Planetary population synthesis

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Outline

1) Planet formation models

Planet growth

Disk structure and evolution

Migration

2) First generation population synthesis models

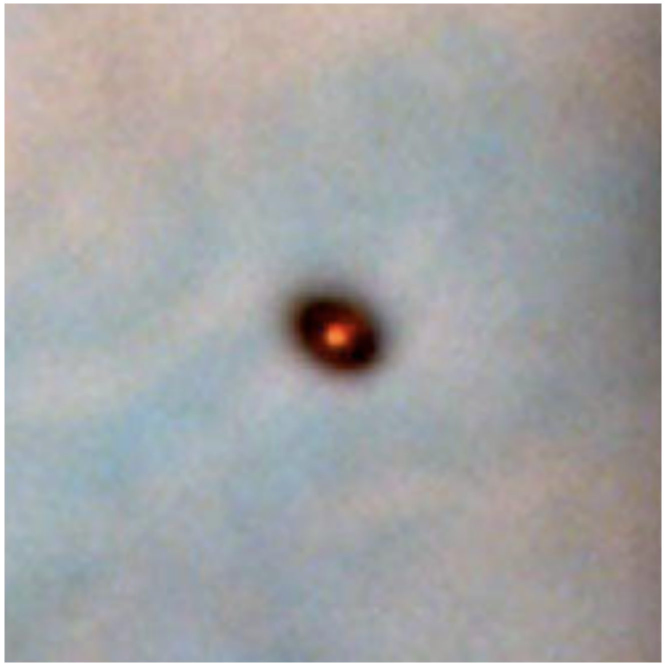
Initial conditions

Reproducing *planet* observations

3) Second generation population synthesis models

Using *disk* observations

Planet formation



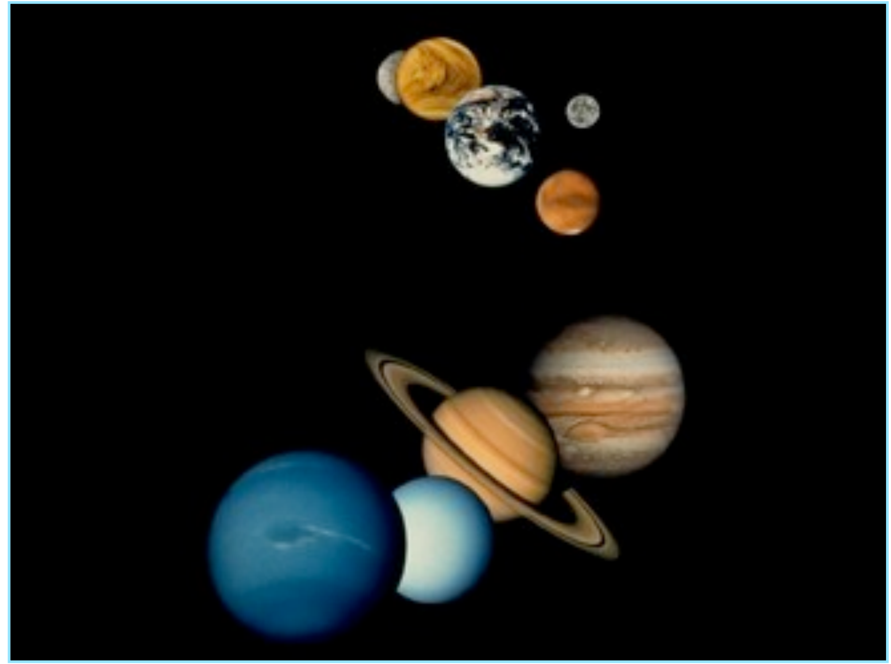
⇒

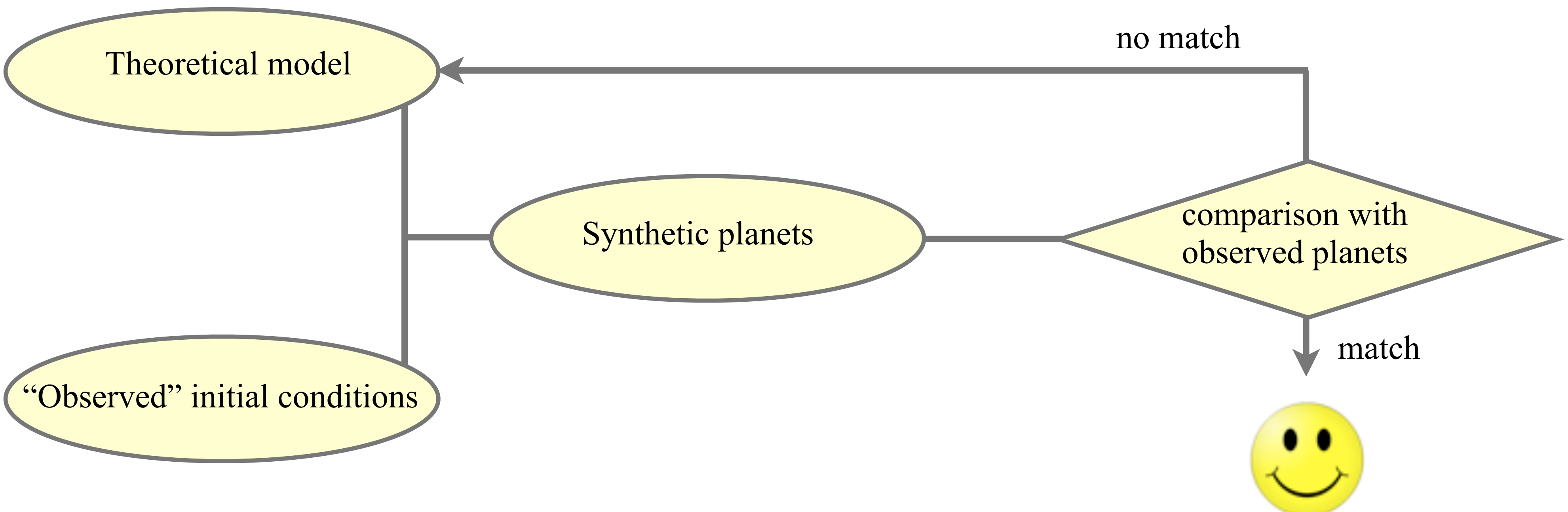
no direct
observation

?

