Population synthesis of exoplanets

SERGEI POPOV

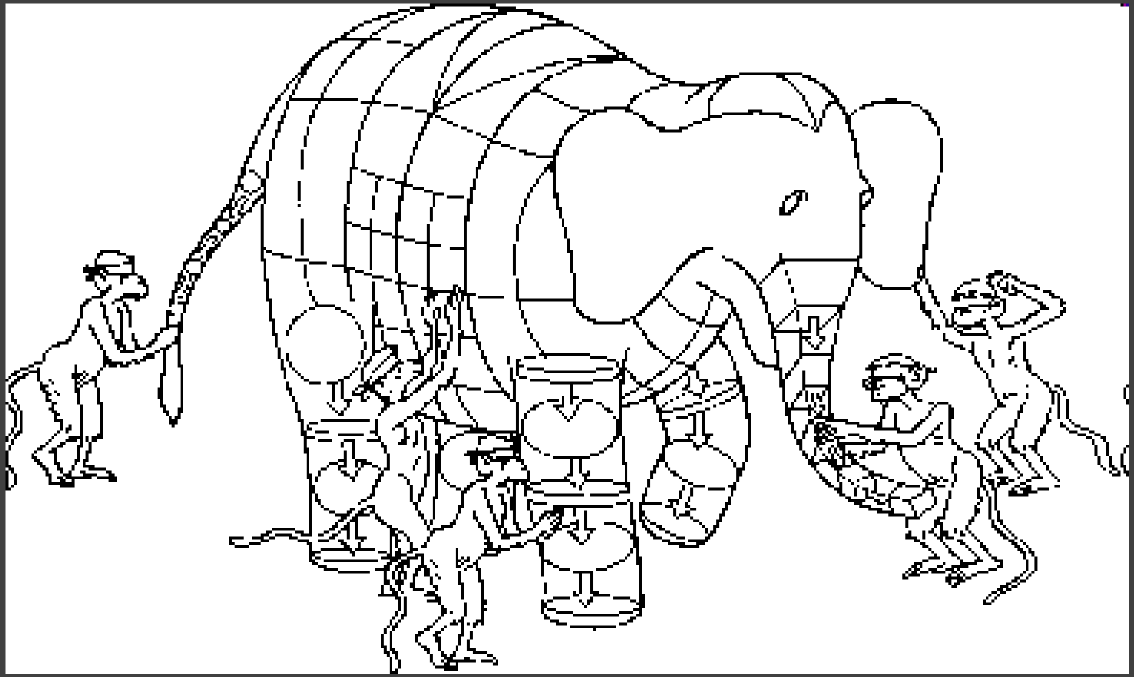
Population synthesis in astrophysics

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.

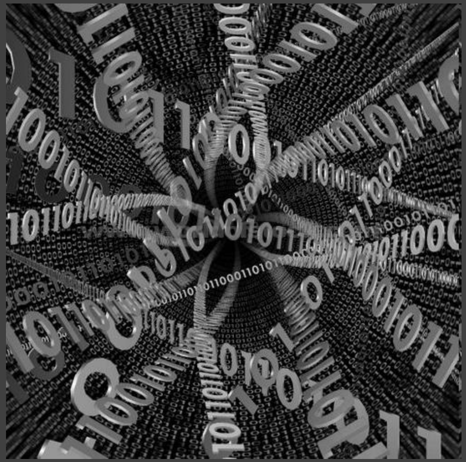
Evolutionary and Empirical

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



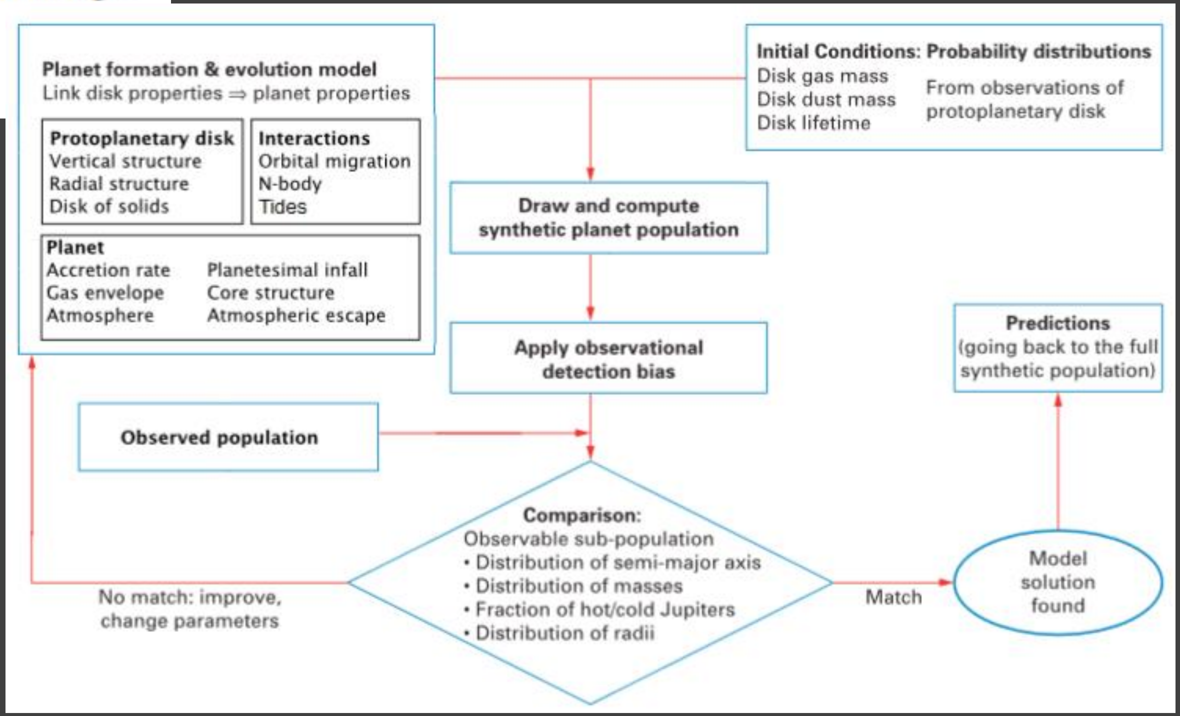
«Artificial universe»

Modeling observations

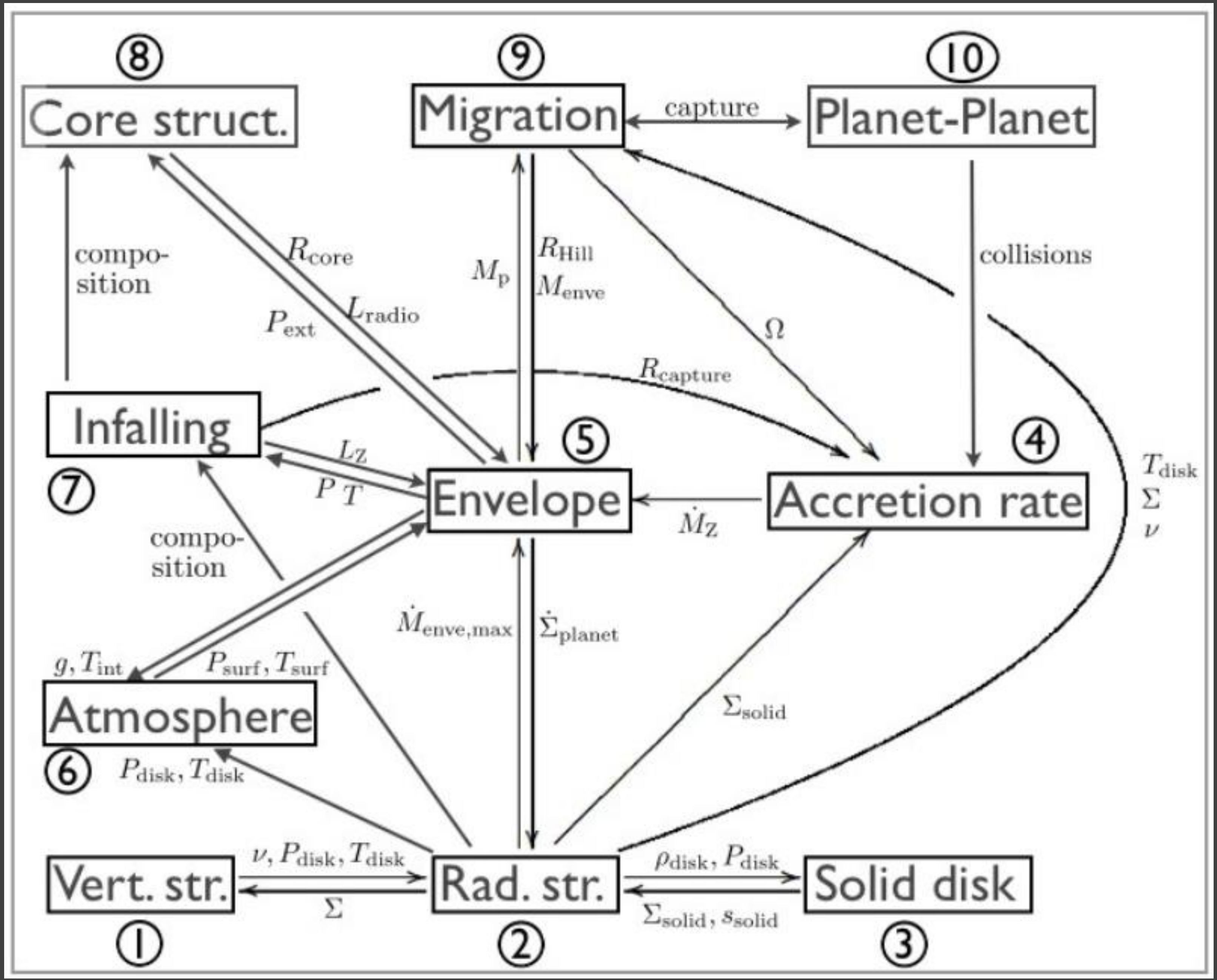
«Artificial observed universe»

Ingredients for planetary PS

1. The structure and evolution of the protoplanetary gas disk
2. The structure and evolution of the disk of solids (dust, pebbles, planetesimals)
3. The accretion of solids leading to the growth of the planetary solid core
4. The accretion of H/He leading to the growth of the planetary gaseous envelope
5. Orbital migration resulting from the exchange of angular momentum
6. N-body interaction among (proto)planets



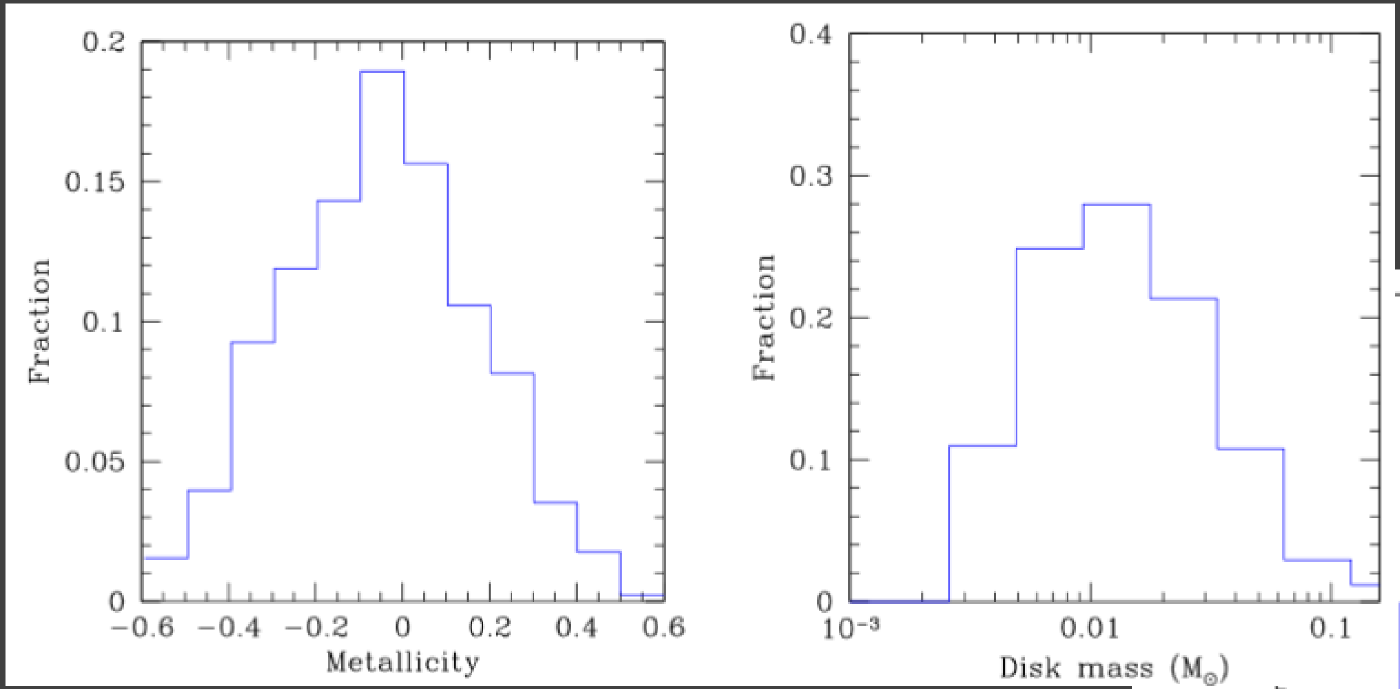
1804.01532



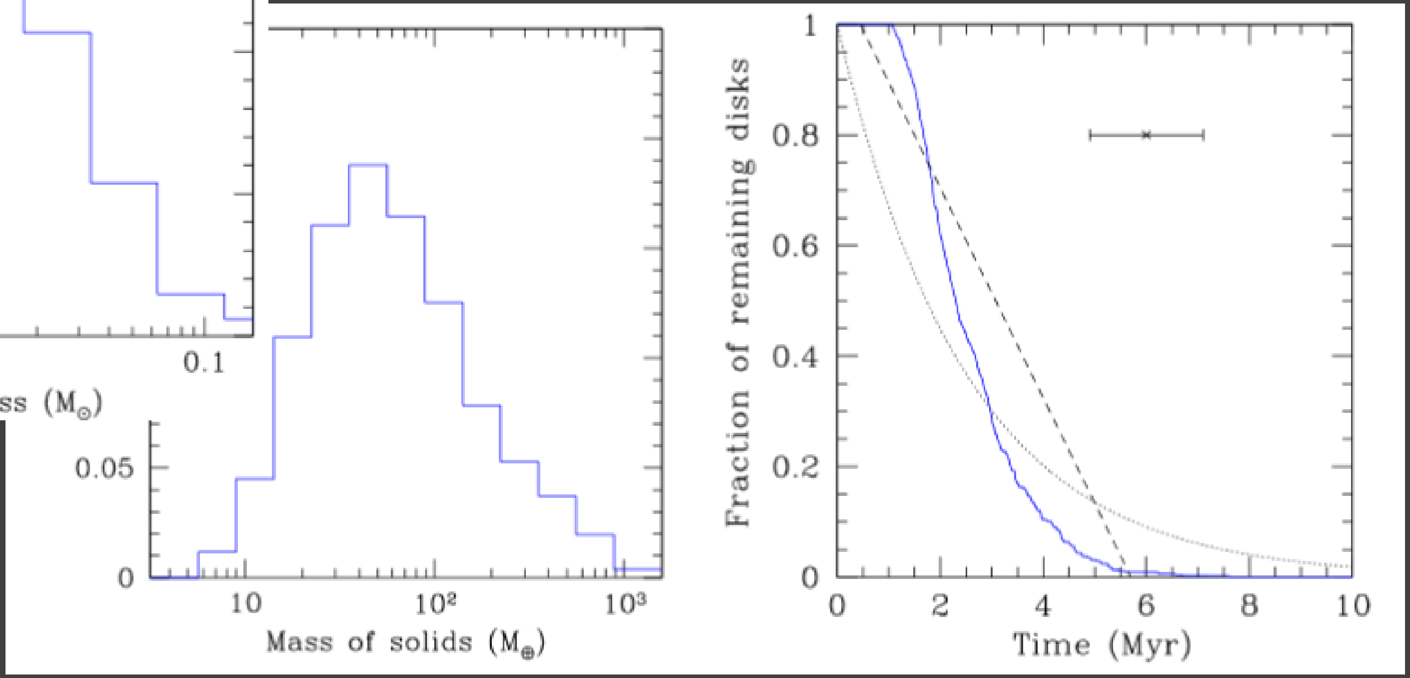
8
Core struct.
9
Migration
capture
10
Planet-Planet
composition
R_{core}
L_{radio}
P_{ext}
M_p
R_{Hill}
M_{enve}
Ω
collisions
$R_{capture}$
Infalling
7
L_Z
P T
5
Envelope
4
Accretion rate
$\dot{M}_Z$
T_{disk}
Σ
ν
composition
$\dot{M}_{enve,max}$
$\dot{\Sigma}_{planet}$
g, T_{int}
P_{surf}, T_{surf}
Atmosphere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

1402.7086

Initial distributions



Initial conditions for discs around 1 solar mass stars.



In addition, initial positions of embryos is also a random parameter.

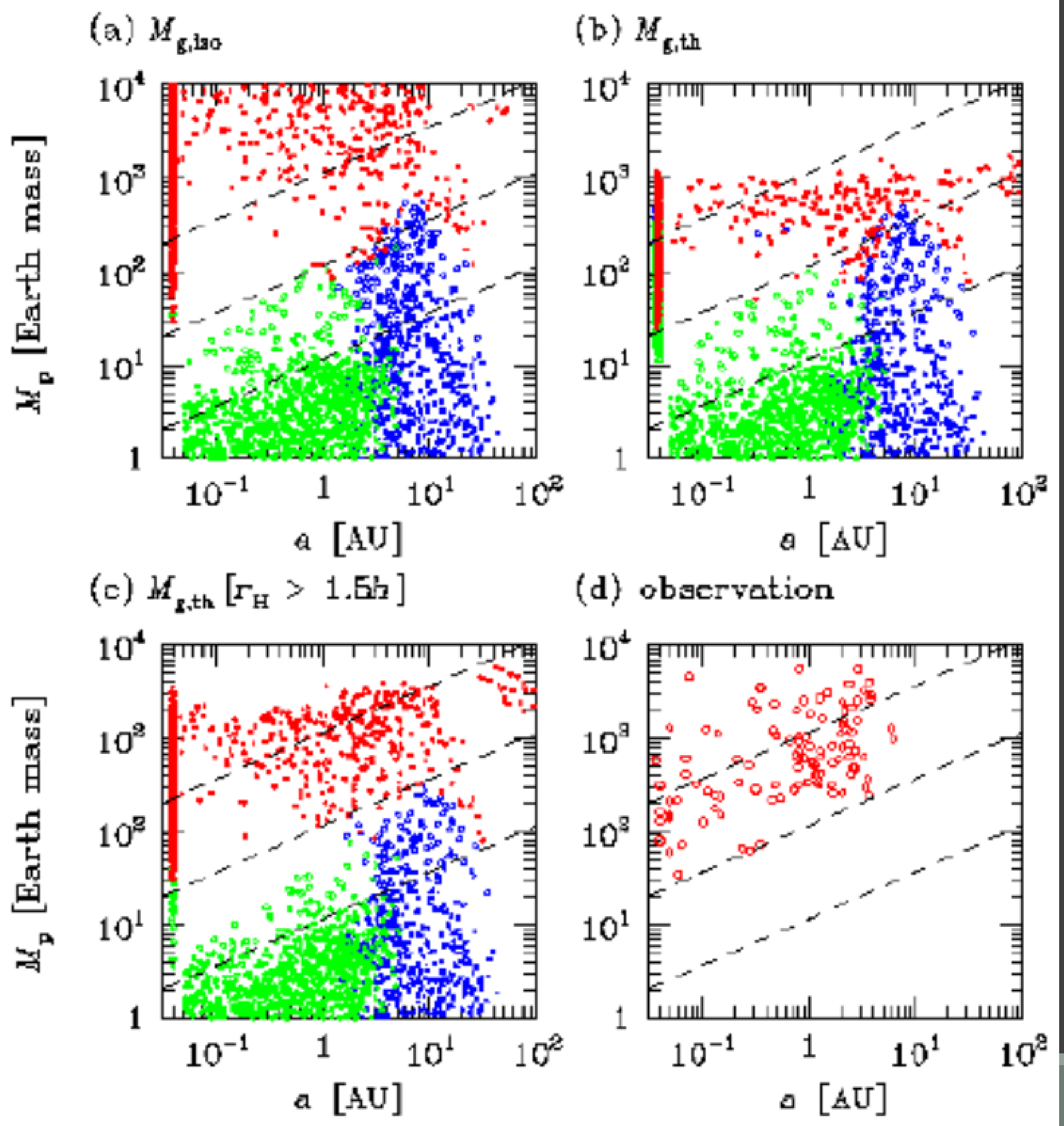
The first PS model for exoplanets

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.

