EXOPLANETS

In general...

- Short chronicle
- The discovery
- Physical and dynamical properties

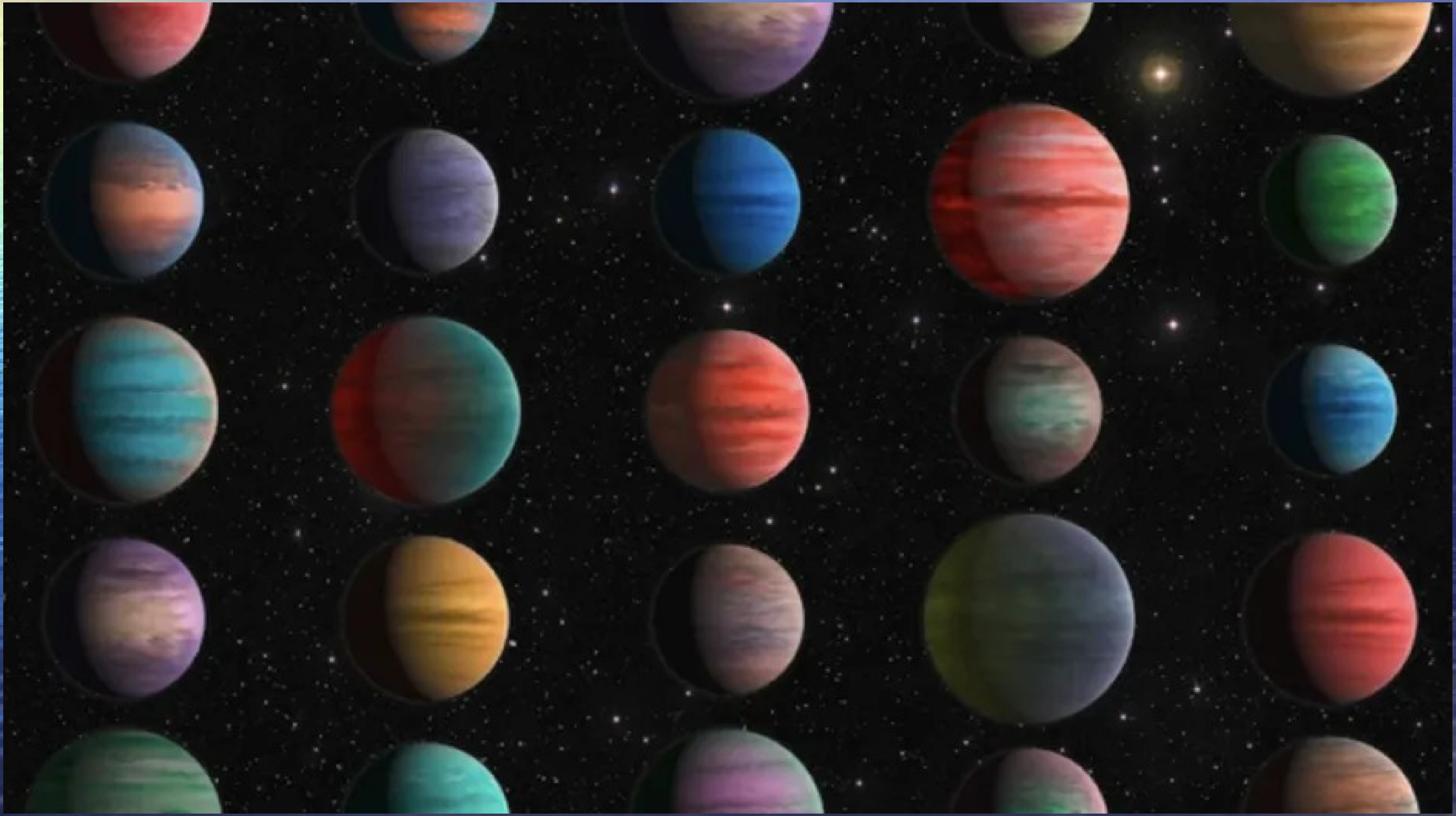
Planet formation

- The standard model (revised)
- From disks to planets

The new planetary systems

- Planetary migration
- Resonances
- Planets in binaries

New worlds: extrasolar planets.



History of the ‘extrasolar planet’ concept

300 bc: Democrito, Epicuro and the atomist cosmology: atomists derive the infinity of space from the infinite number of atoms: a limited number of worlds cannot contain an inifinite number of atoms. For world they mean the set of stars, Earth and all visible things. All the matter in the Universe cannot have given origin to a single system.

Middle ages: 1270 Tommaso D’Aquino and the denial: the power of God can produce more worlds, but they would be useless because similar to ours.

1400-1500: Copernican theories and Galileo observations force to abandon the geocentric theories of Aristotele and embrace the existance of outer planets in the solar system.

Development of 'astrotheology'

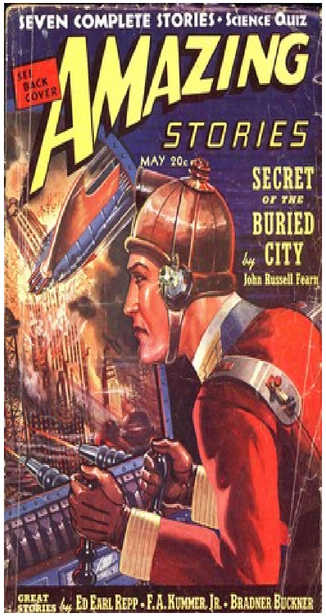
1440 : cardinal and theologist Cusano in his most relevant book "De docta ignorantia" admitted the possibility that God made other worlds populated by rational beings created in His own image and heirs of Christ promises.

Guillame de Vaurouillon (Paris, 1400), Franciscan: are the existance of multiple populated worlds and the redemption brought by Chirst compatible? Yes because only humans made the original sin, not the estraterrestrial who then do not need Christ.

1600 Giordano Bruno: dominican philosofer and friar supported the idea of an inifinite universe populated by and inifinite number of stars each with its own planetary system where intelligent beings grow and thrive. These intelligent beings would also be better than humans...

Vincenzo da Sant'Eraclio (1760) Capuchin friar in his book "Esame teologico-fisico del sistema di chi sostiene abitati da ragionevoli creature i pianeti" deny the existance of other inhabited worlds because contrary to the religion.

Thomas Paine (1800) (philosopher USA) If the Christian salvation is possible only through the divine incarnation, then in all extrasolar worlds God should have died and resurrected.



1920: The first science fiction magazines are born like “Amazing stories” and then “Astounding” with tales of writers like Asimov, Clarke, Heinlein, Bradbudry, Pohl, Hubbard….

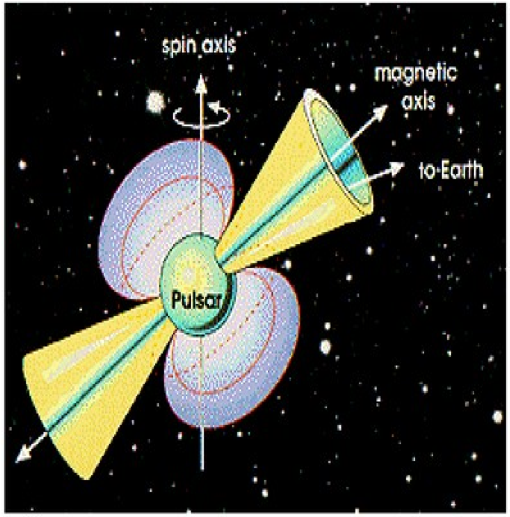
1929 Buck Rogers, 1934 Flash Gordon….

1950: the general optimism about the presence of intelligent life in the Universe collides with the Fermi paradox: If there are so many evolved civilizations, where are the extraterrestrials? Why we do note receive radio signals, space ships or have other proofs of their existance? Counterarguments: timespan of a civilization, distances and the speed of light.

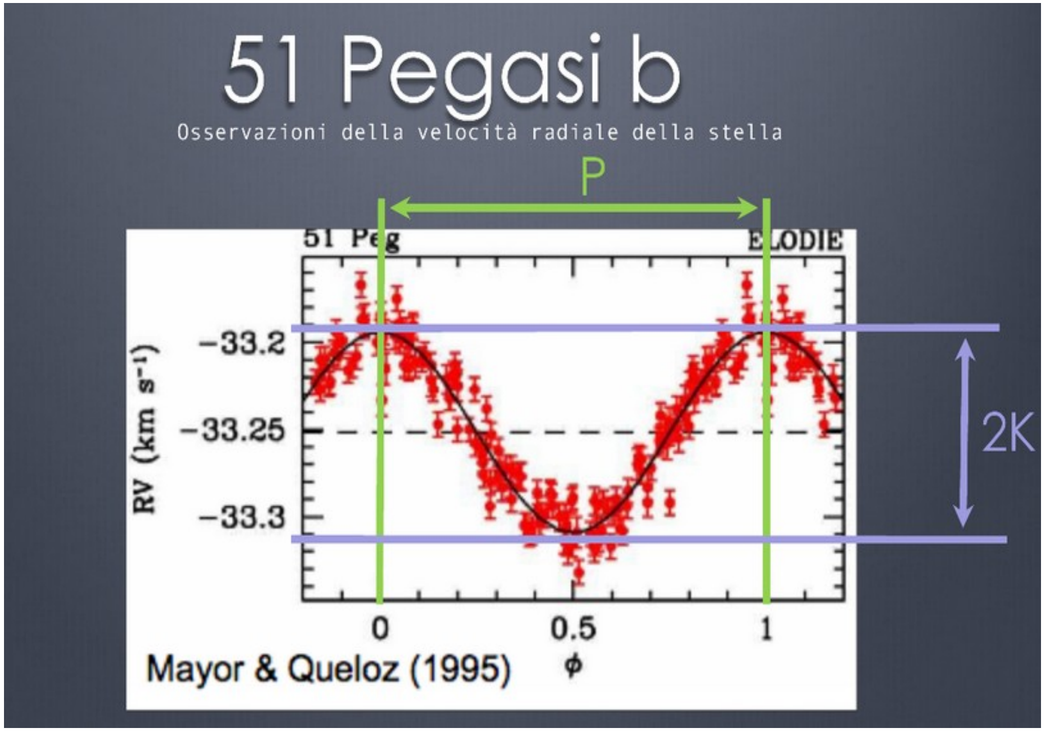
1950: Peter Van de Kamp and the Barnard star. Two Jovian planets orbiting the star. Discovery not confirmed by subsequent observations, it was a problem of oscillation of the poiting system of the telescope. 68 years later, an Earth-like planet has been really discovered around Barnard star (Ribas et al. 2018).

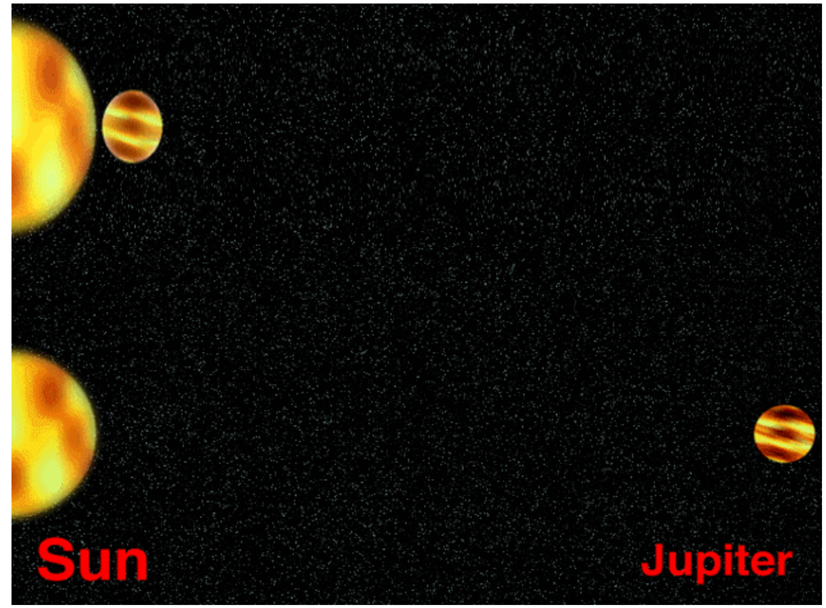
1991: lyne and the pulsar PSR 1829–10. Discovery (subsequently taken back) of the presence of a planet of 3 Earth-masses based on the hanges in the pulsar periodic signal. The modulation in the signal was of 6 months but the authors forgot to take into account in the analysis of the data of the Earth eccentric orbit.

1992: Wolszczan e Frail discovery (confirmed) of two planets around the Pulsar PSR1257 + 12. Did they survive to the supernova phase or did they form from the leftover disk? For sure they are inhabitable



1995: the year of the 'true' discovery!

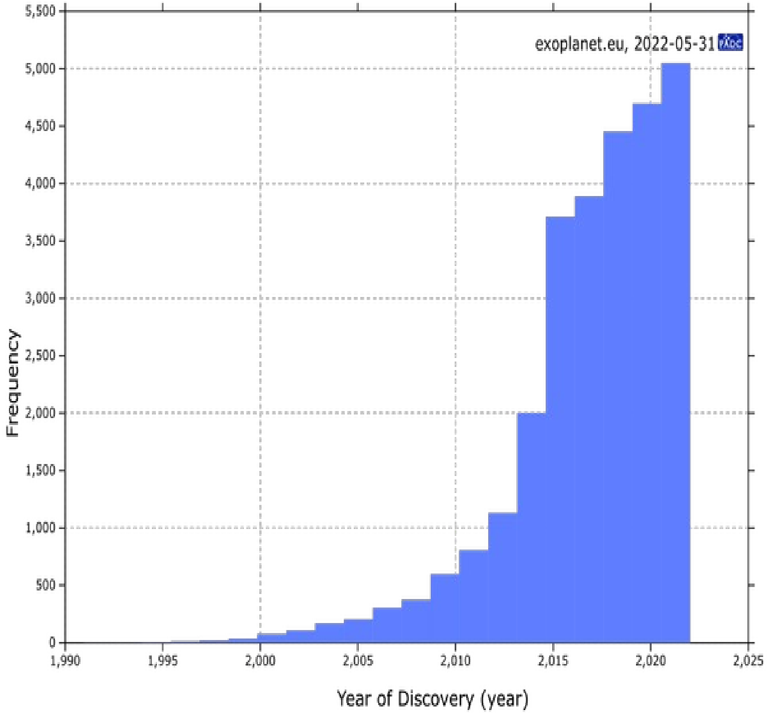




Michel Mayor e Didier Queloz, Nobel prize for Physics in 2019

Mass = 0.47 Jupiter mass
Radius = 1.9 Jupiter radius (enflated by the high temperature ~ 800 K)
Orbital period = 4.23 days
Synchronous rotation (highly probable)
Age: 4 Gyr

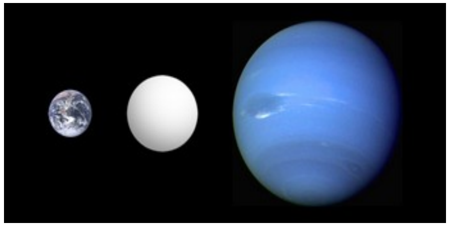

CASSIOPEIA
Enif
51 Pegasi
PEGASUS
Markab
Andromeda



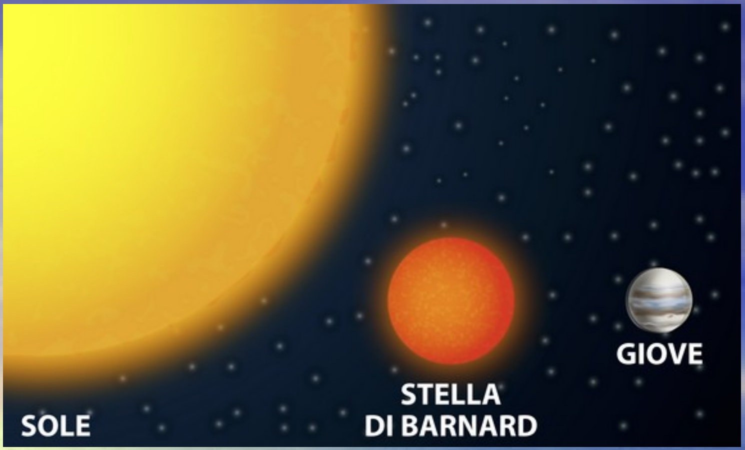
To date (continuosly growing...), 7414 new planets, 5086 planetary systems, 1035 multiplanet systems, 232 planets in binary star systems.

>20% of solar-like stars have Jovian planets.

> 50% have terrestrial planets, super-Earths or neptunian size planets.



1-10 % planets in the habitable zone.



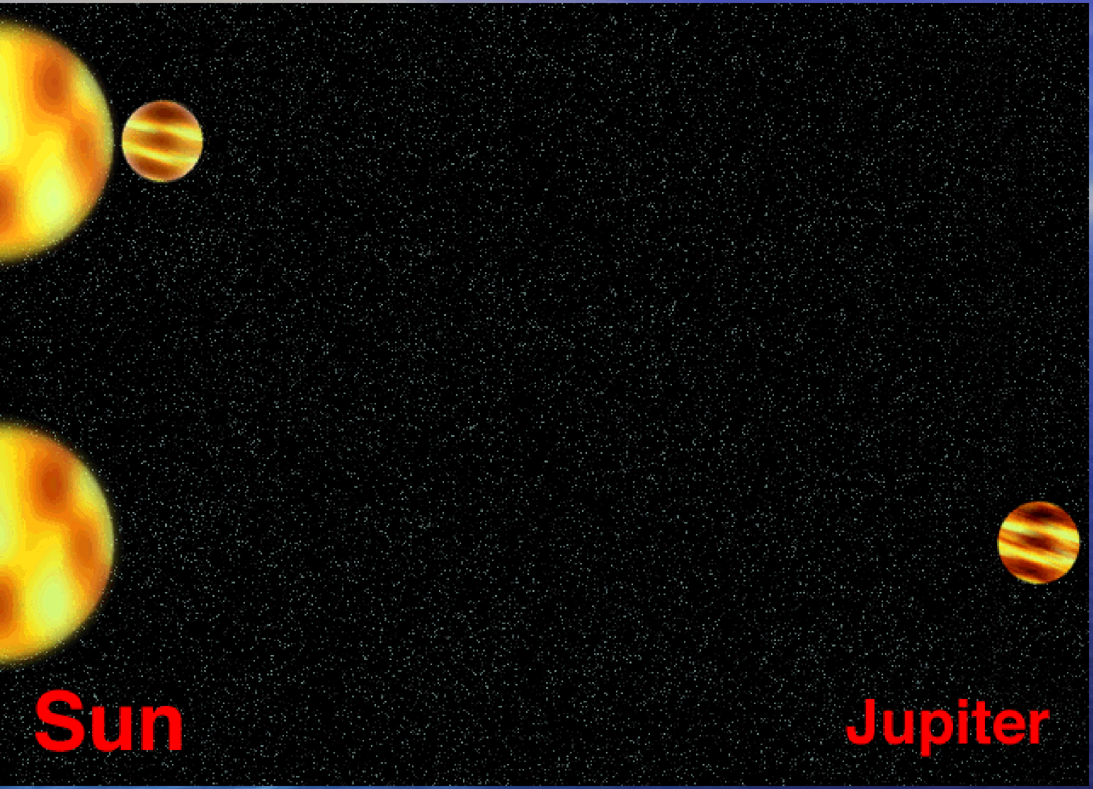
Peter Van de Kamp and the Barnard star: 1 or 2 Jupiter size planets orbiting the star. FAKE (problems with the telescope pointing)

Table 1 | Information on Barnard's star and its planet

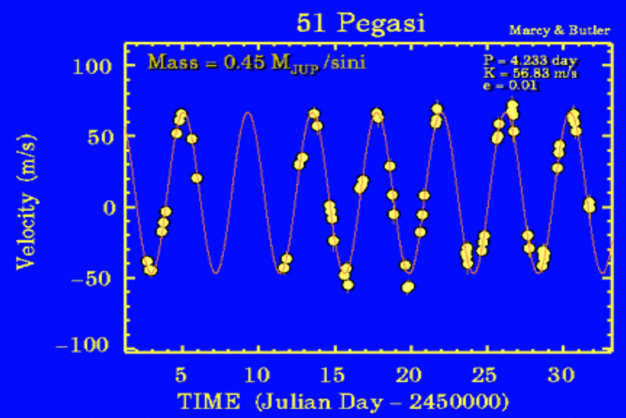
Stellar parameter	Value
Spectral type	M3.5 V
Mass ($M_\odot$)	0.163 ± 0.022
Radius ($R_\odot$)	0.178 ± 0.011
Luminosity ($L_\odot$)	0.00329 ± 0.00019
Effective temperature (K)	$3{,}278 \pm 51$
Rotation period (d)	140 ± 10
Age (Gyr)	7–10
Planetary parameter	**Value**
Orbital period (d)	$232.80^{+0.38}_{-0.41}$
Radial-velocity semi-amplitude (m s^{-1})	1.20 ± 0.12
Eccentricity	$0.32^{+0.10}_{-0.15}$
Argument of periastron (°)	107^{+19}_{-22}
Mean longitude at BJD 2,455,000.0 (°)	203 ± 7
Minimum mass, $M\sin i$ ($M_\oplus$)	3.23 ± 0.44
Orbital semi-major axis (AU)	0.404 ± 0.018
Irradiance (Earth units)	0.0203 ± 0.0023
Maximum equilibrium temperature (K)	105 ± 3
Minimum astrometric semi-amplitude, $\alpha\sin i$ (mas)	0.0133 ± 0.0013

...BUT, twist of fate, there is indeed a planet around the Barnard star!! (Ribas et al., Nature, 2018)

51 Peg b: first exoplanet to be detected (Mayor & Queloz, 1995).

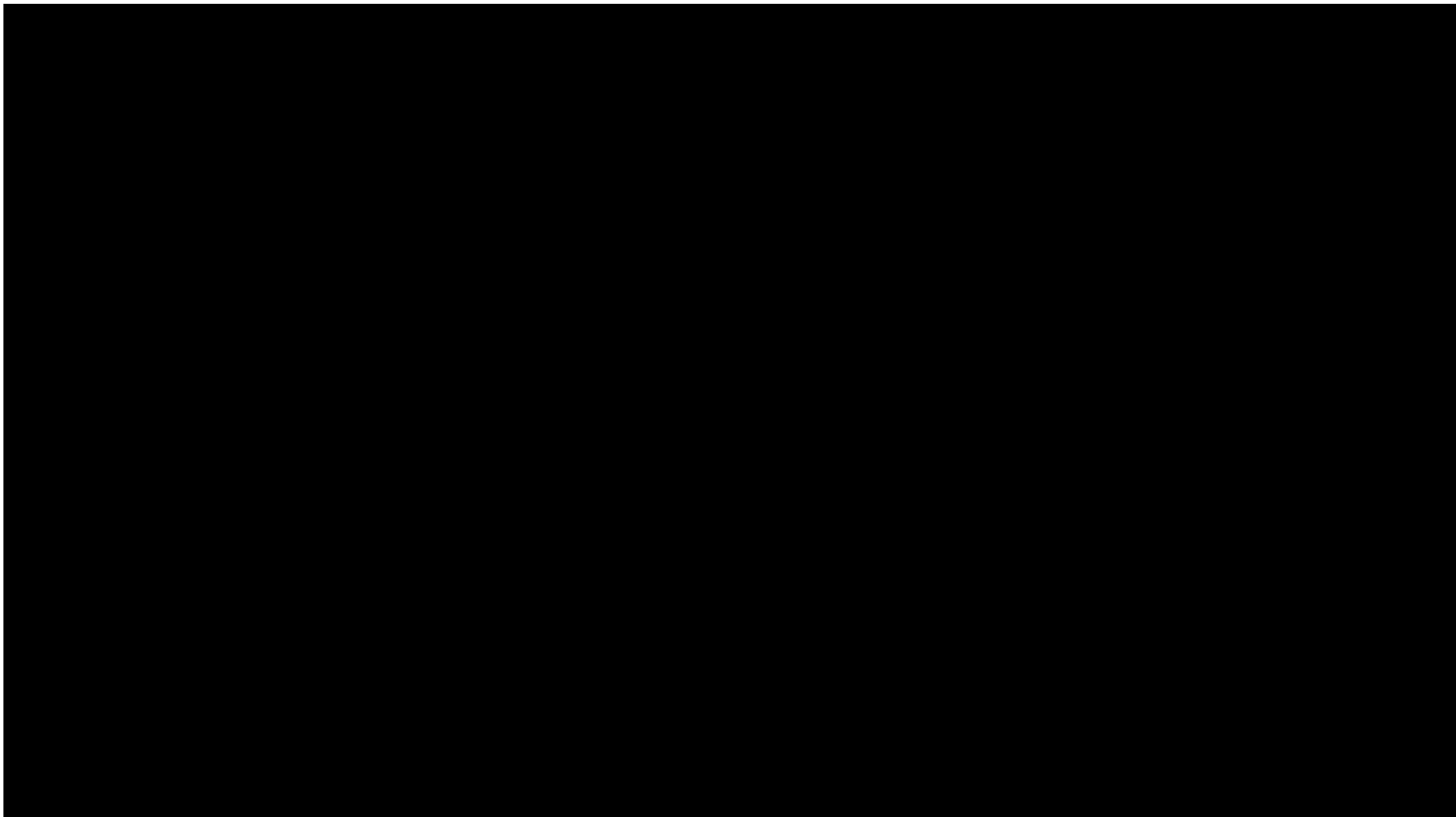


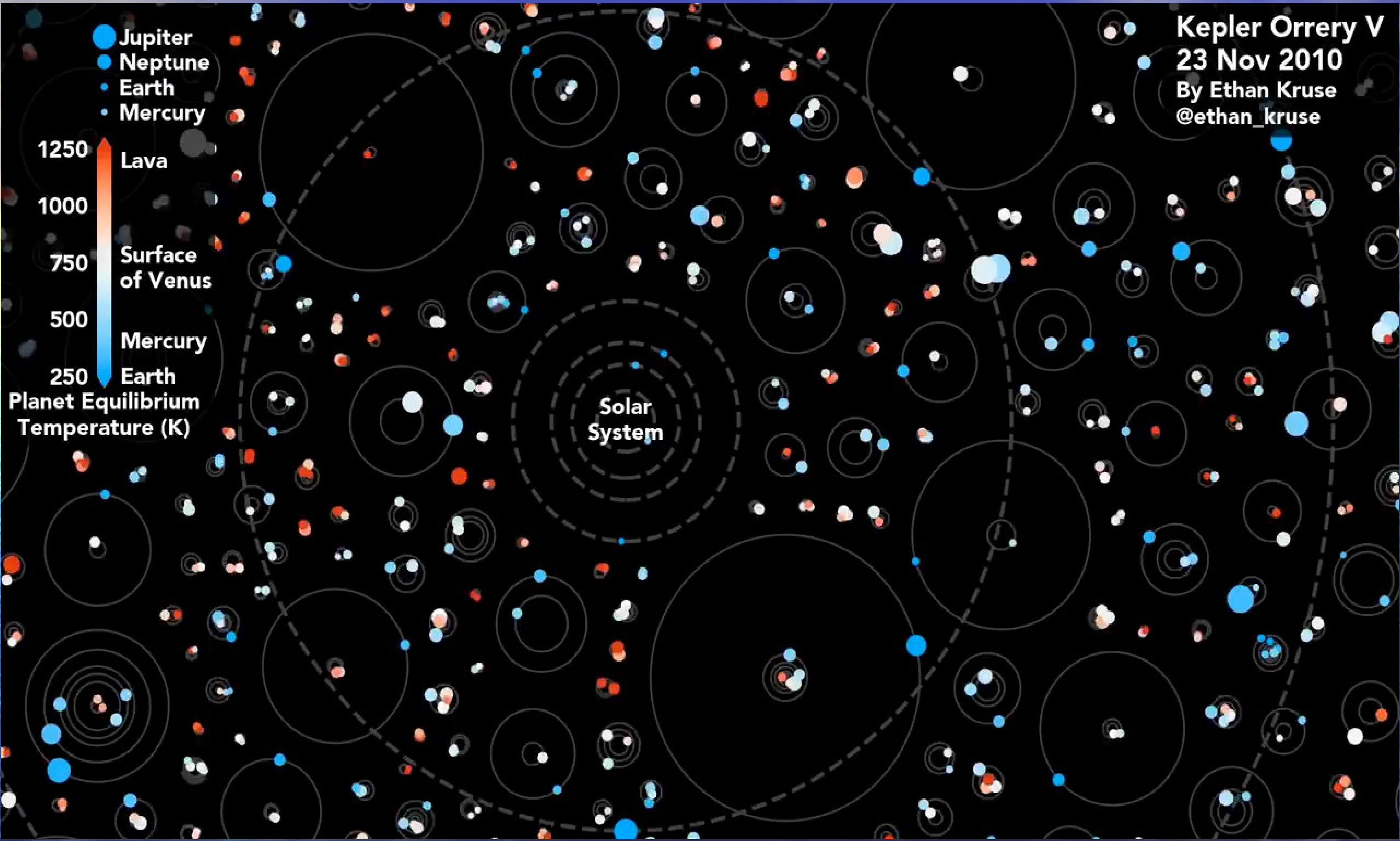
Its radial velocity curve

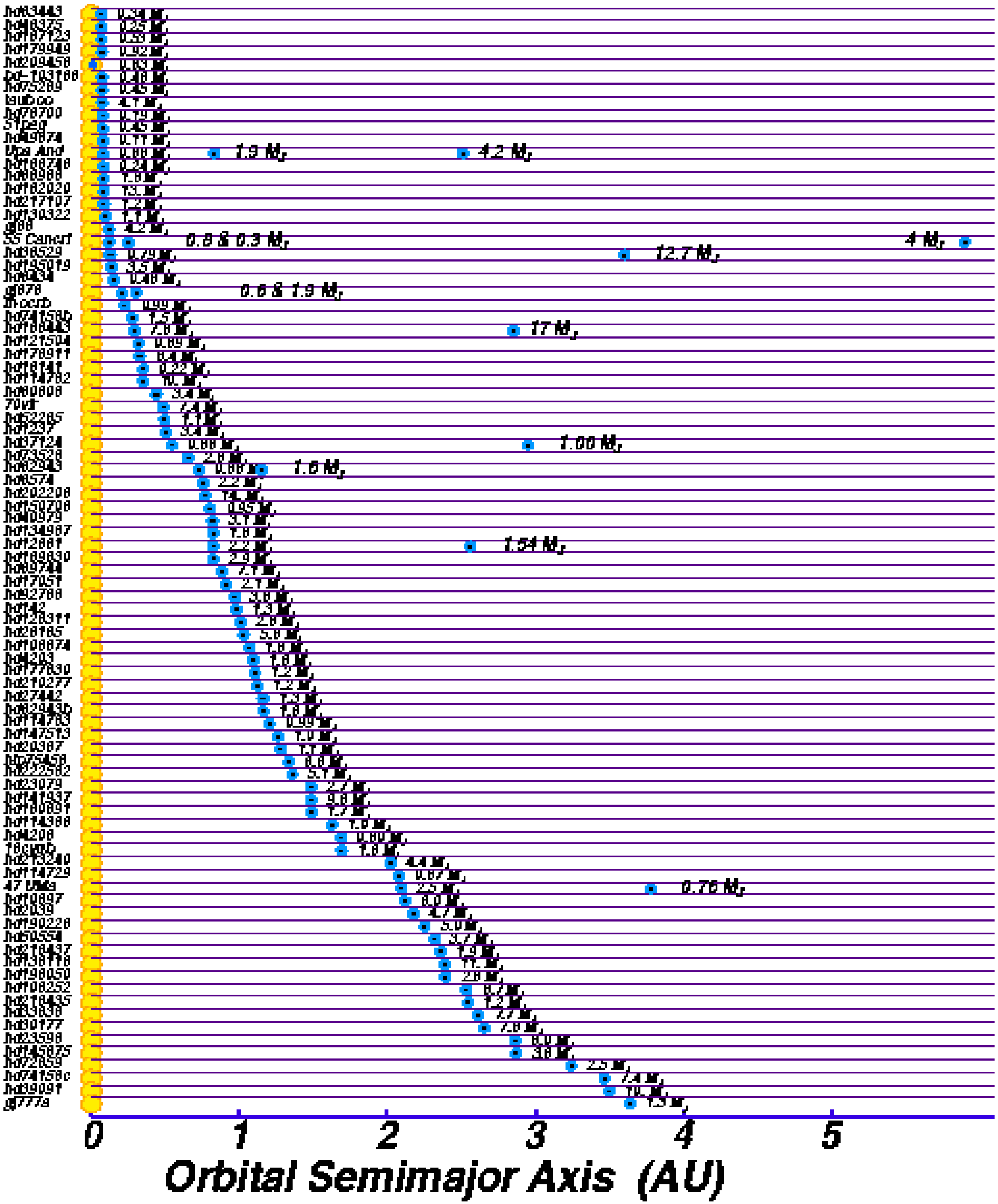


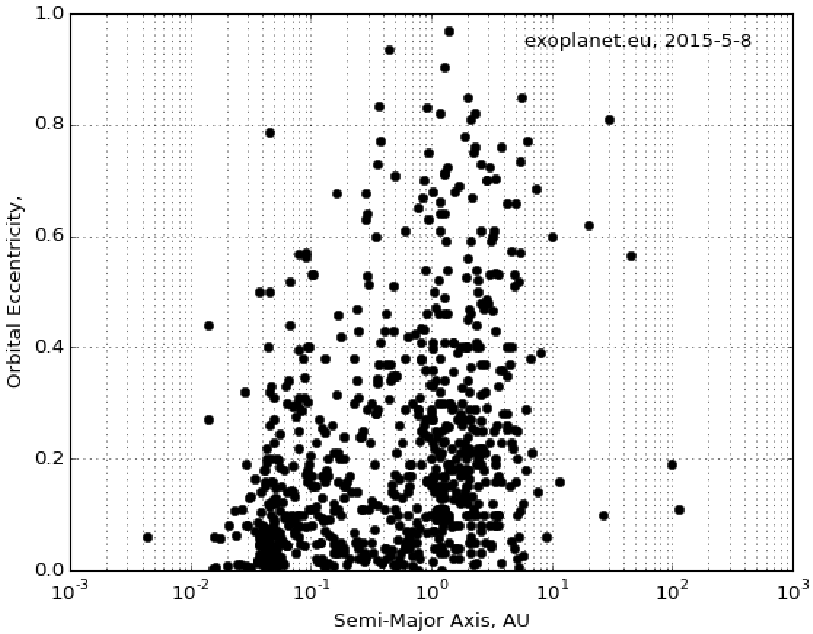
Discovery through the radial oscillation of the star around the system center of mass.

