Planet formation and population synthesis

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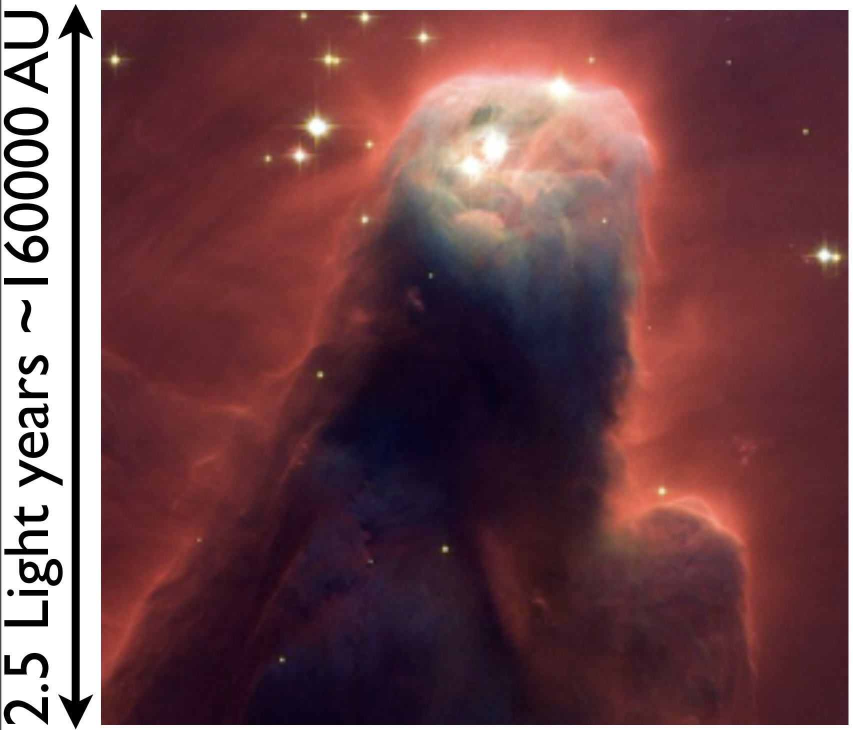
Planet formation

Planet formation

Planet formation

NGC2264

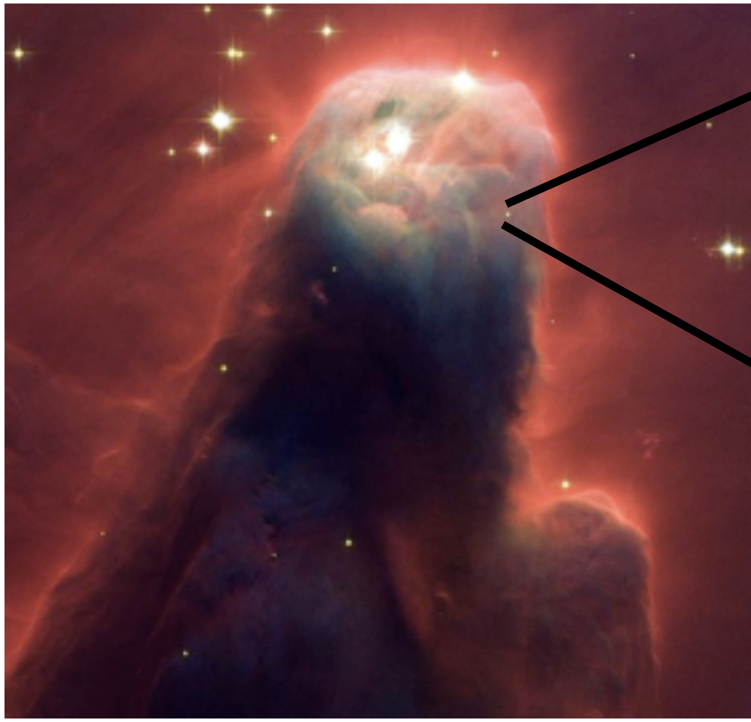


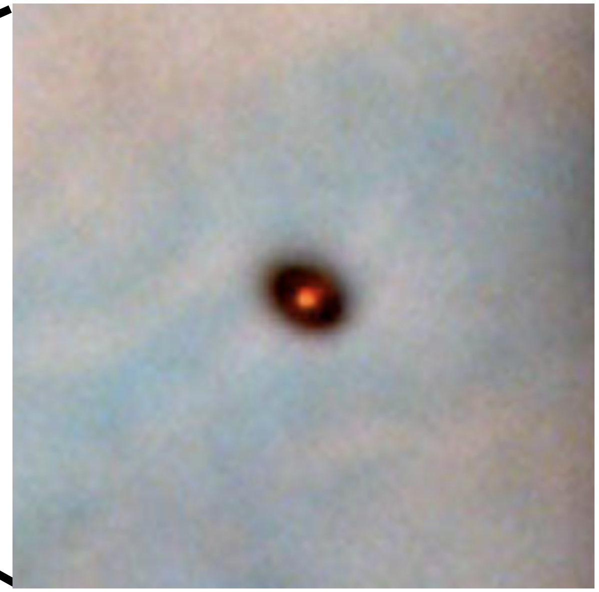
Planet formation

Planet formation

NGC2264

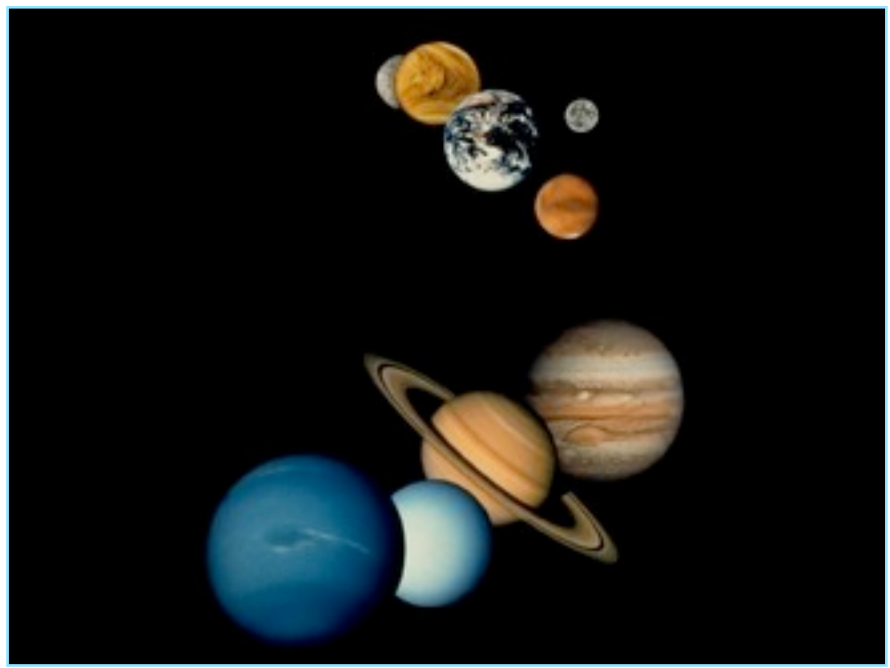
2.5 Light years ~160000 AU



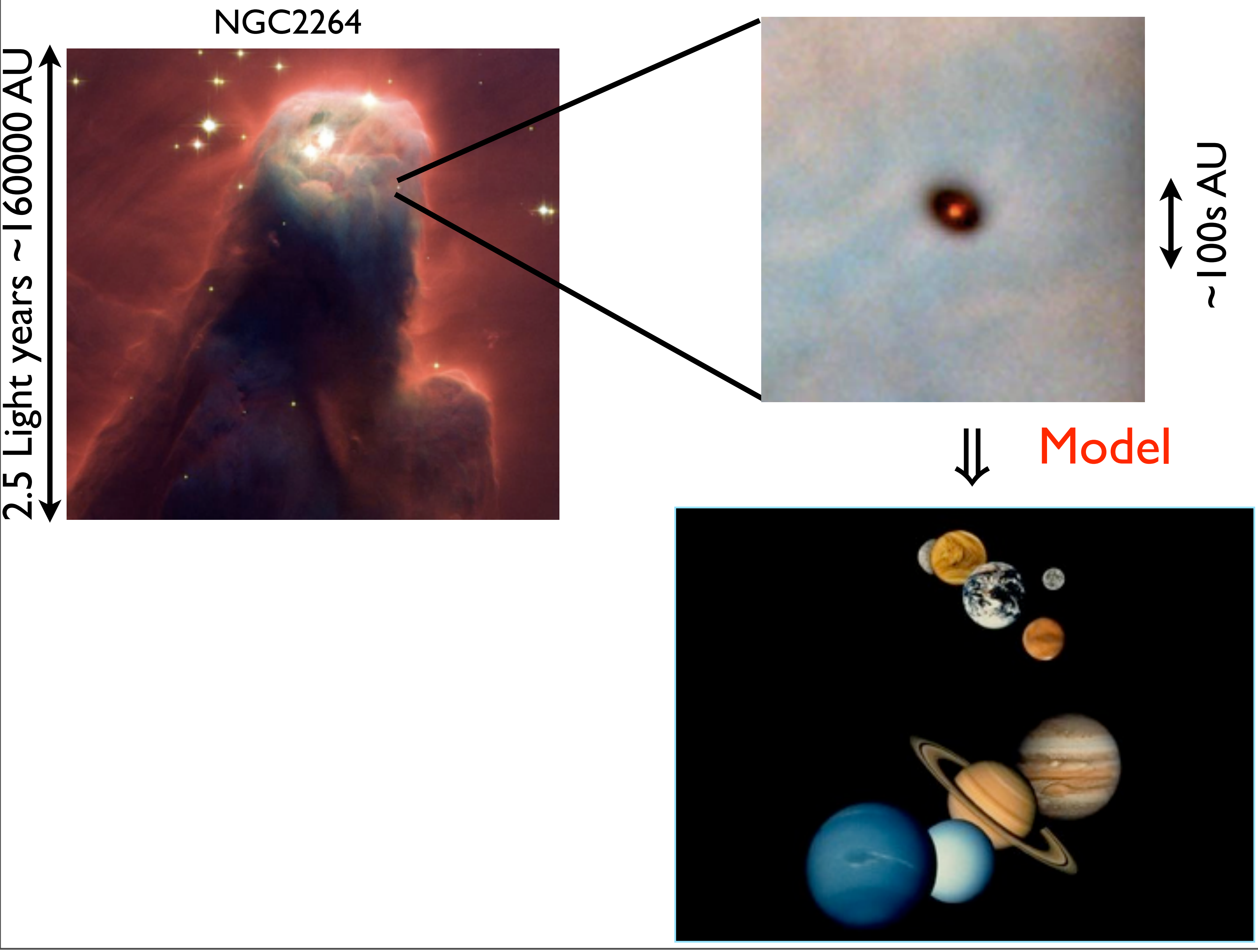


~100s AU

⇓

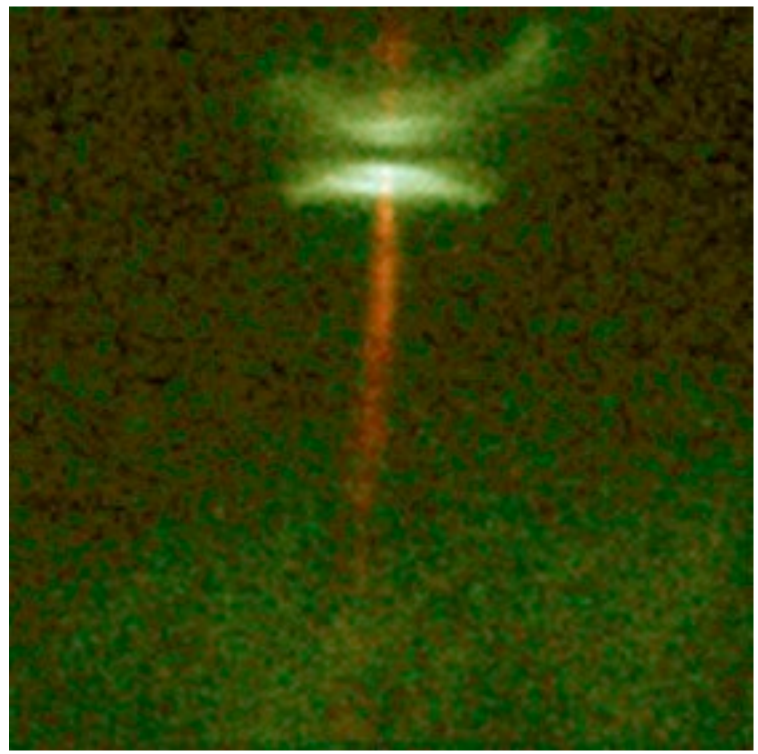


Planet formation



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

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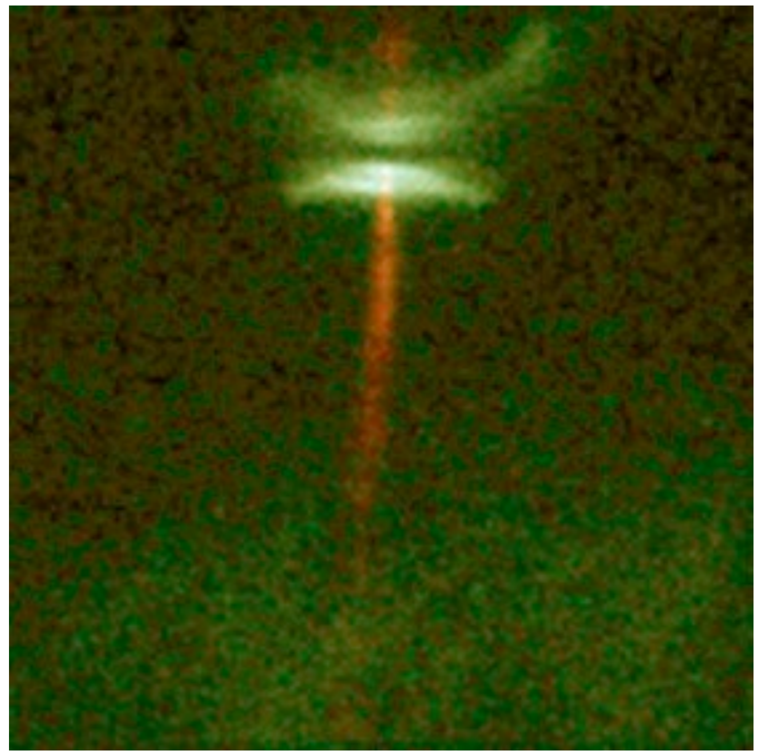

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Protoplanetary disks: observations

Giant planets form by accreting gas from protoplanetary disks

$\Rightarrow$ disks lifetime gives maximum formation time

Giant planets must form in < 10 Myr

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

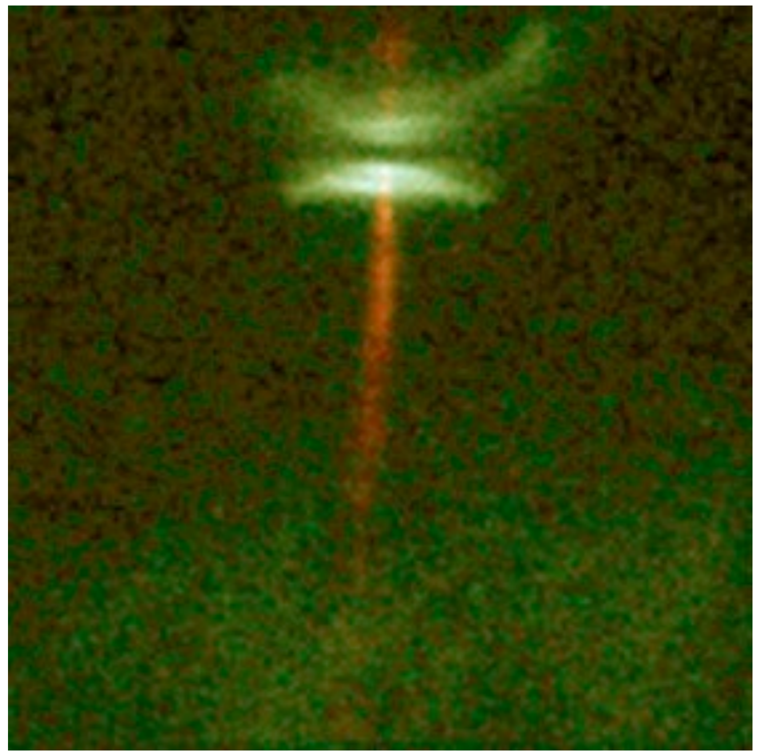
⇒ disks lifetime gives maximum formation time

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_{sun}

Protoplanetary disks in the Orion Nebula; HST



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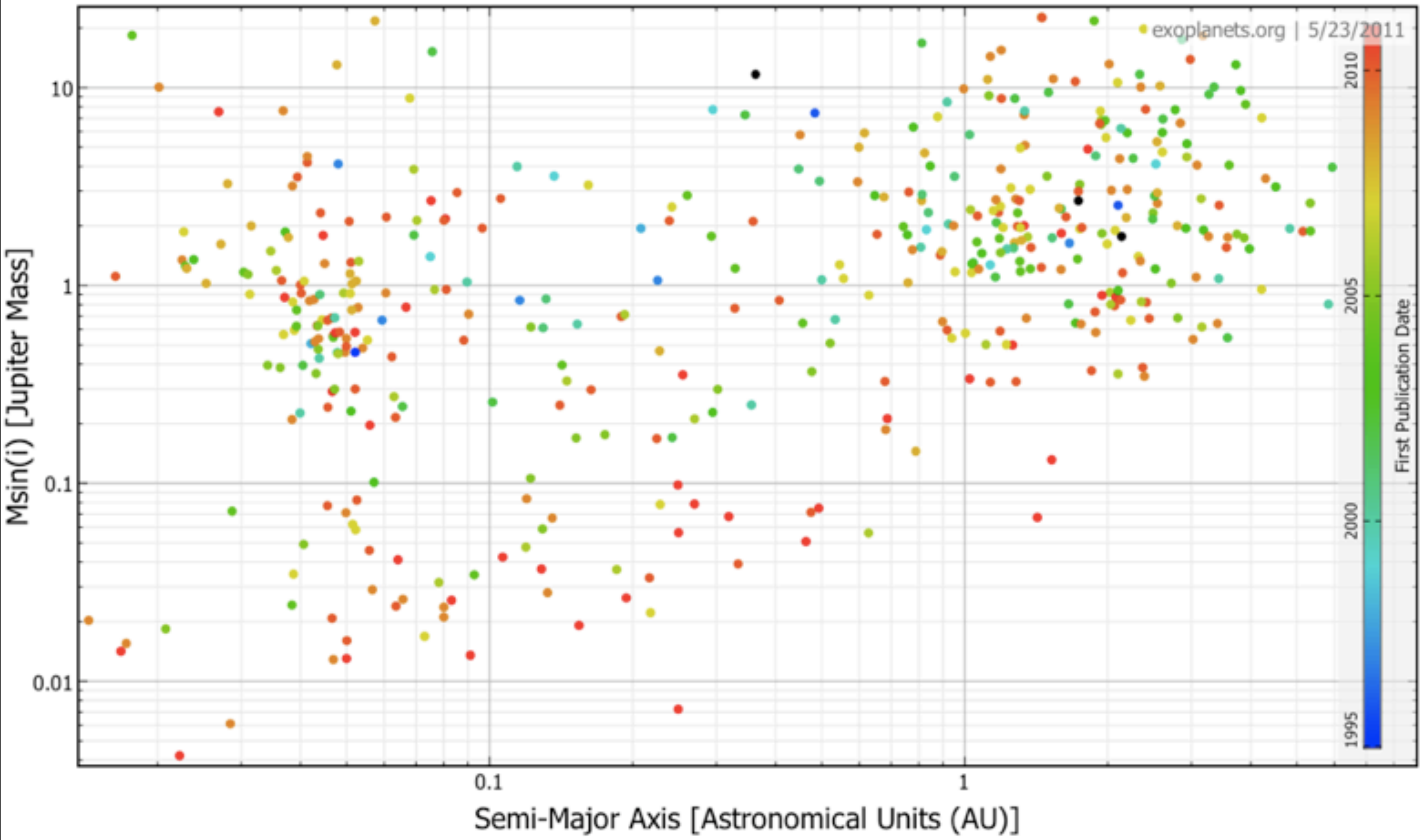
Extrasolar planets: observations



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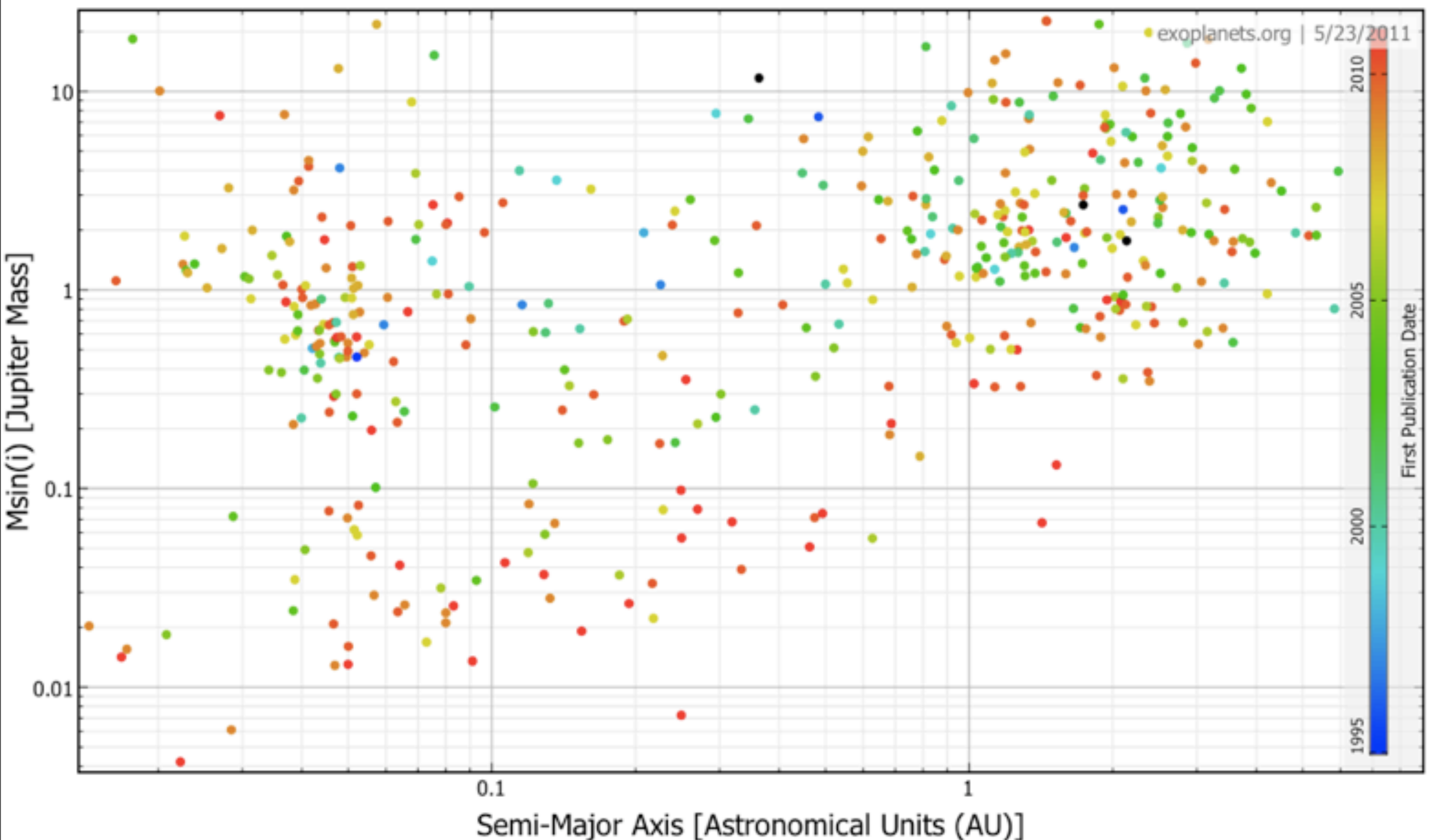


not considered as single objects, but as a population

Extrasolar planets

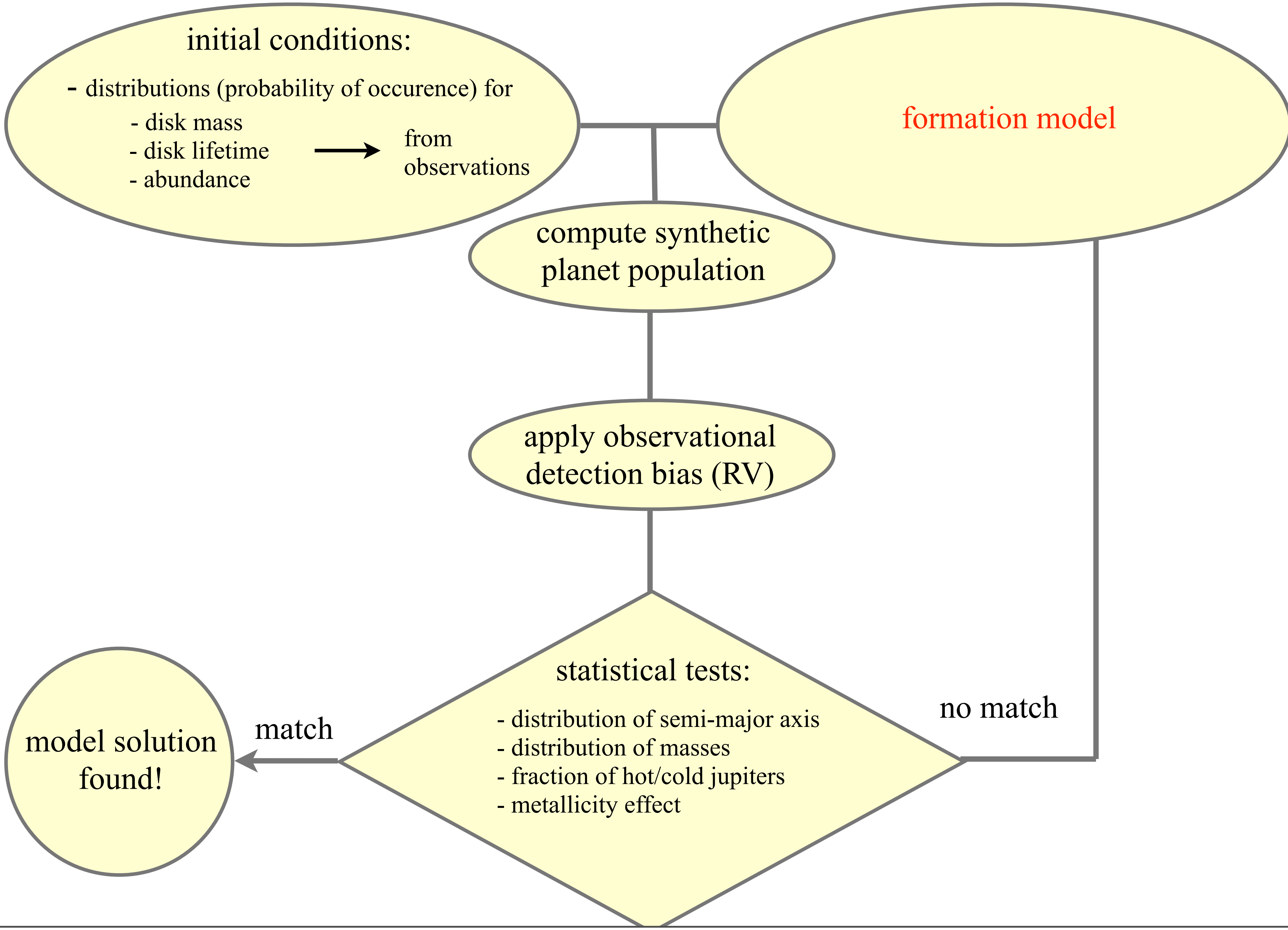
- Huge diversity resulting from different ICs?
  - Protoplanetary disk
  - Metallicity
  - Environement

- To explain the observations, need to take into account

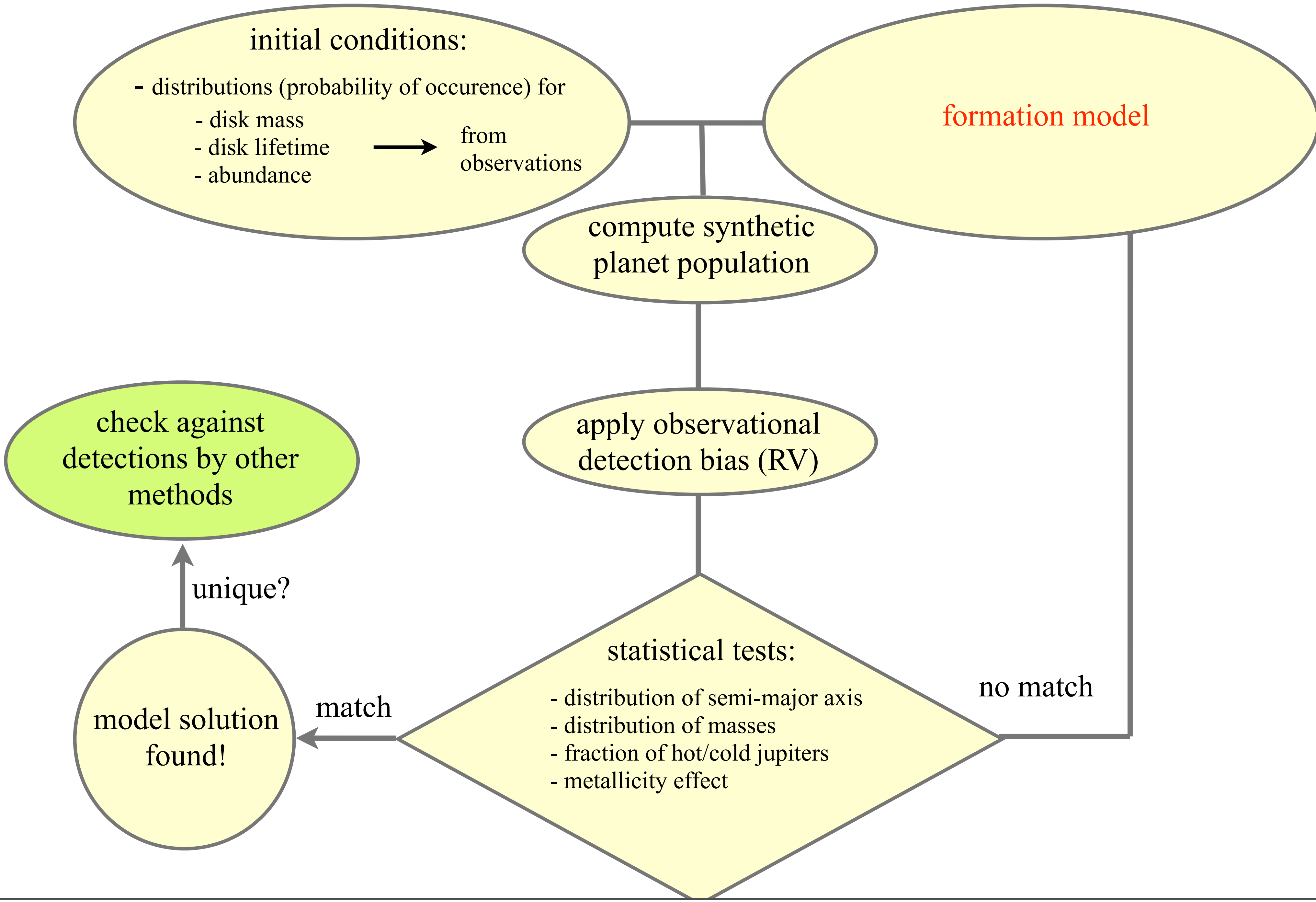
  1) the ICs, with the correct probability laws
  2) the observational biases (RV - microlensing - transit)

