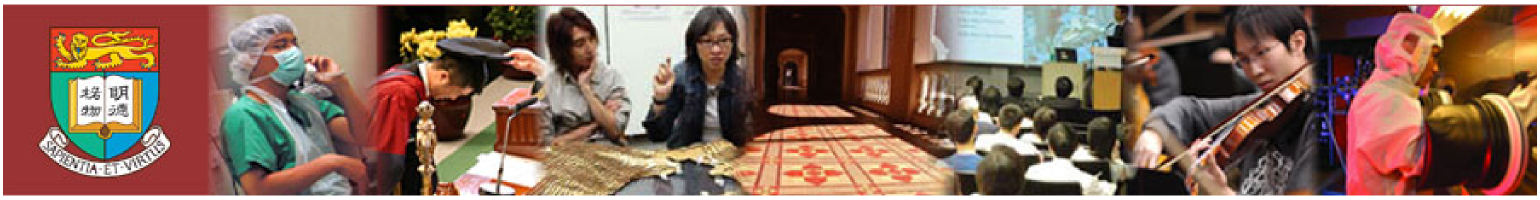


Surviving type I migration (the old and the new):
oligarchic formation of hot Neptunes

D.S. McNeil
R.P. Nelson

Overview

- Hot Neptunes, and why we care

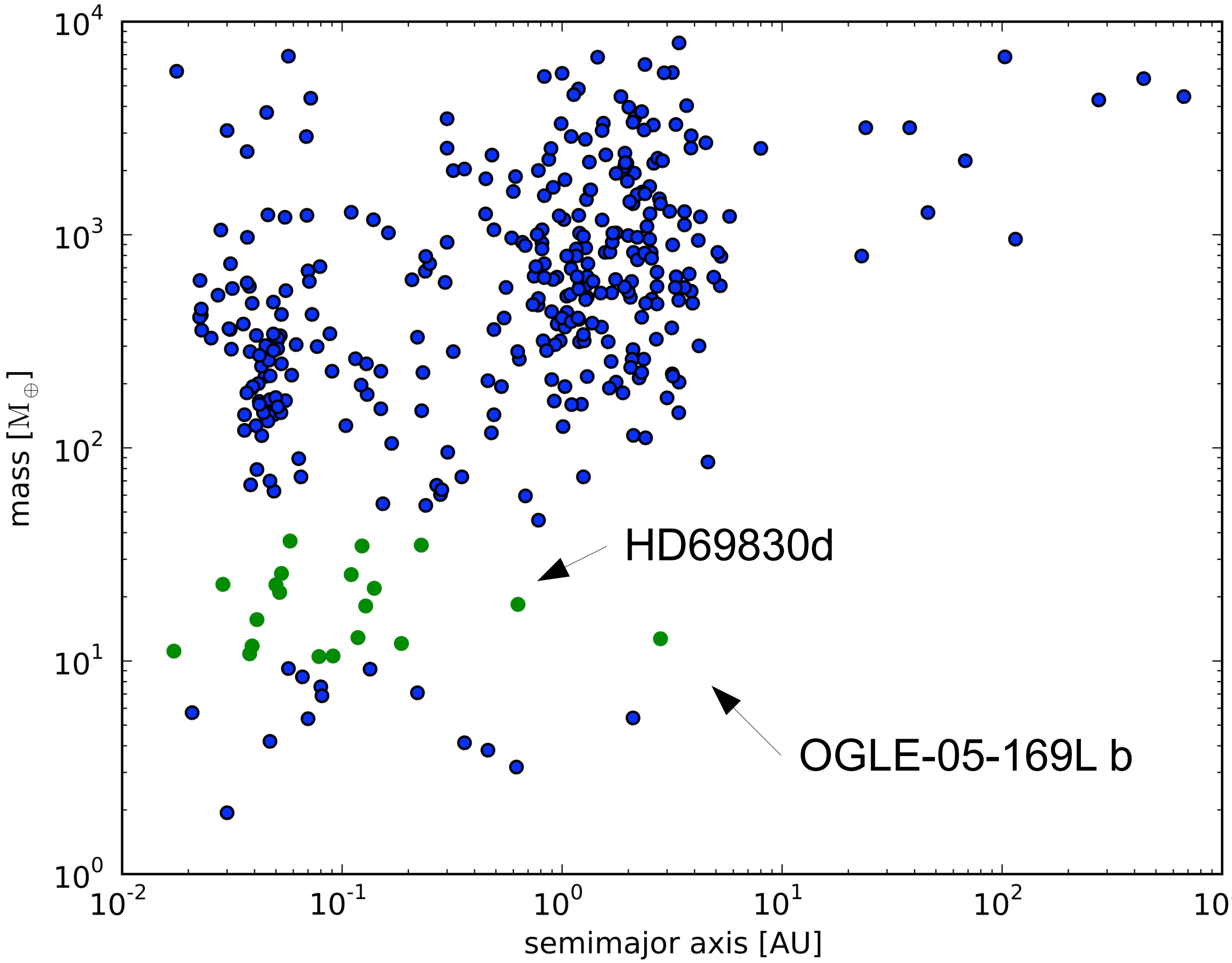
- The old migration:
  - Predictions of the simplest classic oligarchy + type I models

- The new Paardekooper migration
  - A simple toy model
  - A more accurate model

- Where we are now

The exoplanet distribution

(as of August 2009)



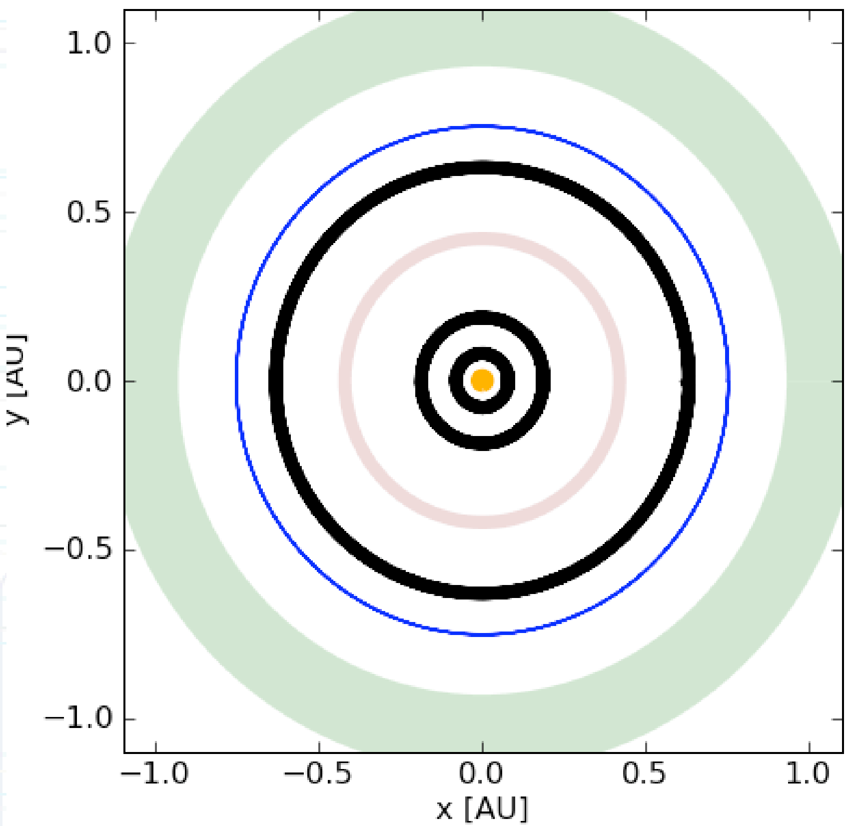
Why are hot Neptunes important?

- large enough to be observable (~20 known)
- large enough to undergo dangerous amounts of type I migration (unlike Earths)
- small enough that they formed via core accretion
- small enough that they can't open a gap and switch to type II

→ excellent probes of type I migration

Our favourite Neptunes

HD69830 (Lovis et al. 2006)



object	mass	a [AU]	ecc.
b	10.5 M_E	0.0785	0.10 ± 0.04
c	12.1 M_E	0.186	0.13 ± 0.06
~~Beichman et al. (2005) asteroid belt~~	25 x AB? (22-64) Sedna?	0.42	
d	18.4 M_E	0.63	0.07 ± 0.07
water?		0.72?	
Lisse et al. (2006) debris disc	> 3 x 10^{17} kg	0.93-1.16	

What does the simplest model (oligarchy + the traditional type I) predict?

