

Planet formation and population synthesis

Yann ALIBERT



European Research Council



- A. Fortier
- F. Carron
- C. Mordasini
- W. Benz
- L. Fouchet
- S. Pfyffer
- N. Cabral
- H. Meheut
- K. Dittkrist

Planet formation

Planet formation

Planet formation

NGC2264

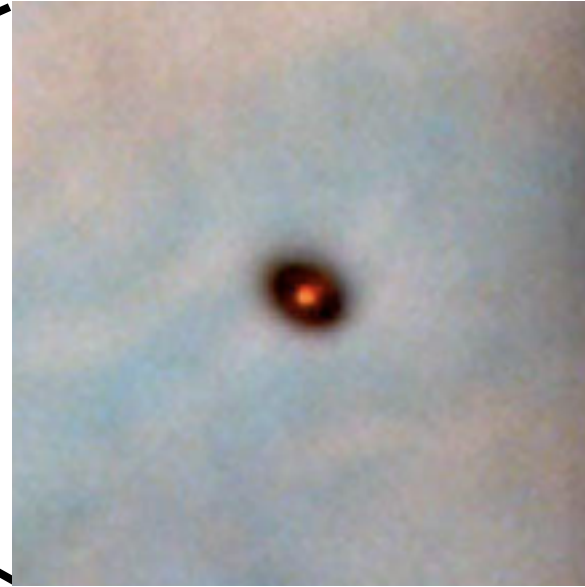
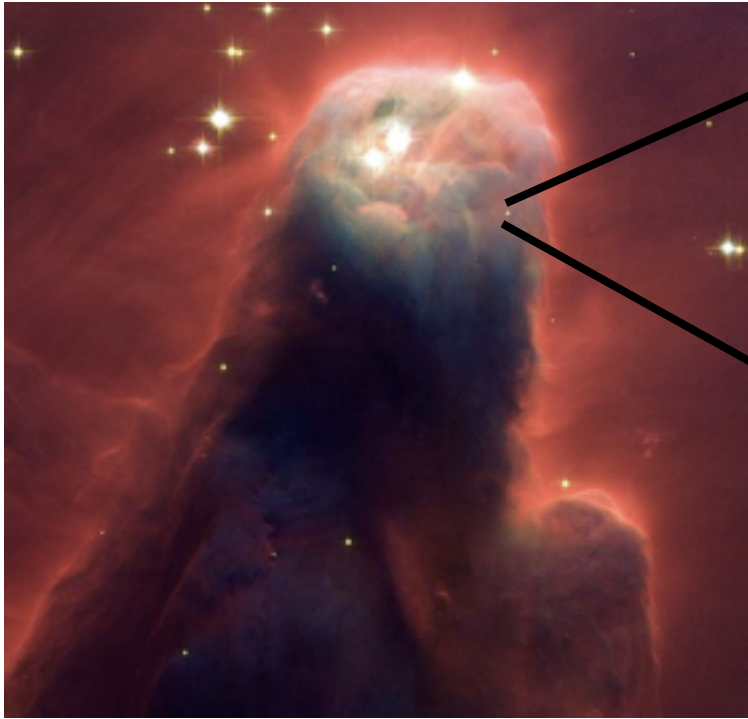
2.5 Light years ~ 160000 AU



Planet formation

NGC2264

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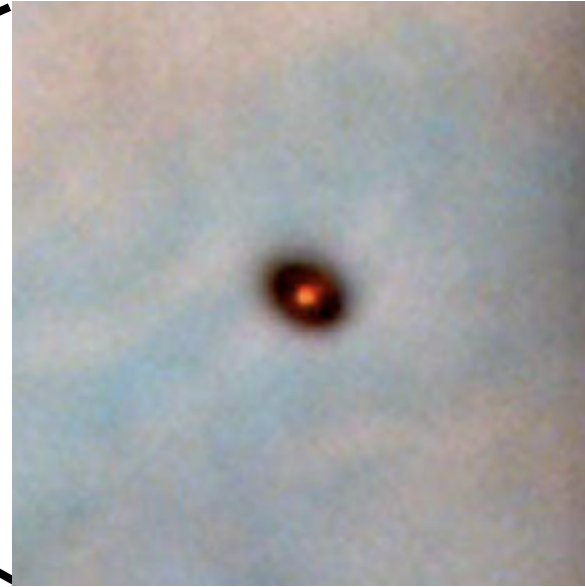
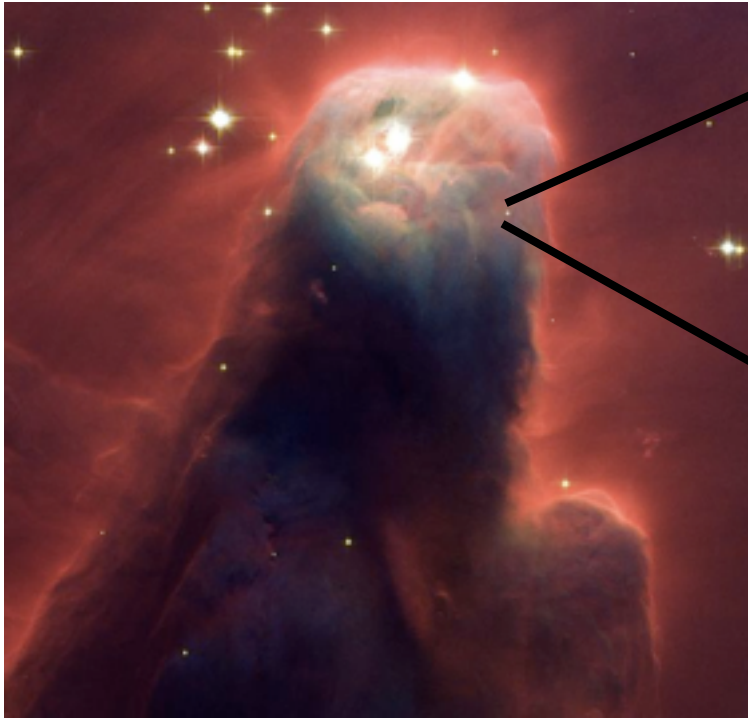


~ 100s AU

Planet formation

NGC2264

2.5 Light years ~ 160000 AU



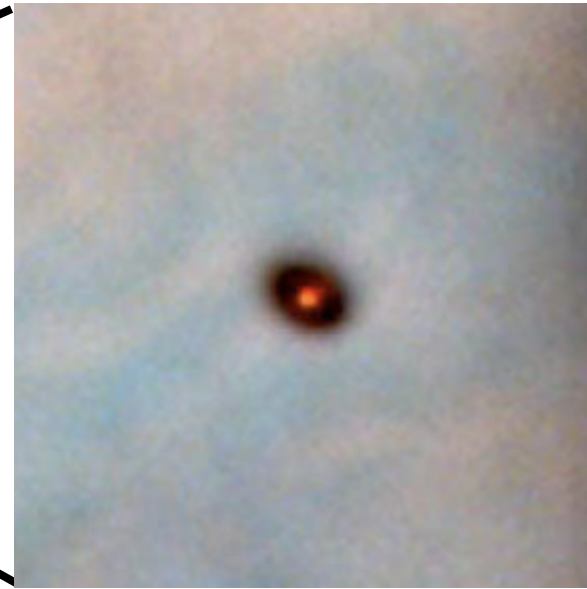
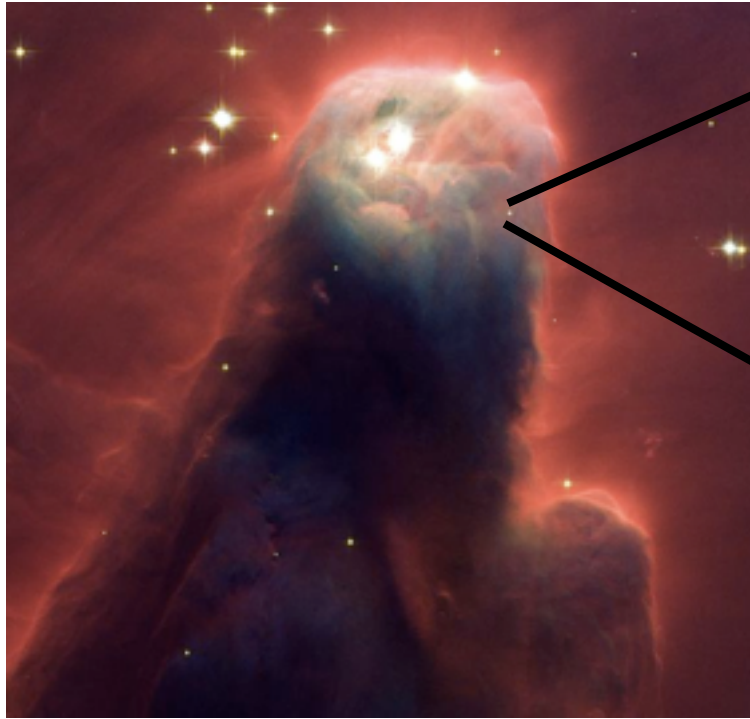
~100s AU



Planet formation

NGC2264

2.5 Light years ~ 160000 AU



~100s AU

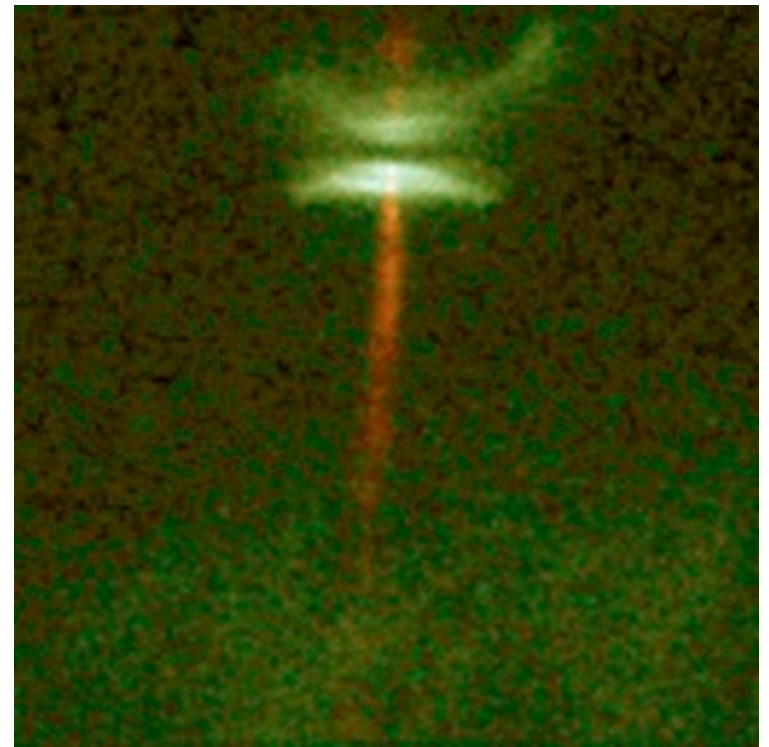
⇓ Model



Protoplanetary disks: observations



Protoplanetary disks in the Orion Nebula; HST



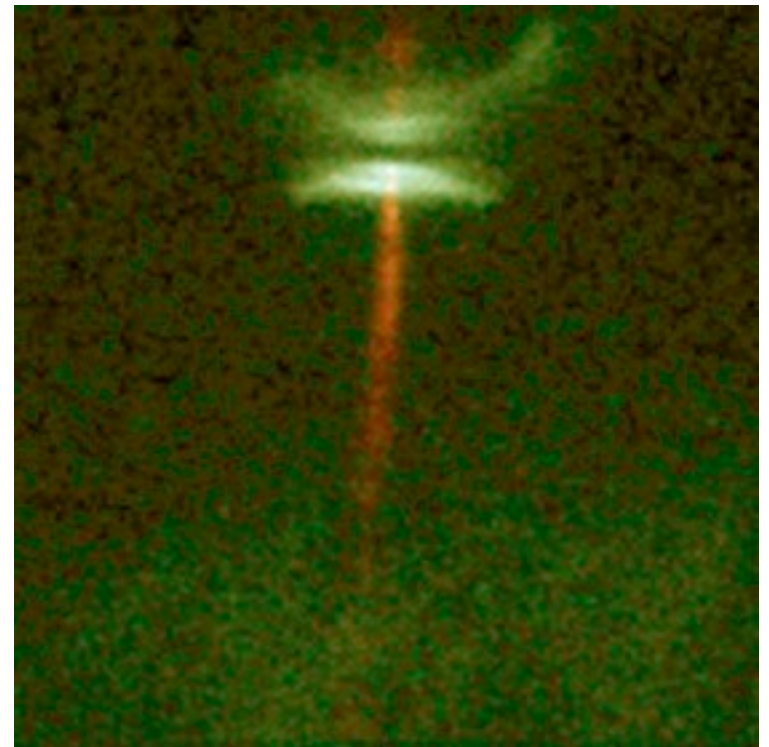
HH-30; Burrows et al.; NASA

Protoplanetary disks: observations

Giant planets form by accreting gas from protoplanetary disks



Protoplanetary disks in the Orion Nebula; HST



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Protoplanetary disks: observations

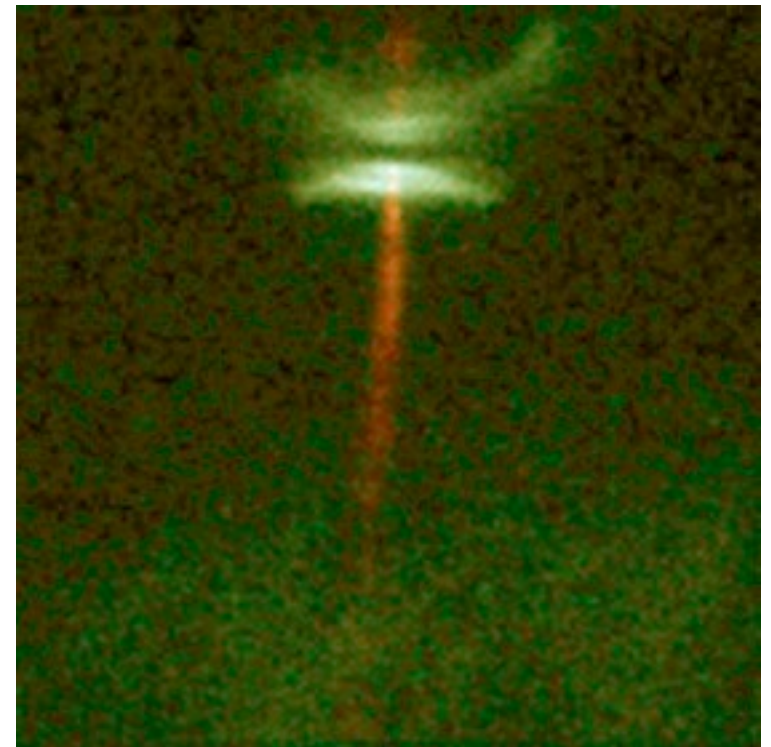
Giant planets form by accreting gas from protoplanetary disks

⇒ disks lifetime gives maximum formation time

Giant planets must form in < 10 Myr



Protoplanetary disks in the Orion Nebula; HST



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Protoplanetary disks: observations

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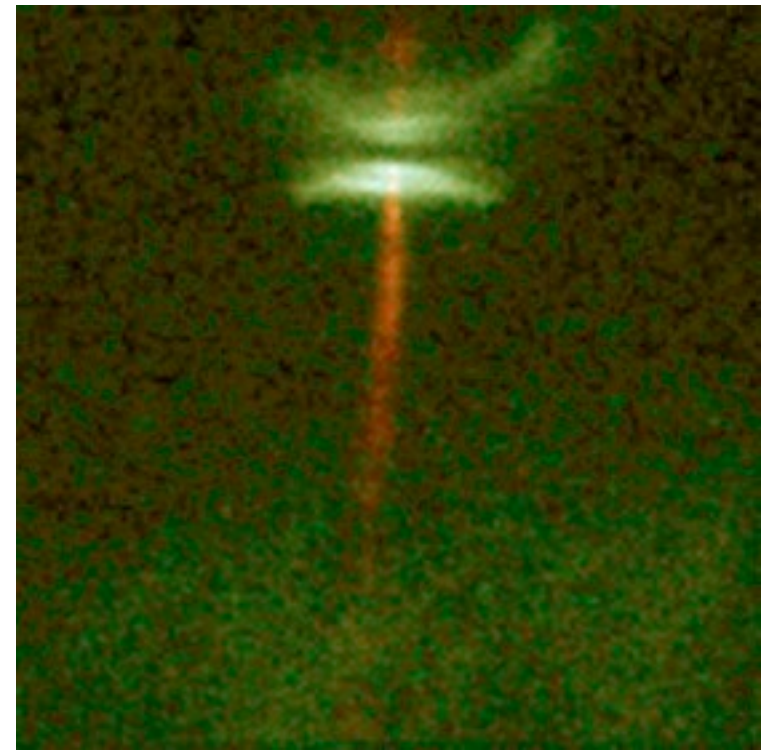
Giant planets must form in < 10 Myr

⇒ disks mass and gas-to-solids ratio give available material

Typical mass from 0.001 to $0.1 M_{\text{sun}}$

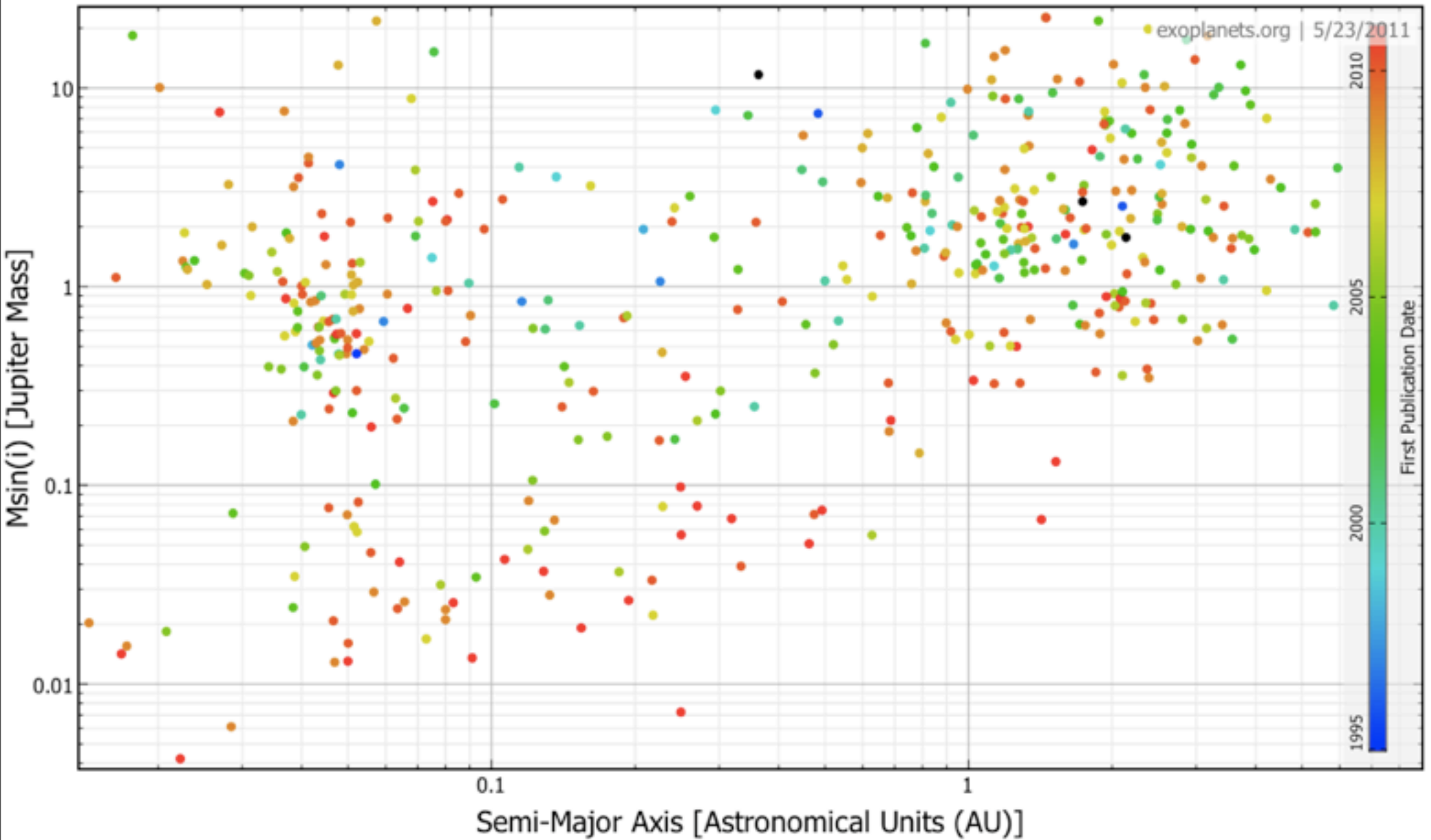


Protoplanetary disks in the Orion Nebula; HST

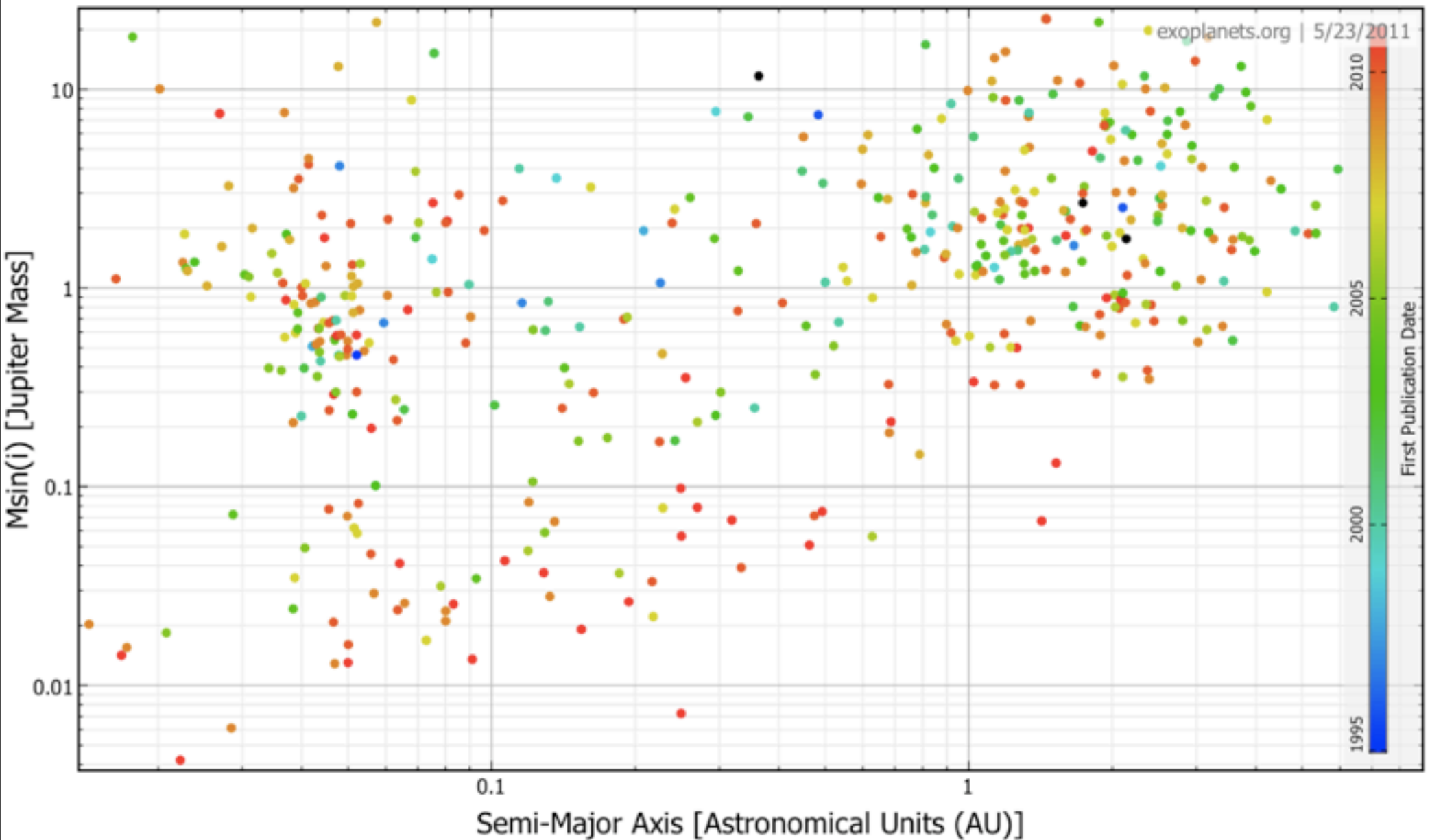


HH-30; Burrows et al.; NASA

Extrasolar planets: observations



Extrasolar planets: observations



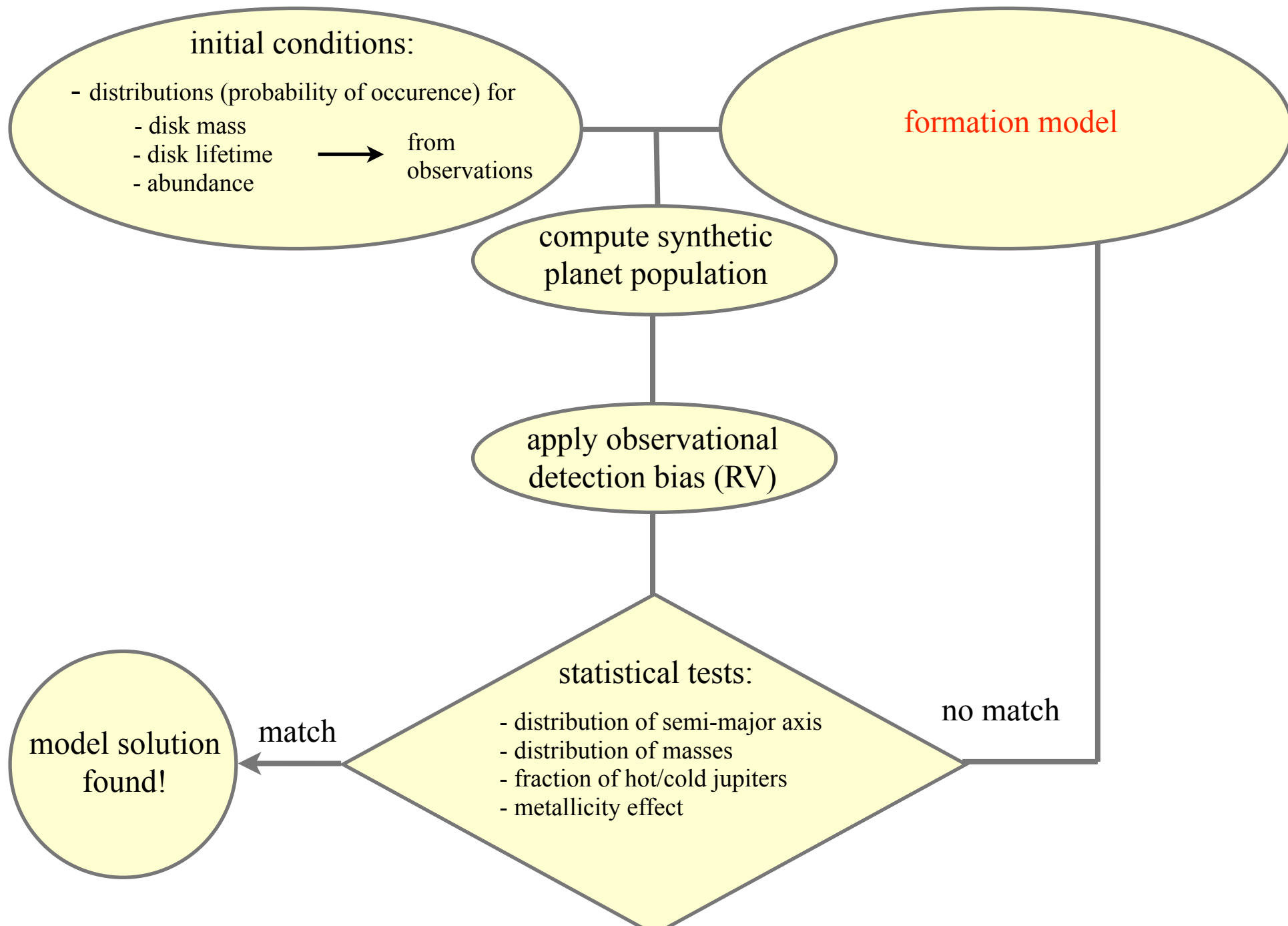
not considered as single objects, but as a population

Extrasolar planets

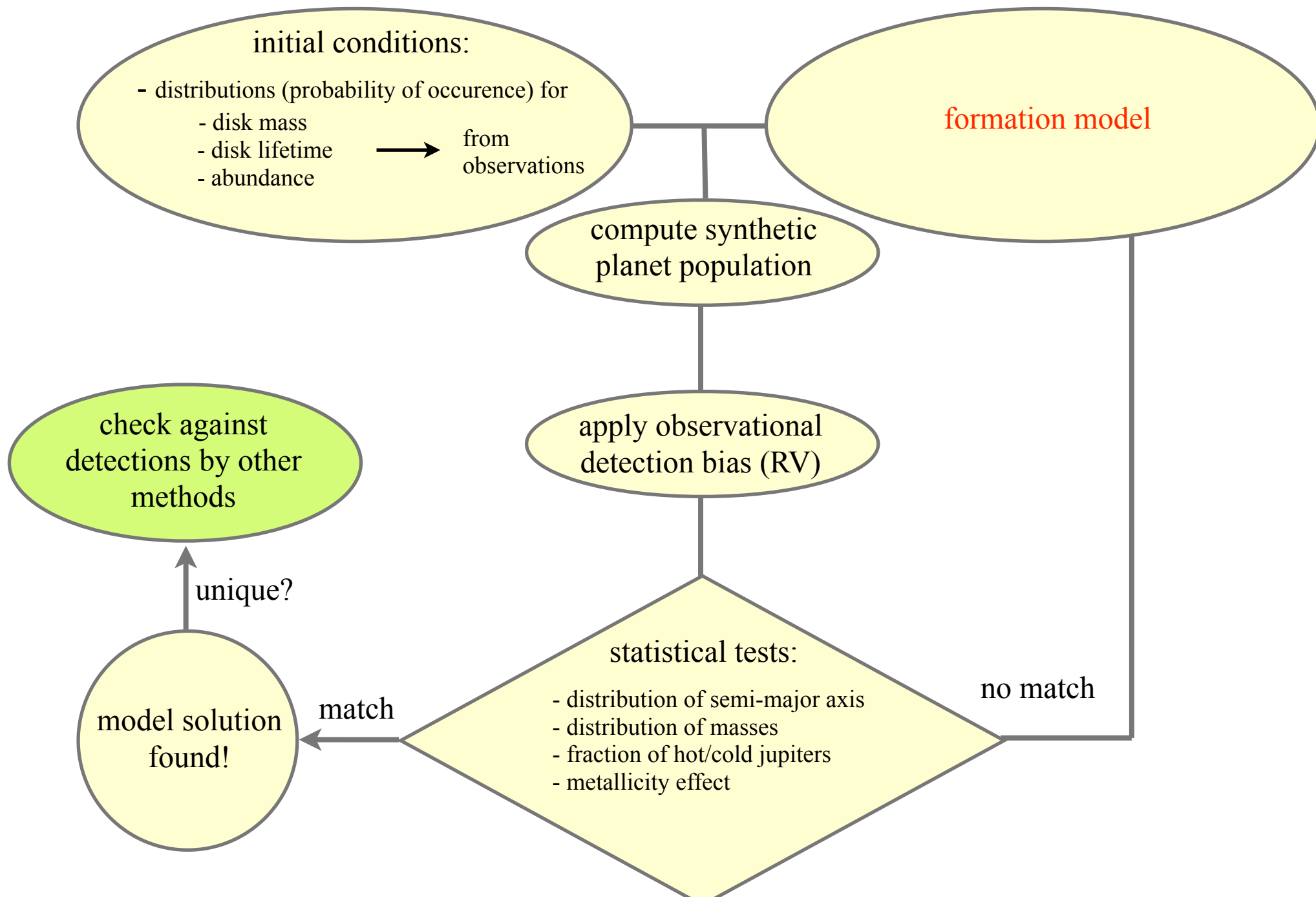
- Huge diversity resulting from different ICs?
 - Protoplanetary disk
 - Metallicity
 - Environement
- To explain the observations, need to take into account
 - 1) the ICs, with the correct probability laws
 - 2) the observational biases (RV - microlensing - transit)