$\Rightarrow$ Population synthesis

Extra-solar planet population synthesis



Extra-solar planet population synthesis

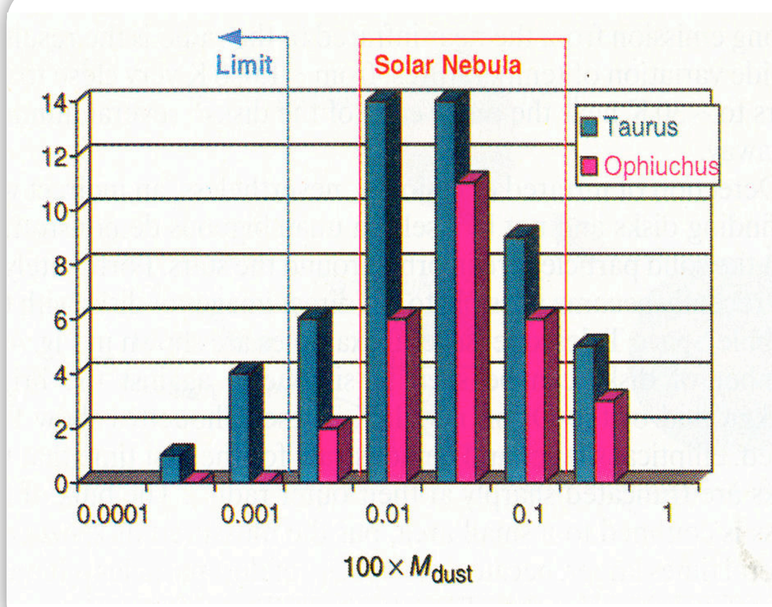


Population synthesis: initial conditions

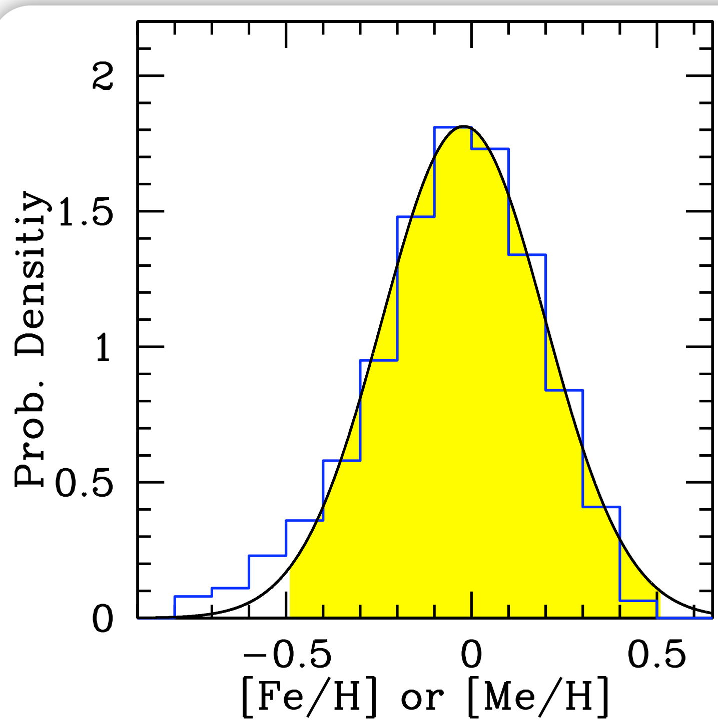
CORALIE survey

⇓

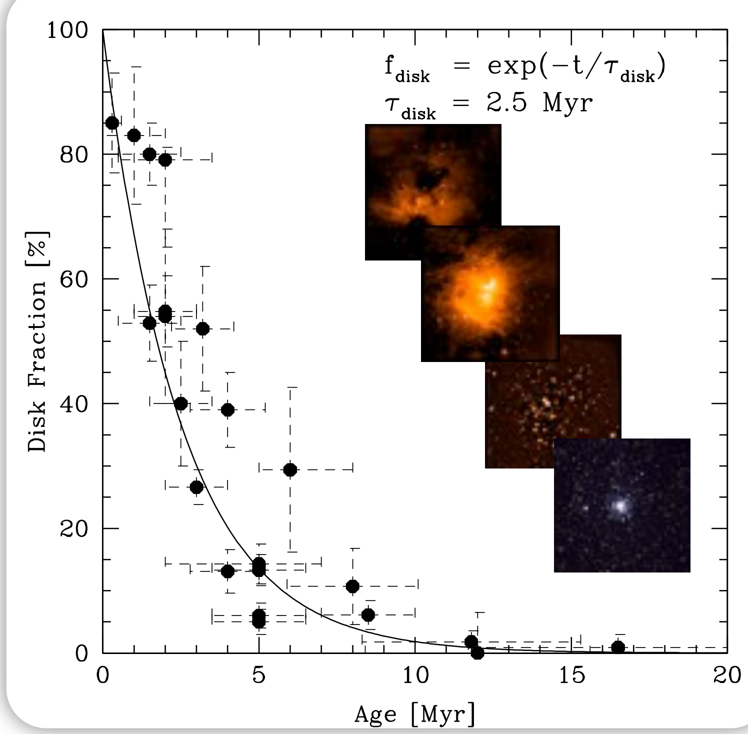
gaussian repartition



Beckwith & Sargent

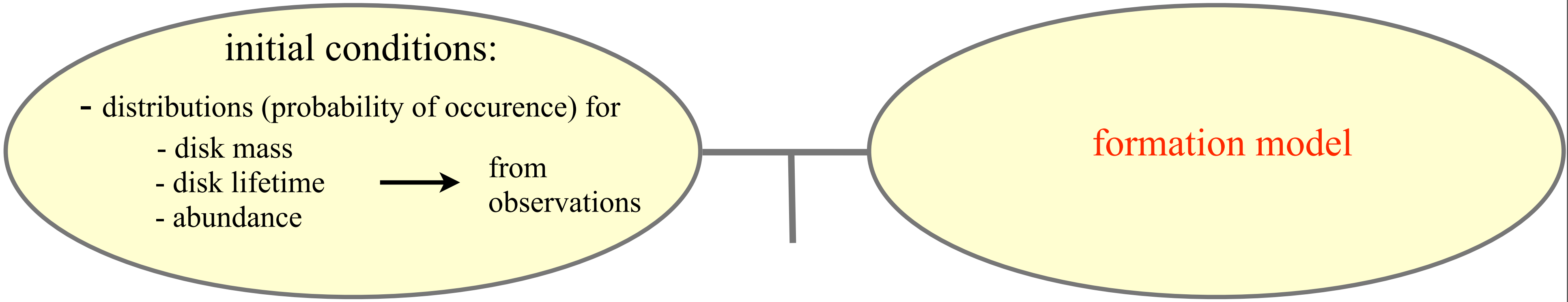


Santos et al. 2003

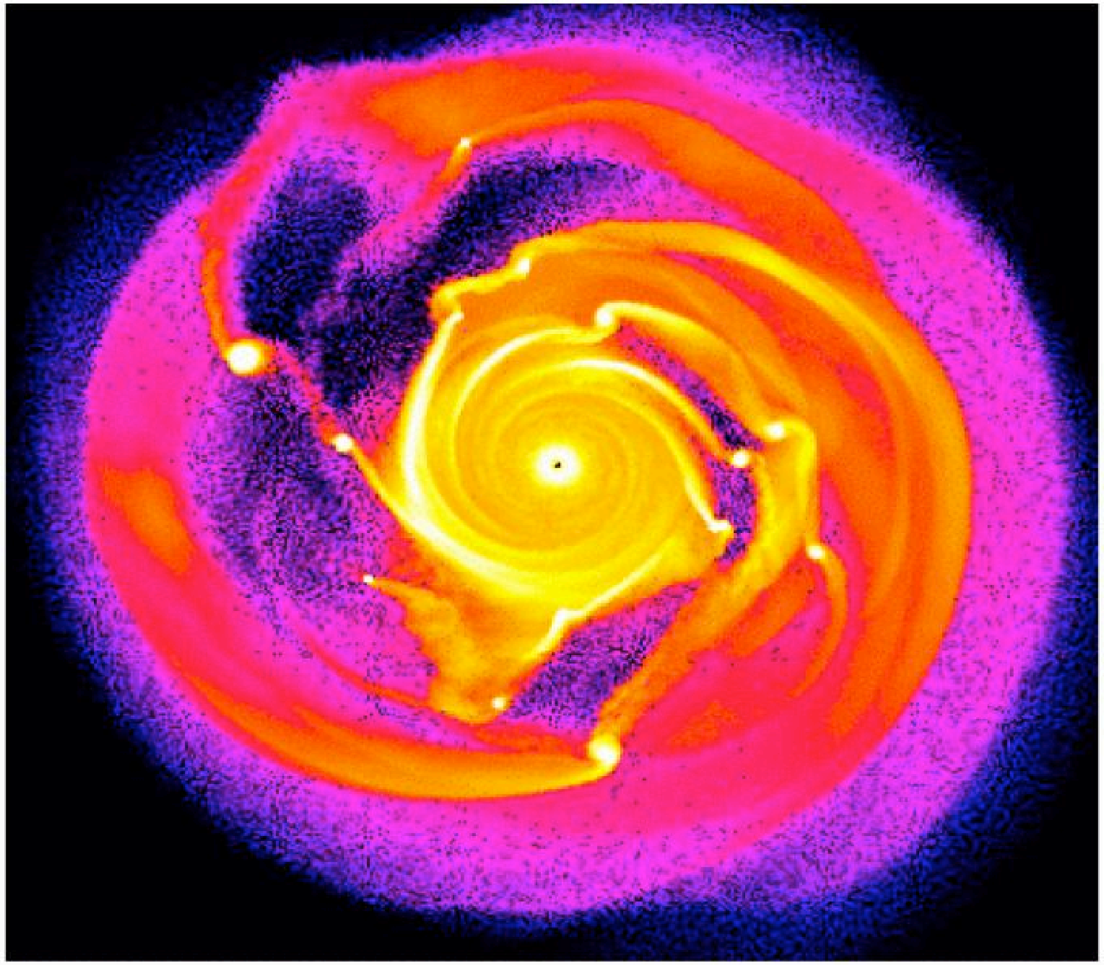


Mamajek 2009

Extra-solar planet population synthesis



The disk instability model



Mayer et al. 2004

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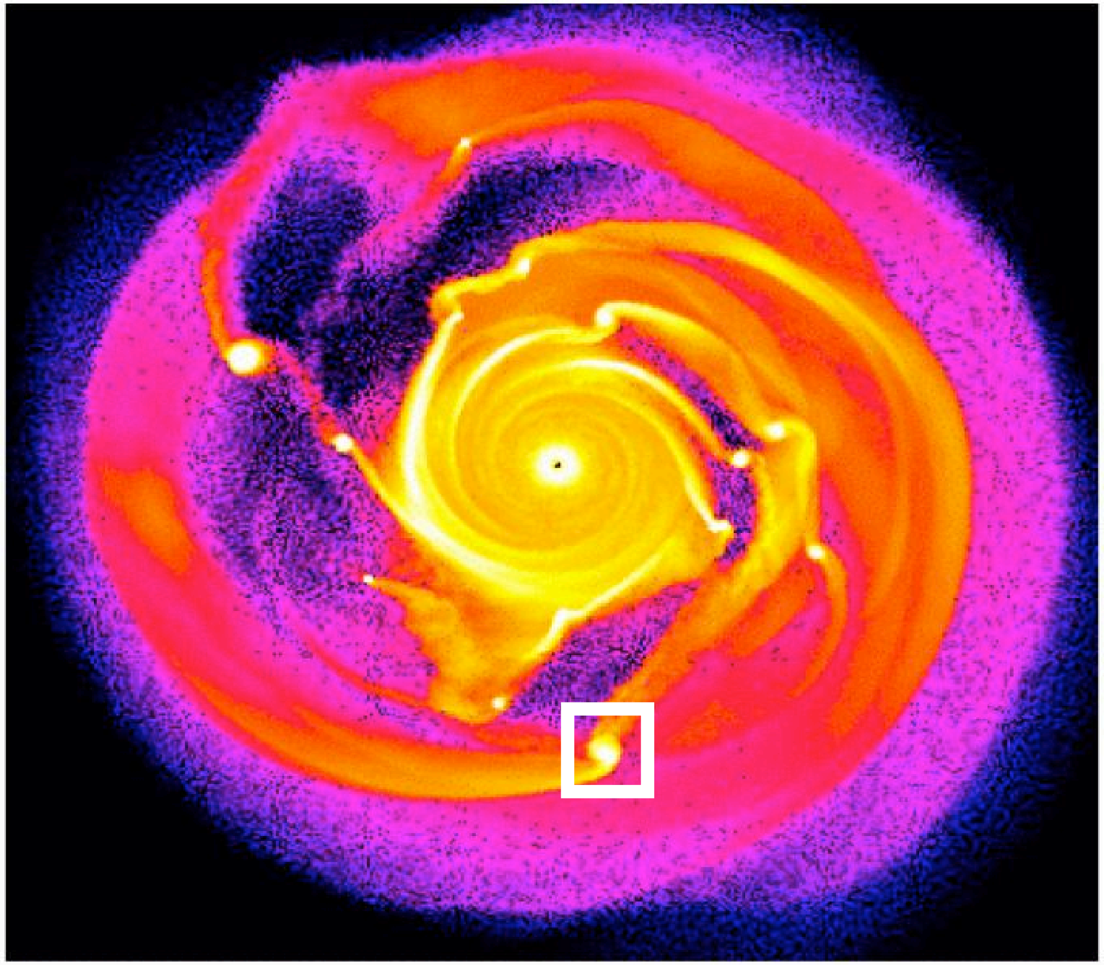

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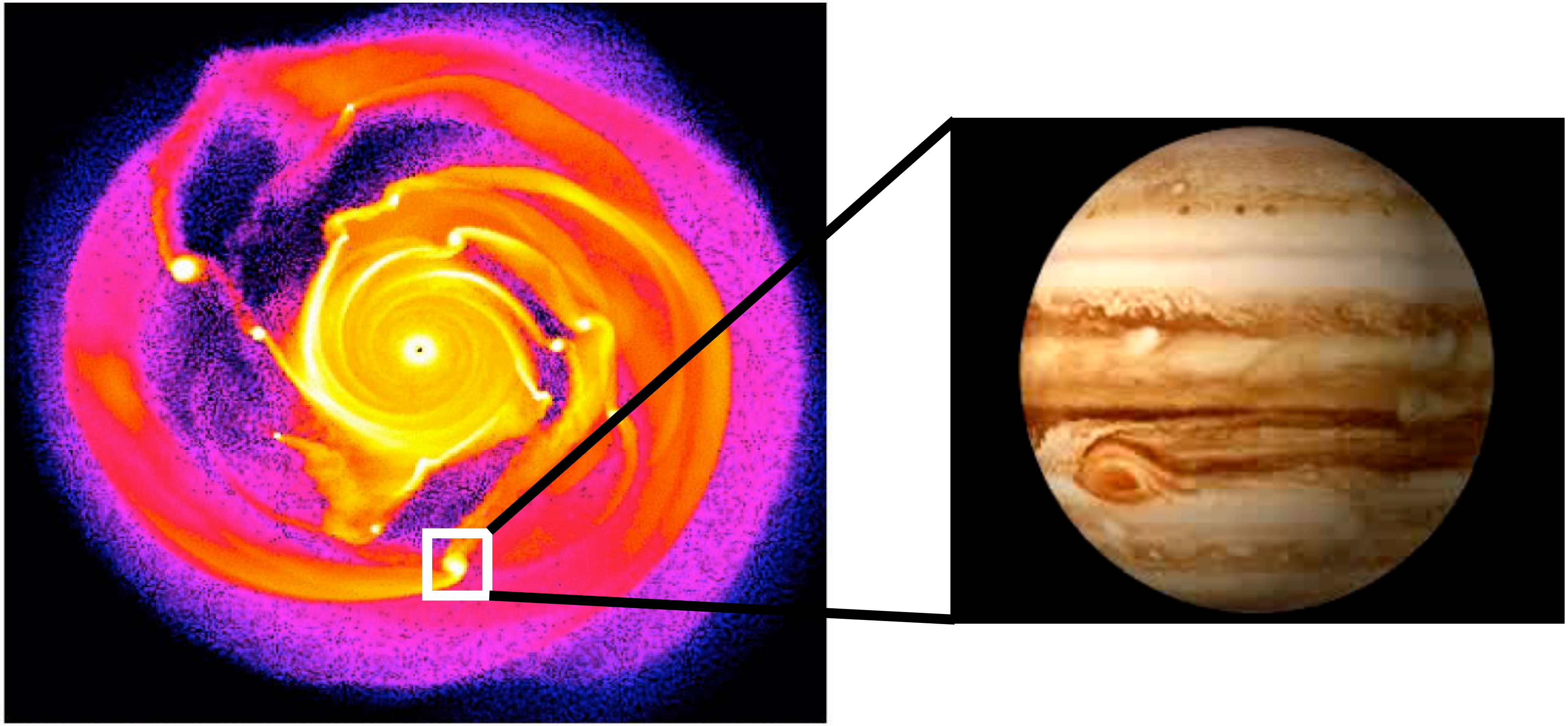

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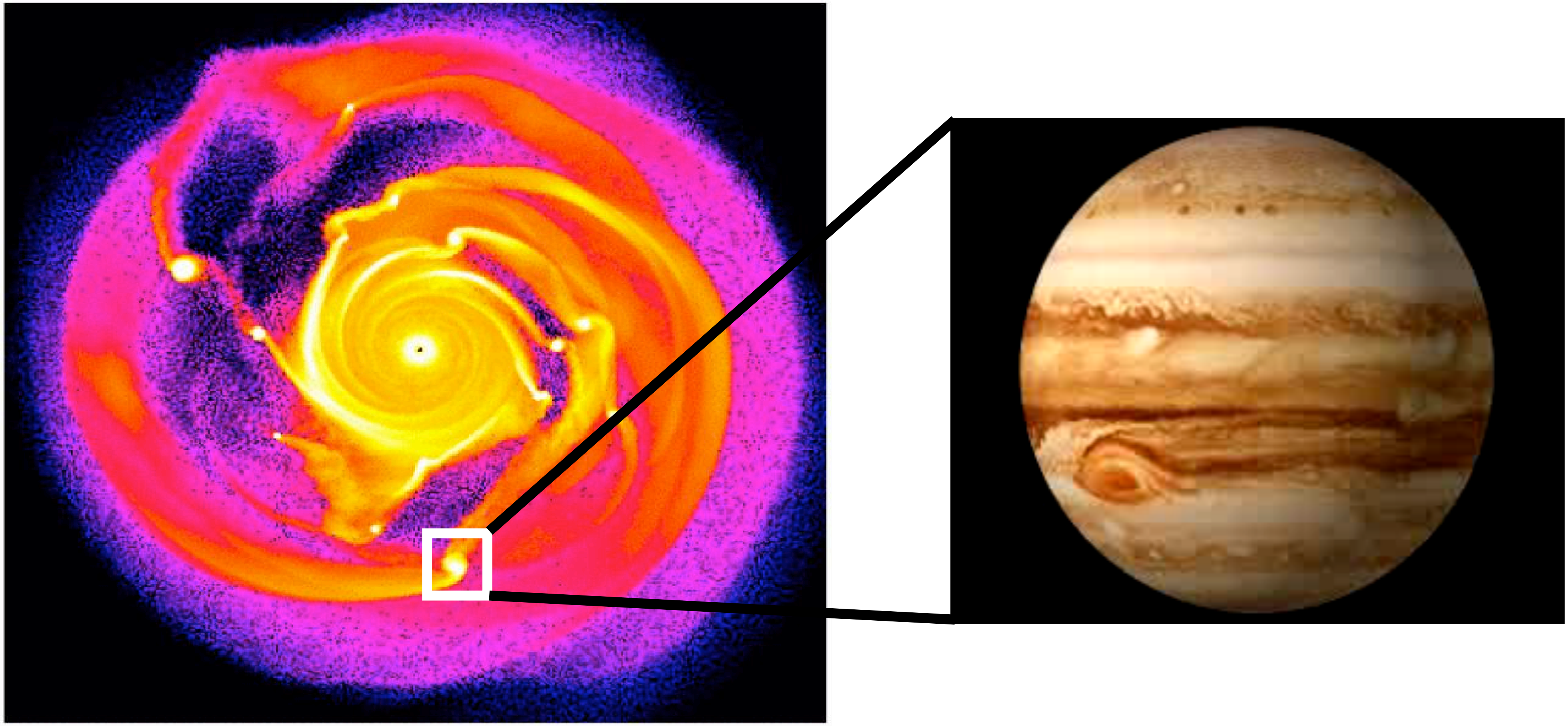


Mayer et al. 2004

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)

⇒

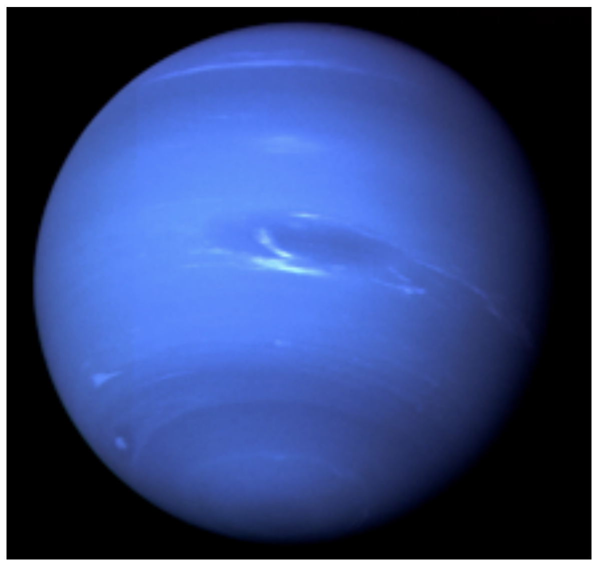
gas giant

The nucleated instability model (2)

⇒

gas giant

ice giant



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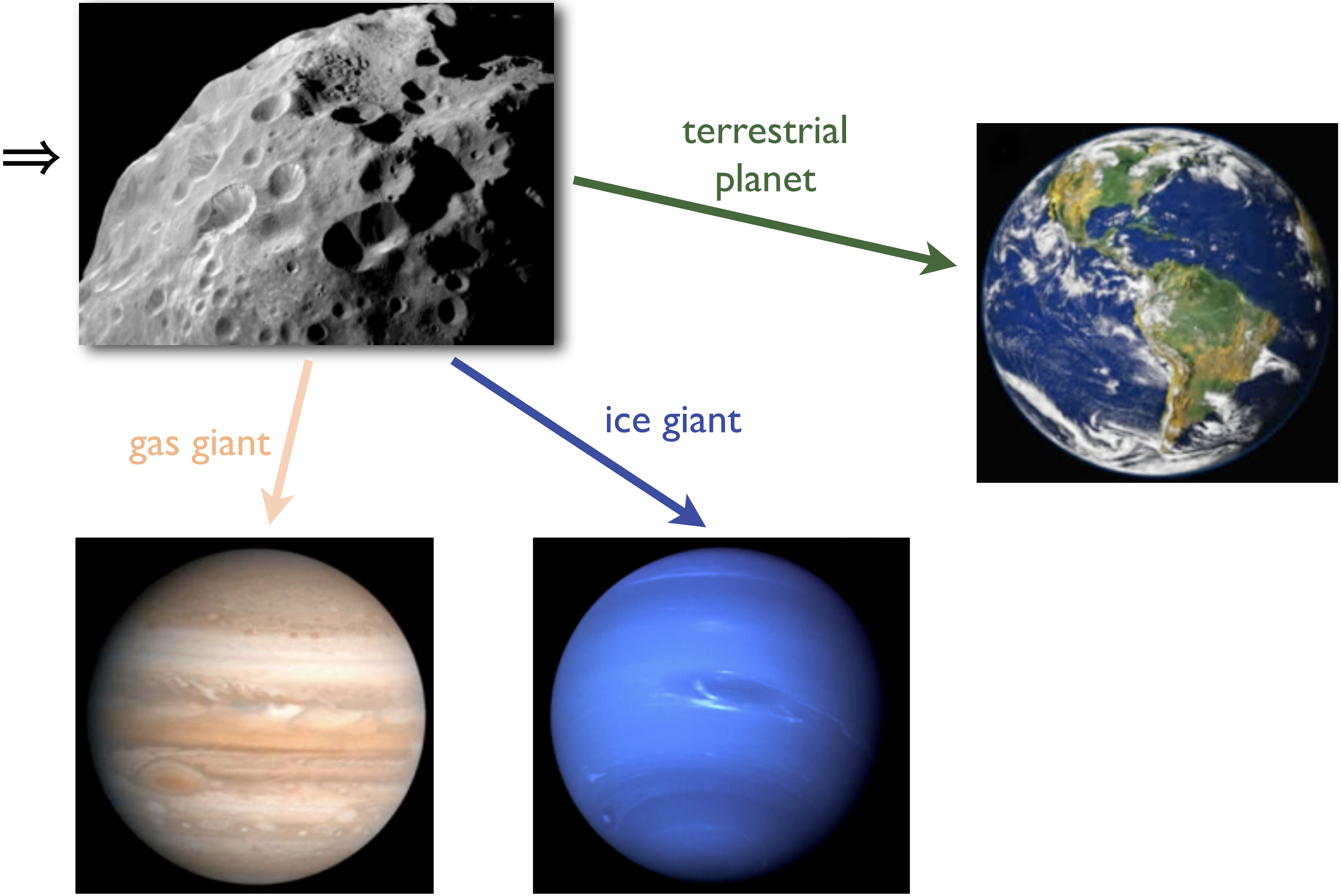


Planet formation model

⇒

Planet formation model

$\Rightarrow$

1- Take an “observed” disk

Planet formation model

⇒

1- Take an "observed" disk

2- Assume planet embryos exist somewhere

Planet formation model

$\Rightarrow$

1- Take an "observed" disk

2- Assume planet embryos exist somewhere

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

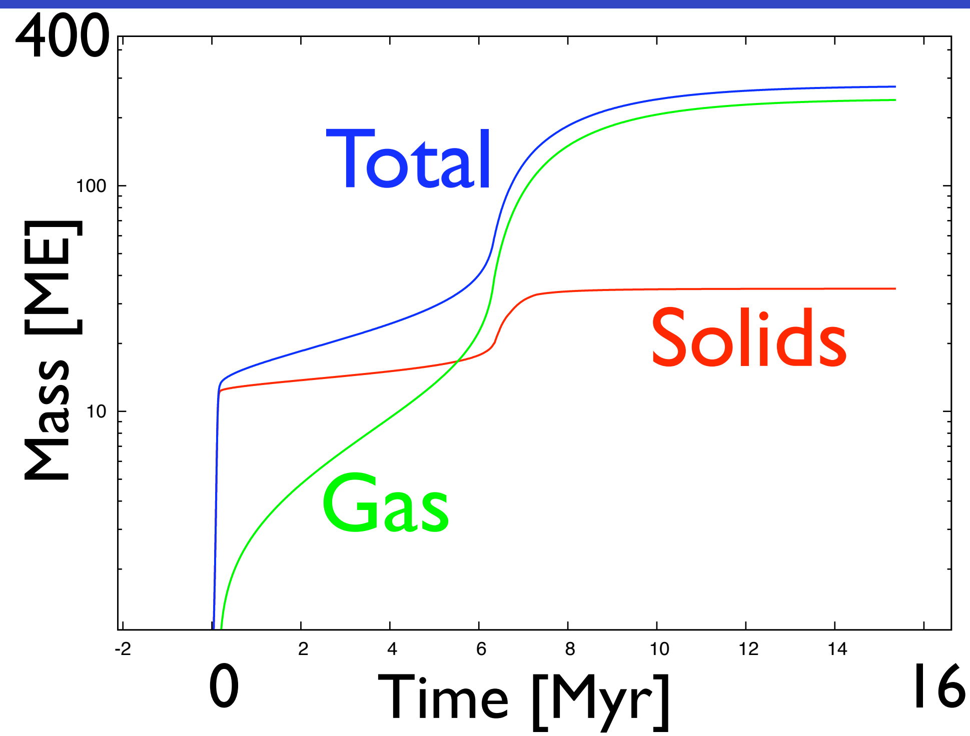
Planet's internal structure

In situ formation of Jupiter at 5.2 AU

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

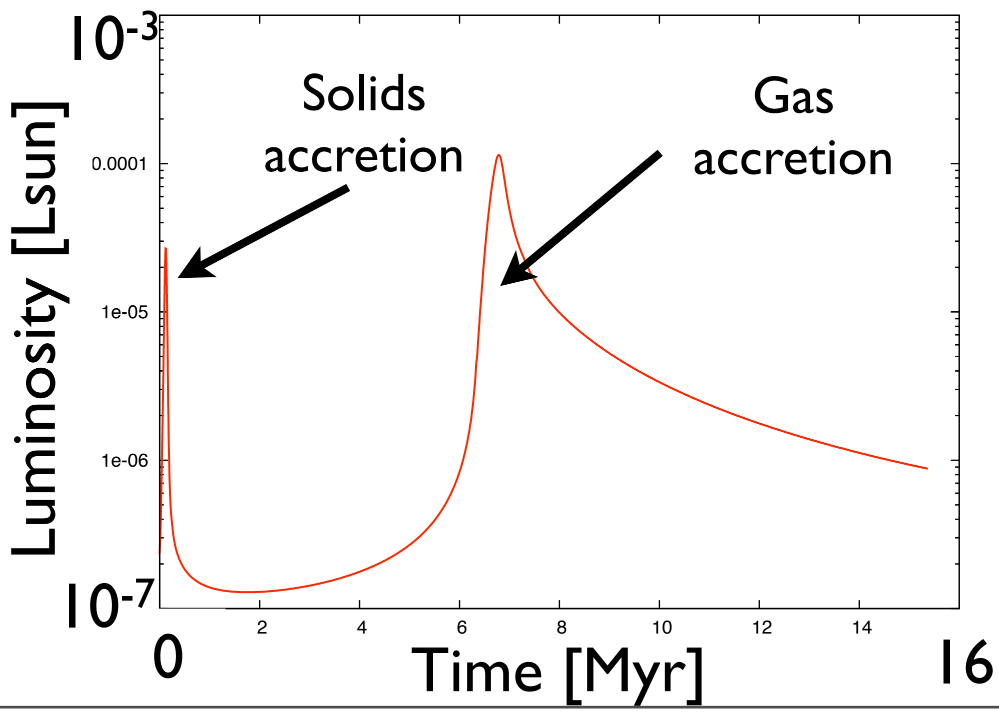
$$M_{\rm disk} \approx 0.03 M_\odot$$

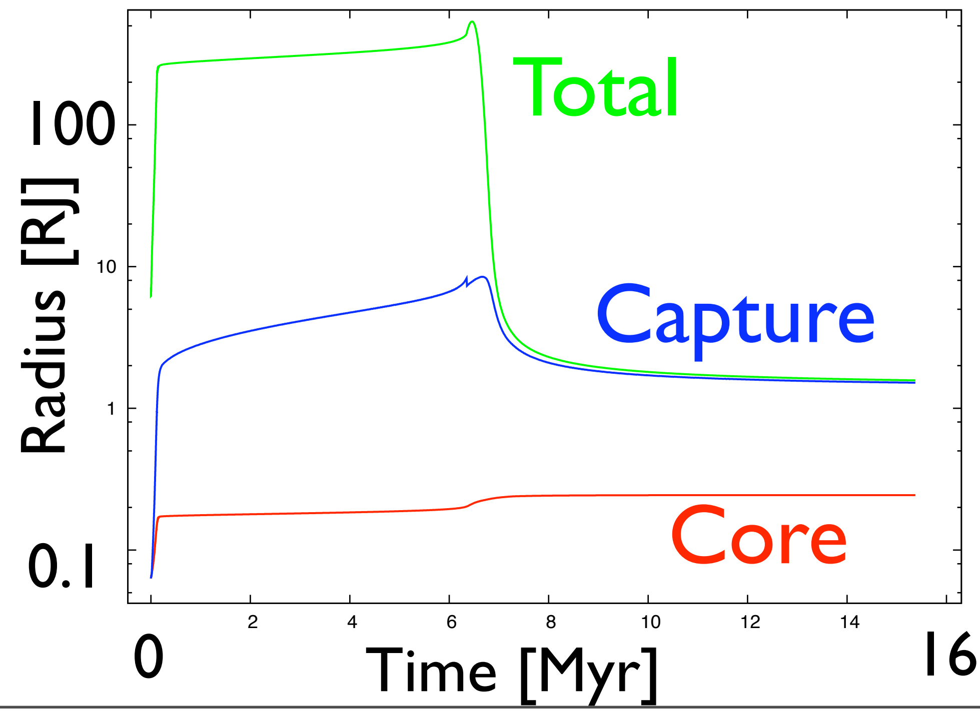
only viscosity



Planet in contact with disk

Planet isolated





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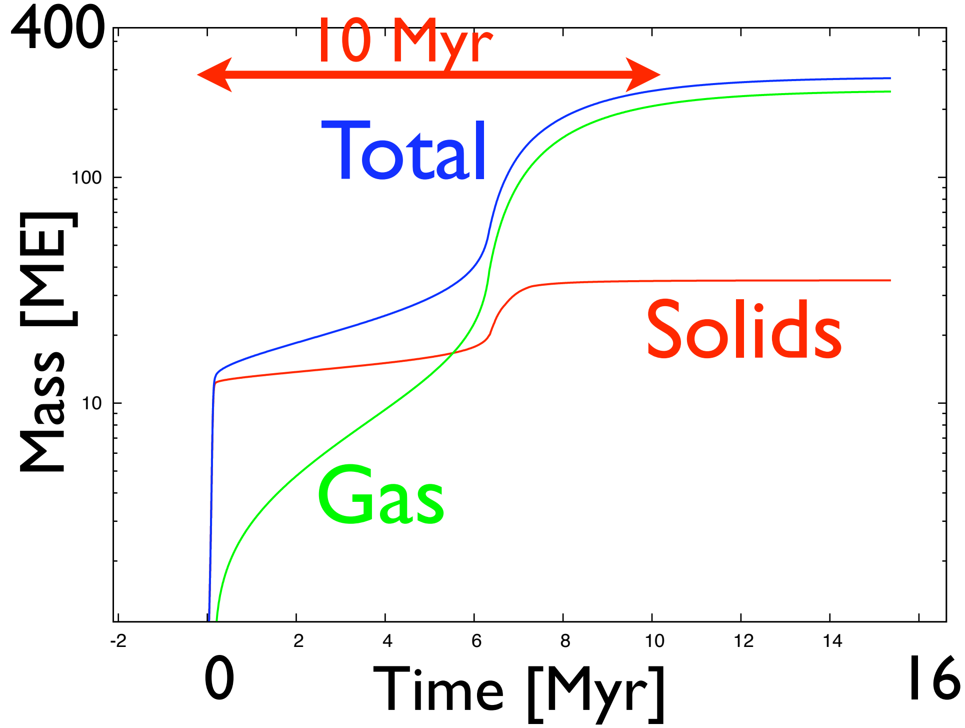

