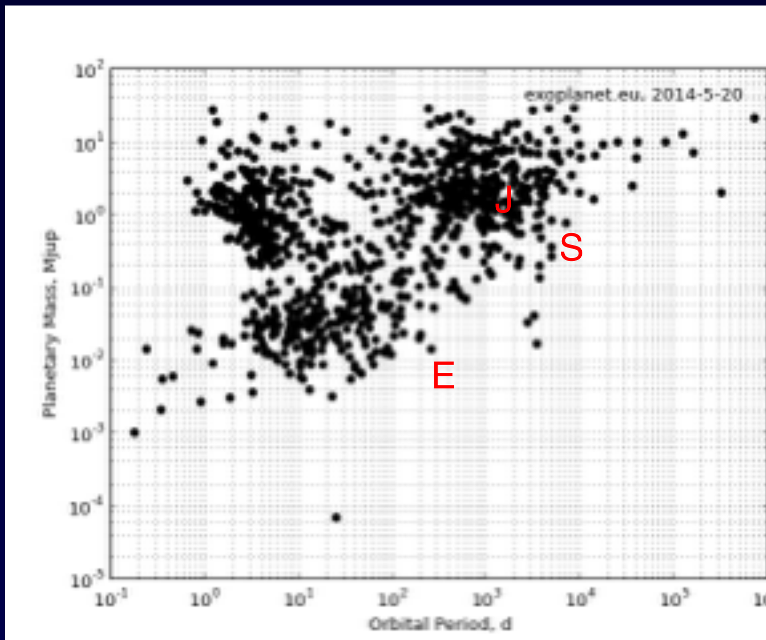
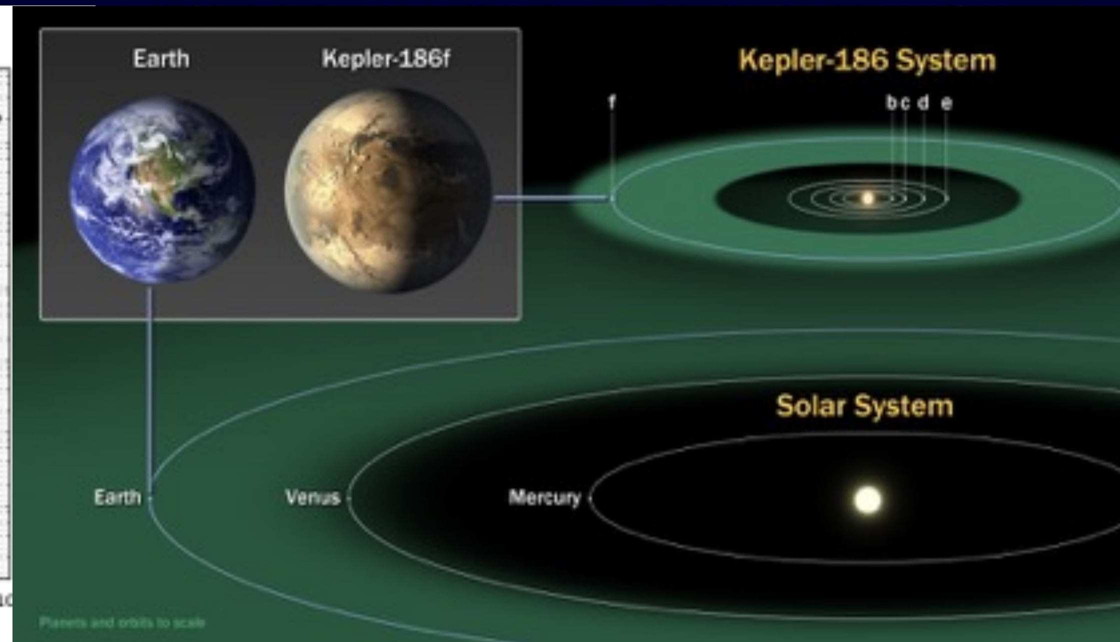
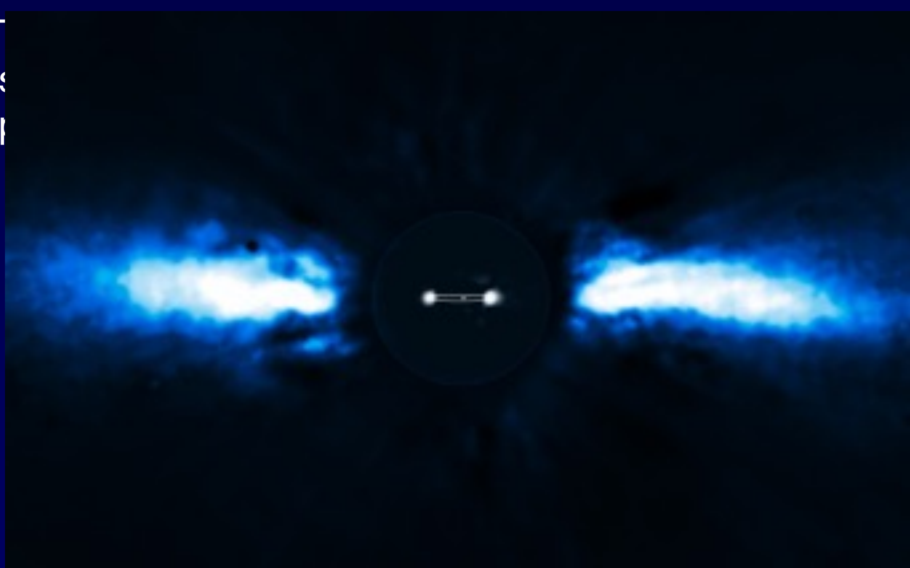
N-body simulations of planet formation: oligarchic growth of planetary systems in thermally evolving protoplanetary discs

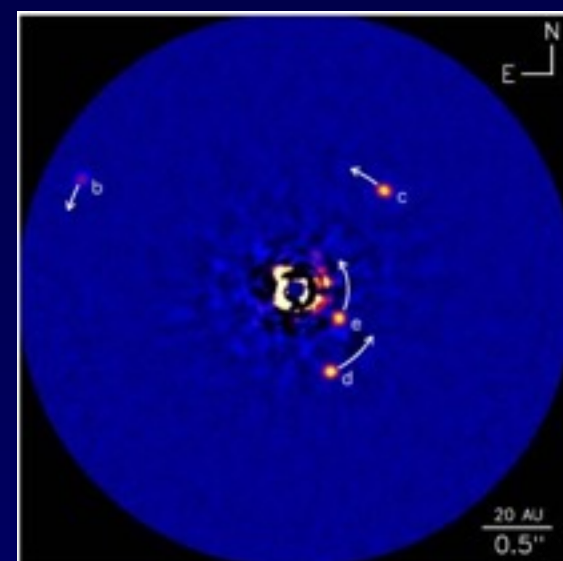
Richard Nelson
Queen Mary, University of London
Gavin Coleman (QMUL), Stephen Fendyke (QMUL)

Queen Mary
University of London


exoplanet.eu, 2014-5-20
Planetary Mass, Mjup
Orbital Period, d
J
S
E


Earth
Kepler-186f
Kepler-186 System
f
b c d e
Solar System
Earth
Venus
Mercury




N
E
b
c
e
d
20 AU
0.5"

The traditional core accretion scenario

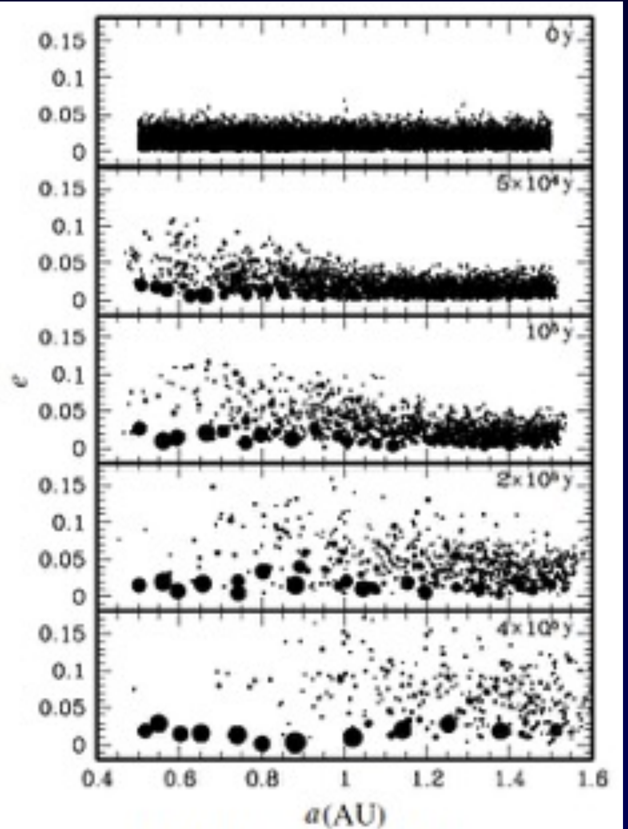
• Formation of planetesimals followed by runaway growth to form planetary embryos

• Oligarchic/orderly growth of planetary embryos

• Giant impacts between embryos form inner terrestrial planets

• Massive cores form beyond the ice line capable of accreting gas envelopes ➔ ice-giant and gas-giant planets

One major flaw is that this picture ignores the role of planetary migration



(Kokubo + Ida 2002)

Question

Can the oligarchic growth picture, combined with a self-consistent disc model and the most up-to-date prescriptions for planet migration, lead to systems of planets that look like those which have been observed?

N-body simulations

N-body simulations with migration, collisional growth and gas accretion onto planetary cores
(Hellary & Nelson 2012, Coleman & Nelson 2014)

Model ingredients

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

• Self-consistent thermally evolving 1D viscous disc model with stellar irradiation and dispersal through a photoevaporative disc wind (Dullemond et al 2011)

• Type I migration with corotation torques (Paardekooper et al 2011, Fendyke & Nelson 2014), and transition to type II migration when gap forms (Lin & Papaloizou 1986)

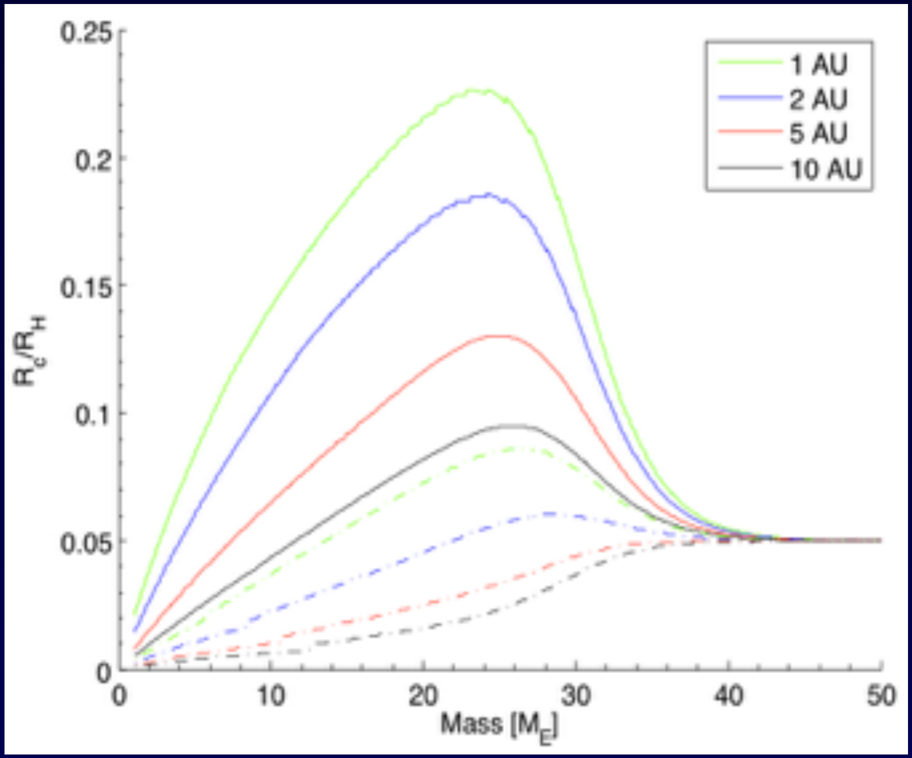
• Gas settling onto planetary cores – enhanced planetesimal capture
(Inaba & Ikoma 2003)

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

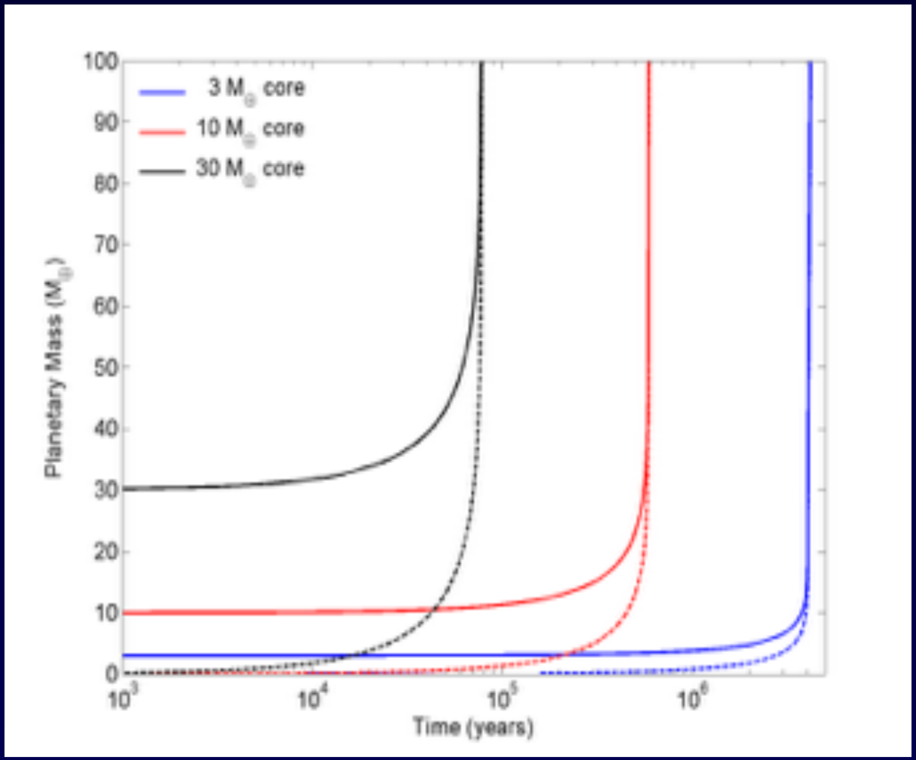
• Simple chemical model that tracks ice-lines and planetary compositions through chemical tagging (Oberg et al 2012)

Variation of parameters:

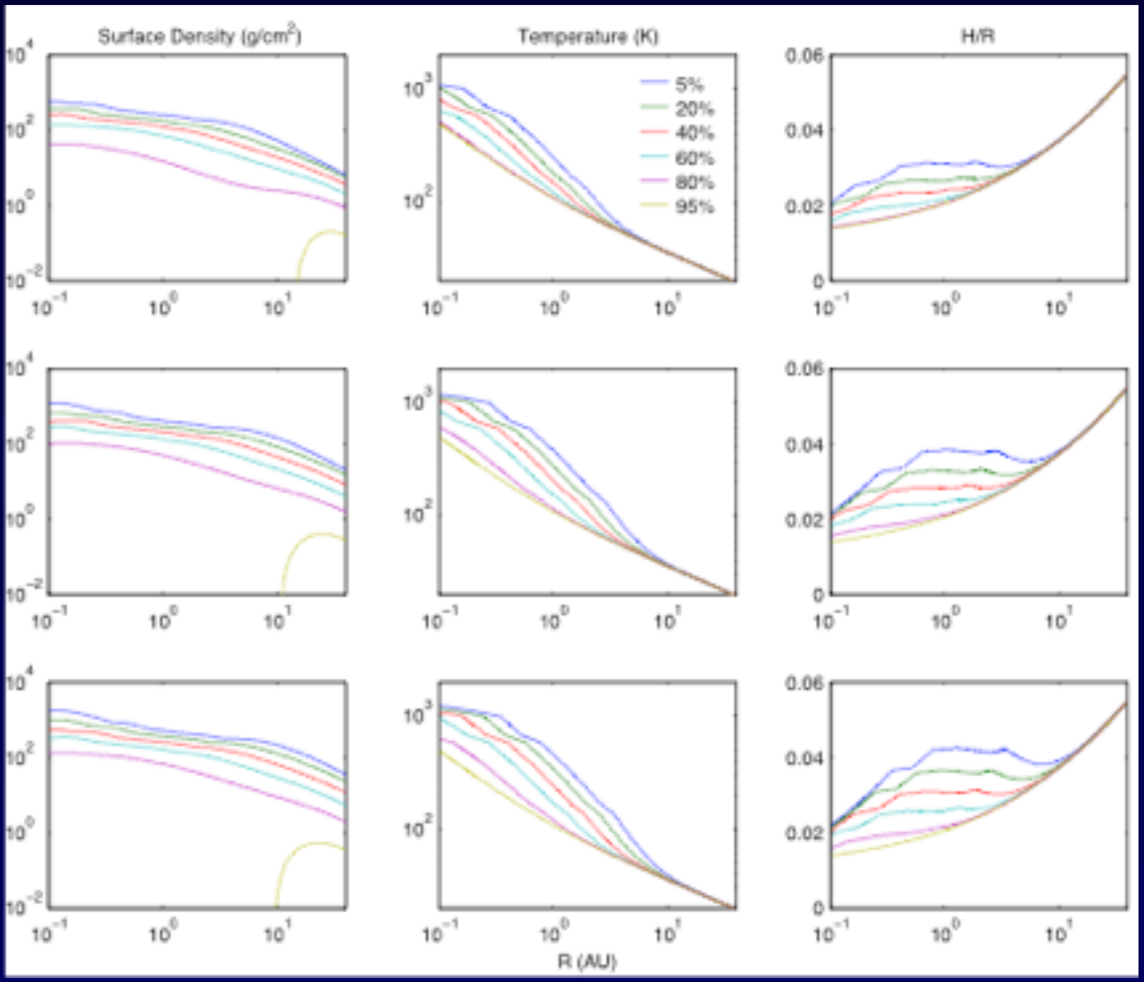
Disc mass (1 – 5 MMSN)
Solids-gas ratio (1 or 2 x solar)
Planetesimal radii (1 or 10 km)



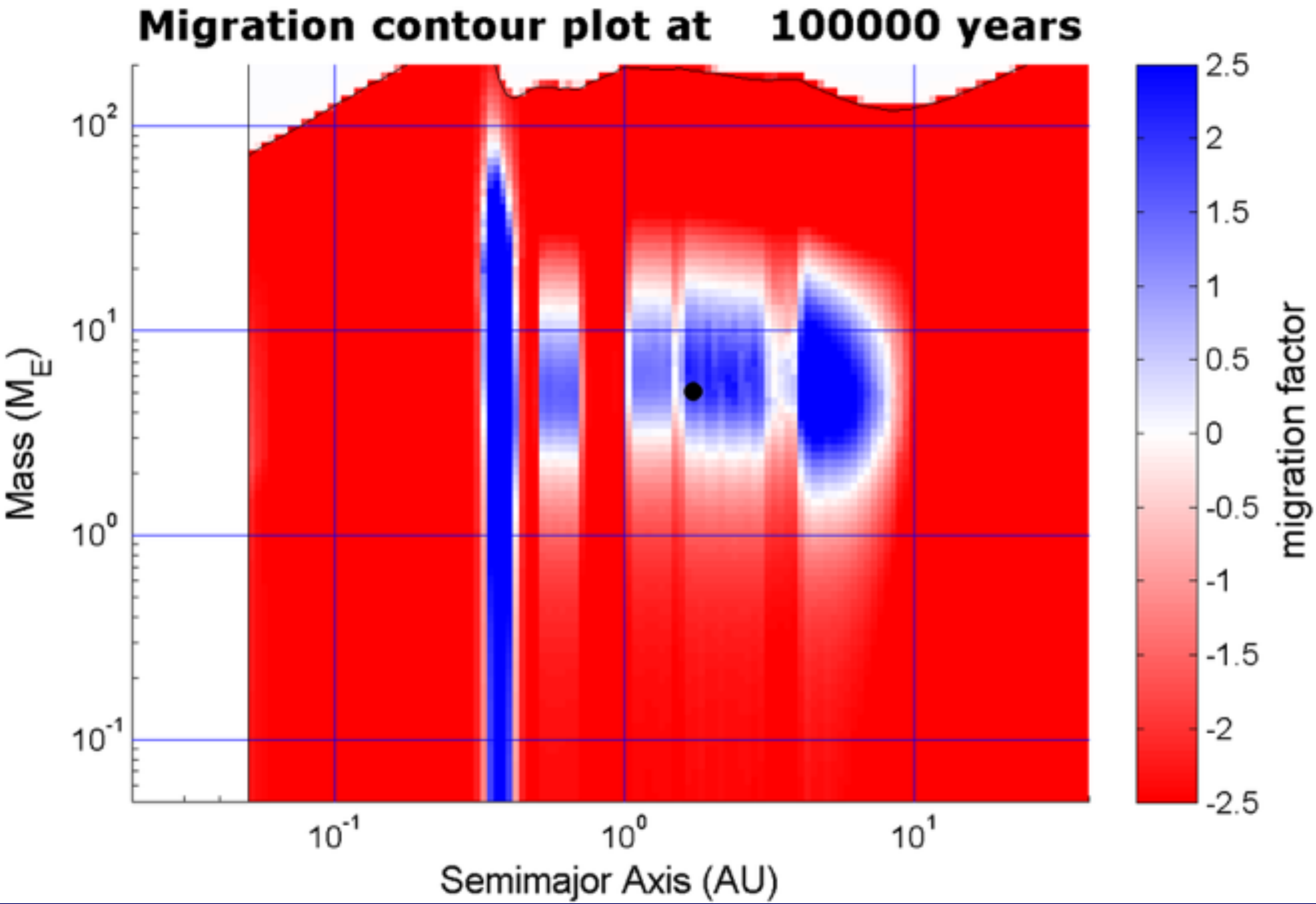
Planetesimal capture radius
(Inaba et al 2003)

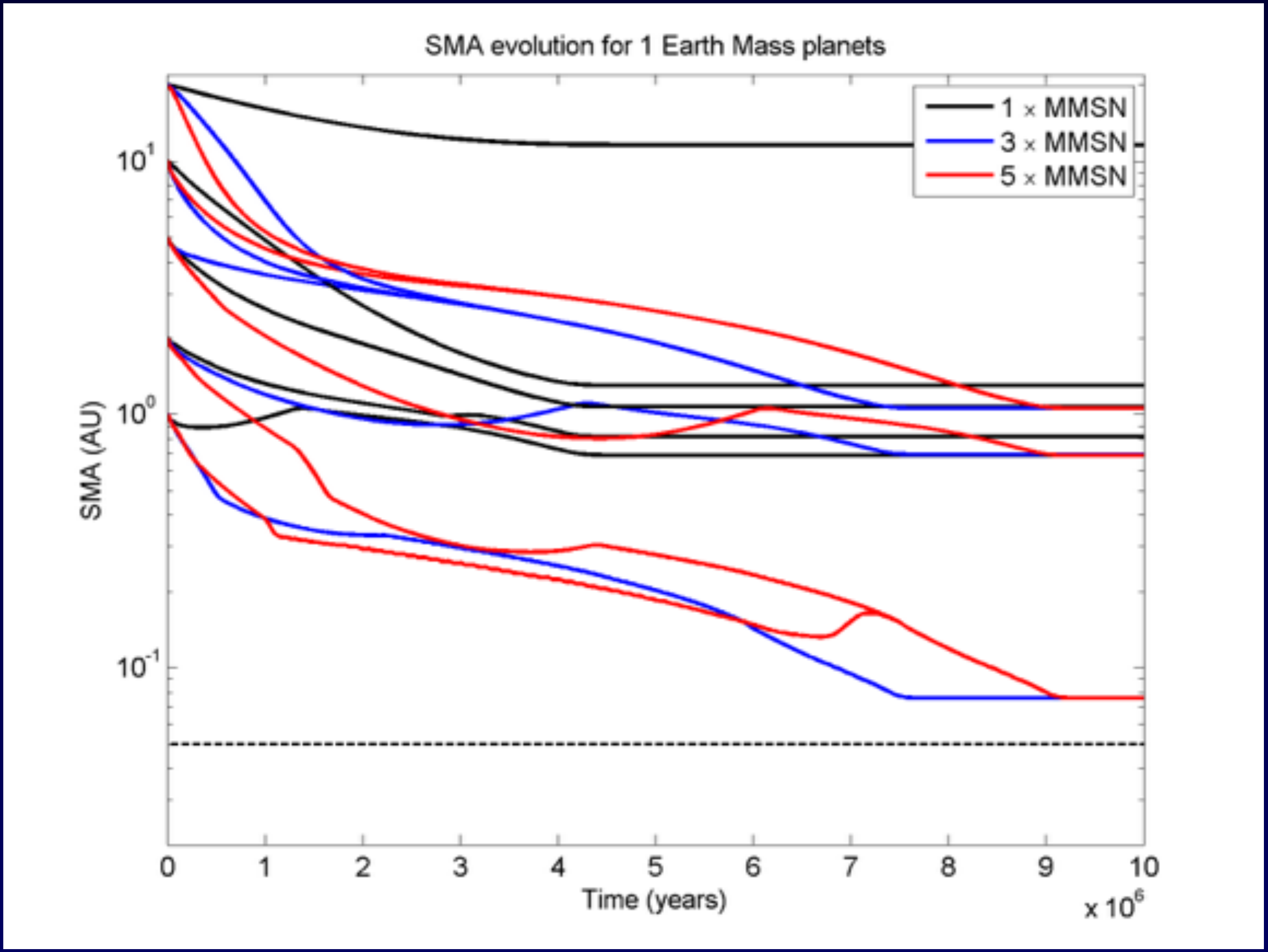


Gas accretion onto cores
(Movshovitz et al 2010)