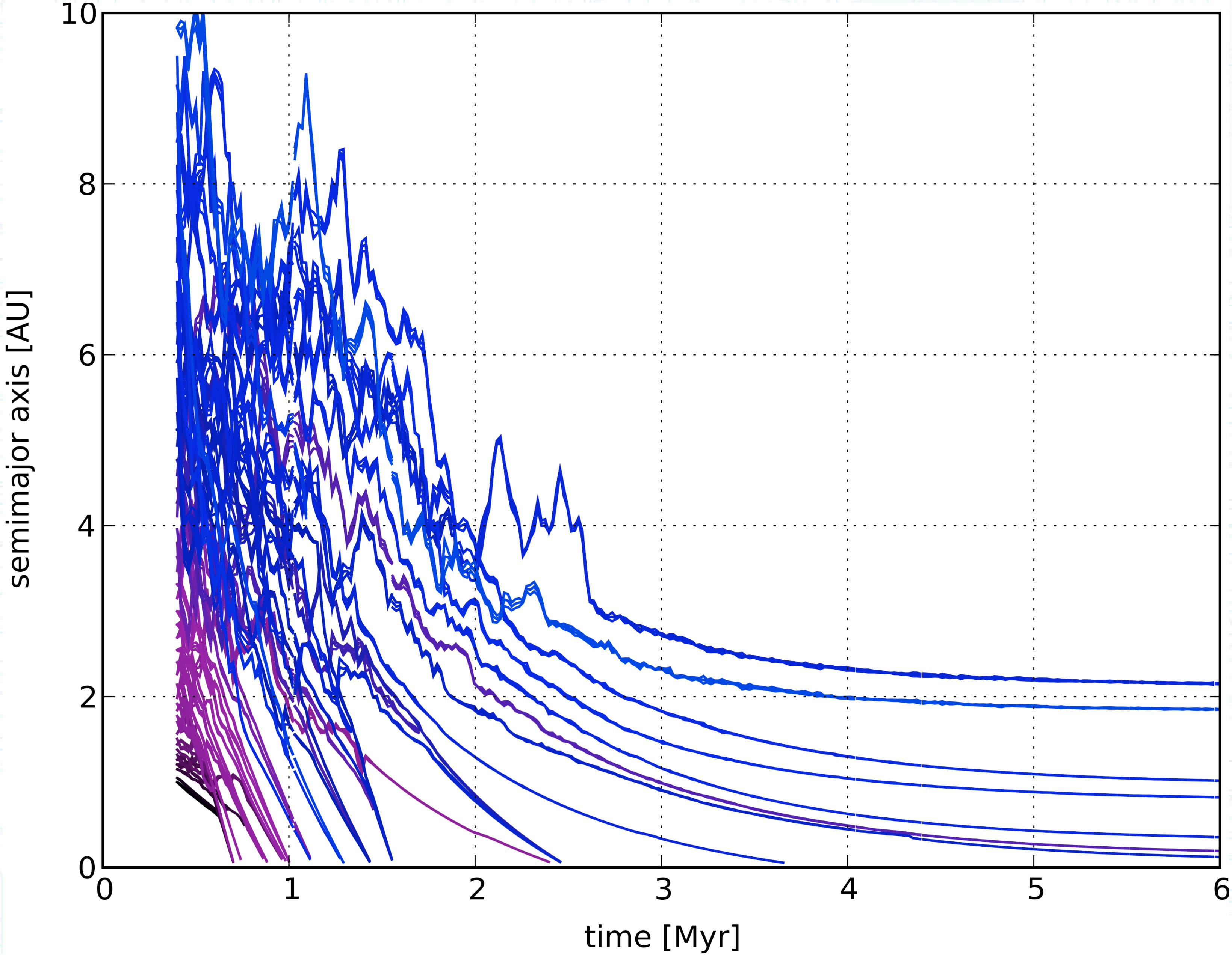
Method: Moderate resolution N-body integrations using multiscale parallel Kepler-adapted symplectic integrator NAOKO [McNeil & Nelson 2009a]

Tanaka et al. (2002) type I torques

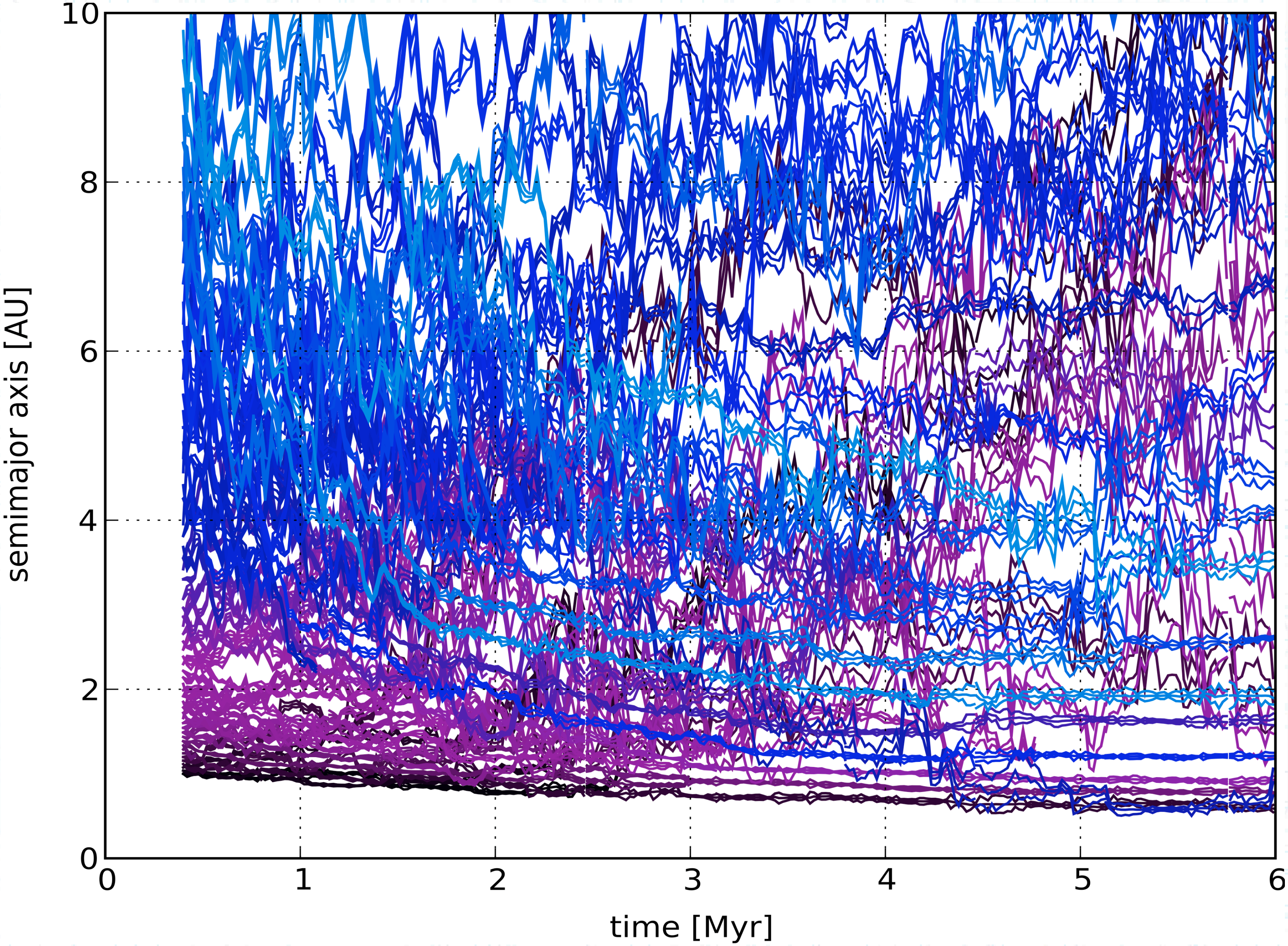
$$\Gamma_{\rm total}(3D) = (1.364 + 0.541\alpha)\left(\frac{M_p}{M_c}\frac{r_p\Omega_p}{c}\right)^2 \sigma_p r_p^4 \Omega_p^2$$

$$\Gamma_{\rm total}(2D) = (1.160 + 2.828\alpha)\left(\frac{M_p}{M_c}\frac{r_p\Omega_p}{c}\right)^2 \sigma_p r_p^4 \Omega_p^2$$

