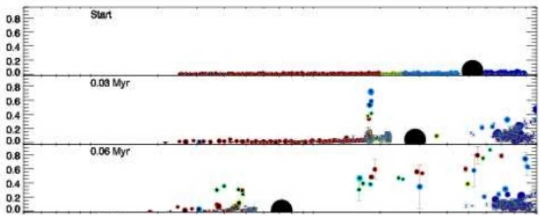
Lecture 5:
Multiple planet systems

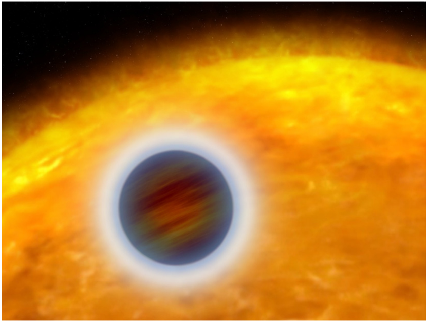


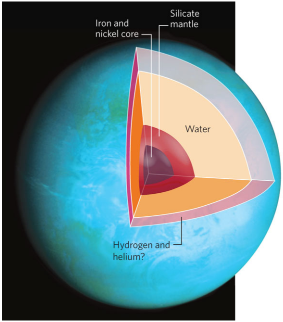
“Planet formation”

April 2016

Bertram Bitsch (Lund Observatory)

Characterisation of exoplanets



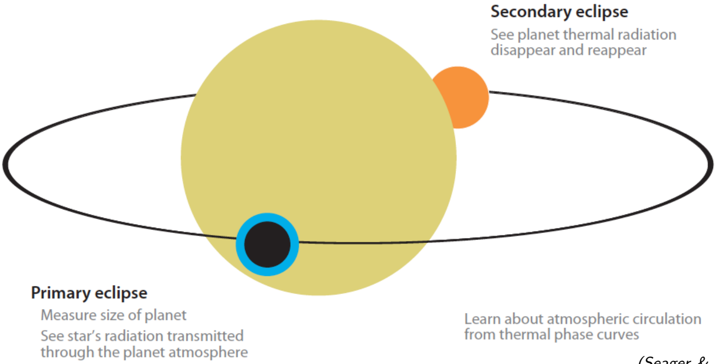


- *Characterisation of an exoplanet:* The determination of physical properties such as mean density and atmospheric composition

⇒ Understanding origin, evolution and diversity of planets

⇒ Search for habitable planets and biomarkers (H_2O, O_3, CH_4, . . .)

Transit spectroscopy



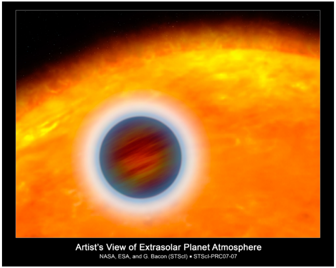
(Seager & Deming 2010)

- Depth of primary eclipse depends on wavelength
- Allows determination of the *transmission spectrum* of planet
- Secondary eclipse gives *emission spectrum*

! Hot Jupiters are excellent for transit spectroscopy

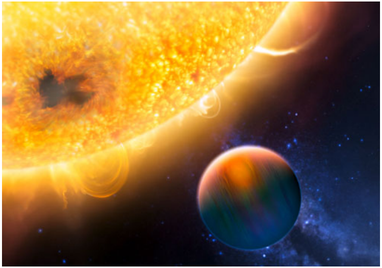
HD 209458 b and HD 189733 b

HD 209458 b



- Discovered 1999
- Distance 47 pc (153 light years)
- Mass 0.714 M_{Jupiter}
- Distance from star 0.047 AU

HD 189733 b



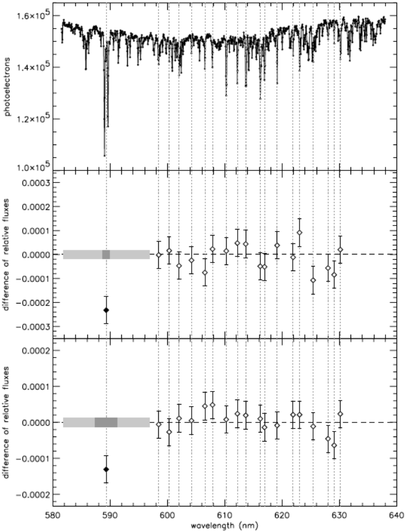
- Discovered 2005
- Distance 19.3 pc (62.9 light years)
- Mass 1.138 M_{Jupiter}
- Distance from star 0.031 AU

! There are other transiting planets closer to Earth, but they are all small and thus not good candidates for transit spectroscopy

First detection of an exoplanet atmosphere

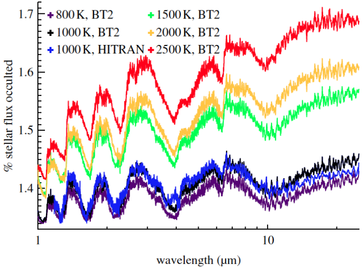
- Need to go to space to get precise enough photometry to see wavelength-dependence of transit depth
- Charbonneau et al. (2002) observed HD 209458 with Hubble Space Telescope
- Top plot shows spectrum of HD 209458 (the star) with clear Na double line around 589.5 nm
- Middle and bottom plot show difference in transit depth for two bandwidths
- The transit is clearly deeper in the Na line

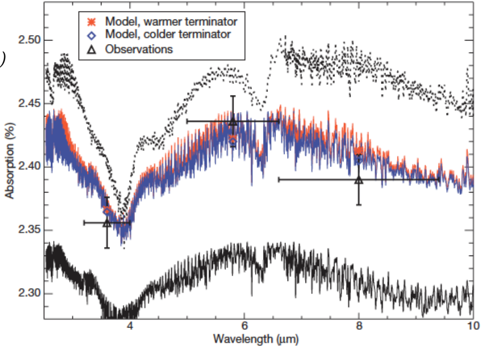
⇒ Detection of Na in the atmosphere of HD 209458 b



Water in HD 189733 b

Pure water transmission spectrum (*Tinetti et al. 2013*)



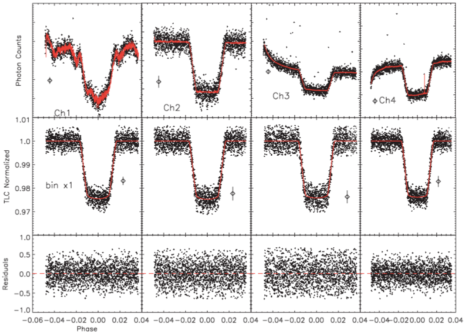


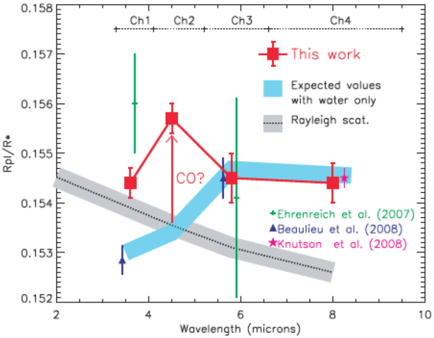
- Tinetti et al. (2007) and Swain et al. (2008) analysed *transmission spectrum* of HD 189733 b taken from primary eclipse with Spitzer
- Found absorption feature of H_2O and CH_4 molecules

! Low signal-to-noise

- Results are also model dependent...

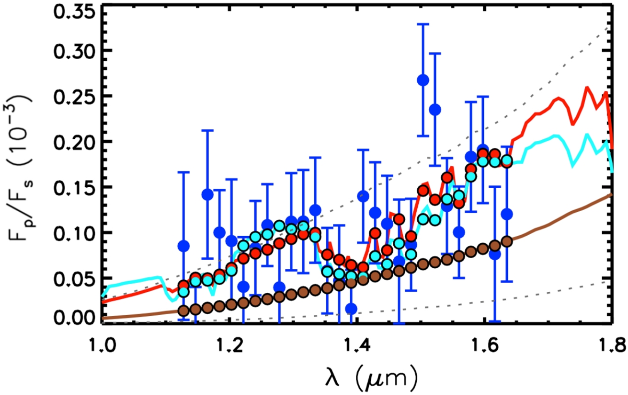
Disputed water





- Problem is not only *random* errors, but *systematic errors*
- The stellar flux out-of-transit is not constant due to instrumental effects
- Compensating for instrumental effects introduces systematic errors
- Désert et al. (2009) used improved model of Spitzer's instrumental effects and find no rise in the planet radius from 3.6 μm to 5.8 μm and hence no evidence for water

More observations: water!

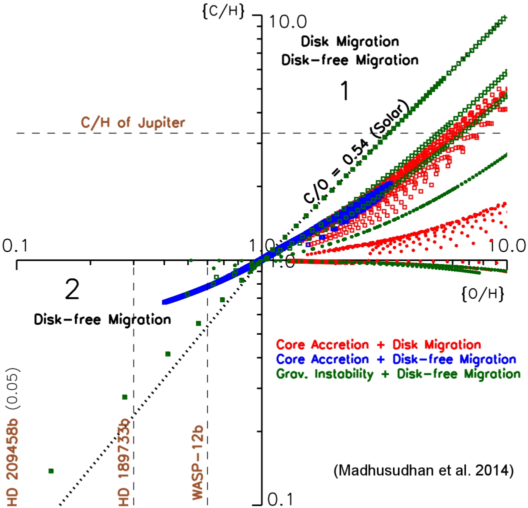


(*Crouzet et al. 2014*)

- New observations are best fitted by close to solar composition or by solar composition
- Sub-solar abundance might be due to clouds or hazes

⇒ More observations needed

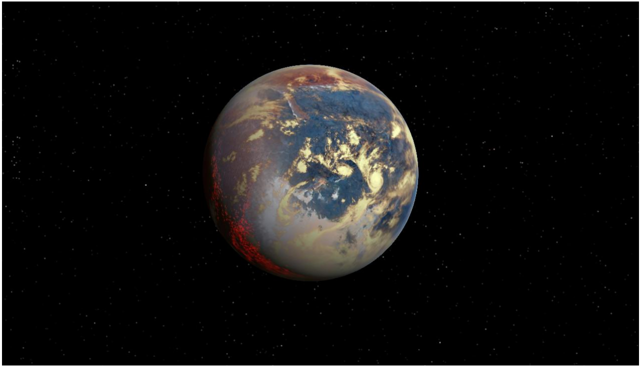
Can the atmosphere tell us anything about the formation?



(Madhusudhan et al. 2014)

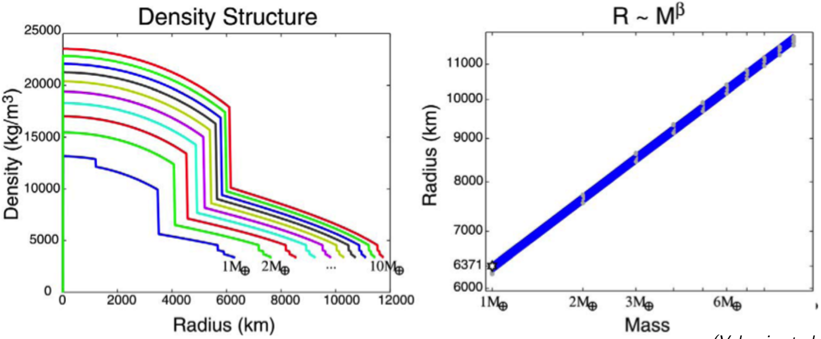
- Composition studies can help to constrain planet formation models!