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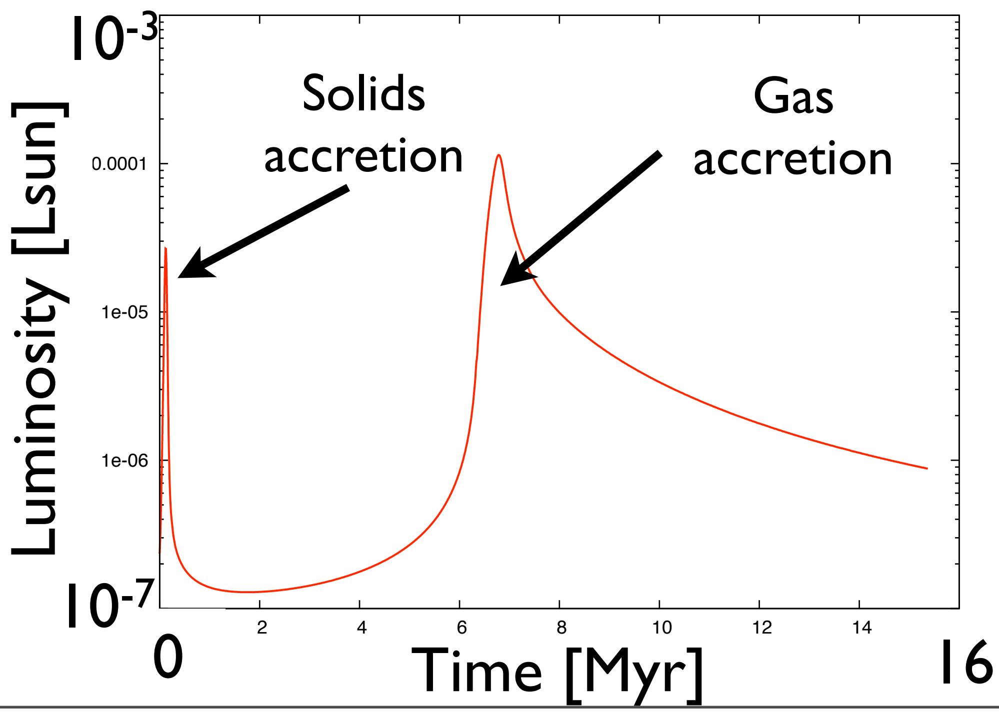
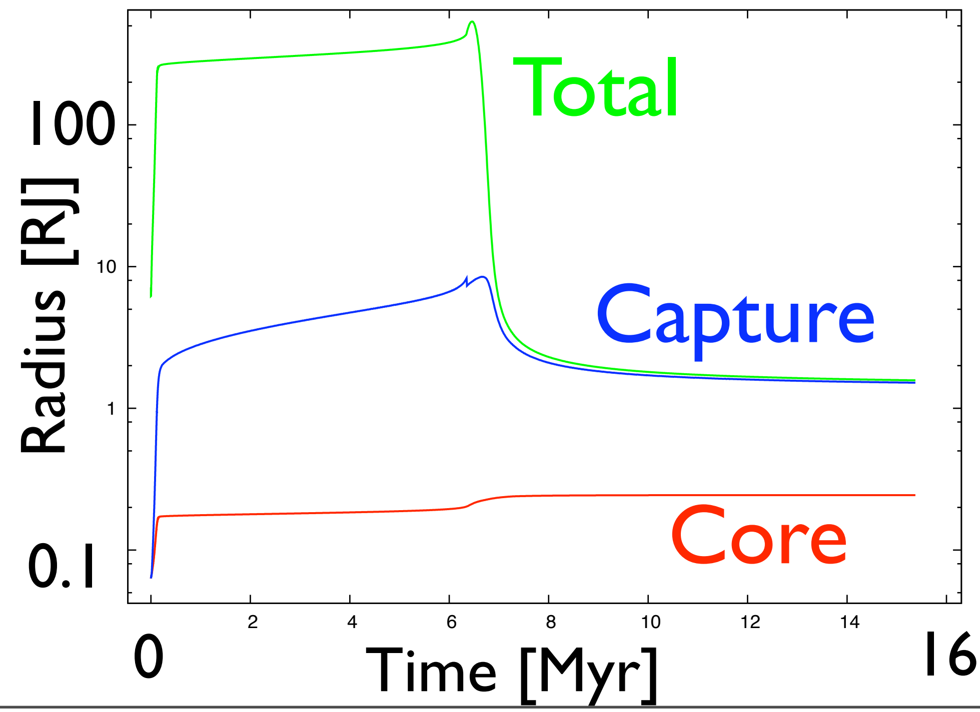
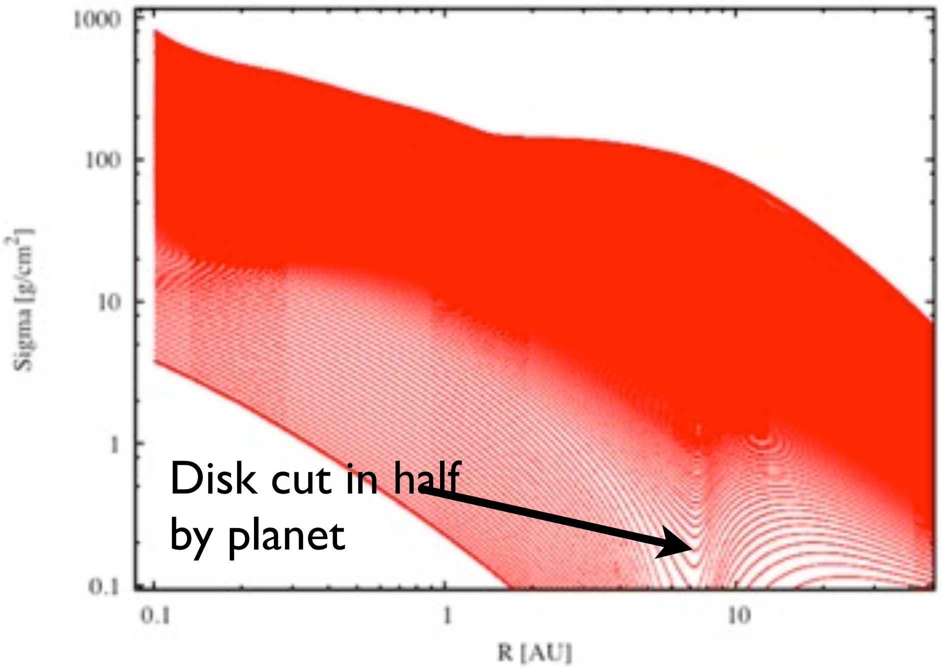




Disk model

Gas surface density



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

Viscosity, photoevaporation, planet accretion

$\Sigma_0 = 880\ \mathrm{g/cm}^2$(ca 4 - 5 x MMSN)

$\alpha = 7 \times 10^{-3}$ $\dot{M}_{\mathrm{wind}} = 2.3 \times 10^{-8} M_\odot/\mathrm{yr}$

Disk model

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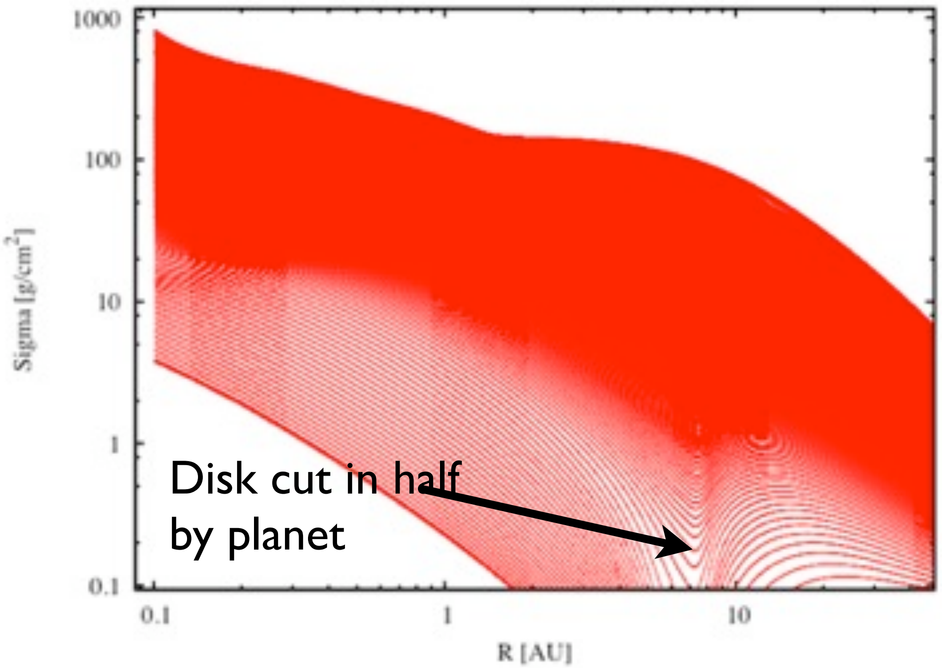

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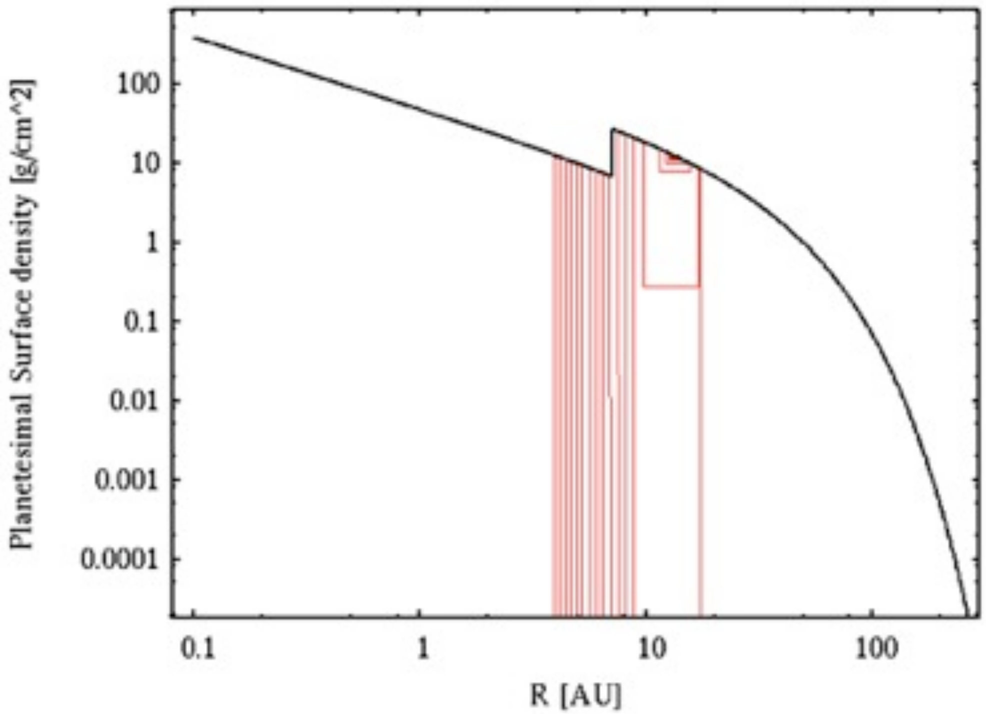
Planetesimal surface density



-Initial profile

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

-Dust/gas ratio $\frac{f_{\mathrm{D/G}}}{f_{\mathrm{D/G},\odot}} = 10^{[\mathrm{Fe/H}]}$

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

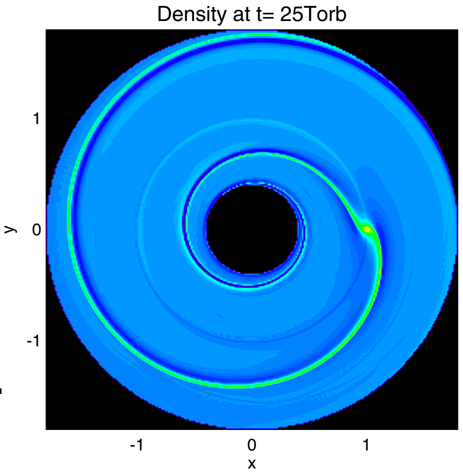
Gas driven migration

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

$$\frac{da_{planet}}{dt} = -2 f_I a_{planet} \frac{\Gamma}{L_{planet}} \qquad L_{planet} \equiv M_{planet}(GM_* a_{planet})^{1/2}$$

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

Tanaka et al. 2002



Baruteau & Masset. 2008

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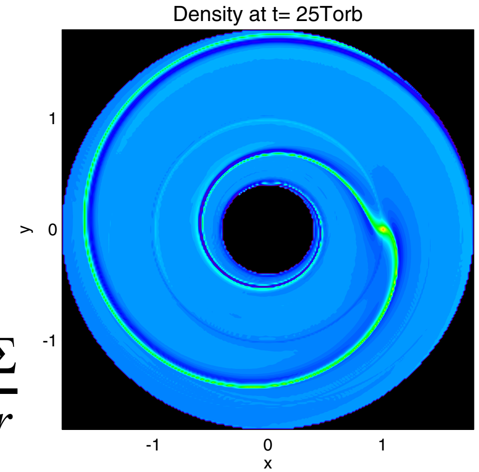

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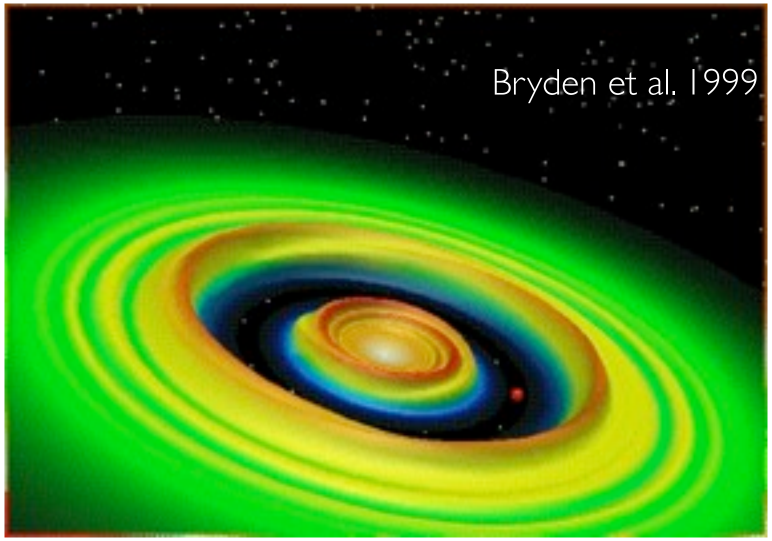


Giant planets (with gap): Type II

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

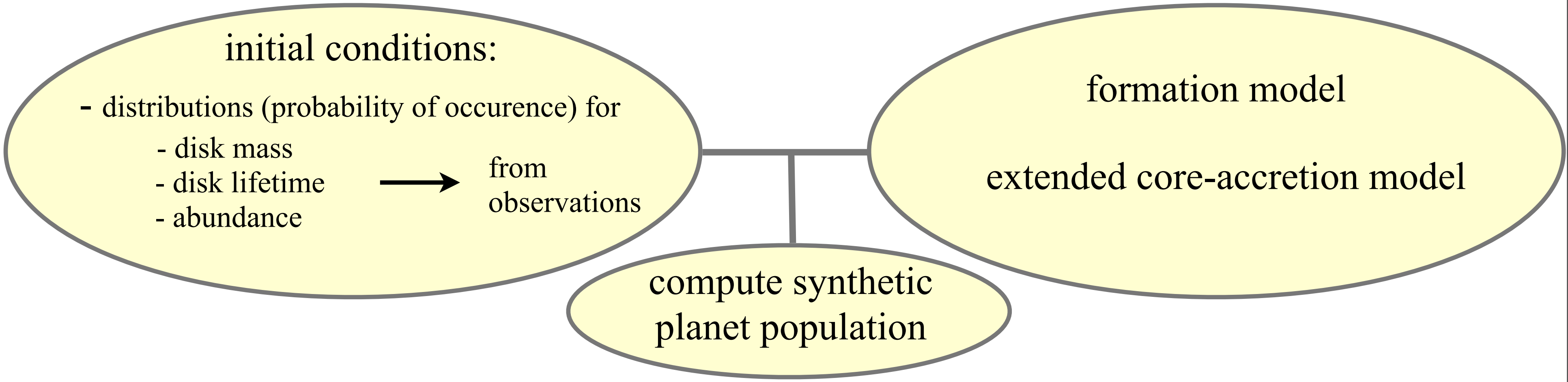
$$\frac{da_{planet}}{dt} = v_{r,gas}$$

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

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

Slow-down

Extra-solar planet population synthesis



Evolutionary tracks: the full population

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

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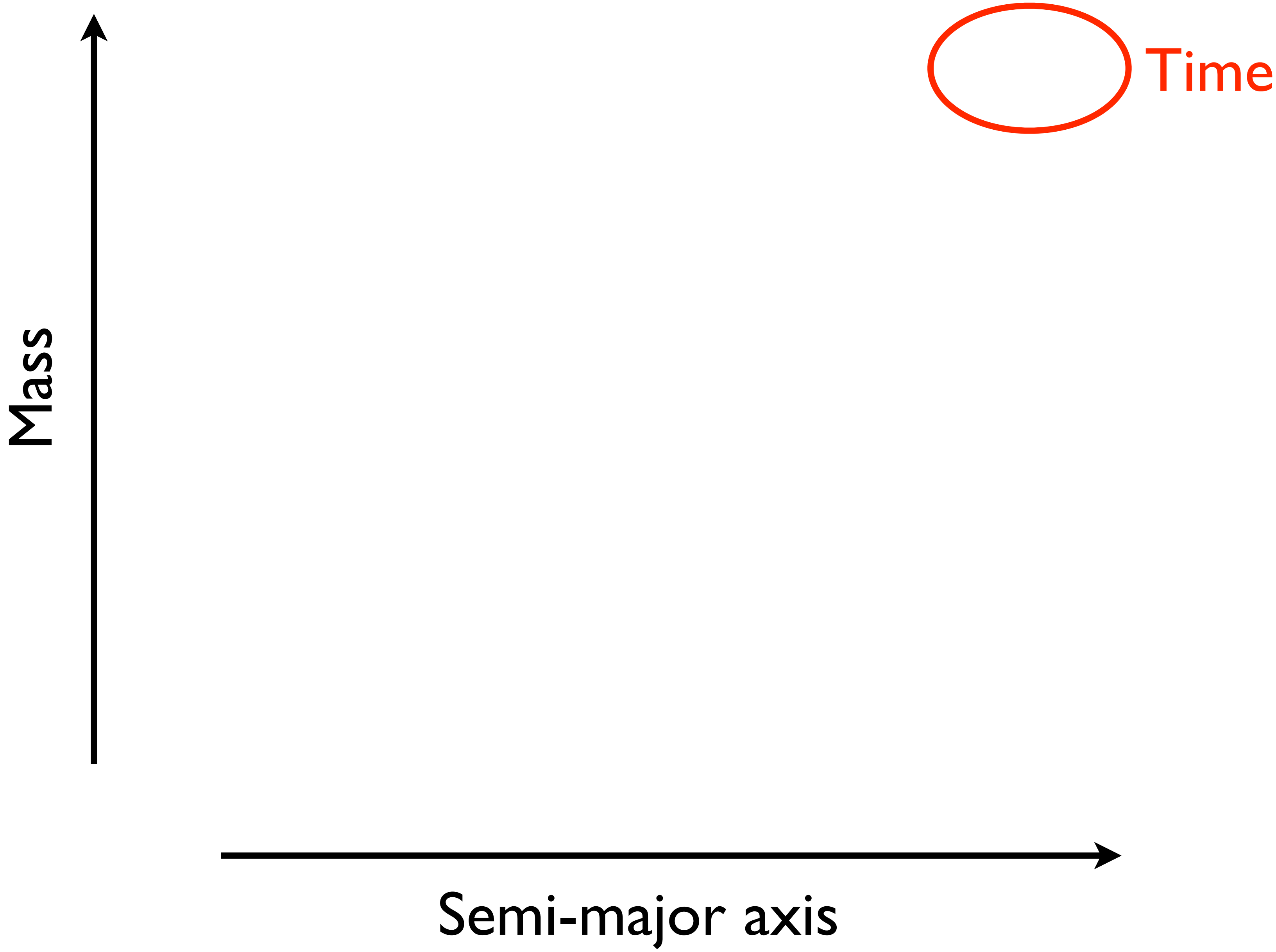

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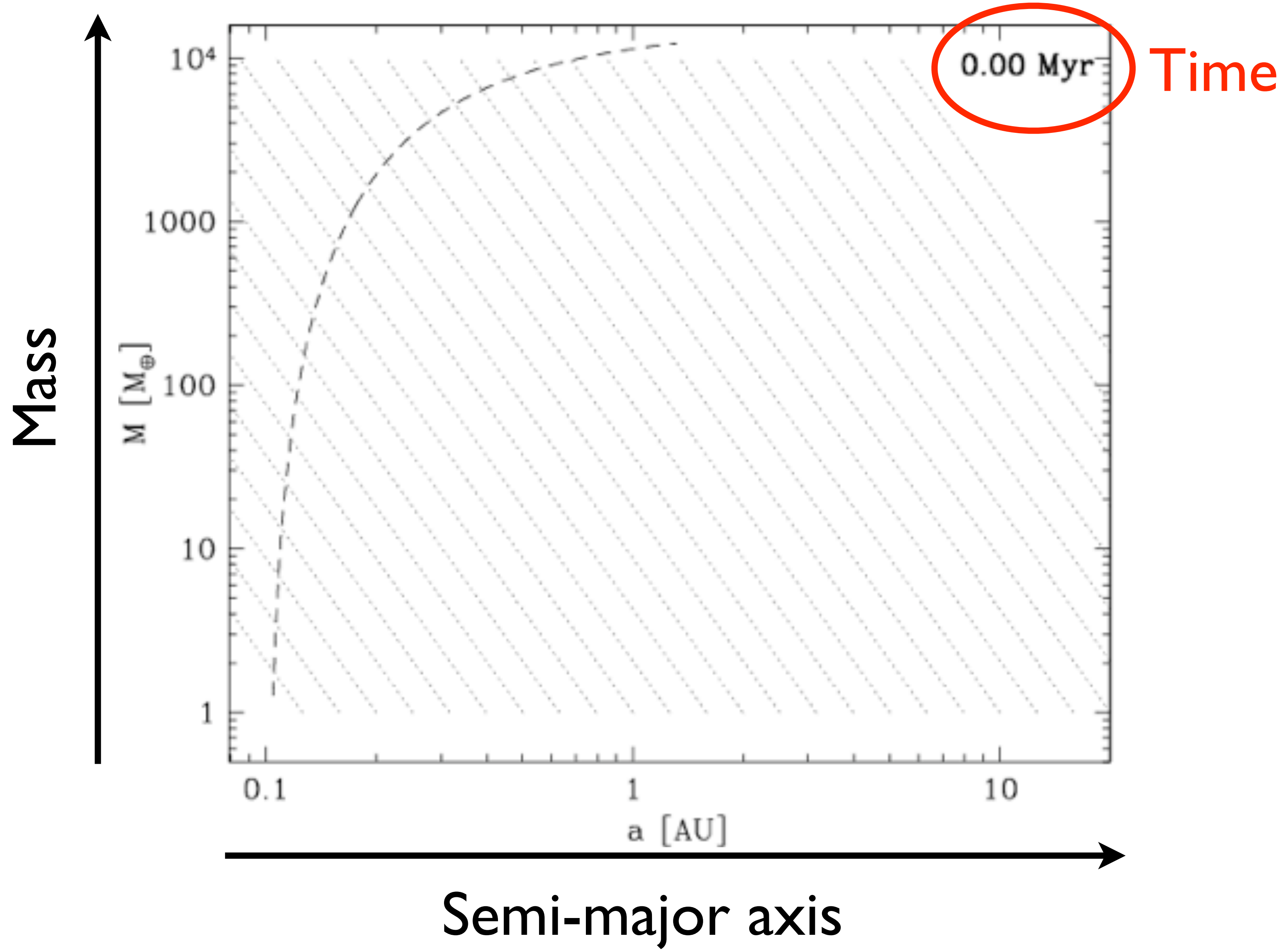

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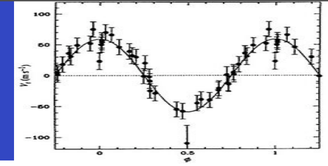
M sin(i) *vs* a



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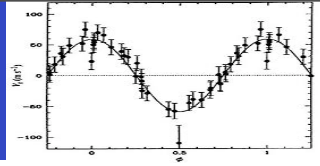
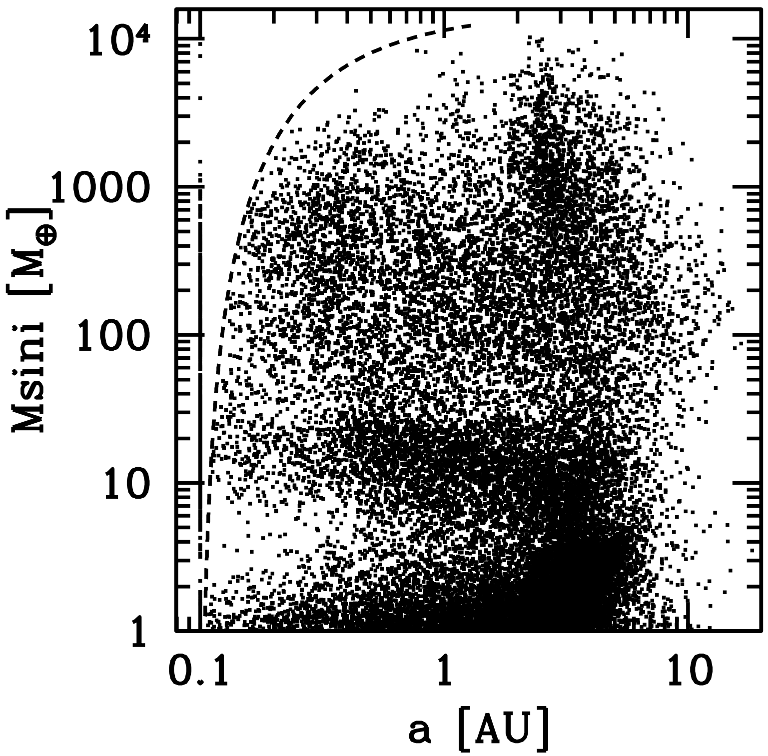


all



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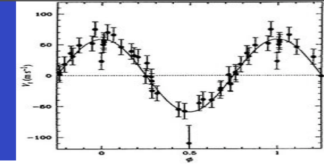

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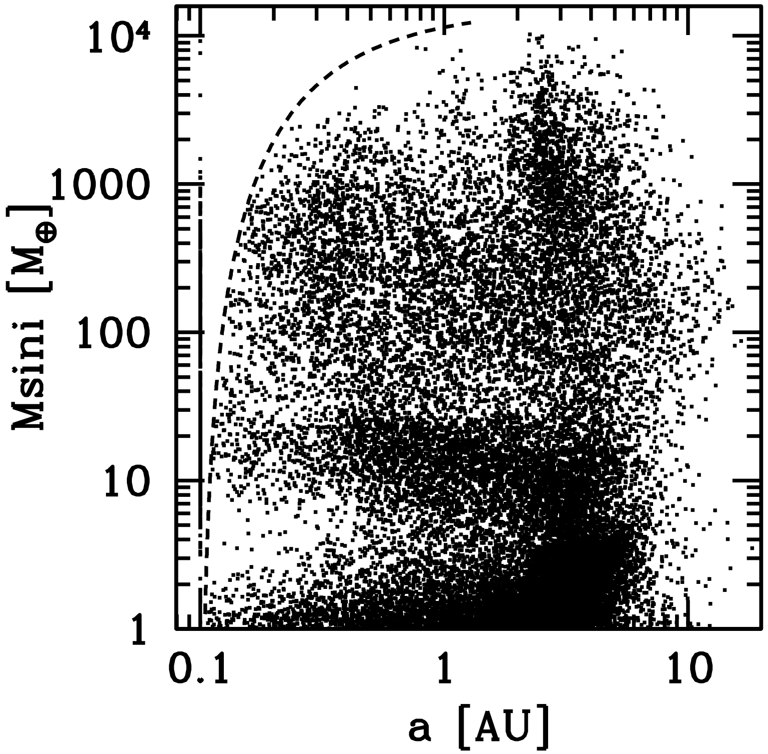
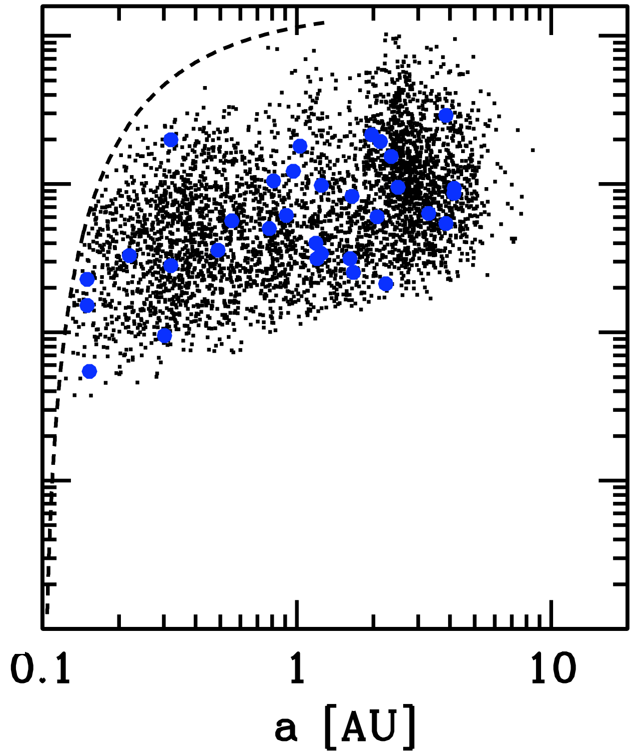
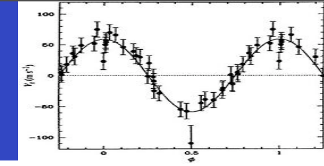
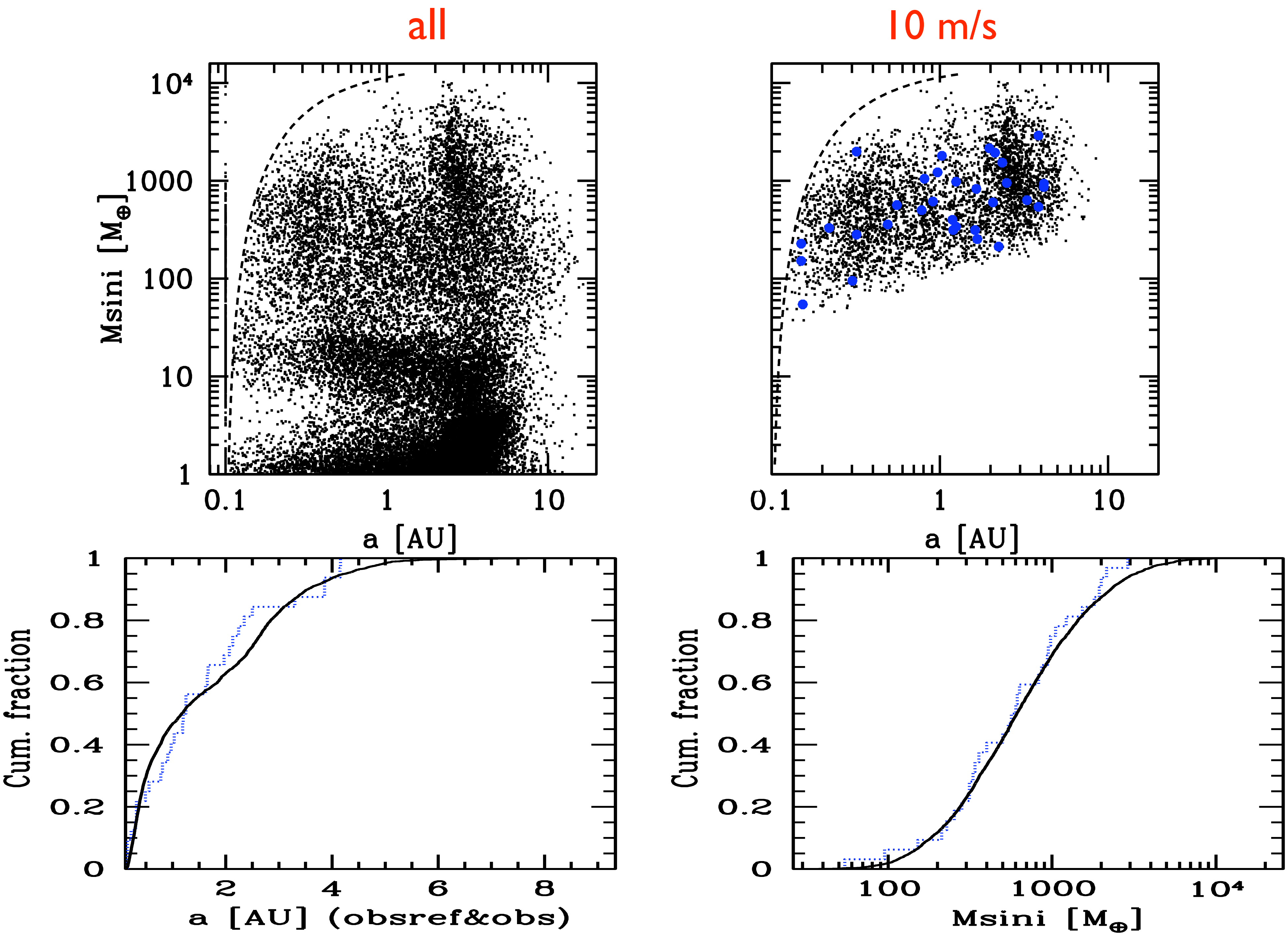


