Planet Population Synthesis

2017 Sagan Exoplanet Summer Workshop

Microlensing in the Era of WFIRST

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PlanetS
National Centre of Competence in Research

UNIVERSITÄT BERN
CSH
CENTER FOR SPACE AND HABITABILITY

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The National Centres of Competence in Research (NCCR)
are a research instrument of the Swiss National Science Foundation

Outlines

1- Exoplanets and population synthesis

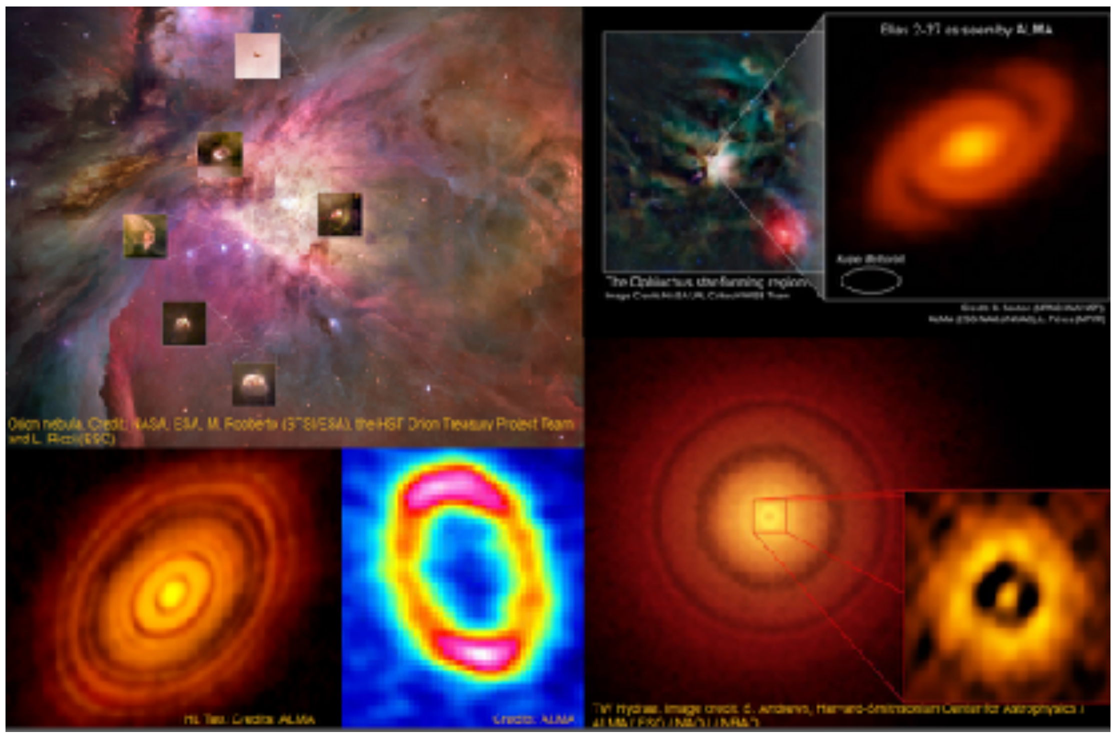
2- From disks to planets: integrated models

