Exoplanets!

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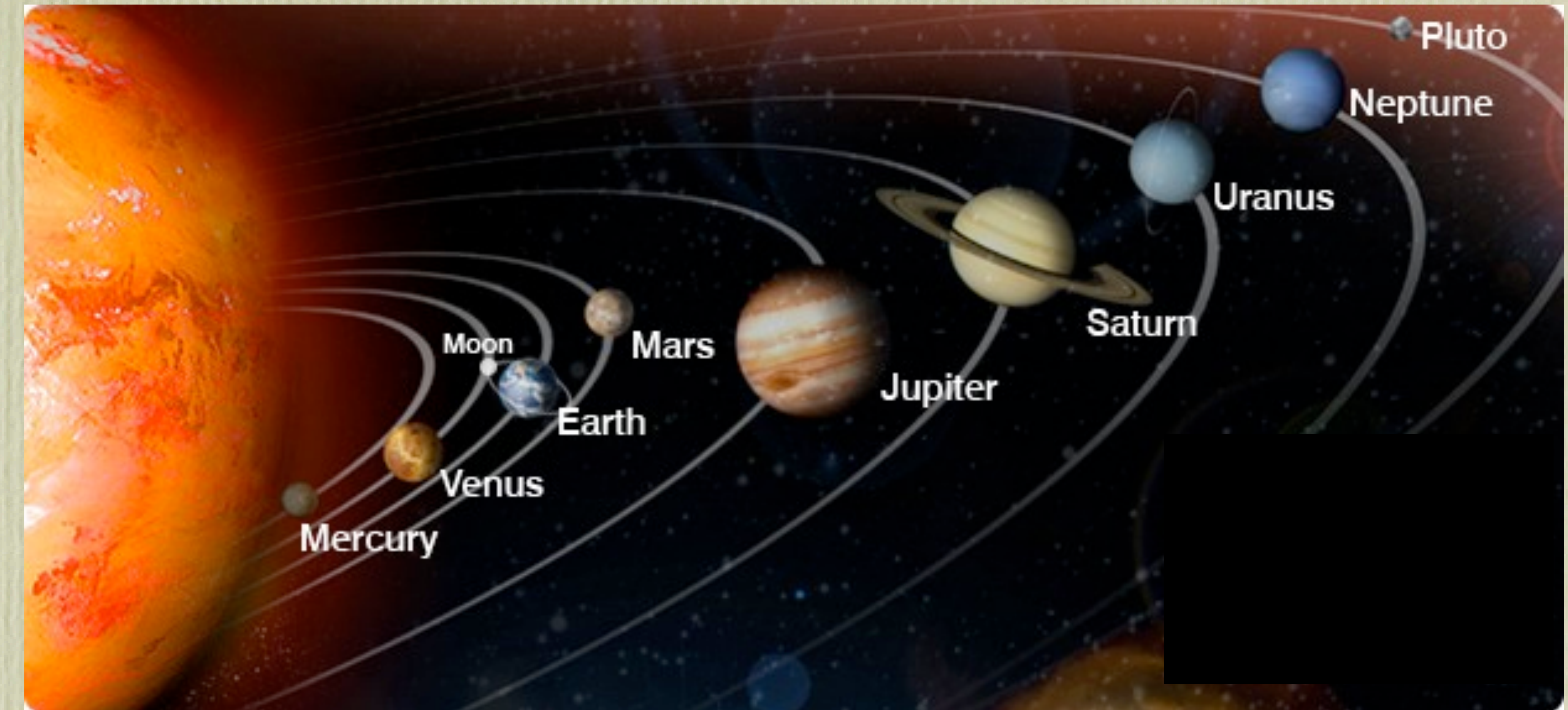
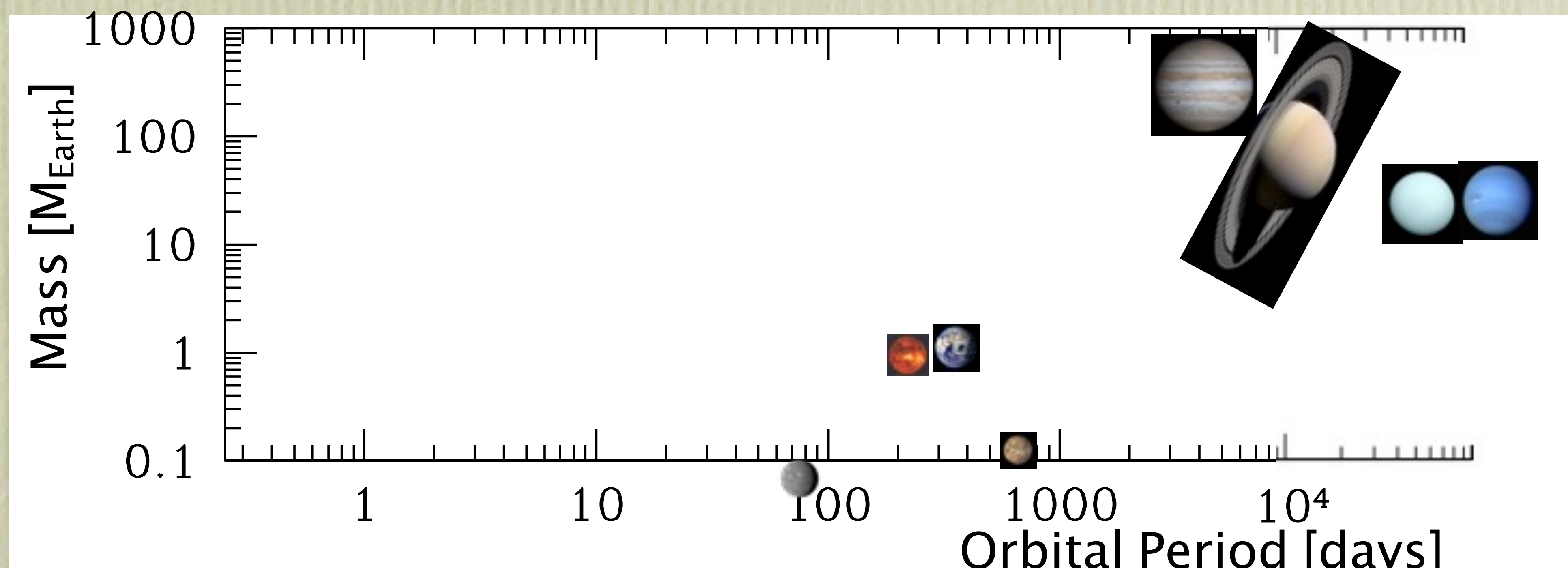
Northwestern

Known planets before 1990:





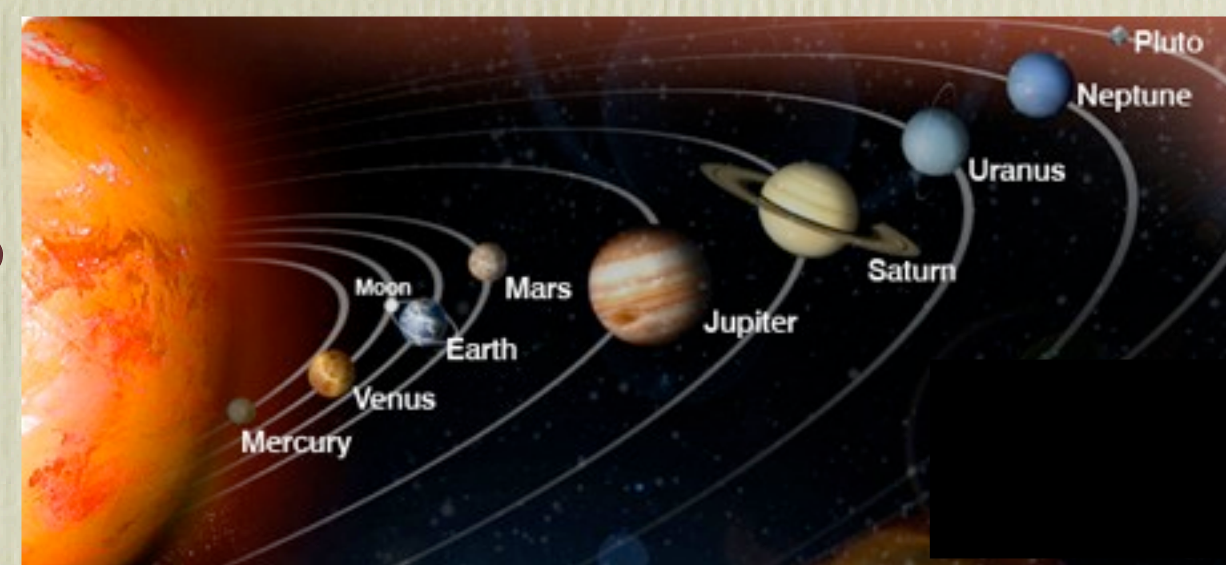
Do other stars host planets?

Driving Questions:

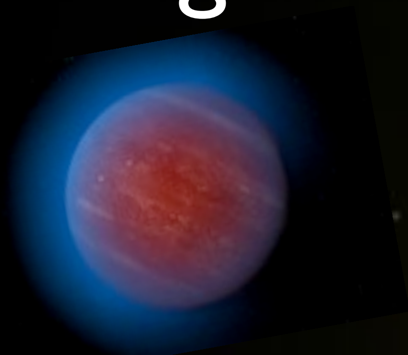
- Does life exist elsewhere?

- How do planets form?

- Is the Solar System special?



First discovery of extrasolar planet (in 1995): 51 Pegasi b



Jupiter-mass

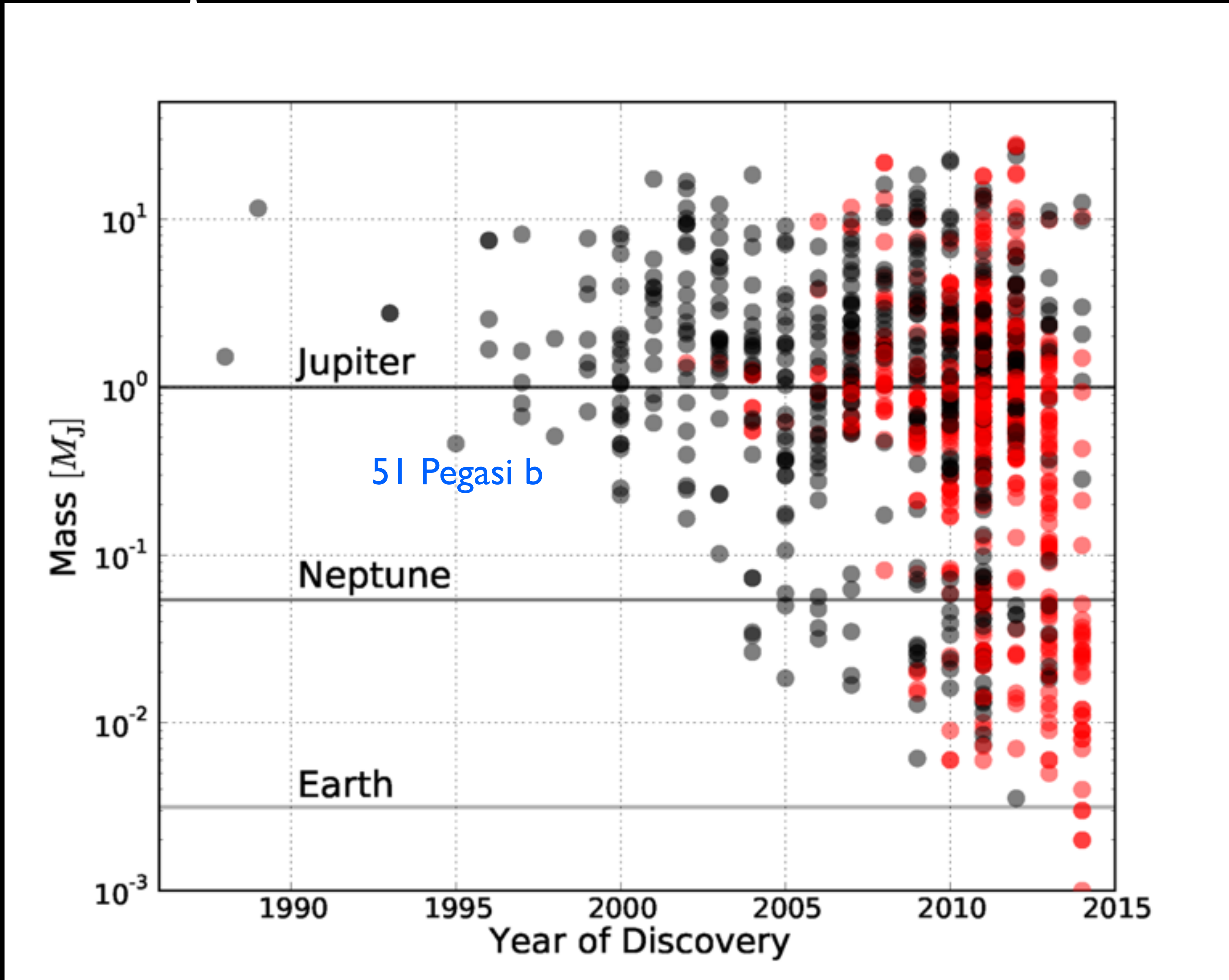
Orbital period: 4 days!

"Hot Jupiter"

1000° C

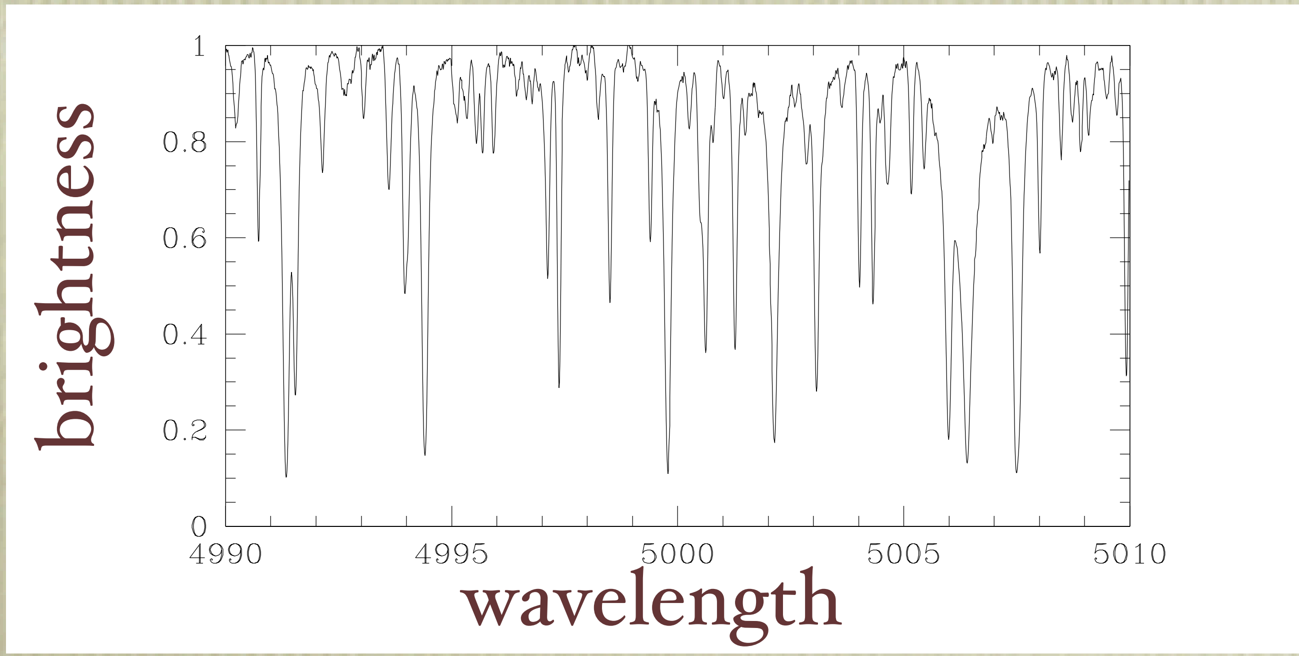
Exoplanet Discoveries

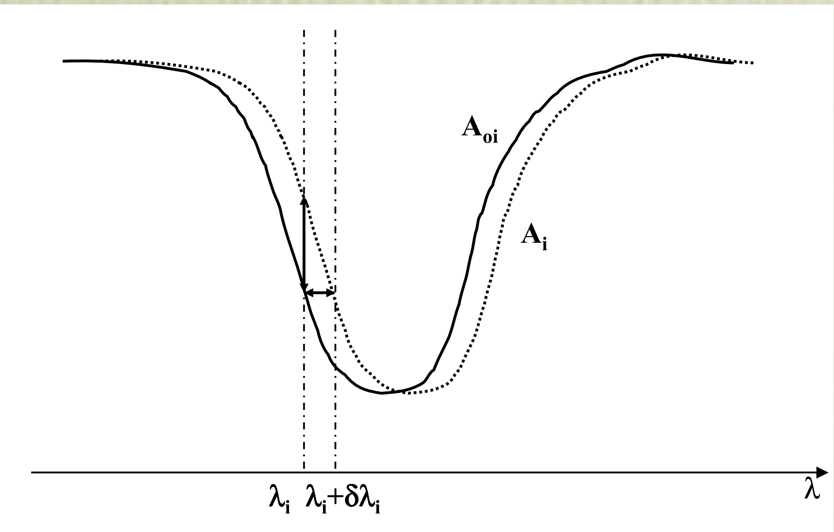
(fig 1 in Laughlin & Lissauer)



