Population synthesis of exoplanets

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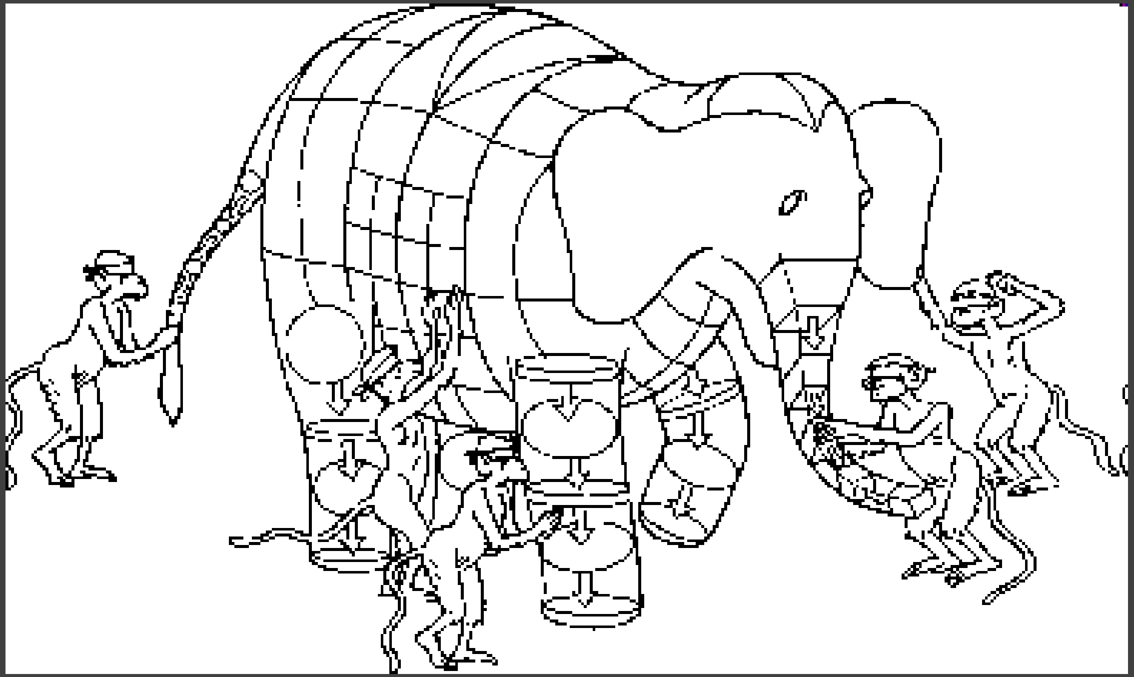
Population synthesis in astrophysics

A population synthesis is a method of a direct modeling of relatively large populations of weakly interacting objects with non-trivial evolution.
As a rule, the evolution of the objects is followed from their birth up to the present moment.

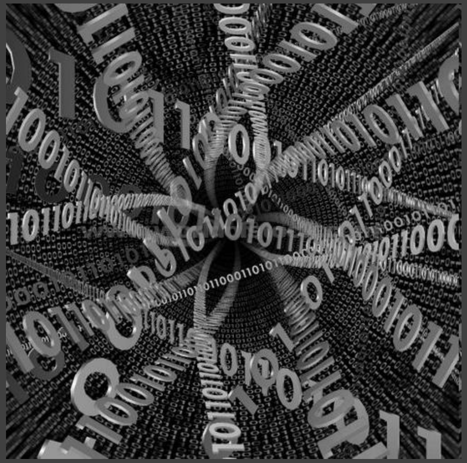
Evolutionary and Empirical

1. Evolutionary PS.
   The evolution is followed from some early stage.
   Typically, an artificial population is formed
   (especially, in Monte Carlo simulations)
2. Empirical PS.
   It is used, for example, to study integral properties
   (spectra) of unresolved populations.
   A library of spectra is used to predict integral properties.

astro-ph/0411792



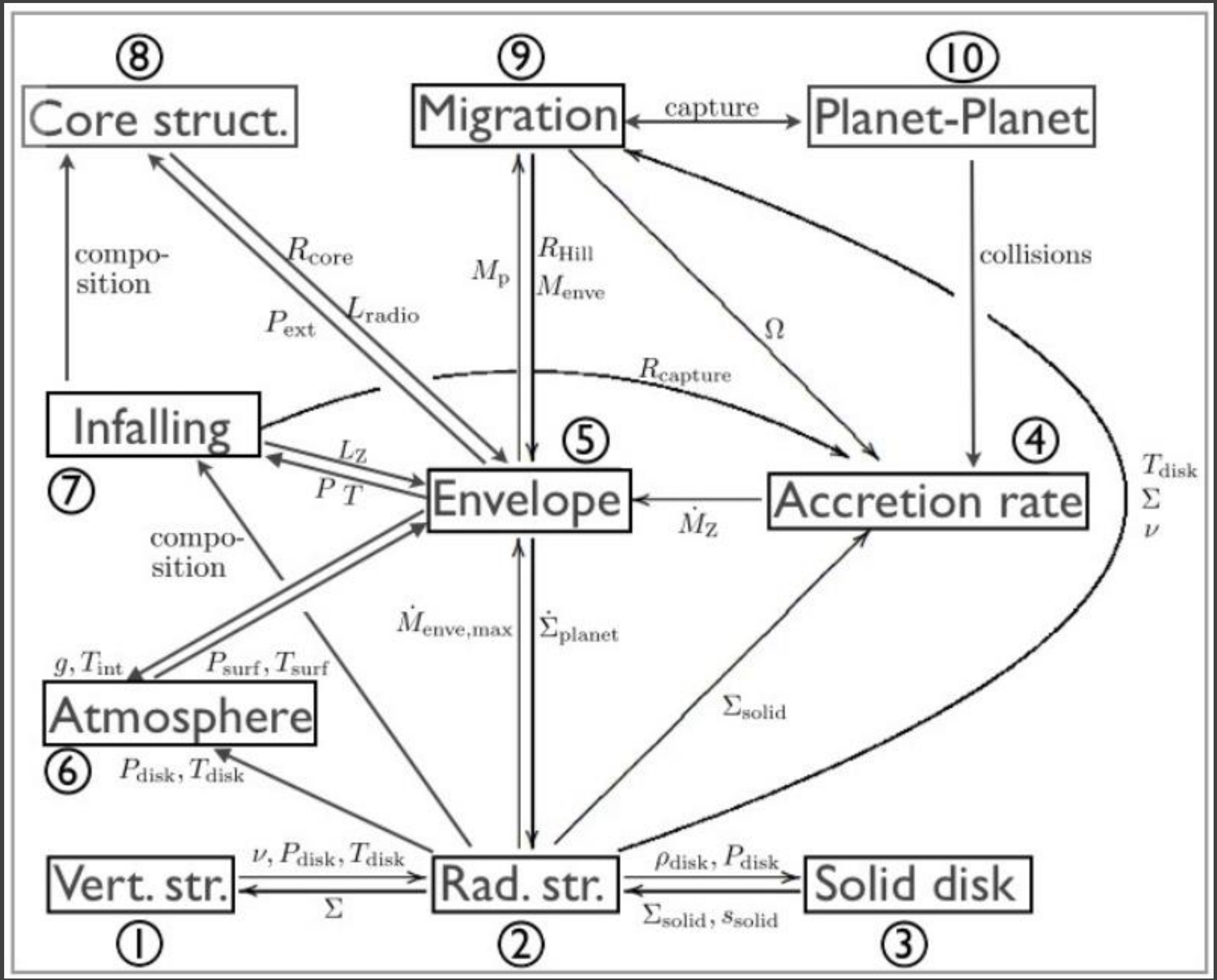
Ingredients:
- initial condition
- evolutionary laws



«Artificial universe»

Modeling observations

«Artificial observed universe»



8
Core struct.
9
Migration
capture
10
Planet-Planet
composition
R_{core}
L_{radio}
P_{ext}
M_p
R_{Hill}
M_{enve}
Ω
collisions
$R_{capture}$
Infalling
7
L_Z
P T
5
Envelope
4
Accretion rate
$\dot{M}_Z$
T_{disk}
Σ
ν
composition
$\dot{M}_{enve,max}$
$\dot{\Sigma}_{planet}$
g, T_{int}
P_{surf}, T_{surf}
Atmosphere
Σ_{solid}
6
P_{disk}, T_{disk}
ν, P_{disk}, T_{disk}
ρ_{disk}, P_{disk}
Vert. str.
Rad. str.
Solid disk
Σ
$\Sigma_{solid}, s_{solid}$
1
2
3

