Implications of Space Microlensing Results for Planet Formation Theory

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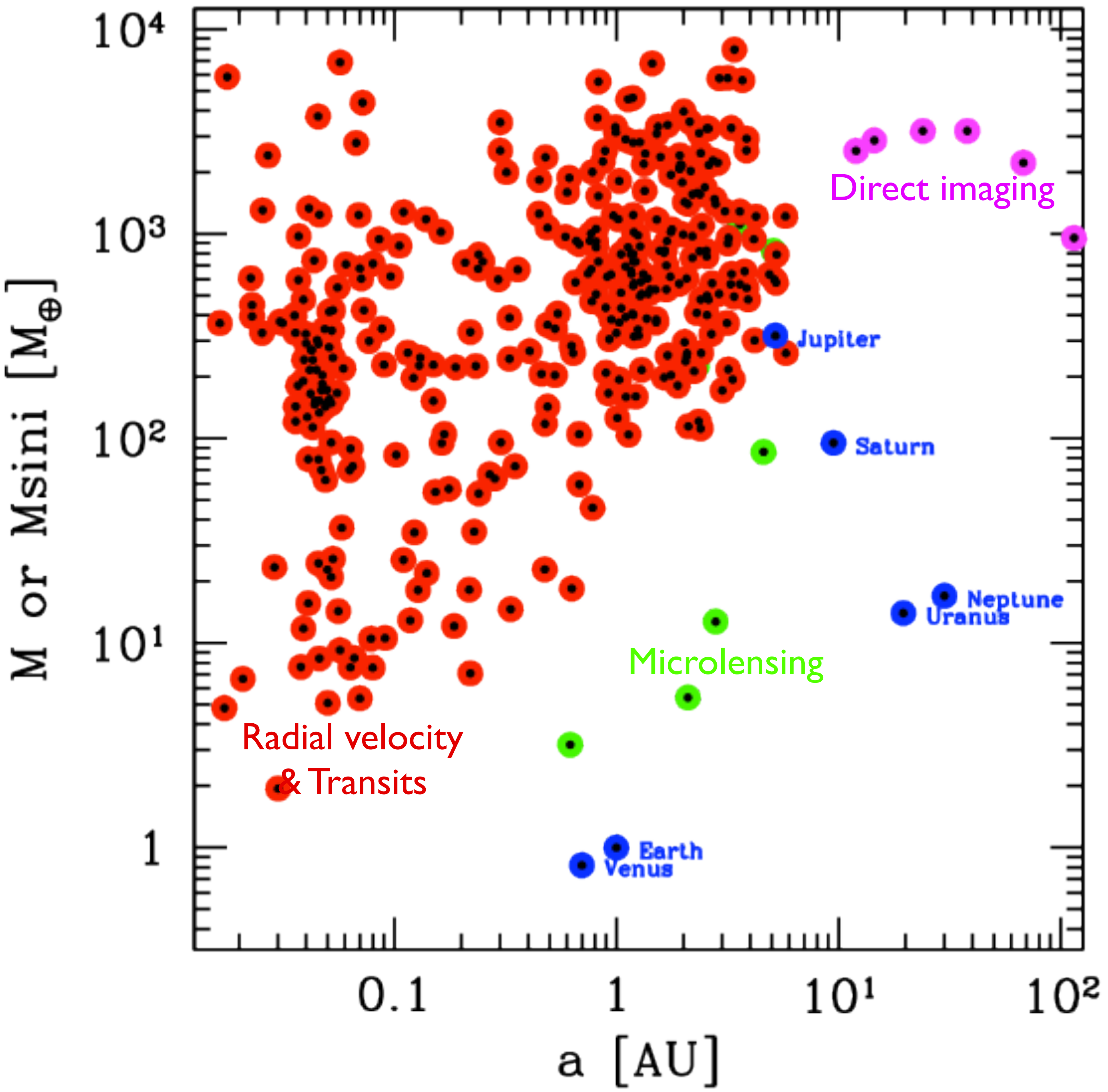


Talk structure

I. Introduction

II. Planet formation modeling

III. Planetary population synthesis

IV. Microlensing and the planetary mass distribution

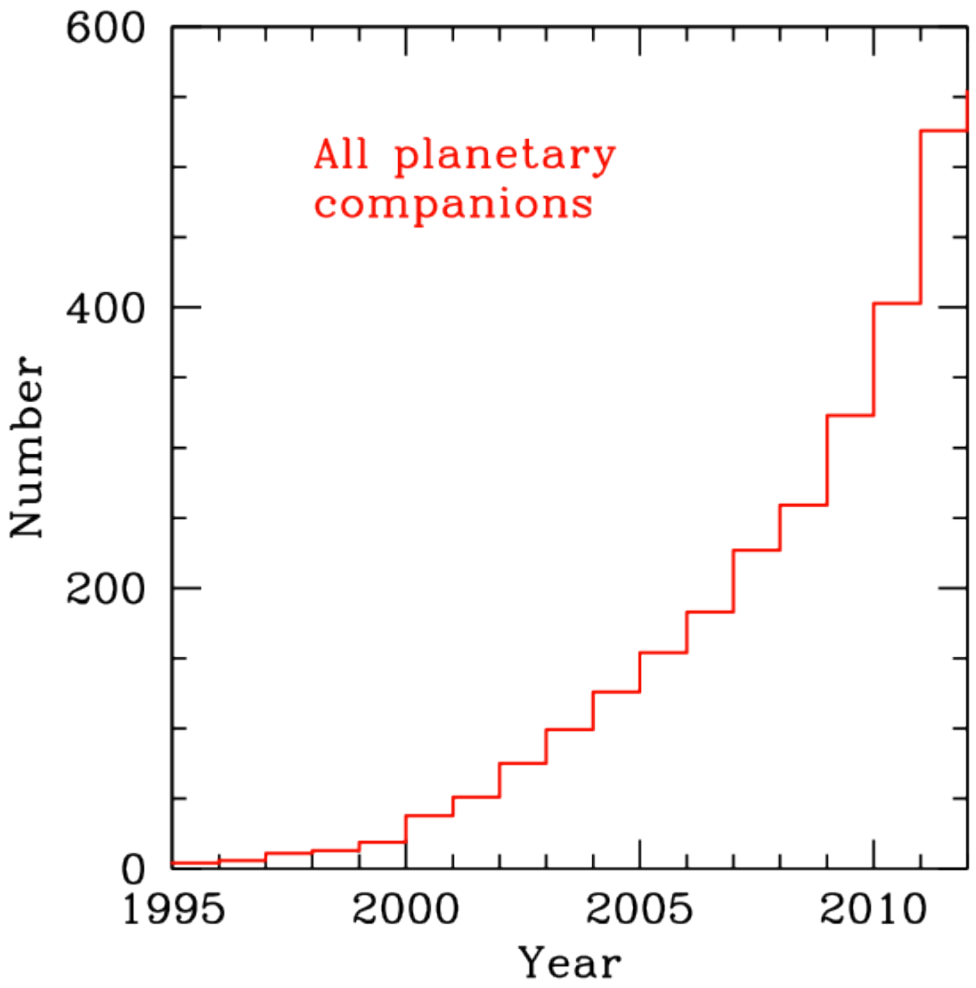
V. Microlensing and the planetary semimajor axis distribution

VI. Towards quantitative comparison

VII. Conclusions

I Introduction

A *quickly* *moving field*



and 2326 KEPLER candidates

14 microlensing detections in 13 systems.

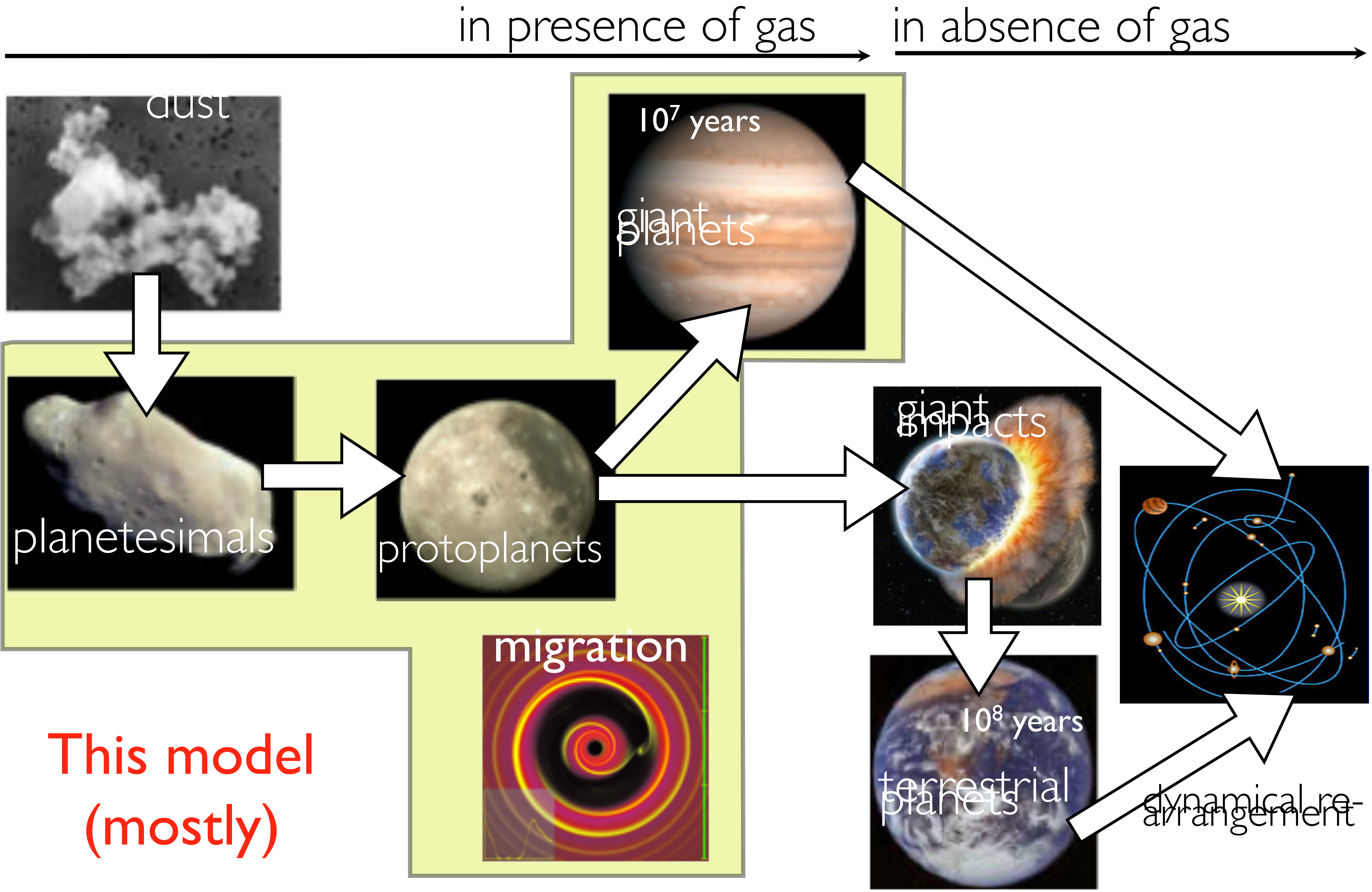
- Phase of rapid progress in observational exoplanet research.
- Large number of detections from space mission (e.g. Kepler) and ground (e.g. HARPS). More to come (WFIRST, GAIA..).
- Field observationally driven. Theory struggles to keep up...

- Difficulty: different techniques constrain different aspects. How to unite?
- Space missions provide observations of a large number of exoplanets. Data can be treated as a statistical ensemble. This could help.
- Improve formation theory
    - statistical comparison
    - use data (constraints) from many complementary techniques

II Planet formation modeling

Planet Formation: stages

Star & circumstellar (or protoplanetary) disk



in presence of gas

in absence of gas

dust

planetesimals

protoplanets

10^7 years

giant planets

migration

giant impacts

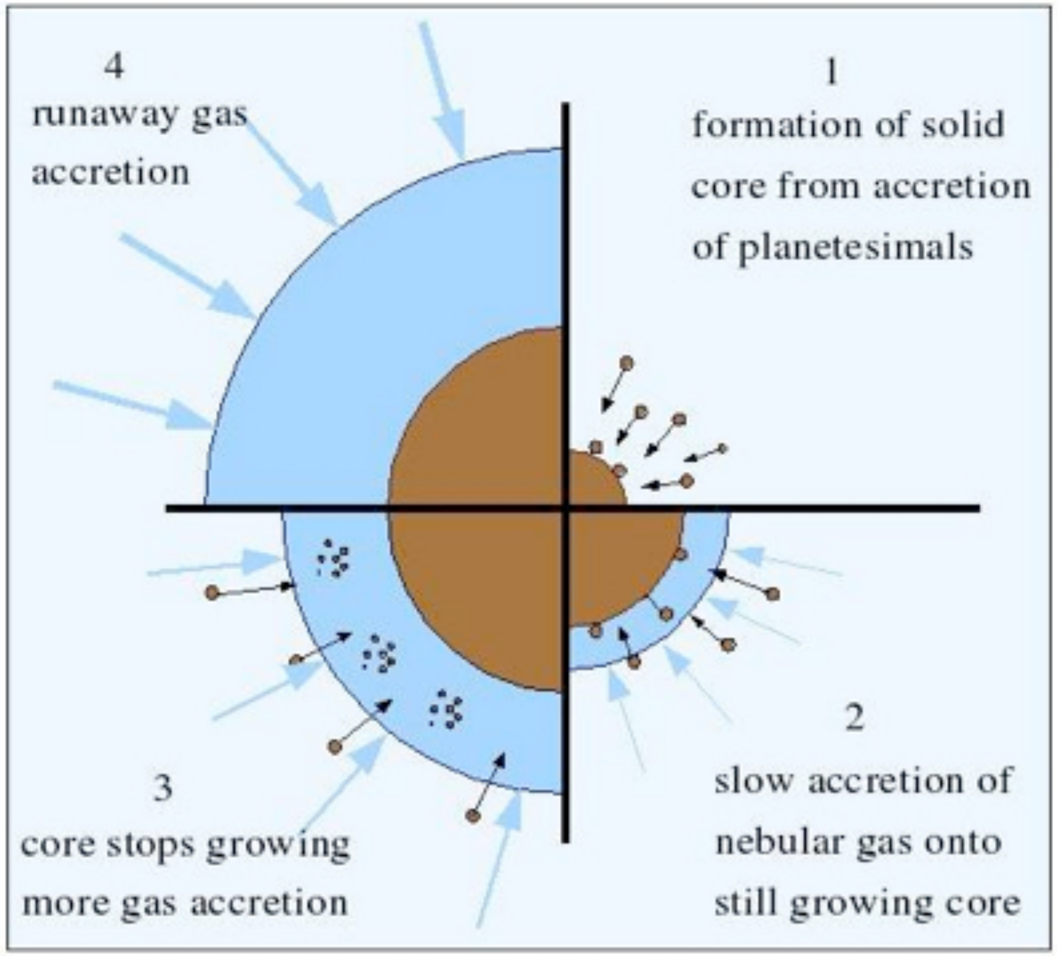
10^8 years

terrestrial planets

dynamical re-arrangement

This model (mostly)

Core Accretion Paradigm



Perri & Cameron 1974, Mizuno et al. 1978, Mizuno 1980, Bodenheimer & Pollack 1986, Pollack et al. 1996

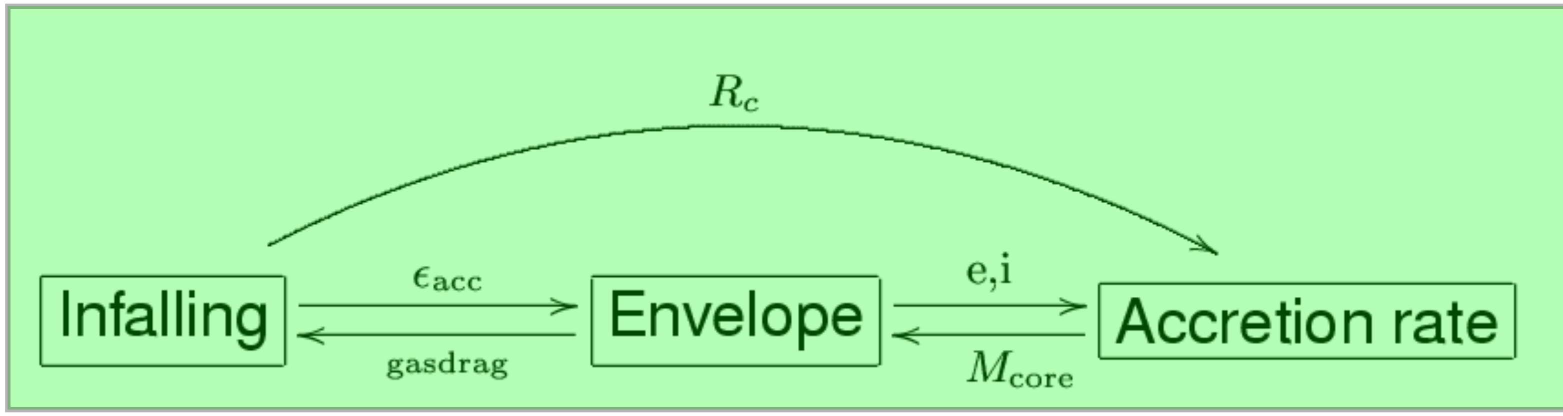
1)Build up critical core
2)Accrete gas

A timing issue!

