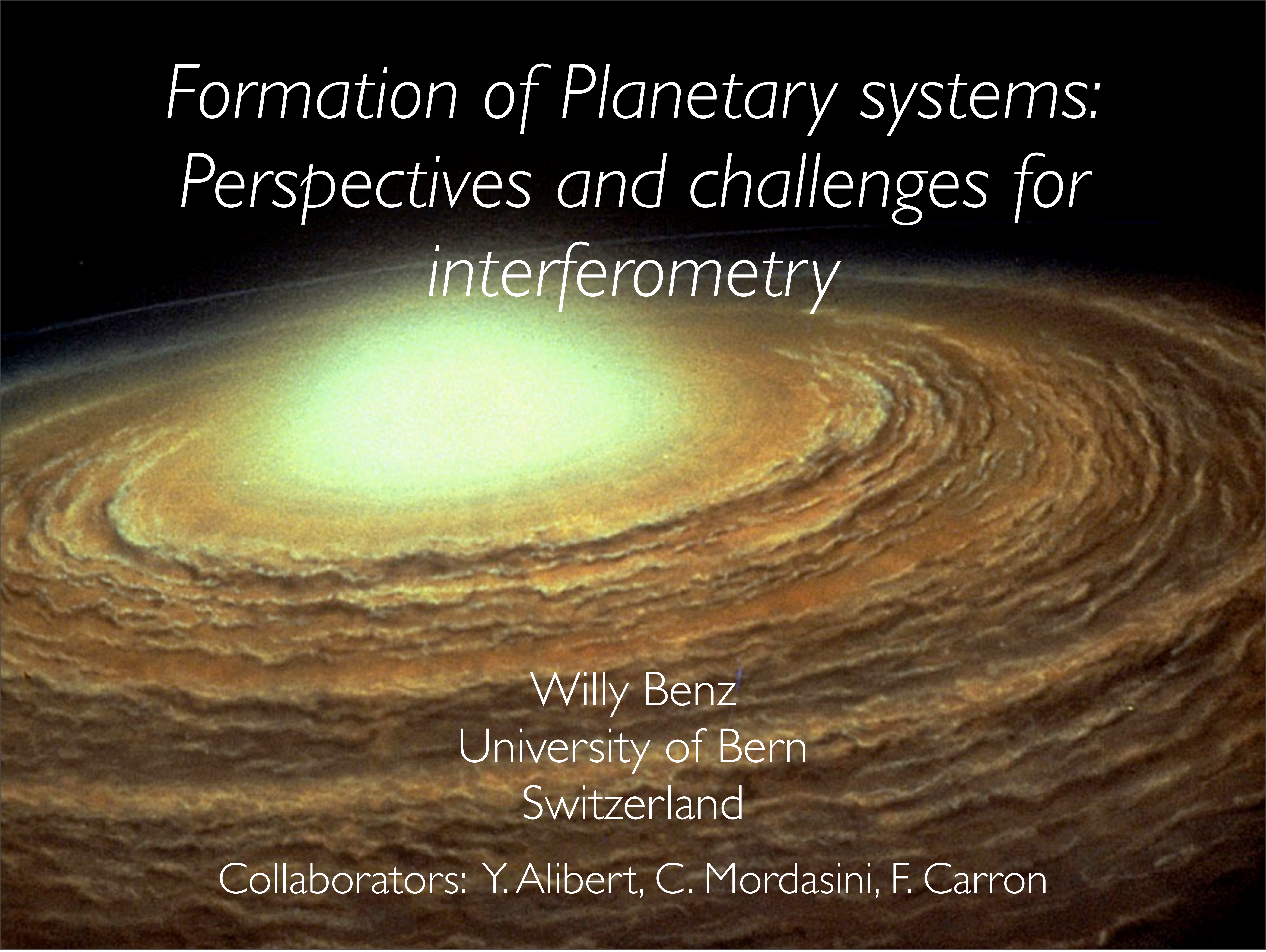


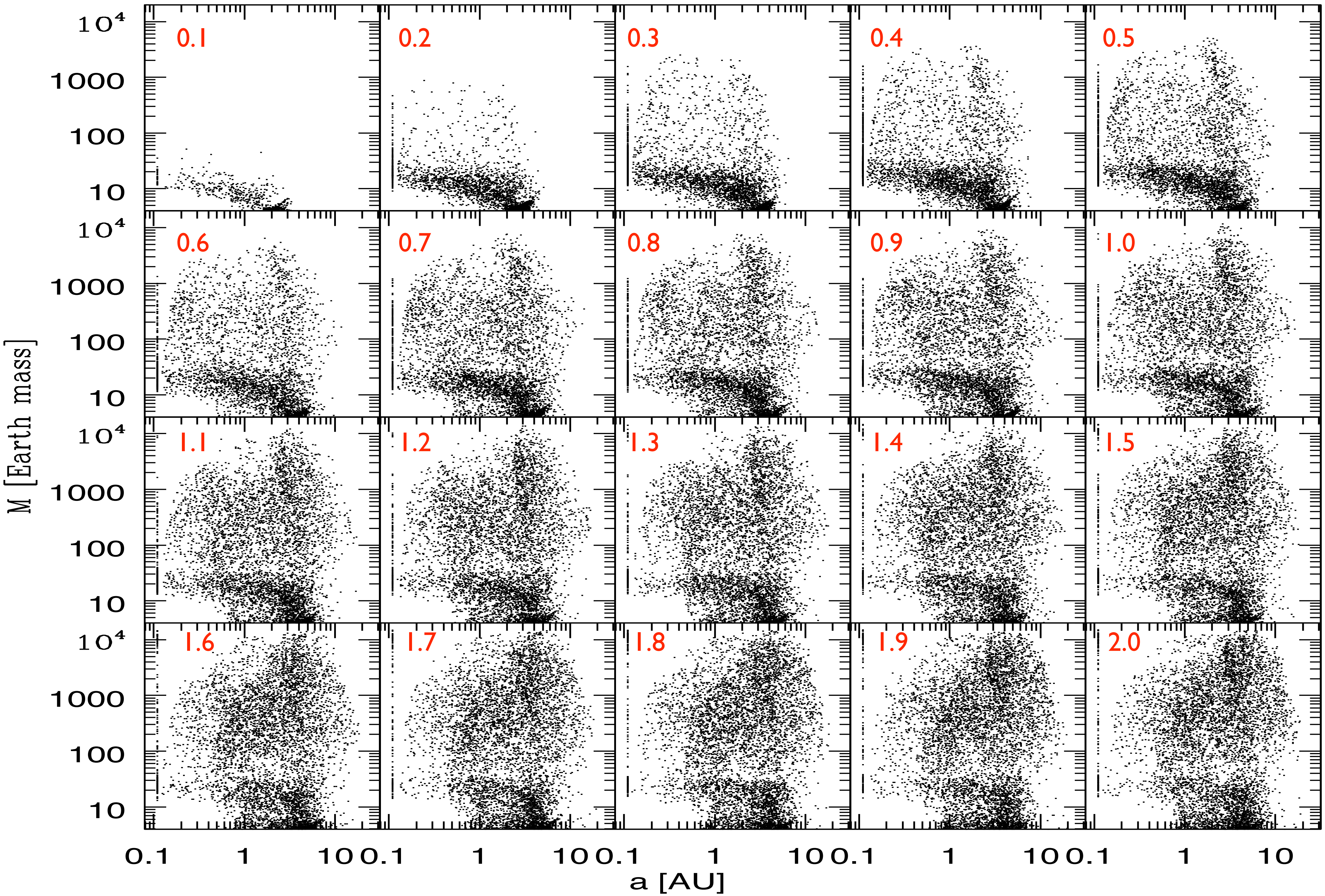
Formation of Planetary systems: Perspectives and challenges for interferometry

Willy Benz
University of Bern
Switzerland

Collaborators: Y. Alibert, C. Mordasini, F. Carron

Planet populations

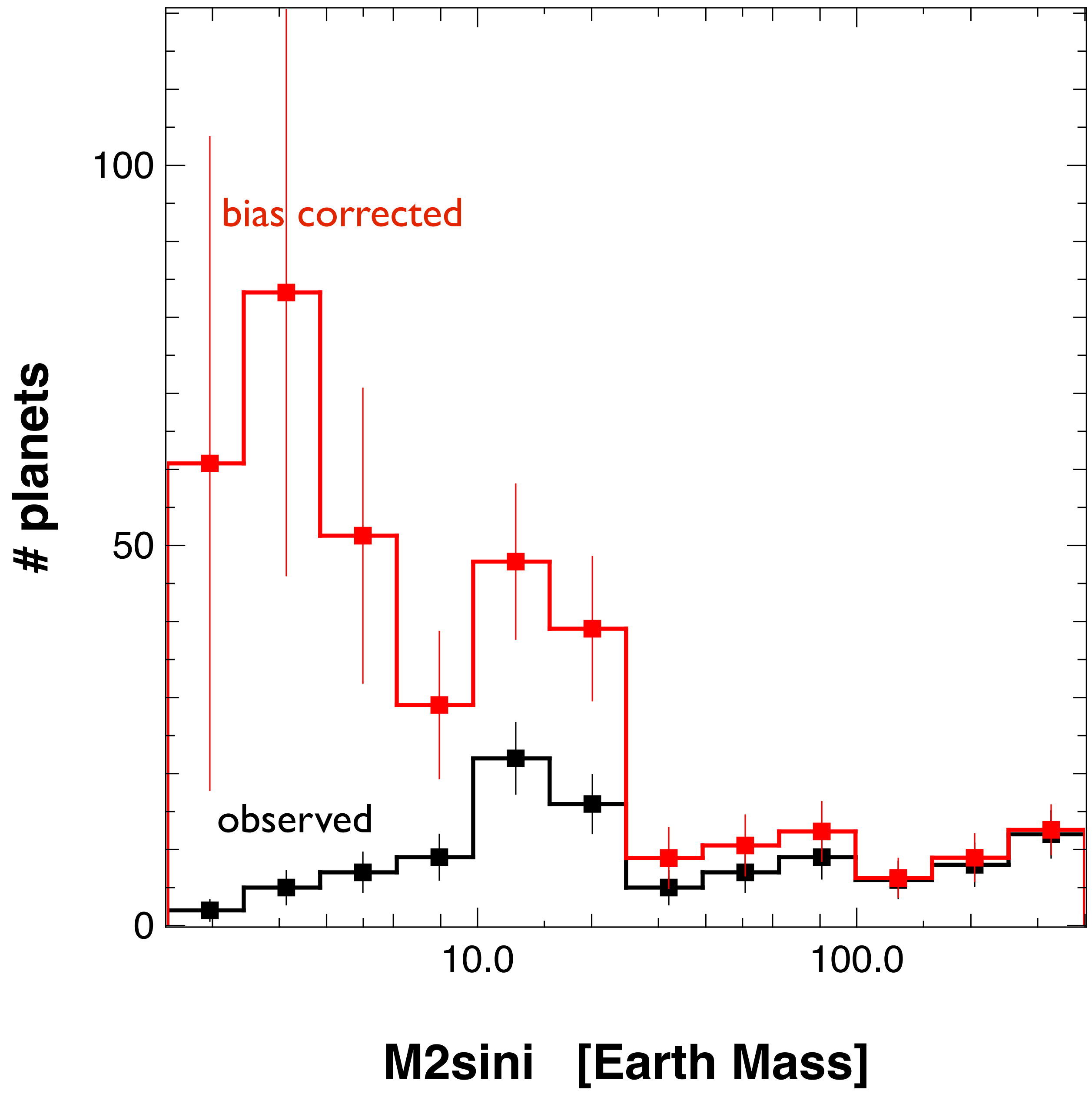
Alibert et al. 2010



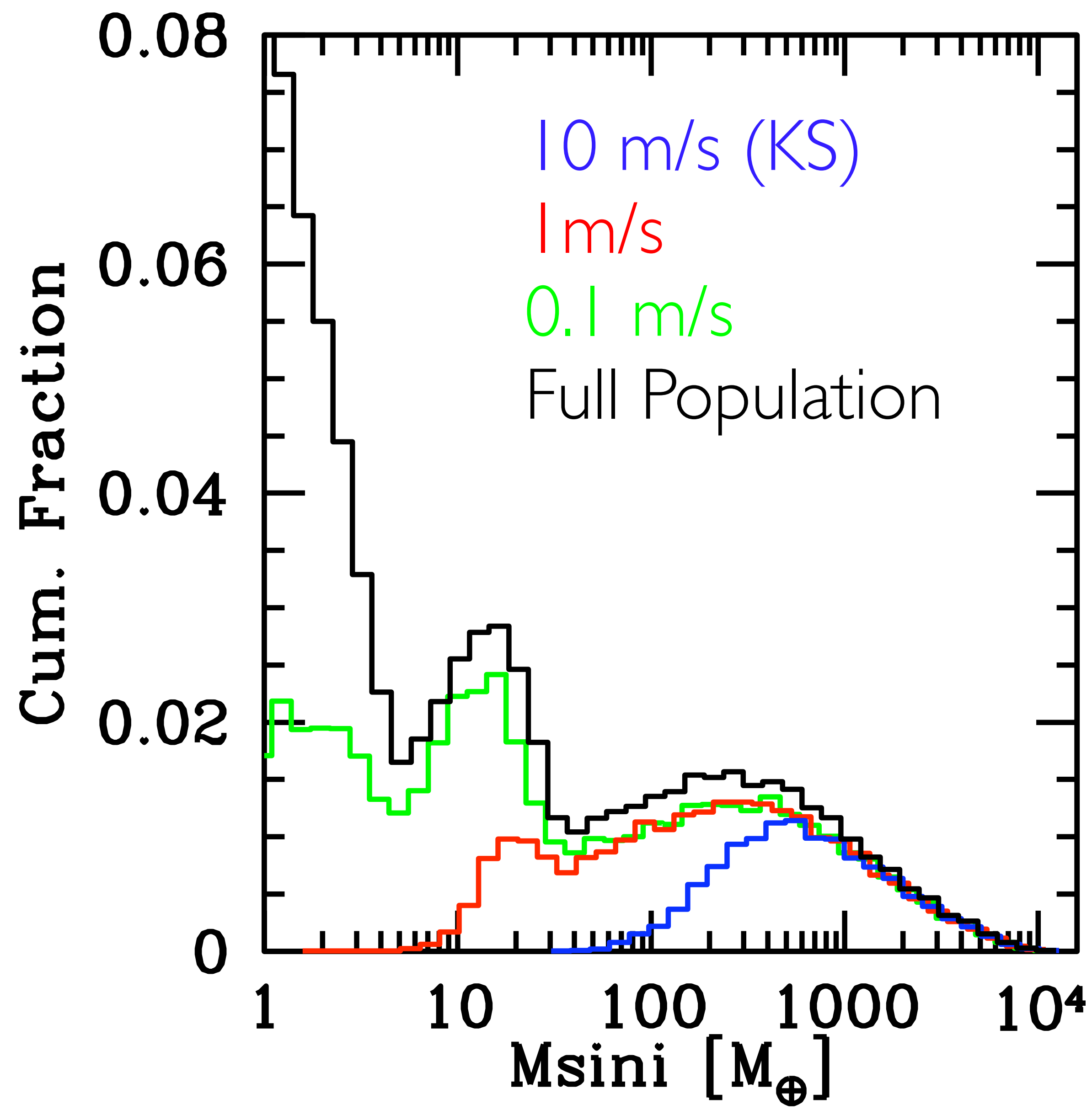
Low (high) mass stars lead to the formation of lower (higher) mass planets, in more (less) compact planetary systems.