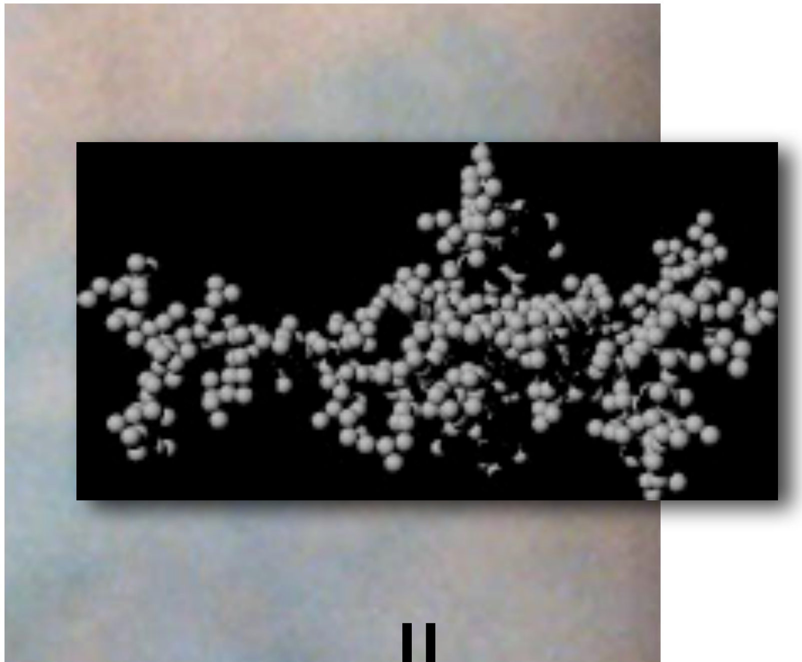
Theoretical
model

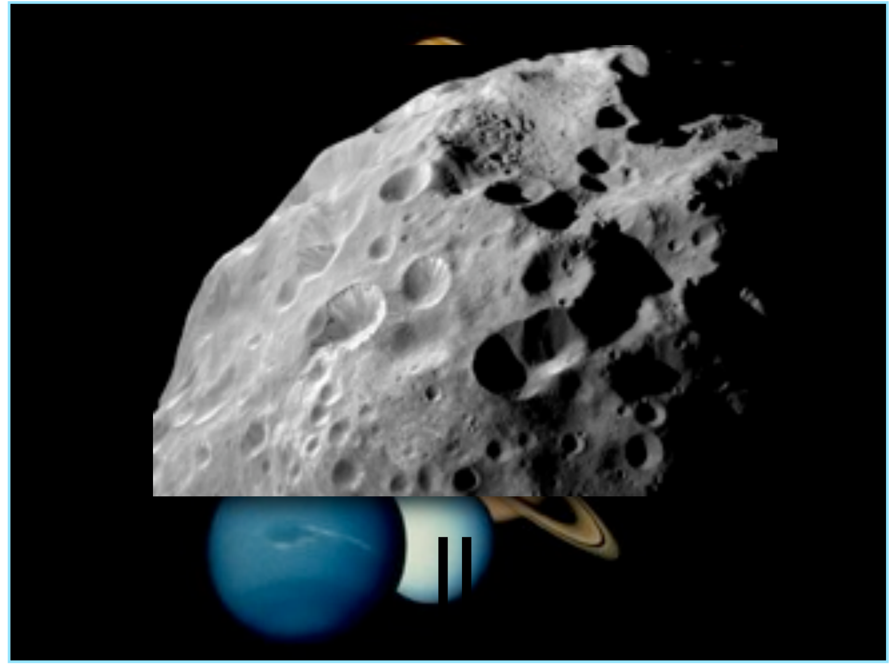
⇒





Planet formation

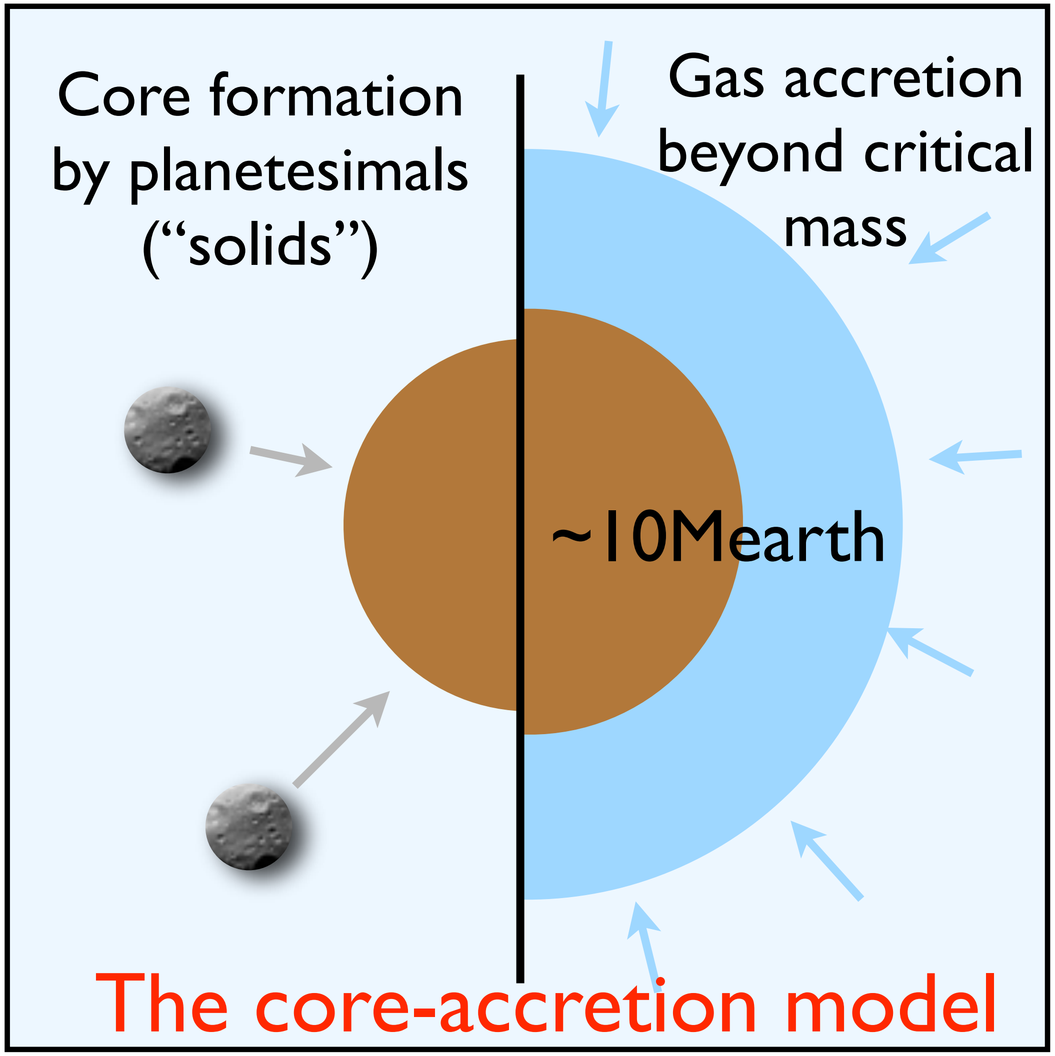


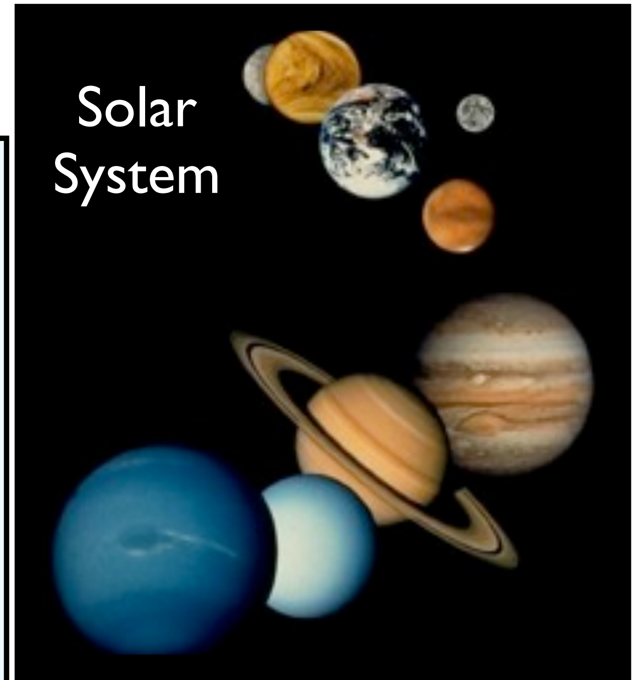


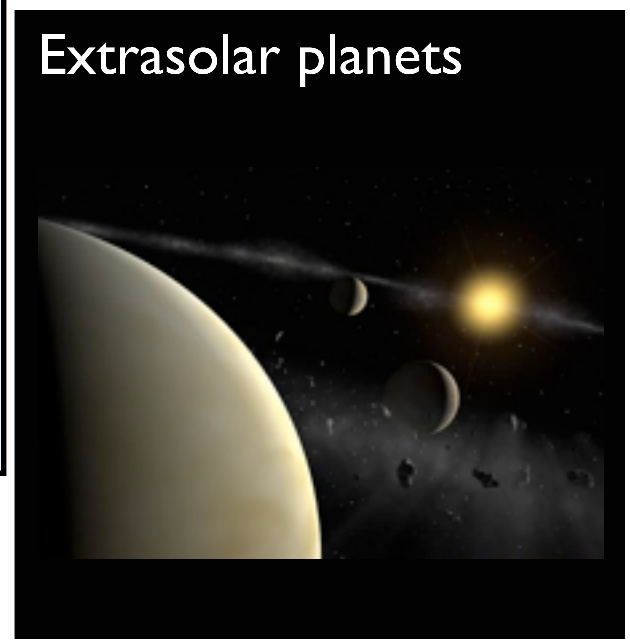
Talk by Kees

This talk

The core accretion paradigm

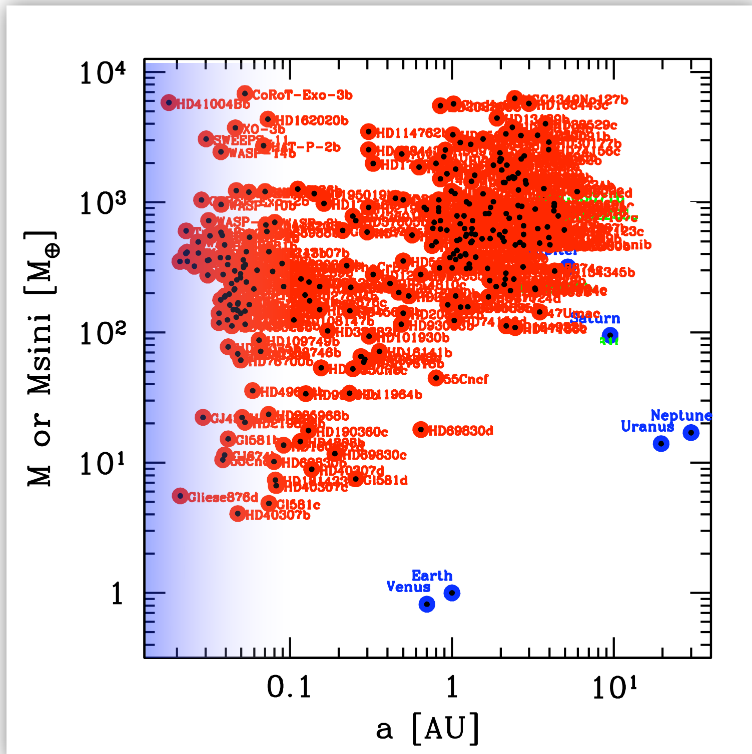


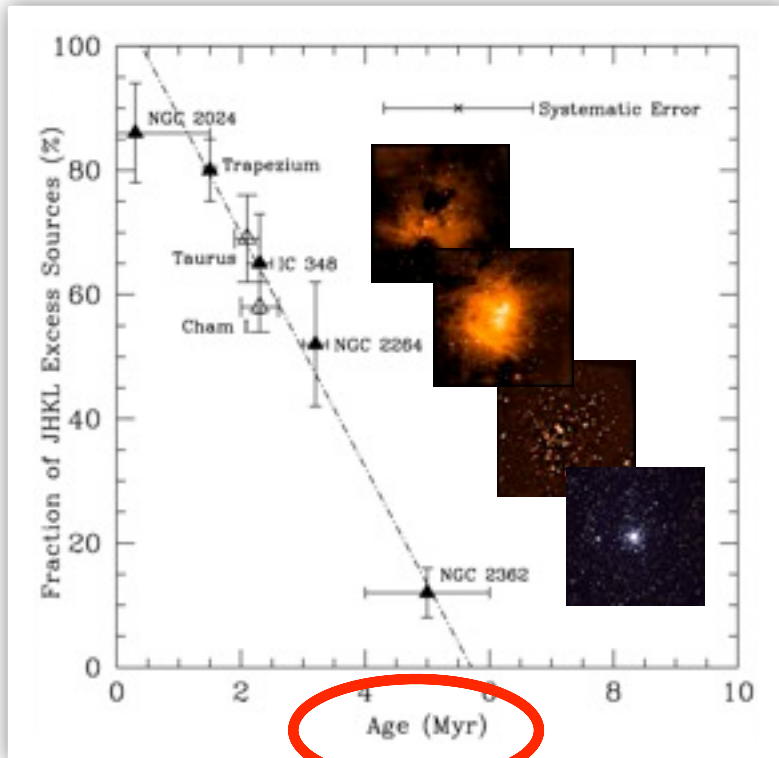




Extended models

1) *"standard" core-accretion model predict formation in few Myr*





In-situ formation seems not possible $\Longrightarrow$ *migration*

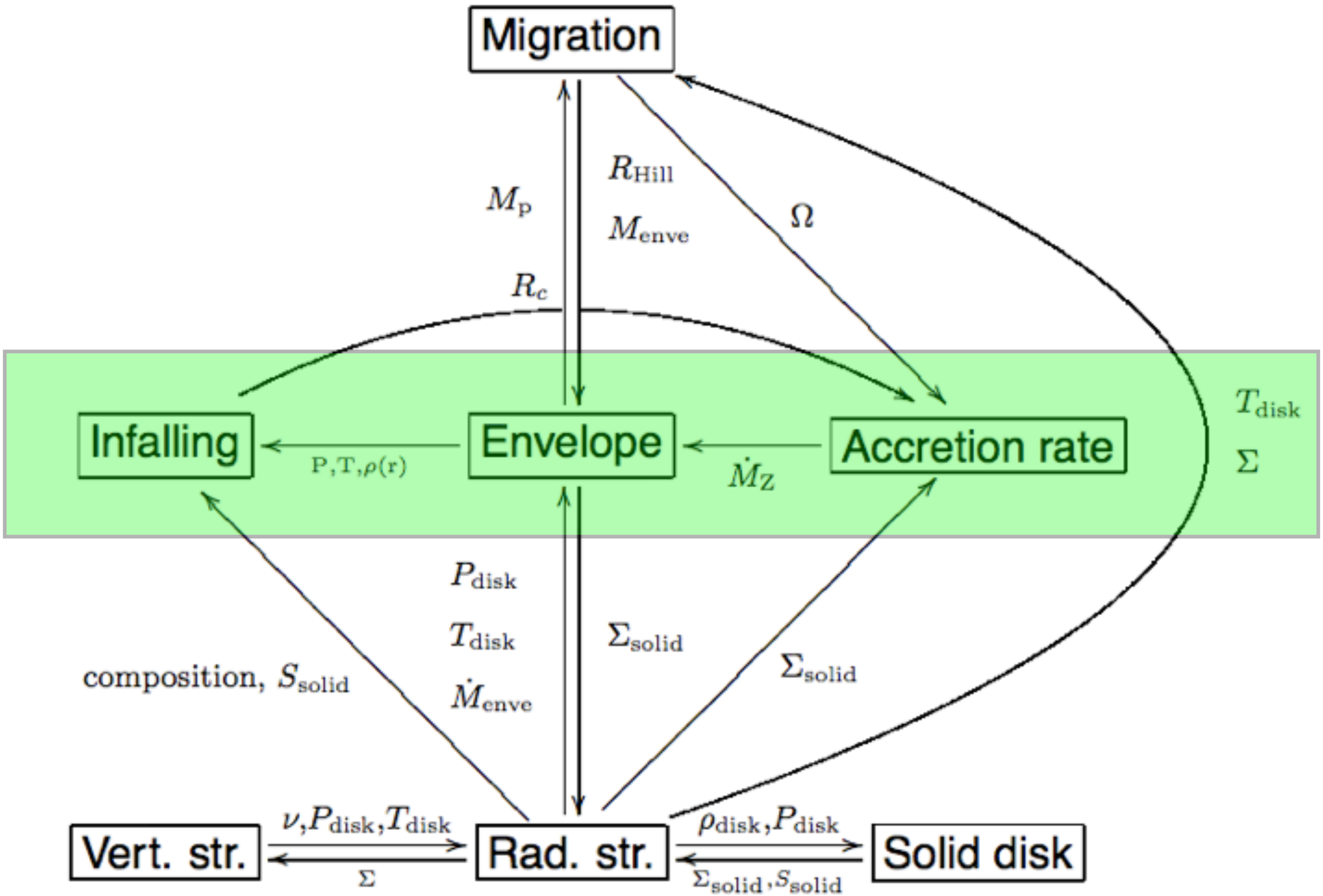
disk evolution $\Longleftarrow$ Evolution in ~Myr

2) *disk evolution*

3) *type I and type II migration*

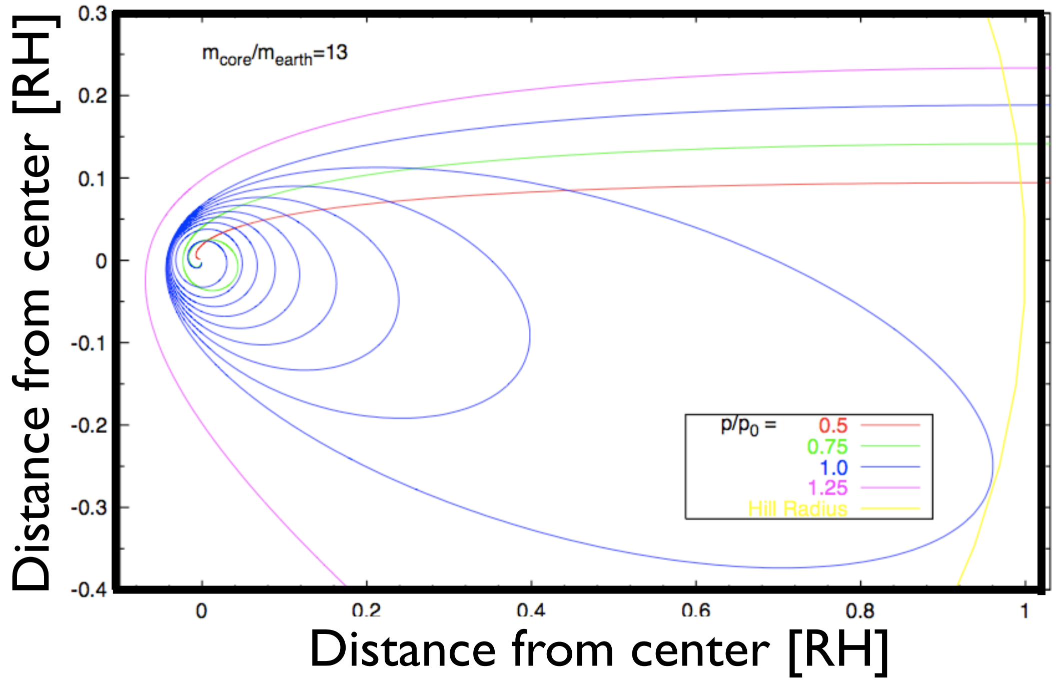
The model is kept as simple as possible: No tricks, everything is "standard" but considered together...

Models overview



Planet's solids accretion rate

$$\frac{dM_Z}{dt} = R_{\rm cap}^2 \Omega \Sigma_{\rm planetesimals} F_{\rm g}(e, i, R_{\rm cap})$$



- Trajectory of planetesimals computed with:
  - gas drag
  - gravity

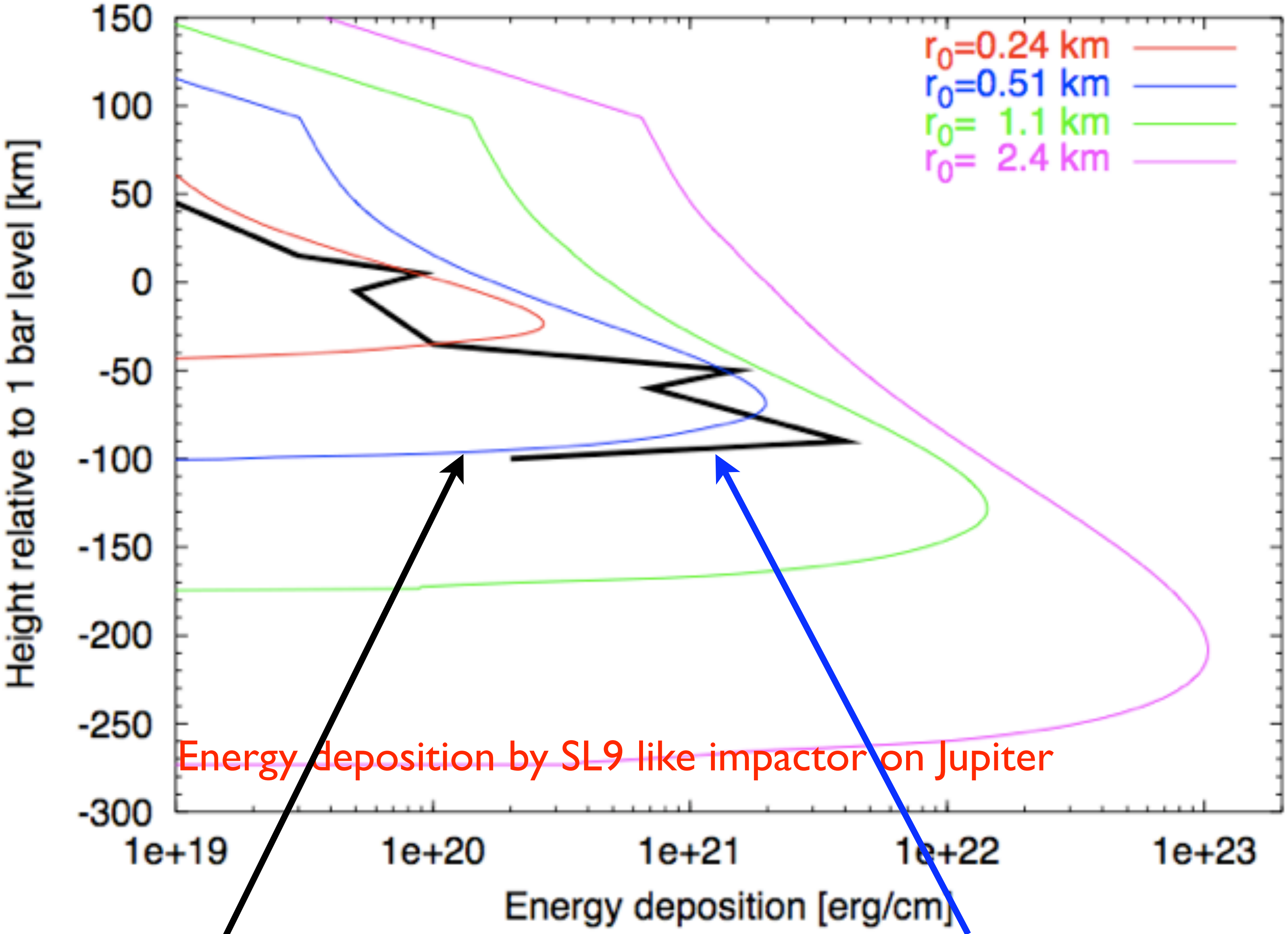
$$m(t)\frac{d^2\vec{x}}{dt^2} = \boxed{-\frac{GM(x)m(t)}{x^2}\tilde{x}} - \boxed{\frac{1}{2}\pi r^2 C_D(Re, Ma)\rho_g v^2 \tilde{v}}$$

- Mass loss due to:
  - radiation from ambiant gas and shock wave:

$$\begin{cases} \frac{dm}{dt} = -\frac{F_{\rm input}\pi r^2(t)}{Q_{\rm abl}} \\ F_{\rm input} = \frac{1}{2}C_H \rho_g v^3 \\ C_H = 10^{-5} \text{ to } \frac{1}{2}C_D \end{cases}$$

  - mechanical effects (Zahnle 1992, MacLow 1996, Korykansky 2002)

Planet's solids accretion rate



Full 3D models (Zahnle & MacLow 1994)

Our (1D) model (Mordasini et al., in prep)

Planet's internal structure

Internal structure equations

1) $$\frac{dr^3}{dm} = \frac{3}{4\pi\rho} \quad \text{mass conservation}$$

2) $$\frac{dP}{dm} = -\frac{G(m + M_{core})}{4\pi r^4} \quad \text{hydrostatic equilibrium}$$

3) $$\frac{dT}{dP} = \nabla_{ad} \text{ or } \nabla_{rad} \quad \text{energy transfer}$$