10 m/s

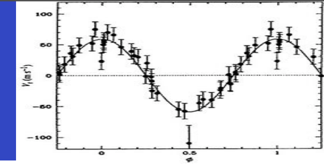


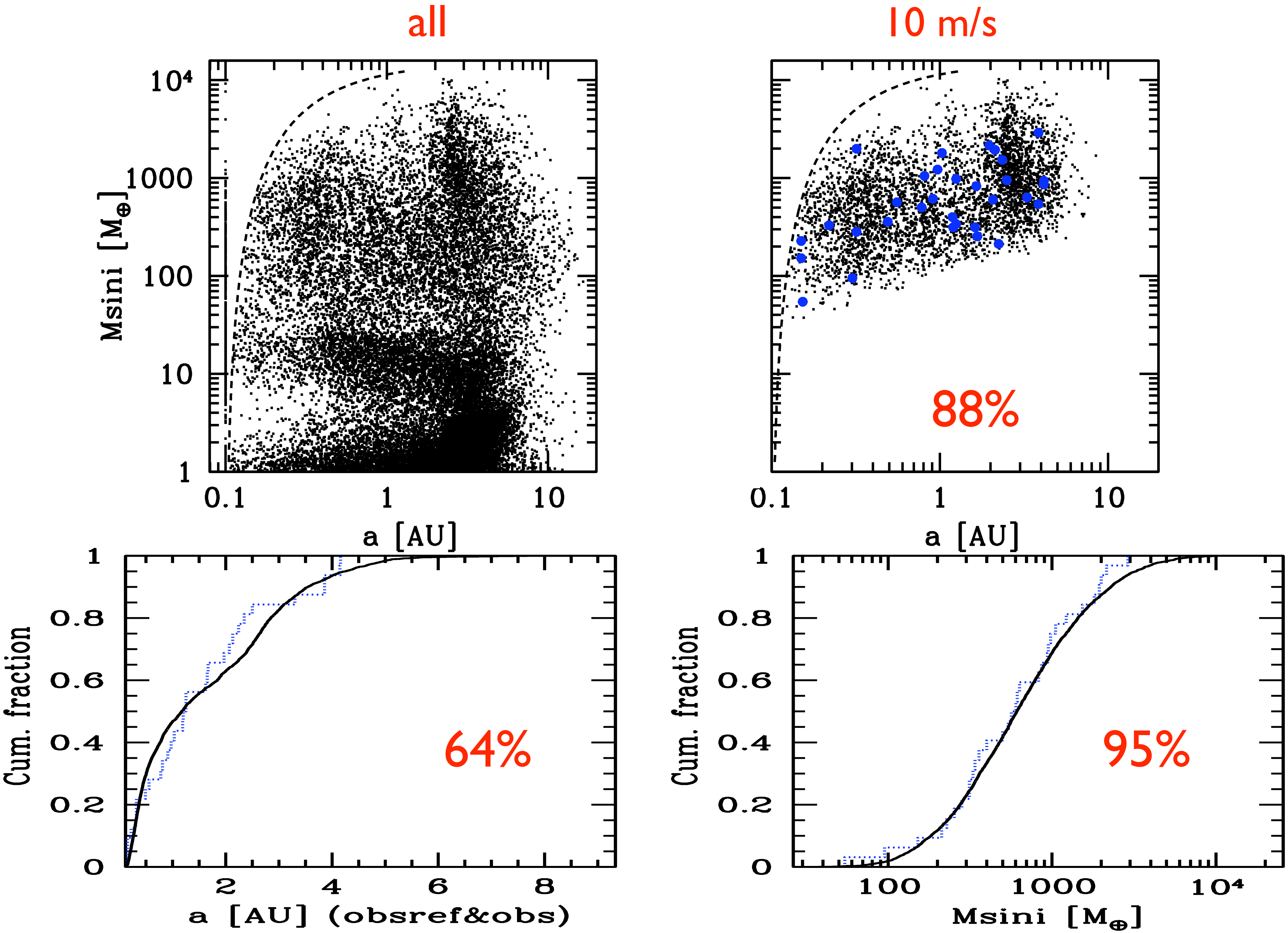
M sin(i) *vs* a




all
10 m/s
Msini [M⊕]
a [AU]
0.1
1
10
10^4
1000
100
10
1
Cum. fraction
a [AU] (obsref&obs)
0
0.2
0.4
0.6
0.8
2
4
6
8
Msini [M⊕]
100
1000
10^4

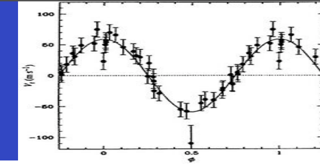
M sin(i) *vs* a



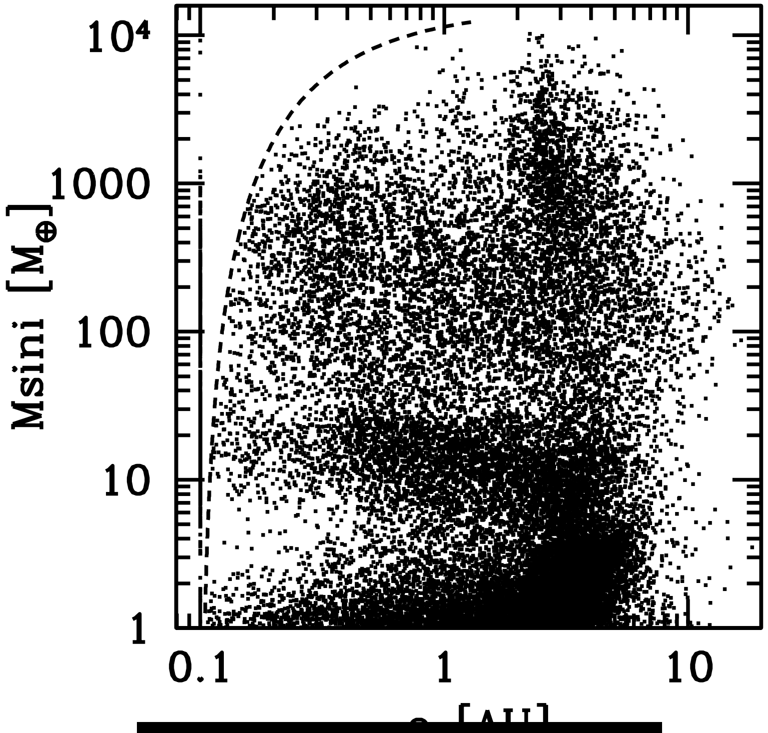


all
10 m/s
10⁴
1000
100
10
1
Msini [M⊕]
0.1
1
10
a [AU]
88%
Cum. fraction
0.8
0.6
0.4
0.2
0
2
4
6
8
a [AU] (obsref&obs)
64%
100
1000
10⁴
Msini [M⊕]
95%

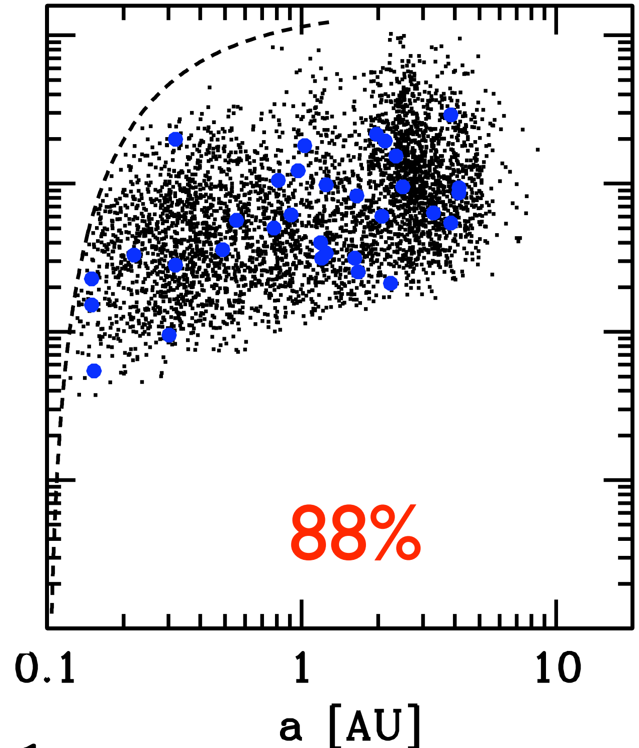
M sin(i) *vs* a

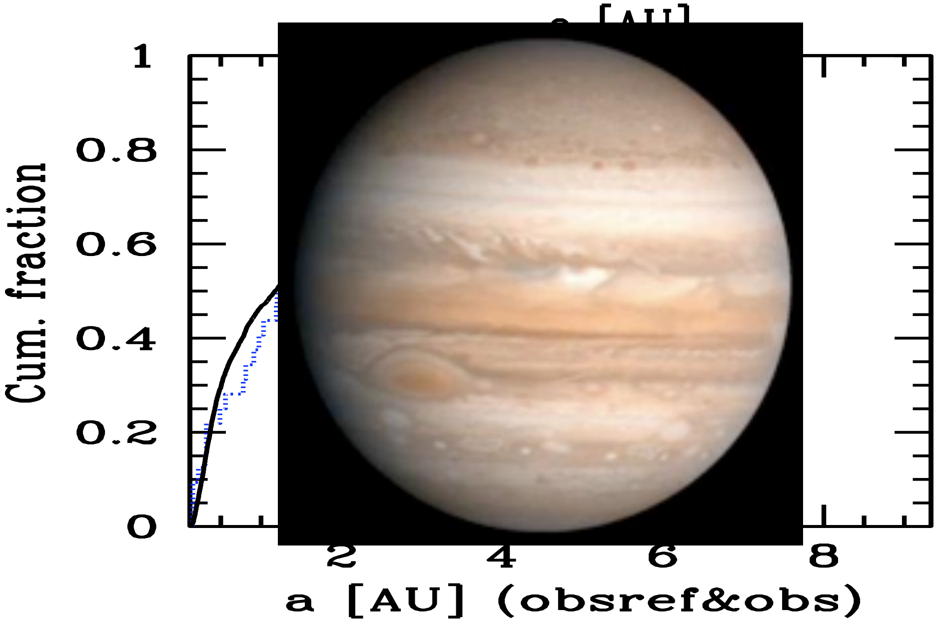


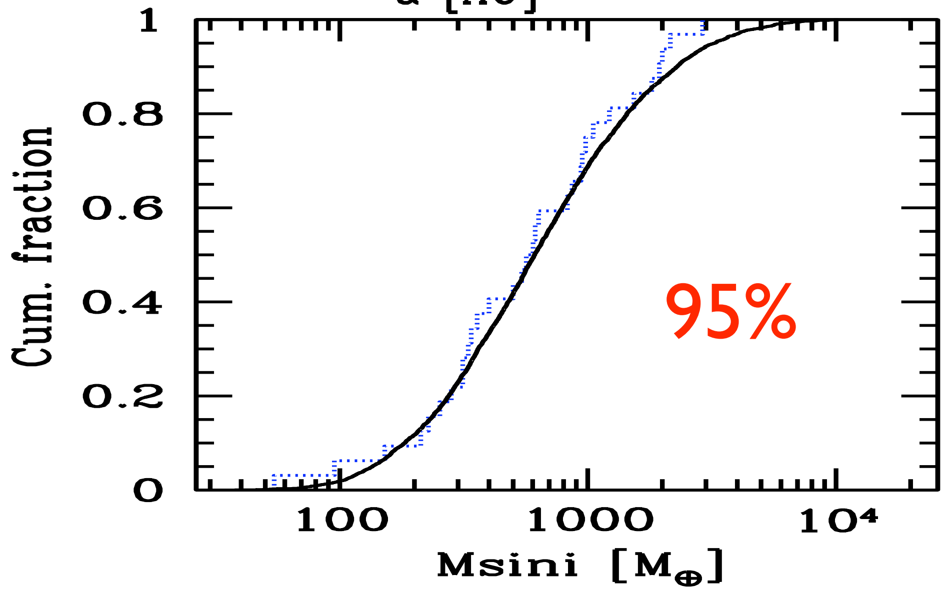
all



10 m/s







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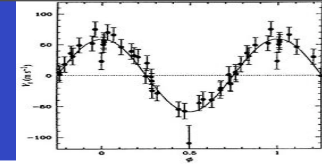
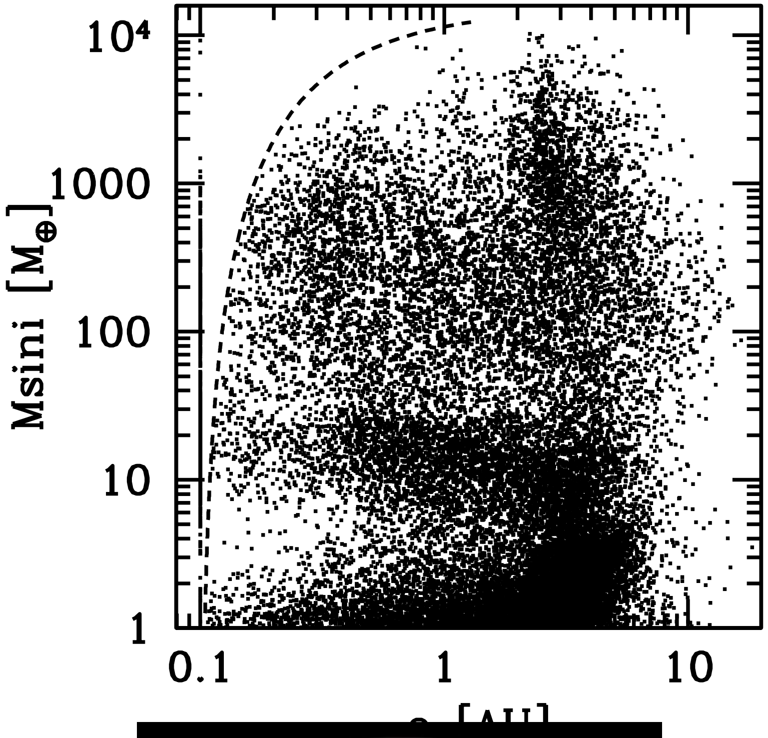
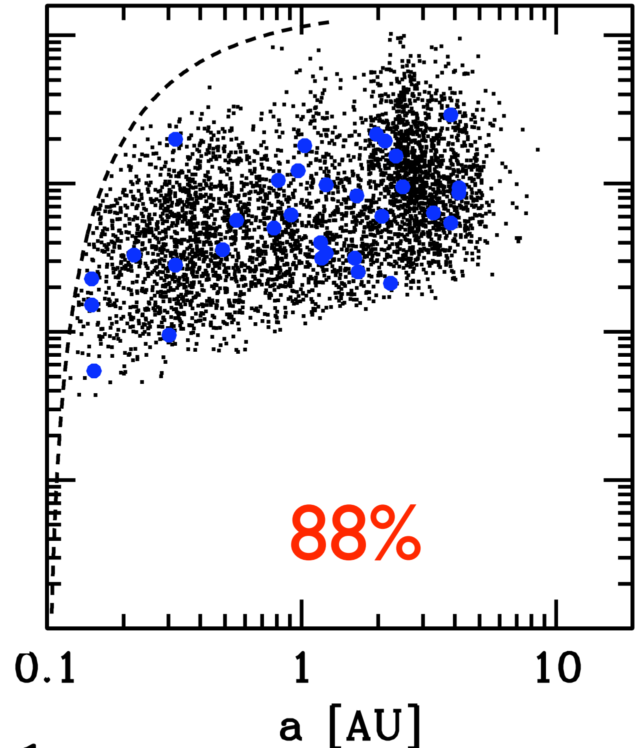
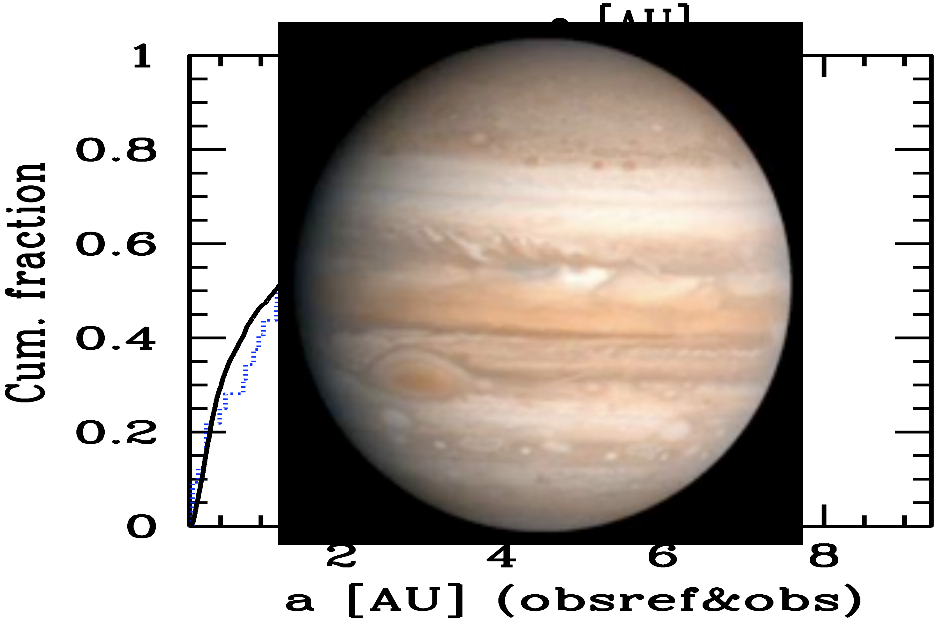


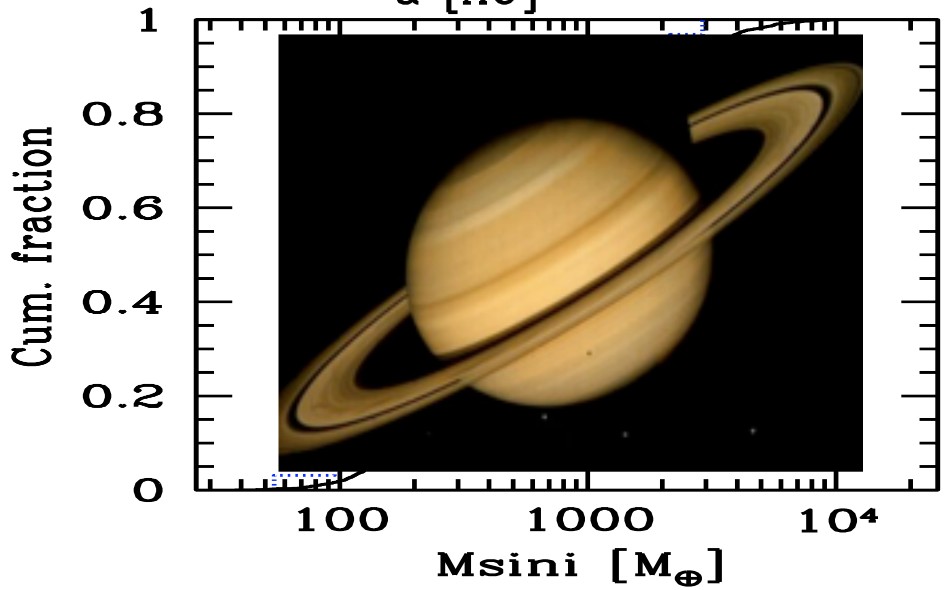
all



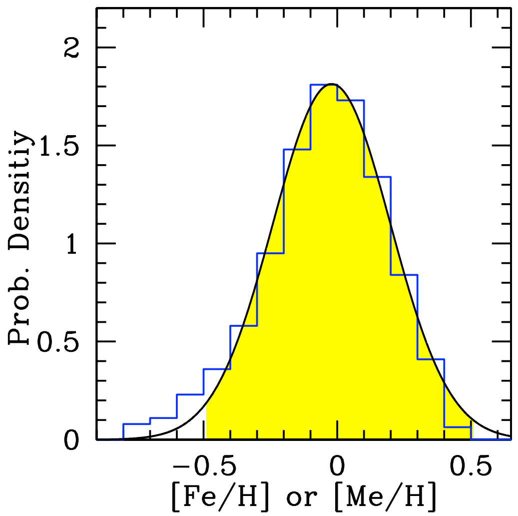
10 m/s

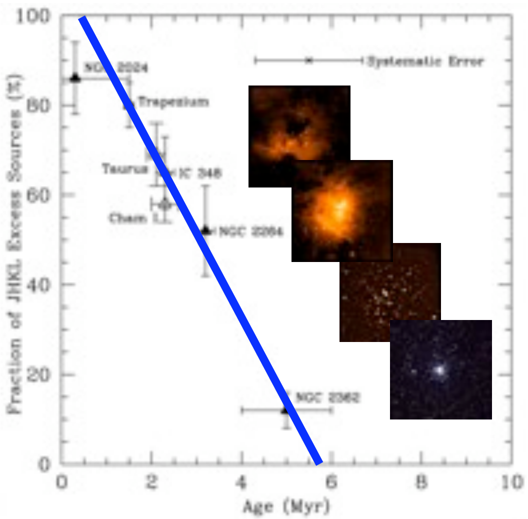


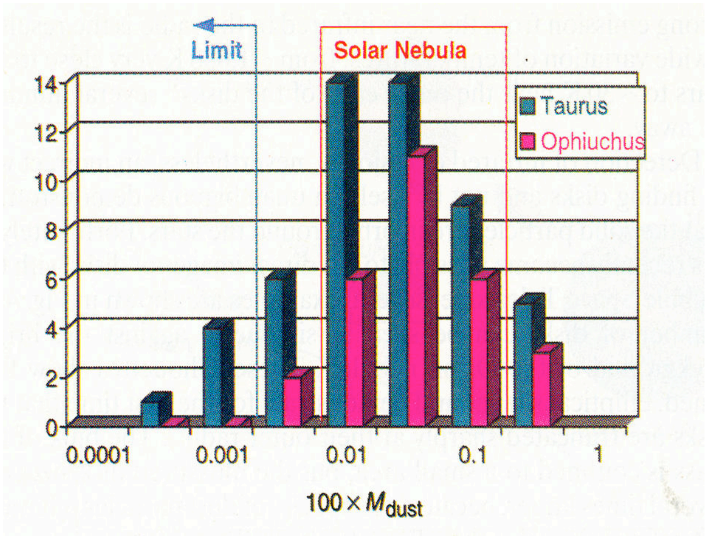




Jupiter & Saturn formation







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

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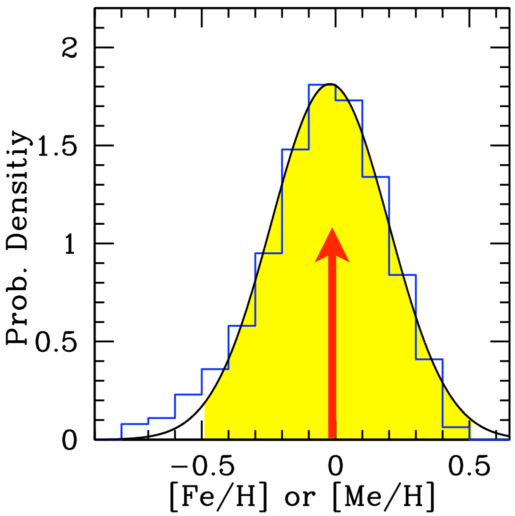

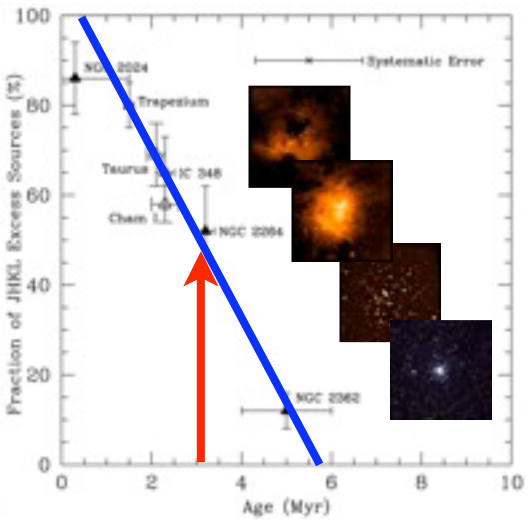

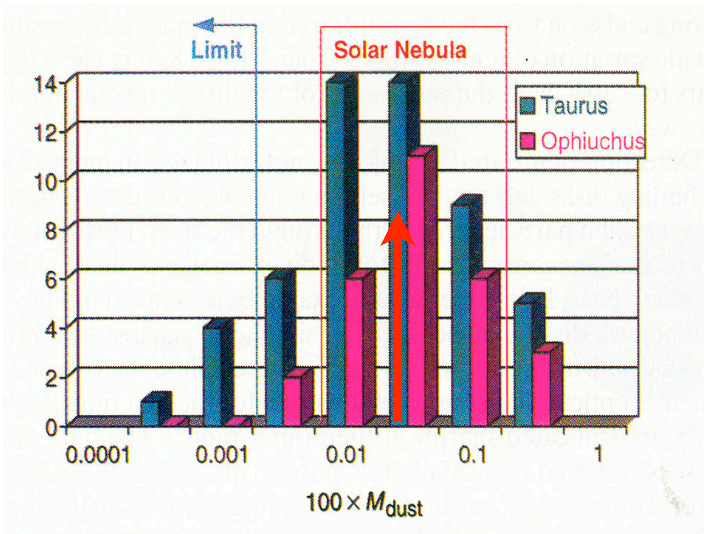

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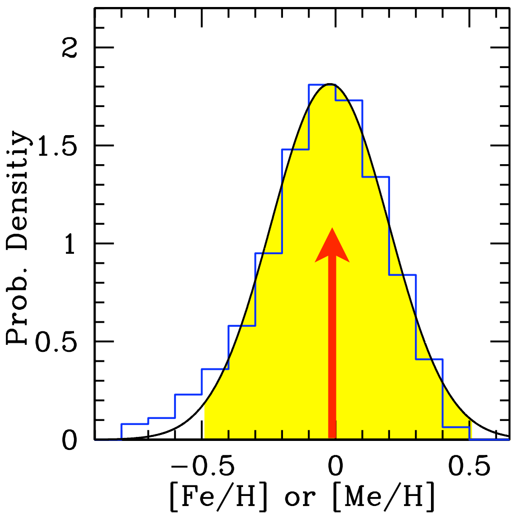
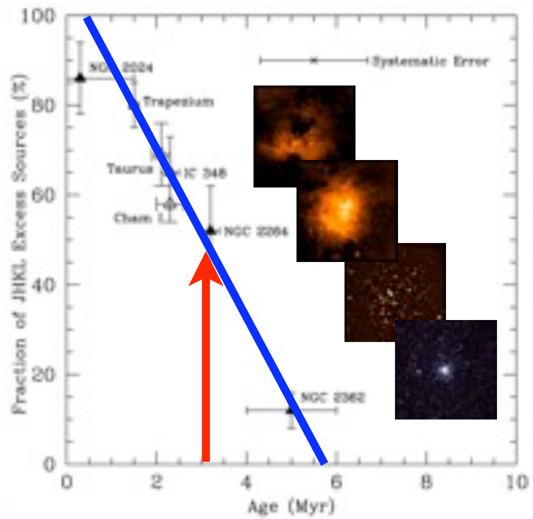
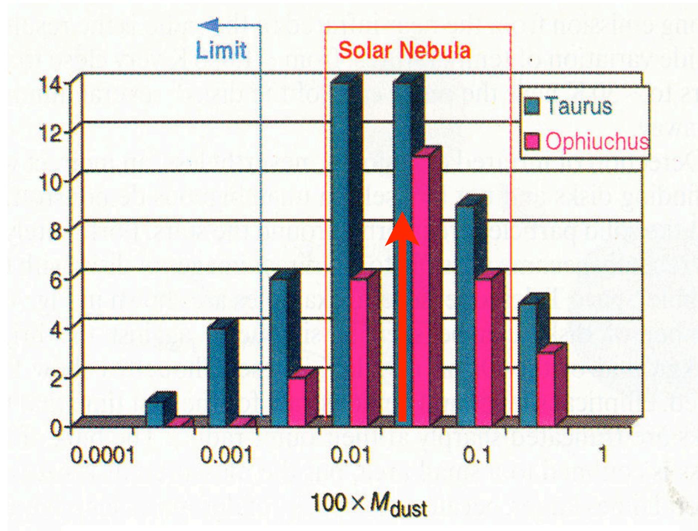
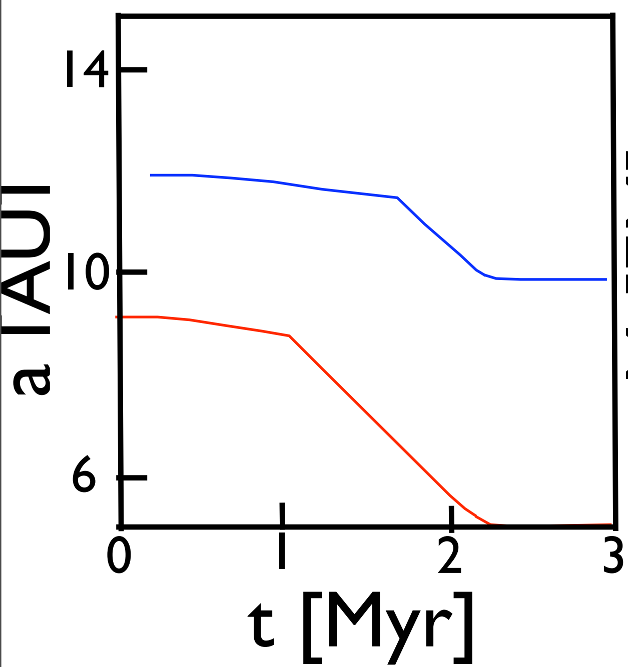
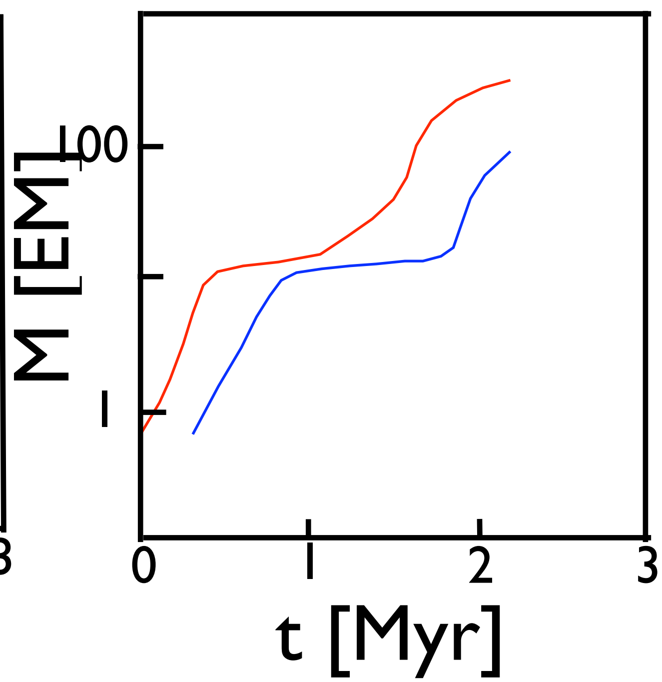