Follow gas and solid accretion of an initially small solid core (ice, rock) surrounded by a gaseous envelope (H2 & He) in the protoplanetary disk consisting itself of gas and planetesimals.

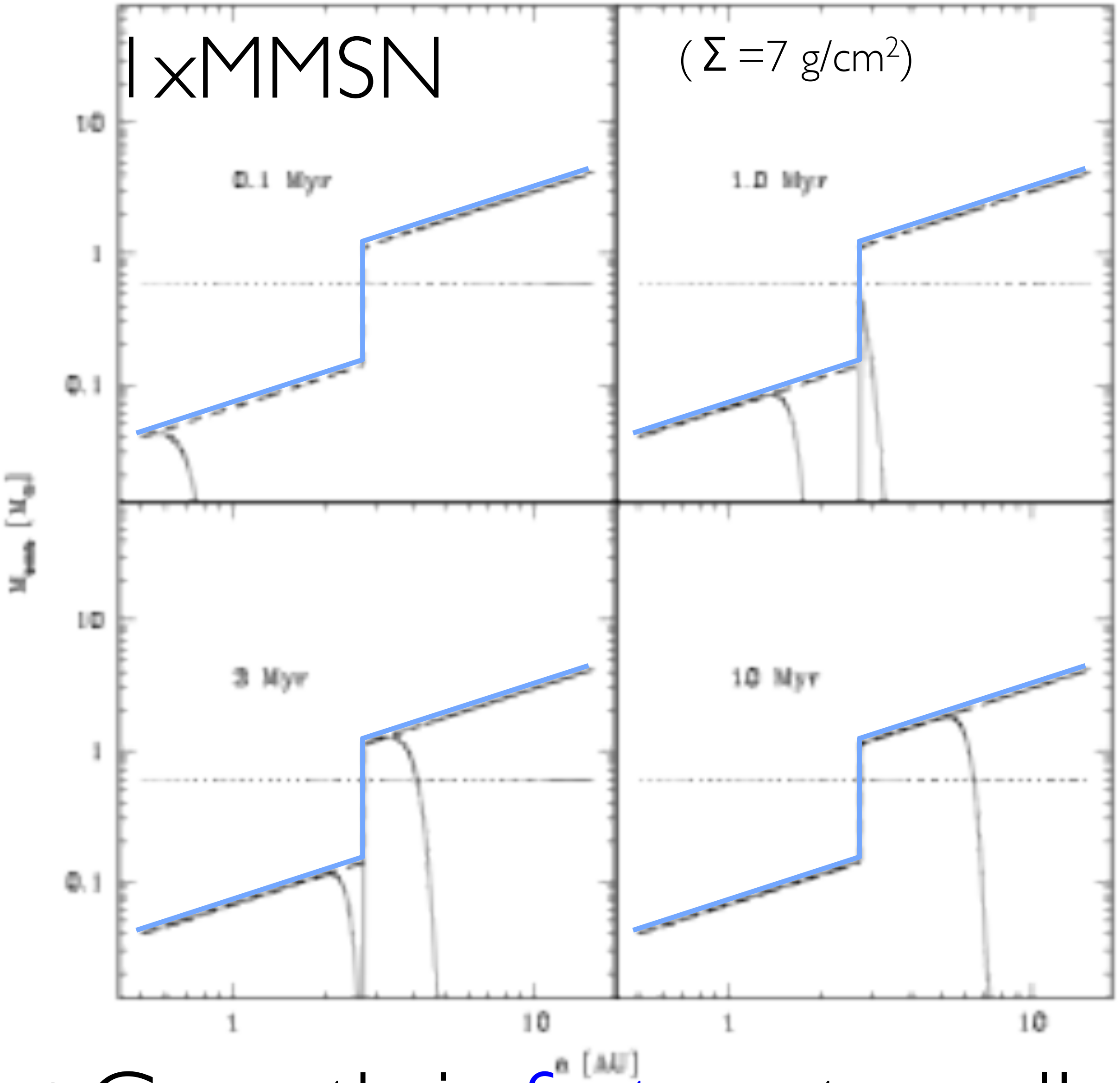
Divide problem in three modules

- *Planetesimal accretion rate*
- *Gas accretion (envelope)*
- *Planetesimal-envelope interaction (infalling)*



Core growth as a function of *a*

Mordasini et al. 2009


1xMMSN

(Σ =7 g/cm^2)

- Growth is faster at small distances
- But stops at smaller masses. No giant planet *in situ.*
- Quick *and* massive: Beyond the iceline (here @ 2.7 AU)
- Higher Σ: Protoplanets more massive & quicker: GP cores

Jupiter in situ formation

Solid accretion: collisional growth from planetesimals

Gas accretion: planetary structure equations

Model assumptions: Pollack et al 1996

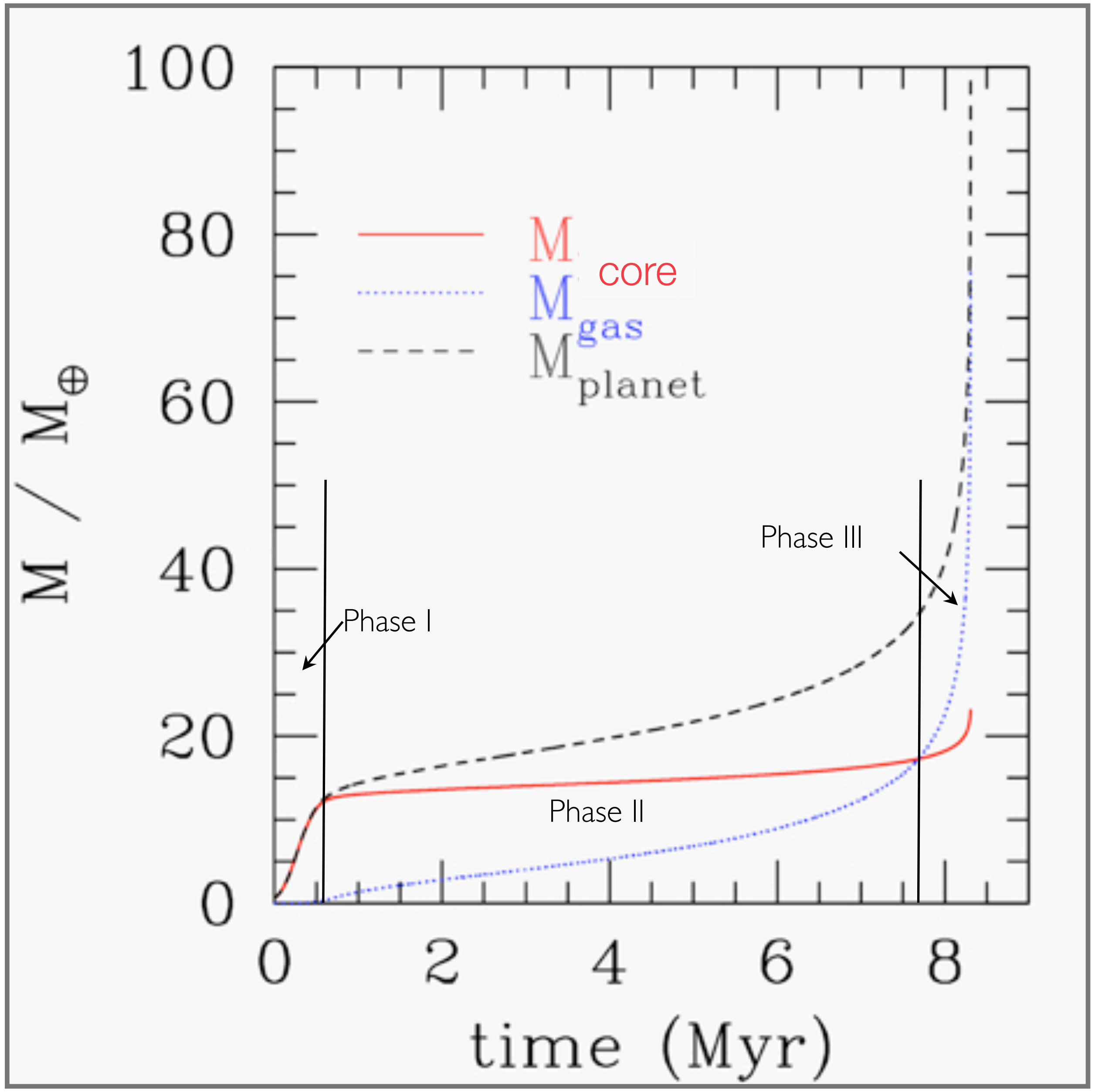
- Constant ambient T and P (no disk evolution)
- In situ formation (no migration)

Phase I: Rapid build up of a core by accretion of planetesimals.

Phase II: Accretion of gas and planetesimals.

Phase III: Runaway gas accretion at $M_{core} > M_{crit}$: rapid growth from ~30 to >100 M_E.

4 x minimum mass solar nebula



Alibert, Mordasini & Benz 2004

Extended core accretion model

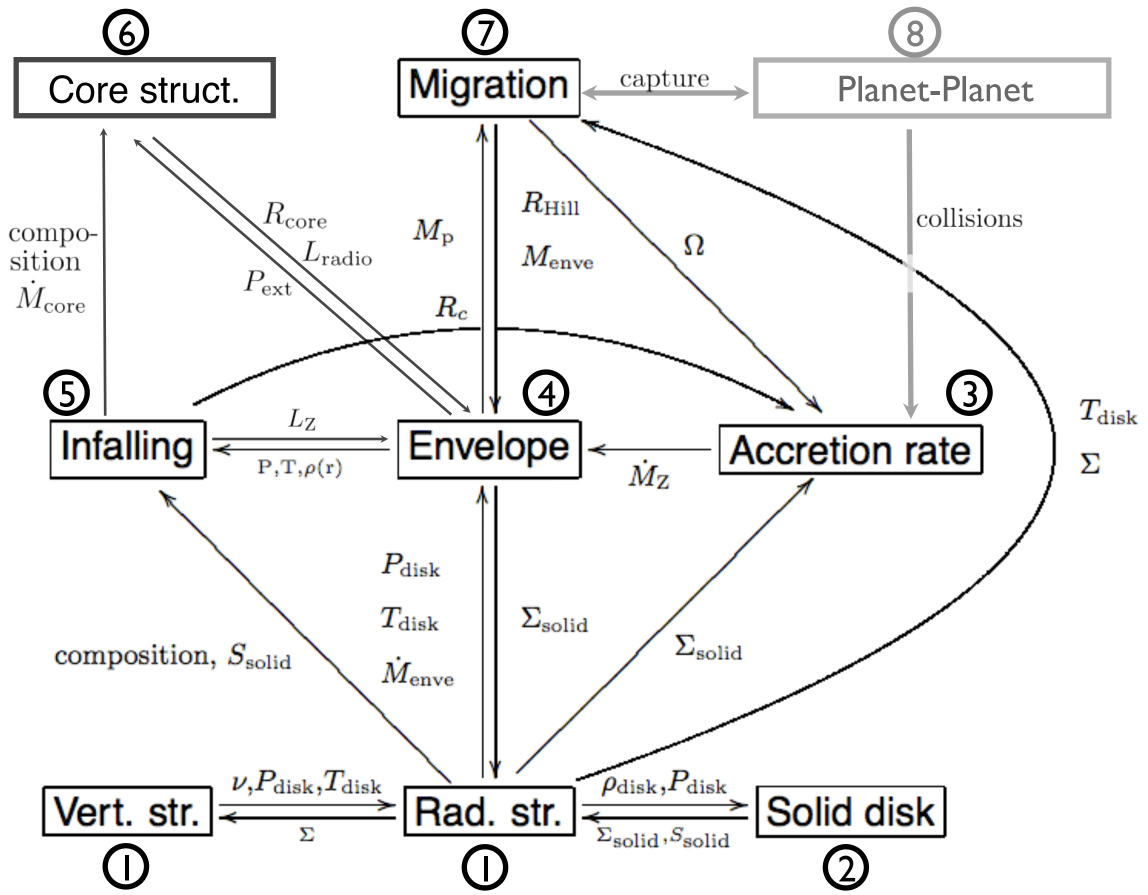
Similar timescales of various processes:

$T_{\text{migration}} \leq T_{\text{formation}} \approx T_{\text{disk evolution}}$

→ *extend model to include in a self consistent way (Alibert, Mordasini, Benz 2004, ++)*

1) *disk evolution* *(1+1 D)* α*-disk with photoevaporation + irradiation (Papaloizou & Terquem 1999, Chiang & Goldreich 1997, Matsuyama et al. 2003, Clarke et al. 2001)*

2) *type I and type II planetary migration* *(Lin & Papaloizou 86; Tanaka et al. 02). Isothermal Type I reduced by constant factor f_1 (free parameter). Updated recently (Paardekooper et al 2010, Dittkrist et al in prep).*



migration module:
type I and II

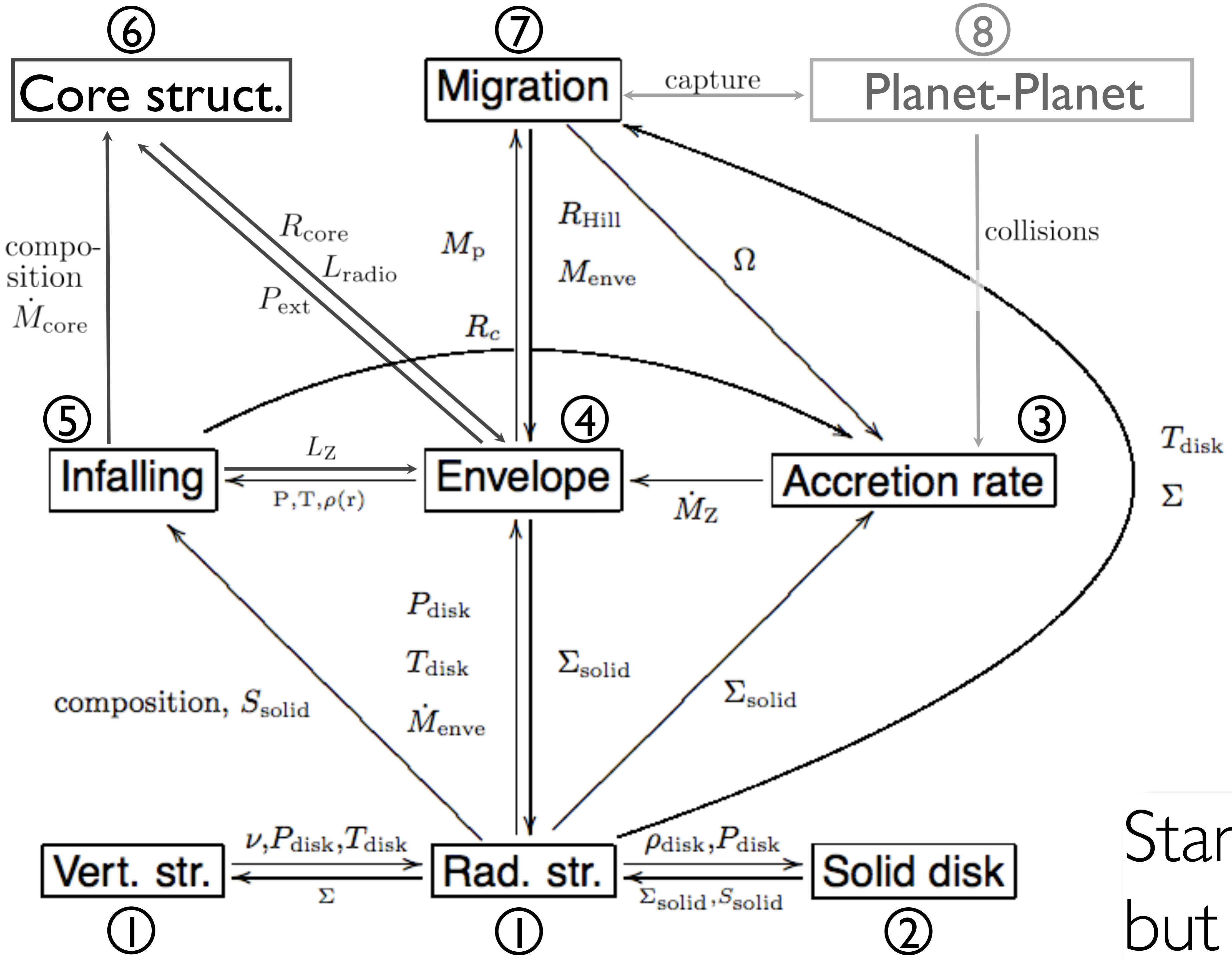
accretion module:
core and envelope growth

