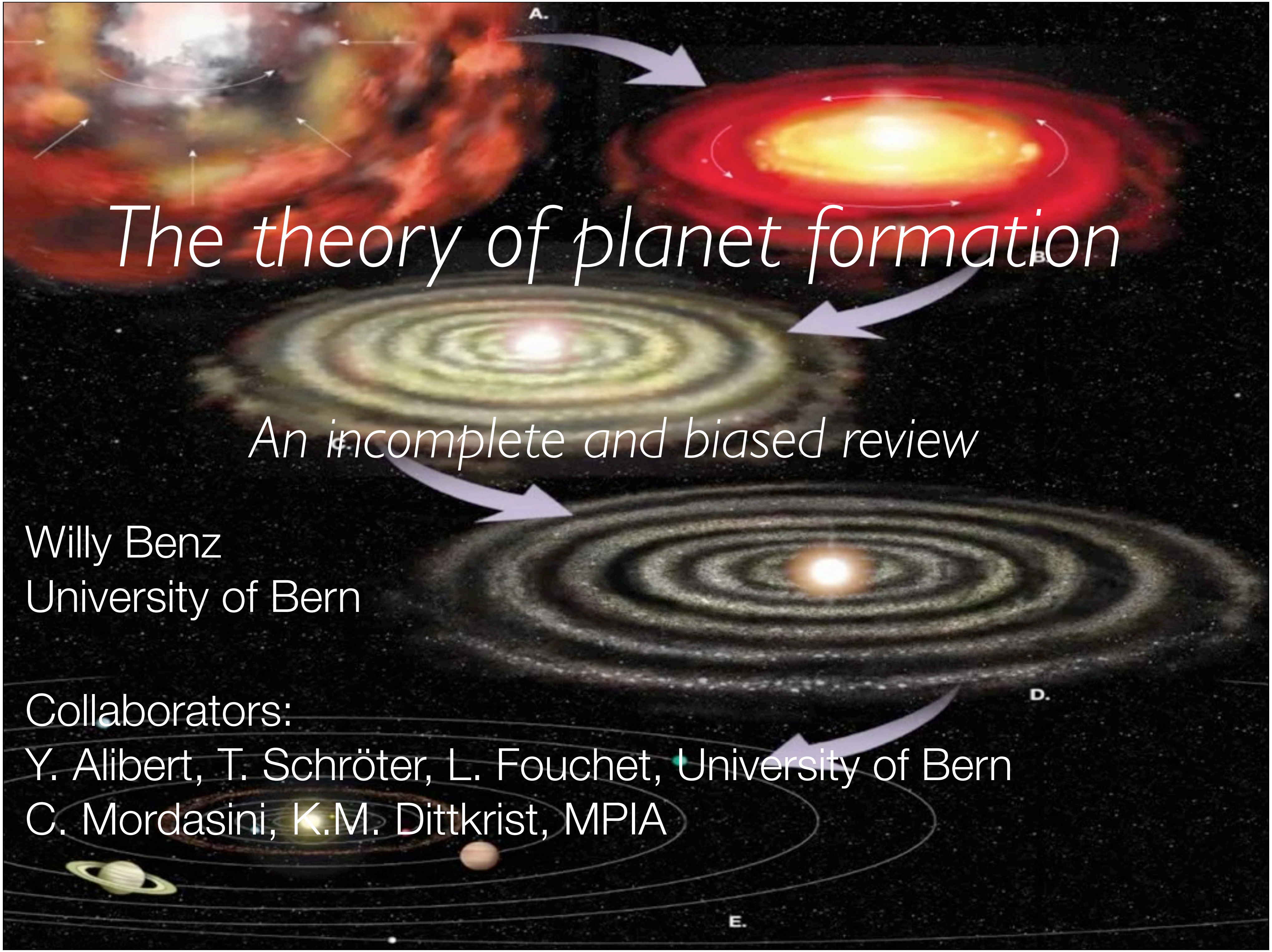


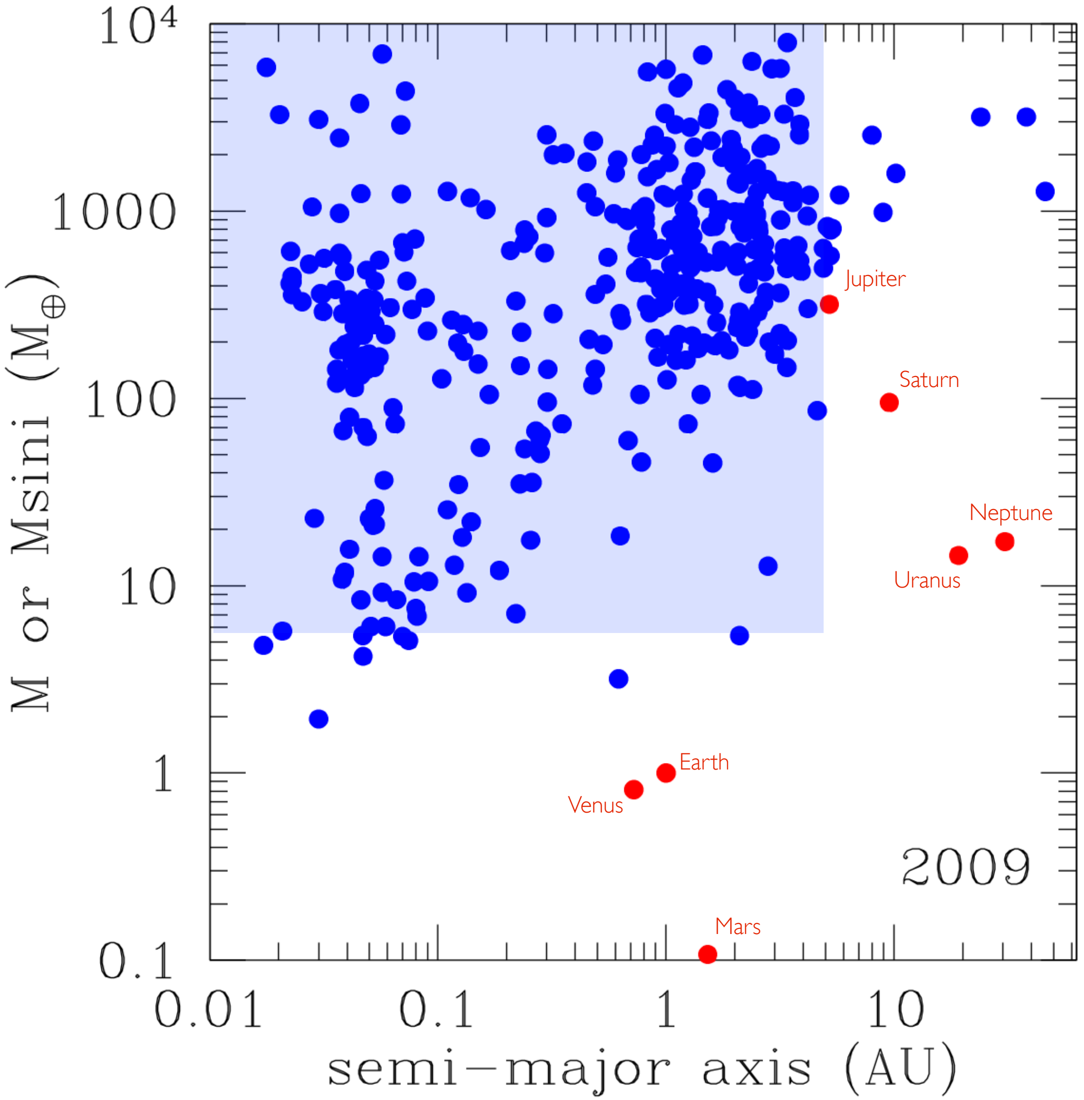
The theory of planet formation

An incomplete and biased review

Willy Benz
University of Bern

Collaborators:
Y. Alibert, T. Schröter, L. Fouchet, University of Bern
C. Mordasini, K.M. Dittkrist, MPIA

Observations & theory



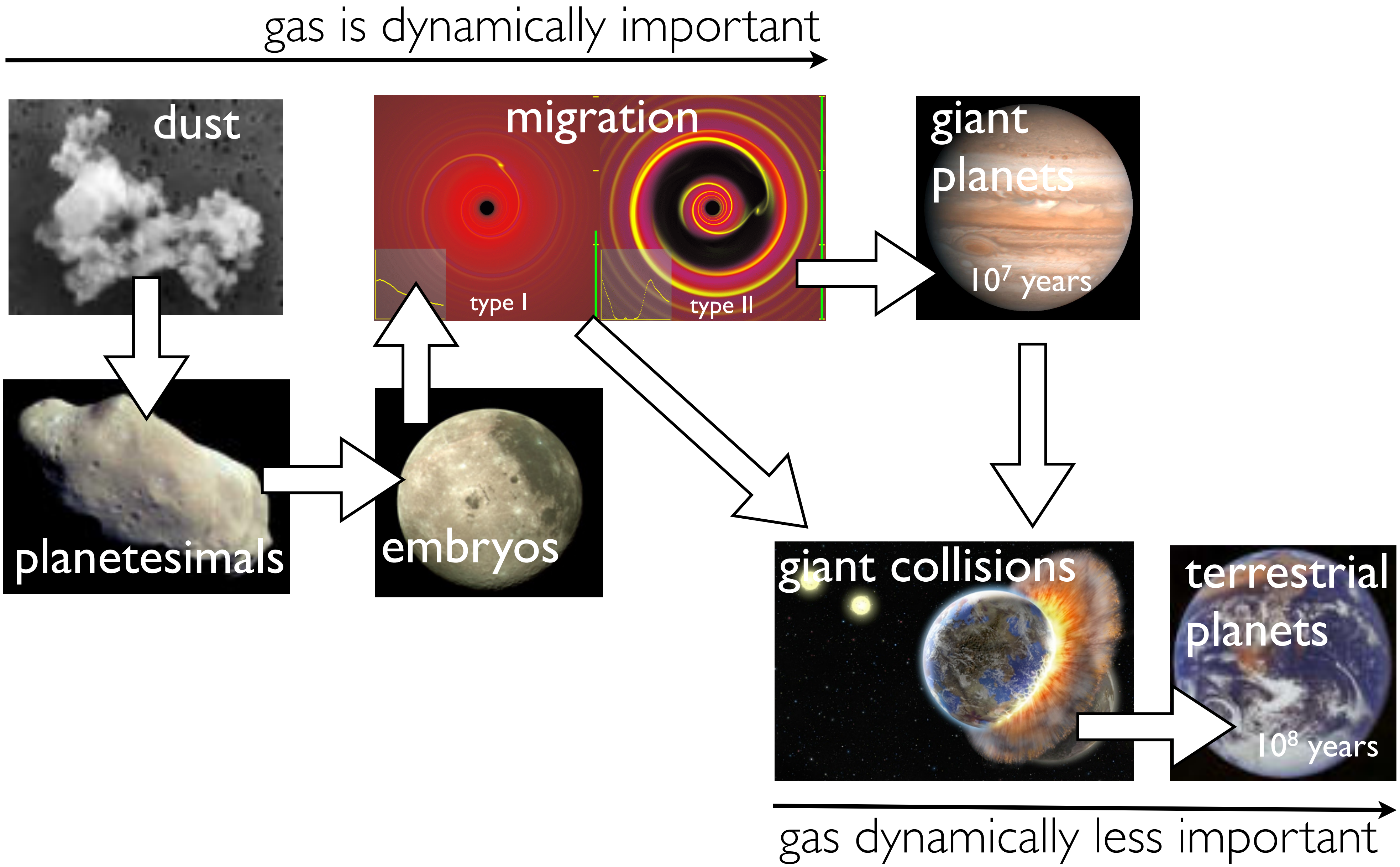
455 planets...

Exoplanets have been found exactly where one did not expect to find them...

points towards serious gaps in our understanding of planet formation as derived from the solar system alone!

there might be more gaps! more data is needed!