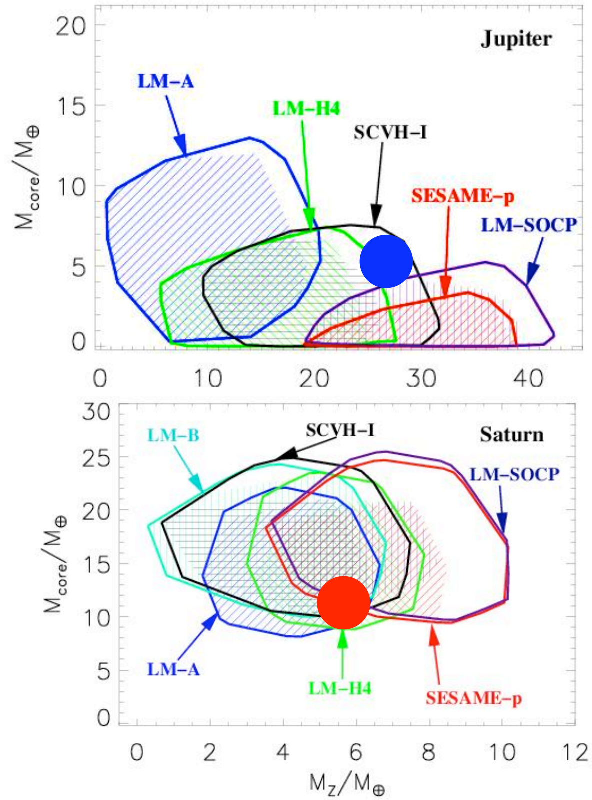








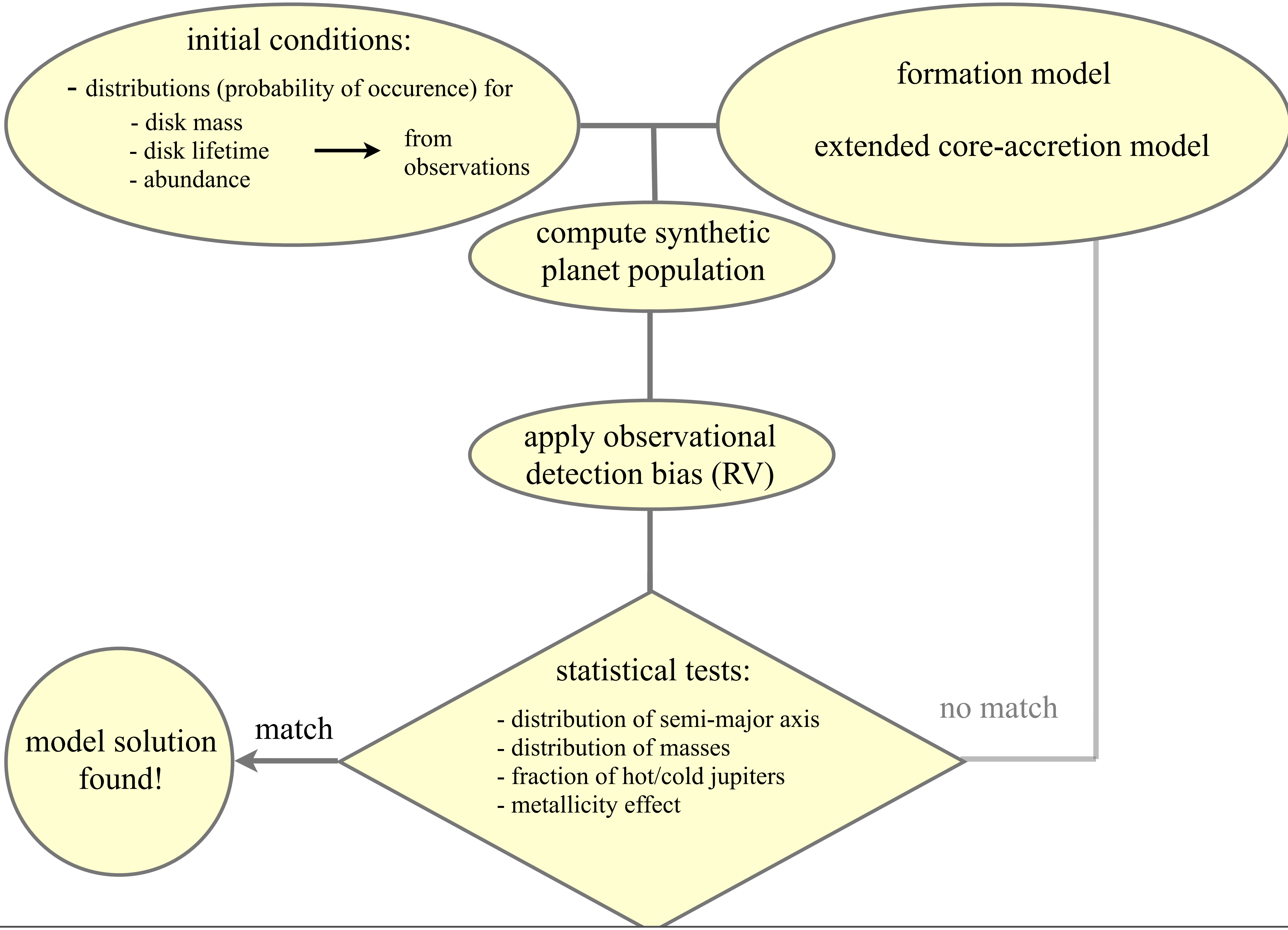
Alibert et al. 2005



Saumon & Guillot 2004

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

Extra-solar planet population synthesis



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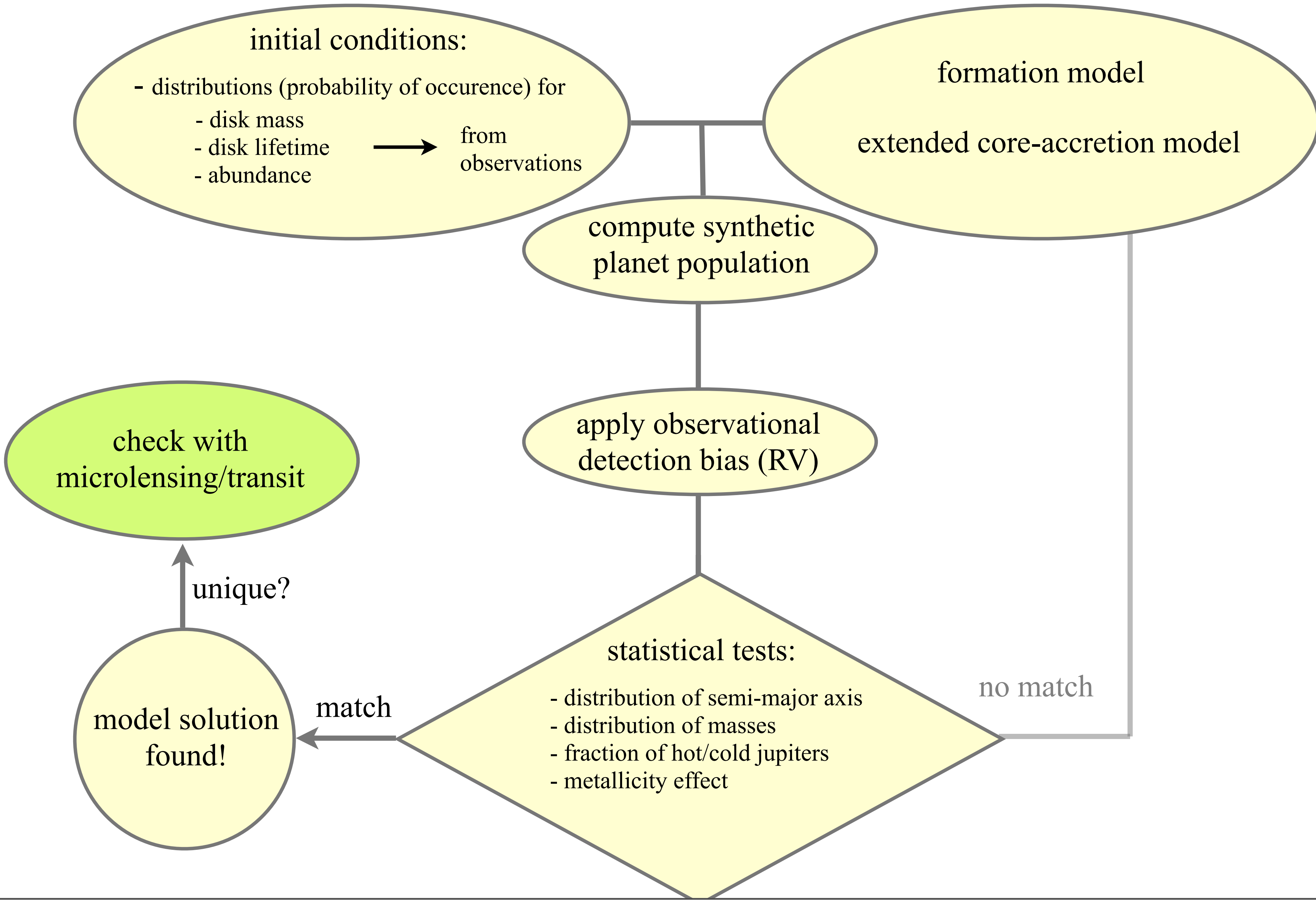
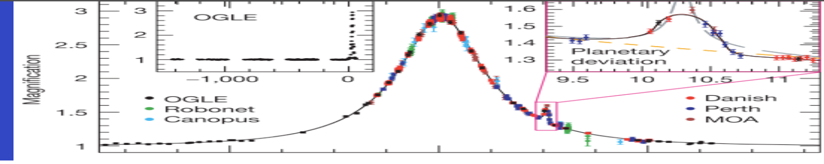
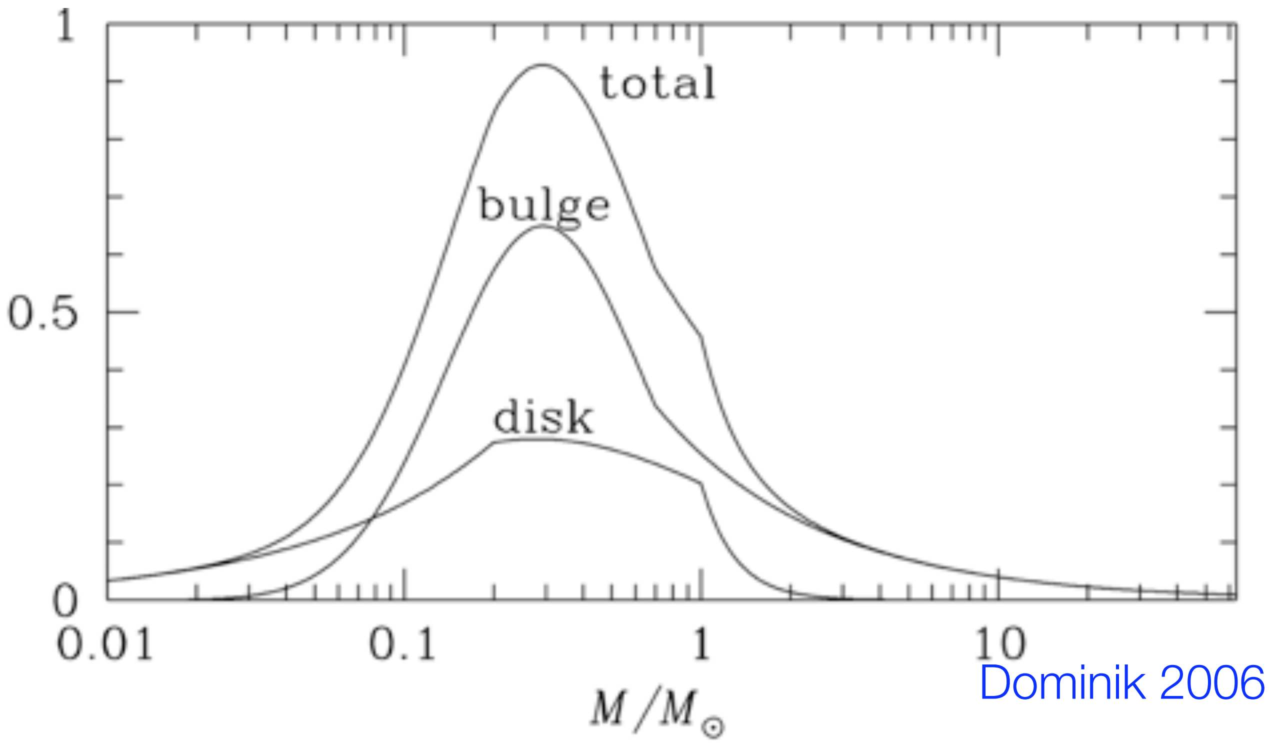


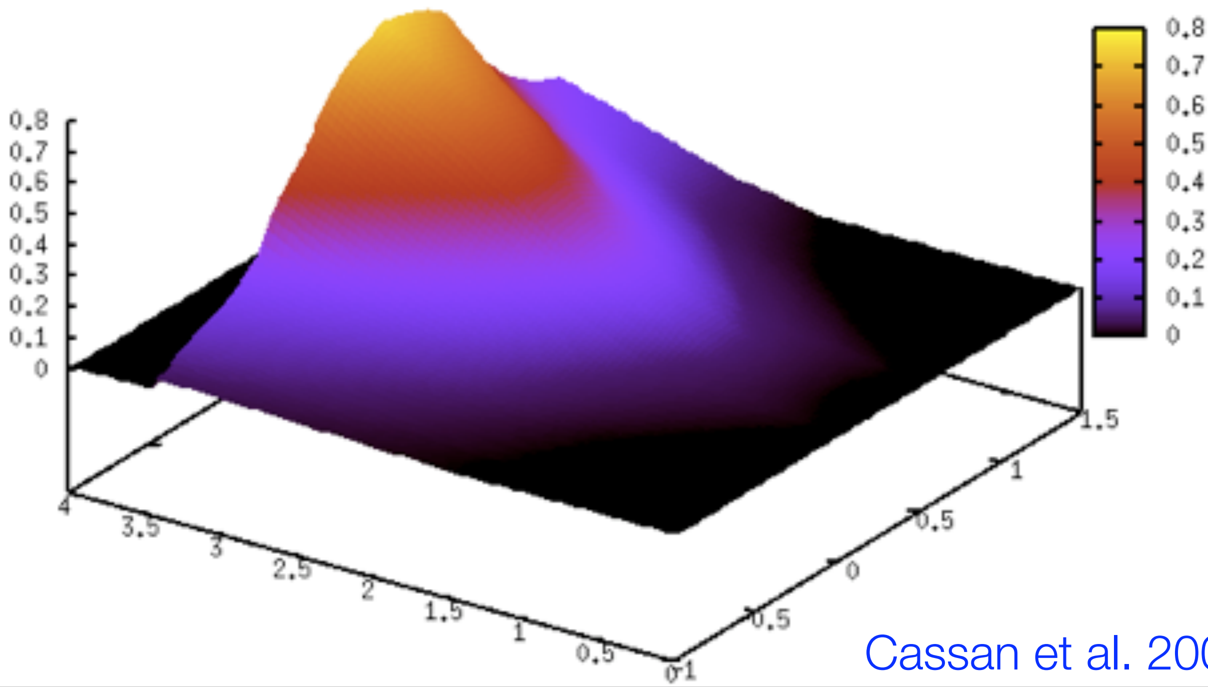
Microlensing





Lens star mass function

Dominik 2006



Detection efficiency

Cassan et al. 2008

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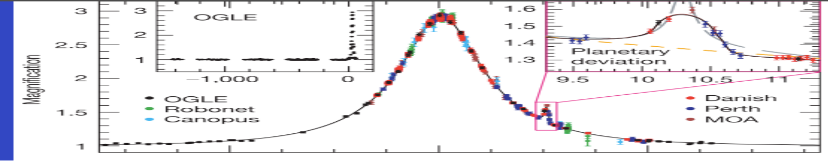

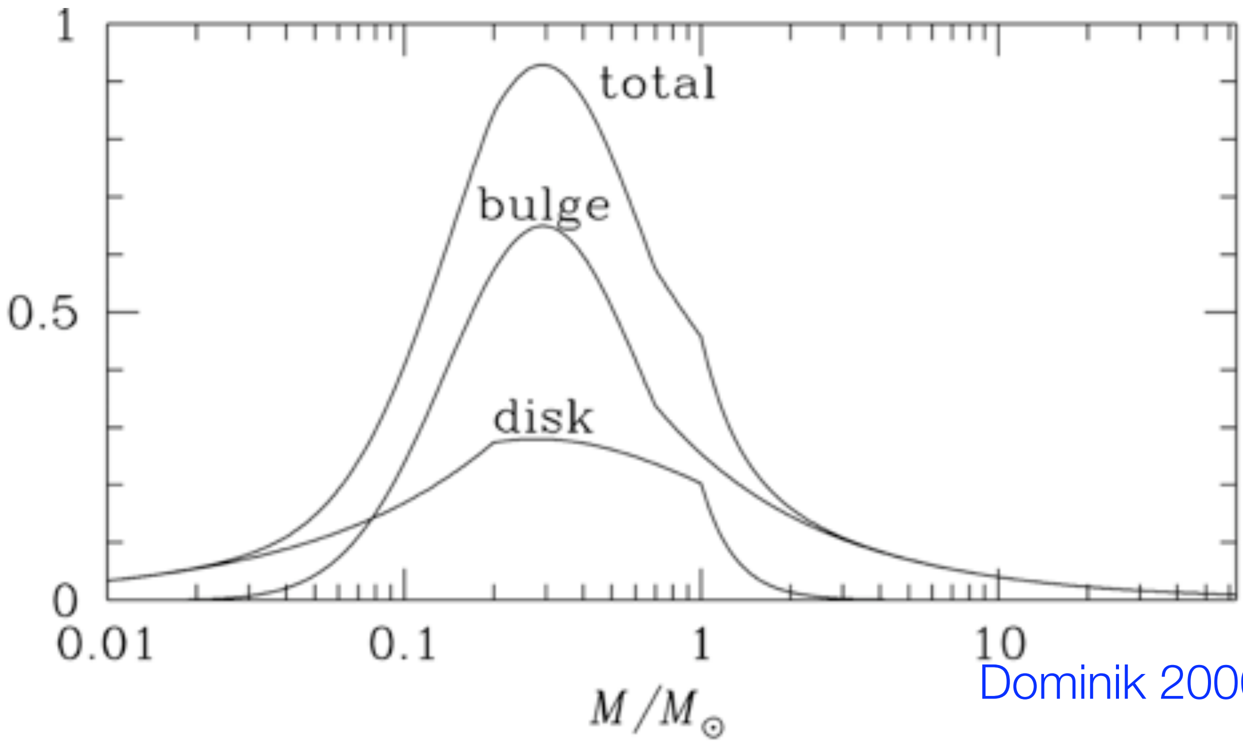

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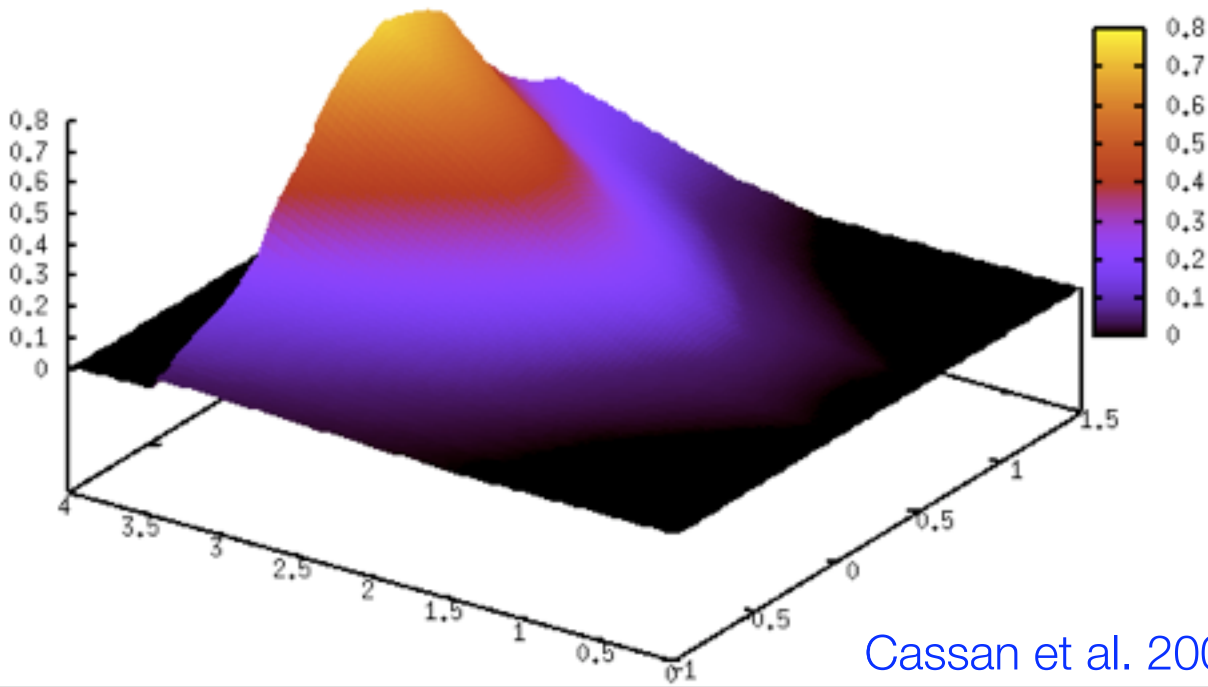

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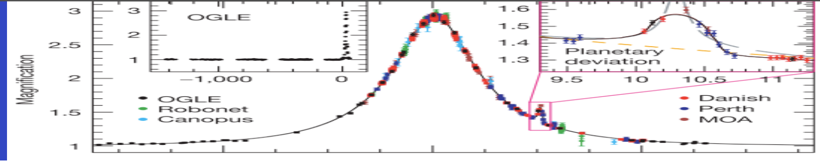
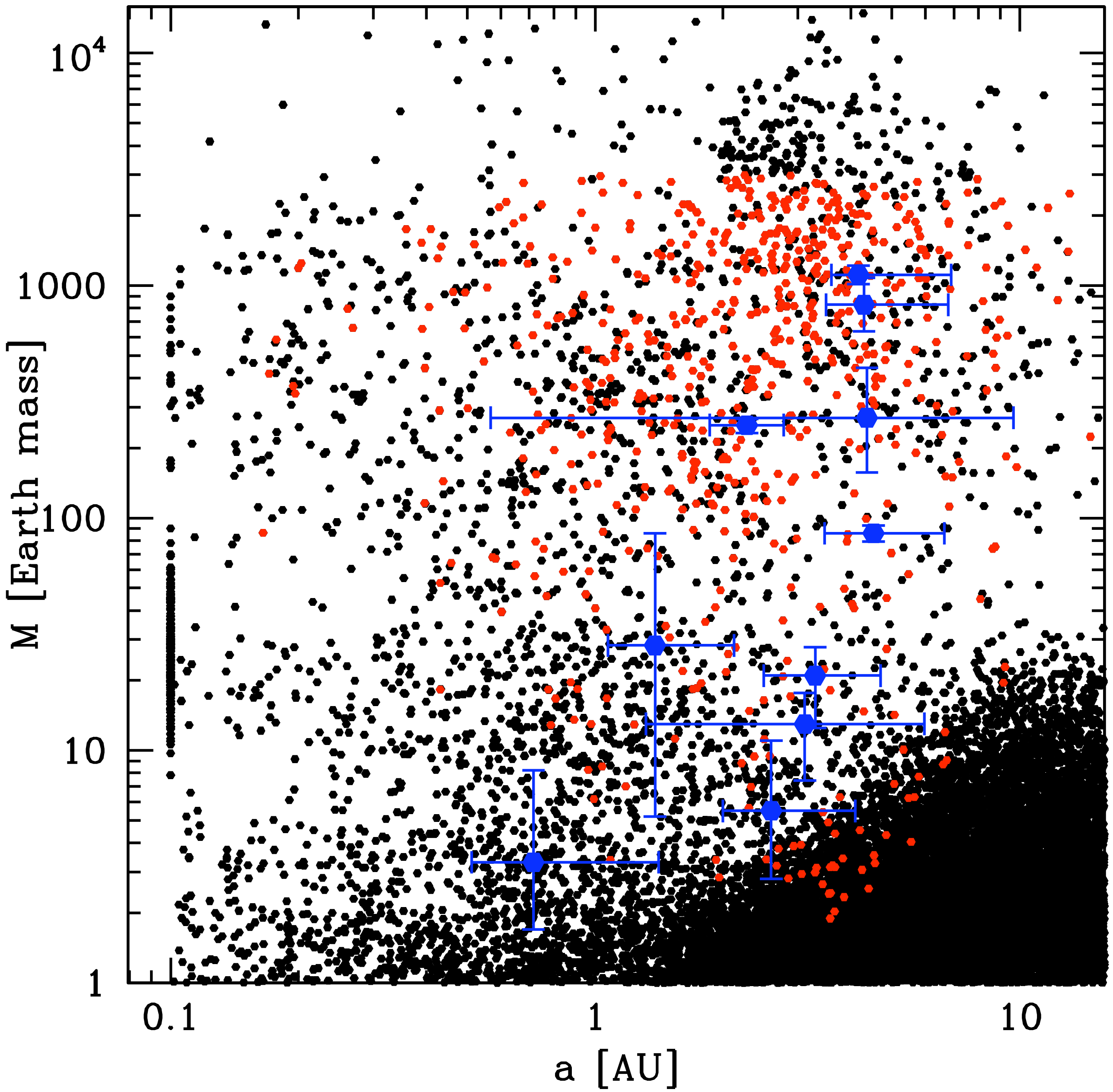
synthetic population observable by microlensing

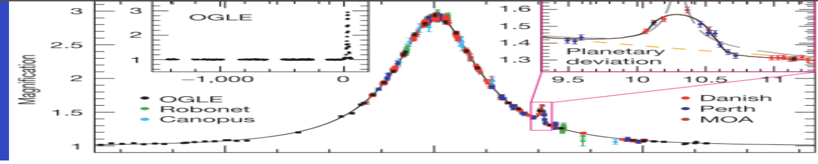
Microlensing

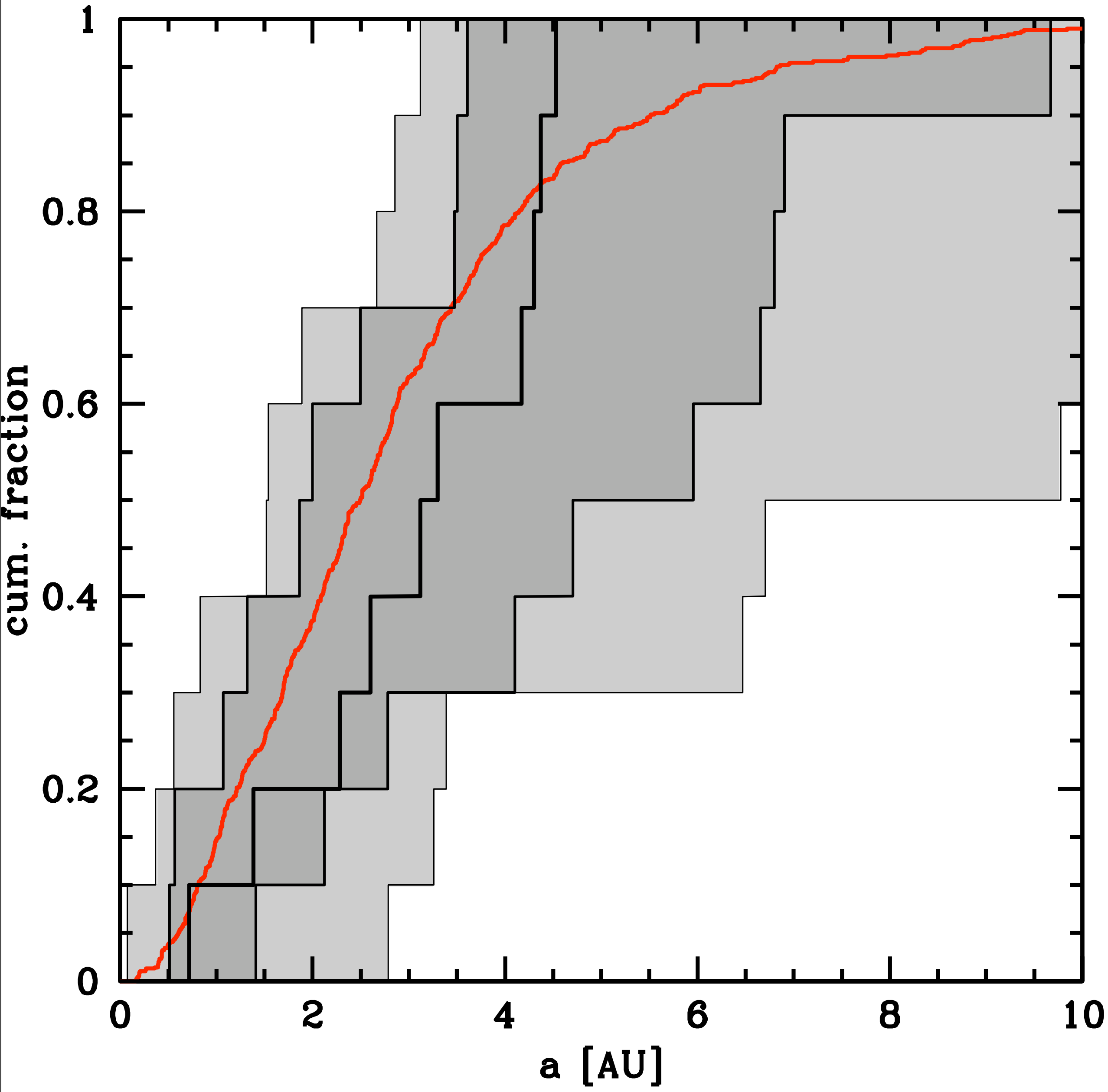


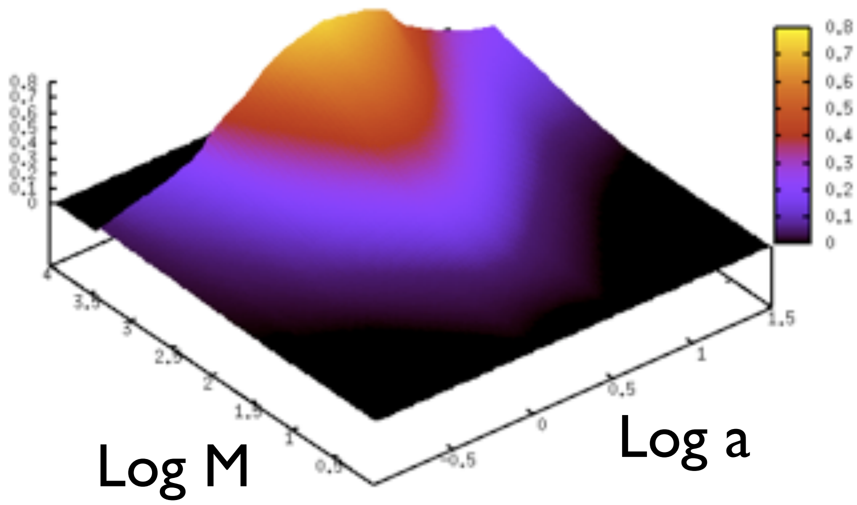


Alibert et al. in prep

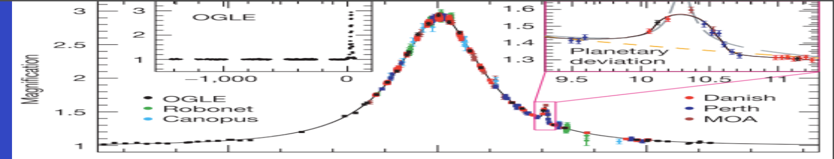
semi-major axis histogram

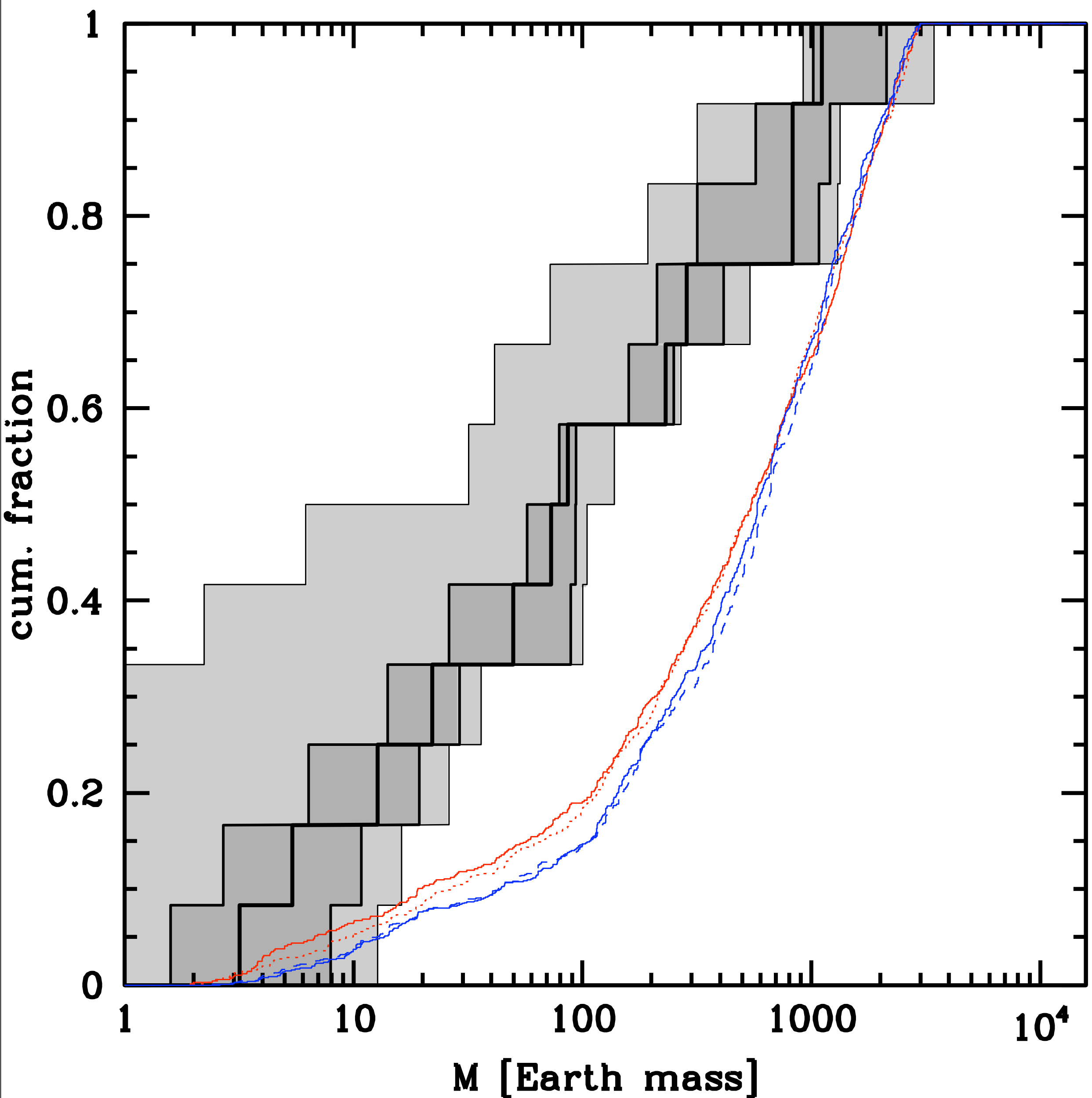


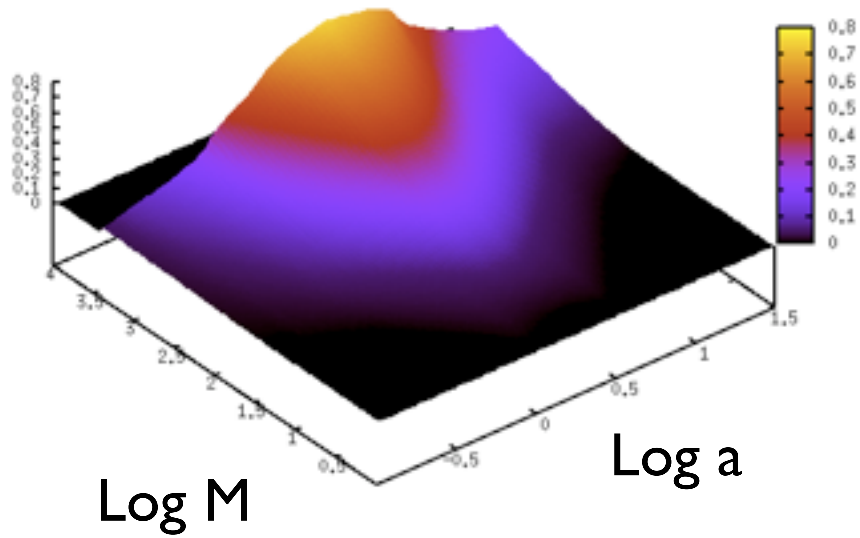




mass histogram

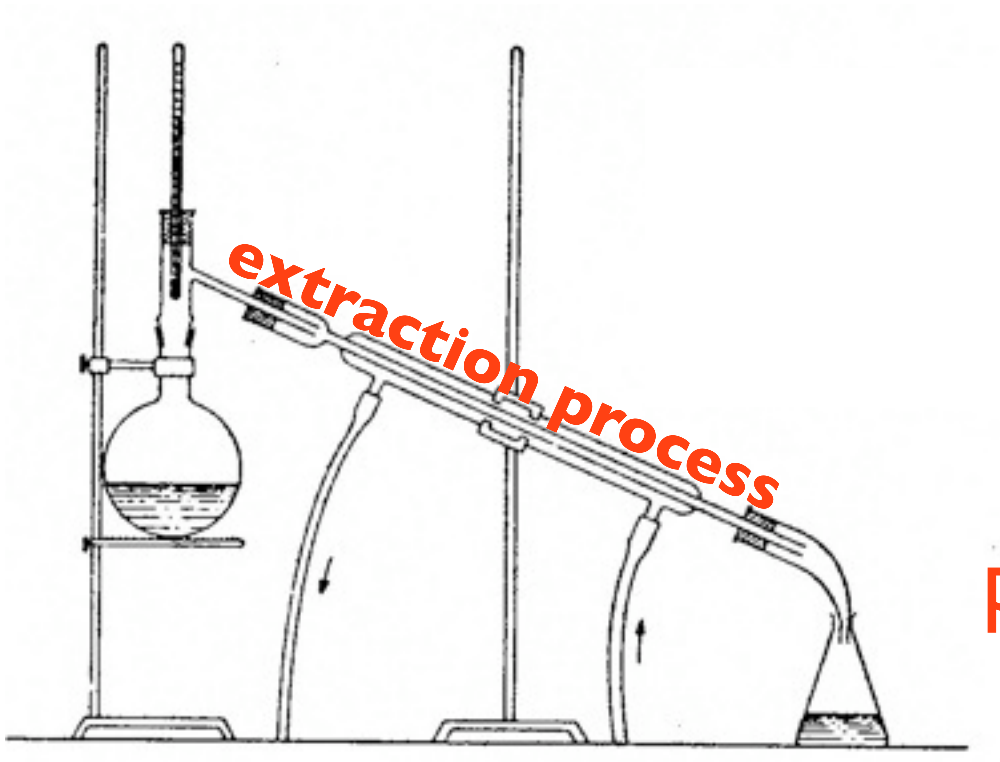






Intermediate conclusion

specialized models



population synthesis

Intermediate conclusion

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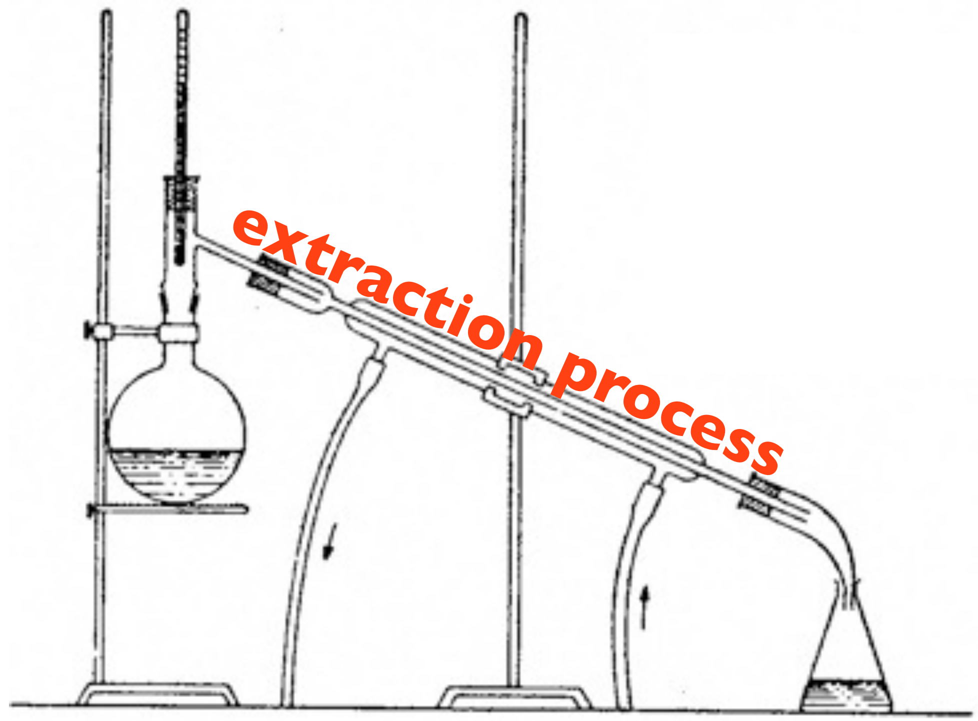