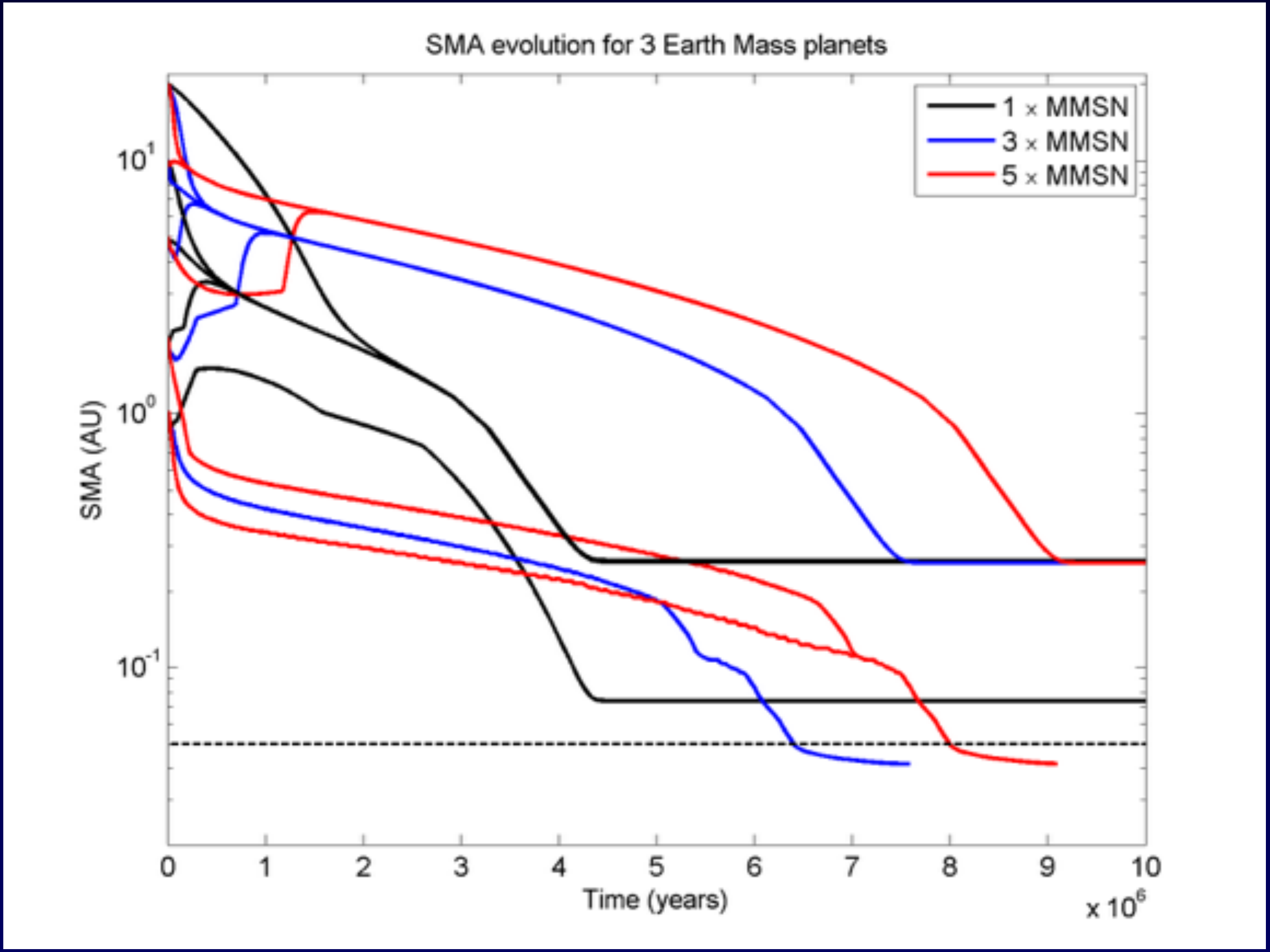


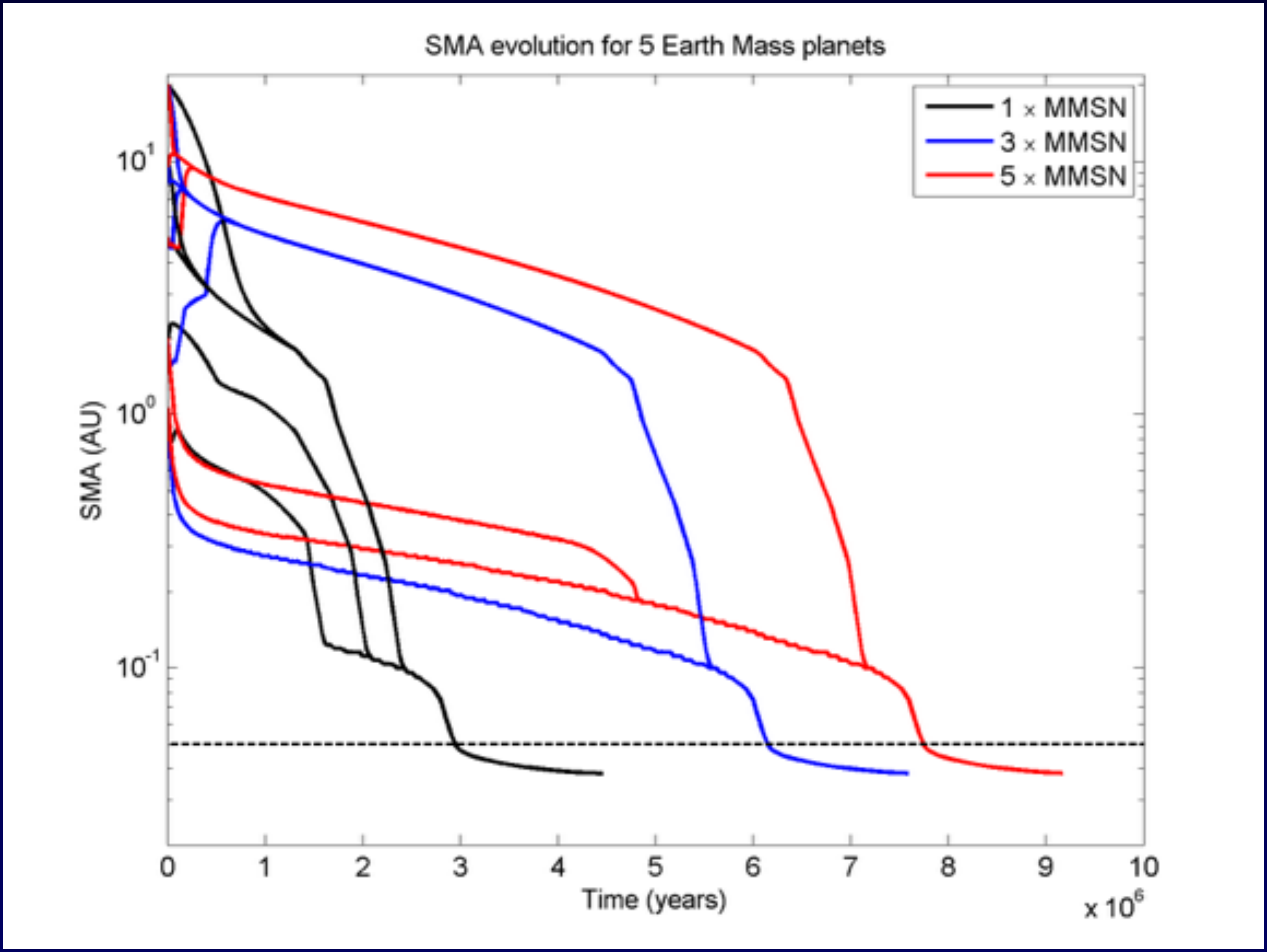
Evolution of viscous disc model

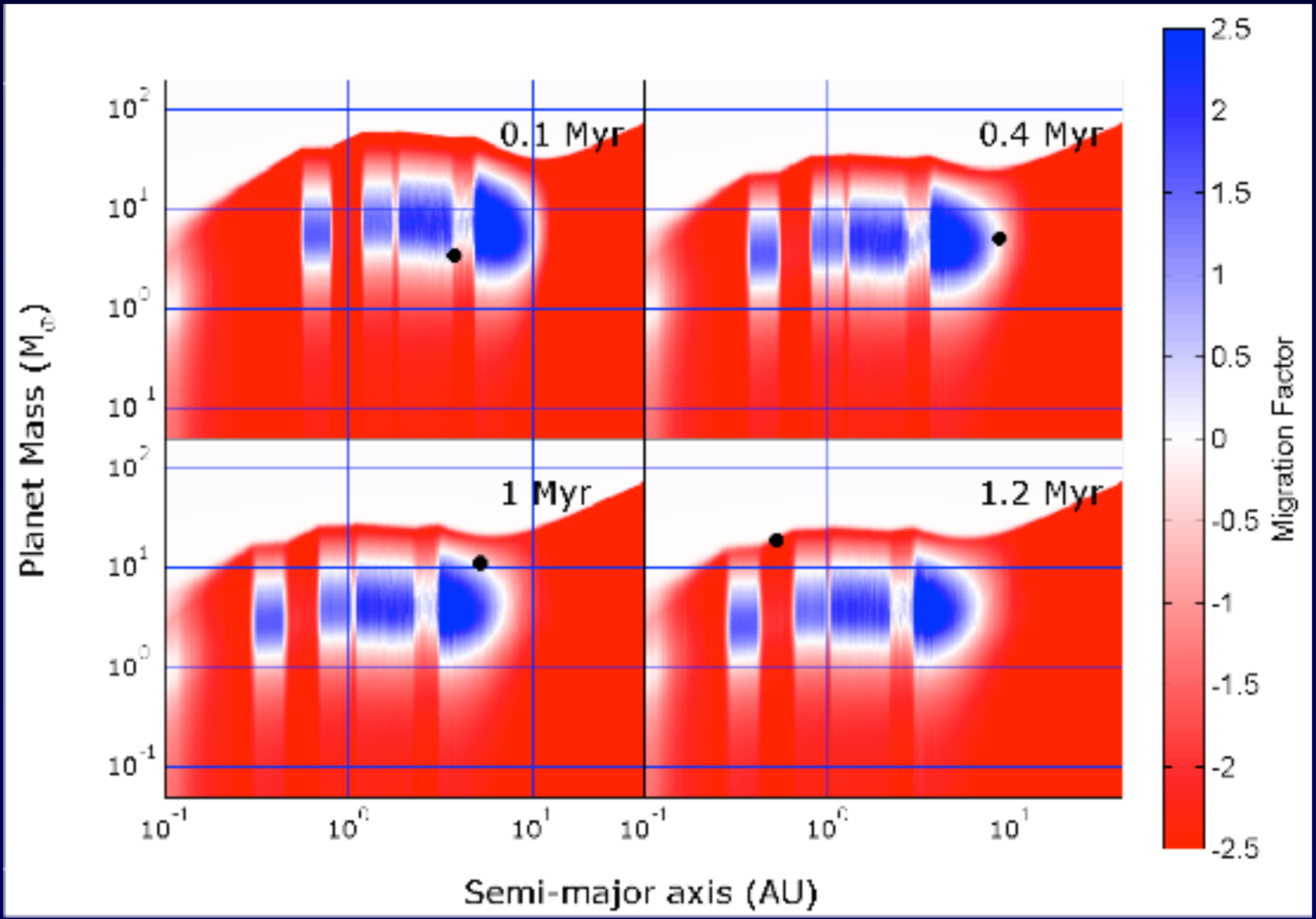

Migration contour plot at 100000 years
Mass (M_E)
10^2
10^1
10^0
10^-1
10^-1
10^0
10^1
Semimajor Axis (AU)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
migration factor



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

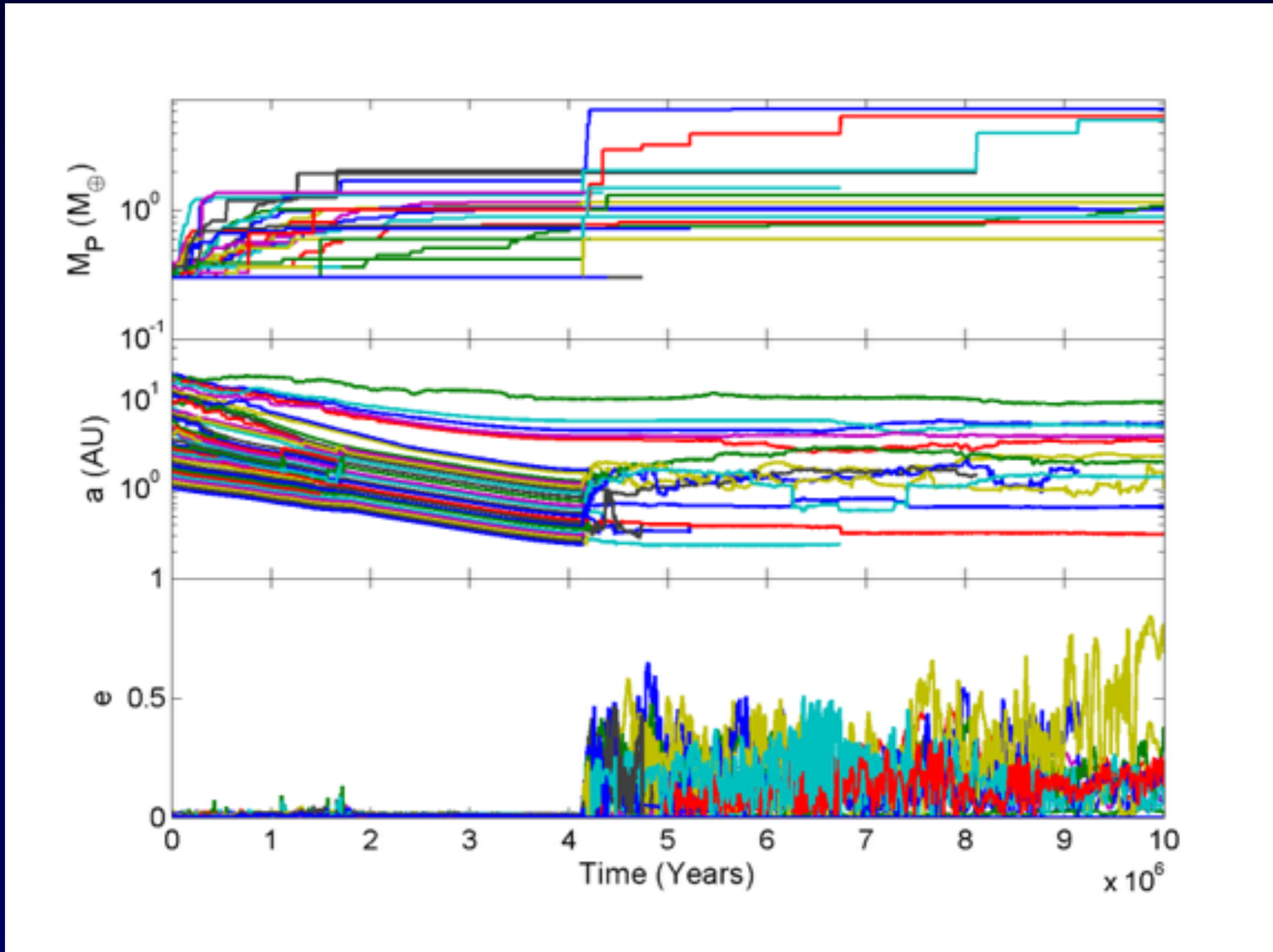

SMA evolution for 3 Earth Mass planets
1 × MMSN
3 × MMSN
5 × MMSN
SMA (AU)
10^1
10^0
10^{-1}
0
1
2
3
4
5
6
7
8
9
10
Time (years)
x 10^6


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

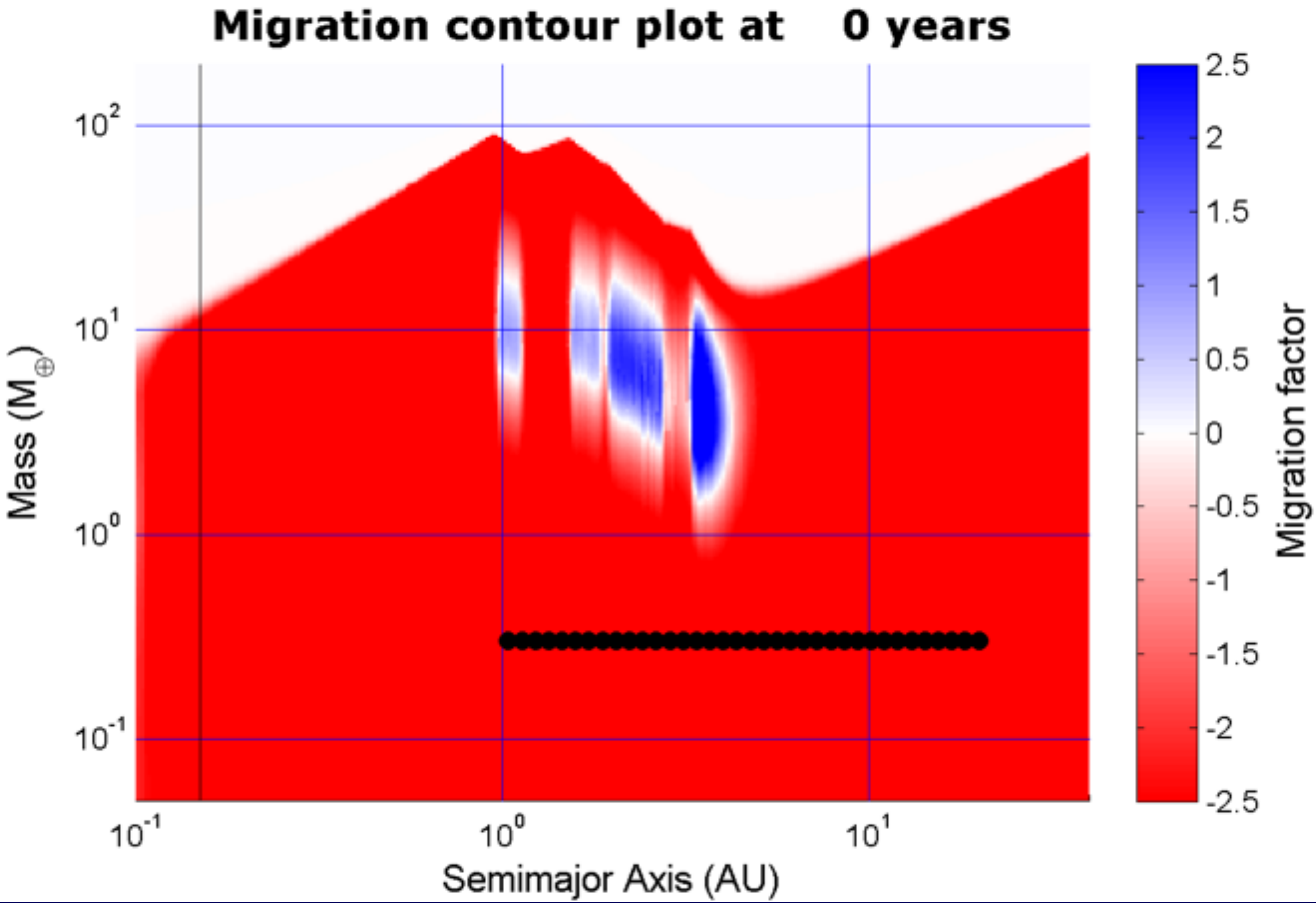


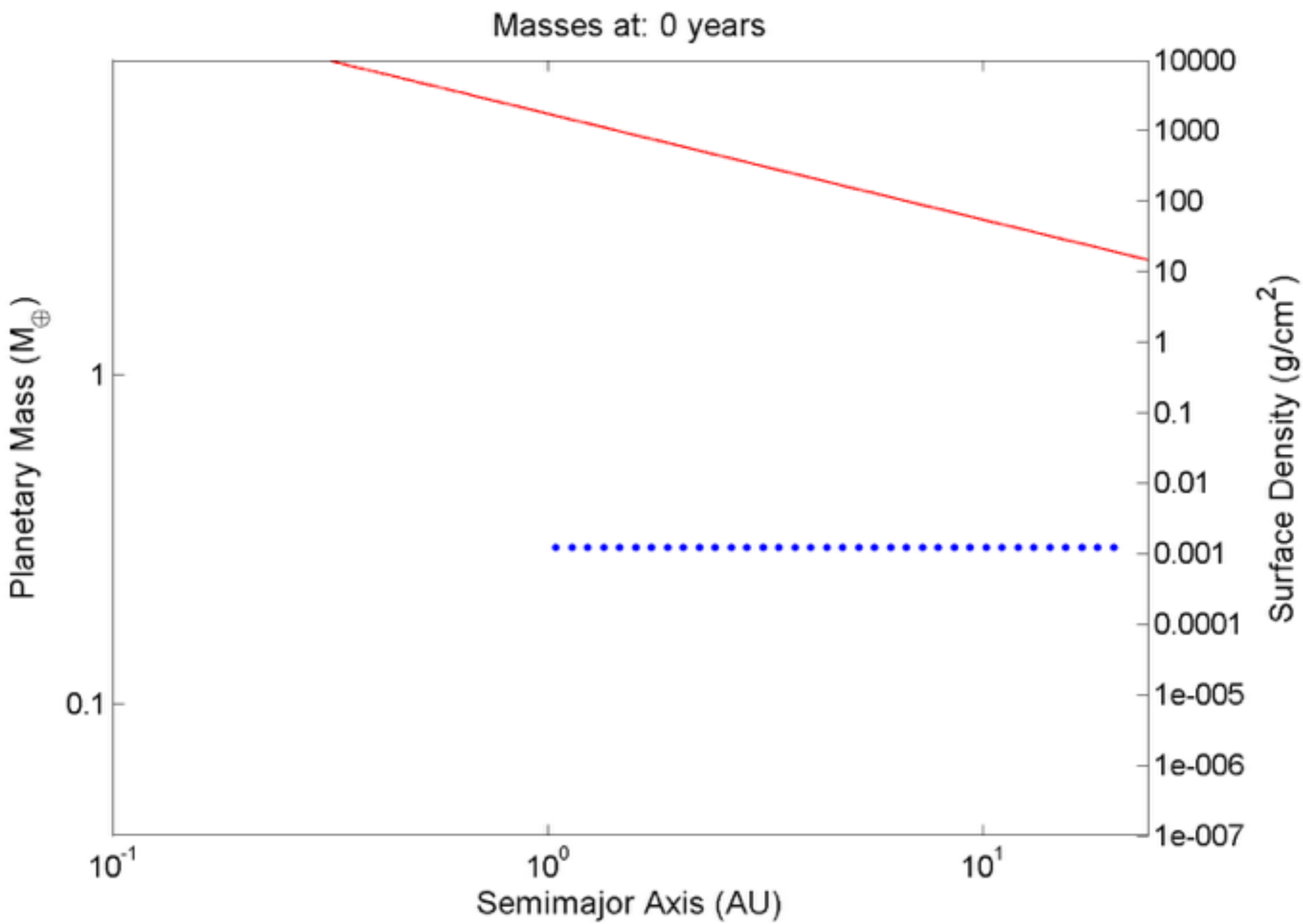
0.1 Myr
0.4 Myr
1 Myr
1.2 Myr
Planet Mass ($M_\oplus$)
Semi-major axis (AU)
Migration Factor