Planet Formation: Stages



gas is dynamically important

dust

planetesimals

embryos

migration

type I

type II

giant planets

10^7 years

giant collisions

terrestrial planets

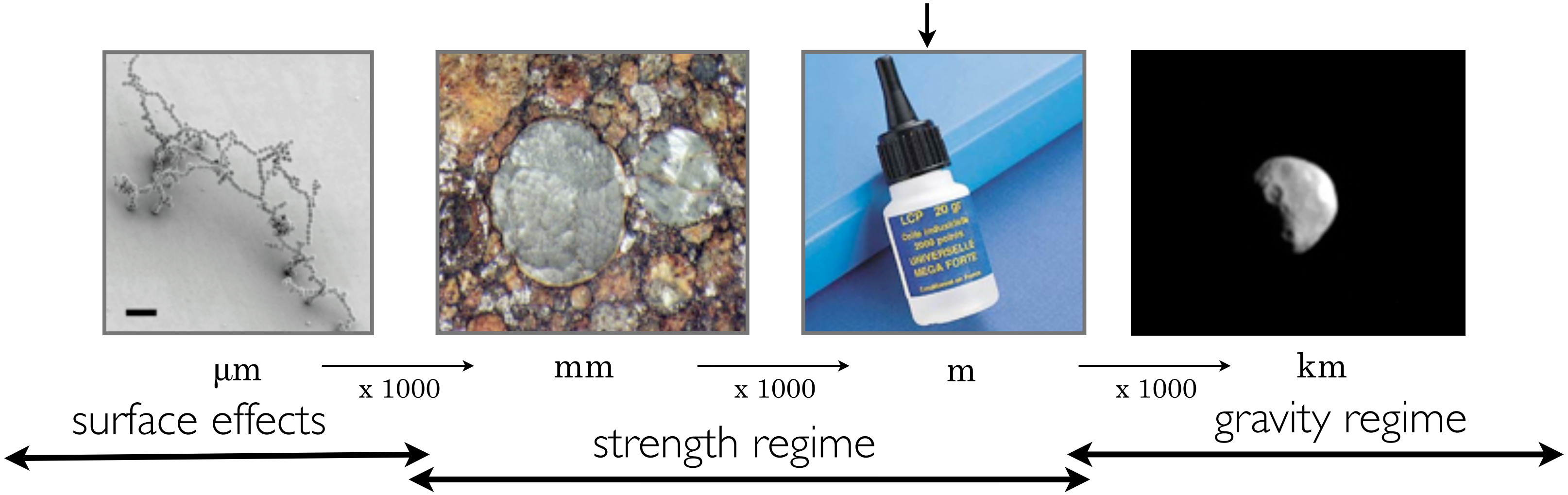
10^8 years

gas dynamically less important

Growth from dust to planetesimals

Classical collisional coagulation

- solids and gas do not orbit the star at the same speed
  - → *gas drag causes dust to drift towards the star*
  - → *gas drag & turbulence determines the relative collision velocities*



maximum relative velocities

μm → x 1000 → mm → x 1000 → m → x 1000 → km

surface effects

strength regime

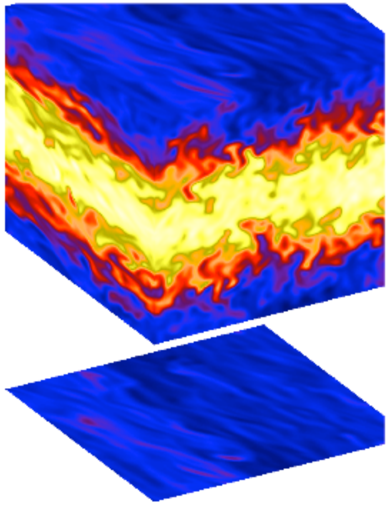
gravity regime

Difficulties:

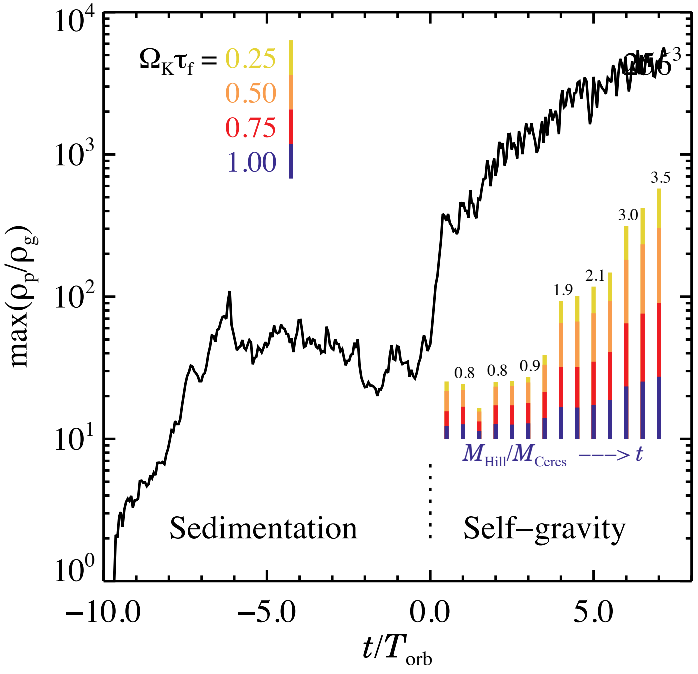
- drift timescale only 100 yr for 1 m body at 1 AU
- what makes meter-sized rocks stick together?
- typical velocities for 1 m bodies lead to destructive collisions

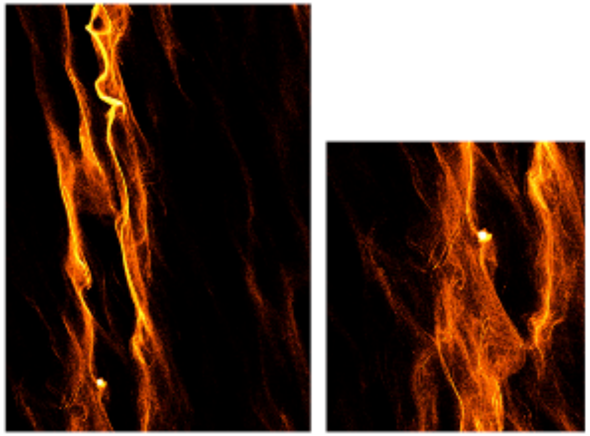
Gravoturbulent planetesimal formation

Dust is trapped *locally* in transient gas vortices in a turbulent disk and eventually becomes gravitationally bound.



Klahr & Johansen 2008





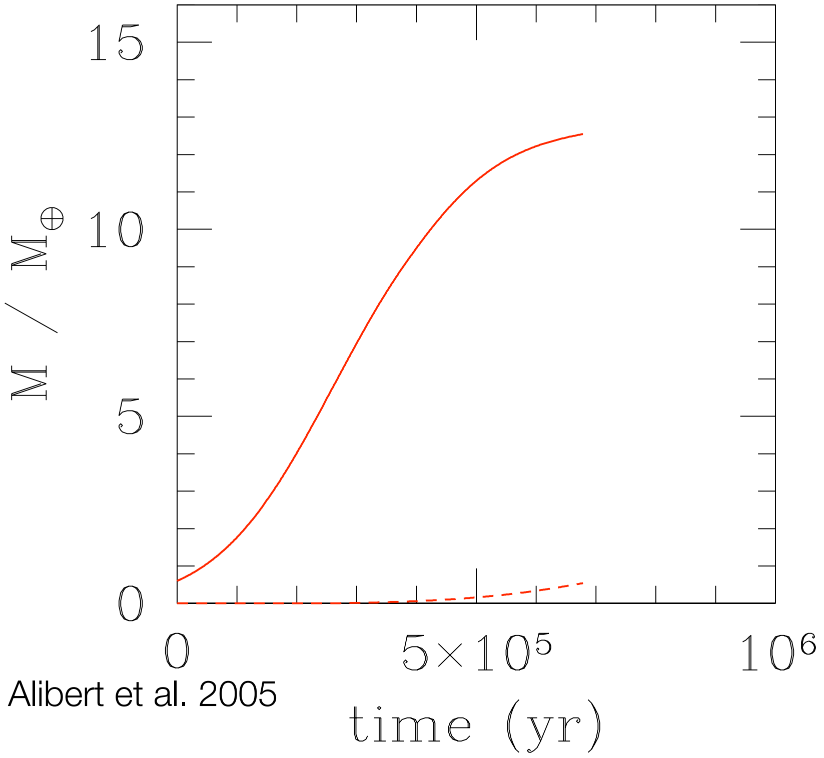
Turbulence aided growth might proceed from pebbles directly to intermediate-sized (100-1000 km) objects.

Are all bodies born that big?

From planetesimals to protoplanets

Semi-analytical rate equations

Rate equations: simplest possible approach.



Alibert et al. 2005

One big body & many small background planetesimals (surface density)

$$\frac{dM}{dt} = F\frac{\Sigma}{h}\pi R^2 \boxed{\left(1 + \frac{v_{esc}^2}{v_{rel}^2}\right)} v_{rel} \quad (= \rho\sigma v)$$

Safronov 1969

Gravitational focussing!

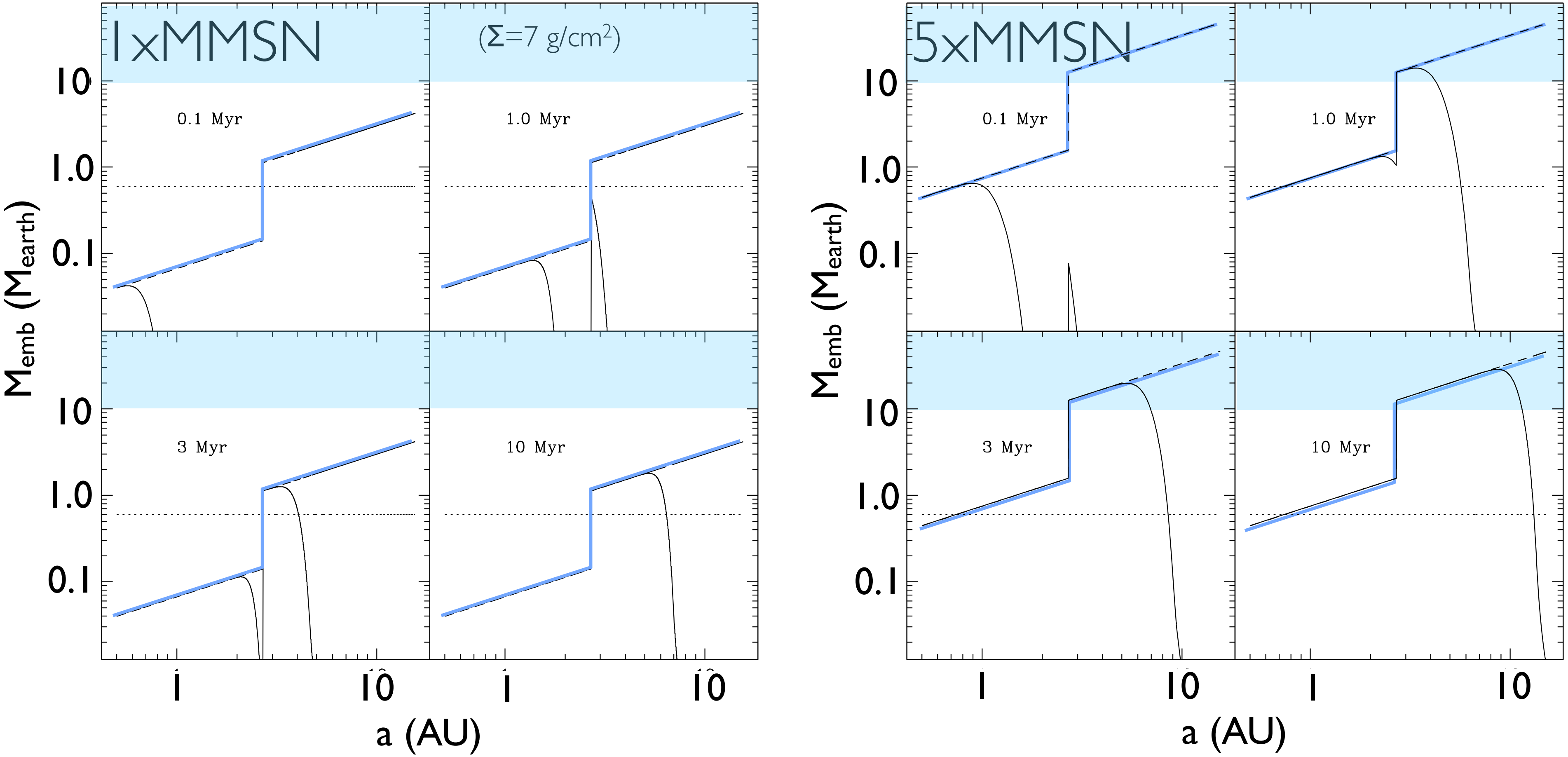
v_{rel} key parameter.

Without radial excursion, growth goes up until the isolation mass is reached: the protoplanet has accreted all planetesimals in its gravitational reach (in the feeding zone, width ca 5 Hills sphere radii).

$$m_{isolation} \approx \frac{(4\pi r^2 \Sigma)^{\frac{3}{2}}}{(3M_\star)^{\frac{1}{2}}} \approx 0.07\left(\frac{a}{1\mathrm{AU}}\right)^3 \left(\frac{\Sigma}{10\mathrm{gcm}^{-2}}\right)^{3/2} M_\oplus$$

Growth as a function of semi-major axis

Mordasini et al. 2009



- Growth proceeds from inside out
- Formation of massive cores ($M > 10\ M_{Earth}$) necessary to build giant planets require massive disks

Beyond the rate equation

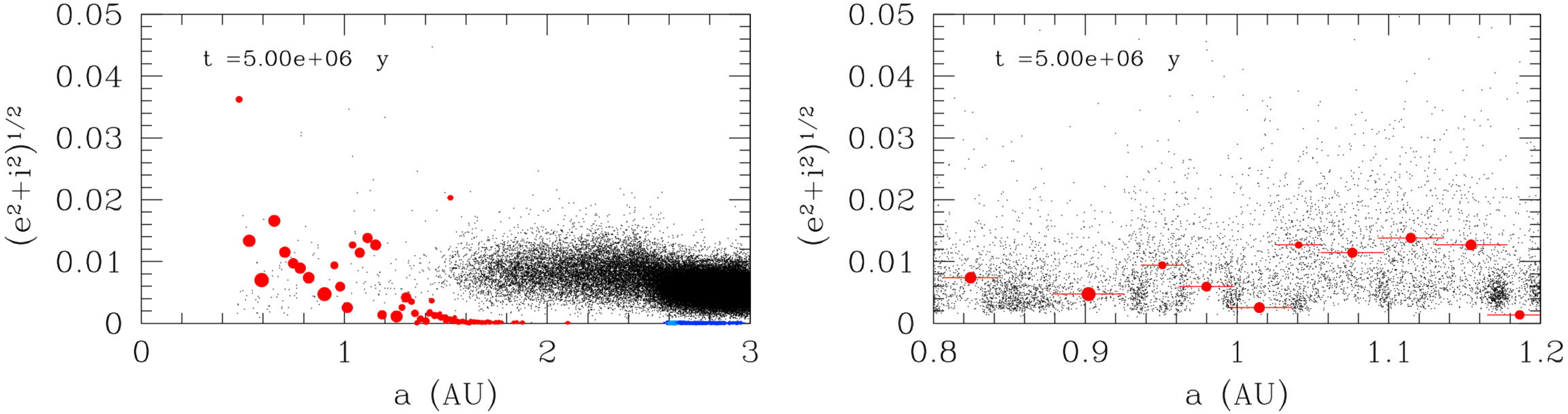
- Monte Carlo method
  - follow explicitely up to 100 million bodies embedded in evolving gas disk
  - processes: relaxation, collisioons, gas drag, and type I migration

