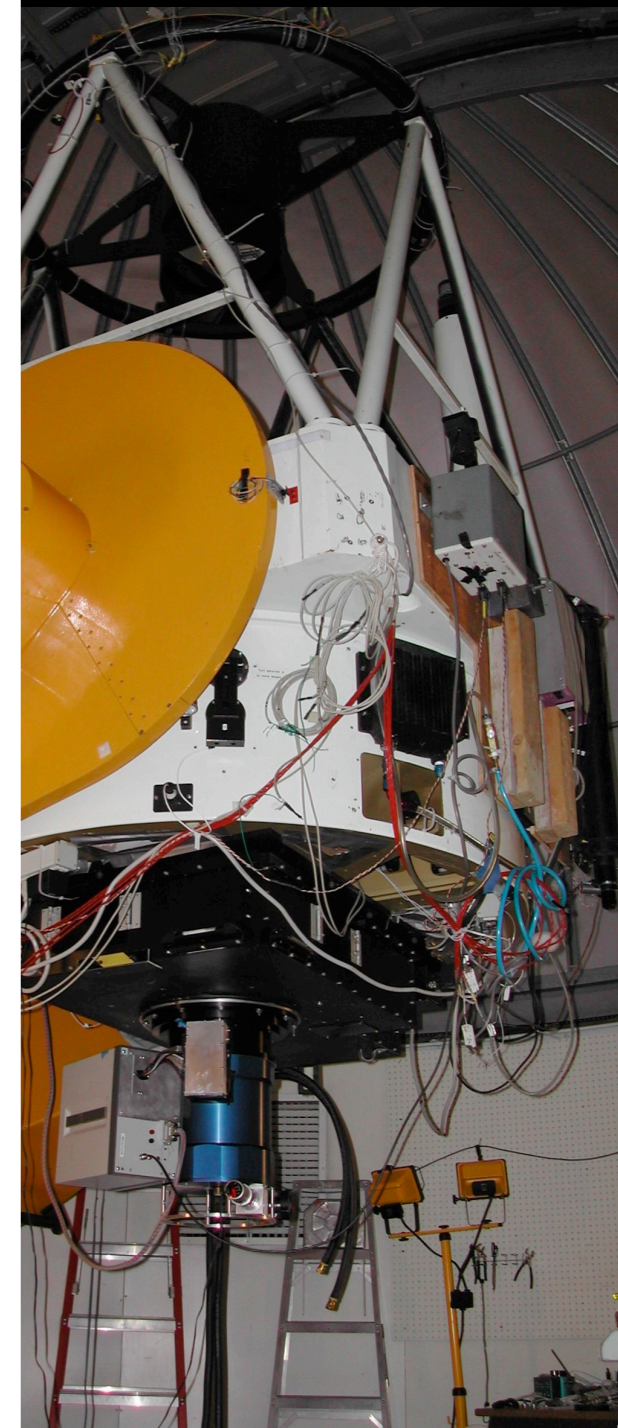
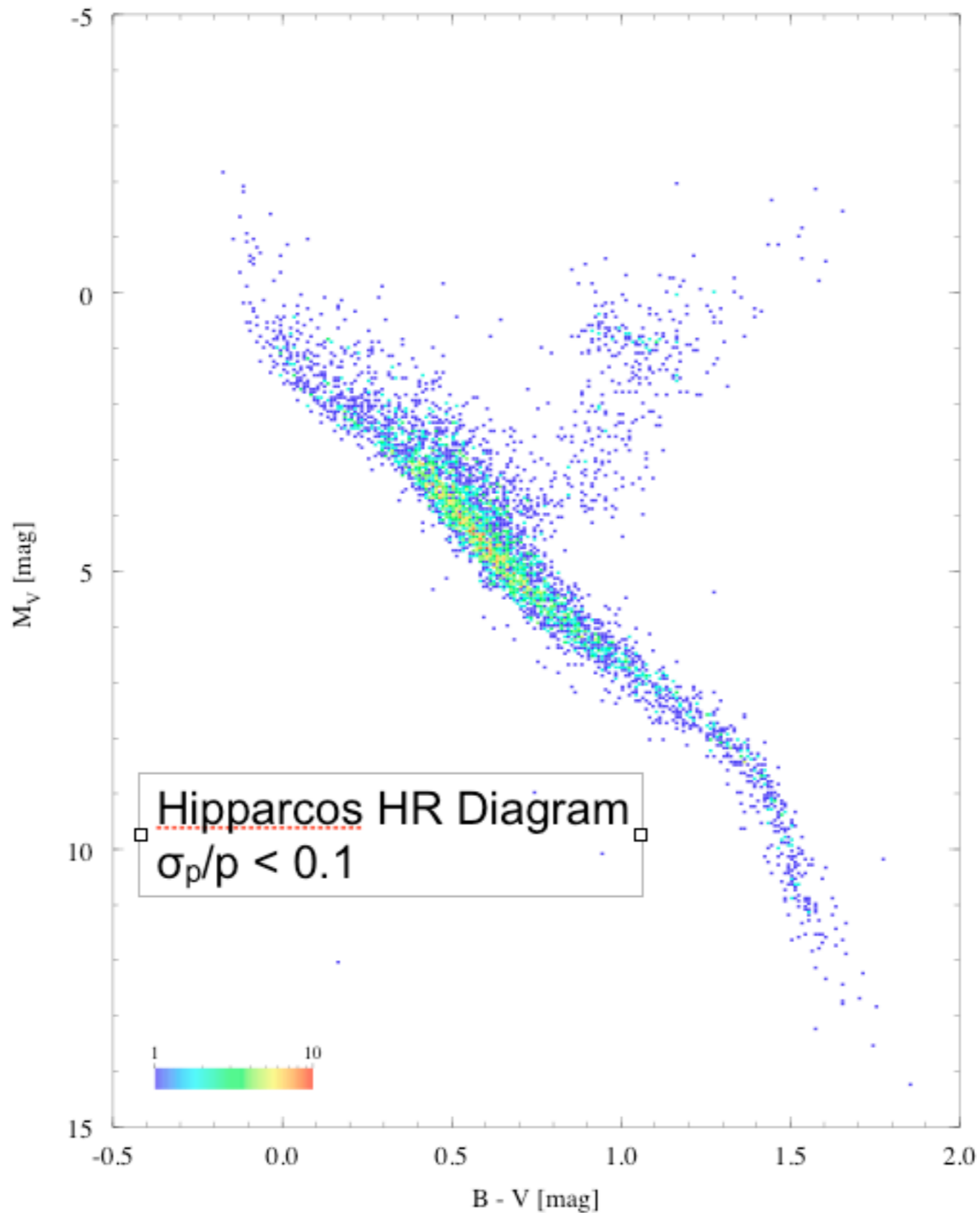
Brown et al. 2012, AJ, 142, 112





