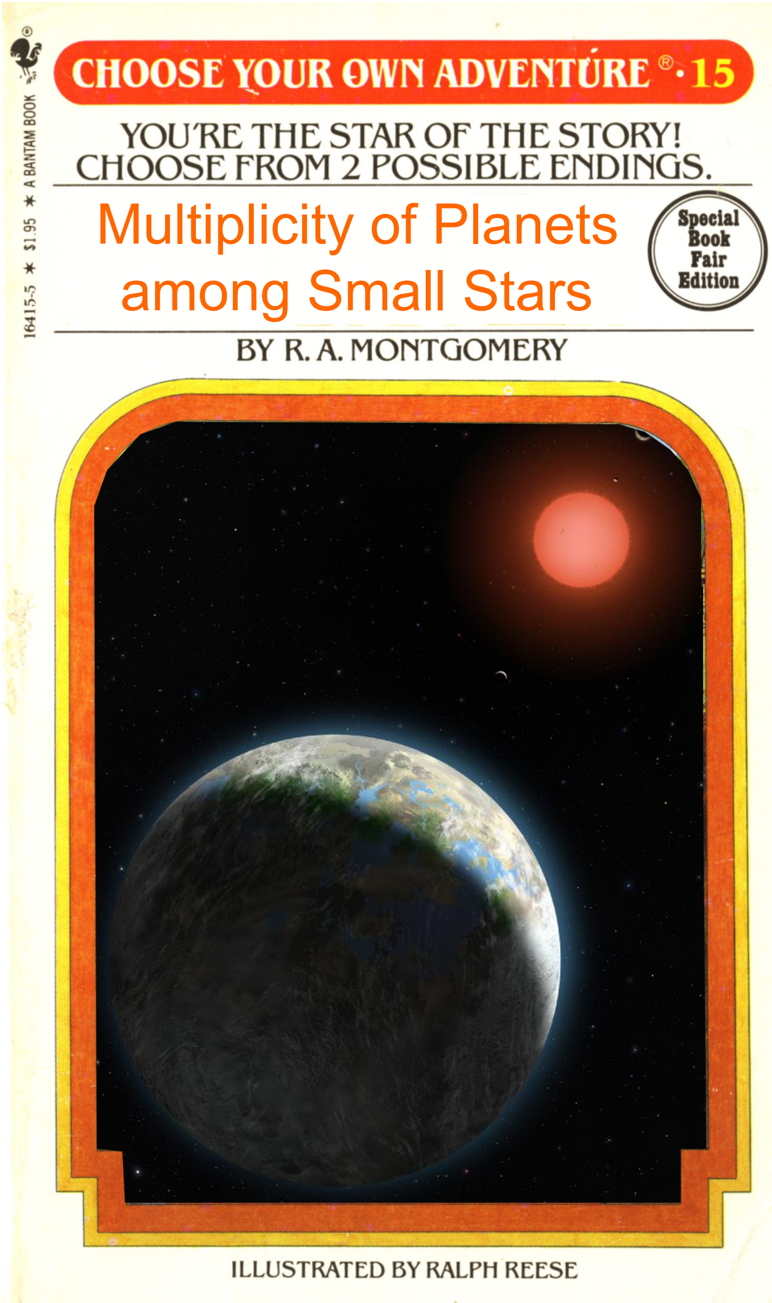
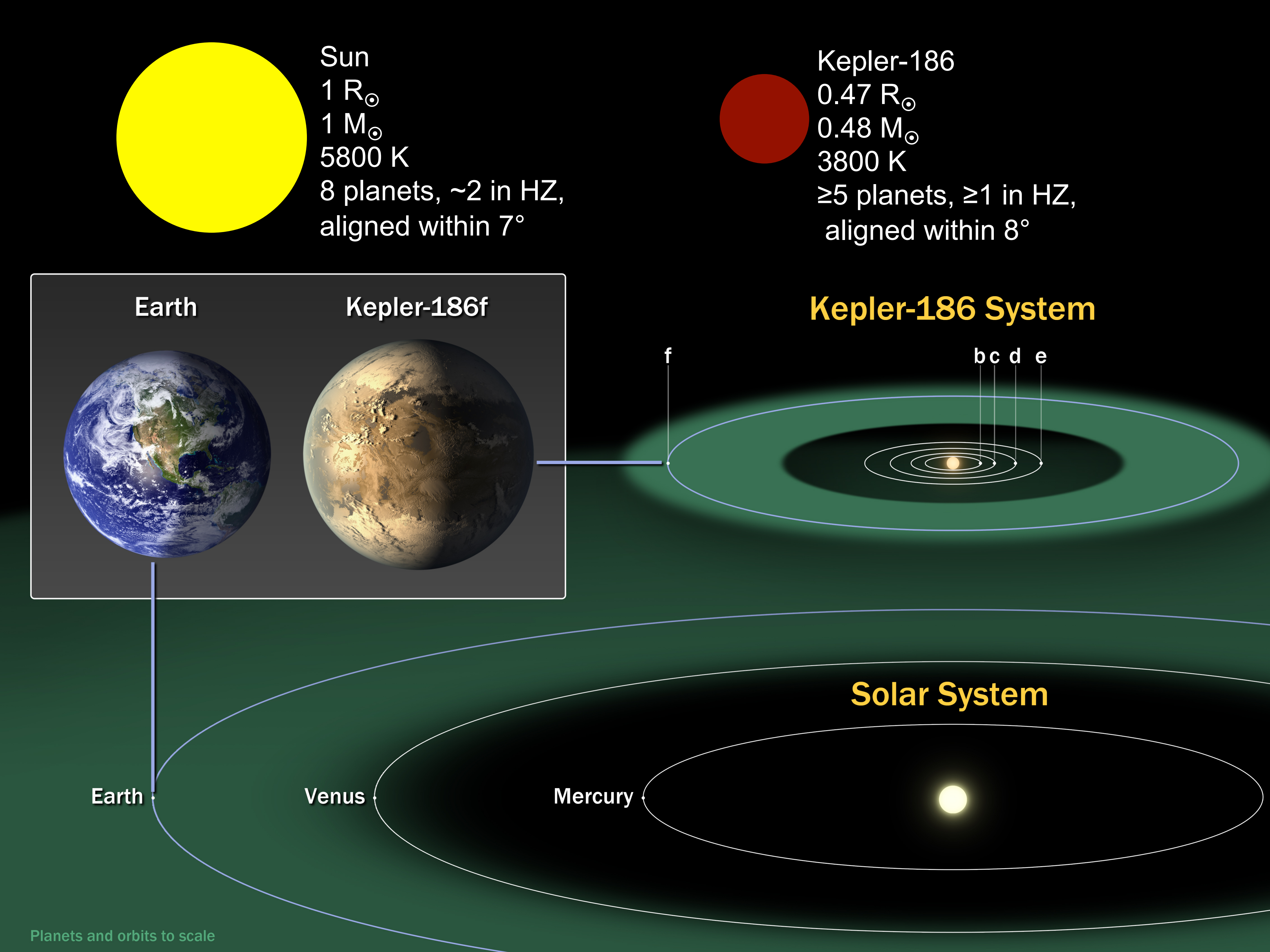


Sarah Ballard
NASA Carl Sagan Fellow
University of Washington

Sagan Symposium
7 May 2015


Sun
1 $R_\odot$
1 $M_\odot$
5800 K
8 planets, ~2 in HZ,
aligned within 7°
Kepler-186
0.47 $R_\odot$
0.48 $M_\odot$
3800 K
≥5 planets, ≥1 in HZ,
aligned within 8°
Earth
Kepler-186f
Kepler-186 System
f
b c d e
Solar System
Earth
Venus
Mercury
Planets and orbits to scale

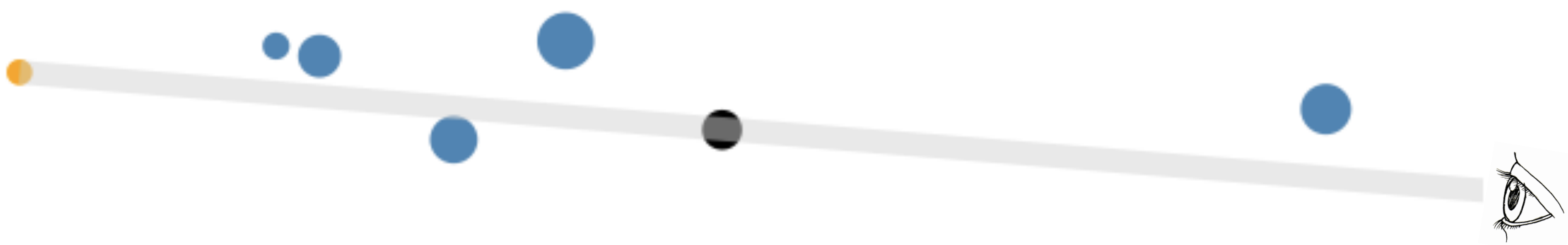
Result from *Kepler*:
2 planets found

Visualization by Yale grad student John Moriarty

Result from *Kepler*:
2 planets found

Visualization by Yale grad student John Moriarty

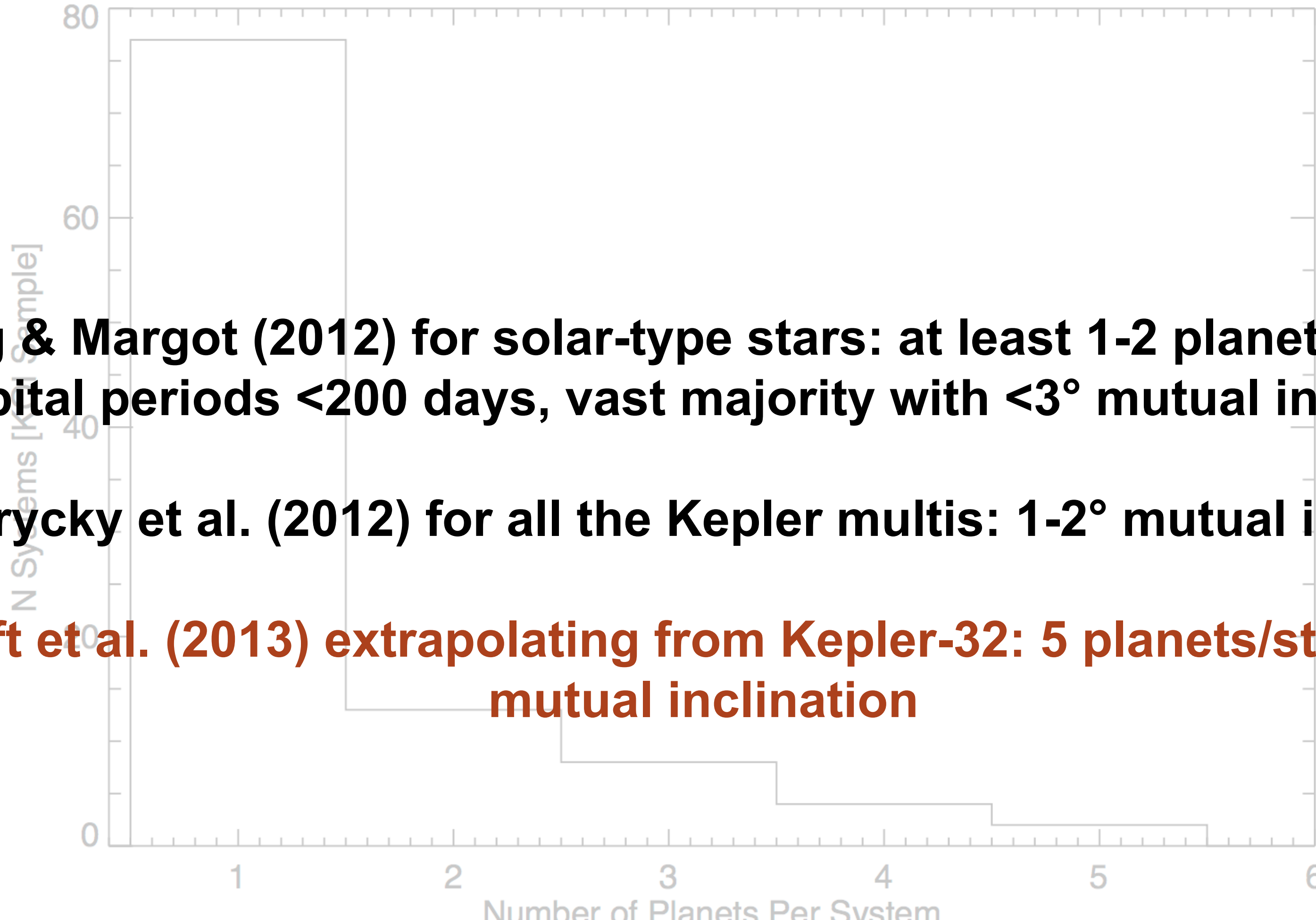
Result from *Kepler*:
1 planet found




Visualization by Yale grad student John Moriarty

Multiplicity Among the M Dwarfs

From the NExSci KOI Database, queried on 4 July 2013

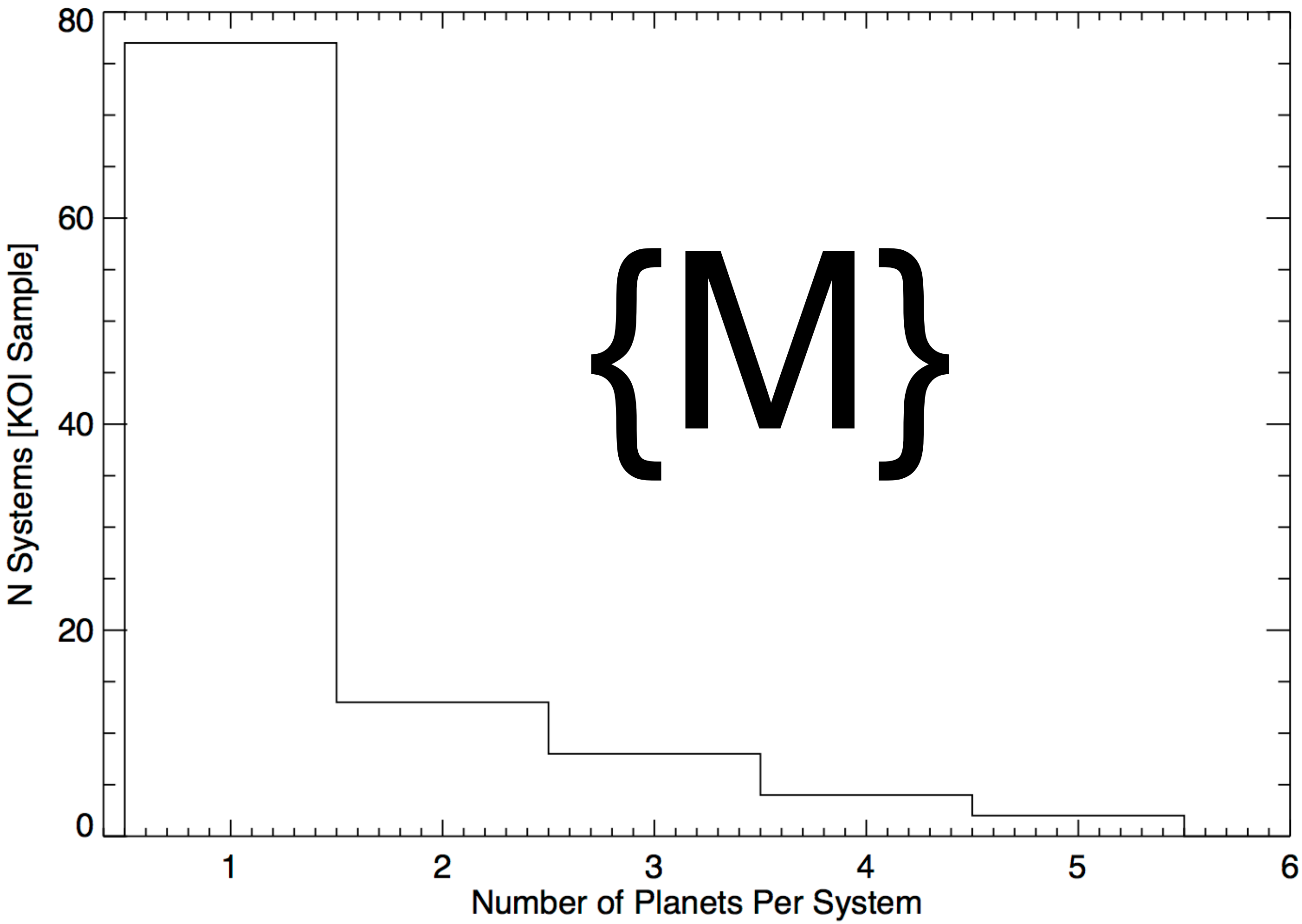


- **Fang & Margot (2012) for solar-type stars: at least 1-2 planets/star with orbital periods <200 days, vast majority with <3° mutual inclination**

