Global models of planetary system formation

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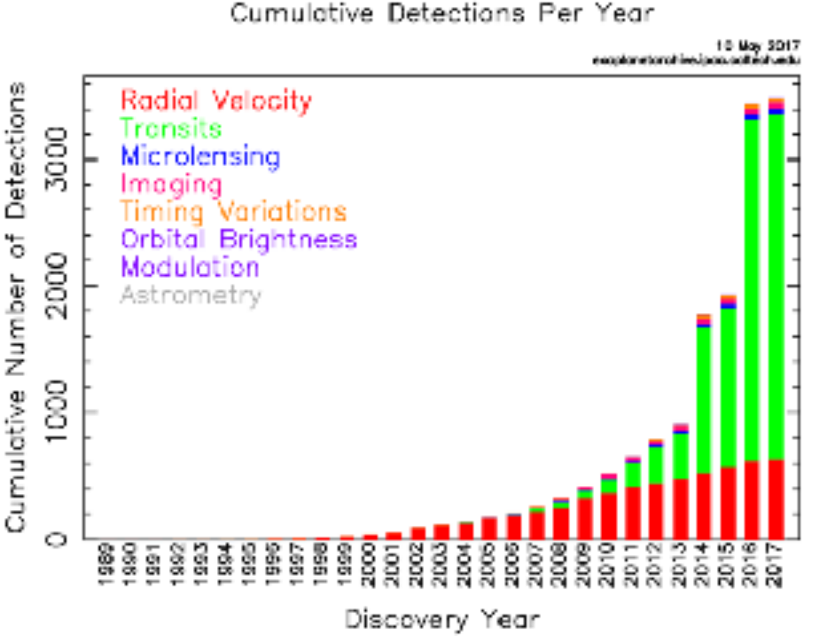
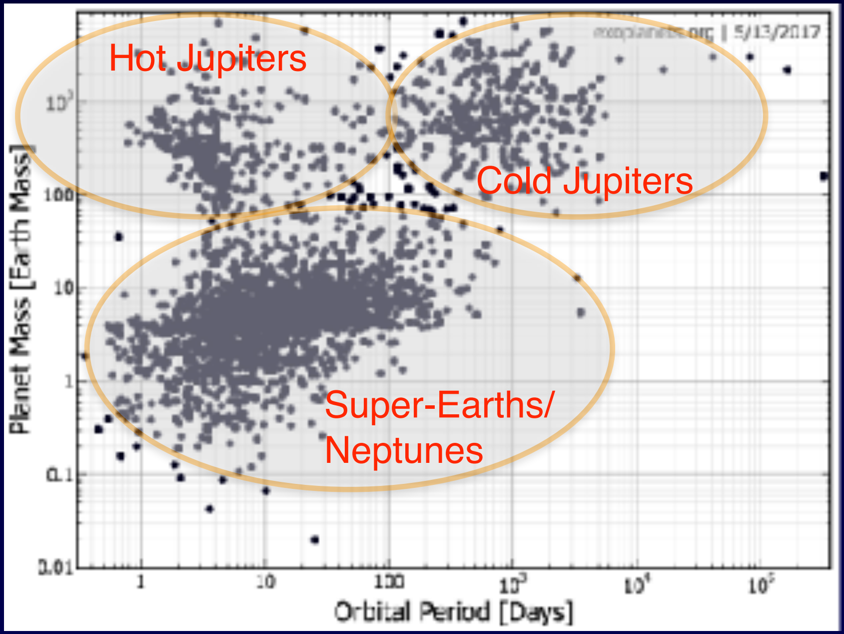


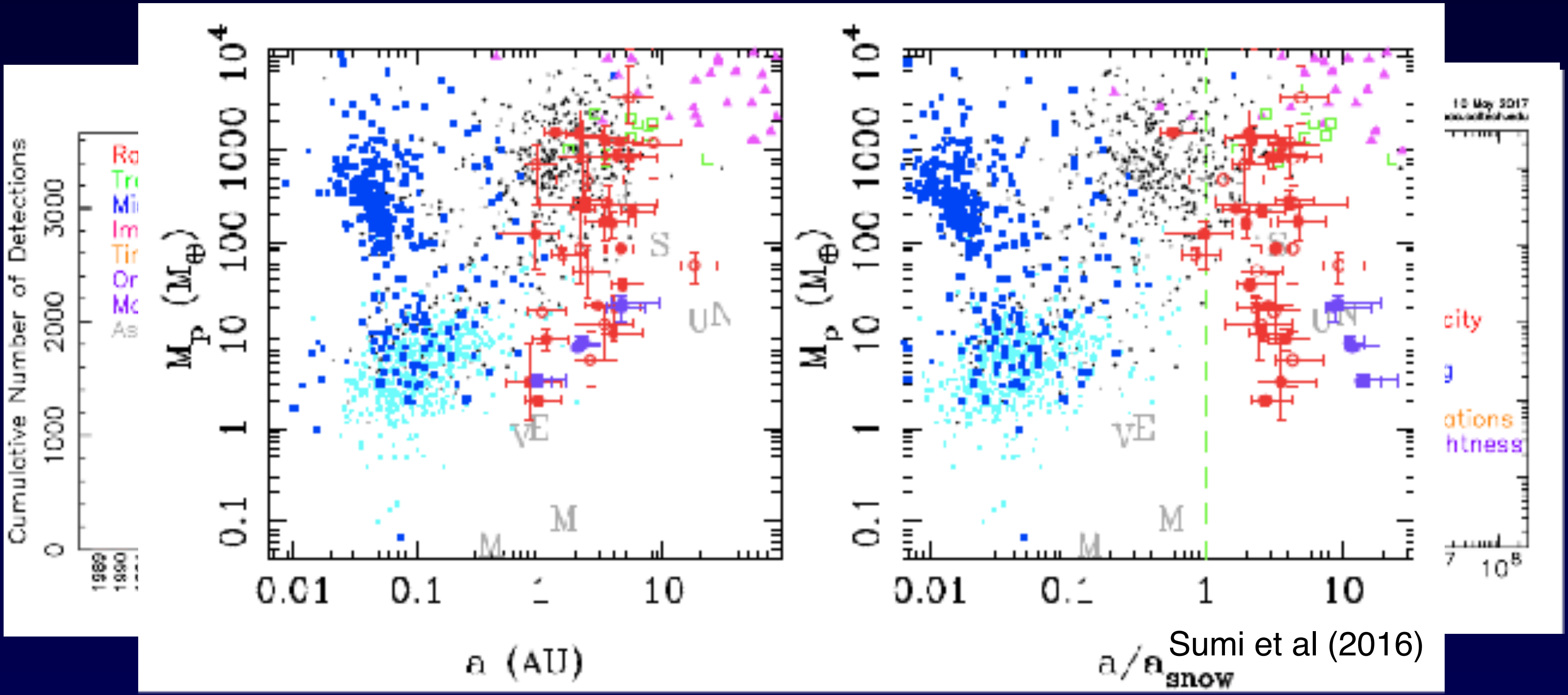
Cumulative Detections Per Year



Hot Jupiters

Cold Jupiters

Super-Earths/
Neptunes

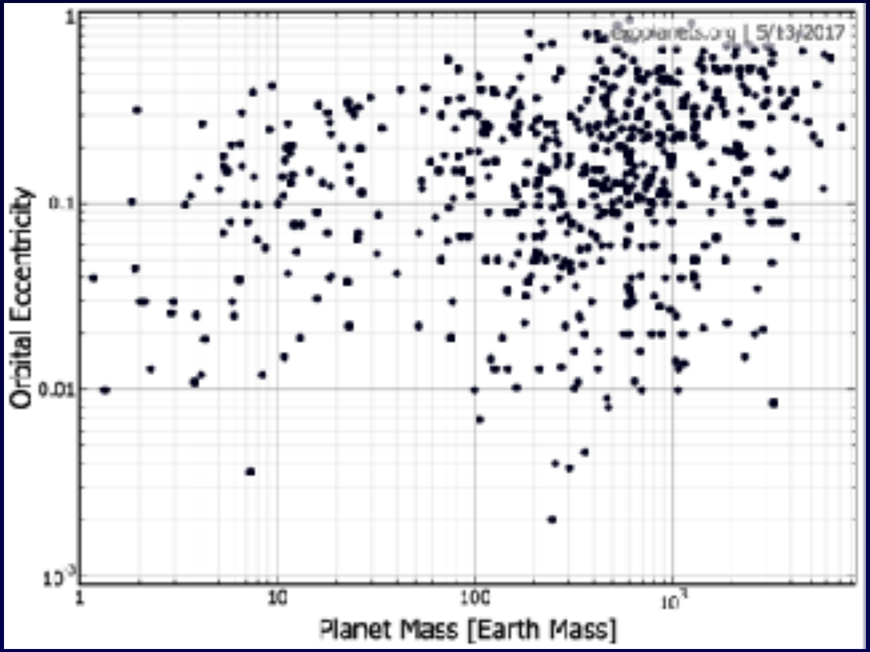


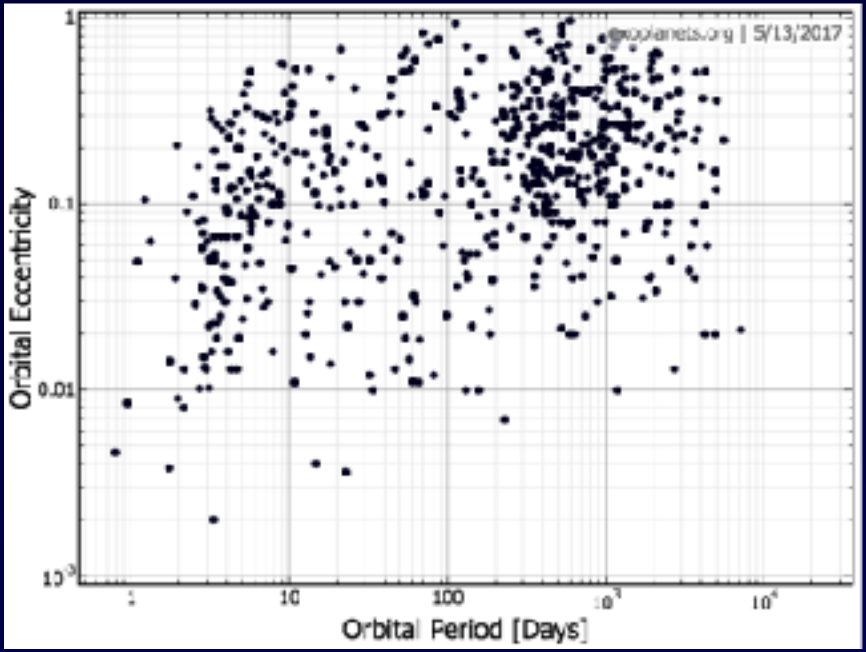
Sumi et al (2016)

Occurence rates

30-50% of FGK stars host an Earth, super-Earth or Neptune with orbital period < 100 days (Fressin+ 2015)

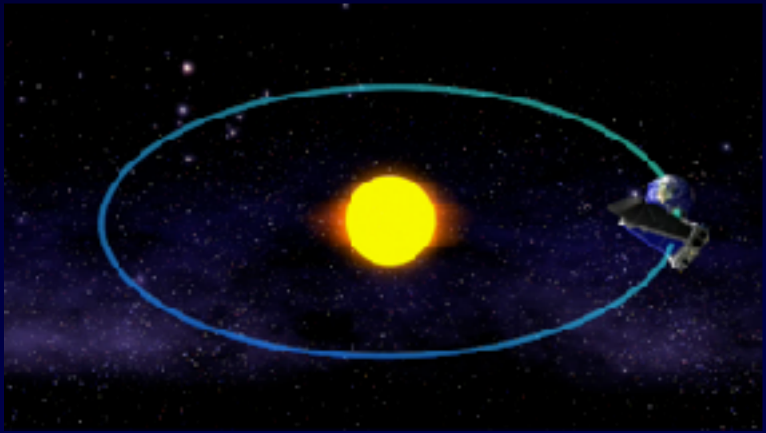
Microlensing survey results -> every star hosts ≥ 1 Neptune-mass planet beyond the snowlike (Sumi et al 2016)

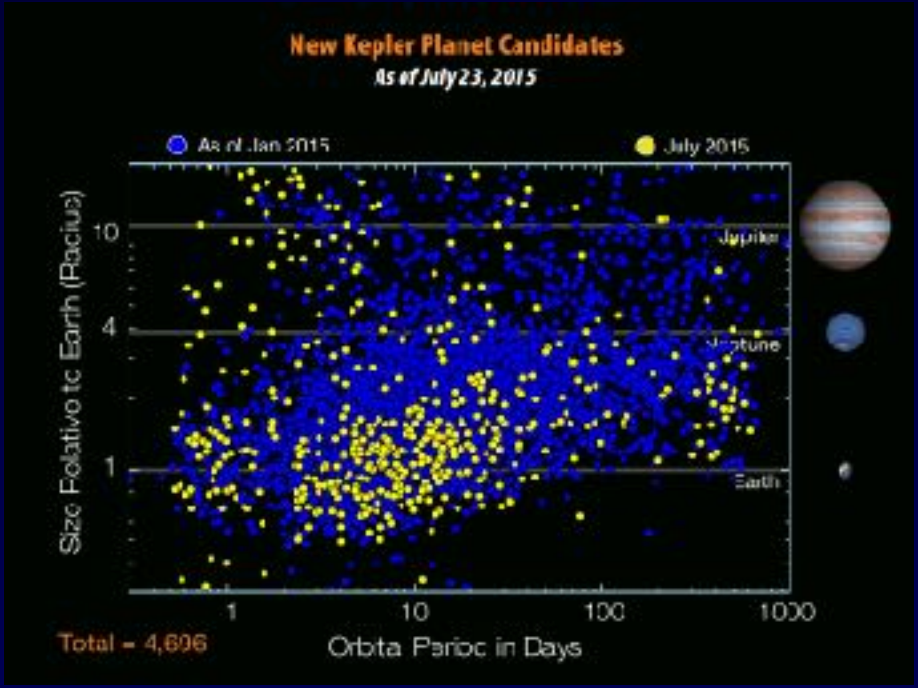




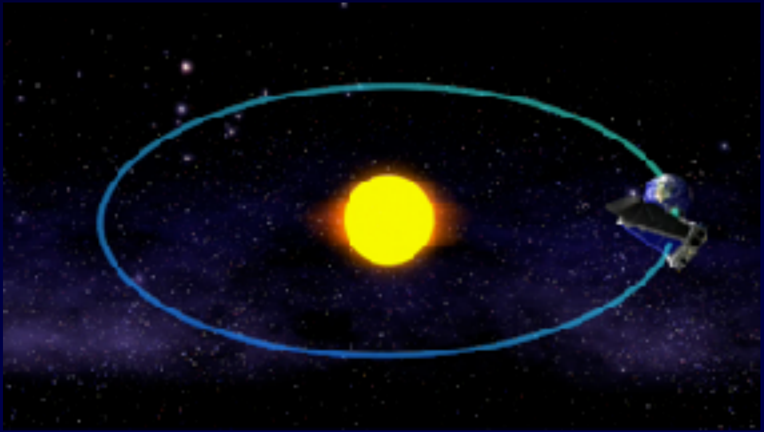
Eccentricities of Kepler super-Earths/Neptunes: e ~ 0.01 for 75% of planets
e ~ 0.1-0.4 for 25% of planets
(Wu & Lithwick 2013)

