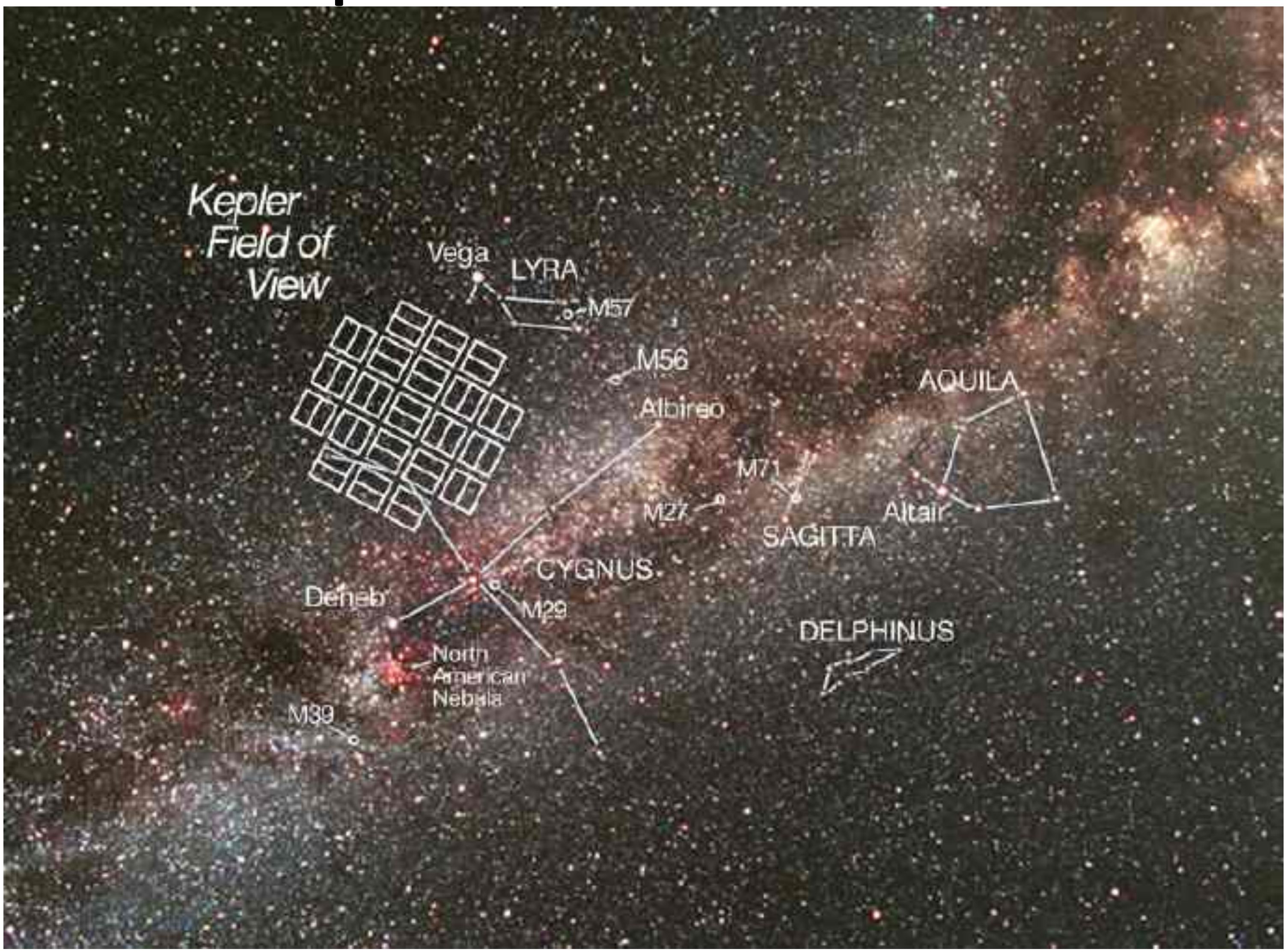
Steve B. Howell
NASA Ames Research Center

Outline

- Stellar Variability a la Kepler
- Vetting (Small) ExoPlanets, Locally
- Other Solar Systems
- Fun, New, Exciting Discoveries

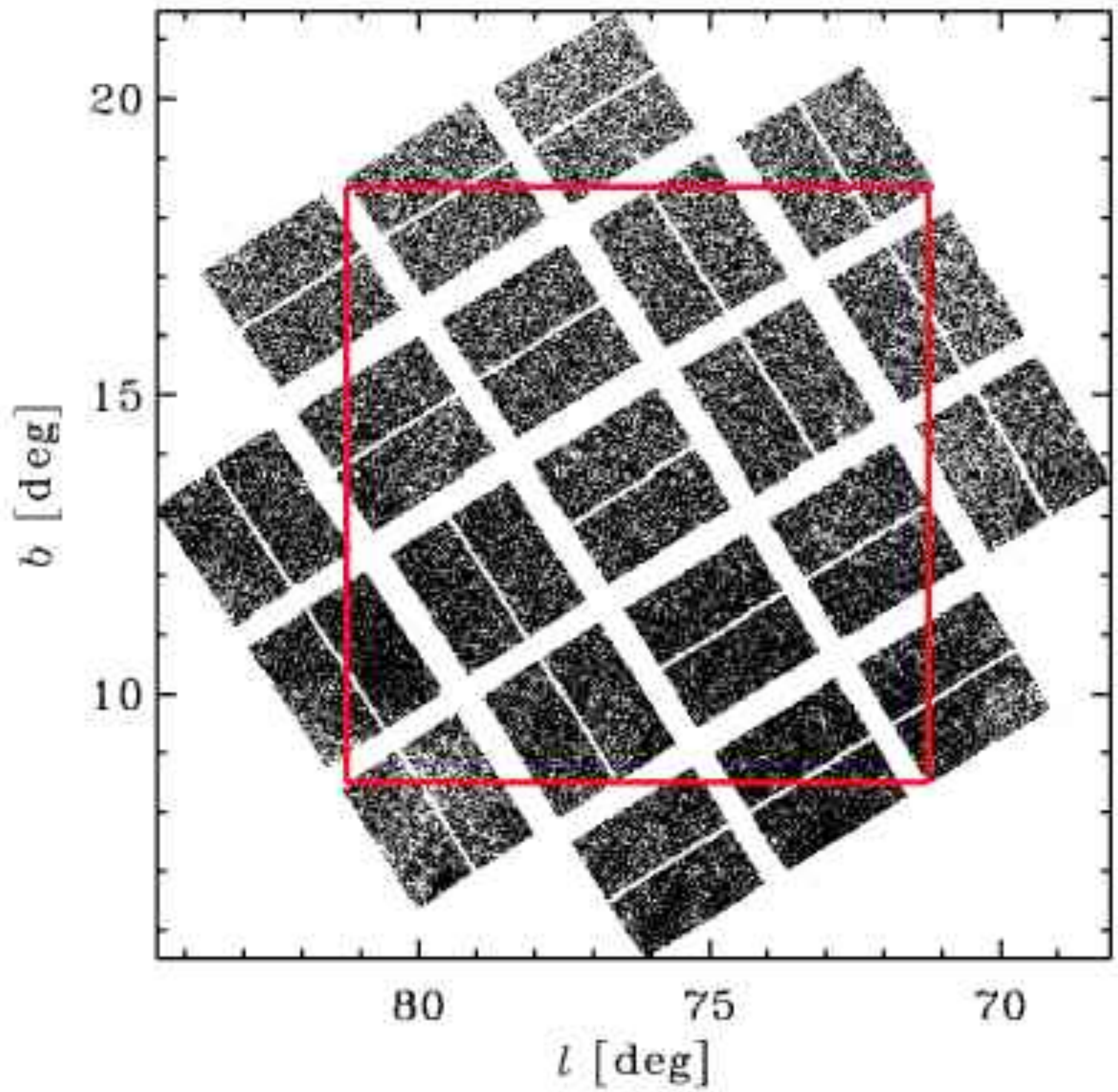
Kepler’s Field of View



Stellar variability

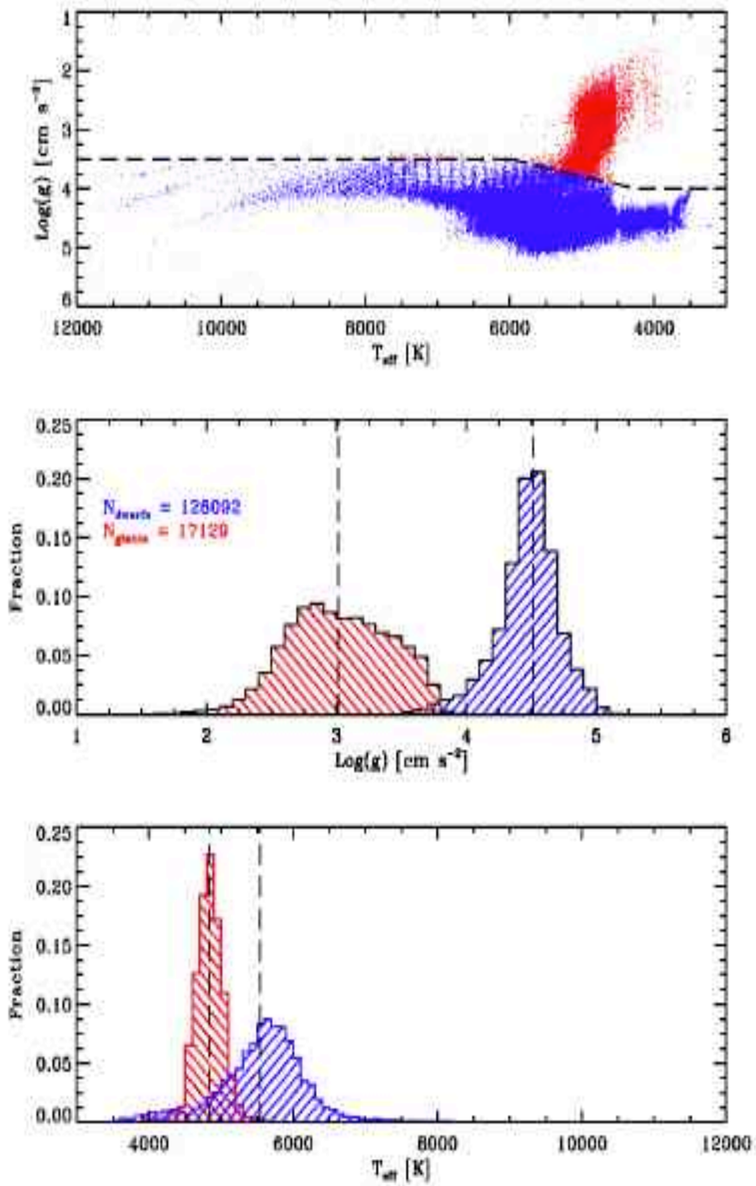
- Take a sample of Kepler stars observed in the first month of operation
- Divide the sample into Dwarfs and Giants
- Examine the underlying variability of the light curves in this data set
- State the findings and discuss what it means for stars
- Ciardi et al. 2011 has details

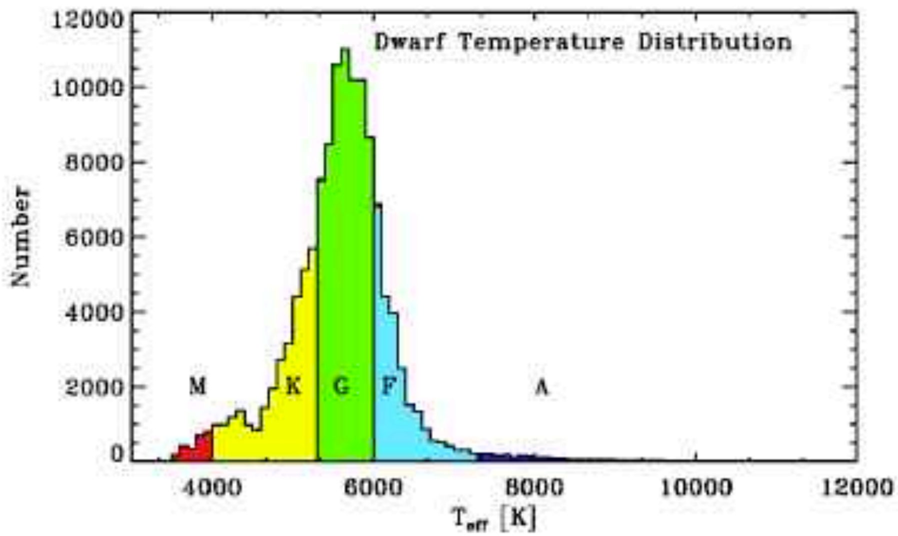
Distribution of sample stars within Kepler FOV

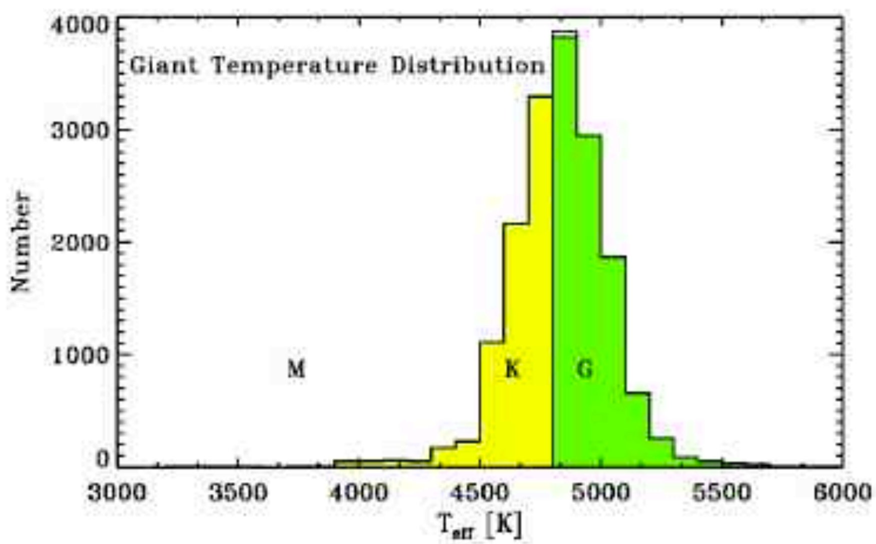


Light curves were 30 minute sampling and 33.5 days long

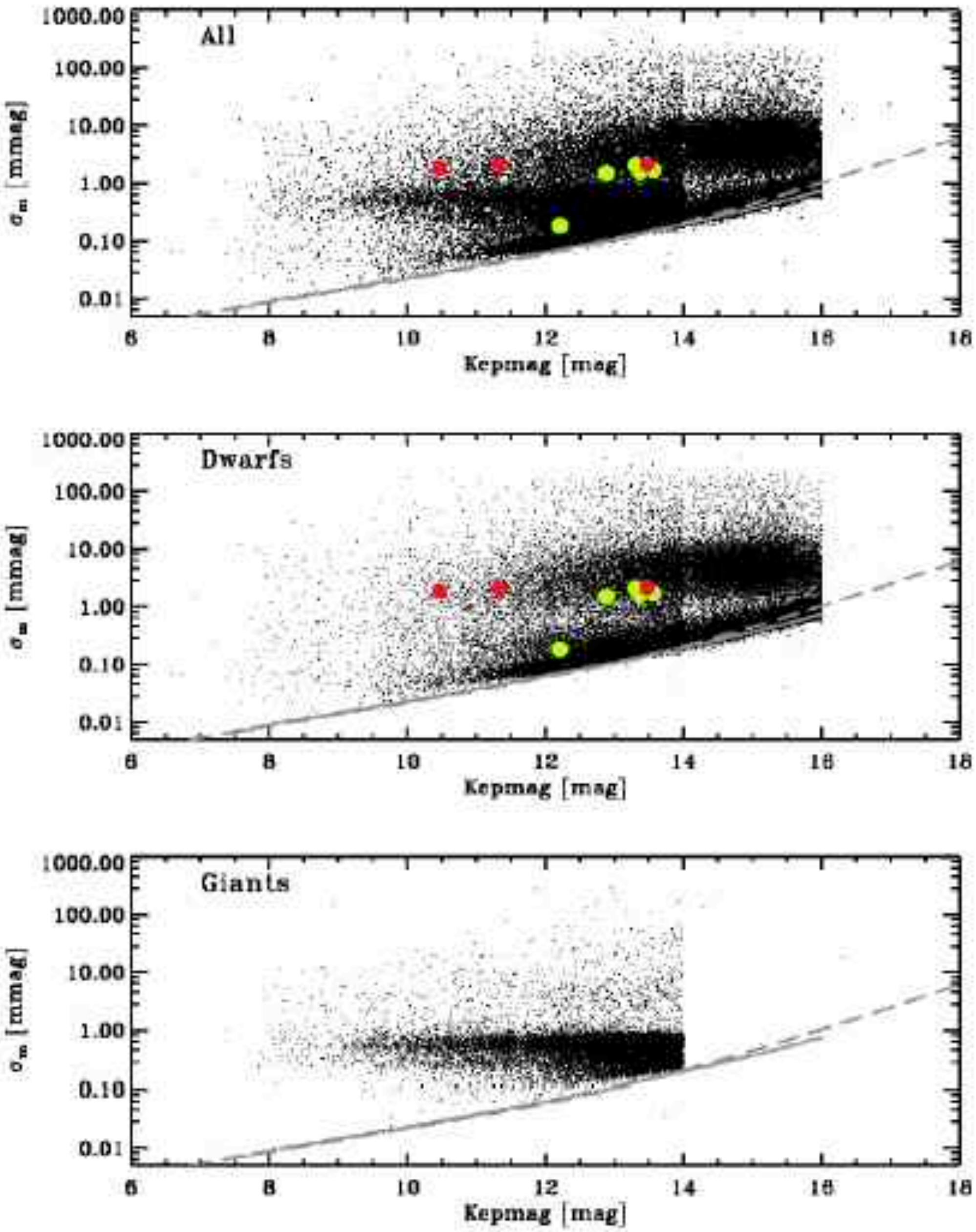
129,000 Dwarfs
17,000 Giants
Separated by KIC photometry used to estimate Teff and log g







