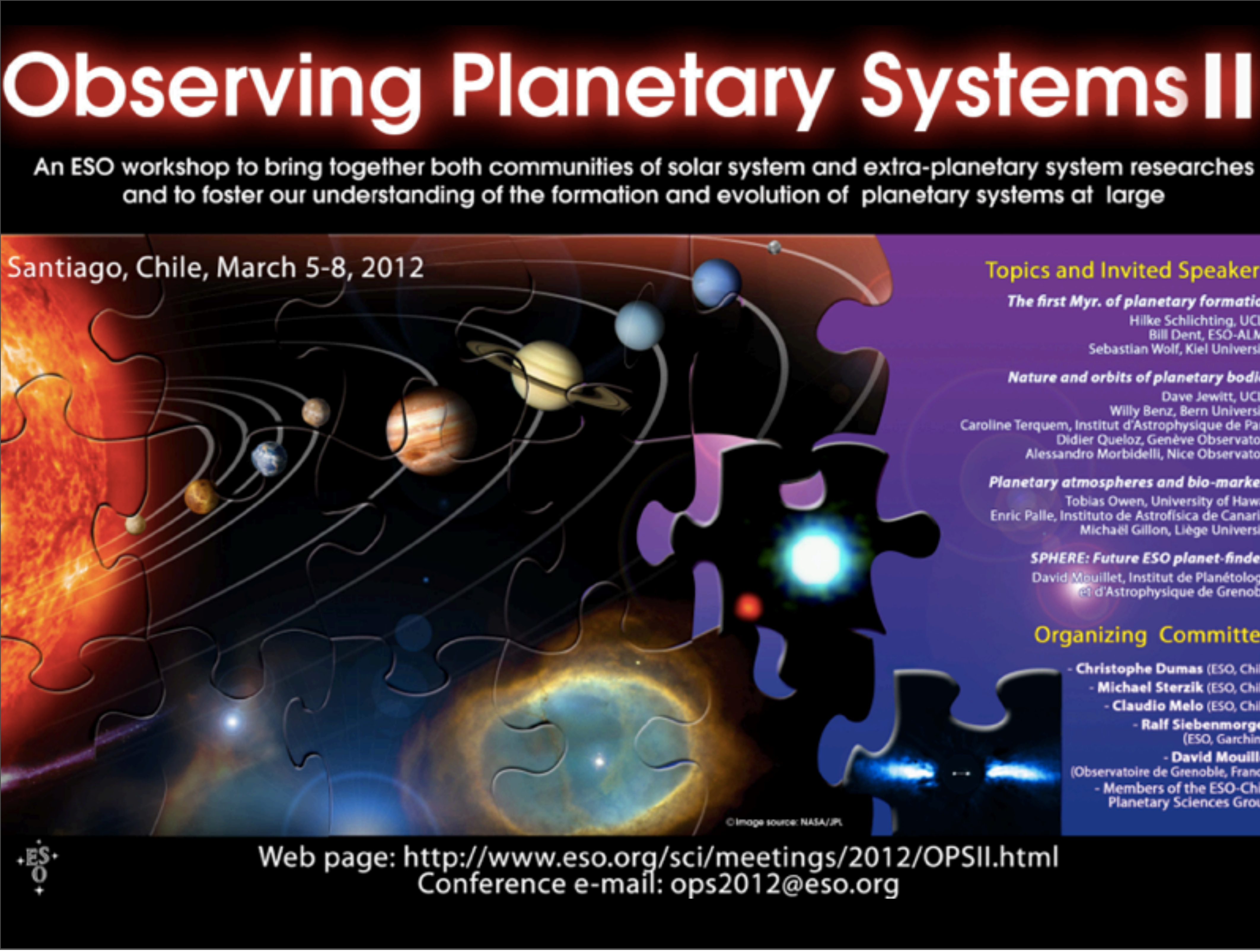
Observing Planetary Systems II
An ESO workshop to bring together both communities of solar system and extra-planetary system researches
and to foster our understanding of the formation and evolution of planetary systems at large
Santiago, Chile, March 5-8, 2012
Topics and Invited Speakers
The first Myr. of planetary formatio
Hilke Schlichting, UCL
Bill Dent, ESO-ALM
Sebastian Wolf, Kiel Universit
Nature and orbits of planetary bodie
Dave Jewitt, UCL
Willy Benz, Bern Universit
Caroline Terquem, Institut d'Astrophysique de Par
Didier Queloz, Genève Observator
Alessandro Morbidelli, Nice Observator
Planetary atmospheres and bio-marker
Tobias Owen, University of Hawa
Enric Palle, Instituto de Astrofísica de Canaria
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SPHERE: Future ESO planet-finder
David Mouillet, Institut de Planétolog
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Organizing Committe
- Christophe Dumas (ESO, Chil
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- David Mouill
(Observatoire de Grenoble, Franc
- Members of the ESO-Chil
Planetary Sciences Grou
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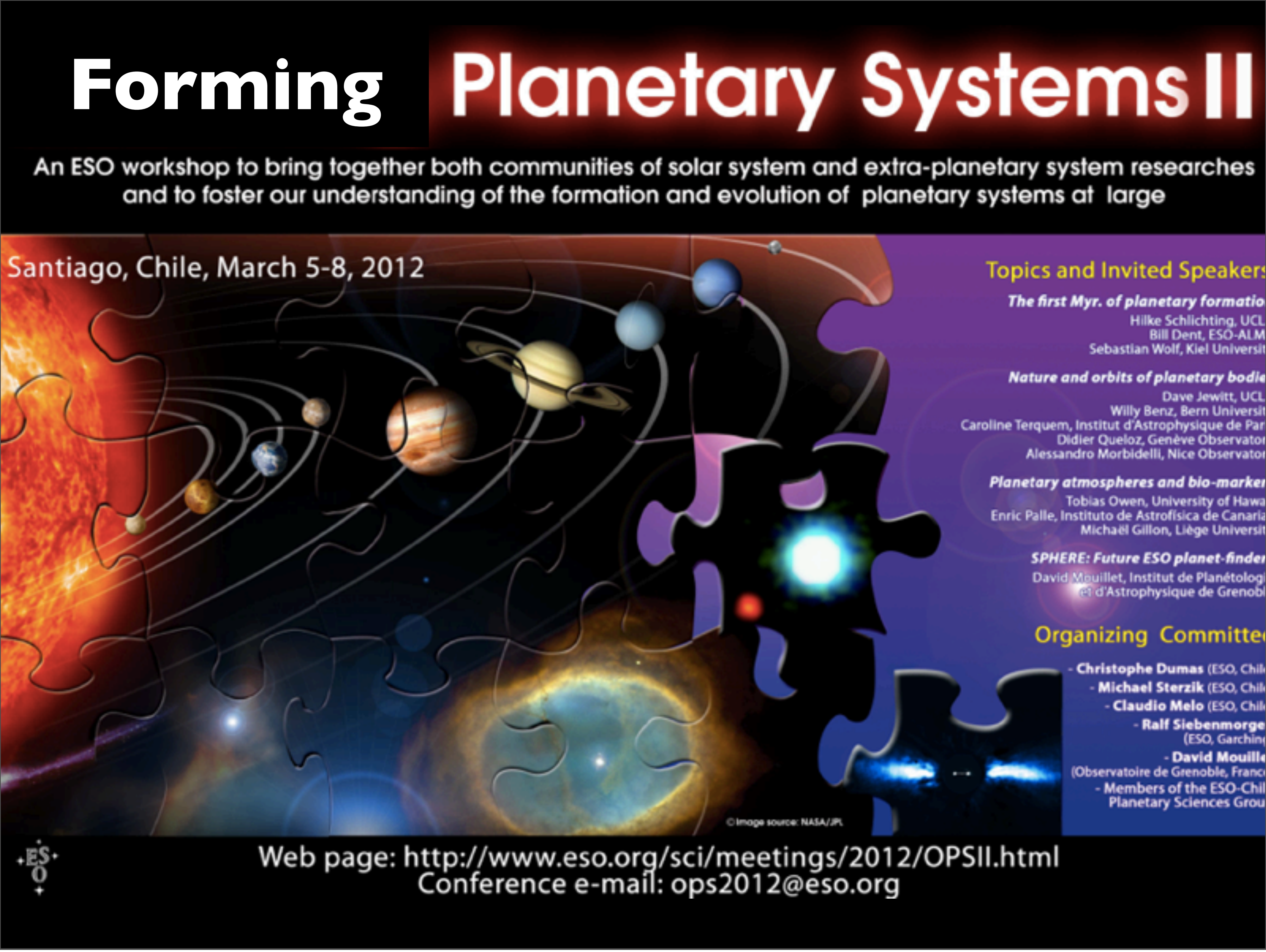
Conference e-mail: ops2012@eso.org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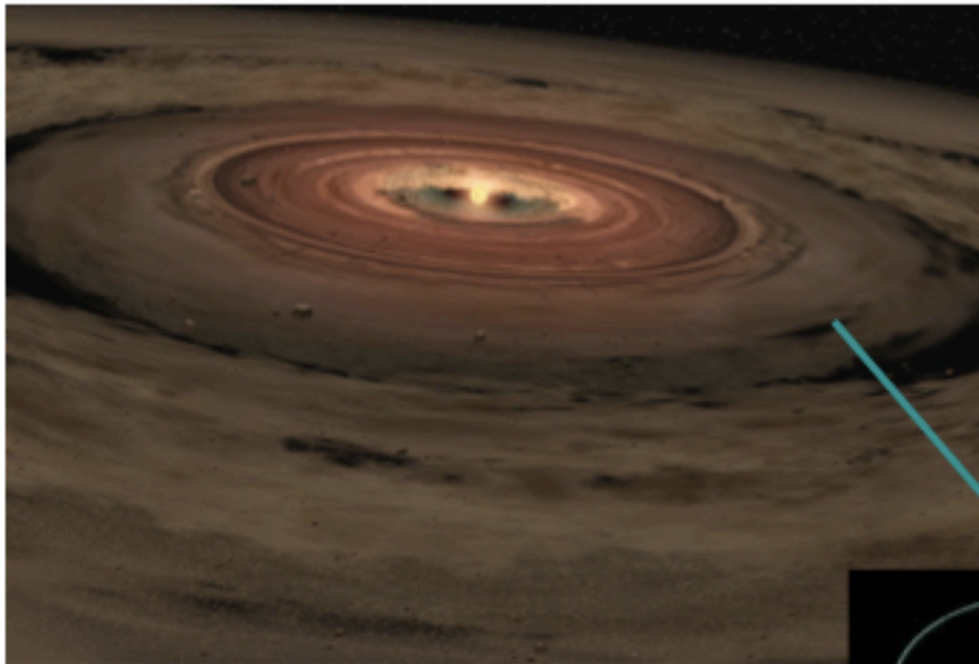
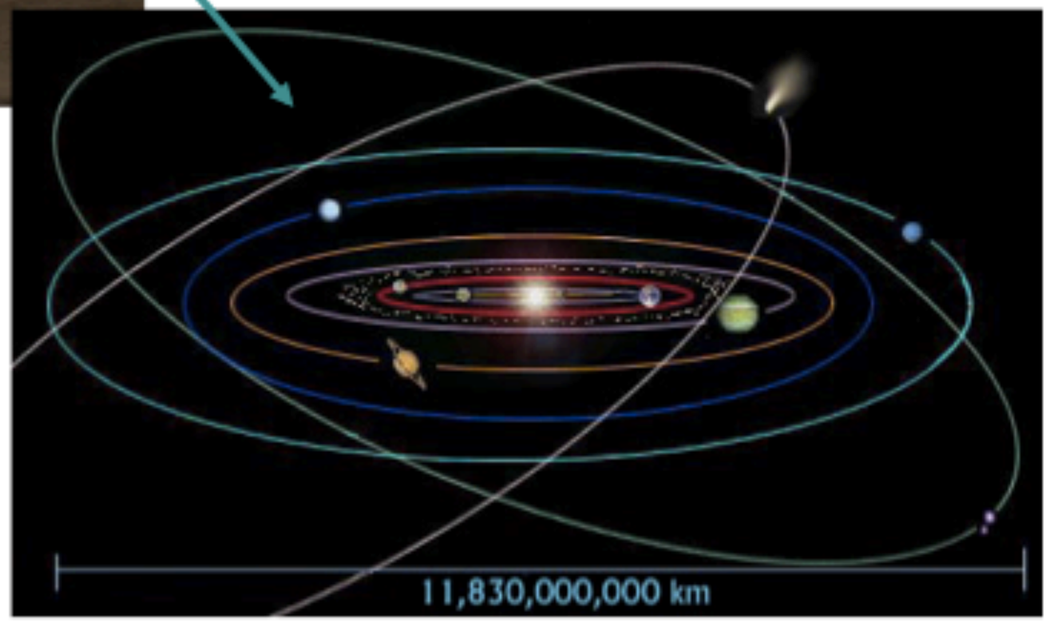
Protoplanetary discs ⇛ Planetary system





From a gas and dust-rich disc to a planetary system

Planet formation

The nucleated instability model (1)

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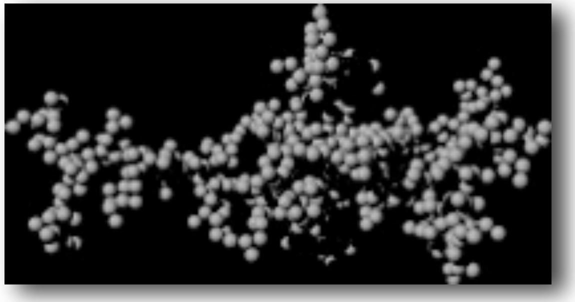

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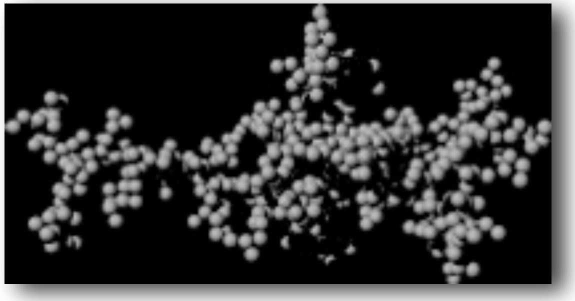

⇒

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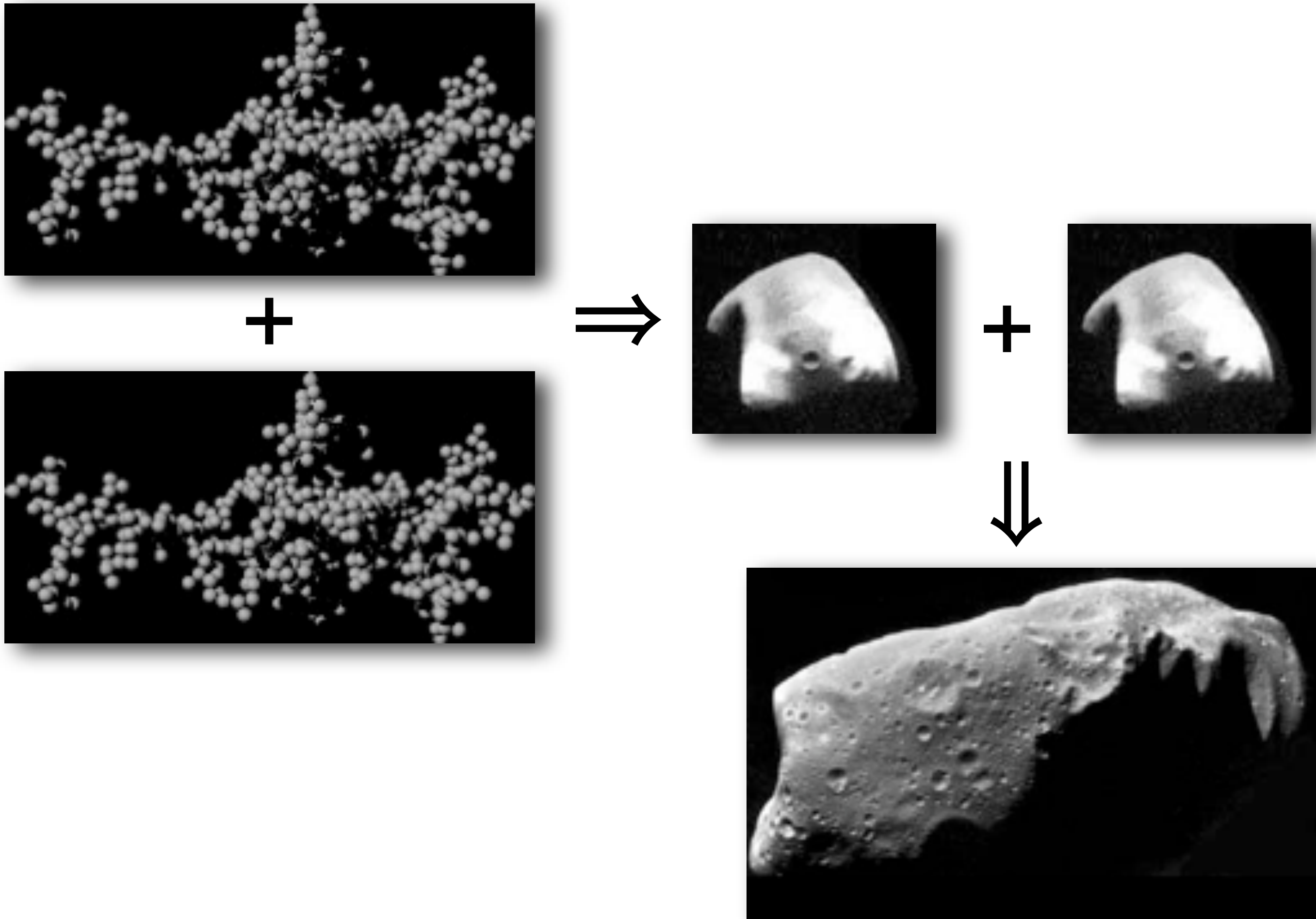

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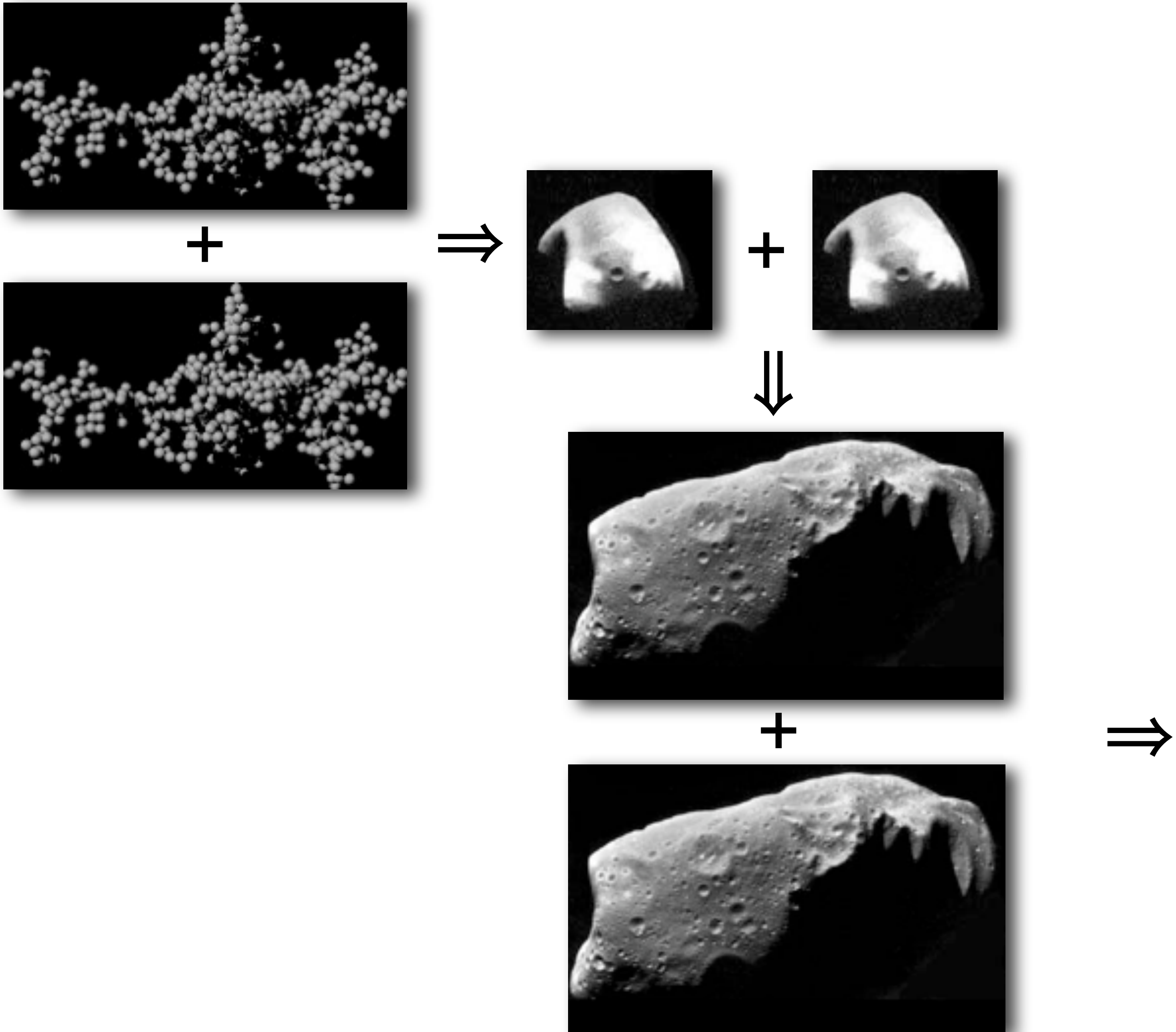

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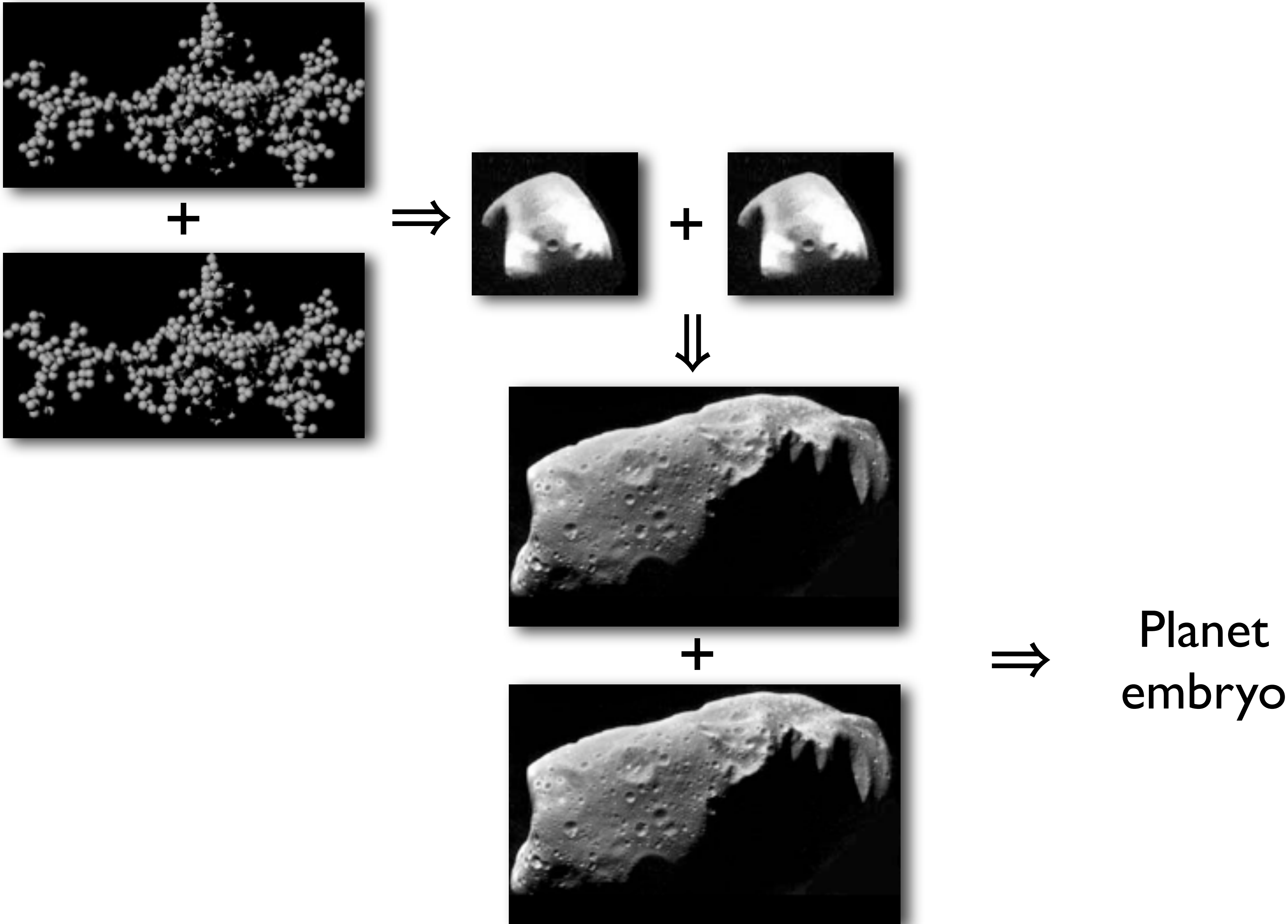

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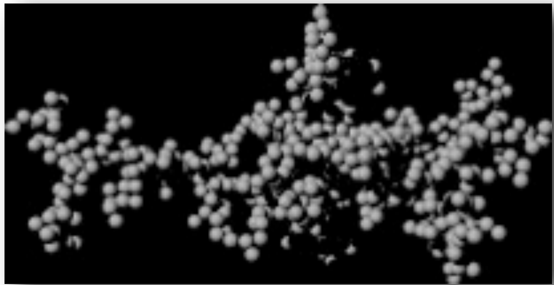

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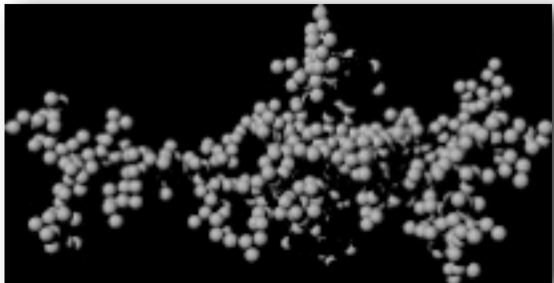


⇒

+

⇓ Gas-solids coupling

Johansen et al. 2007
Boley et al. 2010
Windmark et al. 2012

+

⇒ Planet embryo

The nucleated instability model (2)

$\Rightarrow$ 

The nucleated instability model (2)

⇒

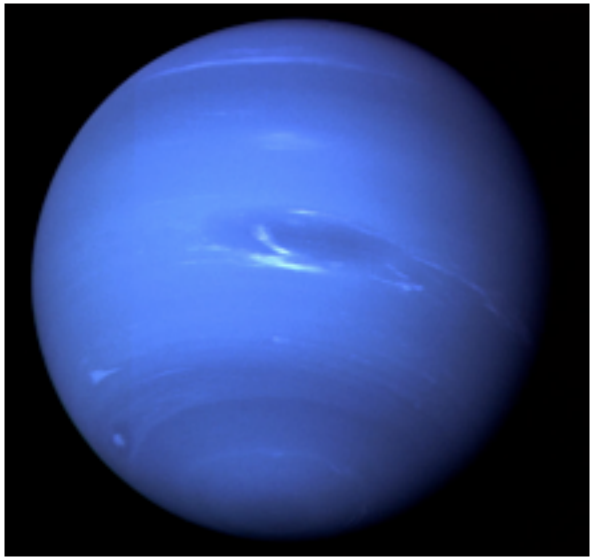
gas giant

The nucleated instability model (2)

⇒

gas giant

ice giant



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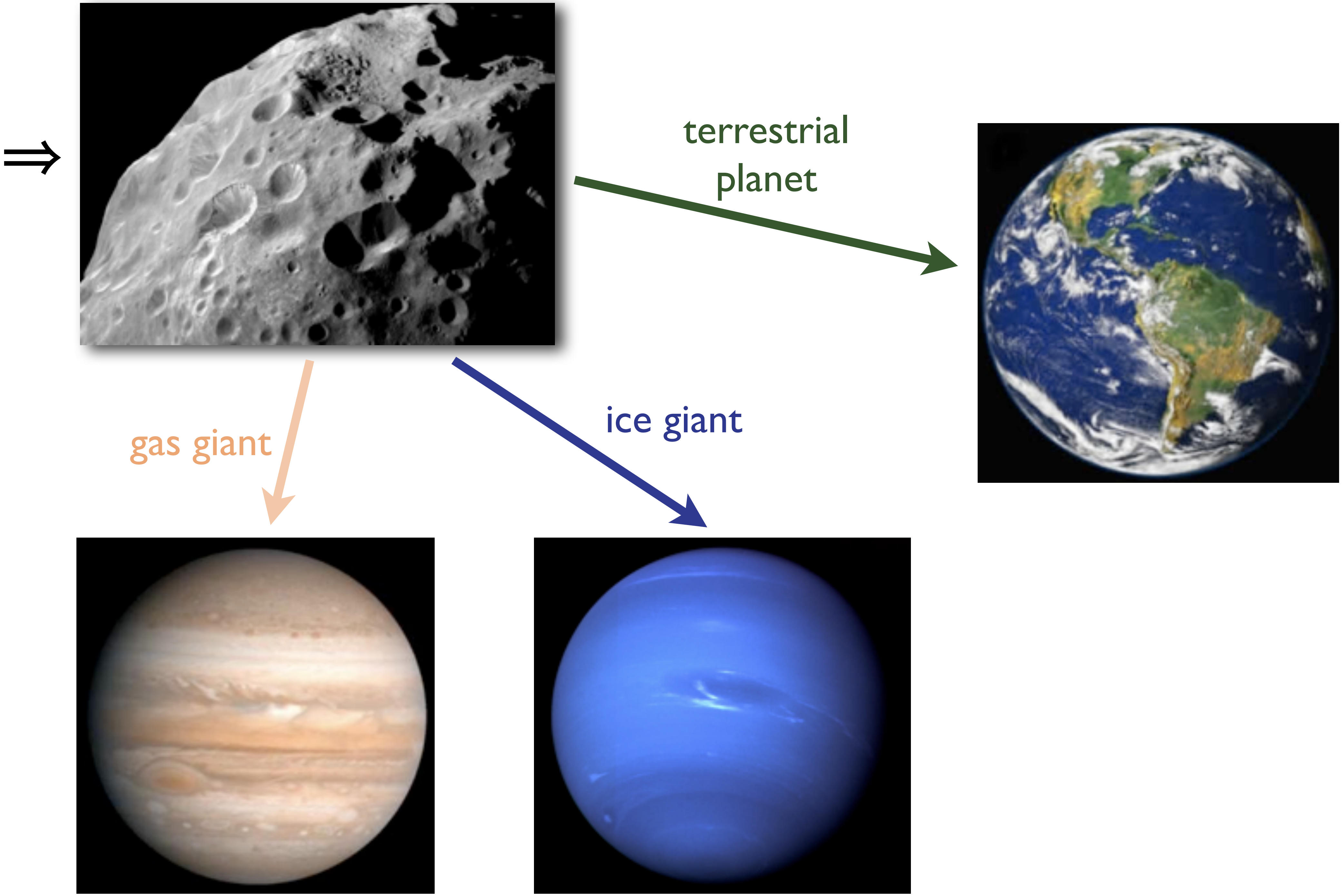


‘Bern II model’

‘Bern II model’

Core

Envelope

‘Bern II model’

Core

Envelope

Rad. str.