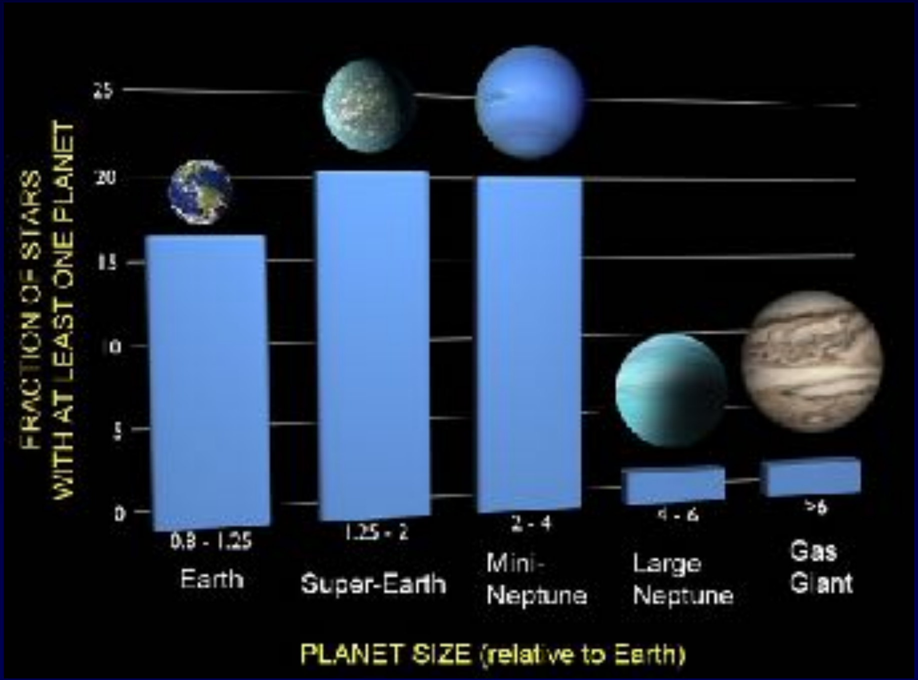
Kepler systems



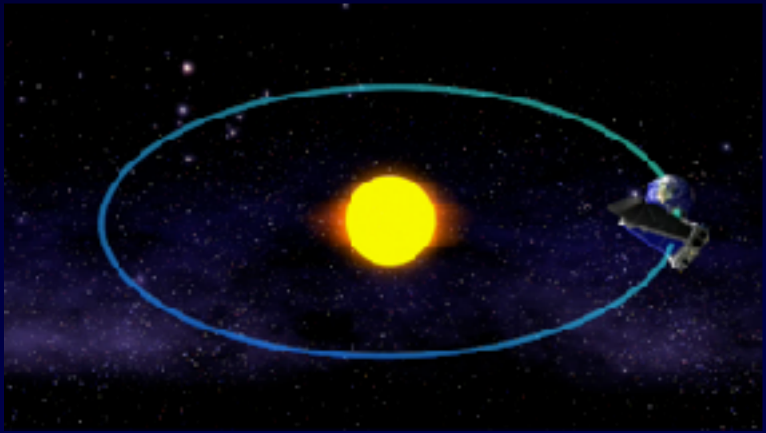


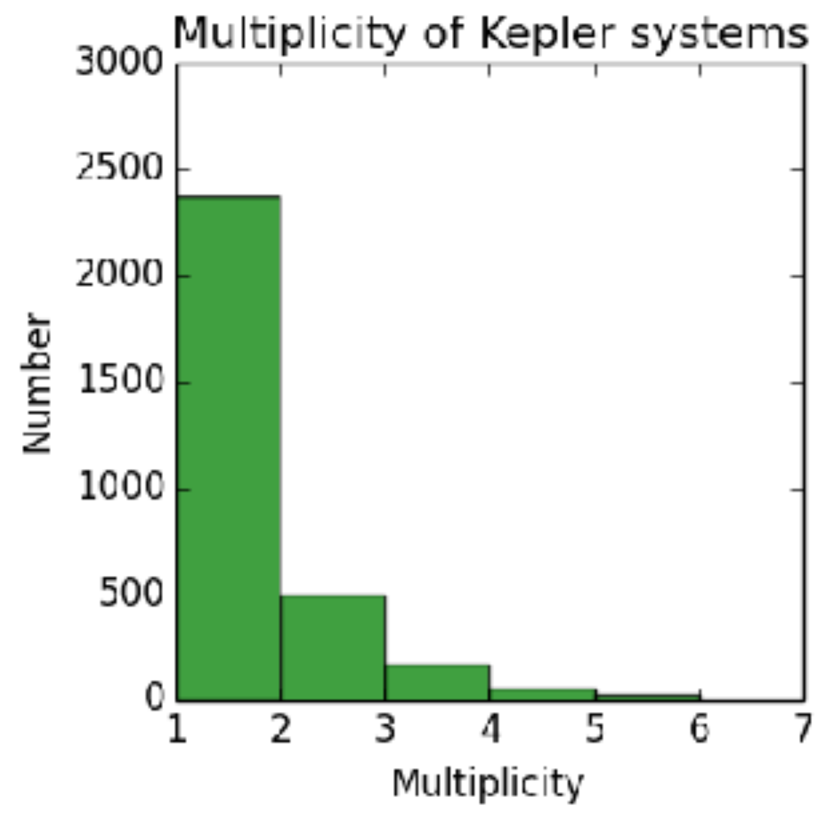
Kepler systems



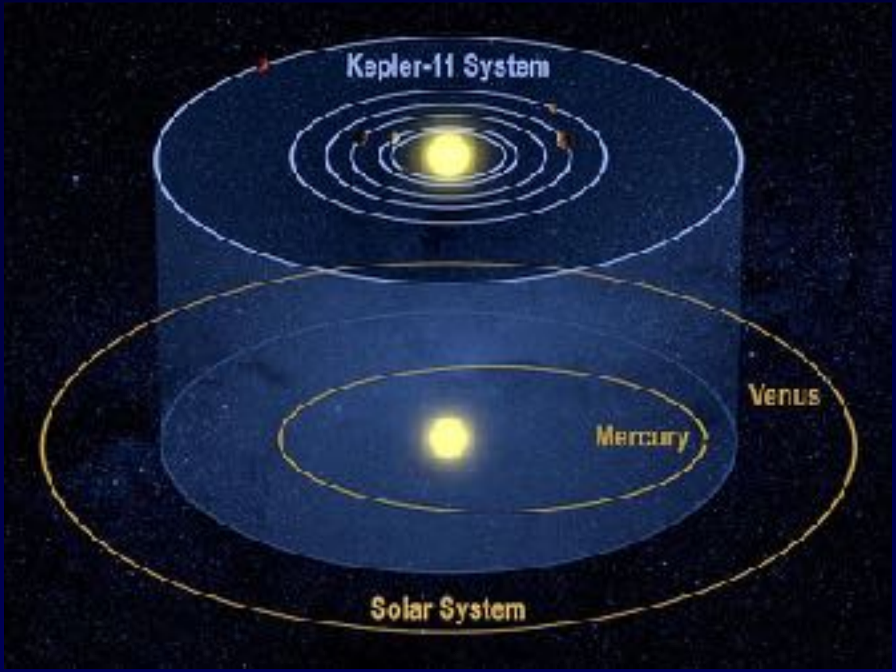


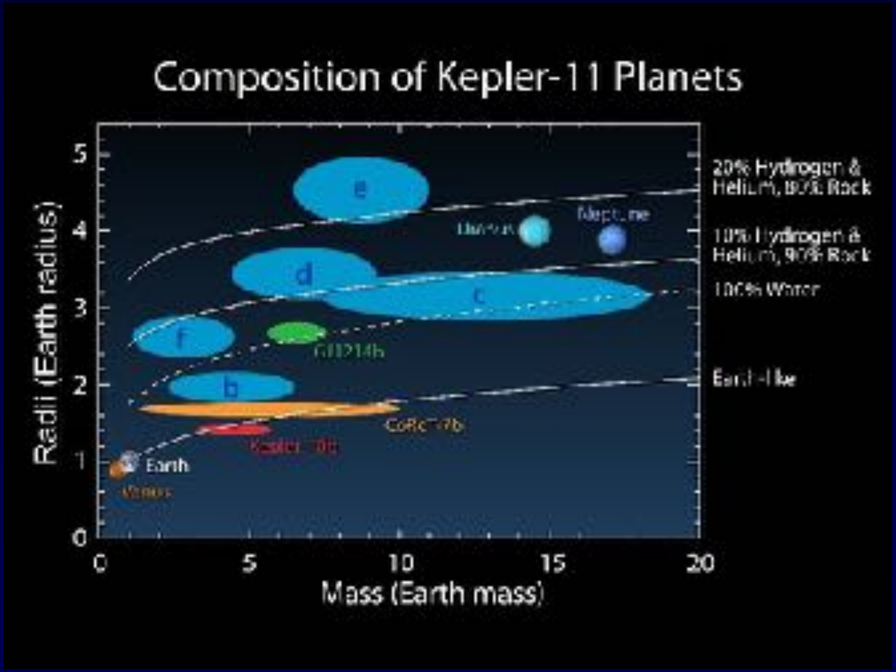
Kepler systems





Kepler 11

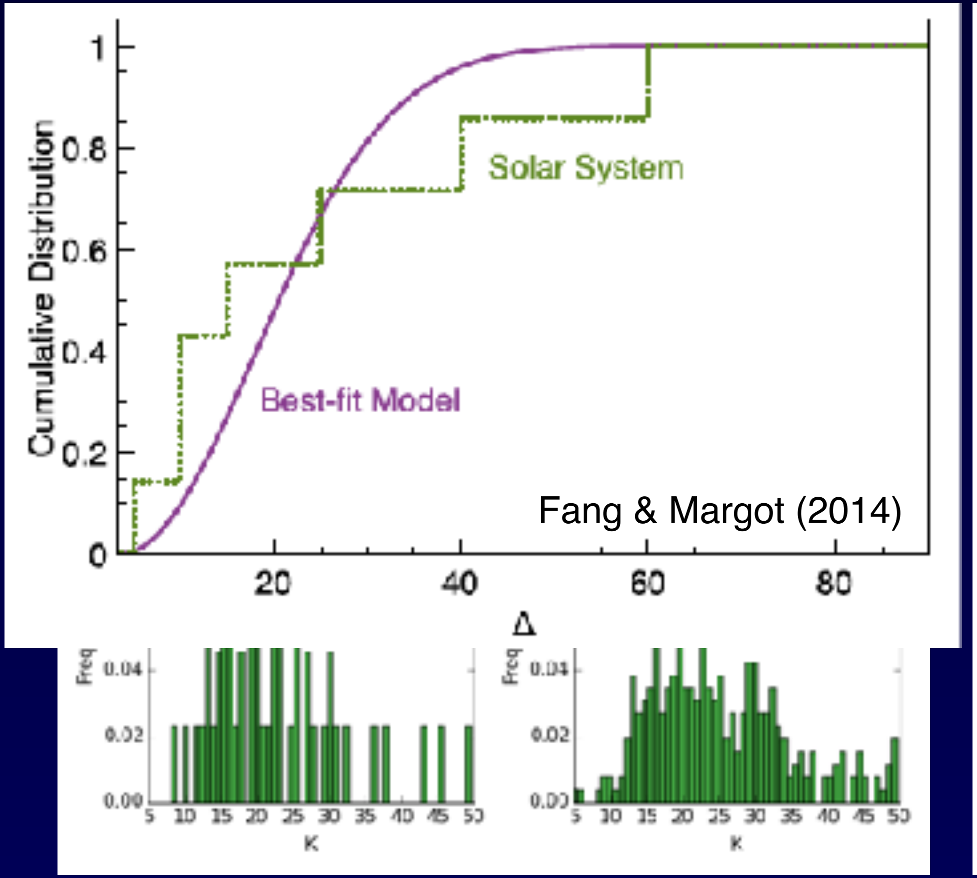




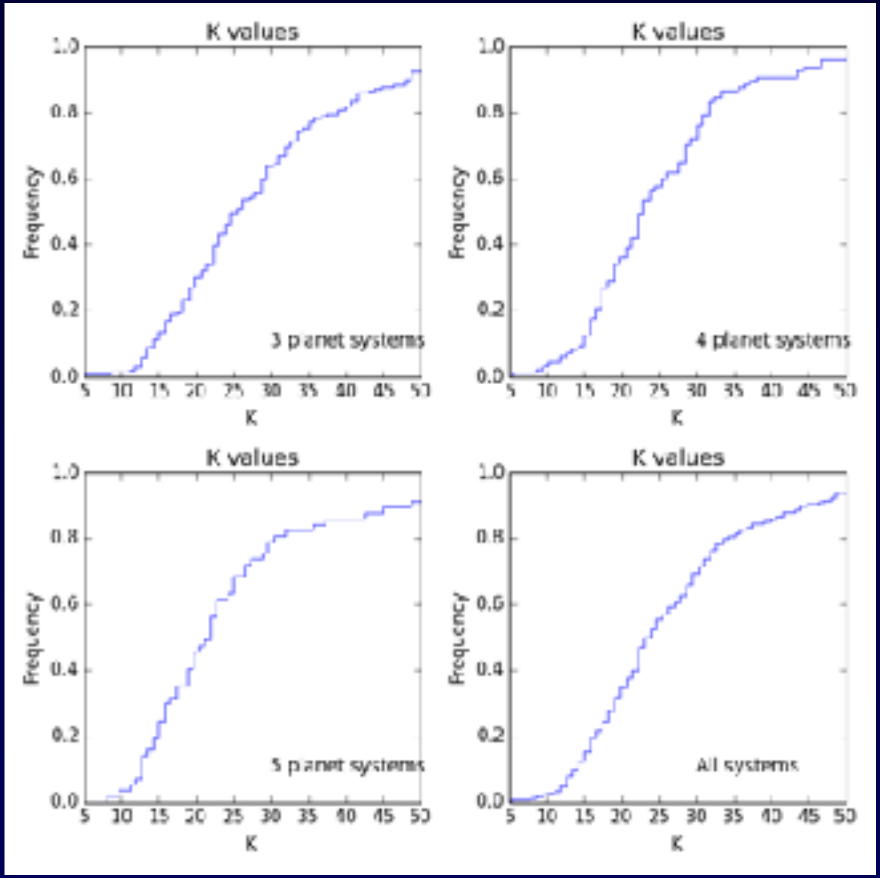
Dynamically stable

- but small perturbations away from observed planet orbital locations render system unstable (Mahajan & Wu 2014)

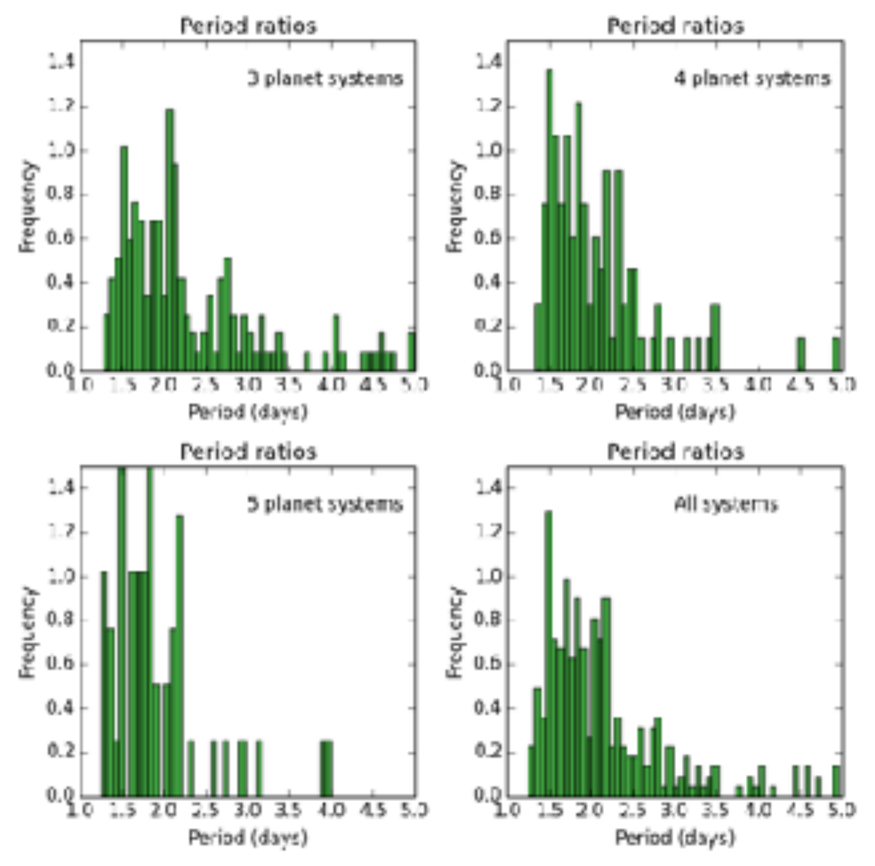
Orbital spacings of multiple systems

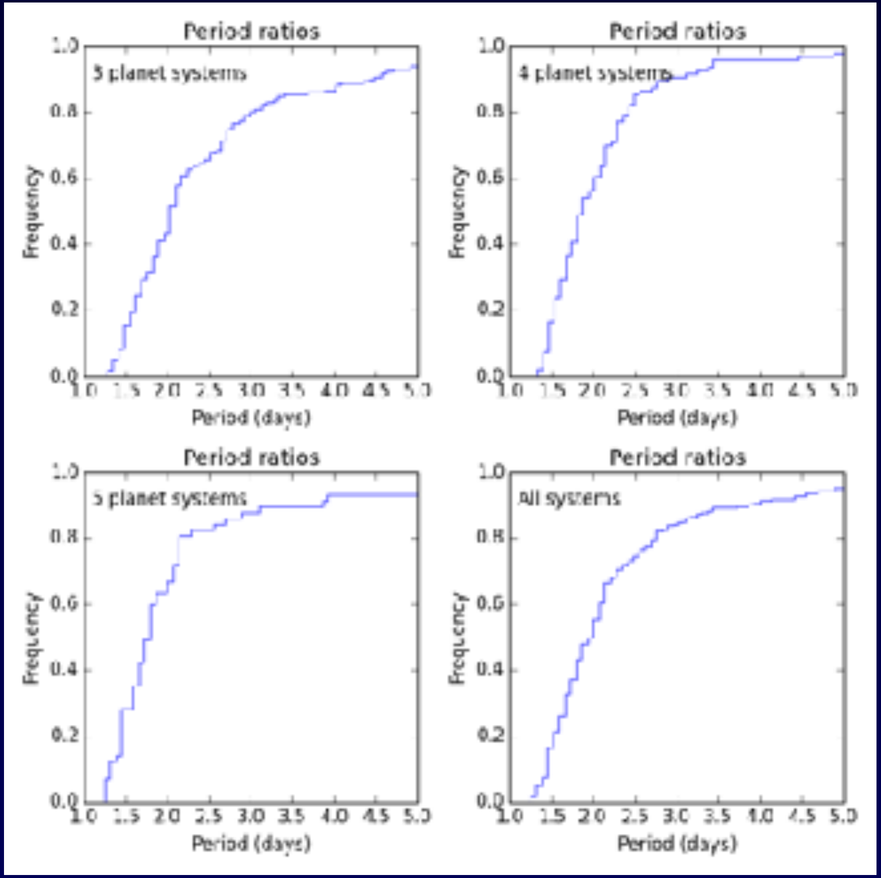


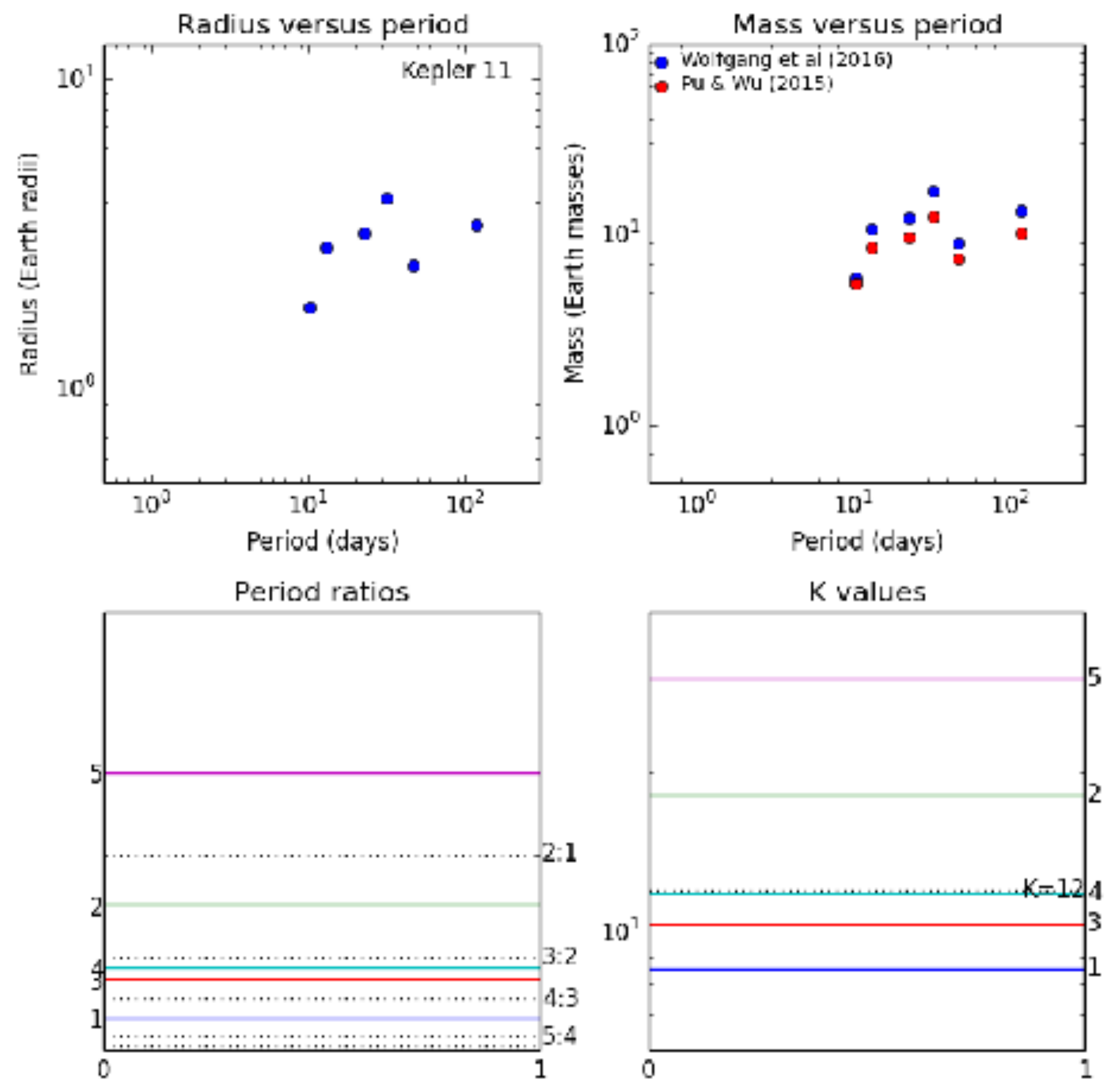
Fang & Margot (2014)