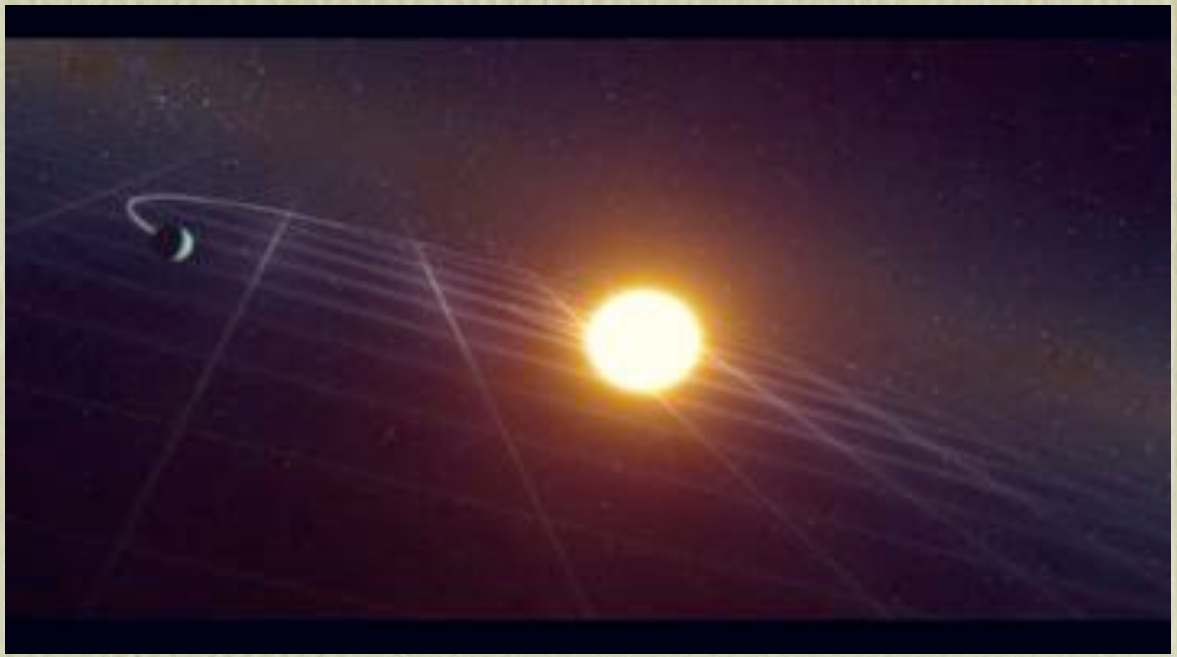
Detection method 1: Radial Velocity ("RV")

stellar spectrum

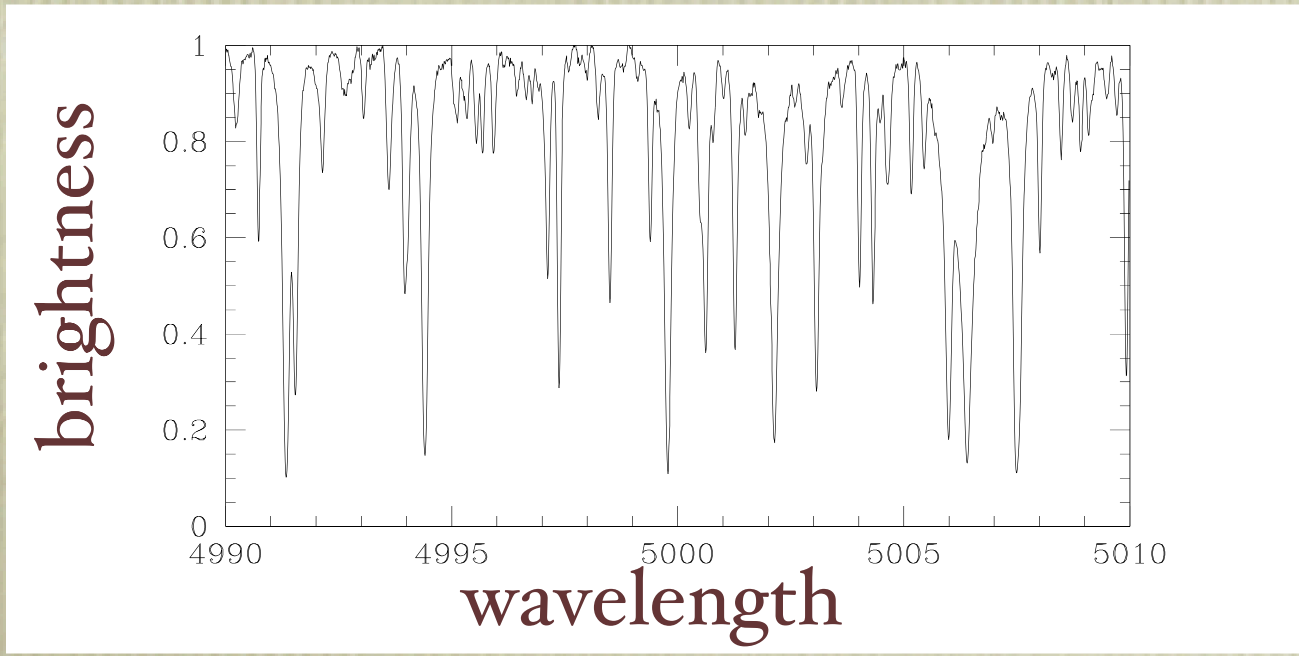


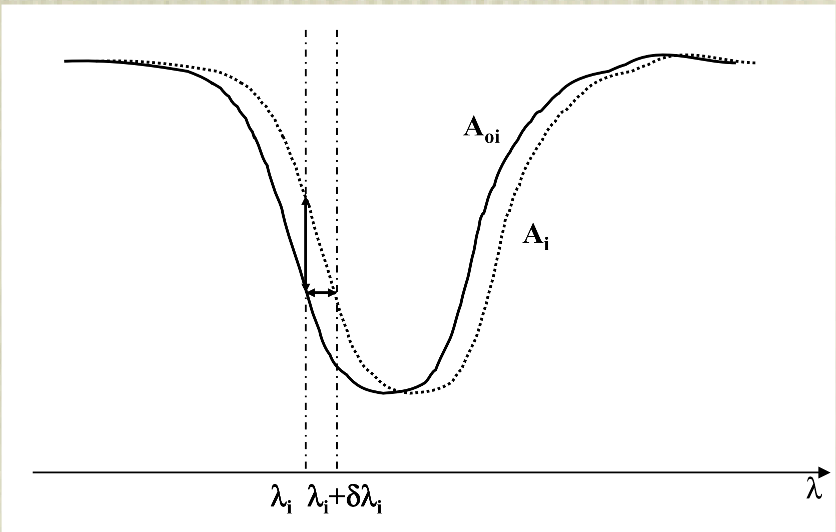


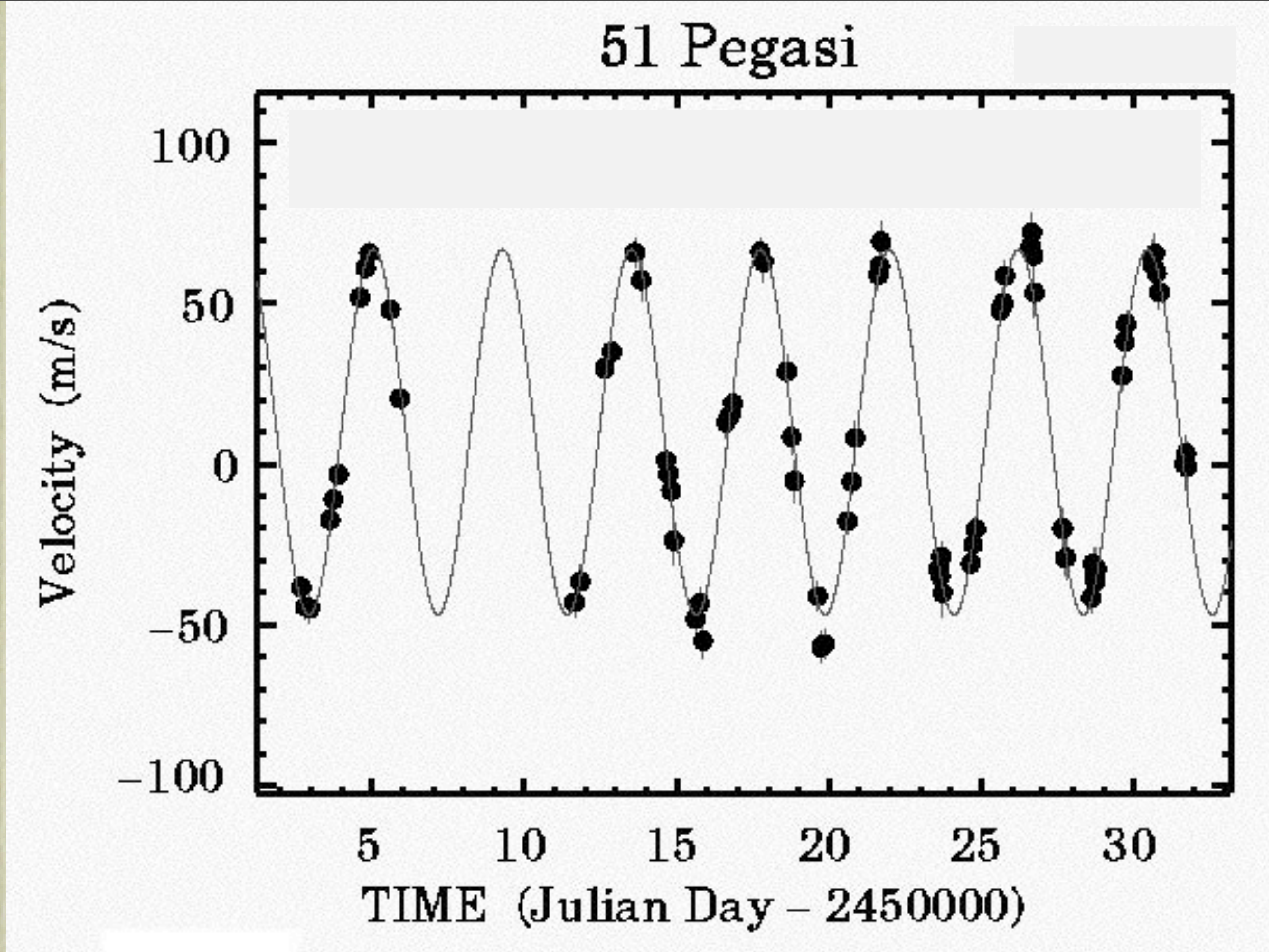
Detection method 1: Radial Velocity ("RV")



stellar spectrum



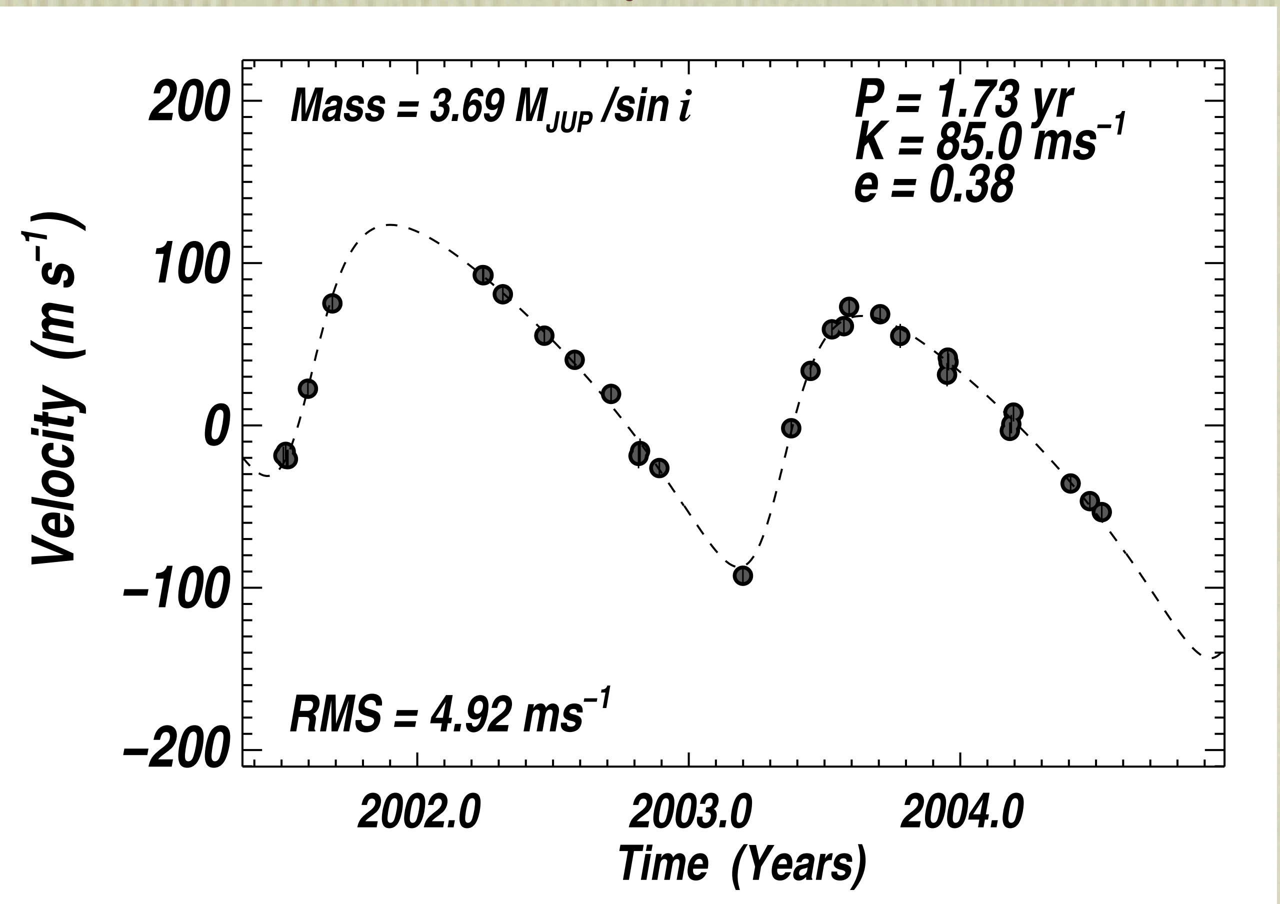




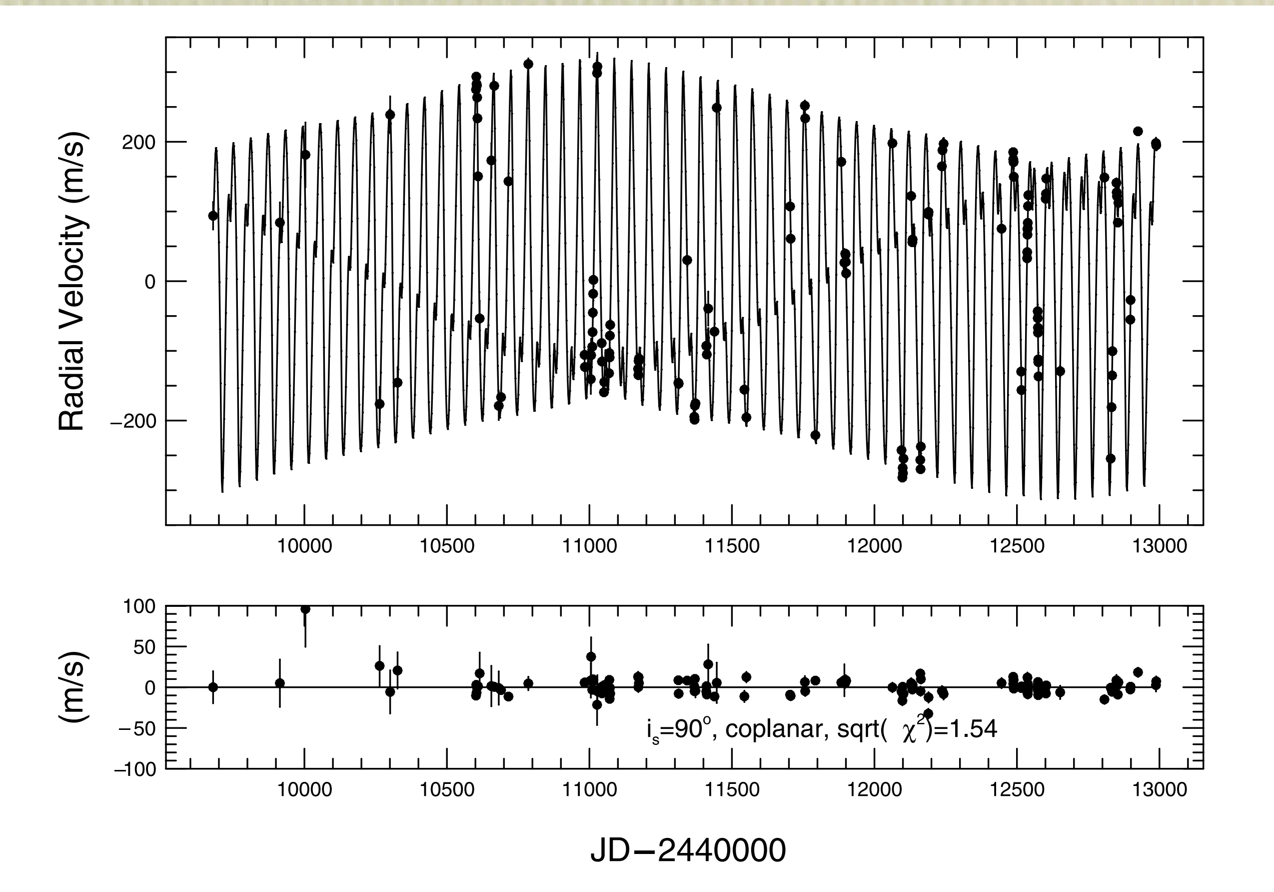
Orbital period: 4.2 days

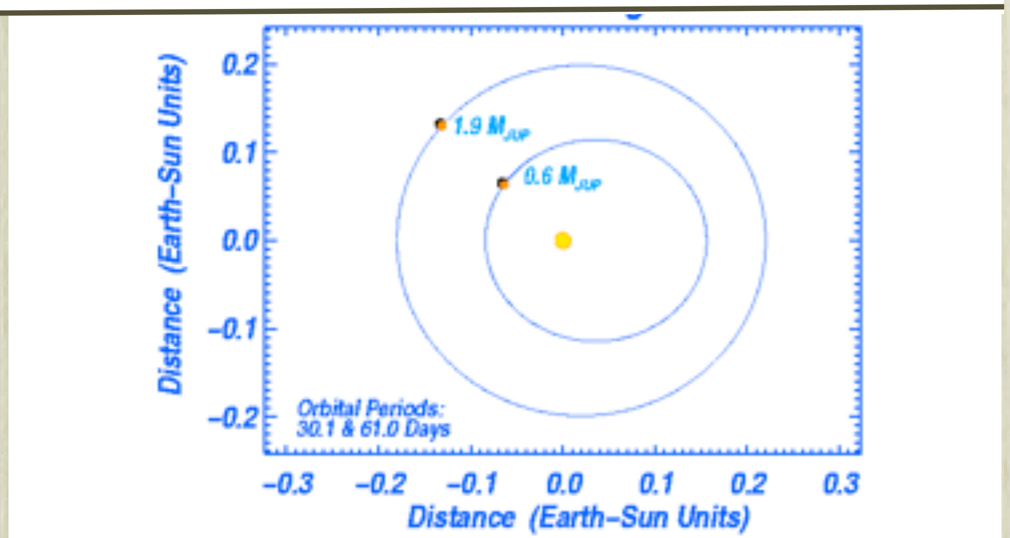
Mass: 0.4 × Jupiter's mass

HD 183263 (Marcy et al. '05)



GJ876 (Laughlin et al. '05)

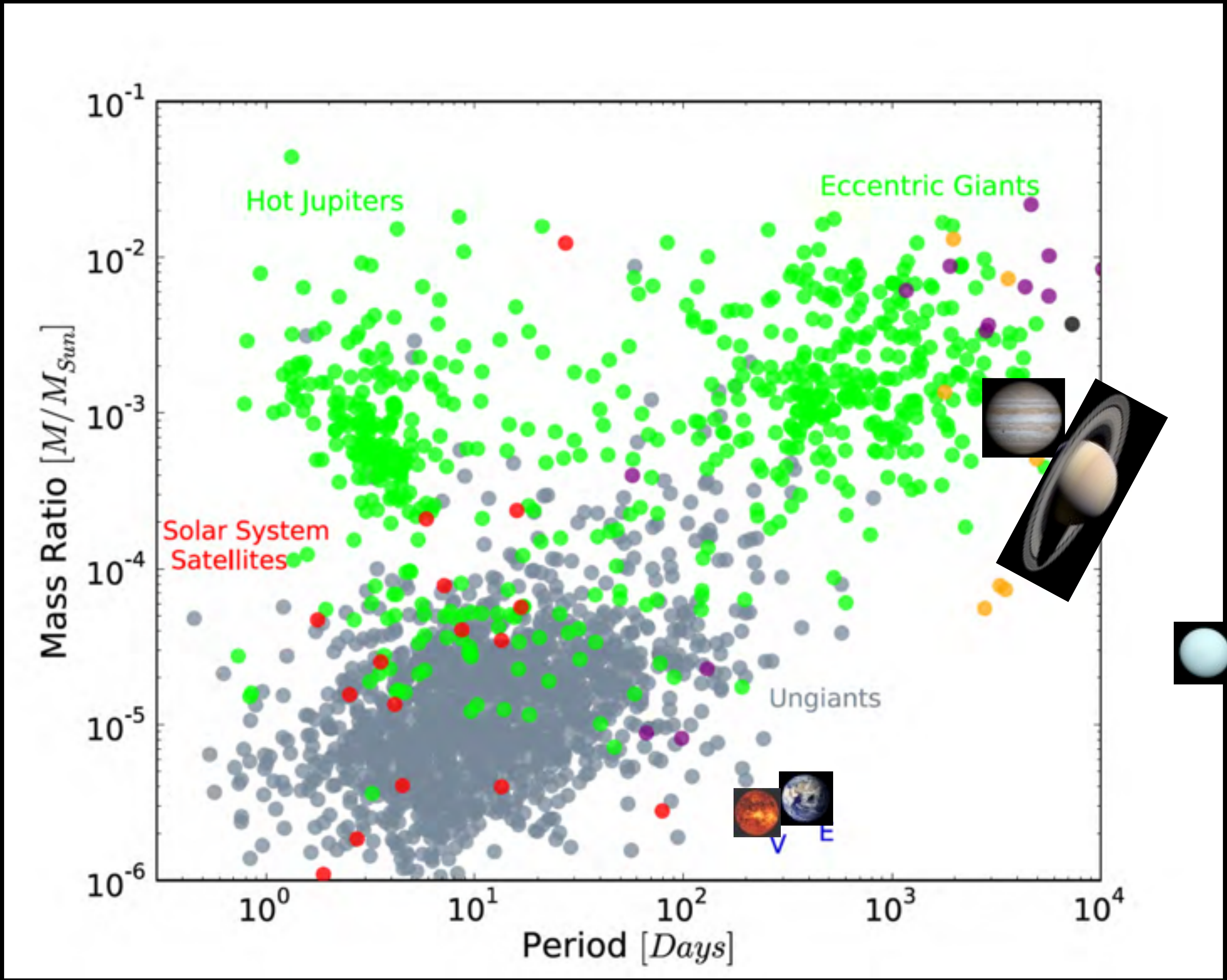


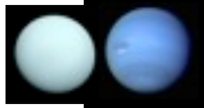


Known Planets

● Measured with RV

(fig 2 in Laughlin & Lissauer)





