Migration, accretion and gap formation by planets embedded in protoplanetary discs

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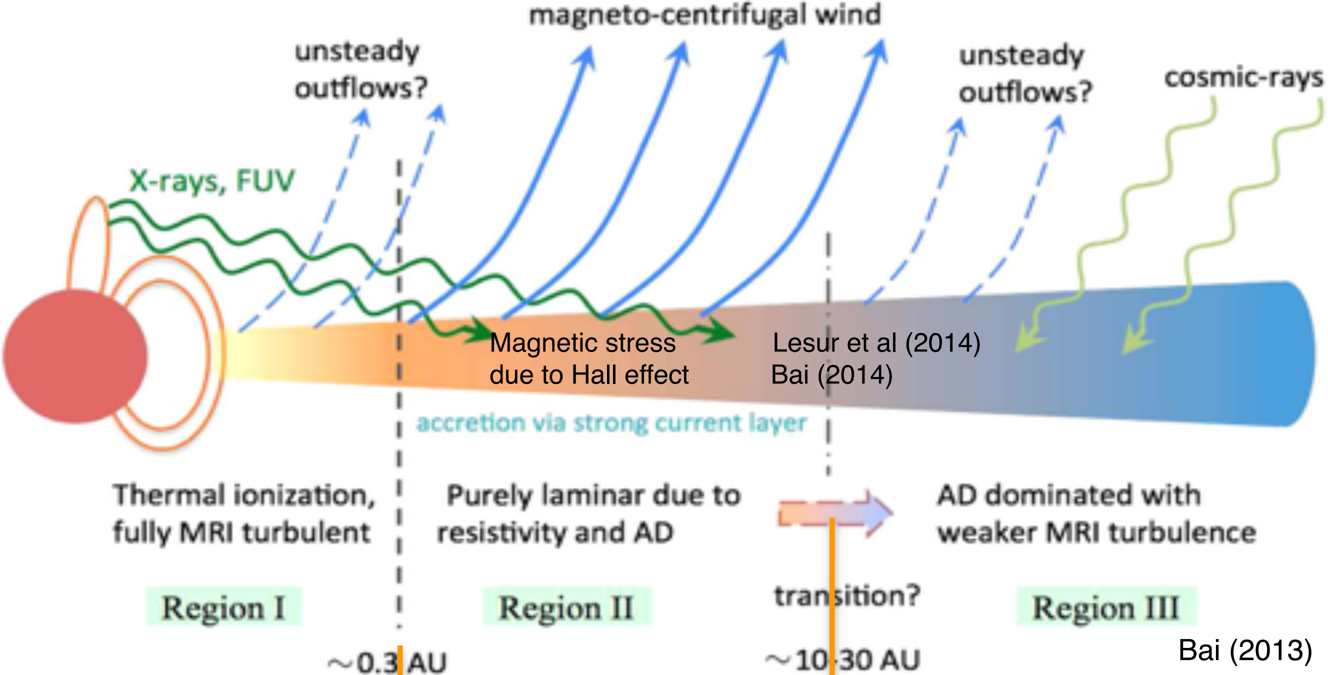
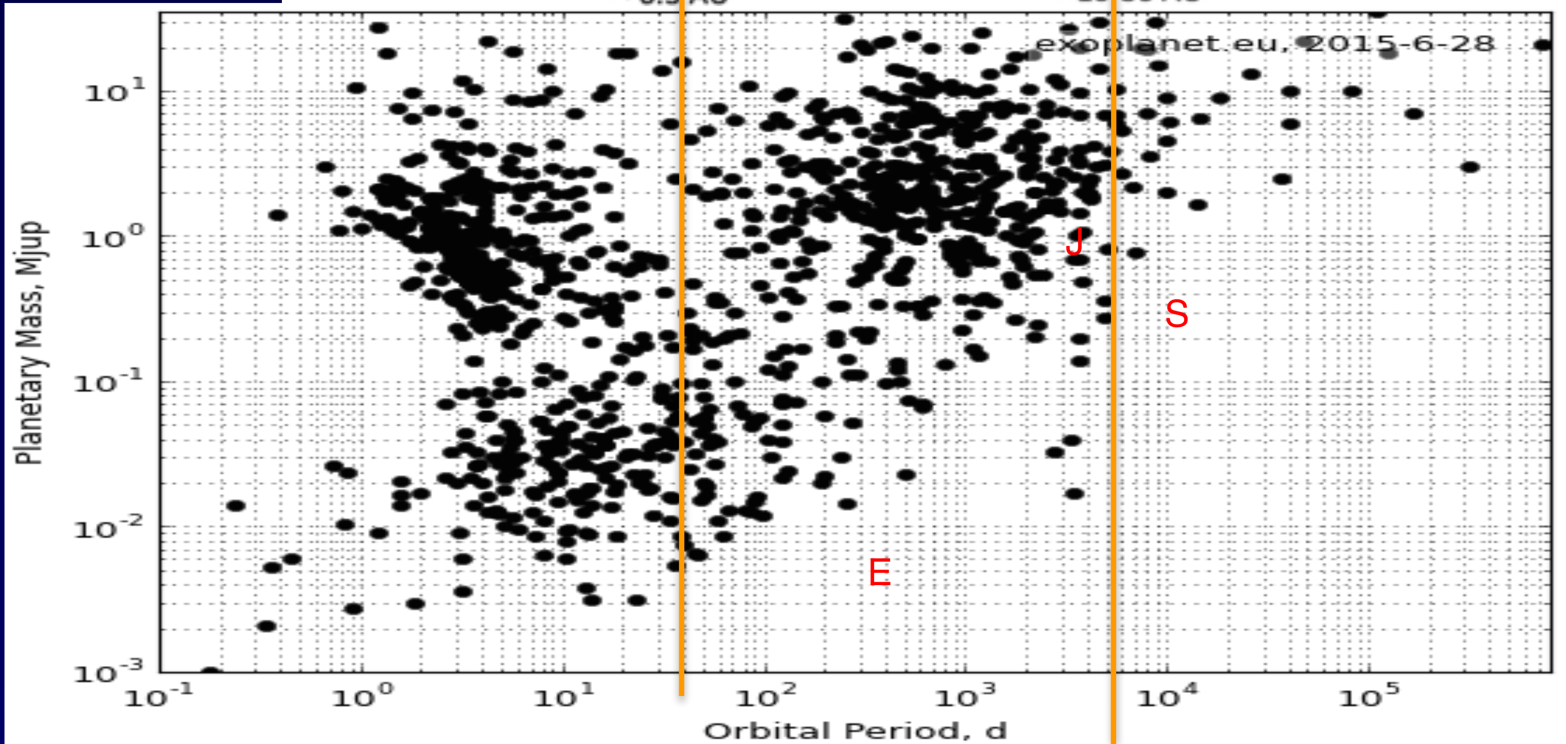
Evidence for migration

- Hot-Jupiters (e.g. 51 Peg) and the numerous “warm” Jupiters with periods ~ 10-20 days
- Short-period coplanar compact systems of super-Earths + Neptunes (e.g. Kepler 11)
- Systems in mean motion resonance (e.g. GJ 876)
  - convergent migration
- Note: misaligned and eccentric systems also indicate that planet-planet scattering and/or Kozai effect may also play an important role in post-formation orbital evolution


magneto-centrifugal wind
unsteady outflows?
unsteady outflows?
cosmic-rays
X-rays, FUV
Magnetic stress due to Hall effect
Lesur et al (2014)
Bai (2014)
accretion via strong current layer
Thermal ionization, fully MRI turbulent
Purely laminar due to resistivity and AD
AD dominated with weaker MRI turbulence
Region I
Region II
transition?
Region III
~0.3 AU
~10-30 AU

Bai (2013)


exoplanet.eu, 2015-6-28
Planetary Mass, Mjup
10^1
10^0
10^-1
10^-2
10^-3
Orbital Period, d
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
J
S
E

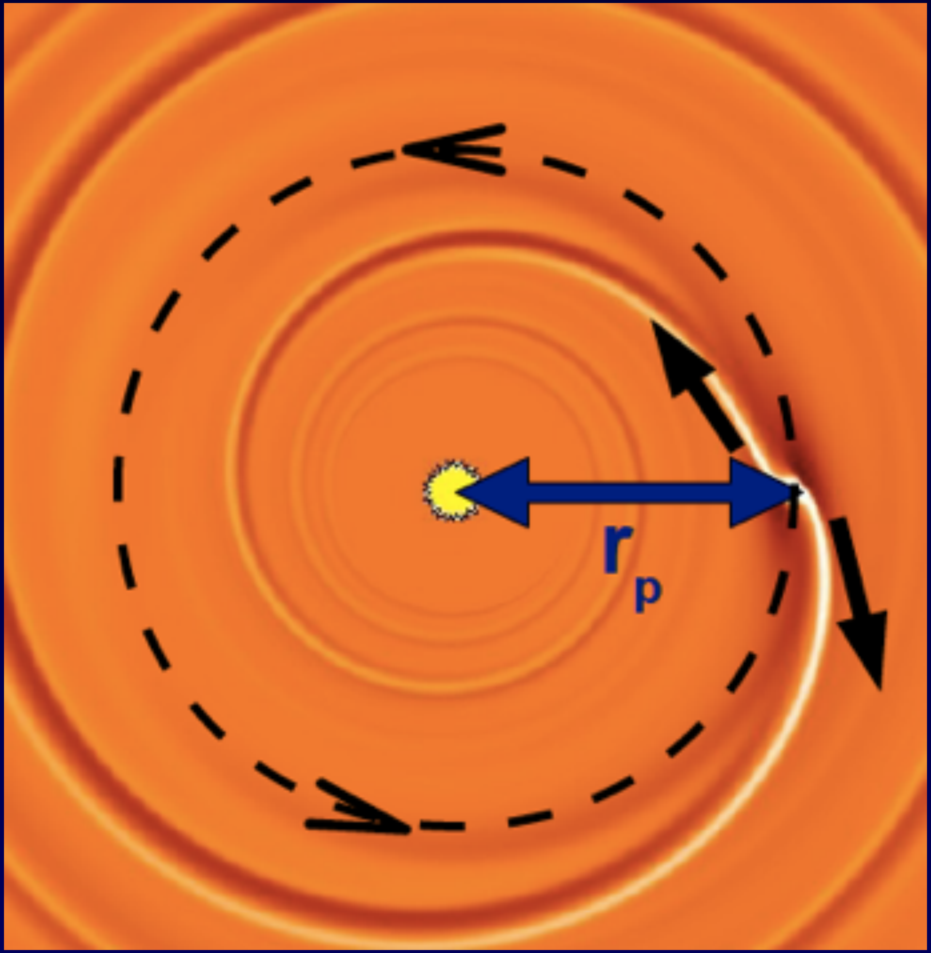
Type I migration of low mass planets

Lindblad torque

- Gravitational interaction between planet and disc leads to the excitation of spiral density waves at Lindblad resonances
  (Goldreich & Tremaine 1978, 1980;
  Lin & Papaloizou 1979, 1984)

- Spiral wave exerts gravitational force on planet - removes angular momentum and drives inward migration

Migration time ~ 70,000 yr for 10 M_{earth} planet at 5 AU in minimum mass solar nebula (MMSN) disc model



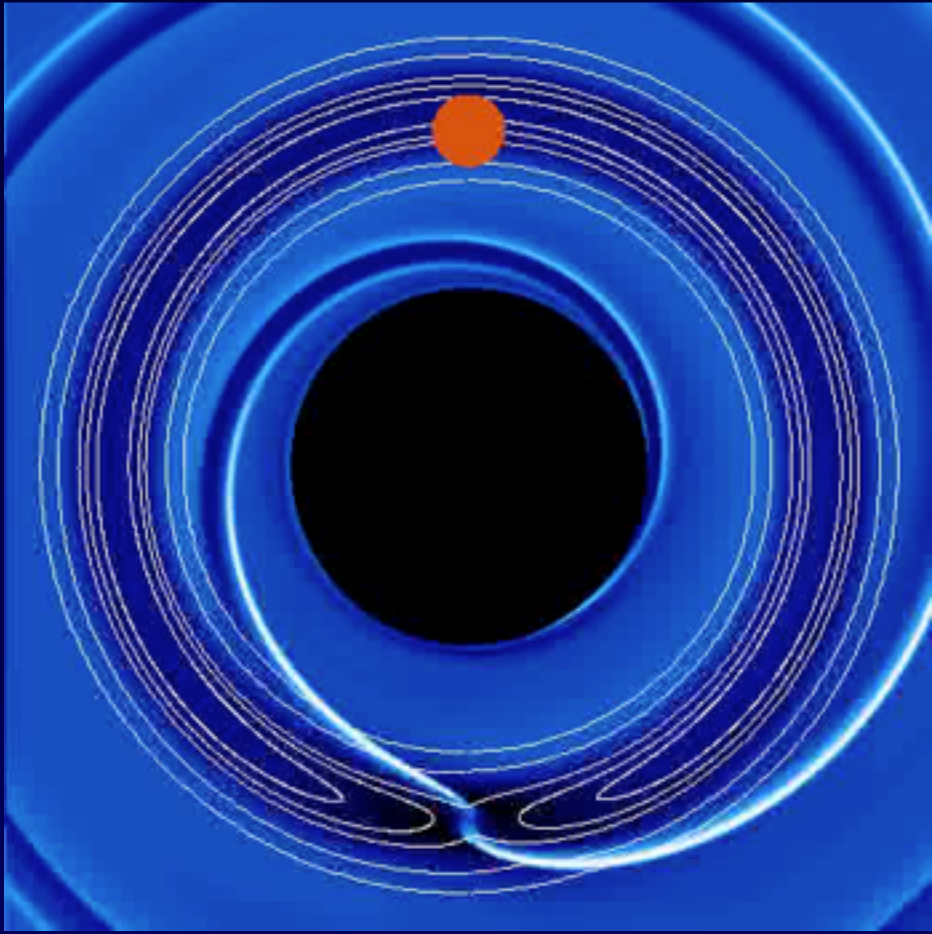
Corotation torque

- Angular momentum is exchanged between planet and material that orbits in the horseshoe region
(Goldreich & Tremaine 1980;
Ward 1991)