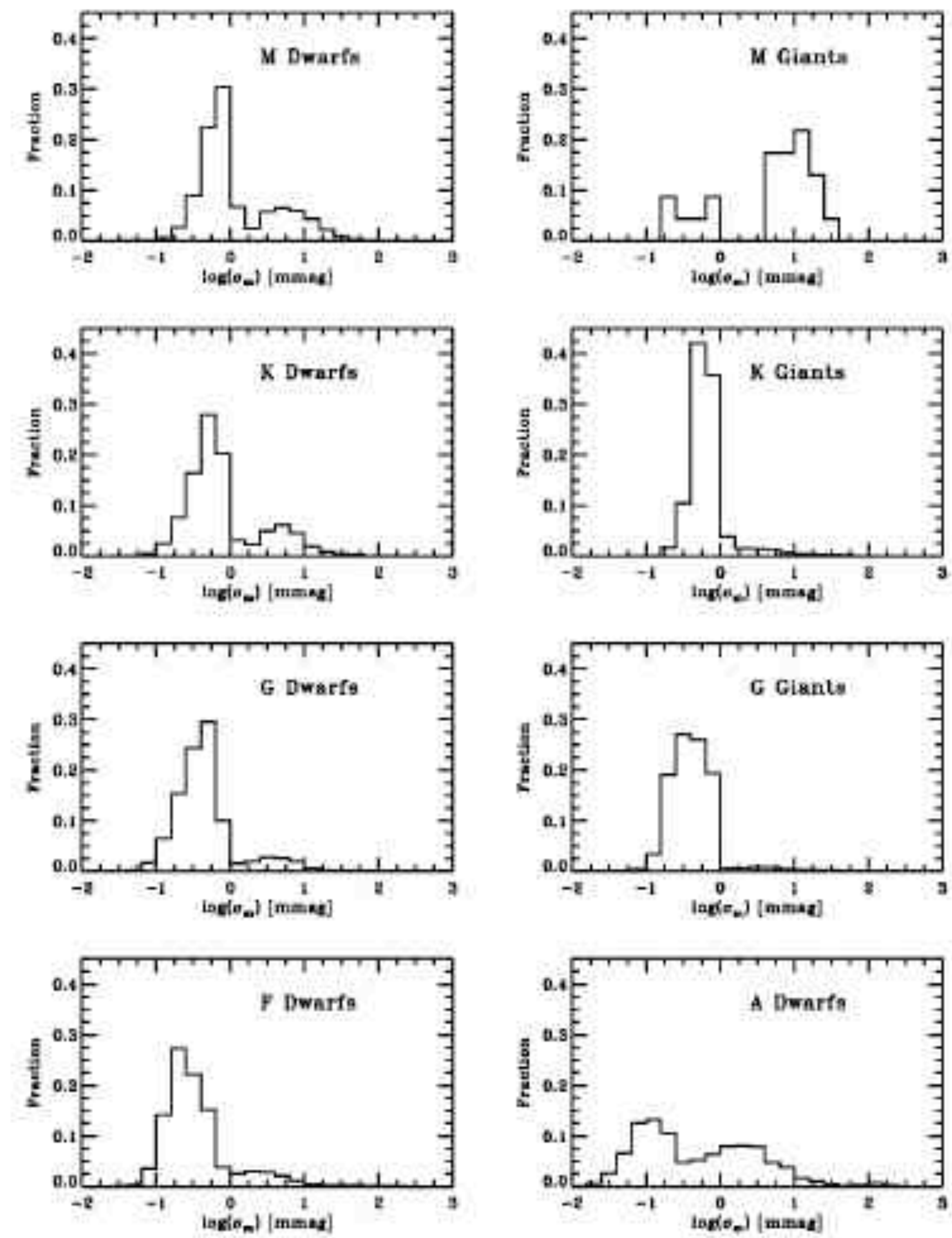
Stars separated by spectral type within each group

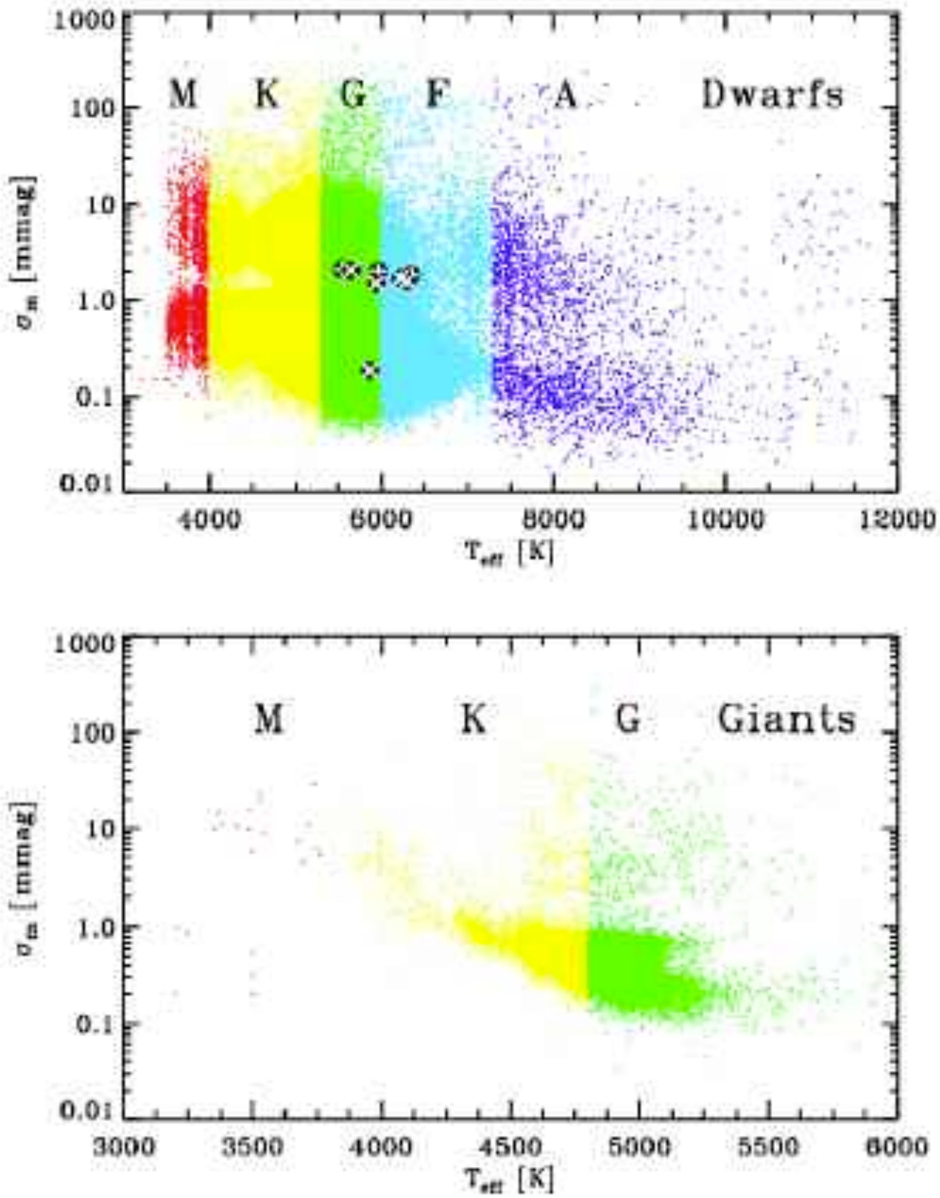


Photometric dispersion vs. Kepler magnitude

Colored dots are exoplanet host stars. The grey lines are two measures of the median uncertainty for the data.

Distribution (Log) of the photometric dispersion separated by Teff, log g





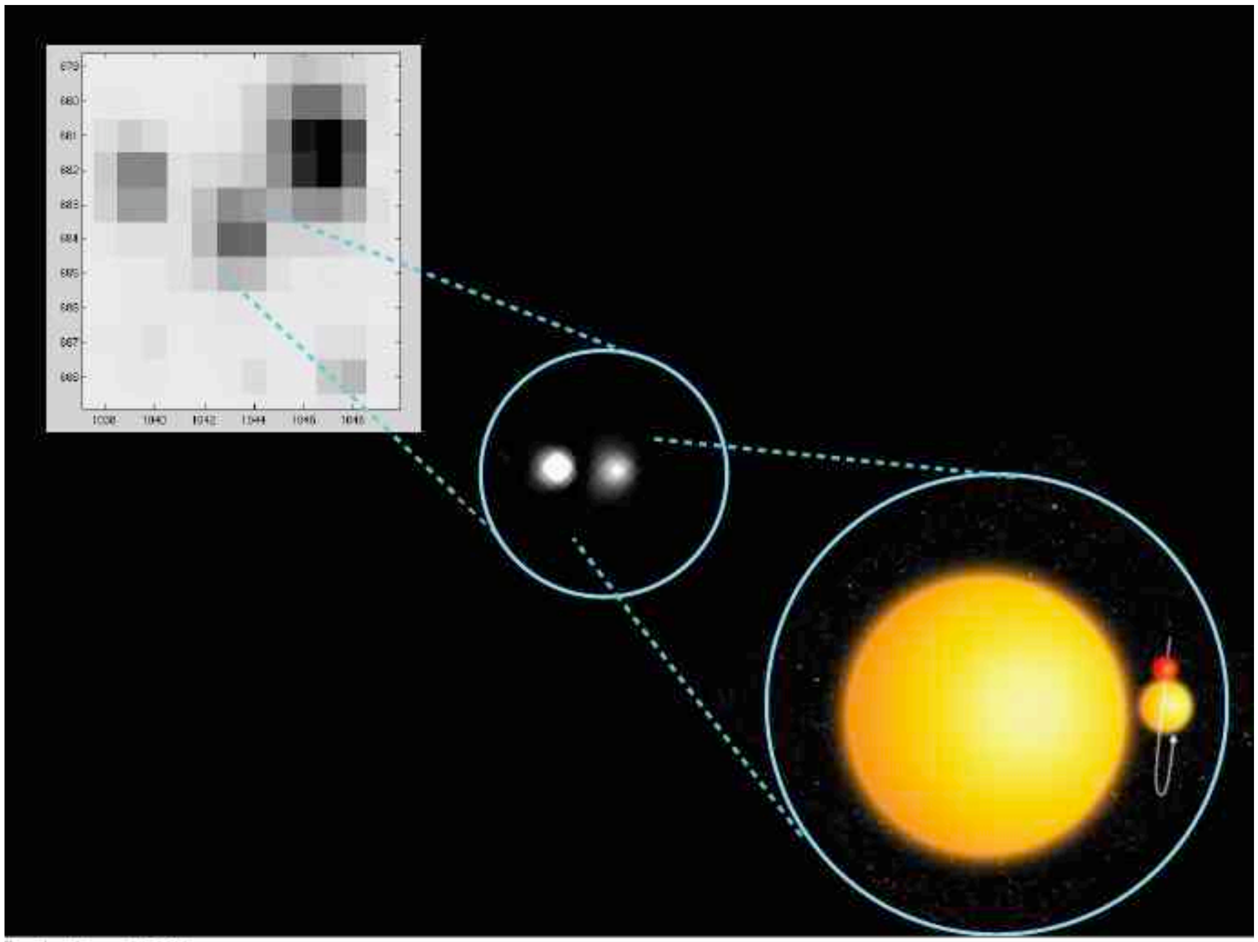
Photometric dispersion for dwarfs, giants separated by Teff.
Known exoplanets marked on top

Stellar Sample Results

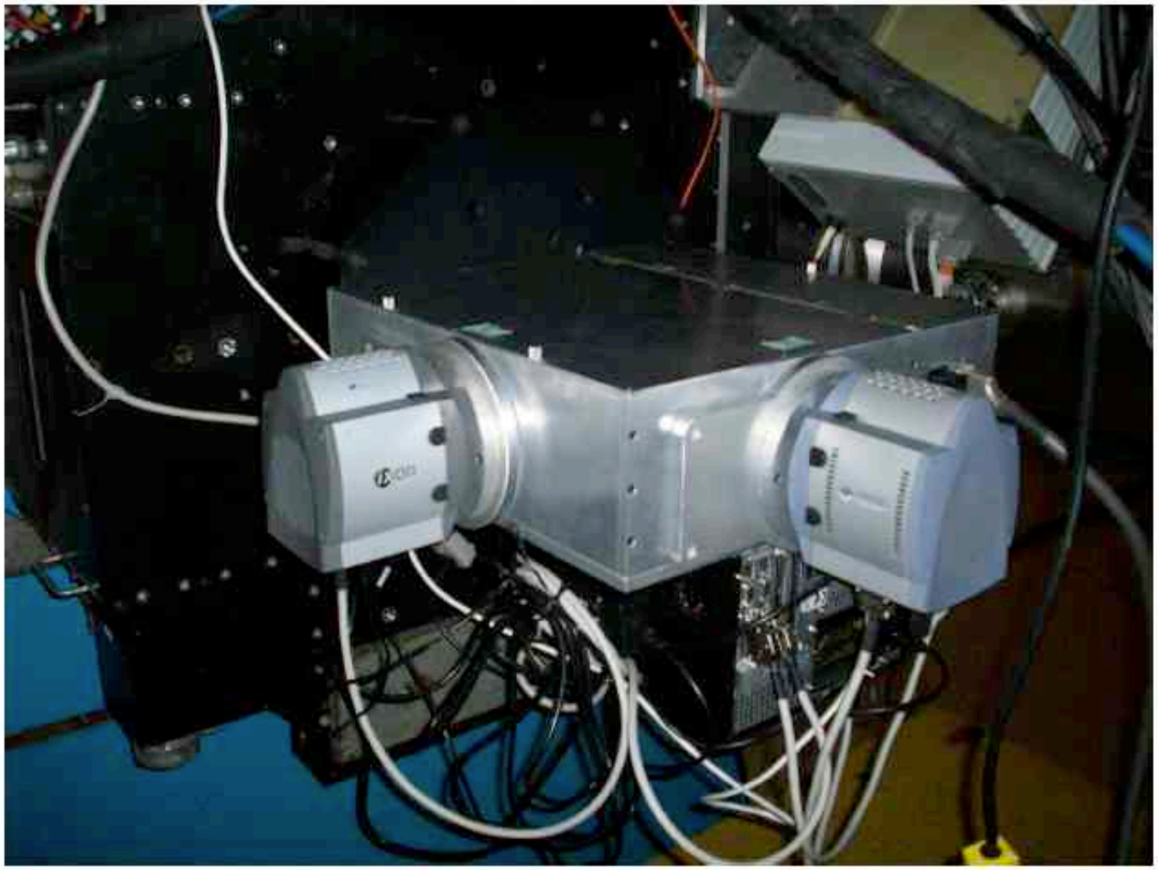
- Using ~140,000 30-min sampled, 33 day long Kepler light curves, we find,
  - 25% of all dwarfs are variable, 100% for the bright stars
  - G dwarfs are the most stable, floor <=0.04mmag
  - All giants are variable
    - (floor ~0.1, 0.3, 10 mmag for G,K,M)
  - Variability fraction increases from 1 day to 33 days
  - Stars closer to galactic plane are more variable
    - May be real (age?) or higher background

Hi-Res Observations

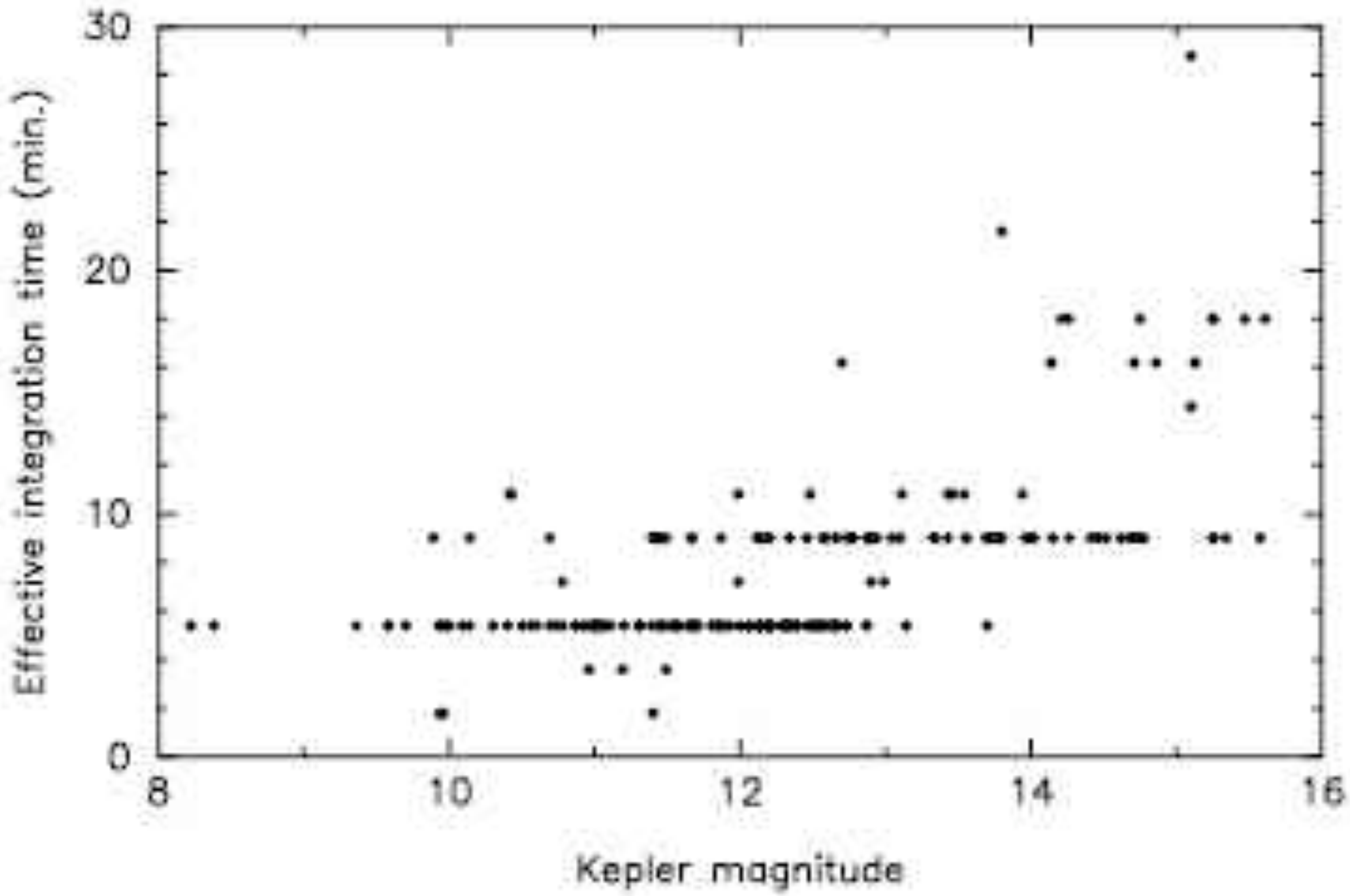
- Kepler exoplanet candidate stars are followed up by ground-based observations
- High resolution imaging is key
- Speckle observations performed at WIYN telescope
- Use duel channel EMCCD camera