‘Bern II model’

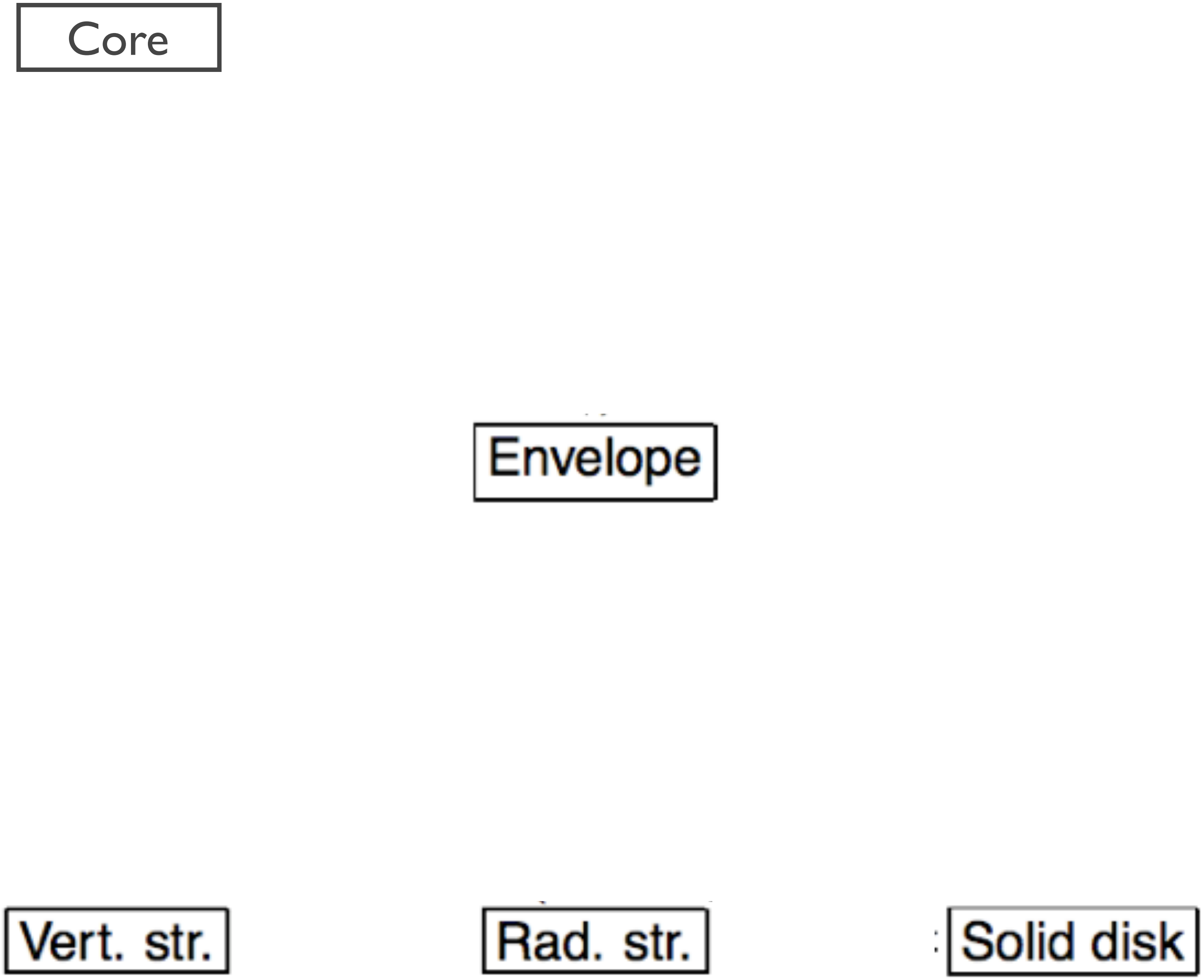
Core

Envelope

Vert. str.

Rad. str.

‘Bern II model’



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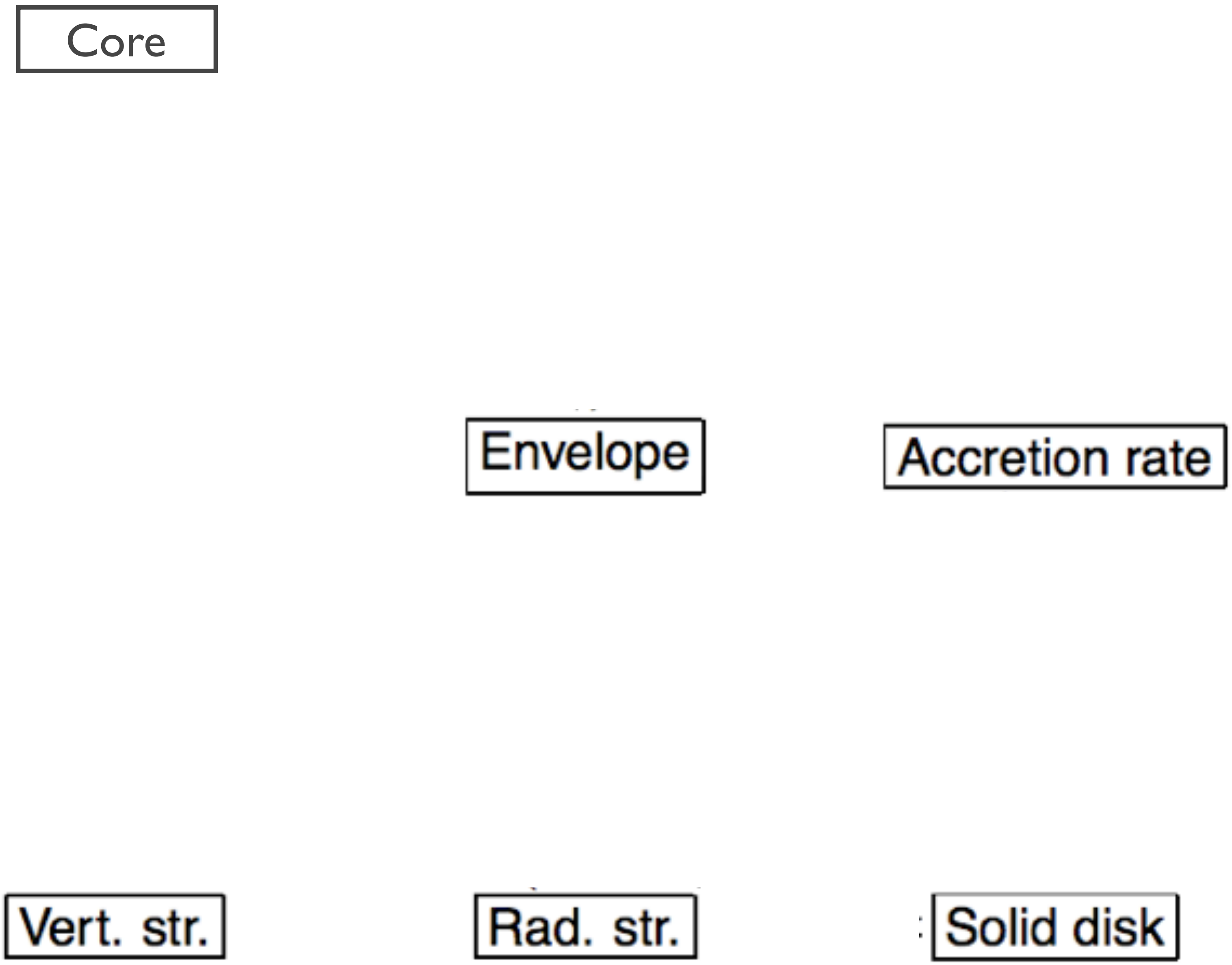

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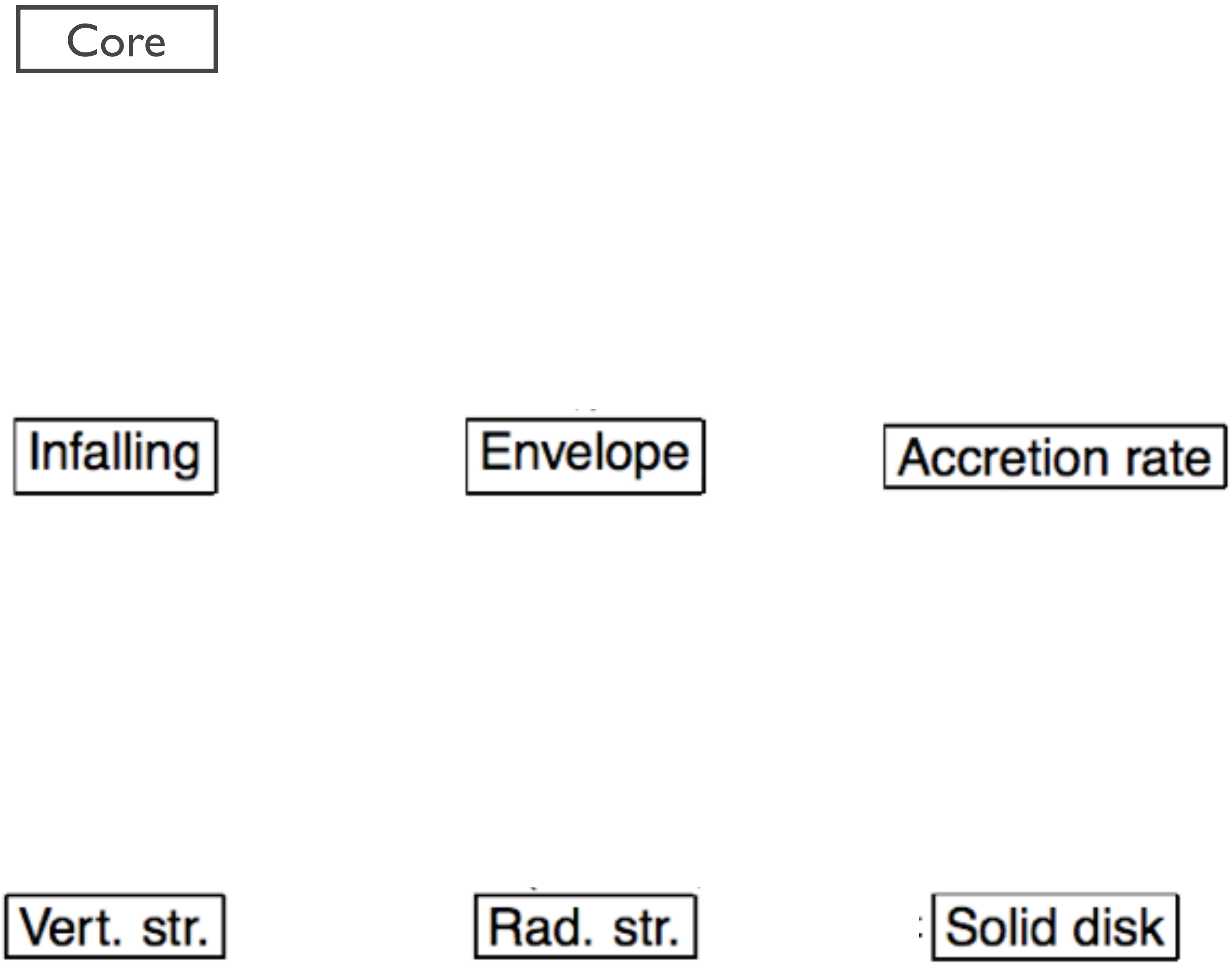

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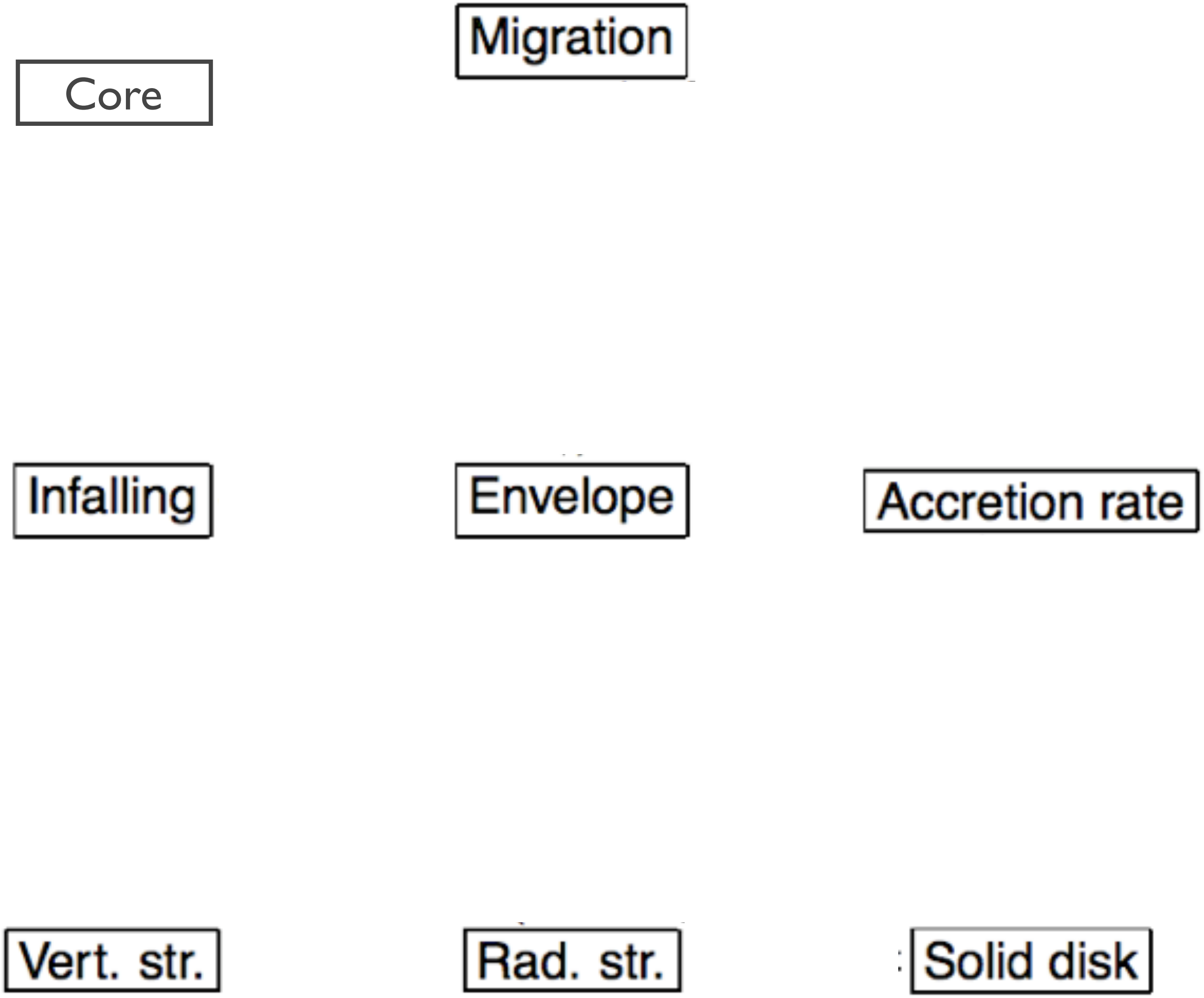

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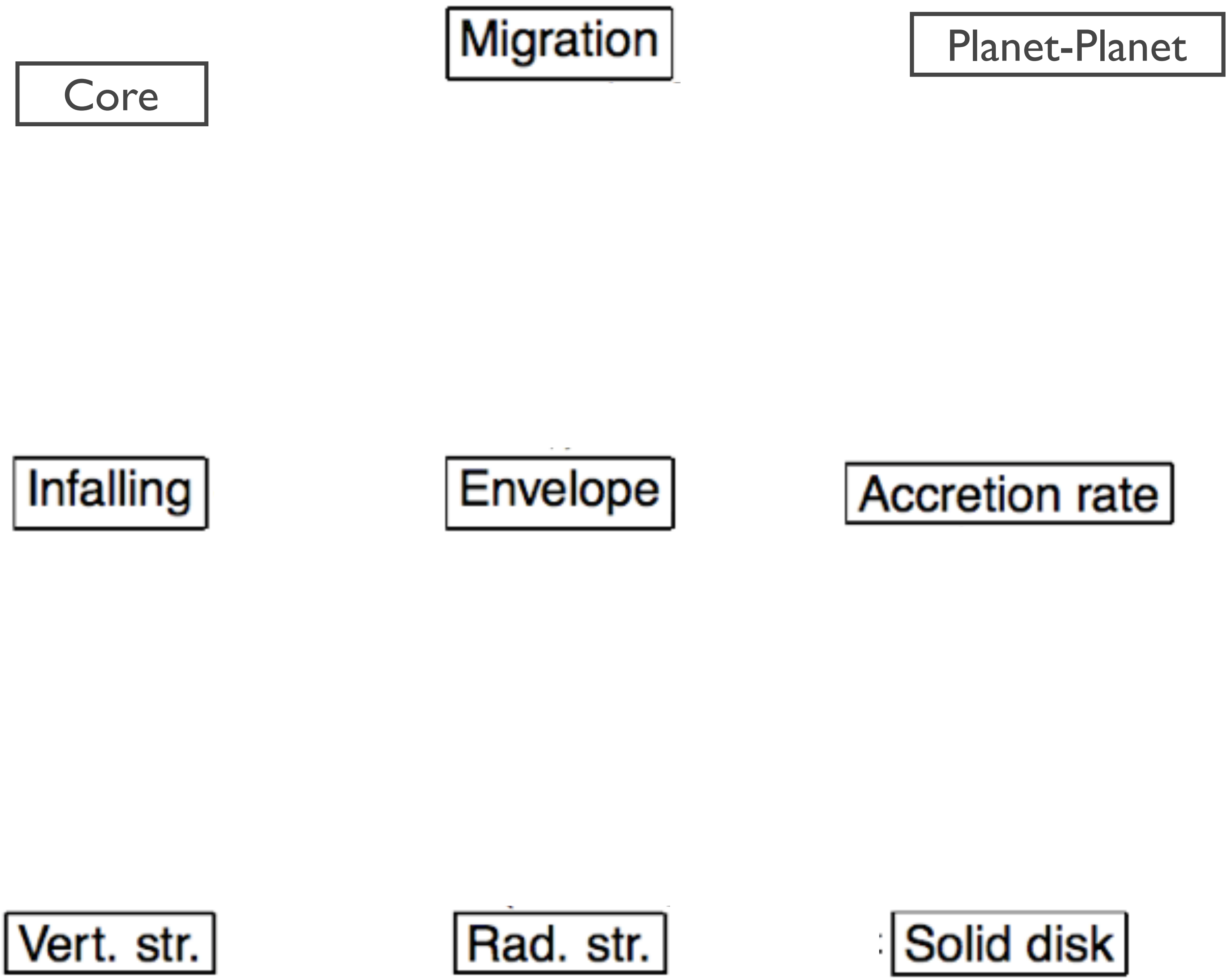

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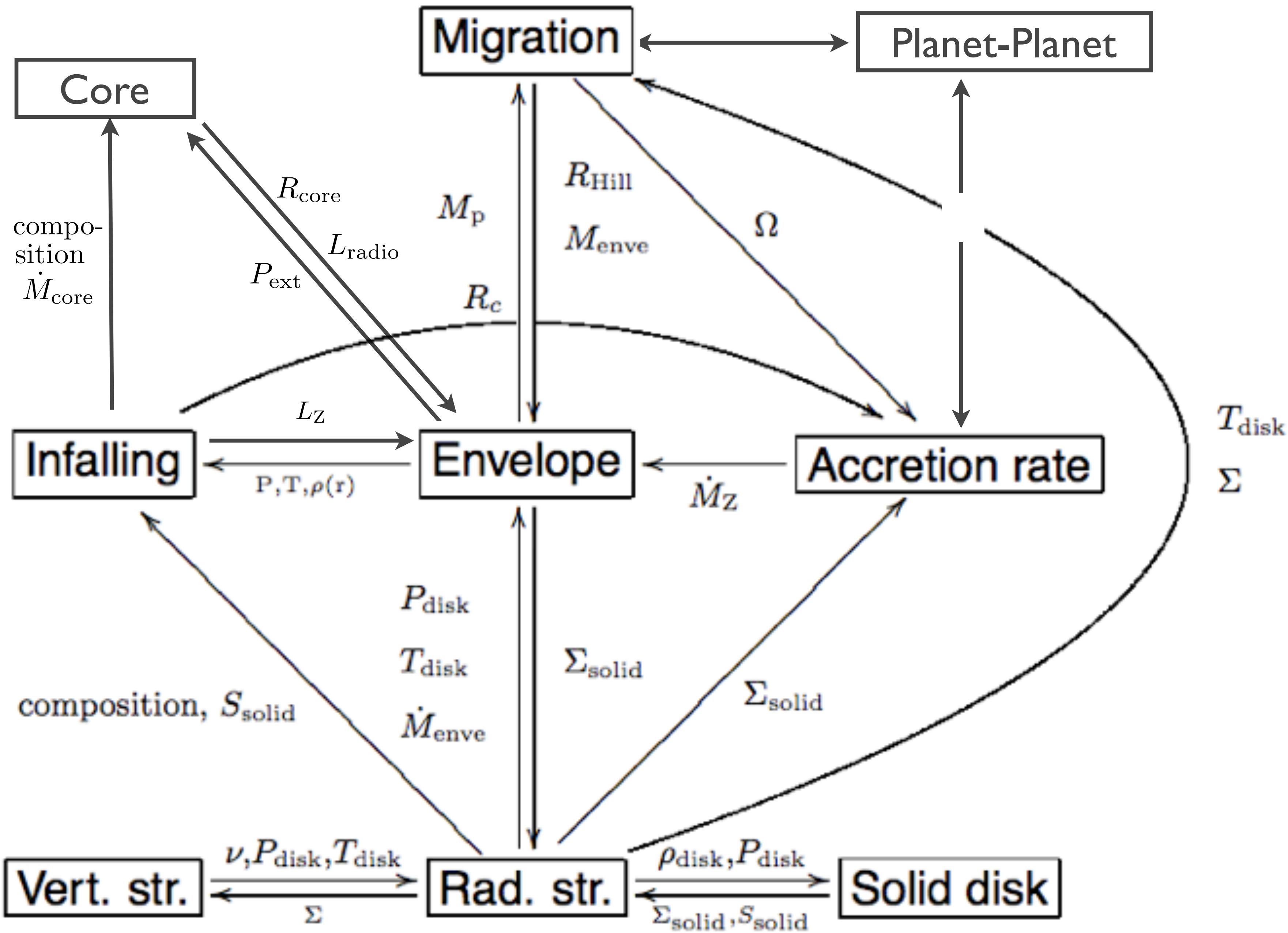

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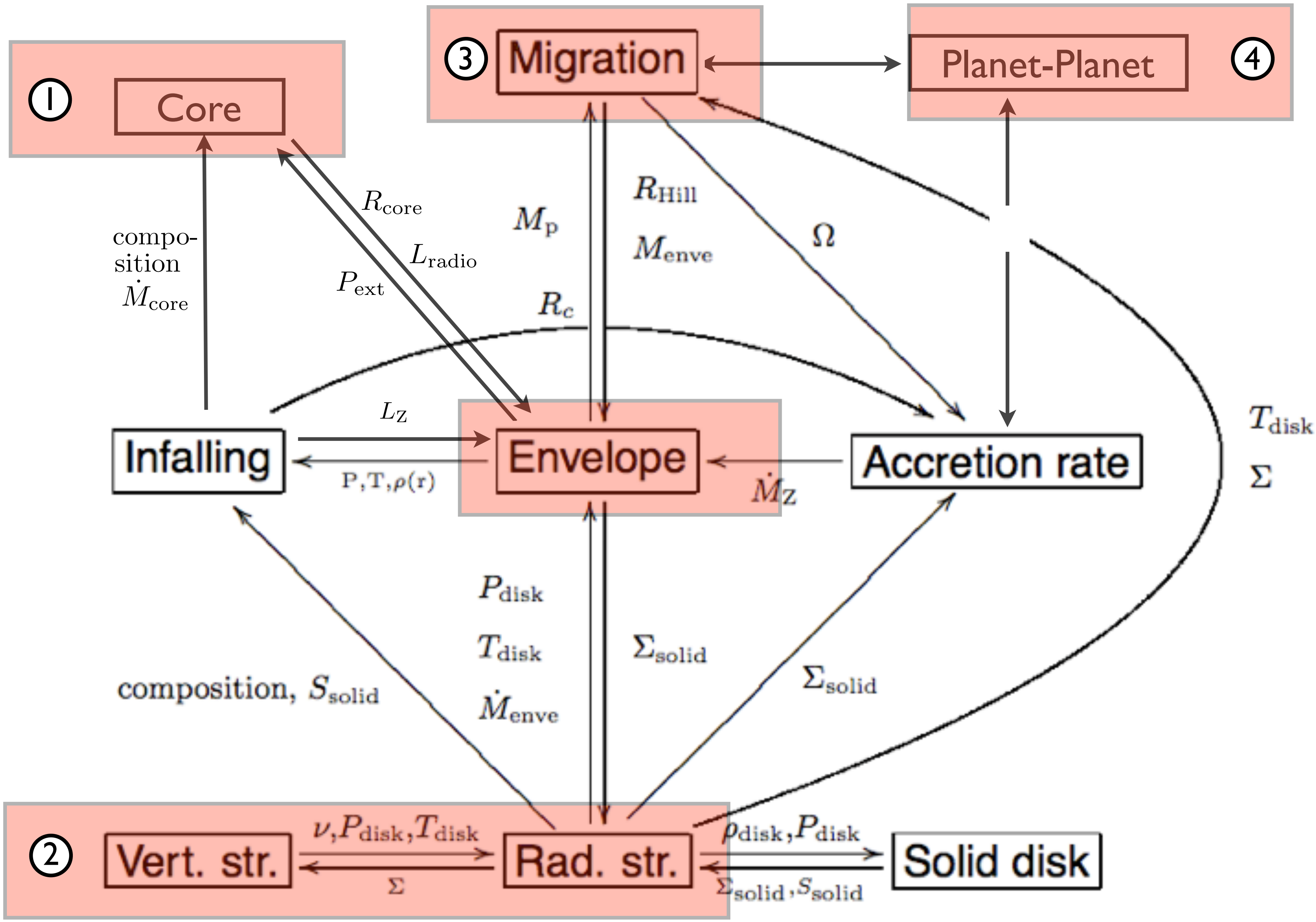

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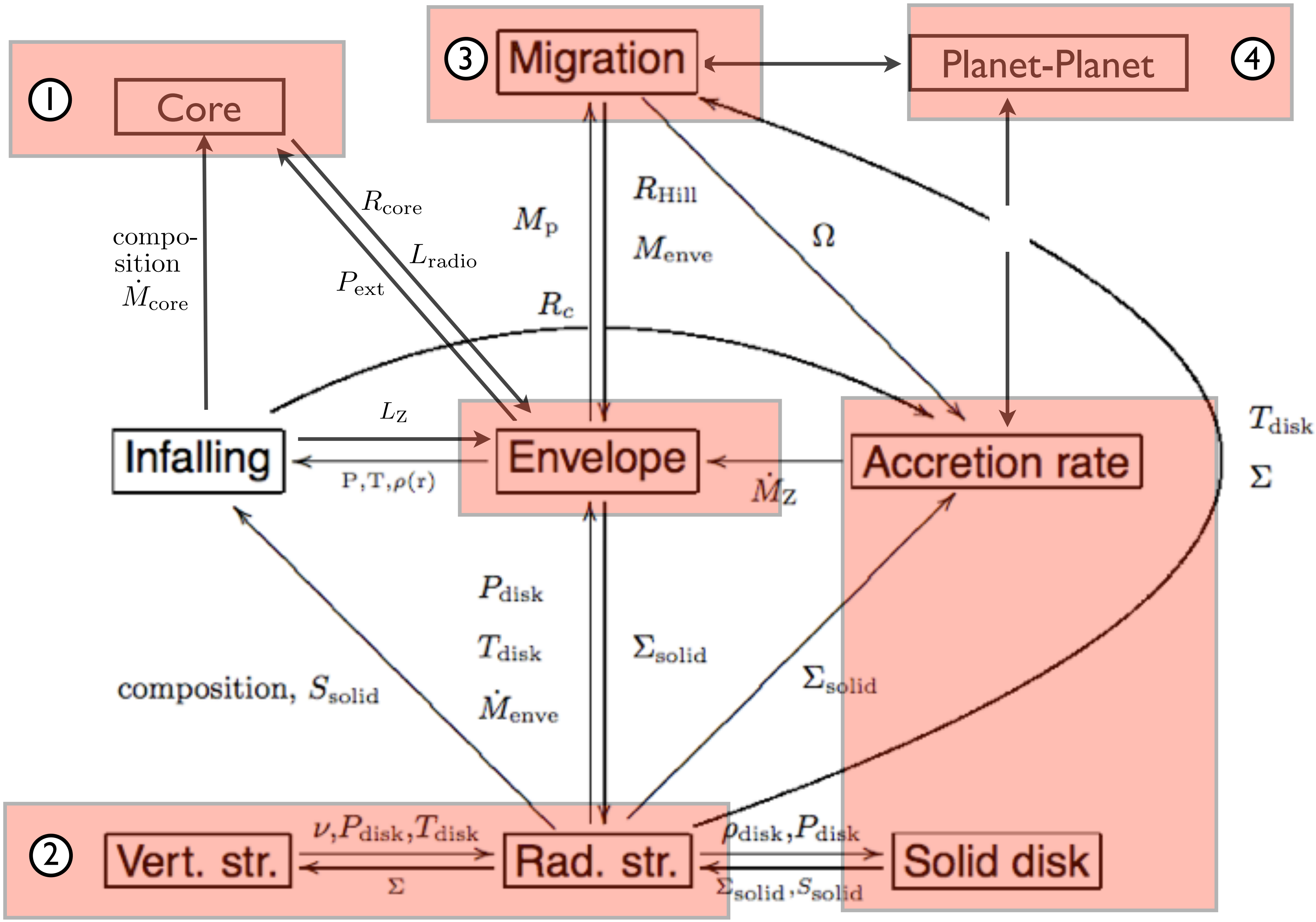


① Planet core structure

Solve internal structure equations for the solid core

- -Differentiated planet
    - -Iron core, silicate mantle, ice layer (if)
- -Simplified EOS. No temperature dependence.