⇒ Population synthesis

Extra-solar planet population synthesis



Extra-solar planet population synthesis

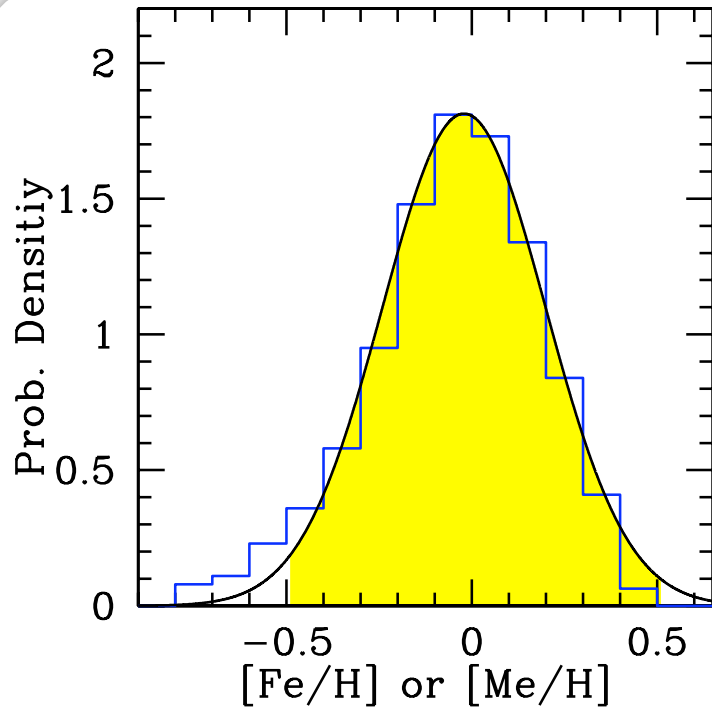


Population synthesis: initial conditions

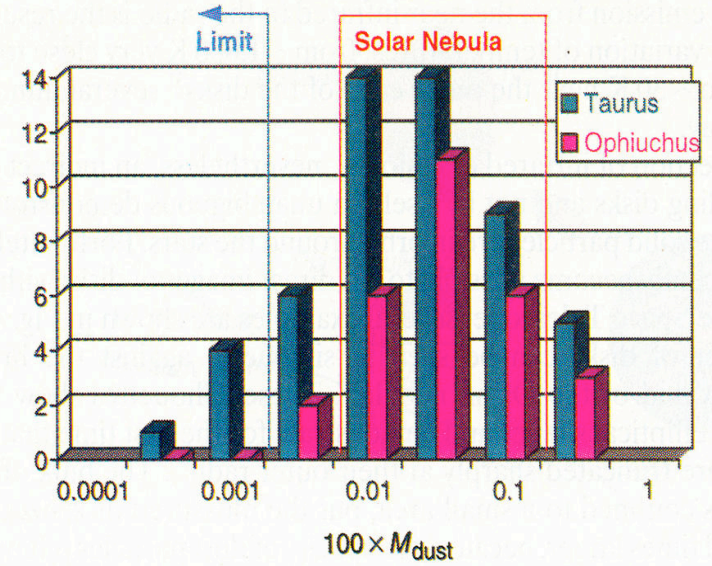
CORALIE survey



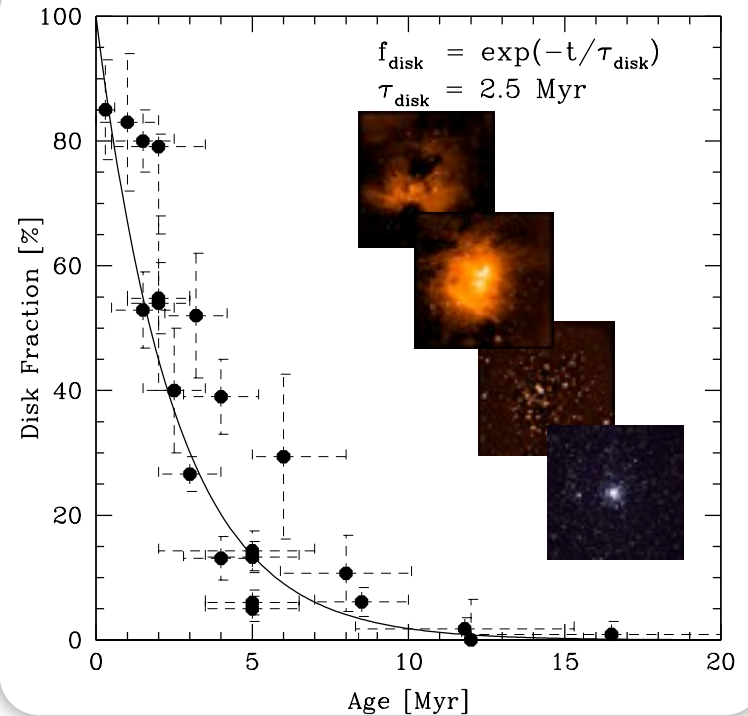
gaussian
repartition



Santos et al. 2003

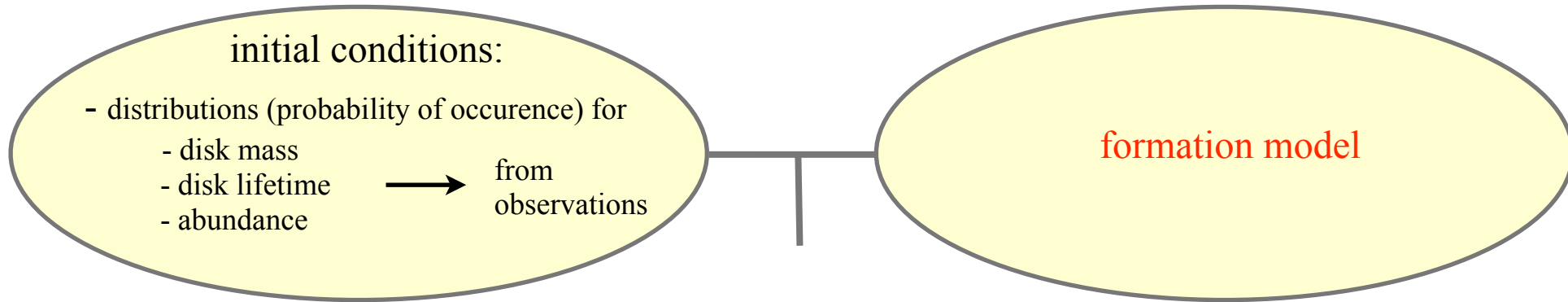


Beckwith & Sargent

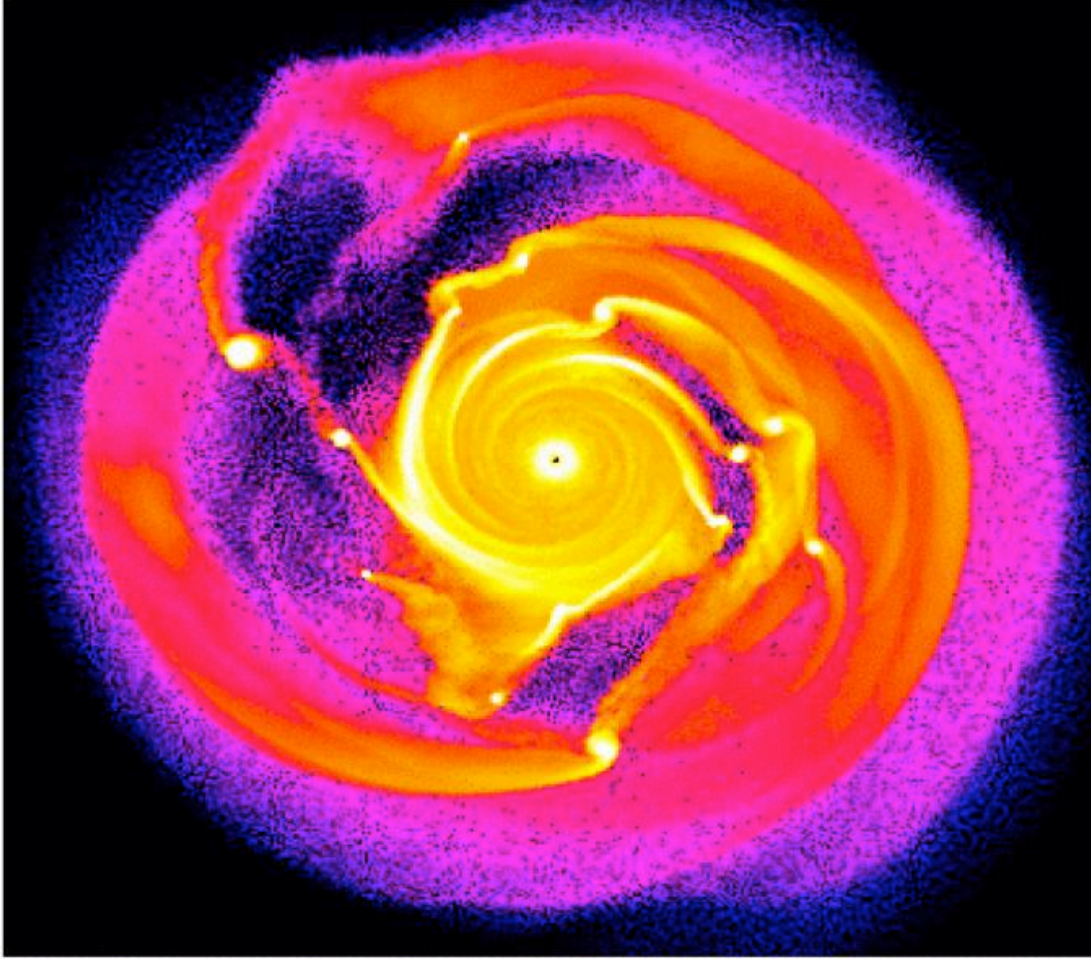


Mamajek 2009

Extra-solar planet population synthesis

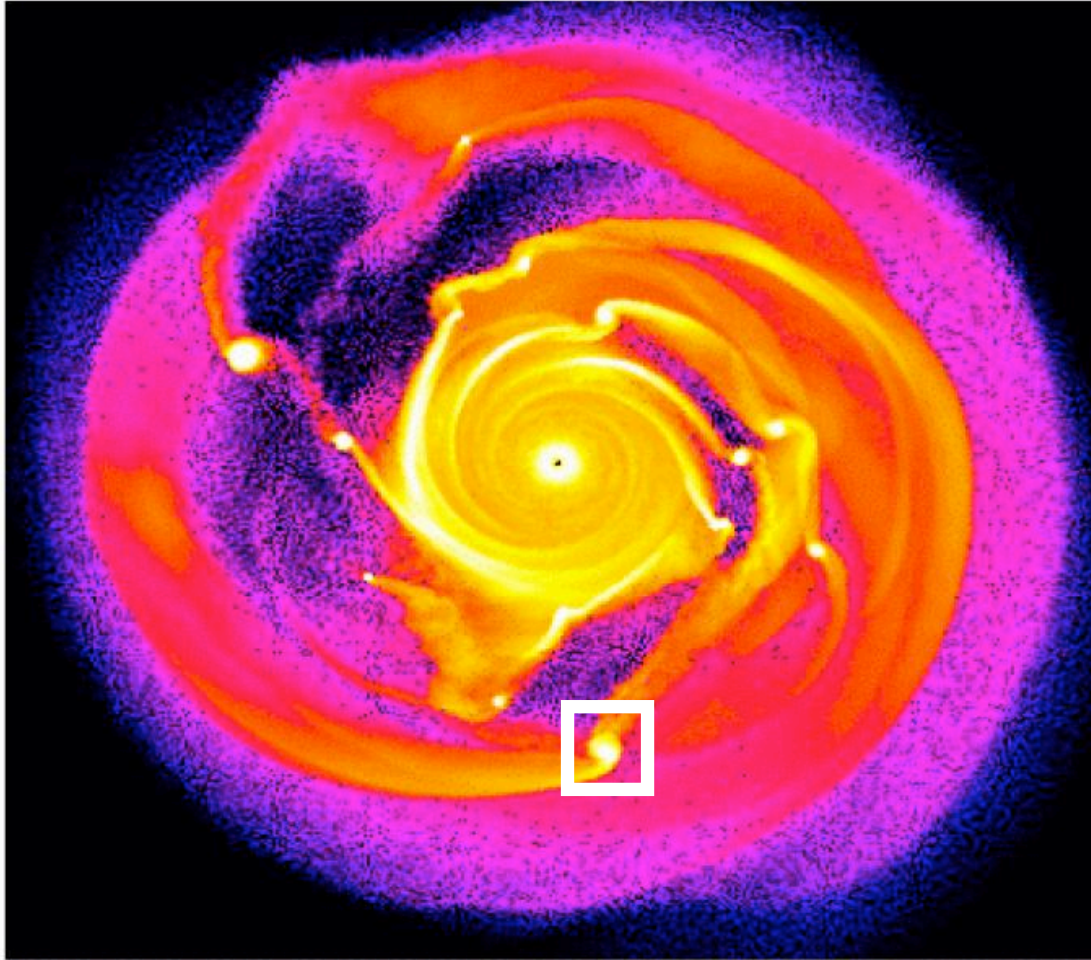


The disk instability model



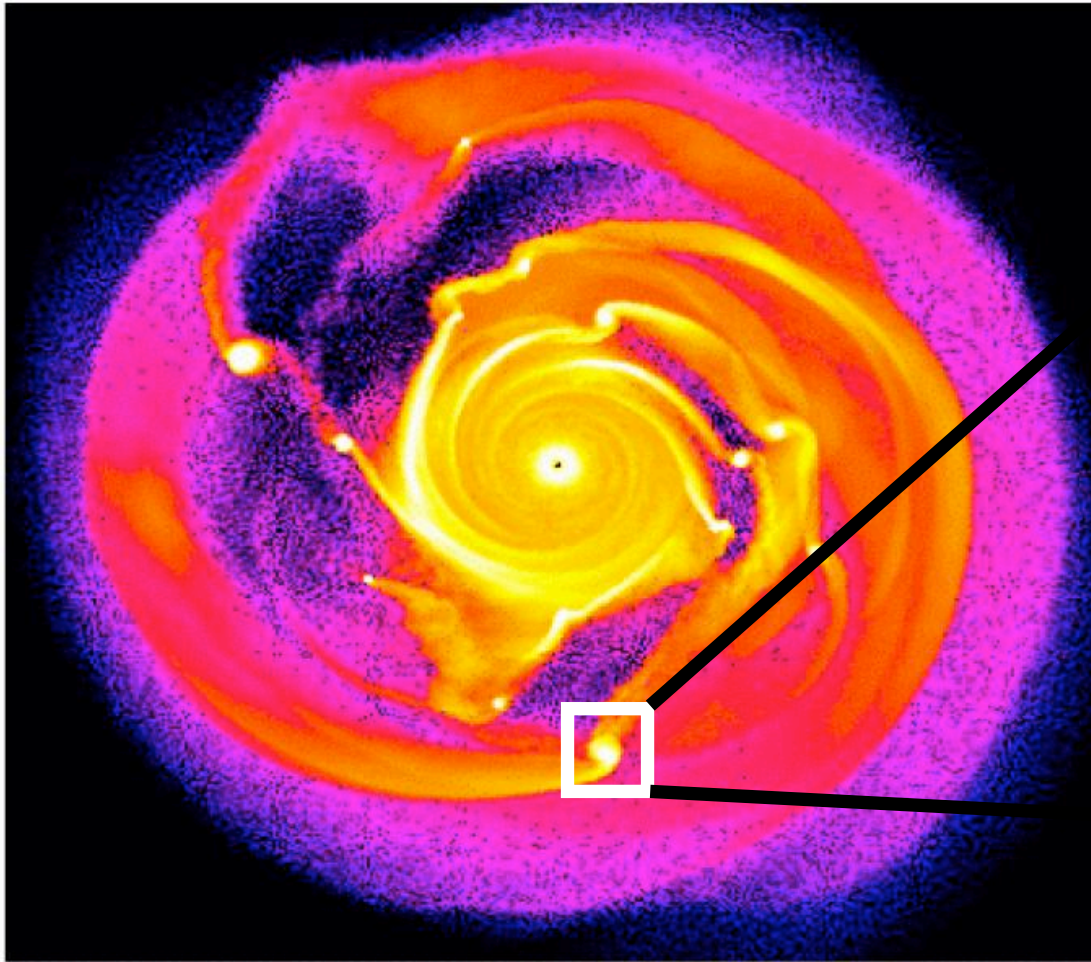
Mayer et al. 2004

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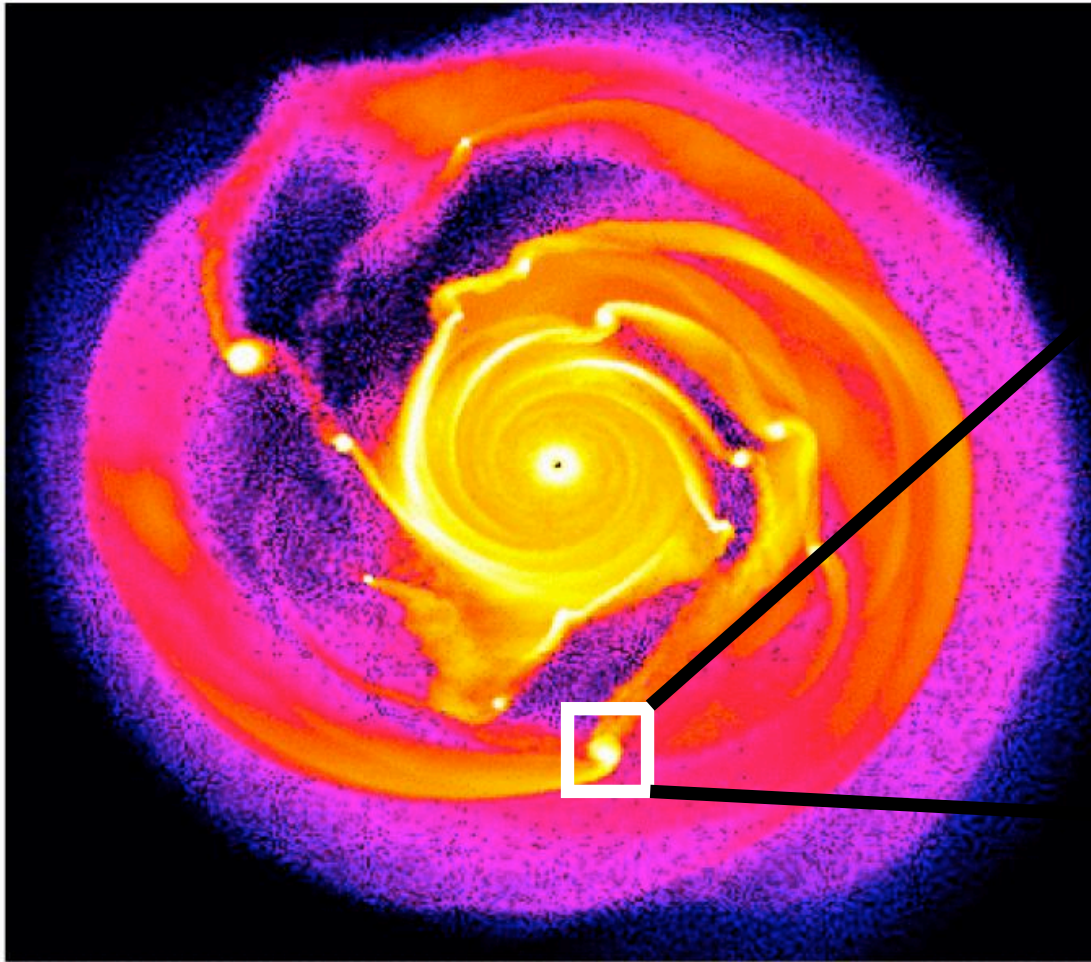
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The disk instability model



Mayer et al. 2004

The disk instability model



Mayer et al. 2004

Clump formation depends critically on disk cooling

⇒ formation of massive planets

⇒ formation in outer parts of the disk

Origin of enrichment in heavy elements?

The nucleated instability model (2)



The nucleated instability model (2)



gas giant

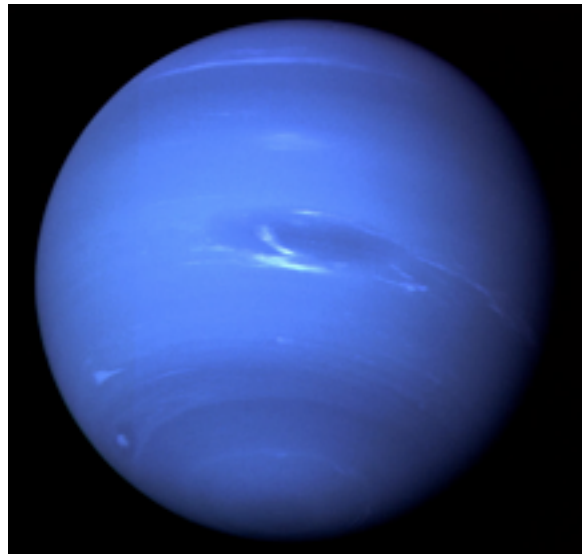


The nucleated instability model (2)



gas giant

ice giant



The nucleated instability model (2)



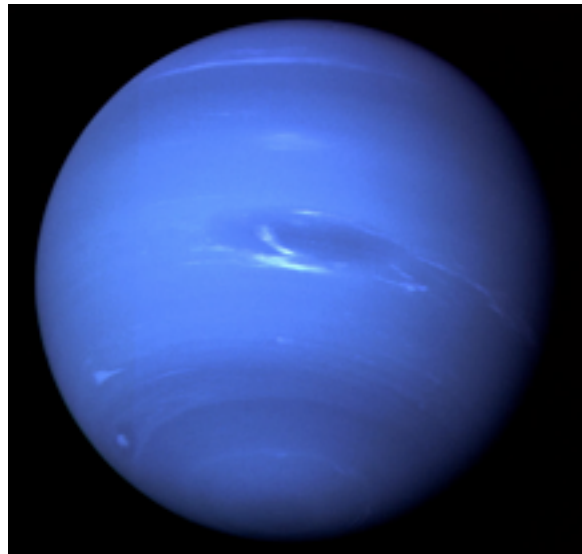
terrestrial planet



gas giant



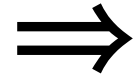
ice giant



Planet formation model



Planet formation model



I - Take an “observed” disk

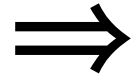
Planet formation model



1- Take an “observed” disk

2- Assume planet embryos exist somewhere

Planet formation model



1- Take an “observed” disk

2- Assume planet embryos exist somewhere

3- Calculate mass growth (solids and/or gas)

Planet's internal structure

In situ formation of Jupiter at 5.2 AU

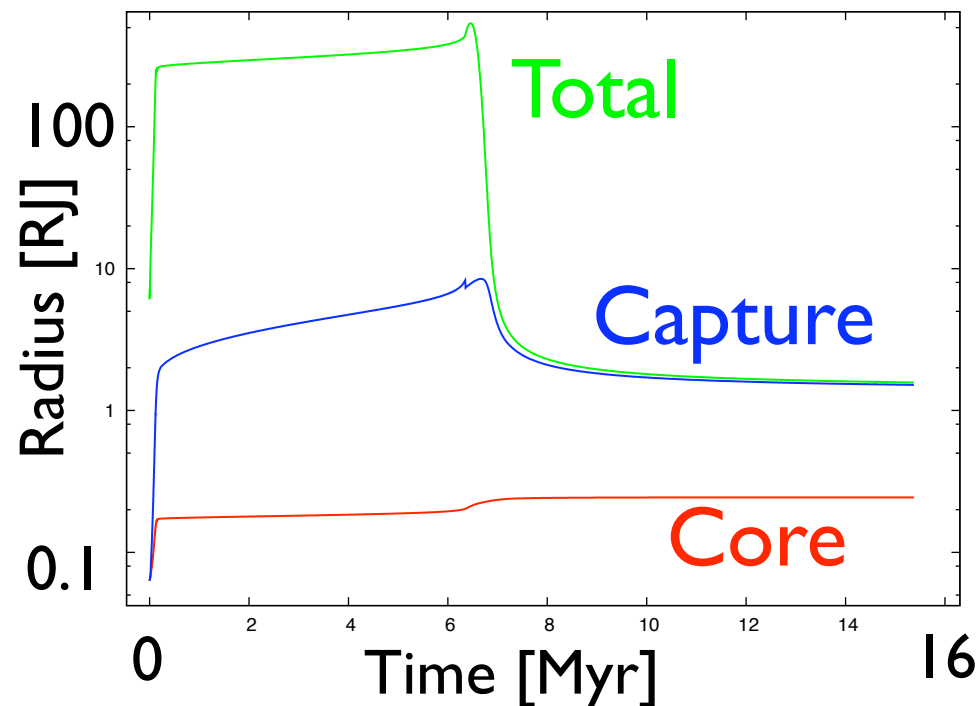
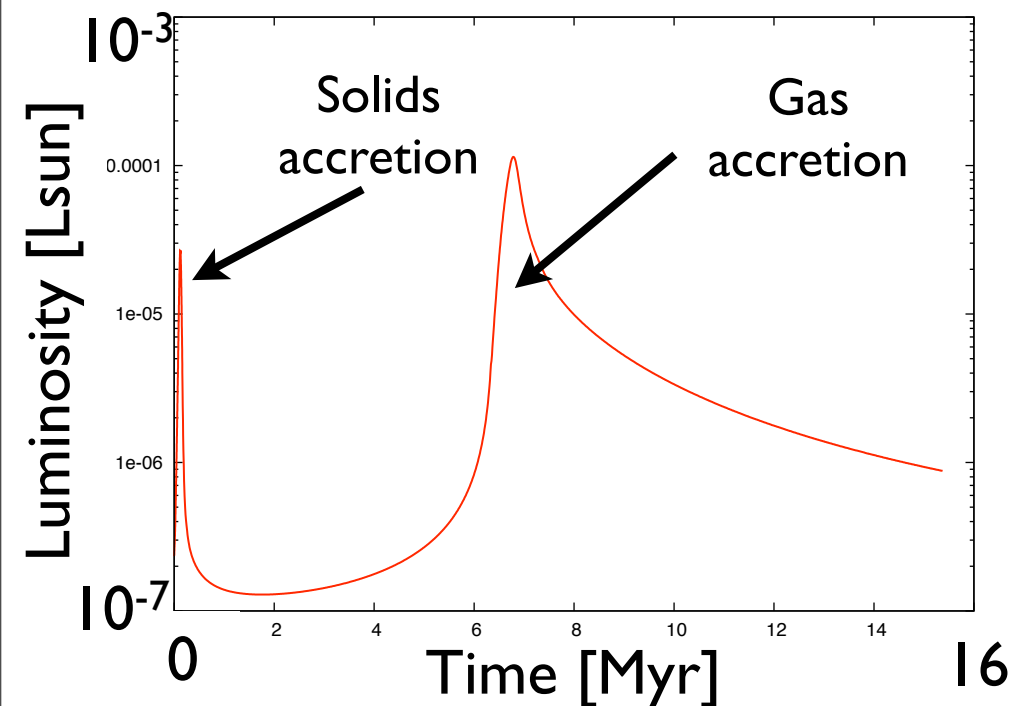
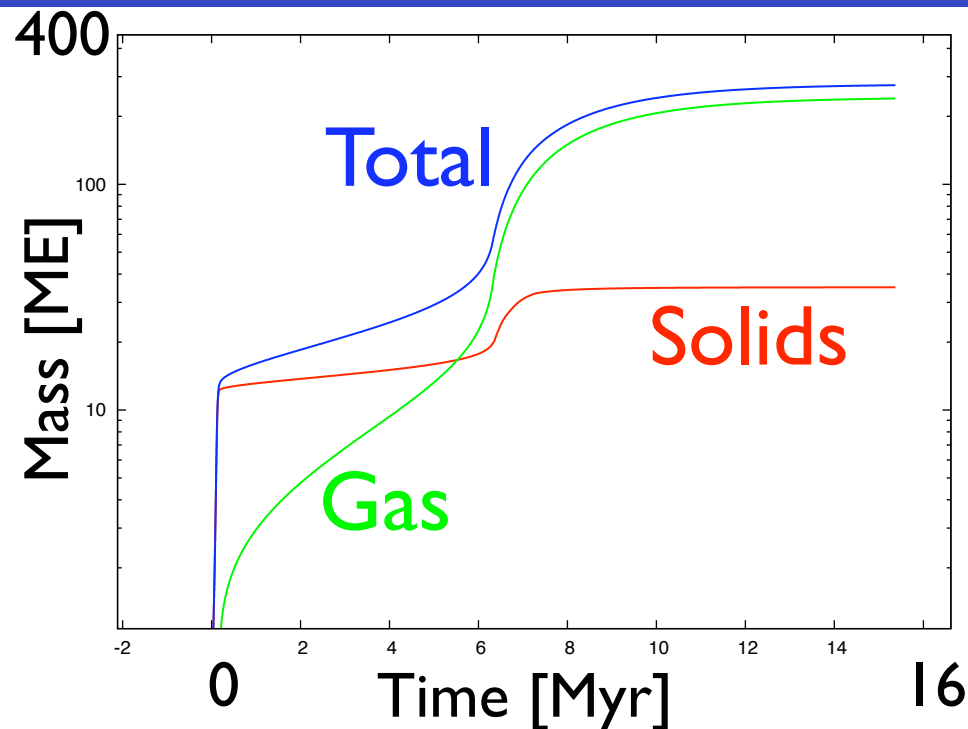
$$\Sigma_{\text{solids}} = 10 \text{g/cm}^2 @ 5.2 \text{AU}$$

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

only viscosity

Planet in contact
with disk

Planet isolated



Planet's internal structure

In situ formation of Jupiter at 5.2 AU

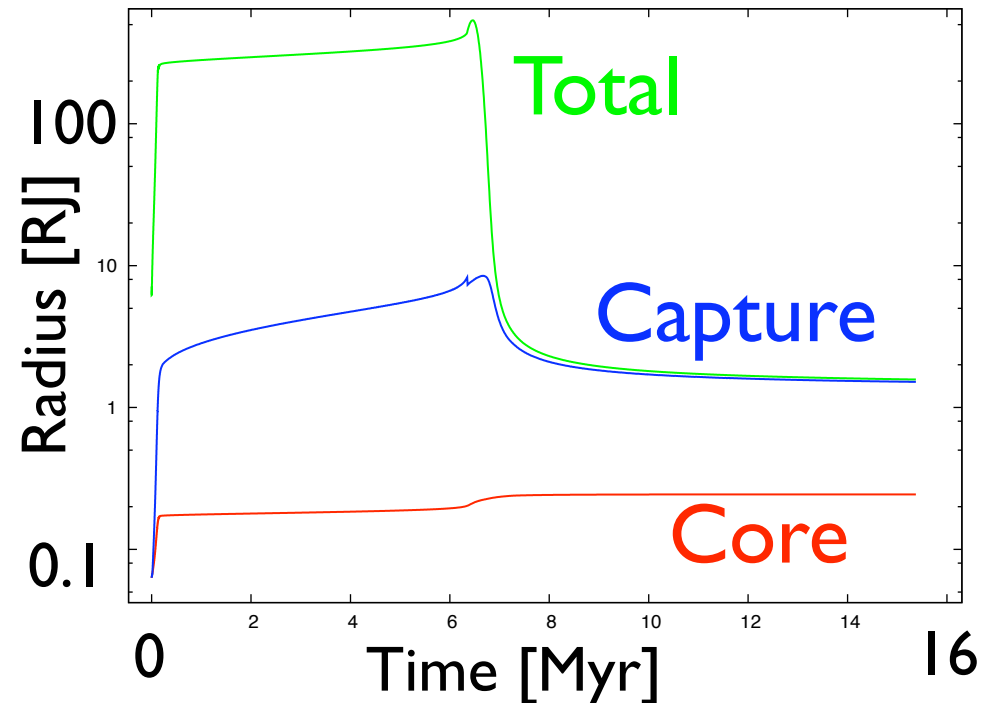
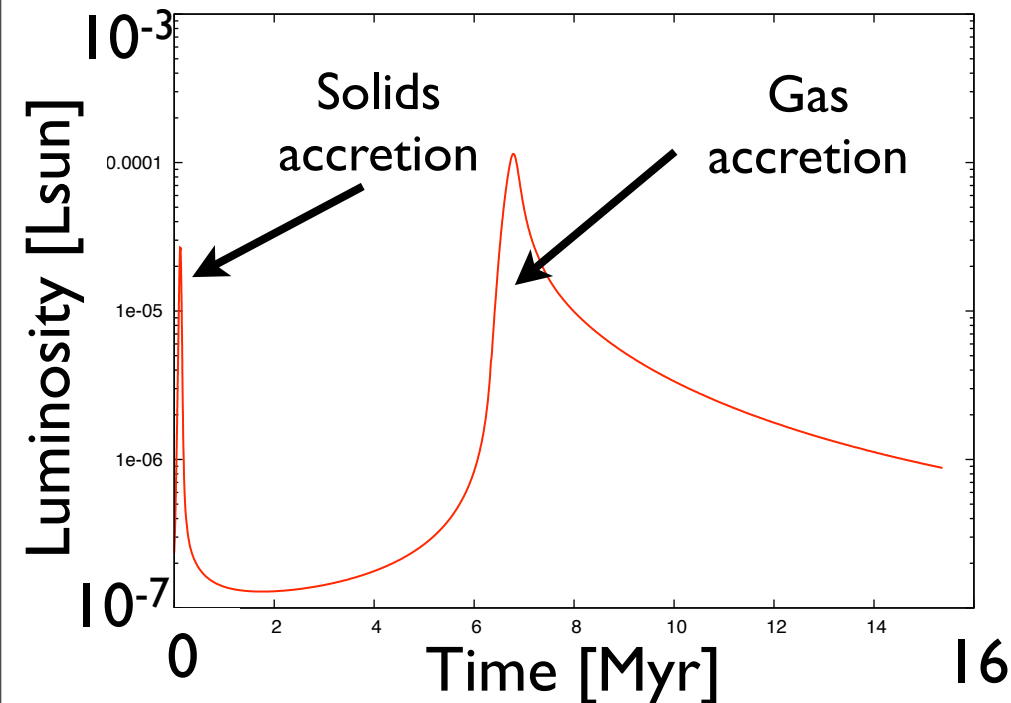
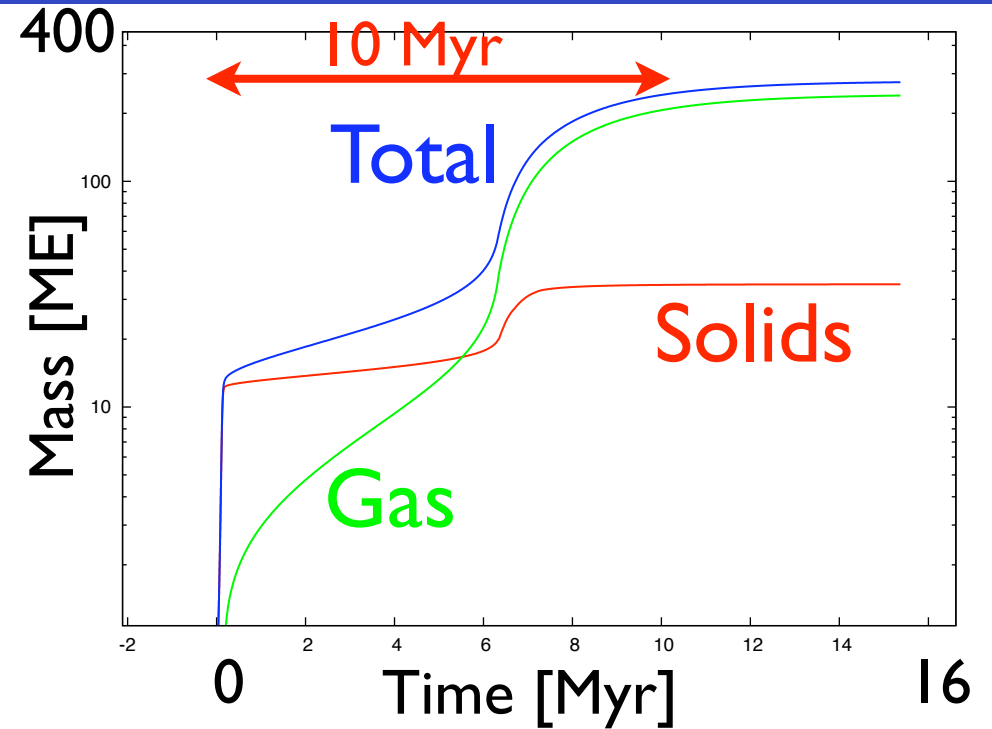
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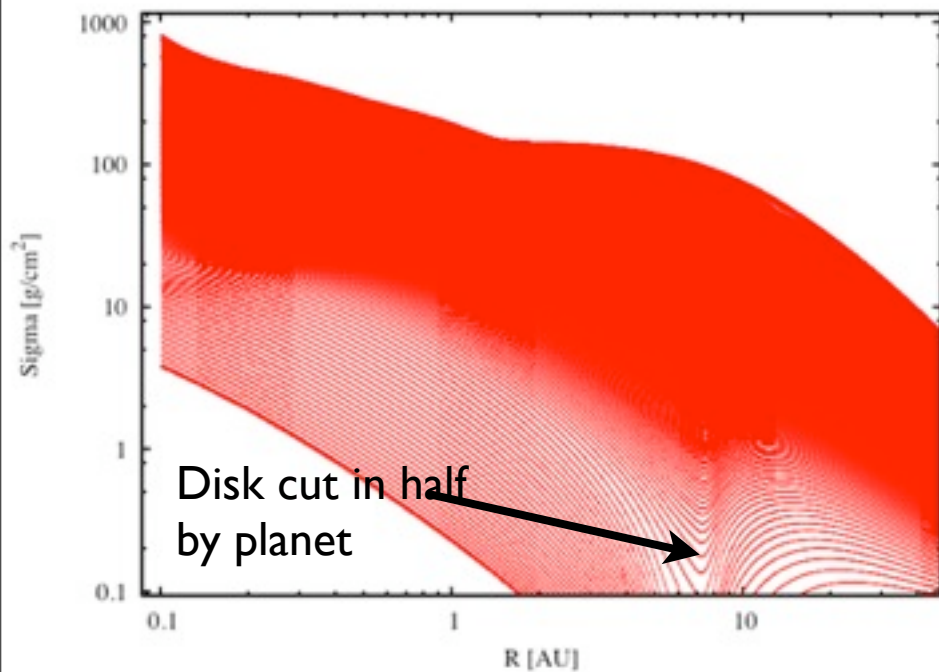
Planet in contact
with disk

