A possible origin of compact systems of hot Super Earths

Christophe Cossou
Sean Raymond & Arnaud Pierens

Bordeaux, France

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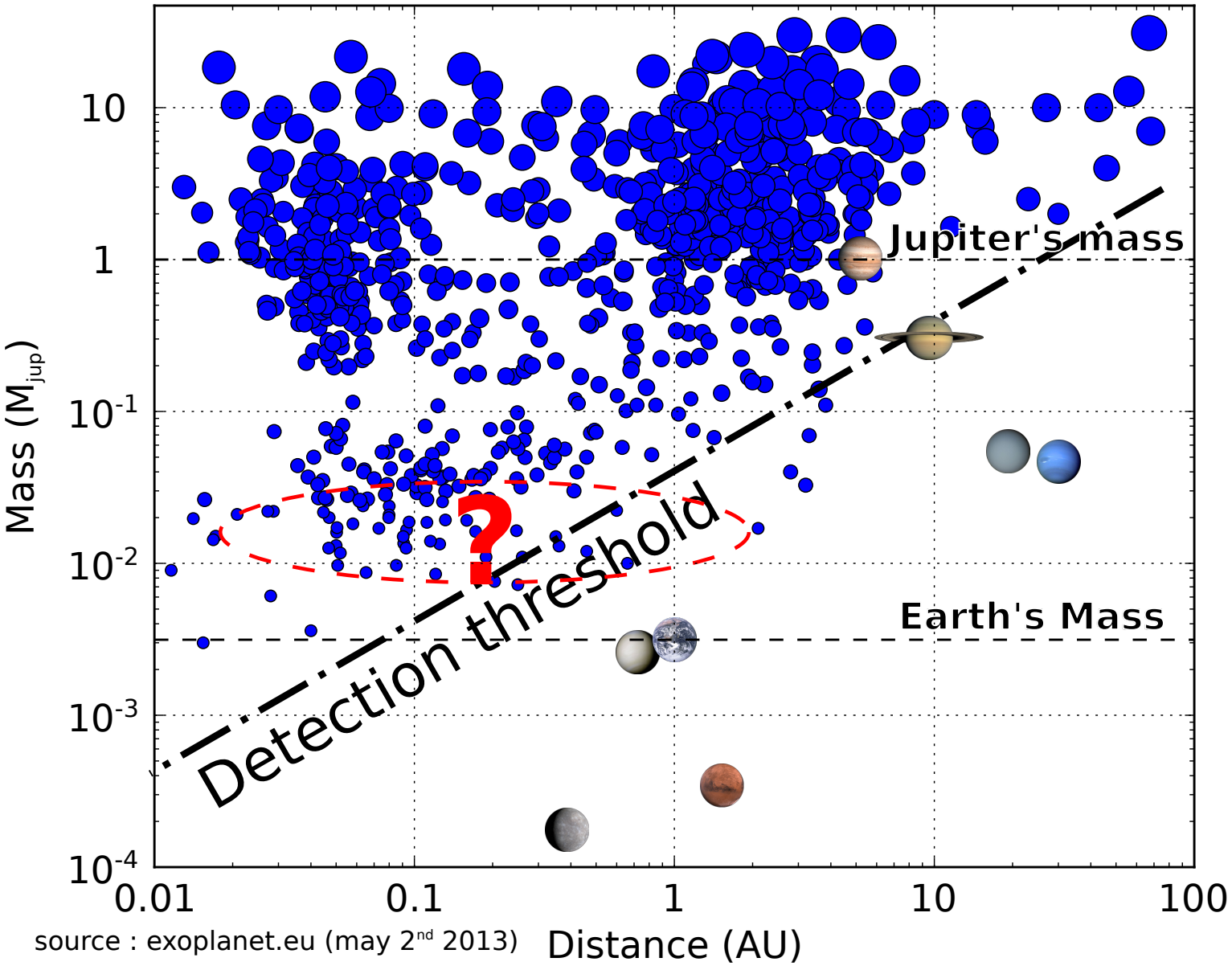
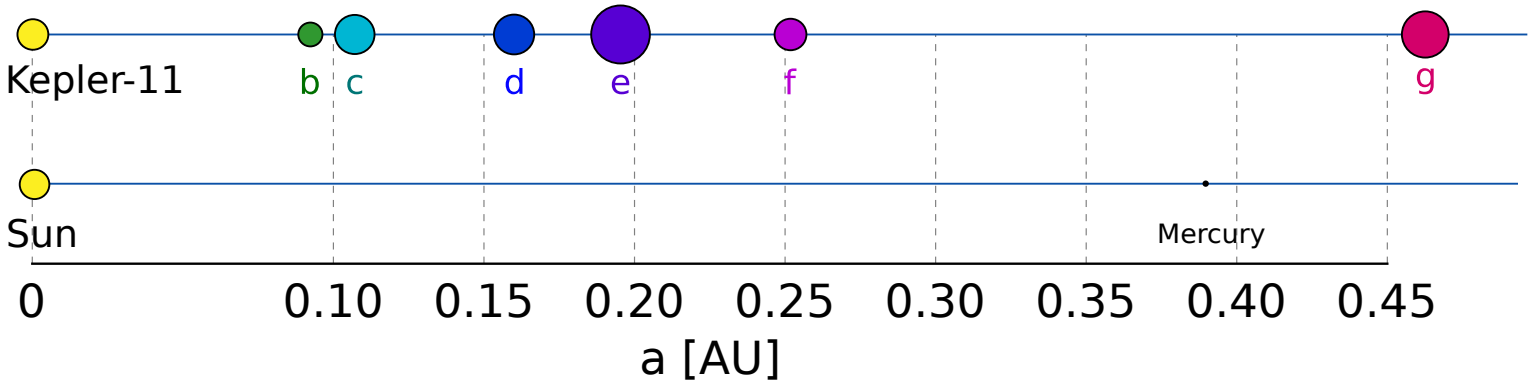
Session 7, Talk : 7.06

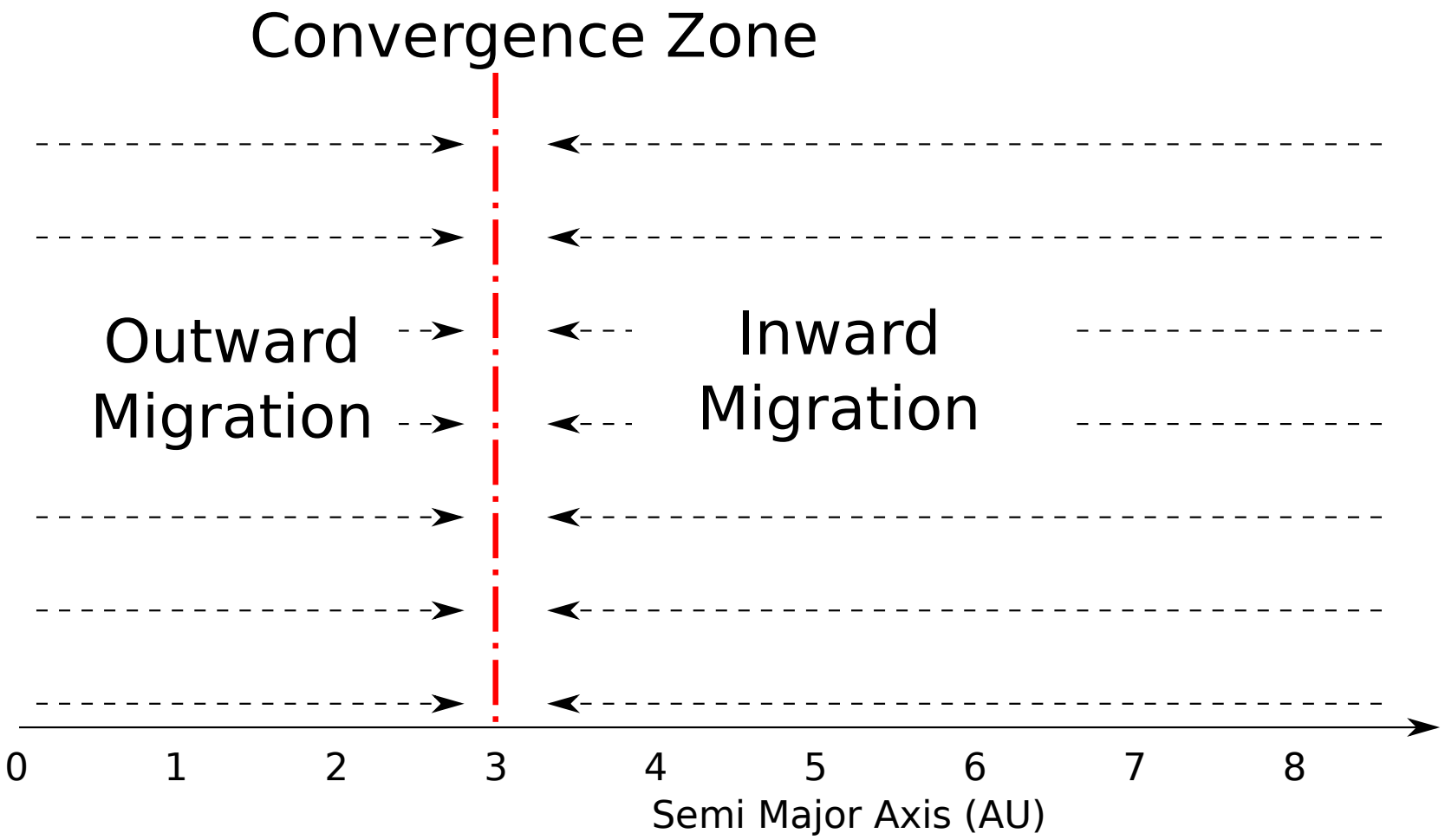


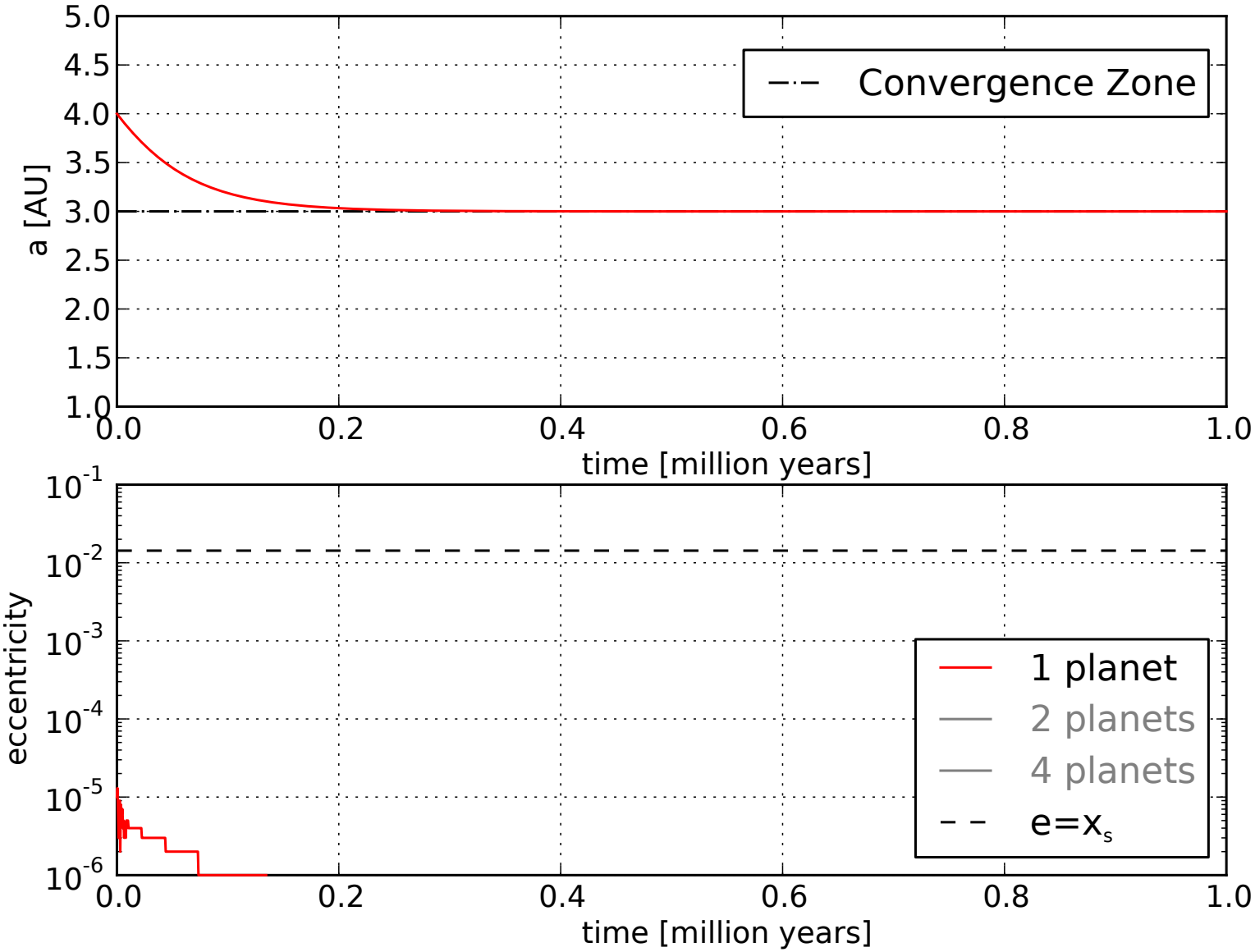
source : exoplanet.eu (may 2nd 2013)