Definition of super-Earth



- Rocky planet with little or no H/He atmosphere
- Mass range 2–10 Earth masses
- Class of planet not present in the solar system
- *Super-Earths are interesting to study because undoubtedly super-Earths will be discovered and characterised in detail before lower-mass terrestrial planets*

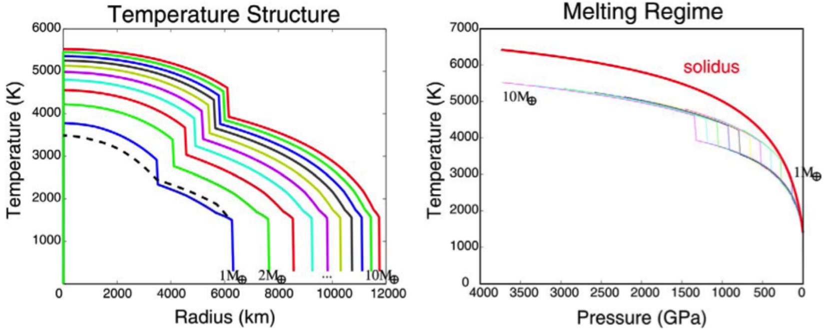
Density structure of super-Earths



(Valencia et al. 2006)

- Super-Earth recipe: mass, composition, equation of state, heat source, heat conduction, convection
- Also need to know core mass fraction (assume 32.59% as for Earth)
- Incompressible planet would have $M \propto R^3$, so $R \propto M^{1/3}$
- Mantle and core are slightly compressible, yielding $R \propto M^{0.26\ldots0.27}$

Temperature structure of super-Earths



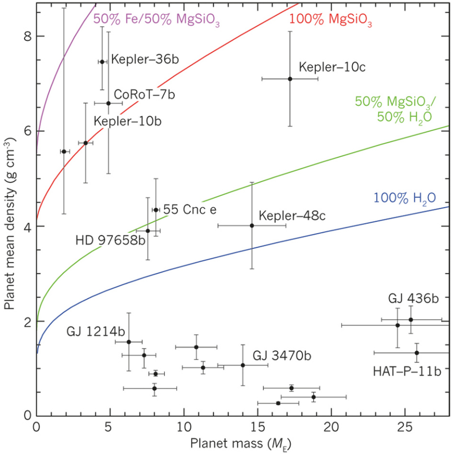
(Valencia et al. 2006)

- Super-Earths have higher interior temperatures because the mass-to-surface ratio is larger (thus more radioactive heat and less efficient heat transport)
- But pressure is much higher ($P_c \propto \rho^2 R^2$), favouring solutions with a completely solid core

⇒ No magnetic field generation (bad news for life!)

- (but still many uncertainties in composition of core and mantle and equation of state)

Density and composition of exoplanets



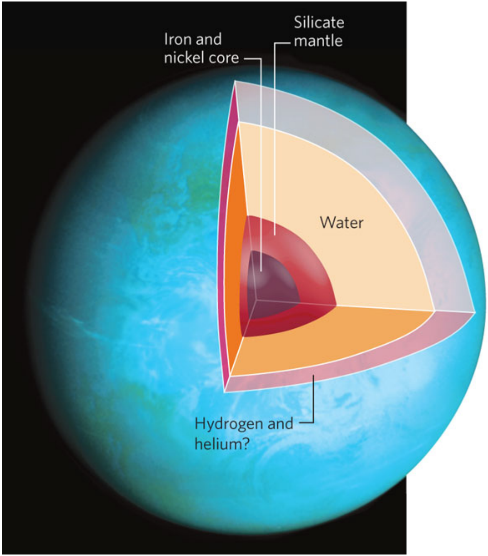
(Mayor et al. 2014)

- By comparing results of structure simulations with observations we can infer the composition of exoplanets

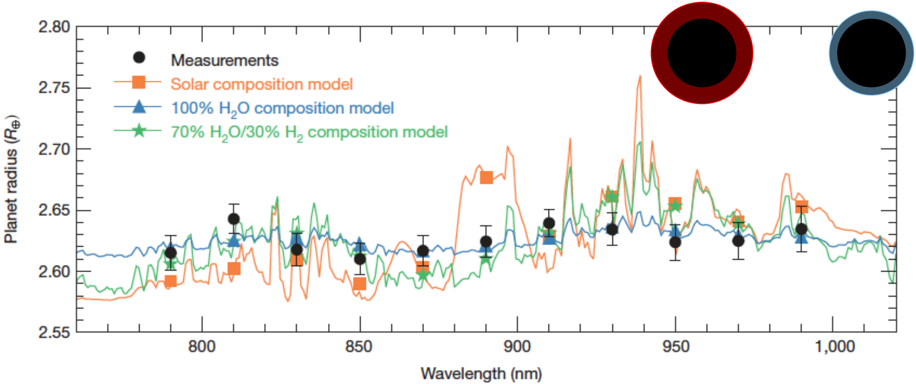
⇒ Super Earth planets have completely different compositions!

Ocean planet

- GJ 1214 b has a mass of 6.6 M_{Earth} and a radius of $2.7 R_{\mathrm{Earth}}$
- Planet probably consists of 3/4 water
- Small atmosphere of H and He
- Ocean planet or melted ice giant?
- Planets with masses 2–10 times the mass of Earth are categorised as *super-Earths*

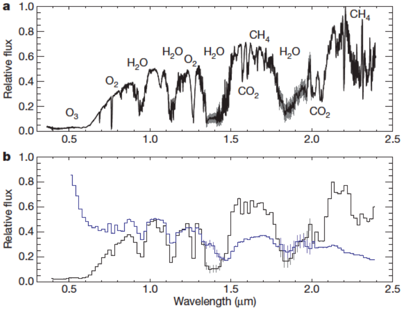


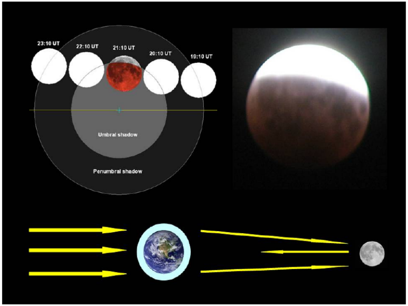
GJ 1214 b atmosphere



- Bean et al. (2010) observed transmission spectrum of GJ 1214 b using VLT telescope
- Spectrum is featureless between 0.8 and 1 μm
- Inconsistent with an extended H/He atmosphere, but consistent with low-scale-height atmosphere consisting of 100% water vapour

Transmission spectrum of Earth

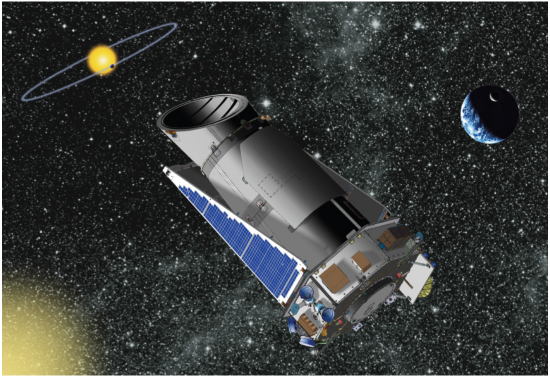




- Pallé et al. (2009) measured transmission spectrum of the Earth from lunar eclipse
- The completely shadowed part of the moon (*umbra*) reflects sun light that has passed through the Earth's atmosphere
- The illuminated part of the moon (*penumbra*) reflects sun light that did not pass through the Earth's atmosphere
- Their ratio gives the transmission spectrum of the Earth

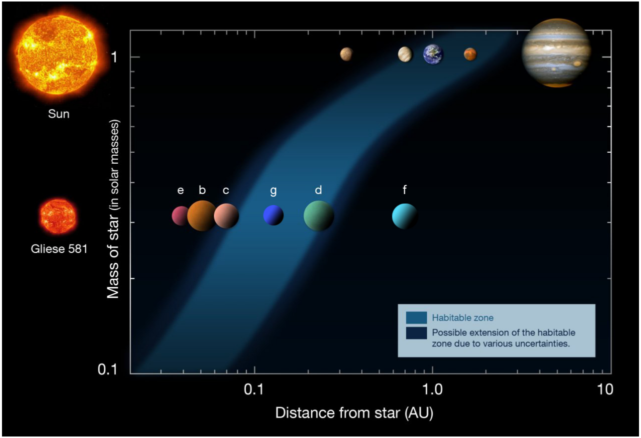
⇒ Biosignatures (O_2, O_3, CH_4) surprisingly visible

Kepler satellite



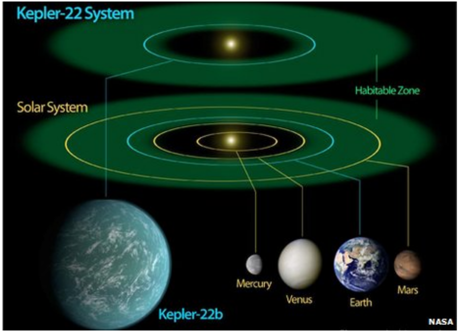
- Kepler satellite (NASA) was launched in 2009
- Monitored 145,000 stars until 2013 when it lost the ability to point accurately
- Goal to find η_{Earth} – the fraction of stars that have Earth-mass planets in the habitable zone

Habitable zone



- Zone were there could be liquid water on the surface of the planet
- But: If a planet is habitable also depends on the atmosphere:
  $\Rightarrow$ see Venus!

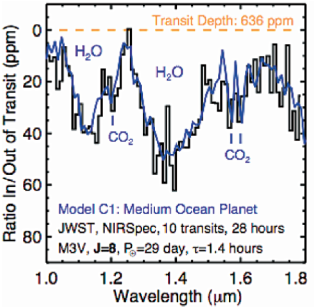
Kepler 22



- Kepler team announced the first super-Earth in the habitable zone in December 2011 *(Borucki et al. 2012)*
- Planet has radius 2.4 $R_\oplus$
- Star is 200 pc away, so no radial velocity follow-up
- *Undoubtedly many super-Earths will be discovered and characterised in detail before lower-mass terrestrial planets*

Future: James Webb Space Telescope

www.jwst.nasa.gov

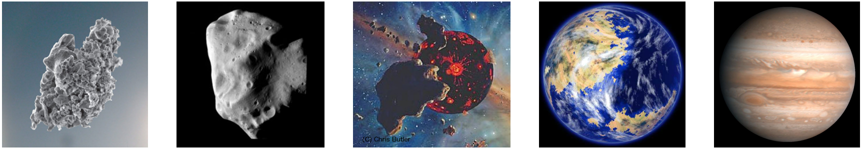


(Seager, Deming, & Valenti 2009)

- James Webb Space Telescope is the successor of the Hubble Space Telescope (expected launch 2018)
- Mirror is 6.5 meter in diameter
- High spectral resolution in the near-infrared and mid-infrared
- Excellent for transit spectroscopy of super-Earths and terrestrial planets

The four steps of planet formation

1. Dust to pebbles
   μm → dm: contact forces during collision lead to sticking
2. Pebbles to planetesimals
   dm → km: gravitational collapse of pebble clouds form planetesimals
3. Planetesimals to protoplanets
   km → 1,000 km: rapid growth of planetesimals via pebble accretion
4. Protoplanets to planets
   Gas giants: 10 $M_\oplus$ core accretes gas ($< 10^7$ years)
   Terrestrial planets: protoplanets collide (10^7–10^8 years)



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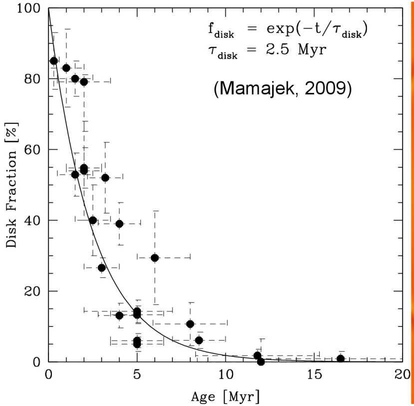
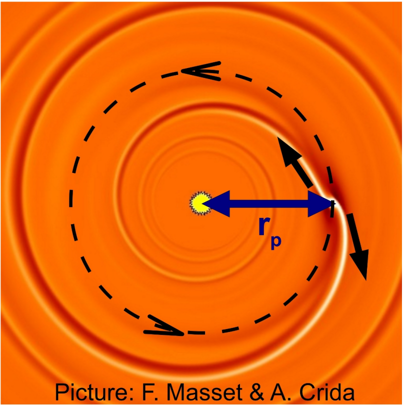
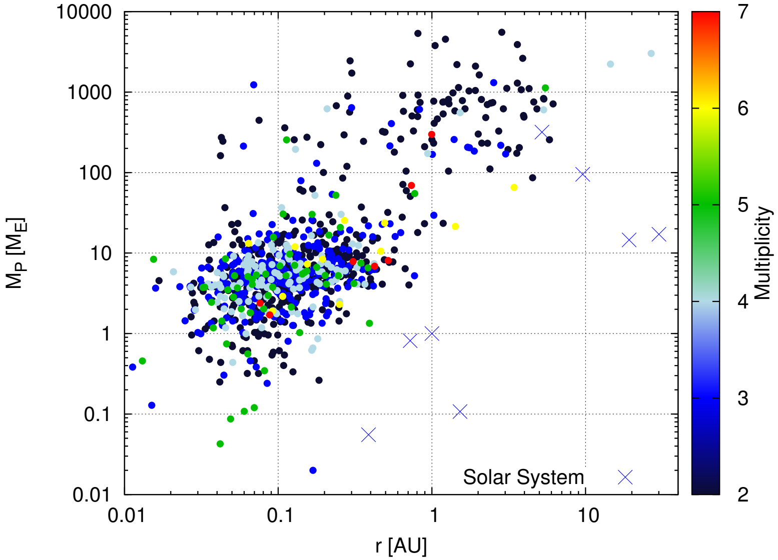