Slow growth in a low mass disc: S111B



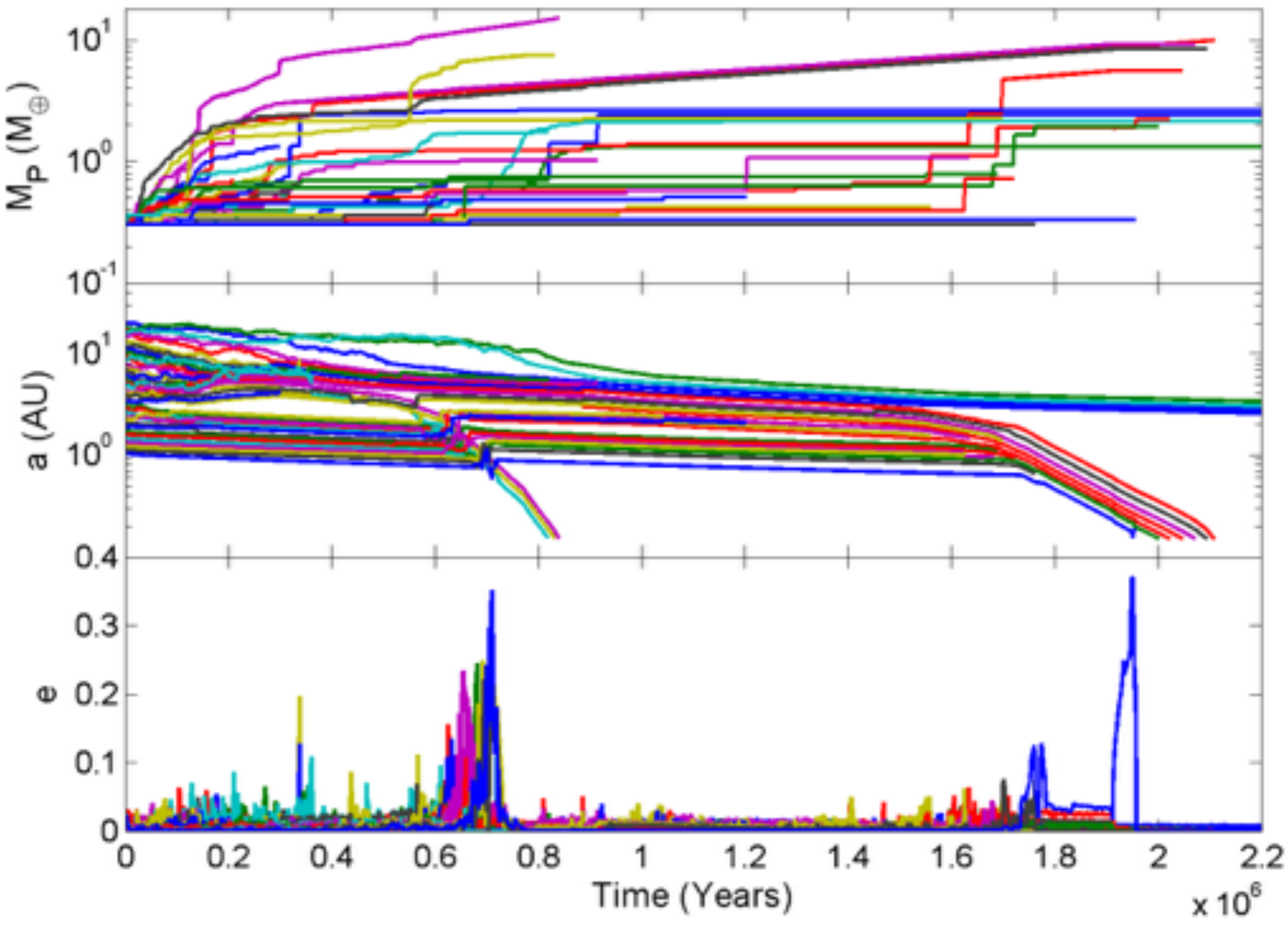
M_P ($M_\oplus$)
10^0
10^{-1}
a (AU)
10^1
10^0
1
e
0.5
0
0 1 2 3 4 5 6 7 8 9 10
Time (Years)
x 10^6


Migration contour plot at 0 years
Mass (M⊕)
10^2
10^1
10^0
10^-1
Semimajor Axis (AU)
10^-1
10^0
10^1
Migration factor
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5

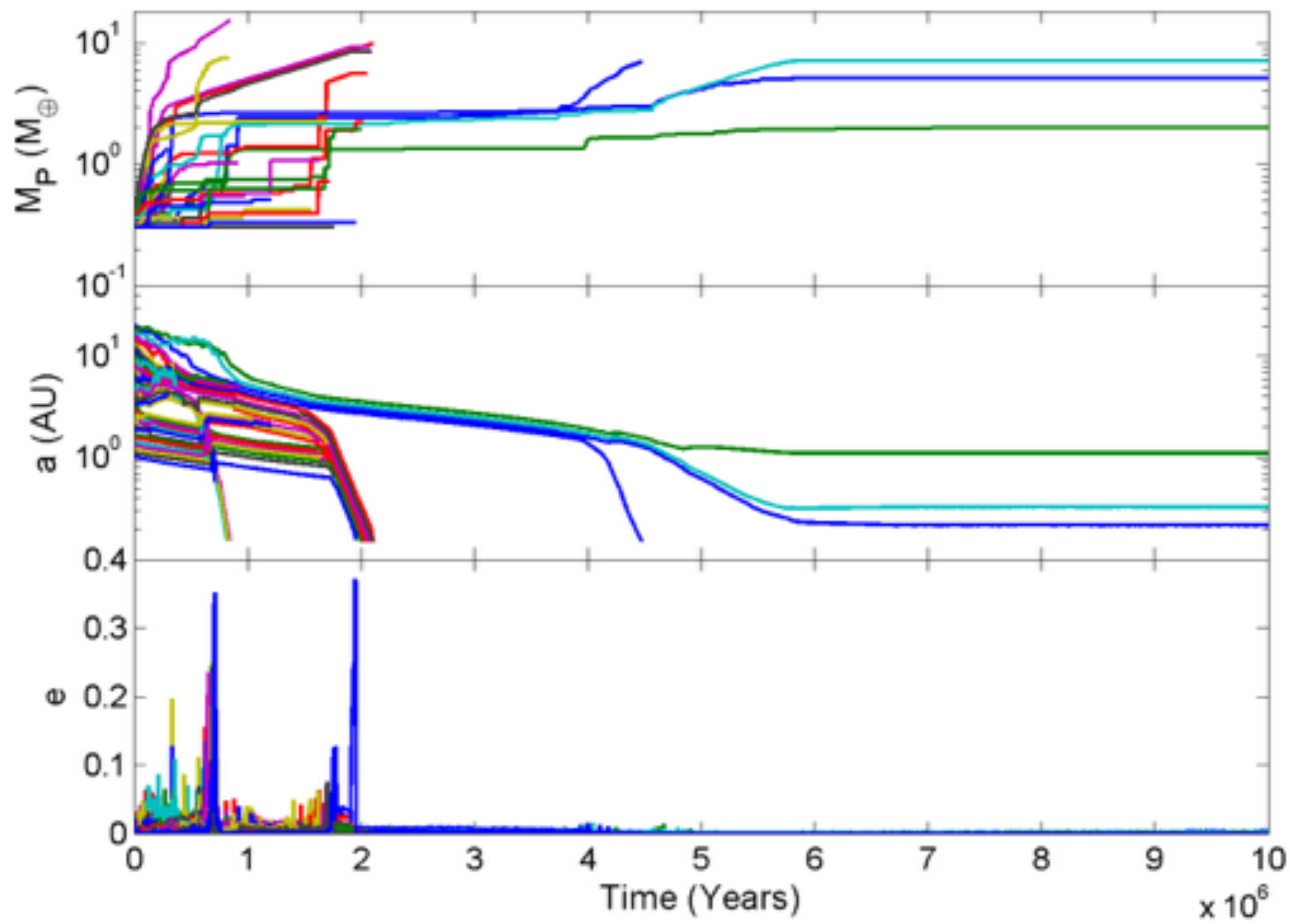


Masses at: 0 years
Planetary Mass ($M_\oplus$)
1
0.1
Surface Density (g/cm^2)
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-005
1e-006
1e-007
10^{-1}
10^{0}
10^{1}
Semimajor Axis (AU)

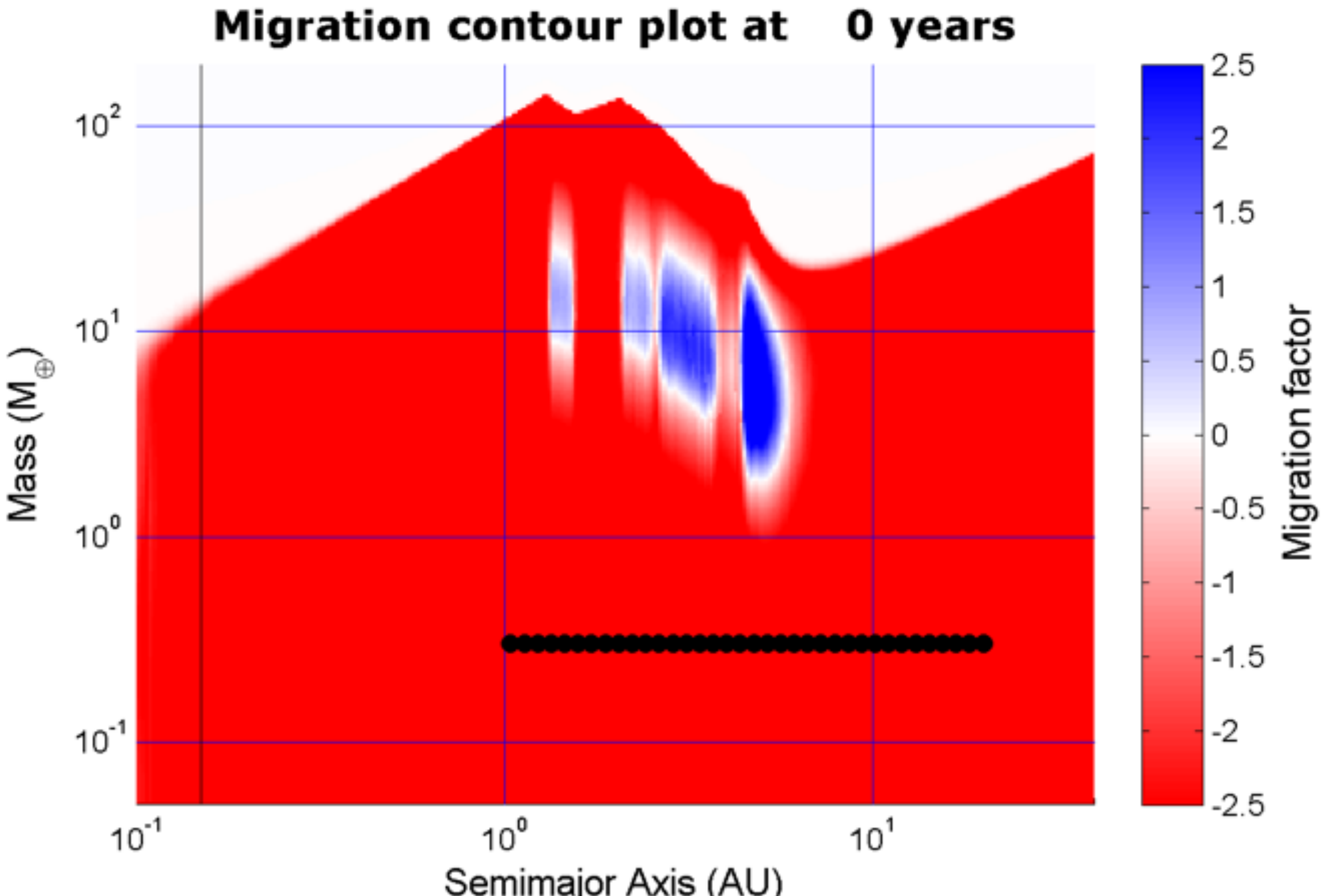
Kamikaze Neptunes: S211A

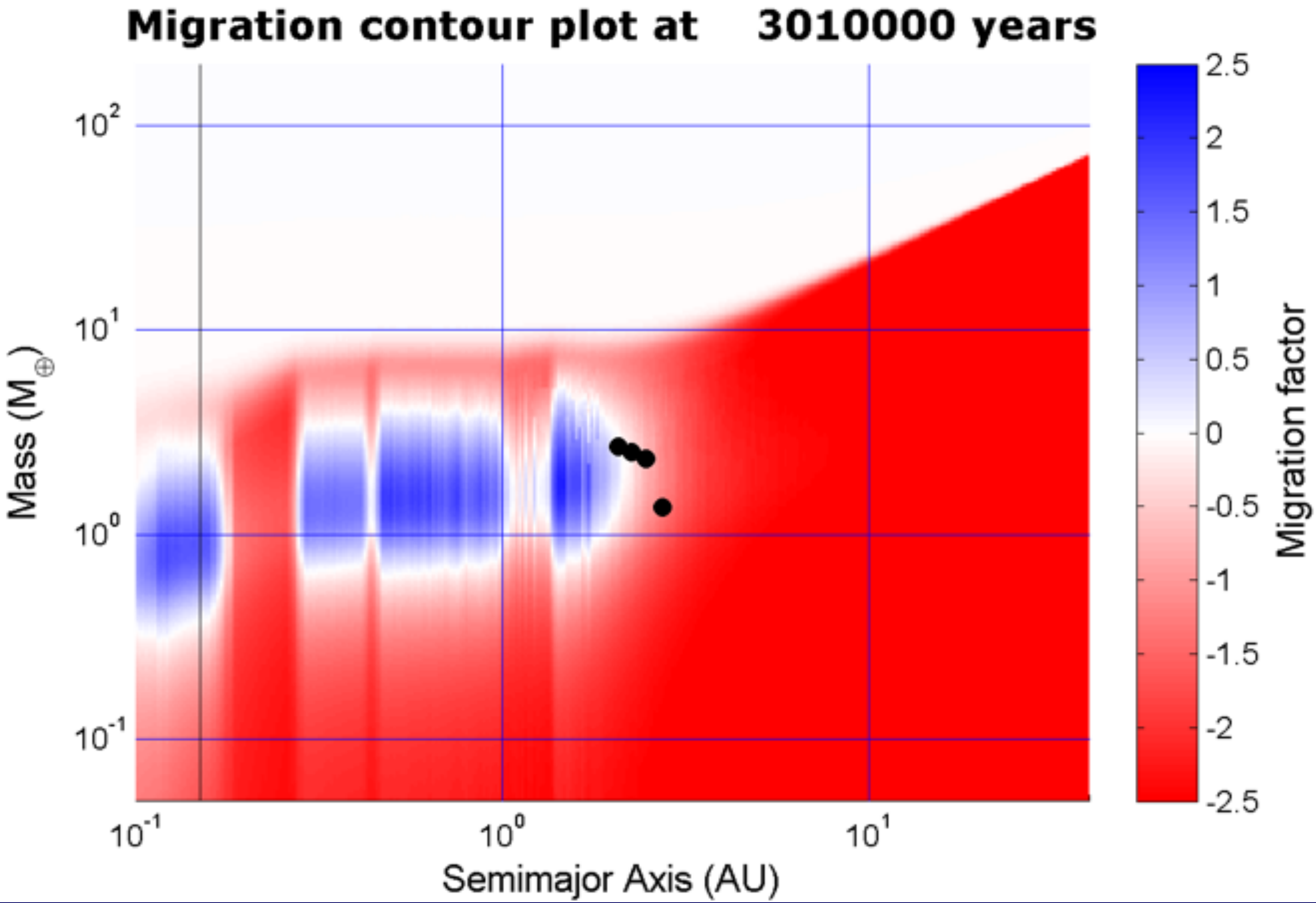


10^1
10^0
10^{-1}
M_P ($M_\oplus$)
10^1
10^0
0.4
a (AU)
0.3
0.2
0.1
0
e
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
Time (Years)
x 10^6

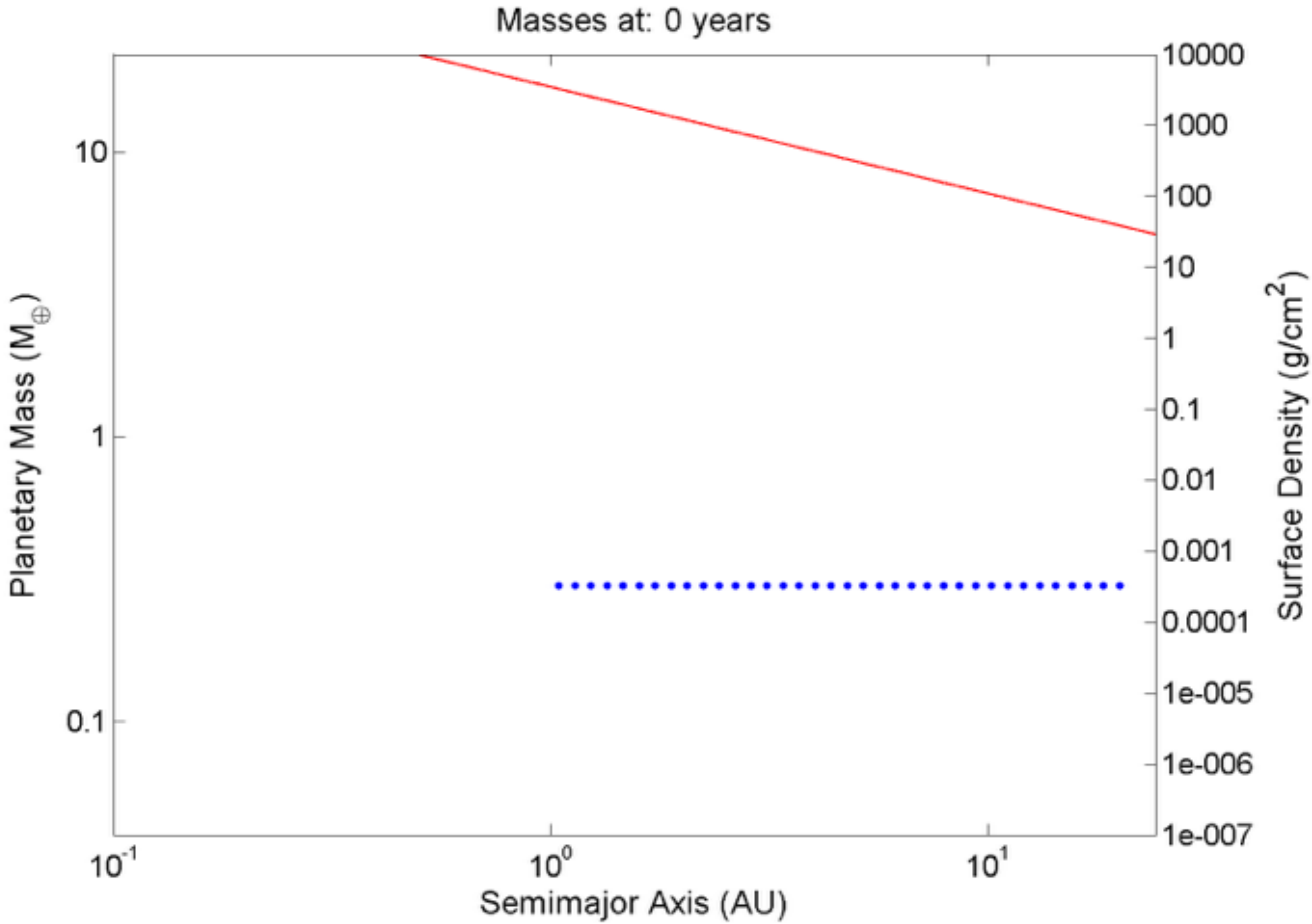


M_P ($M_\oplus$)
10^1
10^0
10^{-1}
a (AU)
10^1
10^0
0.4
e
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
8
9
10
Time (Years)
x 10^6

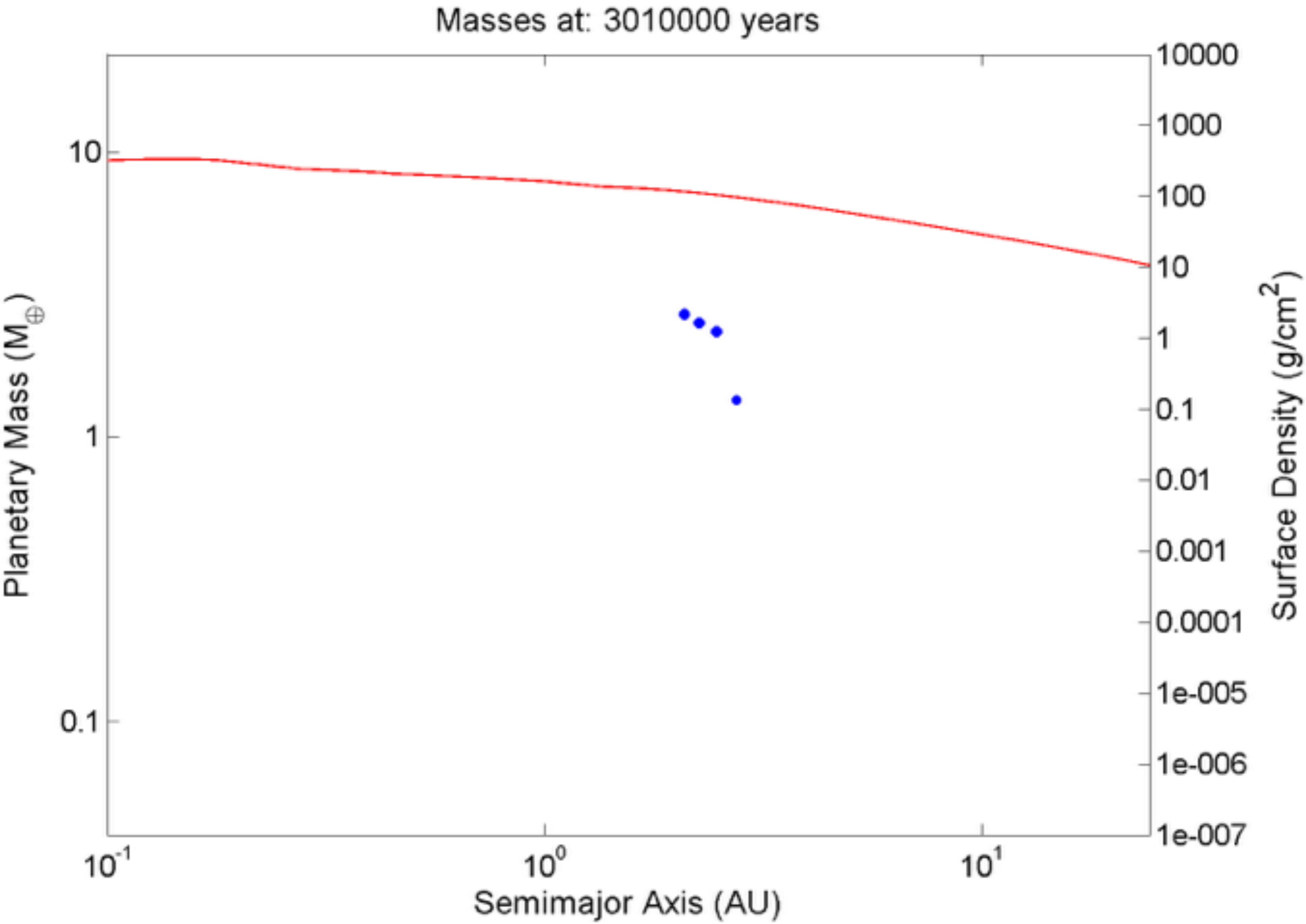

Migration contour plot at 0 years
Mass ($M_\oplus$)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-1}
10^{0}
10^{1}
Semimajor Axis (AU)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Migration factor