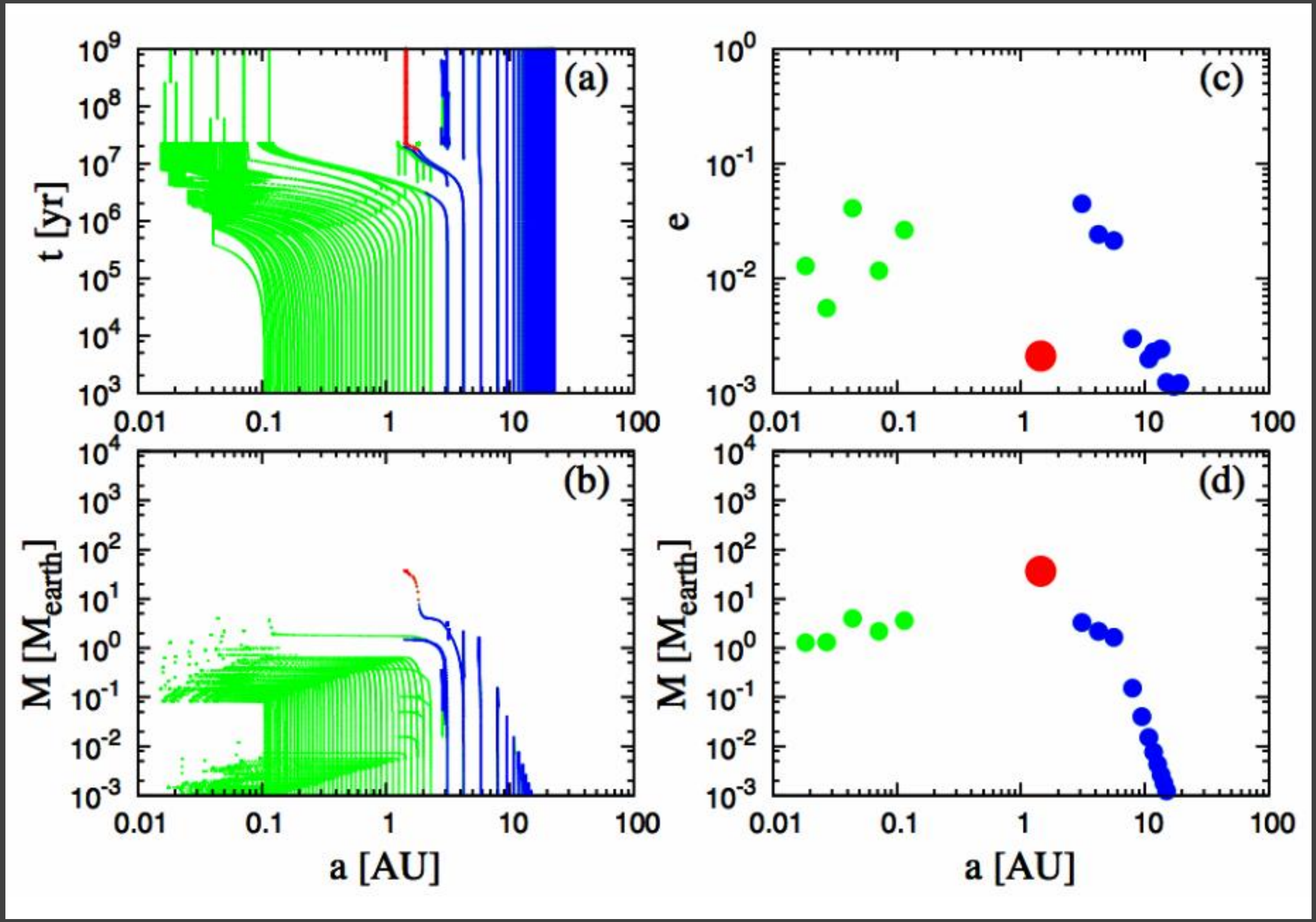
The rate of type I migration
was significantly reduced
to avoid rapid planet displacement.



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

Ida, Lin astro-ph/0312144

Individual tracks



Green - rock

Red - gas

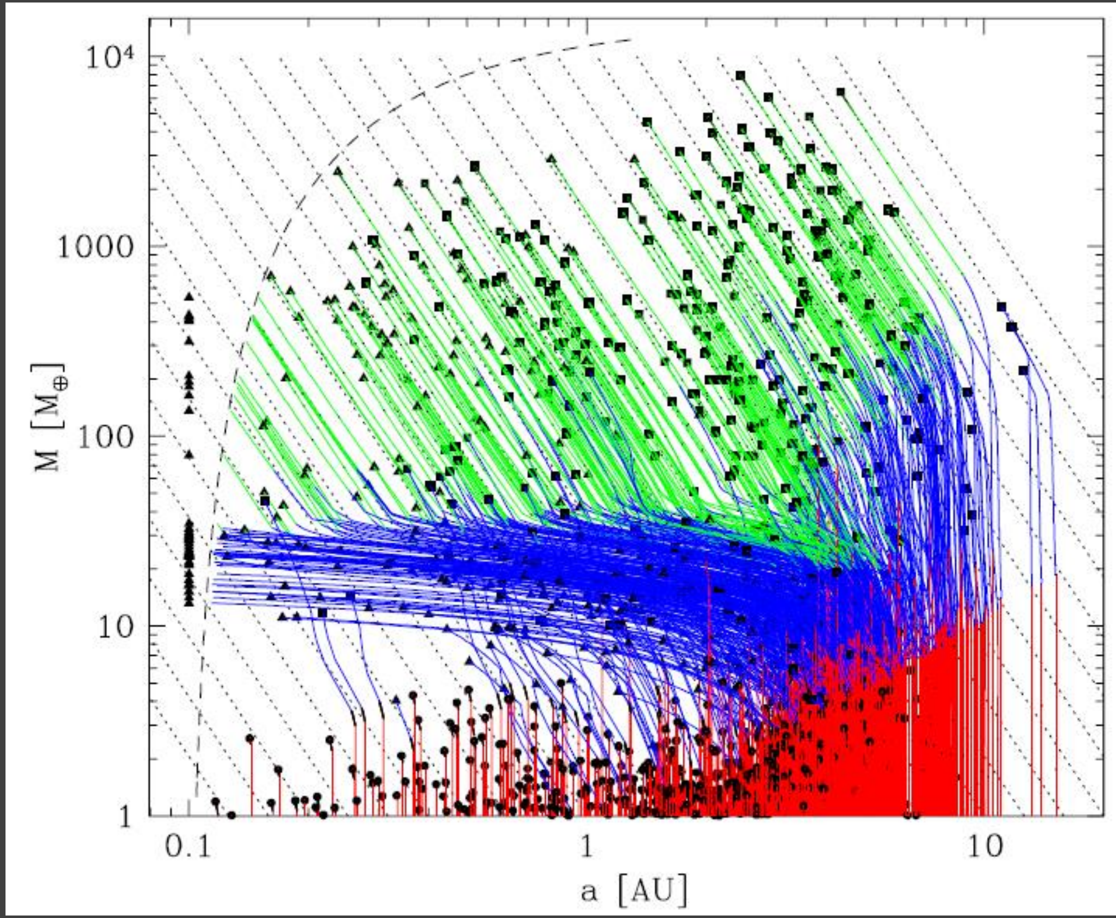
Blue - ice

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

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

Ida, Lin 2013

Mordasini et al. models



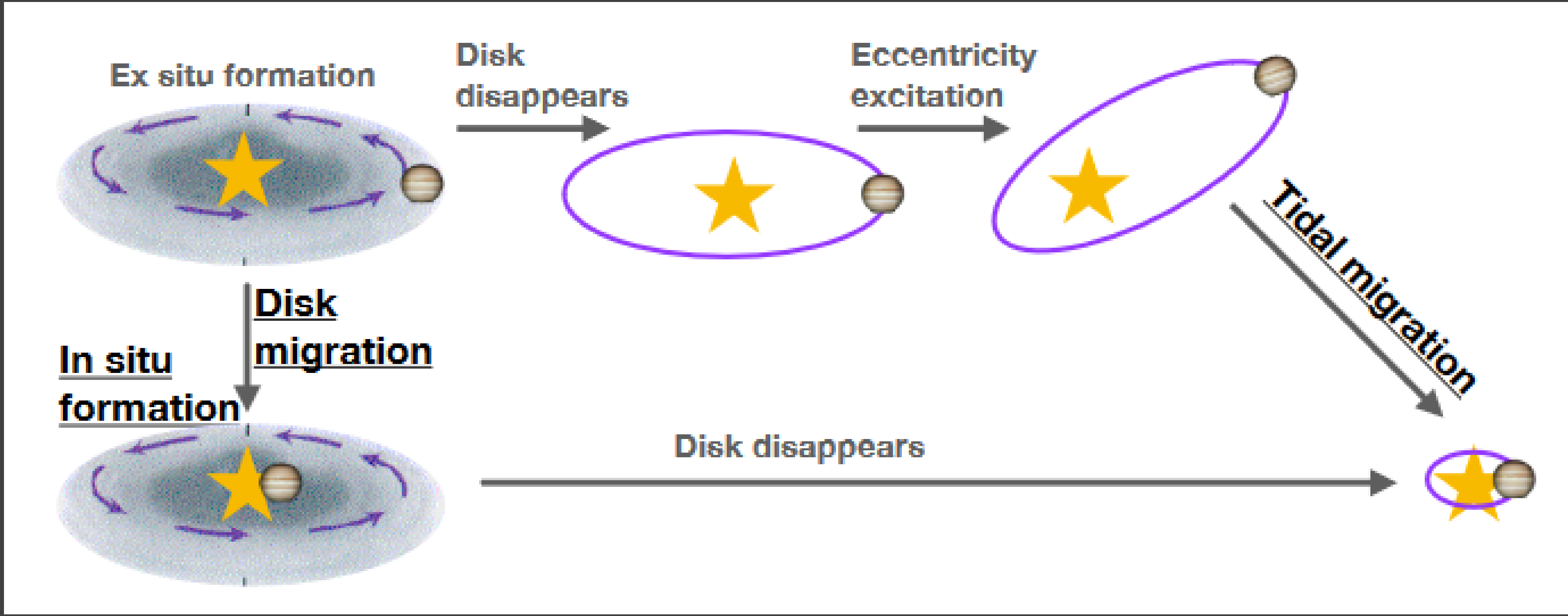
Mordasini et al. published a series of papers (0904.2524, 0904.2542, 1101.0513, 1201.1036) on population synthesis of exoplanets, using an approach generally similar to the one by Ida, Lin.

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

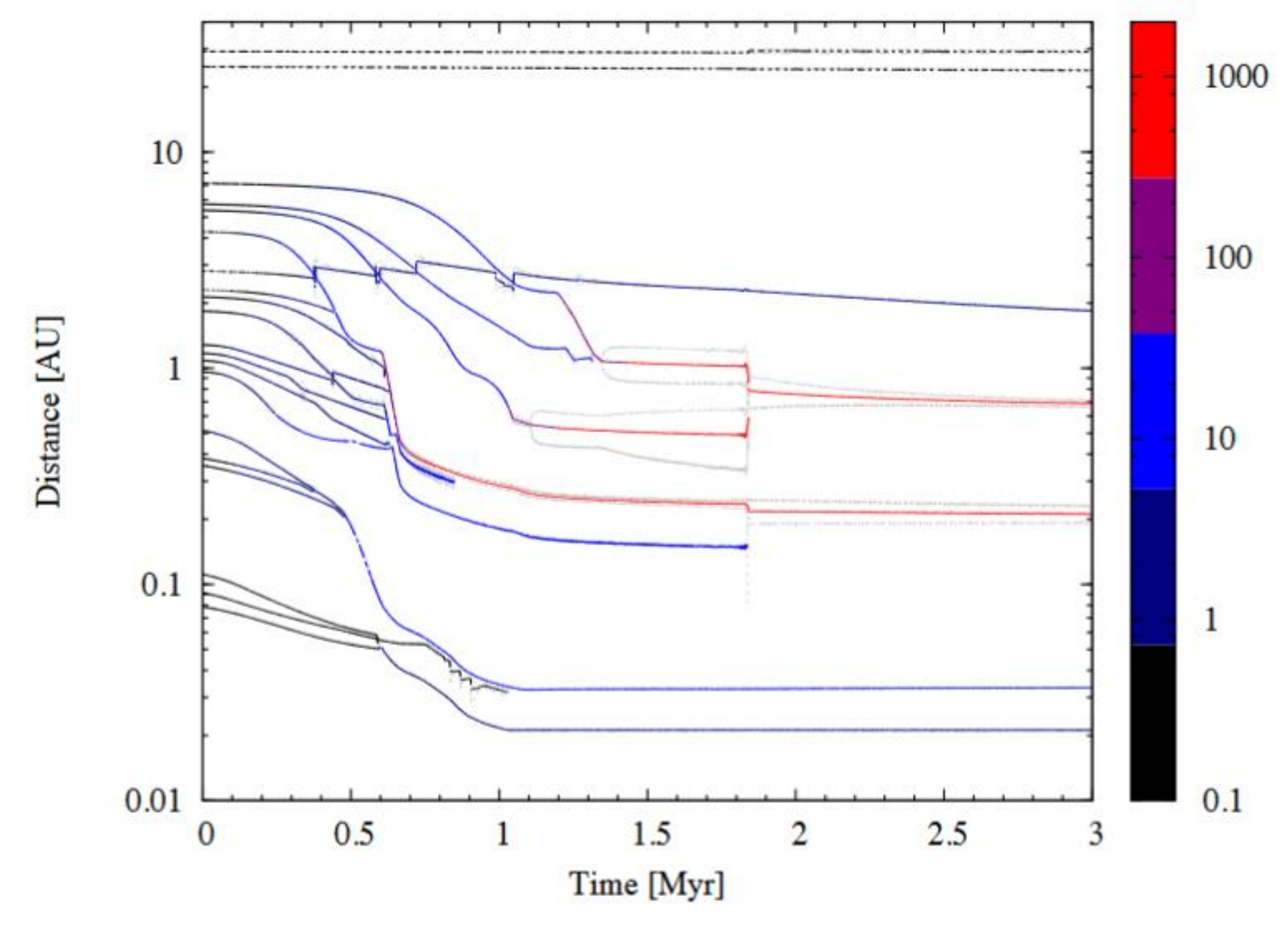
An important step is too include planet-planet interactions.

A separate subject is to follow long-term evolution.