3- Population synthesis: comparison and results

4- Pebbles *versus* planetesimals

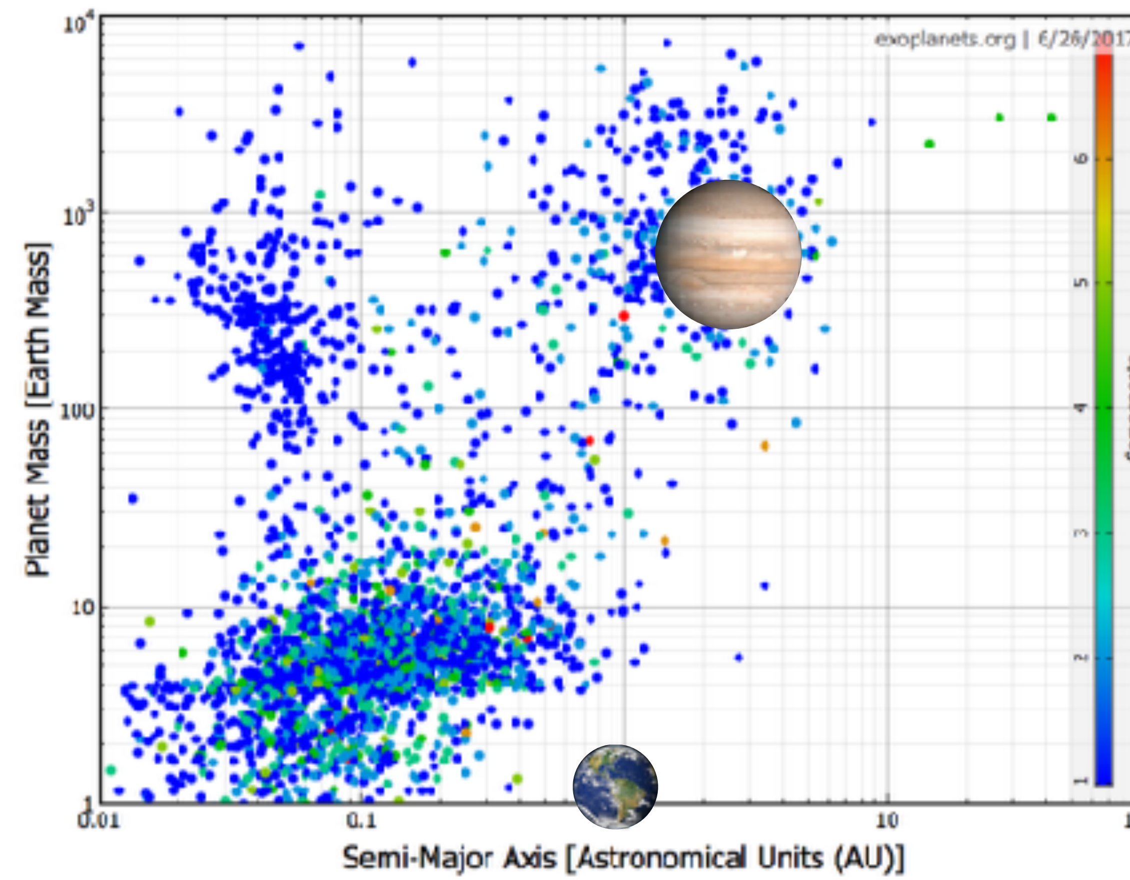
Planet formation models

protoplanetary disks



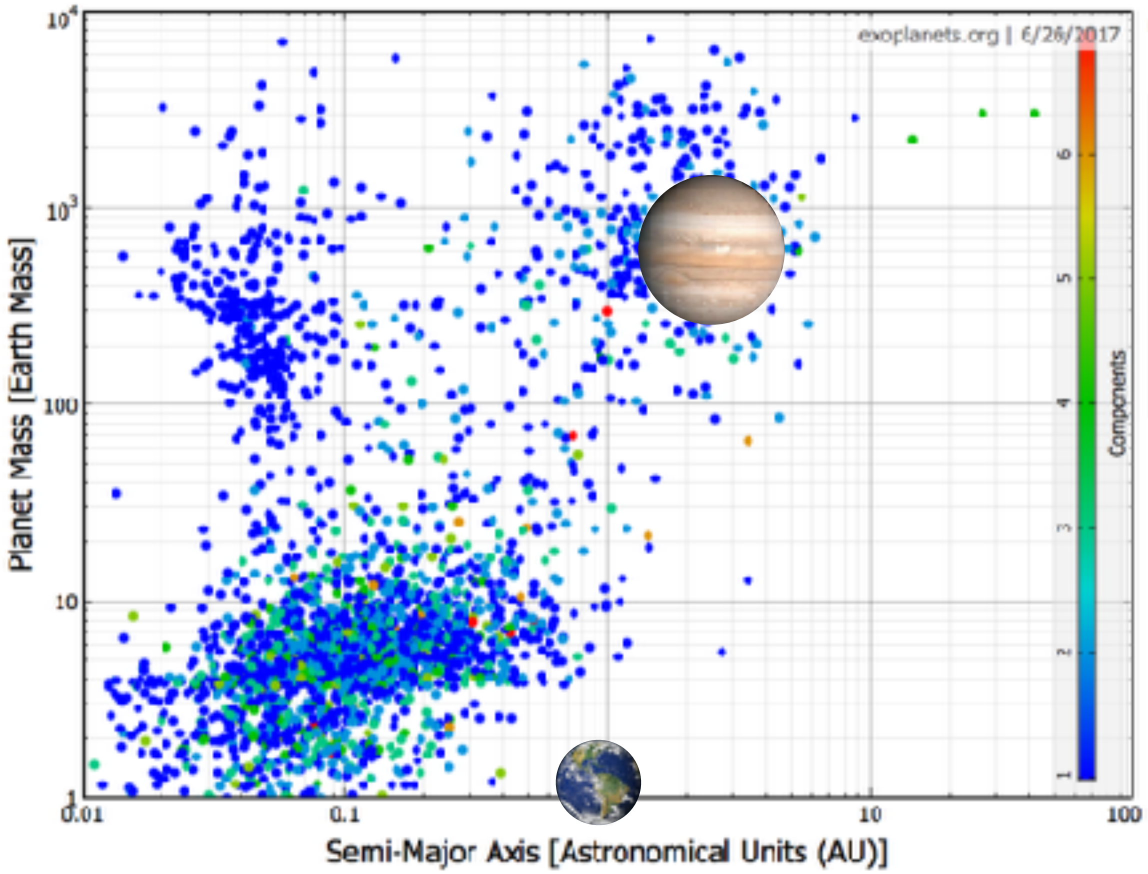
⇒

planets

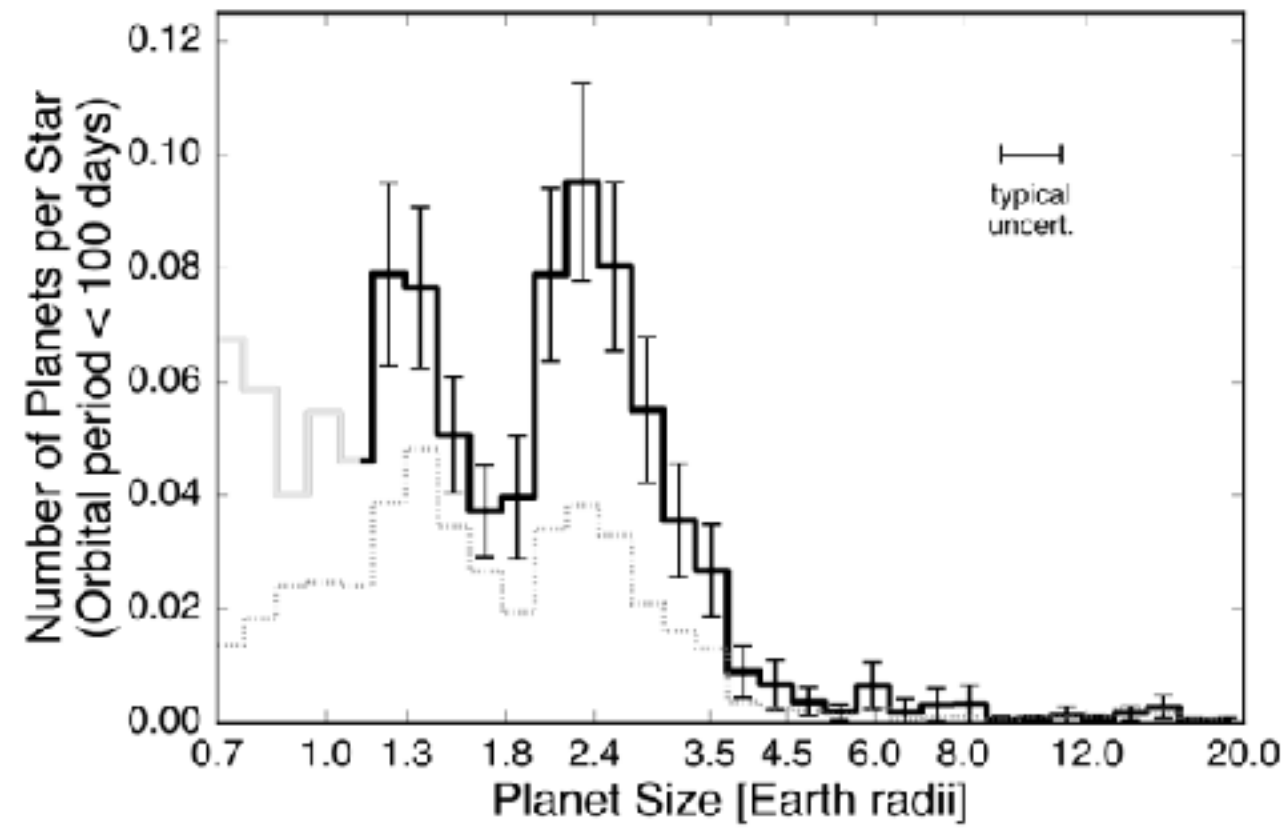


What is the origin of the diversity of planetary systems?

Importance of stellar evolution models



Kepler - bias corrected Fulton et al. 2017



Parameter		HD 10180
Spectral type		G1V
V	[mag]	7.33
$B-V$	[mag]	0.629
π	[mas]	25.39 ± 0.62
M_V	[mag]	4.35
$T_{\rm eff}$	[K]	5911 ± 19
$\log g$	[cgs]	4.39 ± 0.03
[Fe/H]	[dex]	0.08 ± 0.01
L	[$L_\odot$]	1.49 ± 0.02
M_*	[$M_\odot$]	1.06 ± 0.05
$v \sin i$	[km s^{-1}]	<3
$\log R'_{\rm HK}$		-5.00
$P_{\rm rot}(\log R'_{\rm HK})$	[days]	24 ± 3
Age ($\log R'_{\rm HK}$)	[Gyr]	4.3 ± 0.5

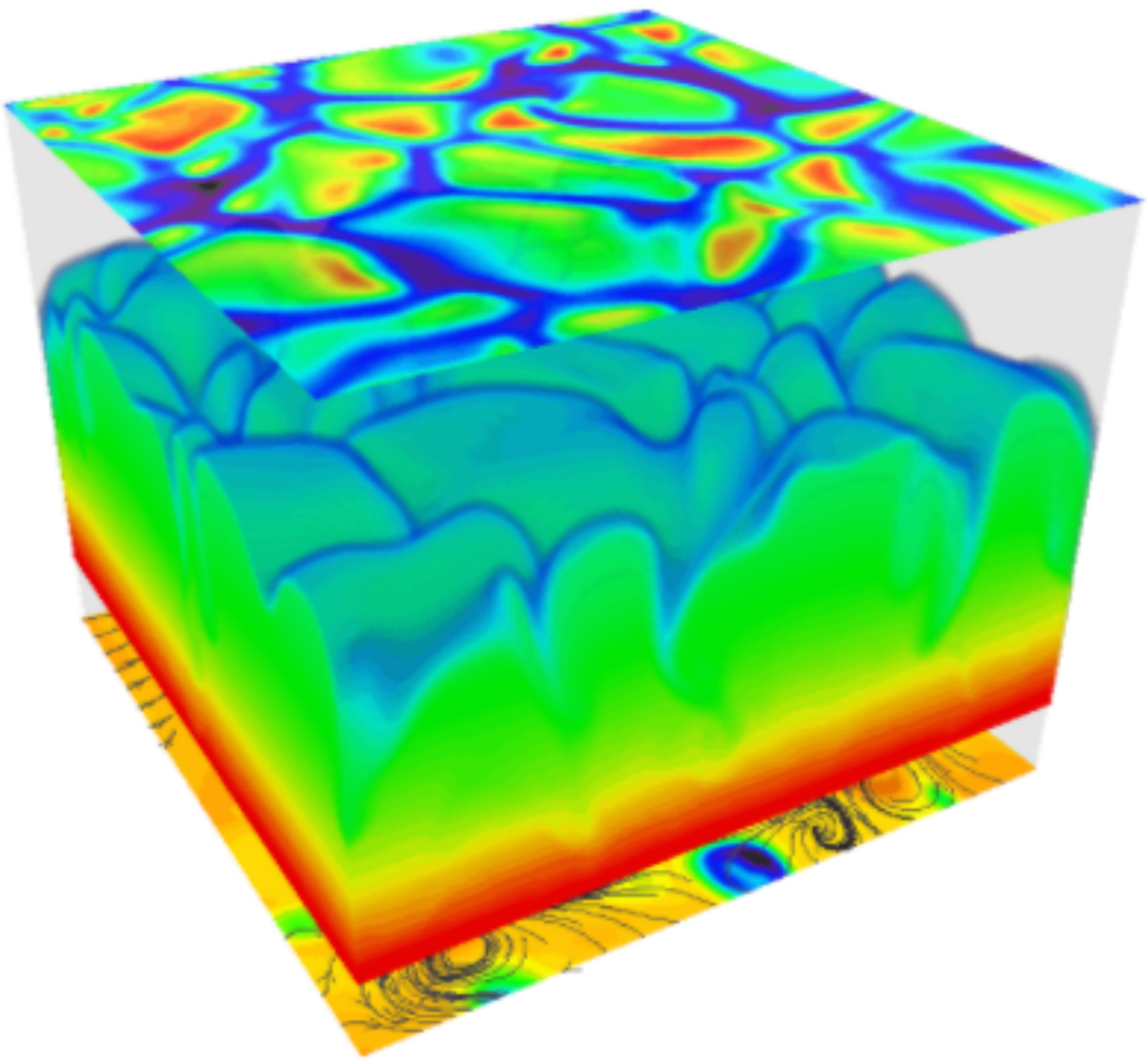
Table 2
Stellar Parameters

KOI	Kepler-ID	KID	$T_{\rm eff}$ (K)	$T_{\rm eff\sigma}$ (K)	$\log g$ (cgs)	$\log g_\sigma$ (cgs)	[Fe/H]	[Fe/H]$_\sigma$	R_* ($R_\odot$)	$R_{*\sigma}$ ($R_\odot$)	ρ_* (g cm^{-3})	$\rho_{*\sigma}$ (g cm^{-3})	Flag	Blend
41	Kepler-100	6521045	5825	75	4.125	0.045	0.02	0.10	1.490	0.035	0.457	0.013	5	3
46	Kepler-101	10905239	5570	134	4.065	0.240	0.30	0.10	1.666	0.415	0.351	0.300	3	4
70	Kepler-20	6850504	5443	74	4.398	0.100	0.00	0.07	0.986	0.095	1.304	0.400	4	3
72	Kepler-10	11904151	5627	44	4.342	0.046	−0.15	0.04	1.056	0.021	1.068	0.008	5	3
82	Kepler-102	10187017	4908	74	4.640	0.100	0.08	0.07	0.716	0.032	3.132	0.304	4	3
85	Kepler-65	5866724	6169	50	4.236	0.035	0.09	0.08	1.424	0.024	0.621	0.011	5	3
89		8056665	6688	342	4.059	0.150	0.21	0.10	1.773	0.357	0.329	0.186	3	3
94	Kepler-89	6462863	6184	83	4.196	0.068	0.11	0.07	1.486	0.139	0.543	0.127	4	3
102		8456679	5705	100	4.311	0.150	0.18	0.10	1.199	0.219	0.867	0.419	3	3
108	Kepler-103	4914423	5845	88	4.162	0.051	0.07	0.11	1.436	0.039	0.513	0.020	5	3