$$L = L_{\text{planetesimals}}$$

Envelope mass derives from the condition $R_{\text{planet}} = R_{\text{Hills}}$

Gas accretion rate limited by disk properties

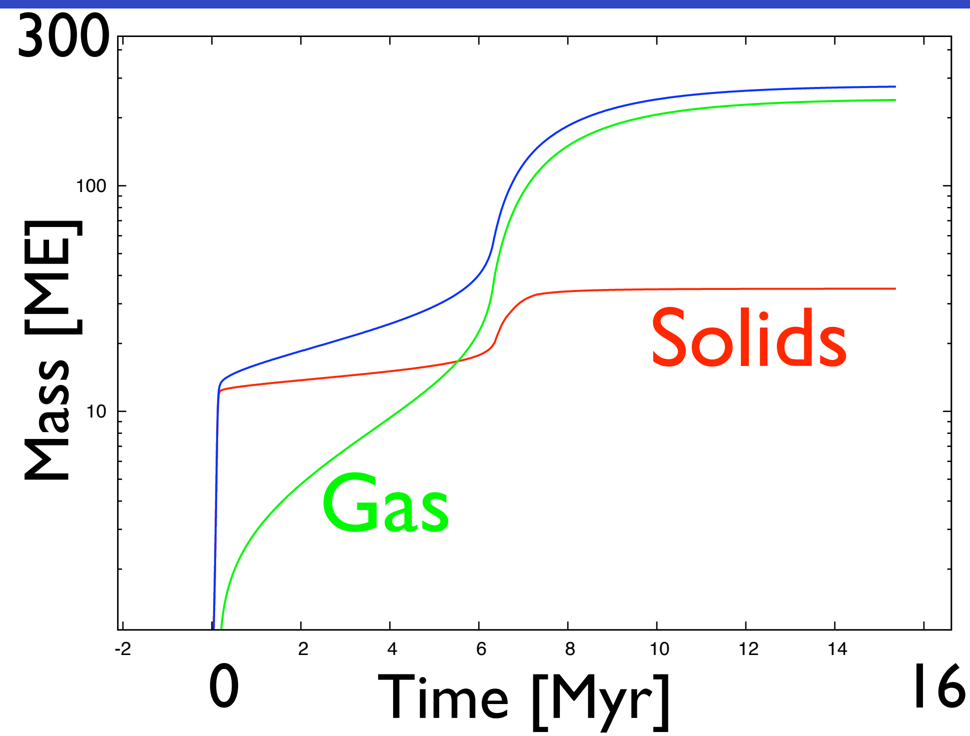
Planet's internal structure

In situ formation of Jupiter at 5.2 AU

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

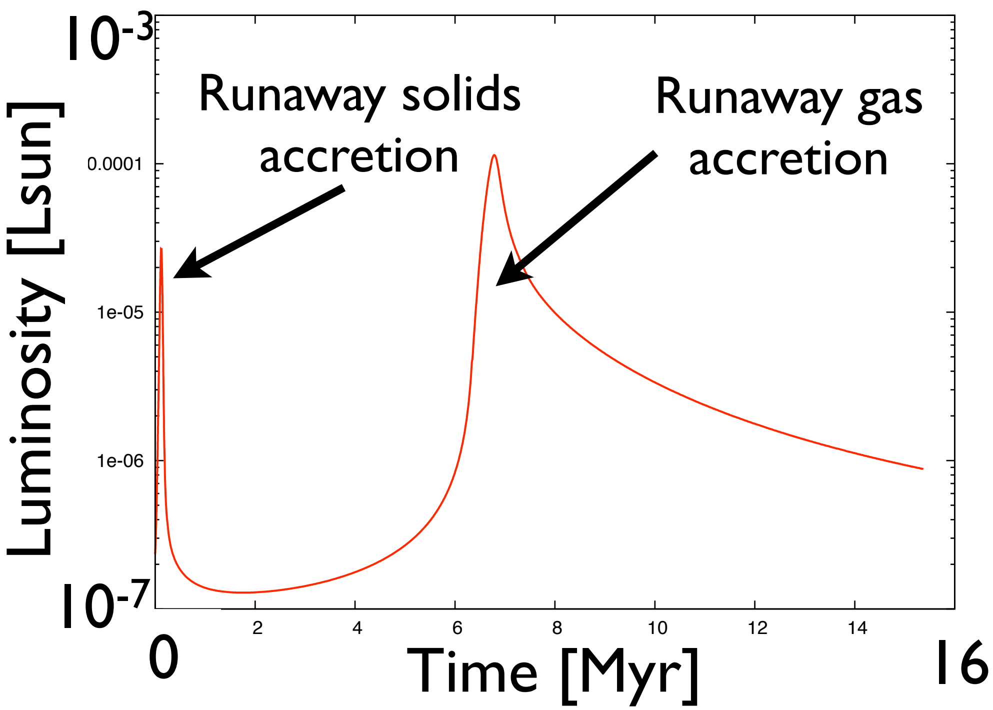
$$M_{\rm disk} \approx 0.03 M_\odot$$

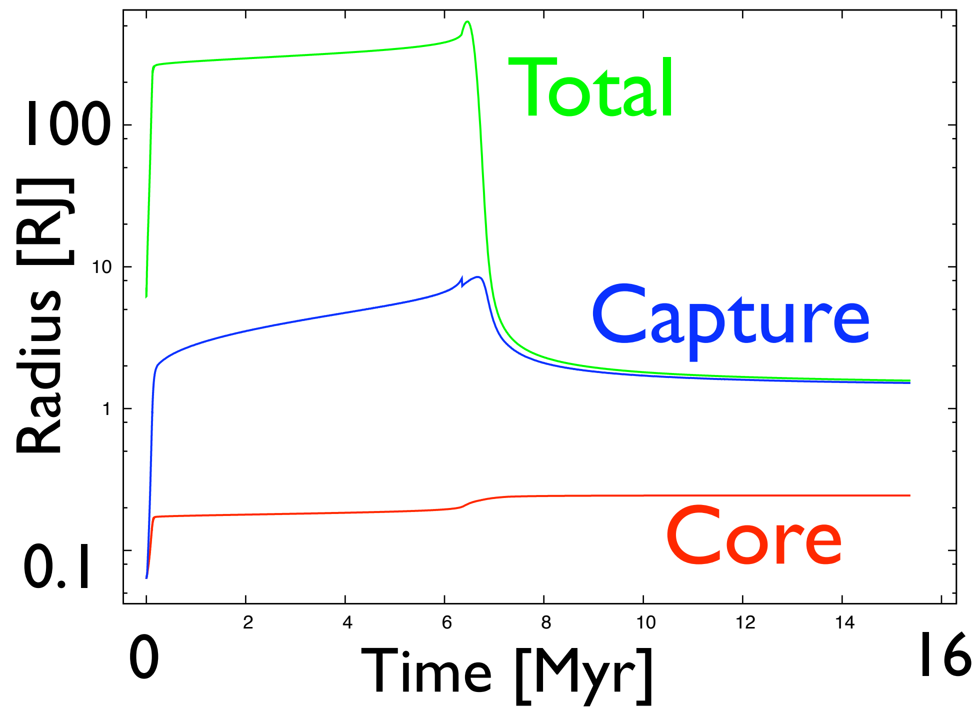
only viscosity



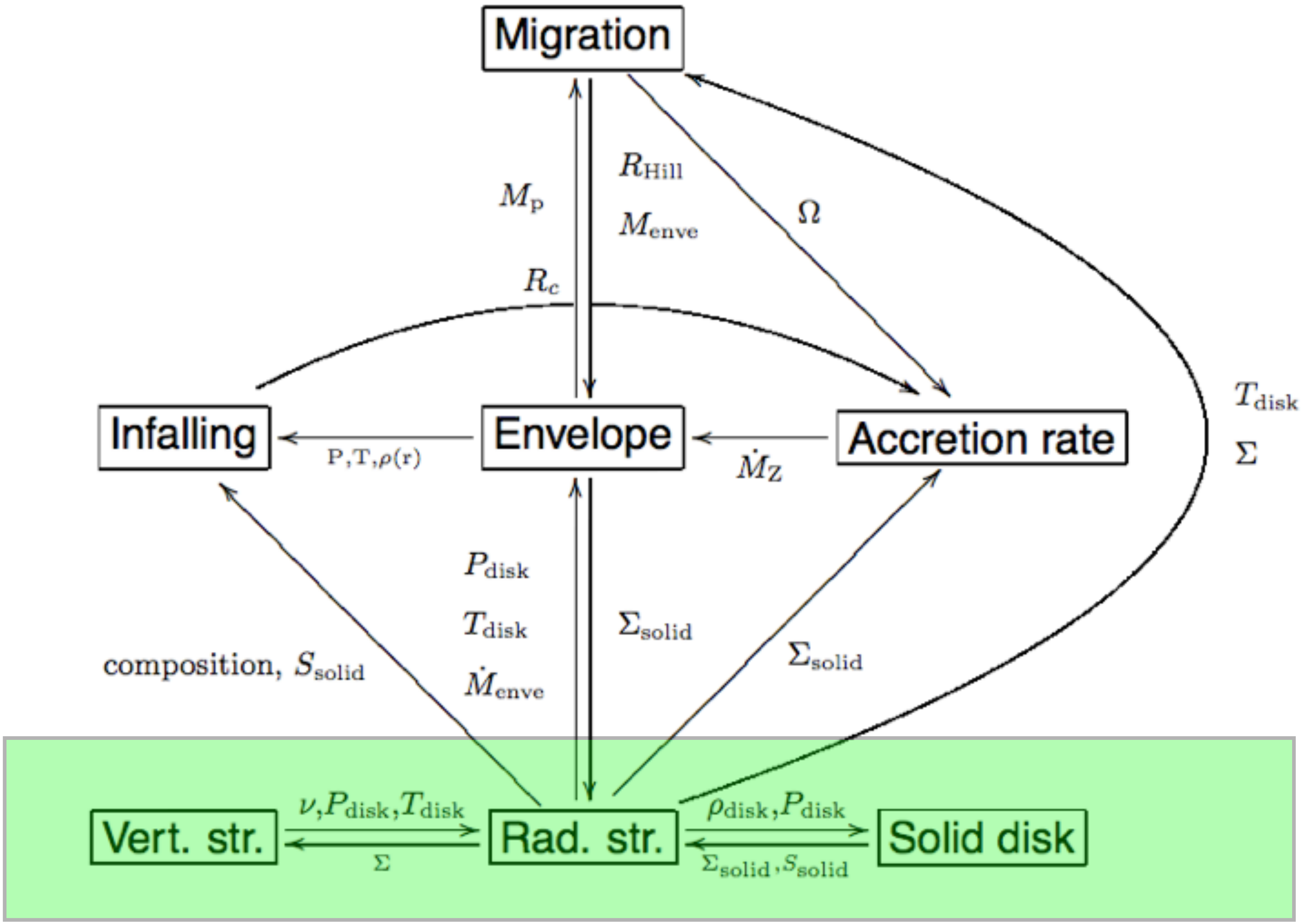
Planet in contact with disk

Planet isolated

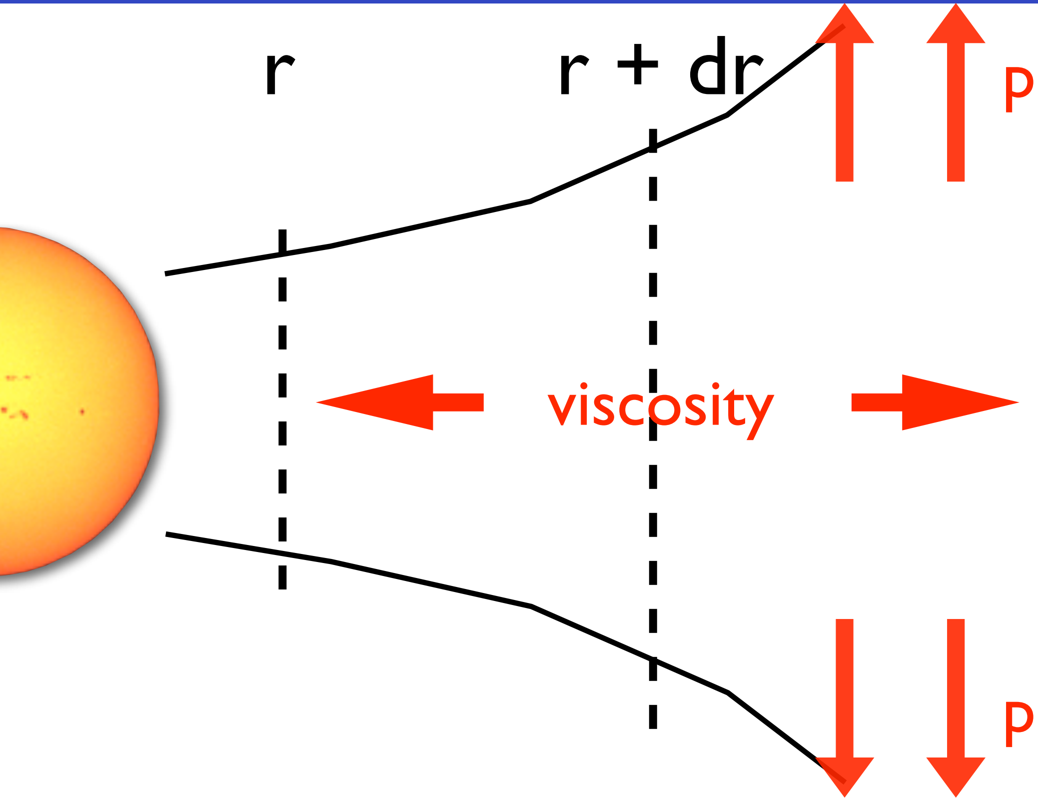




Models overview



Disk model: gas



- hydrostatic equilibrium

$$\frac{1}{\rho}\frac{\partial P}{\partial z} = -\Omega^2 z$$

- energy equation

$$\frac{\partial F}{\partial z} = \frac{9}{4}\rho\nu\Omega^2$$

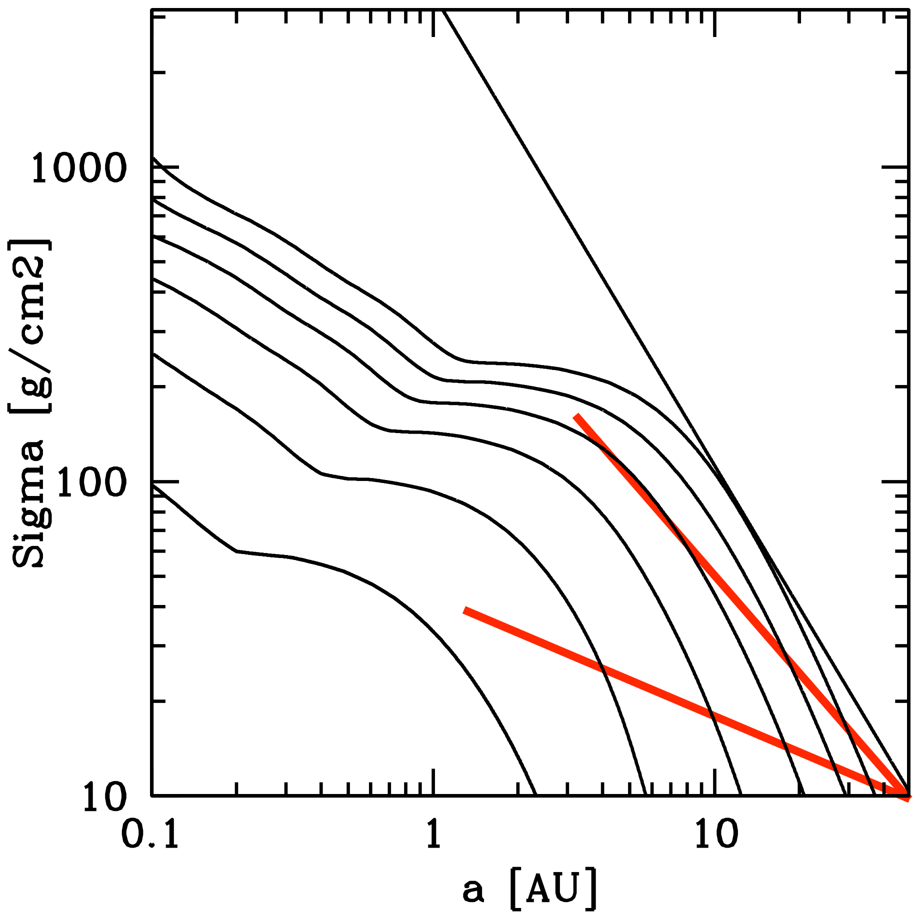
- diffusion equation for radiative flux

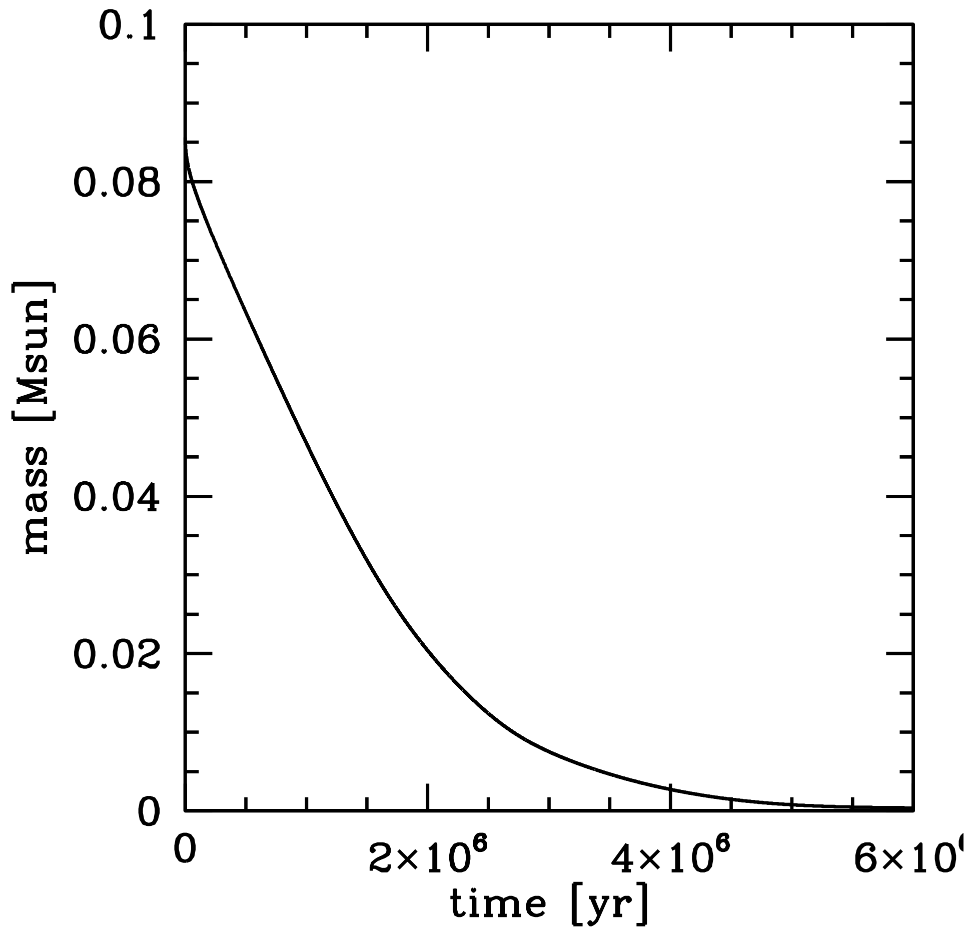
$$F = \frac{-16\pi\sigma T^3}{3\kappa\rho}\frac{\partial T}{\partial z}$$