Initial mass function

Observed mass function



Synthetic mass function

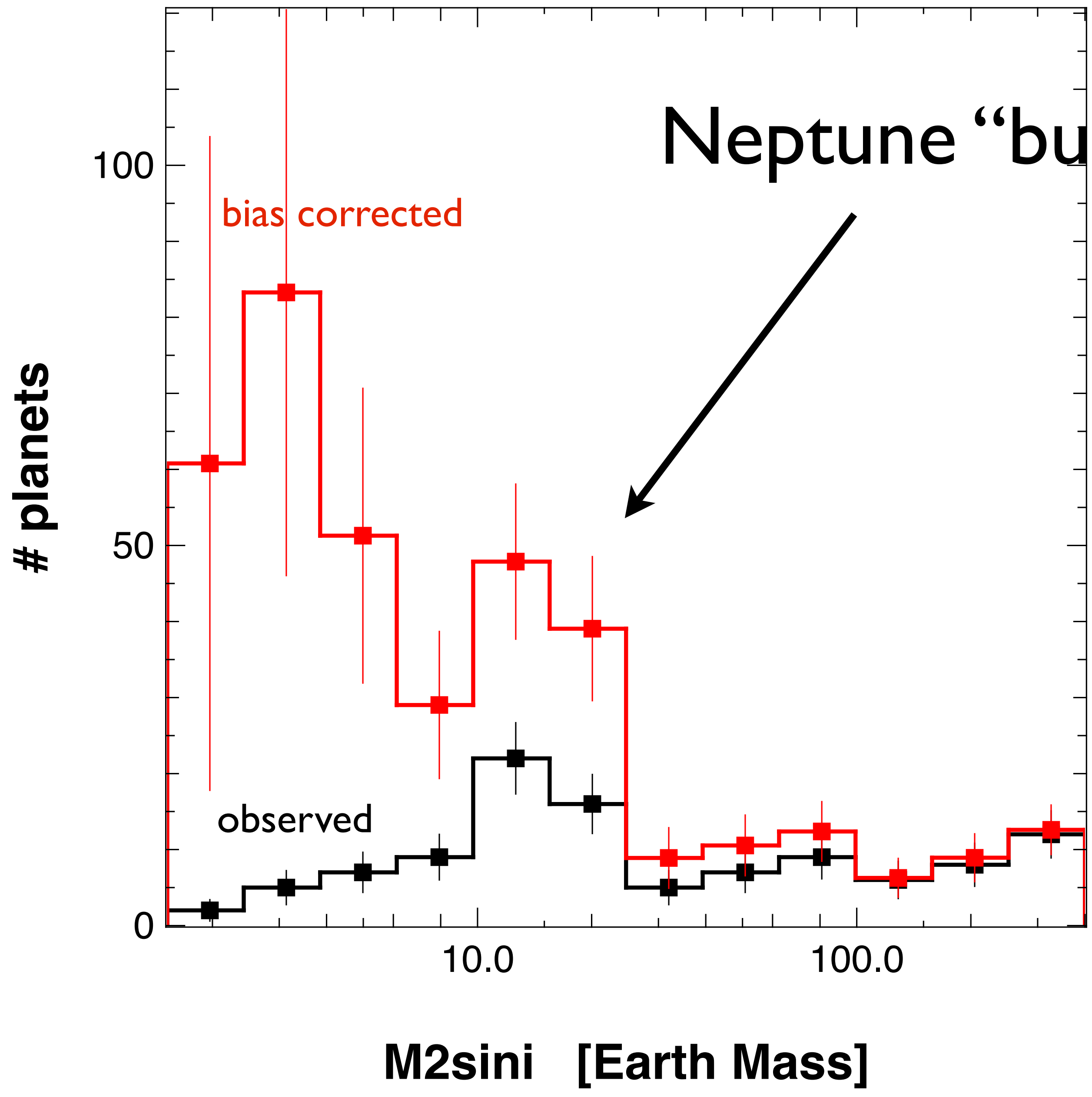


Mayor et al. 2011

Mordasini et al. 2009

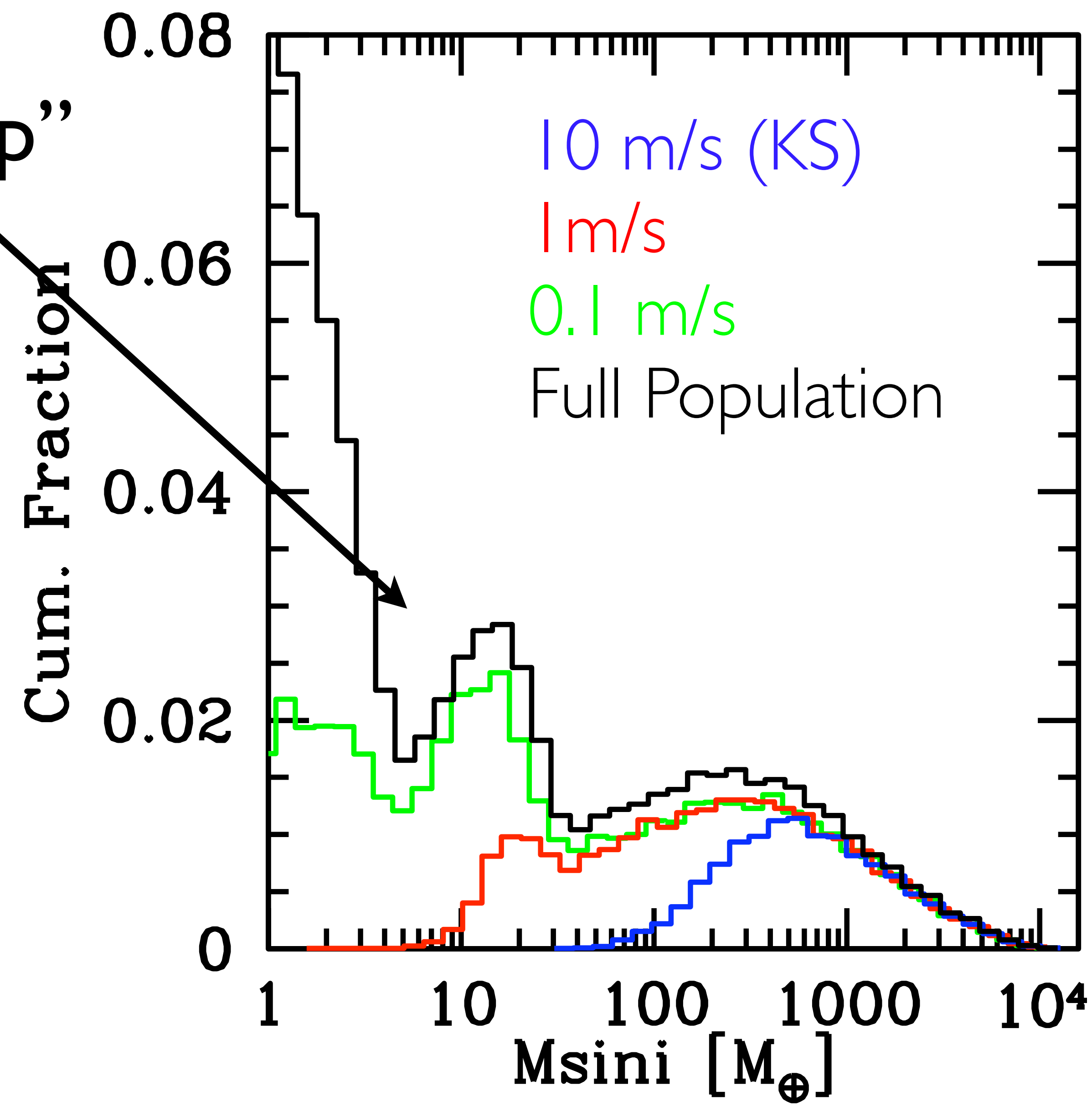
Initial mass function

Observed mass function



Neptune "bump"