- **Fabrycky et al. (2012) for all the Kepler multis: 1-2° mutual inclination**

- **Swift et al. (2013) extrapolating from Kepler-32: 5 planets/star, 1-1.5° mutual inclination**

Multiplicity Among the M Dwarfs



Multiplicity Among the M Dwarfs

We have in hand:

{M}

How likely is M, given a universe with

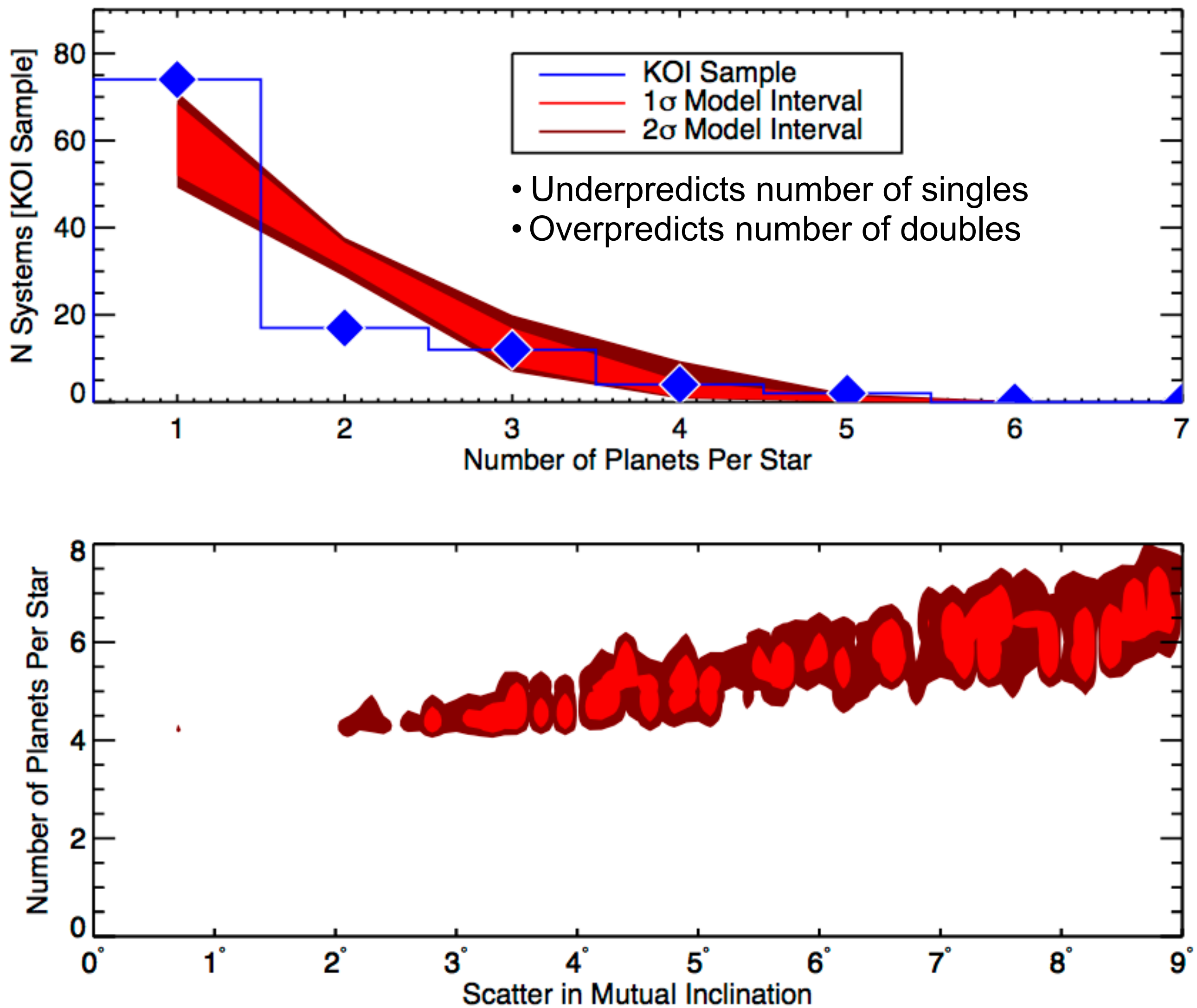
- N planets per star
- that have a scatter *σ* in their mutual inclinations

$$P(\{M\}|N,\sigma) \propto \prod_i$$

Poisson likelihoods of getting M_i multis, compared to what we expect, given μ(N,σ)

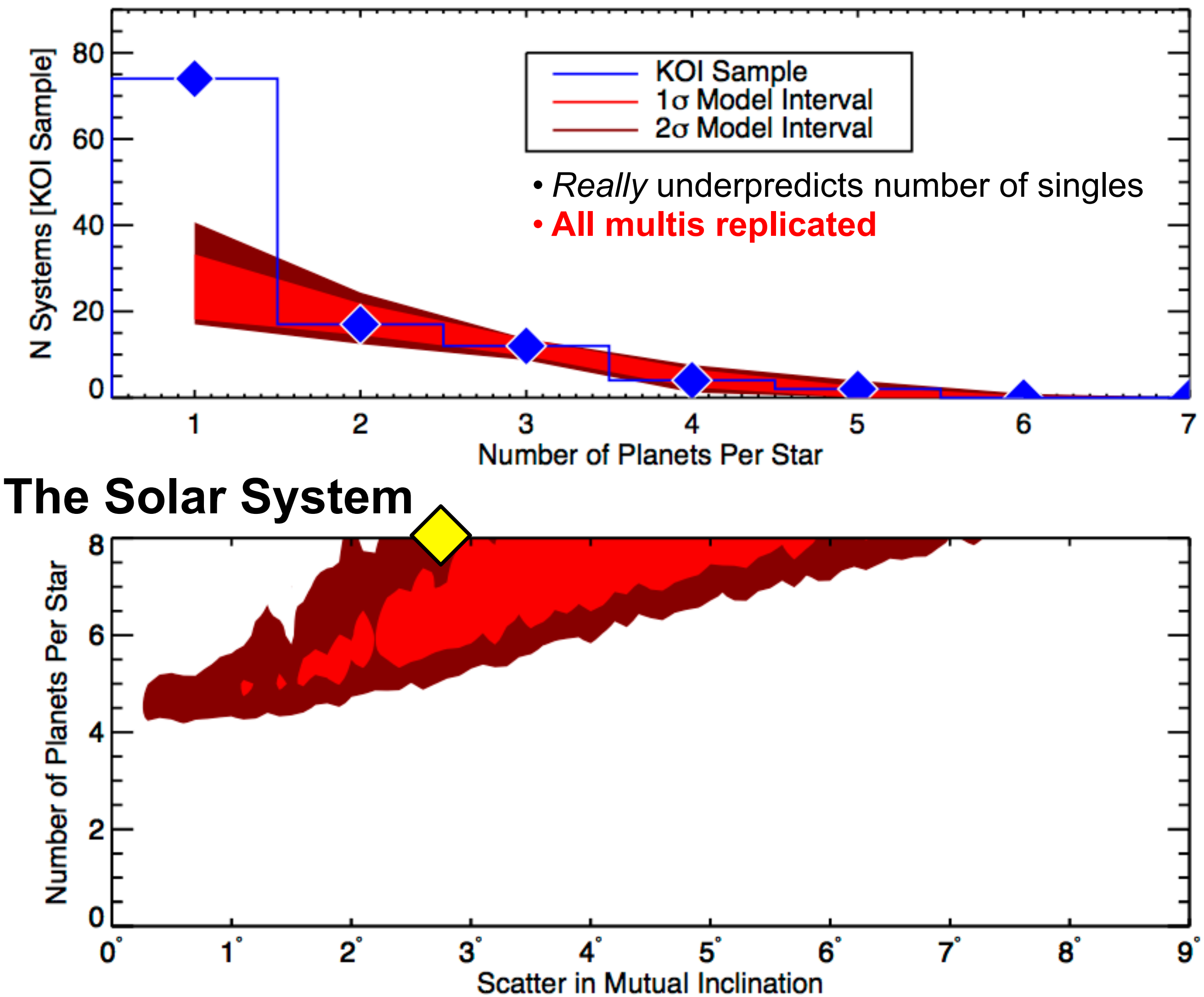
Evaluated empirically

One Mode of Planet Formation: Fit to All Data



Ballard & Johnson (2014)

One Mode of Planet Formation: Fit to Multis



Ballard & Johnson (2014)

Invoking Two Modes of Planet Formation

$$P(\{M\}|N,\sigma) \propto \prod_i \frac{\mu(N,\sigma)^{M_i} e^{\mu(N,\sigma)}}{M_i!}$$

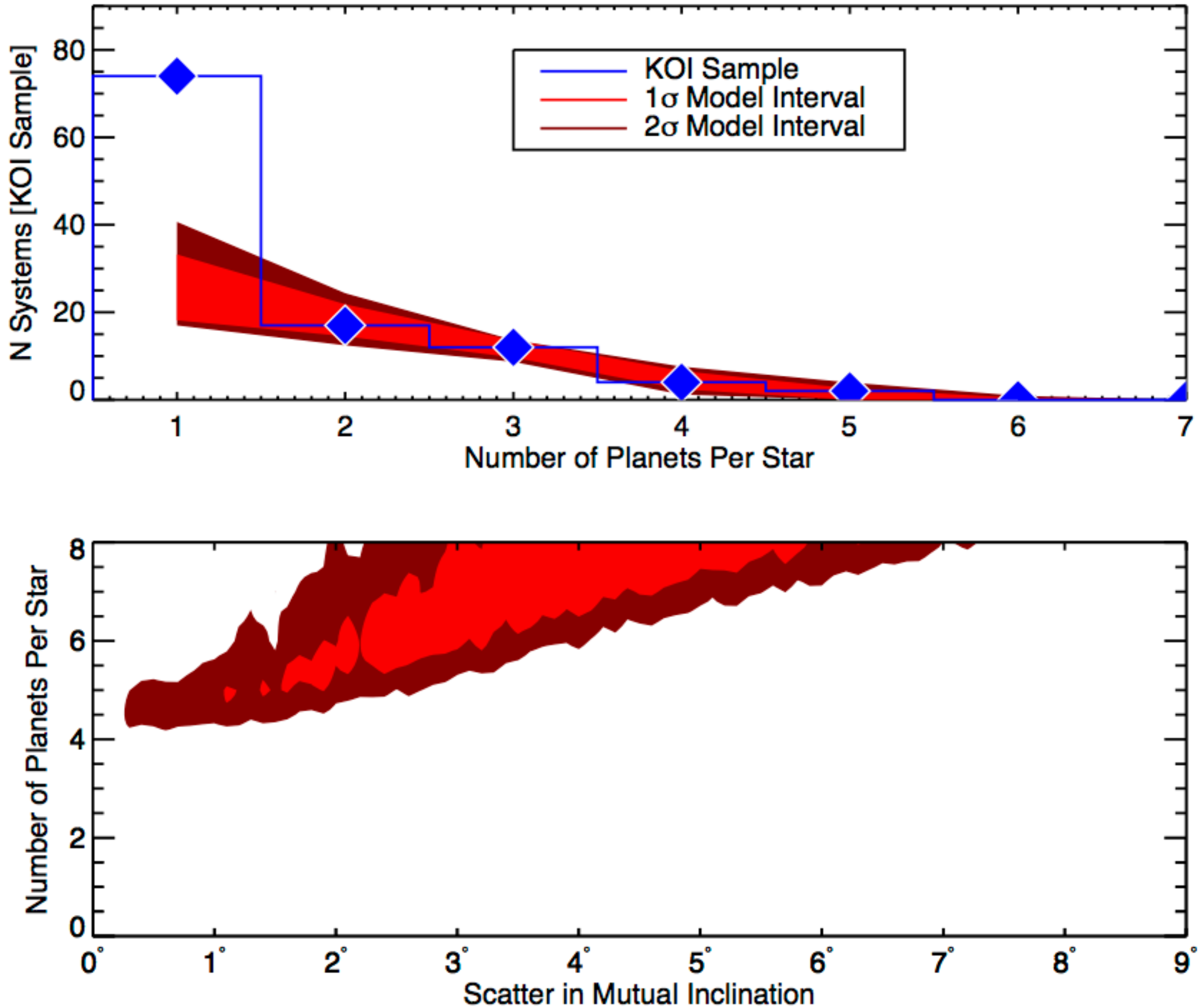
$$\mu'(N,\sigma) = (1-f)\mu(N,\sigma) + f \cdot \delta(i=1)$$

The original population μ(N,σ) occurs sometimes

Supplemented by a population of singly transiting planets the rest of the time

We now evaluate posteriors of N, σ, and f

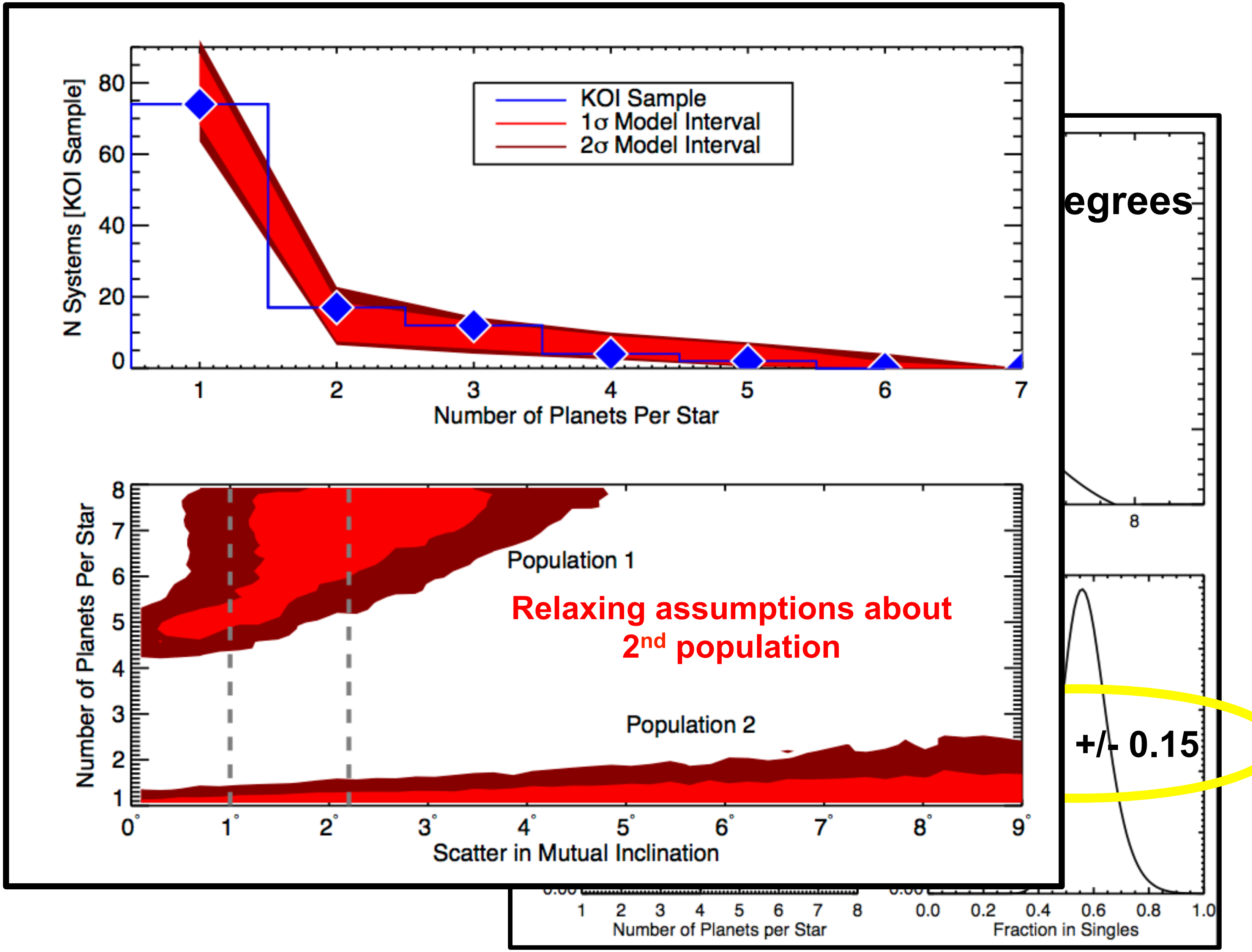
One Mode of Planet Formation: Fit to Multis



Invoking *ad hoc* a population of singly transiting planets...

Ballard & Johnson (2014)

Two Modes of Planet Formation: Fit to All Data



Ballard & Johnson (2014)

Two Modes of Planet Formation: Fit to All Data

What produces the dichotomy?

Could self-excitation be responsible?

Yes: Pu & Wu (2015), Volk & Gladman (2015)

No: Johansen et al. (2012), Becker & Adams (2015, in prep)

Or does the dichotomy originate during formation?