Compact System of hot super earths

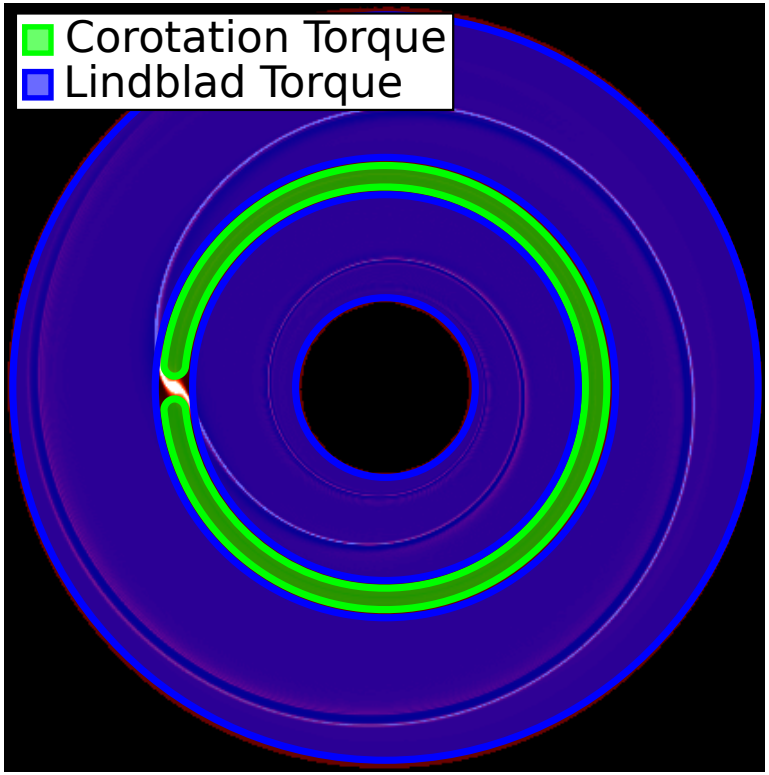
- N-body simulations : Mercury code (Chambers, 1999)
- 1D disk model (solving energy equation)
  - Density profile $\propto R^{-d}$
  - Opacity Table
  - Temperature profile : balance between viscous heating and radiative cooling
- Eccentricity and inclination damping by a gas disk
- Migration from torque formulae (Paardekooper et al., 2011)


Convergence Zone
Outward Migration
Inward Migration
0
1
2
3
4
5
6
7
8
Semi Major Axis (AU)


Convergence Zone
a [AU]
time [million years]
eccentricity
1 planet
2 planets
4 planets
e=x_s
time [million years]

BUT...

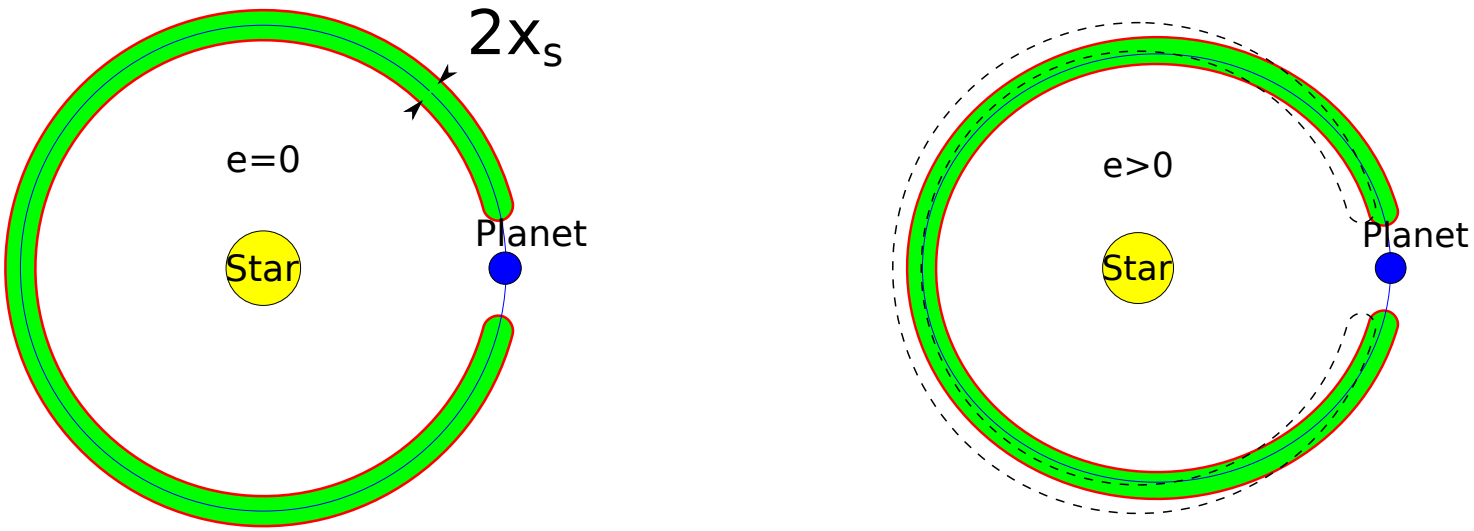
- Lindblad : typically Inward Migration
- Corotation torque : Inward/Outward Migration



Total Torque = Lindblad Torque + Corotation Torque

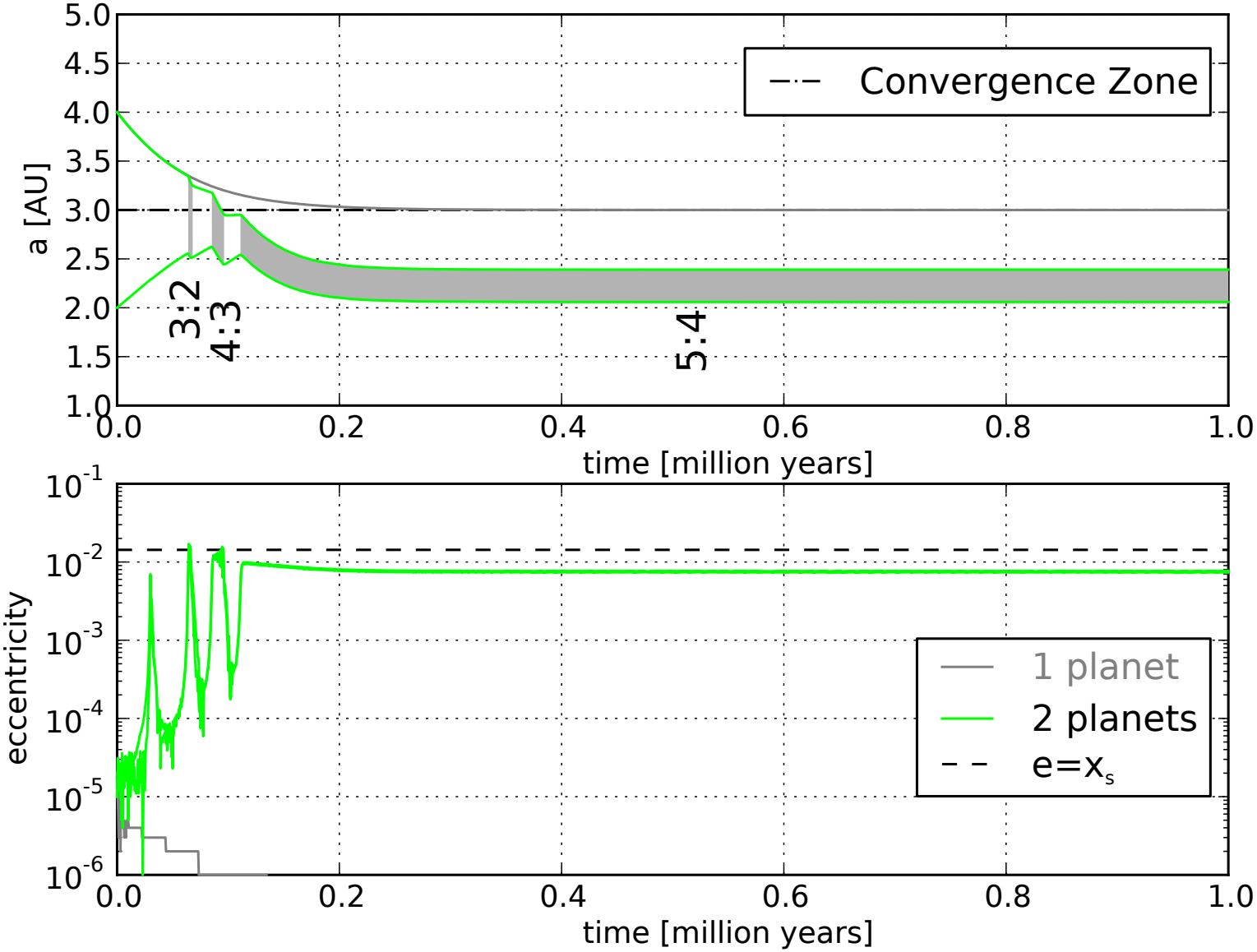
(Bitsch & Kley, 2010)
poster by S. Fendyke (4.22)

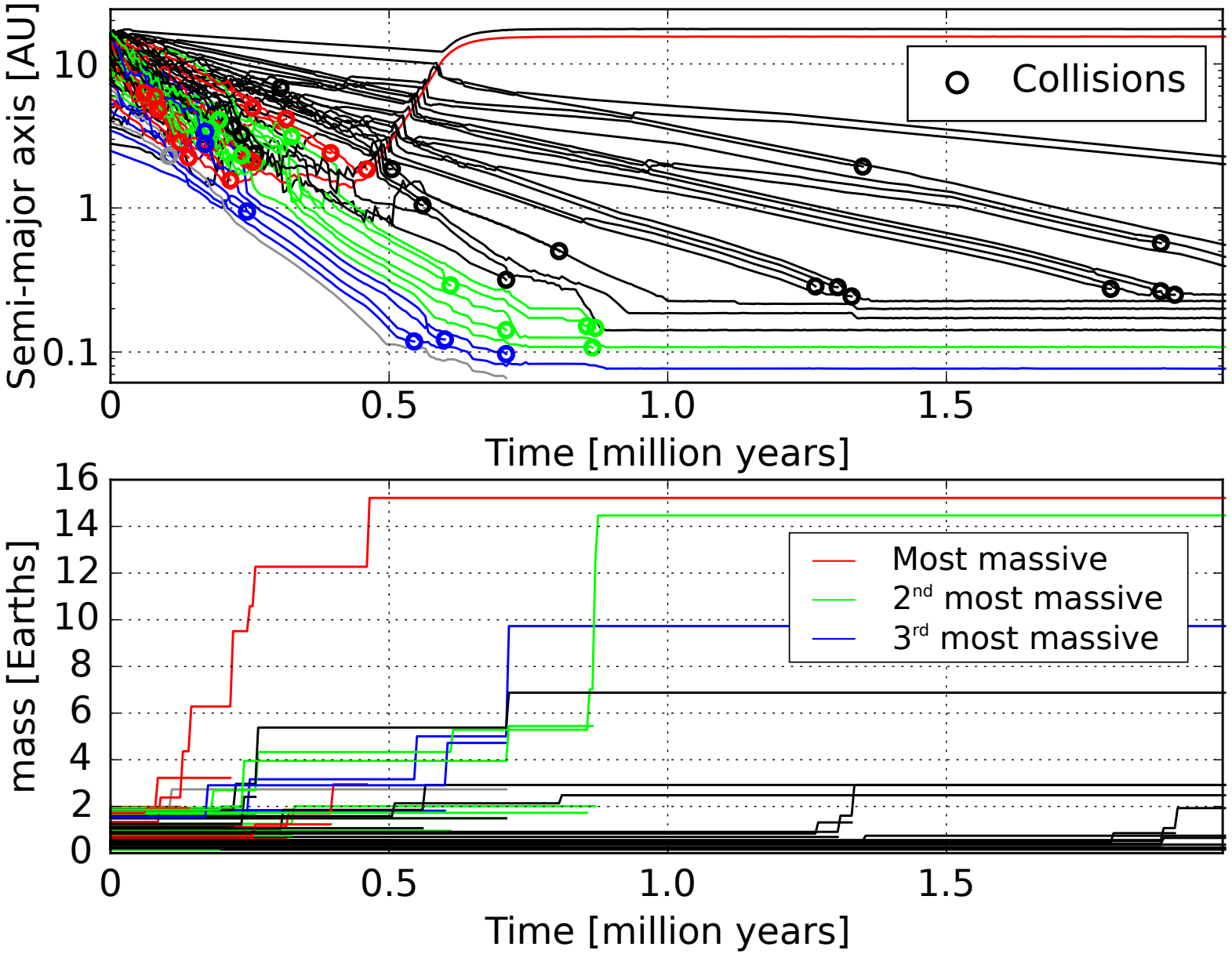
Corotation torque modified by eccentricity