1402.7086

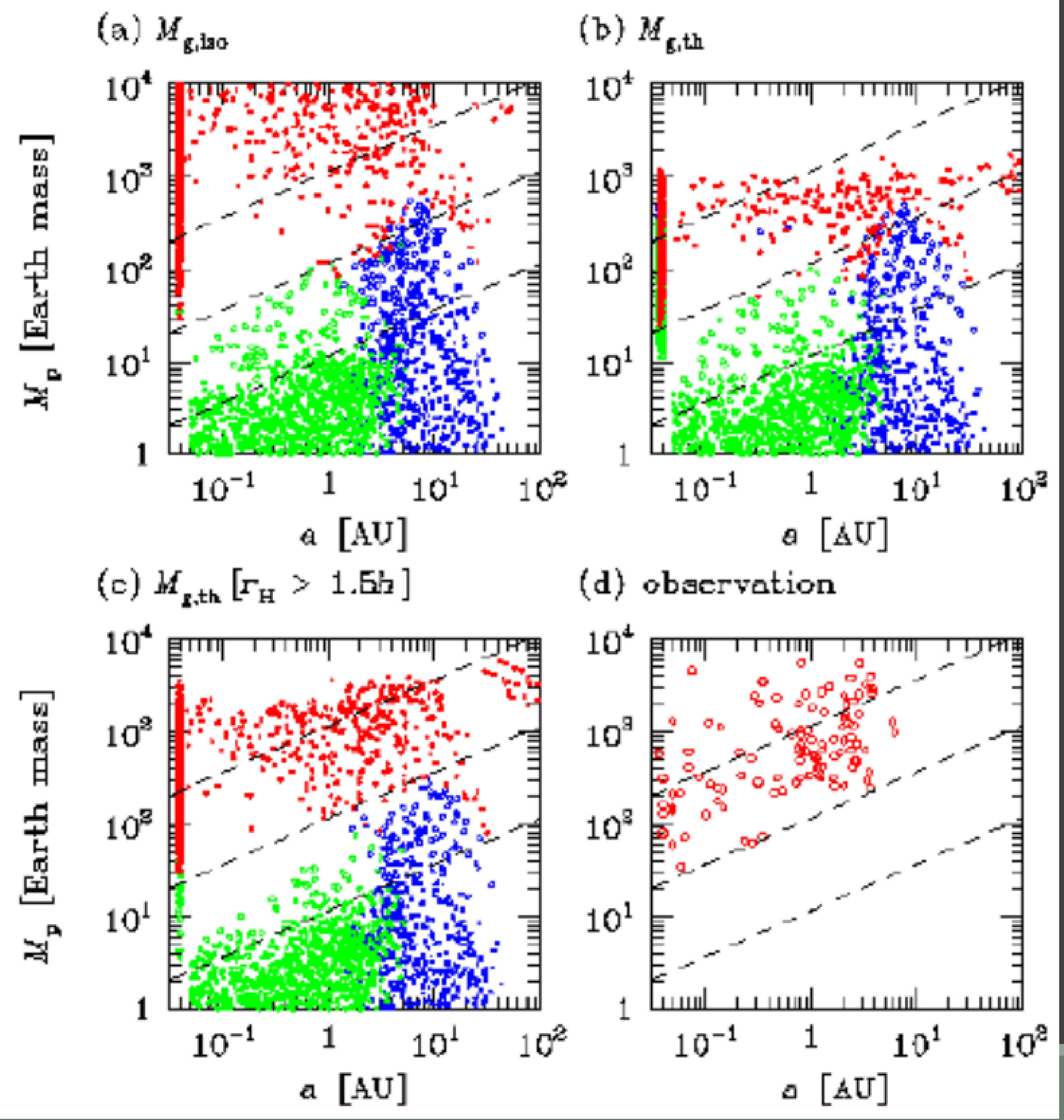
The first PS model for exoplanets

Authors modeled formation and migration (I&II) of exoplanets in order to reproduce so-called “desert” in mass-semi-major axis distribution (masses 10-100 Earth mass, and a<3 AU).

Main ingredients:

- Disk model;
- Accretion model;
- Migration model.

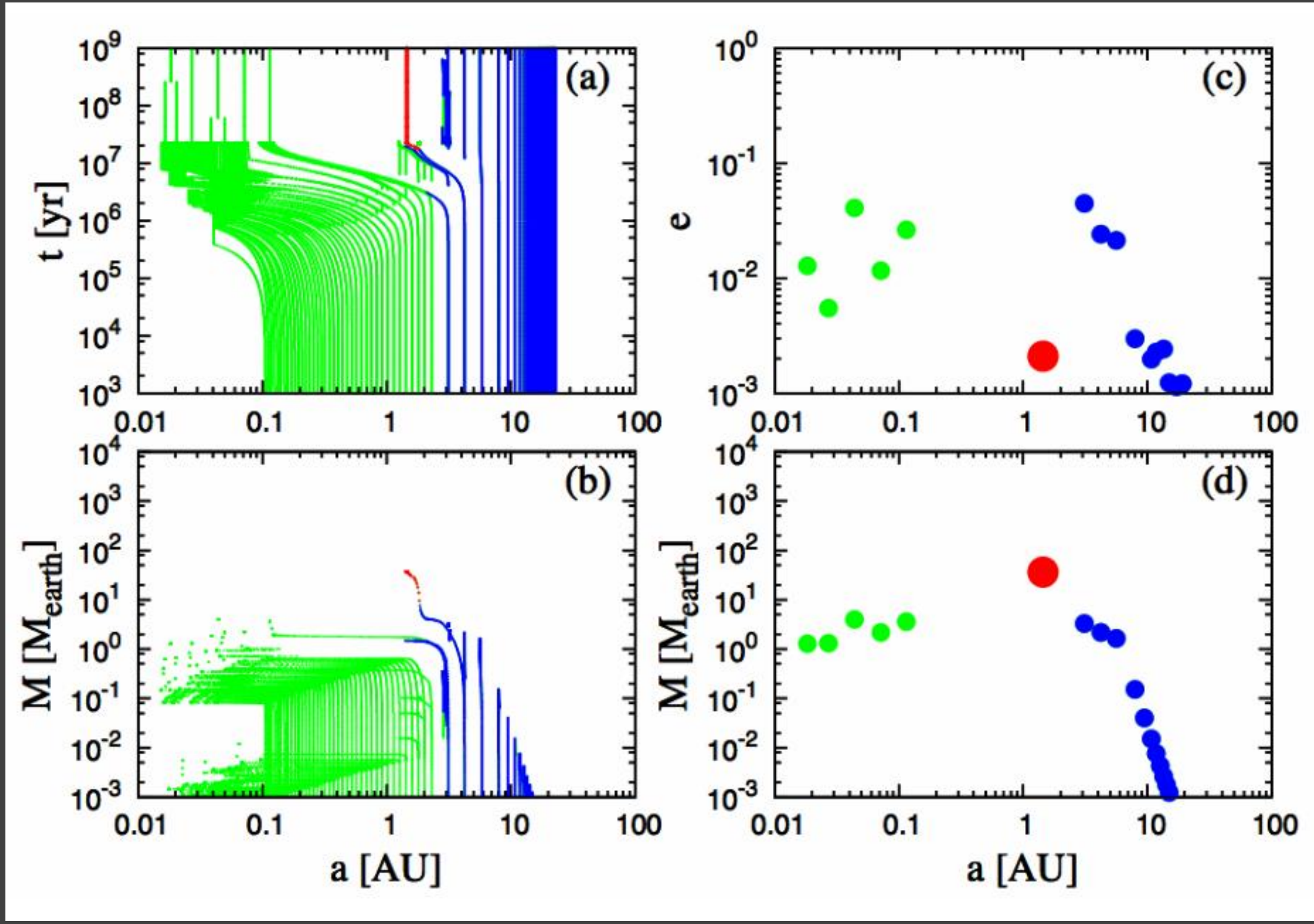
The rate of type I migration
was significantly reduced
to avoid rapid planet displacement.



Red- giants;
green – rocky;
blue – ice.