Alternative variants of hot planets formation

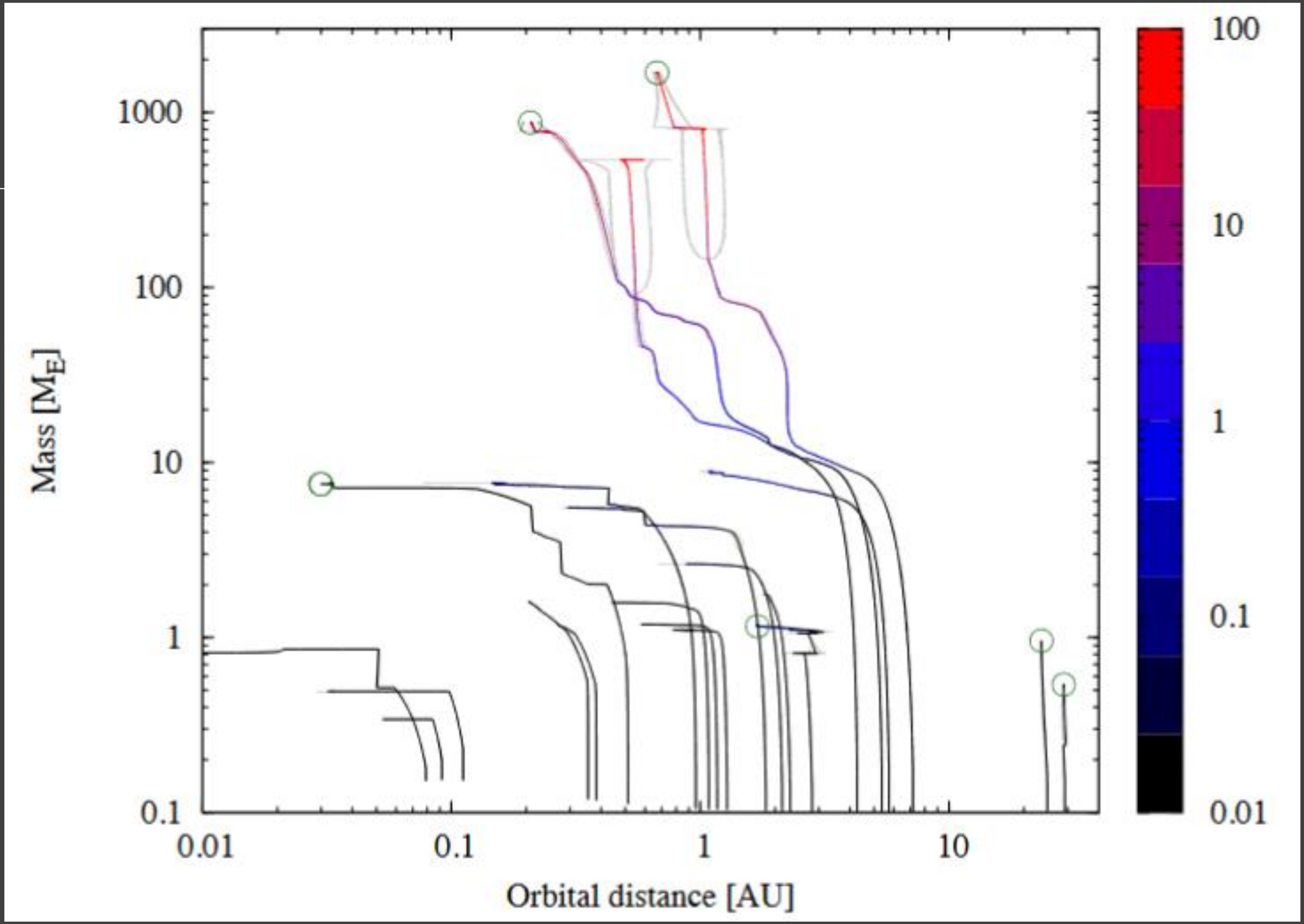


Multi-embryo systems



20 planet embryos with $M=0.1M_{Earth}$

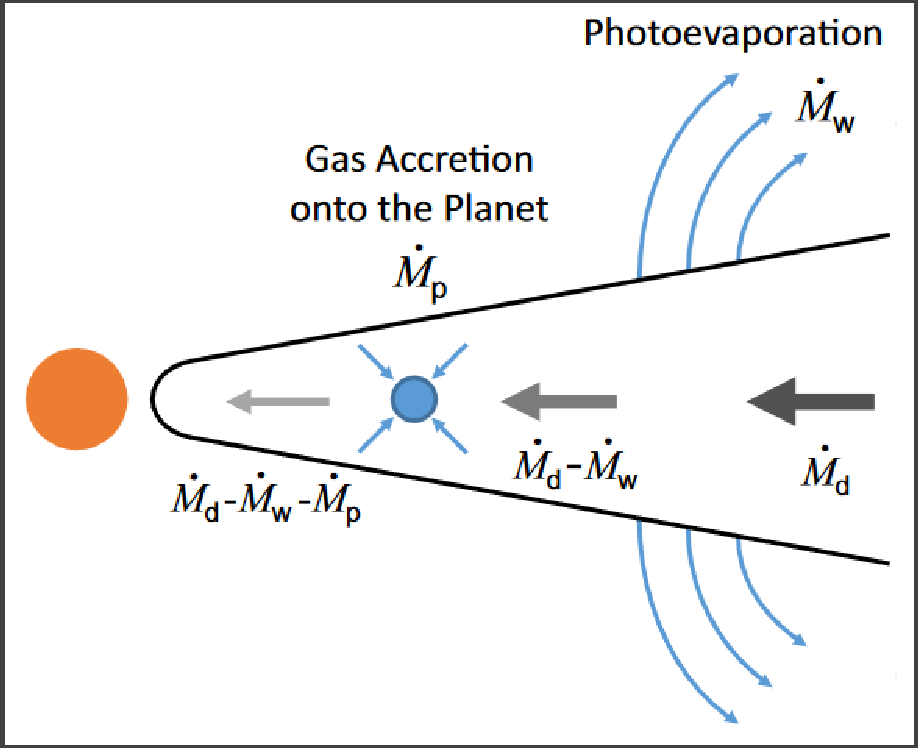
Mass growth

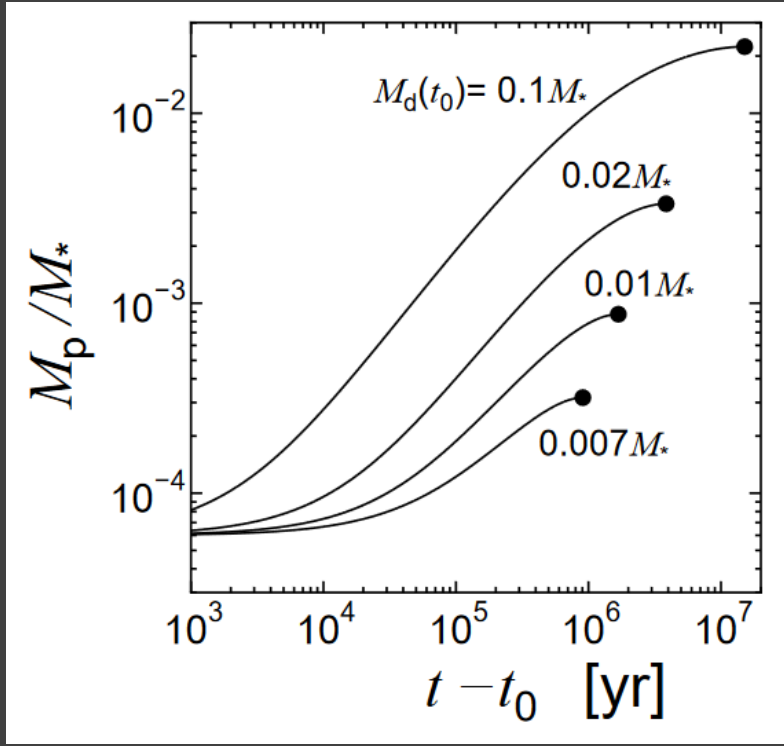


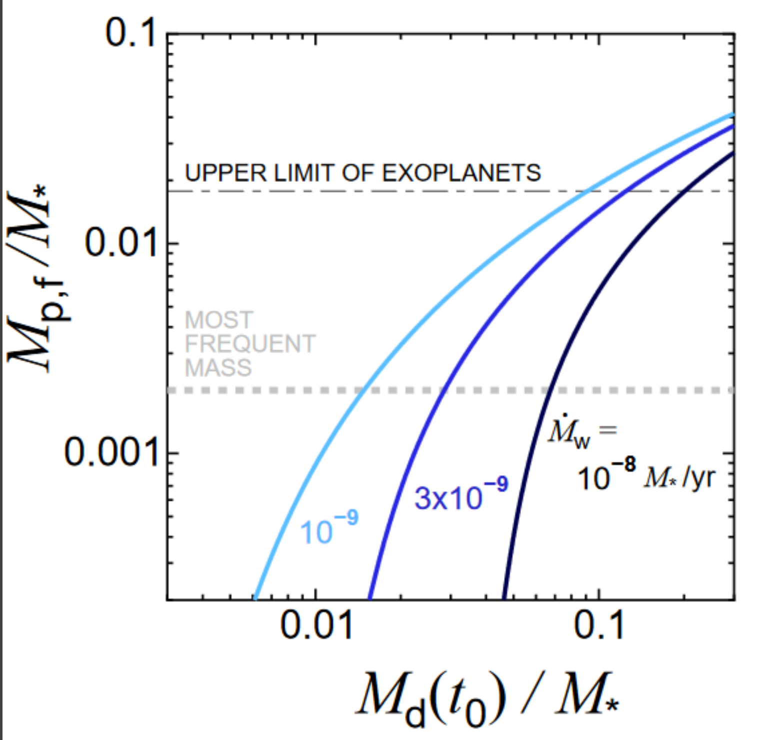
1000
100
10
1
0.1
0.01
0.1
1
10
Mass [M_E]
Orbital distance [AU]
100
10
1
0.1
0.01

Mass growth of a single giant planet

Photoevaporation
might be important

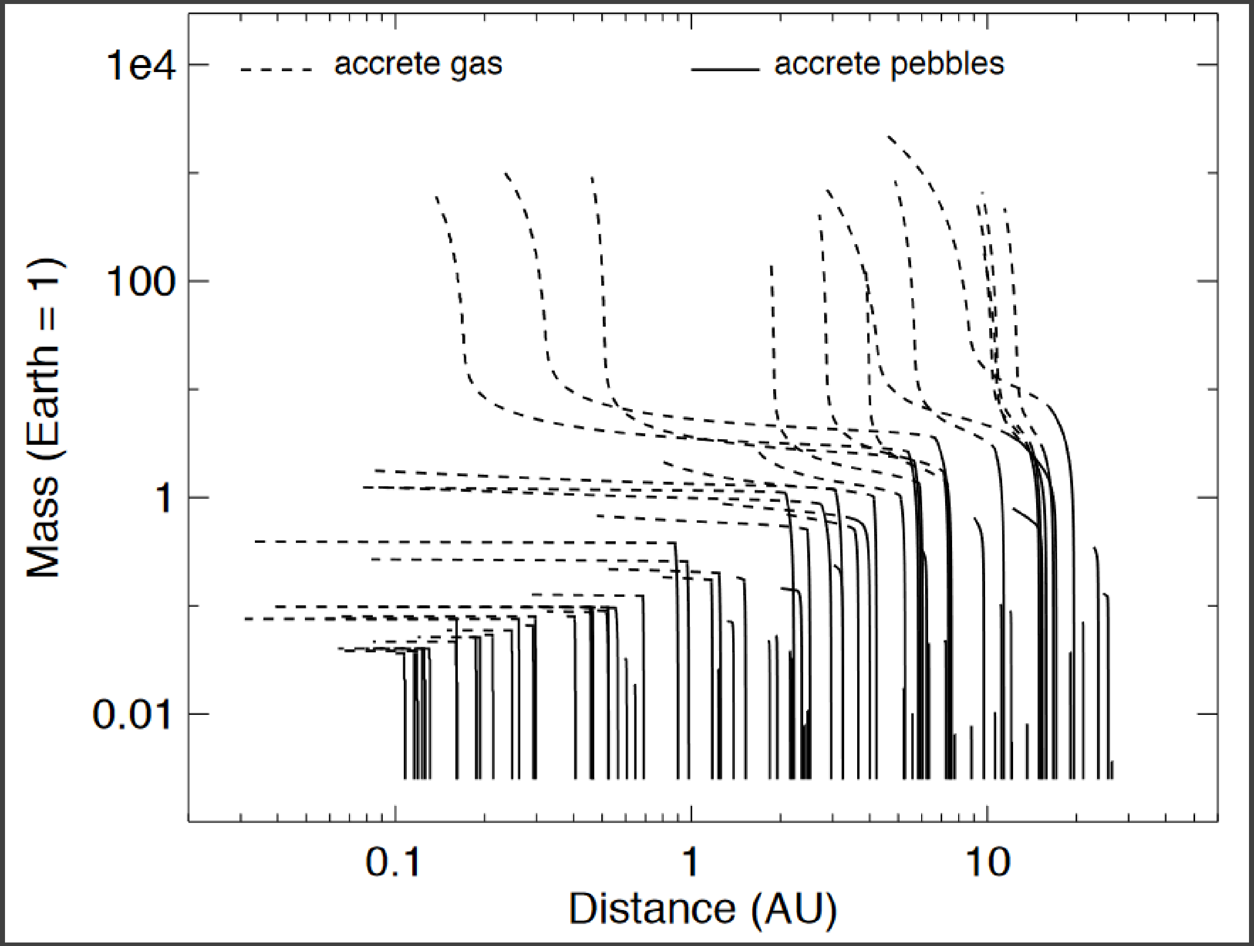


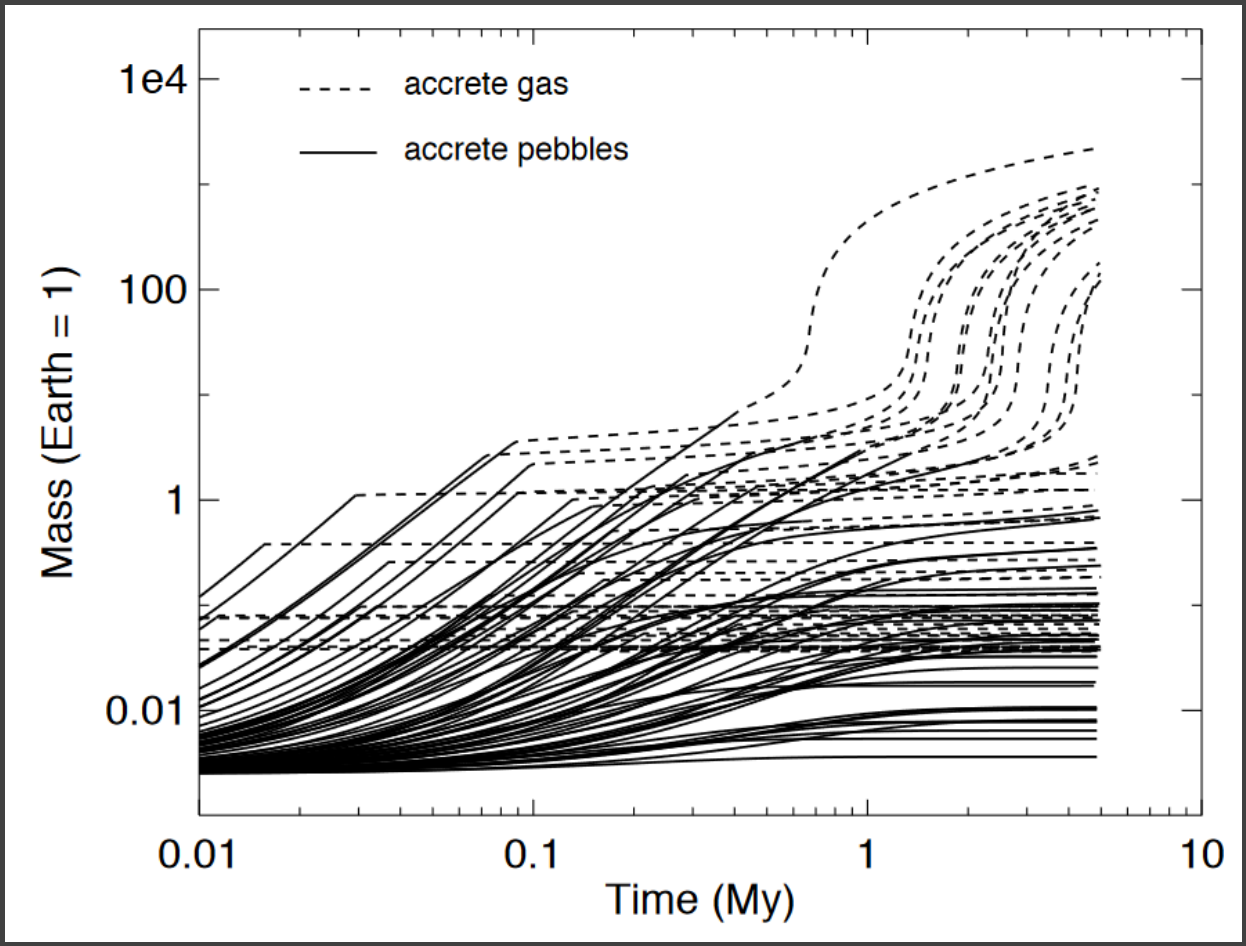




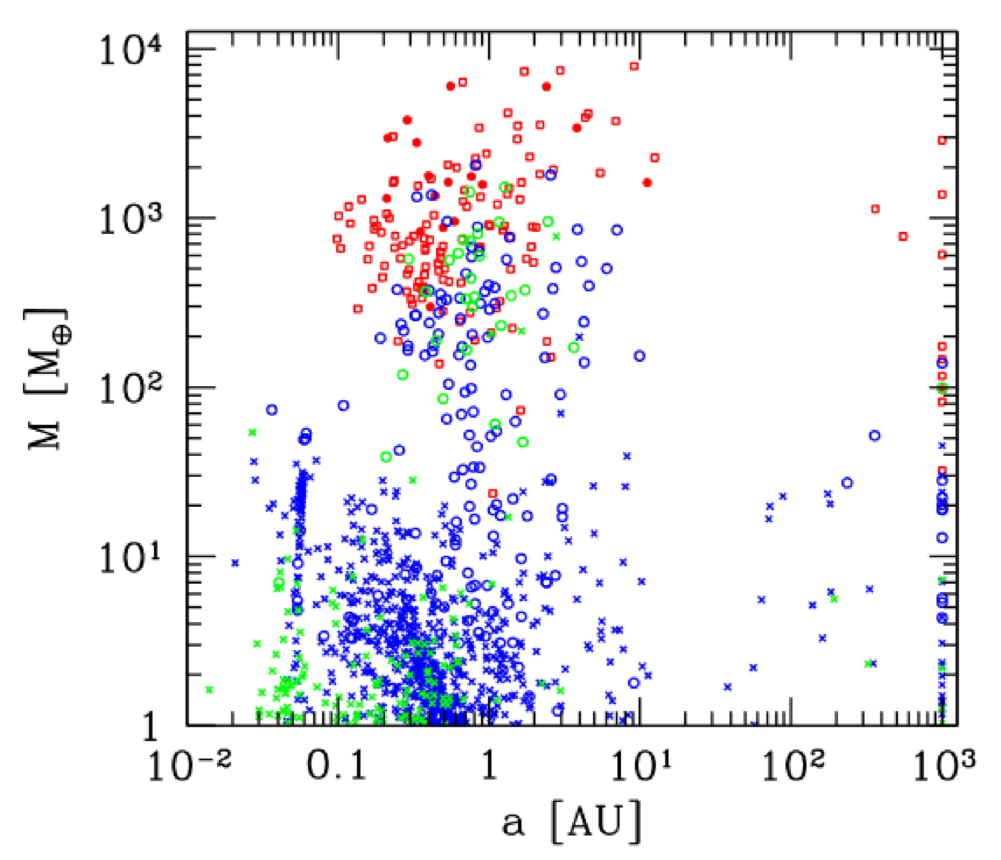
The authors derived universal tracks mass-orbital radius for gas giants.

Peebles and gas accretion

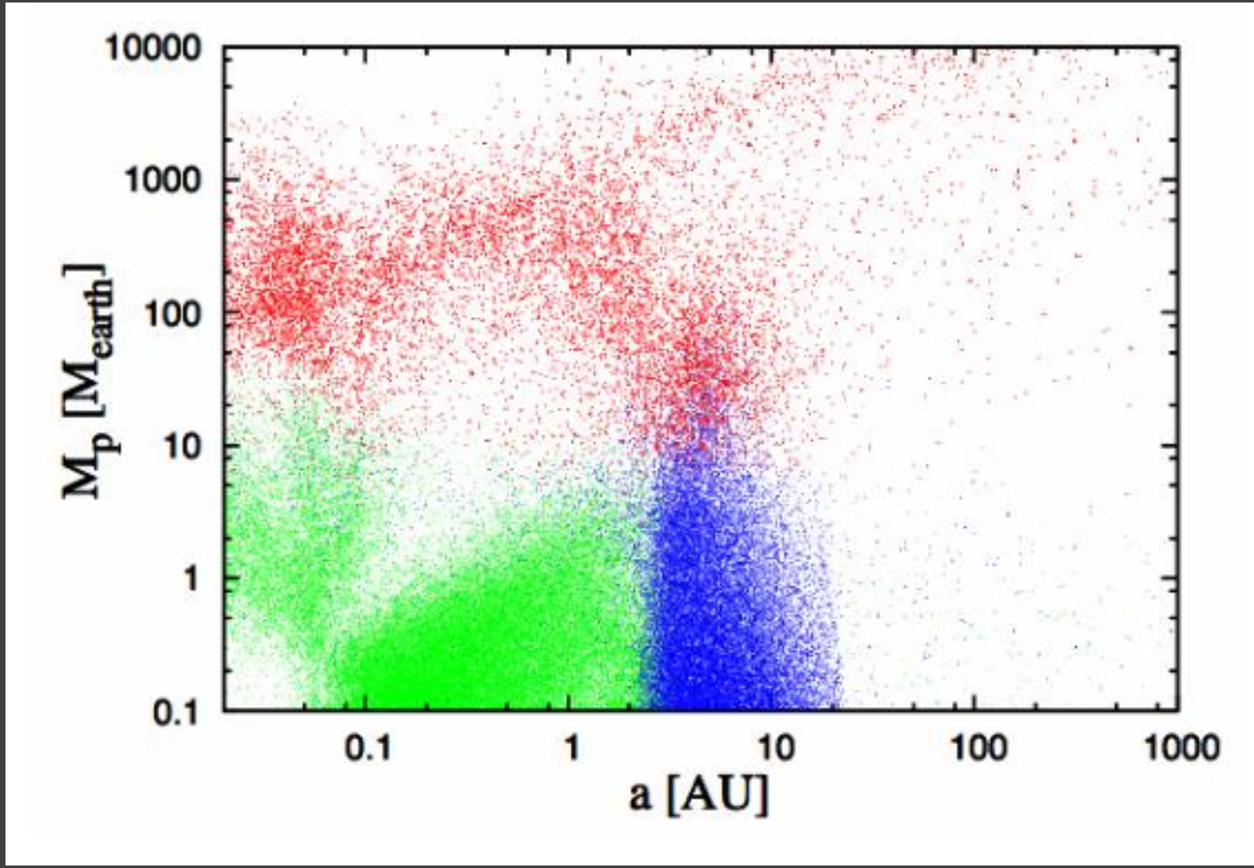




Mass – semi-major axis distribution



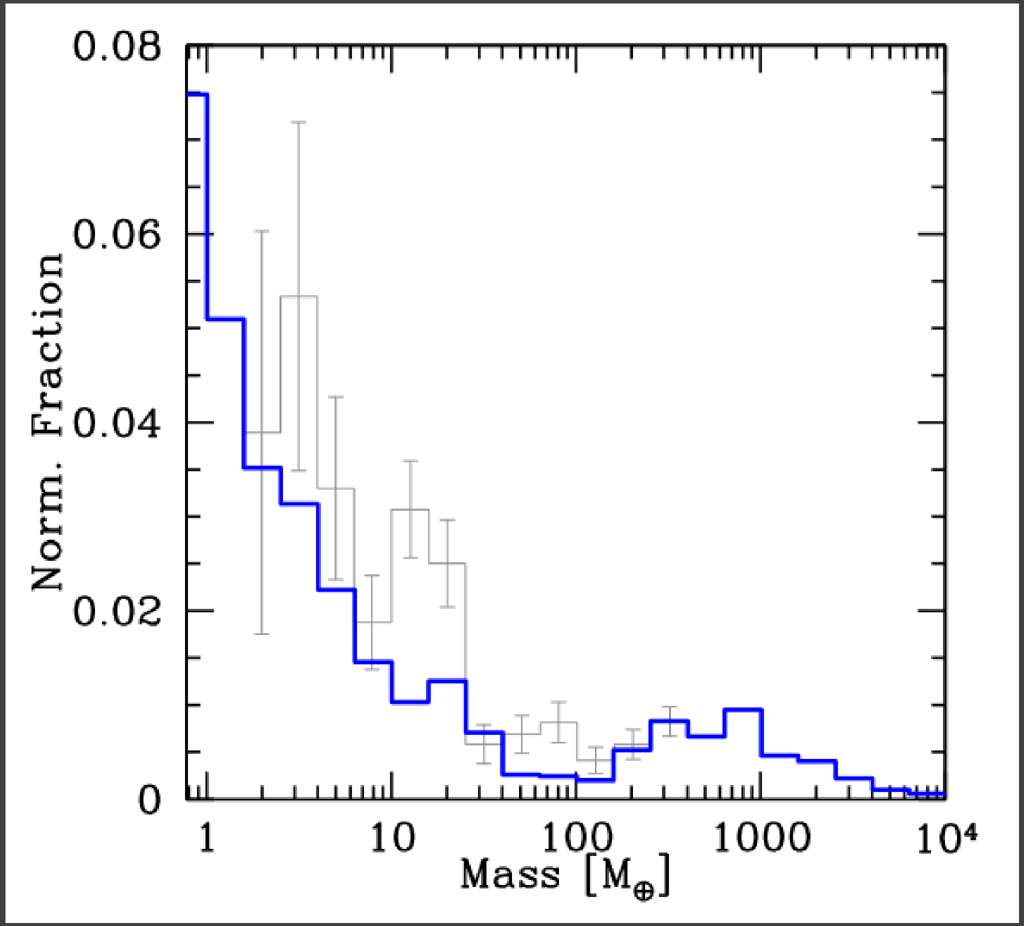
Alibert et al. (2013)