Yes: Johansen et al. (2012)

Ballard & Johnson (2014)

We are exploring dynamical evolution of km-size particles, distributed across a grid of surface density power laws and total mass

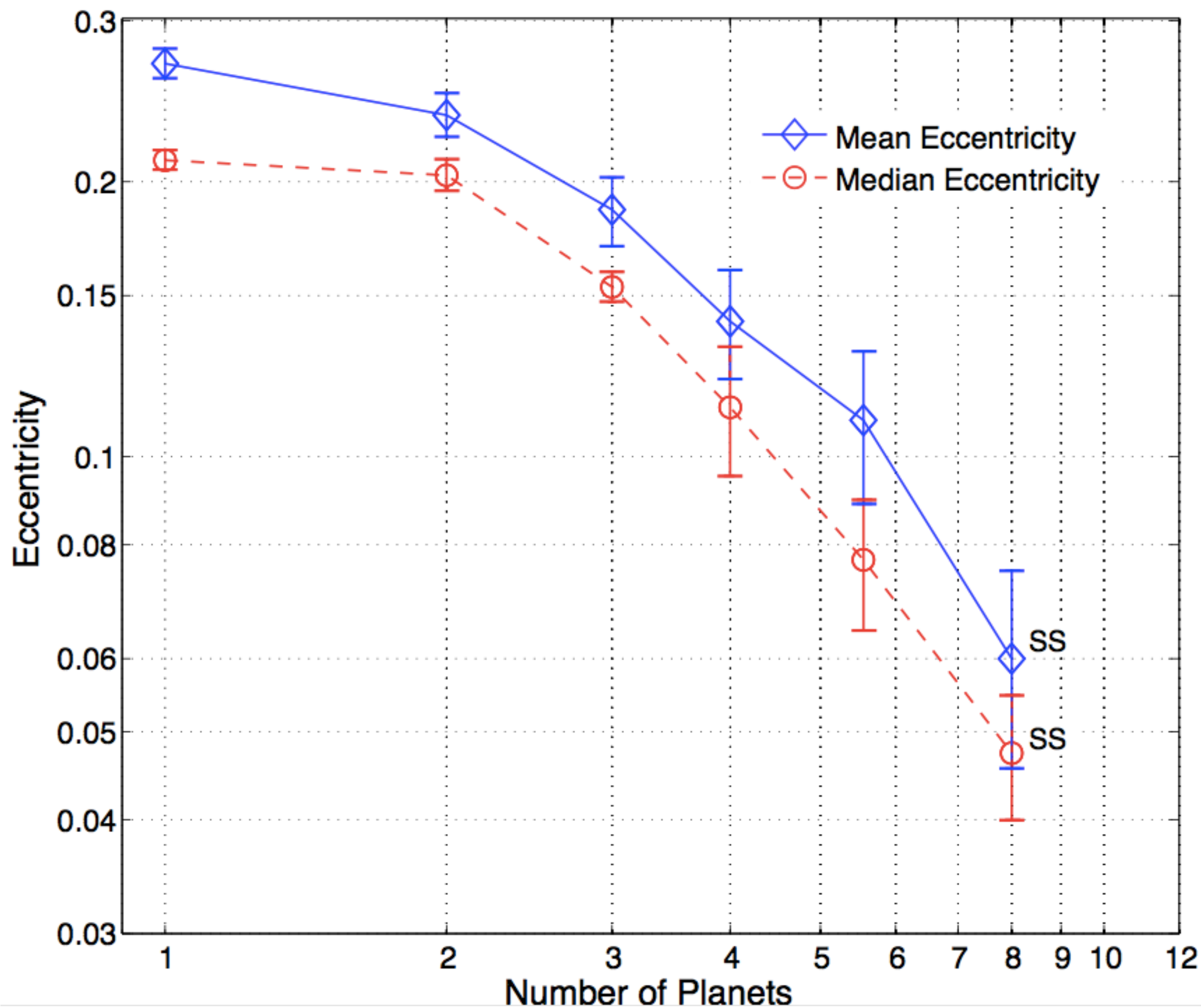
Produce predictions for multiplicity of transits, duration distribution, and period distribution

More clues from observables!

- Stellar age (stellar rotation period, stellar rotation amplitude,galactic height)
- Metallicity
- Planet size (Johansen et al. 2012)
- TTV fraction (Xie et al. 2014)

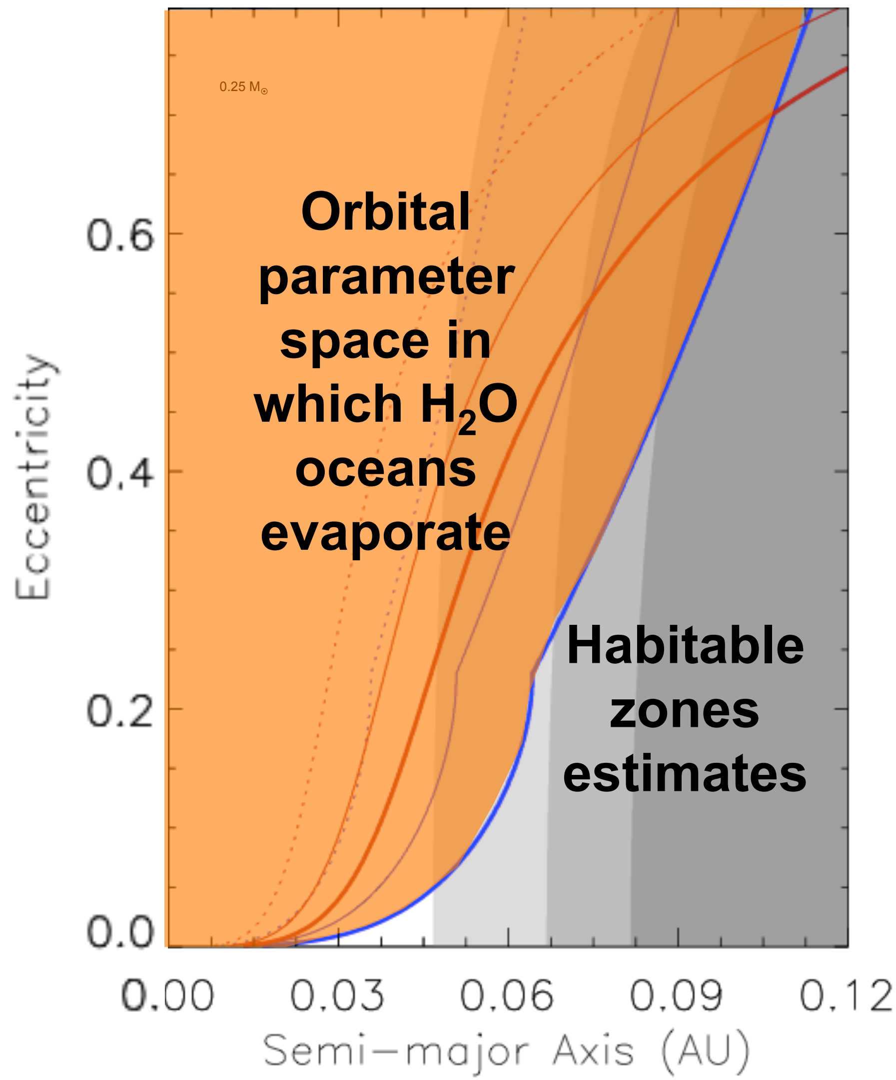
Visualization by Yale grad student John Moriarty

Multiplicity and Habitability

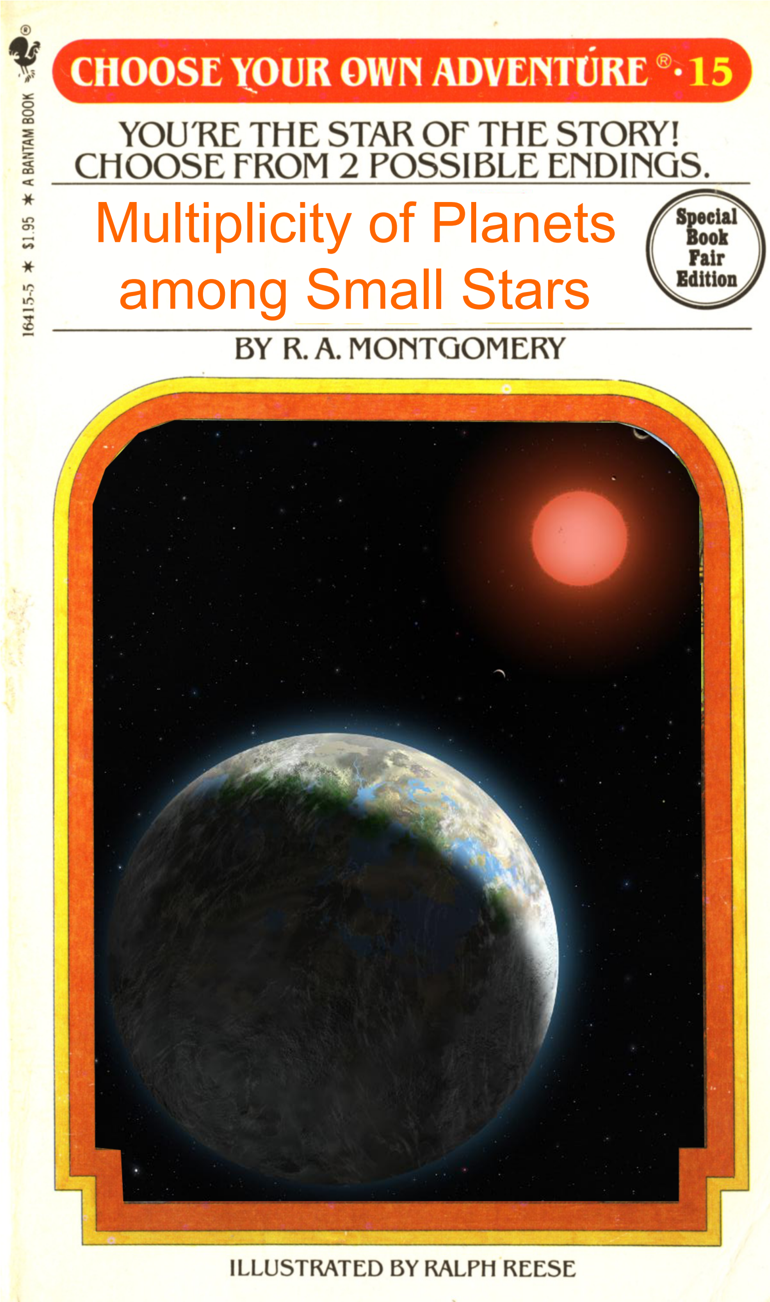


Limbach & Turner, 2014

Even modest eccentricities can sterilize the surface of M dwarf planets



Barnes et al. (2013)



Conclusions

Kepler multiples inform our understanding of the true number of planets per star, and their inclinations

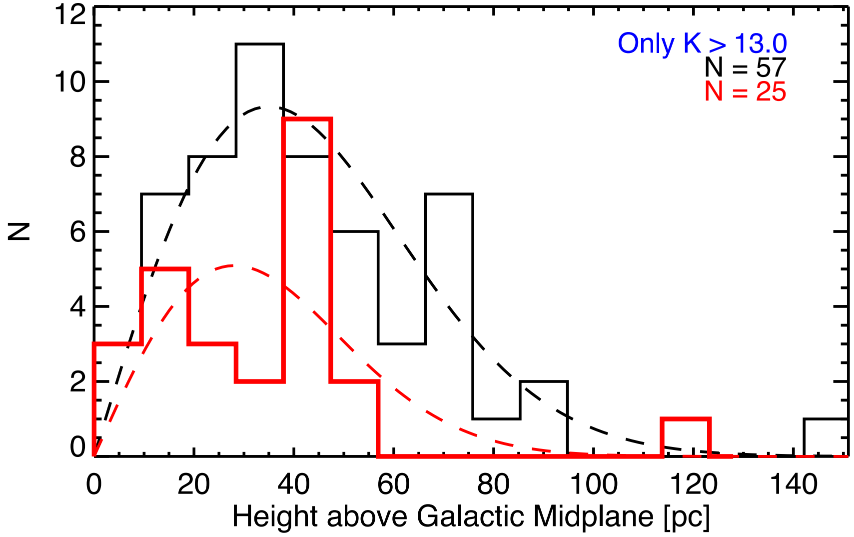
Stars hosting 2 or more planets can be explained with a single model similar to the Solar System, but too many singles to be consistent with this model (robust to selection effects). There are at least five planets per star in these systems

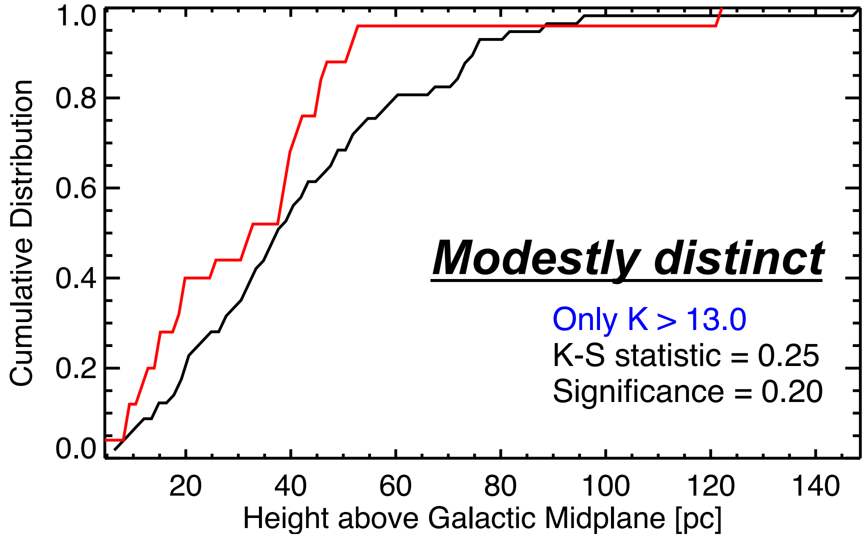
The data better support two scenarios (where each occurs ~50% of the time) by 21:1 odds. Whether dichotomy originates during formation or subsequently, or some combination, remainds to be solved!

Does anything distinguish hosts of singles, versus hosts of multiples?

Does anything distinguish hosts of singles, versus hosts of multiples?

Height above galactic midplane

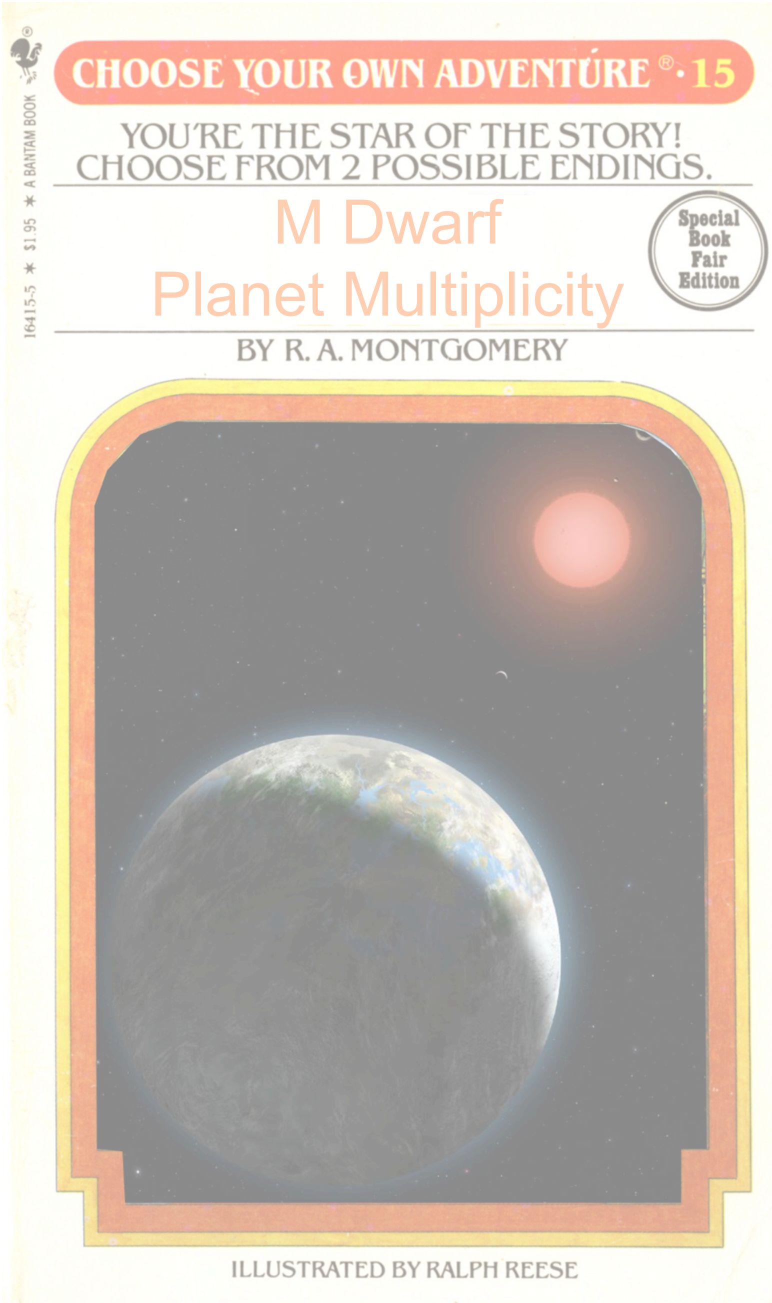




Does anything distinguish hosts of singles, versus hosts of multiples?