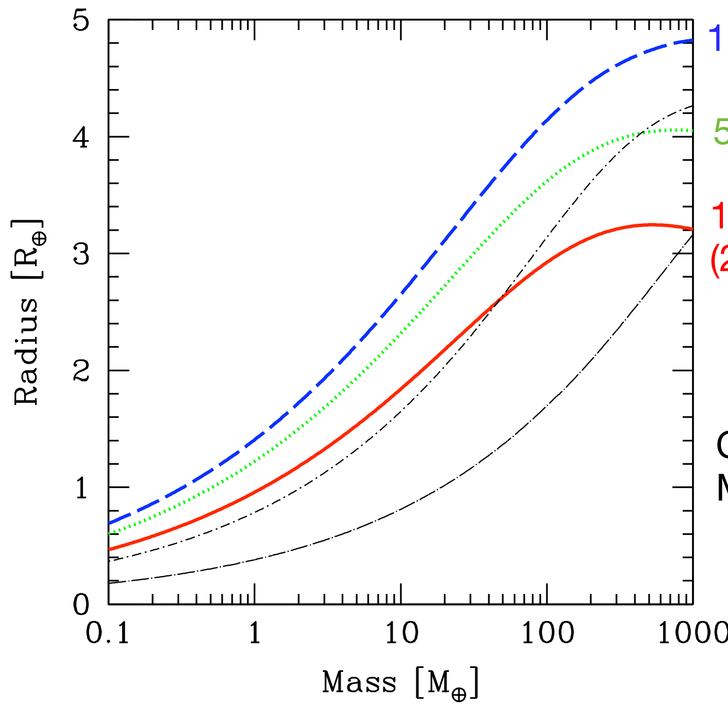
$$\rho(P) = \rho_0 + cP^n$$

Seager et al. 2007

$$\frac{\partial r}{\partial M_r} = \frac{1}{4\pi r^2 \rho} \qquad \frac{\partial P}{\partial M_r} = -\frac{GM_r}{4\pi r^4}$$

- -Include effect of external pressure

$$R_{\rm core} = R_{\rm core}(M_{\rm core}, f_{\rm iron}, f_{\rm ice}, P_{\rm ext})$$



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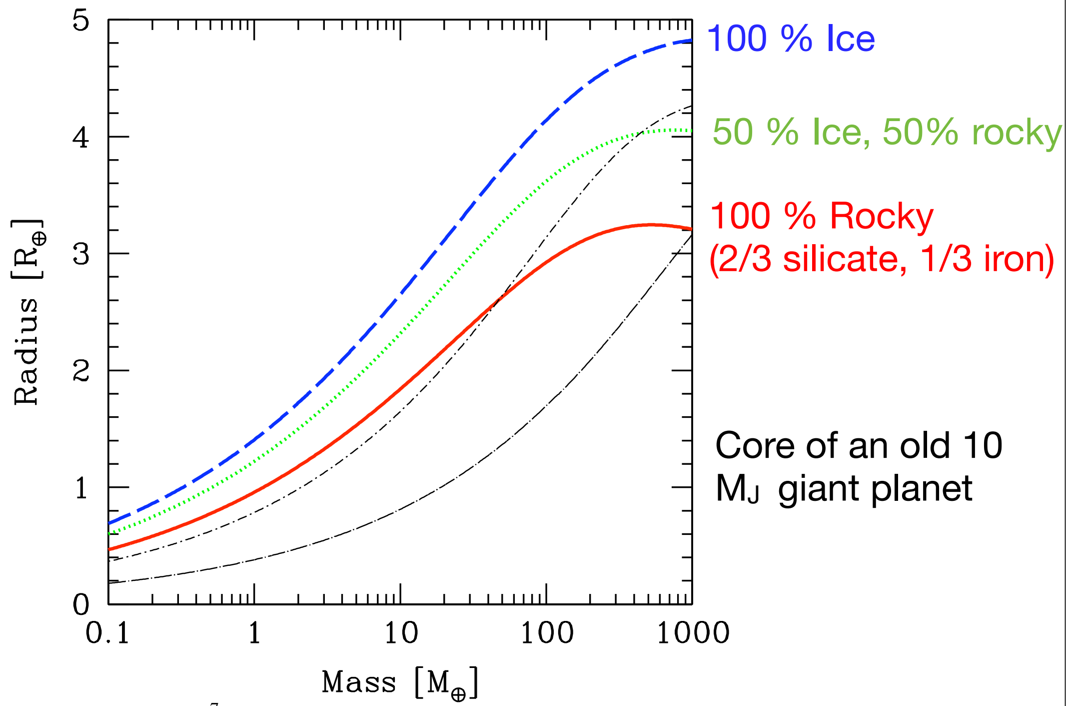
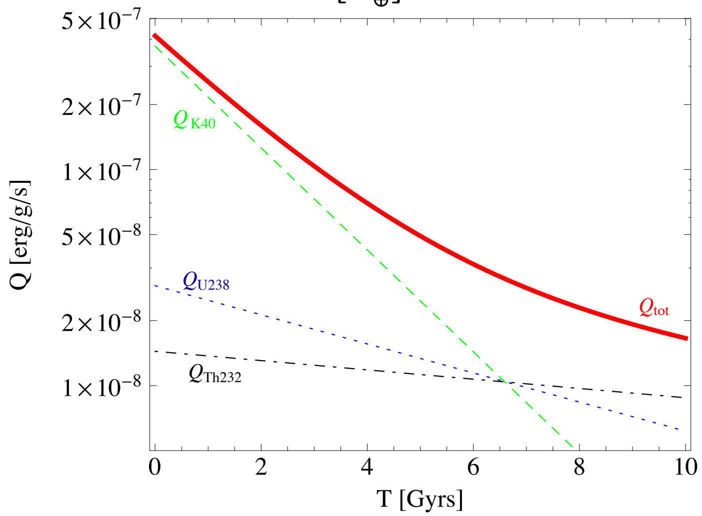


Radiogenic core heating

-Assume chondritic mantle composition

$$Q_{\rm tot}(t) = Q_{0,\rm K}e^{-\lambda_{\rm K}t} + Q_{0,\rm U}e^{-\lambda_{\rm U}t} + Q_{0,\rm Th}e^{-\lambda_{\rm Th}t}$$

$$L_{\rm radio}(t) = Q_{\rm tot}(t) f_{\rm mantle} f_{\rm rocky} M_{\rm Z}$$



① Planet's internal structure: gas

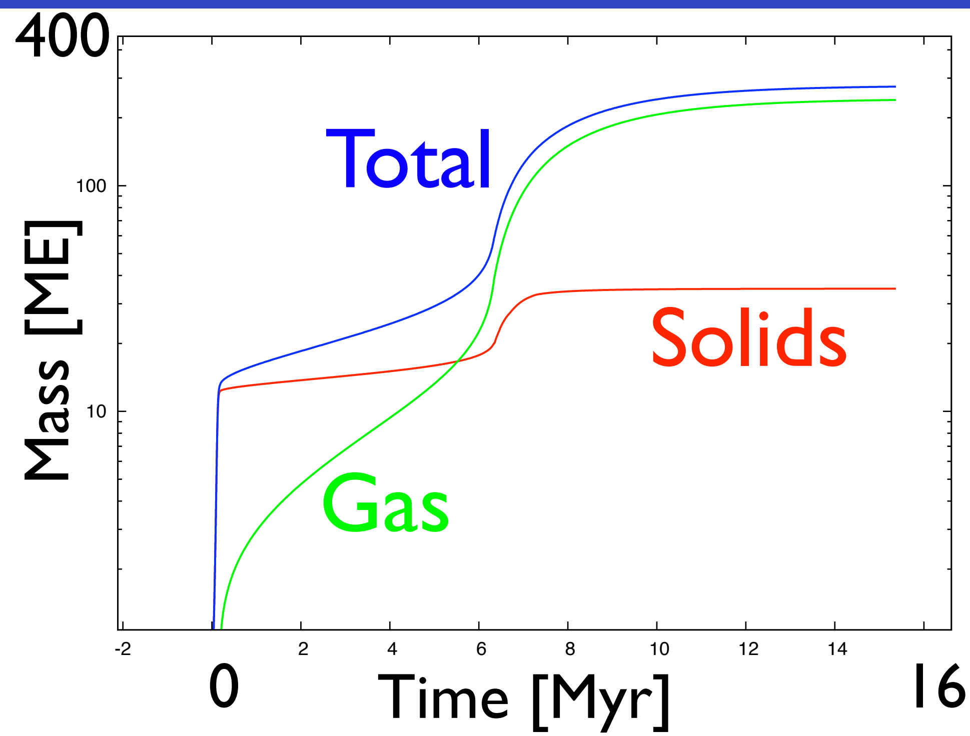
In situ formation of Jupiter at 5.2 AU

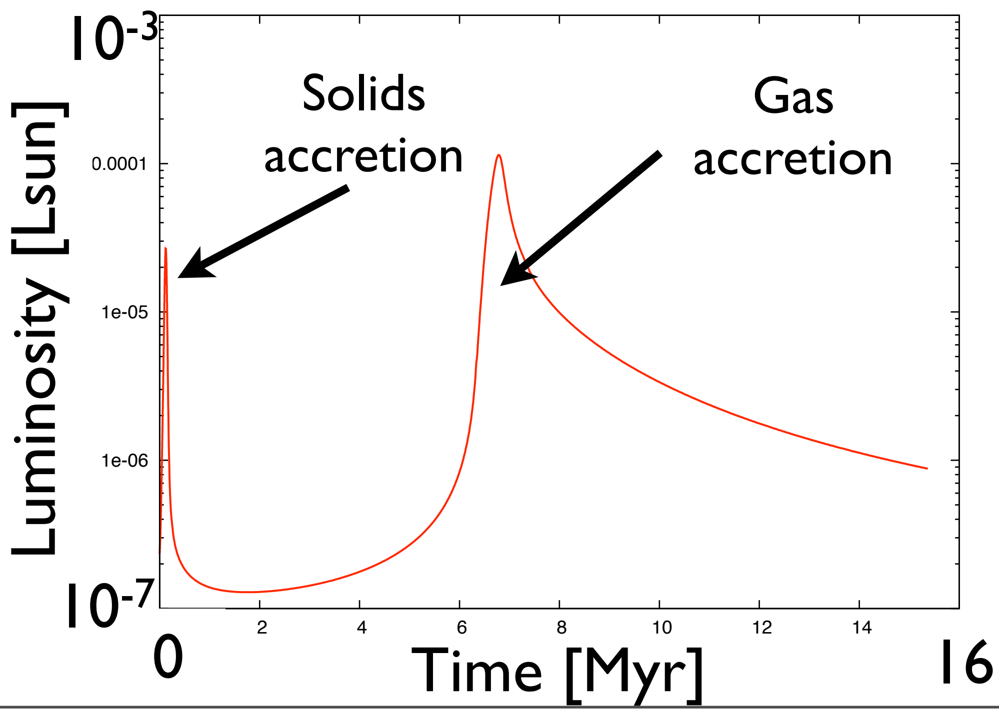
$$\Sigma_{\rm solids} = 10{\rm g/cm}^2 \,@\, 5.2AU$$

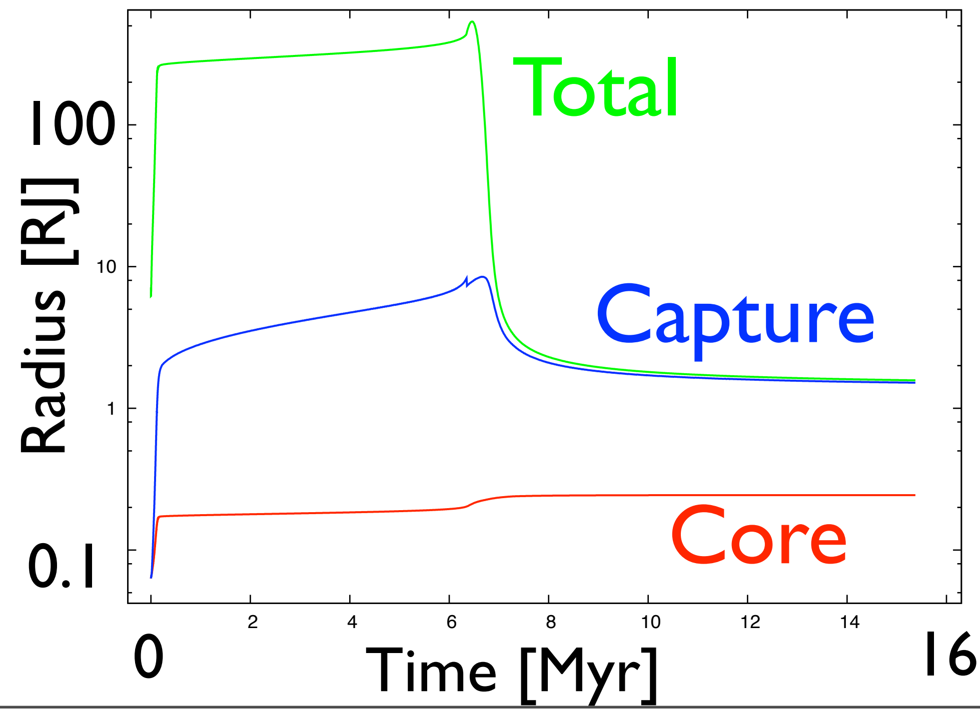
$$M_{\rm disk} \approx 0.03 M_\odot$$

only viscosity

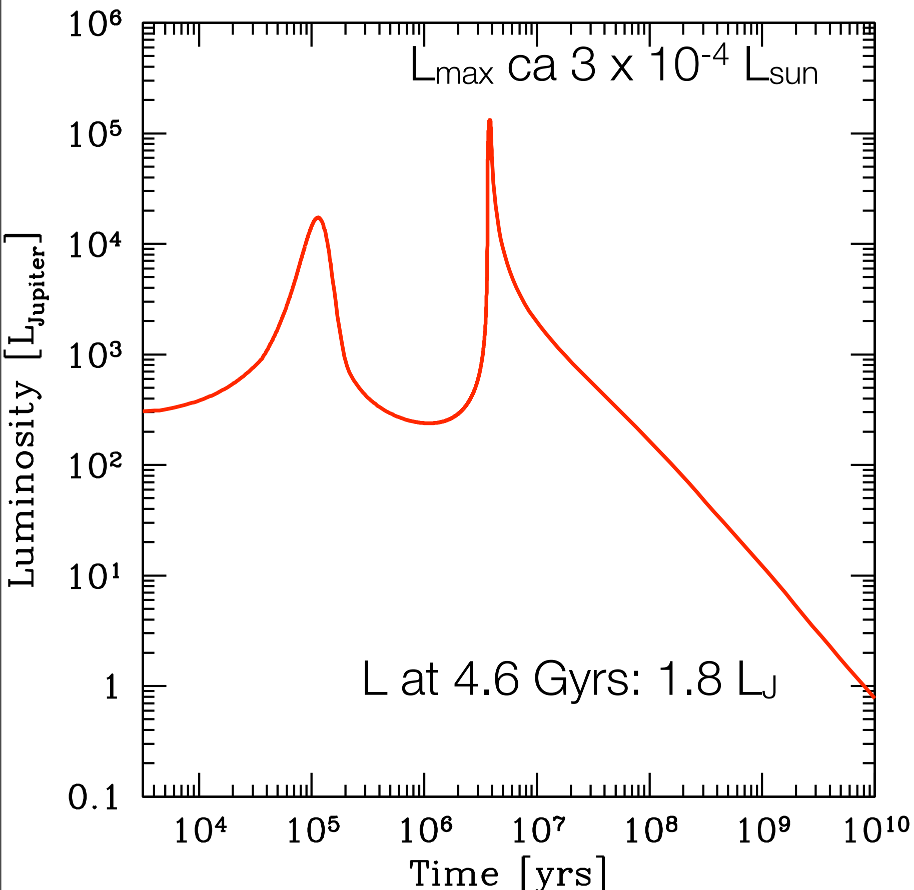
Planet in contact with disk ⟷ Planet isolated ⟷

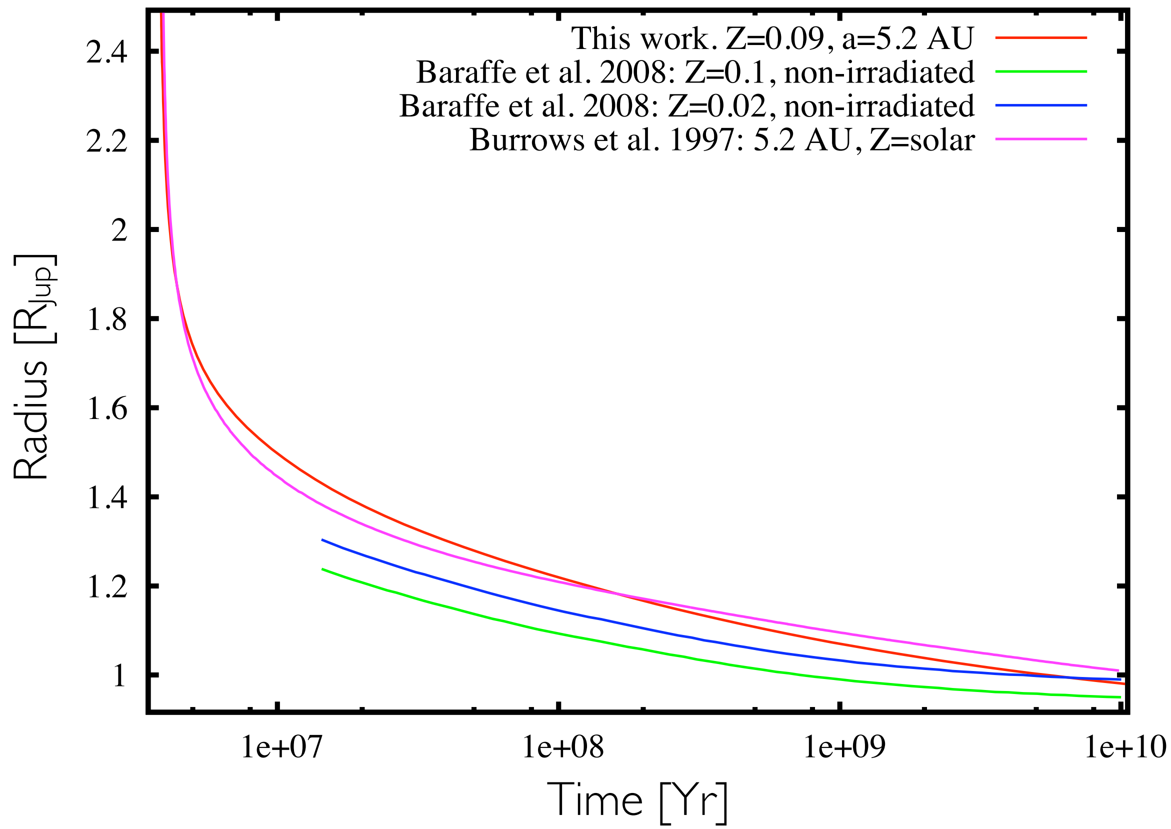






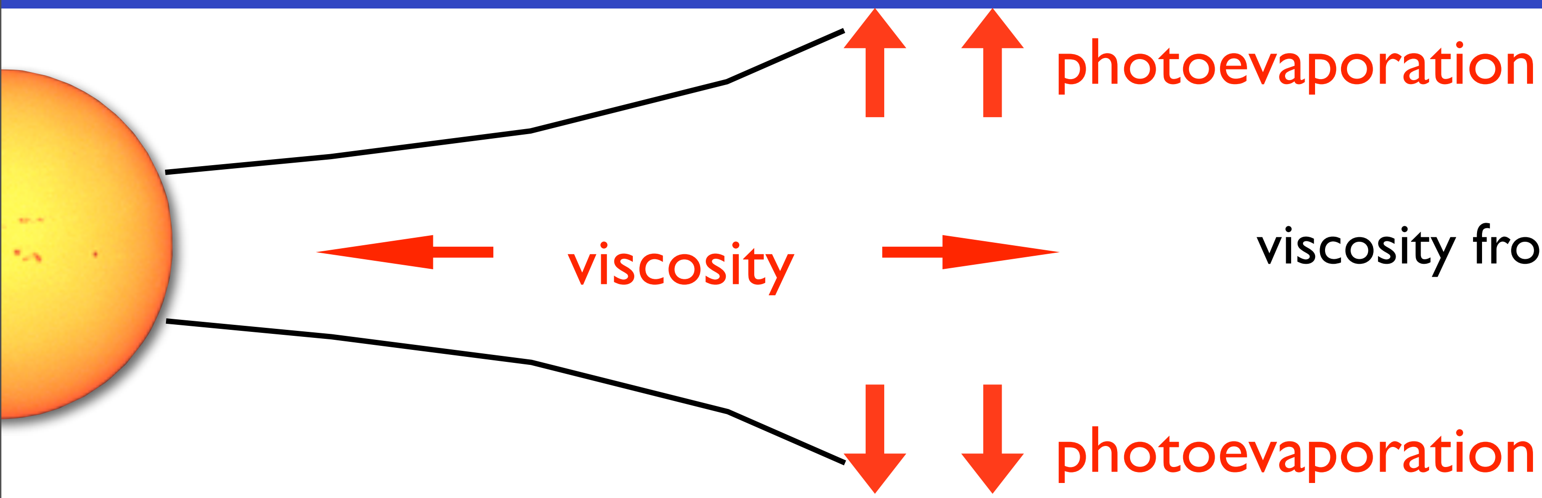
① Planet gas envelope structure - long term evolution





see talk by M. Bonnefoy (friday)

② 1+1D disk model: gas



viscosity from Shakura&Sunyaev

$$\frac{\mathrm{d}\Sigma}{\mathrm{d}t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\tilde{\nu}\Sigma r^{1/2}\right] + \dot{\Sigma}_w(r) + \dot{Q}_{\mathrm{planet}}(r)$$

Viscosity — Photoevaporation — Planet accretion

Vertical & radial structure.

- -constant α $\nu = \alpha c_s H$
- -stellar irradiation included for temperature

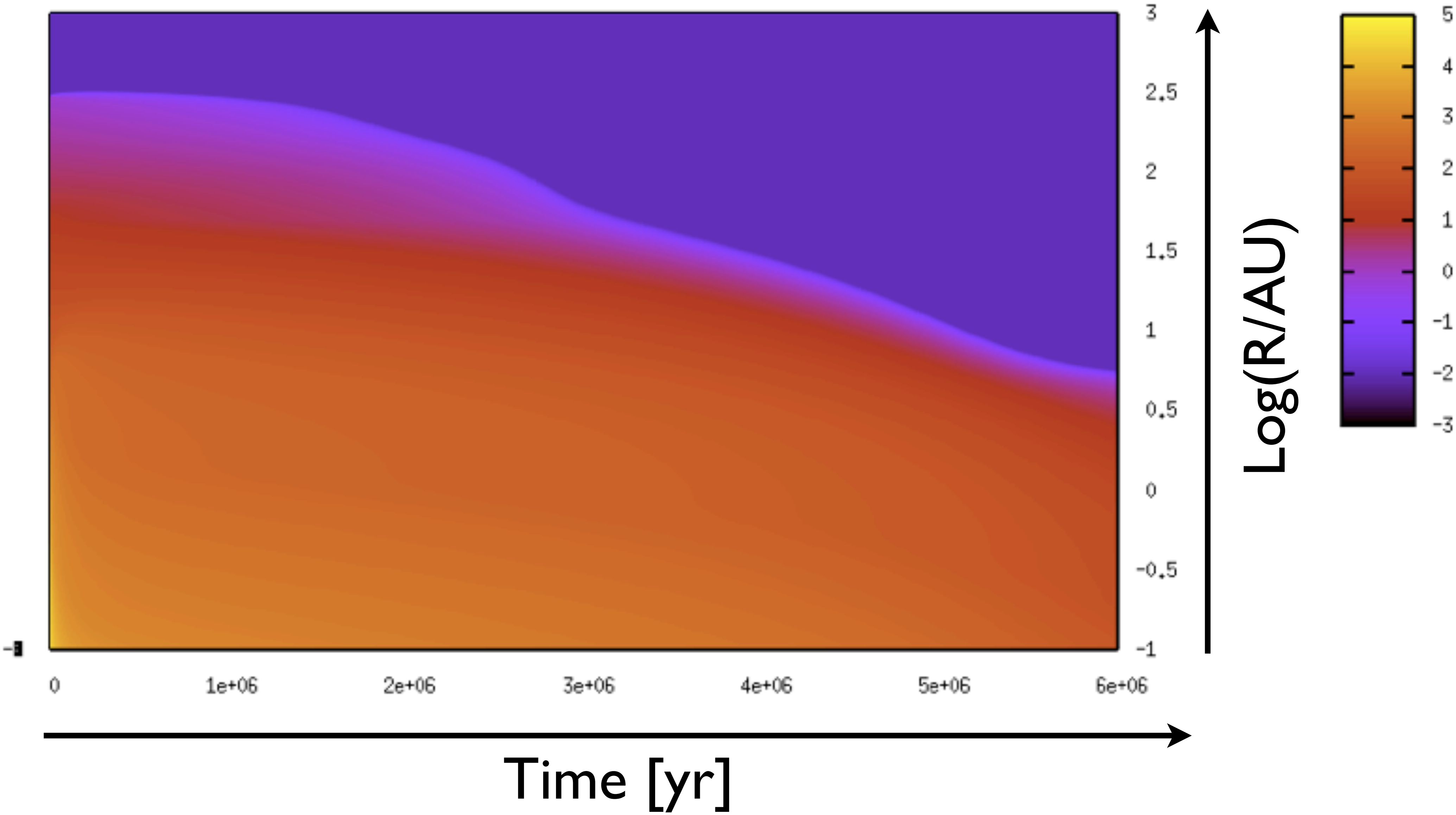
-external photoevaporation

$$\dot{\Sigma}_{w,\mathrm{ext}} = \begin{cases} 0 & \text{for } r < \beta R_{g,\mathrm{I}} \\ \frac{\dot{M}_{\mathrm{wind,ext}}}{\pi(r_{\mathrm{max}}^2 - \beta^2 R_{g,\mathrm{I}}^2)} & \text{otherwise} \end{cases}$$

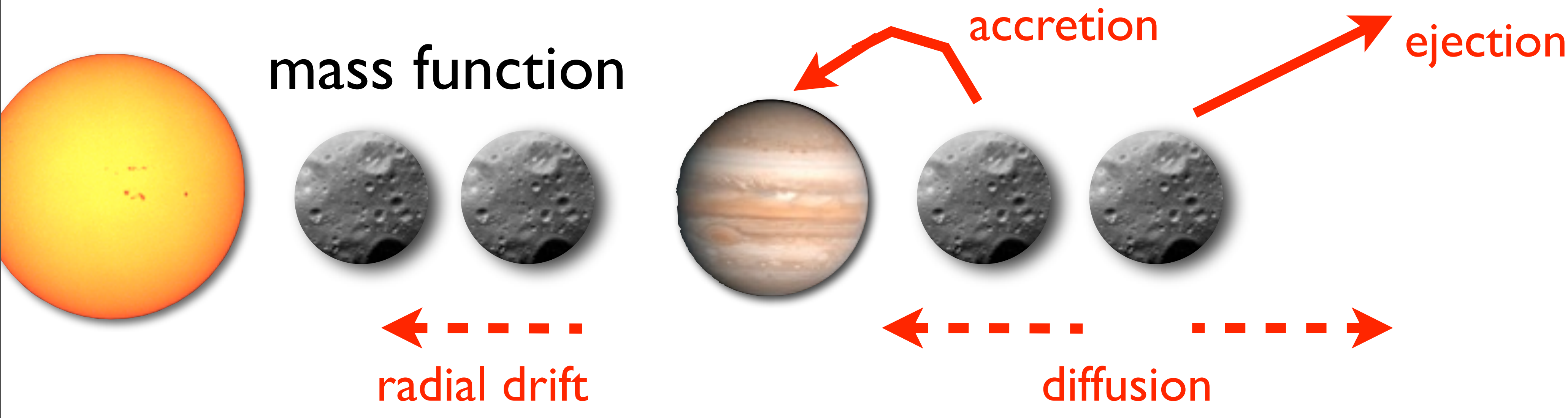
-internal photoevaporation

$$\dot{\Sigma}_{w,\mathrm{int}} = \begin{cases} 0 & \text{for } r < R_{\mathrm{wind}} \\ 2c_{s,\mathrm{II}} n_0(r) u_{\mathrm{ma}} & \text{otherwise} \end{cases}$$

② 1+1D disk model



② 1+1D disk model: solids



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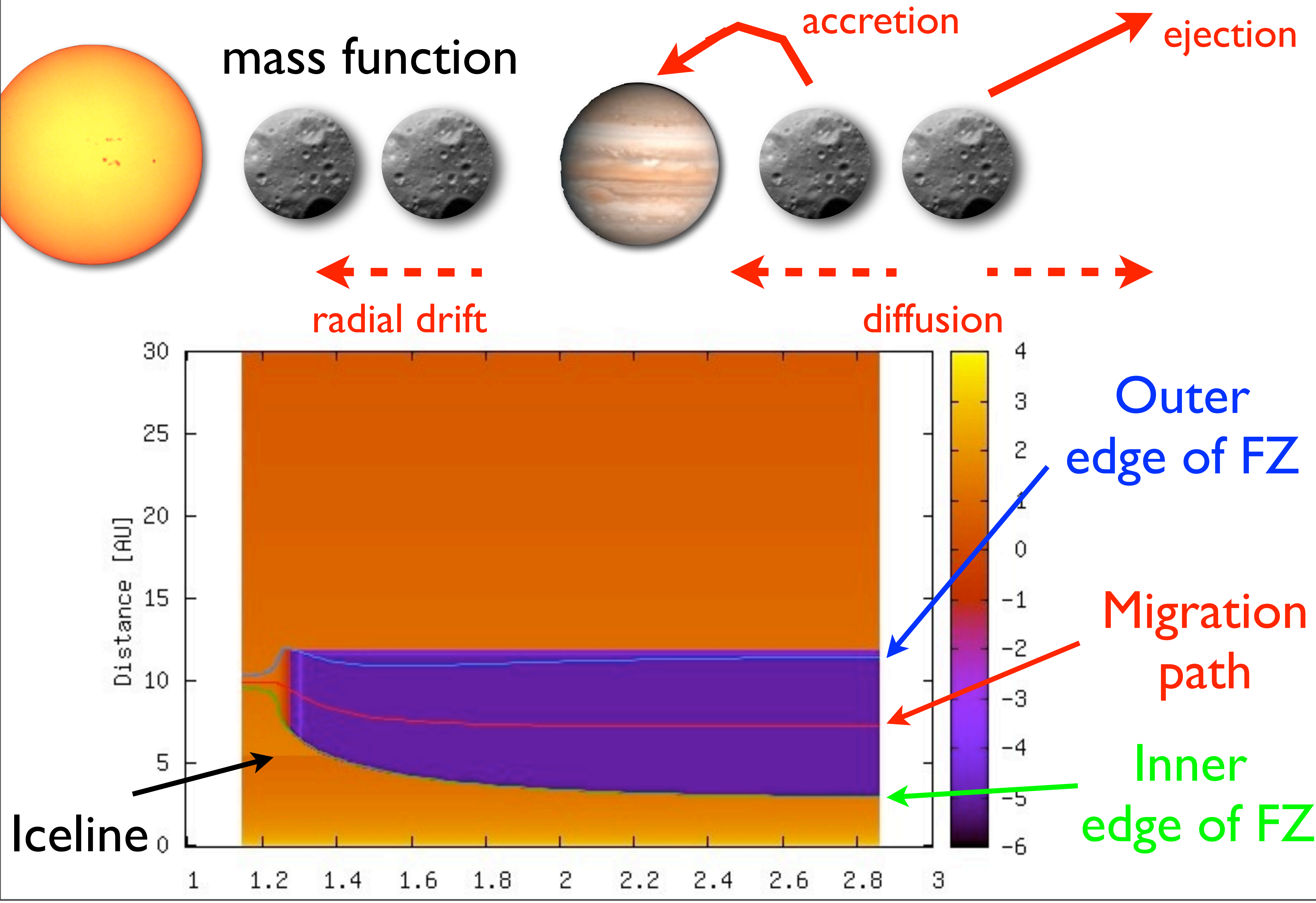
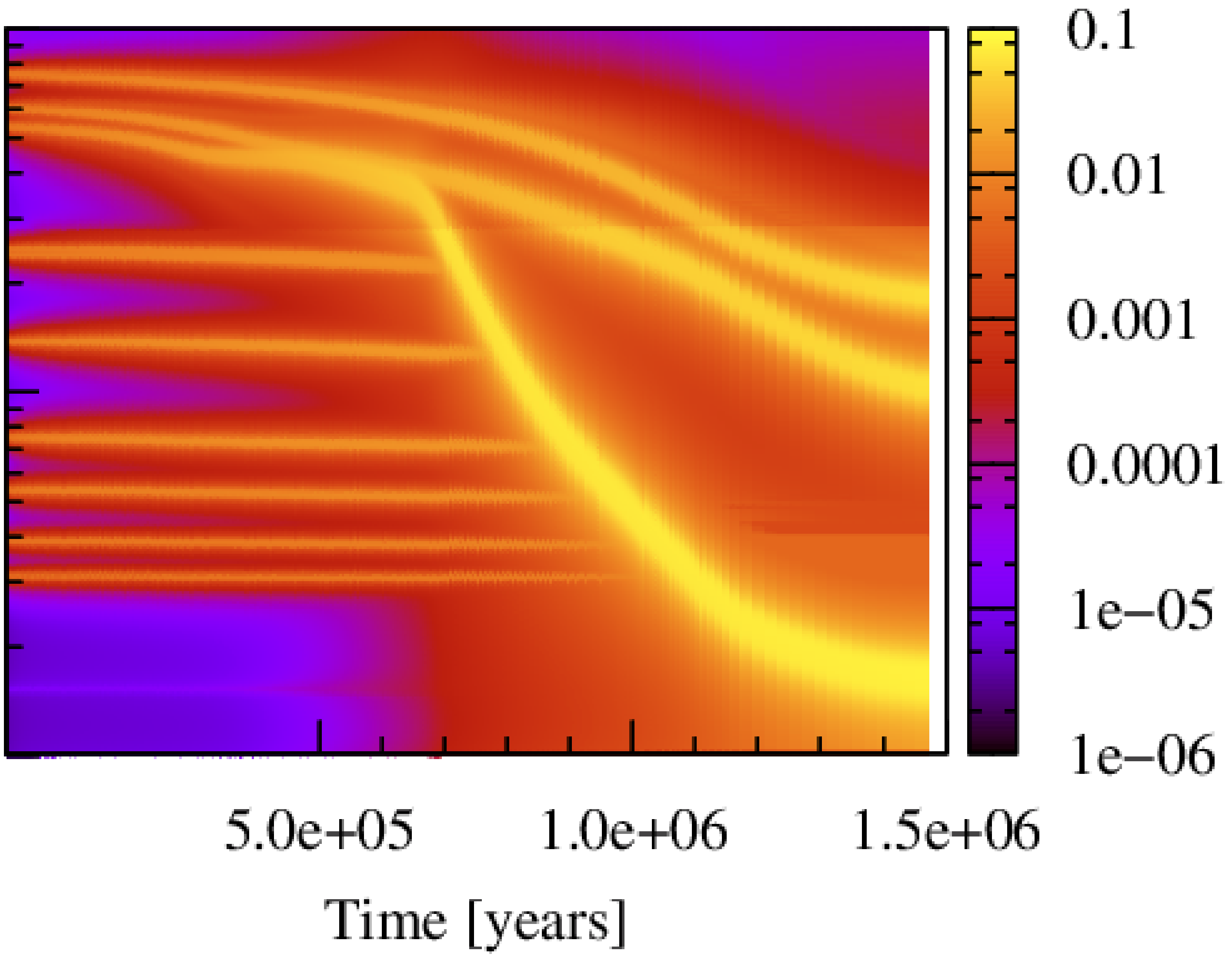