Picture: F. Masset & A. Crida

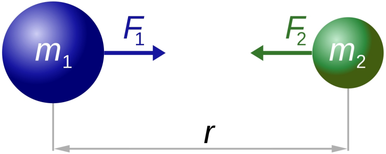
on

Multiplicity



(created with exoplanets.org)

Interactions between big objects: gravity



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

- Increase of mass: increase of gravitational force
- Increase of distance: decrease of gravitational force
- Dominant force for interactions between planetary embryos
- Gravitational force of Jupiter and Saturn are dominant in the solar system

N-Body simulations

- Gravitational interactions between major bodies; gravity from planetesimals is normally not included, as simulations host 1000s of bodies
- Gas drag onto planetesimals and planetary embryos should be included:

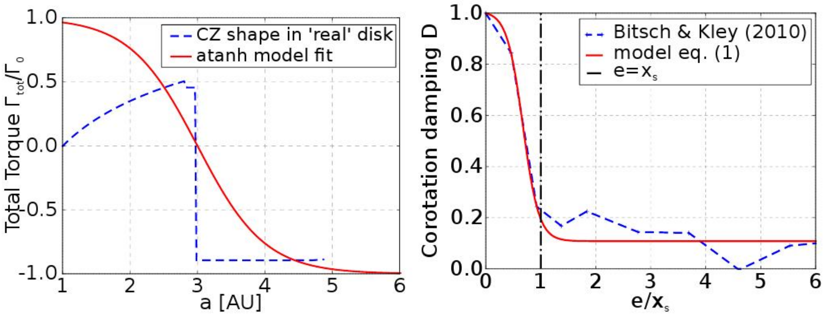
  $\Rightarrow$ damping of eccentricity and inclination:

  $\Rightarrow$ changes collisional outcomes!
- Chaotic behaviour is "normal" in N-Body simulations:
  - Tiny variation of initial conditions (Δv_P, Δr_P) varies results
  - Multiple simulations needed to confirm results: statistics!
- N-Body simulations are numerical experiments that depend on the initial conditions

Setup for outward migration and eccentricity change

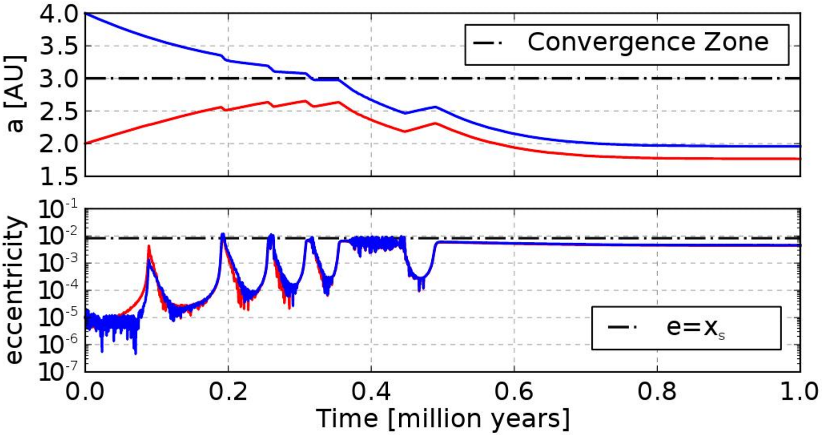
- N-Body simulations with "artificial" zero-migration radius
- Reduction of corotation torque due to eccentricity: $\Gamma_{\rm tot} = \Gamma_L + D\Gamma_C$

Cossou et al. 2013:



- Half-width of horseshoe region: $x_s = 1.16\sqrt{q/(H/r)}$

2 planet scenario

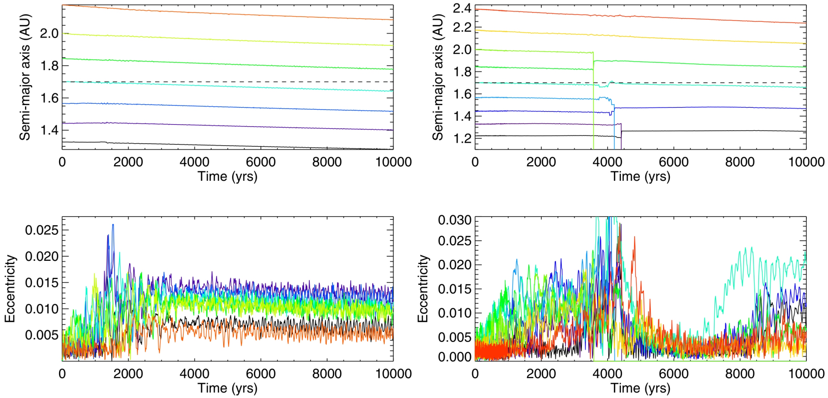


(*Cossou et al. 2013*)

⇒ Planet-planet interactions increase planetary eccentricity

⇒ Increase of eccentricity reduces the corotation torque

Multiple planets in disc



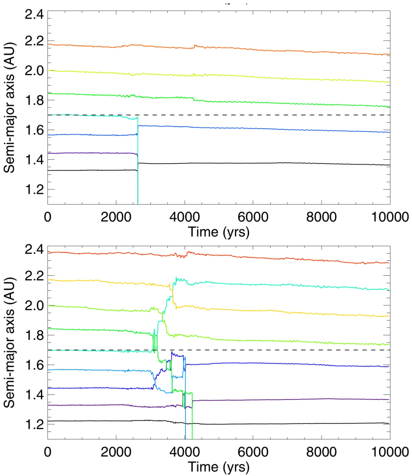
(*Pierens et al., 2013*)

- More planets: more eccentricity growth
- More eccentricity: higher probability of breaking resonances

⇒ higher probability of scattering and planet growth through collisions!

What about turbulence?

Pierens et al. (2013):

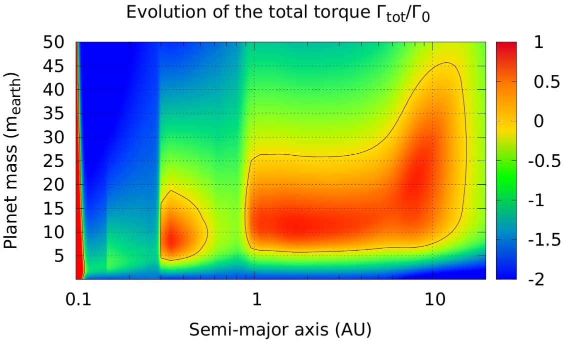


- Turbulence “stirs up” the orbits
- Breaking of resonances can occur

⇒ Close encounters more likely: scattering and collisions more frequent!

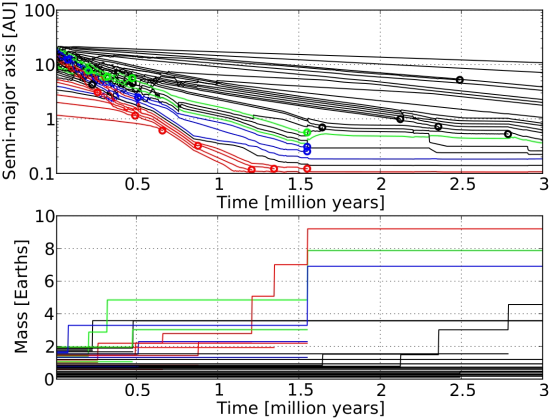
Setup of N-Body simulation: classical growth by embryos

- Distribute embryos ($0.1 - 2.0\mathrm{M}_{\mathrm{Earth}}$) in disc, separated by several mutual Hill radii
- Disc structure determines type-I migration of embryos
- No gas accretion onto cores; No disc evolution!



(*Cossou et al. 2014*)

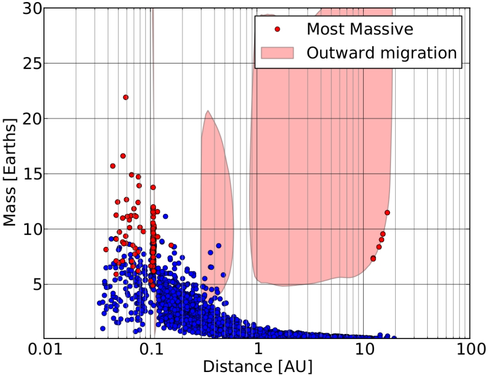
Planets grow by collisions



(*Cossou et al. 2014*)

- Planets can grow through collisions in time
- Massive planets are very close to the star

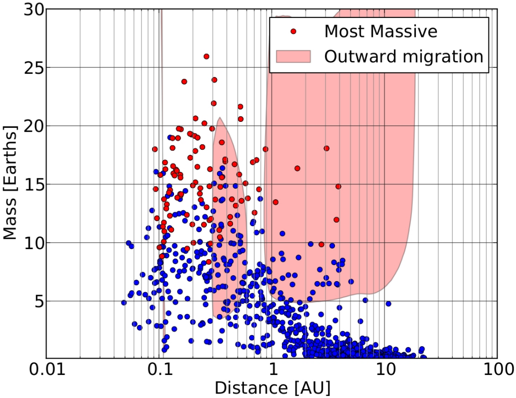
Non-evolving discs



(*Cossou et al. 2014*)

- Only a few cores trapped in outward migration region
- Much more likely to form object of a few Earth masses in inner system
- Can this explain the abundance of Super Earths in inner systems?

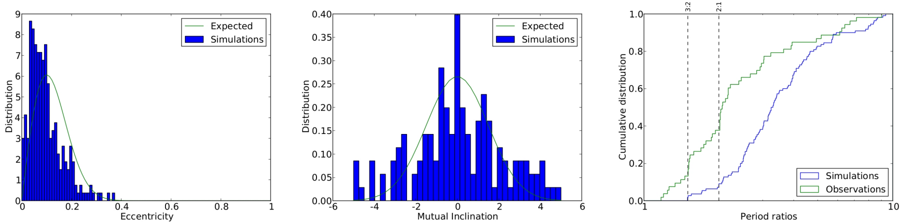
Evolving discs



(*Cossou et al. 2014*)

- Planets in inner disc are less numerous and extend to higher masses: caused by instabilities triggered by disc dissipation (more collisions)!
- Much more massive planets in outer disc

Compare to Observations



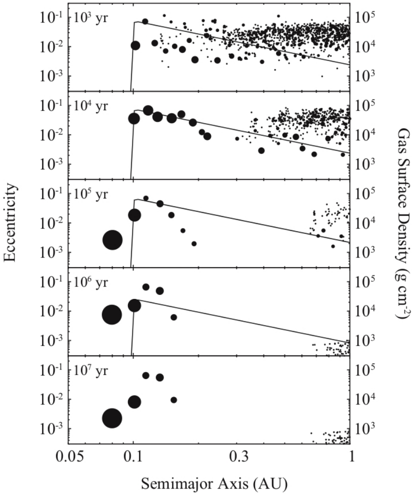
(*Cossou et al. 2014*)

- *e* and *i* distribution of exoplanets is matched
- However resonance occurrence is not matched! Expected as collisions decrease the number of planets, but not generally their radial extend.

Evolution of the disc structure is needed to explain exoplanet population better! ⇒ Much work needs to be done!