Example: Evolution of 65 million bodies 35 km radius between 0.5-3.0 AU

- surface density of MMSN, iceline at 2.6 AU

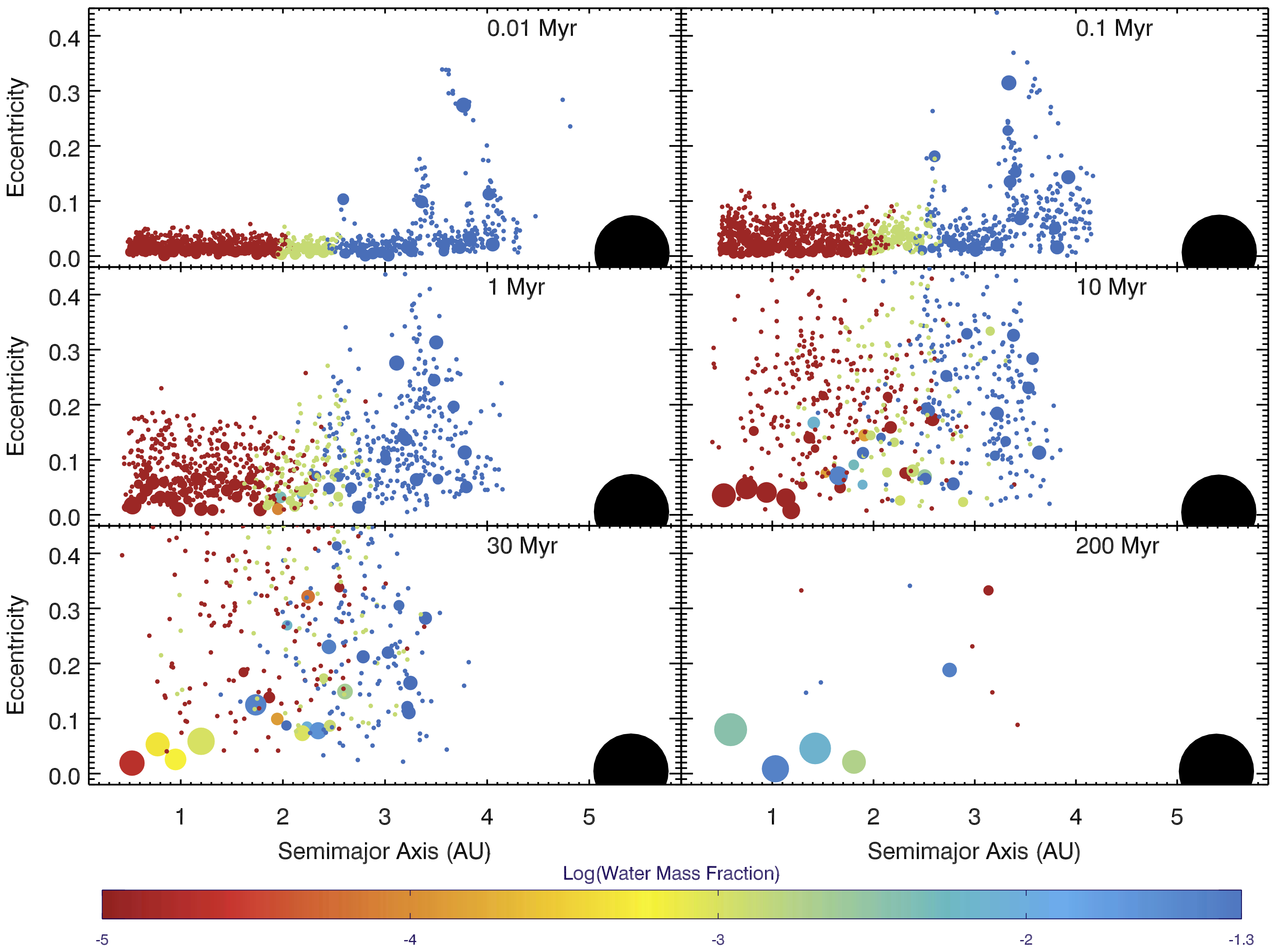
- maximum mass: 0.15 M_{Earth}
- no massive bodies at large distances

Schröter et al. in prep.



How to form the > 10 M_{Earth} cores of giant planets??

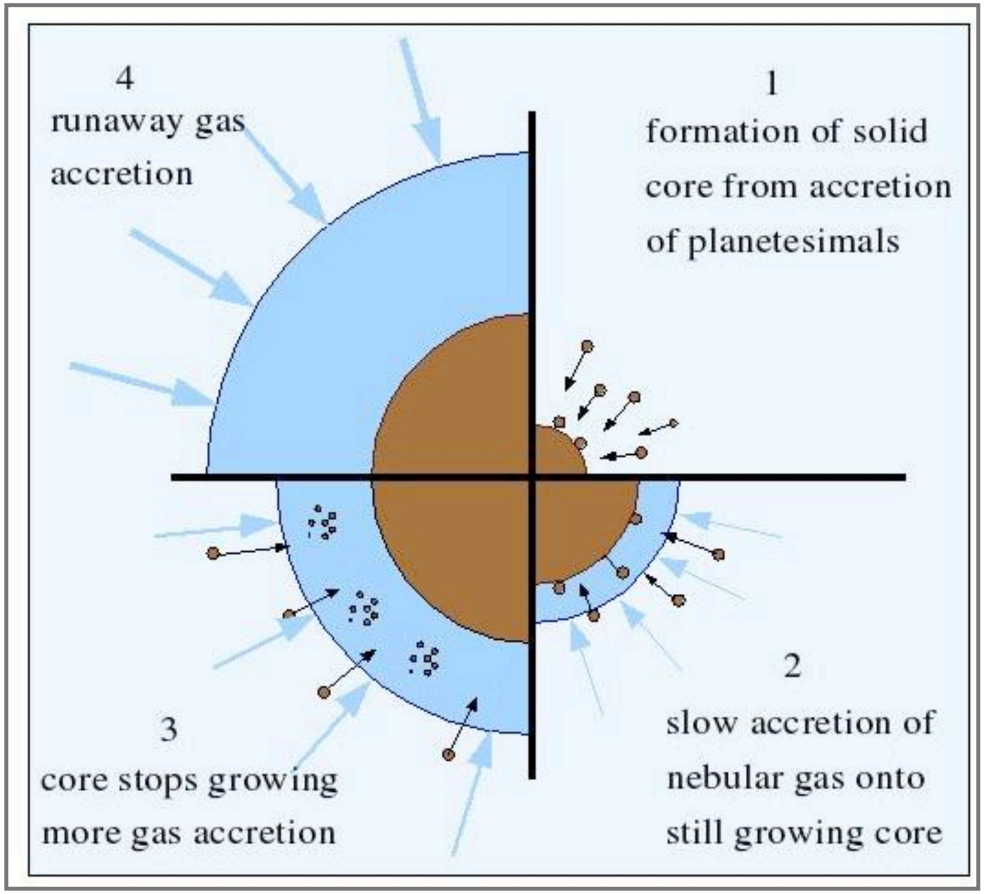
Late stages: Terrestrial planets



Jupiter assumed to be present early on....

Giant planet formation

The core accretion paradigm



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

Basic requirement:

1) Formation of a critical core

a critical core must form through collisional accretion of planetesimals

$M_{crit} \approx 10\ M_{Earth}$

2) Availability of gas

gas must be available to accrete once the critical core has formed

A timing issue!

Timescales

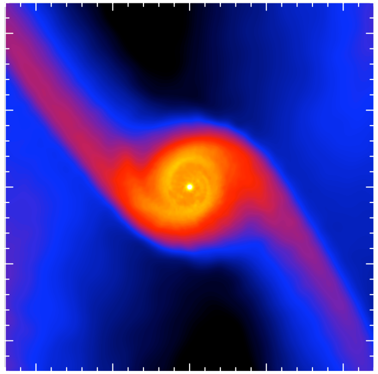
Timescale for specific processes: The heart of the problem

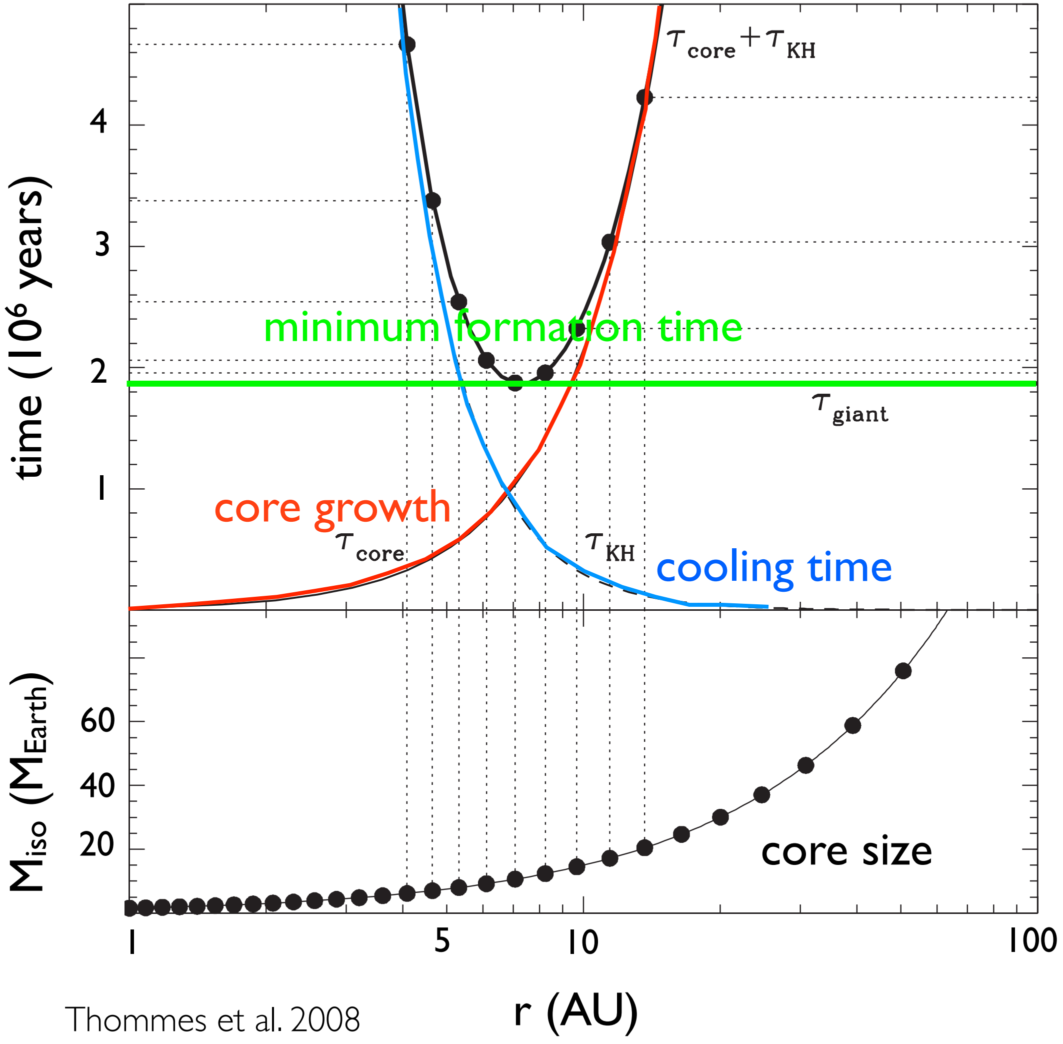
- the growth time of a massive core: Collisional dynamics
  - → function of distance to star
- the core gas accretion time scale: Radiative losses
  - → function of core size
- the gas supply rate from the disk: (Magneto-)Hydrodynamics
  - → function of disk dissipation mechanism
- the migration rate: Interactions
  - → function of core size and disk characteristics

In some regime these timescales are similar, in others they are different

→ *need a self-consistent approach that captures this*

Gas accretion by the core


Ayliffe & Bate 2009



Thommes et al. 2008

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:

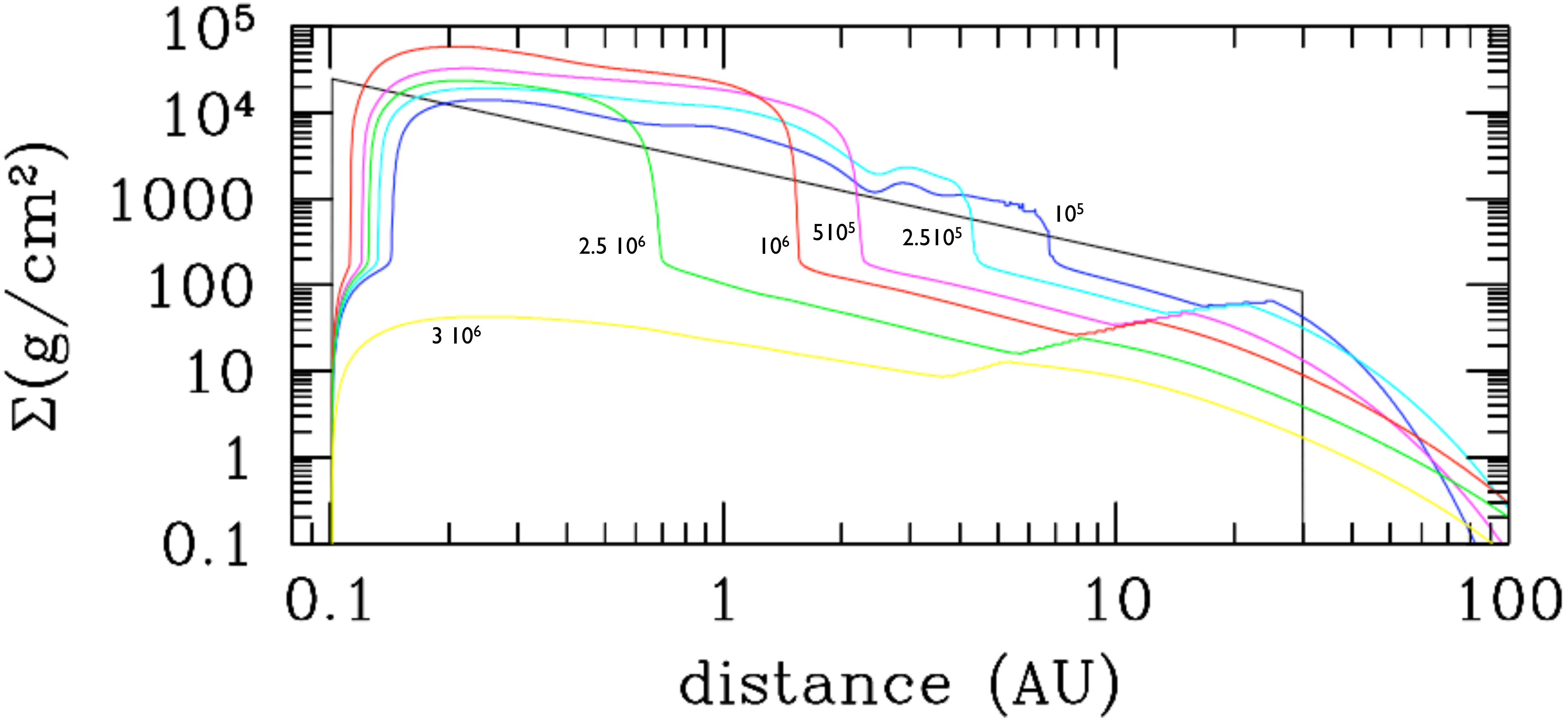
$$R_{\text{planet}} = R_{\text{Hills}}$$

Evolution of the gaseous disk

Example: Irradiated profile with dead-zone and $\alpha = 7 \times 10^{-3}$

Lifetime: ~6 × 10^6 years

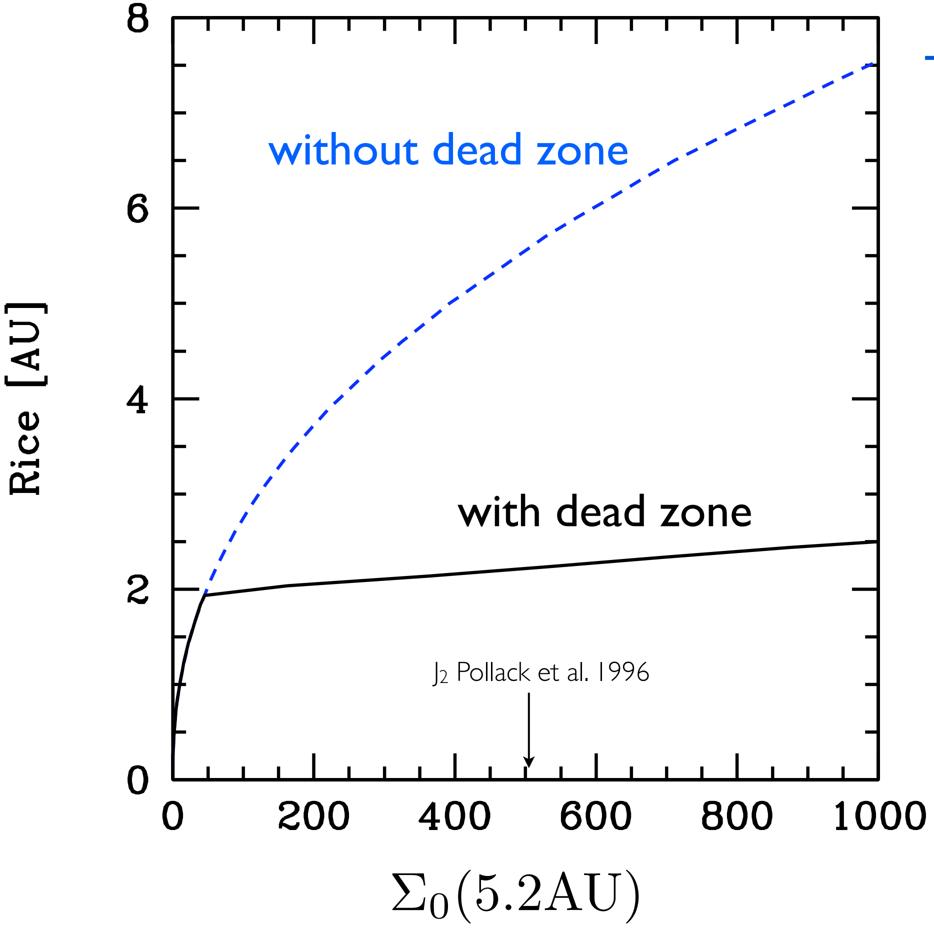
Very simple criterion for dead-zone: $\sum > 100$ g/cm^2
Effective viscosity is obtained by z-averaging



Position of the ice line (IL)

The position of the IL is critical in the core acretion theory. Its position is determined from the characteristics of the disk (e.g. density, alpha, etc.)

$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-3/2}$ $\alpha = 7 \times 10^{-3}$ no irr.



$$\xrightarrow{} \frac{r_{ice}}{\mathrm{AU}} \approx \left(\frac{\Sigma_{5.2\mathrm{AU}}}{10\mathrm{g/cm}^2}\right)^{0.44} \times \left(\frac{M_{star}}{M_\odot}\right)^{0.1}$$

Notes:

- position of IL is a function of the assumed surface density
- for massive disks, the IL can be located at significant distances
- the presence of a dead-zone leads to a closer IL

Migration

- Type I (low mass planets): No gap

Isothermal approximation:

$$\frac{da_{\rm planet}}{dt} = \underset{\substack{\uparrow \\ \text{free parameter: 0 to 1}}}{f_{\rm I}} \left(\frac{da_{\rm planet}}{dt} \right)_{\rm linear}$$

Tanaka et al. 2002

- Type II (high mass planets): Gap formation

→ Disk dominated regime

$$M_{\rm planet} << \Sigma_{\rm P} a_{\rm P}^2 \quad \Longrightarrow \quad v_{\rm mig} = v_{\rm visc} \equiv \frac{3\nu_{\rm P}}{2a_{\rm P}}$$

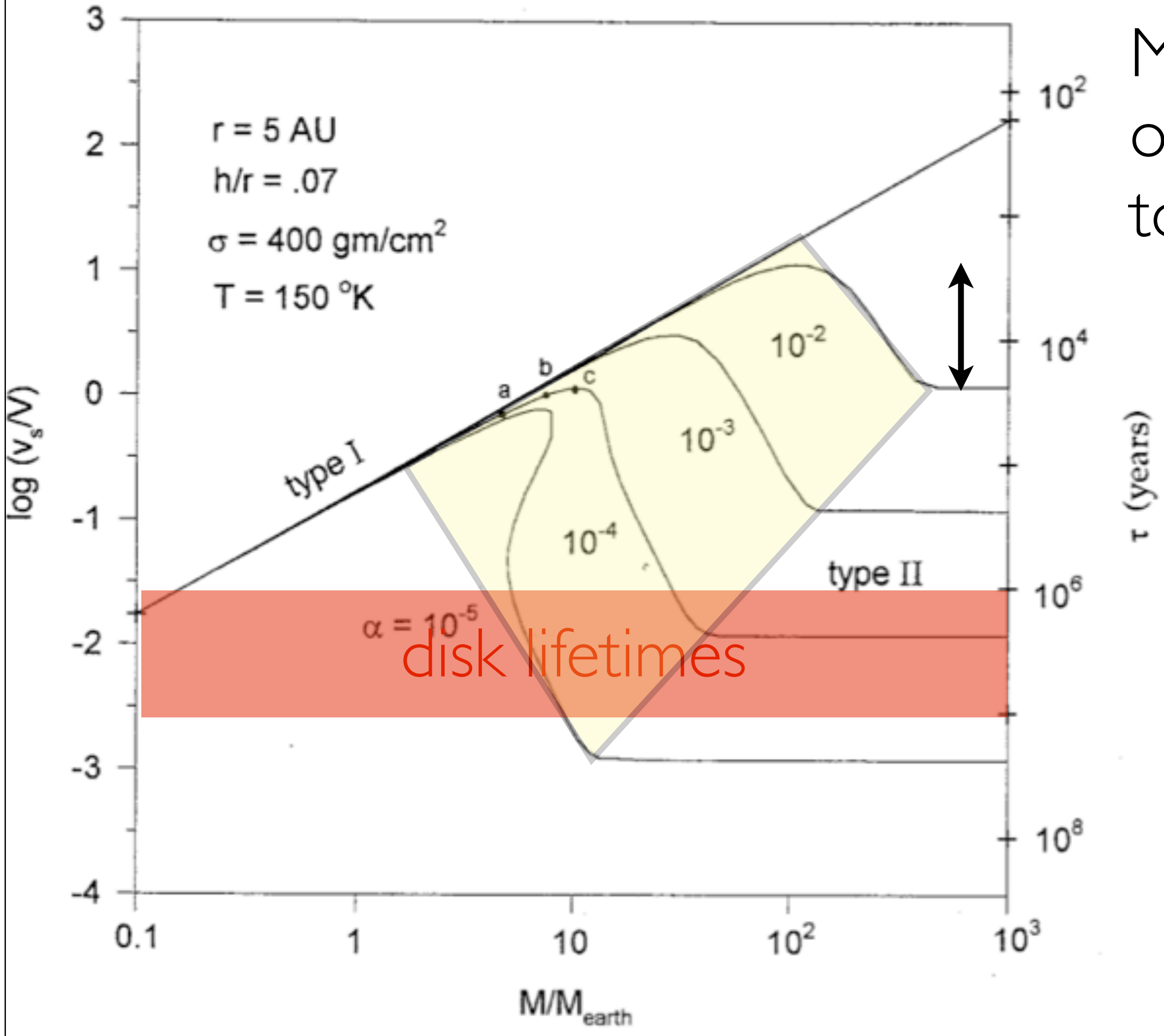
viscous evolution

→ Planet dominated regime

$$M_{\rm planet} >> \Sigma_{\rm P} a_{\rm P}^2 \quad \Longrightarrow \quad v_{\rm mig} = v_{\rm visc} \times \frac{2\Sigma a_{\rm P}^2}{M_{\rm planet}}$$

Ida & Lin 2004

Migration rates



Ward 1997

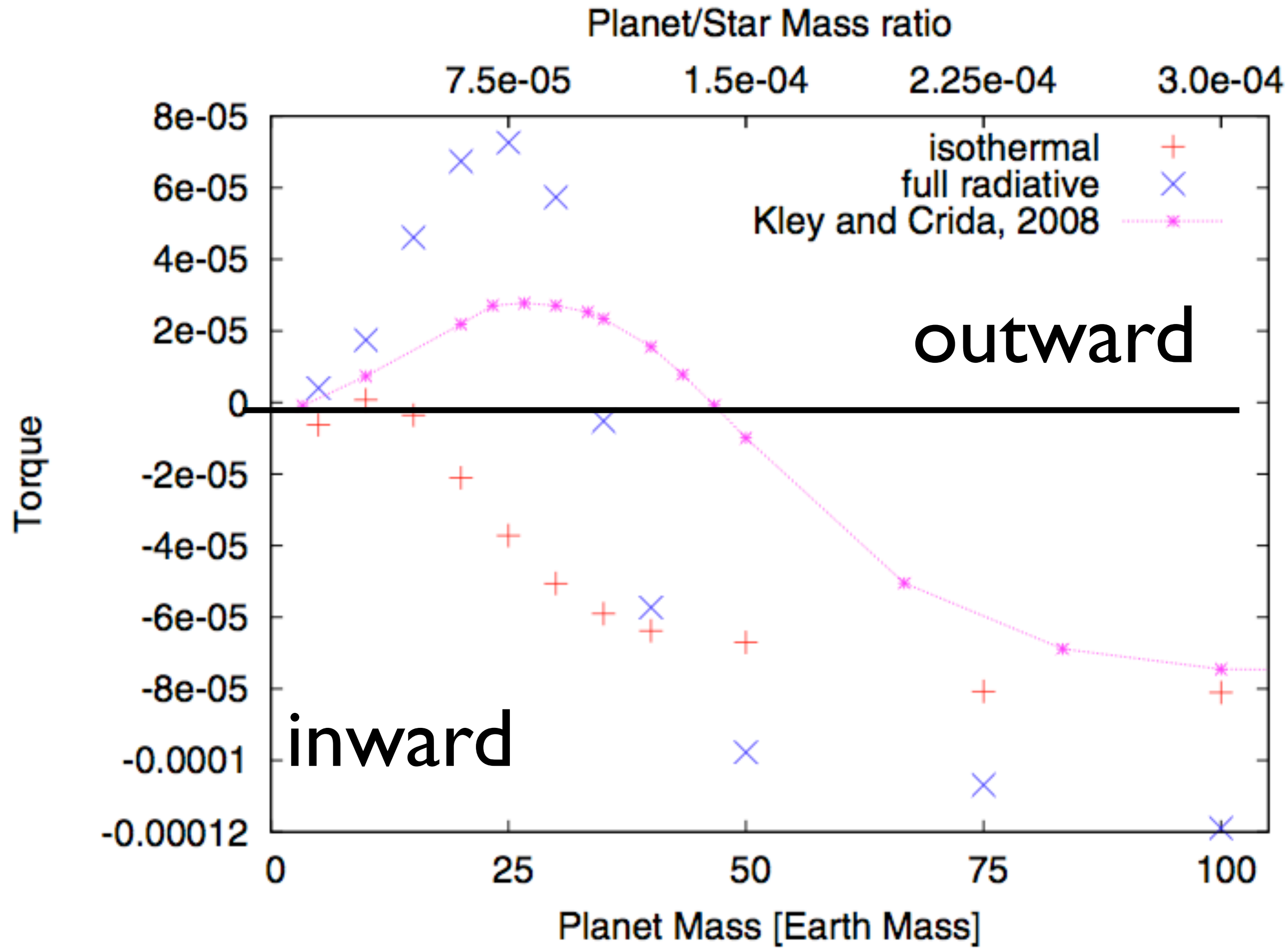
Migration rates change by 1-2 orders of magnitude from type to type II

Type I: Planets seem to migrate so fast that they should all fall into the star within the lifetime of the disk

simple linear theory for iso-thermal disks cannot be the final word!