679
680
681
682
683
684
685
686
687
688
1038
1040
1042
1044
1046
1048

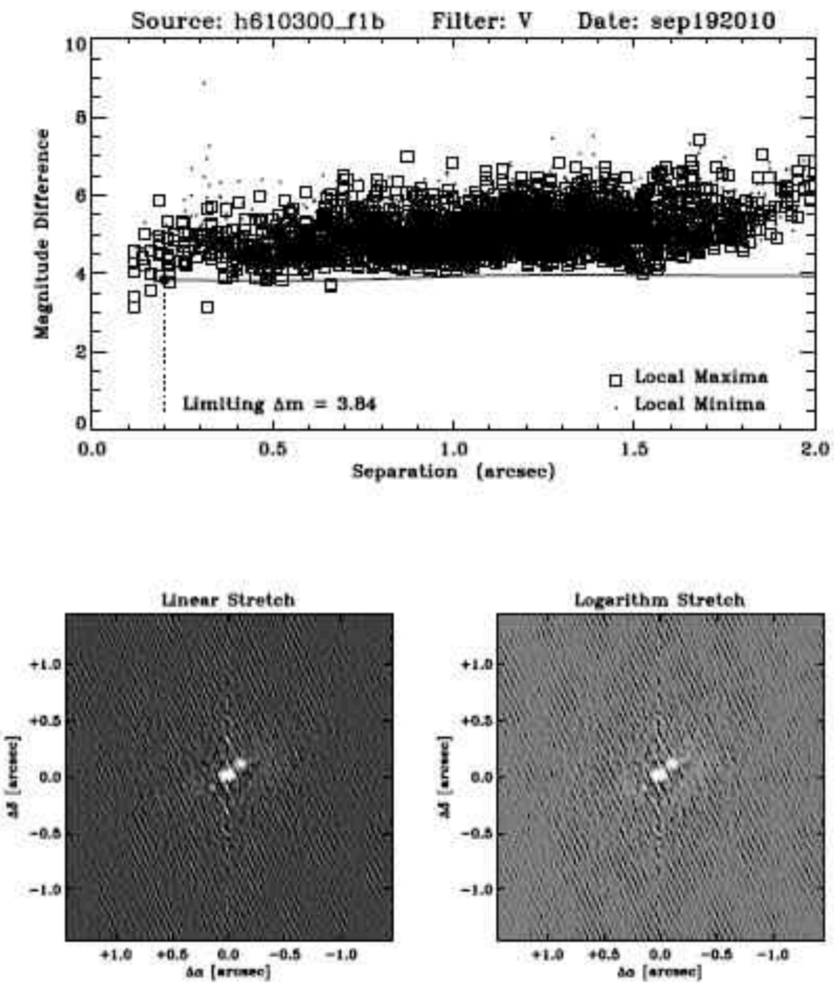
Duel Channel Speckle Camera at WIYN Telescope



Effective Int. Time for Speckle



Reconstructed Speckle Image



Delta Mag for Speckle Observations

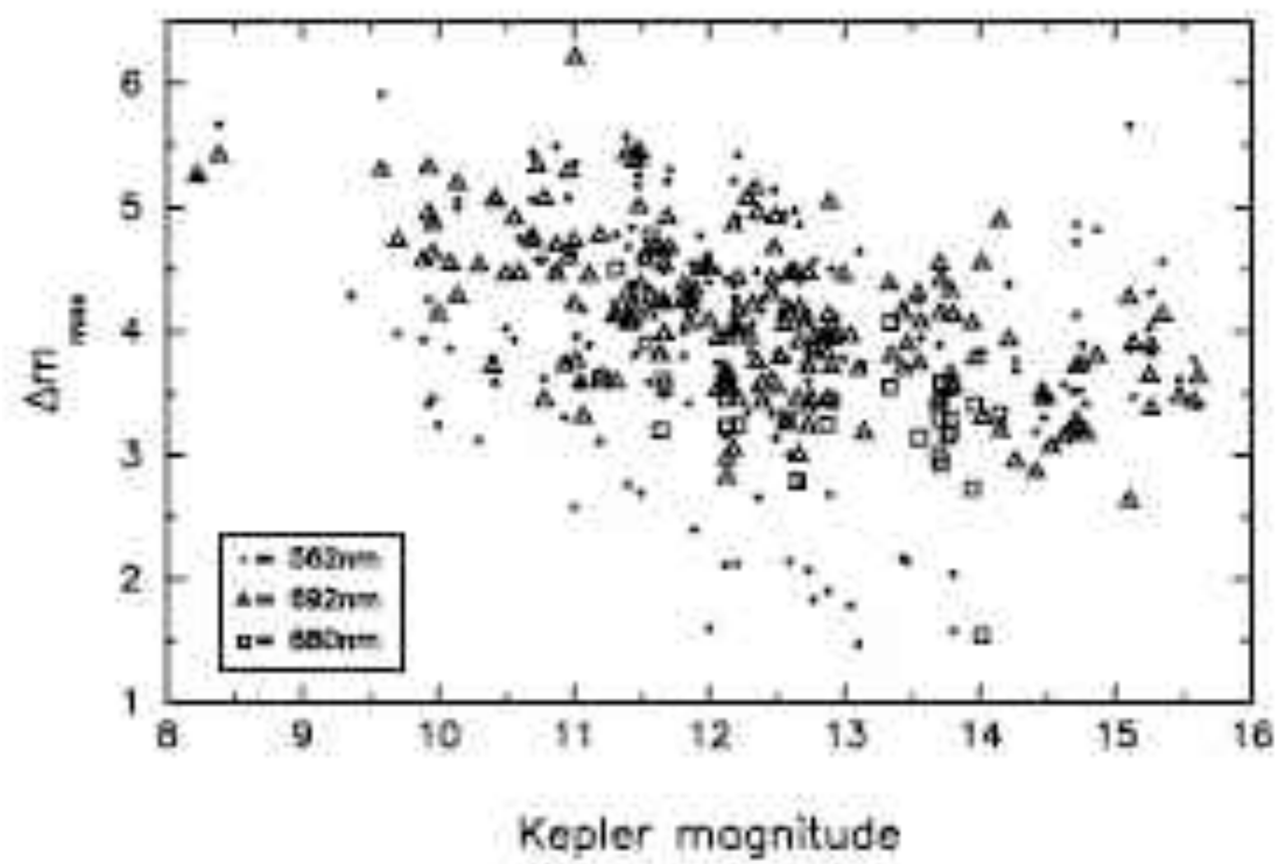
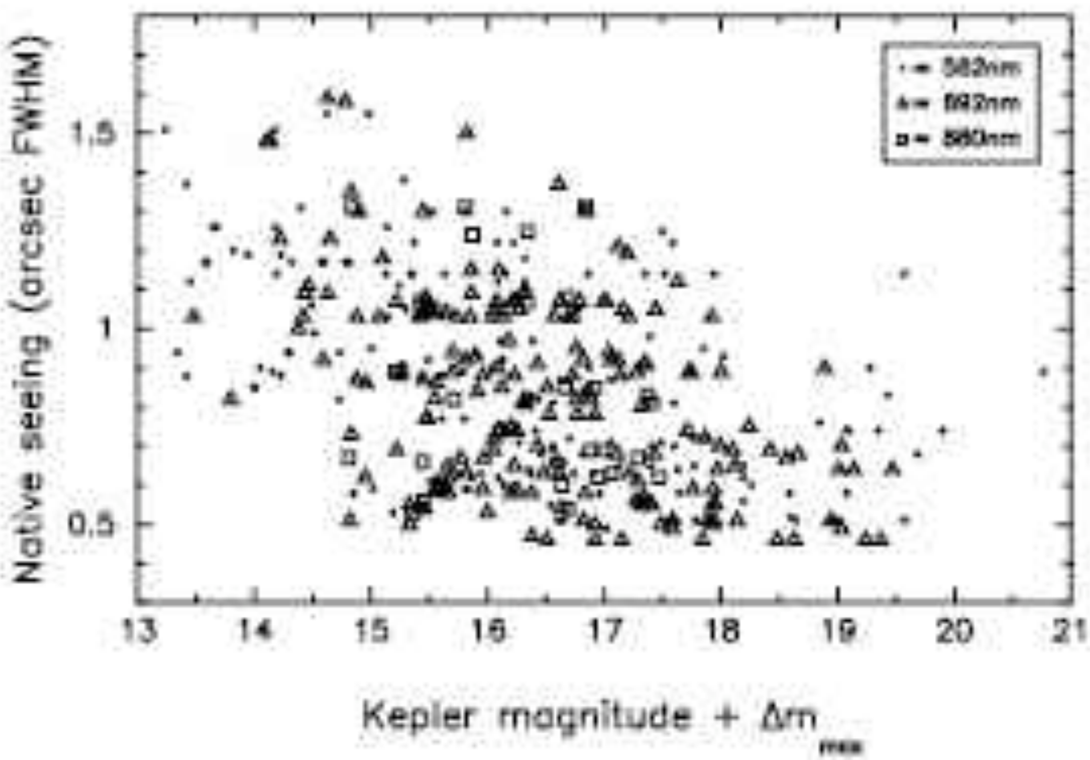
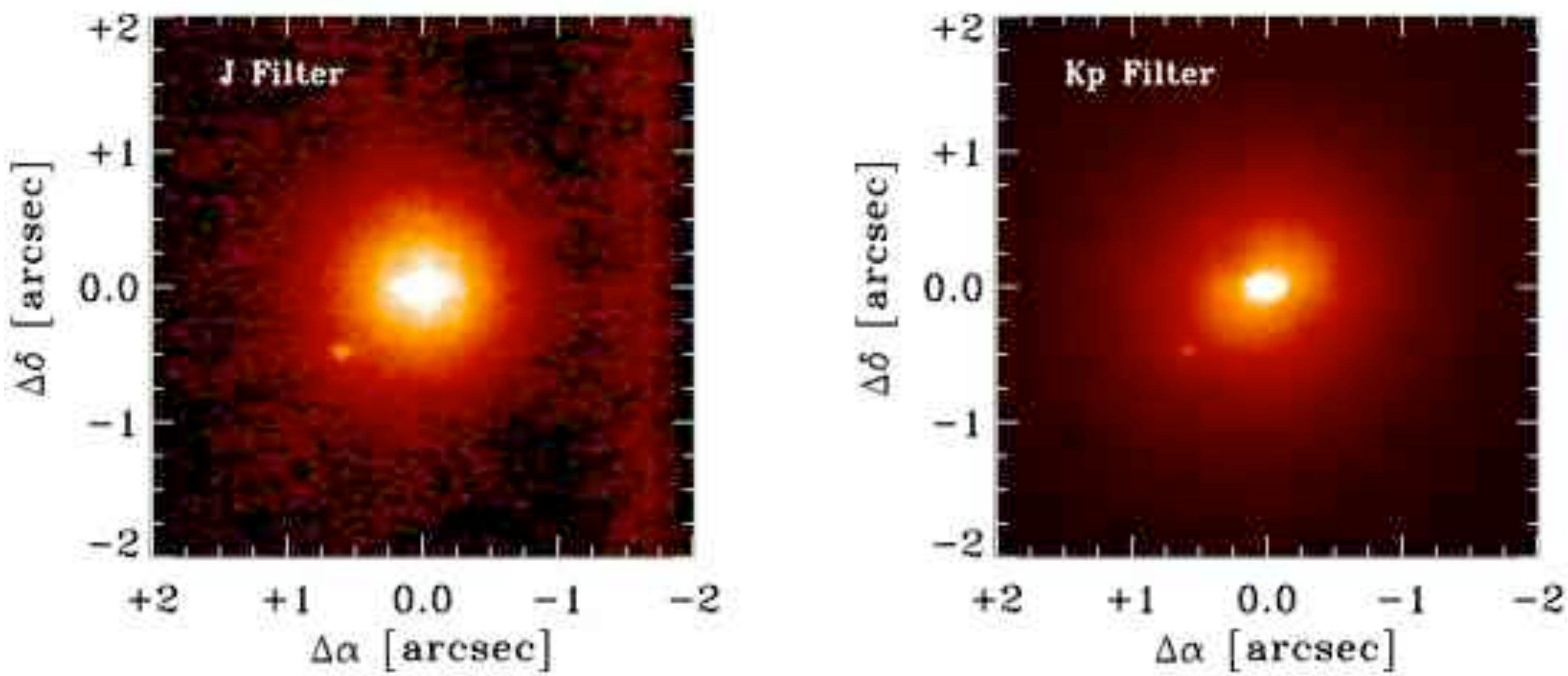
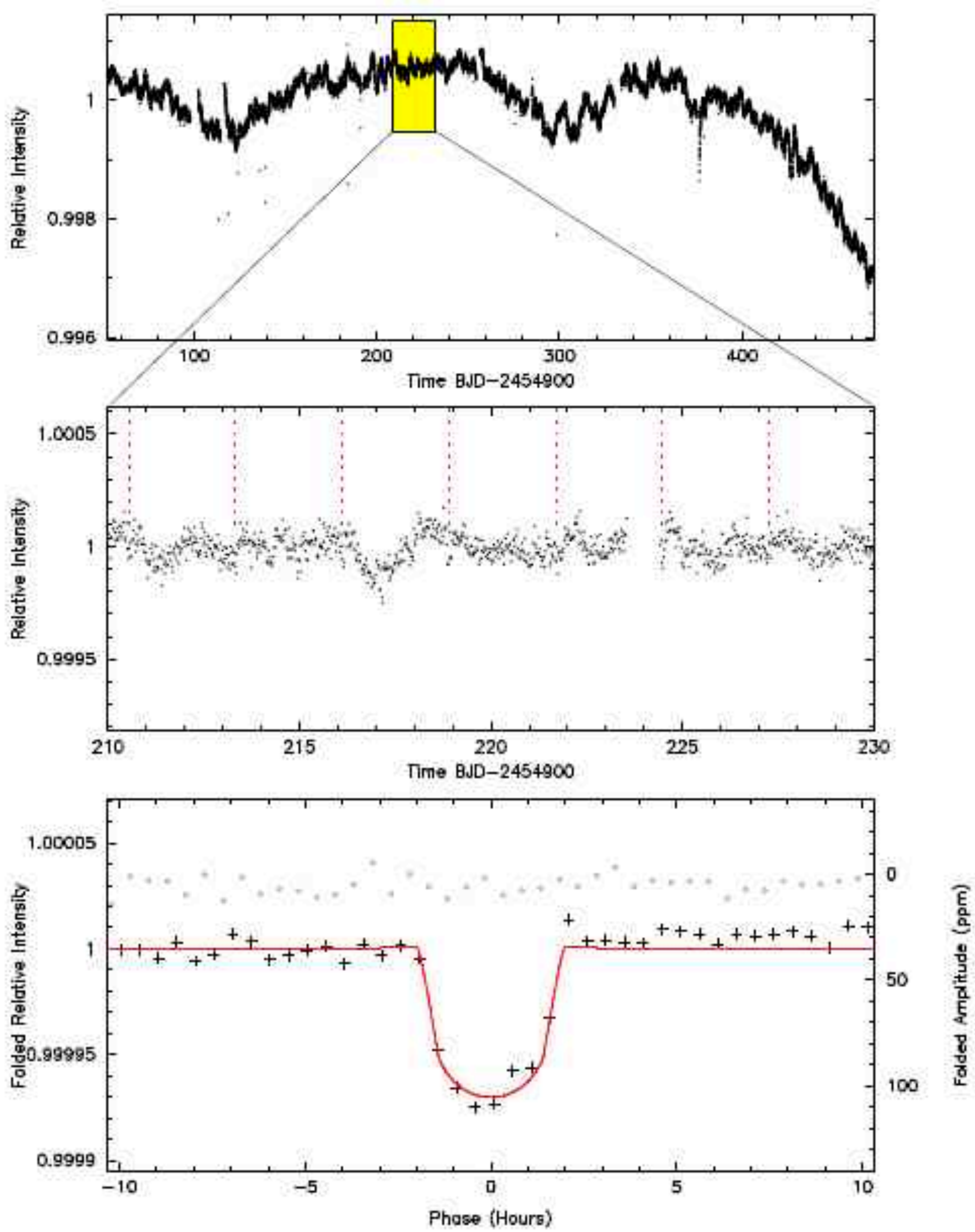