The majority of planet properties are based on stellar evolution models

Stellar evolution

the full numerical approach

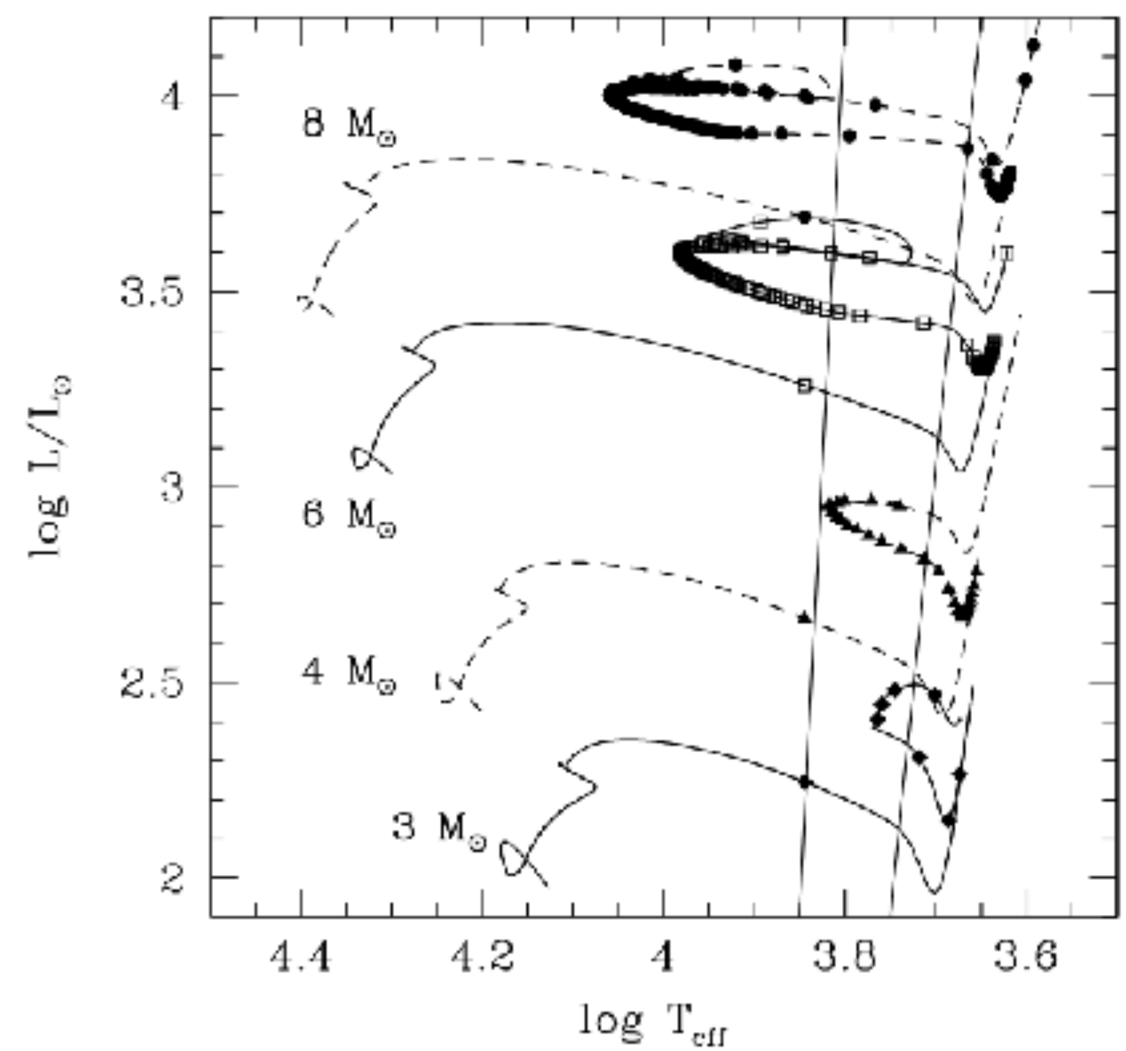


the stellar evolution models

$$\frac{dR}{dM_r} = \frac{1}{4\pi R^2 \rho}, \qquad \frac{dP}{dM_r} = -\frac{GM_r}{4\pi R^4},$$

$$\frac{dL_r}{dM_r} = \epsilon - T\frac{dS}{dt}, \qquad \frac{dT}{dM_r} = -\frac{GM_r T}{4\pi R^4 P}\nabla$$

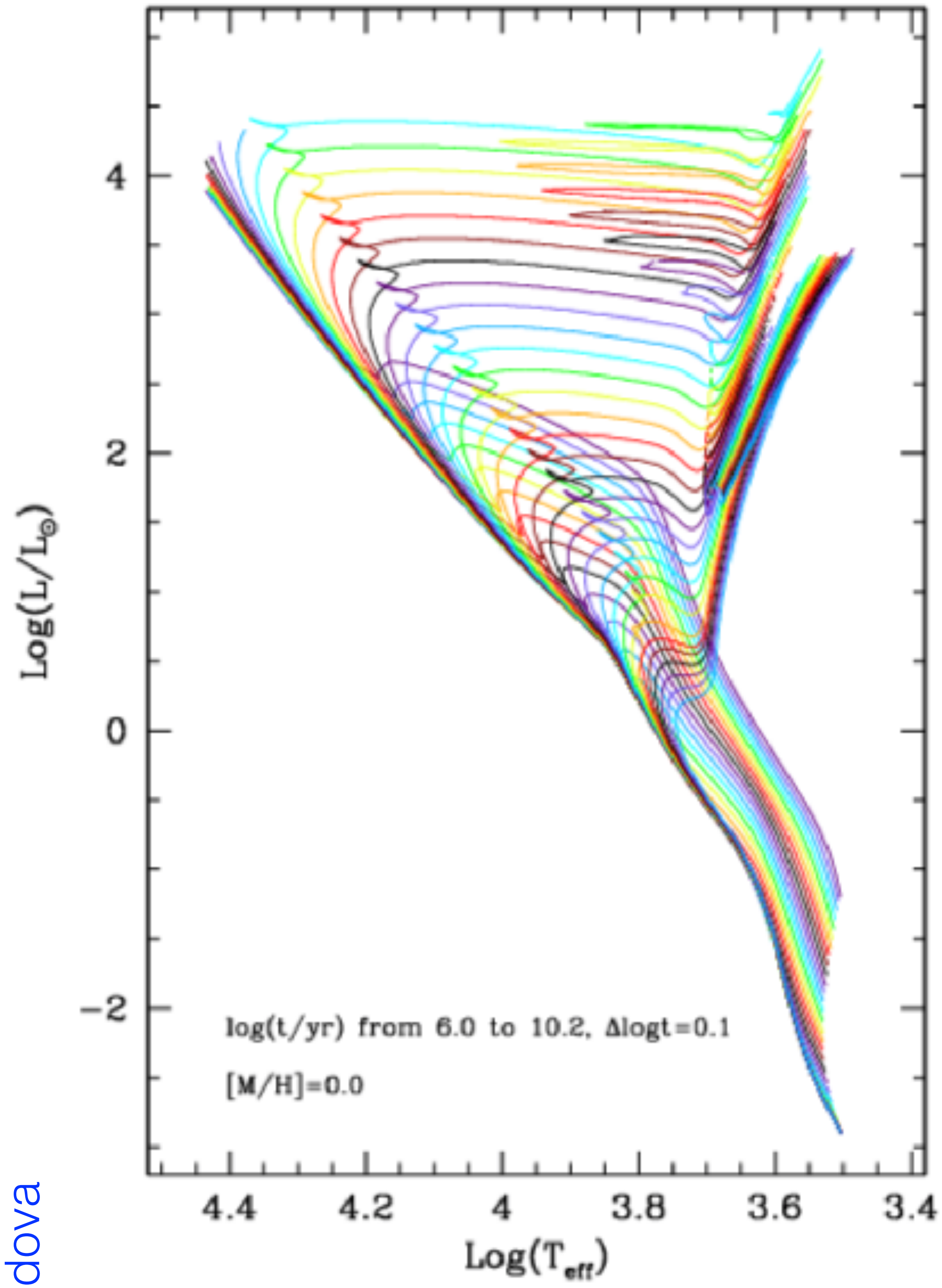
$$L_{\rm conv} = \pi R^2 C_p \Lambda_{\rm ml}^2 \times \left[\left(\frac{\partial T}{\partial R}\right)_s - \left(\frac{\partial T}{\partial R}\right)\right]^{3/2} \sqrt{\frac{1}{2}\rho g \left|\left(\frac{\partial \rho}{\partial T}\right)_P\right|}$$



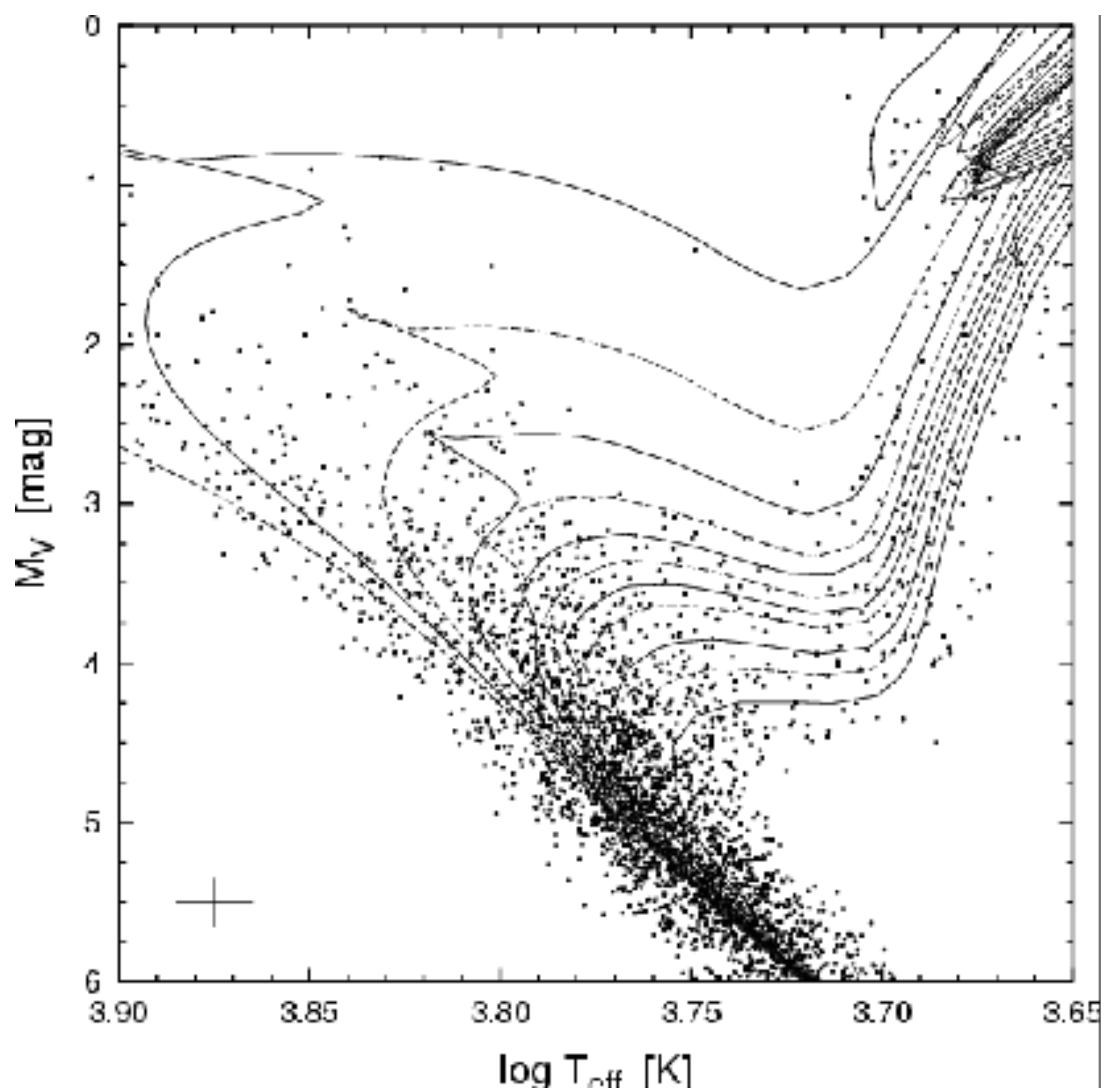
Baraffe et al. 1998, Alibert et al. 1999