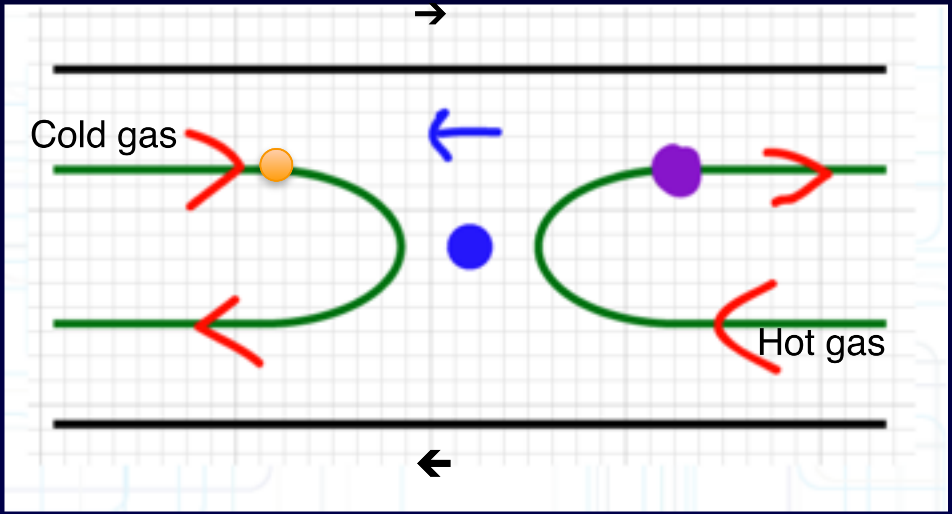
- Over one complete horseshoe orbit there is no net torque for a disc composed of ballistic particles

- Radial gradients in *entropy* and *vortensity* in a gaseous disc can give rise to a sustained corotation torque

- Corotation torque is normally positive - and hence opposes the Lindblad torque



Corotation torque



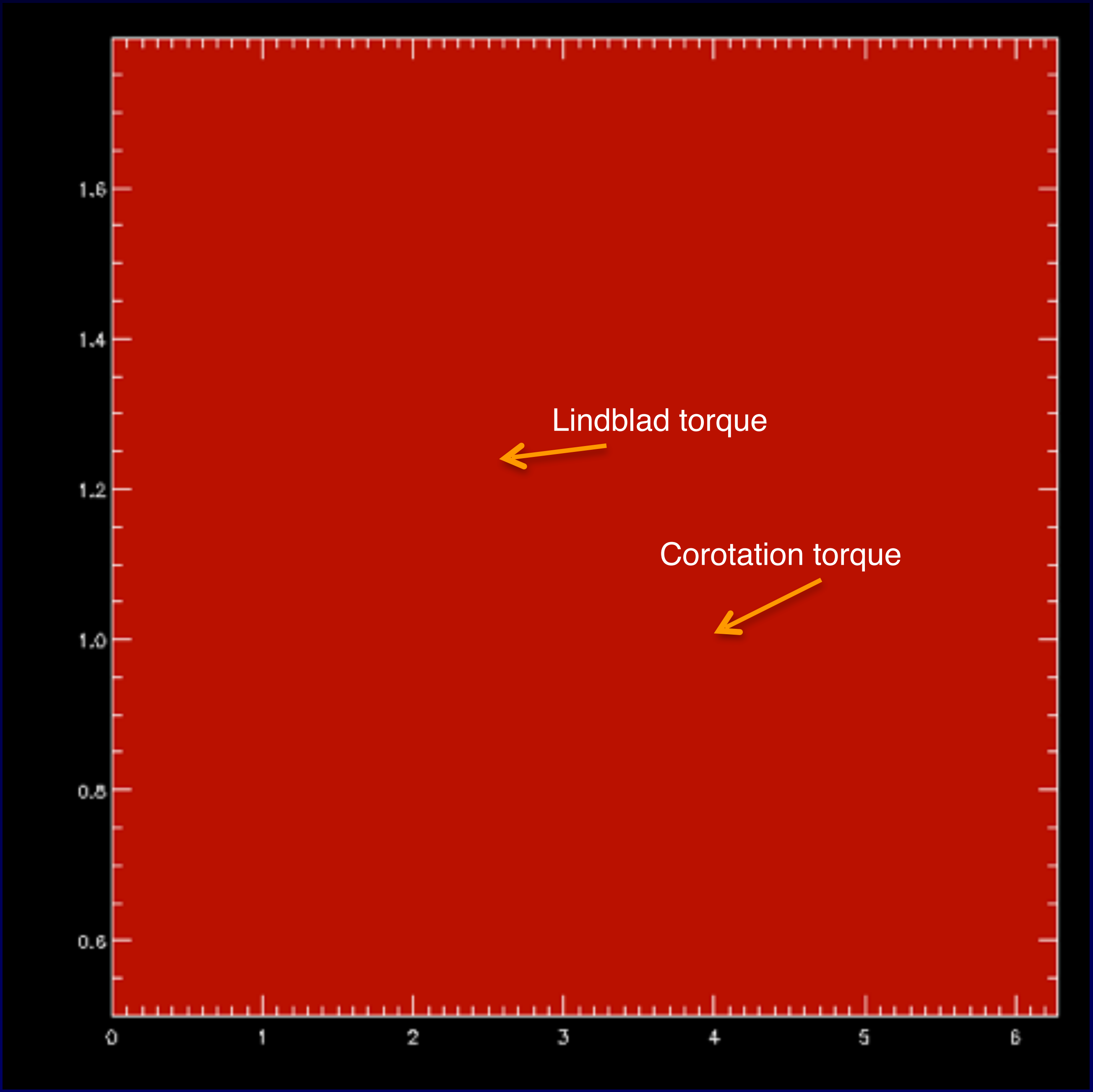
- Consider a disc with a negative radial entropy gradient

- Gas moving on horseshoe orbits while ~ conserving entropy on streamlines leads to a change in density near planet and the creation of a torque (Paardekooper & Mellema 2007; Baruteau & Masset 2008; Pardekooper & Papaloizou 2008)

- A similar argument applies when a vortensity gradient is present in the disc

- Corotation torques are prone to <u>saturation</u> when thermal or viscous diffusion do not occur at the optimal rates

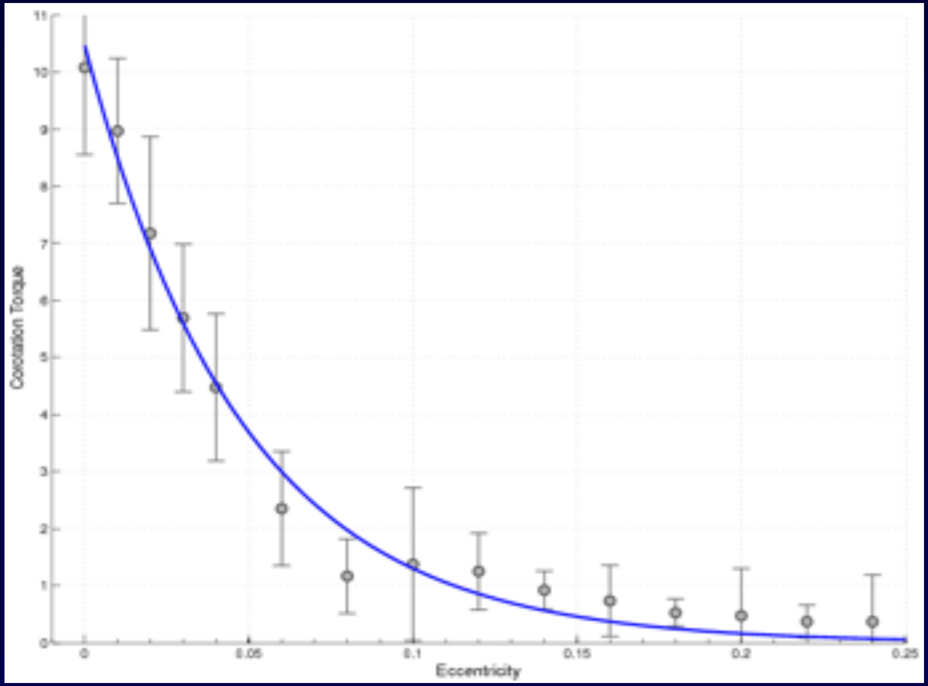
- Optimally unsaturated corotation torques arise when diffusion across the horseshoe region occurs on a time scale ~ 1/2 horseshoe orbit time scale

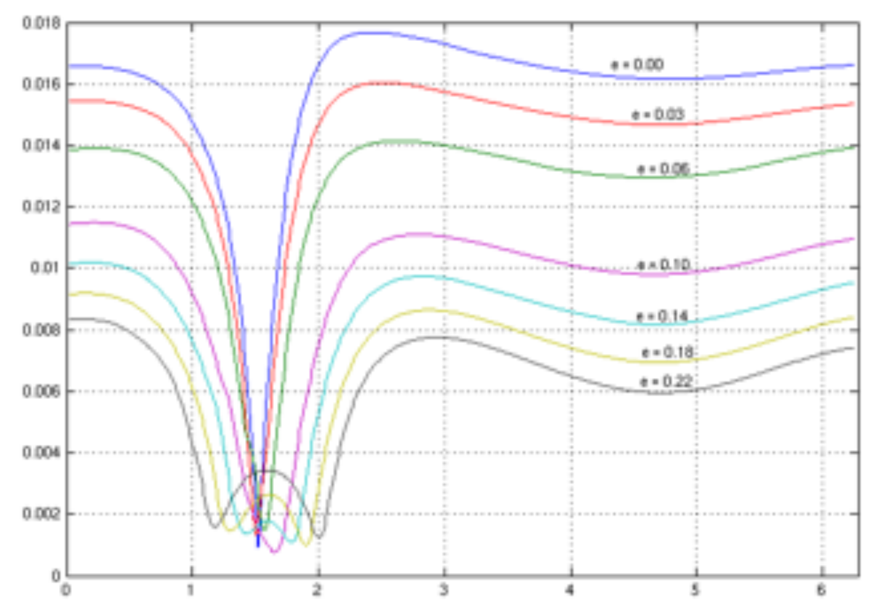


Lindblad torque

Corotation torque

Corotation torque for an eccentric planet



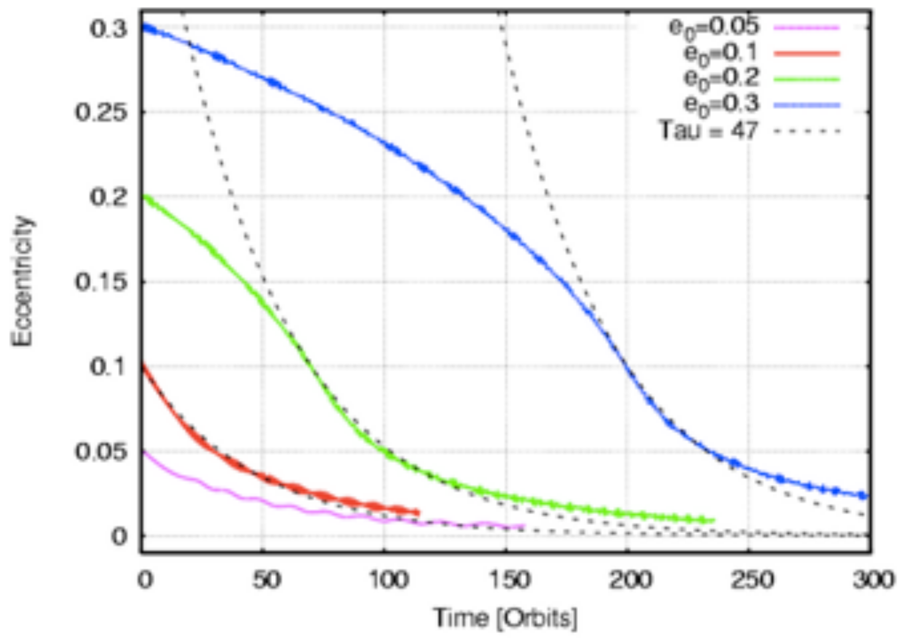


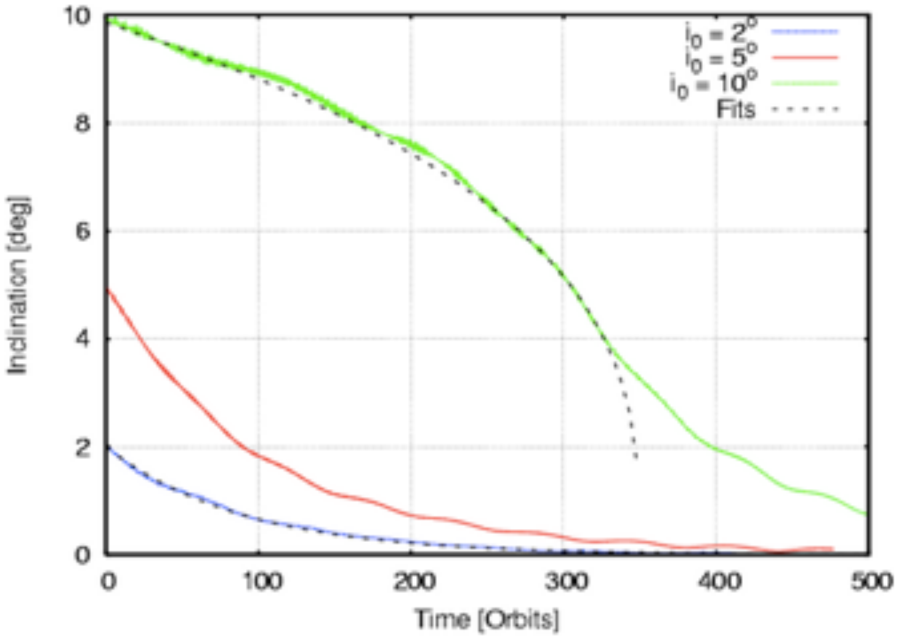
Corotation torques decrease with increasing eccentricity (Bitsch & Kley 2011)