- KeplerCam
- SDSS g,
- Archive data
- 2MASS J
- Yields Stellar
- T_{eff} , $\log(g)$
- Kp (Kepler)
- Radius

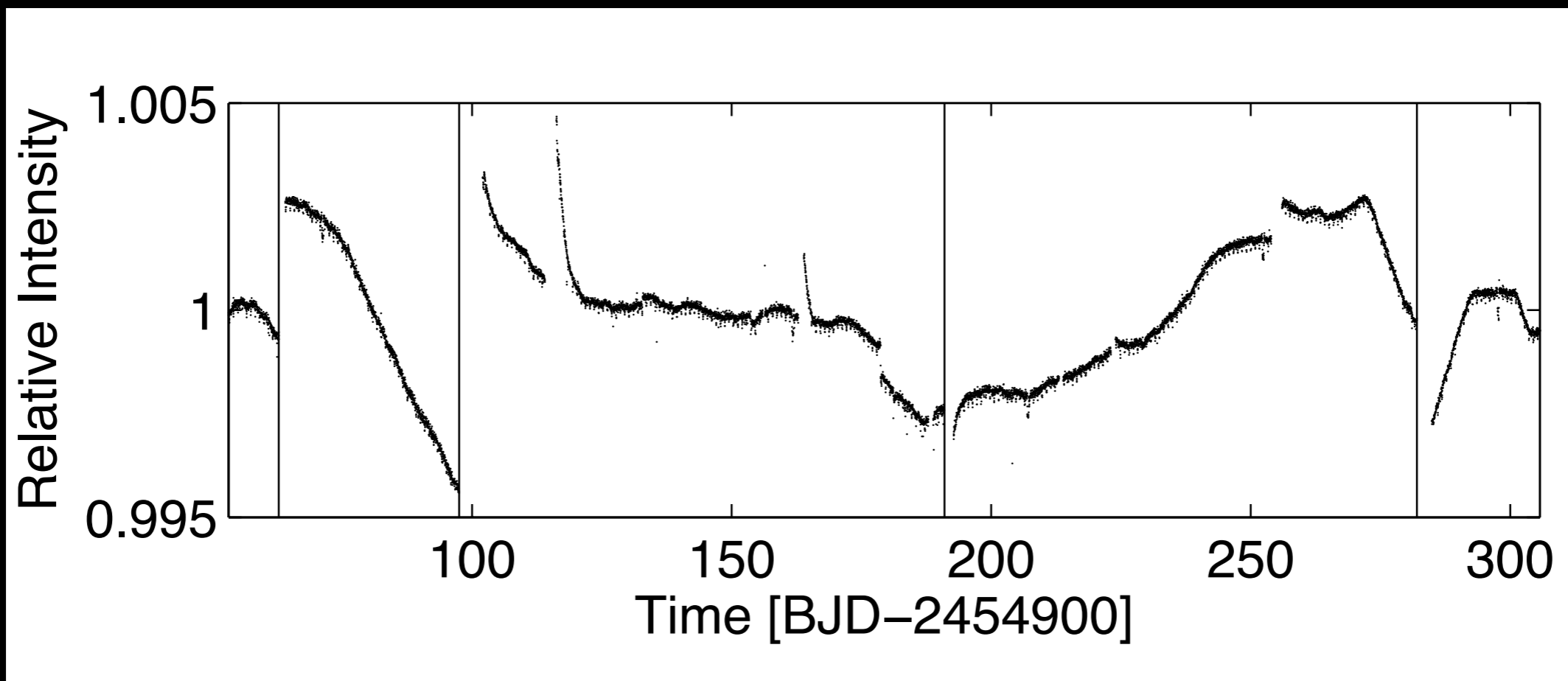
<http://archive.brown.edu>
Brown et al



Factors Affecting Completeness

Multi-Quarter Transit Search:

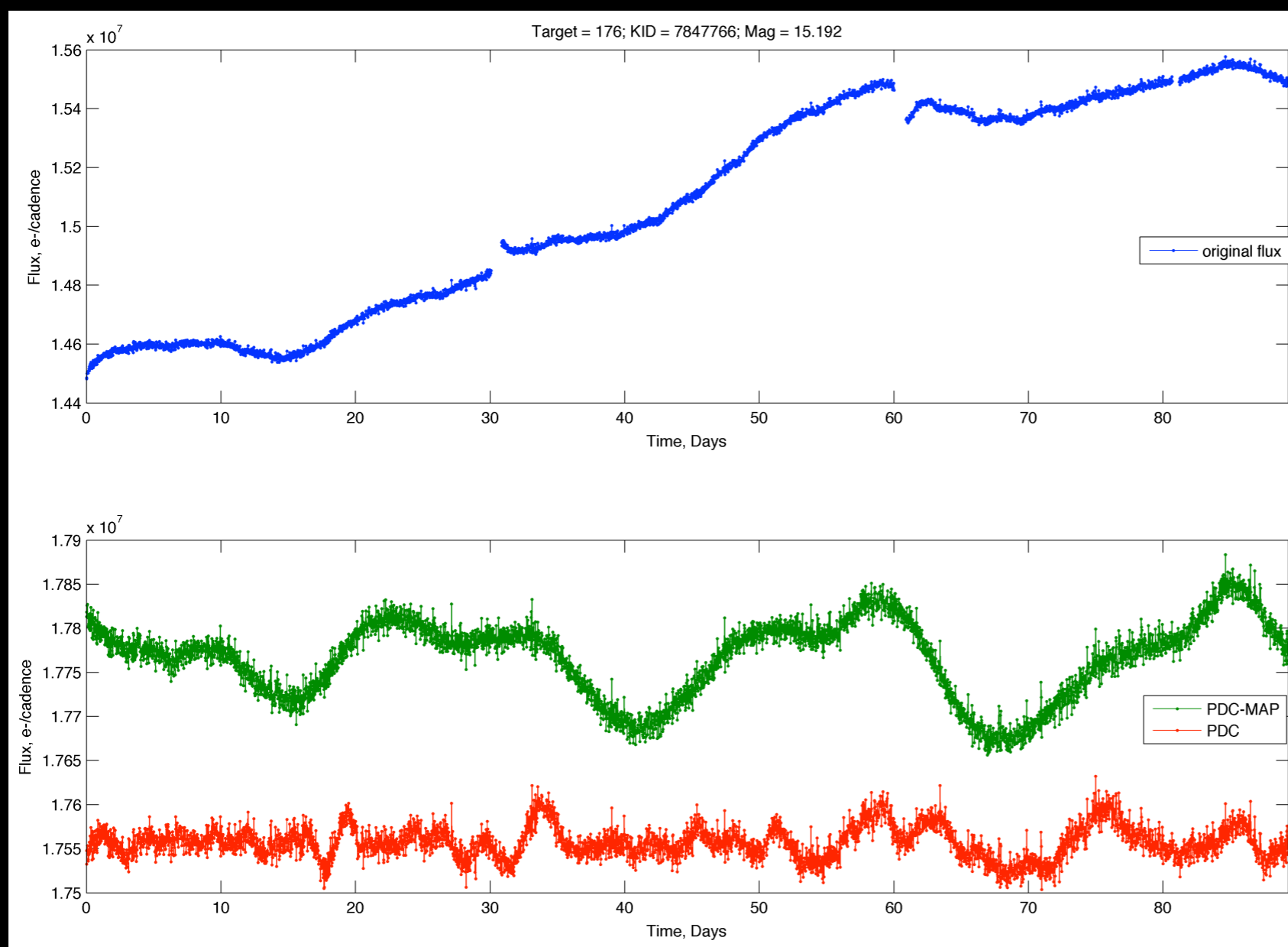
- Feb 2011 catalog: analysis of Q0-Q5 data based on non-pipeline tools to detect long-period events.
- Didn't benefit from pipeline whitening filters



Factors Affecting Completeness

Pre-search Data Conditioning:

First generation filters occasionally introduced high frequency noise. This has been greatly improved with PDC-MAP.