Integrated models and HR diagram

initial condition + stellar evolution = HR diagram



Padova



-> age, other properties

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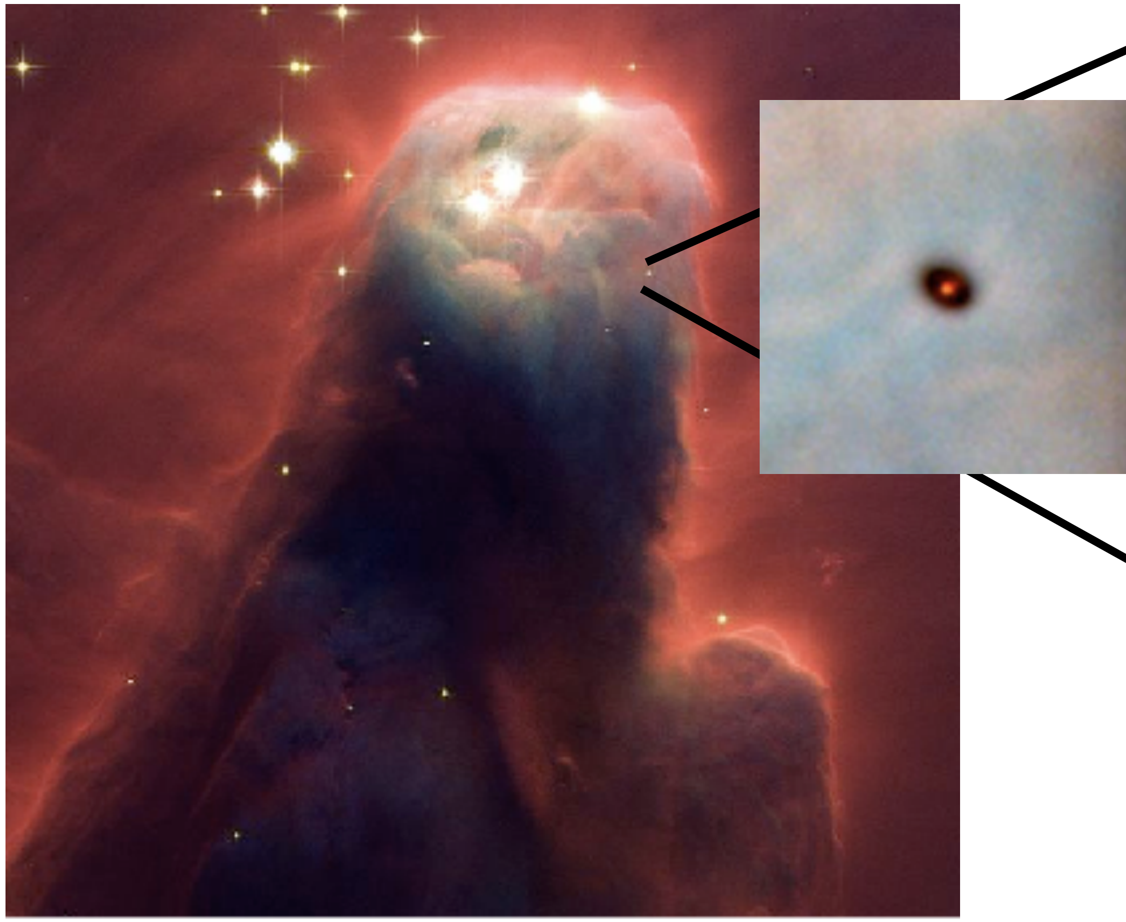
From GMC to present day planets

Giant Molecular Cloud

2.5 Light years ~160000 AU



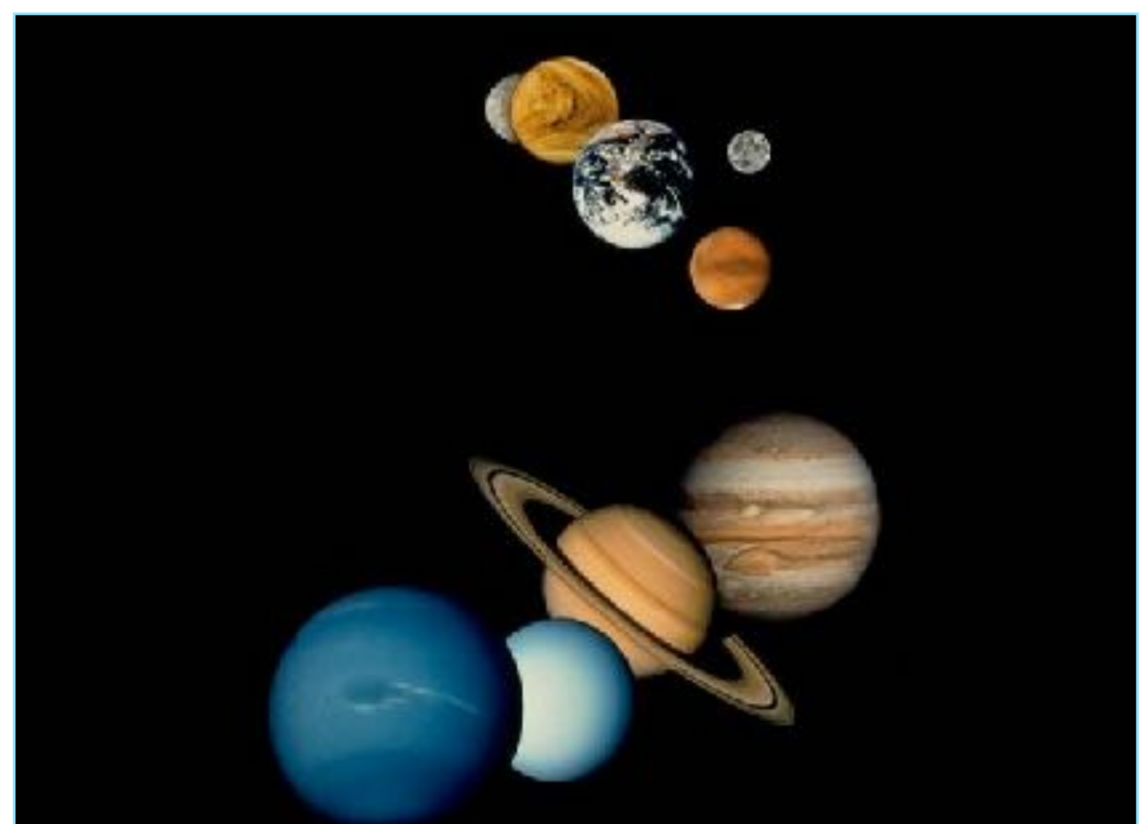
Protoplanetary disk

~100s AU

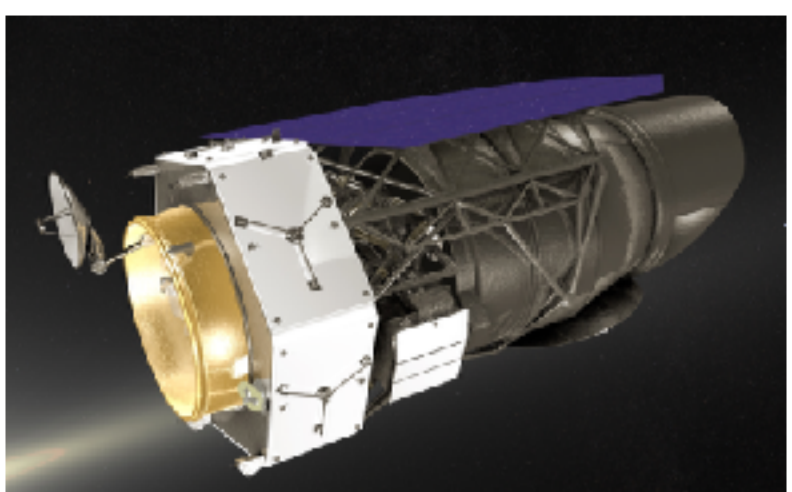
99% gas 1% solids

$T_{\rm disk} < 10^7 {\rm yr}$

$\Downarrow$



$\Leftarrow$



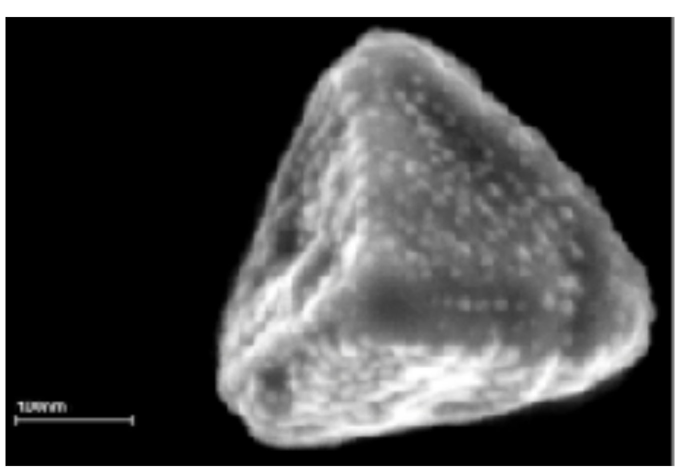
Top down or bottom-up?