Synthetic mass function

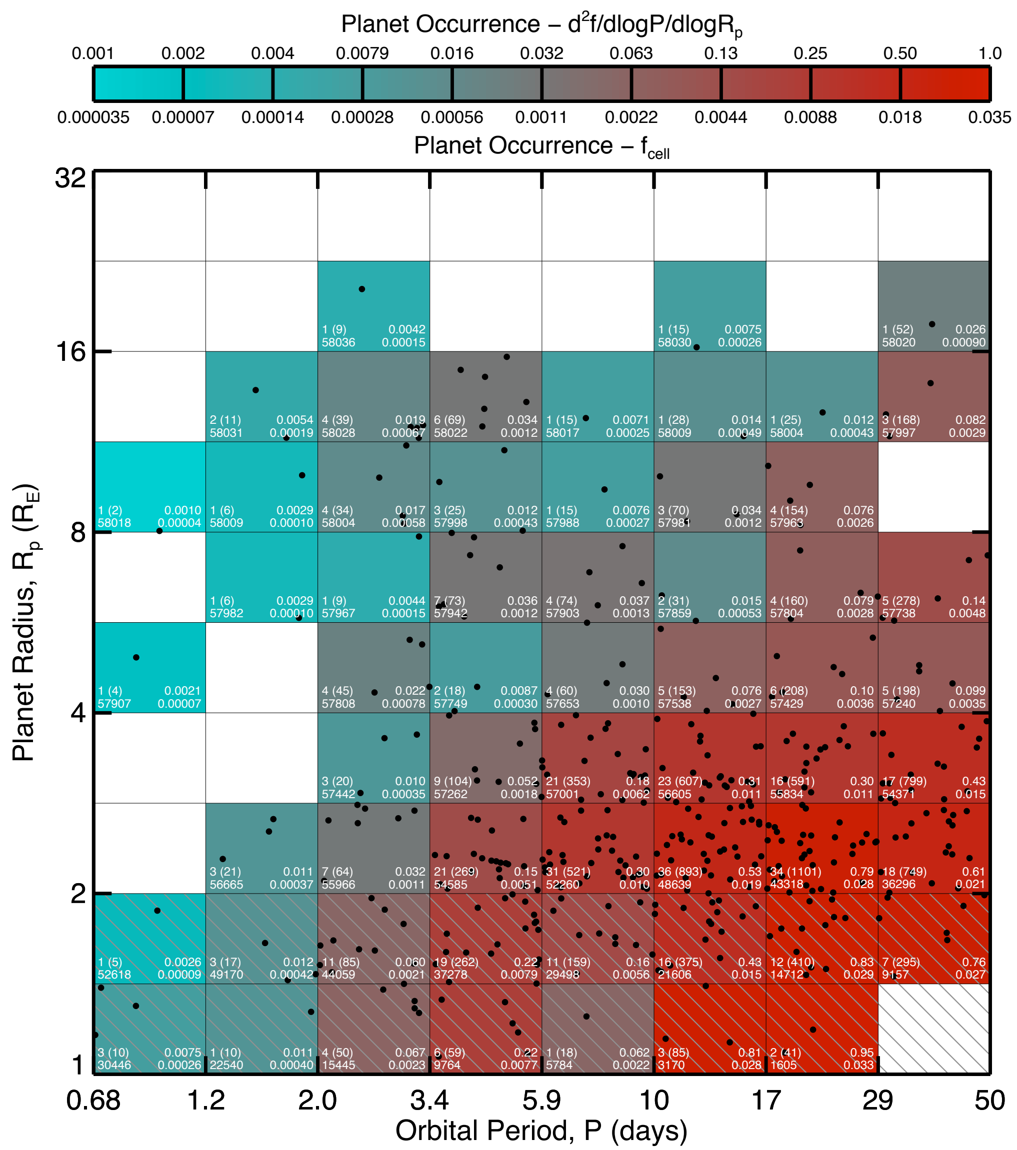


Mayor et al. 2011

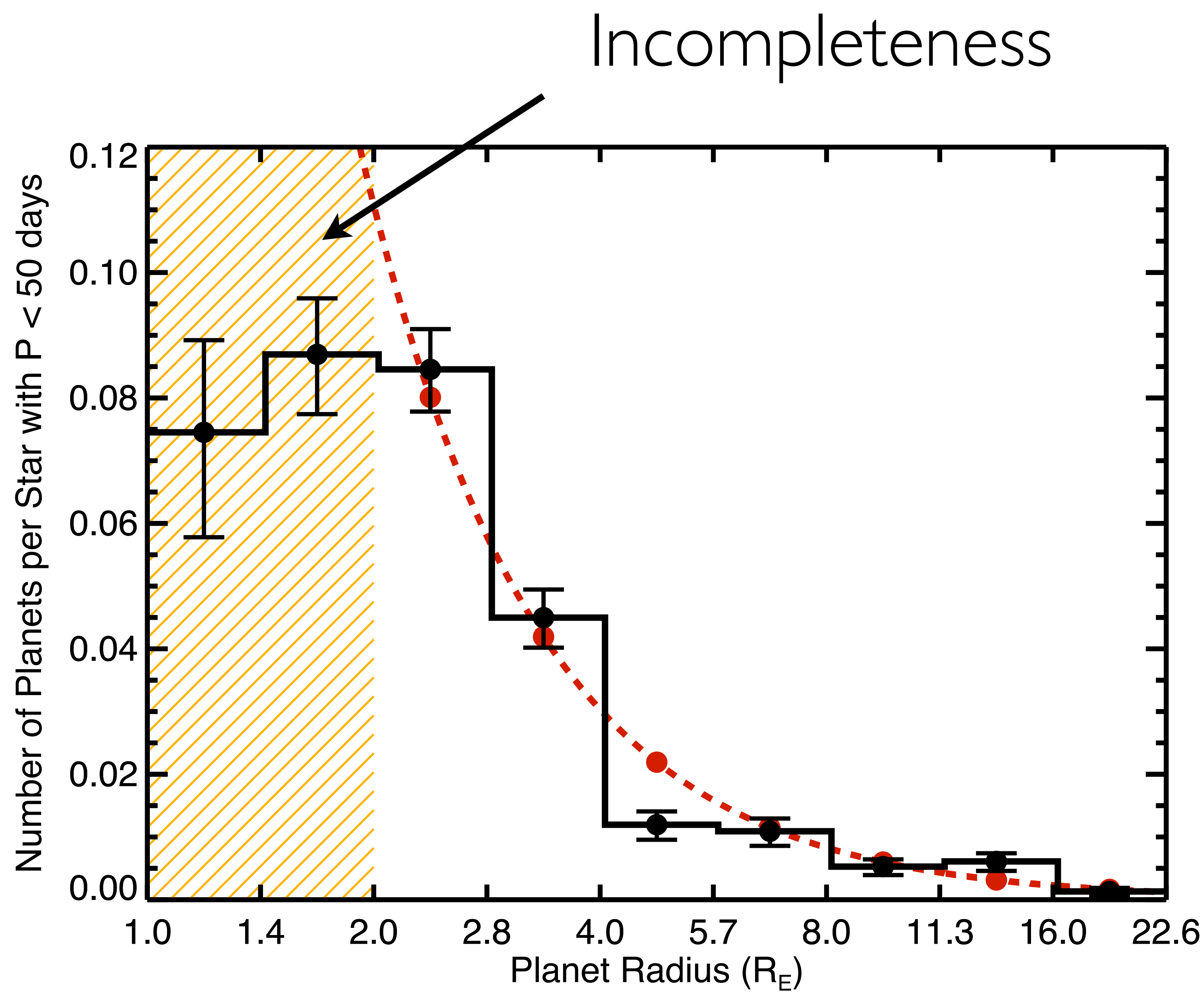
Mordasini et al. 2009

KEPLER: *Occurence and radii*

Howard et al. 2011

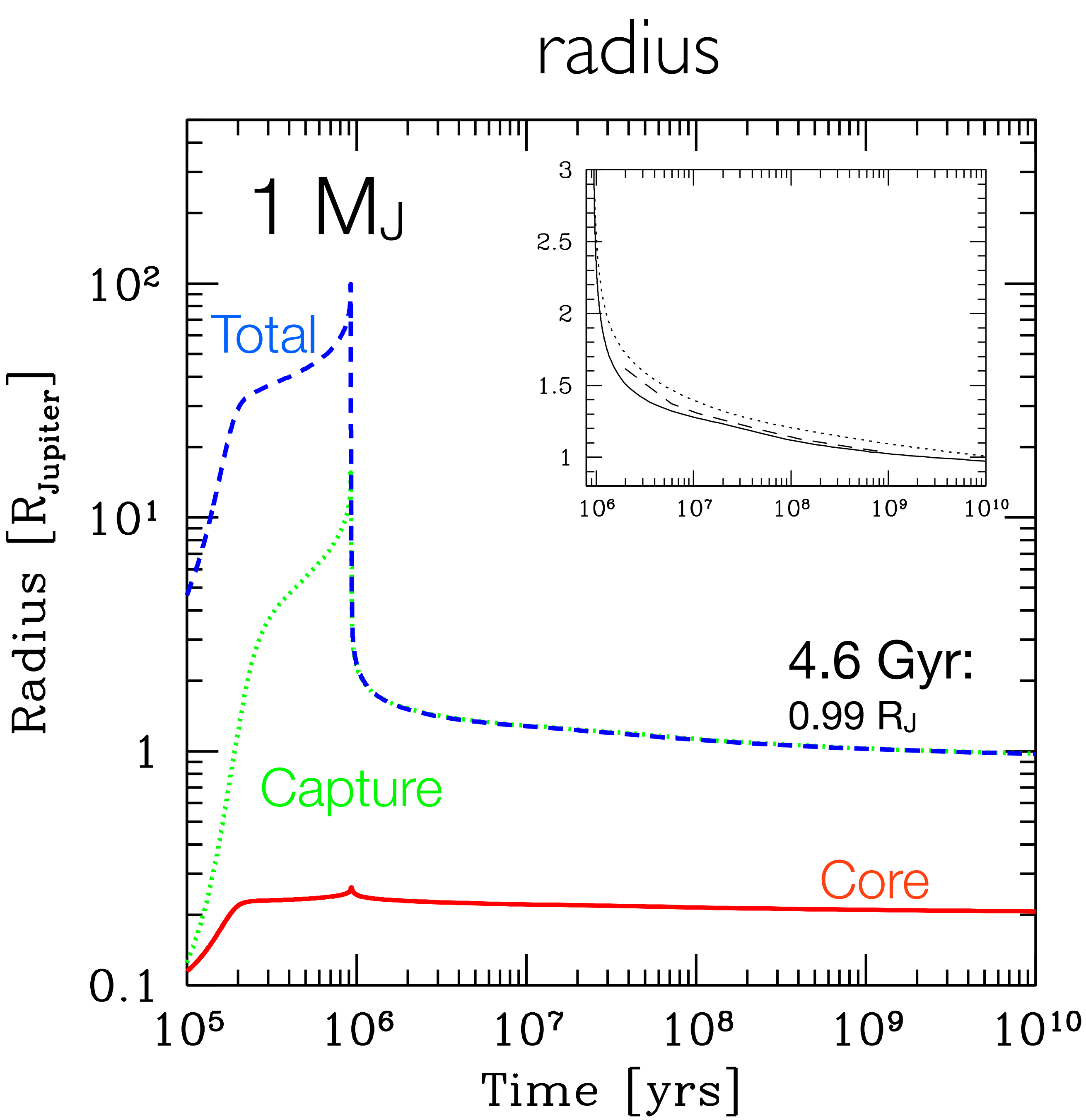


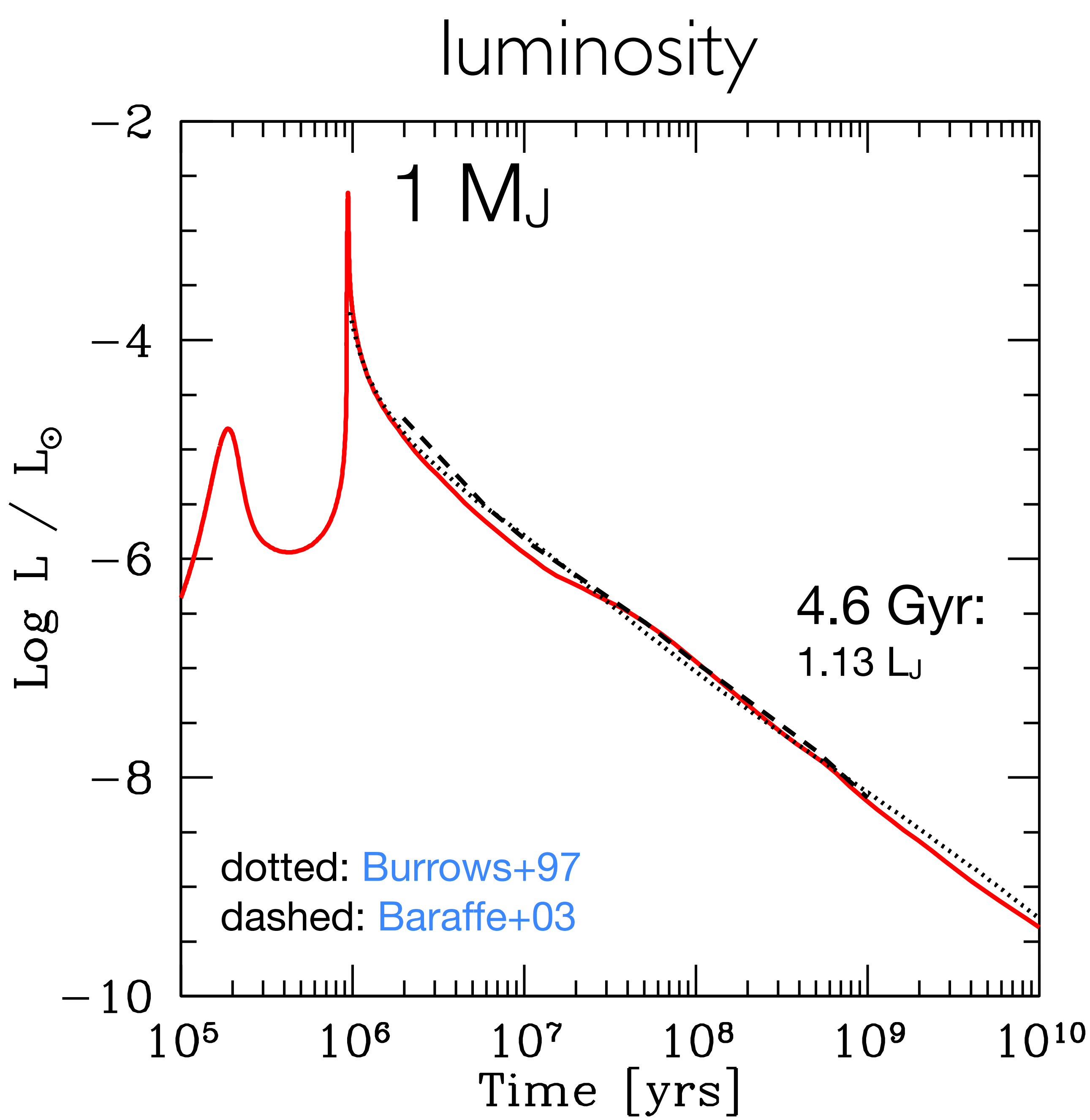
Planet occurence



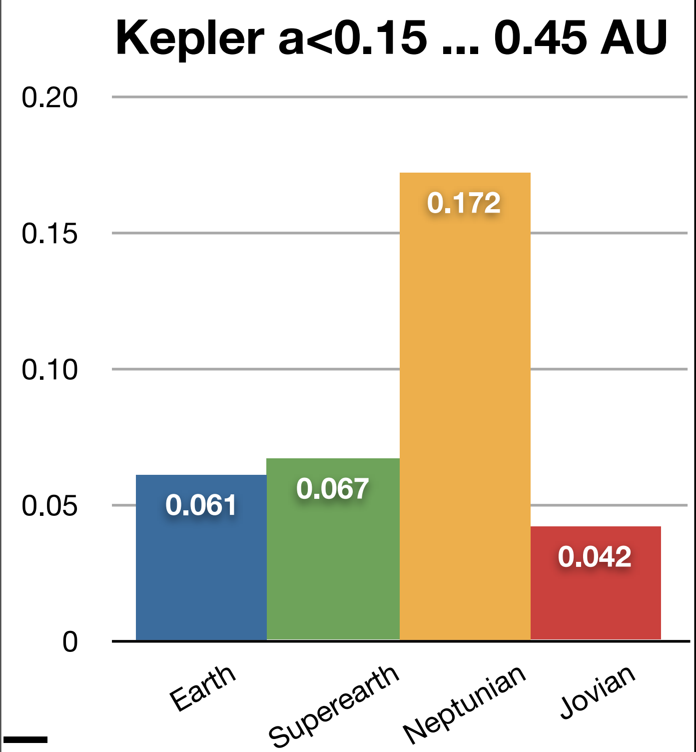
Distribution of radii

Long-term evolution

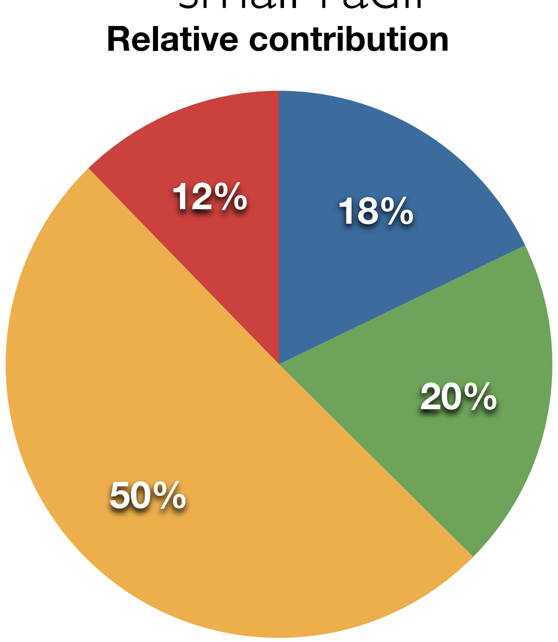




Comparison: Statistics of radii



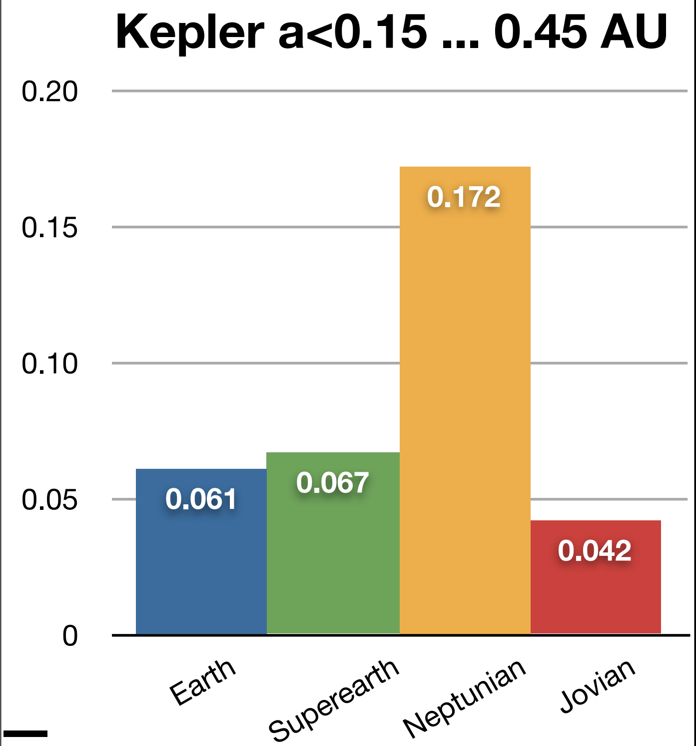
34 %
Incompleteness for small radii



Borucki et al. 2011

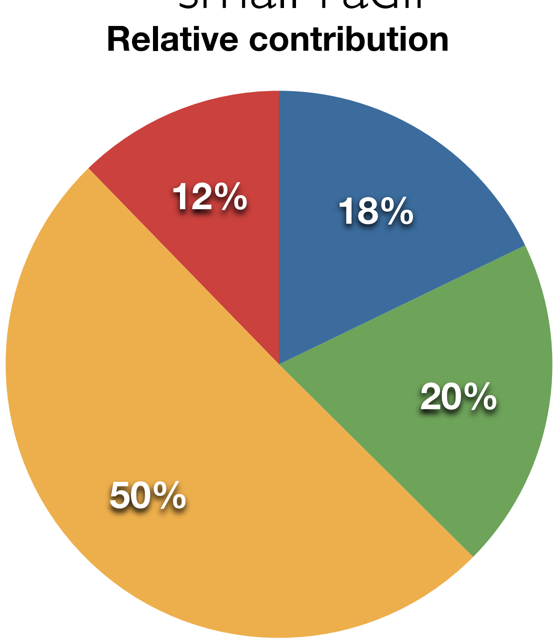
Earth <1.25 Re   Superearth 1.25-2 Re   Neptunian 2-6 Re   Jovian >6 Re

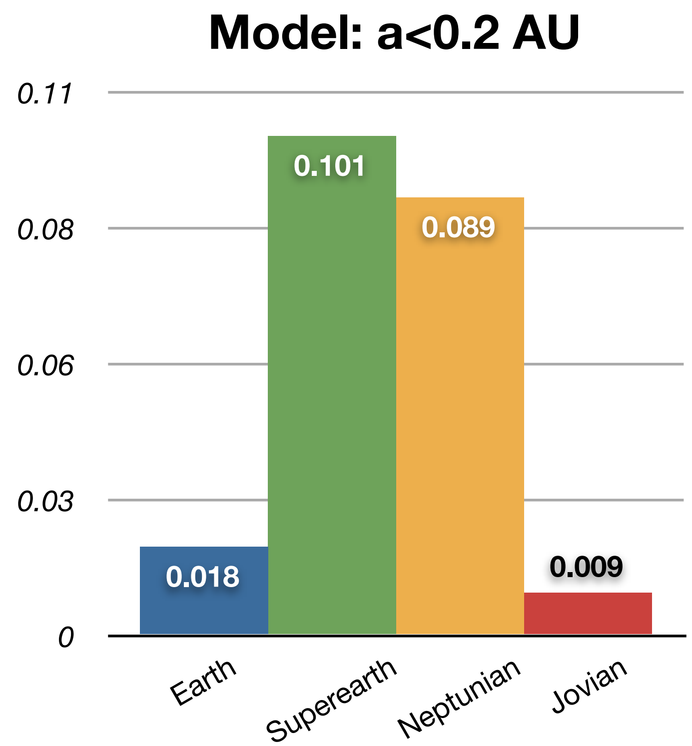
Comparison: *Statistics of radii*



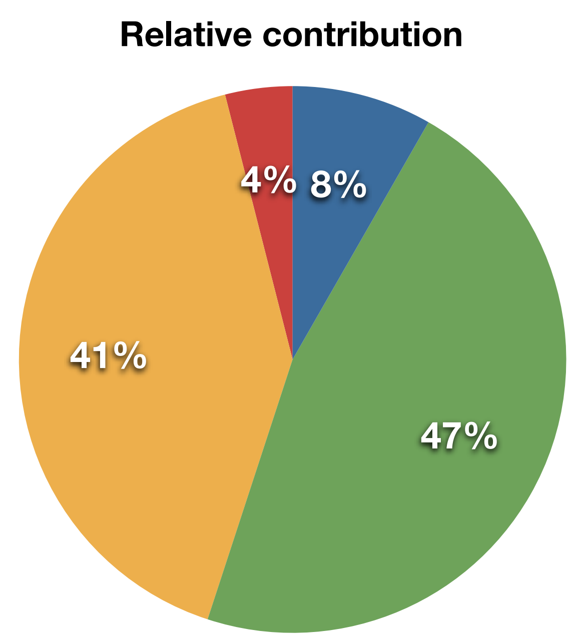
34 %

Incompleteness for small radii





22 %

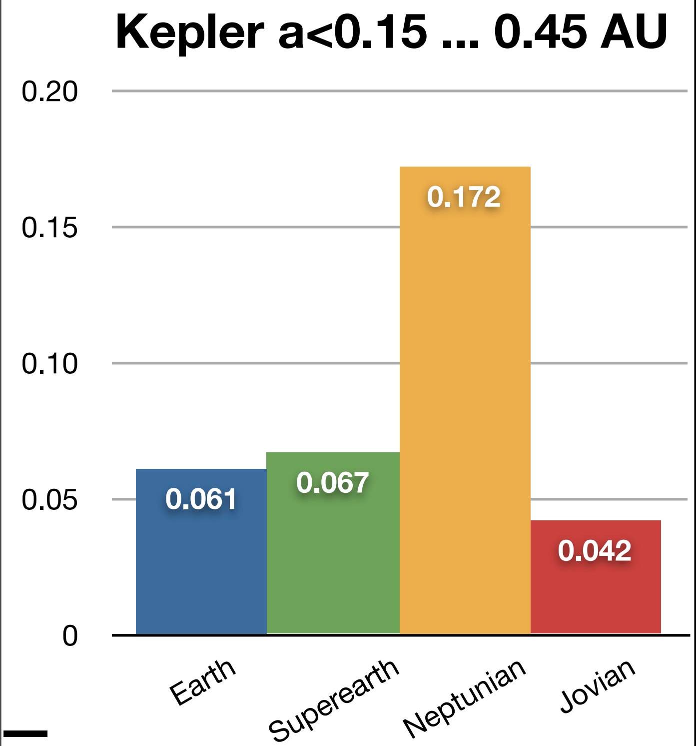


Borucki et al. 2011

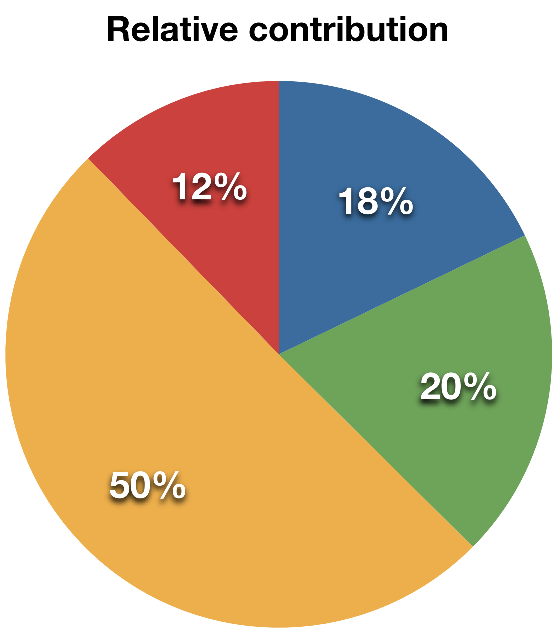
Earth <1.25 Re | Superearth 1.25-2 Re | Neptunian 2-6 Re | Jovian >6 Re