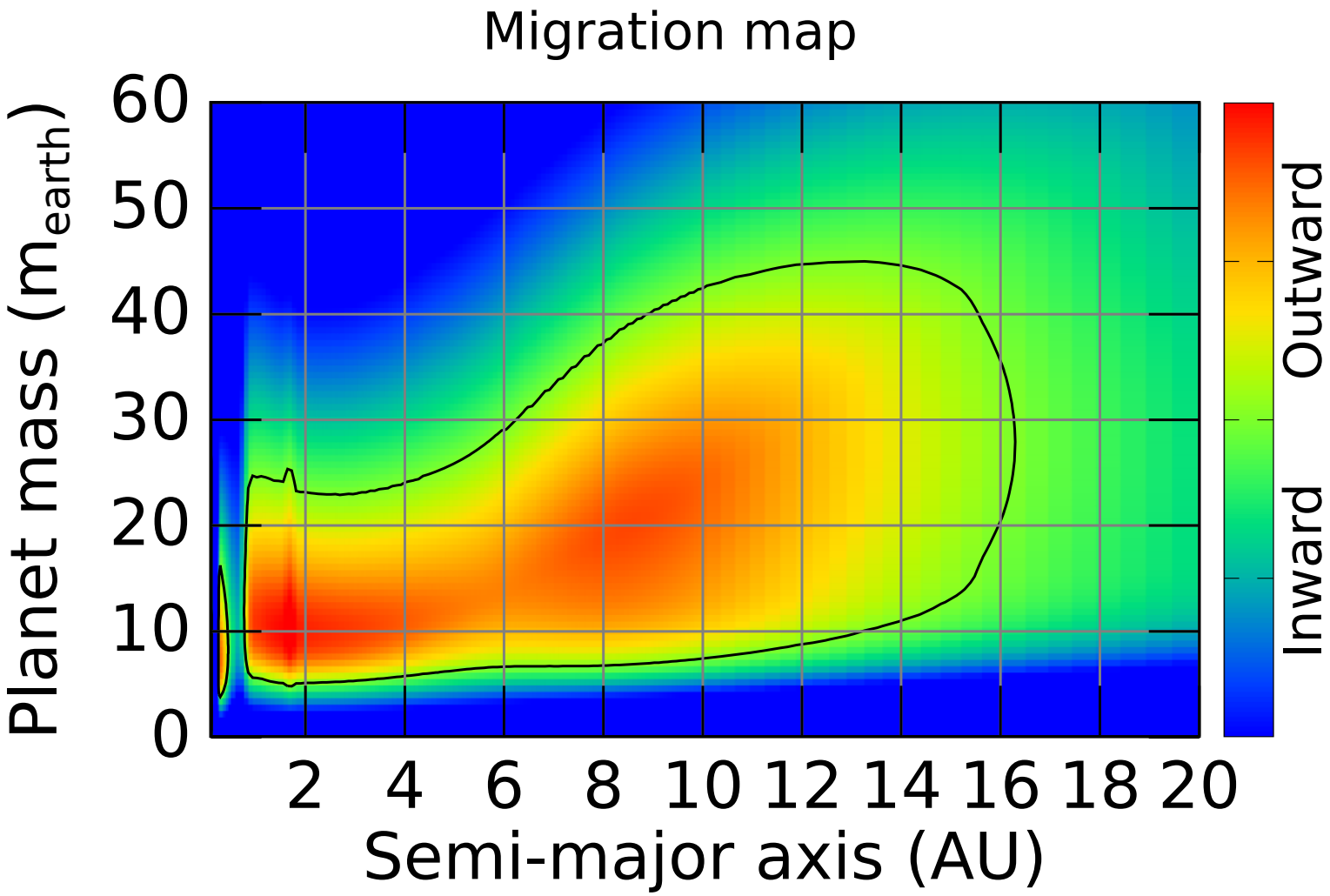


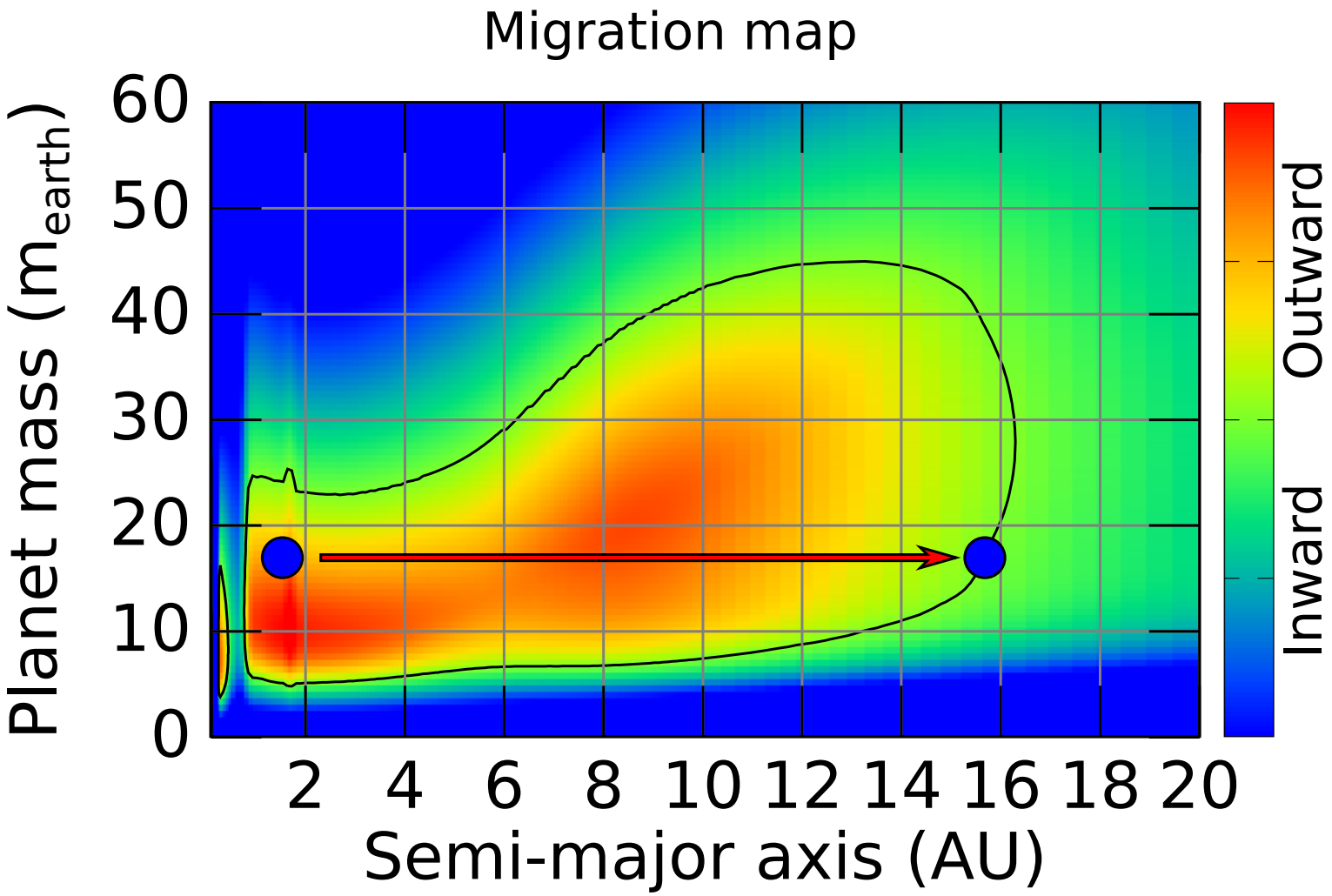
Eccentricity ? In disk ?