disk module
gas and planetesimals

simple modules,
but coupled

Planet formation and evolution model

Based on core accretion paradigm



8 Modules

①1+1D α disk

②Planetesimal disk

③Planet solid accretion

④Planet gas envelope

⑤Envelope-planetesimal

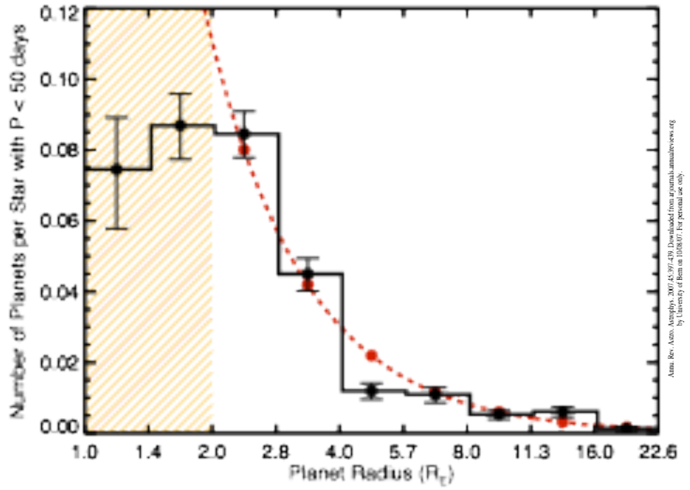
⑥Planet core structure

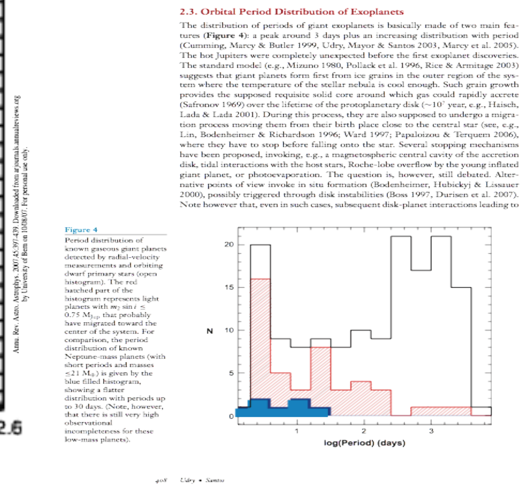
⑦Disk migration

⑧Planet-planet interaction
Growth after disk
dissipation not included

Standard components,
but coupled together

III *Planetary population synthesis* or *How to deal with statistical information*



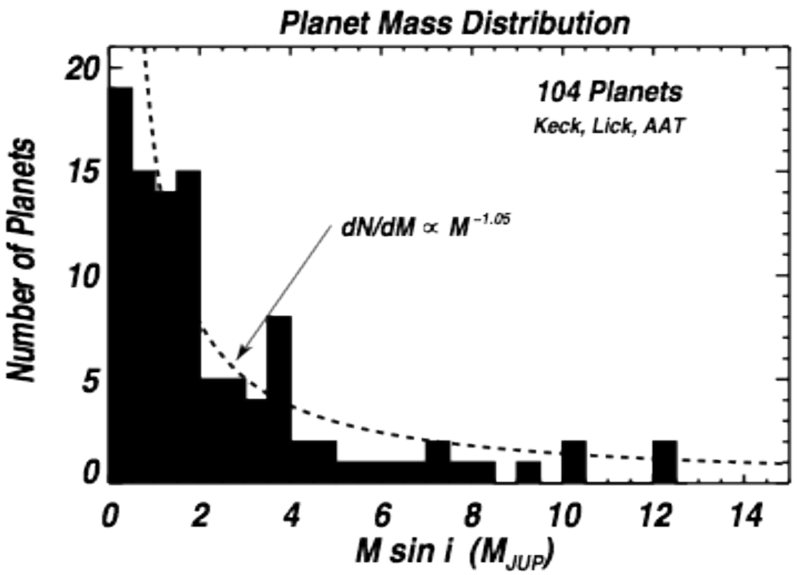


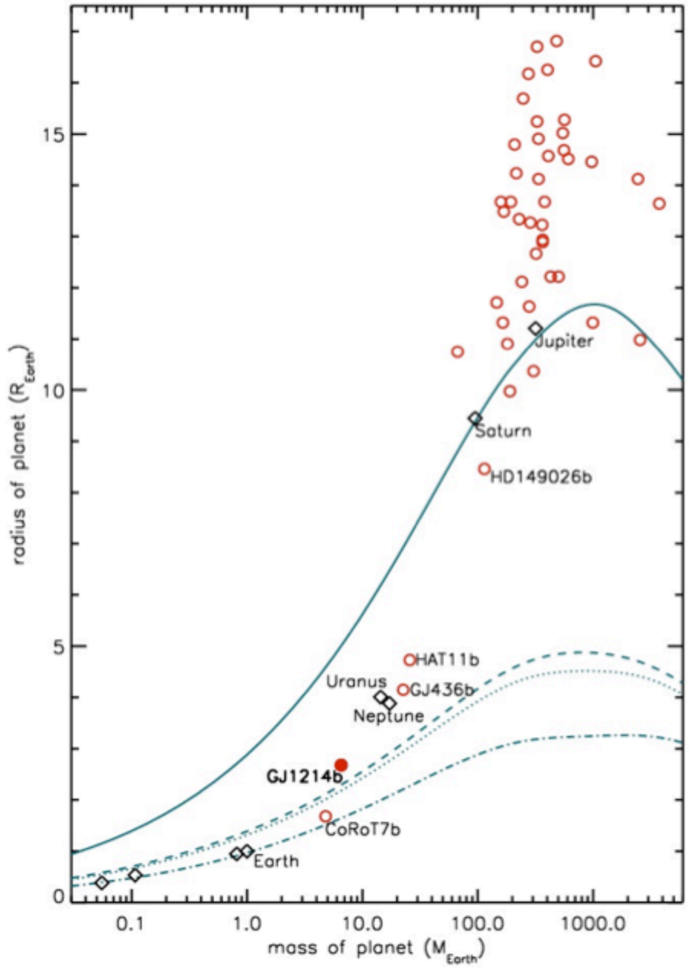
2.3. Orbital Period Distribution of Exoplanets

The distribution of periods of giant exoplanets is basically made of two main features (**Figure 4**): a peak around 3 days plus an increasing distribution with period (Cumming, Marcy & Butler 1999, Udry, Mayor & Santos 2003, Marcy et al. 2005). The hot Jupiters were completely unexpected before the first exoplanet discoveries. The standard model (e.g., Mizuno 1980, Pollack et al. 1996, Rice & Armitage 2003) suggests that giant planets form first from ice grains in the outer region of the system where the temperature of the stellar nebula is cool enough. Such grain growth provides the supposed requisite solid core around which gas could rapidly accrete (Safronov 1969) over the lifetime of the protoplanetary disk (~10^7 year, e.g., Haisch, Lada & Lada 2001). During this process, they are also supposed to undergo a migration process moving them from their birth place close to the central star (see, e.g., Lin, Bodenheimer & Richardson 1996; Ward 1997; Papaloizou & Terquem 2006), where they have to stop before falling onto the star. Several stopping mechanisms have been proposed, invoking, e.g., a magnetospheric central cavity of the accretion disk, tidal interactions with the host stars, Roche-lobe overflow by the young inflated giant planet, or photoevaporation. The question is, however, still debated. Alternative points of view invoke in situ formation (Bodenheimer, Hubickyj & Lissauer 2000), possibly triggered through disk instabilities (Boss 1997, Durisen et al. 2007). Note however that, even in such cases, subsequent disk-planet interactions leading to

Figure 4

Period distribution of known gaseous giant planets detected by radial-velocity measurements and orbiting dwarf primary stars (open histogram). The red hatched part of the histogram represents light planets with $m_2 \sin i \leq 0.75\ M_{Jup}$ that probably have migrated toward the center of the system. For comparison, the period distribution of known Neptune-mass planets (with short periods and masses $\leq 21\ M_\oplus$) is given by the blue filled histogram, showing a flatter distribution with periods up to 30 days. (Note, however, that there is still very high observational incompleteness for these low-mass planets).





Marcy et al. 2005, Udry & Santos 2007, Charbonneau et al. 2009, Howard et al. 2011

Population Synthesis *Principle*

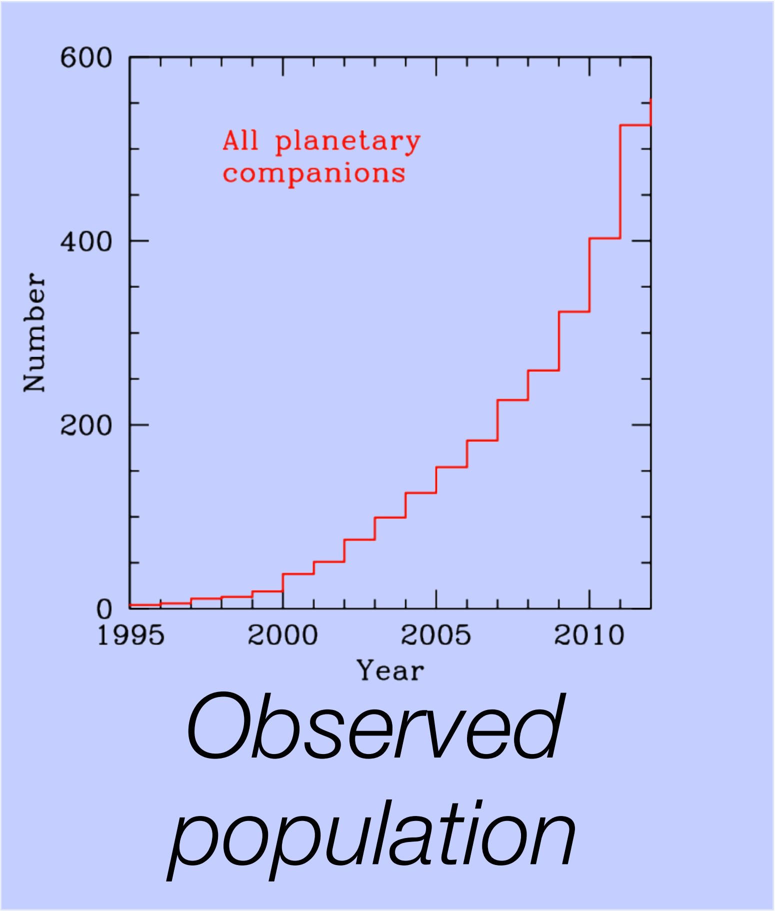
Formation model

Link disk properties ⇒ planet properties

Initial Conditions: Probability distributions & parameters

Disk gas mass
Disk dust mass
Disk lifetime

From observations



Observed population

Draw and compute synthetic planet population

Apply observational detection bias

Comparison:

Observable sub-population
- Distribution of semi-major axis
- Distribution of masses
- Fraction of hot/cold Jupiters
- Distribution of radii

No match: improve, change parameters

Match

Model solution found!

Predictions
(going back to the full synthetic population)

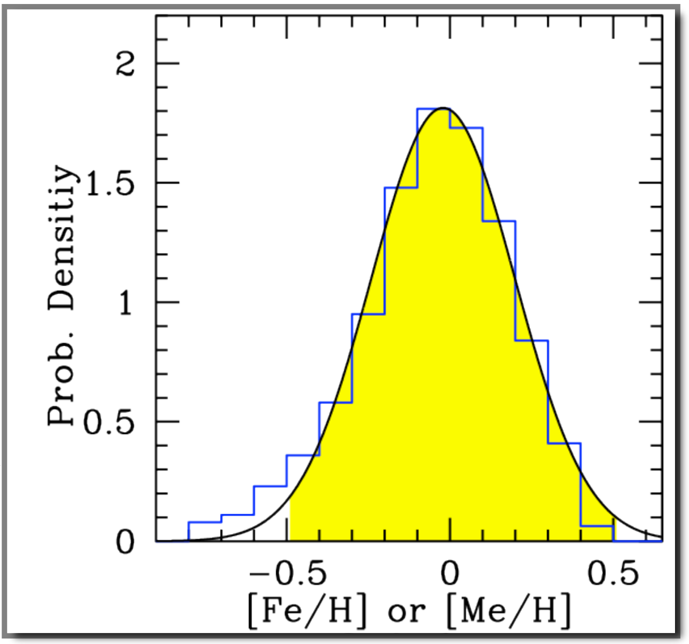
Mordasini et al. 2009a
Mordasini et al. 2009b

Probability distributions

1 Metallicity

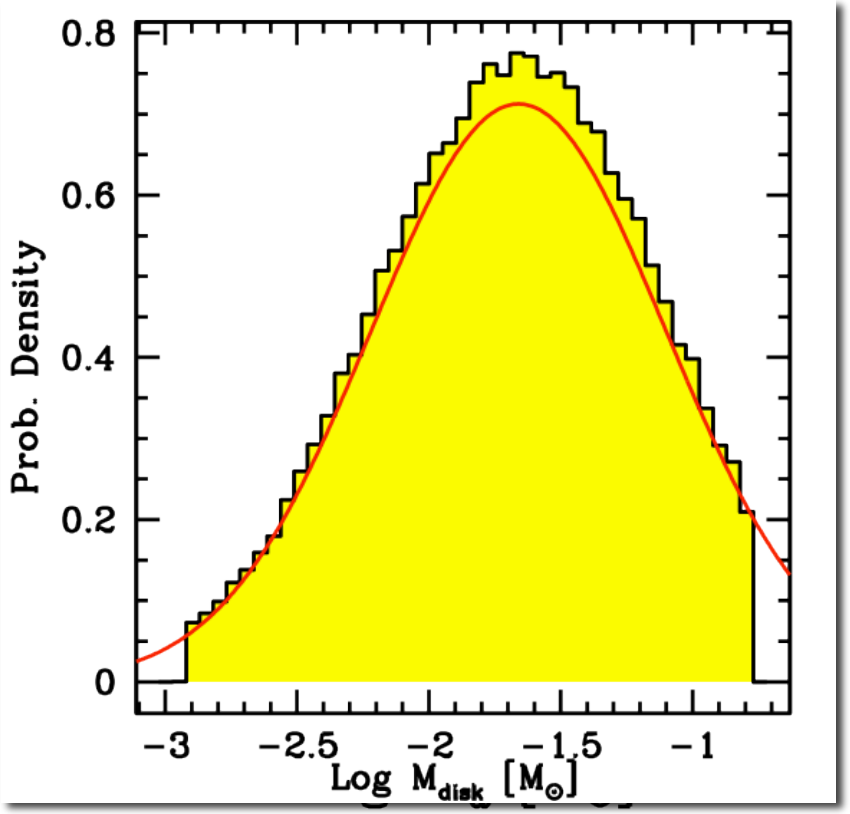
assume same in star and disk

Stellar [Fe/H] from spectroscopy. Gaussian distribution for [Fe/H] with μ ~0.0, σ ~ 0.2. (e.g. Santos et al. 2003)



2 Disk (gas) masses

Thermal continuum emission from cold dust at mm and submm wavelengths (Ophiuchus nebula).