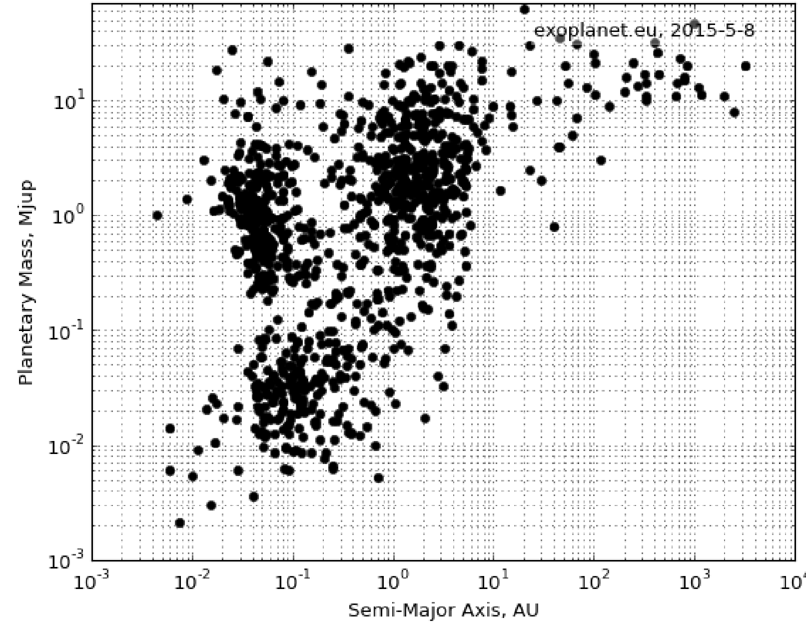
Old orrery based on the solar system.

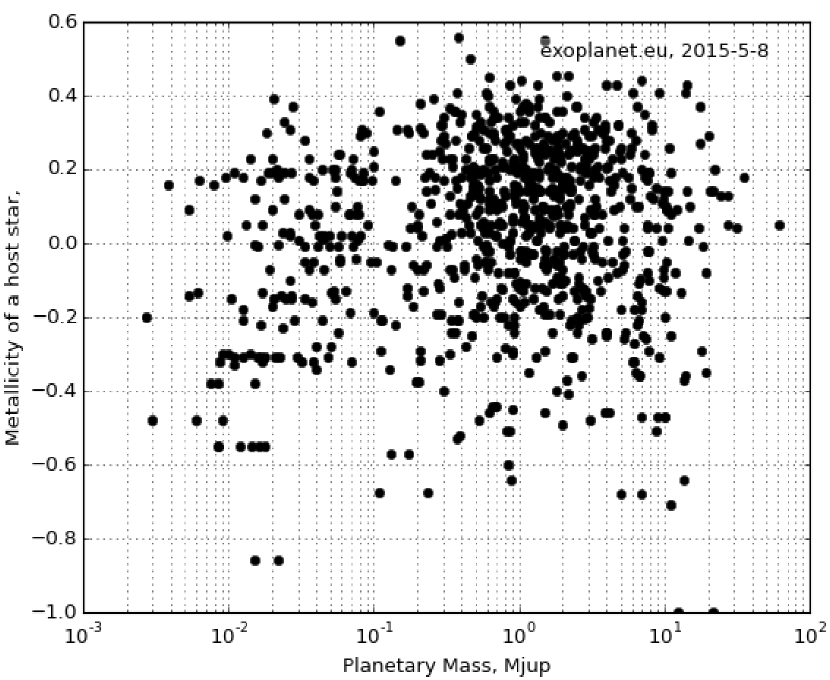


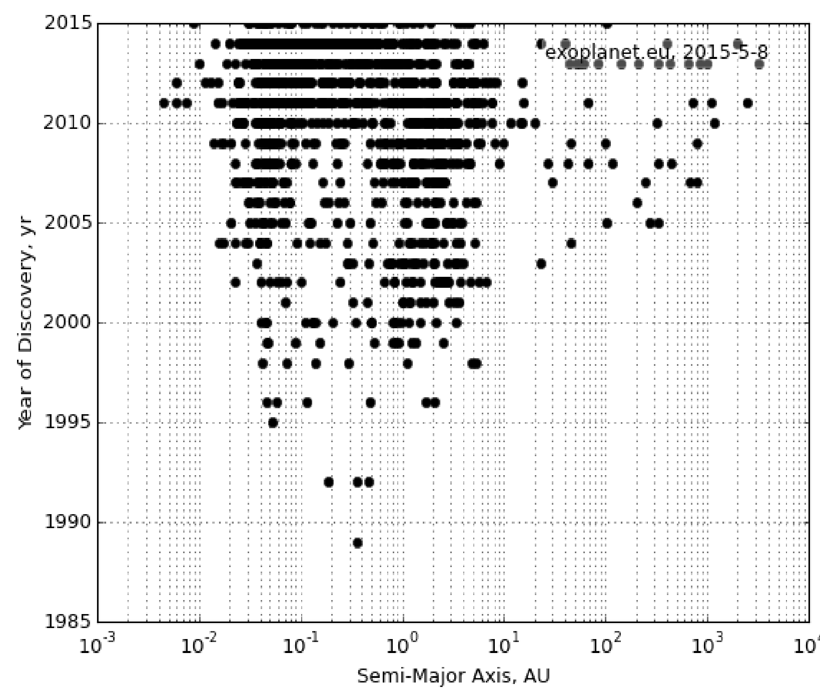

Jupiter
Neptune
Earth
Mercury
1250
1000
750
500
250
Lava
Surface of Venus
Mercury
Earth
Planet Equilibrium Temperature (K)
Solar System
Kepler Orrery V
23 Nov 2010
By Ethan Kruse
@ethan_kruse

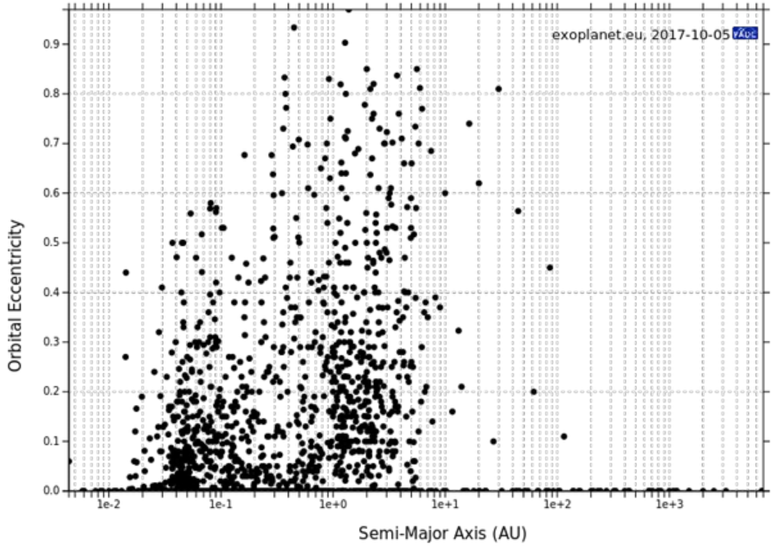

Ups And
1.9 M_J
4.2 M_J
55 Cancri
0.8 & 0.3 M_J
4 M_J
12.7 M_J
0.6 & 1.9 M_J
17 M_J
1.00 M_J
1.6 M_J
1.54 M_J
47 UMa
0.76 M_J
0
1
2
3
4
5
Orbital Semimajor Axis (AU)

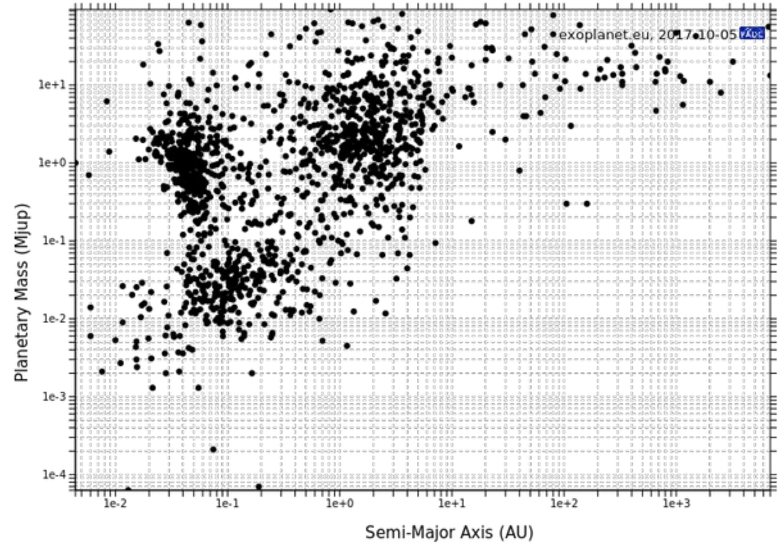

exoplanet.eu, 2015-5-8
Orbital Eccentricity,
Semi-Major Axis, AU
1.0
0.8
0.6
0.4
0.2
0.0
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

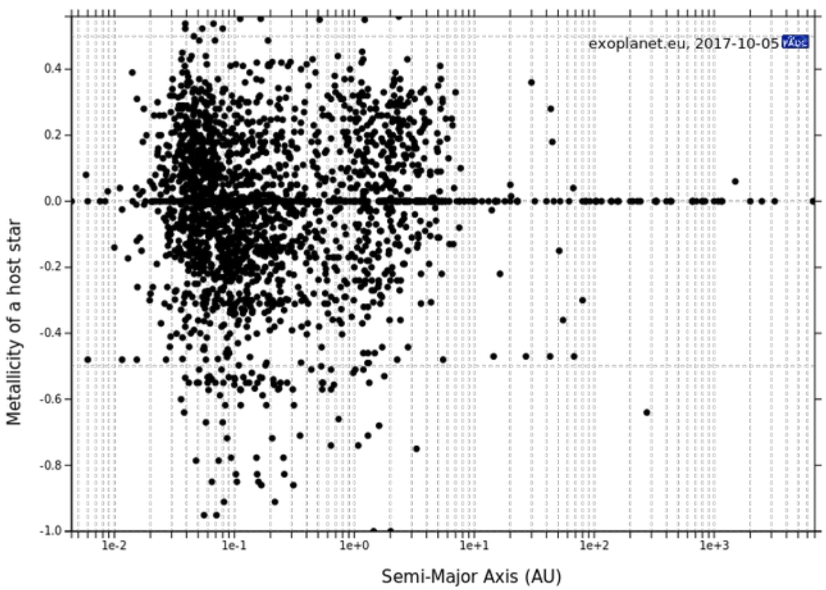

exoplanet.eu, 2015-5-8
Planetary Mass, Mjup
Semi-Major Axis, AU
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

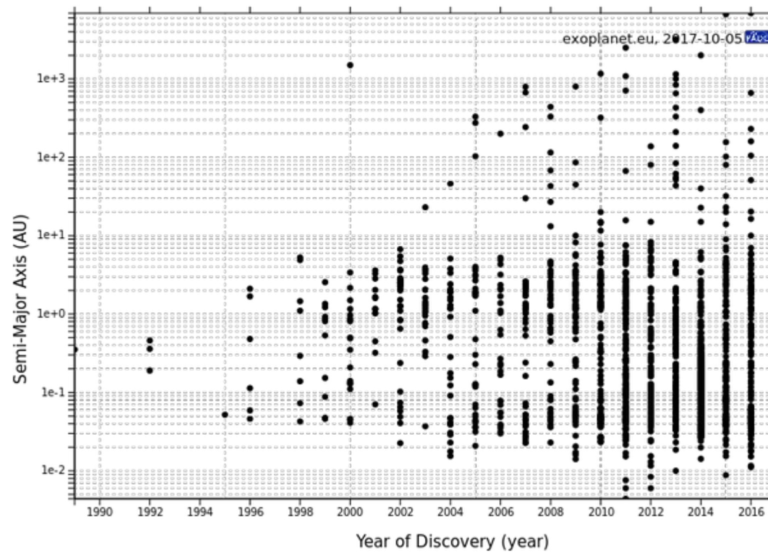

exoplanet.eu, 2015-5-8
Metallicity of a host star,
Planetary Mass, Mjup
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}


exoplanet.eu, 2015-5-8
Year of Discovery, yr
Semi-Major Axis, AU
2015
2010
2005
2000
1995
1990
1985
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}


exoplanet.eu, 2017-10-05
Orbital Eccentricity
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1e-2
1e-1
1e+0
1e+1
1e+2
1e+3
Semi-Major Axis (AU)

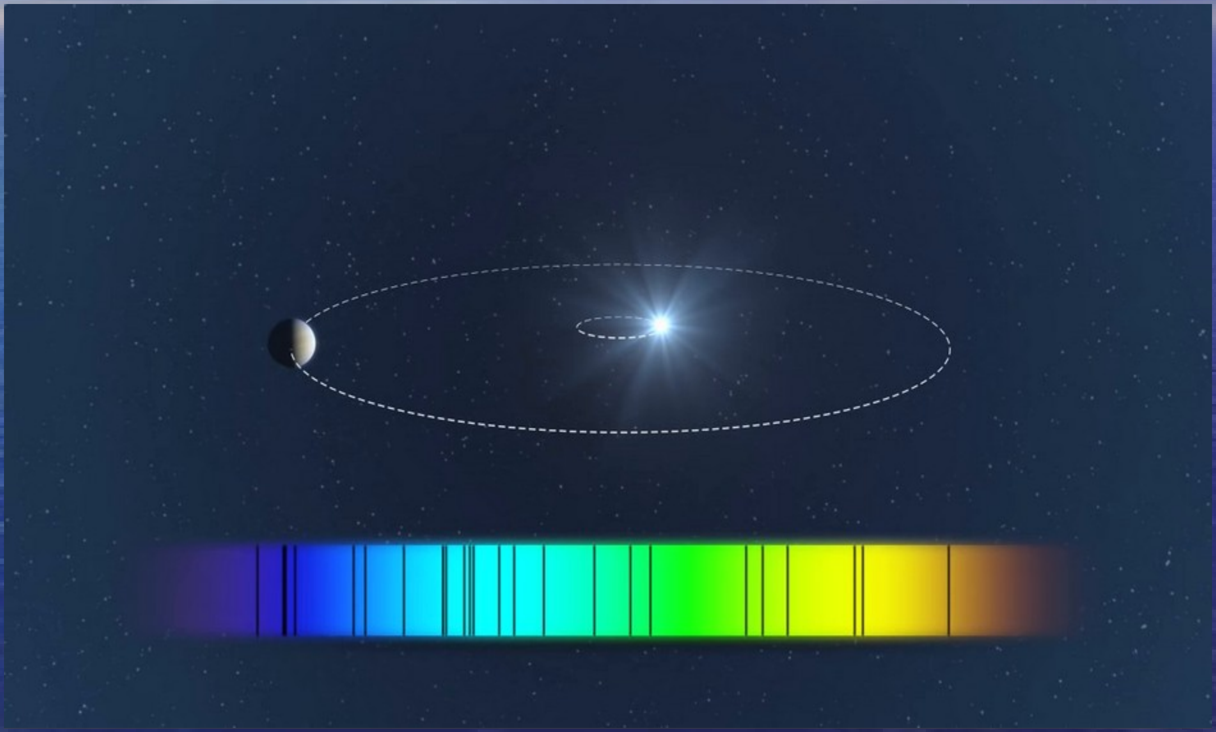

exoplanet.eu, 2017-10-05
Planetary Mass (Mjup)
1e-4
1e-3
1e-2
1e-1
1e+0
1e+1
1e-2
1e-1
1e+0
1e+1
1e+2
1e+3
Semi-Major Axis (AU)


exoplanet.eu, 2017-10-05
Metallicity of a host star
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
1e-2
1e-1
1e+0
1e+1
1e+2
1e+3
Semi-Major Axis (AU)

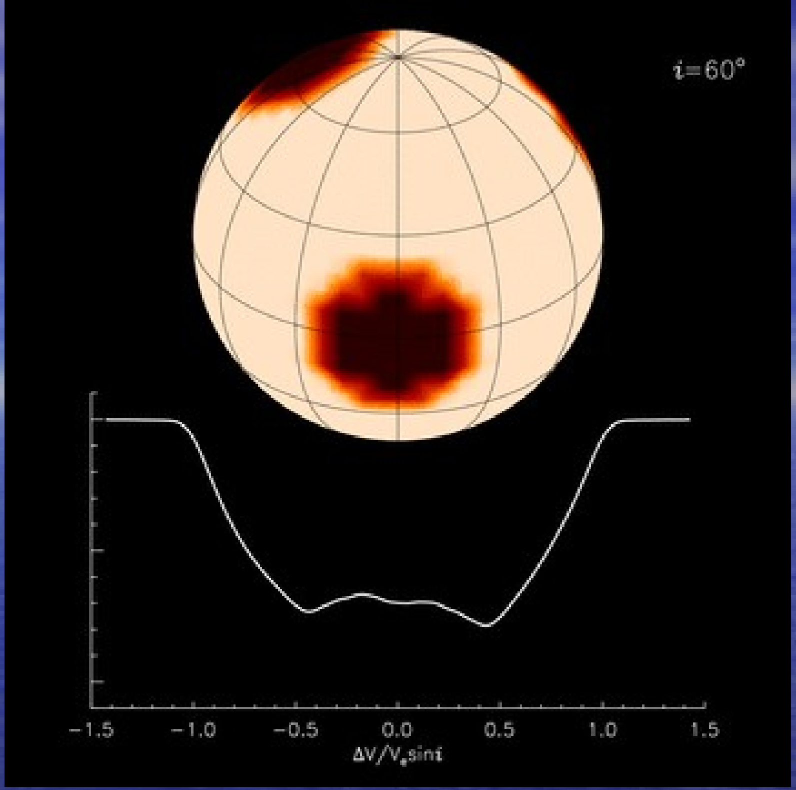

exoplanet.eu, 2017-10-05
Semi-Major Axis (AU)
1e-2
1e-1
1e+0
1e+1
1e+2
1e+3
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
Year of Discovery (year)

Detection methods

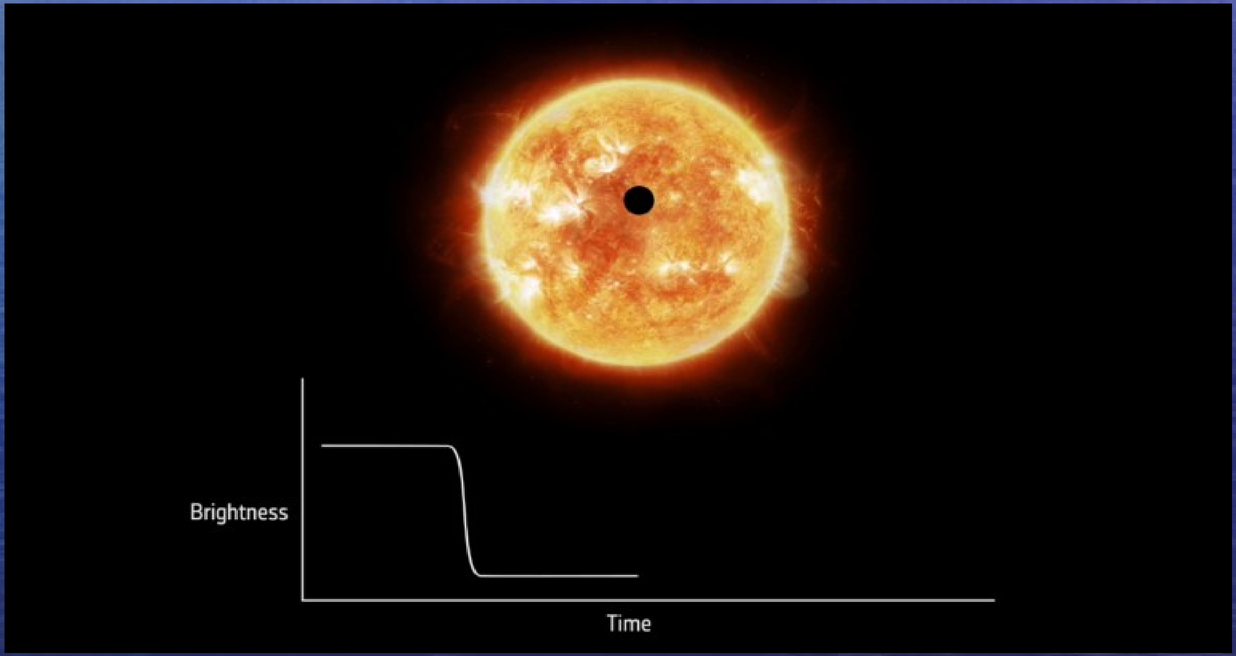
1) **Radial velocity** method: first detections (today about 870). It gives the mass (+/- sin i), semi-major axis and eccentricity.



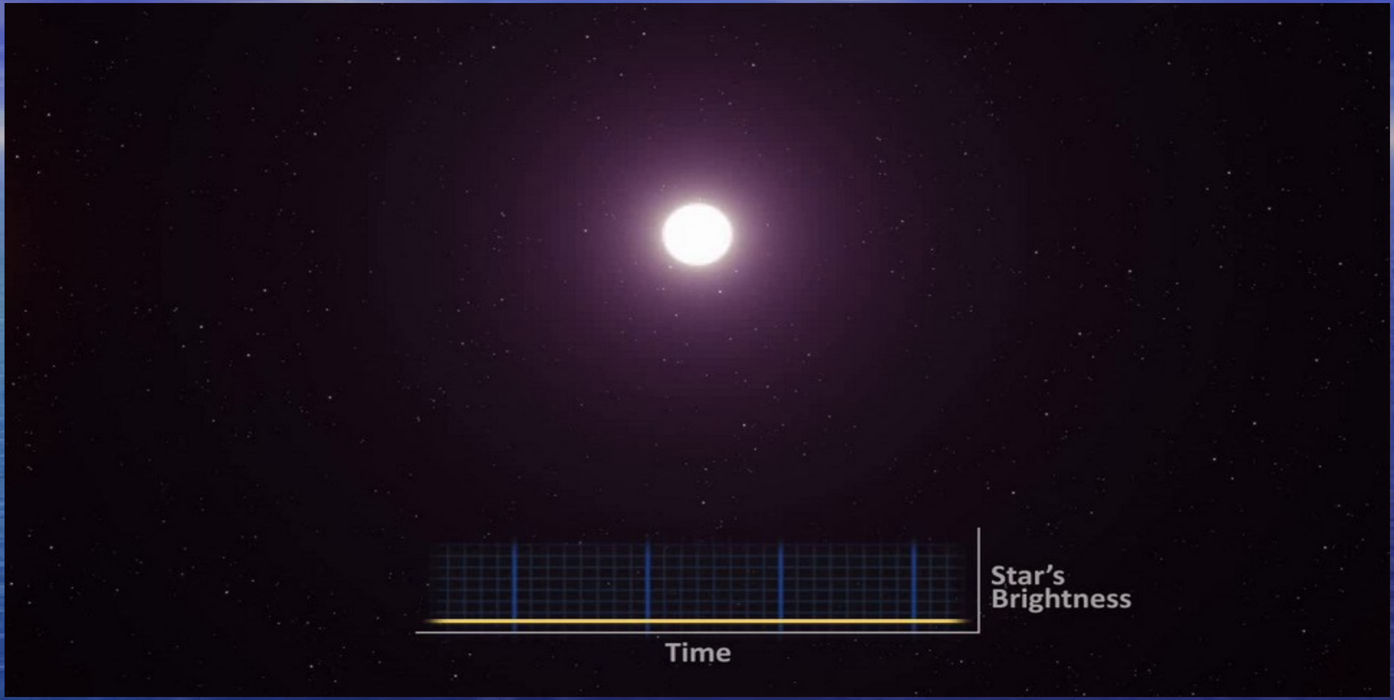
A problem with the radial velocity method: it predicts a planet but in reality the variation in the signal is due to stellar activity. Large spots on the surface and the stellar rotation may change the shape of the absorption line and suggest a fake back-and-forth shift of the line.

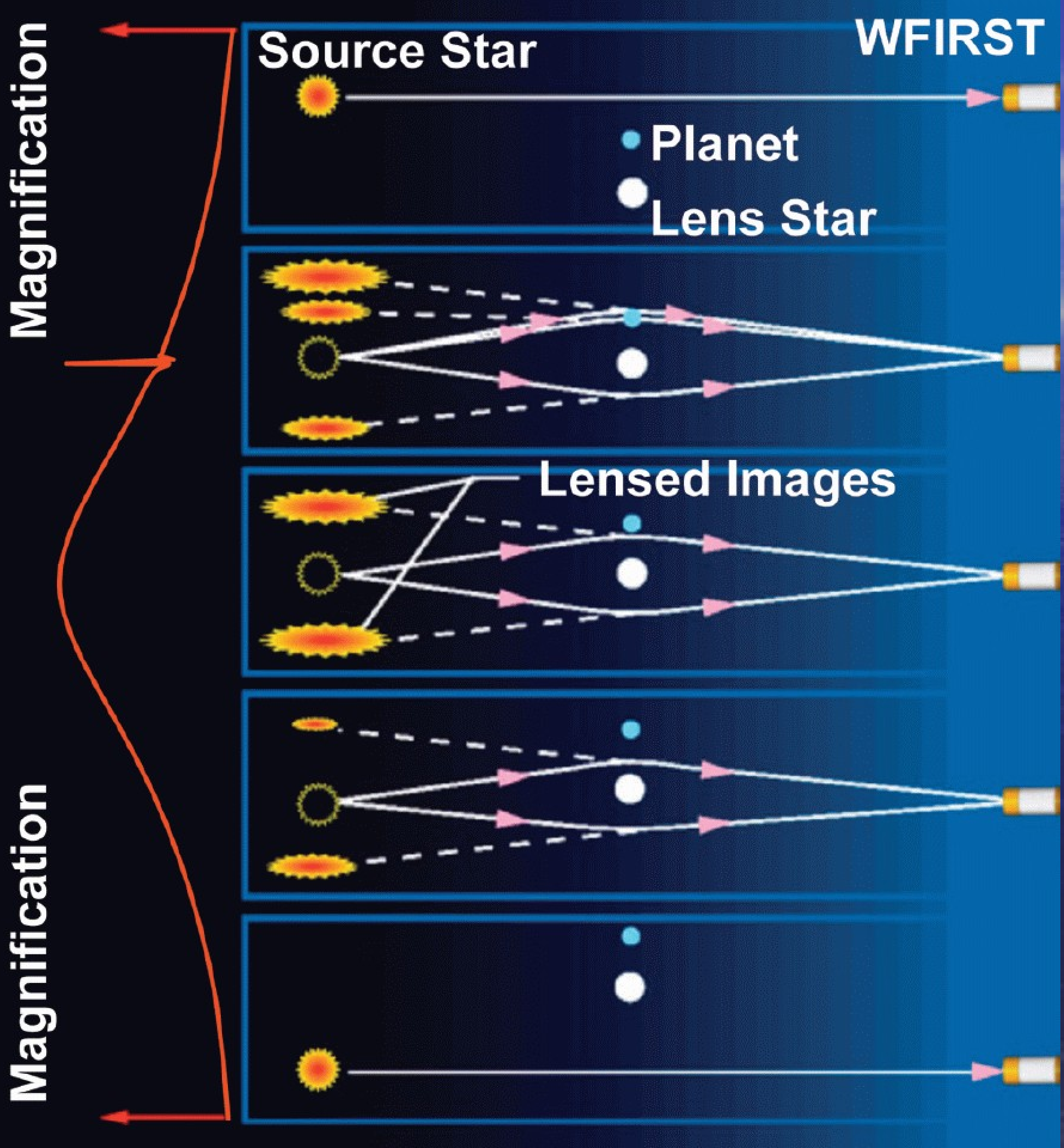


2) Transits (occultation) (COROT, KEPLER, TESS, CHEOPS, PLATO, about 2750 planets). Radius and semi—major axis

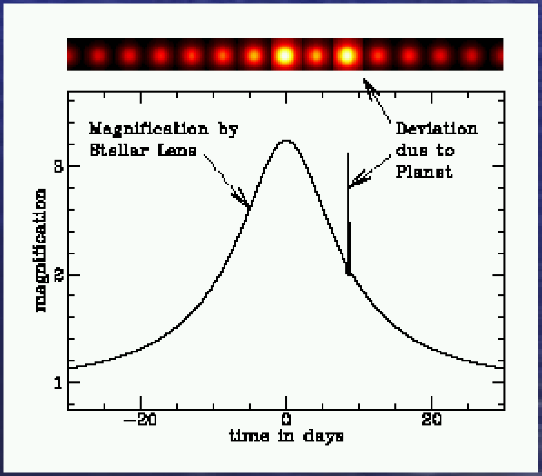


3) **Microlensing** (104 planets): mass and semi-major axis also for very far away planets. (MOA, MACHO, OGLE…).

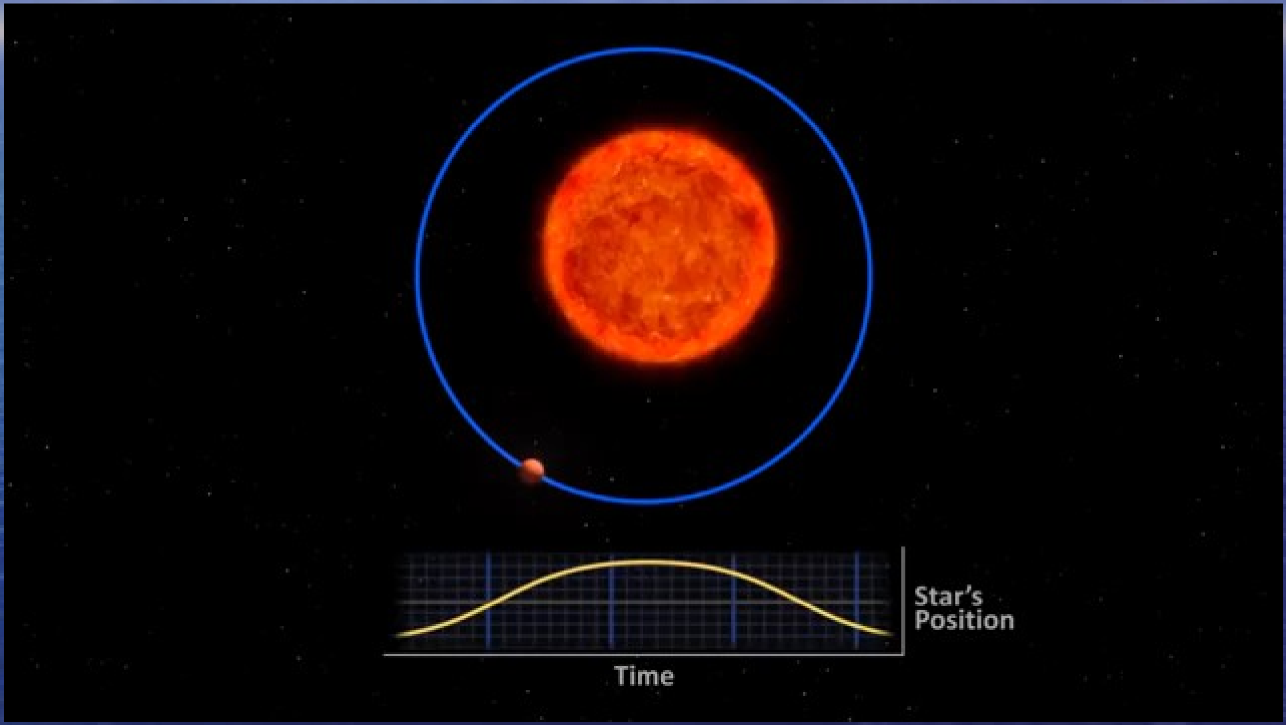




The smaller one detected has only 5 Earth masses...

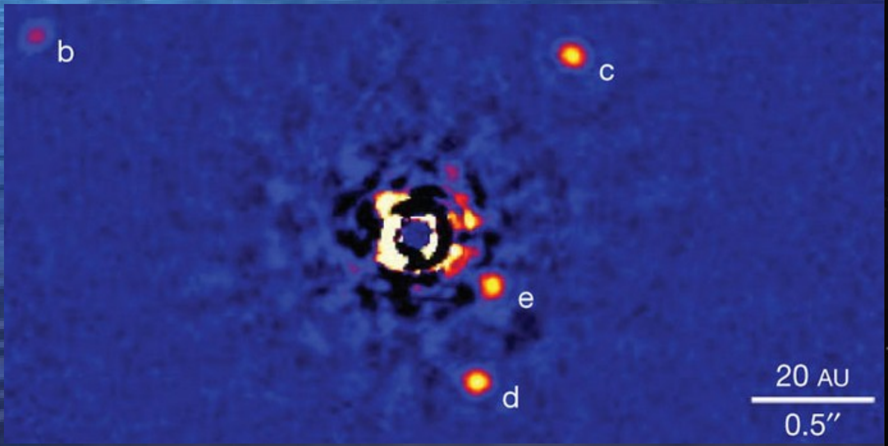


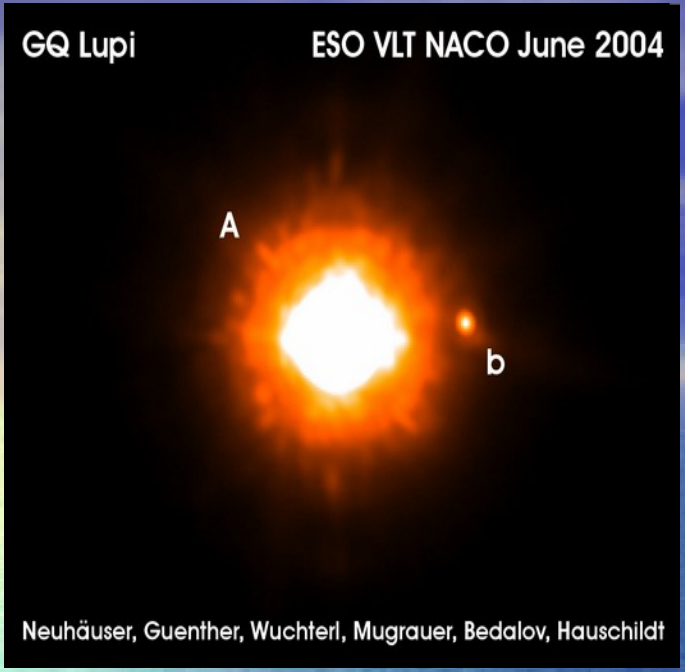
4) Astrometry: (GAIA): only 1 planet at the moment, mass, semi-major axis, eccentricity.



5) Direct imaging. So far 135 objects, but only 44 possible planets.