Formation of Hot Jupiters

- Jupiter-mass planets almost certainly formed outside 1 AU

  (Inside 1 AU: temperature too high & star's gravity too strong)

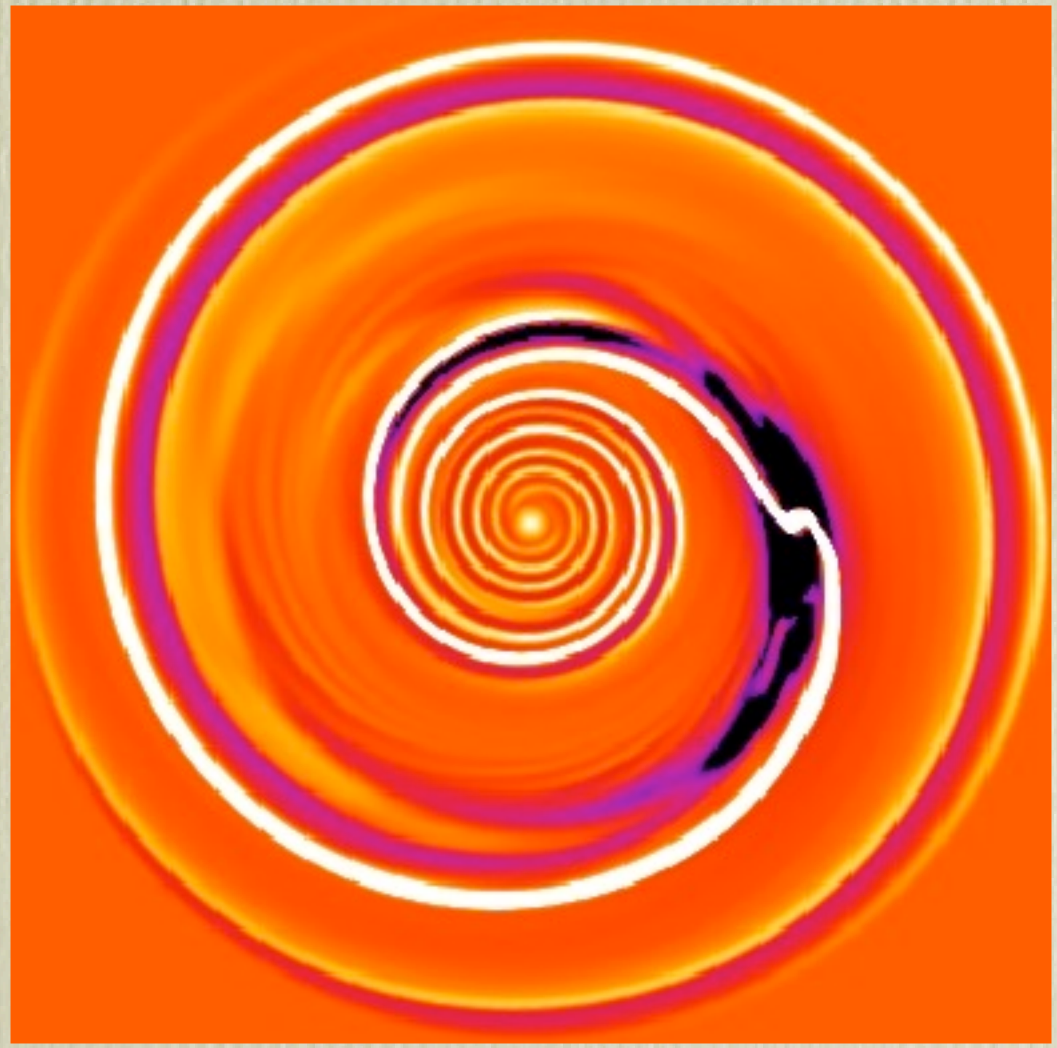
- How did hot Jupiters "migrate" from >1 AU to < 0.1AU?

Hot Jupiters

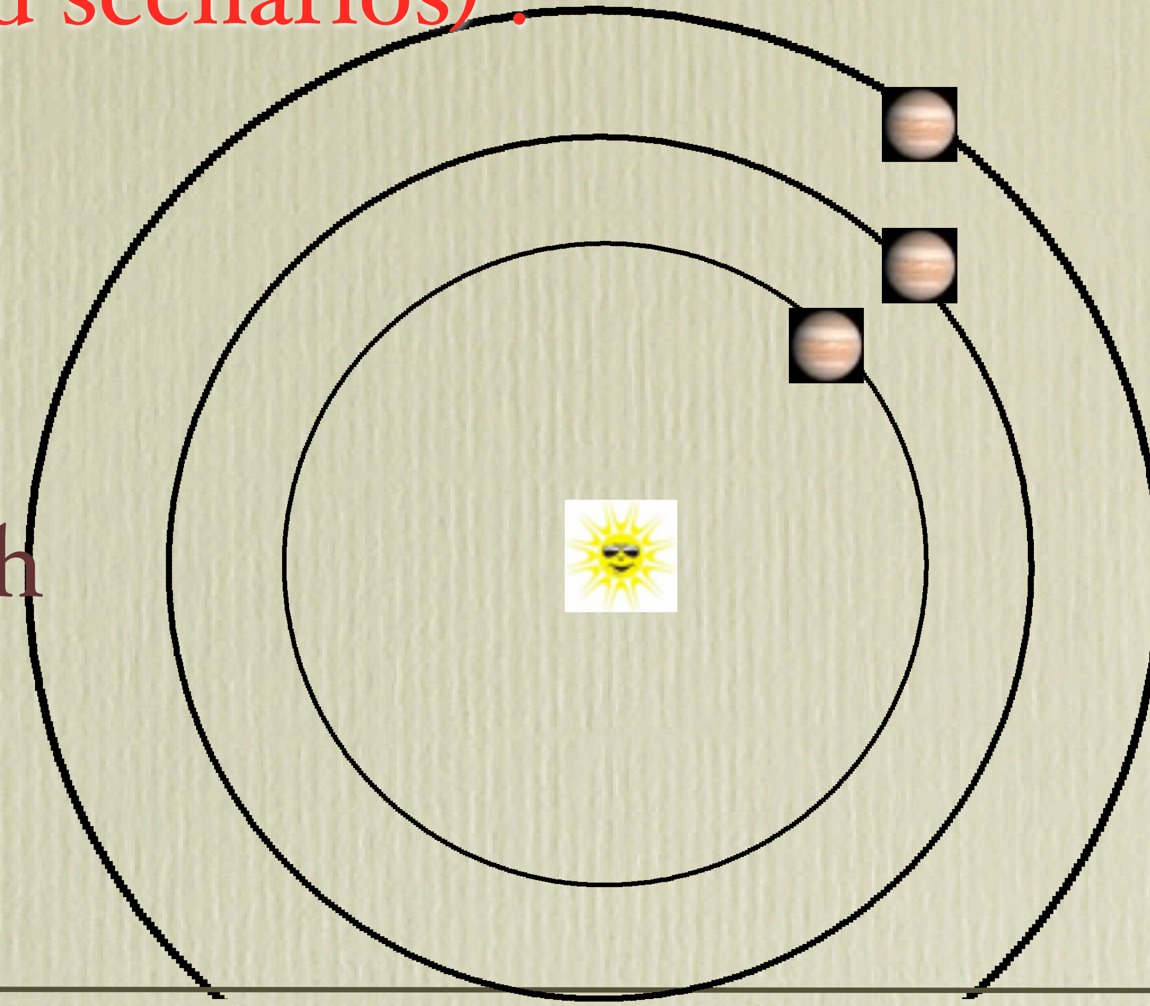
2 types of migration scenarios:

1. Disk Migration

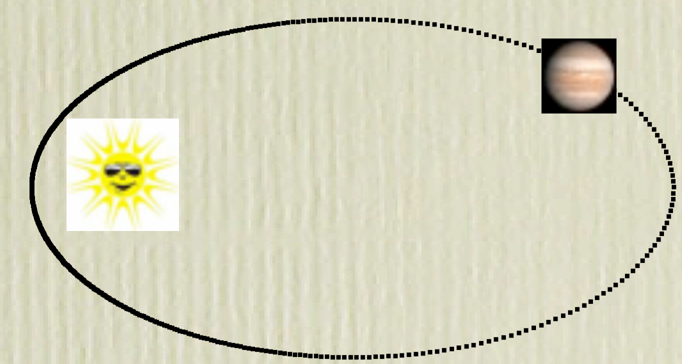
Planet forms in a gas disk,
then is transported along as disk is accreted



2. Interplanetary chaos (& related scenarios) :



- Planet forms far from star, with companions

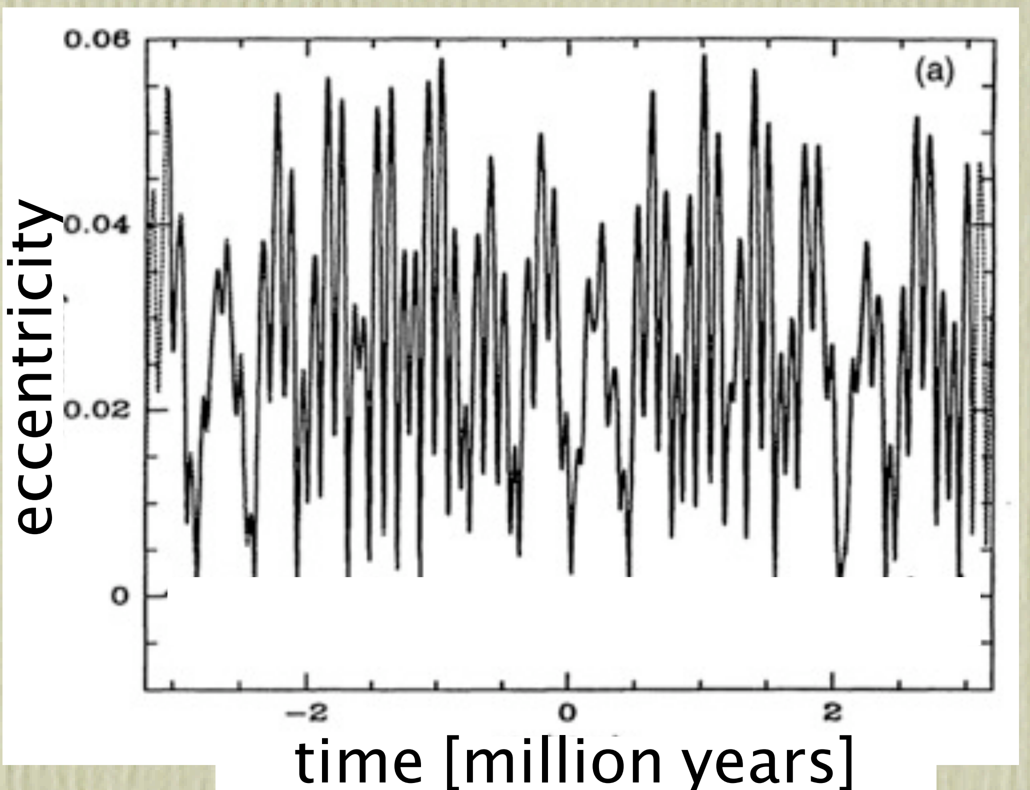


- Innermost planet's eccentricity is excited by other planets

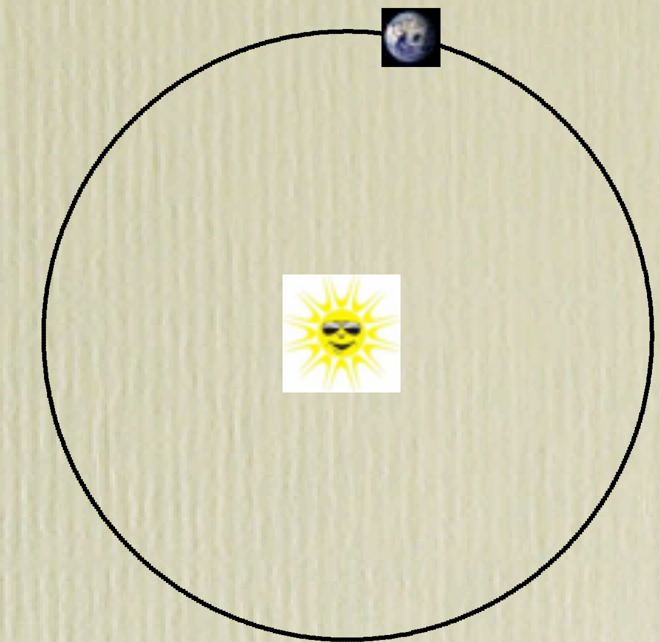
- When planet comes close enough to star, strong tides are raised on planet, circularizing its orbit

Solar system also exhibits chaos

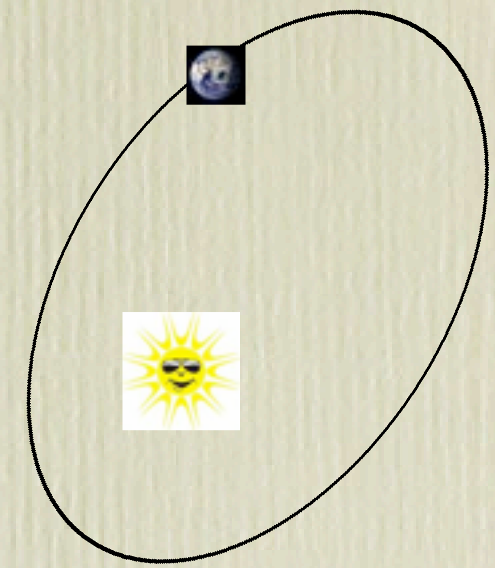
Earth's eccentricity



eccentricity=0 (circle)



eccentricity=0.5 (ellipse)



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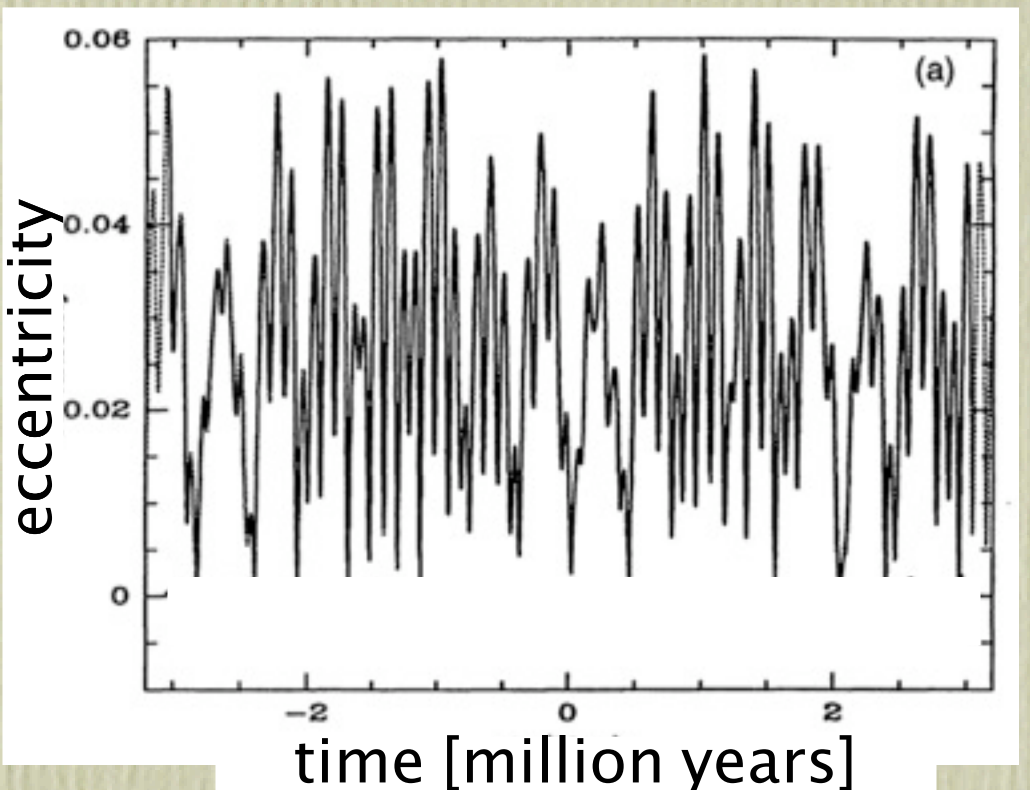
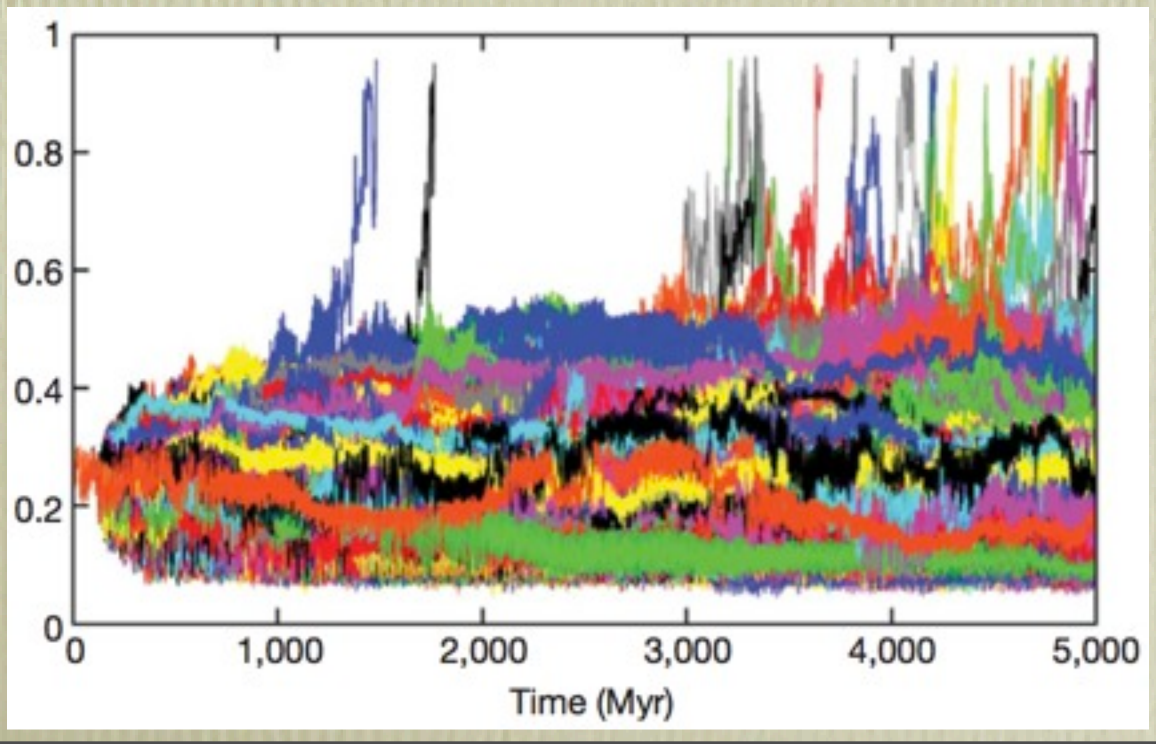
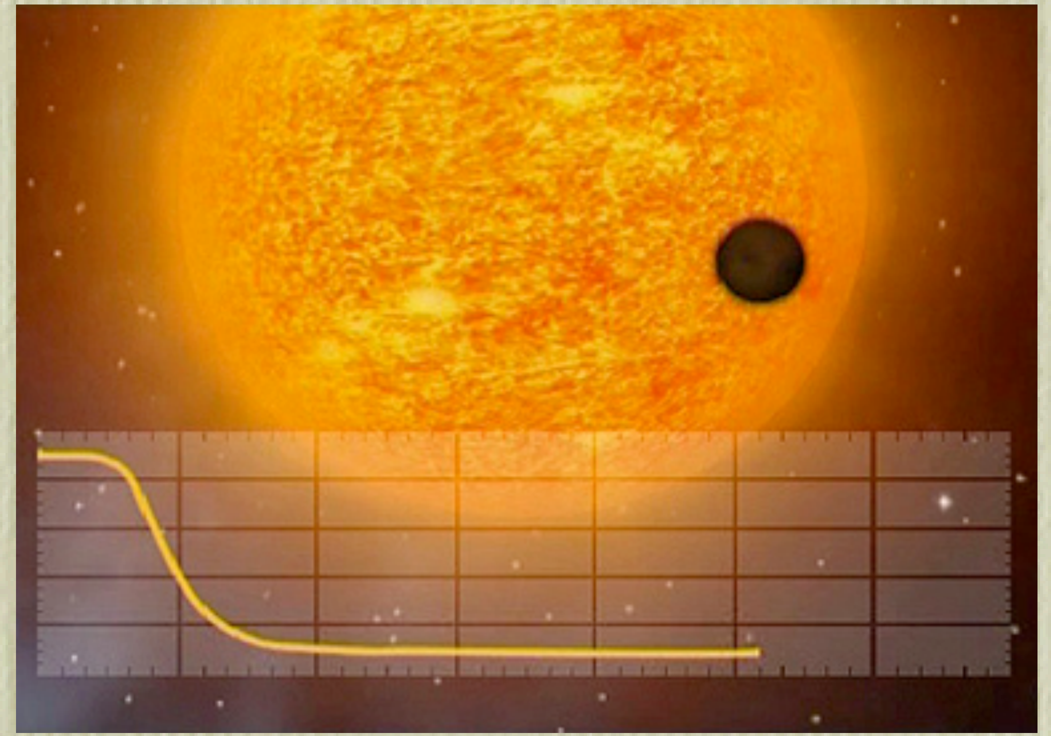