Migration contour plot at 3010000 years
Mass (M⊕)
10^2
10^1
10^0
10^-1
10^-1
10^0
10^1
Semimajor Axis (AU)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Migration factor

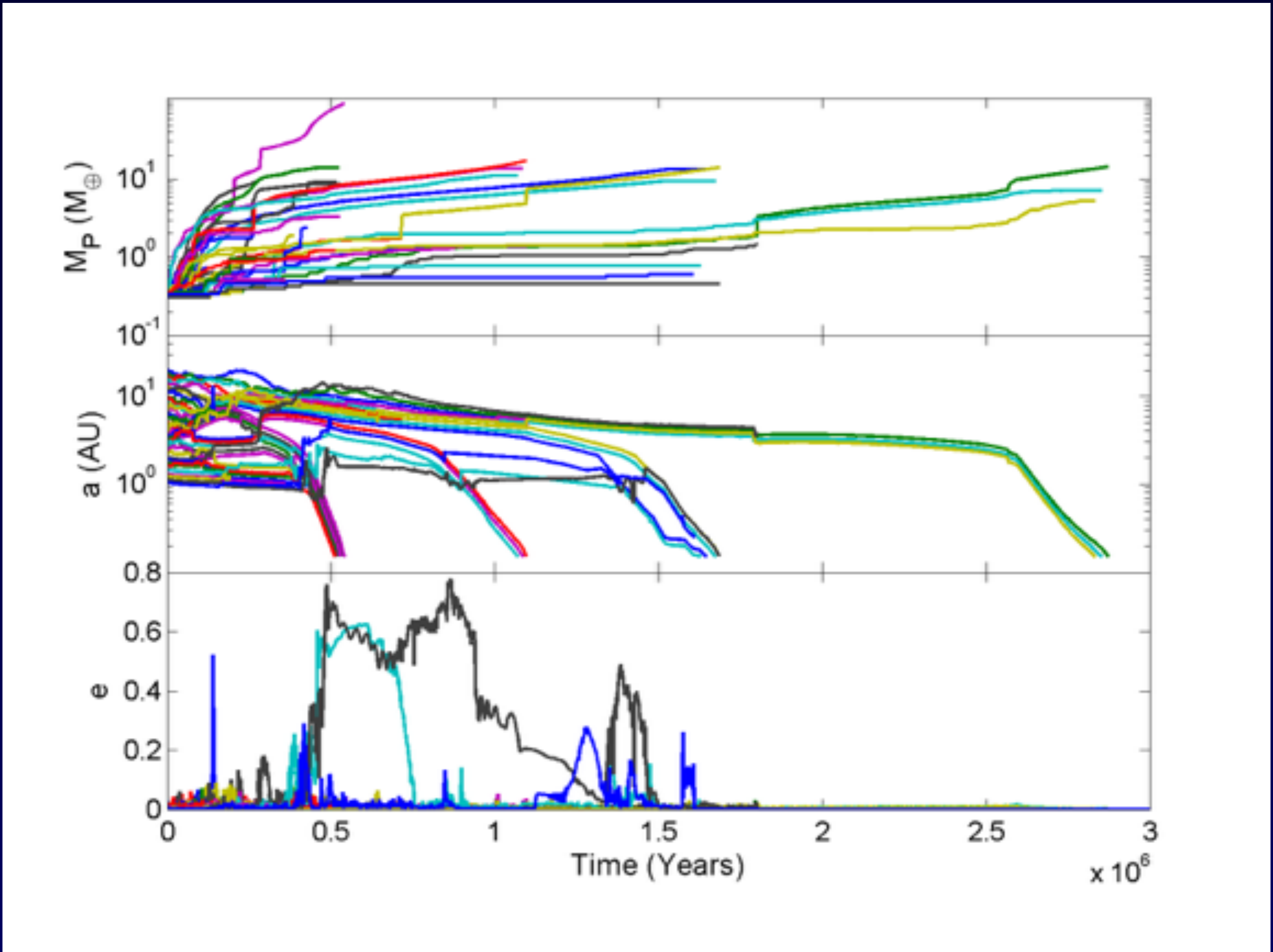


Masses at: 0 years
Planetary Mass ($M_\oplus$)
10
1
0.1
Surface Density (g/cm^2)
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-005
1e-006
1e-007
10^{-1}
10^{0}
10^{1}
Semimajor Axis (AU)

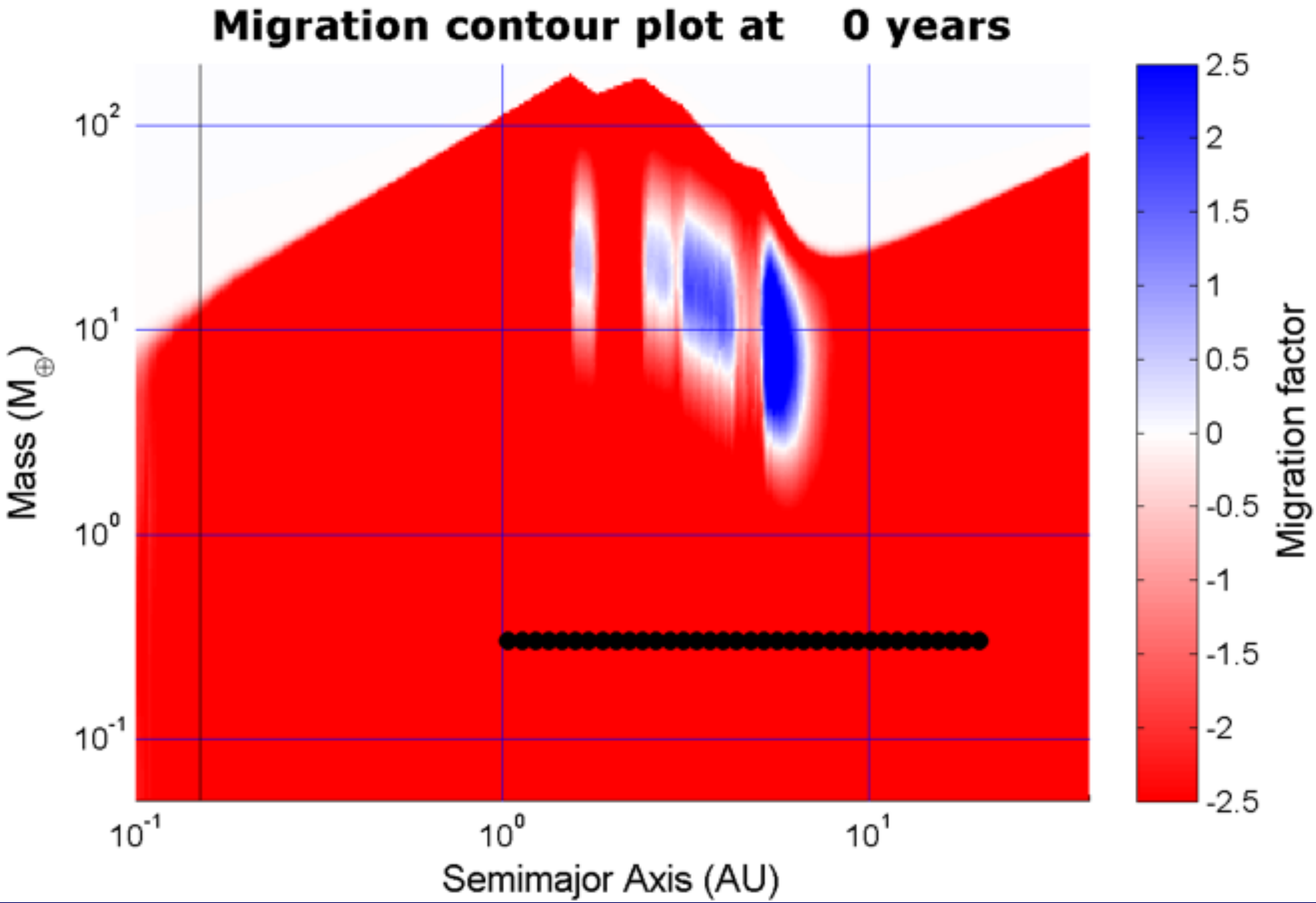


Masses at: 3010000 years
Planetary Mass ($M_\oplus$)
Surface Density (g/cm^2)
Semimajor Axis (AU)
10
1
0.1
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-005
1e-006
1e-007
10^{-1}
10^{0}
10^{1}

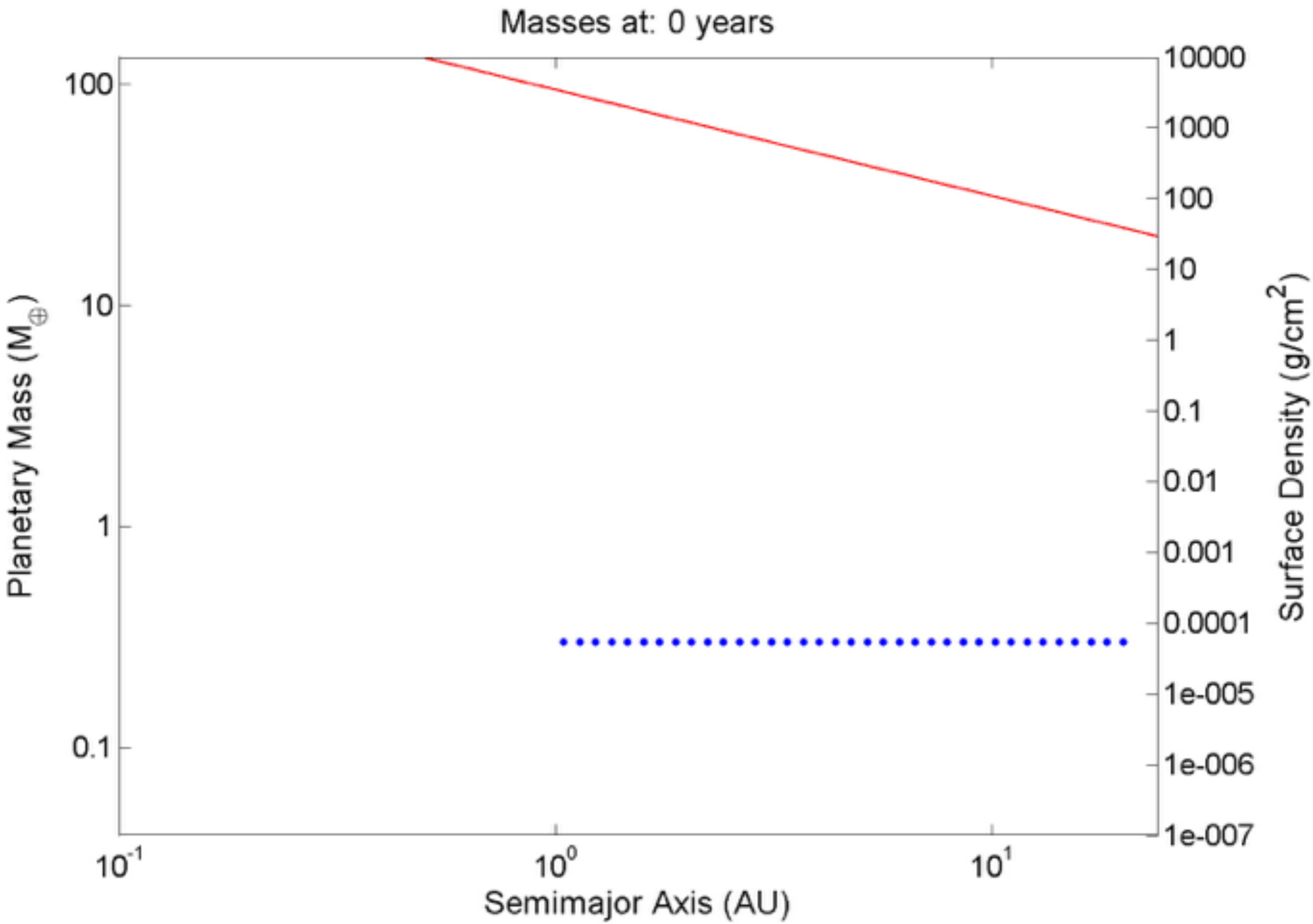
Kamikaze Giants: S221A



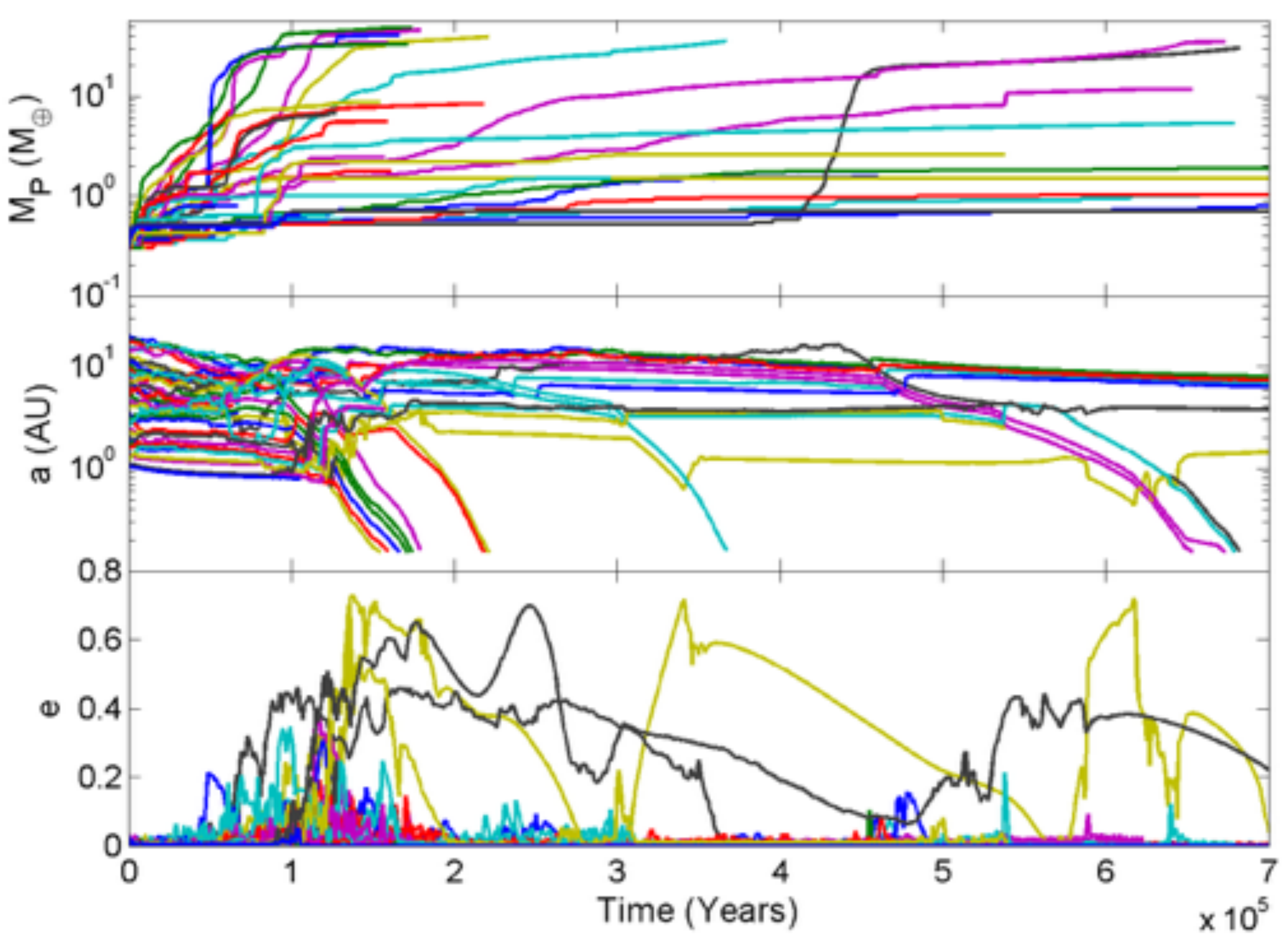
M_P ($M_\oplus$)
a (AU)
e
Time (Years)
x 10^6



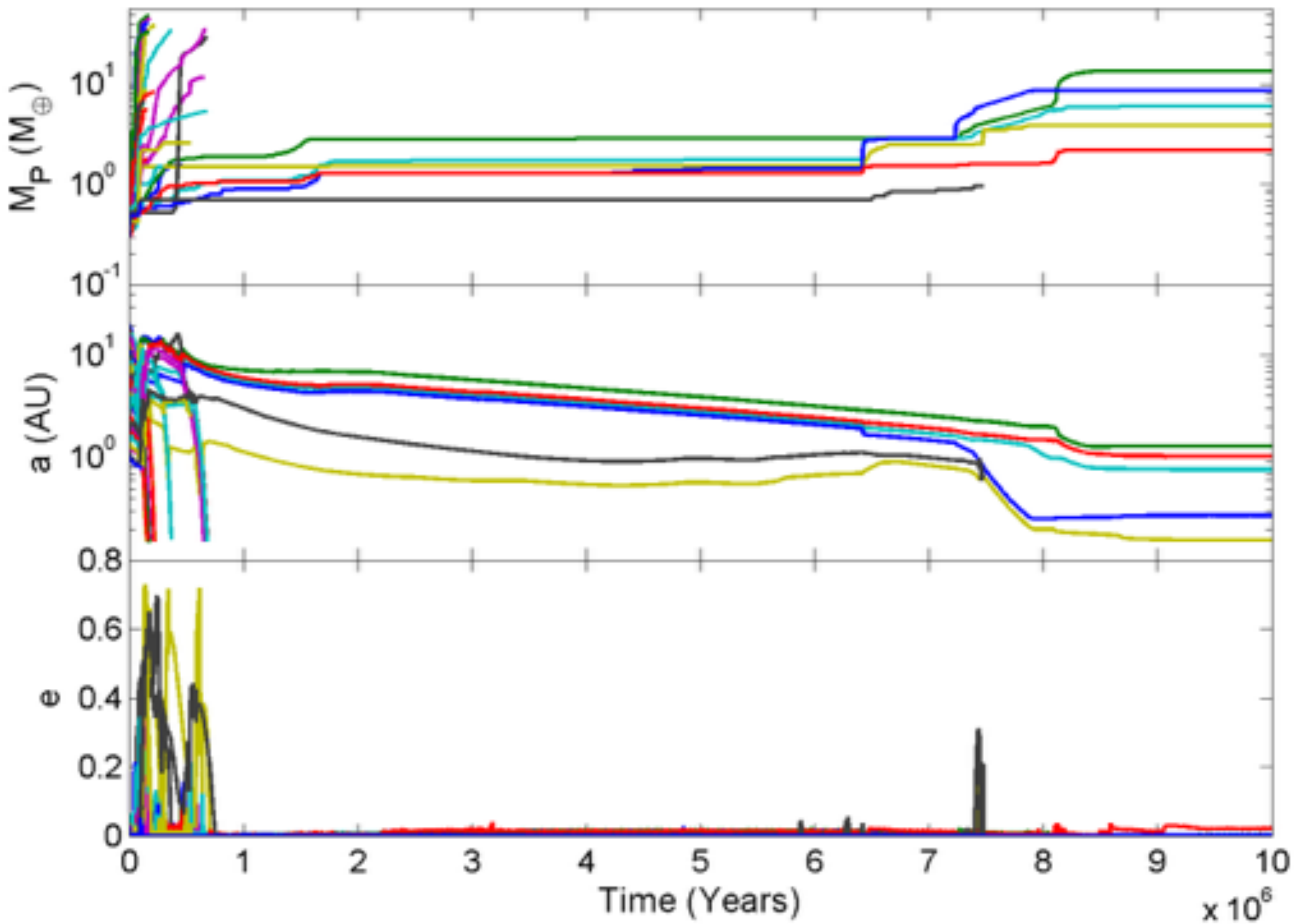
Migration contour plot at 0 years
Mass ($M_\oplus$)
10^2
10^1
10^0
10^{-1}
10^{-1}
10^0
10^1
Semimajor Axis (AU)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Migration factor


Masses at: 0 years
Planetary Mass ($M_{\oplus}$)
Surface Density (g/cm^2)
Semimajor Axis (AU)
100
10
1
0.1
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-005
1e-006
1e-007
10^{-1}
10^{0}
10^{1}