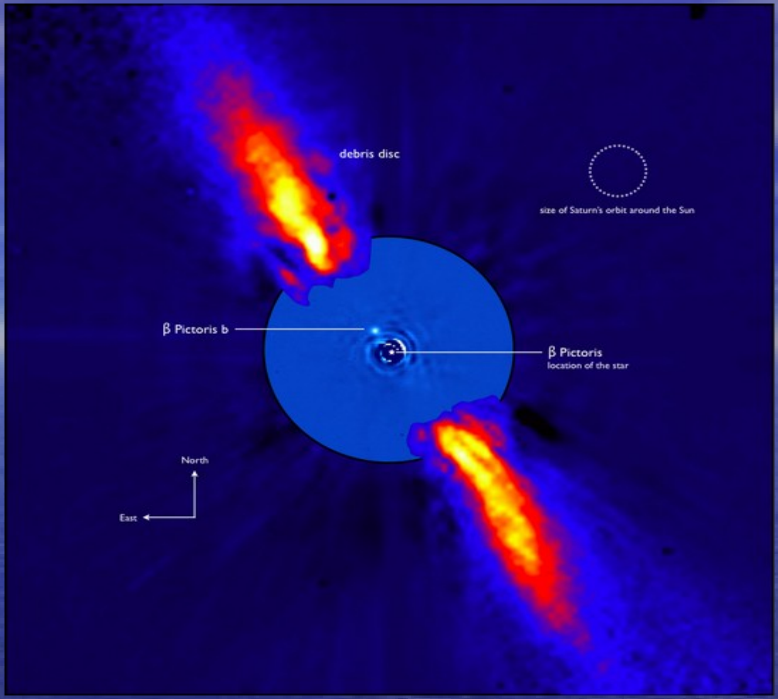
HR 8799



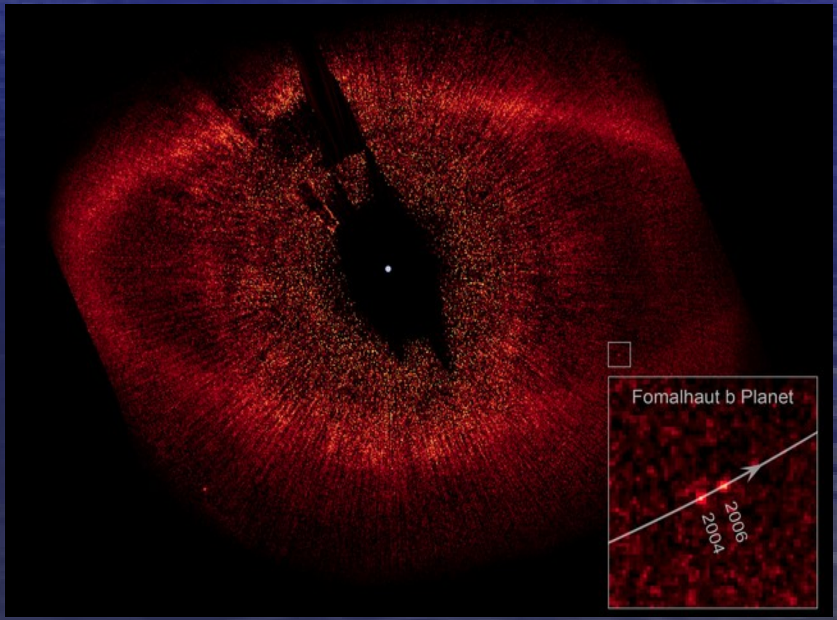


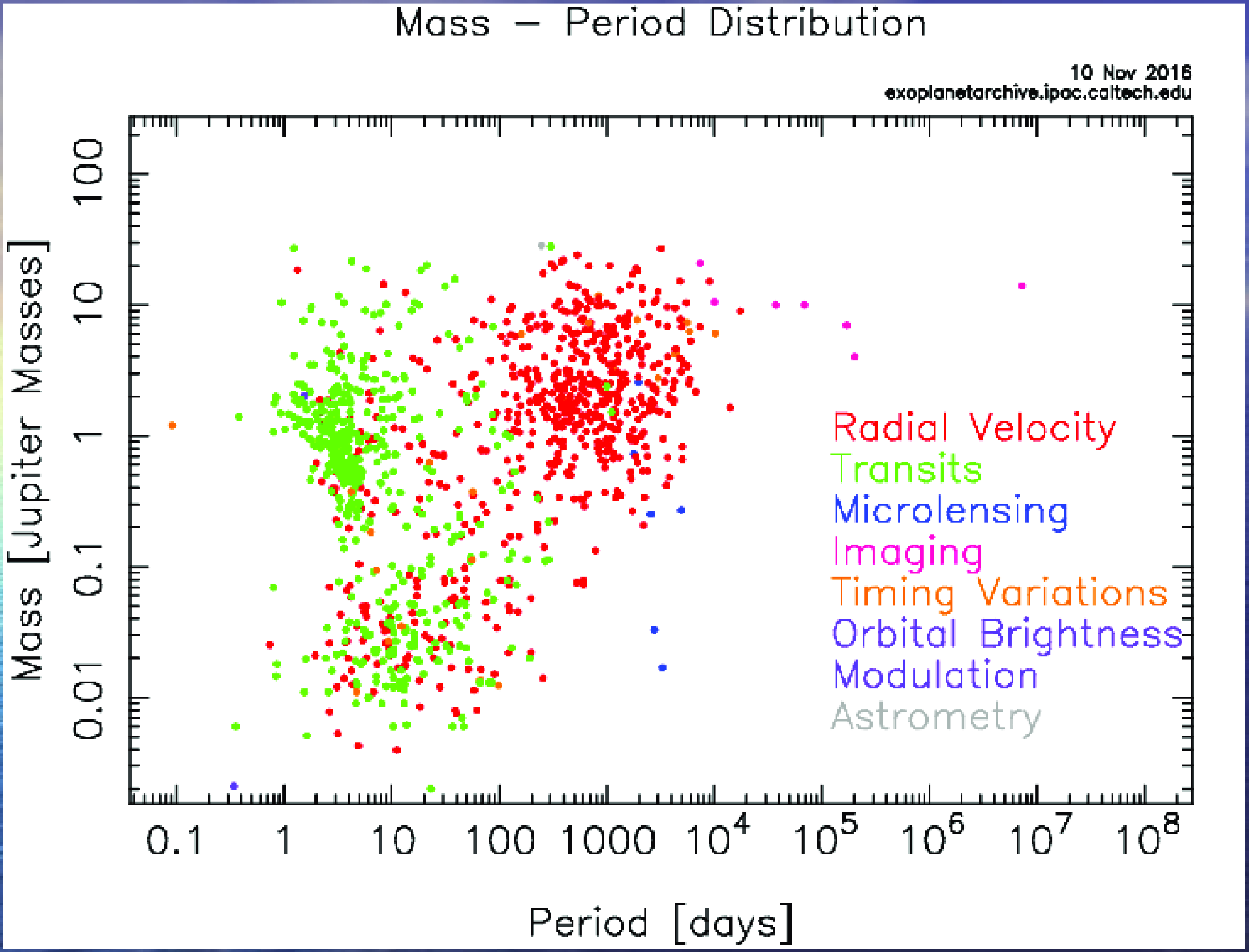
..more direct detection ..

Beta Pic

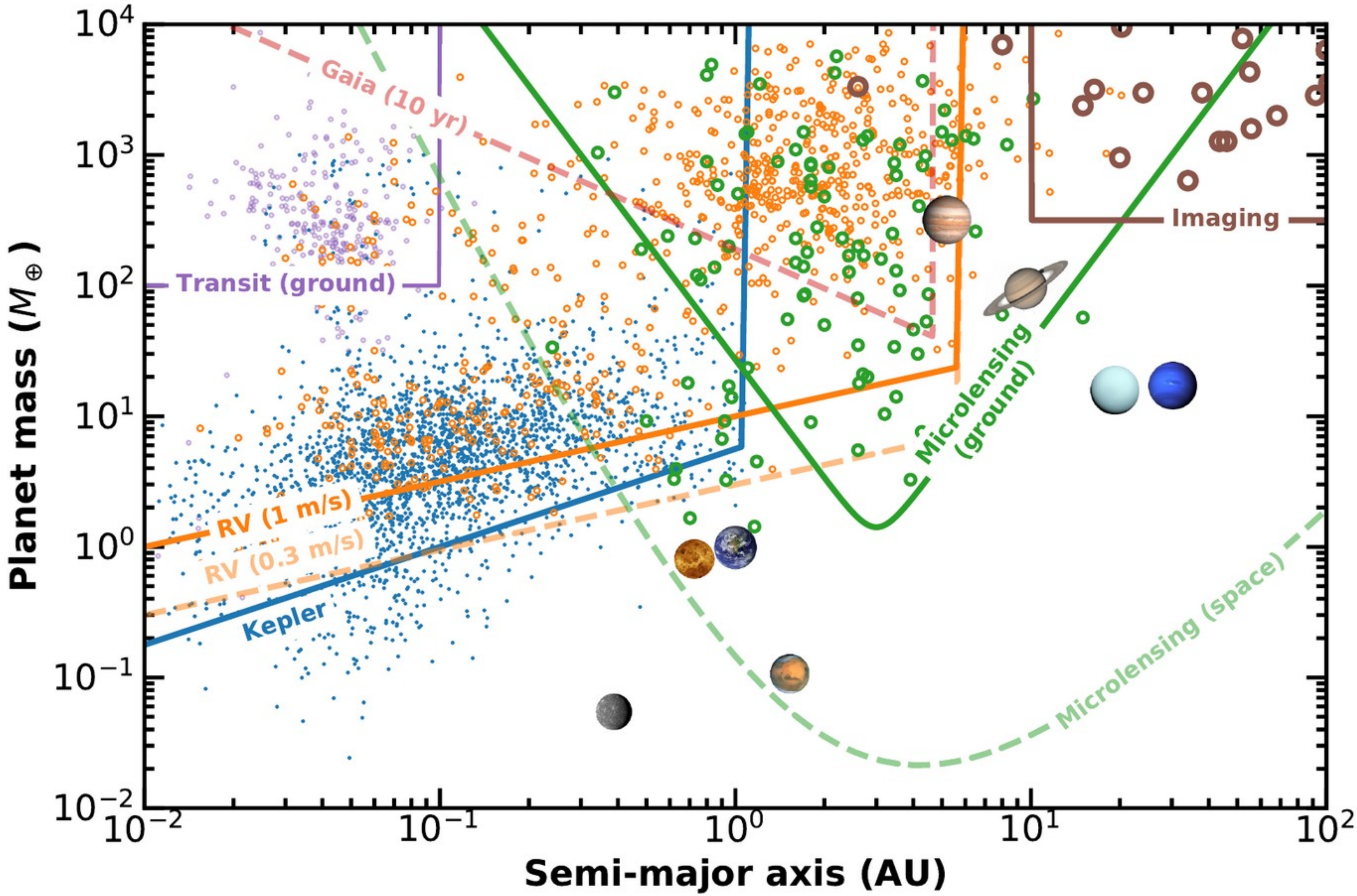


Fomalhaut (?? controversial)



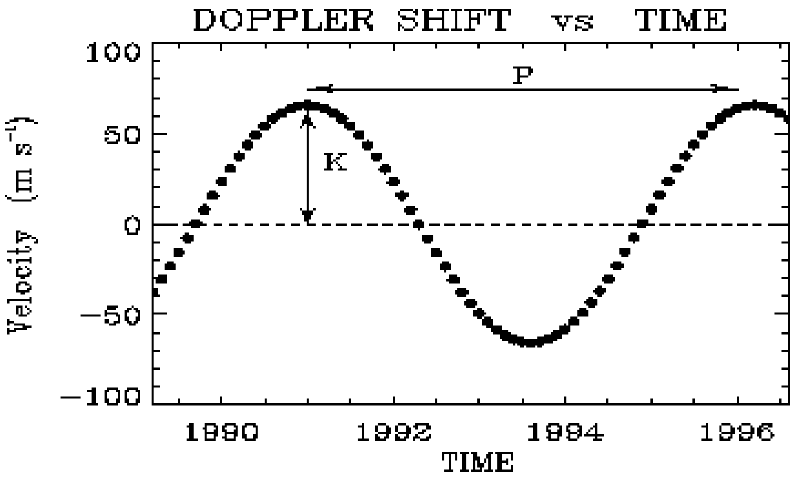


Orbital brightness modulation: orbital phases of a bright planet, change in the star shape due to planet tides...



Gaia (10 yr)
Transit (ground)
Imaging
RV (1 m/s)
RV (0.3 m/s)
Kepler
Microlensing (ground)
Microlensing (space)
Planet mass ($M_\oplus$)
Semi-major axis (AU)

Sinergy between radial velocity and occultation observations.



Kepler:

$$r^3 = \frac{GM_*}{4\pi^2} P^2$$

Observe Period.

$$V_{PL} = \sqrt{GM_*/r}$$

−> Vel. of Planet .

Momentum Conservation:

$$M_{PL} = M_* V_* / V_{PL}$$

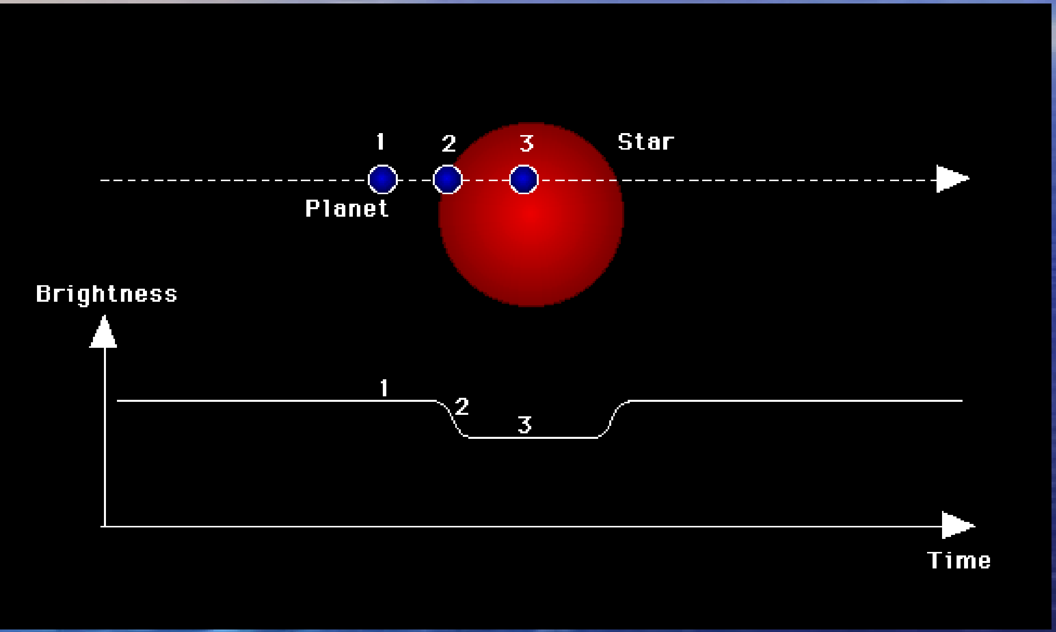
Observe K $= V_* \sin i$

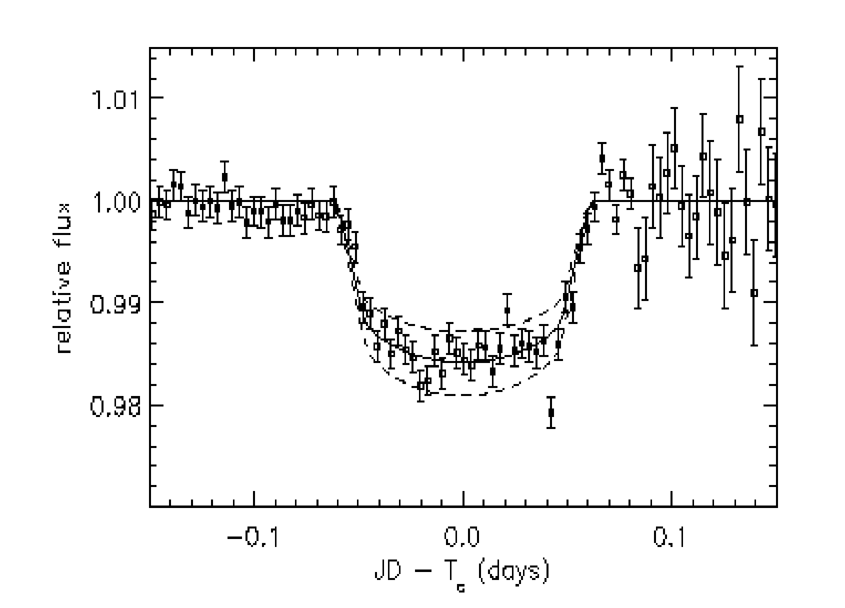
$$==> \; M_{PL} \sin i$$

Orbital data and mass (uncertain by sin i) via RVs

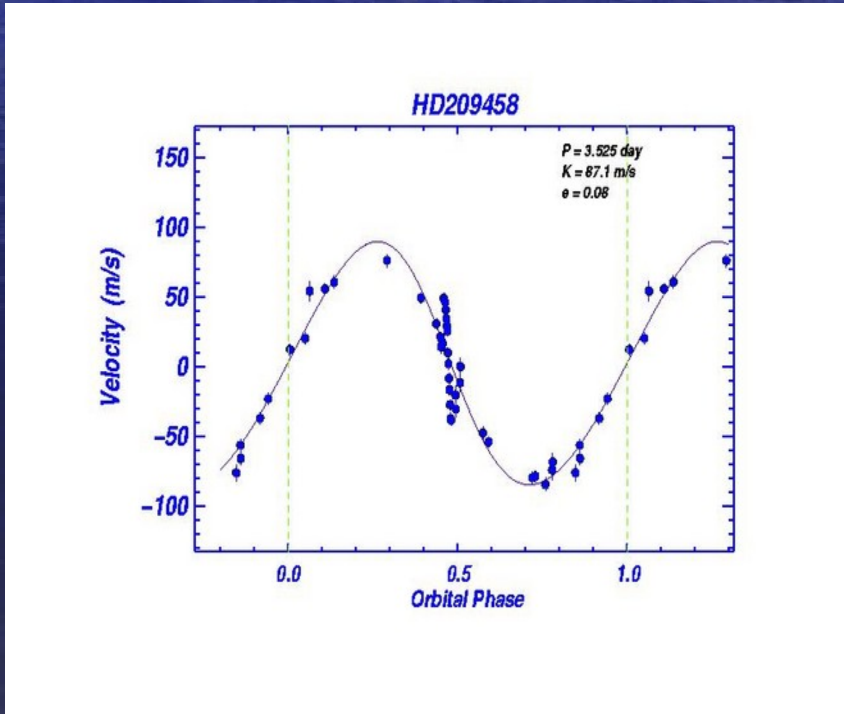
Occultation

HD 209458



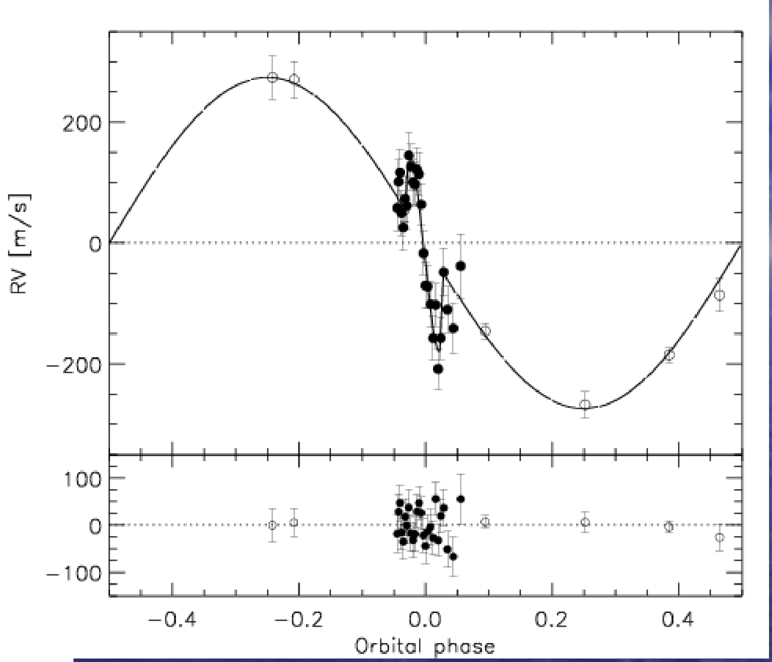


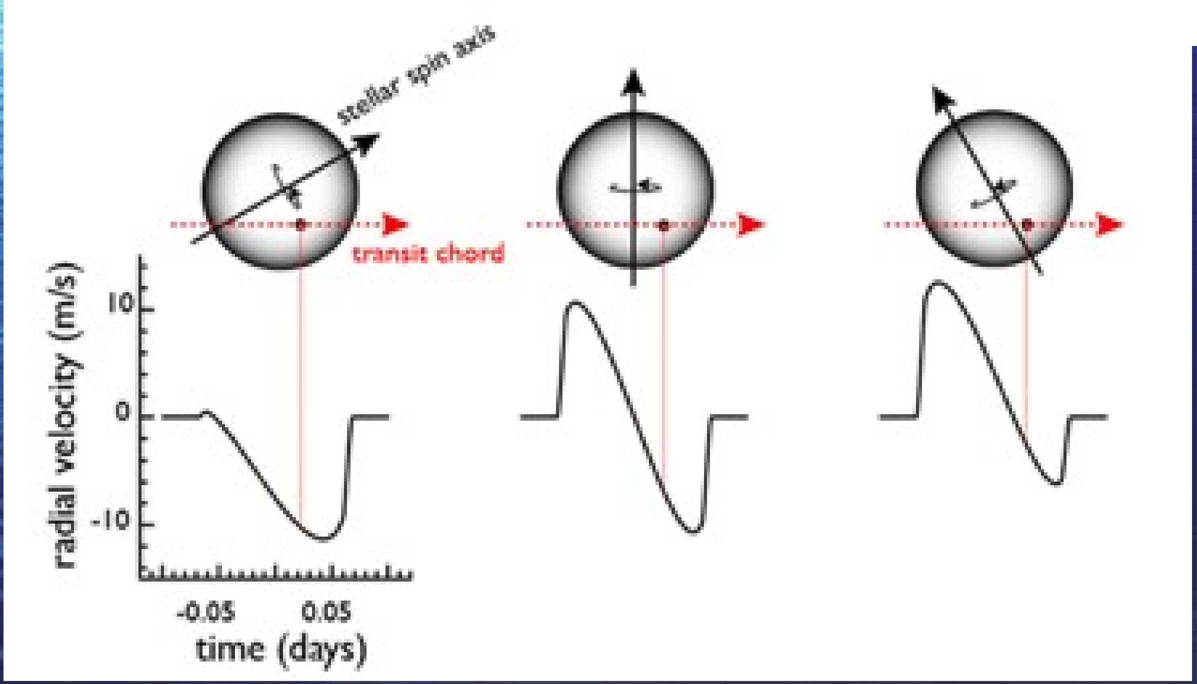
It gives the radius of the planet and orbital period.



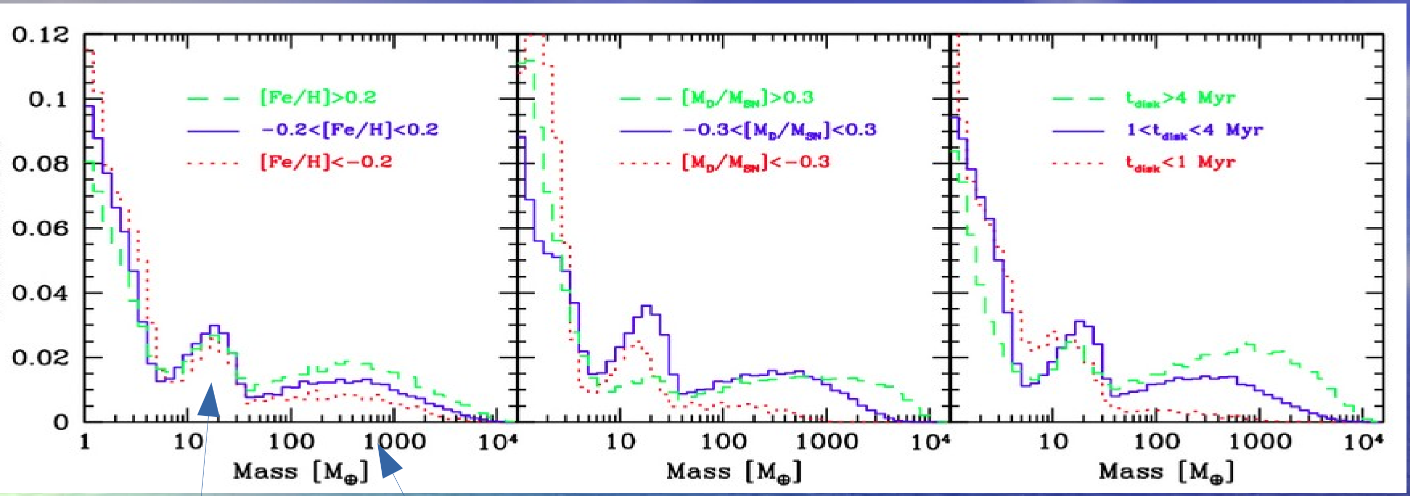
Rossiter-McLaughlin effect: inclination of the planet orbit from RV.

When the planet passes in front of the star, it first shades the left limb and then the other one. The star is rotating so the limbs are affected by the Doppler effect and this appears in the RV

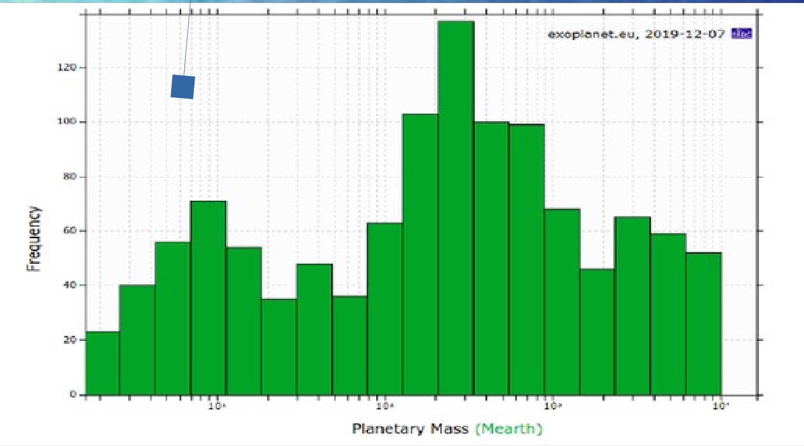




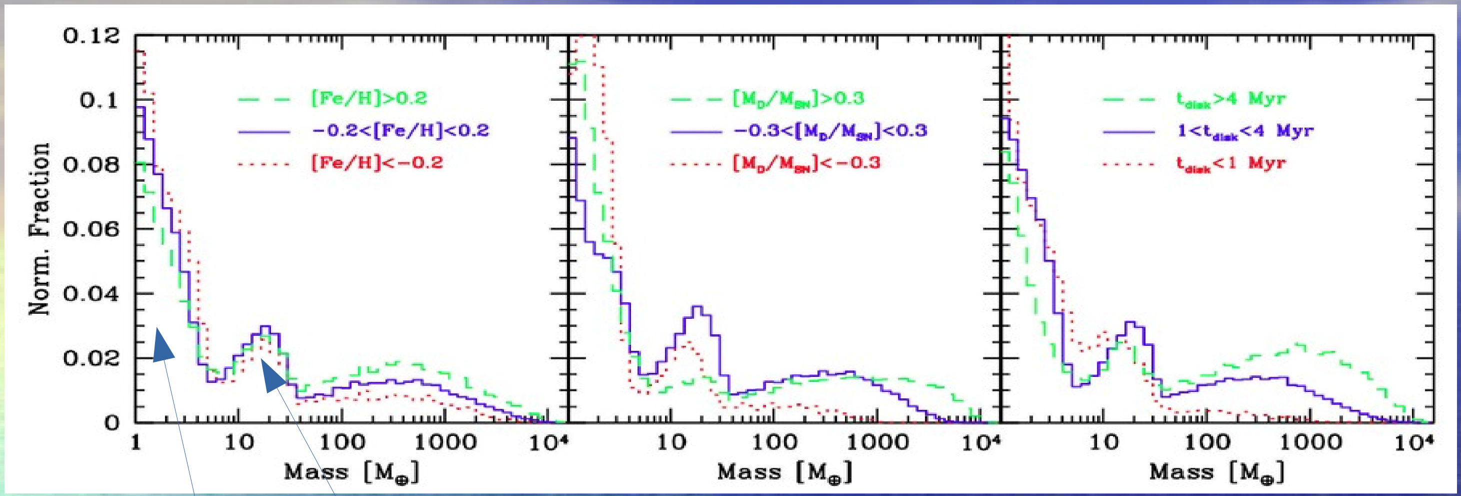
From the shape of the signal, difference from the RV and the Keplerian fit, it is possible to estimate the inclination of the planet orbit respect to the star spin.

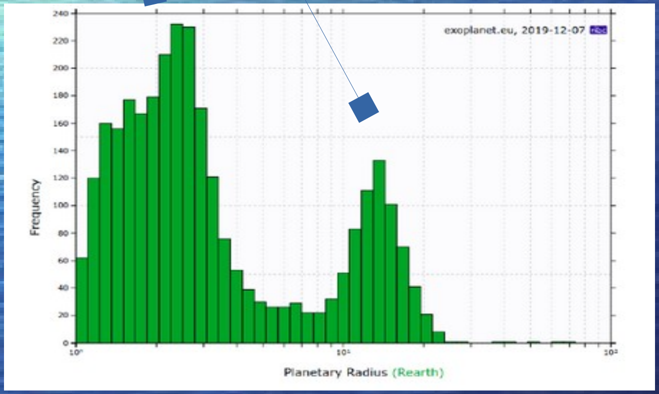


Planet mass distribution theoretically predicted



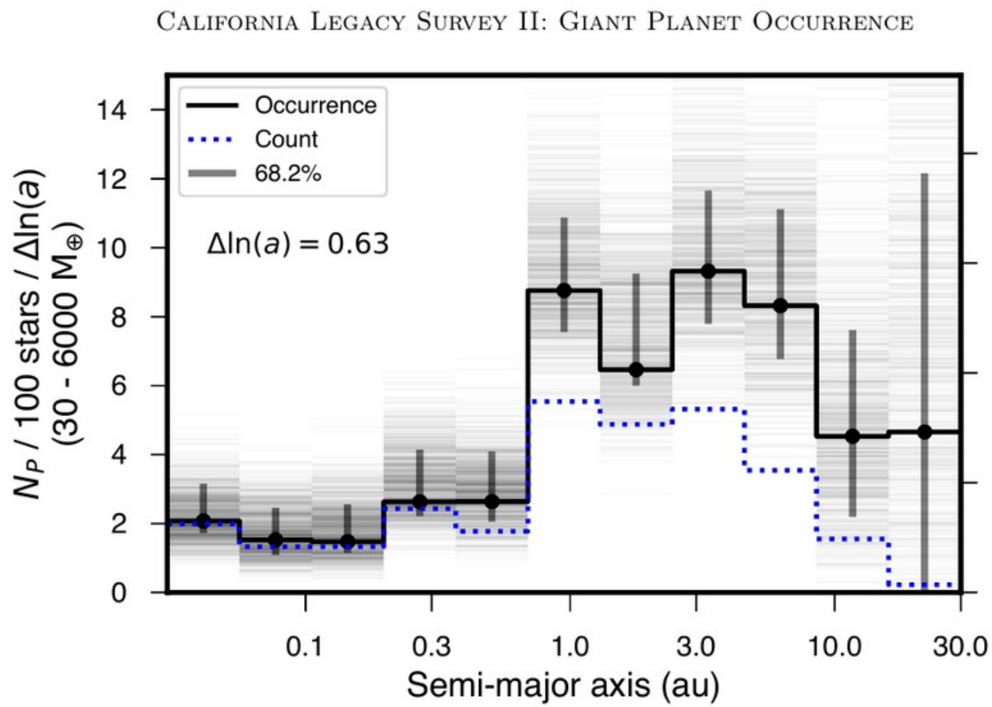
Observed mass distribution (exoplanets encyclopaedia). The agreement is not good but the real distribution is affected by strong observative bias since the data are mostly from radial velocity and small planets are difficult to be found with this method.

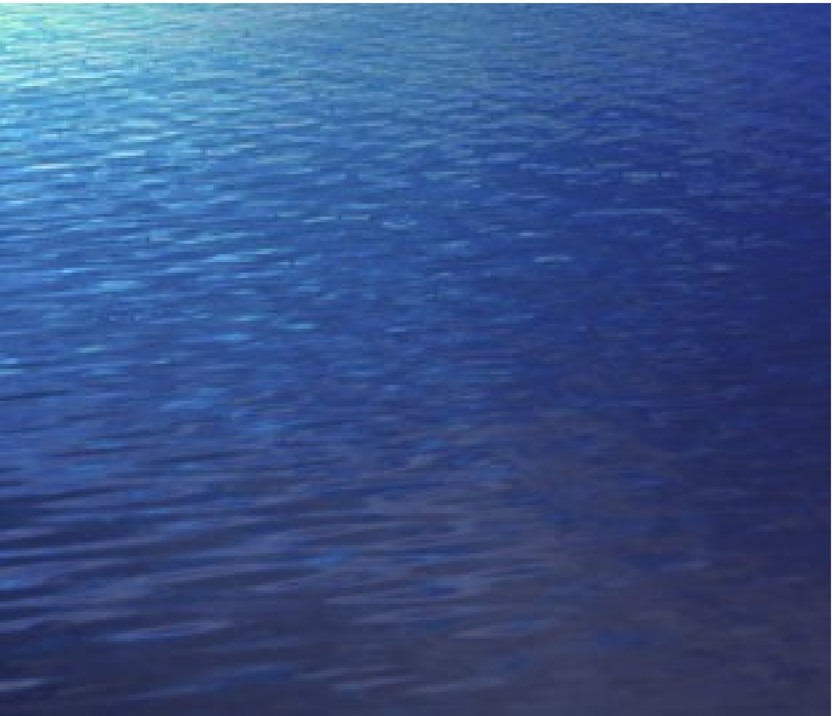


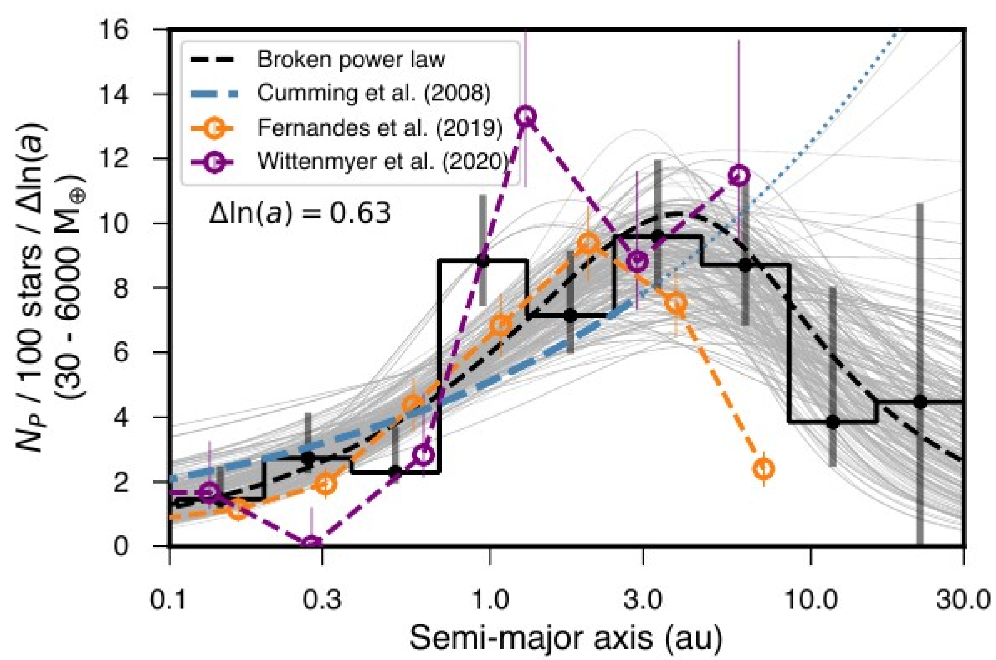


If we compare the models with the radius distribution (mostly due to transit observations) the agreement is much better.