This is due to reduction in width of horseshoe region as e increases (Fendyke & Nelson 2014)

Eccentricity and inclination evolution

- Eccentricity and inclination are damped rapidly for low mass planets - typically a factor ~ $(H/R)^2$ faster than migration time scale

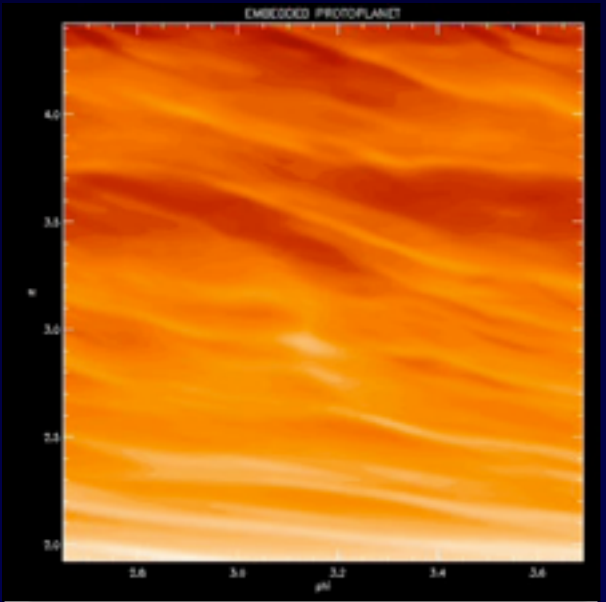


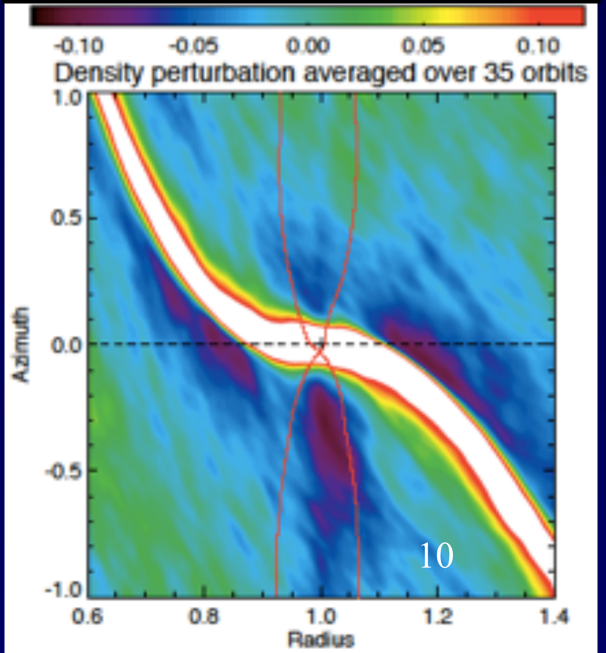


Cresswell et al (2008)

Type I migration - effect of magnetic fields

- If MRI turbulence exists then migration has stochastic component - this averages out over time scales ~ 100s - 1000s orbits (Nelson & Papaloizou 2004, Laughlin et al 2004, Adams & Bloch 2009)
- Fully developed MRI turbulence unsaturates corotation torque (Baruteau & Lin 2010, Baruteau et al 2011)
- New component of coronation torque even for weak field if resistivity is small (Baruteau et al 2011, Guilet et al 2013)
- Strong field: MHD waves instead of corotation torque (Terquem 2003, Fromang et al 2005)





Baruteau et al (2014)

Type I migration - other effects

- A planet may migrate more slowly than theory predicts in a disc with low viscosity - mismatch between vortensity in horseshoe region and local disc creates a drag on migration (Paardekooper 2014)
- The heating effect of a “hot planet” radiating its accretion luminosity into the disc may increase the corotation torque (Benitez-Llambay et al 2015)
- Corotation torques in 3D low viscosity discs may be enhanced compared to 2D (Fung et al 2015)

Type II migration of high mass planets

Gap formation

- Deep gap formation ($\delta\Sigma/\Sigma < 0.1$) occurs if:

  $R_{Hill} > H$ (H=disc thickness)

  +

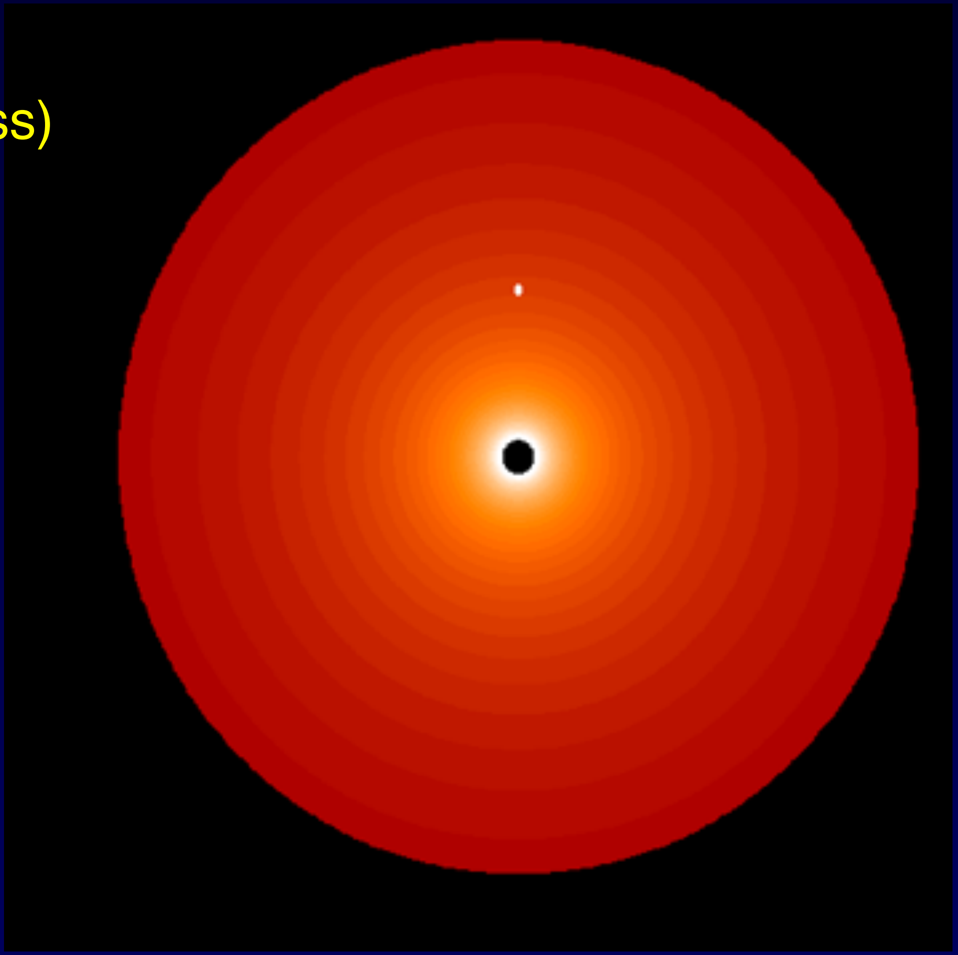
  tidal torque > local viscous torque

- Gap formation criterion:

  (Crida et al 2006)

$$h/q^{1/3} + 50\alpha_{visc}/qh^2 < \sim 1$$

q=Planet-star mass ratio
h= H/R (disc aspect ratio)



$h = 0.05$, $\alpha_{visc} = 0.004$
$\rightarrow$ gap if $q>10^{-3}$.

Deep gap formation for Jupiter mass planet

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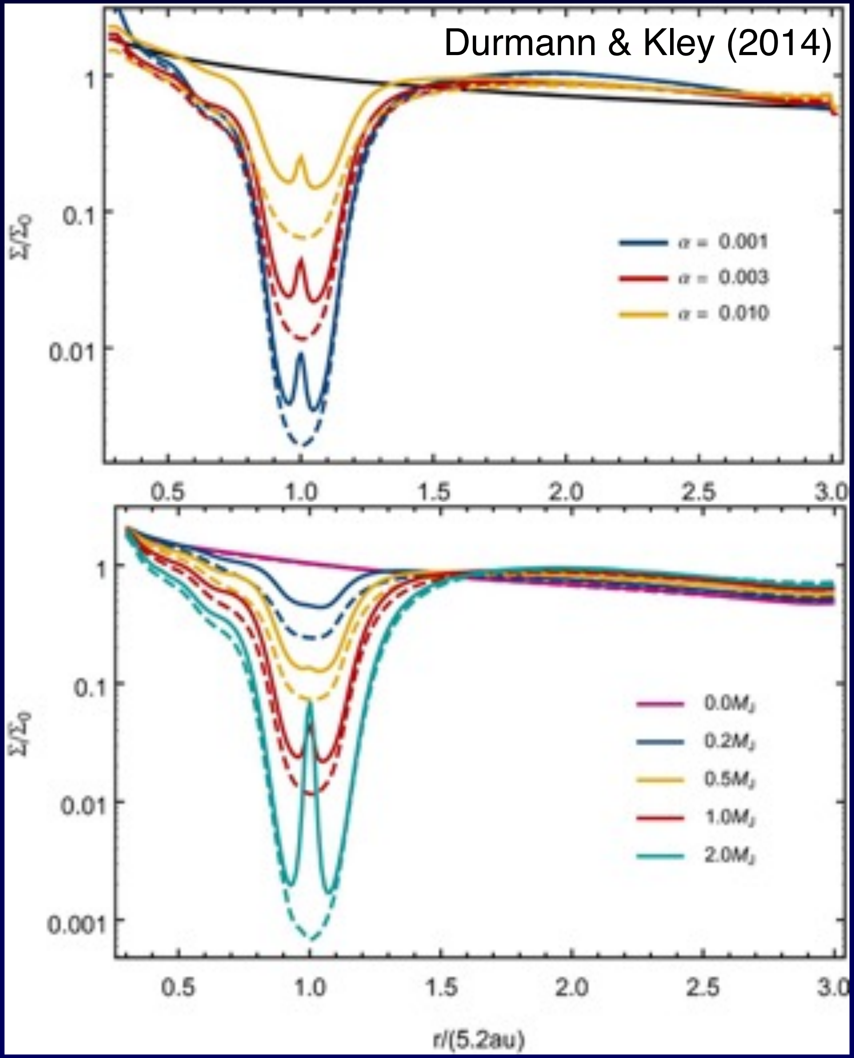

Durmann & Kley (2014)

Deep gap formation for Jupiter mass planet

Migration

- Type II migration occurs for a planet in a deep gap

migration at ~ disc viscous evolution rate (Lin & Papaloizou 1986)

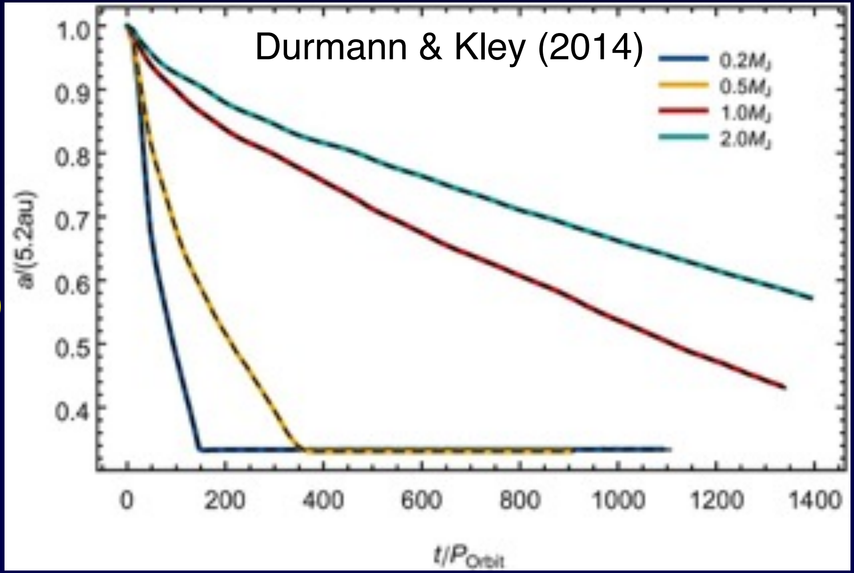
- Migration rates are not precisely equal to the viscous rate