Type I migration: Beyond isothermal

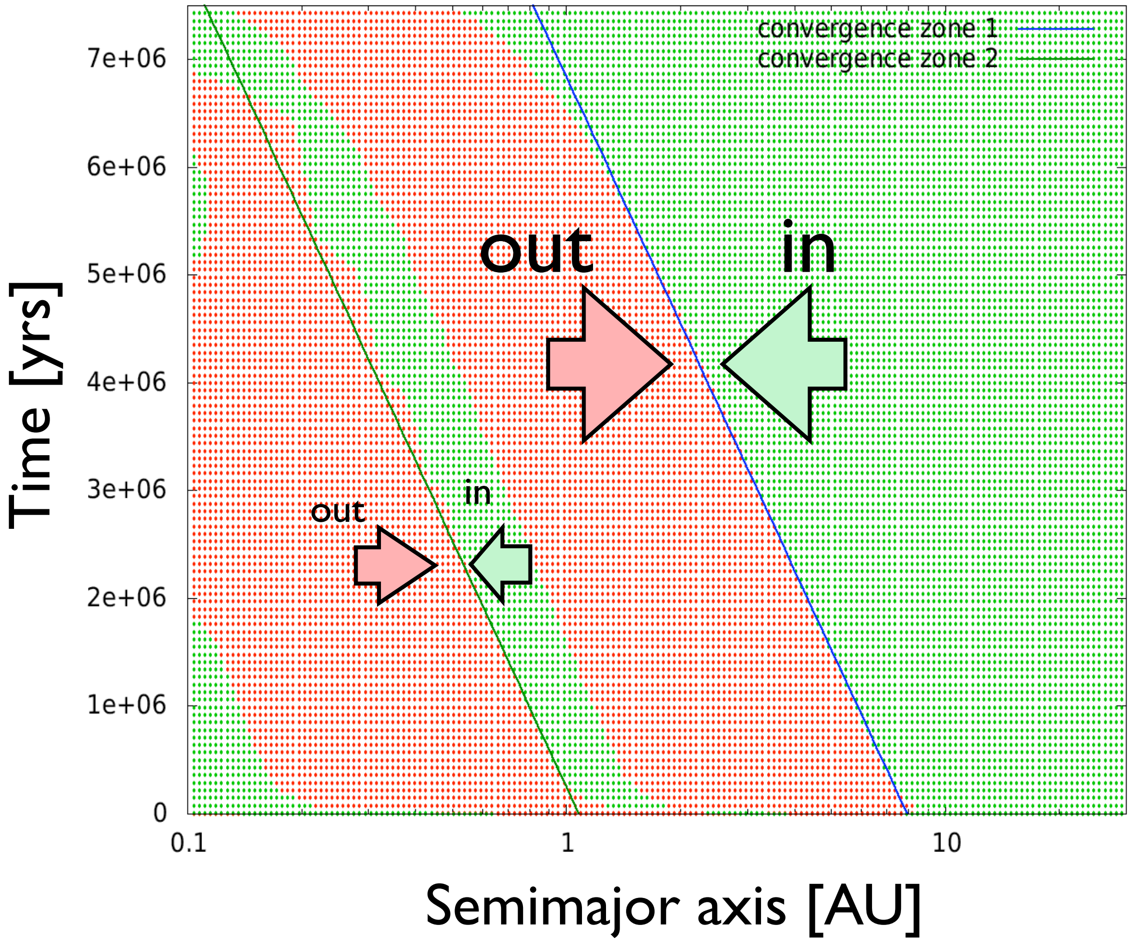
Crida et al. 2006; Baruteau & Masset 2008; Casoli & Masset 2009; Pardekooper et al. 2010; Baruteau & Lin 2010



Kley et al. 2009

Thermodynamics of the disk is essential

Type I convergence zones

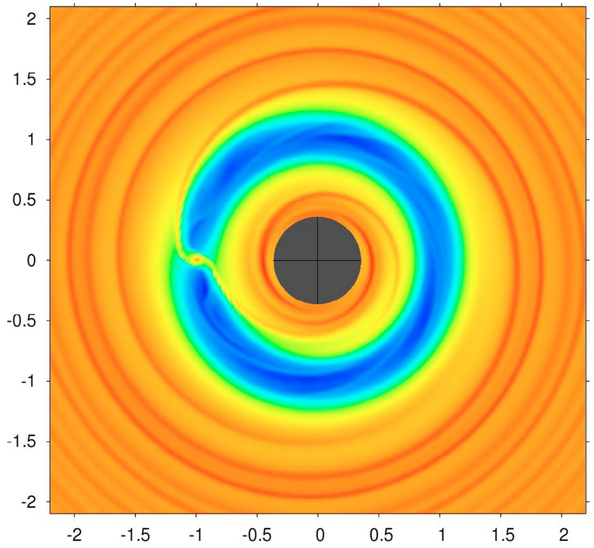


Exact location of convergence will depend upon the detailed structure of the disk

Dittkrist et al. in prep

Mechanism to grow large cores?

Gap formation: Type II migration



Kley & Dirksen 2006

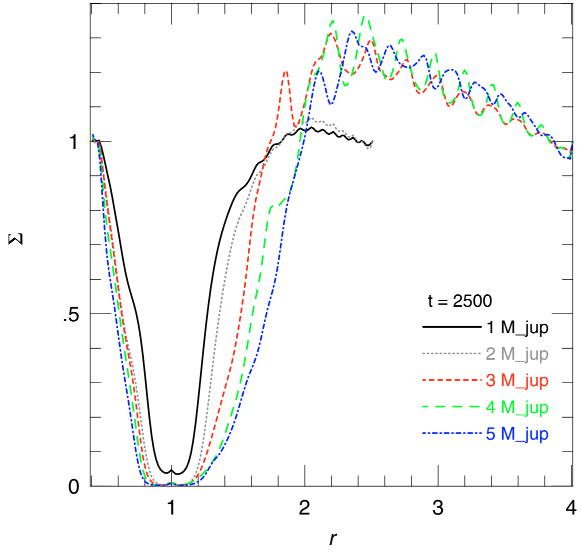
Crida et al. 2006

Transition to type II:
opening of gap

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

function of:

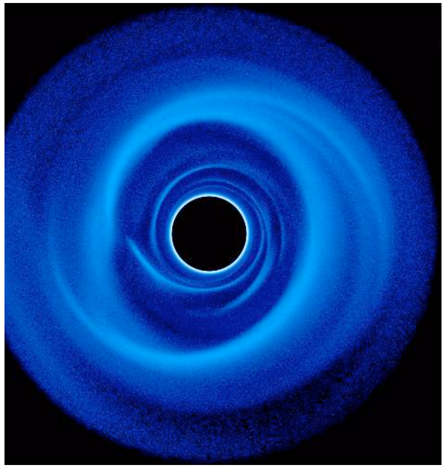
- disk characteristics: H, R
- planet & stellar mass



Large scale signature of planet-disk interaction

observationaly testable!

Wolf & Klahr 2008



Population synthesis

Population synthesis is a tool to:

- use all known exoplanets to constrain planet formation models
- test the implications of new theoretical concepts
- provide a link between theory and observations

Need to compute the formation of many planets

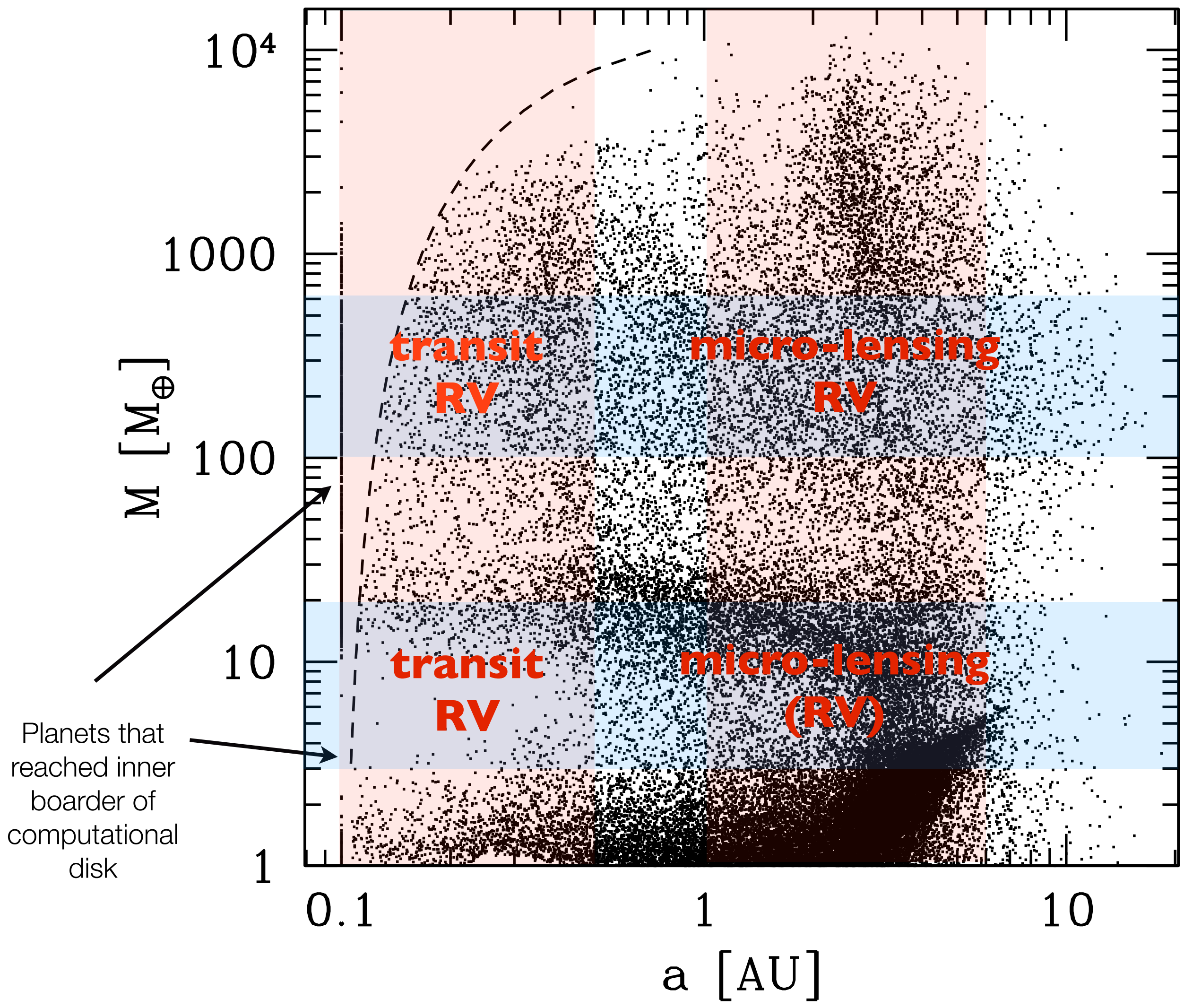
- the approach and the physics must be simplified
- it must capture the key effects
  - → requires separate detailed studies of all components
- several different approaches are useful

One learns a lot even if a synthetic population does not match the observed one!