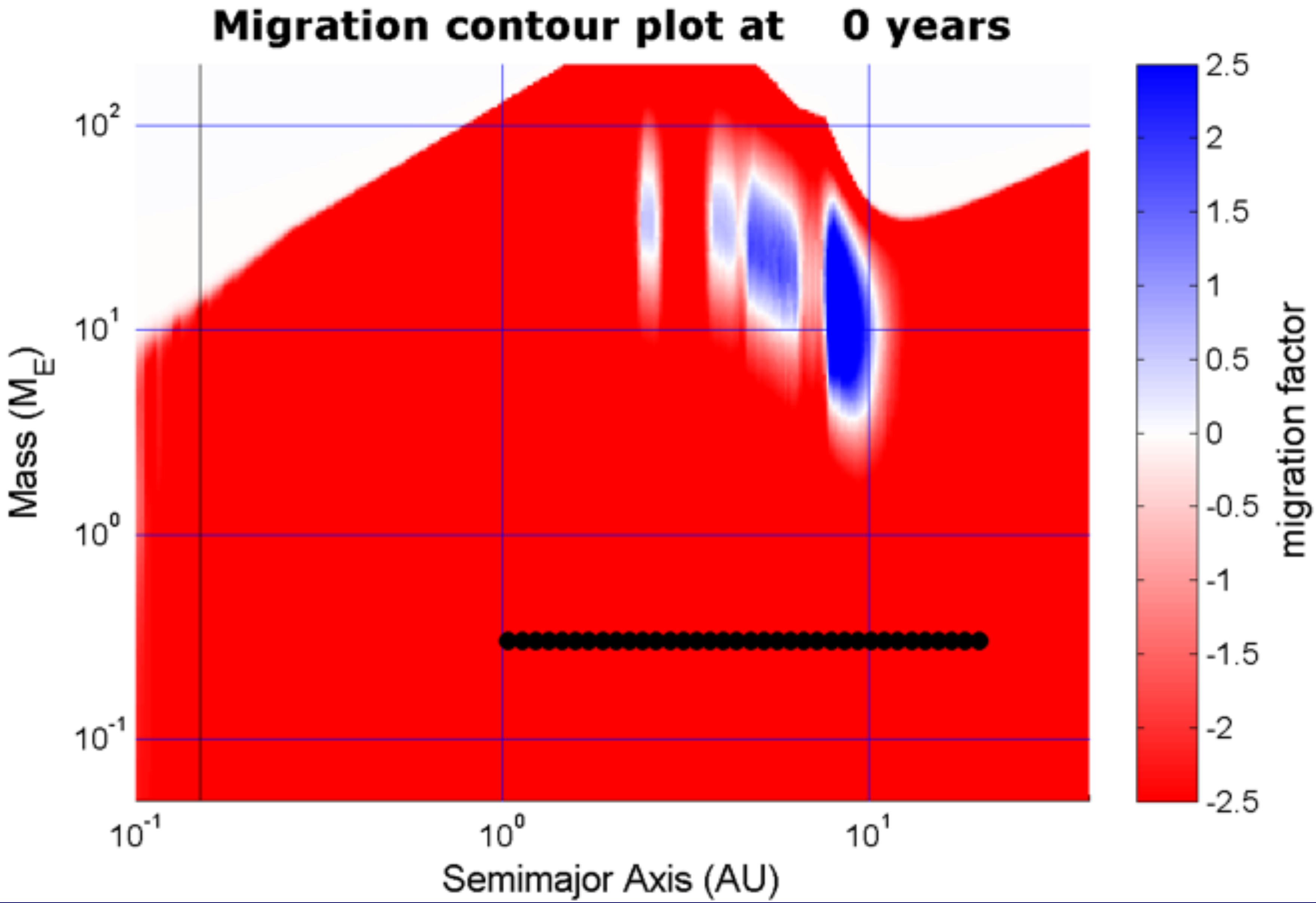
Late forming survivors: S521A

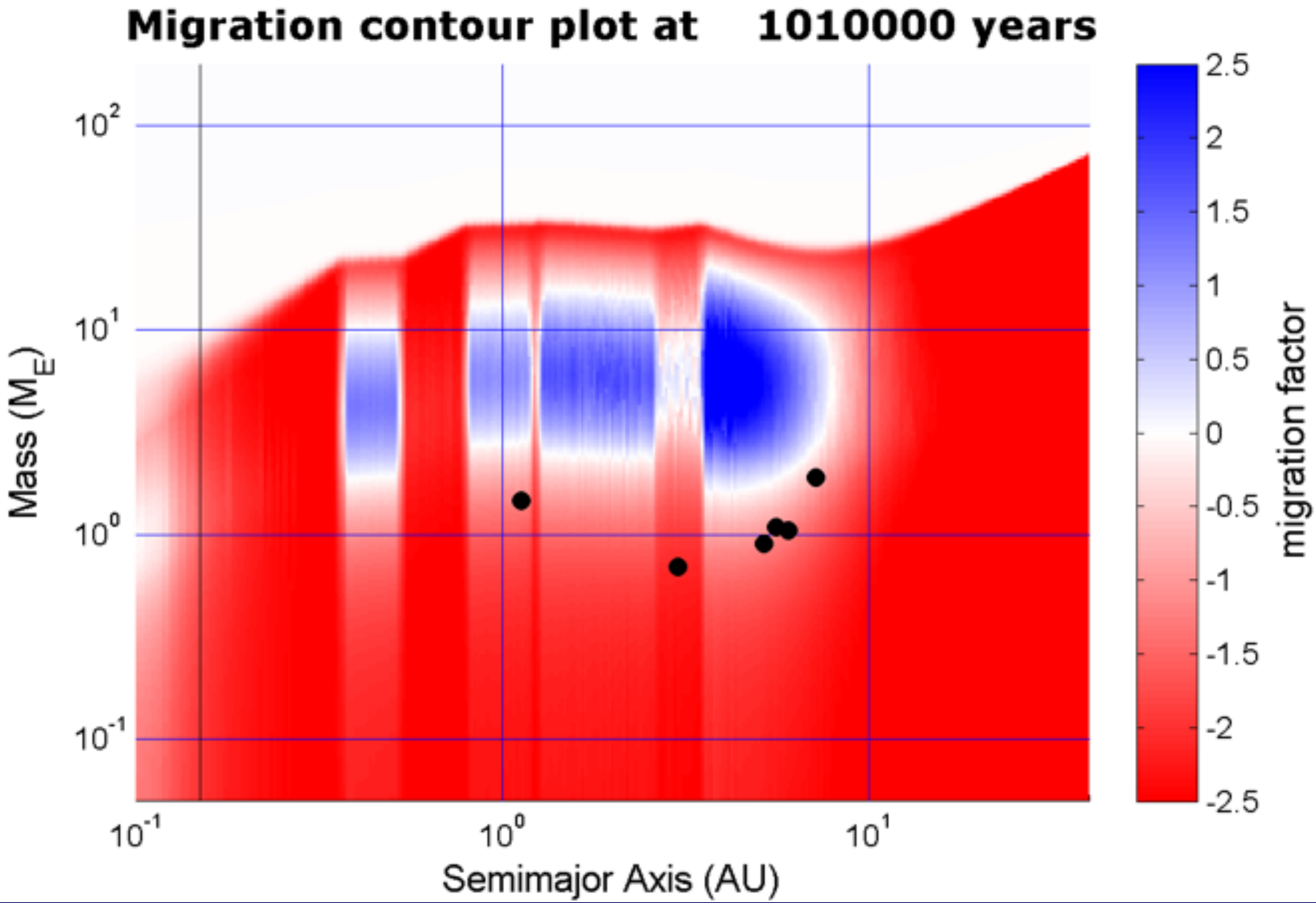


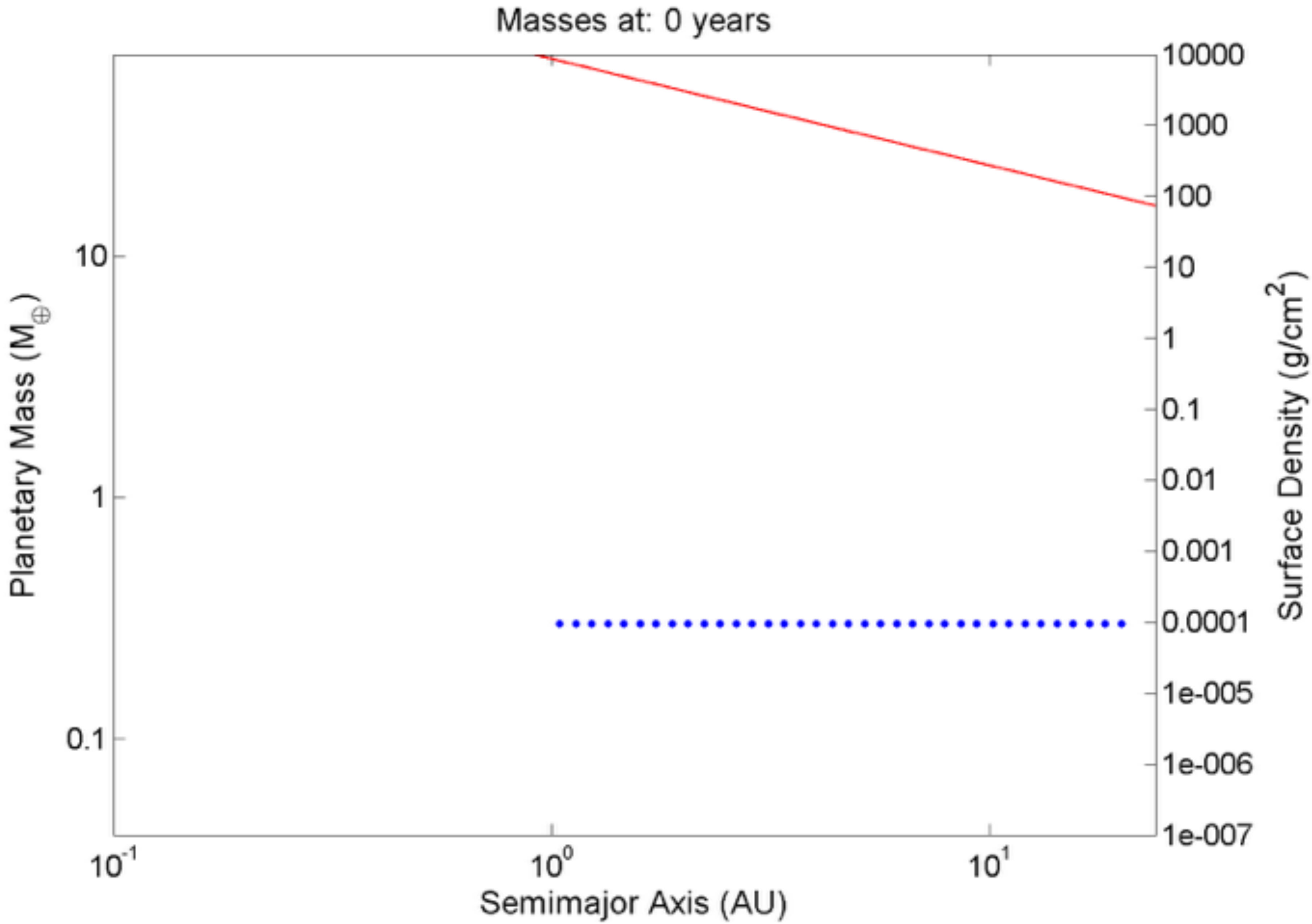
M_P ($M_\oplus$)
10^1
10^0
10^{-1}
a (AU)
10^1
10^0
0.8
e
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
Time (Years)
x 10^5



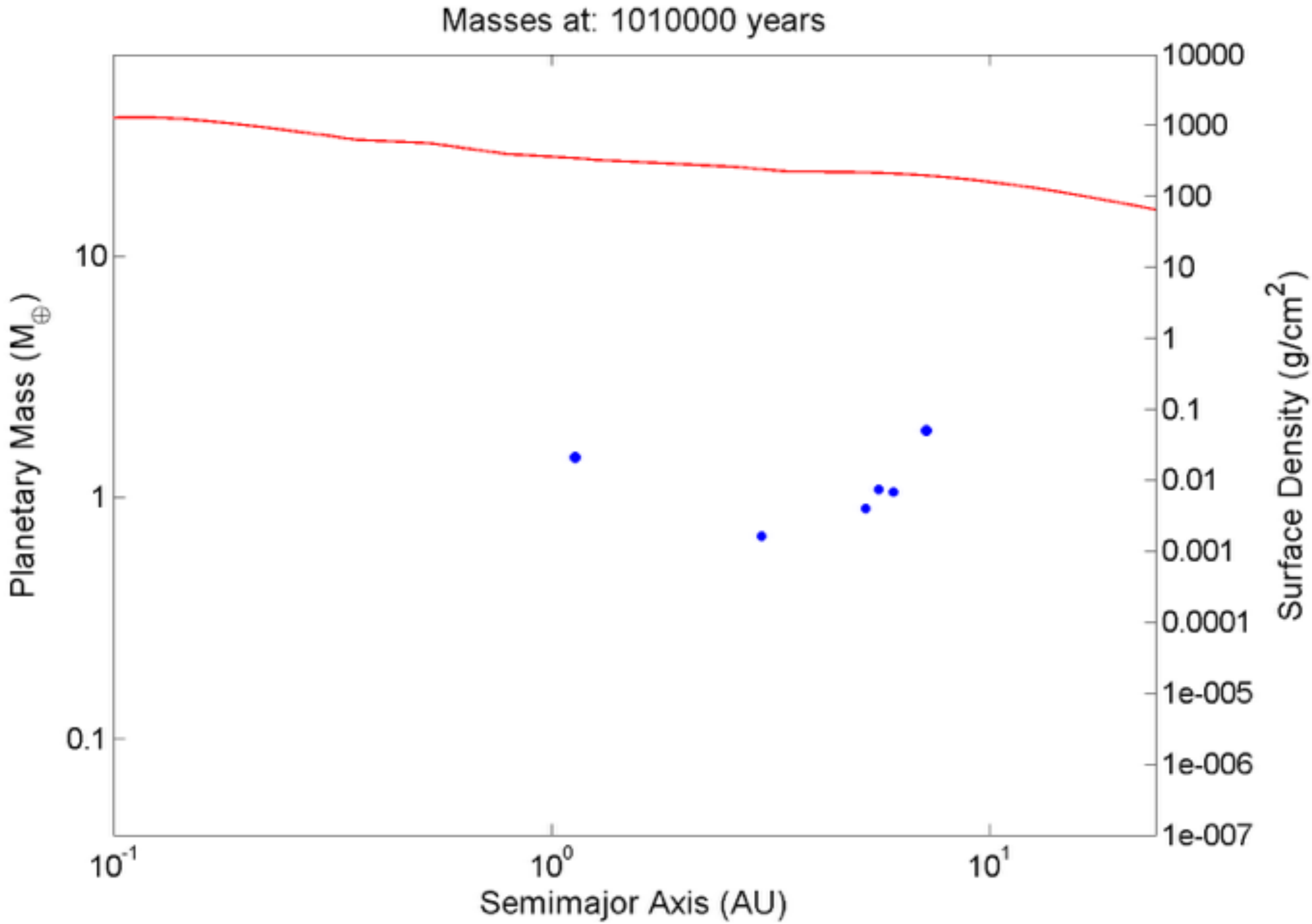
M_P ($M_\oplus$)
a (AU)
e
Time (Years)
x 10^6

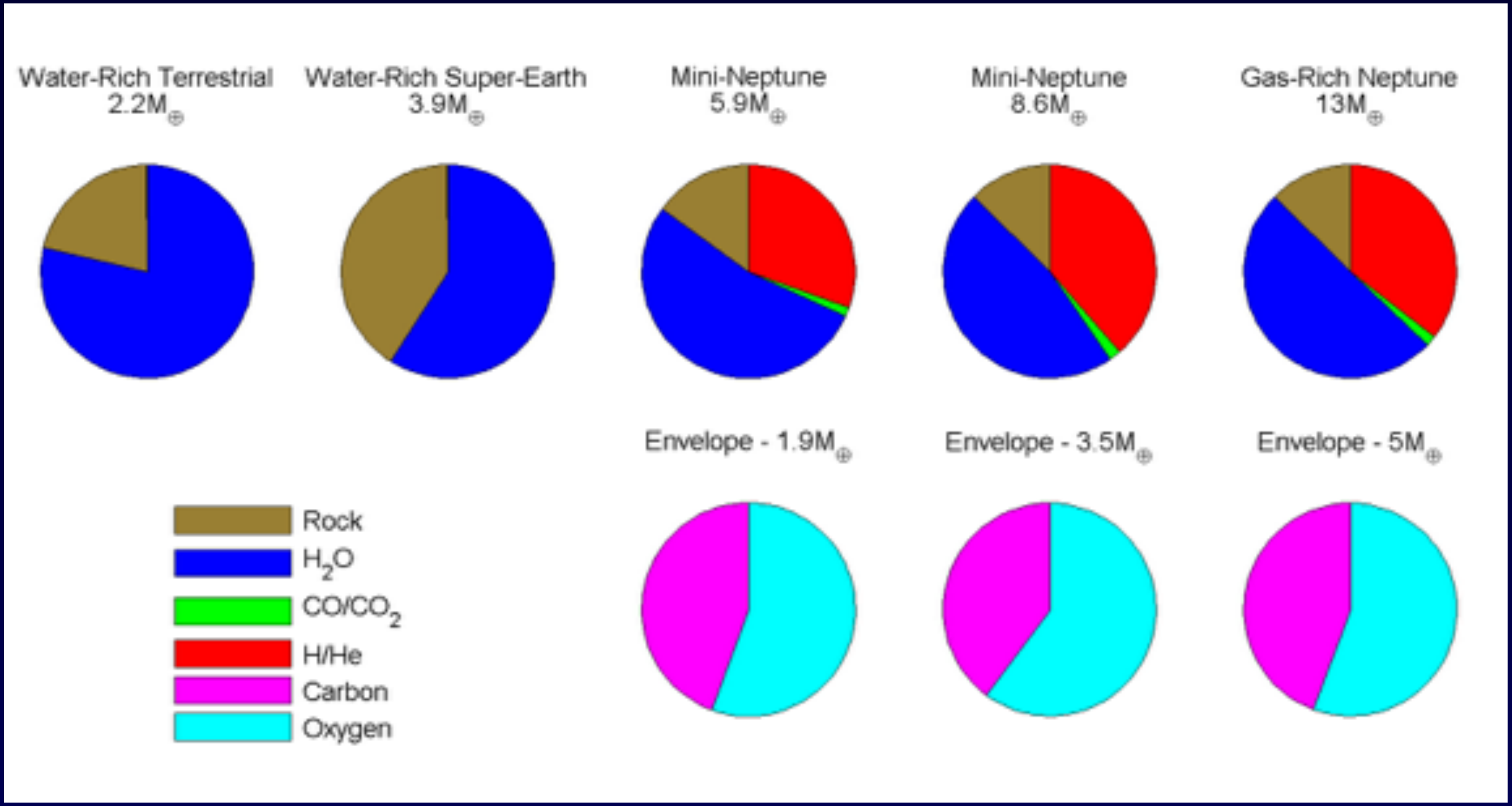

Migration contour plot at 0 years
Mass (M_E)
10^2
10^1
10^0
10^-1
10^-1
10^0
10^1
Semimajor Axis (AU)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
migration factor


Migration contour plot at 1010000 years
Mass (M_E)
Semimajor Axis (AU)
migration factor
10^2
10^1
10^0
10^-1
10^-1
10^0
10^1
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5



Masses at: 0 years
Planetary Mass ($M_\oplus$)
10
1
0.1
Surface Density (g/cm^2)
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-005
1e-006
1e-007
10^{-1}
10^{0}
10^{1}
Semimajor Axis (AU)


Masses at: 1010000 years
Planetary Mass ($M_\oplus$)
Surface Density (g/cm^2)
Semimajor Axis (AU)
10
1
0.1
10^{-1}
10^0
10^1
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-005
1e-006
1e-007



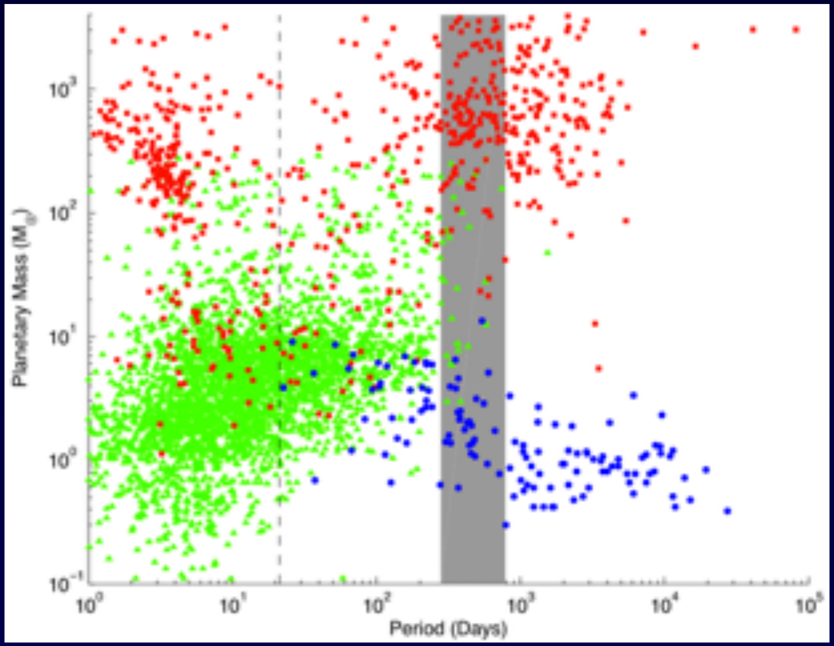
Bulk chemical composition of planets and their gaseous envelopes

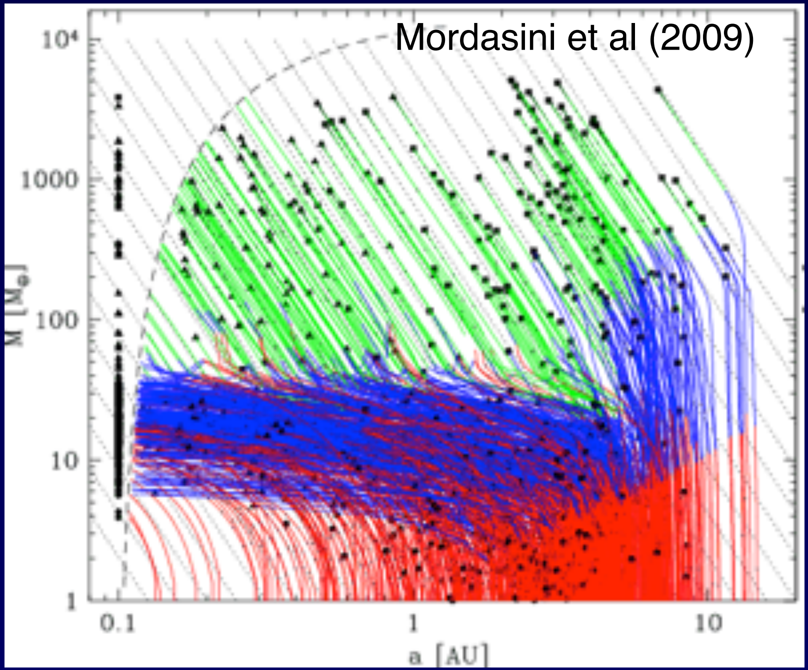
Comparing simulation results with observations

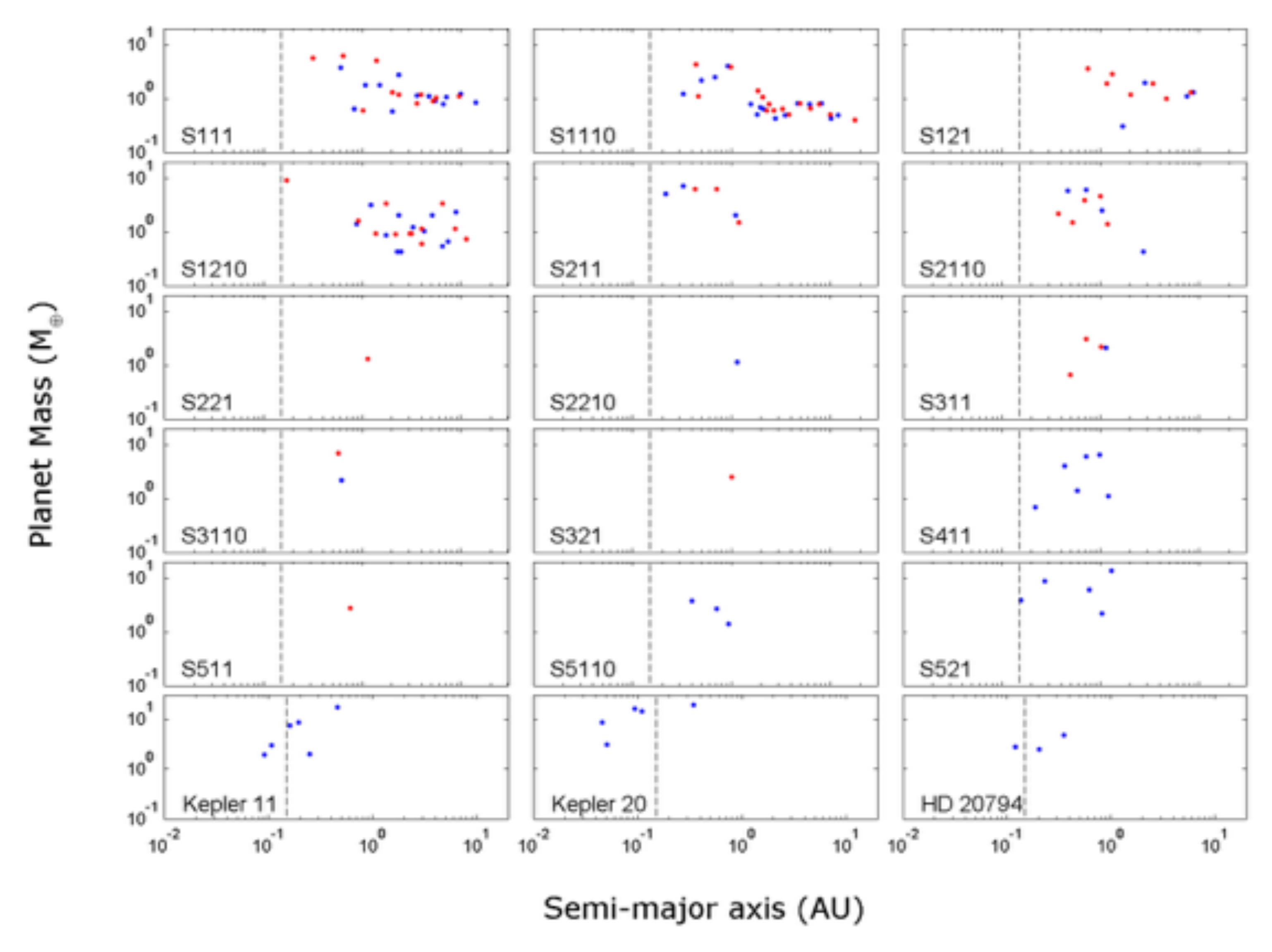
• Model leads to formation of super-Earth and Neptune-mass planets with intermediate orbital periods

• Adopting an inner boundary at 0.15 AU prevents formation of compact systems of super-Earths observed by Kepler (e.g. Kepler 11)

• The model fails to form any gas giants that survive - only two giant planets formed exterior to ~ 1 AU, due to rapid inward migration of cores when their masses $m_p > 15 \, M_{Earth}$







Planet Mass (M⊕)
Semi-major axis (AU)
S111
S1110
S121
S1210
S211
S2110
S221
S2210
S311
S3110
S321
S411
S511
S5110
S521
Kepler 11
Kepler 20
HD 20794

Prelimary results from updated N-body simulations
(Coleman & Nelson 2015a,b In prep.)