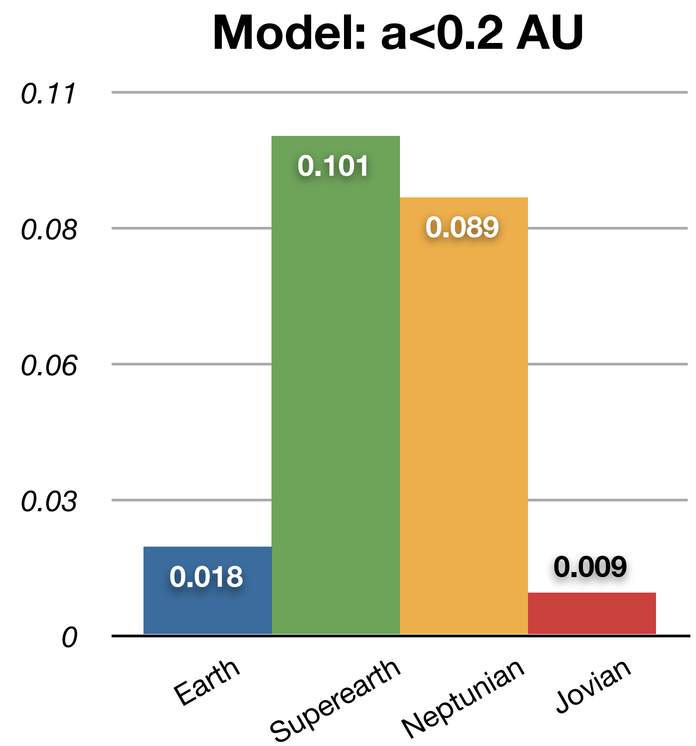
Comparison: Statistics of radii

Borucki et al. 2011

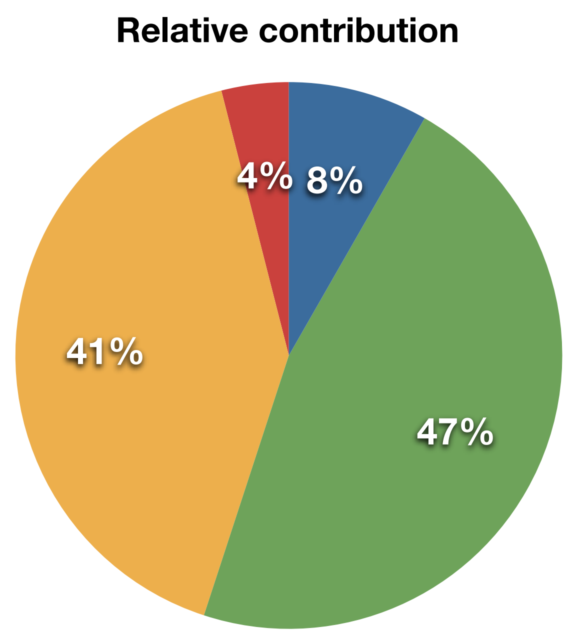


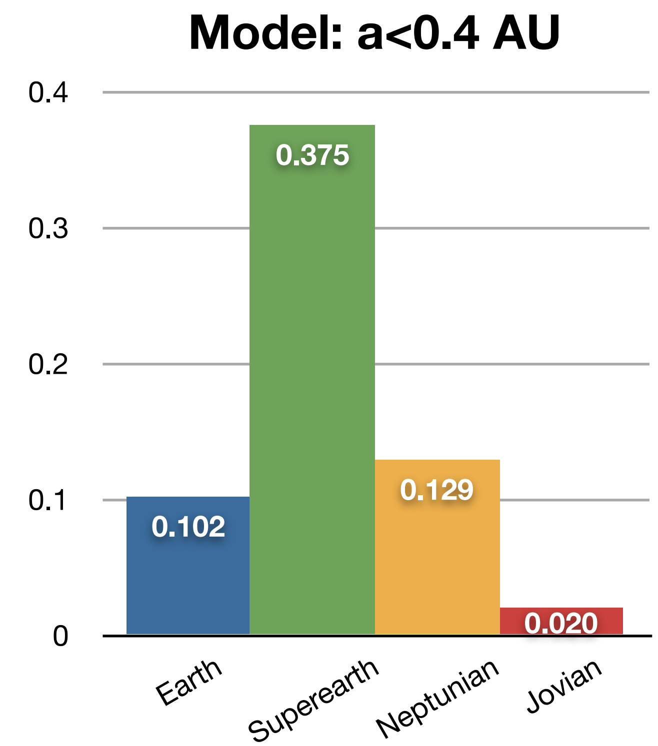
34 %
Incompleteness for small radii



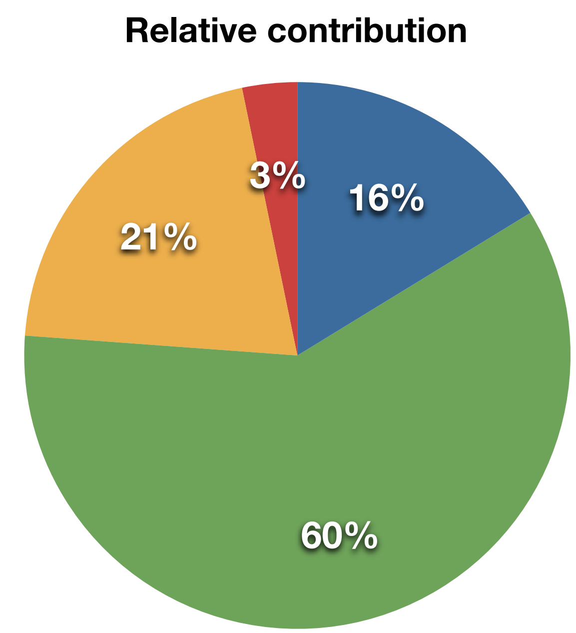


22 %





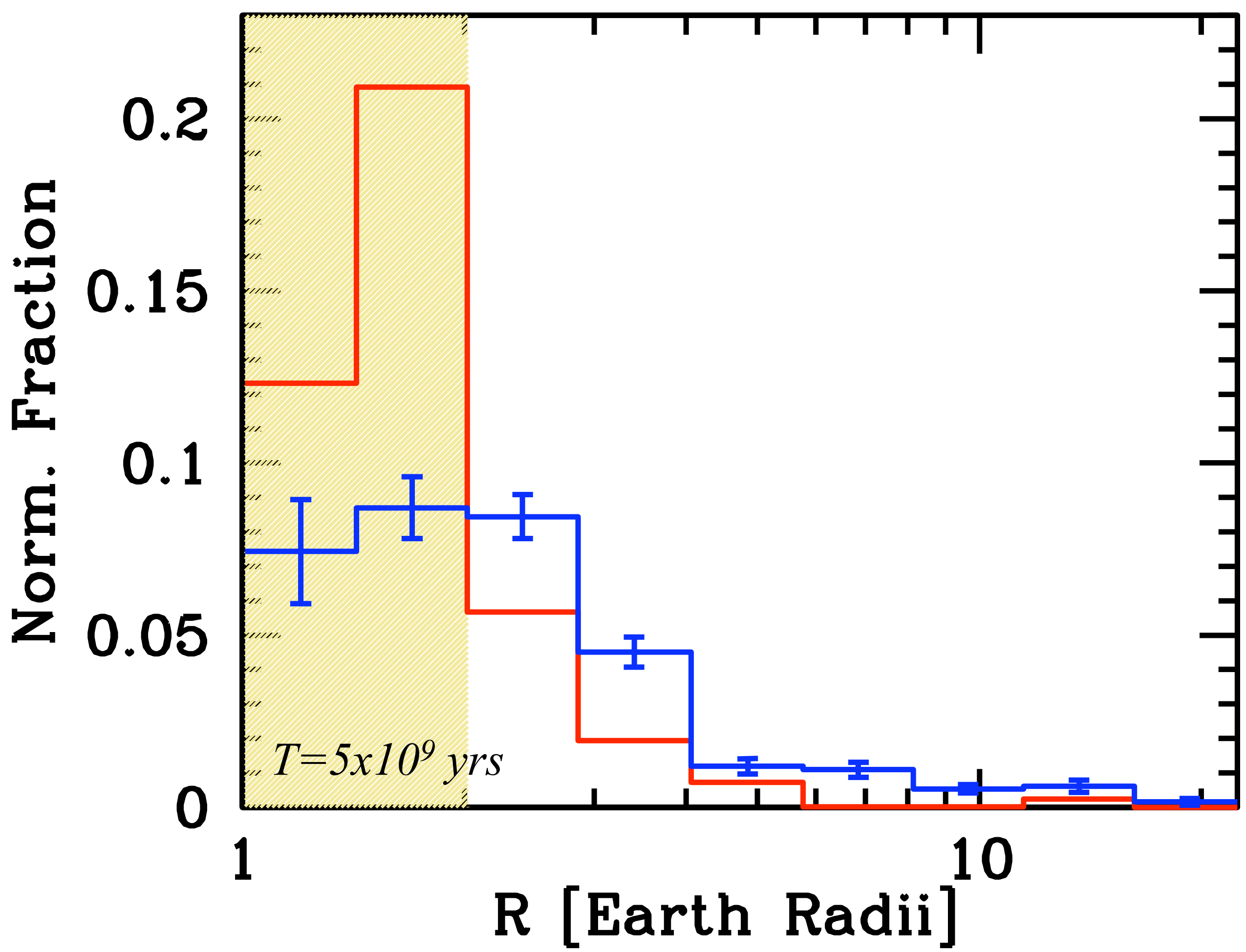
63 %



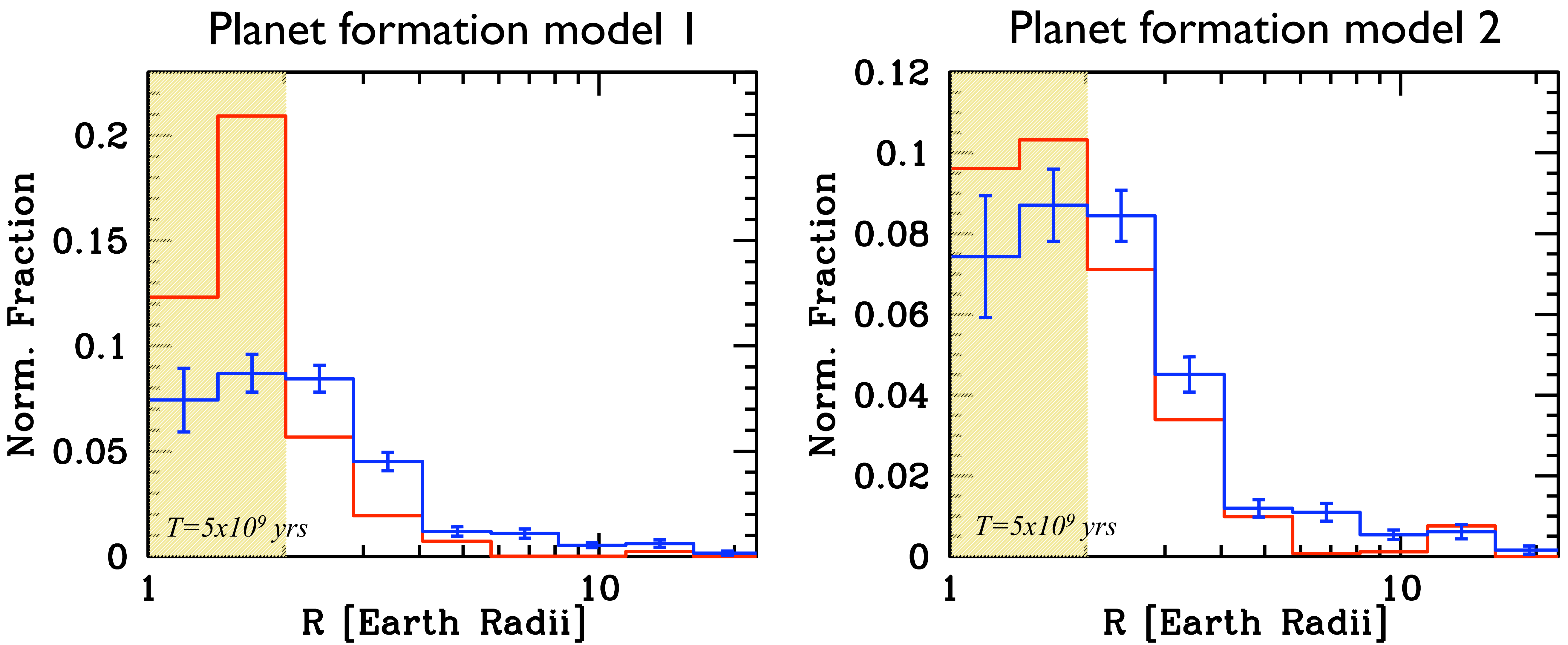
Earth <1.25 Re   Superearth 1.25-2 Re   Neptunian 2-6 Re   Jovian >6 Re