Plate limit for Speckle Observations



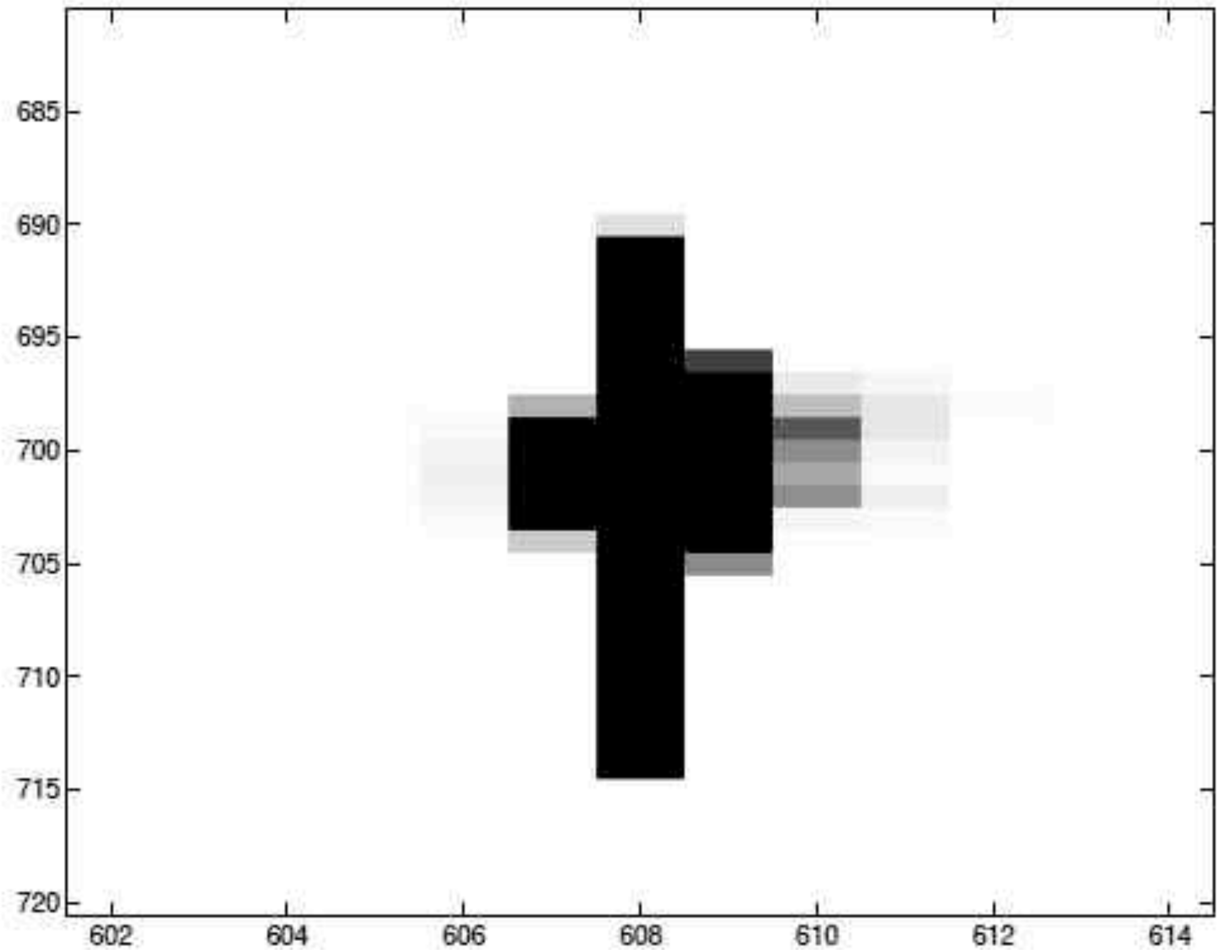
Keck AO – J, K bands



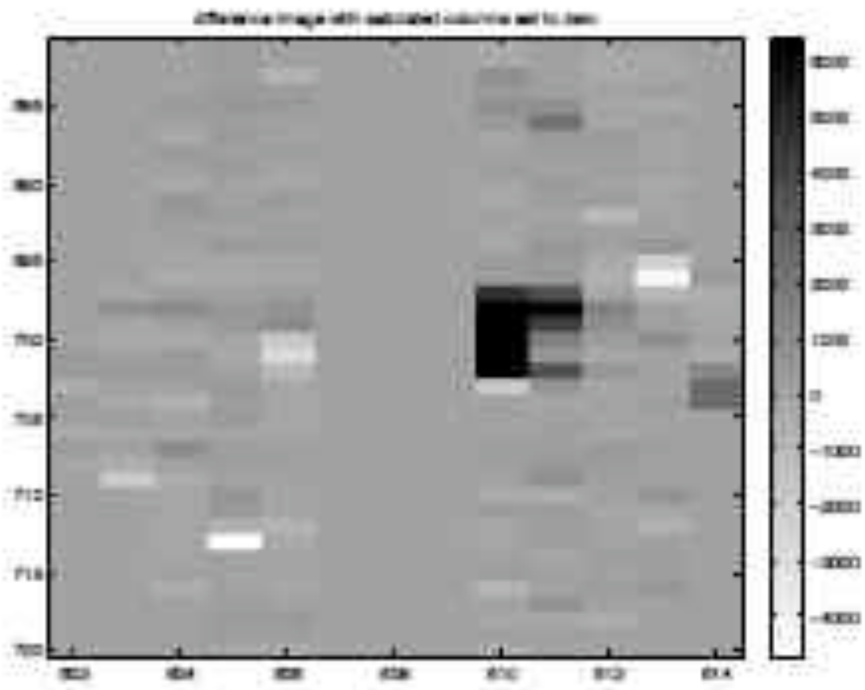


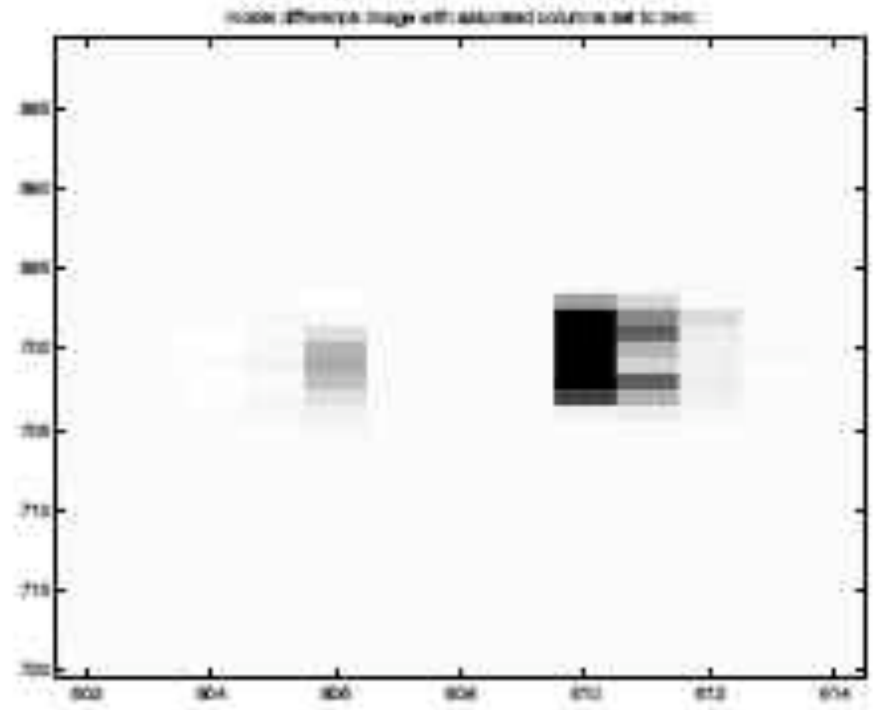
F6IV star with 1.6Re candidate. (top)Raw light curve, (middle)zoom, (bottom) phased transit