Ida, Lin astro-ph/0312144

Individual tracks

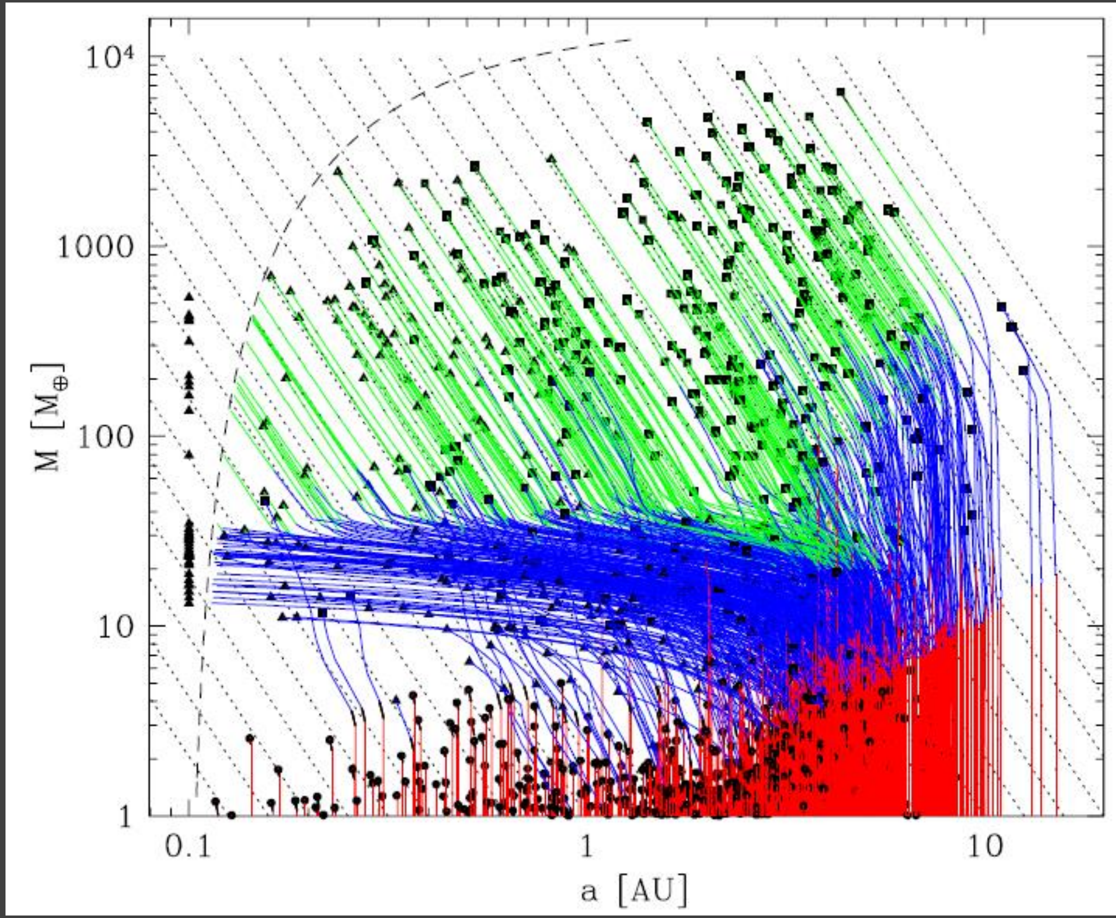


Green - rock
Red - gas
Blue - ice

$$
\begin{aligned}
\tau_{\mathrm{mig1}} &= \frac{a}{\dot{a}} \\
&= \frac{1}{C_1}\frac{1}{3.81}\left(\frac{c_s}{a\Omega_{\mathrm{K}}}\right)^2 \frac{M_*}{M_{\mathrm{planet}}}\frac{M_*}{a^2\Sigma_g}\Omega_{\mathrm{K}}^{-1} \\
&\simeq 1.5\times 10^5 \frac{1}{C_1 f_g}\left(\frac{M_c}{M_\oplus}\right)^{-1}\left(\frac{a}{1\mathrm{AU}}\right) \\
&\quad \times \left(\frac{M_*}{M_\odot}\right)^{3/2} \ \mathrm{yrs.}
\end{aligned}
$$

C_1 = 0.1; $f_{d,0}$=2

Mordasini et al. models



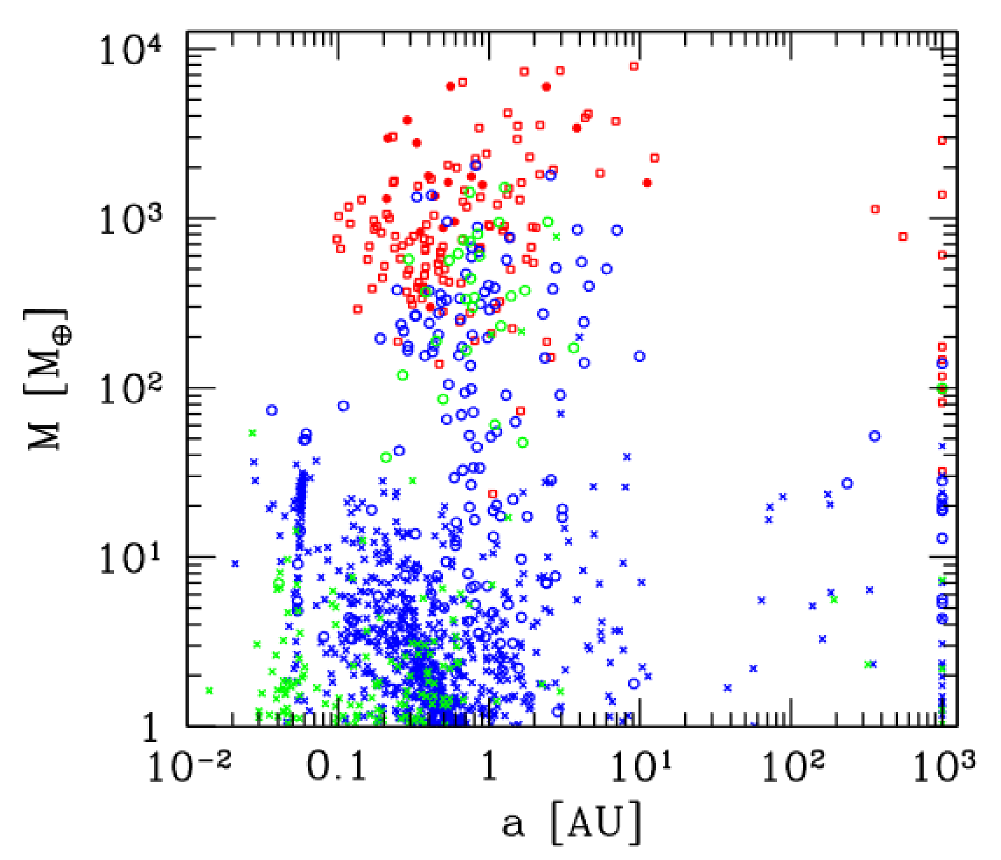
Mordanisi et al. published a series of papers (0904.2524, 0904.2542, 1101.0513, 1201.1036) on population synthesis of exoplanets, using an approach generally similar to the one by Ida, Lin.

Then this studies were continued in 1206.6103, 1206.3303, 1708.00868.
A review is given in 1402.7086.