Jupiter size planets…….


California Legacy Survey II: Giant Planet Occurrence
Occurrence
Count
68.2%
$\Delta\ln(a) = 0.63$
N_P / 100 stars / $\Delta\ln(a)$
(30 - 6000 $M_\oplus$)
N_P / 100 stars
Semi-major axis (au)




Broken power law
Cumming et al. (2008)
Fernandes et al. (2019)
Wittenmyer et al. (2020)
$\Delta\ln(a) = 0.63$
N_P / 100 stars / $\Delta\ln(a)$
(30 - 6000 $M_\oplus$)
Semi-major axis (au)

HD 209458b: Hot Jupiter with tail like a comet...

- Planet: m = 0.69 M_J R= 1.42 ± 0.17 R_J ρ = 0.31 ± 0.07 g/cm^3 T ~ 1200 K

  a= 0.048 AU e=0.0 i=86.1 ± 1.6 deg P=3.52 day

- Star: G0V, 1.05 M_s eta'= 4-6 Gyr [FeH] = 0.04 ± 0.02 150 ly
- M_flow = 3.16 x 10^{23} gr/Gyr

- Observations with HST spectrograph have revealed hydrogen ejected from the planet (absorption of star light during occultation) forming a tail (Vidal & Madjar 2003) possibly because of the high temperature due to star irradiation (10^4 that of Jupiter).
- Atmosphere contains O, C, Na (Charbonneau et al. 2003)

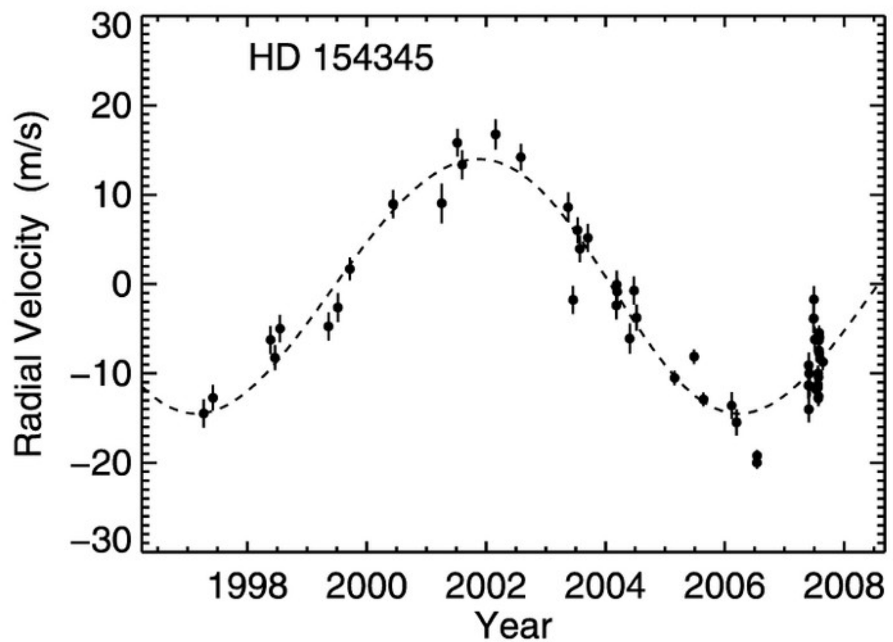
Solar system Jupiter analog (Wright et al. 2008, ApJ L63

Stellar Properties of HD 154345

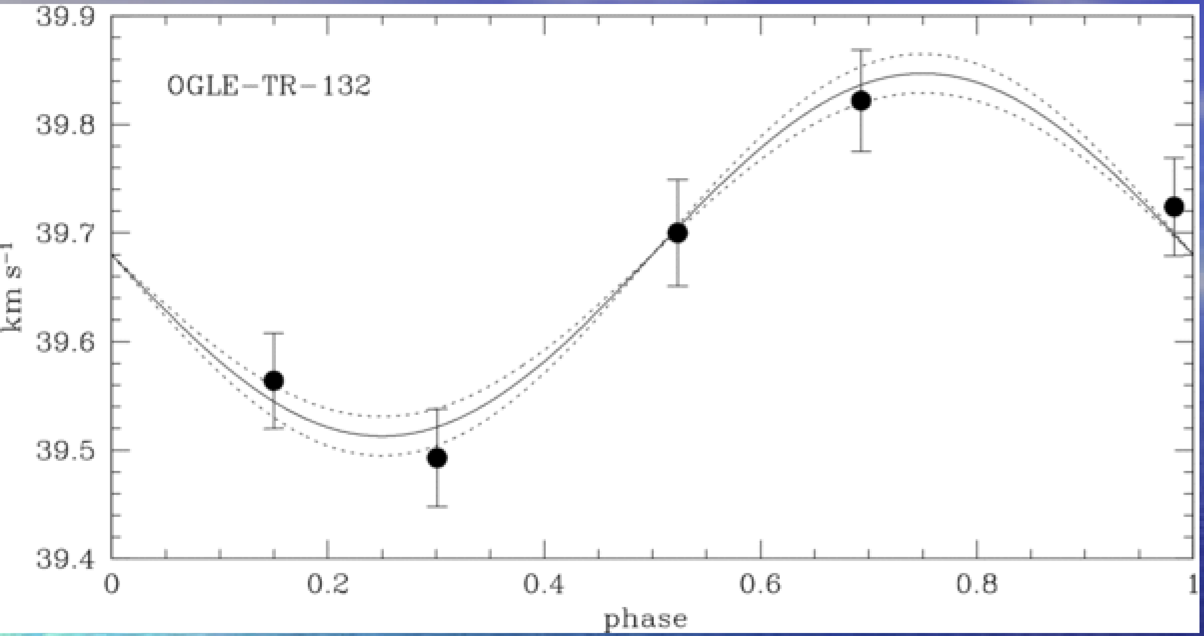
Parameter	Value
Spectral type	G8 V
Hipparcos ID	83389
R.A.	$17^h02^m36.404^s$
Decl.	$+47°04'54.77''$
$B - V$	0.73
V	6.76
Distance	18.06 ± 0.18 pc
M_V	5.48
$T_{\rm eff}$	5468 ± 44 K
log g (cm s^2)	4.537 ± 0.06
[Fe/H]	-0.105 ± 0.03
$v \sin i$	1.21 ± 0.5 km s^{-1}
Mass	$0.88 \pm 0.09\ M_\odot$
Radius	$0.94 \pm 0.03\ R_\odot$

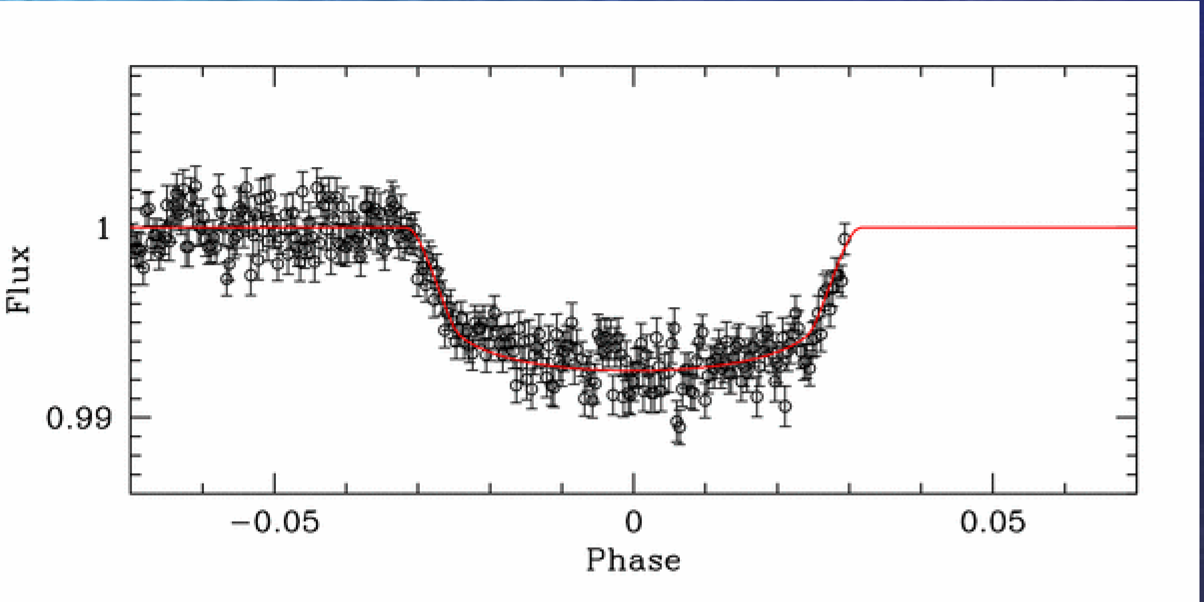
Orbital Properties of HD 154345b

Parameter	Value
P	9.15 ± 0.26 yr
e	0.044 ± 0.046[a]
ω	68° [a]
T_p	JD 2,452,830 $\pm$ 330
K	14.03 ± 0.75 m s^{-1}
$m \sin i$	$0.947 \pm 0.090\ M_{\rm Jup}$
a	4.19 ± 0.26 AU



OGLE-TR-132b



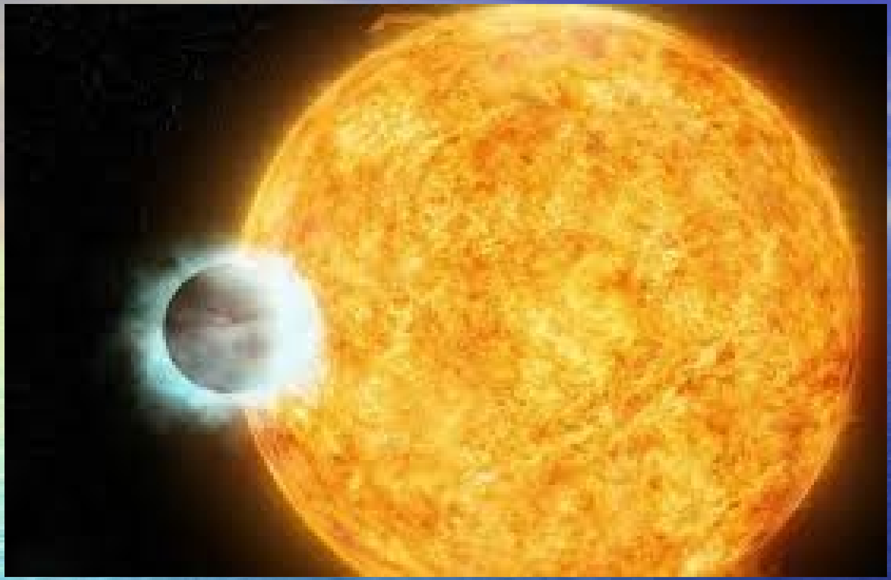


- $R = 1.13 \pm 0.08\ R_J$
- $M = 1.19 \pm 0.13\ M_J$
- $a = 0.036 \pm 0.0008$ AU
- $e = 0$
- $I = 85^o \pm 1^o$
- Star type: F
- Ms = 1.35 ± 0.06 Msun
- [Fe/H] = 0.43 ± 0.18
- Distance: 1500 pc

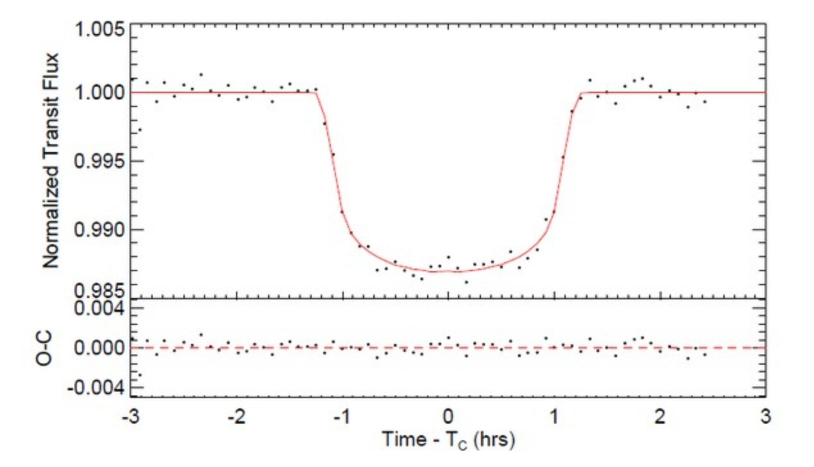
Hot Jupiter

Moutou et al. 2004

KELT-16 b: period=1day, a=0.02 au, T~2500 K, dens=1.4 g/cm^3



Tidal evolution: it might be swallowed by the star on a timescale as short as a few Myr



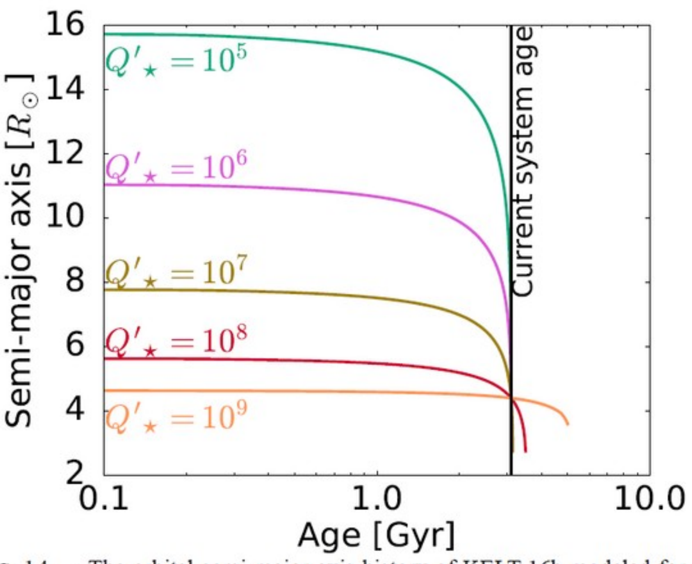
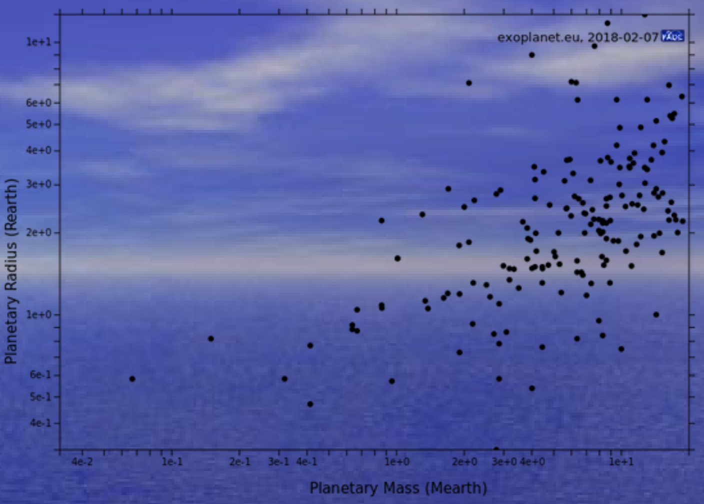


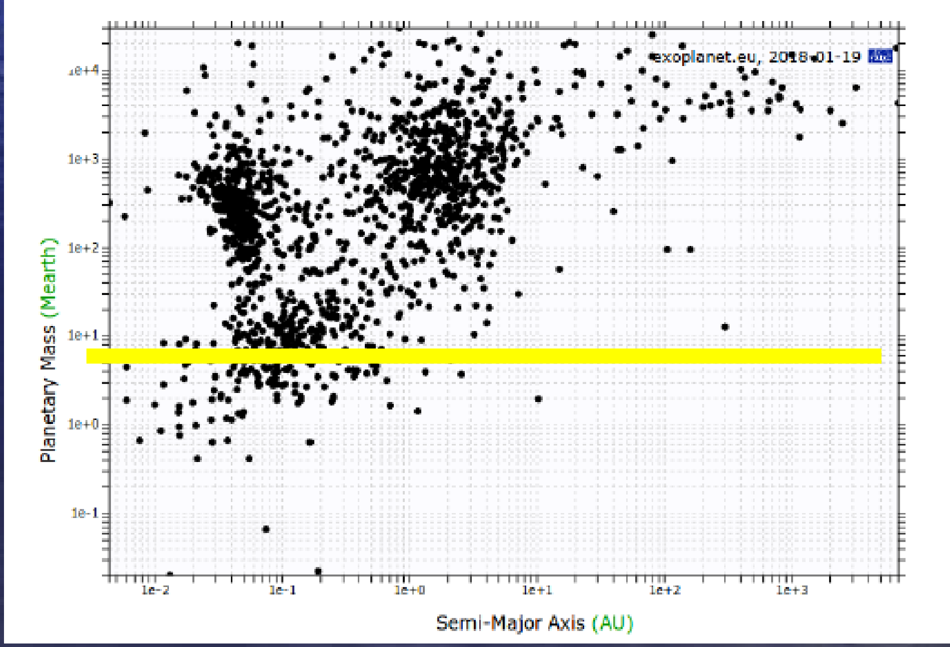
FIG. 14.— The orbital semi-major axis history of KELT-16b modeled for a range of stellar tidal quality factors, Q'_*, where $Q_*'^{-1}$ is the product of the tidal phase lag and the Love number. The black vertical line marks the current system age of 3.1 Gyr.

Rocky-Icy planets: Earths, Super-Earths, Neptunes, super-Neptunes….

Terrestrial planets, Earths and Super-Earths: definition and frequency.



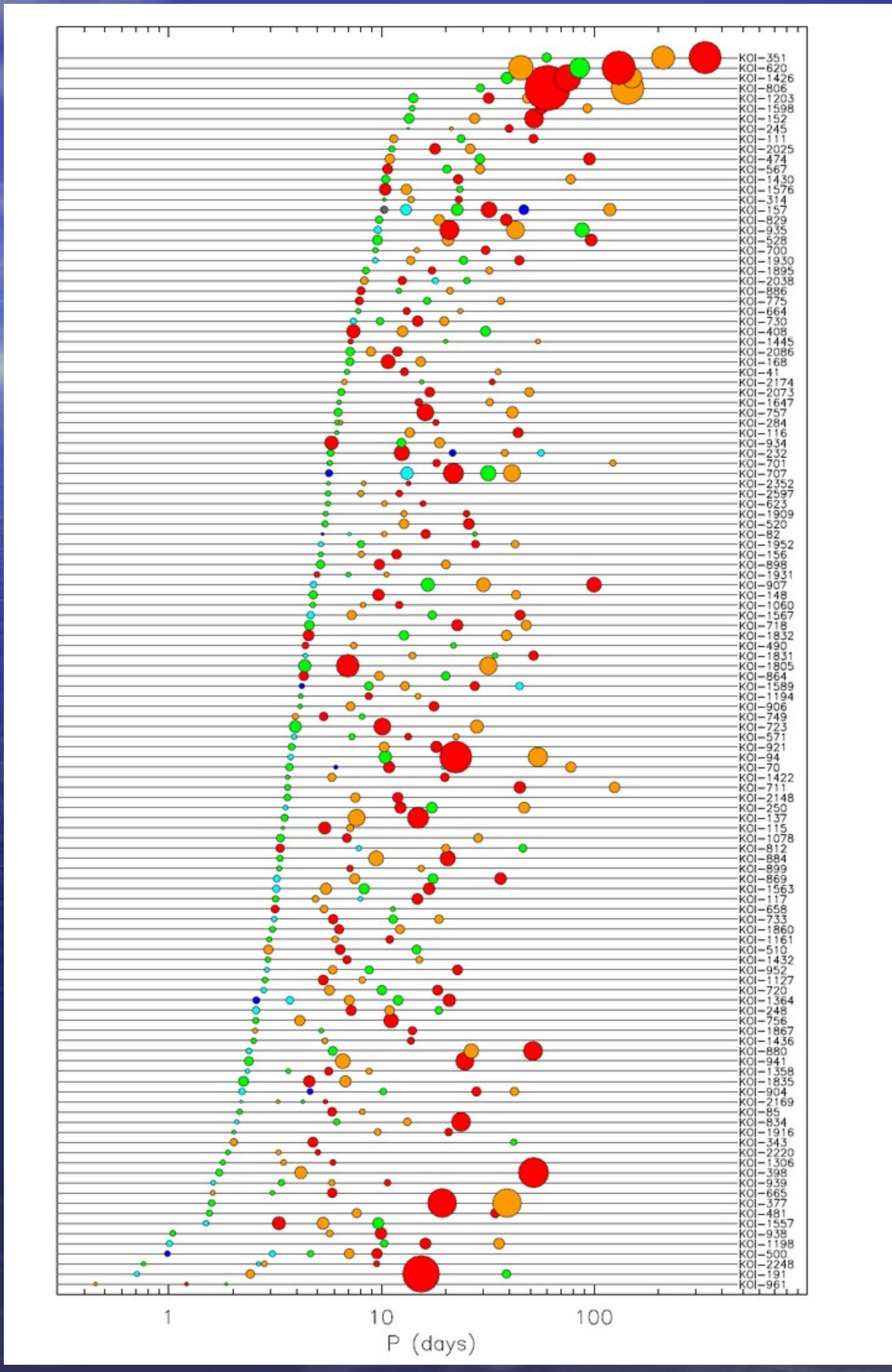
- Mass range: 1-15 Earth masses
- Composition: rocky (high density > 3 g/cm^3), rock+ice, rock+ocean, rock+atmosphere (lower density)
- Frequency: 30-50% of solar mass stars
- No correlation with metallicity: contrary to giant planets.
- Orbital distribution: many hot
- Eccentricity: all values



STIPs (System of Tightly-Packed Inner Planets).

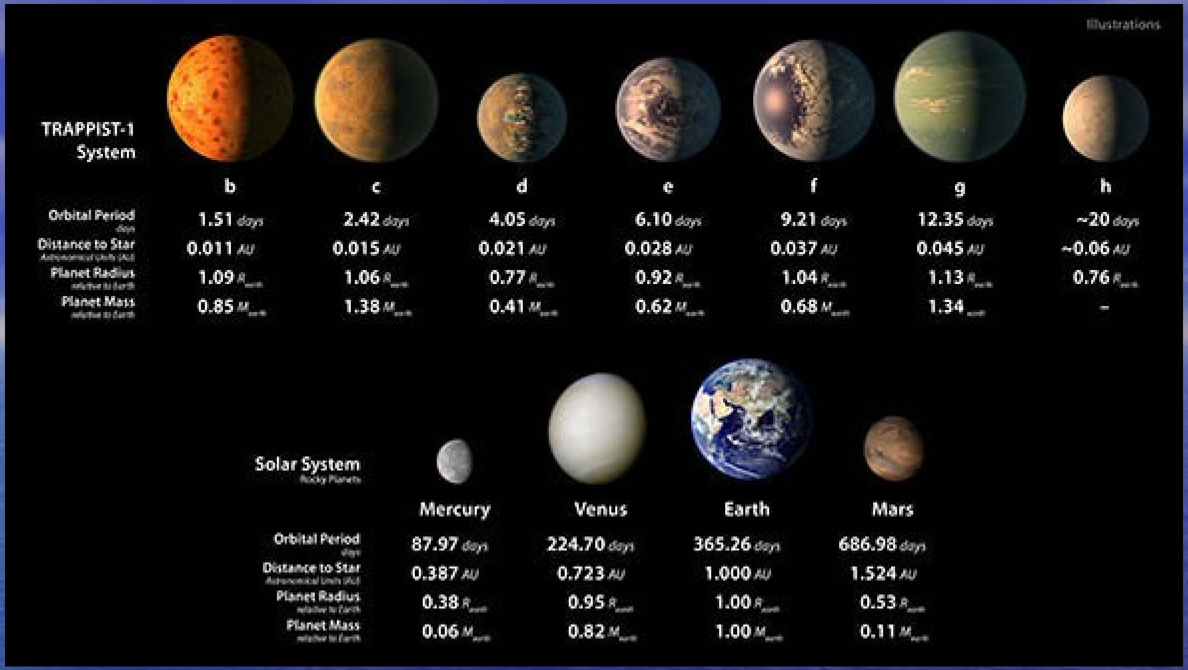
- **Local formation in massive disks (exoplanet MMSN). Rocky planets.**
- **Type I migration. Possible resonant chains. Icy and potentially surrounded by an atmosphere since they formed outwards**
- **Inside-out formation. The first inner planet triggers the formation of the outer ones at dust traps created by its perturbations on the gas or by retreating dead zone.**

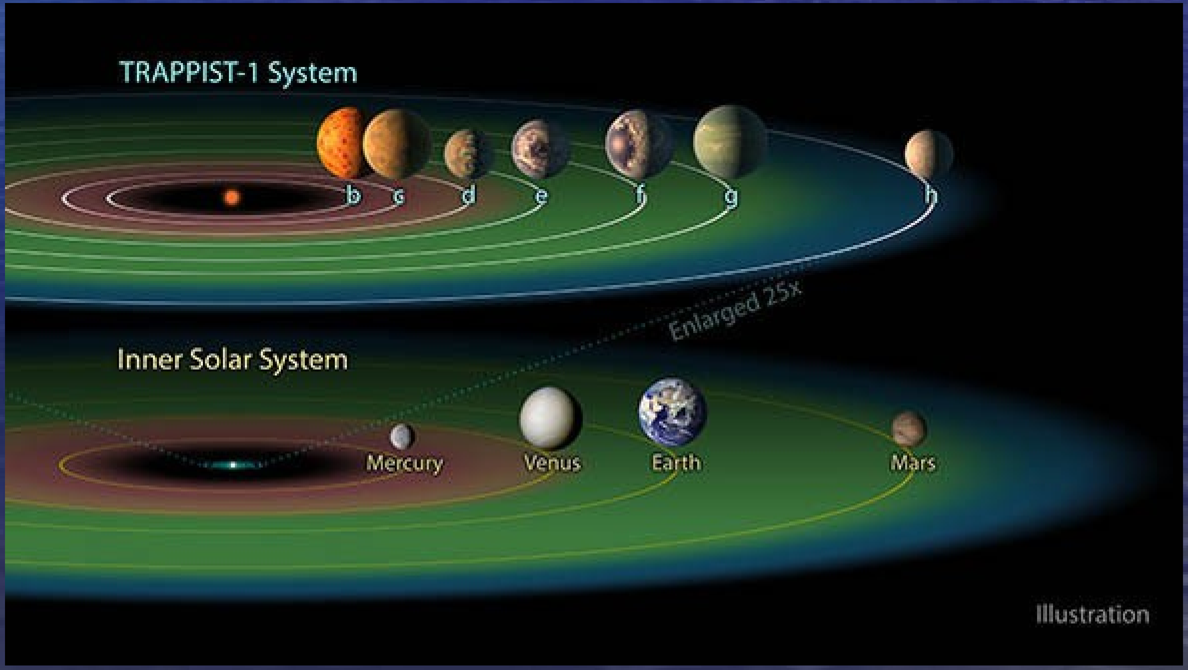
Fabrycky et al. 2014 (watch out! Most are KOIs...)



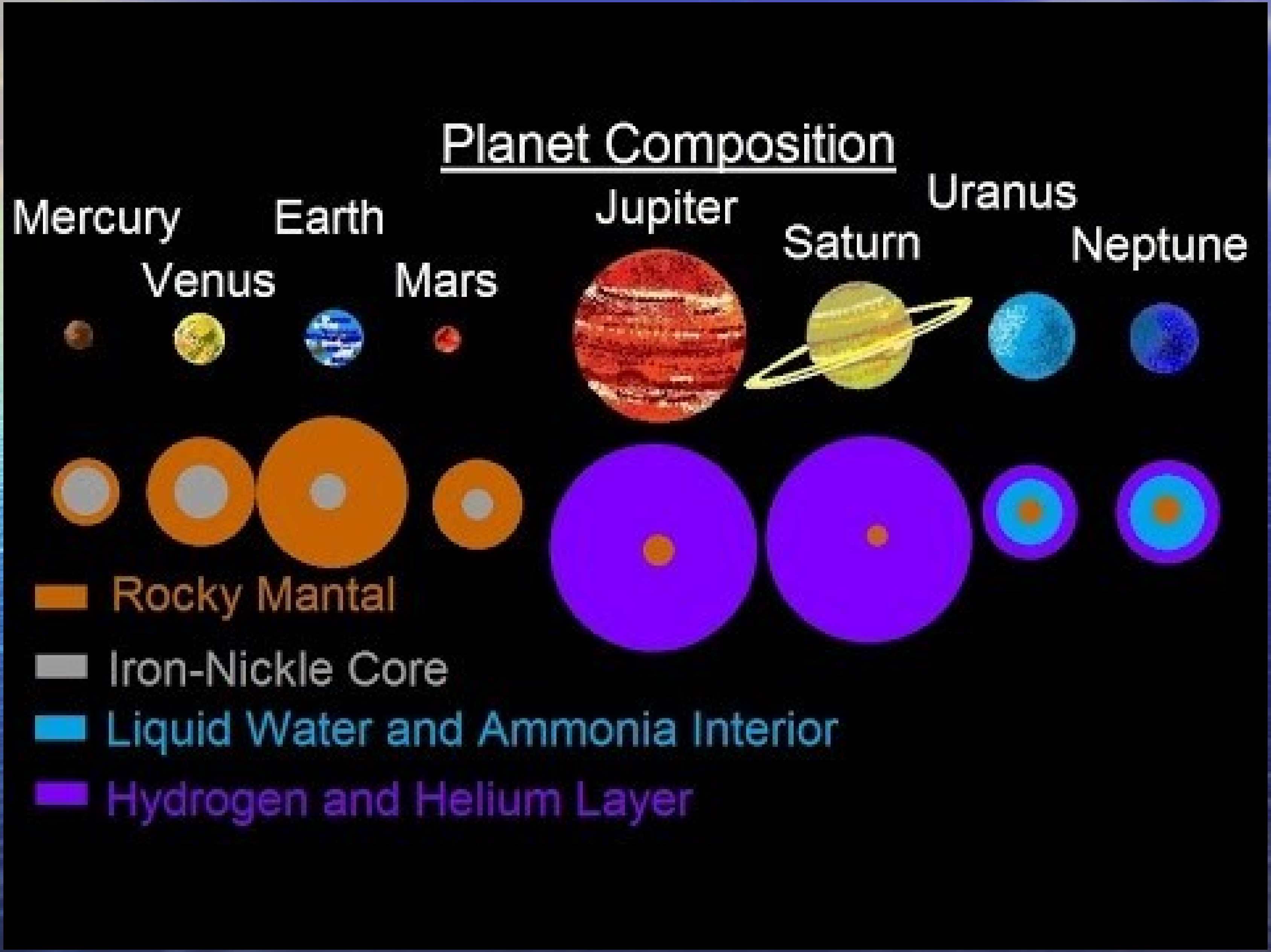
TRAPPIST-1

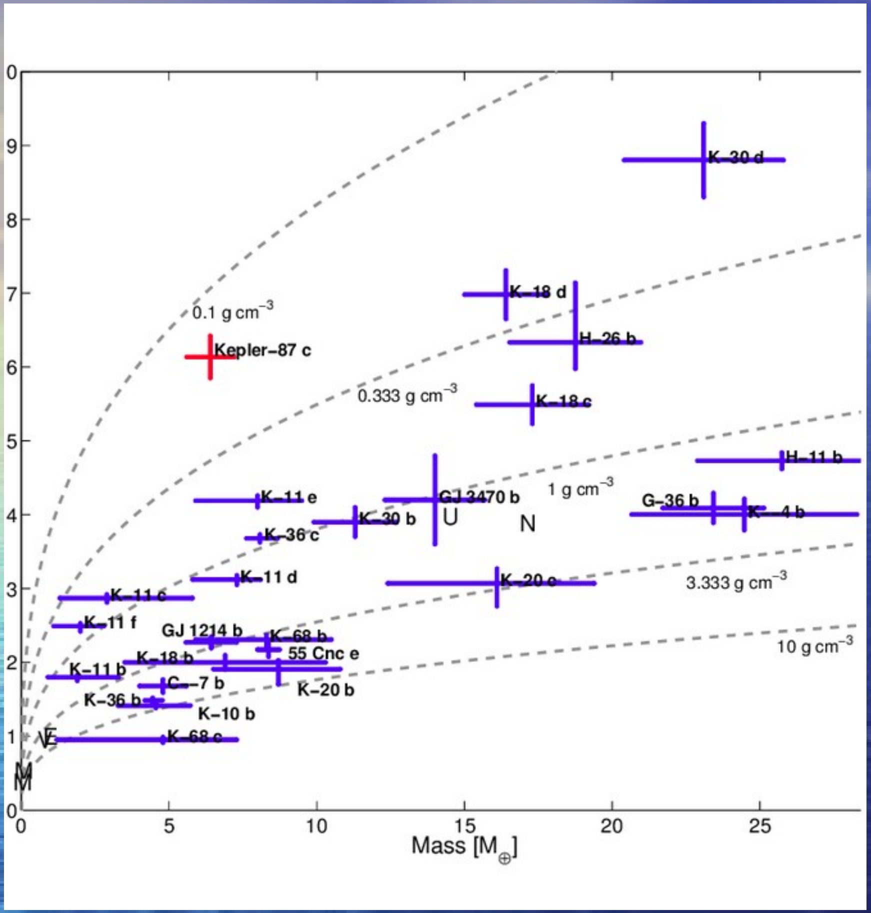
- System with 7 planets (3 in the habitable zone) orbiting a red dwarf with mass $M = 0.08\ M_s$ and $T = 2550$ K.