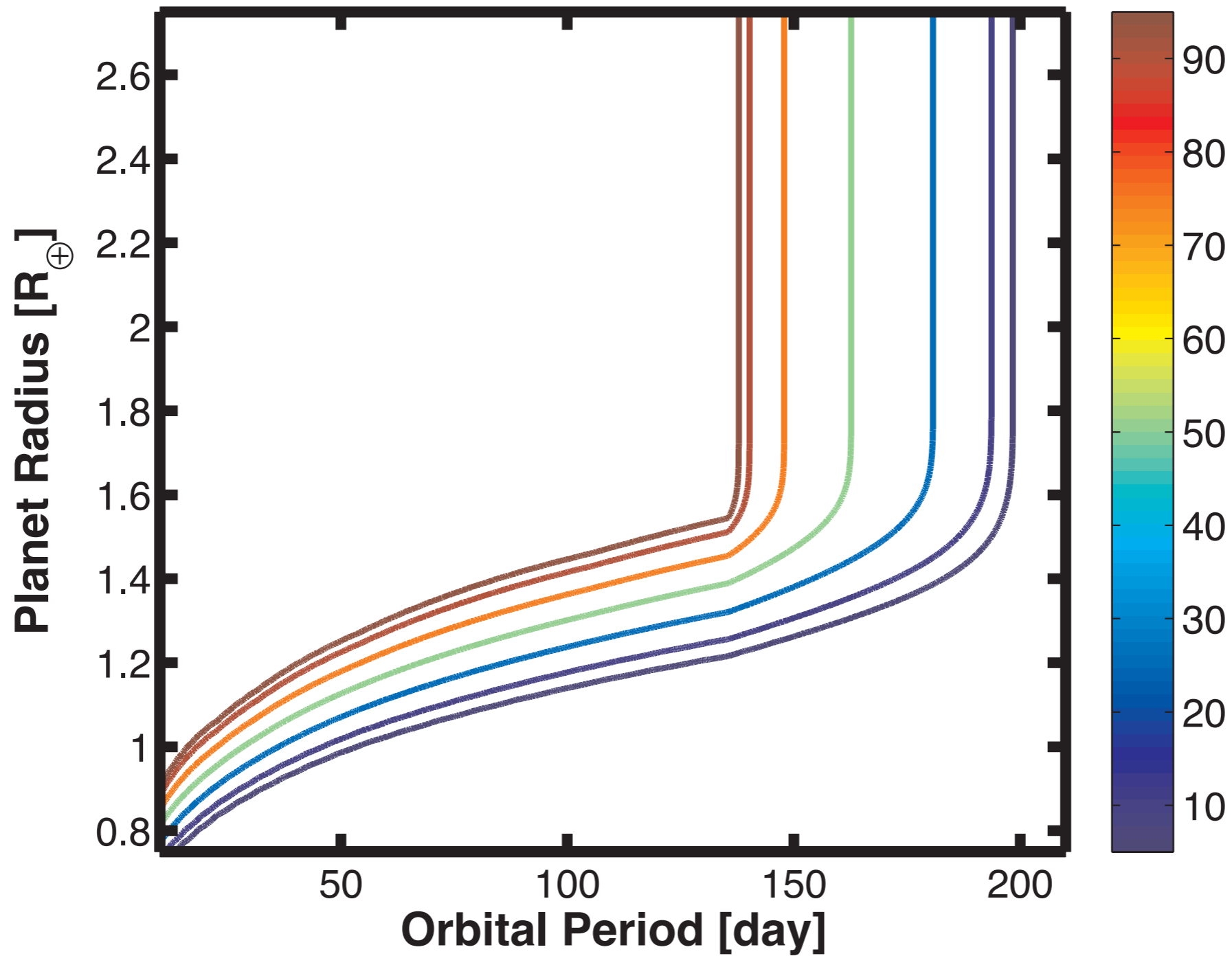
Original flux

PDC

