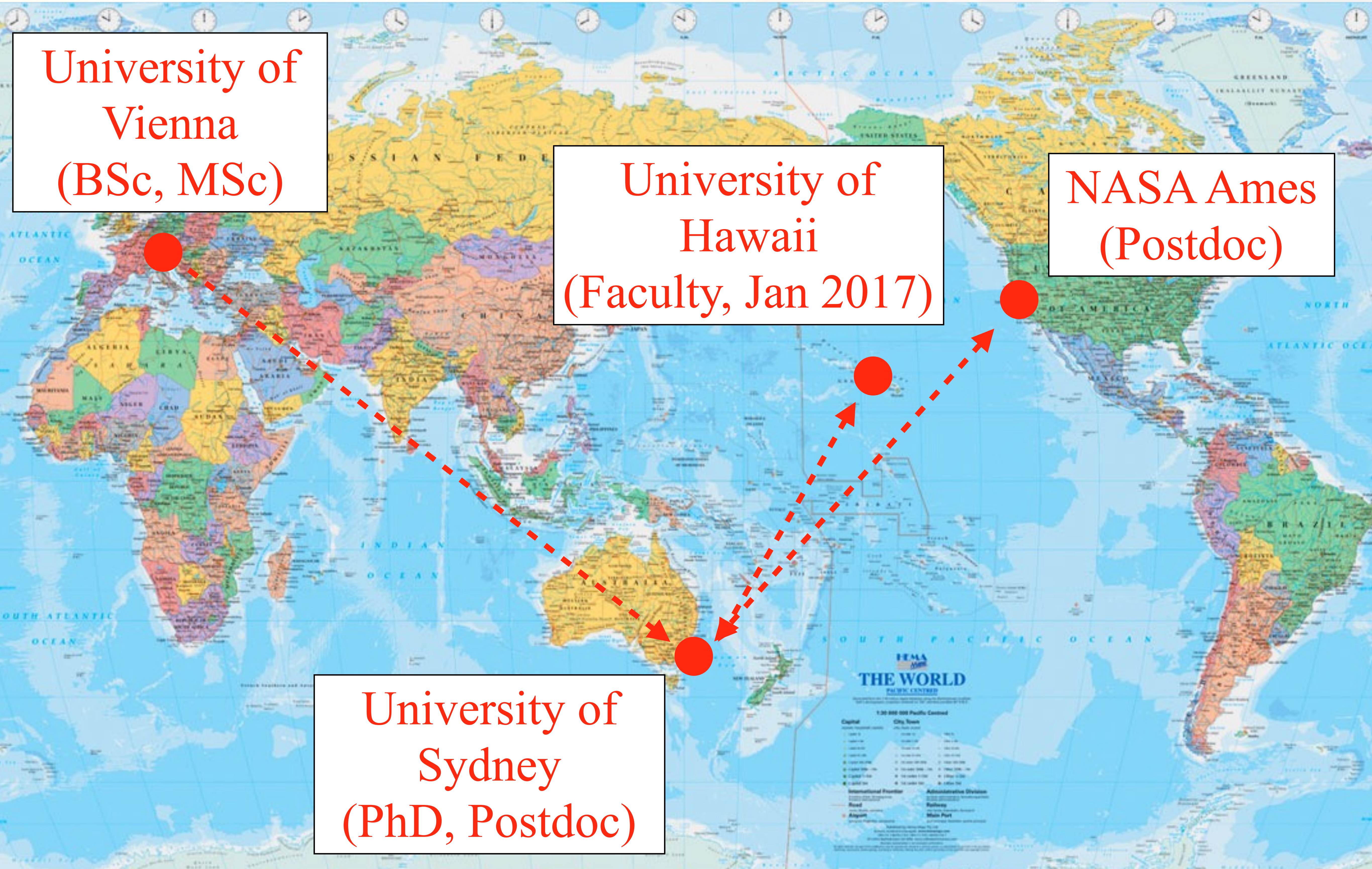
Synergies between Asteroseismology and Exoplanet Science

Daniel Huber

University of Sydney

4th Azores Summer School July 2016

How did I get here?

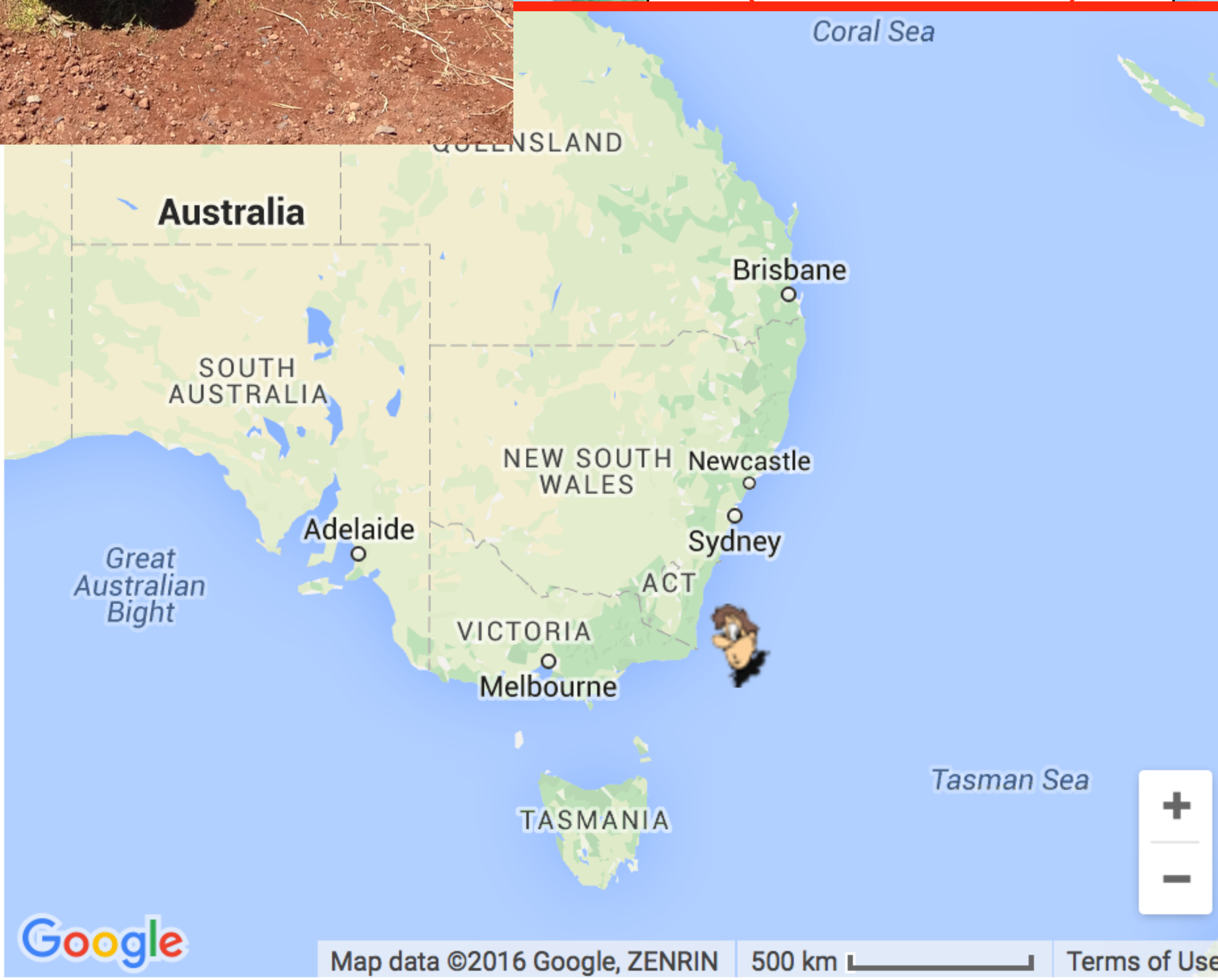


Ho ere?

University of Vienna (BSc, MSc)

NASA Ames (Postdoc)

http://www.antipodesmap.com/



Your Location: **Horta, Portugal**
Coordinates: 38.525822148178136, -28.632156355306506

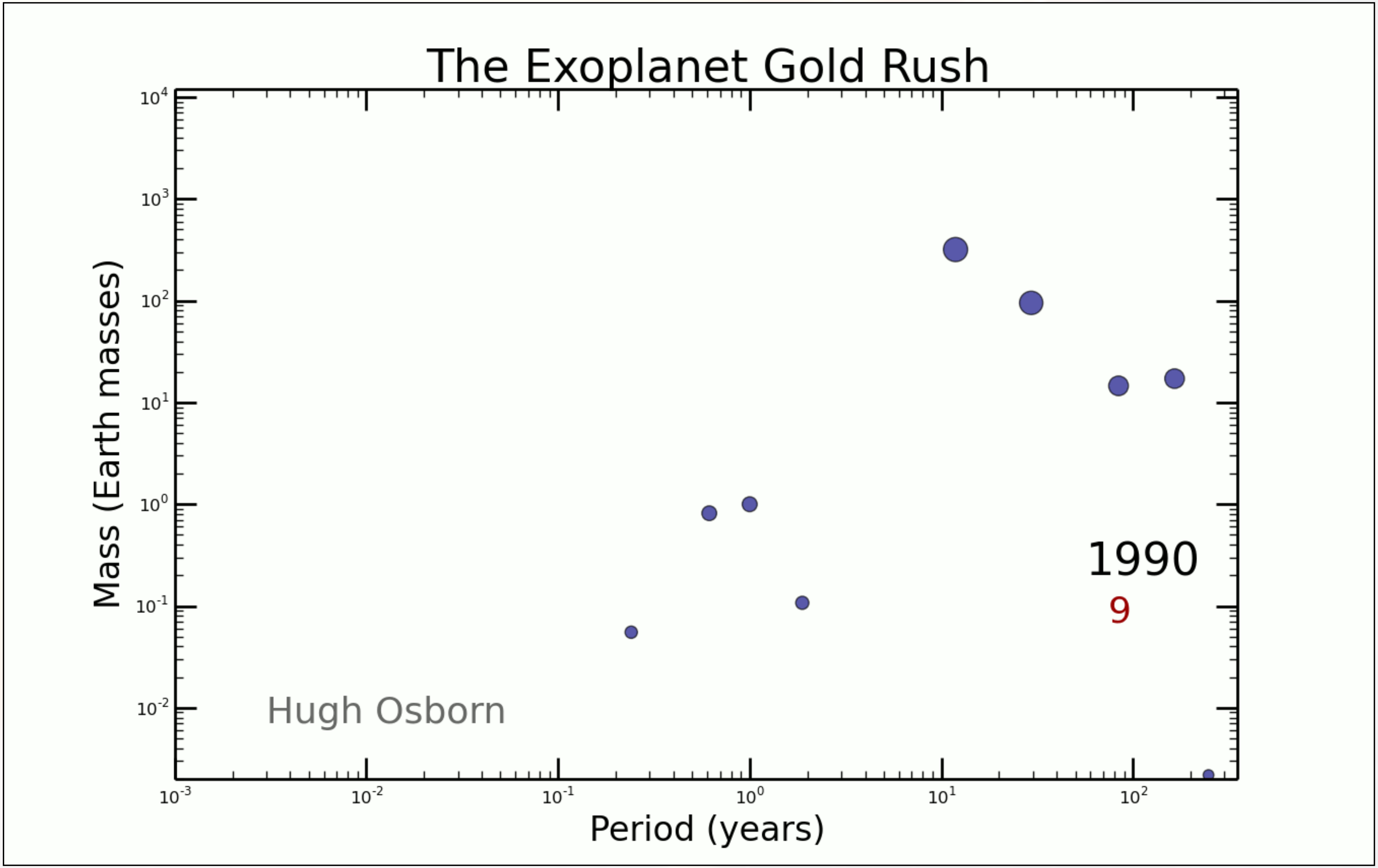
Antipodes Location: **Most likely the ocean. Watch out for sharks.**
Coordinates: -38.525822148178136, 151.3678436446935

Outline

1. Introduction: Know the Star, Know the Planet
2. Exoplanet Radii, Masses & Ages
3. Orbital Eccentricities
4. Obliquities of Exoplanet Systems
5. Chemical Abundances of Exoplanet Host Stars
6. (Brief) Outlook

Introduction:

Know the Star, Know the Planet



The Exoplanet Gold Rush
Mass (Earth masses)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Period (years)
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
1990
9
Hugh Osborn

Key Exoplanet Questions

?

Key Exoplanet Questions

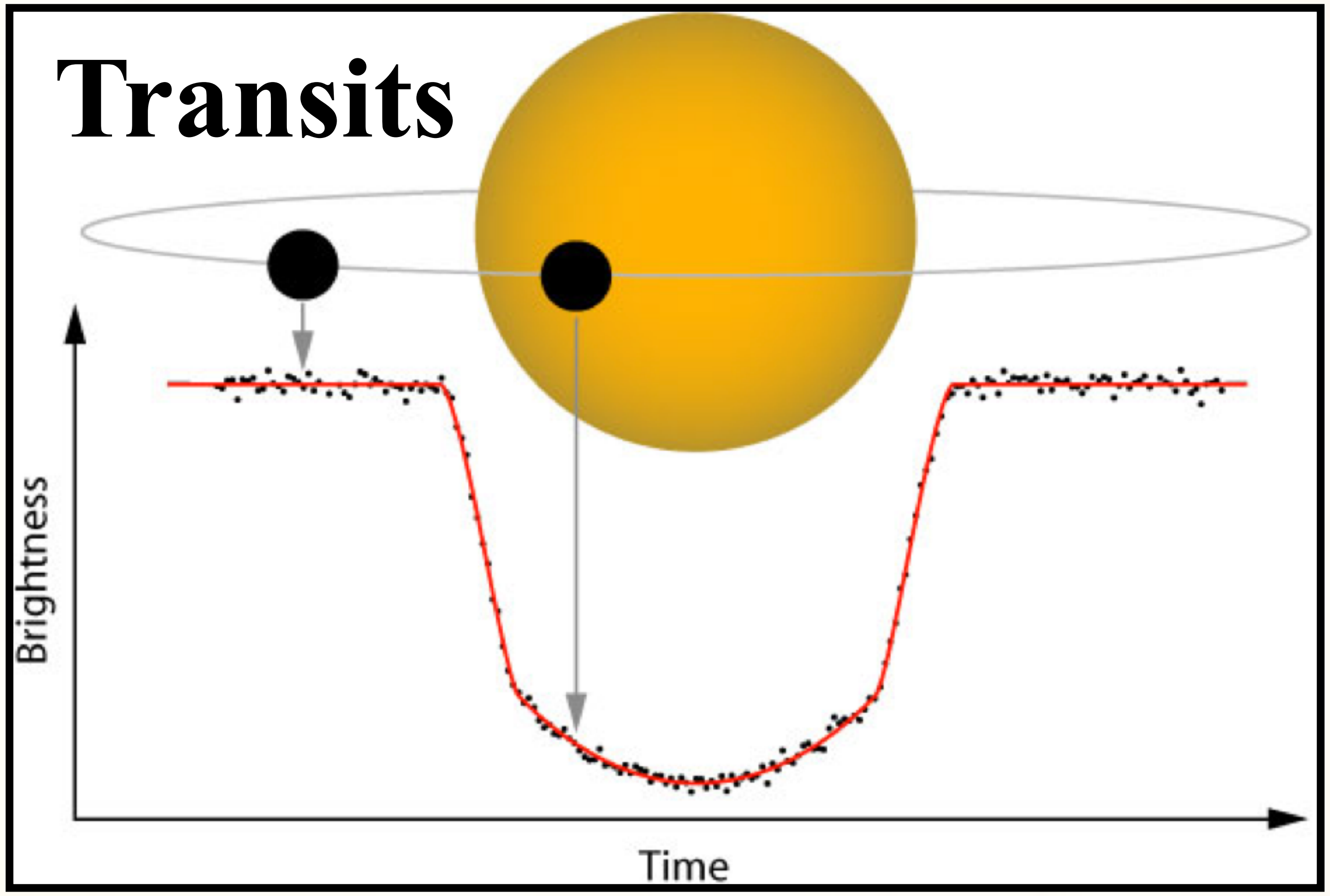
- How did close-in gas giant planets form?
- What are the compositions of exoplanets?
- What are the orbital architectures of typical exoplanet systems?
- What is the occurrence rate of planets as a function of size, spectral type, evolutionary state?
- Are there habitable planets outside the solar system?

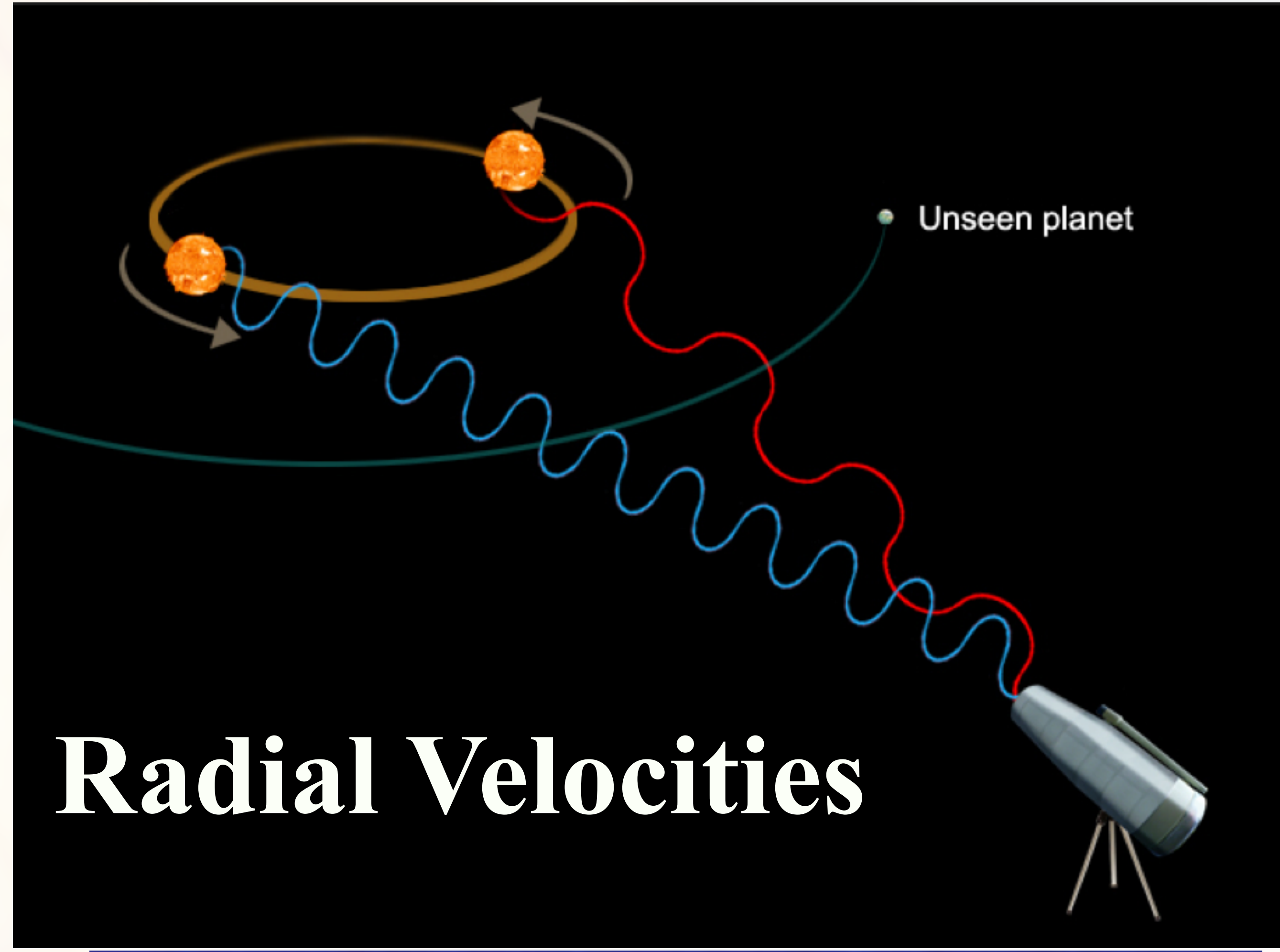
Key Exoplanet Questions

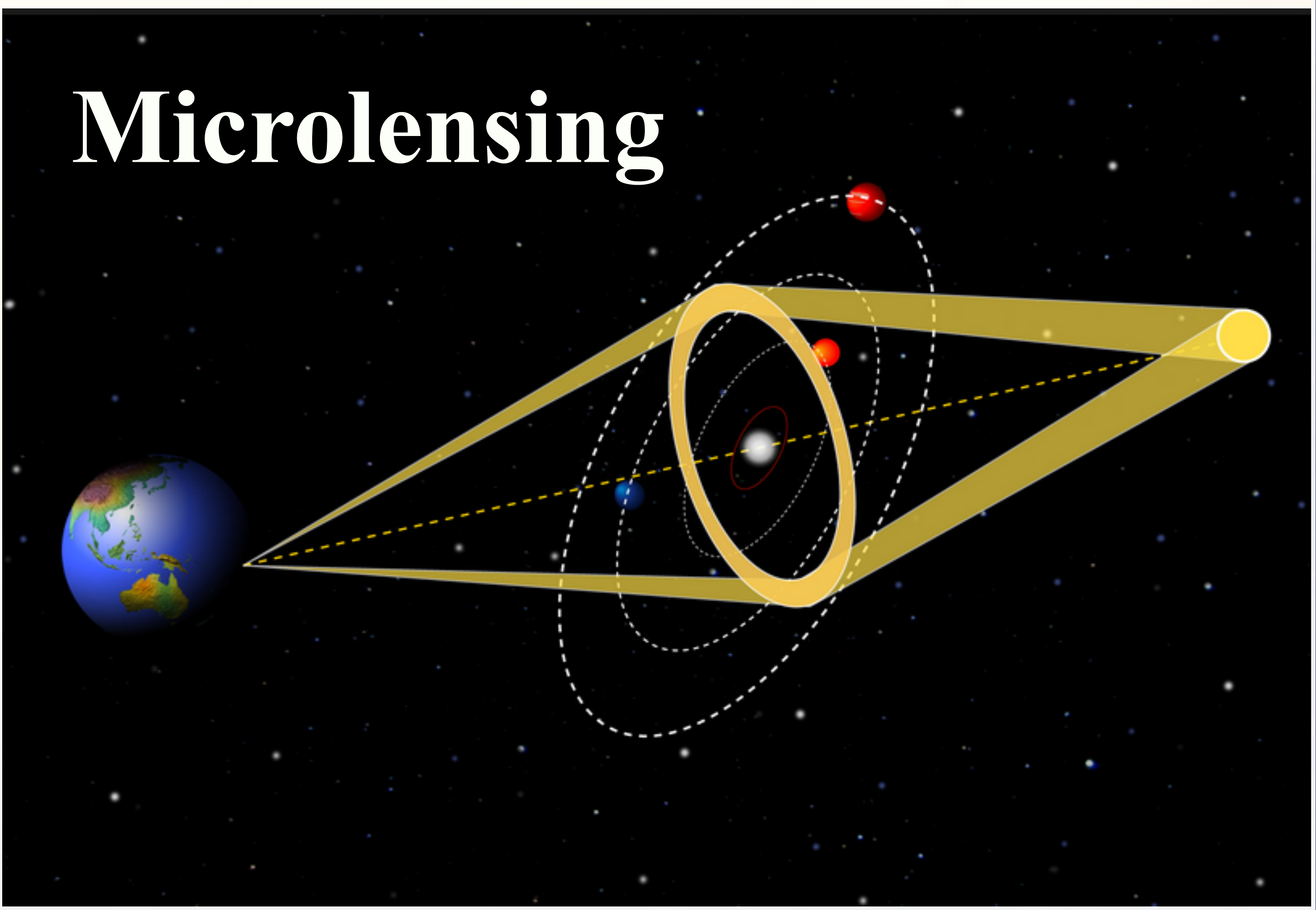
- How did close-in gas giant planets form?

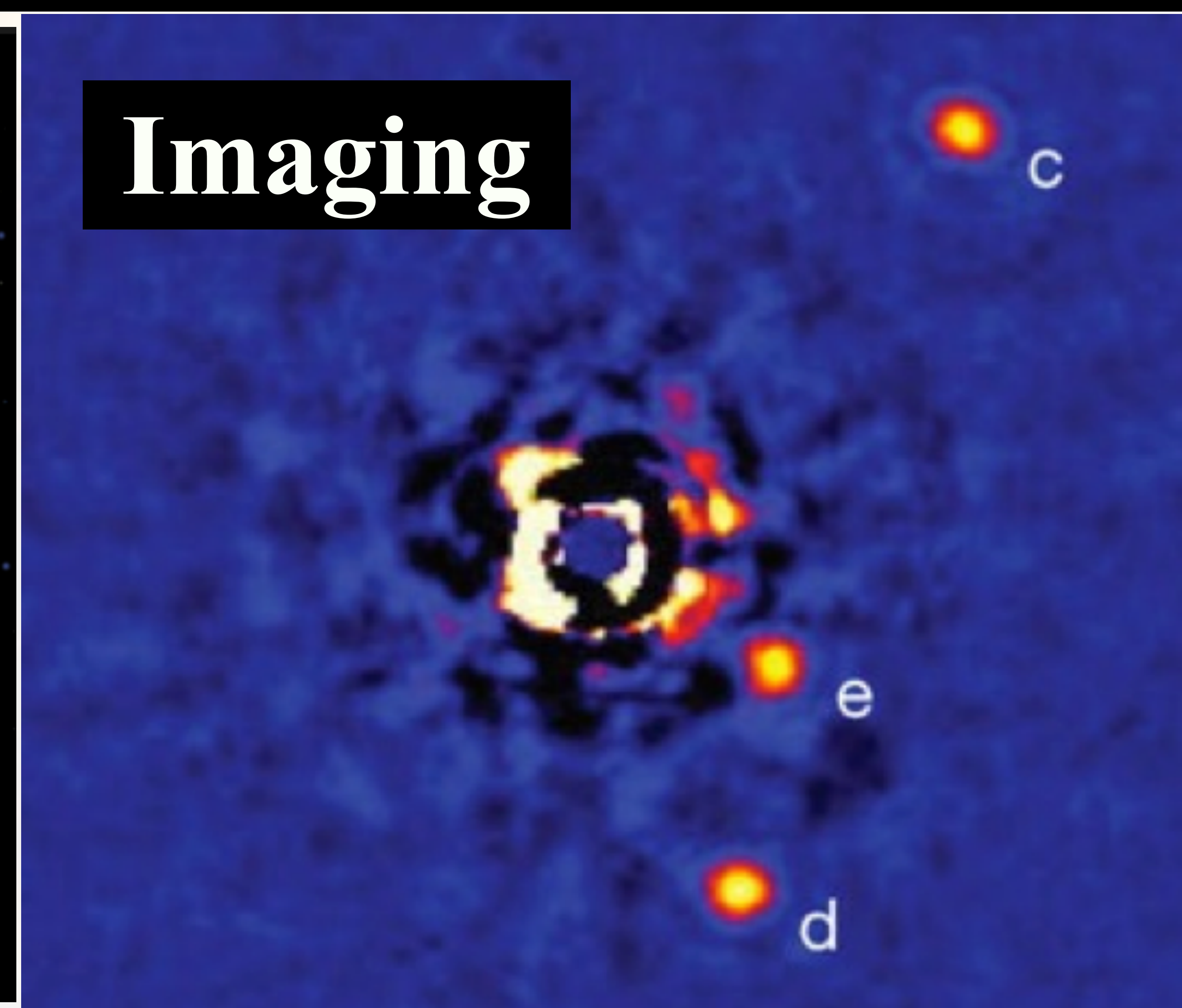
The answer to every one of these questions depends on our understanding of stars!

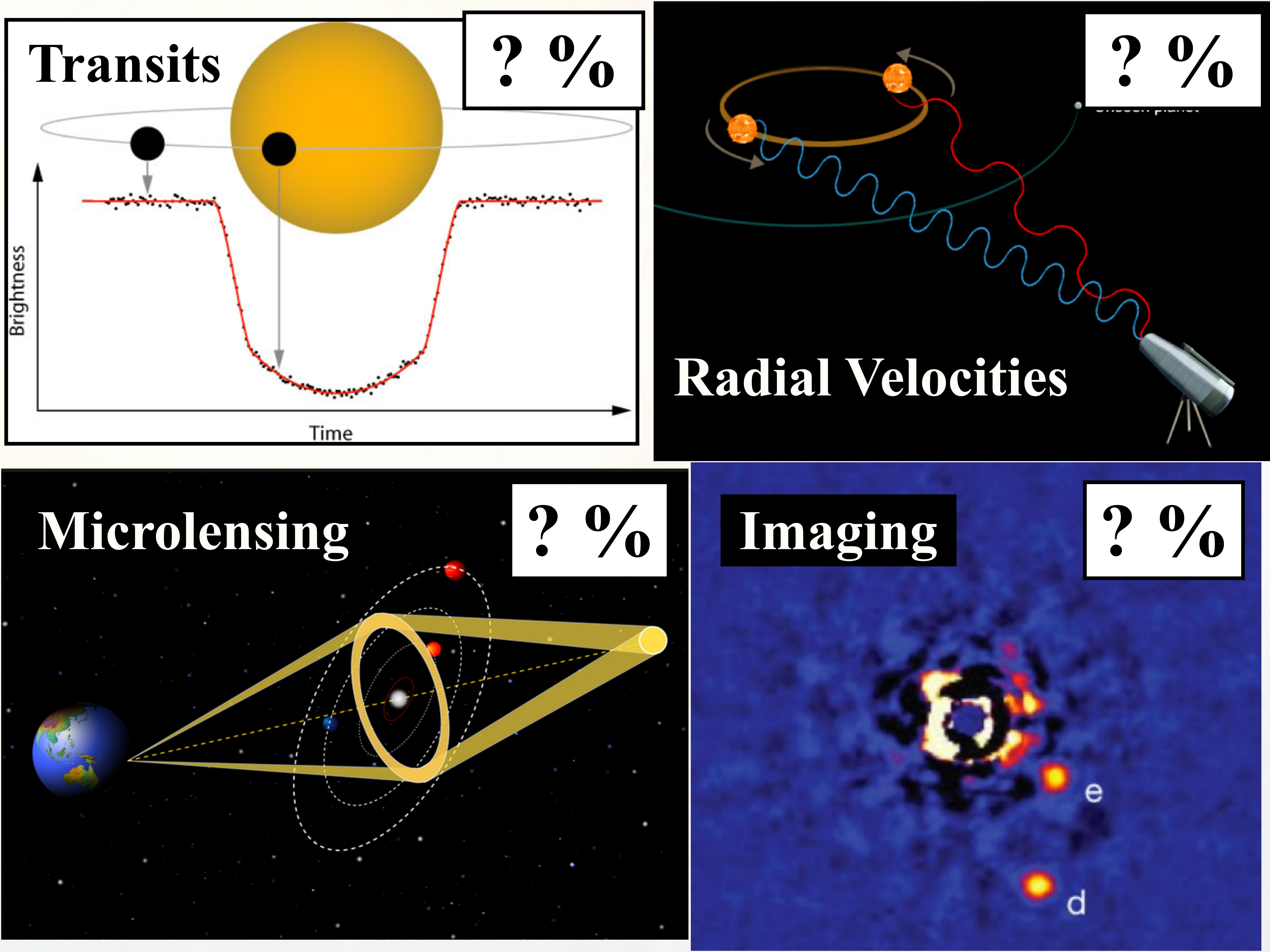
- What is the occurrence rate of planets as a function of size, spectral type, evolutionary state?
- Are there habitable planets outside the solar system?


Transits
Brightness
Time

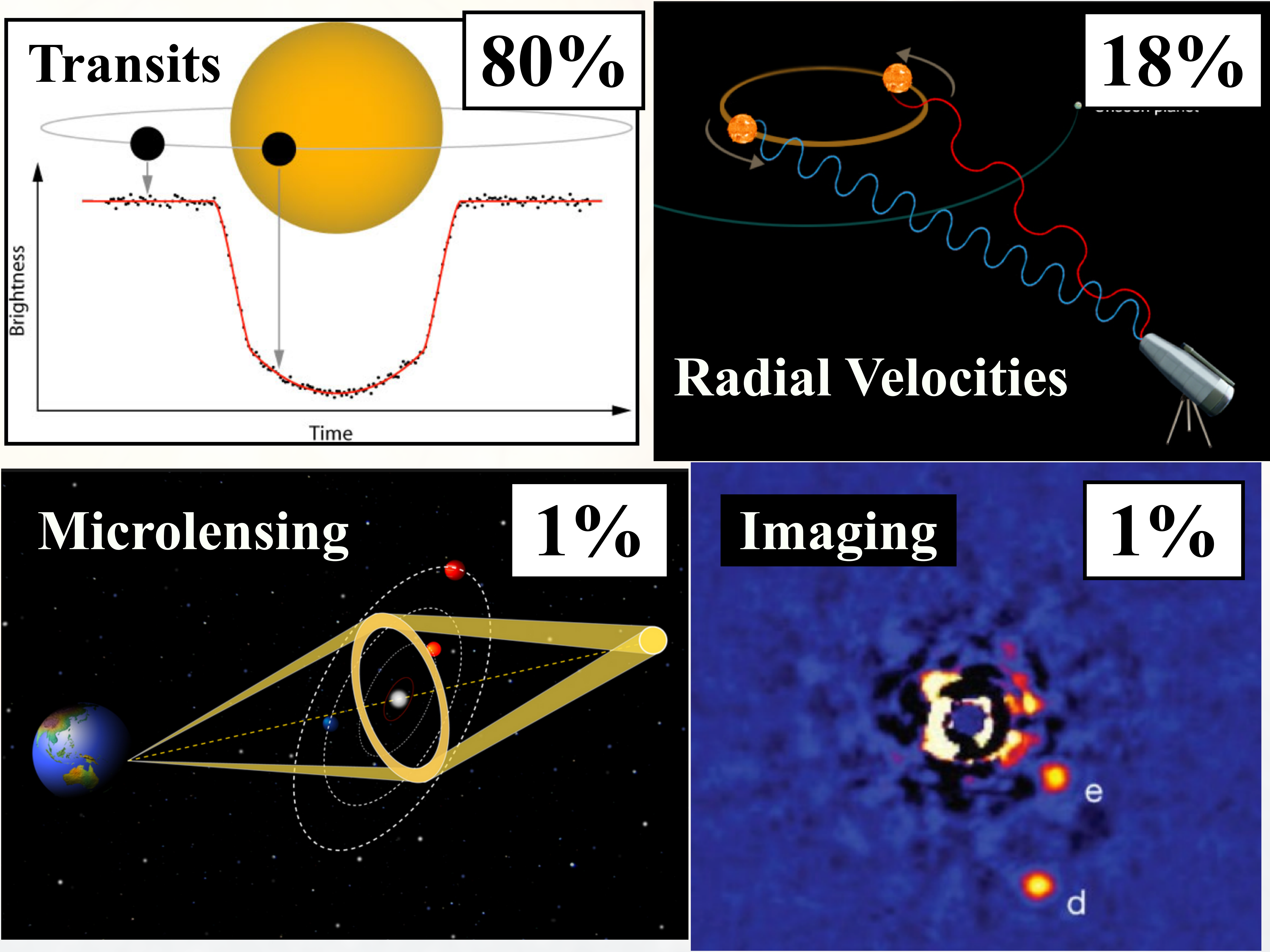

Unseen planet
Radial Velocities

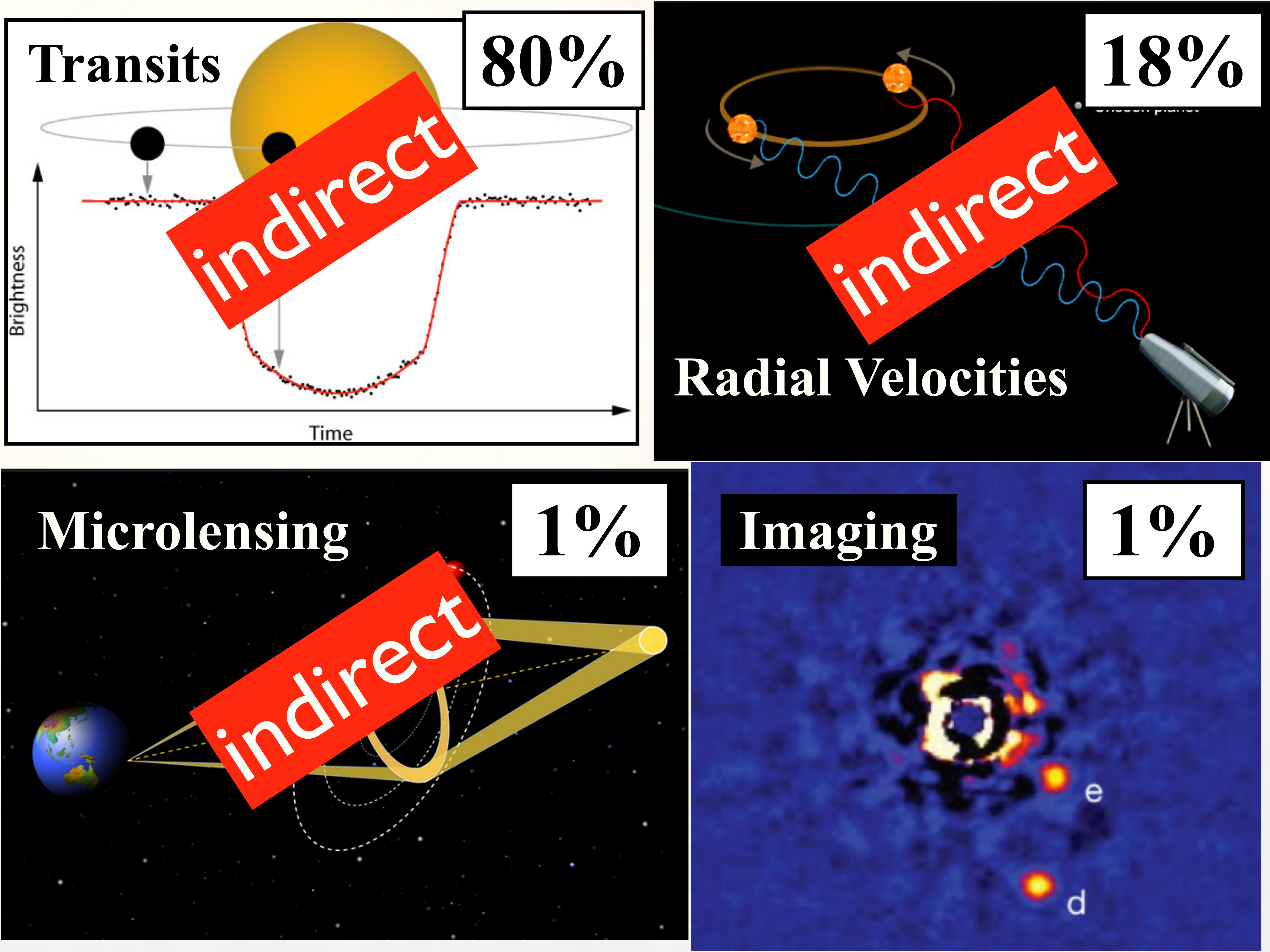

Microlensing


Imaging
c
e
d



Transits
? %
Brightness
Time
? %
Radial Velocities
Microlensing
? %
Imaging
? %
e
d


Transits
80%
Brightness
Time
18%
Radial Velocities
Microlensing
1%
Imaging
1%
e
d