Ida, Lin (2013)

1402.7086

Mass distribution



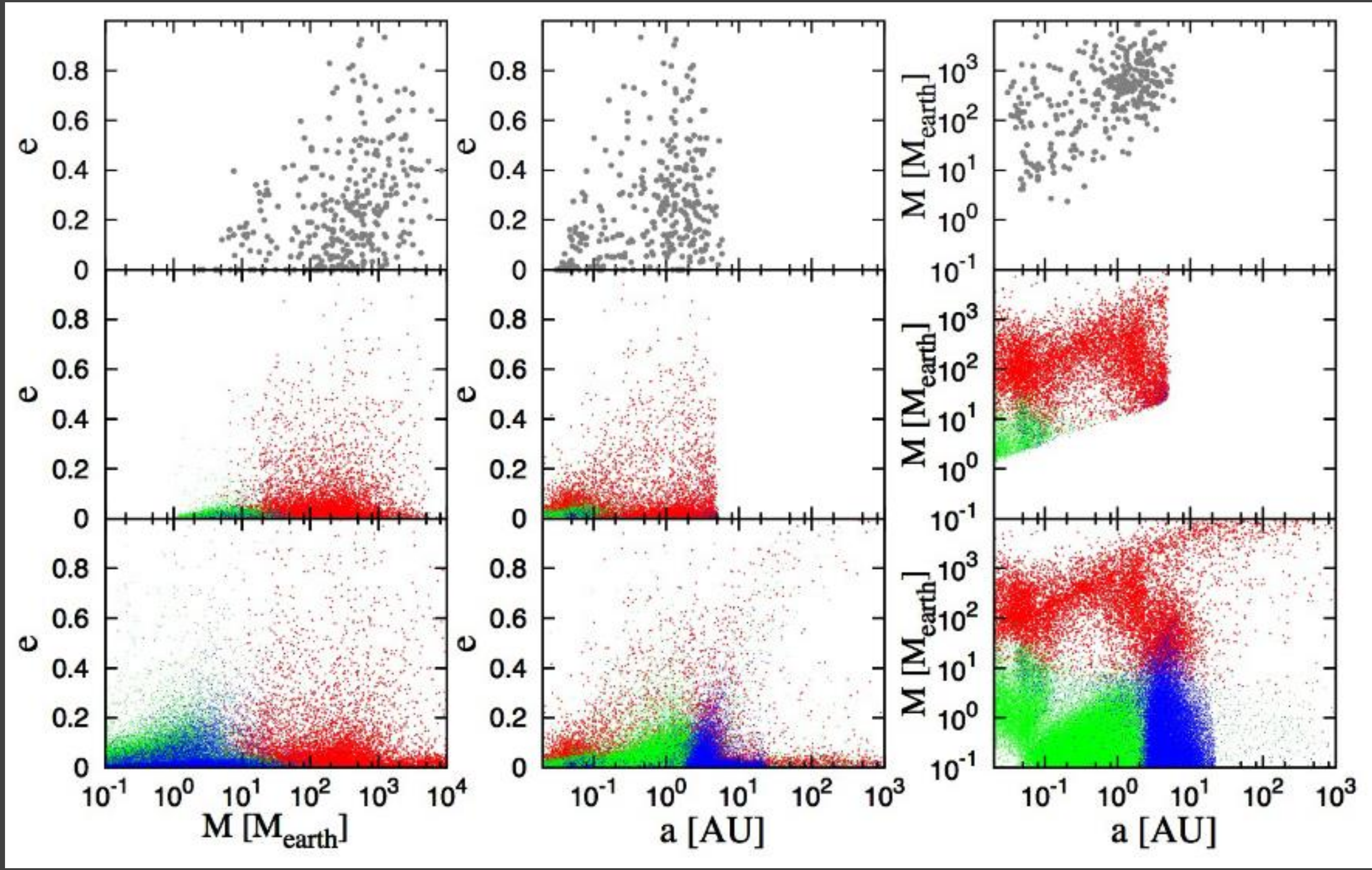
Thick line – computations;

Thin line – bias-corrected data.

Normalization made for $1M_{Jup}$

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

Comparison with observations



Observations

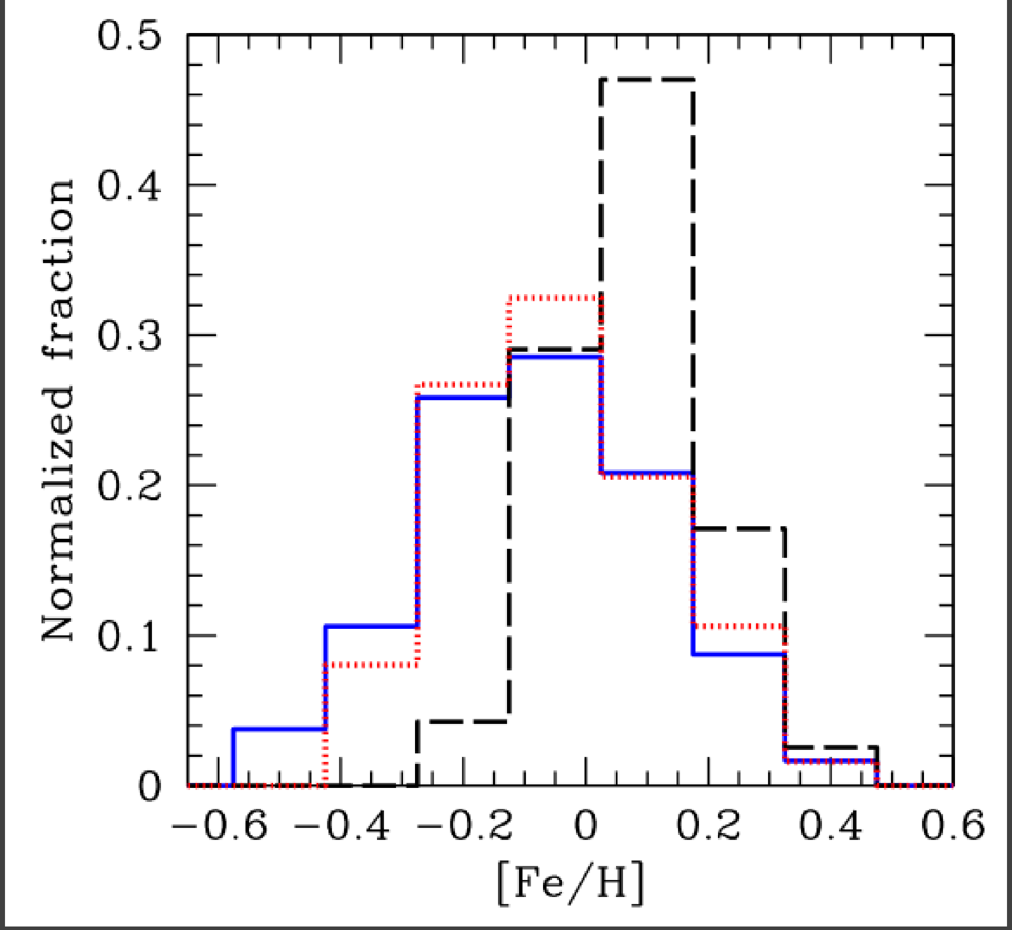
Calculations for observable planets (P_{orb}<10 yrs; v>1 m/s)

Calculations

Ida, Lin (2013)

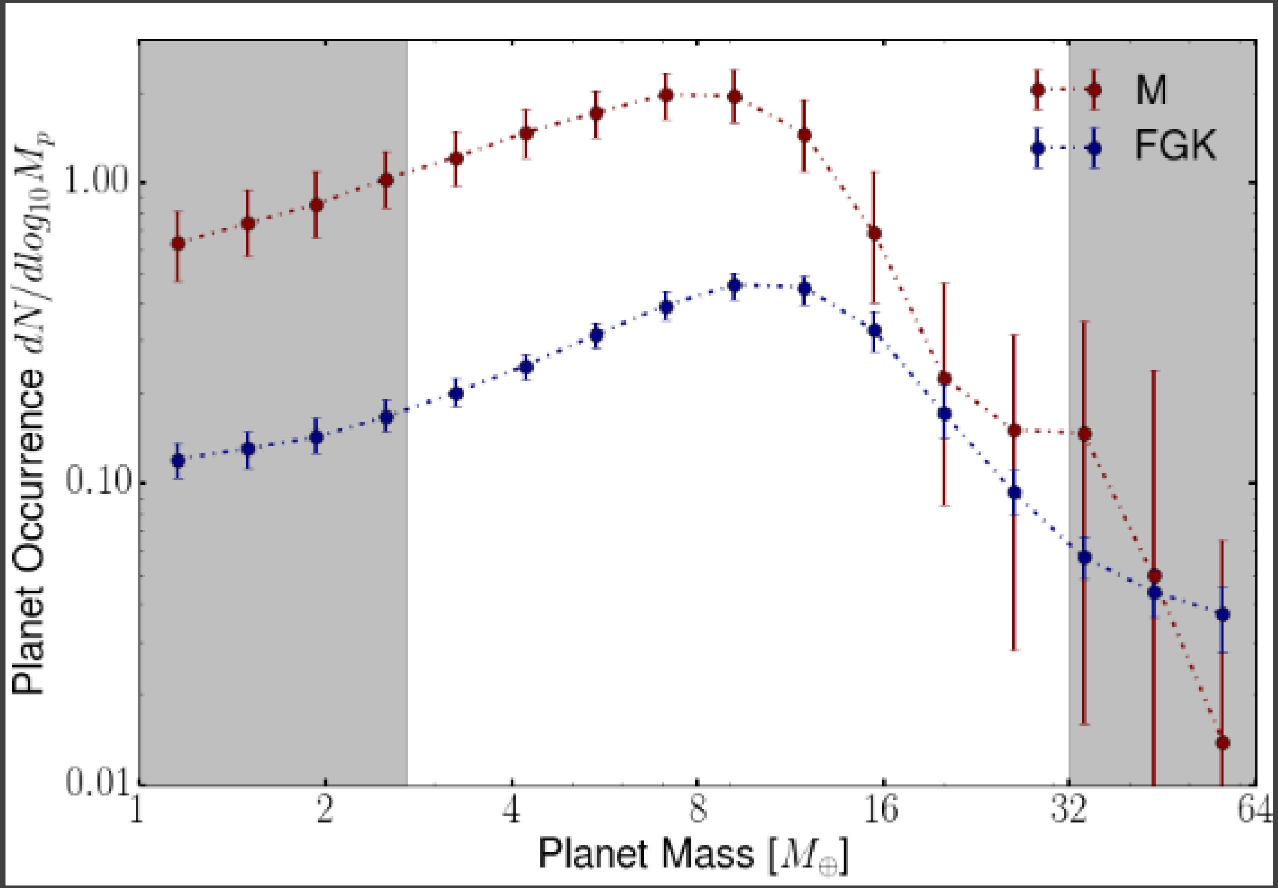
1402.7086, see arXiv:1905.0884 for detailed description of comparison methods

Metallicity effect

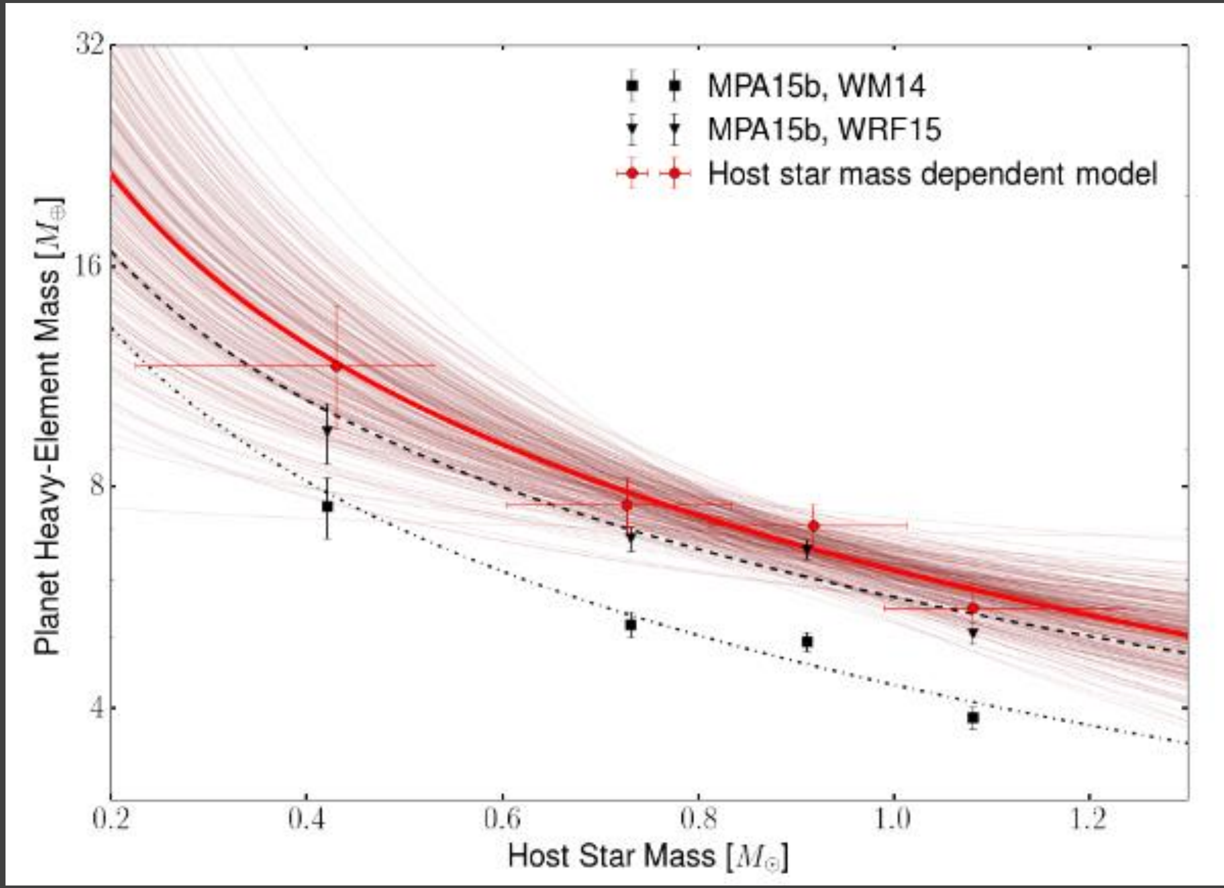


Solid line – all stars.
Dashed line – stars with at least one giant planet.
Dotted line – stars with at least one low-mass planet.

Dependence on the stellar mass

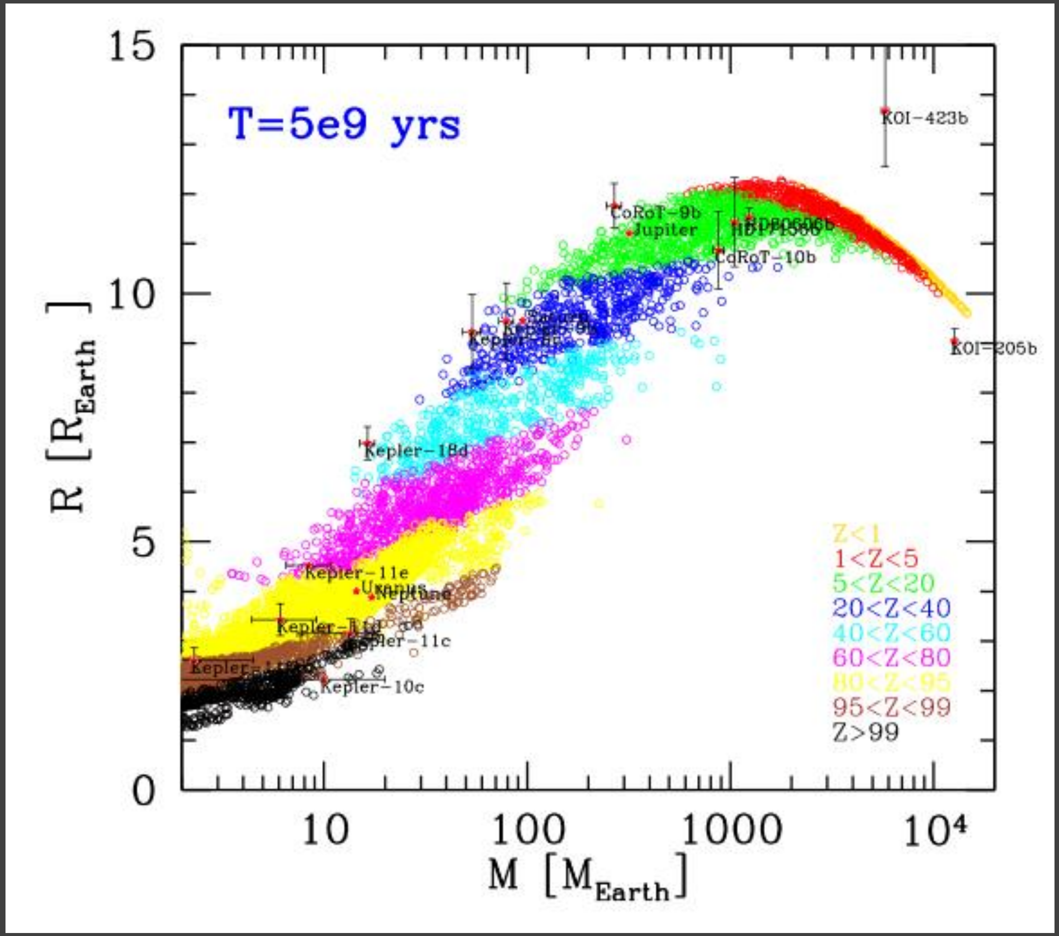


Model-dependent analysis of the Kepler data.