Planet isolated



Disk model

Gas surface density



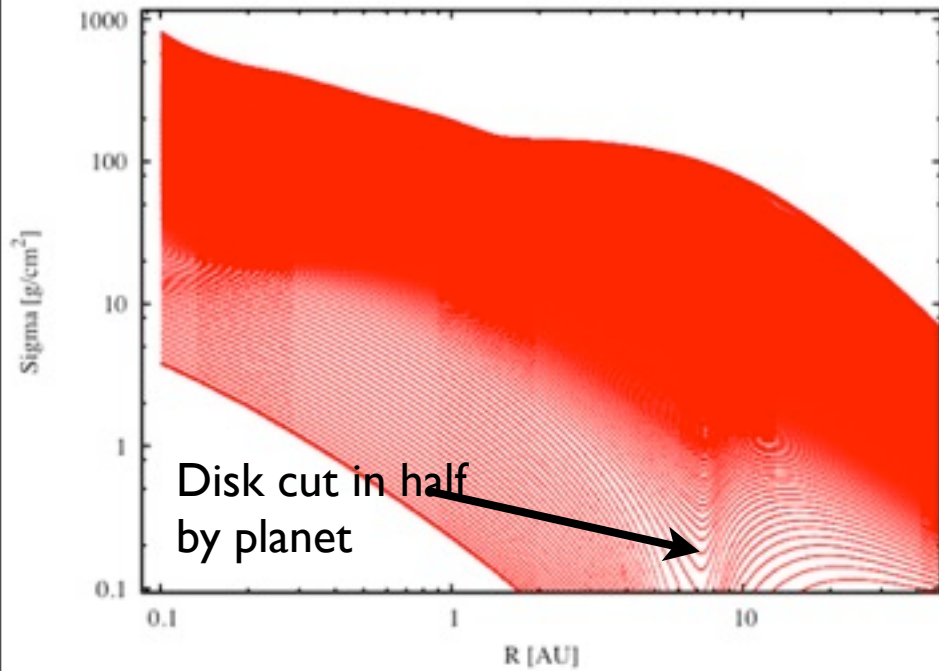
$$\frac{d\Sigma}{dt} = \frac{3}{r} \frac{\partial}{\partial r} \left[r^{1/2} \frac{\partial}{\partial r} \tilde{\nu} \Sigma r^{1/2} \right] + \dot{\Sigma}_w(r) + \dot{Q}_{\text{planet}}(r)$$

Viscosity, photoevaporation, planet accretion

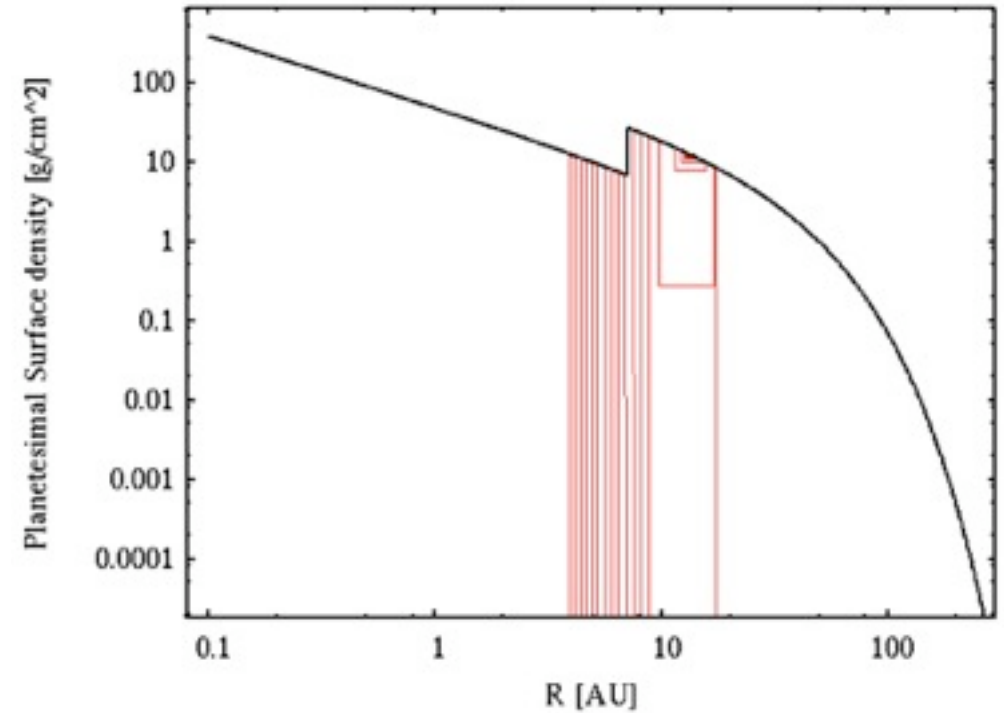
$$\Sigma_0 = 880 \text{ g/cm}^2 \text{ (ca 4 - 5 x MMSN)}$$
$$\alpha = 7 \times 10^{-3} \quad \dot{M}_{\text{wind}} = 2.3 \times 10^{-8} M_{\odot}/\text{yr}$$

Disk model

Gas surface density



Planetesimal surface density



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

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-Initial profile

$$\Sigma_D(r, t = 0) = f_{D/G} f_{R/I} \Sigma(r, t = 0)$$

-Dust/gas ratio

$$\frac{f_{D/G}}{f_{D/G,\odot}} = 10^{[\text{Fe}/\text{H}]}$$

Planetesimal disk evolution only by accretion onto the planet and ejection by the planet

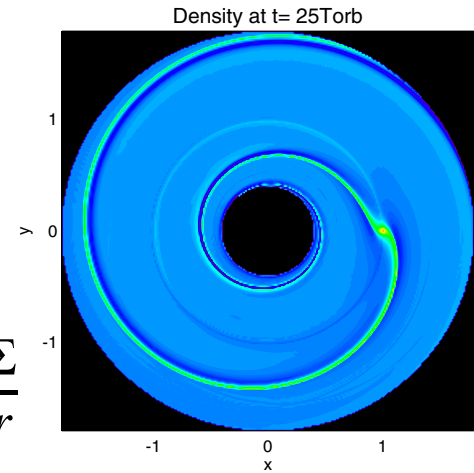
Gas driven migration

Low mass planets (no gap, $M < \text{ca. } 100 M_{\text{earth}}$): Type I

$$\frac{da_{\text{planet}}}{dt} = -2f_{\text{I}} a_{\text{planet}} \frac{\Gamma}{L_{\text{planet}}} \quad L_{\text{planet}} \equiv M_{\text{planet}} (GM_* a_{\text{planet}})^{1/2}$$

$$\Gamma = (1.364 + 0.541\alpha_{\Sigma,P}) \left(\frac{M_{\text{planet}}}{M_*} \frac{r_P \Omega_p}{C_{s,P}} \right)^2 \Sigma_P r_P^4 \Omega_p^2 \quad \alpha_{\Sigma} \equiv \frac{d \log \Sigma}{d \log r}$$

Tanaka et al. 2002



Baruteau & Masset. 2008

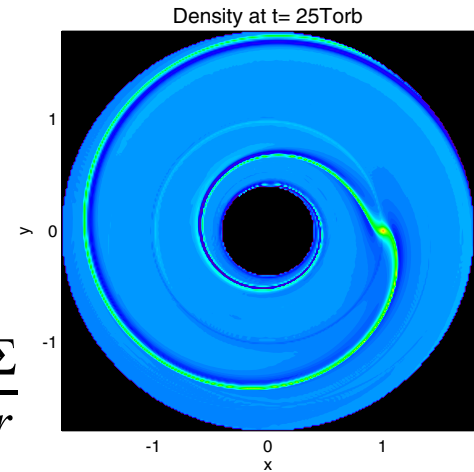
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Tanaka et al. 2002



Baruteau & Masset. 2008

Giant planets (with gap): Type II

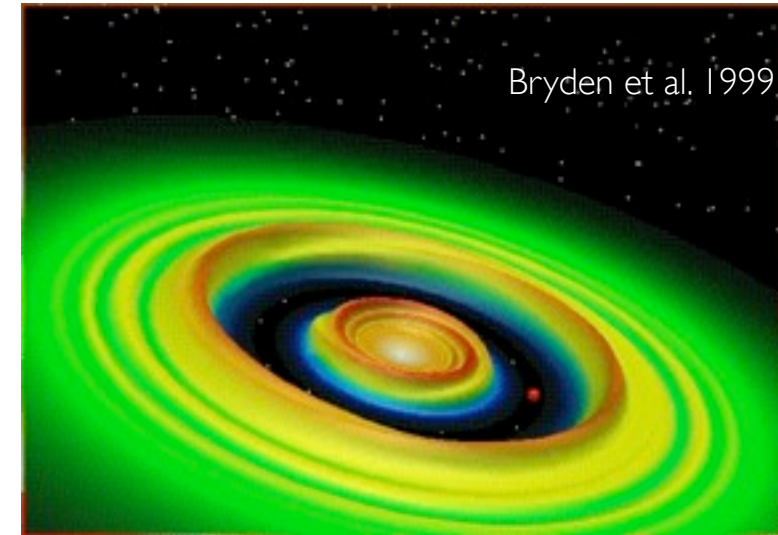
- Disk dominated $M_p < 2 \Sigma a^2$

$$\frac{da_{planet}}{dt} = v_{r,gas}$$

- Planet dominated $M_p > 2 \Sigma a^2$

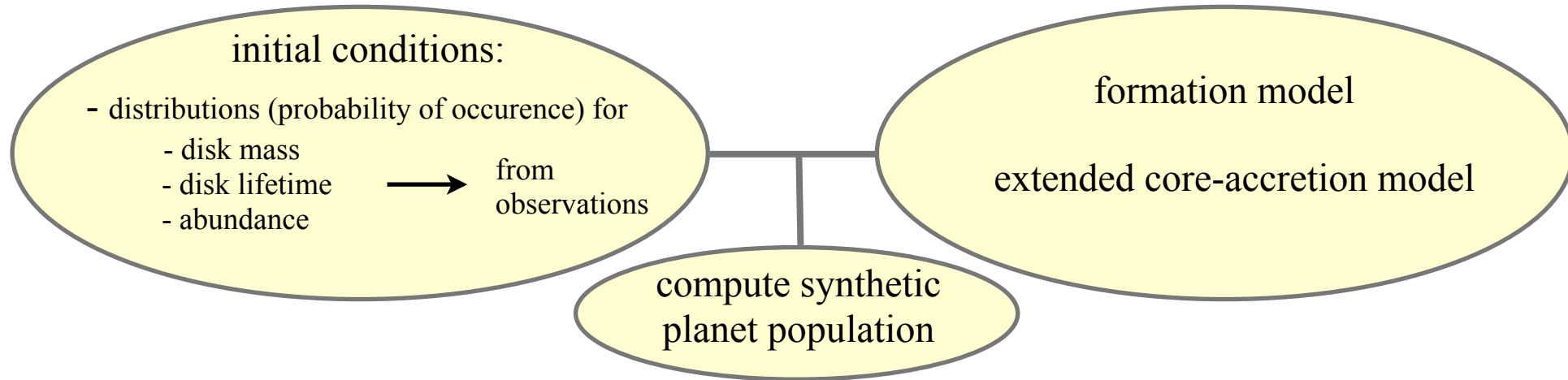
$$\frac{da_{planet}}{dt} = \left(\frac{2 \Sigma a^2}{M_{planet}} \right)^{k_p} v_{r,gas} \quad k_p = \begin{cases} 1 & \text{"fully suppressed"} \\ 1/2 & \text{"partially suppressed"} \end{cases}$$

Slow-down



Bryden et al. 1999

Extra-solar planet population synthesis

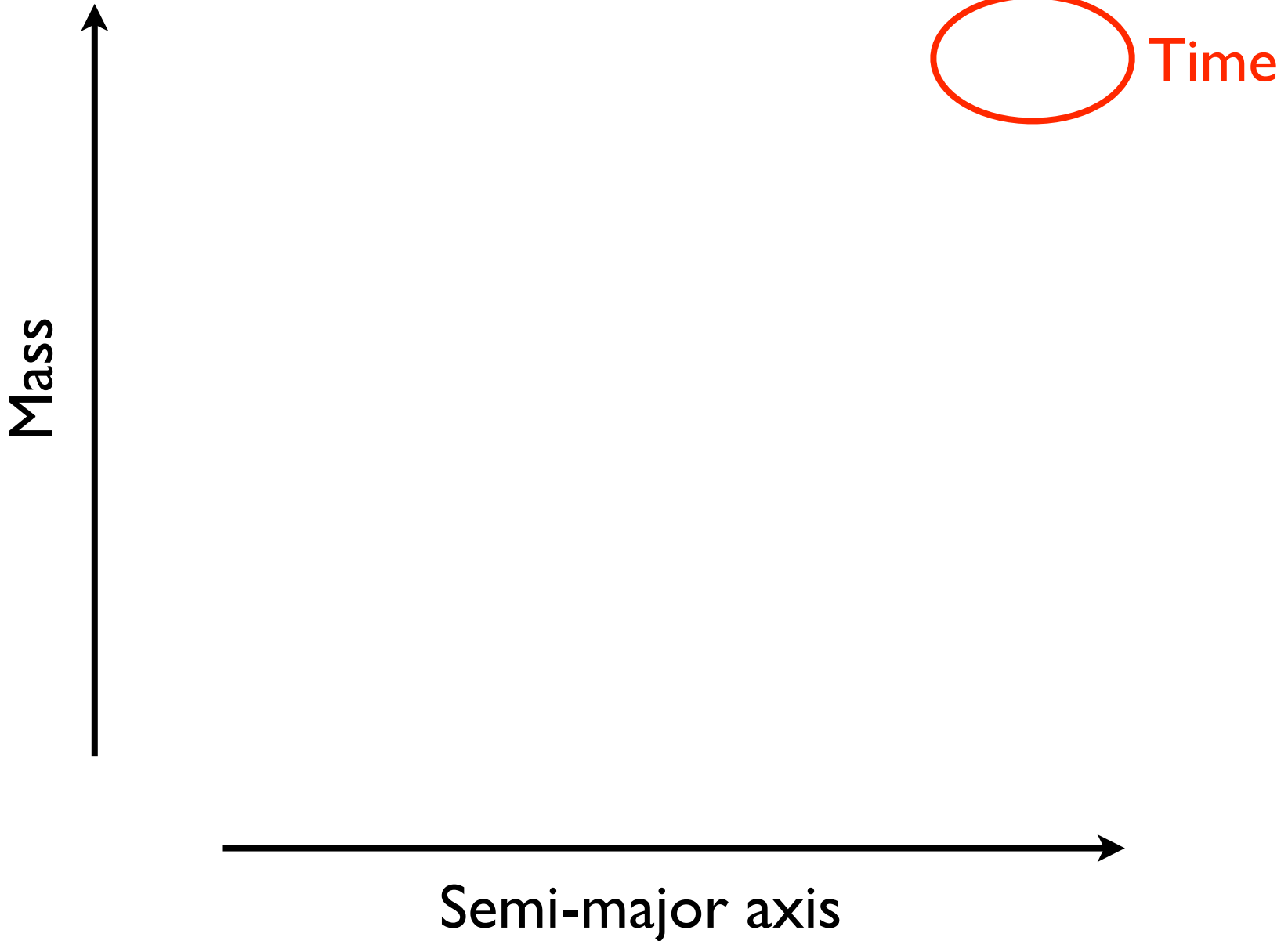


Evolutionary tracks: the full population

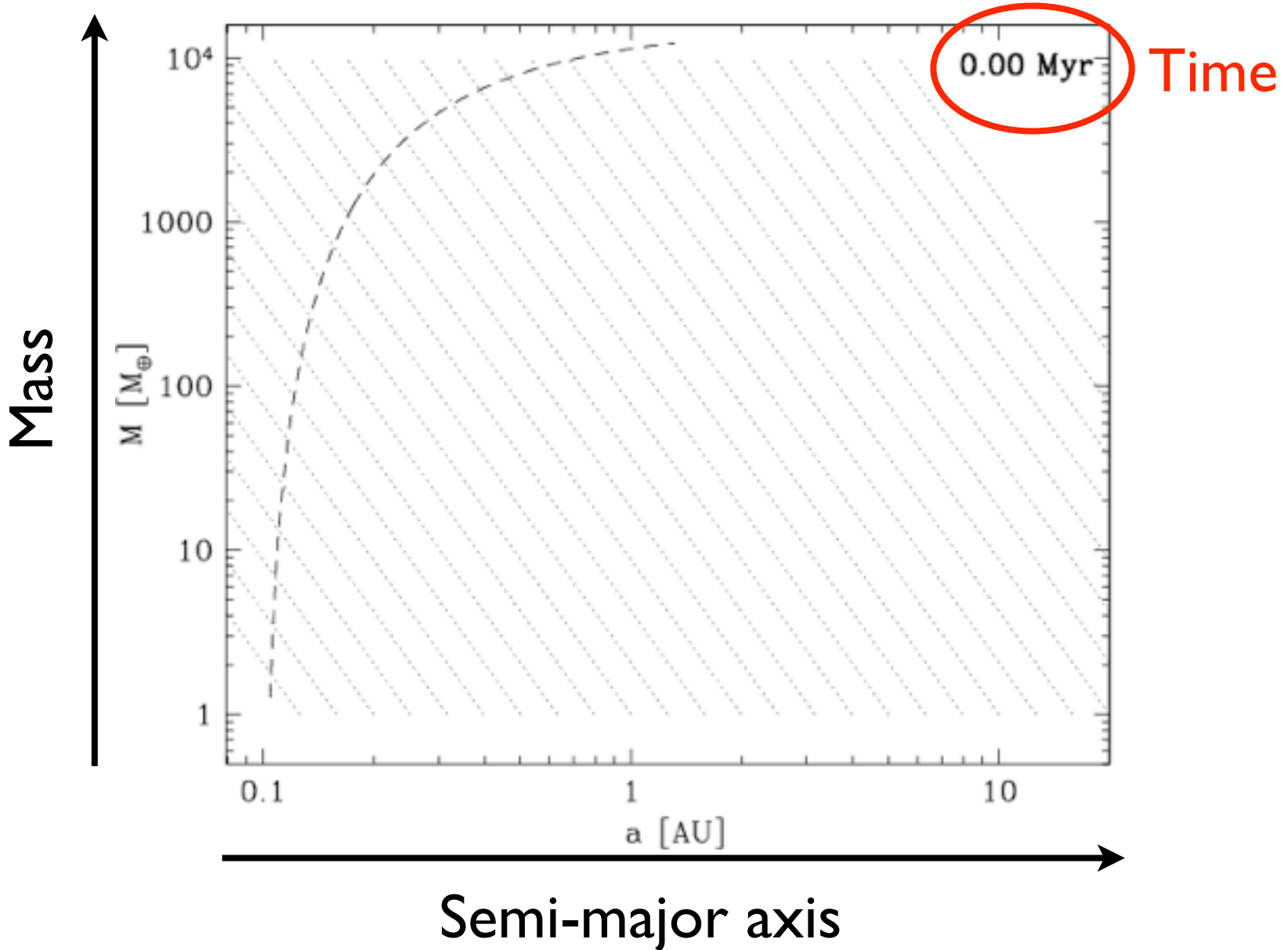
Benz et al., 2006, 2008, Mordasini et al. 2009, Alibert et al. 2010

mardi, 7 juin 2011

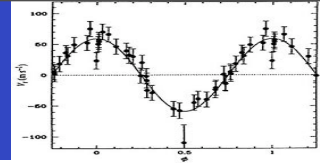
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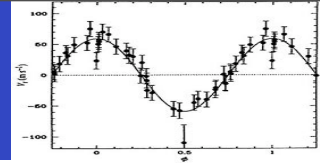
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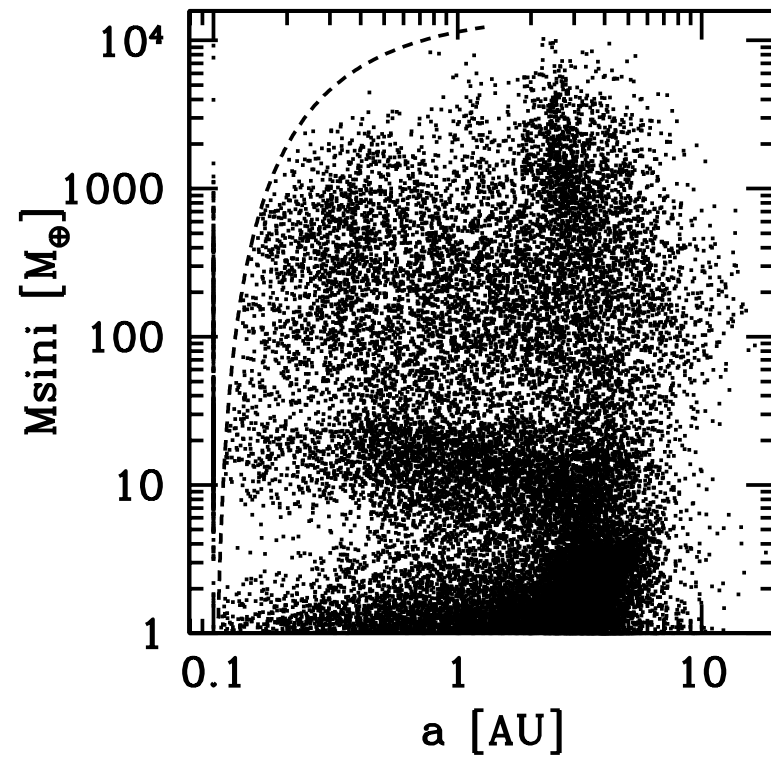
$M \sin(i)$ vs a



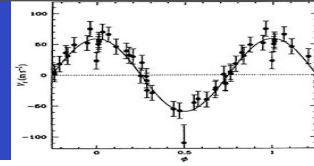
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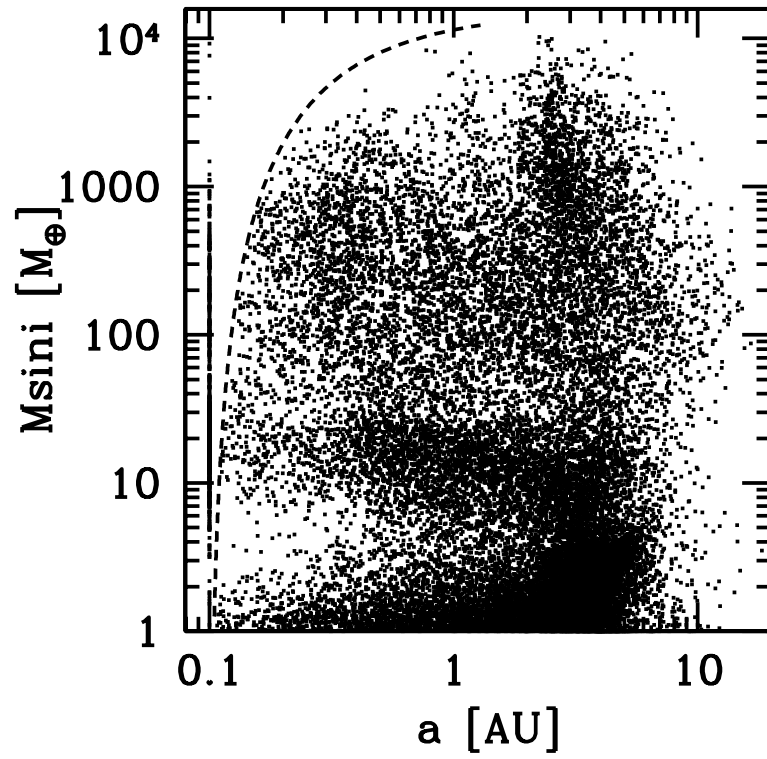
all



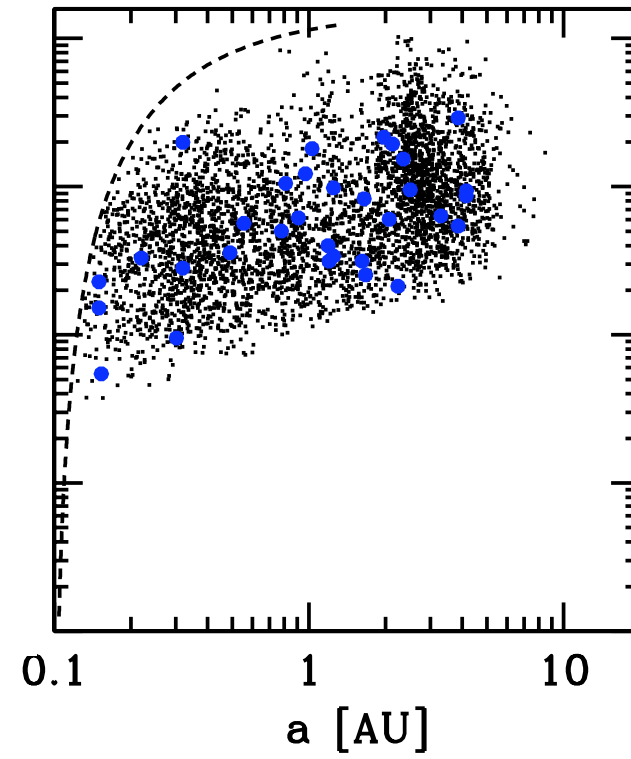
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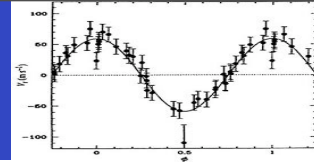
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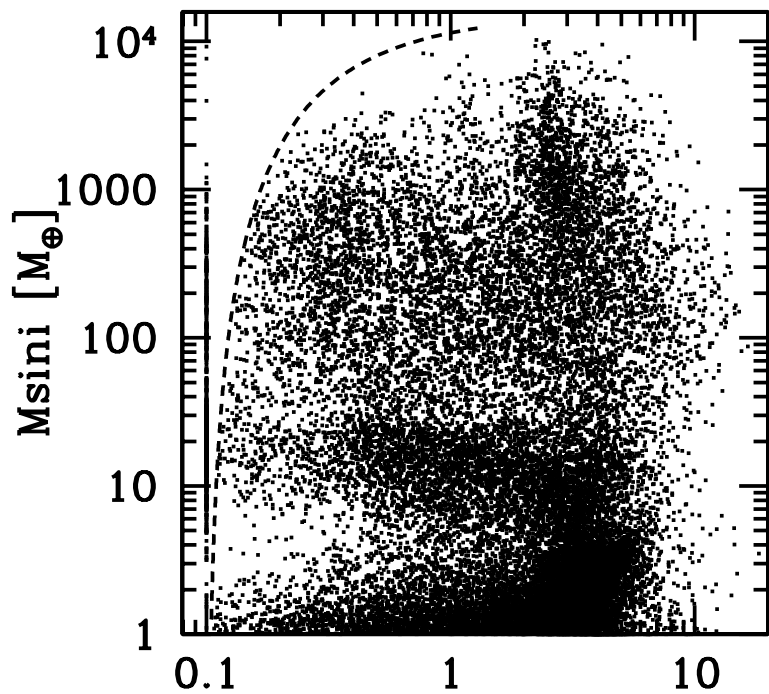
10 m/s



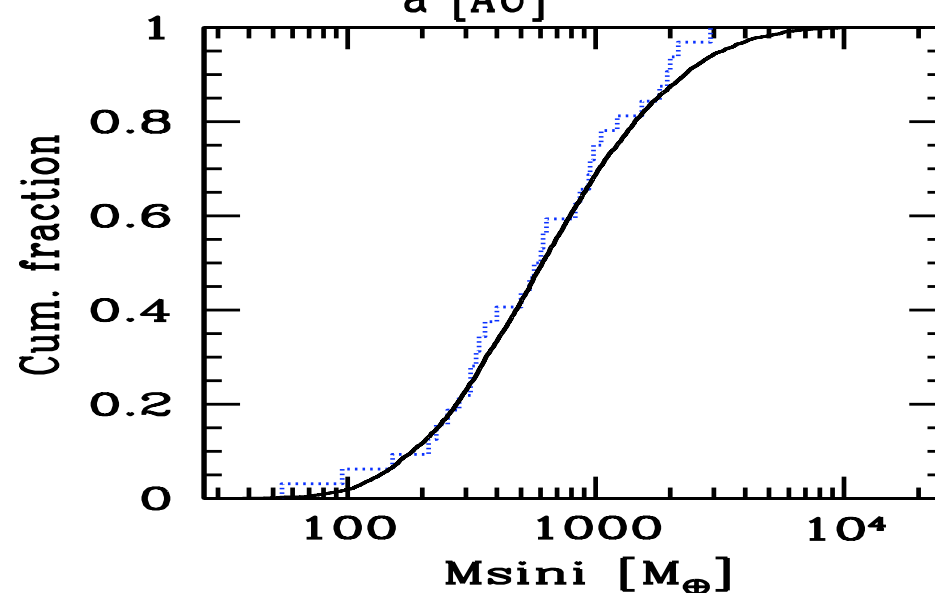
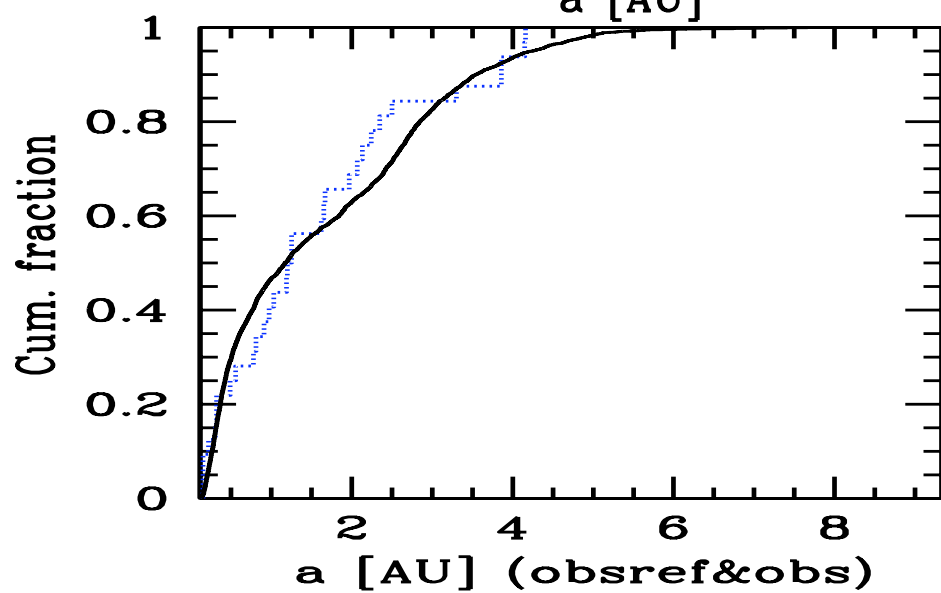
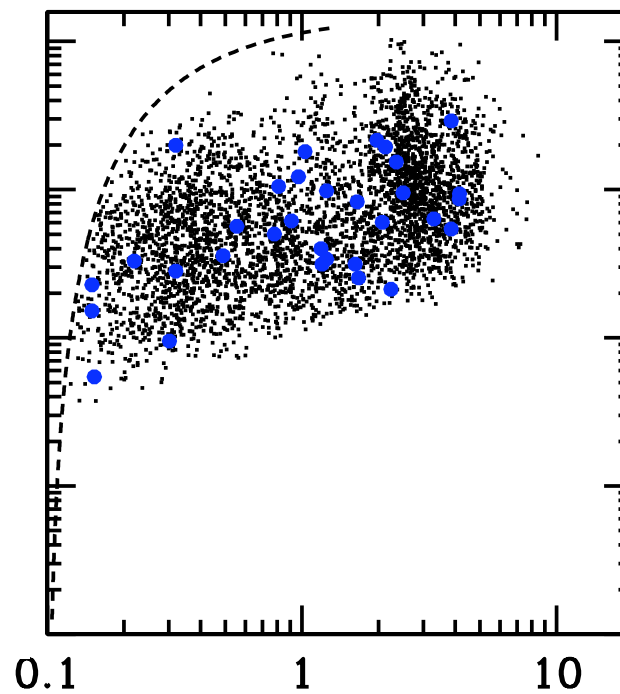
M sin(i) vs a