population synthesis

2005 model

Alibert et al. 2005

isothermal reduced migration

one planet

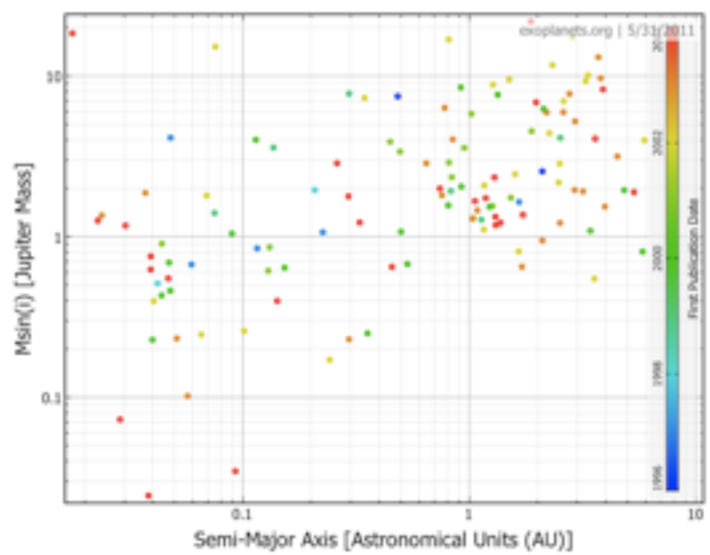
circular orbit

no heating of planetesimals

model α for the gas disk

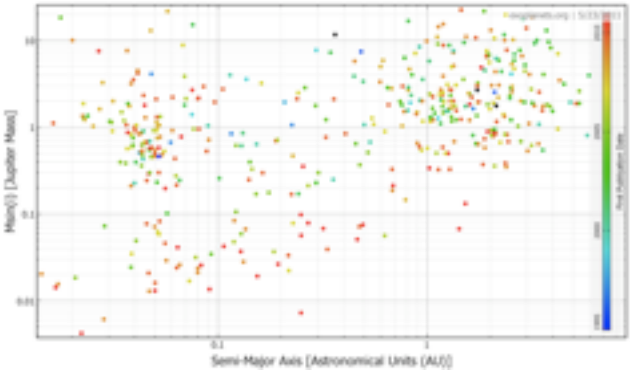
→

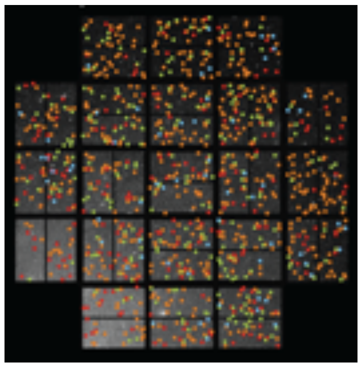
observations



Intermediate conclusion

new observations





new model

type I migration

multi-planet

no circular orbit

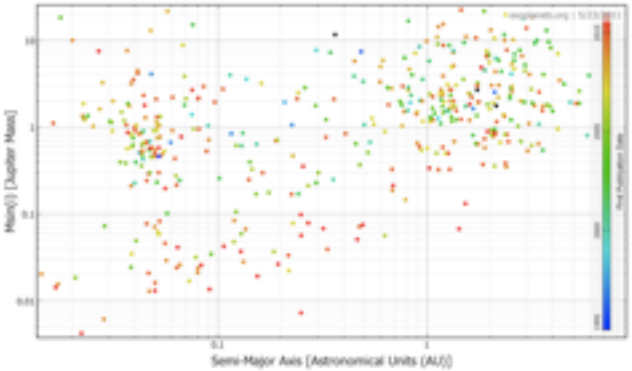
heating of planetesimals

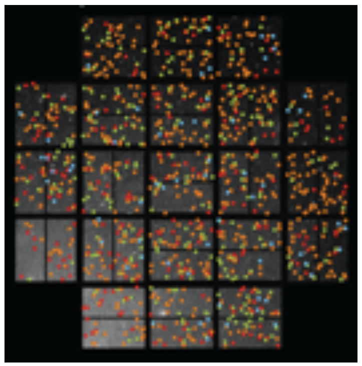
α disk model with irradiation

magnetospheric inner cavity

Intermediate conclusion

new observations





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magnetospheric inner cavity

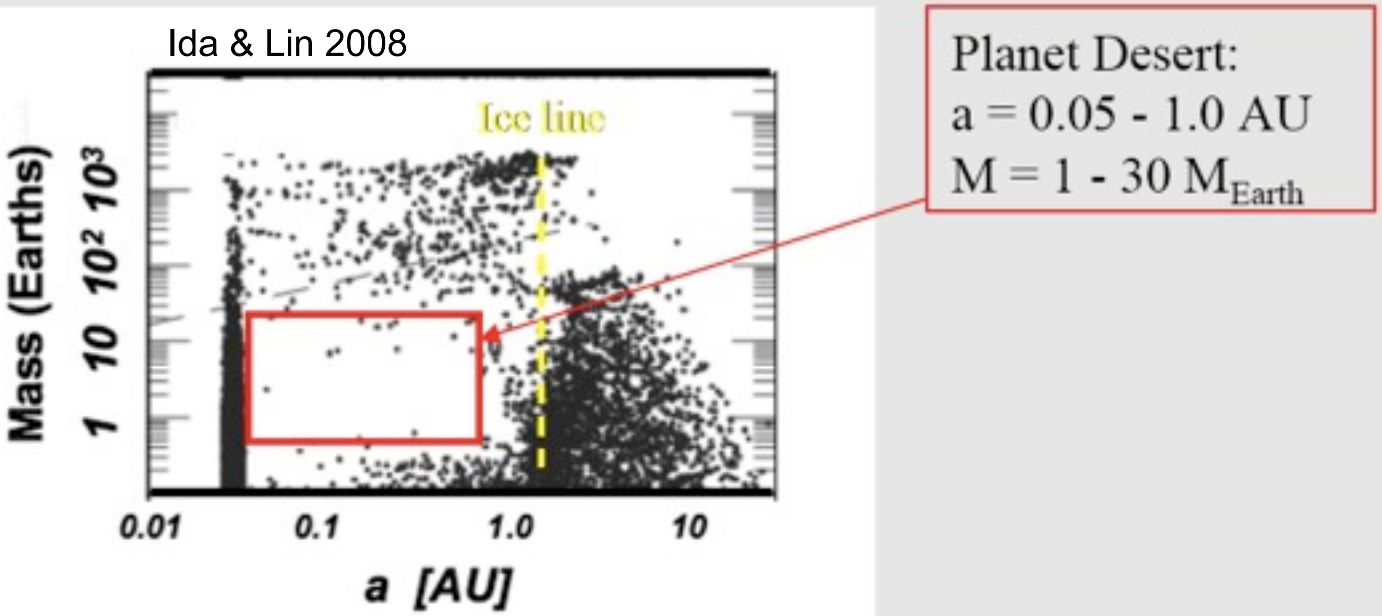
Planet desert

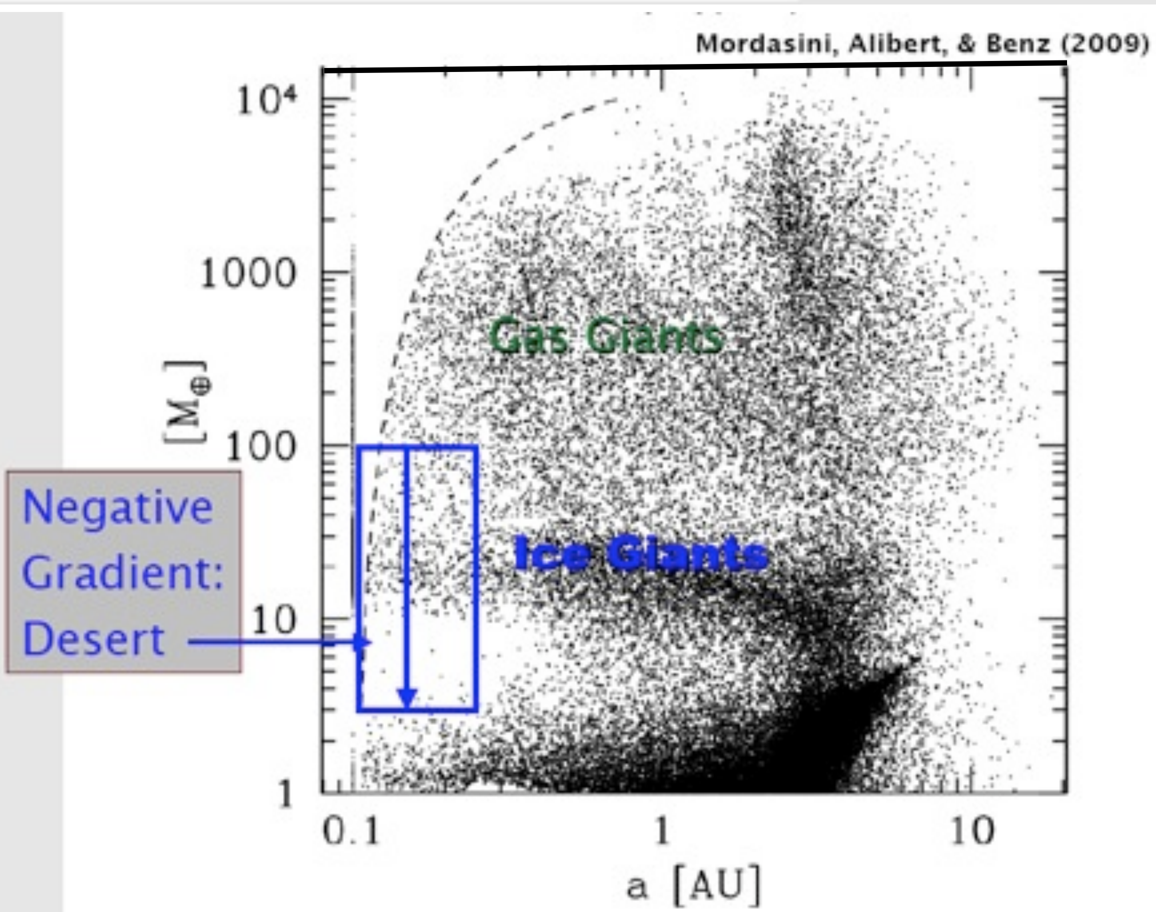
©Ida and Lin 2004

or

Planet oasis

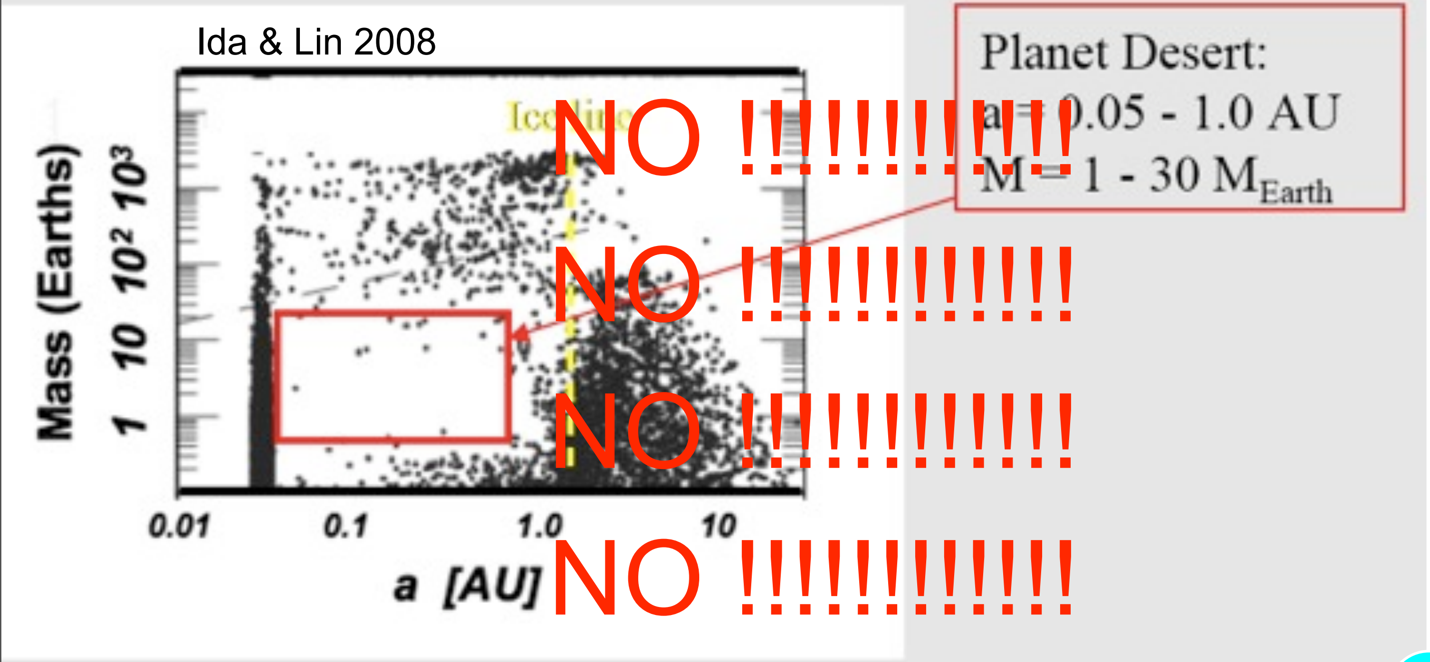
©Boss 2011

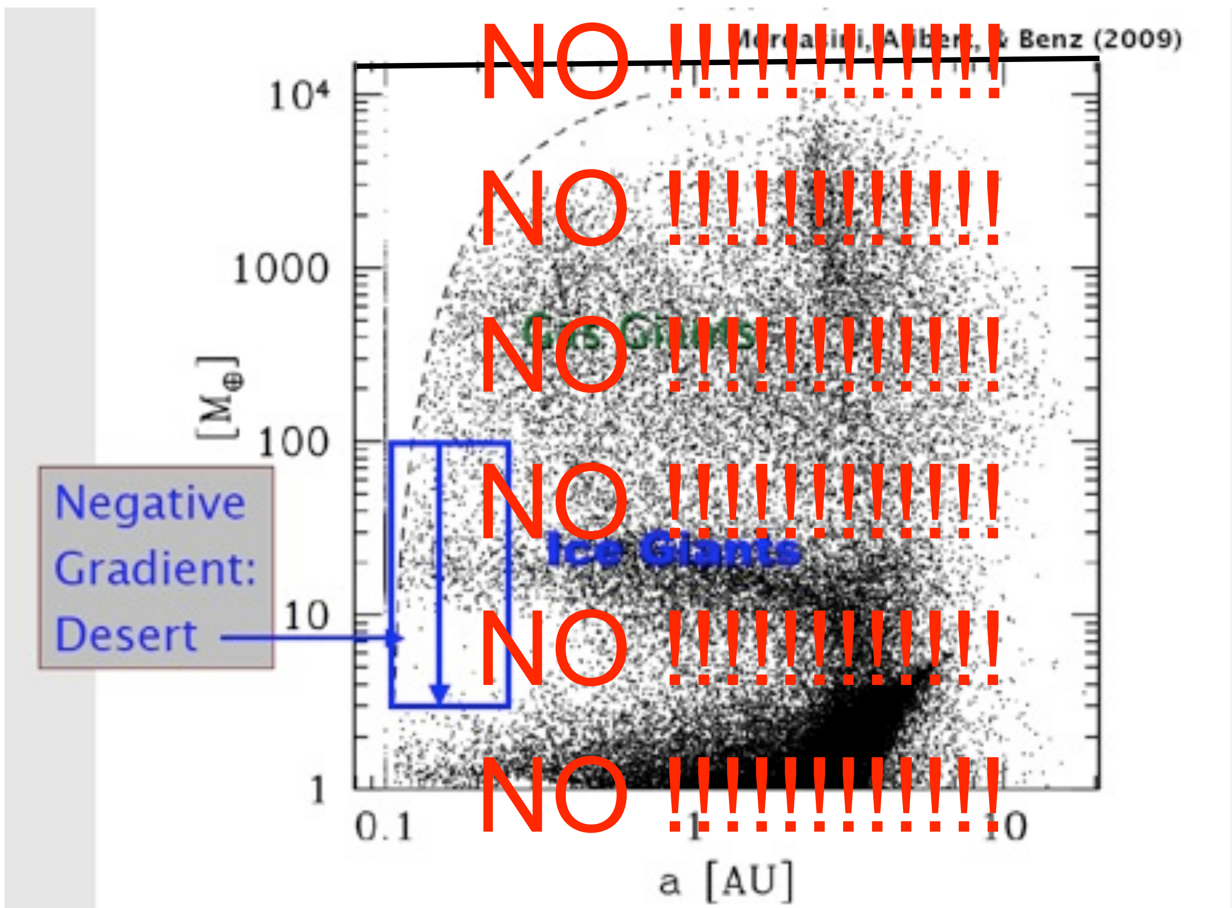




Prediction of planet formation models in the sep-mass plane

(From G. Marcy, IAU 276)





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Kepler data

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

Christoph Mordasini[1], Yann Alibert[1,2], and Willy Benz[1]

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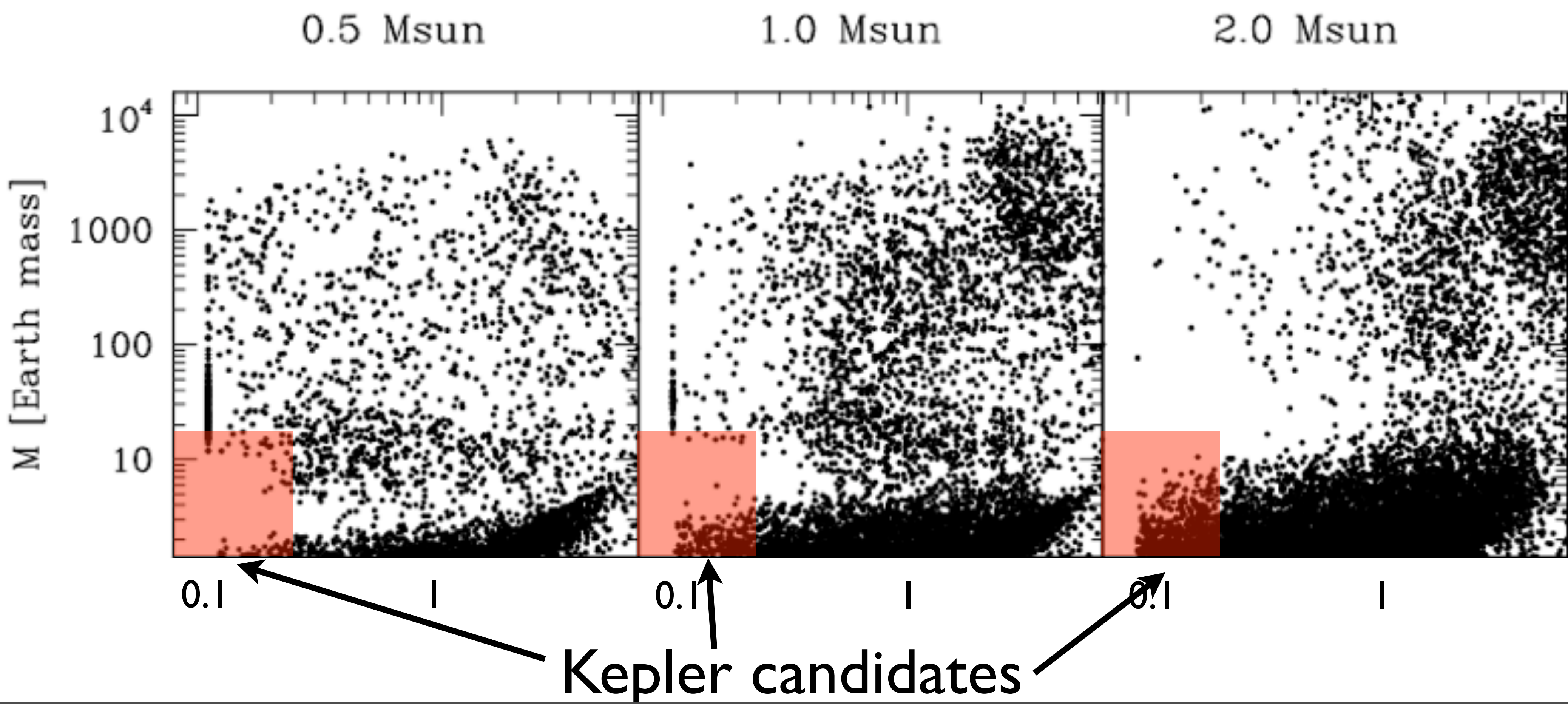
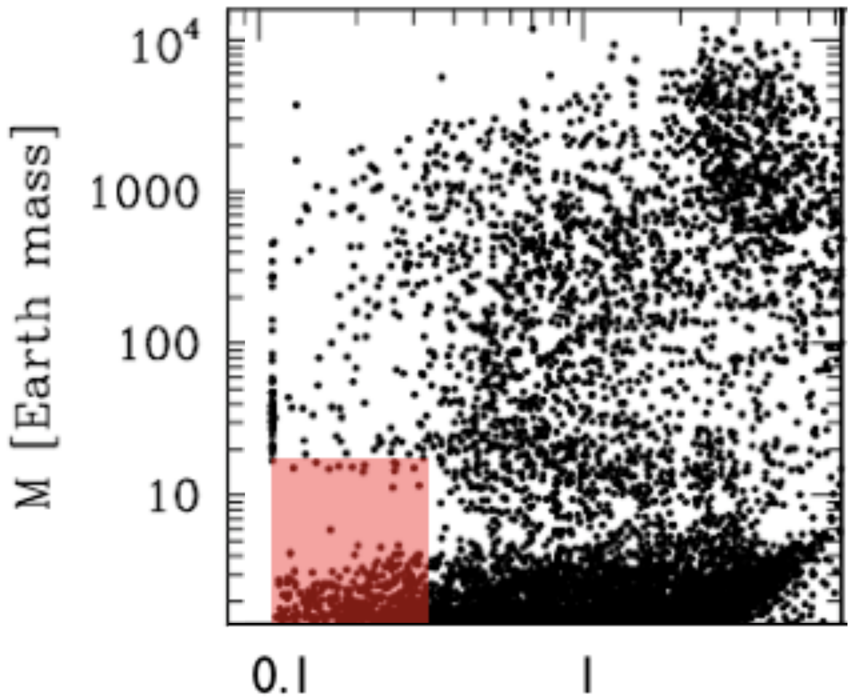


or



1- Modified migration

2- Planet-Planet interactions

Modified migration

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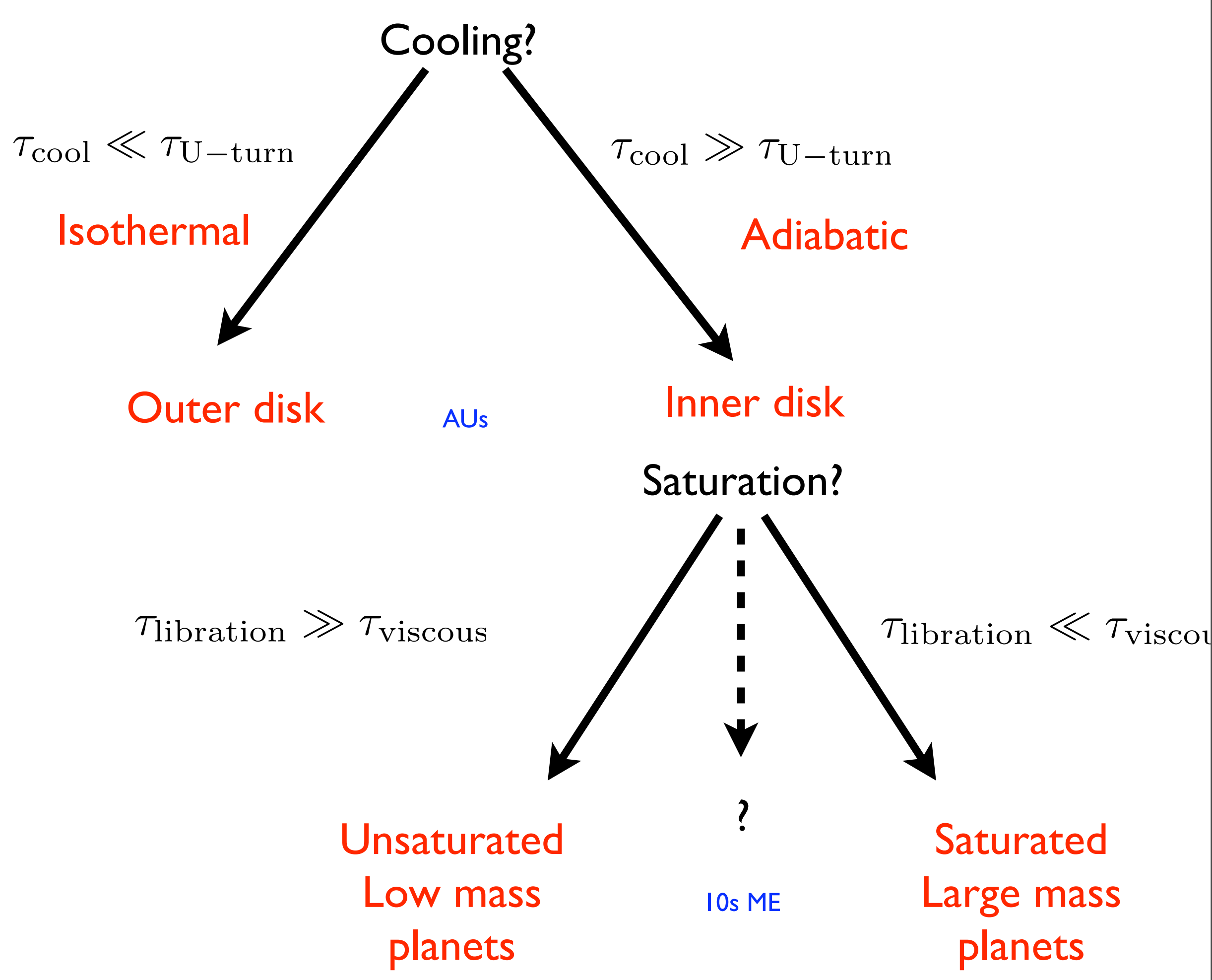
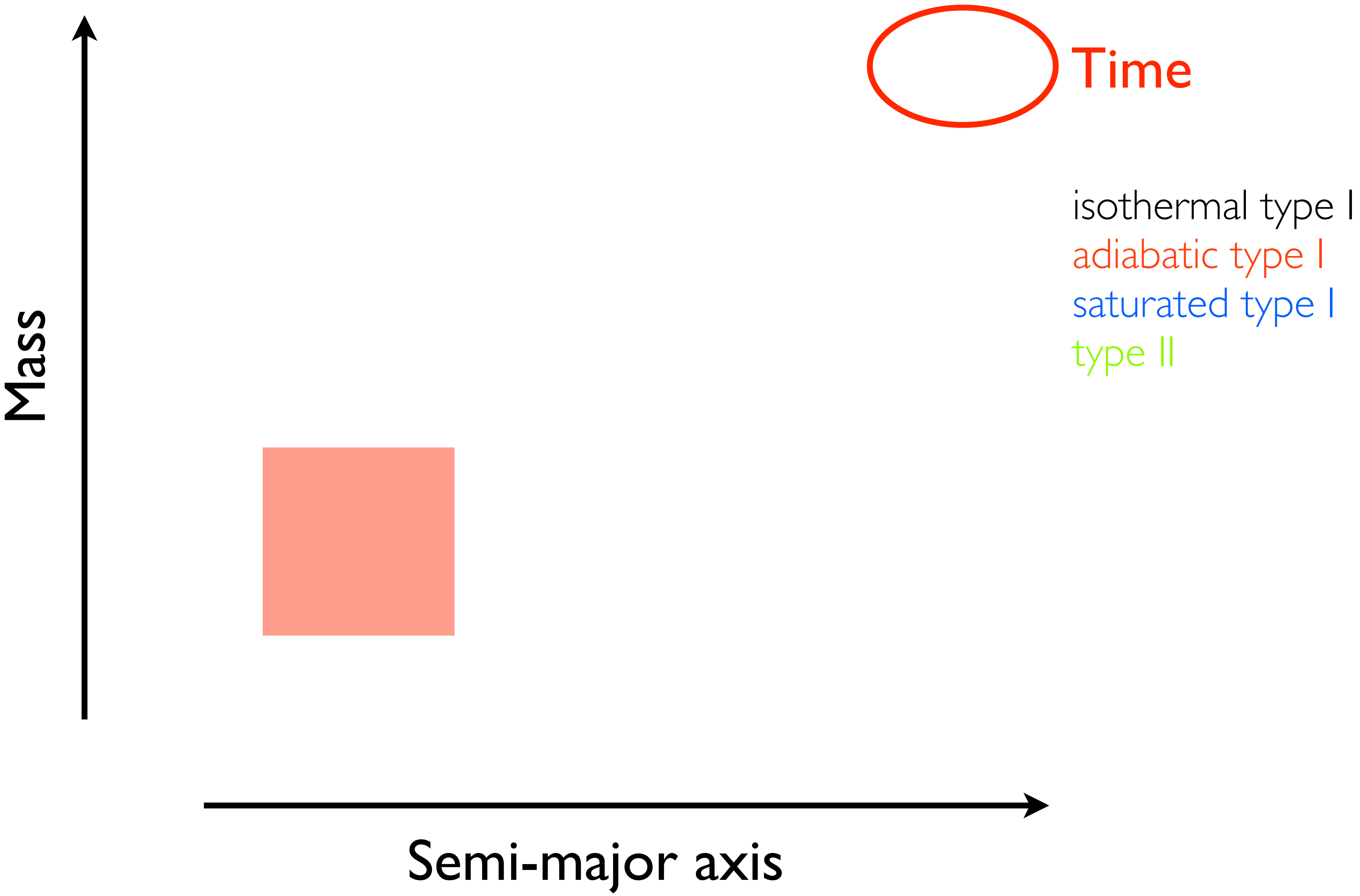


- Locally isothermal (Paardekooper et al. 2010)
- Adiabatic, unsaturated (Paardekooper et al. 2010)
- Adiabatic, saturated (Linblad torques, residual horseshoe drag)
- Reduction of gas surface density (Crida & Morbidelli 07)
- Transition to type II (Crida et al. 2006)