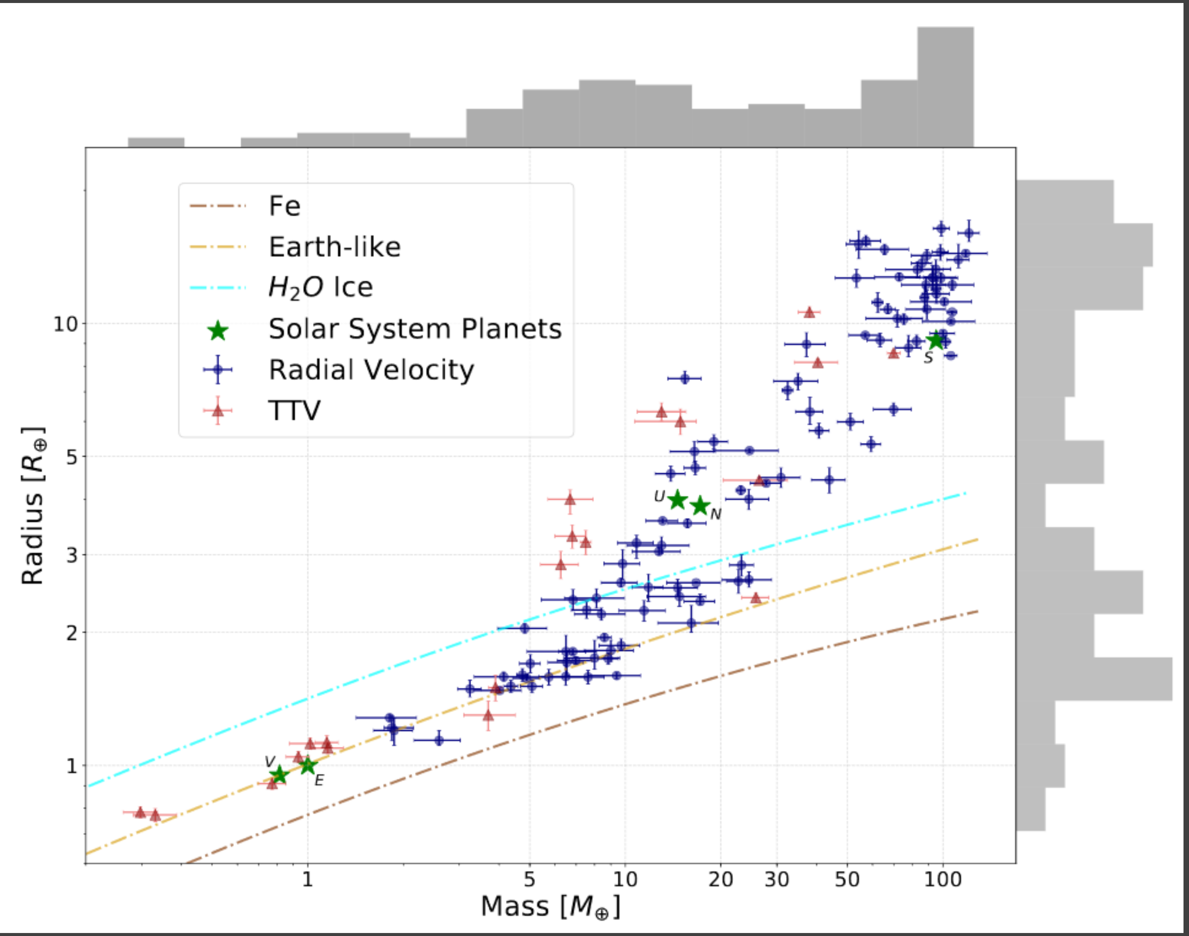
Only near-by planets included. No normal jupiters.

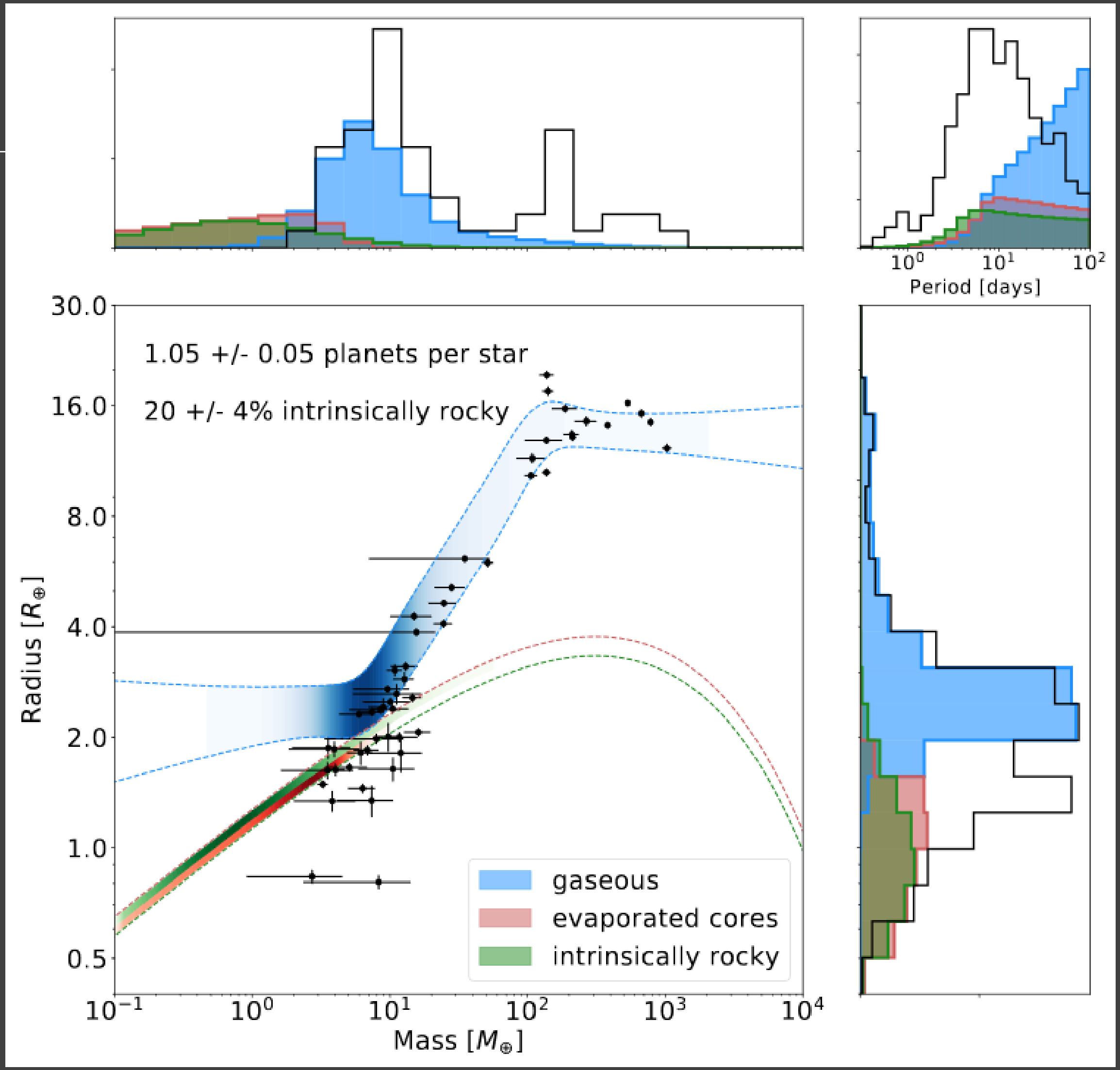
Composition



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

Mass-radius from data





1911.04745

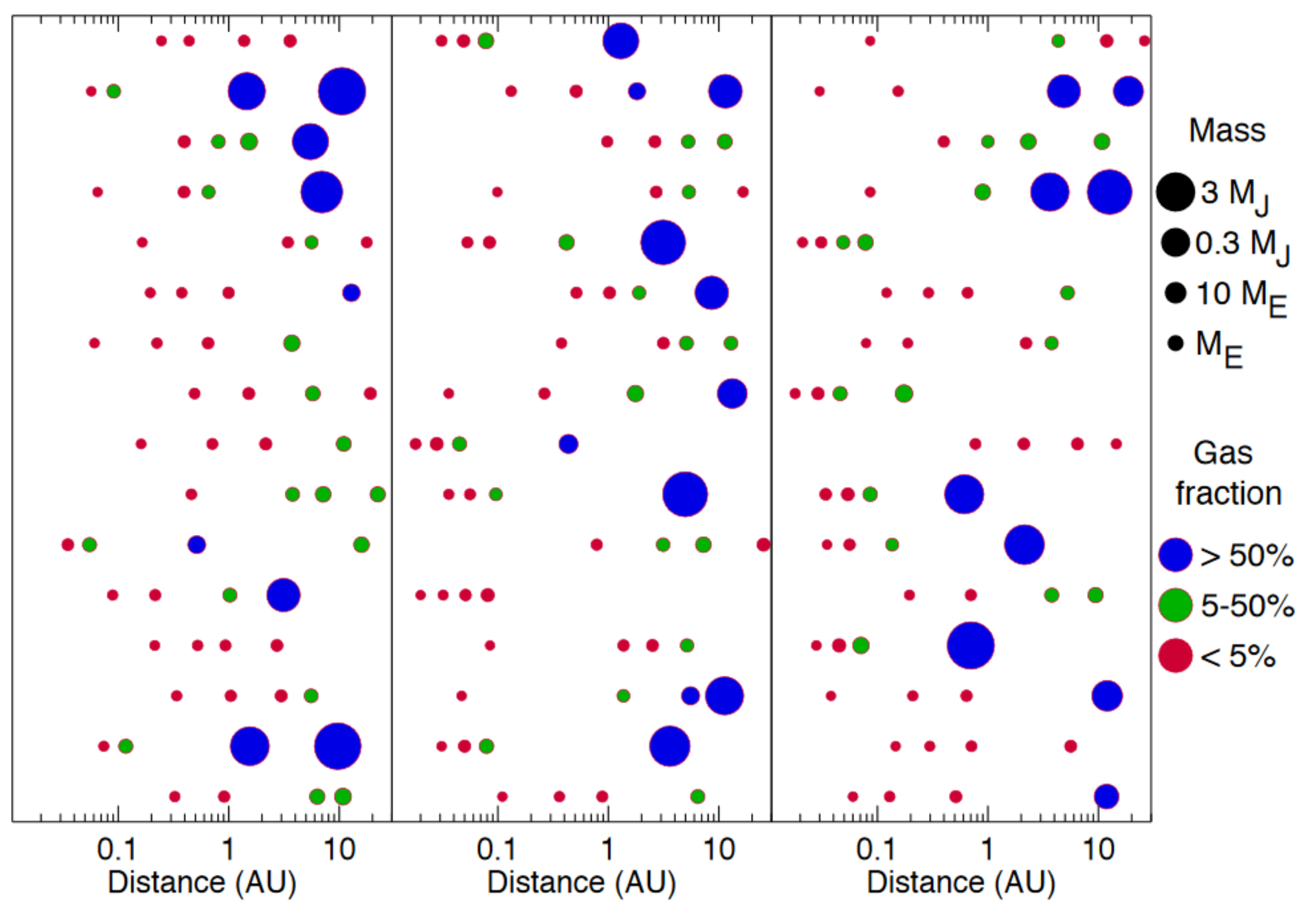
1911.03582

Another population synthesis model

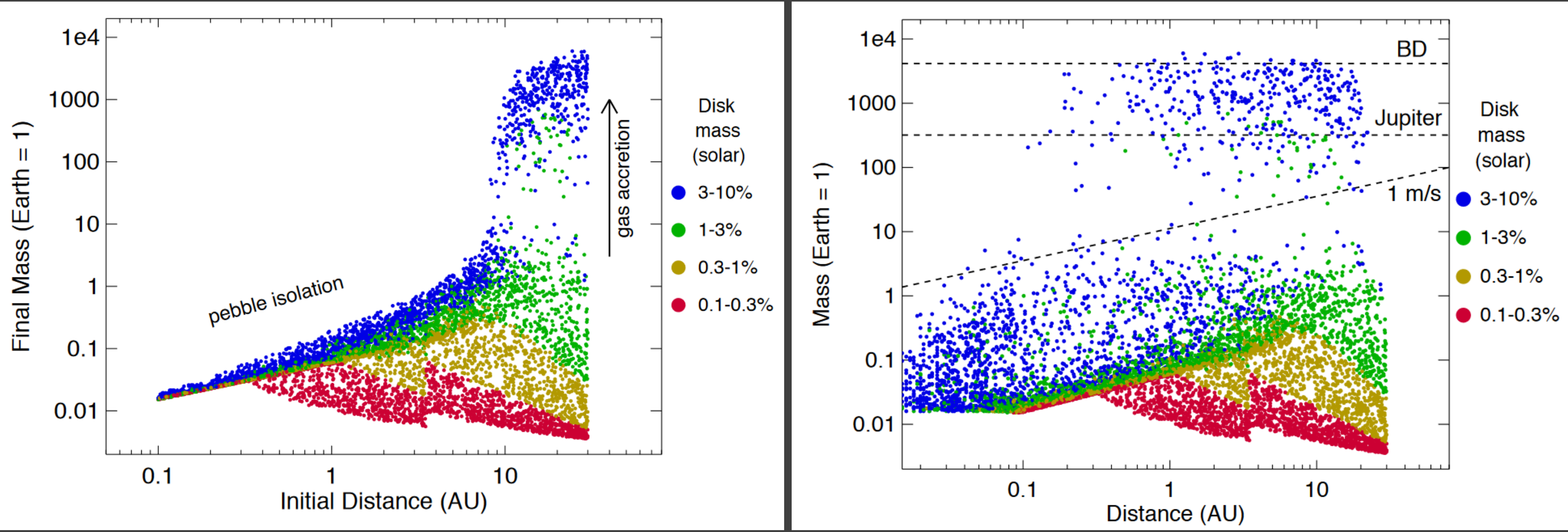
Simple model
with analytical equations.

Model parameters are optimized
to fit known data.

Single and four planet cases
were studied.