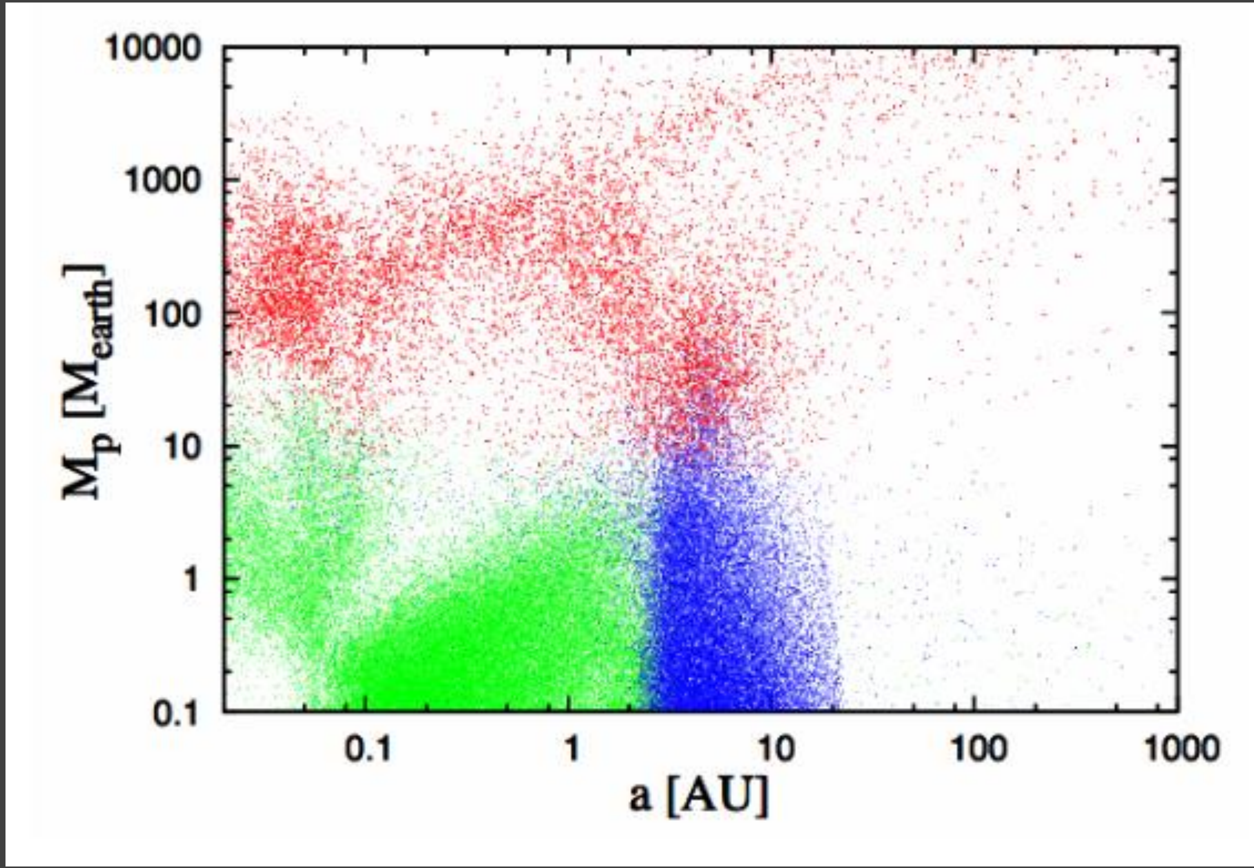
An important step is too include planet-planet interactions.

A separate subject is to follow long-term evolution.

Mass – semi-major axis distribution

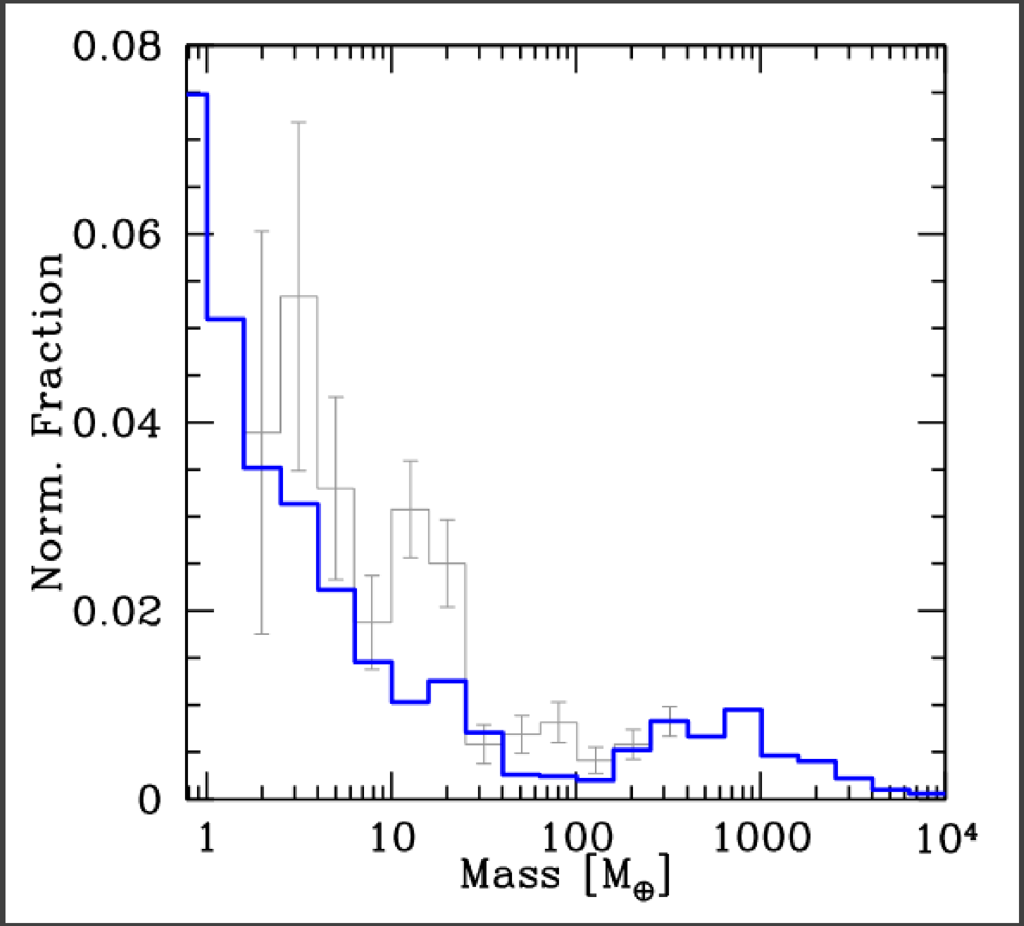


Alibert et al. (2013)



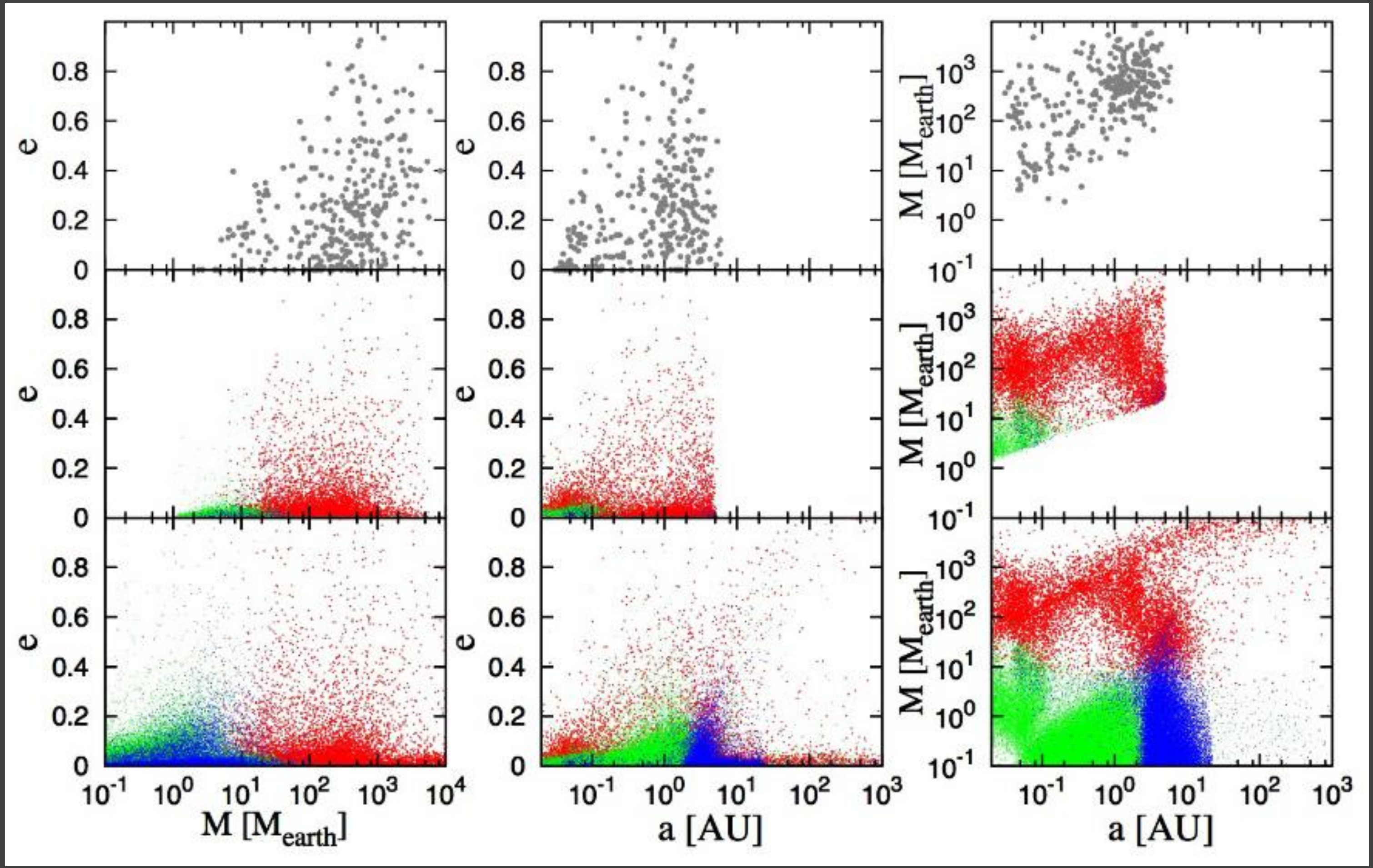
Ida, Lin (2013)

