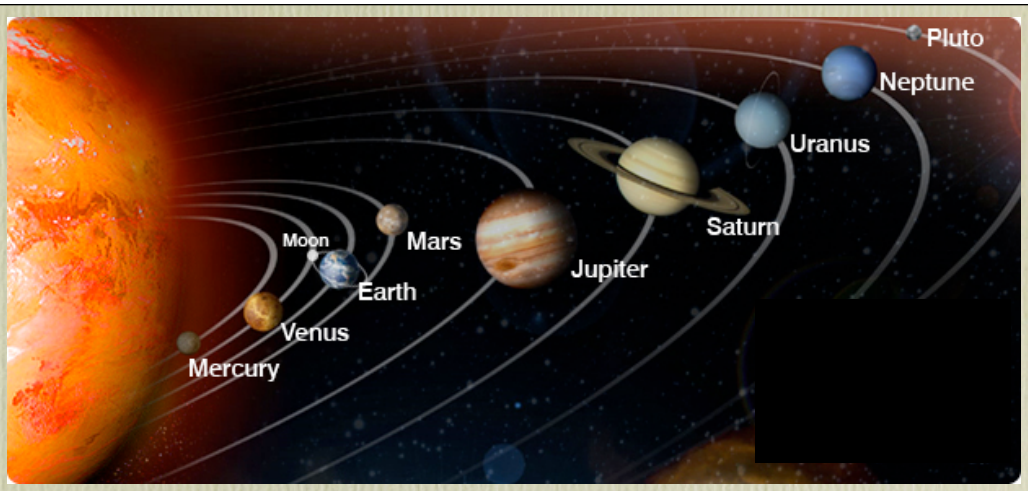
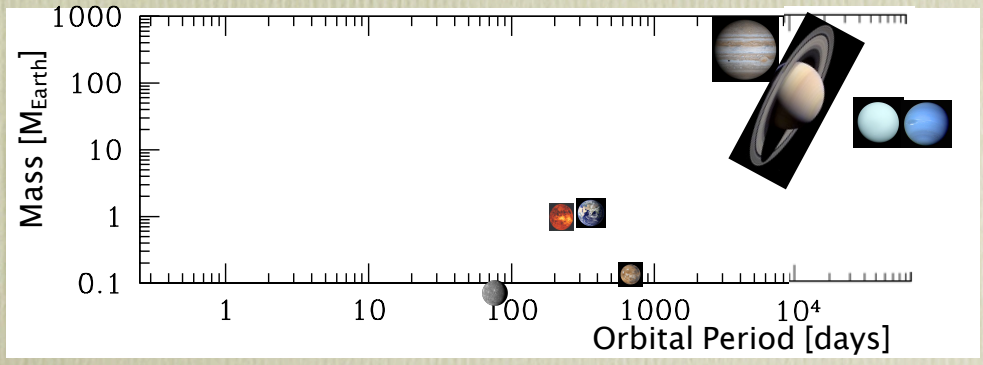
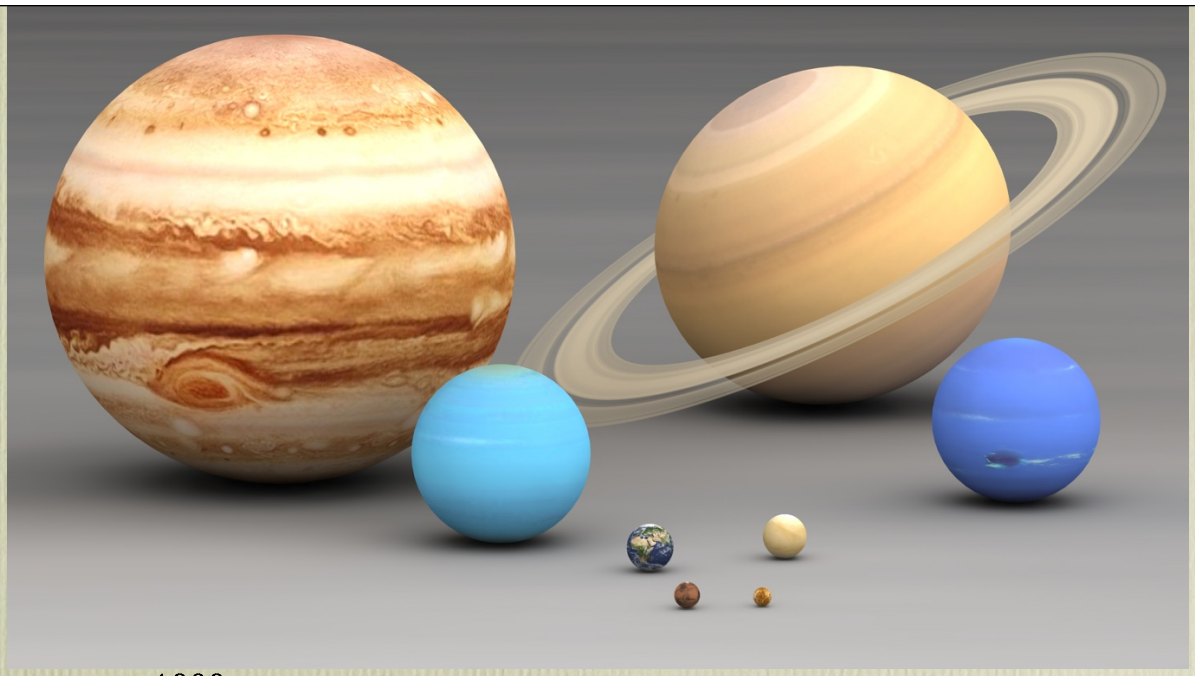
Exoplanets!

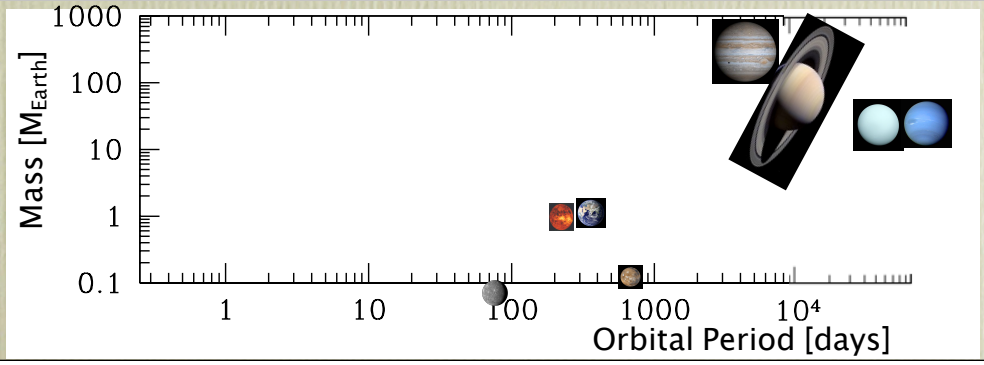
Yoram Lithwick

Known planets before 1990:

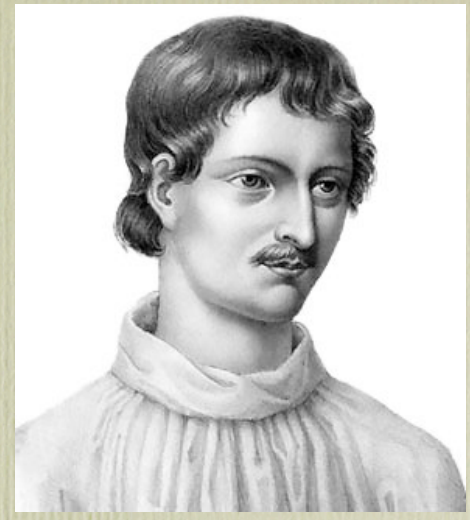







1000
100
10
1
0.1
Mass [M_Earth]
1
10
100
1000
10⁴
Orbital Period [days]

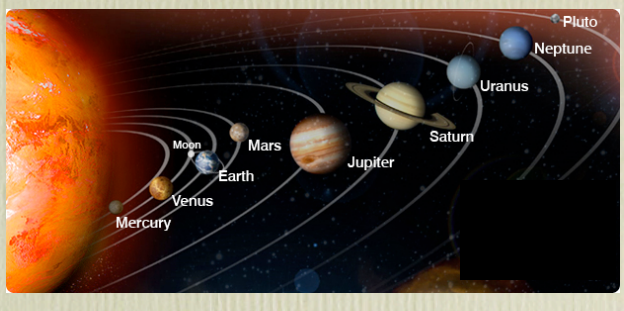

Do other stars host planets?



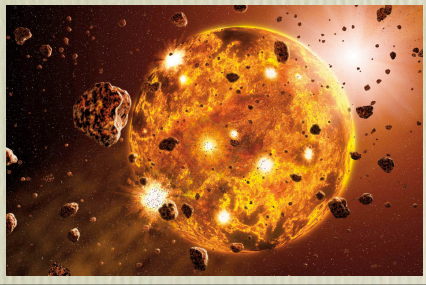
Giordano Bruno
(burned at the stake in 1600)

- Does life exist elsewhere?

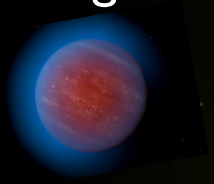
- Is the Solar System special?



- How do planets form?