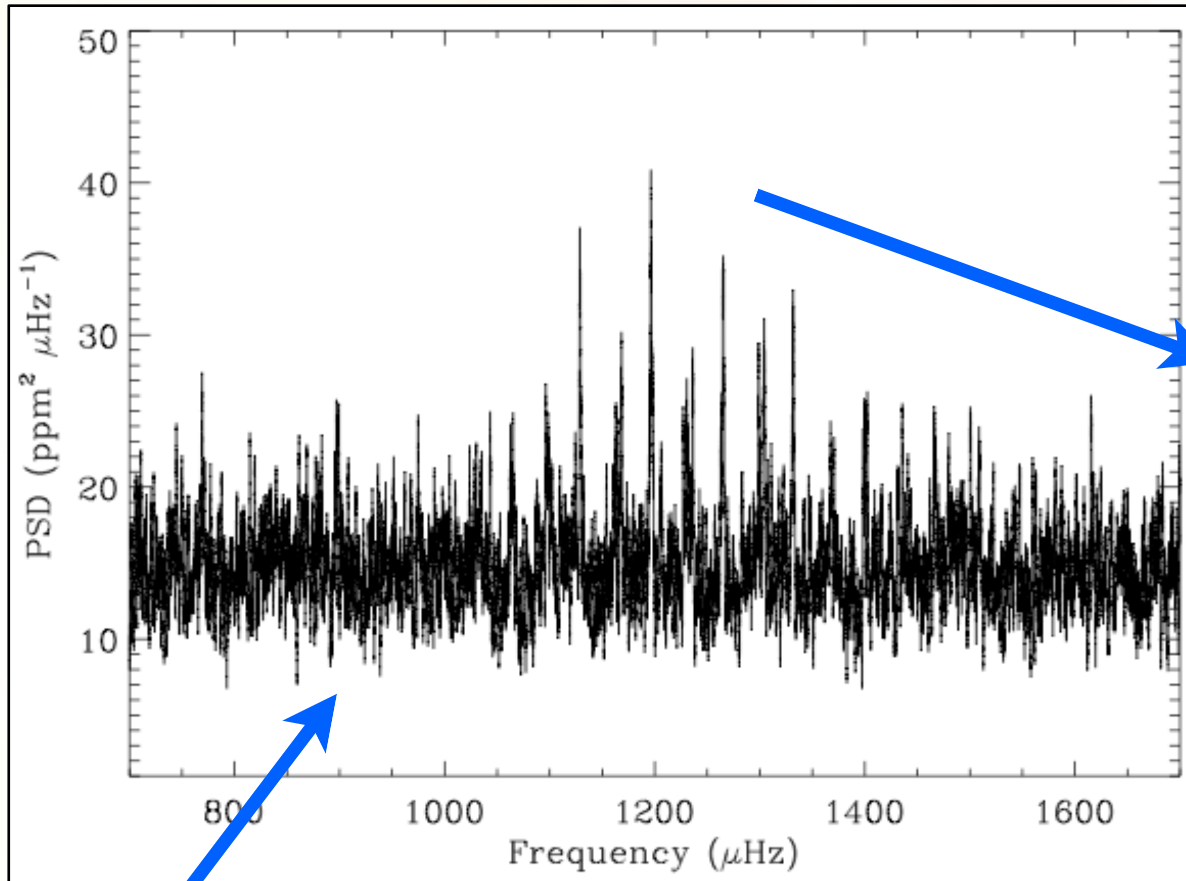
Transits
80%
indirect
Brightness
Time
18%
indirect
Radial Velocities
Microlensing
1%
indirect
Imaging
1%
e
d

Synergy I:

Exoplanet Radii, Masses, and Ages

Kepler-36

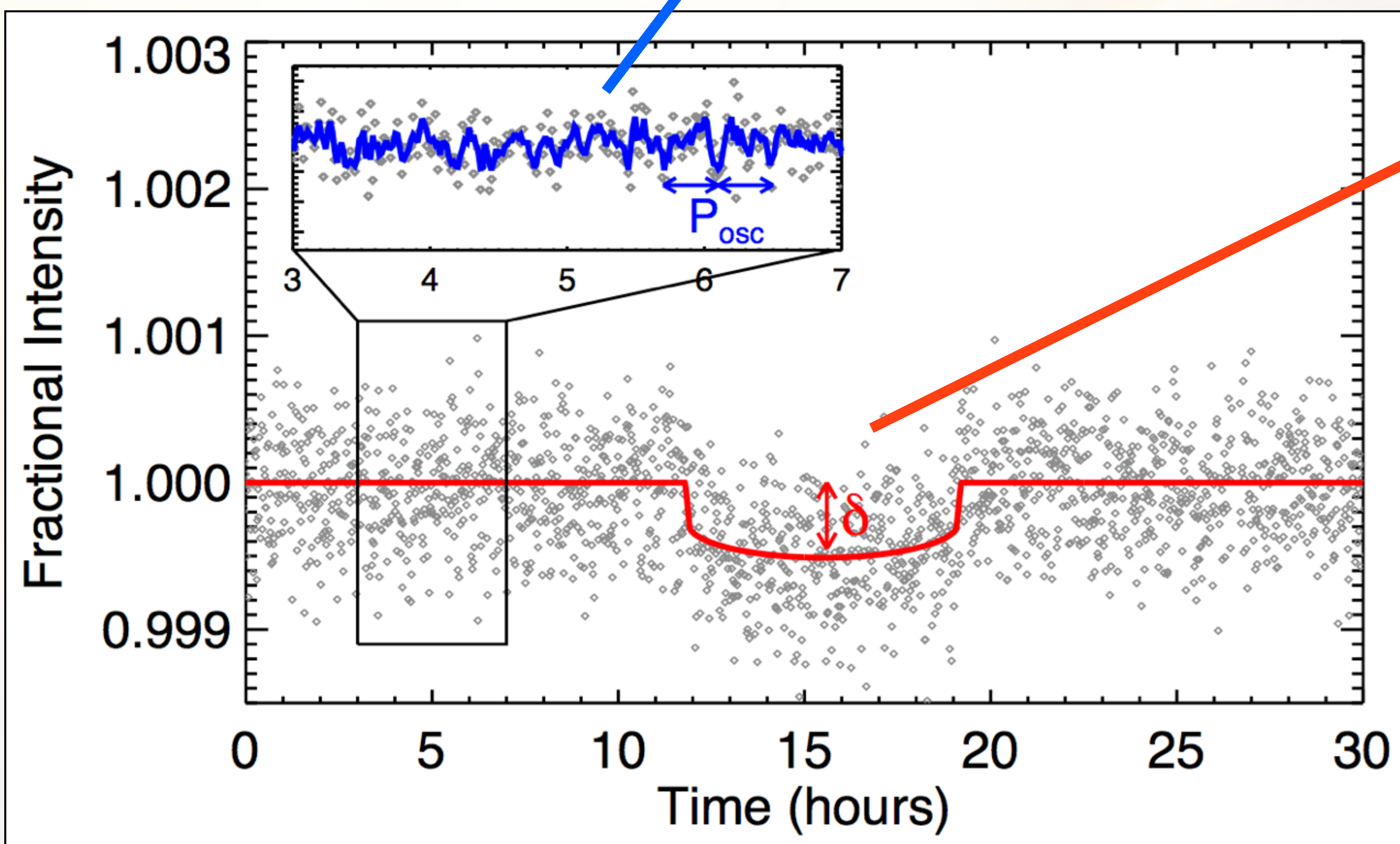
Carter et al. 2012



$M_\star$, $R_\star$, Age

+

$(R_P/R_\star)^2$



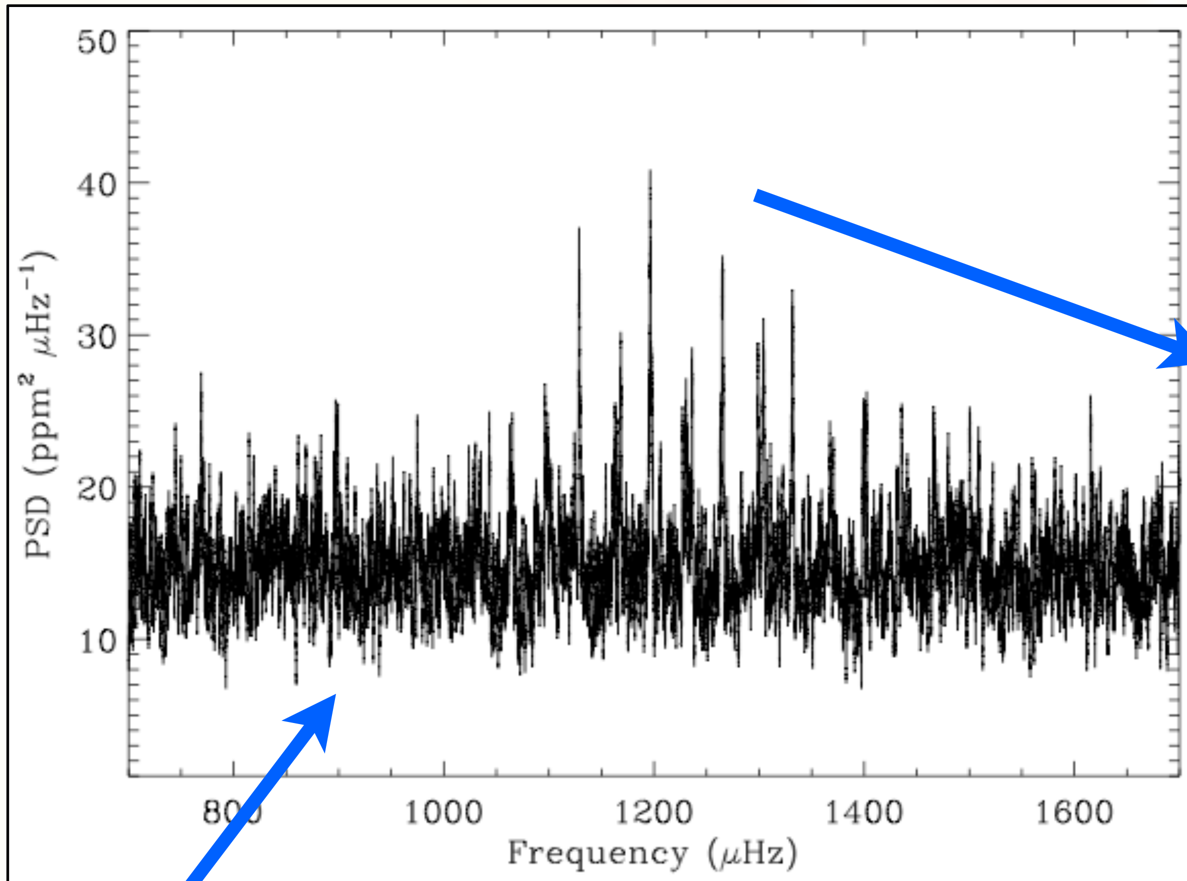
$\downarrow$

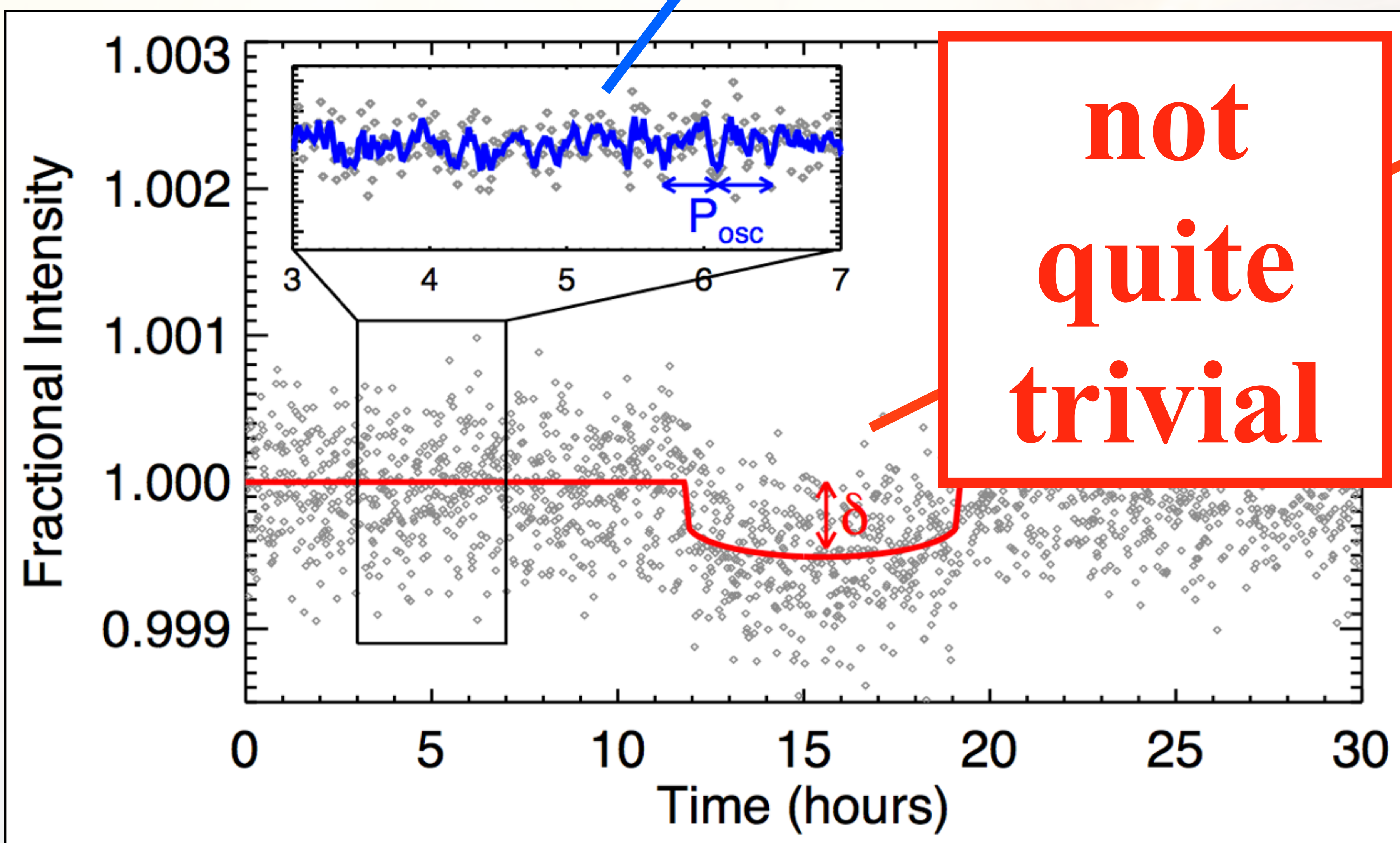
R_P

(<5% uncertainty!)

Kepler-36

Carter et al. 2012





not quite trivial

$M_\star$, $R_\star$, Age

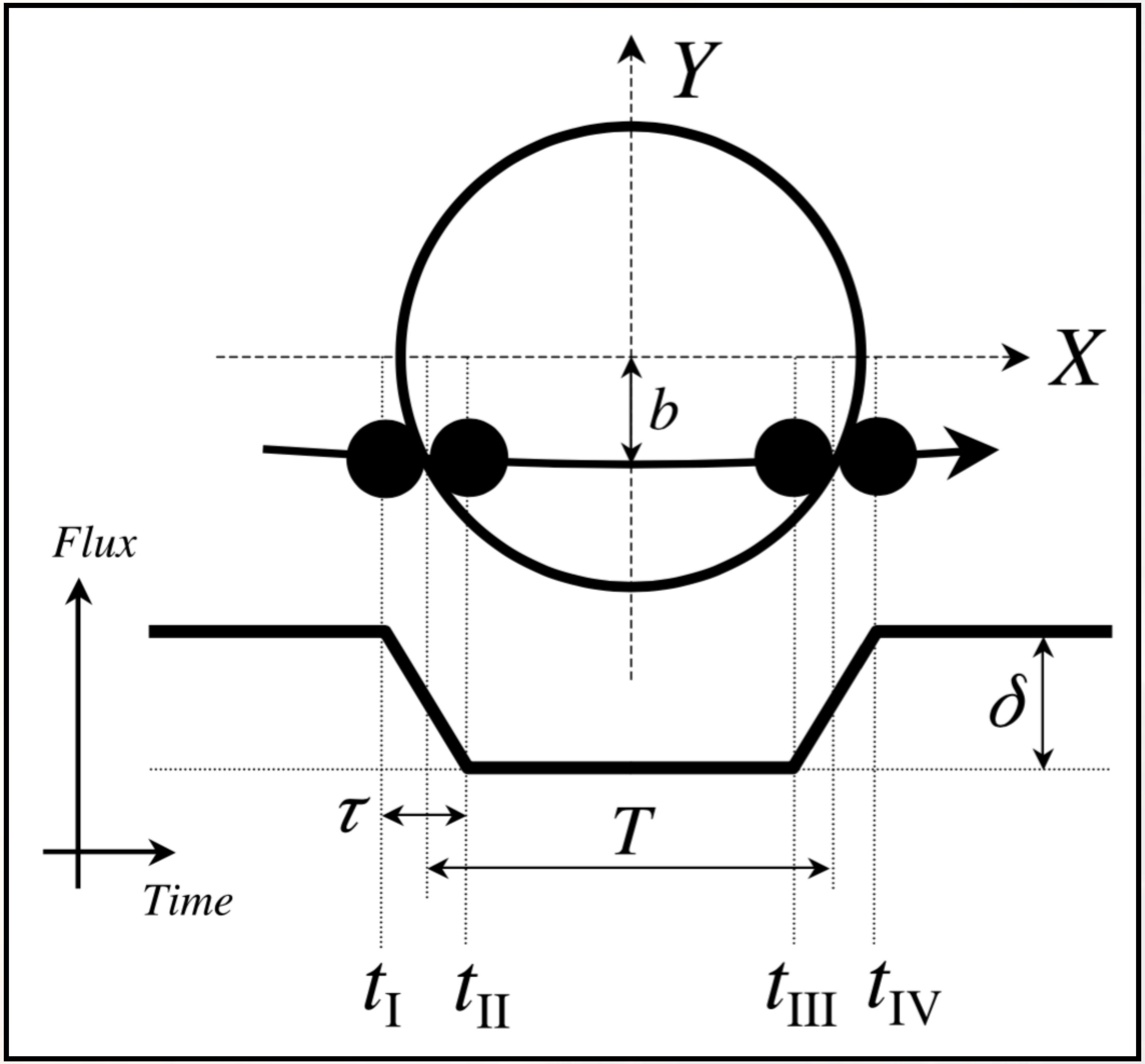
+

$(R_P/R_\star)^2$

↓

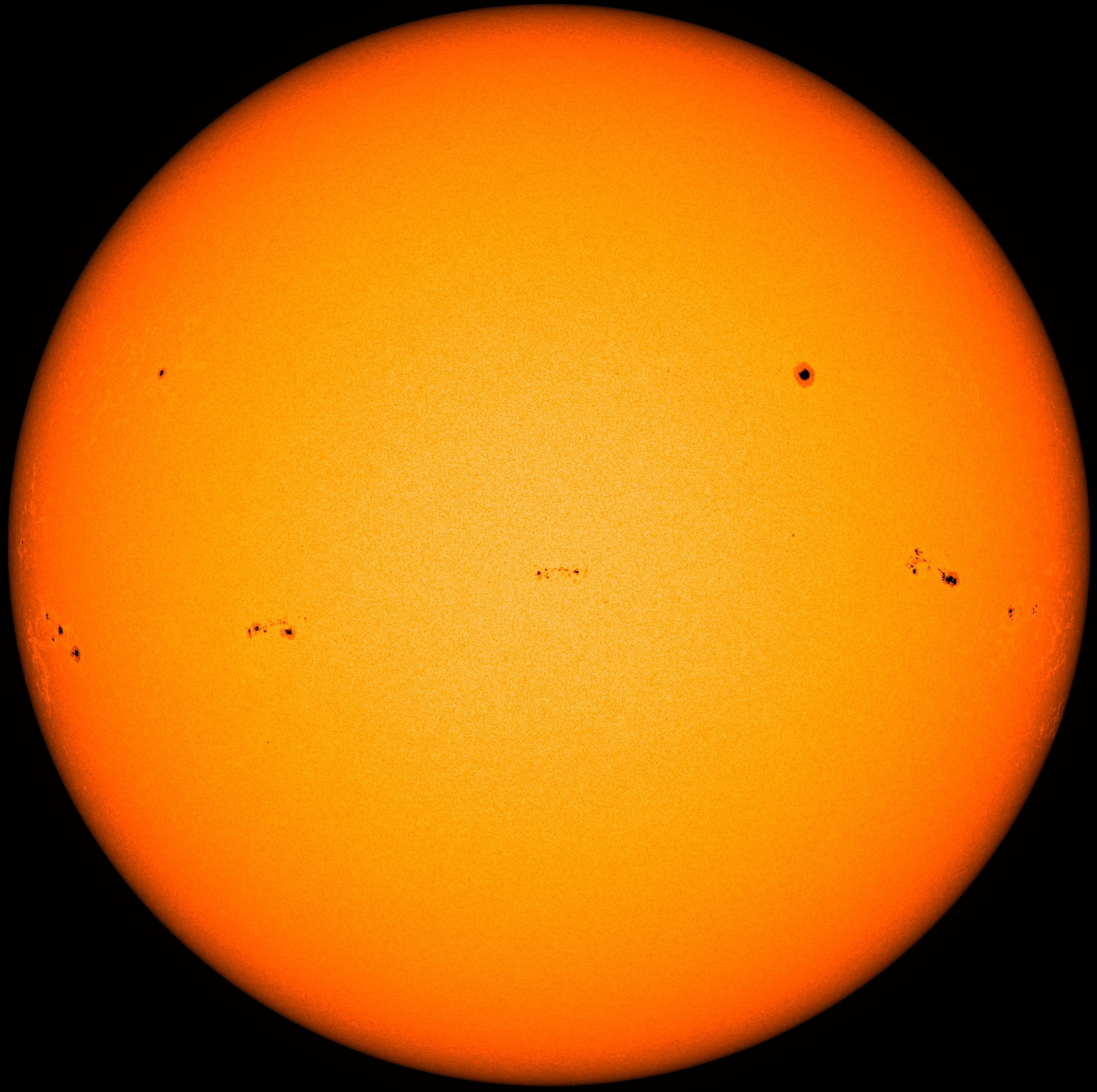
R_P

(<5% uncertainty!)

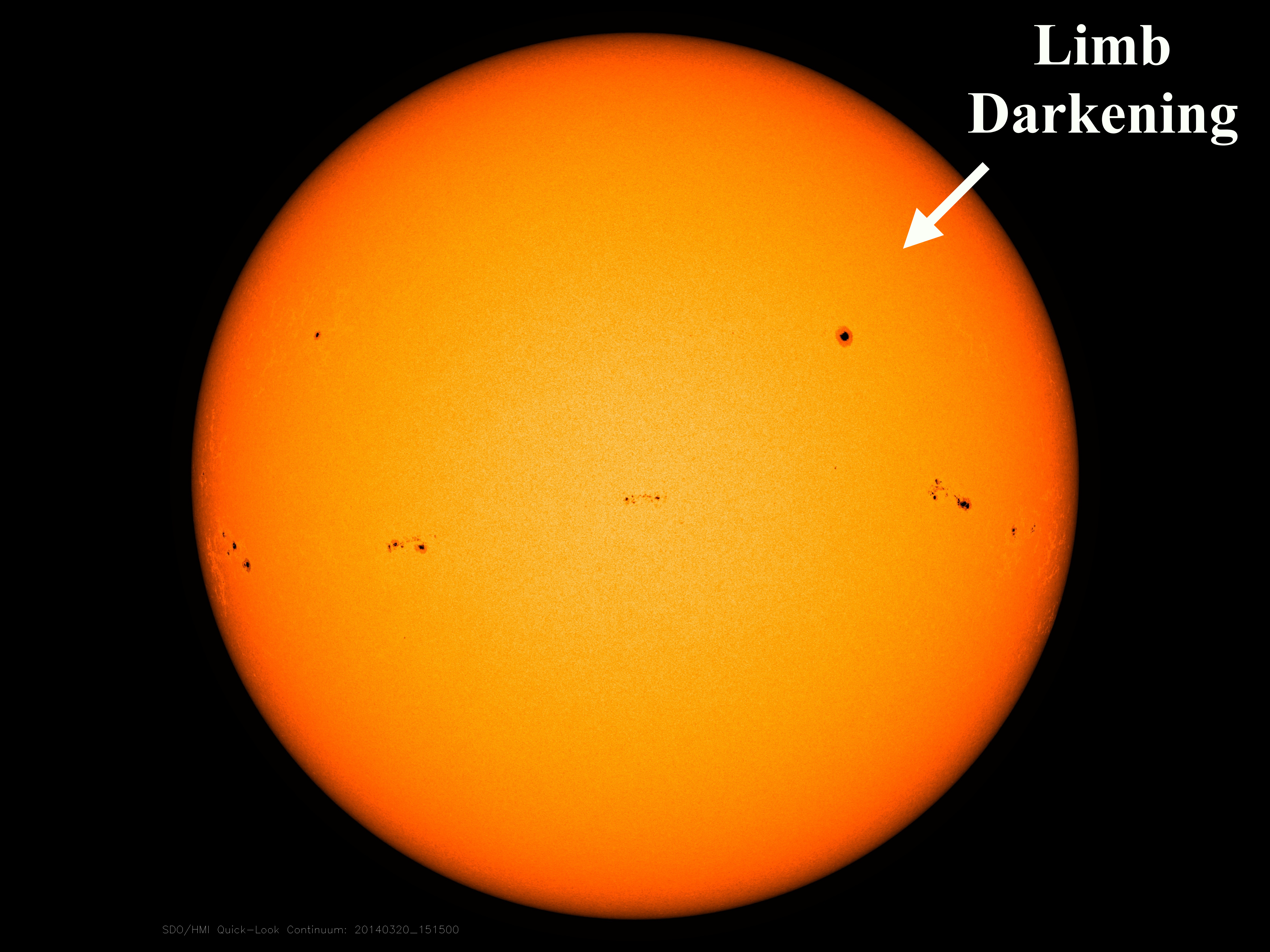


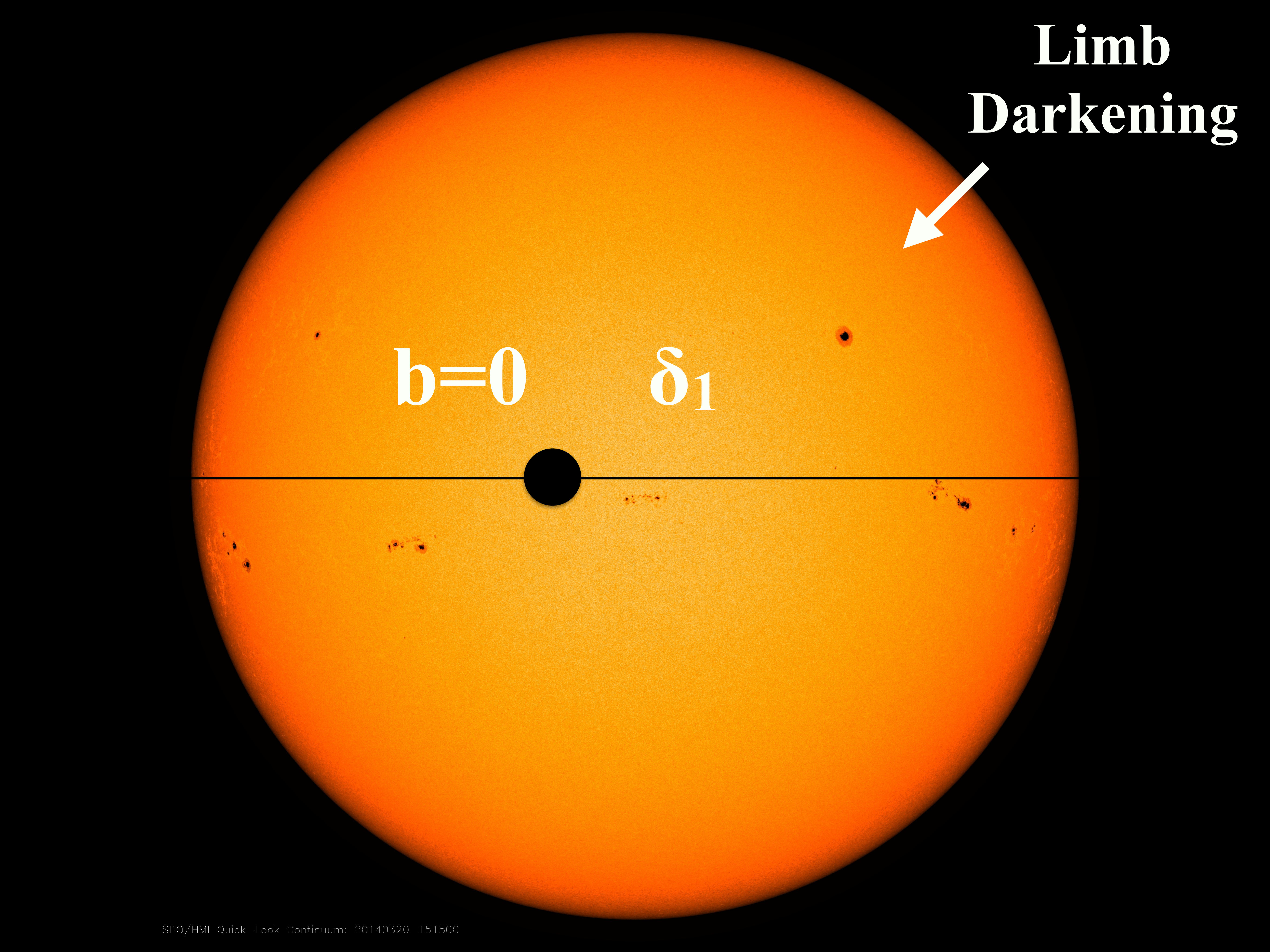
Observables: T = Transit Duration τ = In/Egress Duration

δ = Transit Depth

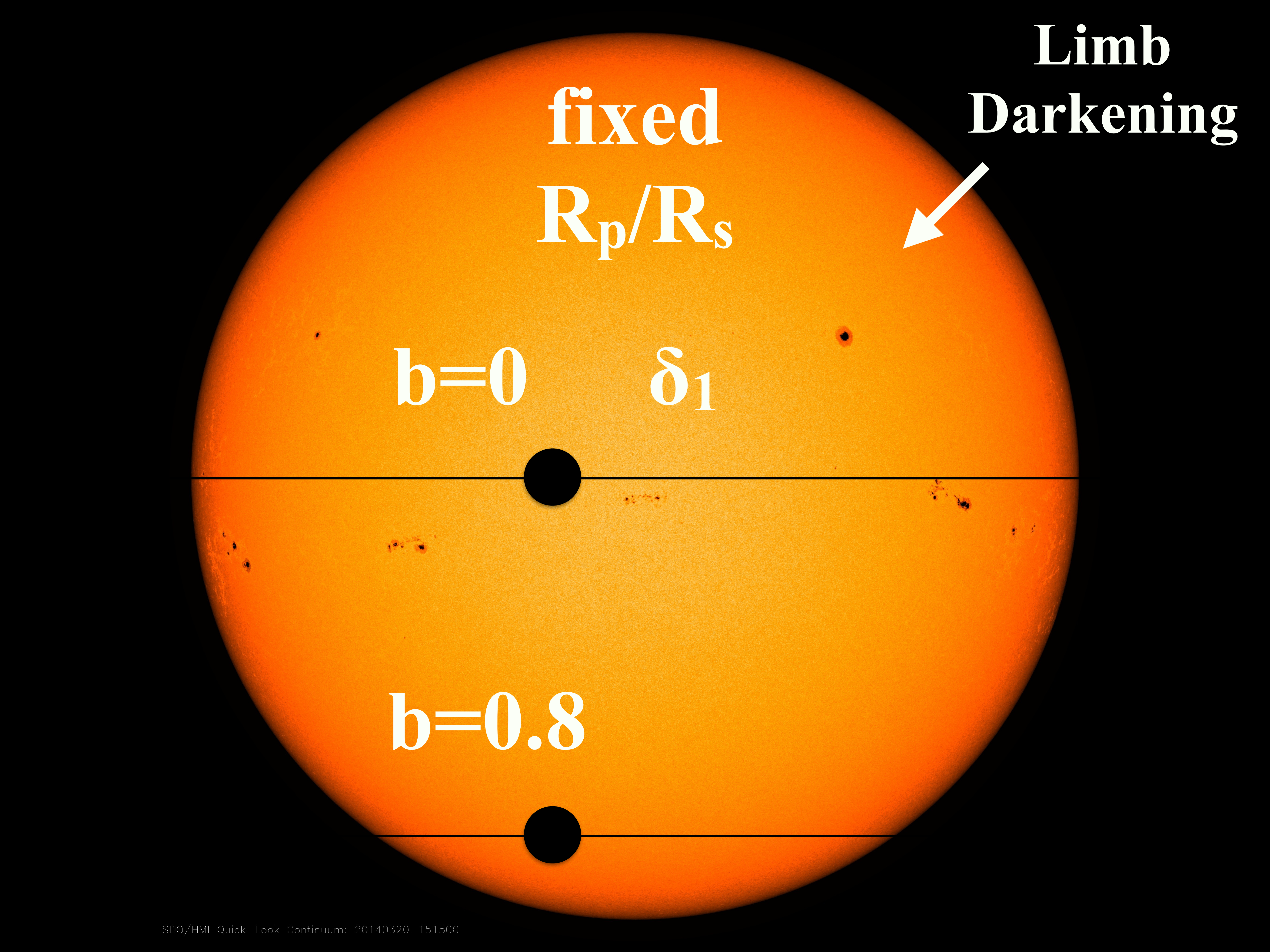


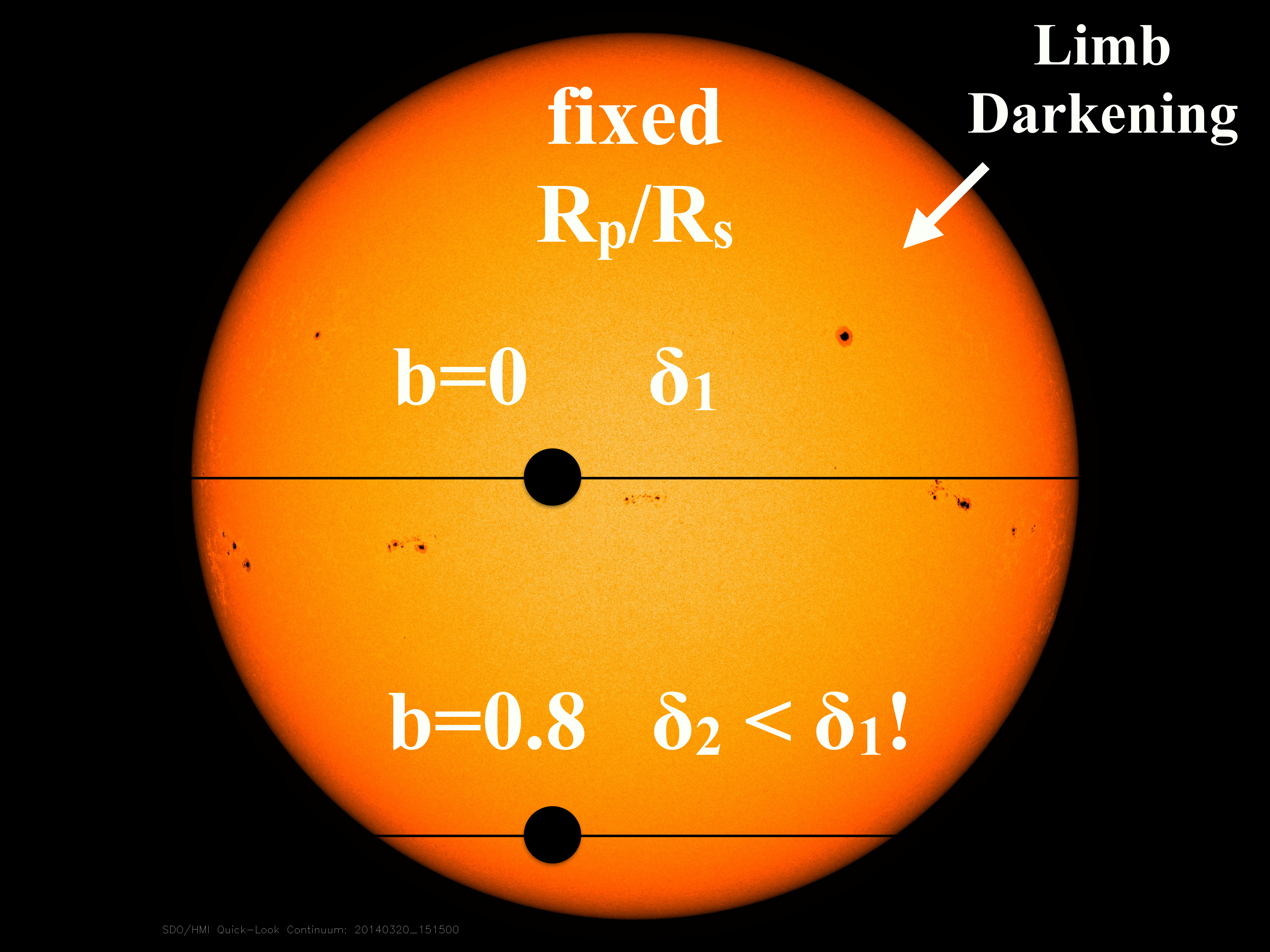
SDO/HMI Quick-Look Continuum: 20140320_151500