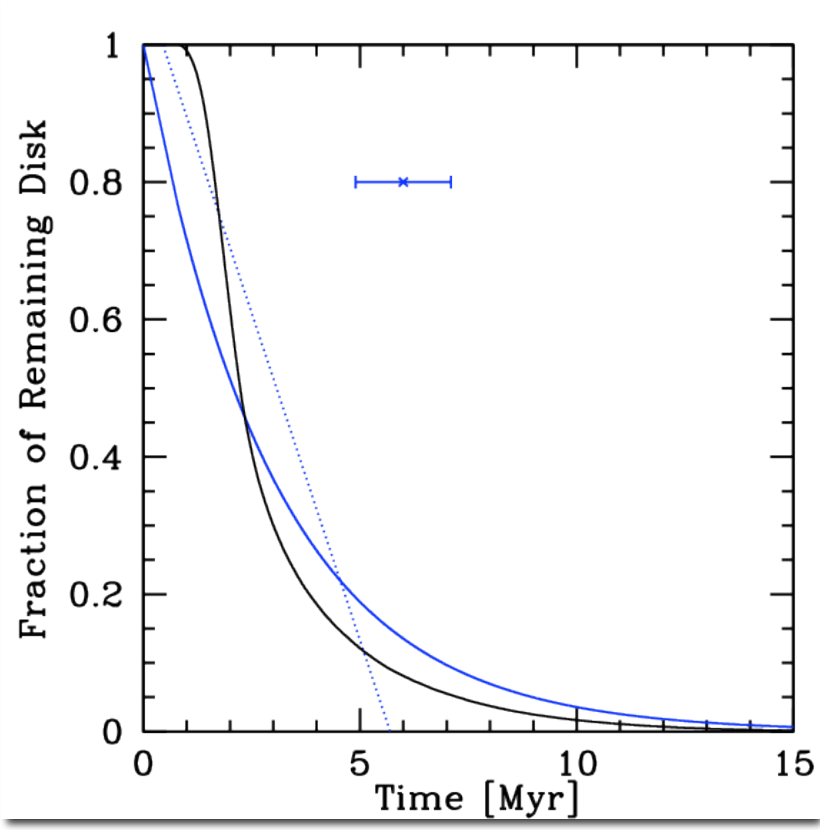


3 Disk lifetime

L-band (3.4 μm) photometry:- excess caused by μ-sized dust @ ~900K

... ok to < 10 AU

Haisch et al. 2001, Fedele et al. 2010



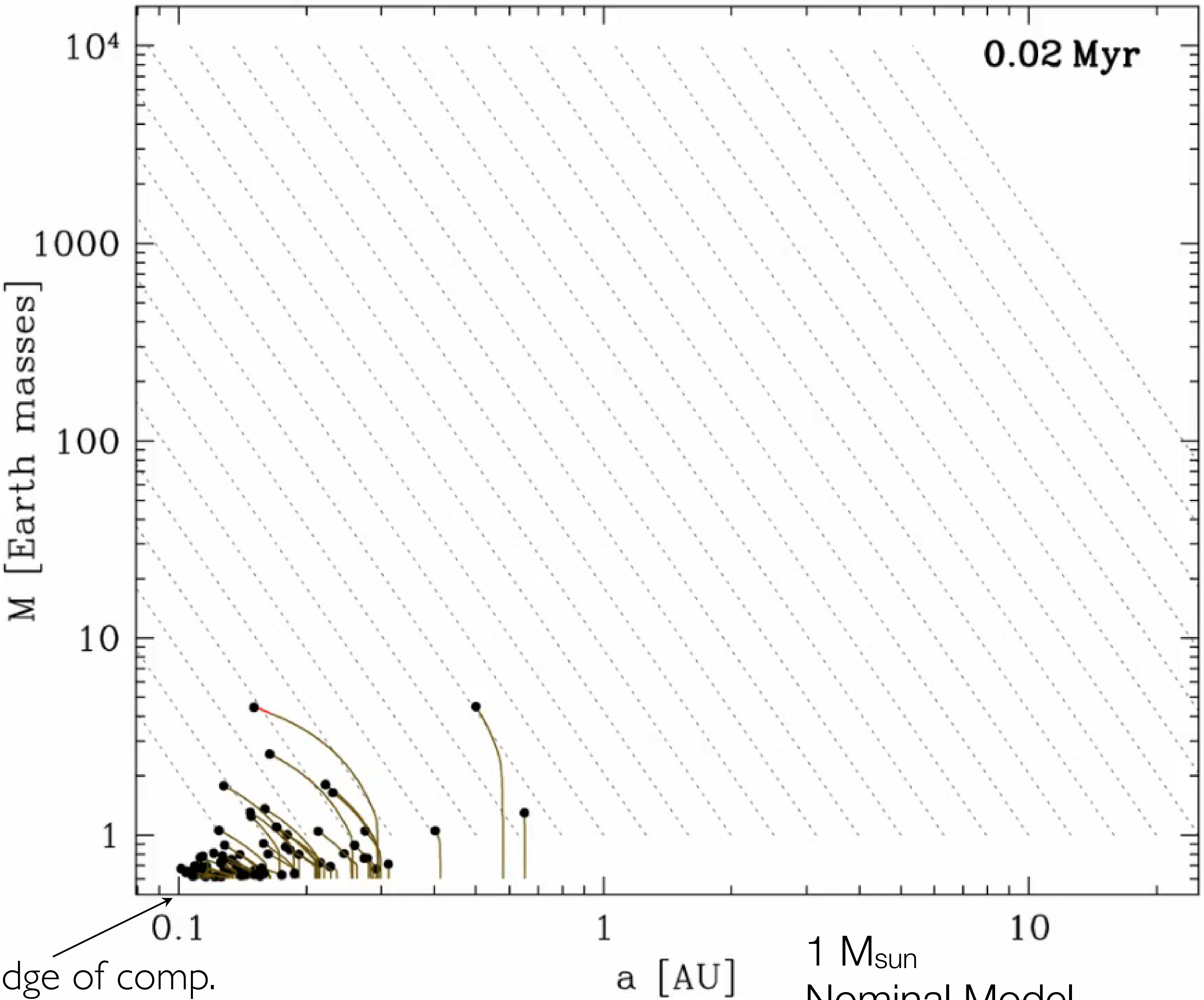
4 Initial semimajor axis of the seed embryo:

Analytical work (Lissauer & Steward 1992) and numerical simulations (Kokubo & Ida 2000): spacing between bodies $\Delta \propto a$

$$p(a)da \propto \frac{da}{\Delta} \propto \frac{da}{a} = dlog(a) \propto const.$$

5 Stellar mass

Formation of the a-M diagram



Random variables:
- **Disk mass**
- **Disk Metallicity**
- **Disk lifetime**
- **Starting position**

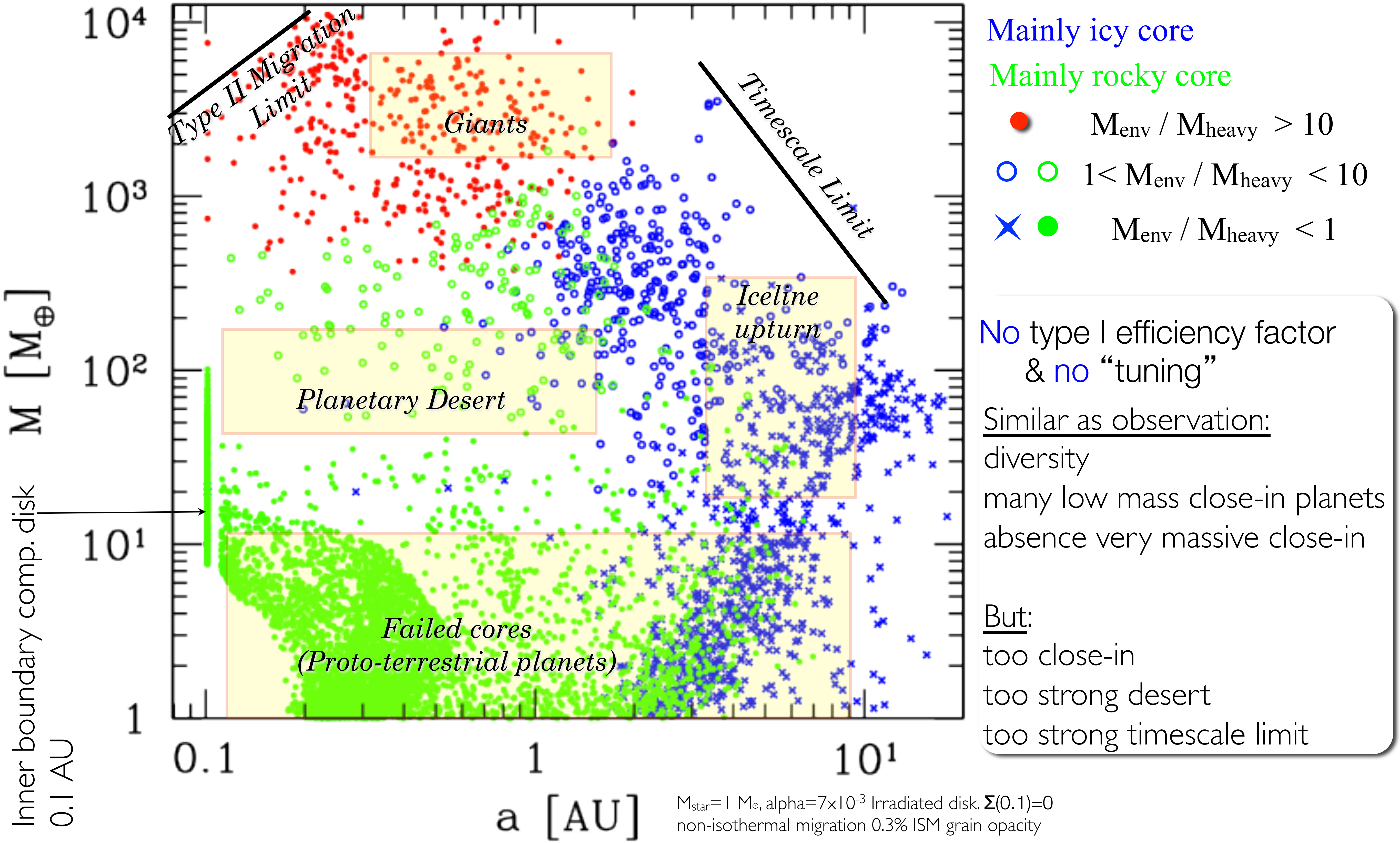
isothermal type I
adiabatic type I
saturated type I
type II

← Starting mass

Edge of comp. disk

1 M_{sun}
Nominal Model.
Non-isothermal Type I.

a-M diagram



No type I efficiency factor & no "tuning"

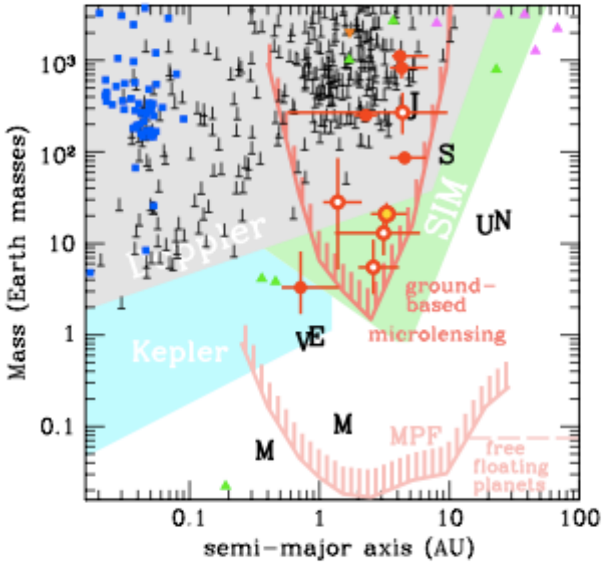
Similar as observation:
diversity
many low mass close-in planets
absence very massive close-in

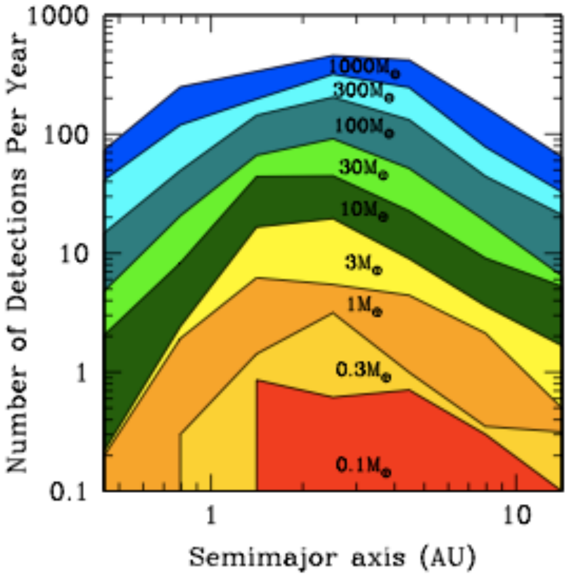
But:
too close-in
too strong desert
too strong timescale limit

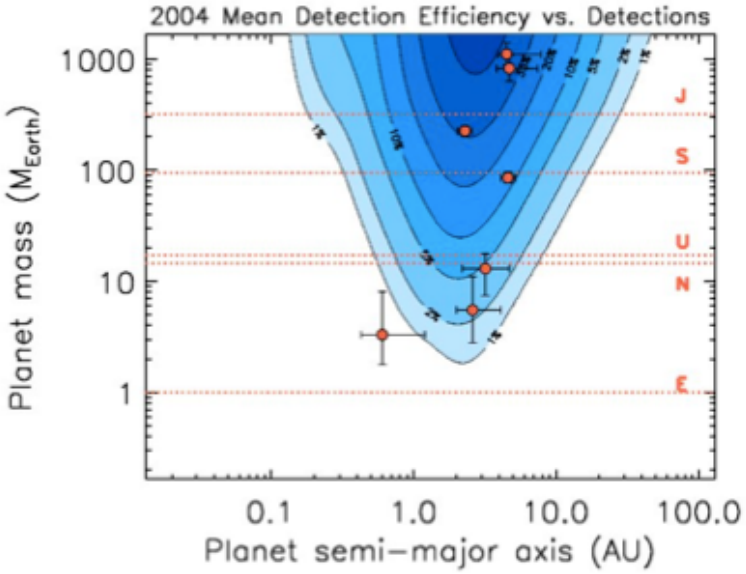
$M_{star}=1\ M_\odot$, alpha=7×10^{-3} Irradiated disk. $\Sigma(0.1)=0$
non-isothermal migration 0.3% ISM grain opacity