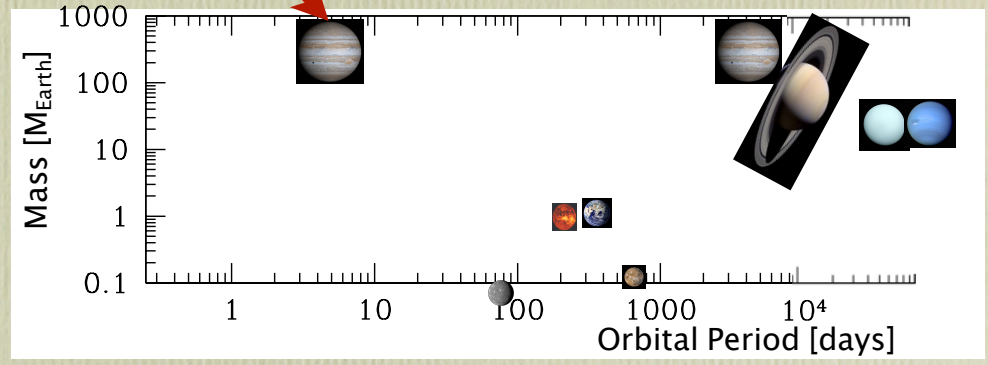
First discovery of extrasolar planet (in 1995): 51 Pegasi b



Jupiter-mass
Orbital period: 4 days!

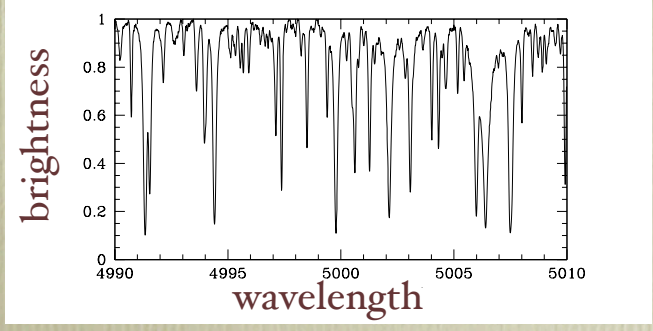
"Hot Jupiter"
1000° C

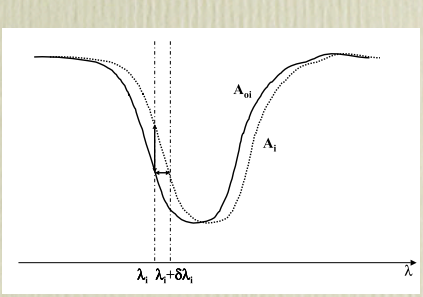
51 Peg b

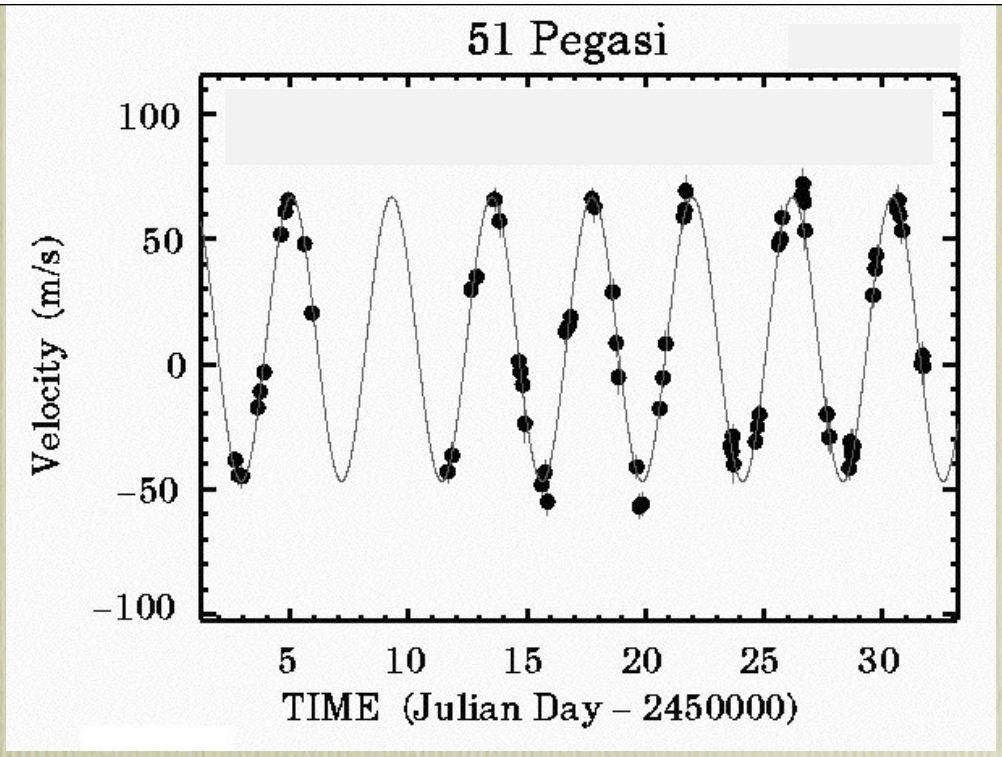

1000
100
10
1
0.1
Mass [M_Earth]
1
10
100
1000
10⁴
Orbital Period [days]

Detection method 1: Radial Velocity ("RV")

stellar spectrum





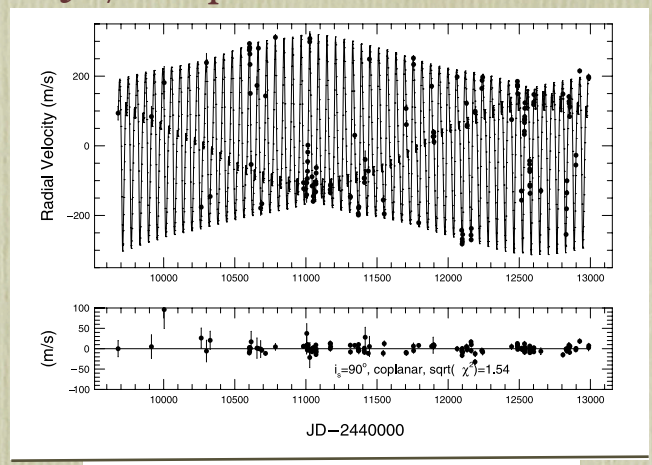


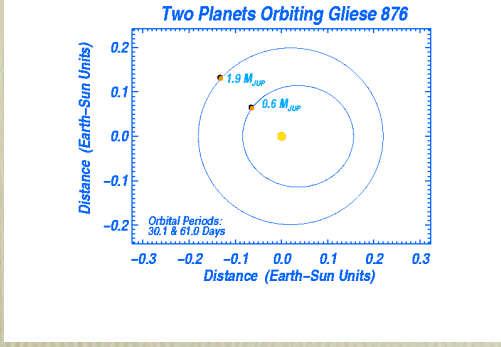
Orbital period: 4.2 days

Mass: 0.4 × Jupiter's mass

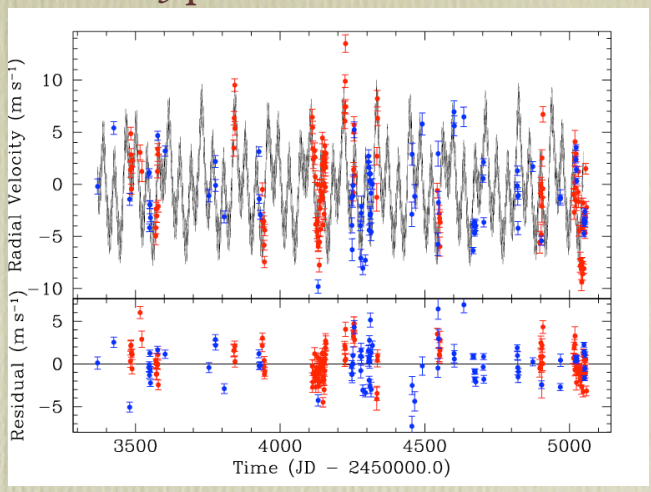
there will be lesson about RV

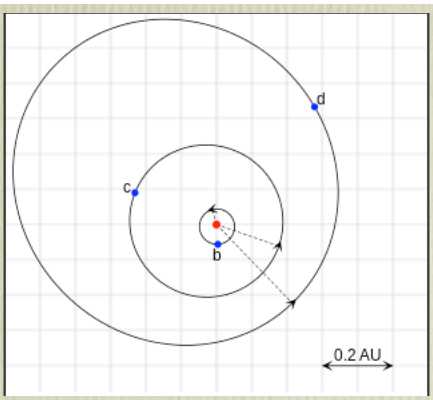
GJ876 (2 planets)