N-Body simulations in the super Earth region

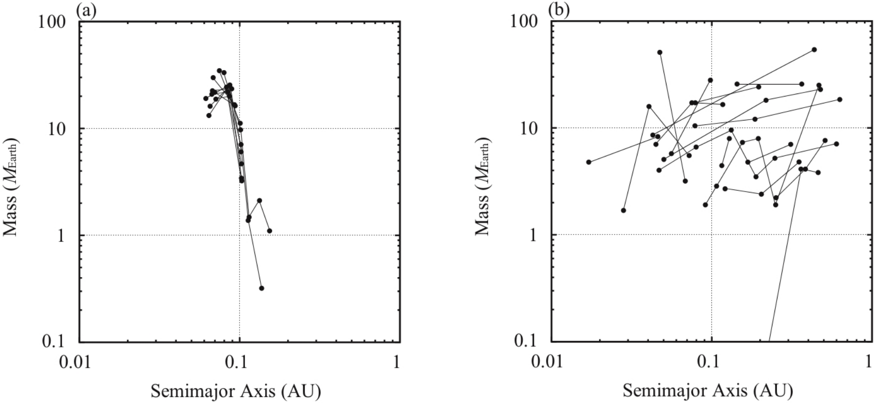
- N-body with gas disc
- Includes damping of e and i
- Includes type-I migration
- Rapid formation of planets at inner edge of the disc
- Size of circle $\propto R_\mathrm{P}$



(*Ogihara et al. 2015a*)

Observations of super Earths

Simulation results: Observations:

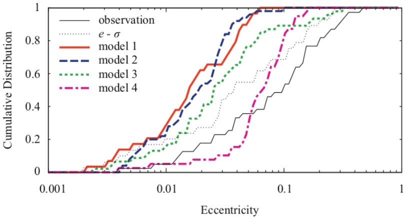


(*Ogihara et al. 2015*)

Result of the simulations:

- Orbital architecture of resultant systems is very compact near the disk inner edge
- The masses of planets monotonically decrease when increasing the semimajor axis

Cumulative Distribution of the planets in the simulations



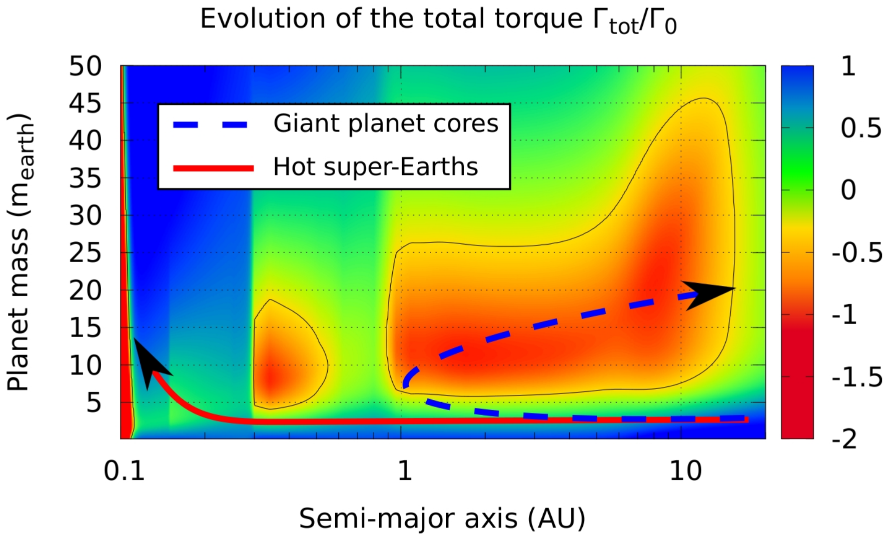
Model	Type-I migration	e, i damping
1	yes	yes
2	yes	yes
3	no	yes
4	yes	no

- $e - \sigma$ is the error corrected distribution
- Eccentricity in simulations is small, because the systems are stable after gas depletion
- Best match with observations, if type-I migration is neglected

$\Rightarrow$ But no mechanism to reduce type-I migration!

$\Rightarrow$ In-situ formation of super-Earths highly unlikely!

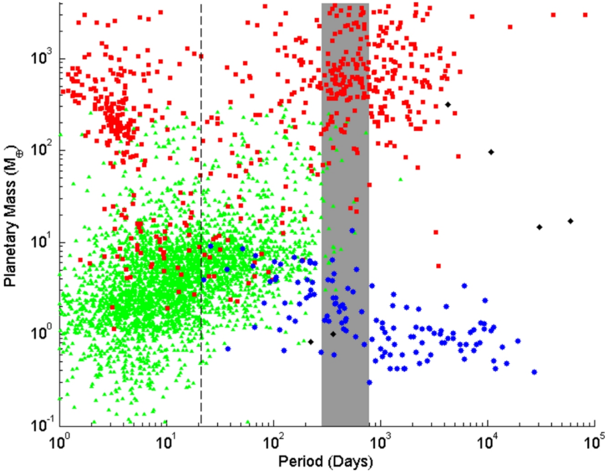
Growth of planets



(*Cossou et al. 2014*)

⇒ What about gas accretion and type-II migration?

Including gas accretion



- RV data, Kepler candidates, Simulations of Coleman & Nelson, 2014

⇒ Migration too strong to allow formation of gas giants

Acceleration of accretion: pebble accretion

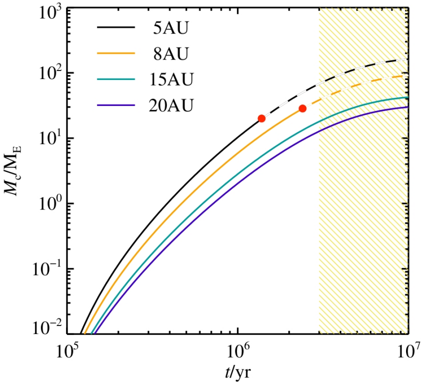
- Small pebbles ($\tau_{\rm f} < 1$) can be easily accreted by planetesimals
- Stokes number $\tau_{\rm f}$ and friction time $t_{\rm f}$:

$$\tau_{\rm f} = t_{\rm f}\Omega_{\rm K} = \frac{\rho_\bullet R}{\rho_{\rm G} c_{\rm s}}\Omega_{\rm K} = \frac{\rho_\bullet R}{\rho_{\rm G} H}$$

- Core growth via pebbles:

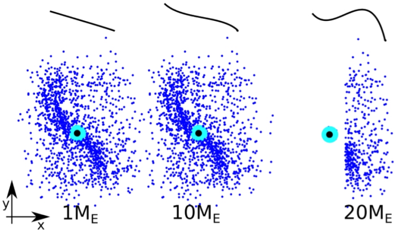
$$\dot{M}_{\rm c} = 2\left(\frac{\tau_{\rm f}}{0.1}\right)^{2/3} r_{\rm H} v_{\rm H} \Sigma_{\rm Peb}$$

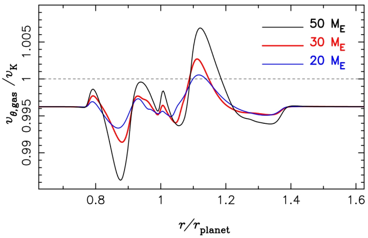
- Growth faster in inner regions of the disc
- Red dots mark pebble isolation mass: gas accretion can start



(*Lambrechts & Johansen, 2012, 2014*)

Halting pebble accretion





- Pebble accretion is stopped when the protoplanet grows massive enough to carve a gap in the pebble distribution
- Gap formation known for Jupiter-mass planets *(Paardekooper & Mellema, 2006)*
- *Lambrechts et al.* (2014) demonstrate that pebble accretion is stopped already at $20\mathrm{M}_{\mathrm{Earth}}$ at 5 AU, with isolation mass scaling as

$$M_{\mathrm{iso}} = 20 \left(\frac{H/r}{0.05} \right)^3 \mathrm{M}_{\mathrm{Earth}}$$

N-body with pebbles

Top plot:

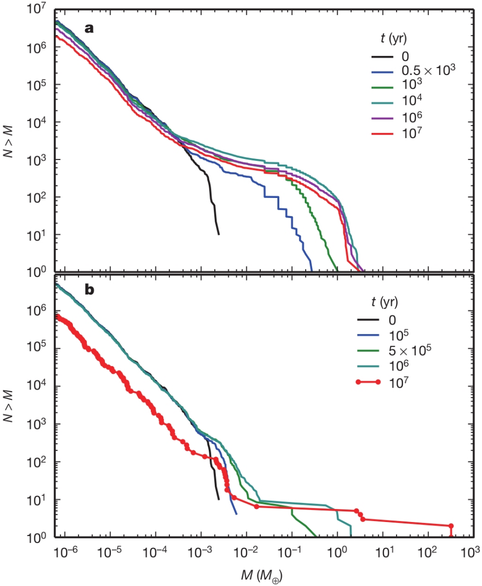
- all pebbles existent at the beginning of the simulations

⇒ No formation of giant planets possible

Bottom plot:

- pebbles formed over the lifetime of the protoplanetary disc

⇒ formation of a few large planets possible



(*Levison et al. 2015*)

N-body with pebbles

Top plot:

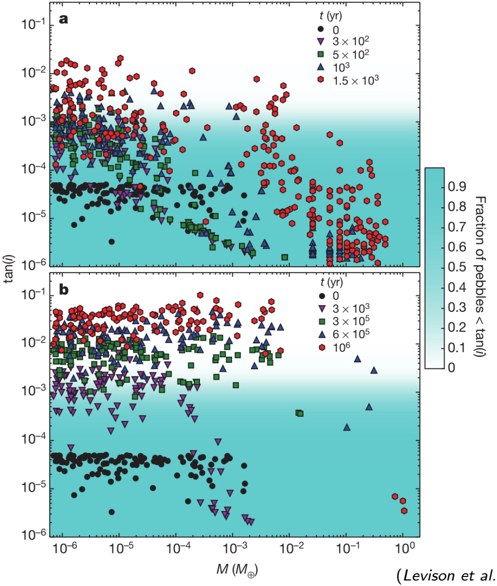
- all pebbles existent at the beginning of the simulations

⇒ no stirring of planetesimals

Bottom plot:

- pebbles formed over the lifetime of the protoplanetary disc

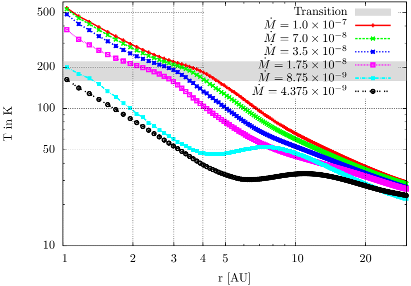
⇒ stirring of small objects hinders their growth



(*Levison et al. 2015*)

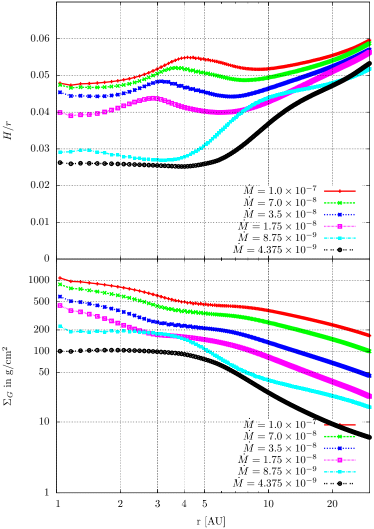
⇒ But simulations are missing disc evolution and planet migration!