① Modified migration



Dittkrist et al. in prep

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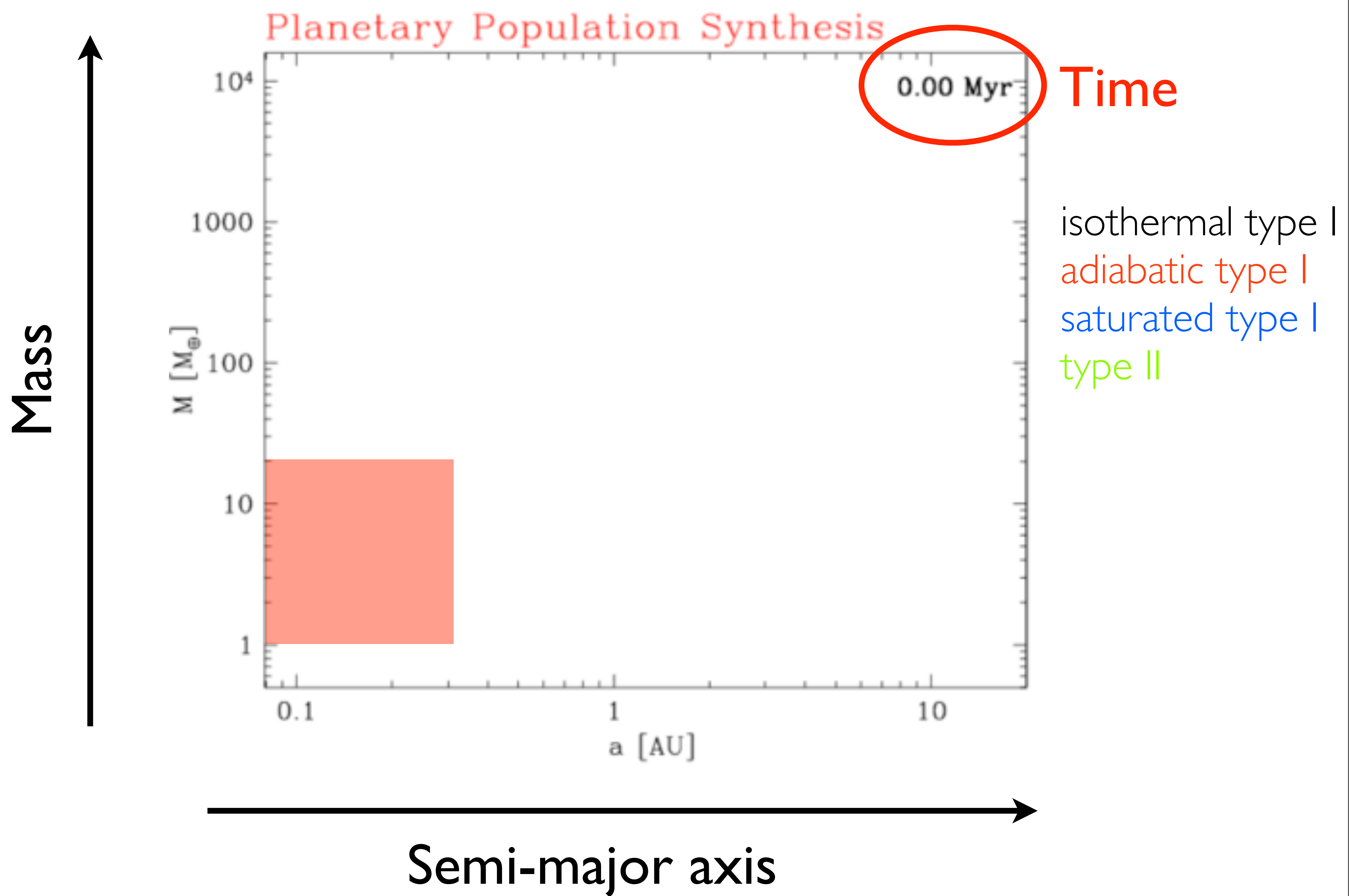


Dittkrist et al. in prep

(III) Multi-planetary systems

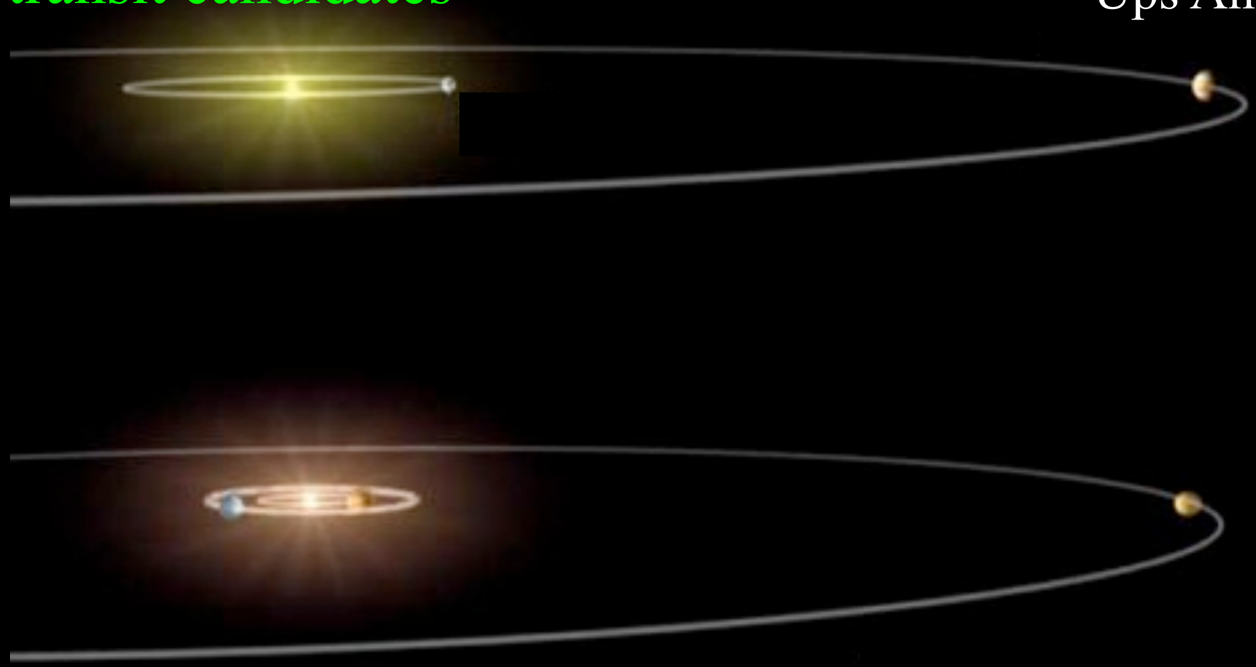
- Present statistics

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, Gl876 : 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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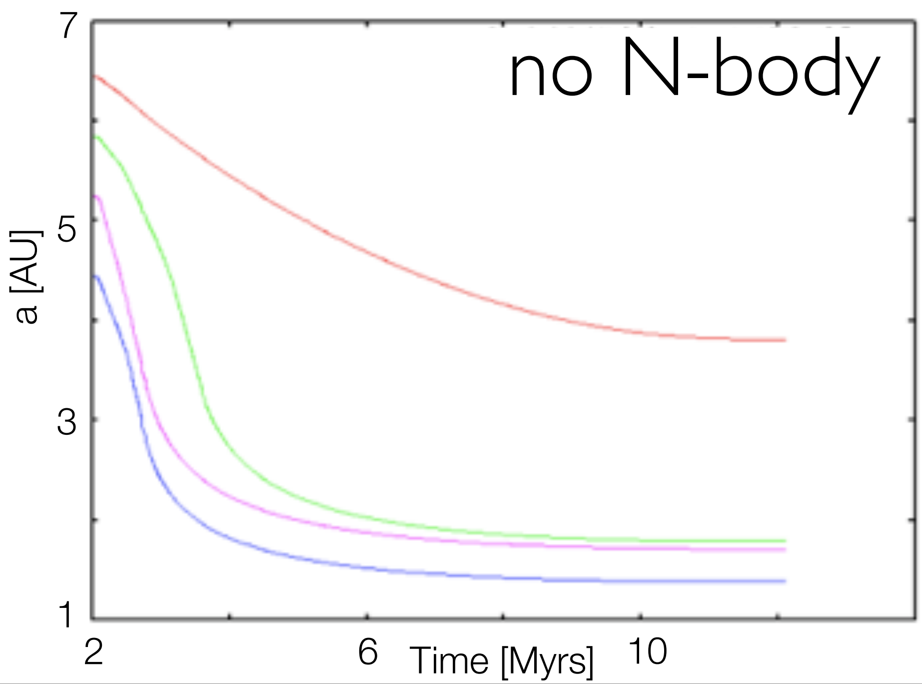
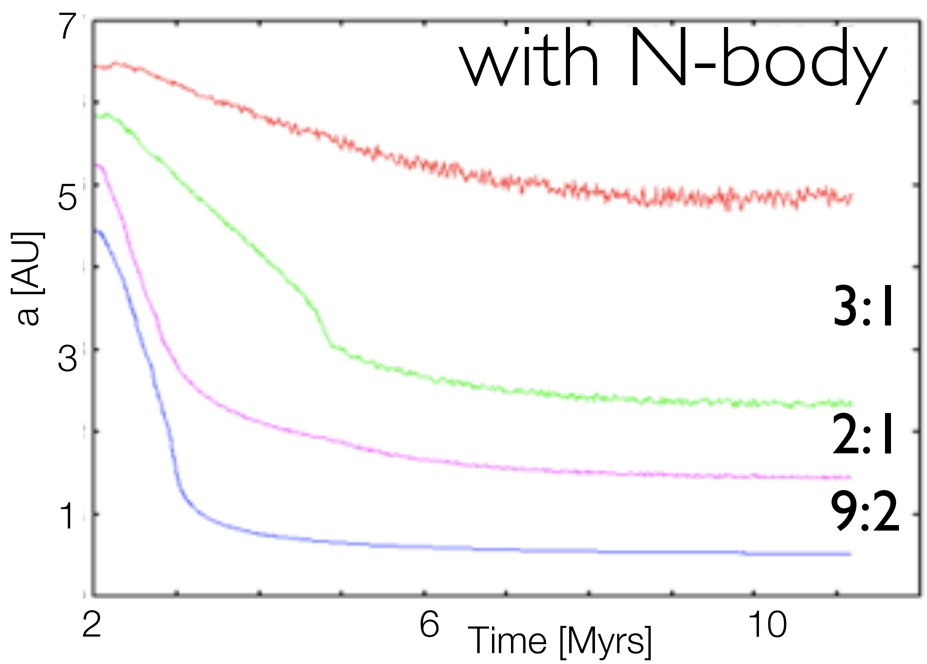


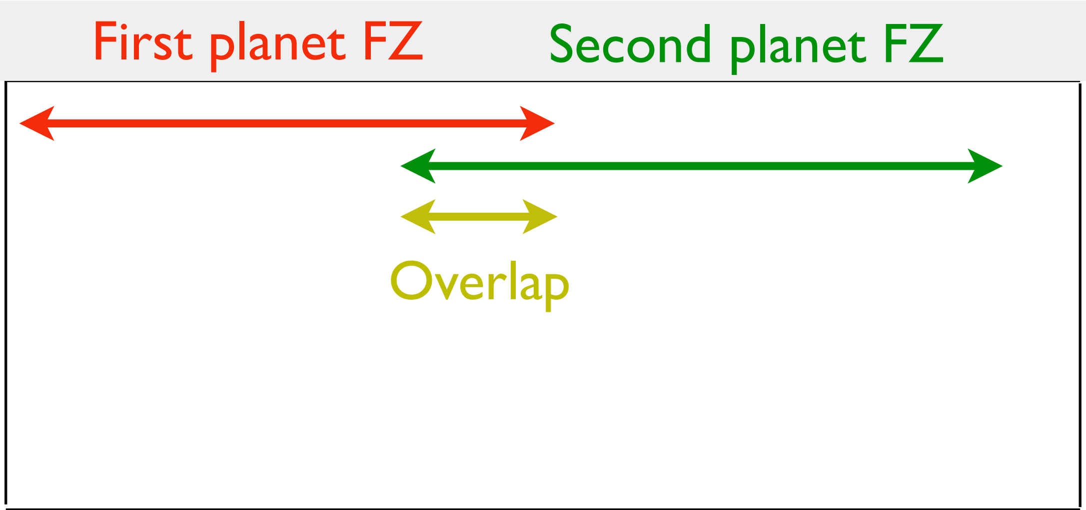


Final mass [M_{Earth}]	without N body	with N body
Planet 1	970	890
Planet 2	975	970
Planet 3	750	430
Planet 4	7	4

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

② Planet-planet interactions

N-body simulations by S. Pfyffer



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 independant

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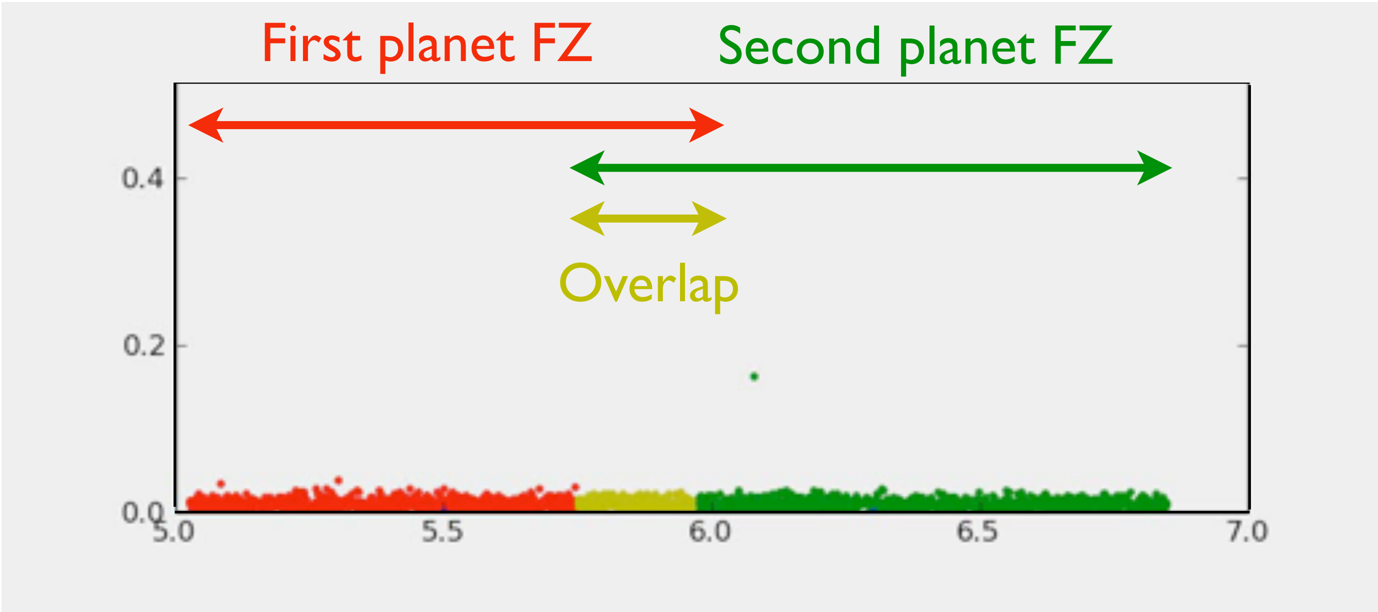

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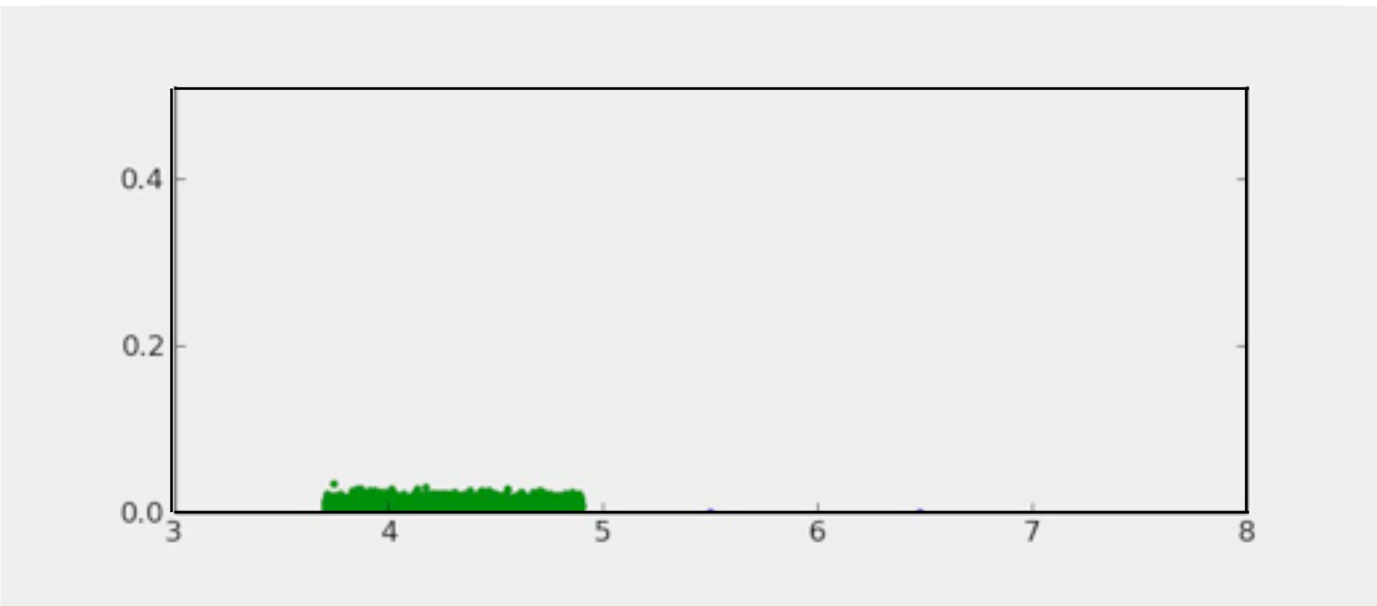

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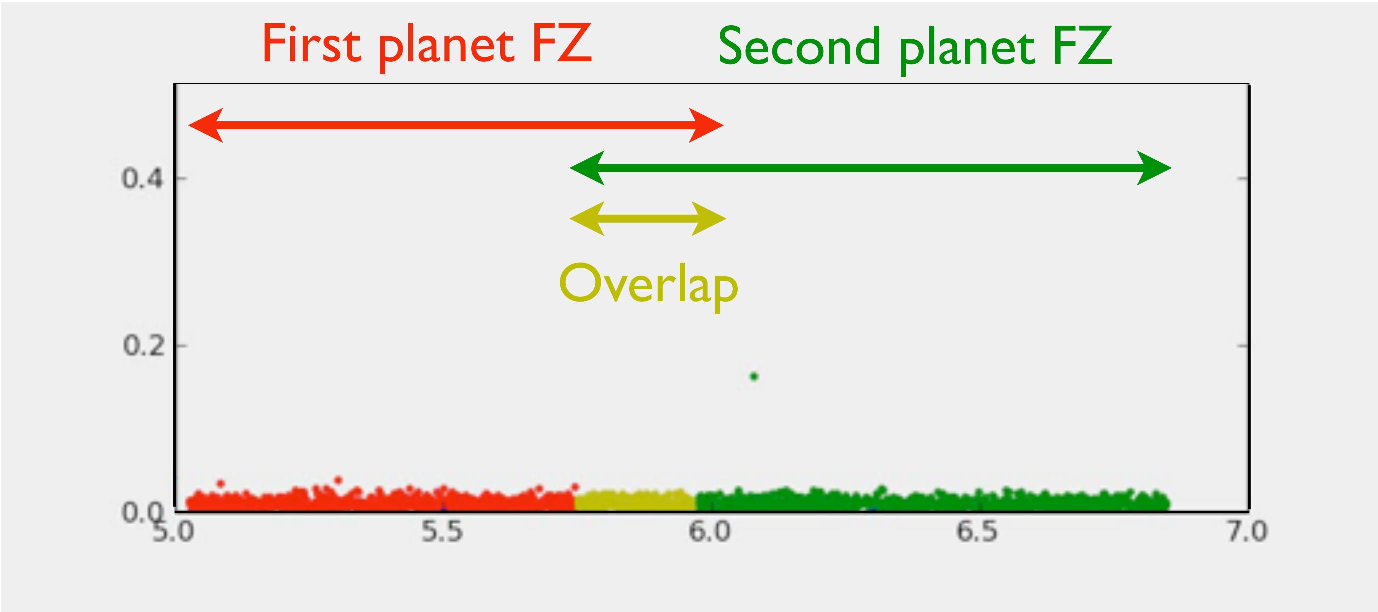

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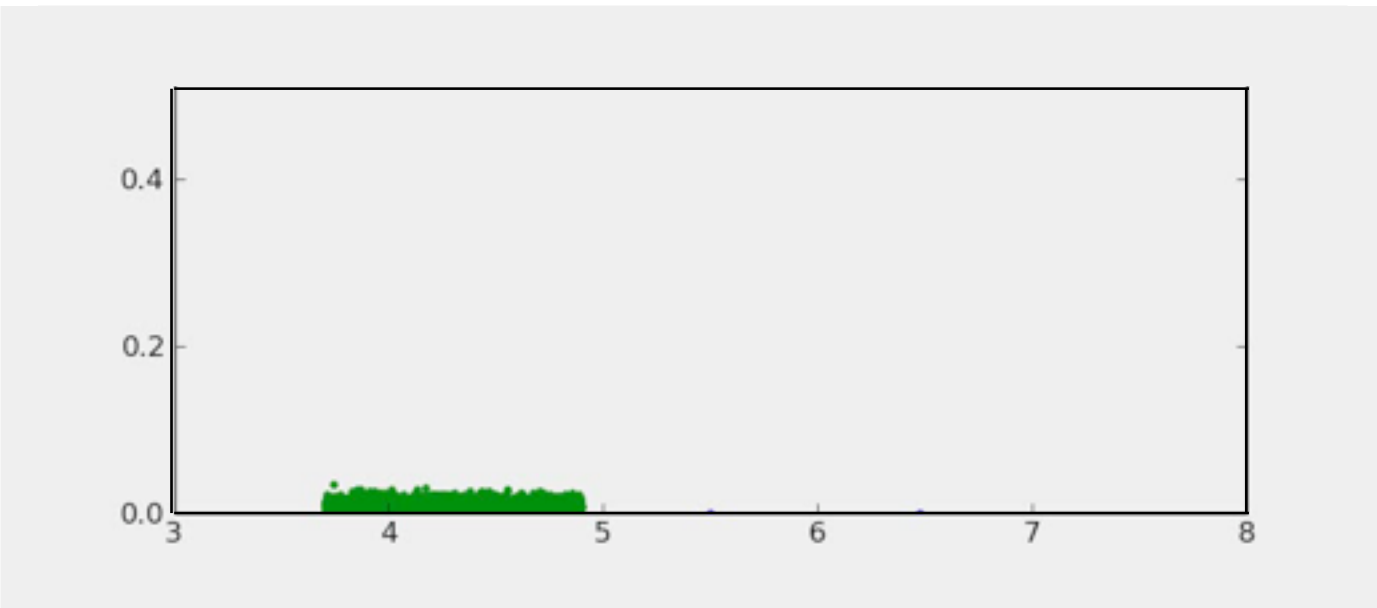

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② Planet-planet interactions

6 times 1 planet | 6 planets - no gravity | 6 planets

Isothermal type I migration / thermal criterion for gap opening

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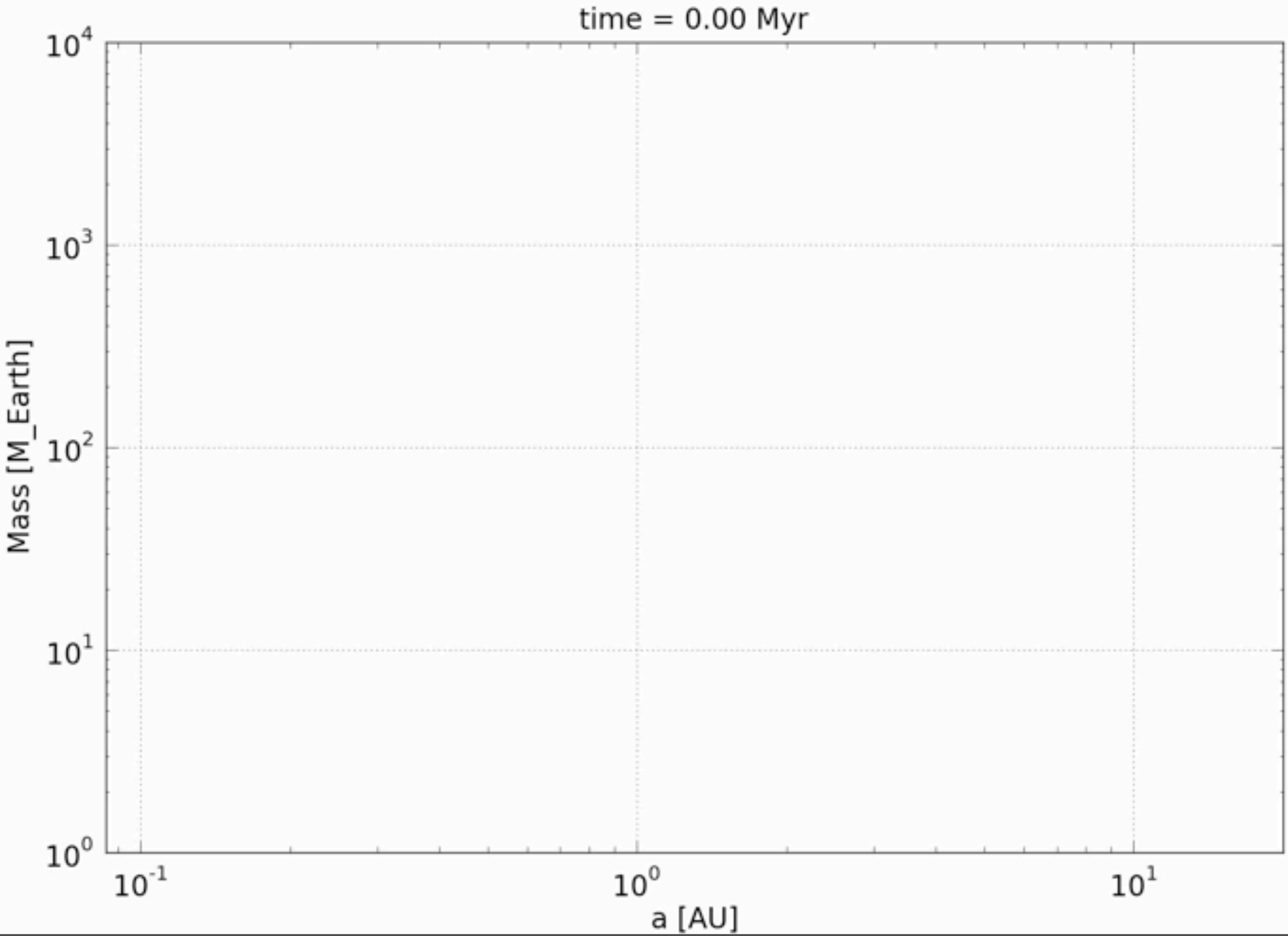

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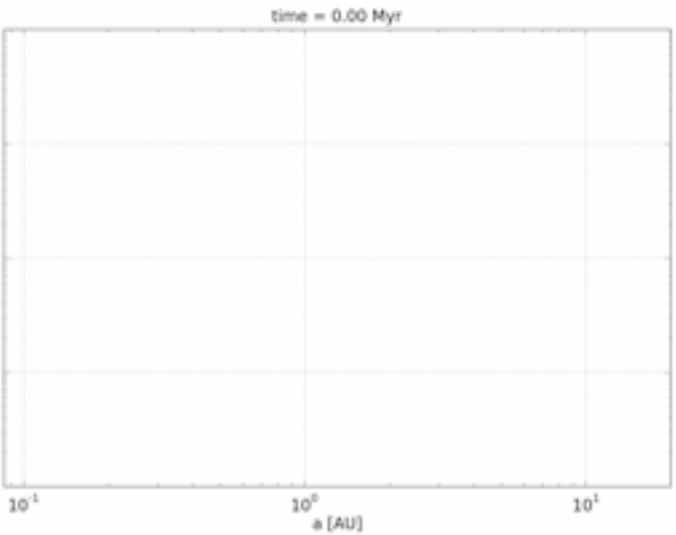

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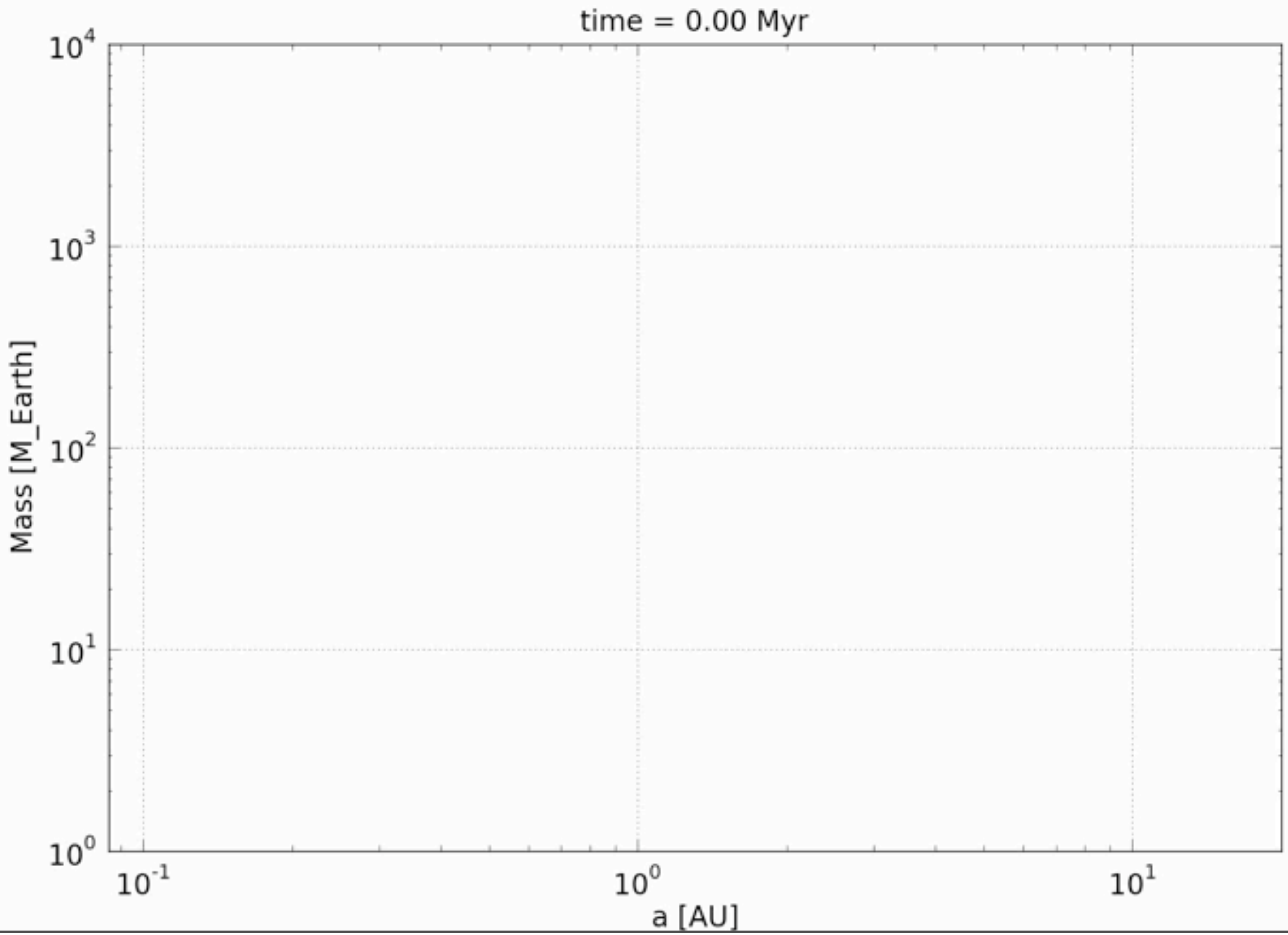