Mass distribution



It is still not absolutely clear,
if the so-called “planetary desert”
exist or not.

Comparison with observations



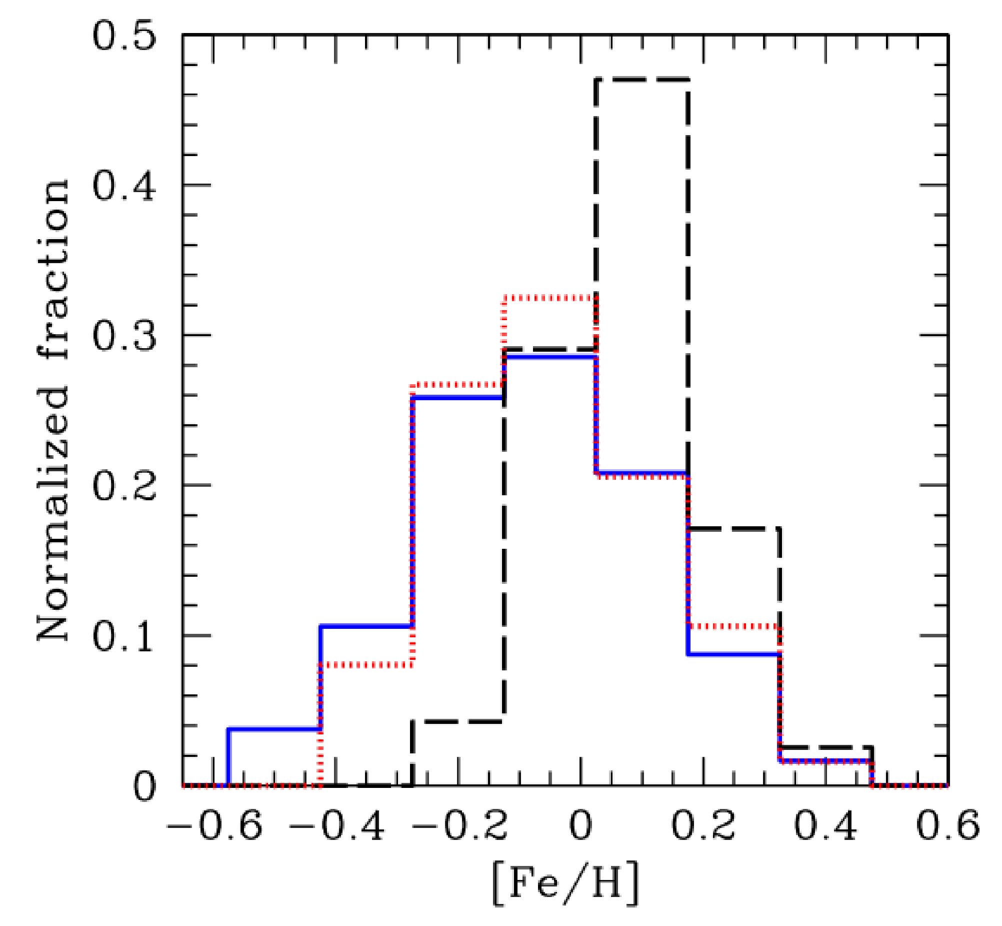
Observations

Calculations for observable planets (P_{orb}<10 yrs; v>1 m/s)

Calculations

Ida, Lin (2013)

Metallicity effect

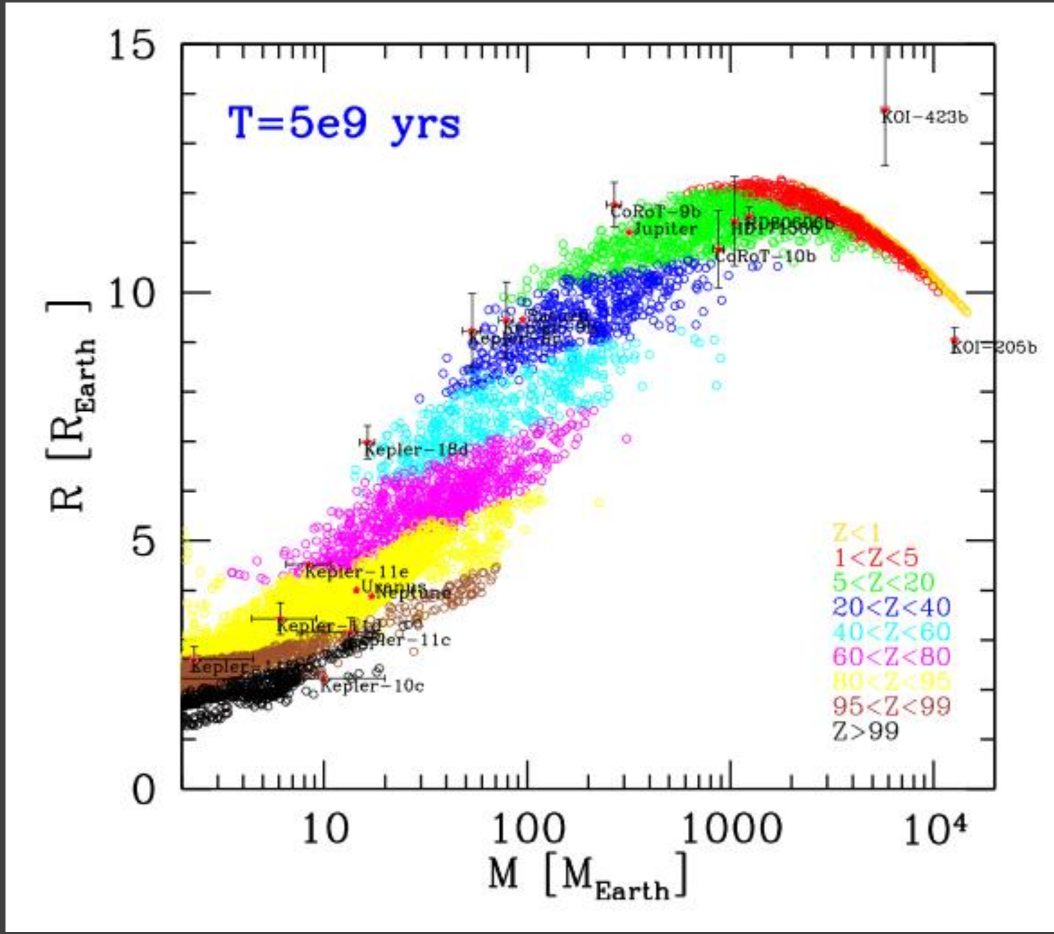


Solid line – all stars.

Dashed line – stars with at least one giant planet.