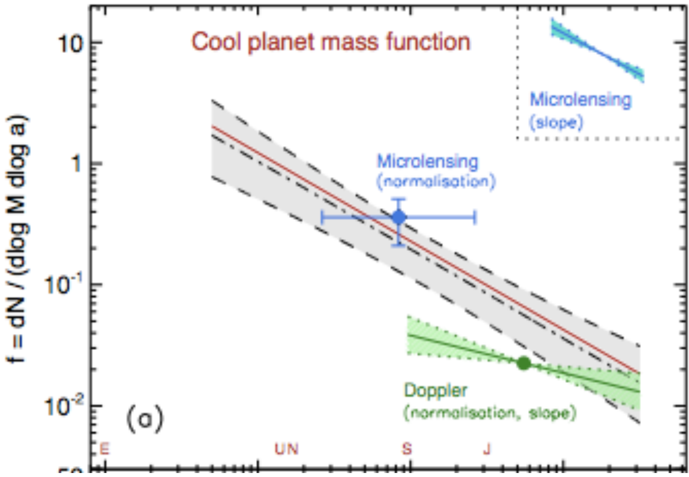
IV *Microlensing to constrain formation models*

a) the planetary mass function





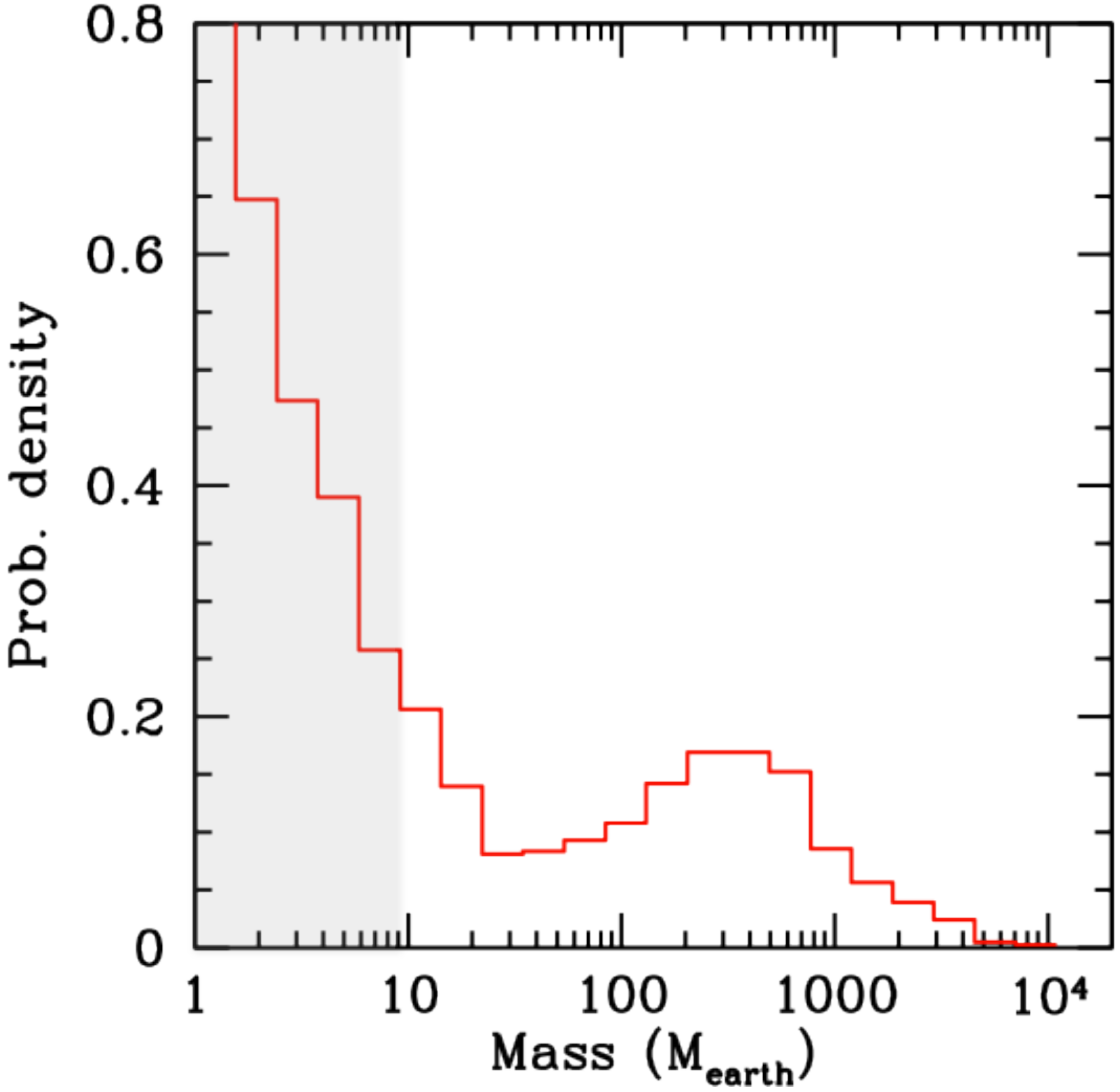




Sumi et al. 2010, Gould et al. 2007, Cassan et al. 2012, Beaulieu et al. 2008

Planetary initial mass function P-IMF

1< a <5 AU

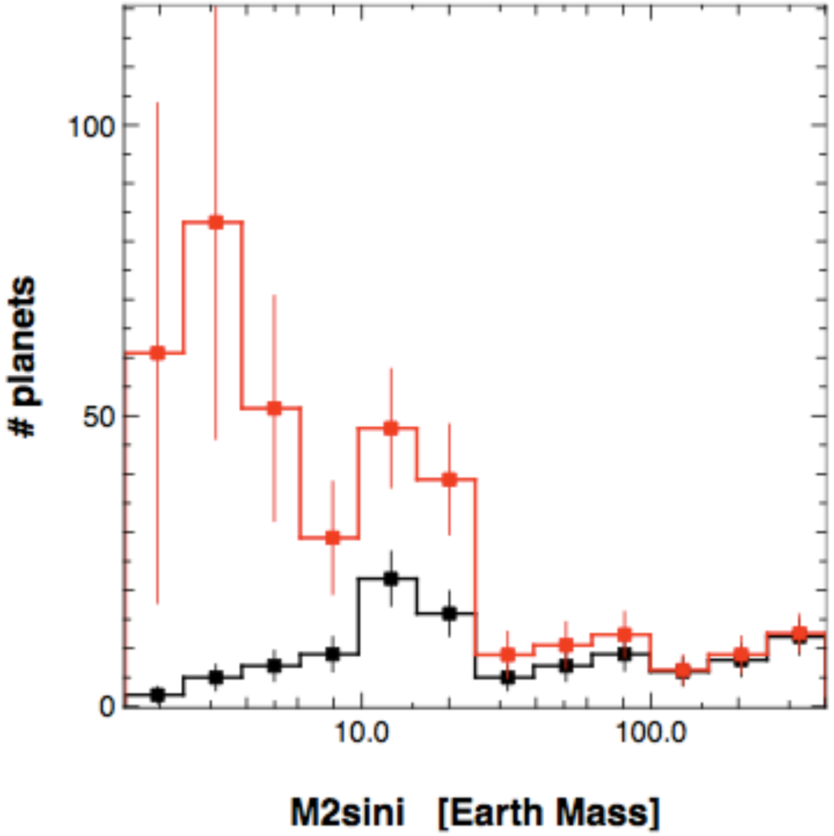


-bimodal. Maxima
-at low masses
-at about 1 M_J

-minimum at ~30 M_E
("planetary desert")

-very interesting part
-solid growth, M_{iso}
-critical mass
-gas accretion
-microlensing zone!

RV Observation



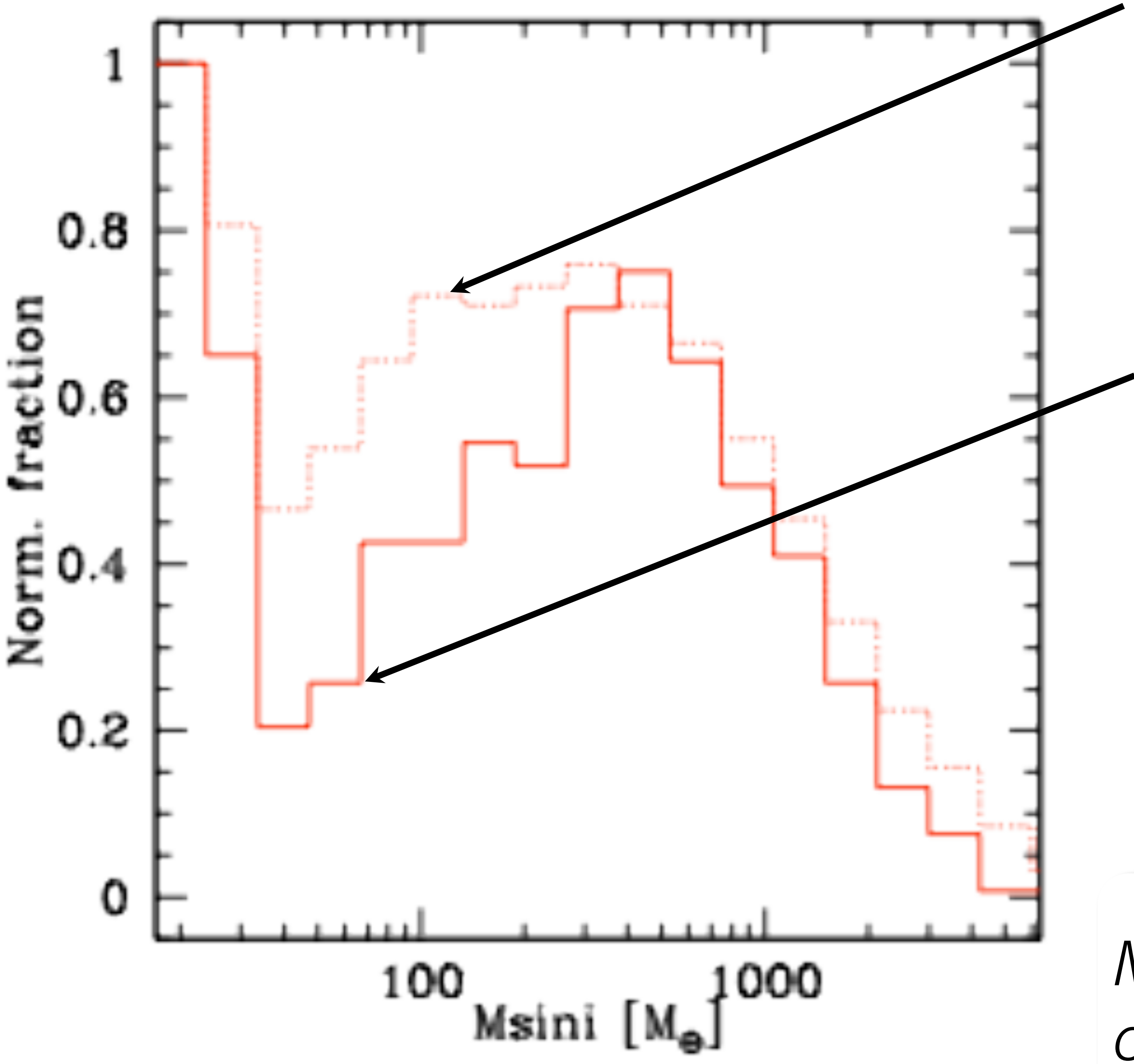
-High precision RV (Mayor et al. 2011)
-HARPS GTO program since 2004
-corrected for obs. bias
-30 M_E discontinuity ?

Beyond power laws

M_{star}=1 $M_\odot$, alpha=7×10^{-3} Irradiated disk. $\Sigma(0.1)=0$
non-isothermal migration 0.3% ISM grain opacity

Example: Depth of the minimum

Dependence on gas accretion rate in runaway



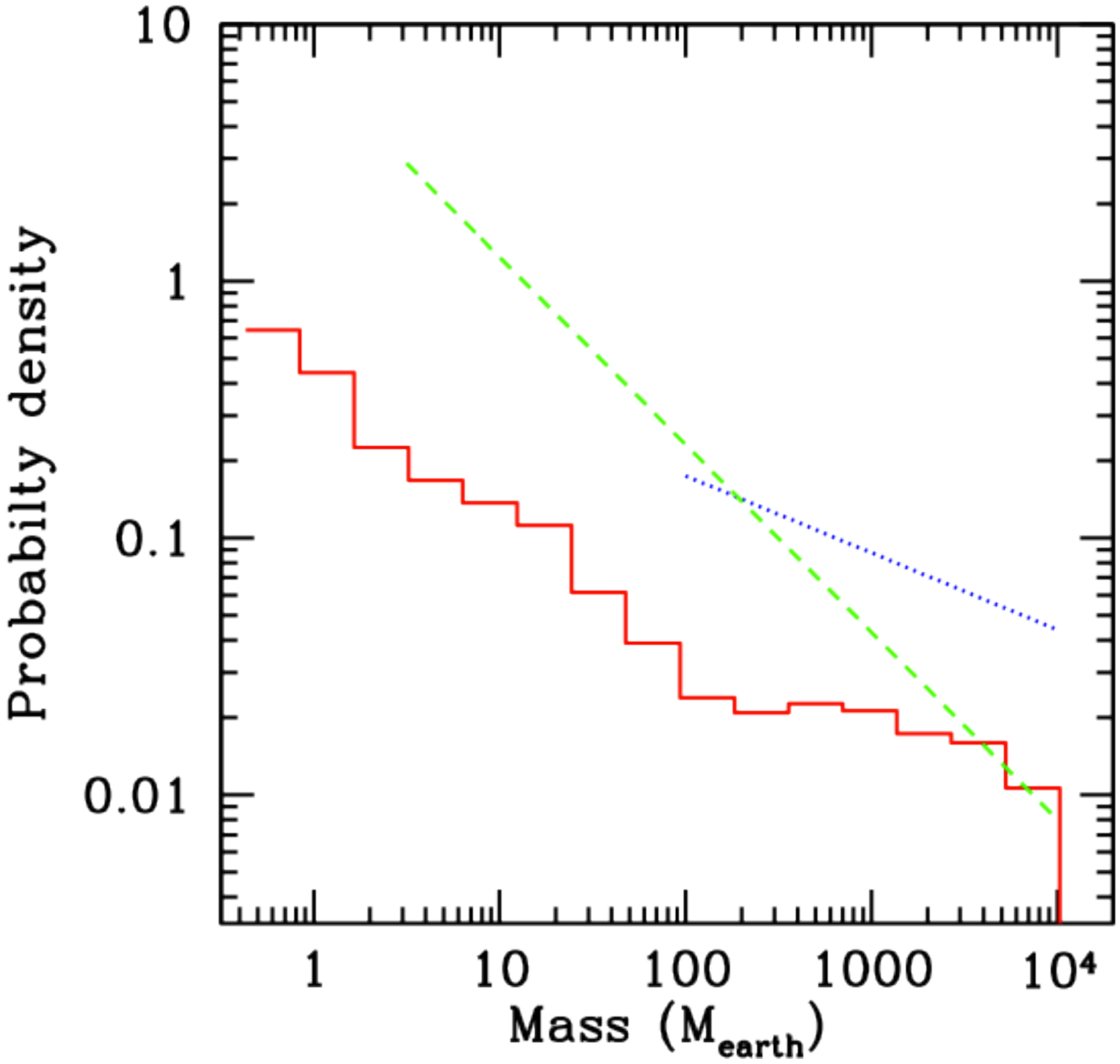
Planetary gas accretion rate limited to disk accretion rate. Shallow minimum.

Planetary gas accretion rate not limited to disk accretion rate for gas already in the planet's hill sphere. Deep minimum.

Mass function central to directly constraining formation theory.

Mordasini et al. 2010

Comparison with RV and ML



Model, all a, M_{star} = 1 M_{sun}

RV: Cumming et al. 2008

ML: Cassan et al. 2012

-model: 1 embryo per disk ⇒ normalization difficult

-2 slopes: very typical for core accretion. Solid result.