New model ingredients

- 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 abundance

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

Simulation results

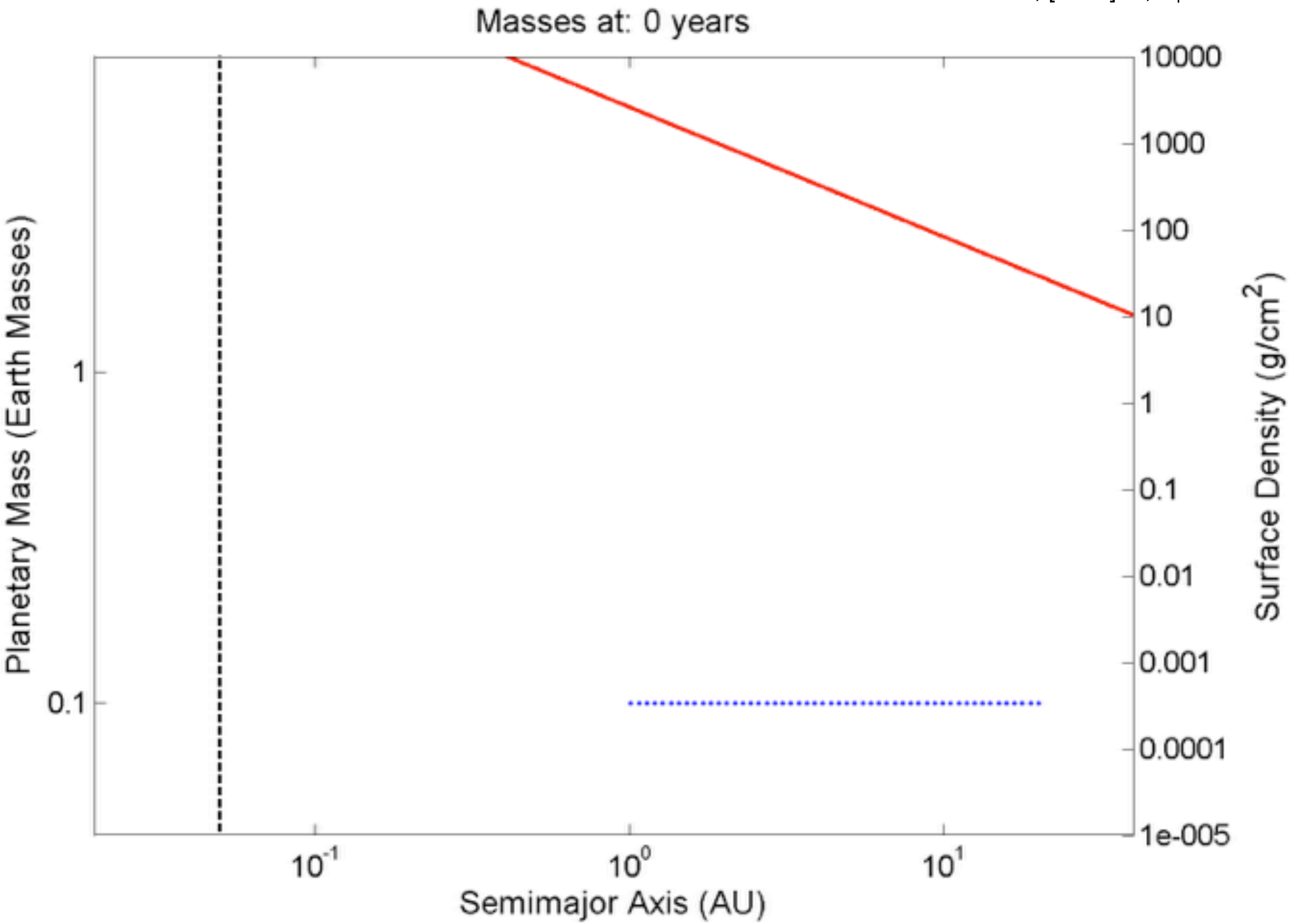
Three basic modes of evolution:

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

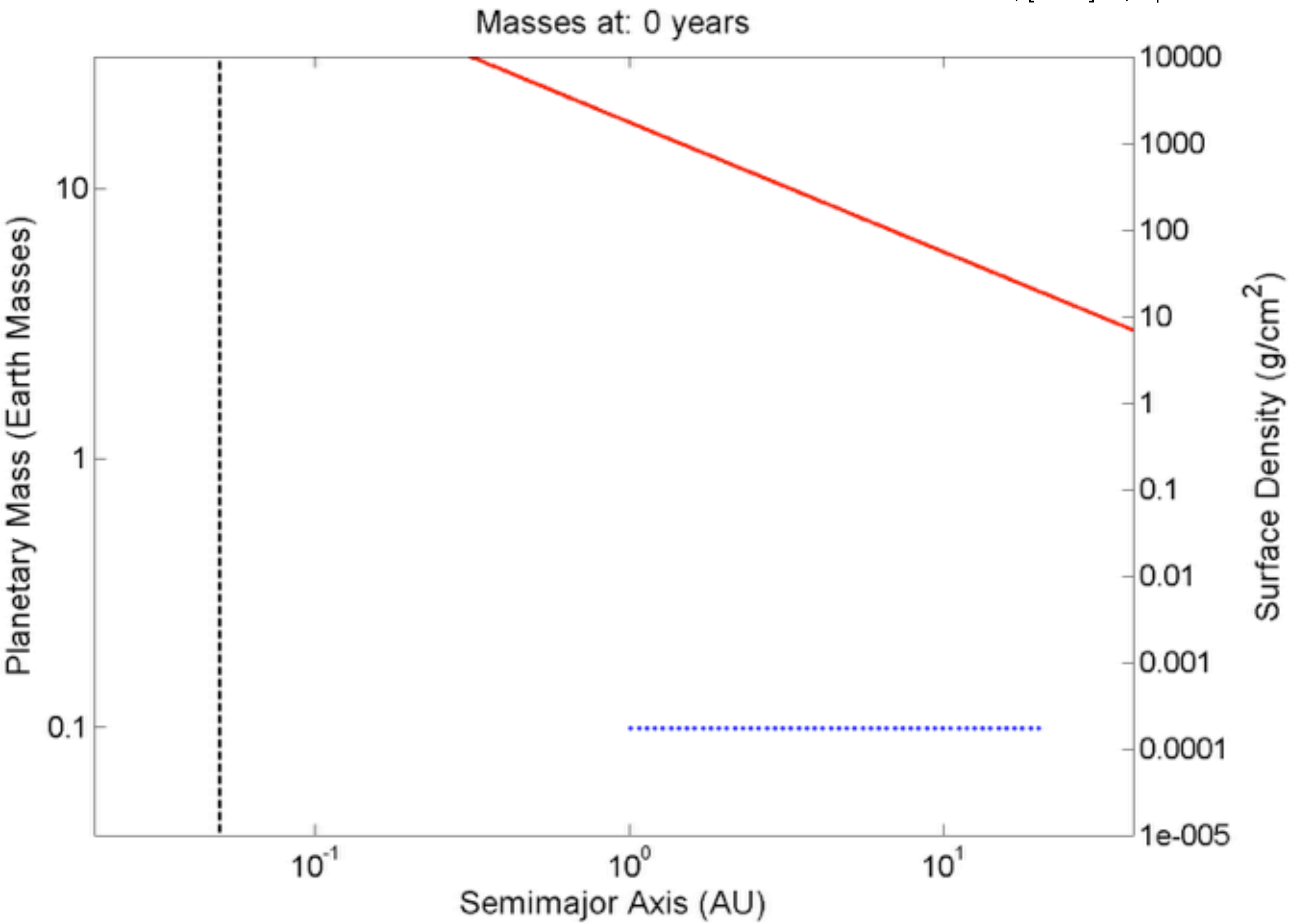
2. Formation of super-Earths + Neptunes with $m_p < 35\ M_{Earth}$.
   Large scale migration. Moderate solid abundance. Small planetesimals/boulders.

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

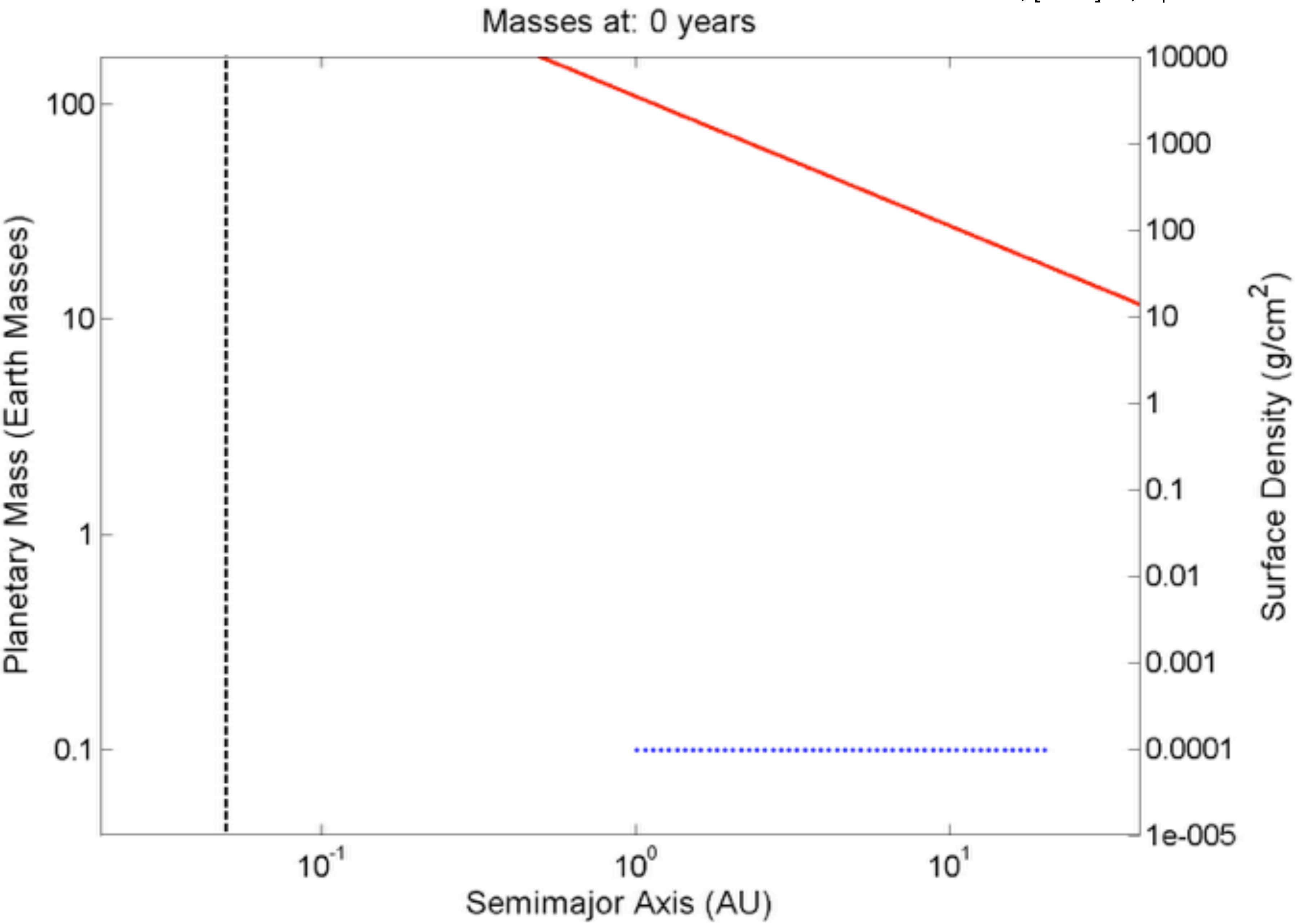
M_{disc}=1.5, [Fe/H]=2, R_{pl}=1 km

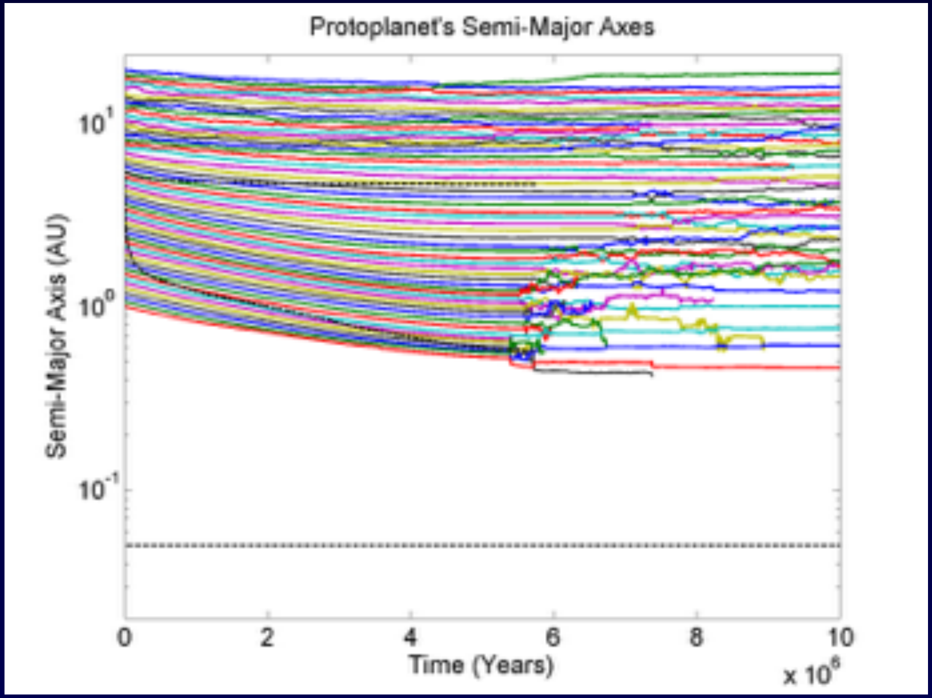


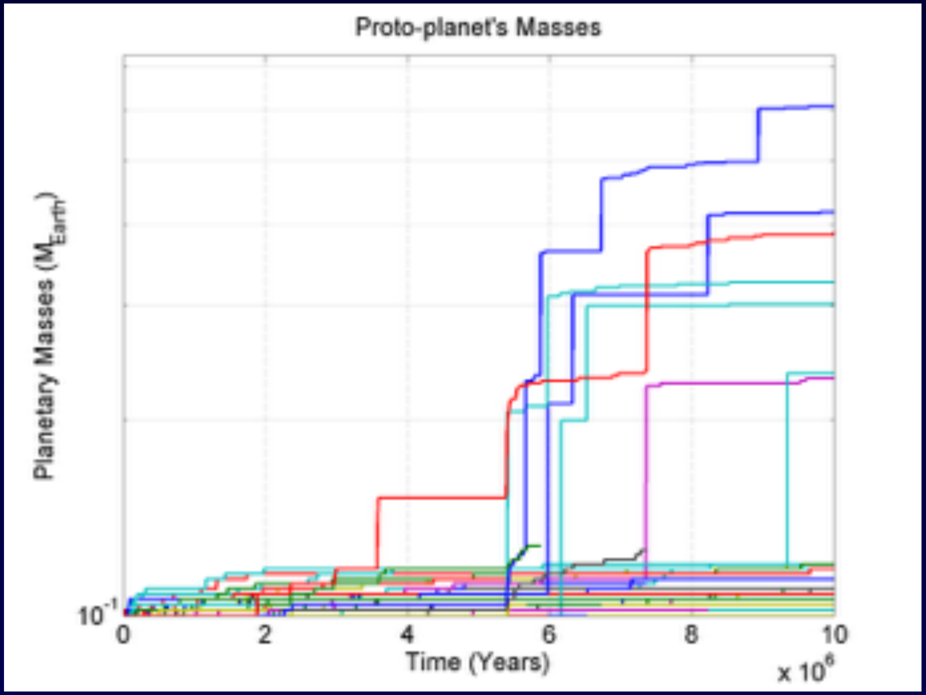
M_{disc}=1, [Fe/H]=2, R_{pl}=100 m



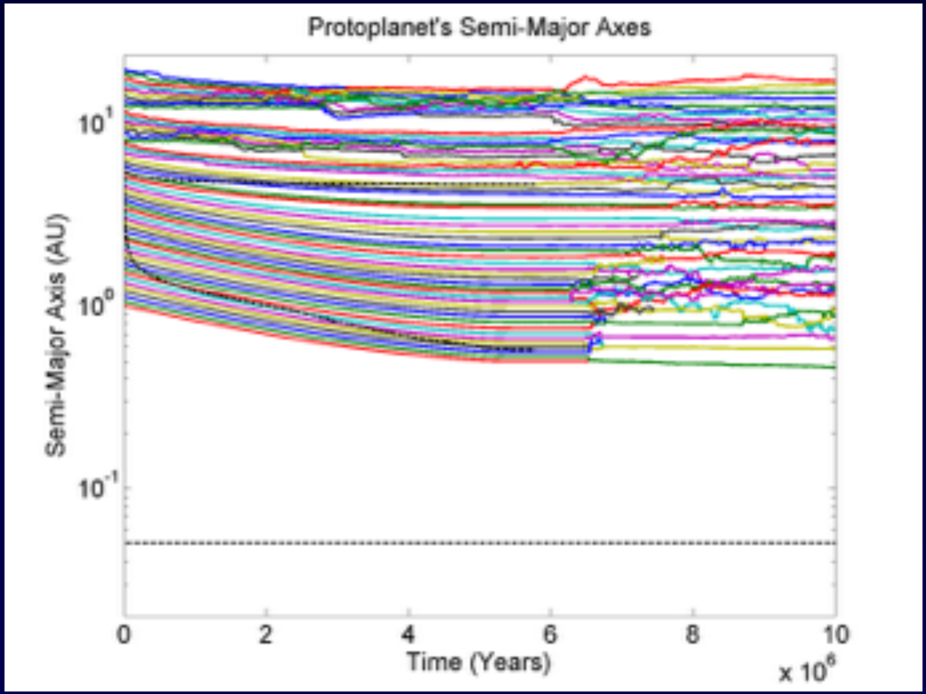
M_{disc}=2, [Fe/H]=2, R_{pl}=10 m

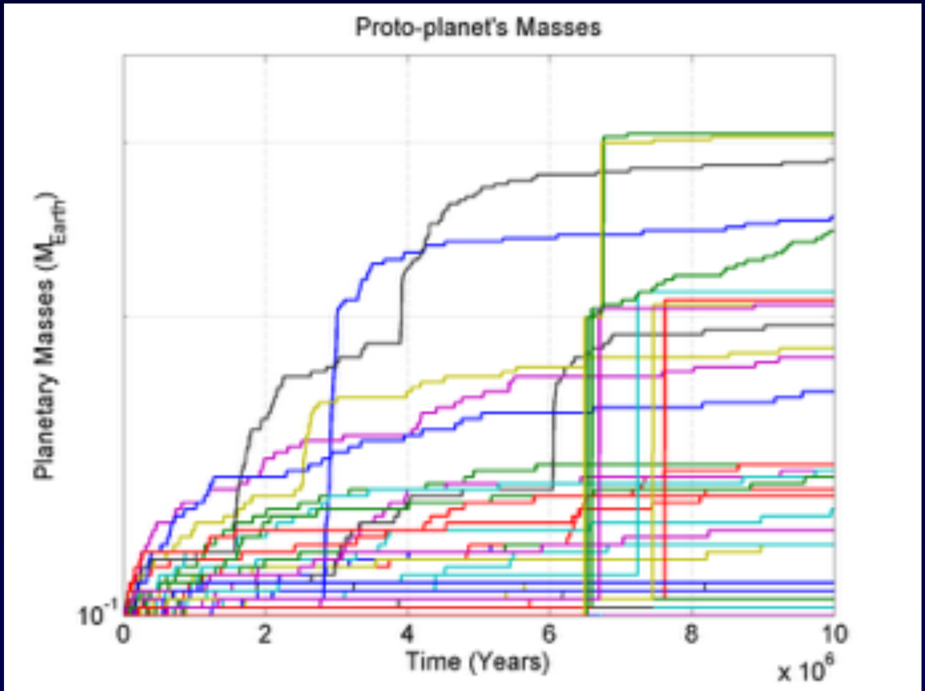




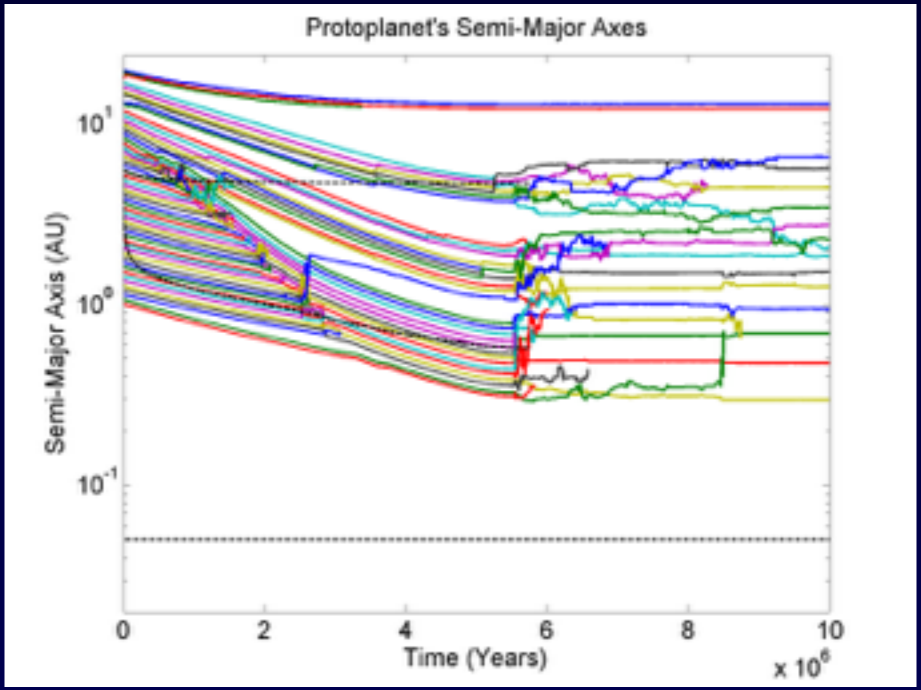


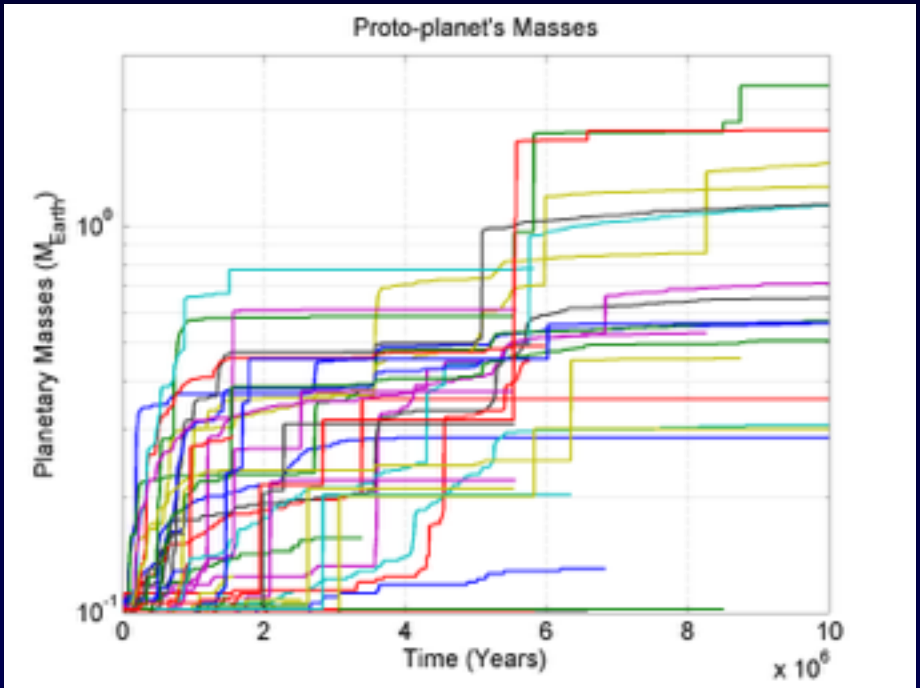
Disc mass = 1.5x MMSN
Metallicity = 0.5 x solar
Planetesimal sizes = 10 km