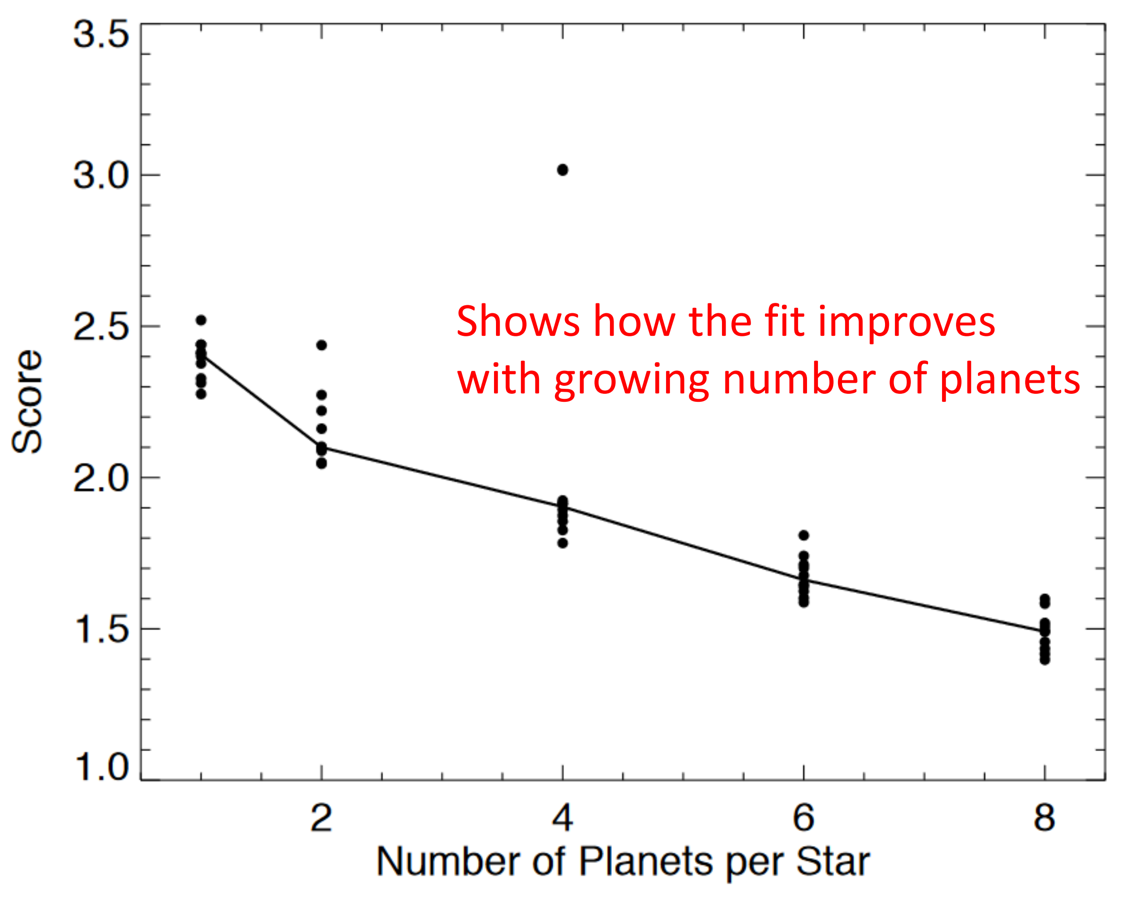


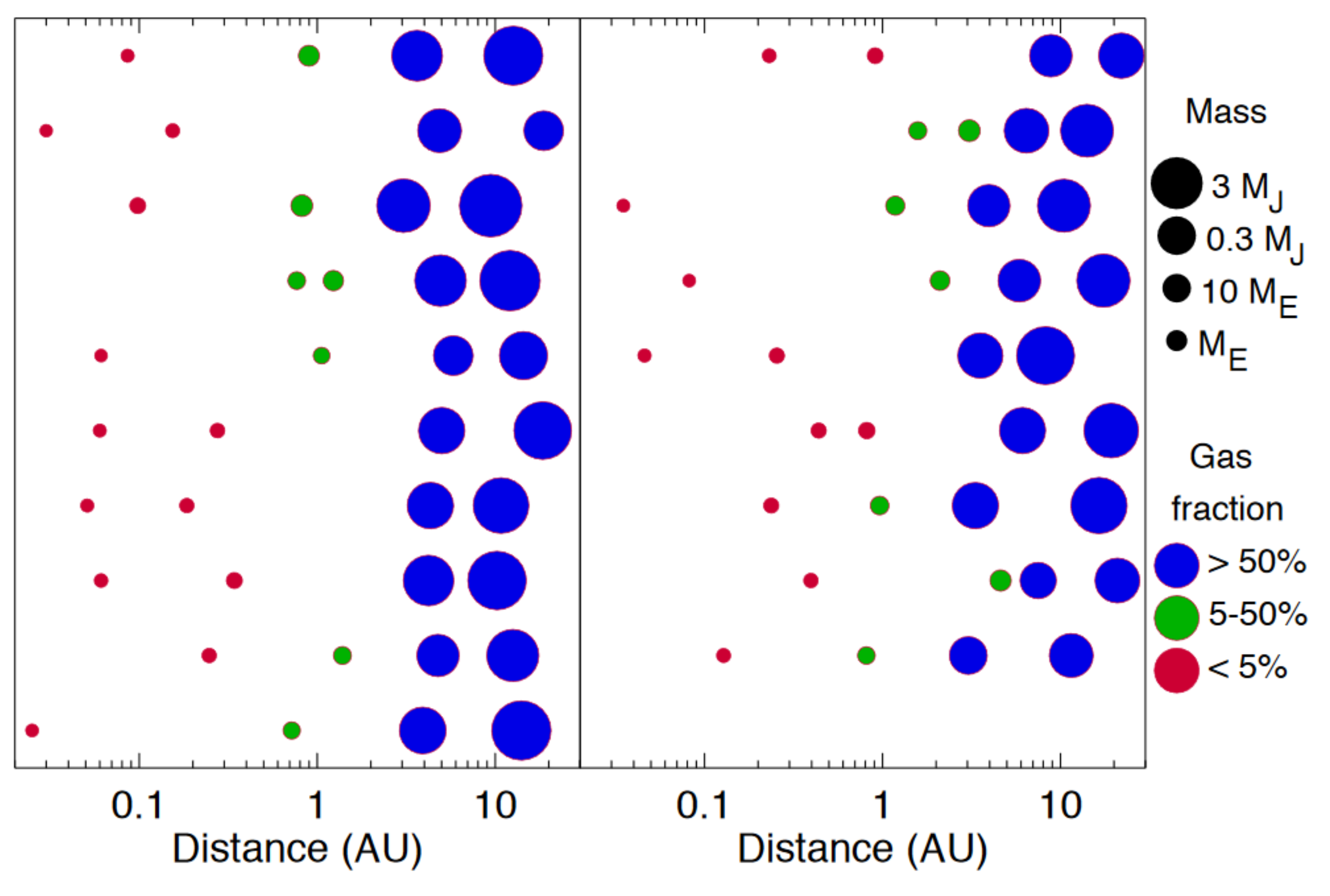
Mass- distance distribution



1808.03293

Number of planets and SoSys analogues





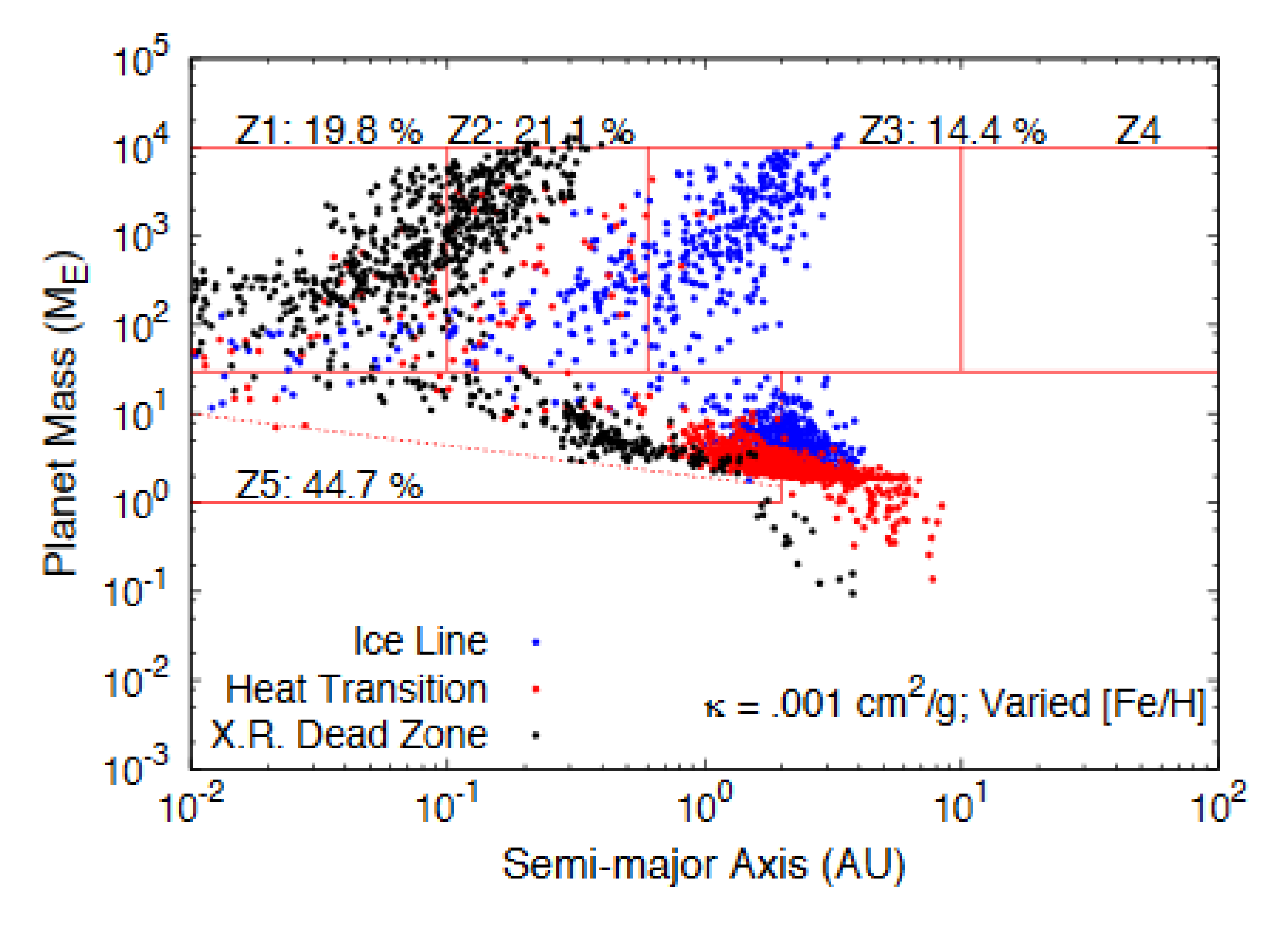
Role of more complicated migration models

Traps (regions of zero net torque)
can slow planet migration (type I).

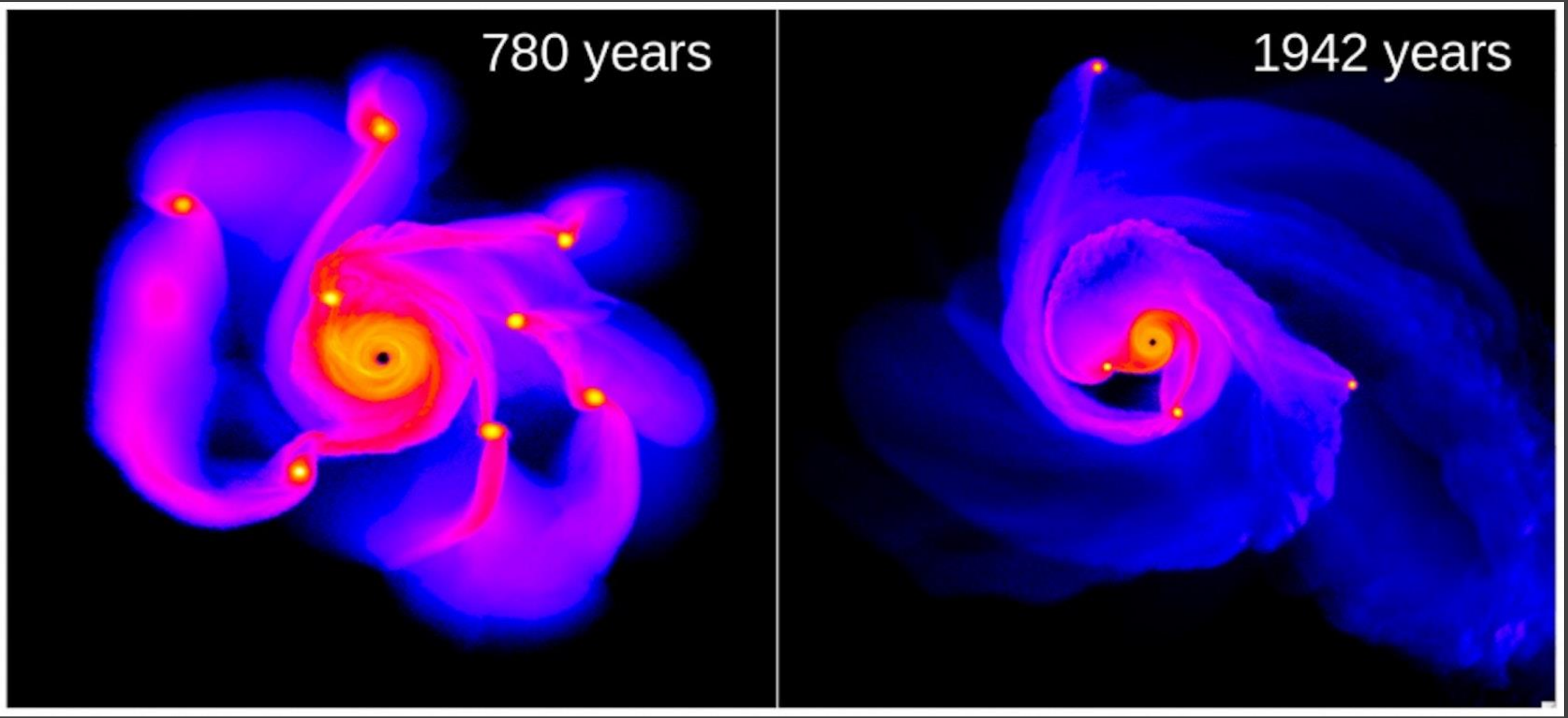
Traps can be related to peculiarities
in density or/and temperature profiles.
For example, an ice line can be such
critical distance, at which planets are trapped.

Heat transition zone – is another trap.
There viscous heating (inside) is changed
by irradiation by the star (outer zone).

X-rays due to magnetospheric accretion
and cosmic rays ionize the disk.
Low ionization produces dead zones in the disk.



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 newer results in 1711.05948. See comparison of models in 1901.08089.

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

Tidal downsizing

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

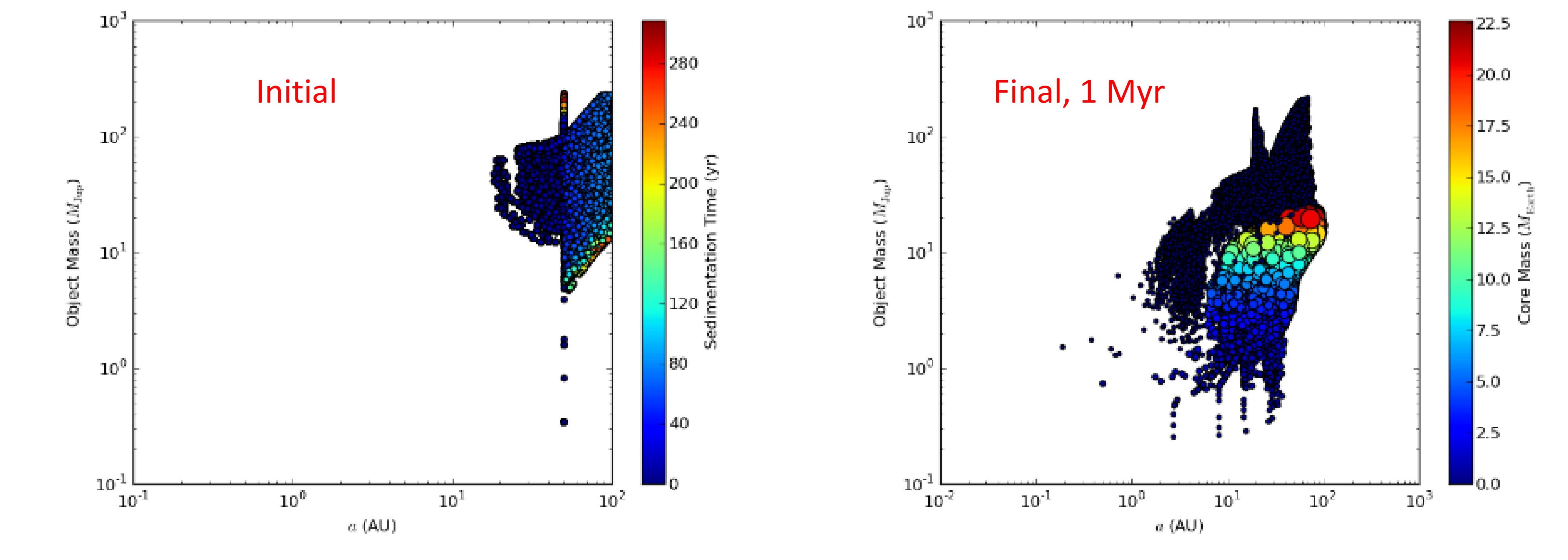
Fragment mass just after fragmentation

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

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

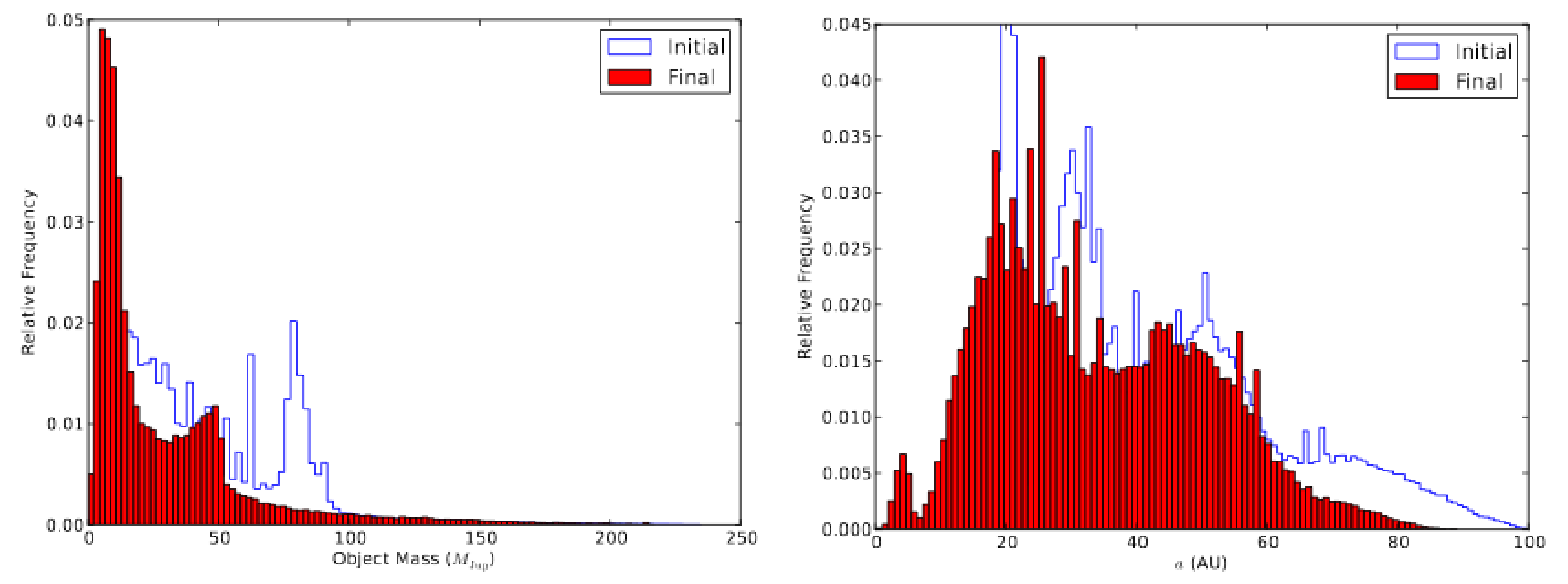
Evolution of a fragment in a disc can result in appearance of a low-mass planet closer to the star, or in appearance of a belt of particles.