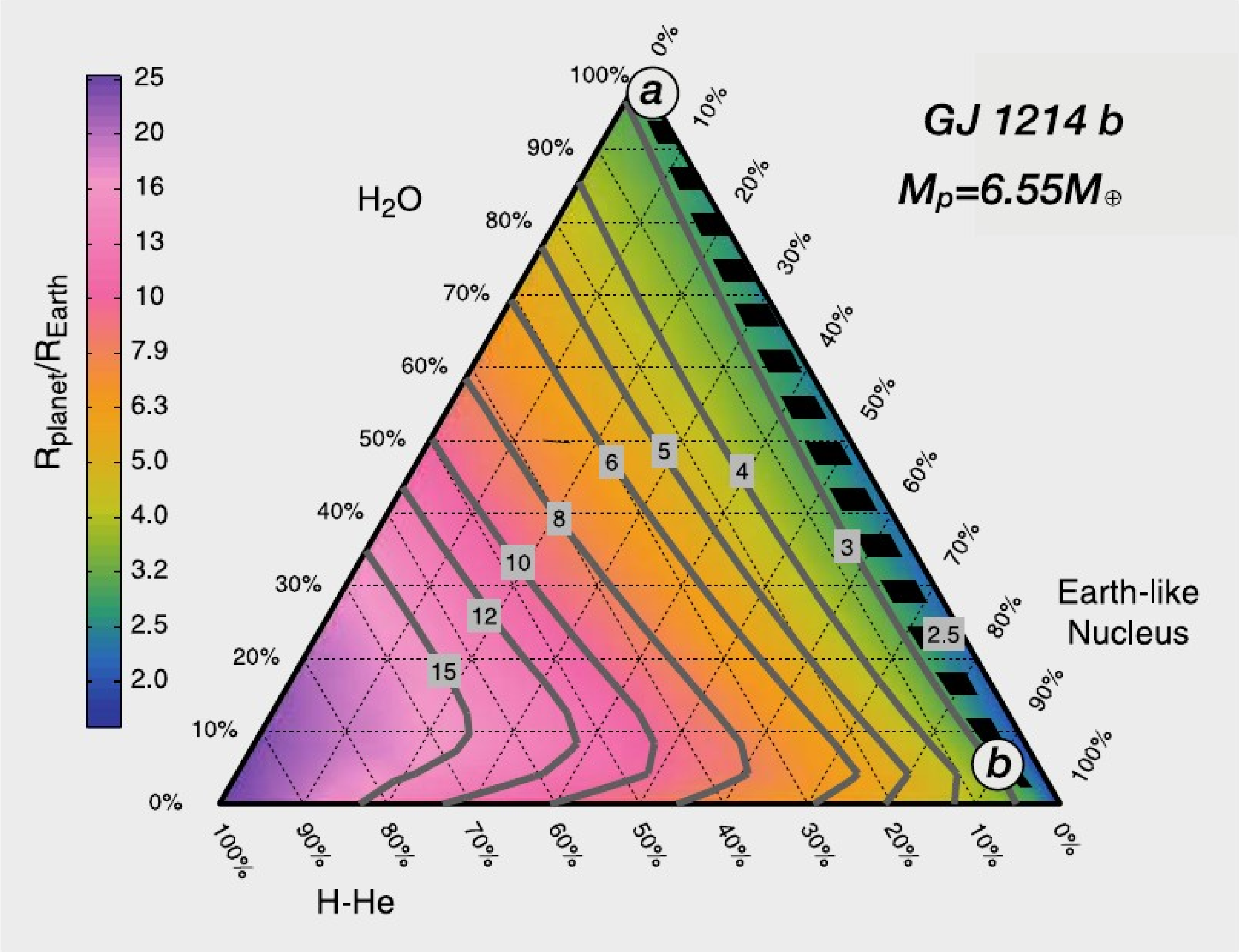
Wide distribution of possible composition among small planets.



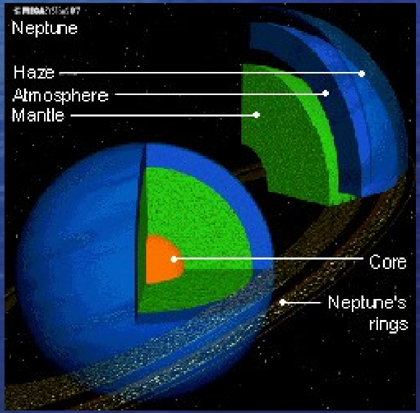


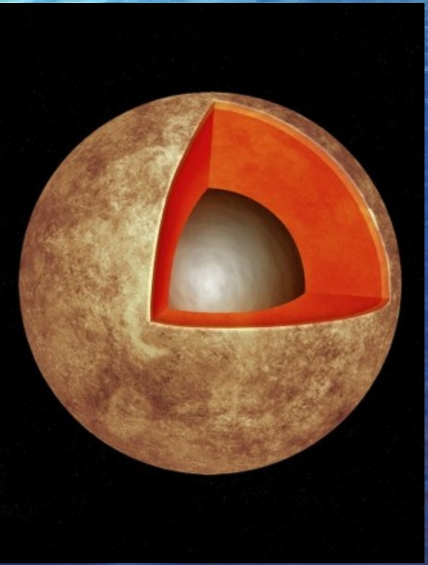
Density of some exoplanets with mass lower than 30 Earth masses. They have been observed with both radial velocity (mass) and transit (radius) so we know the density. Very different values are observed indicating significantly different composition

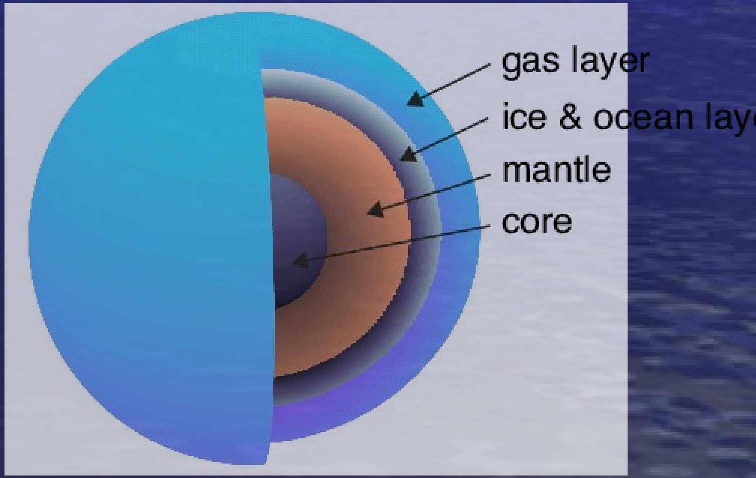
Once fixed the mass, the radius can change by more than a factor 10 depending on the amount of H/He in the atmosphere, the size of the nucleus (rock/ice) and the amount of water present on the surface. (ternary diagrams, Valencia et al., ApJ 775, 2013)



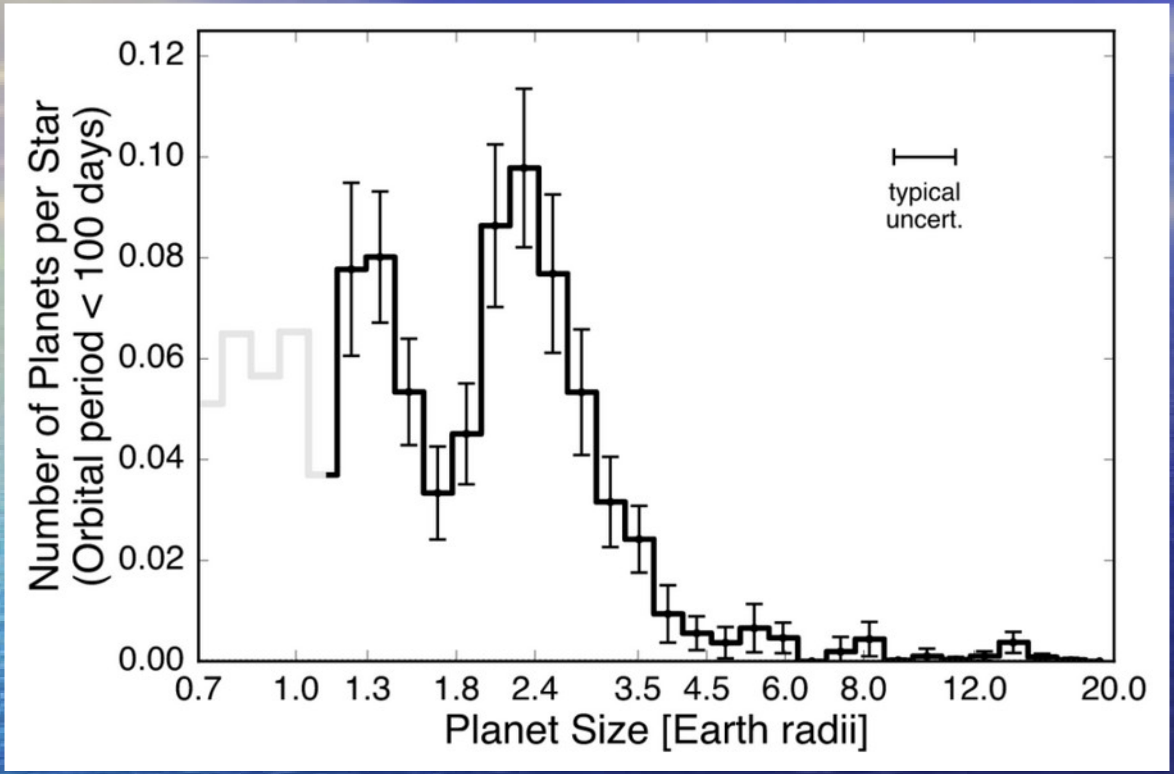
Different possible compositional distributions within planets. It depends on where they form (they can then migrate inwards), from the mass and temperature of the protoplanetary disk etc…







The radius valley between 1.5-2.0 Earth radii



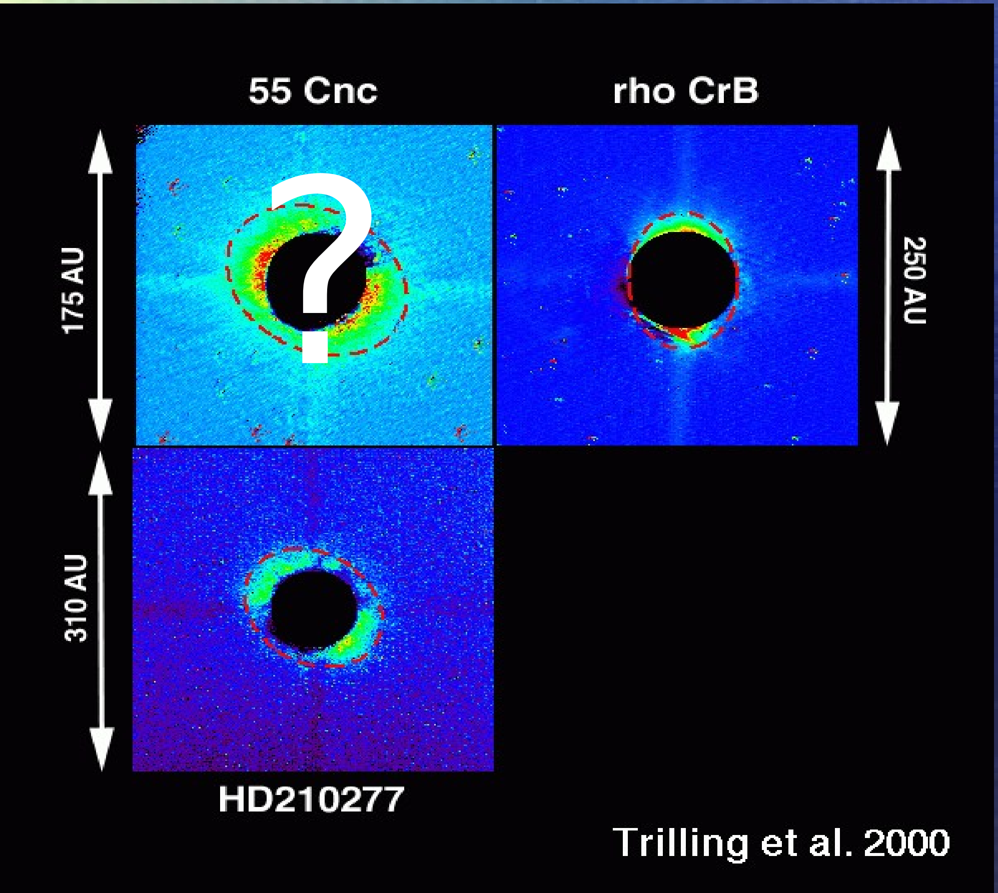
The valley may separate rocky planets from planets with atmosphere.

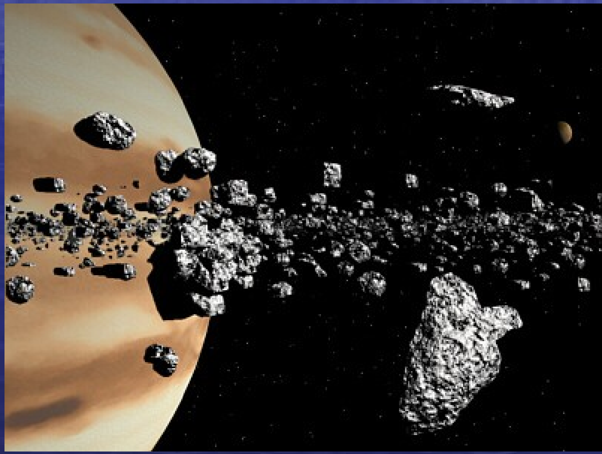
1) XUV photoevaporation
2) Core powered mass loss (heating from the planet)
3) Pebble isolation mass, those experiencing pebble isolation accret more gas because they are cooler.

Additional players in exoplanetary systems: debris disks. Disk made of dust produced by leftover planetesimal belts.

Debris disks

- Dust produced in collisions between leftover planetesimal belts
- They can give hints of the presence of a planet(s).



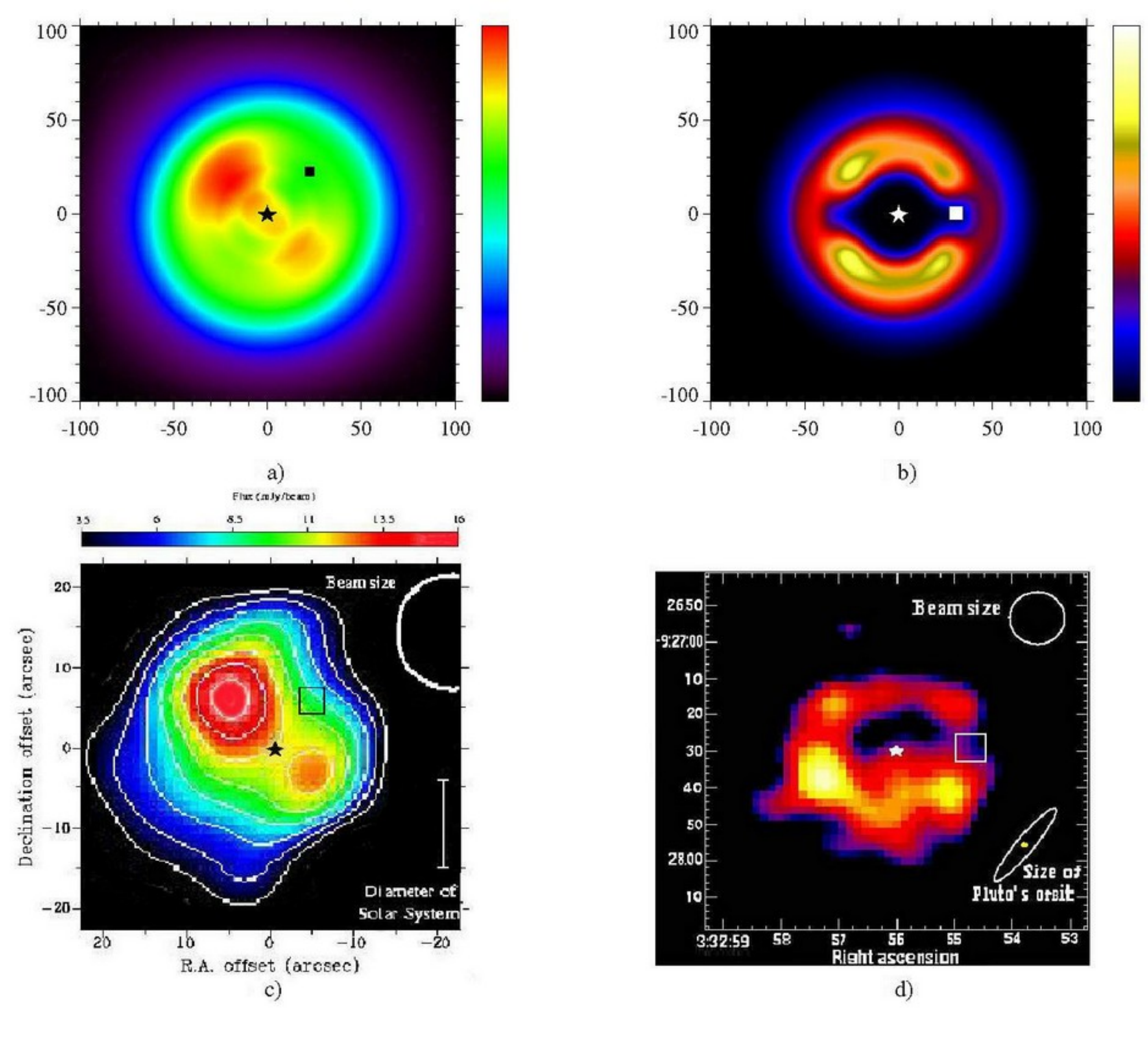


If a planet and a debris disk are observed at the same time, the inclination of the planet orbit can be guessed.

STRUCTURES (SPIRALS, CLUMPS, VOIDS..) CAN SIGNAL THE PRESENCE OF A PLANET AROUND THE STAR.

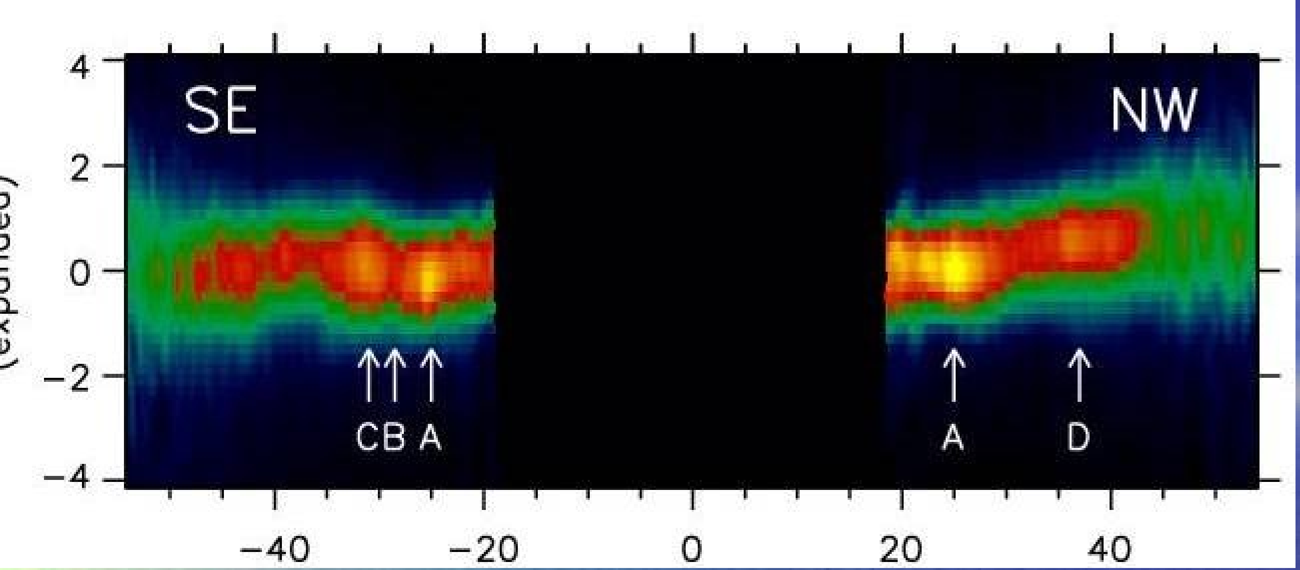
Vega

ε Eridani (Planet (? The star is active) at 3.2 au with M sin i = 256 M_{Earth})



Computer simulations of a dusty disk with a planet inside

Observations of the debris disks at 0.2-3 mm with the J. C. Maxwell telescope in Hawaii



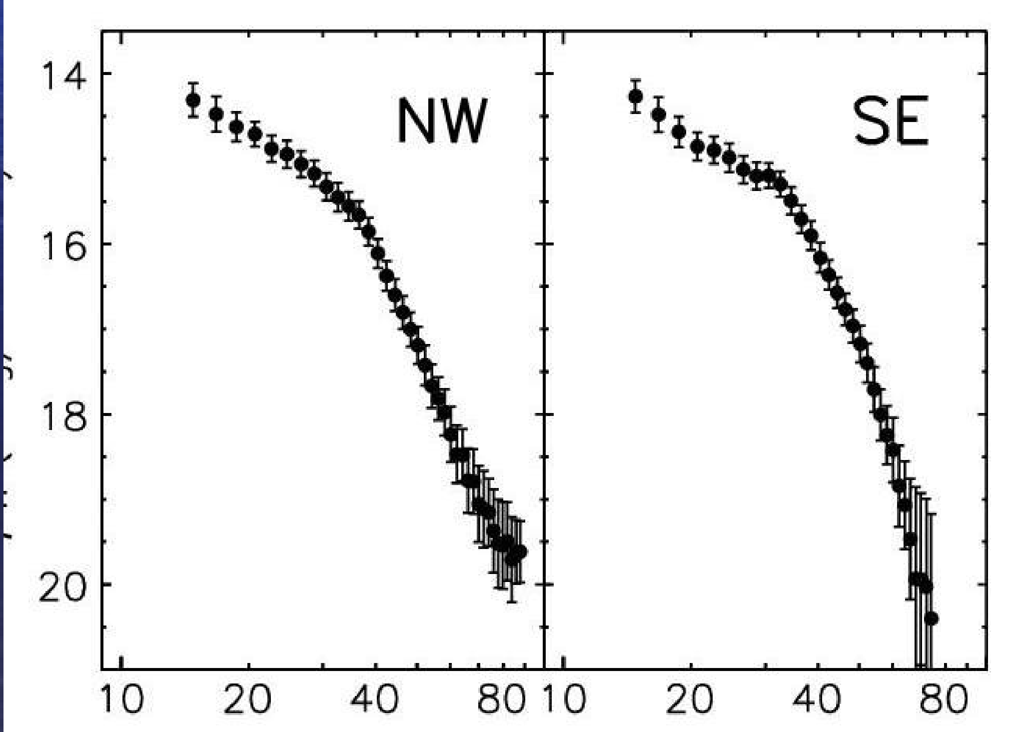
AU Mic (GJ 803)

- M-dwarf star 0.5 M_s
- Age = 22 ± 3 Myr
- Distance about 10 pc
- Asymmetric debris disk

Infrared image with coronograph taken at Keck.

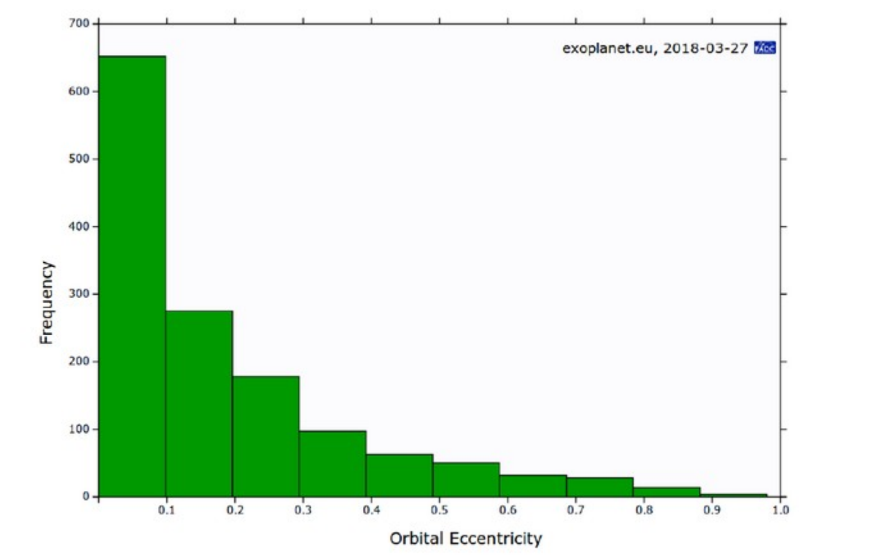
- **Disk mass: 0.01 M_{sun}**
- **T = 40 K (cold)**

Two planets (Neptune size) found by TESS (transits). Period of 8 and 18 days, potentially in resonance (Martioli et al, A&A.



QUESTIONS….some…

- Why we detect lots of Hot/Warm Jupiters while in the solar system both Jupiter and Saturn are beyond 5 au (and well beyond the frost line)?
- What is the border between planet and brown dwarf? At which mass?
- Why do we observe high eccentricities (even larger than 0.8) while in the solar system the planet eccentricity are all small (apart from Mercury and Pluto)?



The standard model

Protostar +Disk

Planetesimal & pebble formation by dust coagulation or G-instability

Formation of Terrestrial planets and core of giant planets (subsequent gas infall) by planetesimal & pebble accumulation

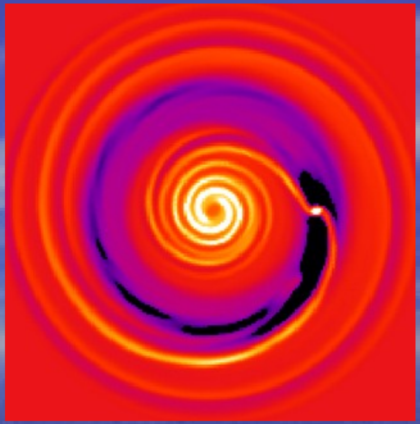
Gas dissipation – final planetary system

Recent Plugins

- Planet migration
- P-P scattering
- Kozai, resonances

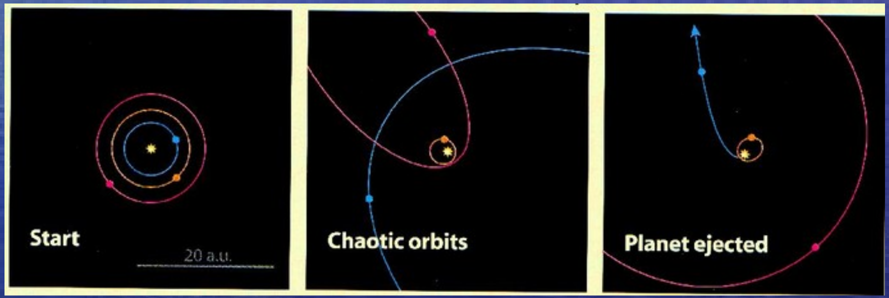
- P-P scattering
- Residual planetesimal scattering
- Tidal interaction with the star

Dynamical evolution:

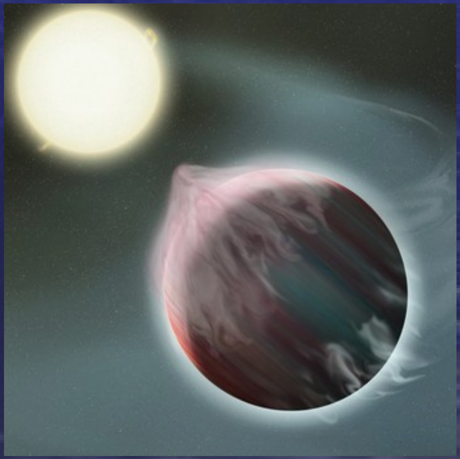


1) Migration by interaction with the disk:

2) P-P scattering

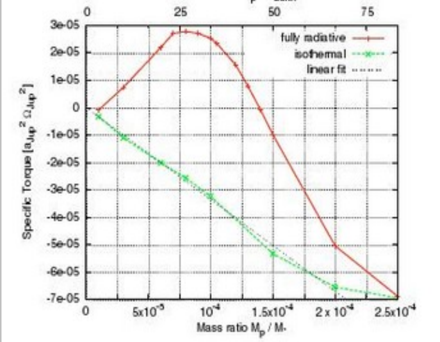


3) Tides



4) Resonances, Kozai, Trojan planets...

Planetary migration: a very complex problem



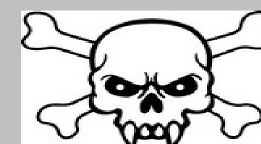
Kley & Crida (2008)

Turbulence (MRI?): stochastic migration

Isothermal, adiabatic, or fully radiative energy equation

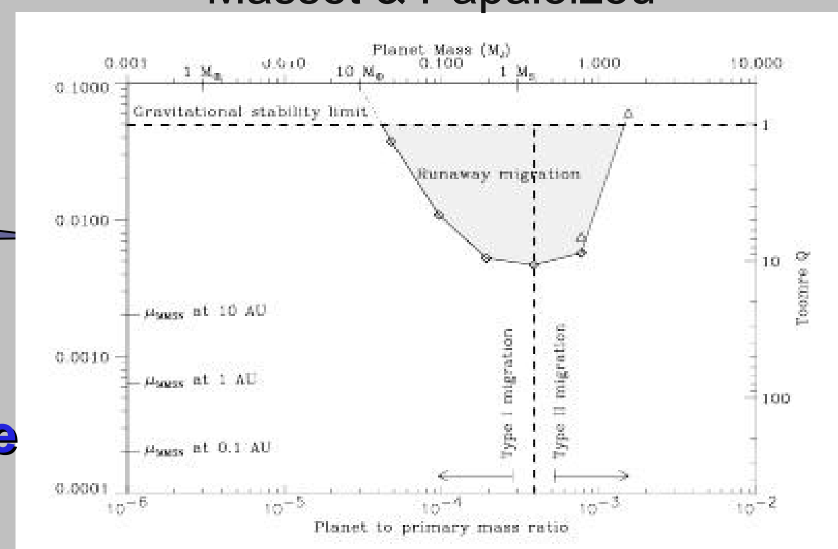
Small planets (1-50 M_E): Type I migration

2D-3D



HS drag

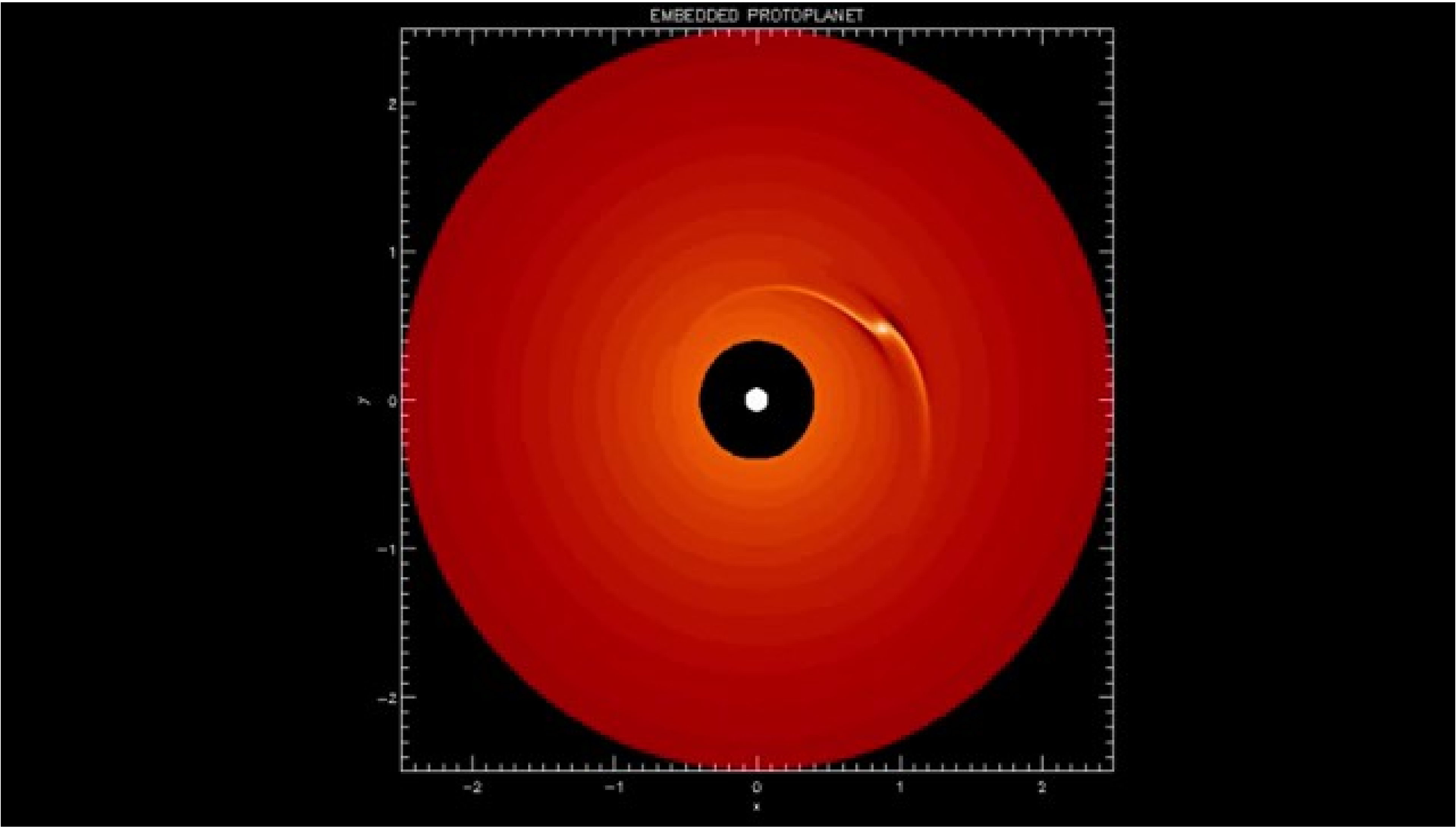
Masset & Papaloizou



Saturn-Jupiter size planets: Type II, III migration

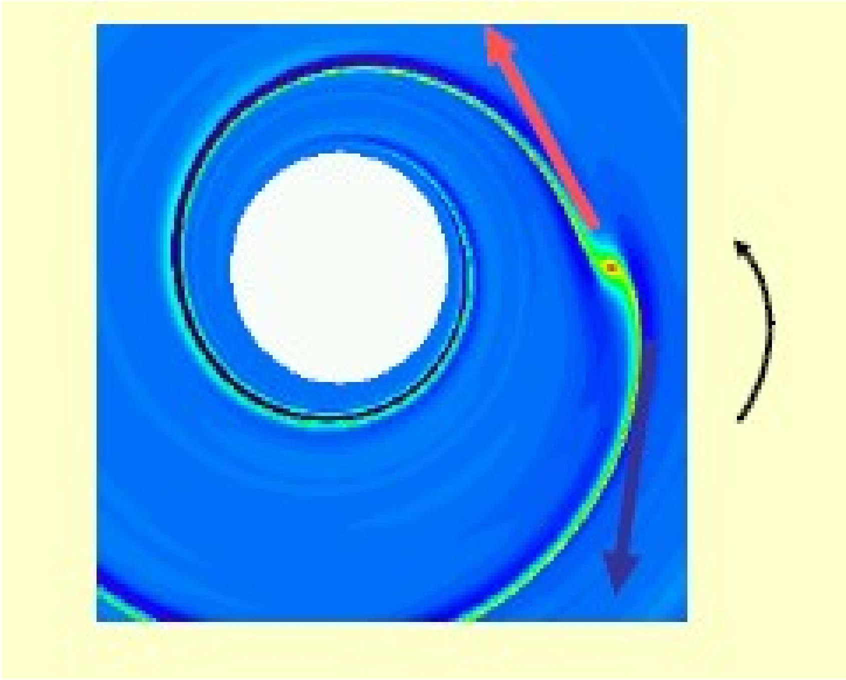
Numerical simulations: resolution close to the planet (CPD handling) and at resonances

Low mass (1-50 M_E) planet: type I migration



The inner wake exerts a positive torque on the planet accelerating it and causing an outward migration

The outer wake exerts a negative torque slowing down the planet and leading to inward migration

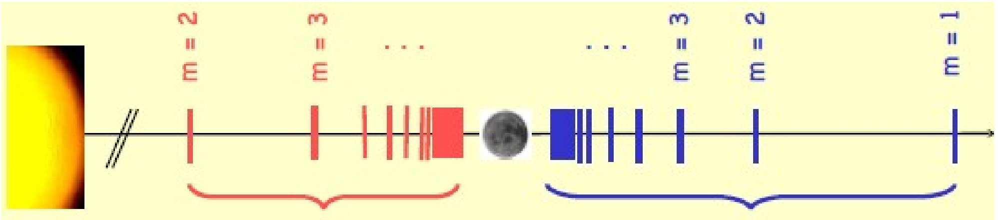


The sum of the two torques, the differential Lindblad torque, is negative and causes inward migration.