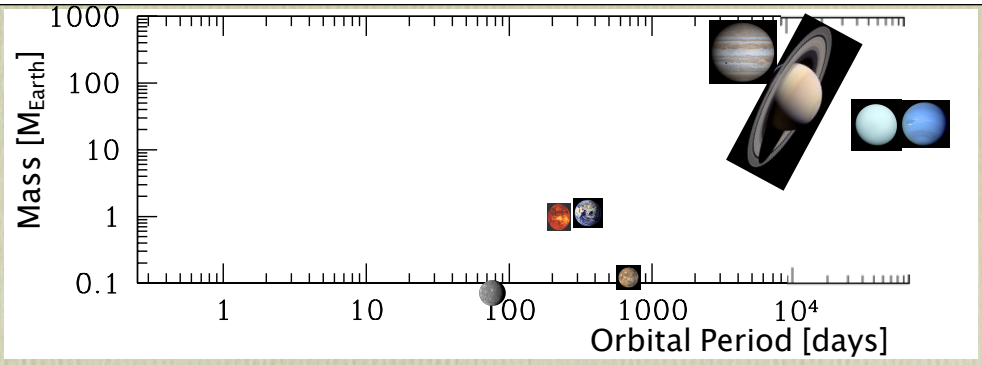




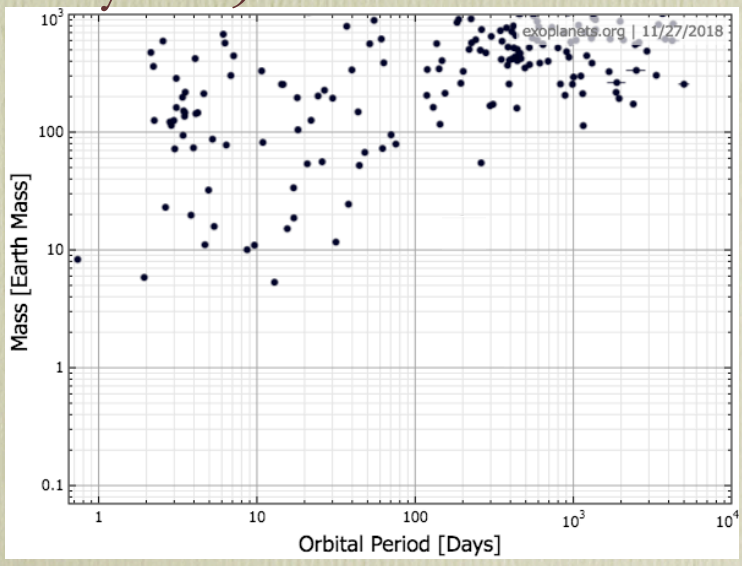
61Vir (3 planets)





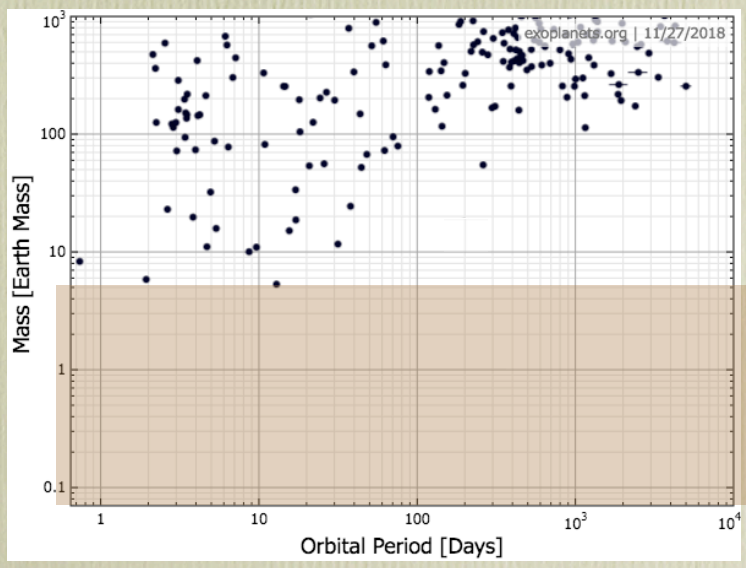


Planet discoveries by 2009:



- For life, probably need:

  - rocky planet

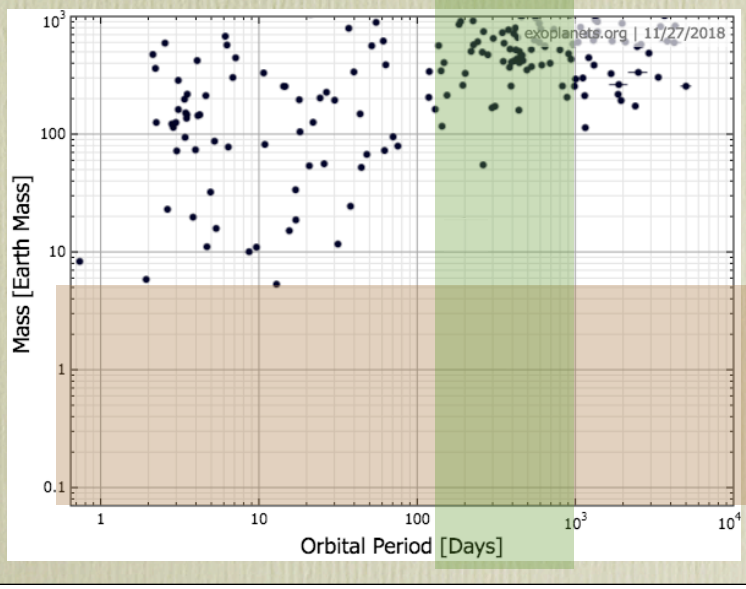


rocky

- For life, probably need:

  - rocky planet
  - liquid water

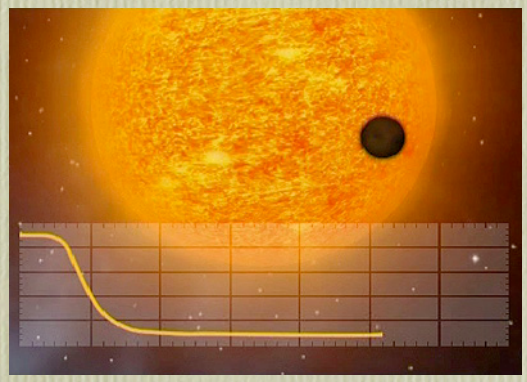
liquid water ("habitable zone")

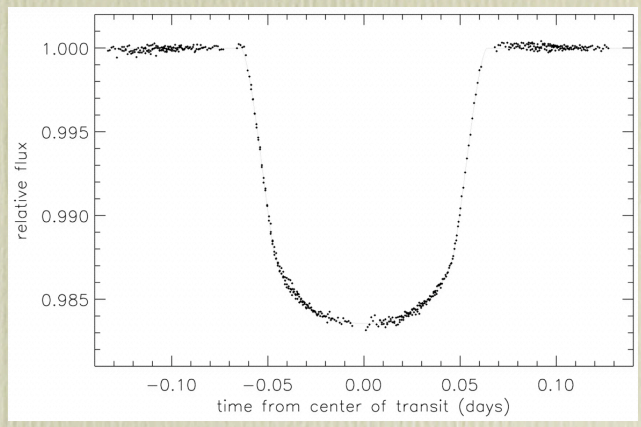


rocky

- RV probably can't find such planets, but:

Detection method 2: Transit





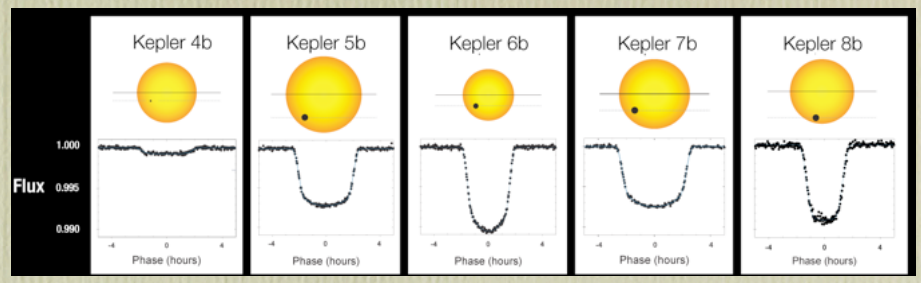
HD 209548 (Brown et al. '01)

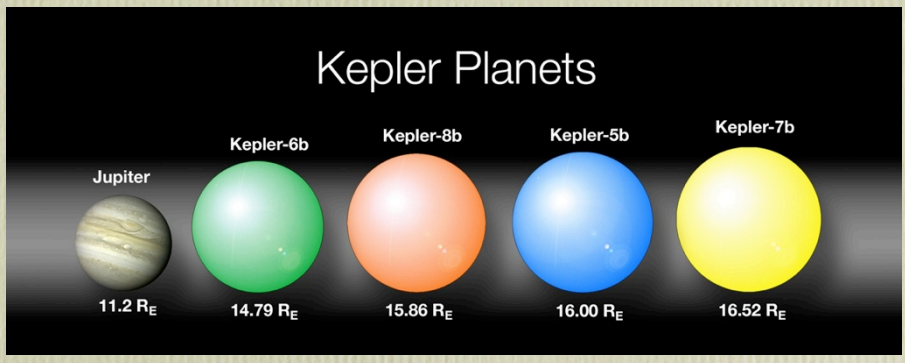
Kepler Telescope

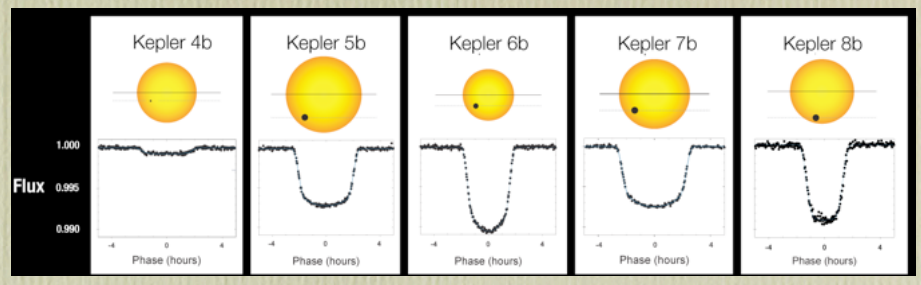
- Launched in 2009, for $500M
- Stared at 150,000 stars, waiting for transits
- Expected to find a few Earth-like planets around Sun-like stars (assuming all other stars have planetary systems like ours)