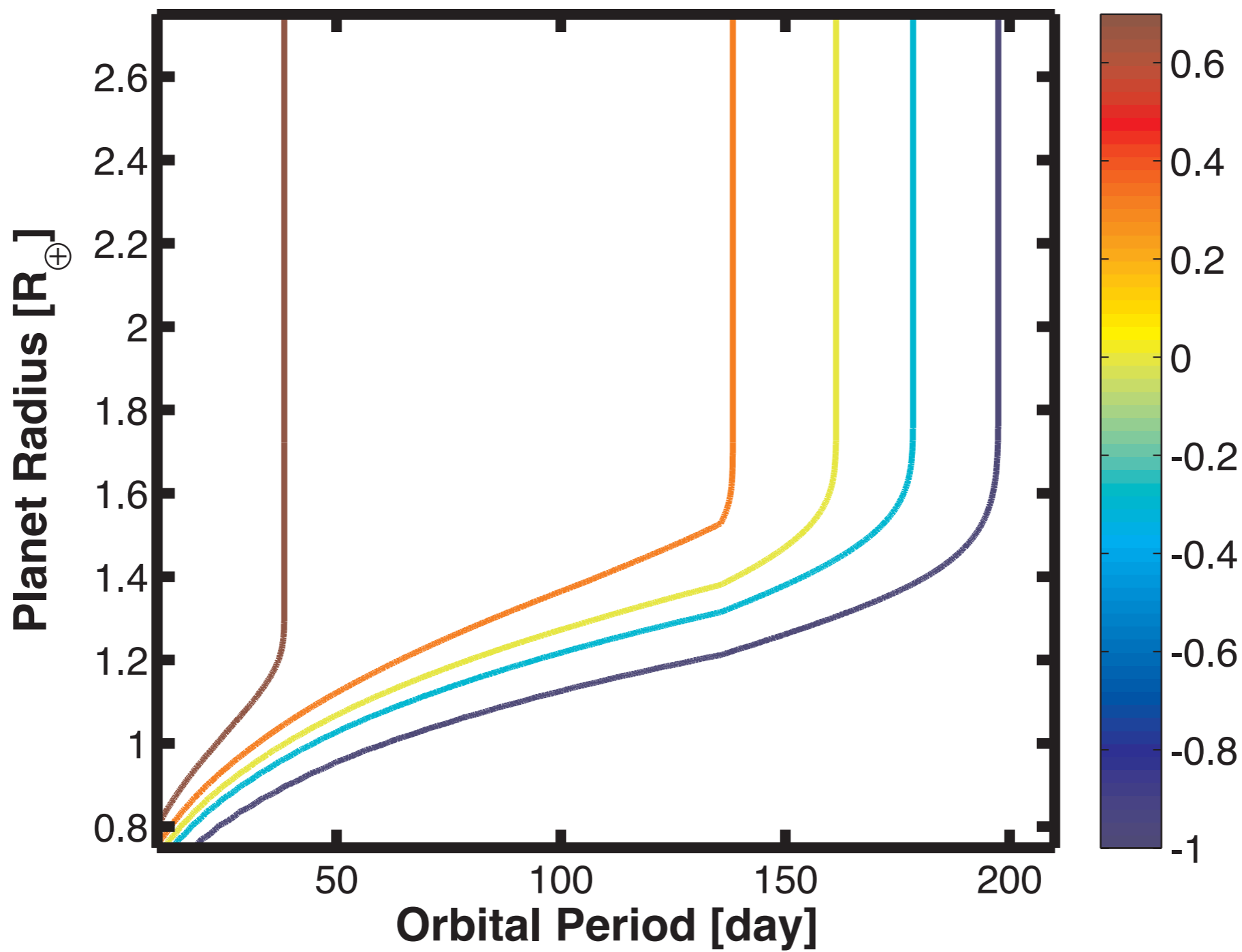
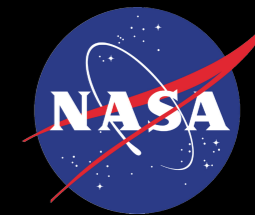
PDC-MAP