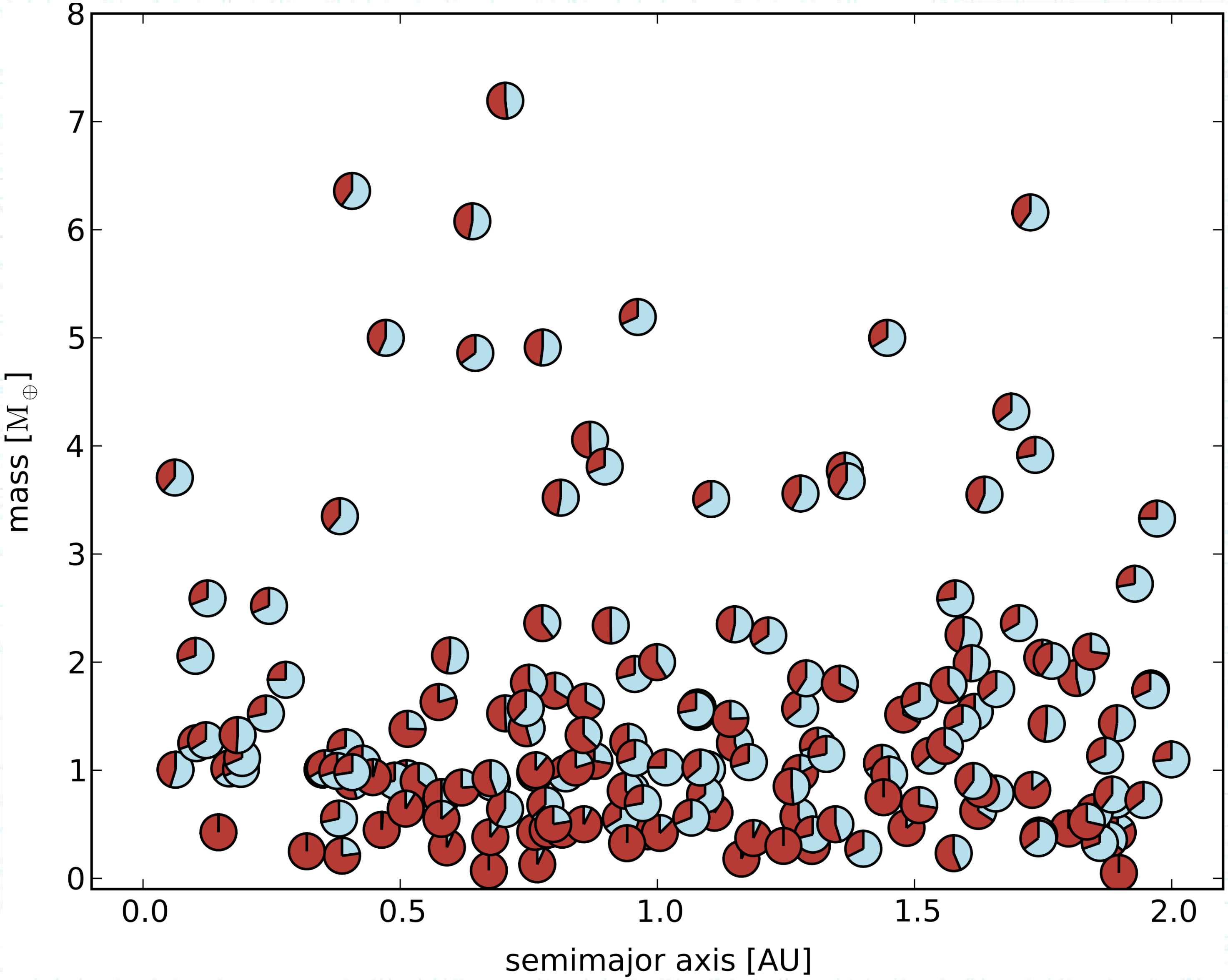
5x, -1, 1.0, 1 Myr



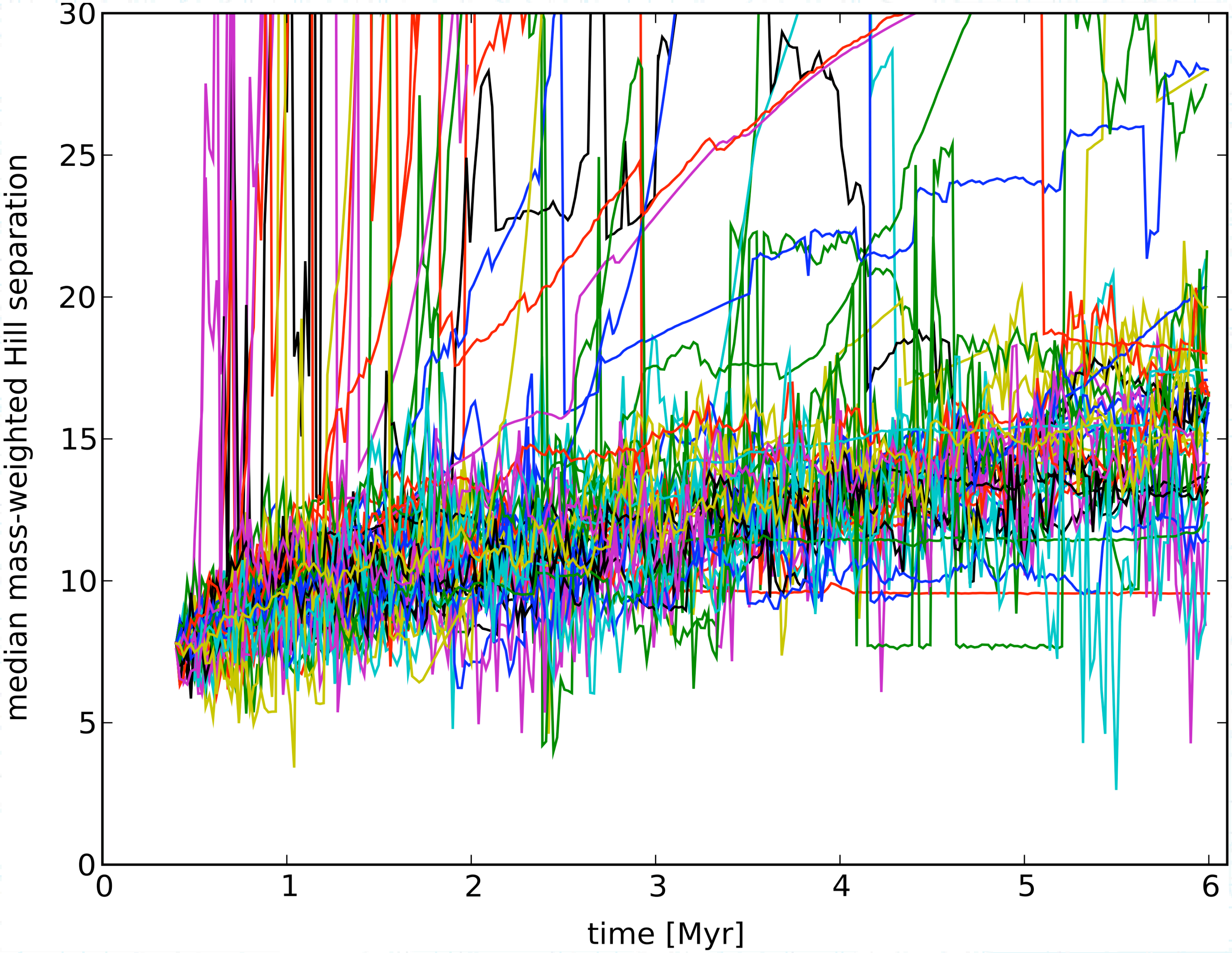
5x, -0.001, 1.0, 1 Myr



Resulting systems: summary [McNeil & Nelson 2009b]



$\tilde{b}$ is **not** 10!



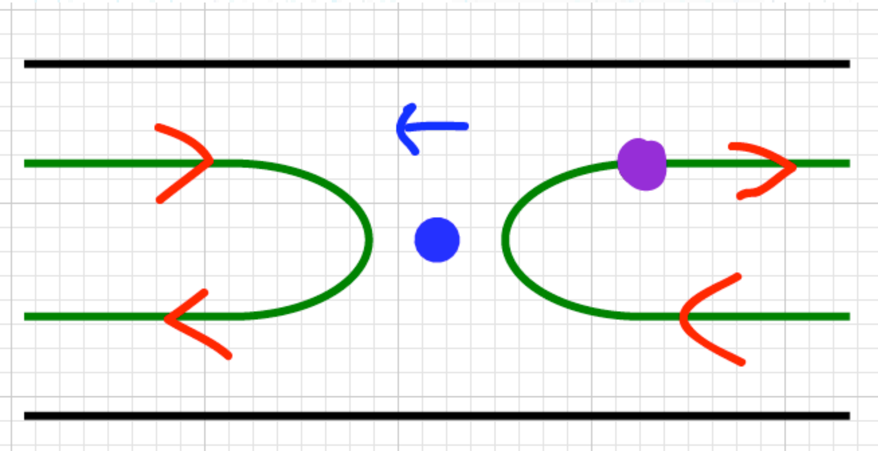
The new type I migration

Paardekooper & Mellema 2006; Baruteau & Masset 2008;
Paardekooper & Mellema 2008; Paardekooper & Papaloizou 2008;
Kley & Crida 2008; Kley, Bitsch, Klahr 2009; Paardekooper et al. 2009

$$\frac{\gamma\Gamma}{\Gamma_0} = \left[-2.5 - 1.7\beta + 0.1\alpha\right] + \left[1.1\left(\frac{3}{2} - \alpha\right)\right] + \left[7.9\frac{\xi}{\gamma}\right]$$