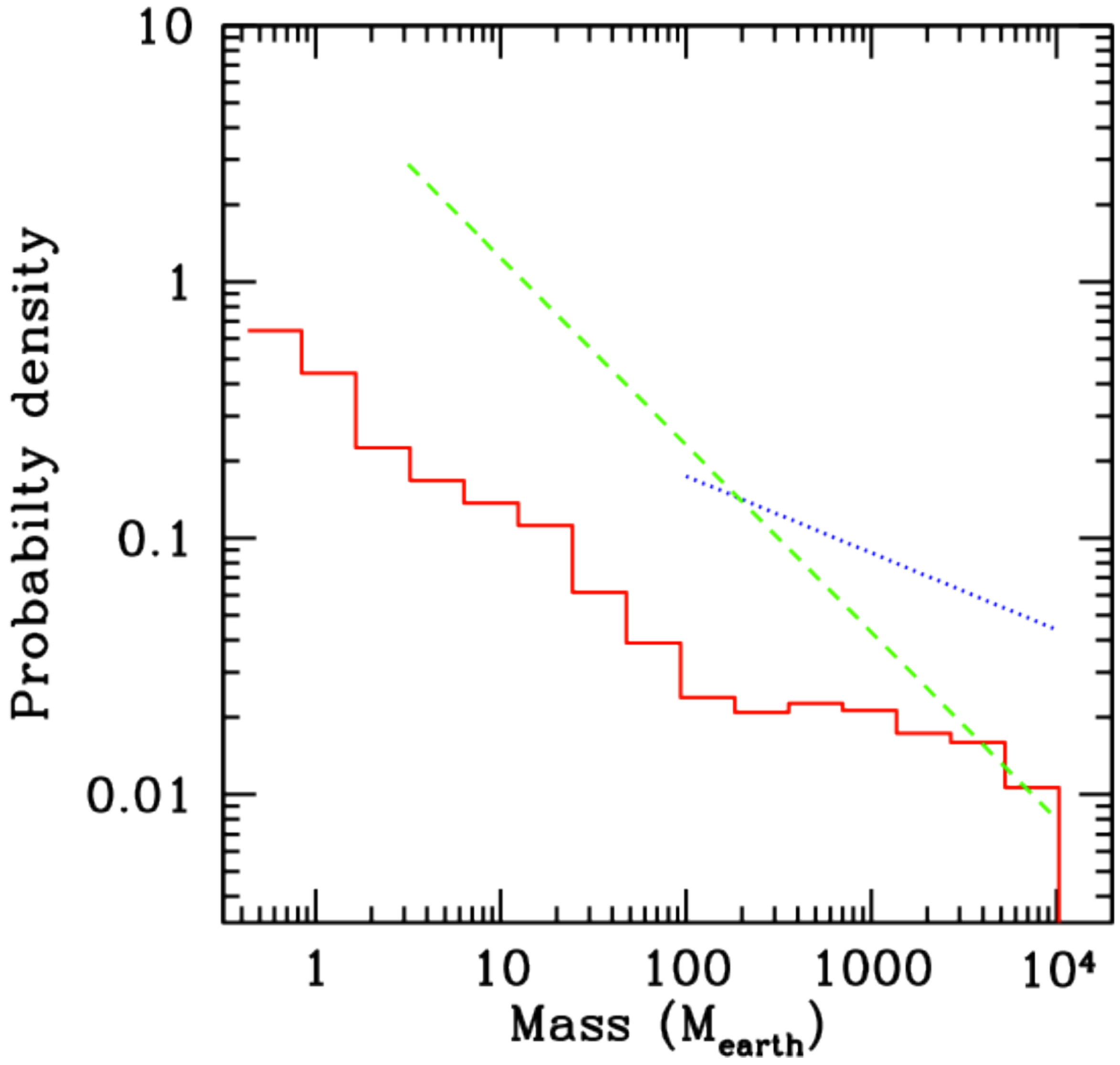
-change in slope: 10-100 M_E

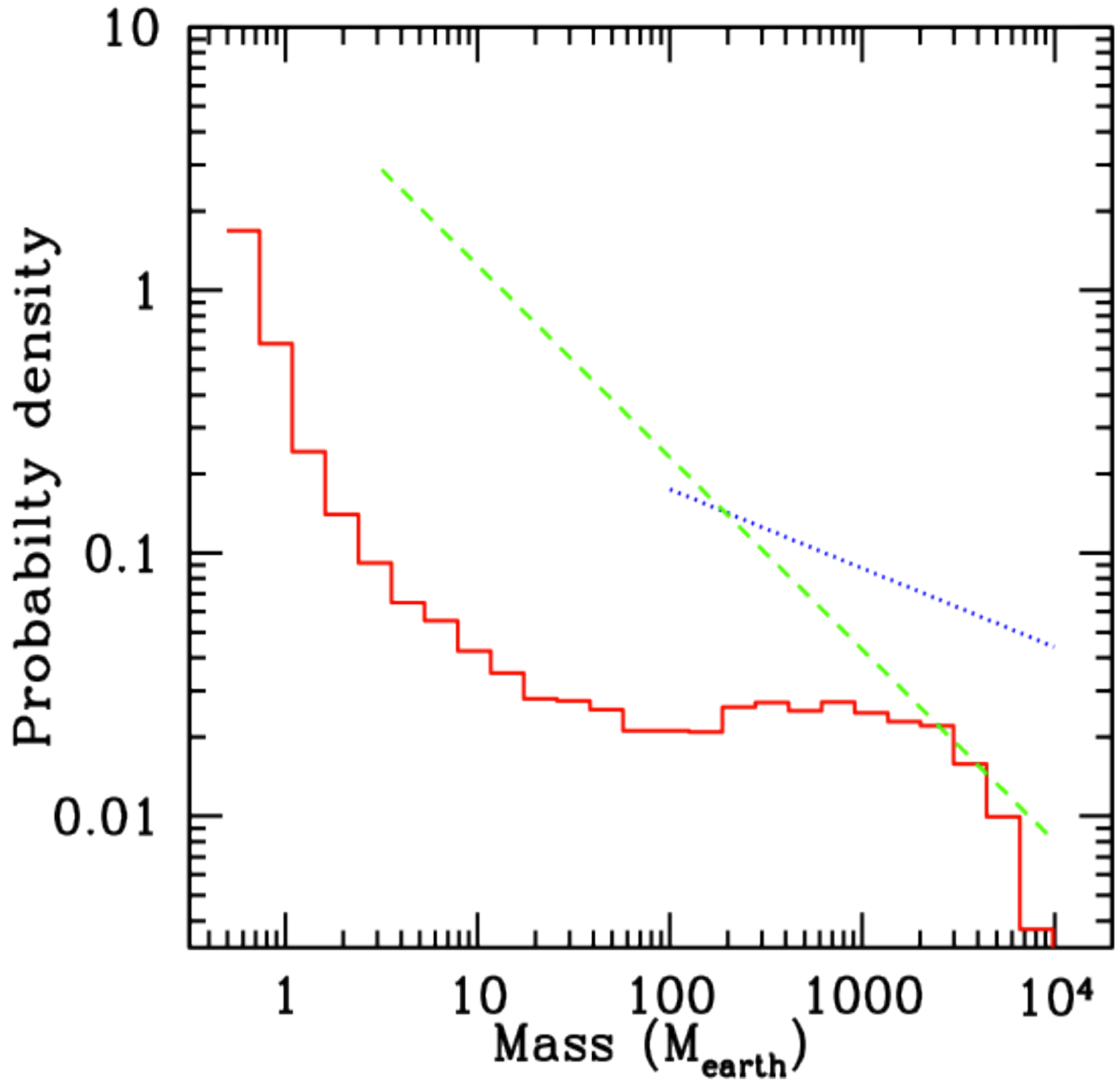
-consistent with observations?

-upper end of the planet mass function ⇔ transition to BD?

Required resolution: 10 - 20 mass bins

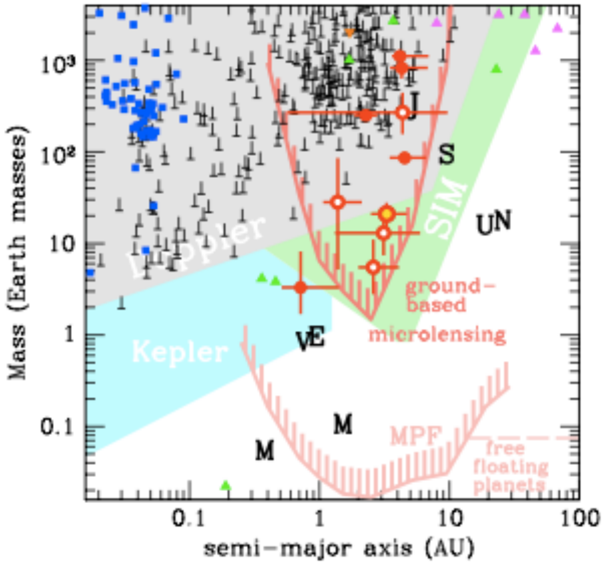
Comparison

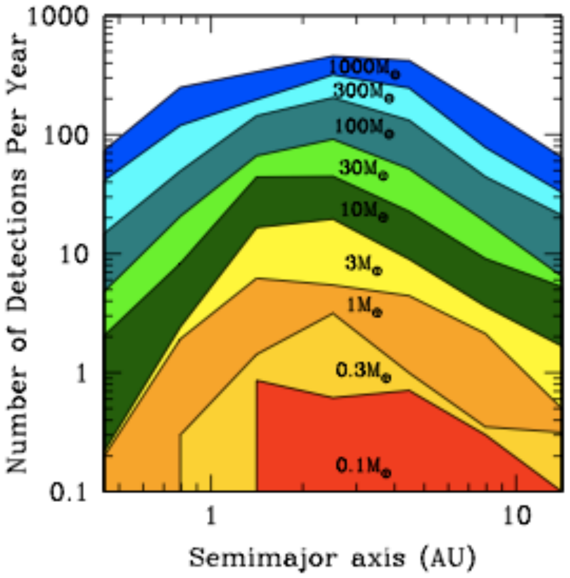

10
1
0.1
0.01
Probabilty density
1
10
100
1000
10^4
Mass (M_{earth})

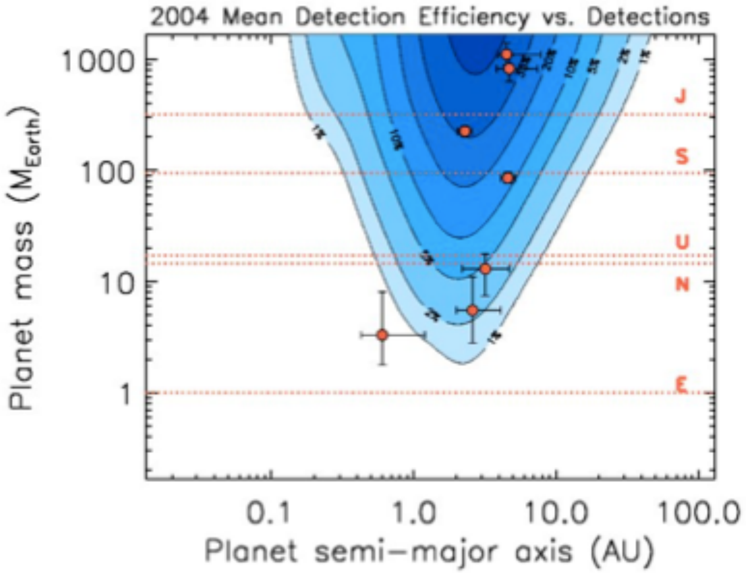

10
1
0.1
0.01
Probabilty density
1
10
100
1000
10^4
Mass (M_{earth})

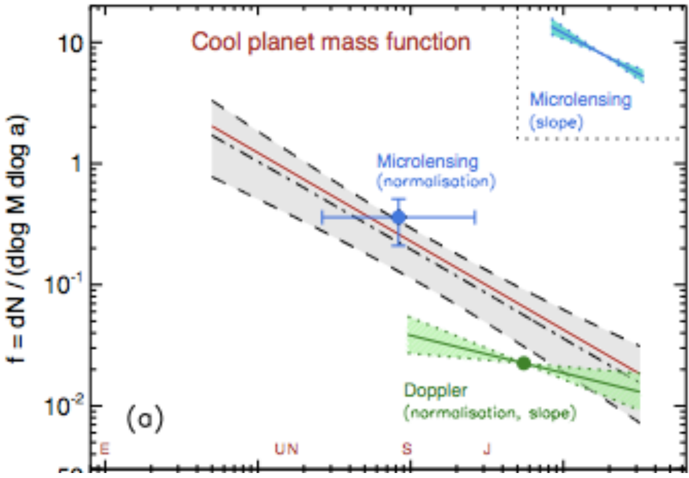
IV *Microlensing to constrain formation models*

b) the semimajor axis distribution









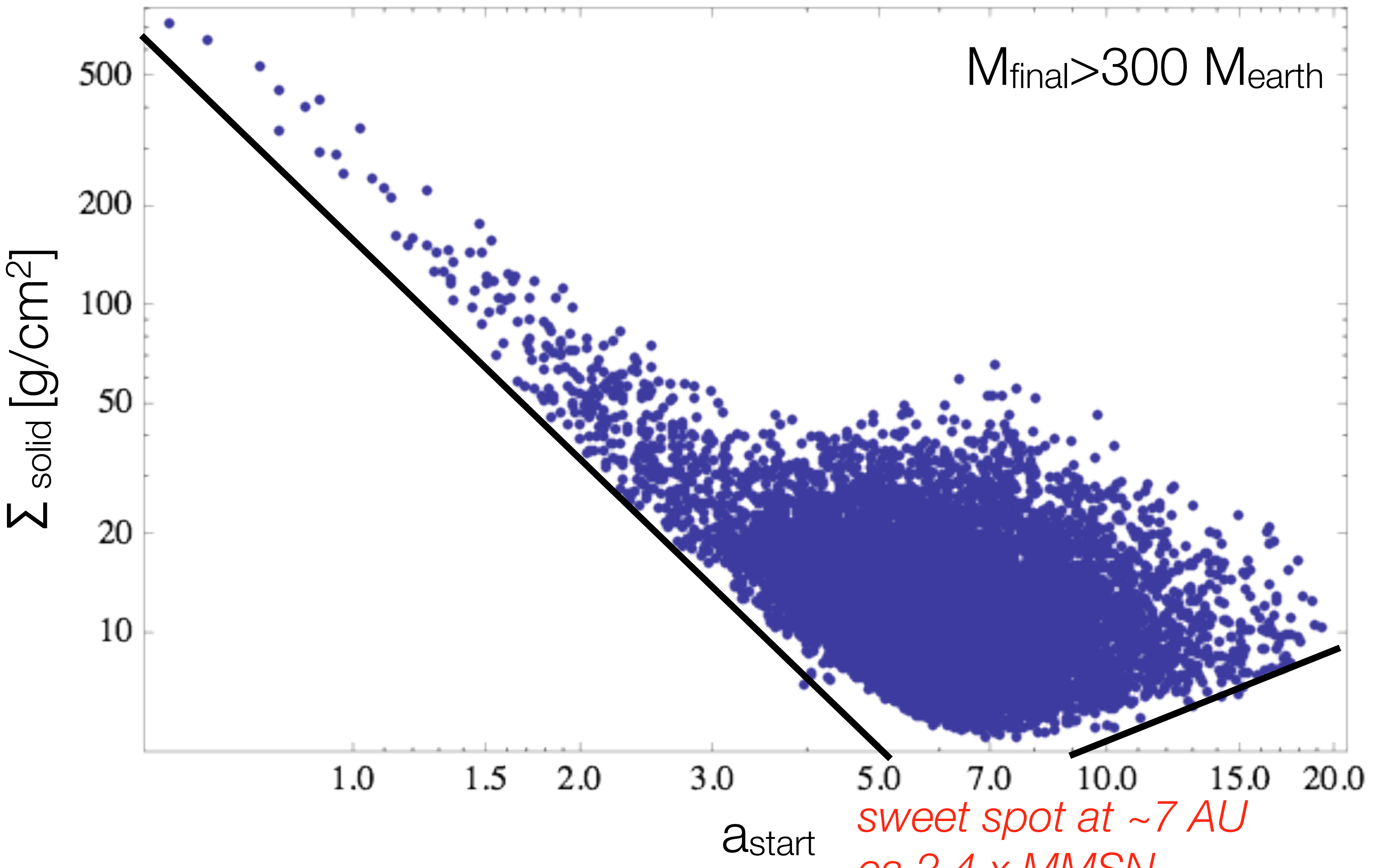
Sumi et al. 2010, Gould et al. 2007, Cassan et al. 2012, Beaulieu et al. 2008

Preconditions for giant planets I

Study a posteriori which initial condition lead to a giant planet

Mordasini et al. 2011

Mstar= 1 Msun
isothermal migration



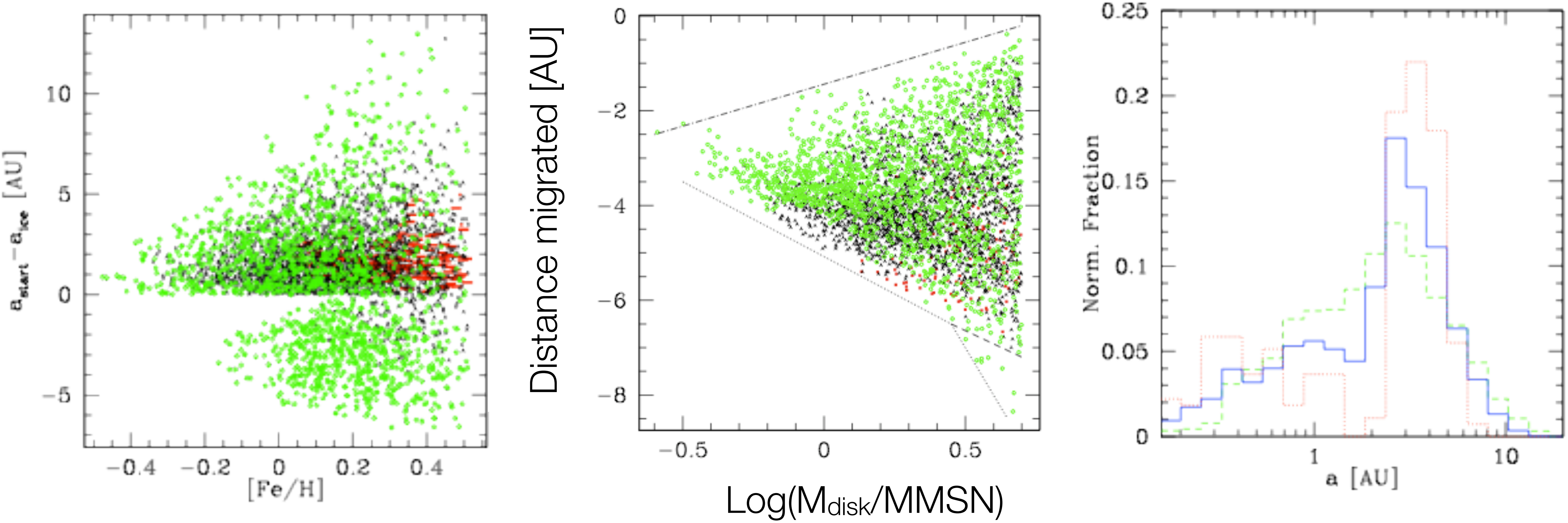
sweet spot at ~7 AU
ca 2.4 x MMSN

Minimal necessary local planetesimal surface density.