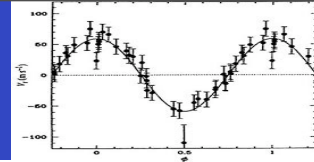
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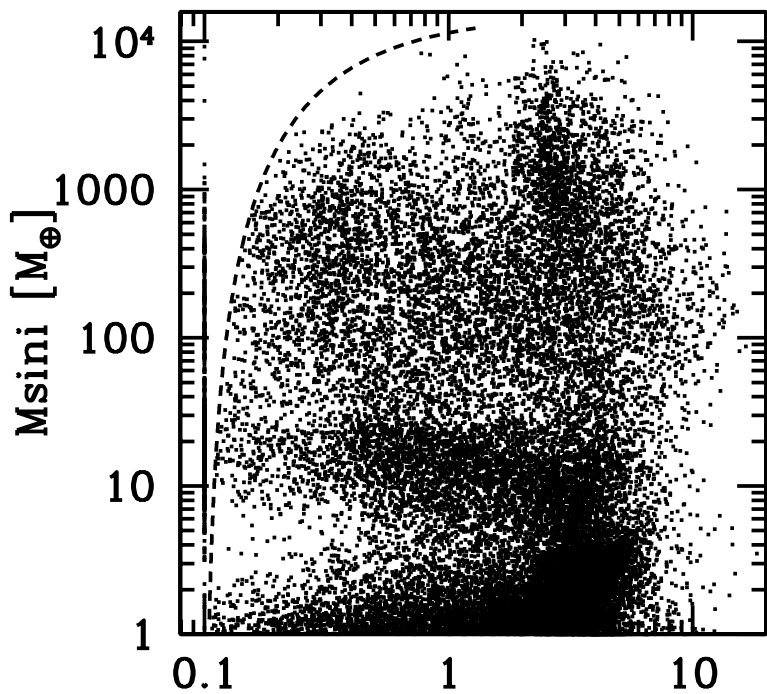
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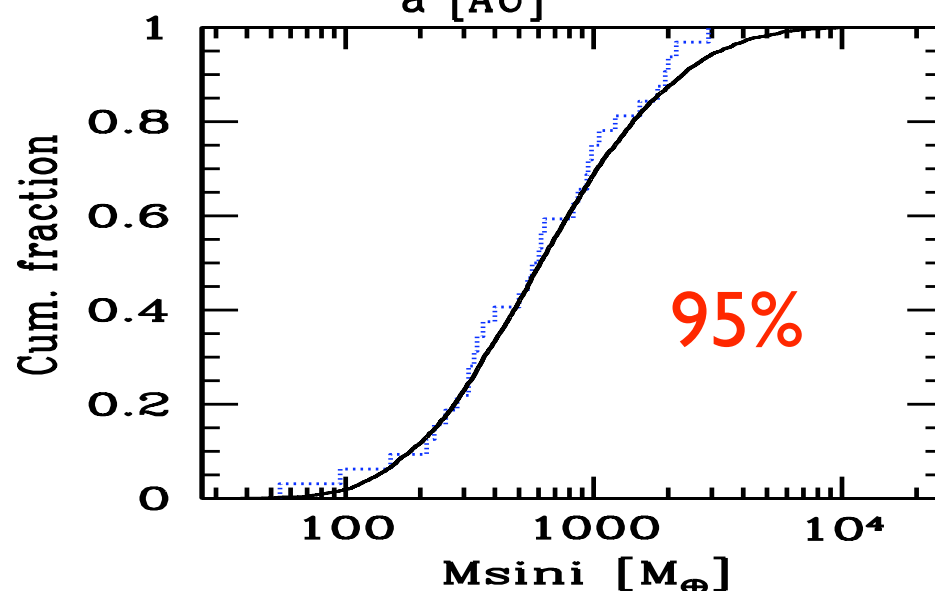
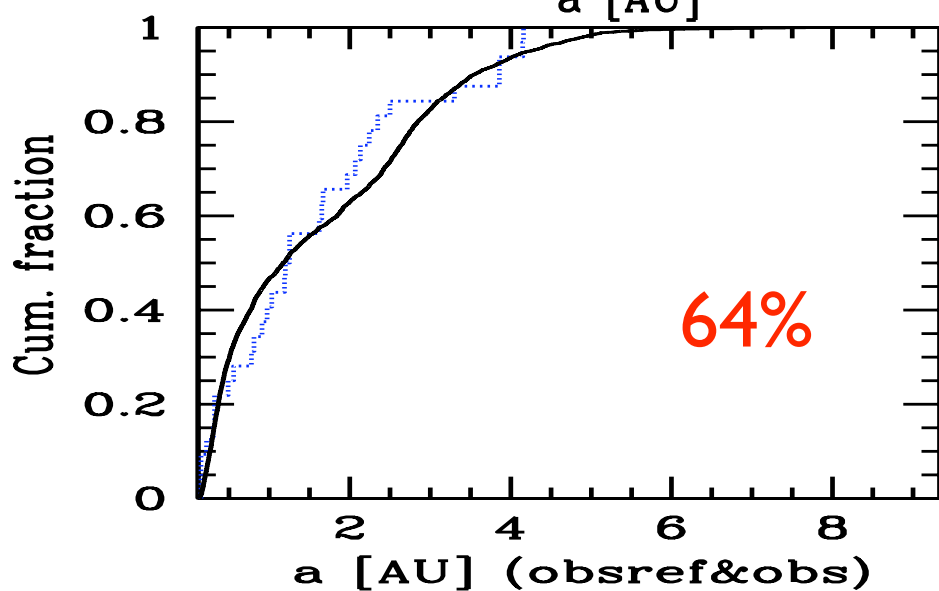
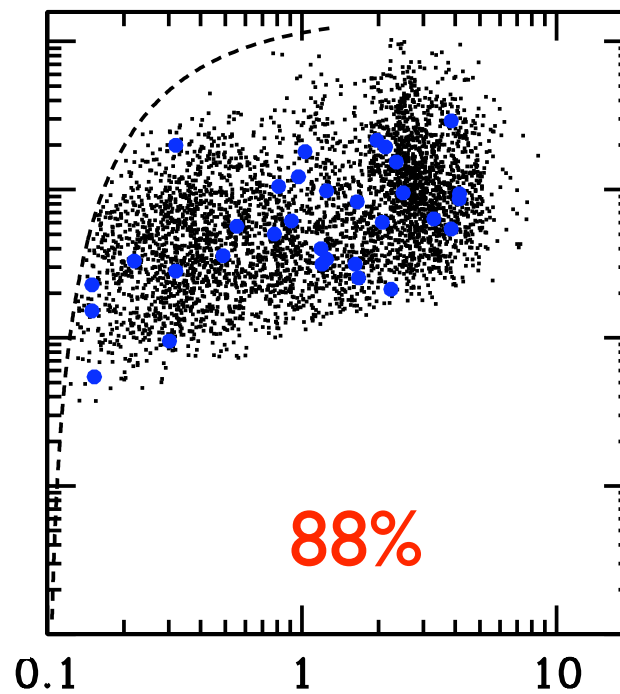
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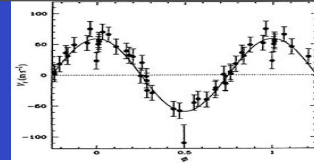
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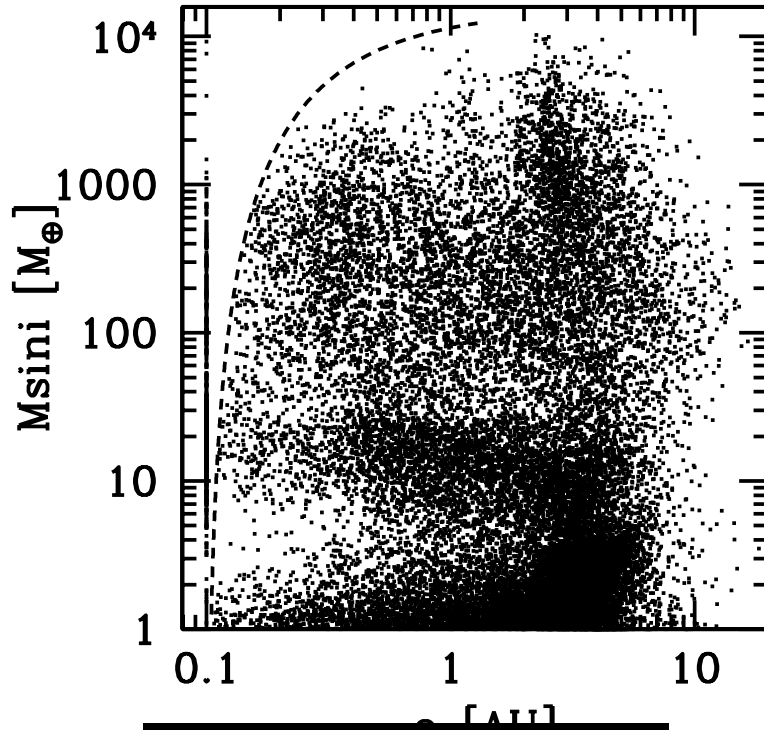
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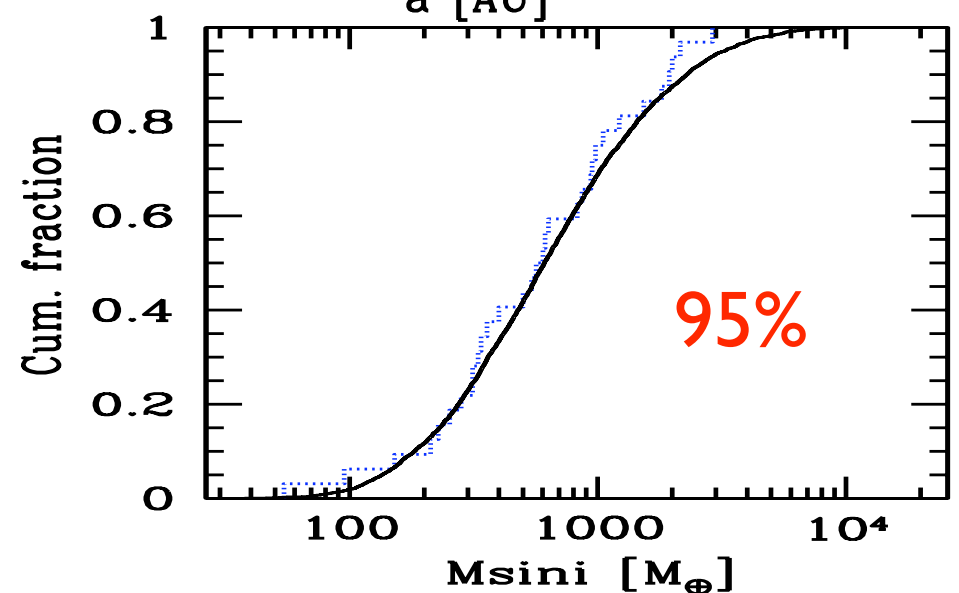
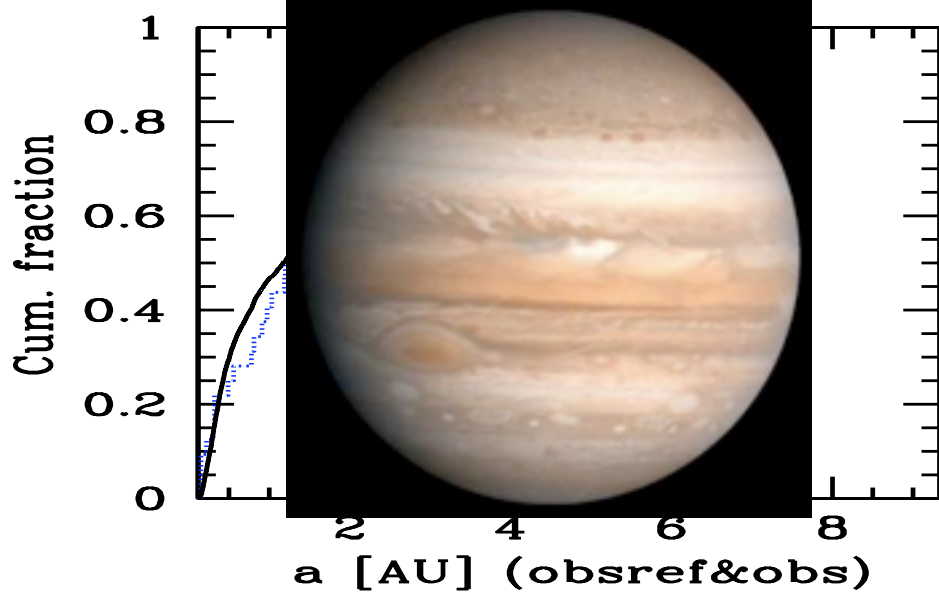
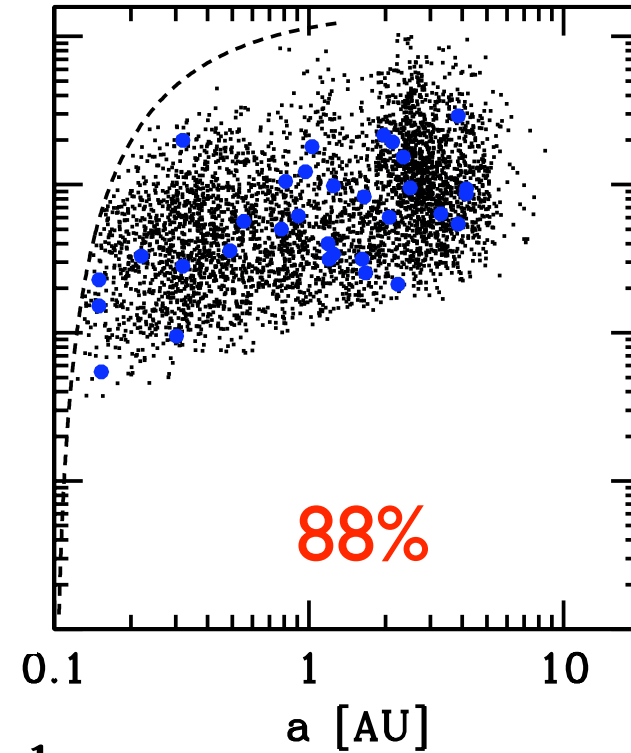
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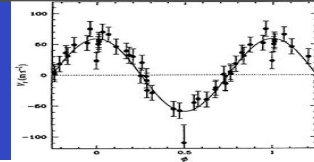
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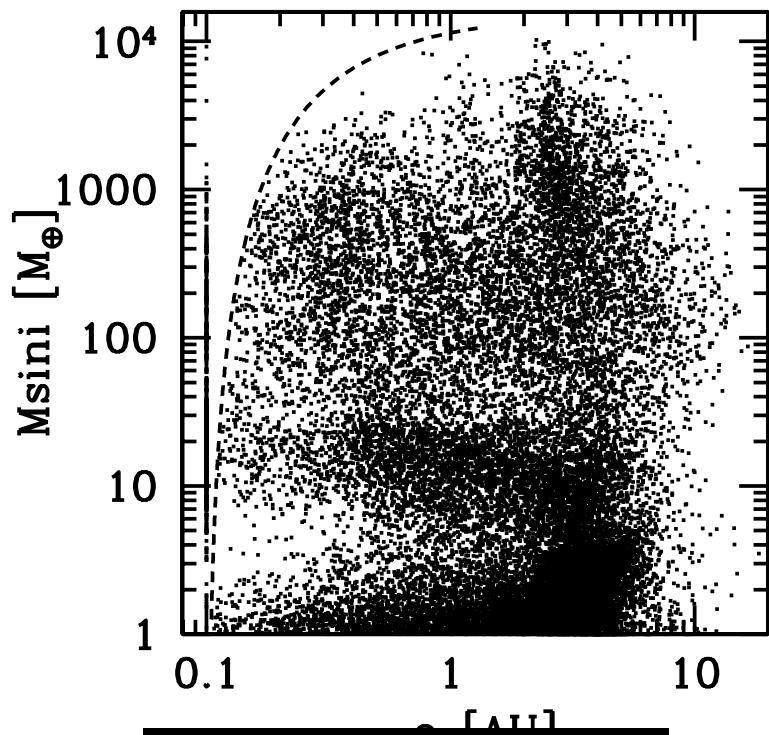
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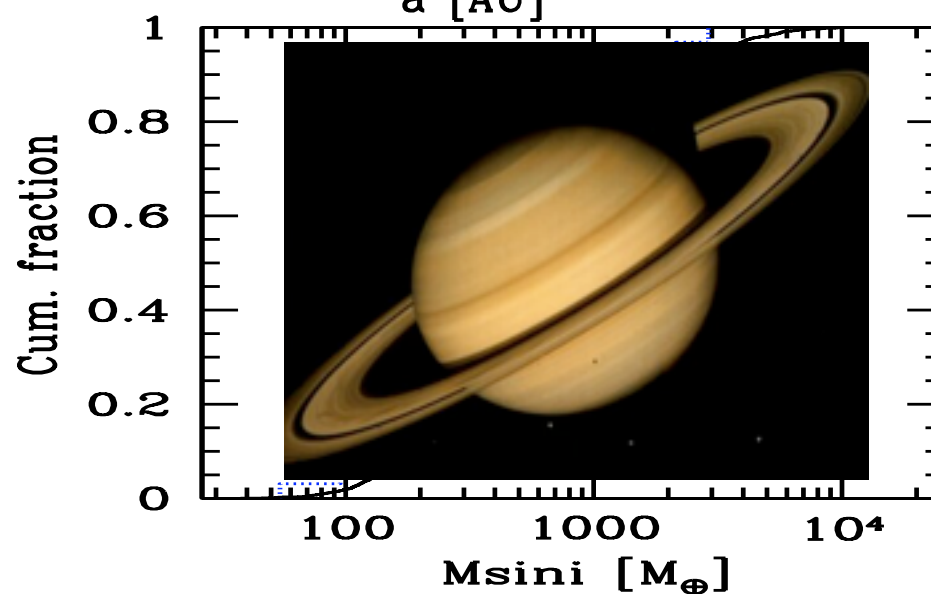
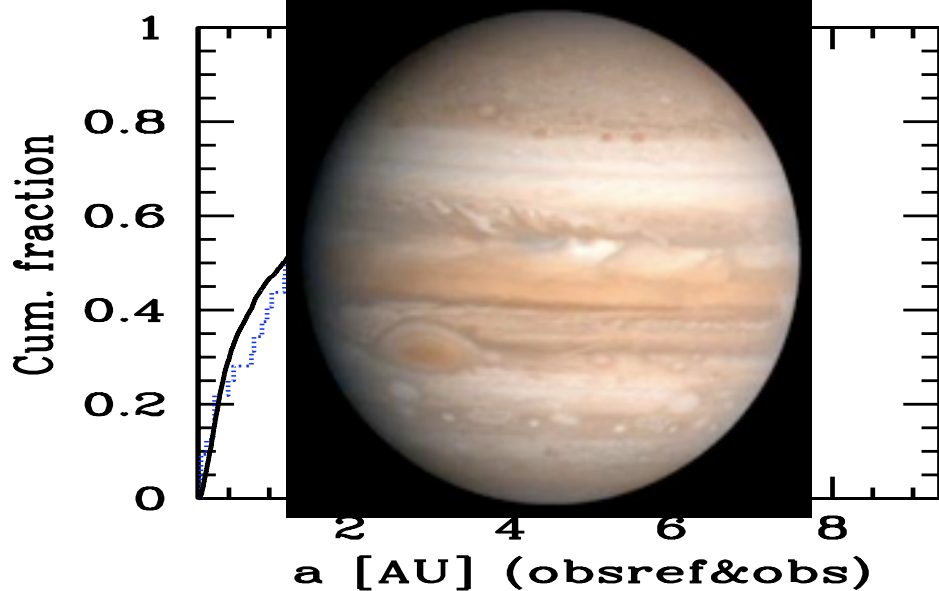
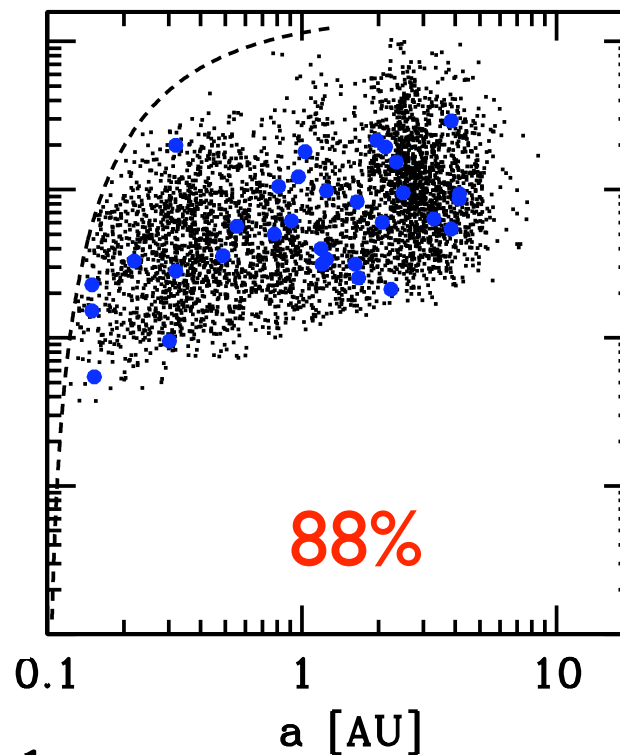
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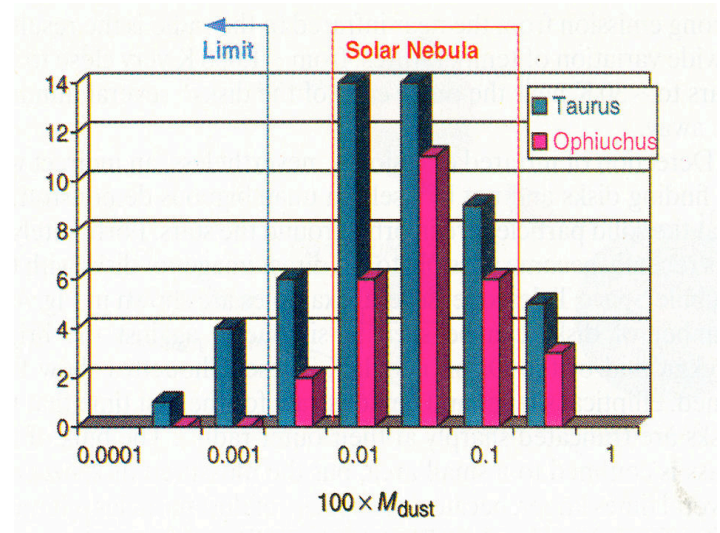
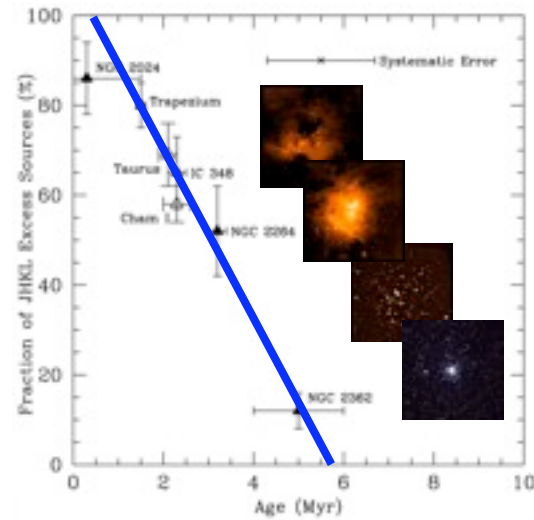
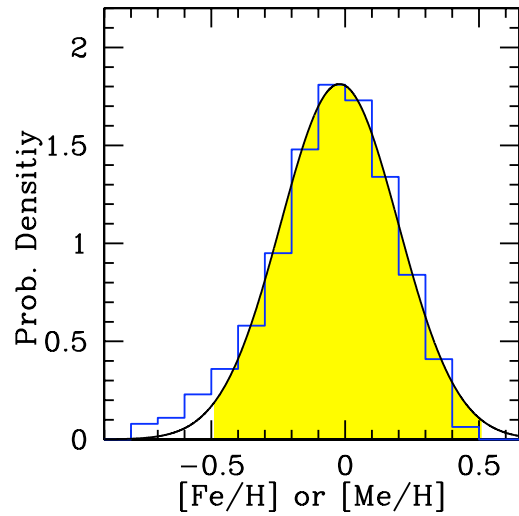
all



10 m/s

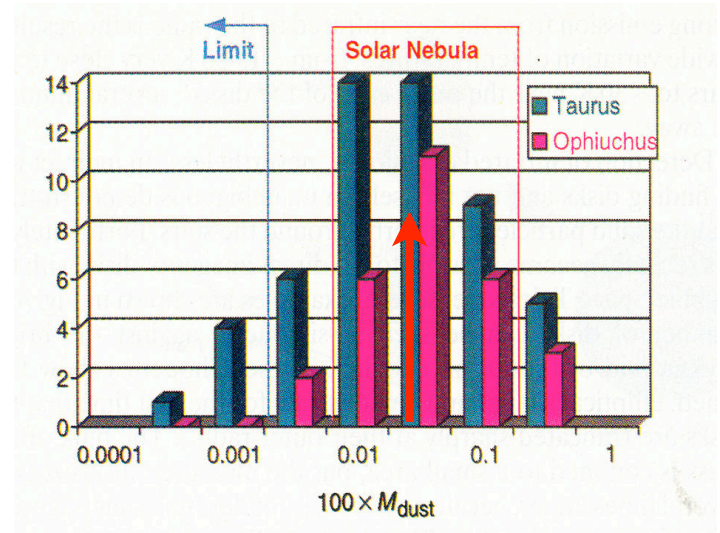
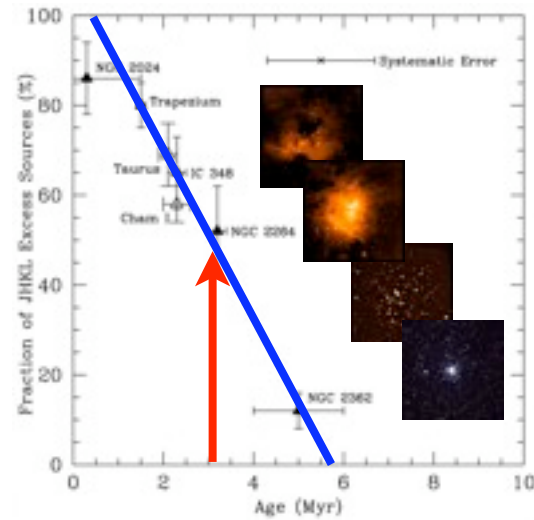
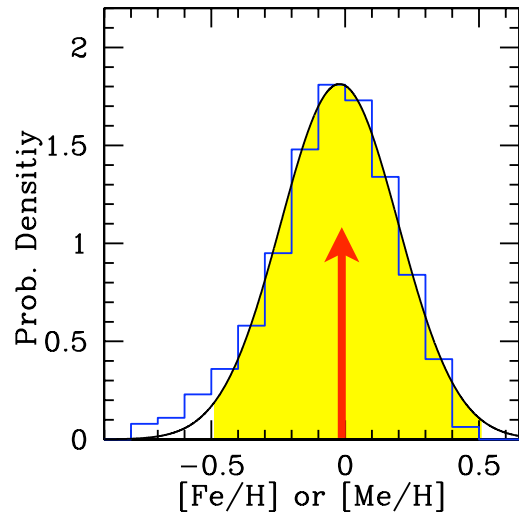


Jupiter & Saturn formation



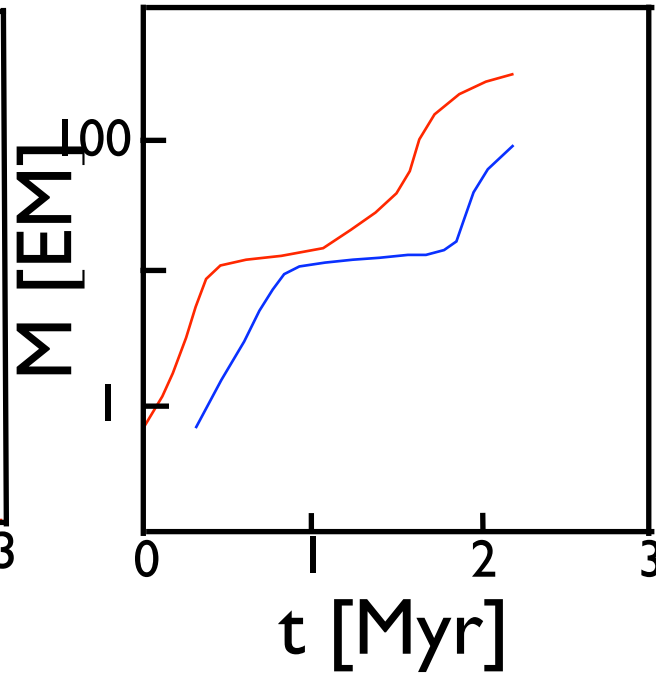
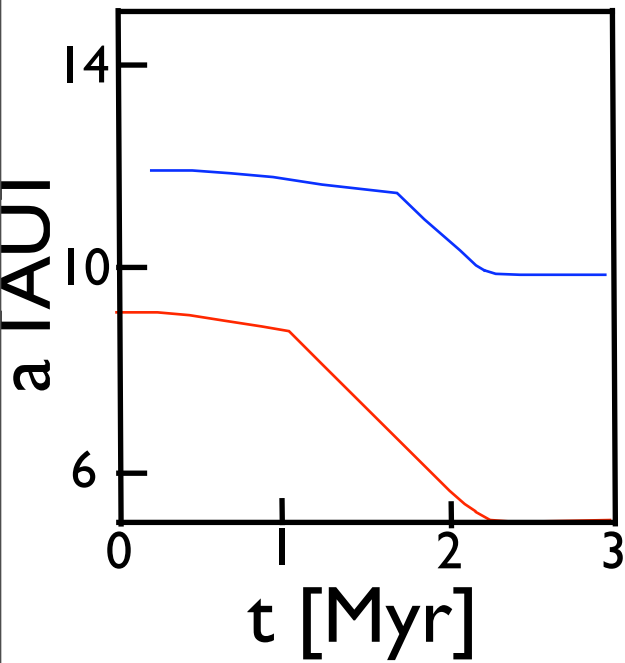
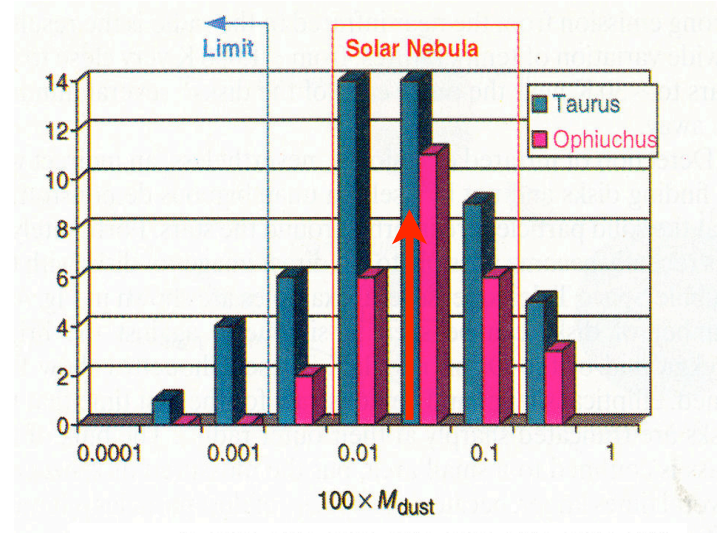
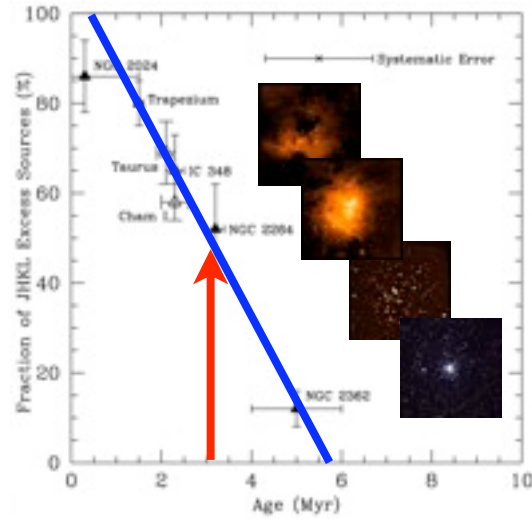
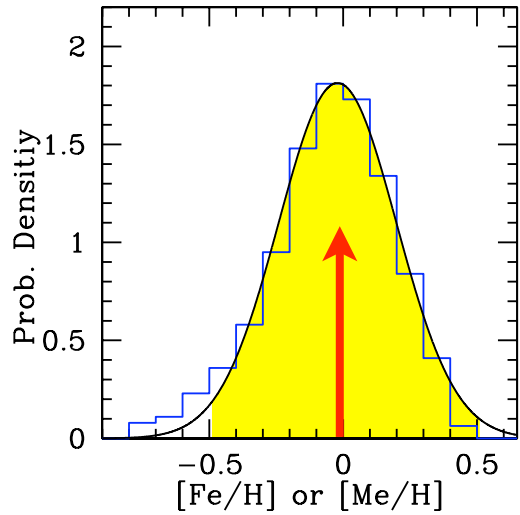
!! only competition for solid accretion - no dynamical interactions between planets !!