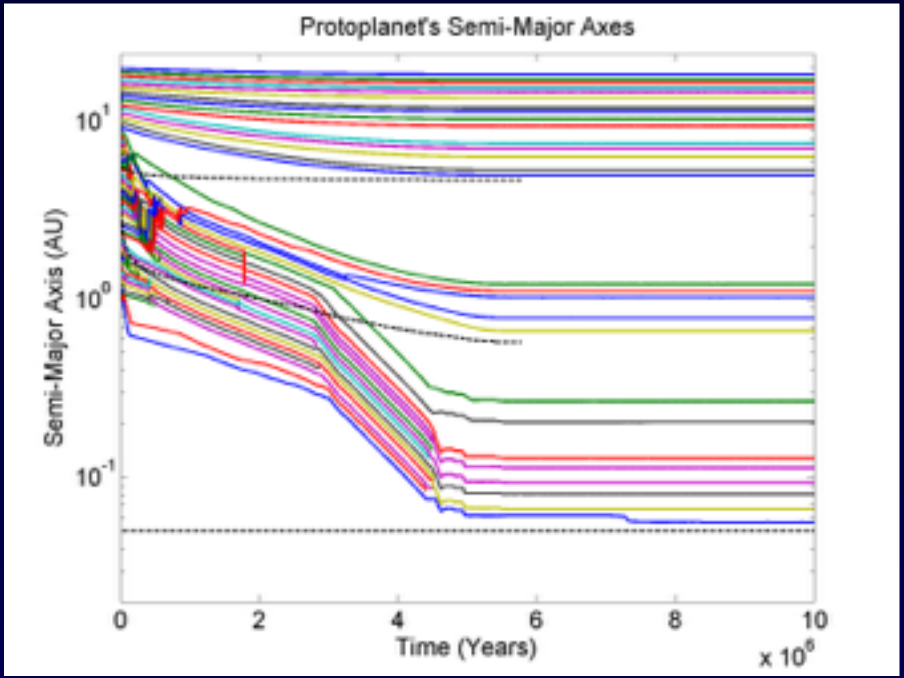


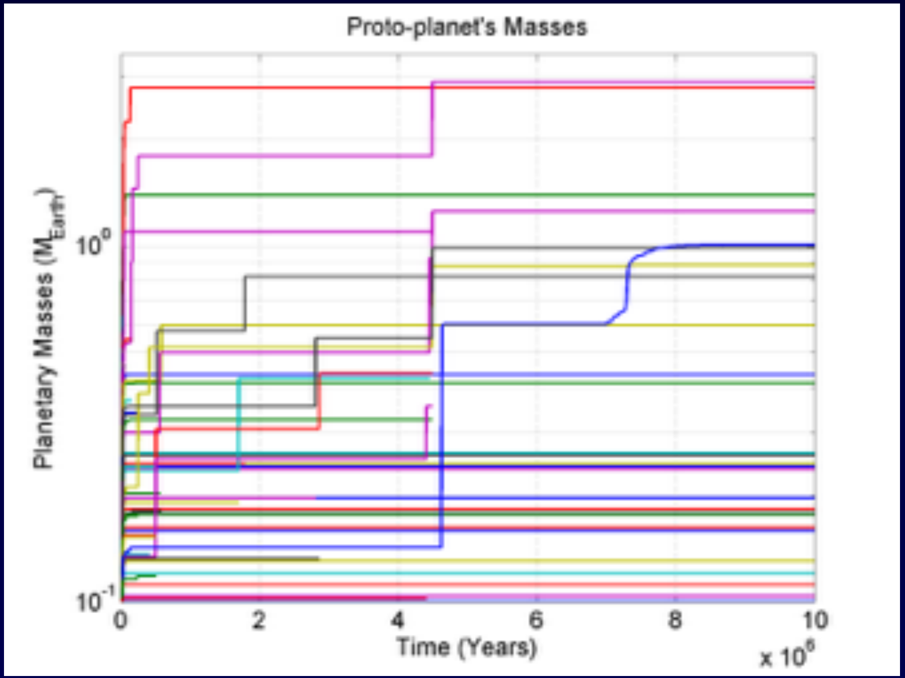
Disc mass = 1.5x MMSN
Metallicity = 0.5 x solar
Planetesimal sizes = 1 km



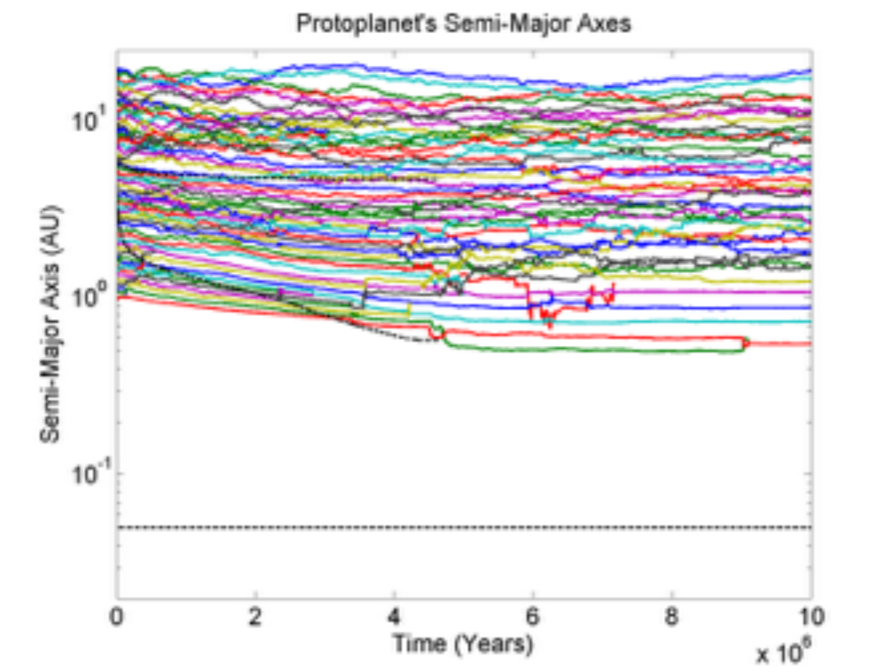


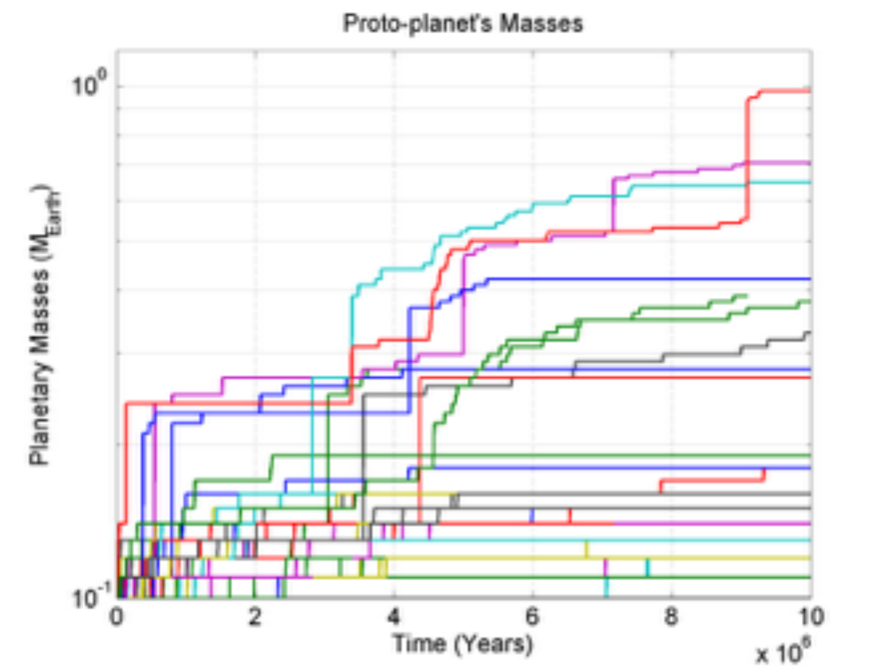
Disc mass = 1.5x MMSN
Metallicity = 0.5 x solar
Planetesimal sizes = 100 m



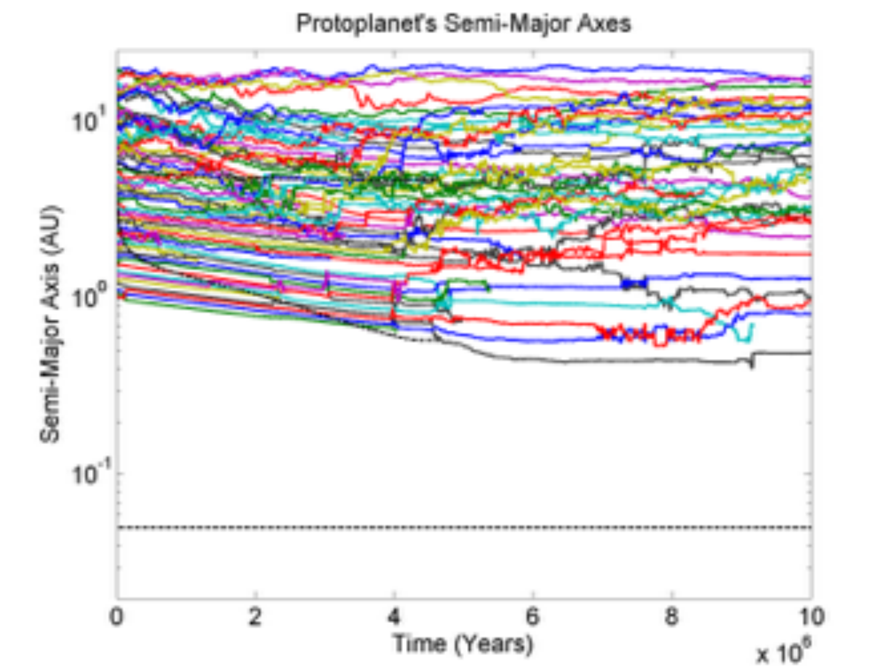


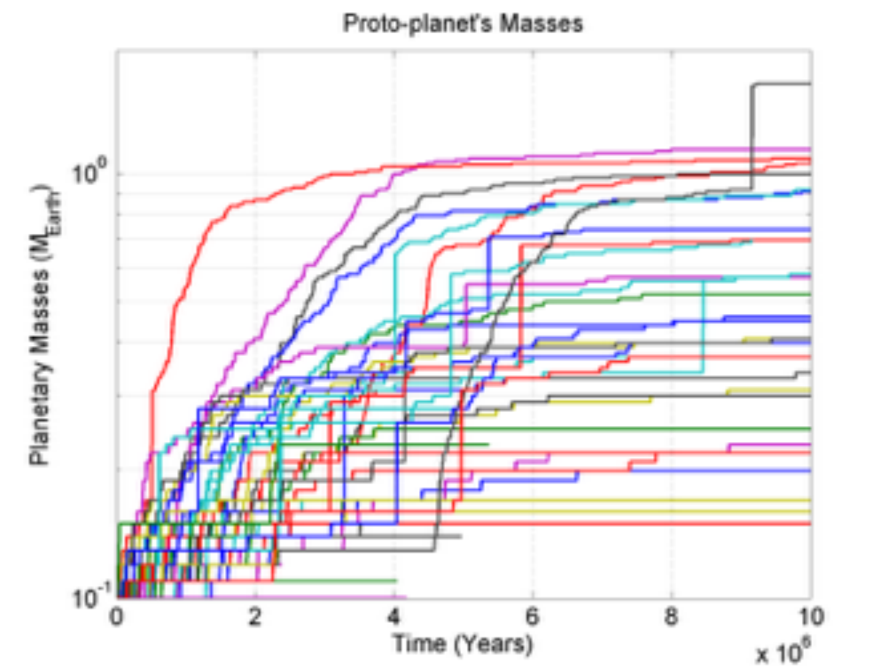
Disc mass = 1.5x MMSN
Metallicity = 0.5 x solar
Planetesimal sizes = 10 m



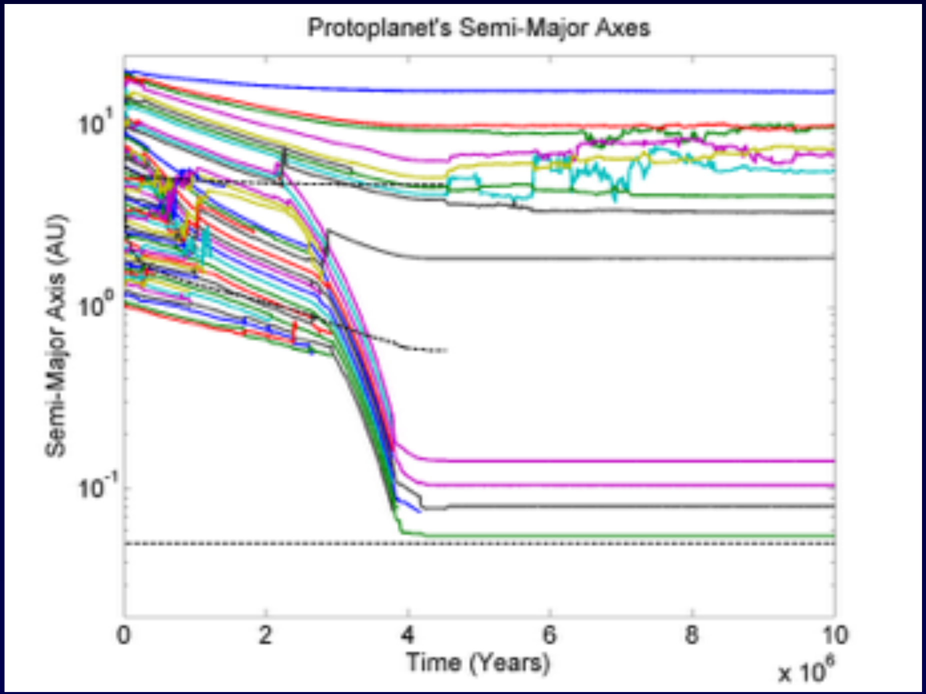


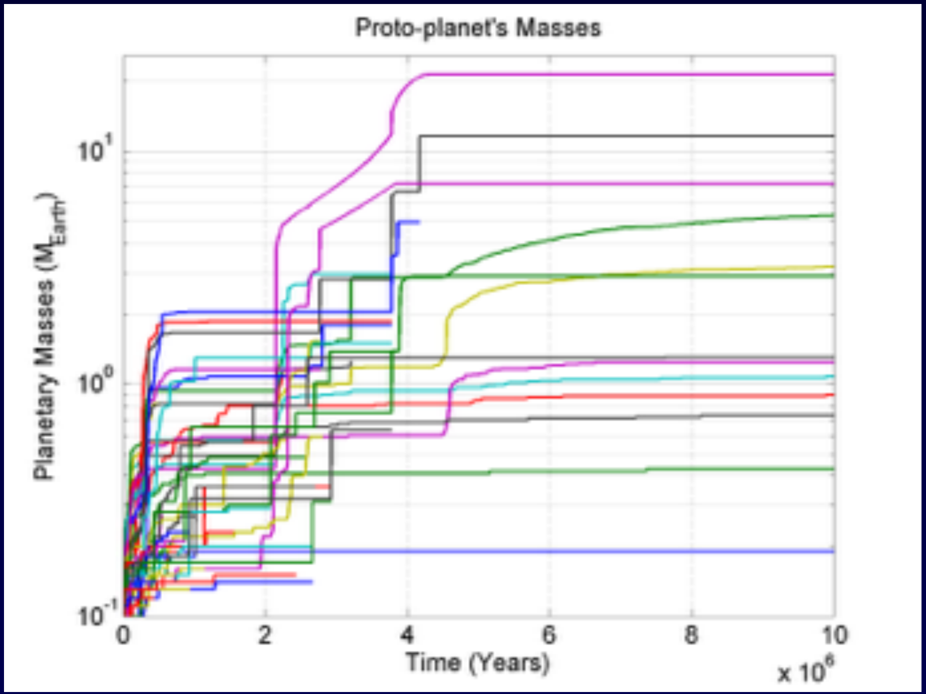
Disc mass = 1 x MMSN
Metallicity = 2 x solar
Planetesimal sizes = 10 km



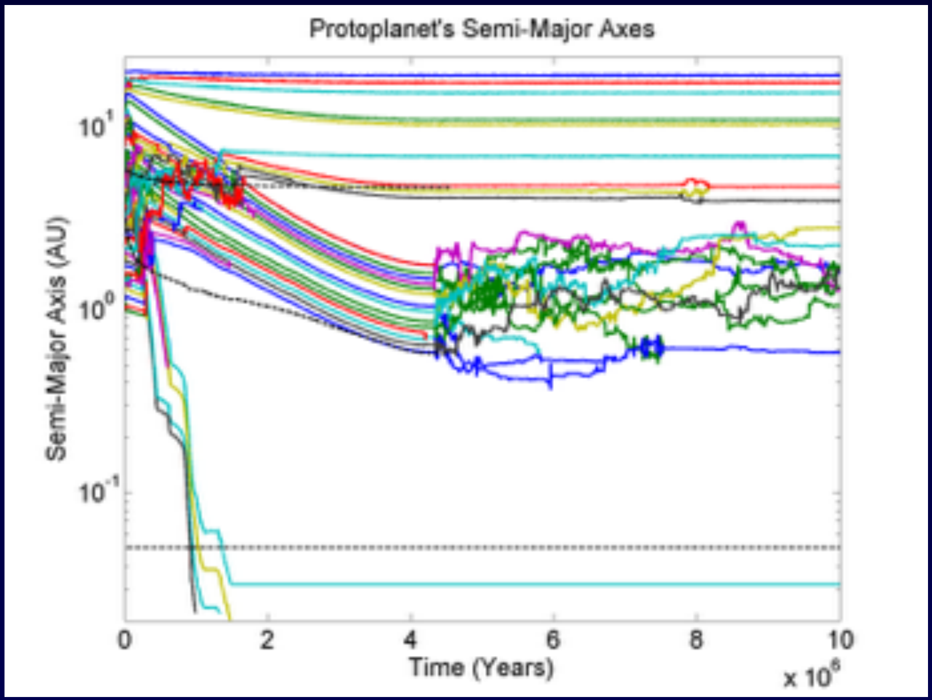


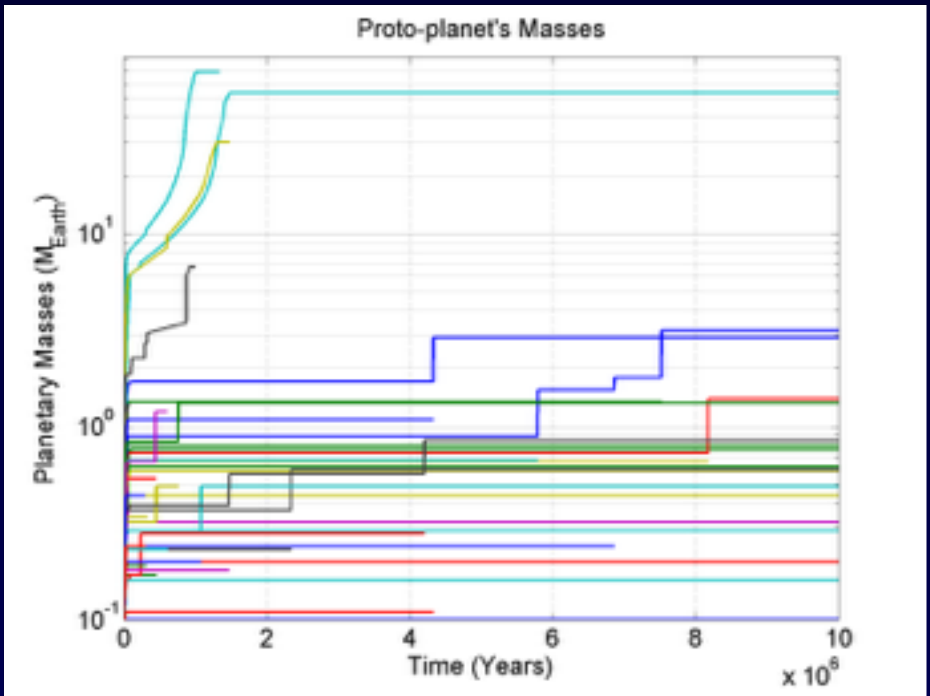
Disc mass = 1 x MMSN
Metallicity = 2 x solar
Planetesimal sizes = 1 km



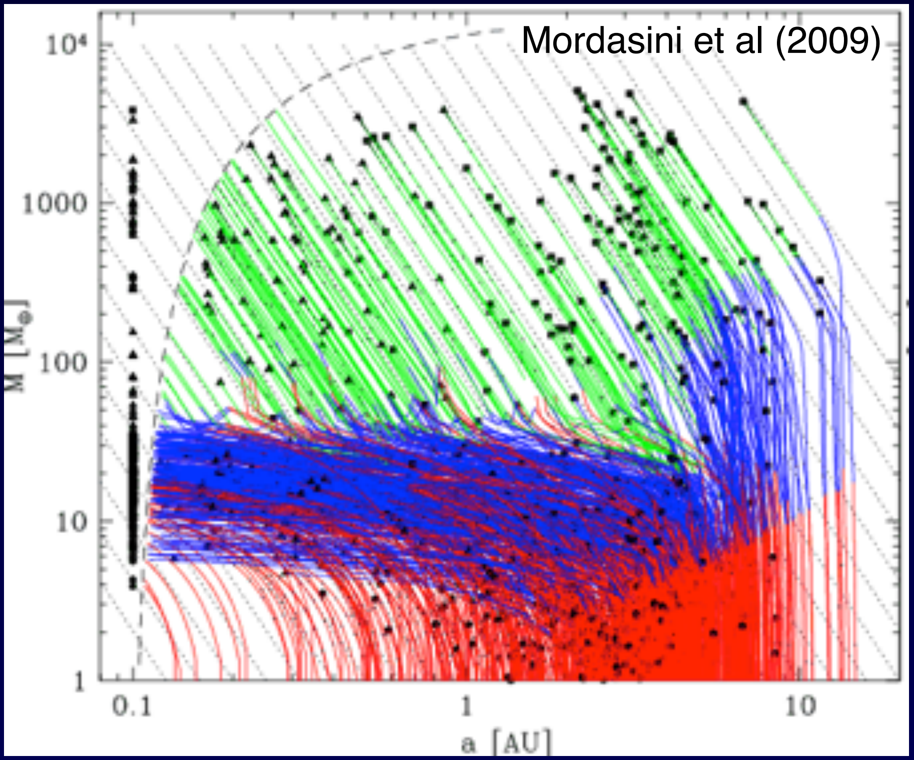


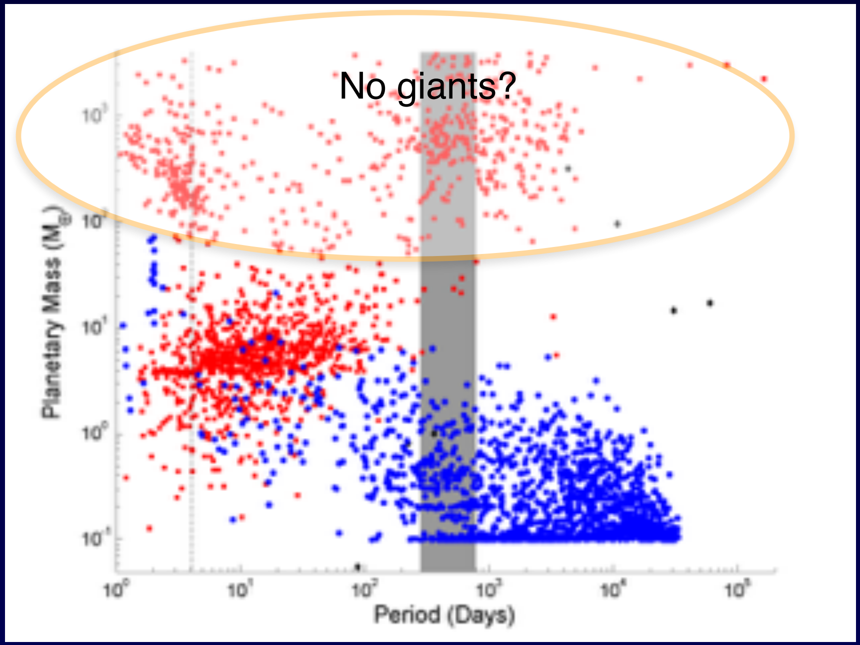
Disc mass = 1 x MMSN
Metallicity = 2 x solar
Planetesimal sizes = 100 m