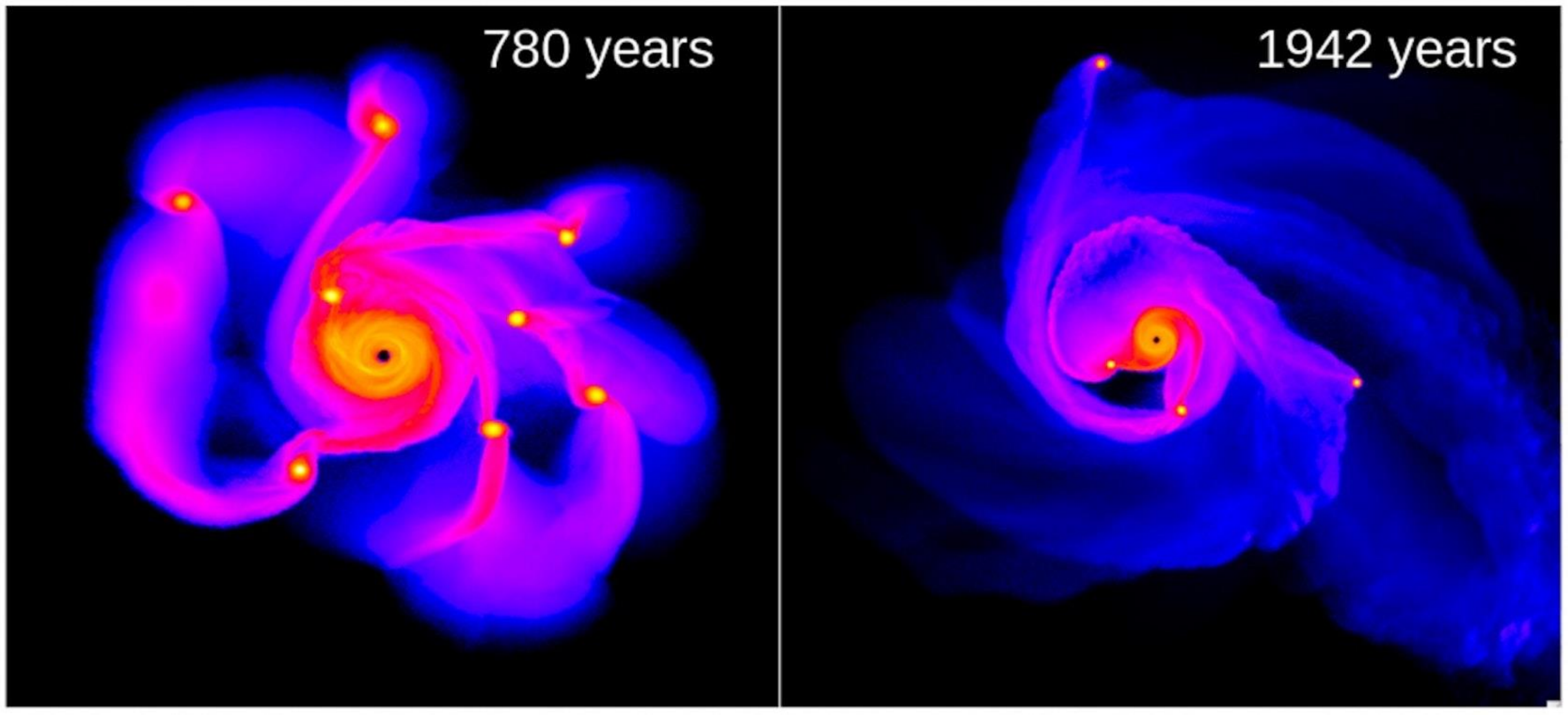
Dotted line – stars with at least low-mass planet.

Composition



Formation and evolution model
allows to estimate the bulk composition of planets.

Another way to form planets



Lucio Mayer & T. Quinn

Gravitational instability in the outer parts of the disc.

Allows to form massive planets out to few tens AU.

Might also work for brown dwarfs and very light stars.

$$Q = \frac{c_s \kappa_e}{\pi G \Sigma} < 1.5 - 1.7,$$

Some new results in 1711.05948

Hypothesis by Nayakshin (2010).
It is possible to make solid planets at low orbits

Tidal downsizing

$$M = M_J = \frac{4\sqrt{2}\pi^3}{3G}\frac{Q^{1/2}c_s^2 H}{(1+\frac{\Delta\Sigma}{\Sigma})}. = \frac{4\sqrt{2}\pi^3}{3G}\frac{Q^{1/2}c_s^2 H}{(1+4.47\sqrt{\alpha})}$$

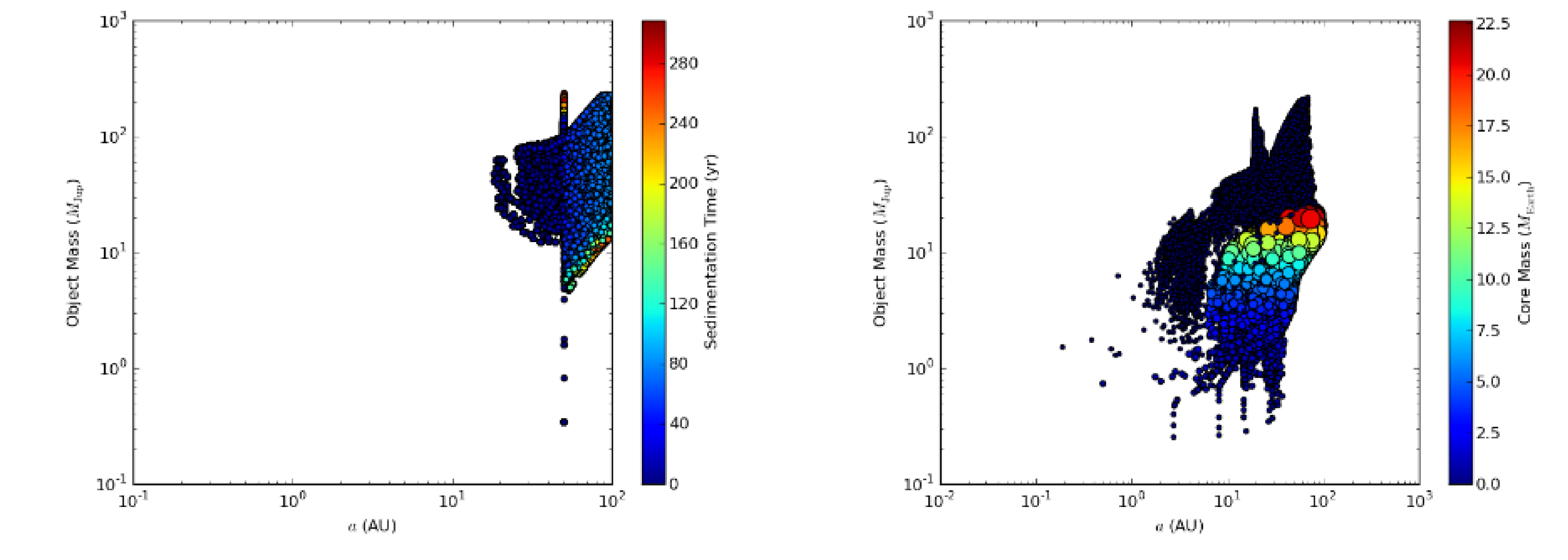
Fragment mass
just after
fragmentation

$$R_H = a_p \left(\frac{q}{3}\right)^{1/3}$$

Hill radius becomes smaller
as a planet migrates towards the star.