Jupiter & Saturn formation

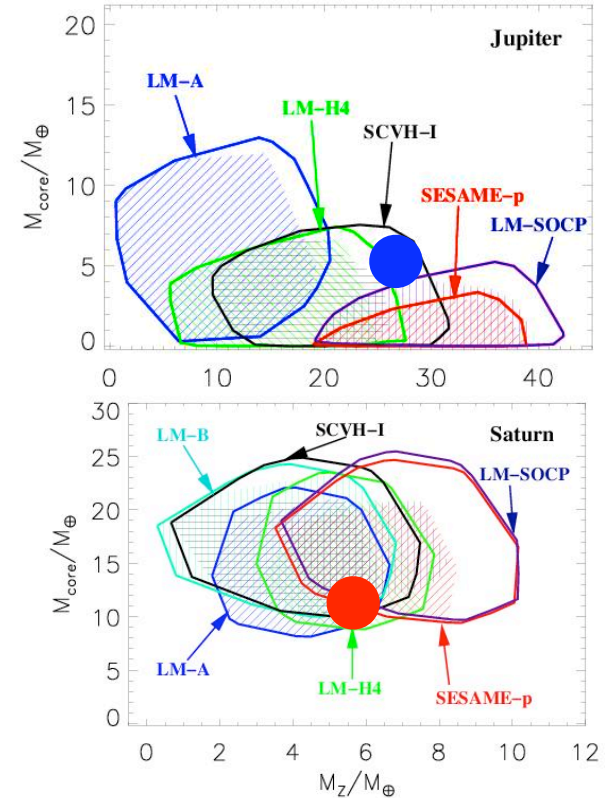


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Jupiter & Saturn formation

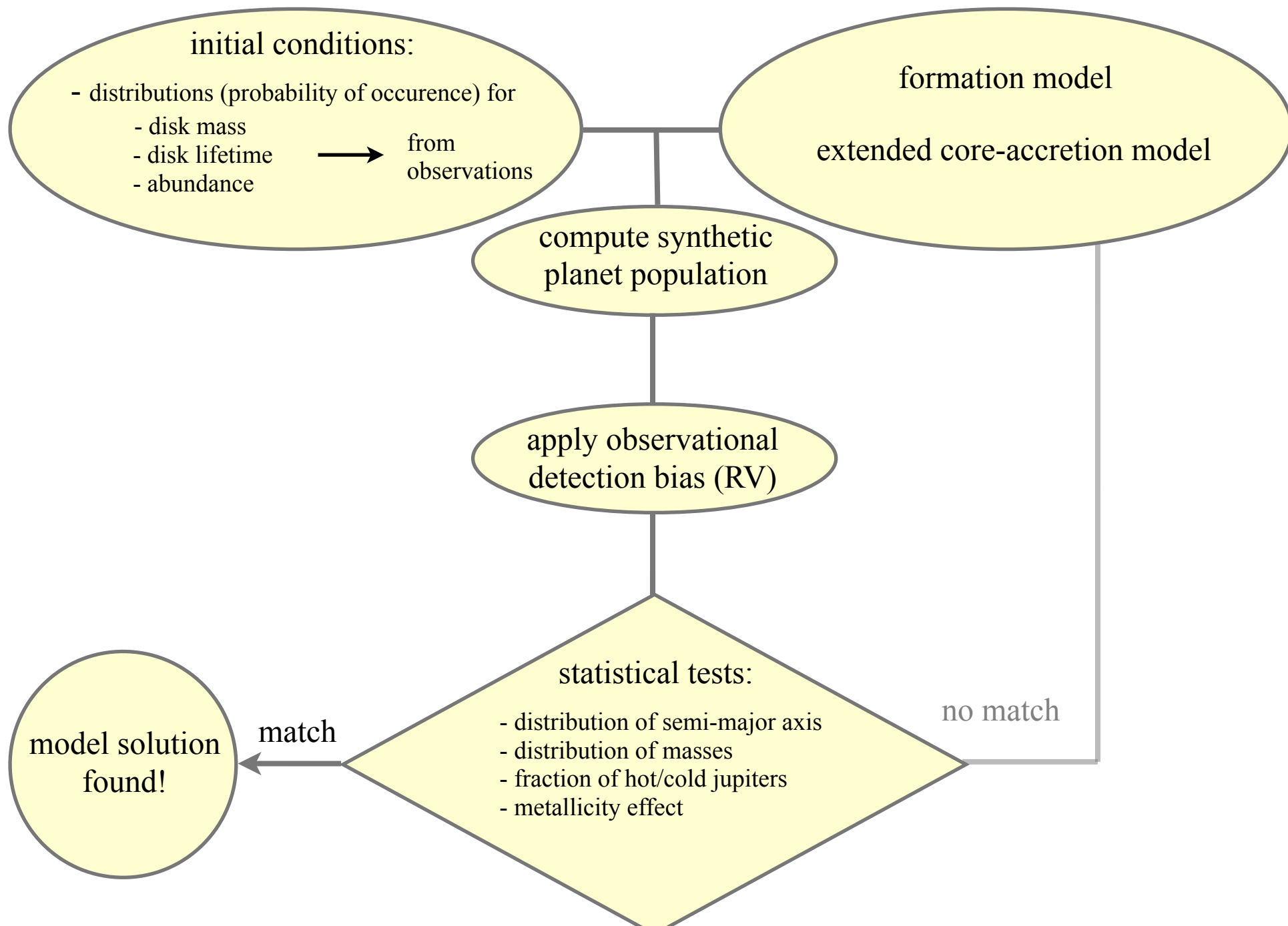


Alibert et al. 2005

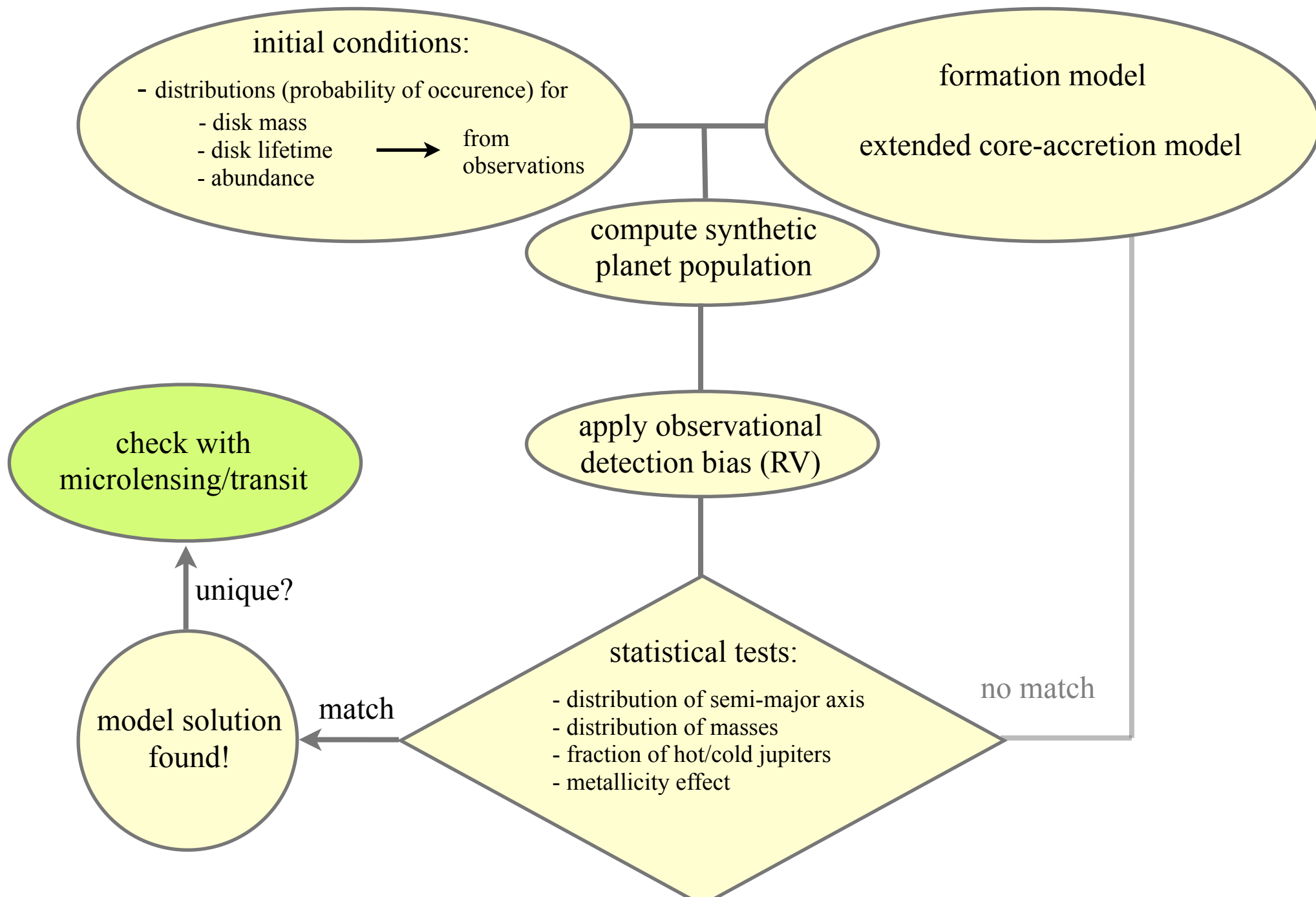


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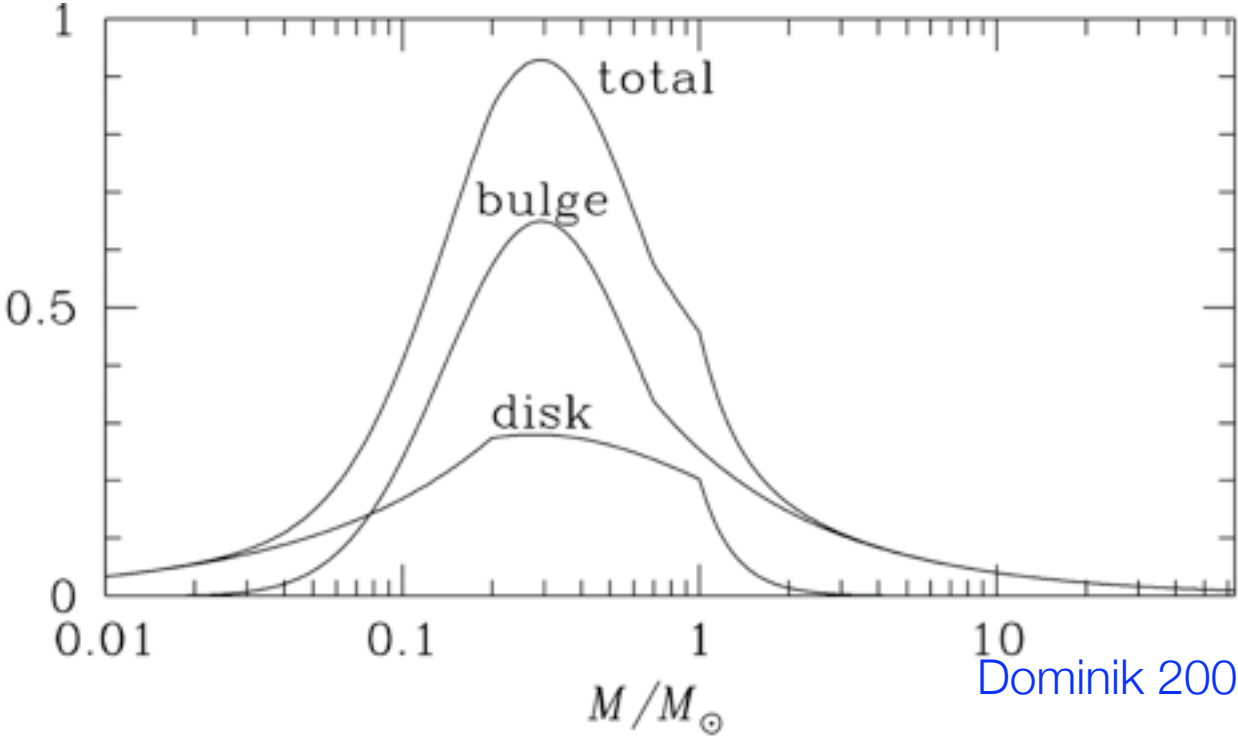
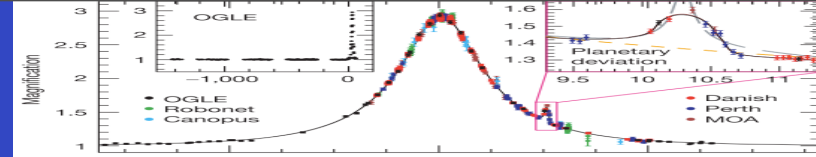
Extra-solar planet population synthesis



Extra-solar planet population synthesis

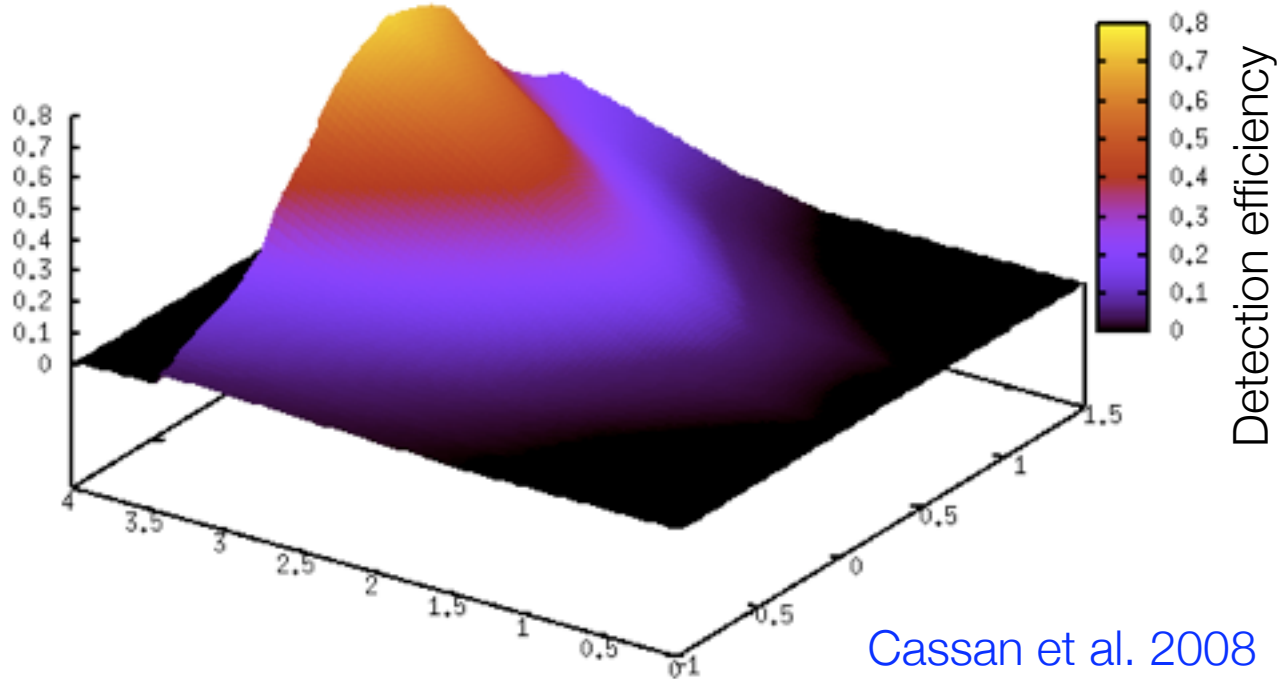


Microlensing



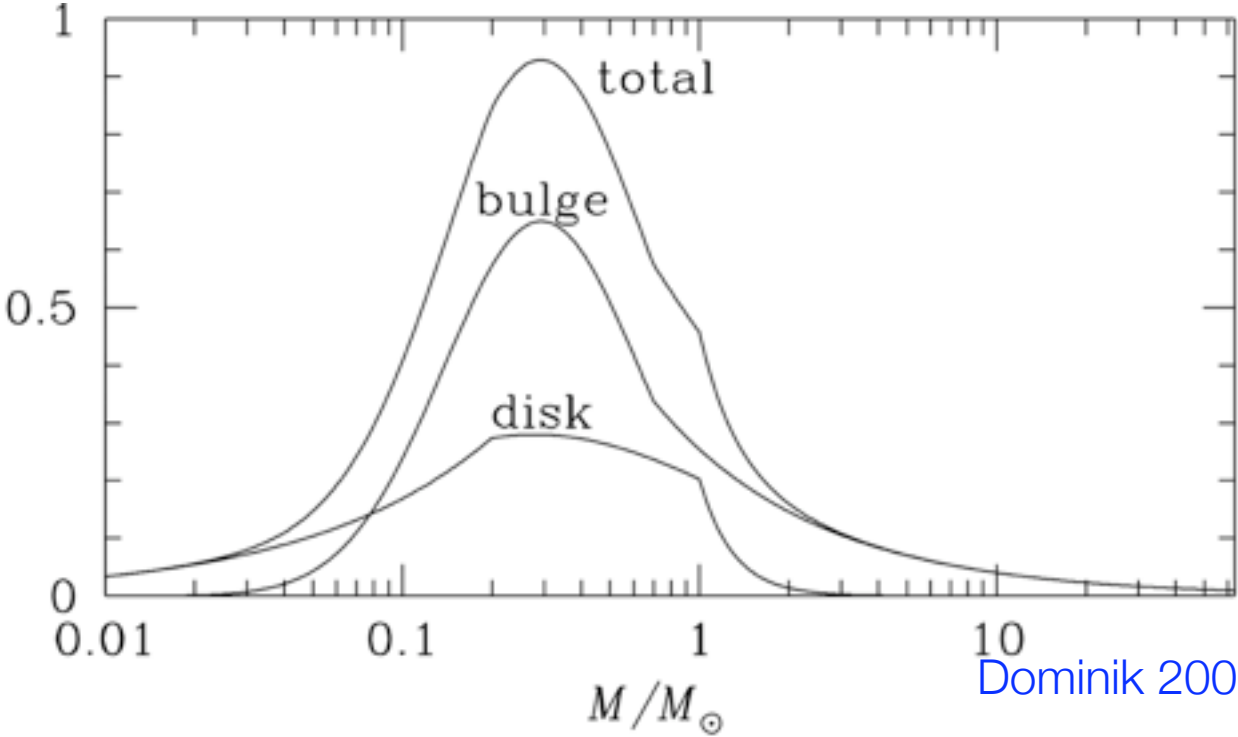
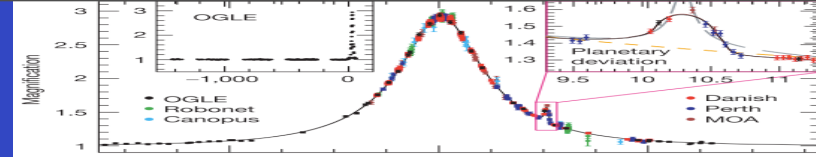
Lens star mass function

Dominik 2006

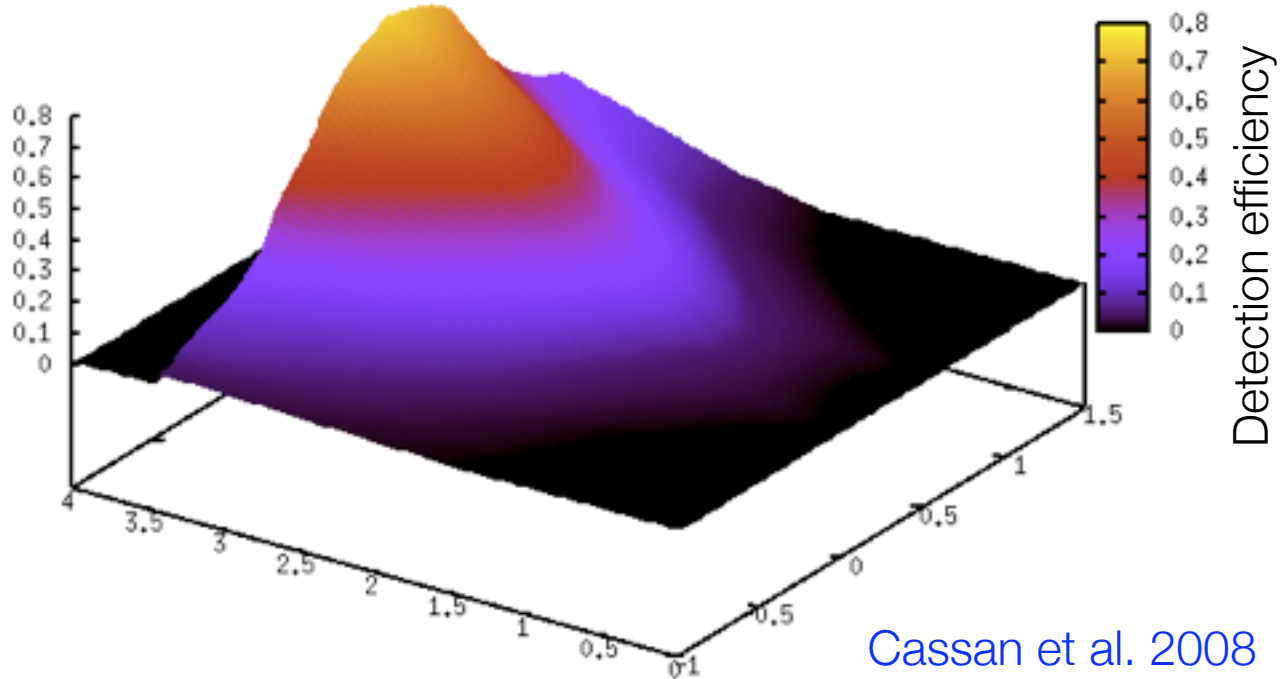


Cassan et al. 2008

Microlensing



Dominik 2006



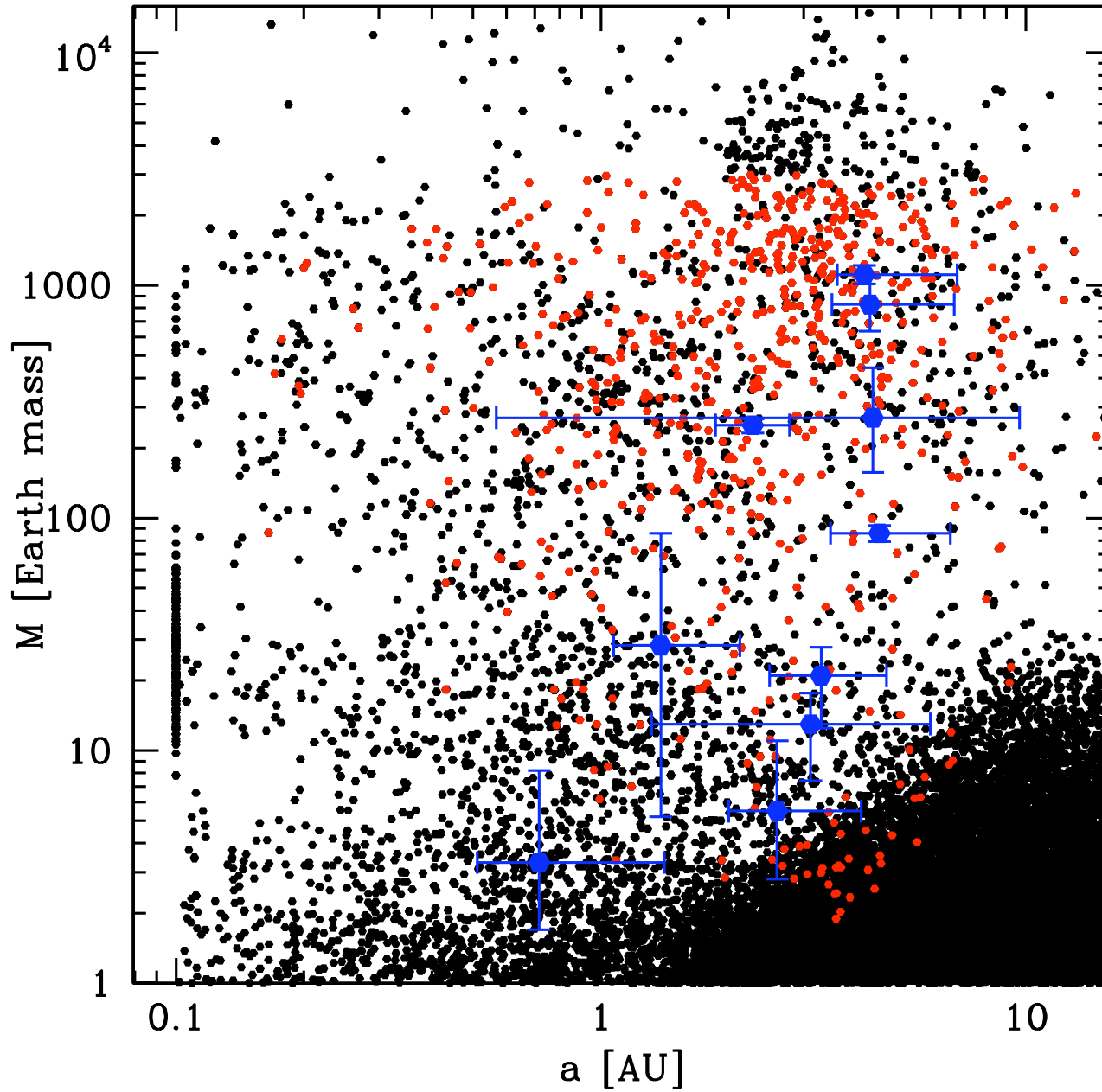
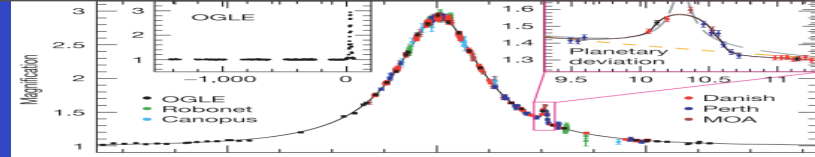
Cassan et al. 2008

Lens star mass function

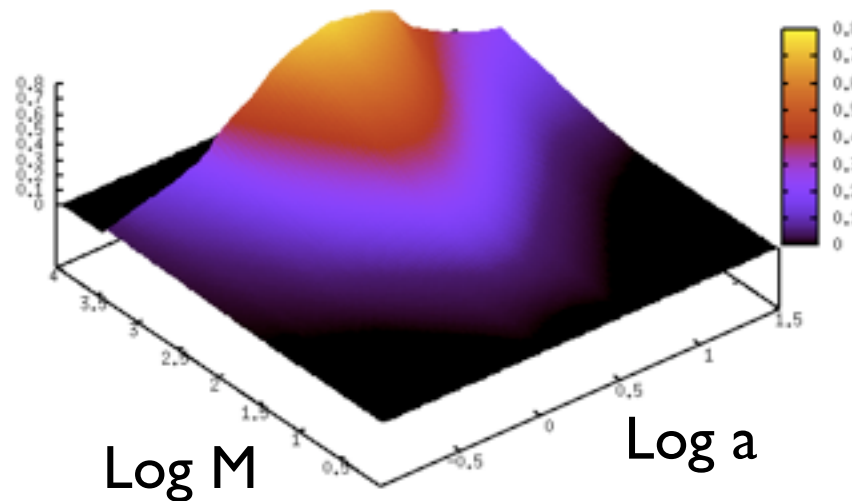
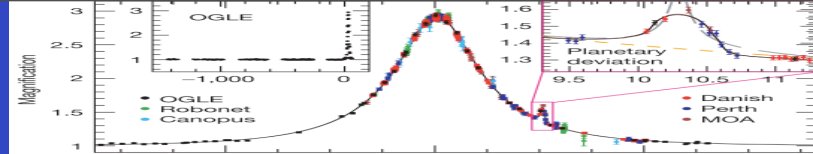
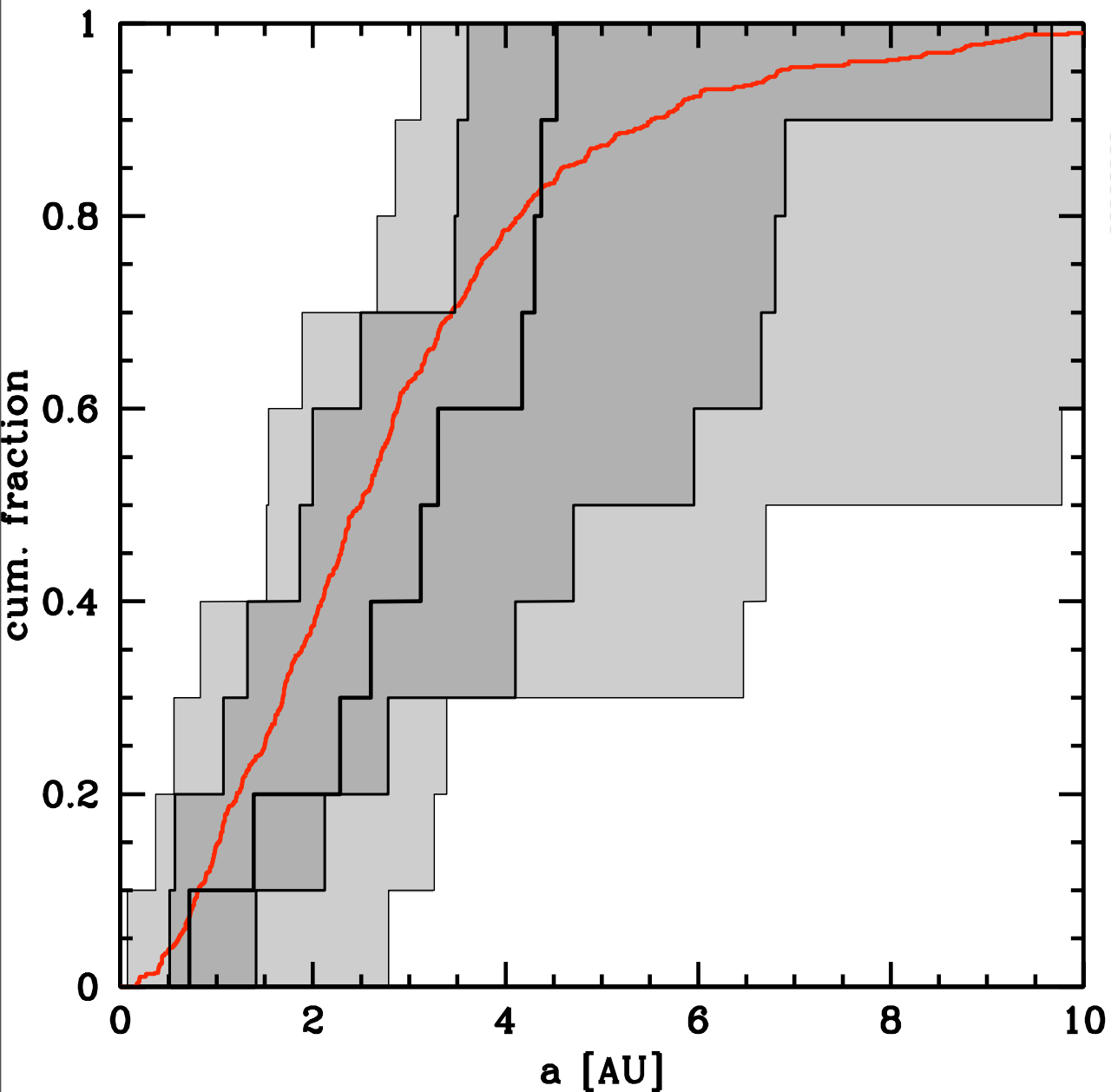
Detection efficiency

synthetic population
observable by
microlensing

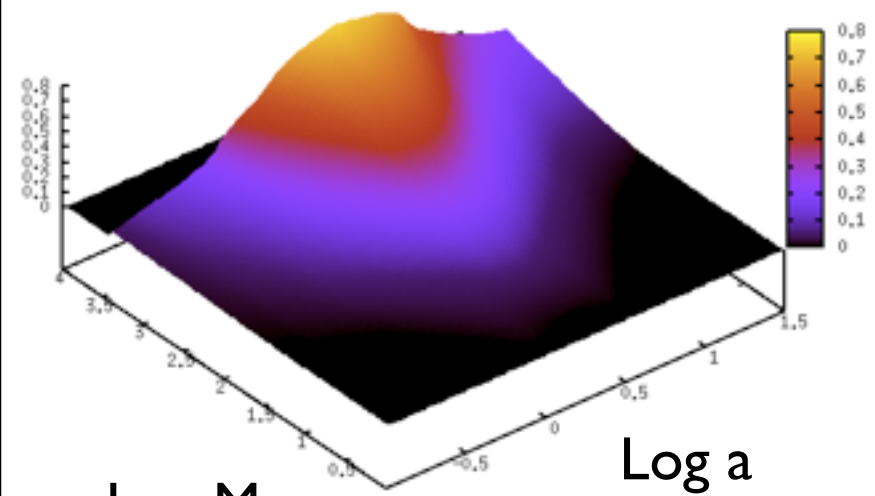
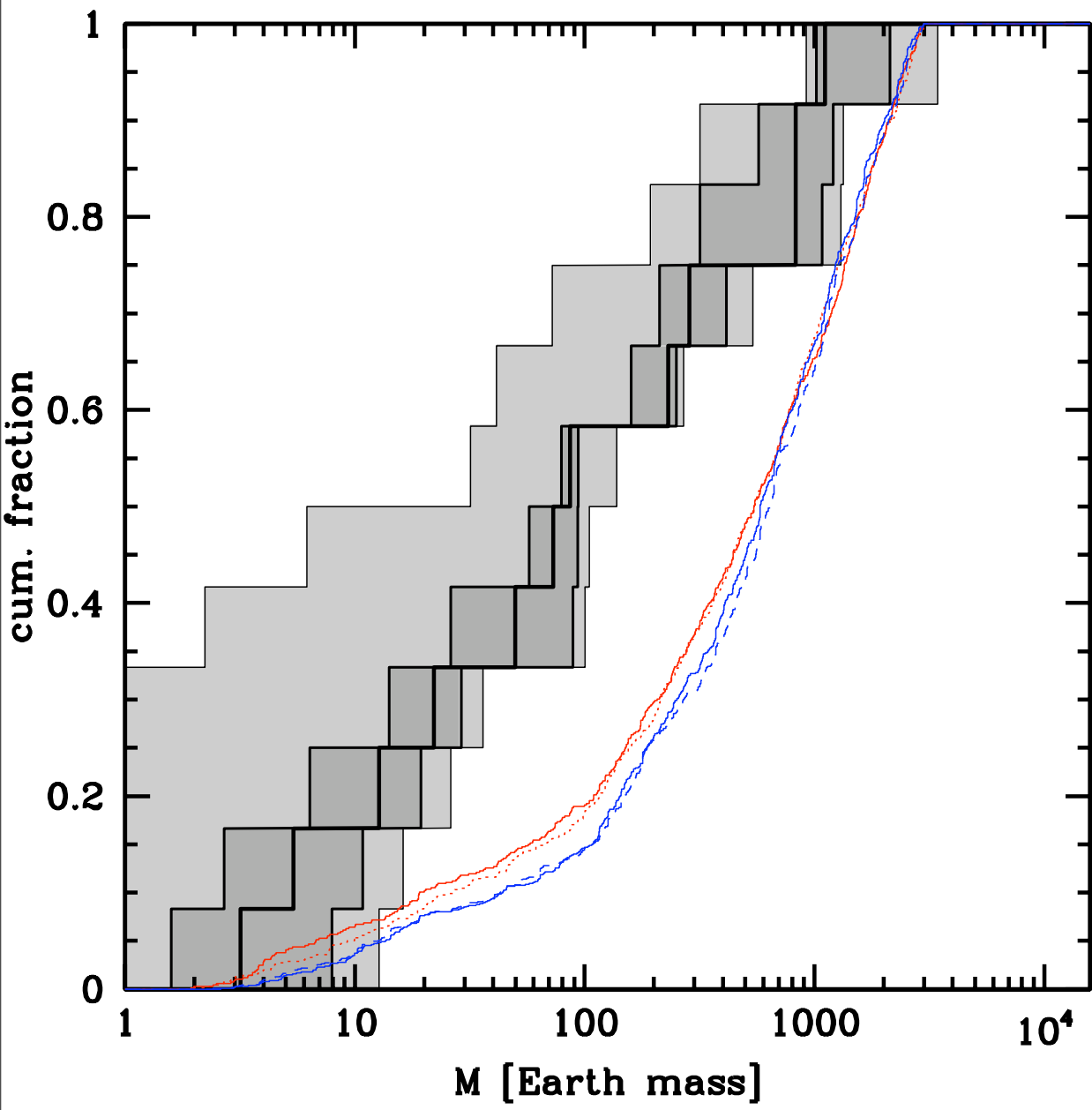
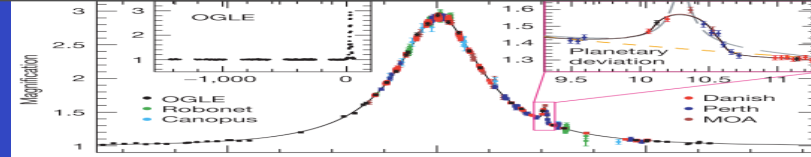
Microlensing



semi-major axis histogram



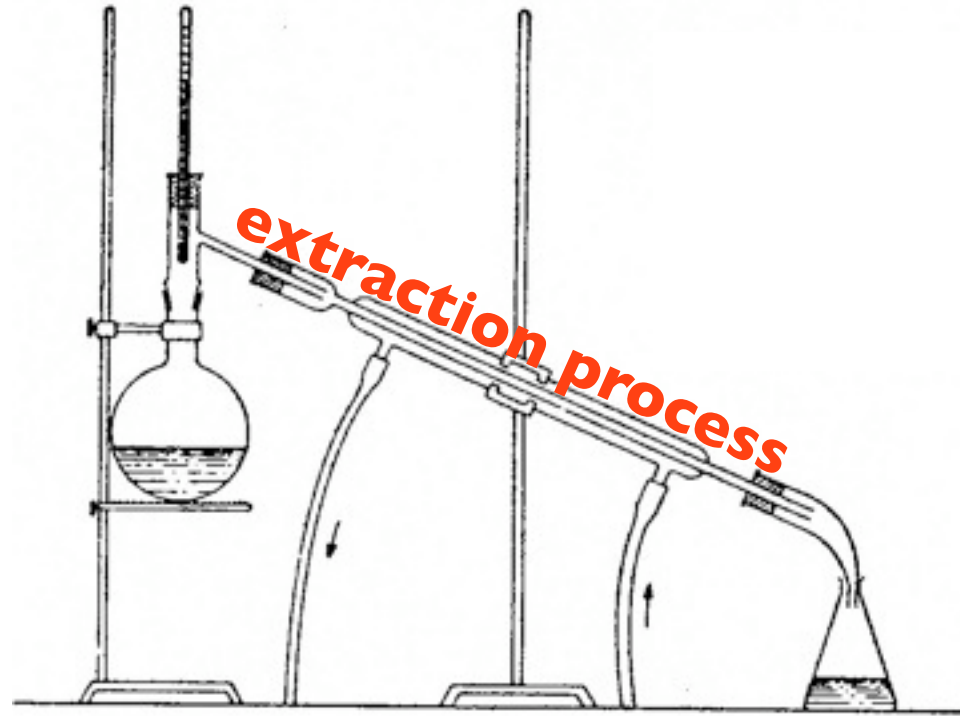
mass histogram



- MF total - 0.5 kpc
- ⋯ MF disk - 0.5 kpc
- MF total - 6 kpc
- - - MF bulge - 6 kpc