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

Photoevaporation model from Veras and Armitage 2004

Disk model: gas





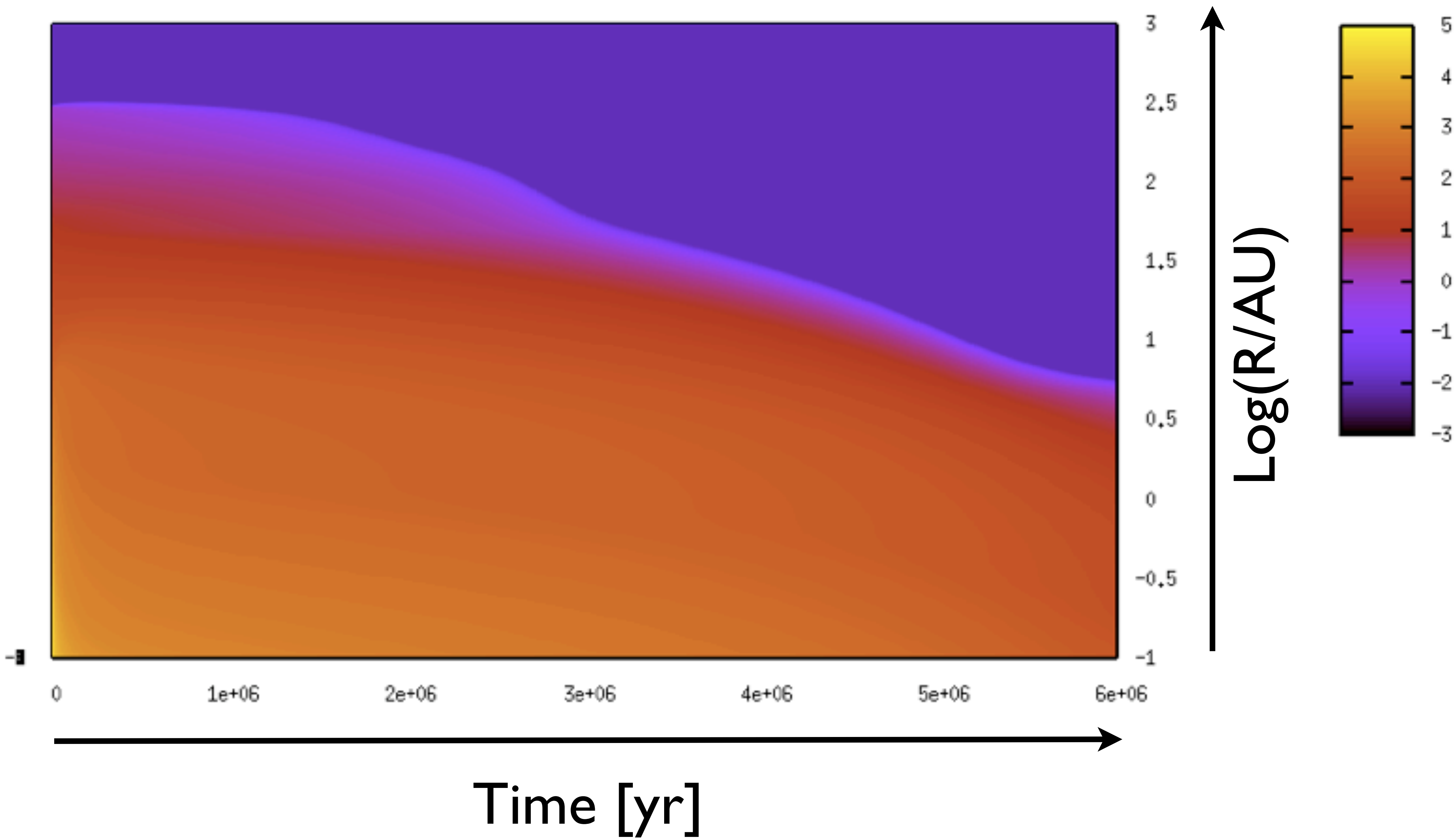
$$R_{\rm in} = 0.1AU$$

$$R_{\rm out} = 300AU$$

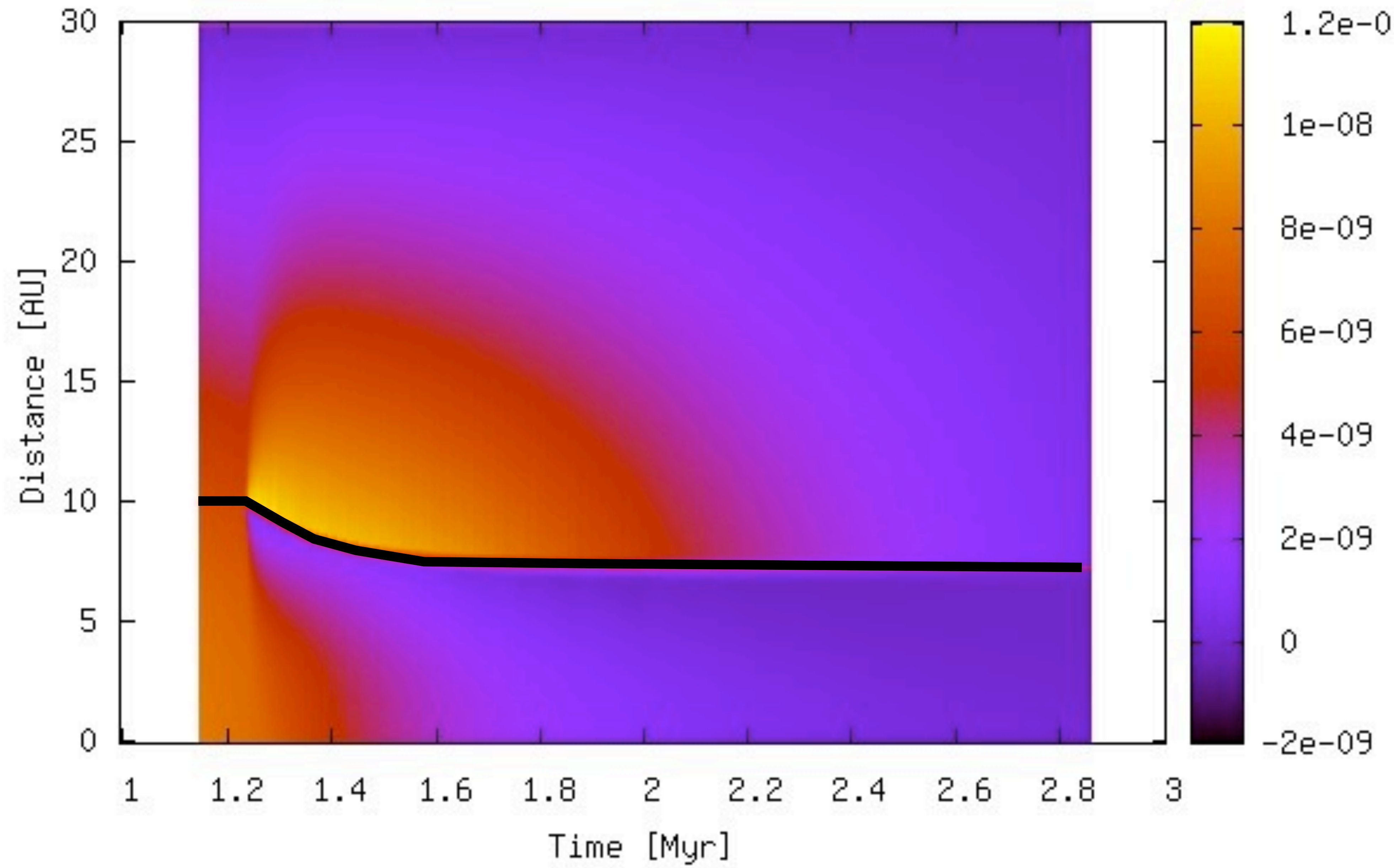
$$M_{\rm W} = 10^{-7} M_\odot / yr$$

Constant viscosity parameter

Disk model: gas

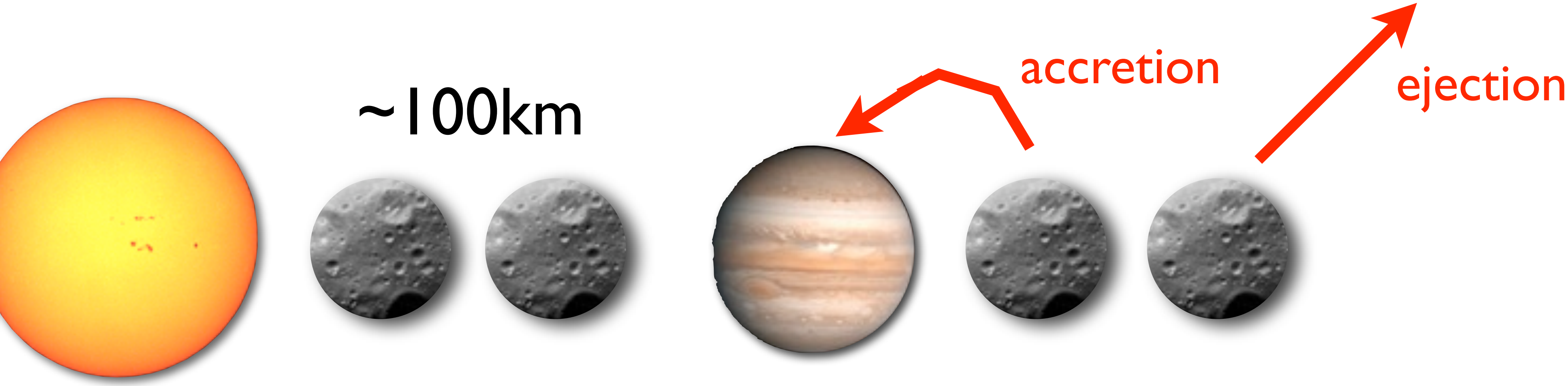


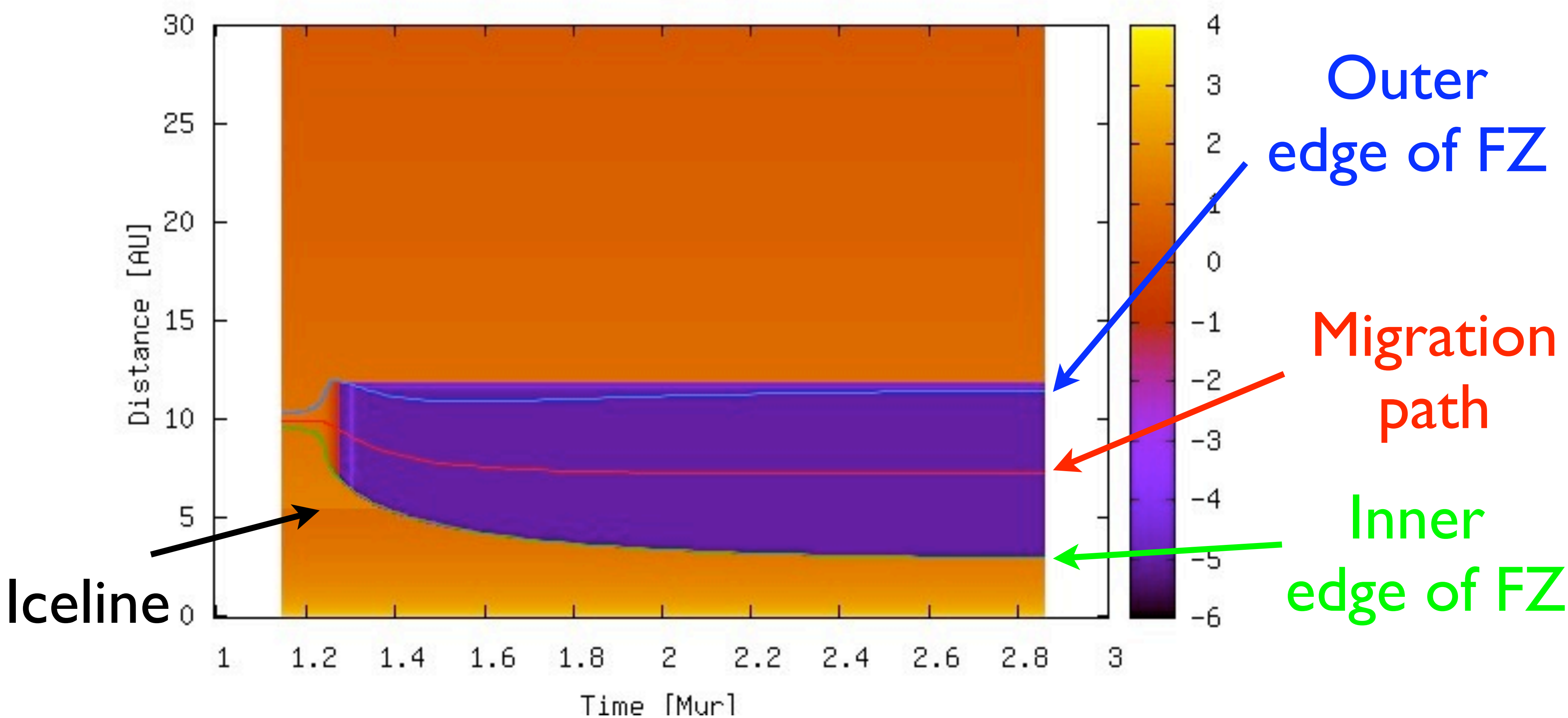
Disk model: gas



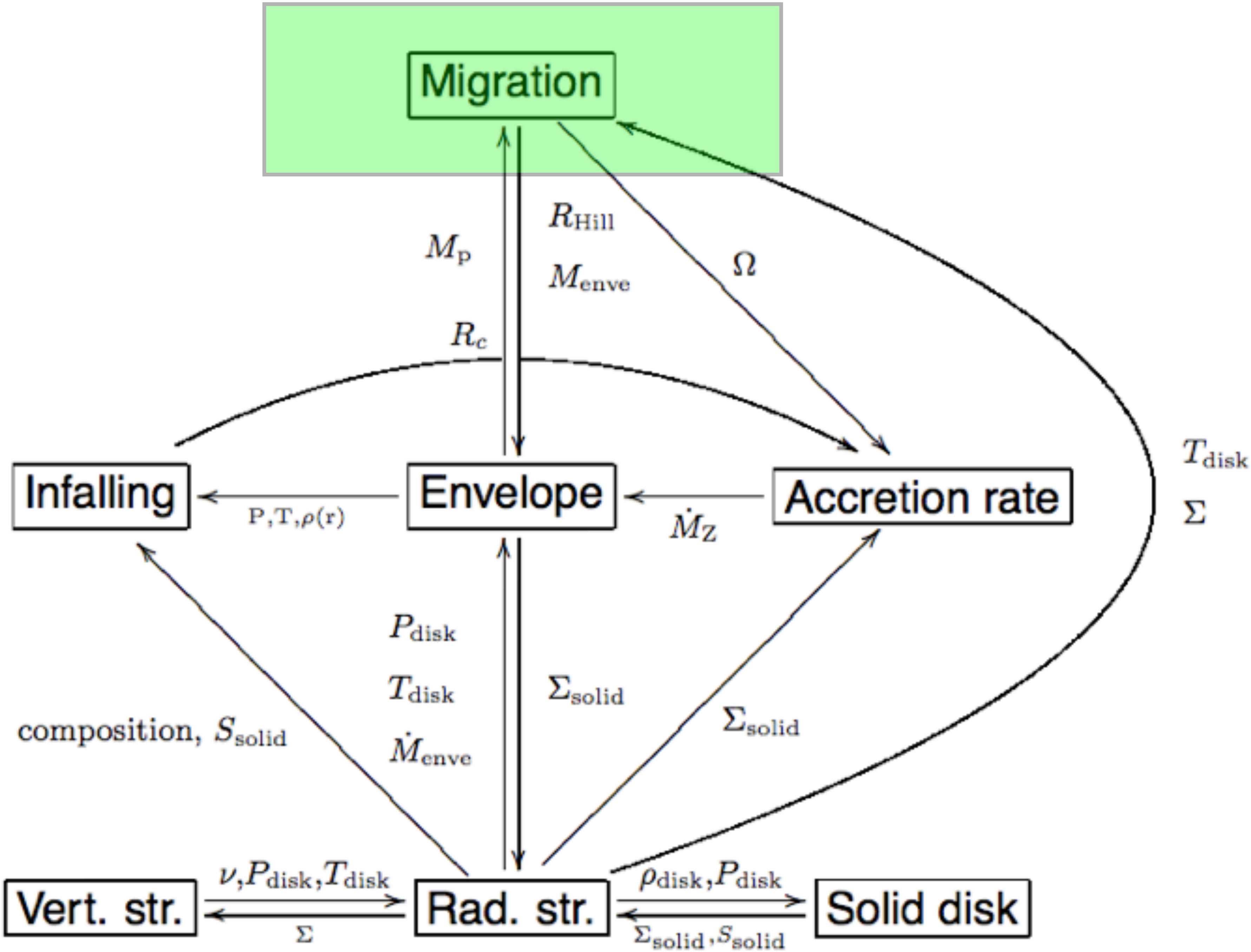
Planet migration path

Disk model: planetesimals





Models overview



Migration - type I

- **Type I (low mass planets):** $R_{\rm Hill} \equiv a_{\rm P} \left(\frac{M_{\rm planet}}{3M_{\rm star}} \right)^{\frac{1}{3}} < H_{\rm disk}$

$$\frac{da_{\rm P}}{dt} = f(\alpha_{\rm disk}) \times \frac{M_{\rm planet}}{M_{\rm star}} \times \frac{\Sigma_{\rm P} a_{\rm P}^2}{M_{\rm star}} \times \left(\frac{c_{\rm P}}{a_{\rm P}\Omega_{\rm P}} \right)^2 \times \Omega_{\rm P}^{-1}$$

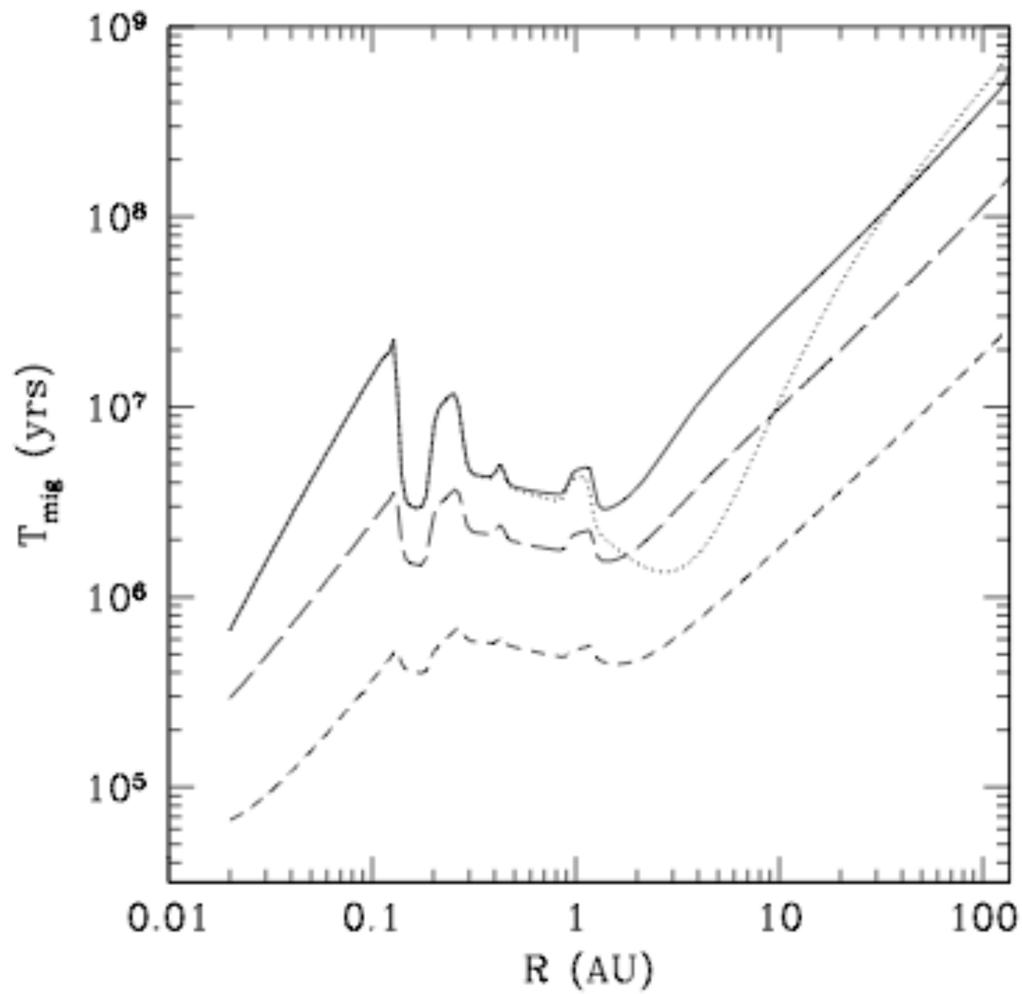
Tanaka, Takeuchi & Ward 2002

$$\alpha_{\rm disk} \equiv \frac{d\ln\Sigma}{d\ln r}$$

Opacity transition regions

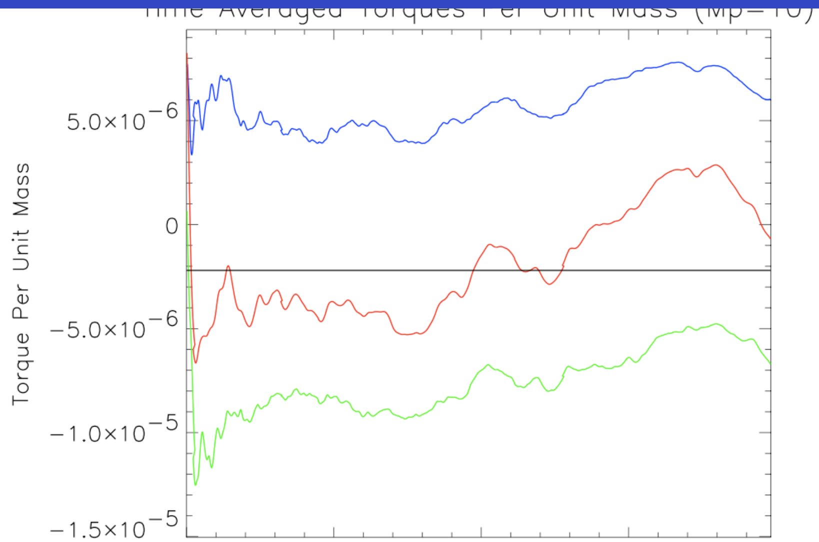
$$\Downarrow$$

$$\alpha_{\rm disk,inside} \neq \alpha_{\rm disk,outside}$$



Menou & Goodman 2004

Migration - type I

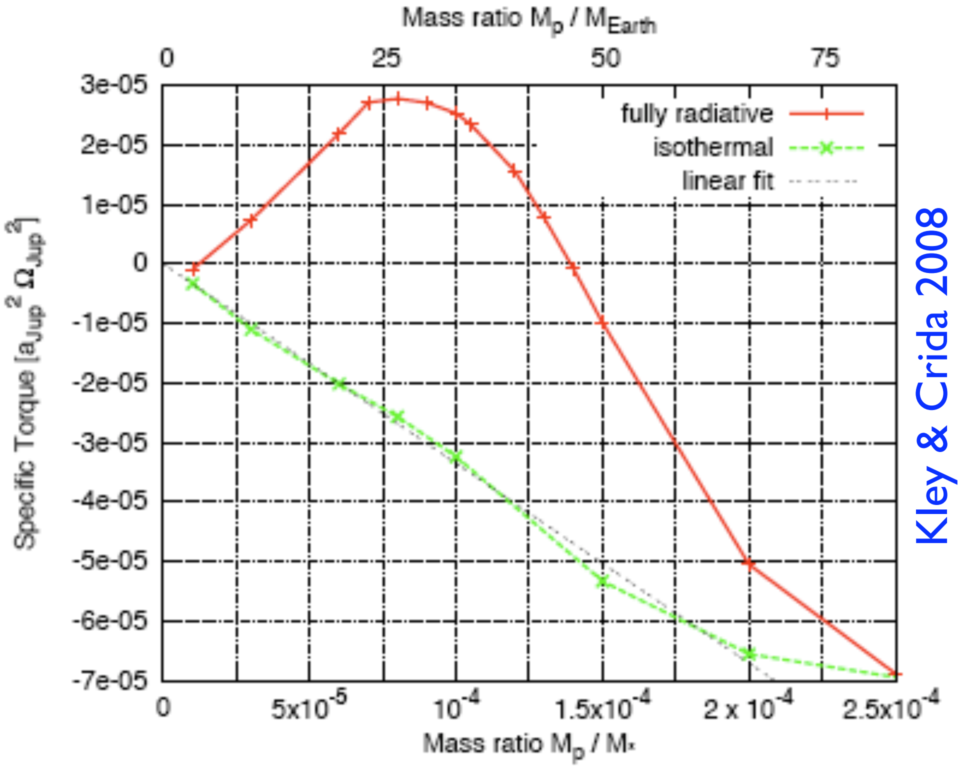


Nelson & Papaloizou 2003

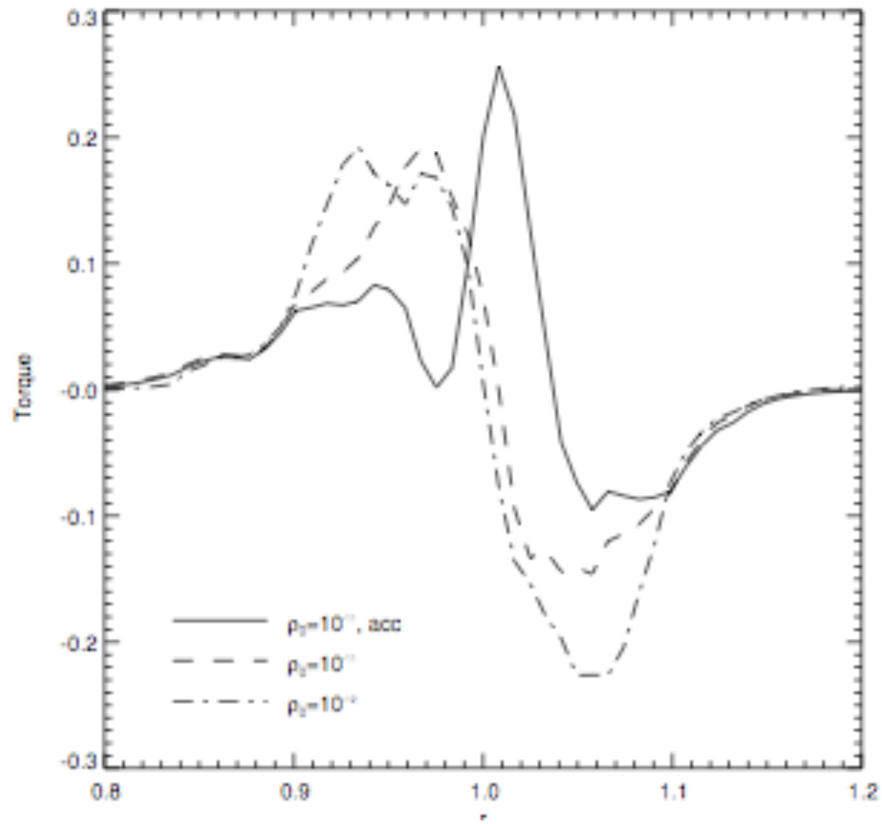
Density fluctuations

$\Downarrow$

"Random walk" migration



Kley & Crida 2008



Paardekooper & Mellema 2007

Thermodynamic effects $\Longrightarrow$ *Outward* migration

Migration - type I

- Type I (low mass planets):

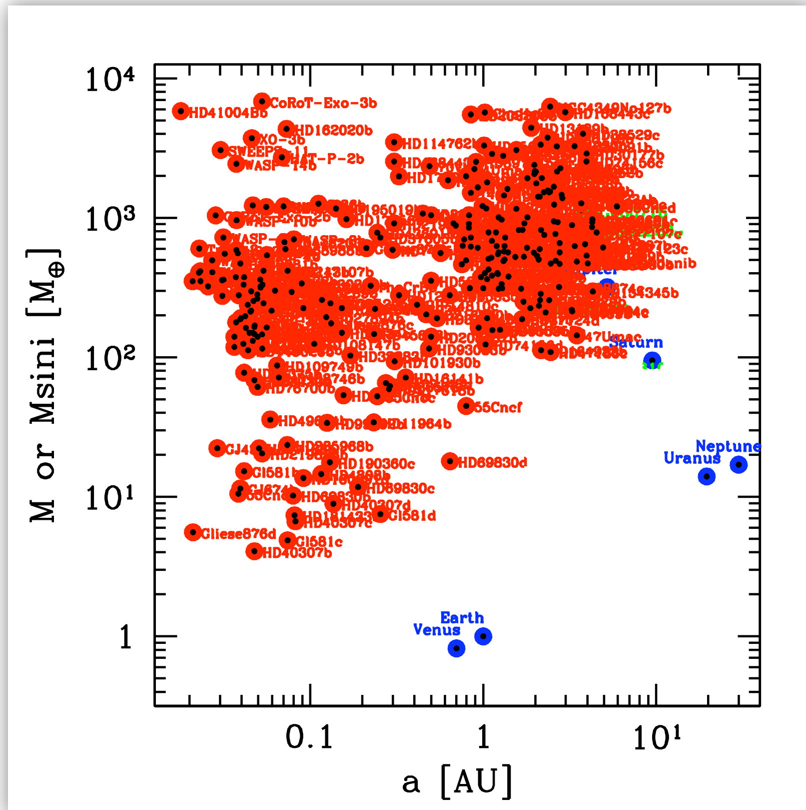
$$\frac{da_{\rm planet}}{dt} = f_{\rm I} \left(\frac{da_{\rm planet}}{dt} \right)_{\rm linear}$$

Tanaka, Takeuchi & Ward 2002

0 to 1

Extrasolar planets

- Huge diversity resulting probably from different ICs:
  - Protoplanetary disk
  - Metallicity
  - Environement