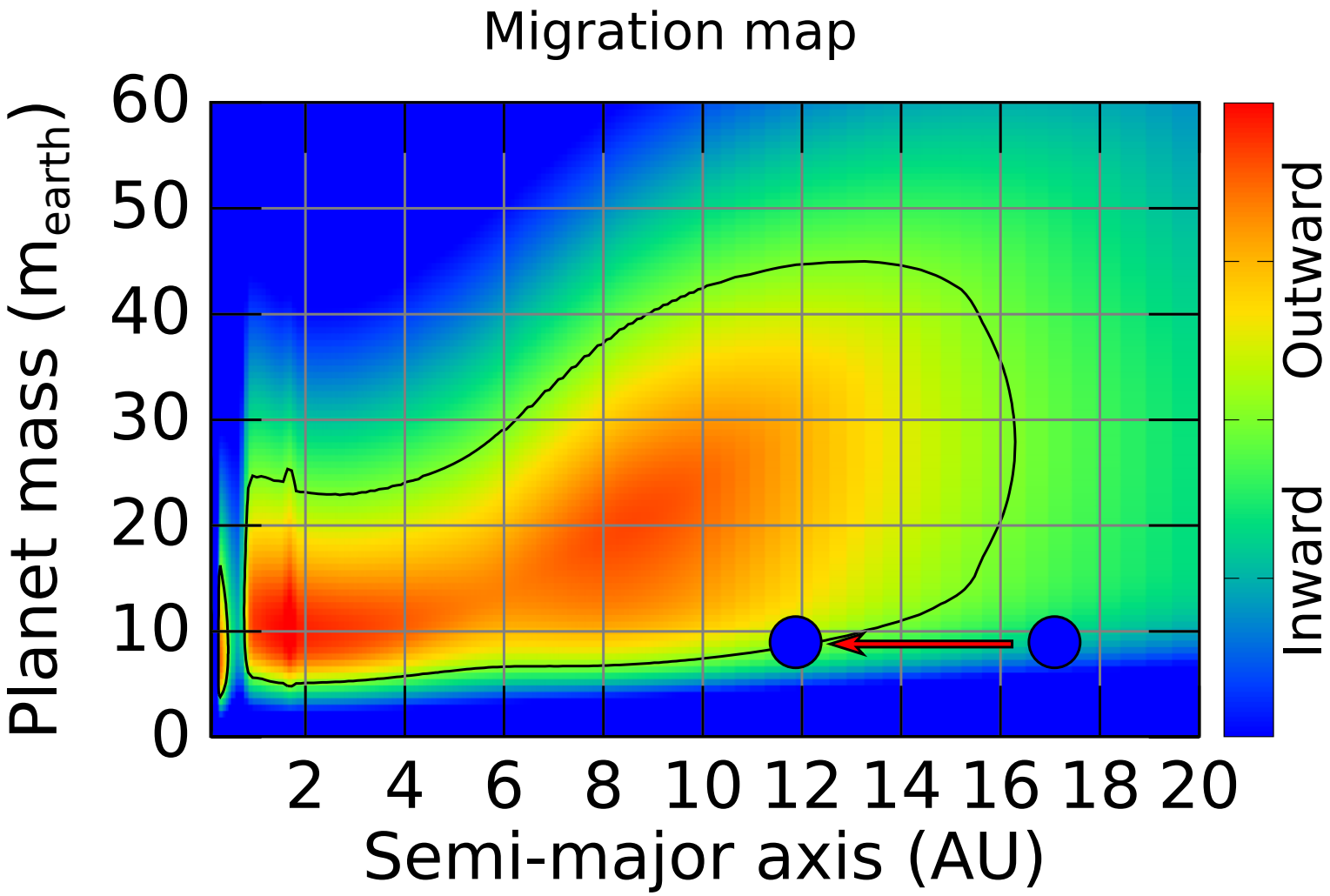
(Cossou et al., 2013) A&A, 553, L2

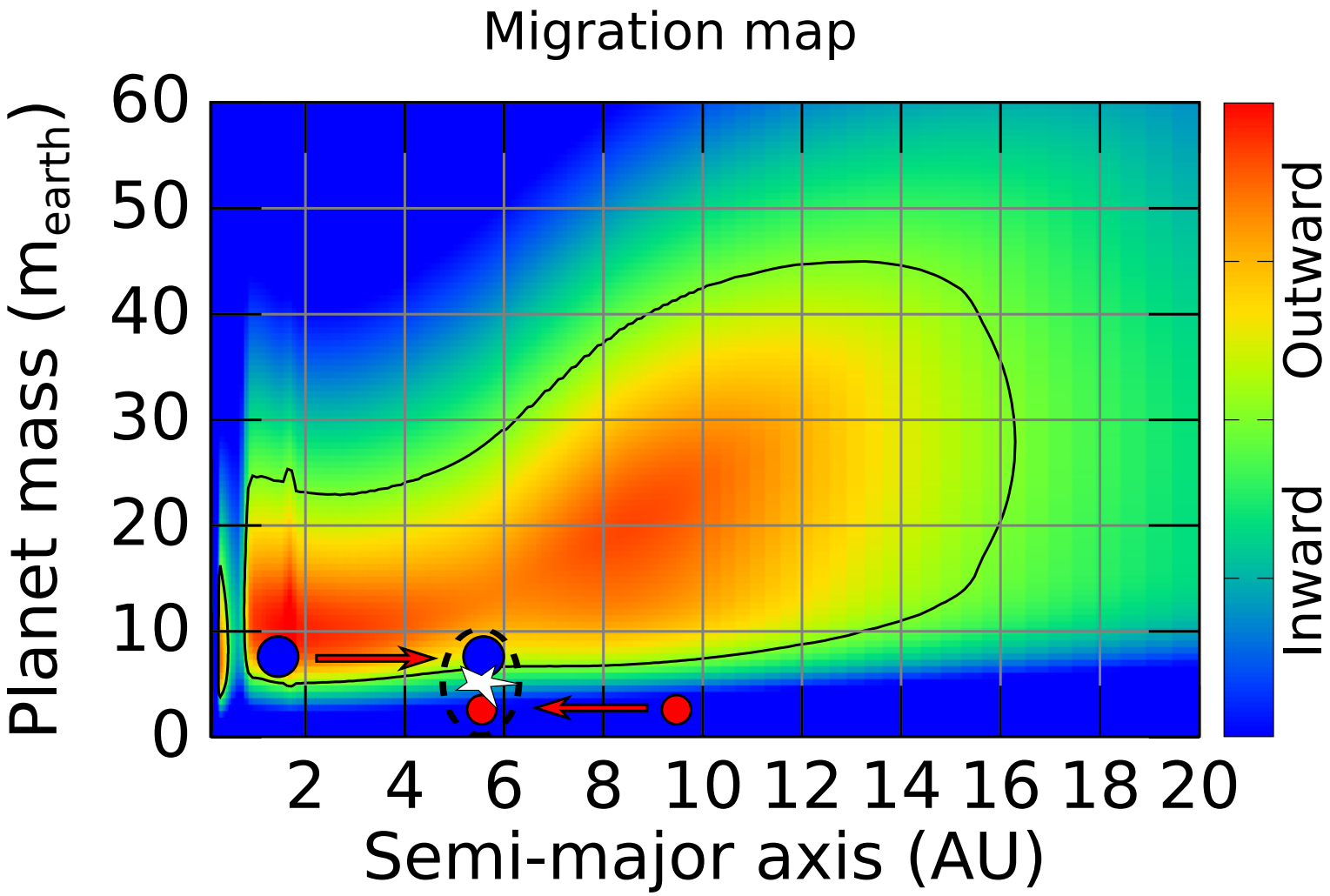


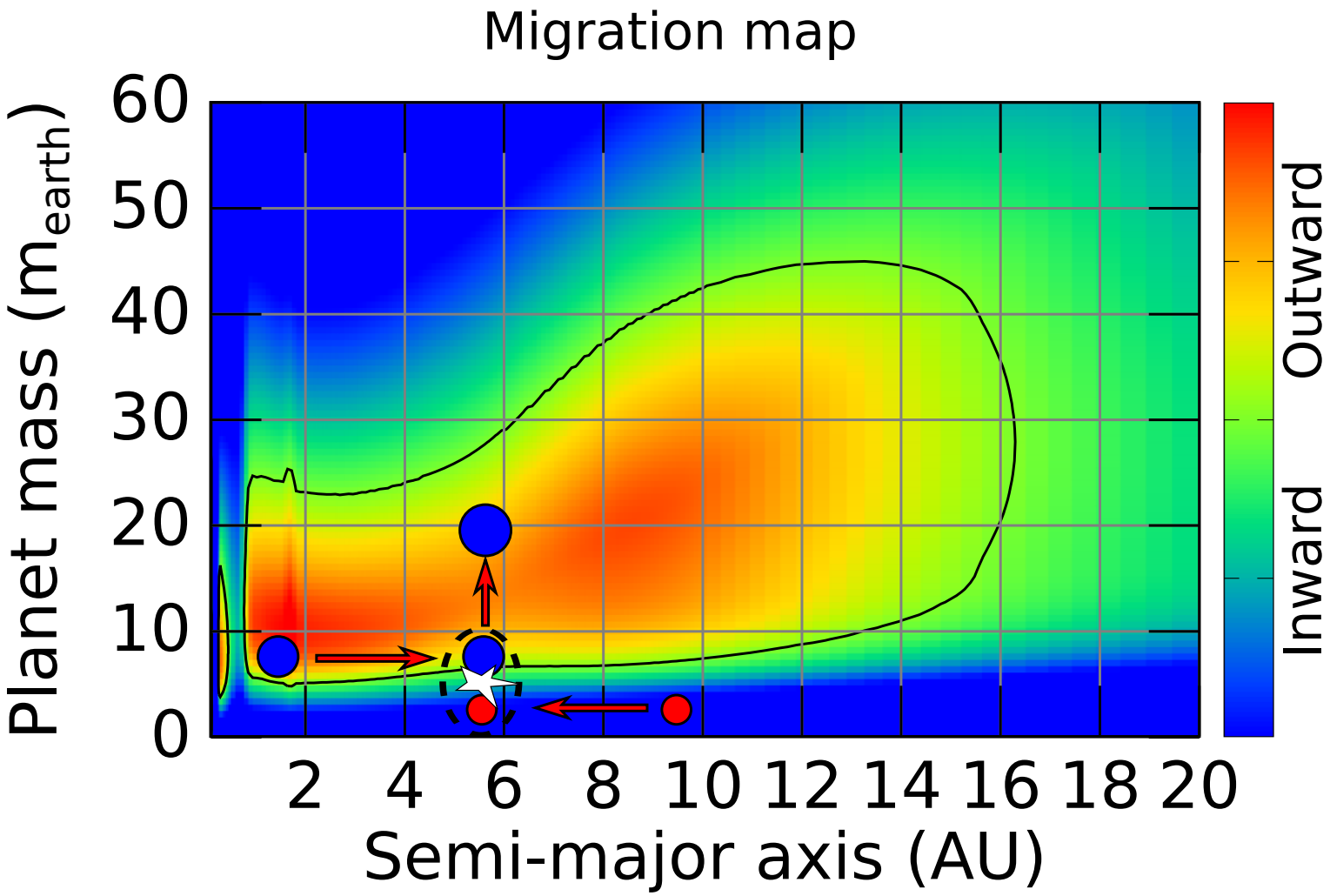

Semi-major axis [AU]
10
1
0.1
0
0.5
1.0
1.5
Time [million years]
Collisions
mass [Earths]
16
14
12
10
8
6
4
2
0
0
0.5
1.0
1.5
Time [million years]
Most massive
2nd most massive
3rd most massive

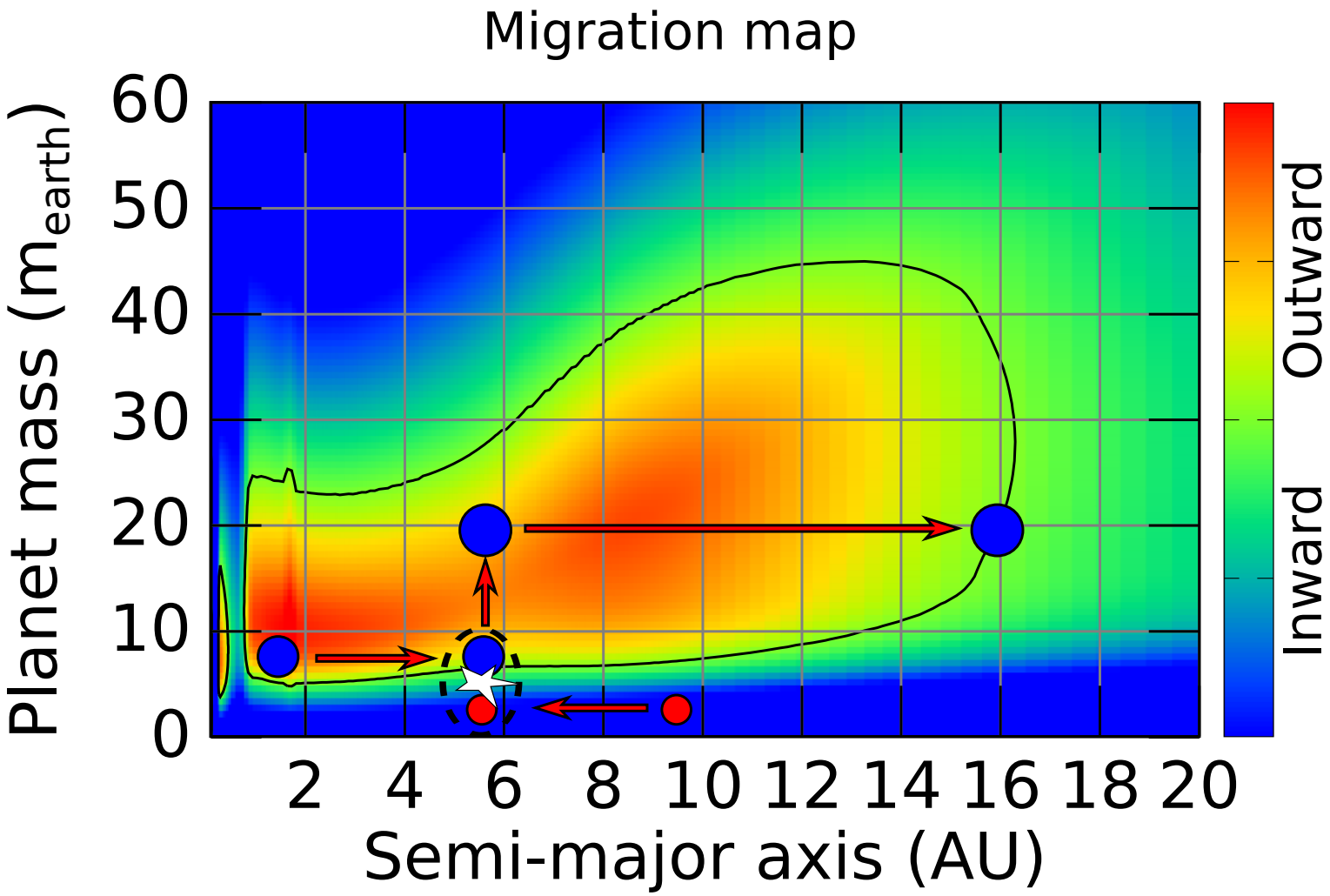

Migration map
Planet mass (m_{earth})
60
50
40
30
20
10
0
2 4 6 8 10 12 14 16 18 20
Semi-major axis (AU)
Outward
Inward

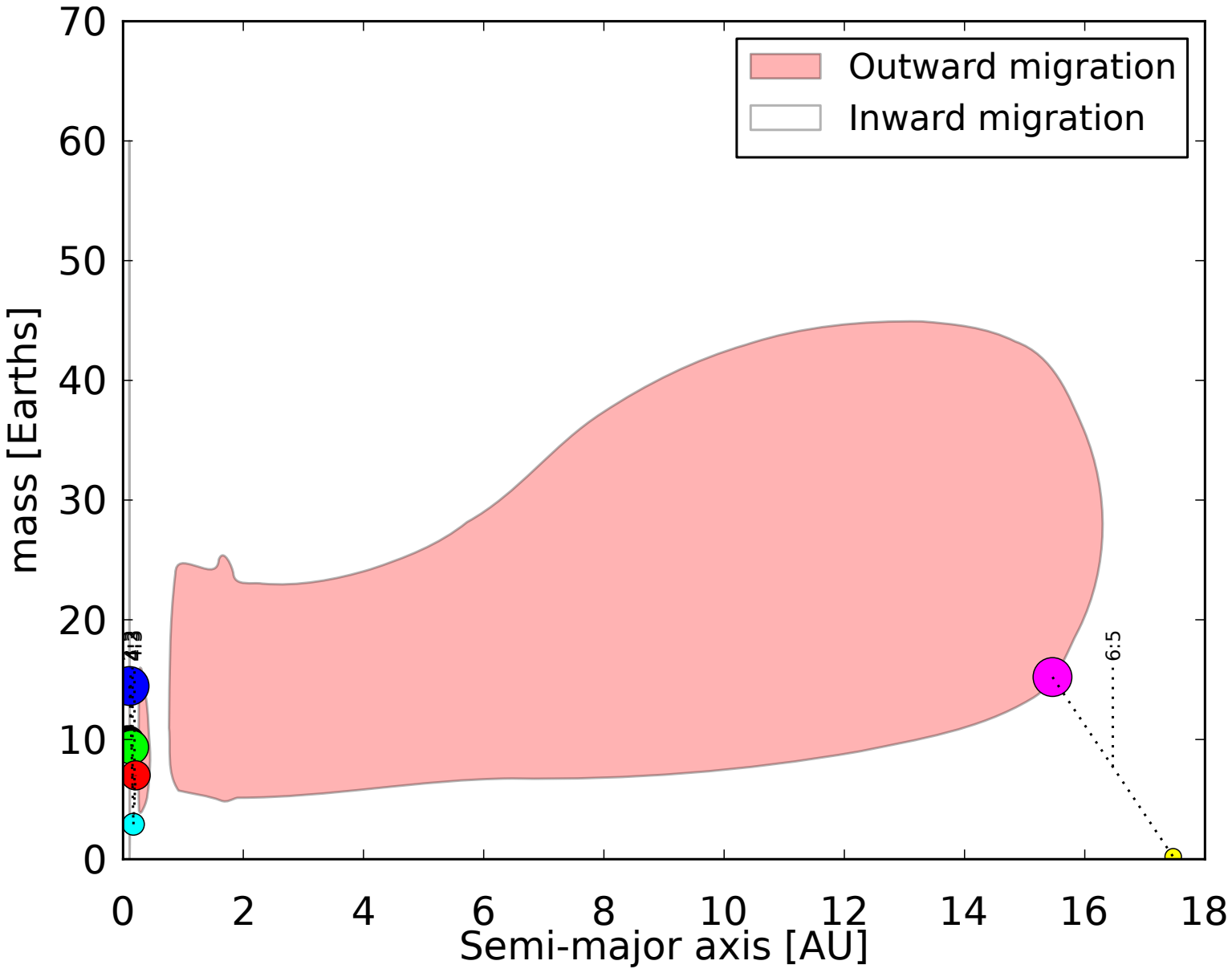

Migration map
Planet mass (m_{earth})
60
50
40
30
20
10
0
2 4 6 8 10 12 14 16 18 20
Semi-major axis (AU)
Outward
Inward