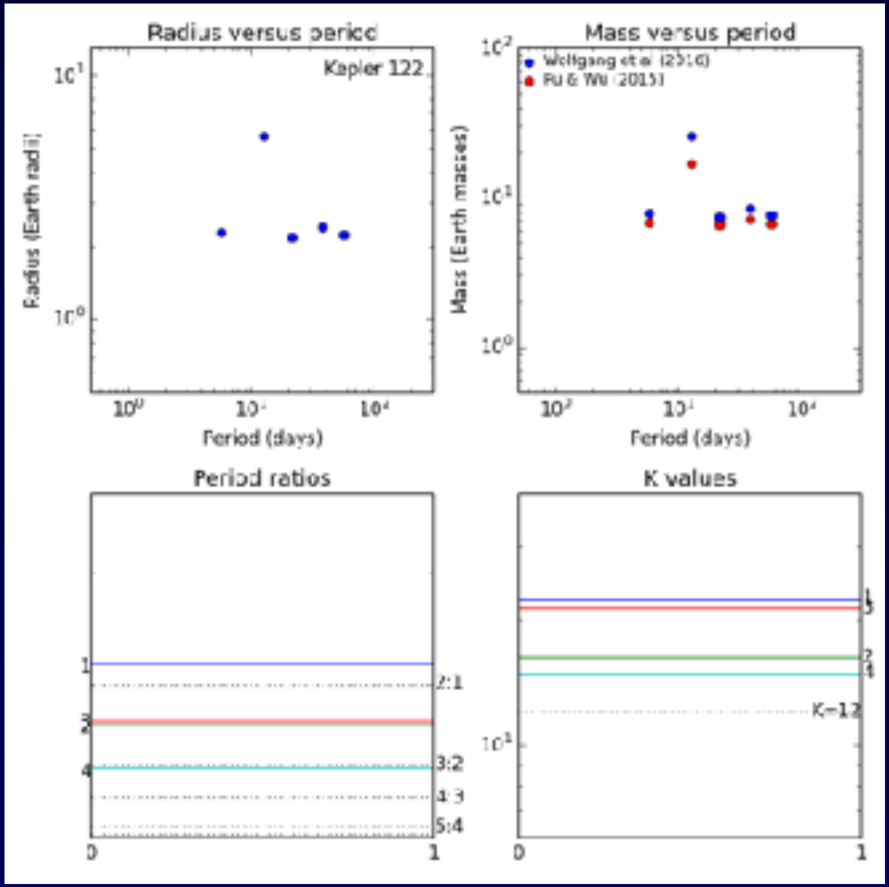


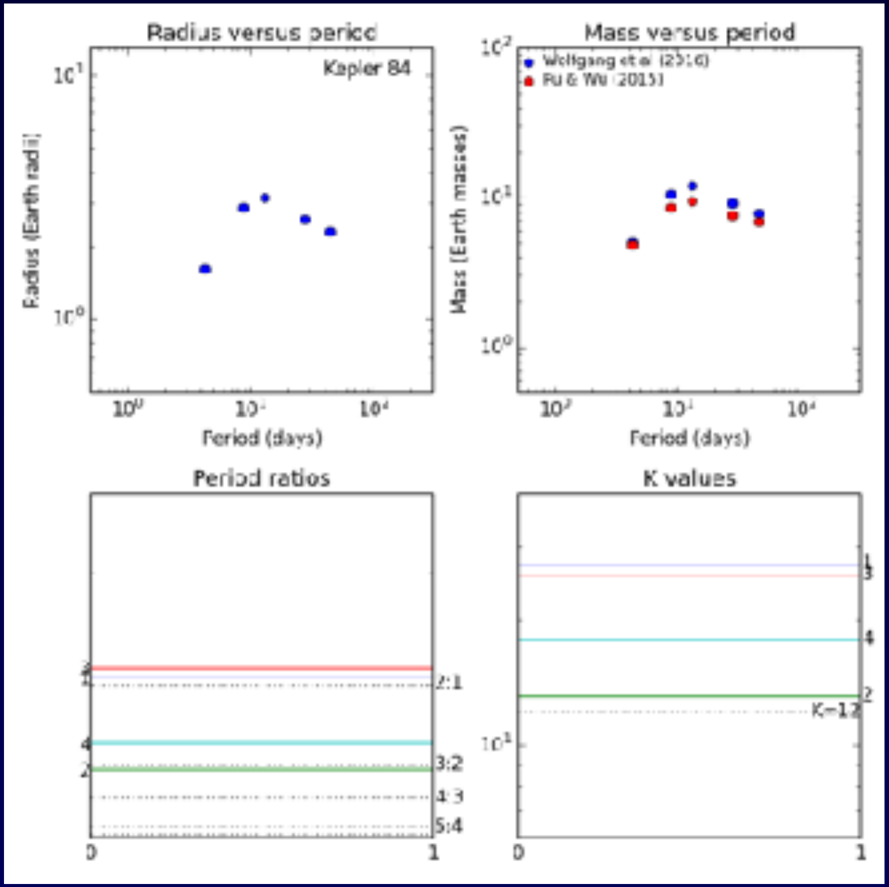
Period ratios of multiple systems

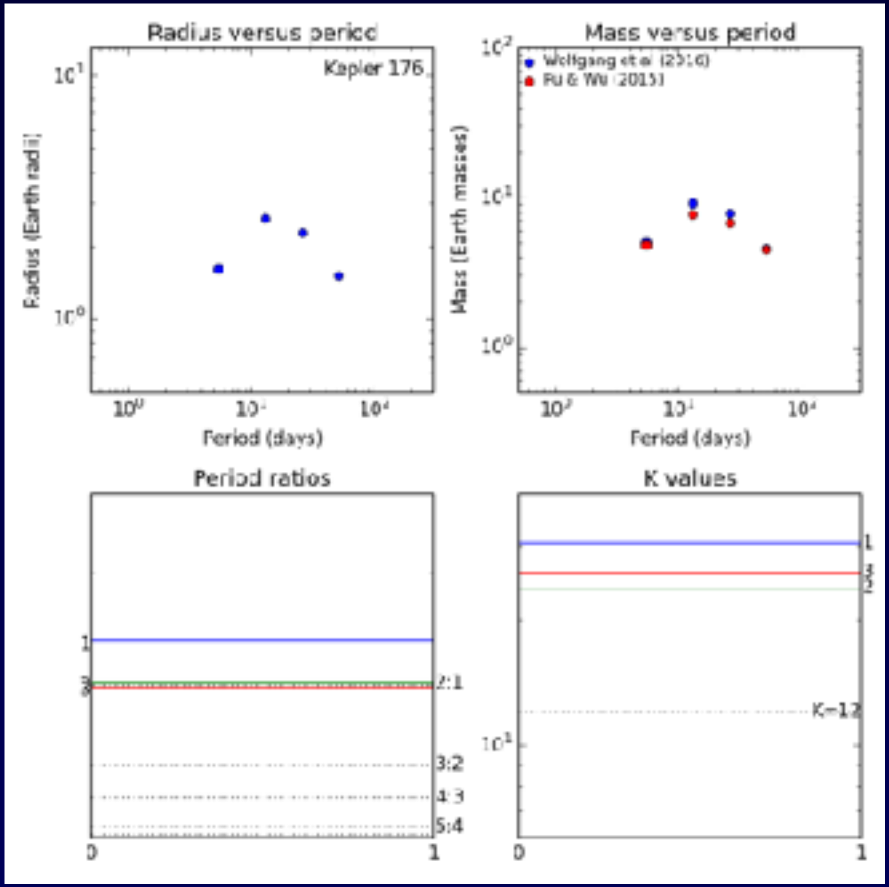


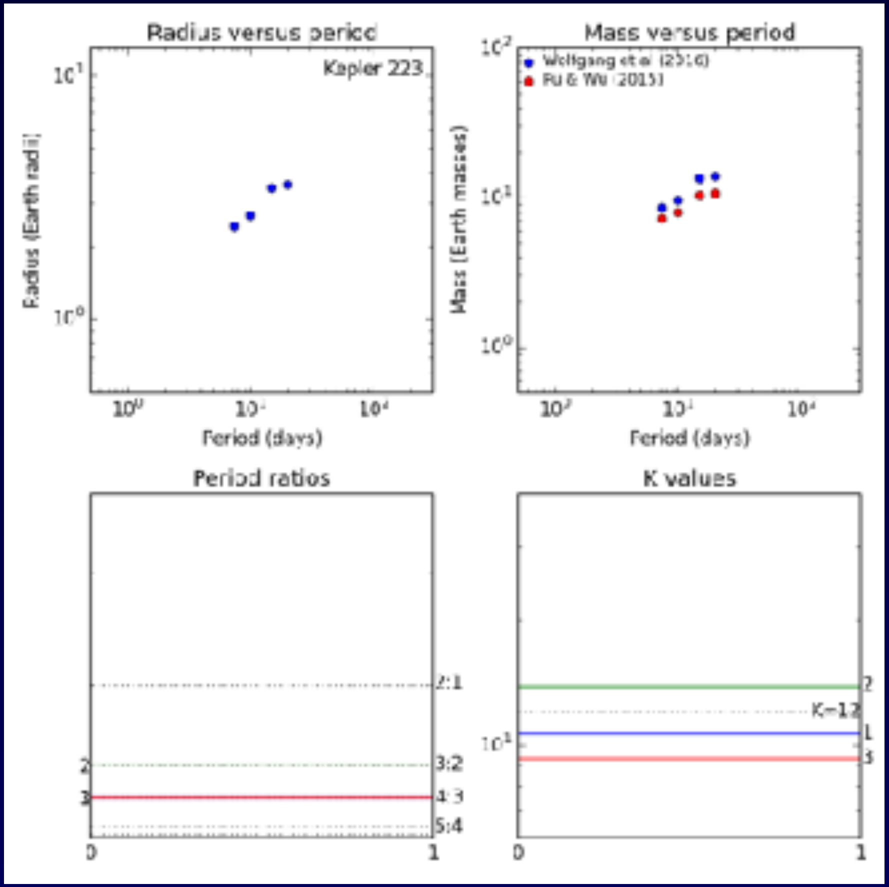



Radius versus period
Kepler 11
Radius (Earth radii)
10^1
10^0
Period (days)
Mass versus period
Wolfgang et al (2016)
Pu & Wu (2015)
Mass (Earth masses)
10^2
10^1
10^0
Period (days)
Period ratios
5
2
4
3
1
2:1
3:2
4:3
5:4
0
1
K values
5
2
K=12
4
3
1
10^1
0
1


Radius versus period
Kepler 122
Radius (Earth radii)
Period (days)
Mass versus period
Wolfgang et al (2016)
Fu & Wu (2015)
Mass (Earth masses)
Period (days)
Period ratios
2:1
3:2
4:3
5:4
K values
K=12

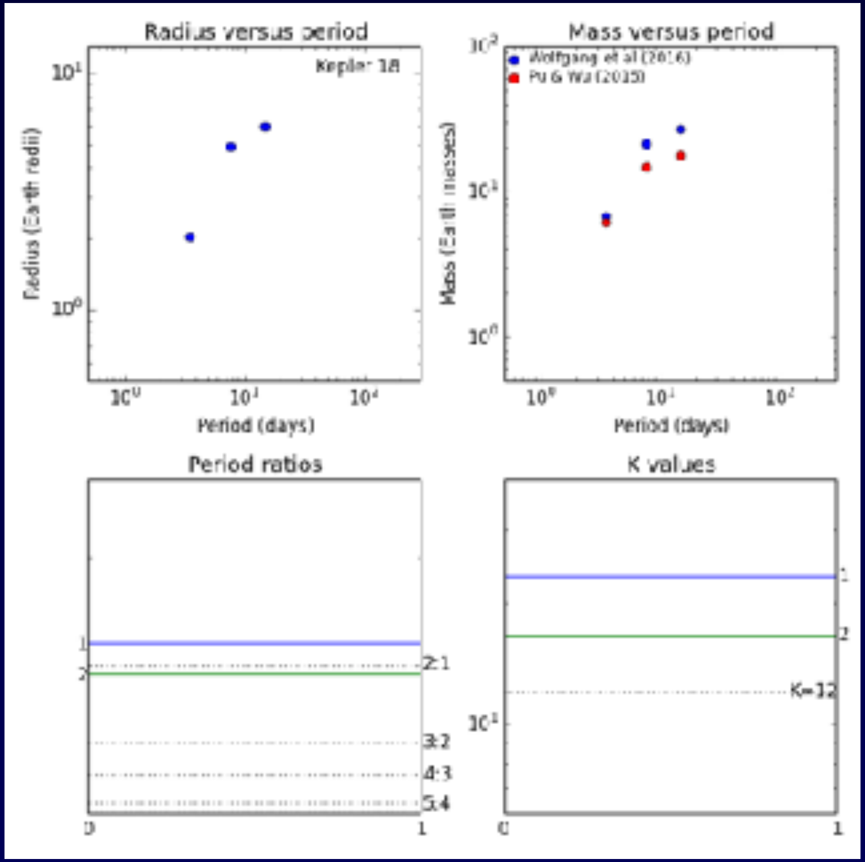

Radius versus period
Kepler 84
Radius (Earth radii)
Period (days)
Mass versus period
Wolfgang et al (2016)
Fu & Wu (2015)
Mass (Earth masses)
Period (days)
Period ratios
2:1
3:2
4:3
5:4
K values
K=12

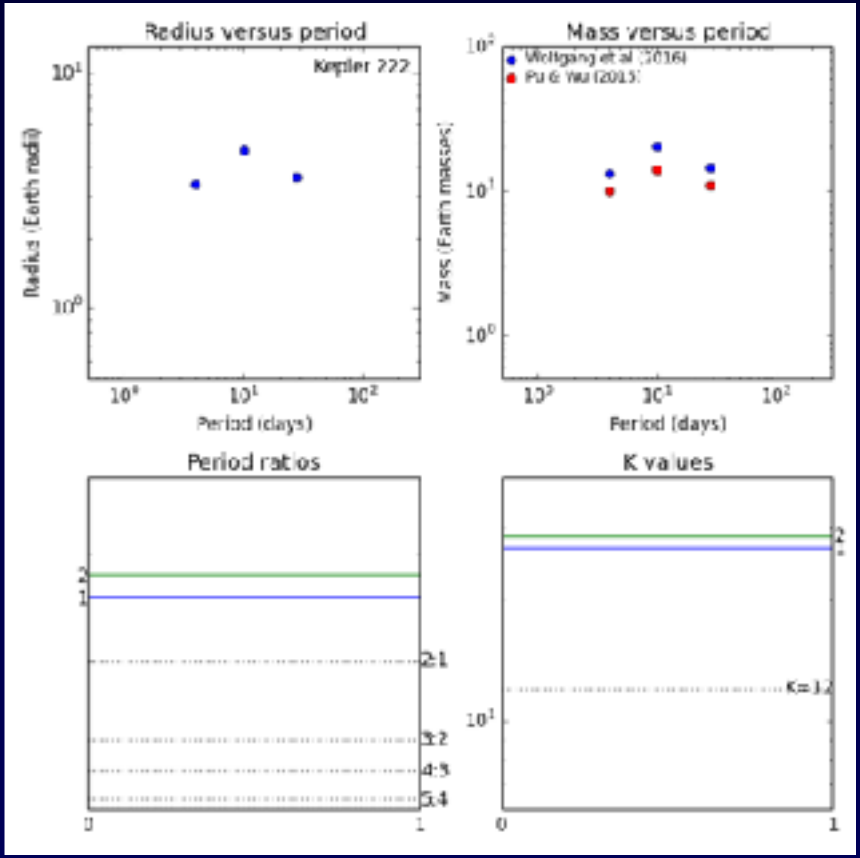




Kepler 223:
4 planets in resonance with period ratio 8:6:4:3 (Mills et al 2016)

Also Trappist-1:
7 planets with period ratios 8:5, 5:3, 3:2, 3:2, 4:3, 3:2


Radius versus period
Kepler 18
10^1
10^0
Radius (Earth radii)
10^0
10^1
10^2
Period (days)
Mass versus period
10^2
Wolfgang et al (2016)
Pu & Wu (2015)
Mass (Earth masses)
10^1
10^0
10^0
10^1
10^2
Period (days)
Period ratios
1
2
2:1
3:2
4:3
5:4
0
1
K values
1
2
K=12
10^1
0
1


Radius versus period
Kepler 222
10^1
10^0
Radius (Earth radii)
10^0
10^1
10^2
Period (days)
Mass versus period
10^2
Wolfgang et al (2016)
Pu & Wu (2015)
Mass (Earth masses)
10^1
10^0
10^0
10^1
10^2
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Period ratios
2
1
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4:3
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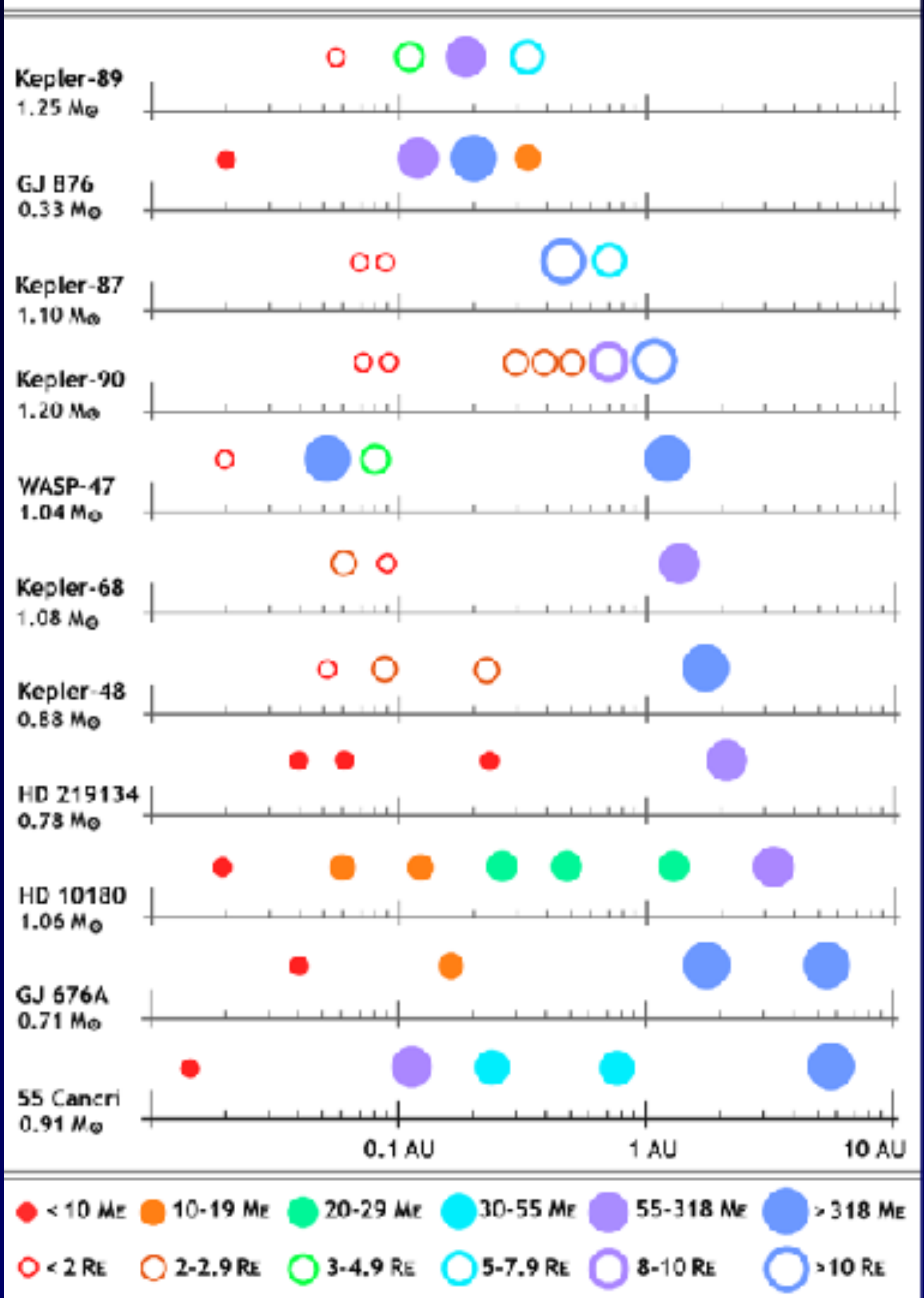
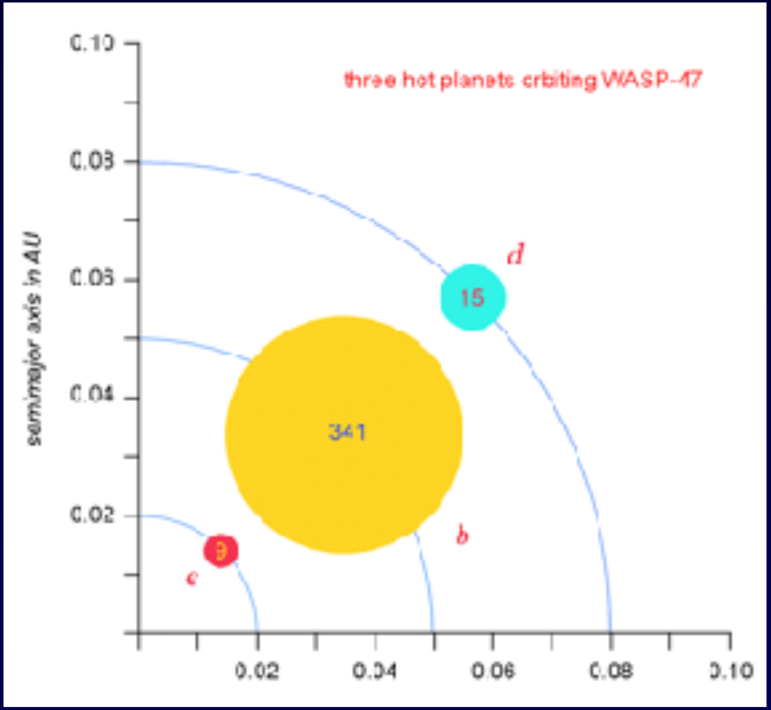
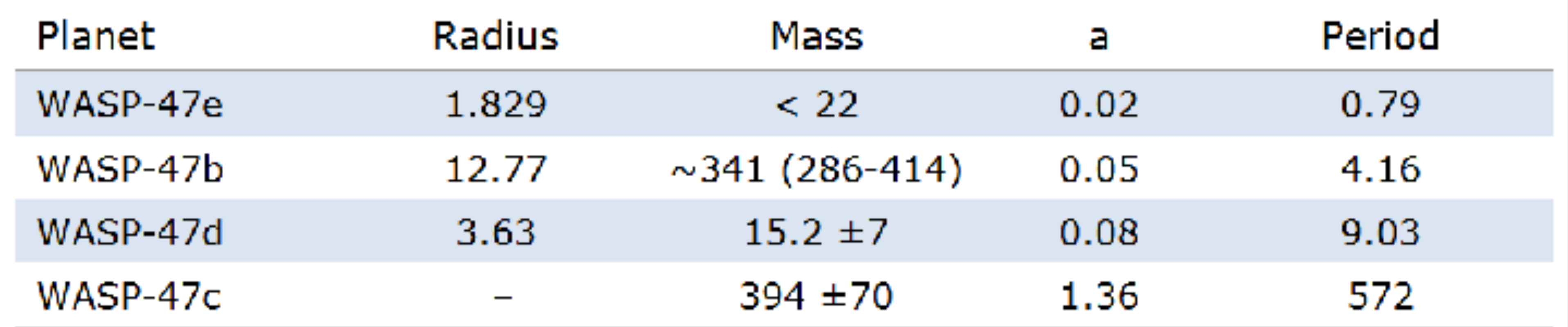
0
1
K values
2
1
K=12
10^1
0
1

Radial velocity surveys also reveal multi planet systems with diverse properties.