Radii statistics

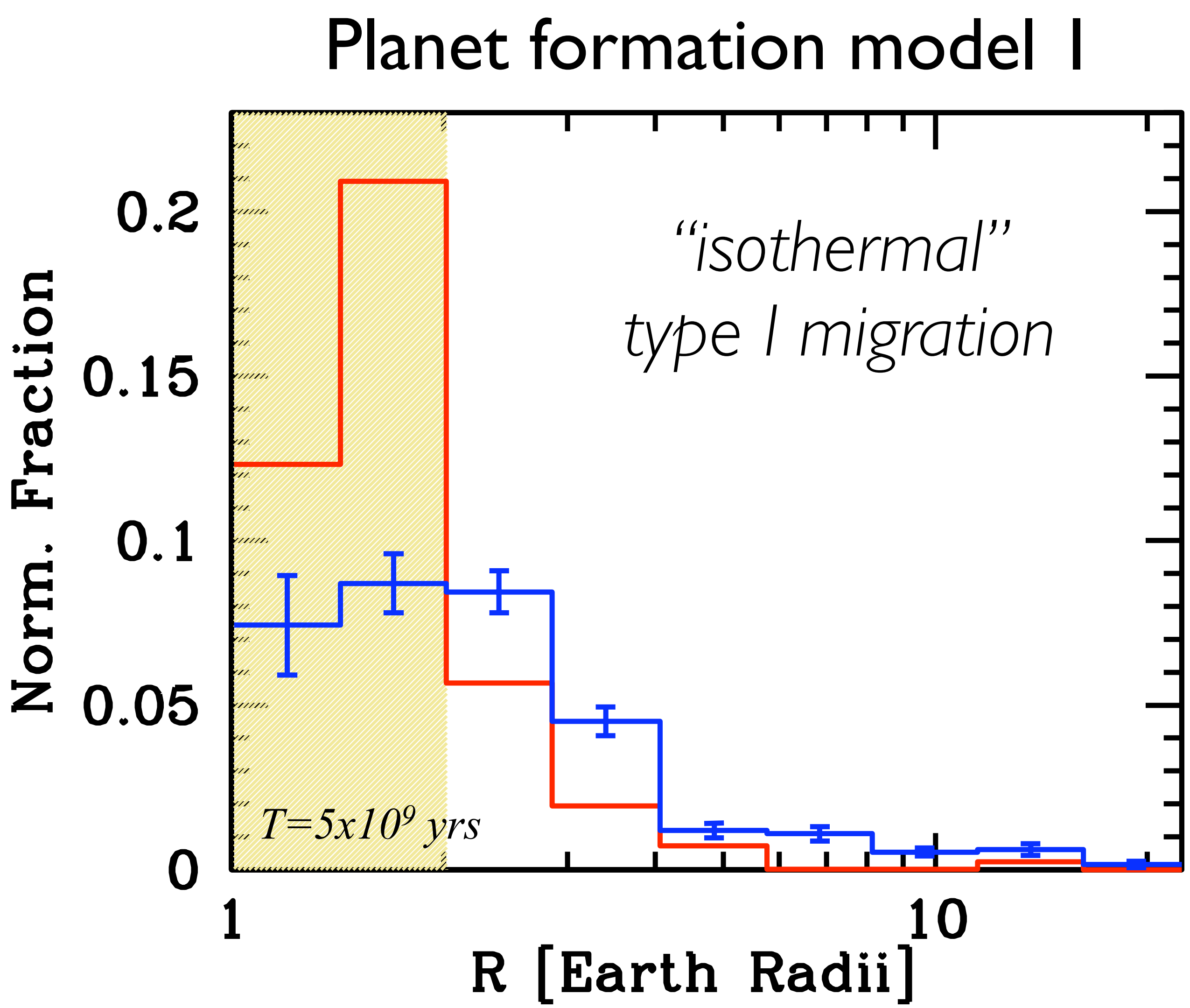
Planet formation model 1

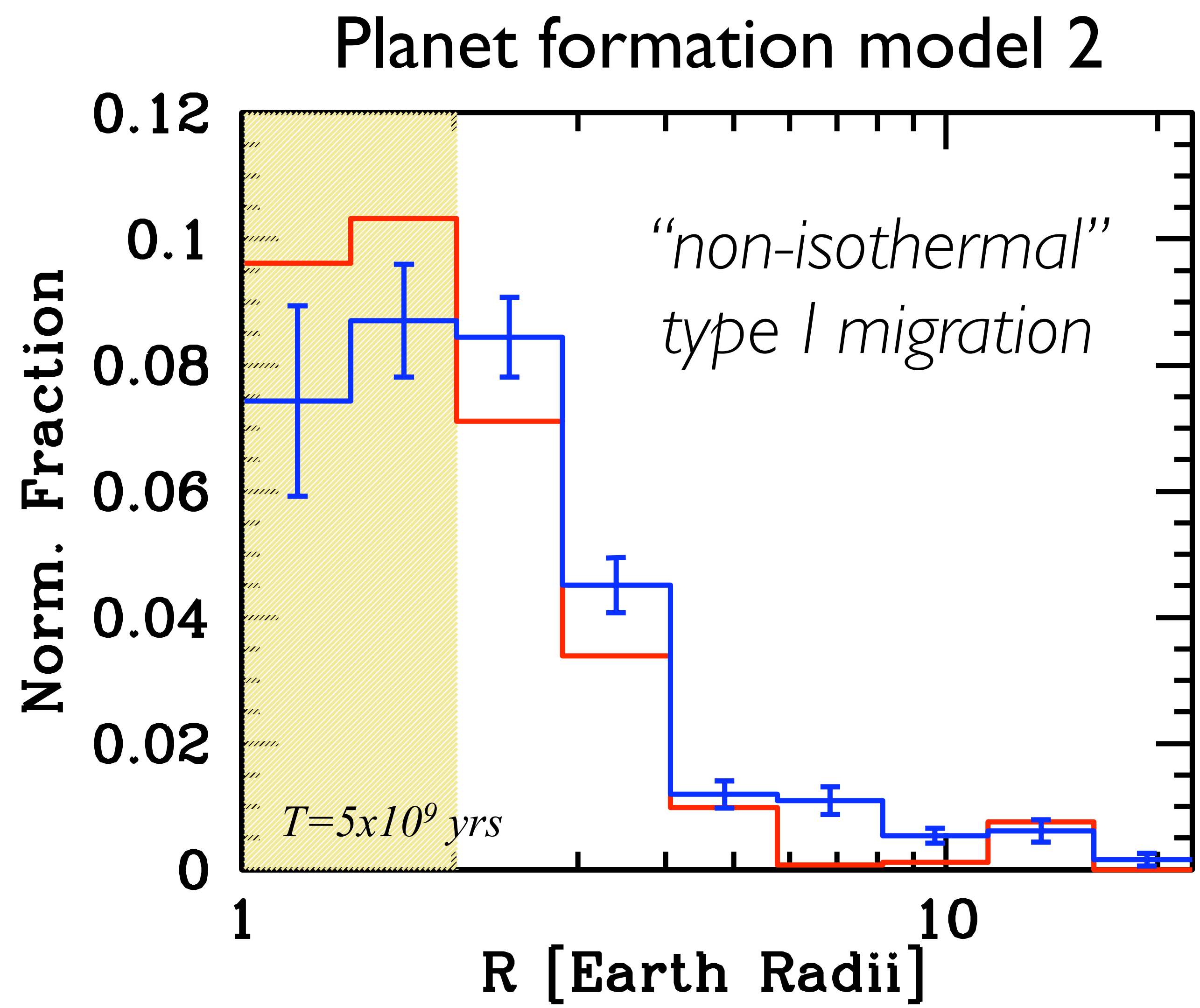


Radii statistics

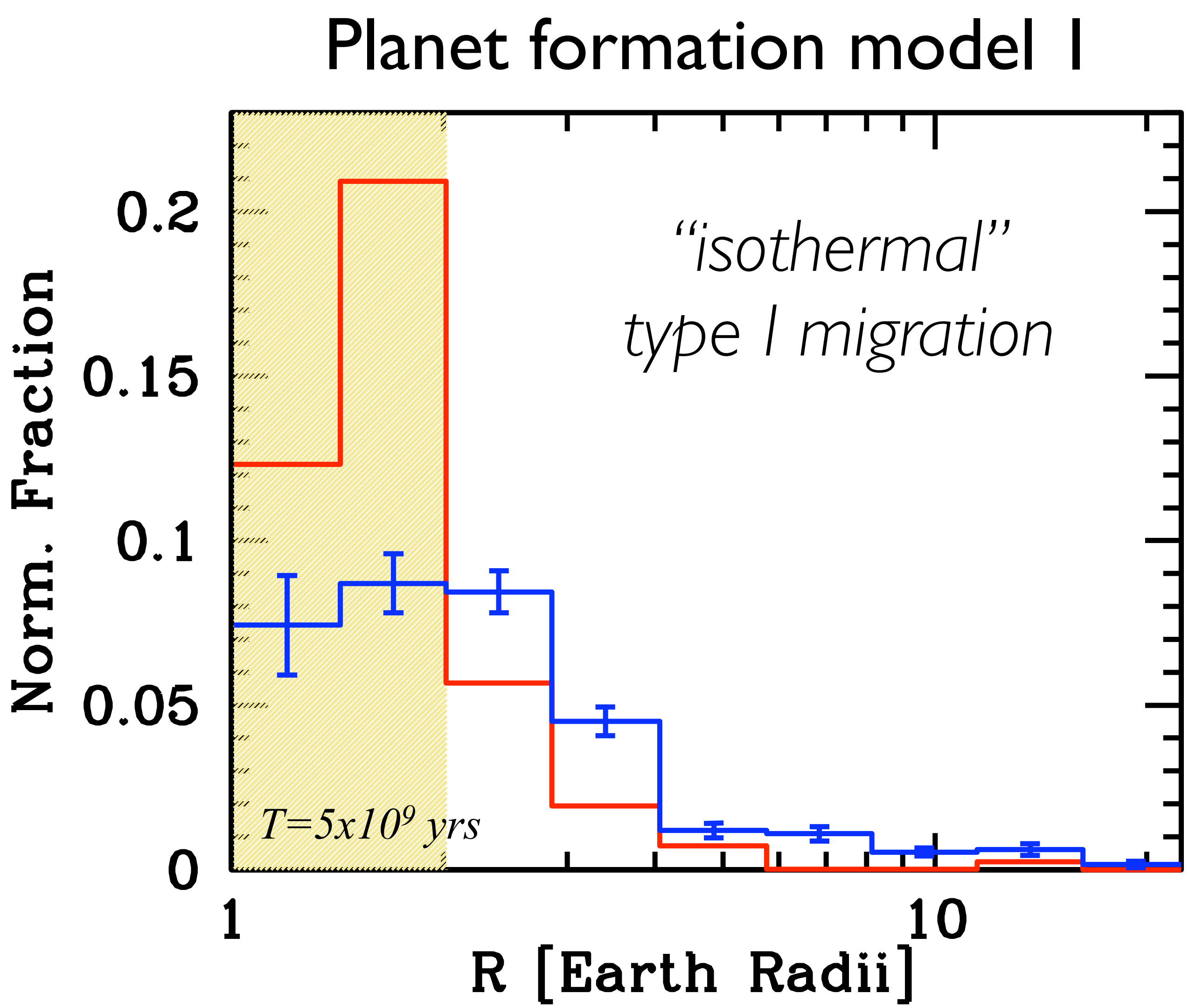


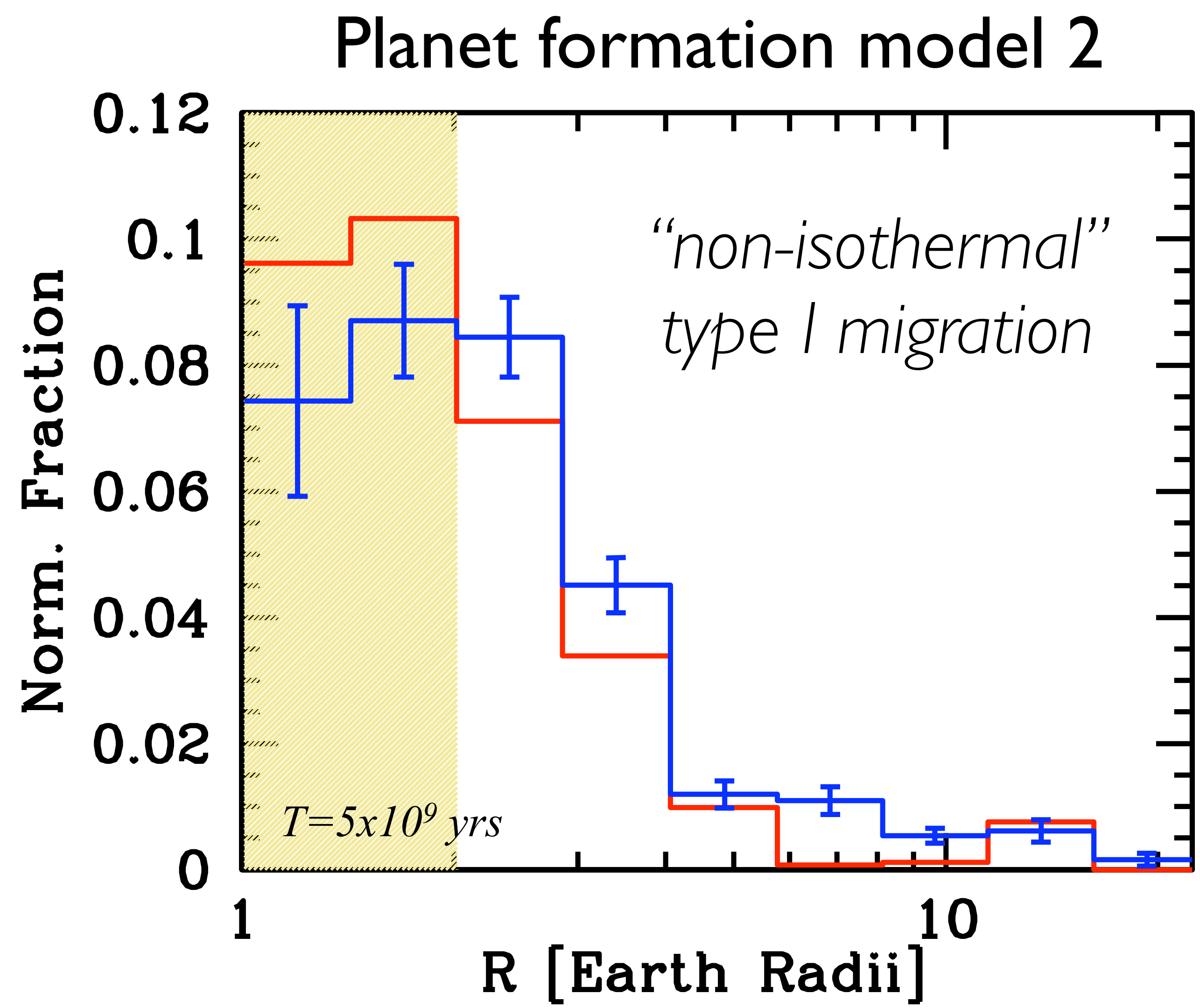
Radii statistics





Radii statistics





Statistical comparisons between observations and models allow to pinpoint the importance of certain physical processes...