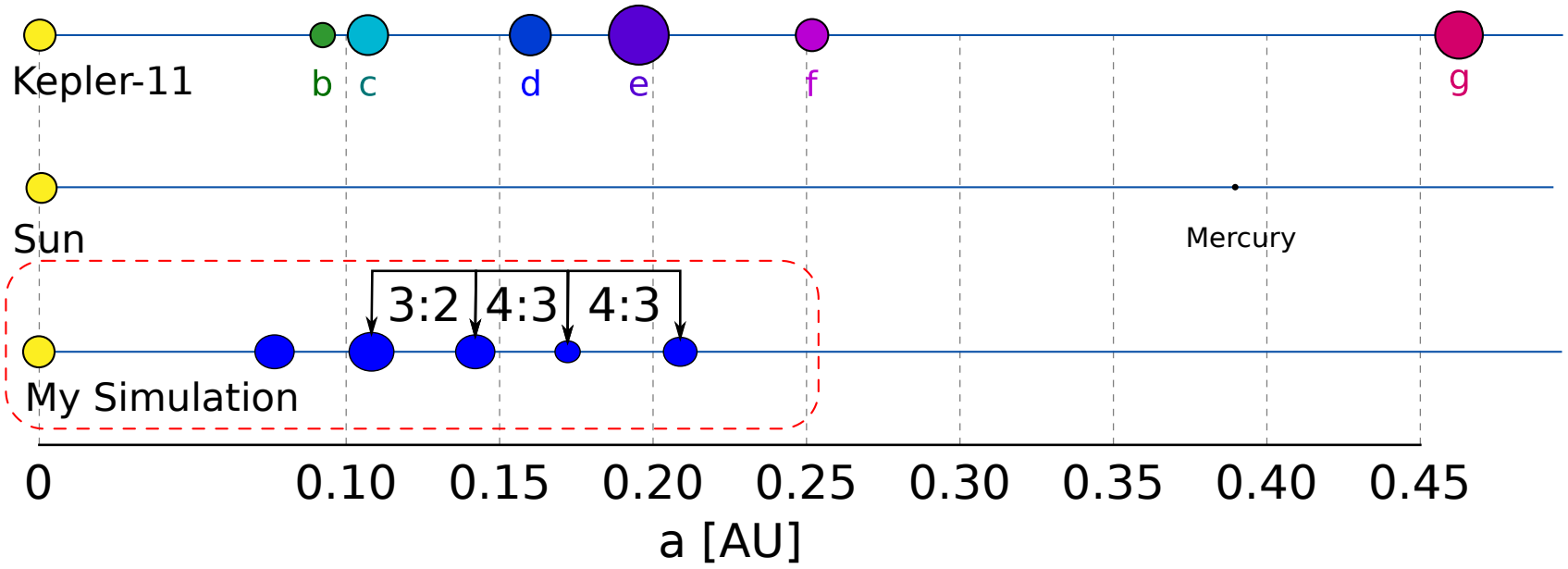

Migration map
Planet mass (m_{earth})
60
50
40
30
20
10
0
2 4 6 8 10 12 14 16 18 20
Semi-major axis (AU)
Outward
Inward

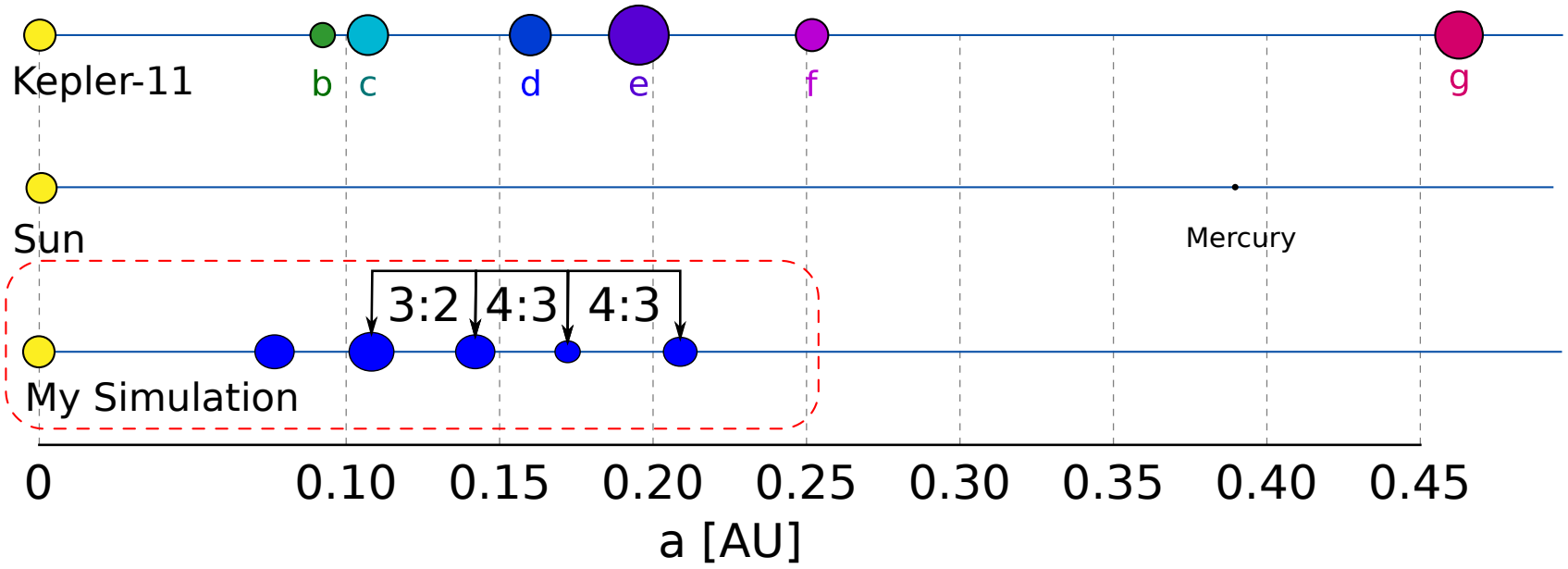

Migration map
Planet mass (m_{earth})
60
50
40
30
20
10
0
2 4 6 8 10 12 14 16 18 20
Semi-major axis (AU)
Outward
Inward


Migration map
Planet mass (m_{earth})
60
50
40
30
20
10
0
2 4 6 8 10 12 14 16 18 20
Semi-major axis (AU)
Outward
Inward


Migration map
Planet mass (m_{earth})
60
50
40
30
20
10
0
2 4 6 8 10 12 14 16 18 20
Semi-major axis (AU)
Outward
Inward


Outward migration
Inward migration
mass [Earths]
Semi-major axis [AU]
0
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16
18
6:5


Kepler-11
b
c
d
e
f
g
Sun
Mercury
3:2
4:3
4:3
My Simulation
0
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
a [AU]