QUESTIONS:

- **What is the origin of the wakes?**
- **Can we compute the differential Lindblad torque?**

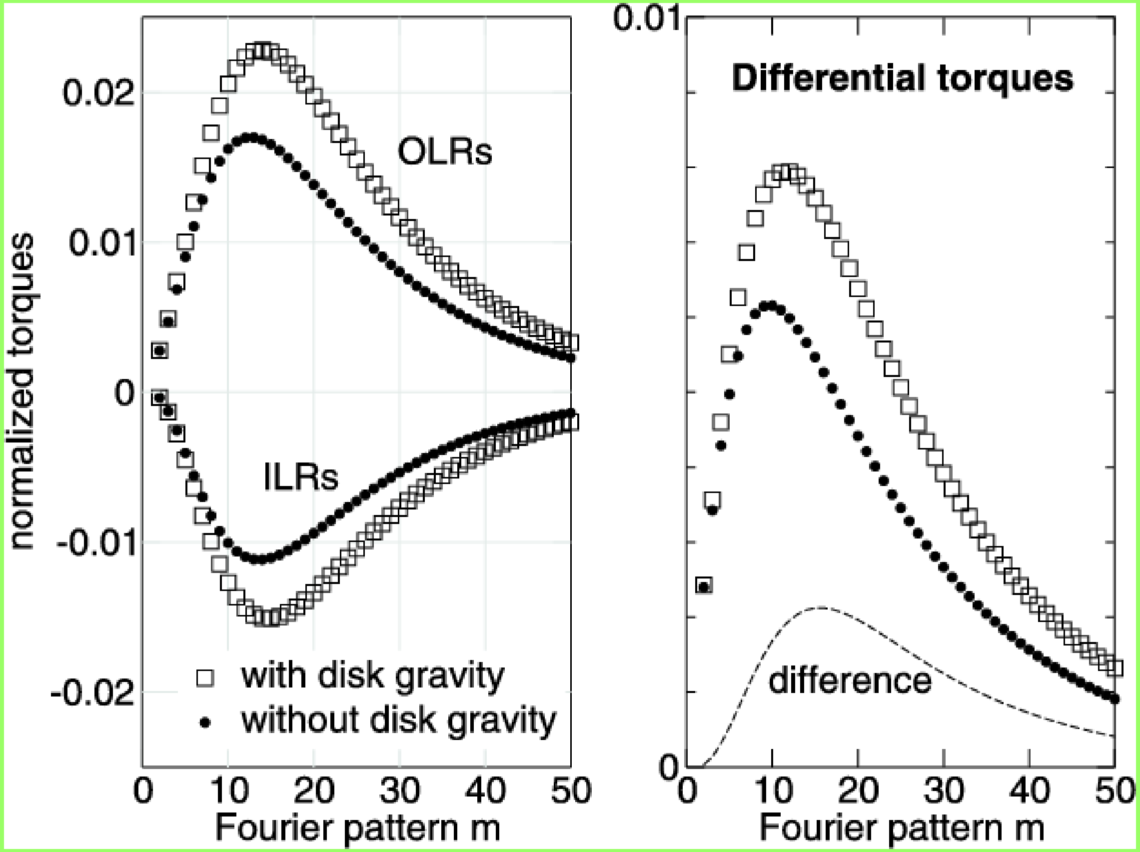
Wakes (2 arms) are given by superposition of sound waves, excited at Lindblad resonances, in a differentially rotating disk.



Lindblad resonances are located in the fluid where

$$(m+k)\,n^p - (m\pm 1)\,n^F - k\,\tilde{\dot{\omega}}^p \mp \tilde{\dot{\omega}}^F$$

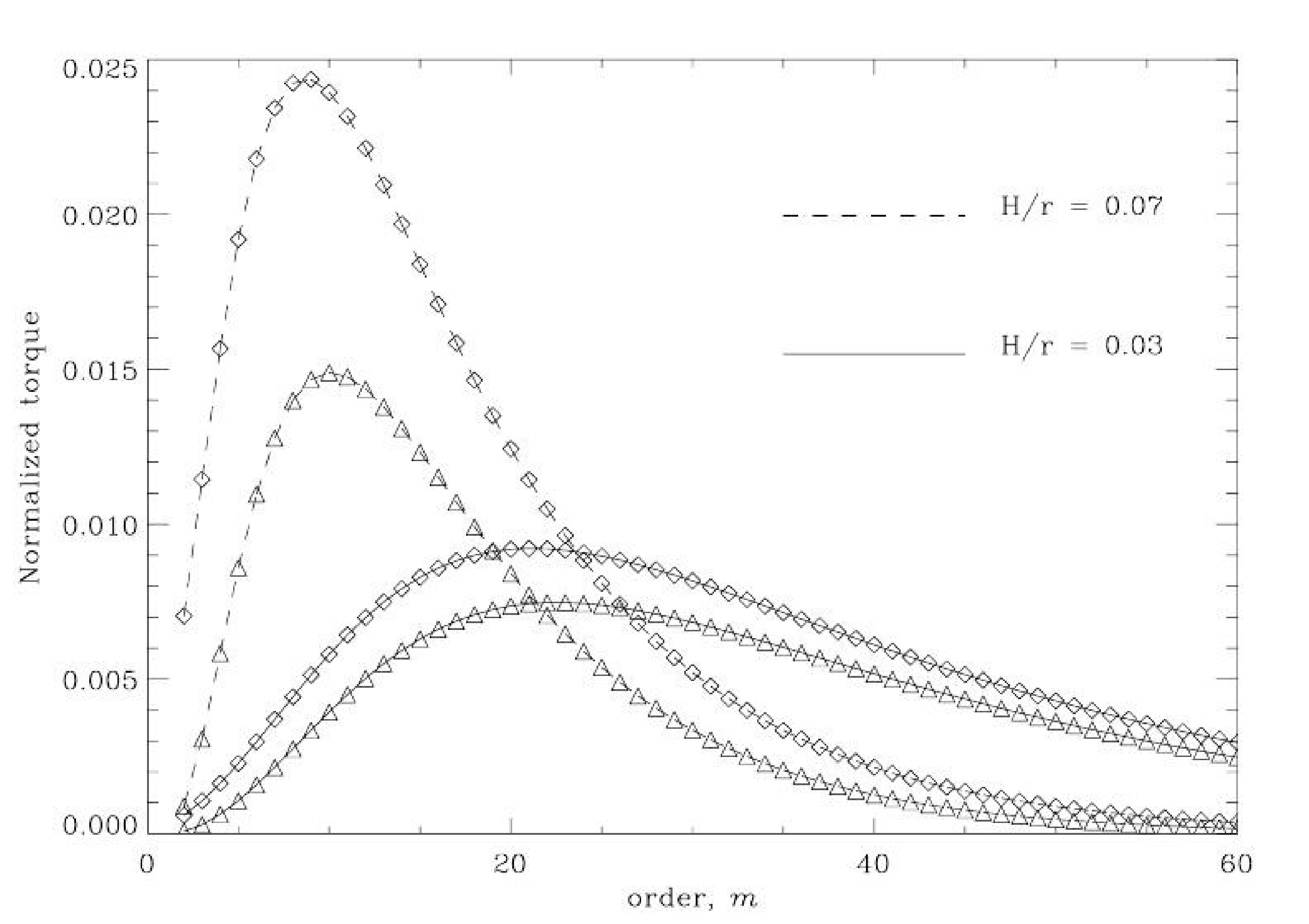
Adding up all the torques at the Lindblad resonances (analitically with the linear approximation or numerically) it is possible to give an expression for the total torque on the planet.



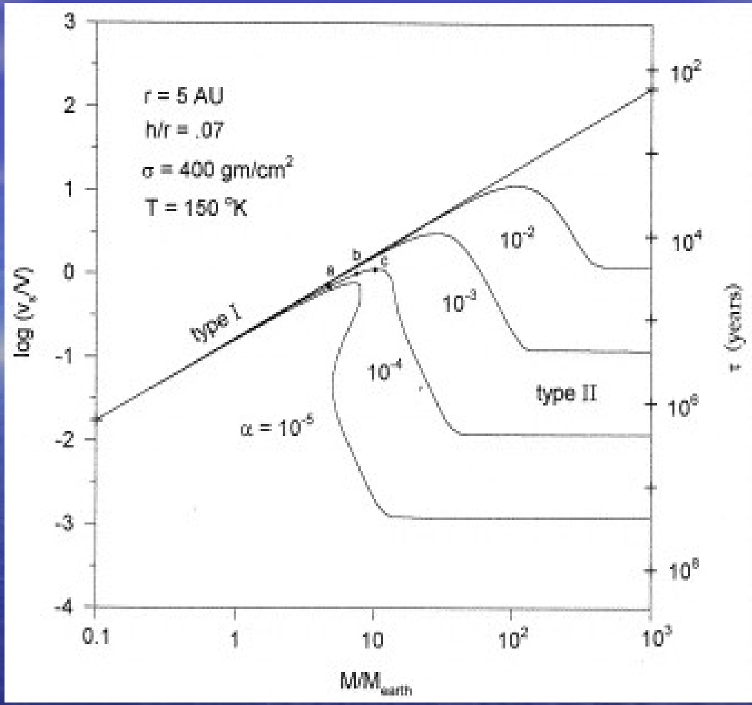
$$T = -(2.5 + 1.7\beta - 0.1\alpha)\left(\frac{0.4}{\epsilon / H}\right)\Sigma\left(\frac{M_p}{M_s}\right)^2 \Omega^2 a^4 / h^3$$

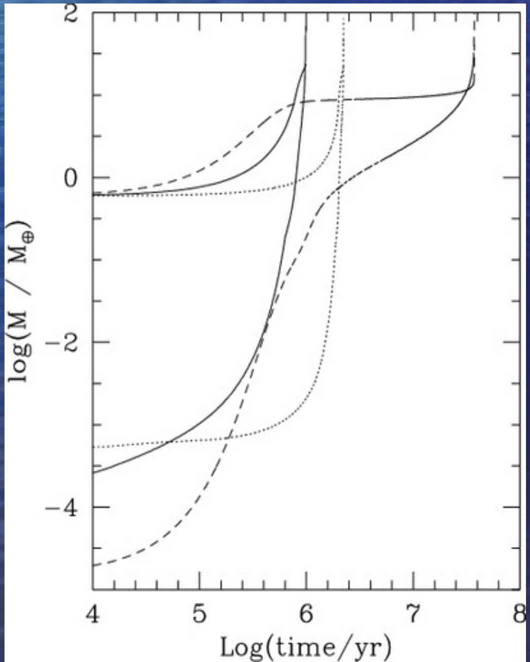
Where α is the exponend of the density power law and β that of the temperature profile

Eample of how the torque depends on the disk parameters



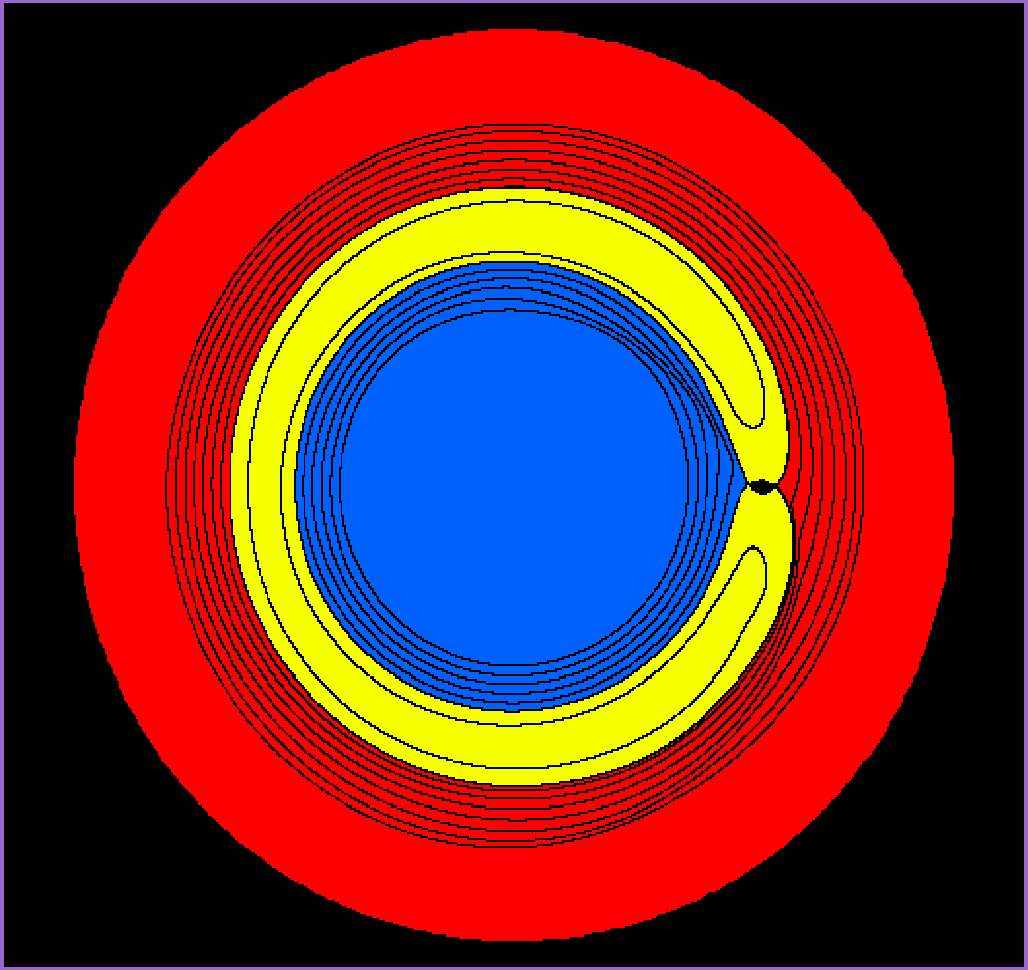
Type I migration too fast! Planetary embryos would fall onto the star before accreting the gas and become gas giants. For this reason Alibert et al. (2004,2005) assumed that the migration speed was a factor 30 lower than that computed. In this way they were able to reproduce with their model of planet formation+migration the observed distribution in mass and orbital elements of exoplanets.





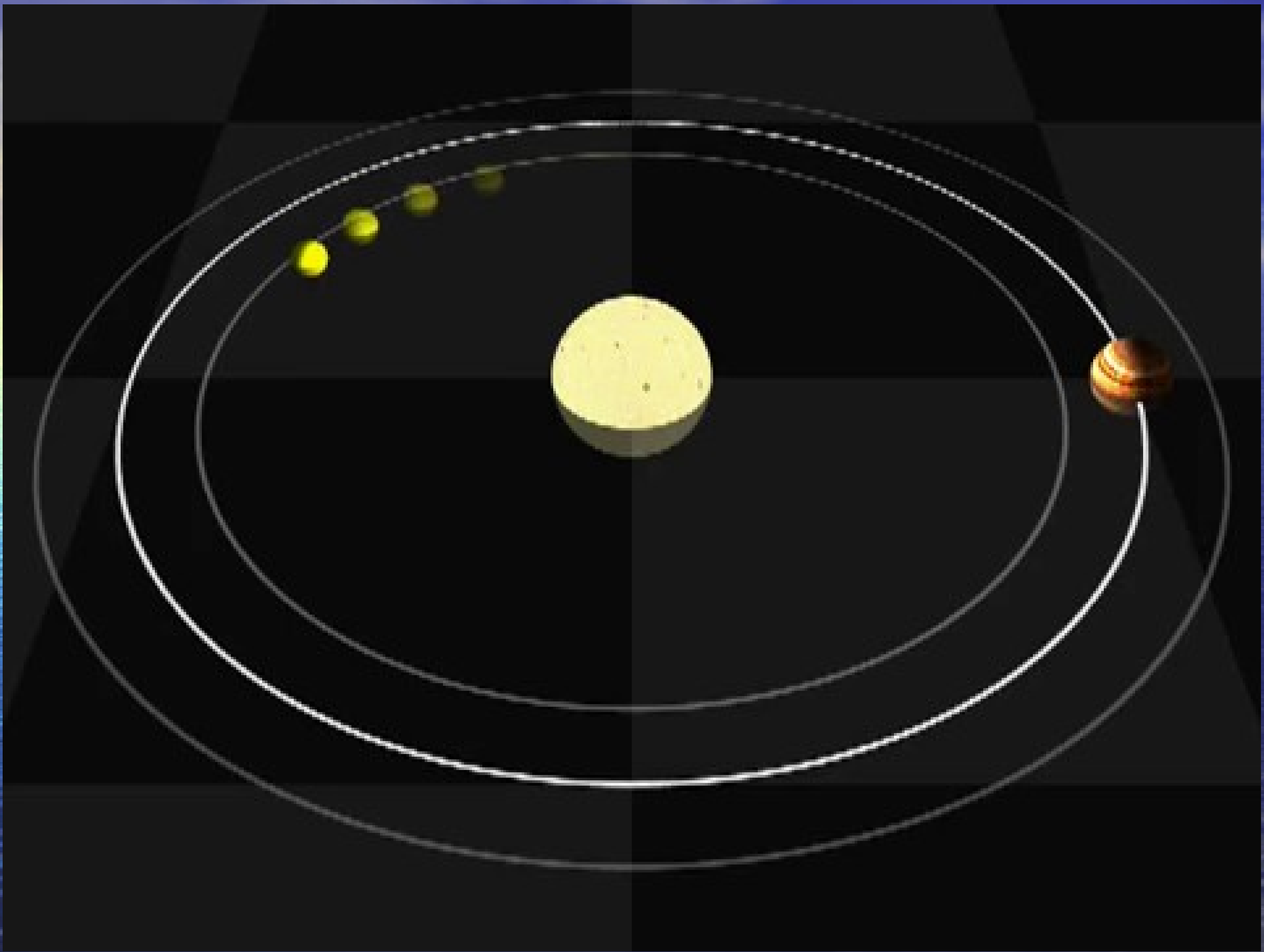
Models of Jupiter formation with migration. Timescales of a few Myr compatible with the lifetime of the disk.

Horseshoe torque

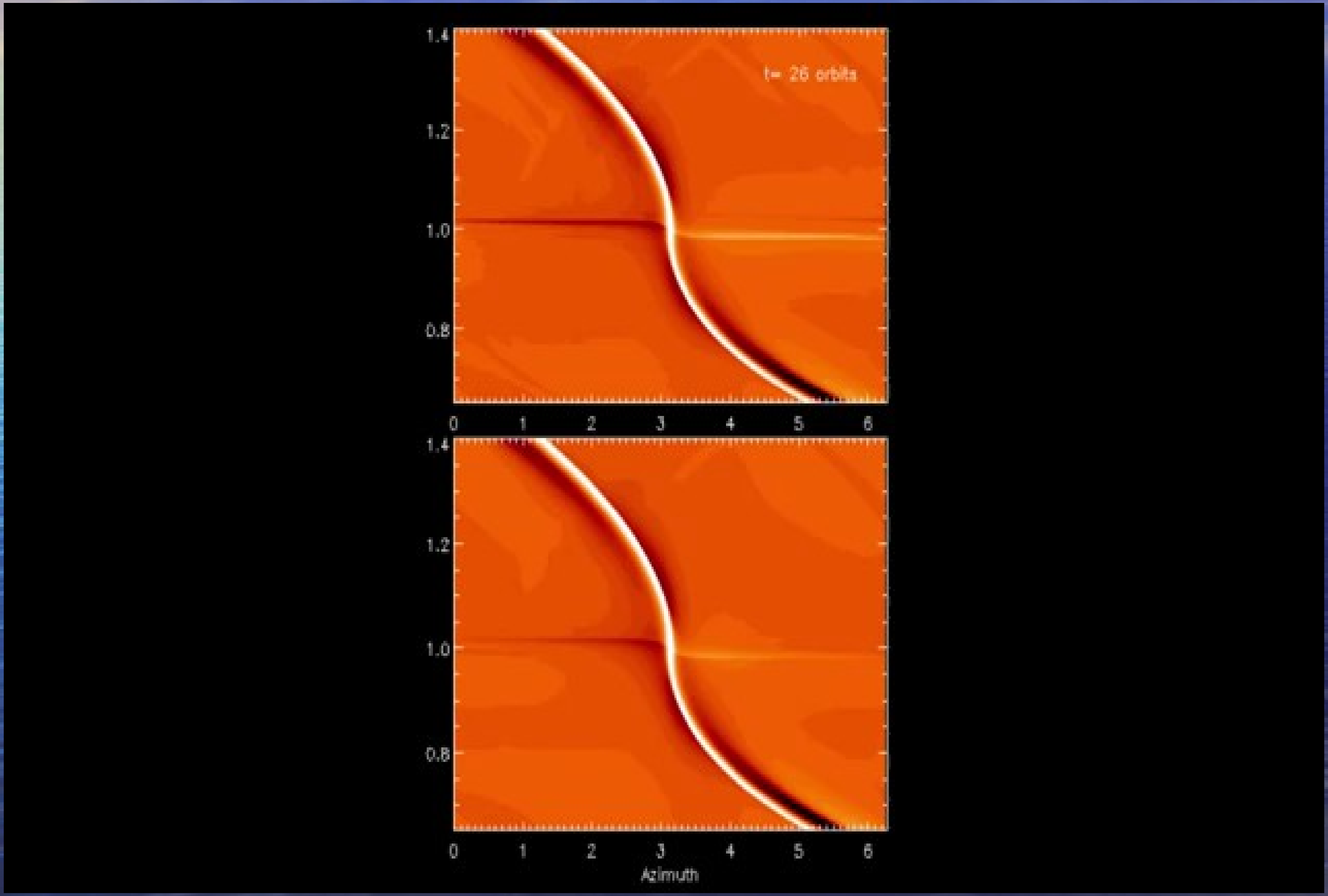


The inner and outer disc
are responsible for the Lindblad torque.

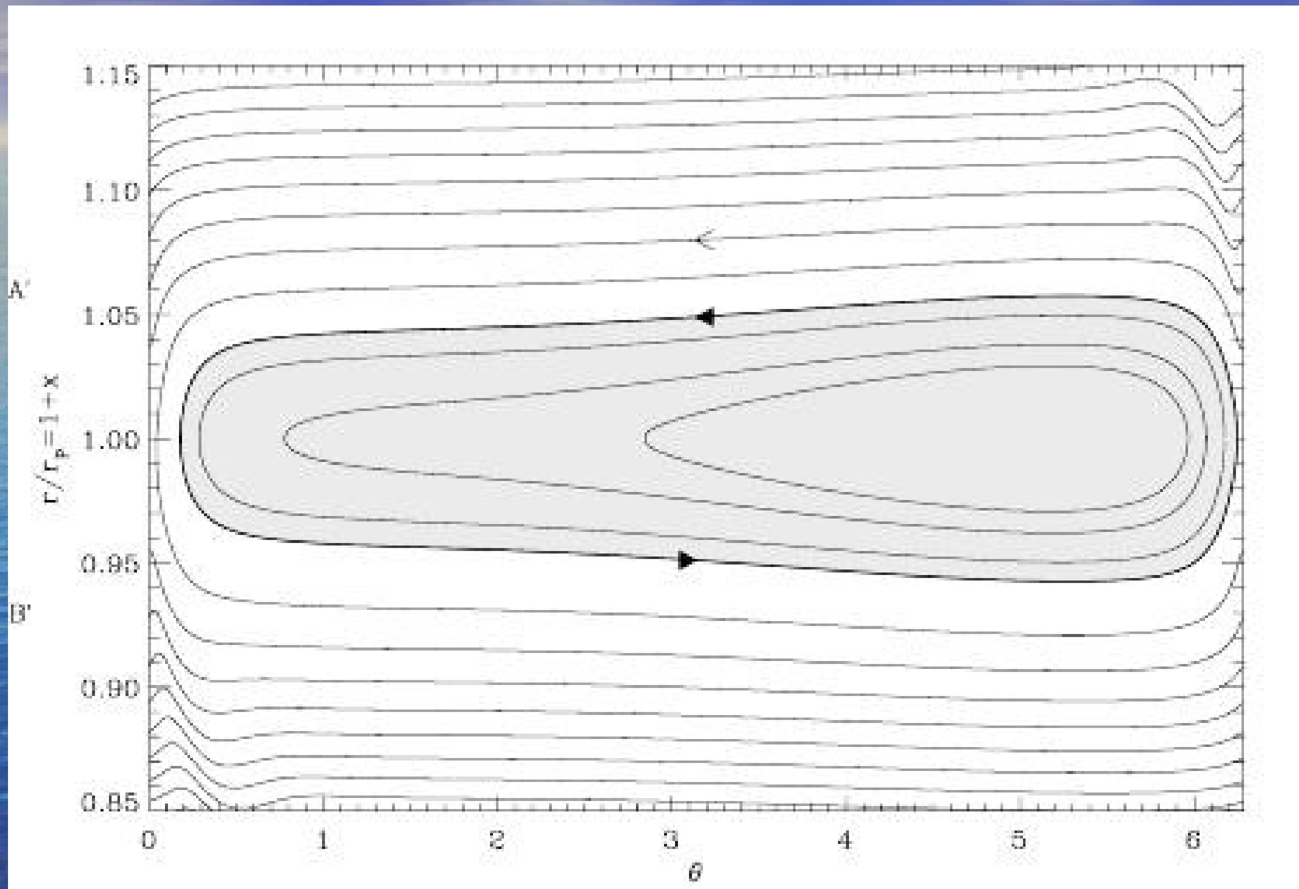
In the horseshoe region,
gas particles make U-turns → exchange of angular momentum with
the planet
→ Corotation torque.



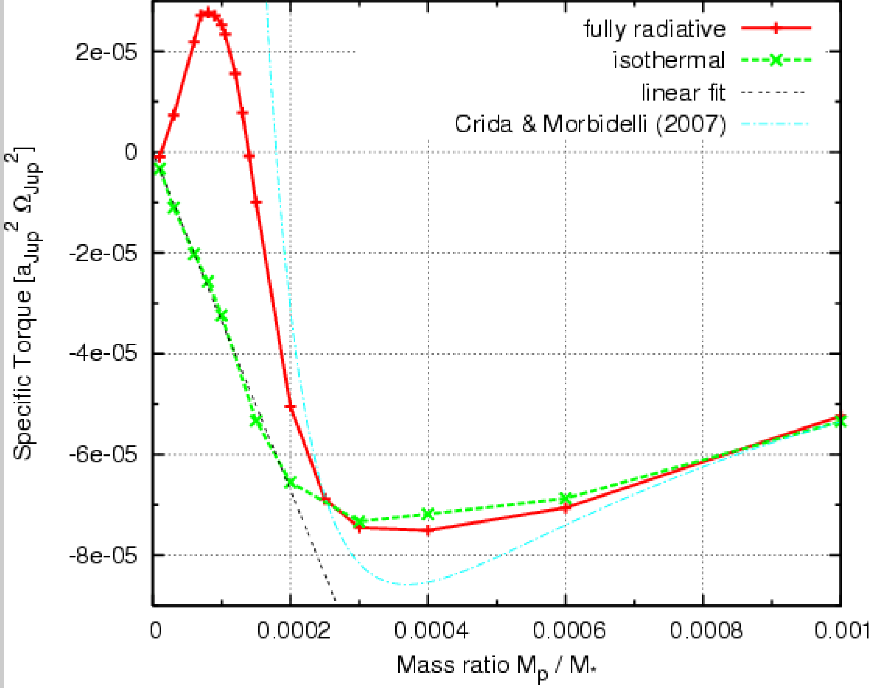
Exchange of angular momentum at the horseshoe region which depends on the temperature and density profile and the viscosity.