② 1+1D disk model: dynamics of solids



$$\frac{de}{dt} = \left.\frac{de}{dt}\right|_{GD} + \left.\frac{de}{dt}\right|_{VS,E} + \left.\frac{de}{dt}\right|_{VS,p}$$

See Poster by A. Fortier

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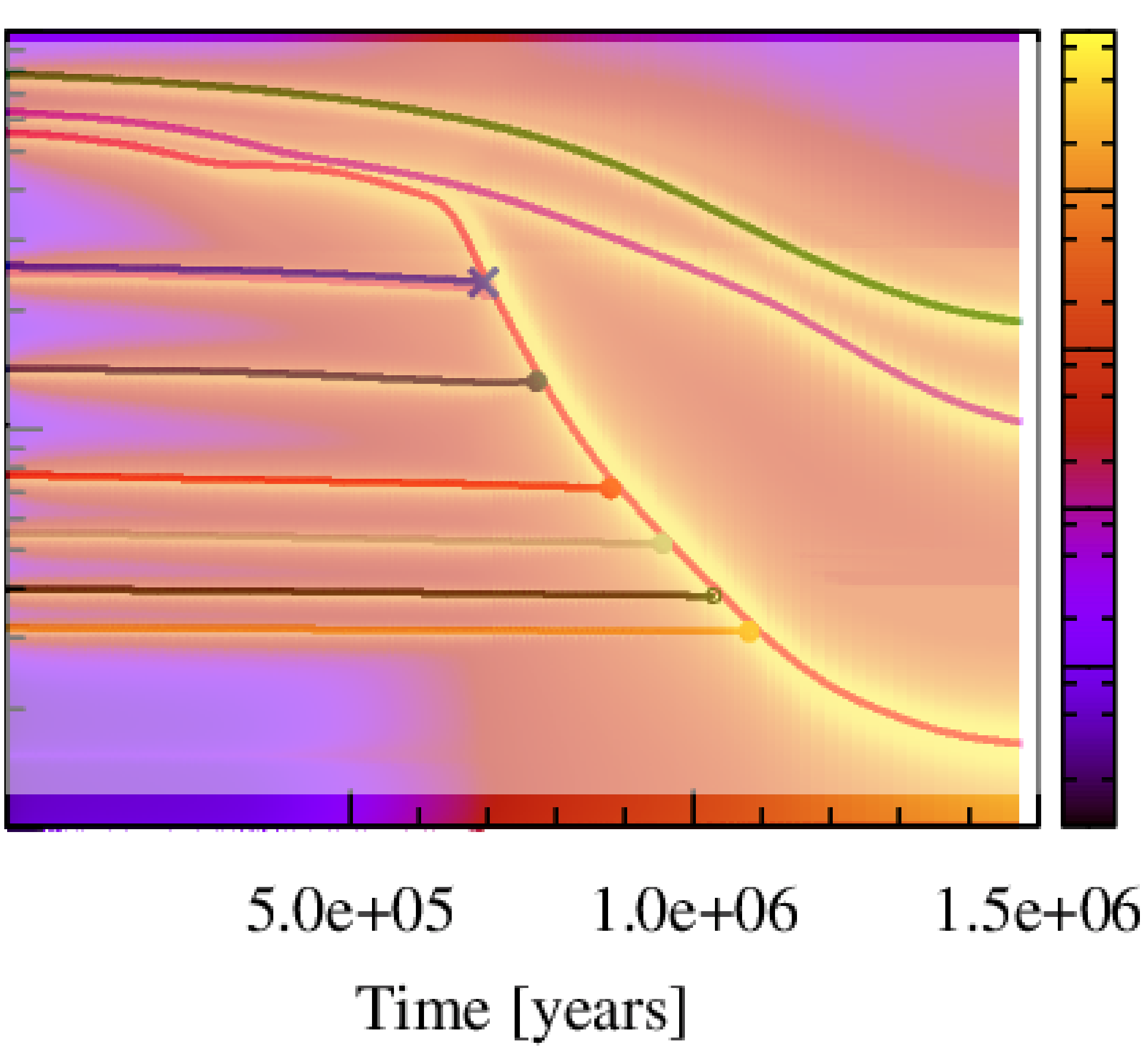

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See Poster by A. Fortier

③ Migration

Low mass planets (no gap, M<ca. 100 M_{earth}): Type I

From Paardekooper et al. 2009

$$\Gamma_{tot} = \sum_{ILR} \Gamma_{LR} + \sum_{OLR} \Gamma_{LR} + \Gamma_{CR} \qquad \frac{dr_p}{dt} = -2r_p \frac{\Gamma_{tot}}{J_p} \qquad J_p = M_p(GM_* r_p)^{1/2}$$

$$\Gamma_{tot} = \frac{1}{\gamma}(C_0 + C_1\alpha + C_2\beta)\Gamma_0 \qquad \Gamma_0 = \left(\frac{q}{h}\right)^2 \Sigma_p^2 r_p^2 \Omega_p^2 \qquad \alpha = \frac{d\log\Sigma}{d\log r} \qquad \beta = \frac{d\log T}{d\log r}$$

Baruteau & Masset. 2008

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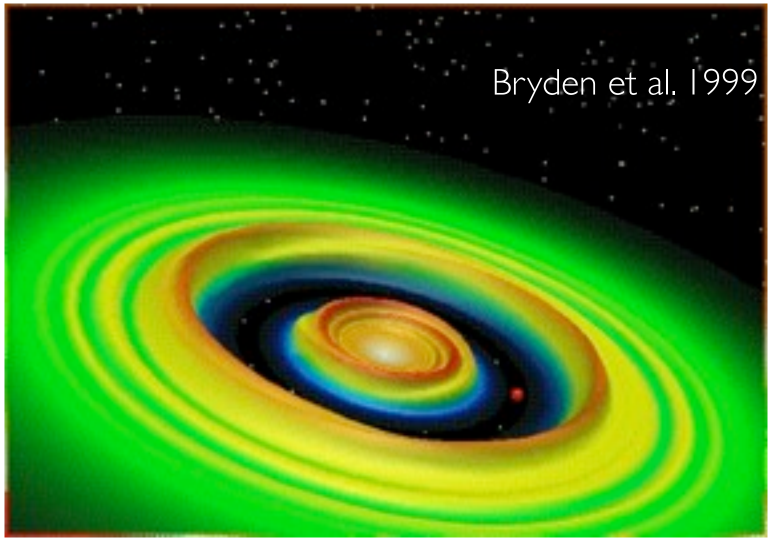


Giant planets (with gap): Type II

- Disk dominated $M_p < 2\Sigma a^2$

$$\frac{da_{\rm planet}}{dt} = v_{\rm r,gas}$$

- Planet dominated $M_p > 2\Sigma a^2$

$$\frac{da_{\rm planet}}{dt} = \left(\frac{2\Sigma a^2}{M_{\rm planet}}\right)^{k_p} v_{r,gas} \qquad k_p = \begin{cases} 1 & \text{"fully suppressed"} \\ 1/2 & \text{"partially suppressed"} \end{cases}$$

Slow-down

③ Migration: why thermodynamics matter?

Entropy

C. Baruteau

Perturbed density

1.04
1.02
1.00
0.98
0.96

r/r_p

1.04
1.02
1.00
0.98
0.96

-3 -2 -1 0 1 2 3

$\varphi - \varphi_p$

-3 -2 -1 0 1 2 3

$\varphi - \varphi_p$

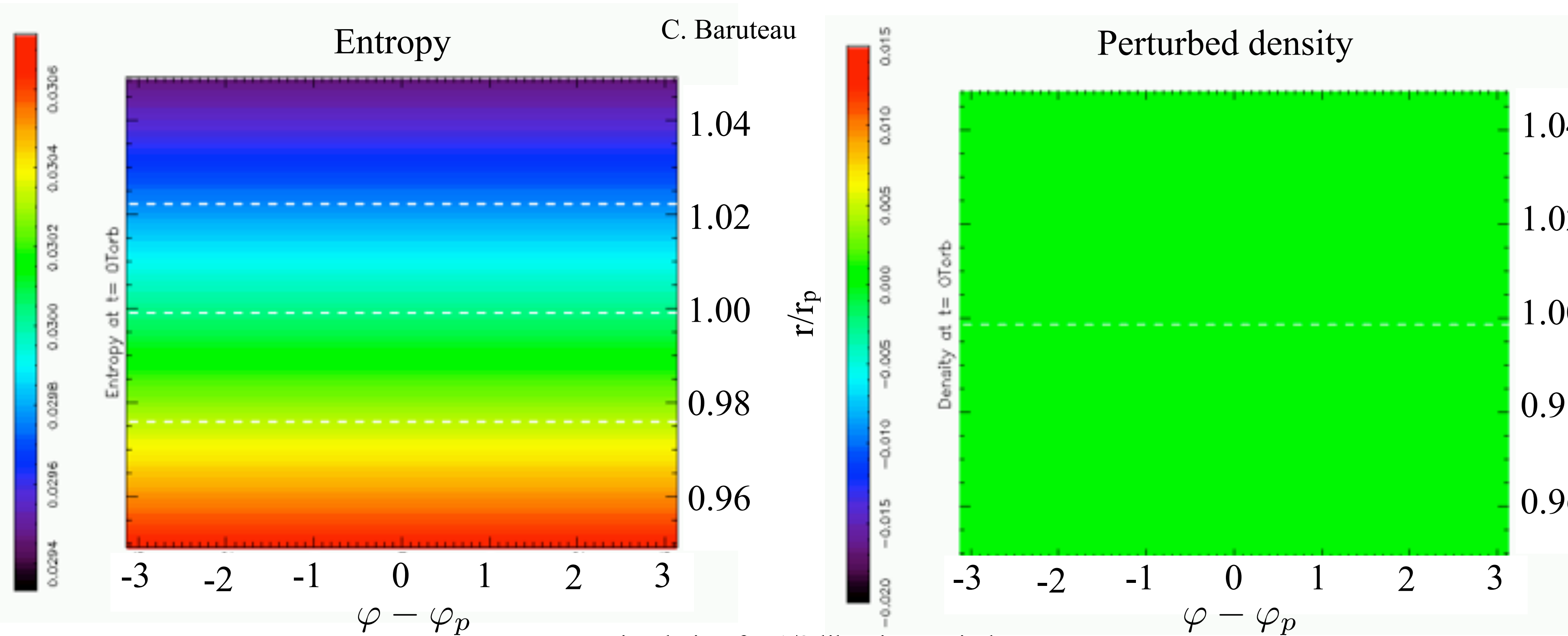
simulation for 1/2 libration period

The exchange of fluid elements lead to an overdensity at shorter radii. This translates into a increased torque pushing the planet outwards...

For this mechanism to work, the fluid has to remain adiabatic during the exchange process. In other words: $\tau_{cool} >> \tau_{u-turn}$

$$\tau_{cool} \approx \frac{\Sigma c_V T}{Q} = \frac{\Sigma c_V T}{2\sigma T_{eff}^4} \qquad \tau_{u-turn} \approx 1.16 \sqrt{\frac{h^3}{\gamma q}} \frac{64}{9\Omega_p}$$

③ Migration: why thermodynamics matter?



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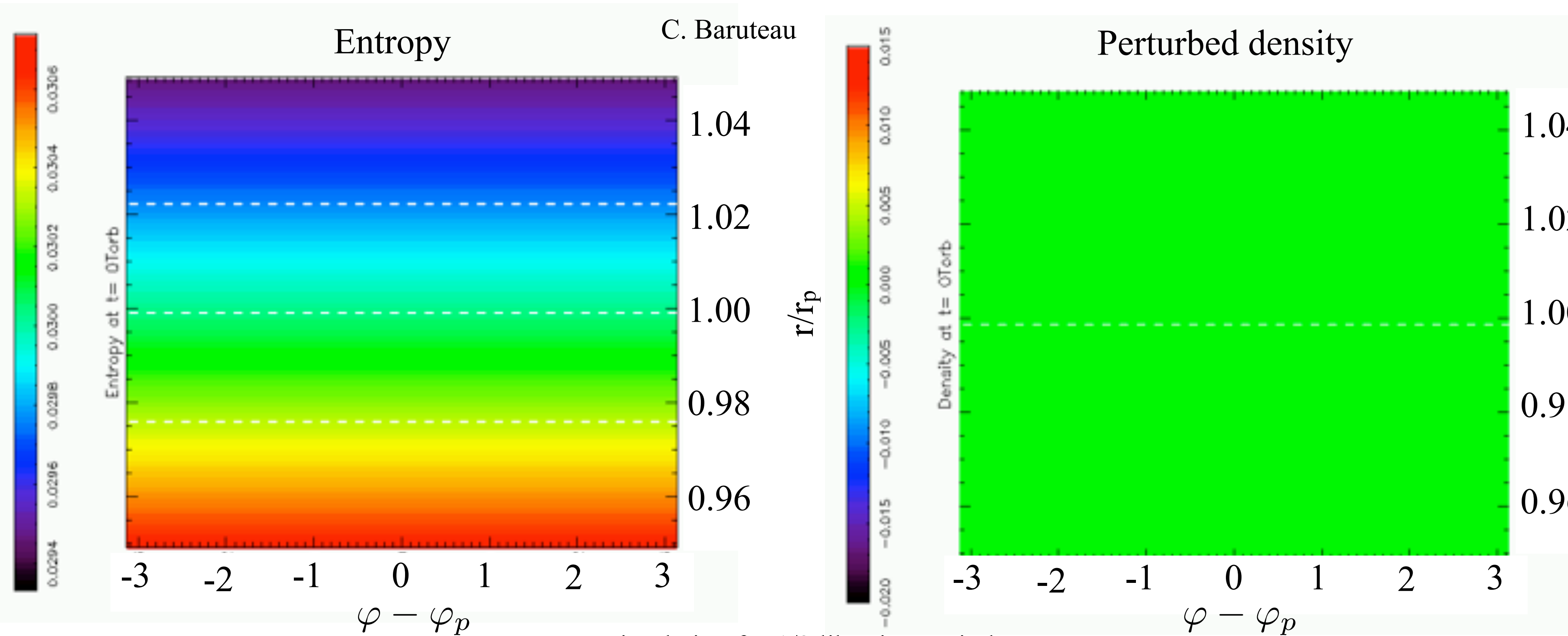

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Unfortunately, after some time, the situation becomes much less clear and the torques begin to saturate...

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$\varphi - \varphi_p$

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$\varphi - \varphi_p$

simulation for 3 libration periods

In other words, unless the viscosity re-establishes the original entropy profile before the torques saturate, the outward migration will not last... The condition for a sustainable outward migration is therefore given by: $\tau_{lib} >> \tau_{visc}$

$$\tau_{lib} = \frac{8\pi r_p}{3\Omega_p x_s} \qquad \tau_{visc} = \frac{(2x_s)^2}{\nu}$$

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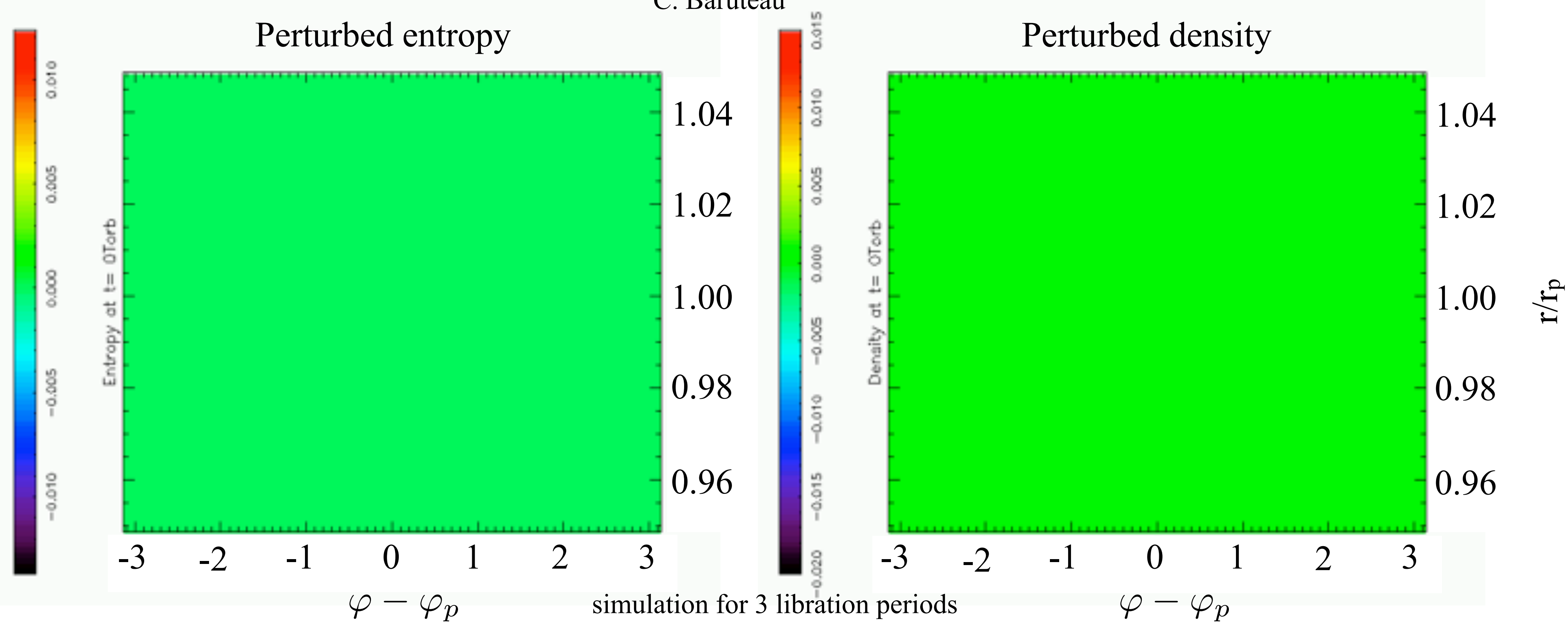

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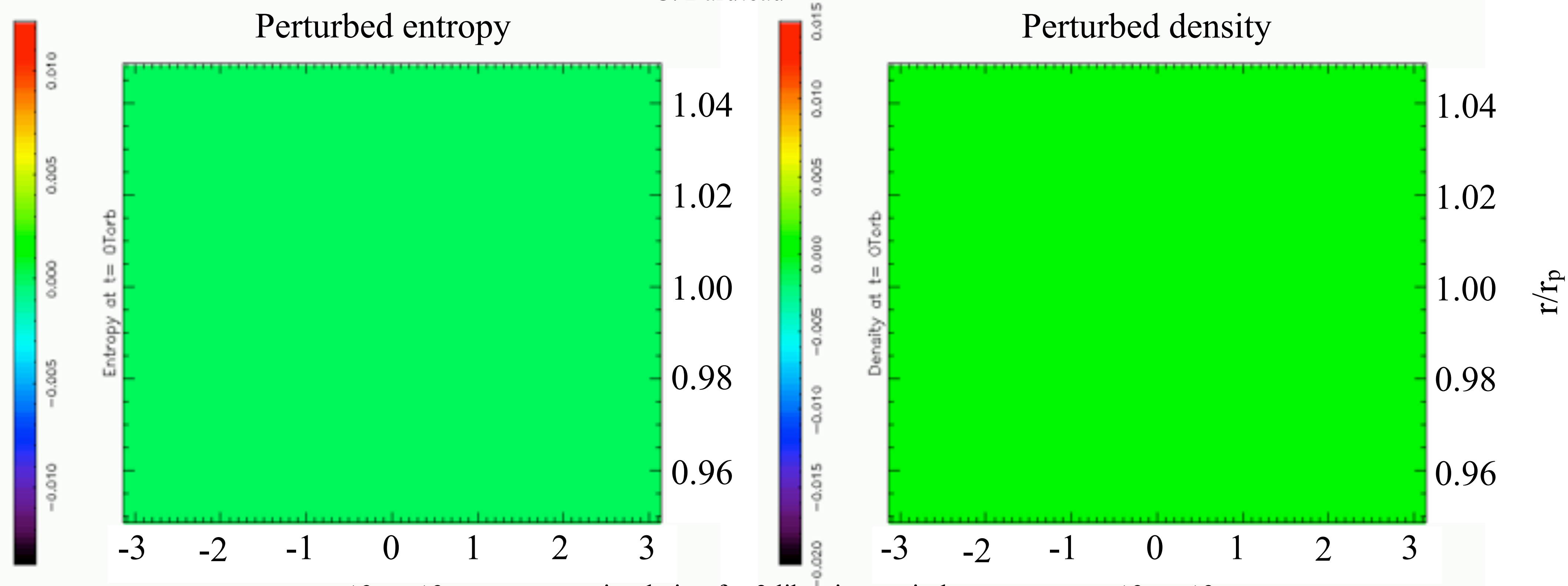
Unfortunately, after some time, the situation becomes much less clear and the torques begin to saturate...

C. Baruteau



simulation for 3 libration periods

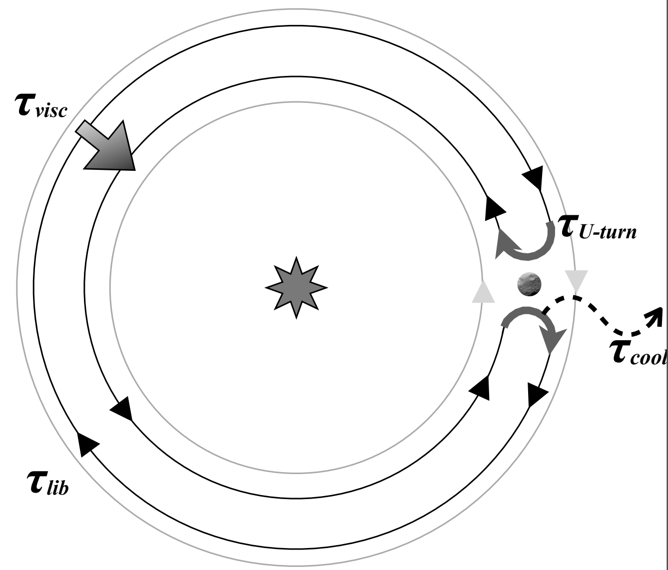
In other words, unless the viscosity re-establishes the original entropy profile before the torques saturate, the outward migration will not last... The condition for a sustainable outward migration is therefore given by: $\tau_{lib} >> \tau_{visc}$

$$\tau_{lib} = \frac{8\pi r_p}{3\Omega_p x_s} \qquad \tau_{visc} = \frac{(2x_s)^2}{\nu}$$

③ Migration and timescales

From Paardekooper et al. 2009

Cooling?



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From Paardekooper et al. 2009

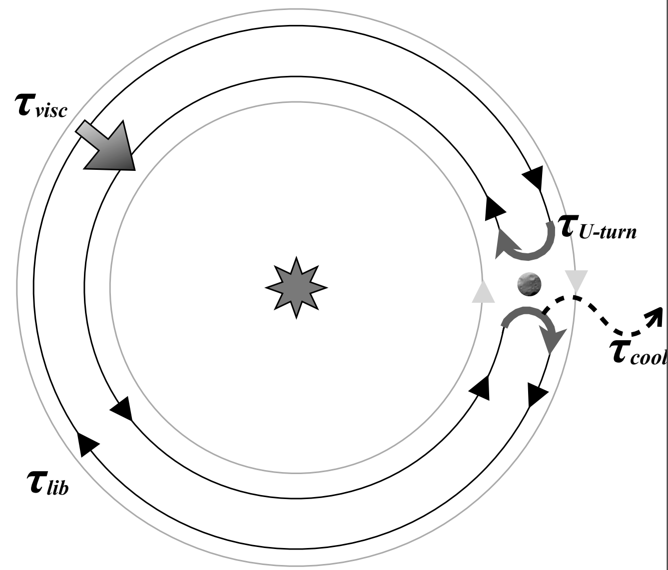
Cooling?

$\tau_{\rm cool} \ll \tau_{\rm U-turn}$

Isothermal

$\tau_{\rm cool} \gg \tau_{\rm U-turn}$

Adiabatic



Outer disk AUs Inner disk

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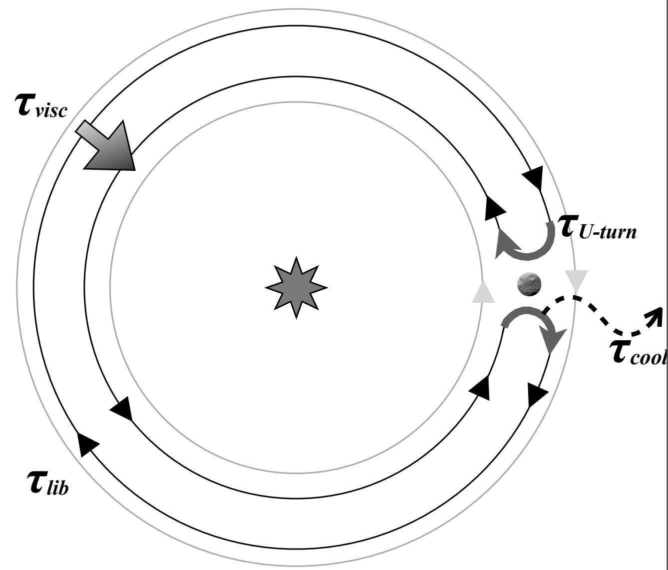

Cooling?

$\tau_{\rm cool} \ll \tau_{\rm U-turn}$ → Isothermal → Outer disk

$\tau_{\rm cool} \gg \tau_{\rm U-turn}$ → Adiabatic → Inner disk

AUs

Saturation?

$\tau_{\rm libration} \gg \tau_{\rm viscous}$ → Unsaturated → Low mass planets

? → 10s ME

$\tau_{\rm libration} \ll \tau_{\rm viscous}$ → Saturated → Large mass planets

③ Migration and timescales

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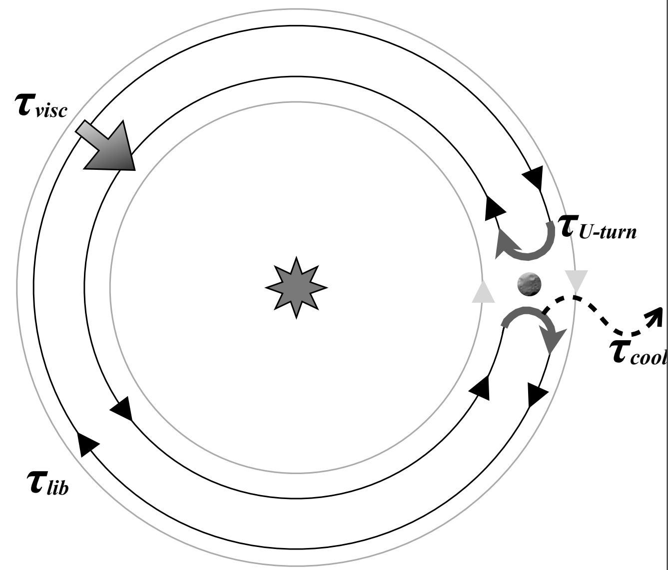

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$\tau_{\mathrm{cool}} \ll \tau_{\mathrm{U-turn}}$
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Outer disk
in

AUs

Inner disk

Saturation?

$\tau_{\mathrm{libration}} \gg \tau_{\mathrm{viscous}}$

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Unsaturated
Low mass planets
out

?
10s ME

Saturated
Large mass planets
in

④ Planet-planet interactions

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-Explicit N-body between planets with disk-planet interaction and collisions of planets.
-Eccentricity damping of planets (Nelson& Fogg 07), planetesimal ecc. as in Pollack et al. (96).
-Uniform planetesimal density in overlapping feeding zones.