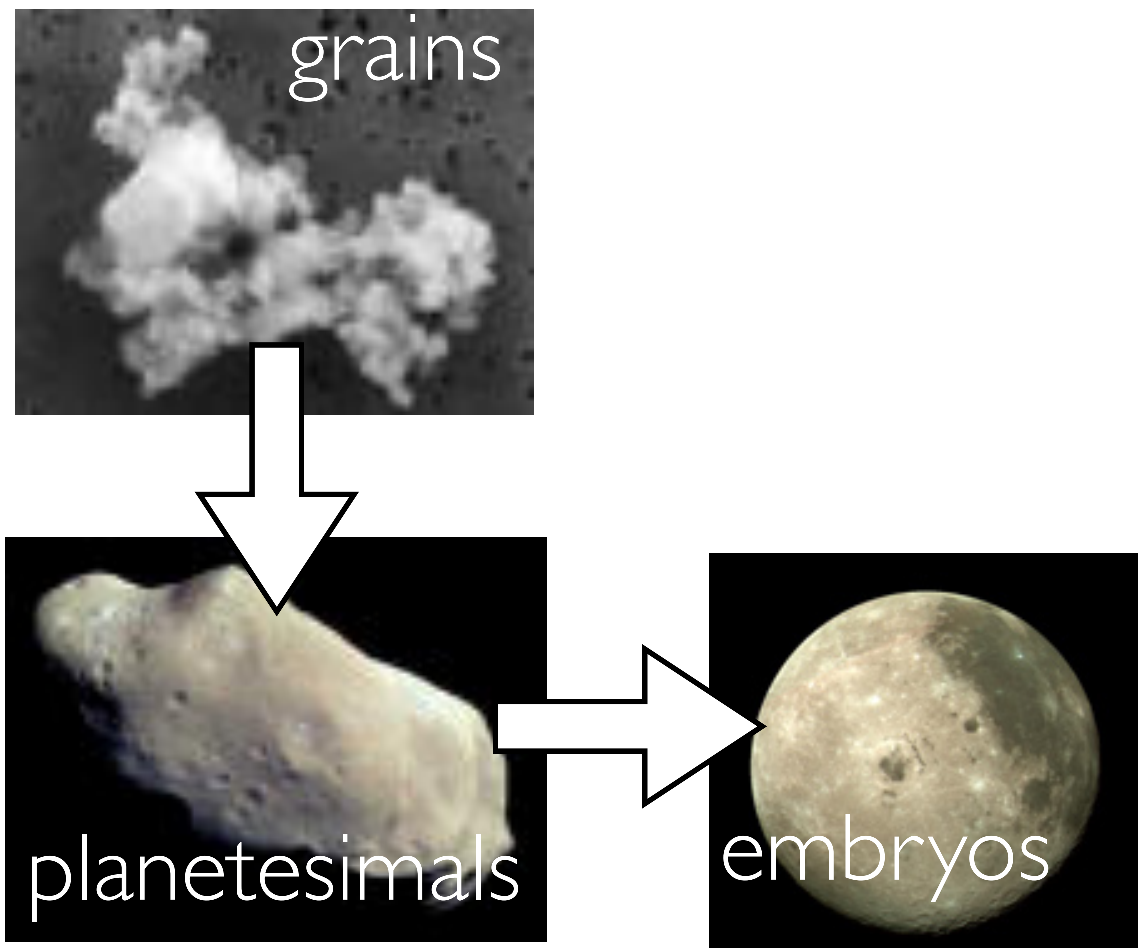
Planet Formation

in presence of gas

in absence of gas

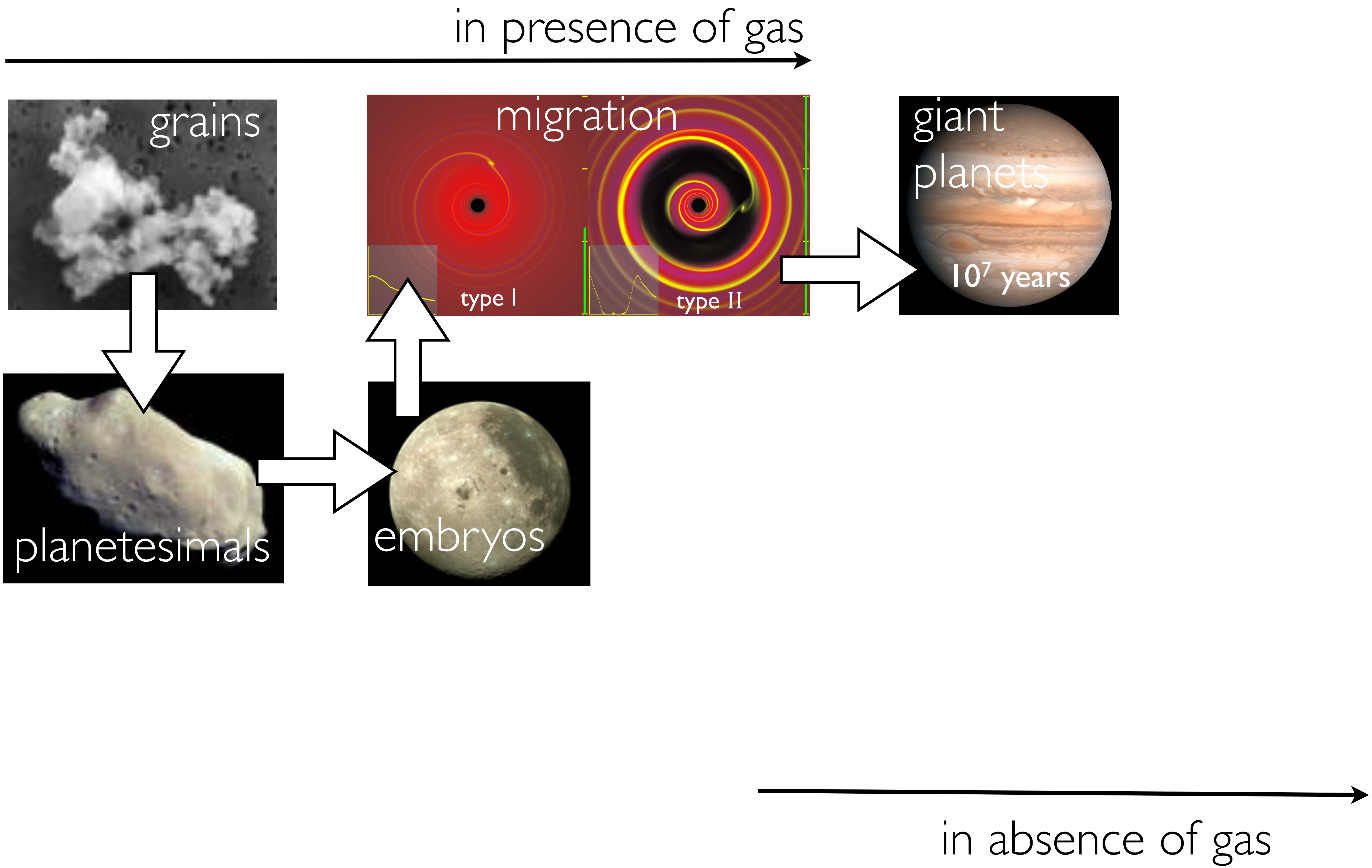
Planet Formation

in presence of gas

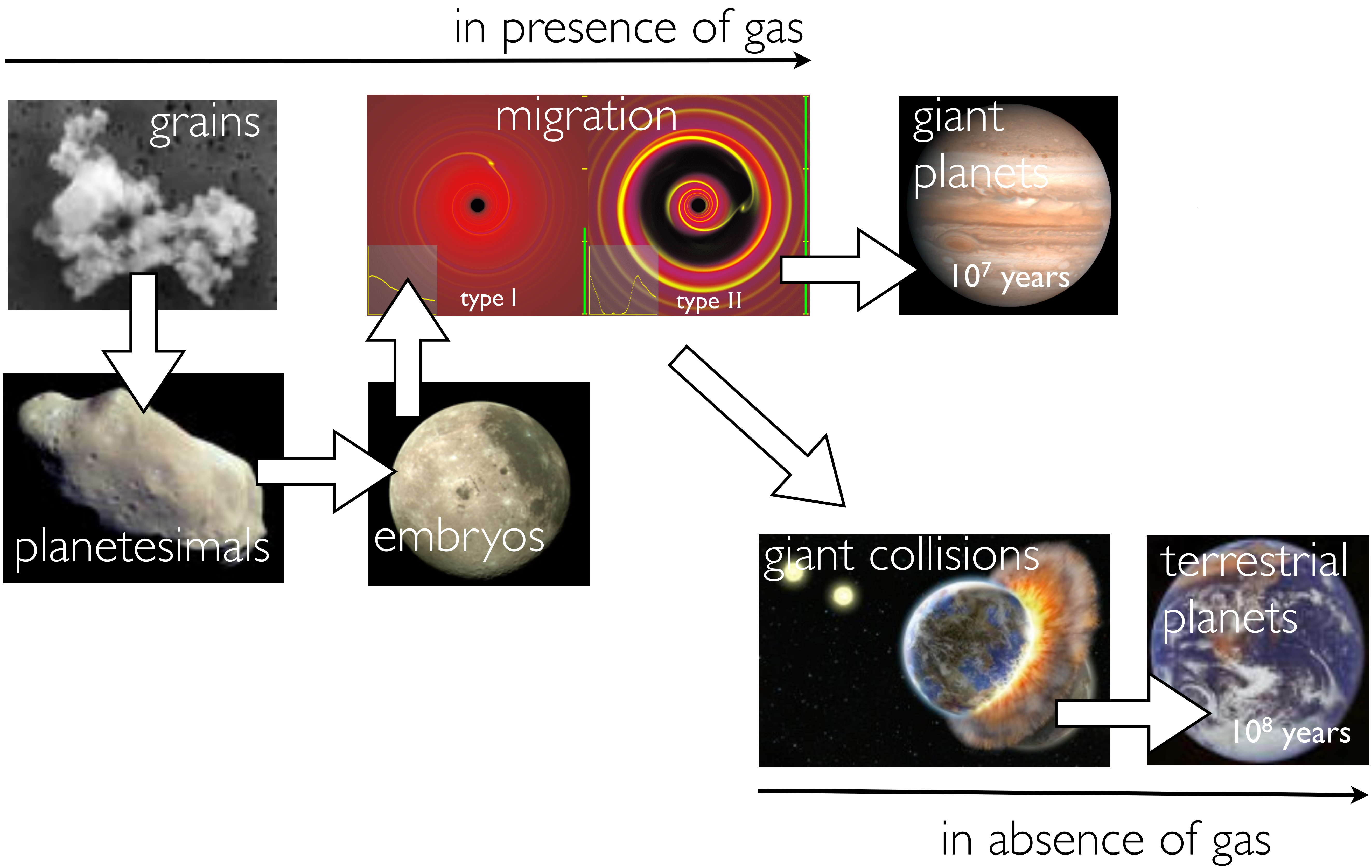


in absence of gas

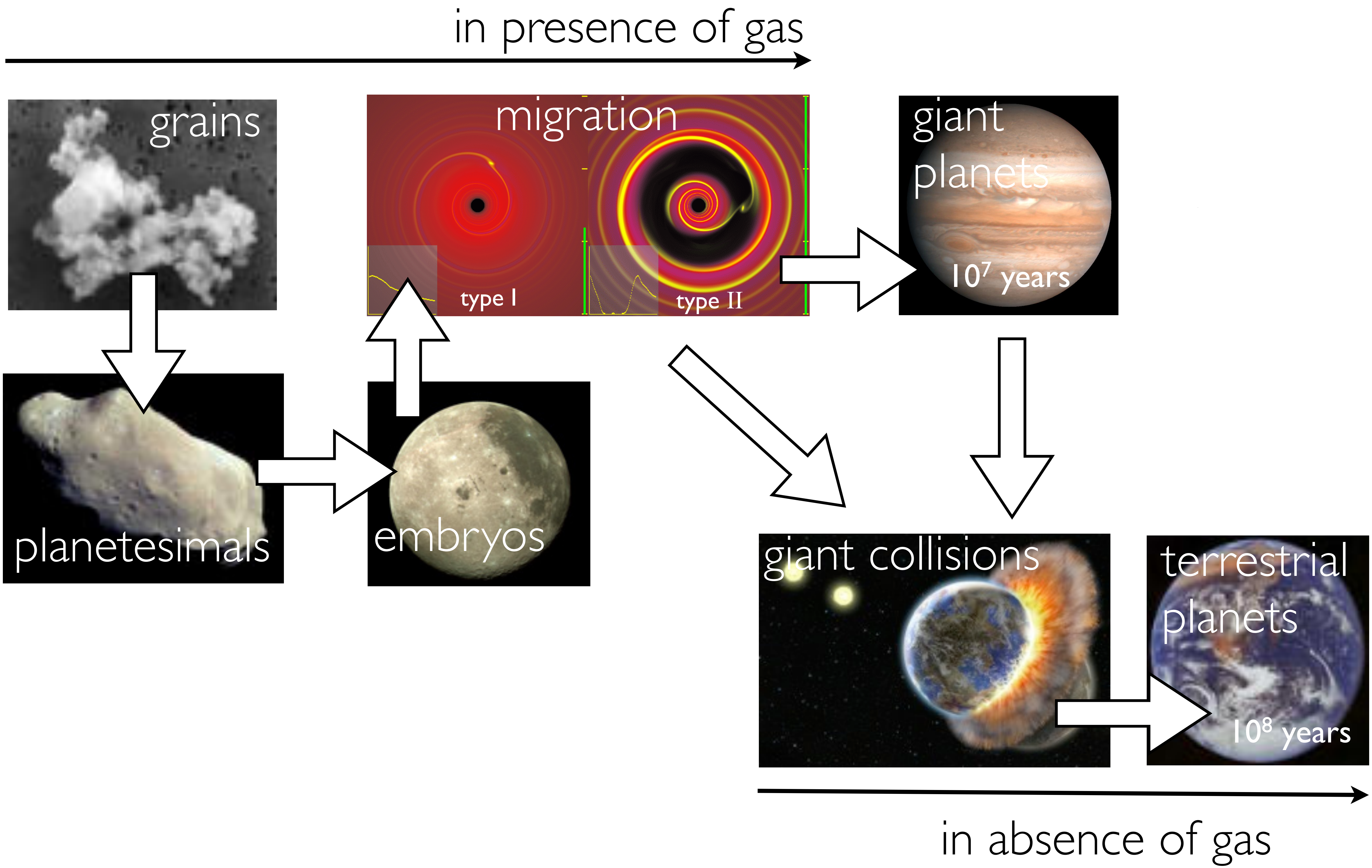
Planet Formation



Planet Formation

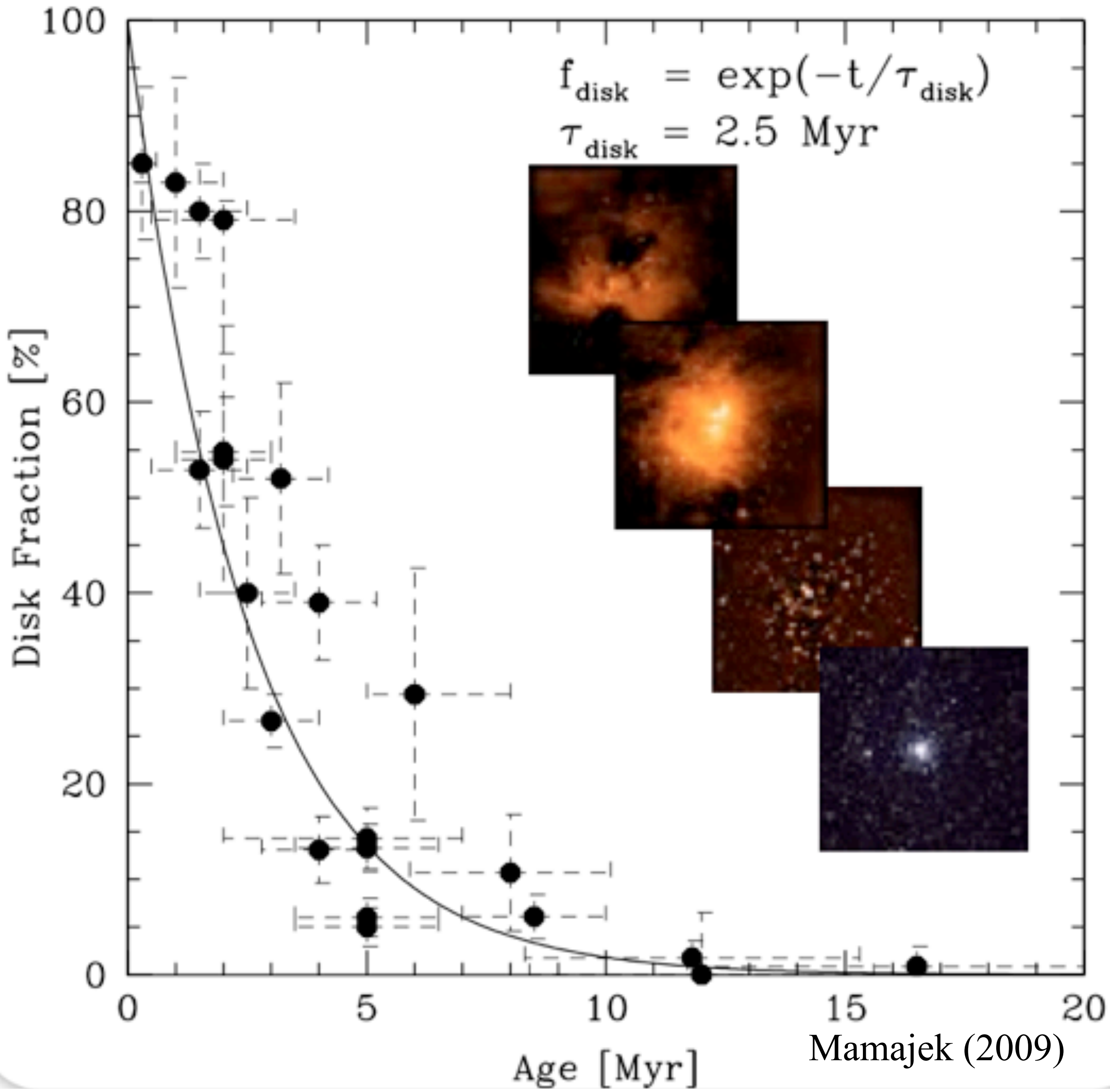


Planet Formation



Disk *lifetimes*

The distribution of disk lifetimes can be obtained by determining the fraction of stars in nearby young stellar clusters that still show the presence of a disk through IR excess.



Mamajek (2009)

The lifetime of proto-planetary disks is of order a few million years

This is the time available to form gaseous planets and to move them around...

Planet-disk interactions

Planet - disk interactions

surface density   Simulations by P. Armitage

Note:

- planet generates non-axisymmetric potential
- this potential generates density waves
- density waves result in torques on planet
- torques change angular momentum

Small mass planets: No gap

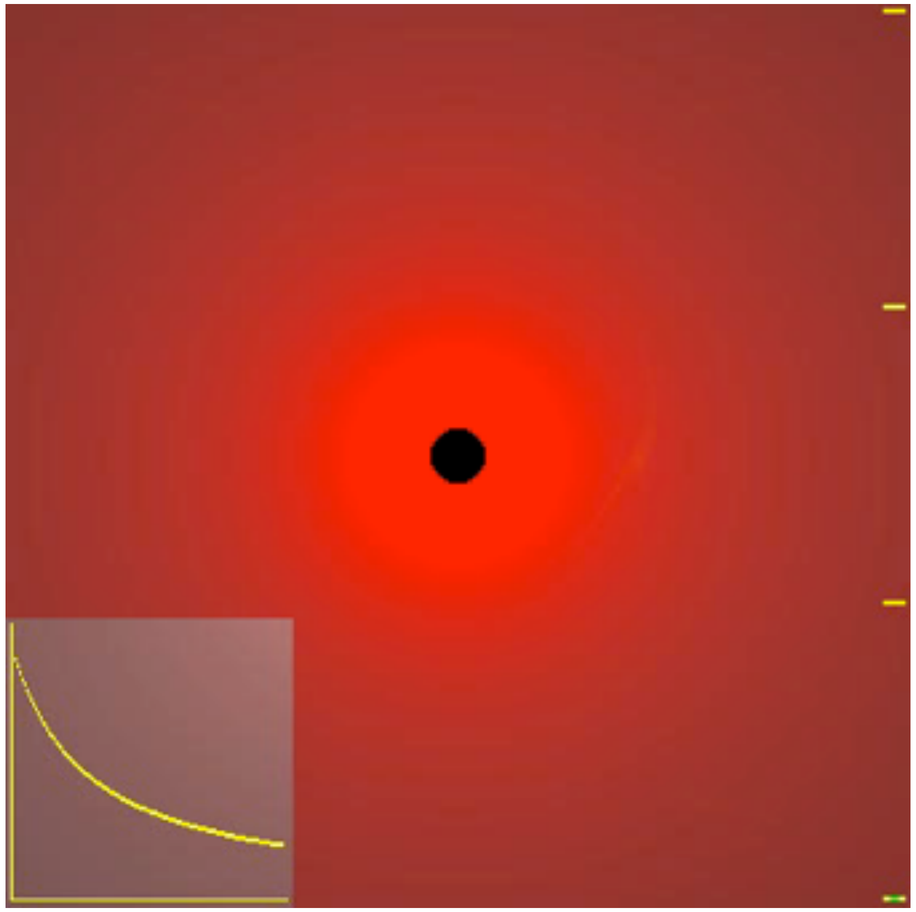
→ type I migration

Massive planets: Gap

→ type II migration

Planet-disk *interactions*

Planet - disk interactions



surface density   Simulations by P. Armitage

Note:

- planet generates non-axisymmetric potential
- this potential generates density waves
- density waves result in torques on planet
- torques change angular momentum

Small mass planets: No gap

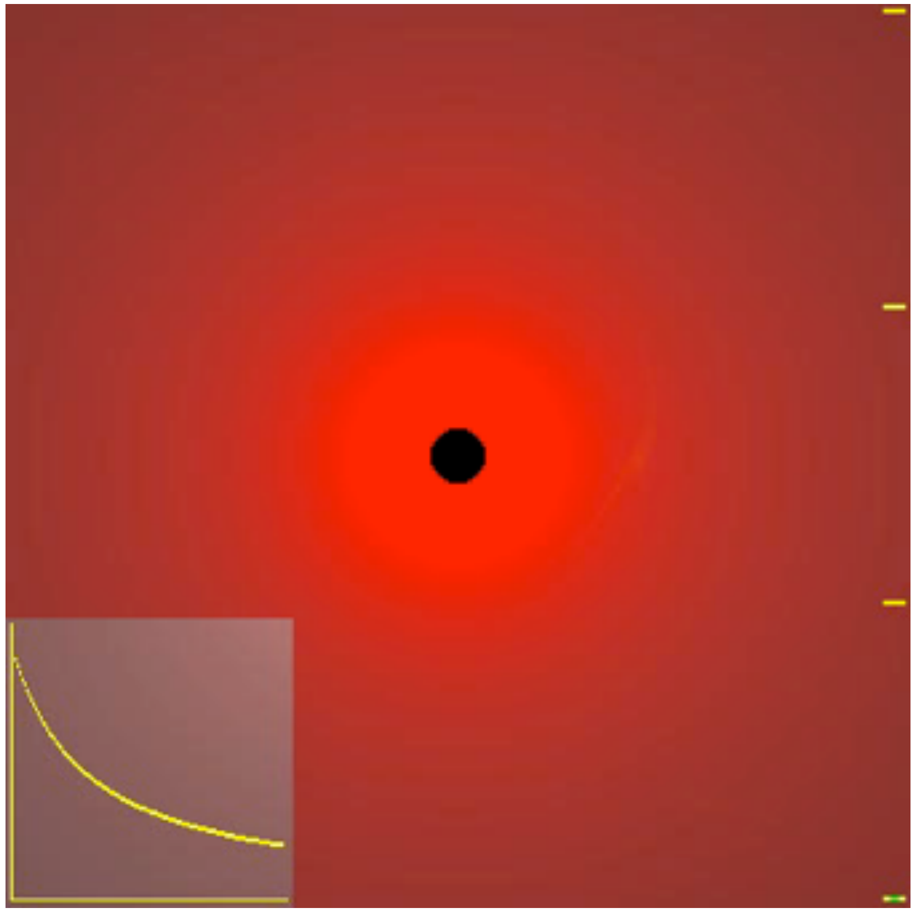
→ type I migration

Massive planets: Gap

→ type II migration

Planet-disk *interactions*

Planet - disk interactions



Simulations by P. Armitage

Note:

- planet generates non-axisymmetric potential
- this potential generates density waves
- density waves result in torques on planet
- torques change angular momentum

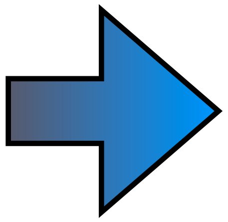
Small mass planets: No gap

→ type I migration

Massive planets: Gap

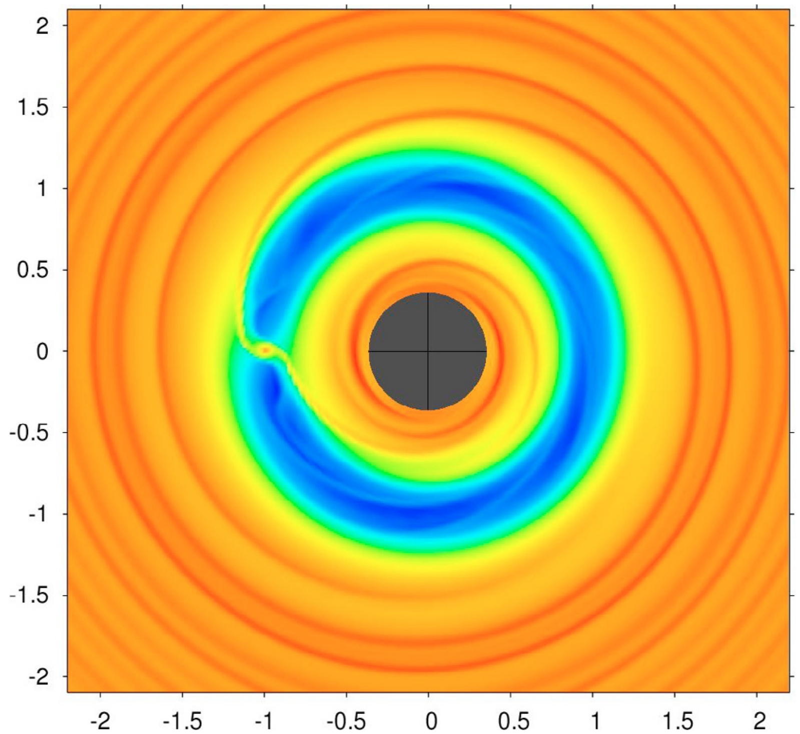
→ type II migration

Large scale signature of planet-disk interactions

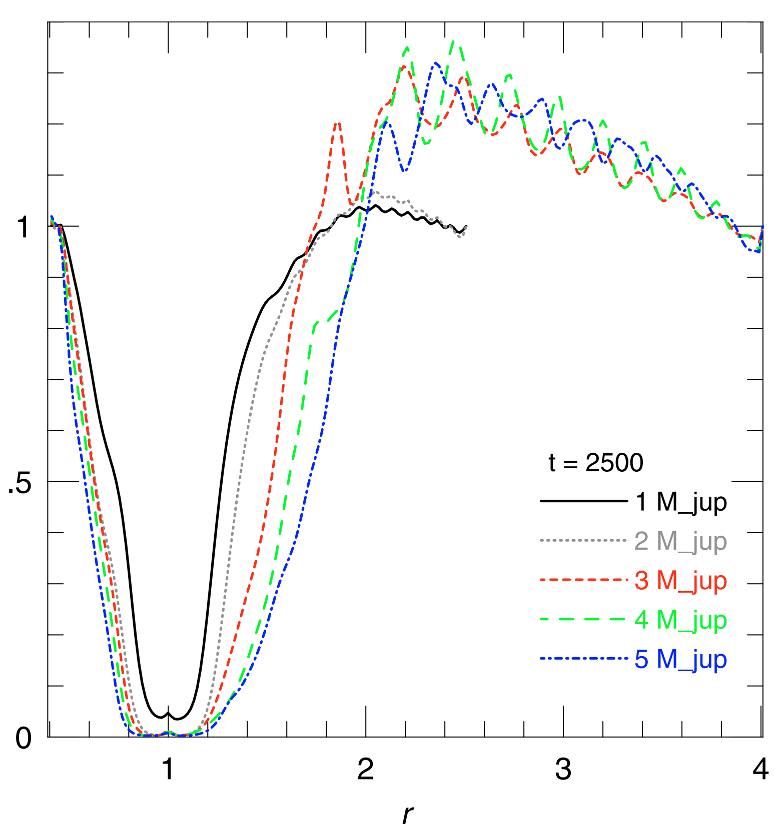


observationally testable!

Gap formation: Type II migration



Kley & Dirksen 2006



Crida et al. 2006

Transition to type II: opening of gap

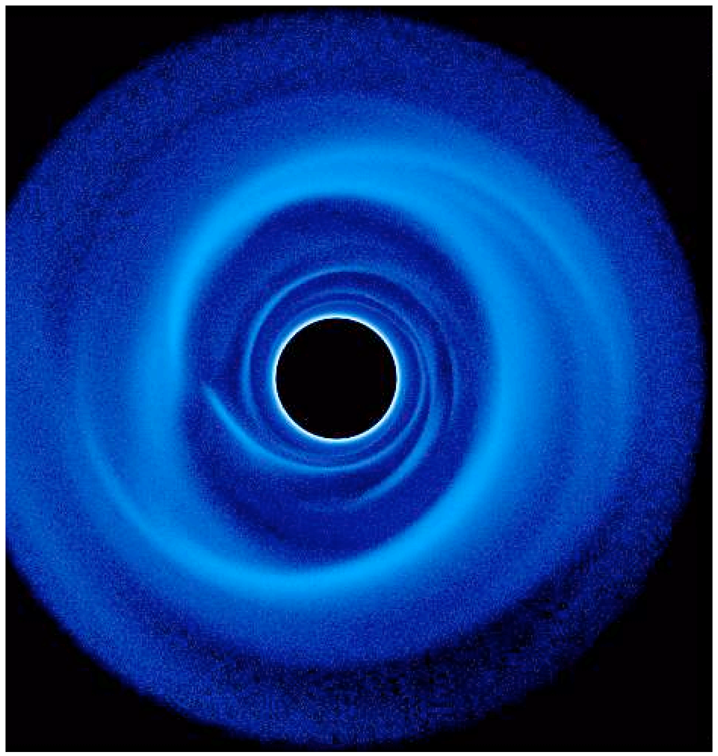
$$\frac{3}{4}\frac{H}{R_{\mathrm{H}}} + \frac{50}{q\mathcal{R}} \lesssim 1$$

Gap opening citerion is a function of:

- mass of star and planet
- structure of disk
- viscous transport

observationally testable!