Synthetic population

Nominal model, no irradiation, no dead zone

alpha= 7×10^{-3}, f_I=0.001, M=1 $M_\odot$



Planets that reached inner boarder of computational disk

Diversity in initial conditions leads to planet diversity

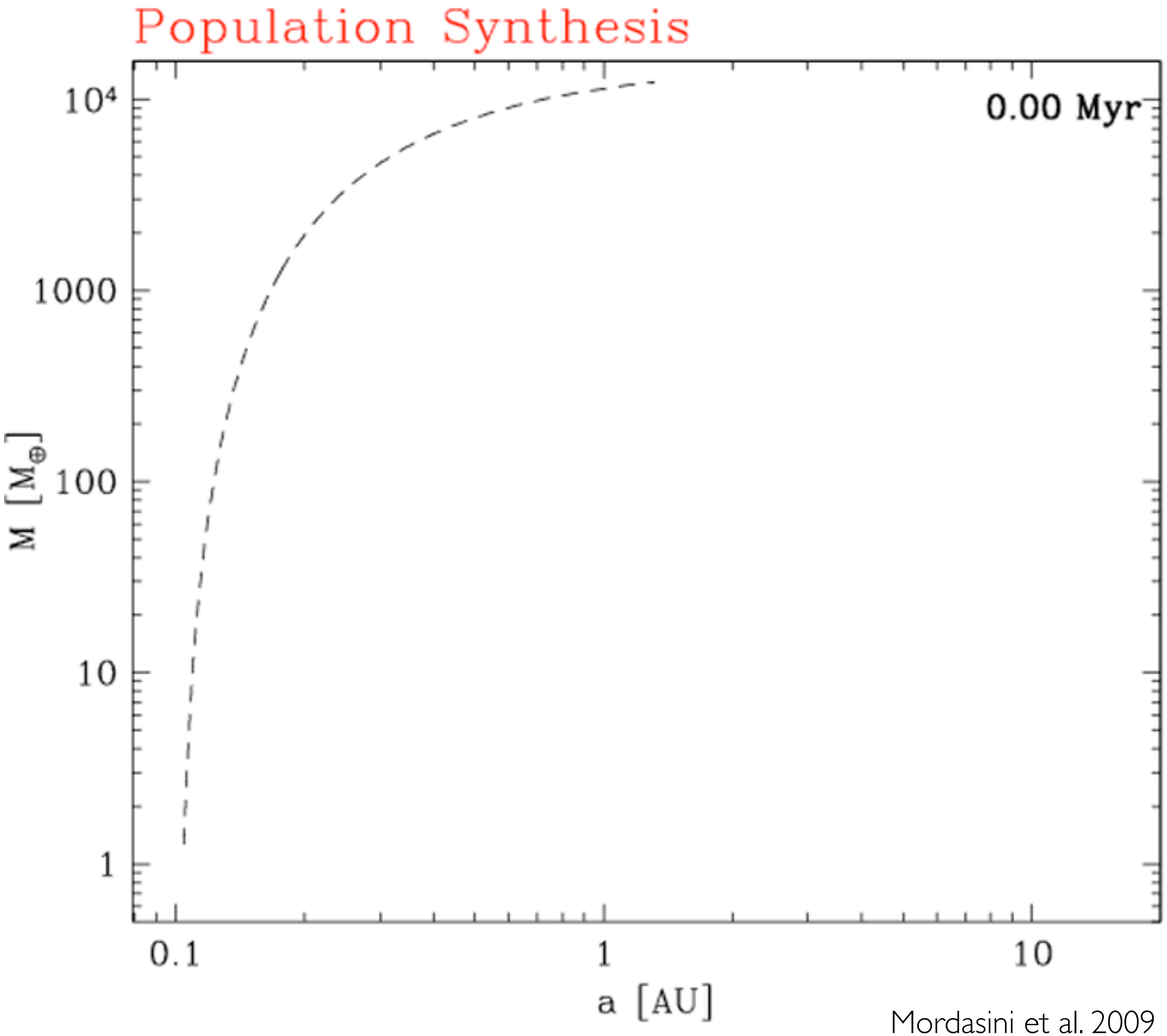
The distribution of planets in the a-M plane is not uniform

Different techniques probe different regions of the a-M plane

Mordasini et al. 2009
see also: Ida & Lin 2004,...,2010

Formation tracks

Nominal model: Isothermal migration only



Mordasini et al. 2009

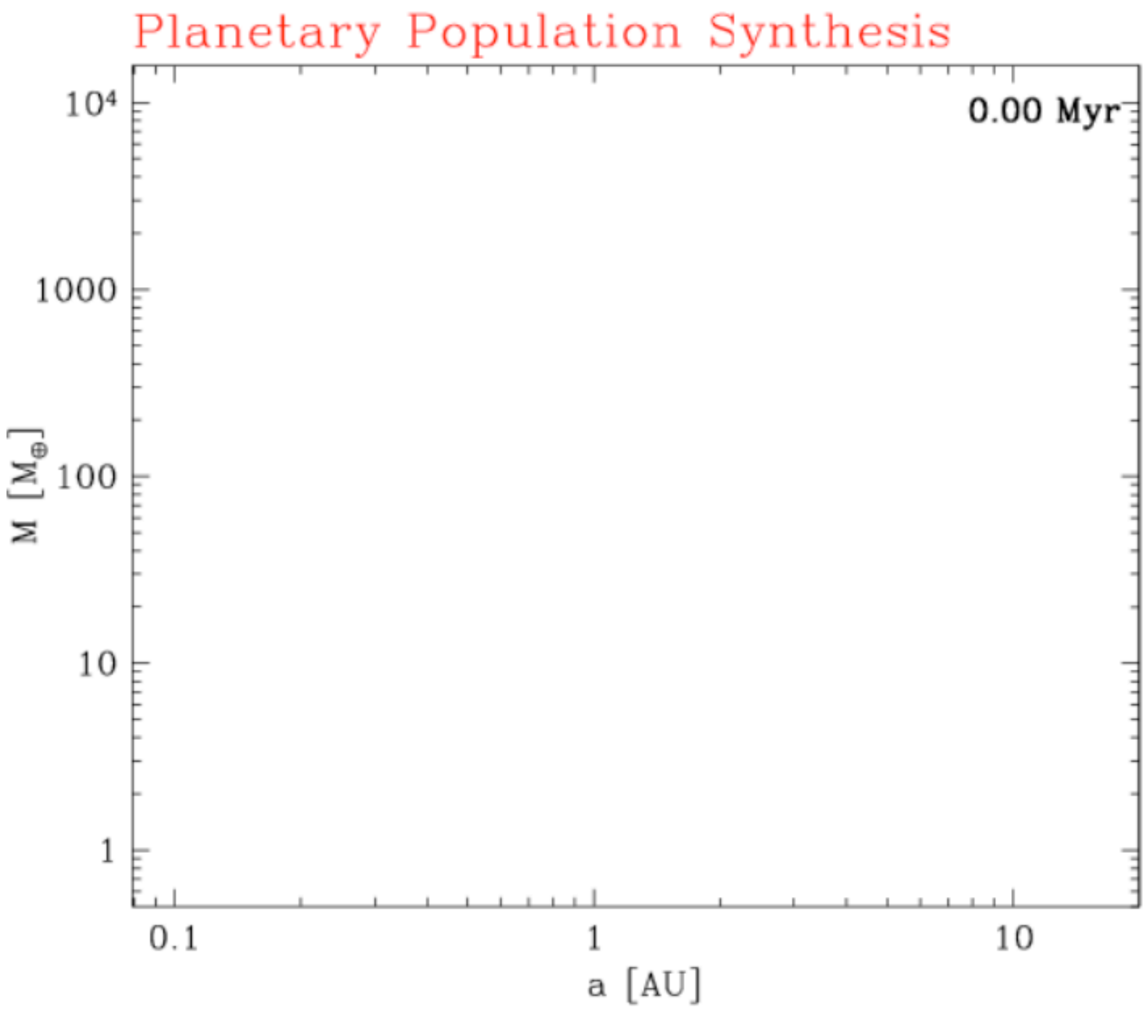
M_{star}=1 $M_\odot$
Nominal model

Type I migration
(Analytical rate reduced by f_I)

Type II migration
(Disk dominated: M_p<$M_{disk,loc}$)

Type II migration
(Planet dominated: M_p>$M_{disk,loc}$ & disk limited gas accretion)

Formation tracks



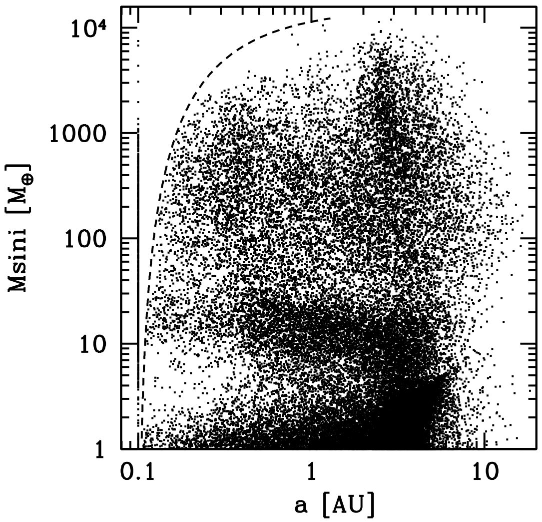
isothermal type I
adiabatic type I
saturated type I
type II

interactions between growing planets will play a key role!

Comparison with observations

(nominal model)

full synth. population

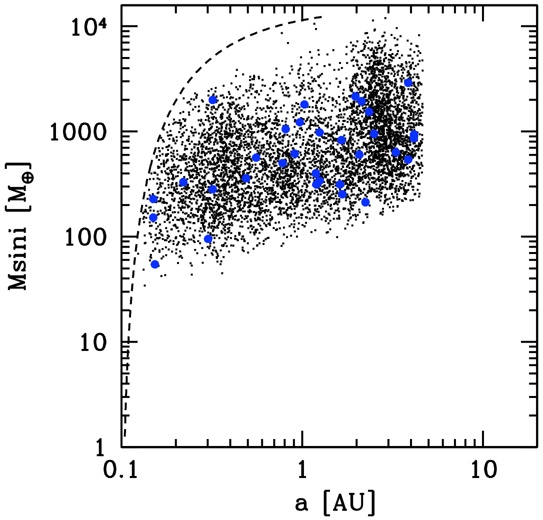


RV detection bias

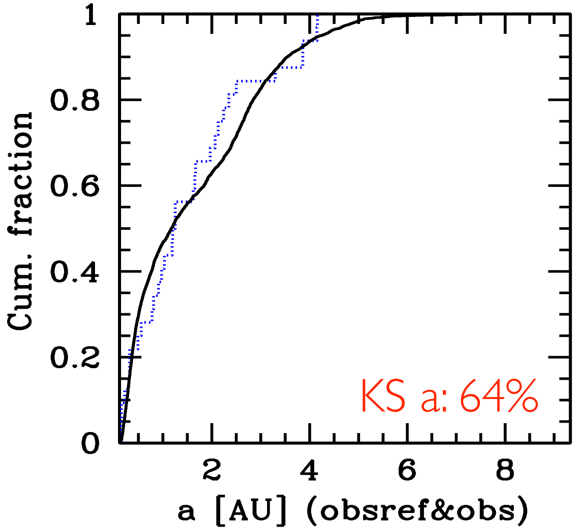
observ. comp. sample

- $0.7 < M_{star} < 1.3$
- $e < 0.3$
- one planet / star
- single host stars
- $K_{RV} > 10$ m/s