Initial and final semi-major axis distribution

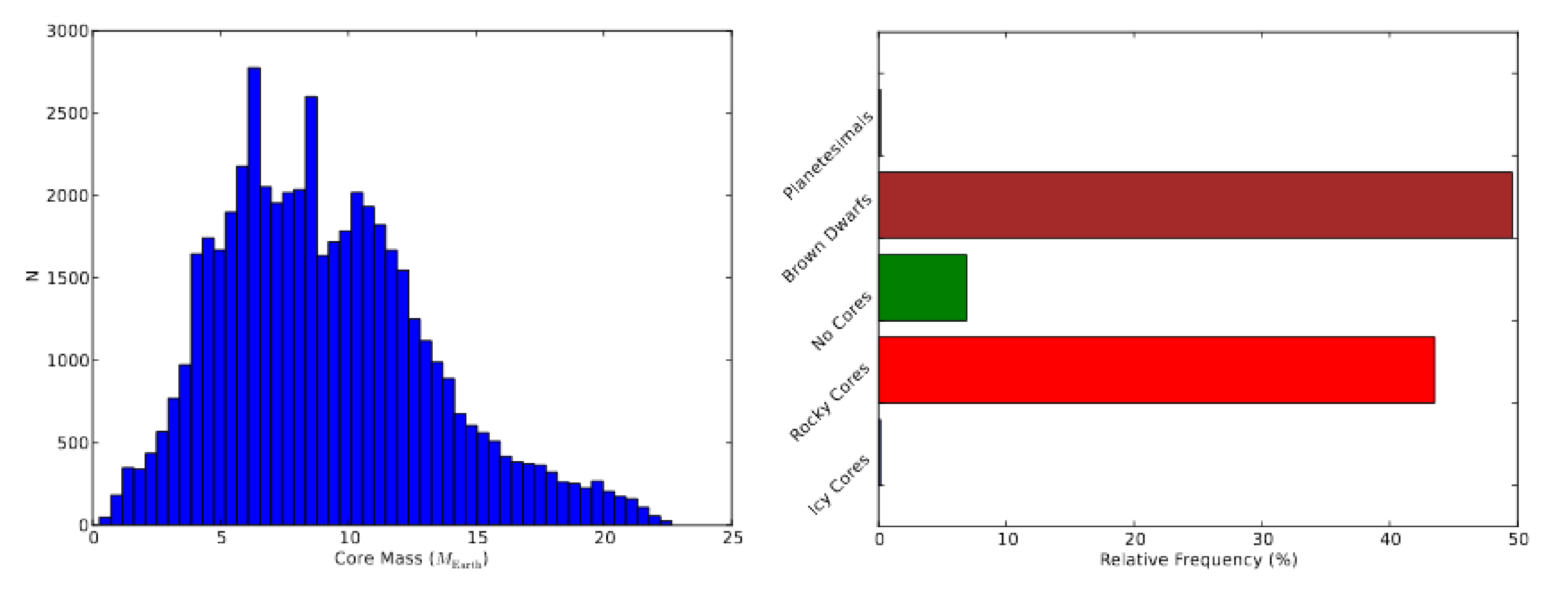


45% survived
20% formed solid cores

Mass and semi-major axis distribution

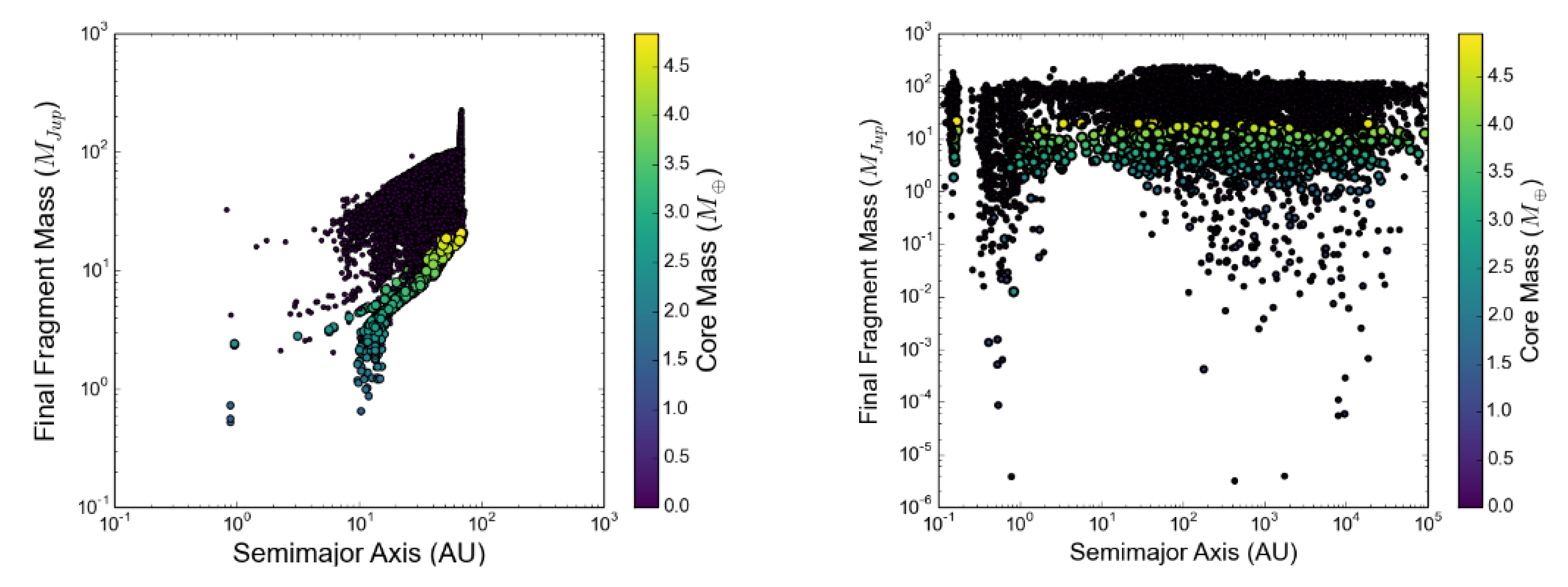


Mass distribution and planet types



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

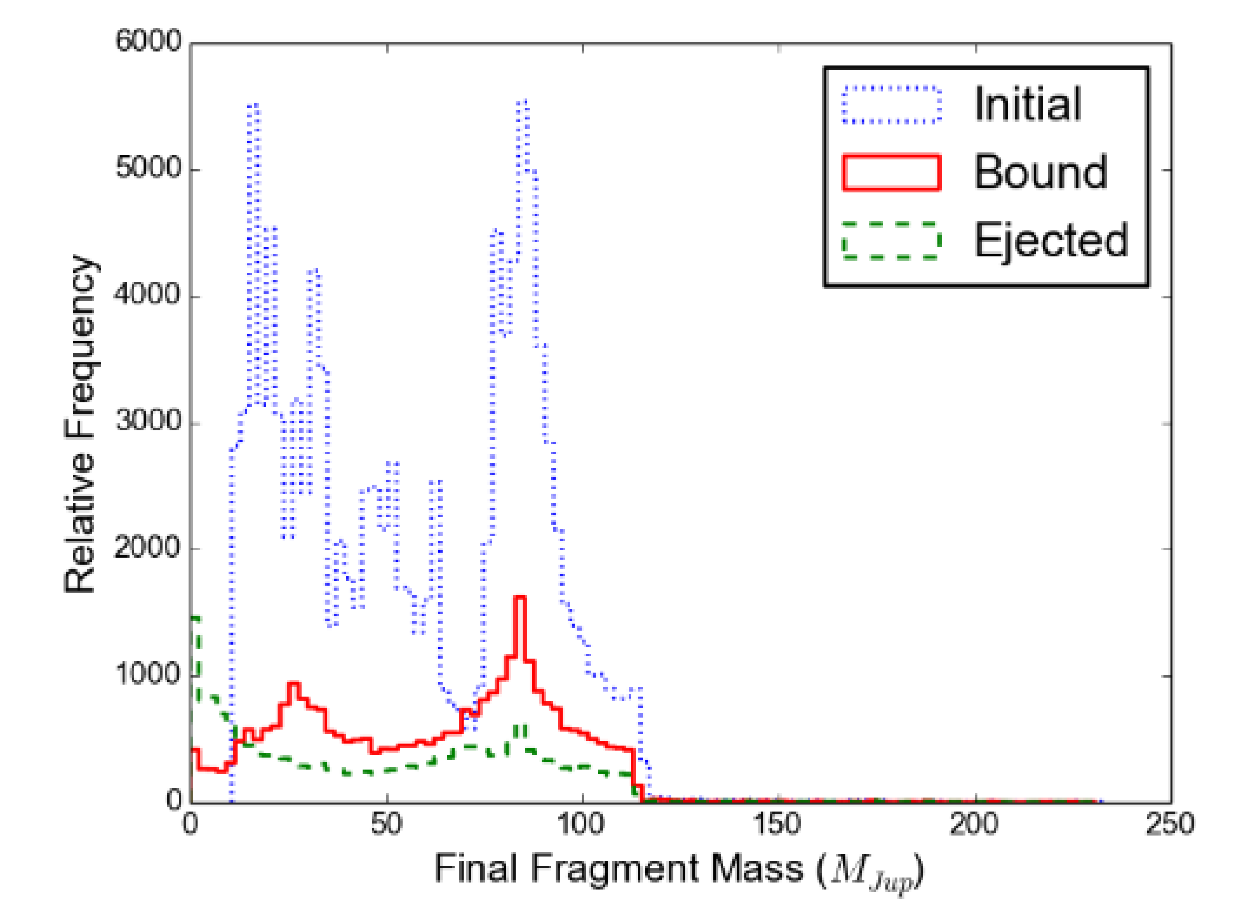
Role of fragment-fragment interaction



Interaction off

Interaction on

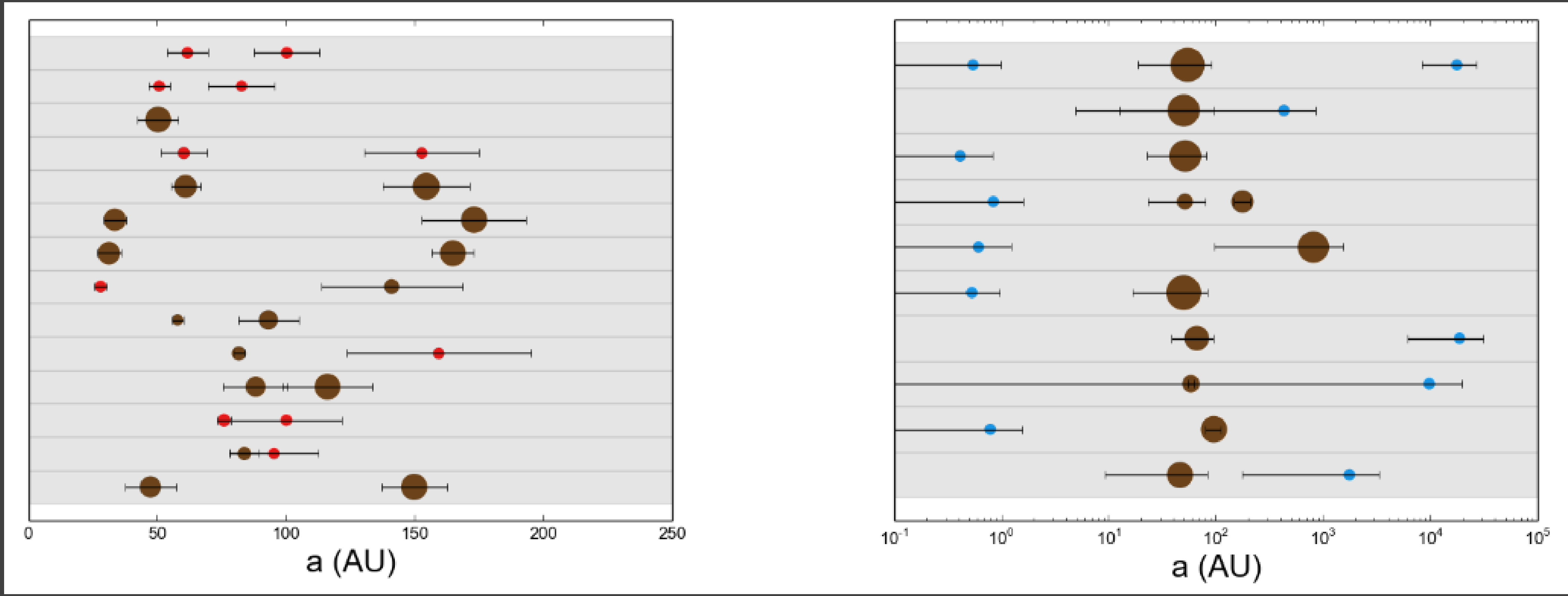
Ejection



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

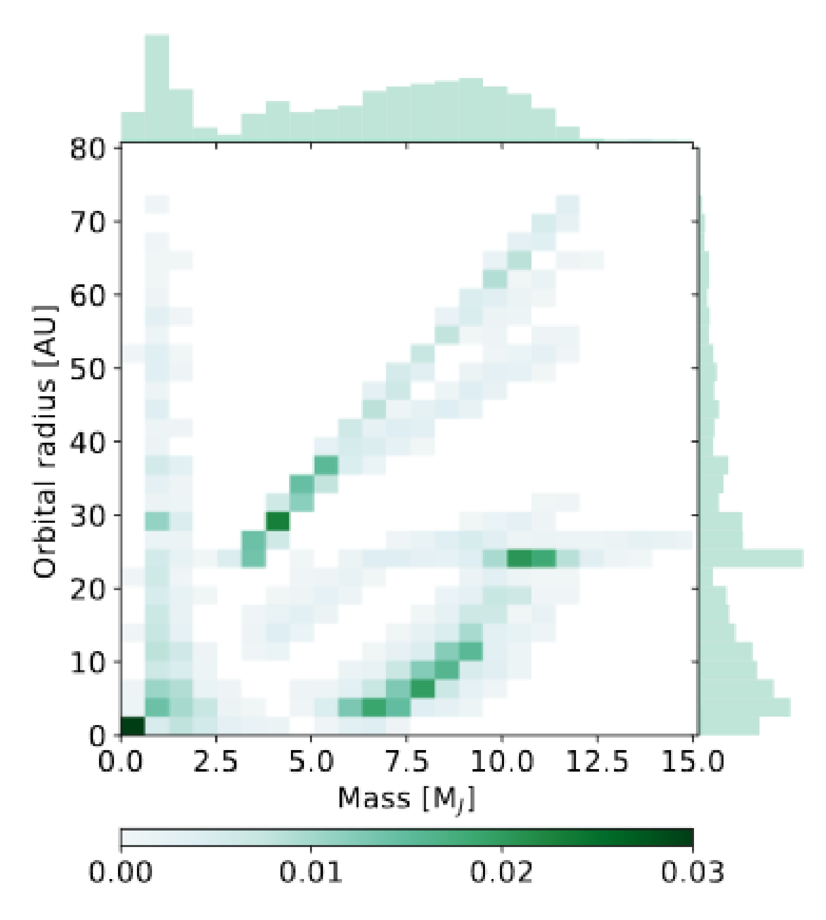
Brown – brown dwarfs;
Red – gas giants;
Blue – rocky (>50%).



Typical systems

Non-typical systems

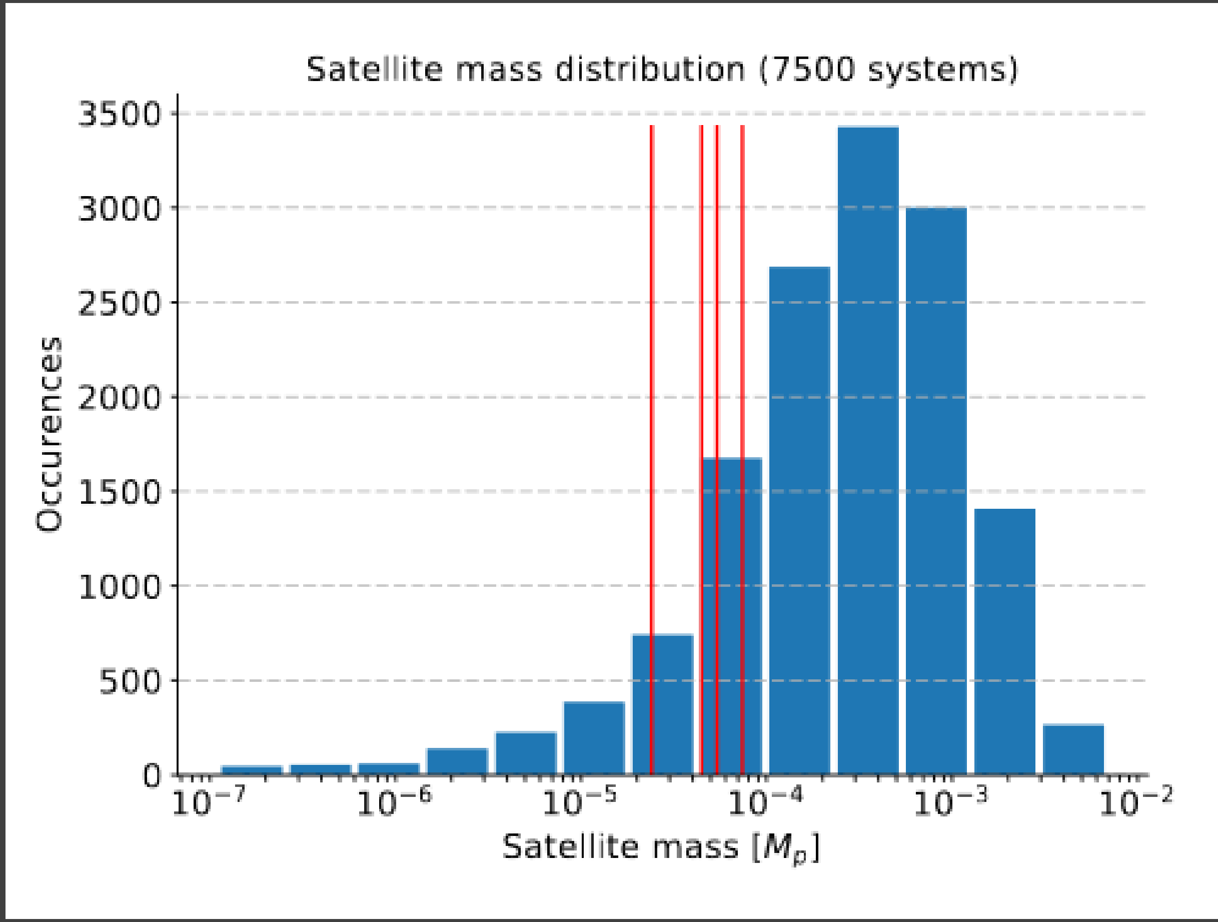
Another example of population synthesis of planets formed by instability

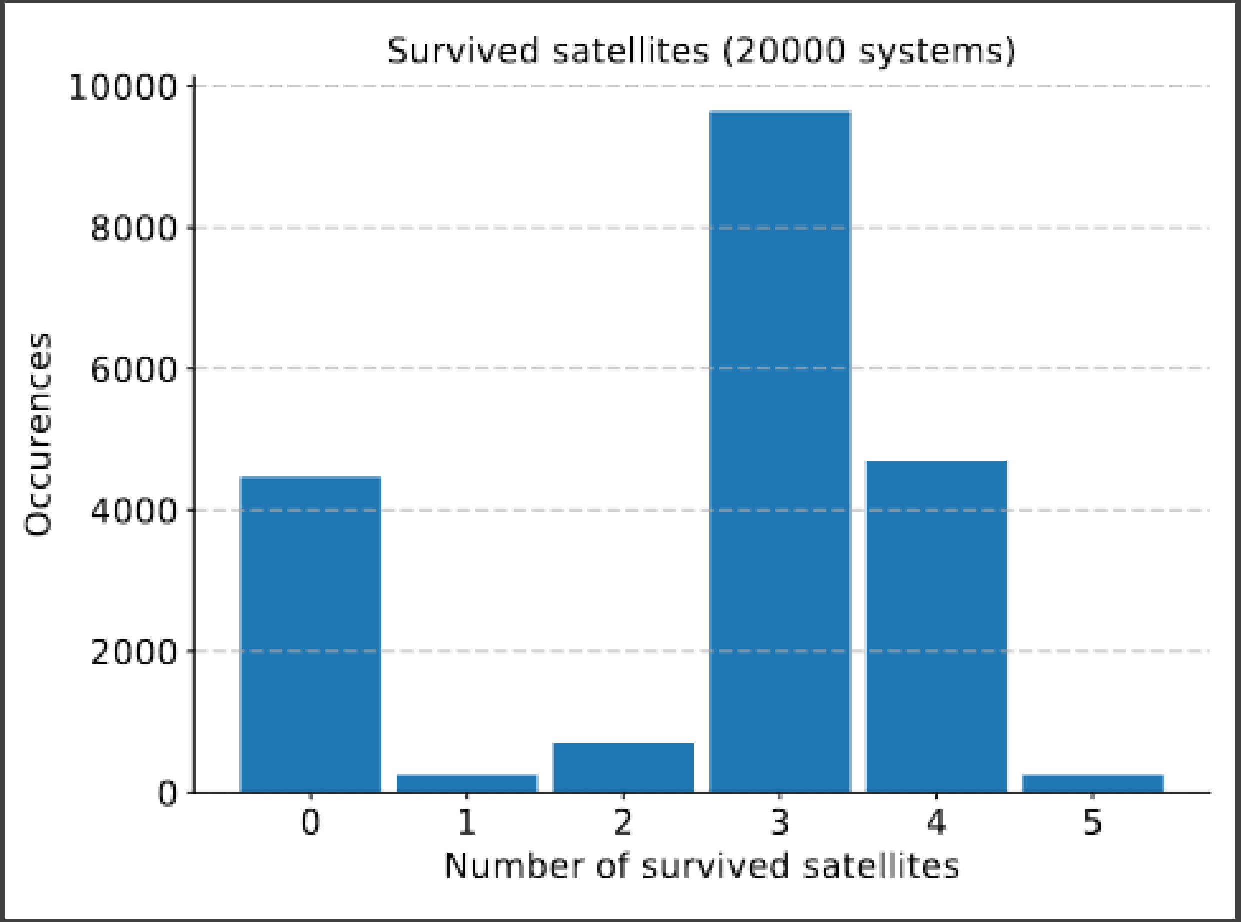


Many uncertainties.

This picture summarizes all the models,
calculated for different assumptions and parameters.

Population synthesis of Galilean satellites



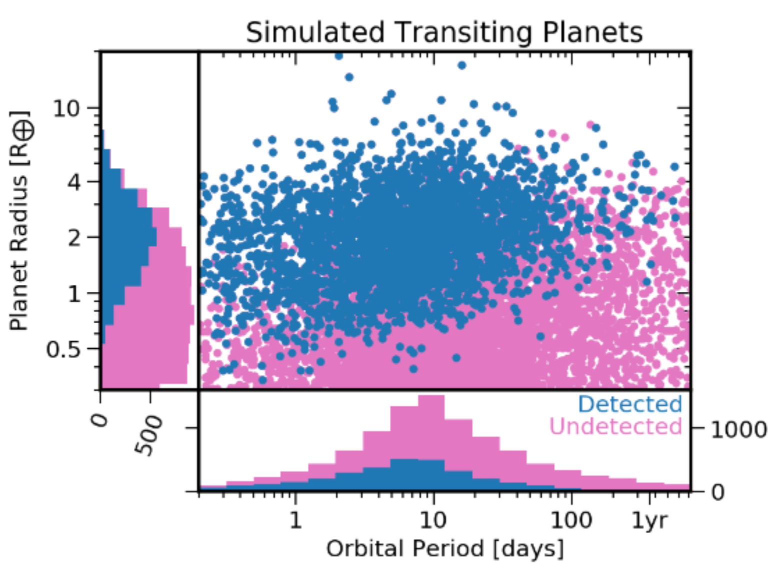


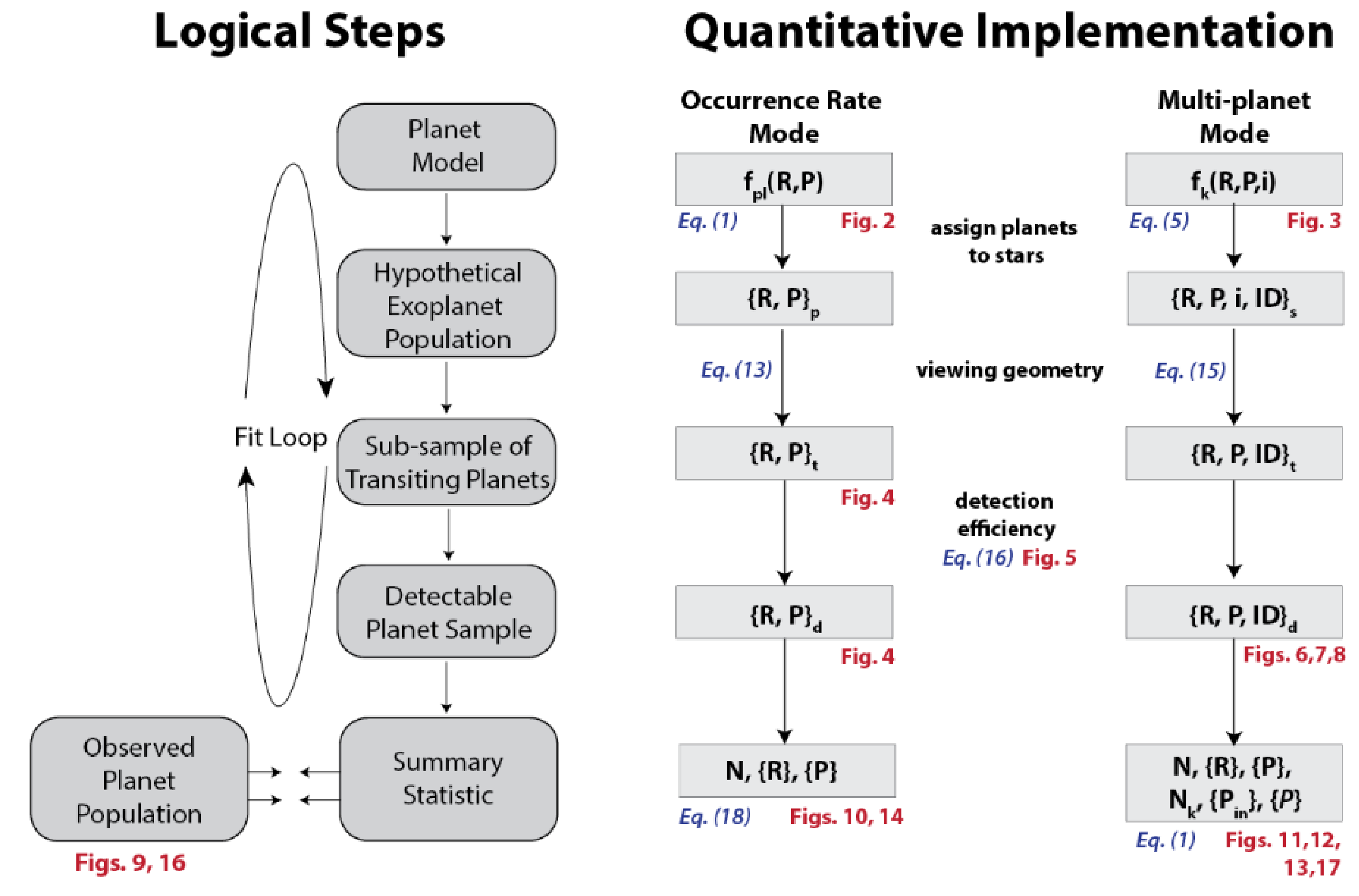
1801.06094

How to compare calculations with data

After calculations are made it is necessary to compare it with observational data.