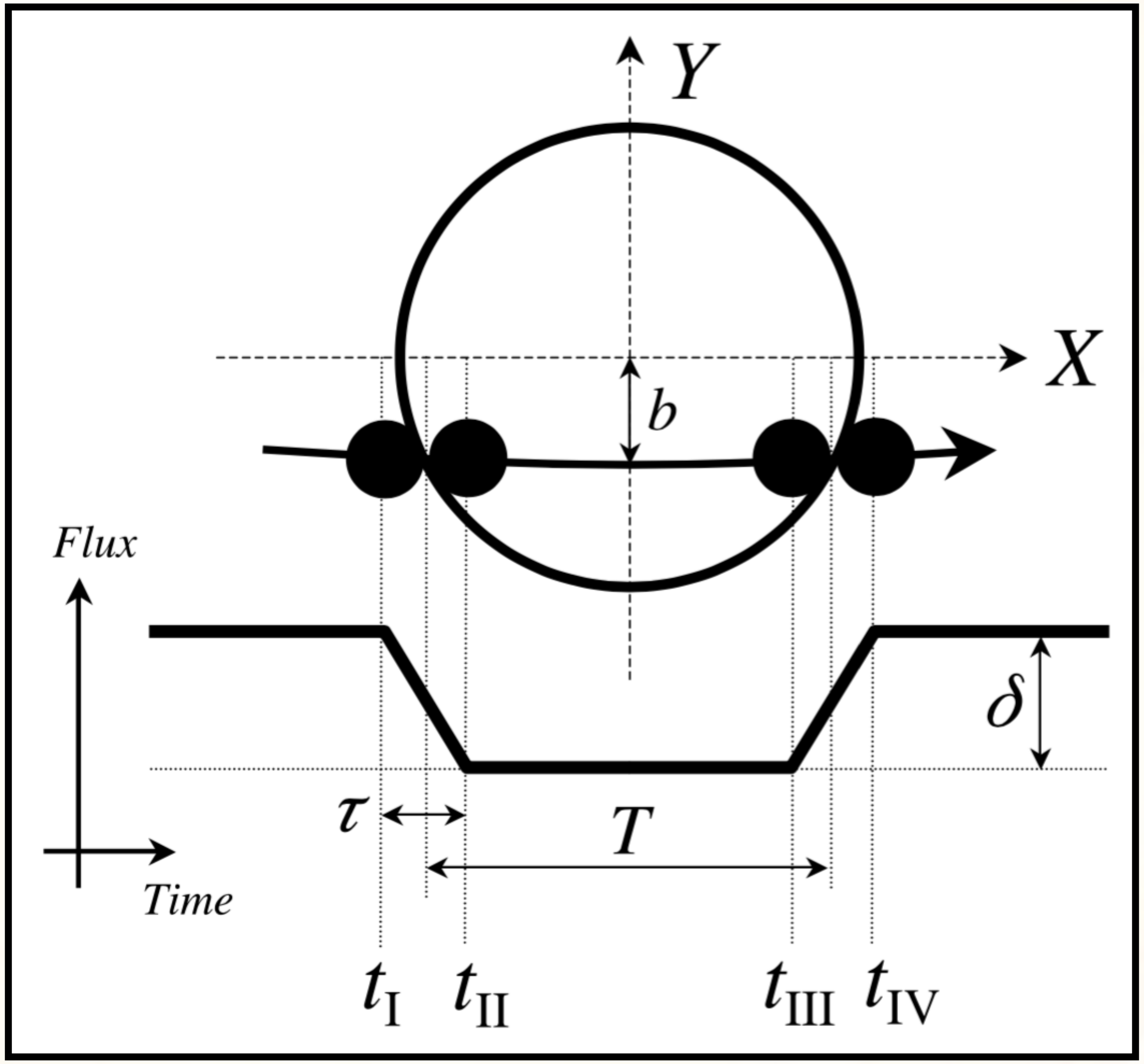

Limb
Darkening
SDO/HMI Quick-Look Continuum: 20140320_151500



Limb
Darkening
b=0
δ_1
SDO/HMI Quick-Look Continuum: 20140320_151500

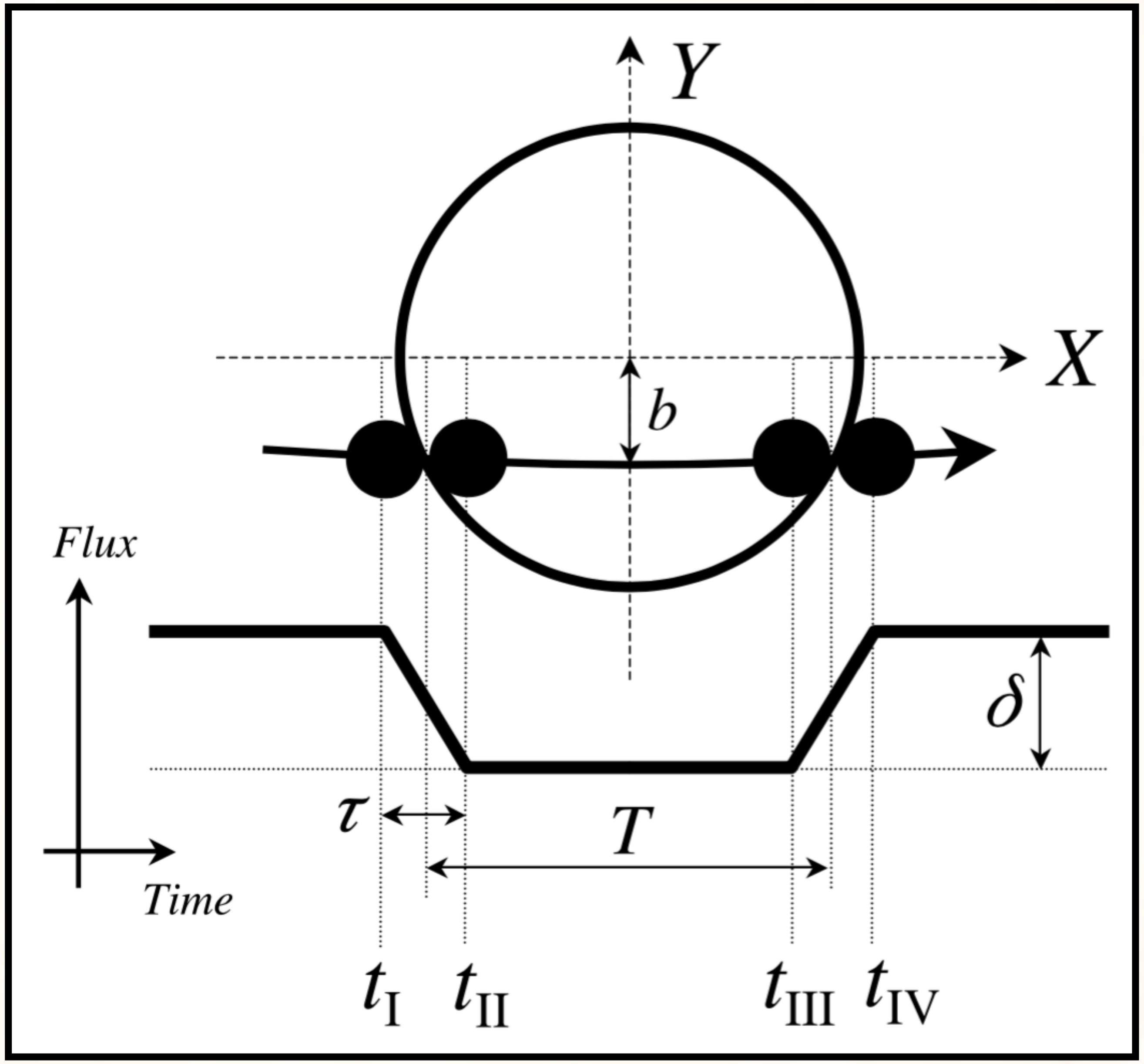

Limb
Darkening
fixed
R_p/R_s
b=0
δ_1
b=0.8
SDO/HMI Quick-Look Continuum: 20140320_151500


Limb
Darkening
fixed
R_p/R_s
b=0
δ_1
b=0.8
$\delta_2 < \delta_1$!
SDO/HMI Quick-Look Continuum: 20140320_151500



$$\boxed{T_{\mathrm{full}} \equiv t_{\mathrm{III}} - t_{\mathrm{II}}}$$

$$\boxed{T_{\mathrm{tot}} \equiv t_{\mathrm{IV}} - t_{\mathrm{I}}}$$



$$T_{\text{full}} \equiv t_{\text{III}} - t_{\text{II}}$$

$$T_{\text{tot}} \equiv t_{\text{IV}} - t_{\text{I}}$$

for circular orbits and

$R_p << R_\star << a$:

(see Saeger & Mallen-Ornelas 2003 or Winn 2010 for rigorous derivation)

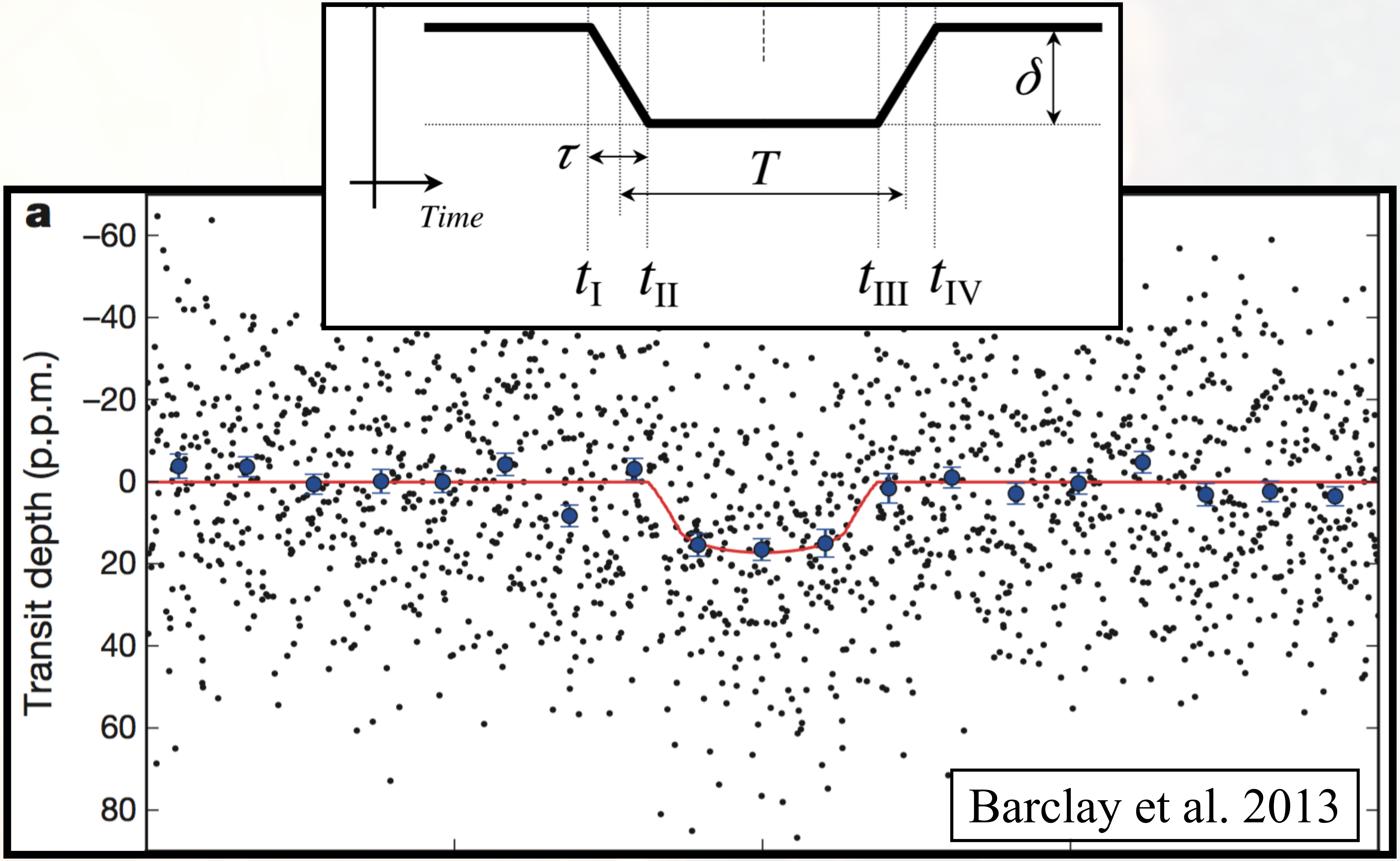
$$b^2 = \frac{(1-\sqrt{\delta})^2 - (T_{\text{full}}/T_{\text{tot}})^2(1+\sqrt{\delta})^2}{1-(T_{\text{full}}/T_{\text{tot}})^2}$$

$$\frac{R_\star}{a} = \frac{\pi}{2\delta^{1/4}} \frac{\sqrt{T_{\text{tot}}^2 - T_{\text{full}}^2}}{P}$$

now use Kepler's 3rd law …

$$\boxed{\rho_{\star,\mathrm{transit}} = \frac{3\pi}{GP^2}\left(\frac{a}{R_\star}\right)^3}$$

Big Result 1: Transits can be used to directly measure the mean stellar density



T = Transit Duration

τ = In/Egress Duration

δ = Transit Depth

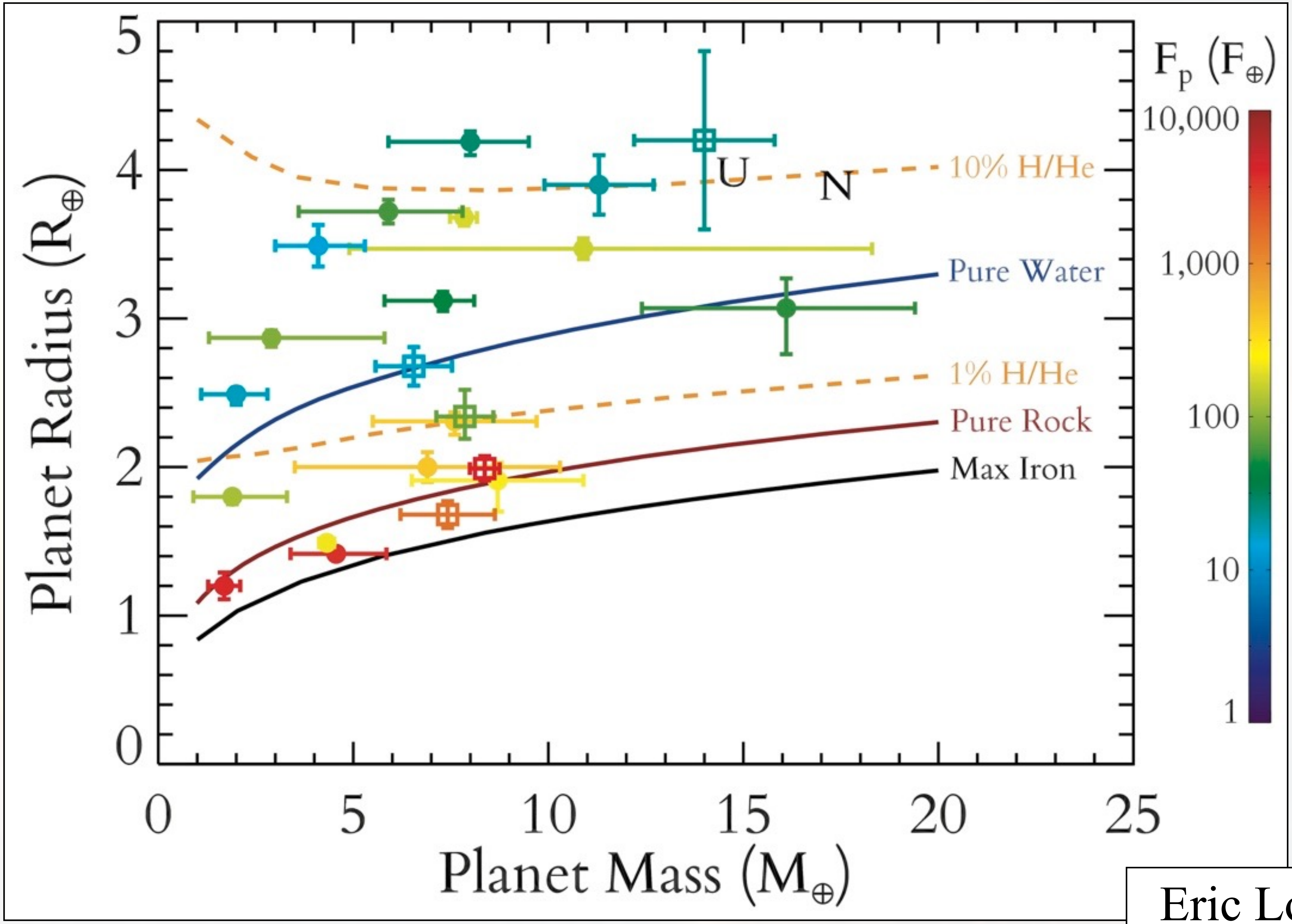
Hard to measure for low S/N Transits!

$$\boxed{\rho_{\star,\mathrm{transit}} = \frac{3\pi}{GP^2}\left(\frac{a}{R_\star}\right)^3}$$

Big Result 1: Transits can be used to directly measure the mean stellar density

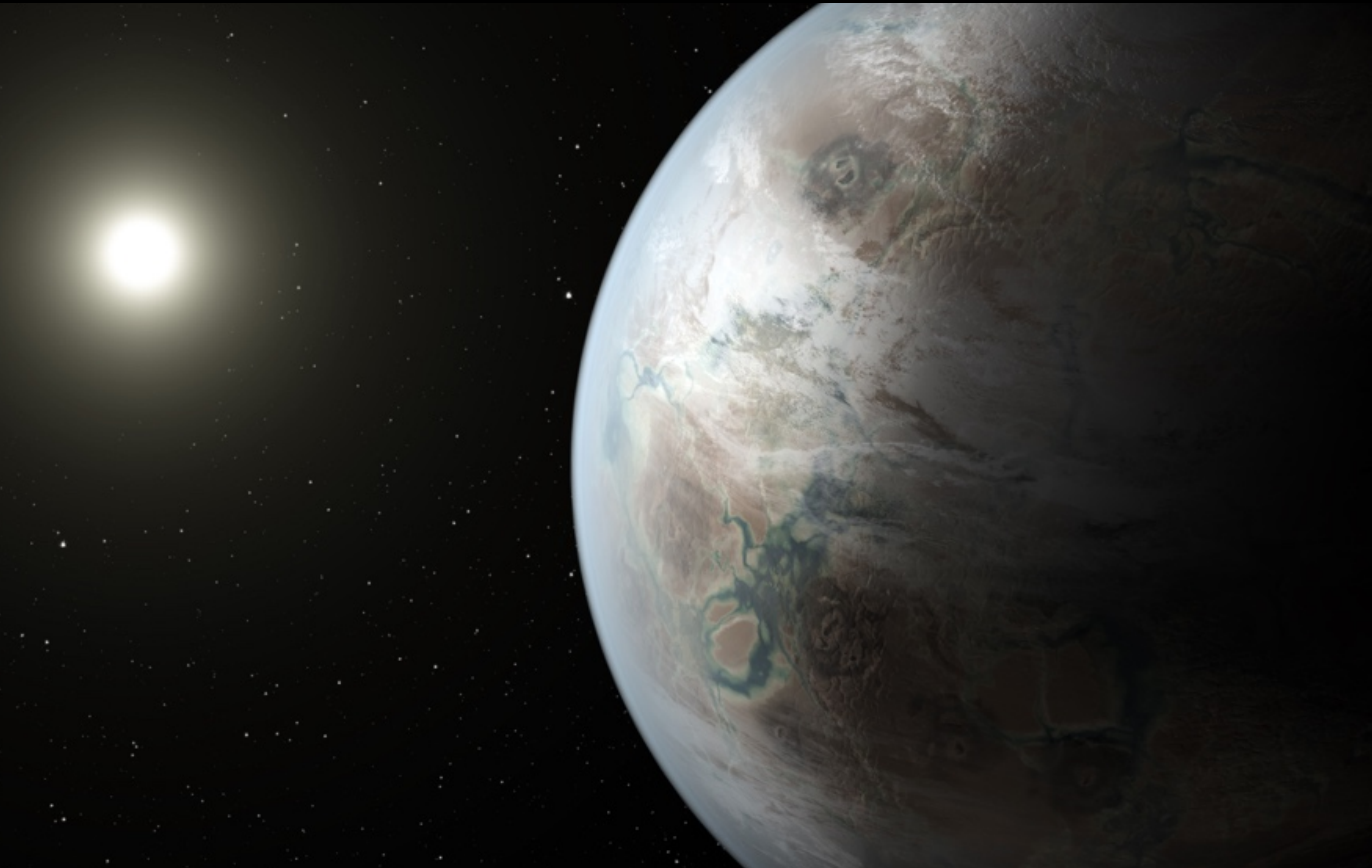
Big Result 2: Asteroseismic Density can yield vastly improved transit parameters

Precise Planet Radii are key to determine their compositions



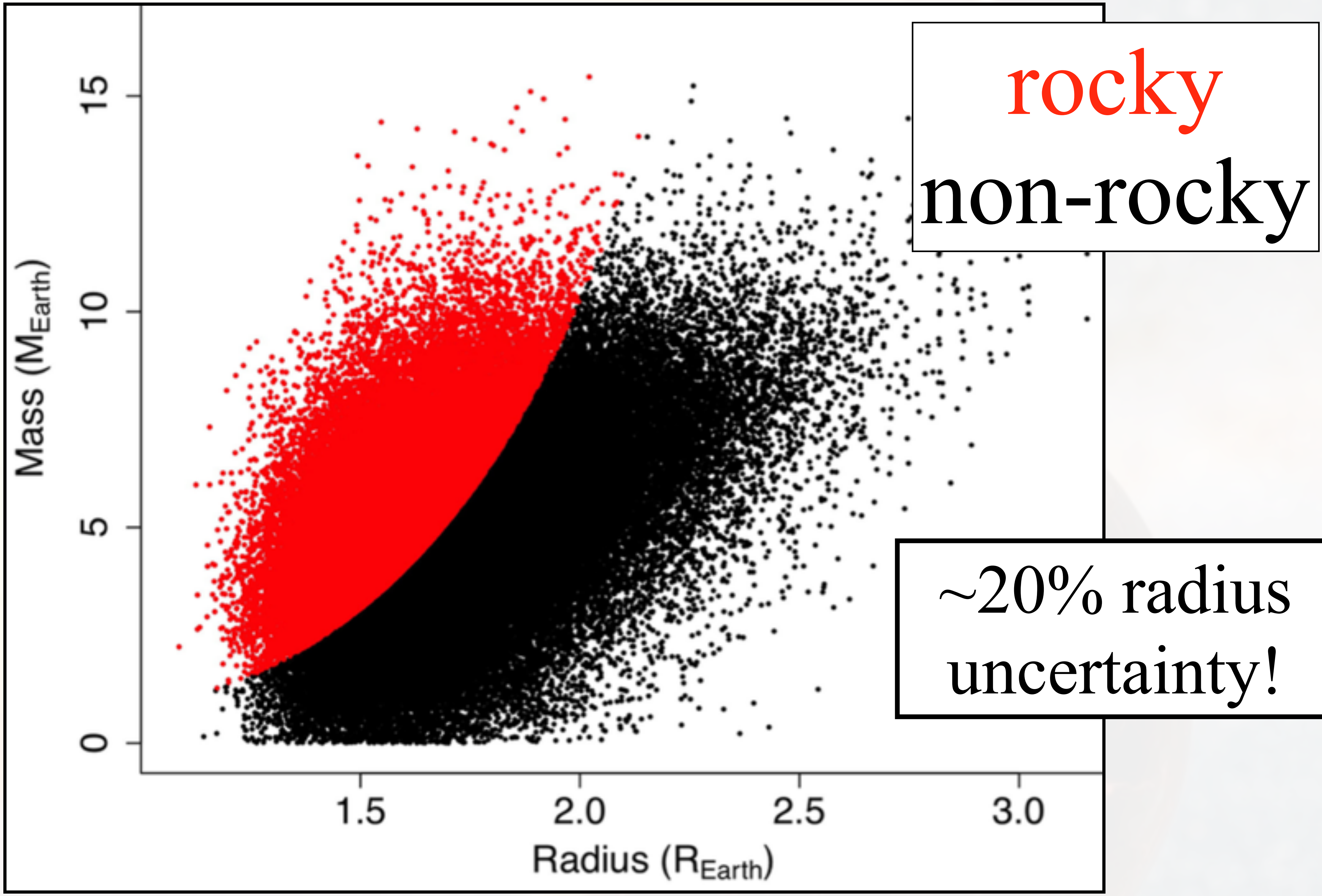
Eric Lopez

Kepler-452b: A Rocky World?



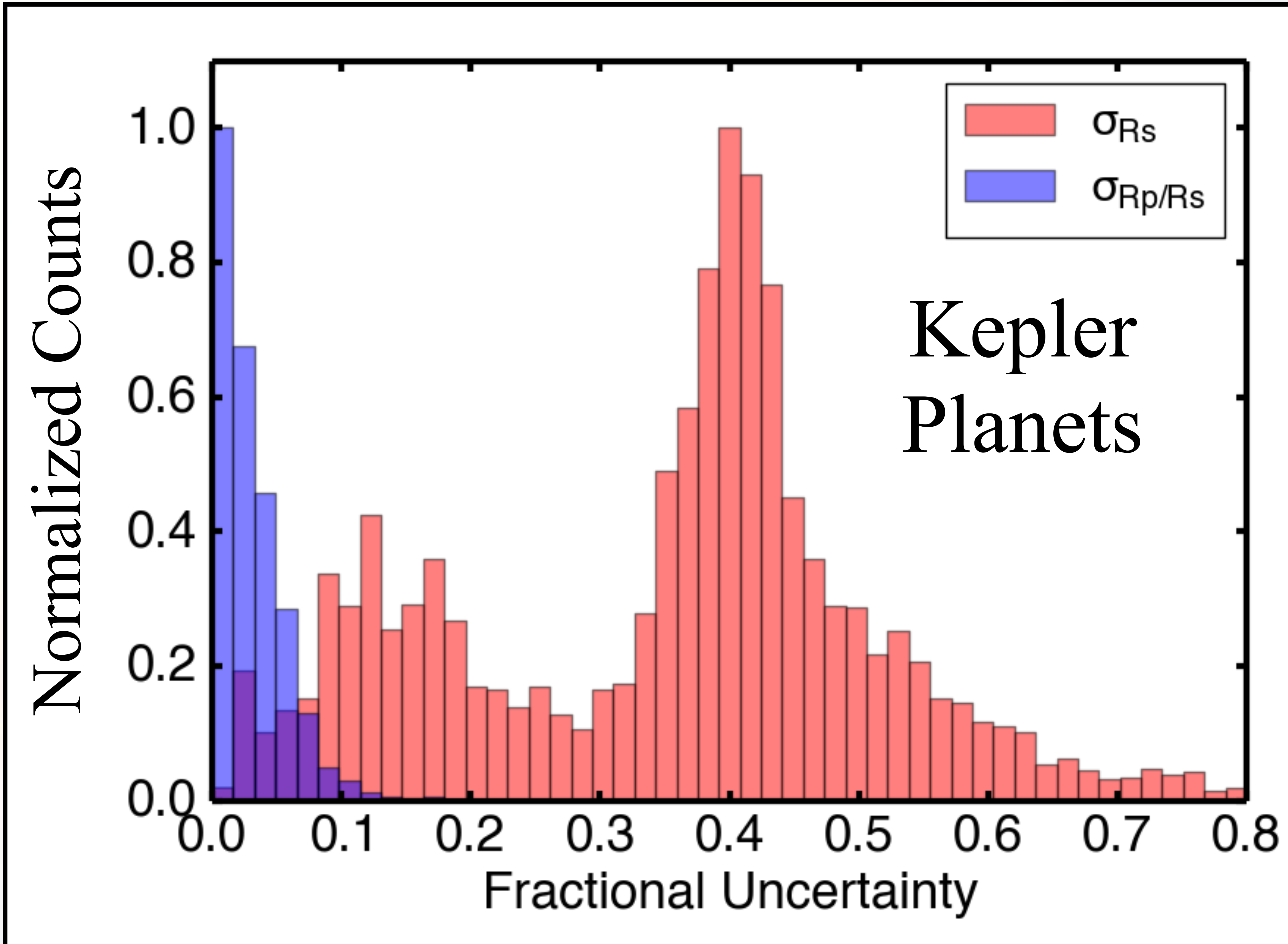
Kepler-452b: A Rocky World?

Kepler-452b: A Rocky World?



Jenkins et al. 2015

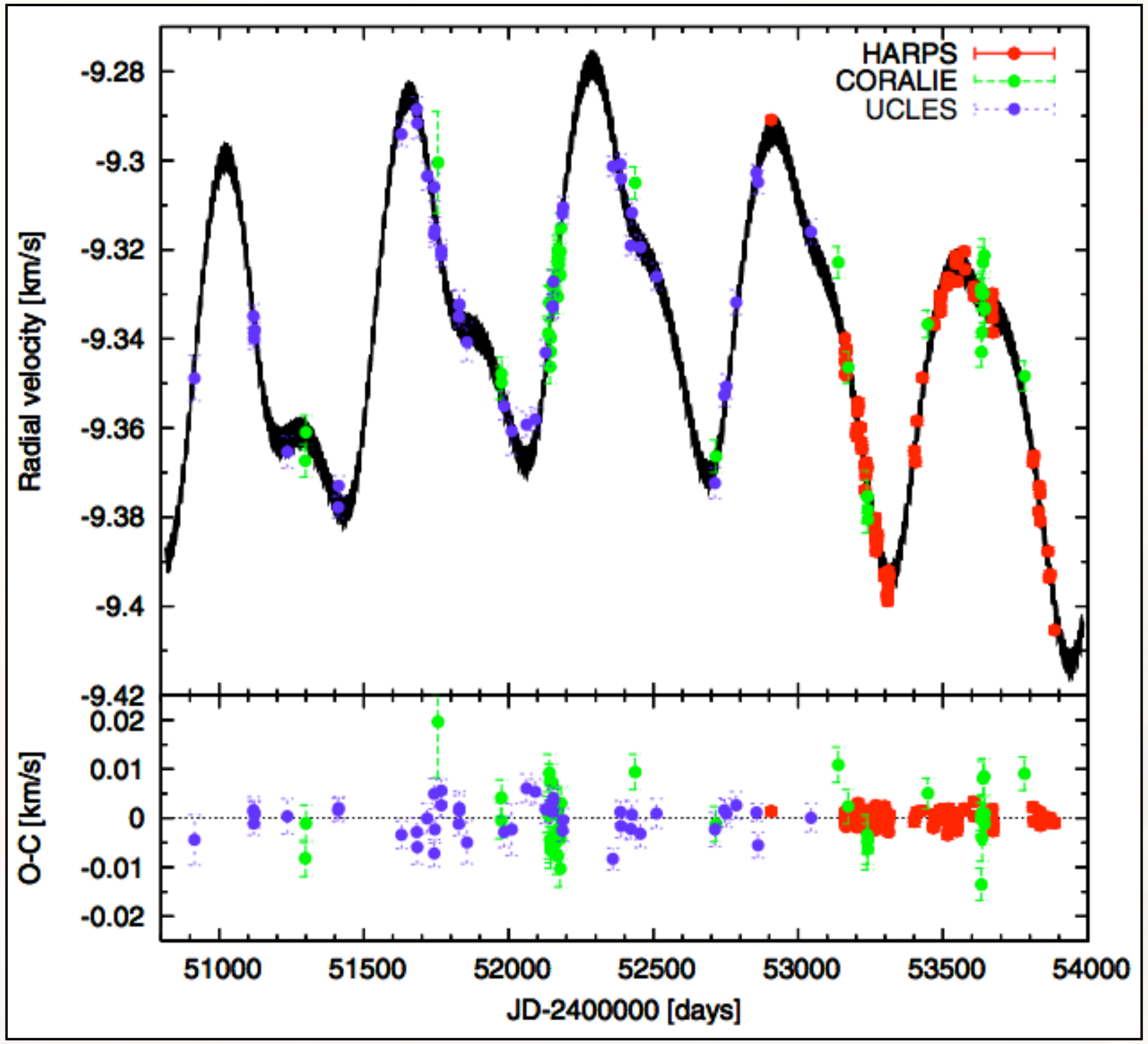
The Culprit: Stellar Parameters!