Intermediate conclusion

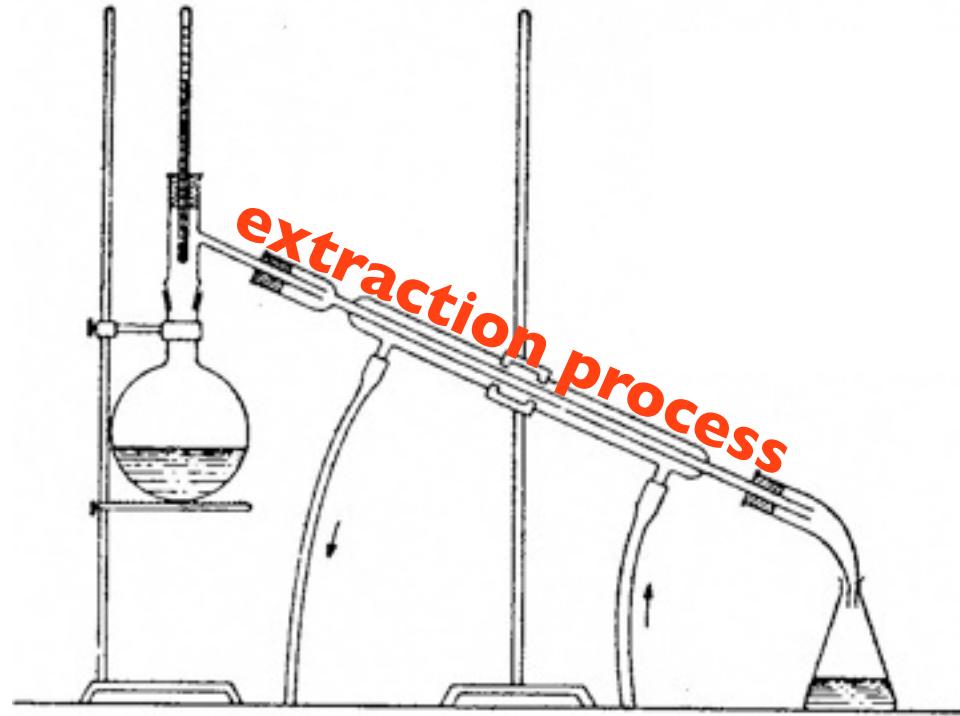
specialized
models



population
synthesis

Intermediate conclusion

specialized
models



population
synthesis

2005 model

- isothermal reduced migration
- one planet
- circular orbit
- no heating of planetesimals
- model α for the gas disk



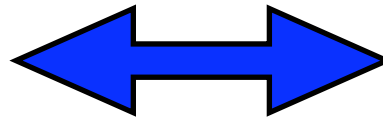
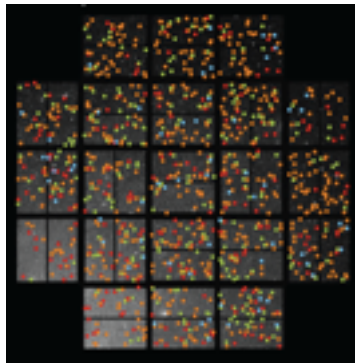
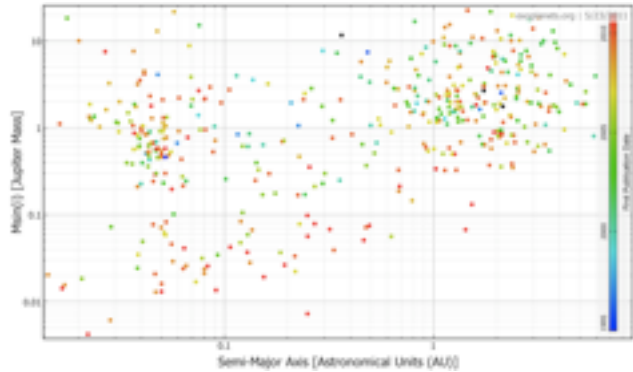
observations



Alibert et al. 2005

Intermediate conclusion

new observations

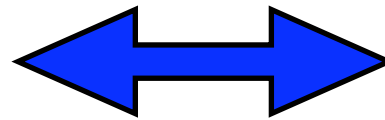
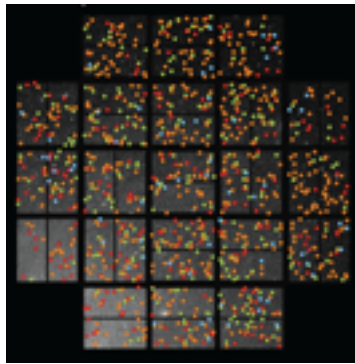
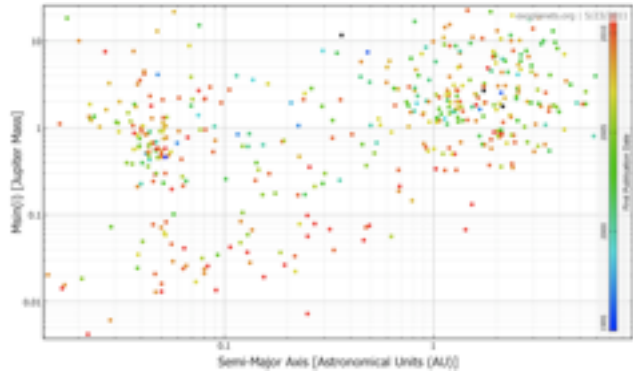


new model

- type I migration
- multi-planet
- no circular orbit
- heating of planetesimals
- α disk model with irradiation
- magnetospheric inner cavity

Intermediate conclusion

new observations



new model

type I migration

multi-planet

no circular orbit

heating of planetesimals

α disk model with irradiation

magnetospheric inner cavity



Planet desert

©Ida and Lin 2004

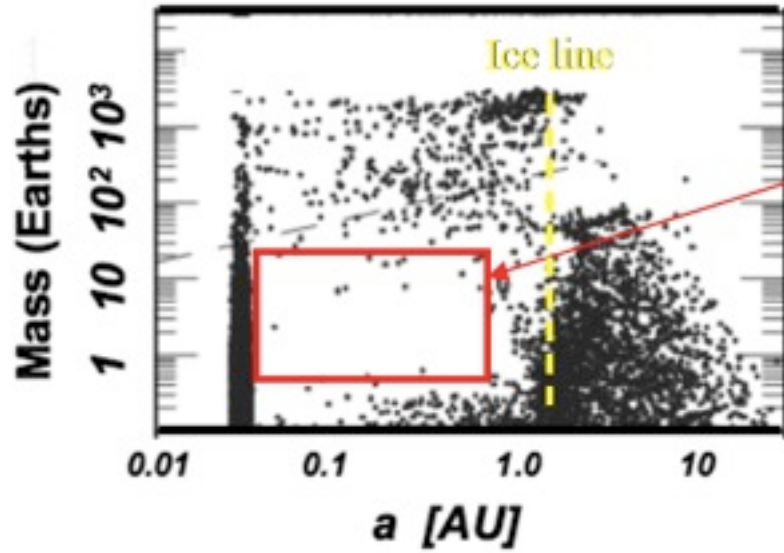
or



Planet oasis

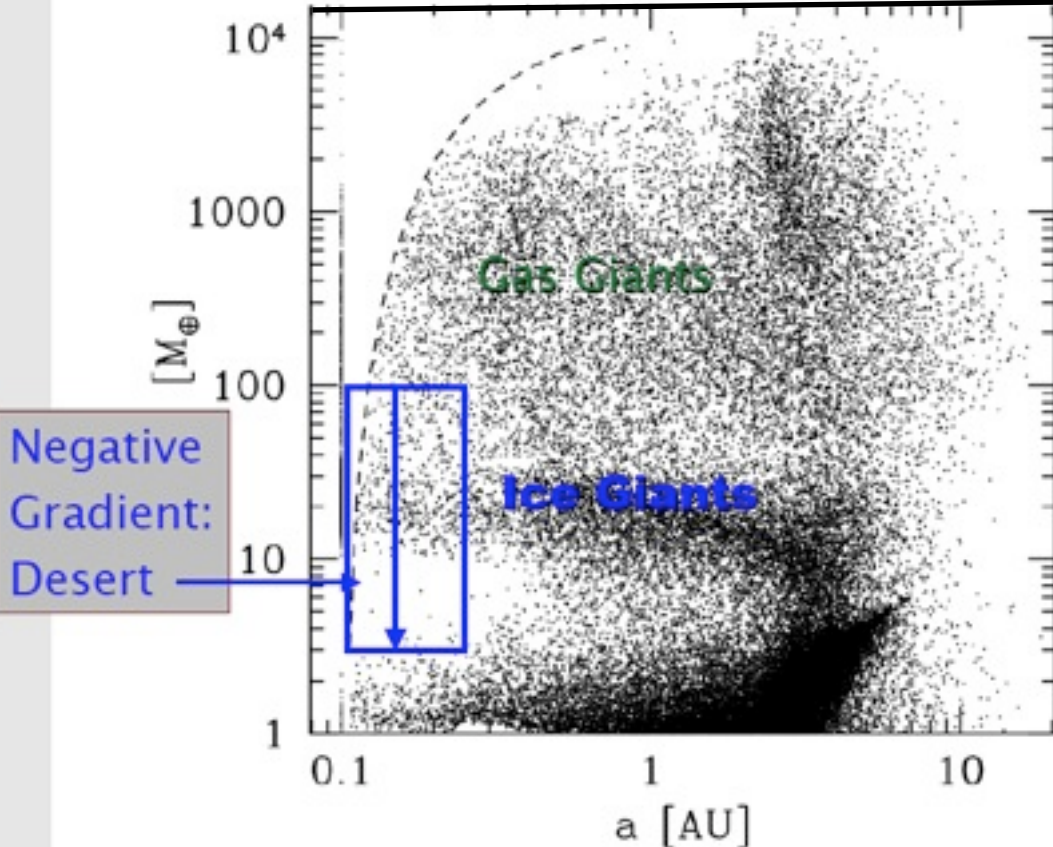
©Boss 2011

Ida & Lin 2008



Planet Desert:
 $a = 0.05 - 1.0 \text{ AU}$
 $M = 1 - 30 M_{\text{Earth}}$

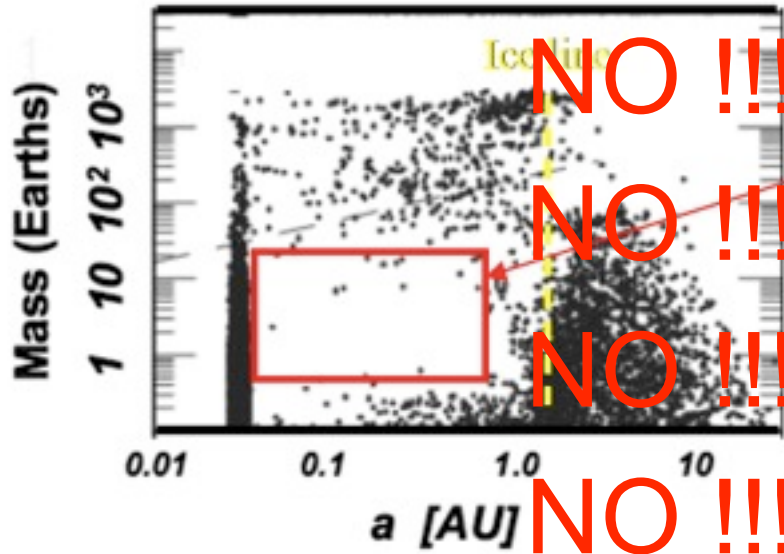
Mordasini, Alibert, & Benz (2009)



Prediction of planet formation models in the sep-mass plane

(From G. Marcy, IAU 276)

Ida & Lin 2008

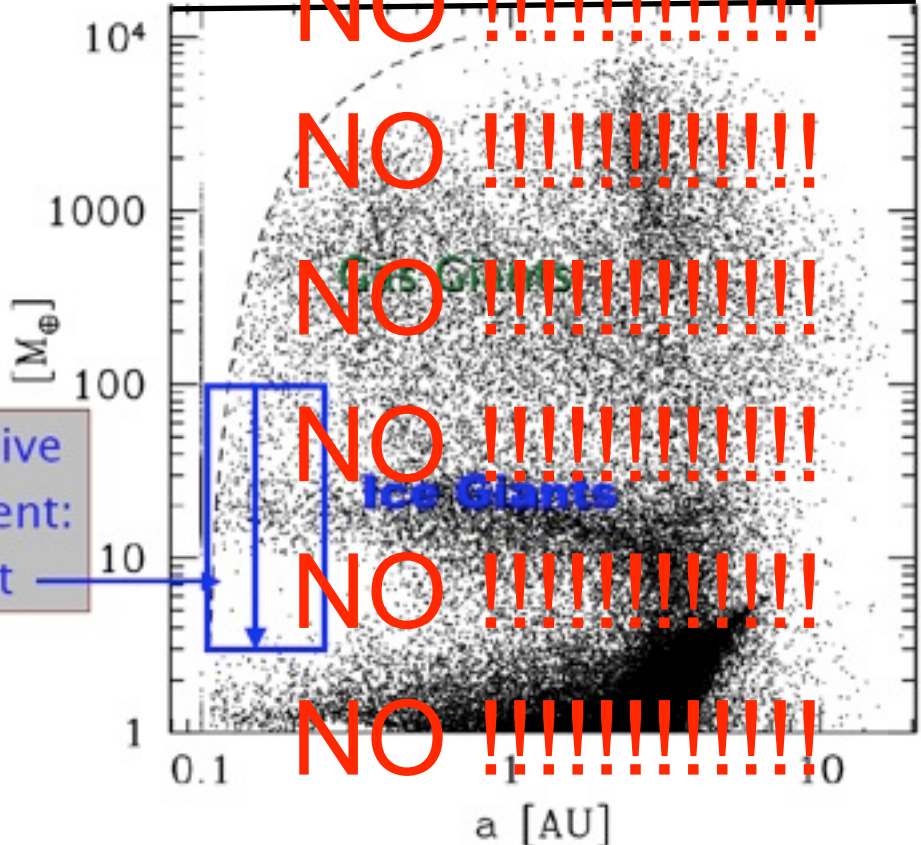


Planet Desert:
 $a = 0.05 - 1.0 \text{ AU}$
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NO !!!!!!!!!!!!!!!
 NO !!!!!!!!!!!!!!!
 NO !!!!!!!!!!!!!!!
 NO !!!!!!!!!!!!!!!

Prediction of planet formation models in the sep-mass plane

Morbidelli, Alibert, & Benz (2009)



Negative Gradient:
 Desert

NO !!!!!!!!!!!!!!!
 NO !!!!!!!!!!!!!!!
 NO !!!!!!!!!!!!!!!
 NO !!!!!!!!!!!!!!!
 NO !!!!!!!!!!!!!!!

(From G. Marcy, IAU 276)

Extrasolar planet population synthesis I: Method, formation tracks and mass-distance distribution

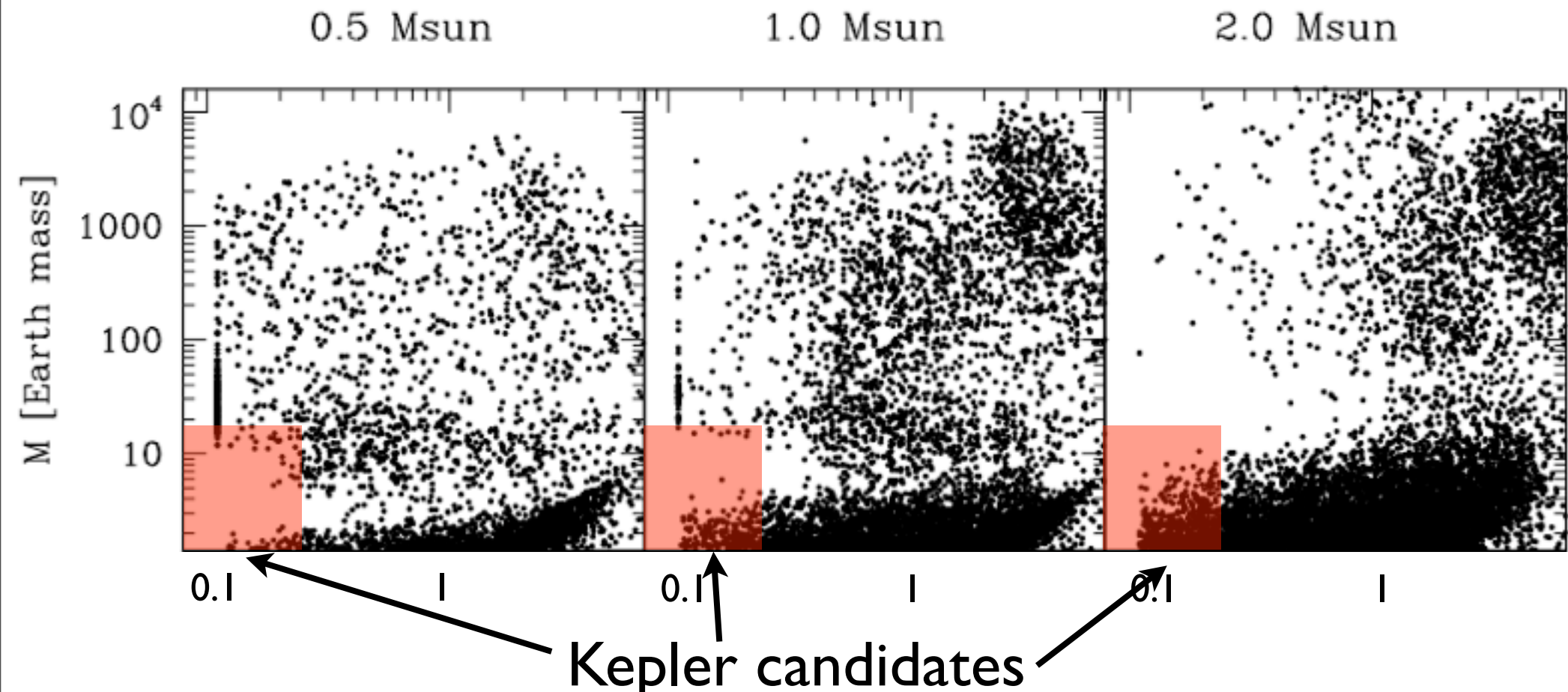
Christoph Mordasini¹, Yann Alibert^{1,2}, and Willy Benz¹

We therefore caution that our synthetic planetary populations are incomplete for masses less than a few earth masses for $a < a_{\text{ice}}$ and less than a few $10 M_{\oplus}$ for $a > a_{\text{ice}}$.

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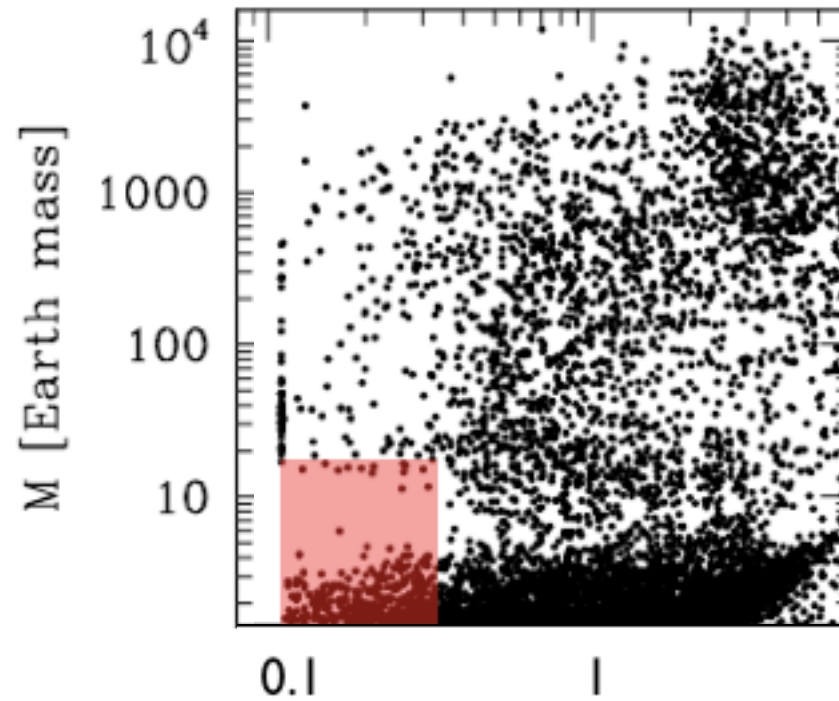
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or



1- Modified migration

2- Planet-Planet interactions

① Modified migration

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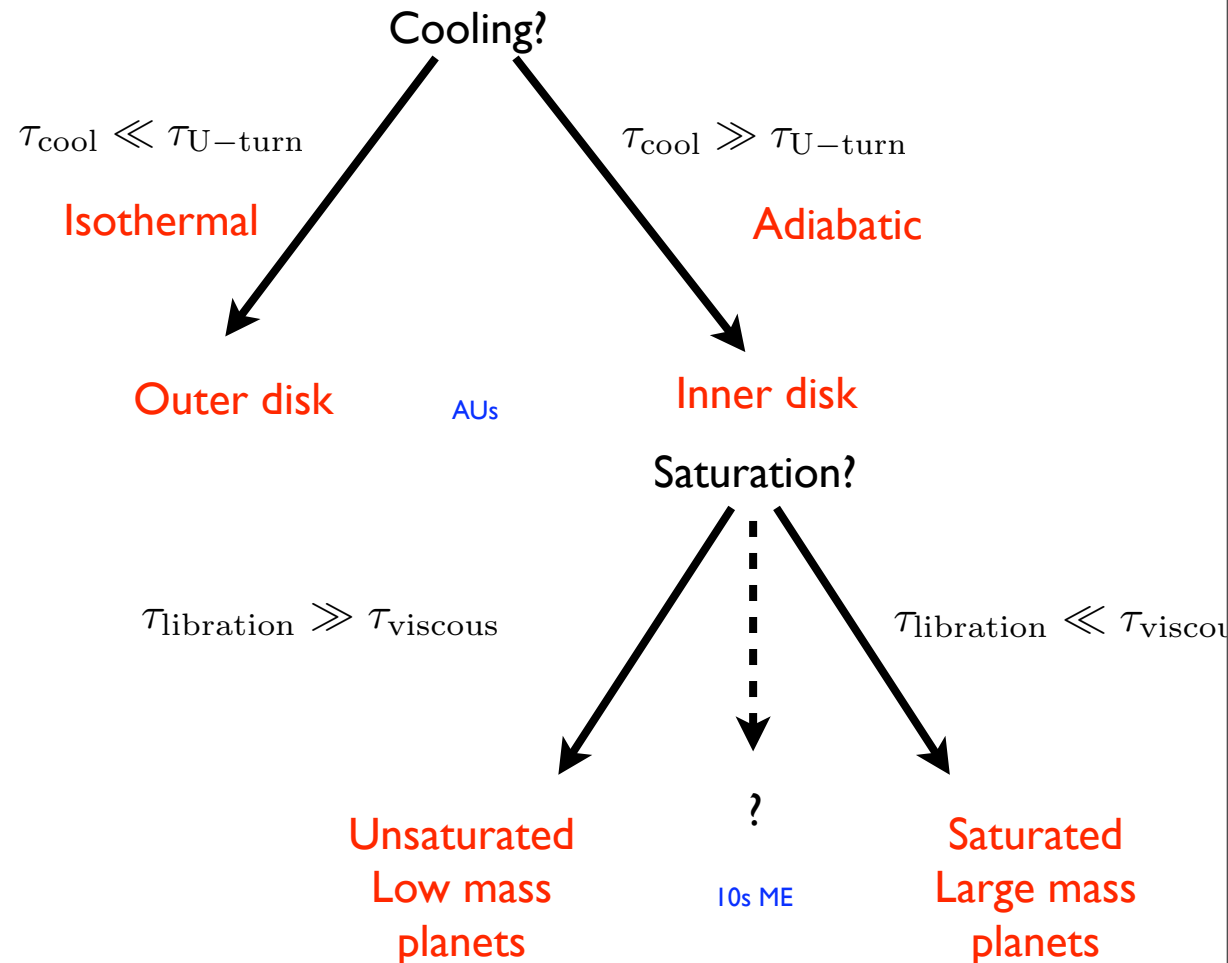
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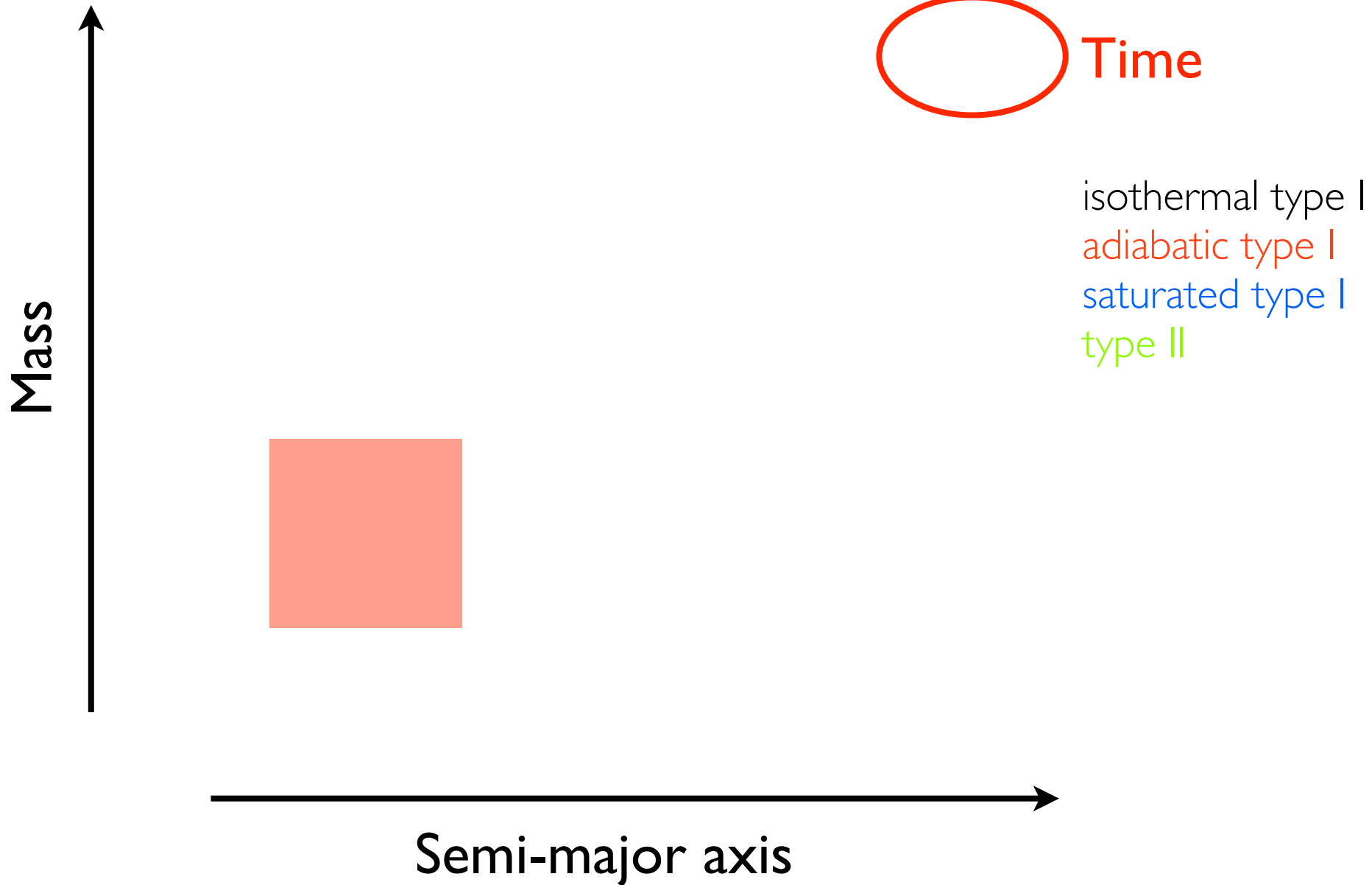
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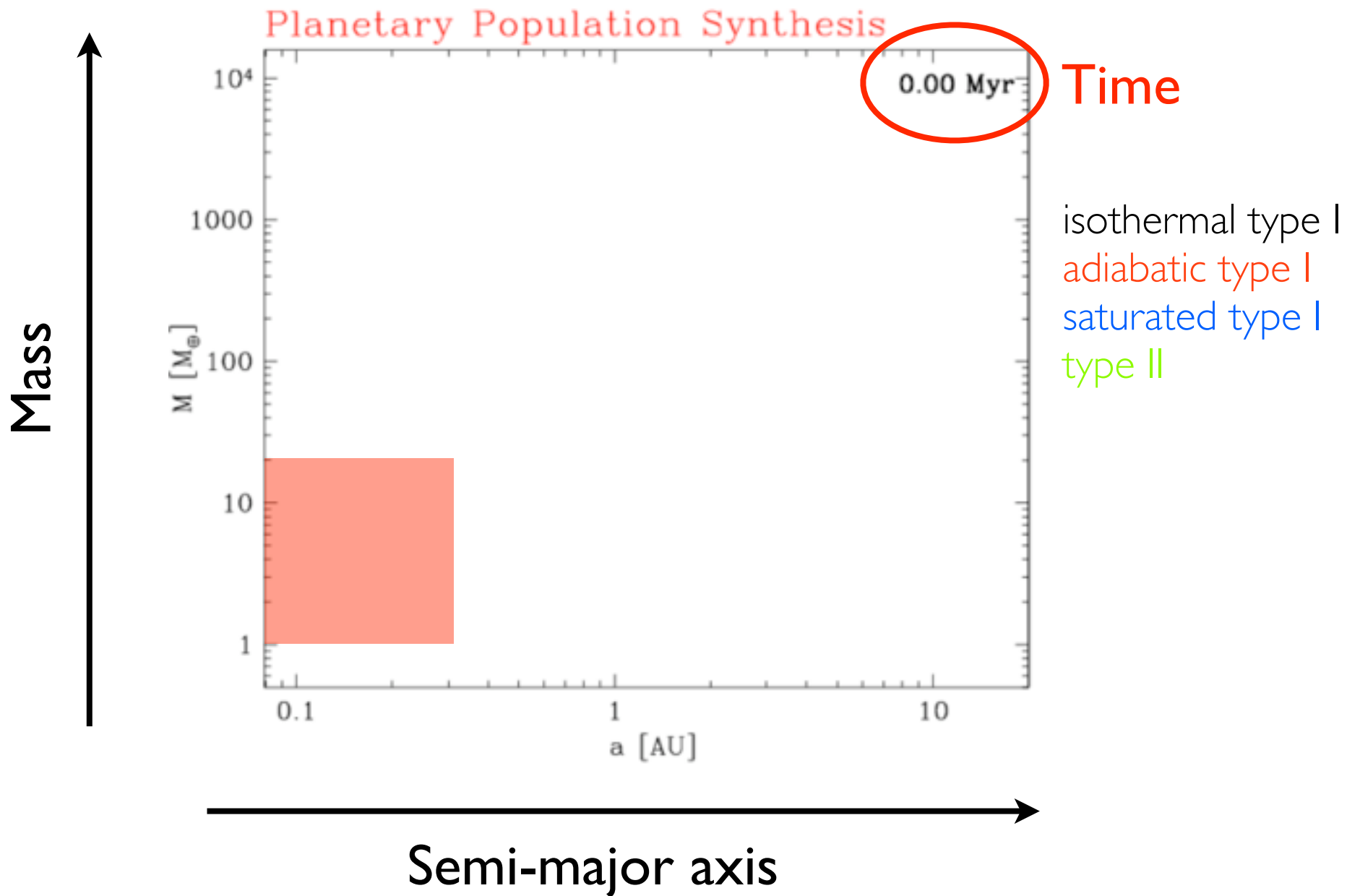


- Locally isothermal (Paardekooper et al. 2010)
- Adiabatic, unsaturated (Paardekooper et al. 2010)
- Adiabatic, saturated (Linblad torques, residual horseshoe drag)
- Reduction of gas surface density (Crida & Morbidelli 07)
- Transition to type II (Crida et al. 2006)