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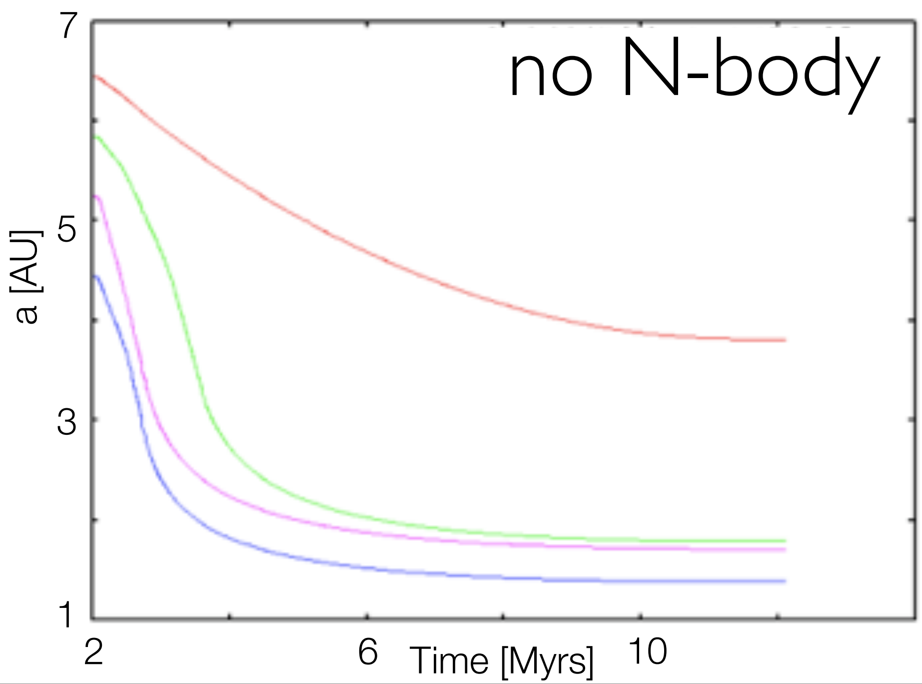
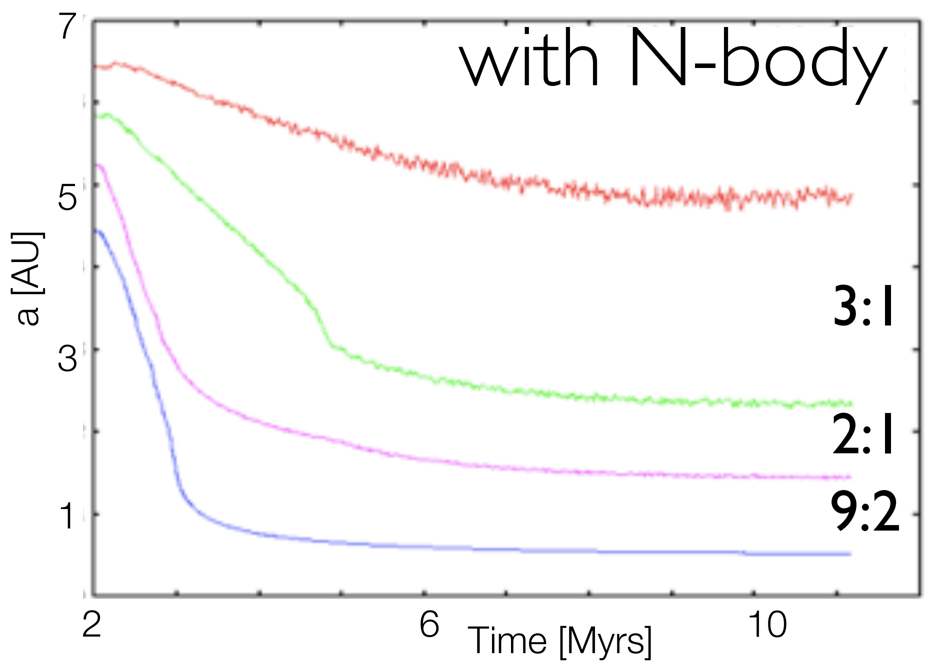


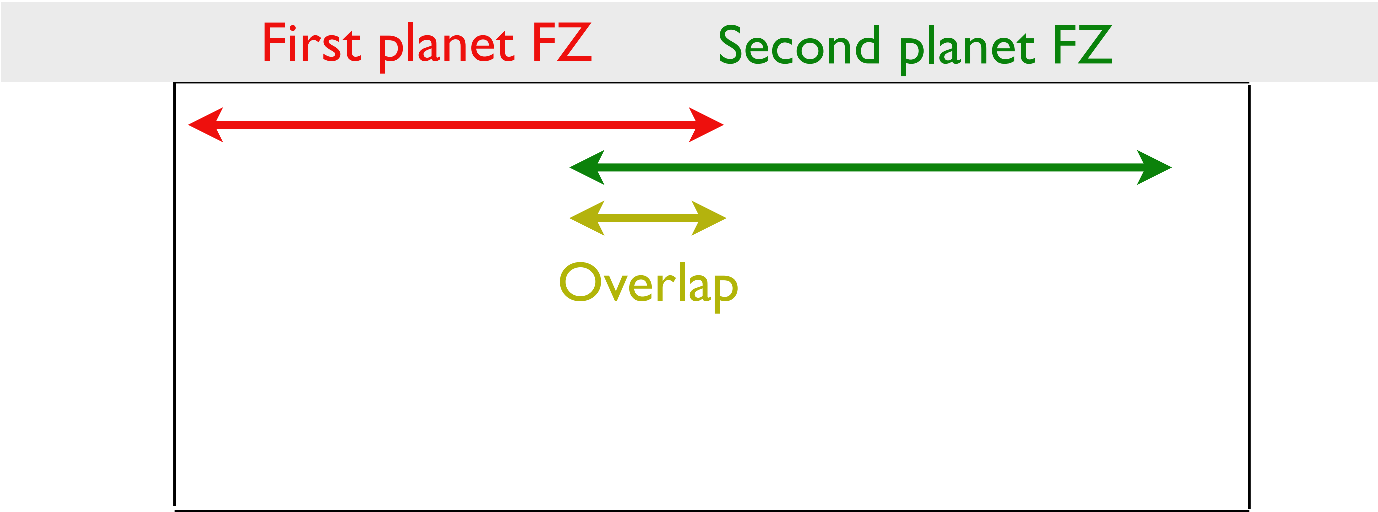


Final mass [M_{Earth}]	without N body	with N body
Planet 1	970	890
Planet 2	975	970
Planet 3	750	430
Planet 4	7	4

Study
-solar system
-resonant systems
-ejection (far out planets)
-population synthesis

④ Planet-planet interactions

N-body simulations by S. Pfyffer



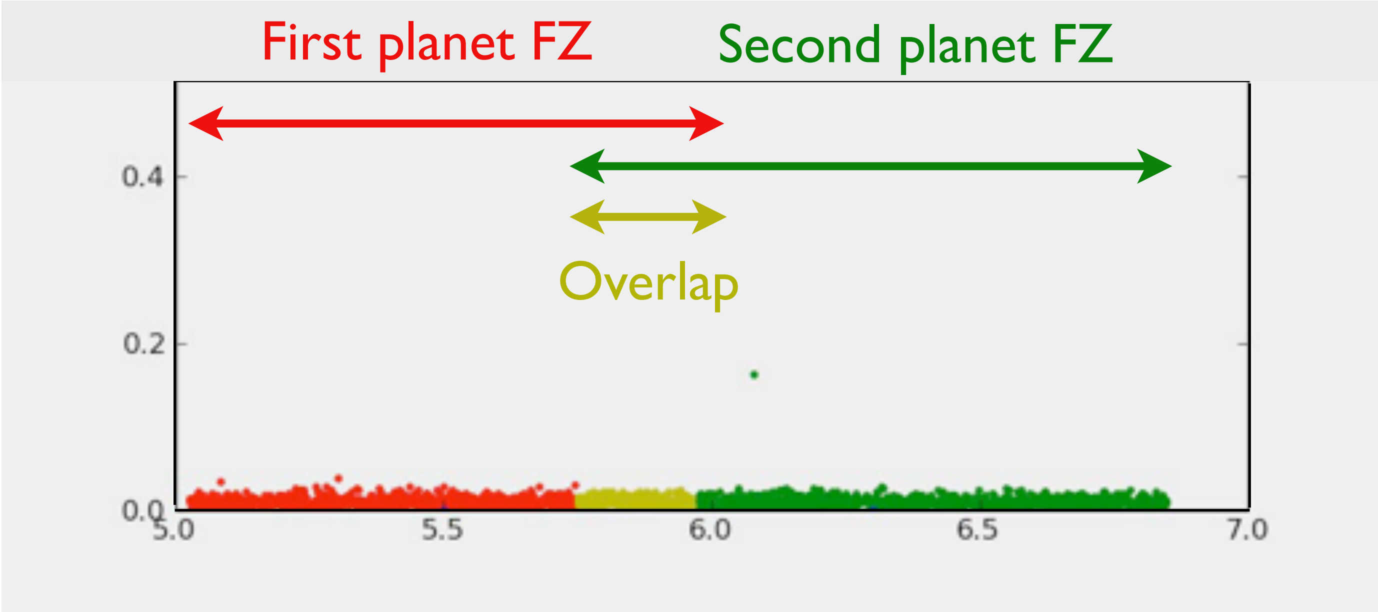
Uniform surface density and excitation in the common FZ

Planetesimal transport to the outermost planet

The internal structures of the two planets are no more independant

④ Planet-planet interactions

N-body simulations by S. Pfyffer



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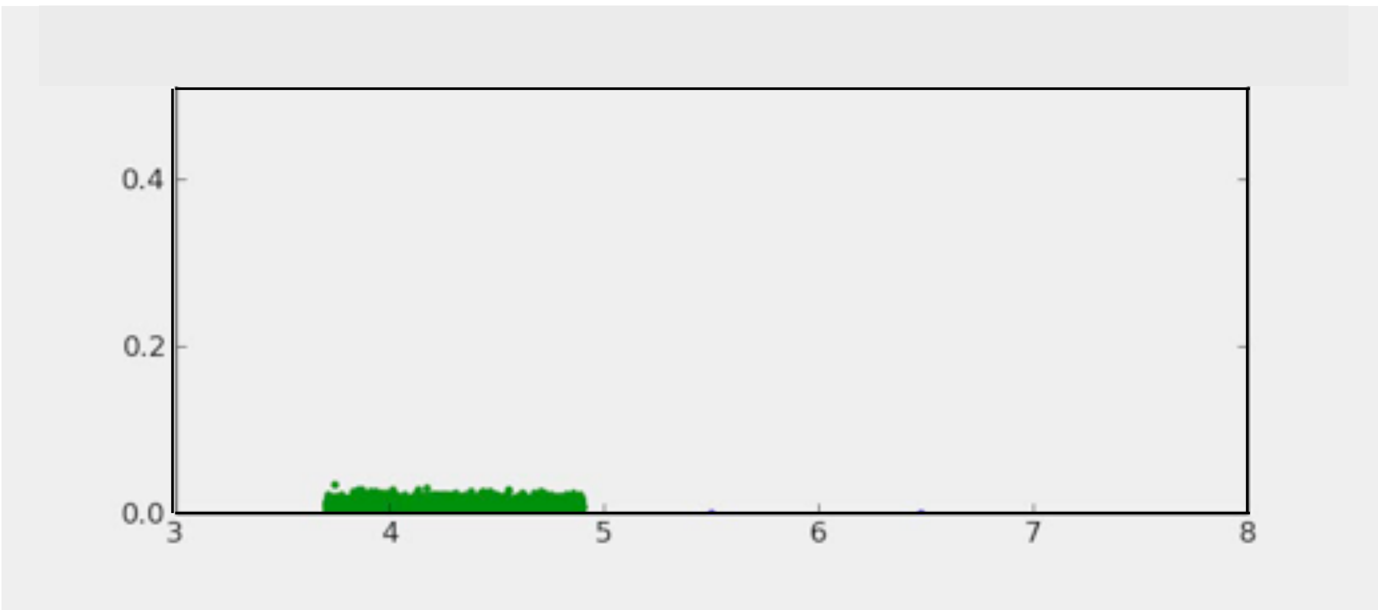

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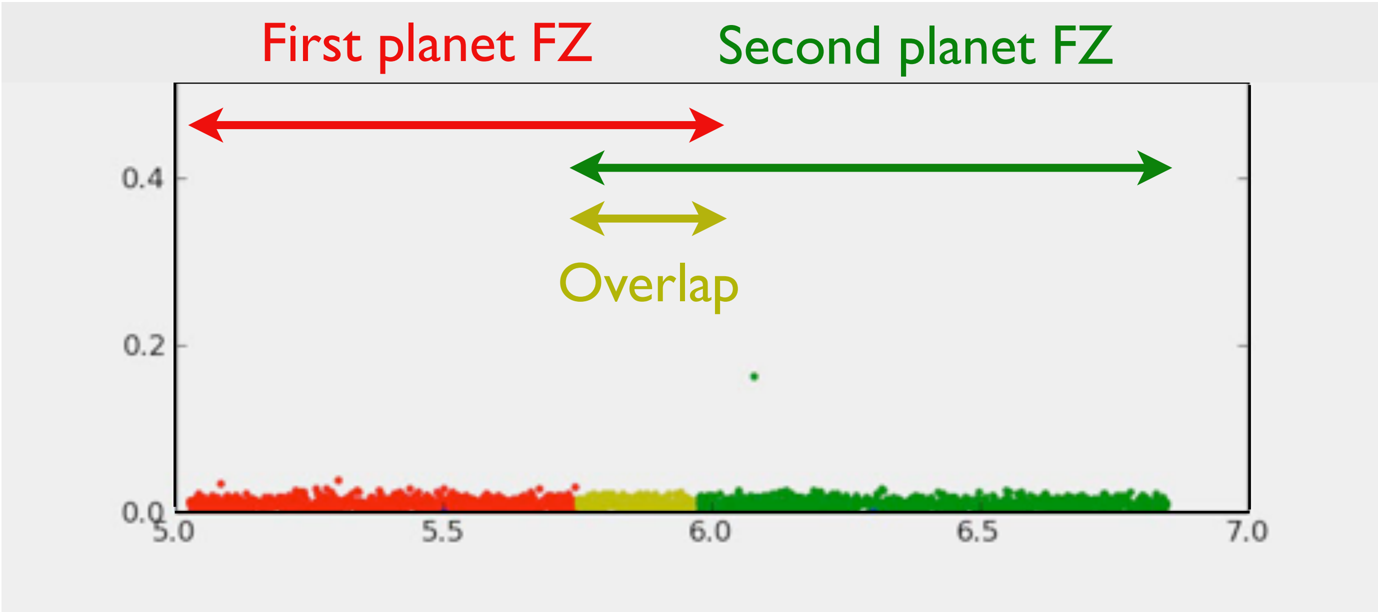

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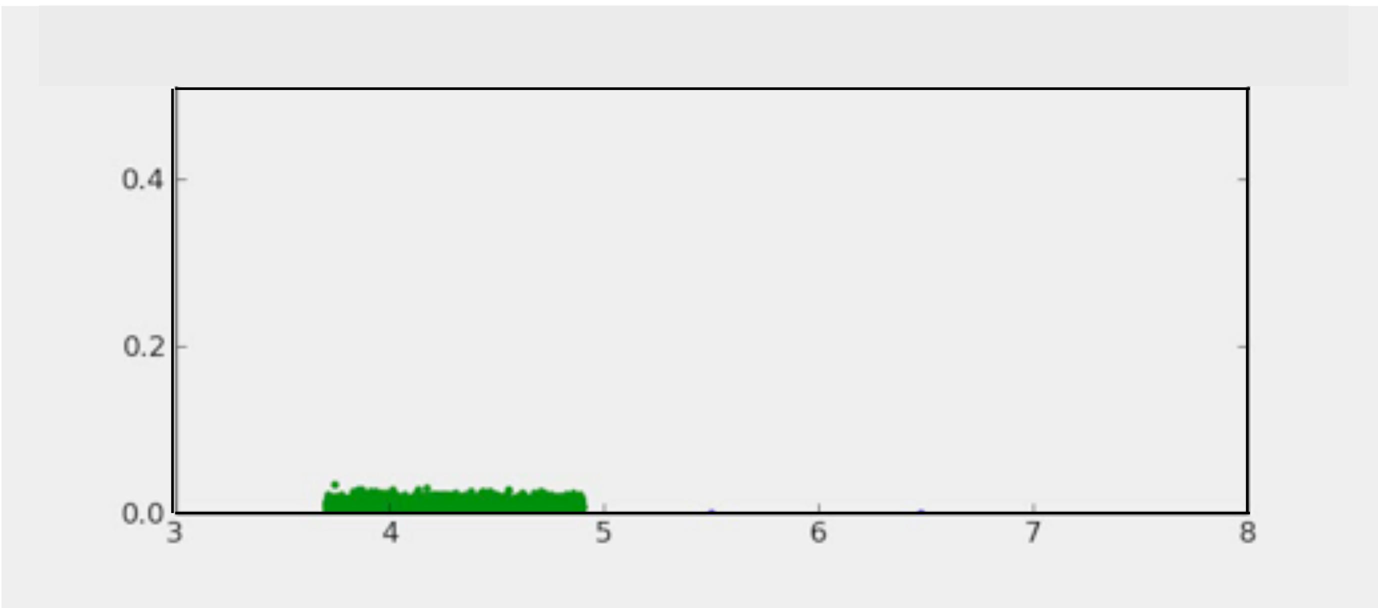
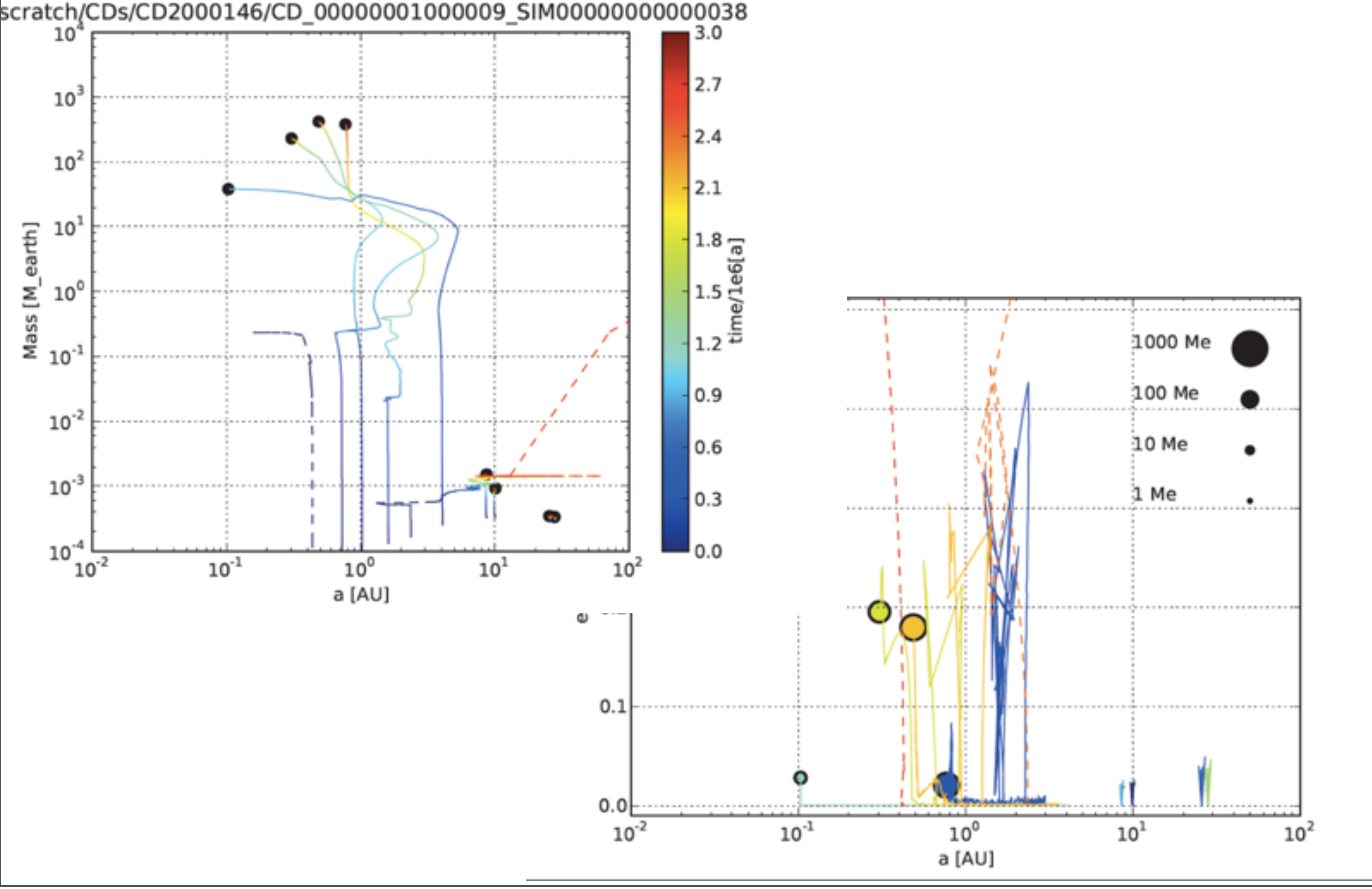


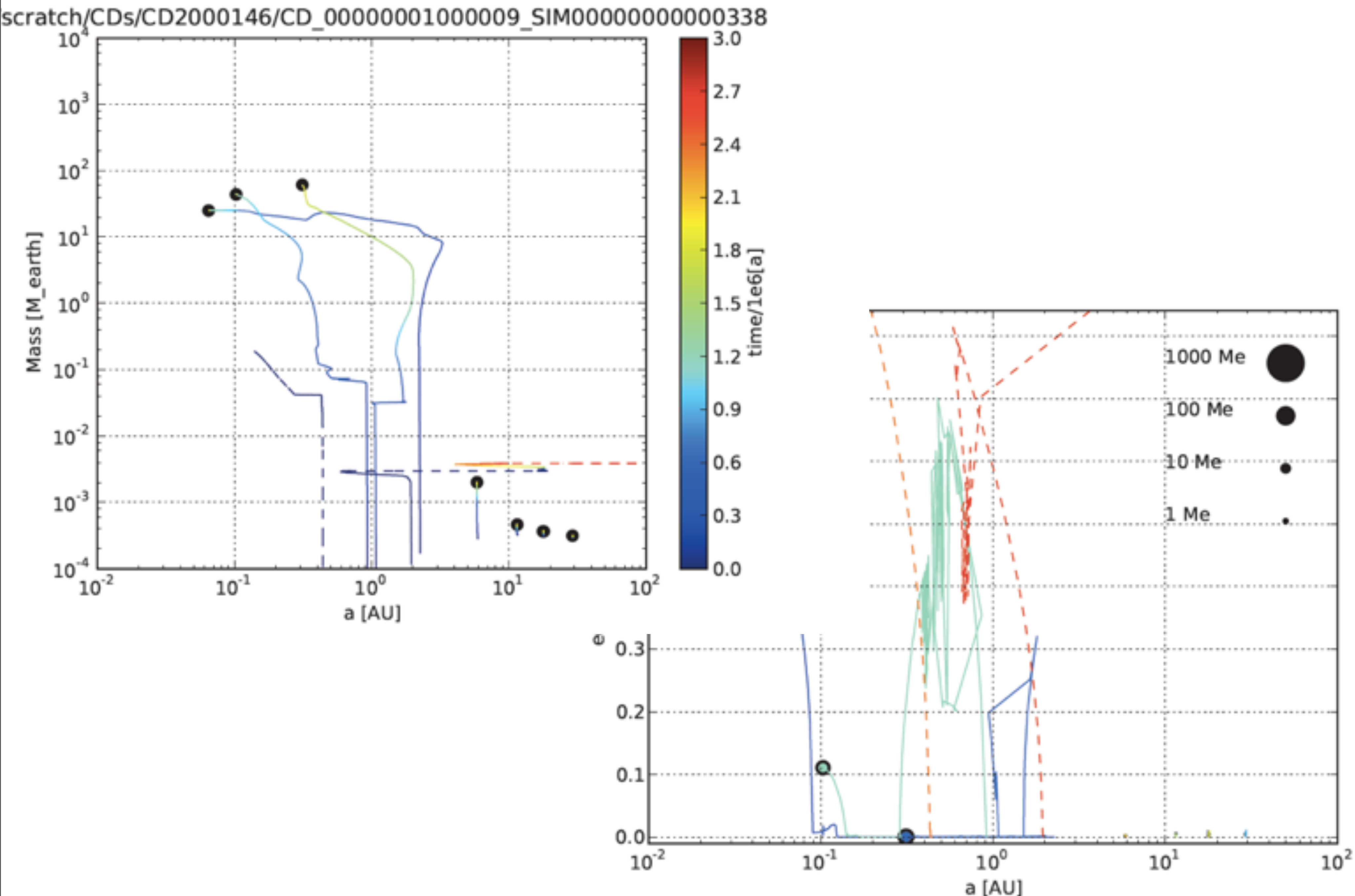
Planetesimal transport to the outermost planet

The internal structures of the two planets are no more independant

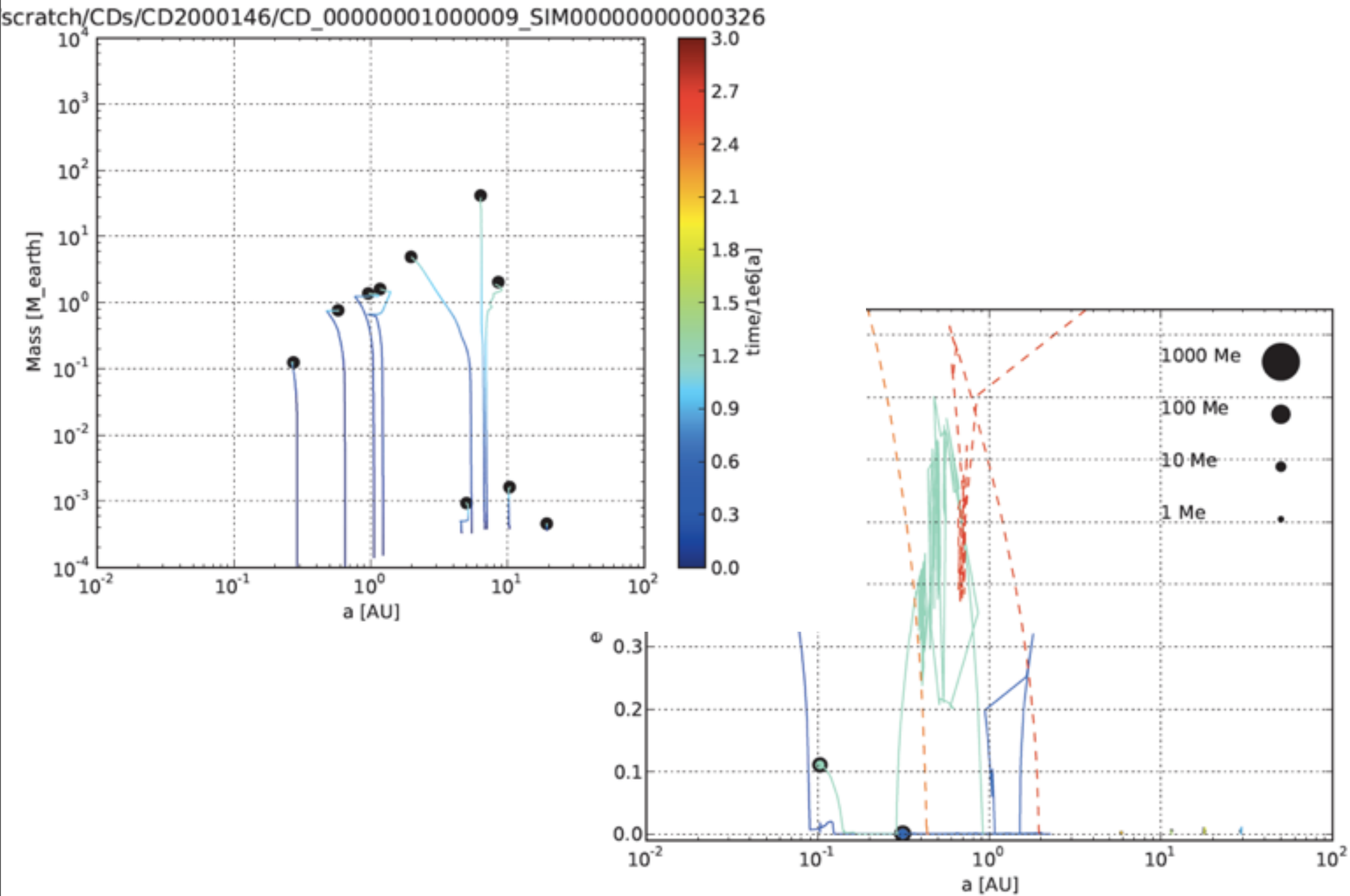
a system with three giants and one HN



a system with three HN



a system with TWO Earths at 1 AU



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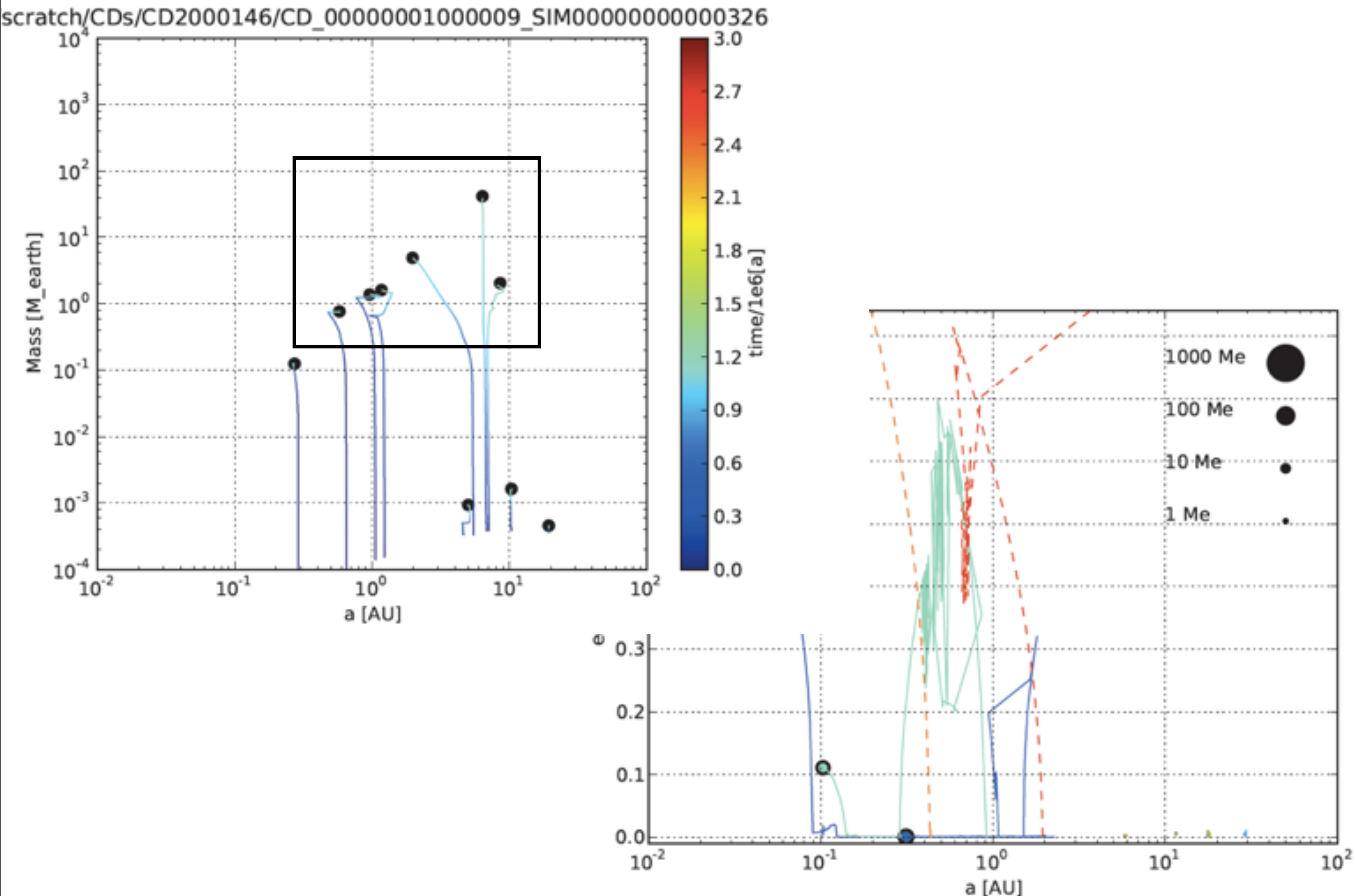
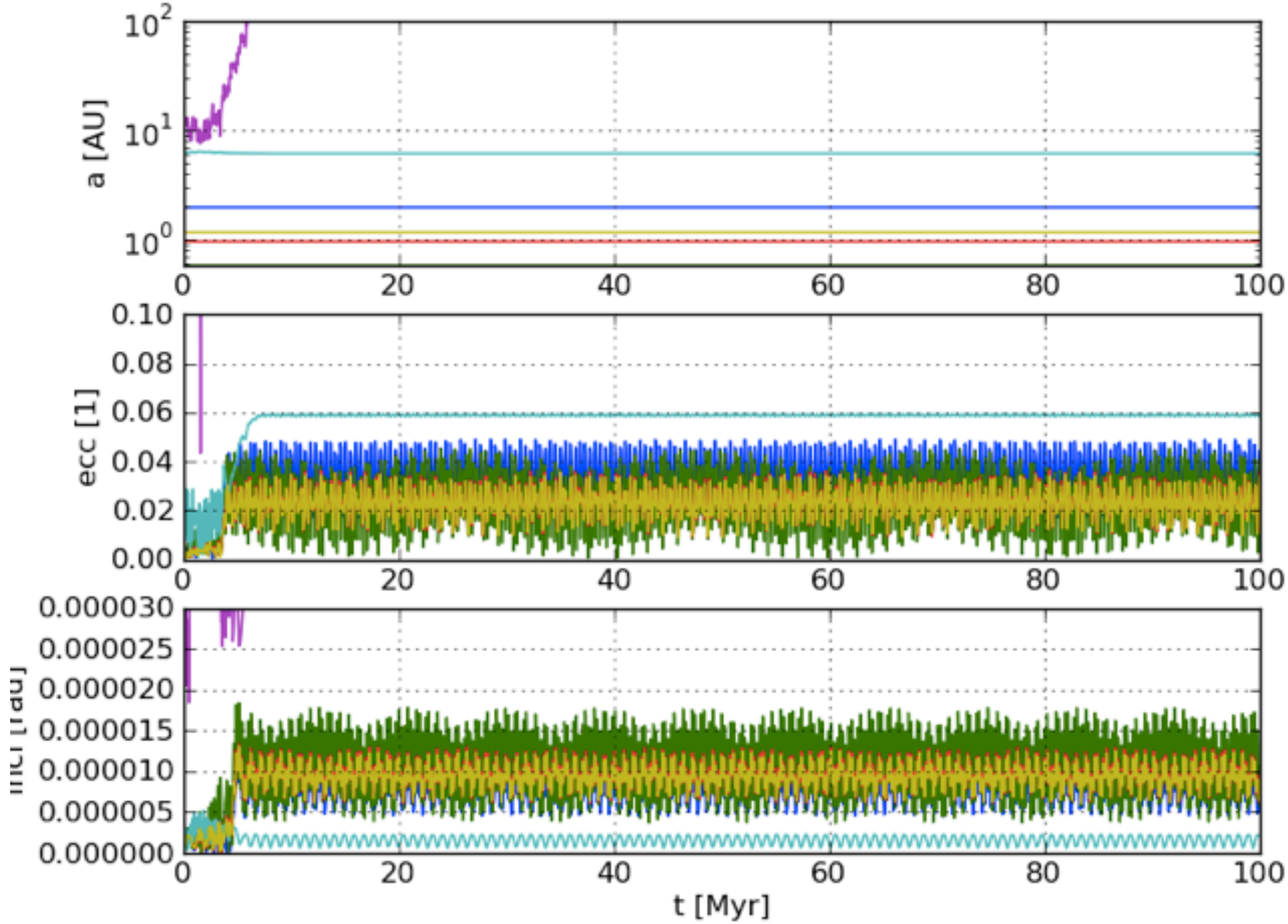
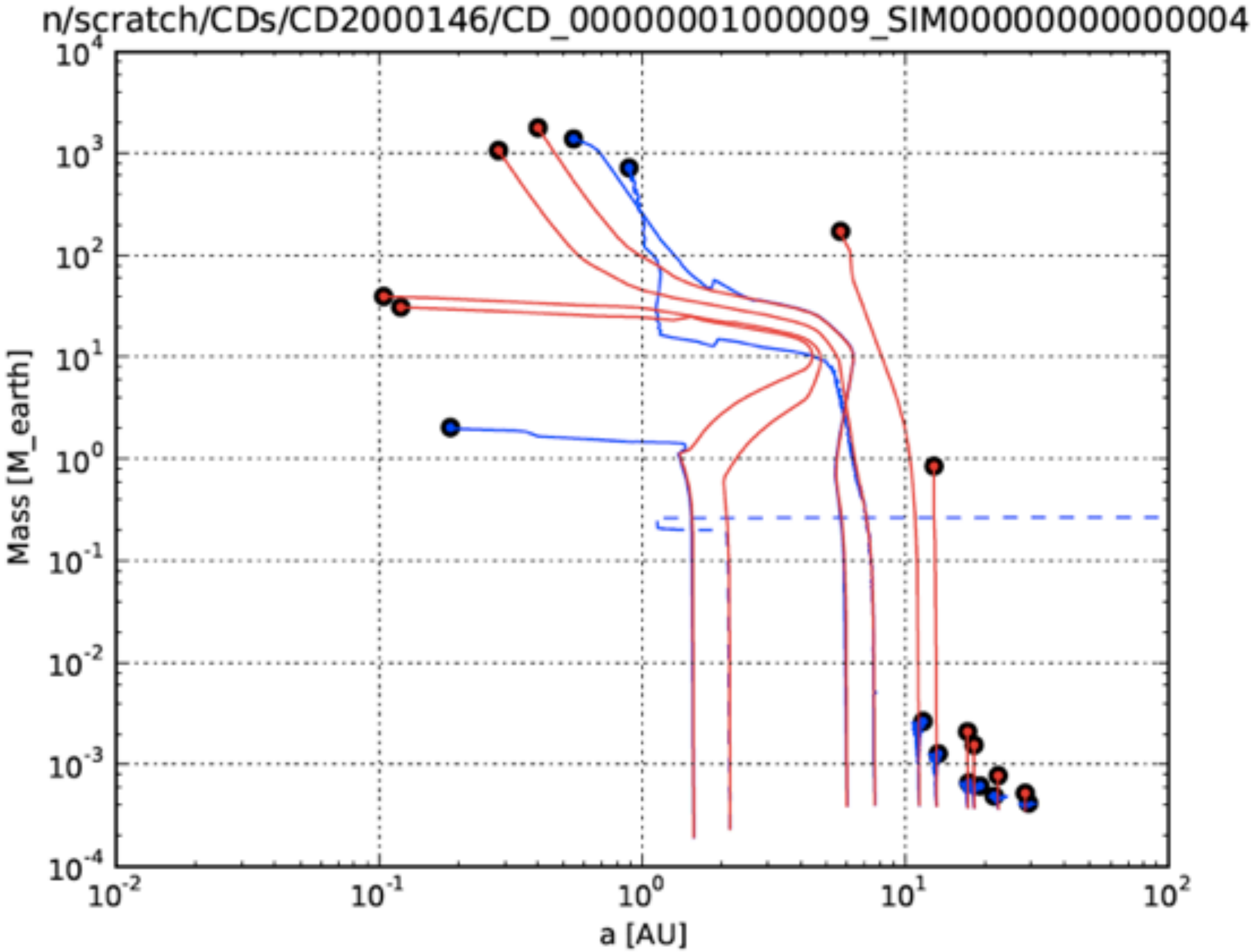