Wasp 47 and similar systems





Planet	Radius	Mass	a	Period
WASP-47e	1.829	< 22	0.02	0.79
WASP-47b	12.77	~341 (286-414)	0.05	4.16
WASP-47d	3.63	15.2 ±7	0.08	9.03
WASP-47c	–	394 ±70	1.36	572

Planet formation models - an unbiased perspective…

In situ formation: Migrate large amount of solids (100 M_{Earth}) into inner disc regions and grow via giant impacts

Pros: By construction can obtain systems with observed numbers of planets and their spacings

Cons: Formation will be rapid (< 1 Myr), but migration and influence of gas disc is ignored.
Cannot explain single short-period planets.

Inside-out formation: Collect solids at disc inner edge and grow a sequence of planets one after the other

Pros: Can lead to systems of compact super-Earths as observed

Cons: Does not explain longer period systems -> treats short-period super-Earths as “special”.
MHD turbulence in inner disc regions maybe disruptive of planet formation.

Concurrent migration and growth: Build planets at range of distances and migrate when sufficiently massive

Pros: Can explain planetary systems with broad range of semi-major axes. Explains known resonant systems.

Cons: Generates too many resonant systems - require these to be unstable in the long-term.

Type I migration of low mass planets

Lindblad torque

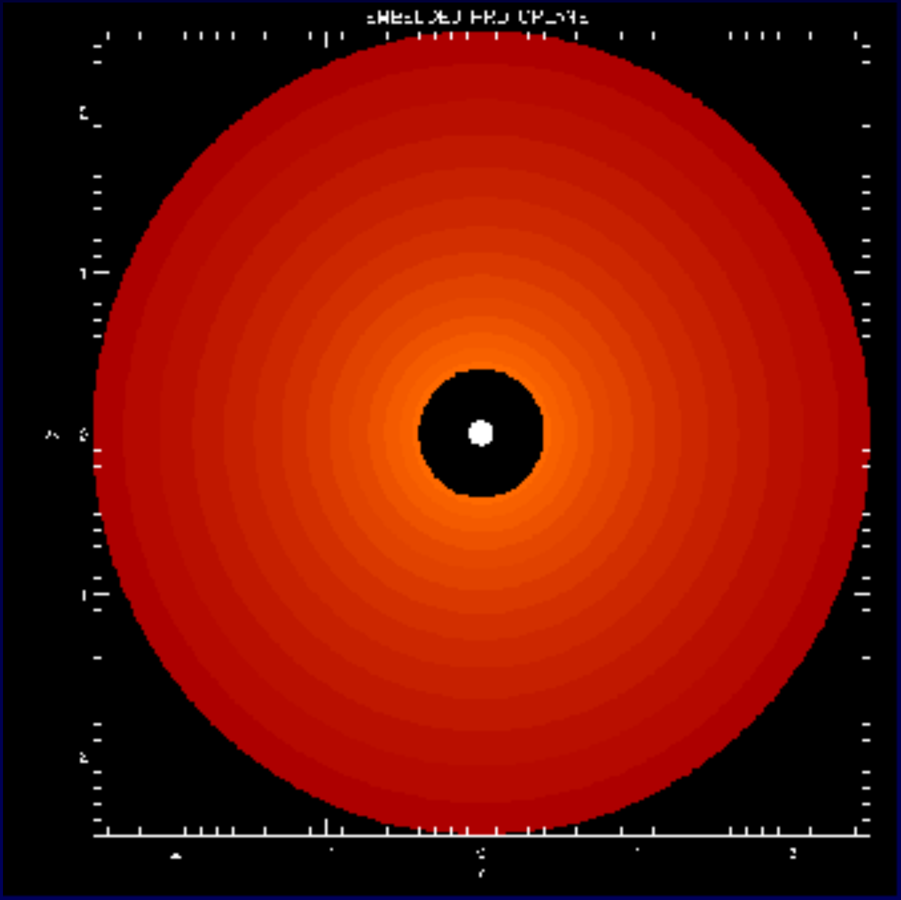
- Gravitational interaction between planet and disc leads to the excitation of spiral density waves at Lindblad resonances
  (Goldreich & Tremaine 1978, 1980;
  Lin & Papaloizou 1979, 1984)
- Spiral wave exerts gravitational force on planet - removes angular momentum and drives inward migration
- Total Lindblad torque scales as:

$$\Gamma_0 = (q/h)^2 \Sigma_p r_p^4 \Omega_p^2$$

q = M_p / M_* planet/star mass ratio
Σ = gas surface density
Ω = angular velocity
h = aspect ratio H/r
X_p = X at the planet location.

Σ(MMSN @1AU) =>
migration time [years] ≈ $1/q$

→ 300000 yrs for an Earth ,
→ 20000 yrs for a Neptune !



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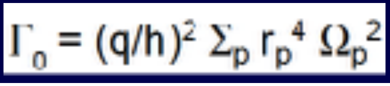

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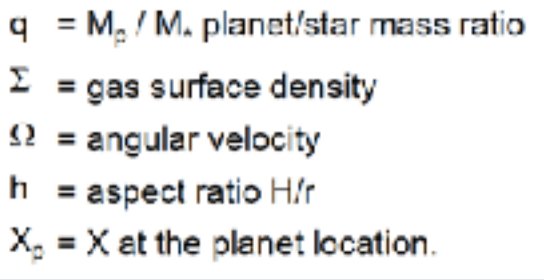

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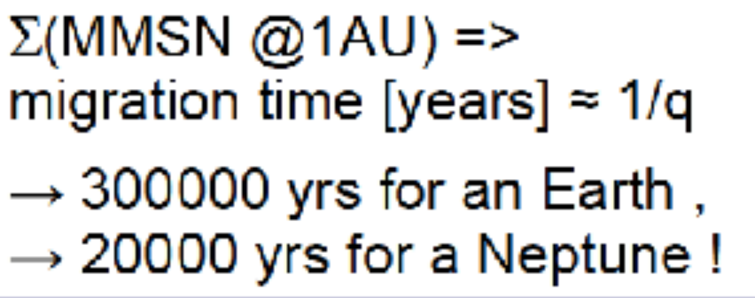

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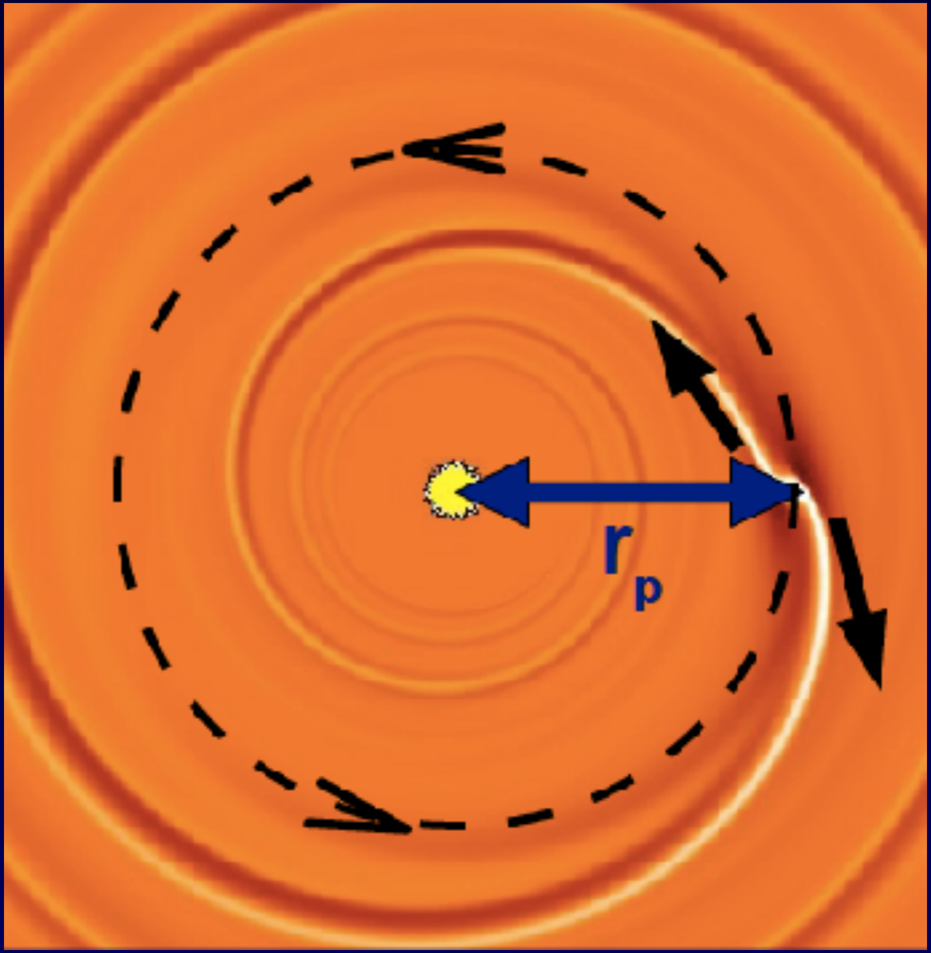
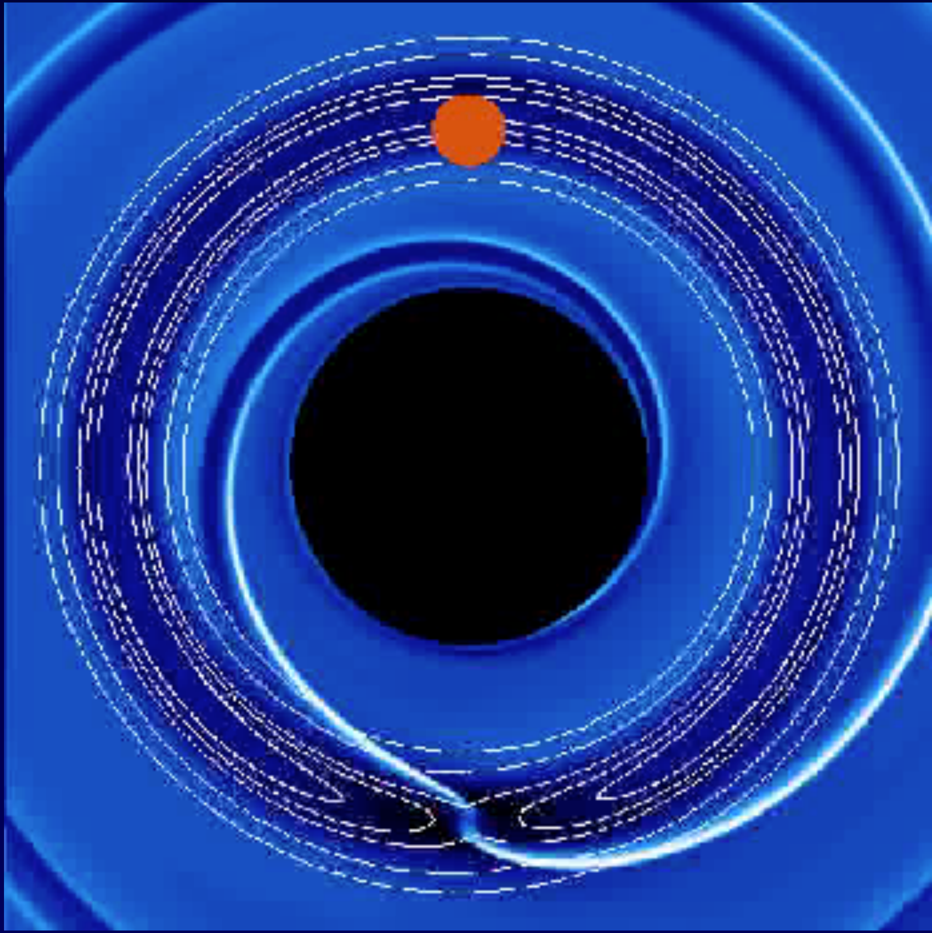
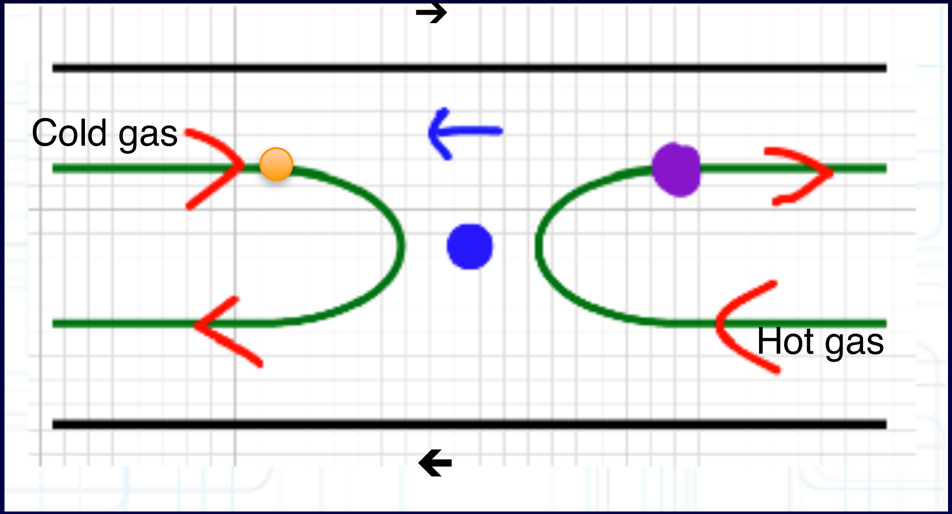


Corotation torque

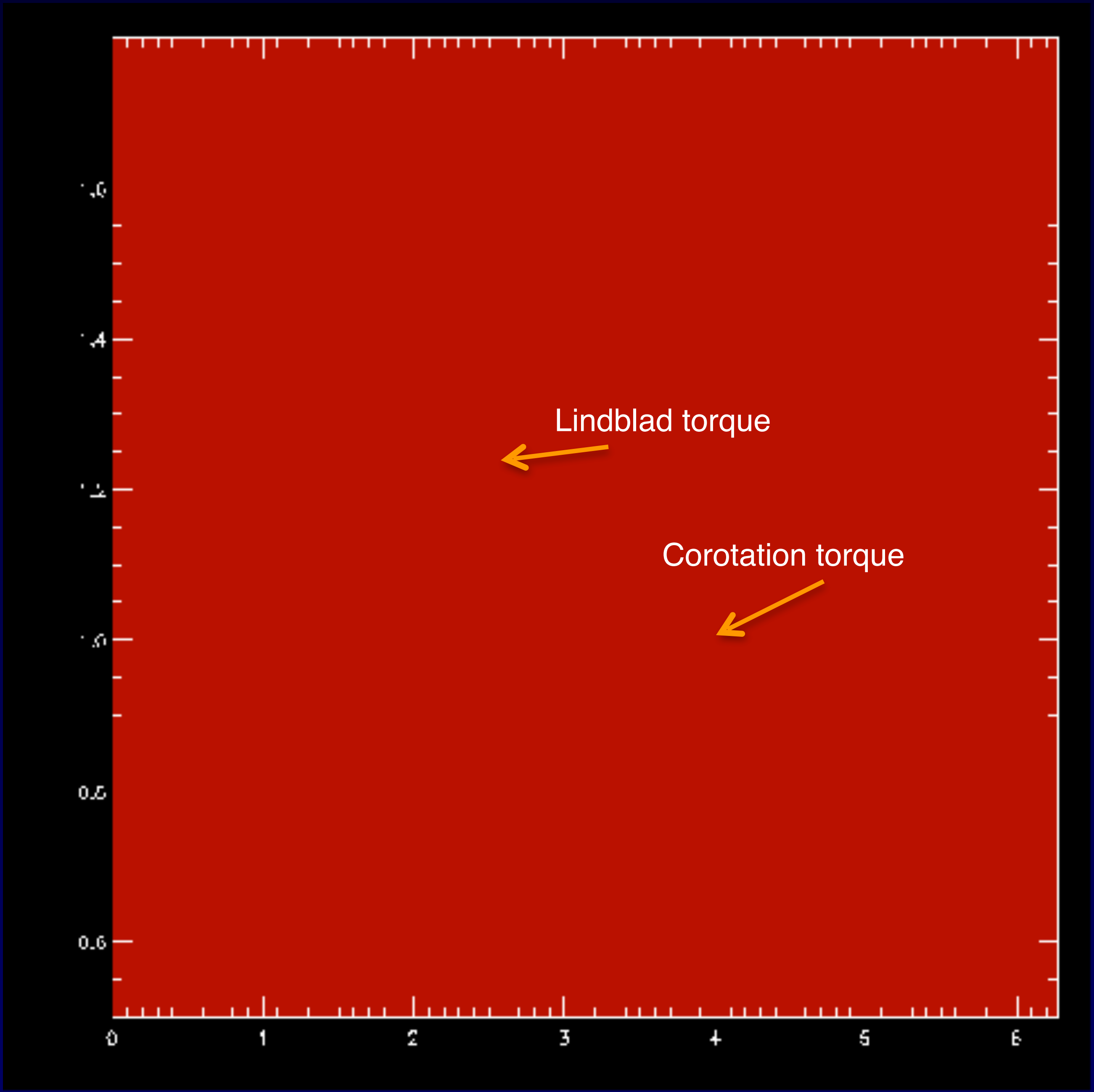
- Angular momentum is exchanged between planet and material that orbits in the horseshoe region
(Goldreich & Tremaine 1980;
Ward 1991, Masset 2001)
- Over one complete horseshoe orbit there is no net torque for a disc composed of ballistic particles
- Radial gradients in *entropy* and *vortensity* in a gaseous disc can give rise to a sustained corotation torque (e.g. Paardekooper et al 2010)



Corotation torque saturation - a simple argument



- We consider a disc with a negative radial entropy and temperature gradient.
- Case 1: Adiabatic evolution. The orange fluid element exchanges no heat with its surroundings - no horseshoe drag
- Case 2: Locally isothermal evolution. The orange fluid element instantaneously adjusts thermally to its surroundings - no horseshoe drag
- Case 3: Orange fluid element thermally equilibrates with its surroundings after 1/2 horseshoe orbit - optimal corotation torque
- See Paardekooper & Mellema (2006); Baruteau & Masset (2008); Pardekooper & Papaloizou (2008); Paardekooper et al (2010, 2011)
- A similar argument applies when a vortensity gradient is present in the disc where viscosity is required for unsaturating coronation torque



Lindblad torque

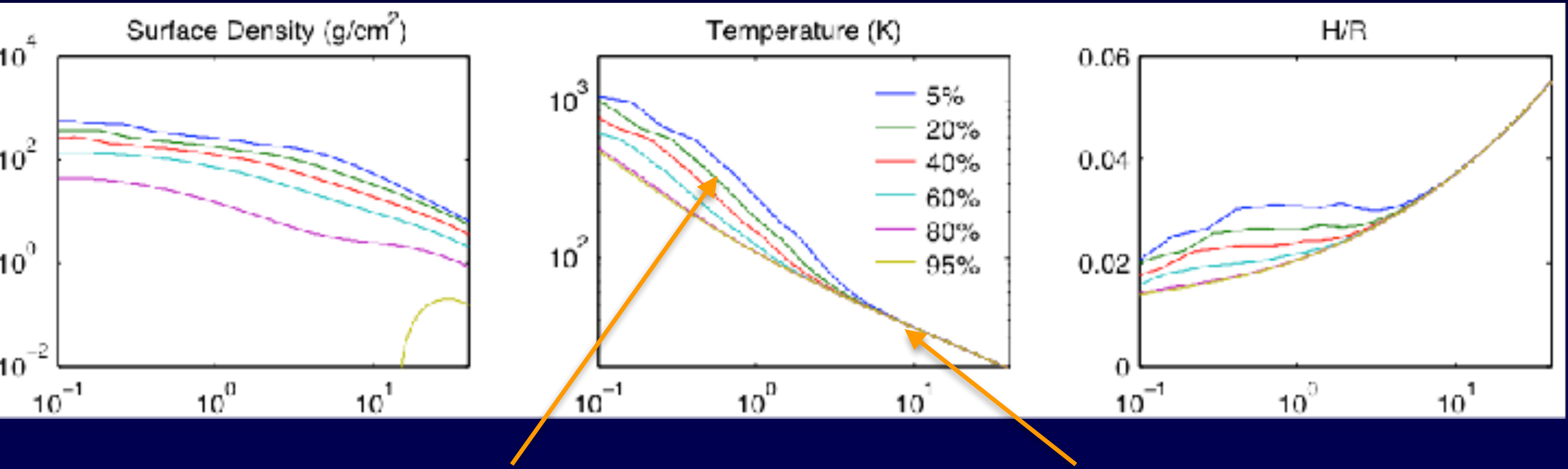
Corotation torque

Note

Viscosity and thermal diffusion are required to unsaturate the corotation torque.