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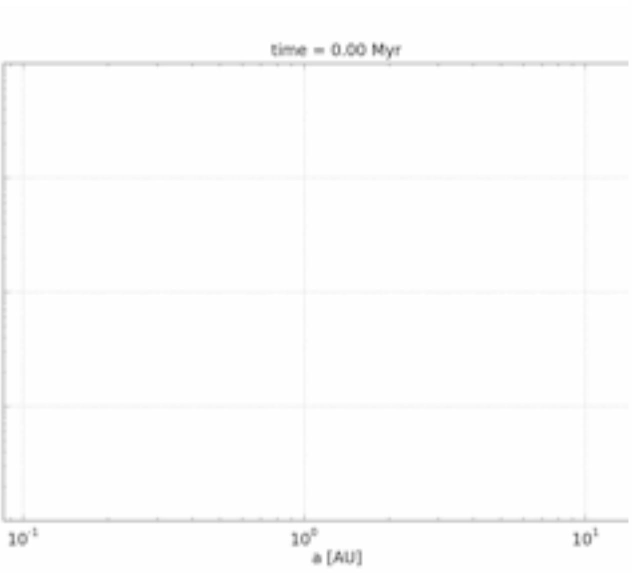
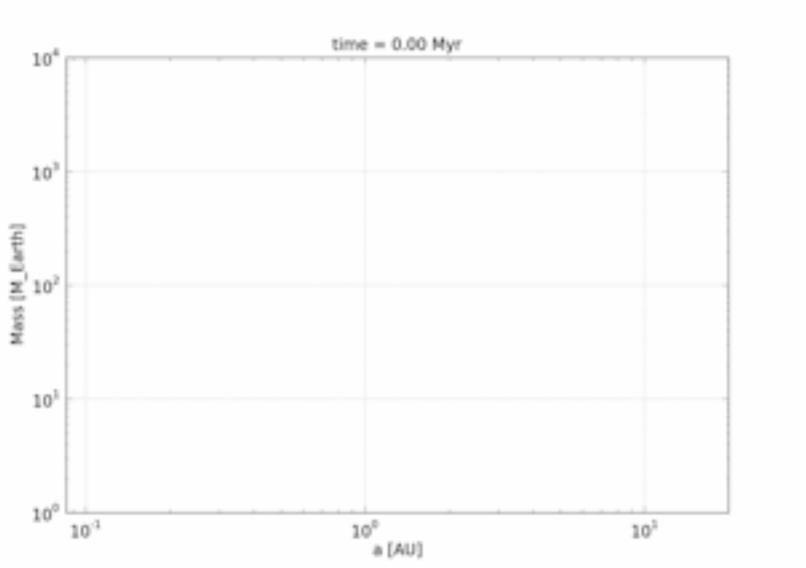
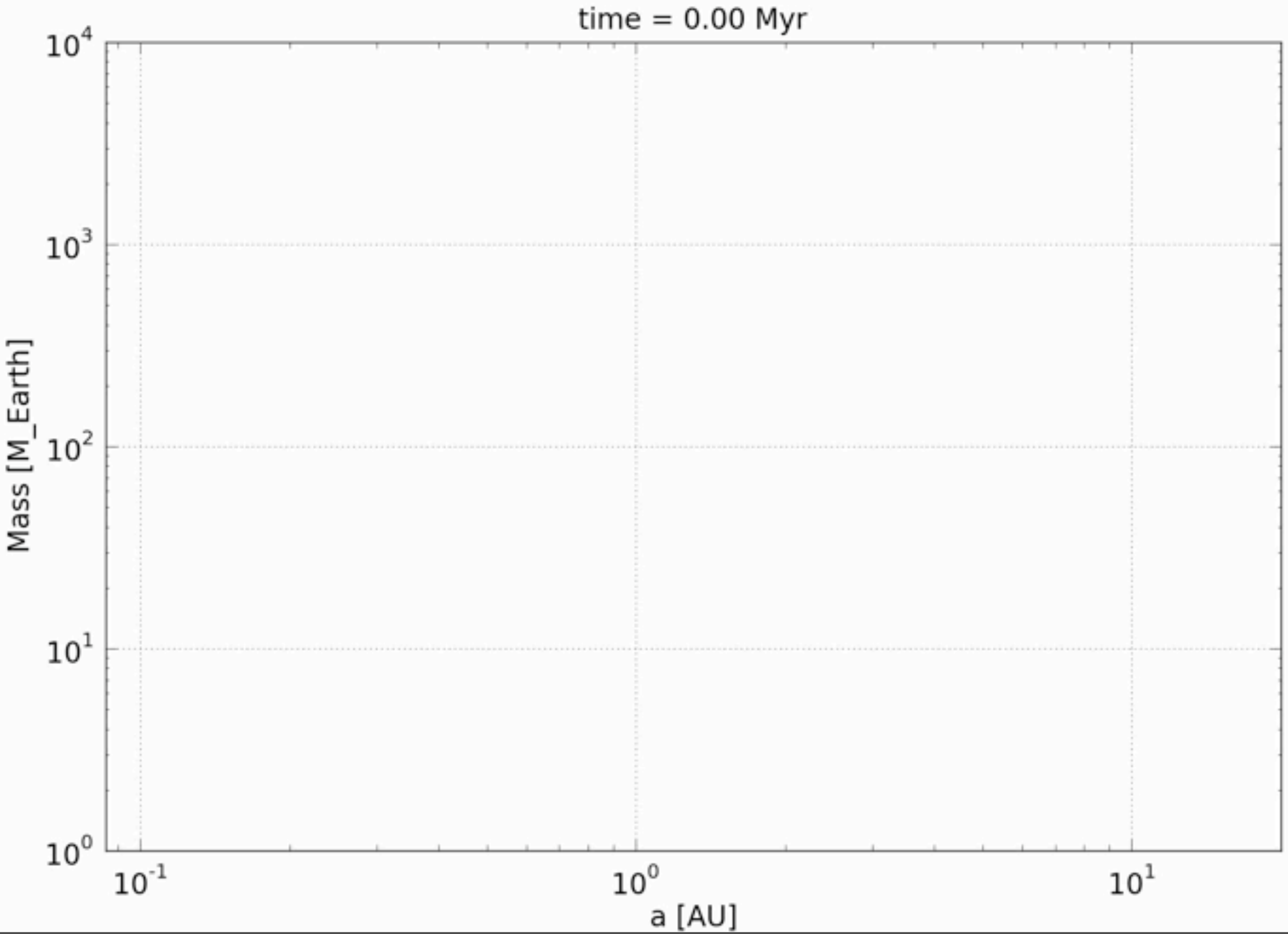




Isothermal type I migration / thermal criterion for gap opening

② Planet-planet interactions

6 times 1 planet   6 planets - no gravity   6 planets



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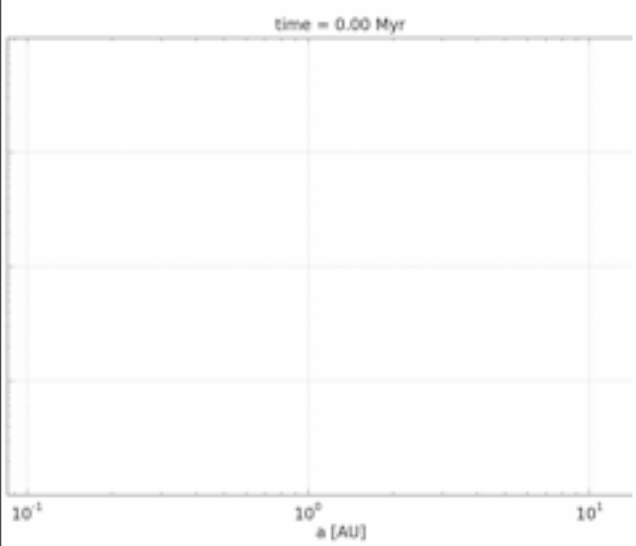

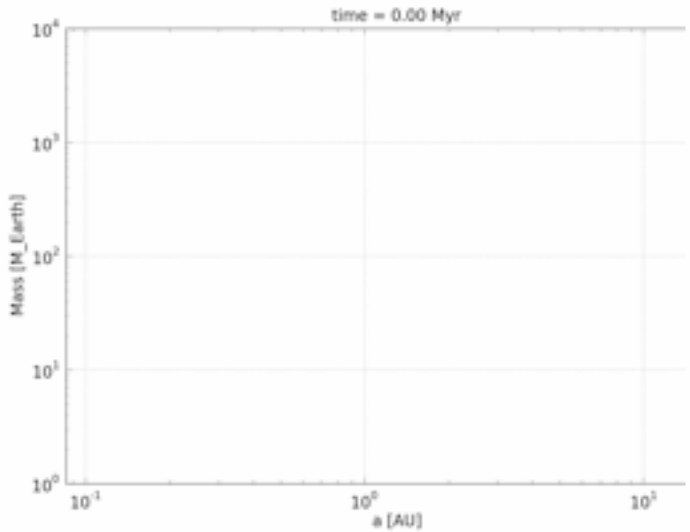

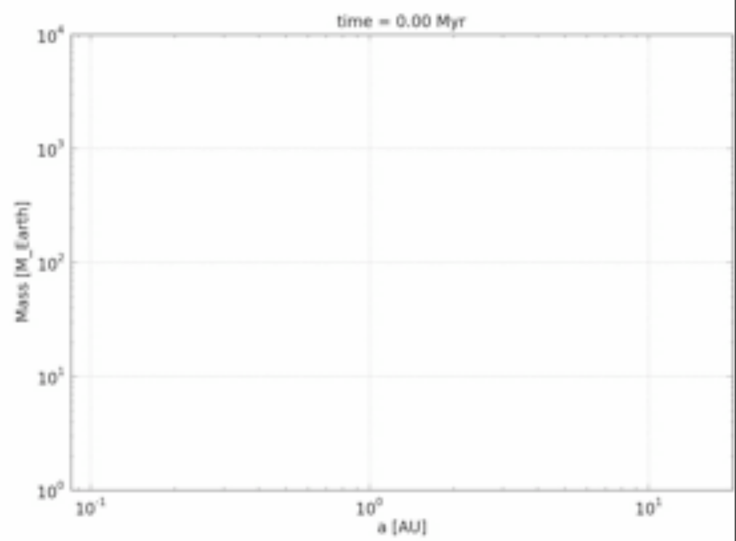

Isothermal type I migration / thermal criterion for gap opening

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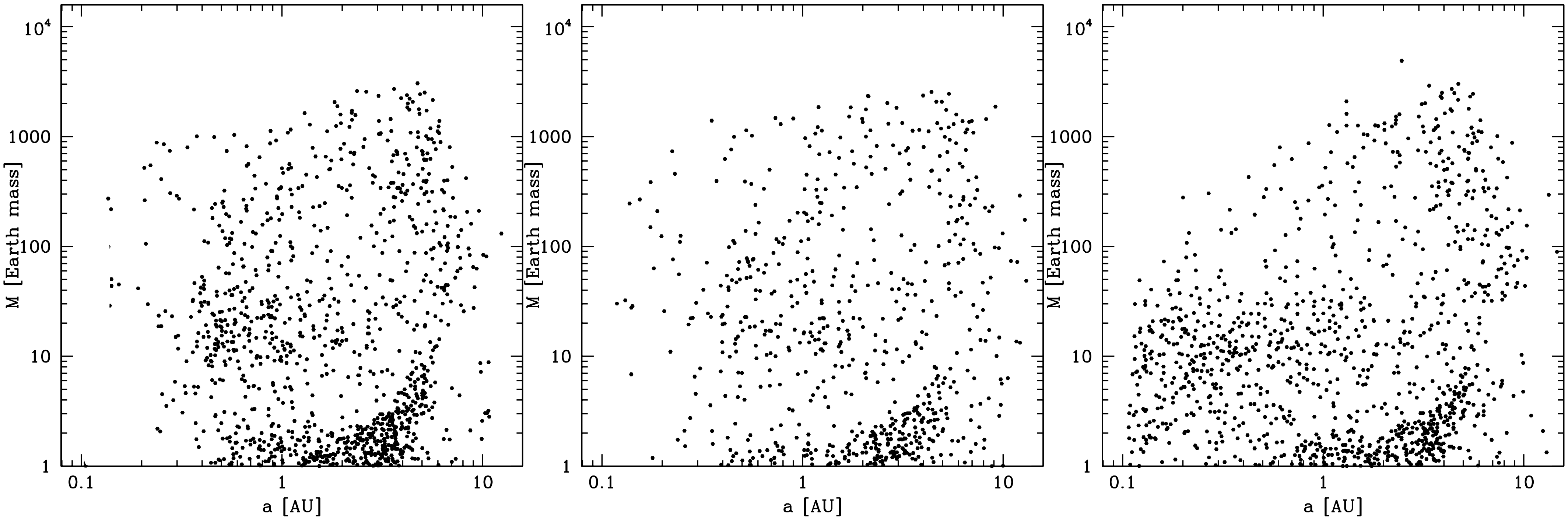

Isothermal type I migration / thermal criterion for gap opening

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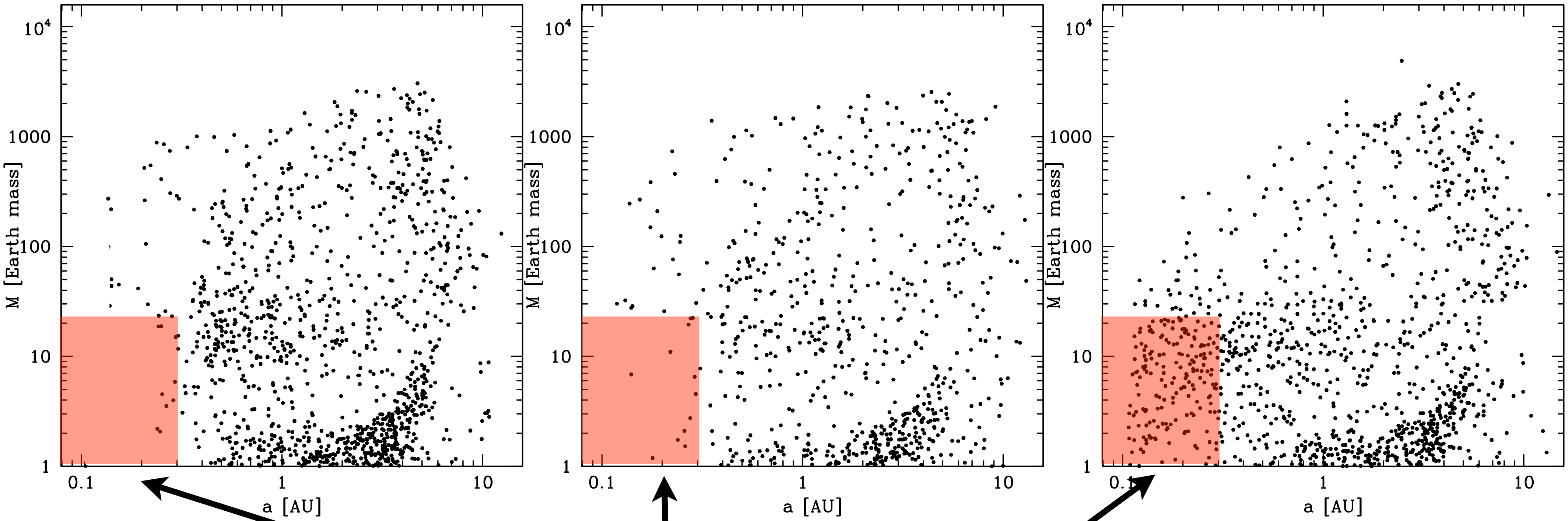
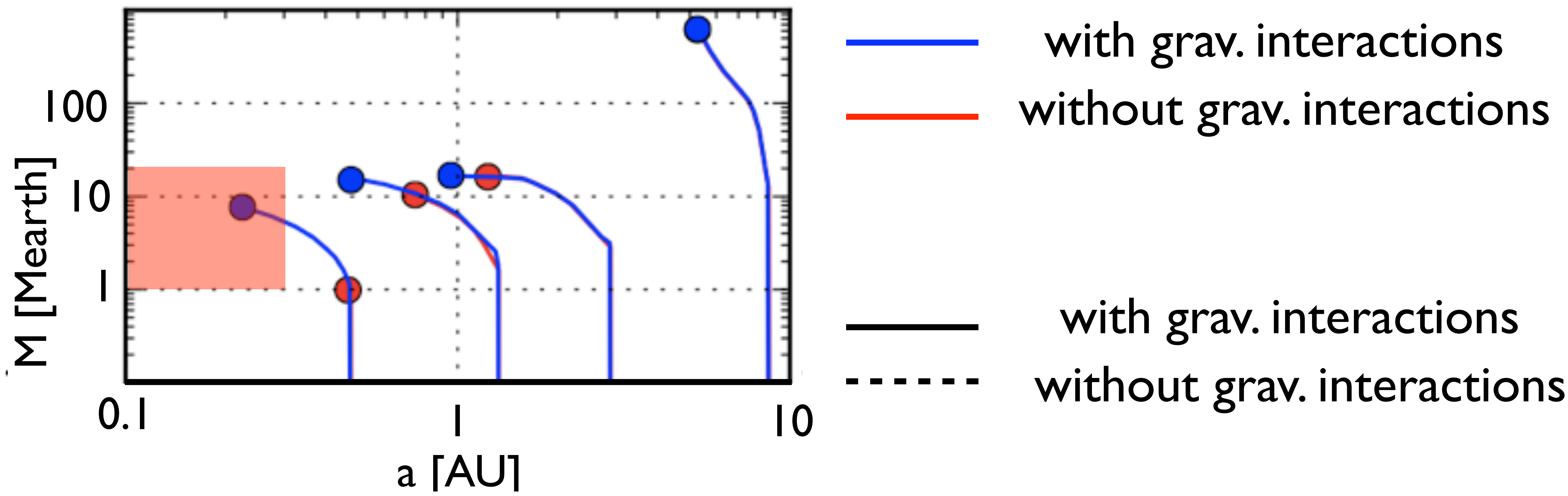
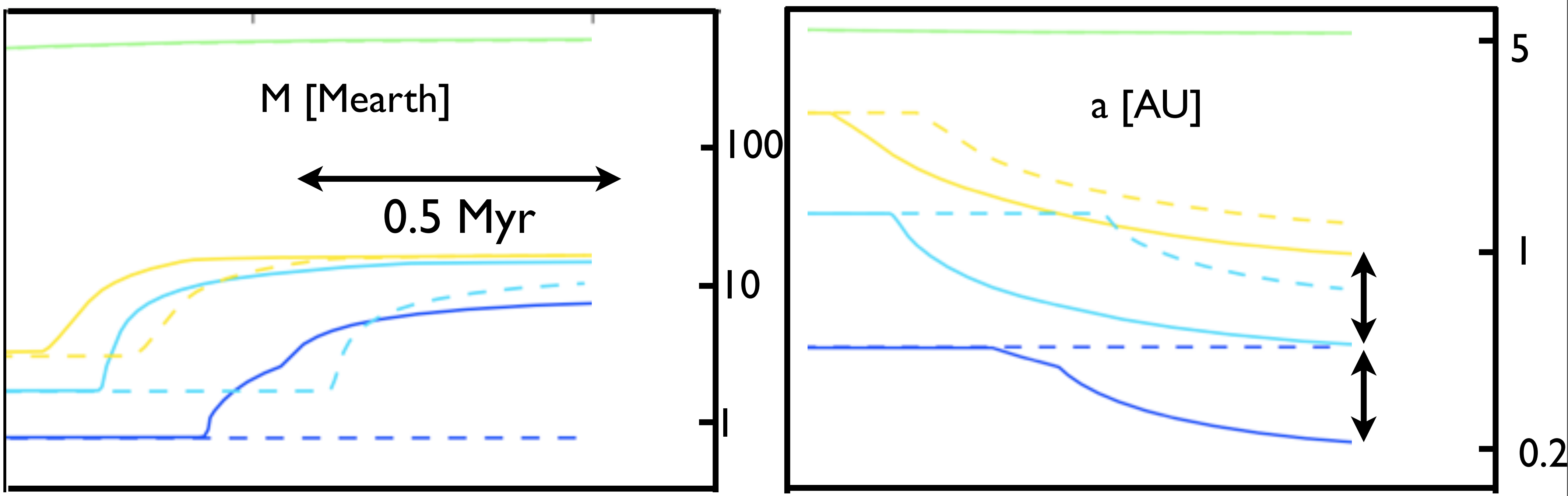


Kepler candidates

Isothermal type I migration / thermal criterion for gap opening

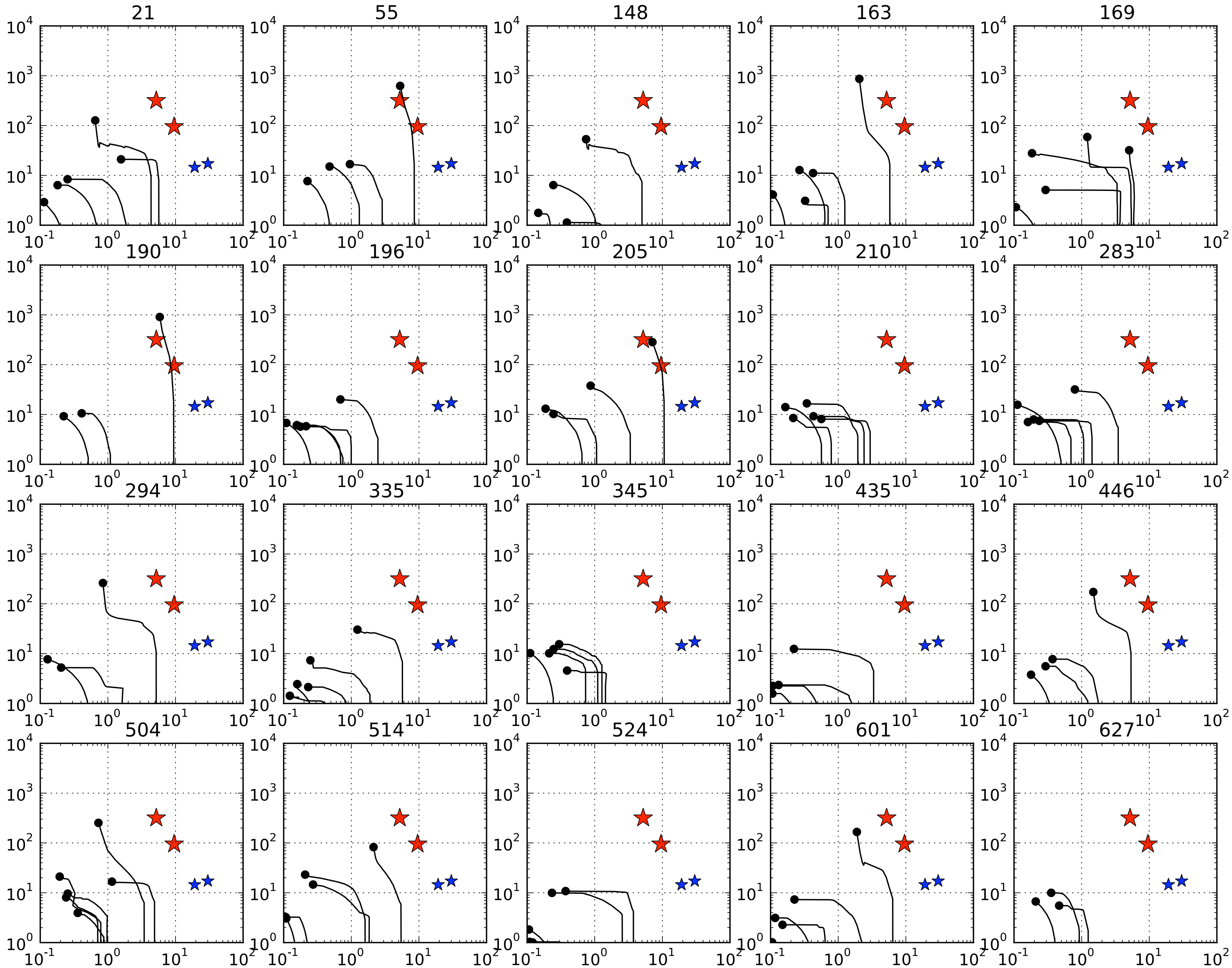
② Planet-planet interactions





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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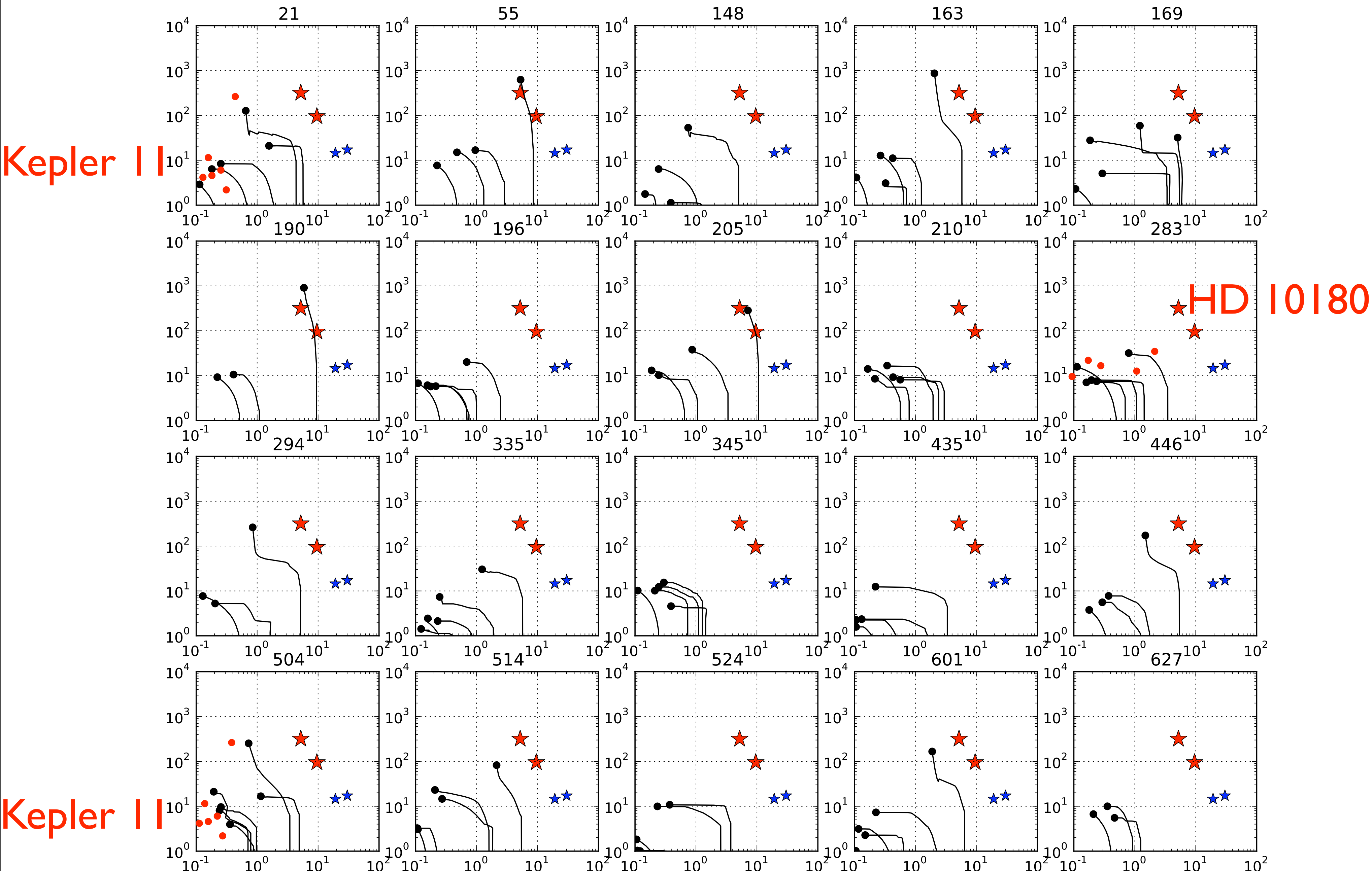


Isothermal type I migration / thermal criterion for gap opening

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

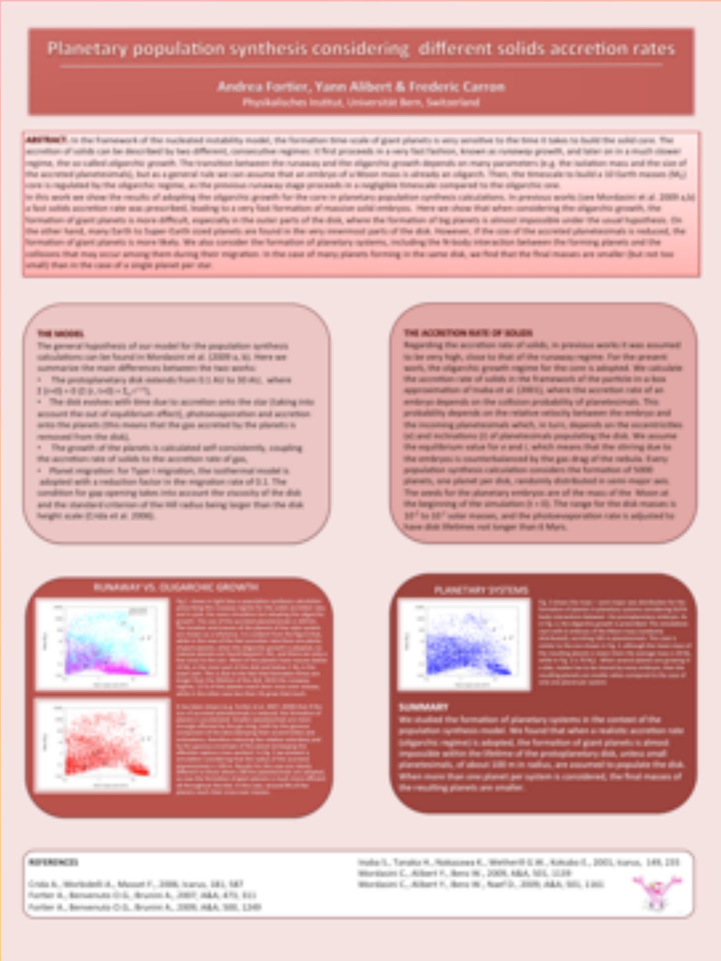
Disk models including irradiation and B effect

and...

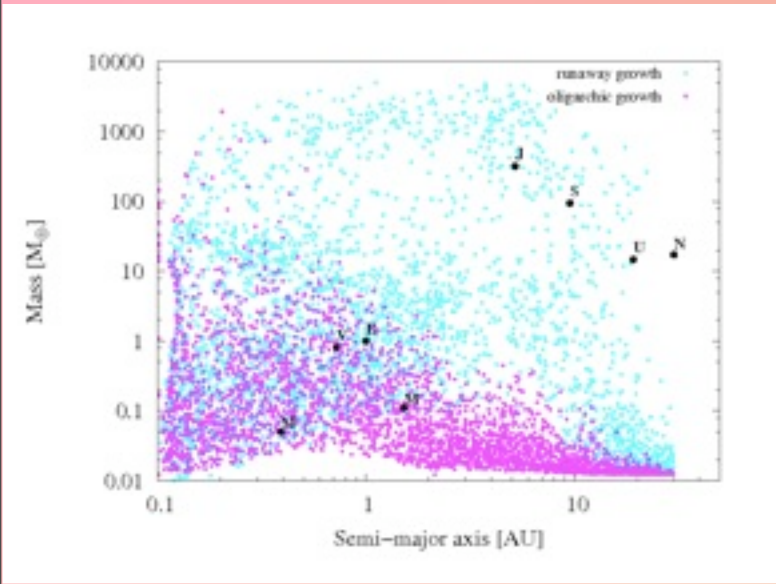
Planetary population synthesis considering different solids accretion rates

A. Fortier, Y. Alibert and F. Carron

Physikalisches Institut, Universität Bern, Switzerland

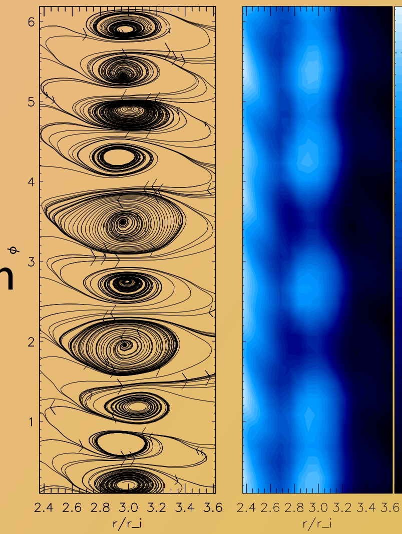


The pink poster!



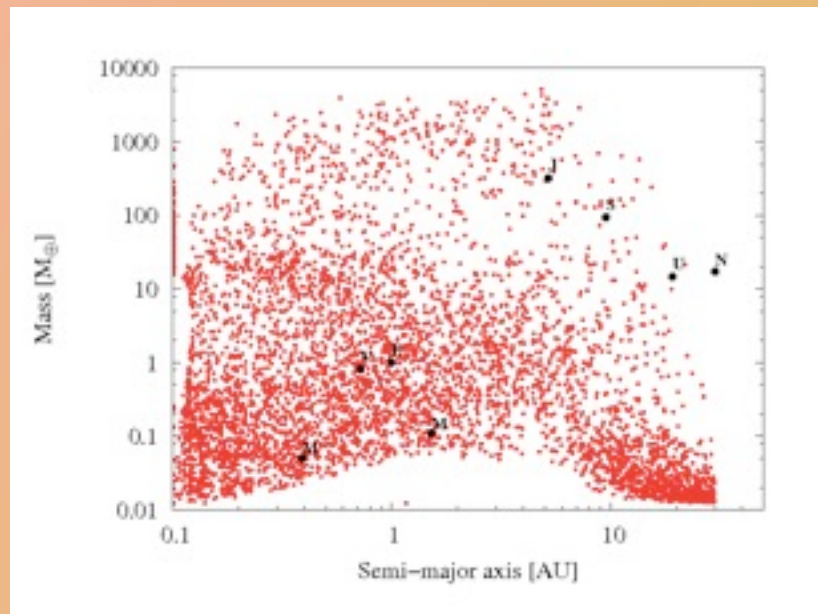
Runaway vs. Oligarchic growth for the core

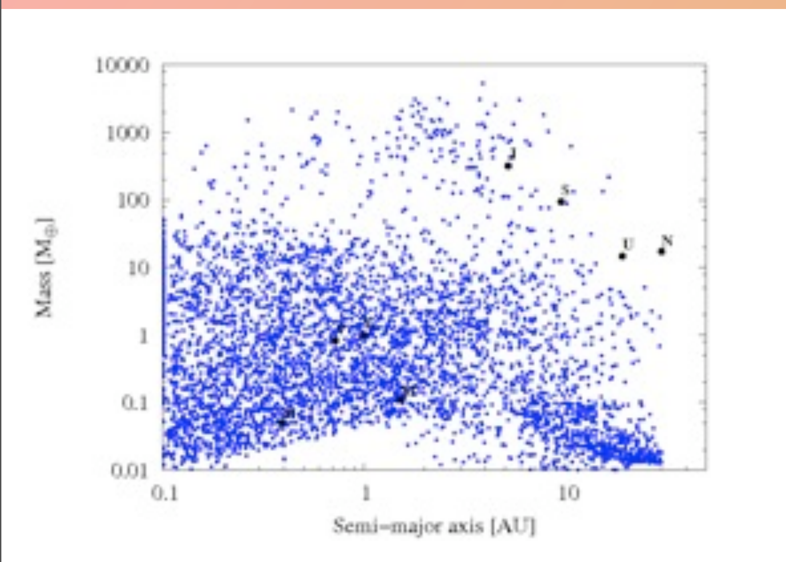
- Initial mass: Moon mass
- Planetesimals radii: 100 km
- Runaway: giant planets are all over the disk
- Oligarchic: almost NO giant planets can form before the disk dissipates



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

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
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Disk models including irradiation and B effect

Conclusions

Models reproduce:

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Jupiter & Saturn (bulk composition - atm. composition)

produce planet desert

Recent developments:

Planet-planet interactions } may explain the planet oasis

Type I migration rate }

Disk models including irradiation and B effect

Can we form the Solar System using same models?

we don't know... yet!