Kepler Saturated Image

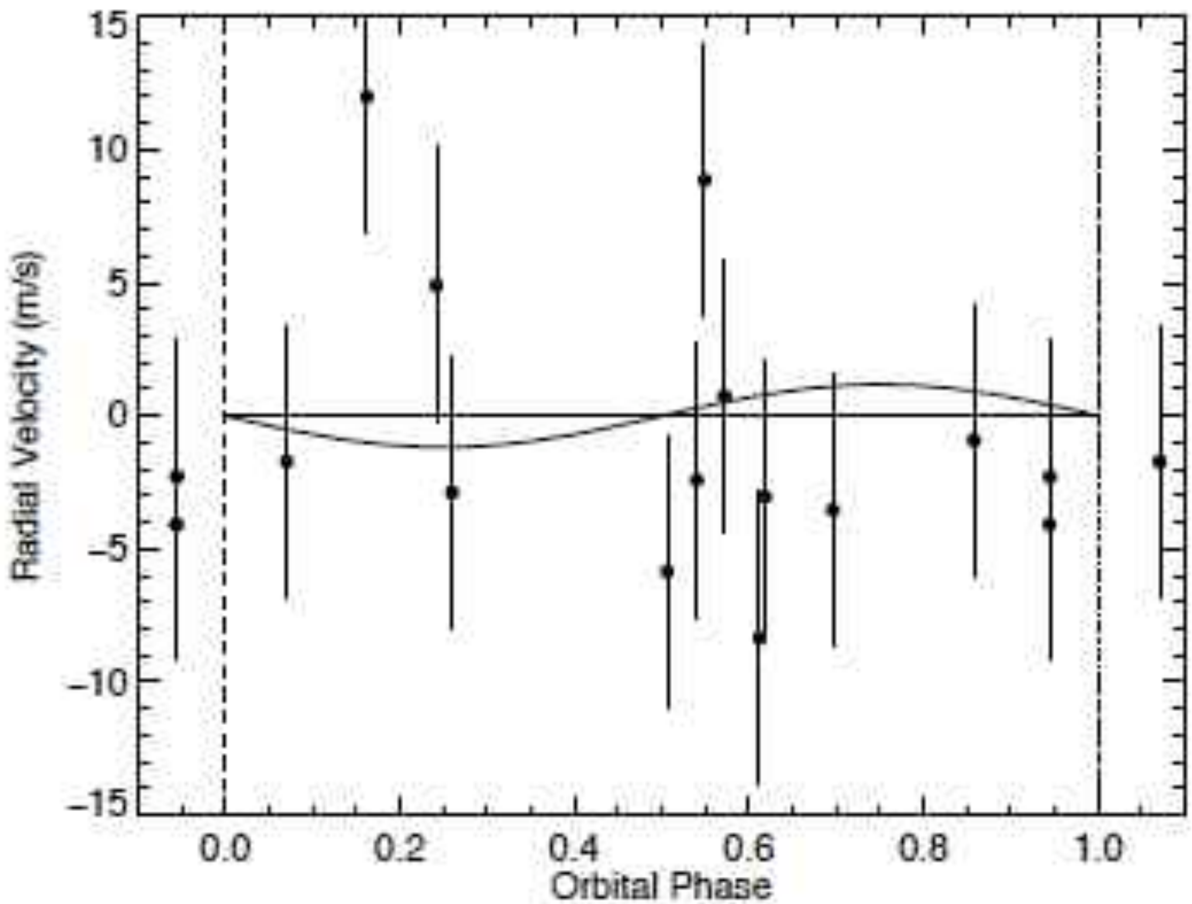


Kepler Difference image – Real, Model

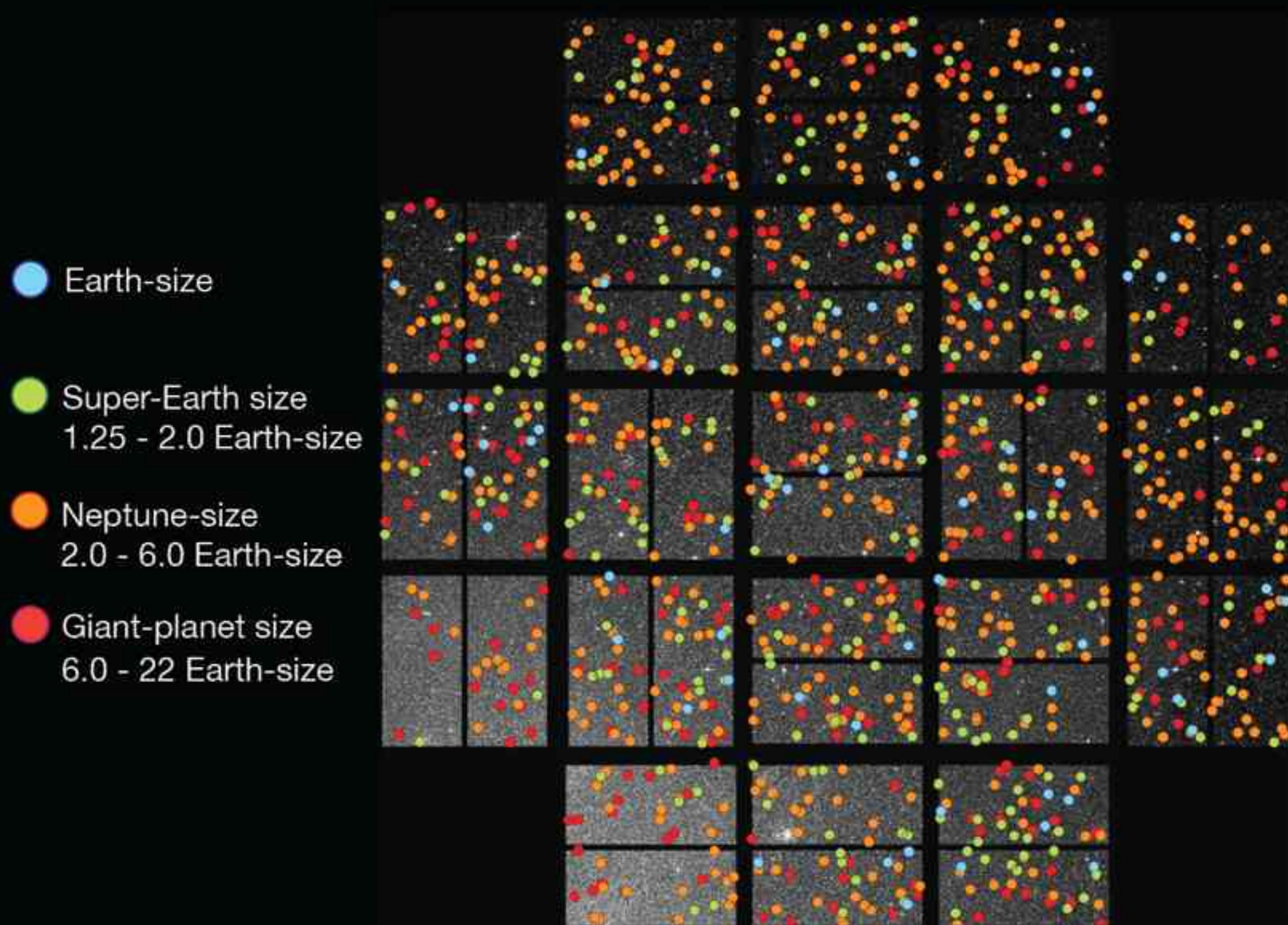




Keck Hi-Res velocities – not even close

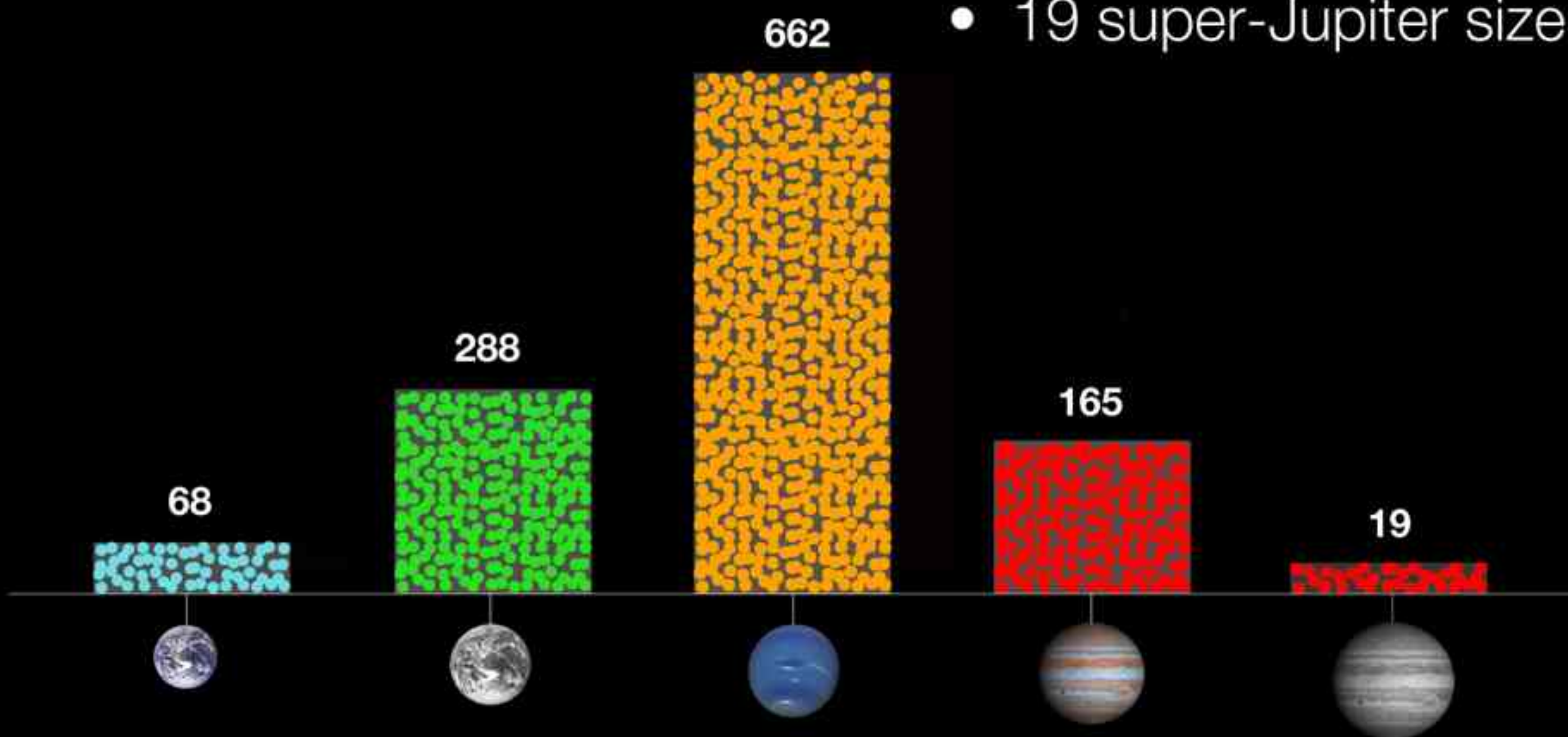


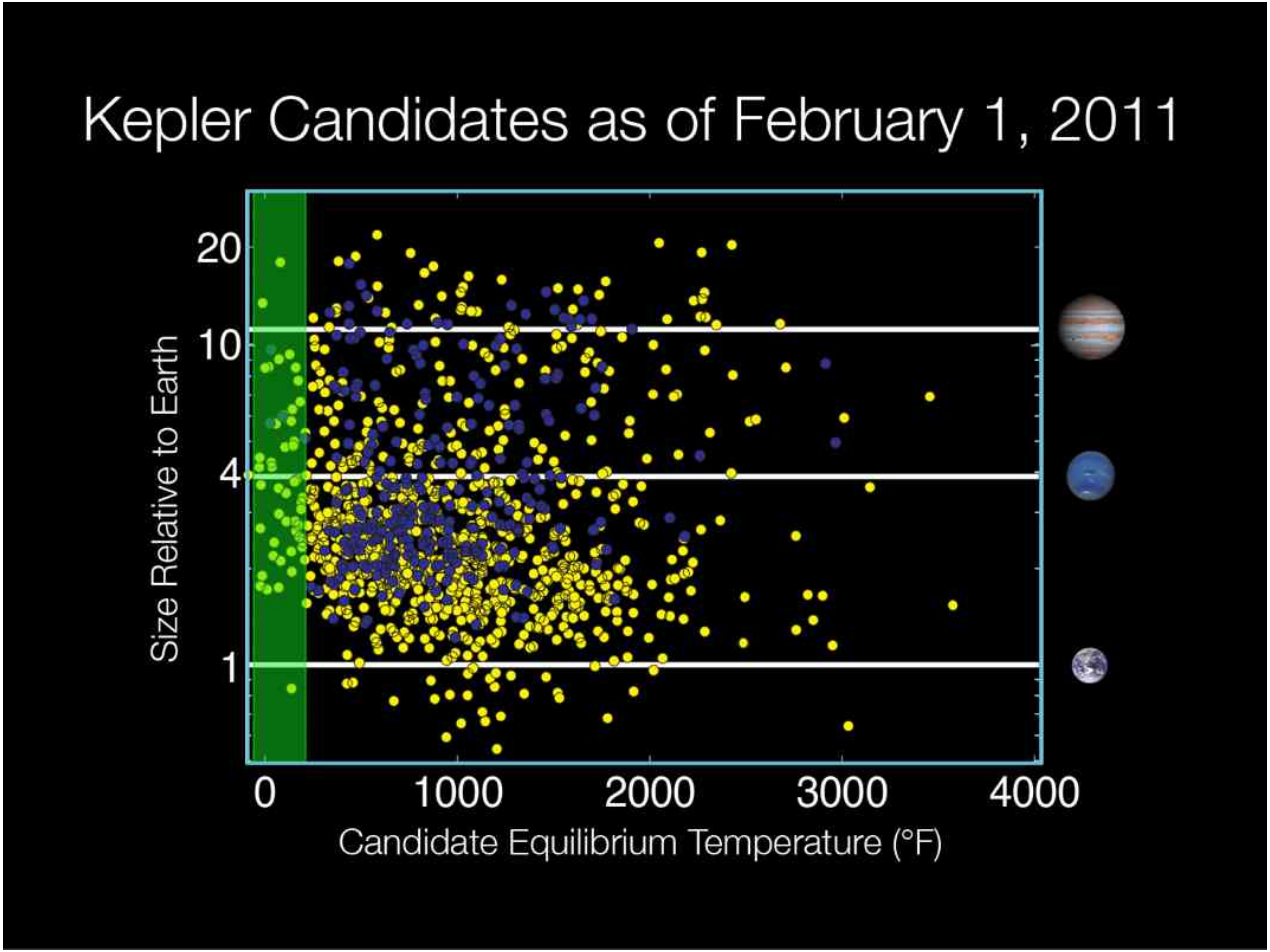
Locations of Kepler Planet Candidates



Numbers of Planet Candidates

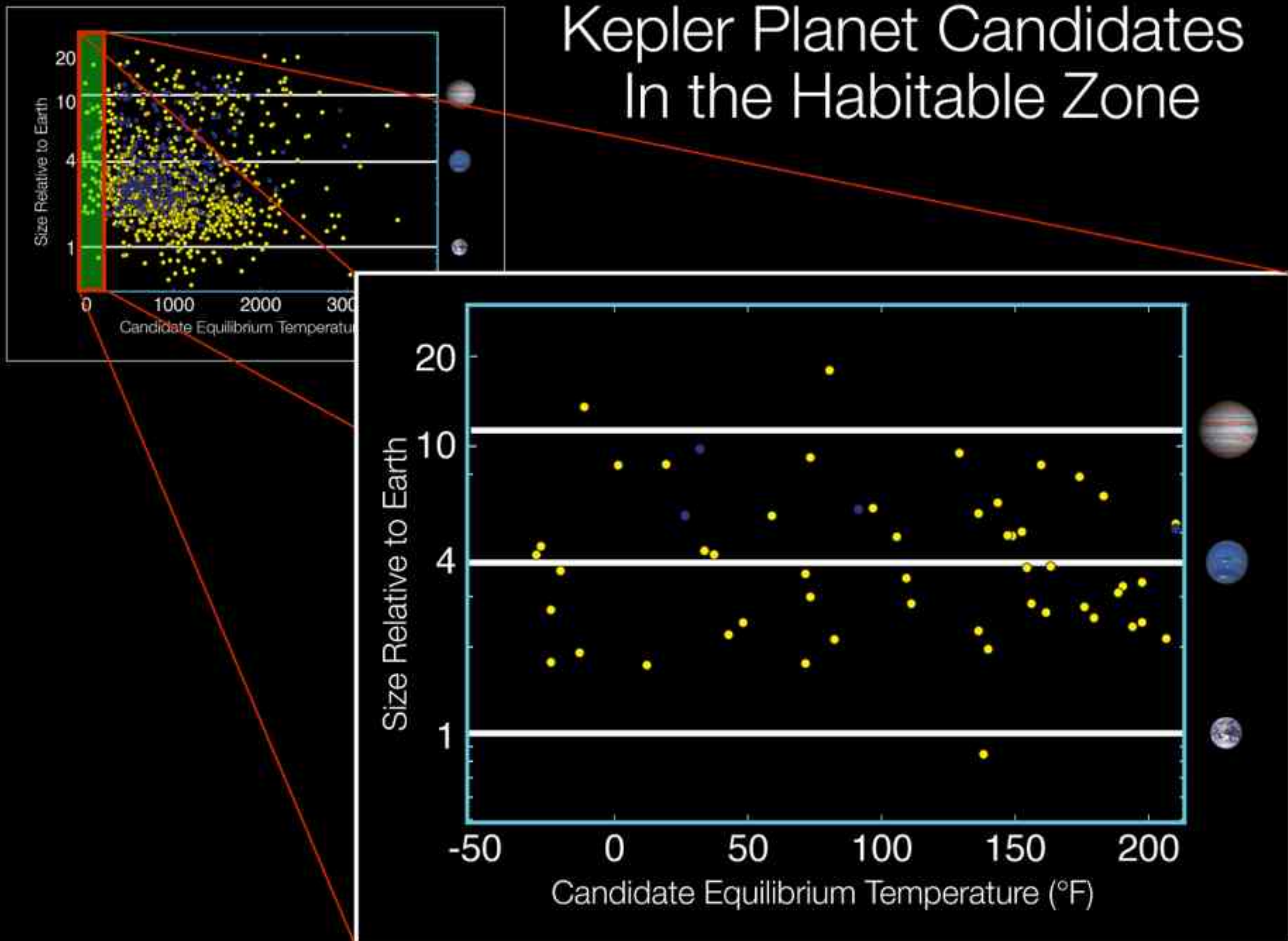
- 68 Earth-size
- 288 super-Earth size
- 662 Neptune size
- 165 Jupiter size
- 19 super-Jupiter size



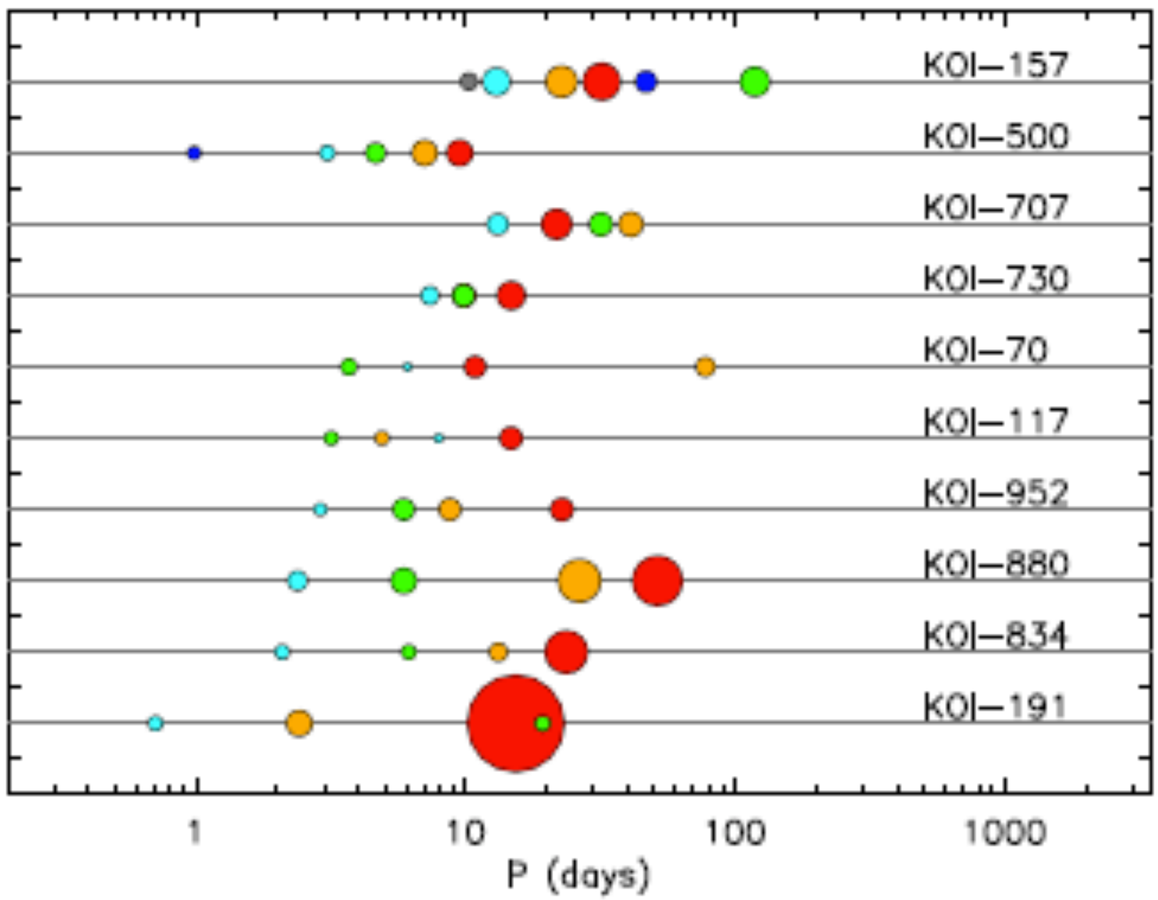


Kepler Candidates as of February 1, 2011
Size Relative to Earth
20
10
4
1
0
1000
2000
3000
4000
Candidate Equilibrium Temperature (°F)

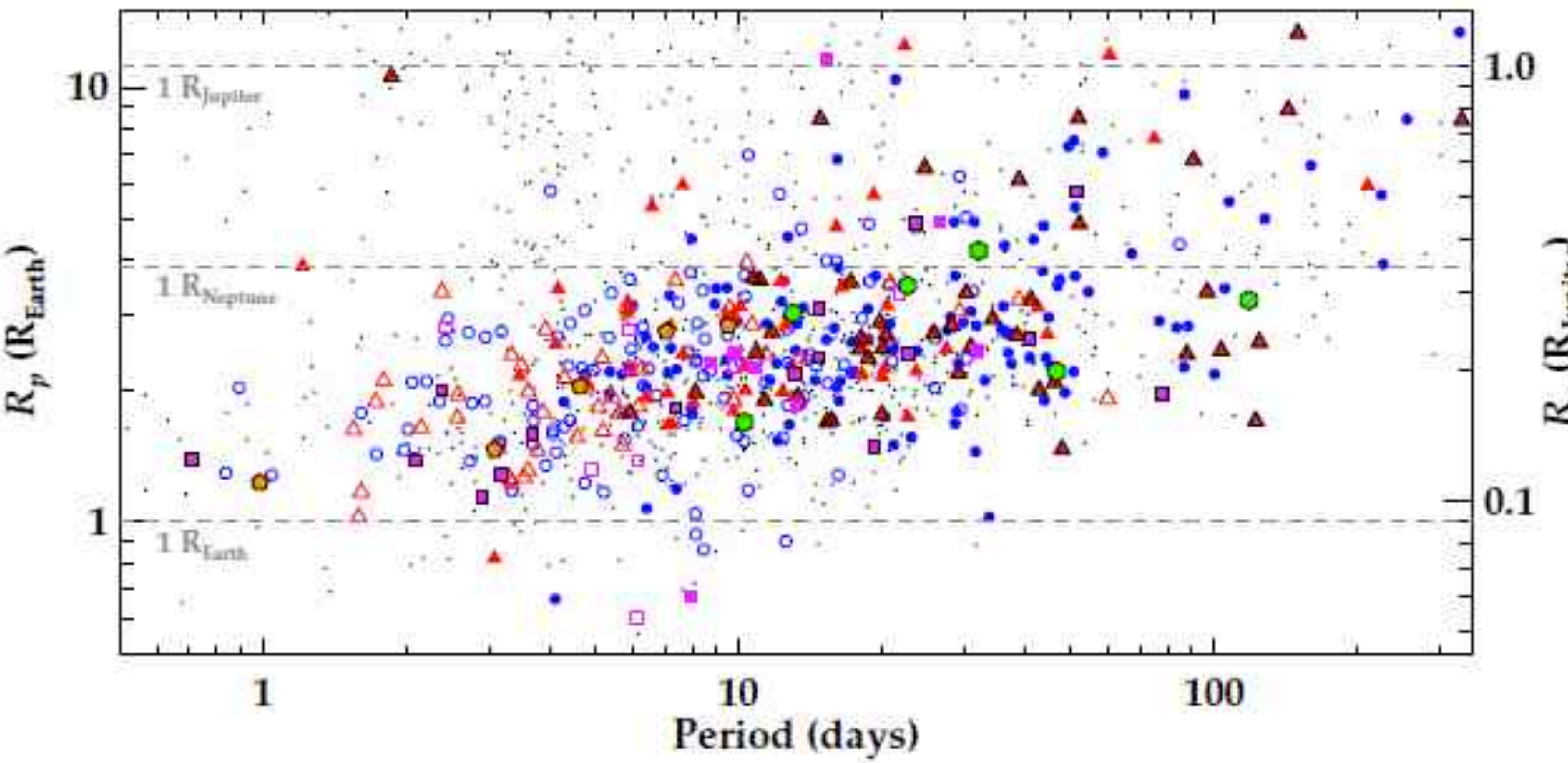
Kepler Planet Candidates In the Habitable Zone