long term stability?



System or no system?

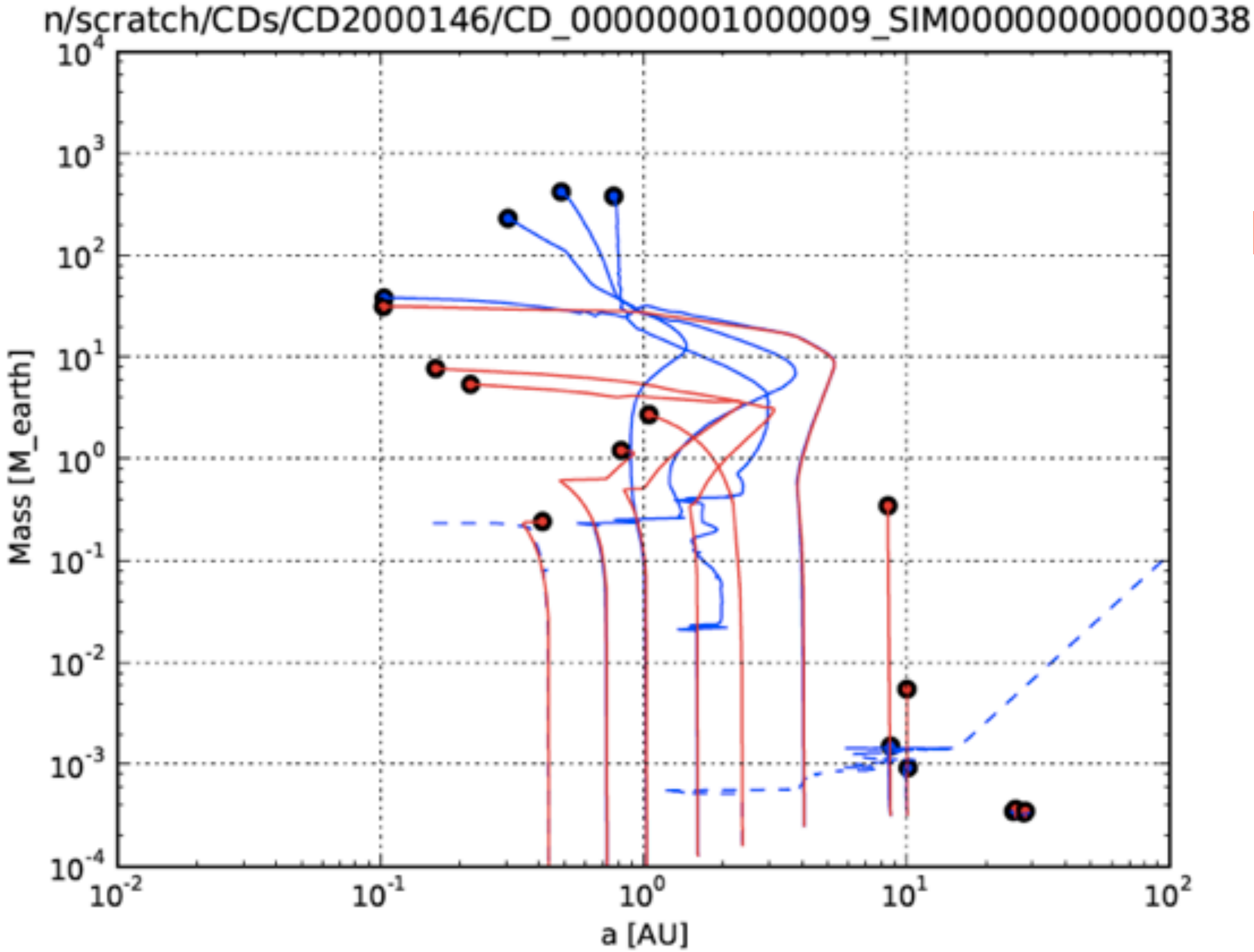


System

Independant

Blue planets are less massive than red ones (competition)

System or no system?

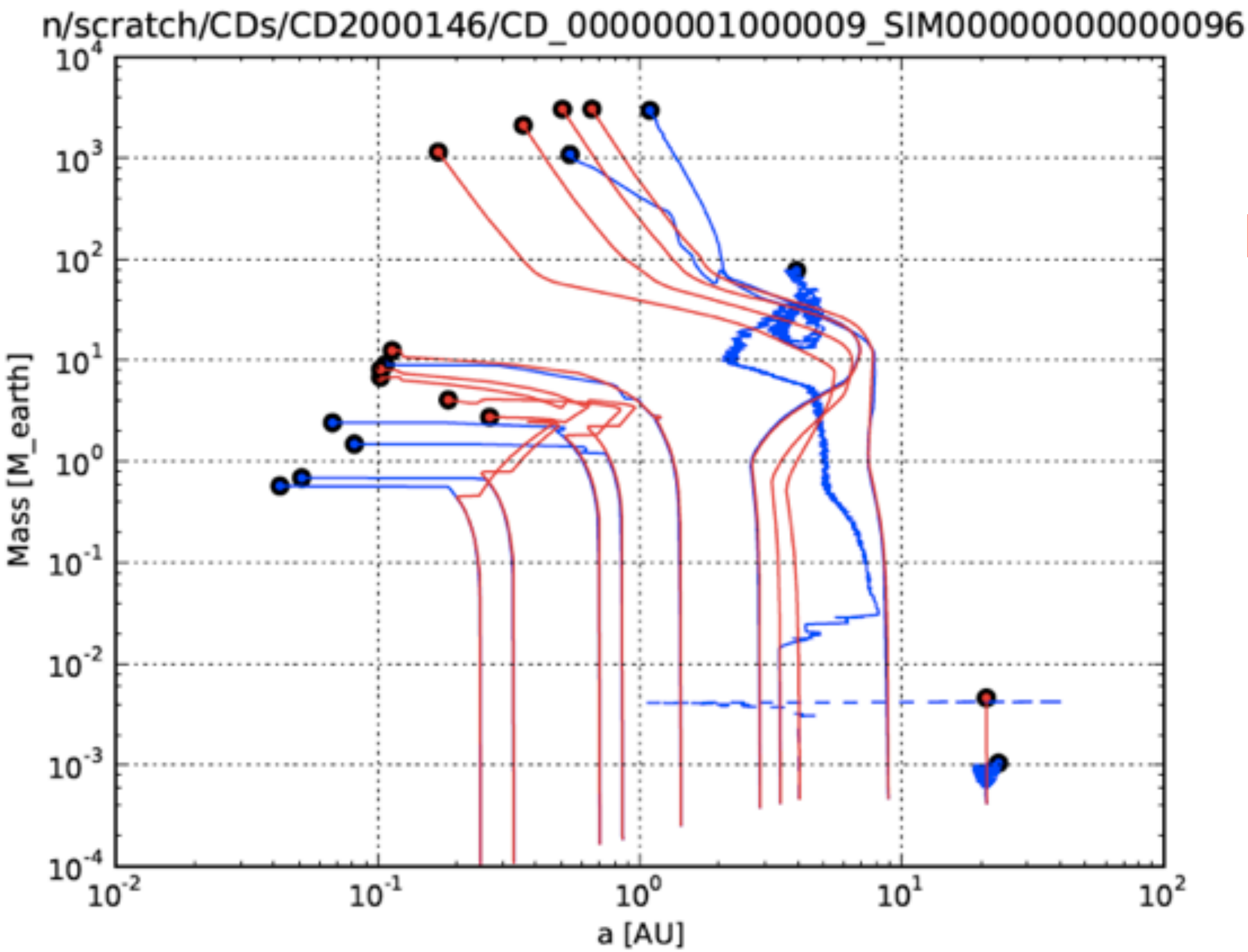


System

Independant

Blue planets can be more massive than red ones (sometimes)

System or no system?



System

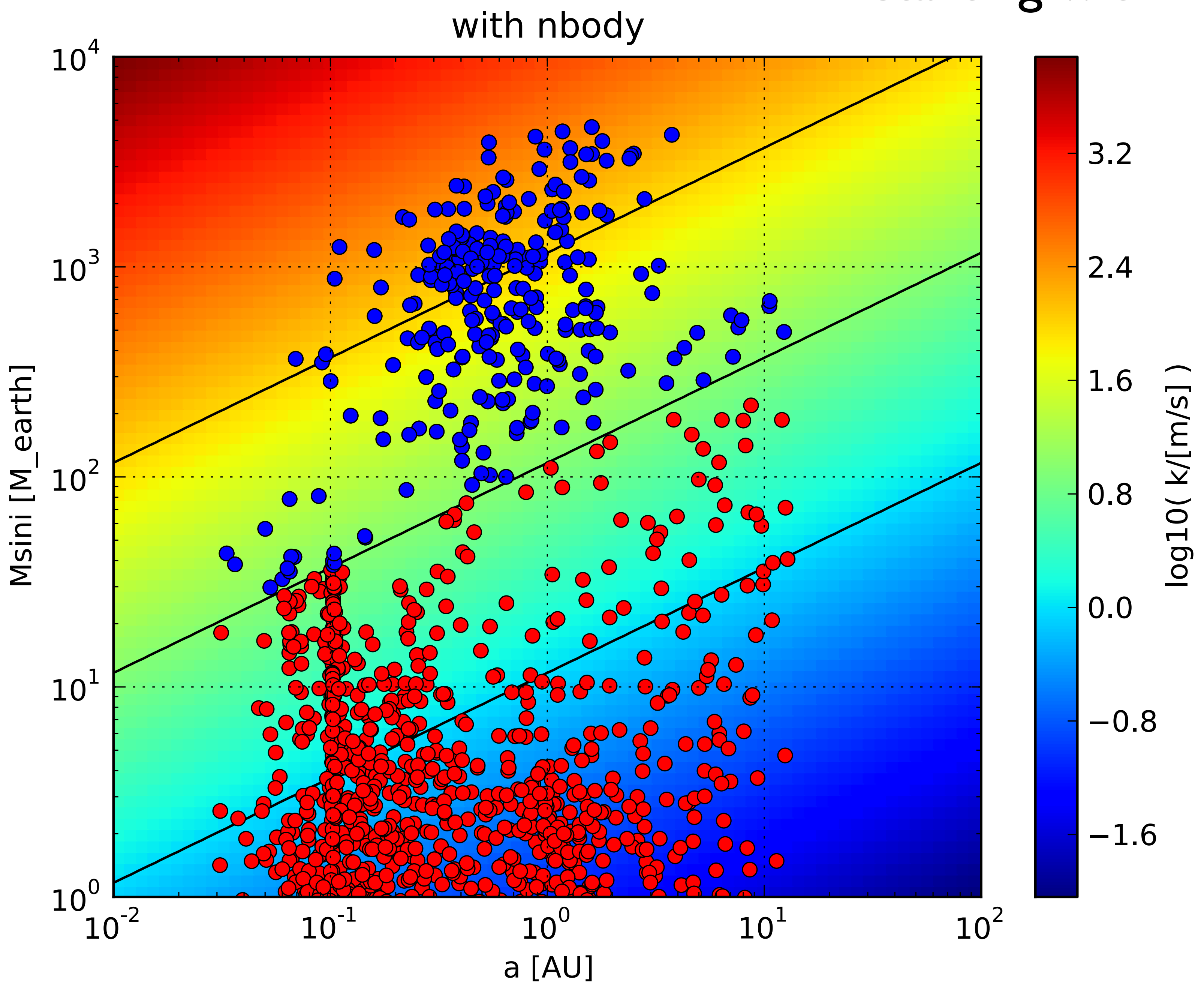
Independant

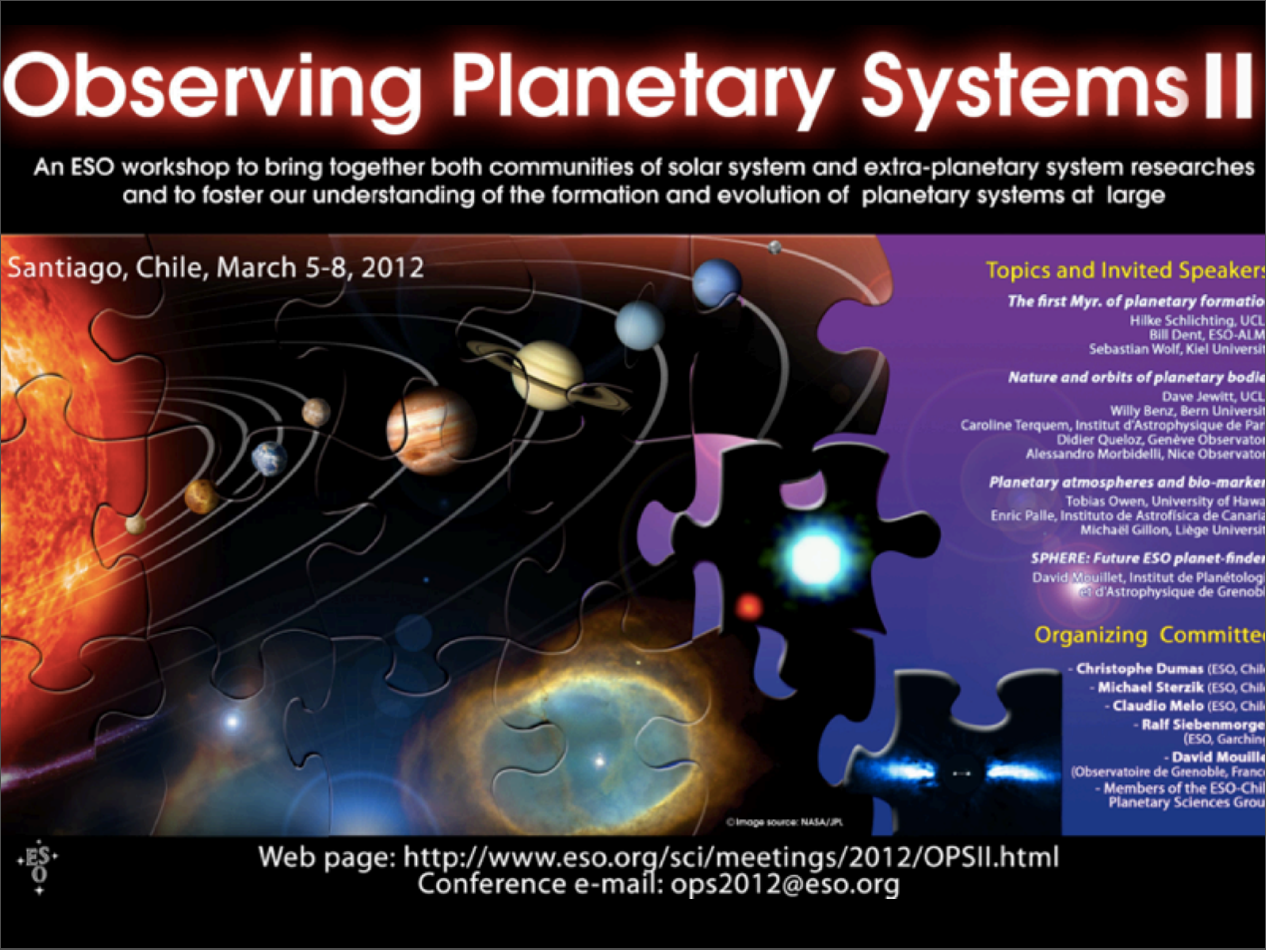
Massive red planets are in general closer than blue ones

Low mass blue planets are in general closer than red ones

a-M diagram

starting with 10 planets




Observing Planetary Systems II
An ESO workshop to bring together both communities of solar system and extra-planetary system researches
and to foster our understanding of the formation and evolution of planetary systems at large
Santiago, Chile, March 5-8, 2012
Topics and Invited Speaker
The first Myr. of planetary formatio
Hilke Schlichting, UCL
Bill Dent, ESO-ALM
Sebastian Wolf, Kiel Universit
Nature and orbits of planetary bodie
Dave Jewitt, UCL
Willy Benz, Bern Universit
Caroline Terquem, Institut d'Astrophysique de Par
Didier Queloz, Genève Observator
Alessandro Morbidelli, Nice Observator
Planetary atmospheres and bio-marker
Tobias Owen, University of Hawa
Enric Palle, Instituto de Astrofisica de Canaria
Michaël Gillon, Liège Universit
SPHERE: Future ESO planet-finder
David Mouillet, Institut de Planétologi
et d'Astrophysique de Grenob
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- Michael Sterzik (ESO, Chil
- Claudio Melo (ESO, Chil
- Ralf Siebenmorge
(ESO, Garchin
- David Mouill
(Observatoire de Grenoble, Franc
- Members of the ESO-Chil
Planetary Sciences Grou
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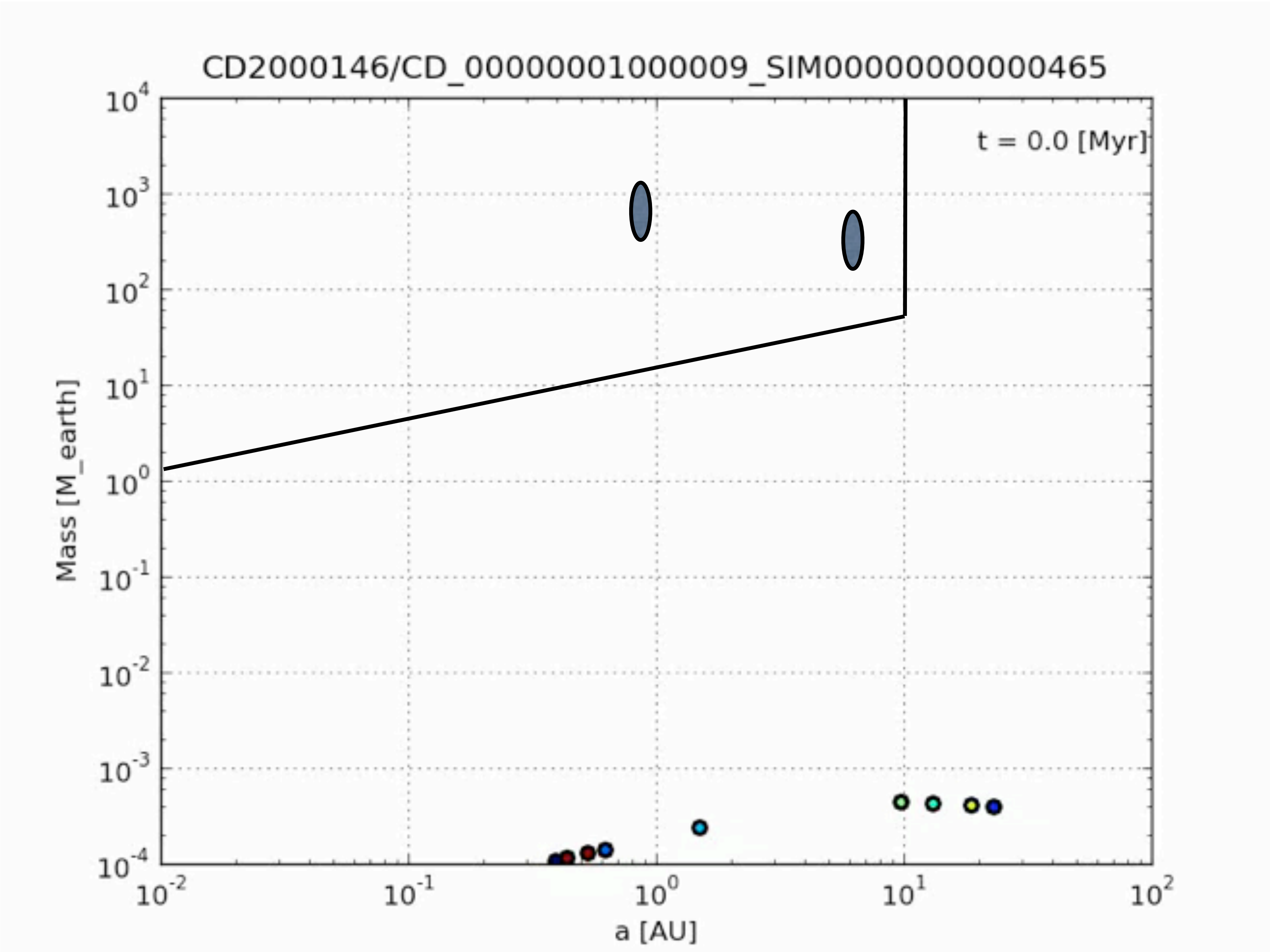
Web page: http://www.eso.org/sci/meetings/2012/OPSII.html
Conference e-mail: ops2012@eso.org

HD 134987



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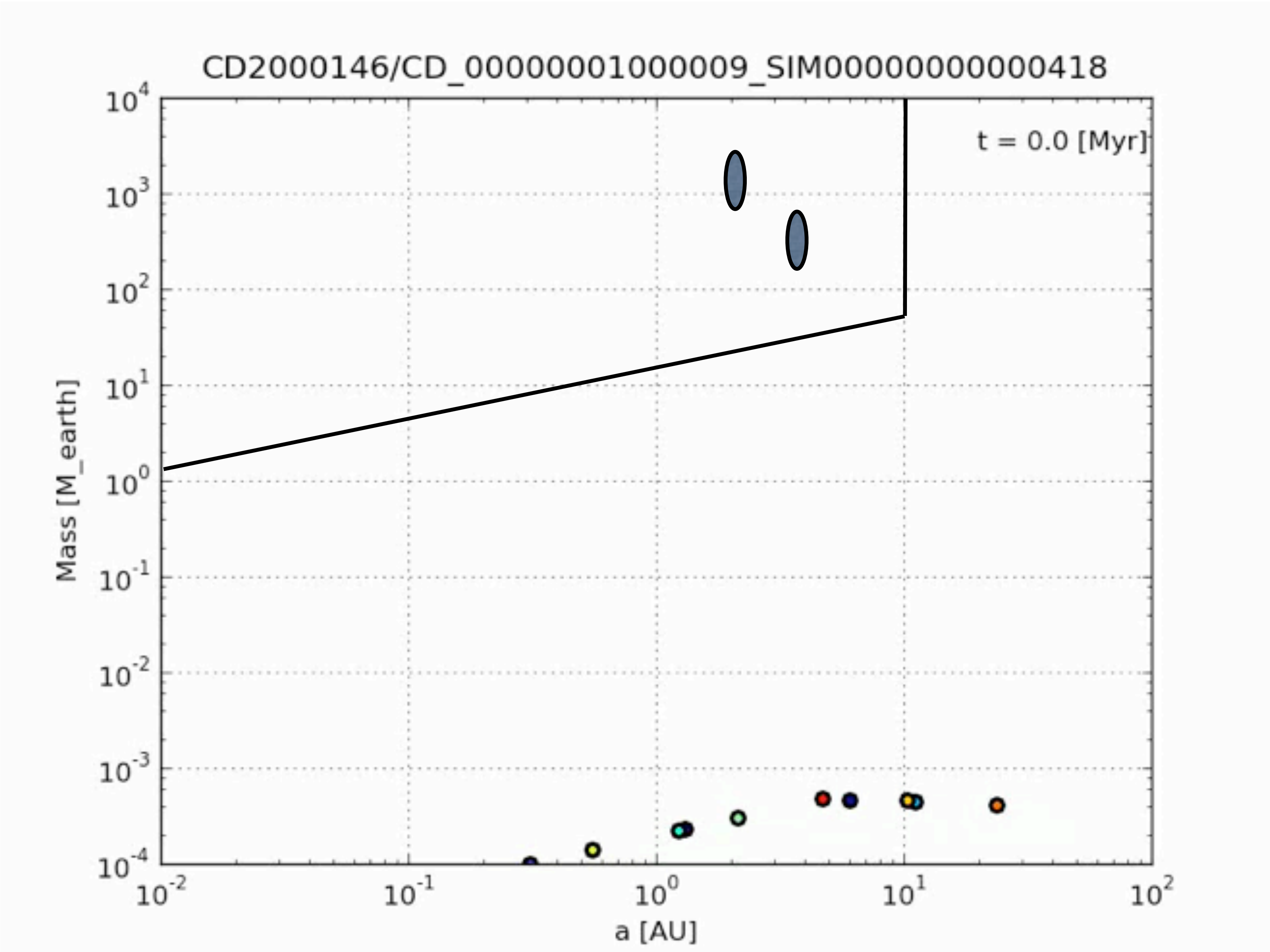
Mass [M_earth]
a [AU]
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

47 UMa



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Mass [M_earth]
a [AU]
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10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-2
10^-1
10^0
10^1
10^2