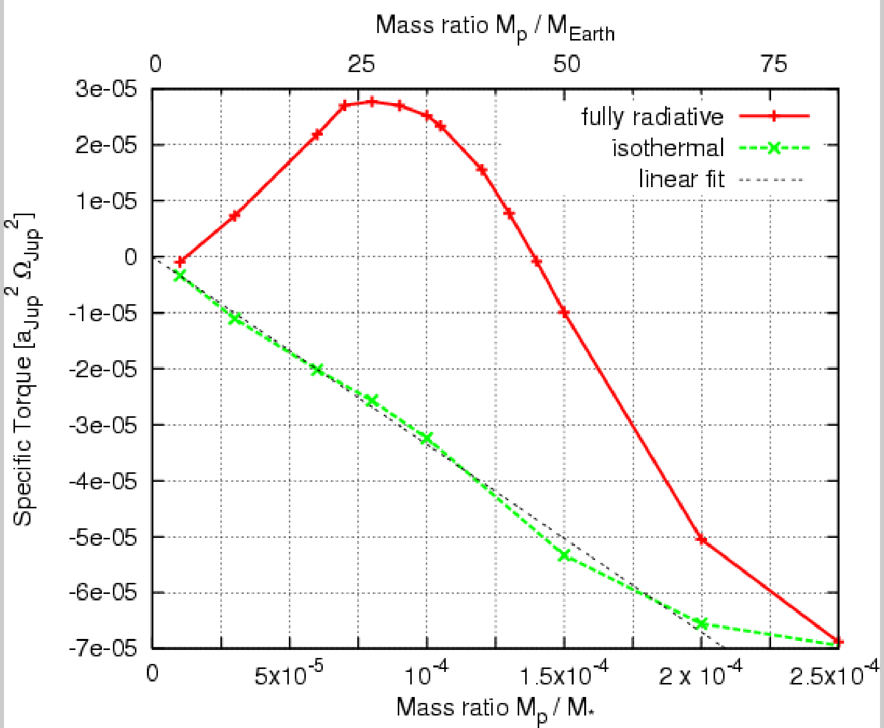


Gas enters from above and escapes below since the lines are not symmetric.



$$T_{HS} = 6 \pi \nu a \Sigma \Omega_p x_s \frac{d \log(\$ SIGMA / B)}{d \log r}$$

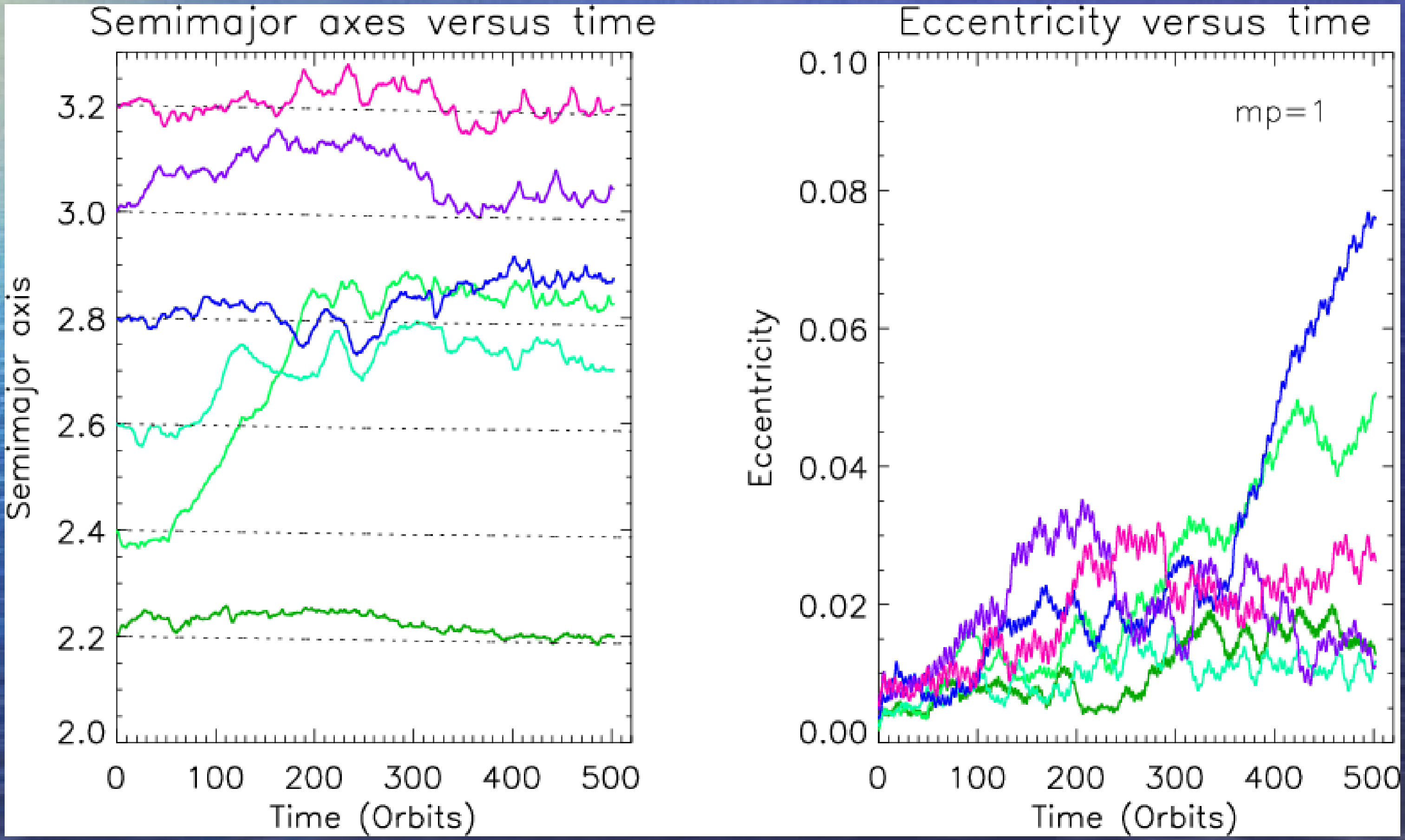




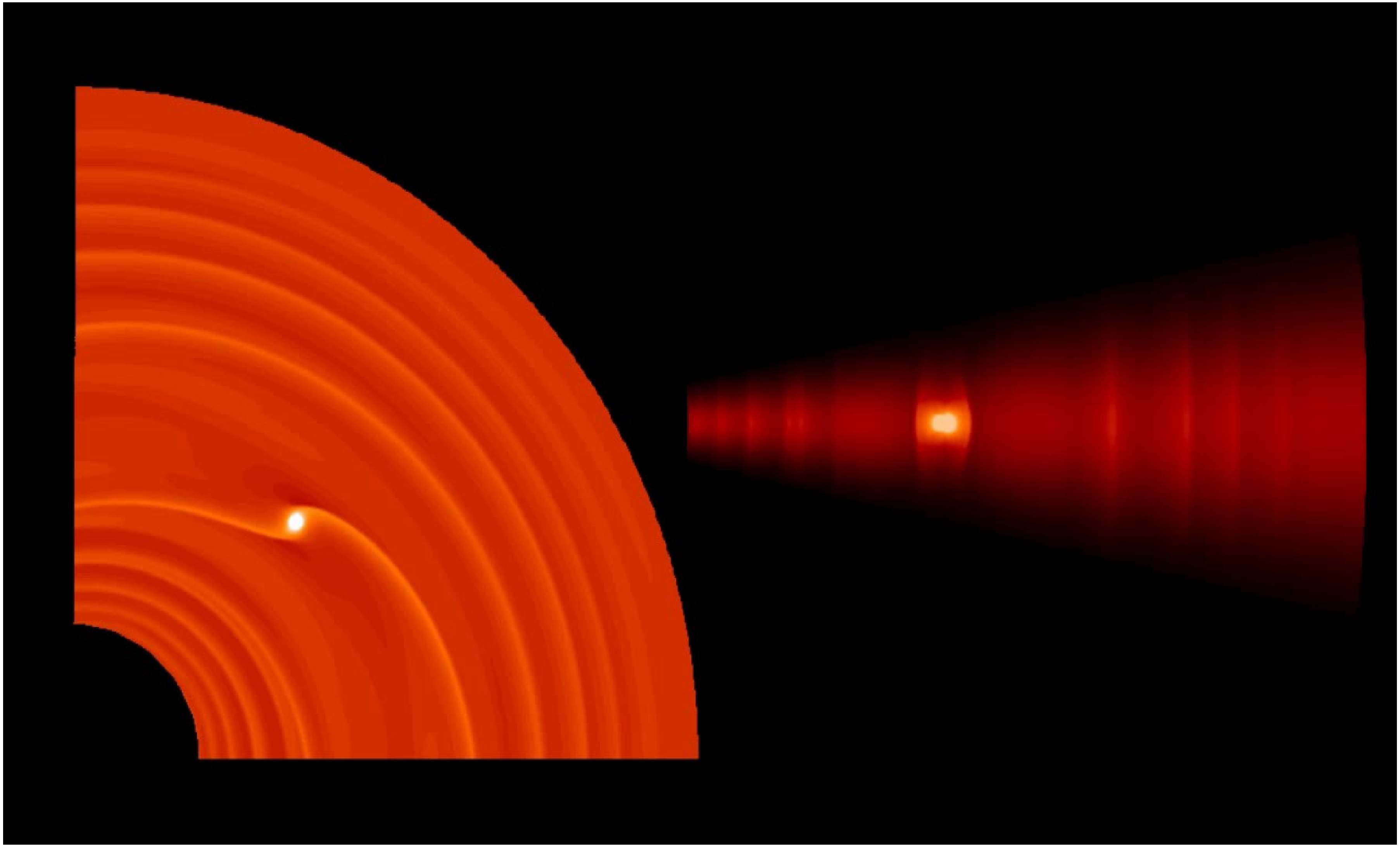
Type I migration can be reversed for radiative disks (Kley & Crida (2008) due to the horseshoe torque.

Up to 40 Earth masses the torque is positive. This is important for Jupiter size planets where the core is about 10-30 M_E Before gas infall they migrate outwards and after the gas infall (very rapid, 1 kyr) they undergo type II migration potentially skipping the critical fast inward migration phase.

Nelson (2005). Large scale turbulence can cause a stochastic migration of planets overcoming the Lindblad torques.



Type II migration: Jupiter size planets



$$T_{OS} \approx a^4 \Omega^2 \Sigma \left(\frac{M_p}{M_z} \right)^2 \left(\frac{a}{\Delta} \right)^3 \qquad \Delta = max(H, R_{Hill})$$

$$T_\nu = -2\pi r^3 \nu \Sigma \left(\frac{\partial \Omega}{\partial r} \right)$$

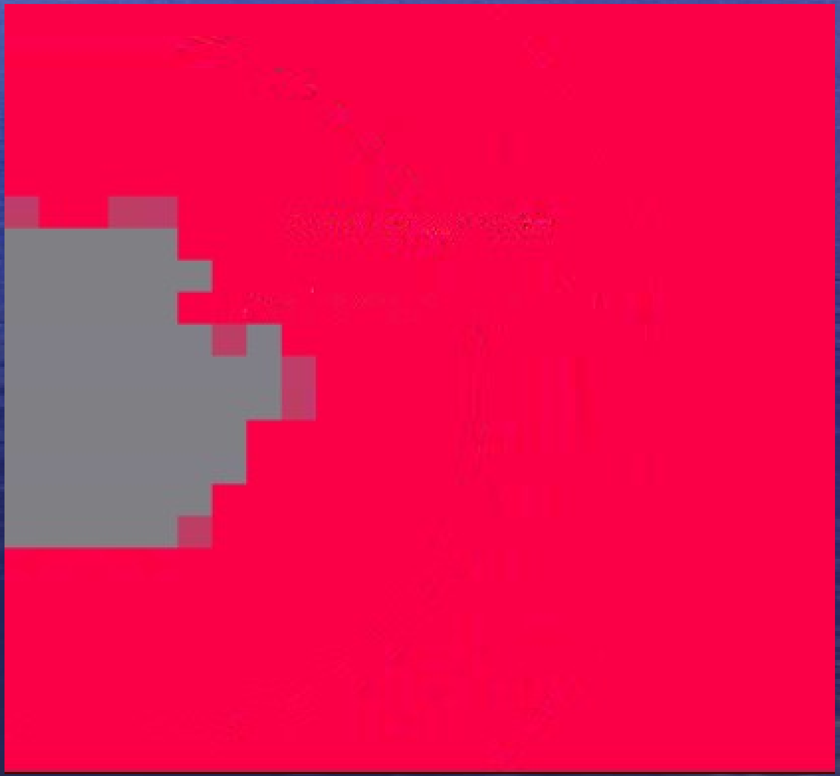
Gap opening criterium: $T_{OS} > T_\nu$

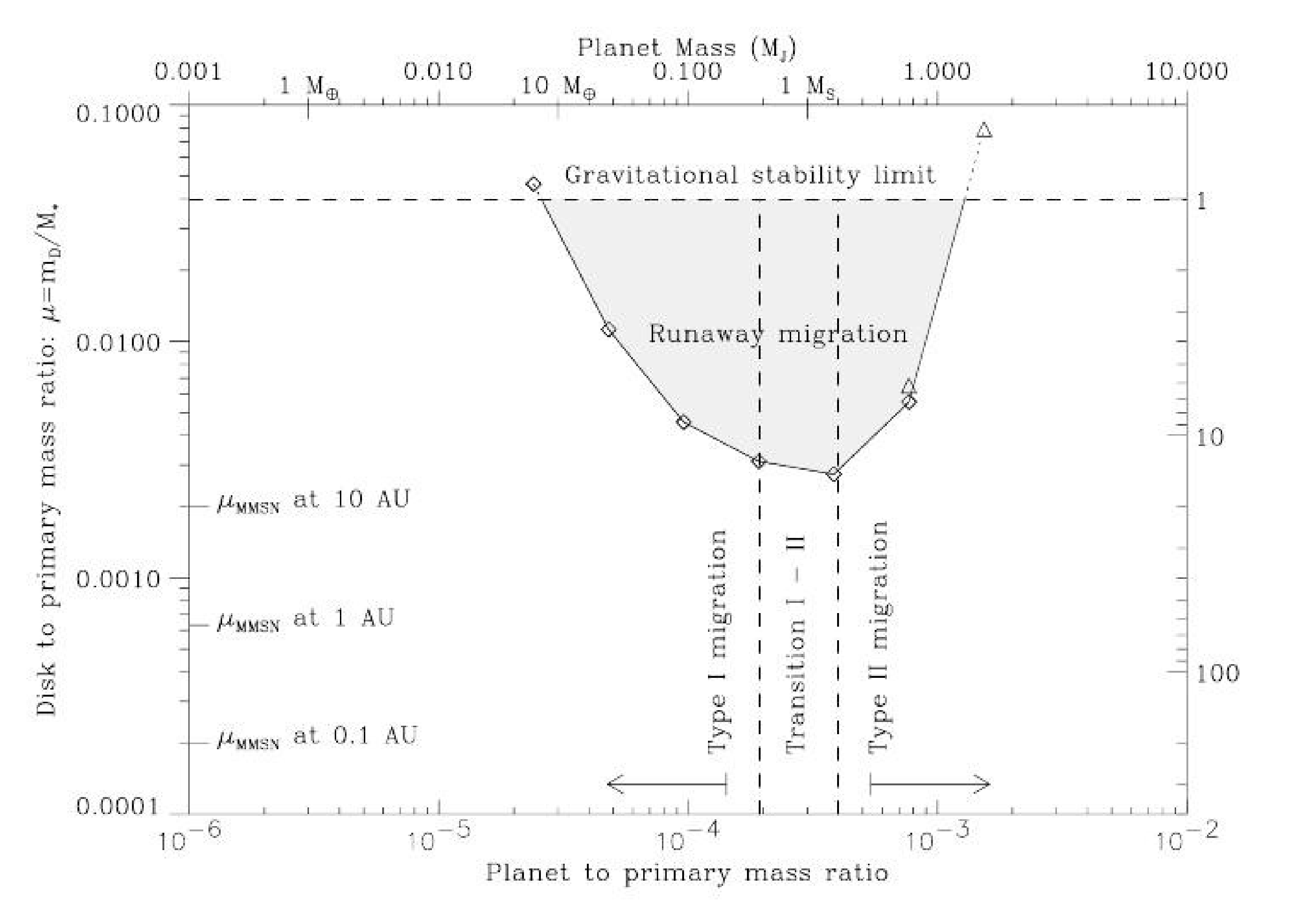
The gas is pushed away by the resonance perturbations which overcome the viscosity push of matter towards the planet.

$$\frac{dr_p}{dt} \sim \frac{3\nu}{2r_p}$$

Type III or runaway migration

Different colors are tracking different fluid elements that then evolve.





Planet Mass (M_J)
0.001
1 $M_\oplus$
0.010
10 $M_\oplus$
0.100
1 M_S
1.000
10.000
0.1000
0.0100
0.0010
0.0001
Disk to primary mass ratio: $\mu=m_D/M_*$
Gravitational stability limit
Runaway migration
1
10
100
μ_{MMSN} at 10 AU
μ_{MMSN} at 1 AU
μ_{MMSN} at 0.1 AU
Type I migration
Transition I – II
Type II migration
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Planet to primary mass ratio

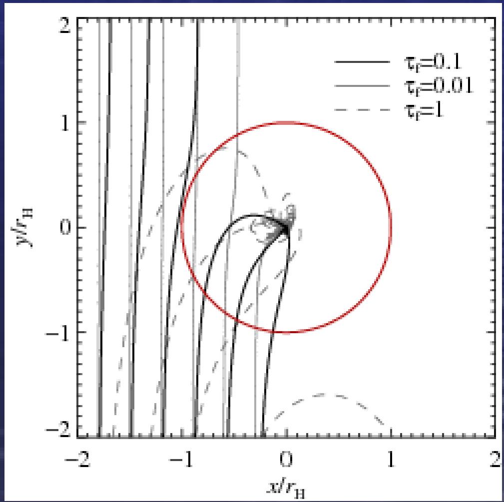
Planetary formation: new ways to form planets on a short timescale

Terrestrial planet formation: the new fast way: pebble accretion and formation during the circumstellar disk lifetime.

Direct formation of a few large planetsimals (instability) > 1000 km

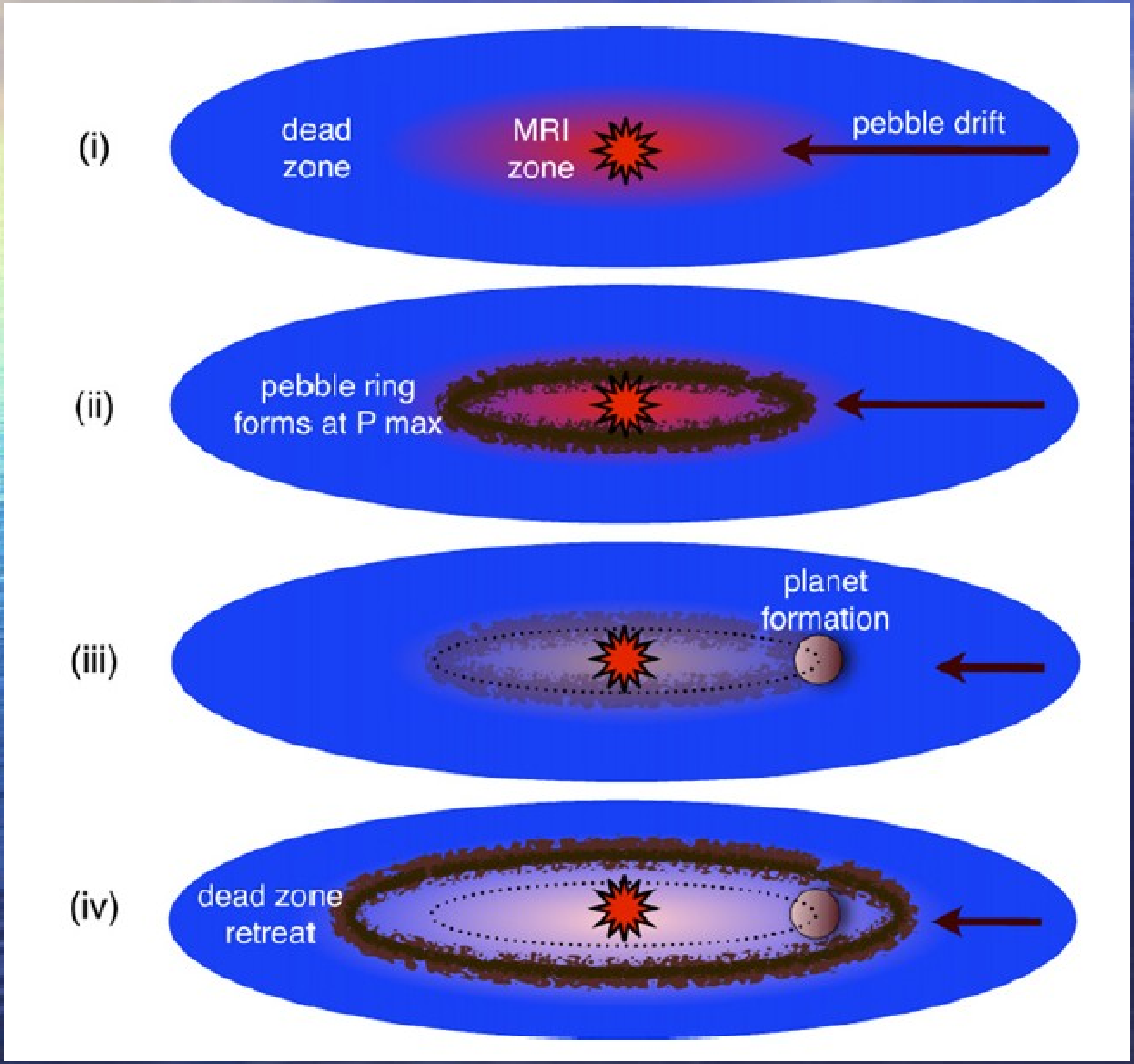
→

Pebbles fast accretion due to difference in velocity between embryo and gas dominated pebbles. (Ormel & Khlar, 2010)



Fast accretion terminates when gas disappears.

Inside-out planet formation (Chatterje and Tan 2014).

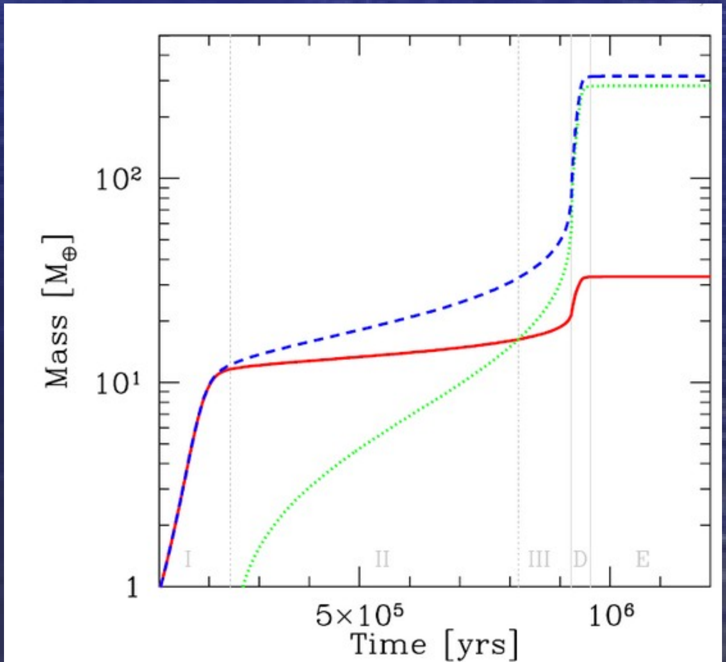


Pebbles drift until they find the end of the dead zone where there is a pressure trap. First planet form. The inner edge of the dead zone gets farther out because the disk dissipates and more disk is ionized. The process repeats at the new dust trap. Etc….
IT REQUIRES A DEAD ZONE.

Giant planets formation: 1- the old way, core accretion

- Planetesimals accrete into a solid core (runaway, oligarchic etc…)
- The growing core attracts a gas envelope
- When the gas pressure is overcome by the core gravity, runaway gas accretion (reduction in opacity due to local dust growth helps..)
- Run out of gas: accretion ends (dissipation of the disk, gap formation etc..

** Migration by interaction with the disk is included



Mordasini, Alibert & Benz…..

Giant planets formation: the new era, pebble accretion…...

Old way: most of the mass in planetesimals, their accumulation forms the core

New way: most of the mass in pebbles, their fast accretion leads to a fast core growth

Pebble accretion favored by: 1) embryo atmosphere that slows down pebbles (but also planetesimals) increasing the cross section (Chambers 2014)

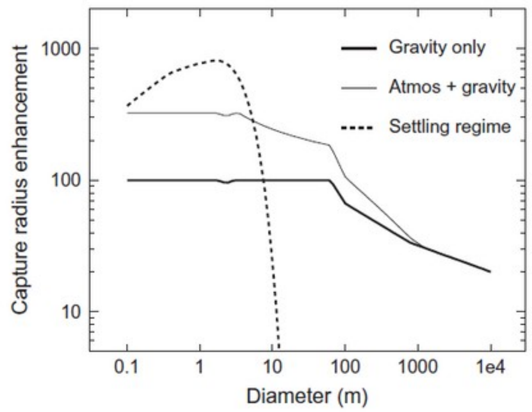


Fig. 7. Contributions to the capture radius enhancement for an embryo at 5 AU due to different physical processes at 0.4 My in the simulation shown in Fig. 1. The thick, solid curve shows the capture radius enhancement due to gravitational focusing as a function of particle diameter. The thin, solid curve shows the enhancement due to gravitational focusing and atmospheric capture. The dashed curve shows the capture radius enhancement due to pebble accretion.

2) Pebble dynamics in proximity of the embryo is affected by the coupling with the gas. This coupling increase the settling of pebbles on the embryo (Ormel and Klahr, 2010) (as for terrestrial planets)

Attention: pebbles can be either primordial or outcome of planetesimal collisions...

The new generation

Only large planetesimals are formed and most mass in pebbles

Pebbles accretion leads to fast formation of planets

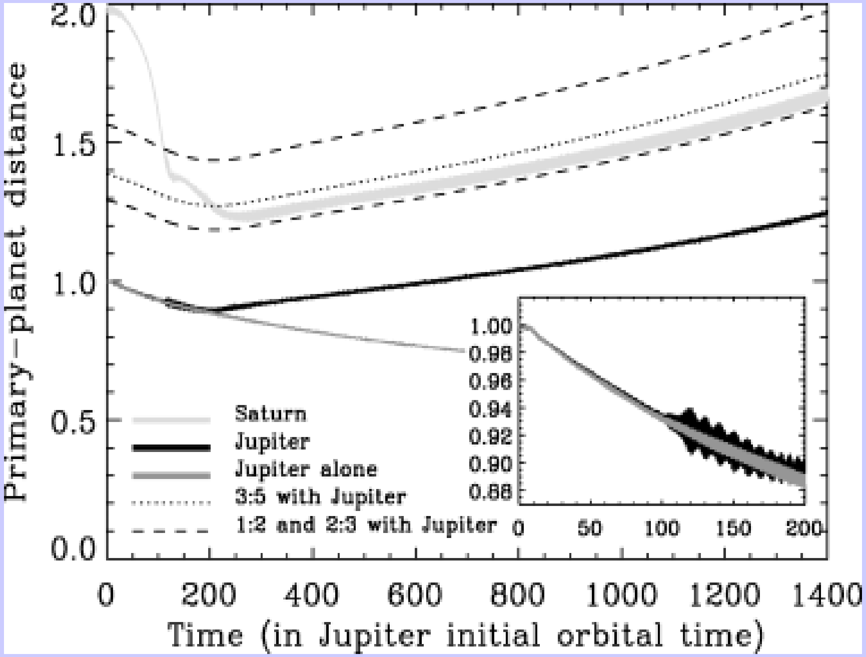
Main problem: during runaway growth most pebbles are lost by radial drift. You need planetesimal collision to produce second generation pebbles.

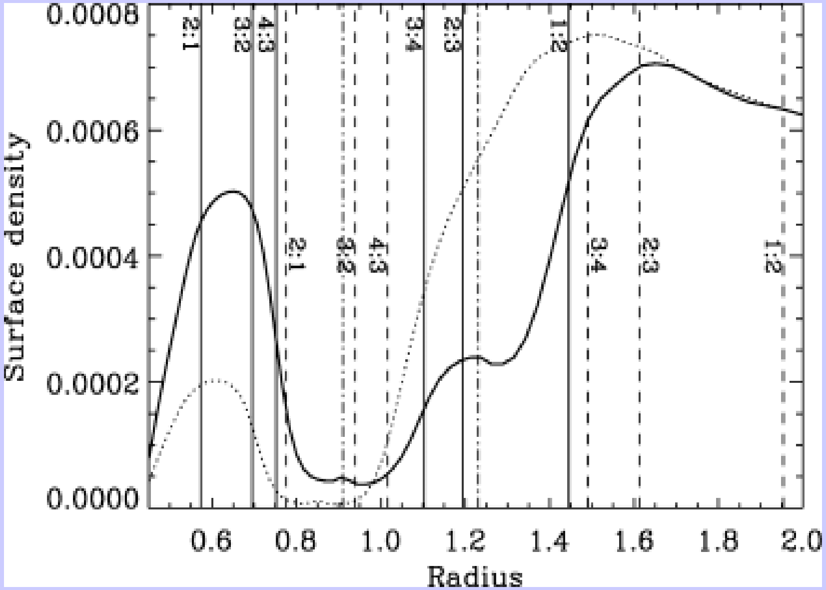
The old generation

Planetesimals of various sizes are formed, runaway growth and oligarchic growth possibly speeded up by pebble accretion.

Main problem: planetesimal formation process and its efficiency.

What about Jupiter and Saturn? Why didn't they migrate very close to the sun? Coupled migration while trapped in resonance!





Masset & Snellgrove (2001): Jupiter and Saturn trapped in a 3:2 resonance migrates outwards.

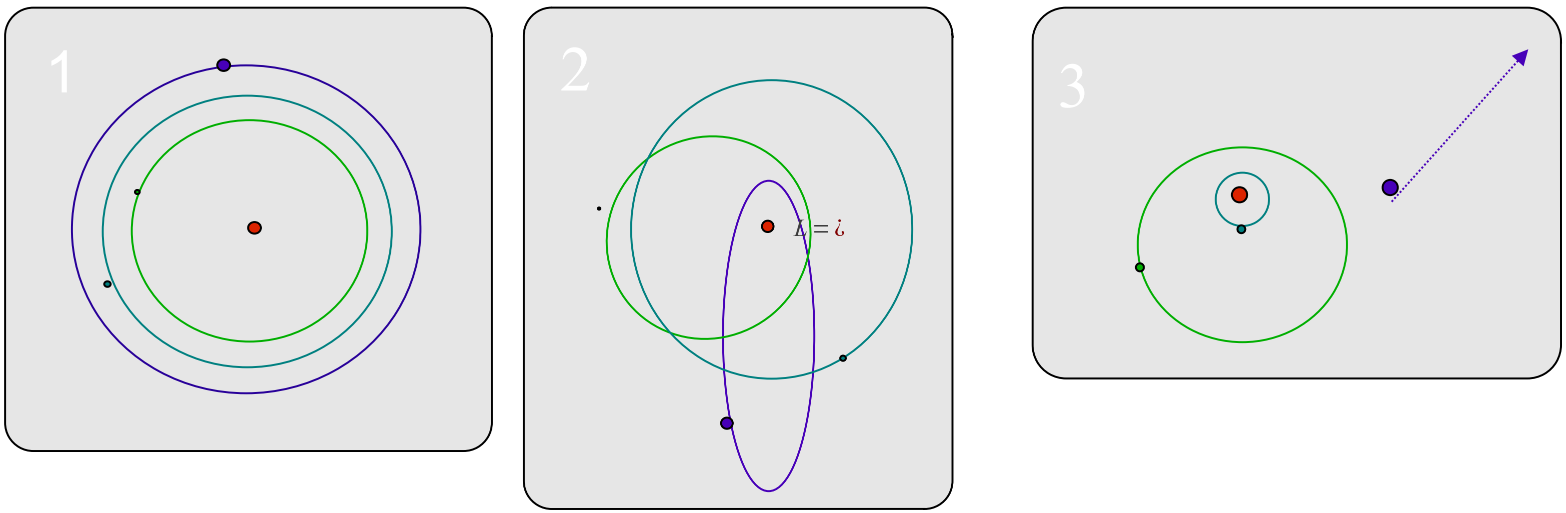
Jupiter excites inner Lindblad resonances, Saturn the outer ones. A positive torque is obtained

$$T_{OS} \approx a^4 \Omega^2 \Sigma \left(\frac{M_J}{M_{star}}\right)^2 \left(\frac{a_J}{\Delta}\right)^3$$

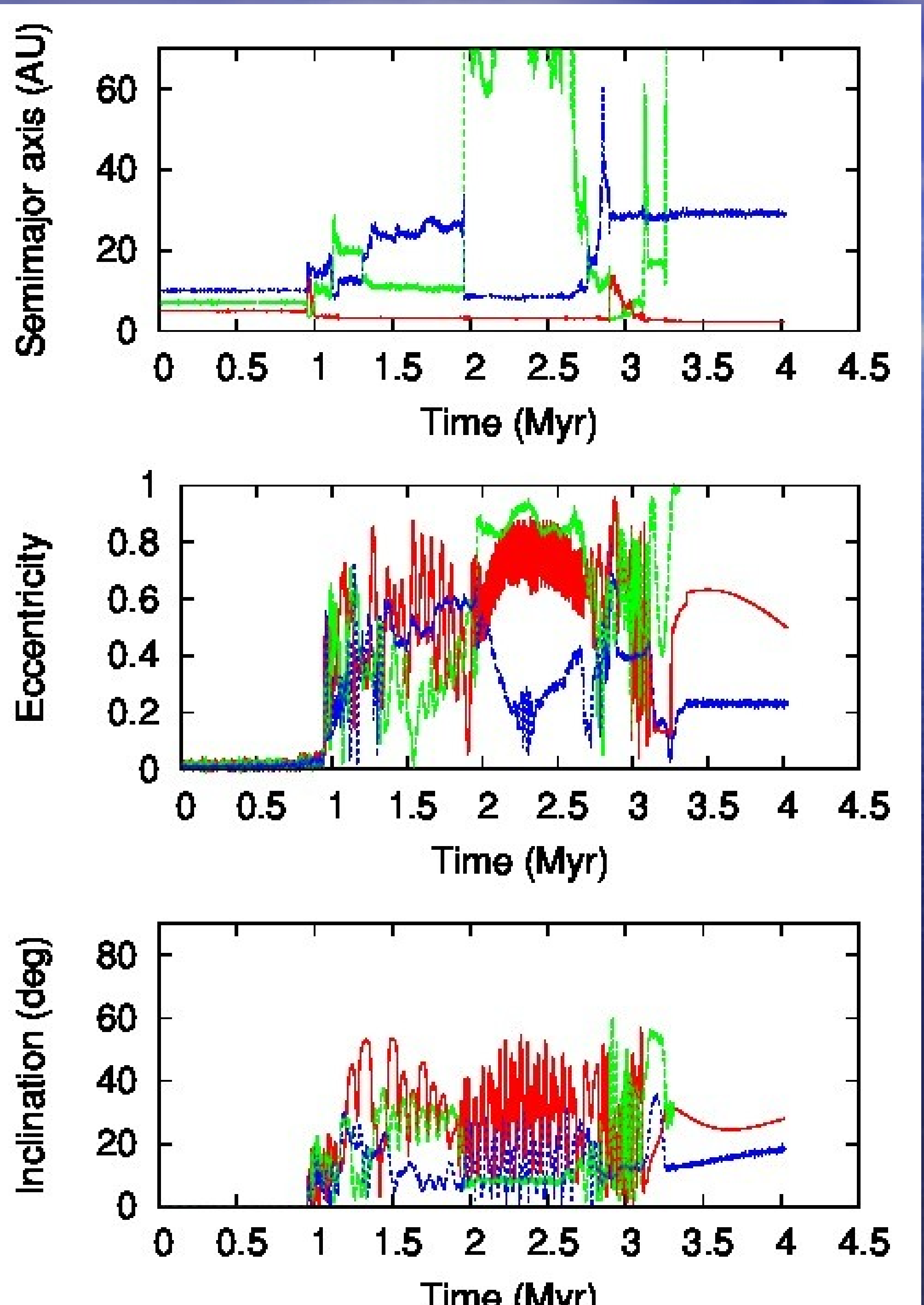
$$\frac{M_S}{M_J} < \left(\frac{2}{3}\right)^{(1/3)}$$

How do planets achieve large e and small q?