Implications: Corotation torques will only be effective in disc regions where thermal or viscous diffusion operate on the appropriate time scales ~ horseshoe libration time scale

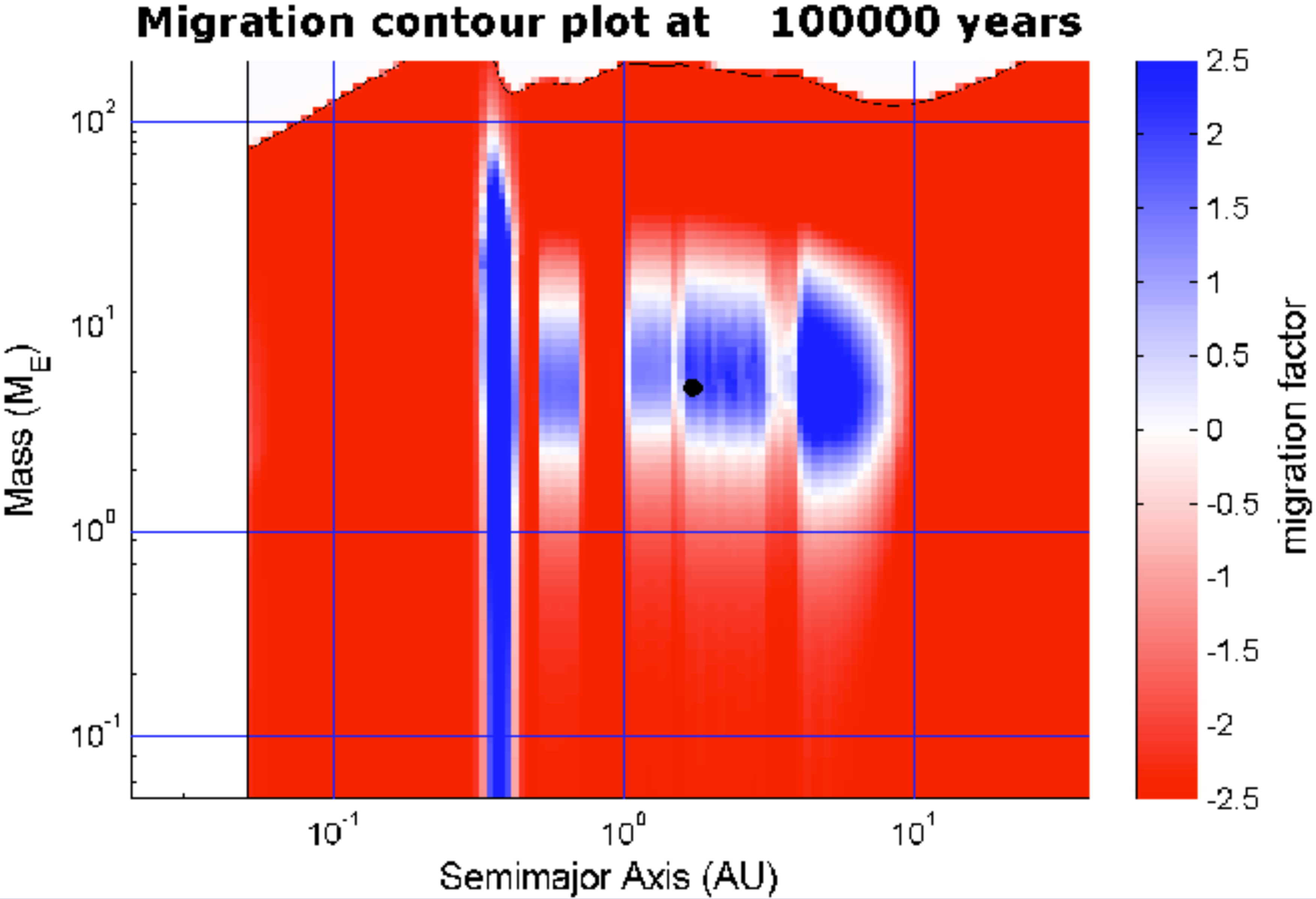
Evolution of an irradiated viscous disc model with mass ~ MMSN



Viscous heating dominates

Irradiation heating dominates

Balance of Lindblad and corotation torques in irradiated viscous disc



Type II migration of high mass planets

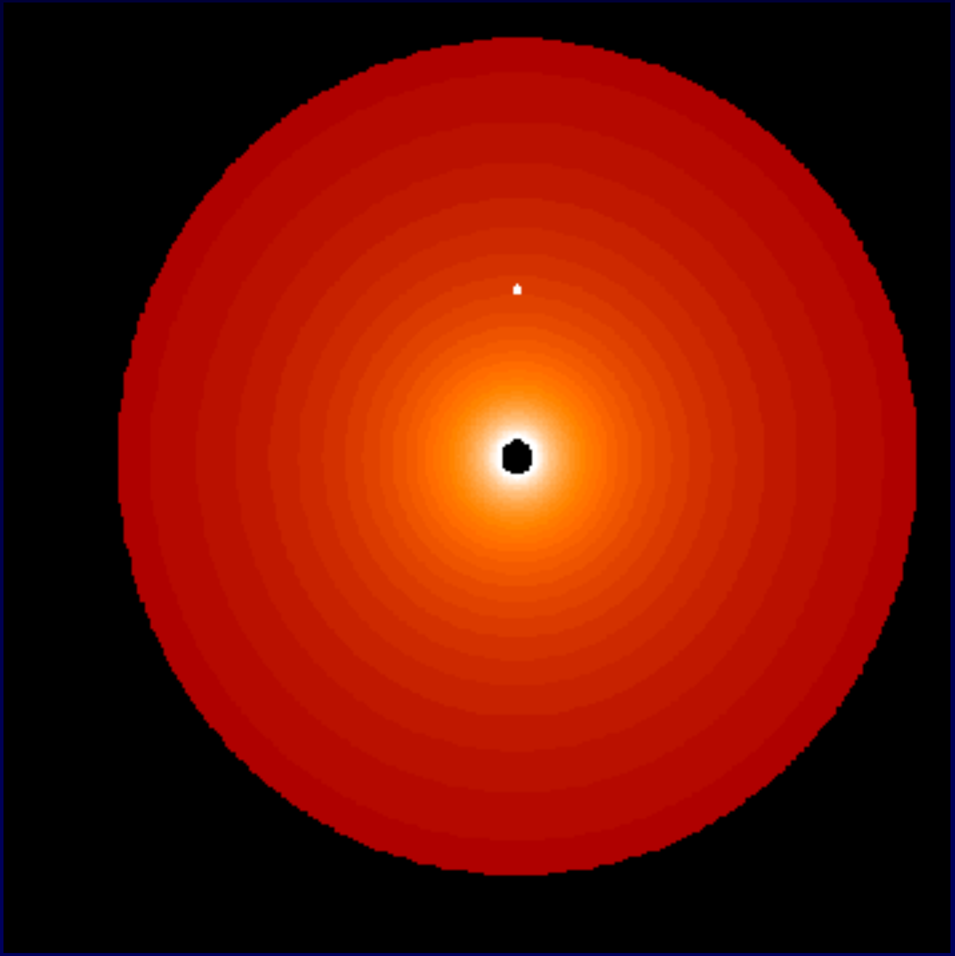
Gap formation

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

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

+

tidal torque > local viscous torque



- Gap formation criterion:
(including pressure effects - 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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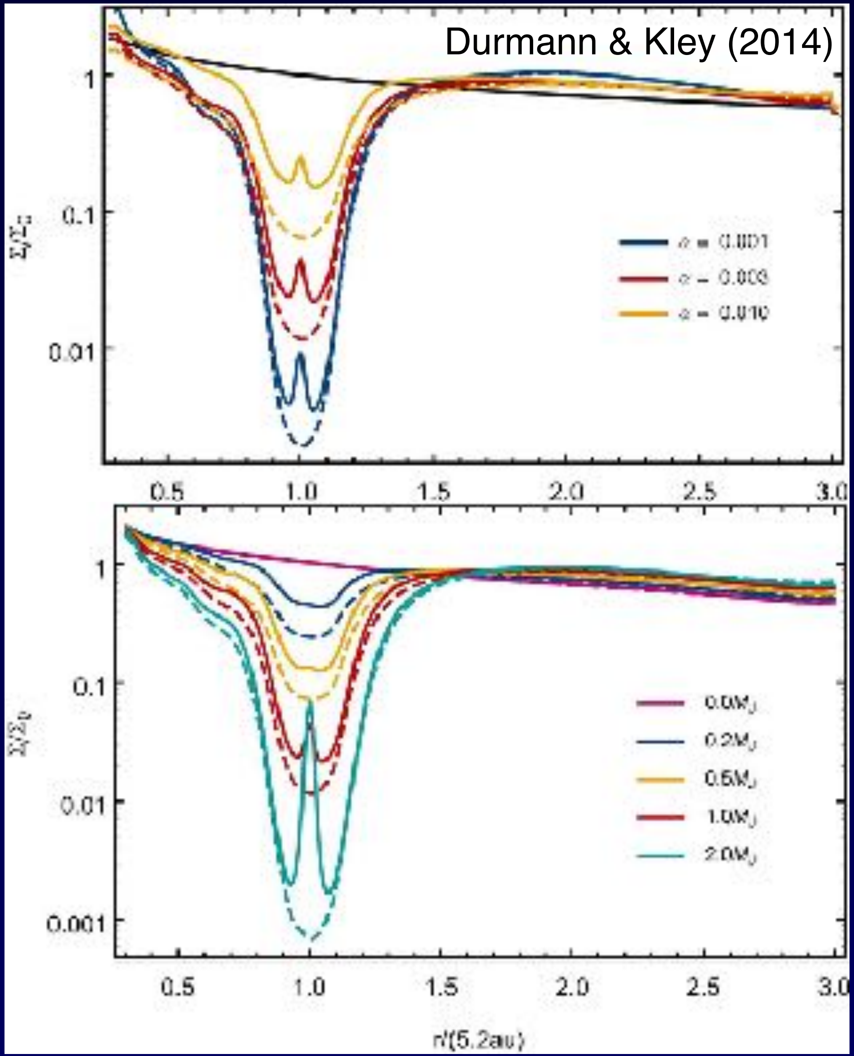

Durmann & Kley (2014)

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)

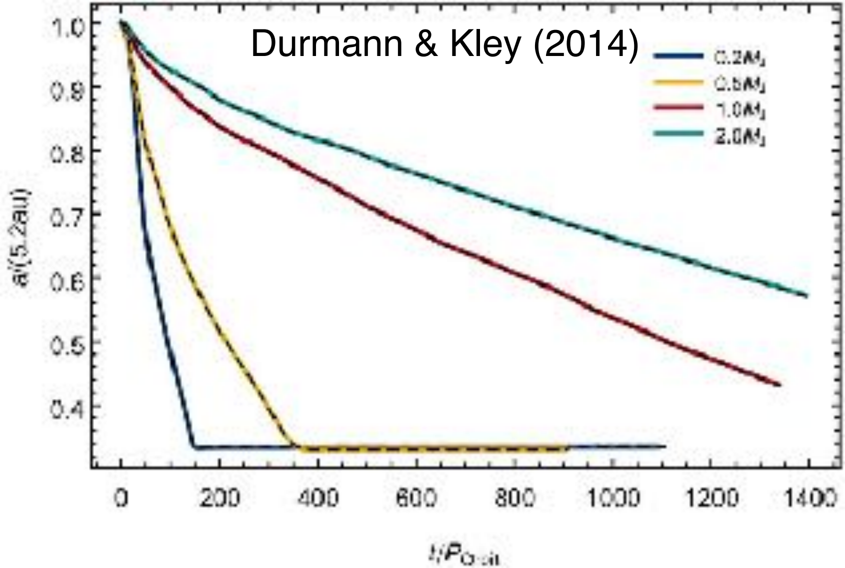
- Migration rates are not precisely equal to the viscous rate

  (Duffel 2014; Durmann & Kley 2014)

- Large disc masses:
  migration rate ~ 5 x viscous rate

- Small disc masses:
  migration rate ~ 0.5 x viscous rate

- Detailed torque balance matters!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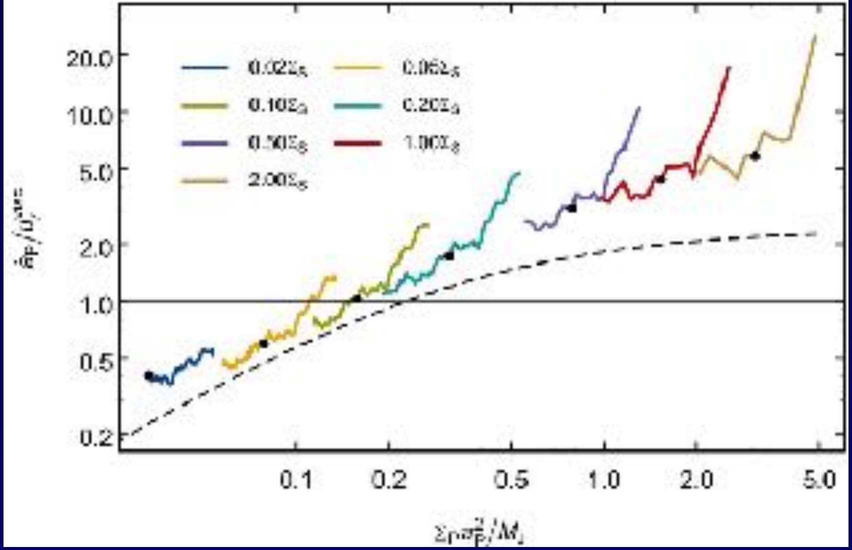
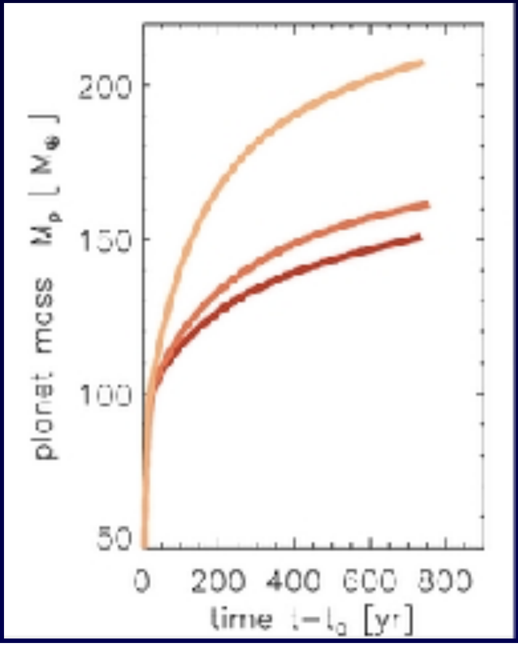
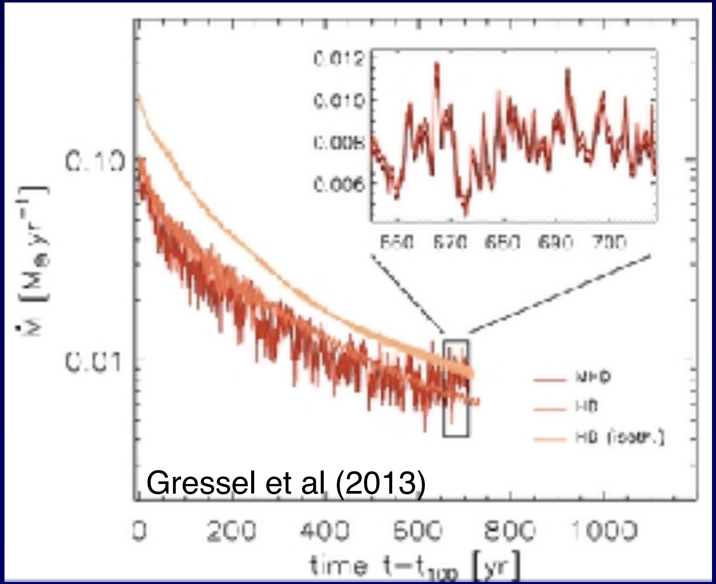


Gas accretion

- Simulations agree:
  disc supplies gas through the gap to the planet at viscous supply rate ~ 10^{-5} Jupiter / year
  (Bryden et al 1999; Kley 1999, Lubow et al 1999)

  - note that numerical effects prevent accretion rate onto the planet being determined accurately!
  (Szulágy et al 2014)
- Gas accretion can be at a much faster rate during gap formation, building a Jovian planet in ~ 10^3 yr



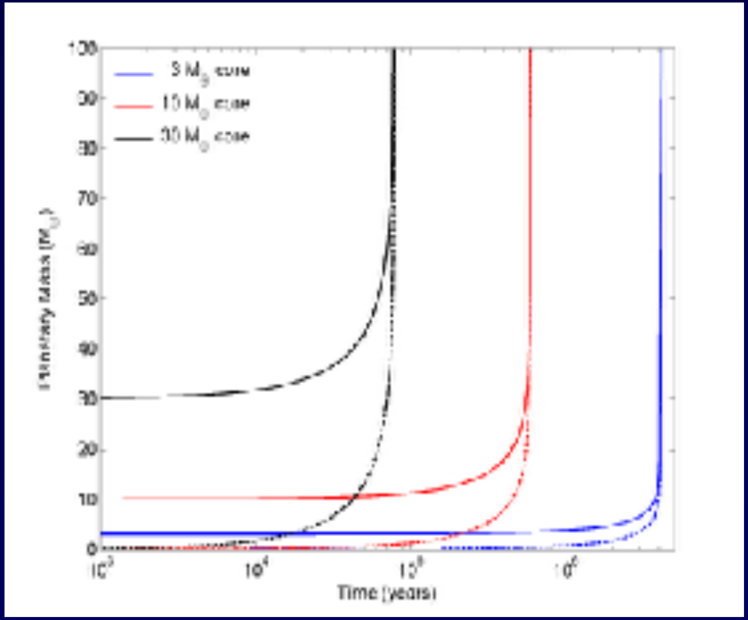


Gressel et al (2013)