- To explain the observations, need to take into account

  1) the ICs, with the correct probability laws
  2) the observational biases

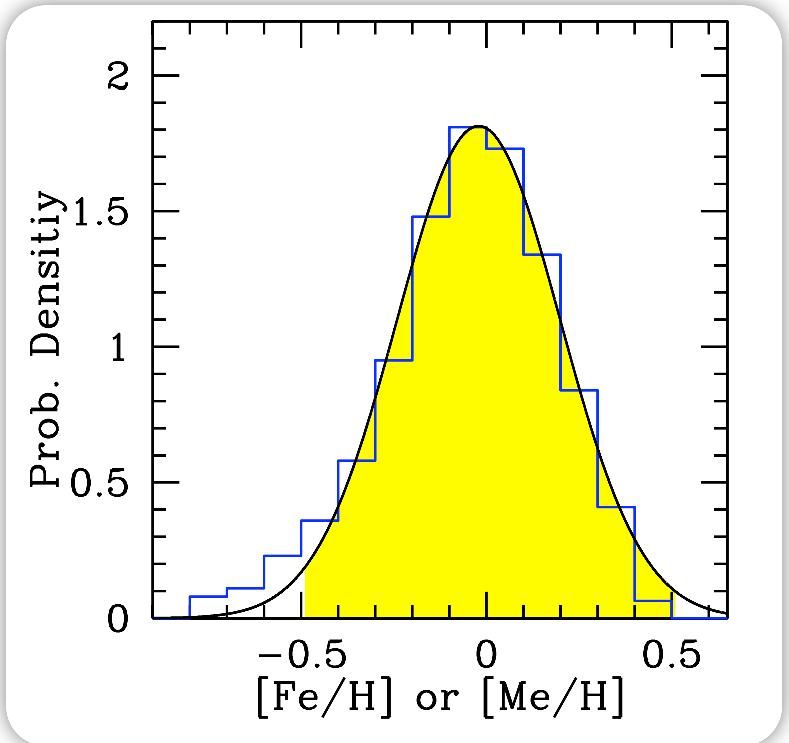
⇒ Monte-Carlo approach

Initial conditions

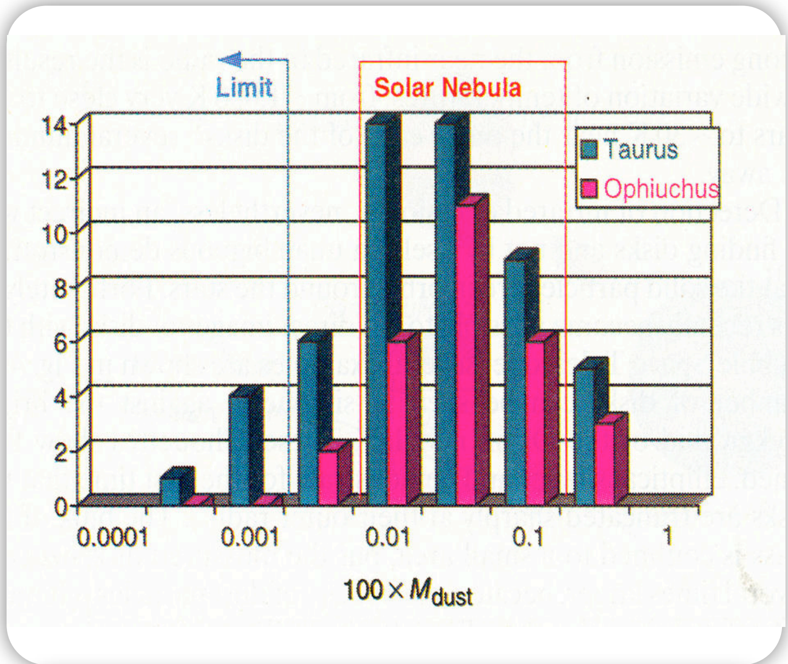
CORALIE survey

⇓

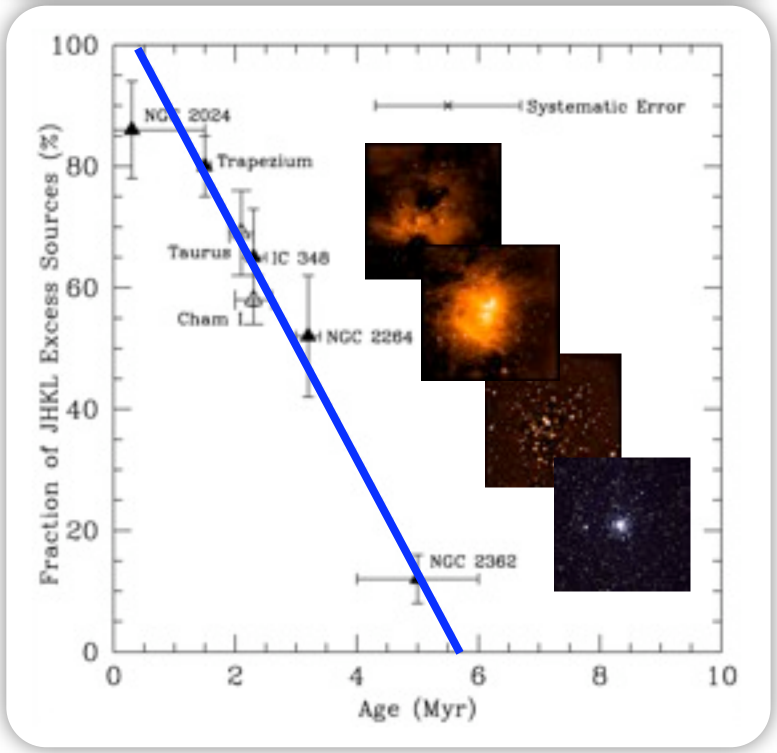
gaussian repartition



Santos et al. 2003

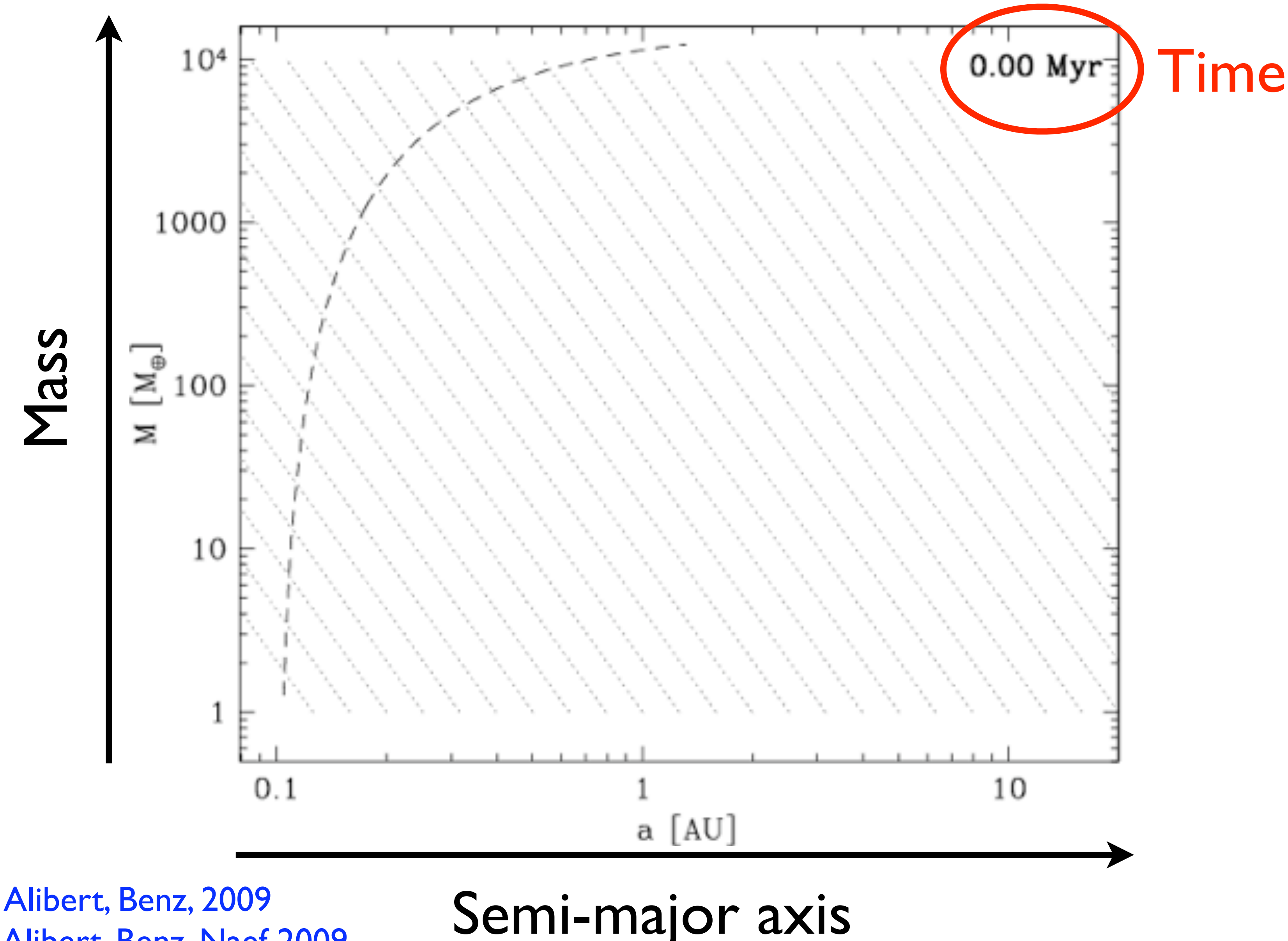


Beckwith & Sargent



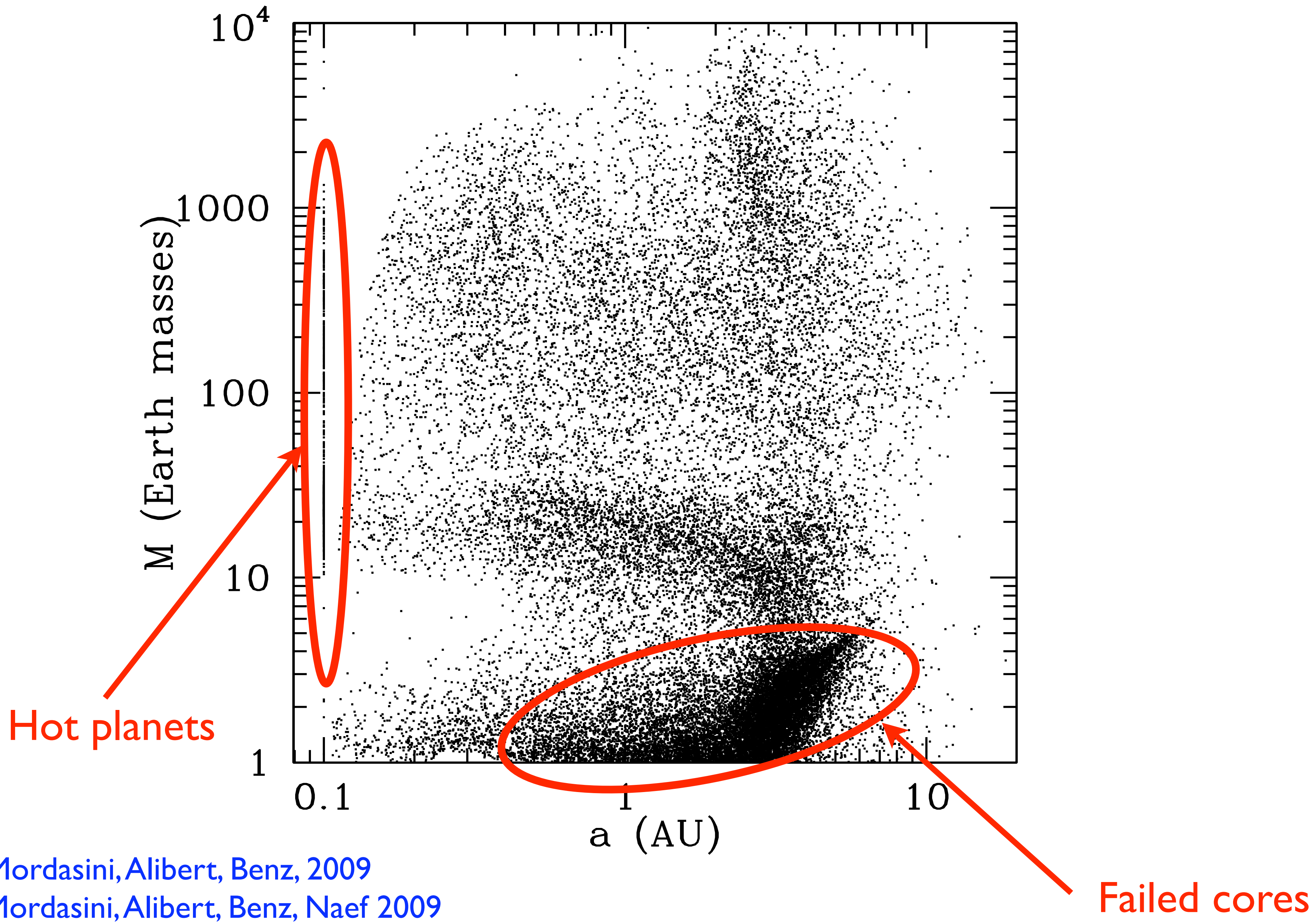
Haisch et al. 2001

Evolutionary tracks: the full population



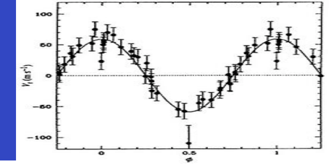
Mordasini, Alibert, Benz, 2009
Mordasini, Alibert, Benz, Naef 2009

Theoretical population

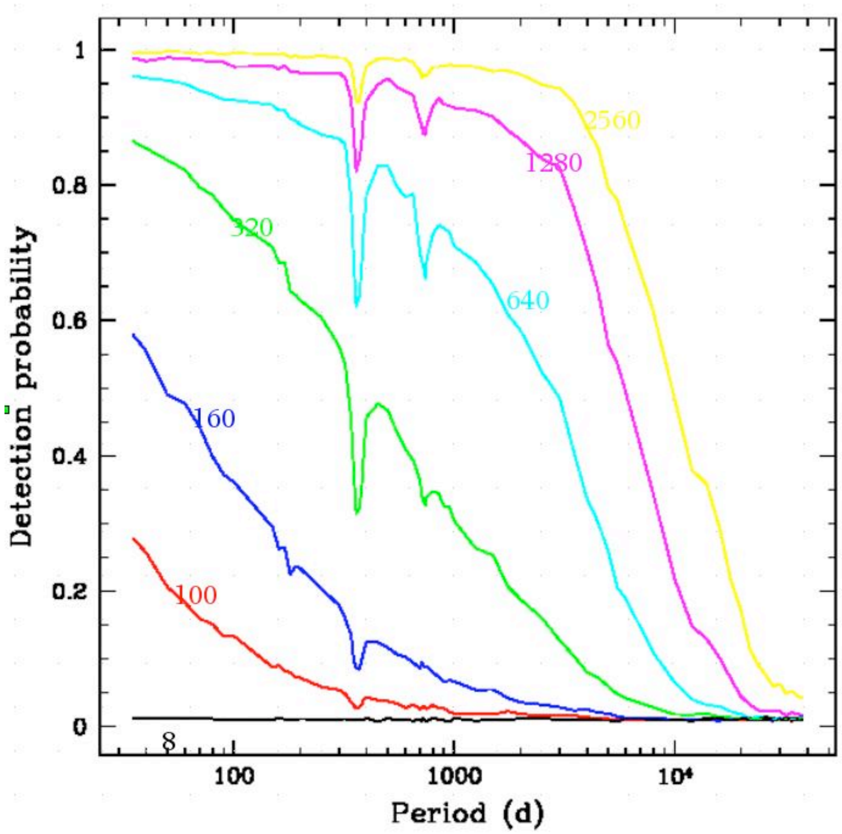


Mordasini, Alibert, Benz, 2009
Mordasini, Alibert, Benz, Naef 2009

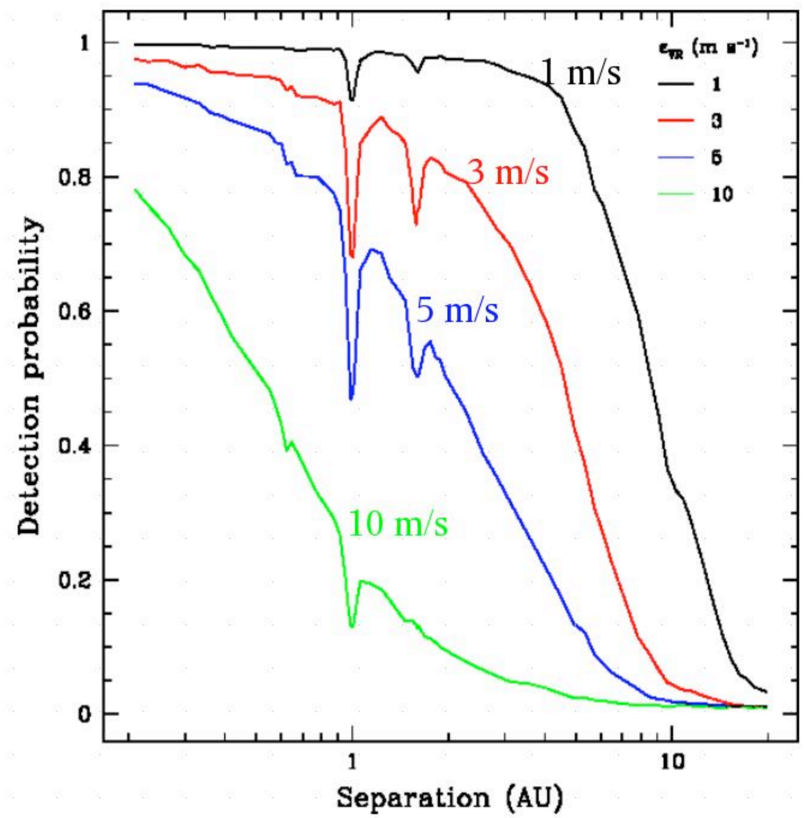
Bias (radial velocities)



Elodie



1 M_J

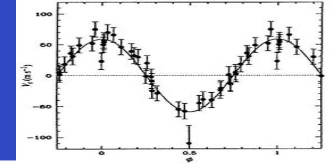


Monte-Carlo simulations by D. Naef

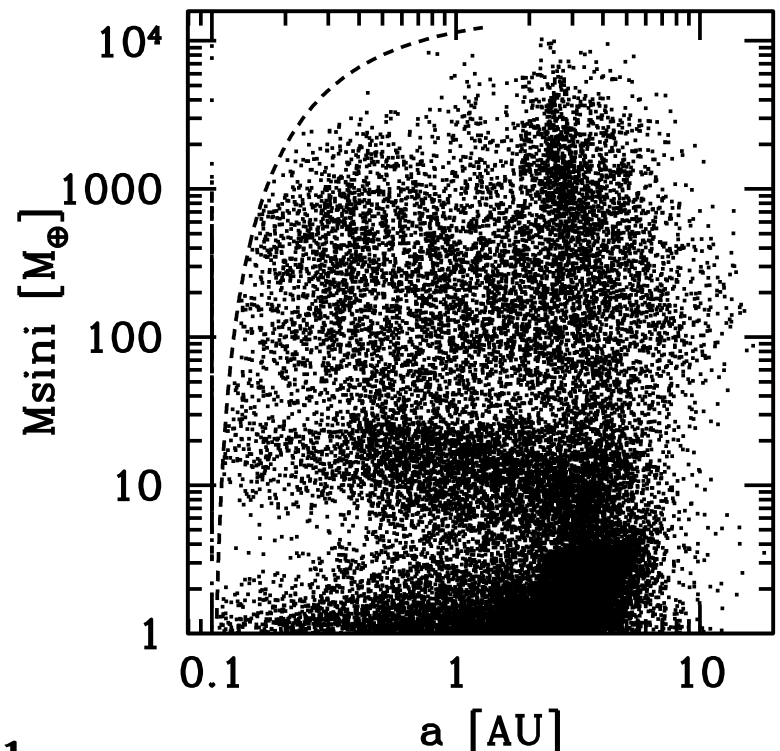
eccentricity, mass, period, observation schedule...