1) Planet-Planet scattering: at the end of the chaotic phase a planet is ejected, one is injected on a highly eccentric orbit that will be tidally circularized to the pericenter, one is sent on an outer orbit



Weidenschilling & Marzari (1996), Rasio and Ford (1996), version with 2 planets

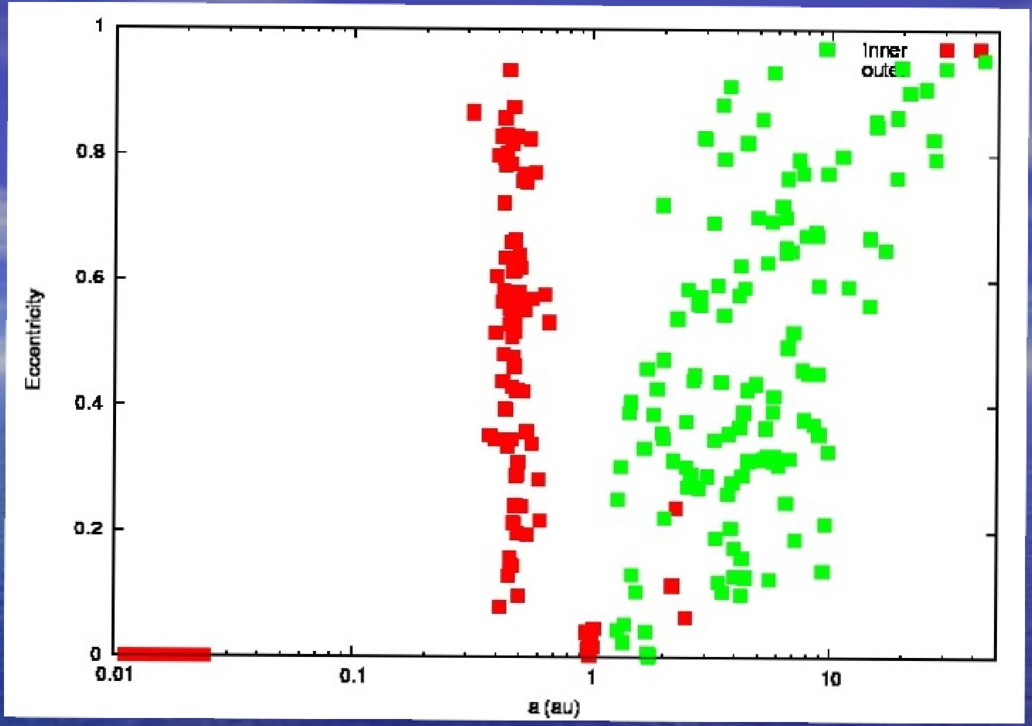


Energy conservation

$$E = -\frac{G M_s}{2}\left[\frac{m_1}{a_1}+\frac{m_2}{a_2}+\frac{m_3}{a_3}\right]$$

$$a_i \approx \frac{G M_s m_i}{2E}$$

Dynamical tide decouples the planets and the inner one is circularized on a short timescale and it becomes a H/W Jupiter.



$$\Delta L_{\rm tide} \sim -\frac{32\sqrt{2}}{15}\tilde{w}_0^2\tilde{Q}^2\xi\exp\left(-\frac{4\sqrt{2}}{3}w_+\xi\right)$$
$$\times\left[1-\frac{9}{2^{14}(\tilde{w}_0\xi)^4}\exp\left(\frac{4\sqrt{2}}{3}\tilde{\sigma}\xi\right)\right]L_{\rm pl},$$
$$\Delta E_{\rm tide} \sim -\frac{16\sqrt{2}}{15}\tilde{w}_0^3\tilde{Q}^2\xi\exp\left(-\frac{4\sqrt{2}}{3}w_+\xi\right) \quad (2)$$
$$\times\left[1+\frac{3}{2^7(\tilde{w}_0\xi)^2}\exp\left(\frac{2\sqrt{2}}{3}\tilde{\sigma}\xi\right)\right]^2E_{\rm pl}, \quad (3)$$

Rougue planets: alias free floating planets, detached from their star (~ 100)

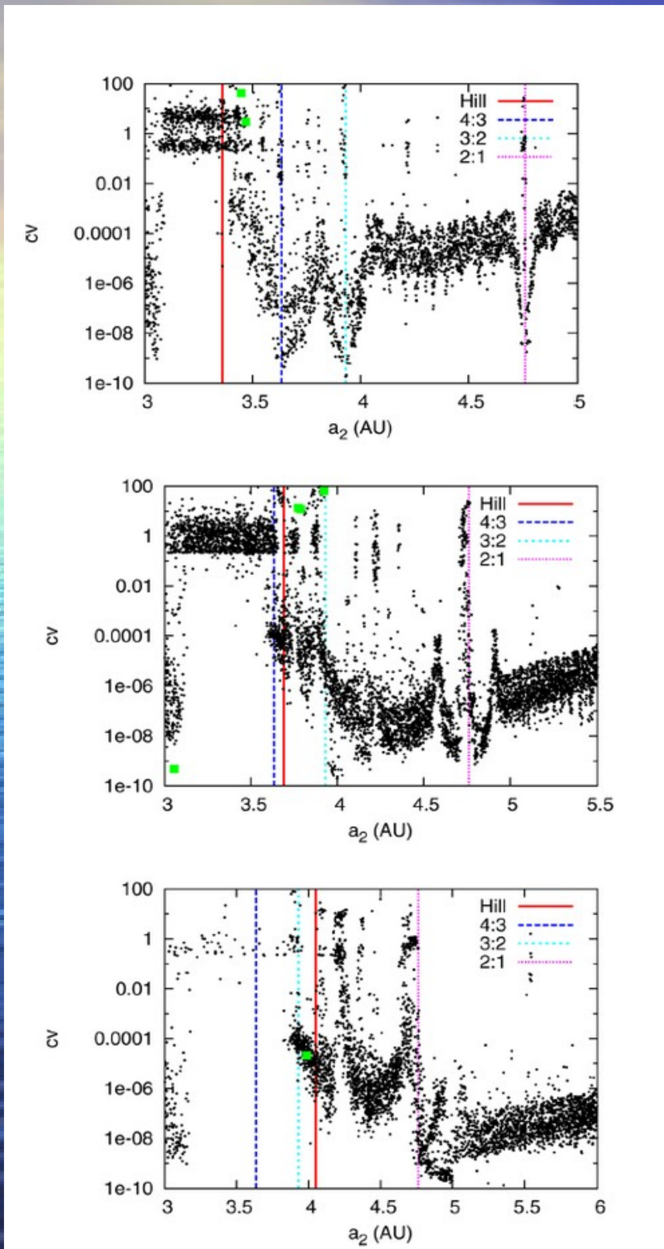
-Direct imaging

-Short gravitational lensing events

Origin: P-P scattering, stellar flybys, interaction with the binary stars in a circumbinary system

PSO J318.5-22

Stability limit for 2 planets $\Delta_c \sim 2\sqrt{3}\,R_H$



$$R_H = \left(\frac{m_1 + m_2}{3 M_s}\right)^{(1/3)} \left(\frac{a_1 + a_2}{2}\right)$$

$$M_P = M_{Neptune}$$

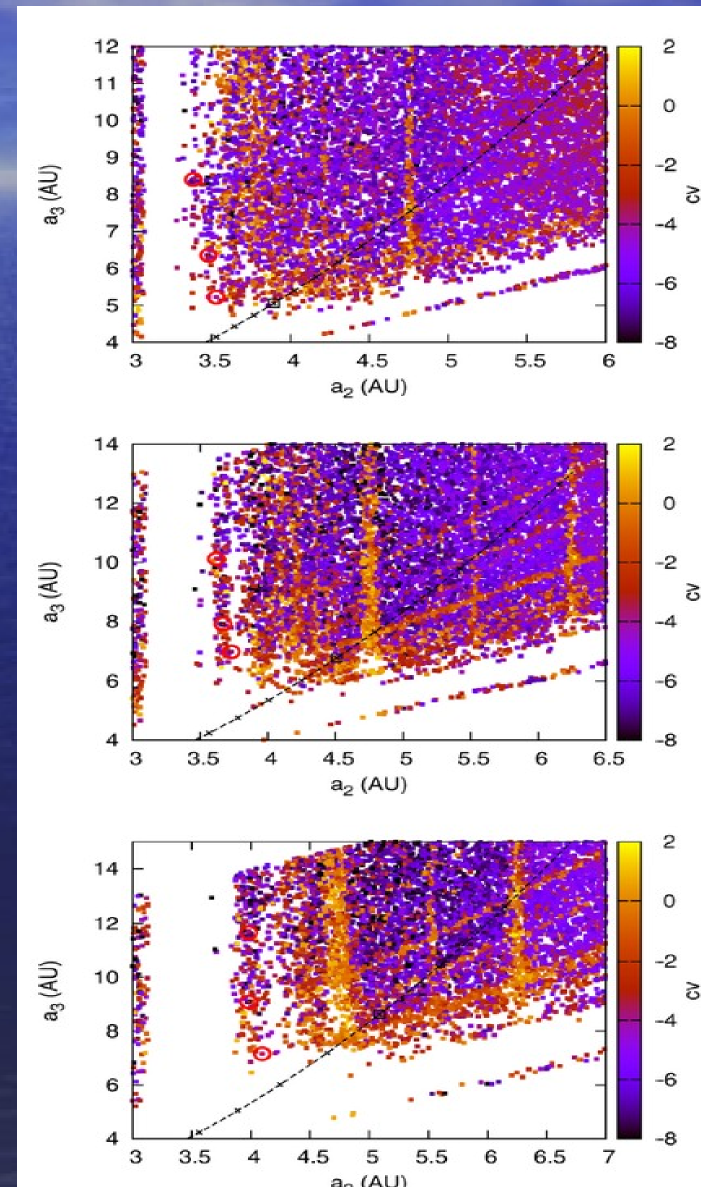
$$M_P = M_{Saturn}$$

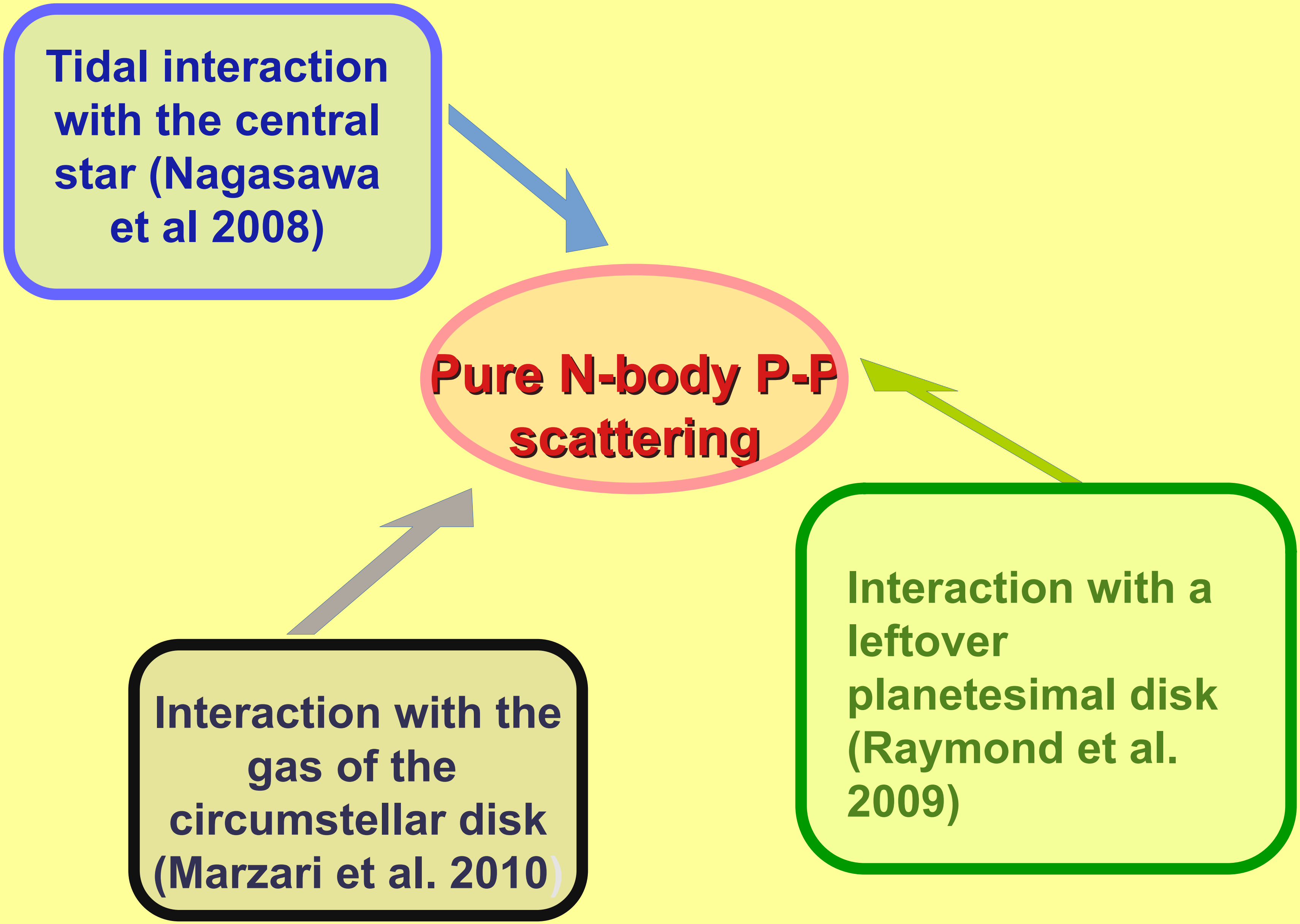
$$M_P = M_{Jupiter}$$

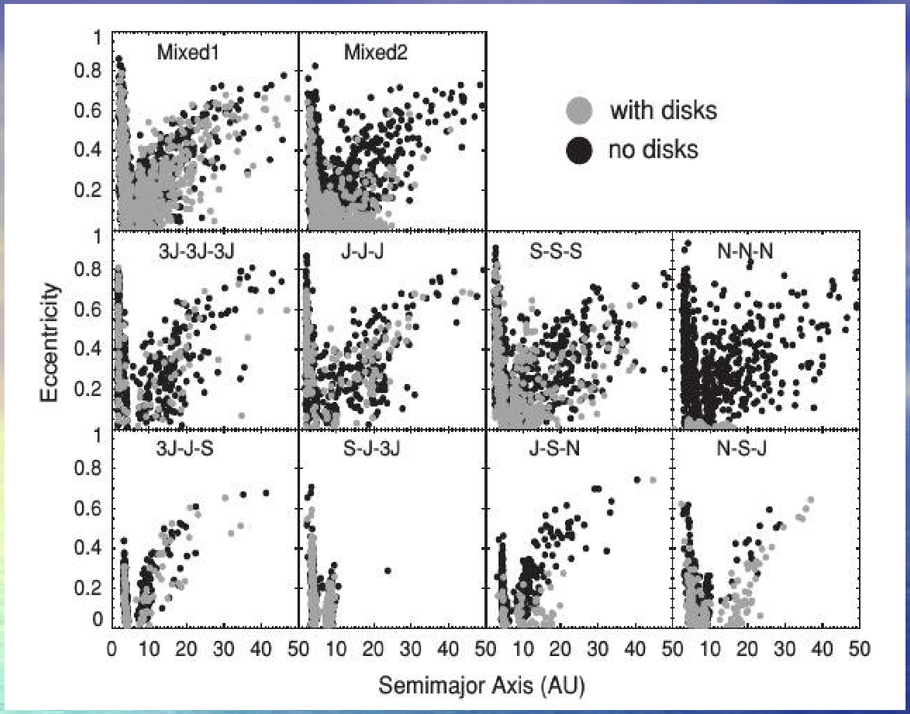
Marzari (2014)

Stability limit for 3 planets

$$a_{i+1} = a_i + K\,R_H$$

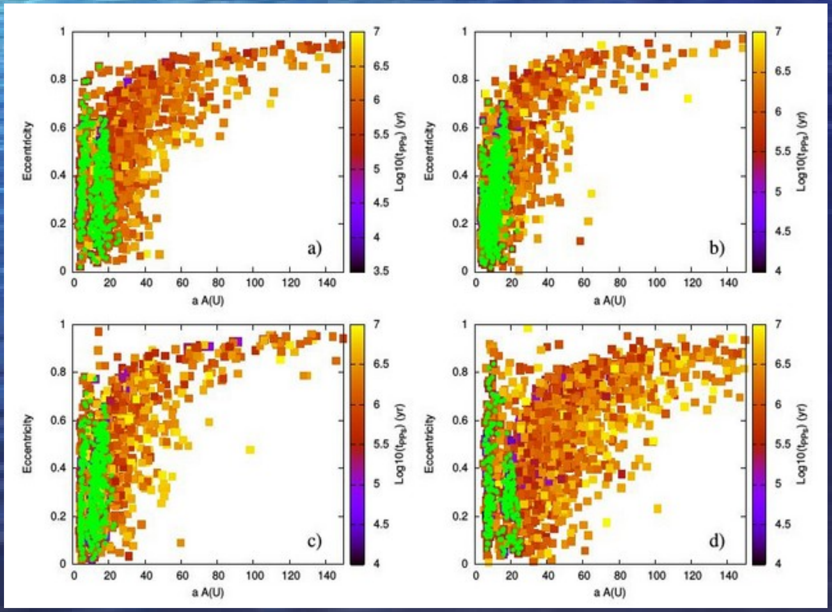



Tidal interaction with the central star (Nagasawa et al 2008)
Pure N-body P-P scattering
Interaction with the gas of the circumstellar disk (Marzari et al. 2010)
Interaction with a leftover planetesimal disk (Raymond et al. 2009)



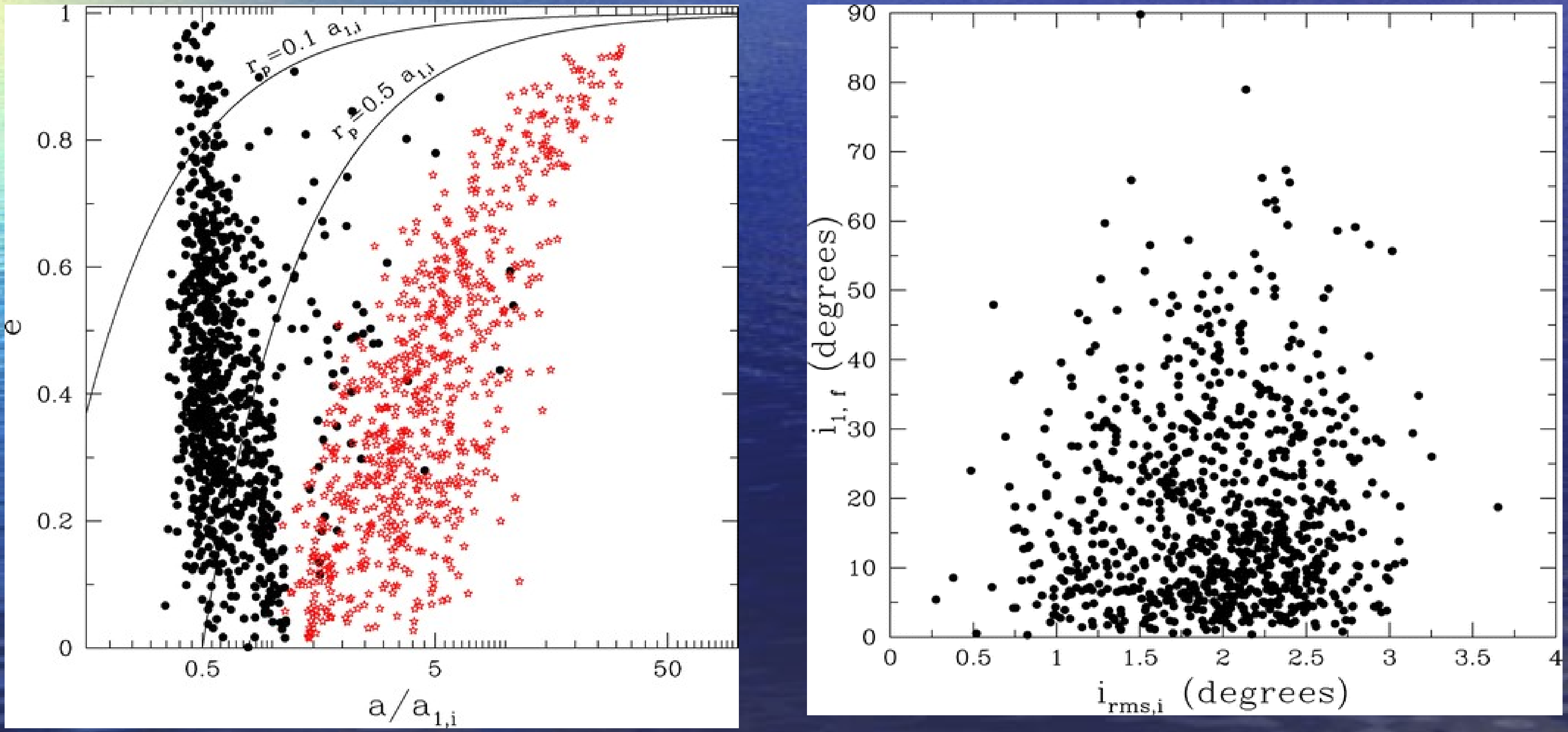
Planetesimal disks and P-P scattering:

- Lower eccentricities and inclinations for outer low-mass planets after P-P scattering (Raymond 2009, 2010)
- Possible formation of mini Oort clouds by scattered planetesimals (Raymond & Armitage 2013)
- Lower fraction of debris disks co-existing with the final planet system (Marzari 2014)



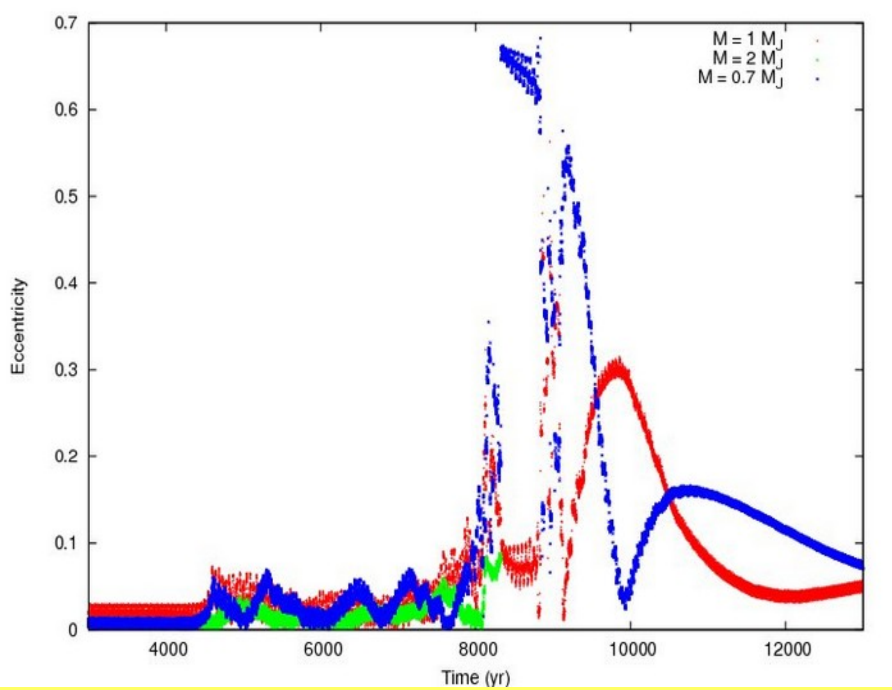
Green dots are systems which might retain a debris disk.

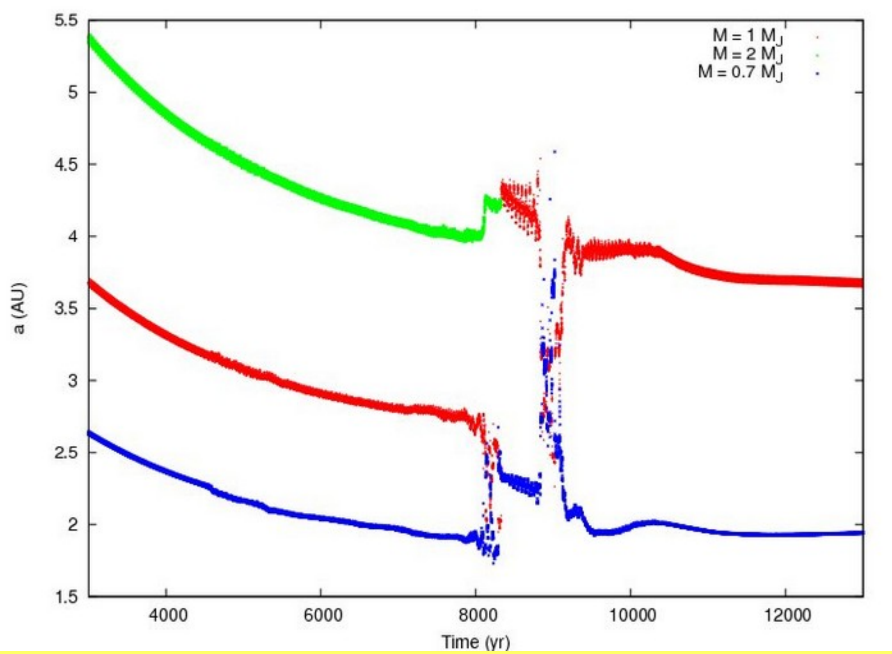
Eccentricity and inclination excitation. Outcome of many simulations with 3 initial planets within the instability limit by Chatterjee et al. (2008).



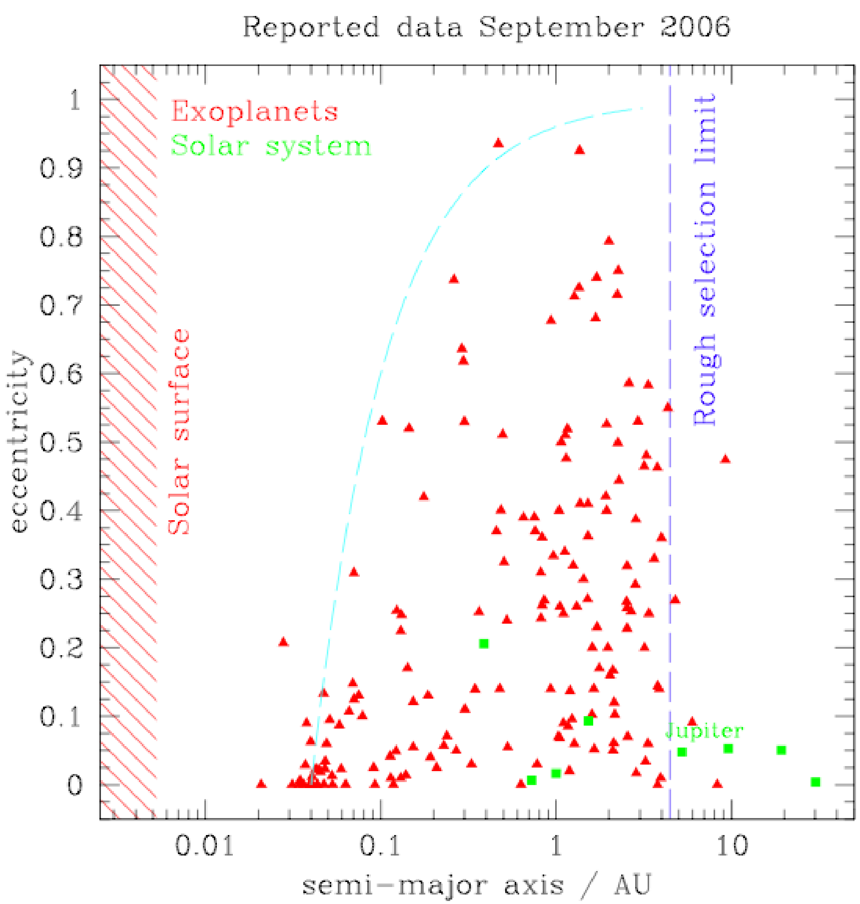
Example of 'Jumping Jupiters'. The density of the disk is MMSN/2. Code used is FARGO (RK5 modified to have variable stepsize). One planet (1 M_J) merges with another one (0.7 M_J) after a sequence of close encounters.

Eccentricity evolution after P-P scattering: damping or excitation because of corotation resonance saturation?





Tidal migration of eccentric orbits



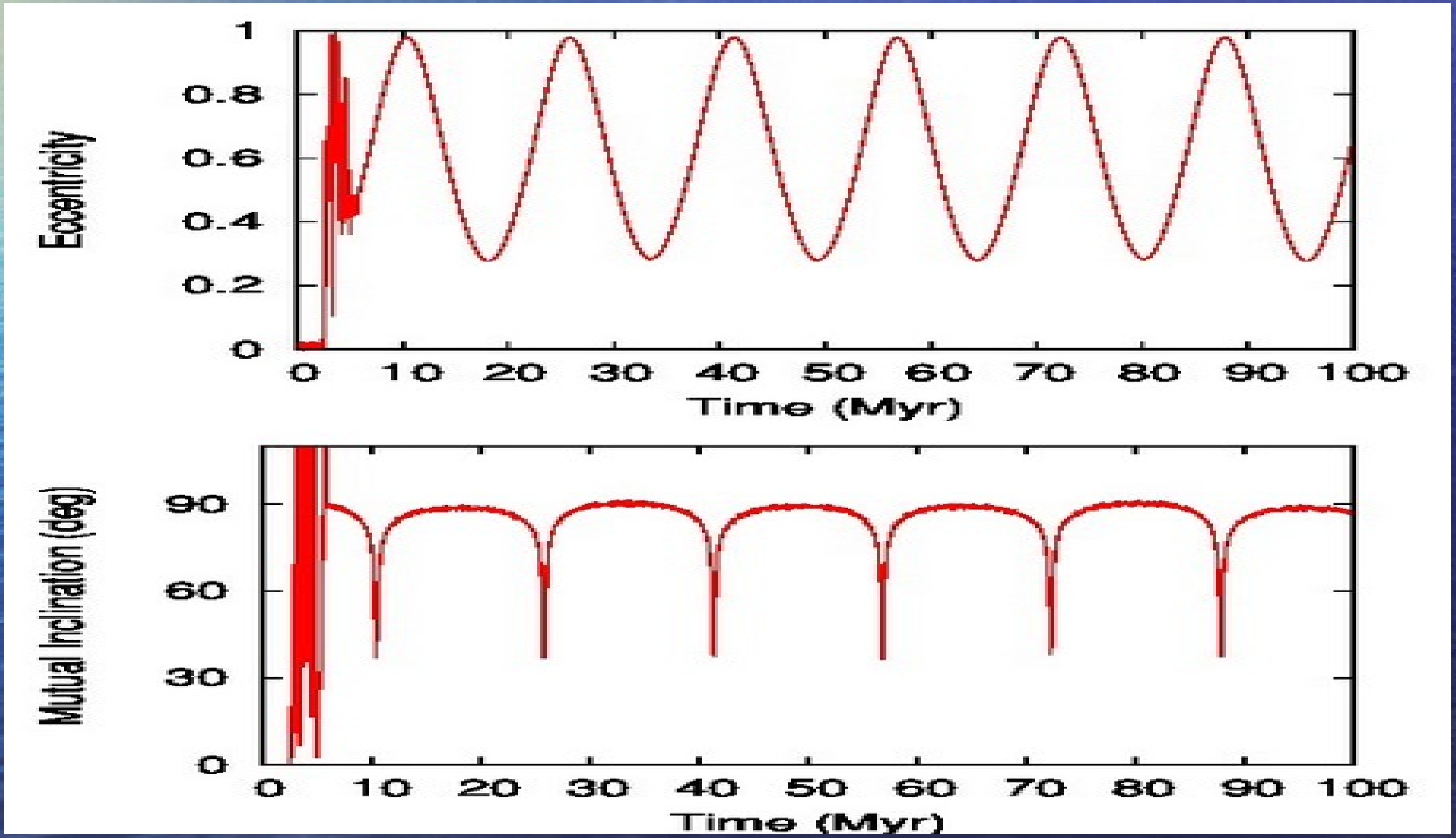
Maximum e declines with distance from the star: tidal circularization. Energy is dissipated but the angular momentum J is preserved.

$$J=\frac{m_p m_s}{m_p+m_s}\sqrt{G\left(M_s+M_p\right)}\sqrt{a\left(1-e_p^2\right)}$$

$$a_f=a\left(1-e^2\right)=q\left(1+e_p\right)\approx 2q$$

Kozai mechanism; invoked for the first time to explain the large eccentricity of the planet in the binary system 16 Cyn B.

$$L = \sqrt{GM\left(1-e^{2}\right)}\cos(i) \qquad arcos\left(\sqrt{\frac{3}{5}}\right) \approx 39.2^{o}$$

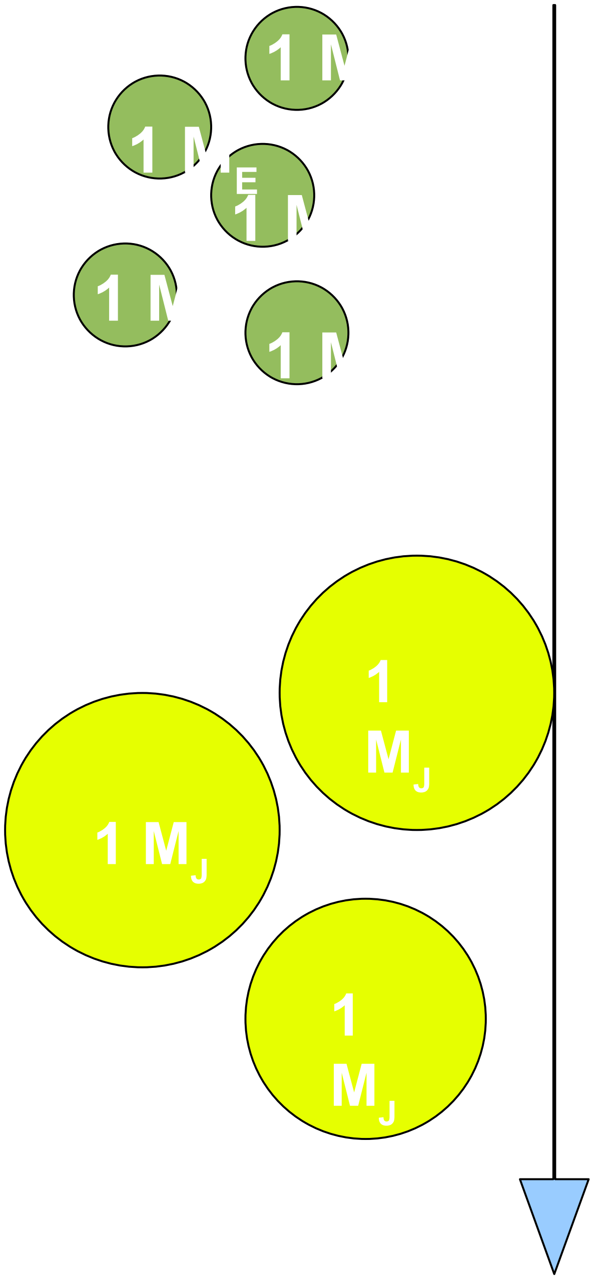


Some hot questions for evening meditation:

- Initial disk mass: MMSN or MMEN (more massive)?
- Disk viscosity: MRI? Other kind of instabilities leading to turbulence?
- Gaps, spirals etc. on disks. Can we discern the origin?
- Contribution of photoevaporation to the disk dissipation
- Transition disks: planets or photoevaporation?
- Gas accretion on the planet after gap formation

- Mechanism, size distribution and timing of planetesimal formation
- Relevance of pebble accretion
- Fraction of giant planets vs. super Earths
- Relevance of gas-planet interaction for its migration. Does P-P scattering + tidal forces do all the job?
- MM resonances: why so few if convergent migration occurs?

Single steps of accretion well studied: it is the temporal evolution with the simultaneous mass accretion that is still difficult



- Type I migration or stochastic random walk
- P-P scattering
- Mutual impacts and accretion

- Type II, Type III migration
- Eccentricity excitation (corotation resonance saturation...)
- P-P scattering
- Resonance capture
- Residual planetesimal scattering
- Gas accretion onto the planet

There are many weird planets out there, and theory must explain them all!