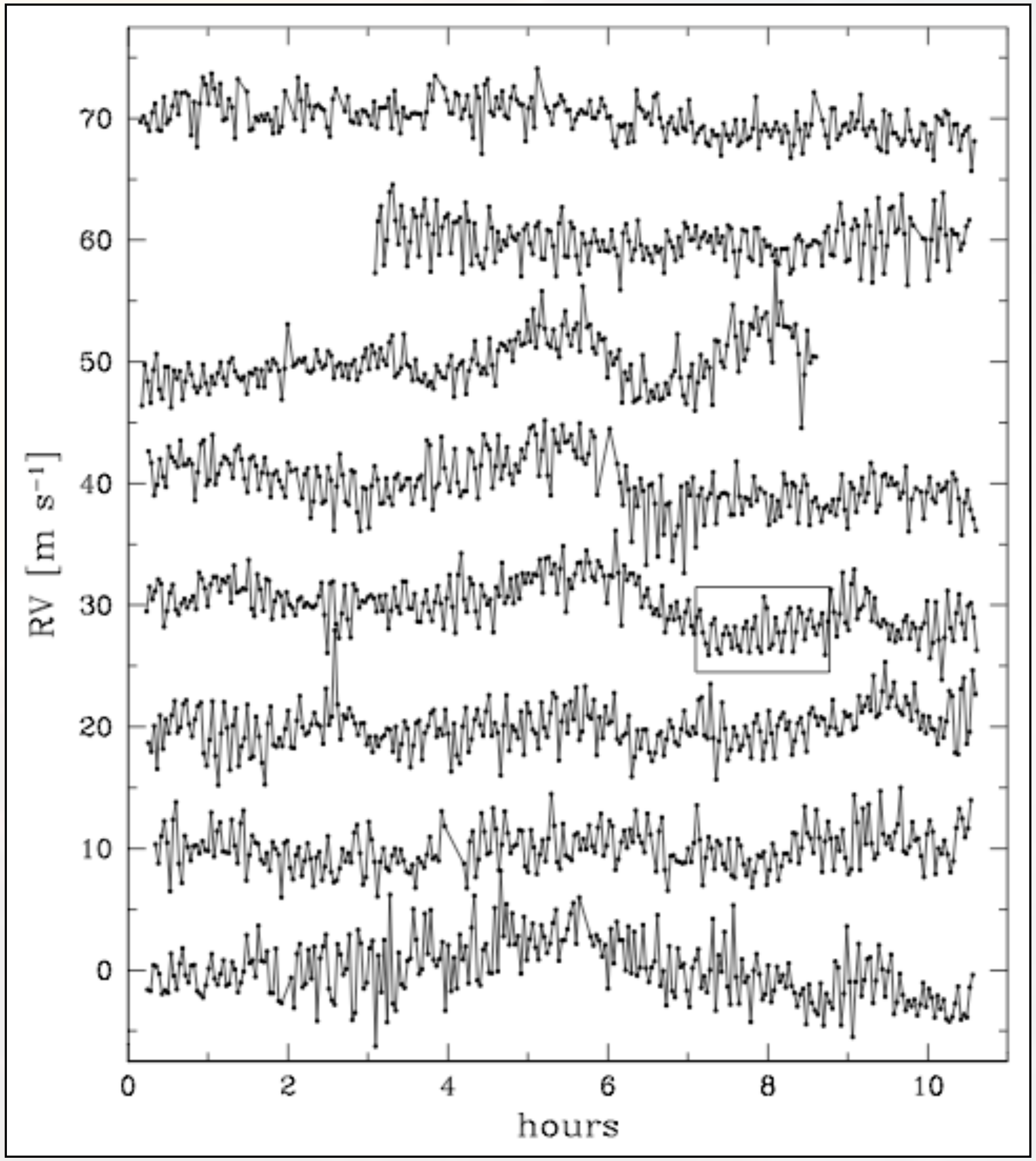
Life Before Kepler: μ Ara

HARPS RVs, G3V, V = 5.5 mag

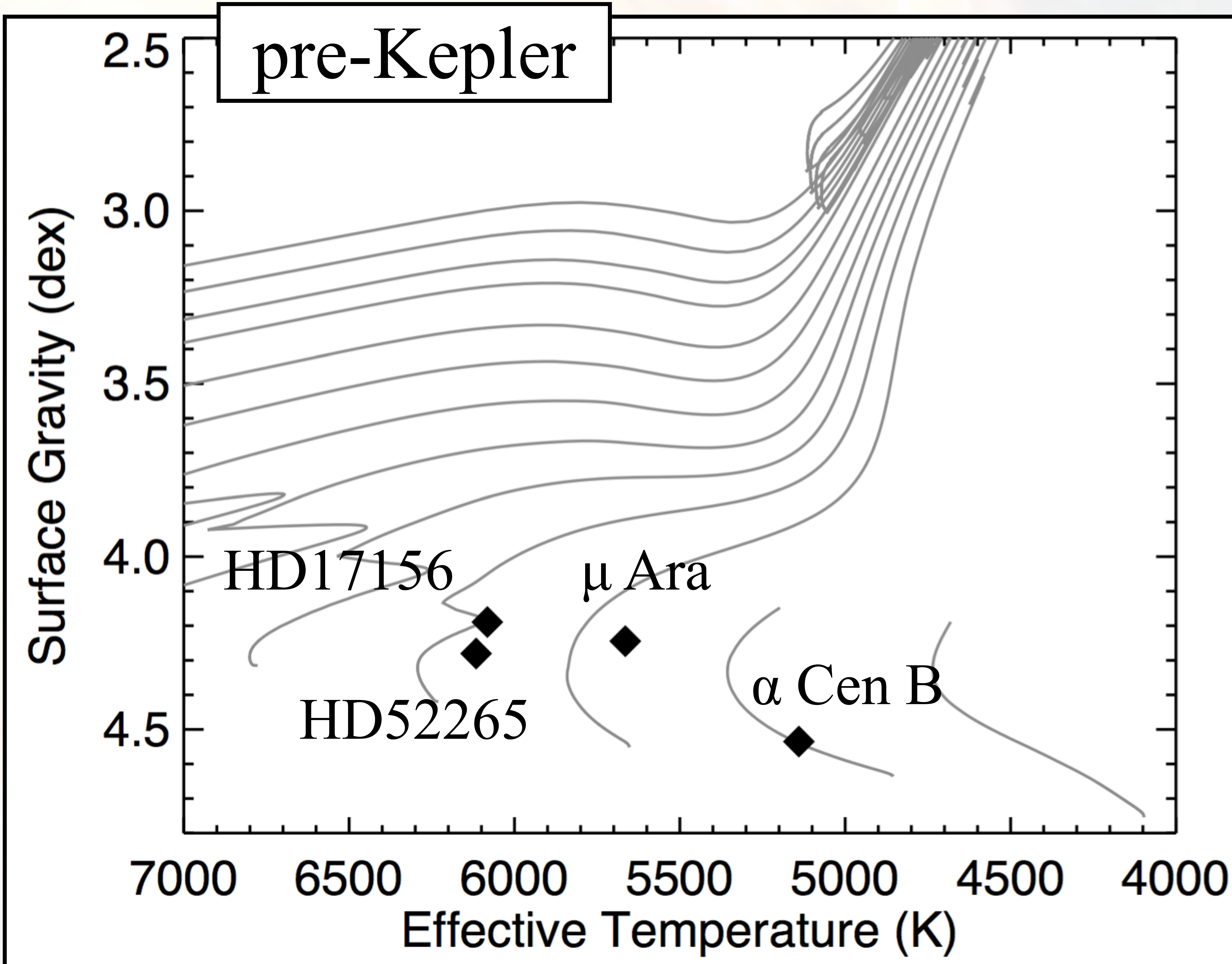
4 planets, Msin(i) ~ 13M⊕ -1.7MJ

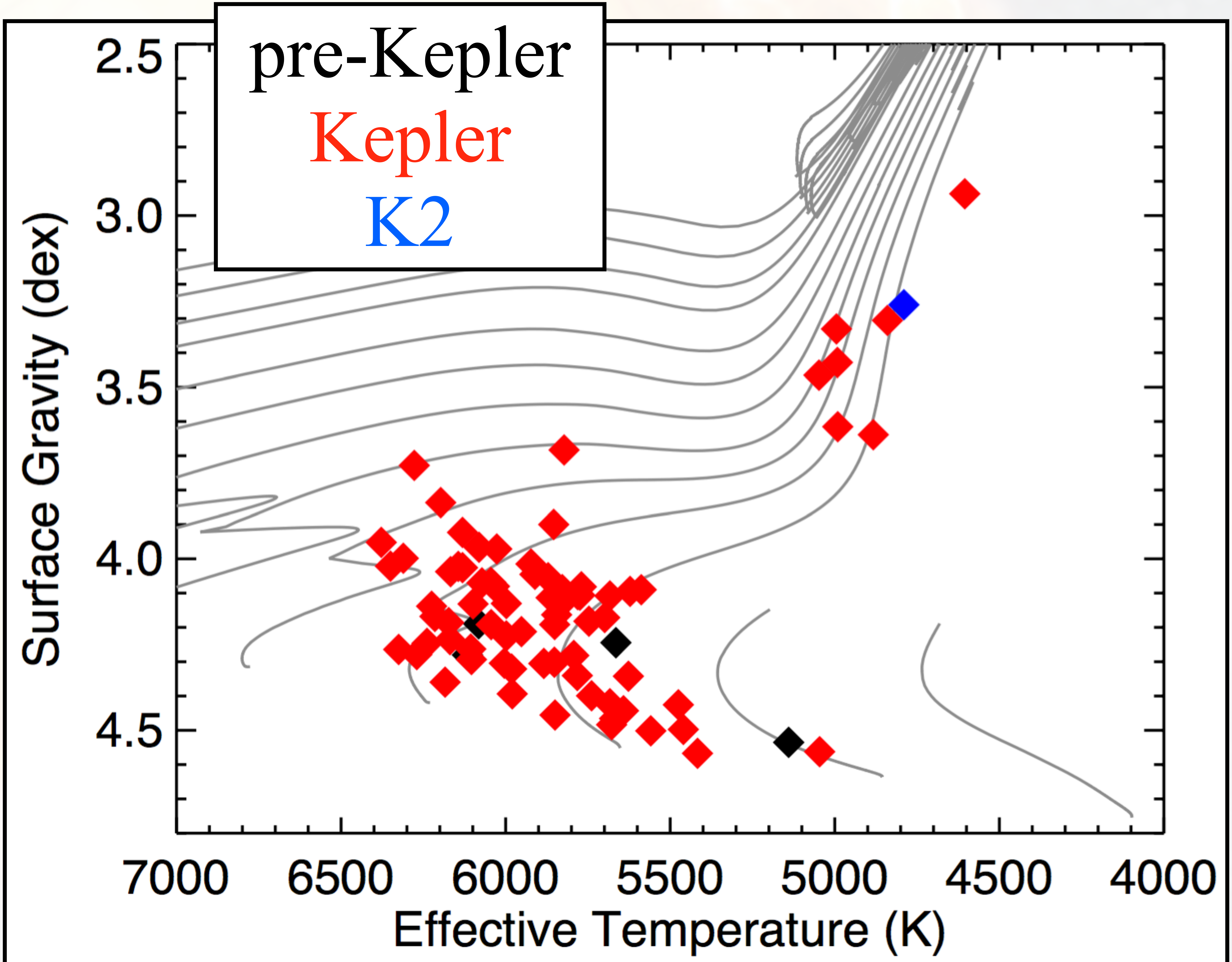


Santos et al. 2004, Pepe et al. 2007

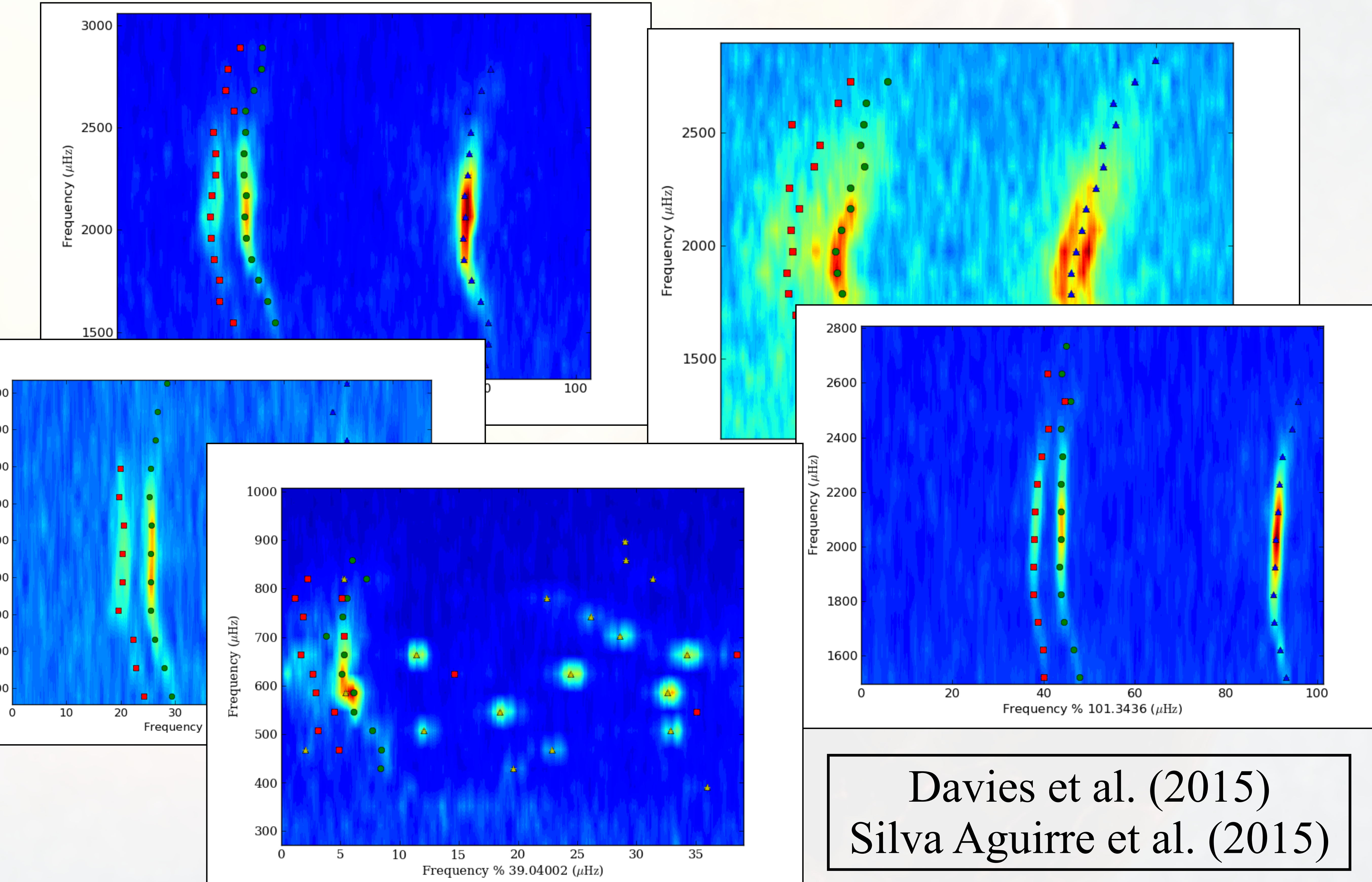


Bouchy et al. 2005, Bazot et al. 2005


pre-Kepler
Surface Gravity (dex)
2.5
3.0
3.5
4.0
4.5
HD17156
μ Ara
HD52265
α Cen B
7000
6500
6000
5500
5000
4500
4000
Effective Temperature (K)

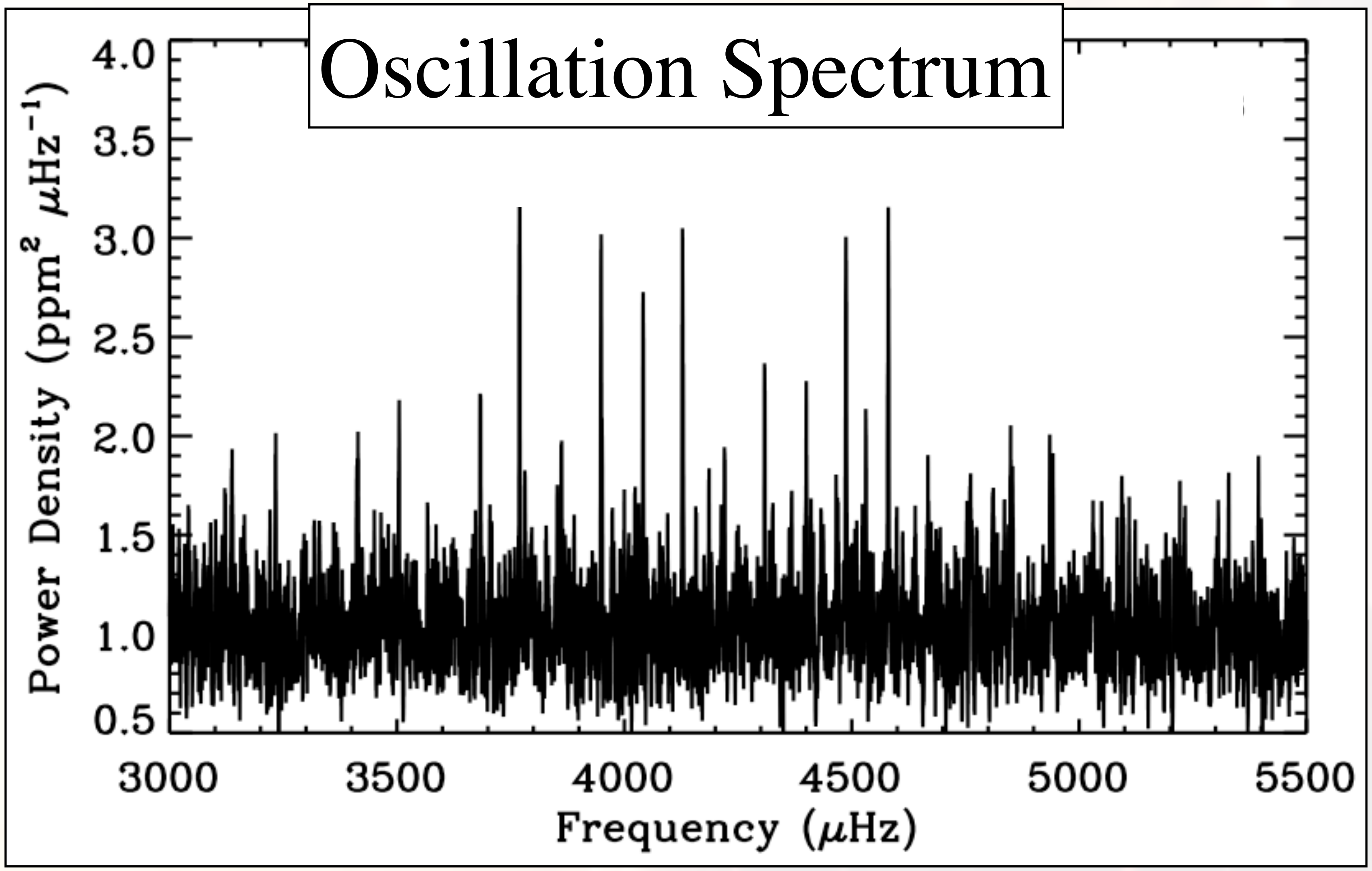

pre-Kepler
Kepler
K2
2.5
3.0
3.5
4.0
4.5
Surface Gravity (dex)
7000
6500
6000
5500
5000
4500
4000
Effective Temperature (K)

Beyond Radii: Ages of Planet Hosts



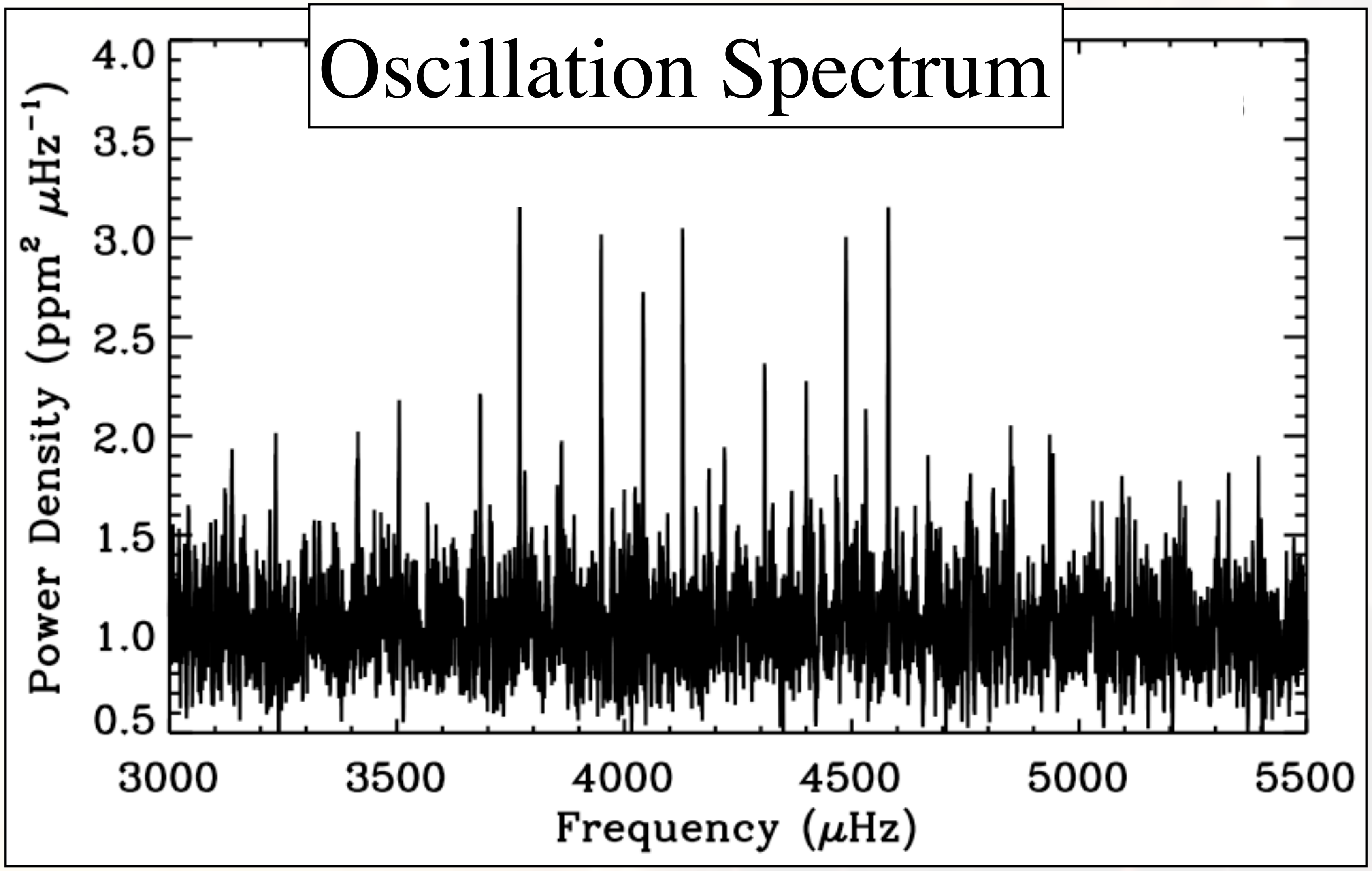
Davies et al. (2015)
Silva Aguirre et al. (2015)

Kepler-444 = HIP94931



Campante et al. 2015

Kepler-444 = HIP94931



T_{eff} ~ 5000K, [Fe/H] ~ -0.6, high proper motion!

Asteroseismology + Spectroscopy:

$R = 0.75 +/- 0.01\ R_\odot$

$M = 0.76 +/- 0.04\ M_\odot$

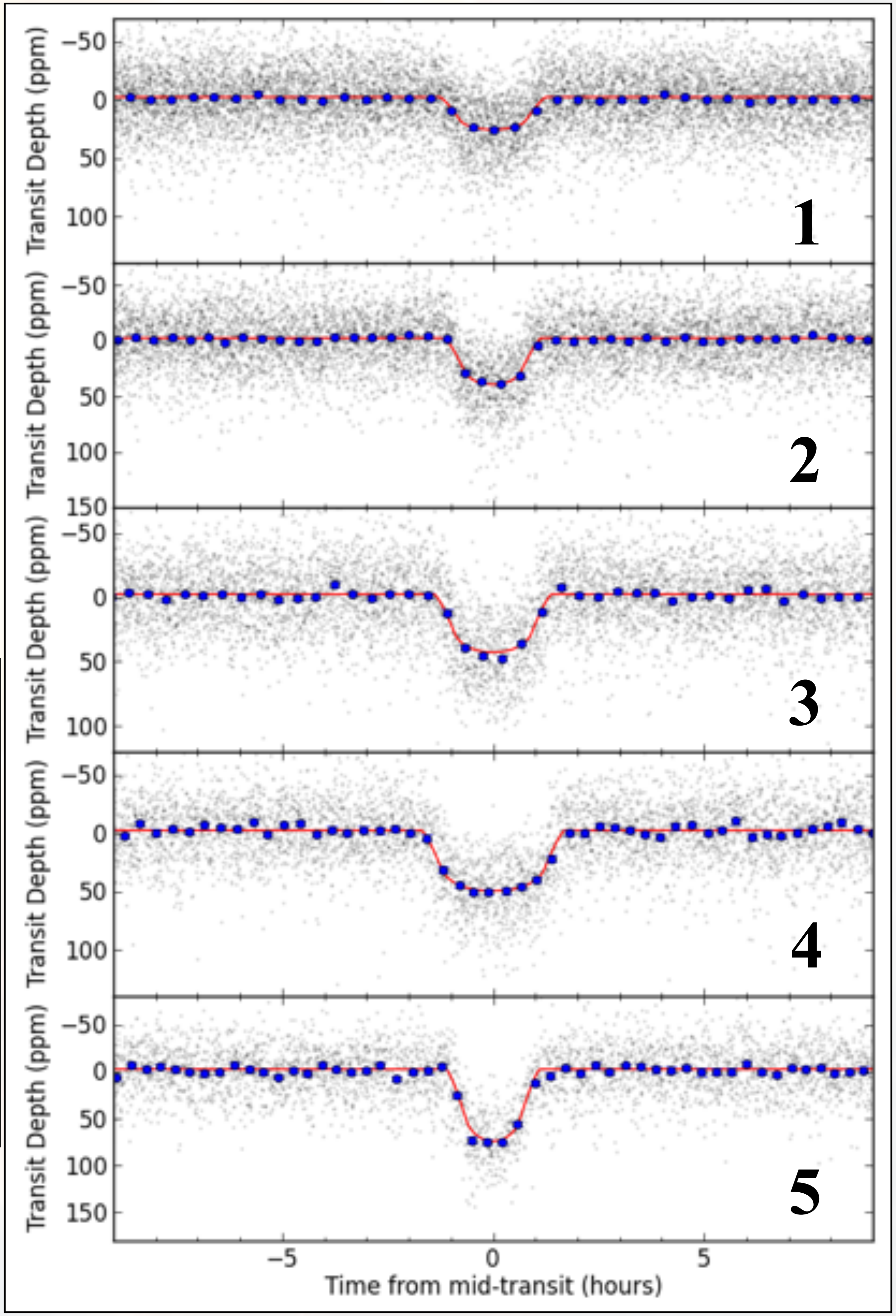
Age = 11.2 +/- 0.9 Gyr

Campante et al. 2015

5 transiting planets: all smaller than Earth, all with periods < 10 days!

$R_{01} = 0.395 \pm 0.015\ R_\oplus$
$R_{02} = 0.499 \pm 0.025\ R_\oplus$
$R_{03} = 0.511 \pm 0.018\ R_\oplus$
$R_{04} = 0.535 \pm 0.017\ R_\oplus$
$R_{05} = 0.725 \pm 0.061\ R_\oplus$

Campante et al. 2015



5 transiting planets: all smaller than Earth, all with periods < 10 days!

~ 100 km!

$R_{01} = 0.395 \pm 0.015\ R_{\oplus}$

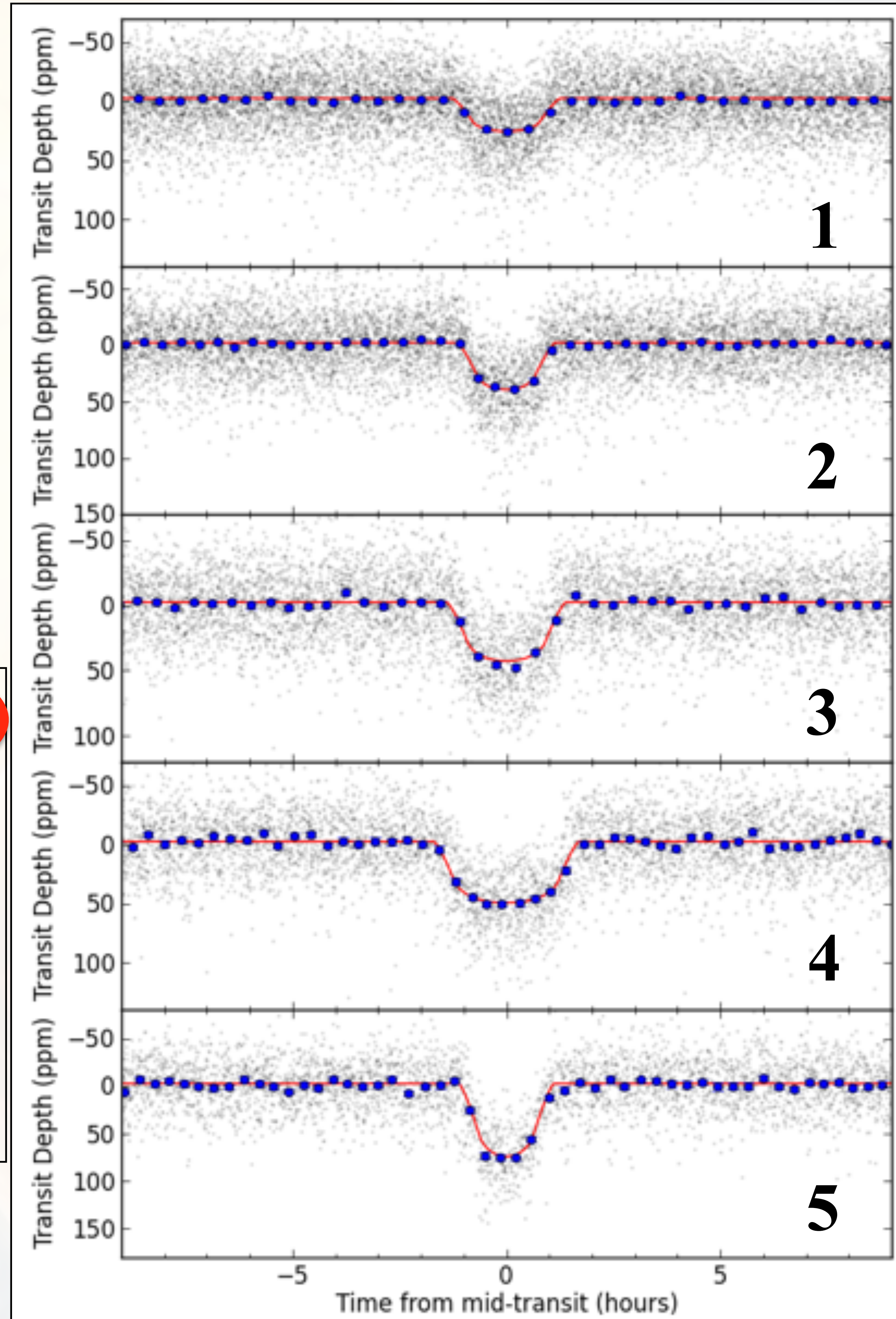
$R_{02} = 0.499 \pm 0.025\ R_{\oplus}$

$R_{03} = 0.511 \pm 0.018\ R_{\oplus}$

$R_{04} = 0.535 \pm 0.017\ R_{\oplus}$

$R_{05} = 0.725 \pm 0.061\ R_{\oplus}$

Campante et al. 2015



Santa Cruz
Da Graciosa
Carapacho
~ 100 km
Biscoitos
Serreta
Terceira
Praia da
Vitória
Angra do
Rosais
Velas
São Jorge
Calheta
Topo
Cedros
Ilha do Faial
Horta
Ilha do Pico
Lajes Do Pico

4.6 Gyr
Moon
Mercury
Mars
Earth
11.2 Gyr
b
c
d
e
f

Synergy II:
Orbital Eccentricities

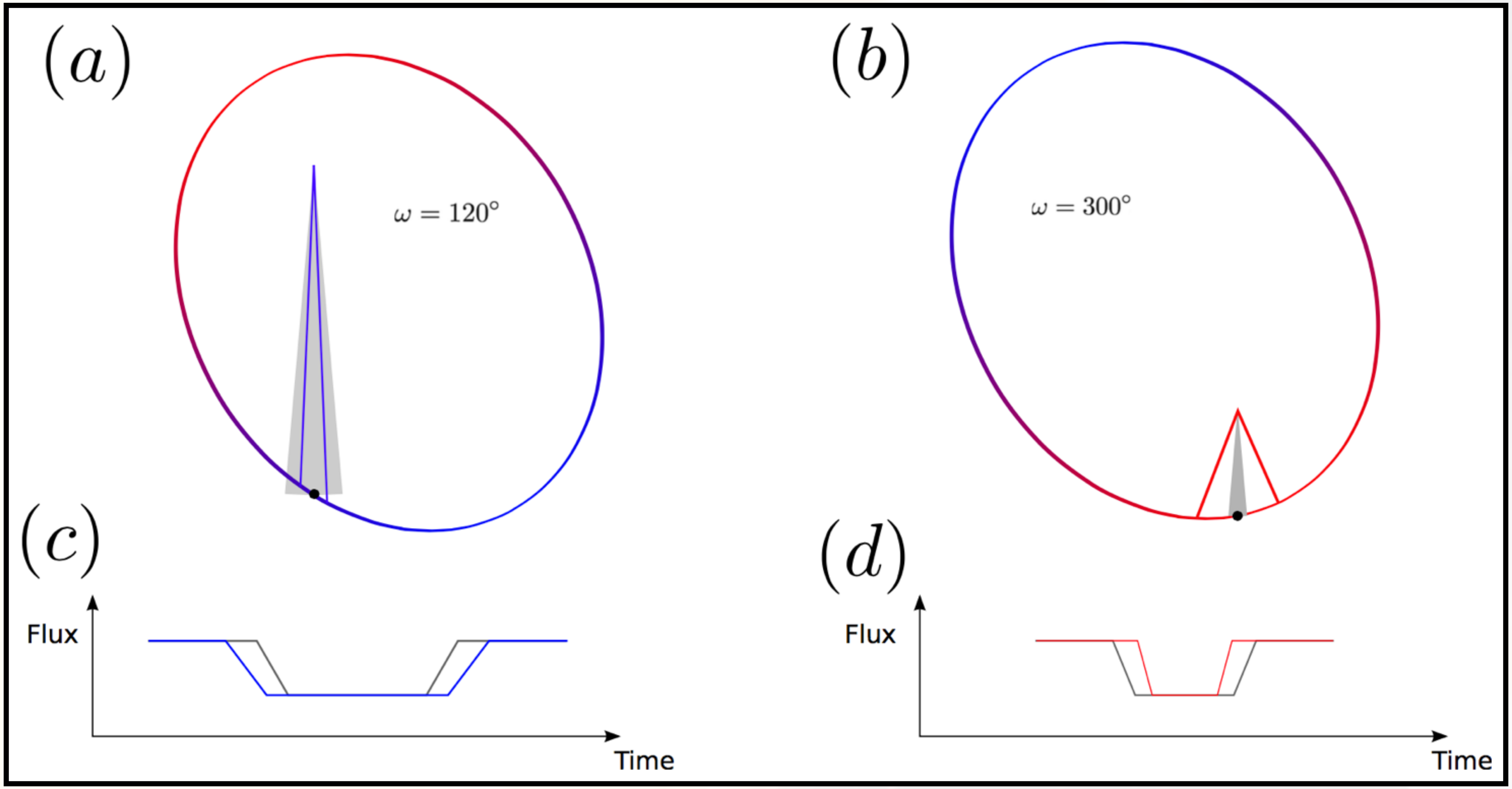
$$\rho_{\star,\mathrm{transit}} = \frac{3\pi}{GP^2}\left(\frac{a}{R_\star}\right)^3$$

Big Result 1: Transits can be used to directly measure the mean stellar density

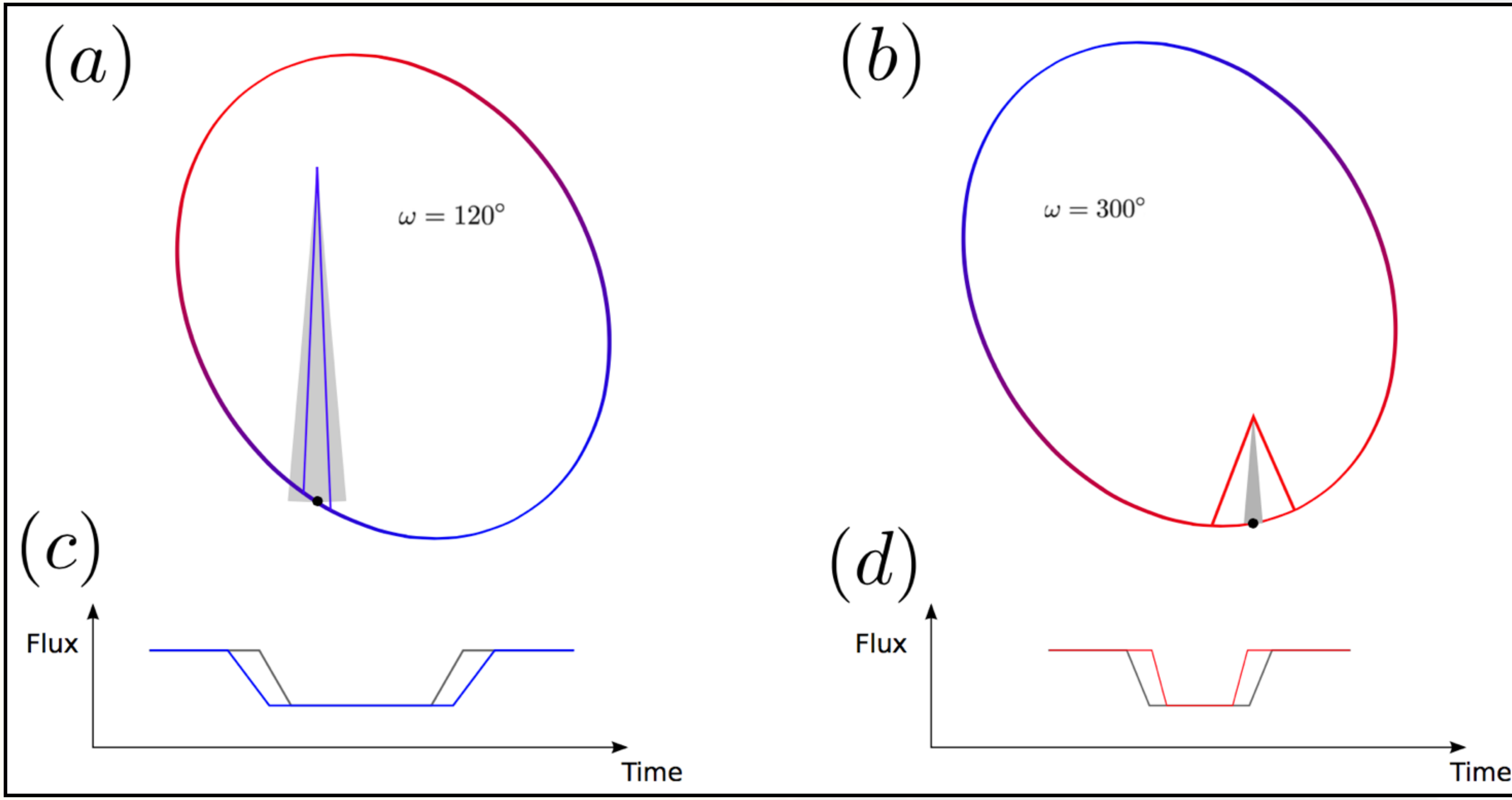
$$\boxed{\rho_{\star,\mathrm{transit}} = \frac{3\pi}{GP^2}\left(\frac{a}{R_\star}\right)^3}$$

Big Result 1: Transits can be used to directly measure the mean stellar density

Assumes circular orbits!



Van Eylen & Albrecht 2015



$$\frac{\rho_\star}{\rho_{\star,\mathrm{transit}}} = \frac{(1 - e^2)^{3/2}}{(1 + e \sin\omega)^3},$$

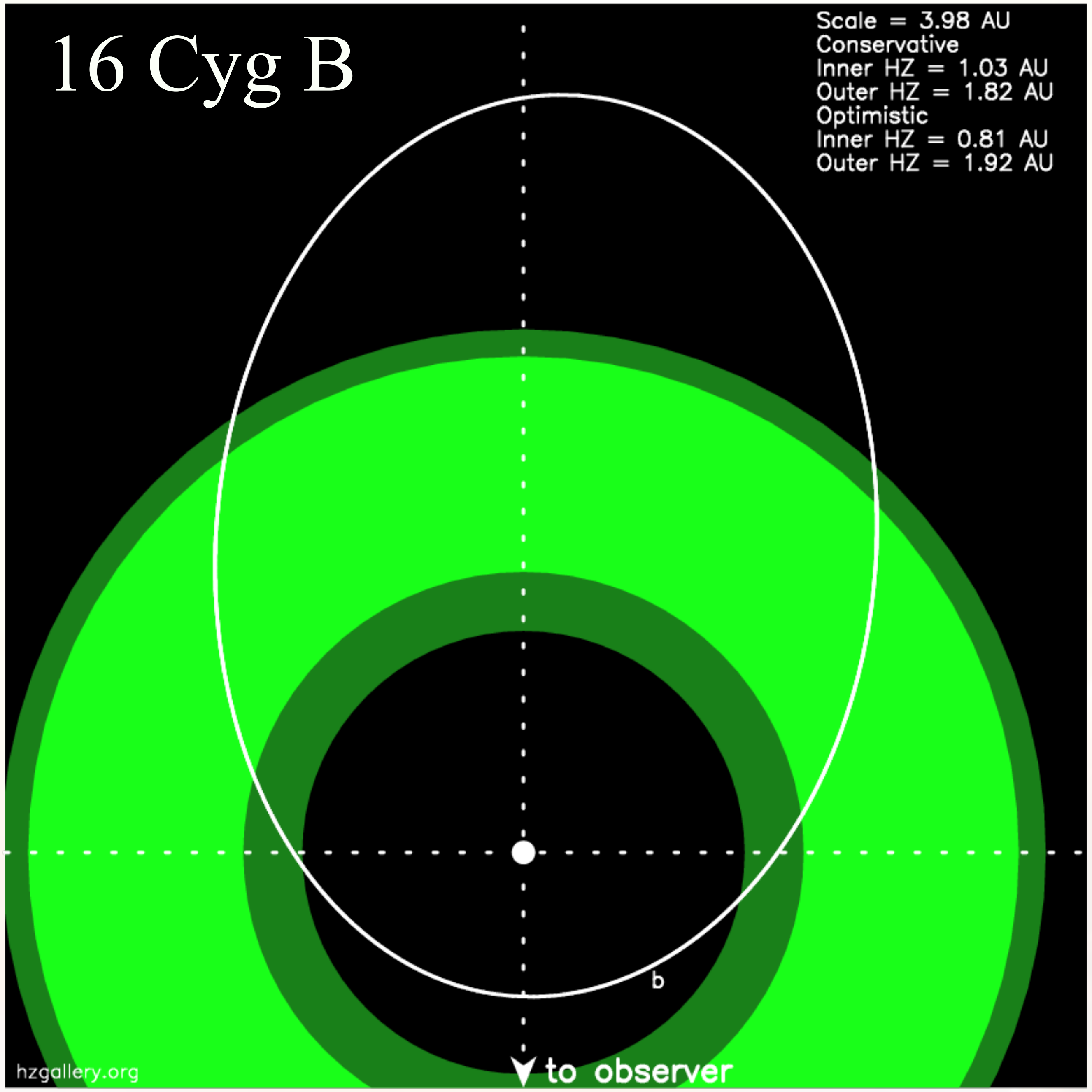
seismic density lifts degeneracies to constrain eccentricities

Van Eylen & Albrecht 2015

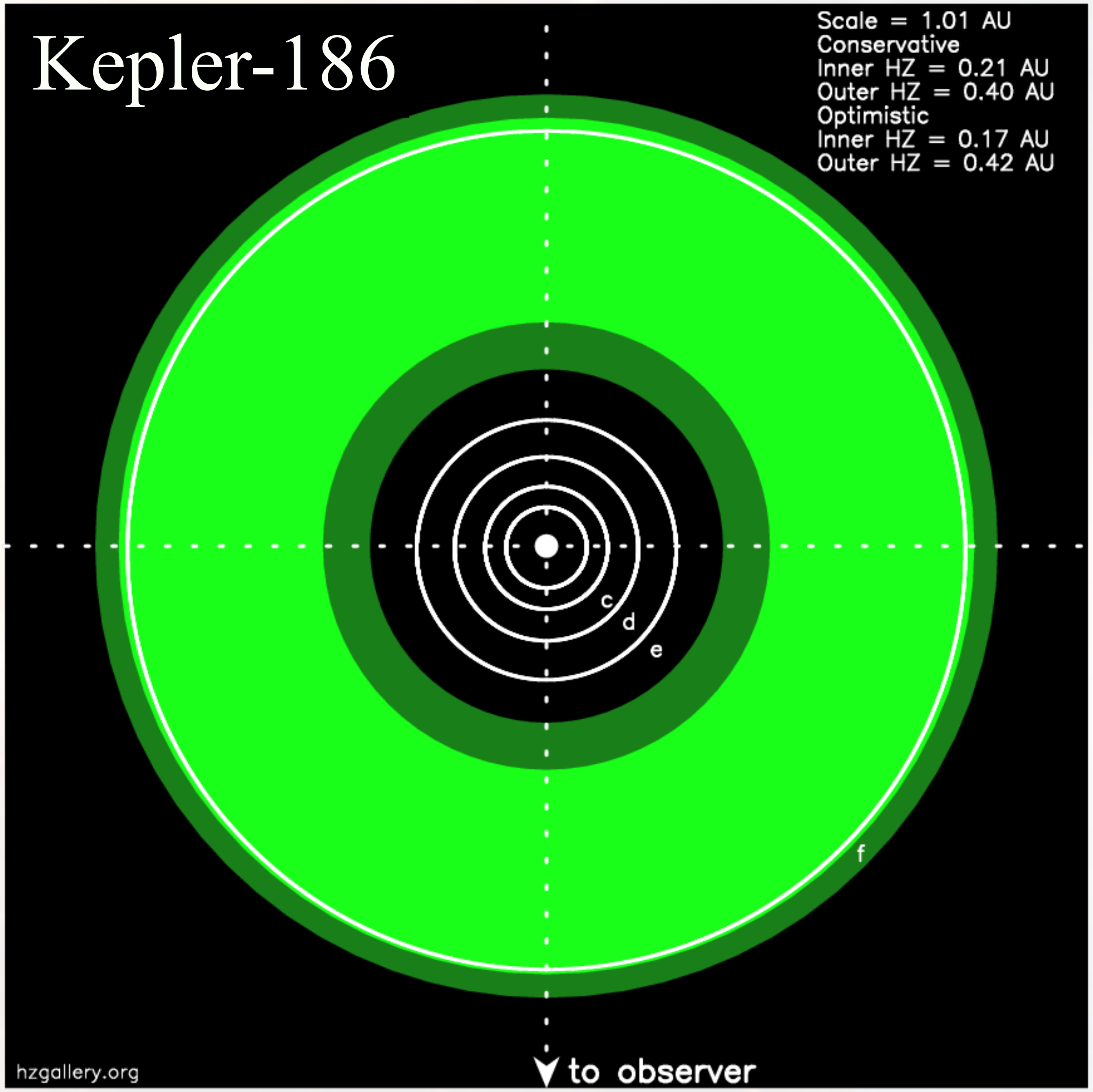
Why are exoplanet eccentricities important?