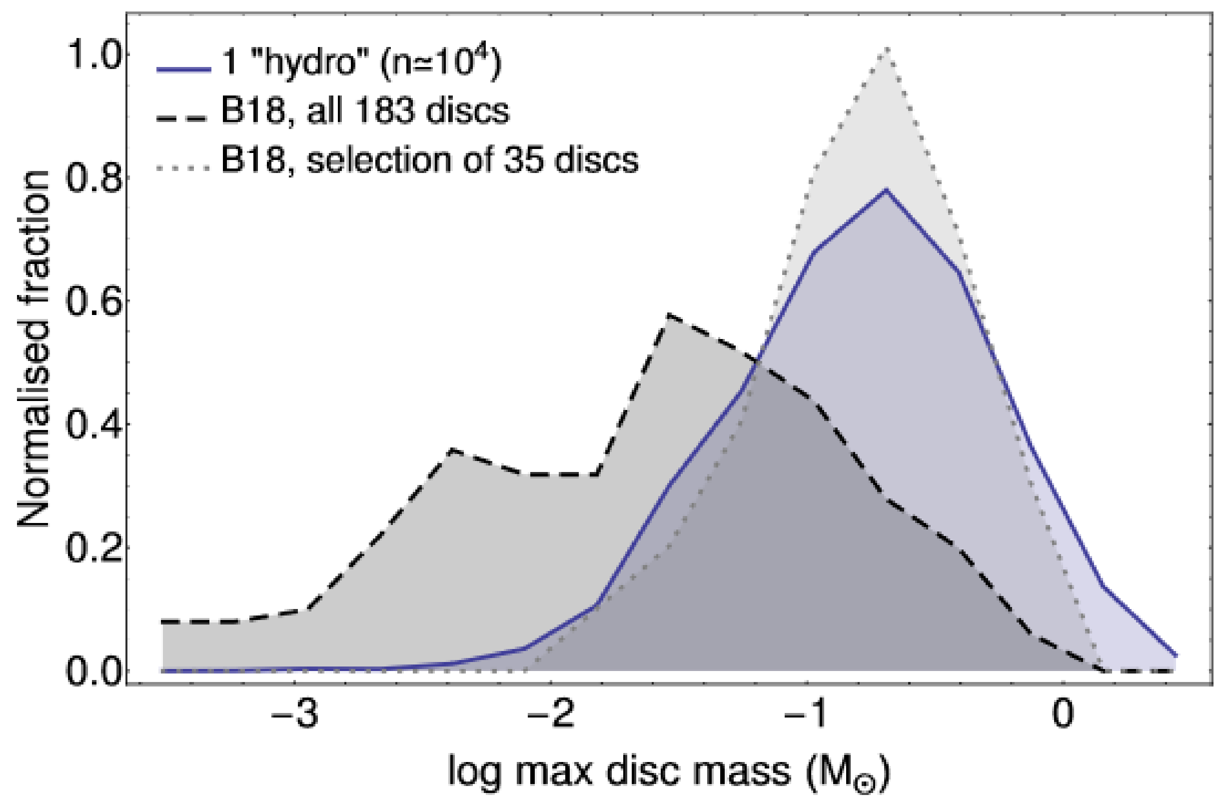
For the case of transiting planets a special script was written.

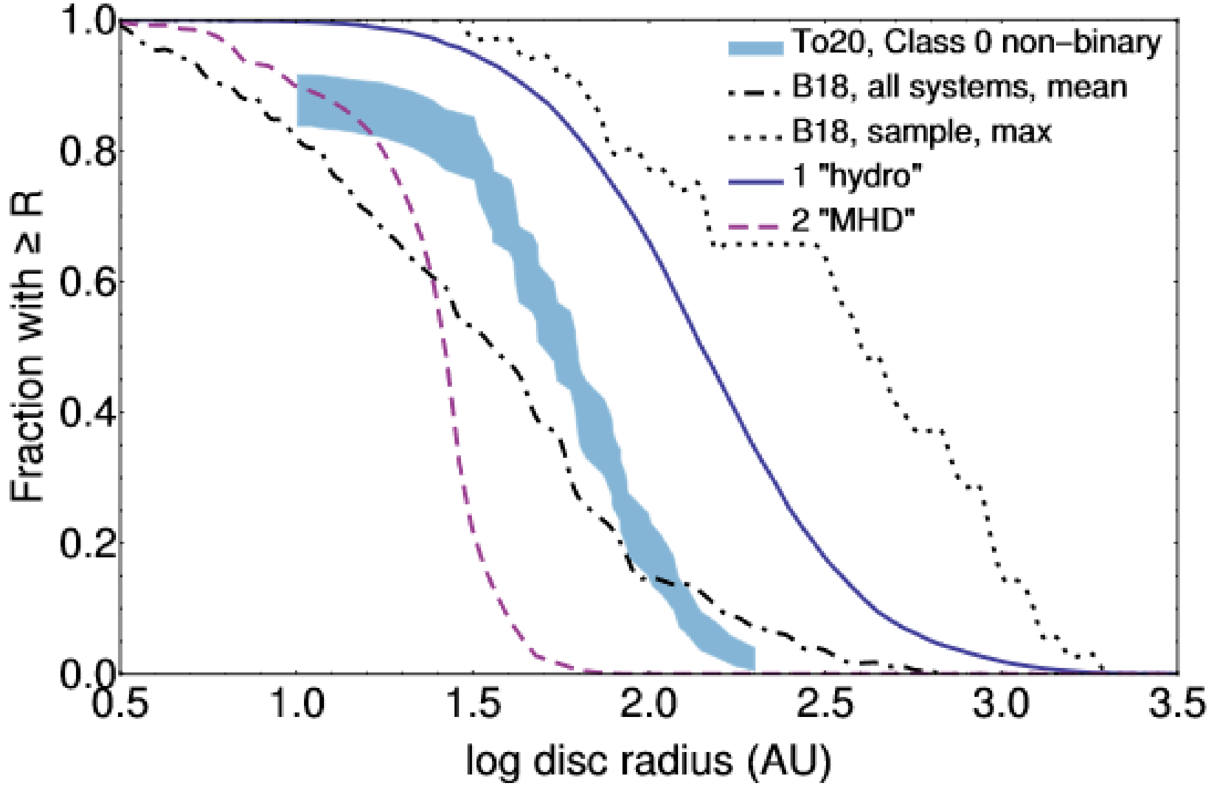




1805.08211

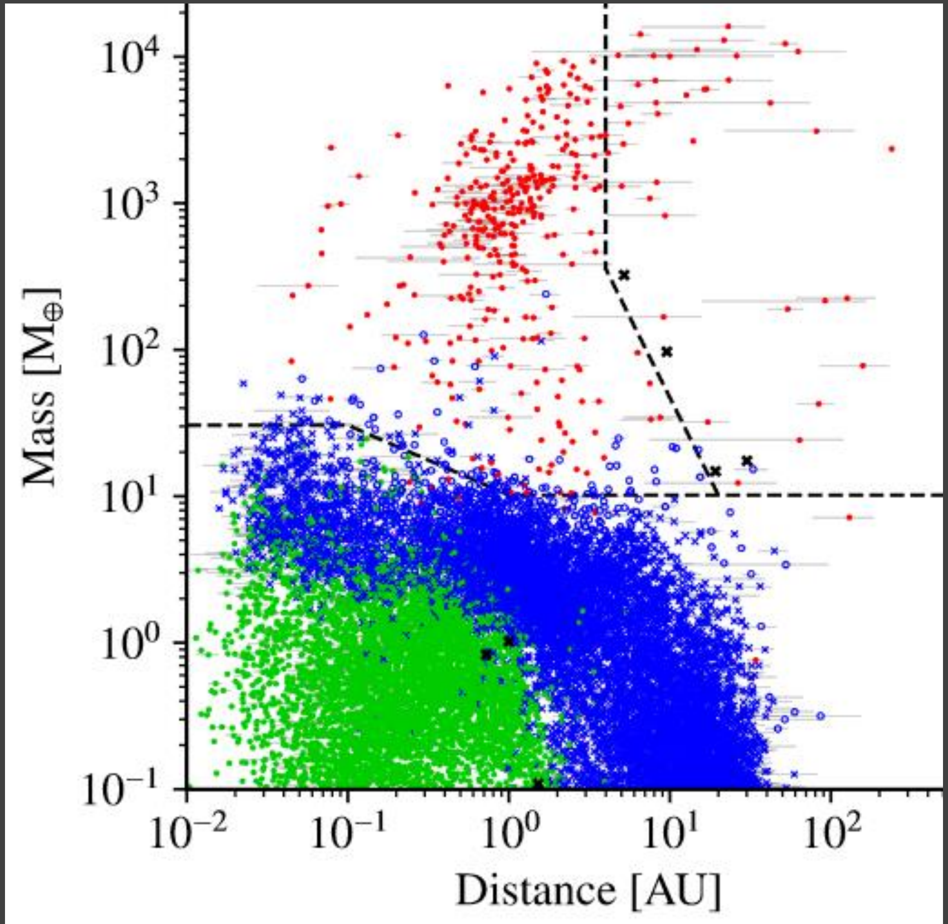
Population synthesis of protoplanetary discs

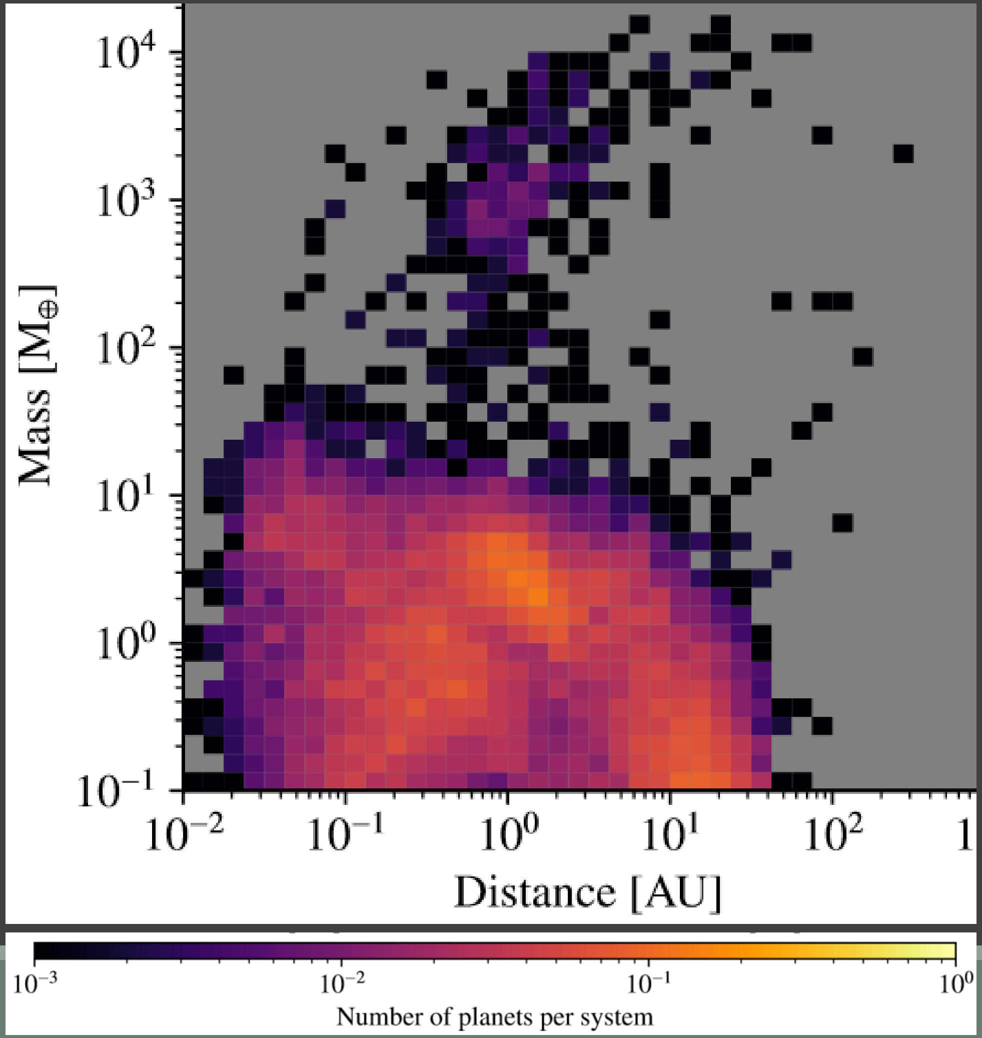




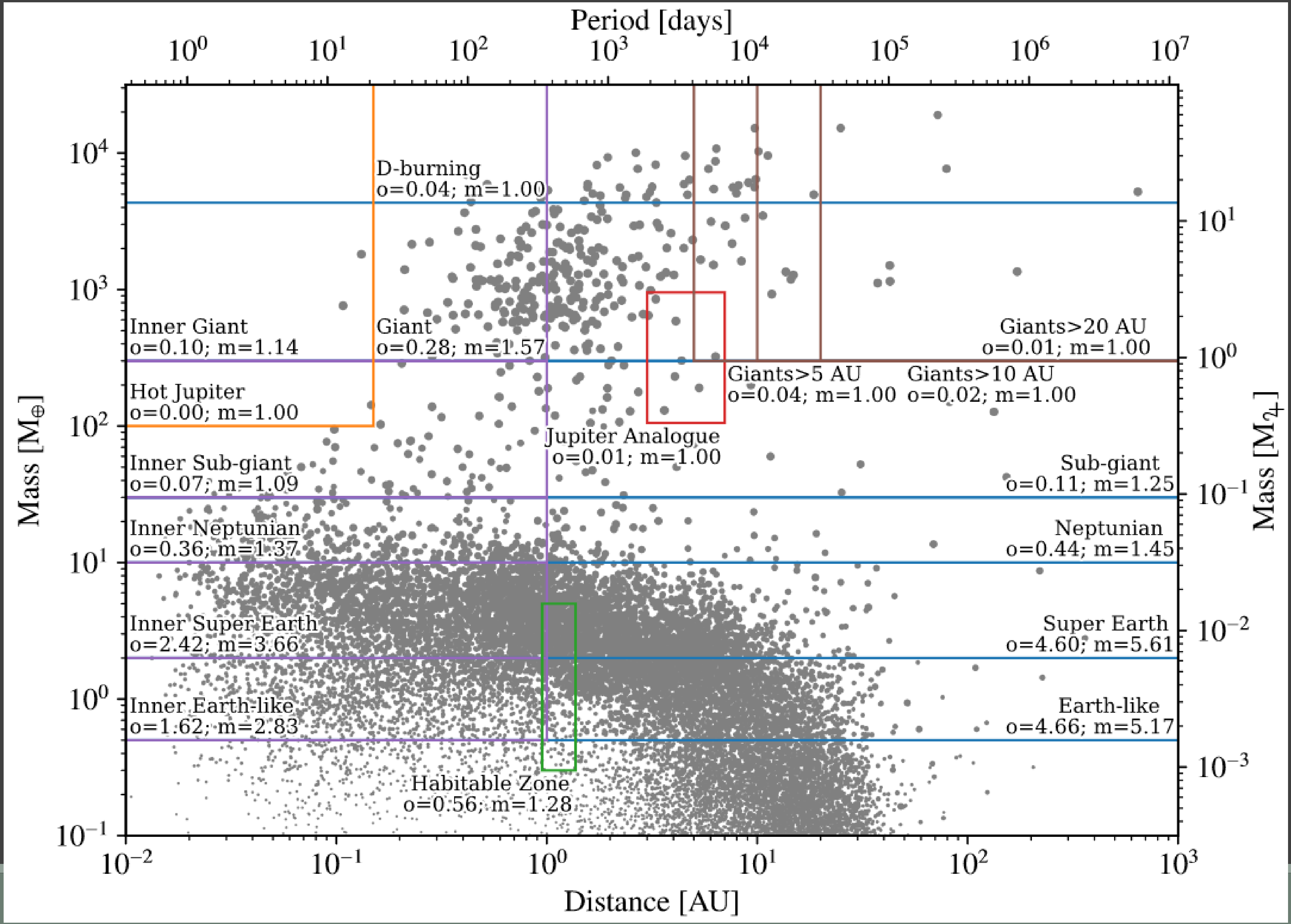
2011.05996

New population synthesis models





All at 5 Gyrs.


Period [days]
Distance [AU]
Mass [M⊕]
Mass [M♃]
D-burning
o=0.04; m=1.00
Inner Giant
o=0.10; m=1.14
Giant
o=0.28; m=1.57
Giants>20 AU
o=0.01; m=1.00
Hot Jupiter
o=0.00; m=1.00
Giants>5 AU
o=0.04; m=1.00
Giants>10 AU
o=0.02; m=1.00
Jupiter Analogue
o=0.01; m=1.00
Inner Sub-giant
o=0.07; m=1.09
Sub-giant
o=0.11; m=1.25
Inner Neptunian
o=0.36; m=1.37
Neptunian
o=0.44; m=1.45
Inner Super Earth
o=2.42; m=3.66
Super Earth
o=4.60; m=5.61
Inner Earth-like
o=1.62; m=2.83
Earth-like
o=4.66; m=5.17
Habitable Zone
o=0.56; m=1.28

2007.05562

Literature

- 1402.7086 Planet Population Synthesis. W. Benz et al.
- 1804.01532 Planetary population synthesis. C. Mordasini
- 2007.05561-3 New Mordasini et al. synthesis