arXiv:1203.1383

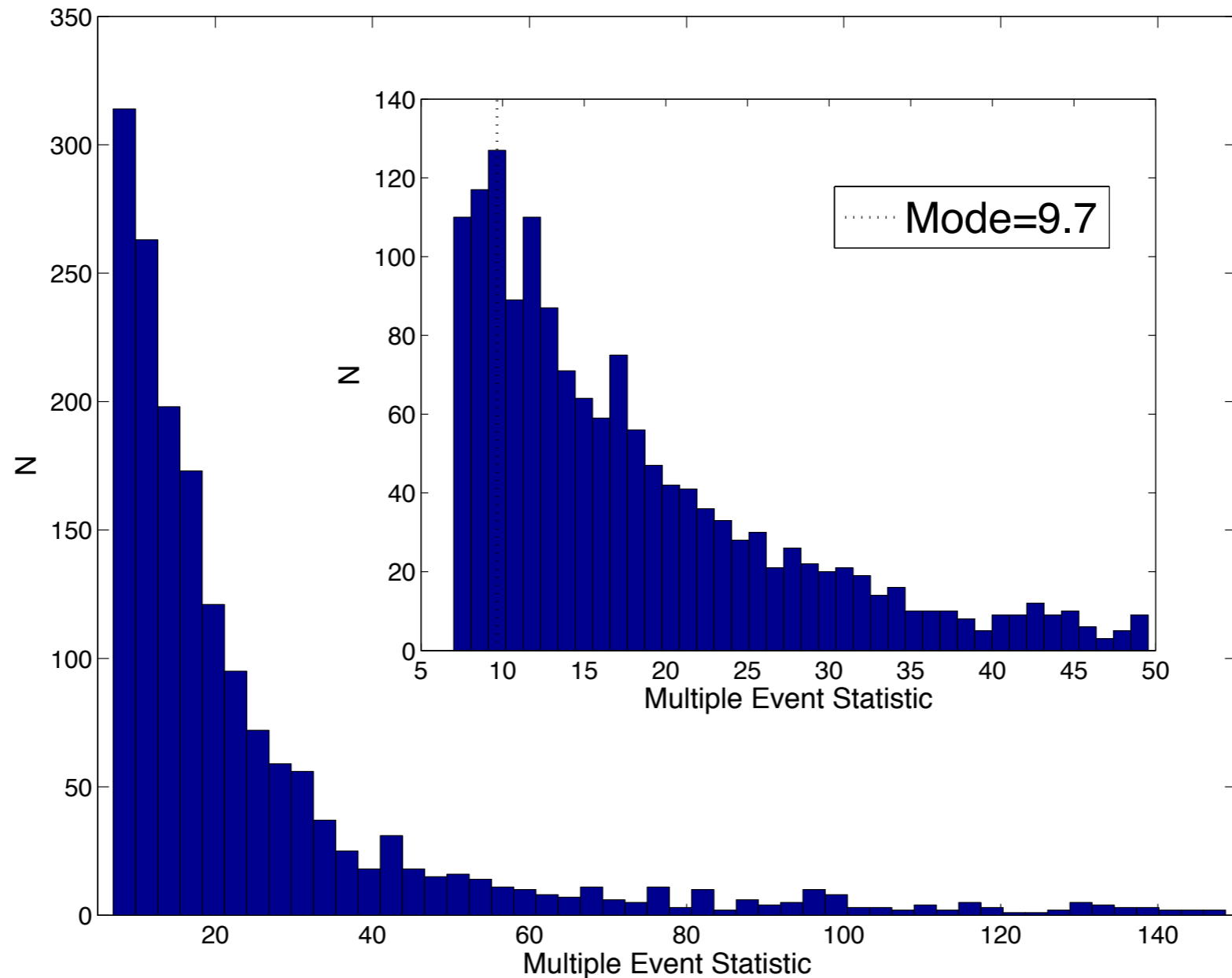
Percent Completeness



Completeness Including Transit Probability

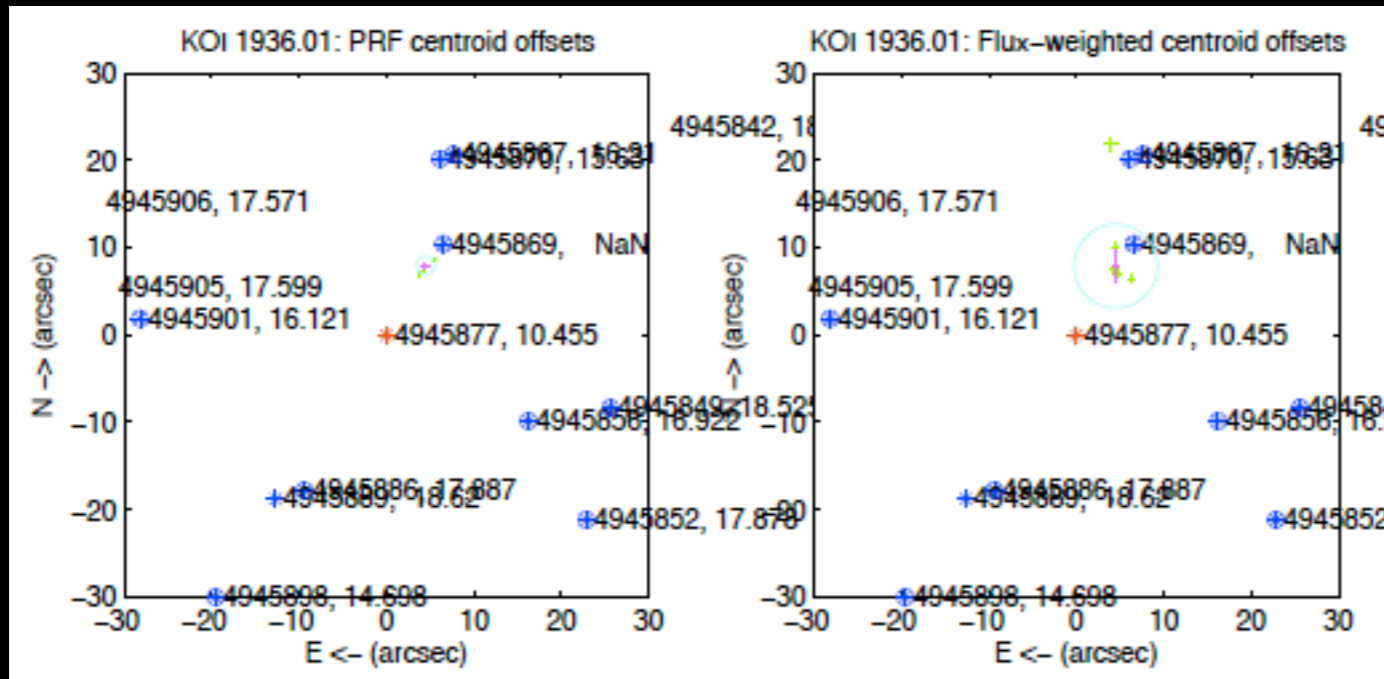


Histogram of Total SNR