➥observational bias

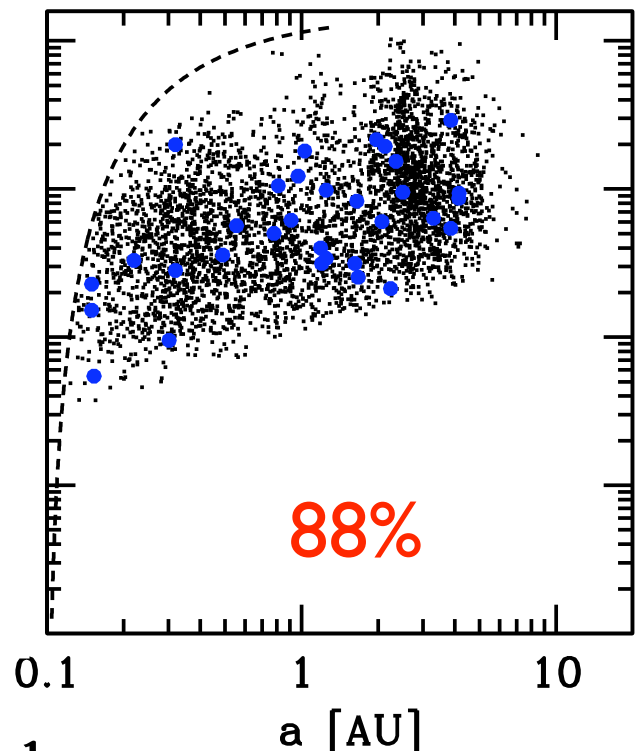
M sin(i) *vs* a

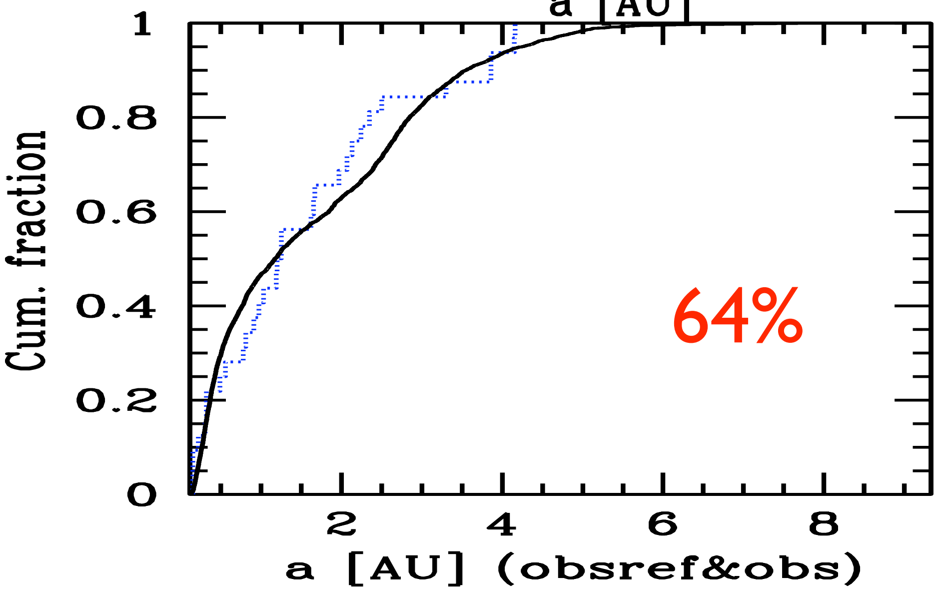


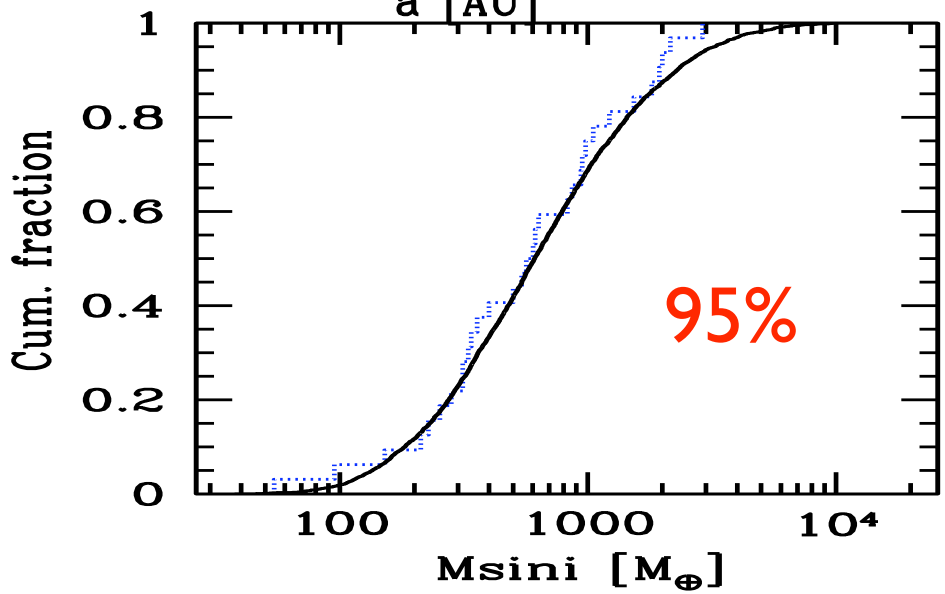
all



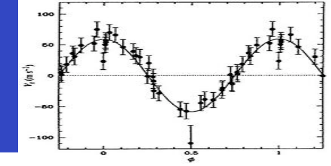
10 m/s

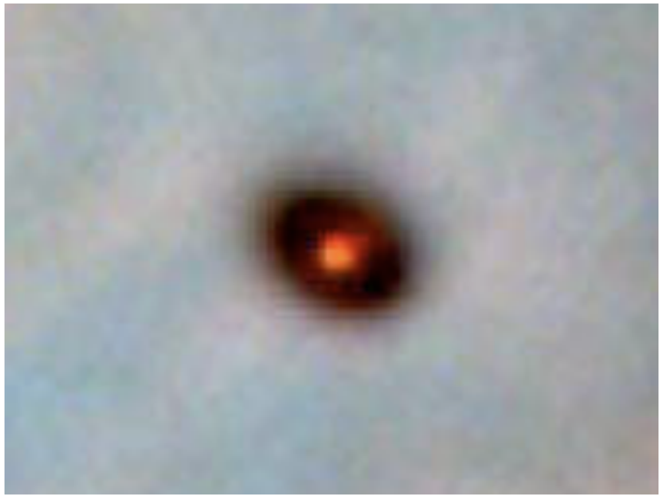




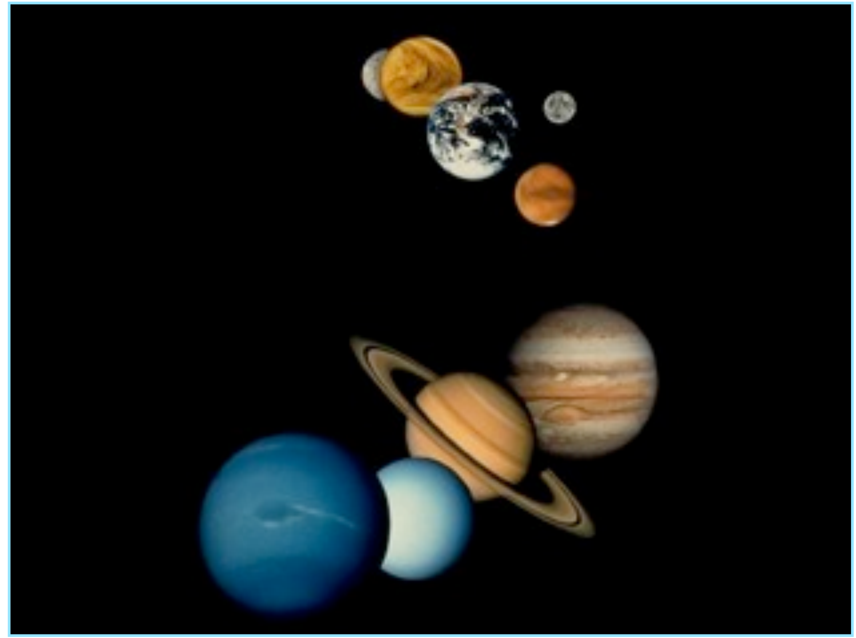


Influence of disk





⇒



an “observed” disk...

⇒ Disk lifetime ?

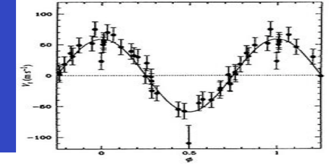
⇒ Disk mass ?

⇒ Heating sources ?

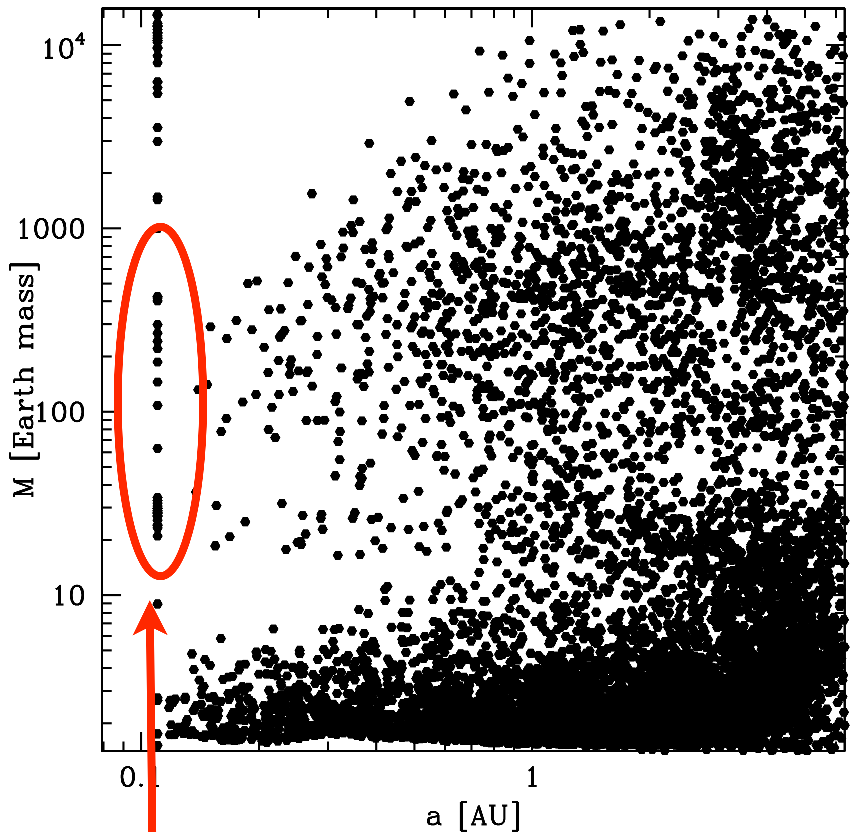
⇒ SED and evolution ?

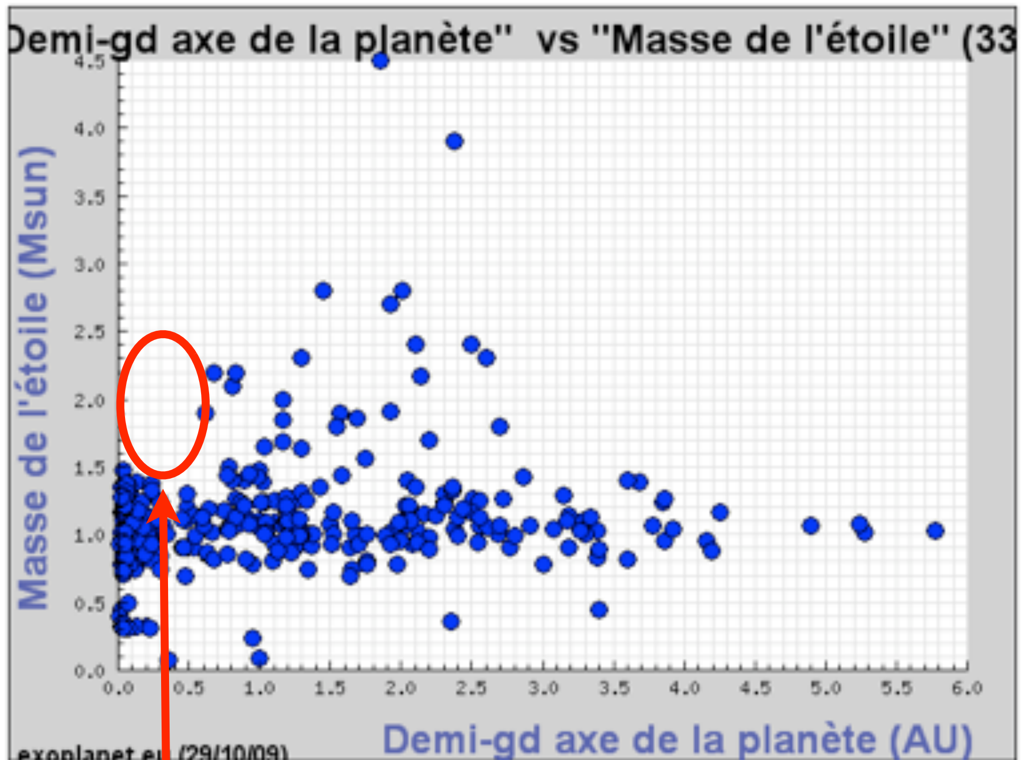
Consequences on planetary population

Disk lifetime ?



2.0 Msun





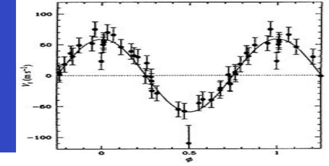
No observed hot planets around stars > 1.5 Msun

disk lifetime effect ? (e.g. Johnson et al. 2007)

Hot Planets
around massive stars

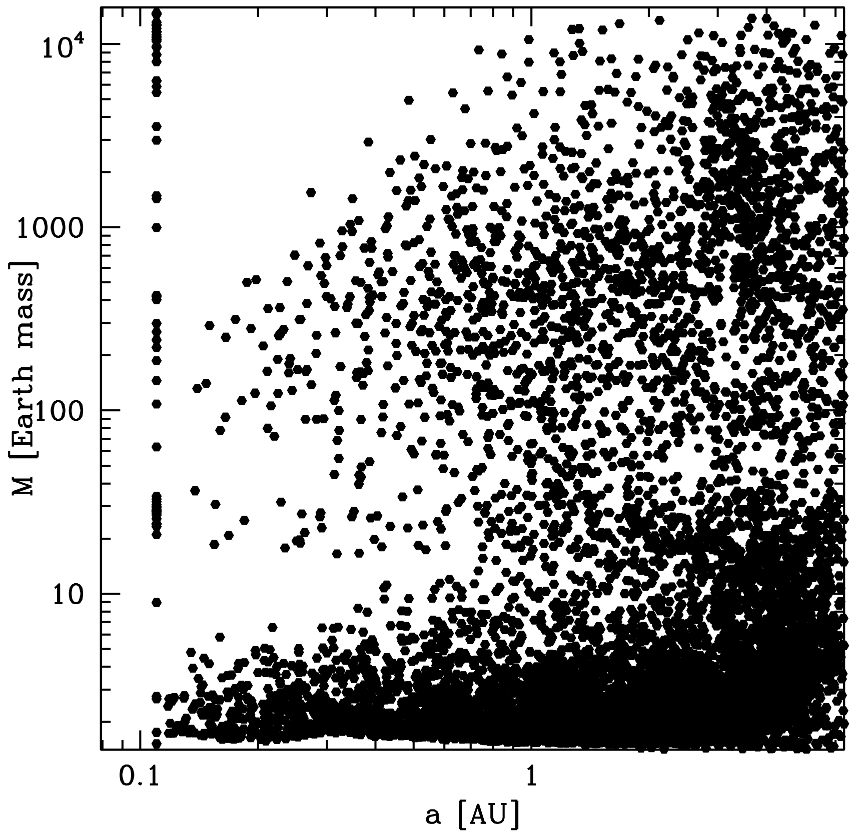
Alibert, Mordasini, Benz, in prep

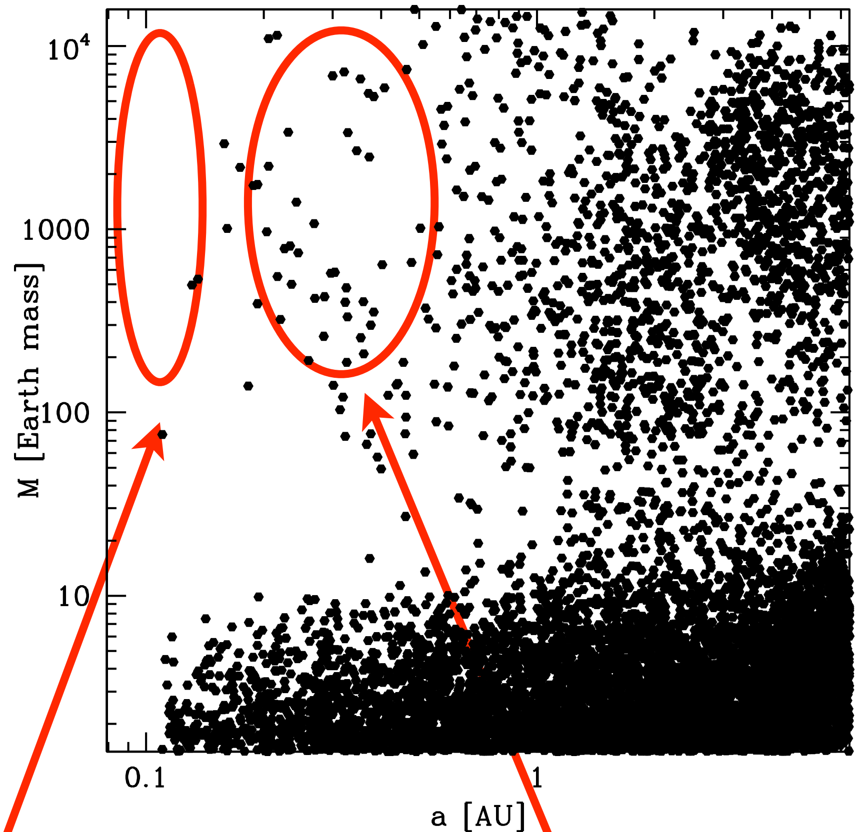
Disk lifetime ?



$$T_{\mathrm{disk}} \propto M_{\mathrm{star}}^{0} \qquad T_{\mathrm{disk}} \propto M_{\mathrm{star}}^{-1/2} \text{ for } M > 1.5 M_{\odot}$$

Kennedy & Kenyon (2009)



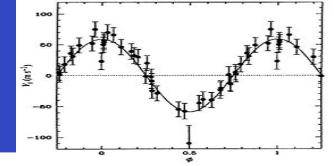


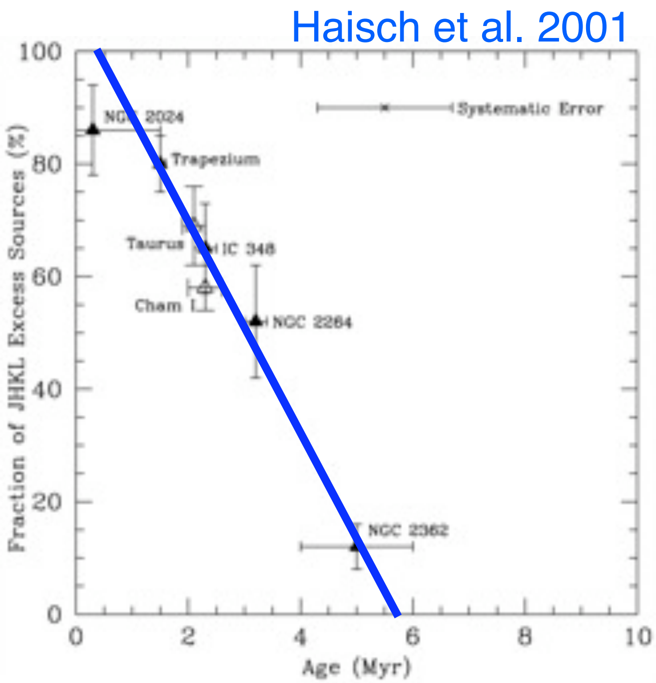
no Hot Planets

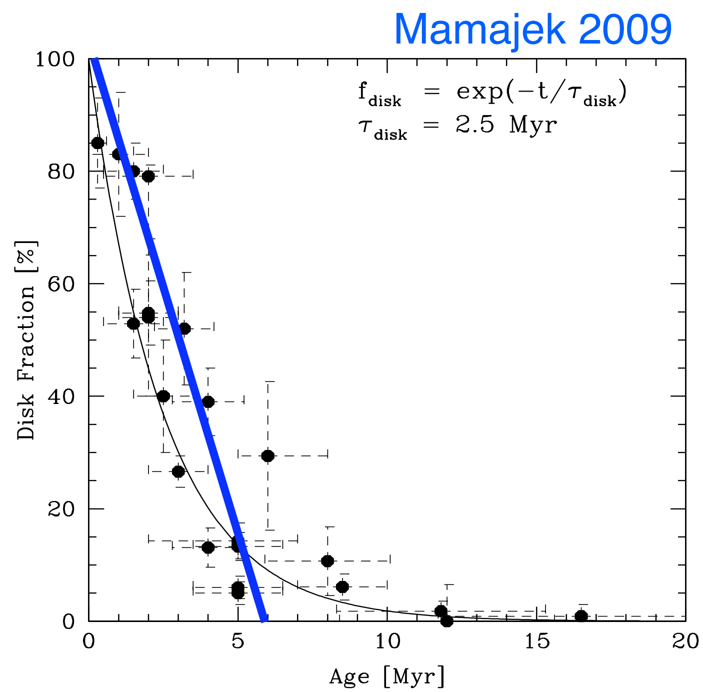
few warm planets
statistical comparison with obs ?