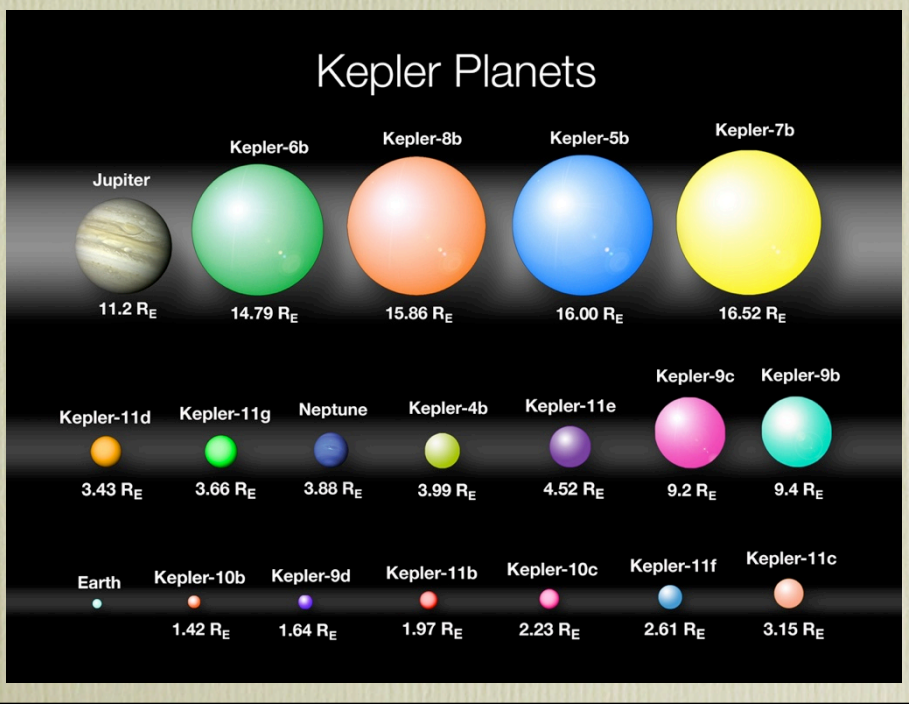
Kepler Telescope

- Launched in 2009, for $500M
- Stared at 150,000 stars, waiting for transits
- Expected to find a few Earth-like planets around Sun-like stars
  - Number actually found: 0


Kepler 4b
Kepler 5b
Kepler 6b
Kepler 7b
Kepler 8b
Flux
1.000
0.995
0.990
Phase (hours)


Kepler Planets
Jupiter
Kepler-6b
Kepler-8b
Kepler-5b
Kepler-7b
11.2 R_E
14.79 R_E
15.86 R_E
16.00 R_E
16.52 R_E


Kepler 4b
Kepler 5b
Kepler 6b
Kepler 7b
Kepler 8b
Flux
1.000
0.995
0.990
Phase (hours)


Kepler Planets
Jupiter
11.2 R_E
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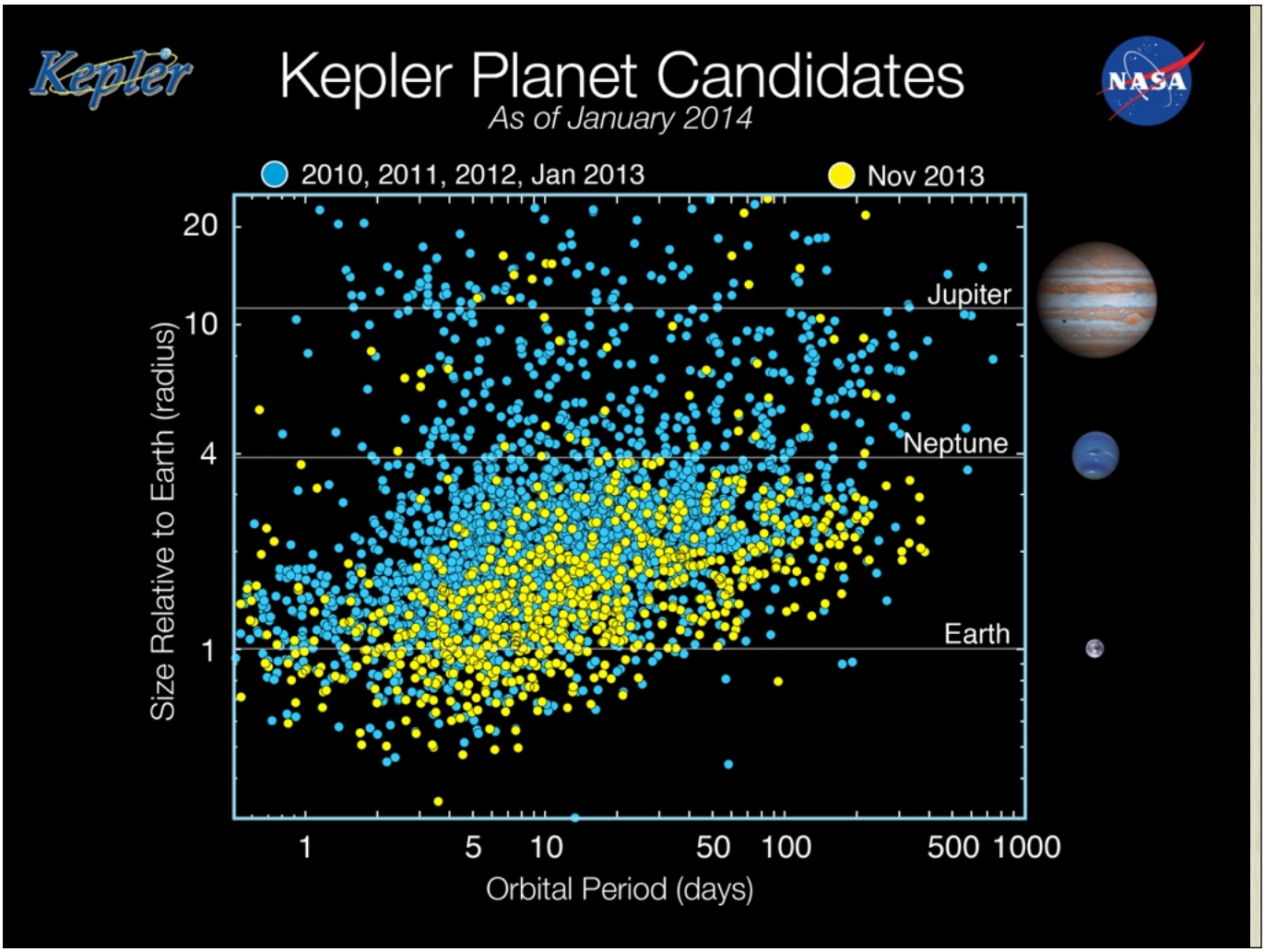
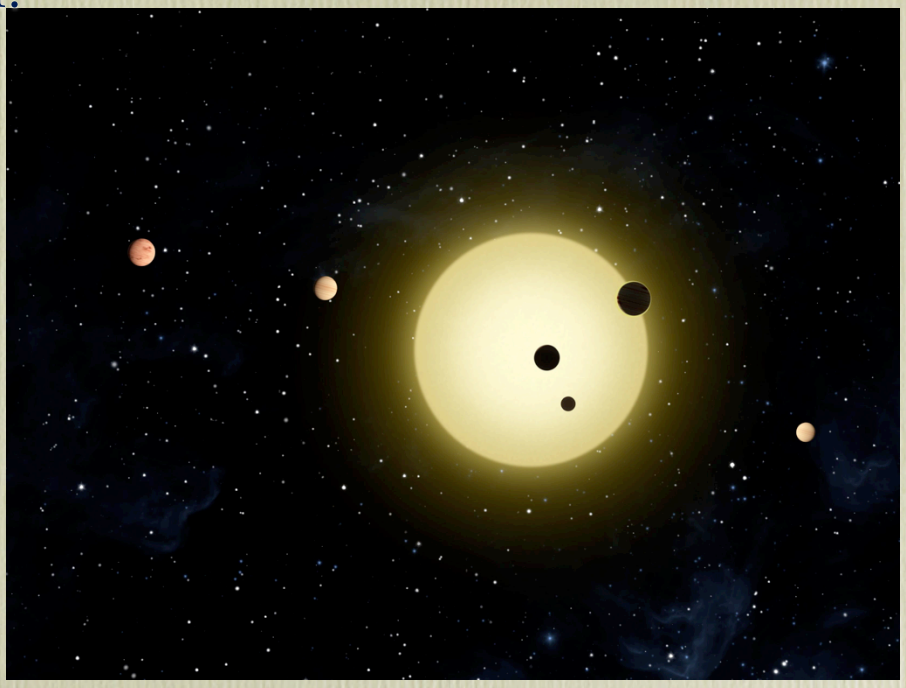
Kepler-5b
16.00 R_E
Kepler-7b
16.52 R_E
Kepler-11d
3.43 R_E
Kepler-11g
3.66 R_E
Neptune
3.88 R_E
Kepler-4b
3.99 R_E
Kepler-11e
4.52 R_E
Kepler-9c
9.2 R_E
Kepler-9b
9.4 R_E
Earth
Kepler-10b
1.42 R_E
Kepler-9d
1.64 R_E
Kepler-11b
1.97 R_E
Kepler-10c
2.23 R_E
Kepler-11f
2.61 R_E
Kepler-11c
3.15 R_E