?

Why are eccentricities important?



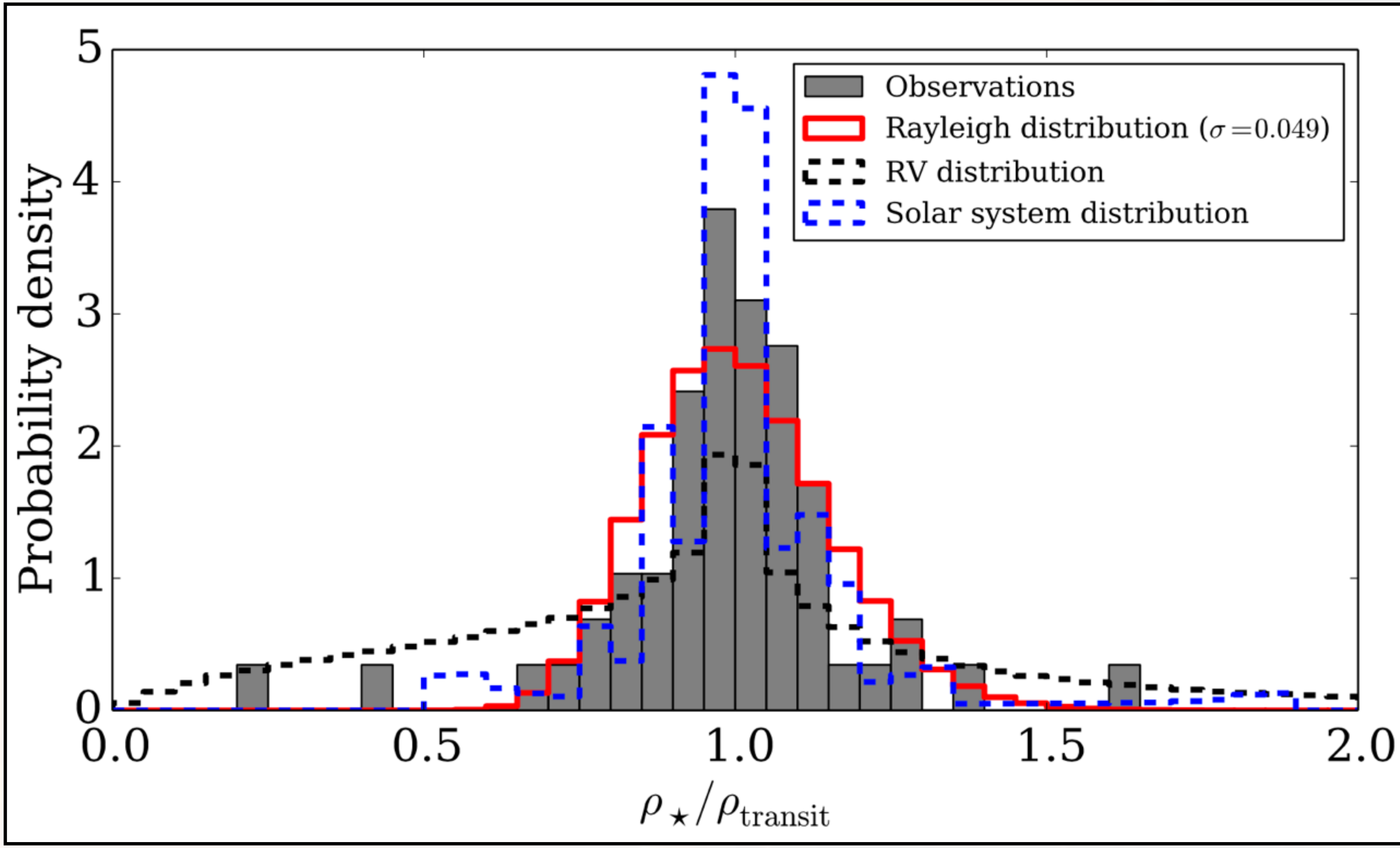
Cochran et al. 1997



Quintana et al. 2014

Time spent in habitable zone depends on eccentricity

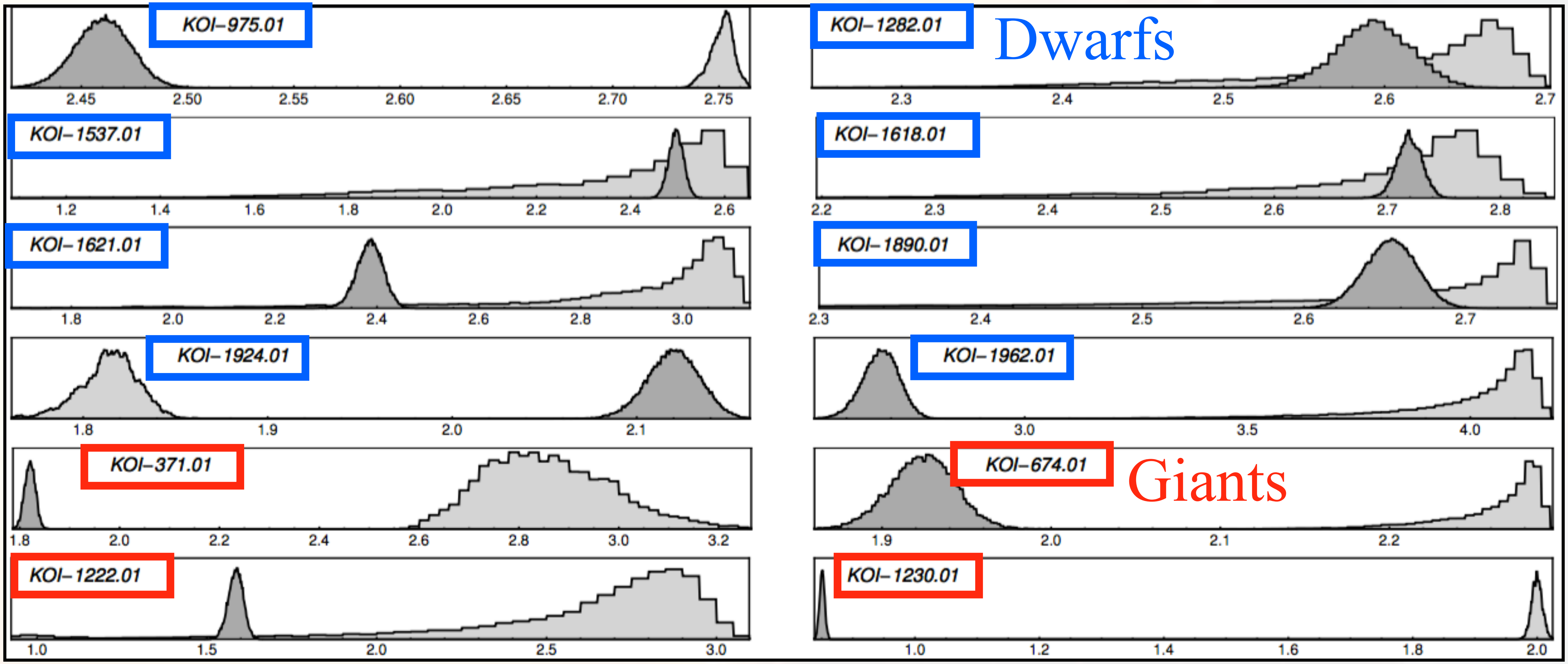
Eccentricities of Small Planets



Small planets are preferentially on circular orbits!

Van Eylen & Albrecht 2015

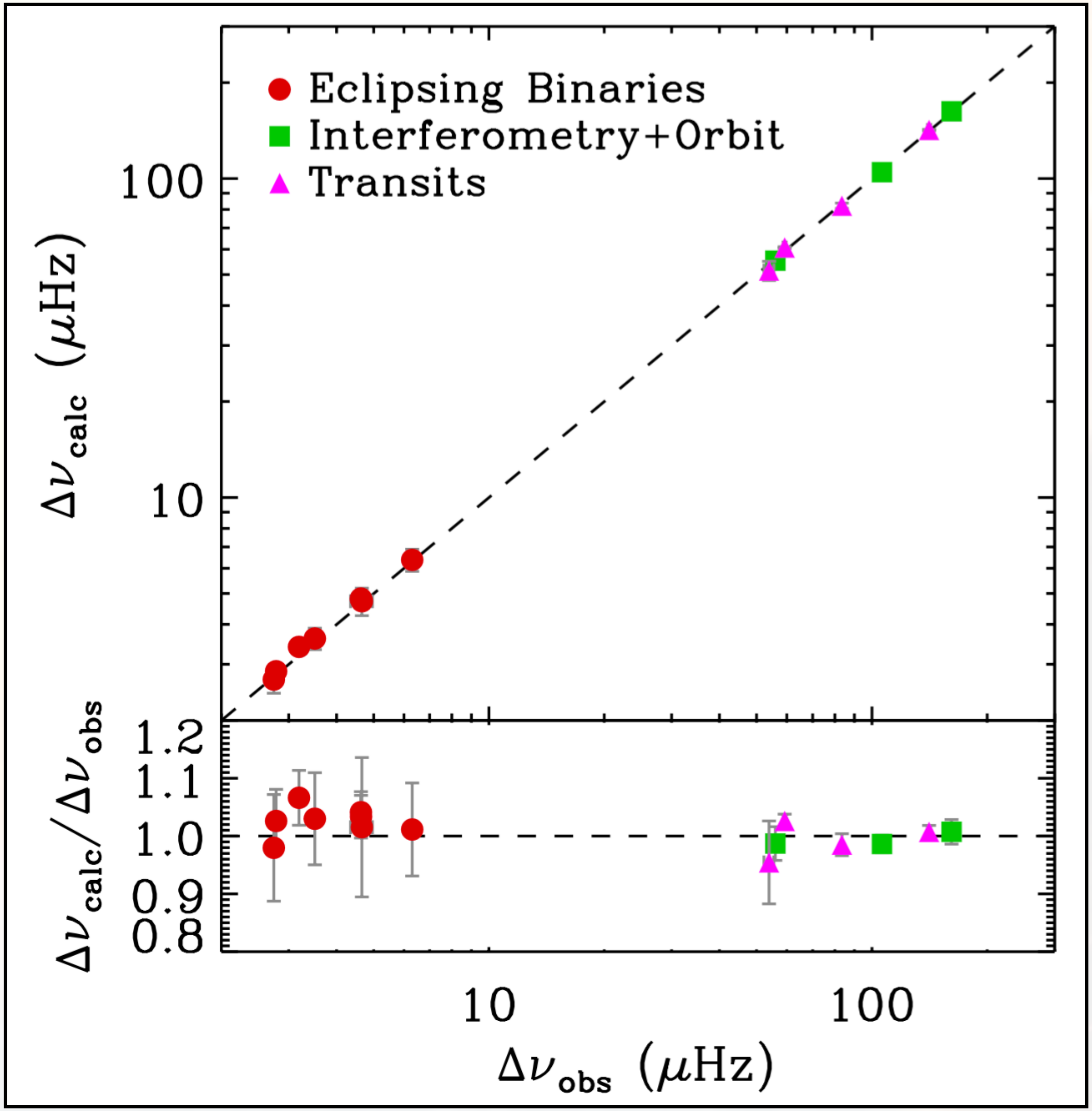
Testing for False-Positives



- $\rho_\star$ / $\rho_{transit}$ can be used to identify false positives
- Important: $\rho_{transit}$ may not always be reliable (Kepler-91!)

Sliski & Kipping 2015

Testing Asteroseismic Densities



TrES-2
(Southworth et al. 2010)

HAT P-7
(Southworth et al. 2011)

HD17156
(Nutzman et al. 2011)

Kepler-14
(Southworth et al. 2011)

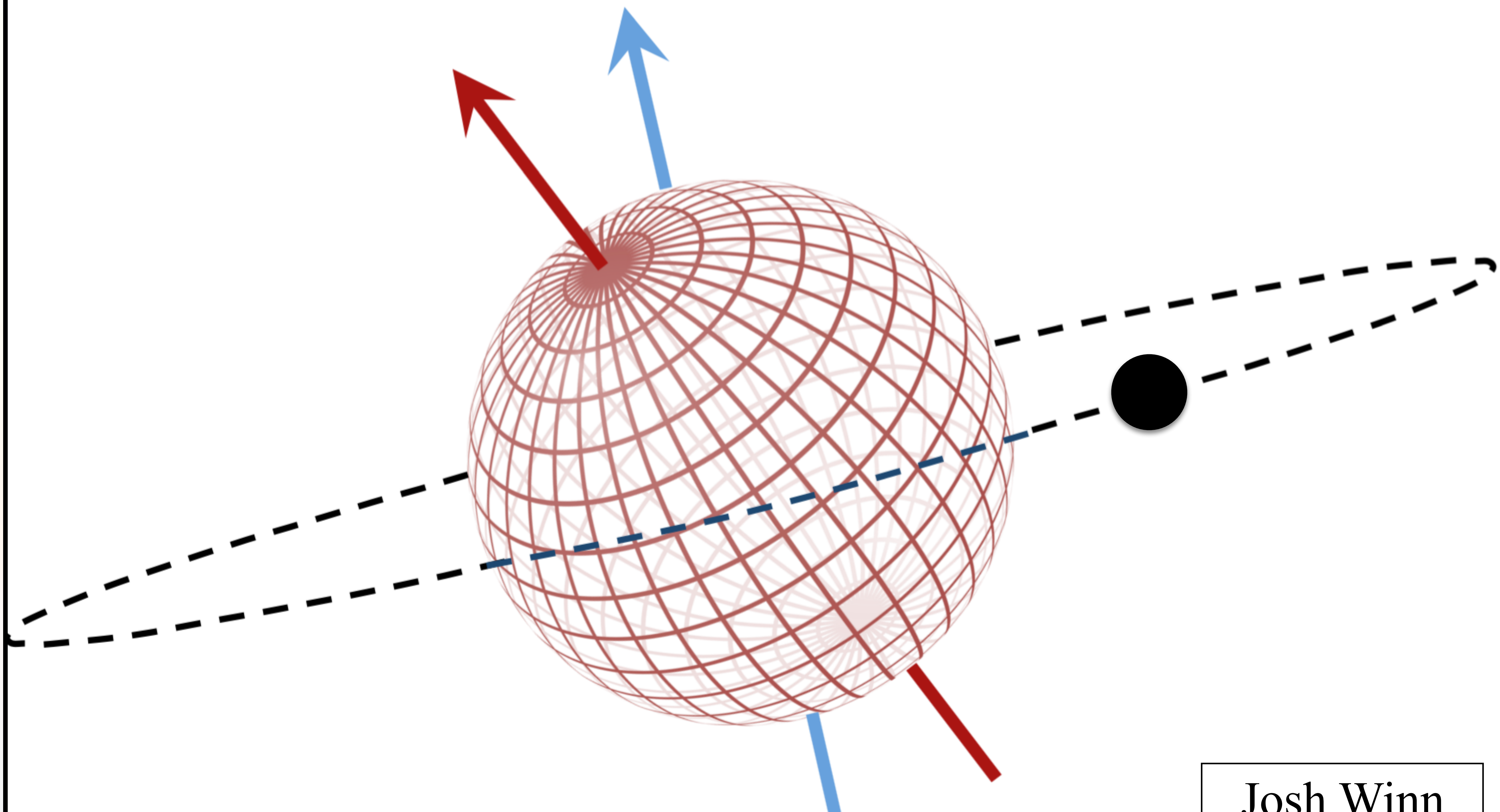
Huber 2015 + new EB's from Gaulme et al. (2016)

Synergy III:

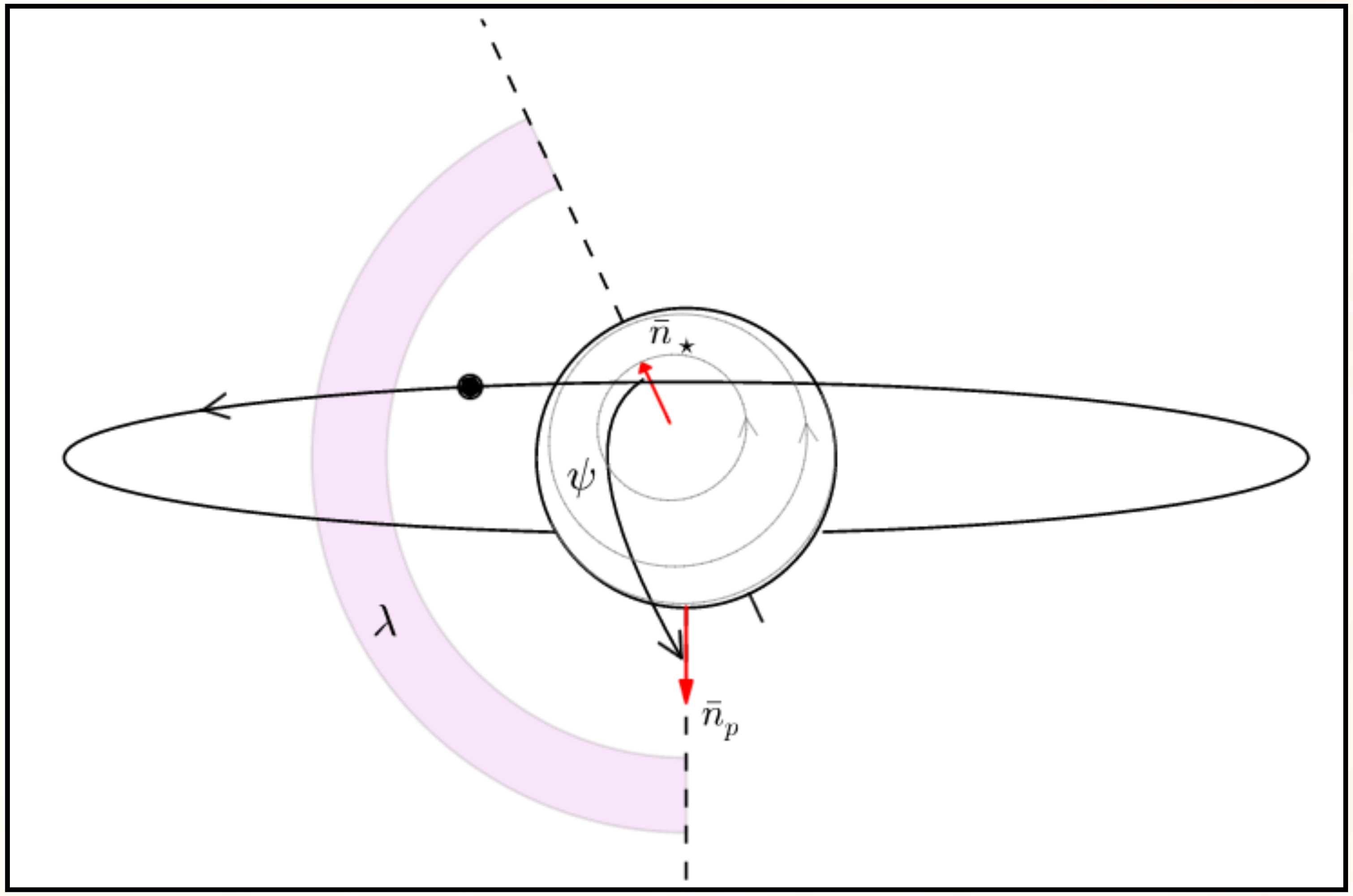
Obliquities of Exoplanet Systems

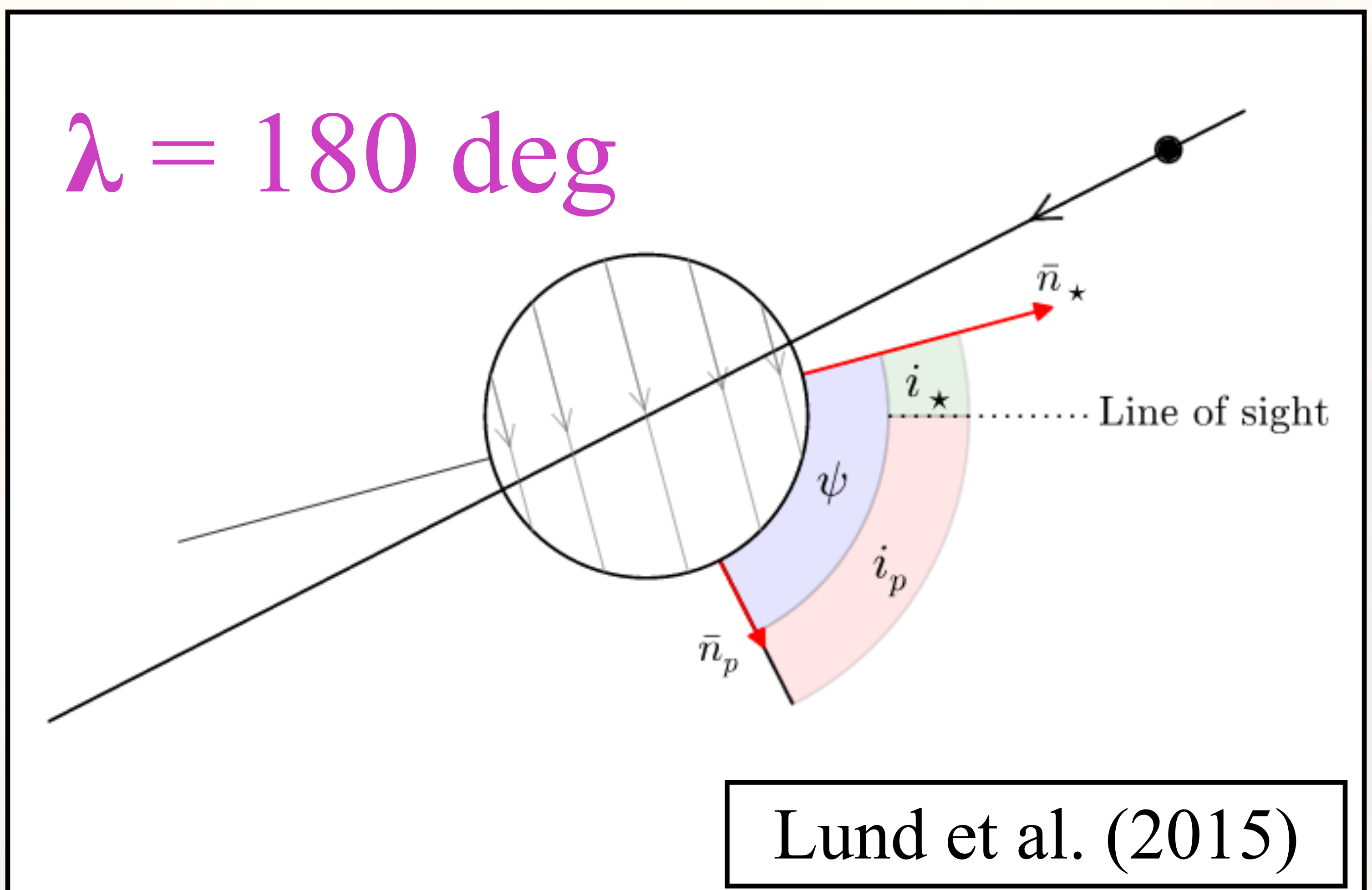
Obliquity

Angle between the **spin** and **orbital** vectors



Josh Winn





Ψ = angle between spin-axis and orbit normal (obliquity)

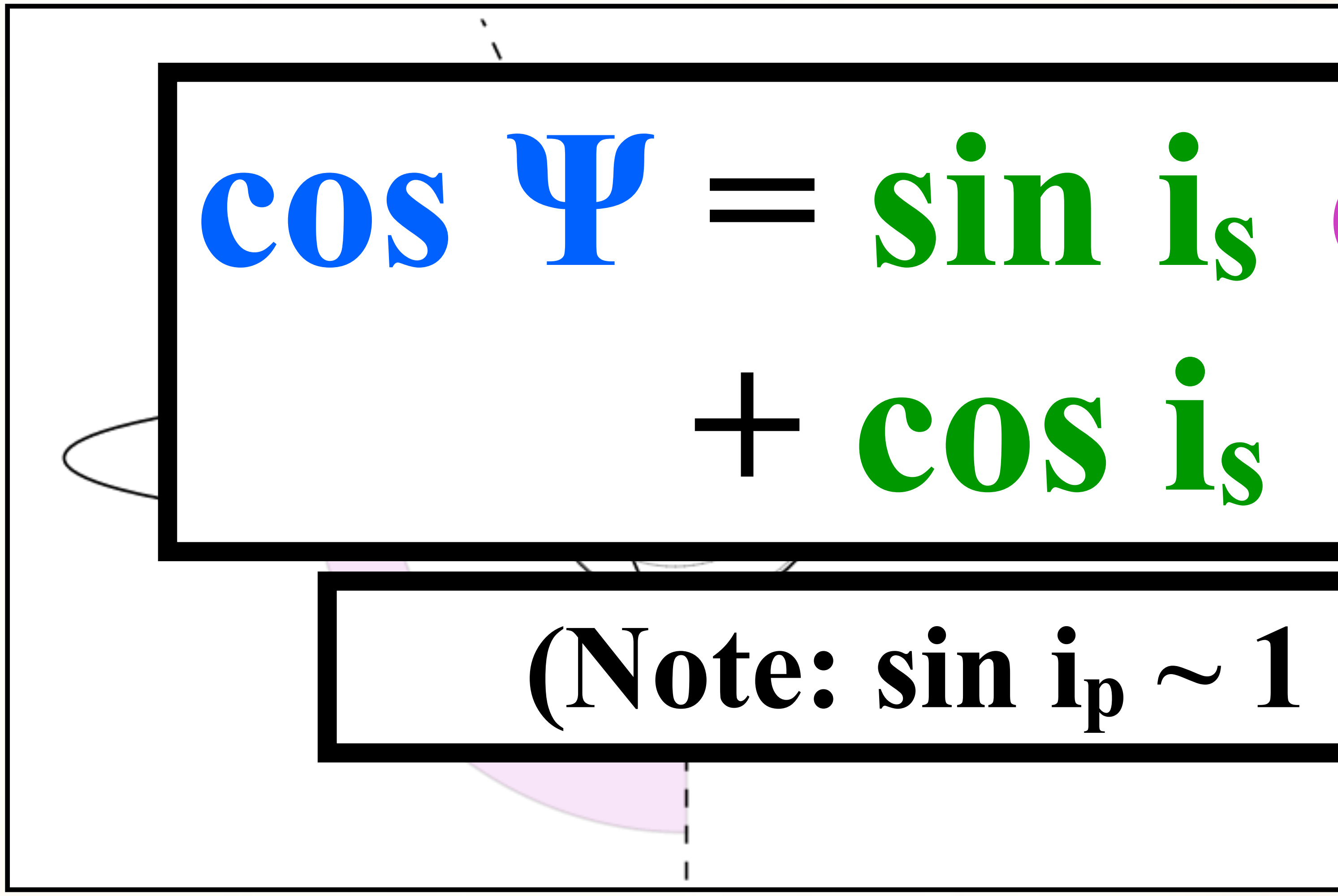
λ = sky-projected angle between spin-axis and orbit normal

$\mathbf{i_s}$ = line of sight spin-axis angle

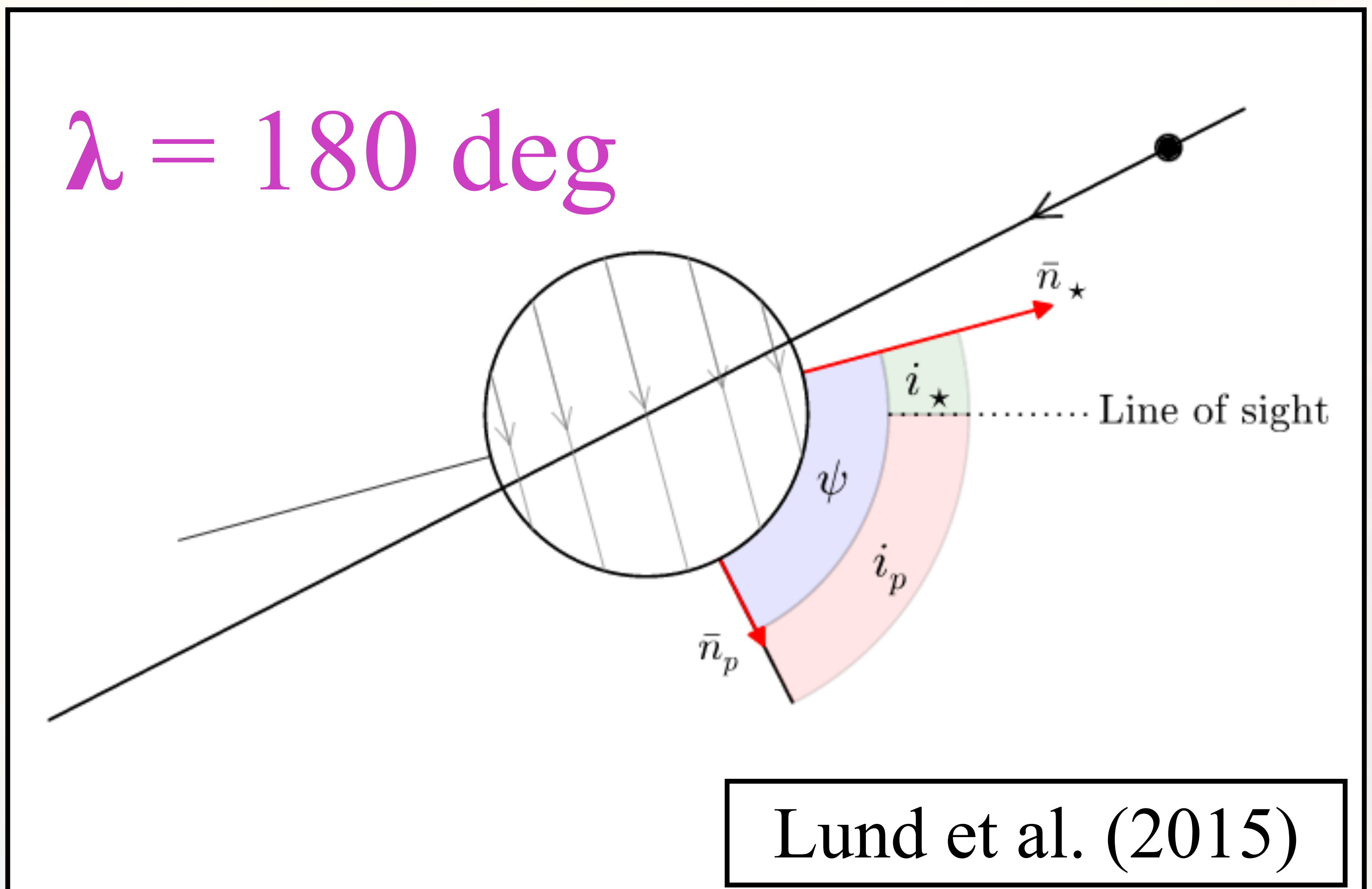
$\mathbf{i_p}$ = line of sight orbit inclination

$$\cos\Psi = \sin i_s \cos\lambda \ \sin i_p + \cos i_s \sin i_p$$

(Note: $\sin i_p \sim 1$ for transits)