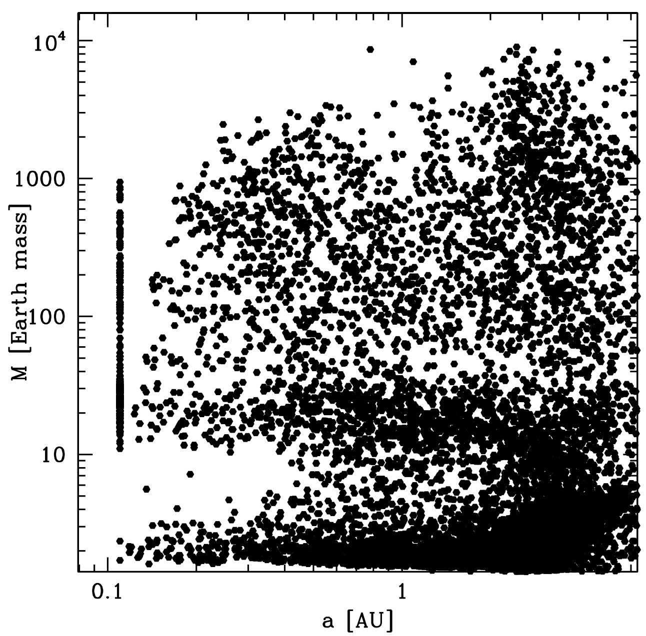
Alibert, Mordasini, Benz, in prep

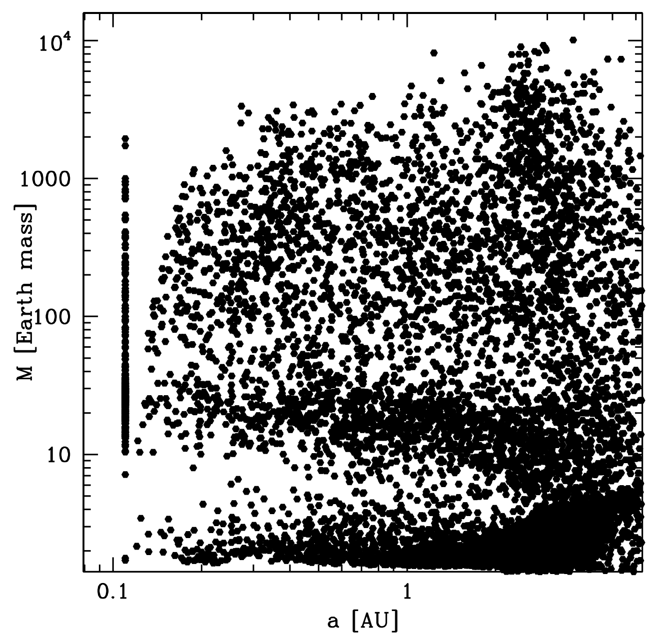
Disk lifetime ?



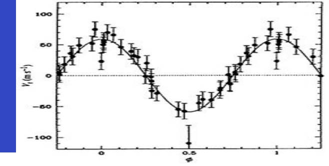


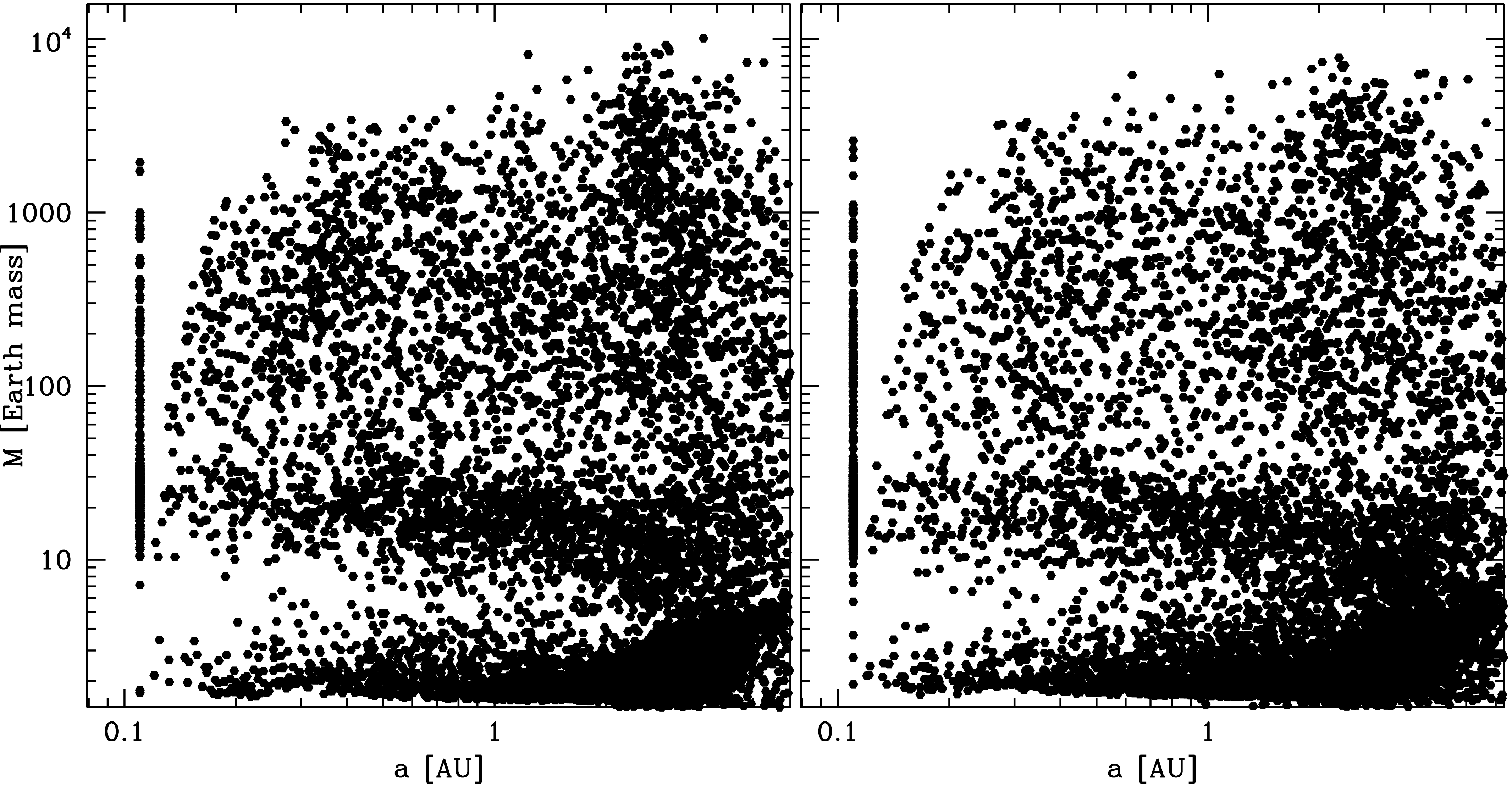






Disk lifetime ?

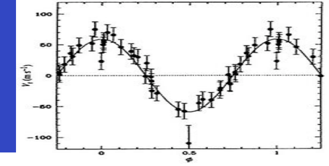


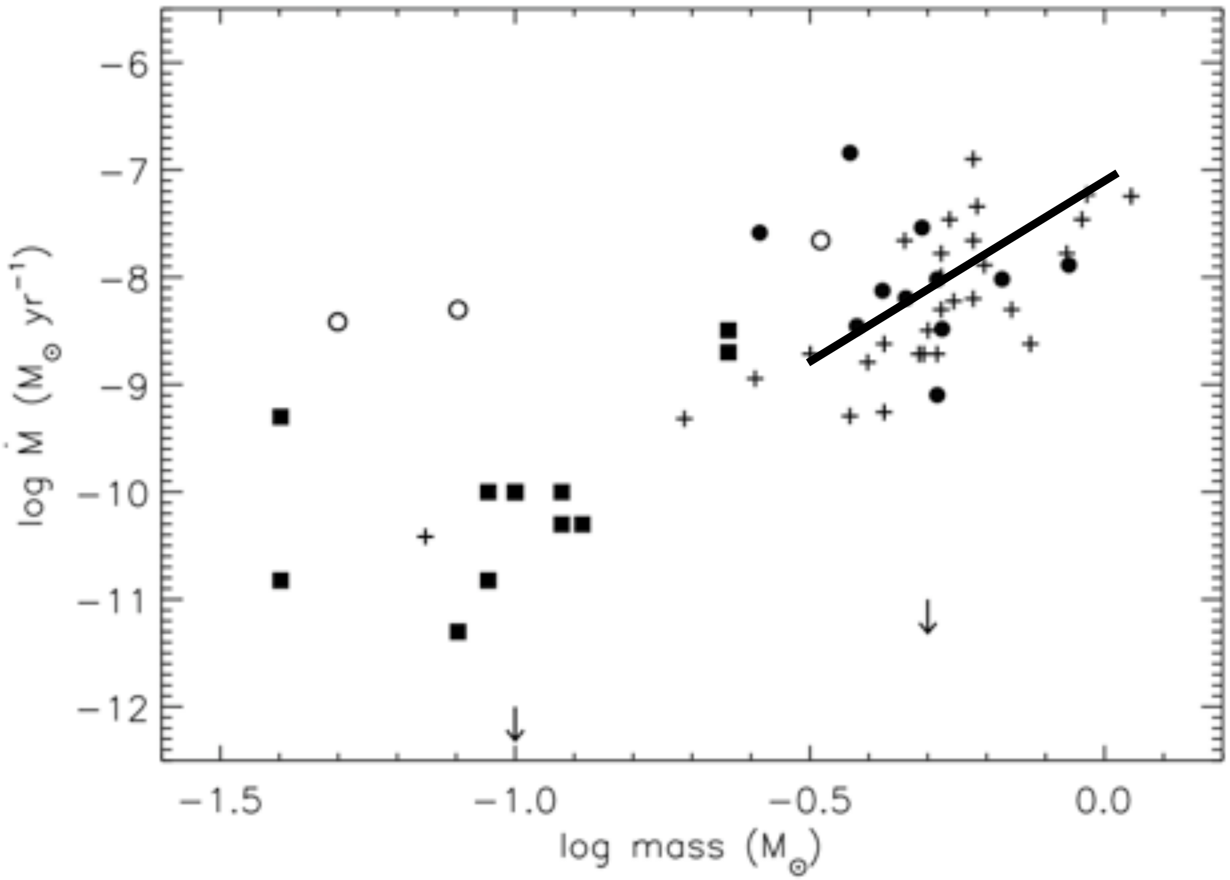


With correlation

Without correlation

Disk mass ?





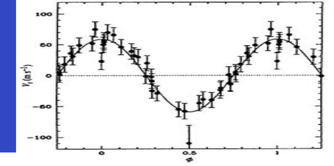
Muzerolle et al. 2003

assume $M_{\rm disk} \propto M_{\rm star}^{\alpha_D}$

α_D adjusted to reproduce the $\dot{M}_{\rm disk}$ *versus* $M_{\rm star}$ relation

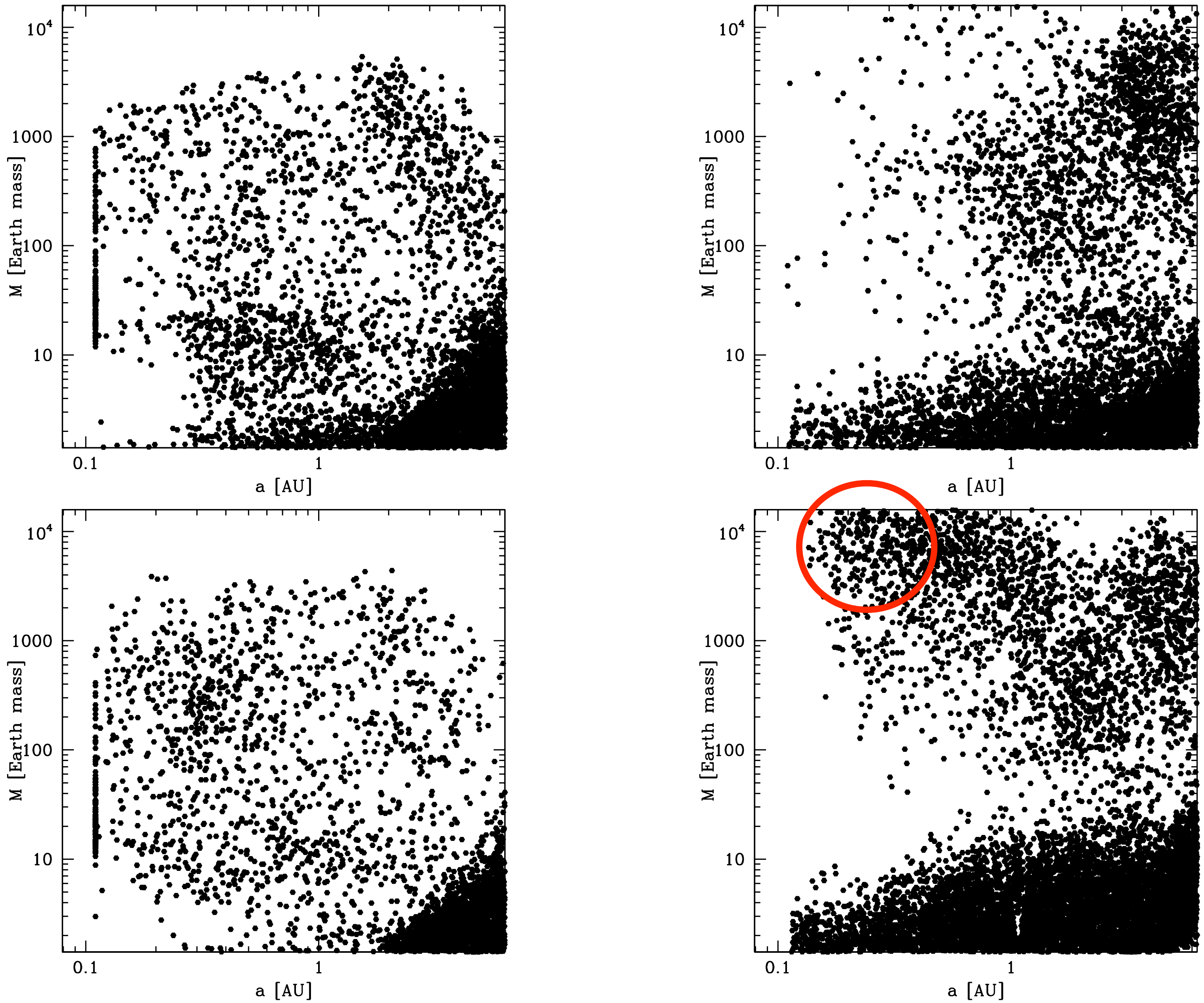
!! see also dependance of the active zone with Mstar !!

Disk mass ?



$M_{disk} \propto M_{star}^0$

$M_{disk} \propto M_{star}^2$

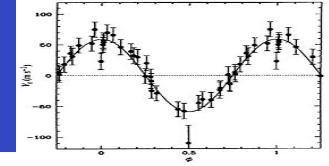


Alibert, Mordasini, Benz, in prep

0.5 M_{sun}

2.0 M_{sun}

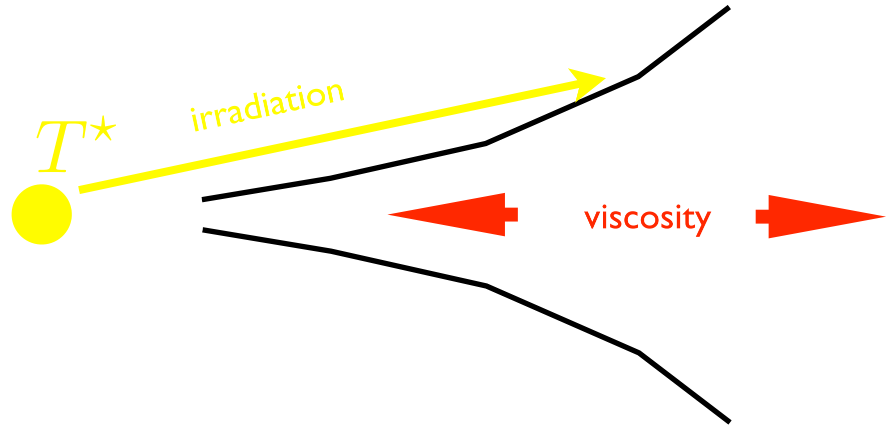
Heating sources ?



Heating sources

1) viscous heating

$$\Gamma_{\rm visc} = \frac{9}{4}\rho\nu\Omega^2$$



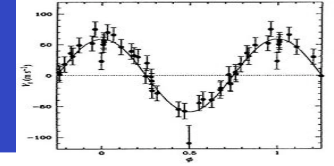
2) irradiation

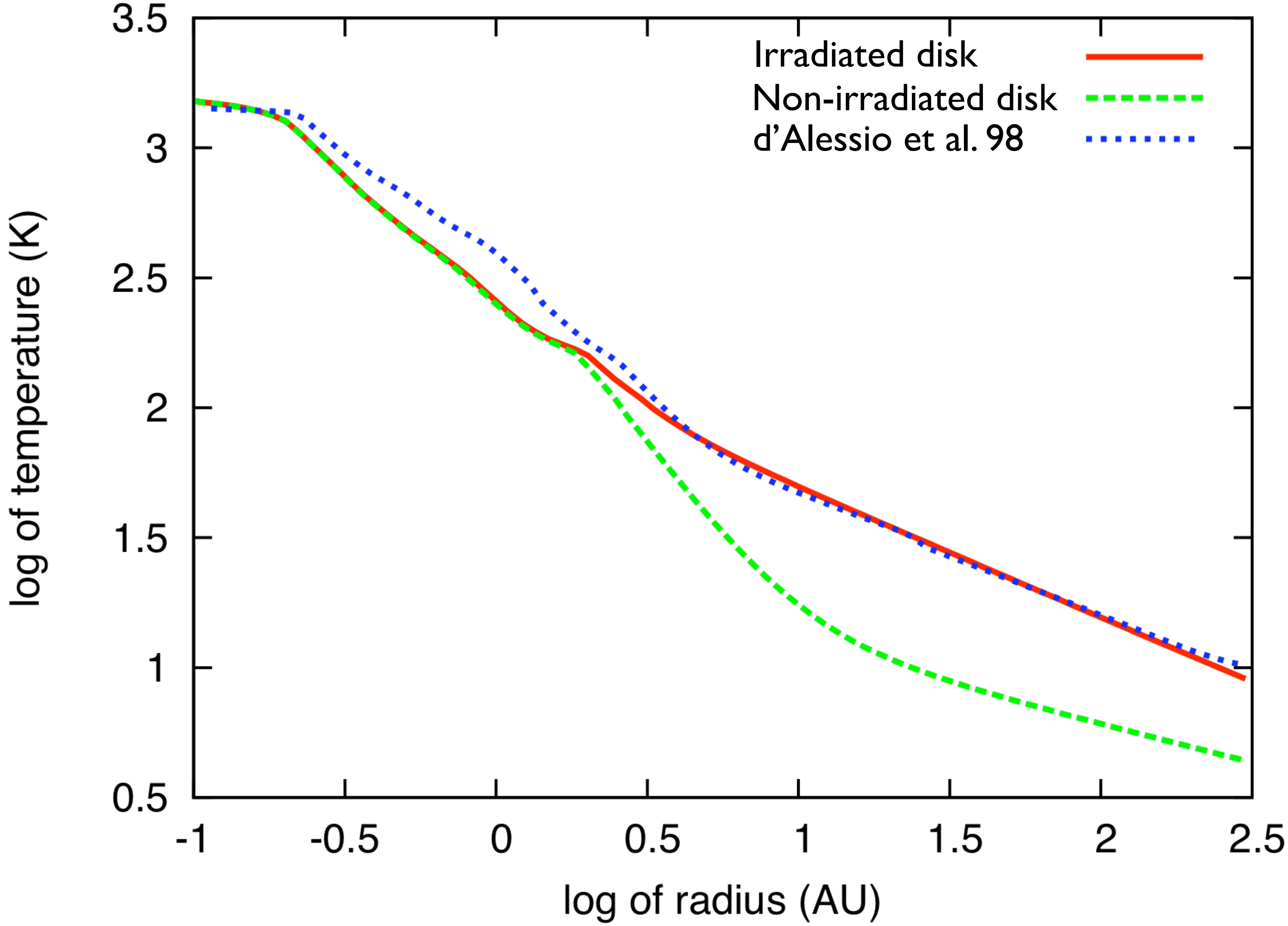
$$T_{irr} = T_* \left[\frac{2}{3\pi}\left(\frac{R_*}{r}\right)^3 + \frac{1}{2}\left(\frac{R_*}{r}\right)^2 \left(\frac{H}{r}\right)\left(\frac{\mathrm{d}\ln H}{\mathrm{d}\ln r} - 1\right)\right]^{1/4}$$

eq. value: 9/7

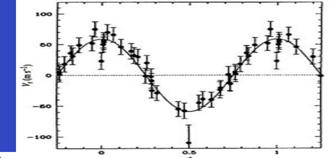
irradiation flux added to the surface flux (due to mass accretion)