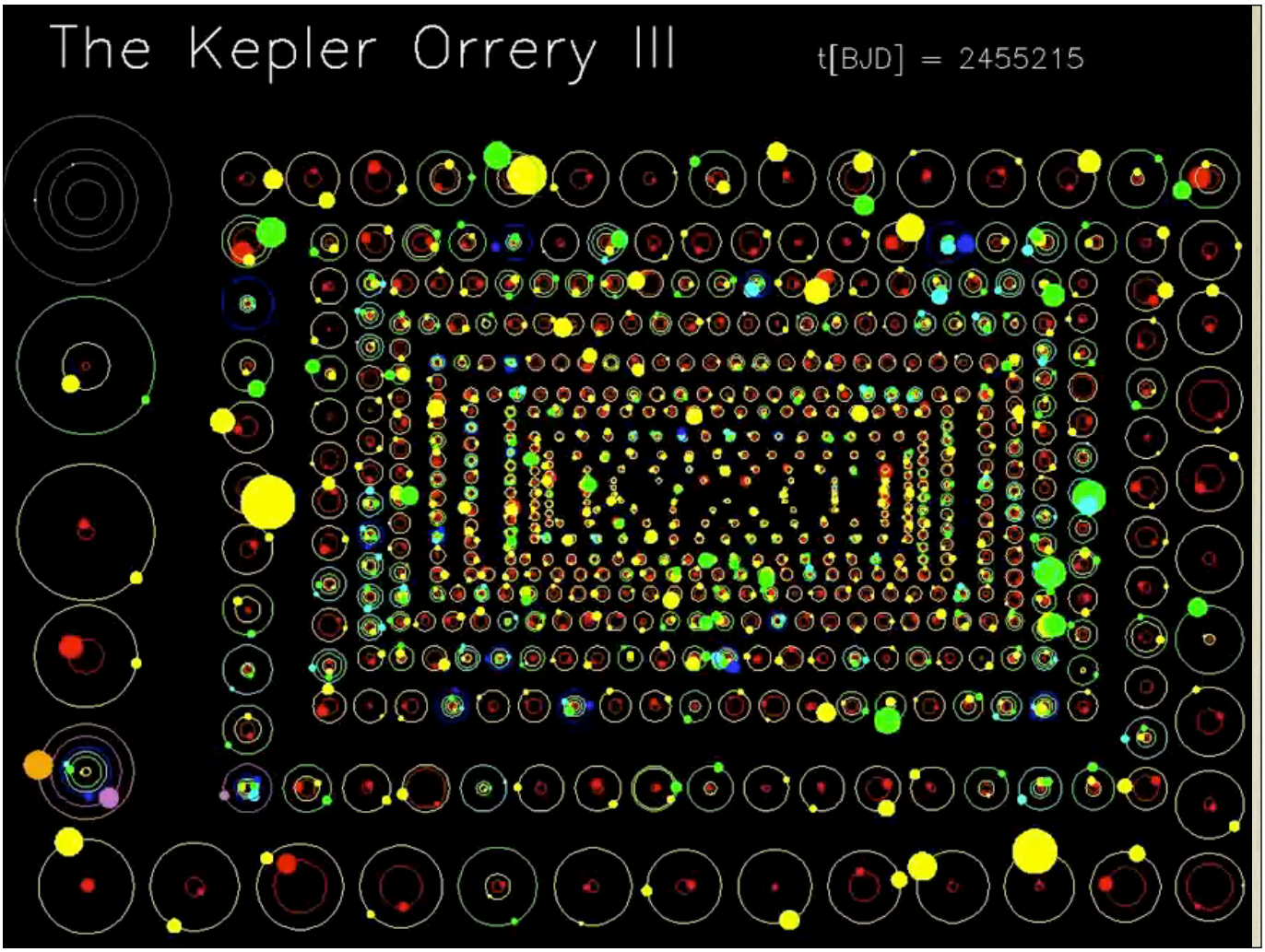

Kepler
Kepler Planet Candidates
As of January 2014
NASA
2010, 2011, 2012, Jan 2013
Nov 2013
Size Relative to Earth (radius)
20
10
4
1
Jupiter
Neptune
Earth
1
5
10
50
100
500
1000
Orbital Period (days)

Packed planetary Systems!

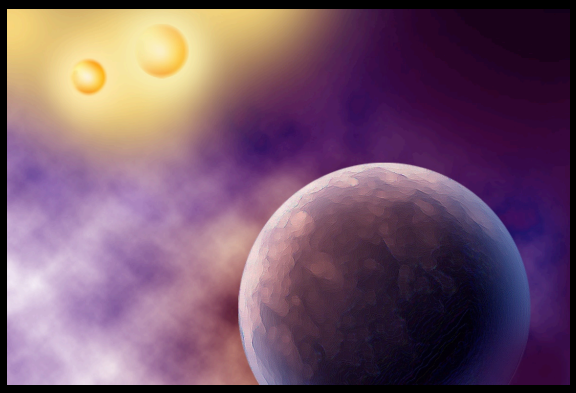
Kepler-11:



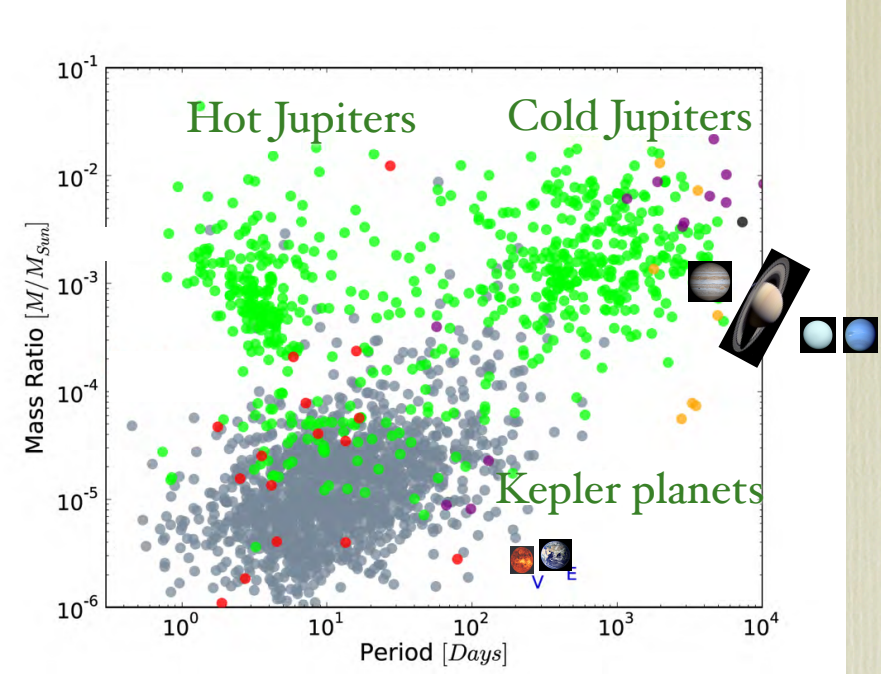
- 6 planets
- Whole system fits within Venus's orbit
- All 6 are larger than Earth and smaller than Neptune
- And, they all transit


The Kepler Orrery III
t[BJD] = 2455215

Circumbinary planets



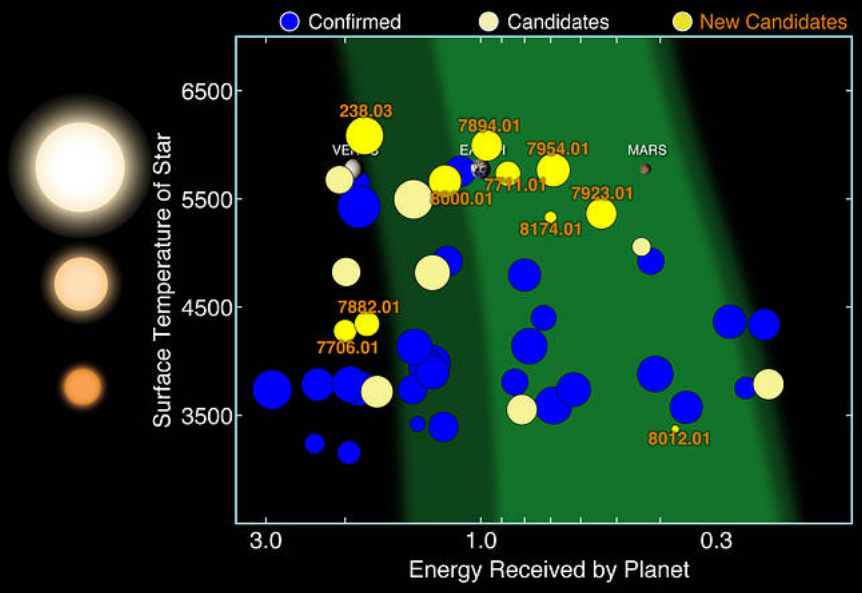
Kepler's Final Tally



- ~4,200 planets
- mass: between Earth & Neptune (mostly)
  periods: inward of Mercury (mostly)
- around 30% of stars have "Kepler planets"

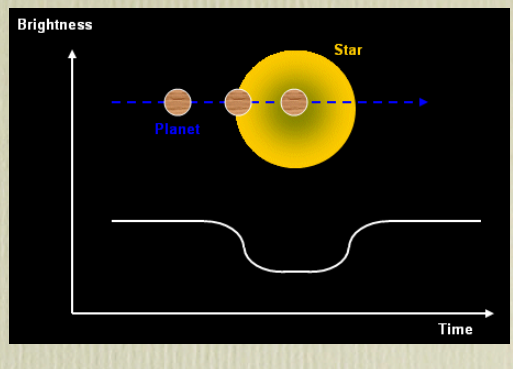
Kepler Habitable Zone Planets

As of June 2017



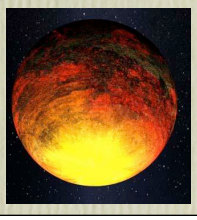
What are these planets made of?