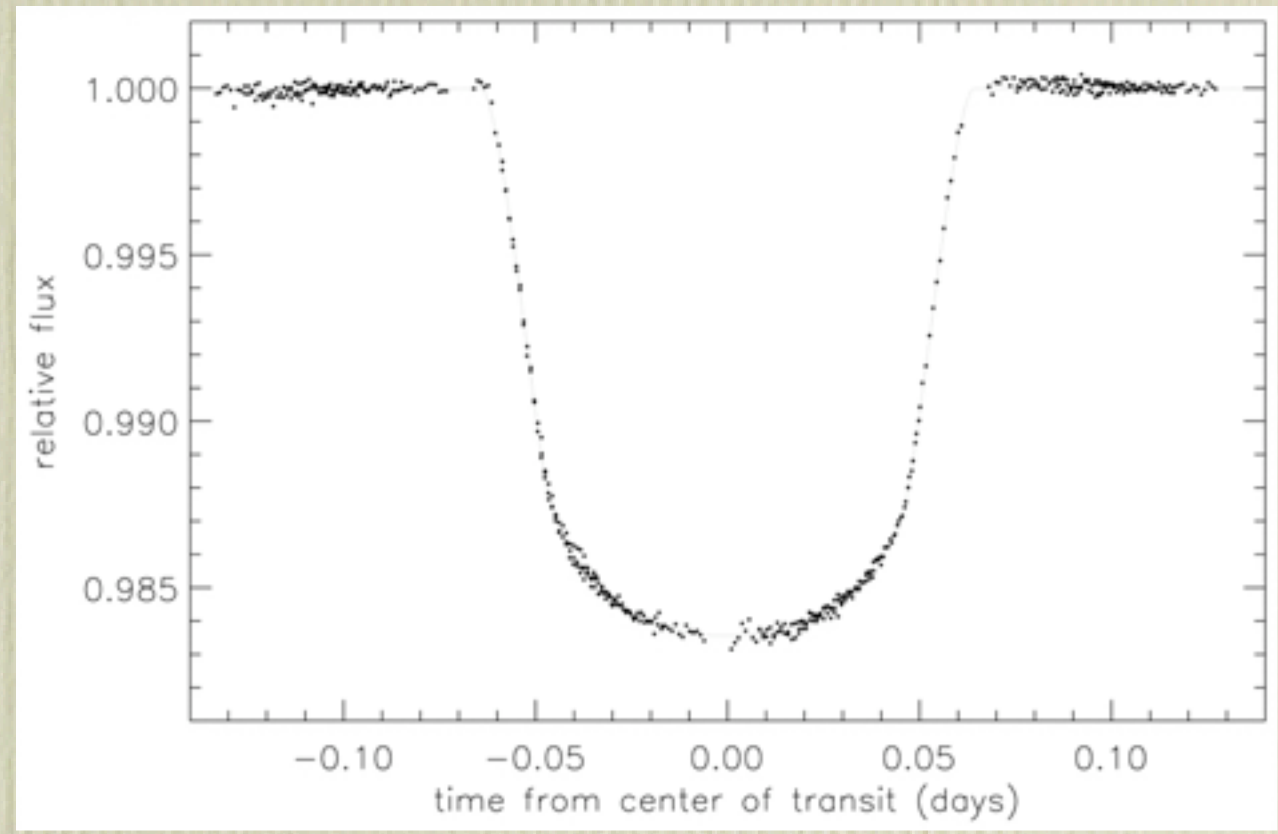
Mercury's eccentricity



- Solar system unstable! Lucky we haven't lost Mercury yet

Detection method 2: Transit

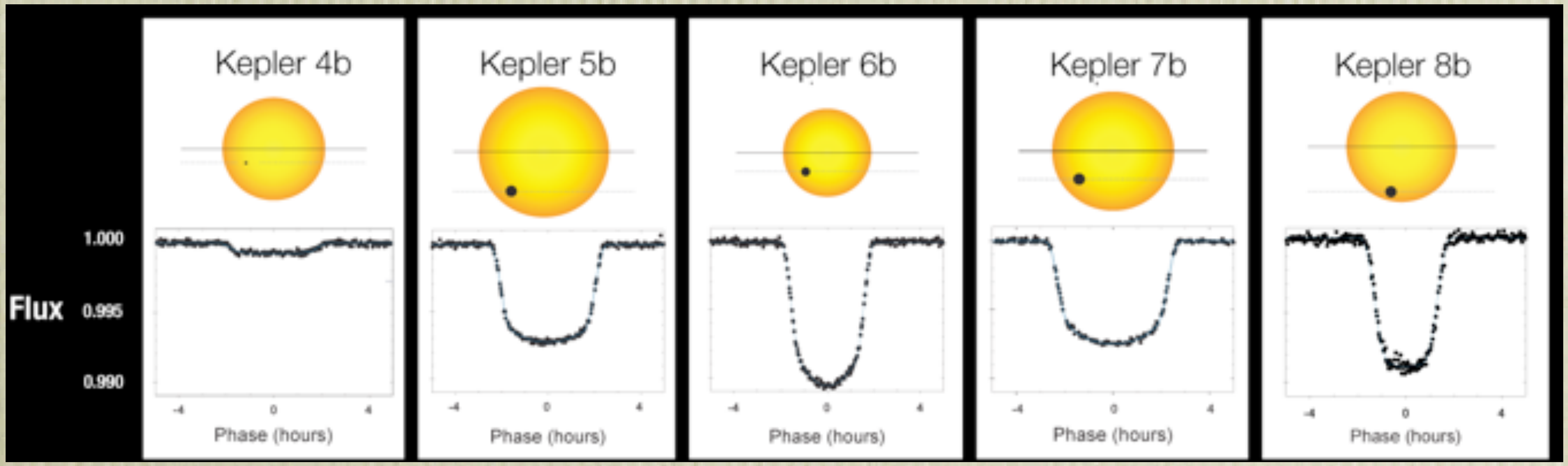




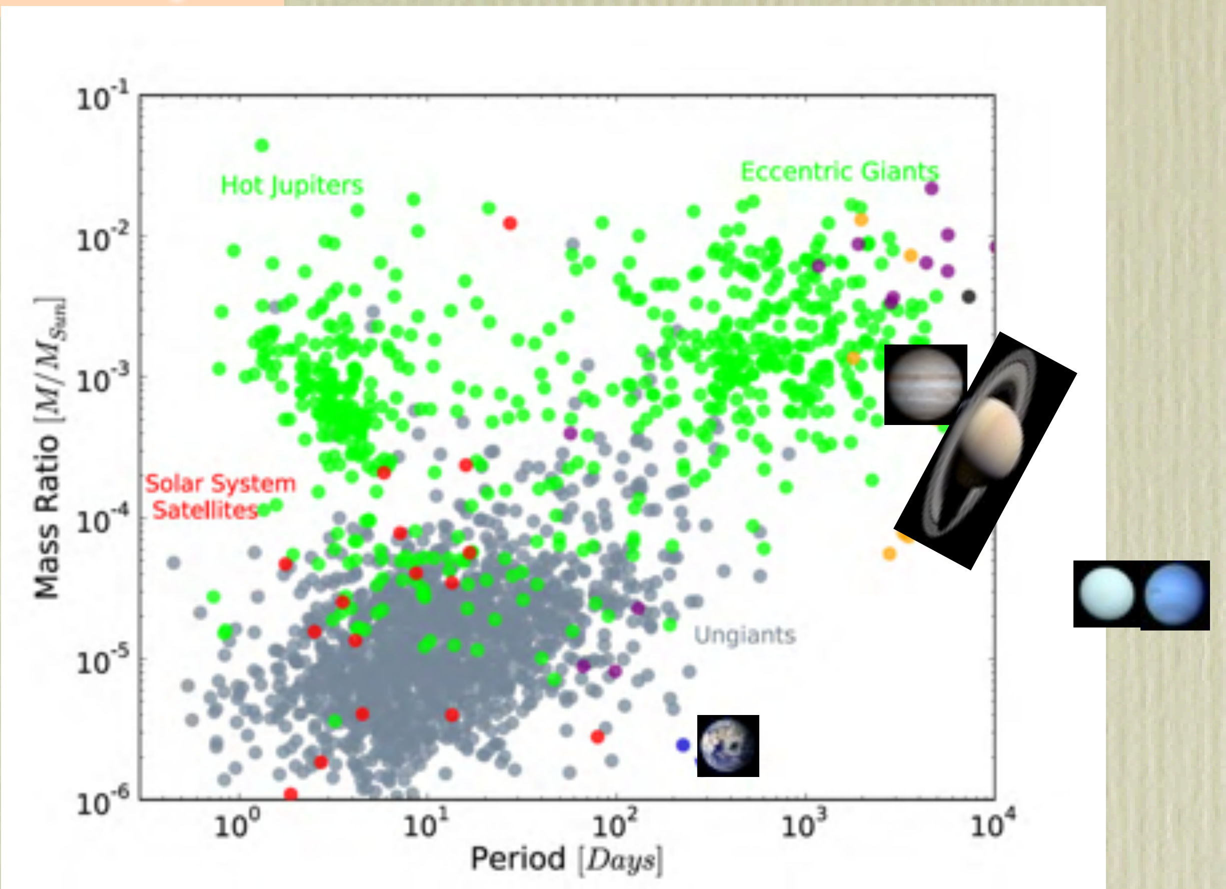
HD 209548 (Brown et al. '01)

Kepler Telescope

Transit detector extraordinaire

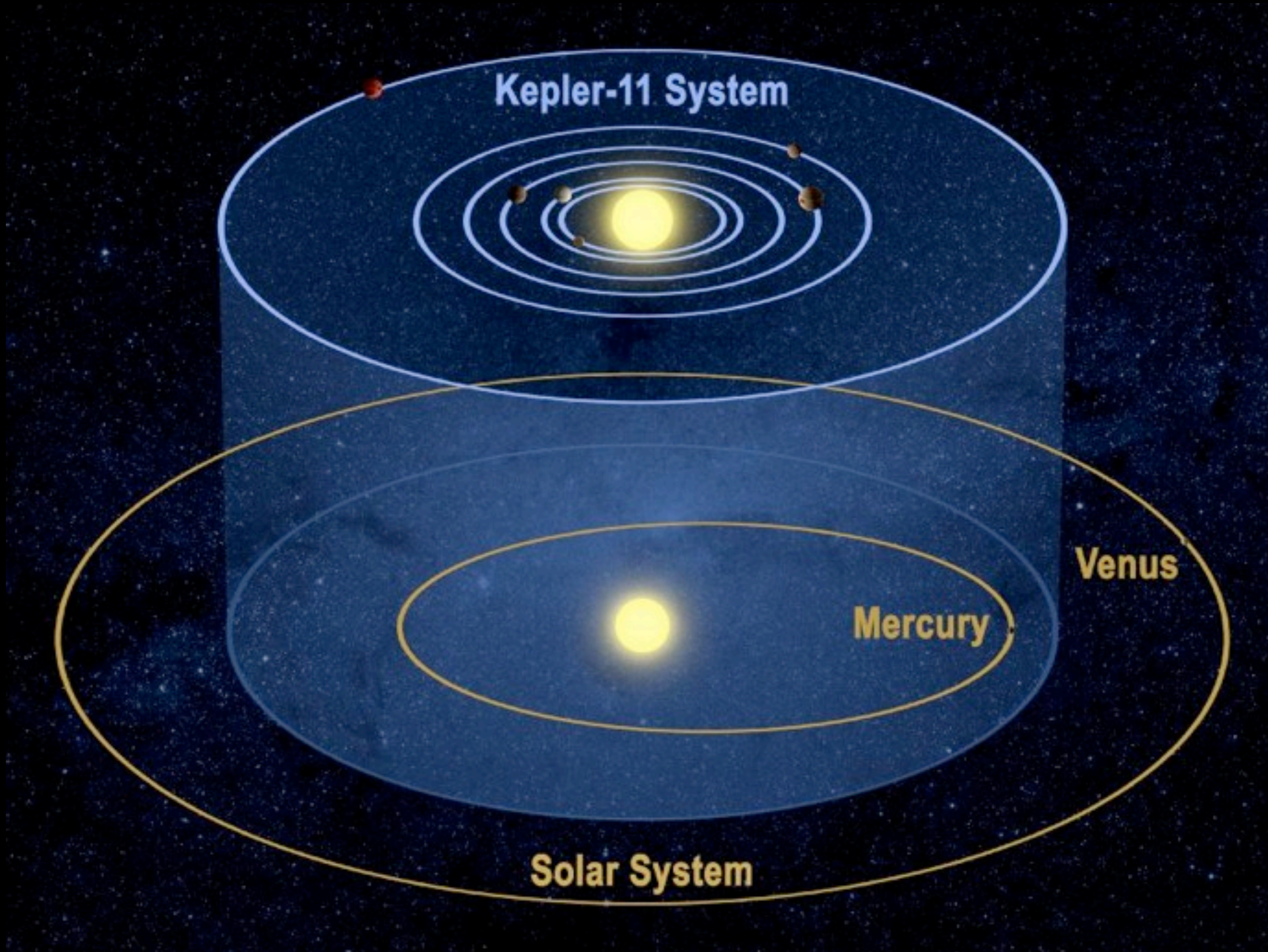


Kepler's Bounty:

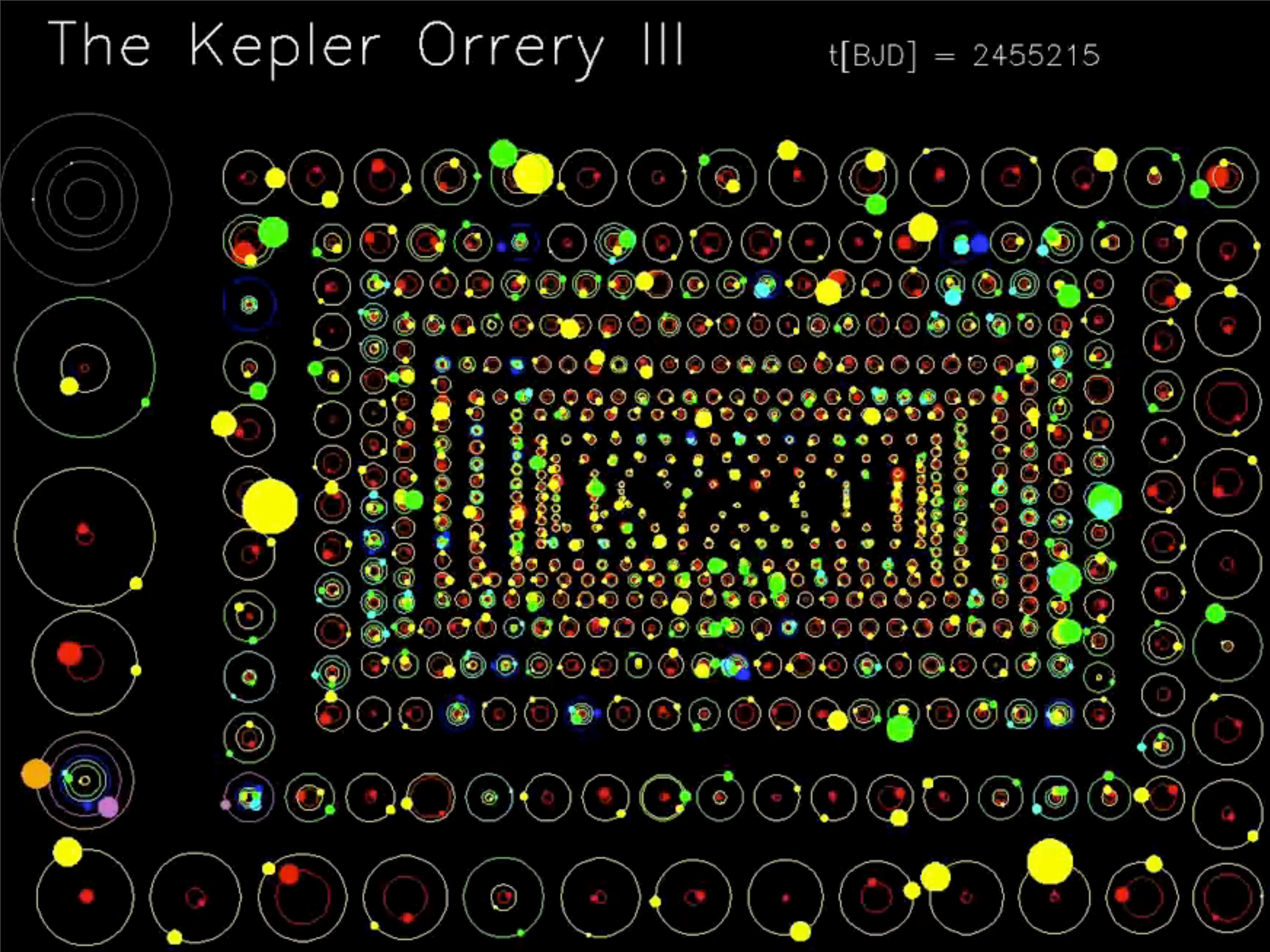


- ~4,200 "planetary candidates" (~1000 are "confirmed planets")
- mass: between Earth & Neptune (mostly)
  periods: inward of Mercury (mostly)
- 20-30% of stars have "Kepler planets" ("Ungiants")