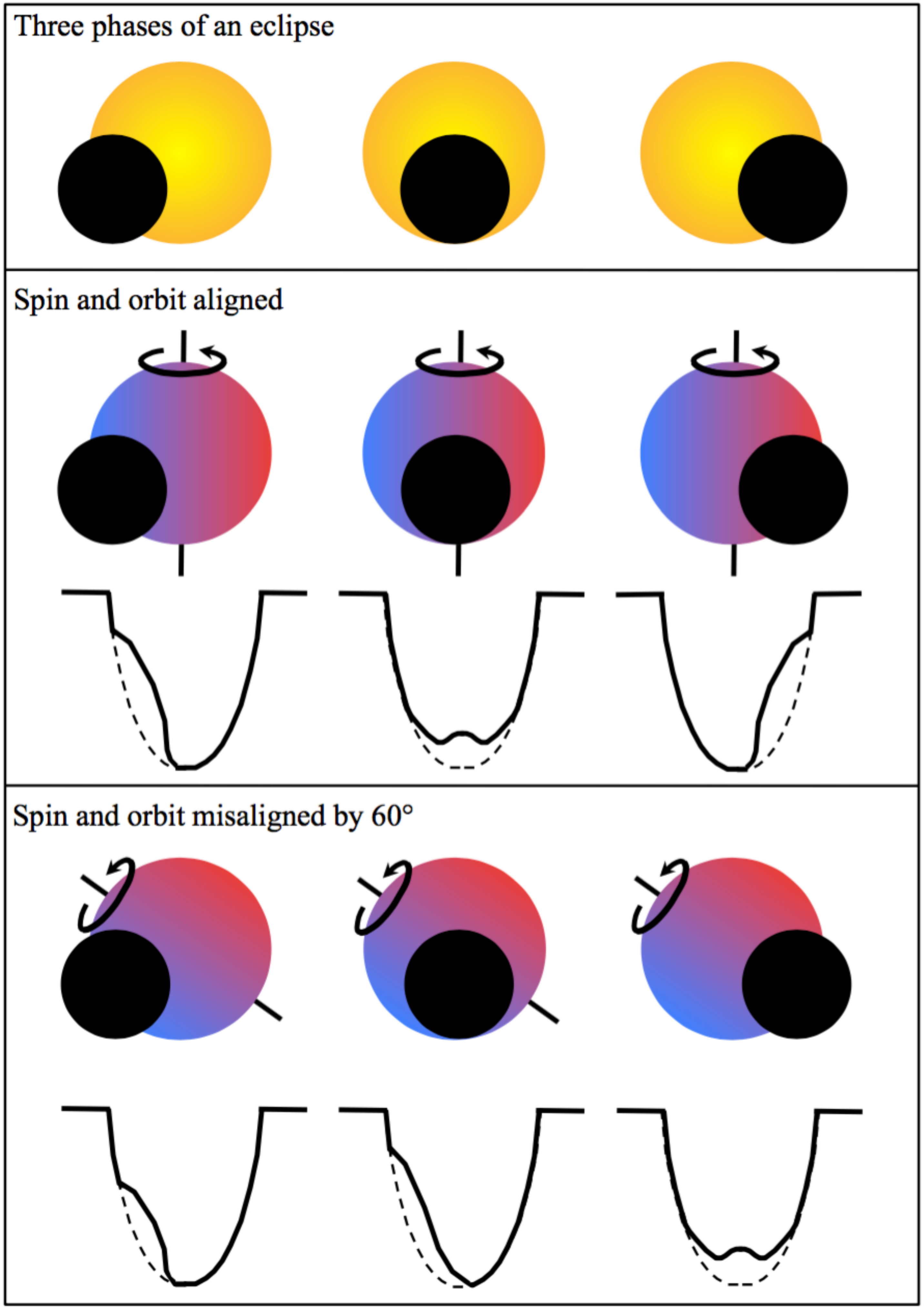


ed angle between spin-axis and orbit normal



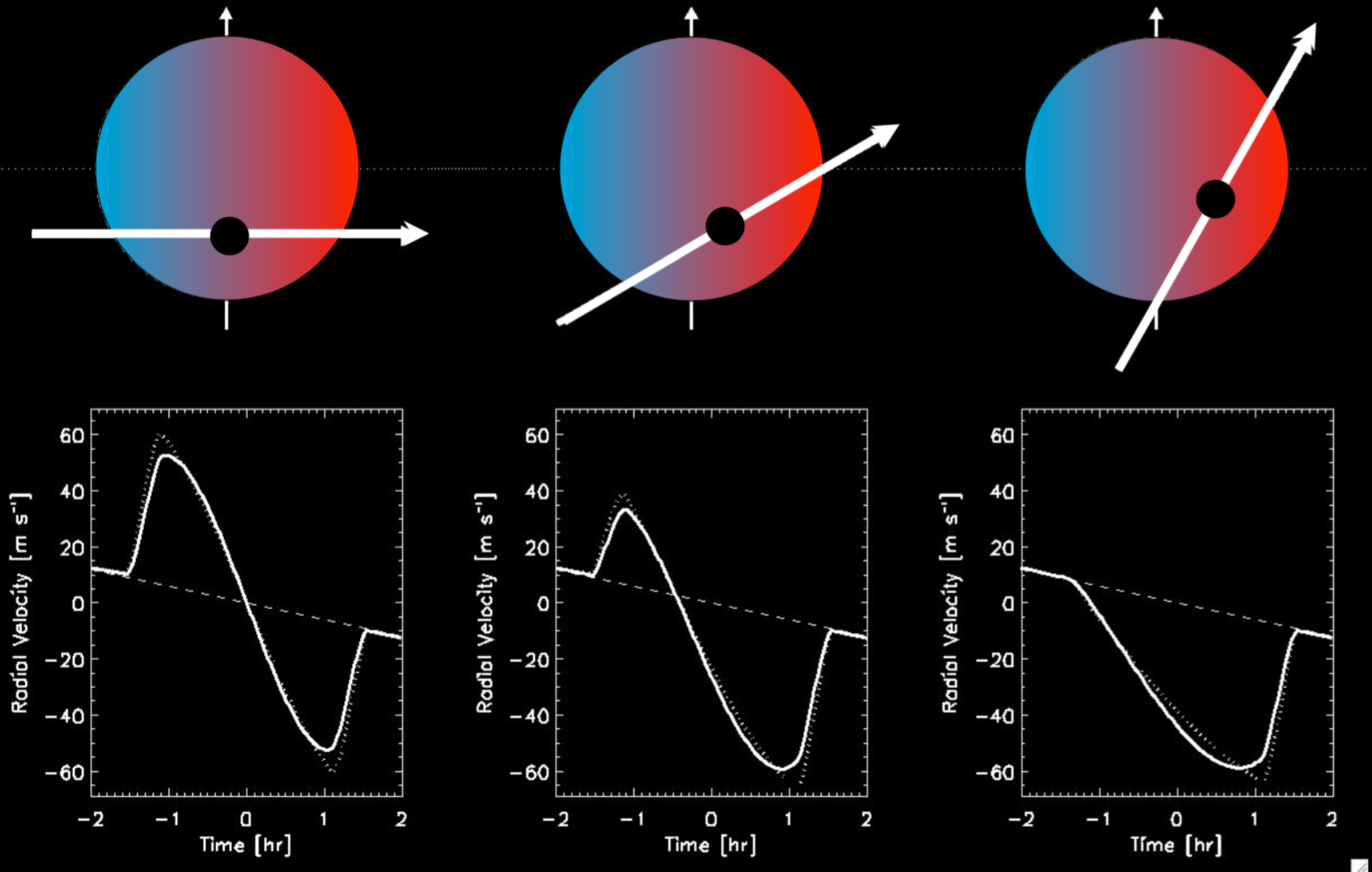
i_s = line of sight spin-axis angle

i_p = line of sight orbit inclination

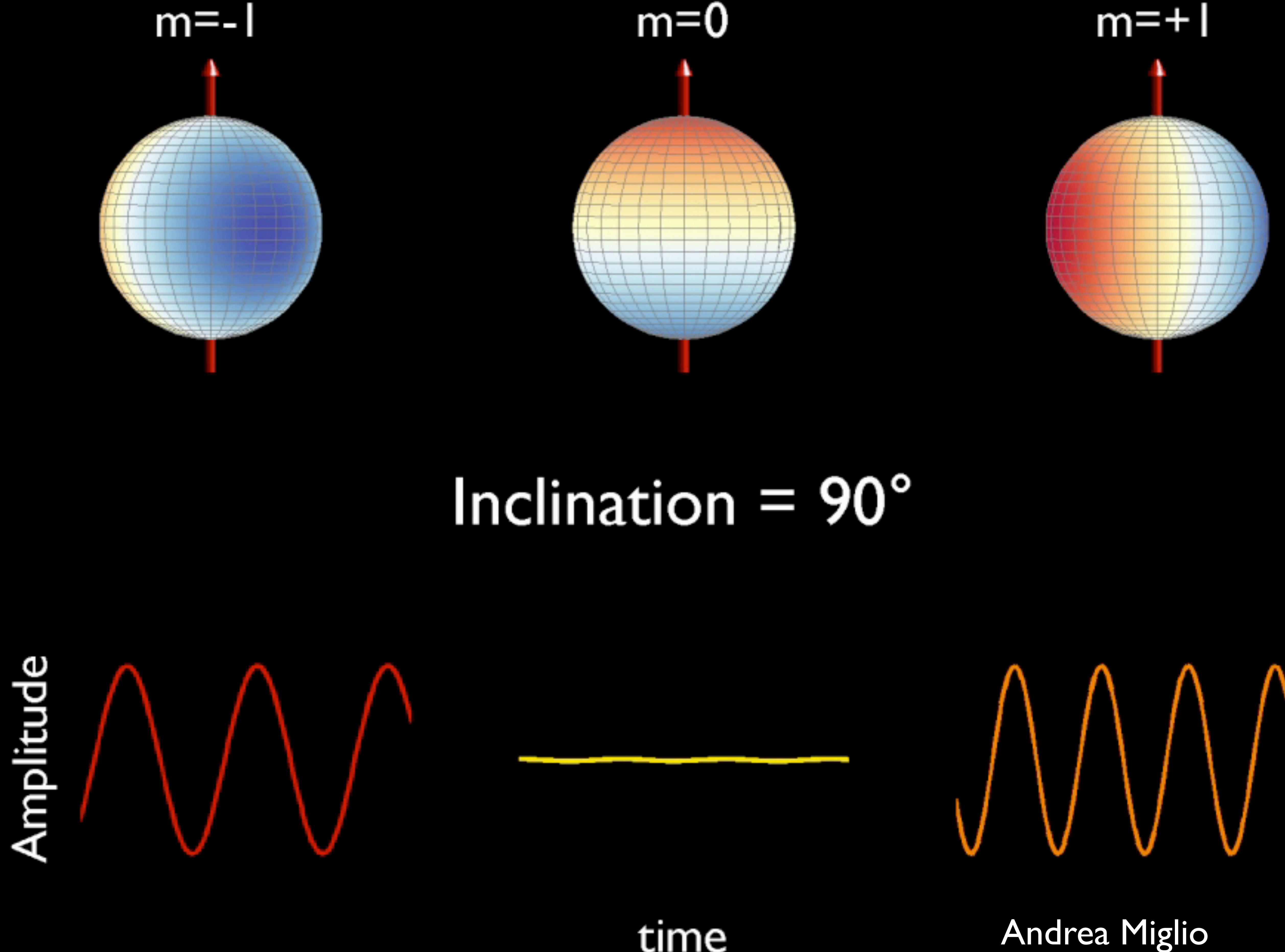


Rossiter-McLaughlin Effect

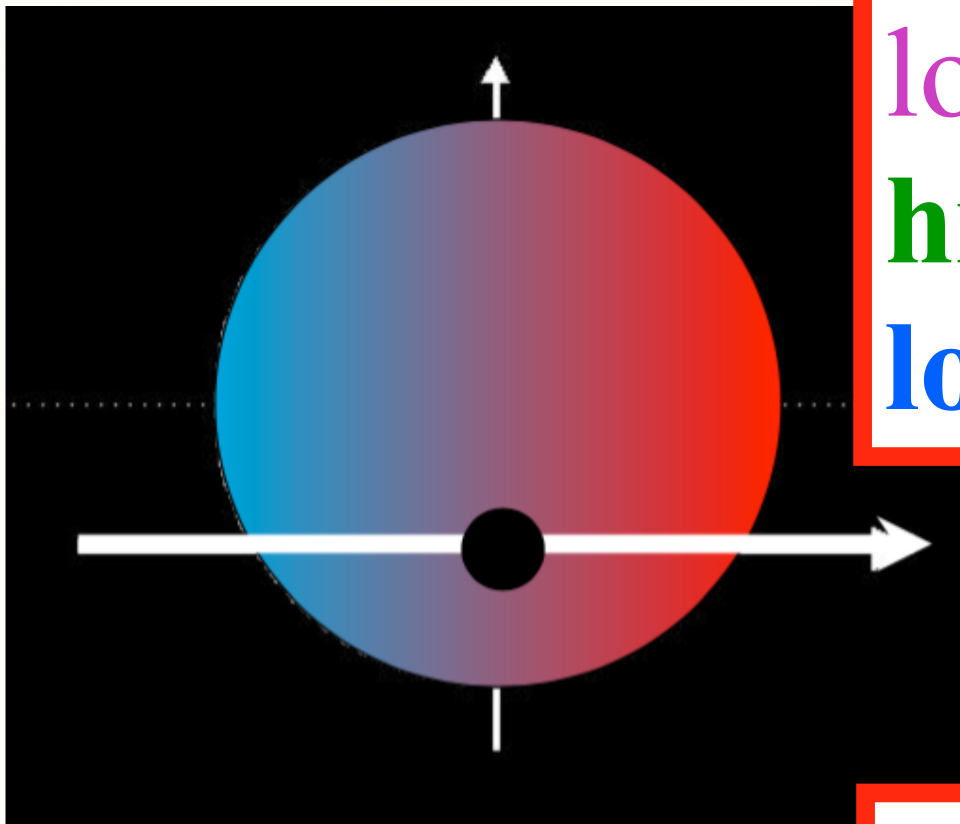
- transit “distorts” spectral line and hence radial velocity signal
- measures projected obliquity λ
- scales with planet size



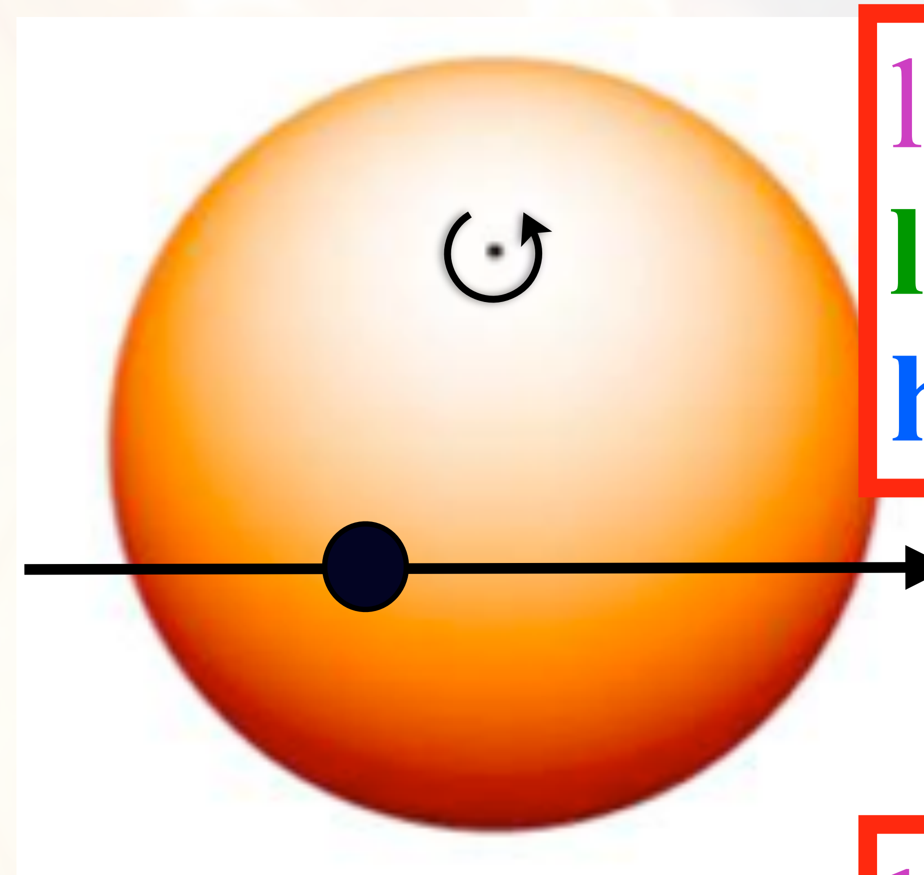
λ = 0 deg λ = 30 deg λ = 60 deg



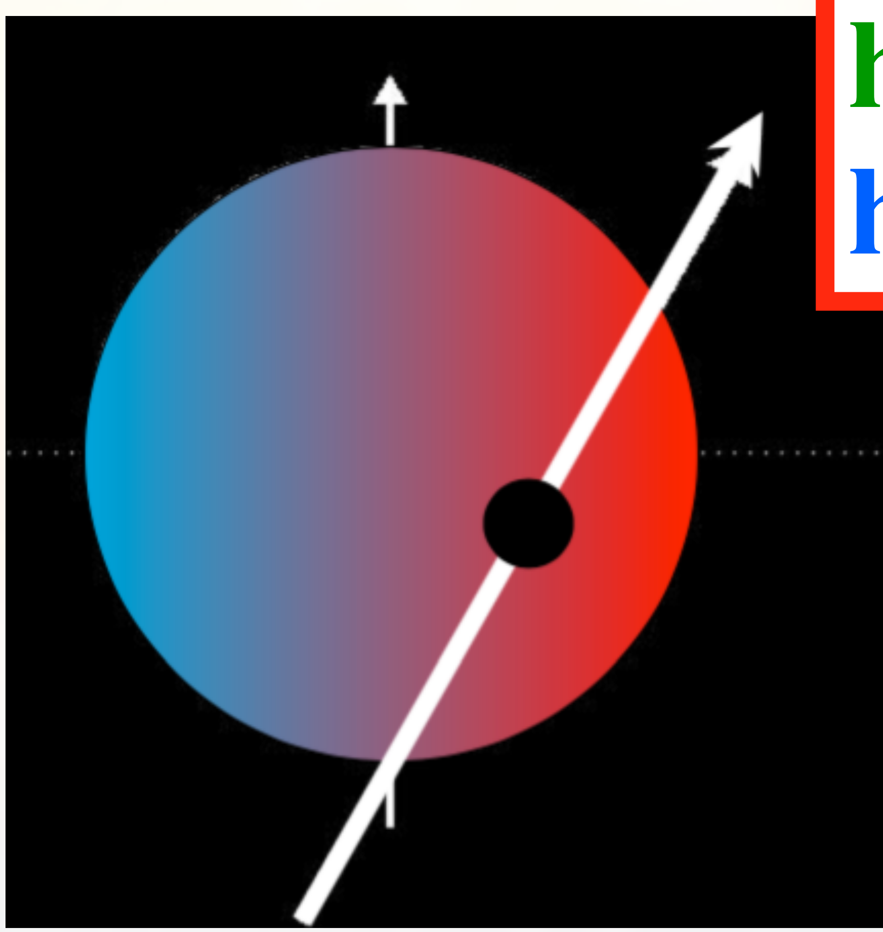
Andrea Miglio
University of Birmingham, UK



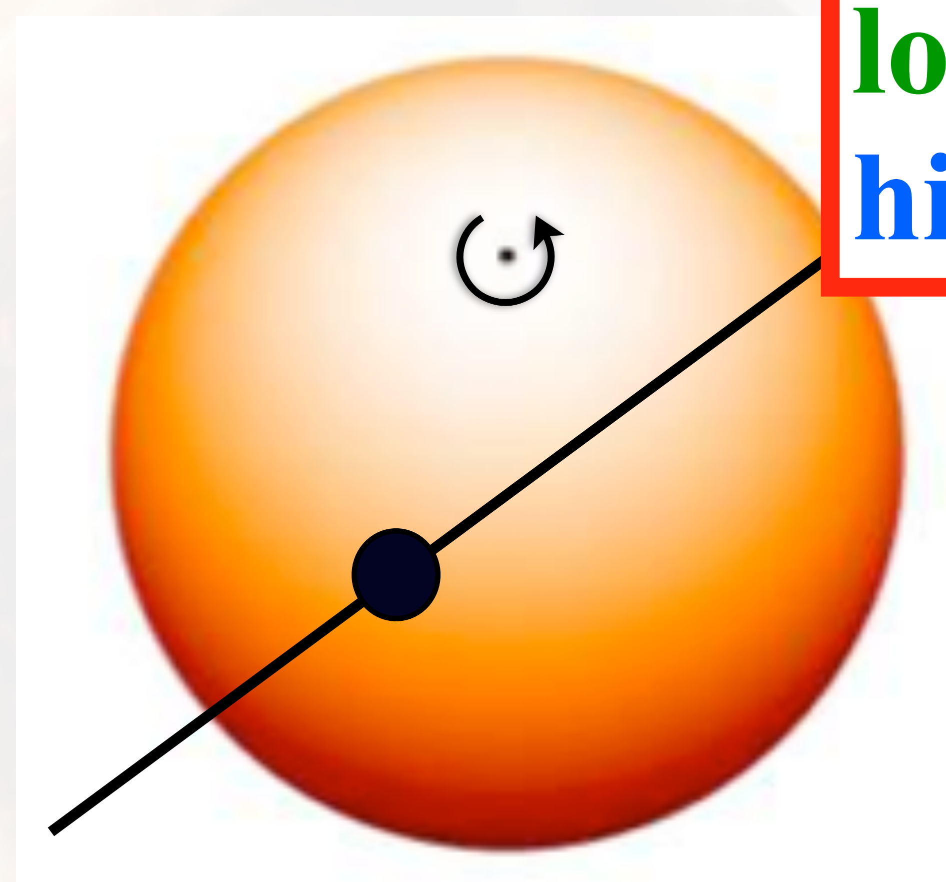
low λ
high i_s
low Ψ



low λ
low i_s
high Ψ



high λ
high i_s
high Ψ

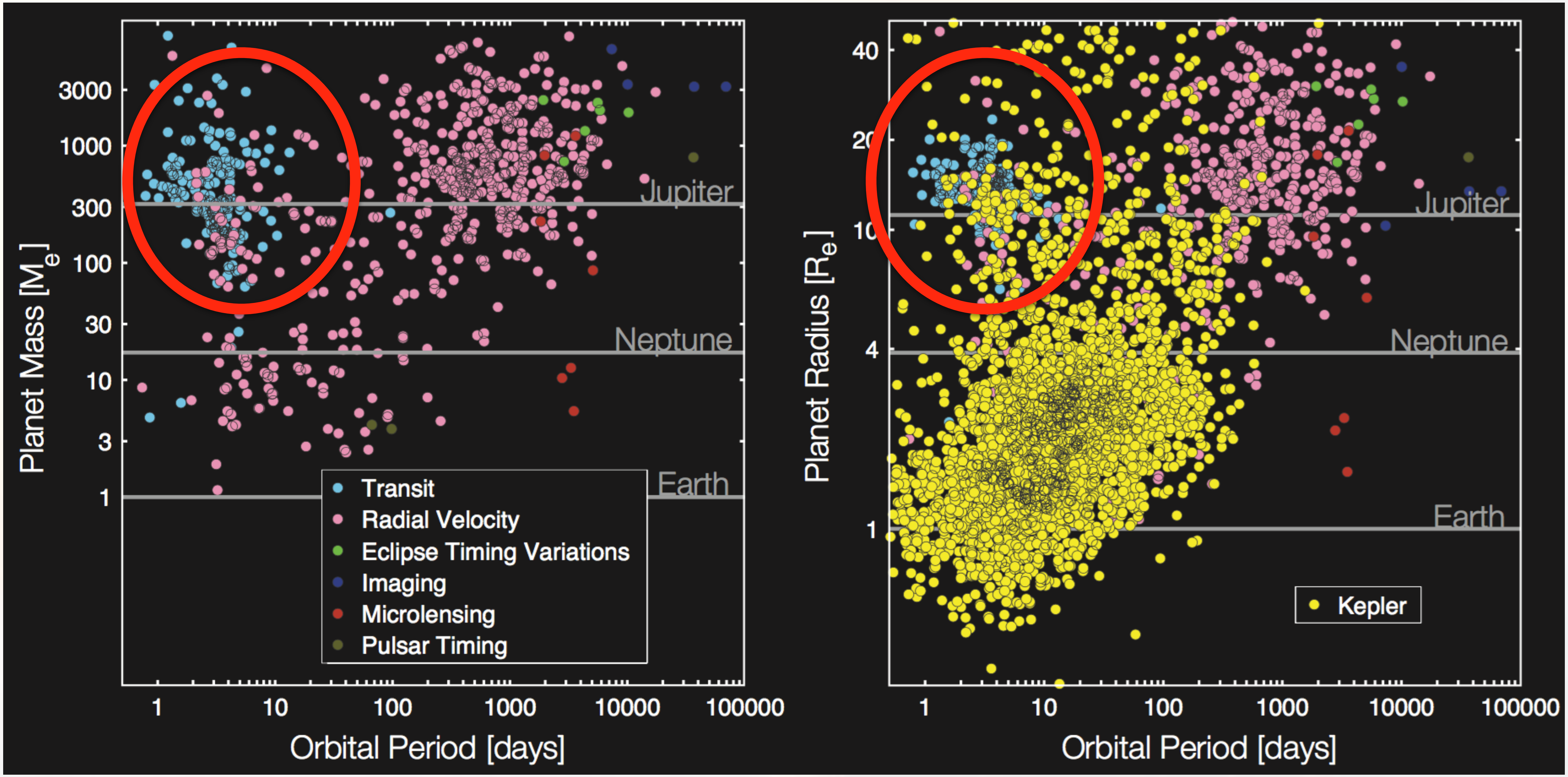


high λ
low i_s
high Ψ

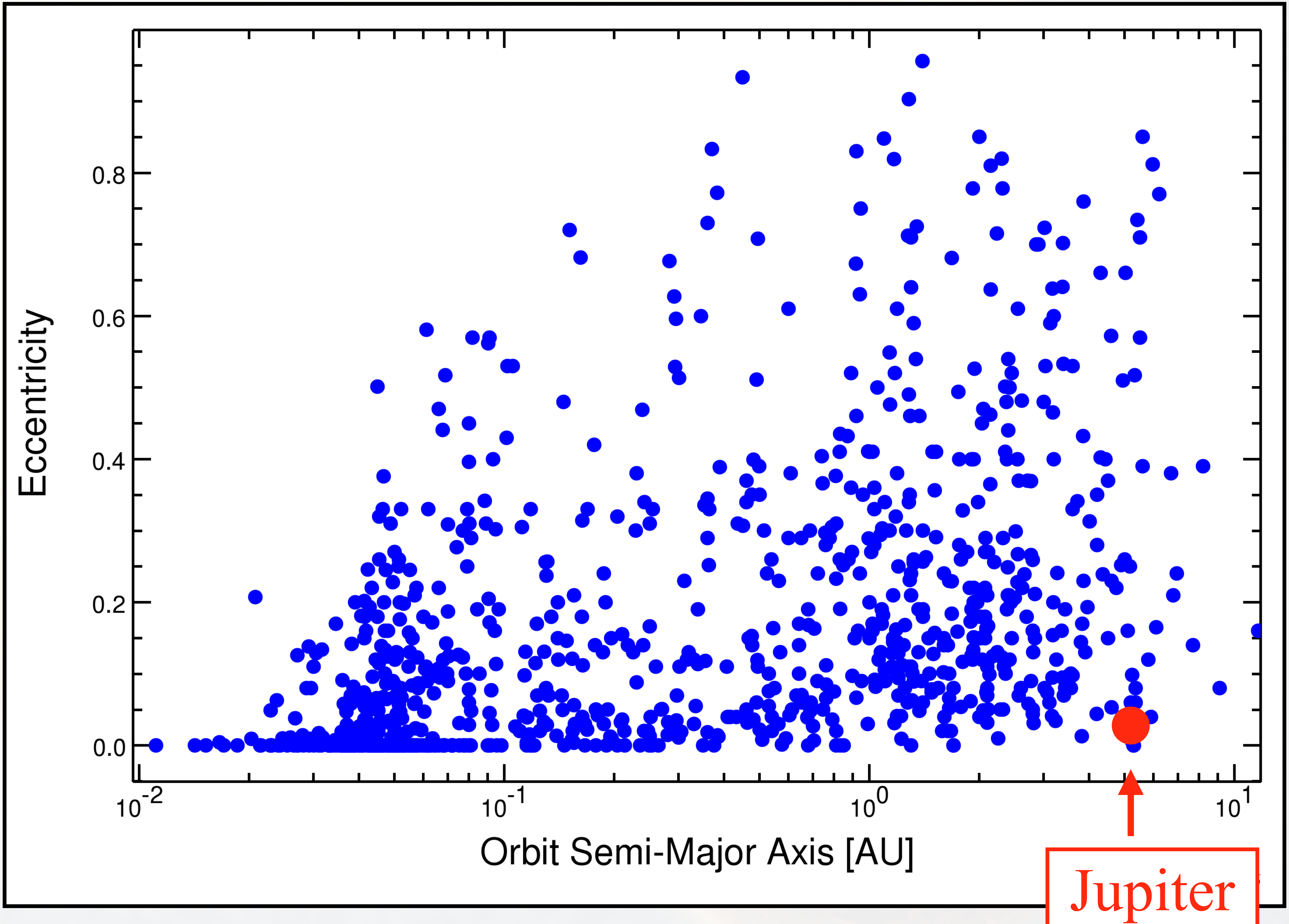
What can we learn from obliquities about exoplanets?

?

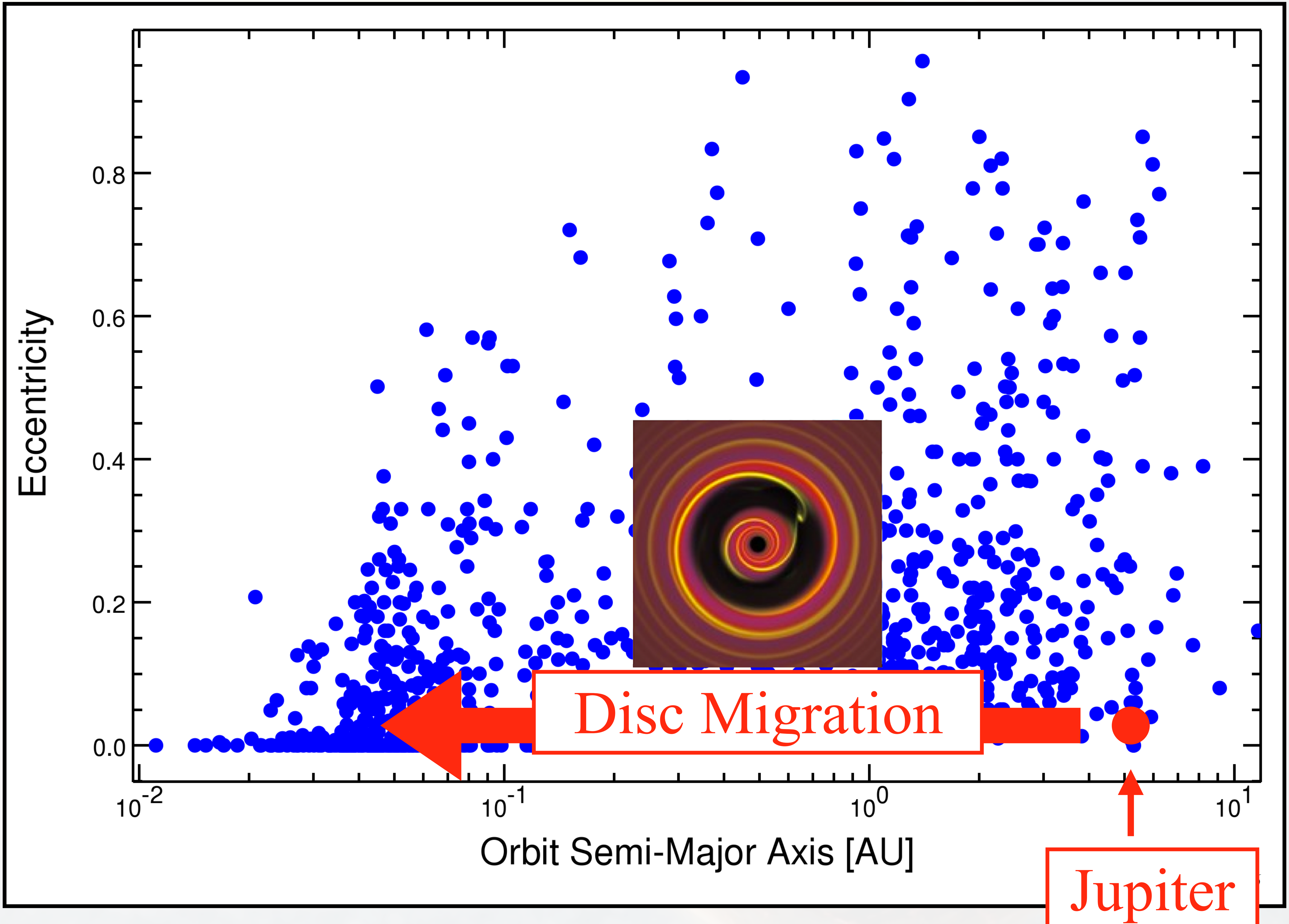
A 20 year old puzzle: How did hot Jupiters form?



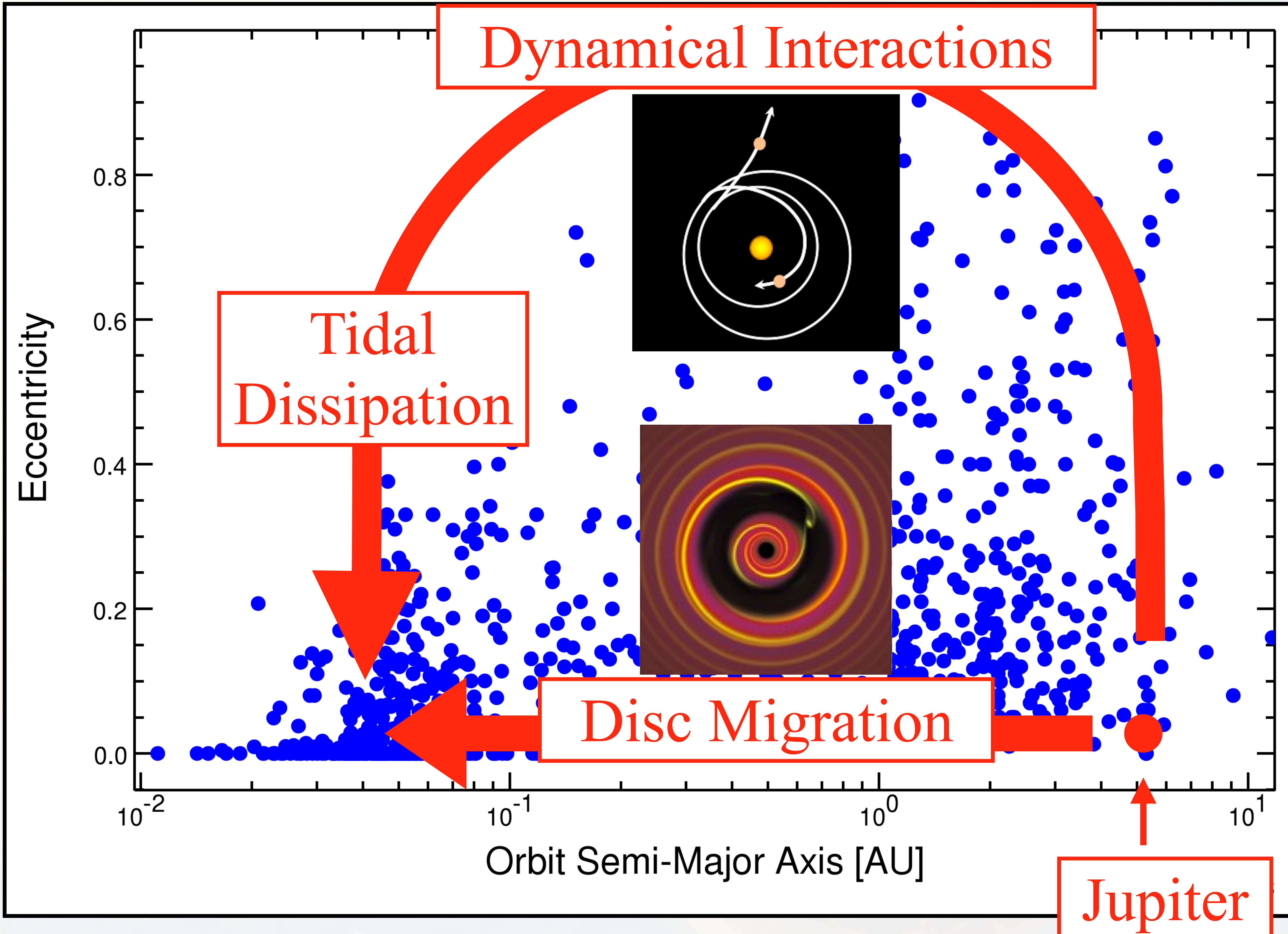
Batalha (2015)



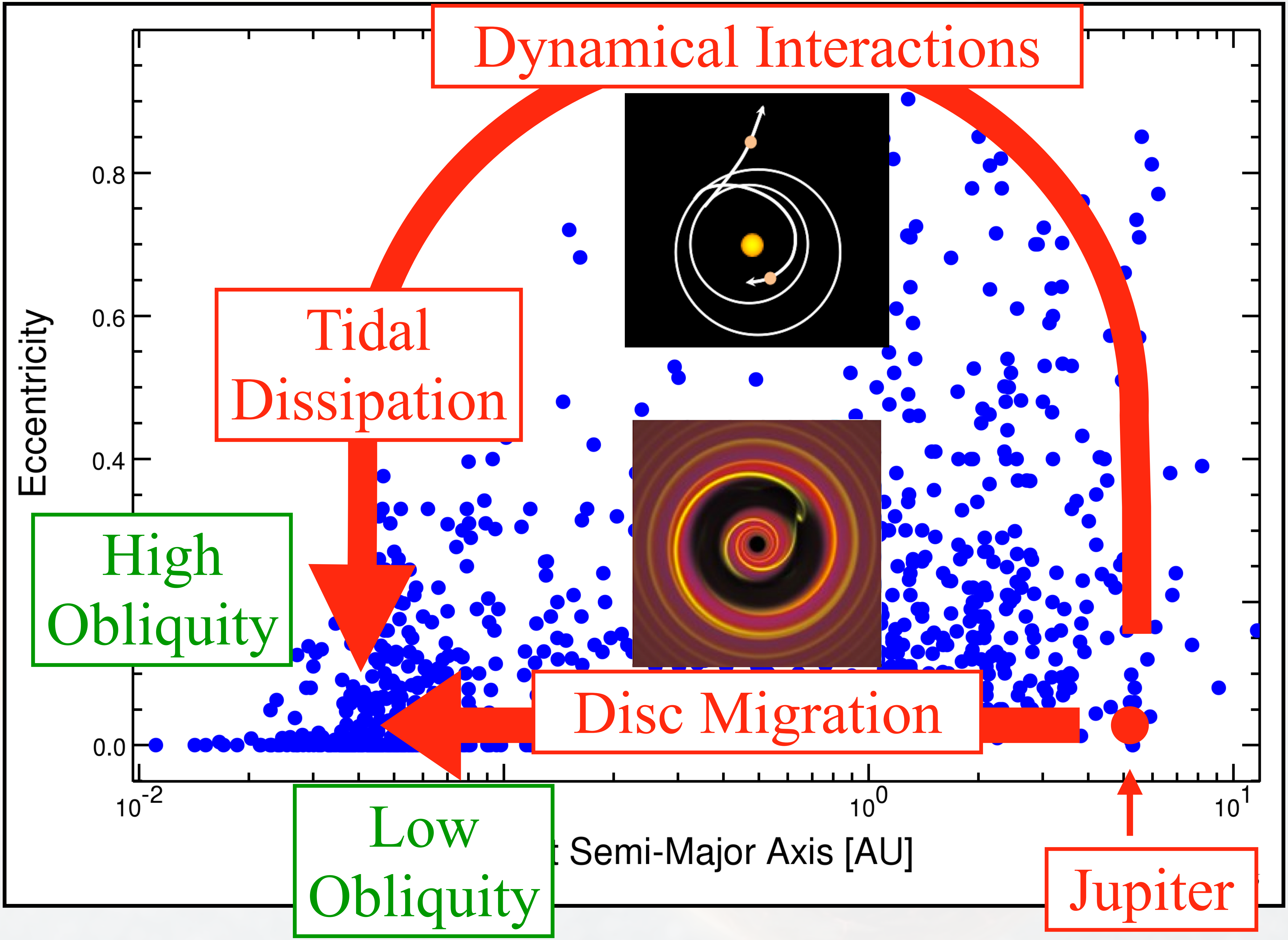
Eccentricity
0.0
0.2
0.4
0.6
0.8
10^{-2}
10^{-1}
10^{0}
10^{1}
Orbit Semi-Major Axis [AU]
Jupiter



Eccentricity
0.8
0.6
0.4
0.2
0.0
10-2
10-1
100
101
Orbit Semi-Major Axis [AU]
Disc Migration
Jupiter

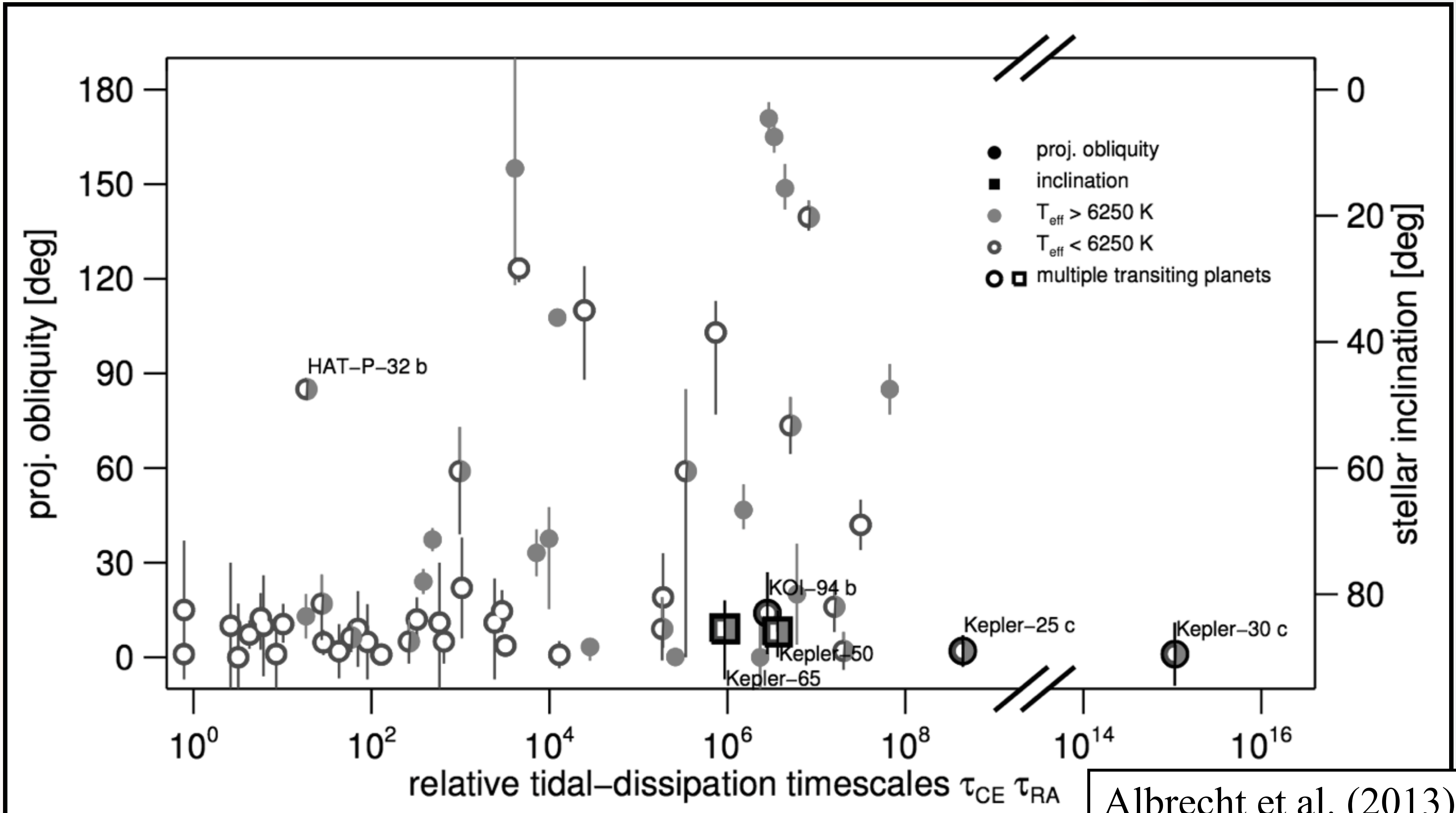


Dynamical Interactions
Tidal Dissipation
Disc Migration
Jupiter
Eccentricity
0.0
0.2
0.4
0.6
0.8
10^{-2}
10^{-1}
10^{0}
10^{1}
Orbit Semi-Major Axis [AU]



Dynamical Interactions
Tidal Dissipation
High Obliquity
Low Obliquity
Disc Migration
Jupiter
Eccentricity
0.8
0.6
0.4
0.0
10^{-2}
10^{0}
10^{1}
t Semi-Major Axis [AU]

Hot Jupiters are preferentially misaligned!