Disc structure evolution



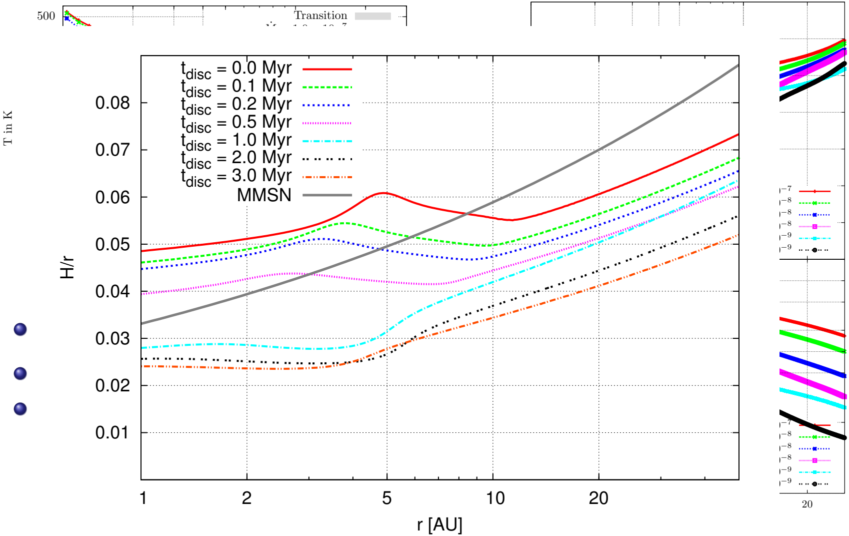
- $\dot{M}$ decreases with decreasing Σ
- $\dot{M} = 3\pi\nu\Sigma = 3\pi\alpha H^2\Omega_{\rm K}\Sigma$
- Evolution in time follows Hartmann et al. 1998 equation:

$$\log\left(\frac{\dot{M}}{M_\odot/\mathrm{yr}}\right) = -8.00 - 1.40 \log\left(\frac{t_{\rm disc} + 10^5\mathrm{yr}}{10^6\mathrm{yr}}\right) .$$



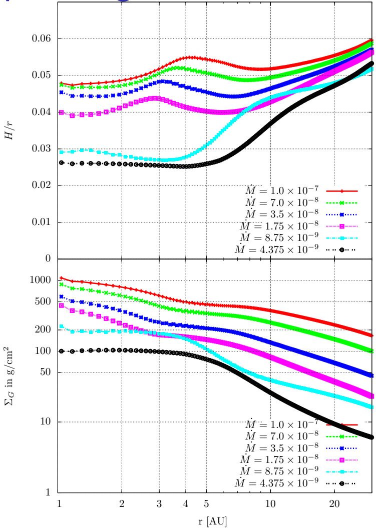
(*Bitsch et al., 2015a*)

Disc structure evolution

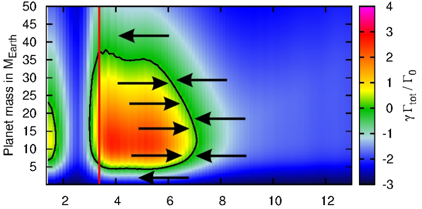


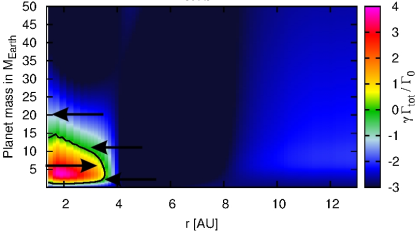
(*Bitsch et al., 2015a*)

Type-I migration in evolving discs



$\dot{M} = 3.5 \times 10^{-8} M_\odot/\mathrm{yr}$



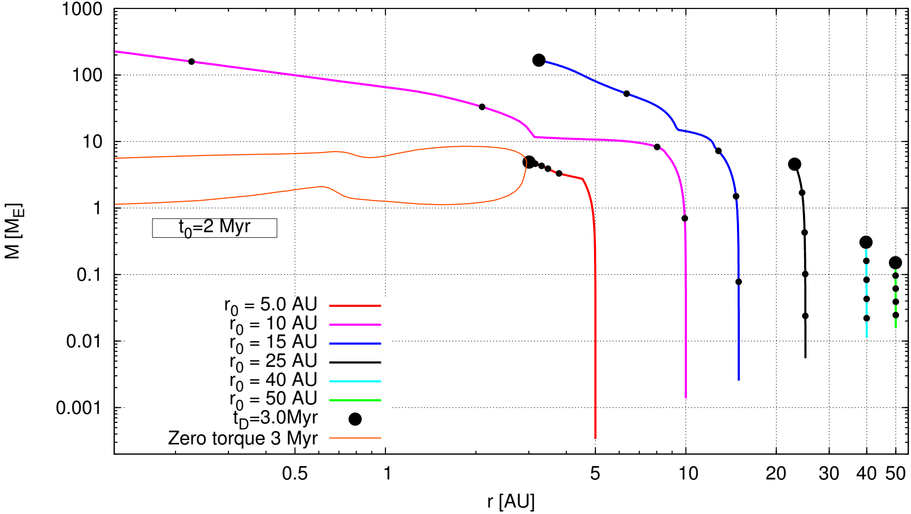


$\dot{M} = 8.75 \times 10^{-9} M_\odot/\mathrm{yr}$

Outward migration in regions where H/r decreases with increasing r!

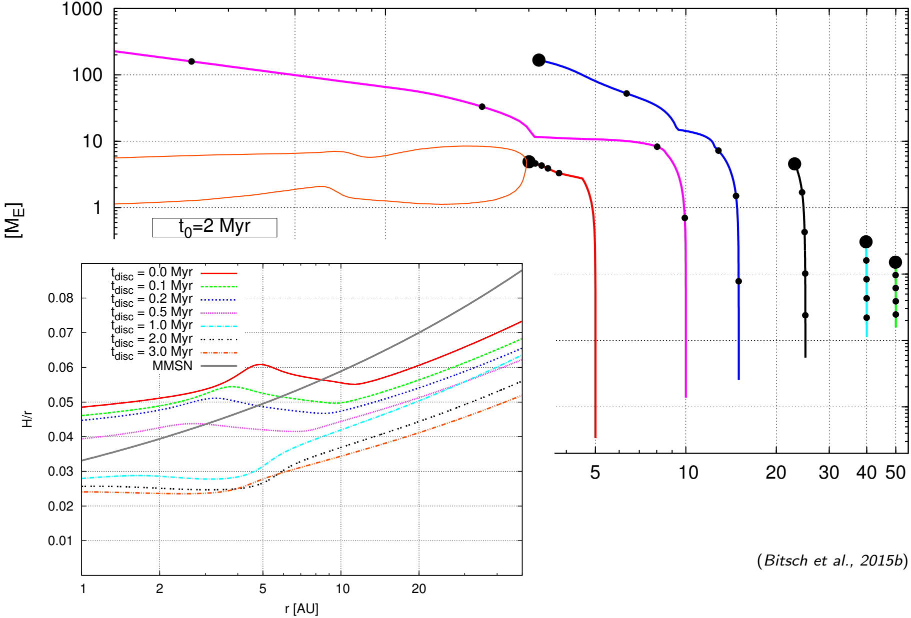
(*Bitsch et al., 2015a*, torque formula from *Paardekooper et al. 2011*)

Evolution tracks of single seeds



(*Bitsch et al., 2015b*)

Evolution tracks of single seeds

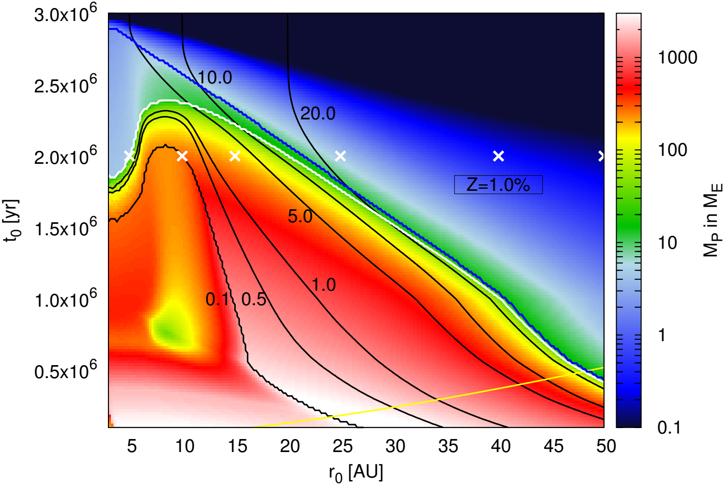


(*Bitsch et al., 2015b*)

Planet formation in evolving disc

Everything below blue line: pebble isolation reached

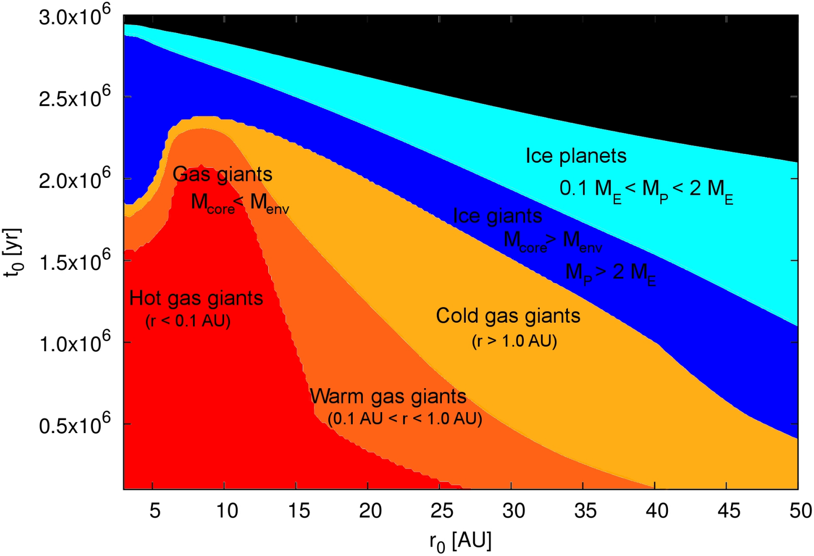
Everything above white line: $M_{\rm core} > M_{\rm env}$



t_0 formation time of planetary seed; r_0 starting orbital distance

(*Bitsch et al.,2015b*)

Overview of planetary classes

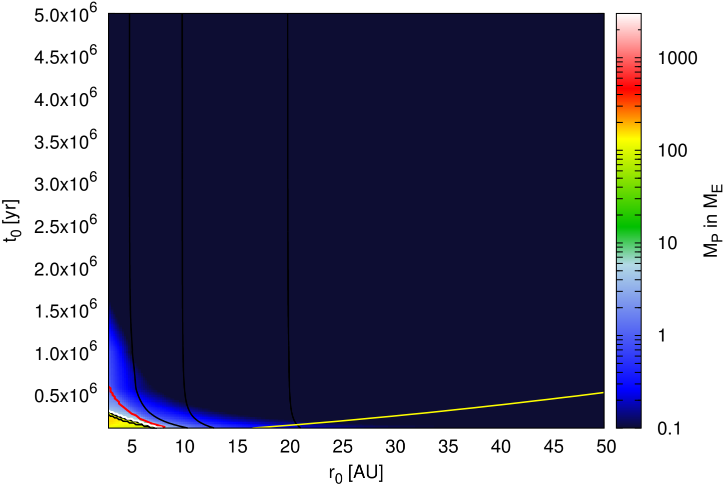


(*Bitsch et al., 2015b*)

Planet formation via planetesimal growth with $Z_{\mathrm{pla}} = 8.0\%$

Everything below red line: planetesimal isolation reached

Everything above white line: $M_{\mathrm{core}} > M_{\mathrm{env}}$



t_0 formation time of planetary seed; r_0 starting orbital distance (*Bitsch et al., 2015b*)

Planet formation via planetesimal growth with $Z_{\mathrm{pla}} = 8.0\%$

Everything below red line: planetesimal isolation reached

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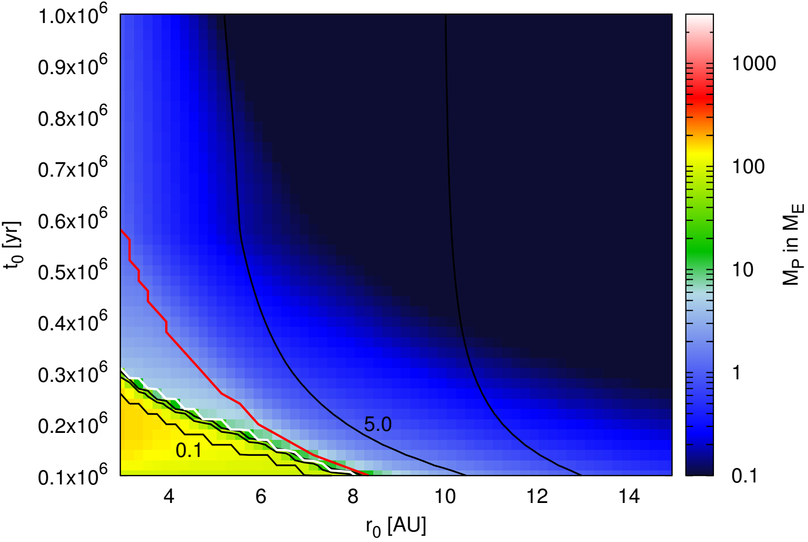
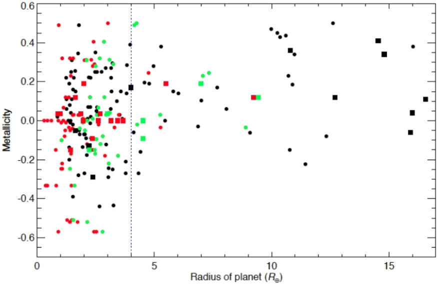


t_0

2015b)