“Kitchen-sink” planet formation simulations

Model ingredients

- Planetary embryos + planetesimals/boulders (Mercury-6, Chambers 1996)
- Viscous disc model with stellar irradiation and photoevaporative disc wind (Lynden-Bell & Pringle 1974, Dullemond et al 2011)
- Disc cavity interior to 0.05 AU (stellar magnetosphere)
- Transition to higher disc viscosity when T > 1000 K
- Type I migration with corotation torques (Paardekooper et al 2011, Fendyke & Nelson 2014), + transition to type II migration when gap forms (Lin & Papaloizou 1986)
- 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/boulder radii: R_{pl} = 10m, 100m, 1km, 10km

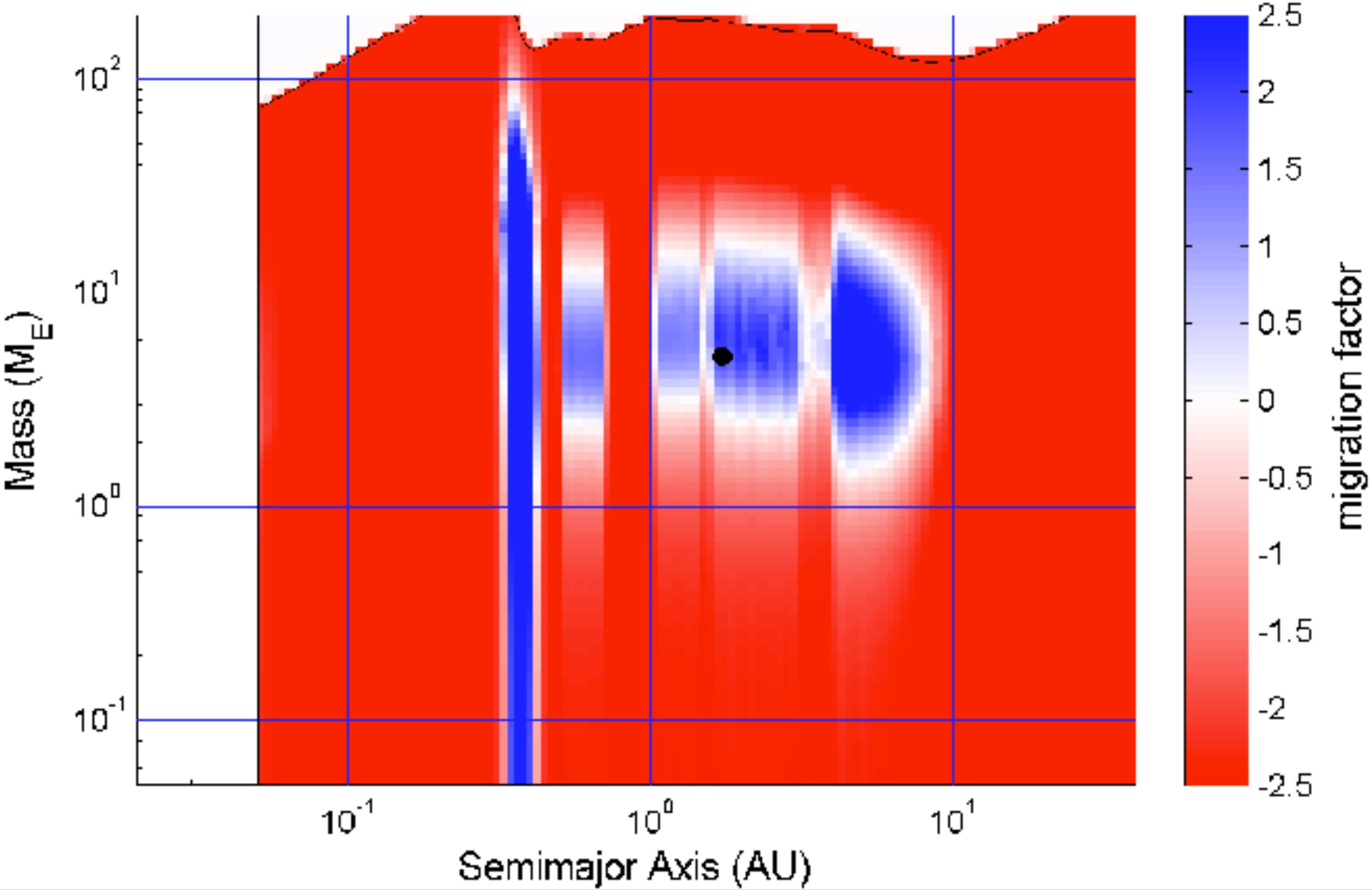
See Hellary & Nelson (2012), Coleman & Nelson (2014), Coleman & Nelson (2016a,b for more details)

Question: Can a planet formation scenario in which planetary embryos mutually collide, accrete planetesimals/boulders and migrate through type I & II, lead to systems of planets similar to those that have been observed.

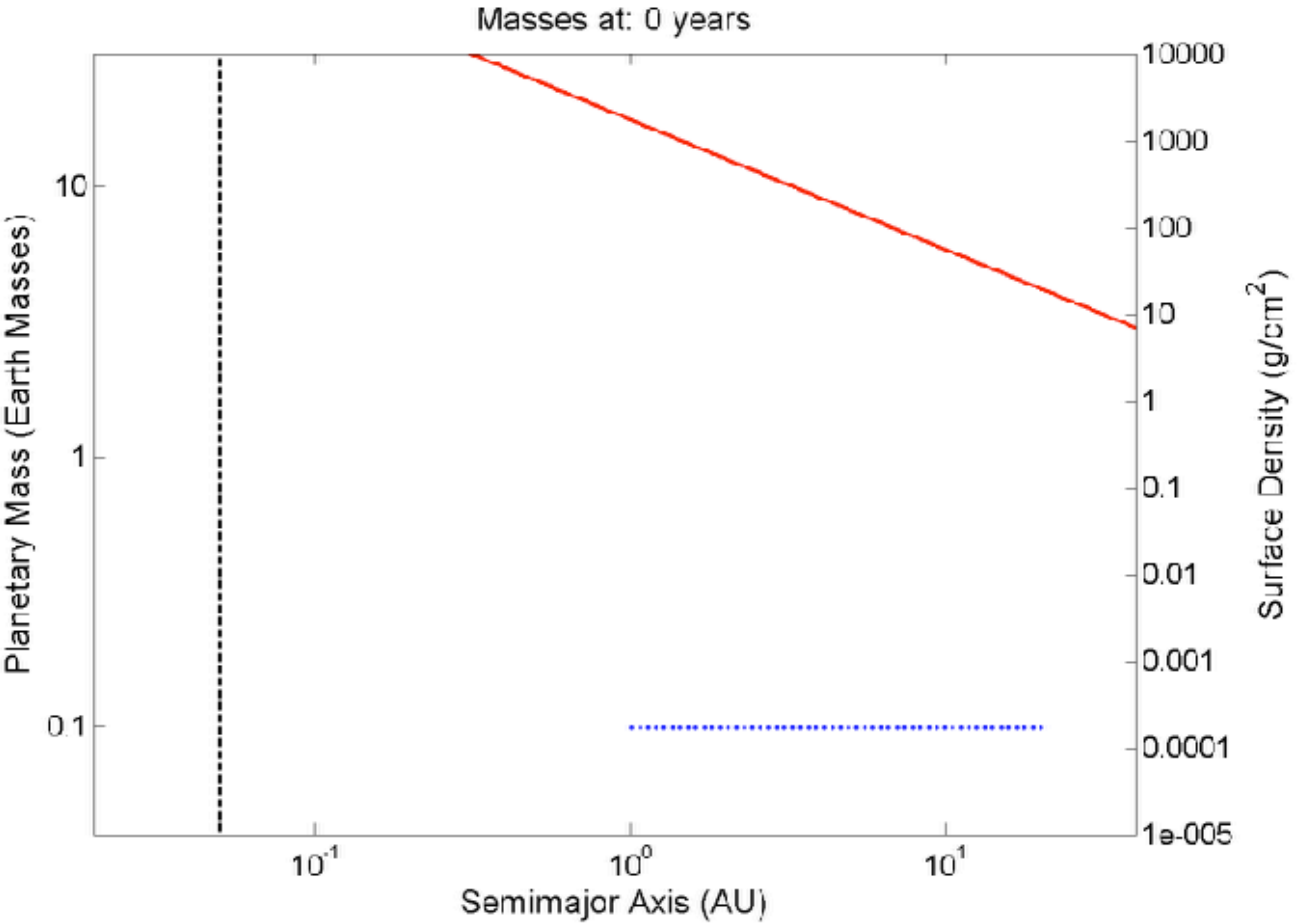
i.e. Can such a model produce the diversity of planets observed in the mass versus period diagram? Can such a model generate multiple systems of super-Earths as observed by Kepler and R.V. surveys?

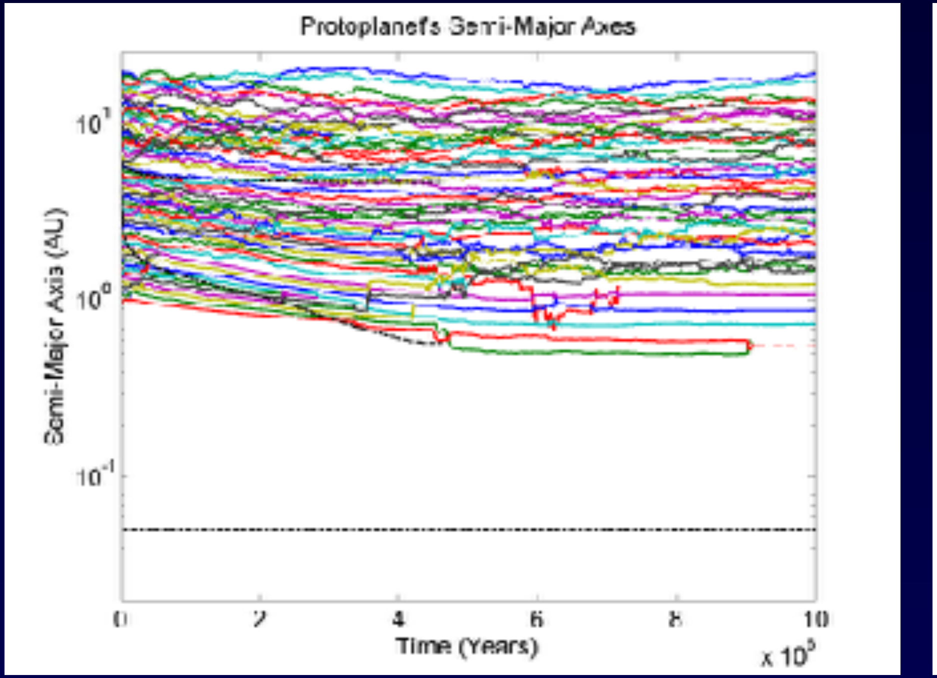
Evolution in smooth discs

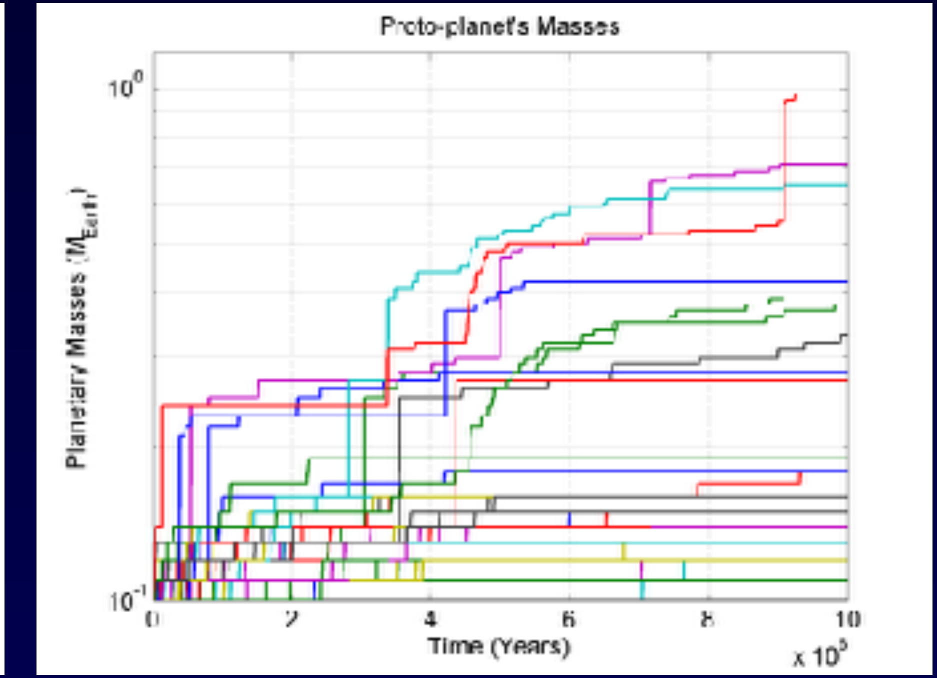
Migration contour plot at 100000 years



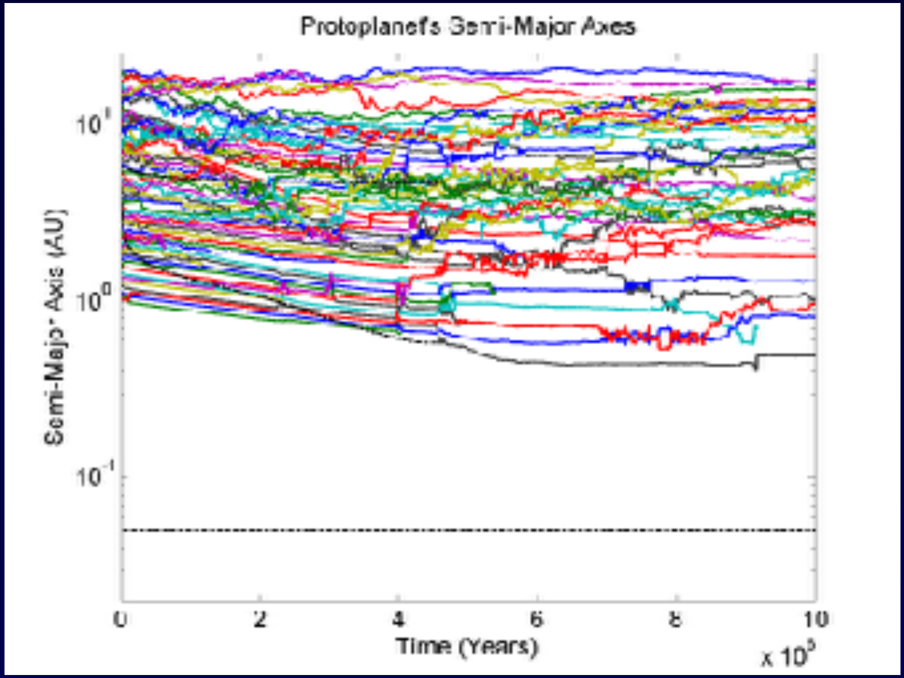
M_{disc}=1, [Fe/H]=2, R_{pl}=100 m

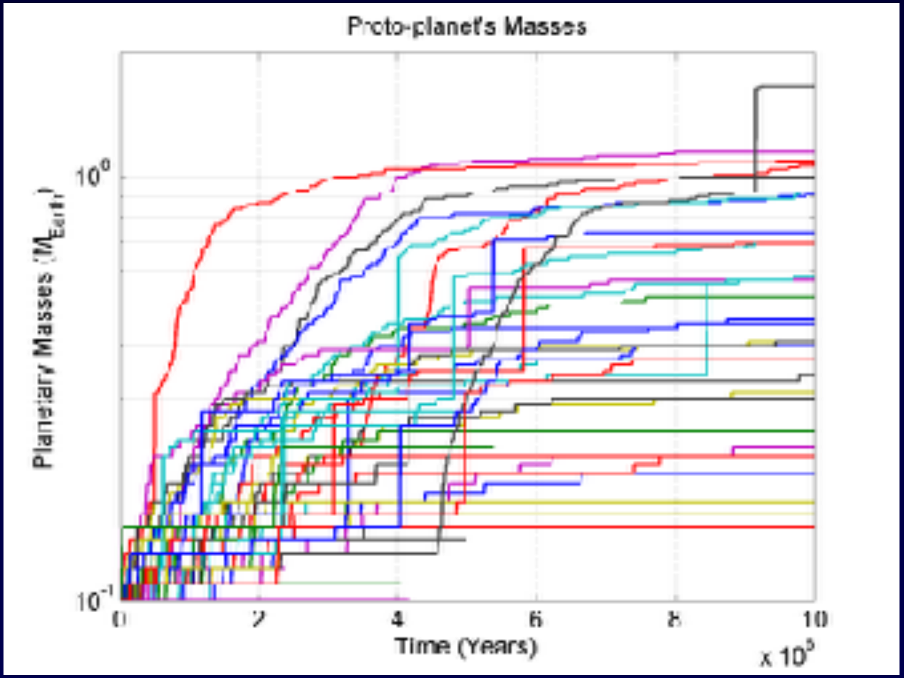




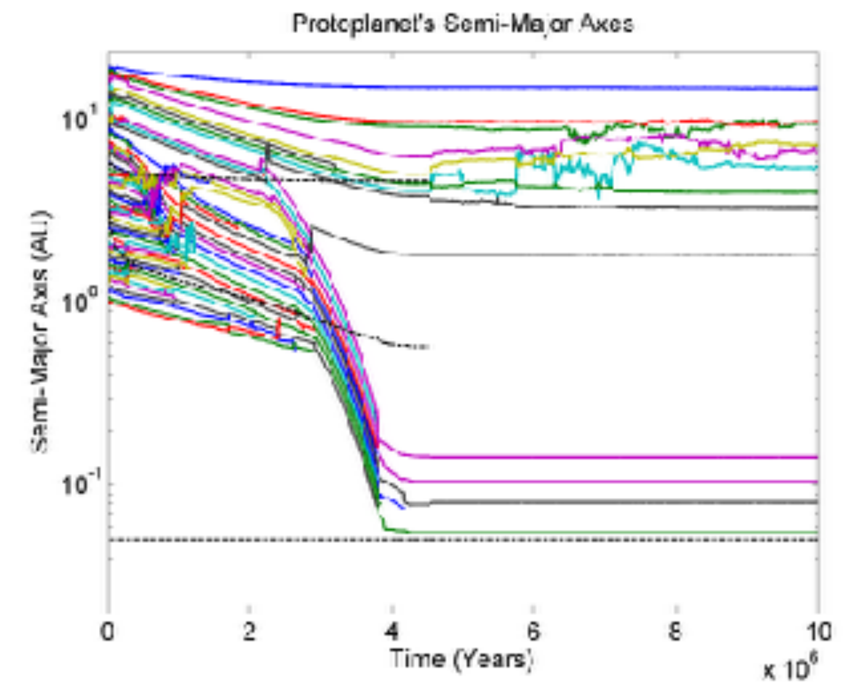


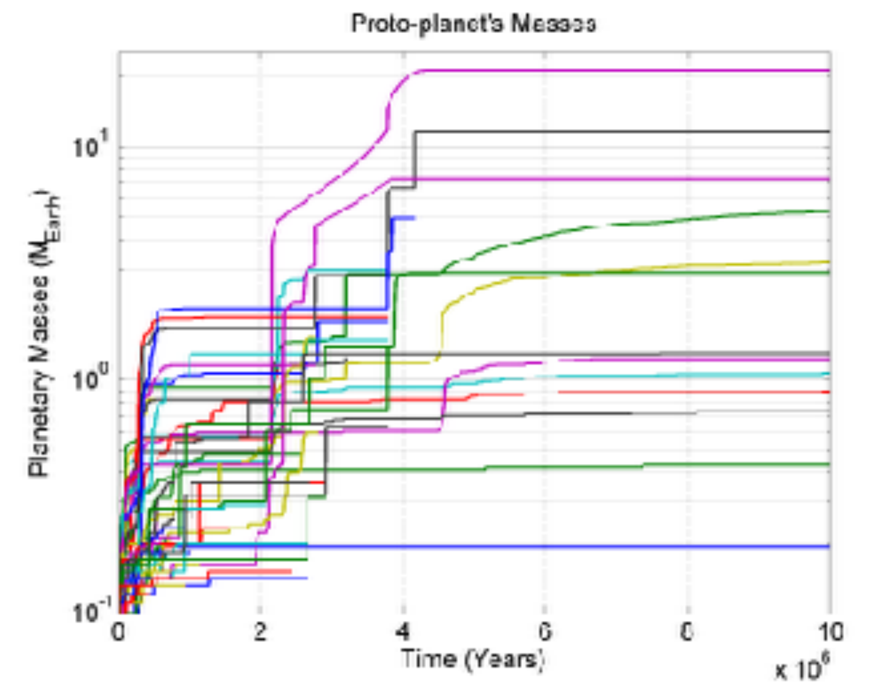
Disc mass = 1 x MMSN
Metallicity = 2 x solar
Planetesimal sizes = 10 km