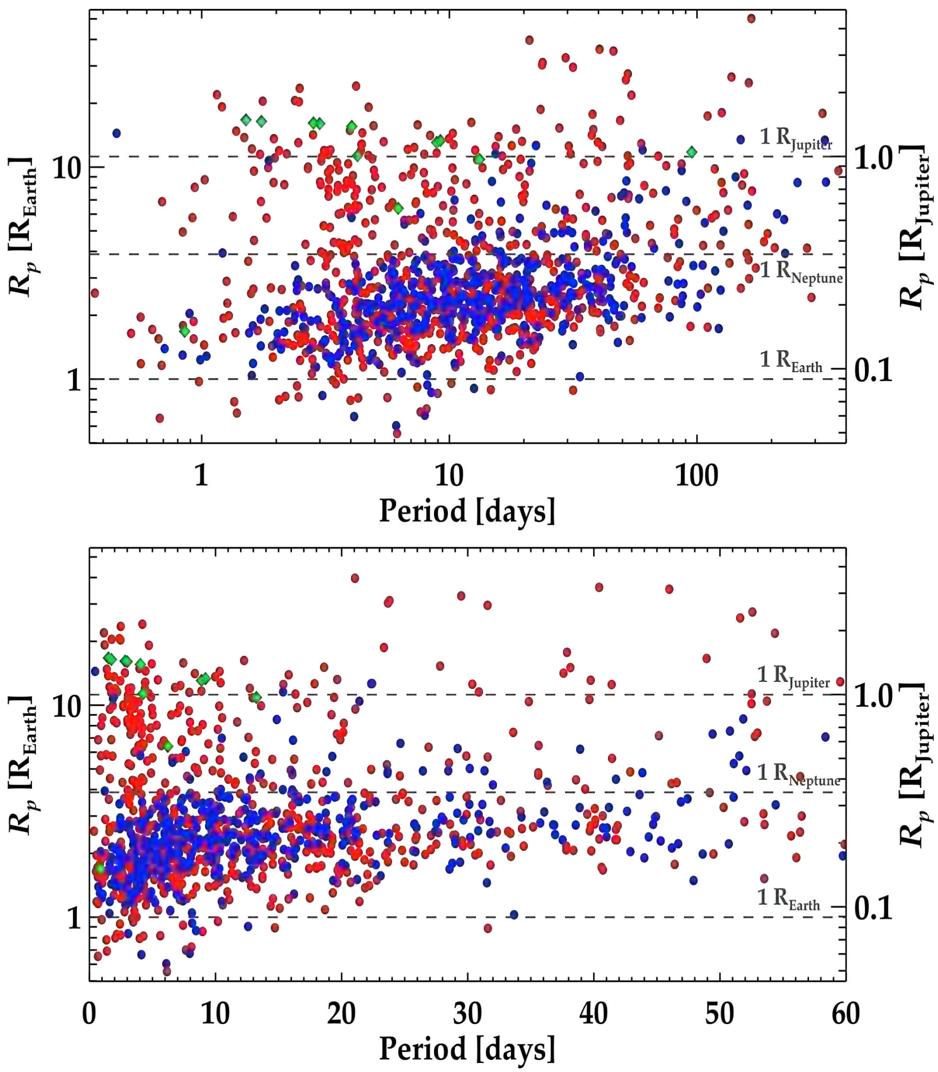


Multiple Planet Systems



Multi’s by Period and Radius





Kepler finds very few giant planets in systems of multiple planets

Top log scale

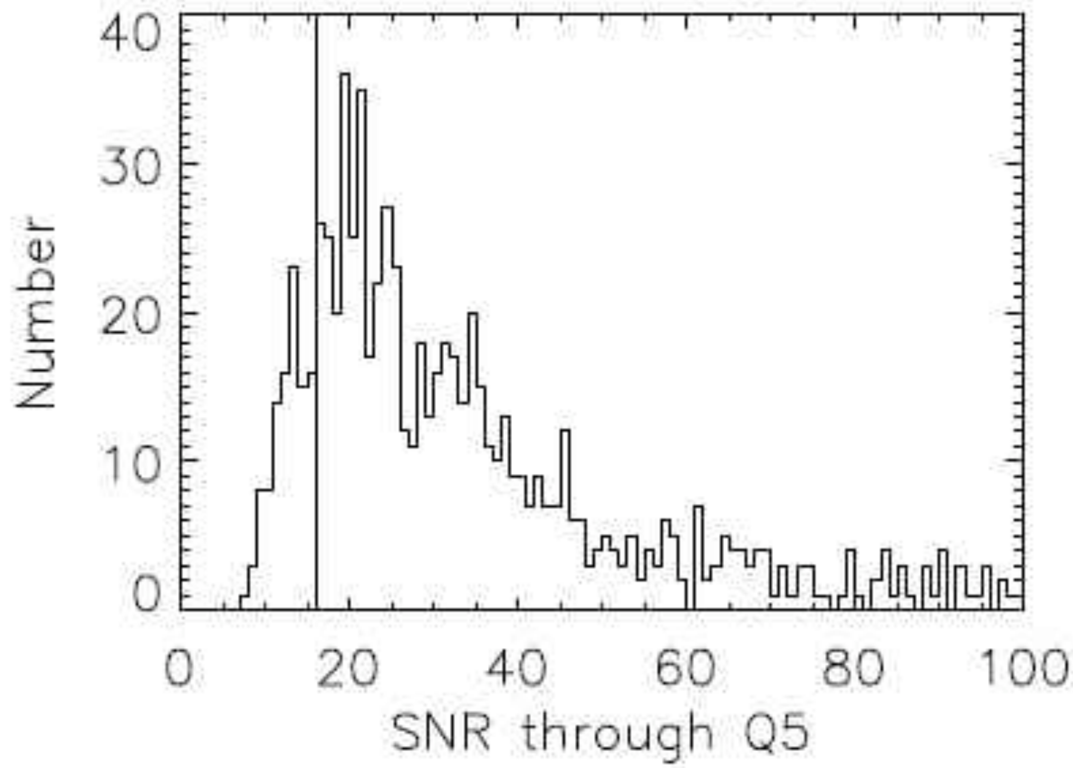
Bottom linear scale

Single planets = red

Multiples = blue

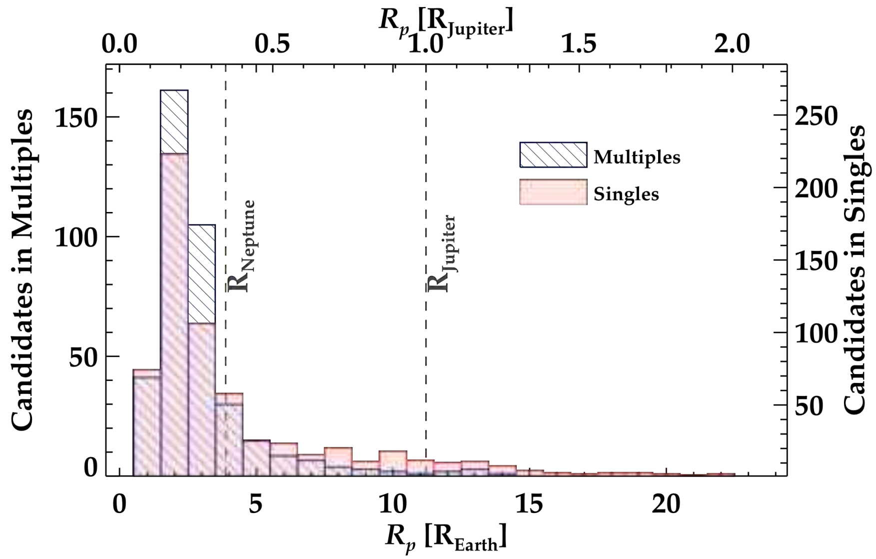
CoRoT = green

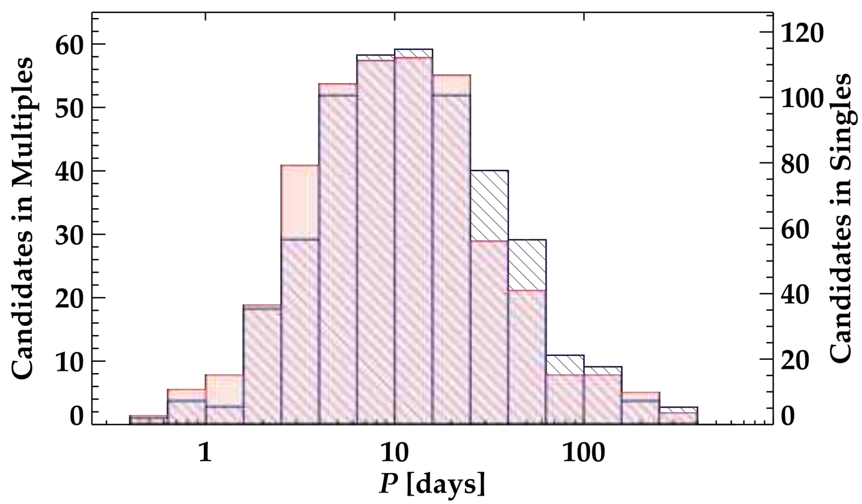
Lots of Small Planets



Smallest planets still missed due to few low S/N transit events

Comparison by Single or Multiple

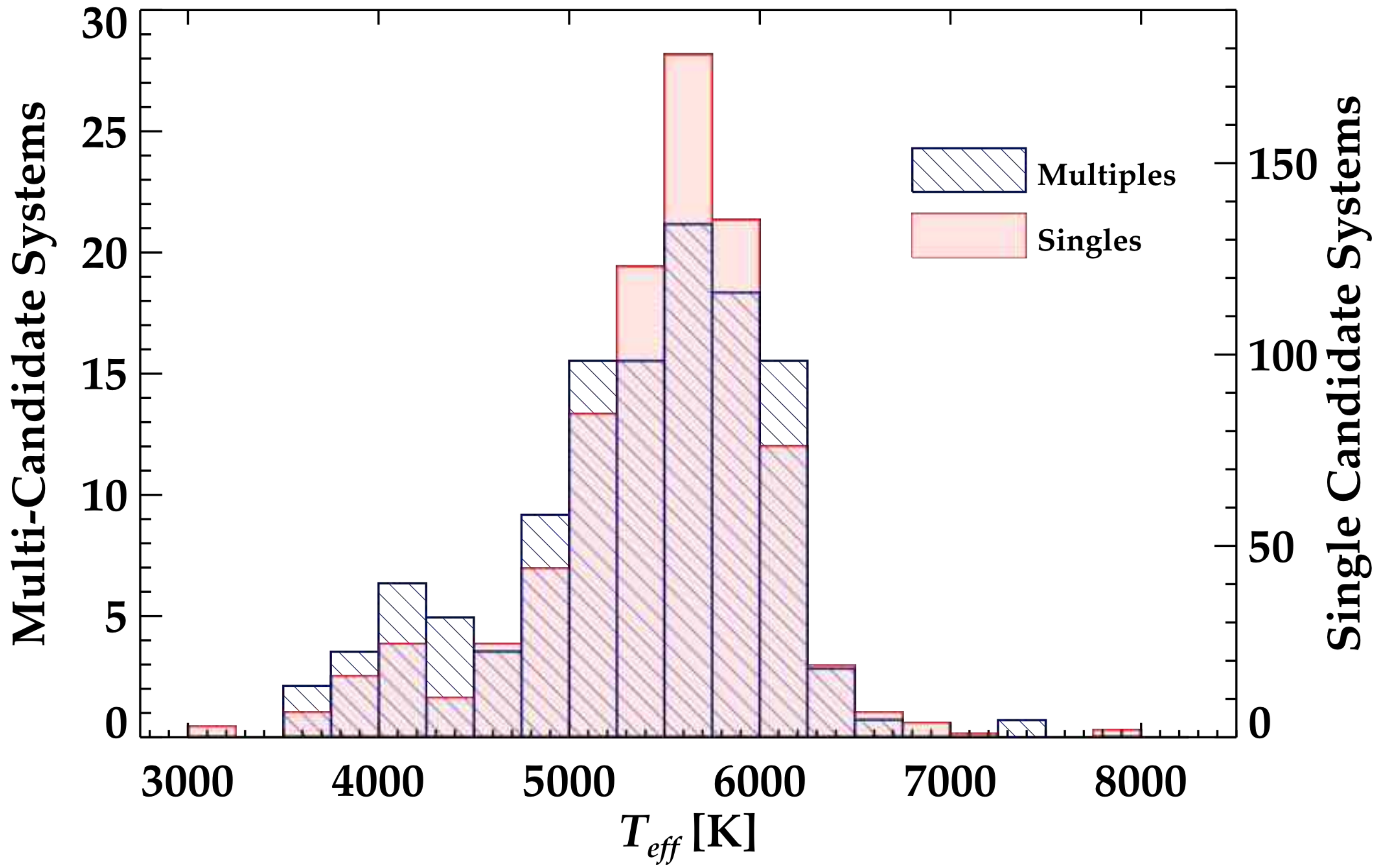




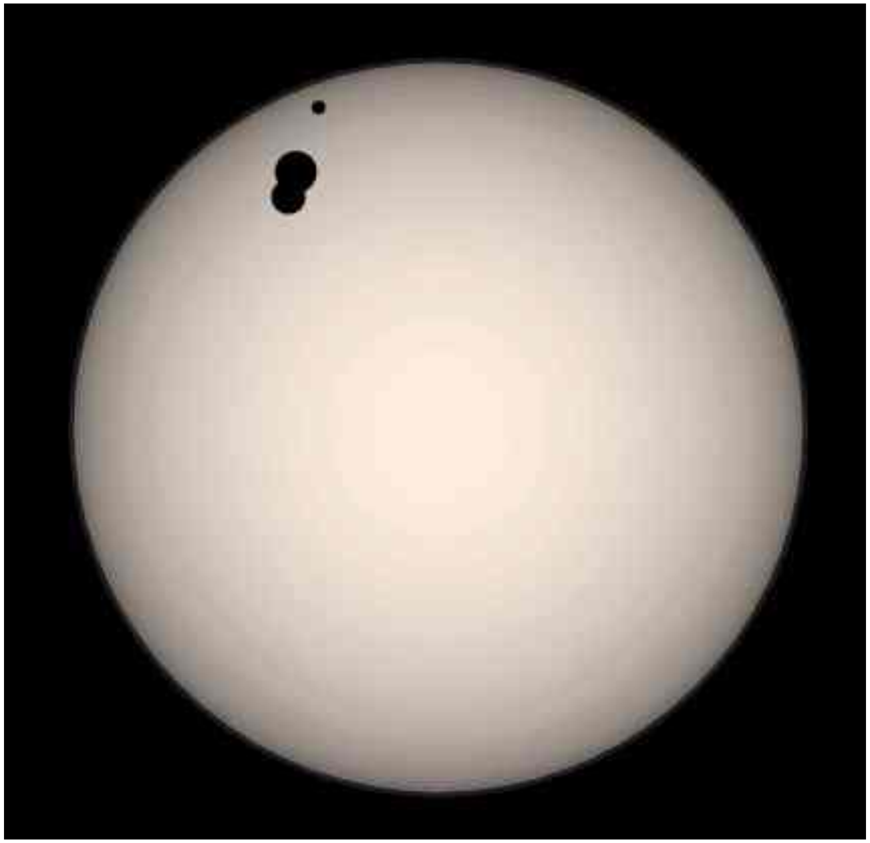
Normalized area Histograms for multiple and single planet systems.

Planets smaller than Neptune dominate both samples,
But more so for the multiple systems

Host Star Effective Temperature - a proxy for stellar mass

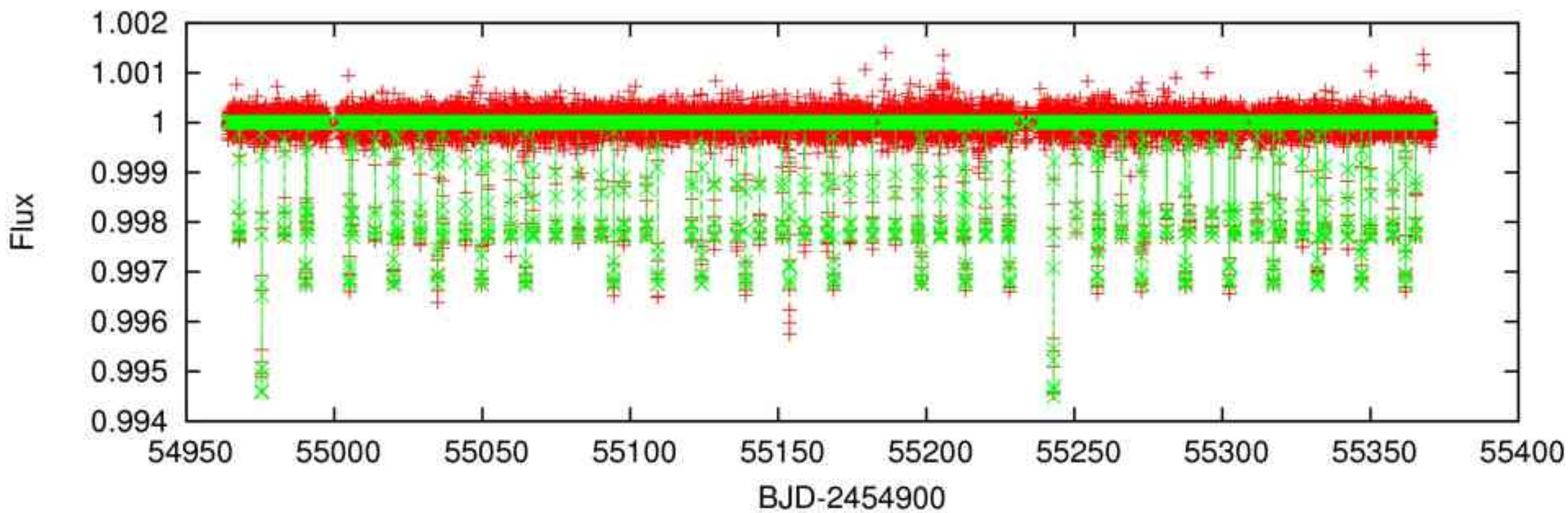


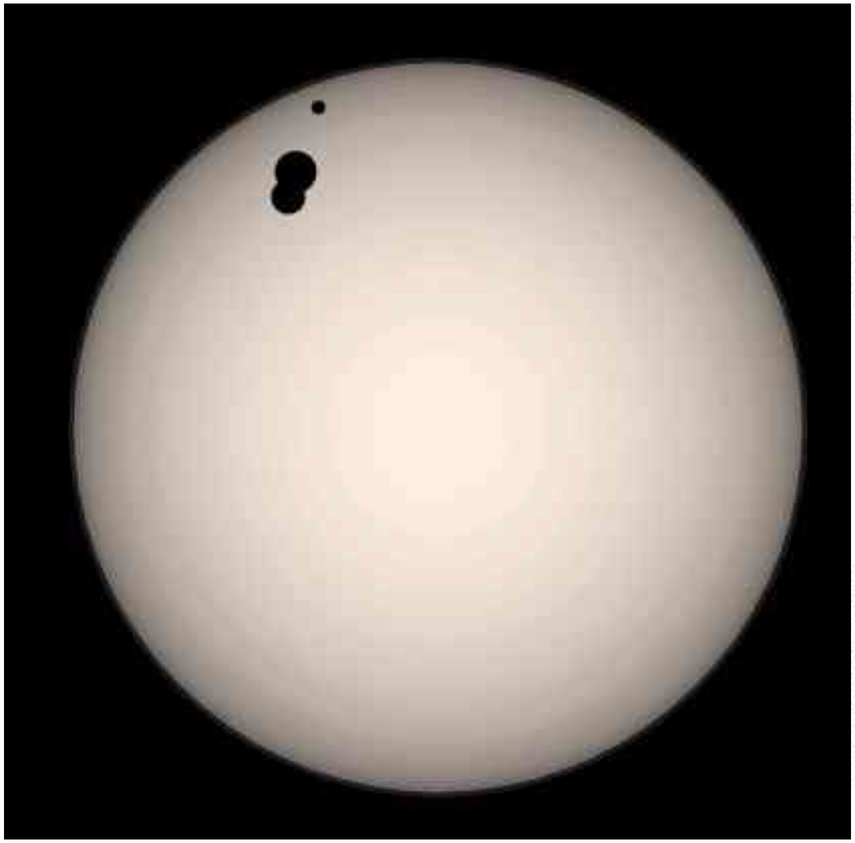
May show that single planets are more common around hotter stars

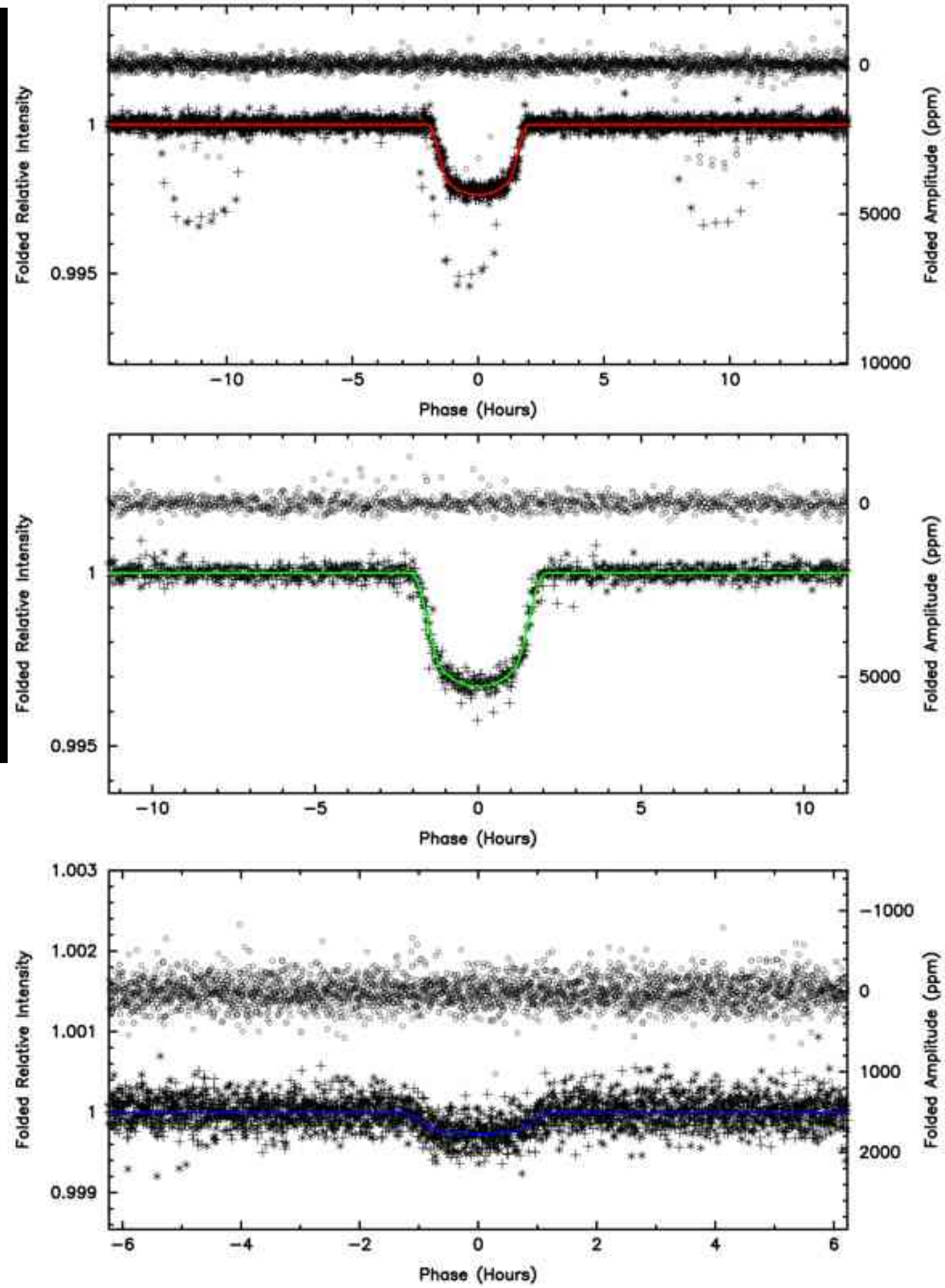


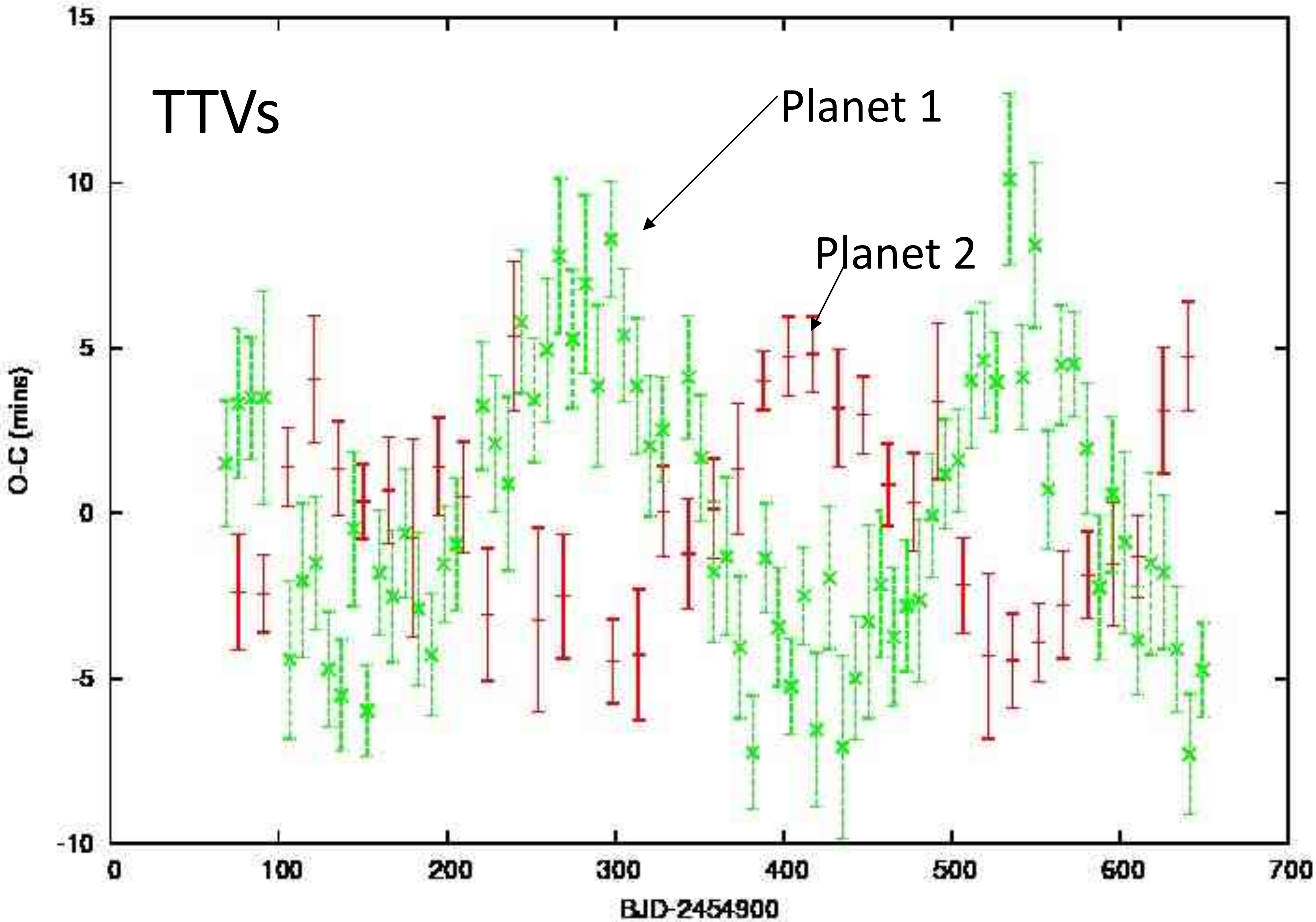
3 planet system

- 7.6, 14.9, 3.5 days
- 6.0, 8.6, 2.3 Rearth
- RV and TTV detection of larger planets.
- Possible RV detection of inner planet