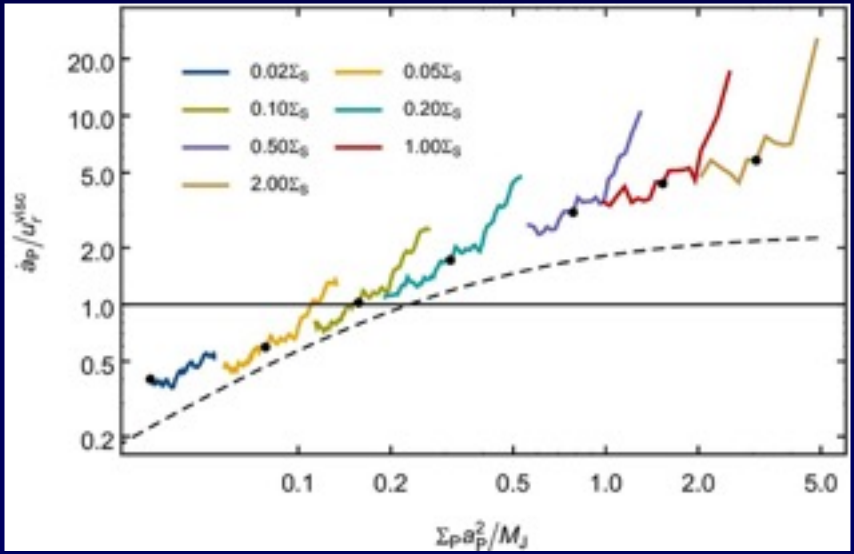
  (Duffel 2014, Durmann & Kley 2014)

- For large disc masses migration rate > viscous rate

- For low disc masses migration rate < viscous rate

- Residual mass in the gap matters!





Gas accretion

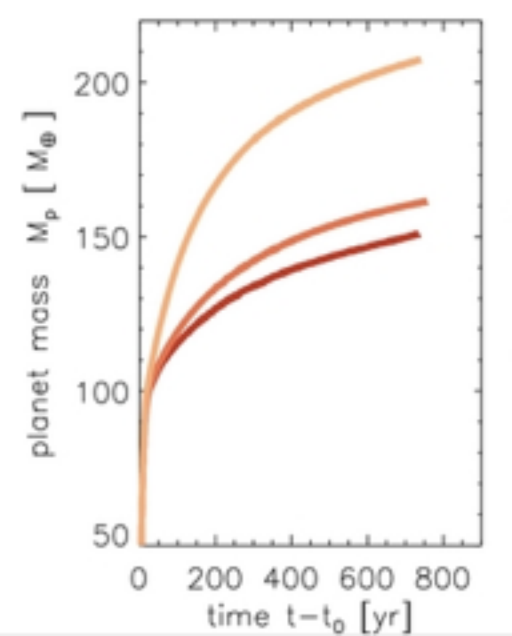
- Almost all simulations agree that the disc supplies gas through the gap to the planet at the viscous supply rate ~ 10^{-5} Jupiter / year

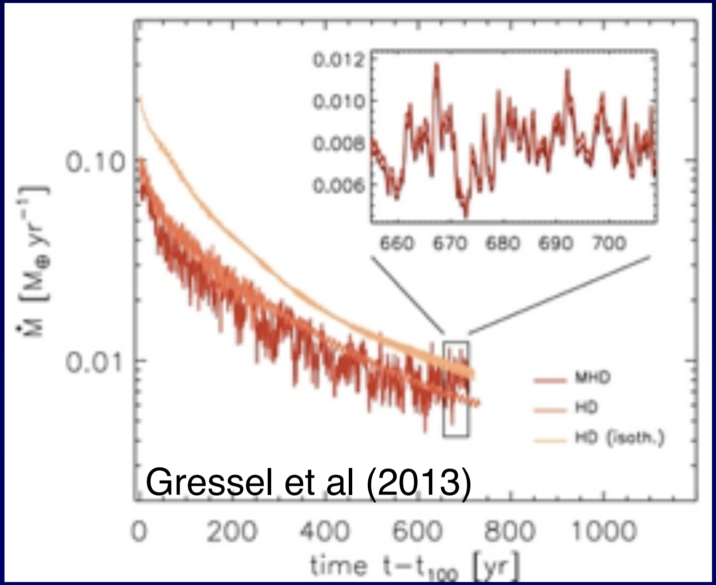
  - but note that numerical effects prevent accretion rate onto the planet being determined accurately!

- During gap formation gas accretion can be at a much faster rate, building a Jovian planet in ~ 10^3 yr

- In 3D gas accretion onto planet largely occurs from high latitudes and not through a flat circumplanetary disc

- The addition of magnetic fields makes life more interesting…





Gressel et al (2013)

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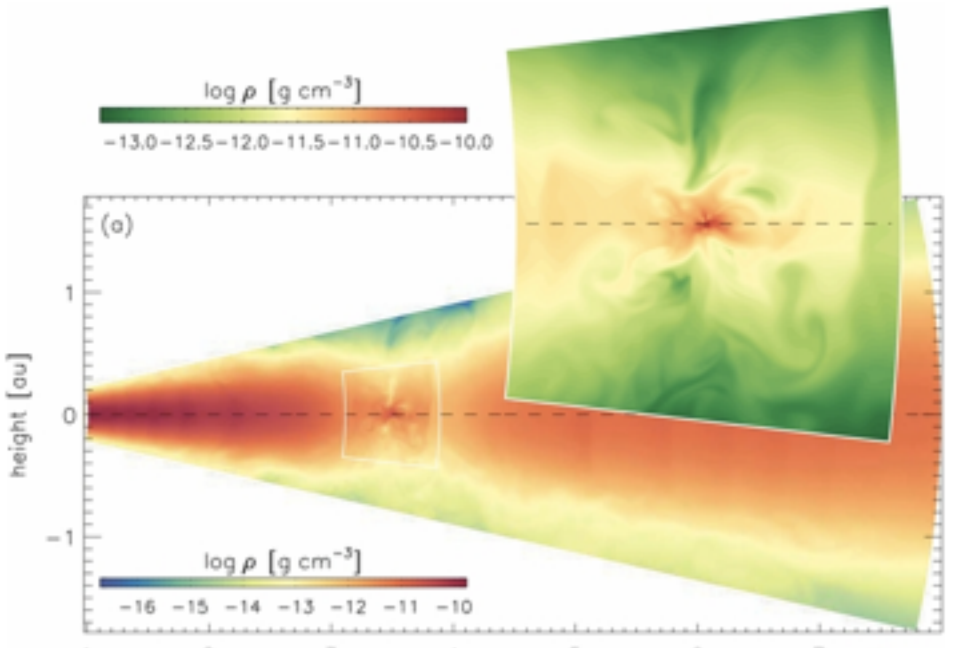
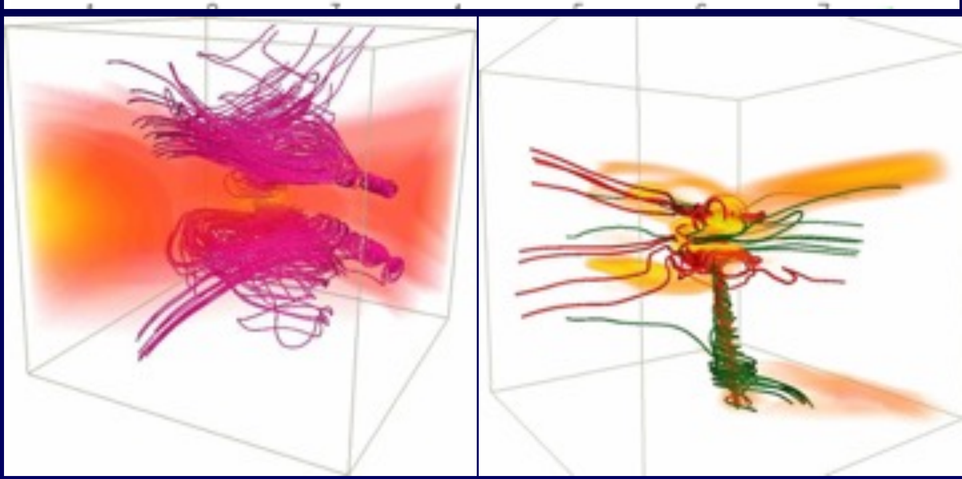
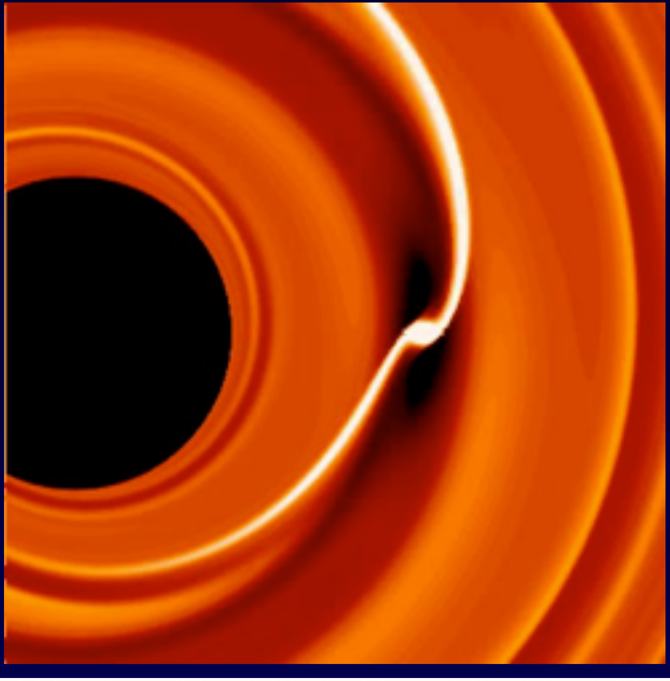


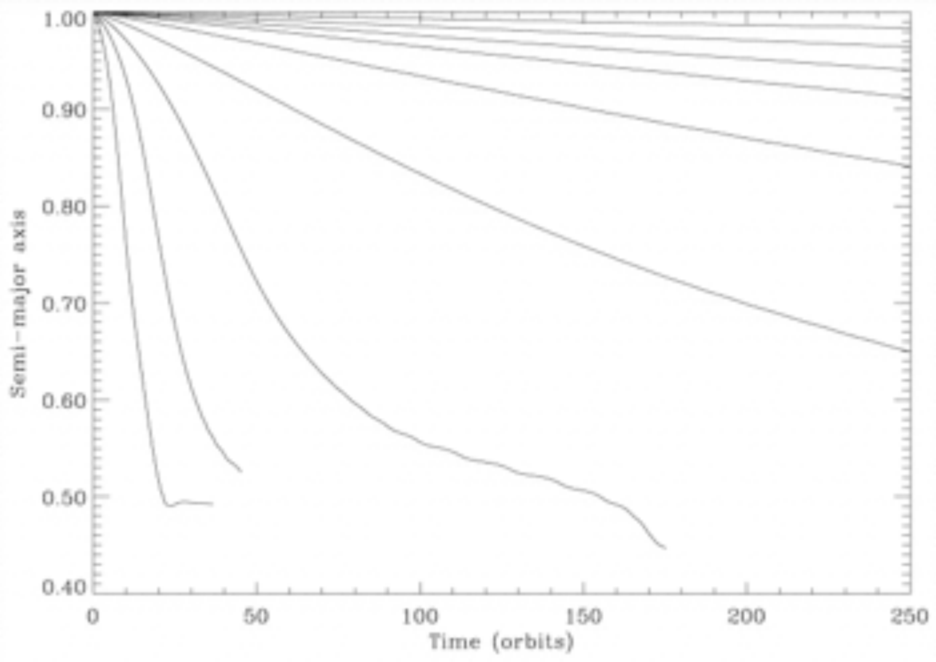


Type III migration of intermediate mass planets

Type III migration



- Operates for ~ Saturn mass planets in disc models with mass ~ 3 x MMSN (Masset & Papaloizou 2003)
- Require partial gap
- Flow-through of gas past planet orbit during migration acts to propel planet inward at a rate that scales with the migration rate → runaway!
- Large scale migration can occur in a few 10s of orbits
- Forms an important part of the Grand Tack model for the Solar System