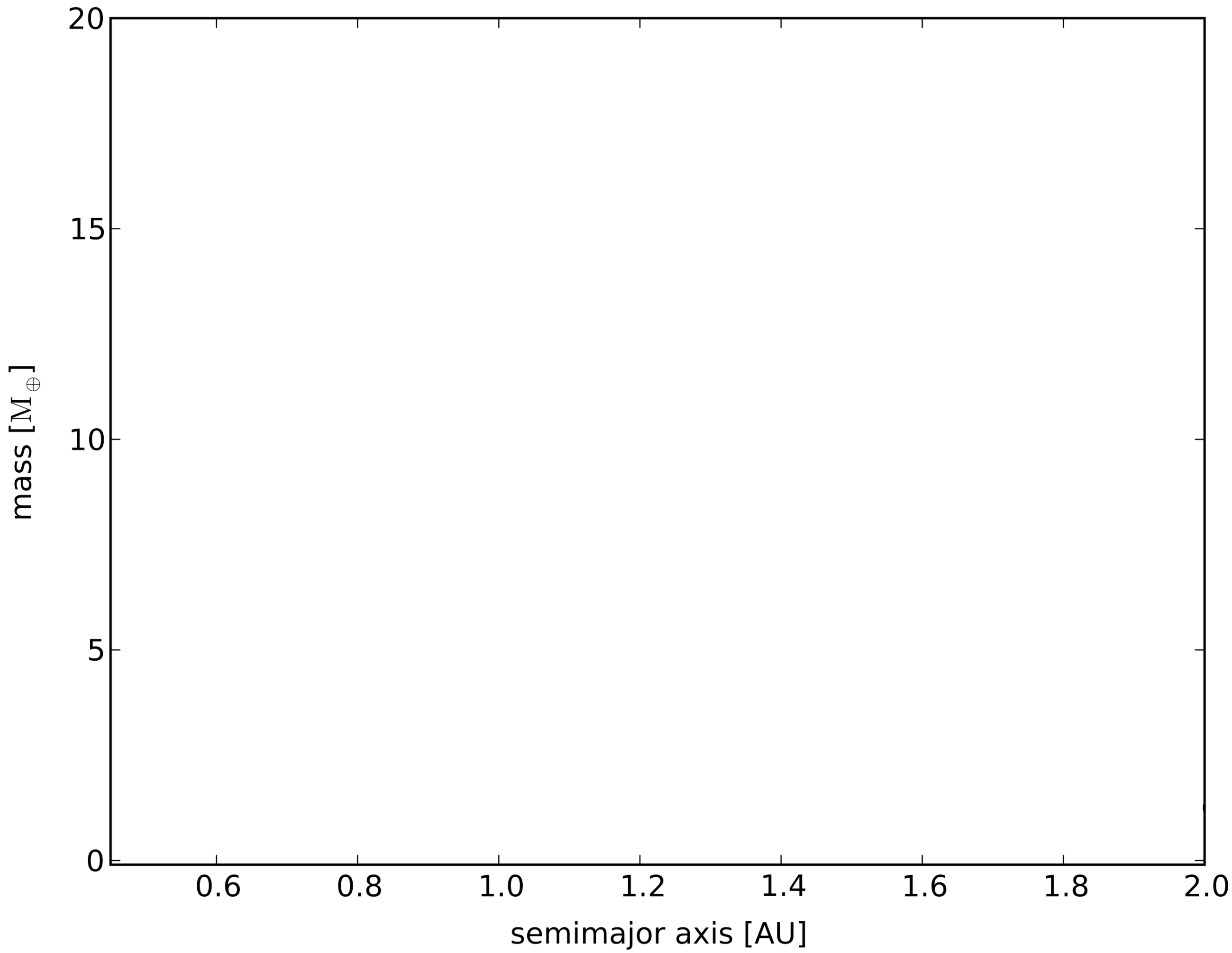
Lindblad torques — Barotropic corotation — Non-barotropic corotation