Tantalizing evidence (2σ) that the multiplistic, coplanar systems reside:

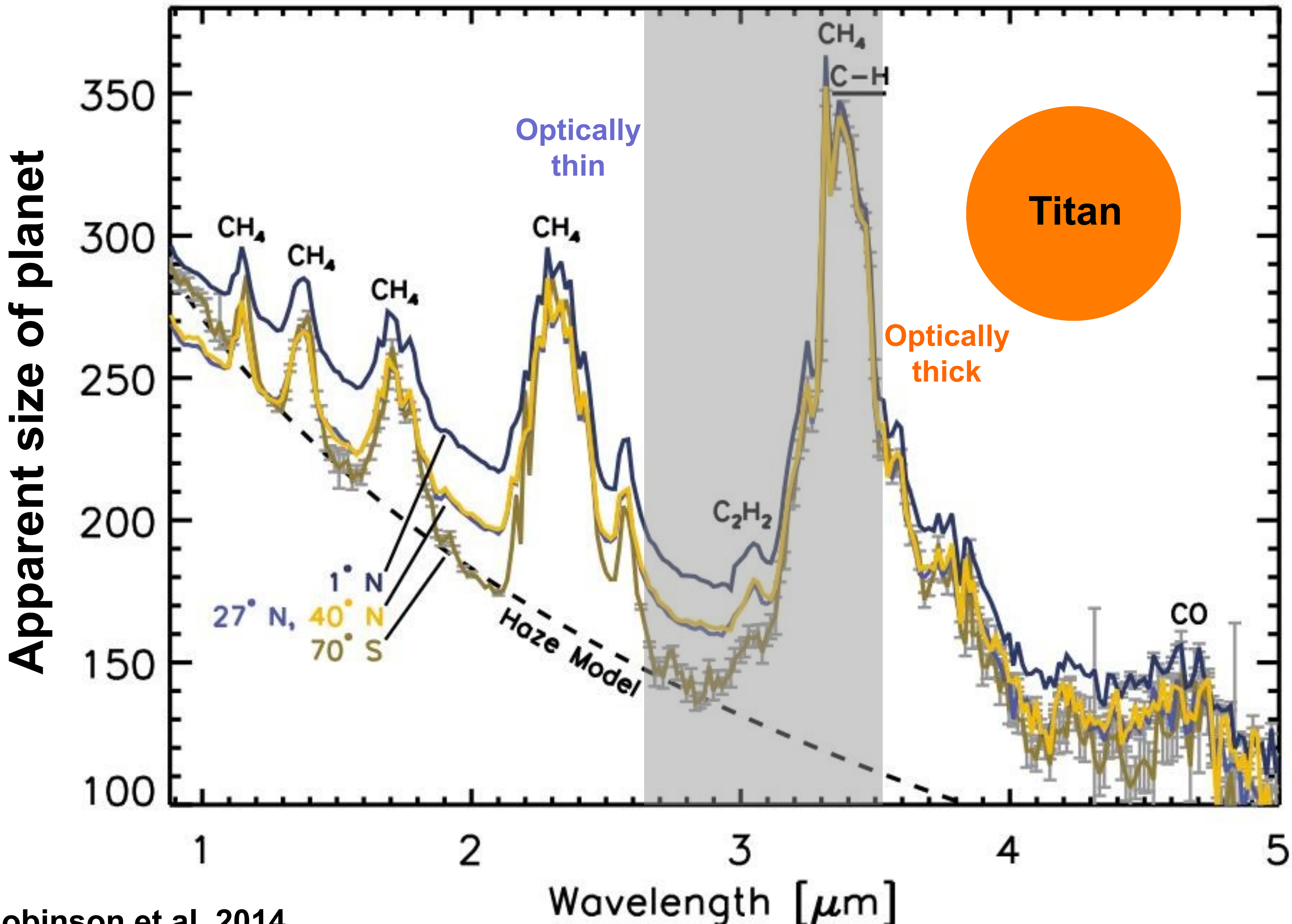
- **Around more rapidly rotating stars**
- **Closer to the midplane**
- **Around metal-poorer stars**



Outline

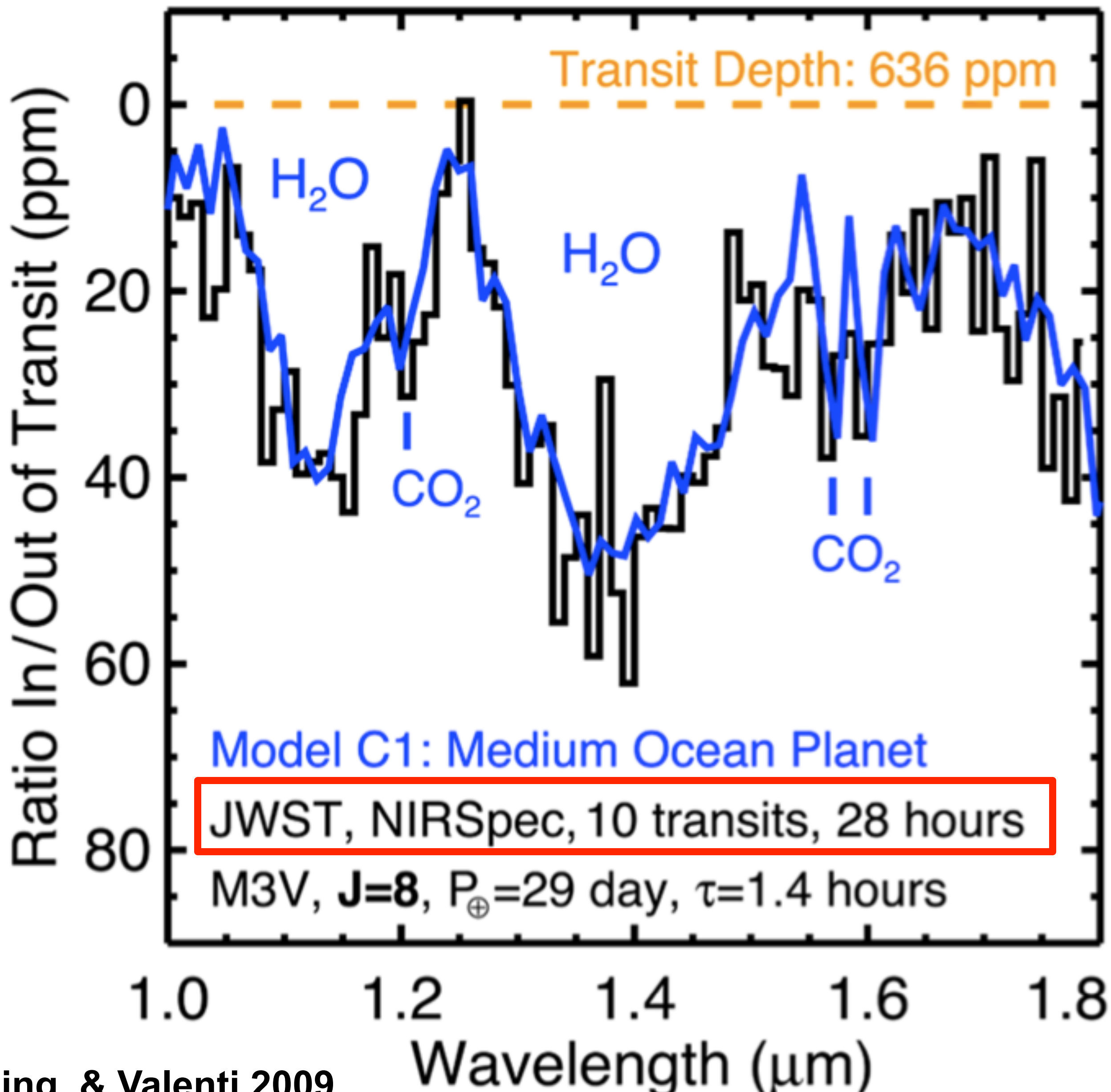
- Why M dwarfs? And why recently?
- What is a "typical" exoplanetary architecture in the universe?
- Multiplicity and habitability: what's next?
  - The ultimate goal, and the roadmap to get there

Close to home…



Robinson et al. 2014

…and further afield



Seager, Deming, & Valenti 2009

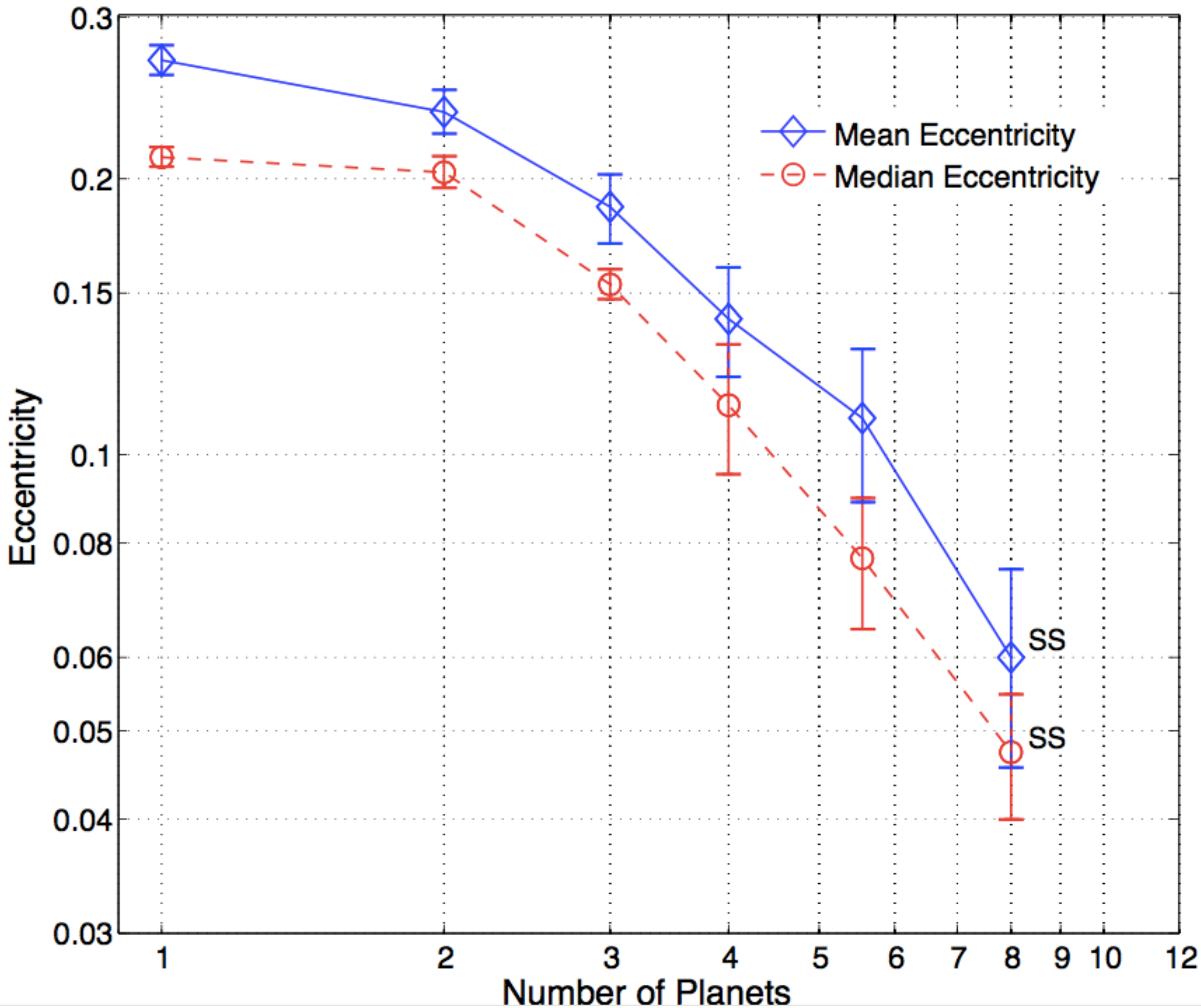
"Major Spectroscopic Features and Signal-to-Noise of a Transiting Earth for a Total Co-added Observation Time of 200 hr, for a 6.5 m Space-Based Telescope for the Sun and M stars"

Feature	G2V	M0V	M1V	M2V	M3V	M4V	M5V	M6V	M7V	M8V	M9V
O_3	16.9	9.1	9.7	8.9	8.6	9.2	9.4	9.5	9.6	8.6	9.6
H_2O	4.8	5.0	6.0	6.2	6.6	7.9	10.5	13.0	14.7	14.9	18.9
CO_2	8.5	9.7	11.7	12.3	13.3	16.1	22.2	28.2	32.5	33.7	43.4
H_2O	11.0	12.8	15.5	16.4	17.7	21.6	30.1	38.5	44.6	46.4	60.2
CH_4	2.0	2.5	3.1	3.3	3.6	4.5	6.5	8.5	9.9	10.5	13.8
O_3	6.2	7.8	9.5	10.3	11.2	13.9	20.0	26.3	30.9	32.7	43.2
CO_2	5.9	7.5	9.2	9.9	10.9	13.5	19.5	25.8	30.4	32.2	42.6

Kaltenegger & Traub (2009)

…assuming every transit is observed, 200 hours of transit data for a planet in the habitable zone of an M3V star (period of 25 days) will require a 4.9 year baseline

Multiplicity and Habitability



Limbach & Turner, 2014

TESS Science Goals and Drivers

MIT-led Mission: NASA, Orbital Sciences, Harvard-SAO

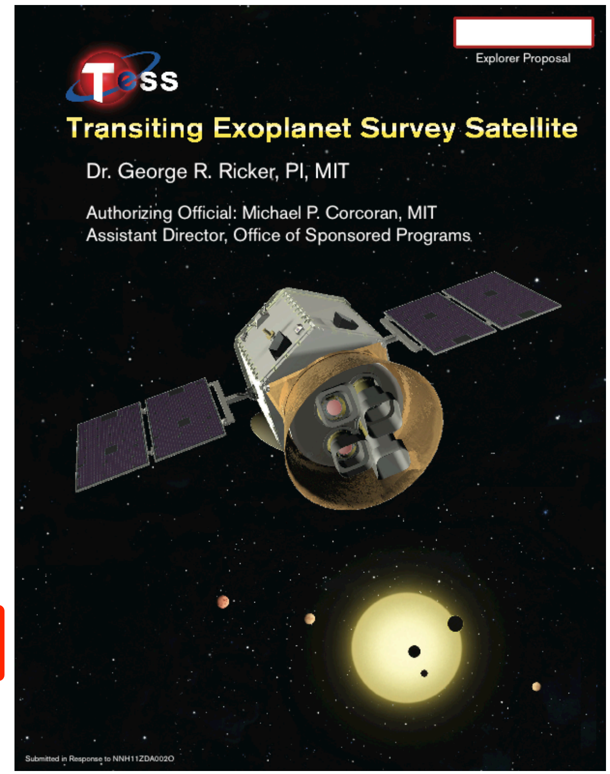
Discover Transiting Earths and SuperEarths around Bright, Nearby Stars

- Rocky planets
- Water worlds
- Habitable zone planets

Discover 1000+ Exoplanets

All Sky Survey of Bright Stars

- ~40000 deg^2 (~400 x Kepler)
- F, G, K dwarf stars: 4.5 to 12 magnitude
- M stars known within 50 pc (=150 l-yr)
- 500,000 stars in two years