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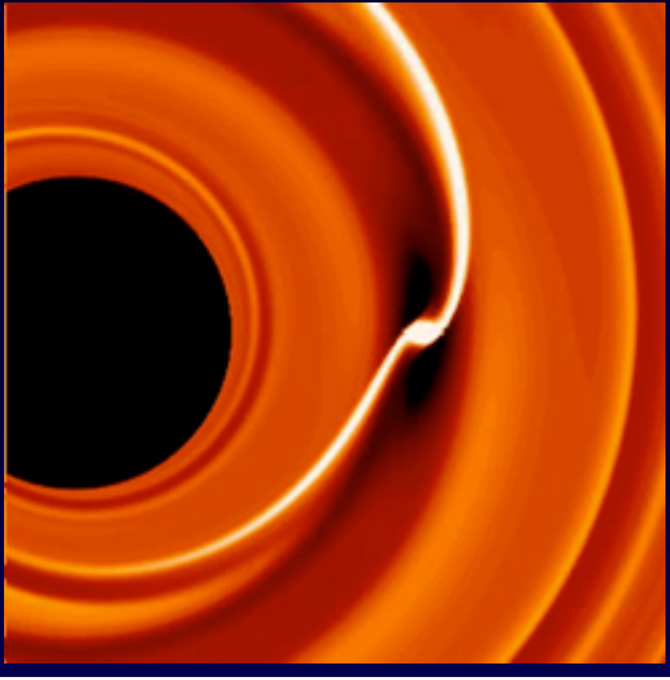


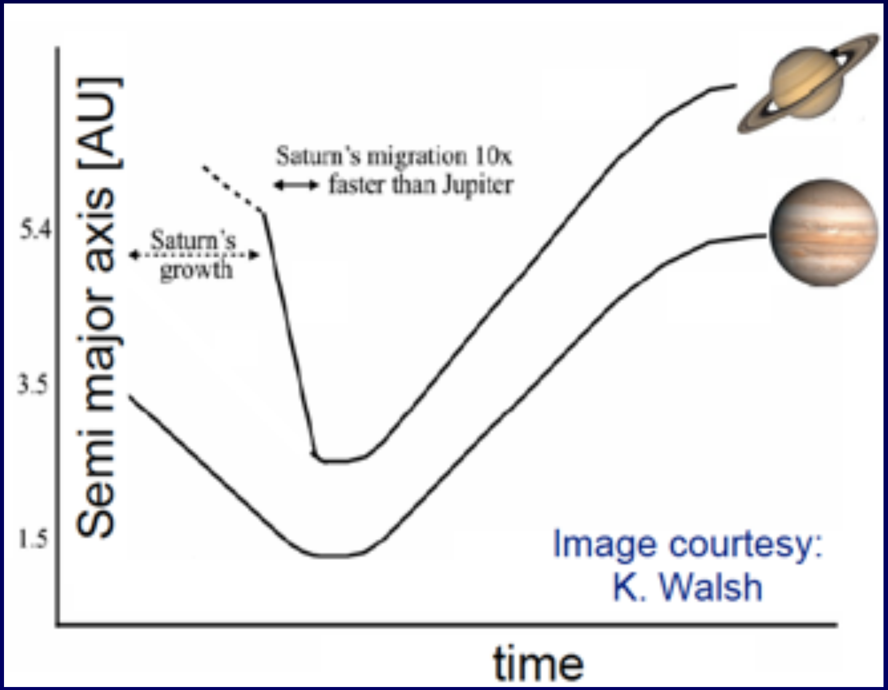


Image courtesy:
K. Walsh

N-body simulations of planet formation with migration and gas accretion

N-body simulations with migration, collisional growth and gas accretion onto planetary cores

(Hellary & Nelson 2012, Coleman & Nelson 2014, Coleman & Nelson In prep.)

Model ingredients

- Gravitationally interacting planetary embryos + planetesimals (Mercury-6, J. Chambers)

- Self-consistent thermally evolving viscous disc model with stellar irradiation and dispersal through a photoevaporative disc wind (Dullemond et al 2011)

- Disc cavity interior to 0.05 AU (stellar magnetosphere)

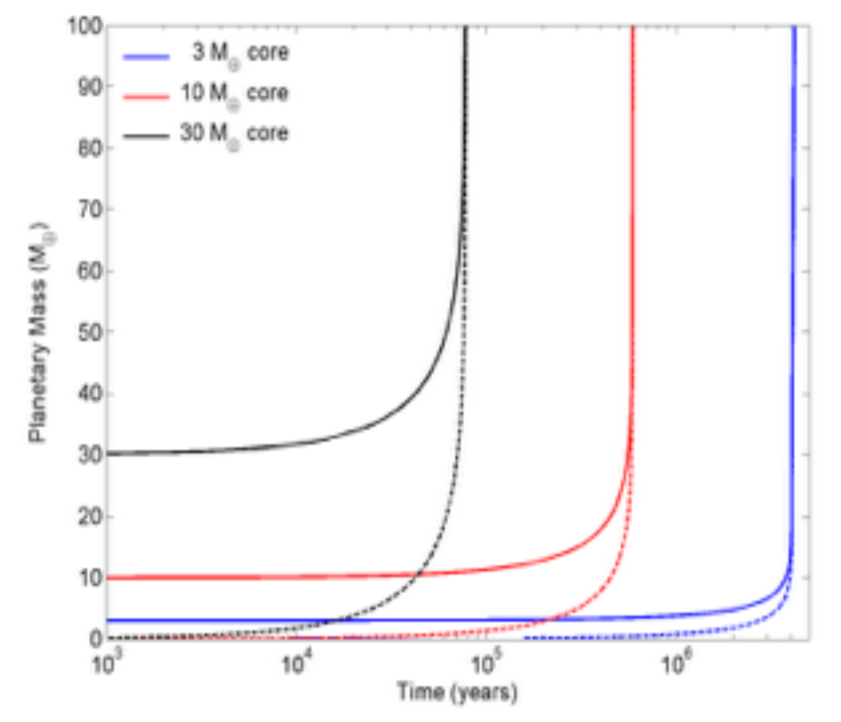
- Transition to higher disc viscosity when T > 1000 K

- Consistent treatment of dust opacity and solids abun

- Type I migration with corotation torques (Paardekooper and transition to type II migration when gap forms (Lin

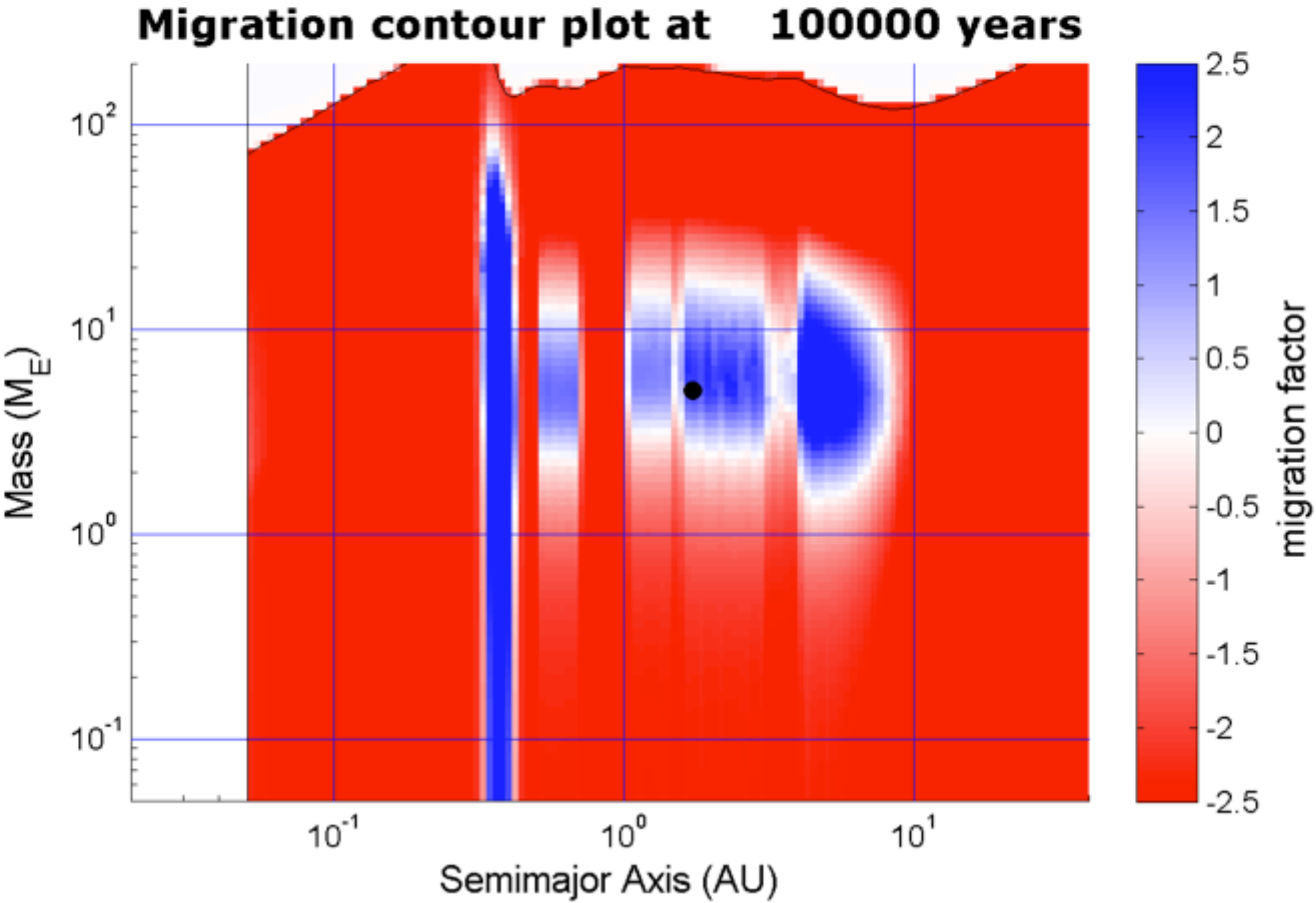
- Gas settling onto planetary cores – enhanced planet (Inaba & Ikoma 2003)

- Gas accretion for cores with mass > 3 Earth masses (Movshovitz et al 2010)