Inside: available mass criterion
-Migration relaxes the condition somewhat
Outside: timescale criterion
-Only long living disk make giants at low Σ_{solid} at large distances

Semimajor axis distribution

$M_p > 300\ M_{Earth}$ Mstar= 1 Msun   isothermal migration   Mordasini et al. 2011



Preferred starting location

-embryos of giant-planets-to-be come from outside the iceline (cf Ida & Lin 2004).

-high [Fe/H]: start also inside.

Typical migration distance

-about 3 AU. Not so much...

Upturn at a few AU ~ observed.

-interesting region 1-10 AU

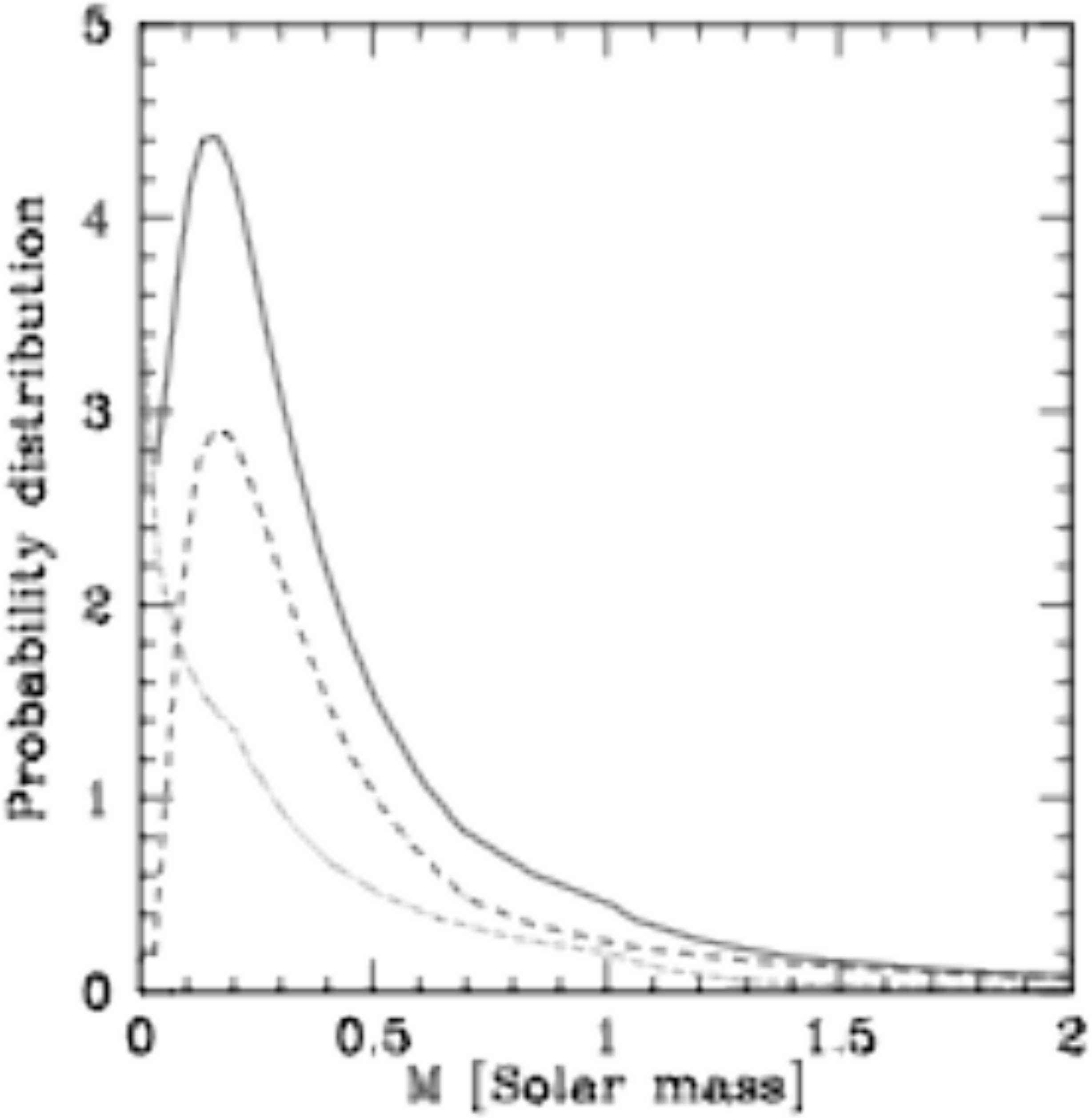
-dependent on iceline

-constrains protoplanetary disk structure (temperature, dead zone) & migration.

IV *Towards quantitative comparison*

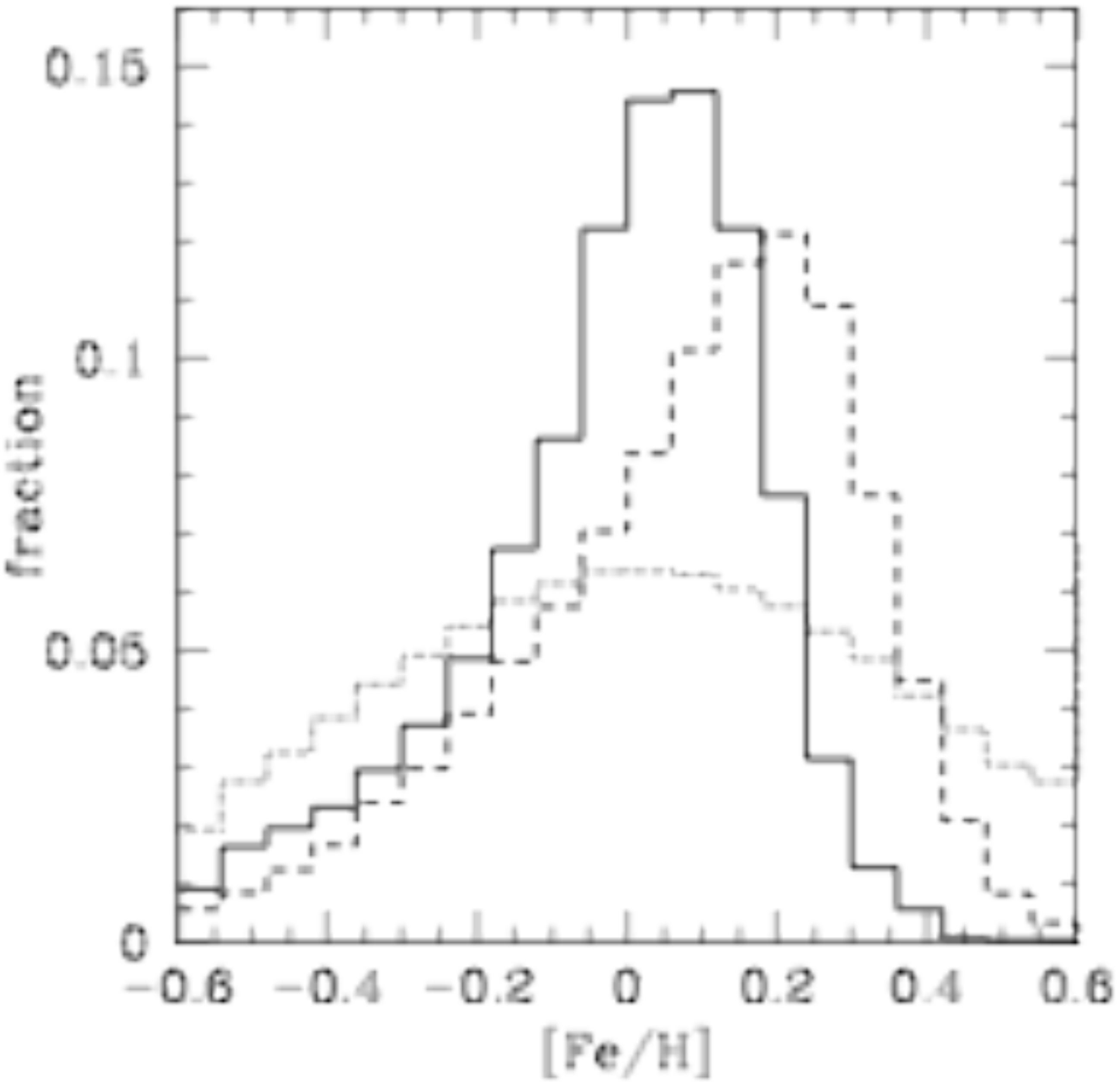
Lens star properties

Lens star mass function



Lens mass function following Dominik 2006. All lenses (solid line), disk (dotted line) and bulge (dashed line).

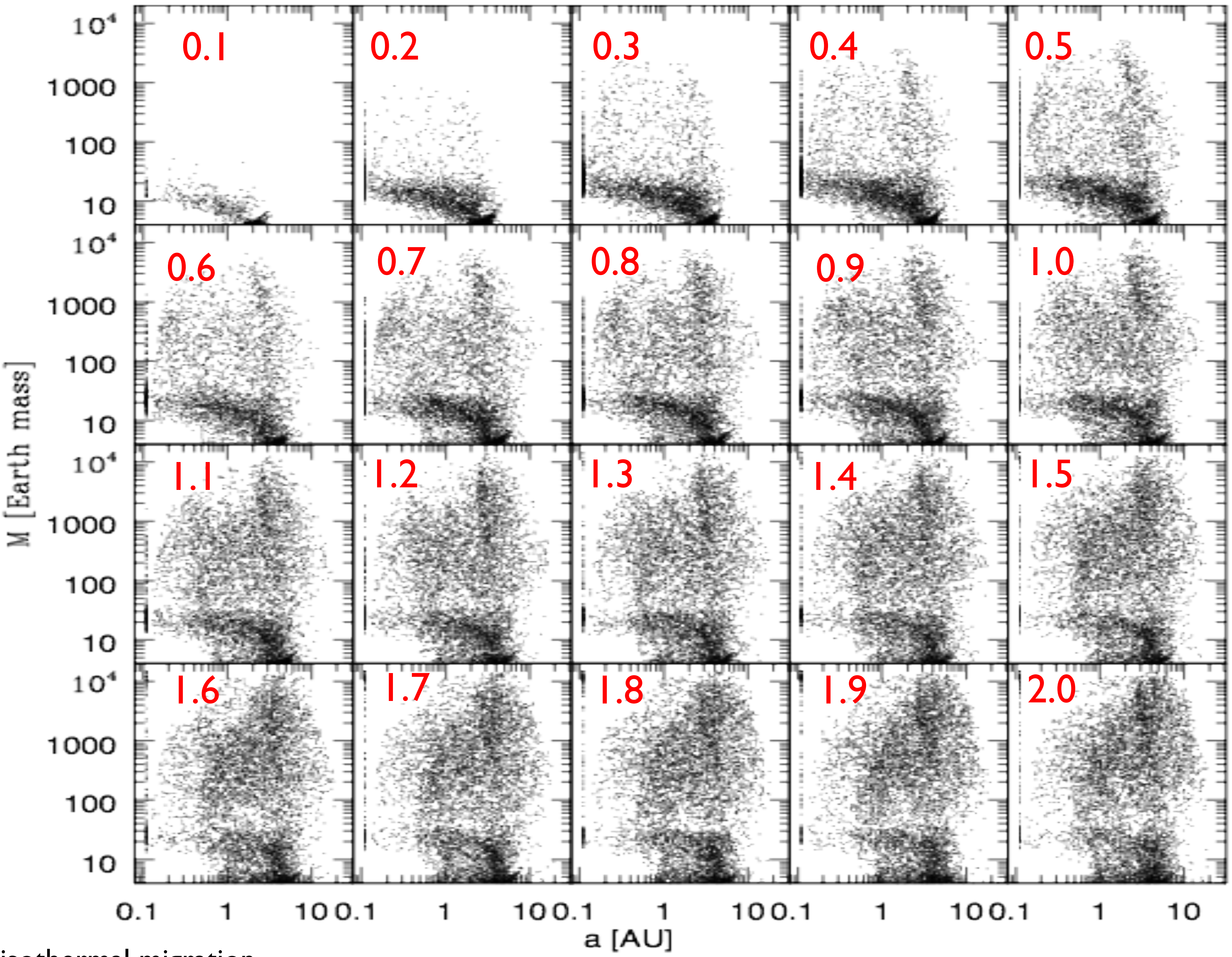
Lens star metallicity



[Fe/H] of MS stars between 0.1 and 2.0 $M_\odot$ from the Besançon Galactic Model. 0.5, 4, and 6 kpc from the Sun (solid,dashed, dotted line)

Synthetic population: M_{star}

Alibert et al. 2011



isothermal migration

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

$$\alpha_D = 1.2$$

$$T_{\rm disk} \propto M_{\rm star}^{-1/2}$$ for

$$M > 1.5 M_\odot$$

Kennedy & Kenyon (2009)

The lower the stellar mass,
-the more compact the planetary systems (Keplerian frequency effect)
-the lower the giant planet number & masses (disk mass effect).