Protoplanetary disk

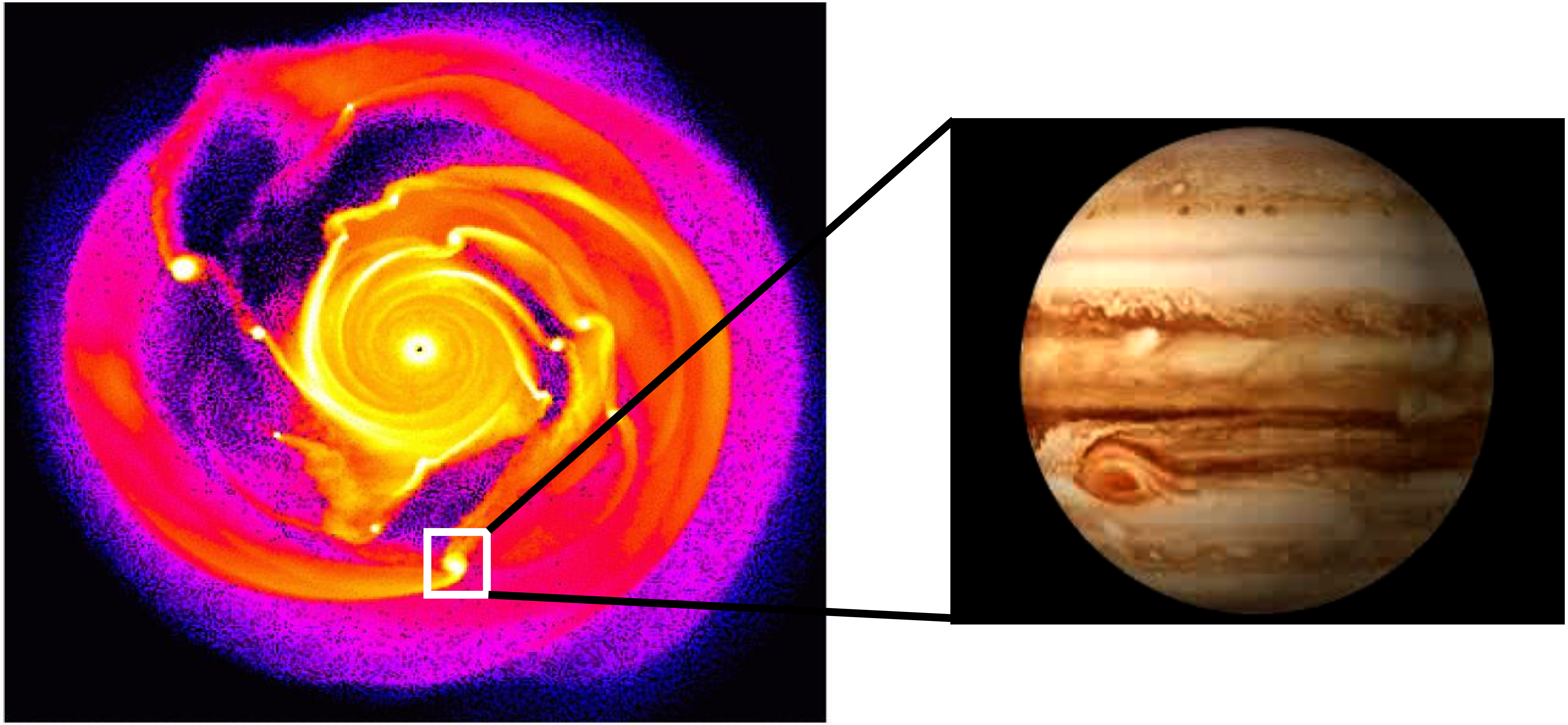
GI/DI model

Core-accretion model

pre-solar grain



Top-down models: the disk instability model



Clump formation depends critically on disk cooling

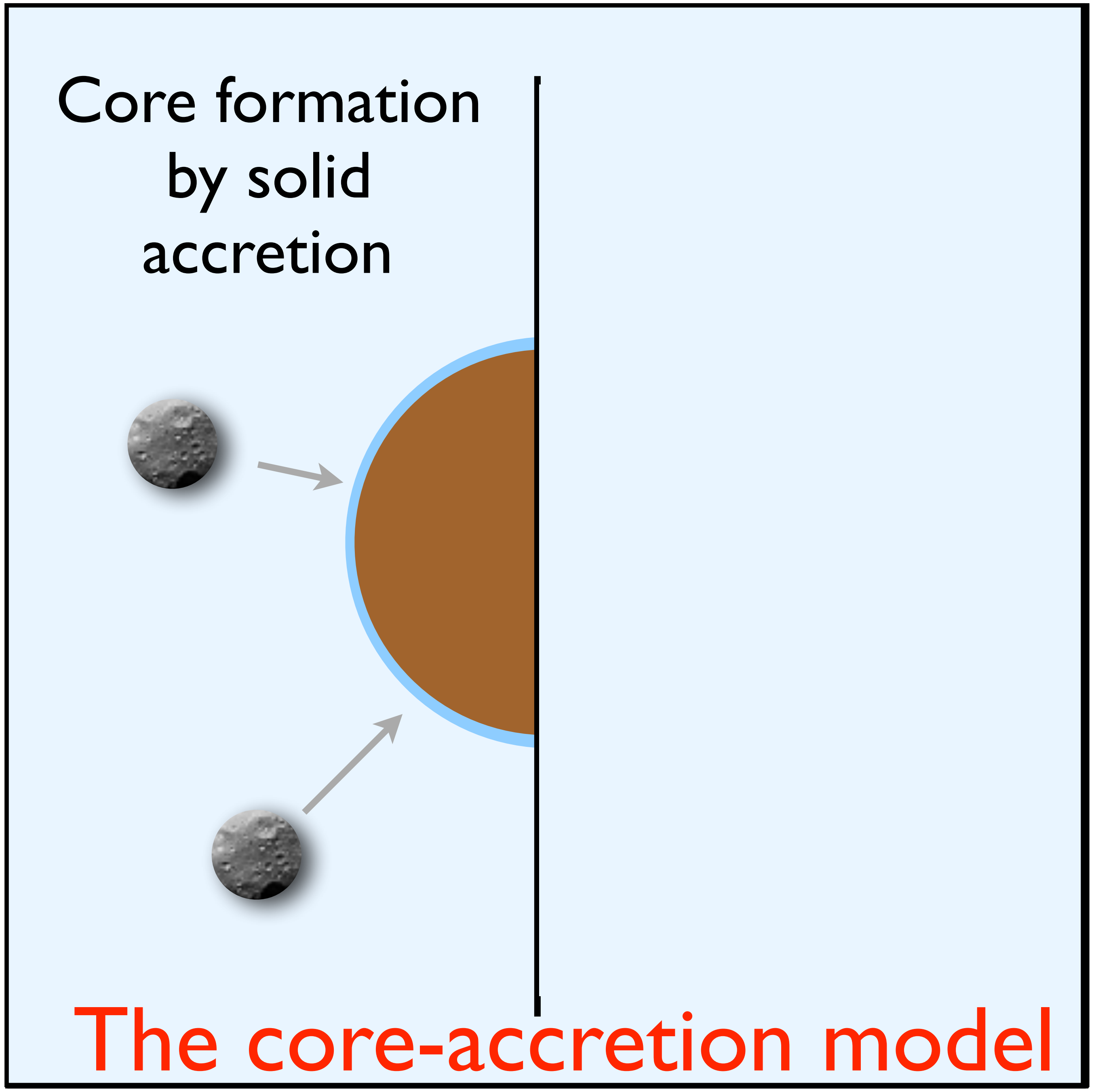
⇒ formation of massive planets

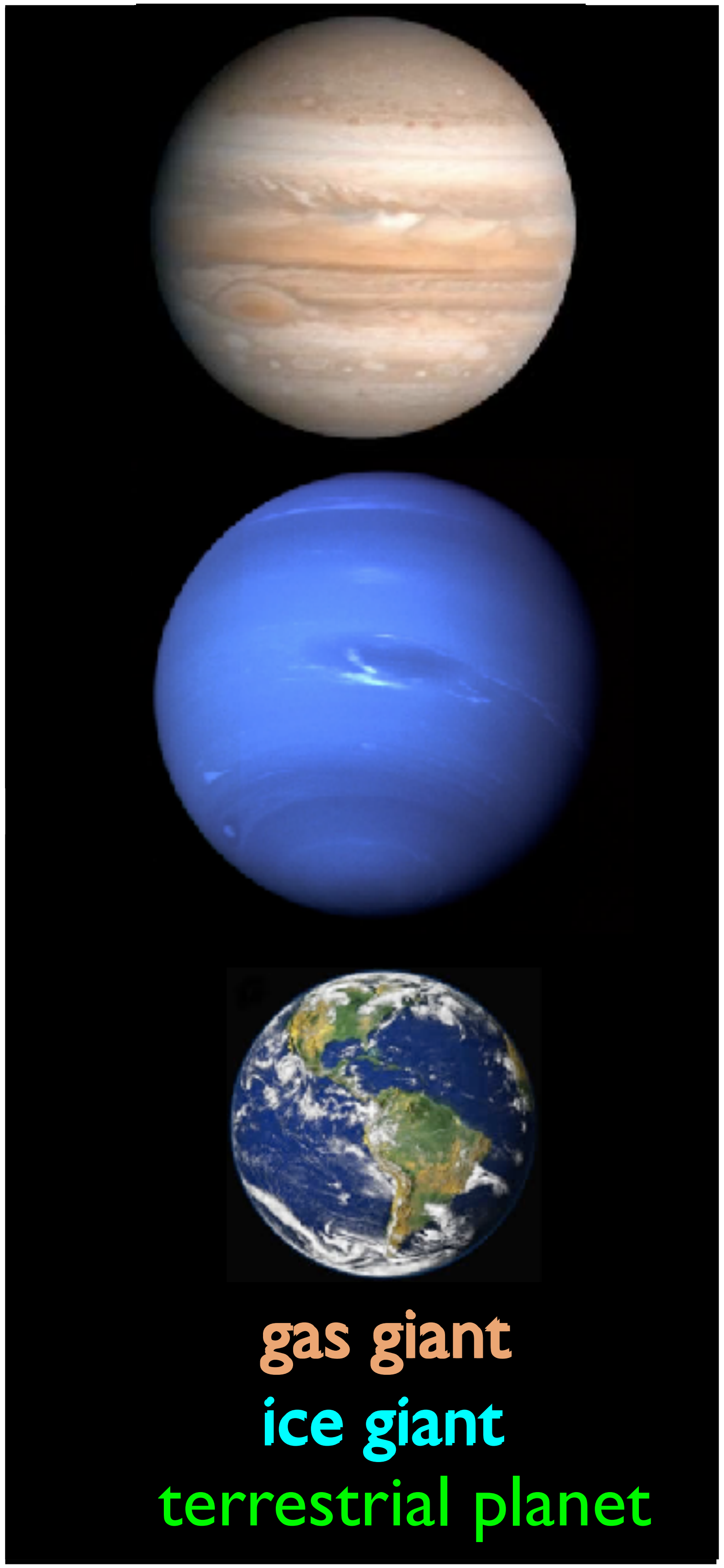
⇒ formation in outer parts of the disk

Origin of enrichment in heavy elements/formation of low mass (Earth,Neptune) planets?