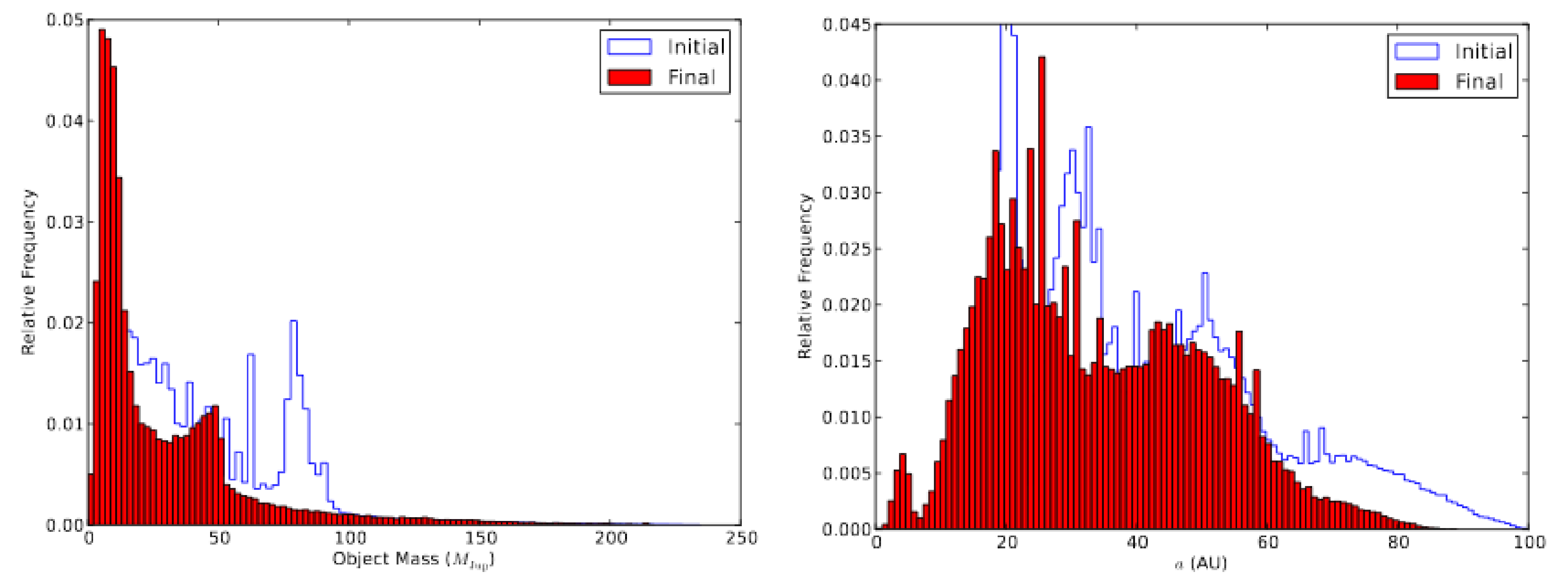
Evolution of a fragment is a disc can result in appearance of a low-mass planet closer to the star, or in appearance if a belt of particles.

Initial and final semi-major axis distribution

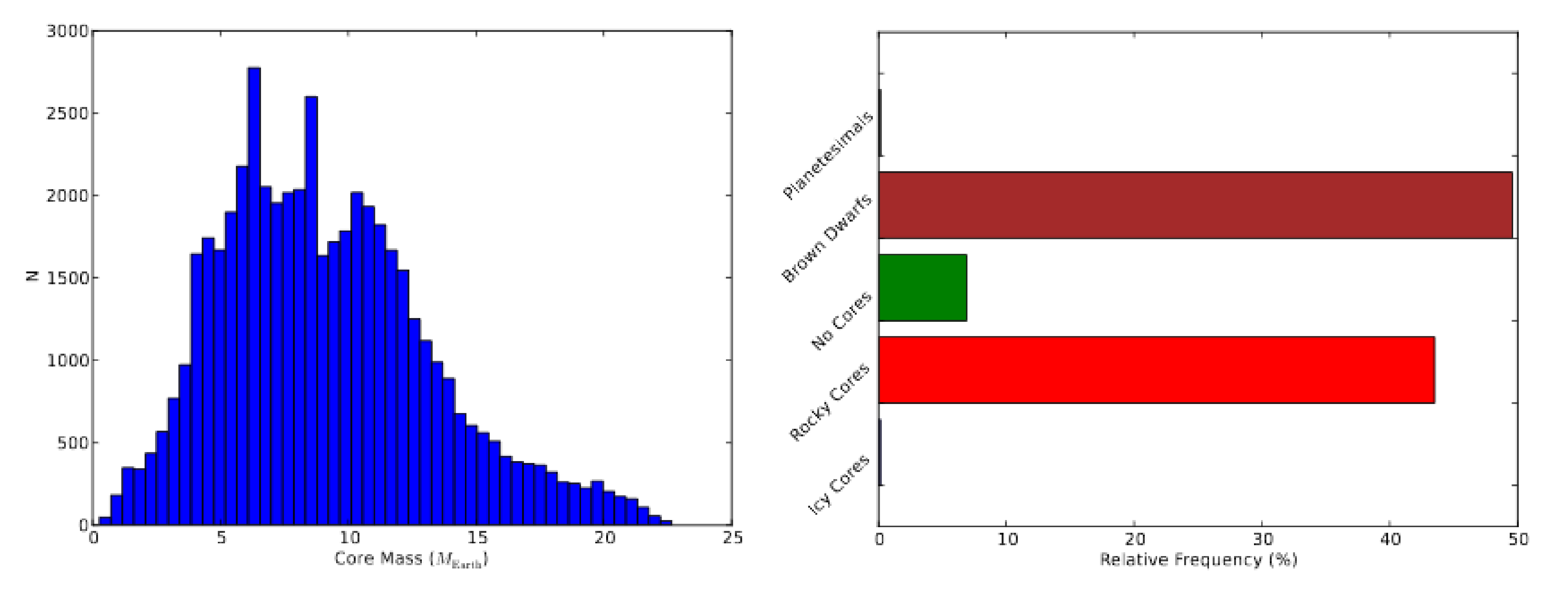


1304.4978

Mass and semi-major axis distribution

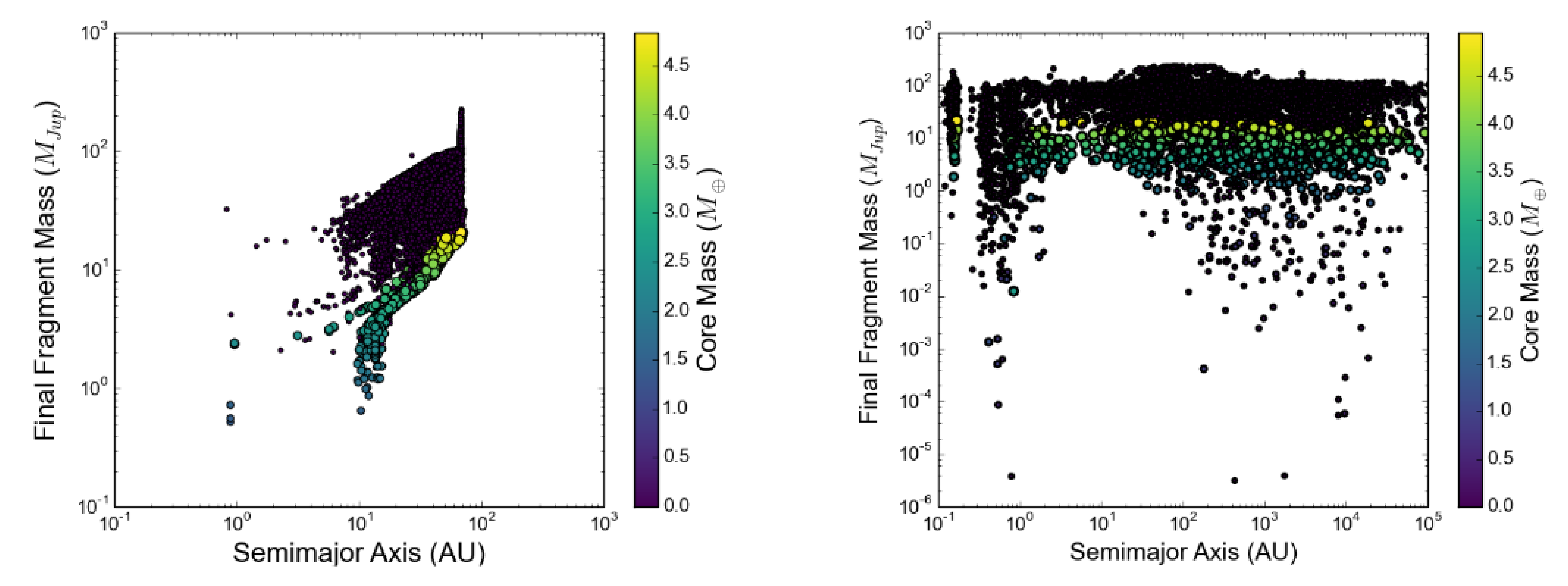


Mass distribution and planet types



Many brown dwarfs (and even low-mass stars for some parameters) can be produced via this channel.