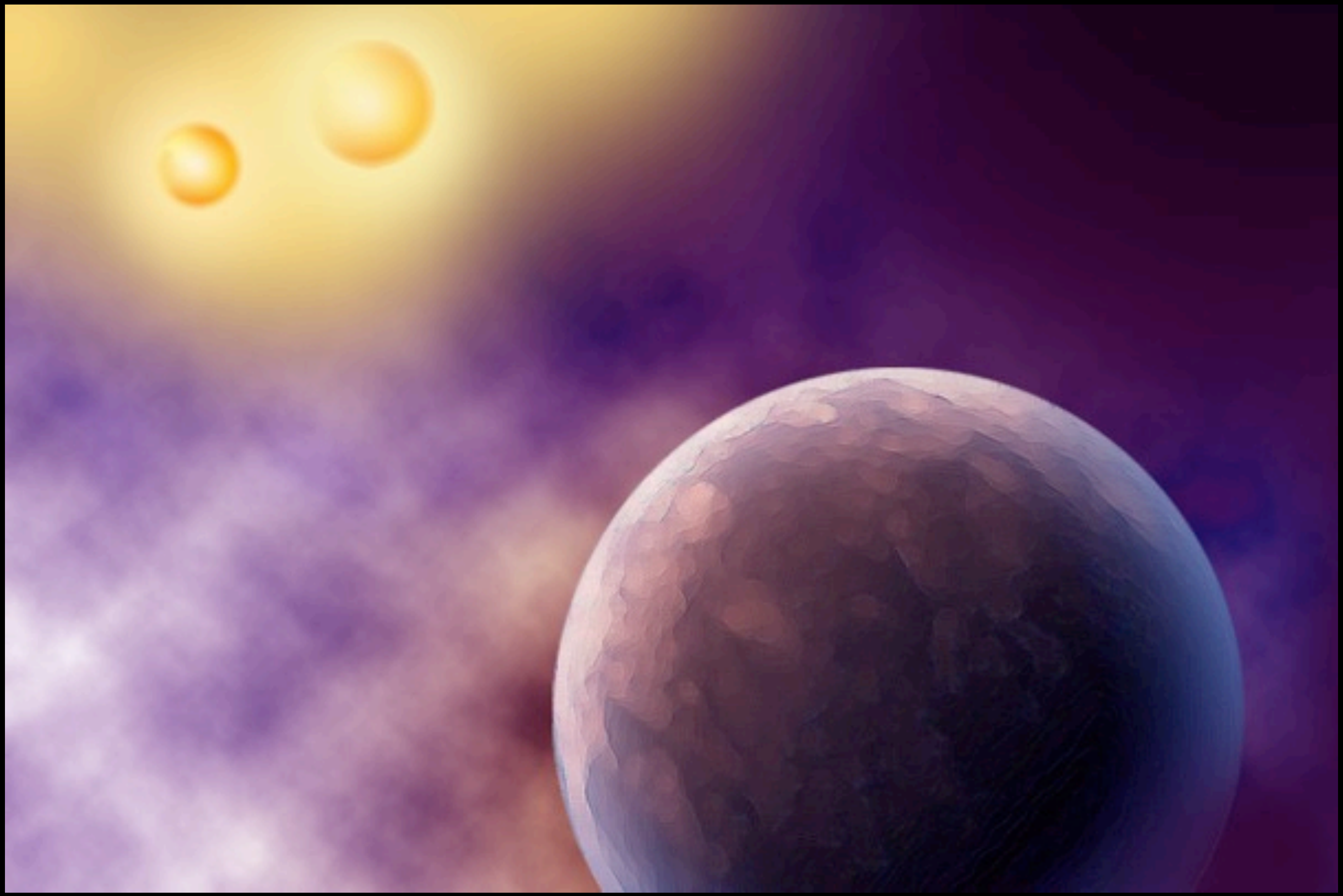
“Packed” planetary systems



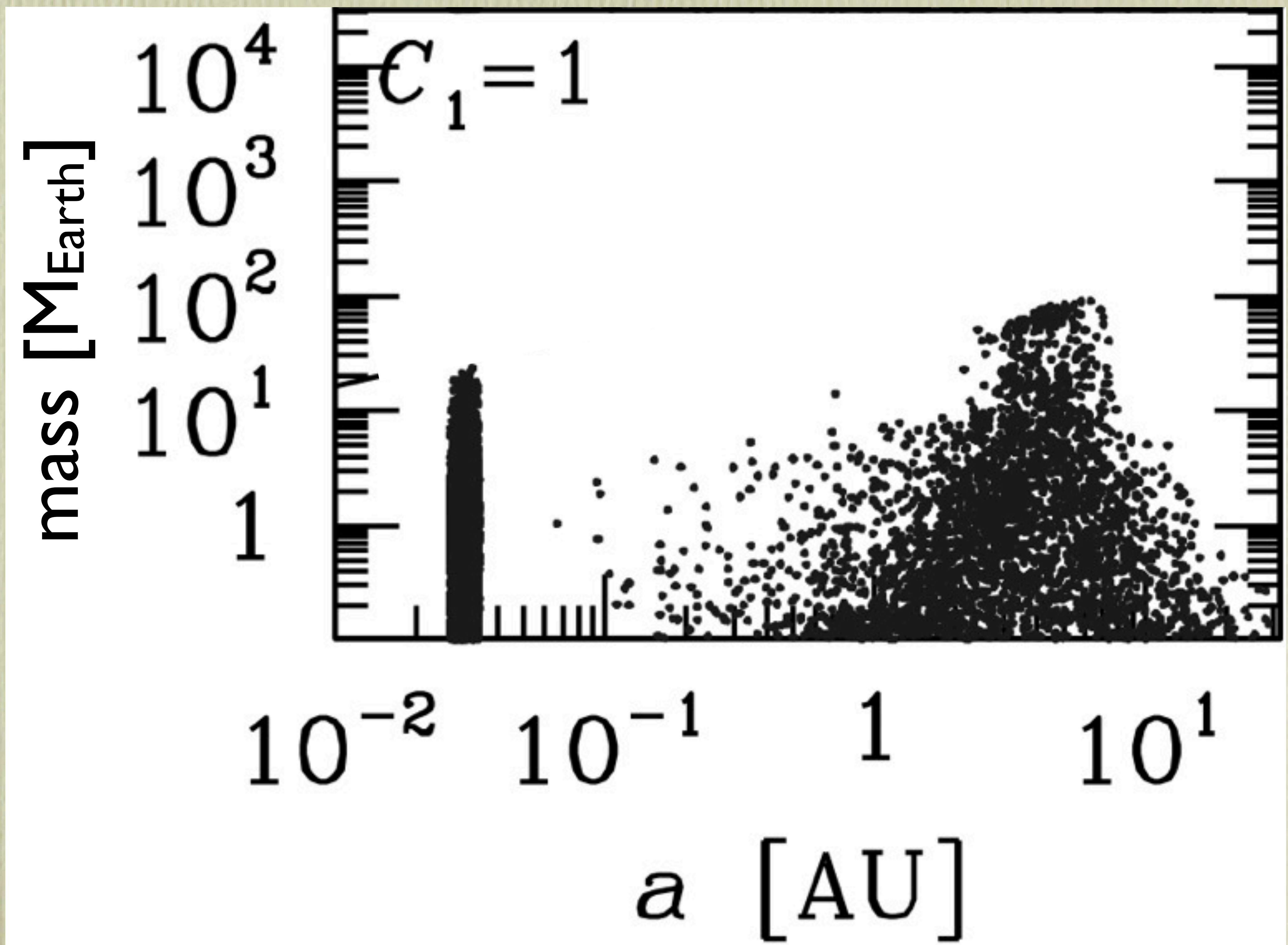
Entire Kepler-11 planetary system
(6 planets known)
fits inside the orbit of Venus


The Kepler Orrery III
t[BJD] = 2455215

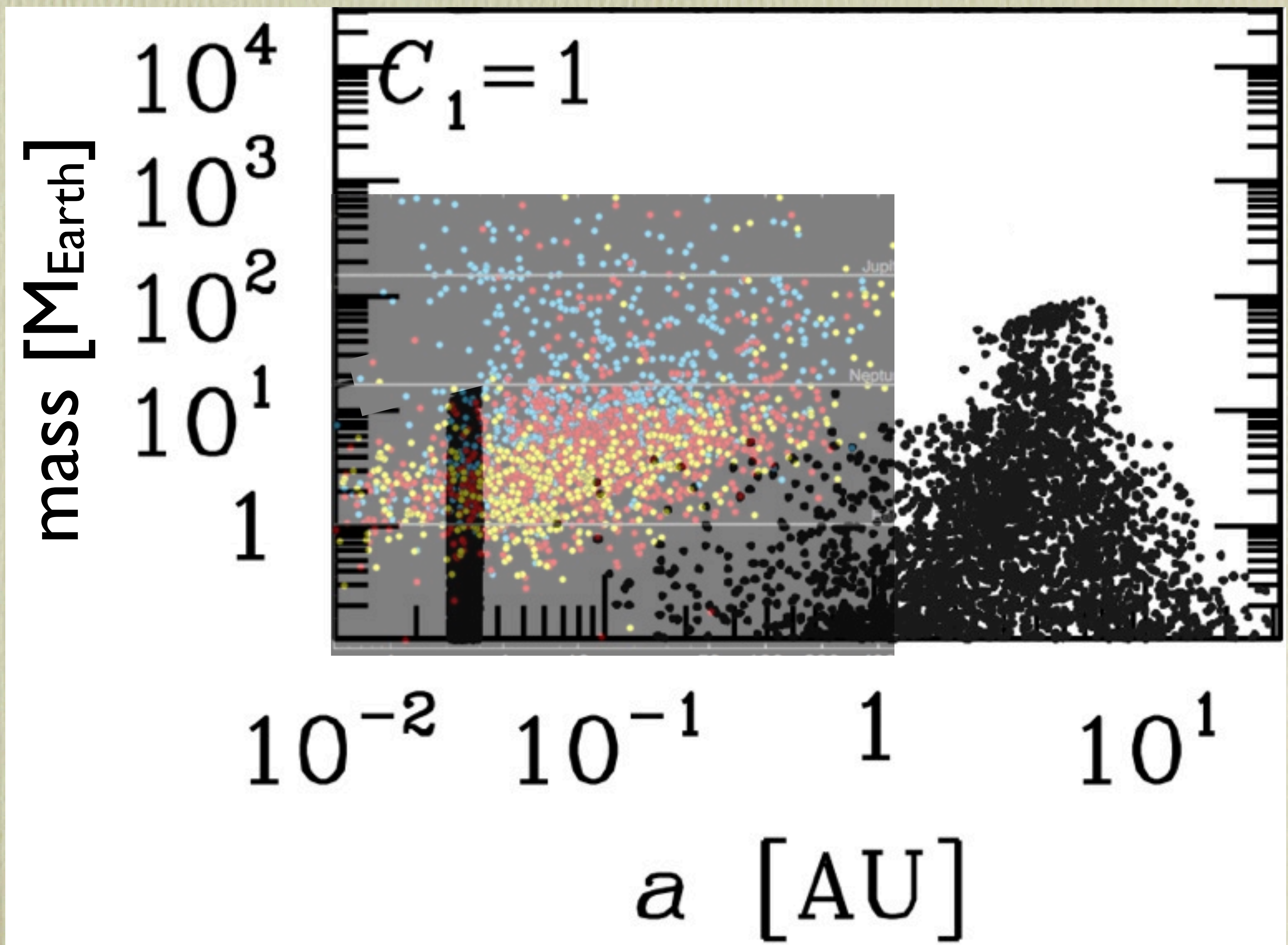
Circumbinary planets



Prediction:

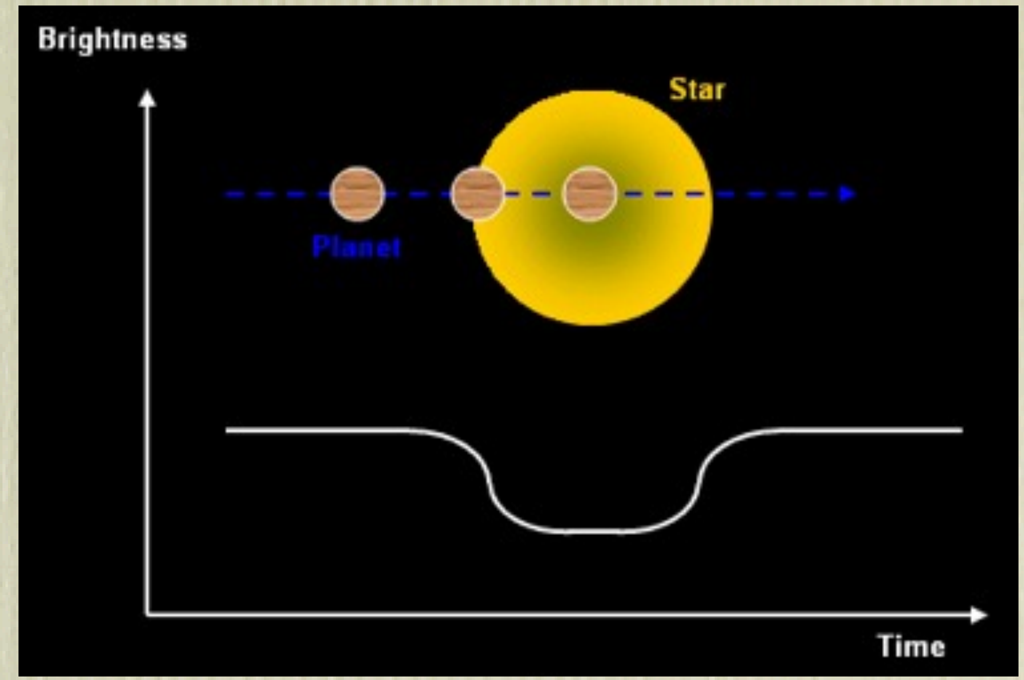


(Ida & Lin '08)



(Ida & Lin '08)

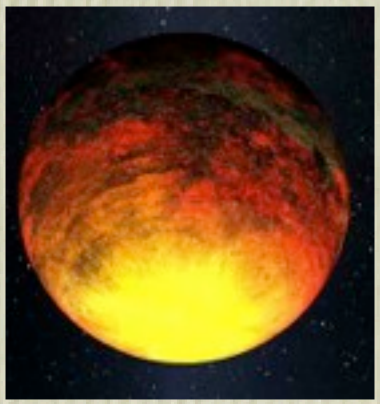
What are these planets made of?



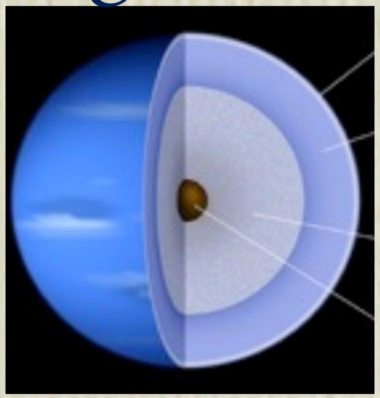
- Kepler measures:
  planet radius (transit depth)
  & period/semimajor axis (transit times)

- Would also like to know:
  eccentricity
  & mass

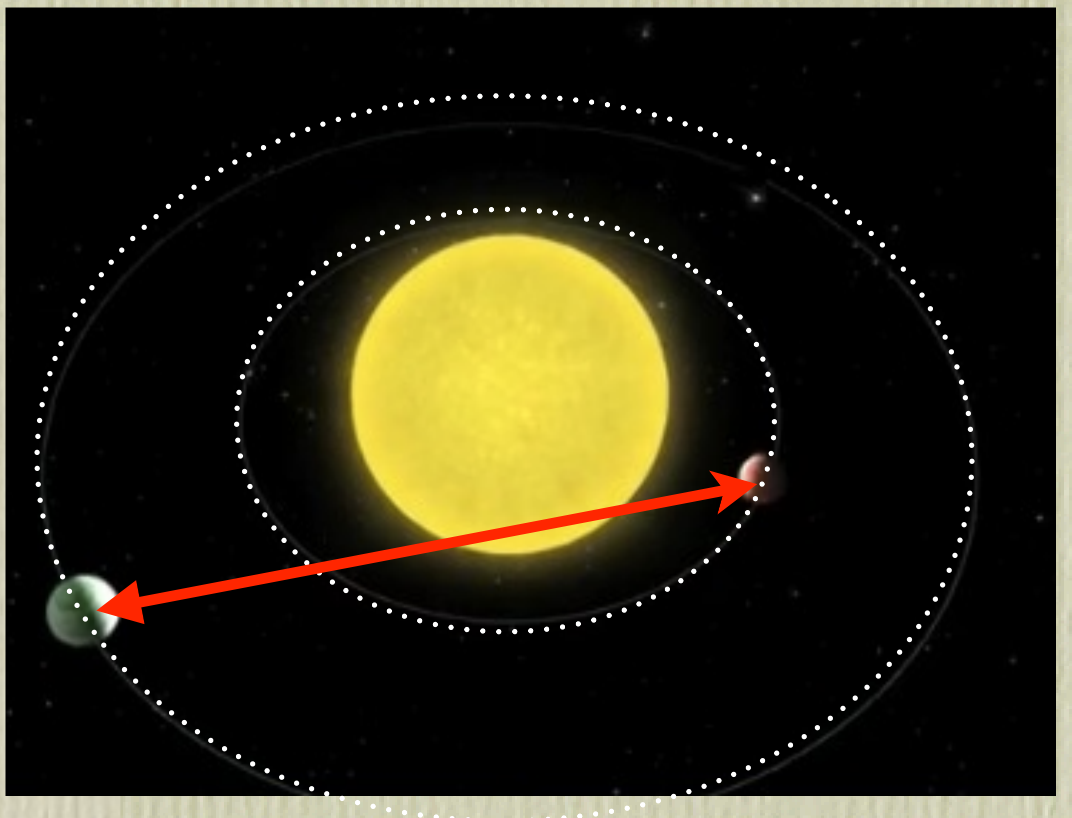
rock?

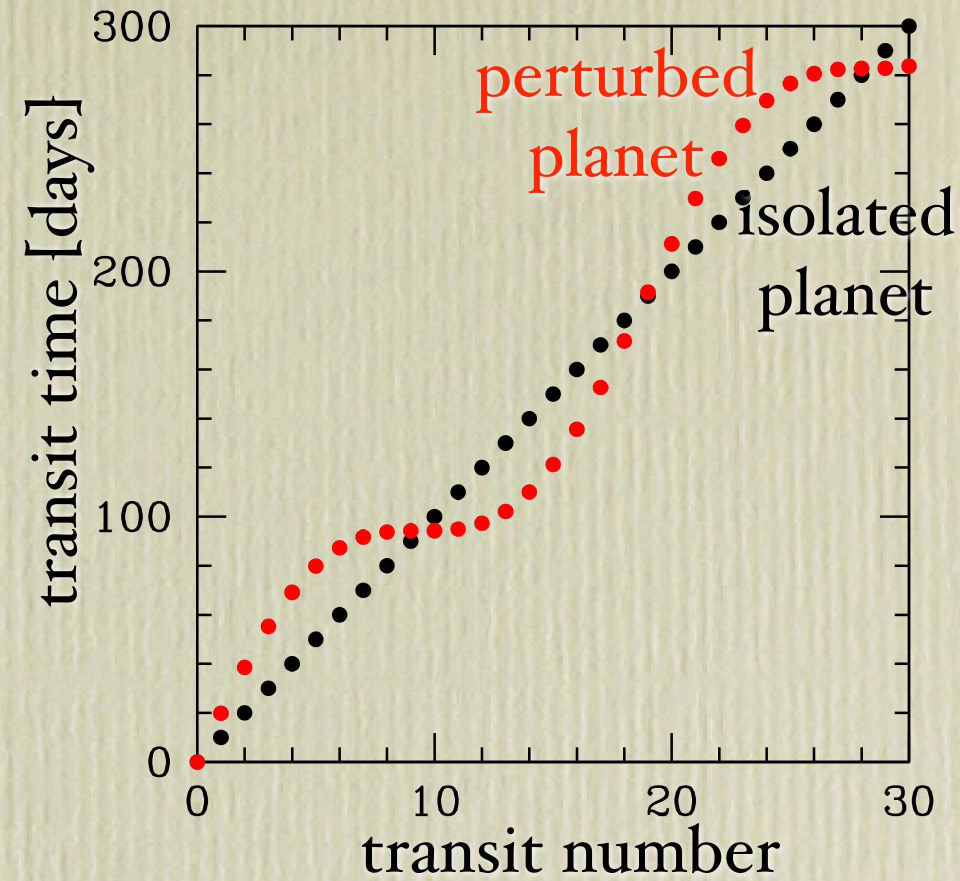


gas?