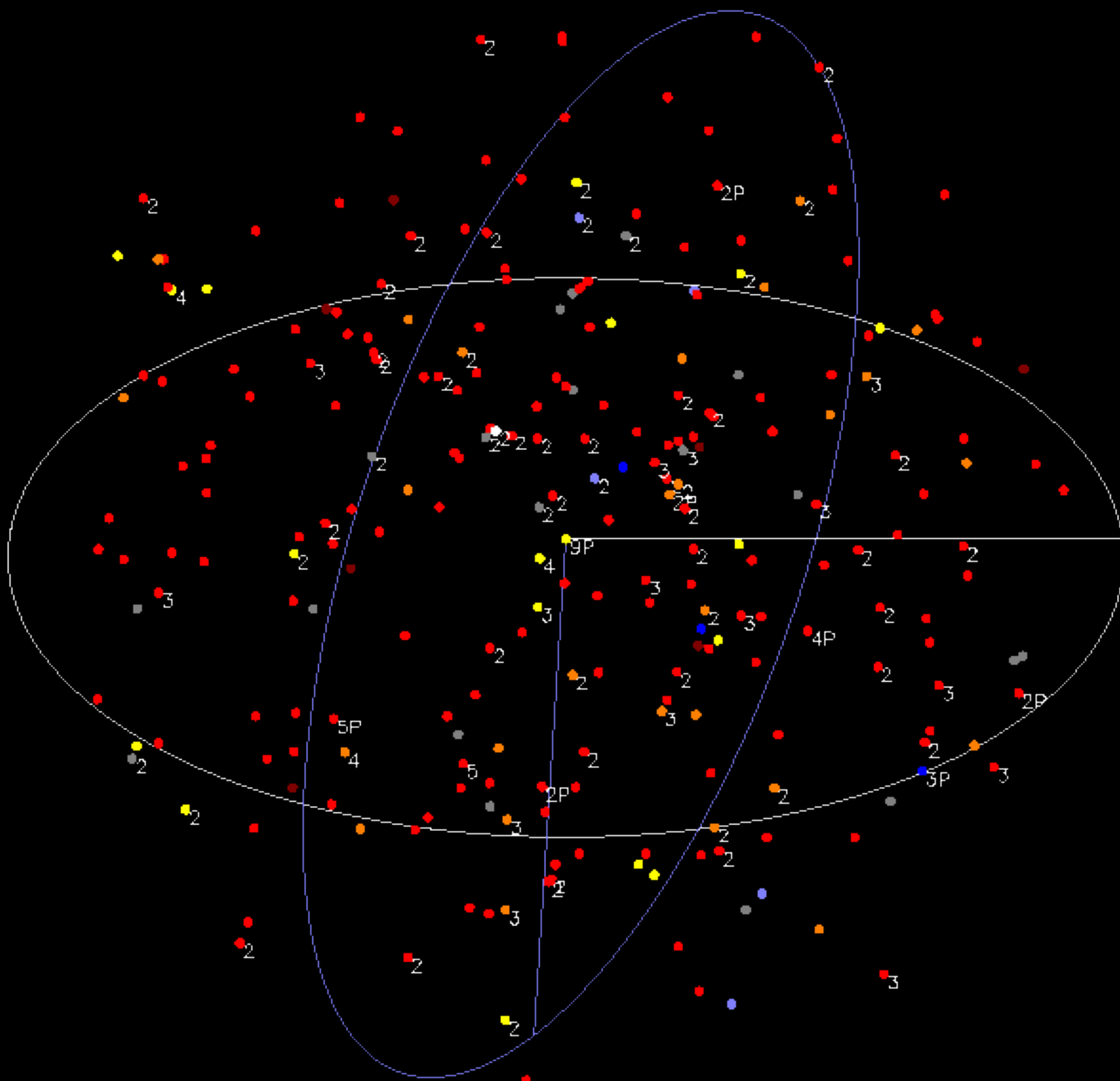


Image: Riedel, Henry, & RECONS group

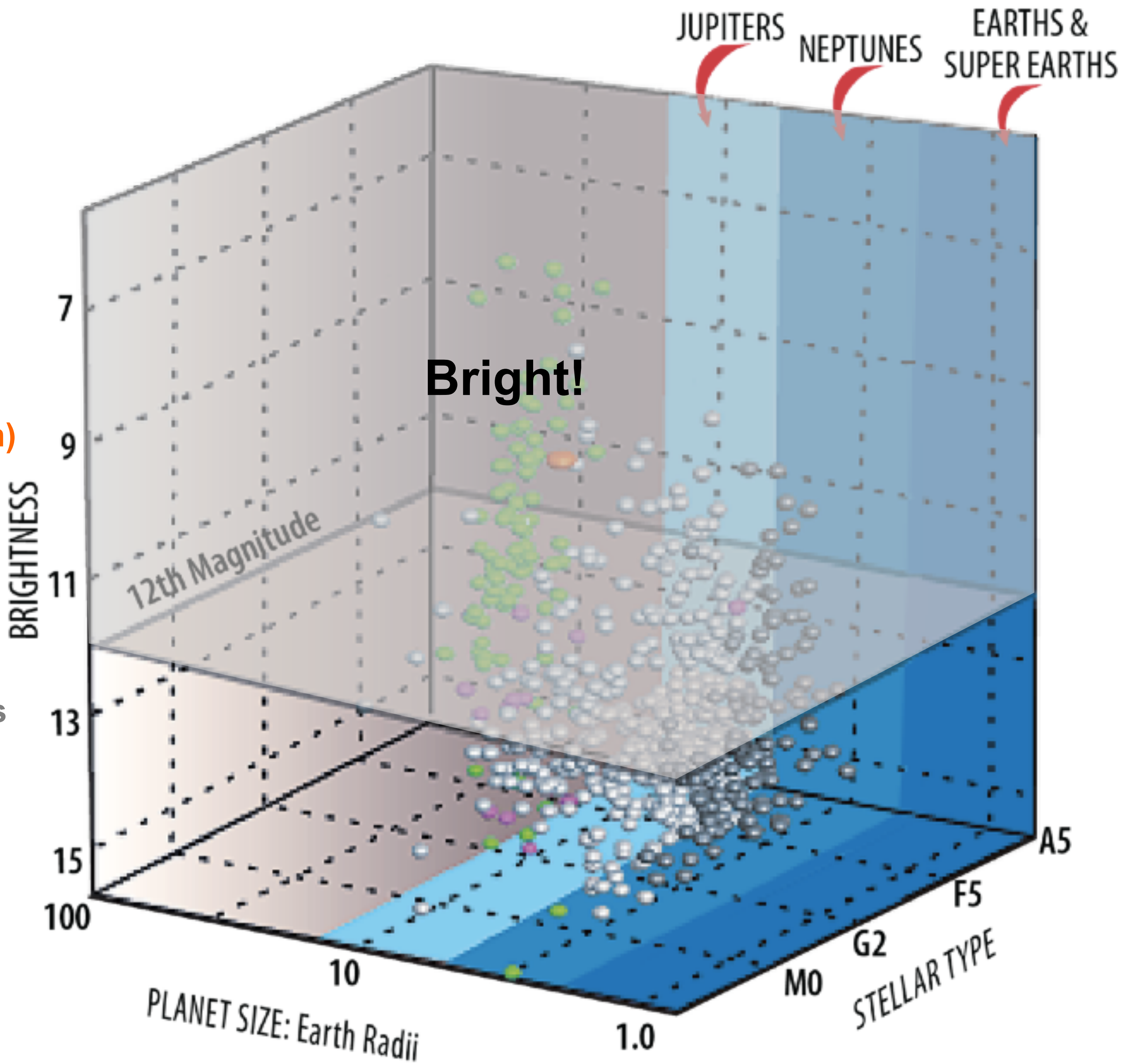
Discovered by:

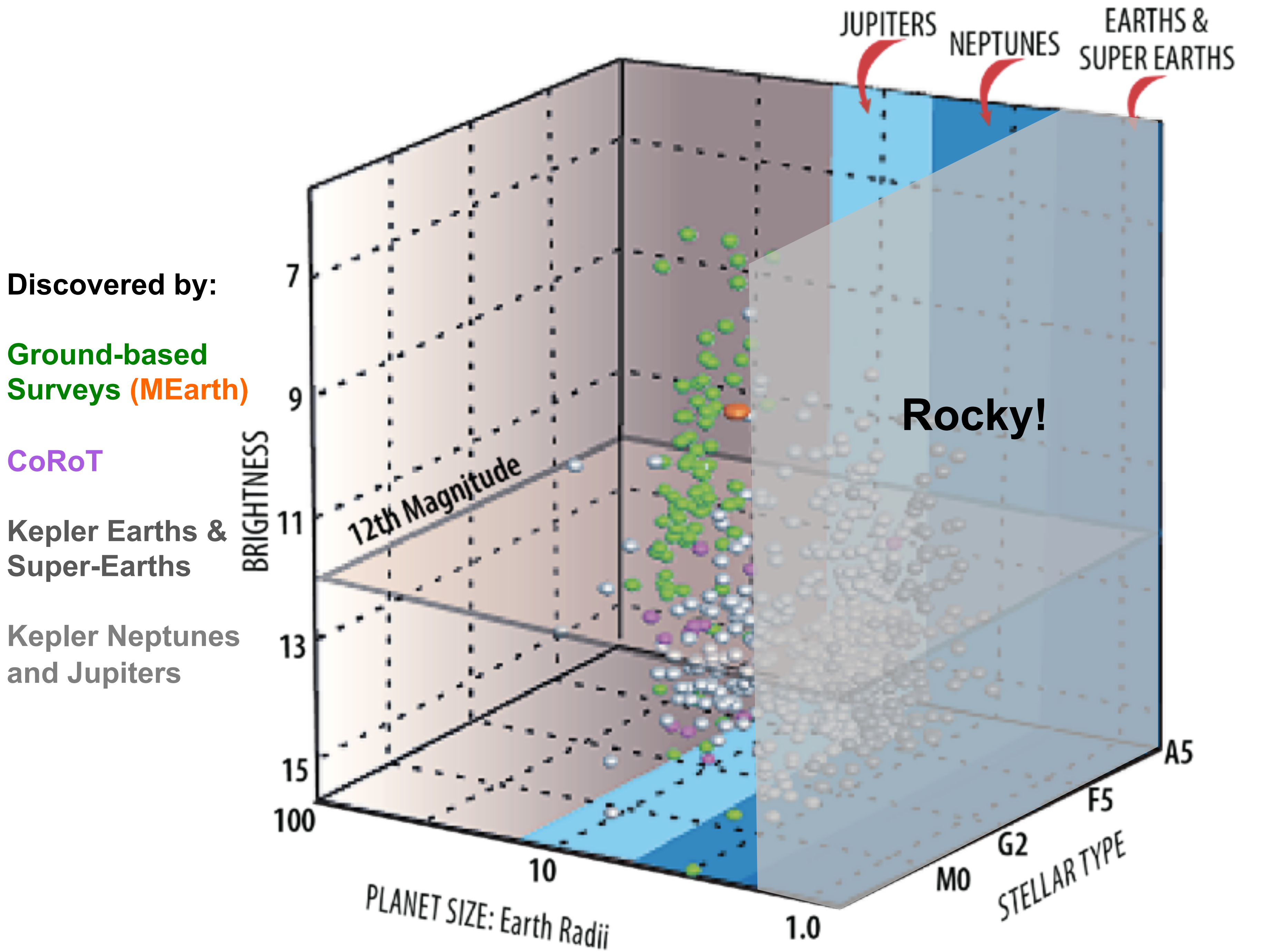
Ground-based Surveys (MEarth)

CoRoT

Kepler Earths & Super-Earths

Kepler Neptunes and Jupiters





Discovered by:
Ground-based Surveys (MEarth)
CoRoT
Kepler Earths & Super-Earths
Kepler Neptunes and Jupiters
JUPITERS
NEPTUNES
EARTHS & SUPER EARTHS
Rocky!
12th Magnitude
BRIGHTNESS
7
9
11
13
15
100
10
1.0
PLANET SIZE: Earth Radii
M0
G2
F5
A5
STELLAR TYPE

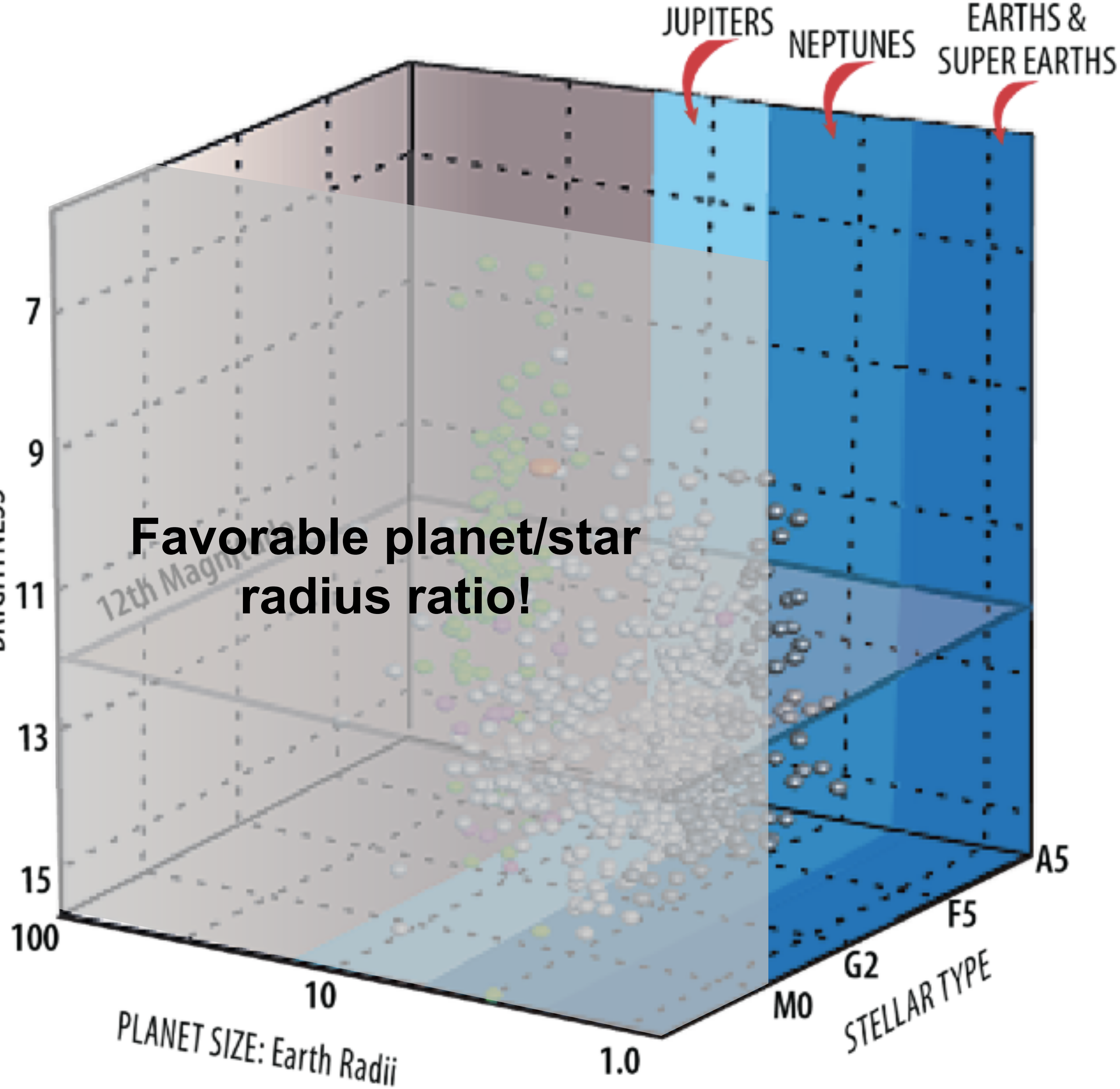
Discovered by:

Ground-based Surveys (MEarth)

CoRoT

Kepler Earths & Super-Earths

Kepler Neptunes and Jupiters



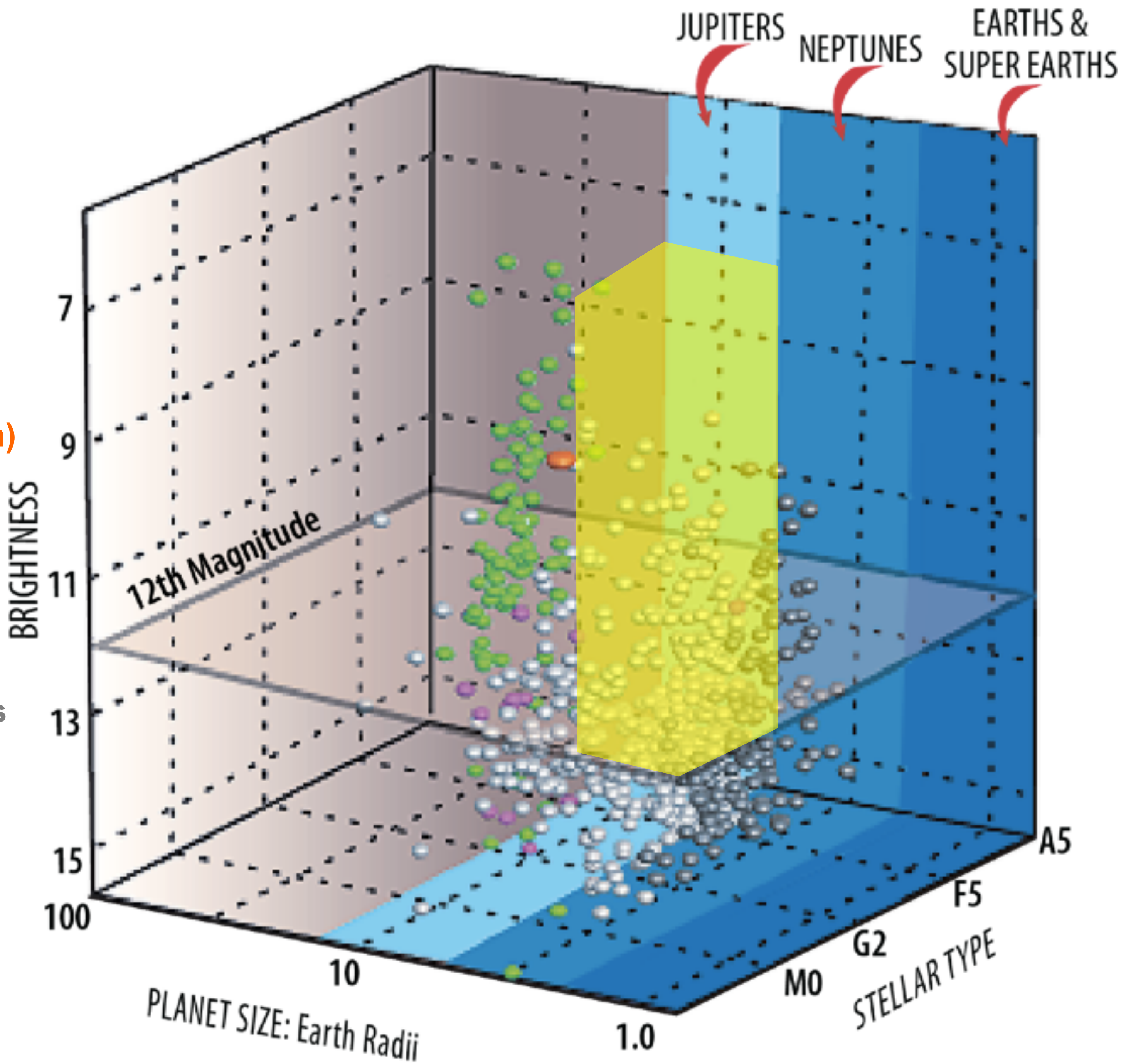
Discovered by:

Ground-based Surveys (MEarth)

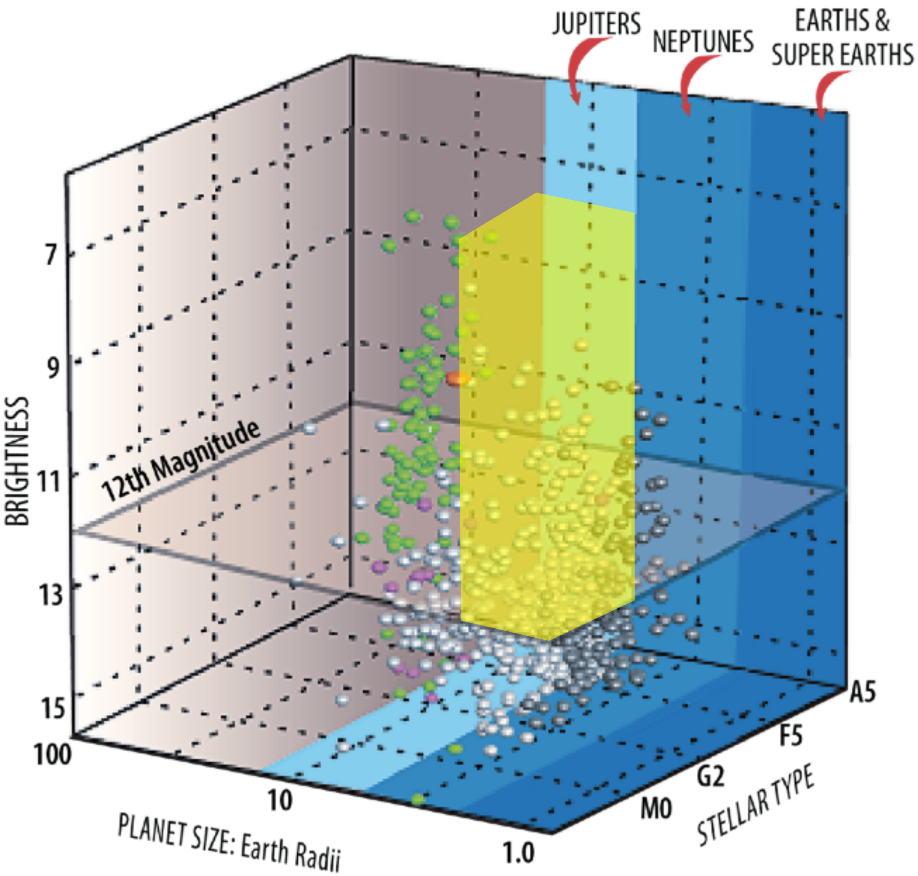
CoRoT

Kepler Earths & Super-Earths

Kepler Neptunes and Jupiters



~a handful of *Kepler* planets



Dozens of *TESS* planets

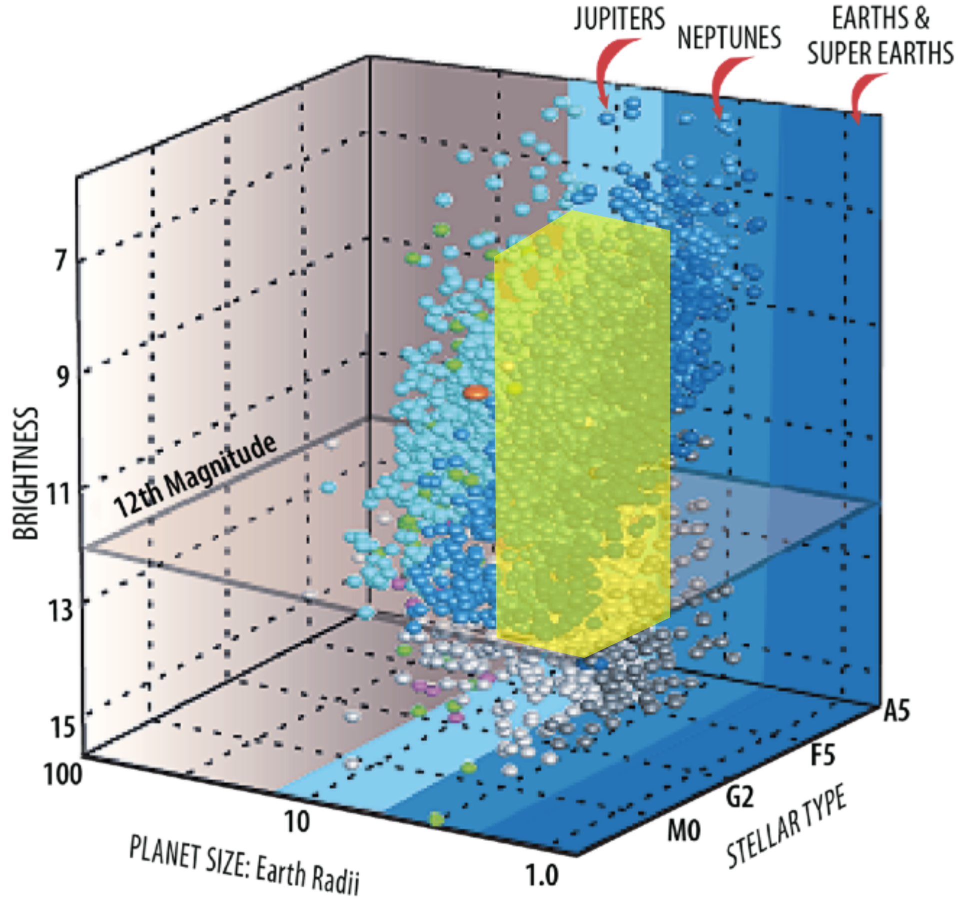
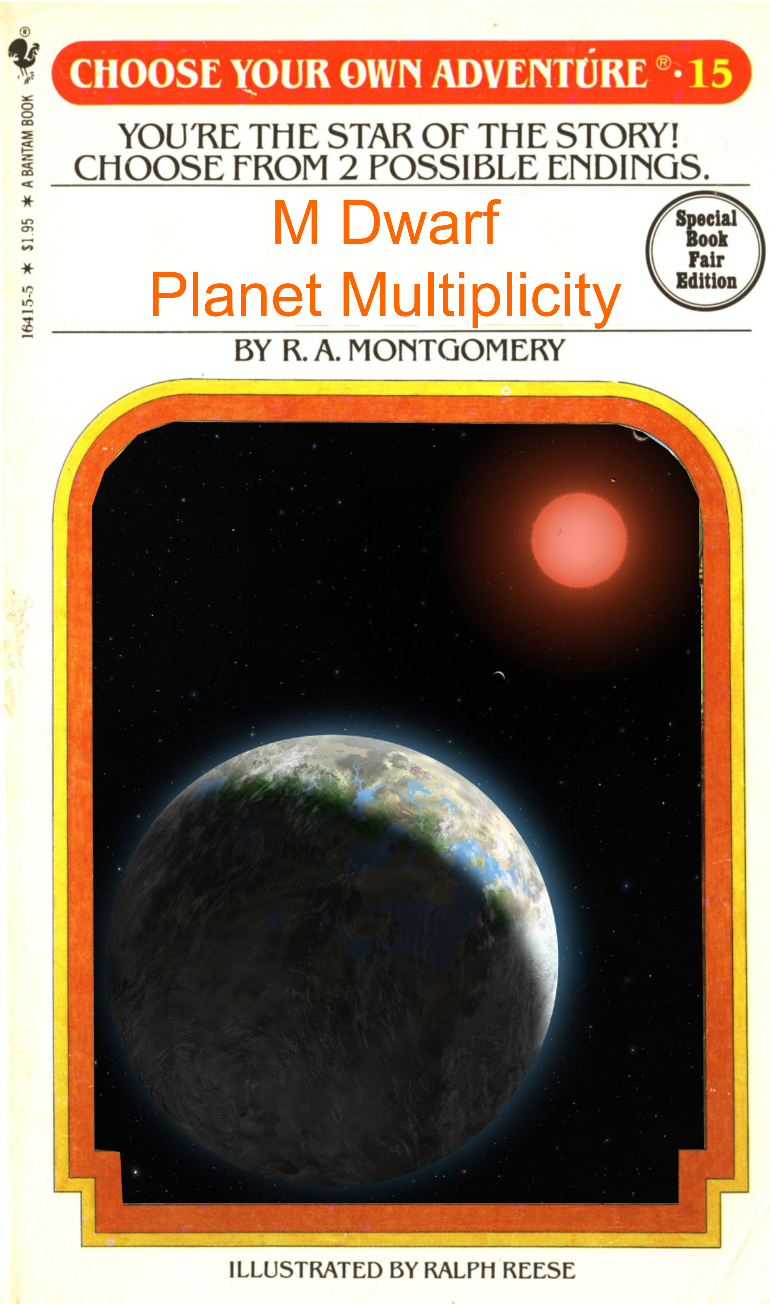


Figure from D. Charbonneau



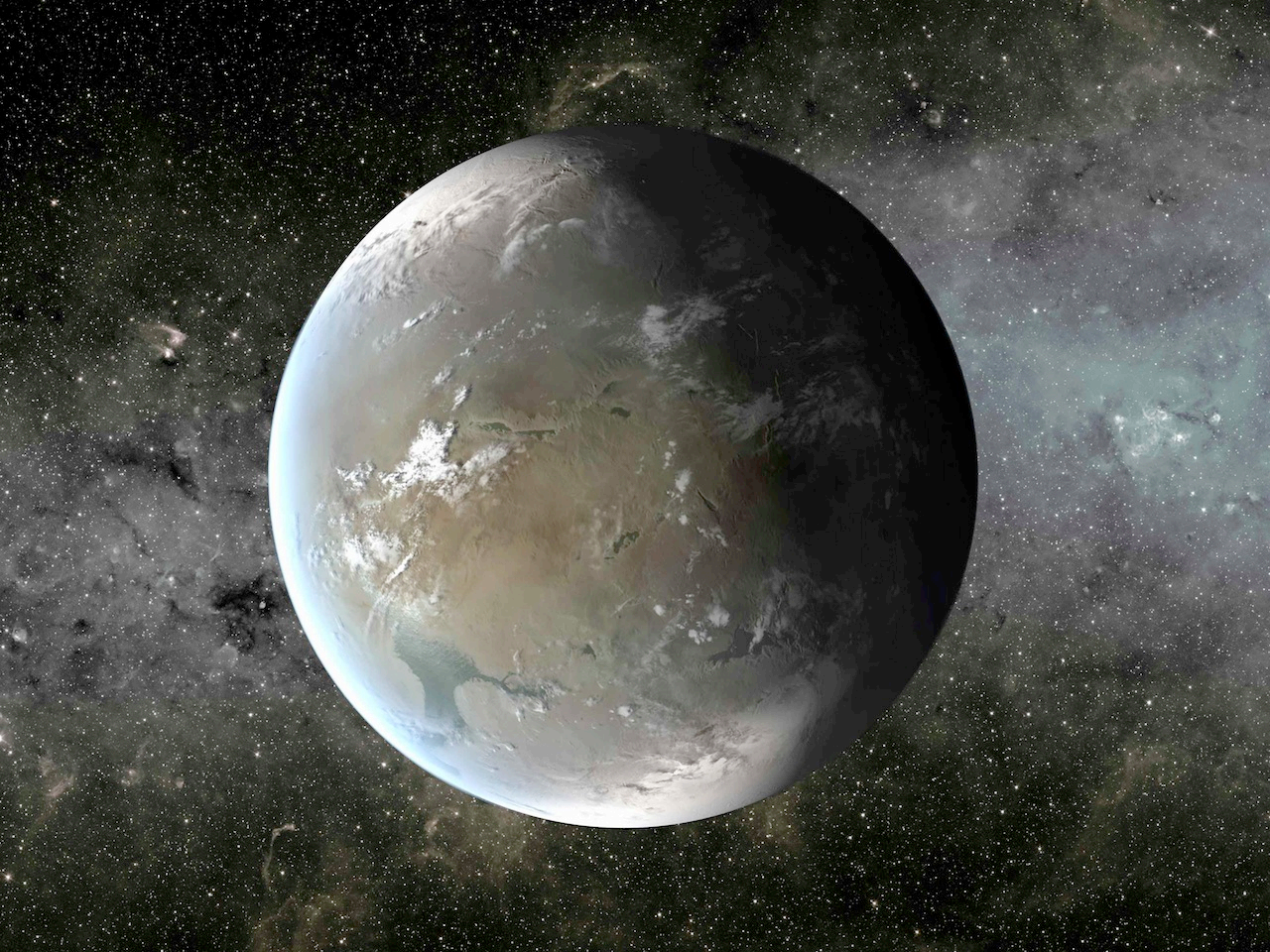
Conclusions

Kepler multiples inform our understanding of the true number of planets per star, and their inclinations

Stars hosting 2 or more planets can be explained with a single model similar to the Solar System, but too many singles to be consistent with this model (robust to selection effects)

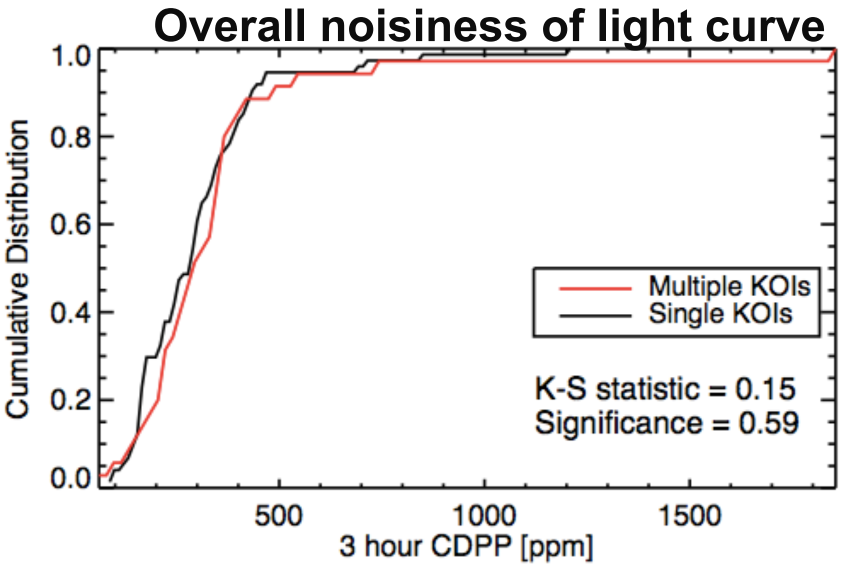
The data better support two scenarios (where each occurs ~50% of the time) by 21:1 odds. Metallicity, rotation period, and galactic height modestly predictive.