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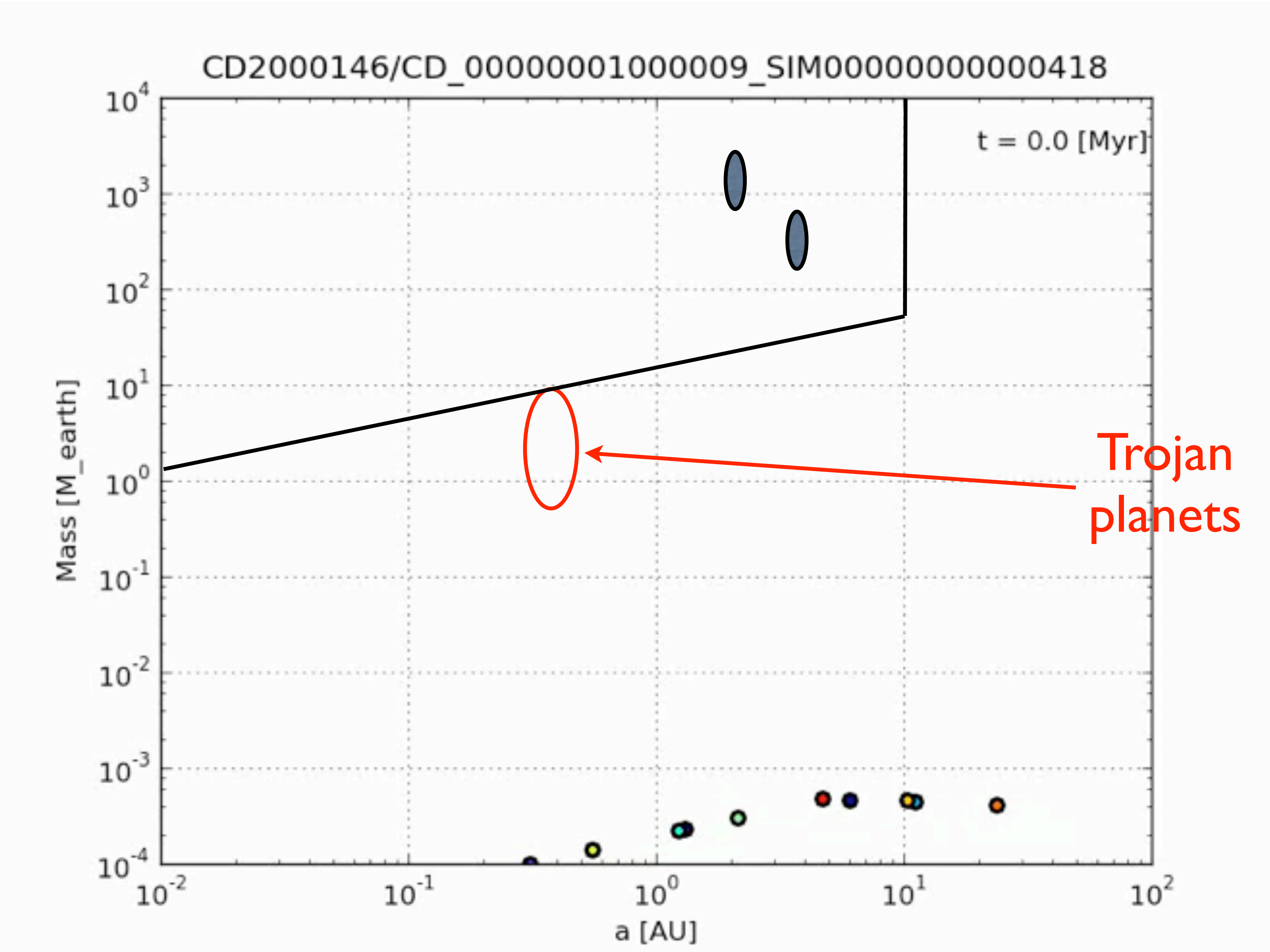
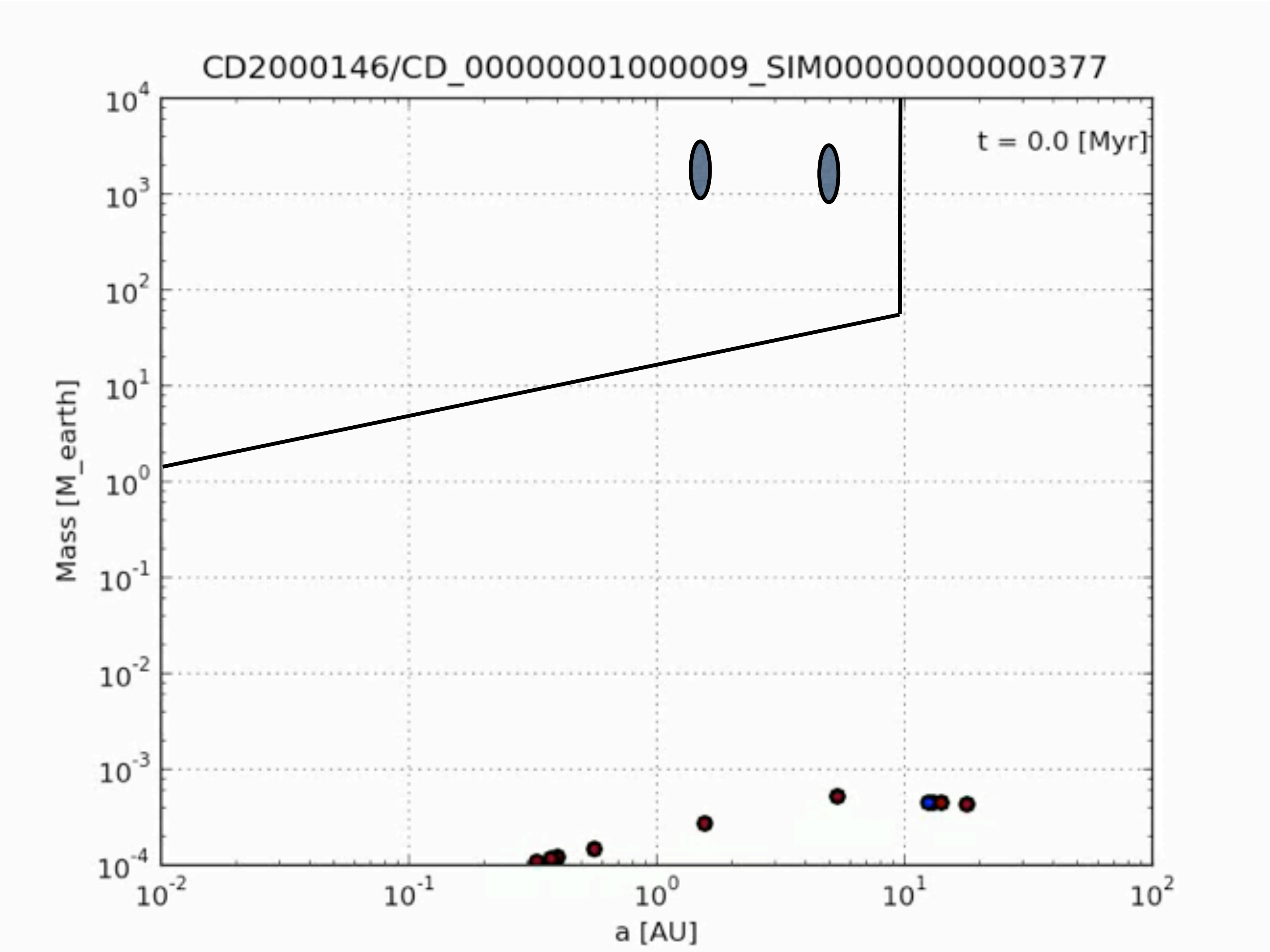


CD2000146/CD_00000001000009_SIM0000000000418
t = 0.0 [Myr]
Mass [M_earth]
a [AU]
Trojan planets

HD 183263



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t = 0.0 [Myr]
Mass [M_earth]
a [AU]
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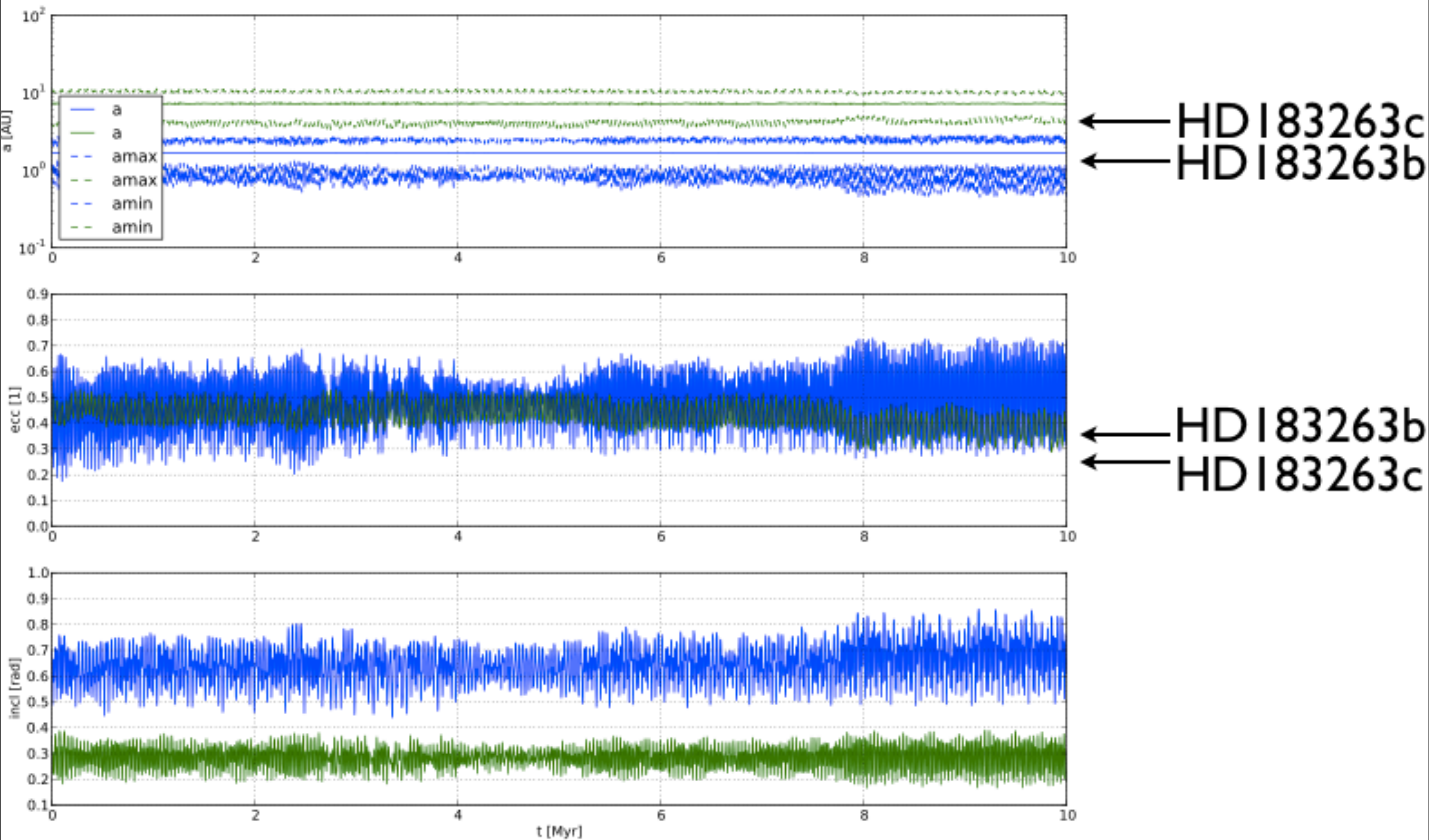
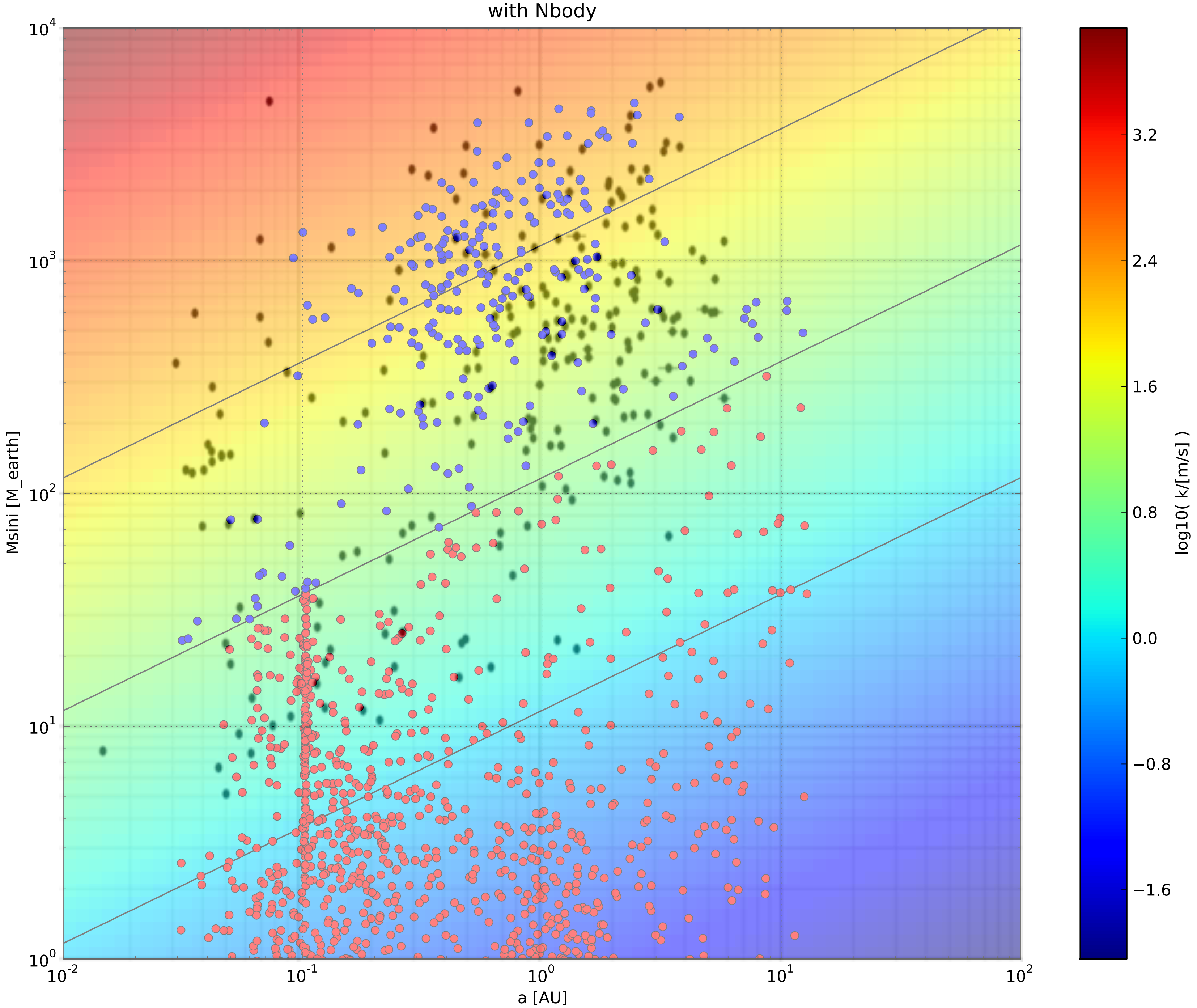
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-2
10^-1
10^0
10^1
10^2

HD 183263 long term evolution - 10 Myr



a-M diagram compared with all planets



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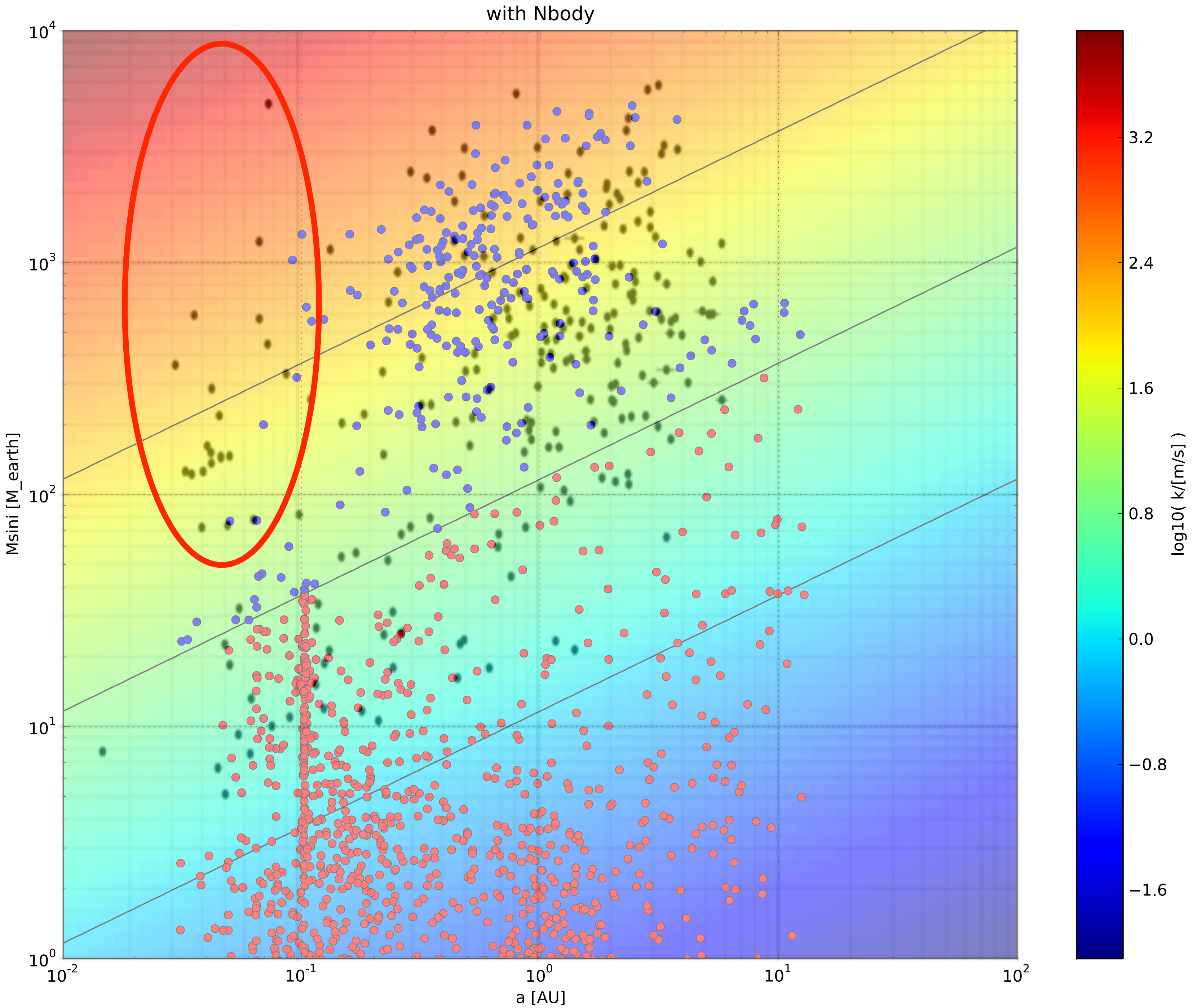

Conclusions

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Planet formation models have to include

- planets internal structure
- disk (solids and gas) modelisation
- their interactions

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$$N\,\text{planets} \gg N \times \text{planet}$$

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What about long term evolution?

Conclusions

Future models will have to include

- particular approach for planetesimals
    - shepperding effect
    - gap in planetesimal disk
- interactions induced through the disk
    - common gap
    - modified migration

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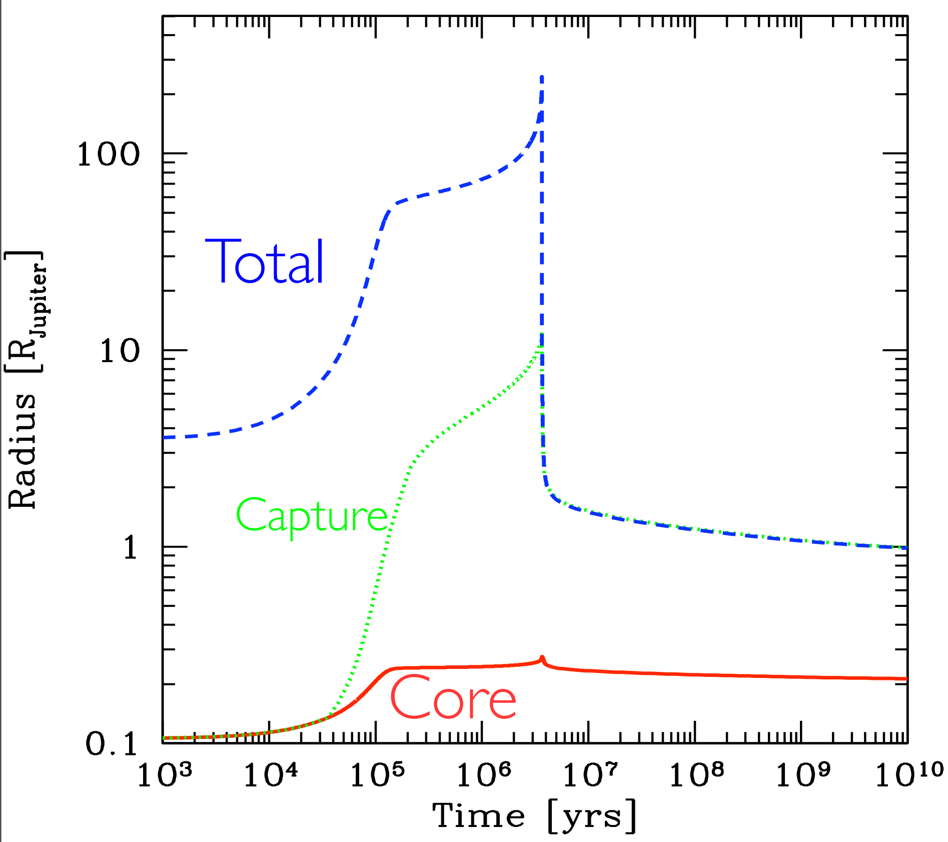
POPULATION SYNTHESIS

① Planet gas envelope structure - long term evolution



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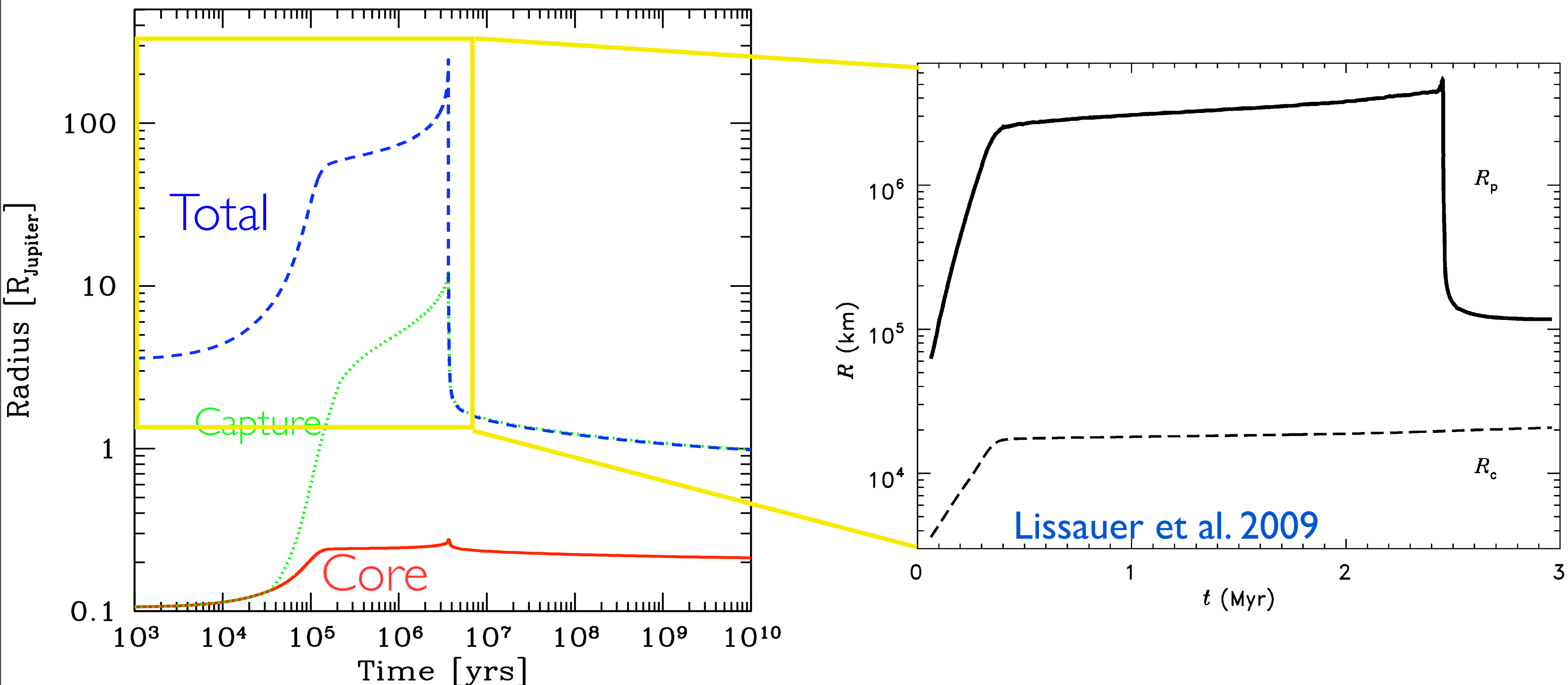

- Attached & detached (collapse) phase: Lissauer et al. 2009 & Broeg et al. in prep well reproduced.

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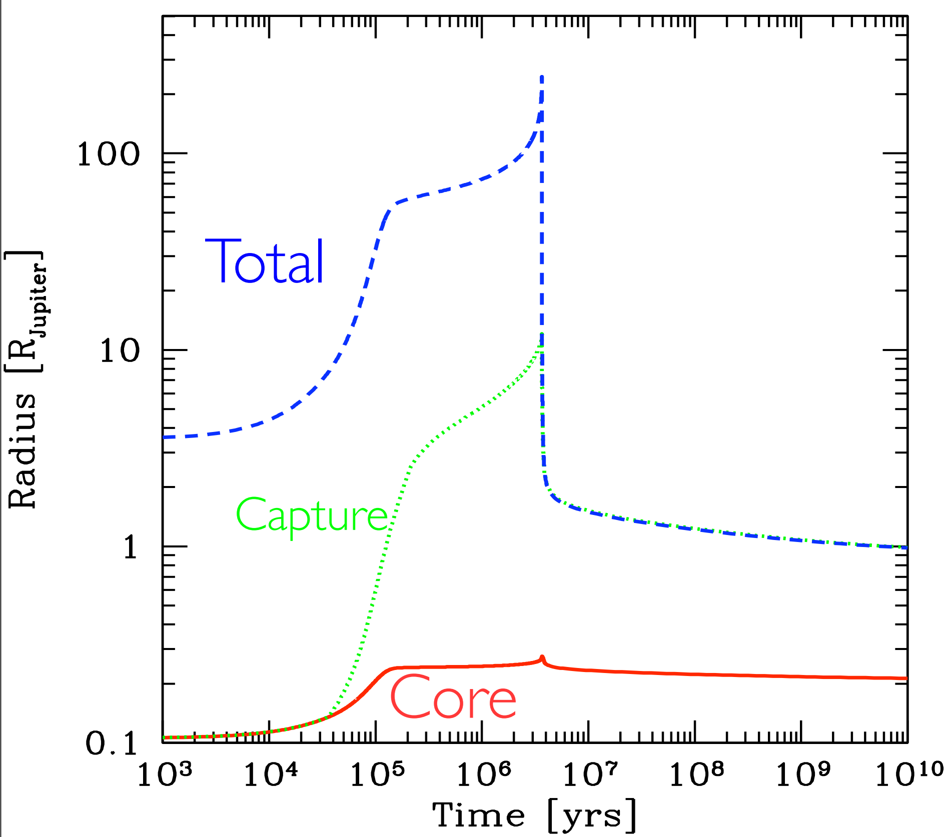

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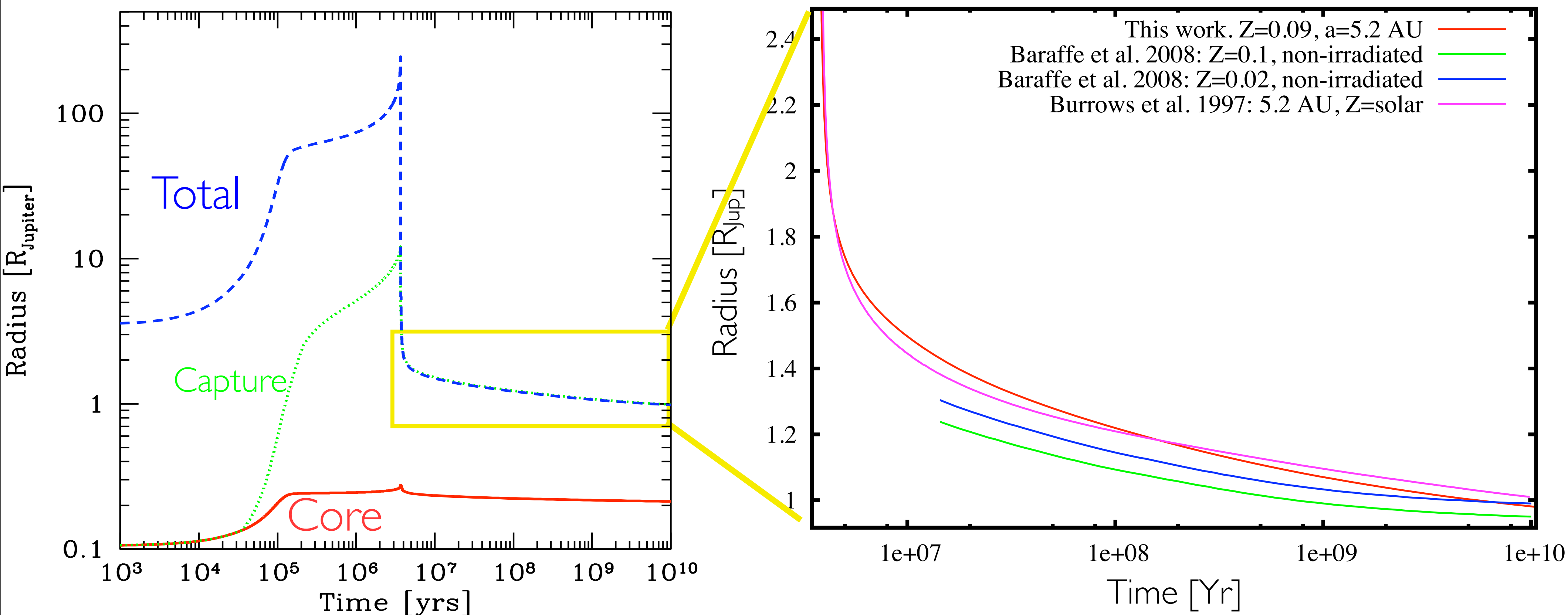

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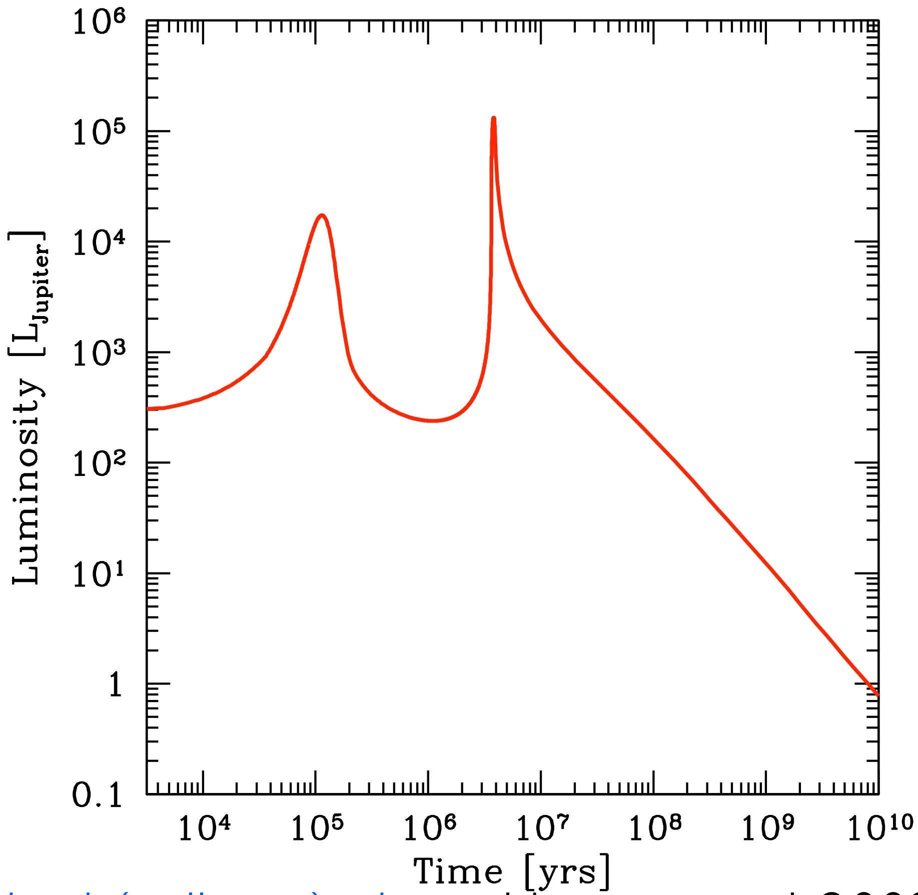

L_{max} ca 3×10^{-4} L_{sun}

L at 4.6 Gyrs: 1.8 L_J

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- Long term evolution of radii agree to typically 10 % compared to Baraffe et al. or Burrows et al. models.
- Agreement for luminosities to factor 2. Tendency to too high R and L at late times.