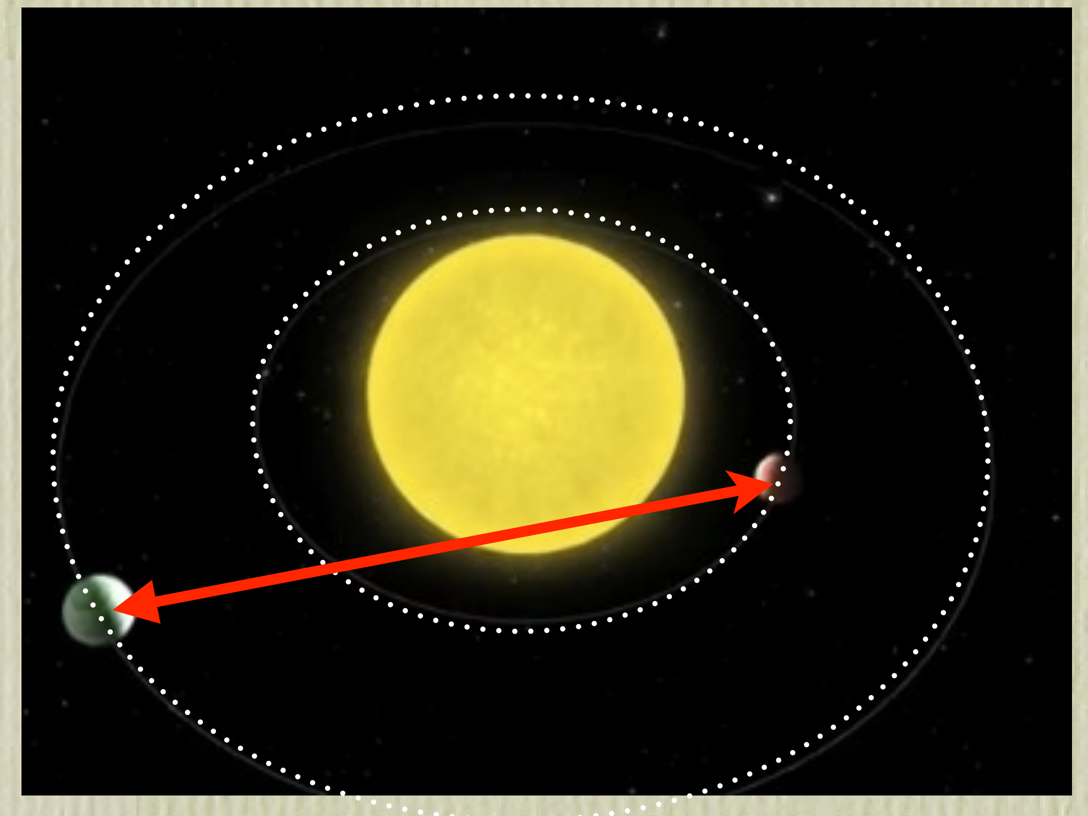


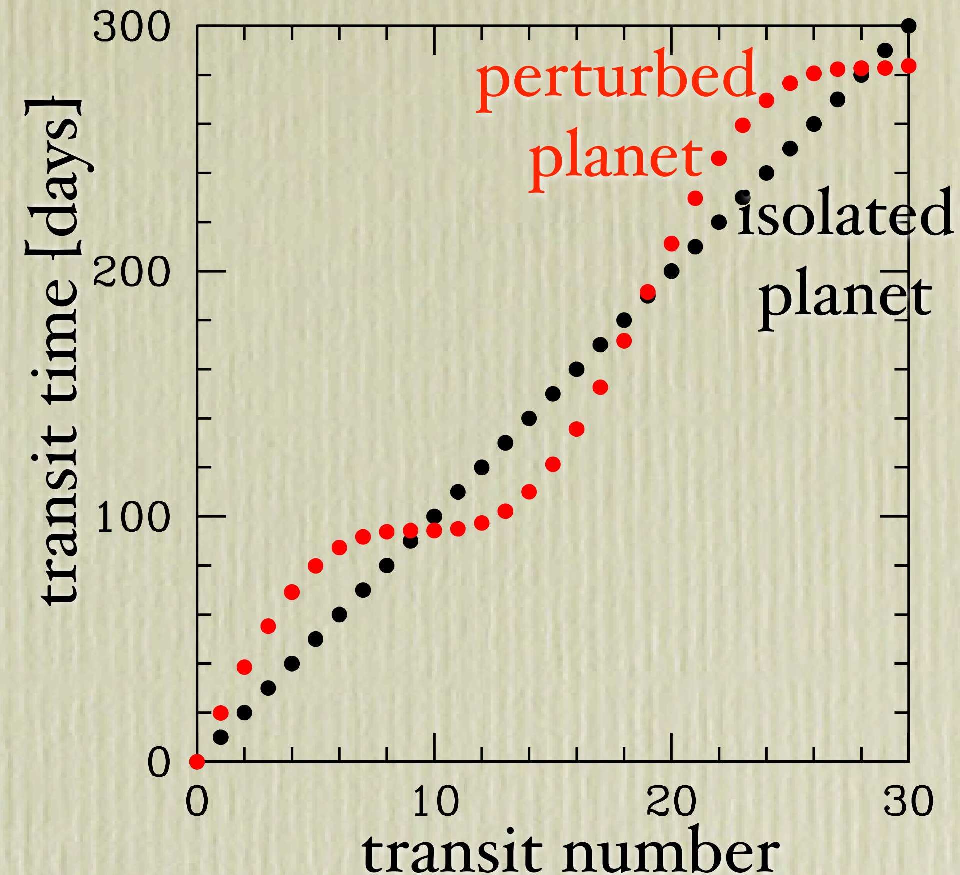
Transit Time Variations (TTV)



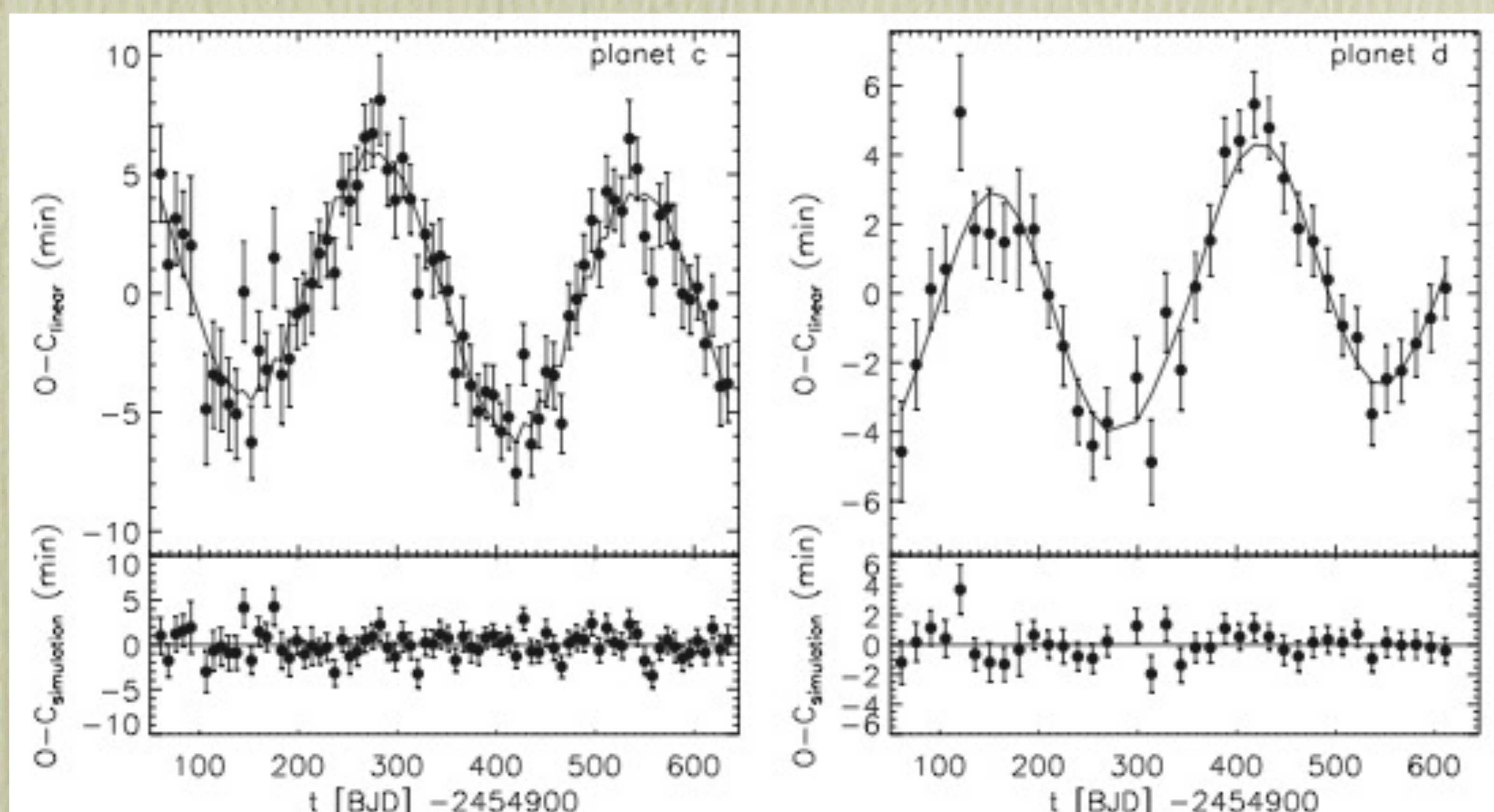


Transit Time Variations (TTV)





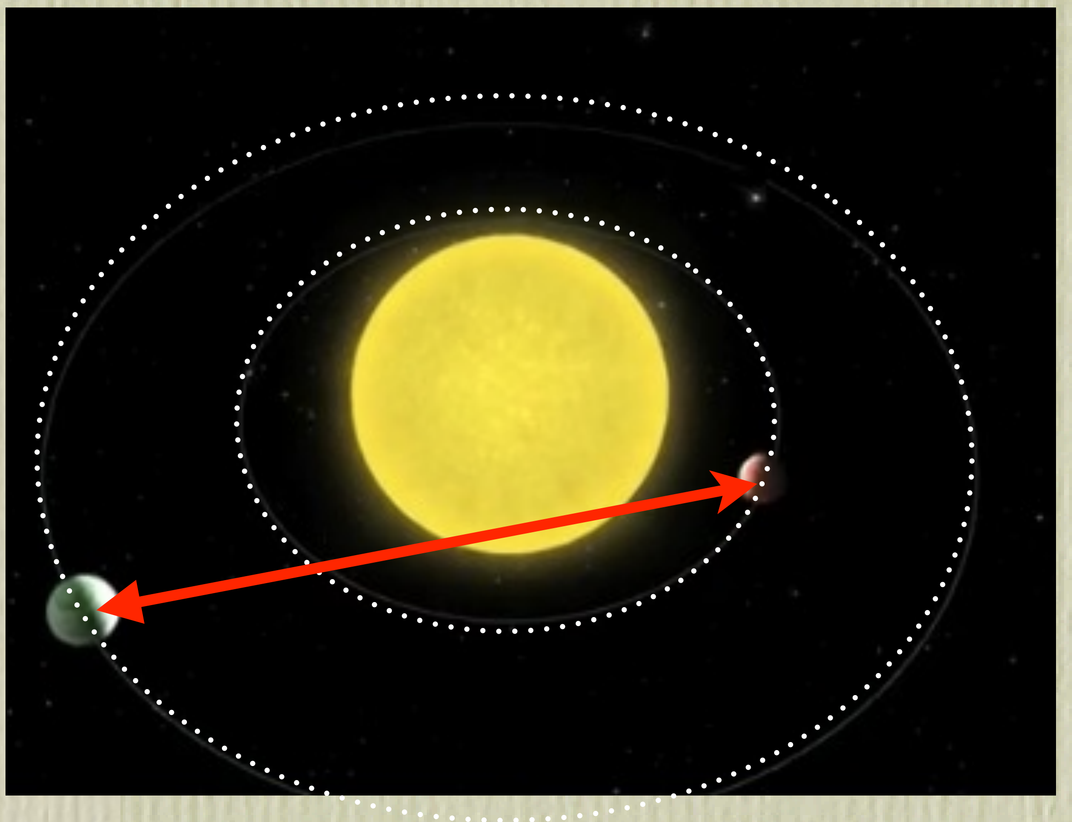
Remove slope

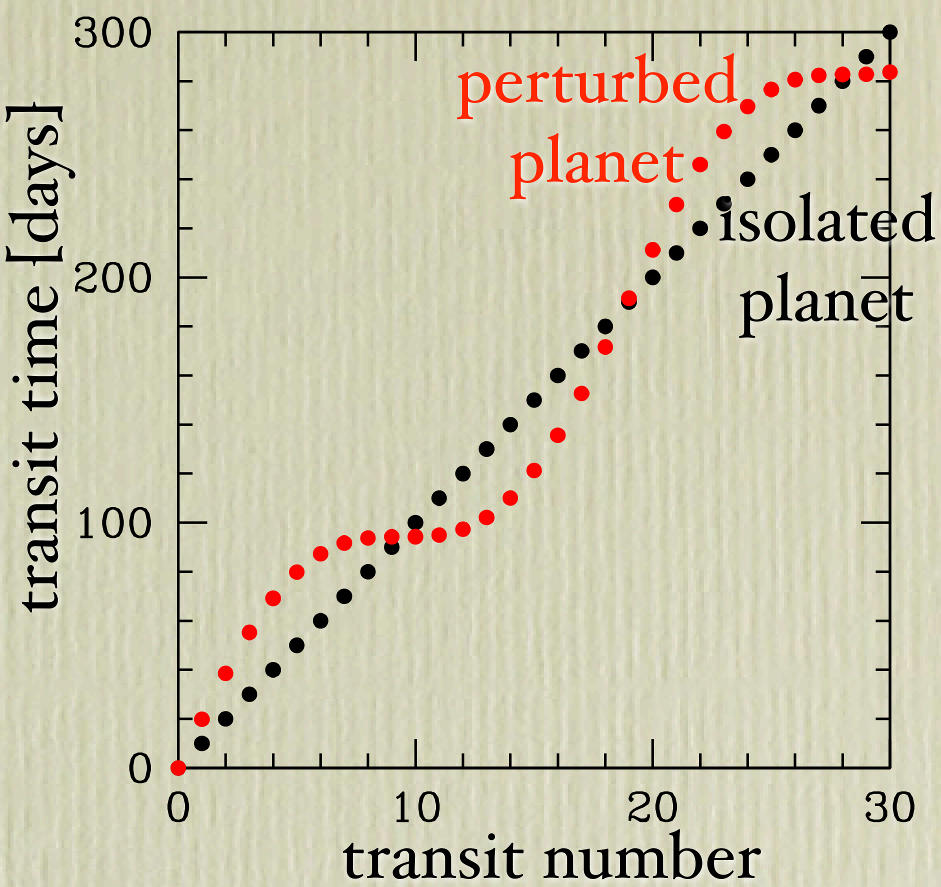


Kepler 18

(Cochran et al. '11)

Transit Time Variations (TTV)





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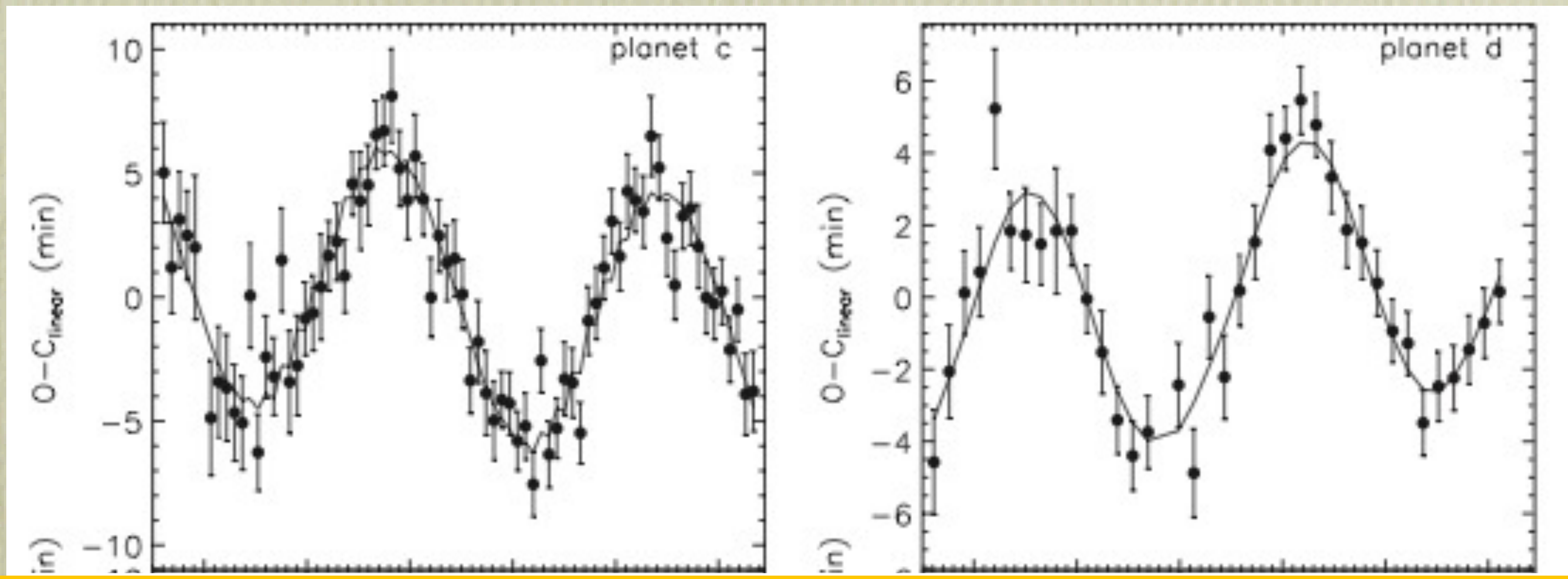