Bottom up model: the core accretion model

$T_{\rm disk} < 10^7 {\rm yr}$

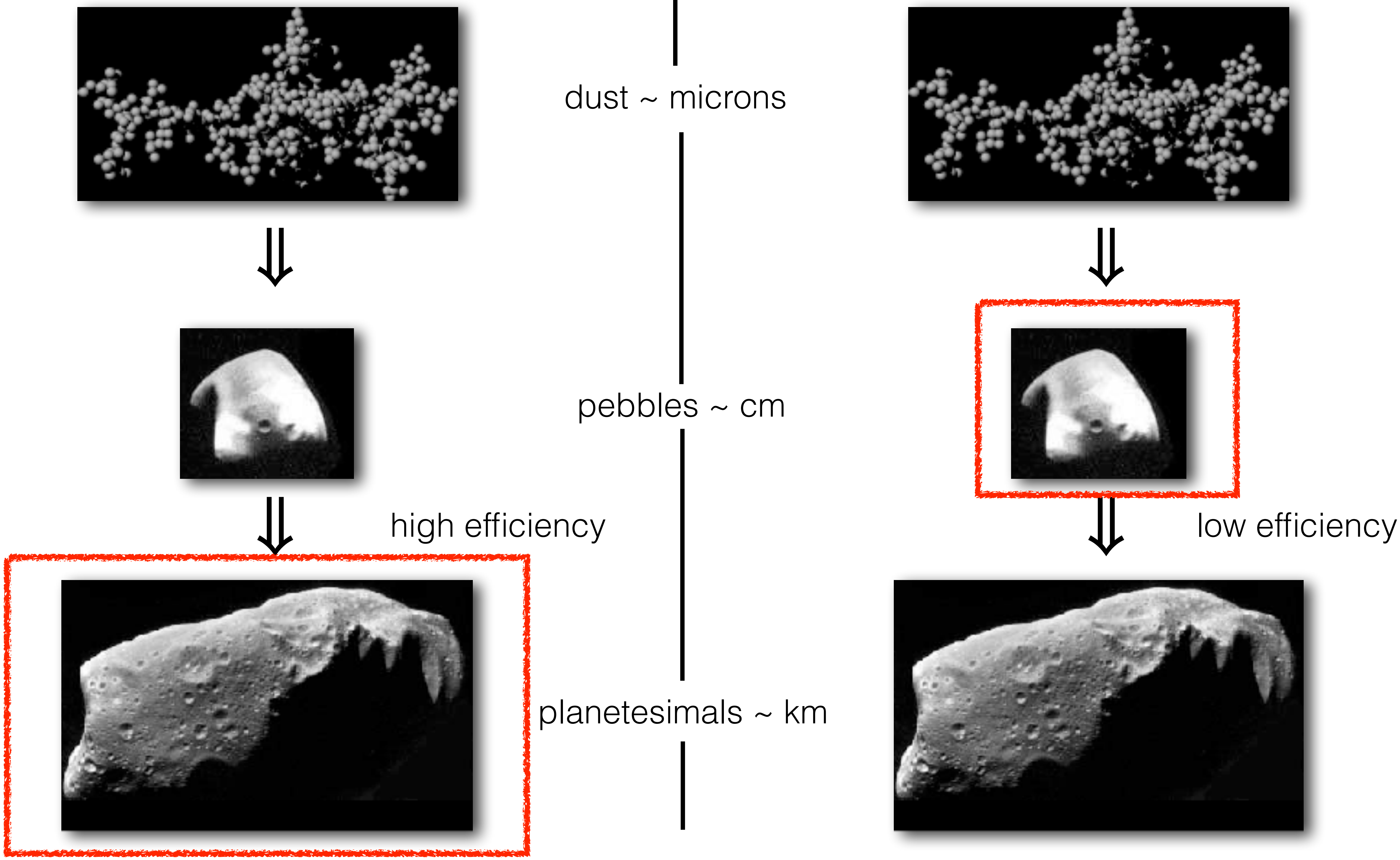




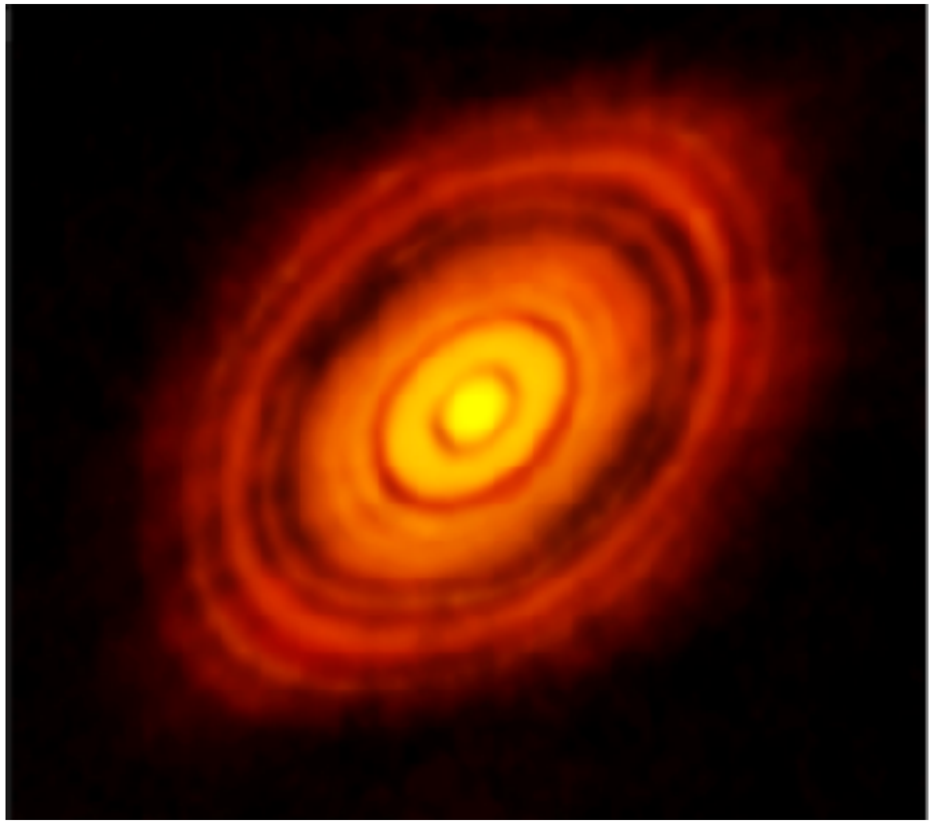
What are these solids?