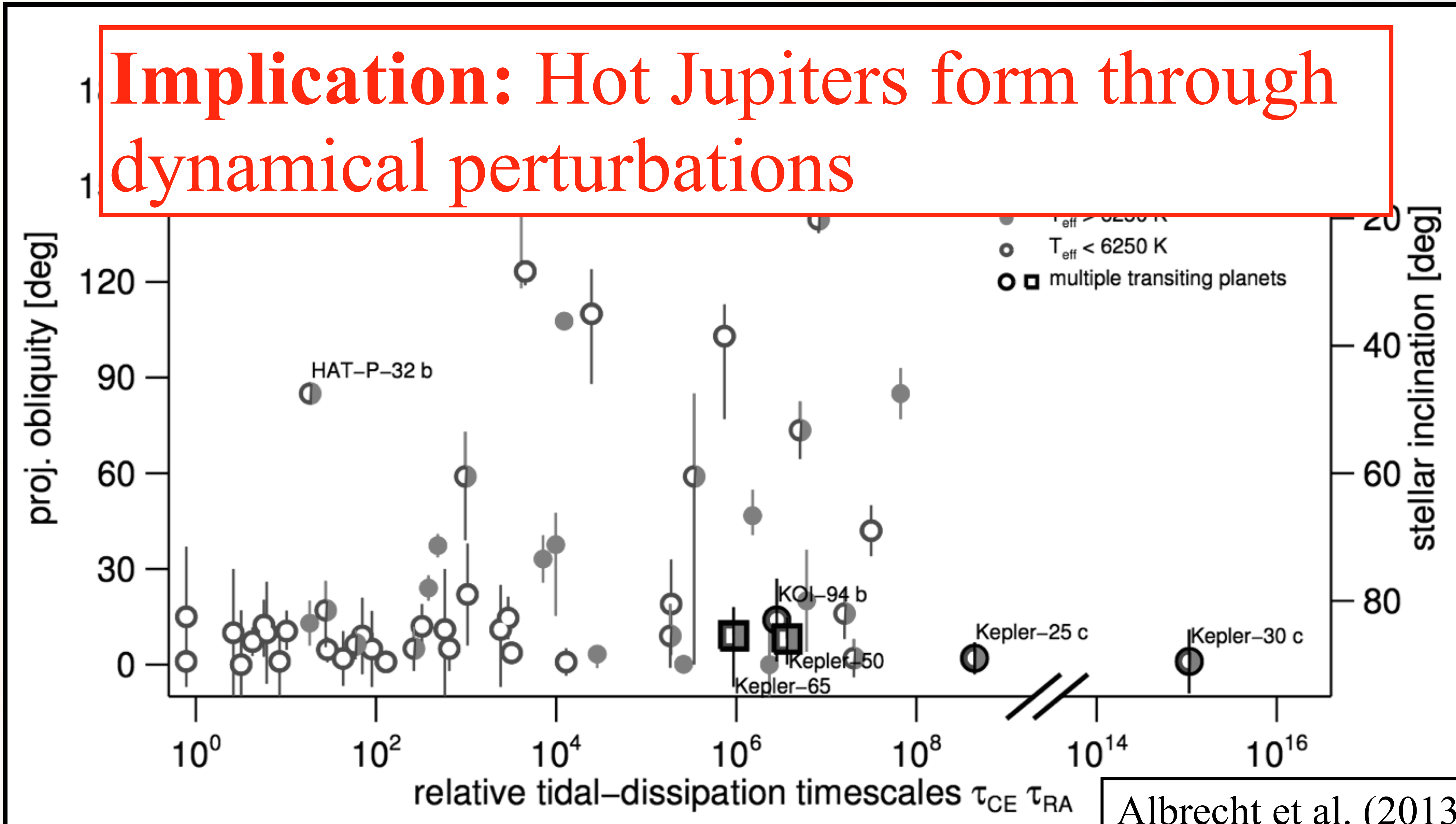


Albrecht et al. (2013)

easy to re-align ⟷ hard to re-align

Hot Jupiters are preferentially misaligned!

Implication: Hot Jupiters form through dynamical perturbations



Albrecht et al. (2013)

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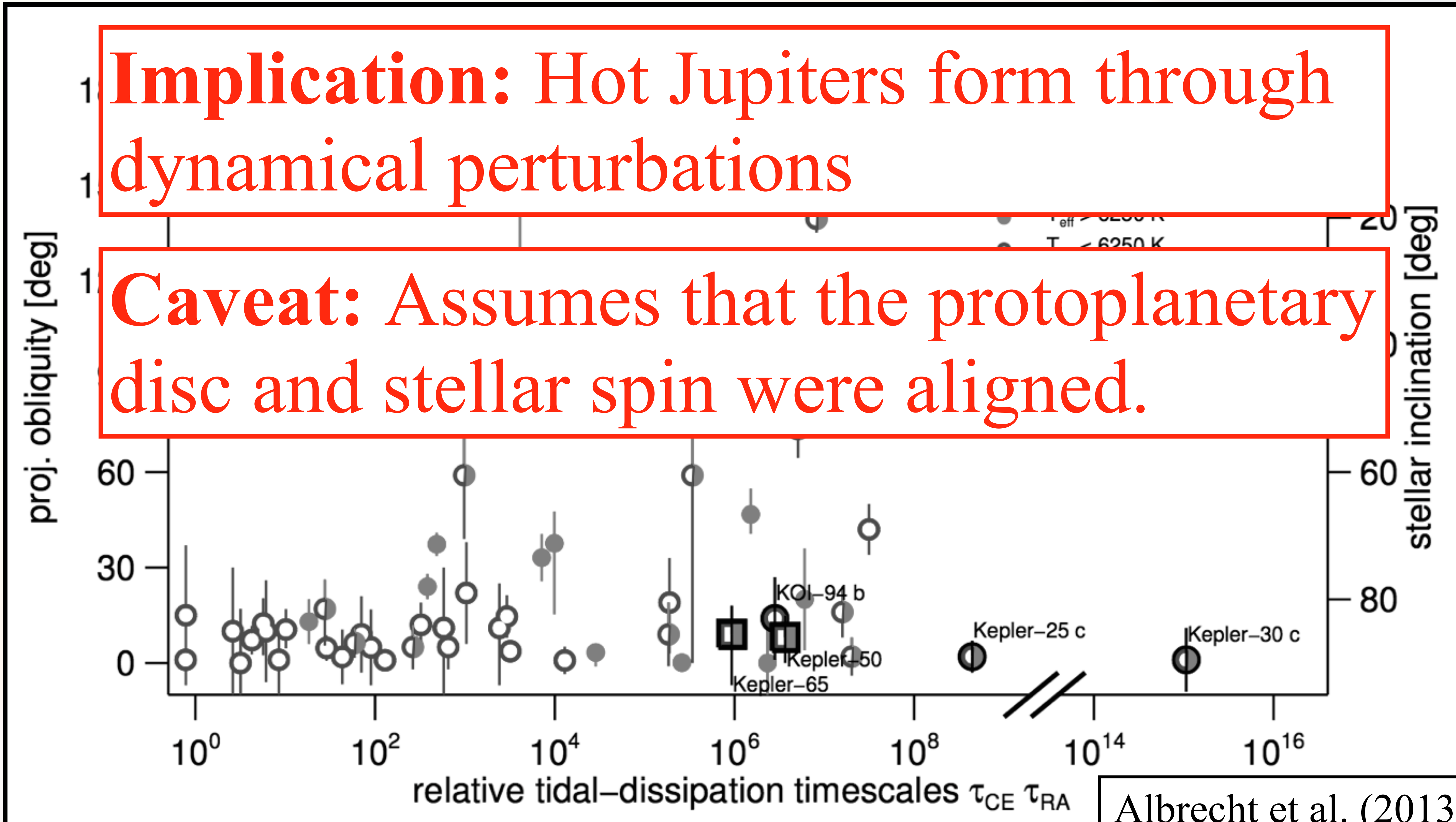
Hot Jupiters are preferentially misaligned!



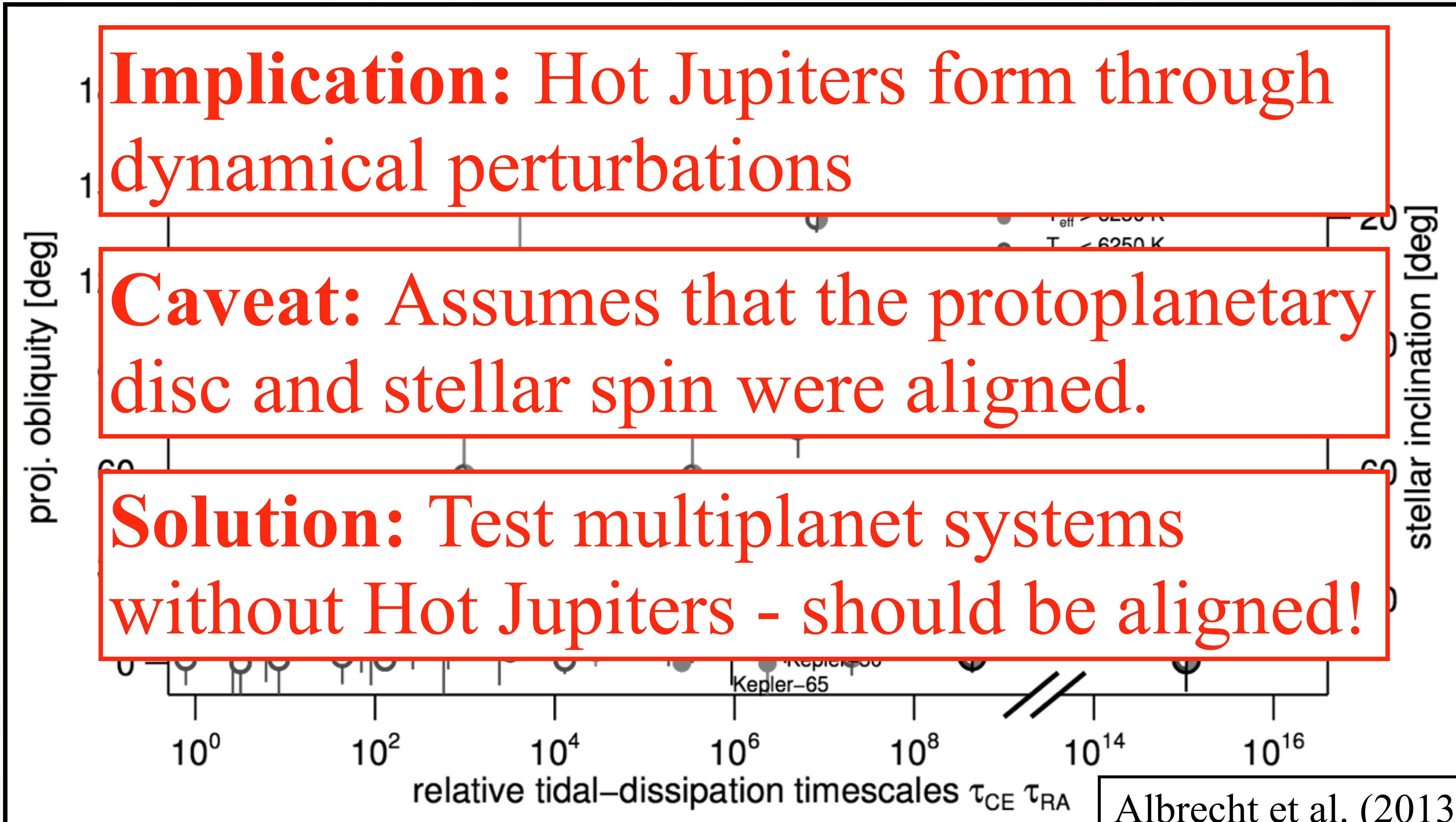
Implication: Hot Jupiters form through dynamical perturbations

Caveat: Assumes that the protoplanetary disc and stellar spin were aligned.

Albrecht et al. (2013)

easy to re-align ⟷ hard to re-align

Hot Jupiters are preferentially misaligned!



Implication: Hot Jupiters form through dynamical perturbations

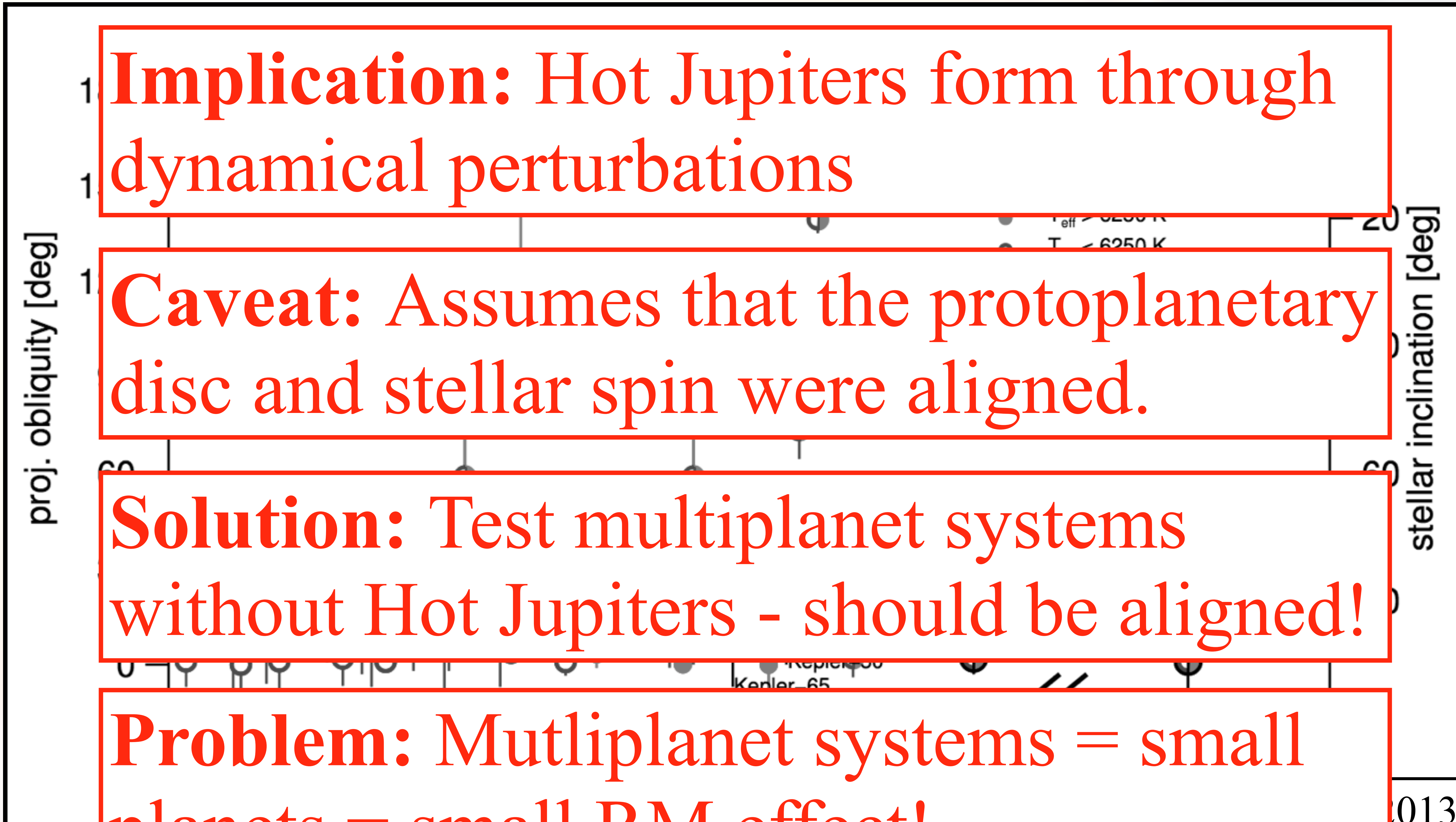
Caveat: Assumes that the protoplanetary disc and stellar spin were aligned.

Solution: Test multiplanet systems without Hot Jupiters - should be aligned!

Albrecht et al. (2013)

easy to re-align ⟷ hard to re-align

Hot Jupiters are preferentially misaligned!



Implication: Hot Jupiters form through dynamical perturbations

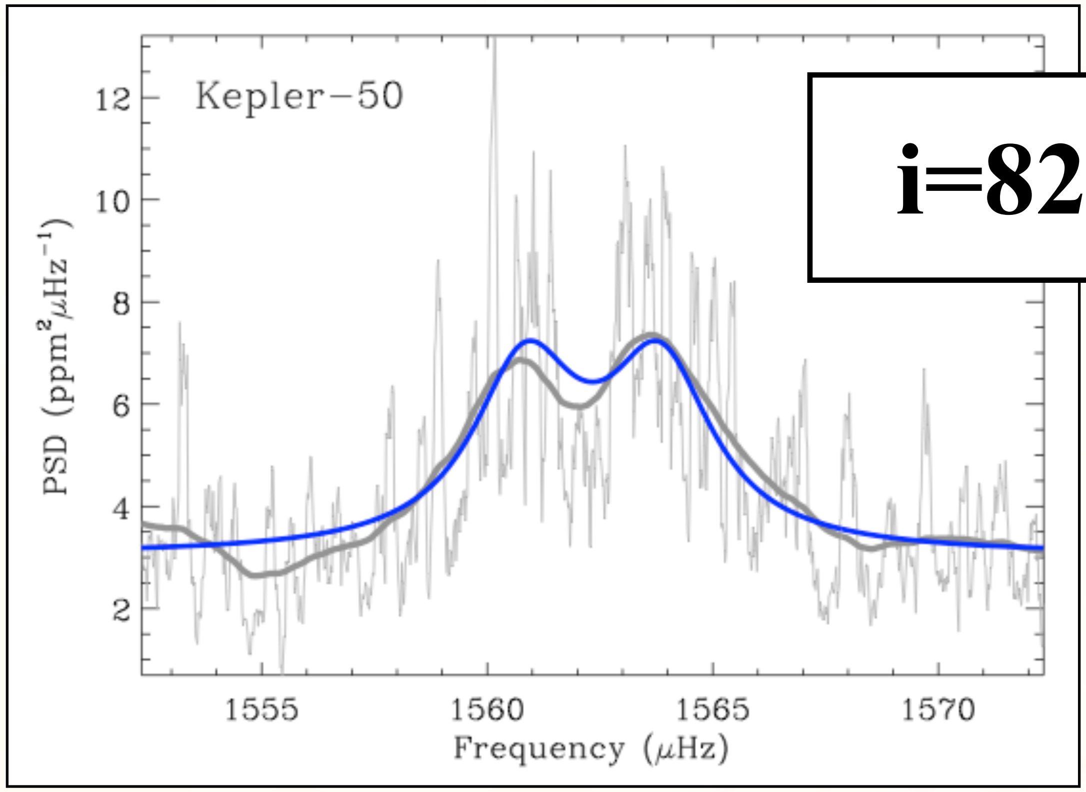
Caveat: Assumes that the protoplanetary disc and stellar spin were aligned.

Solution: Test multiplanet systems without Hot Jupiters - should be aligned!

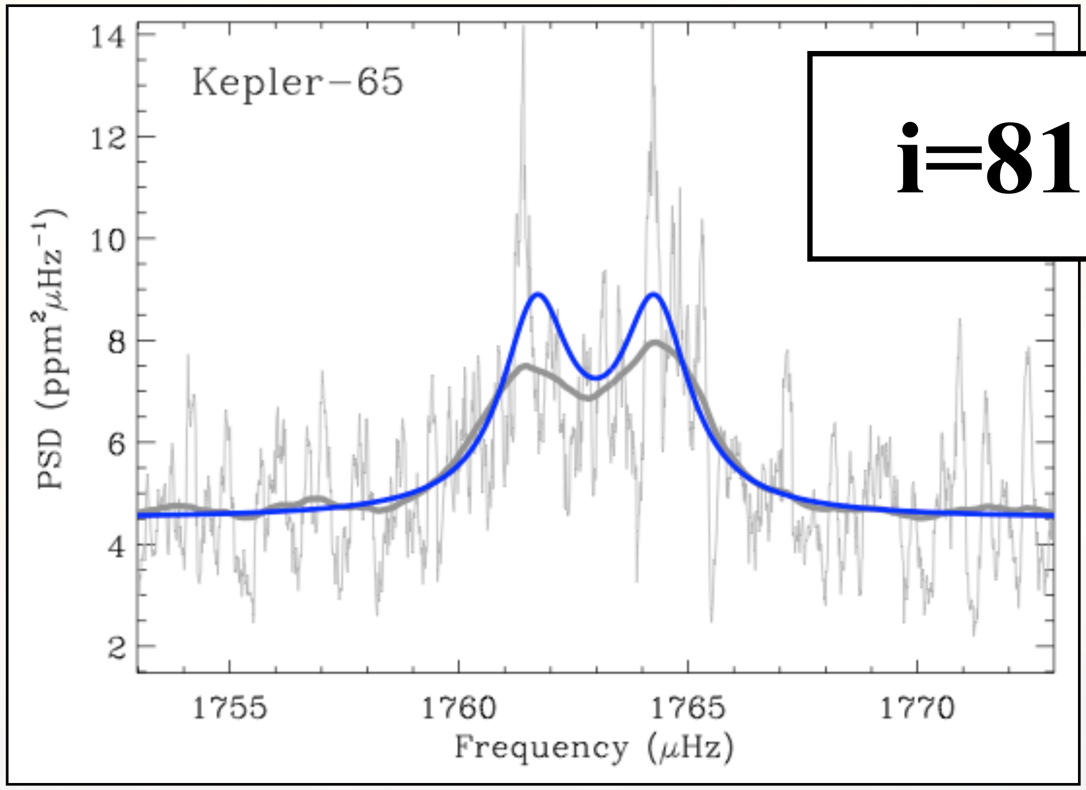
Problem: Mutliplanet systems = small planets = small RM effect!

easy to re-align ⟷ hard to re-align

Asteroseismic Obliquities



$i=82^{+8}_{-7}$



$i=81^{+9}_{-16}$

Kepler-50

$R_b = 1.7\ R_\oplus$ $P_b = 7.8d$
$R_c = 2.2\ R_\oplus$ $P_c = 9.4d$

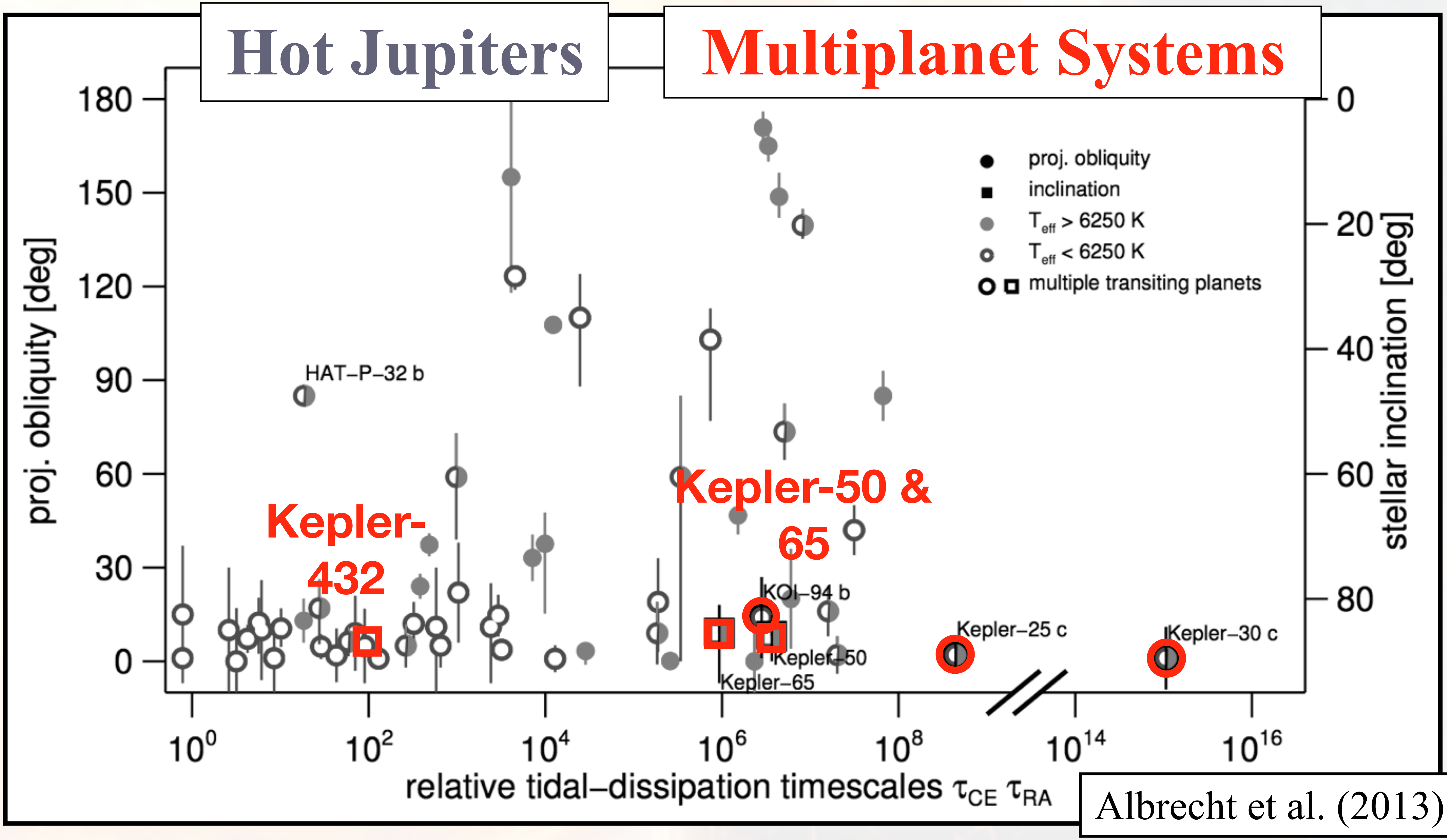
aligned

Kepler-65

$R_b = 1.4\ R_\oplus$ $P_b = 2.2d$
$R_c = 2.6\ R_\oplus$ $P_c = 5.9d$
$R_d = 1.5\ R_\oplus$ $P_d = 8.1d$

aligned

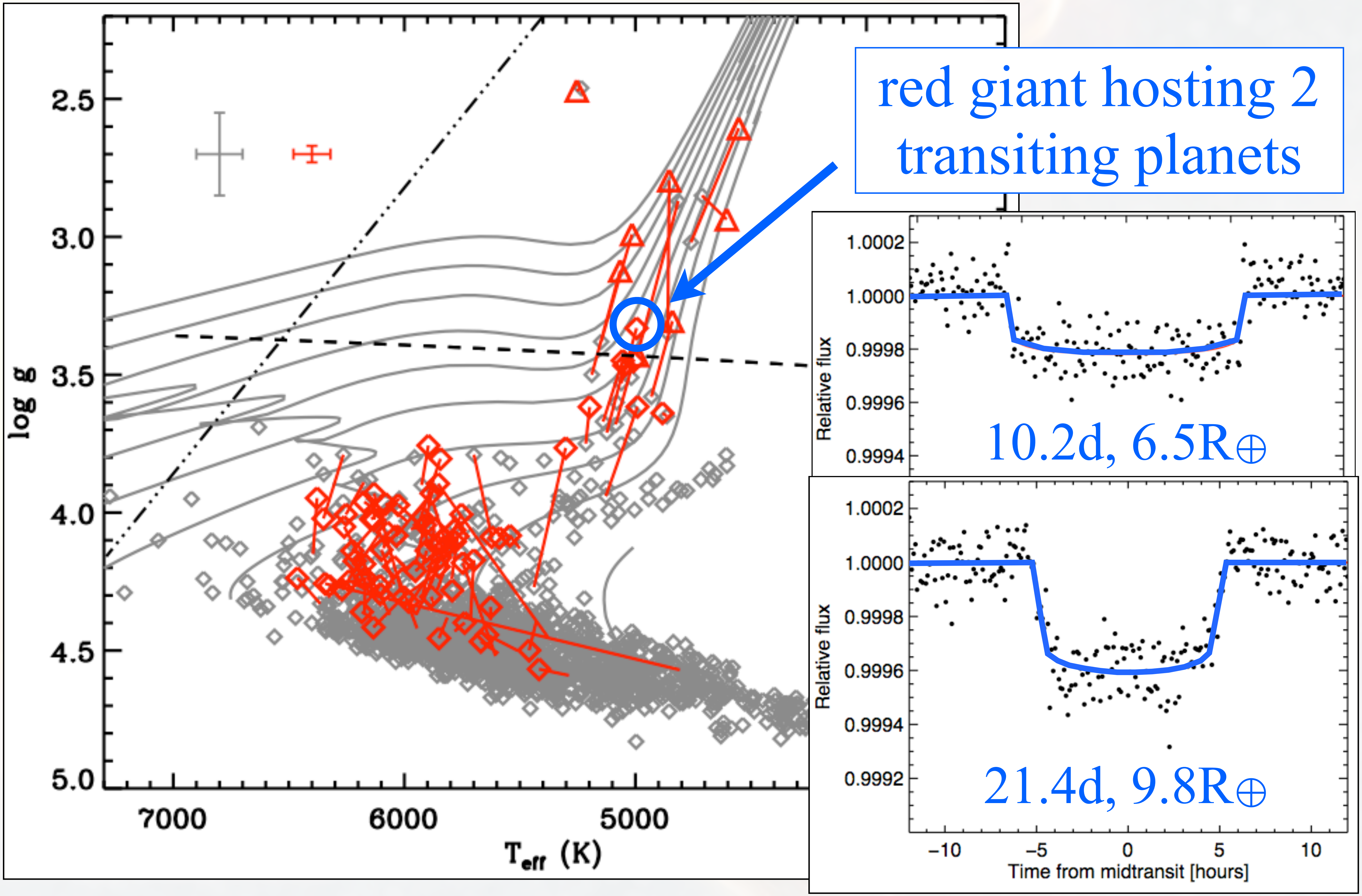
Chaplin et al. (2013)



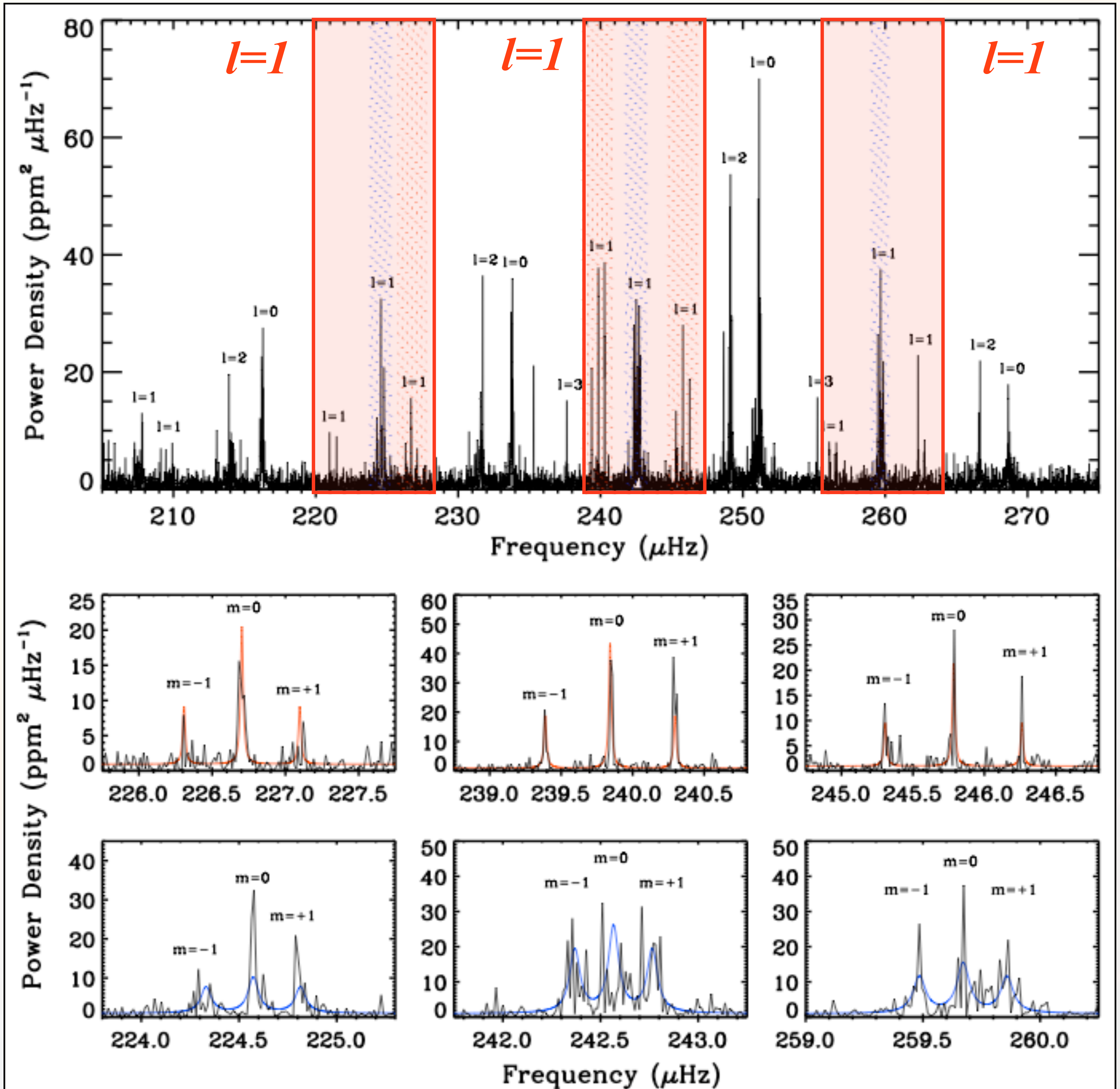
easy to re-align ⟷ hard to re-align

Do Hot Jupiters form differently than multiplanet systems?

The Oddball: Kepler-56



Kepler-56 Asteroseismology

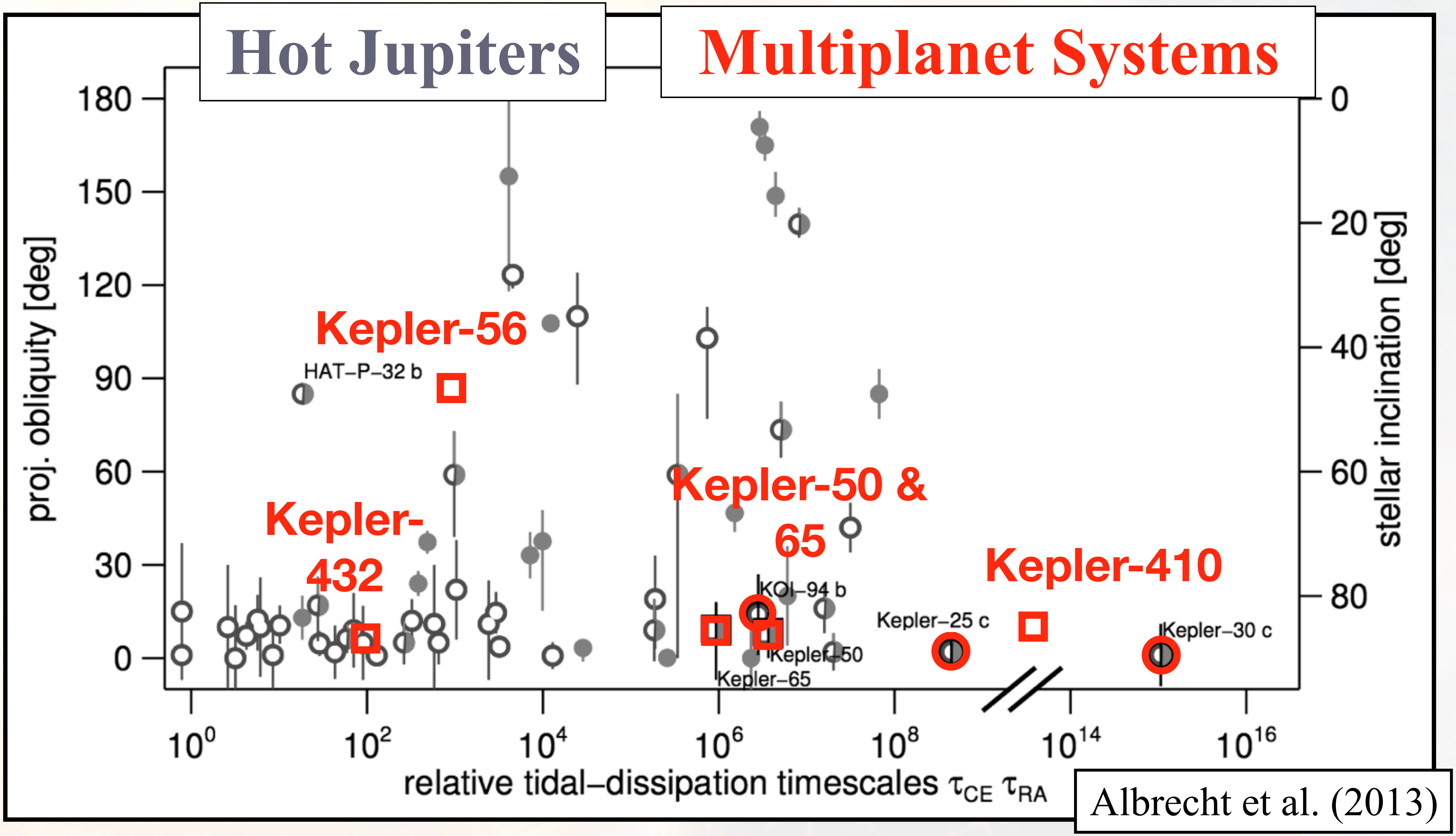


~50 individual frequencies detected

mixed *l=1* modes are split into triplets by rotation

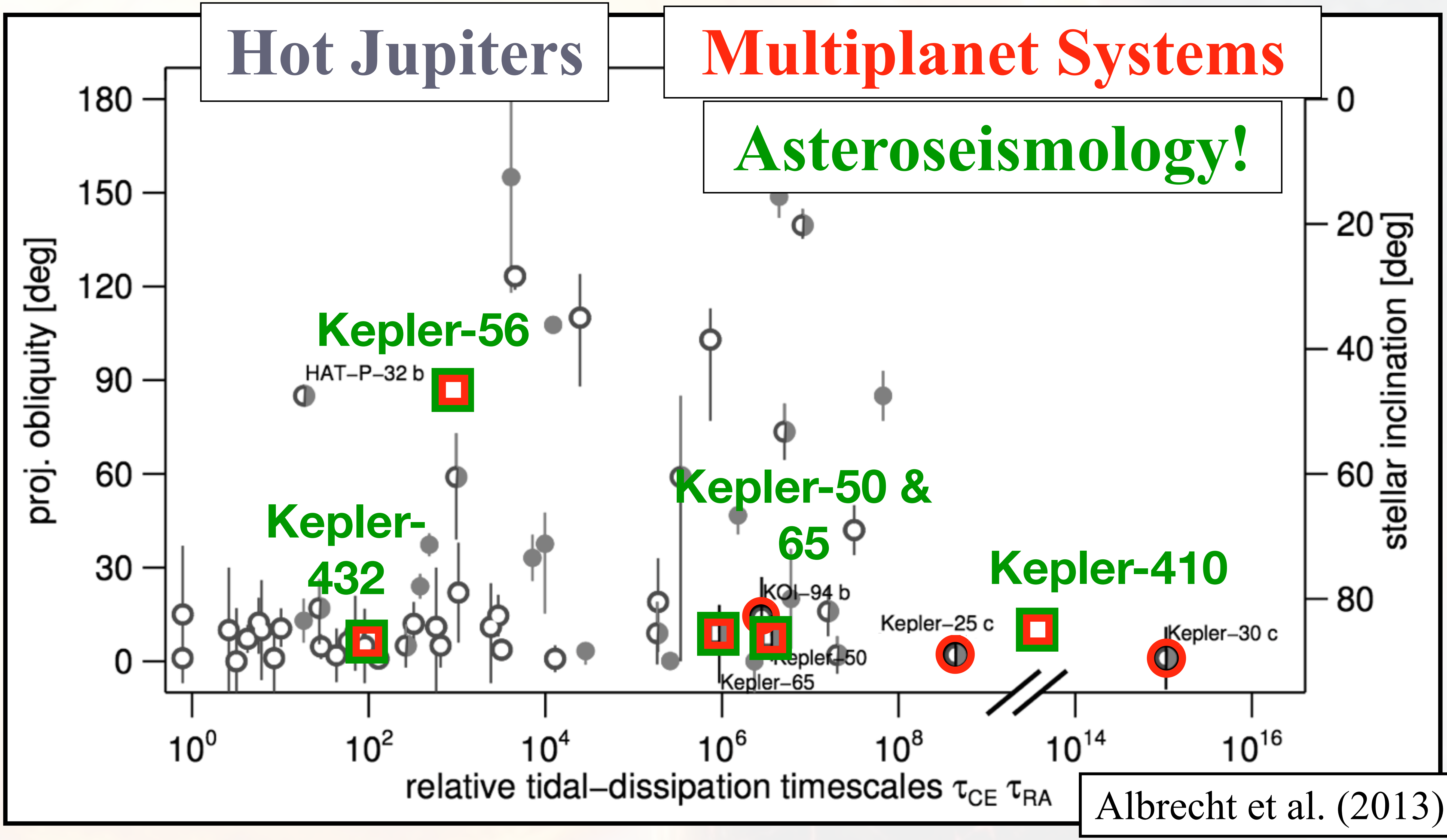
i ~ 45°!