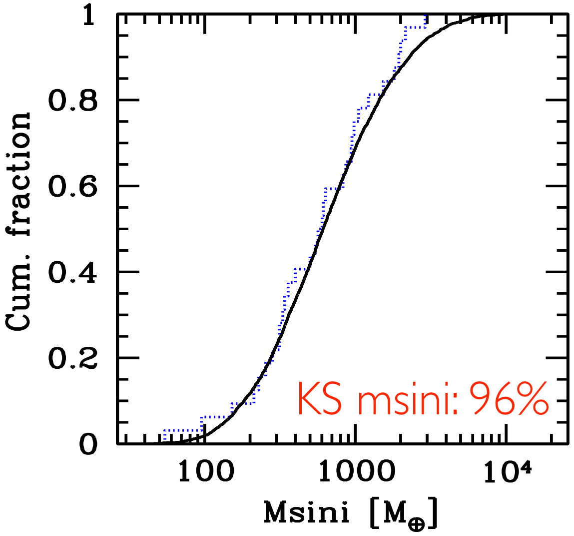
detectable sub-population



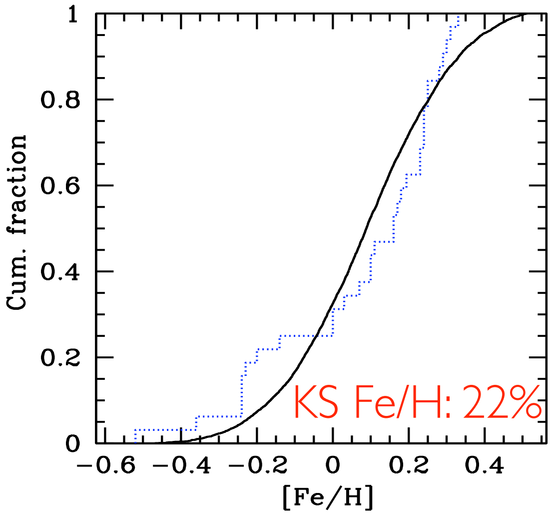
semi-major axis



m sini

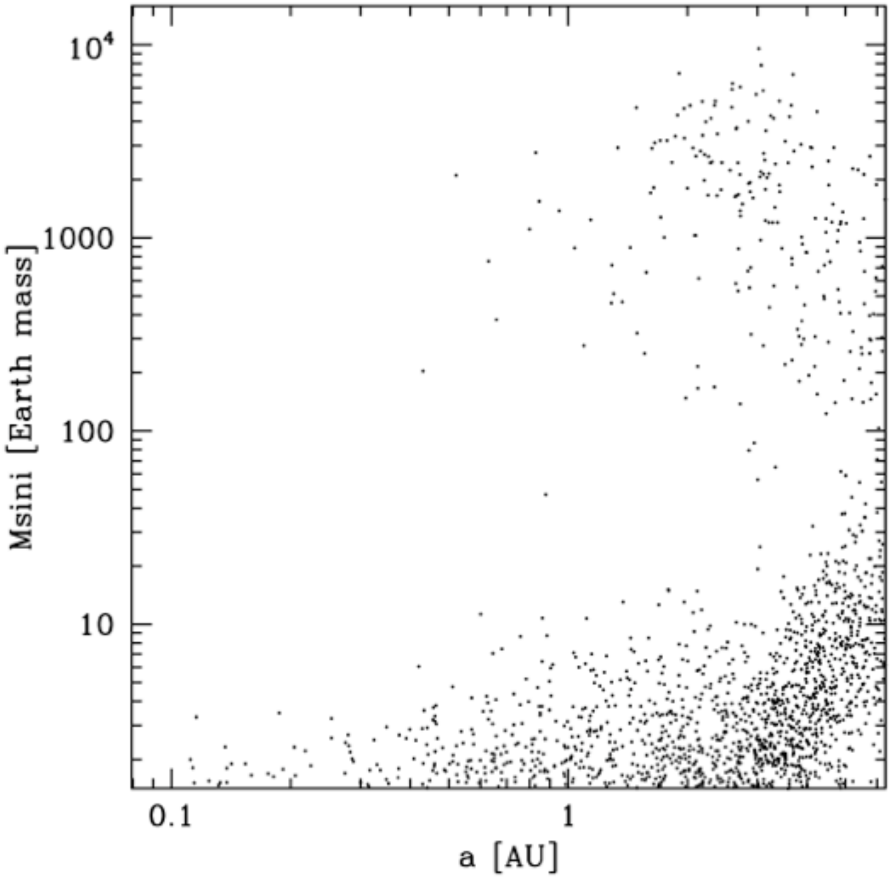


Fe/H

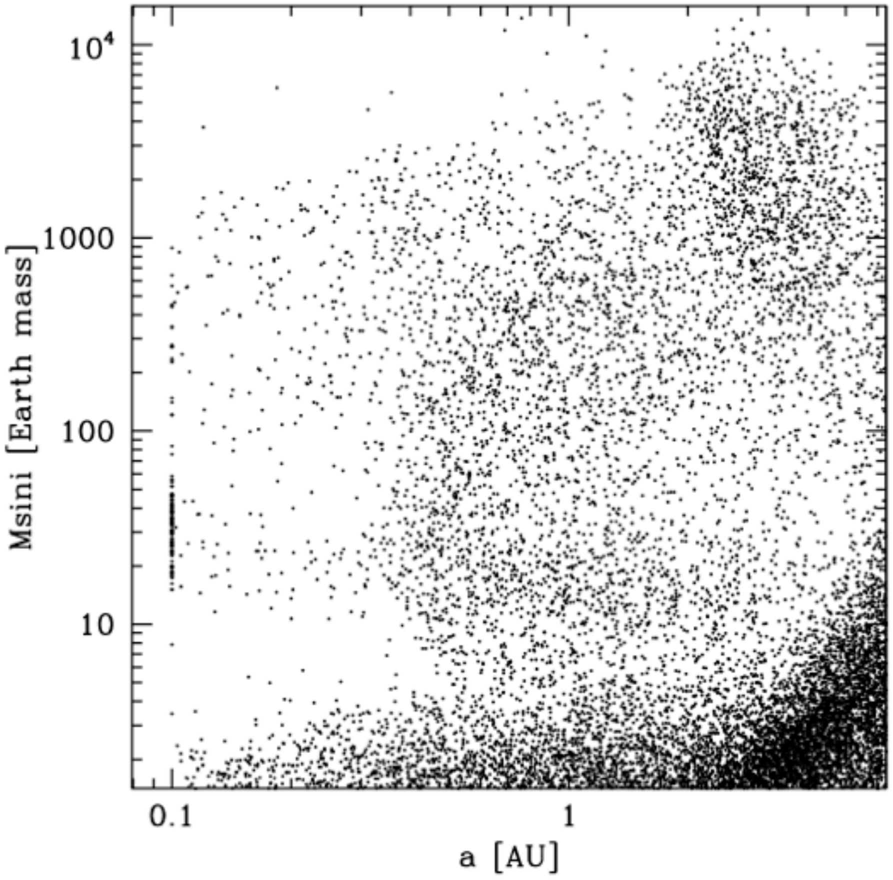


Structure of the disk: Irradiation

With irradiation



Without irradiation



Fouchet et al. 2010

transition between type I and type II migration

Beyond a solar mass

The mass of the central star enters in:

- the value of the Keplerian frequency
  - → accretion timescale of solids
  - → viscous dissipation in alpha-disk

$$\Omega = \sqrt{\frac{GM}{a^3_{planet}}}$$

- the value of the Hills radius
  - → size of feeding zone
  - → the size of the envelope at early times

$$R_H = a_{planet} \left(\frac{M_{planet}}{3M_{star}} \right)^{1/3}$$

- the type I & II migration rate
  - → extent of migration

- the position of the iceline
  - → the location of increased surface density

$$\frac{R_{ice}}{1AU} \approx \left(\frac{\Sigma_{5.2AU}}{10g/cm^2} \right)^{0.44} \left(\frac{M}{M_\odot} \right)^{0.1}$$

Alibert et al. 2010

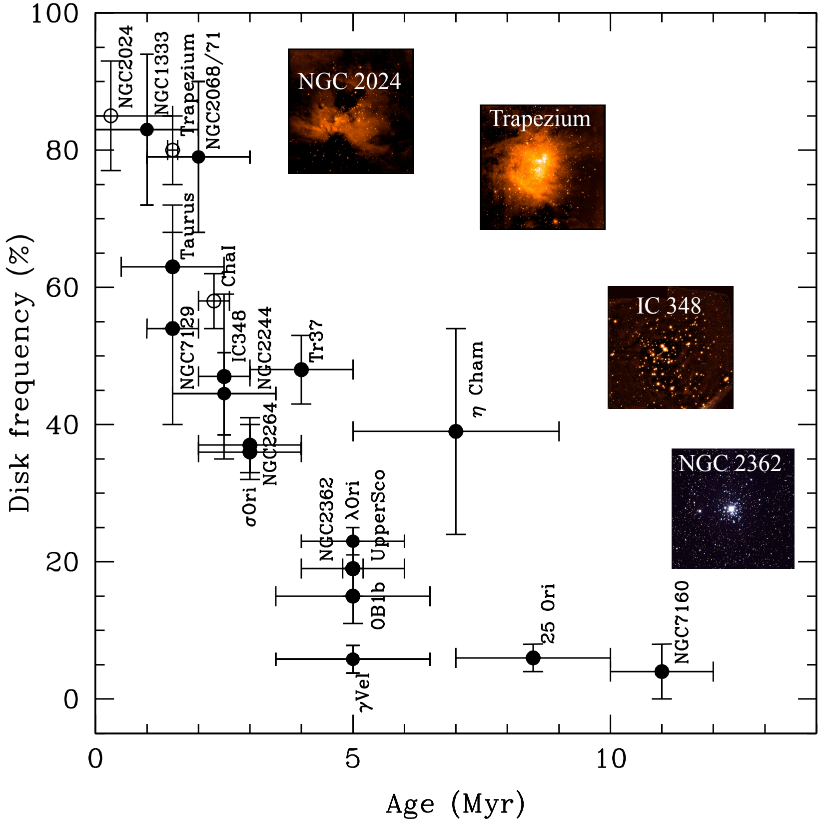
- characteristics of circumstellar disk
  - → mass and lifetime of disk
  - → disk structure