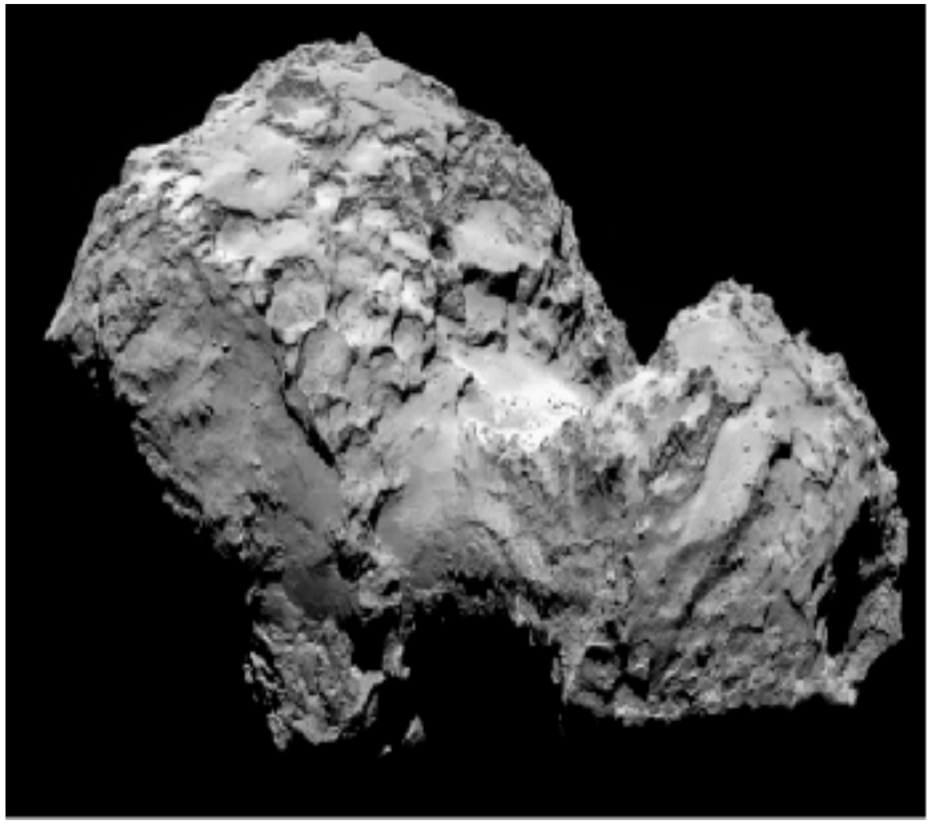
Planetesimals-based model

Pebbles-based model



Planet formation: the players





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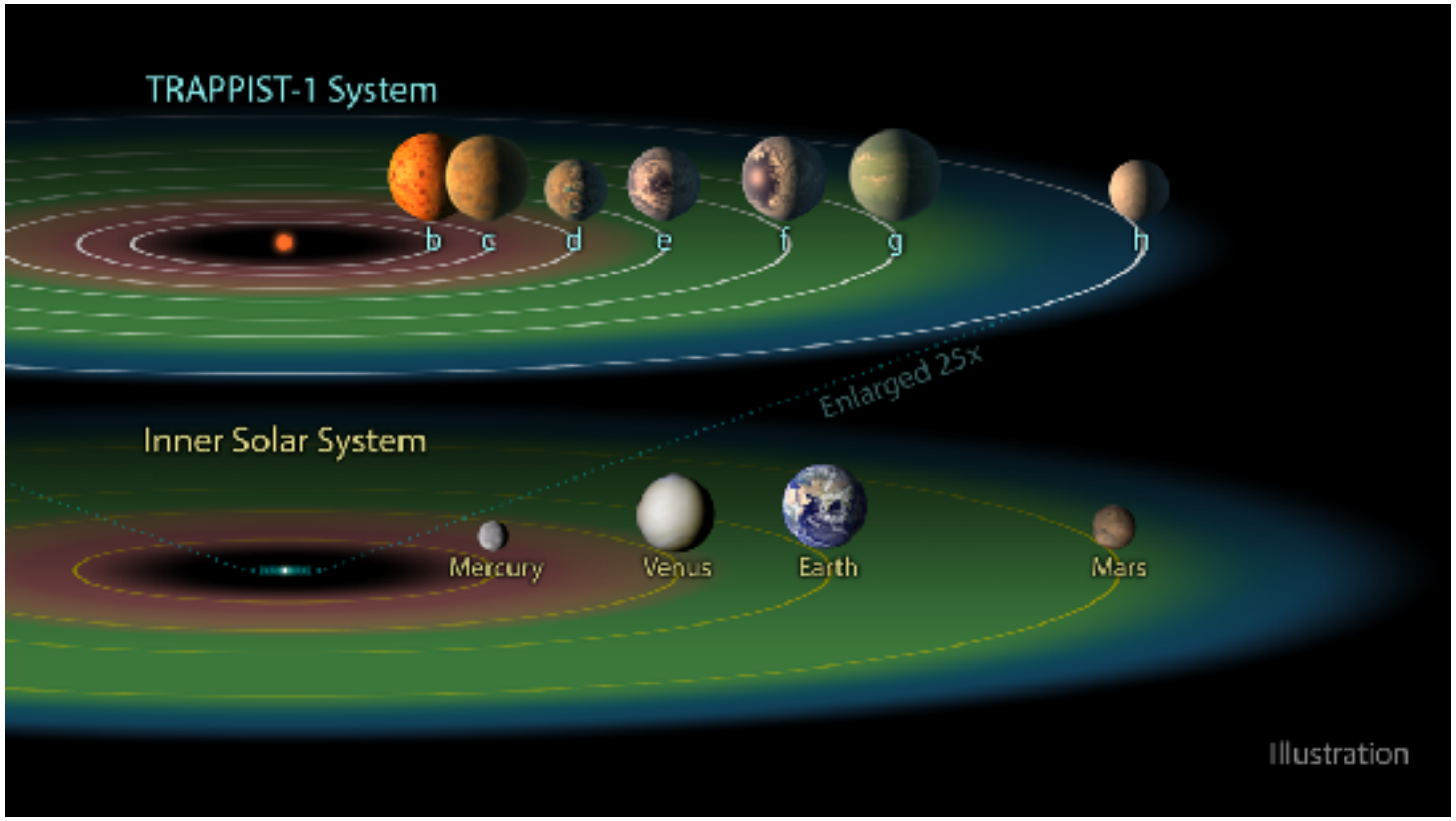
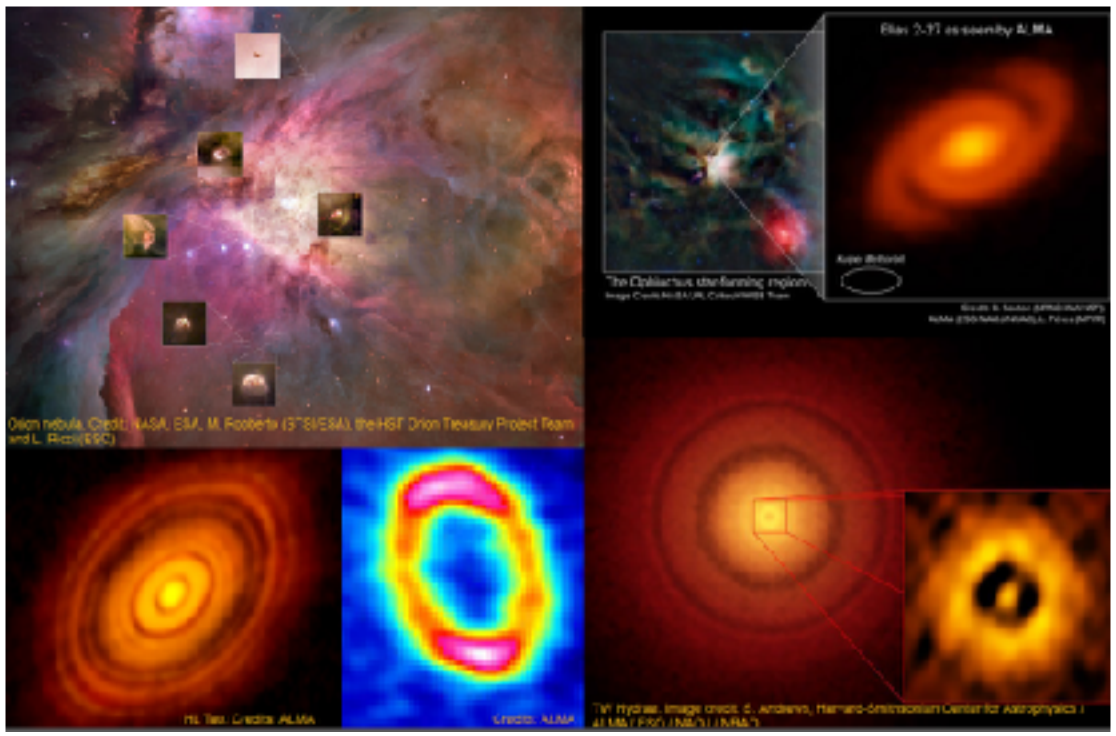


Planet formation: the interactions

- solid-solid interactions
- gas disk structure and evolution
- solid accretion
- solid-gas disk interactions
- planet-disk interactions
- planet internal structure and gas capture
- planet-planet interactions