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

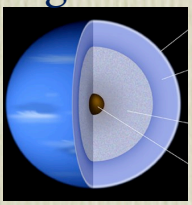


- Would also like to know: mass

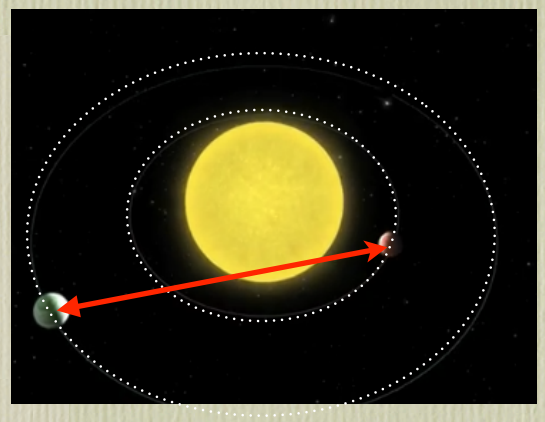
rock?

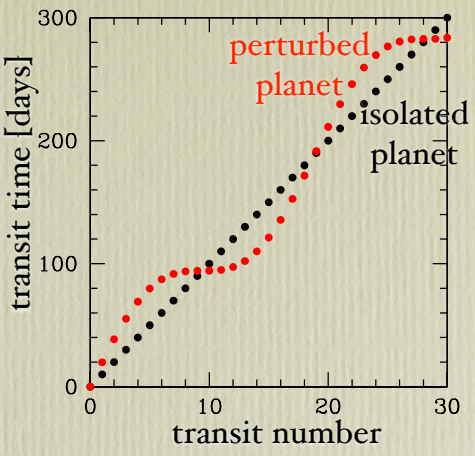


gas?

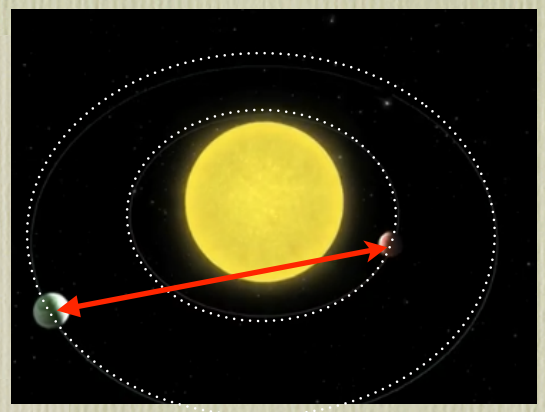


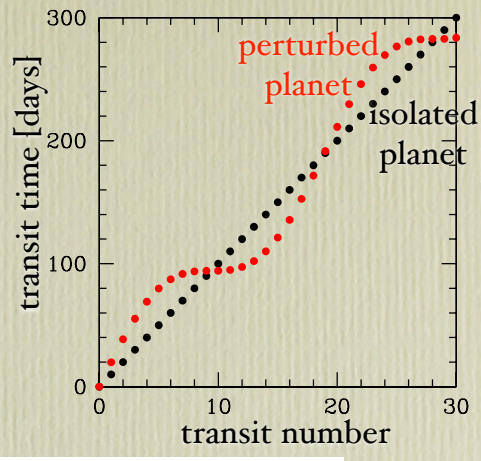
Transit Time Variations (TTV)



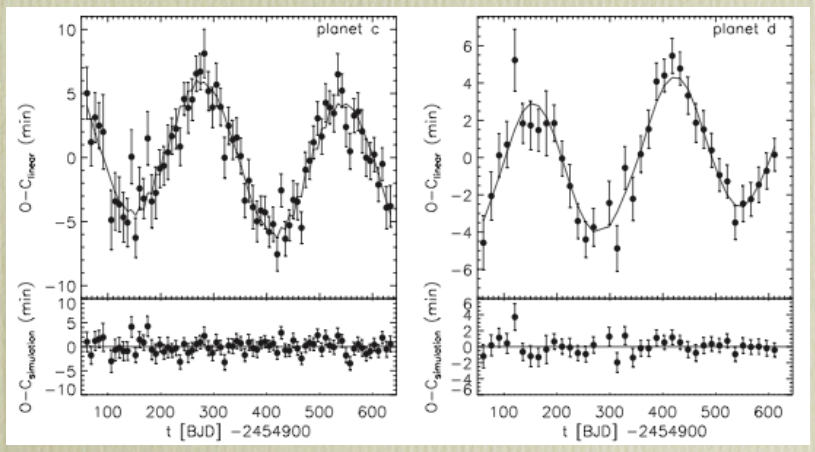


Transit Time Variations (TTV)





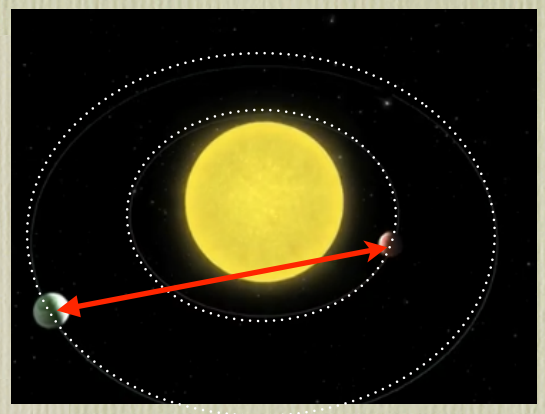
Remove slope

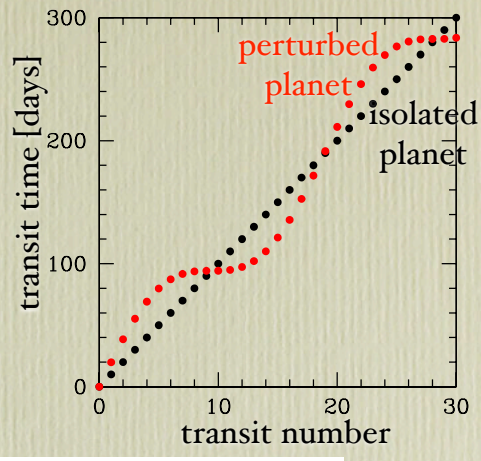


Kepler 18

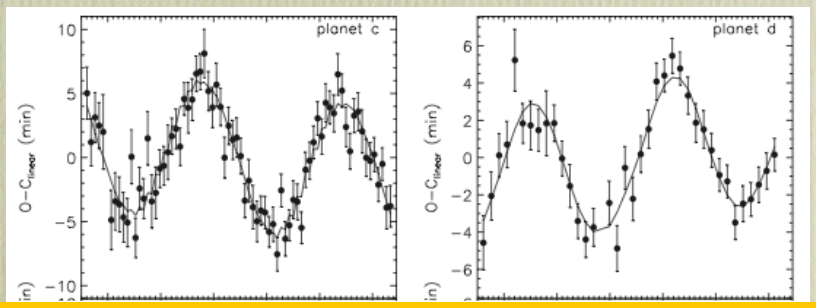
(Cochran et al. '11)

Transit Time Variations (TTV)