Characteristics of circumstellar disks

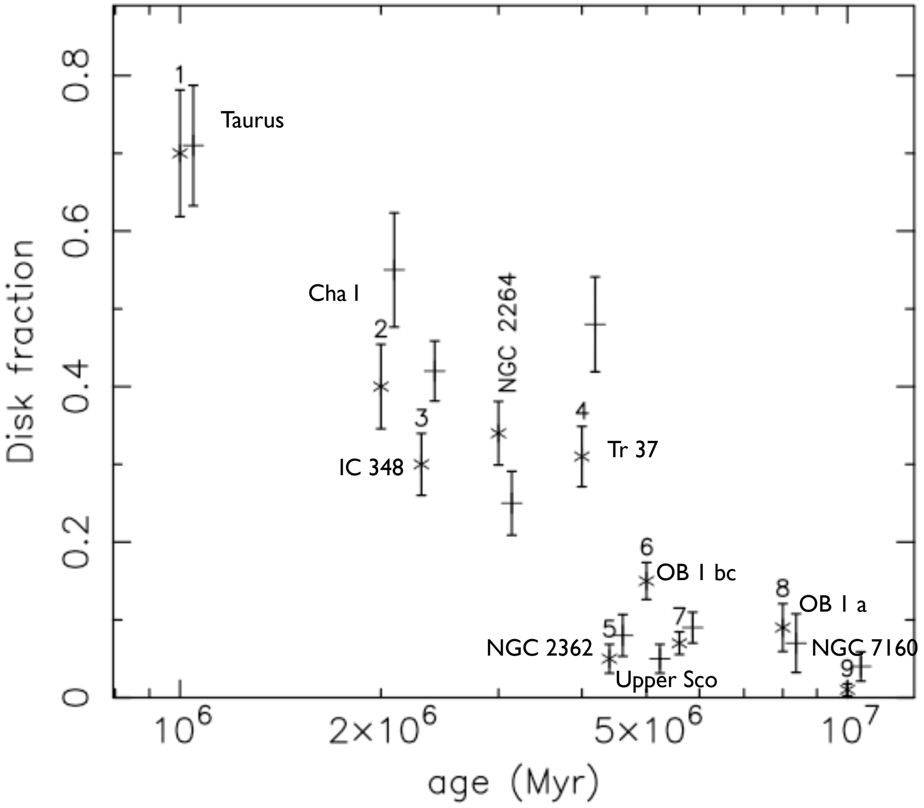
1) overall cluster lifetime

fractions of stars showing evidence for a disk

Hernandez et al. 2008



Kennedy & Kenyon 2009

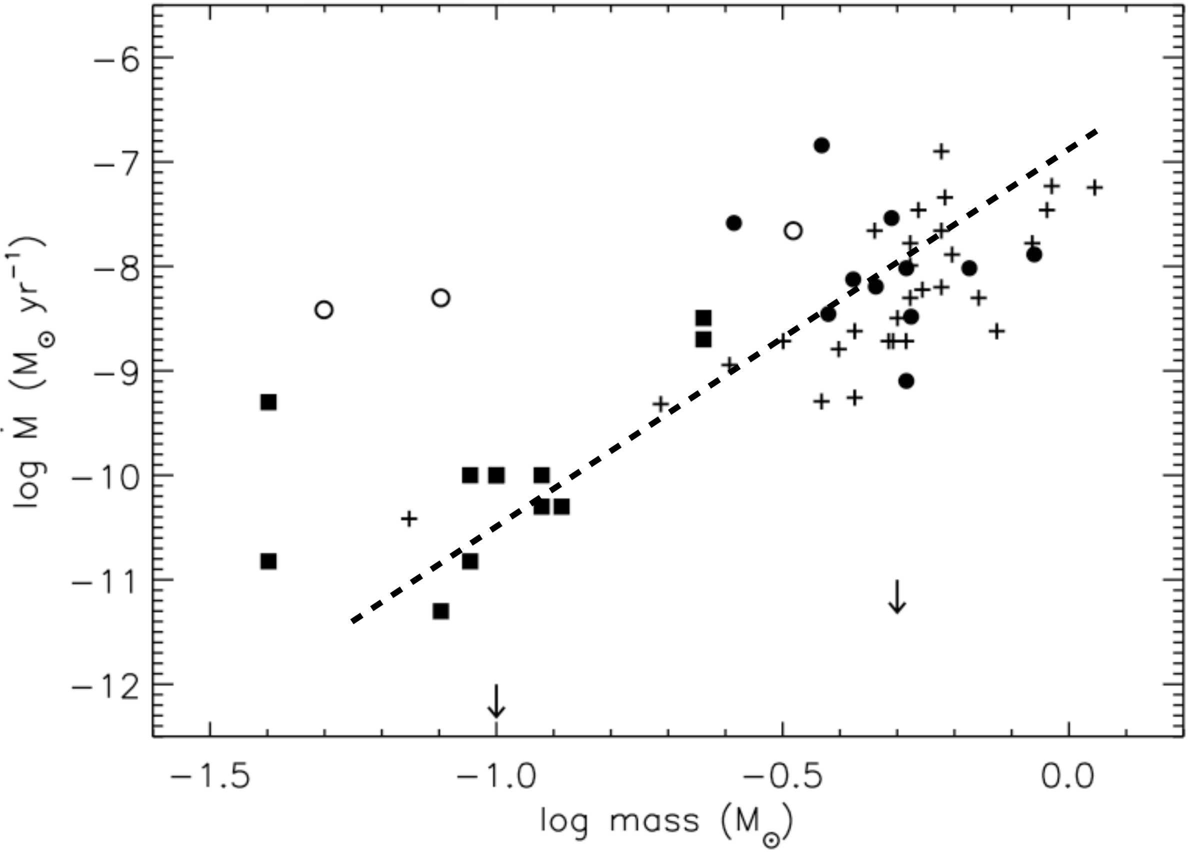


disks disappear in about 5-7 Myr

→ formation timescale for giant gaseous planets

M_{disk} as a function of M_{star}

Muzerolle et al. 2003



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

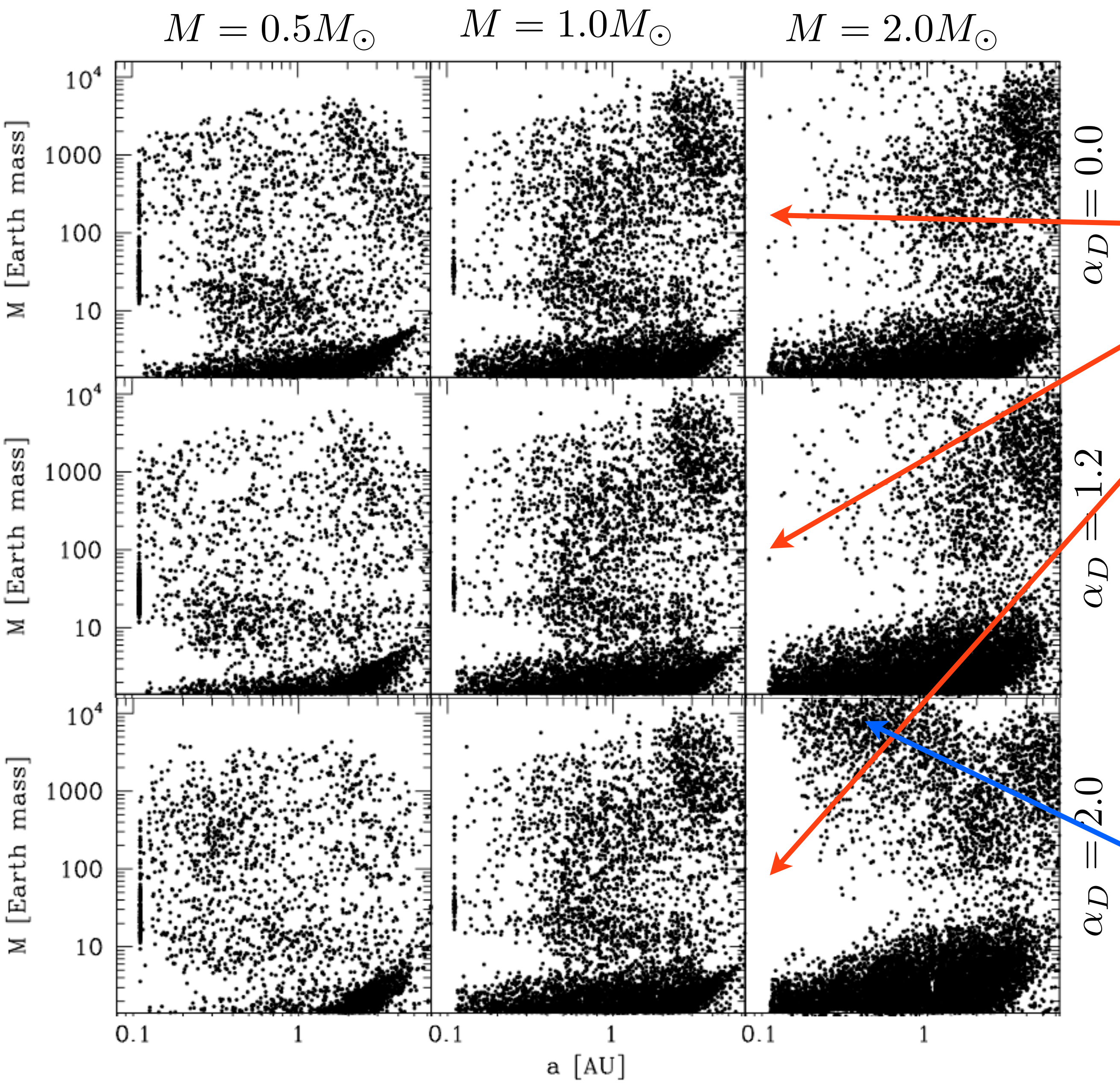
α_D adjusted to reproduce the

$\dot{M}_{disk}$ versus $M_{\rm star}$ relation

using the alpha-disk model

we find $M_{disk} \propto M_{star}^{1.2}$ reproduces this observation

Expected planet populations



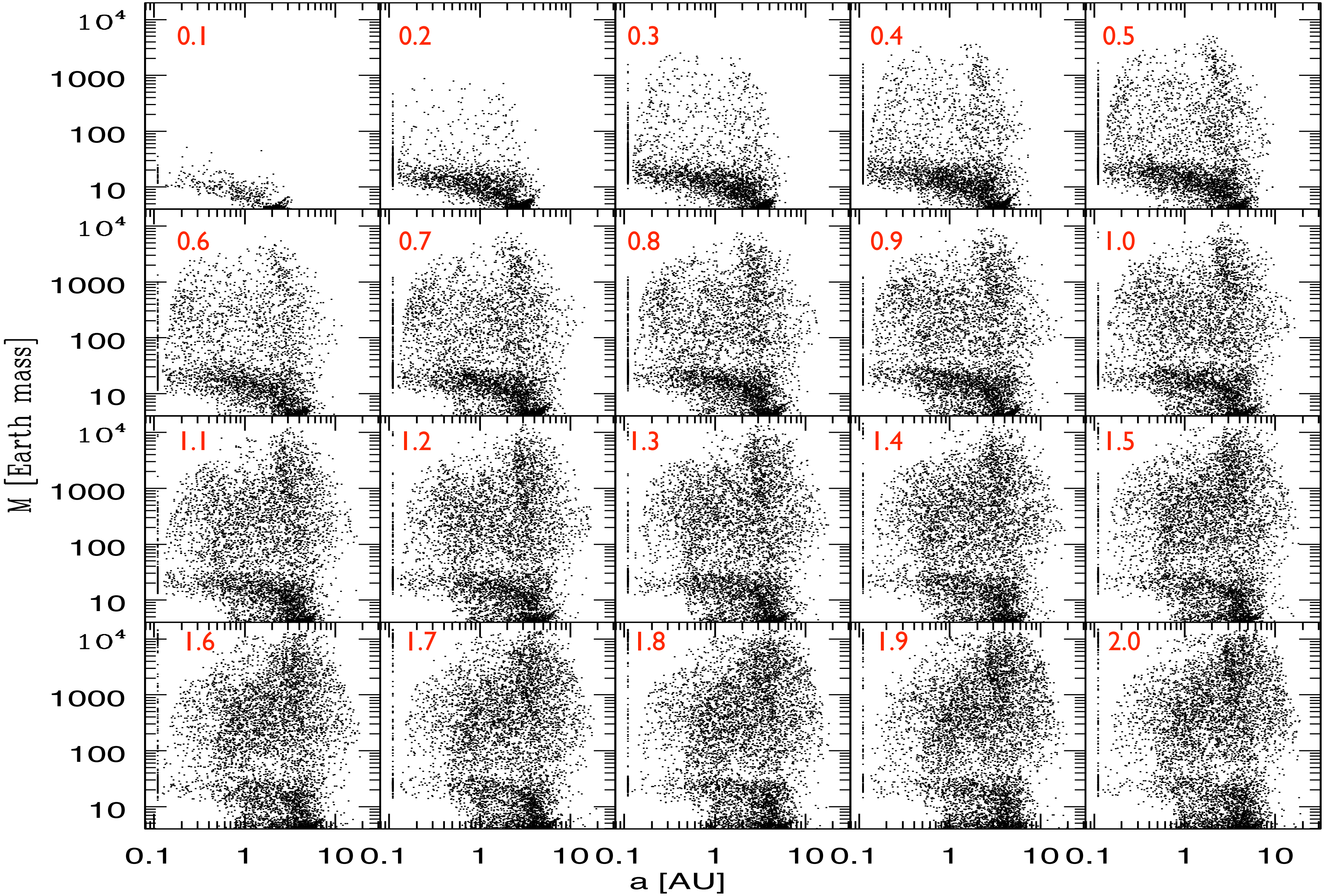
Alibert et al. 2010

no hot jupiters
(correct)

Changing stellar mass results in significant changes in the planet population

very massive warm planets
(not observed)

Planet *populations*

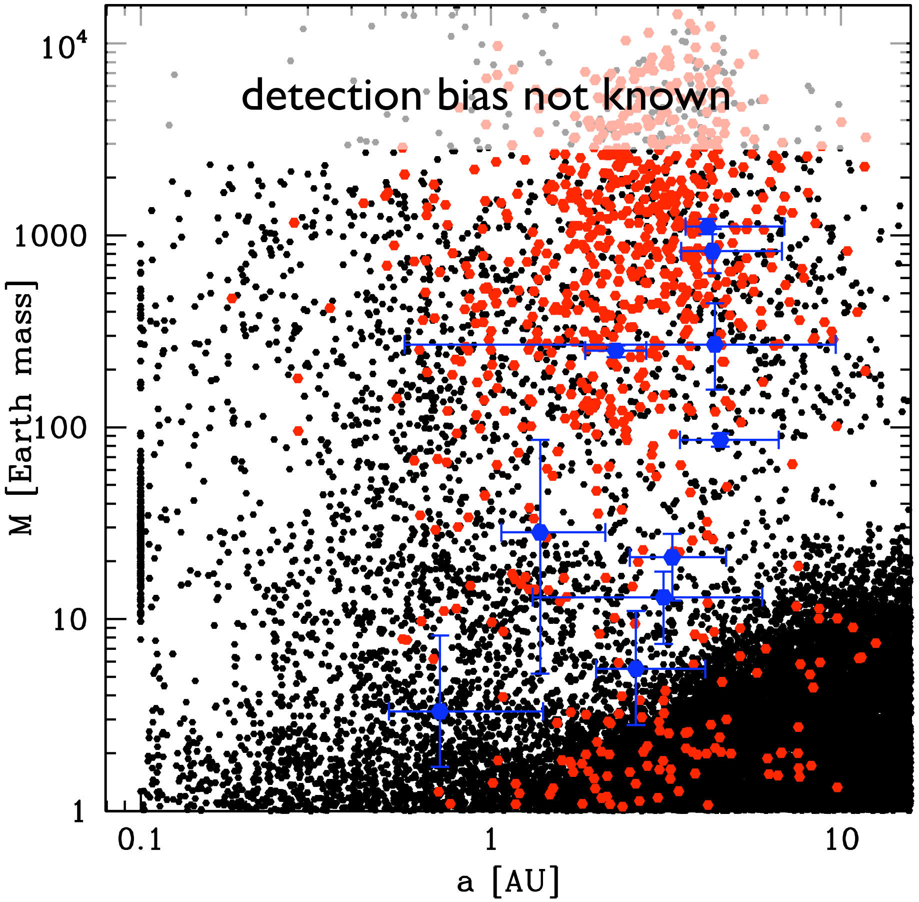


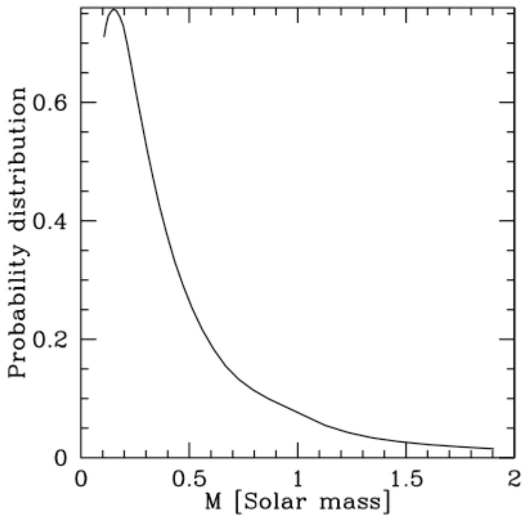
Low (high) mass stars lead to the formation of lower (higher) mass planets, in more (less) compact planetary systems.

Micro-lensing planet searches

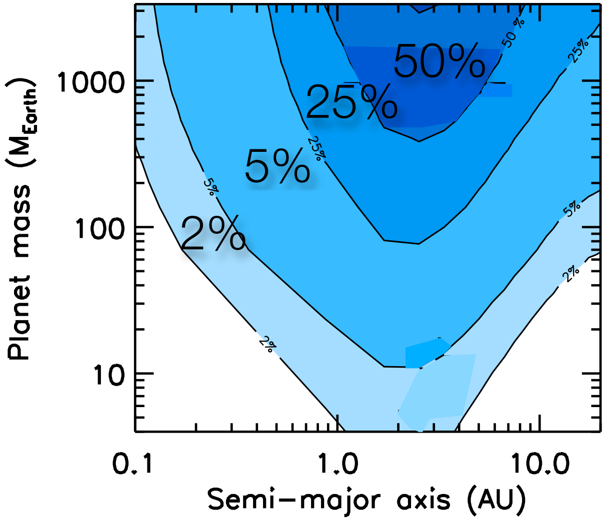
Alibert et al. 2010

- ● synthetic planets
- ● potentially detectable planet
- ● actually detected planet





Expected distribution of the mass of the stars acting as lenses



Detection efficiency of the PLANET microlensing network (Cassan et al. 2008).

Probing a very different region of parameter space!

Conclusions

- The discovery of the whole population of exoplanets is essential to provide important constraints on formation models
- Different detection techniques provide different constraints
- A comprehensive theory of planet formation is still not available:
  - pieces are available but dont fit together...
  - some pieces are still missing...
- Important ingredients missing
  - Characteristics of proto-planetary disks as a function of host star
    - mass, structure, lifetime, composition

    → we are missing some of the initial and boundary conditions
  - Systems in the making

    → we only see essentially old systems (end products)!