NBCT can be > LT + BCT → outward motion

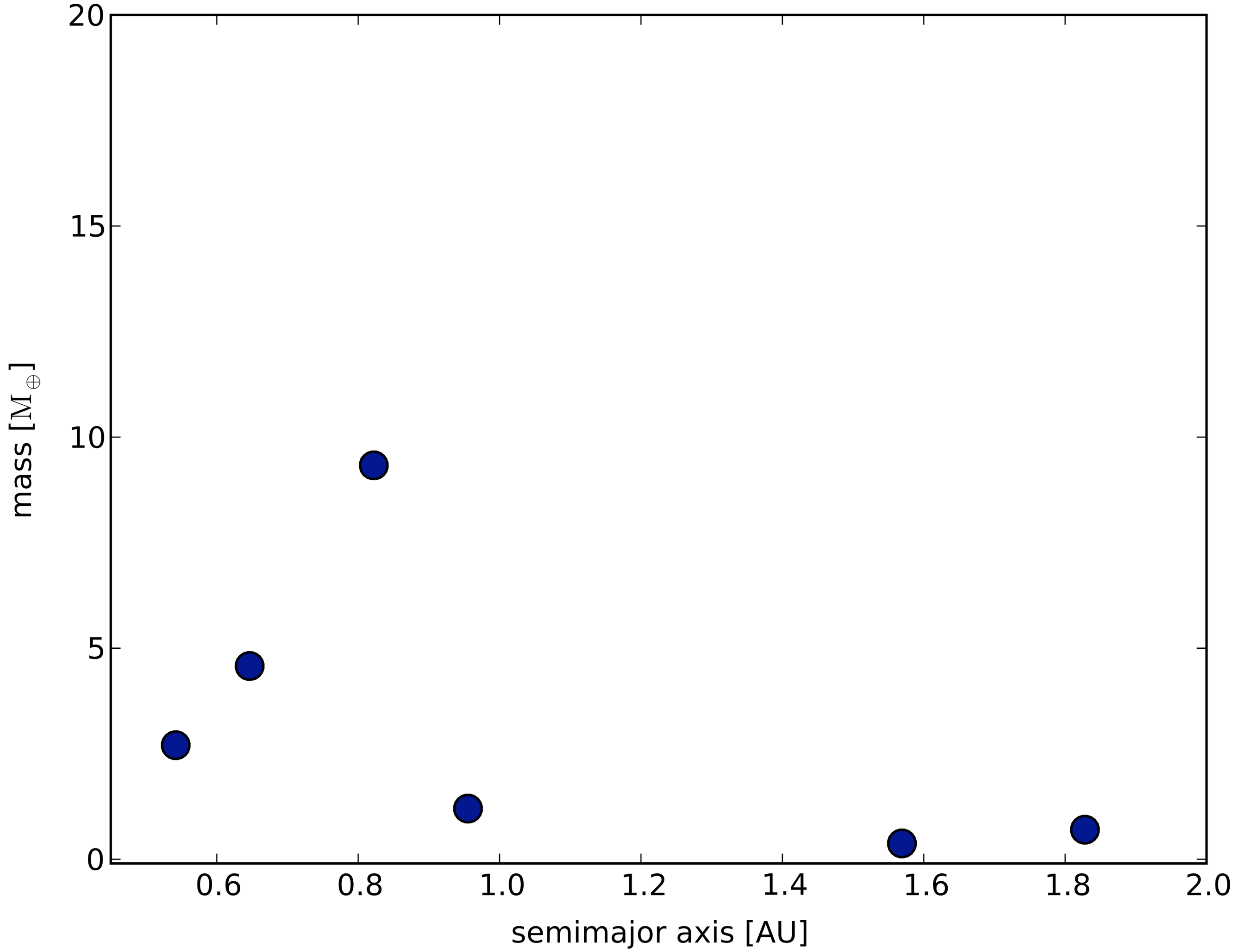


Must avoid saturation: $f[\tau_{lib}/\tau_{diff}] = ?$

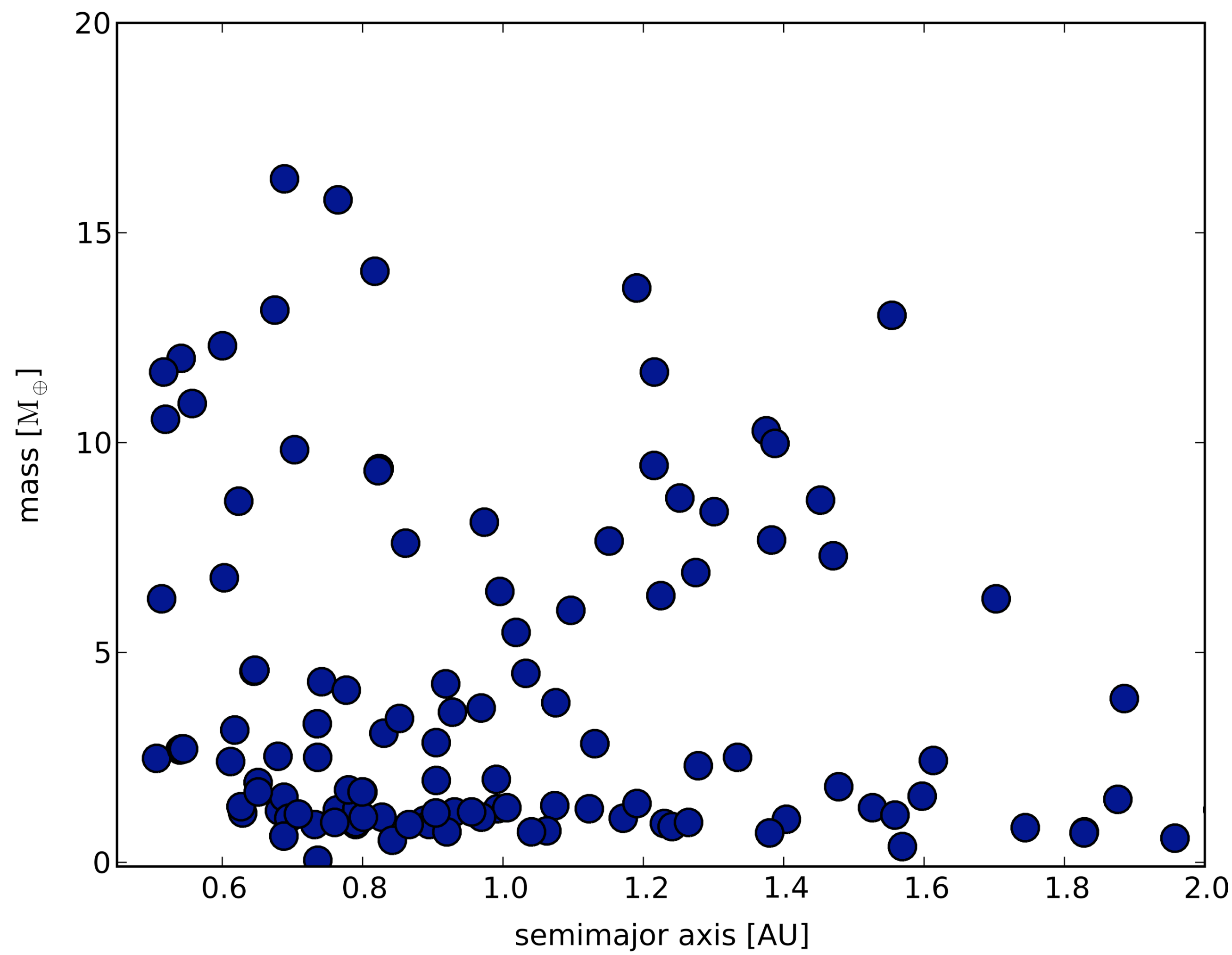
Our first toy model, without NBCT

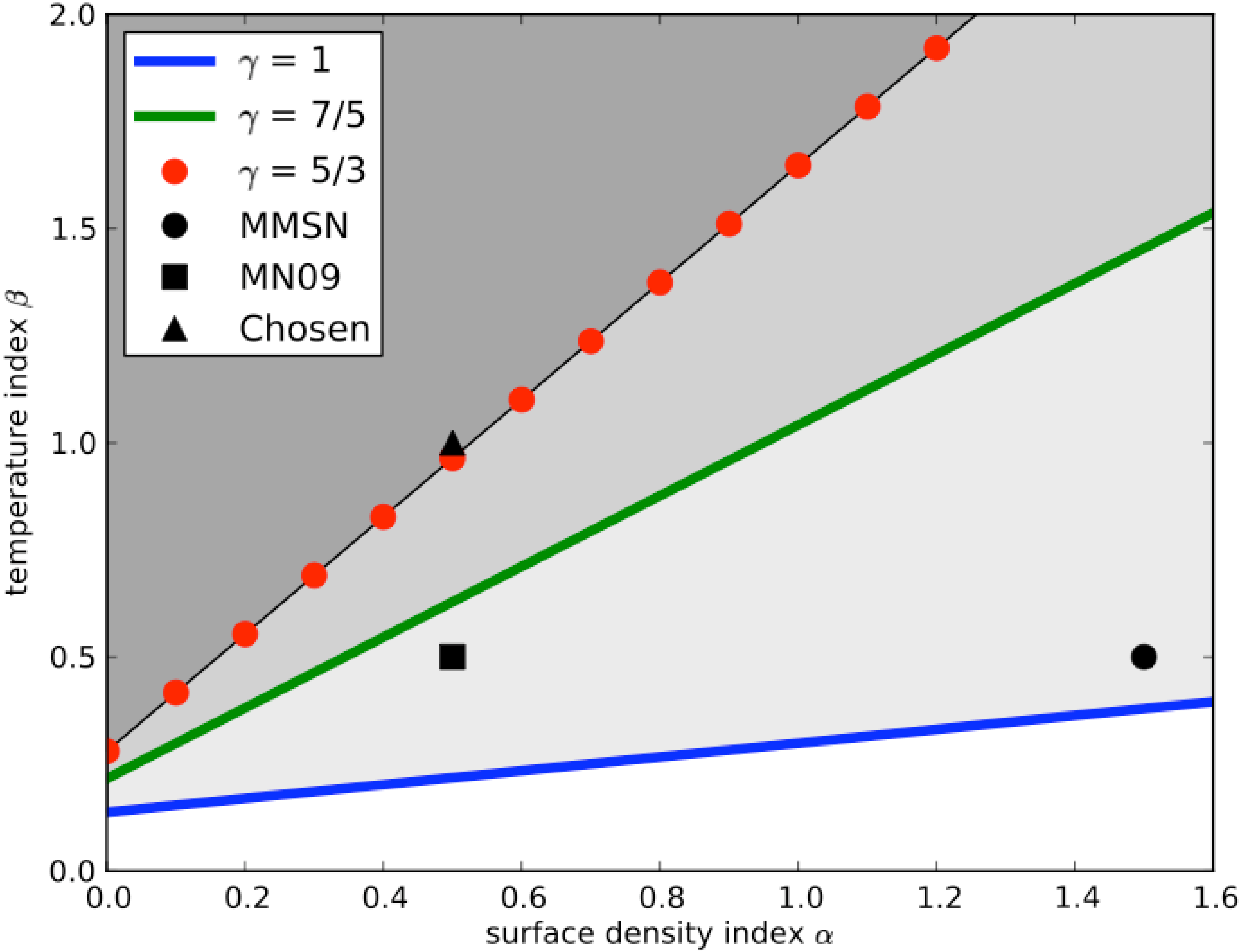


Our very first run with NBCT

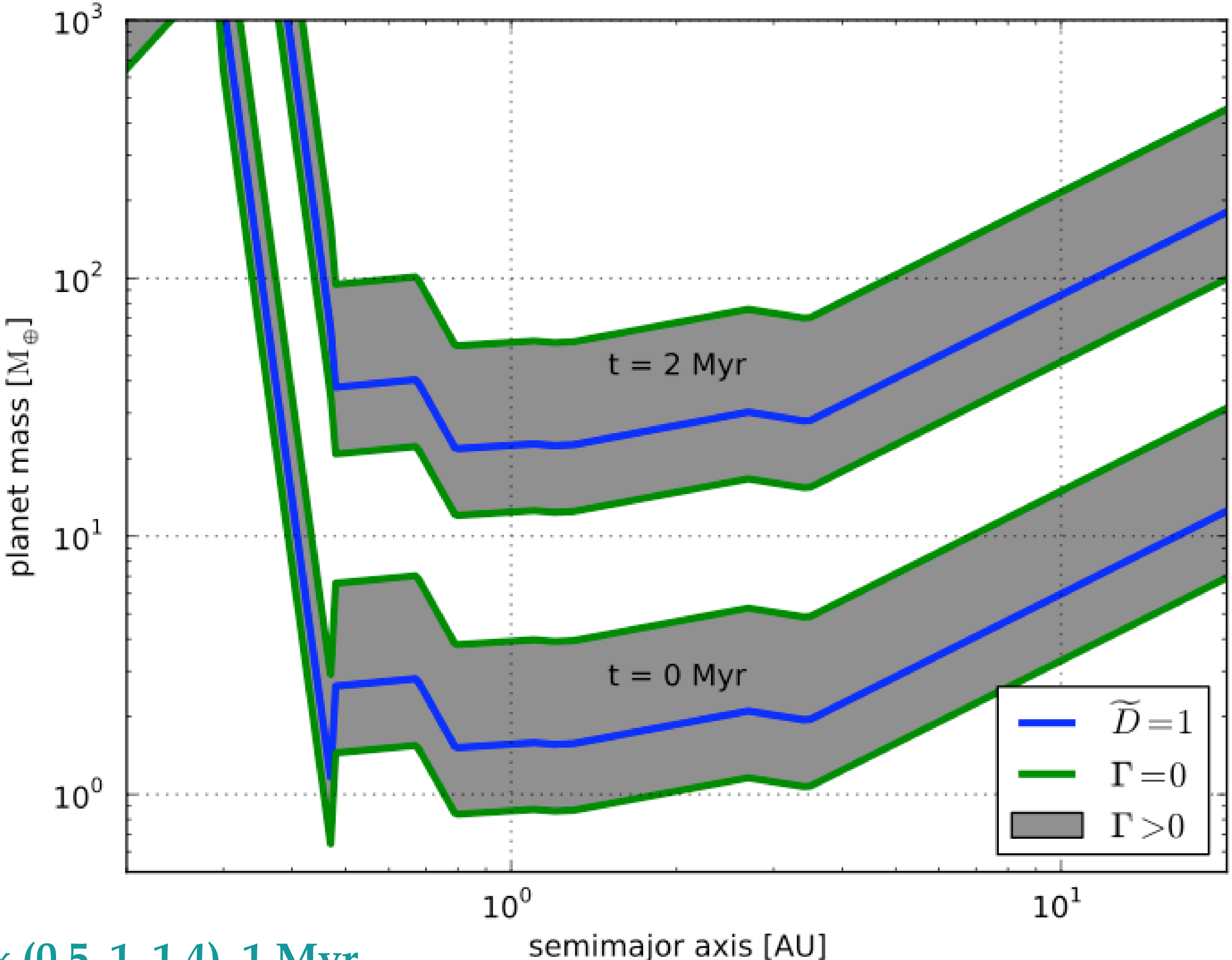


Combined runs with diffusion fudge factor in [0.1..10]