Remove slope



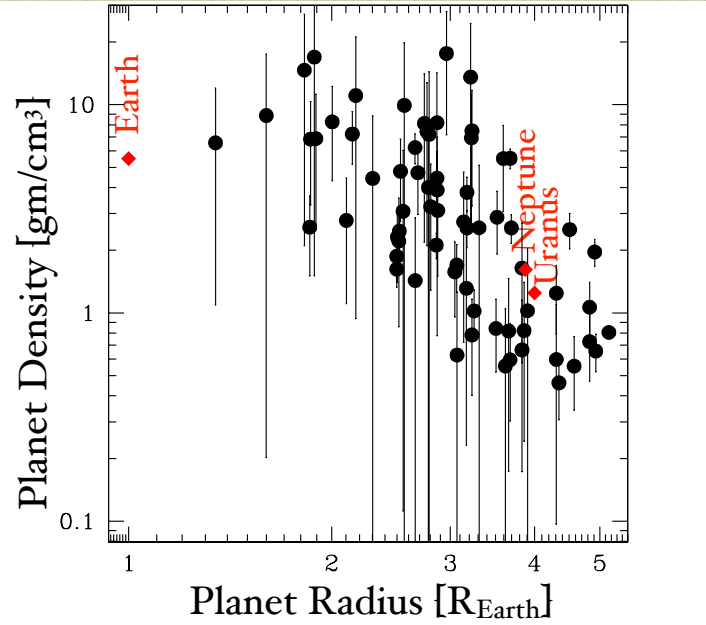
Kepler 18

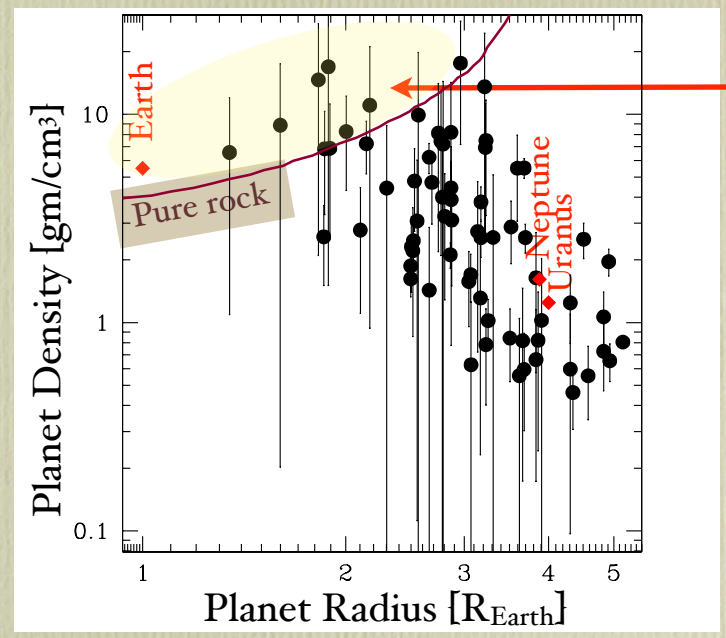
(Cochran et al. '11)

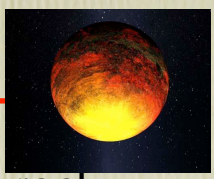
$e_c = 0\ [\pm 0.0003]$ $e_d = 0\ [\pm 0.0003]$

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

Density of 70 Exoplanets from TTV (Hadden & Lithwick)

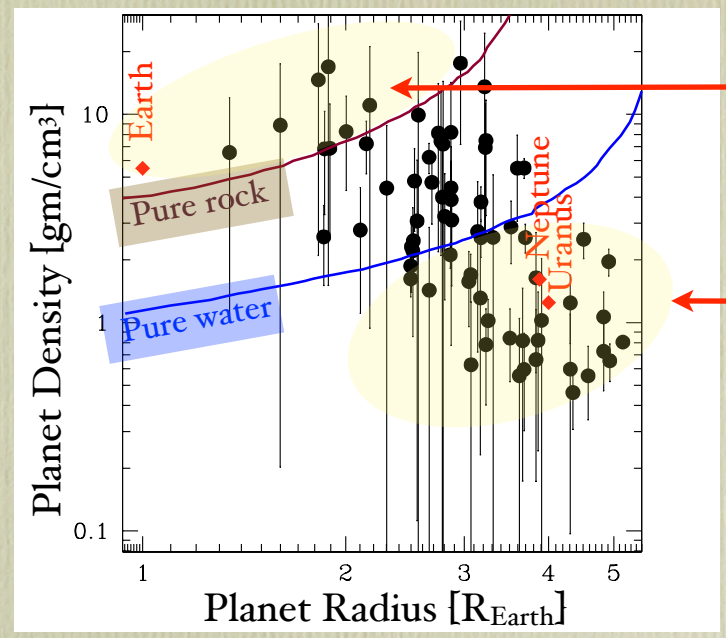


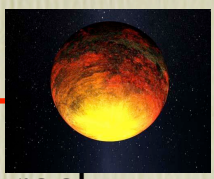




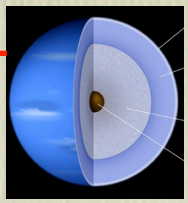
rocky

- Small ones rocky (or even denser)





rocky

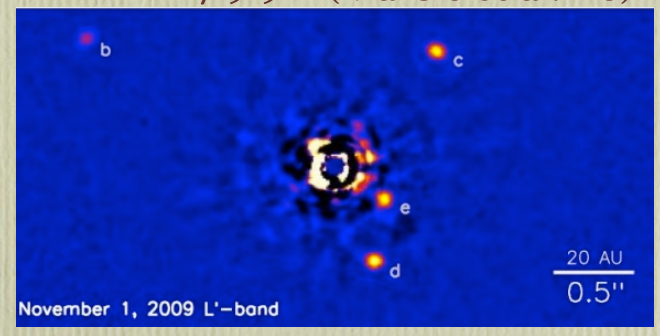


gas

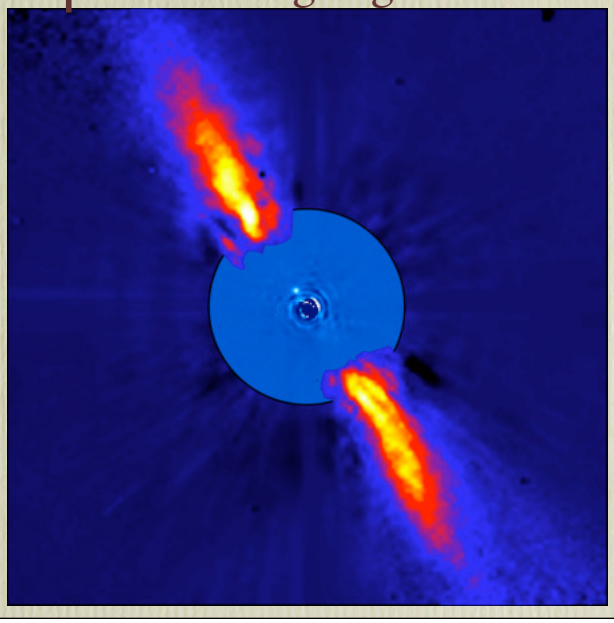
- Bigger ones covered in gas. Up to ~50% of mass in gas.
  Surprising: closer to star than Mercury &
  not much bigger than Earth.

Detection method 3: Direct Detection

HR 8799 (Marois et al. '10)

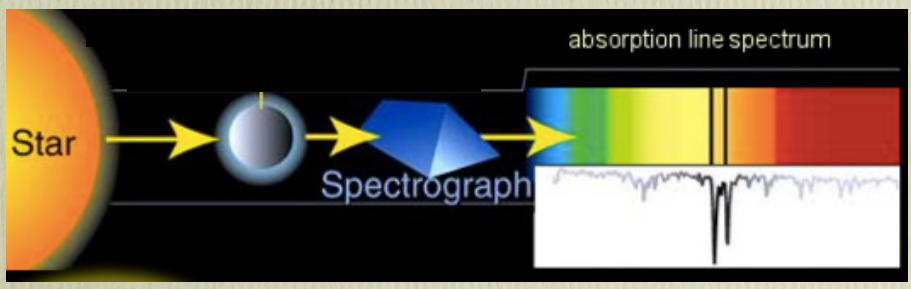


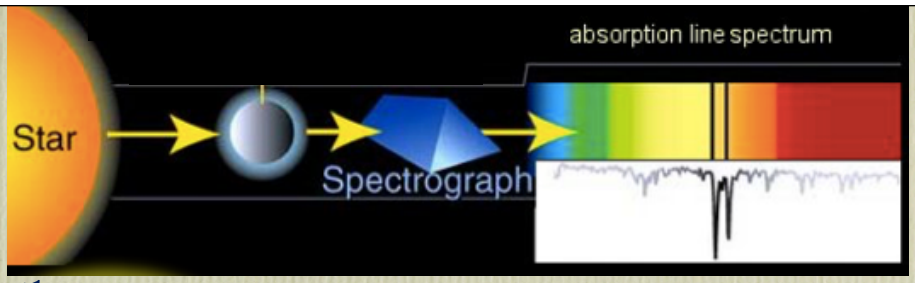
β Pic (Lagrange et al. '10)