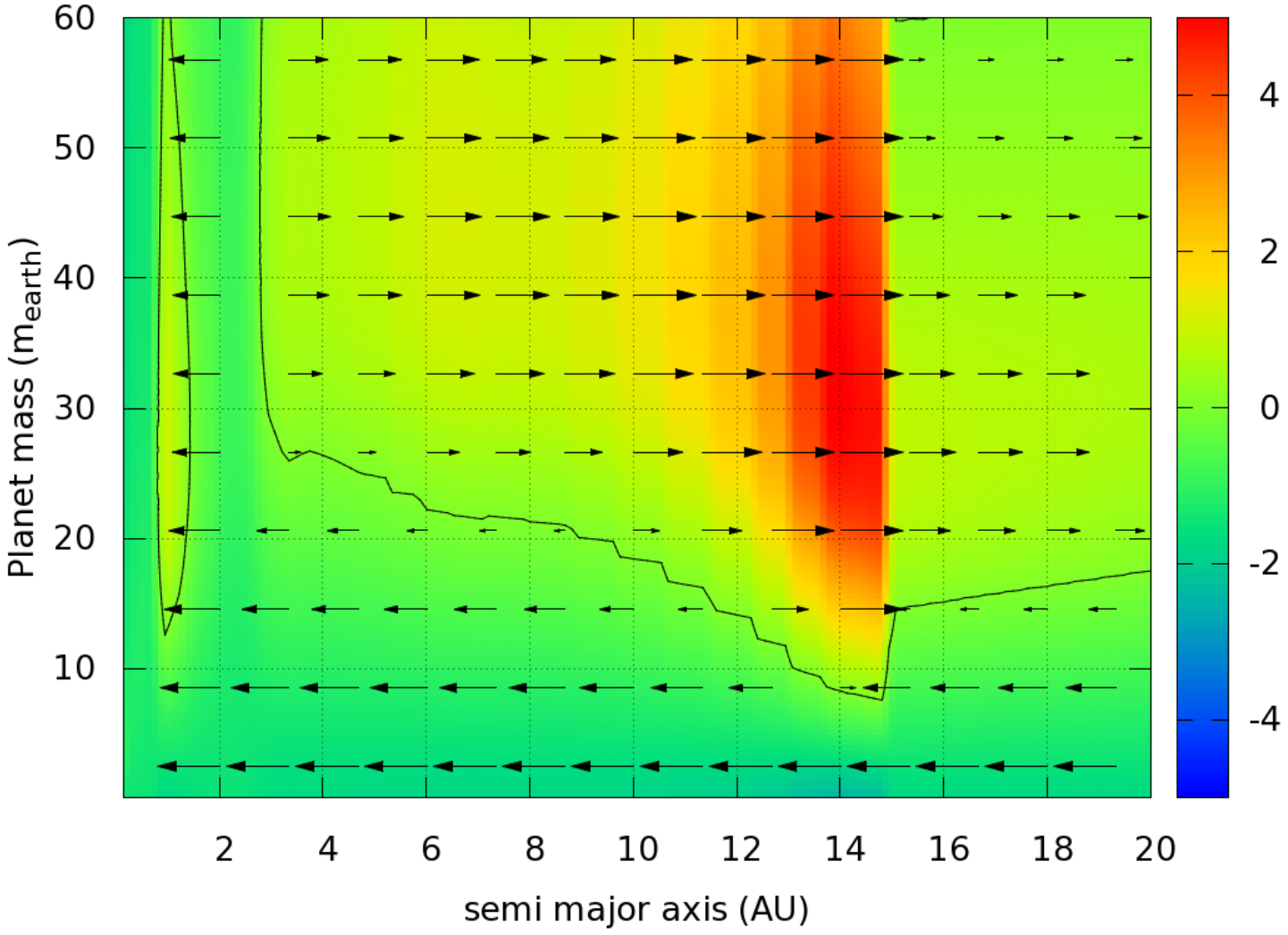


- Presence of Resonances
- High sensitivity to migration map

Disk parameters : Density

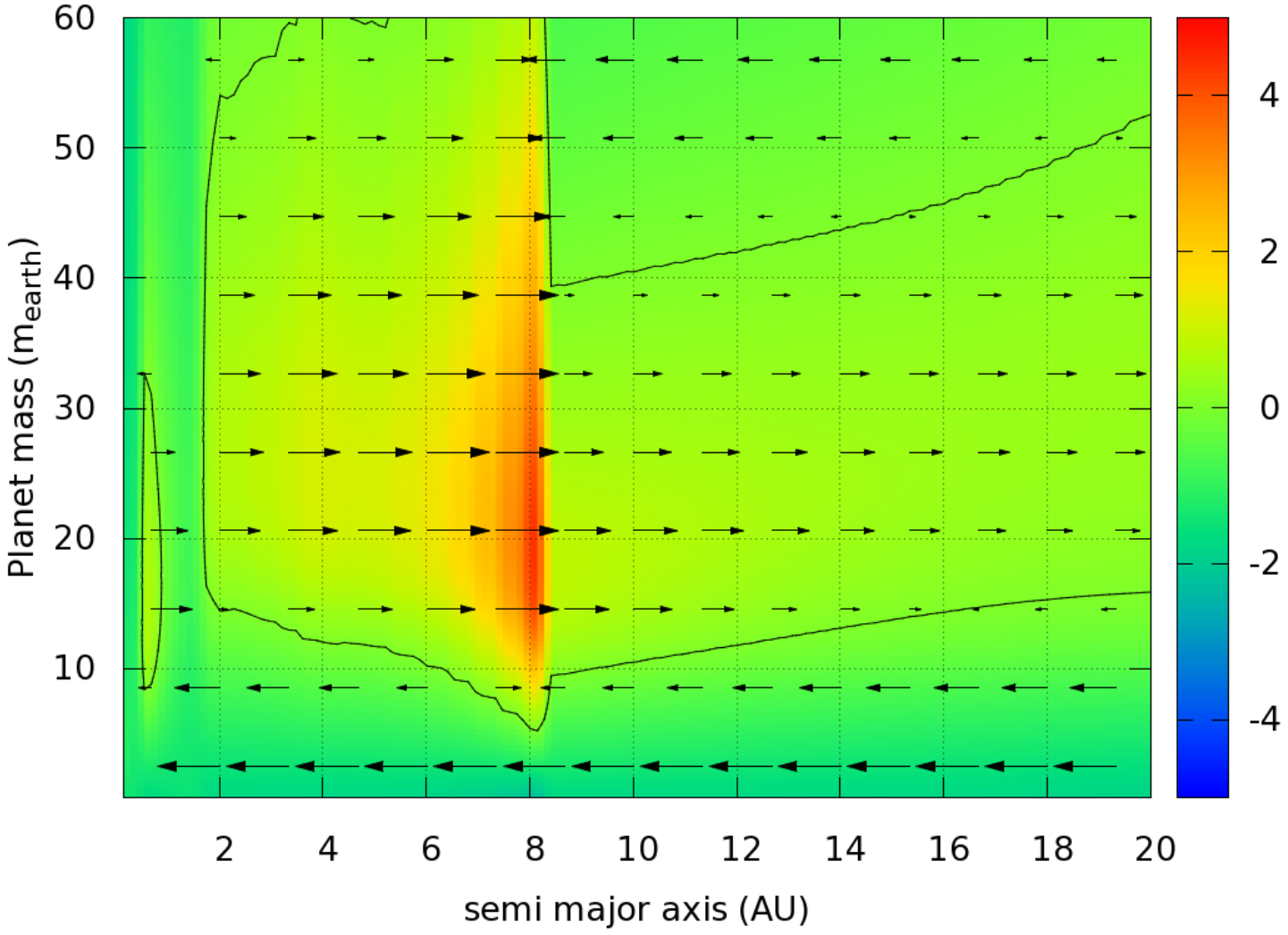
$$\Sigma(R) = 1500.0 \times R^{-1/2}\ \mathrm{g/cm^2}$$

Evolution of the total torque Γ_{tot}/Γ_0



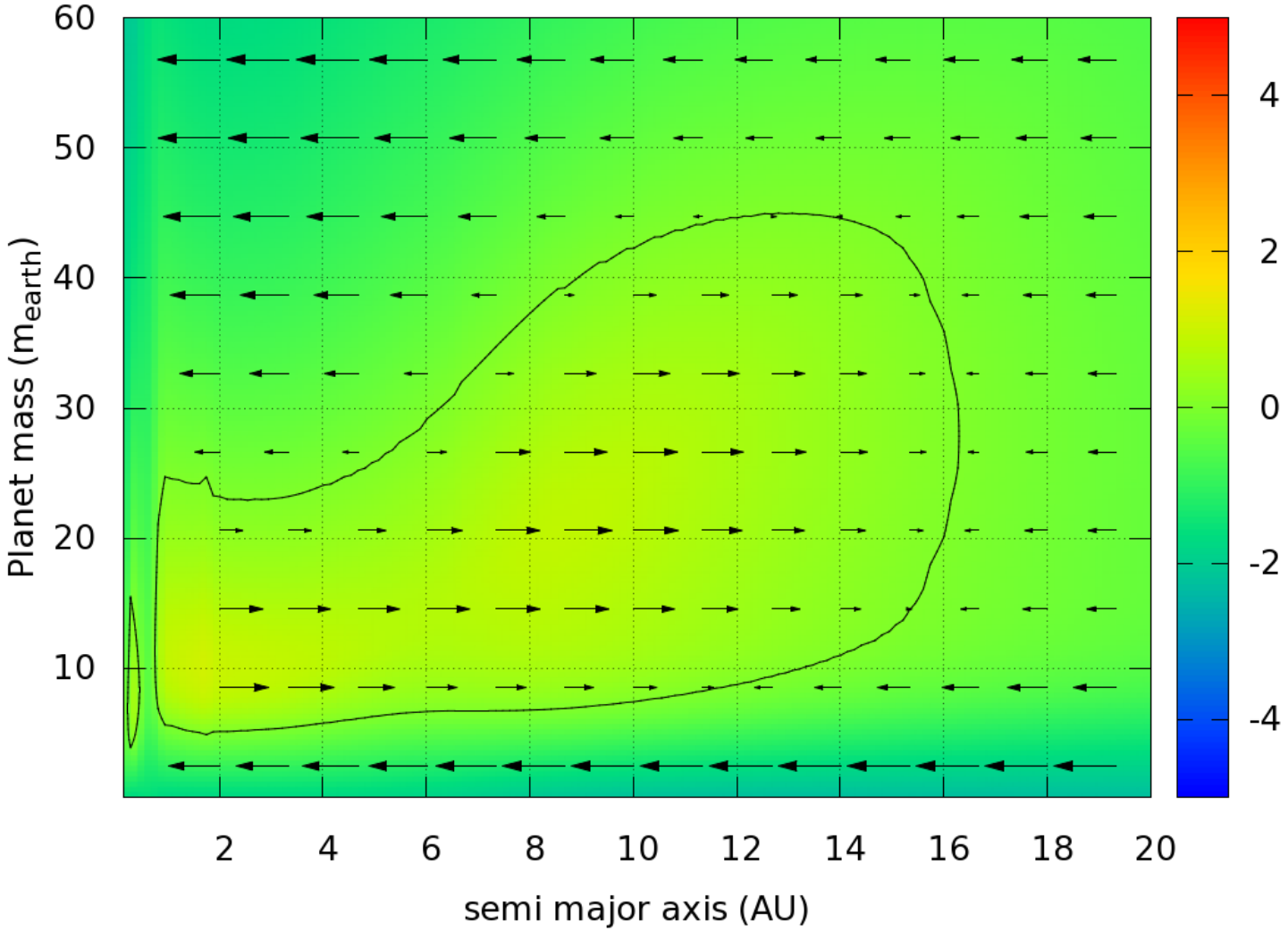
$$\Sigma(R) = 0800.0 \times R^{-1/2}\ \mathrm{g/cm^2}$$

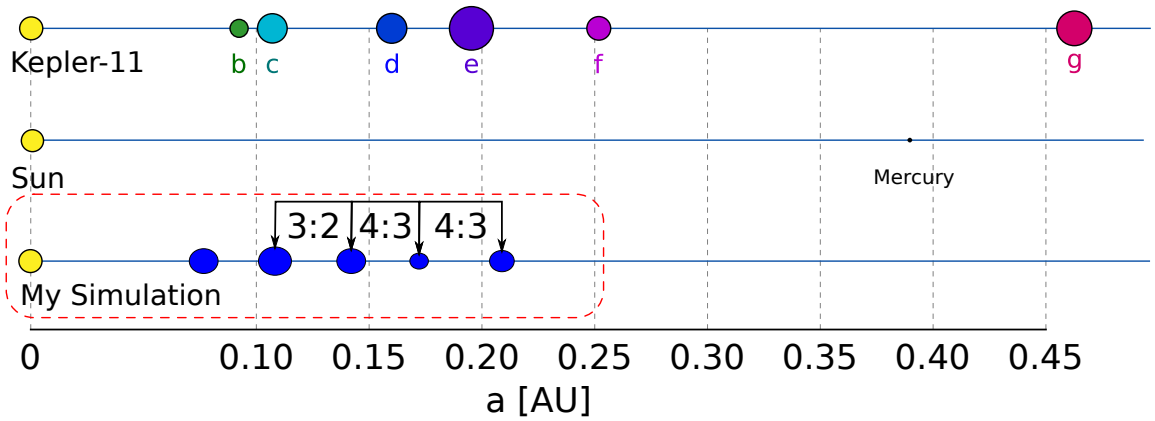
Evolution of the total torque Γ_{tot}/Γ_0



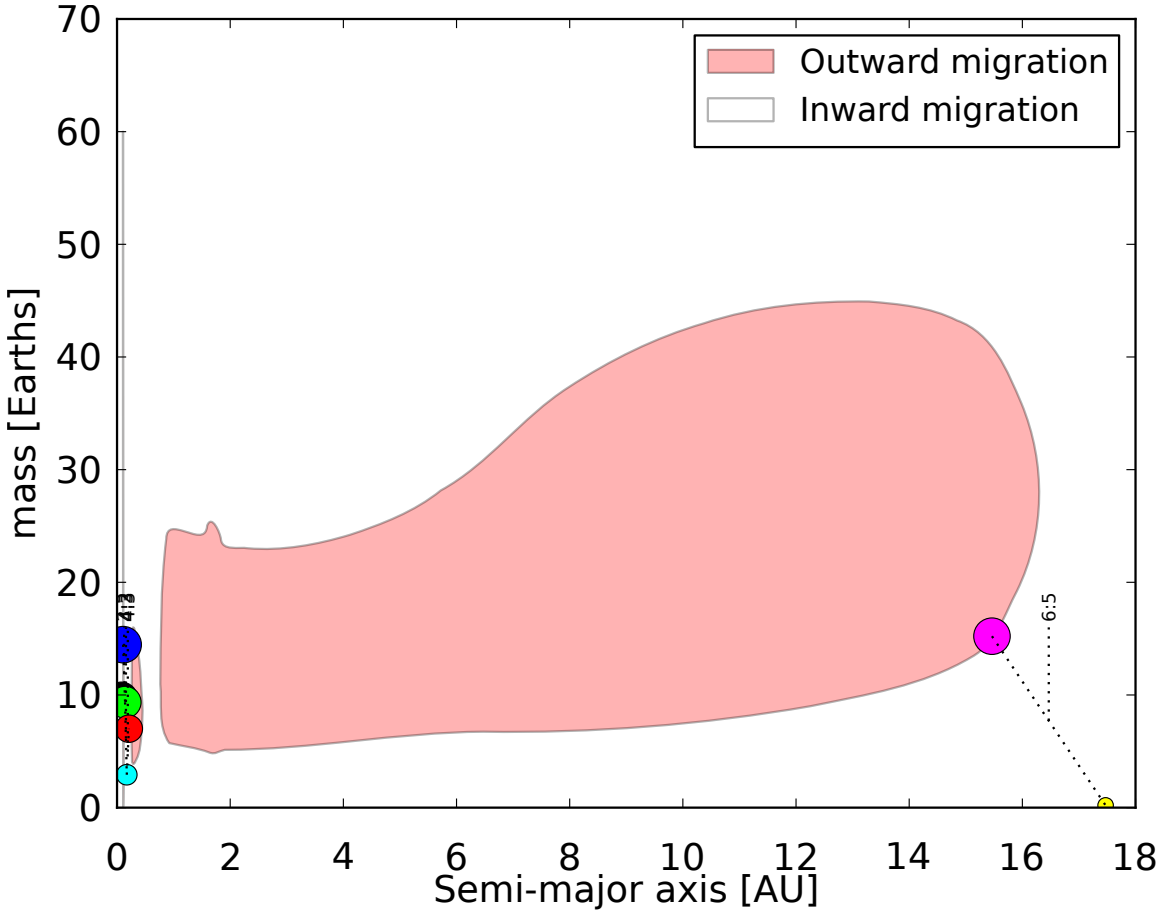
$$\Sigma(R) = 0300.0 \times R^{-1/2}\ \mathrm{g/cm^2}$$