Wolf & Klahr 2008



Planet migration

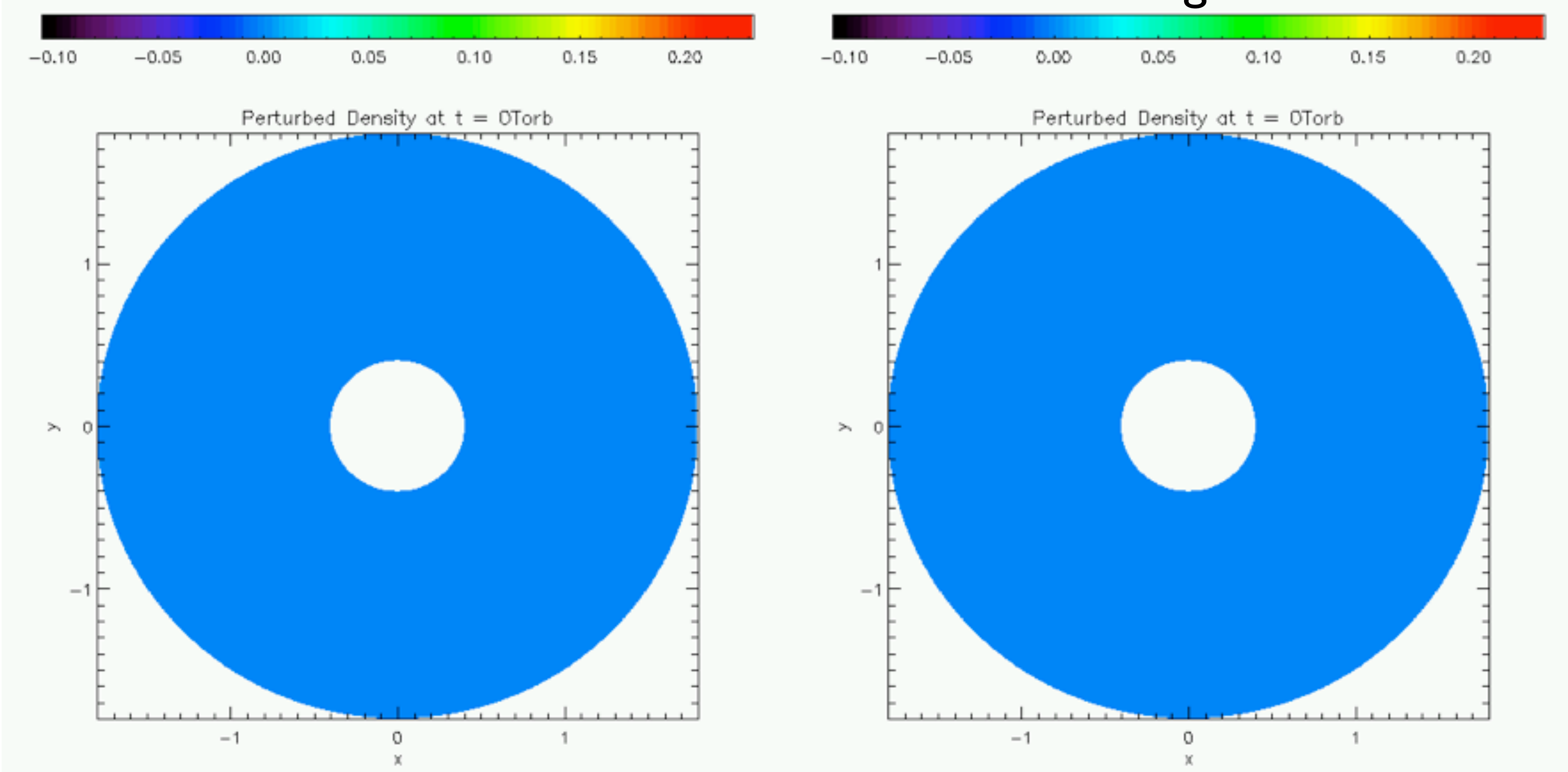
inertial frame

rotating frame

Simulations by C. Baruteau

Planet migration

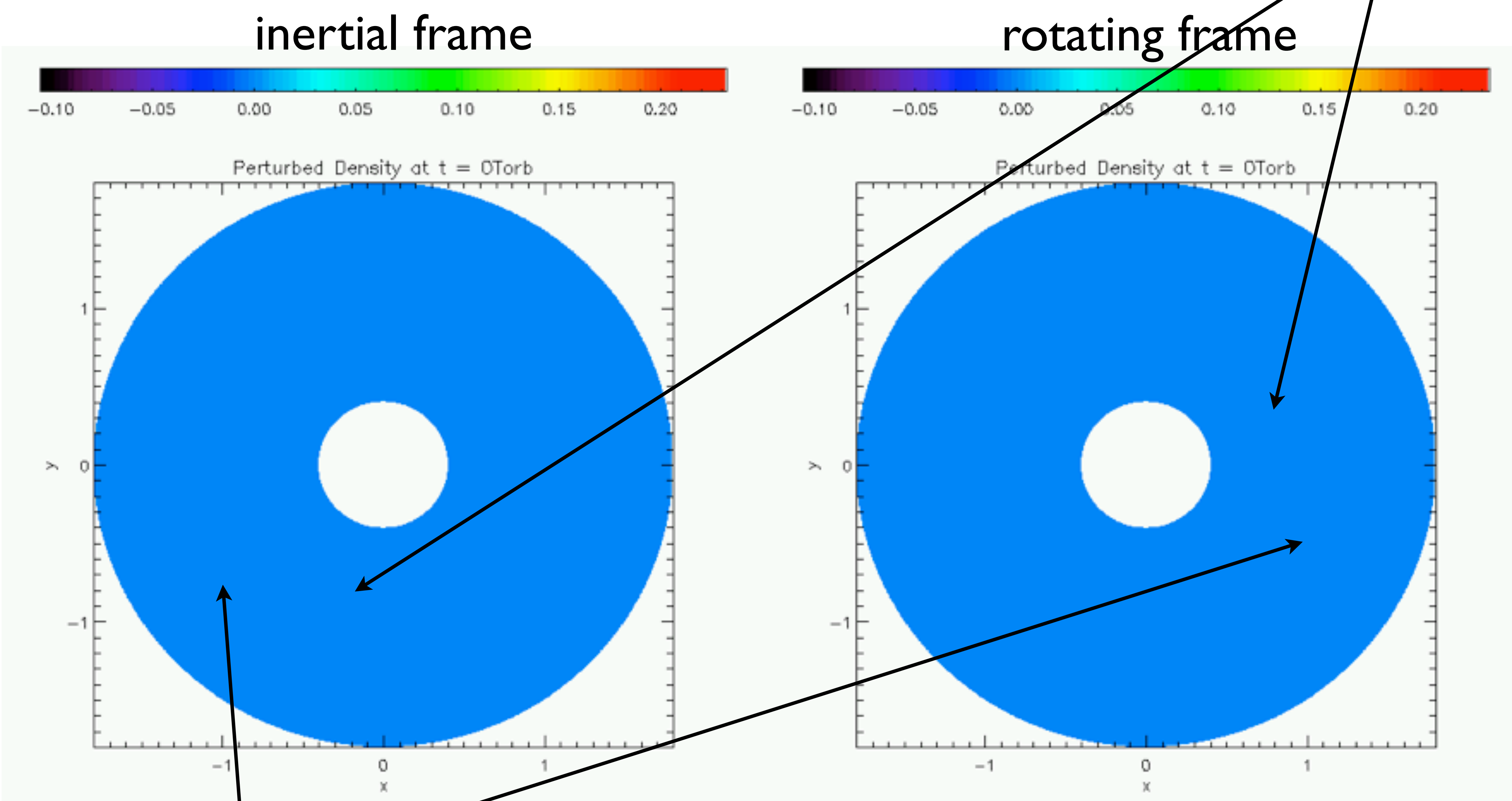
inertial frame rotating frame



Simulations by C. Baruteau

Planet migration

forward pull: Outwards migration

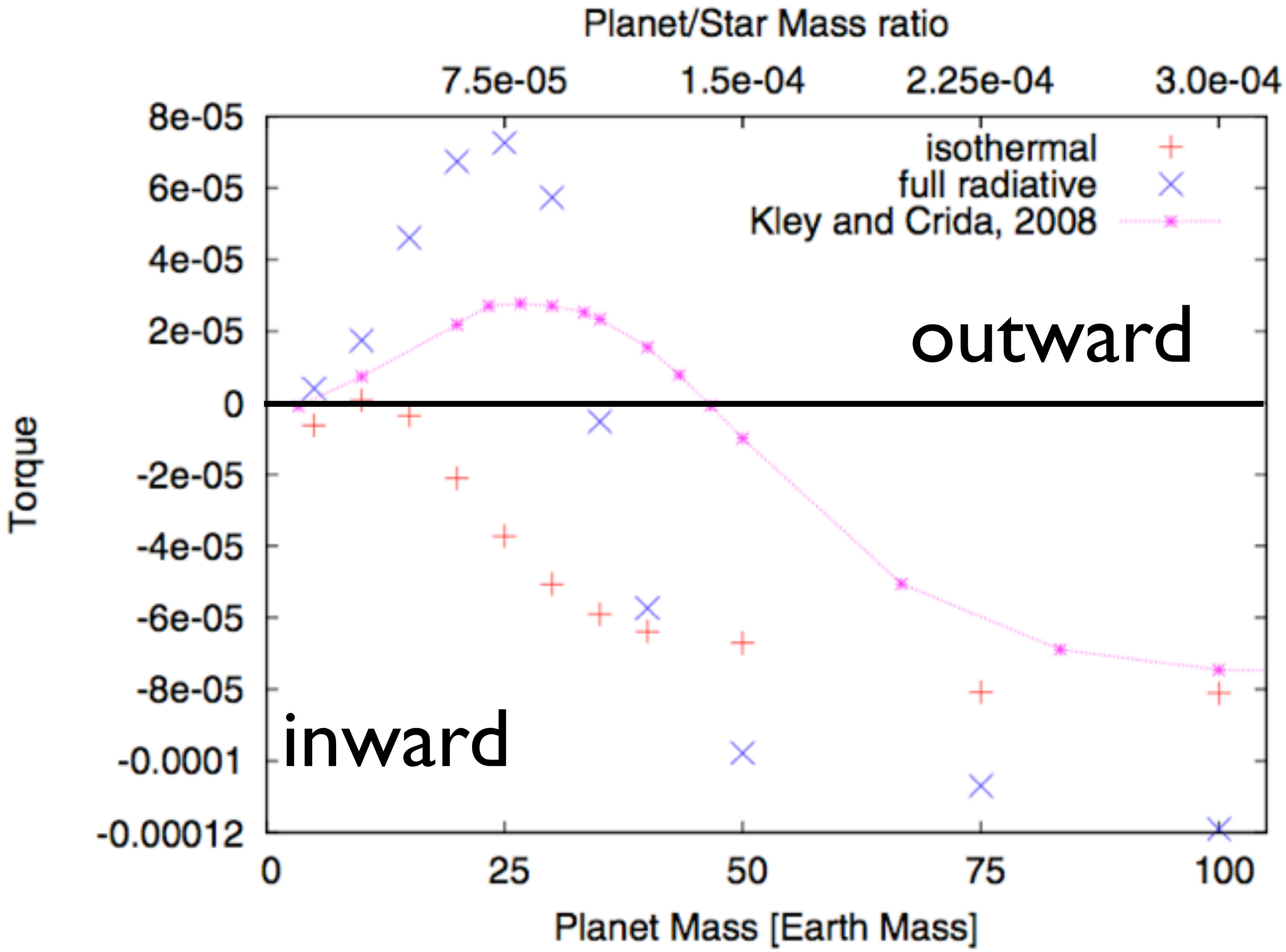


Simulations by C. Baruteau

backward pull: Inwards migration

Type I migration: Thermodynamics

Crida et al. 2006; Baruteau & Masset 2008; Casoli & Masset 2009; Pardekooper et al. 2010; Baruteau & Lin 2010



Kley et al. 2009

Thermodynamics of the gaseous disk is essential

Why does 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

$\varphi - \varphi_p$

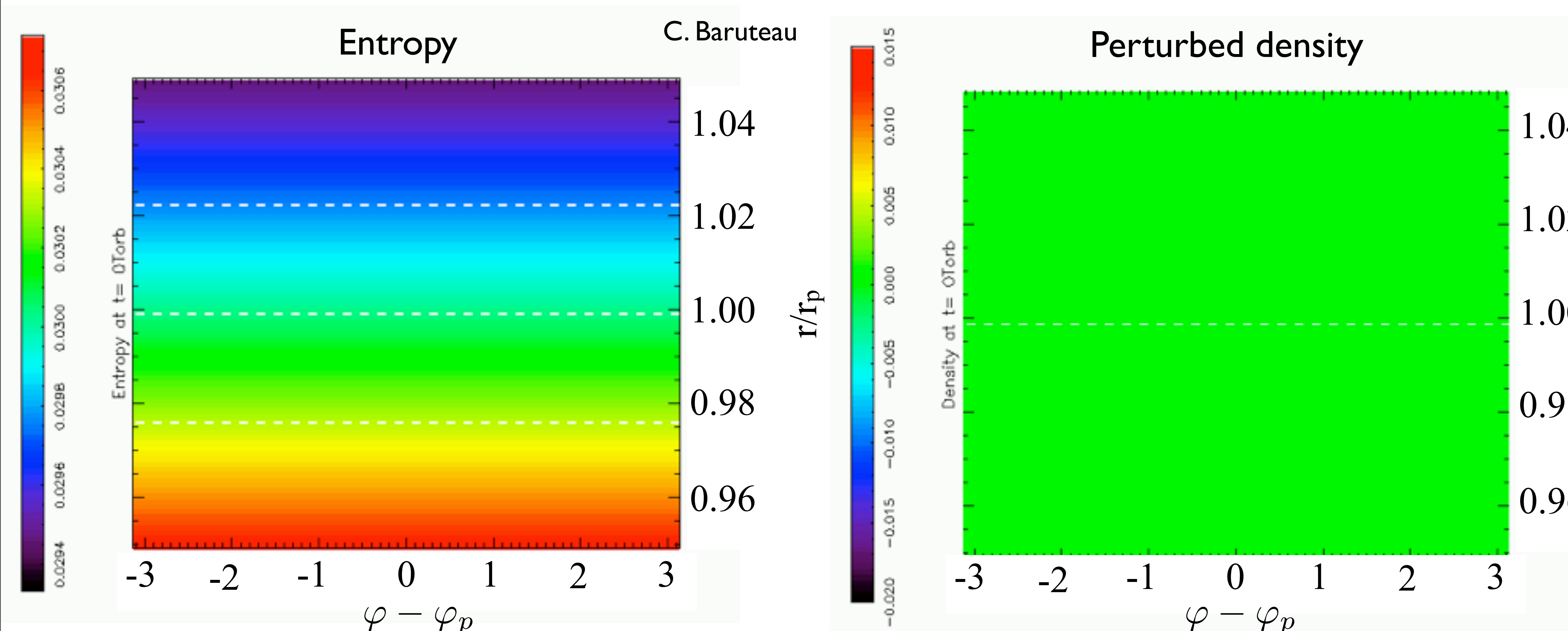
simulation for 1/2 libration period

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

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

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

Why does thermodynamics matter?



simulation for 1/2 libration period

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

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

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

Long term saturation

C. Baruteau

Perturbed entropy

1.04
1.02
1.00
0.98
0.96

-3 -2 -1 0 1 2 3

$\varphi - \varphi_p$

Perturbed density

1.04
1.02
1.00
0.98
0.96

r/r$_p$

-3 -2 -1 0 1 2 3

$\varphi - \varphi_p$

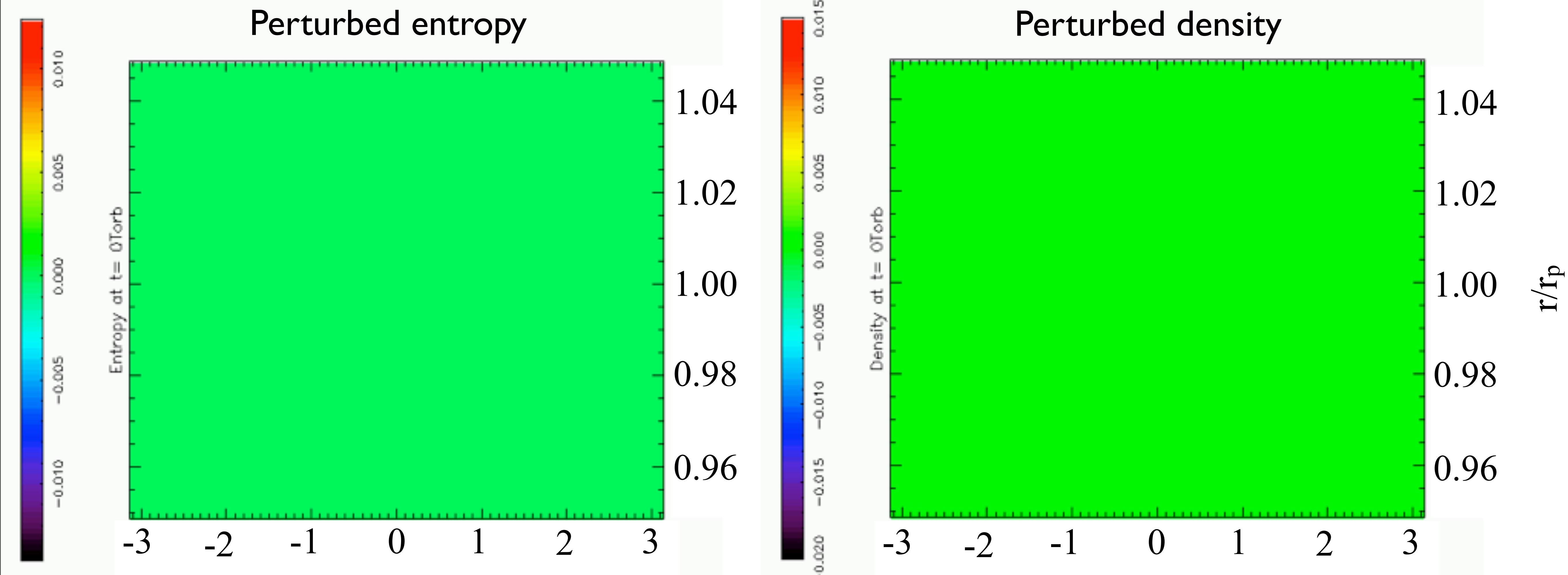
simulation for 3 libration periods

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: $\tau_{lib} >> \tau_{visc}$