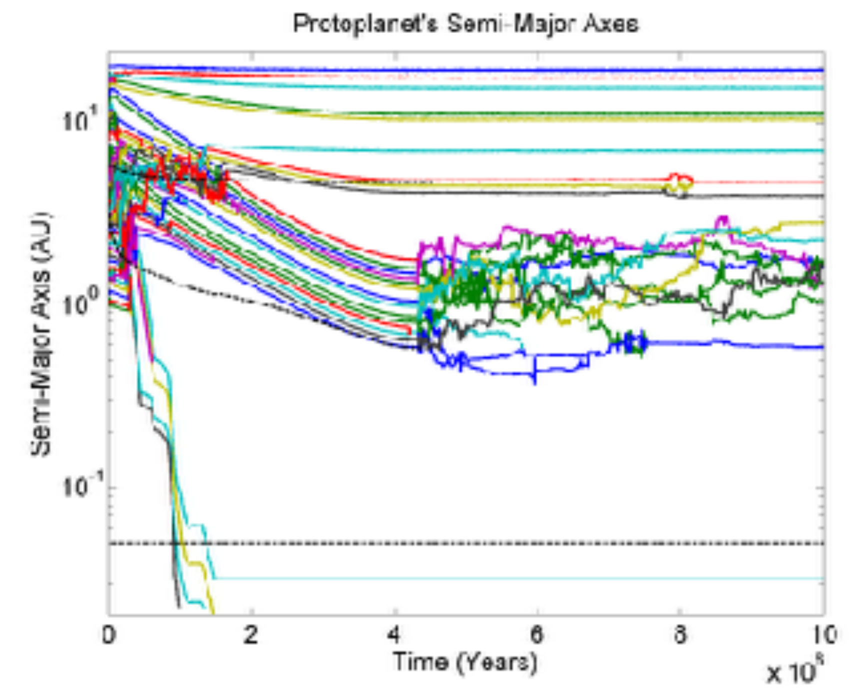


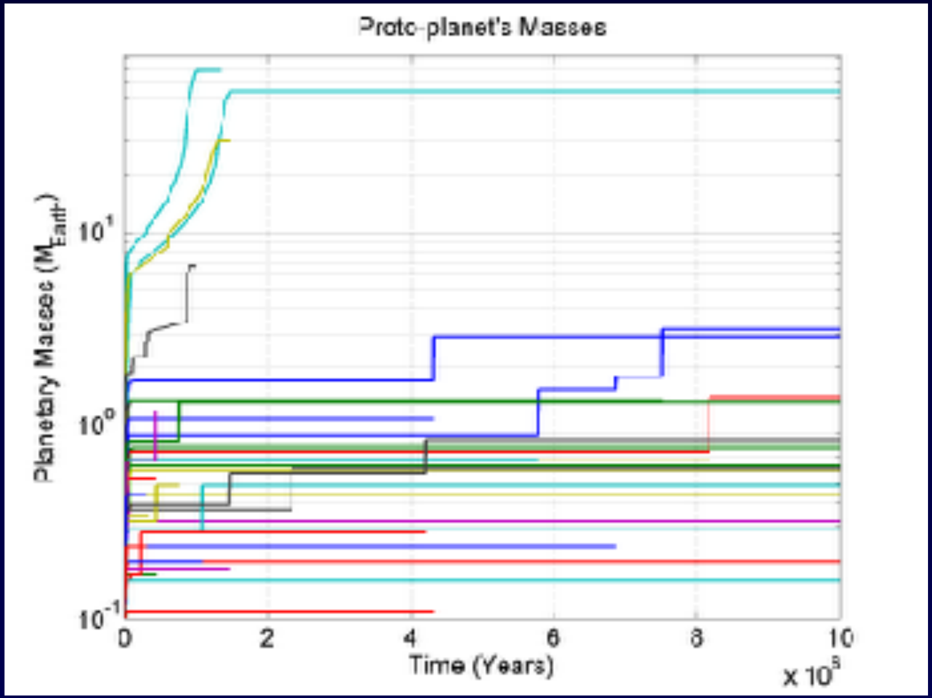
Disc mass = 1 x MMSN
Metallicity = 2 x solar
Planetesimal sizes = 1 km





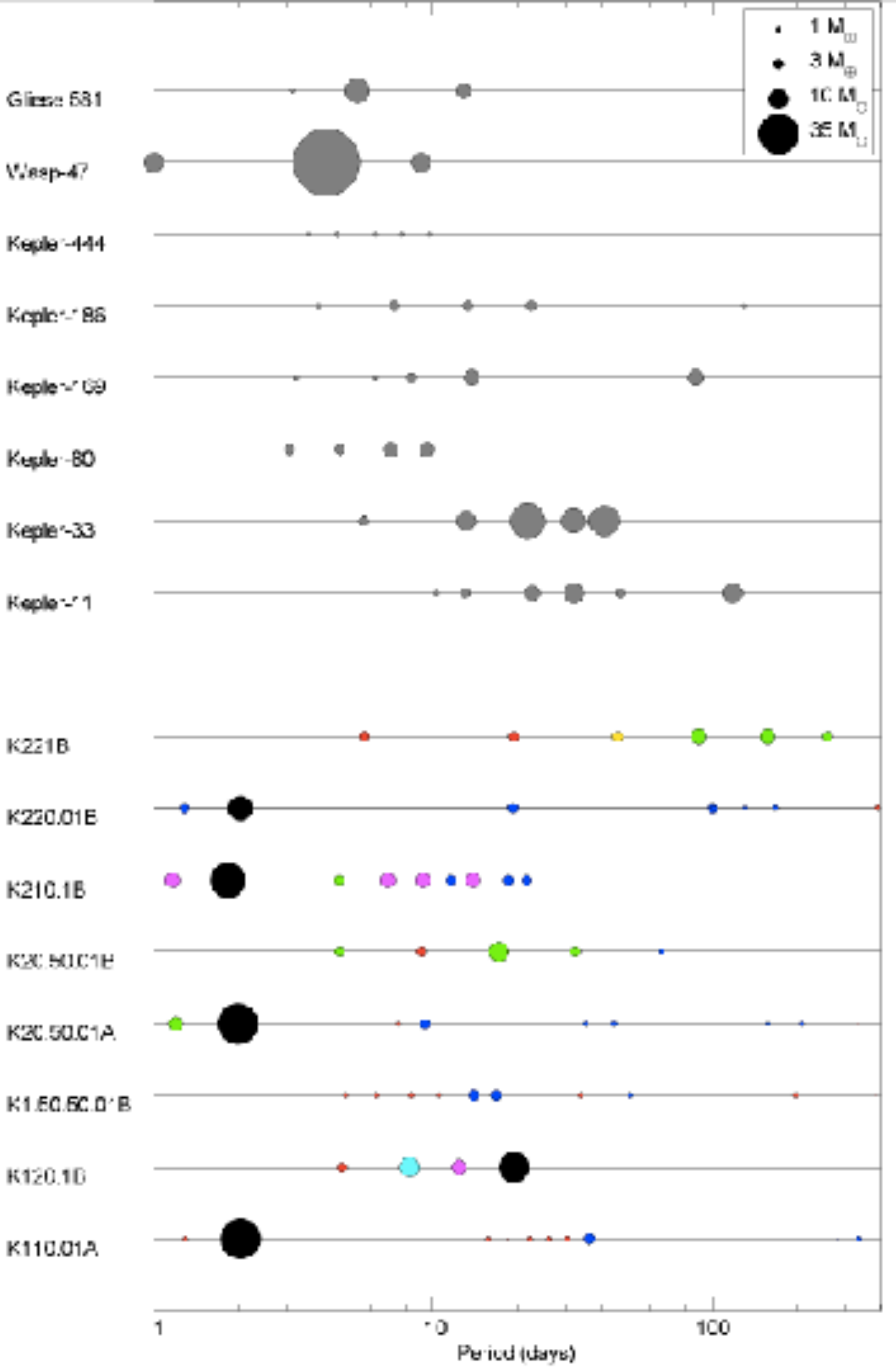
Disc mass = 1 x MMSN
Metallicity = 2 x solar
Planetesimal sizes = 100 m

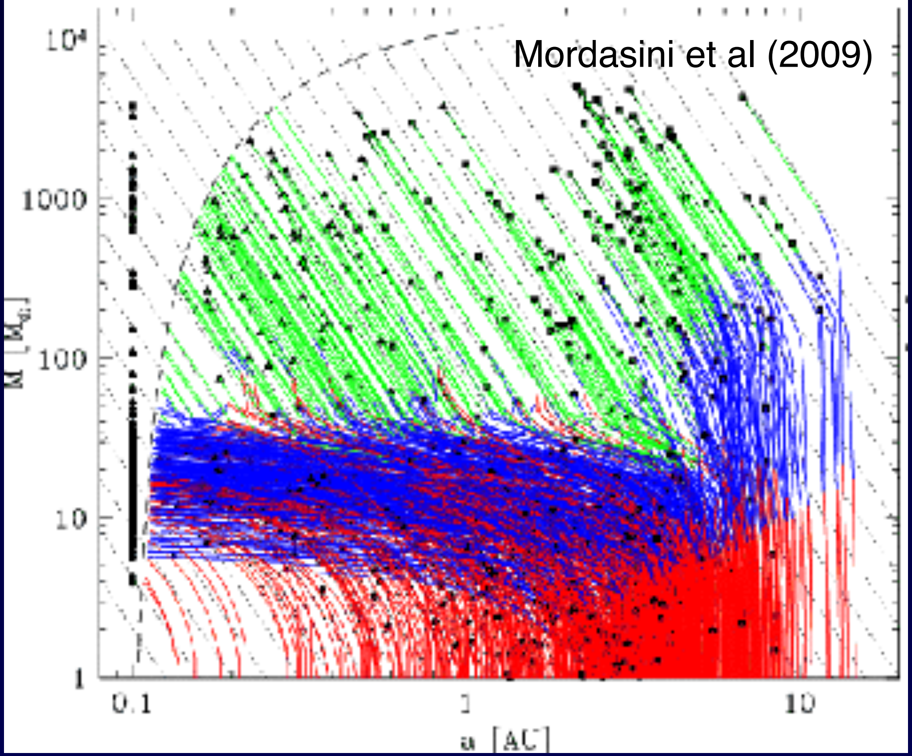


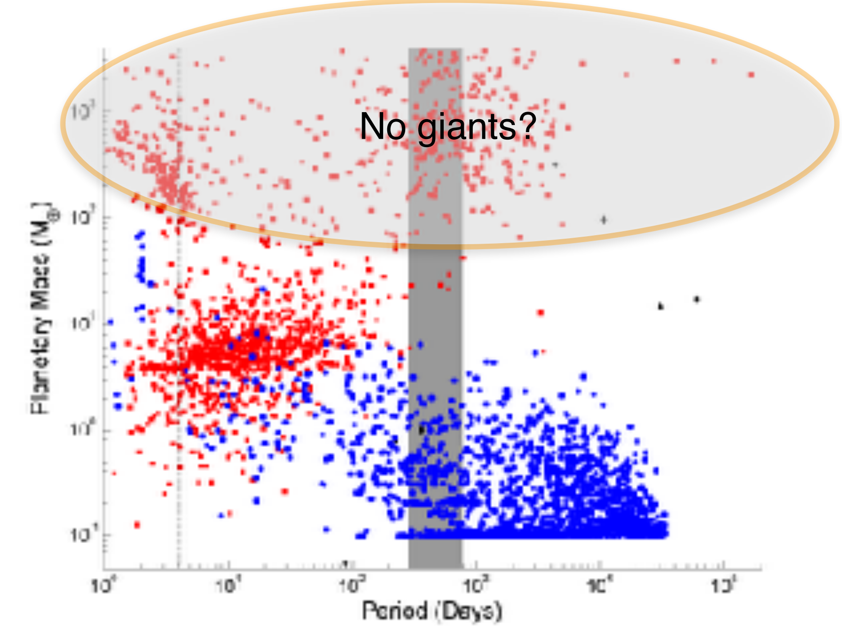


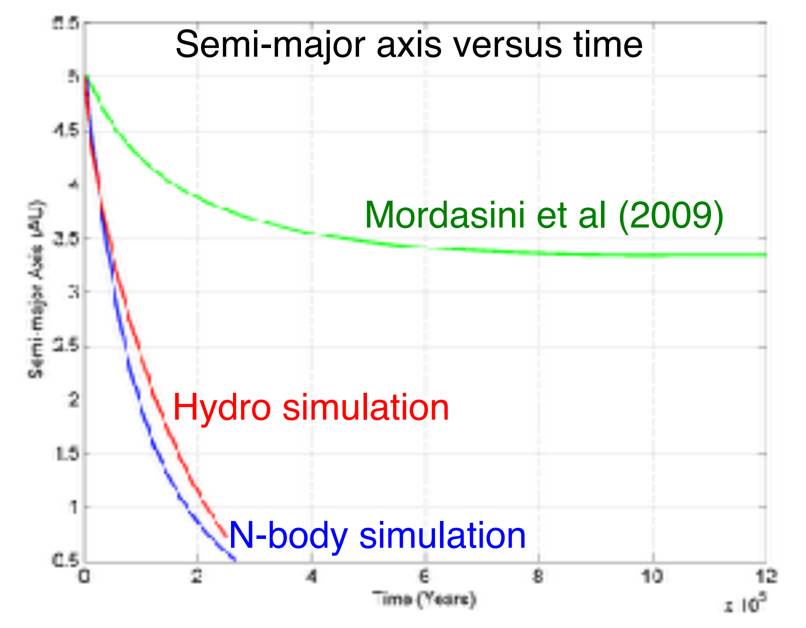
Disc mass = 1 x MMSN
Metallicity = 2 x solar
Planetesimal sizes = 10 m

Efficient growth and migration only occurs for small planetesimals and boulders for disc masses ~ MMSN

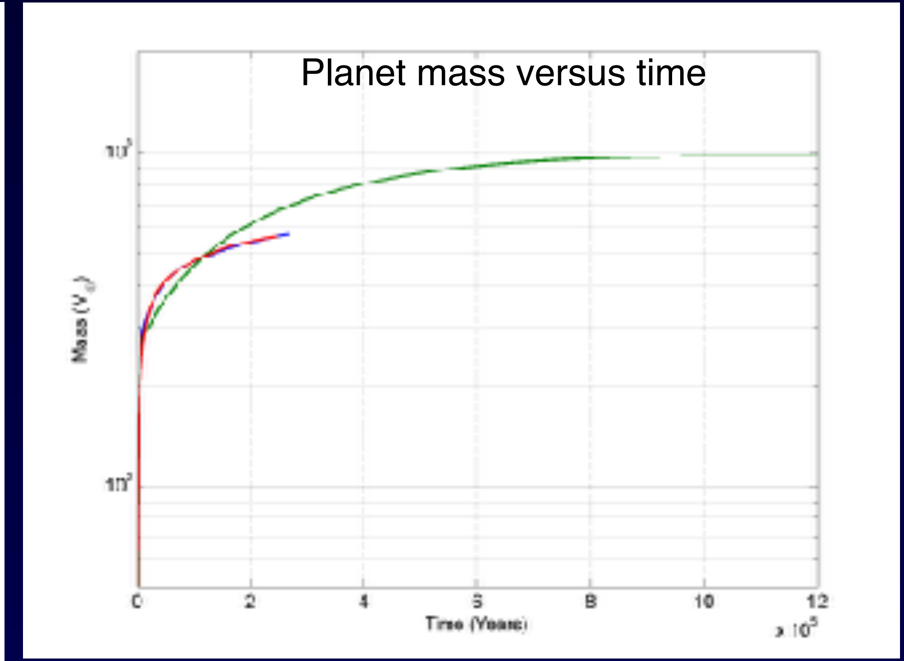

1 $M_\oplus$
3 $M_\oplus$
10 $M_\oplus$
35 $M_\oplus$
Gliese 581
Wasp-47
Kepler-444
Kepler-186
Kepler-169
Kepler-80
Kepler-33
Kepler-11
K221B
K220.01B
K210.1B
K20.50.01B
K20.50.01A
K1.50.50.01B
K120.1B
K110.01A
1
10
100
Period (days)


Mordasini et al (2009)

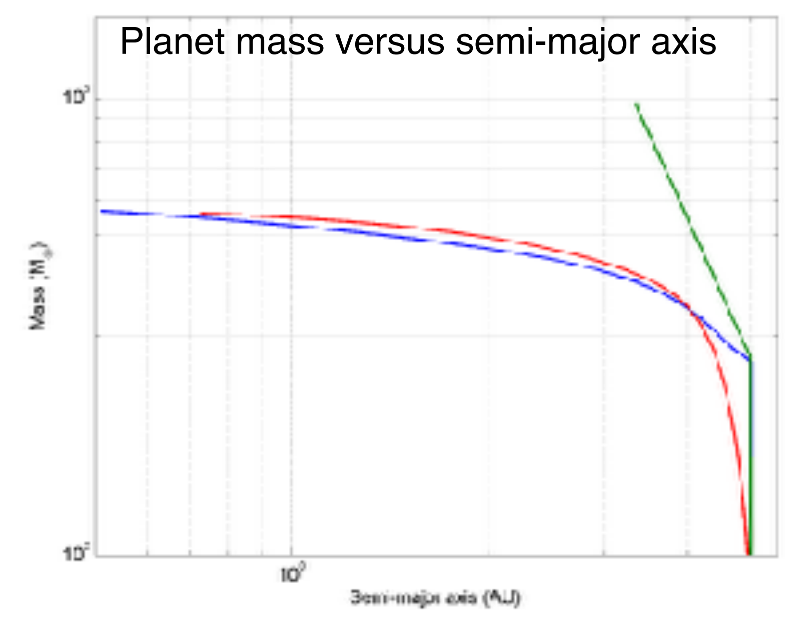

No giants?