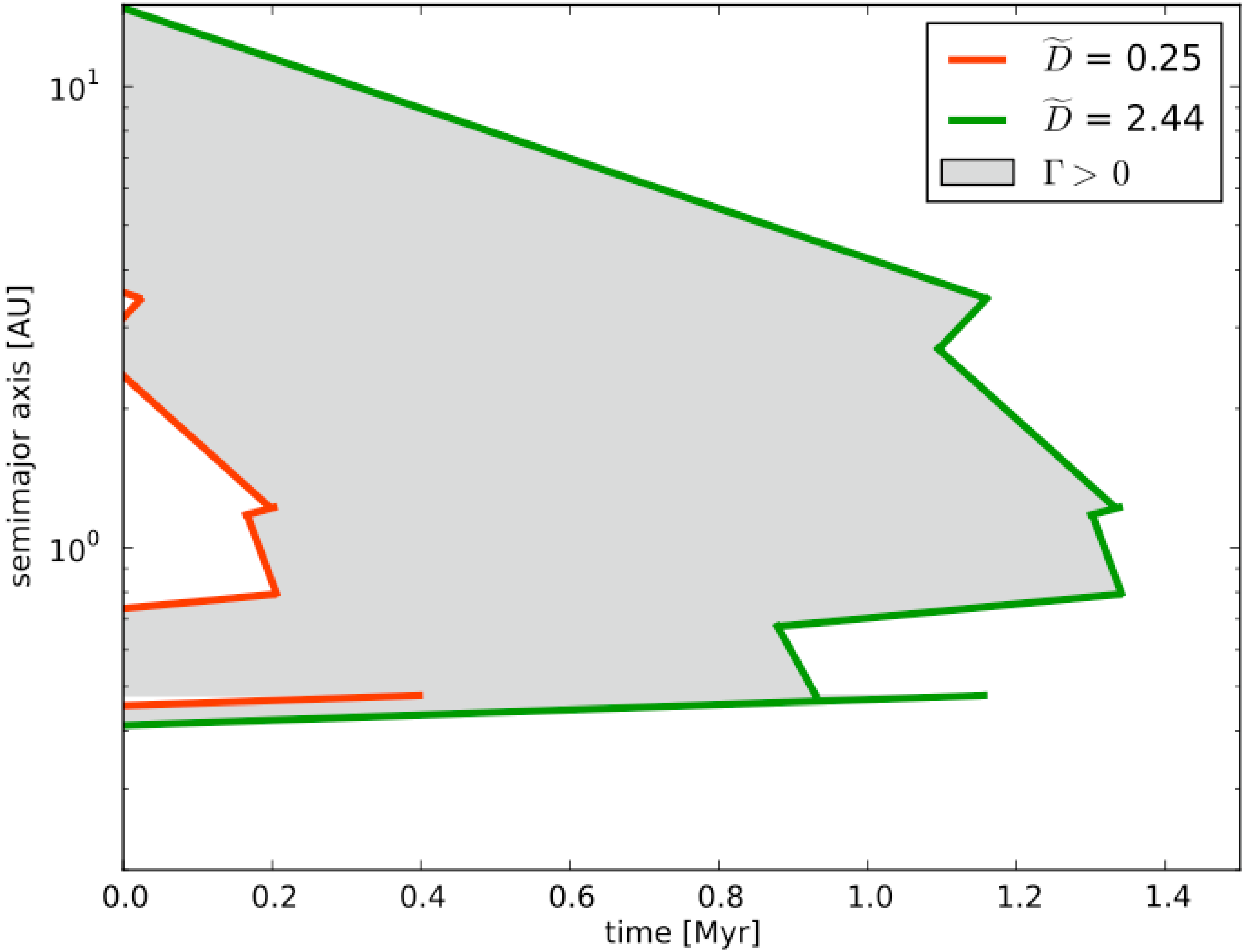




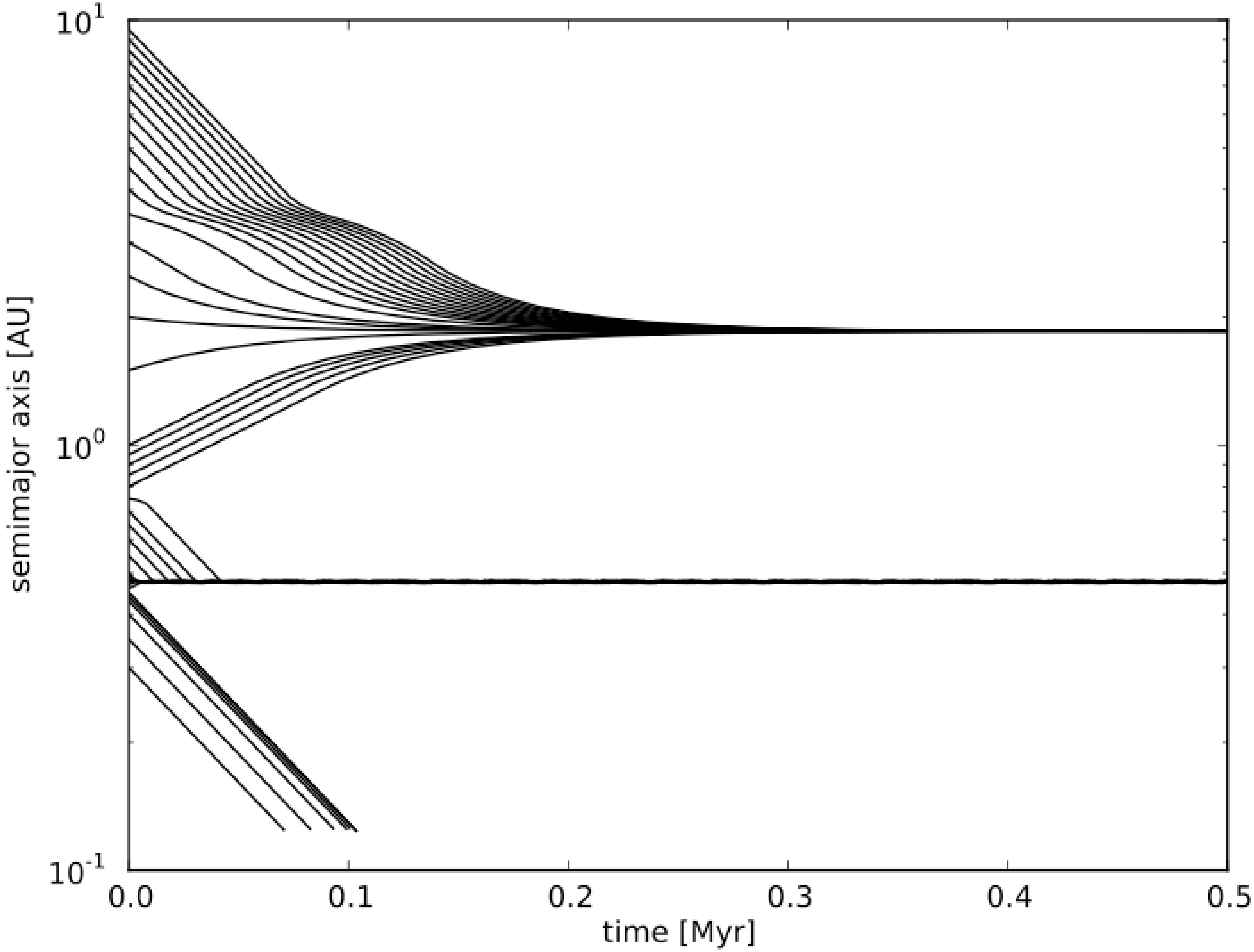
γ = 1
γ = 7/5
γ = 5/3
MMSN
MN09
Chosen
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
temperature index β
surface density index α