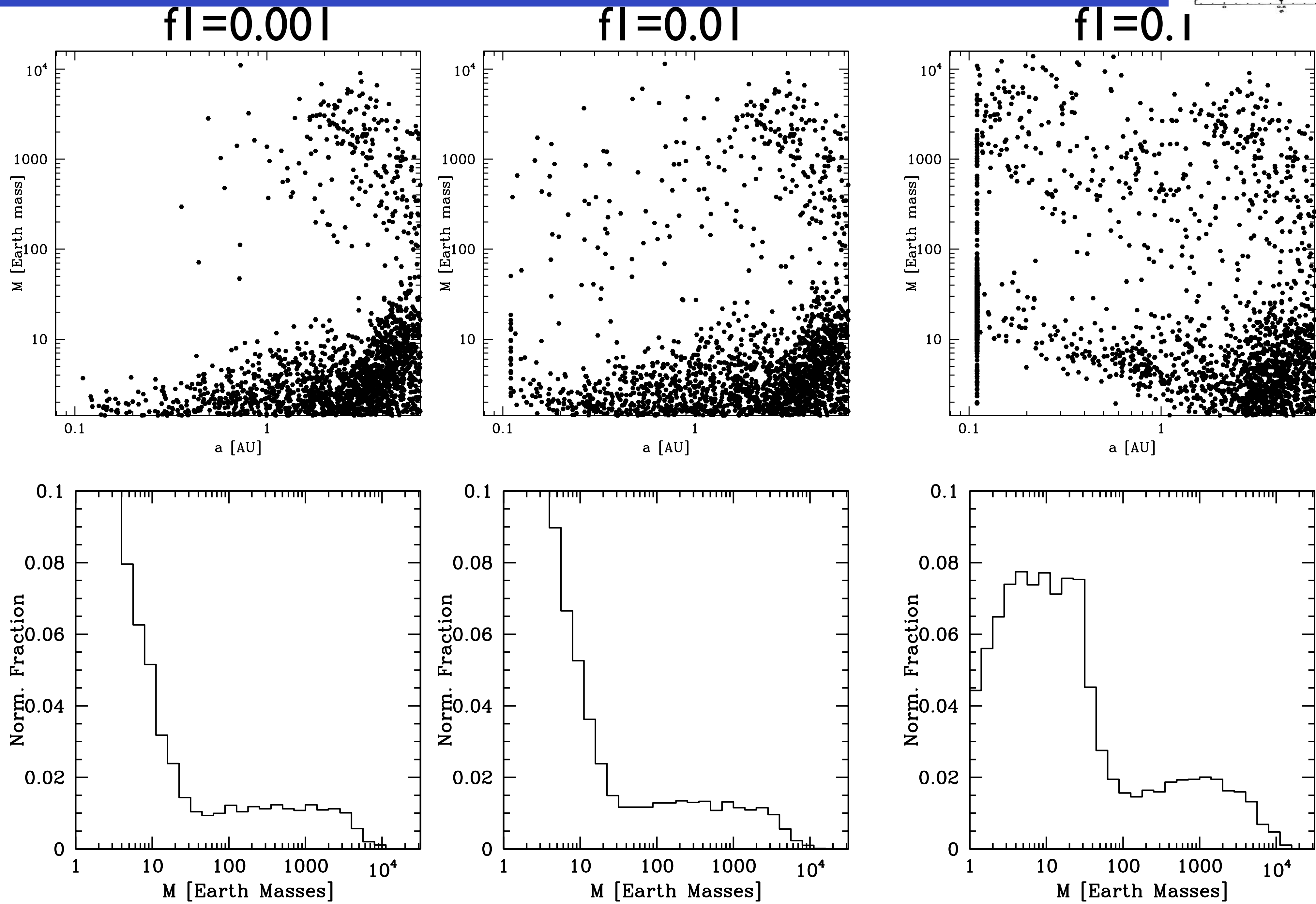
Heating sources ?





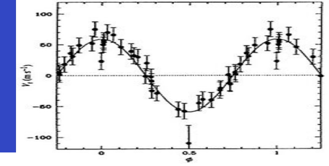
Heating sources ?



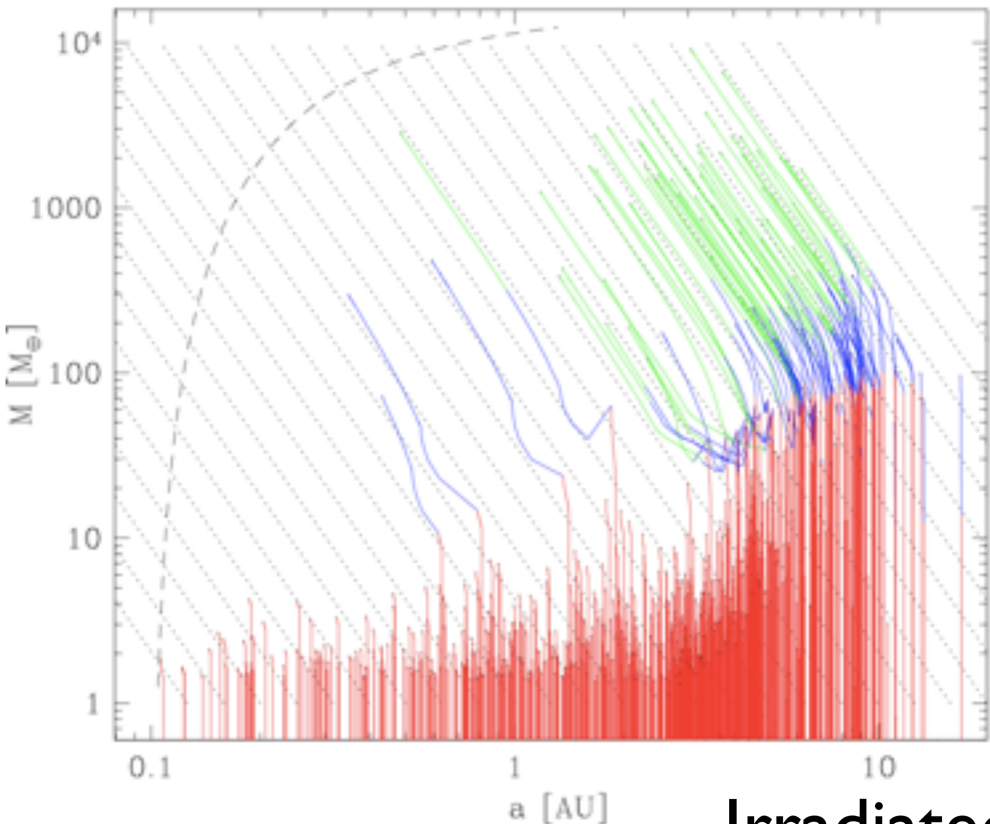


Fouchet, Alibert, Mordasini, Benz, in prep

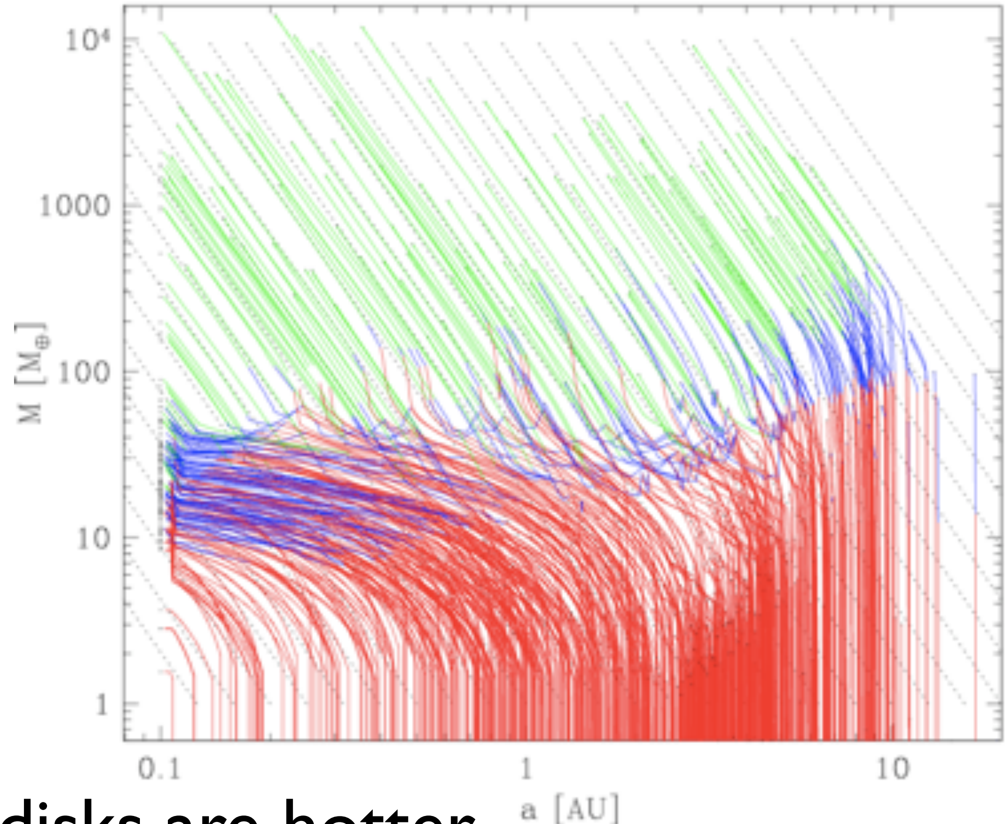
Heating sources ?



fI=0.001



fI=0.1



Irradiated disks are hotter

$\Downarrow$

H/R larger than non irradiated

$\Downarrow$

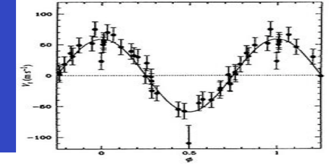
type II for larger masses

$\Downarrow$

need larger type I migration to collect mass

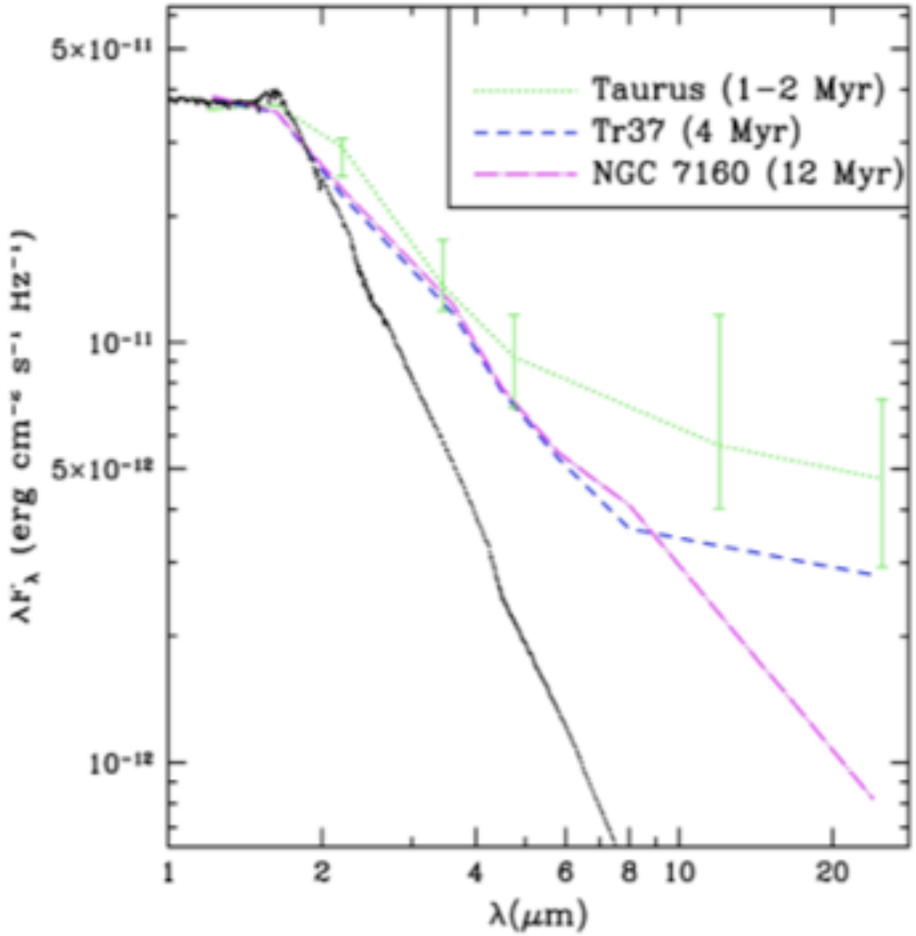
newastart/noFL/irr/
P1.0

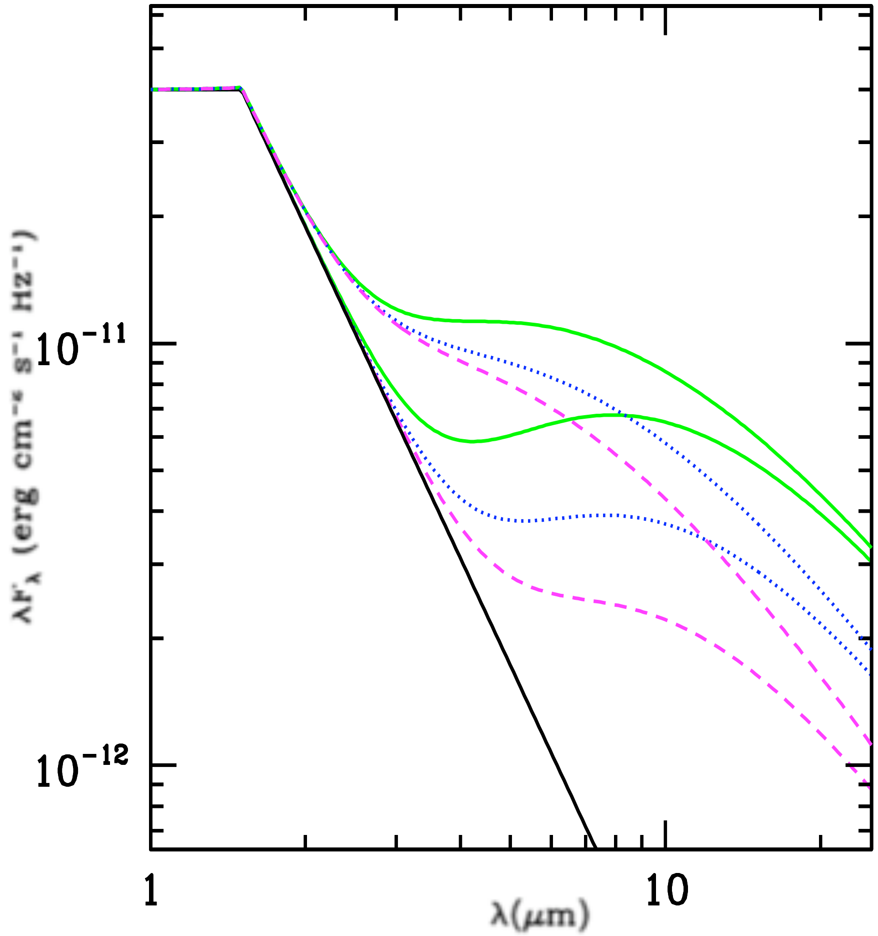
SED and evolution ?



No inclination, gas and dust in equilibrium, etc...

Sicilia-Aguilar et al. 2006

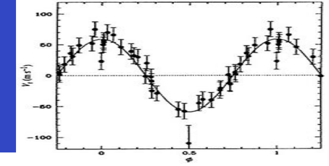


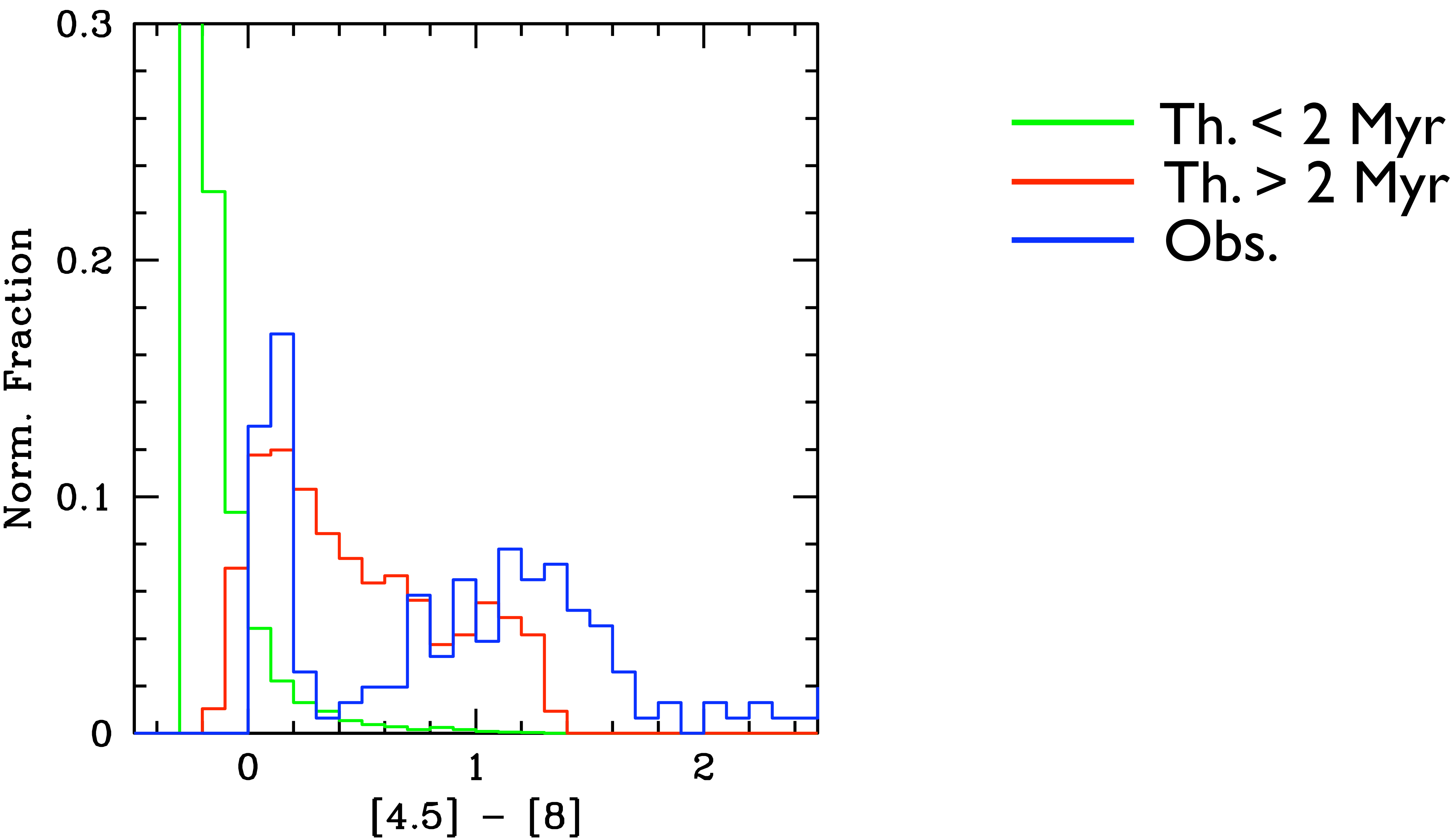


Rdisque = 0.05AU -> 300AU
Sigma(@5AU) = 900g/cm2

homologous depletion of disks (Thayne's talk)

SED and evolution ?





Many thanks to Luisa Rebull and collaborators for providing the unpublished Spitzer photometry

Conclusions

- first generation extended models allow quantitative predictions and can:
  - reproduce the diversity of the exoplanets
  - fit RV data for G stars, with high KS values

- disk structure and evolution is a key ingredient for these models

- second generation of models will focus on comparison with disks:
  - disk properties for different stellar type
  - disk evolution / SED