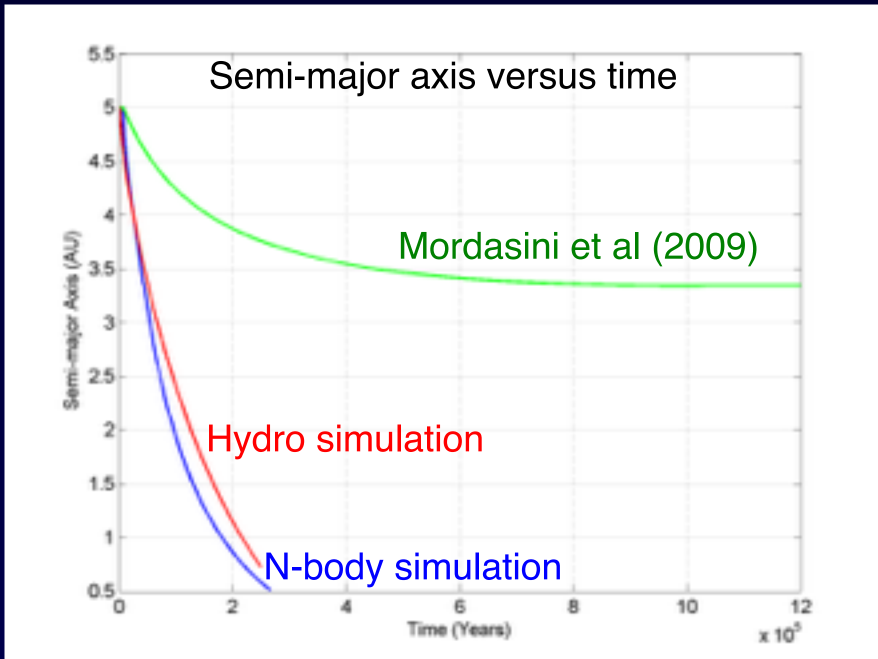


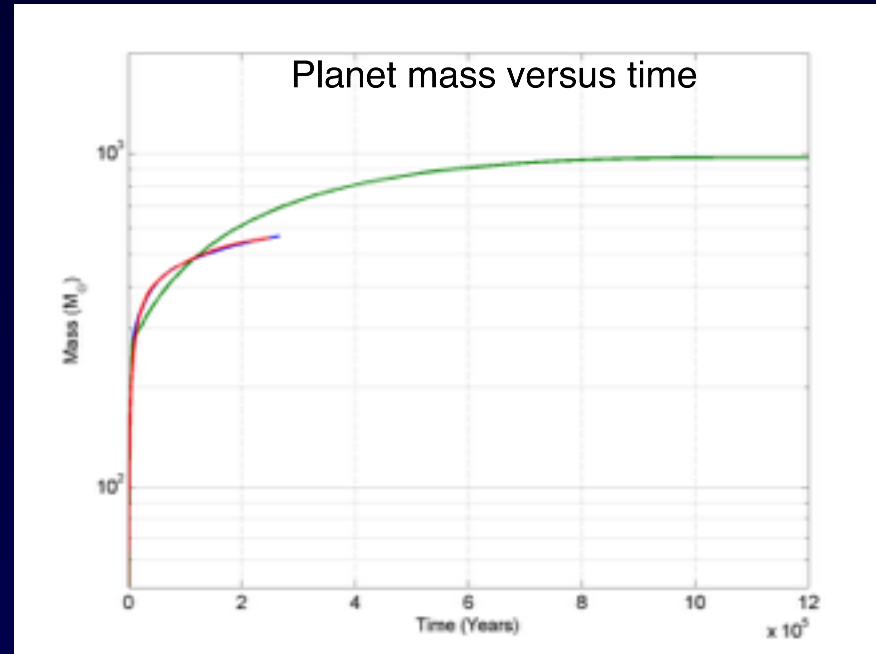
Disc mass = 1 x MMSN
Metallicity = 2 x solar
Planetesimal sizes = 10 m

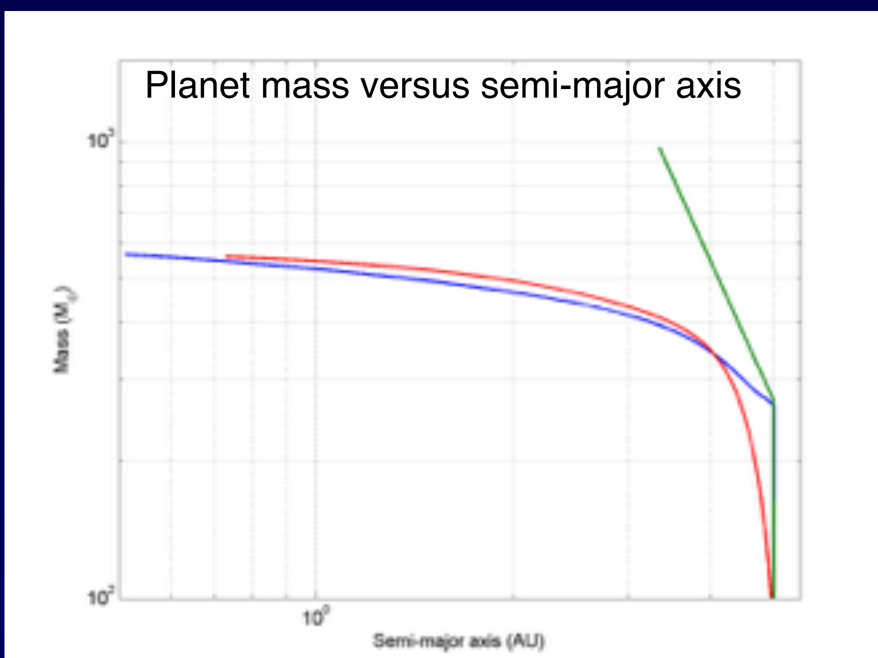

Mordasini et al (2009)
10⁴
1000
100
10
1
M [M⊕]
0.1
1
10
a [AU]

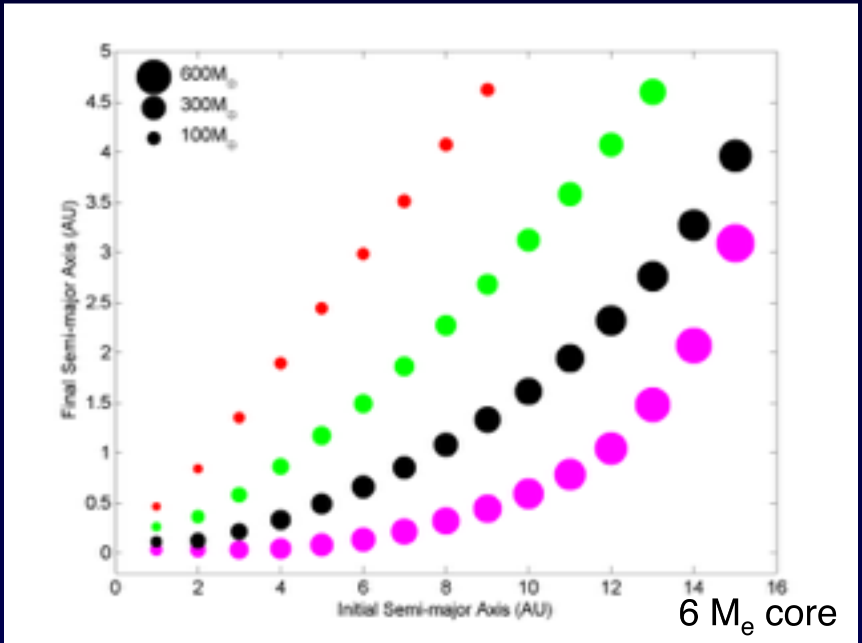

No giants?
Planetary Mass (M⊕)
Period (Days)

Giant planet formation and survival


Semi-major axis versus time
Mordasini et al (2009)
Hydro simulation
N-body simulation
Semi-major Axis (AU)
Time (Years)
x 10^5


Planet mass versus time
Mass (M⊕)
Time (Years)
x 10^5


Planet mass versus semi-major axis
Mass (M⊕)
Semi-major axis (AU)



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

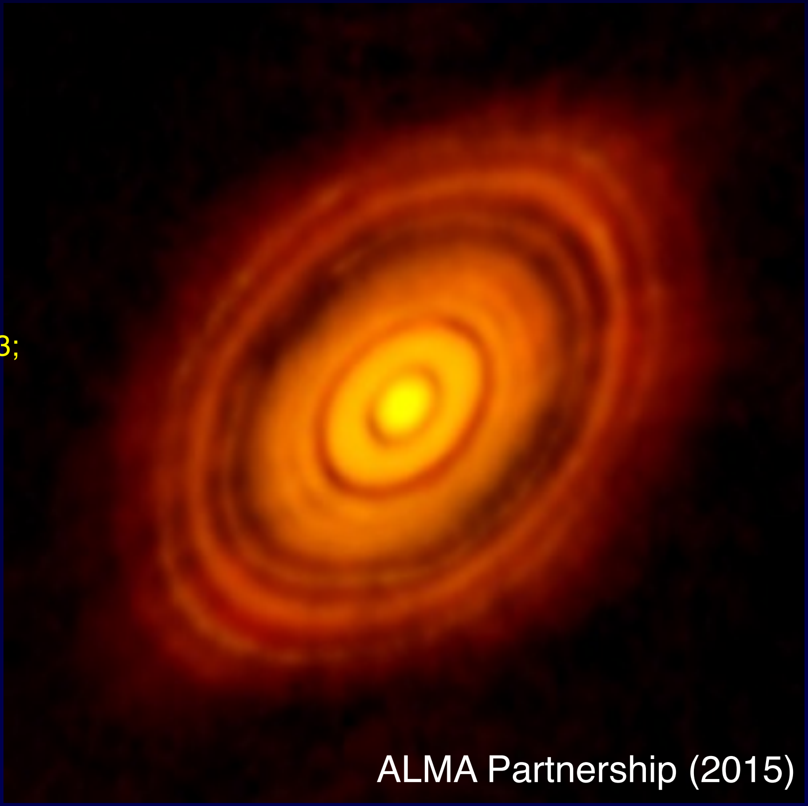
How to maintain cores at large distance and avoid rapid inward type I migration?

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

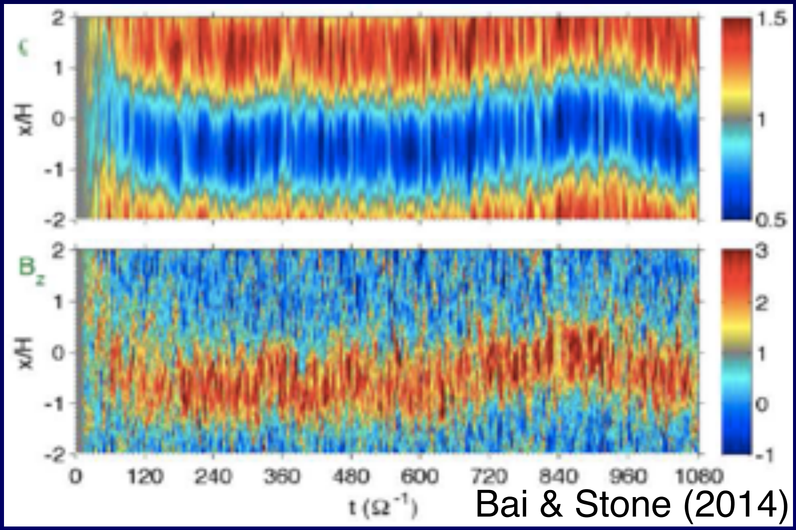
Zonal flows observed in MHD simulations of disc turbulence (Papaloizou & Steinacker 2003; Papaloizou & Nelson 2003; Johansen et al 2009; Bai & Stone 2014)

A simple toy model:

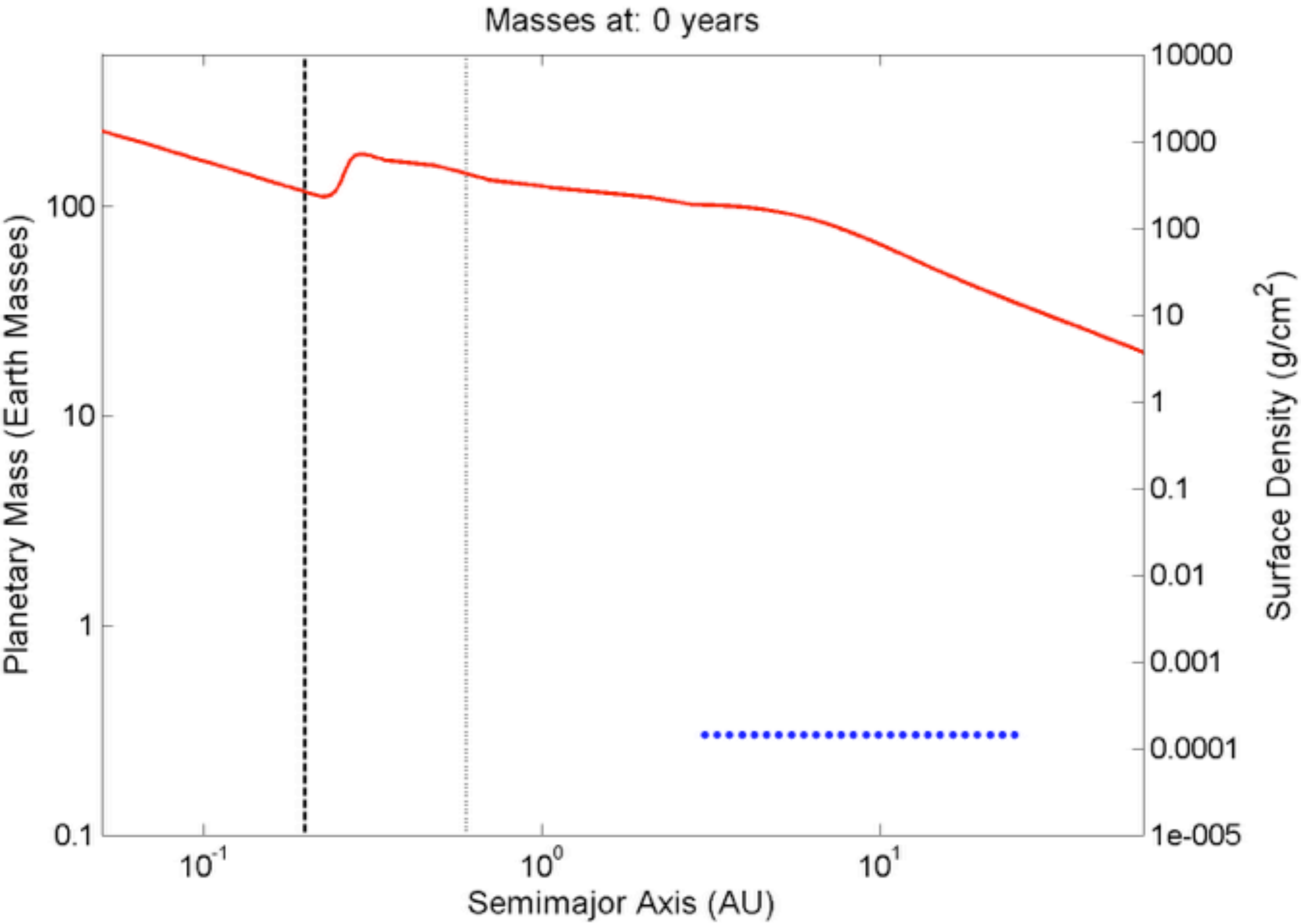
- Choose radii where viscous α varies by ~ 50%
- Set life time of *zonal flows* ~ 50,000 local orbits
- Choose new radius to apply zonal flow after life time has elapsed



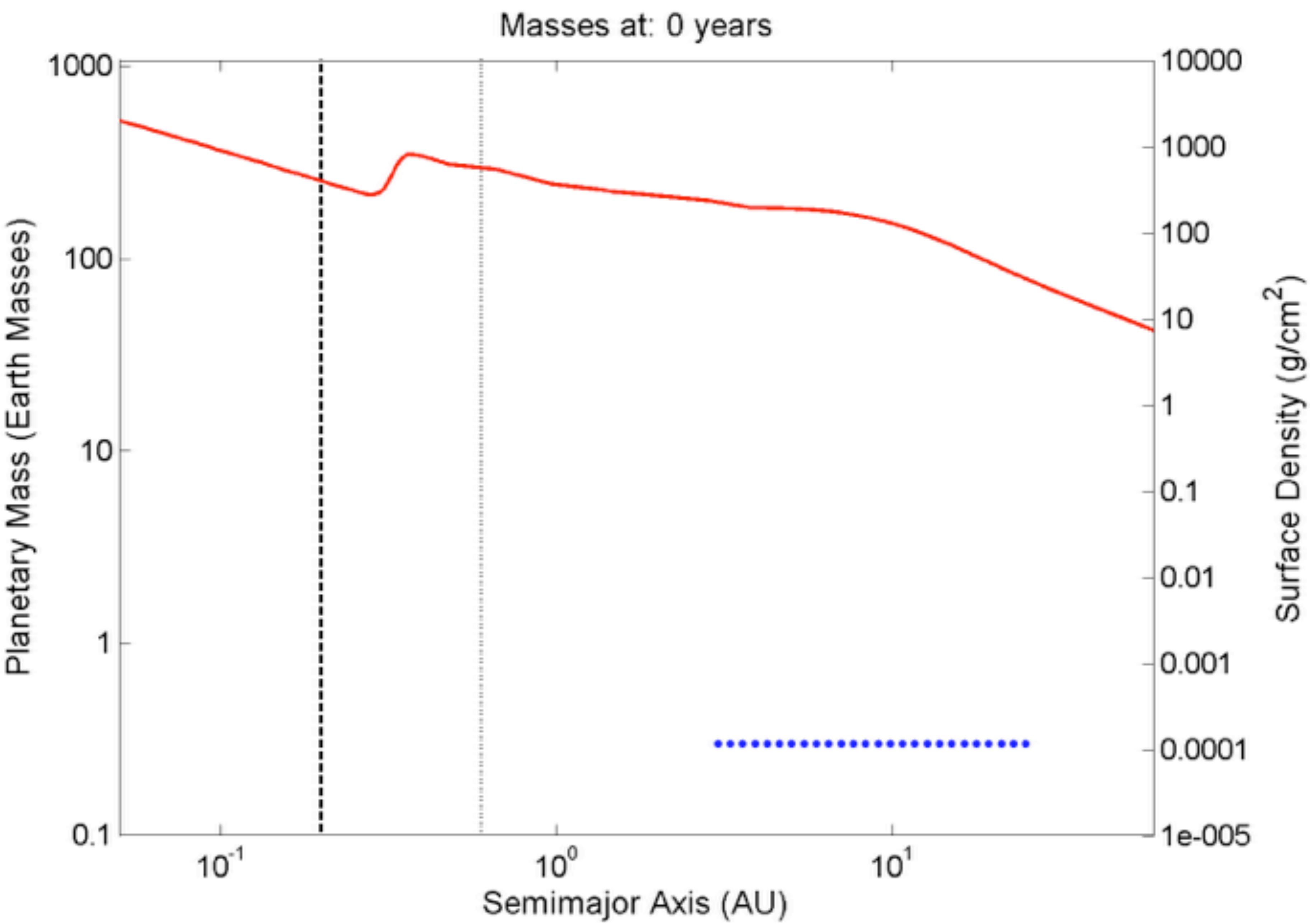
ALMA Partnership (2015)



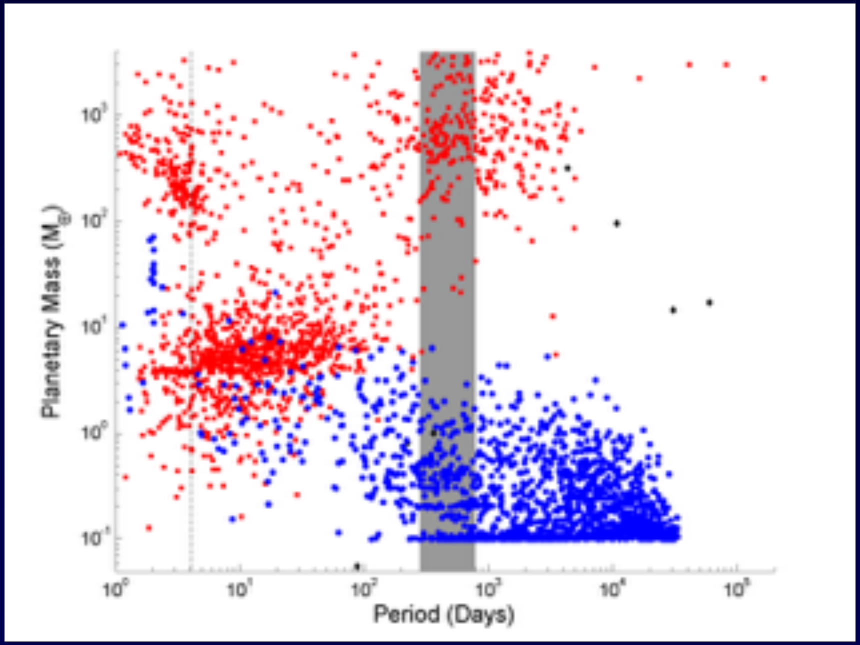
Bai & Stone (2014)



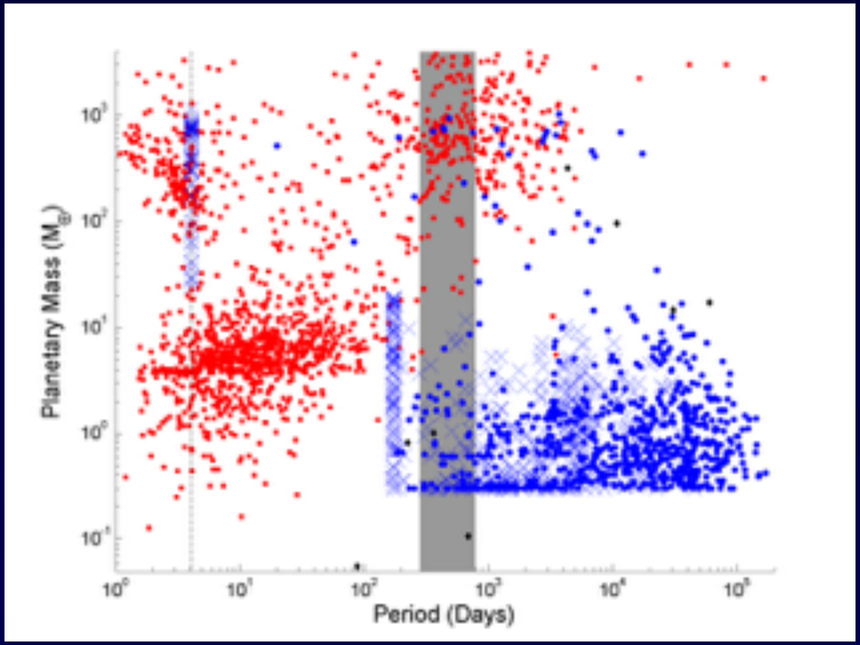
Masses at: 0 years
Planetary Mass (Earth Masses)
100
10
1
0.1
Surface Density (g/cm^2)
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-005
10^{-1}
10^{0}
10^{1}
Semimajor Axis (AU)



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



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…

• Slow or no type II migration at large and small orbital radii may explain the observed period distribution for giant exoplanets