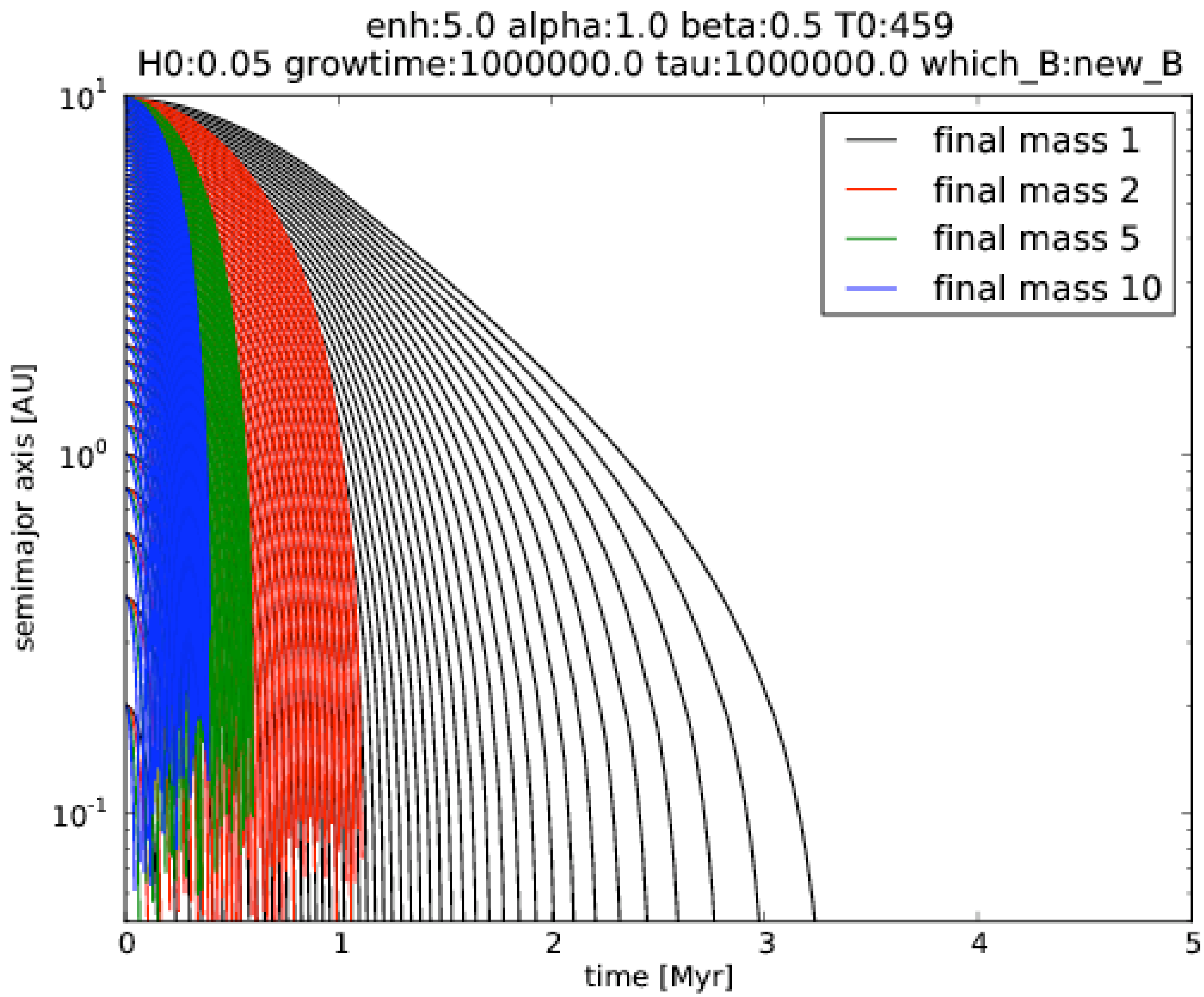
5x (0.5, 1, 1.4), 1 Myr

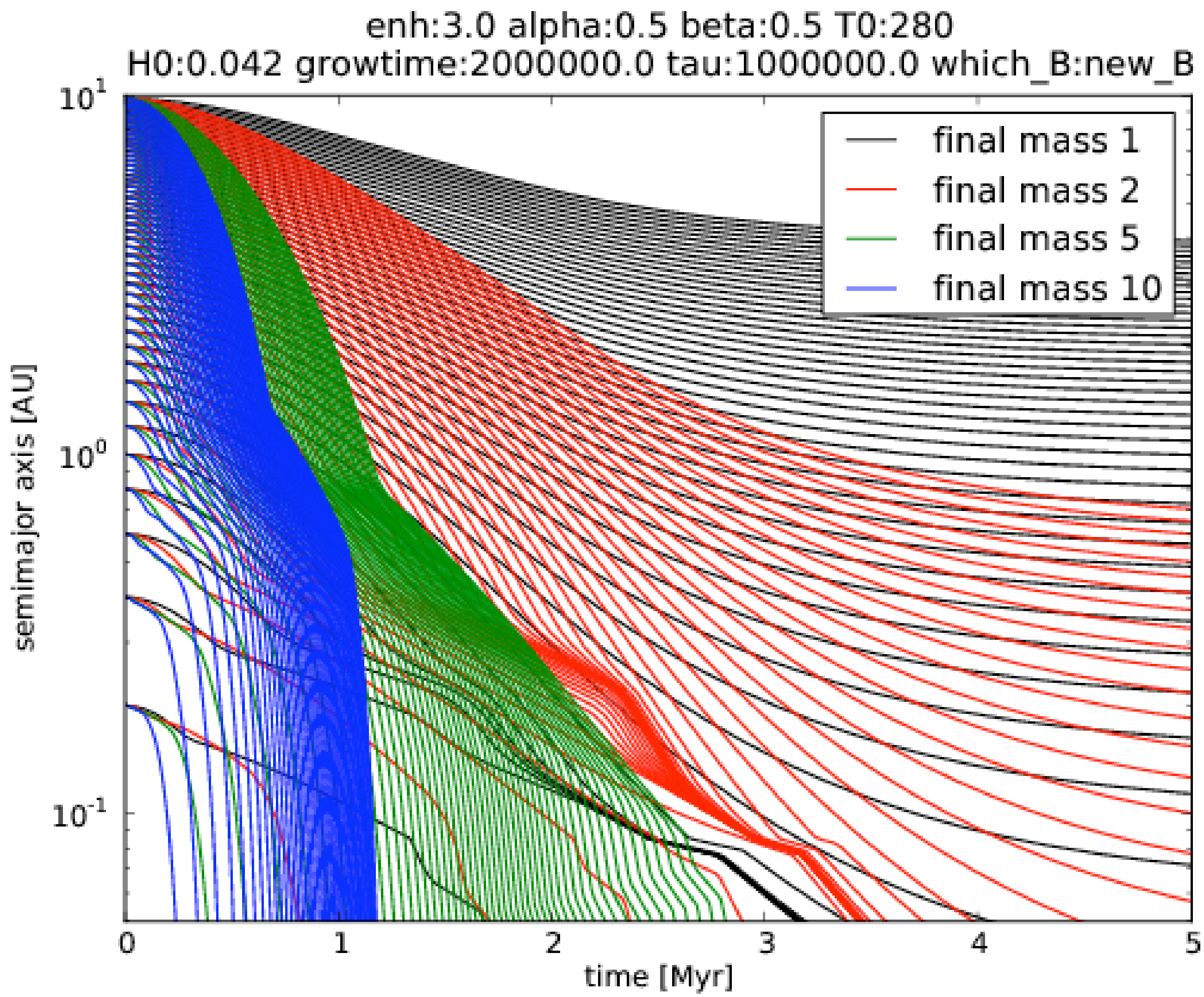


$\widetilde{D}$ = 0.25
$\widetilde{D}$ = 2.44
$\Gamma > 0$
10^1
10^0
semimajor axis [AU]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
time [Myr]