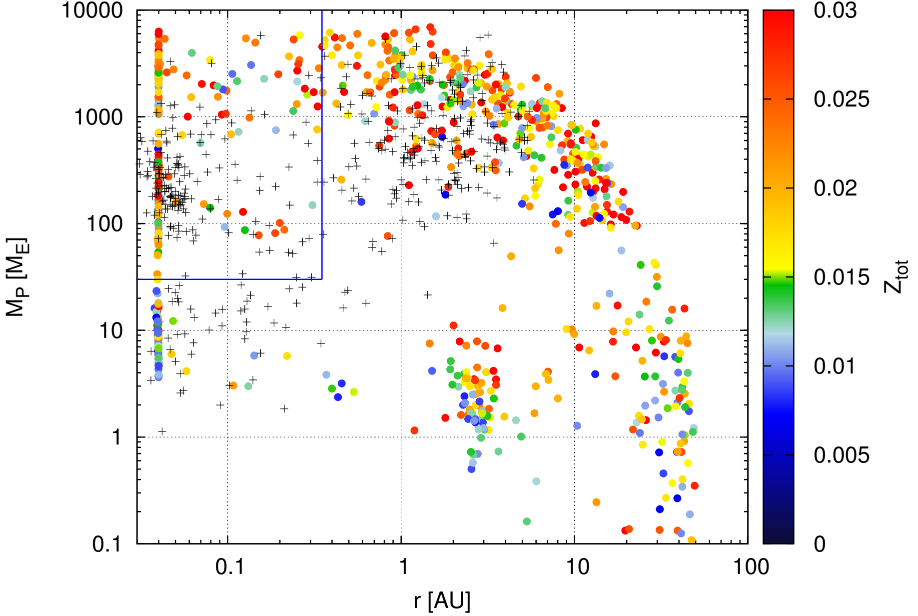
Randomization of parameters

- Metallicity: following Gaussian distribution with median at $[\mathrm{Fe/H}] = 0.0678$ (*Cassagrande et al. 2011*)
- Time parameters:
  - Lifetime of the disc, median at 3 Myr
  - Starting time of planetary seed
- Starting location of planetary seed: [0.1 : 50] AU

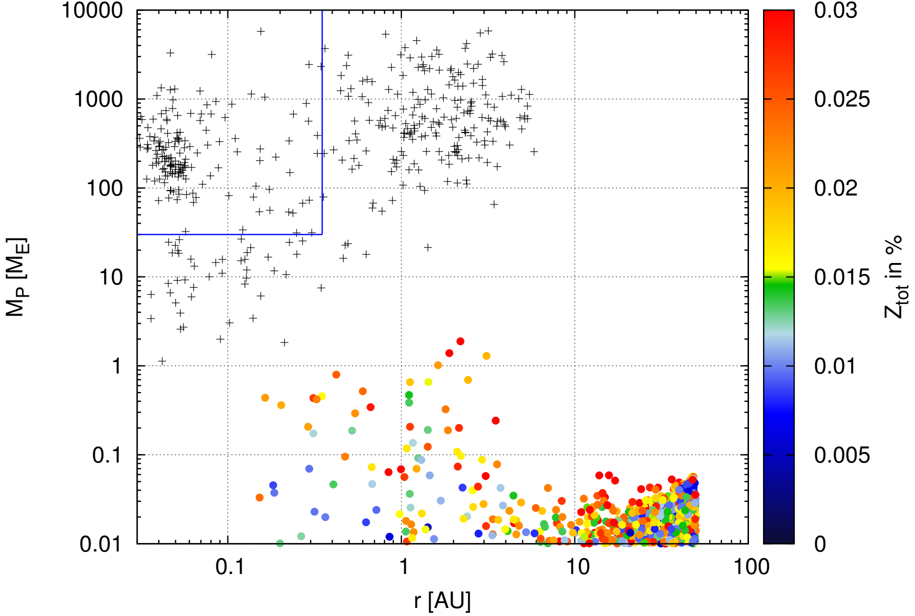


(*Buchhave, Latham, Johansen, et al.*, 2012)

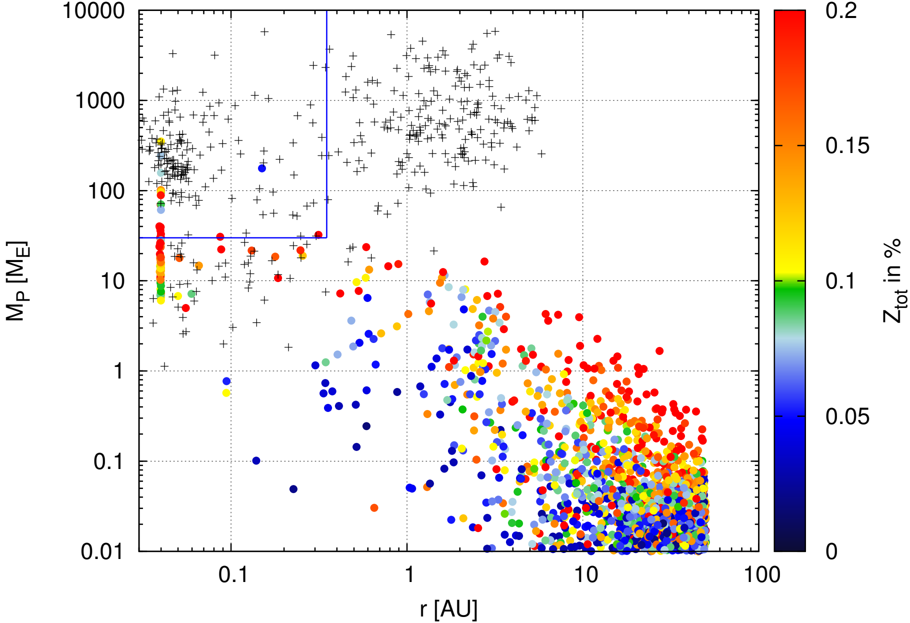
Planet formation via pebble accretion



Planet formation via planetesimal accretion



Planet formation: Z_{pla} increased by a factor of 10:

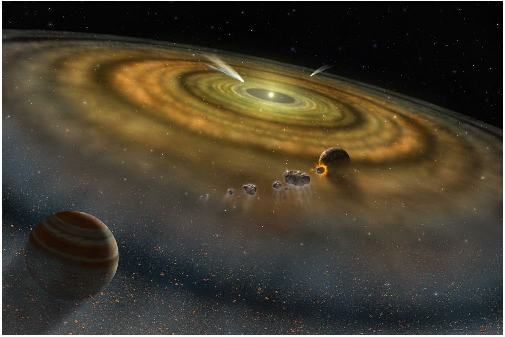


Giant planets migrate a lot

Giant planets open a gap in the disc and migrate in type-II migration, however:

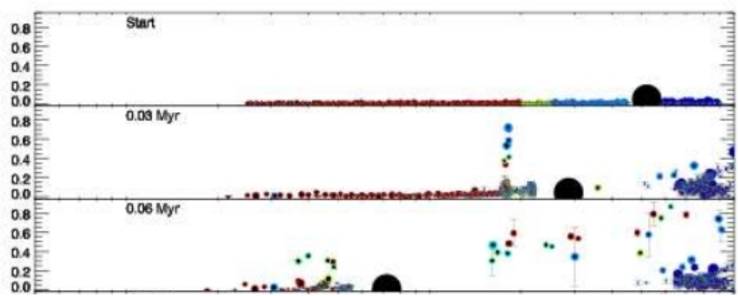
- Before reaching gap opening mass, they migrate in type-I migration (migration time $\propto 1/q$)
- If formed too close to the host star or if accretion is too slow, planets will become a hot gas giant

$\Rightarrow$ What happens to the inner system when a gas giant migrates through?



Early evolution with moving giant planet

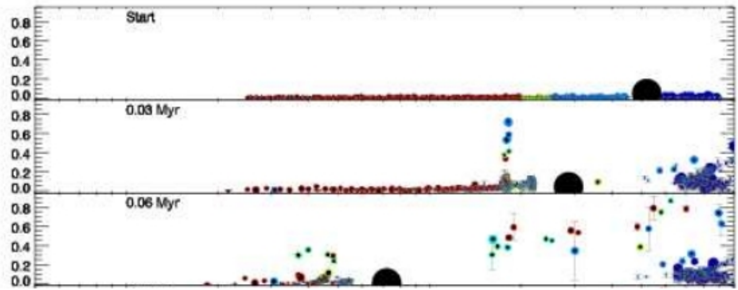
- Gas giant moves inwards and scatters planetesimals
- Planetesimals caught in resonances with planet



(*Raymond et al. 2006*)

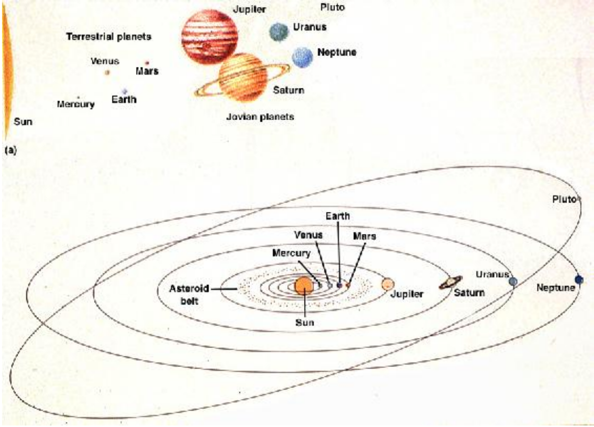
Long term evolution with moving gas giant

- Gas giant moves inwards and scatters planetesimals
- Formation of terrestrial planets with good water content possible: okay for exo-planet systems, but not for the Solar System!



(*Raymond et al. 2006*)

Structure of the solar system today



Mercury	0.39 AU	Jupiter	5.20 AU
Venus	0.72 AU	Saturn	9.54 AU
Earth	1.00 AU	Uranus	19.2 AU
Mars	1.52 AU	Neptune	30.06 AU

Early formation of the Solar System

Assumptions:

- Giant planets already formed: ⇒ see next slides!
- Inner disc filled with planetesimals and embryos
- Dissipation of the gas disc after a few Myr

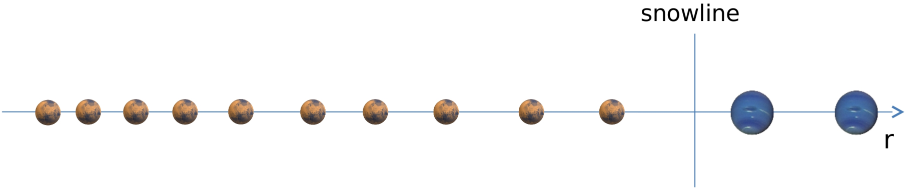
But we do not know:

- Exact position and eccentricity of giant planets?
- Mass of planetesimals and embryos in the inner system?
- When does the disc exactly dissipate?

Constraint: outcome must match the Solar System of today, e.g.

- Planetary masses & orbits
- Structure and distribution of the asteroid belt
- Accretion time-scales (Earth: 50-100Myr (Kleine et al. 2009); Mars: few Myr (Dauphas & Pourmand 2011))
- Water content of terrestrial planets

Initial conditions for giant planets

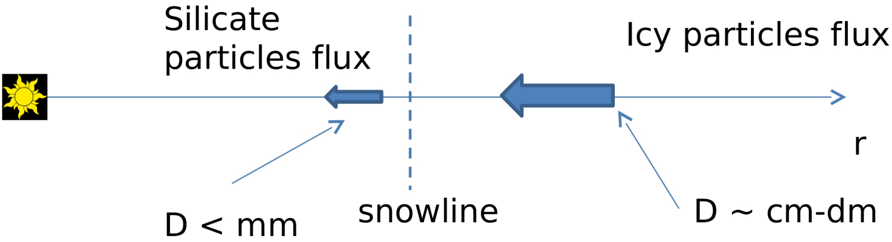


- At the disappearance of the disc of gas, in the outer system protoplanets were 100 times more massive than in the inner system, while the local clock is 10 times slower.

⇒ How can that be???

- The presence of ice should just increase the local surface density of solid mass by $\sim$2 (just 1.2 if one trusts the 67P rock/ice ratio!)