Huber et al. (2013)



easy to re-align ⟷ hard to re-align

Do Hot Jupiters form differently than multiplanet systems?

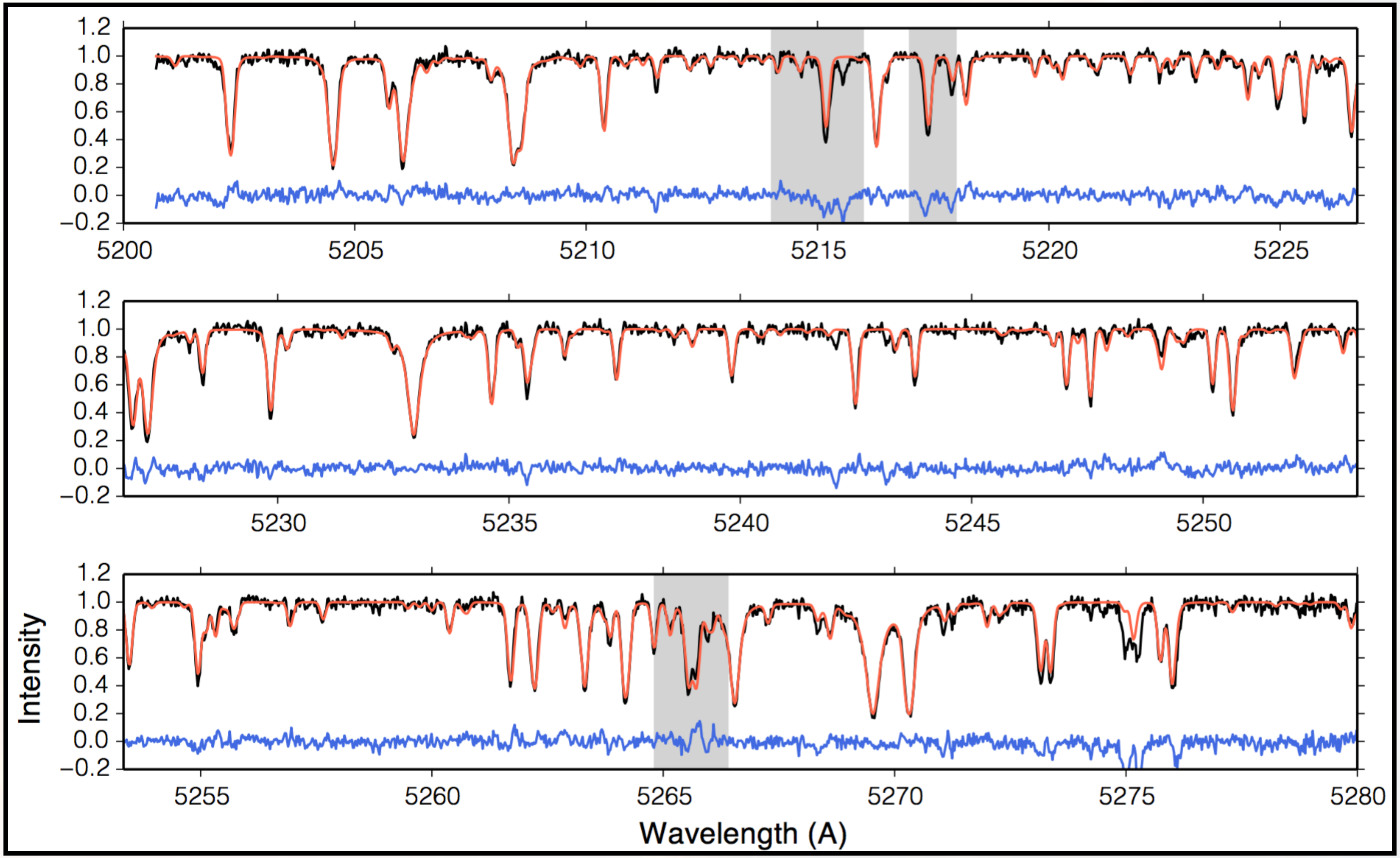


easy to re-align ⟷ hard to re-align

Do Hot Jupiters form differently than multiplanet systems?

Synergy IV: Chemical Abundances of Exoplanet Host Stars

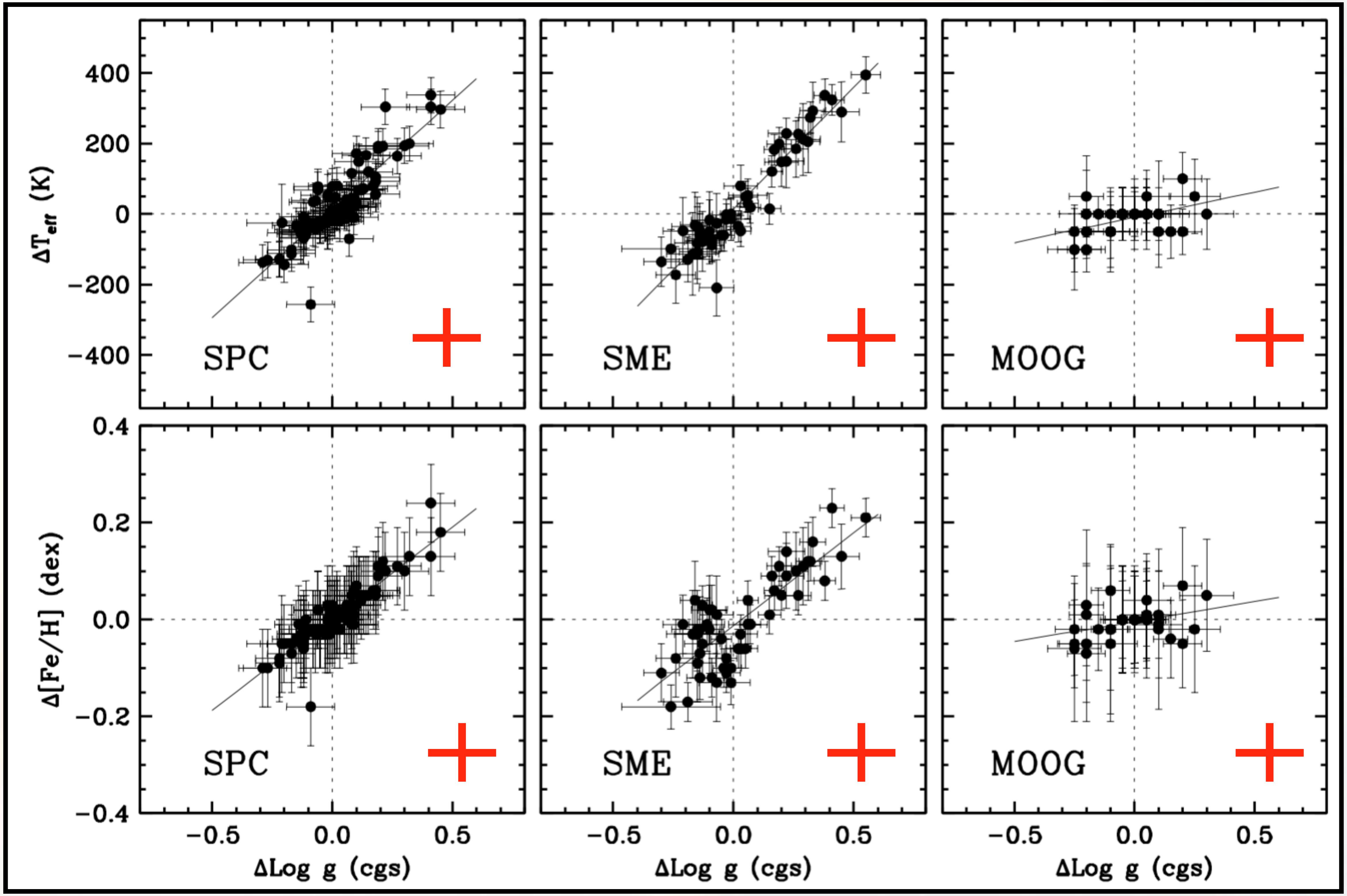
High-Resolution Spectroscopy



Key Parameters: T_{eff}, log(g), [Fe/H]

Petigura (2015)

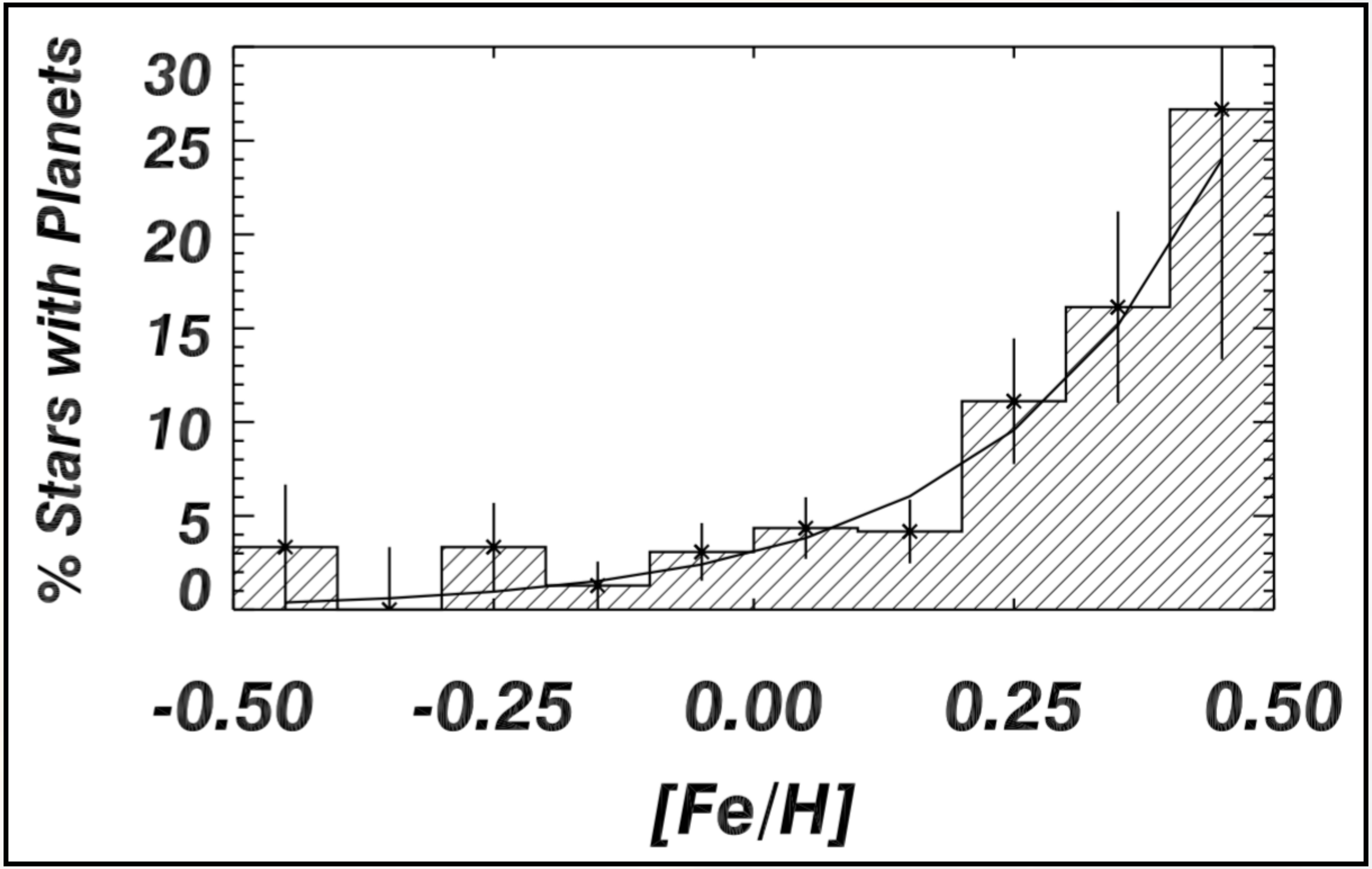
T_{eff}-log(g)-[Fe/H] Degeneracies



Torres et al. (2012)

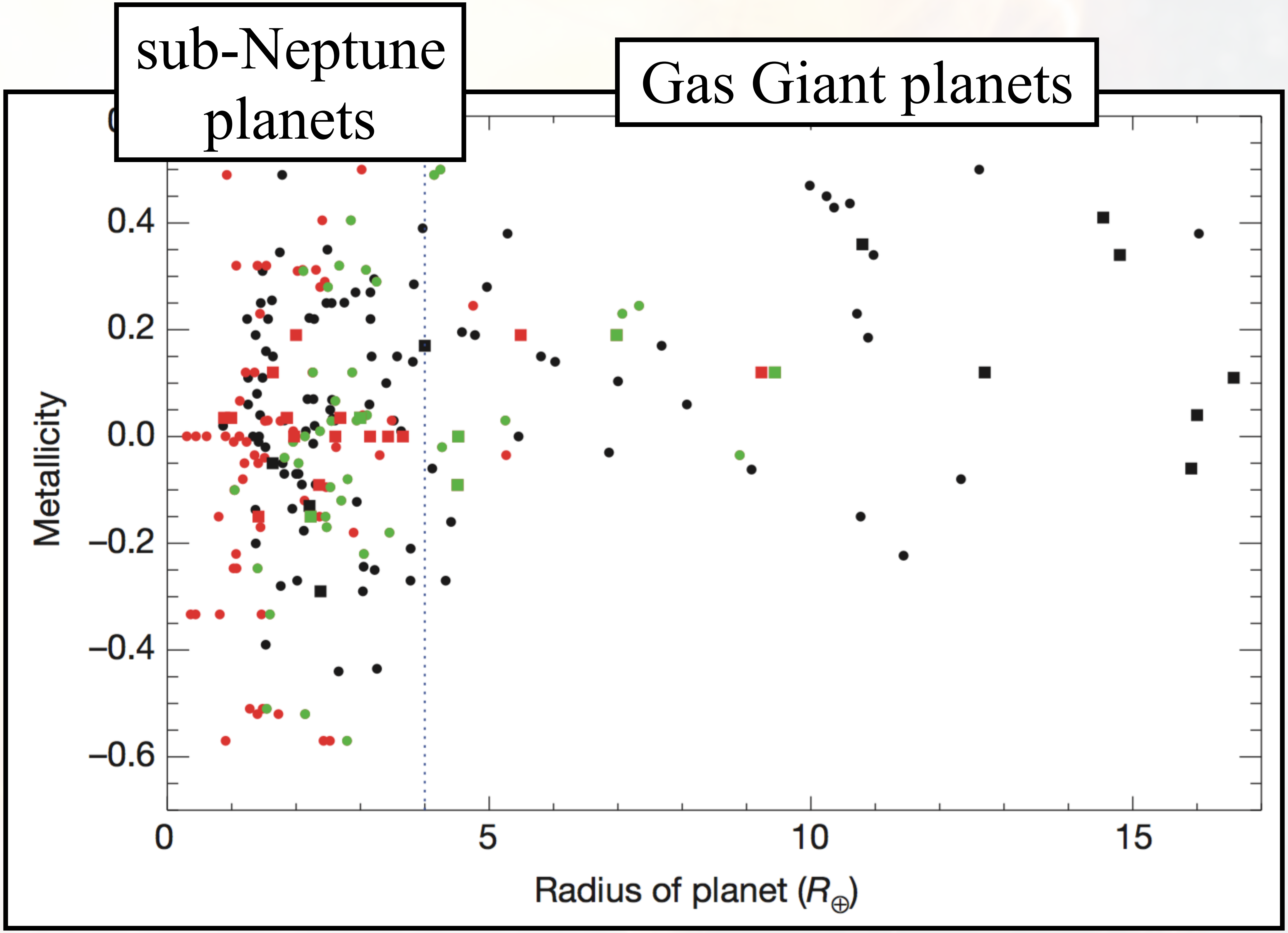
Typical Error Bars!

The Planet-Metallicity Correlation



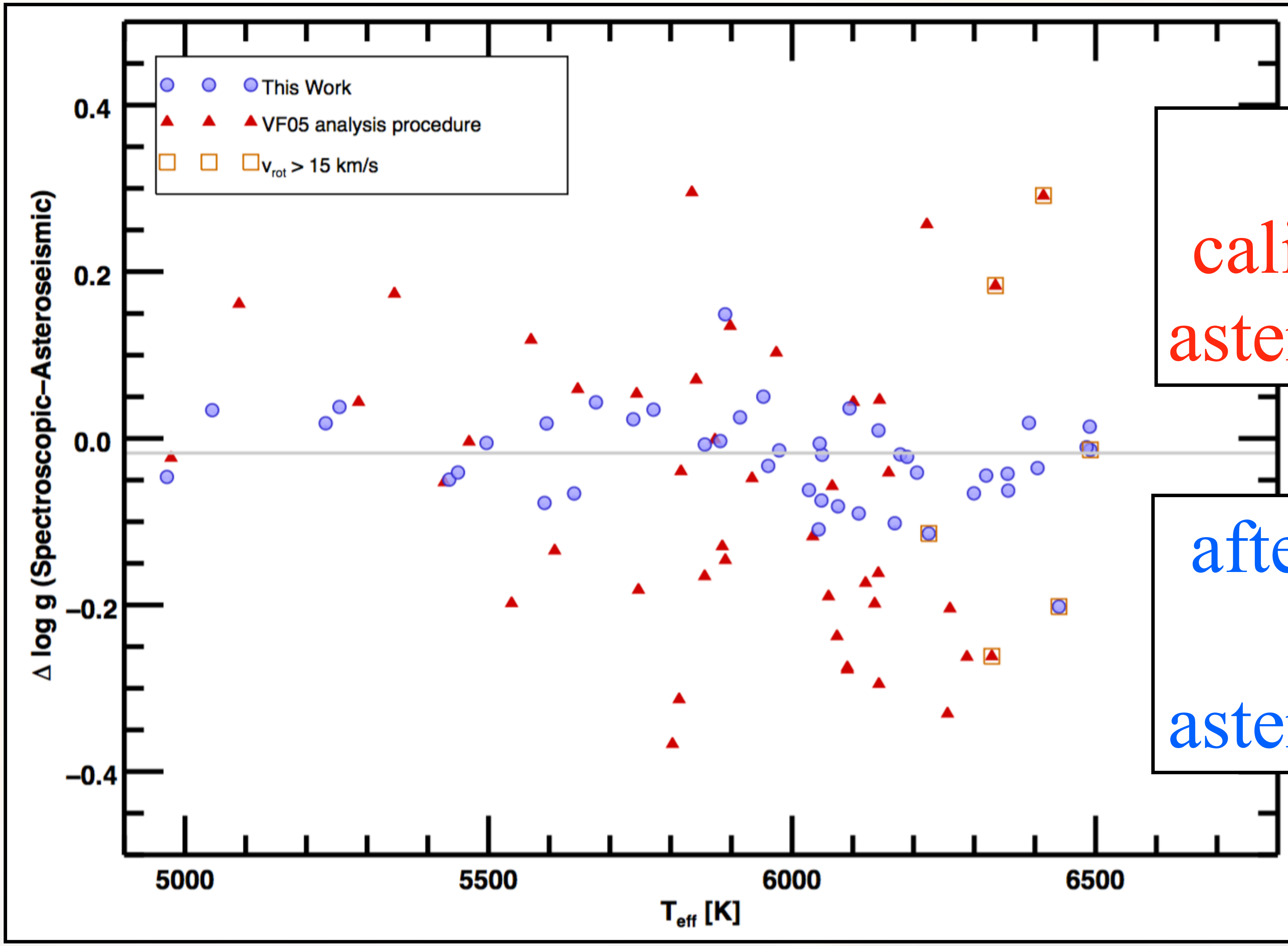
Gonzalez 1997, Santos et al. 2004, Fischer & Valenti 2005

The Planet-Metallicity Correlation



Buchhave et al. 2012, Nature

Asteroseismology + Spectroscopy



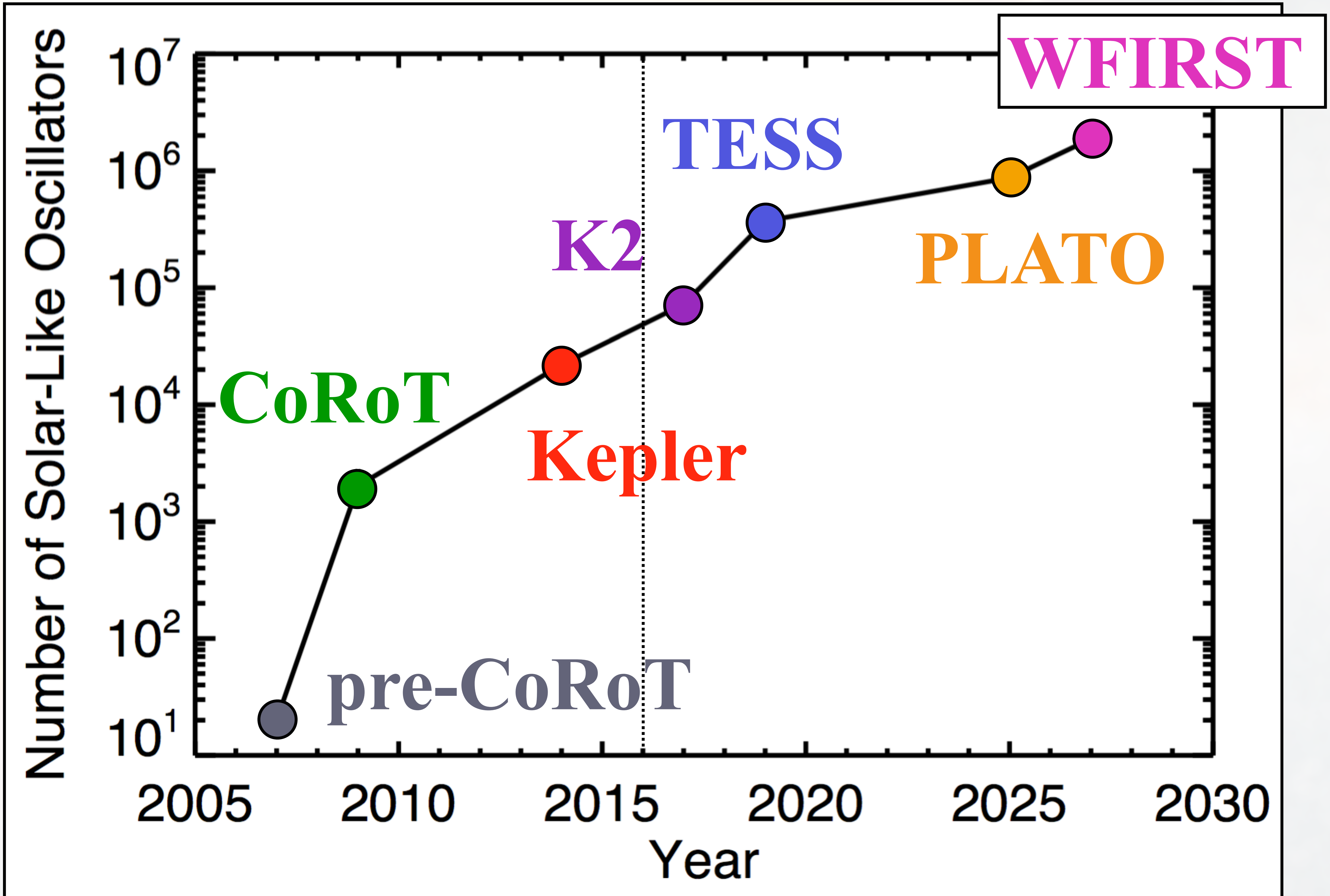
before calibration with asteroseismology

after calibration with asteroseismology

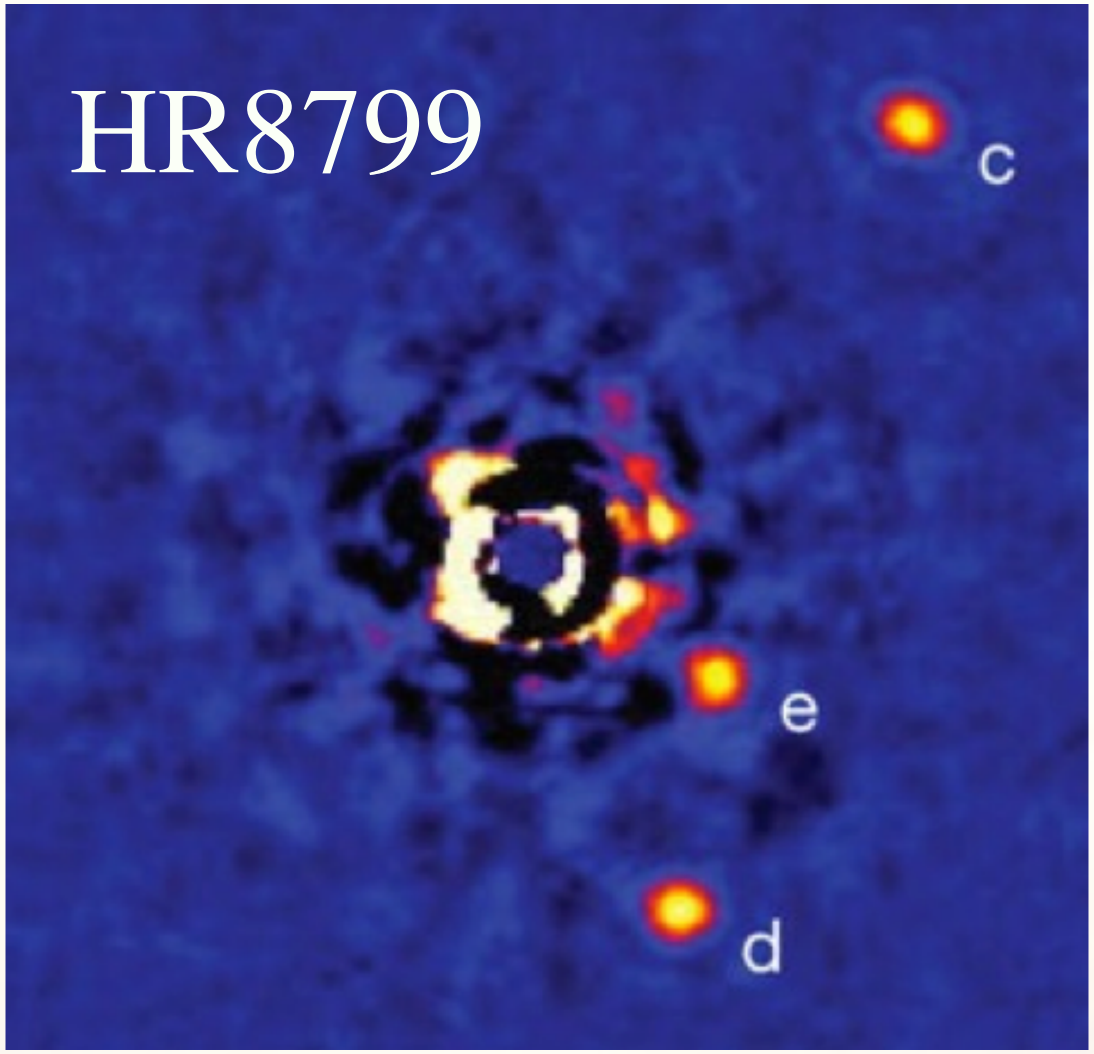
Brewer et al. 2016

Outlook: Where do we go from here?

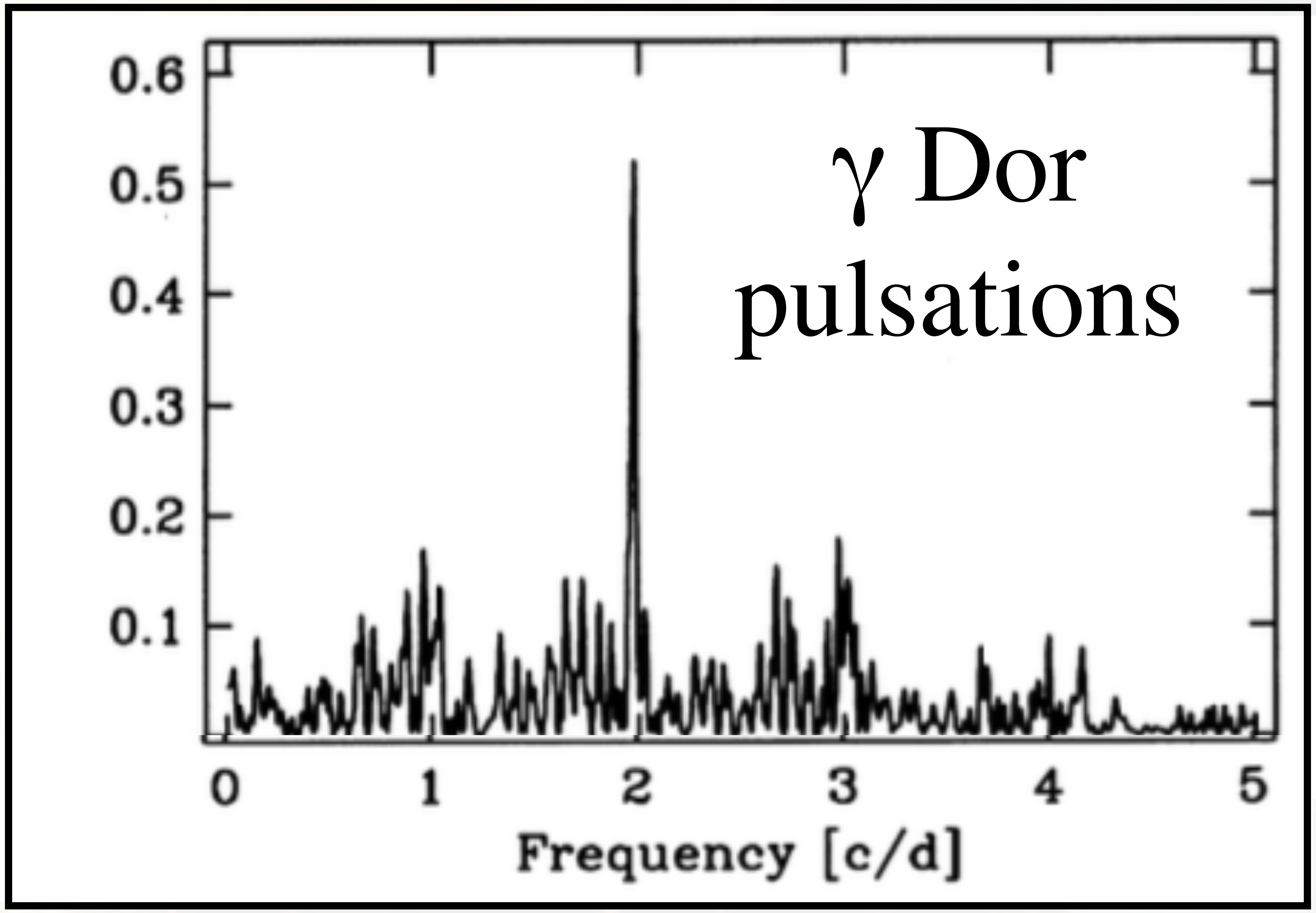
Asteroseismology Revolution



Future: Planets orbiting A Stars



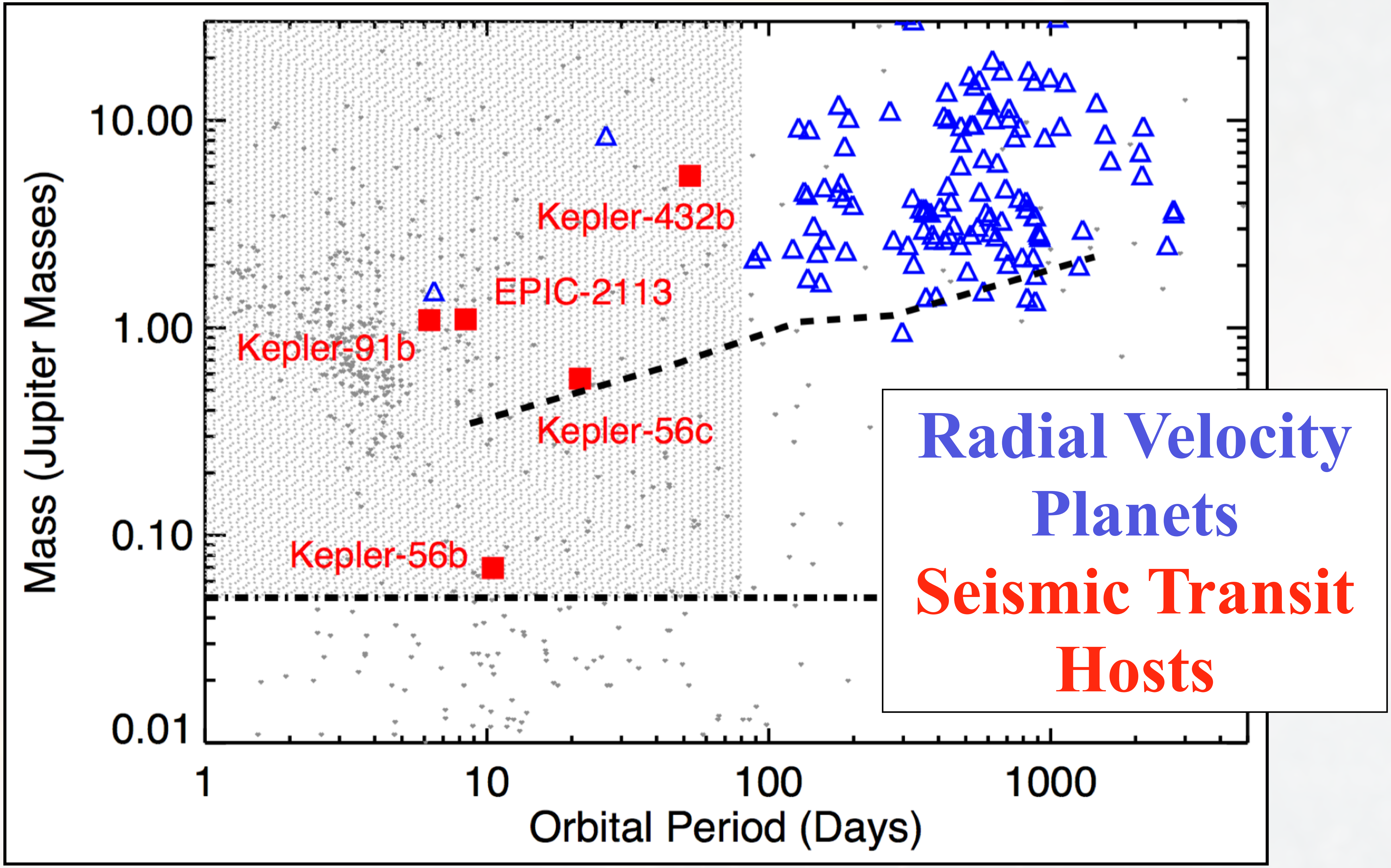
Marois et al. 2010



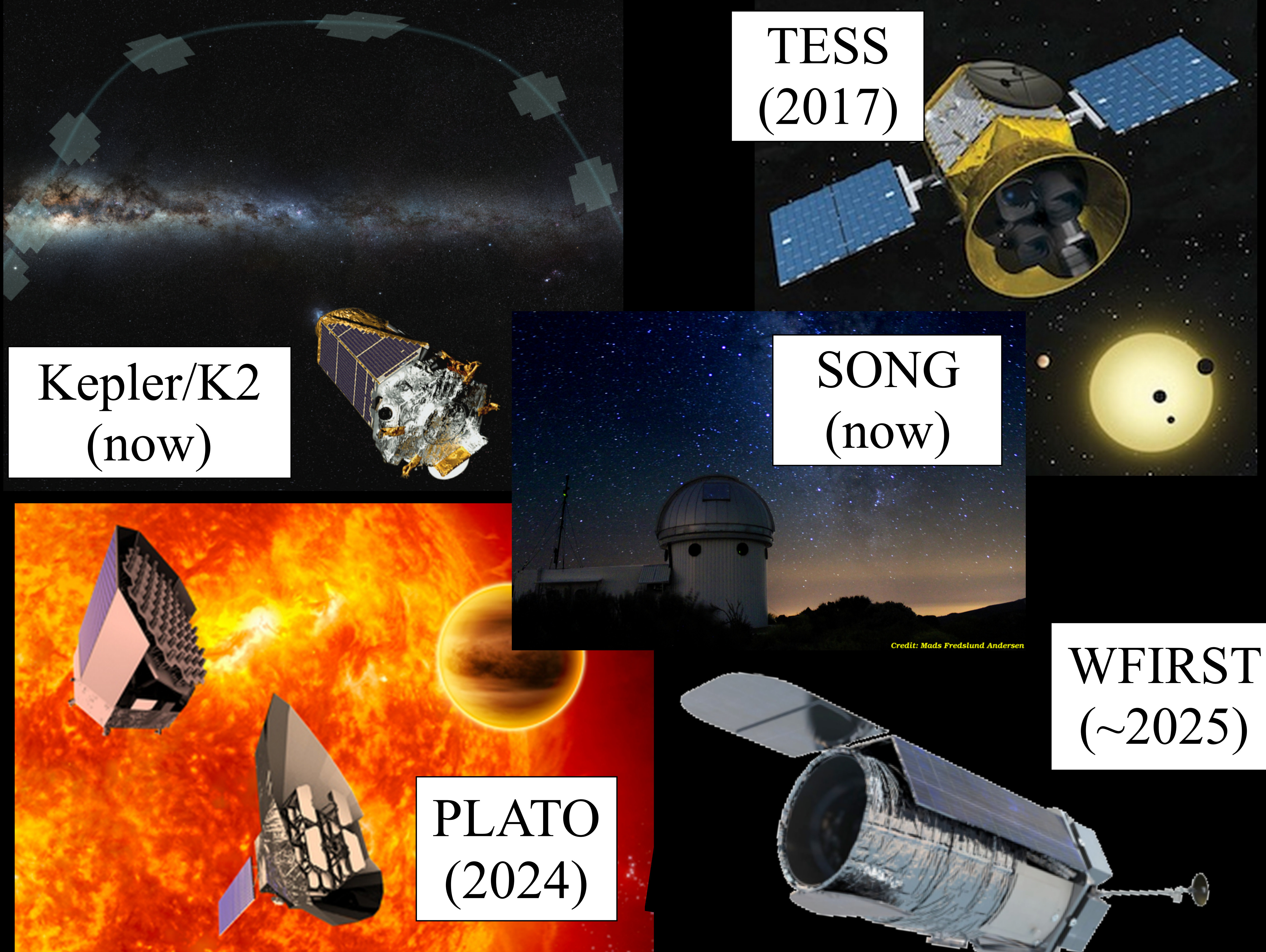
Zerbi et al. 1999

Asteroseismology of A stars will be crucial to characterize young planets!

Future: Giants Orbiting Giants



~100,000+ expected oscillating giants from TESS!


TESS
(2017)
Kepler/K2
(now)
SONG
(now)
Credit: Mads Fredslund Andersen
WFIRST
(~2025)
PLATO
(2024)