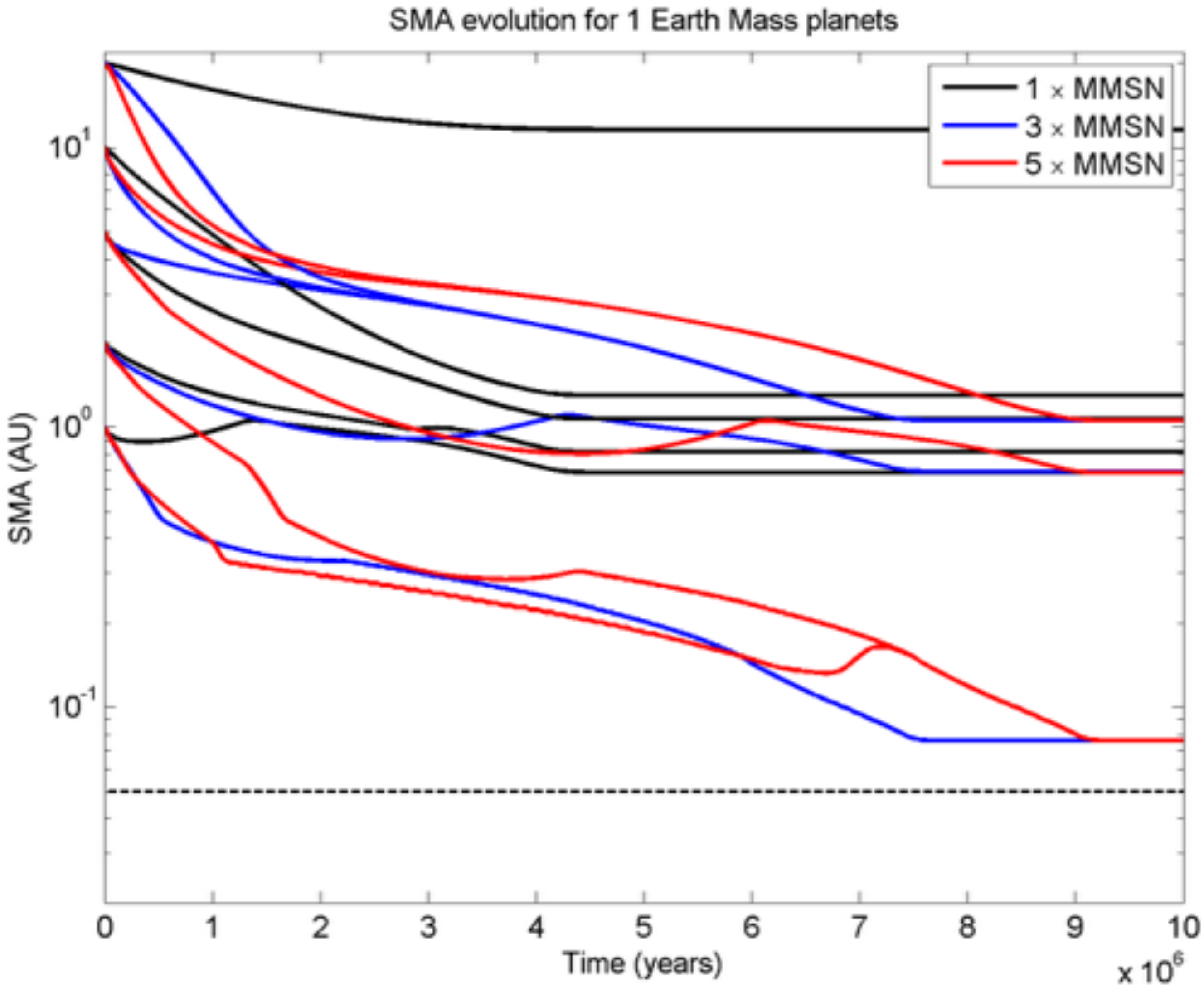


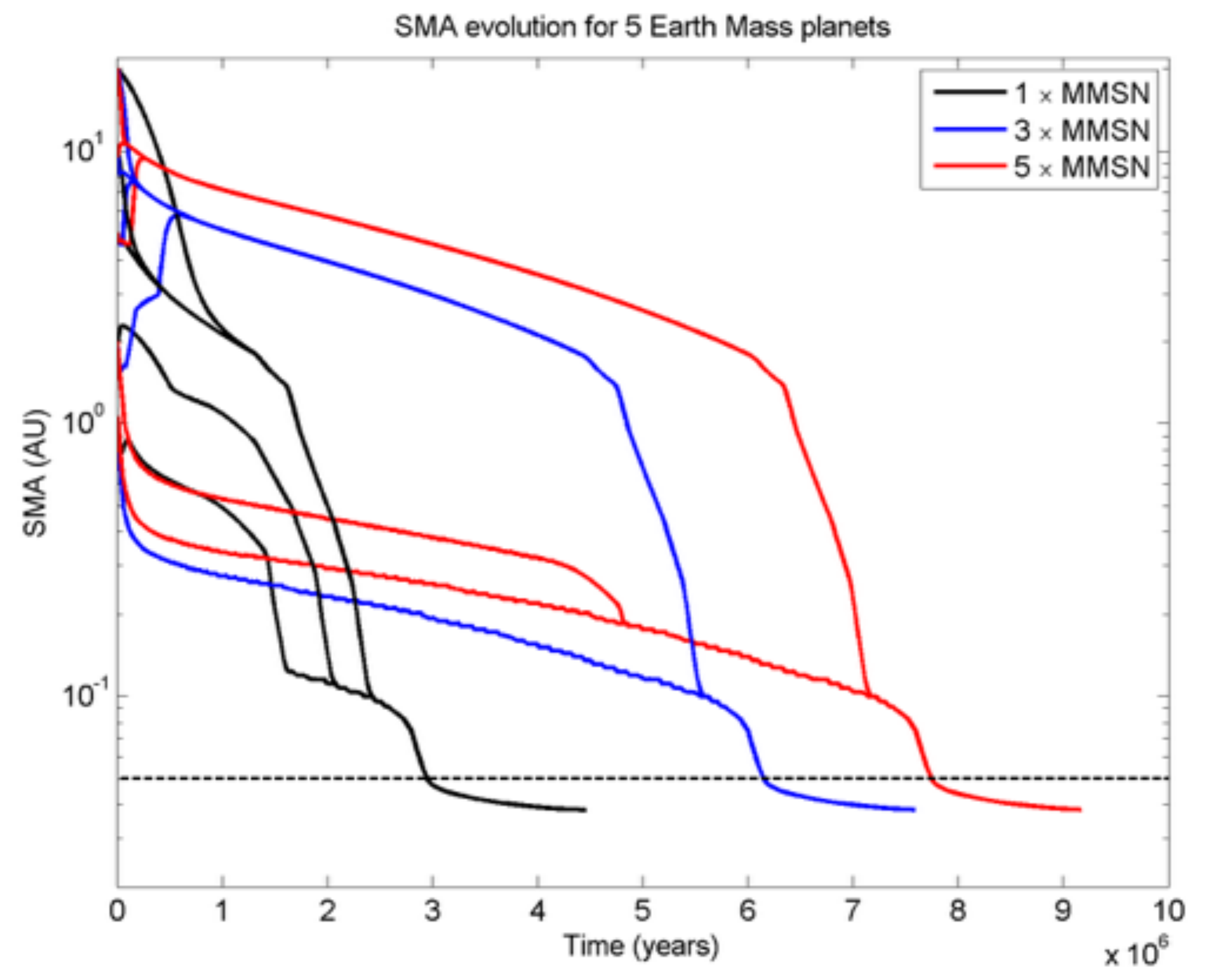
Model parameters

Disc masses: 1, 1.5, 2 x MMSN
Metallicity values: [Fe/H] = 0.5, 1 , 2 x Solar
Planetesimal radii: R_{pl} = 10m, 100m, 1km, 10km



Migration contour plot at 100000 years


SMA evolution for 1 Earth Mass planets
1 × MMSN
3 × MMSN
5 × MMSN
SMA (AU)
10^1
10^0
10^{-1}
0
1
2
3
4
5
6
7
8
9
10
Time (years)
x 10^6


SMA evolution for 5 Earth Mass planets
1 × MMSN
3 × MMSN
5 × MMSN
SMA (AU)
10^1
10^0
10^-1
Time (years)
0
1
2
3
4
5
6
7
8
9
10
x 10^6

Simulation results

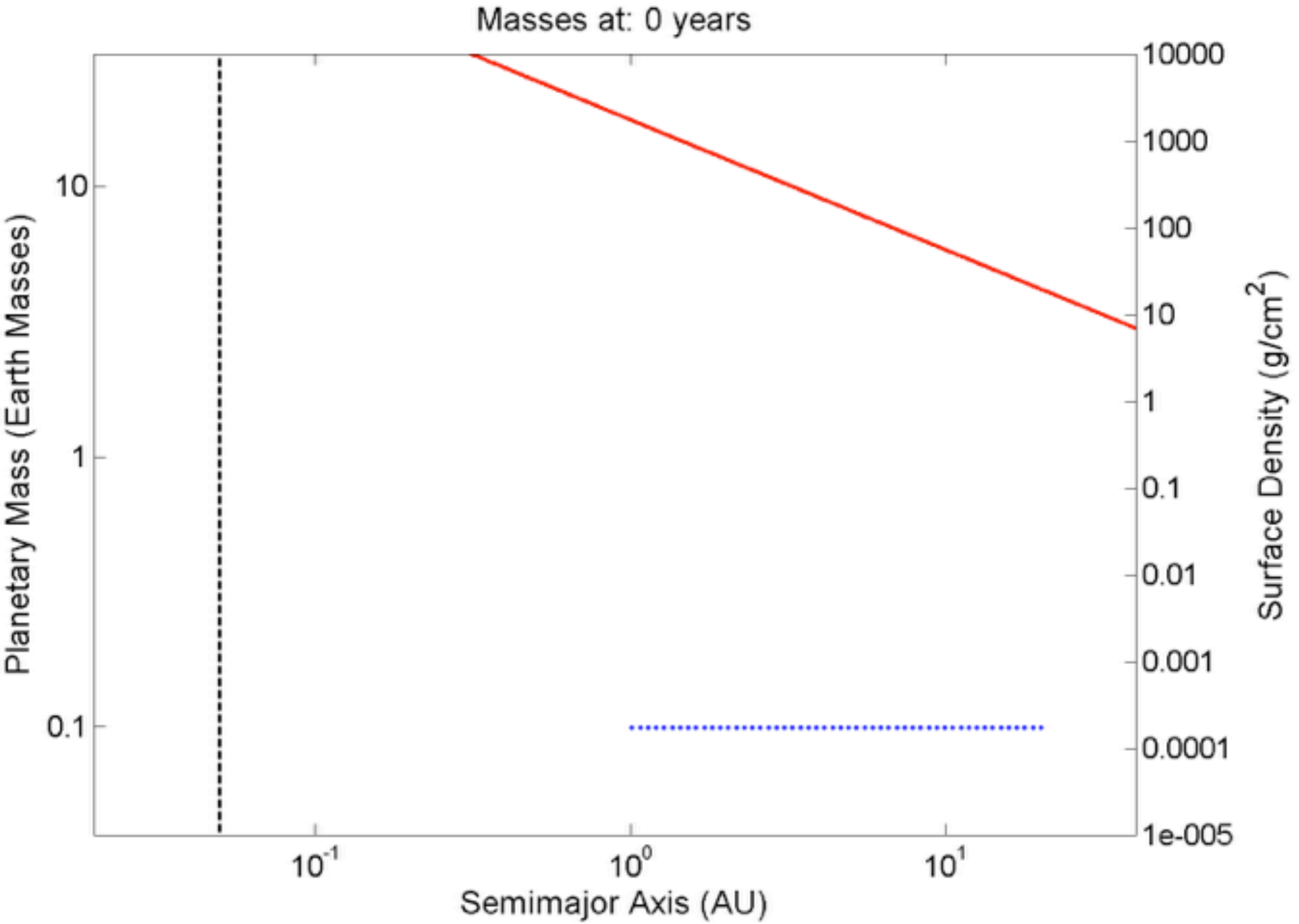
Three basic modes of evolution:

1. Modest growth to $m_p < 2\ M_{Earth}$ prior to disc dispersal.
   Modest levels of migration. Low solid abundance. Large planetesimals.

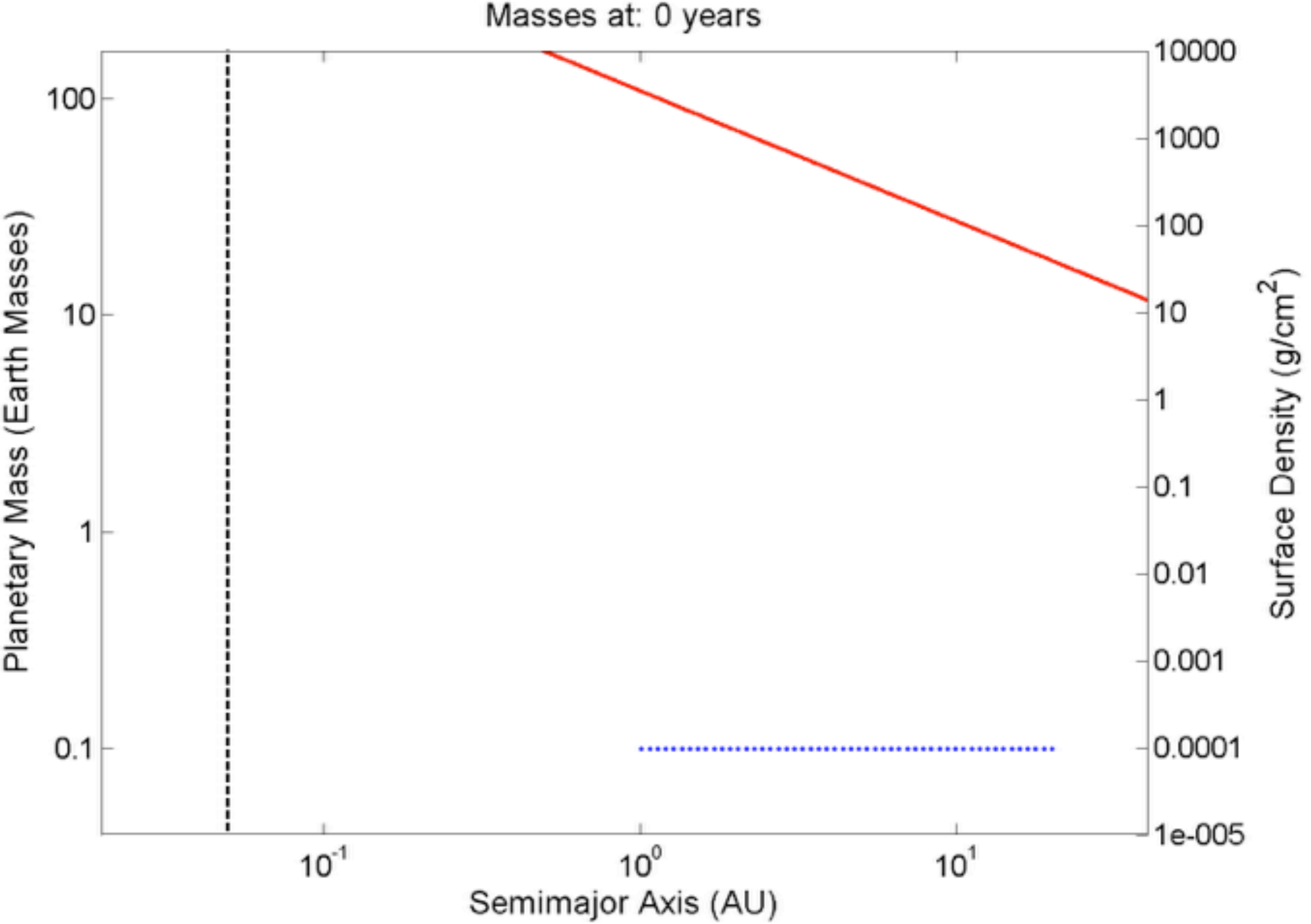
2. Formation of super-Earths + Neptunes with $m_p < 35\ M_{Earth}$.
   Large scale migration. Moderate solid abundance. Small planetesimals/boulders.