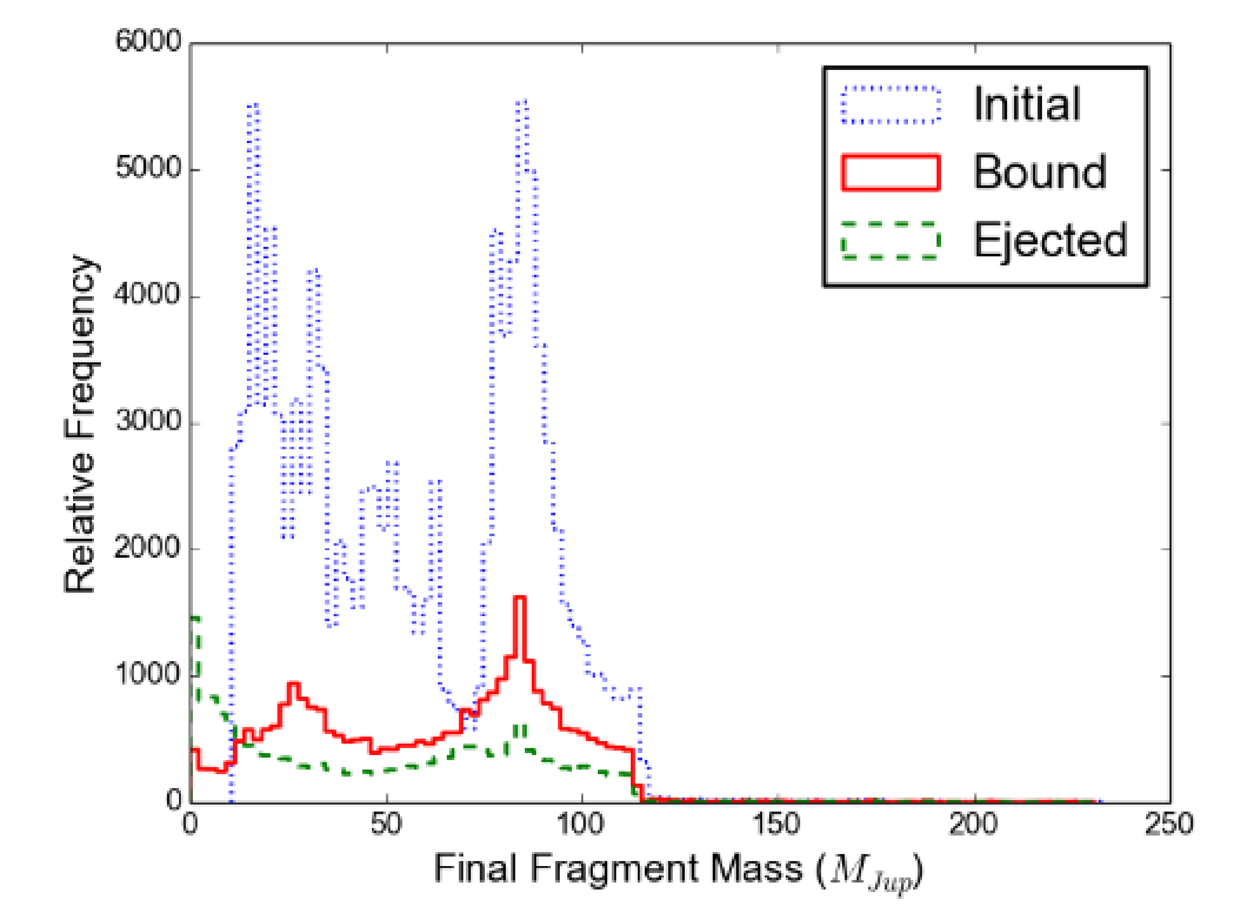
Role of fragment-fragment interaction



Interaction off

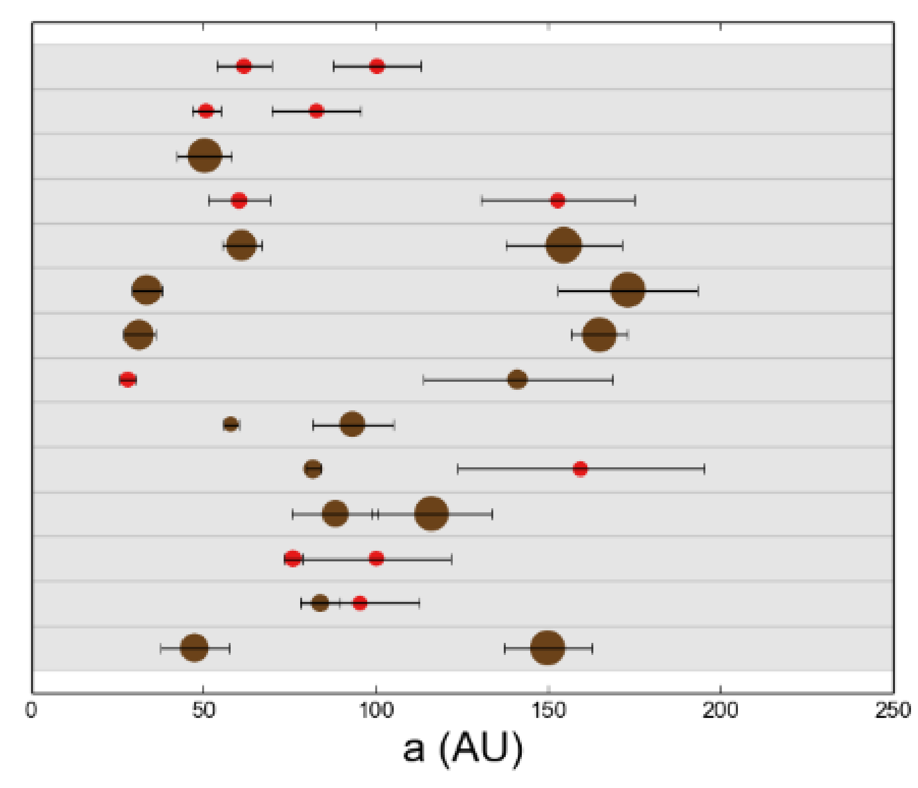
Interaction on

Ejection

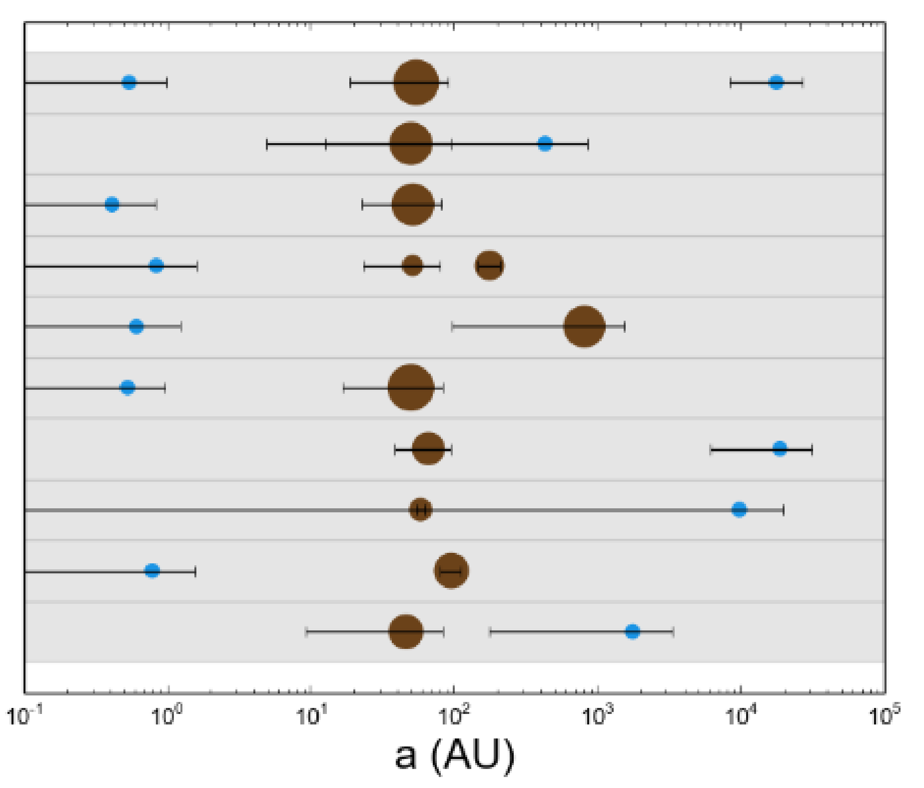


Many fragments are ejected.
So, this mechanism of planet formation can be an important contributor to the population of free-floating planets and brown dwarfs.

System architecture



Typical systems



Non-typical systems

Literature

- 1402.7086 Planet Population Synthesis W. Benz et al.