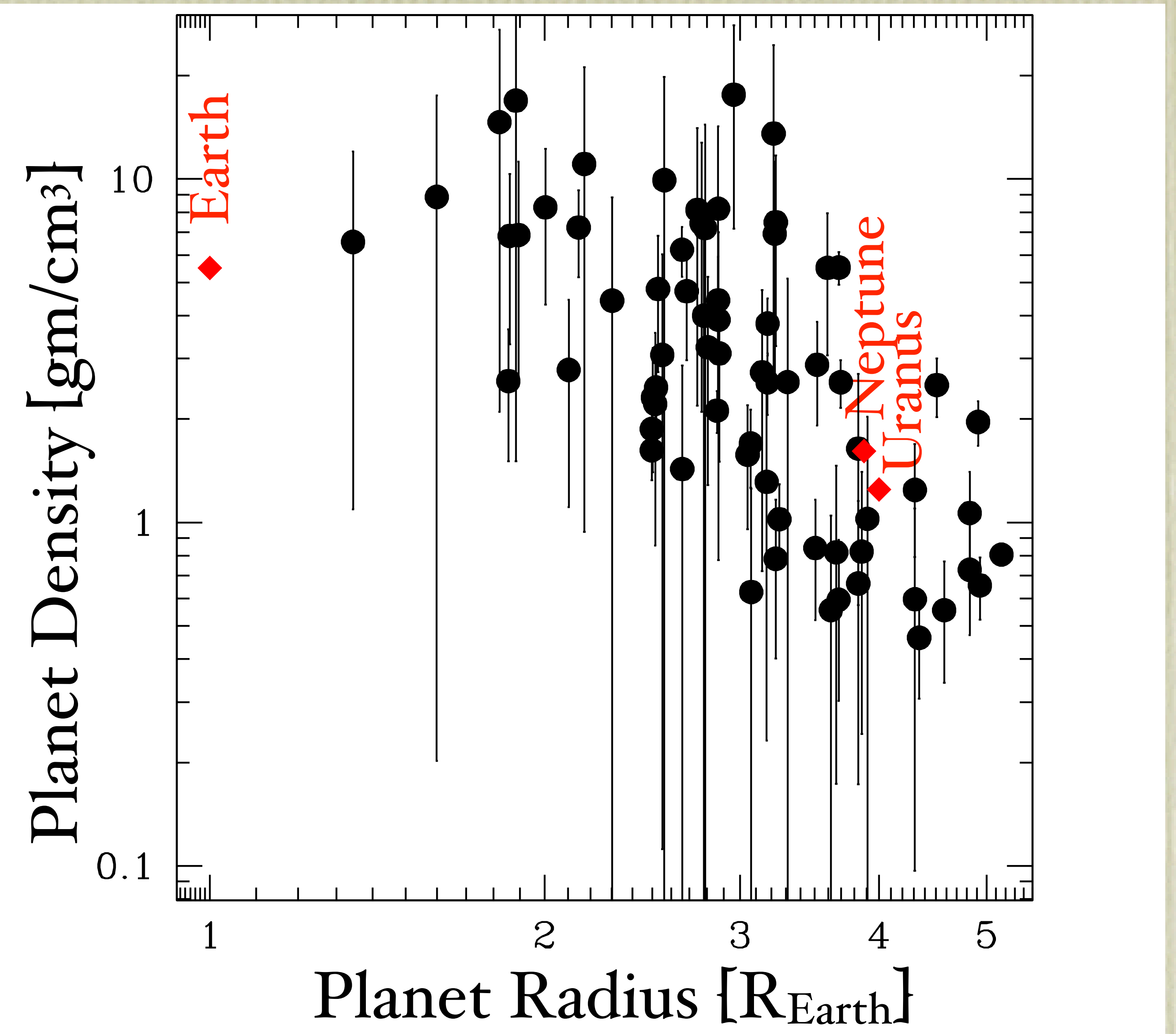
Kepler 18

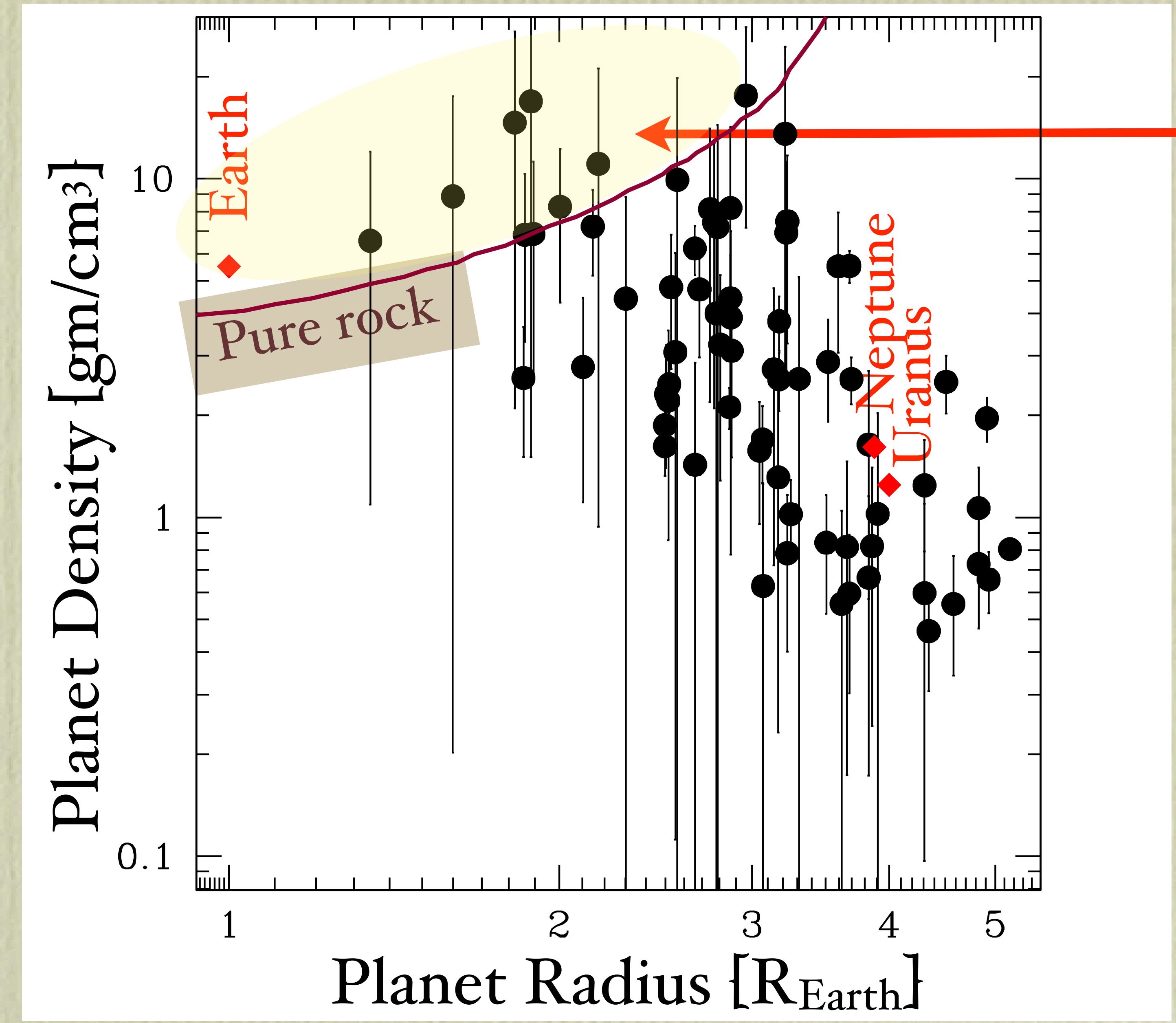
(Cochran et al. '11)

$e_c = 0\ [\pm 0.0003]$ $e_d = 0\ [\pm 0.0003]$

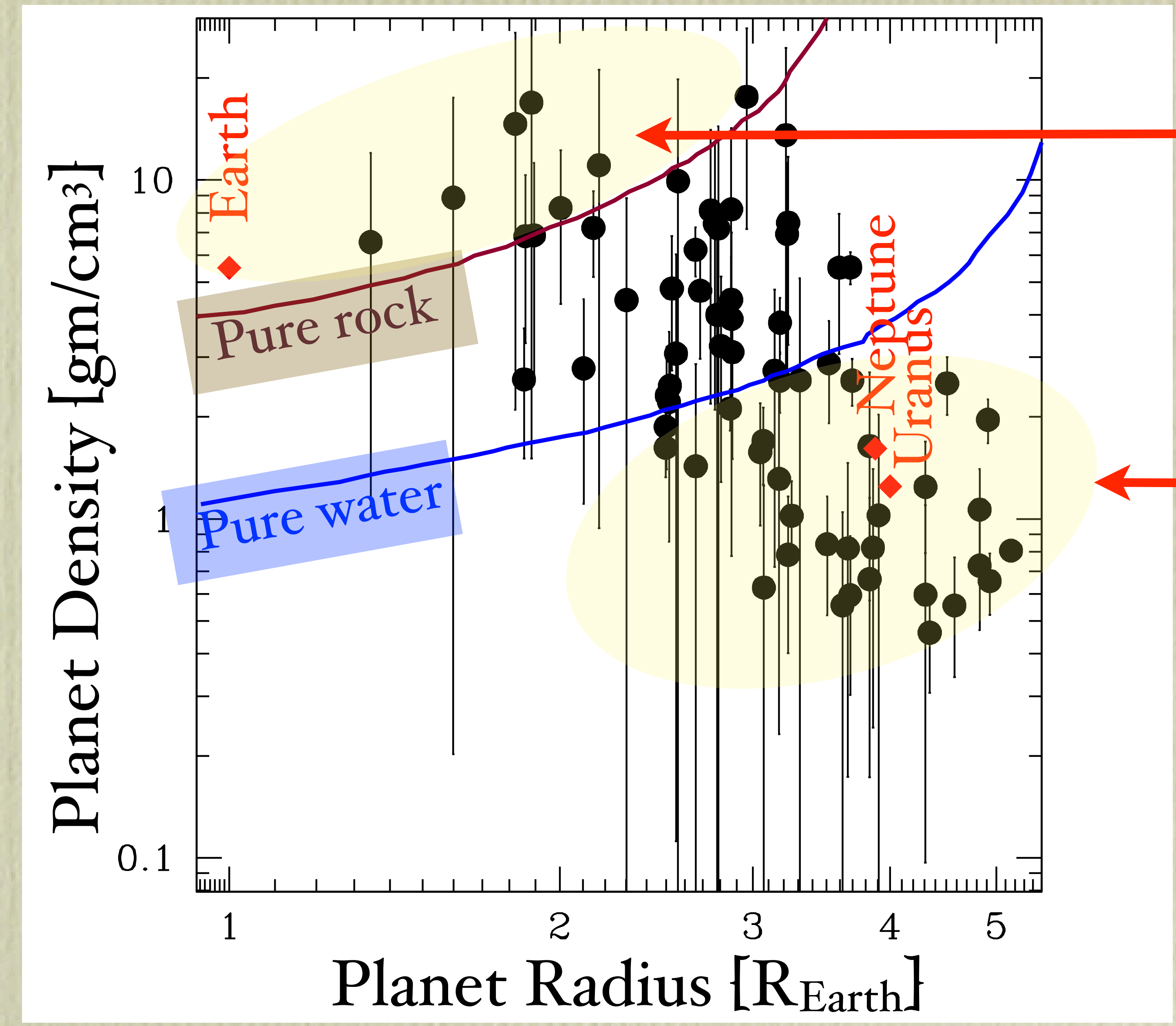
$M_c = 17 M_{Earth}$ $M_d = 16 M_{Earth}$

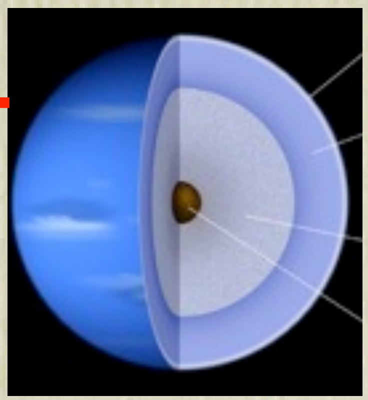
Density of 70 Exoplanets from TTV (Hadden & Lithwick)



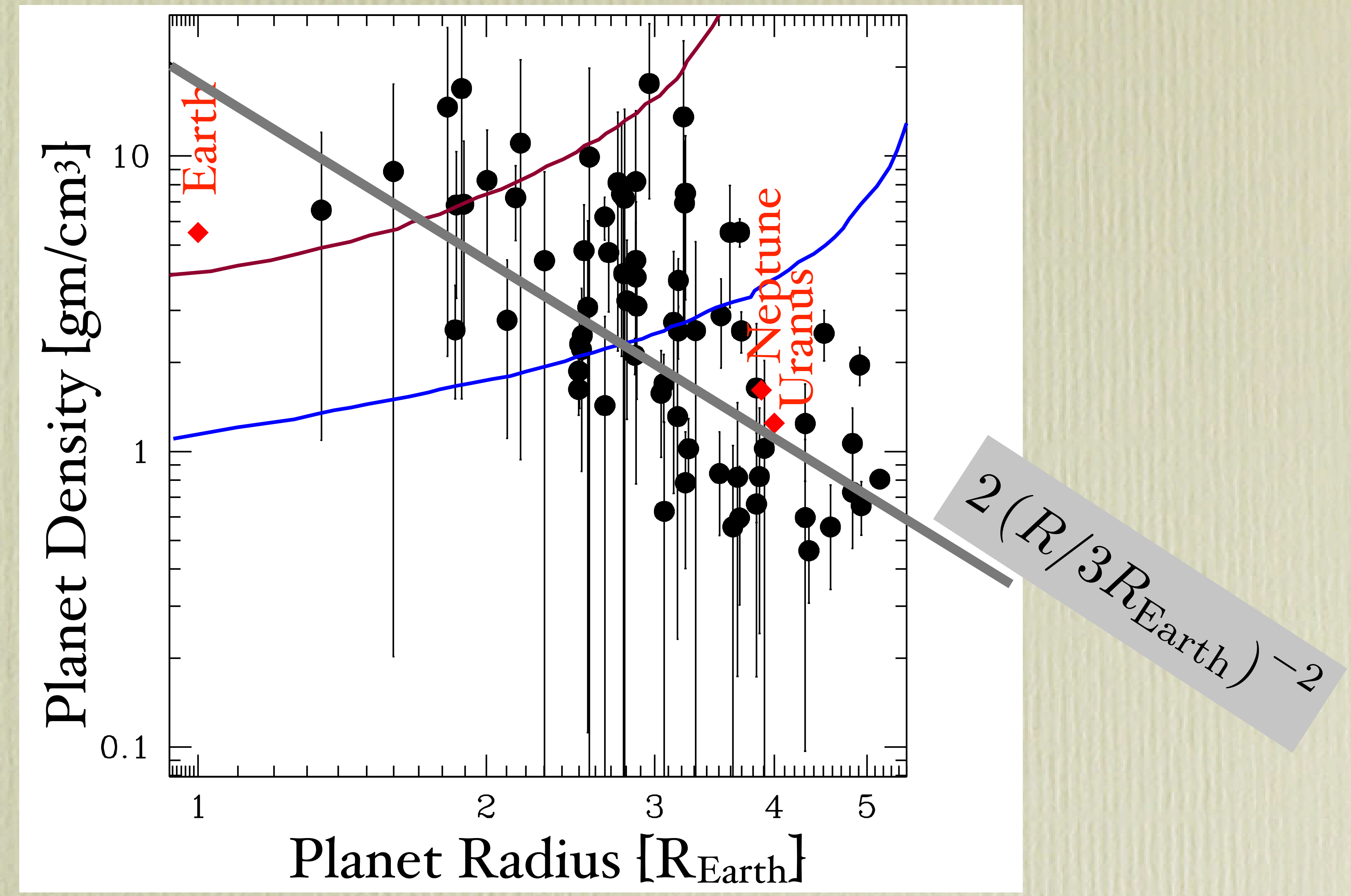


- Small ones rocky (or even denser)





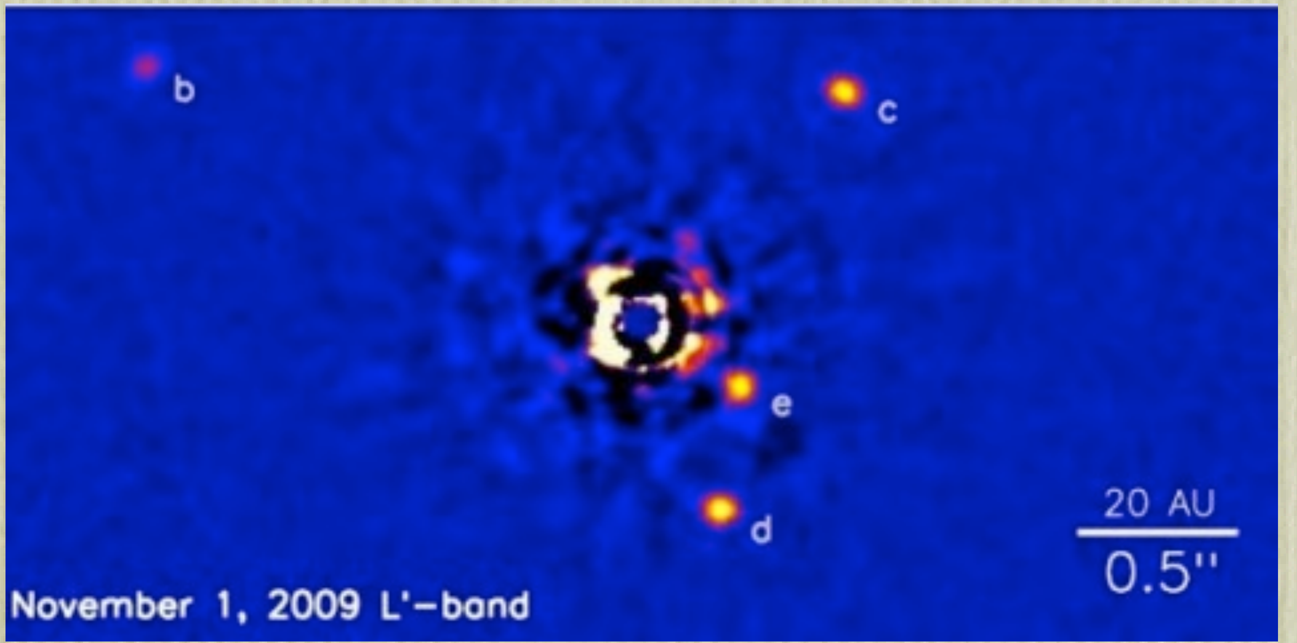
- Bigger ones covered in gas. Up to ~50% of mass in gas.
  Surprising: closer to star than Mercury &
  not much bigger than Earth.