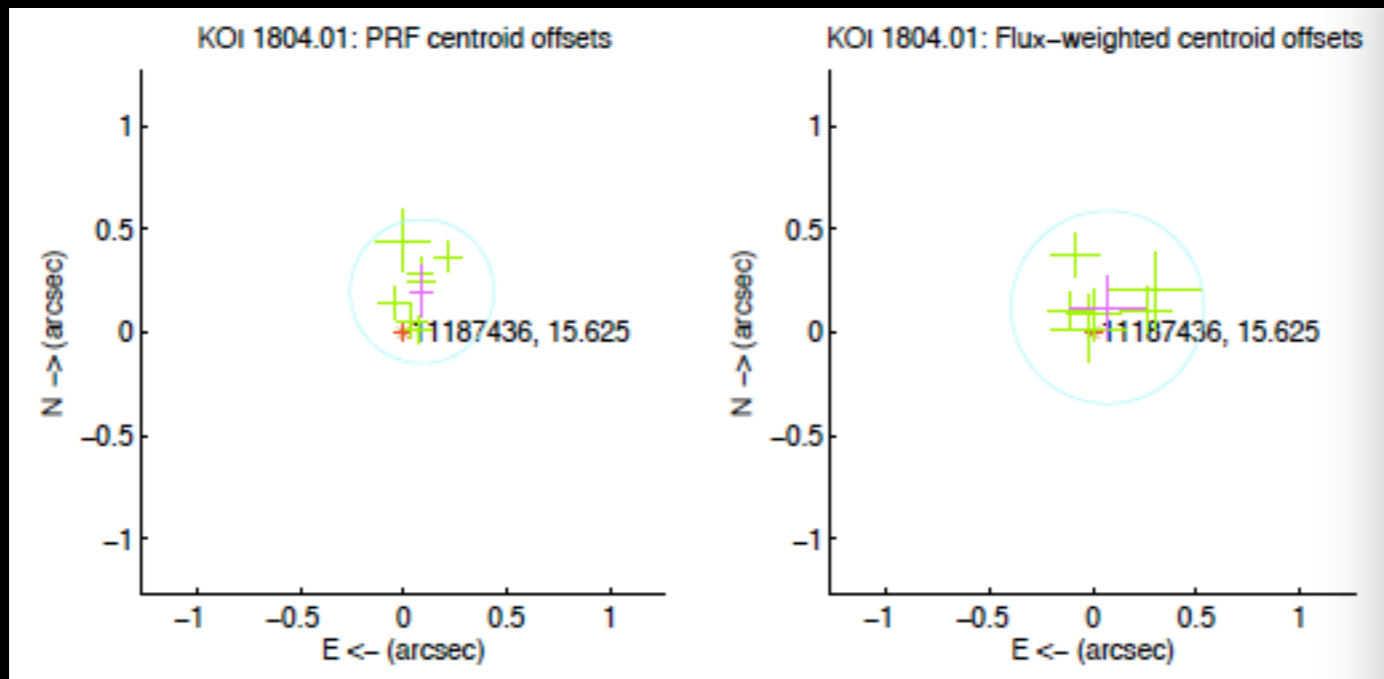
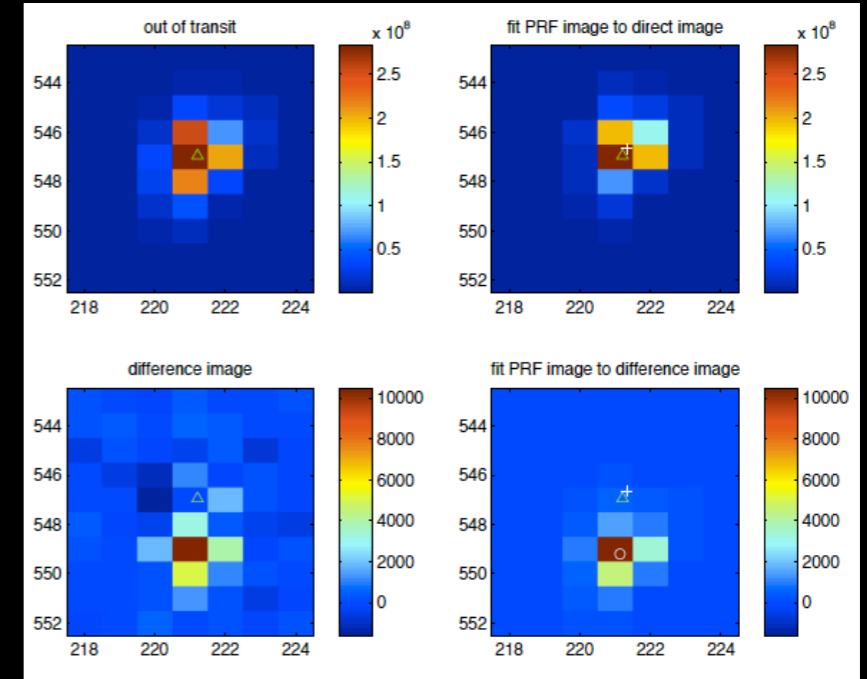


Turn-over at 9.7-sigma implies pipeline incompleteness. This should be greatly improved with PDC-MAP reprocessing.