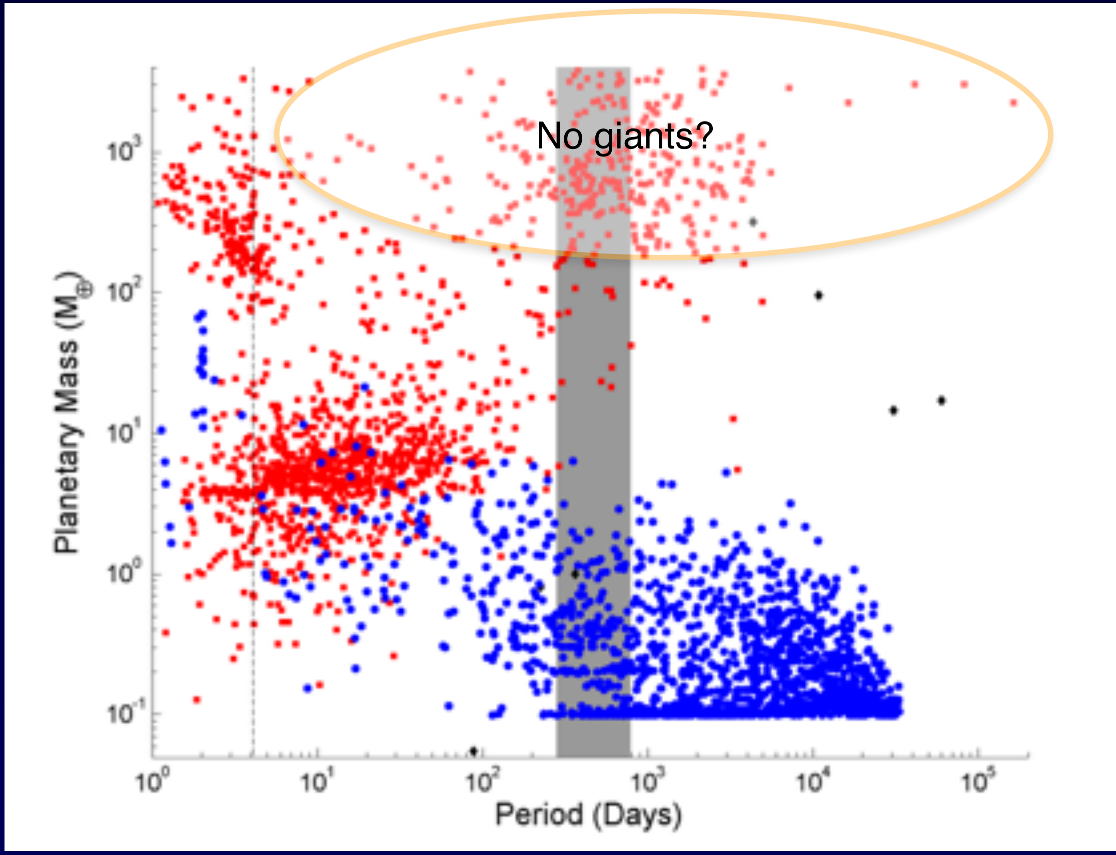
3. Formation of giant planets with $m_p > 35\ M_{Earth}$.
   Large scale migration. Large solid abundance. Small planetesimals/boulders.

$M_{disc}=1$, [Fe/H]=2, $R_{pl}=100$ m

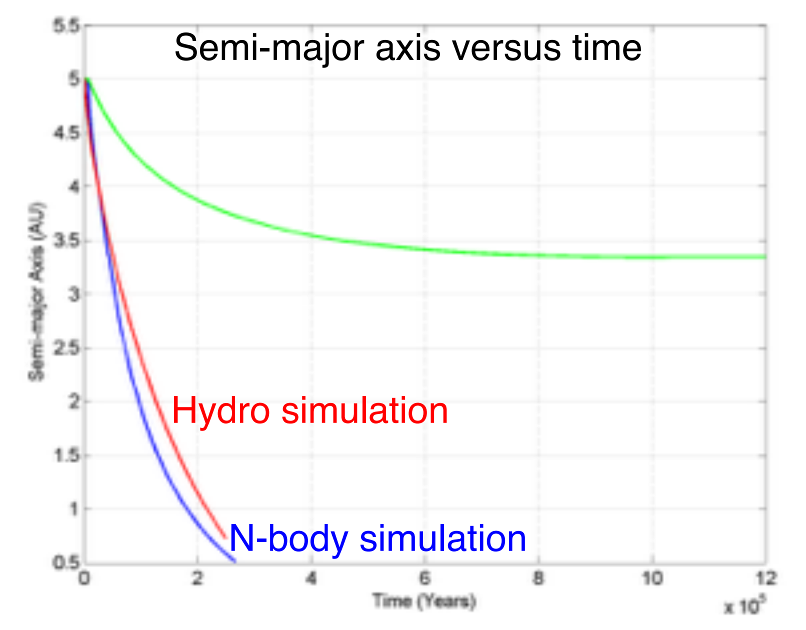


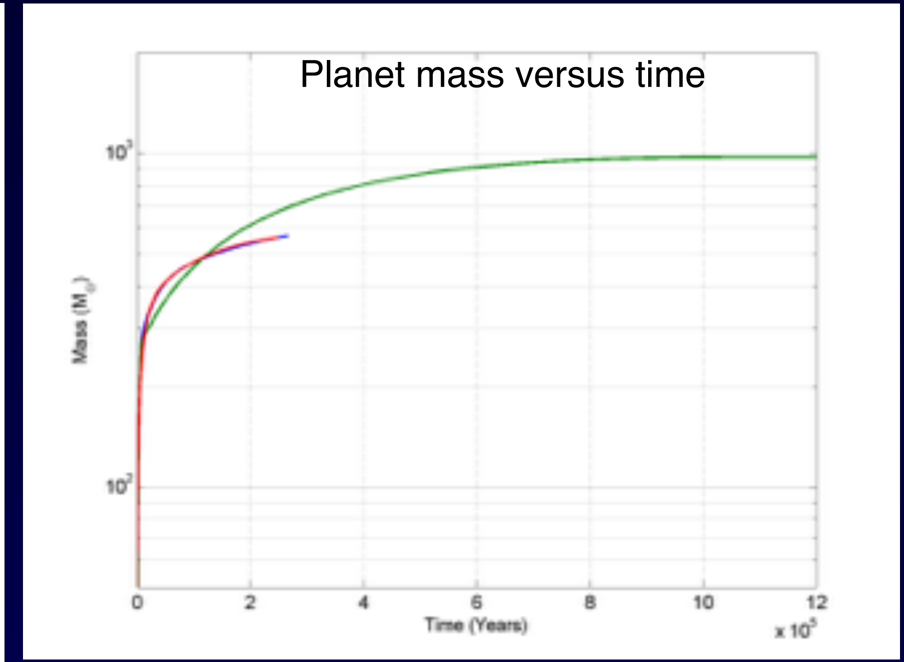
M_{disc}=2, [Fe/H]=2, R_{pl}=10 m

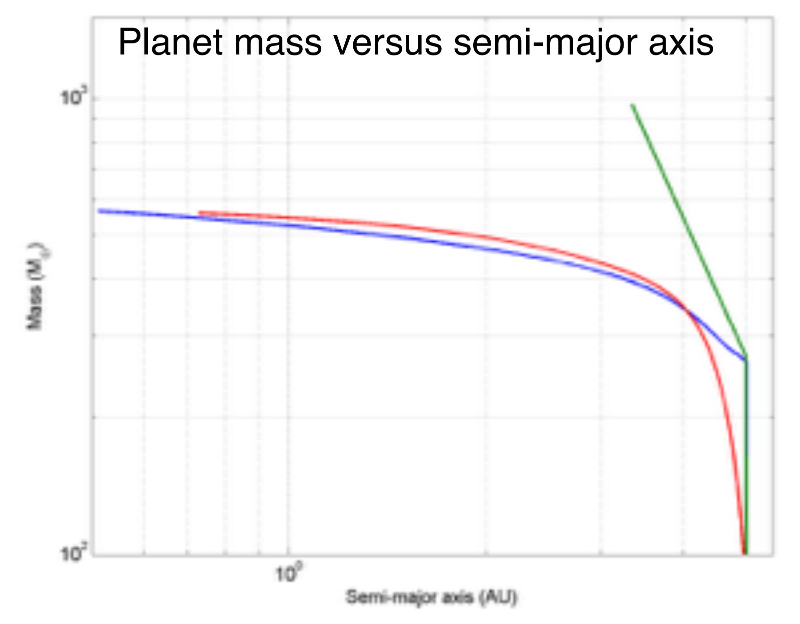


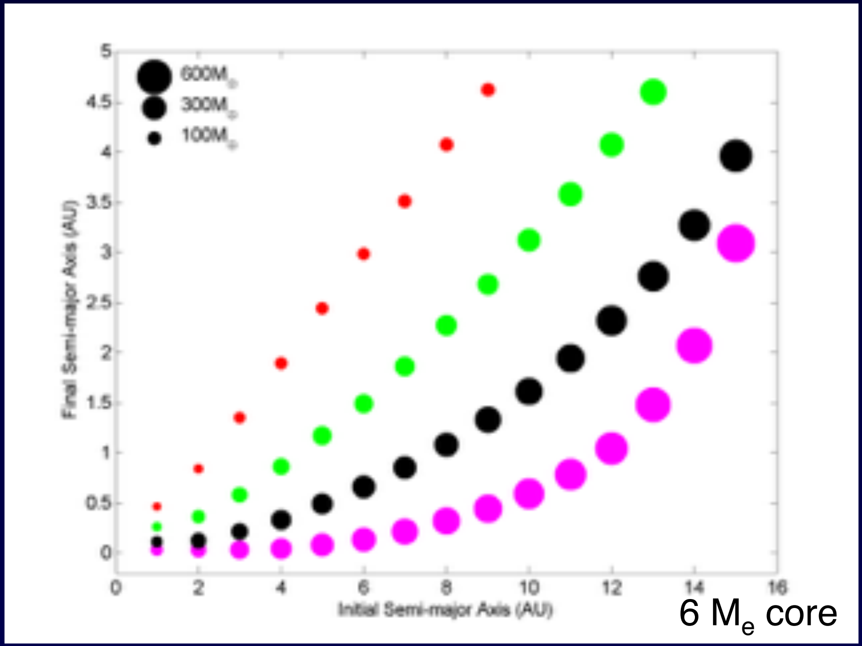

No giants?
Planetary Mass ($M_\oplus$)
10^3
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
Period (Days)

Giant planet formation and survival


Semi-major axis versus time


Planet mass versus time


Planet mass versus semi-major axis



6 M_e core

Forming a Jovian mass planet that orbits at ~ 5 AU requires rapid gas accretion and type II migration to initiate at ~ 14 AU

How to maintain cores at large distance and avoid rapid inward type I migration?

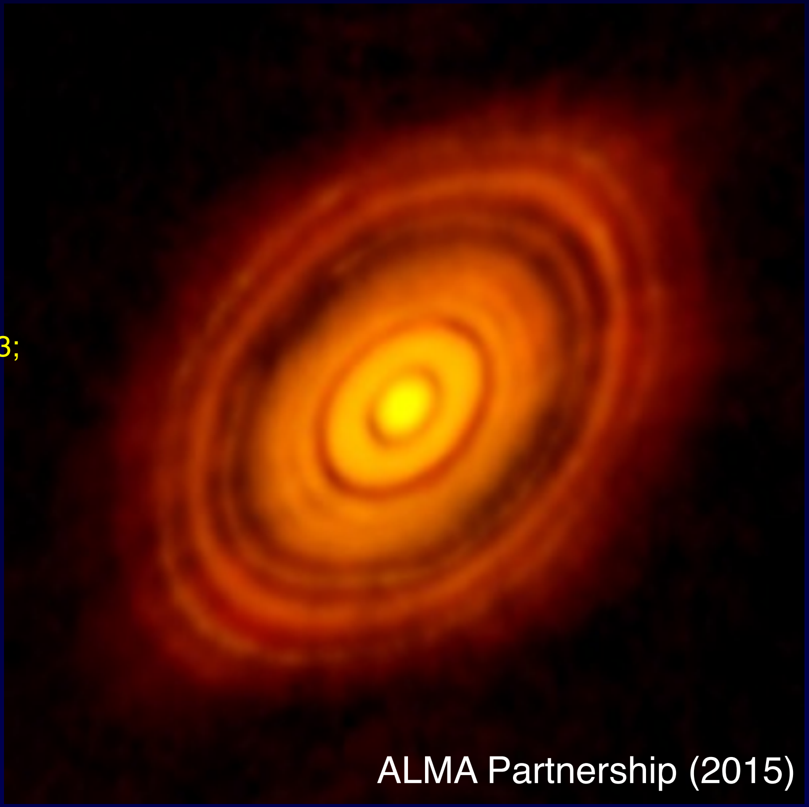
Structuring of disc due to variations in viscous stresses may create regions where corotation torque prevents type I migration for bodies with $m_p \sim 30\ M_{Earth}$

Zonal flows observed in MHD simulations of disc turbulence (Papaloizou & Steinacker 2003; Papaloizou & Nelson 2003; Johansen et al 2009; Bai & Stone 2014)