① Modified migration



① Modified migration

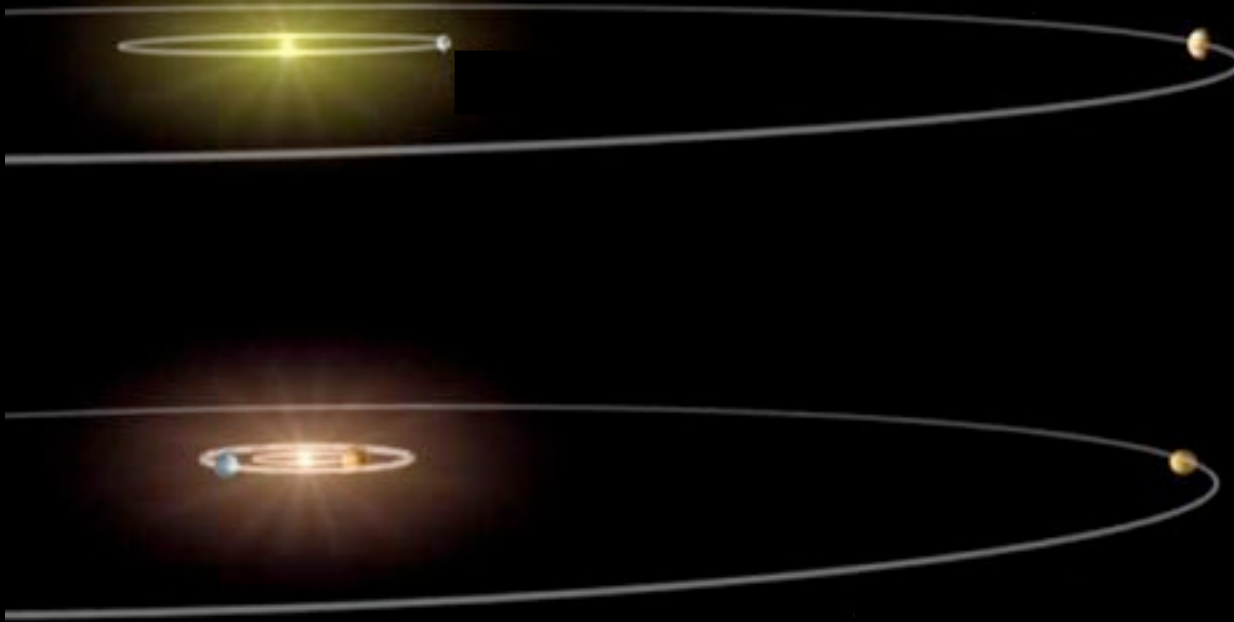


(III) Multi-planetary systems

- Present statistics

RV: 108 planets in 41 systems:
~ 25 % of known exoplanets
+ transit candidates

- Most of them with 2 planets
- HD10180: 7 planets
- 55 Cnc : 5 planets
- Mu Ara, G1876 : 4 planets
- Ups And, HD69830, HD40307: 3 planets



- longest-running programmes

--> largest fraction of multi-planet systems
Planets mainly form in multi-planet systems

**Need for multi-planet
formation models!**

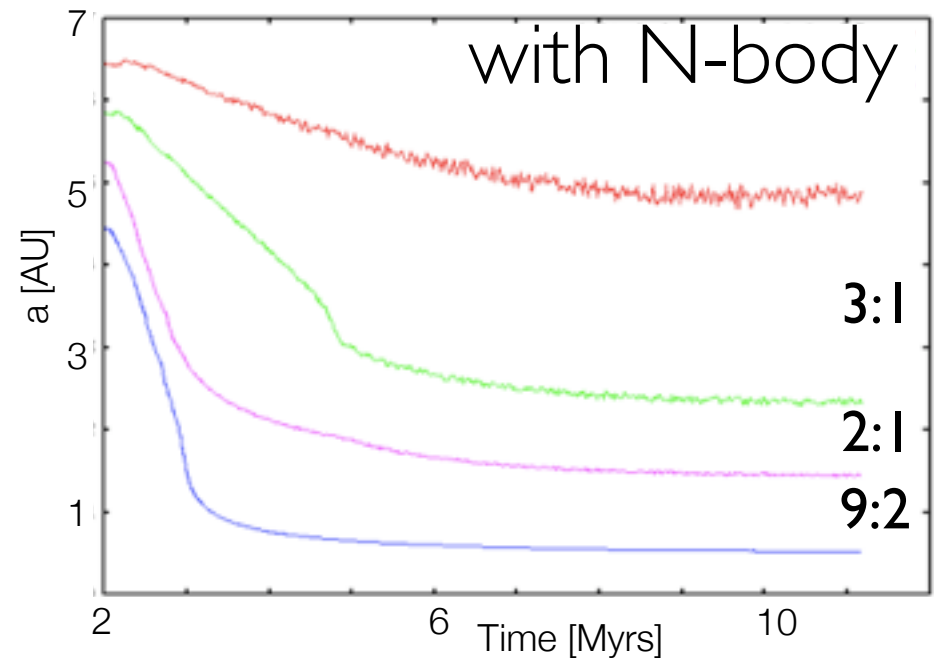
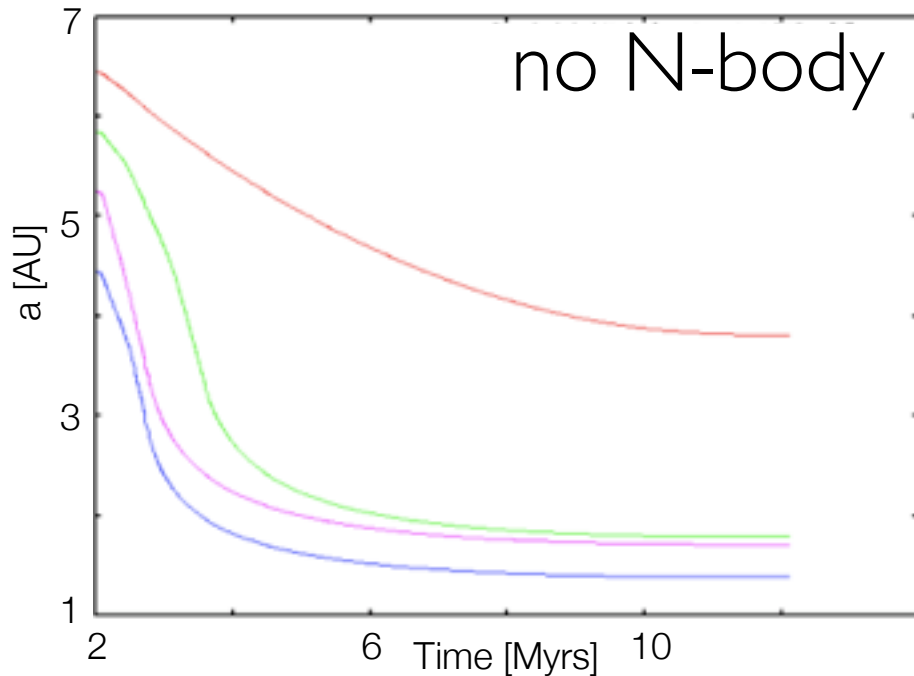
② Planet-planet interactions

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- Explicit **N-body** between planets with disk-planet interaction and collisions of planets.
- Eccentricity **damping** of planets (Nelson& Fogg 07), planetesimal ecc. as in Pollack et al. (96).
- Uniform** planetesimal density in overlapping feeding zones.

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Final mass [M_{Earth}]	without N body	with N body
Planet 1	970	890
Planet 2	975	970
Planet 3	750	430
Planet 4	7	4

Study

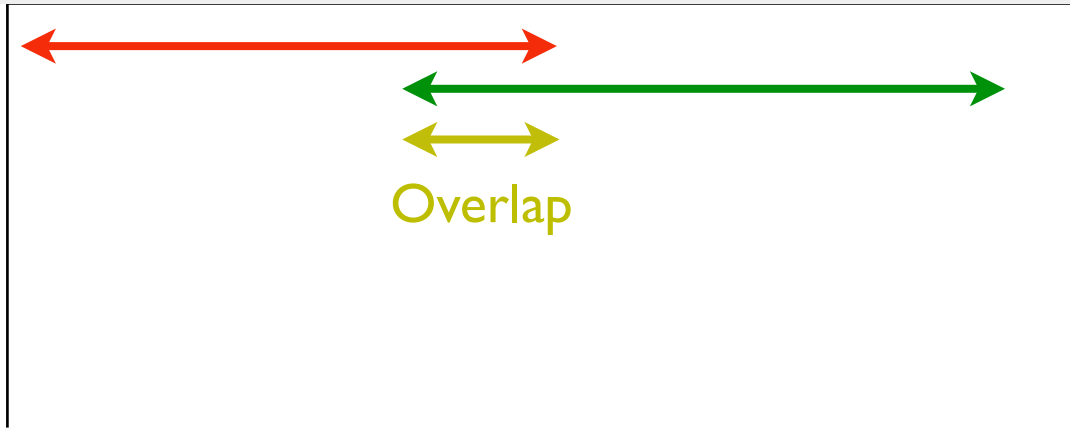
- solar system
- resonant systems
- ejection (far out planets)
- population synthesis

② Planet-planet interactions

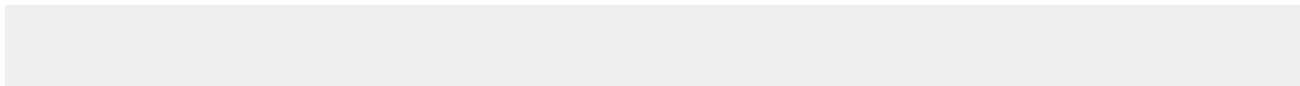
N-body simulations by S. Pfyffer

First planet FZ

Second planet FZ



Uniform surface density
and excitation in the
common FZ

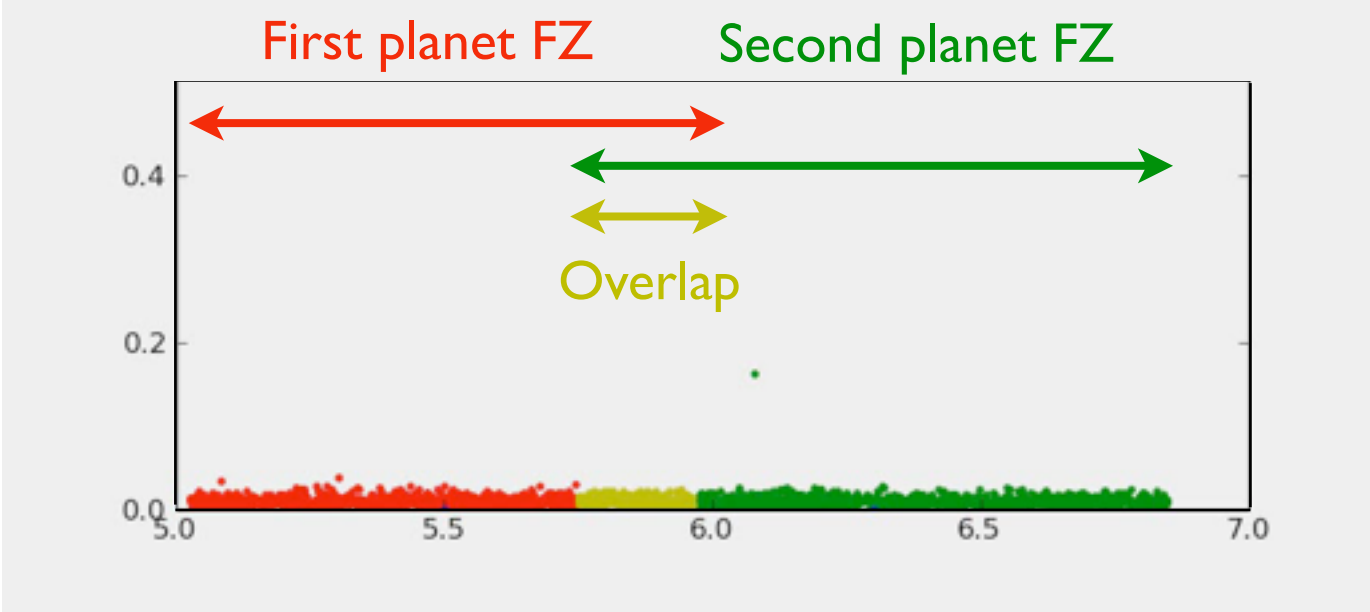


Planetesimal transport
to the outermost planet

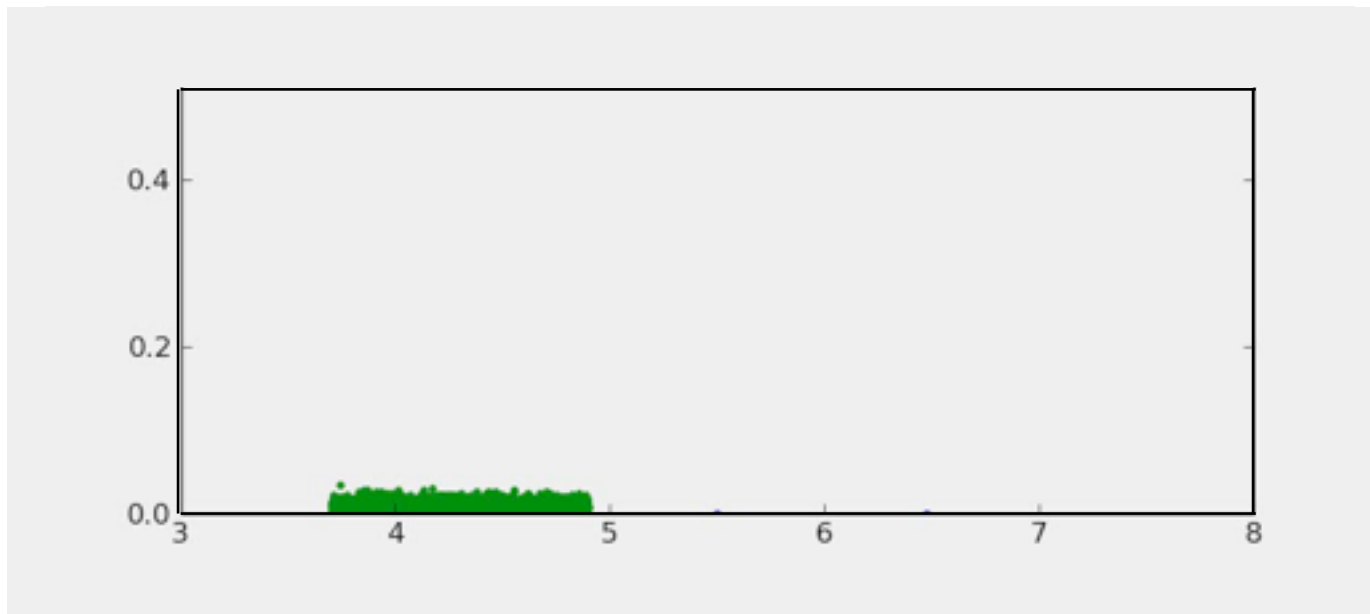
The internal structures of the two planets are no more independent

② Planet-planet interactions

N-body simulations by S. Pfytter



Uniform surface density and excitation in the common FZ

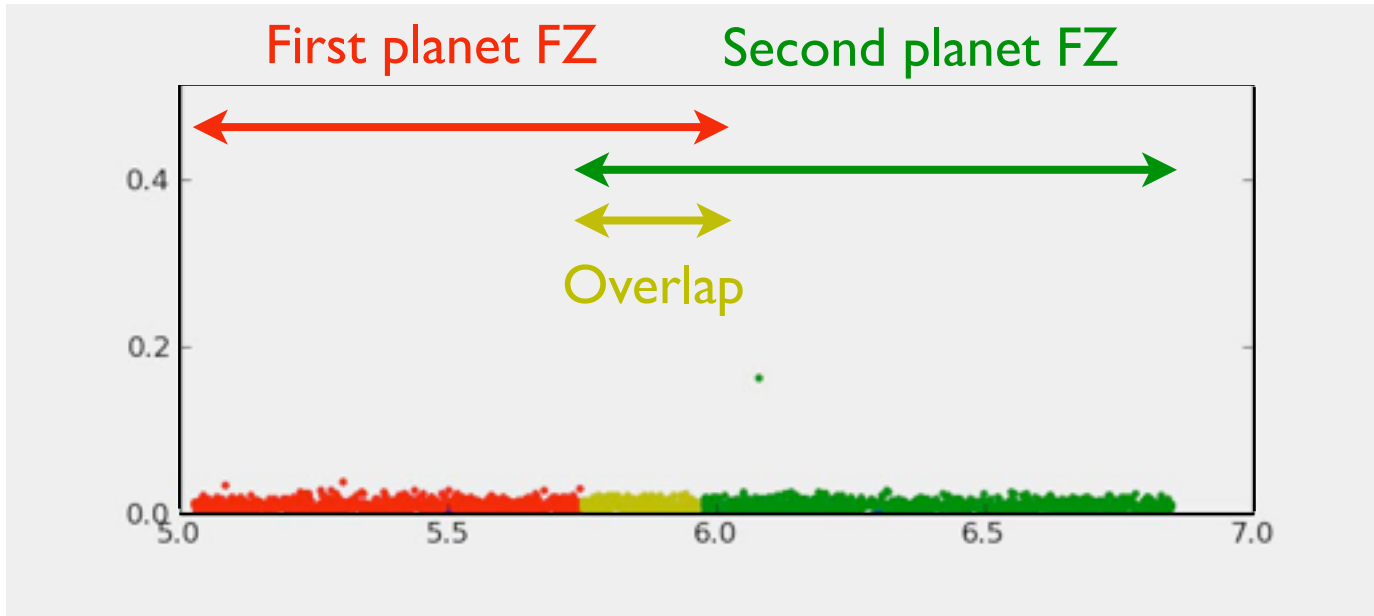


Planetesimal transport to the outermost planet

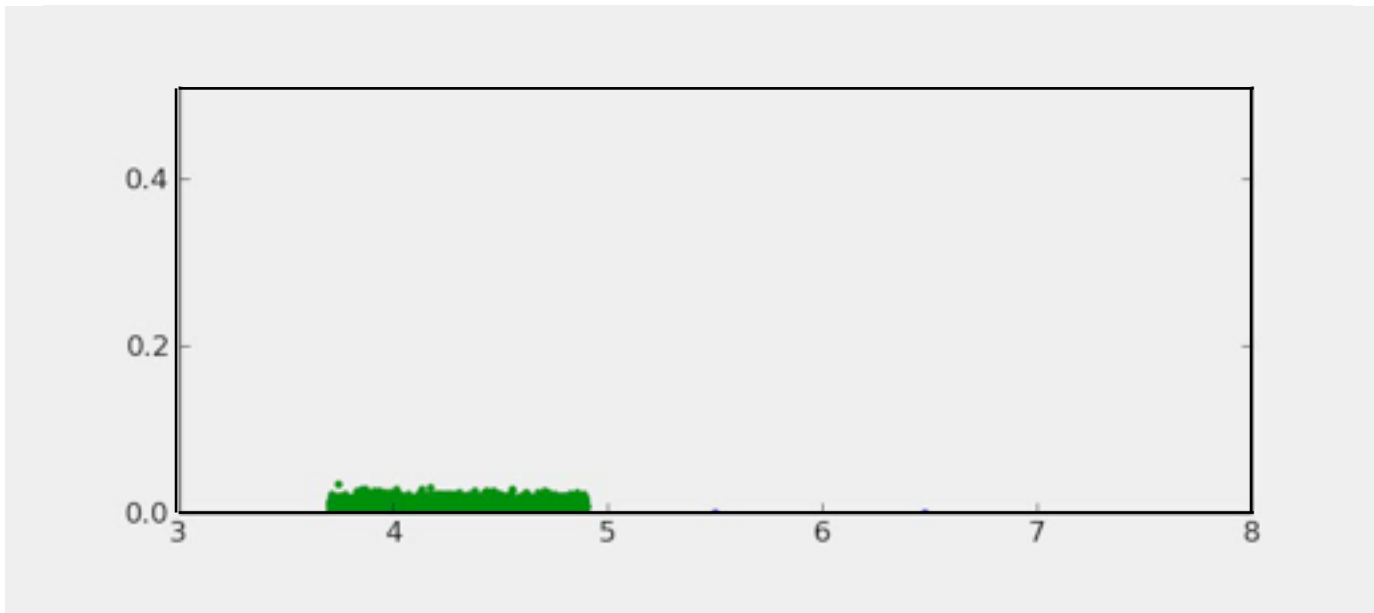
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Uniform surface density and excitation in the common FZ



Planetesimal transport to the outermost planet

The internal structures of the two planets are no more independent

② Planet-planet interactions

6 times 1 planet

6 planets - no gravity

6 planets

Isothermal type I migration / thermal criterion for gap opening

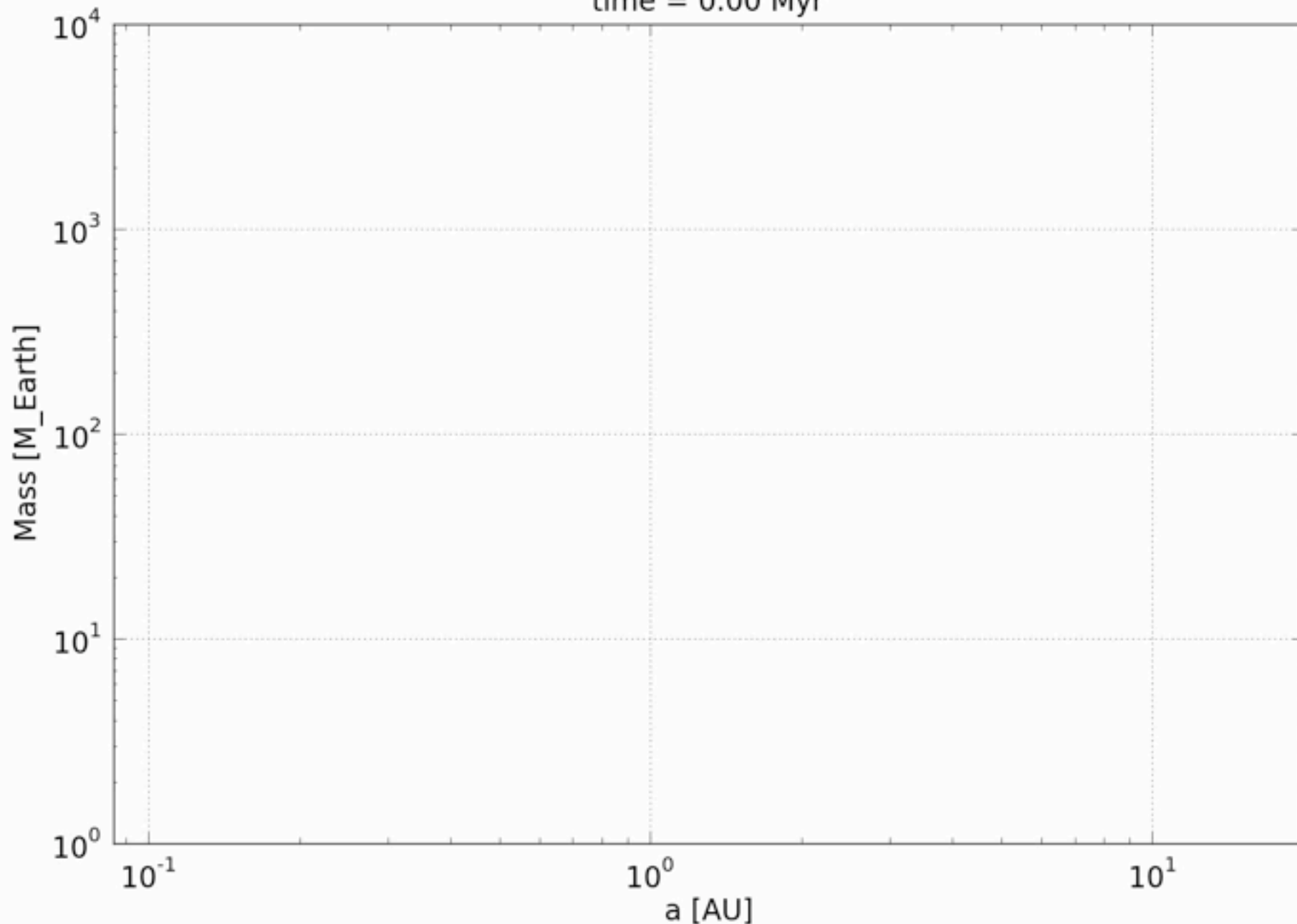
② Planet-planet interactions

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time = 0.00 Myr

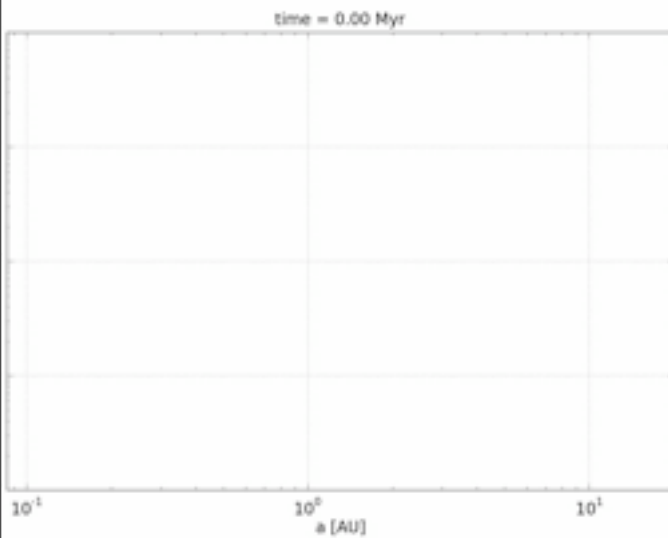


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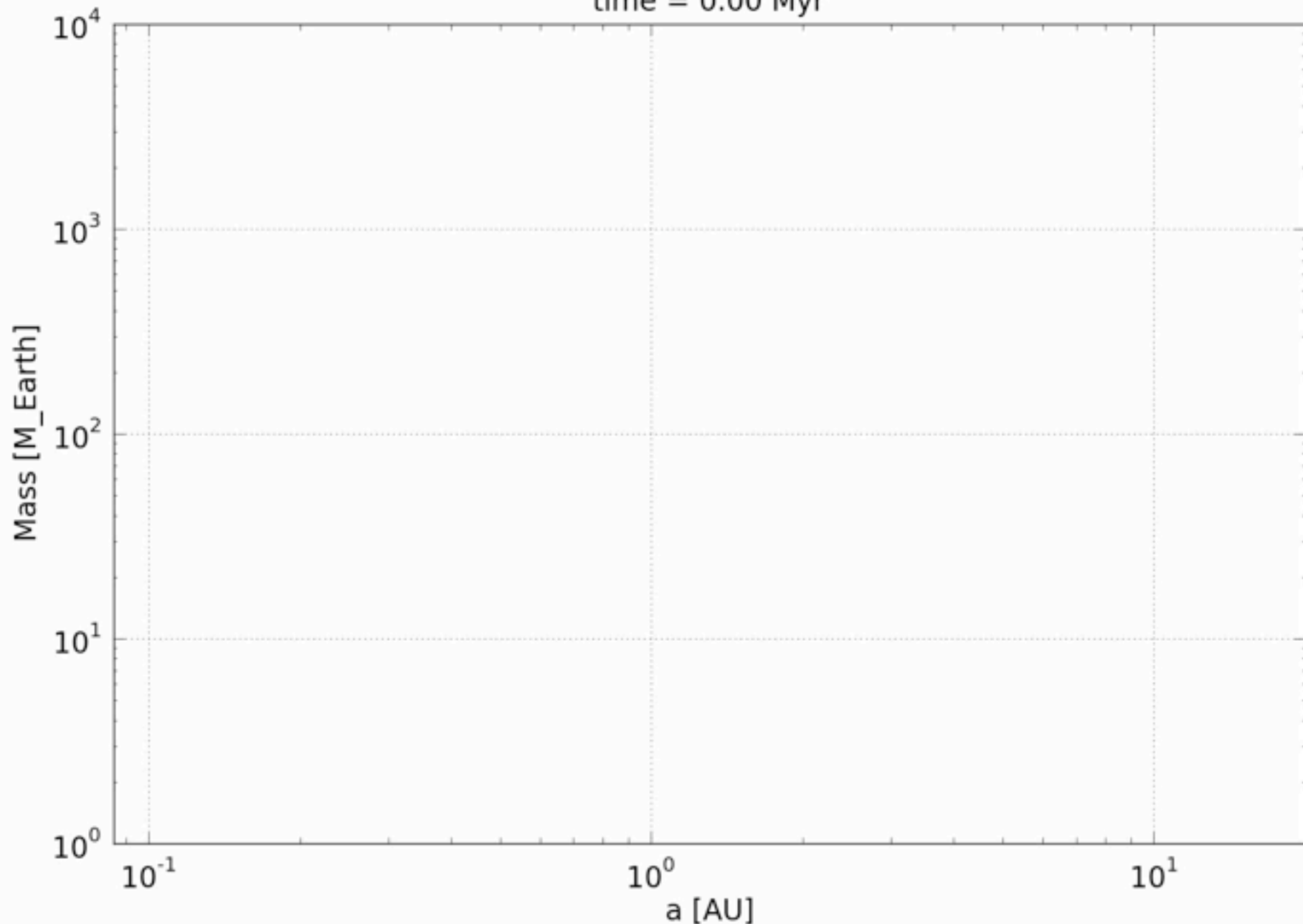
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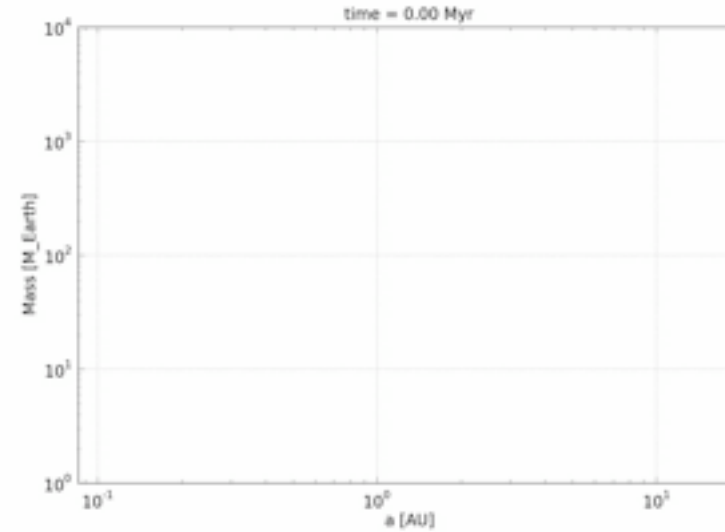
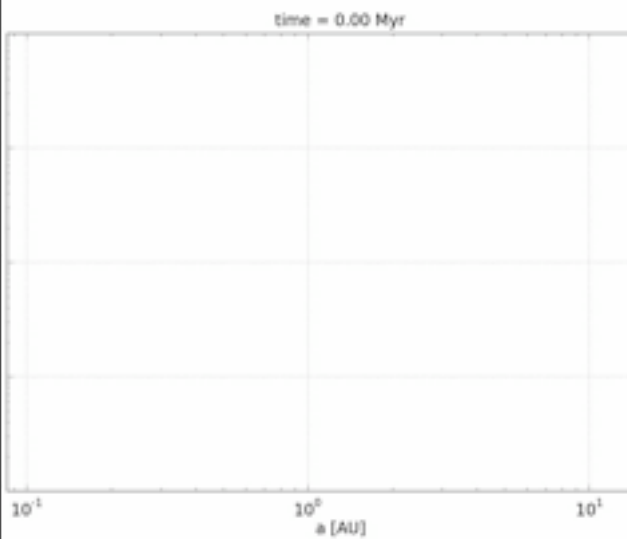


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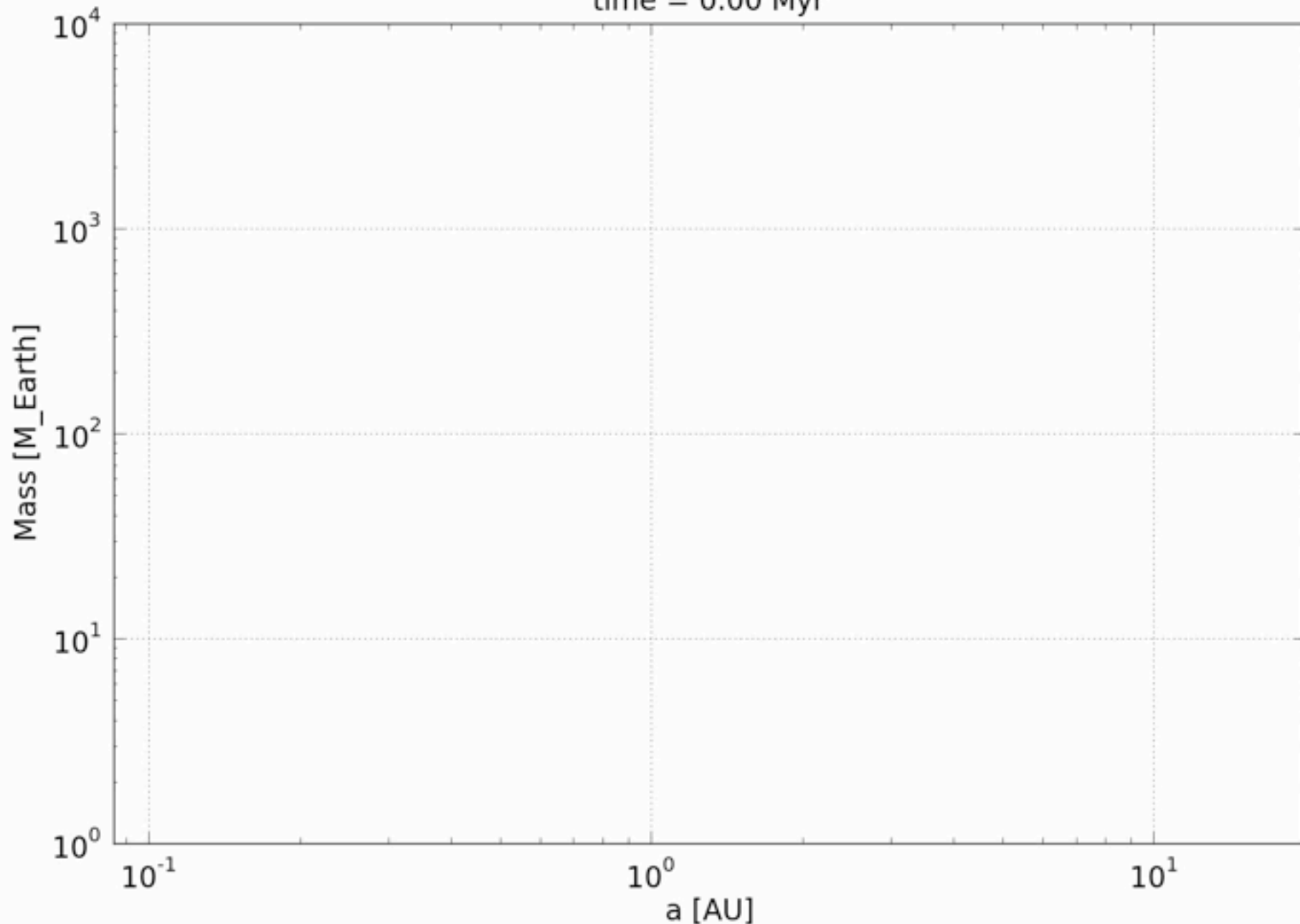
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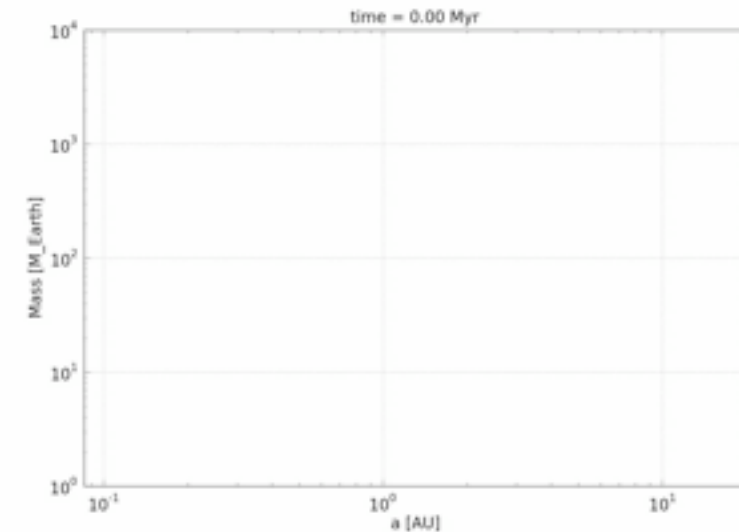
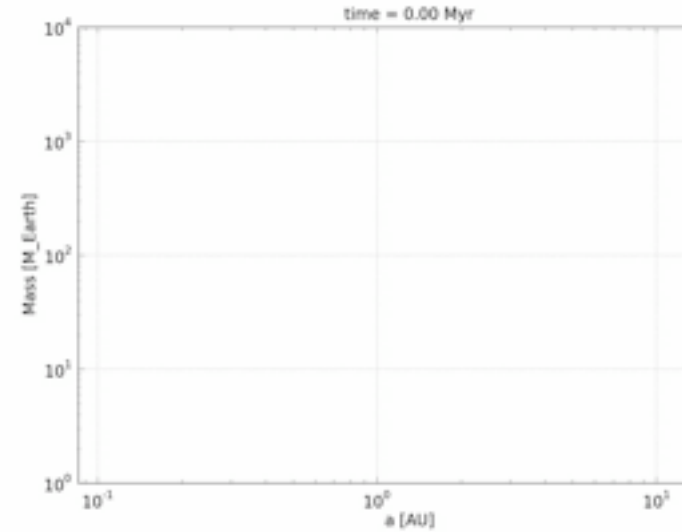
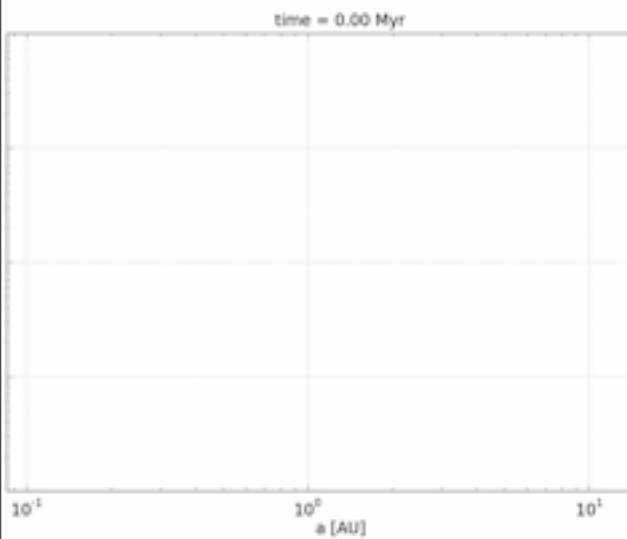