Evolution of the total torque Γ_{tot}/Γ_0

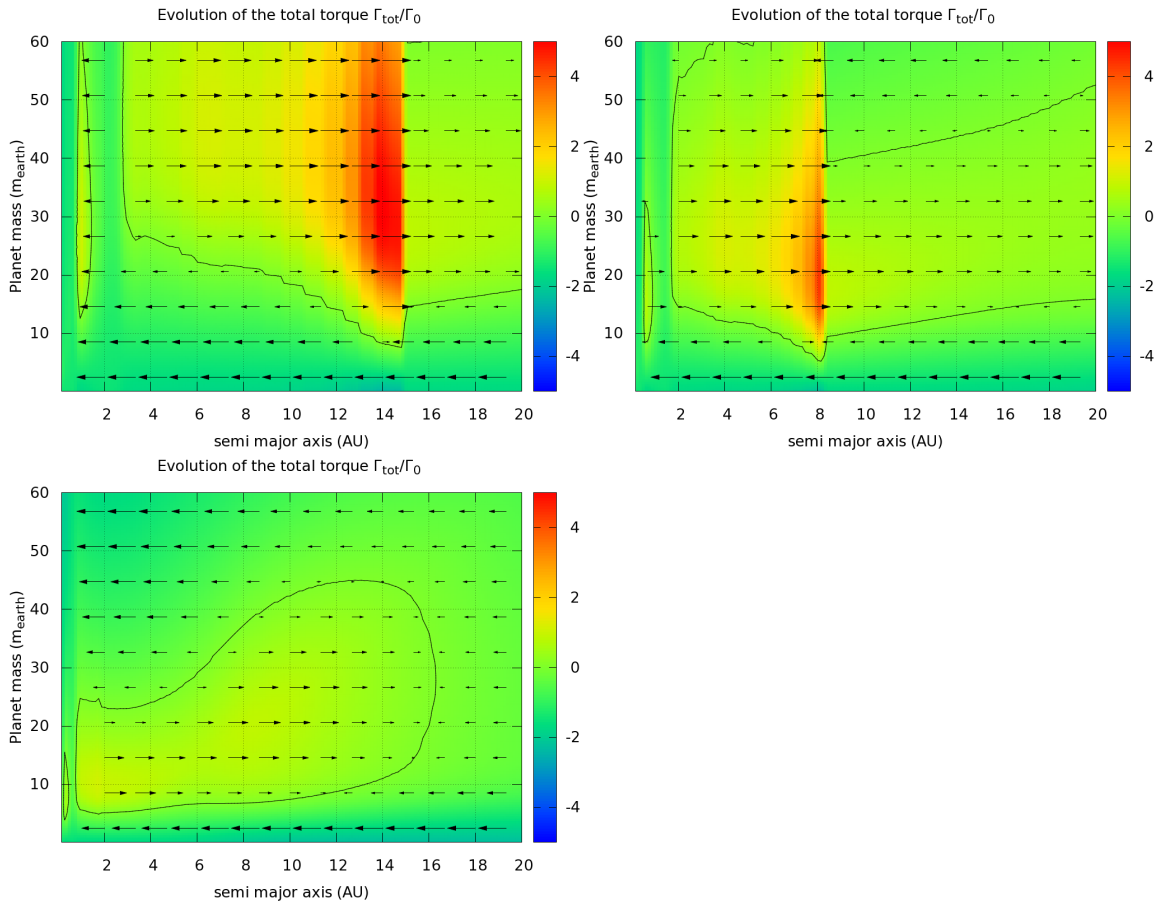




1. Compact Systems of Hot Super Earths



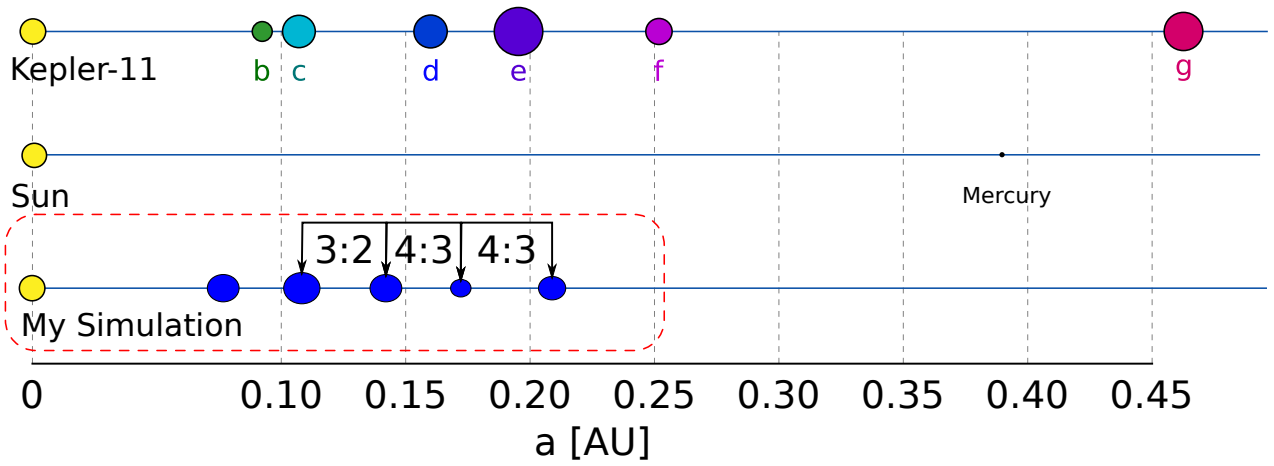
1. Compact Systems of Hot Super Earths
2. Jupiter candidates also



1. Compact Systems of Hot Super Earths
2. Jupiter candidates also
3. Disk parameters

- Turbulence
- Photo-evaporation
- Gas accretion
- Volatile content

1. Compact Systems of Hot Super Earths
2. Jupiter candidates also
3. Disk parameters
4. Ongoing...



Take home message

Multiple planets do NOT converge at Convergence Zone !

Christophe COSSOU christophe.cossou@u-bordeaux1.fr (post-doc ?)

b/h = 0.6
adiabatic index = 1.40
mean molecular weight = 2.35
viscosity type = alpha (Alpha-prescription, with constant alpha)
alpha = $5 \cdot 10^{-3}$
opacity type = hure (Opacity table from (Hure, 2000))

disk : $R \in [0.1; 100]\,\mathrm{AU}$
initial surface density = $300 \cdot R^{-1/2}\,\mathrm{g/cm^2}$
inner smoothing width = $0.005\,\mathrm{AU}$

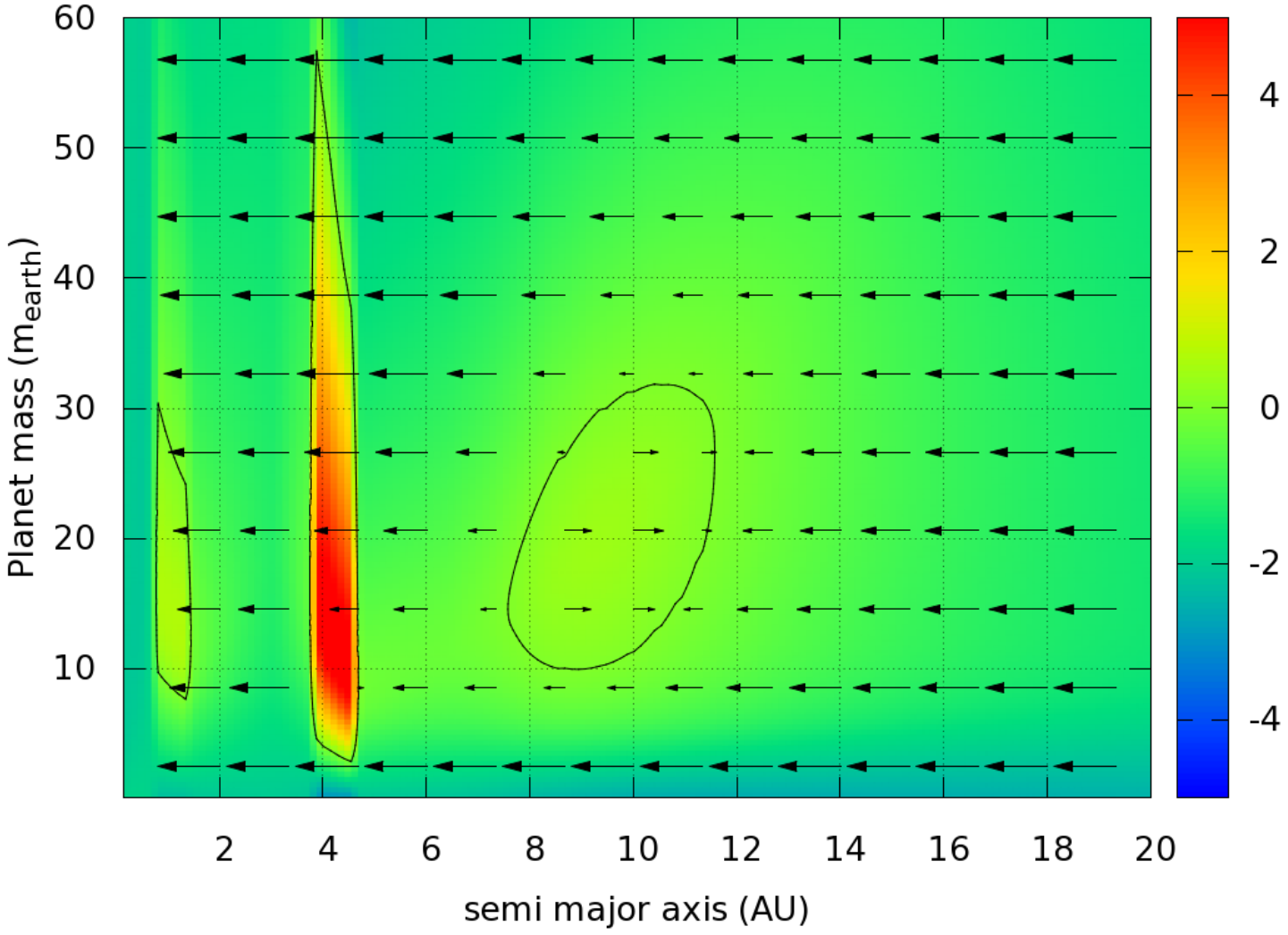
include turbulence = False
include irradiation = True
Stellar surface temperature = 5700 K
Stellar radius = $4.65 \cdot 10^{-3}$ AU
Disk Albedo = 0.5

Opacity

- (Bell & Lin, 1994)
- (Zhu & Hartmann, 2008)
- (Huré, 2000) (**opacity table**)

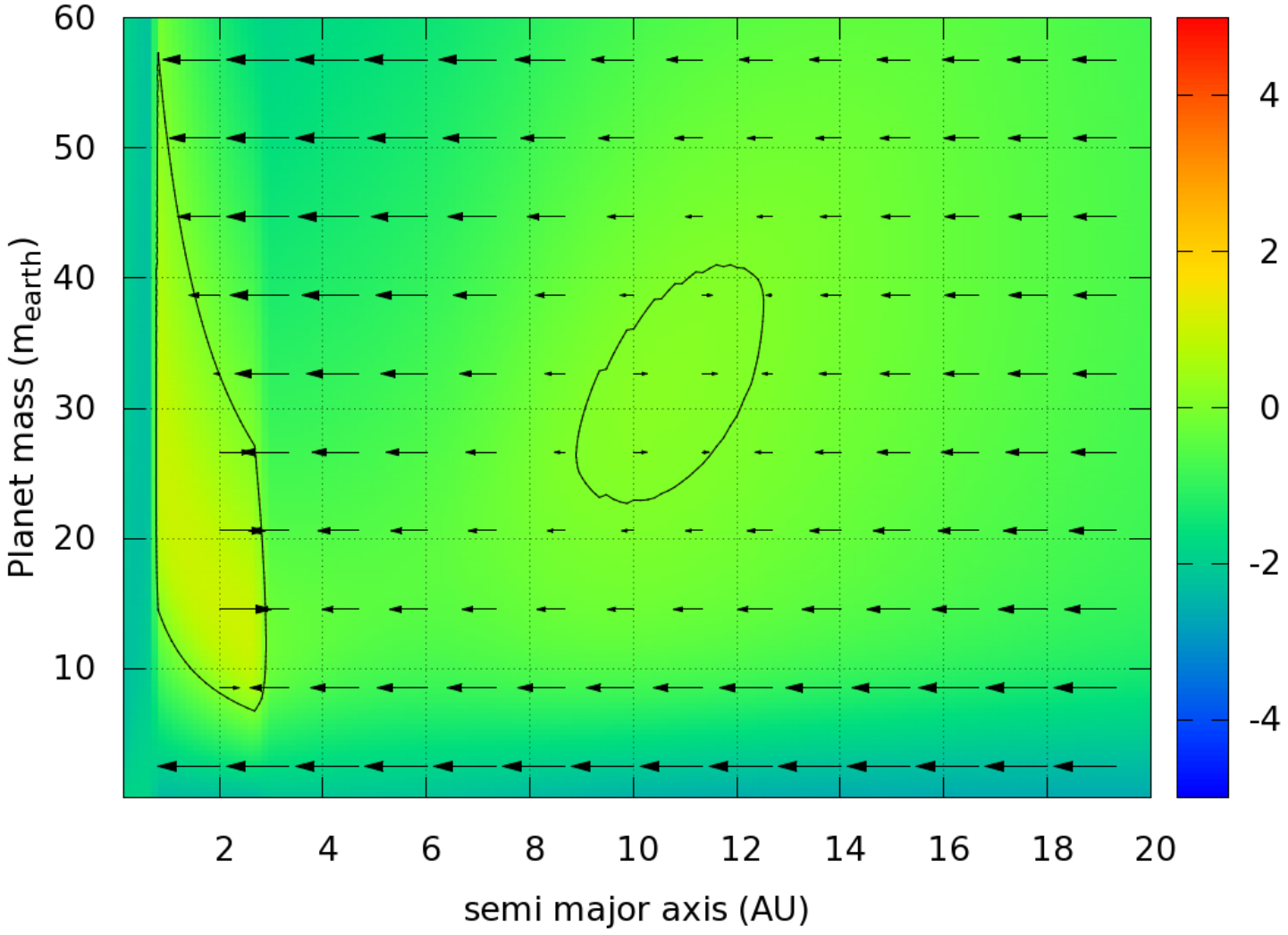
opacity laws (Bell & Lin, 1994)