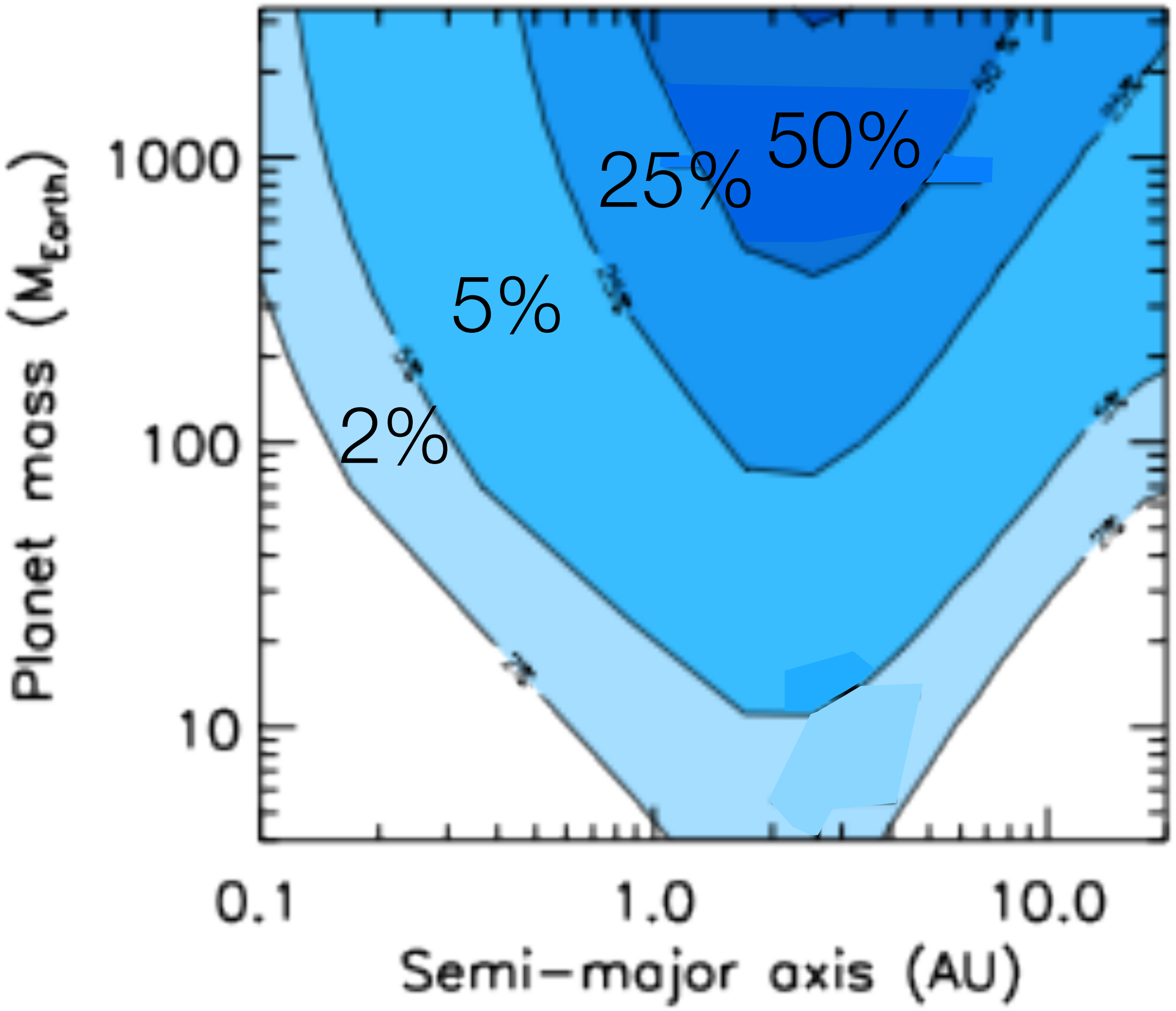
Mass distribution (>100 M_E)

$$M_{\rm planet} = M_{{\rm planet},1M_\odot} \times \left(\frac{M_{\rm star}}{M_\odot}\right)^\gamma$$

$$\alpha_D = 1.2 \Rightarrow \gamma = 0.9$$

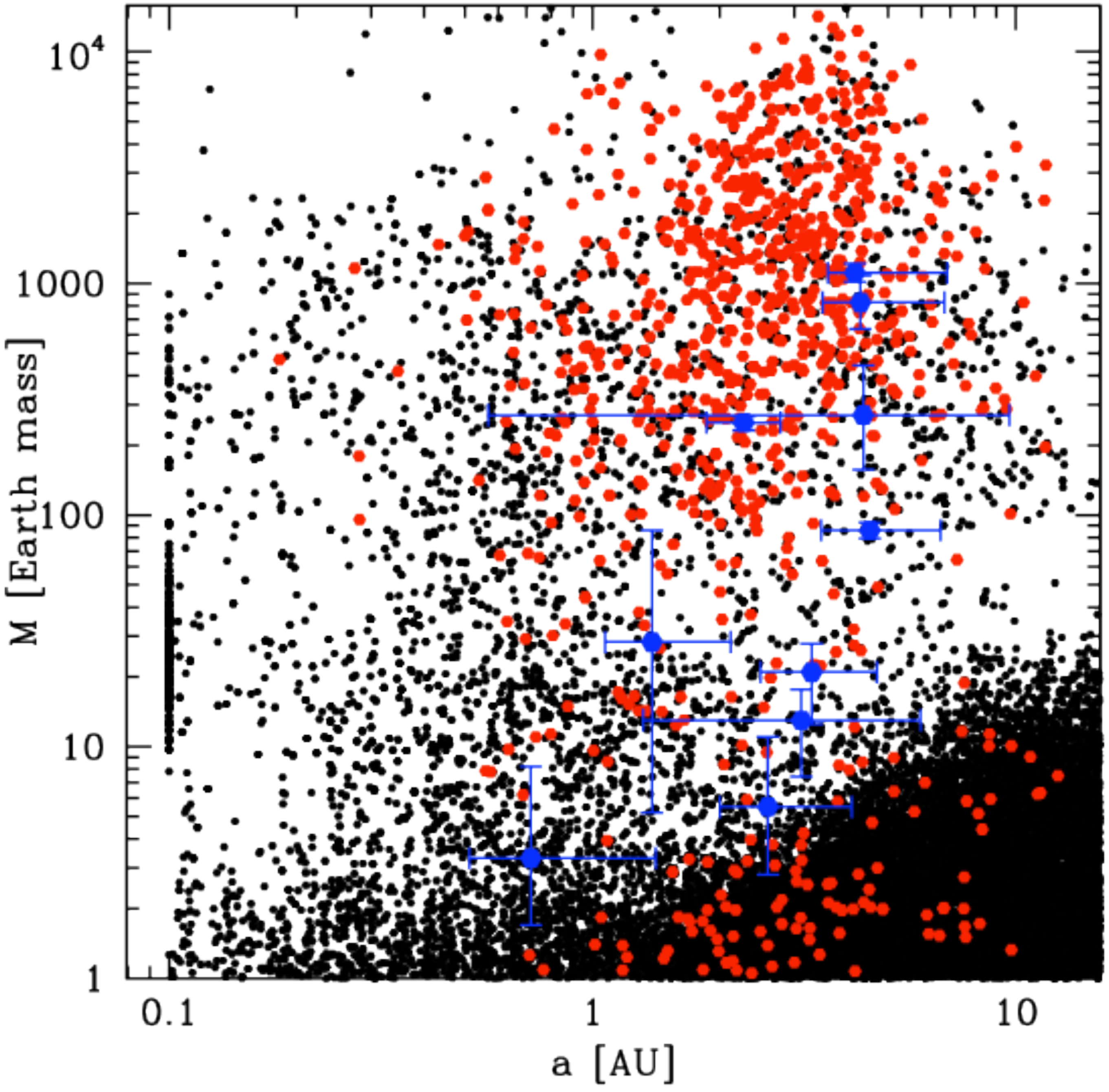
Detection bias & synthetic planets

PLANET detection efficiency 2004



Cassan, Sumi & Kubas 2008, see also
Cassan et al. 2012

Synthetic detectable planets



V *Conclusions*

Conclusions

- The discovery of a large population of planets is providing important clues toward a better understanding of planet formation.
  -crucial to understand migration, accretion

- A precise measurement of the planetary mass function from 1 to 10^4 M_E, at a distance of 1 to 5 AU is extremely helpful for planet formation theories.

- For an accurate comparison, the observational detection bias should be very well characterized and homogeneous (as for KEPLER, HARPS).

- Additional physical information about the host star / lens, in particula its mass and metallicity multiply the impact on planet formation theory.

Thanks!

The essence of population synthesis

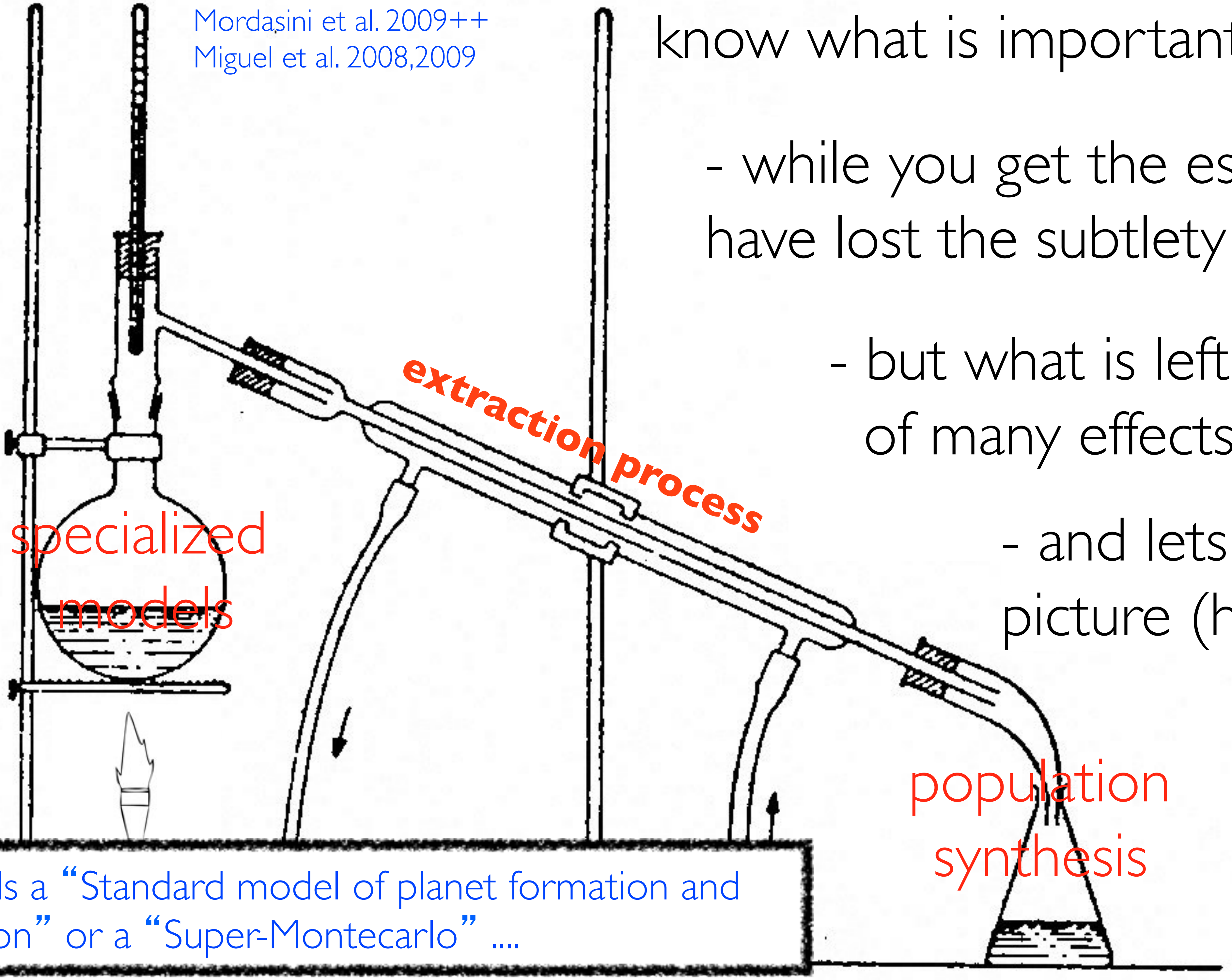
Ida & Lin 2004++
Thomes et al. 2008
Mordasini et al. 2009++
Miguel et al. 2008,2009

- you need specialized models to know what is important

- while you get the essence, you have lost the subtlety of the original

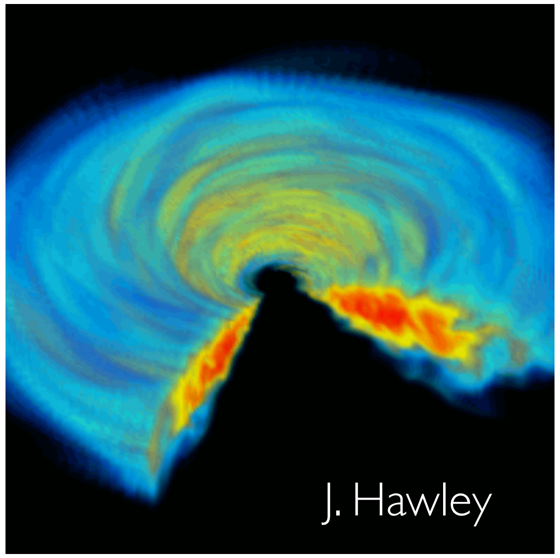
- but what is left is a concentrate of many effects

- and lets you see the big picture (hopefully)



Towards a “Standard model of planet formation and evolution” or a “Super-Montecarlo” ....

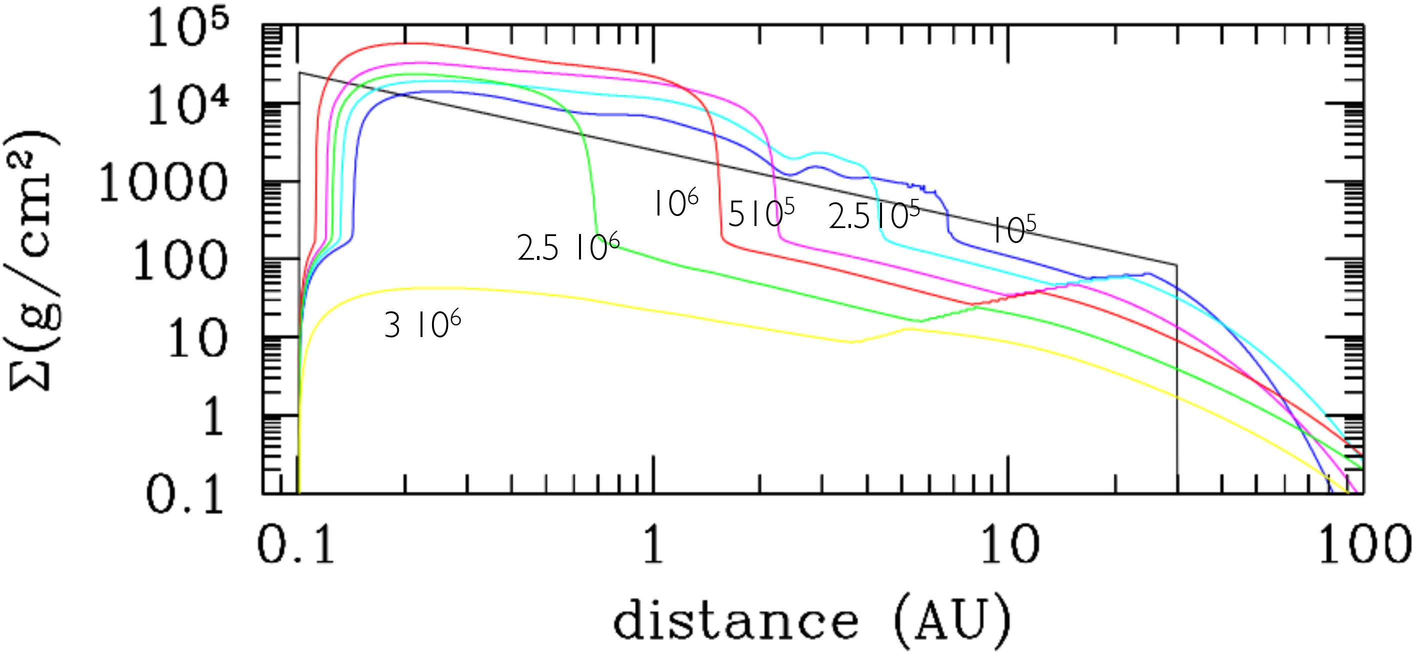
Distill how *strongly*?



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

$$\rho\frac{\partial \mathbf{v}}{\partial t} + (\rho\mathbf{v}\cdot\nabla)\mathbf{v} = -\boldsymbol{\nabla}\left(P + \frac{B^2}{8\pi}\right) - \rho\boldsymbol{\nabla}\Phi + \left(\frac{\mathbf{B}}{4\pi}\cdot\boldsymbol{\nabla}\right)\mathbf{B} + \eta_V\left(\boldsymbol{\nabla}^2\mathbf{v} + \frac{1}{3}\boldsymbol{\nabla}(\boldsymbol{\nabla}\cdot\mathbf{v})\right)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \boldsymbol{\nabla}\times(\mathbf{v}\times\mathbf{B} - \eta_B\boldsymbol{\nabla}\times\mathbf{B})$$



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

$$\Sigma(r) = \Sigma_0\left(\frac{r}{r_0}\right)^{-\alpha} e^{-t/\tau}$$

How simple is still good enough?