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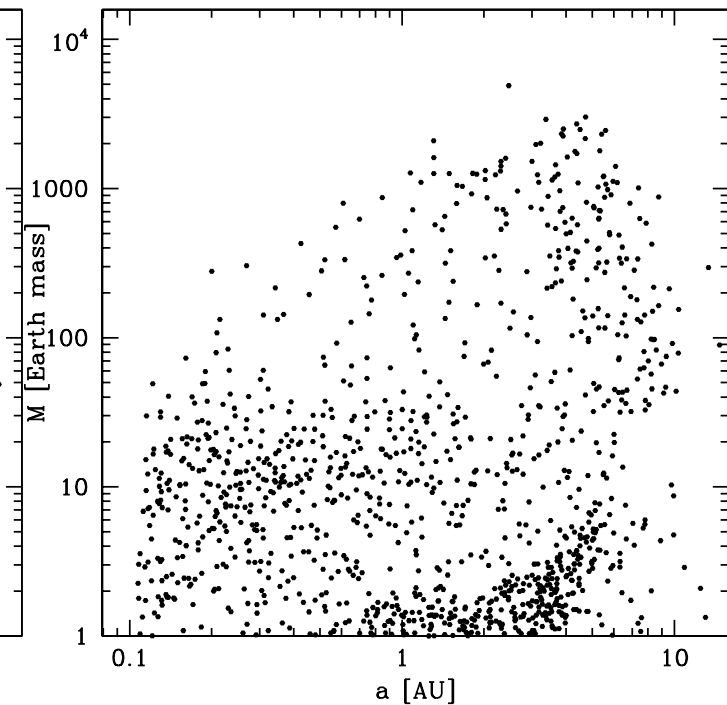
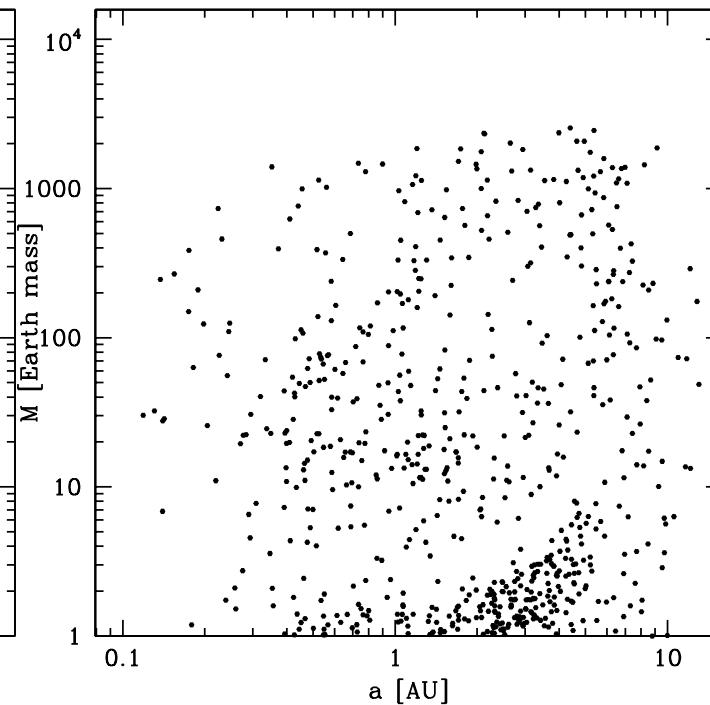
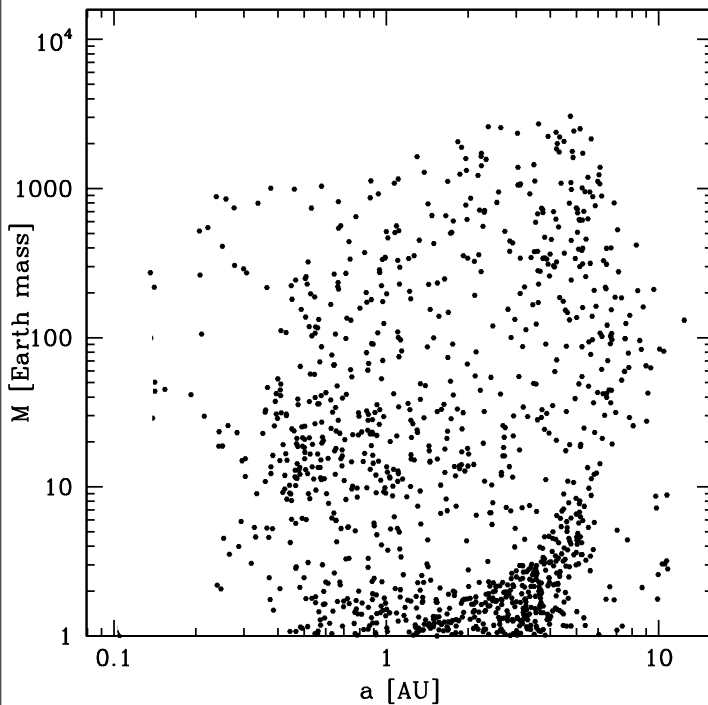
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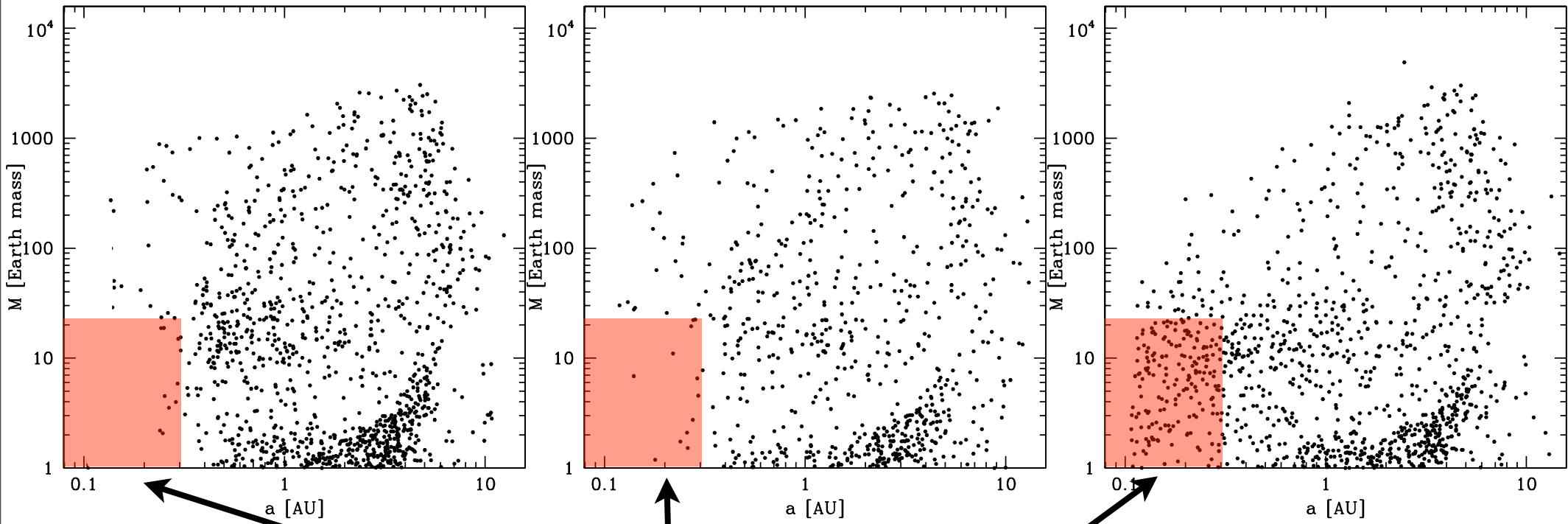
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6 planets - no gravity

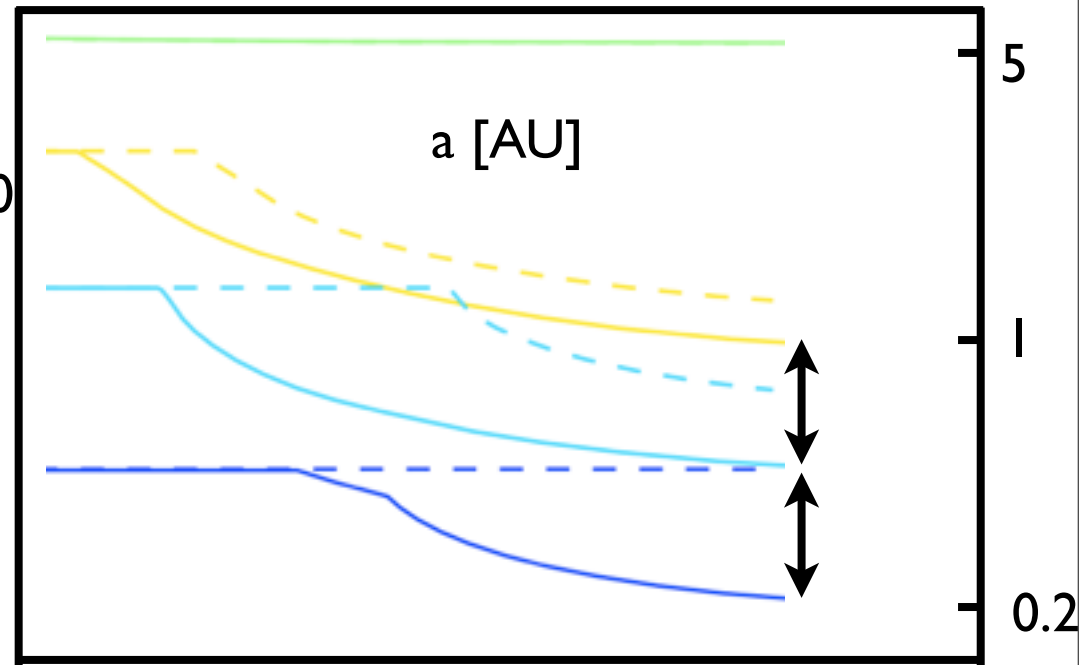
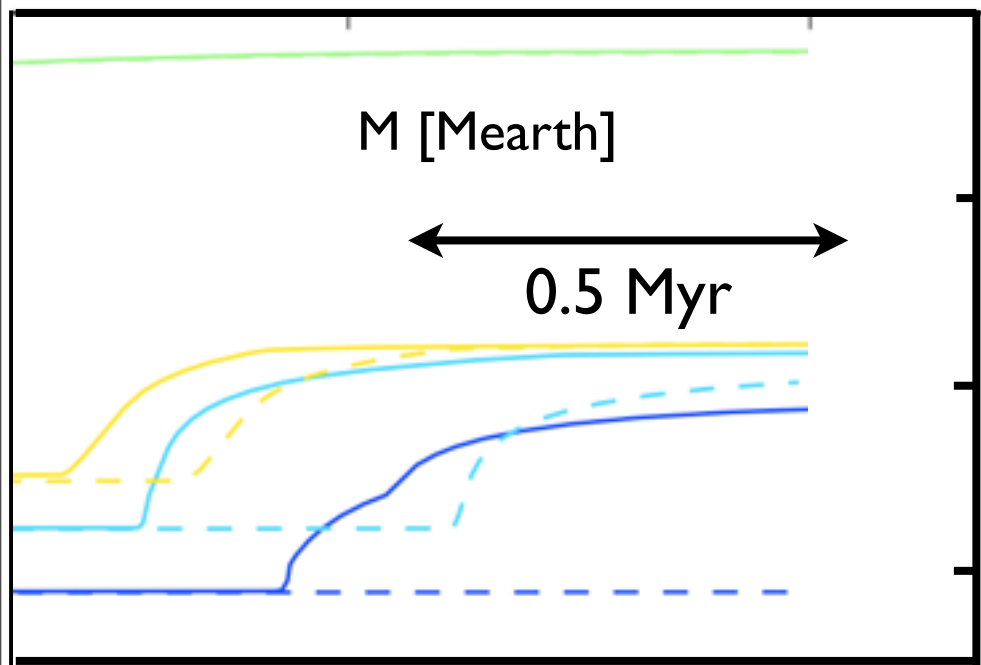
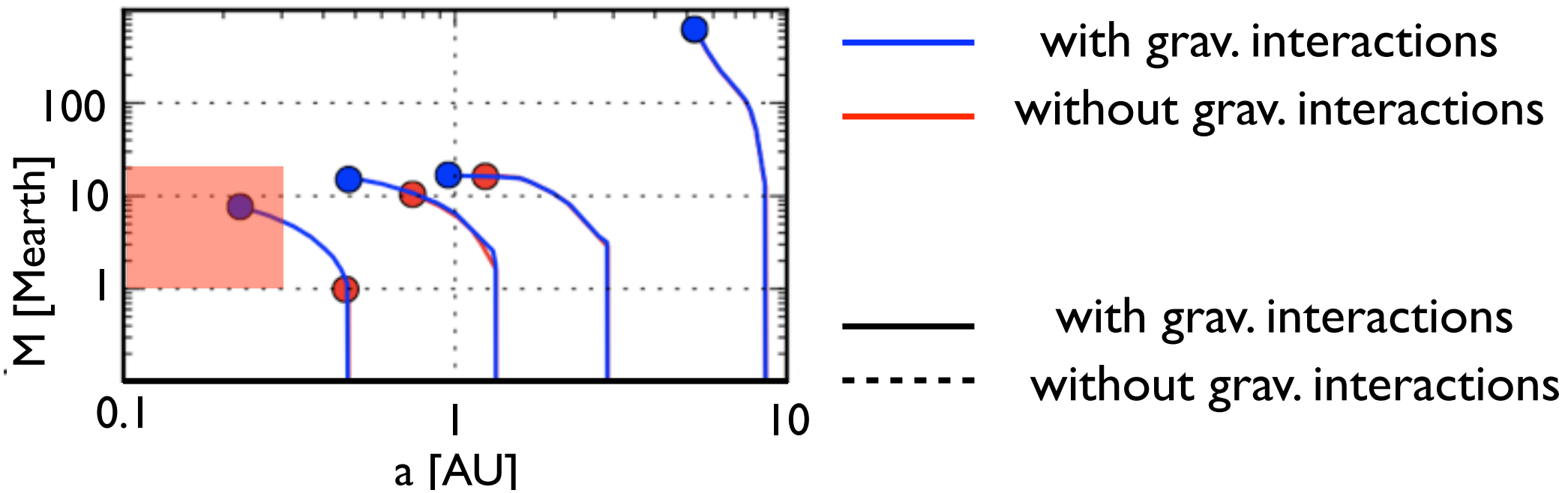
6 planets



Kepler candidates

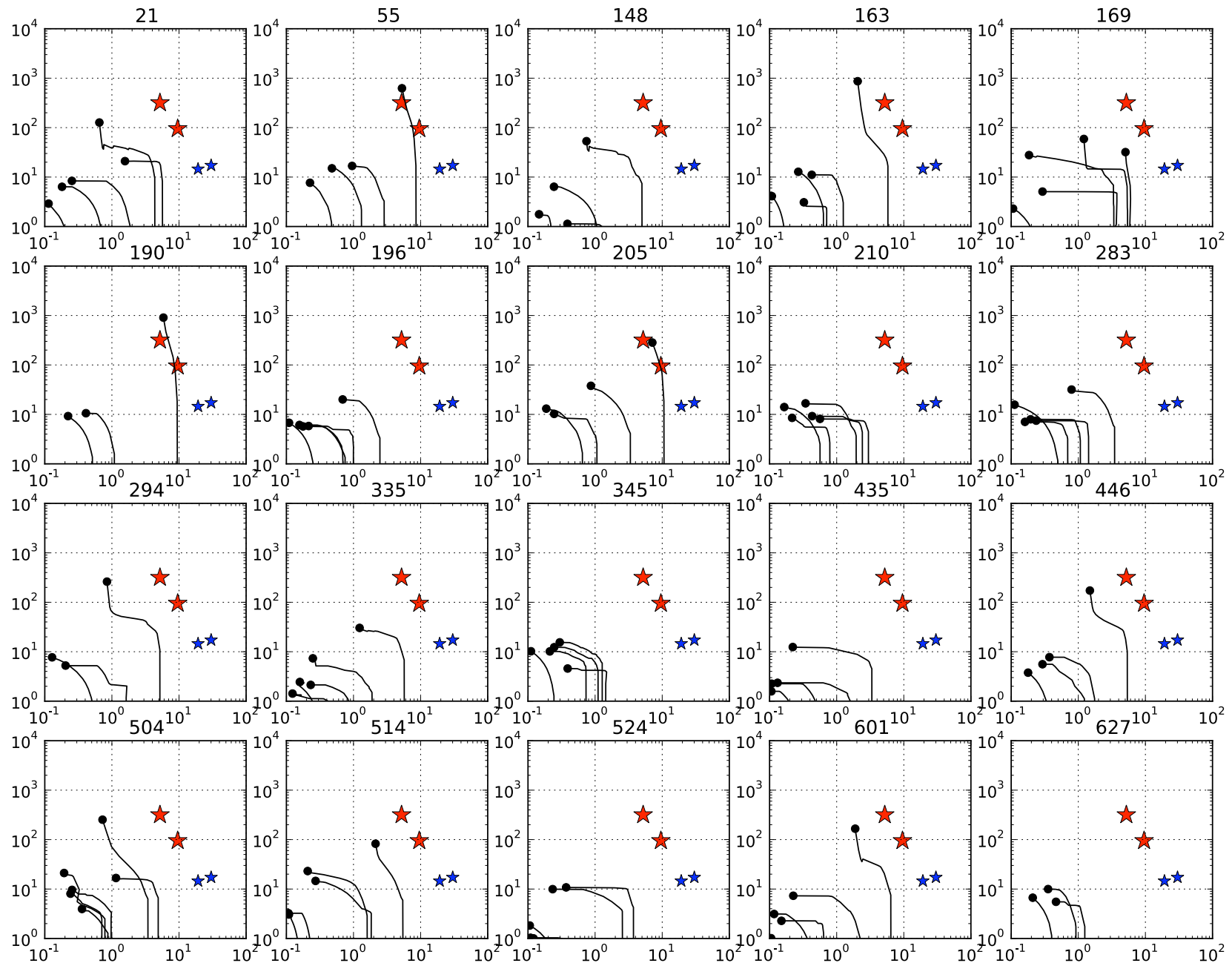
Isothermal type I migration / thermal criterion for gap opening

② Planet-planet interactions



Isothermal type I migration / thermal criterion for gap opening

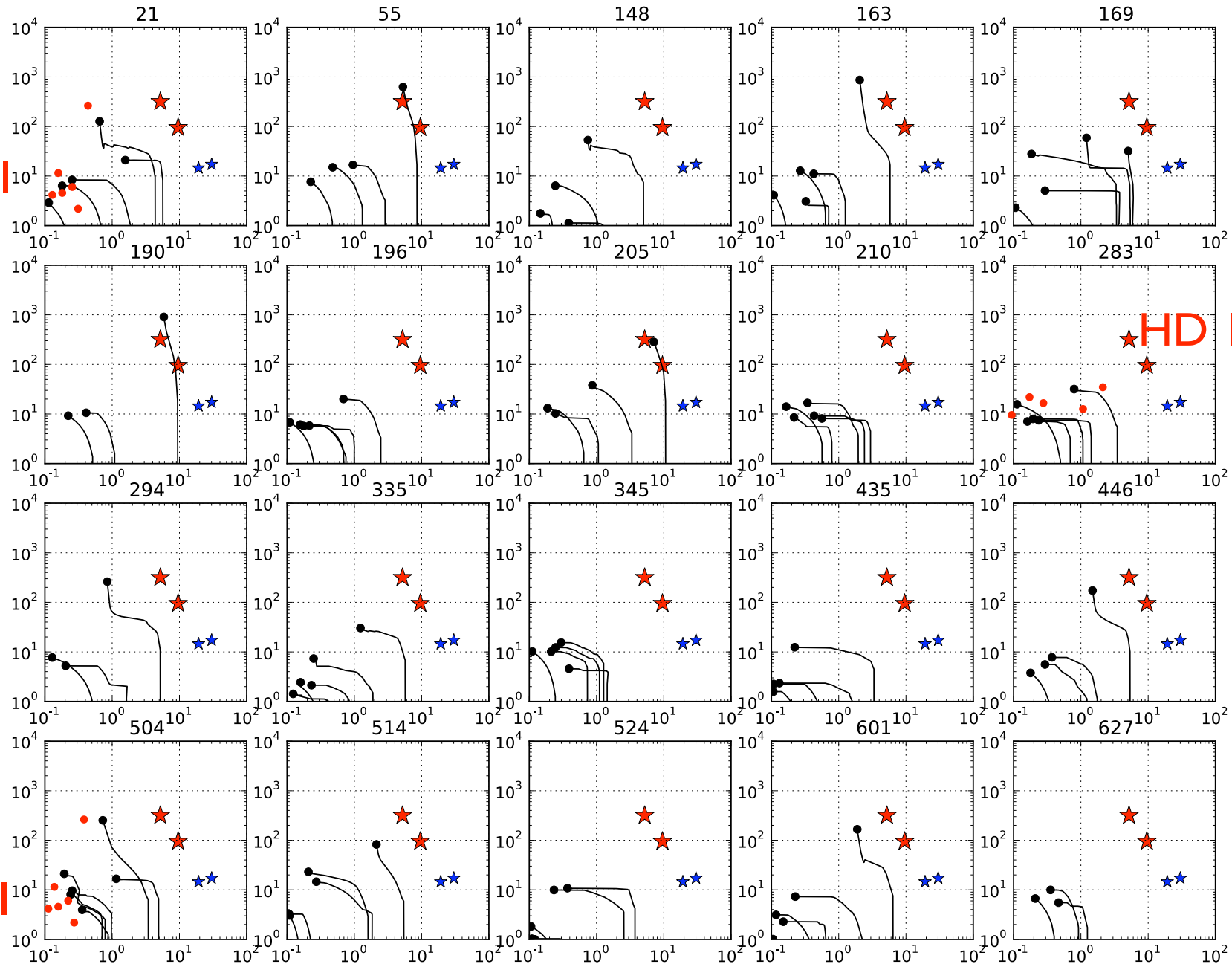
② Planet-planet interactions



Isothermal type I migration / thermal criterion for gap opening

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Kepler I I



Kepler I I

Isothermal type I migration / thermal criterion for gap opening

Conclusions

Models reproduce:

aM for sub-sample of planets (10 m/s, no system, ...)

Jupiter & Saturn (bulk composition - atm. composition)

produce planet desert

Recent developments:

Planet-planet interactions

Type I migration rate

}

may explain the planet oasis

Disk models including irradiation and B effect

and...

Planetary population synthesis considering different solids accretion rates

A. Fortier, Y. Alibert and F. Carron
Physikalisches Institut, Universität Bern, Switzerland

Planetary population synthesis considering different solids accretion rates

Andrea Fortier, Yann Alibert & Frederic Carron
Physikalisches Institut, Universität Bern, Switzerland

ABSTRACT: In the framework of the nucleated instability model, the formation time scale of giant planets is very sensitive to the time it takes to build the solid core. The accretion of solids can be described by two different, consecutive regimes: it first proceeds in a very fast 'fallout', known as runaway growth, and later on in a much slower regime, the so called oligarchic growth. The transition between the runaway and the oligarchic growth depends on many parameters (e.g. the rotation mass and the size of the accreted planetesimals), but as a general rule we can assume that an embryo of a few Earth masses is already an oligarch. Here, the transition to build a 10 Earth mass (10 M_{\oplus}) core is regulated by the oligarchic regime, as the previous runaway stage proceeds in a negligible timescale compared to the oligarchic one. In this work we show the results of adapting the oligarchic growth for the core in planetary population synthesis calculations, in previous works (see Morbidoni et al. 2009) a 10 Earth solid accretion rate was assumed, leading to a very fast formation of massive solid embryos. Here we show that when considering the oligarchic growth, the formation of giant planets is more difficult, especially in the outer parts of the disk, where the formation of big planets is almost impossible under the usual hypothesis. On the other hand, many Earth to Super Earth sized planets are found in the very innermost parts of the disk. However, if the size of the accreted planetesimals is reduced, the formation of giant planets is more likely. We also consider the formation of planetary systems, including the friendly interaction between the forming planets and the collisions that may occur among them during migration. In the case of many planets forming in the same disk, we find that the final masses are smaller (but not too small) than in the case of a single planet per disk.

THE MODEL:
The general hypothesis of our model for the population synthesis calculation can be found in Morbidoni et al. (2009) & 16. Here we summarize the main differences between the two works:
• The protoplanetary disk extends from 0.1 AU to 100 AU, where $\Sigma(r) = 0.02 \text{ g cm}^{-2} (r/1 \text{ AU})^{-1.5}$.
• The disk evolves with time due to accretion onto the star (taking into account the out of equilibrium effect), photoevaporation and accretion onto the planets (this means that the gas accreted by the planets is removed from the disk).
• The growth of the planets is calculated self-consistently, coupling the accretion rate of solids to the accretion rate of gas.
• Planet migration: for Type I migration, the isothermal model is adopted with a reduction factor in the migration rate of 0.1. The condition for gas opening takes into account the viscosity of the disk and the standard criterion of the Hill radius being larger than the disk height scale (D'Almeida et al. 2006).

THE ACCRETION RATE OF SOLIDS:
Regarding the accretion rate of solids, in previous works it was assumed to be very high, close to that of the runaway regime. For the present work, the oligarchic growth regime for the core is adopted. We calculate the accretion rate of solids in the framework of the gambler's ruin approximation of Ida et al. (2003), where the accretion rate of an embryo depends on the collision probability of planetesimals. This probability depends on the relative velocity between the embryo and the incoming planetesimals which, in turn, depends on the eccentricities (e) and inclinations (i) of planetesimals populating the disk. We assume the equilibrium value for e and i, which means that the stirring due to the embryo is counterbalanced by the gas drag of the nebula. In any population synthesis calculation consider the formation of 1000 planetesimals, one planet per disk, randomly distributed in semi major axis. The seeds for the planetary embryos are of the mass of the Moon at the beginning of the simulation ($t = 0$). The range for the disk masses is 10^2 to 10^3 solar masses, and the photoevaporation rate is adjusted to have disk lifetimes not longer than 6 Myrs.

RUNAWAY VS. OLIGARCHIC GROWTH
[Two plots showing growth curves for runaway and oligarchic regimes]

PLANETARY SYSTEMS
[A plot showing the distribution of planetary systems]

SUMMARY
We studied the formation of planetary systems in the context of the nucleated instability model. The formation of giant planets is almost impossible within the lifetime of the protoplanetary disk, unless small planetesimals, of about 100 Earth radii, are assumed to populate the disk. When more than one planet per system is considered, the final masses of the resulting planets are smaller.

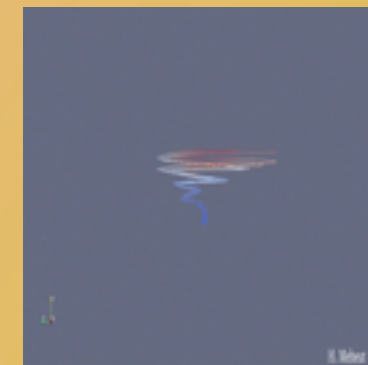
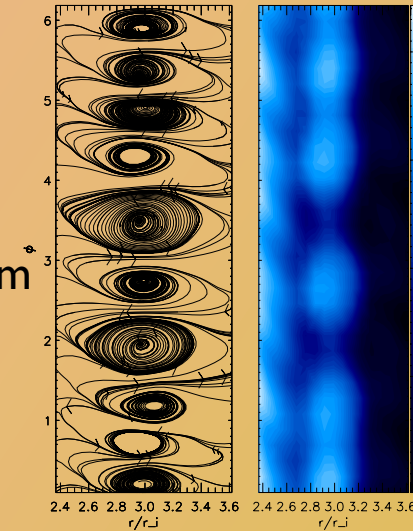
REFERENCES
Crida S., Morbidoni A., Masset F., 2006, Icarus, 181, 587
Fortier A., Benmoult O-G., Brunini A., 2007, A&A, 471, 811
Fortier A., Benmoult O-G., Brunini A., 2009, A&A, 505, 1240
Ida S., Tanaka H., Matsumura K., Wetherill G.W., Kokubo T., 2003, Icarus, 168, 233
Morbidoni C., Alibert Y., Benz W., 2009, A&A, 502, 2229
Morbidoni C., Alibert Y., Benz W., Naoz S., 2009, A&A, 505, 1301

The pink poster!



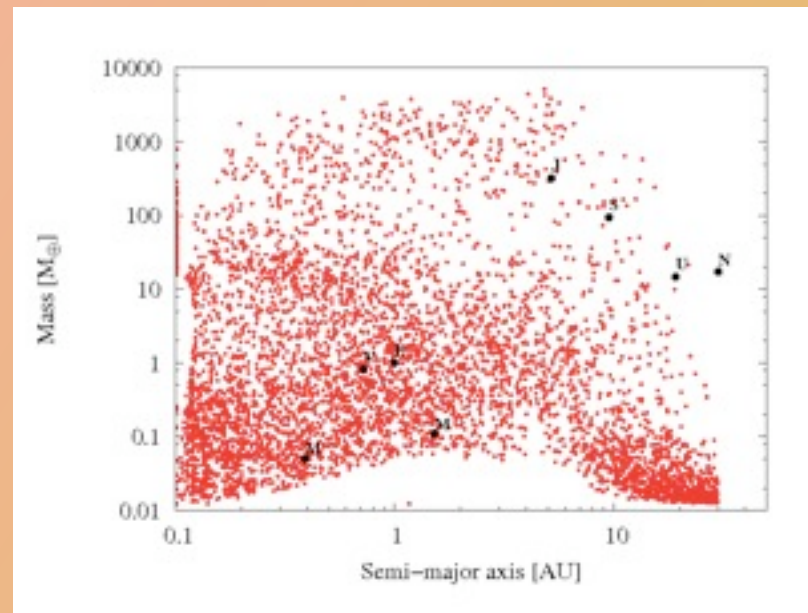
Runaway vs. Oligarchic growth for the core

- Initial mass: Moon mass
- Planetesimals radii: 100 km
- **Runaway**: giant planets are all over the disk
- **Oligarchic**: almost NO giant planets can form before the disk dissipates



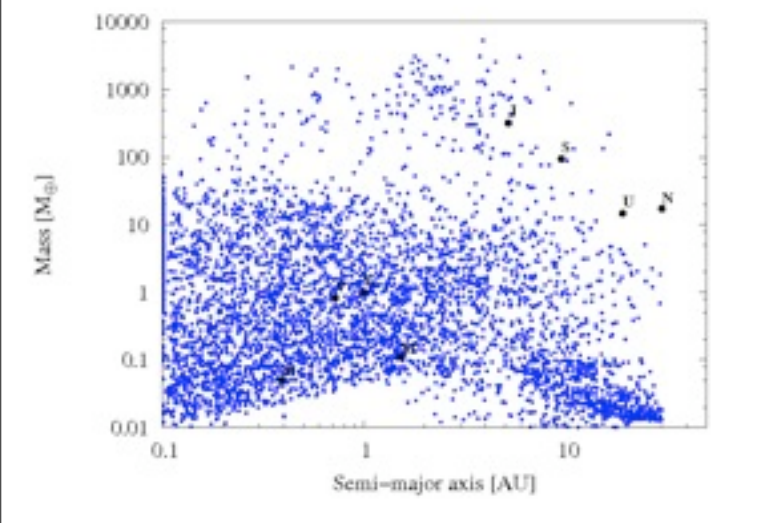
Oligarchic growth: one planet per disk

- Initial mass: Moon mass
- Planetesimals radii: 100 m
- Giant planets can form everywhere in the disk



N-body planet population synthesis

- Initially: 6 seeds of the Moon mass
- Oligarchic growth
- Planetesimals radii: 100 m
- Giant planets can form everywhere in the disk but the mean mass is lower than when one planet per disk is considered



Conclusions

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Can we form the Solar System using same models?

we don't know...

yet!