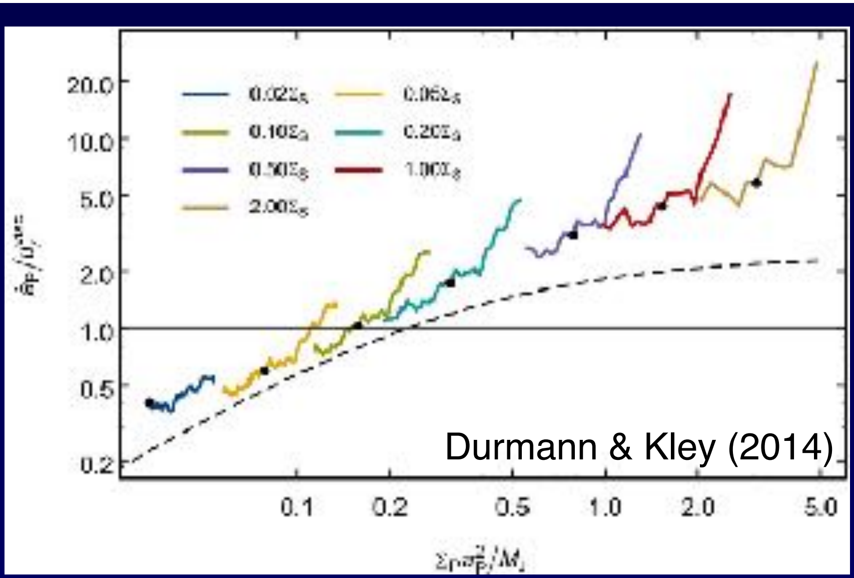
Semi-major axis versus time



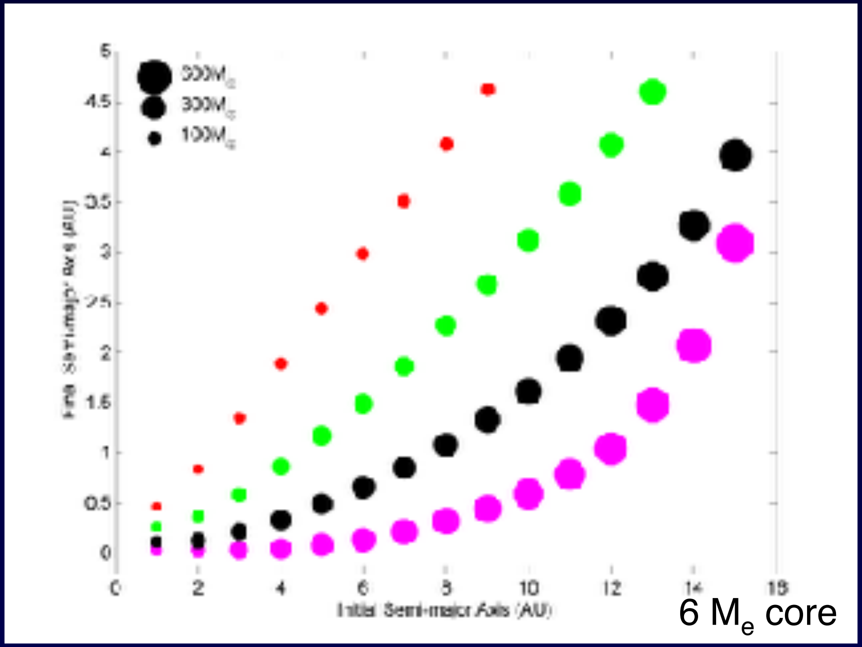
Planet mass versus time



Planet mass versus semi-major axis



Durmann & Kley (2014)



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?

Evolution in radially structured discs

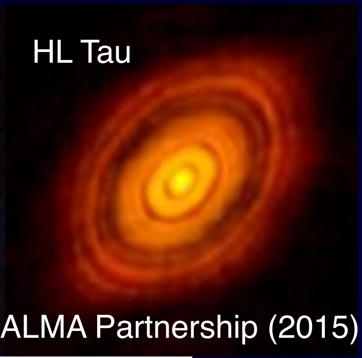
Radial variations in viscosity create planet traps where corotation torque prevents type I migration

Zonal flows observed in MHD simulations of disc turbulence (Papaloizou & Steinacker 2003; Johansen et al 2009; Bai & Stone 2014, Kunz & Lesur 2014; Bethune et al 2016).

Discs observed to be radially structured (e.g. ALMA partnership 2015; Zhang et al 2016)

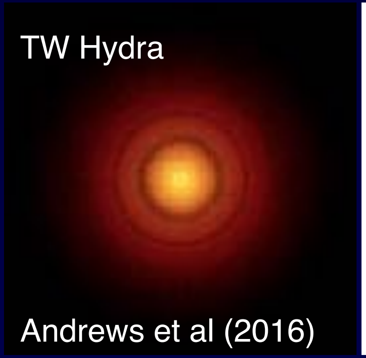
A simple toy model:

Allow viscous stress to vary by 50% at local radii
- create systems of *zonal flows* with finite lifetimes



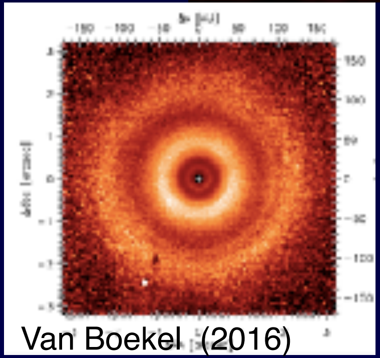
HL Tau

ALMA Partnership (2015)

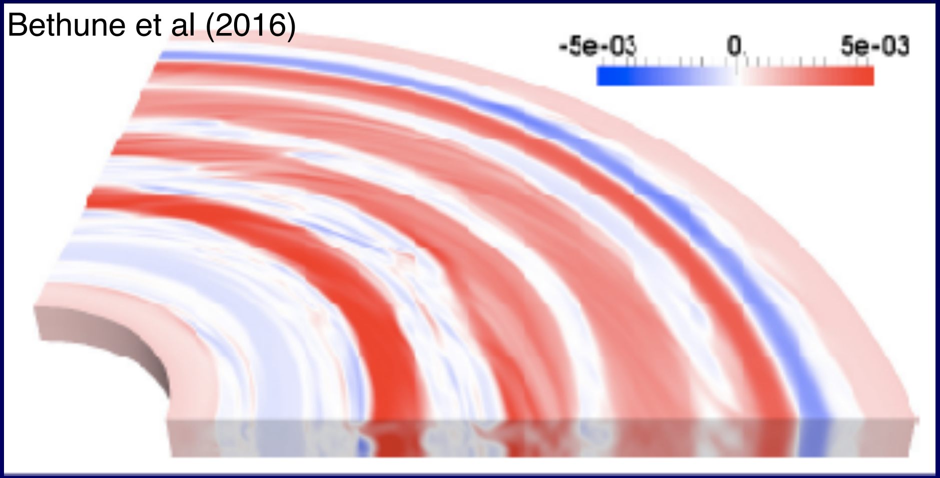


TW Hydra

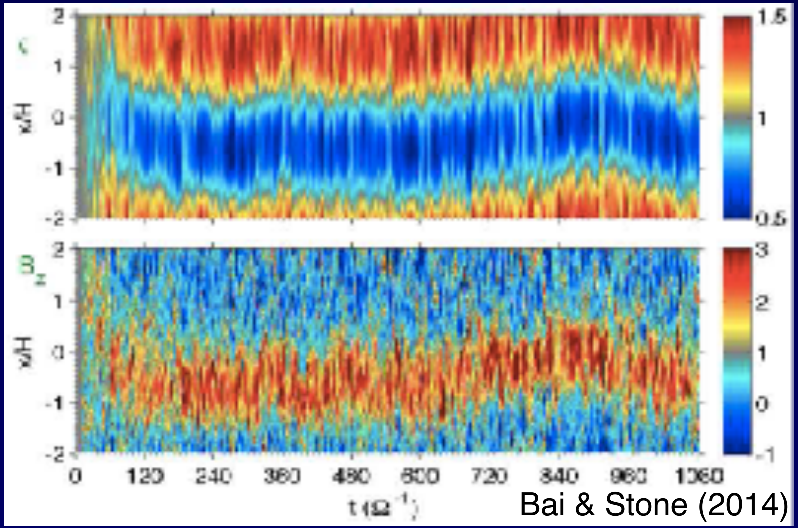
Andrews et al (2016)



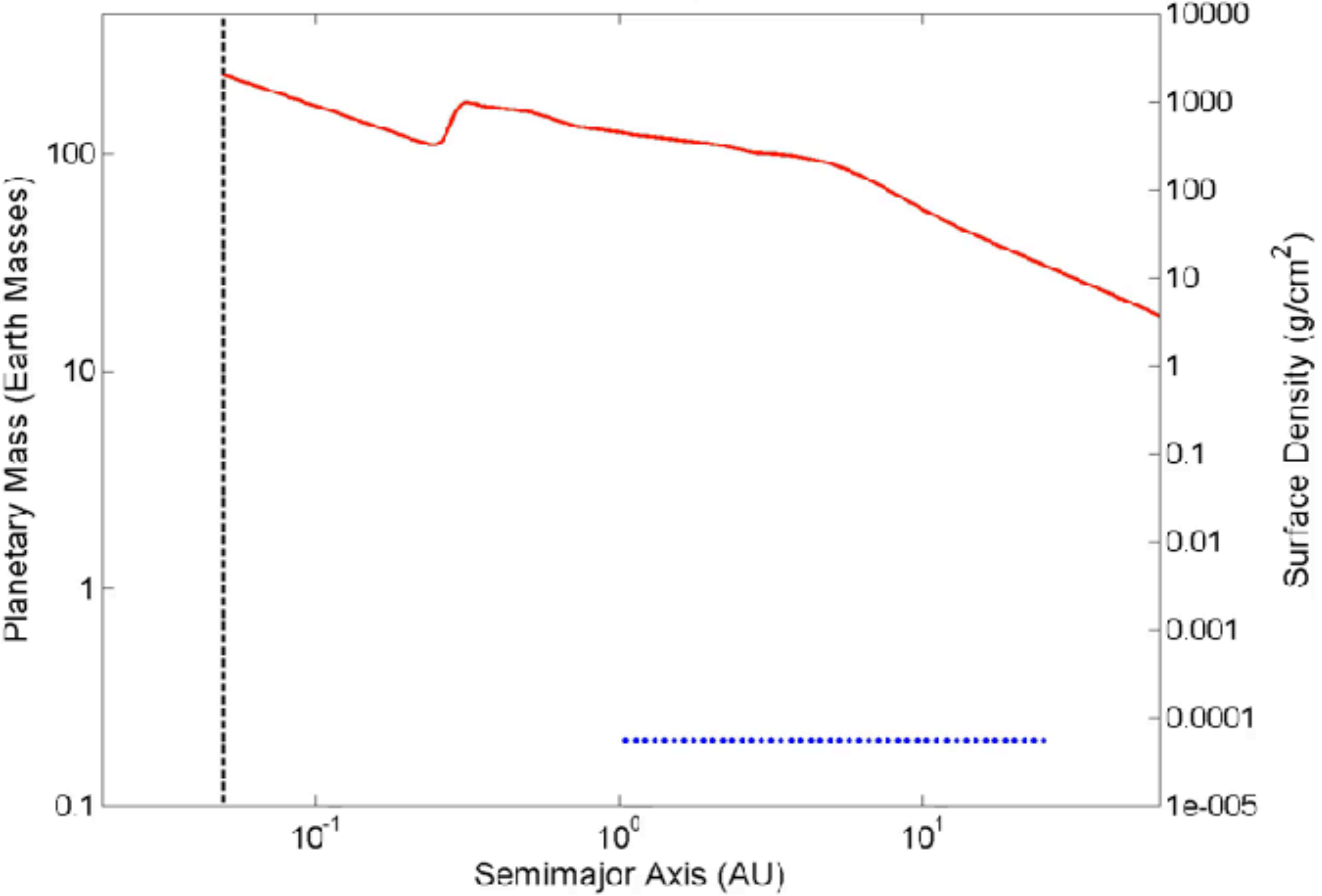
Van Boekel (2016)



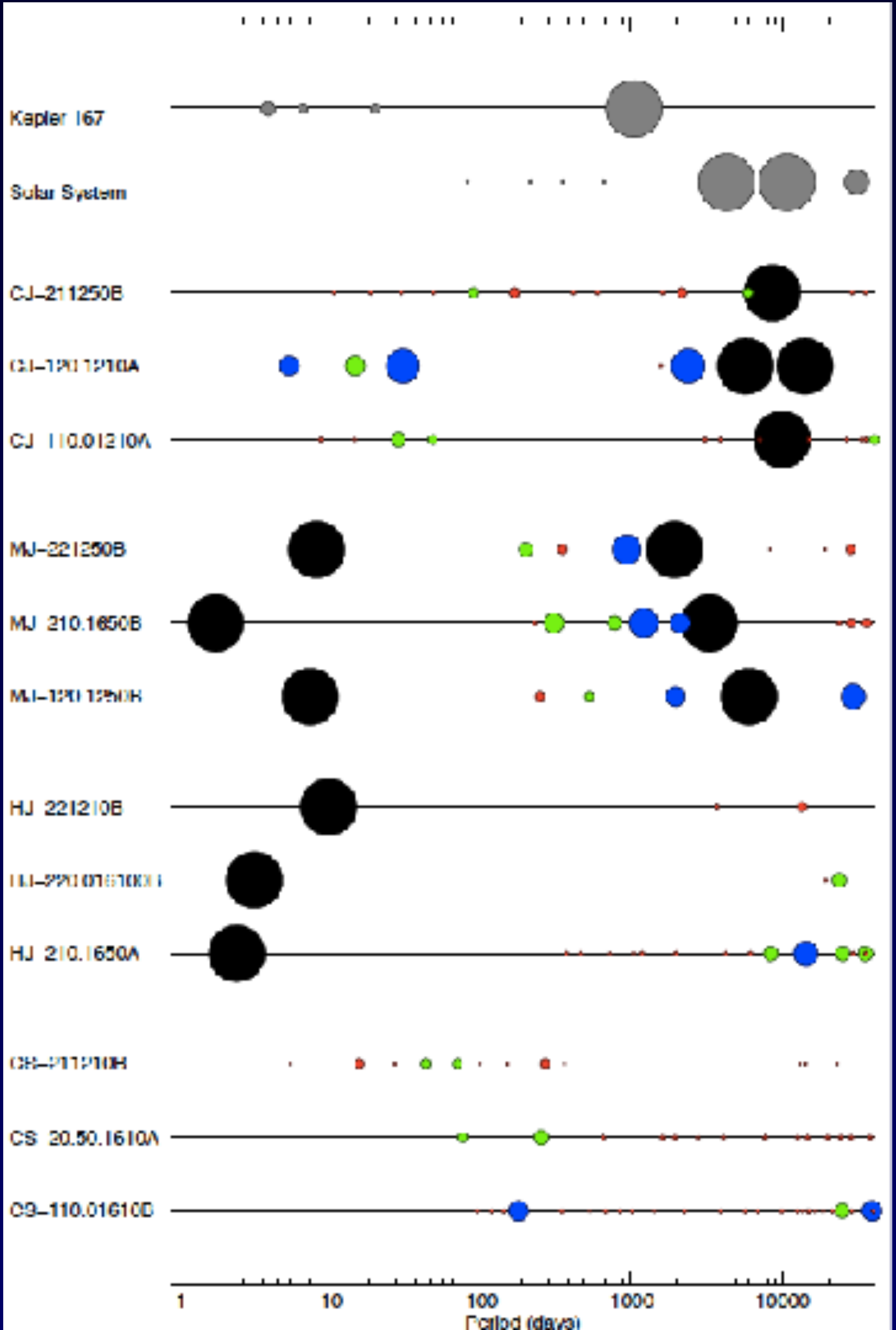
Bethune et al (2016)

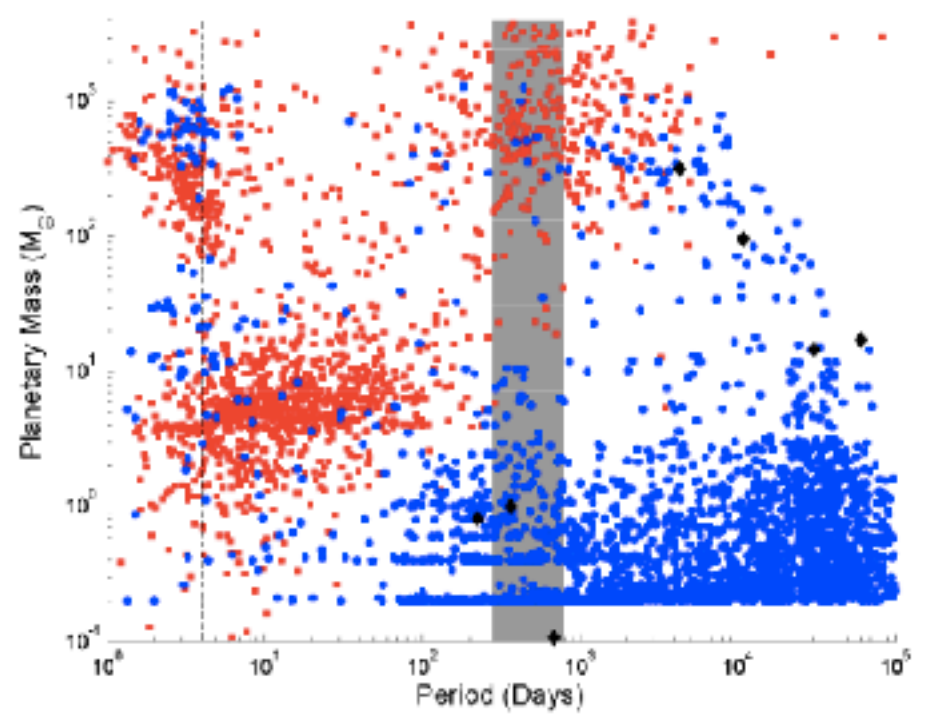


Bai & Stone (2014)

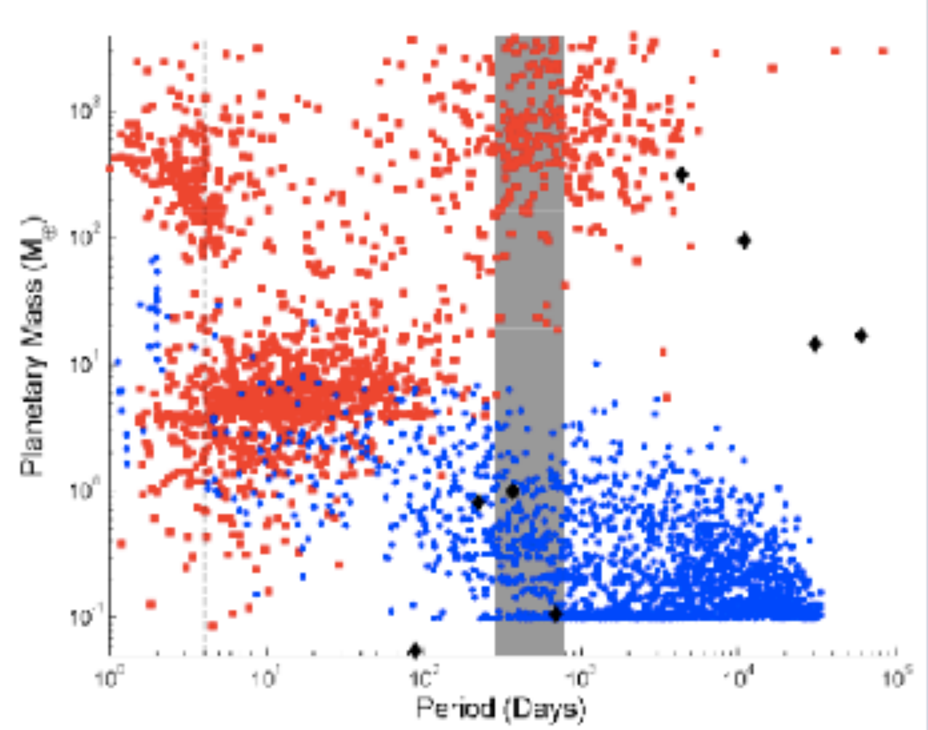


Masses at: 0 years


Kepler 167
Solar System
CJ–211250B
CJ–120.1210A
CJ–110.01210A
MJ–221250B
MJ–210.1650B
MJ–120.1250B
HJ–221210B
HJ–220.0161000
HJ–210.1650A
CS–211210B
CS–20.50.1610A
CS–110.01610B
1
10
100
1000
10000
Period (days)



Radially-structured disc



Smooth disc

Question: Can a planet formation scenario in which planetary embryos mutually collide, accrete planetesimals/boulders and migrate through type I & II, lead to systems of planets similar to those that have been observed.

i.e. Can such a model produce the diversity of planets observed in the mass versus period diagram? Can such a model generate multiple systems of super-Earths as observed by Kepler and R.V. surveys?

Answer: Yes.

But.

Radial structuring of the disc is required for giant planet formation in viscous disc models.

Resonances are much more common outcome in simulations than observed
- require resonances to be unstable in the long term (see Izidoro et al 2017)