Evolution of the total torque Γ_{tot}/Γ_0



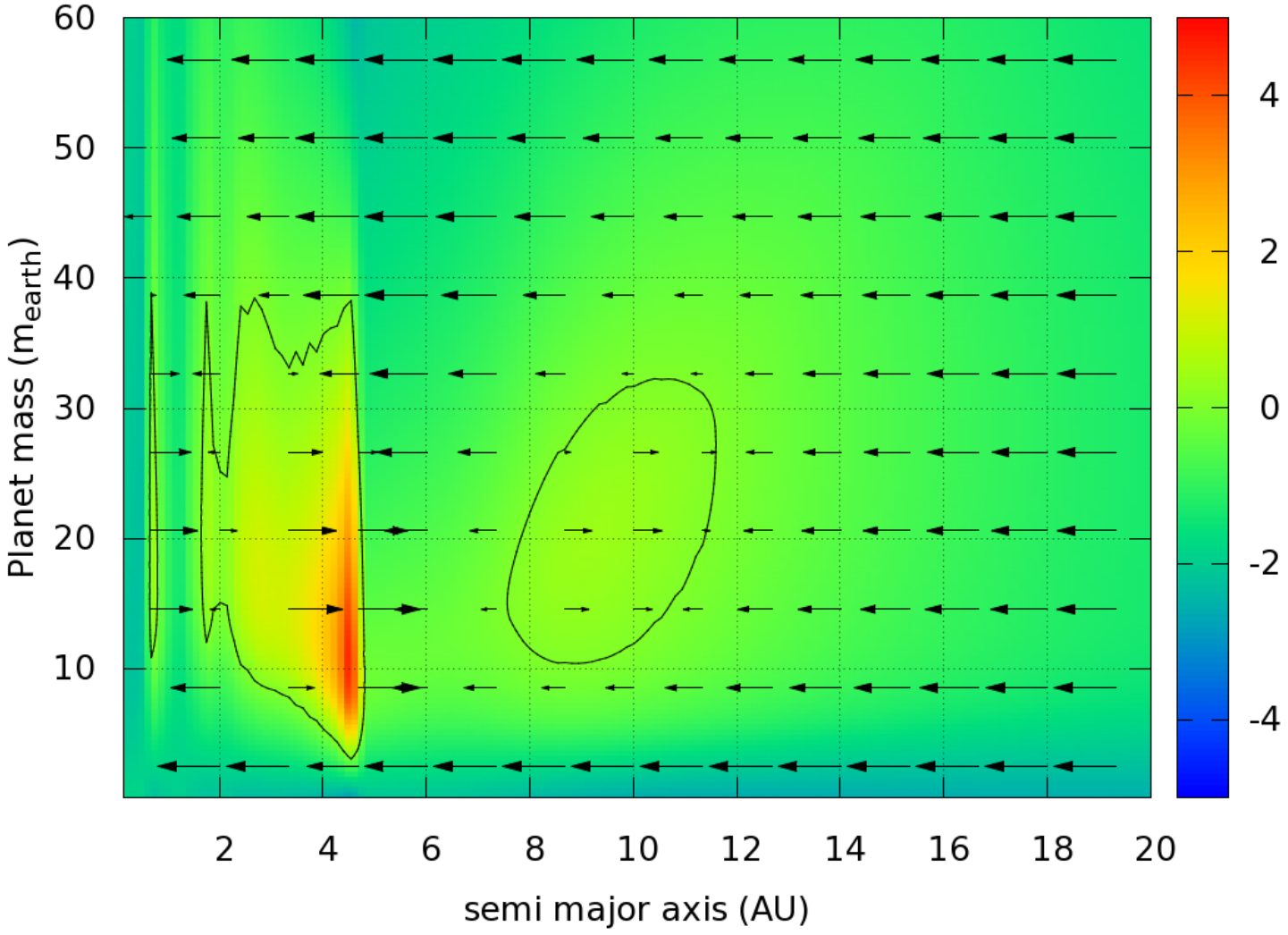
opacity laws (Zhu & Hartmann, 2008)

Evolution of the total torque Γ_{tot}/Γ_0

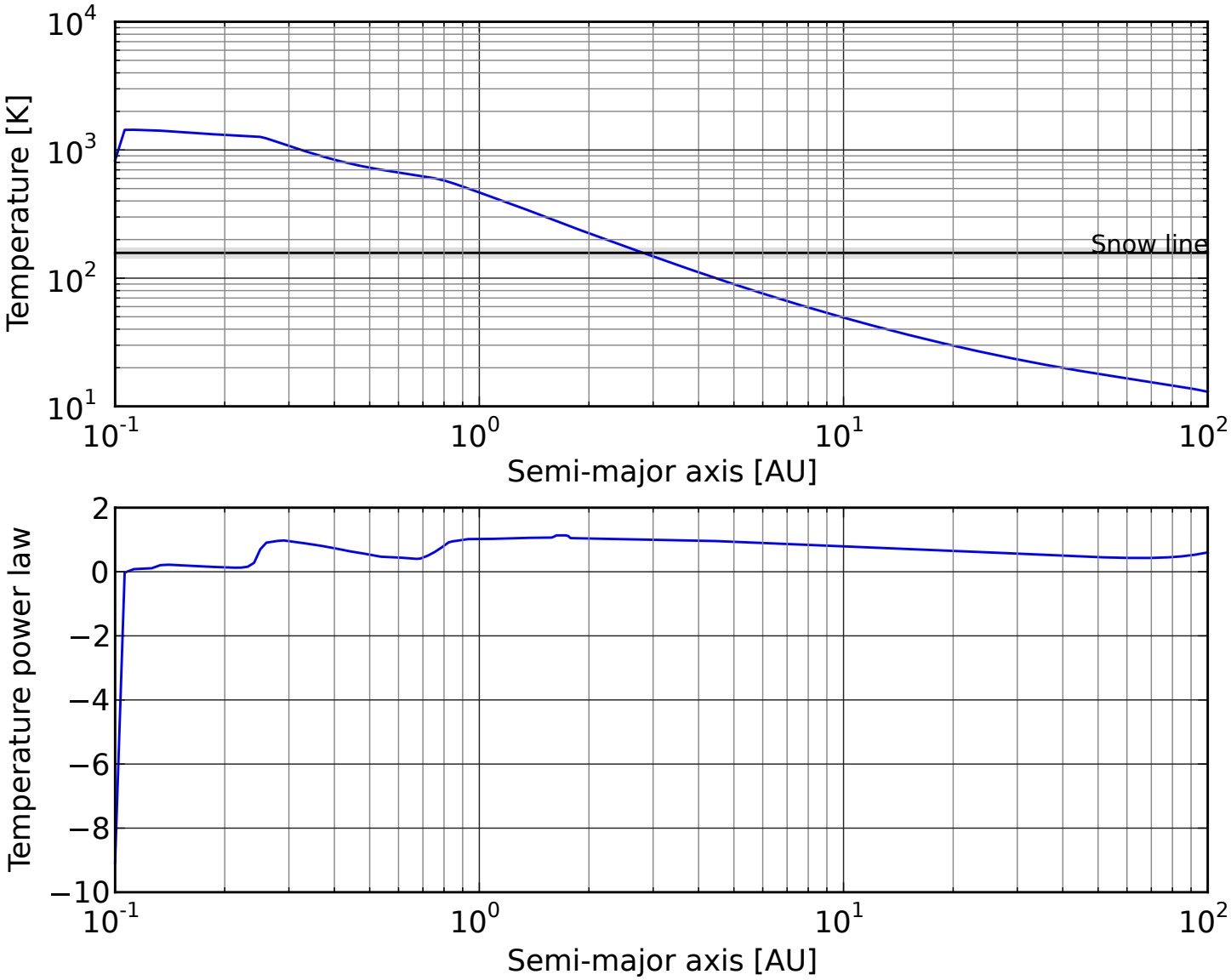


opacity table (Huré, 2000)

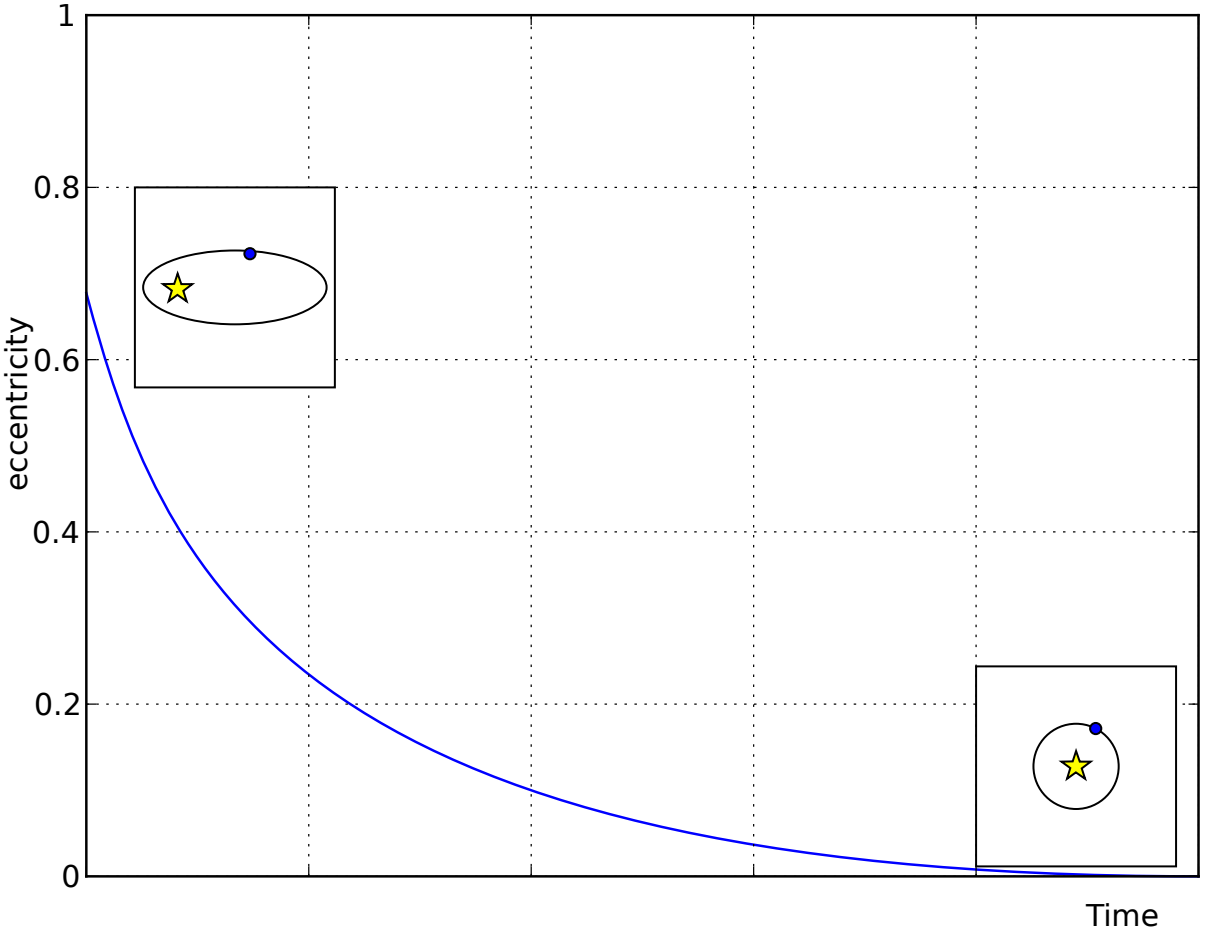
Evolution of the total torque Γ_{tot}/Γ_0



Temperature profile



eccentricity damping



inclination damping