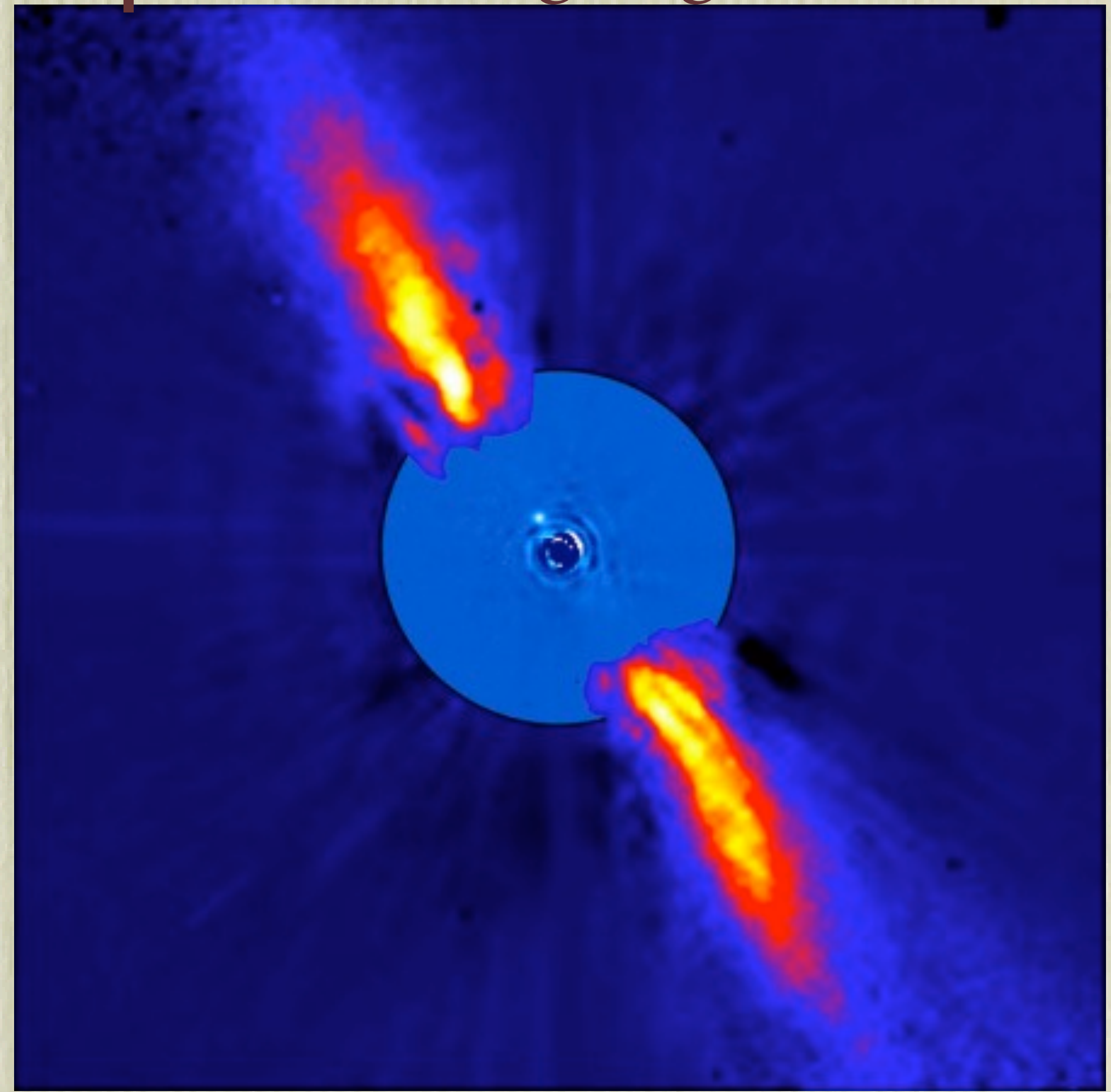
- Modest increase in size leads to big decrease in density
- Suggests homogeneous population: rock & varying amounts of gas

Detection method 3: Direct Detection

HR 8799 (Marois et al. '10)



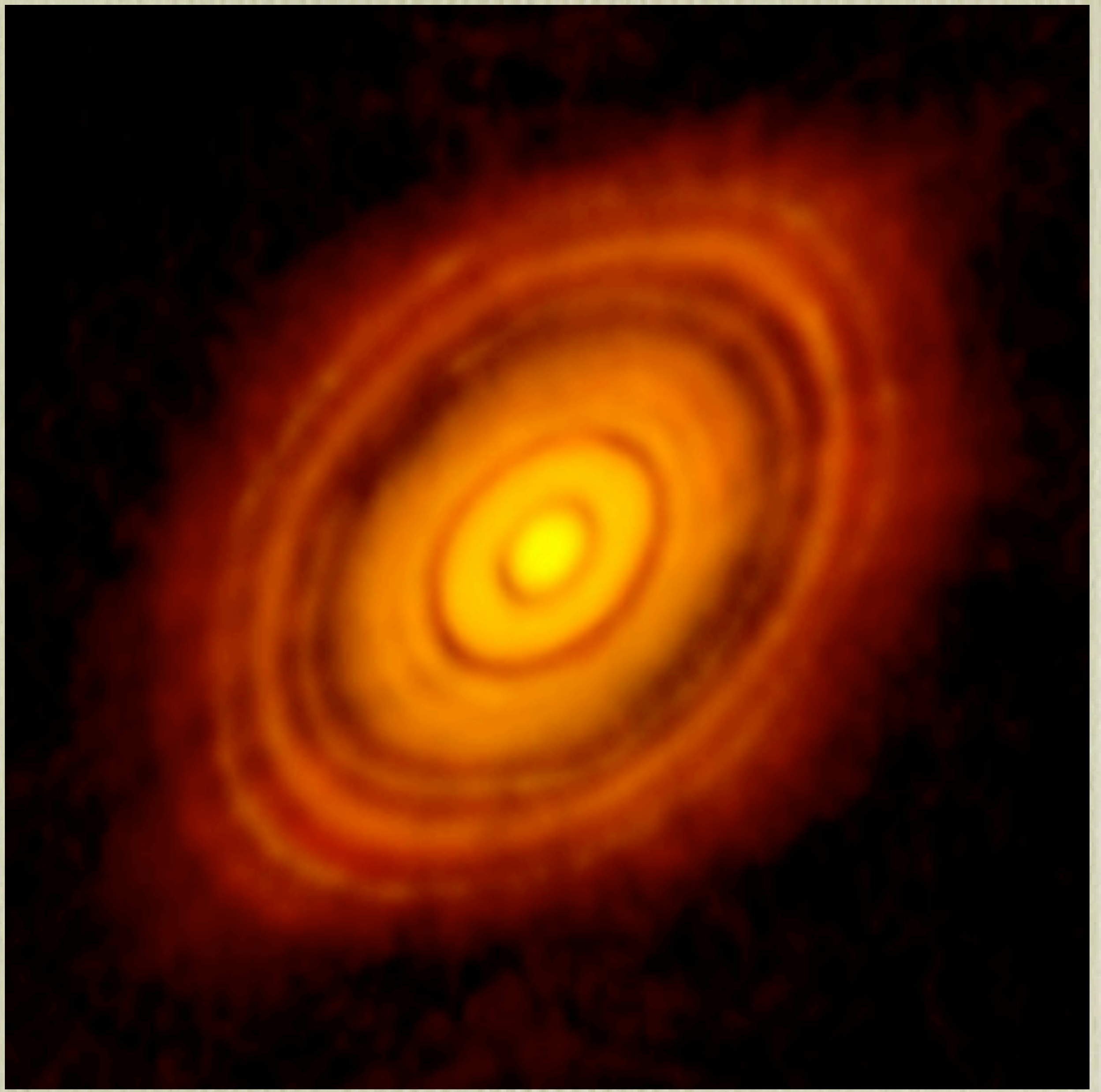
β Pic (Lagrange et al. '10)



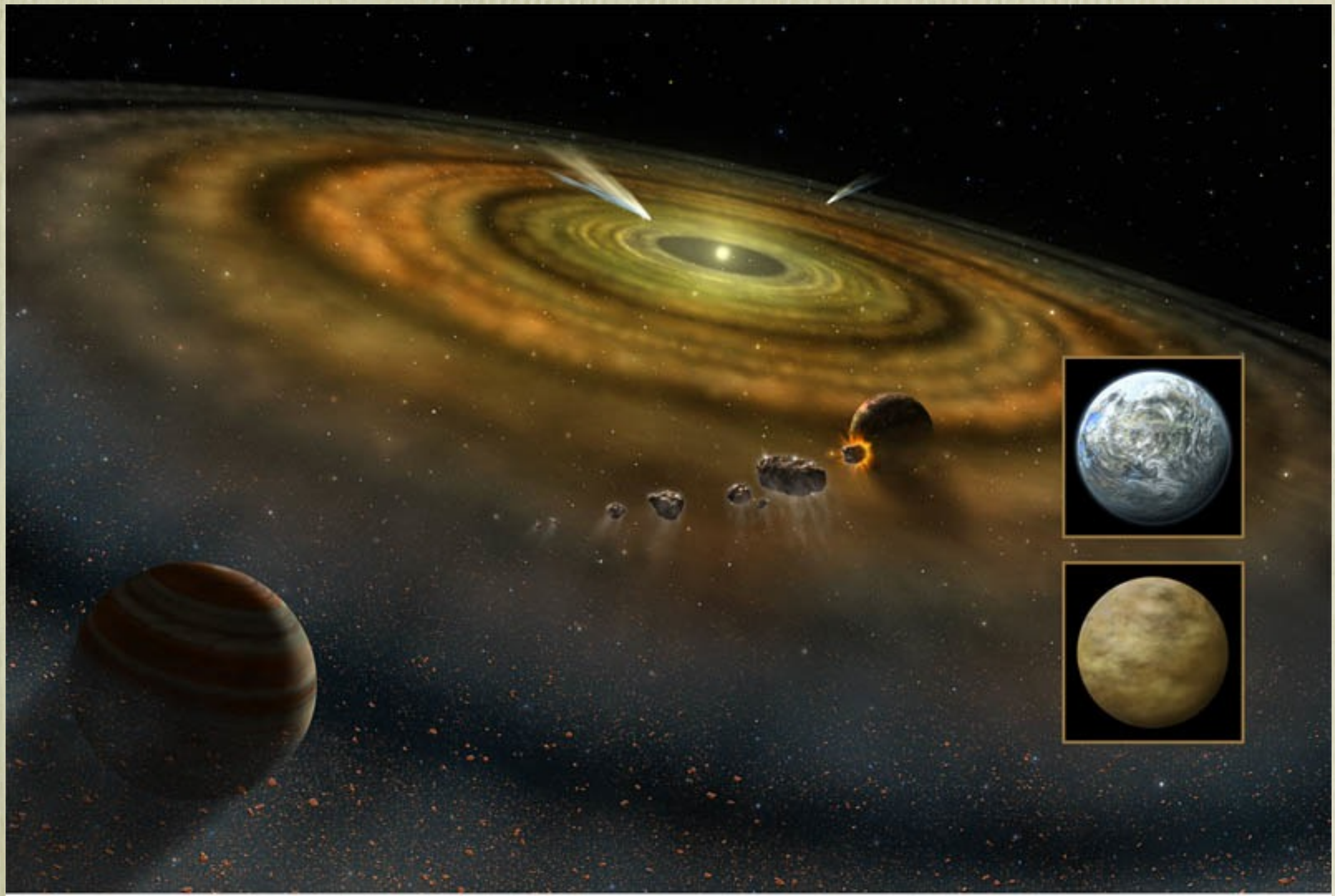
How do planets form?

First step: Collapse of gas clouds

Formation of star and disk



Formation of planets from disk



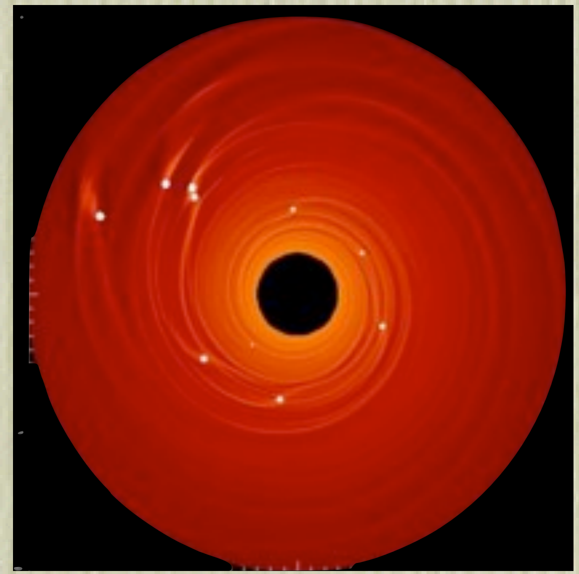
How did “Kepler planets” form?

Migration vs. in Situ

Migration

(e.g., Terquem & Papaloizou ′07, Ida & Lin ′10)

- Planets form far from star, then migrate inwards in gas disk



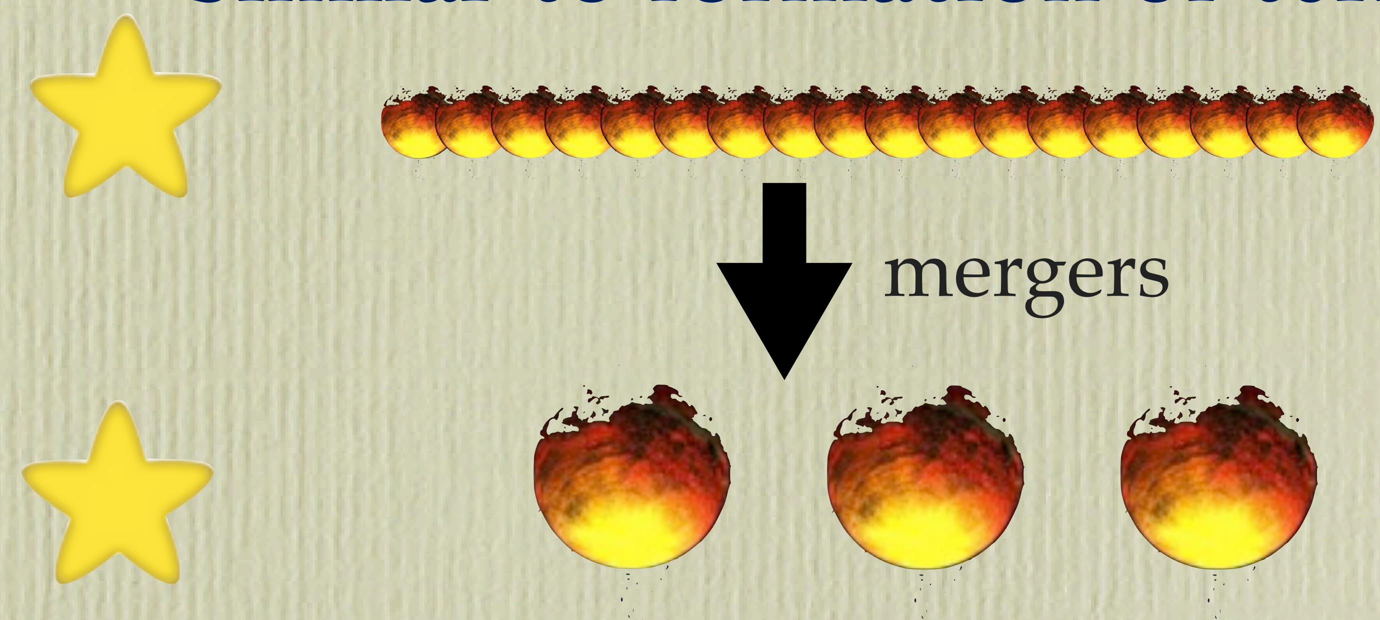
Problem: Too FAST!

In situ

(e.g., Hansen & Murray '12, Chiang & Laughlin `13)

Similar to formation of terrestrial planets

(but closer-in, more material)

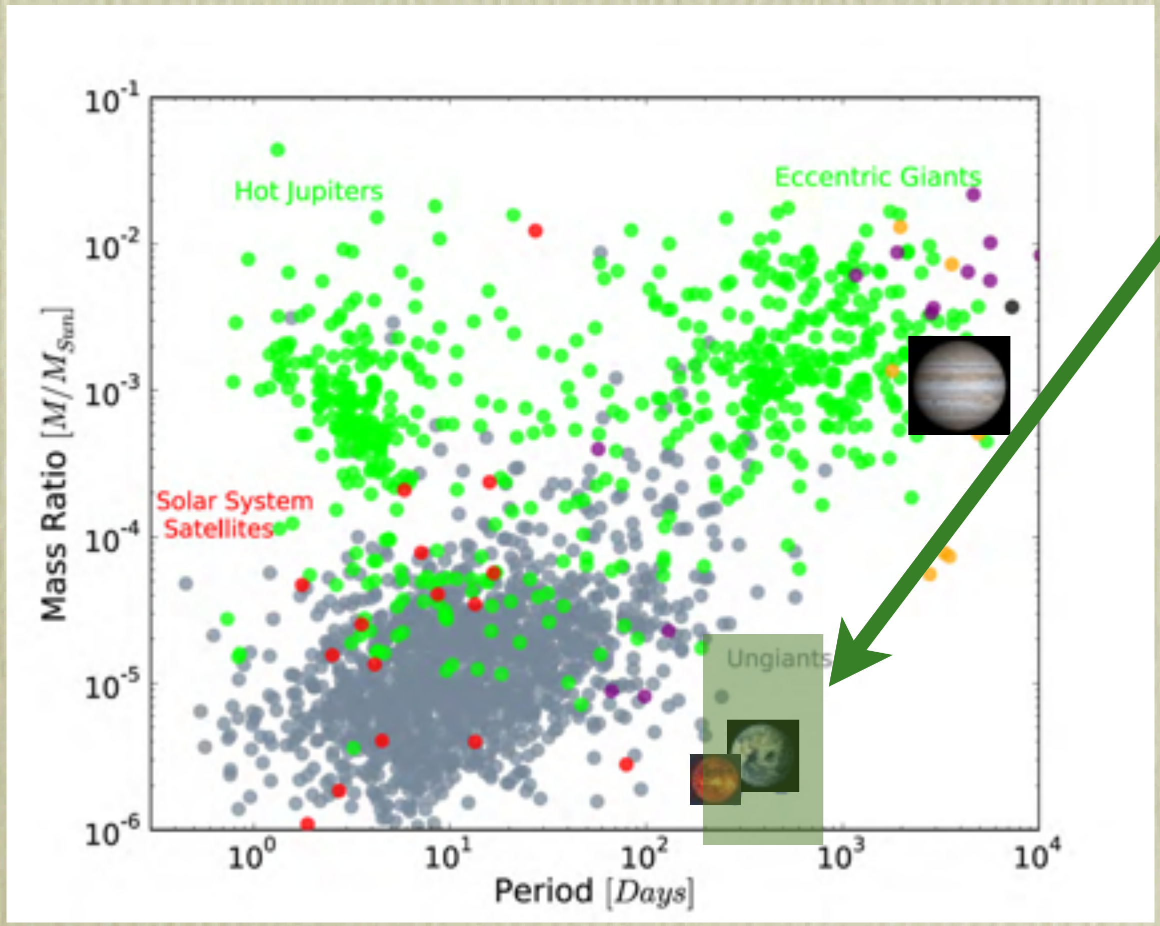


Problem:

- Gassy atmosphere ⇒ gas disk

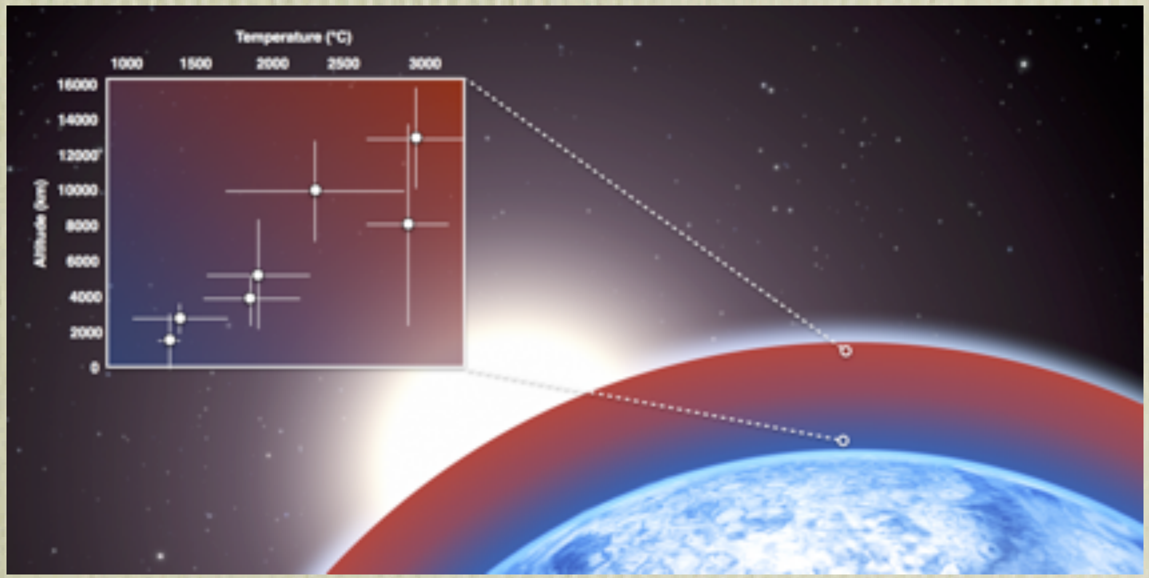
Future:

- Finding more planets, with RV, transit, & direct detection. And other methods too (microlensing, astrometry, etc)
- Finding rocky planets in the "habitable zone"



Future:

- Finding more planets, with RV, transit, & direct detection. And other methods too (microlensing, astrometry, etc)
- Finding rocky planets in the "habitable zone"
- Characterizing their atmospheres



- Biosignatures (oxygen?)...