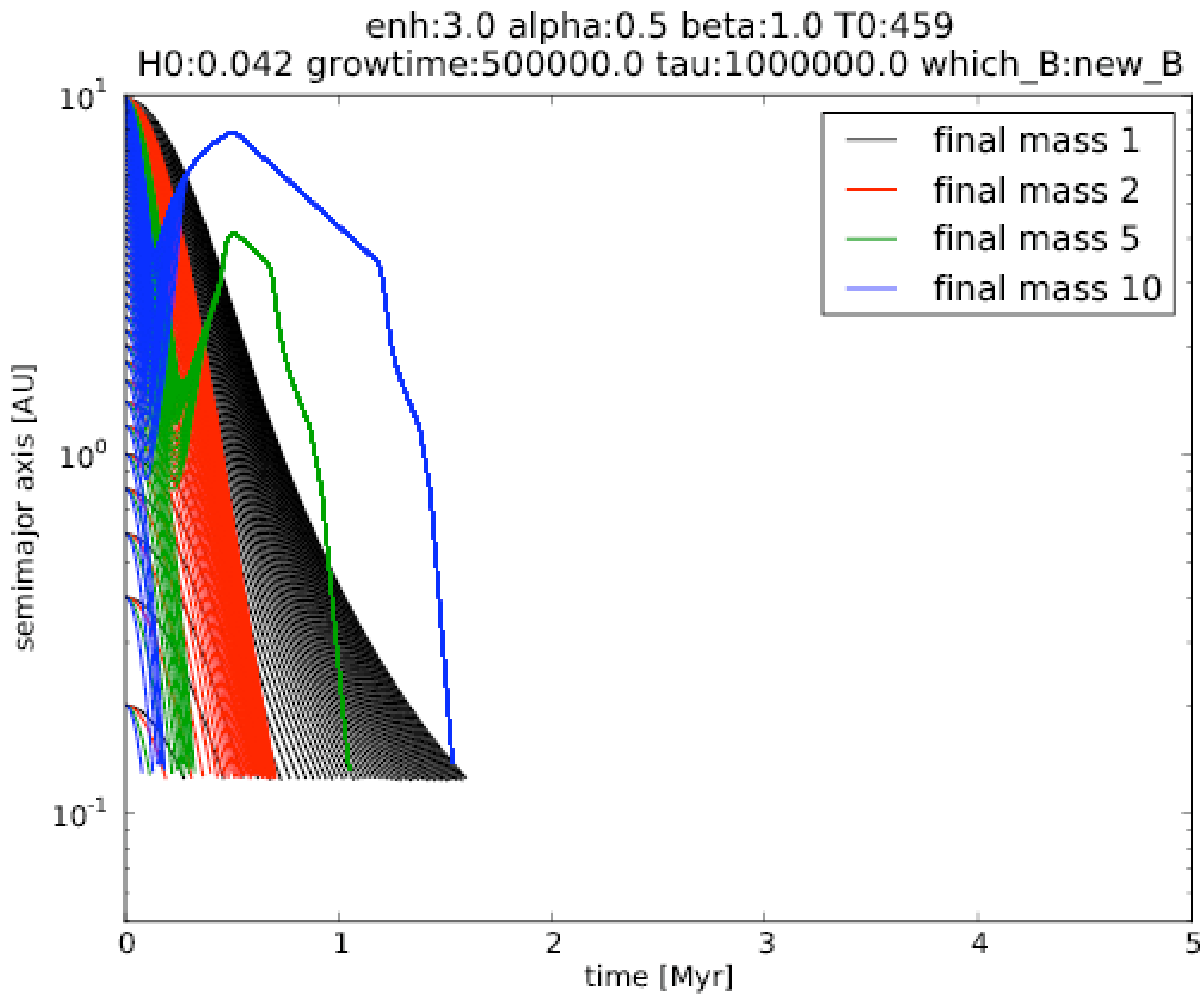


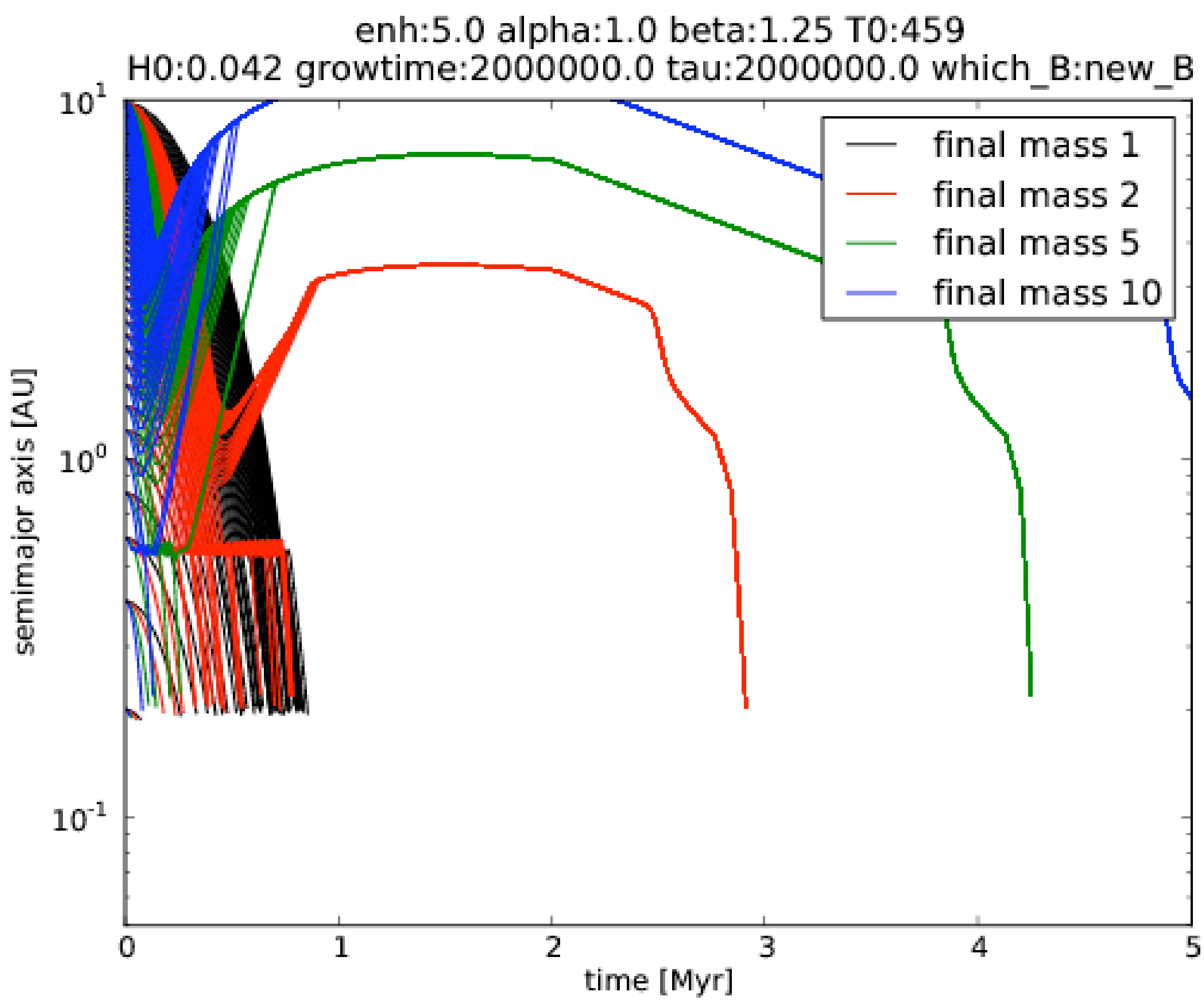
10^1
10^0
10^{-1}
semimajor axis [AU]
0.0
0.1
0.2
0.3
0.4
0.5
time [Myr]

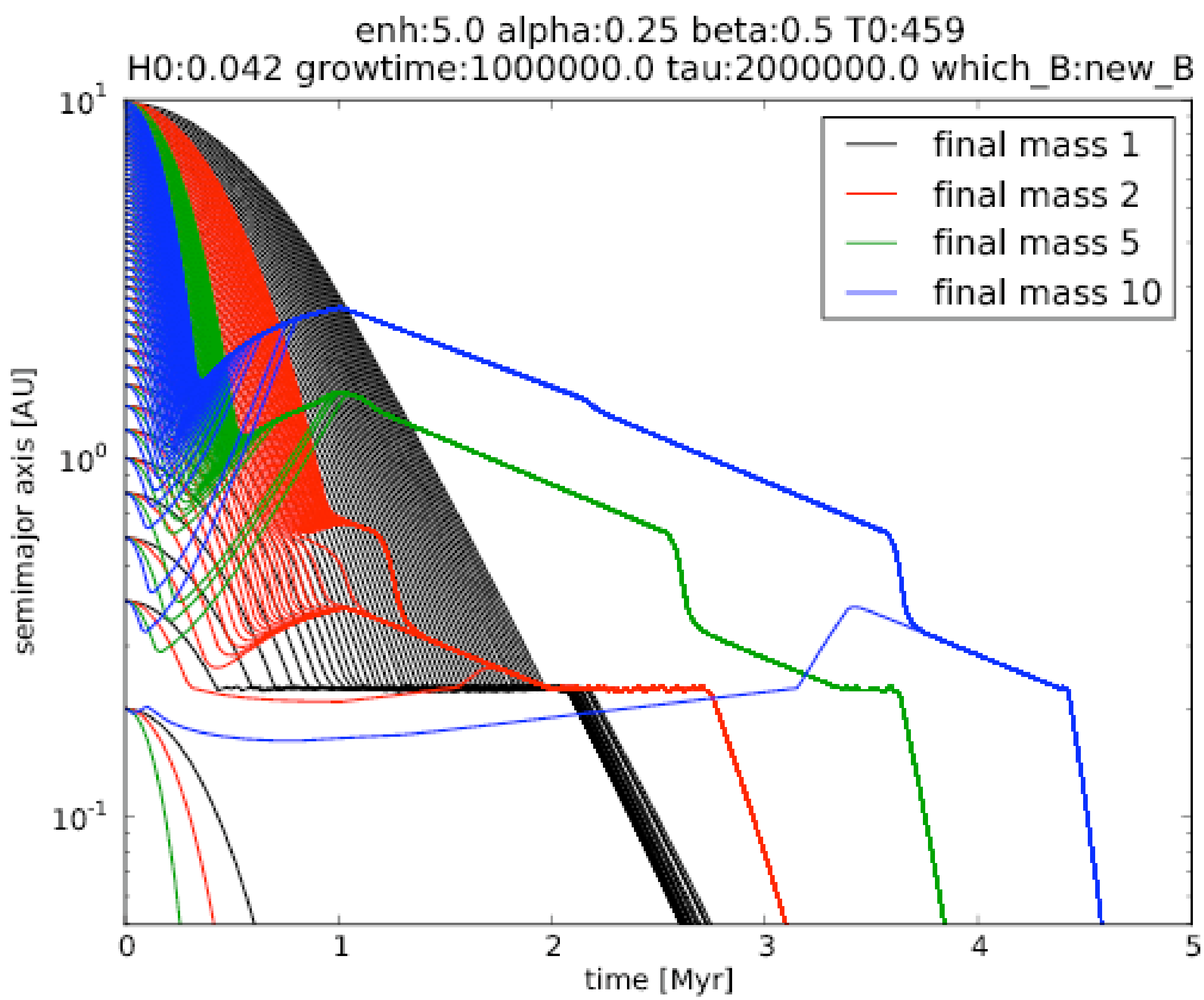

enh:5.0 alpha:1.0 beta:0.5 T0:459
H0:0.05 growtime:1000000.0 tau:1000000.0 which_B:new_B
semimajor axis [AU]
time [Myr]
final mass 1
final mass 2
final mass 5
final mass 10



enh:3.0 alpha:0.5 beta:0.5 T0:280
H0:0.042 growtime:2000000.0 tau:1000000.0 which_B:new_B
final mass 1
final mass 2
final mass 5
final mass 10
semimajor axis [AU]
time [Myr]


enh:3.0 alpha:0.5 beta:1.0 T0:459
H0:0.042 growtime:500000.0 tau:1000000.0 which_B:new_B
final mass 1
final mass 2
final mass 5
final mass 10
semimajor axis [AU]
time [Myr]
10¹
10⁰
10⁻¹
0
1
2
3
4
5


enh:5.0 alpha:1.0 beta:1.25 T0:459
H0:0.042 growtime:2000000.0 tau:2000000.0 which_B:new_B
final mass 1
final mass 2
final mass 5
final mass 10
semimajor axis [AU]
time [Myr]



enh:5.0 alpha:0.25 beta:0.5 T0:459
H0:0.042 growtime:1000000.0 tau:2000000.0 which_B:new_B
final mass 1
final mass 2
final mass 5
final mass 10
semimajor axis [AU]
time [Myr]

Conclusions

Multiple lukewarm Neptune systems are excellent tests of type I migration physics because they're so hard to form

The simplest oligarchy + TTW type I migration models fail badly, dramatically underpredicting the mass

Paardekooper-style type I migration is very promising but frustratingly sensitive [McNeil & Nelson ~~2009c~~ 2010a!]