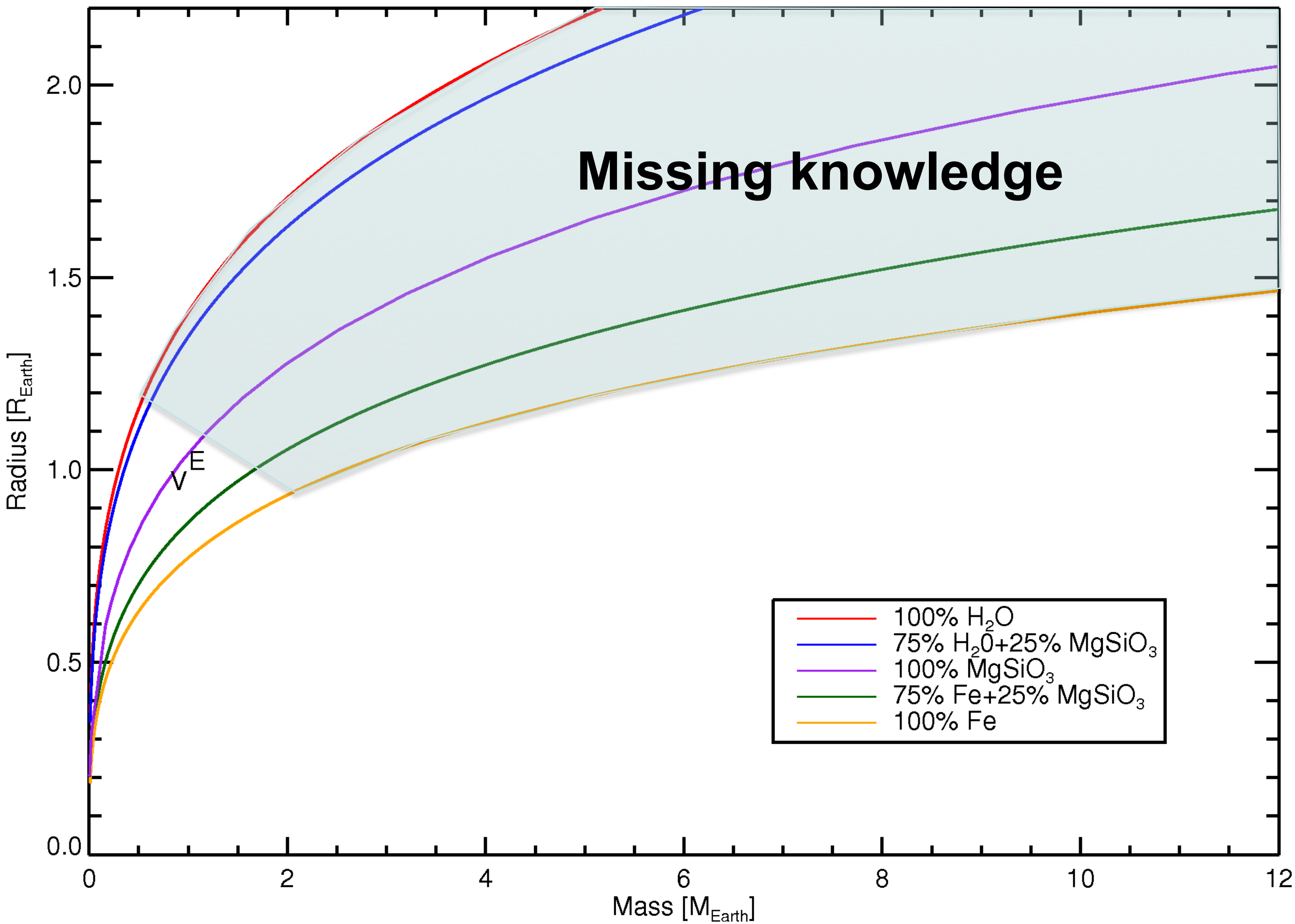
The big picture: setting ourselves up for the highest exoplanet science return for JWST



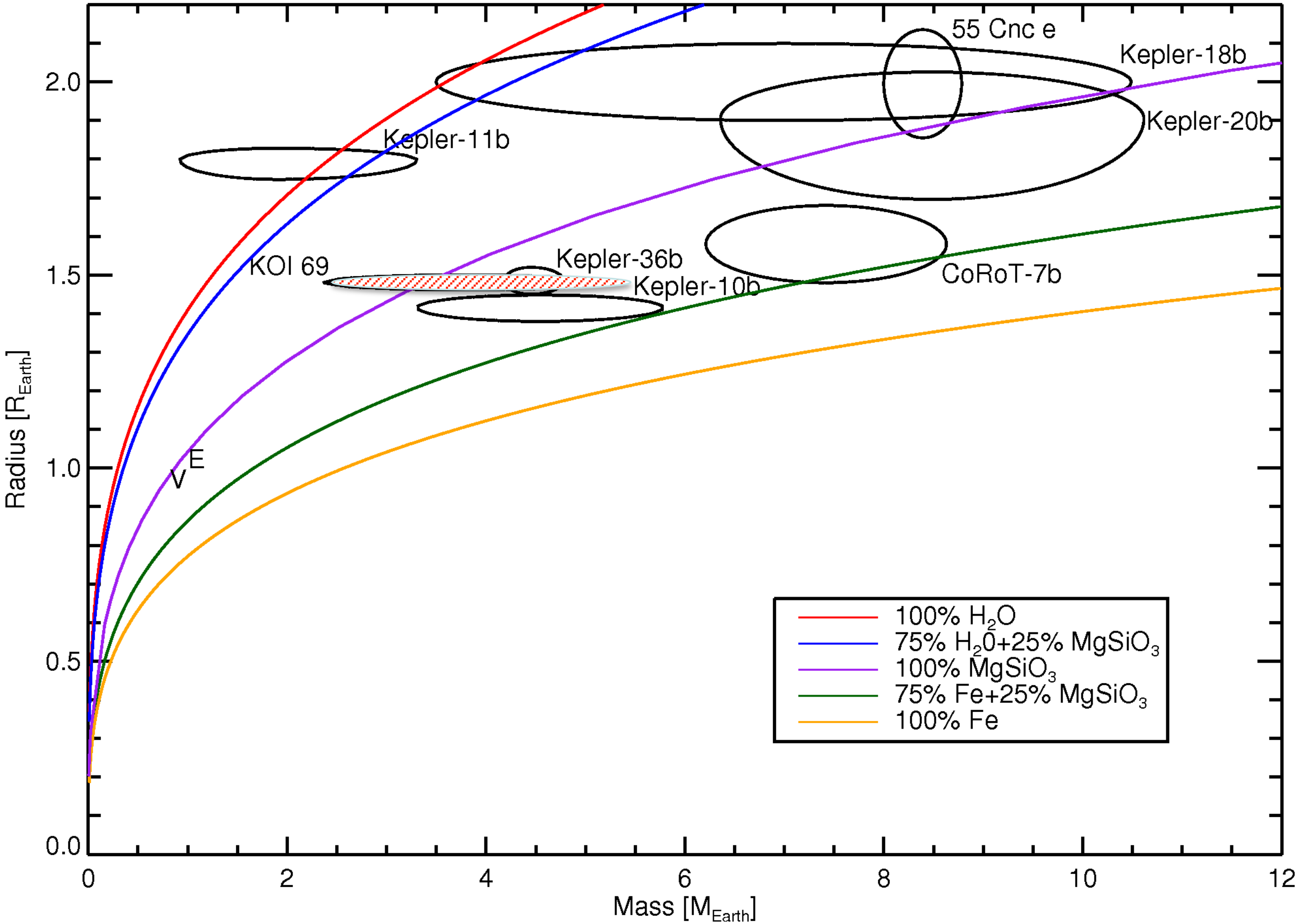
Selection Bias Sanity Check

Black = singles, Red = multiples





Missing knowledge
V
E
100% H_2O
75% H_20+25% $MgSiO_3$
100% $MgSiO_3$
75% Fe+25% $MgSiO_3$
100% Fe
Radius [R_{Earth}]
Mass [M_{Earth}]
0.0
0.5
1.0
1.5
2.0
0
2
4
6
8
10
12



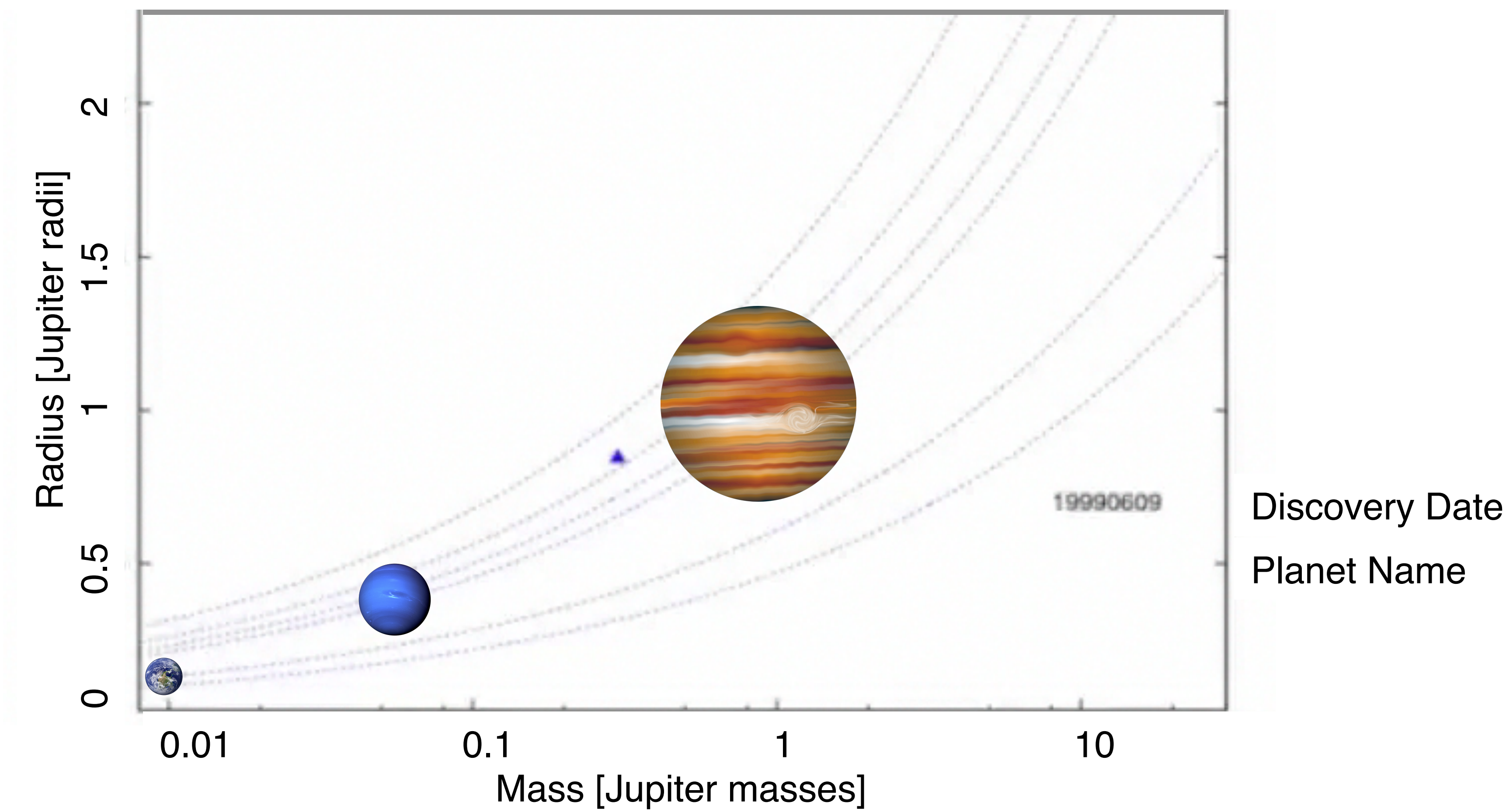
55 Cnc e
Kepler-18b
Kepler-20b
Kepler-11b
KOI 69
Kepler-36b
Kepler-10b
CoRoT-7b
V
E
100% H2O
75% H20+25% MgSiO3
100% MgSiO3
75% Fe+25% MgSiO3
100% Fe
Radius [REarth]
Mass [MEarth]
0.0
0.5
1.0
1.5
2.0
0
2
4
6
8
10
12

Pair Discussion

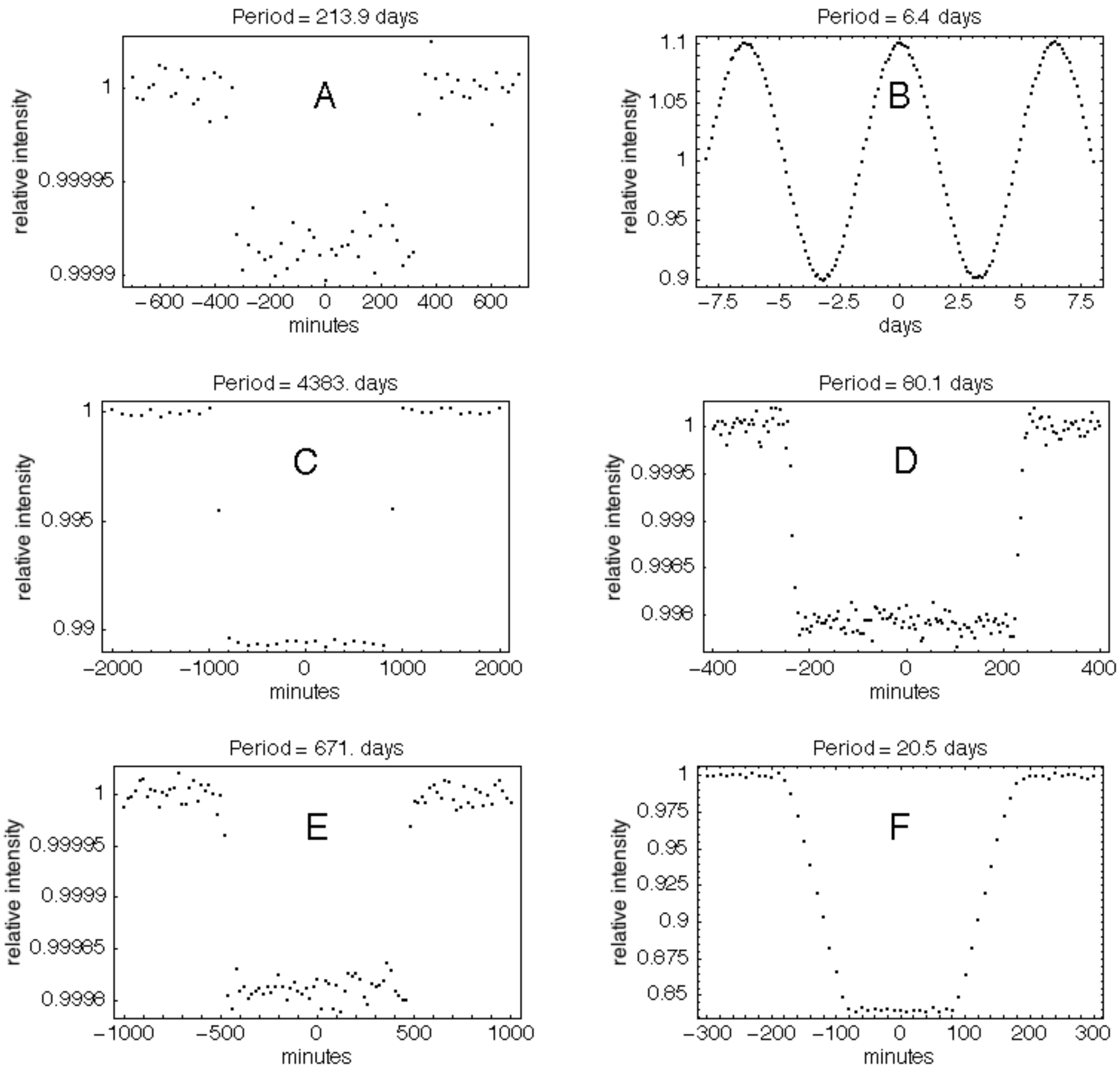
- How is the transit affected by:
  - Planet size?
  - Planet mass?
  - Star mass?
  - Semi-major axis?

- Would you expect to see more or less planets in transit for a system that had an inclination slightly less than 90 degrees?