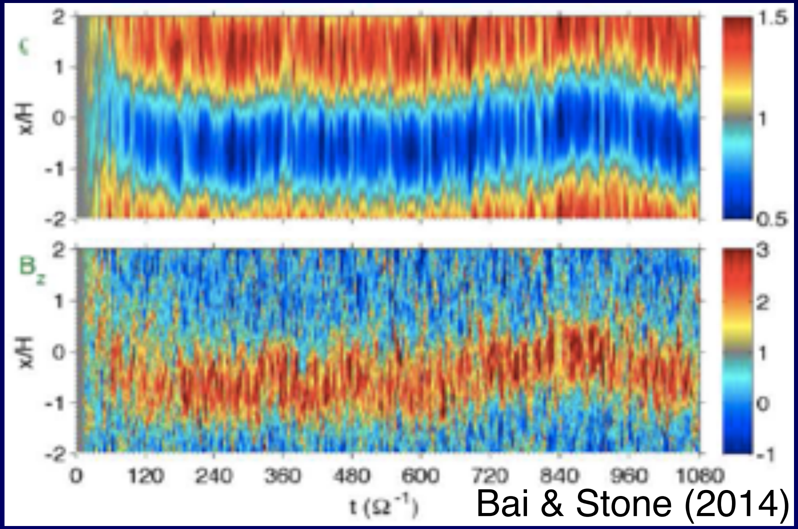
Surface density transitions may also occur at ice-line and inner edge of dead zone (Kretke & Lin 2010)

A simple toy model:

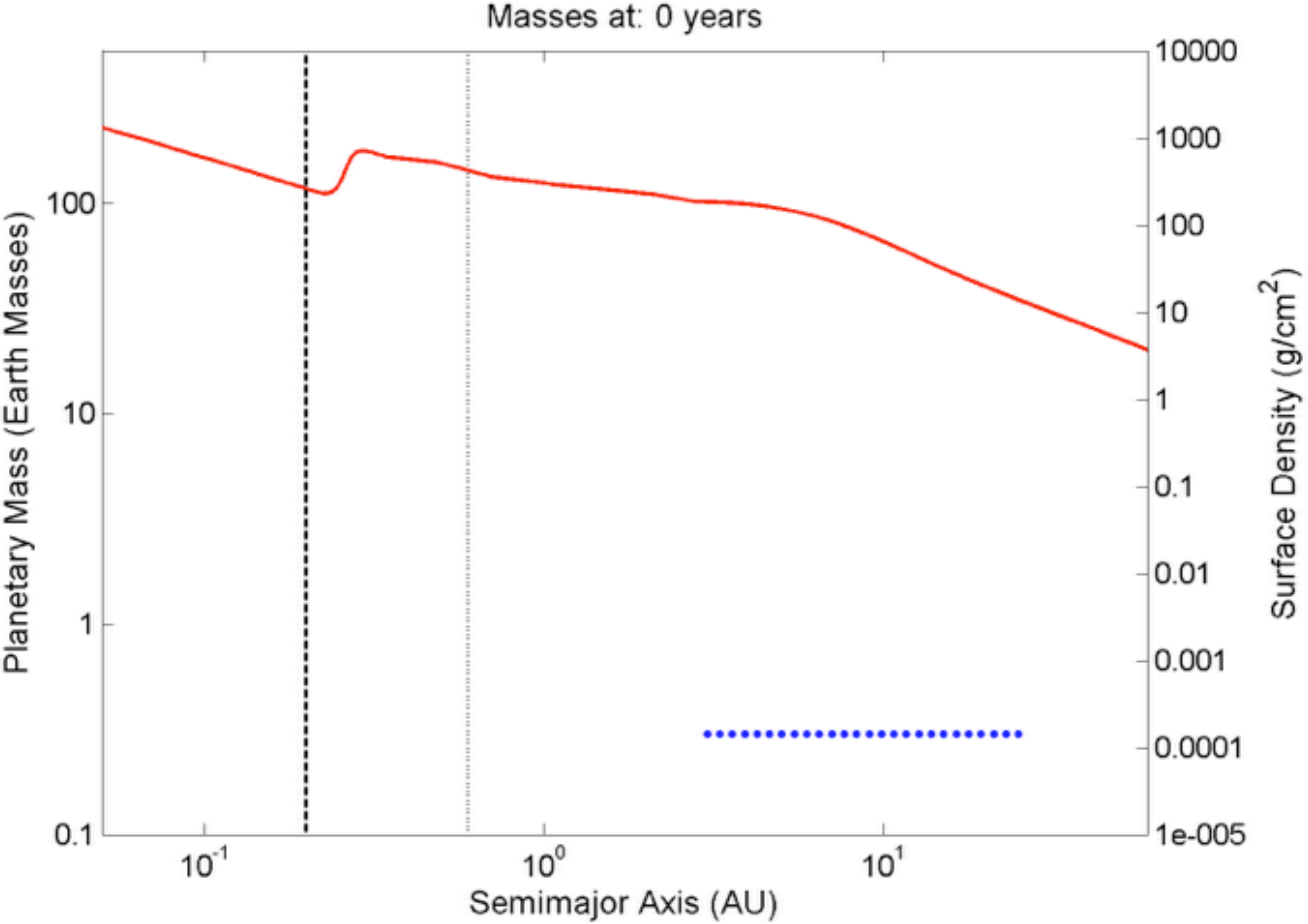
- Choose radii where viscous α varies by ~ 50%
- Set life time of *zonal flows* ~ 50,000 local orbits
- Choose new radius to apply zonal flow after life time has elapsed

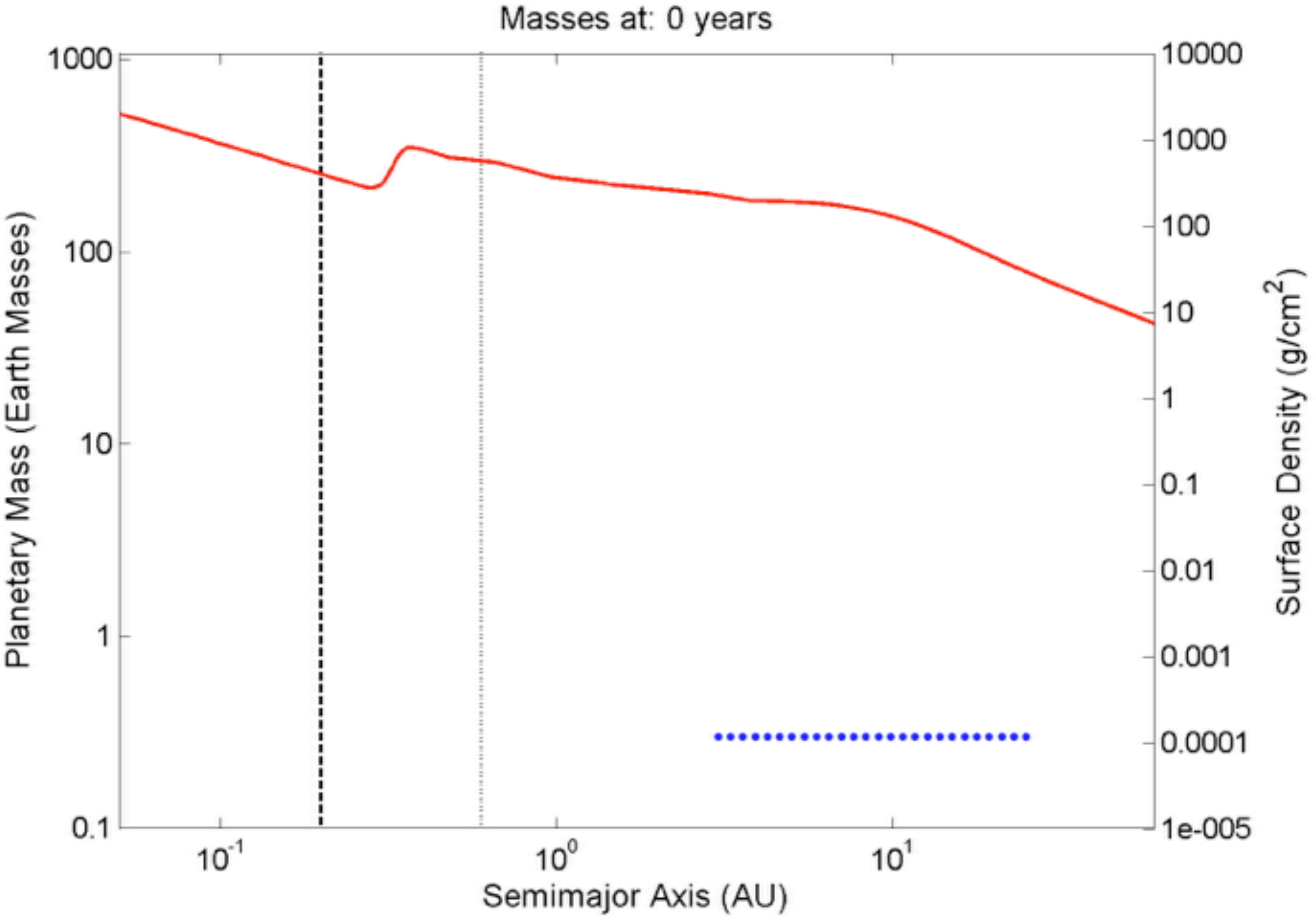


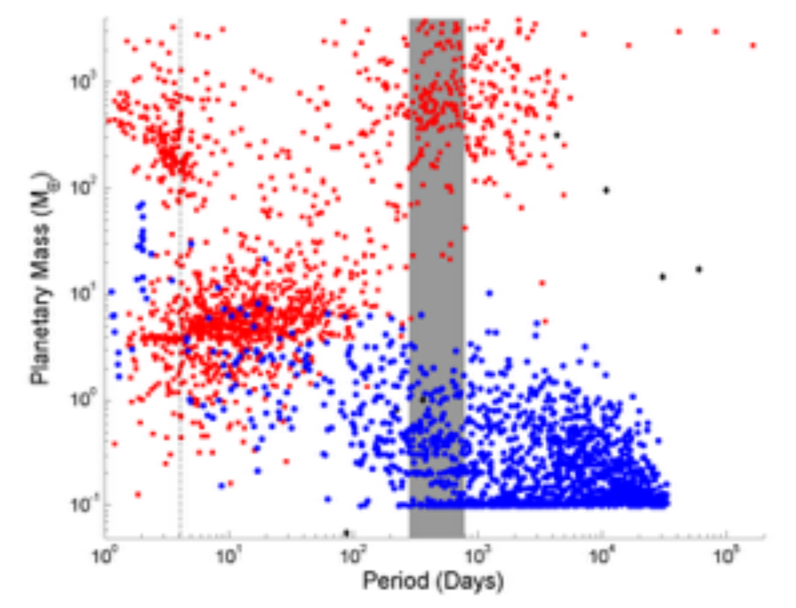
ALMA Partnership (2015)



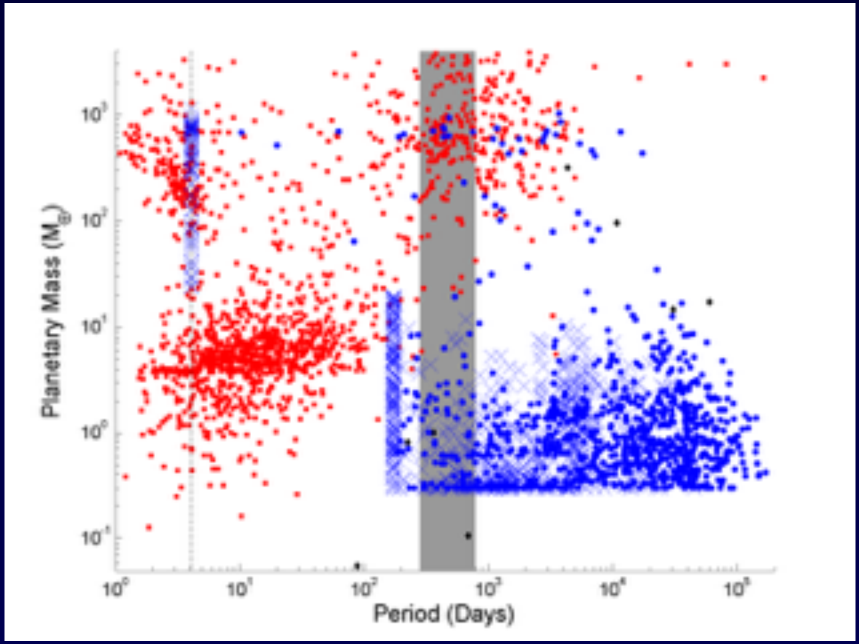
Bai & Stone (2014)


Masses at: 0 years
Planetary Mass (Earth Masses)
0.1
1
10
100
Surface Density (g/cm^2)
1e-005
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
Semimajor Axis (AU)
10^{-1}
10^0
10^1


Masses at: 0 years
Planetary Mass (Earth Masses)
1000
100
10
1
0.1
Surface Density (g/cm^2)
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-005
10^{-1}
10^{0}
10^{1}
Semimajor Axis (AU)



No zonal flows



Zonal flow runs

Conclusions

- Compact short-period systems of super-Earths and Neptunes are produced in N-body simulations

- Formation of short-period planets around low metallicity stars (e.g Kaptyen’s star, Kepler 444) requires planetary growth through boulder or pebble accretion rather than planetesimal accretion

- Formation and survival of giant planets requires significant slowing of migration at distances ~ 10-20 AU from central star. Zonal flows may provide a mechanism for achieving this…