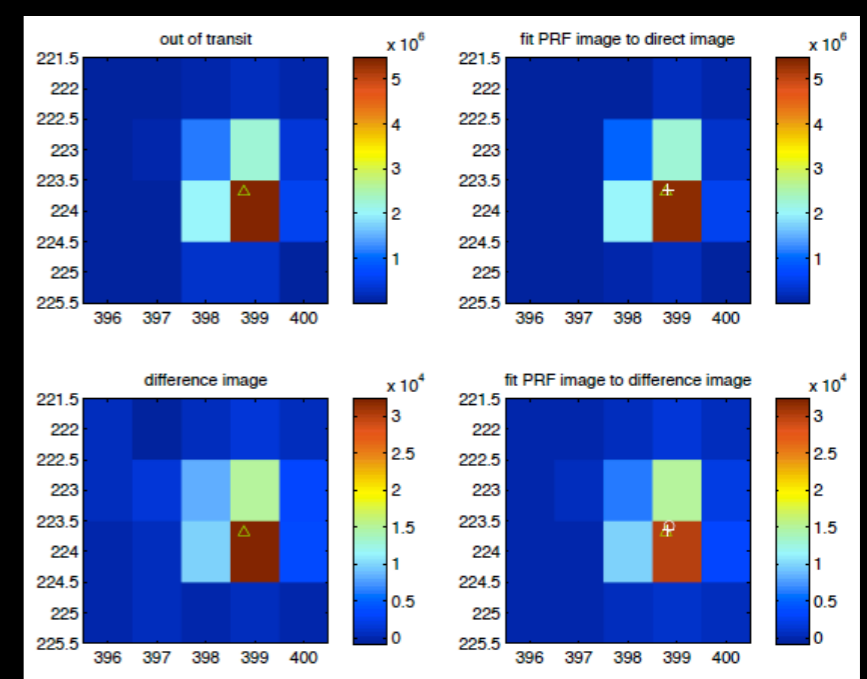
Improved Vetting Statistics

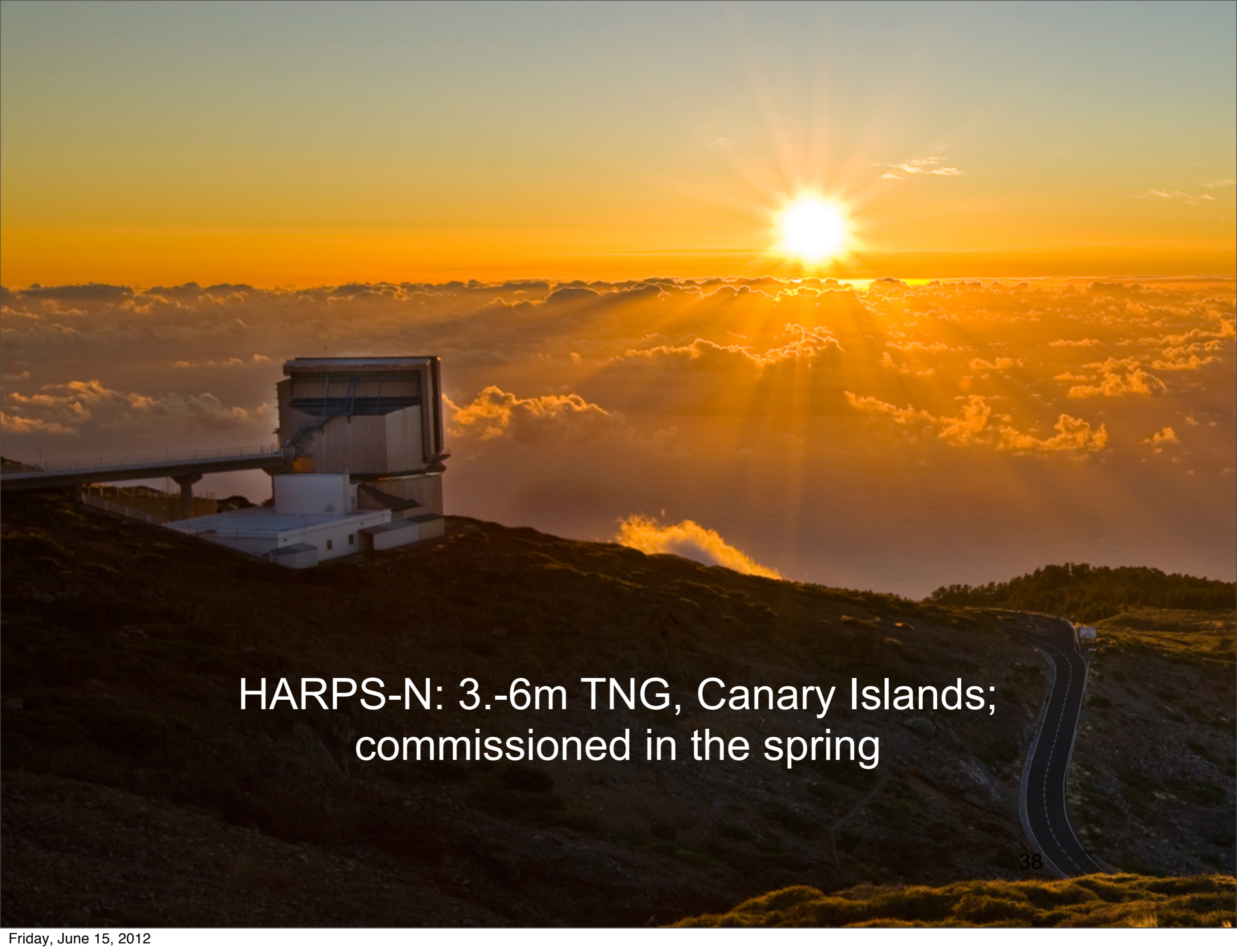


9.1 arcsec source offset



0.2 arcsec source offset





HARPS-N: 3.-6m TNG, Canary Islands;
commissioned in the spring