The great dichotomy of the solar system



Silicate particles flux

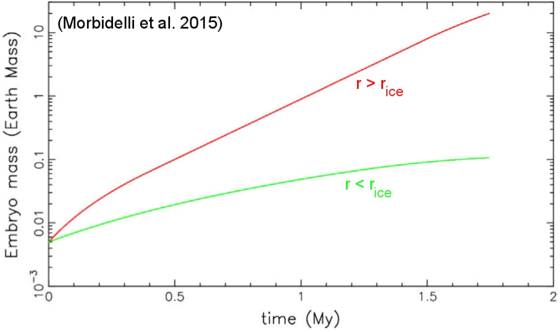
Icy particles flux

r

D < mm

snowline

D ~ cm-dm

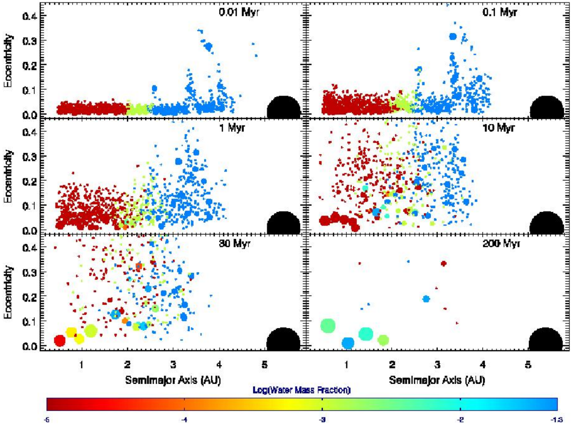


(Morbidelli et al. 2015)

Jupiter and Saturn on circular orbits

- Disc of planetesimals and planetary embryos interior to Jupiter
- Jupiter and Saturn formed at their current orbits and do not migrate

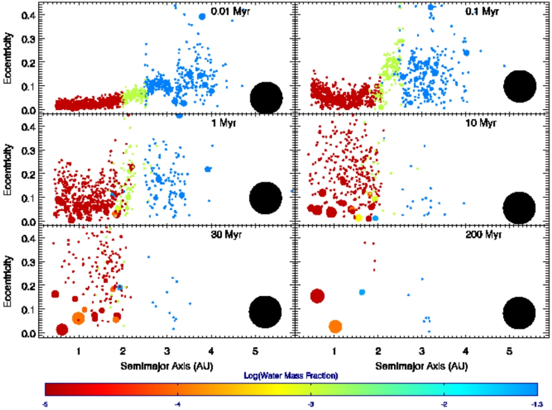
Raymond et al. 2009:



Jupiter and Saturn on eccentric orbits

- Jupiter and Saturn have eccentricity of $e = 0.1$ in simulation
- Currently: $e_{\mathrm{Jup}} = 0.048$ and $e_{\mathrm{Sat}} = 0.055$

Raymond et al. 2009:

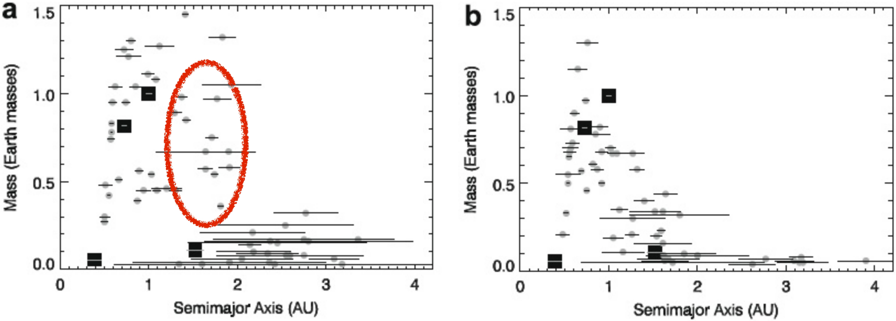


Problem of Mars

Raymond et al. 2009:

Jupiter & Saturn in resonance

$e_{\mathrm{Jup}} = e_{\mathrm{Sat}} \approx 0.1$

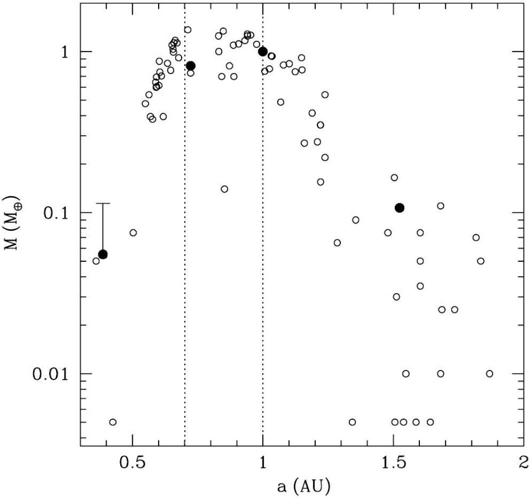


Mars too small!

Earth forms dry!

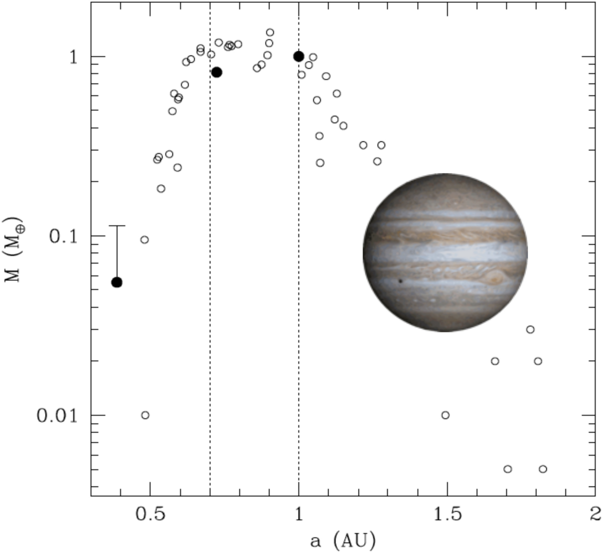
Formation from a small annulus 0.7AU$< r <$ 1.0AU

Hansen, 2009:



Formation from a small annulus 0.7AU$< r <$ 1.0AU

Hansen, 2009:



Two massive planets in resonance: outward migration

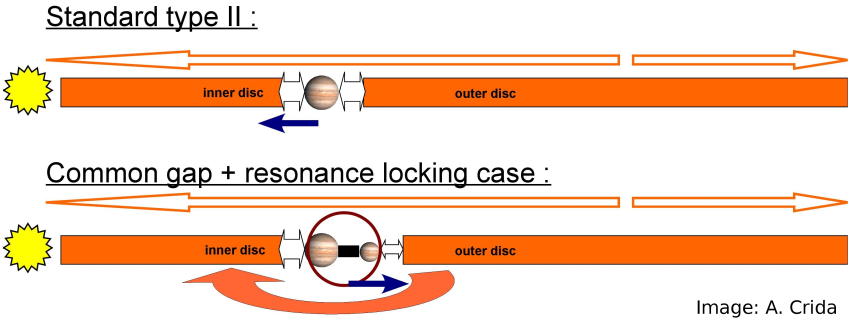
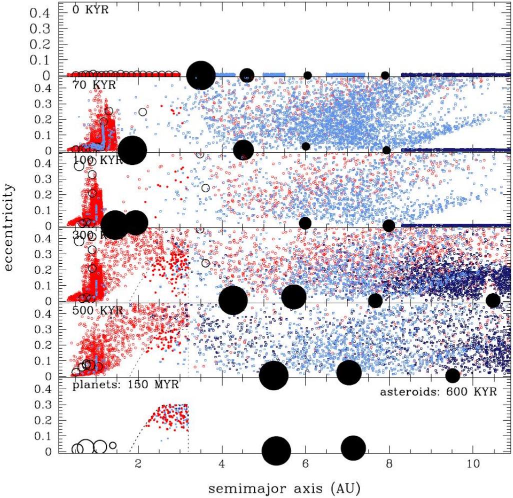


Image: A. Crida

- $M_{out} < M_{in}$ a smaller negative torque acts from the outer disc than a positive torque from the inner disc (*Masset & Snellgrove, 2001*)
- Works best if mass ratio is between $1/4$ and $1/2$ (*Morbidelli & Crida, 2007*)
- Application to the Solar System: Grand Tack scenario (*Walsh et al. 2011*)

Grand Tack Scenario for inner Solar System

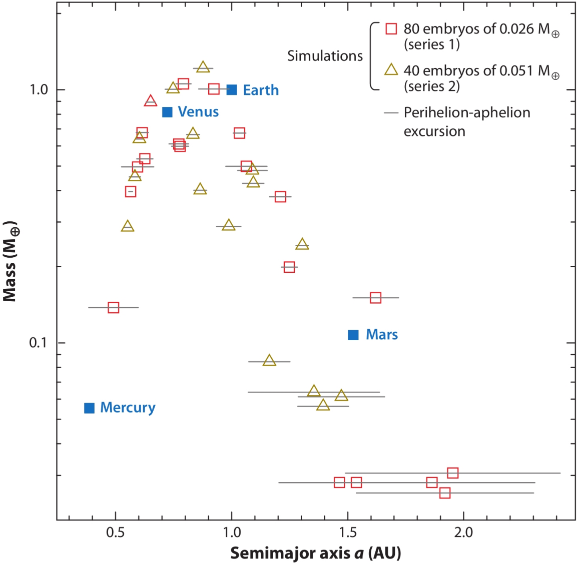


(*Walsh et al. 2011*)

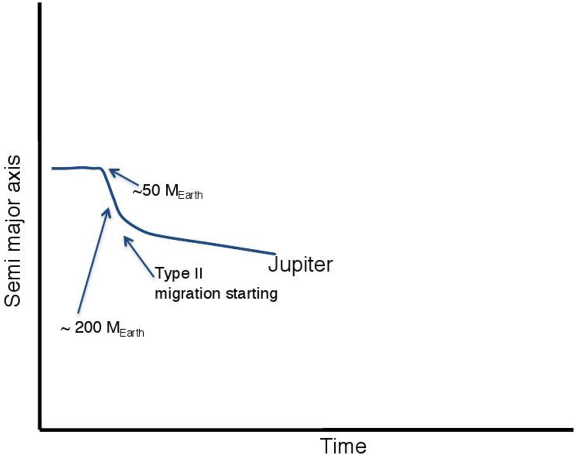
⇒ Populates also the asteroid belt!

Formation of Mars

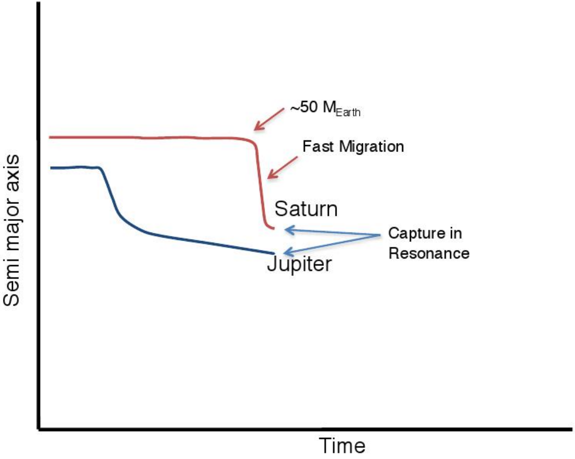
Walsh et al. 2011



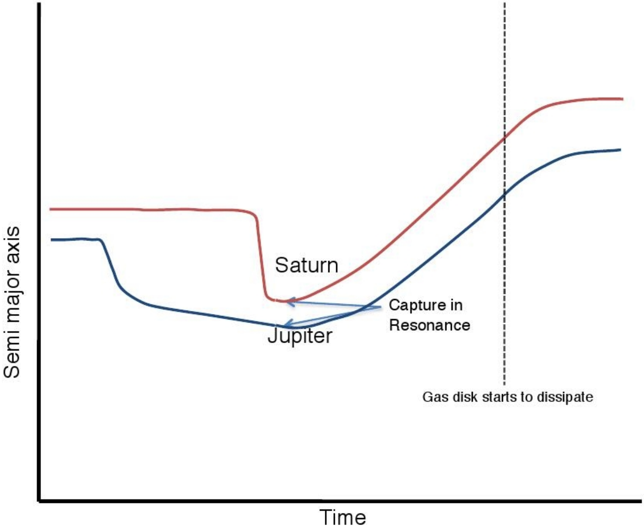
Migration of Jupiter



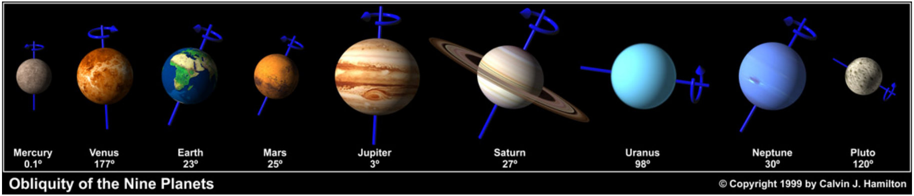
Migration of Jupiter and Saturn



Migration of Jupiter and Saturn



Obliquity in the solar system

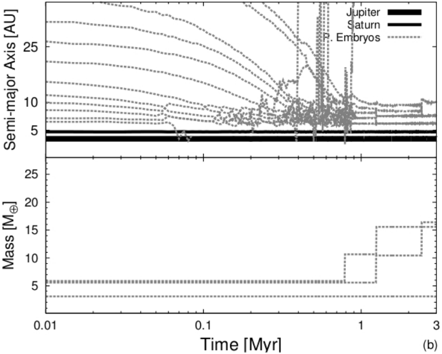


- Most planets have a large obliquity (spin-axis orientations)
- Especially interesting for the gas giants: if inflow of gas produces them, why different obliquity?