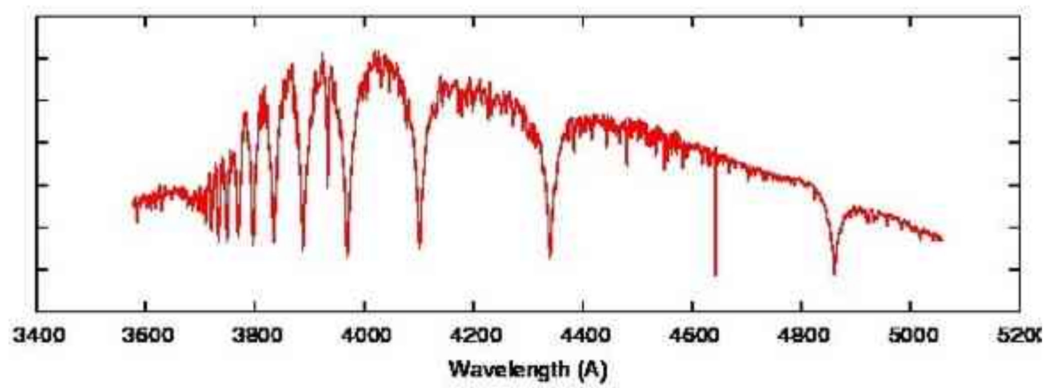



Folded Relative Intensity
Folded Amplitude (ppm)
Phase (Hours)
1
0.995
0
5000
10000
−10
−5
0
5
10
Folded Relative Intensity
Folded Amplitude (ppm)
Phase (Hours)
1
0.995
0
5000
−10
−5
0
5
10
Folded Relative Intensity
Folded Amplitude (ppm)
Phase (Hours)
1.003
1.002
1.001
1
0.999
−1000
0
1000
2000
−6
−4
−2
0
2
4
6

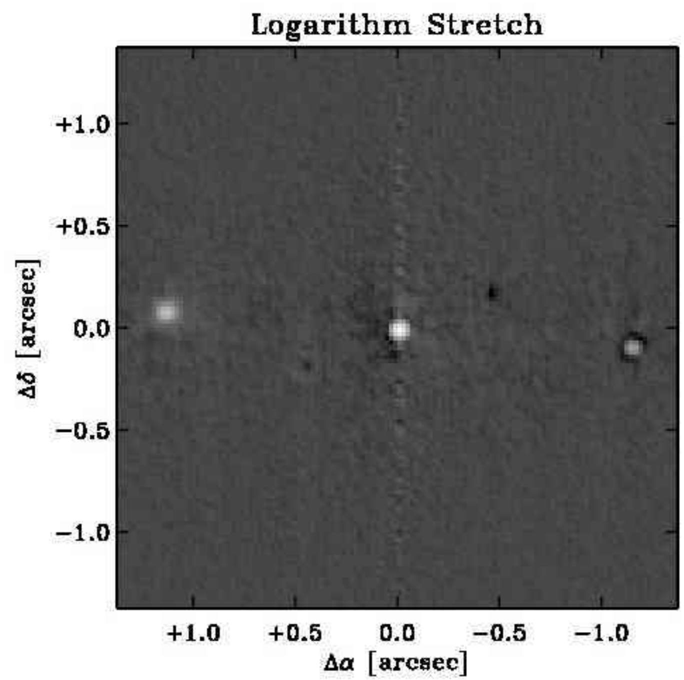

TTVs
Planet 1
Planet 2
O-C (mins)
BJD-2454900
15
10
5
0
-5
-10
0
100
200
300
400
500
600
700

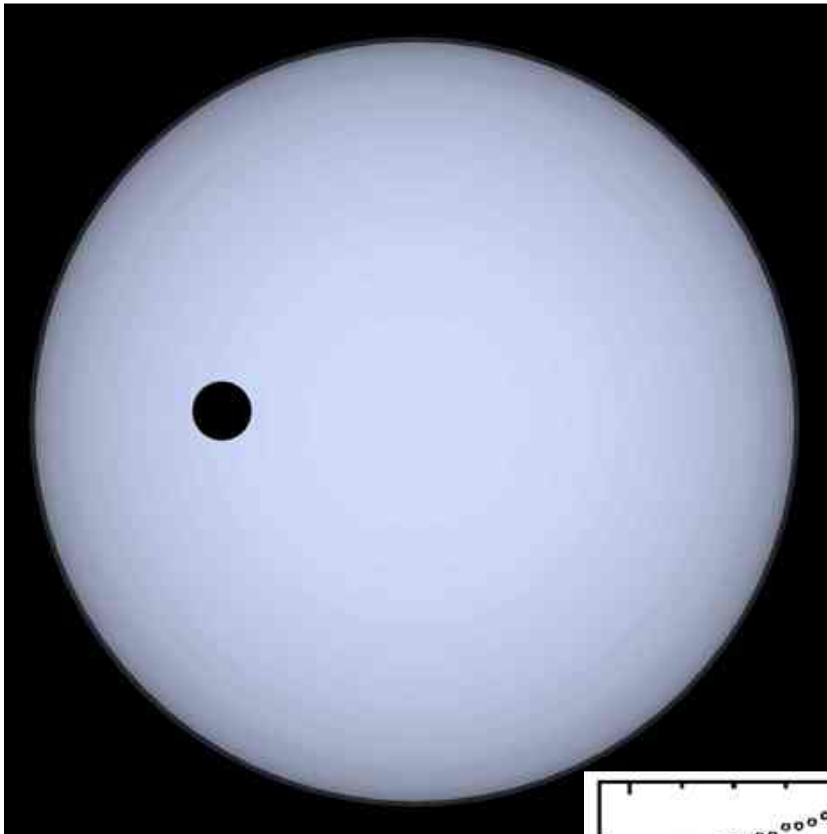
Spectroscopy & Speckle Followup

- Spectra 4-m Kitt Peak
  - A-star ~8850 K
  - Broad Balmer series
  - Not suitable for high-precision RV



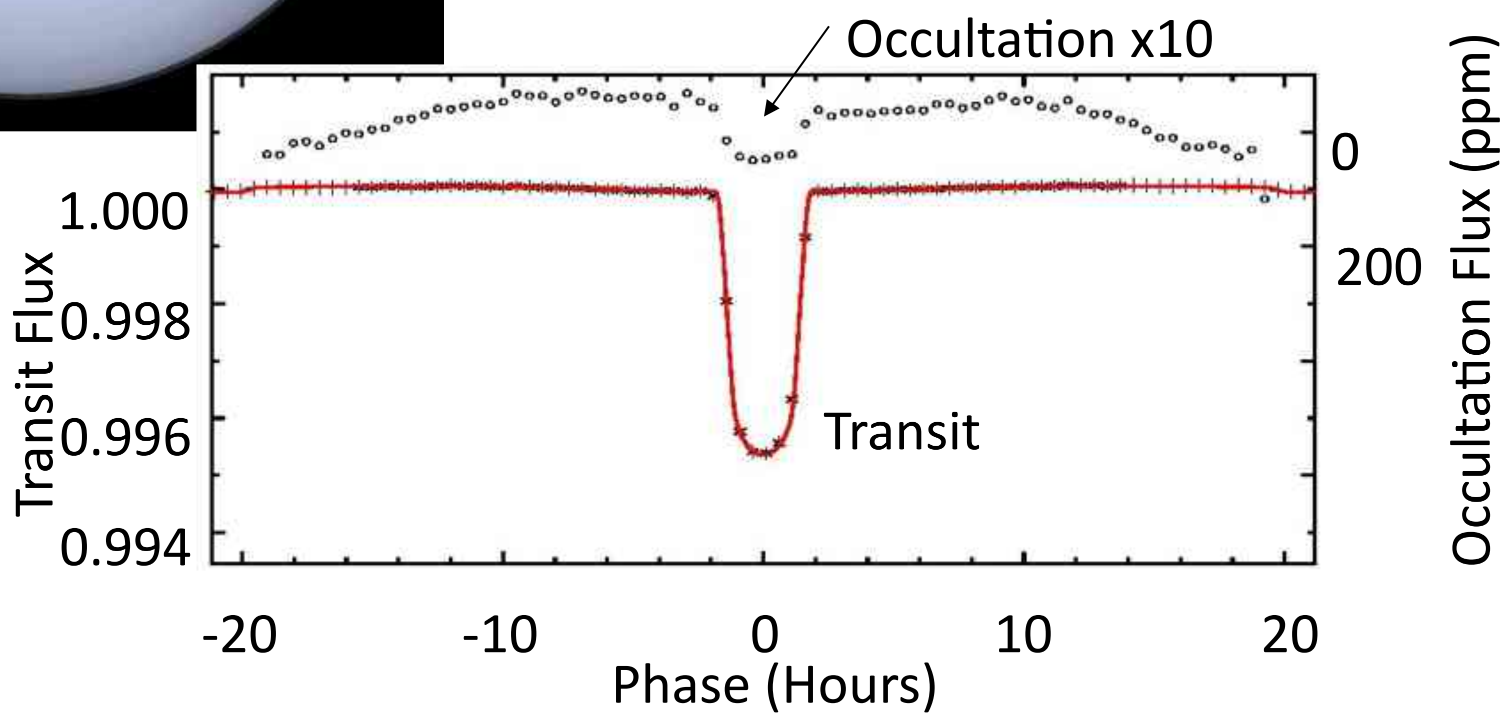
- WIYN Speckle
  - 2nd star detected
    - 1.2” separation
  - Kepler: 4”/pixel
  - Dilution is
    - 32%
  - Transit is deeper than observed
- Spitzer confirmed

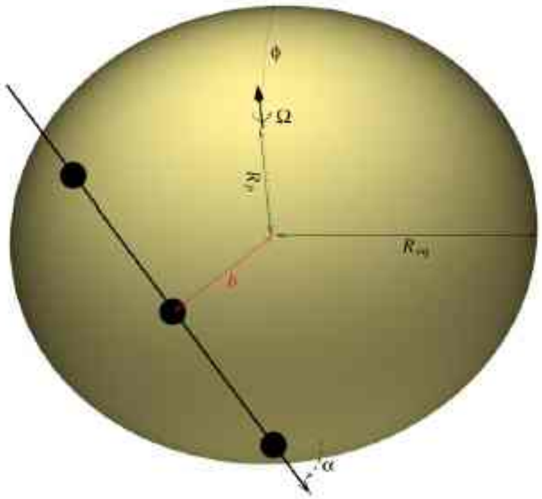




1 planet

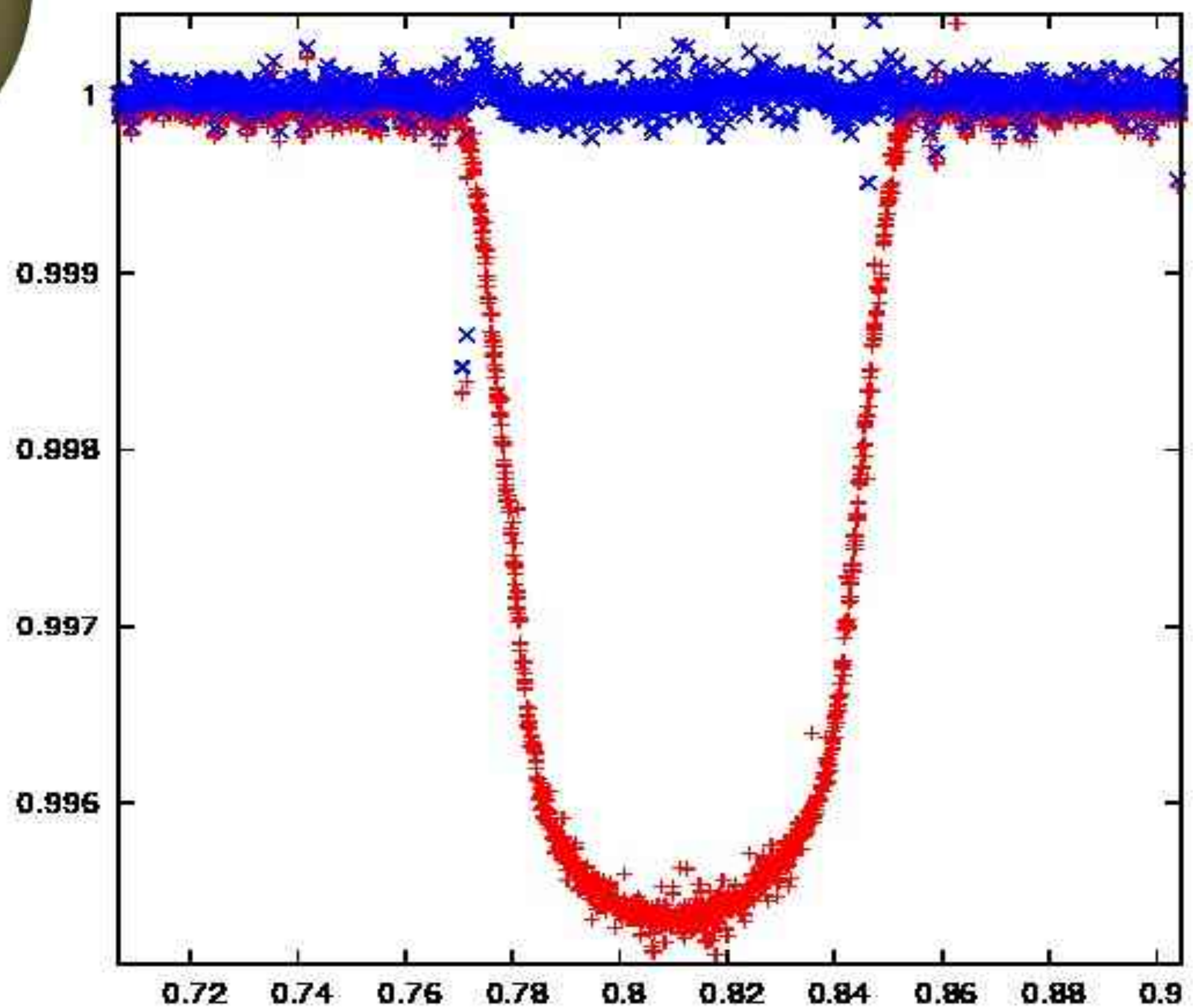
- Period = 1.8 days
- 1.2 Rjupiter
- 3.5 Mjupiter
- Phase, ellipsoidal and Doppler variability
- Teff=3625 K (6500 F)

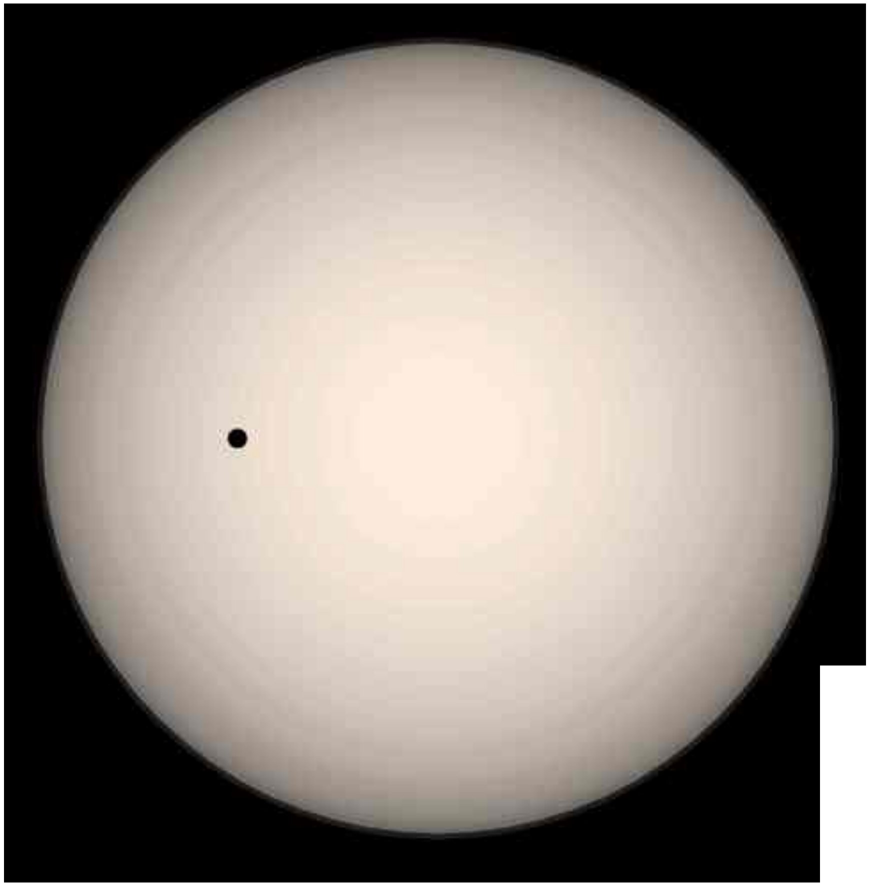




Stellar Rotation (van Zeipel effect)