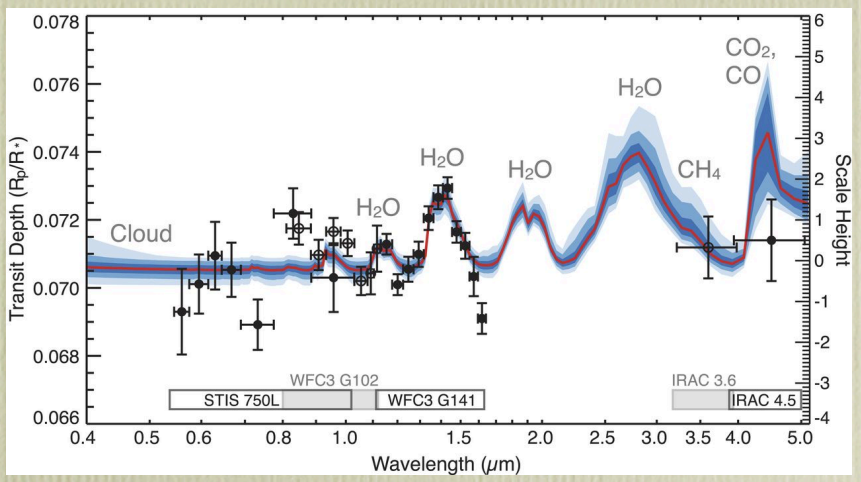
Beyond mass, radius & period

Next step: spectrum



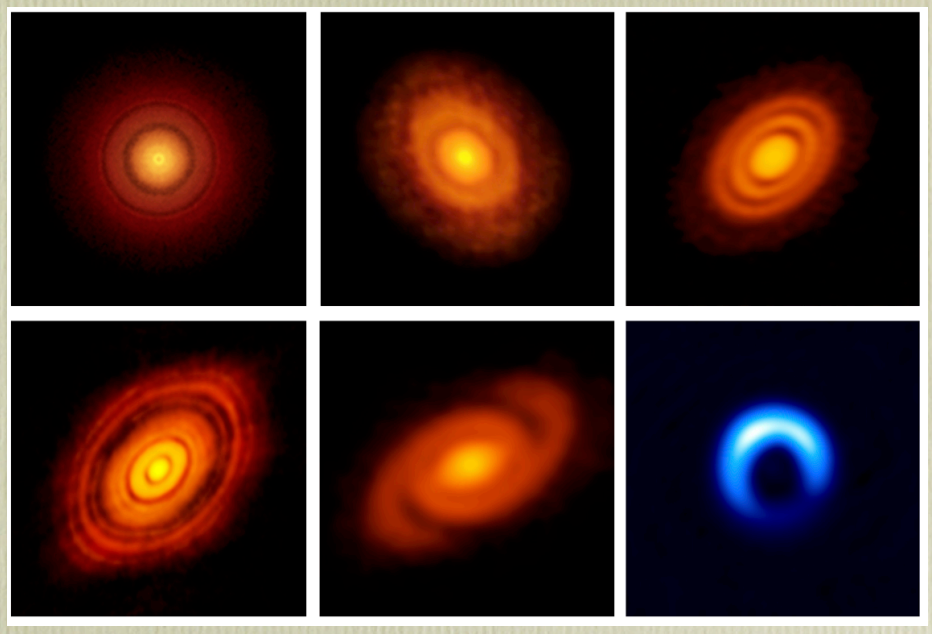


Hat-P-26b



- Hard to do for Kepler's planets (too far away)
- New telescope (TESS) just launched to find nearby candidates
- Biosignatures (oxygen?)...

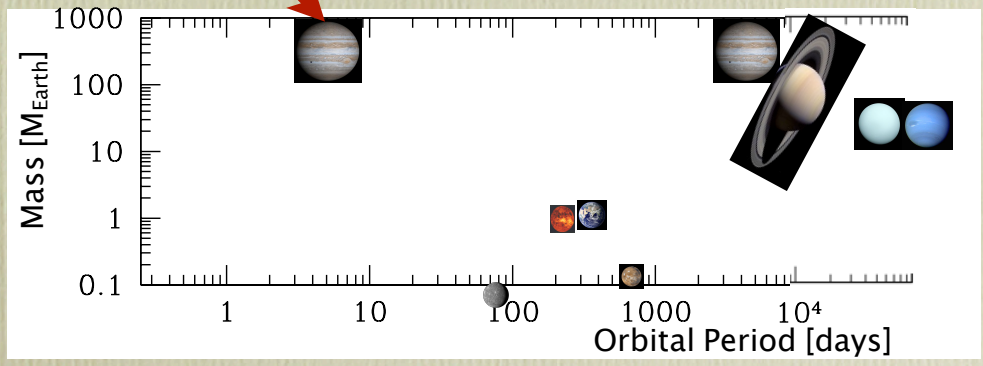
Planet-forming Disks!



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?

51 Peg b

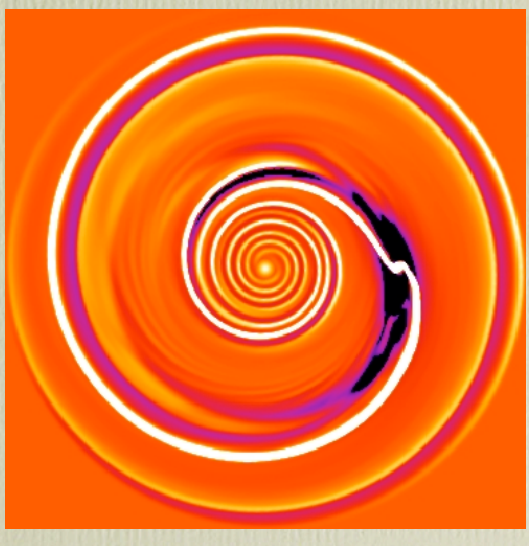


Hot Jupiters

2 types of migration scenarios:

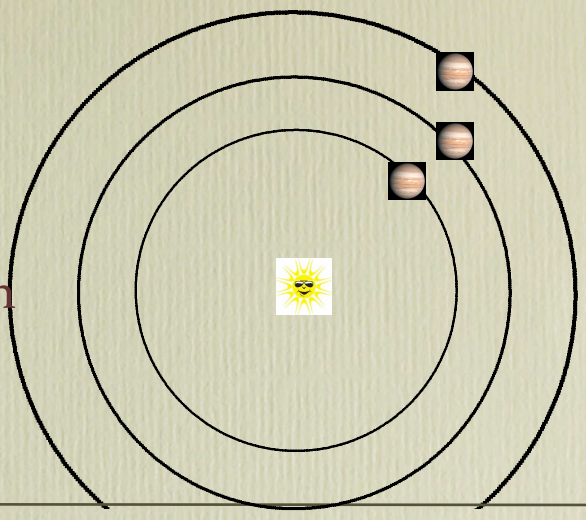
1. Disk Migration

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

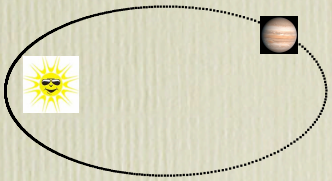


2. Interplanetary chaos:

- Planet forms far from star, with companions



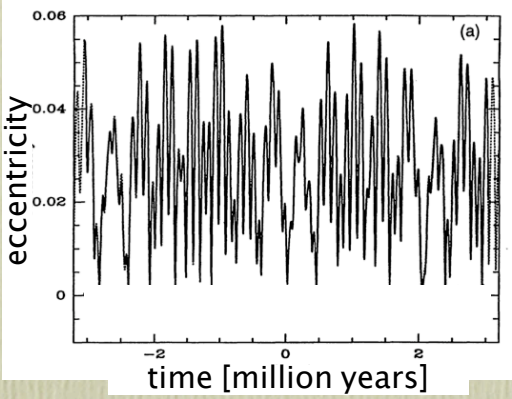
- Innermost planet's eccentricity is excited by other planets



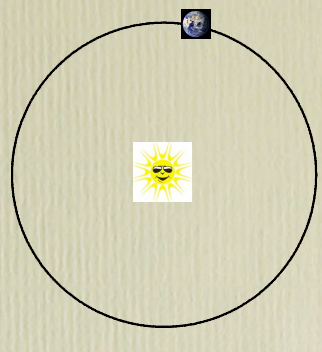
- When planet comes close enough to star, strong tides are raised on planet, circularizing its orbit

Solar system also exhibits chaos

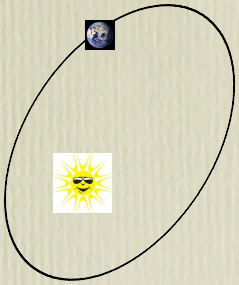
Earth's eccentricity



eccentricity=0 (circle)

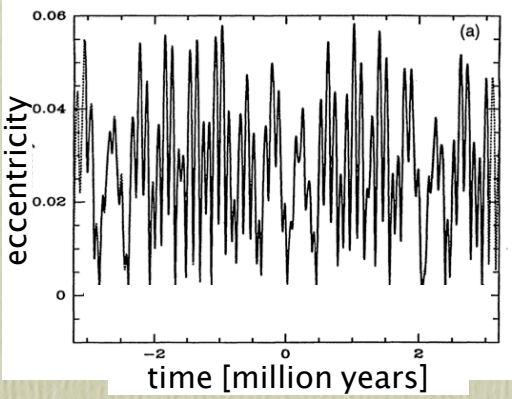


eccentricity=0.5 (ellipse)

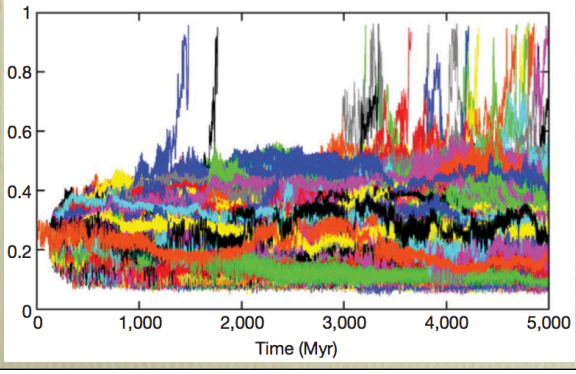


Solar system also exhibits chaos

Earth's eccentricity



Mercury's eccentricity



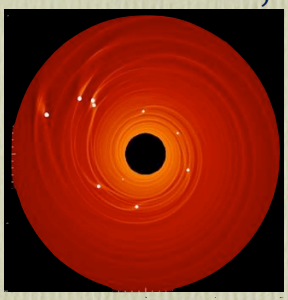
- Solar system unstable! Lucky we haven't lost Mercury yet

How did “Kepler planets” form?

Two possibilities:

Migration

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



In situ