“The Well-Tempered Exoplanets”



Video: Prof. Gaspar Bakos



Synthetic transits around sun:

A = close-in Earth

B = variable star

C = Jupiter

D = “Neptune” (5 R_E)

E = "SuperEarth” (10 R_E)

F=binary star

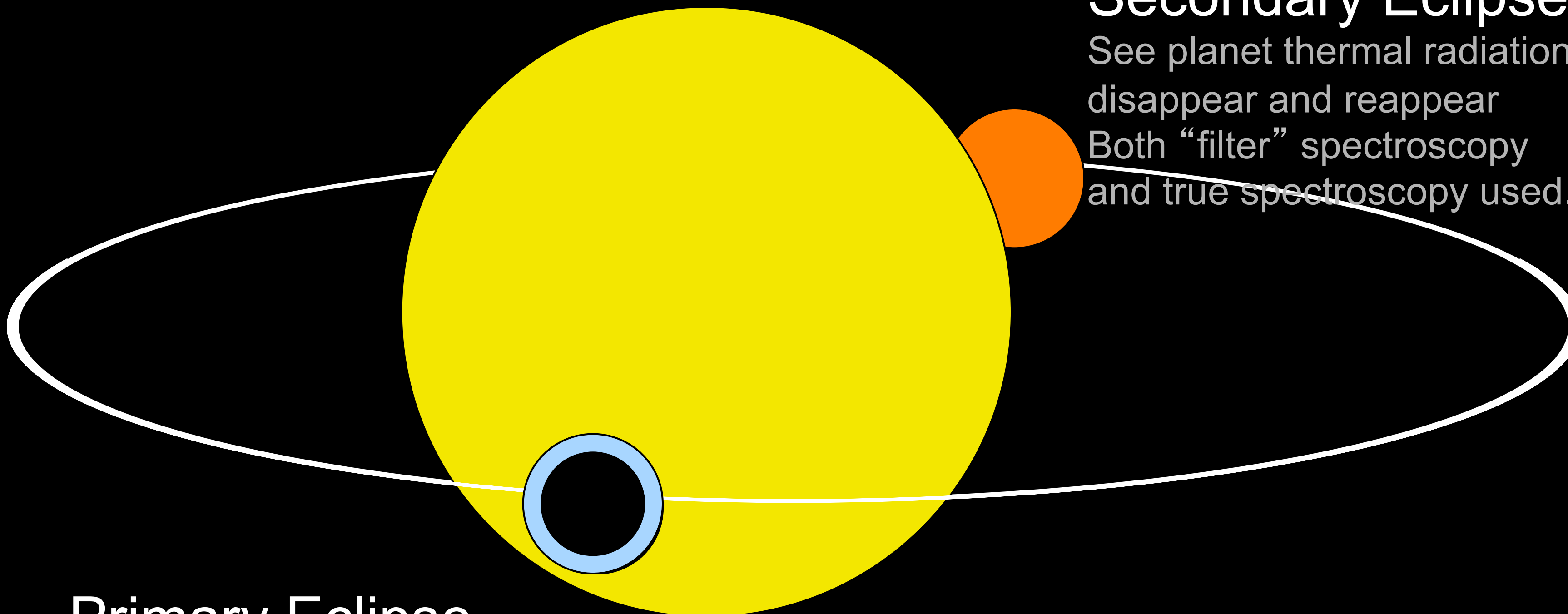
All images: R_{star}=1.0 R_{sun}

What Can We Learn From Transits?

Secondary Eclipse

See planet thermal radiation disappear and reappear

Both “filter” spectroscopy and true spectroscopy used.



Primary Eclipse

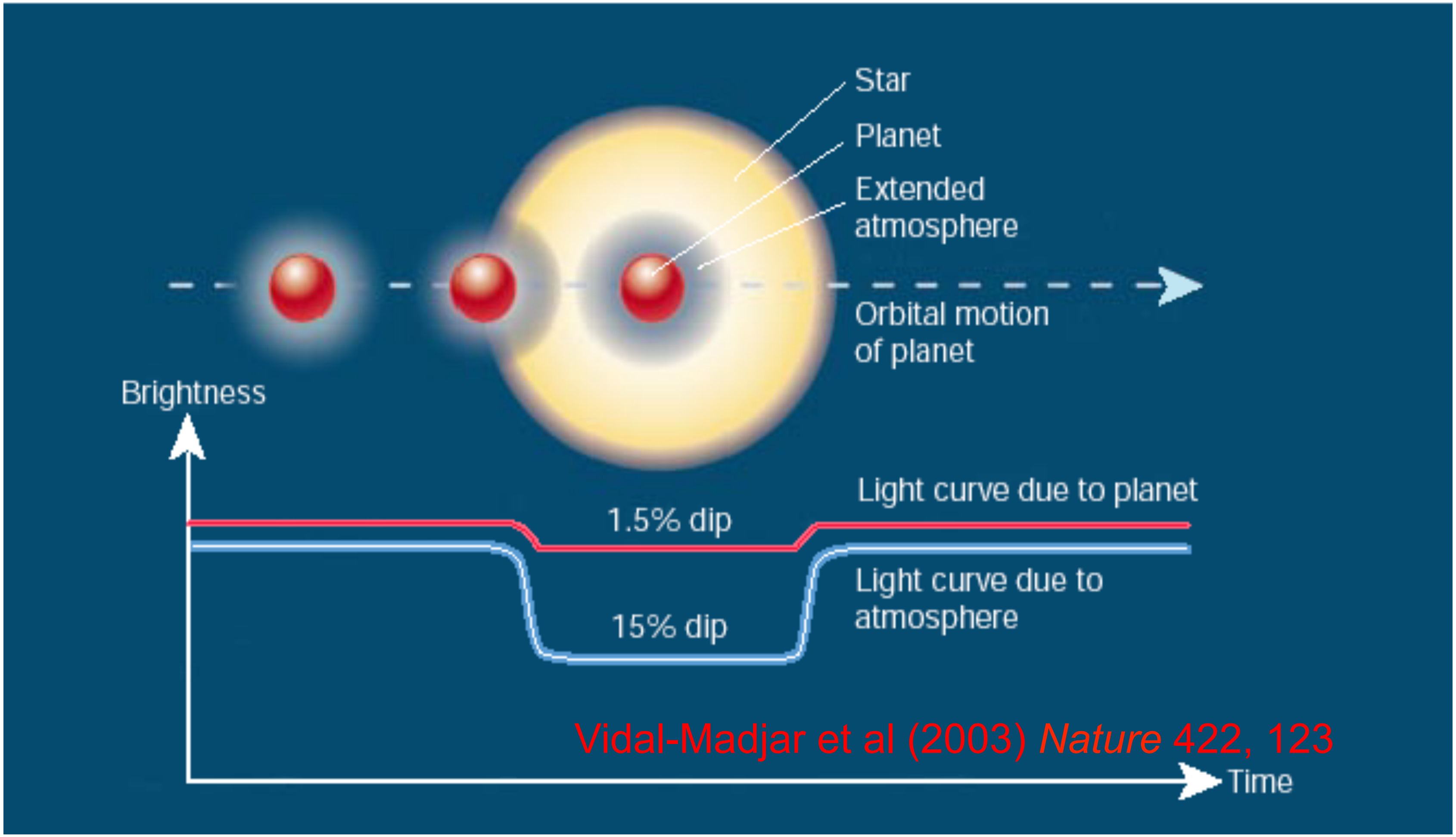
Measure size of planet

See star’s radiation transmitted through the planet atmosphere.

Used high-resolution vis spectrometer or lower-res IR

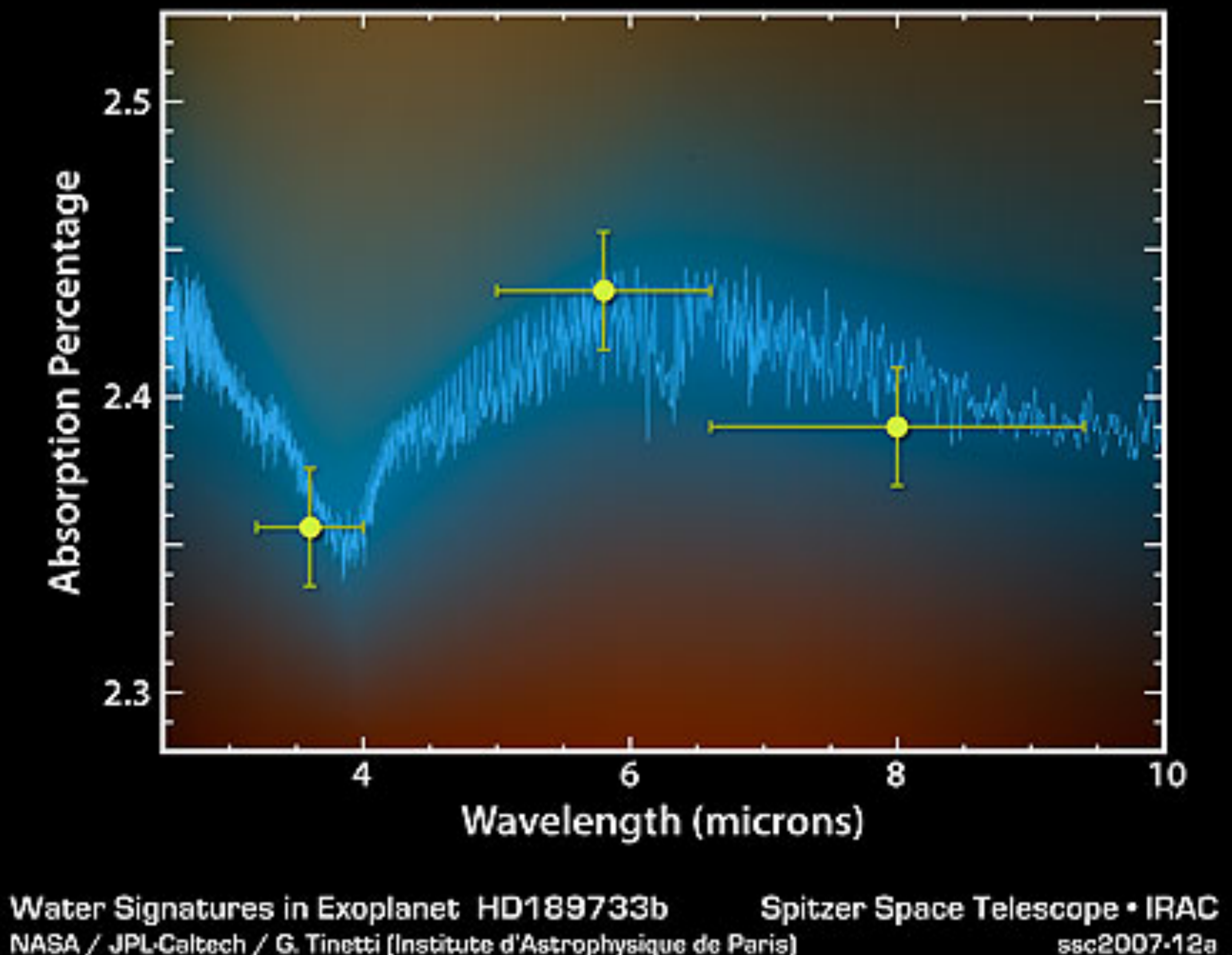
Learn about atmospheric circulation from thermal phase curves

Transmission Spectroscopy



In some cases, the planet's atmosphere is sufficiently "puffy" that light from the star can pass through it during the transit. Molecules in the planet's atmosphere can be detected this way.

Transmission Spectroscopy

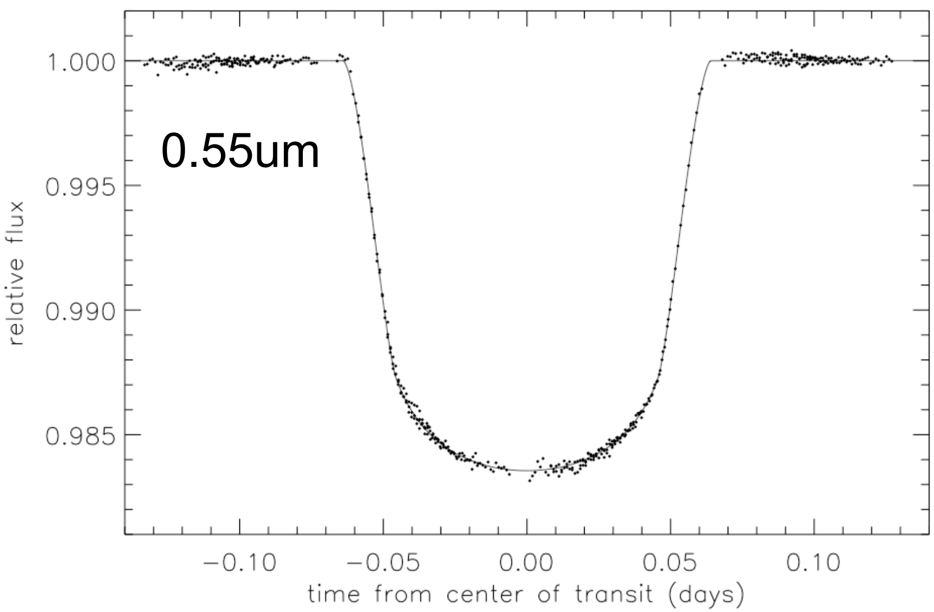


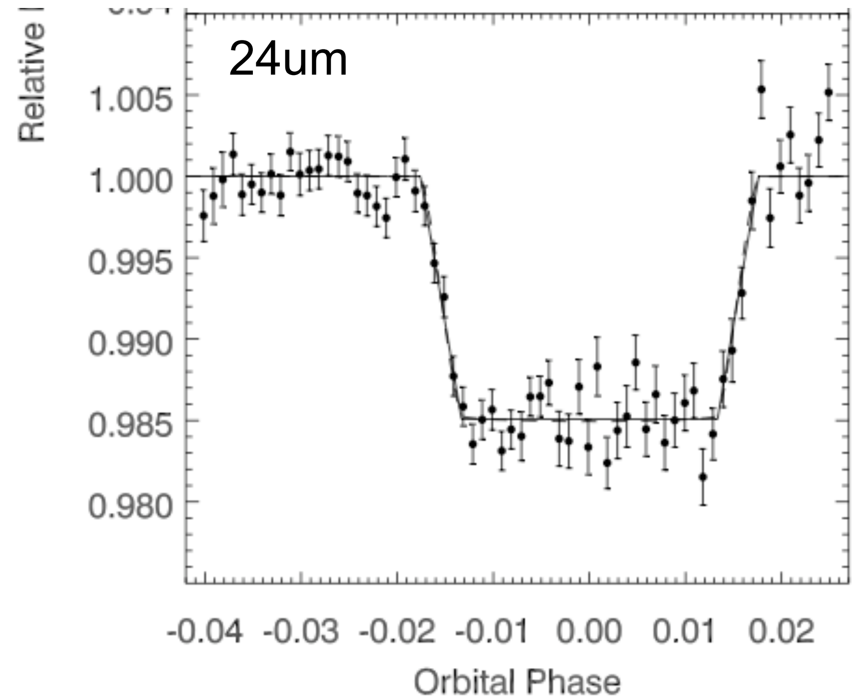
- Differential observations taken at different filter bands in and out of transit.

Secondary Eclipse

- Builds on the transit discovery to characterize the planet
  - Technically a “direct detection” method.
- Uses a telescope to watch the planet pass BEHIND its parent star.
- This "secondary eclipse" can be measured to determine exactly how much light is coming from just the planet.
  - Works best in the IR where Ls/Lp ~ 100 vs in the visible, where Ls/Lp > 10000
  - Secondary eclipses at different infrared wavelengths reveal planetary temperature, composition and the shape of the planetary orbit.

Transits at Different Wavelenths





HST: Brown et al., 2001.

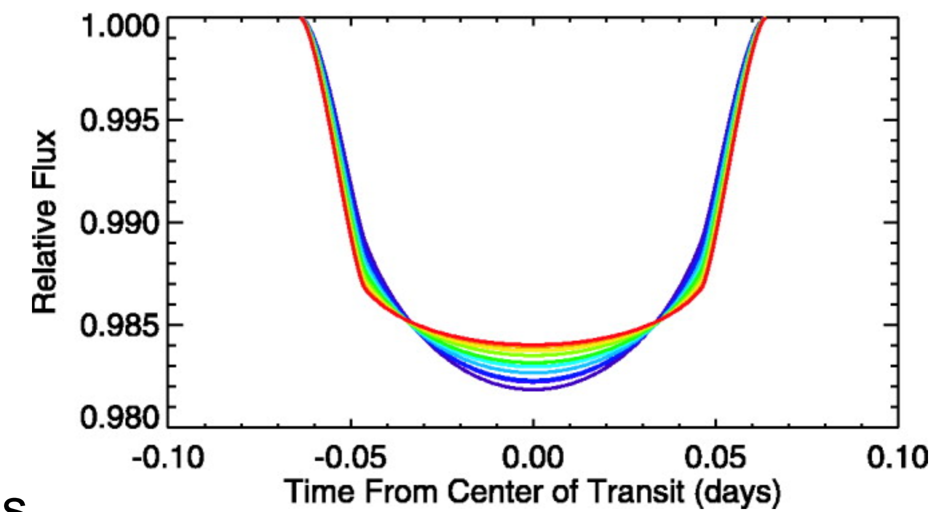
Spitzer: Richardson et al., 2006.

How big is this planet?

What differences can you see between the lightcurves?

Limb Darkening

- Limb darkening: the diminishing of intensity in a star image from the center to the edge or “limb”.
- Longer pathlengths at the limb reach τ=1 at a higher, cooler atmospheric levels.
- At blue wavelengths small changes in temperature result in large drops in brightness.
- At red and infrared wavelengths changes in temperature result in very small changes in brightness.
- Stars look a different size at different wavelengths



Knutson et al. 2006