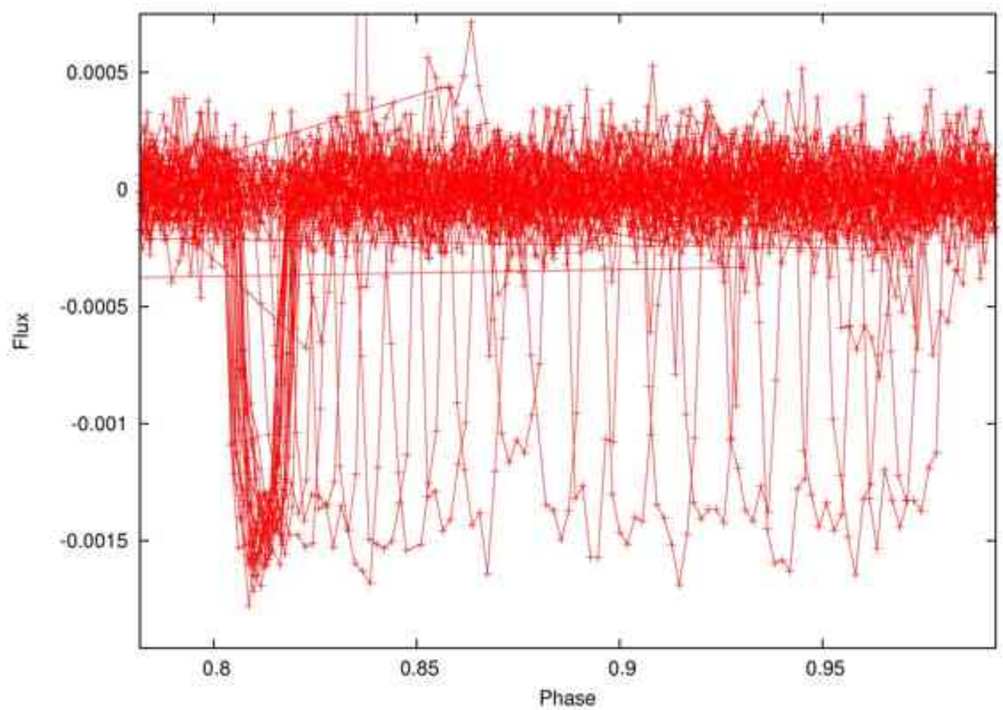
- Vsini~100 km/s
- Distorts star
- Limb-darkening is not symmetric
- Gravity darkening

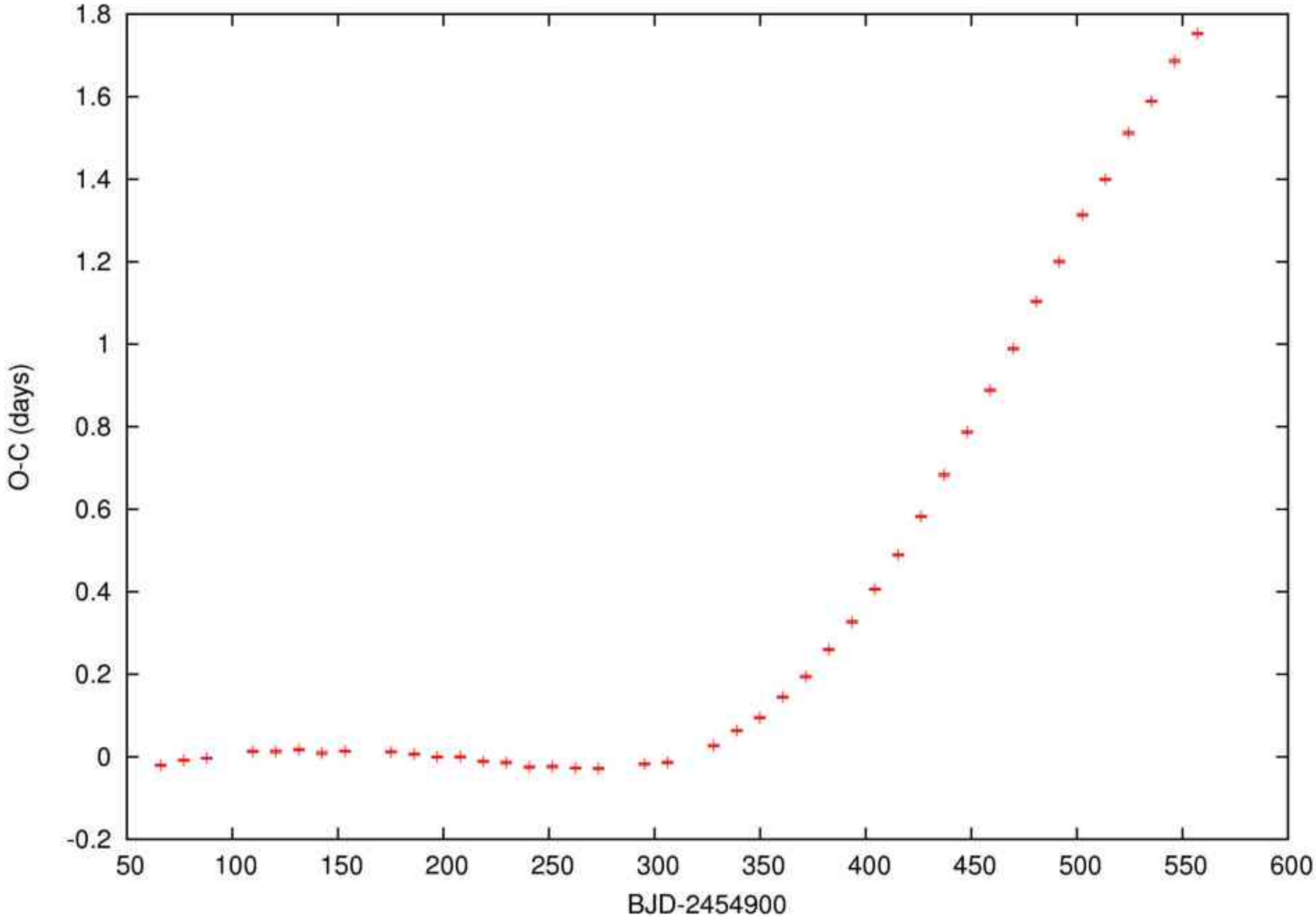




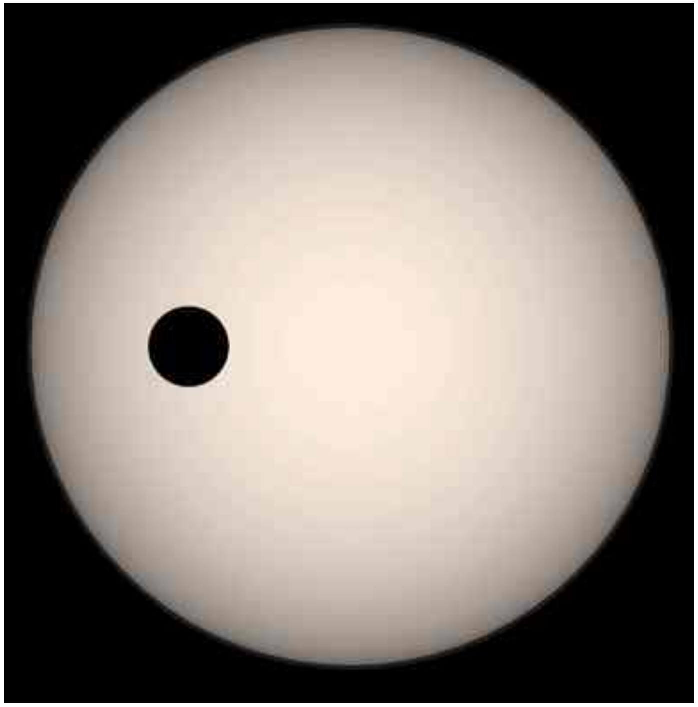
Large TTVs

- 1 planets
- 10.9 days
- 2.5 Rearth
- Larger TTV
- Another planet/star?



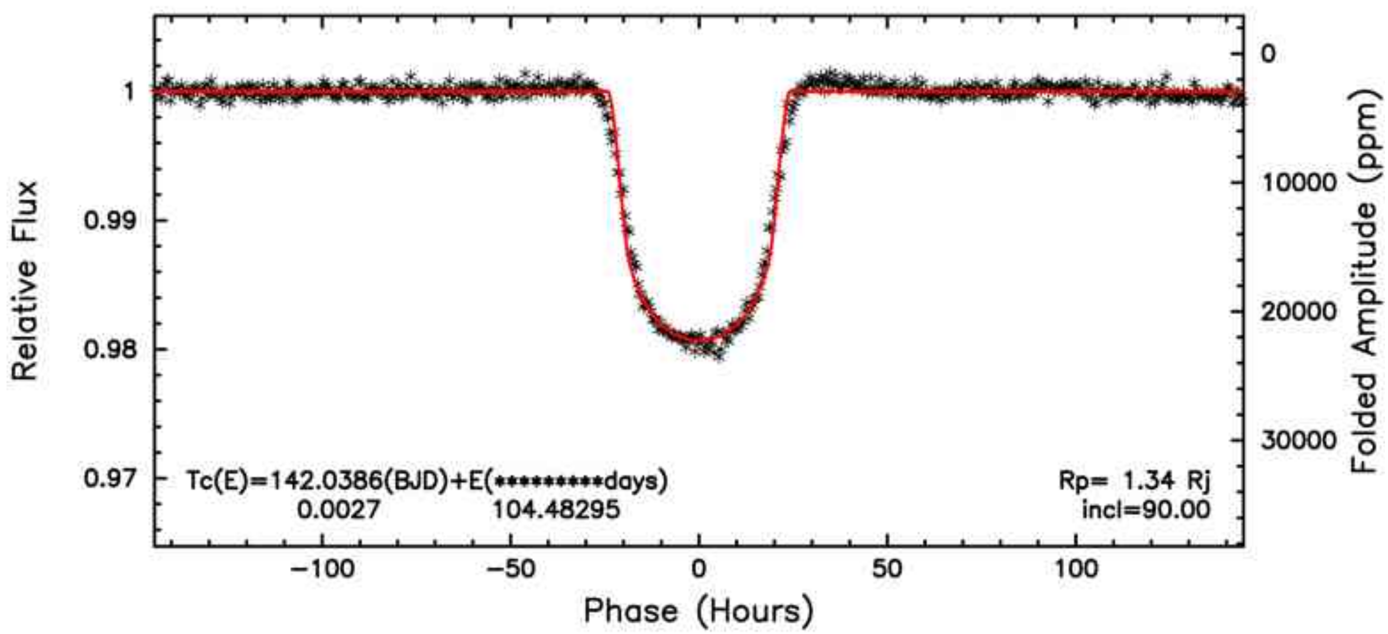


O-C (days)
BJD-2454900
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
50
100
150
200
250
300
350
400
450
500
550
600

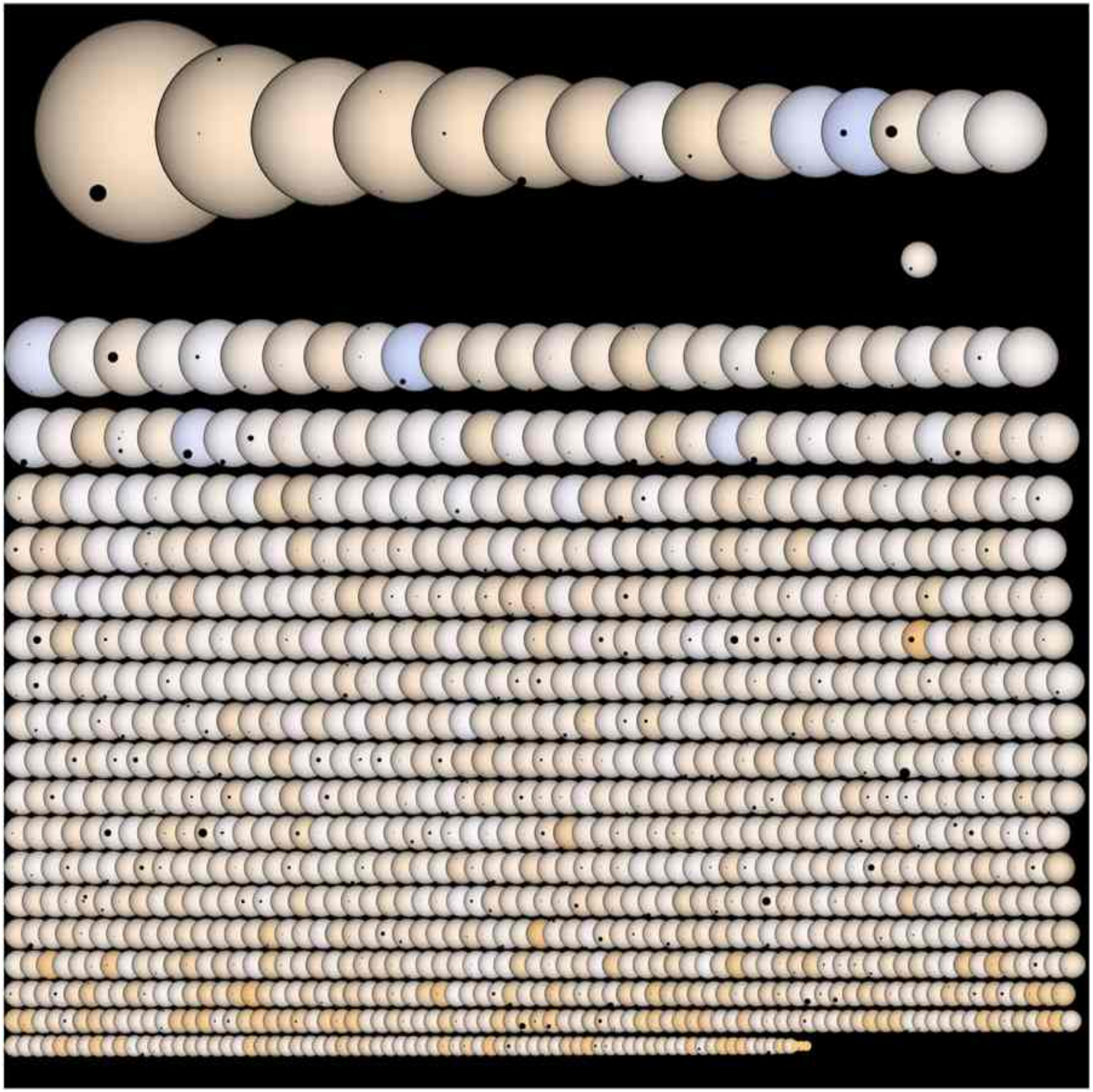


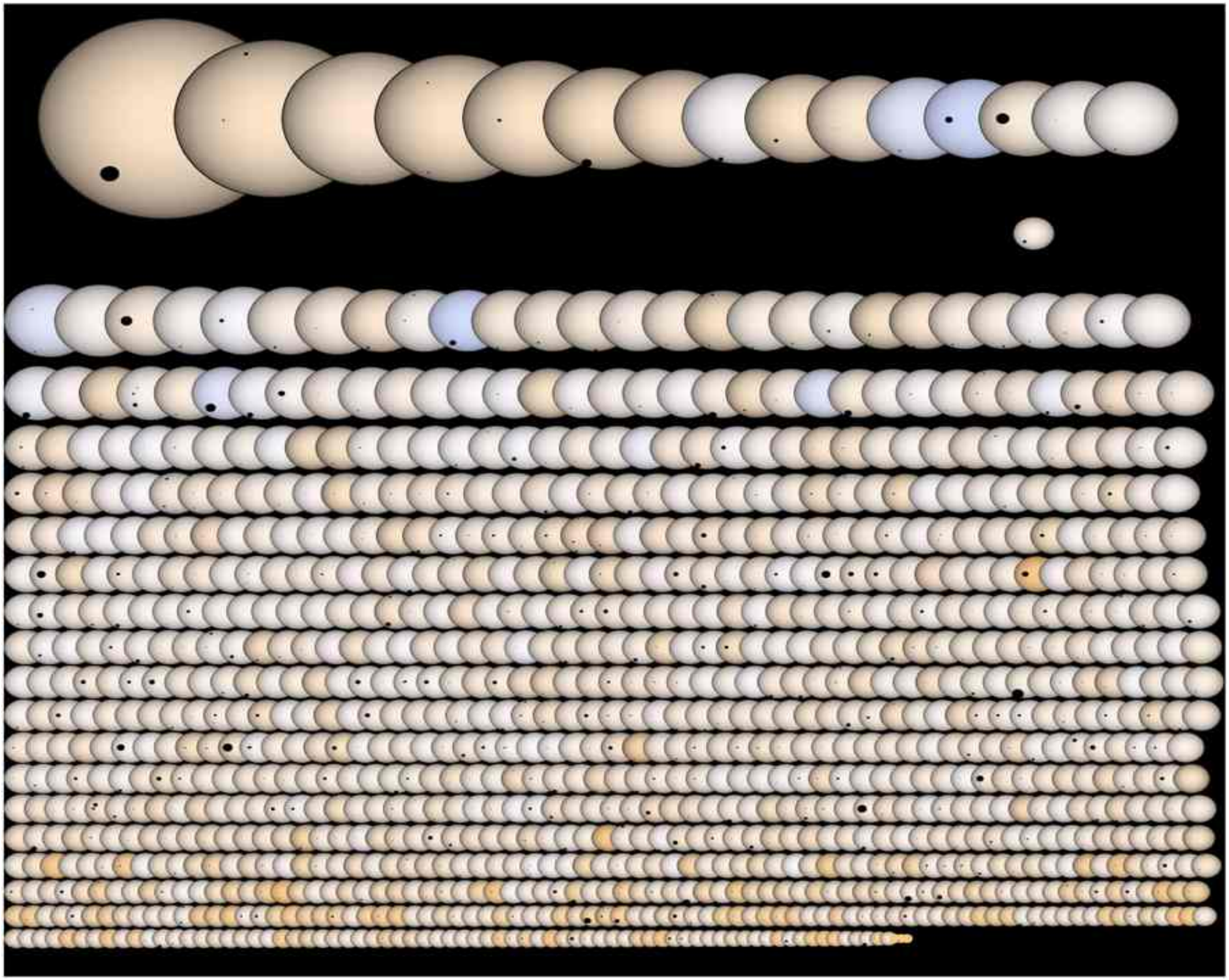
Long Period

- 1 planet
- 10000 days (30 years)
- 1.3 Rj
- 48 hour transit!
- Outer solar system



- All current KOIs
- 1820 KOIs
- Size to scale
- Colours match eye response
- Actual limb-darkening
- Modeled impact parameter





- Image by Jason Rowe, See: http://www.flickr.com/photos/astroguy/5548755082/

Kepler's Large,Close-In Planets