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

Long term saturation

C. Baruteau



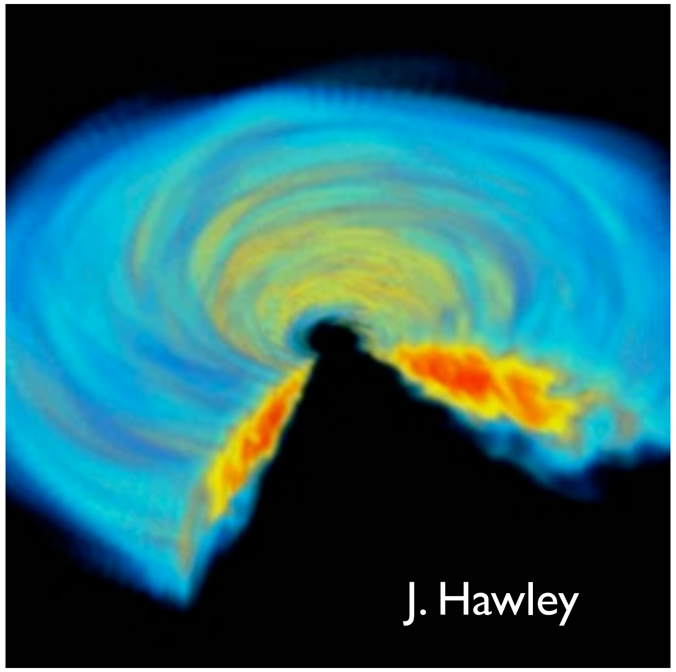
$\varphi - \varphi_p$ simulation for 3 libration periods $\varphi - \varphi_p$

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: $\tau_{lib} >> \tau_{visc}$

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

Evolution & structure of the gas disk

Full MHD calculation



$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (1)$$

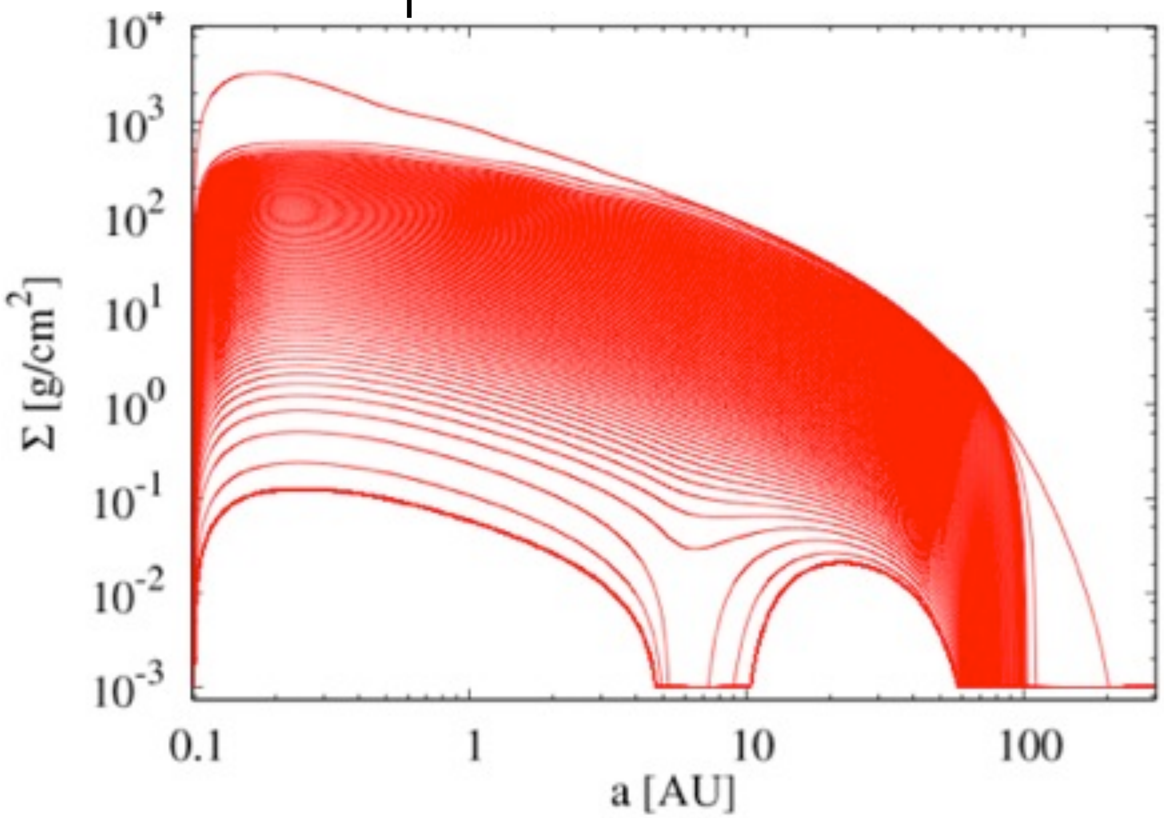
$$\rho \frac{\partial \mathbf{v}}{\partial t} + (\rho \mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla \left(P + \frac{B^2}{8\pi} \right) - \rho \nabla \Phi + \left(\frac{\mathbf{B}}{4\pi} \cdot \nabla \right) \mathbf{B} \quad (2)$$

$$\frac{\partial \rho \epsilon}{\partial t} + \nabla \cdot (\rho \epsilon \mathbf{v}) = -P \nabla \cdot \mathbf{v} \quad (3)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \quad (4)$$

all the physics... good enough?

alpha-disk model



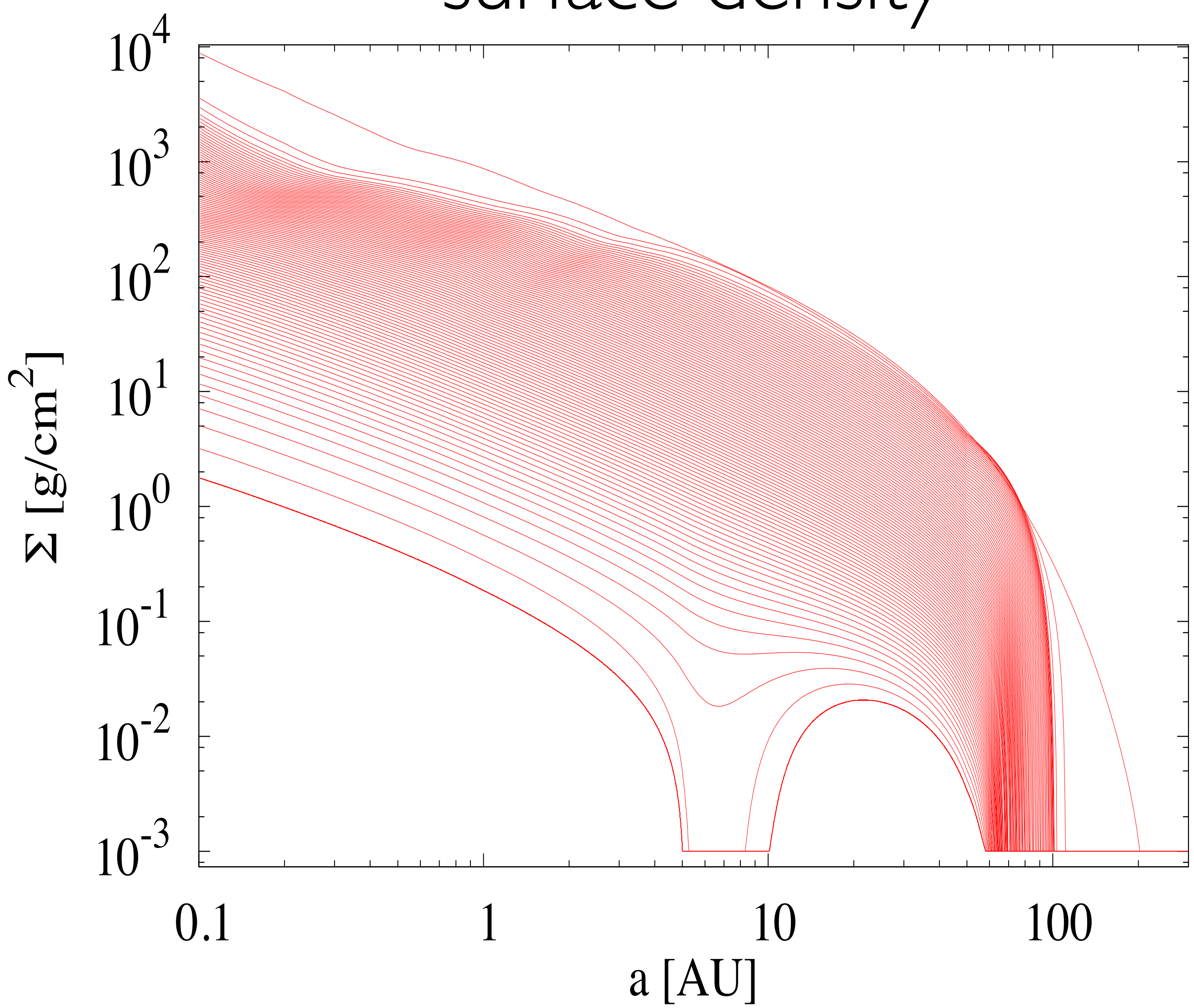
$$\frac{d\Sigma}{dt} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2} \frac{\partial}{\partial r} \tilde{\nu} \Sigma r^{1/2} \right] + \dot{\Sigma}_w(r)$$

viscous evolution:

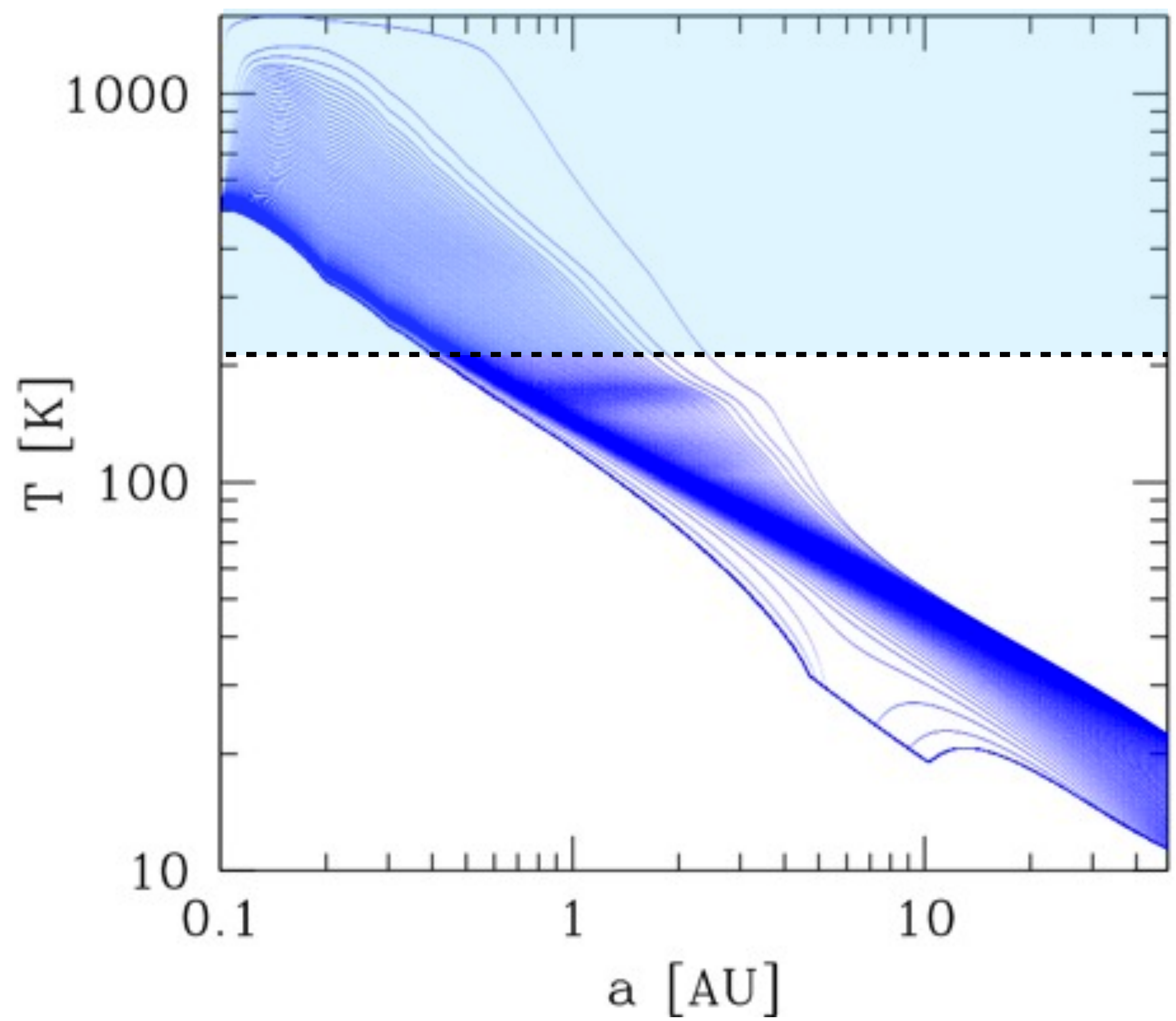
- -stellar irradiation
- -external photo-evaporation (Matsuyama+ 2003)
- -internal photo-evaporation (Clarke+ 2001)
- -updated initial profile (Andrews+ 2009)

Evolution & *structure of the gas disk*

surface density



mid-plane temperature



The near IR probes the planet forming regions of the disks both the gas and the dust

Conclusions

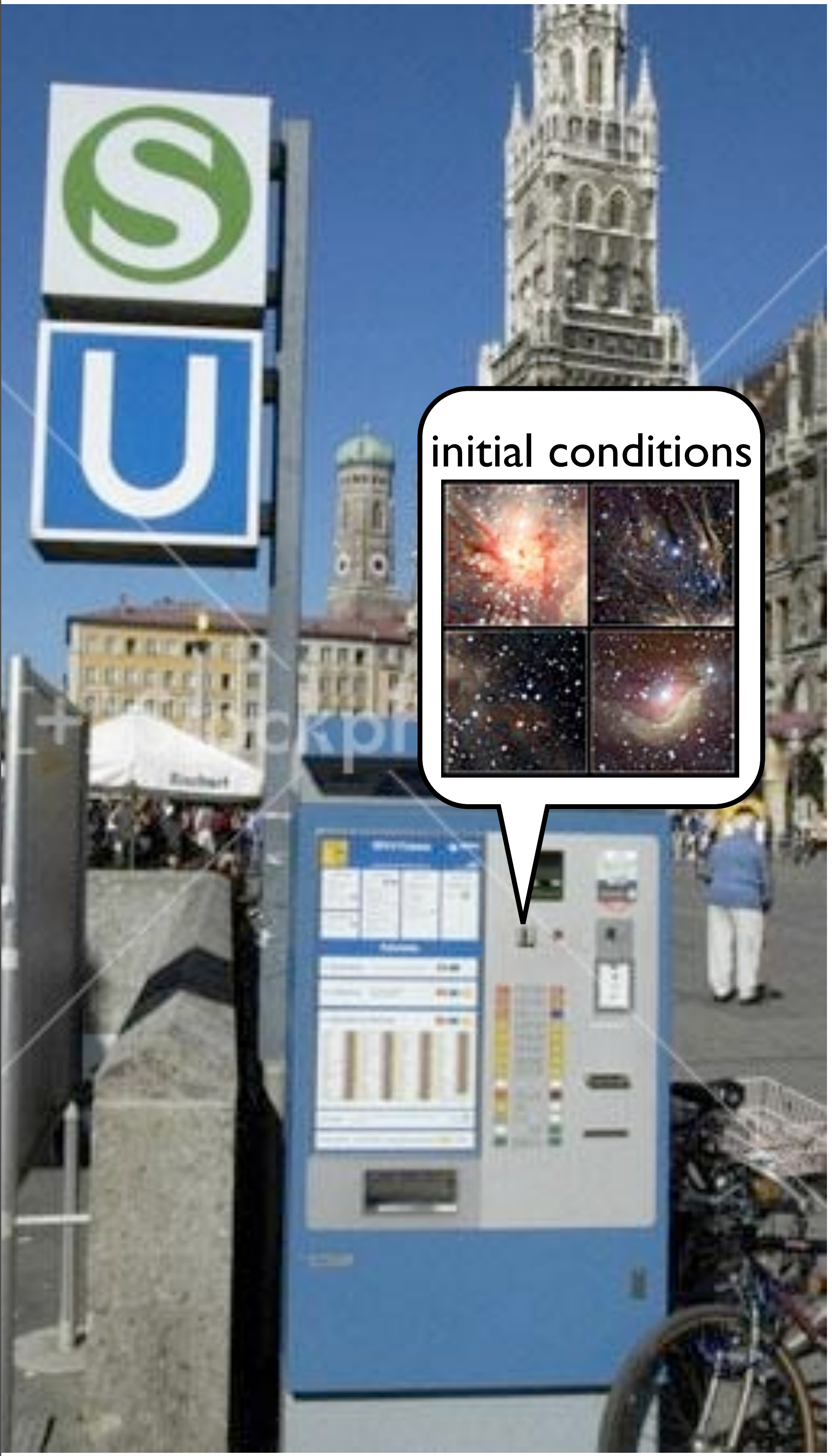
Theory of planet formation is evolving fast and has changed significantly during the past 15 years.

Unfortunately, theory still lags behind observations. Theorists are always surprised by discoveries and try to explain them. Predictions are rare...

Population synthesis is a powerful tool to explore models. Observations by different techniques provide different constraints. But the modeling is extremely complex... You need to have many things right...

One would like to see the formation process in action... To get individual process right...


S
U


initial conditions


initial conditions
end product

initial conditions

end product

Challenge for interferometry

?

see inside the box...

Challenge for interferometry

?

see inside the box...