① Planet gas envelope structure - equations

e.g. Bodenheimer & Pollack 1986

1-D radial structure equations (similar to stellar structure)

$$\frac{dm}{dr} = 4\pi r^2 \rho \qquad \frac{dP}{dr} = -\frac{Gm}{r^2}\rho$$

$$\frac{dl}{dr} = 4\pi r^2 \rho \left(\epsilon - T\frac{\partial S}{\partial t}\right) \qquad \frac{dT}{dr} = \frac{T}{P}\frac{dP}{dr}\nabla$$

Mass conservation
Hydrostat. equilibrium
Energy conservation
Energy transport

$$\nabla = \frac{d\ln T}{d\ln P} = \min(\nabla_{\mathrm{ad}}, \nabla_{\mathrm{rad}}) \qquad \nabla_{\mathrm{rad}} = \frac{3}{64\pi\sigma G}\frac{\kappa l P}{T^4 m}$$

Additional energy source:
impacting planetesimals

Gas accretion rate given by ability to radiate away energy (T_{KH})

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Gas accretion rate given by ability to radiate away energy (T_{KH})

Gas accretion rate in runaway (M_{core}>~10 M_E)

Accretion rate in the disk

(flow of gas usually towards the star)

$$\dot{M}_{disk} = 3\pi\tilde{\nu}\Sigma + 6\pi r\frac{\partial \tilde{\nu}\Sigma}{\partial r}$$

Planet cannot accrete more than disk gives

$$\frac{dM_{XY}}{dt} = Min\left[\frac{dM_{struct}}{dt}, k_{\rm Lub}\dot{M}_{disk}\right]$$

① Planet gas envelope structure - boundary conditions

1. Attached phase

- low mass planets (M_{core}< ca.10-20 M_{Earth})
- pre gas runaway accretion
- structure goes smoothly to Hill or accretion radius
- boundary conditions: background nebula

$$R = \frac{R_A}{1+R_A/R_H} \qquad P = P_{neb}$$

$$\tau = \max(\rho_{neb}\kappa_{neb}R, 2/3) \qquad T_{int}^4 = \frac{3\tau L_{int}}{8\pi\sigma R^2}$$

$$T^4 = T_{neb}^4 + T_{int}^4 \qquad l(R) = L_{int}.$$

❶ Planet gas envelope structure - boundary conditions

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2. Detached phase

- gas runaway accretion
- structure has a free outer radius
- rapid collapse of radius to ~2 R_J
- upper boundary: accretion shock
- high mass planets
- disk and gap formation regulate dM_{XY}/dt

$$\dot{M}_{XY} = \dot{M}_{max} \qquad v_{ff} = \left[2GM\left(1/R - 1/R_H\right)\right]^{1/2}$$

$$P = P_{neb} + \frac{\dot{M}_{XY}}{4\pi R^2}v_{ff} + \frac{2g}{3\kappa} \qquad \tau = \max(\rho_{neb}\kappa_{neb}R, 2/3)$$

$$T^4_{int} = \frac{3\tau L_{int}}{8\pi\sigma R^2} \qquad T^4 = (1-A)T^4_{neb} + T^4_{int}$$

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3. Evolution M=cst.

- Eddington approximation (gray atmosphere)

$$P = \frac{2g}{3\kappa} \qquad T^4_{int} = \frac{L_{int}}{4\pi\sigma R^2}$$
$$T_{equi} = 280\,\mathrm{K}\left(\frac{a}{1\mathrm{AU}}\right)^{-\frac{1}{2}}\left(\frac{M_*}{M_\odot}\right) \qquad T^4 = (1-A)T^4_{equi} + T^4_{int}$$

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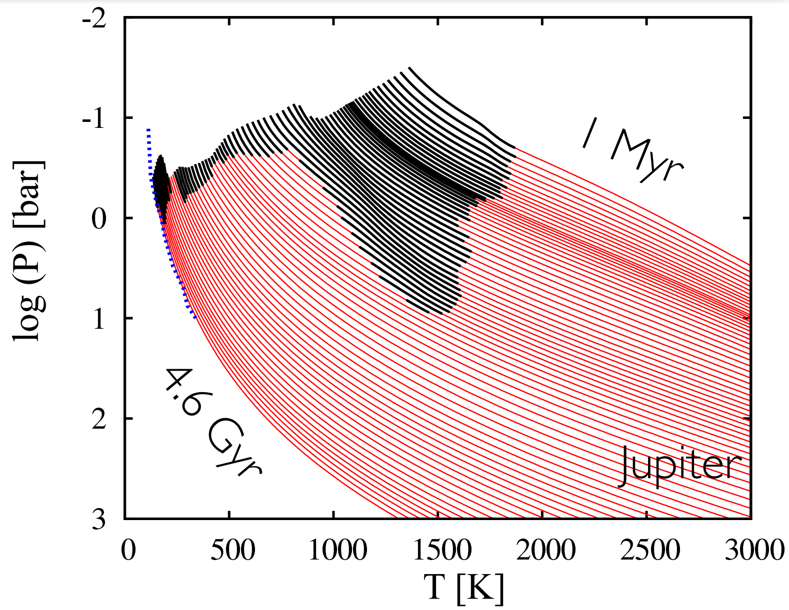
- high mass planets
- disk and gap formation regulate dM_{XY}/dt

$$\dot{M}_{XY} = \dot{M}_{max} \qquad v_{ff} = [2GM\,(1/R - 1/R_H)]^{1/2}$$
$$P = P_{neb} + \frac{\dot{M}_{XY}}{4\pi R^2}v_{ff} + \frac{2g}{3\kappa} \qquad \tau = \max(\rho_{neb}\kappa_{neb}R, 2/3)$$
$$T_{int}^4 = \frac{3\tau L_{int}}{8\pi\sigma R^2} \qquad T^4 = (1-A)T_{neb}^4 + T_{int}^4$$

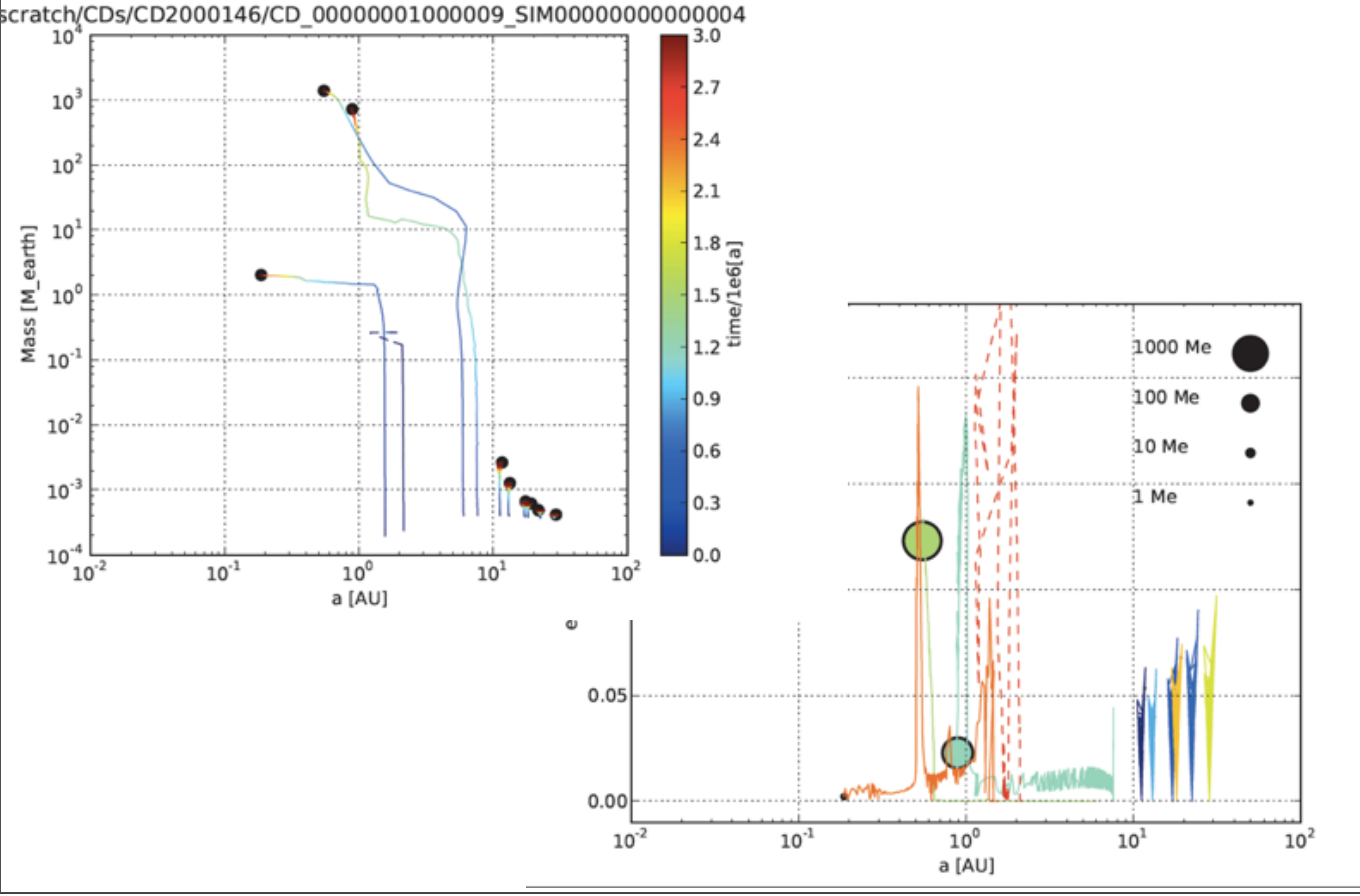
3. Evolution M=cst.

- Eddington approximation (gray atmosphere)

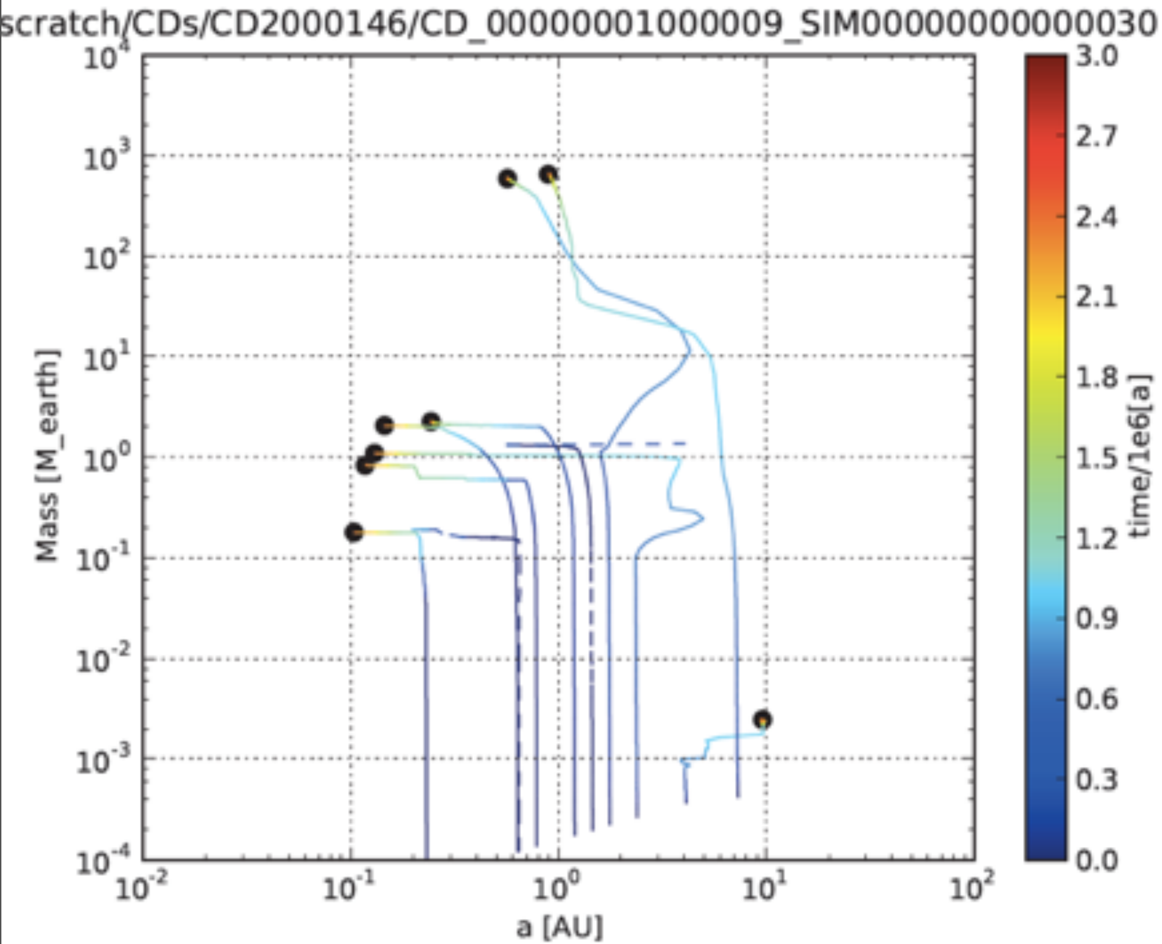
$$P = \frac{2g}{3\kappa} \qquad T_{int}^4 = \frac{L_{int}}{4\pi\sigma R^2}$$
$$T_{equi} = 280\,\mathrm{K}\left(\frac{a}{1\mathrm{AU}}\right)^{-\frac{1}{2}}\left(\frac{M_*}{M_\odot}\right) \qquad T^4 = (1-A)T_{equi}^4 + T_{int}^4$$

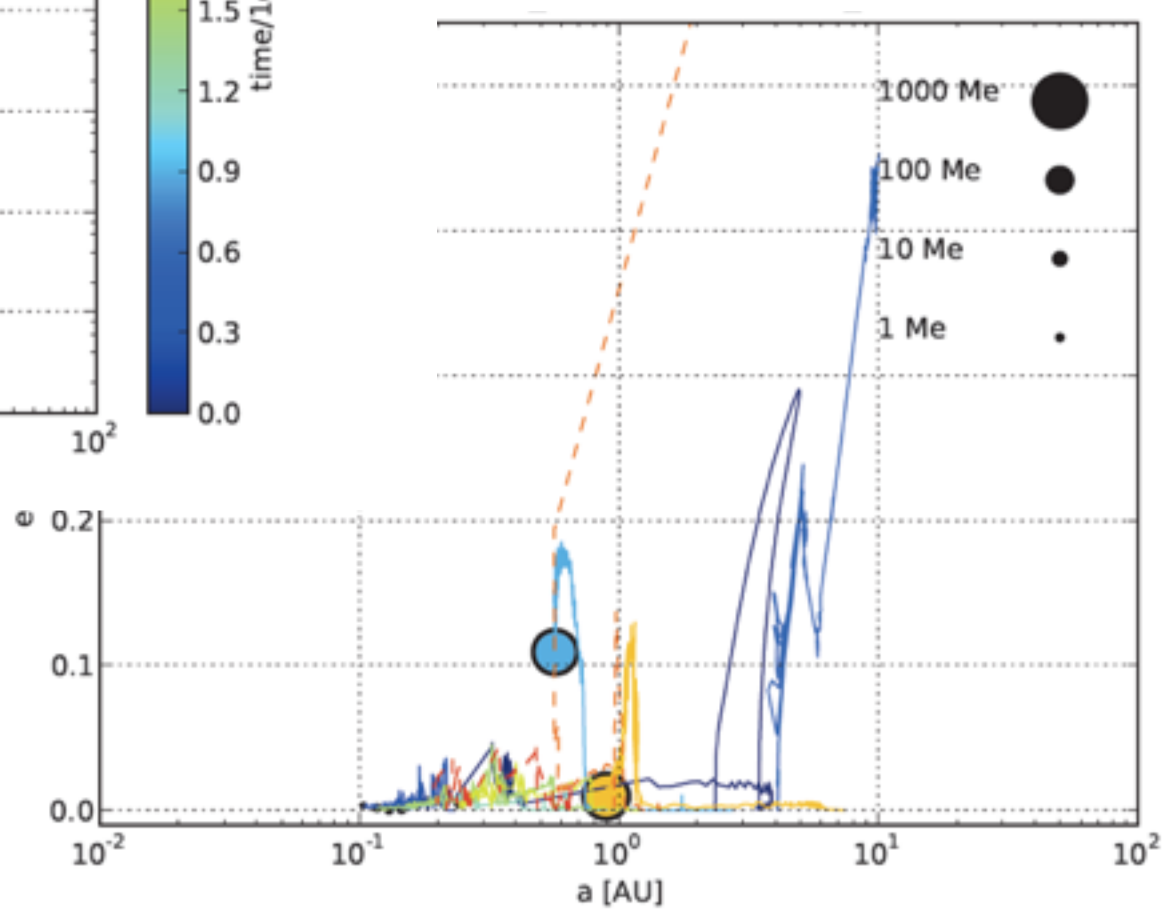


a system with two giants and one SE

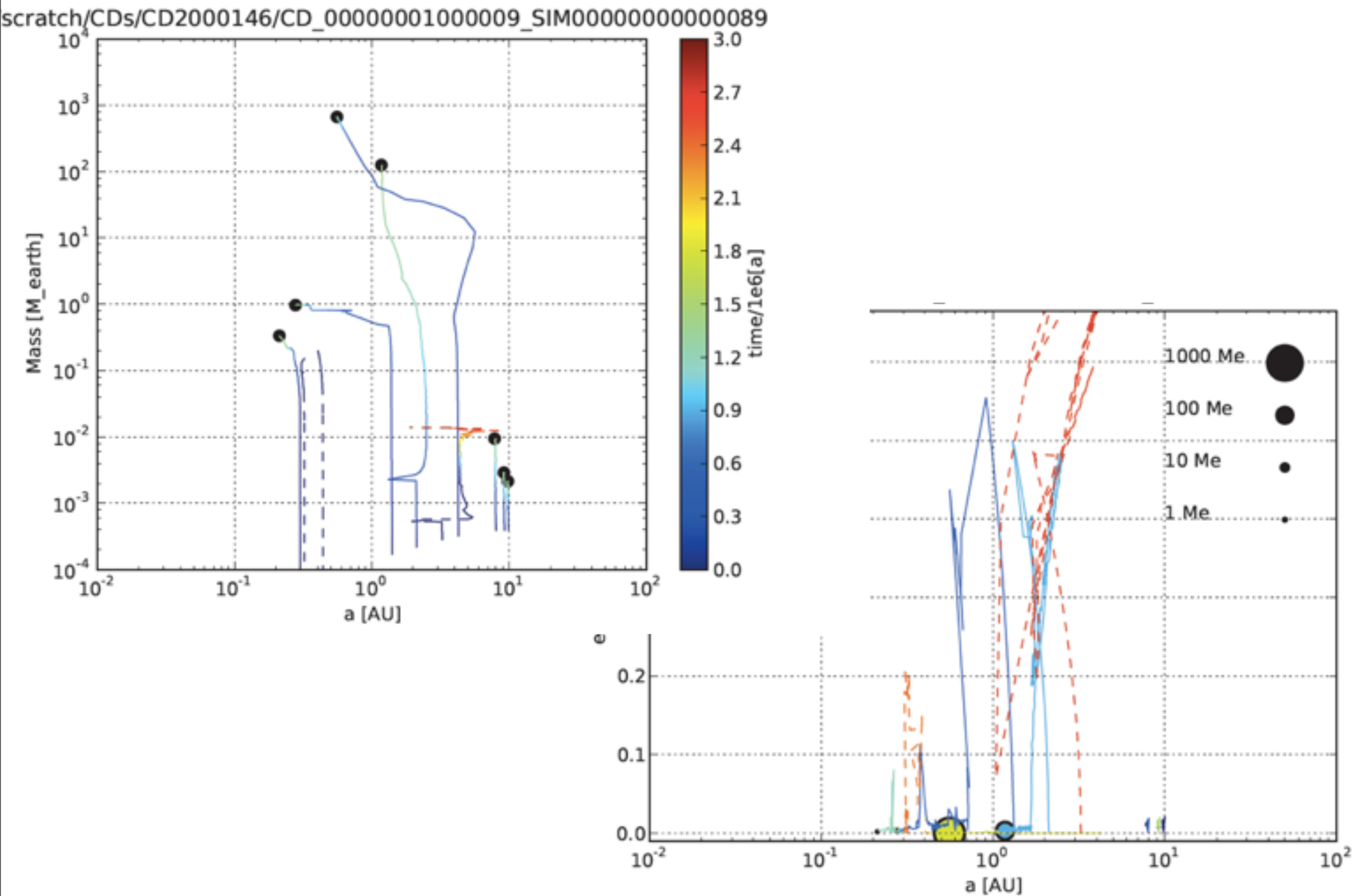


a system with two giants and many HSE

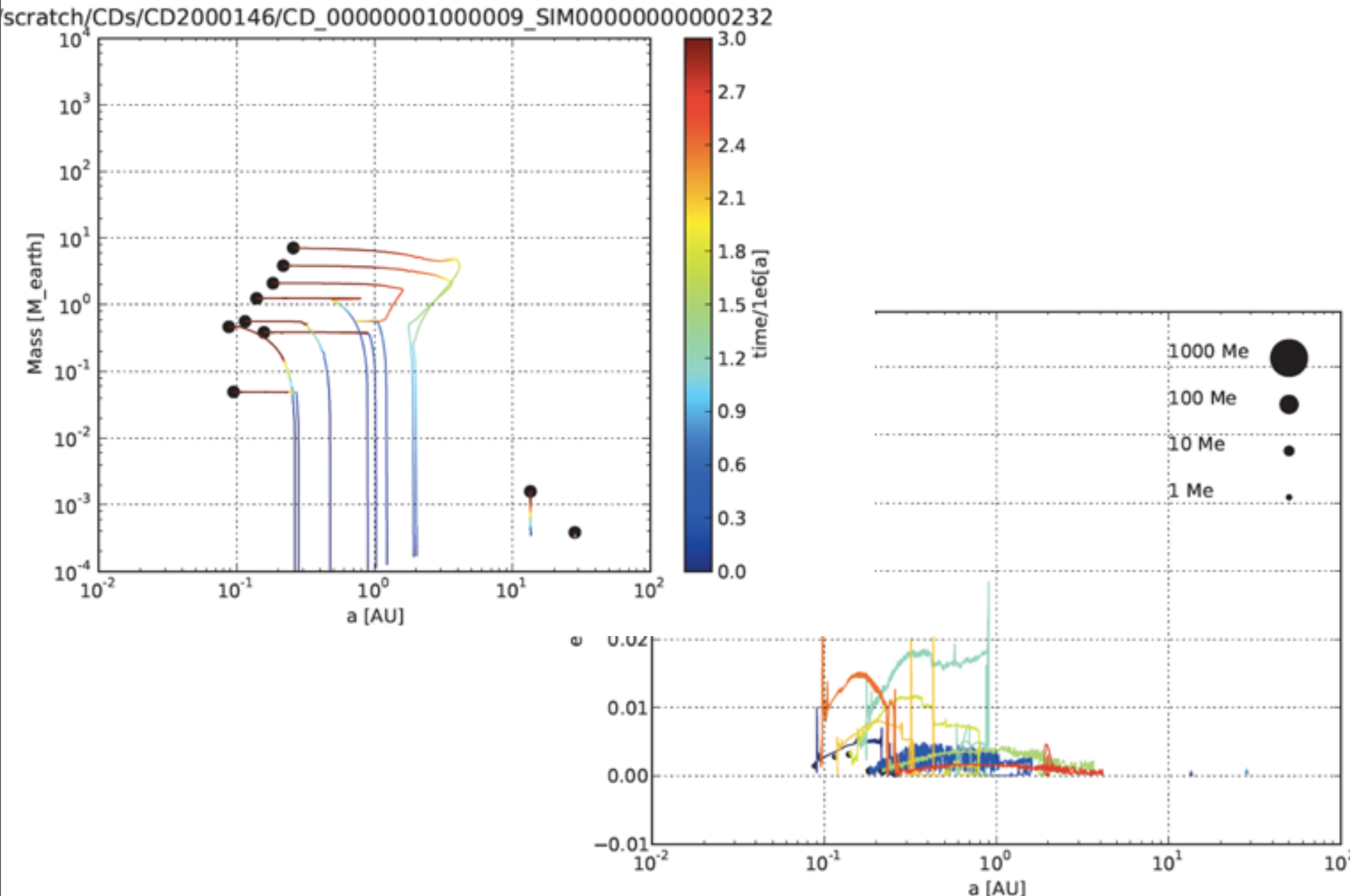




a system with two giants, no SE, no HN

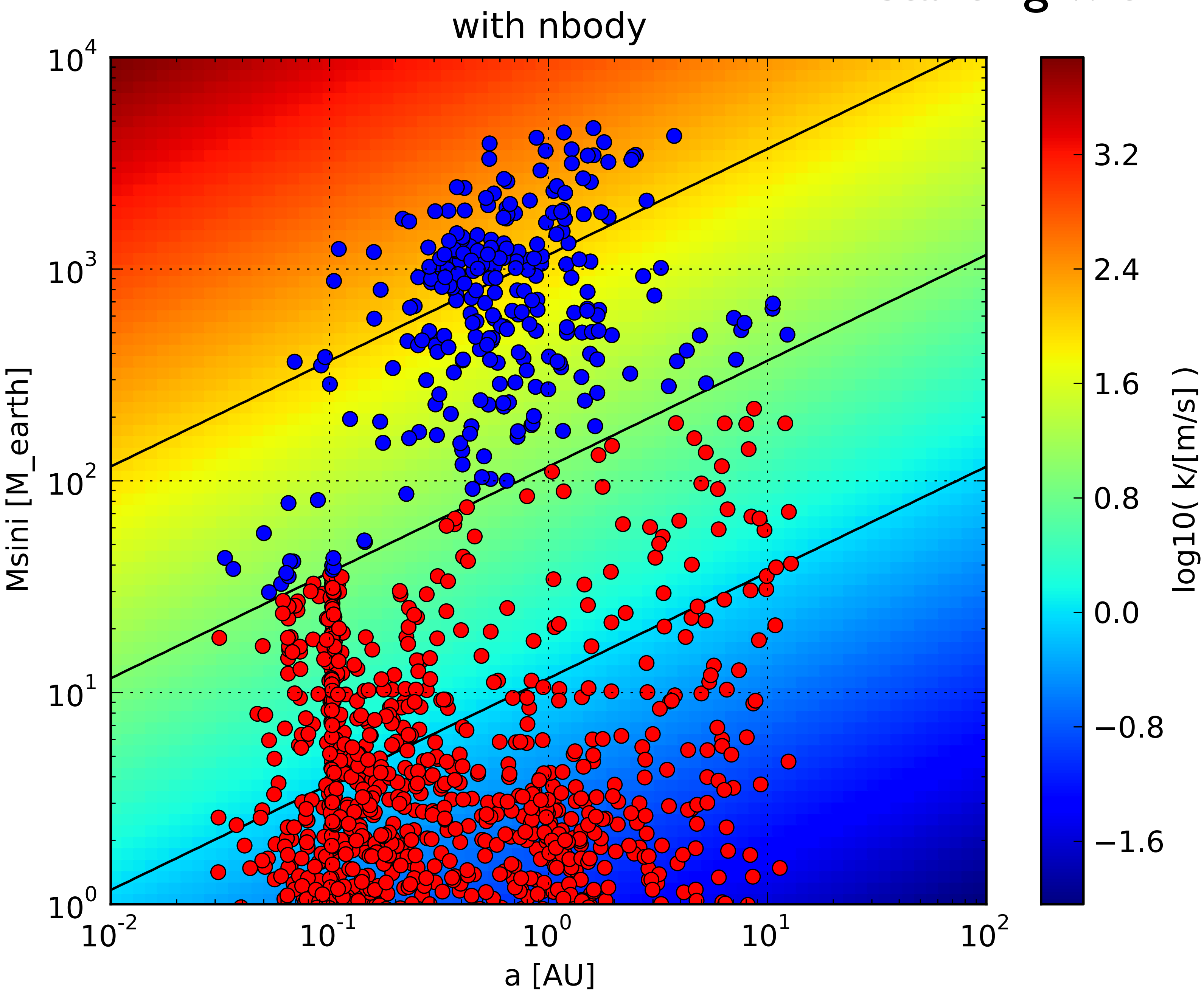


a system with four SE



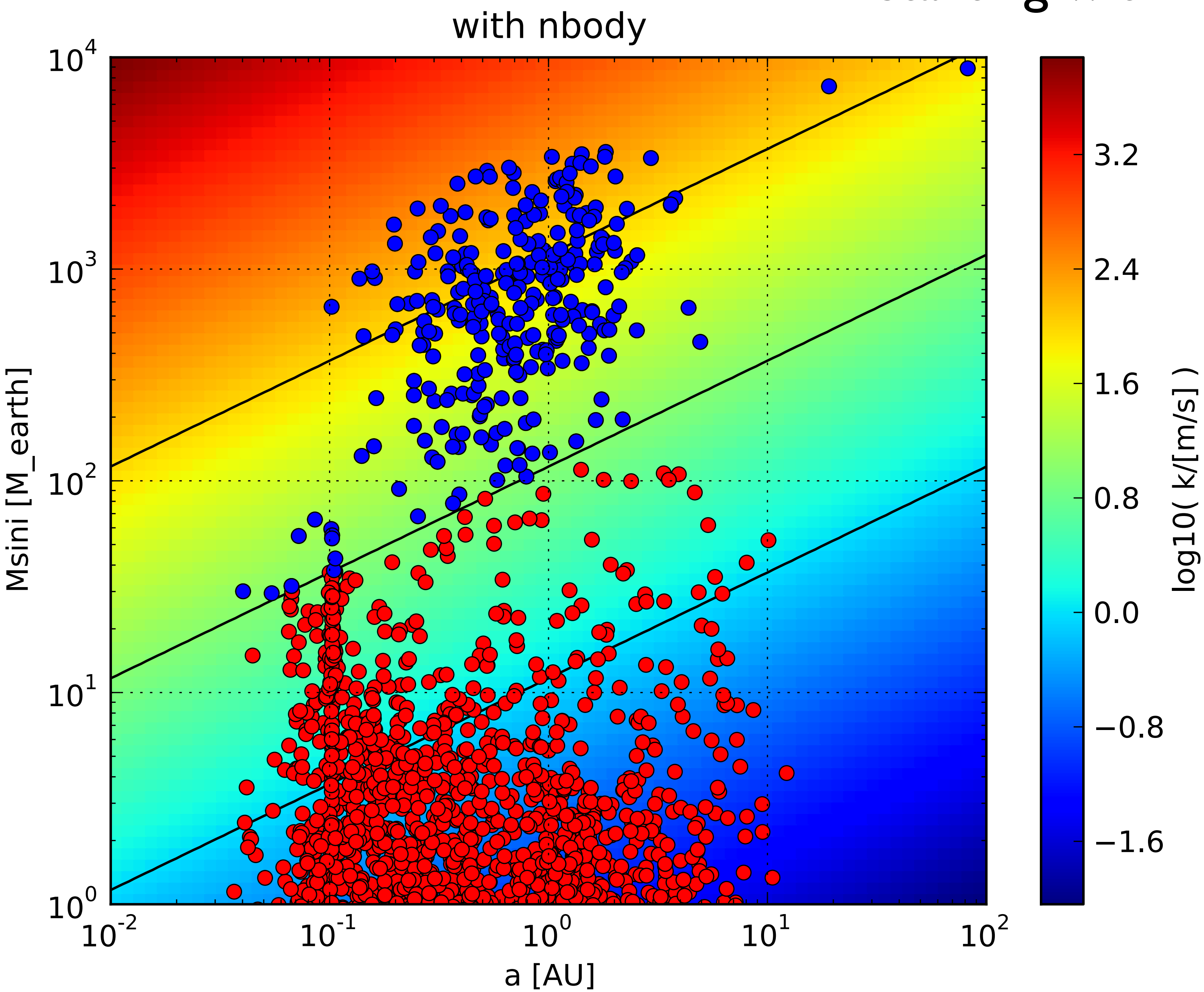
a-M diagram

starting with 10 planets



10 *vs* 20 planets

starting with 20 planets



stability of the Trojan planets