⇒ Secular spin-orbit resonances between the giant planets can produce the obliquity during their migration in the gas free disc

⇒ Uranus: tilting requires giant impacts

Ice giant formation via impacts

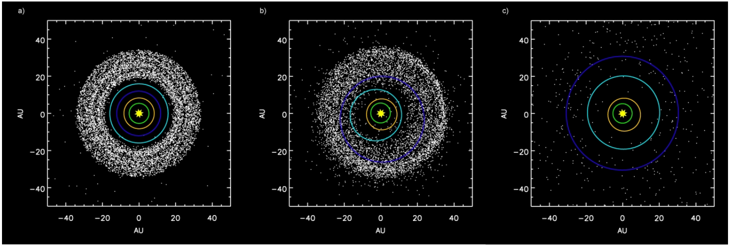


- N-body simulations of embryos (a few Earth masses) outside of Saturn and Jupiter to form the ice giants
- Difficult to match obliquity and mass ratio of the ice giants
  ⇒ formation of the ice giants is still a challenge! (*Izidoro et al. 2015*)
- Scattering of a body to the outer solar system...

What comes after the gas disc dissipates?

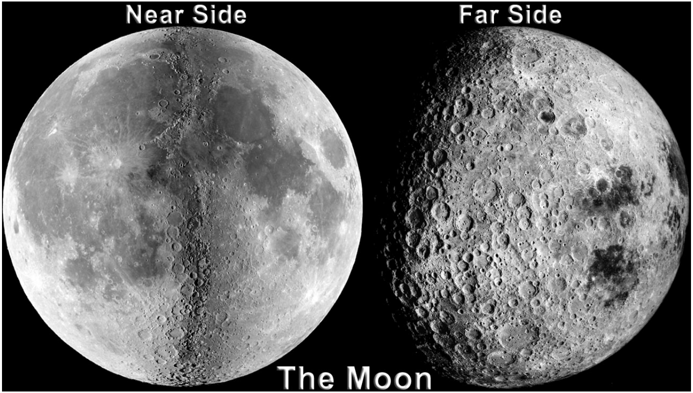
- Jupiter, Saturn, Uranus and Neptune are in a resonant, compact (between 5 and 15 AU) configuration, on circular orbits and there remains a dense belt of planetesimals outside
- This is not the case now!

⇒ Interactions with the outer planetesimal belt triggered a late instability in the system



⇒ Can explain comets in the Oort cloud!

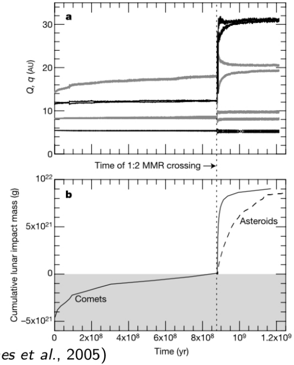
Evidence for the late instability?



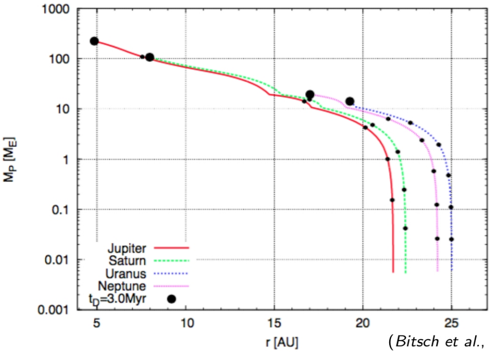
- Craters on Mars and Moon imply heavy bombardment!
- Last giant impact on the moon: a few 100 Myr after the birth of the Solar System!

⇒ Bombardment can be explained through the Nice model

Initial conditions of the Nice model



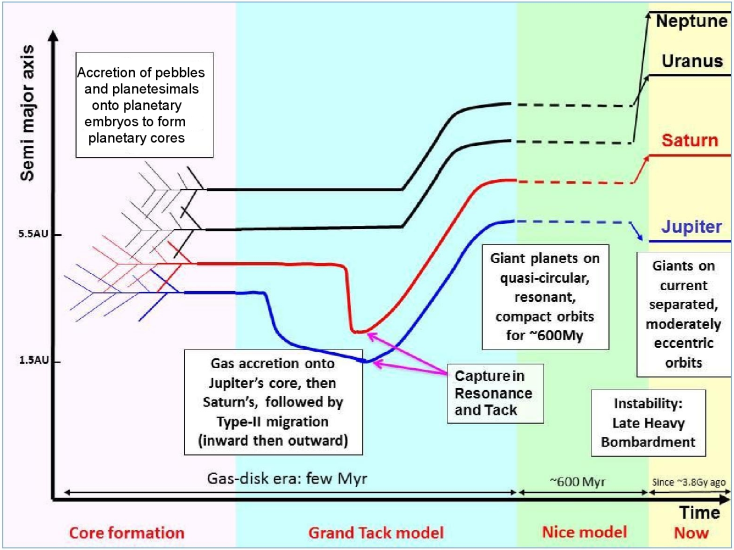
(*Gomes et al.*, 2005)



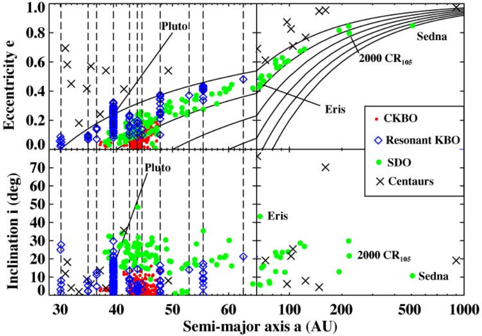
(*Bitsch et al.*, 2015)

- In the Nice model the giant planets orbit initially in a compact configuration
- Natural consequence of planetary migration combined with rapid pebble accretion
- Orbital architecture of the Nice model can be explained if the planetary embryos emerge after 1.5-2 Myr in initial orbits between 20 and 25 AU

Evolution of the Solar System



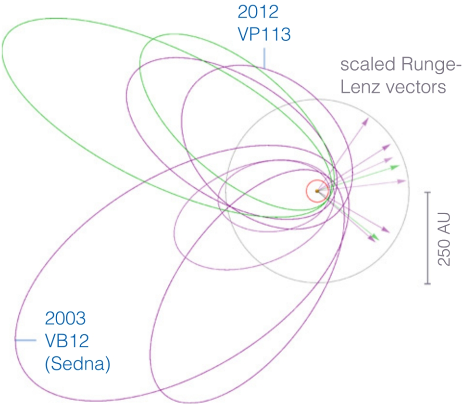
Classification of trans-Neptunian objects



(Chiang et al. 2007)

- Kuiper belt objects reside beyond the orbit of Neptune
- Can we learn something from the orientation of the outer objects?

Outer objects in the solar system

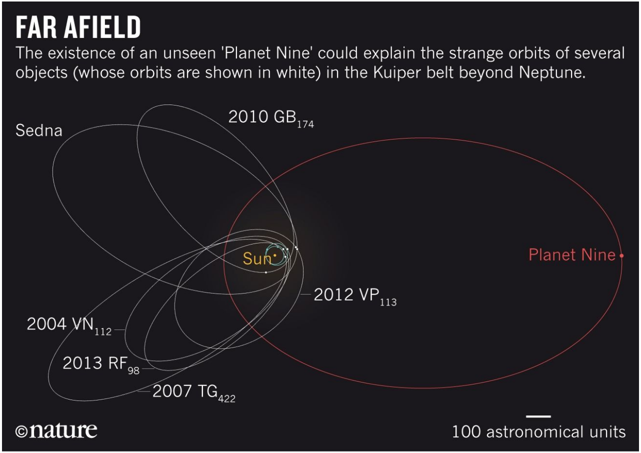


(Batygin & Brown, 2016)

- Runge-Lenz vector describes shape and orientation of the orbit
- Orbits are physically confined! But they should be random...

⇒ What can cause this confinement?

Cause of the confinement



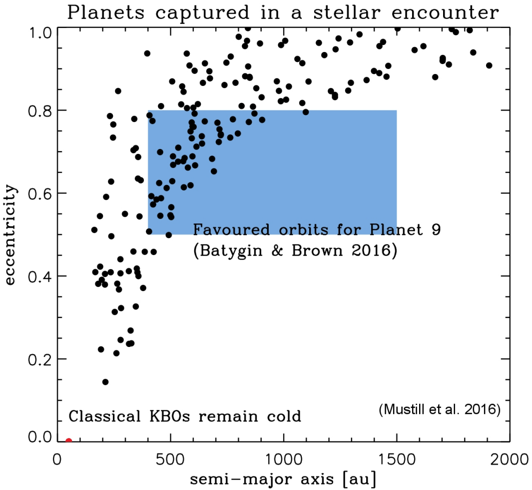
FAR AFIELD

The existence of an unseen 'Planet Nine' could explain the strange orbits of several objects (whose orbits are shown in white) in the Kuiper belt beyond Neptune.

(*Batygin & Brown, 2016*)

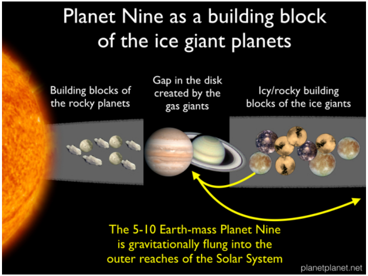
- Orbital properties can be best explained through a $\sim 10\ M_{\mathrm{Earth}}$ companion with $a \sim 600$ AU and $e \sim 0.6$

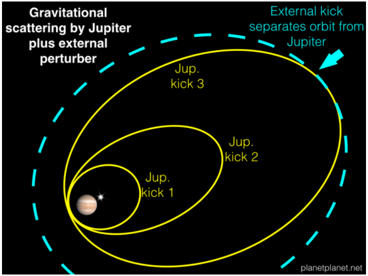
Formation of Planet 9: capture during stellar flyby?



- Sun born in cluster: Stellar flybys common
- Capture from a stellar flyby?
- $\sim 2\%$ probability to capture a body with Planet 9's speculated attributes

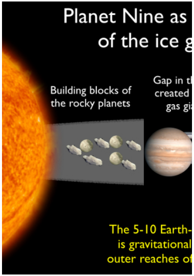
Formation of Planet 9: scattering of embryo?

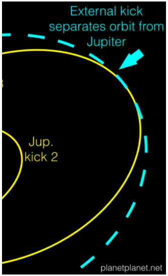




- Scattering event during assembly of the ice giants? (see Izidoro et al. 2015)
- Requires that sun is still embedded in the cluster phase to constrain orbit
- Scattering can not happen during the Nice instability, because then Oort cloud objects would have the same orbit as planet 9!

Formation of Plar o?





- Scattering event ? (see Izidoro et al. 2015)
- Requires that sur phase to constrain orbit
- Scattering can no lity, because then Oort cloud object lanet 9!

⇒ BUT: planet 9 still needs to be found!

Summary

- Characterisation of exoplanets can help to constrain formation theories
- Formation of giant planets at large orbits possible only with pebble accretion, even large Z does not work for planetesimal accretion
- Migration of the giant planets determines the structure of the resulting planetary systems
- Giant planets played a major role in the formation of the inner solar system