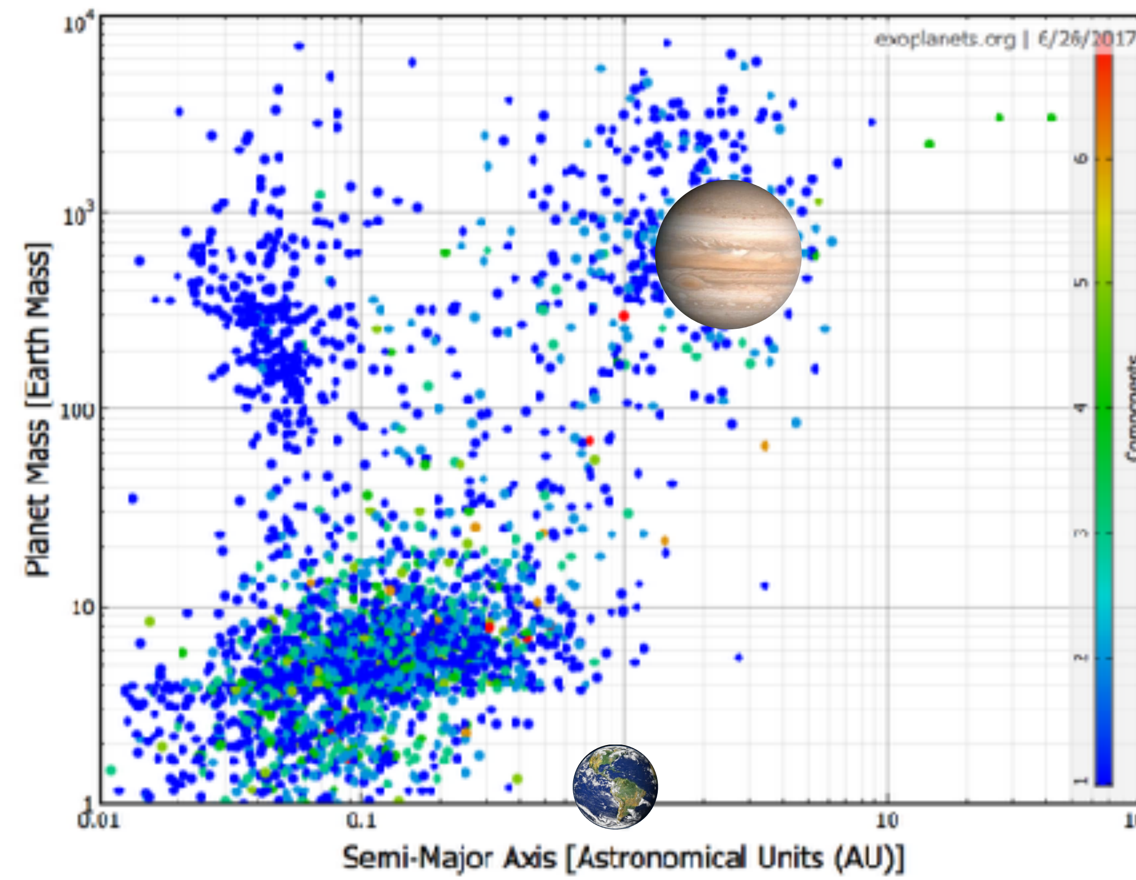
Integrated models

protoplanetary disks



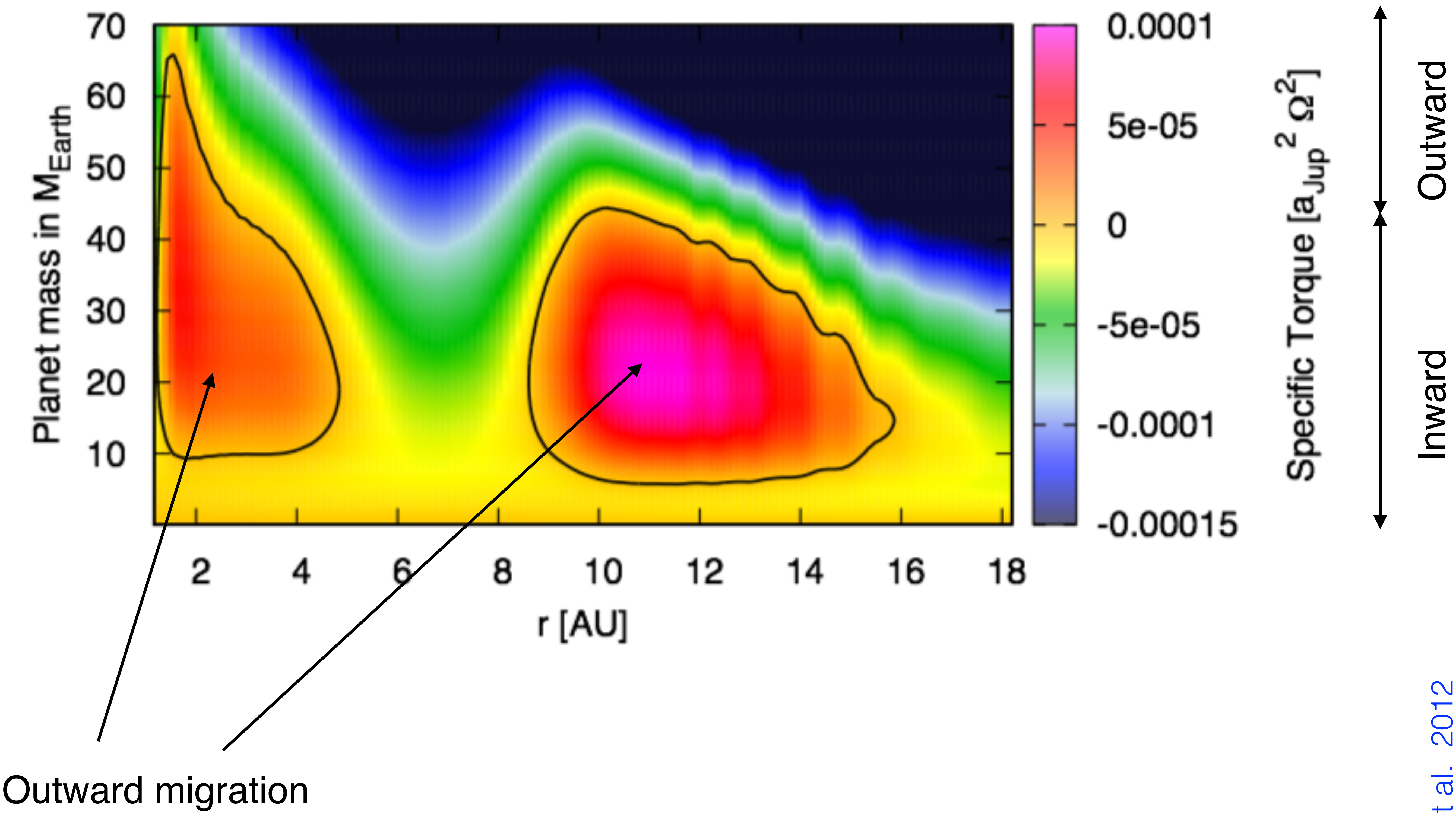
$\Rightarrow$

planets



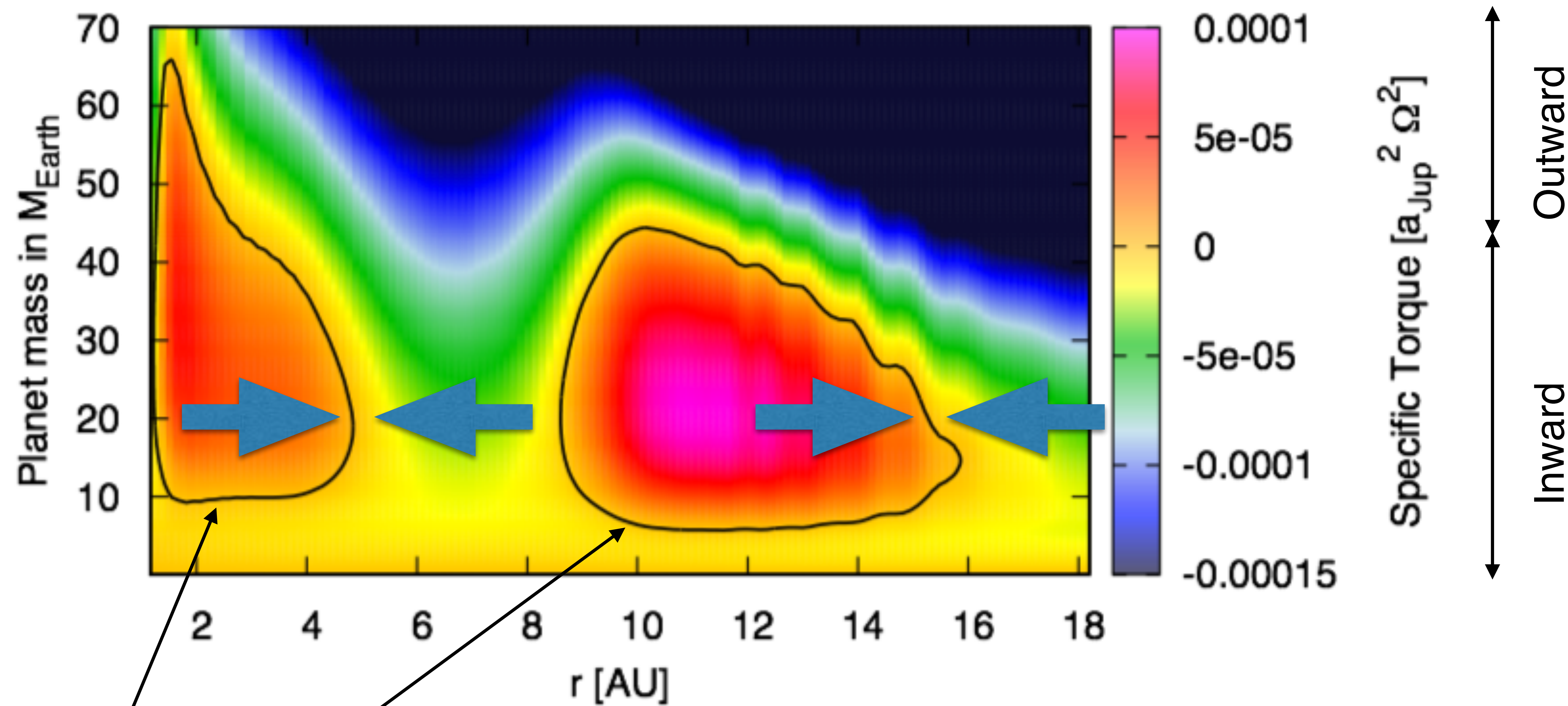
What is the effect of the combined processes in shaping planetary systems?

Integrated models



Bitsch et al. 2012

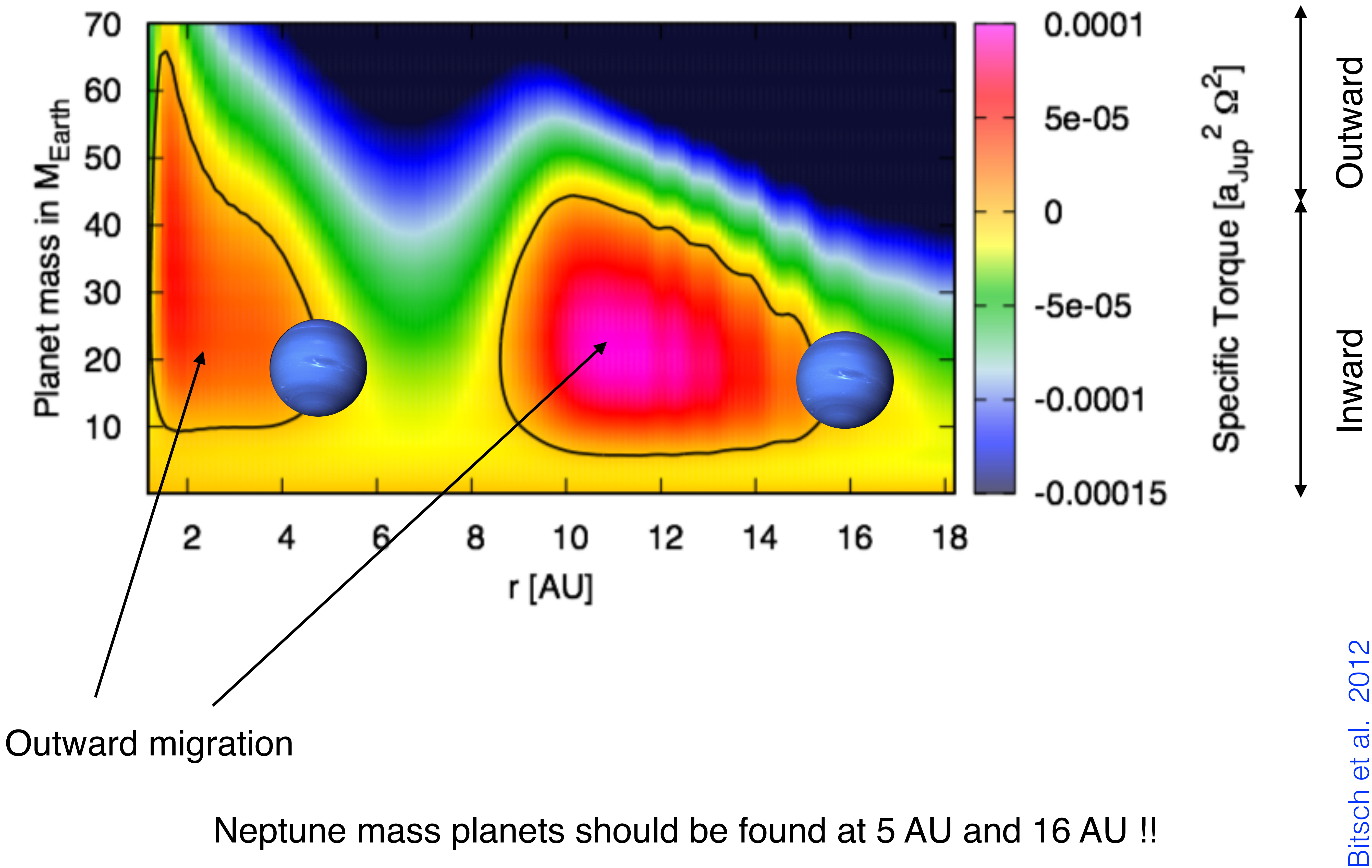
Integrated models



Outward migration

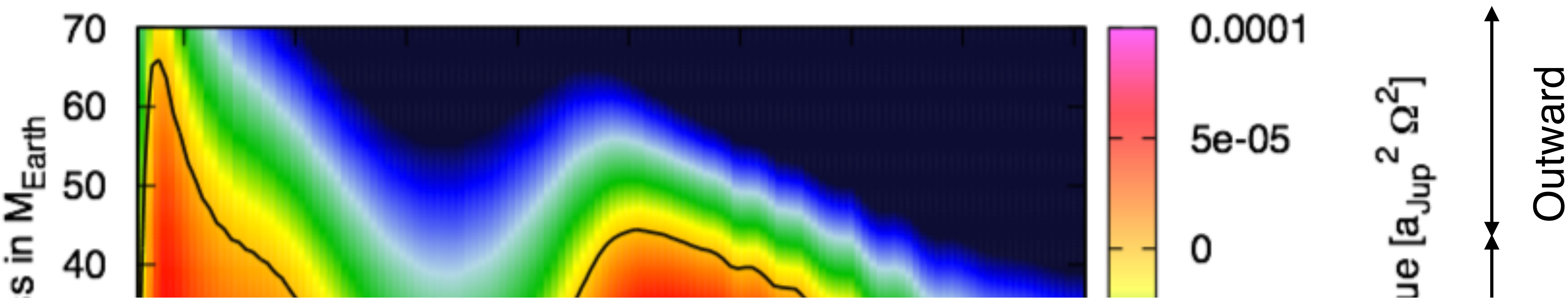
Bitsch et al. 2012

Integrated models



Neptune mass planets should be found at 5 AU and 16 AU !!

Integrated models



The observed mass/period distribution of planets is the result of combined processes

Inward

Migration / disk evolution / planetary growth

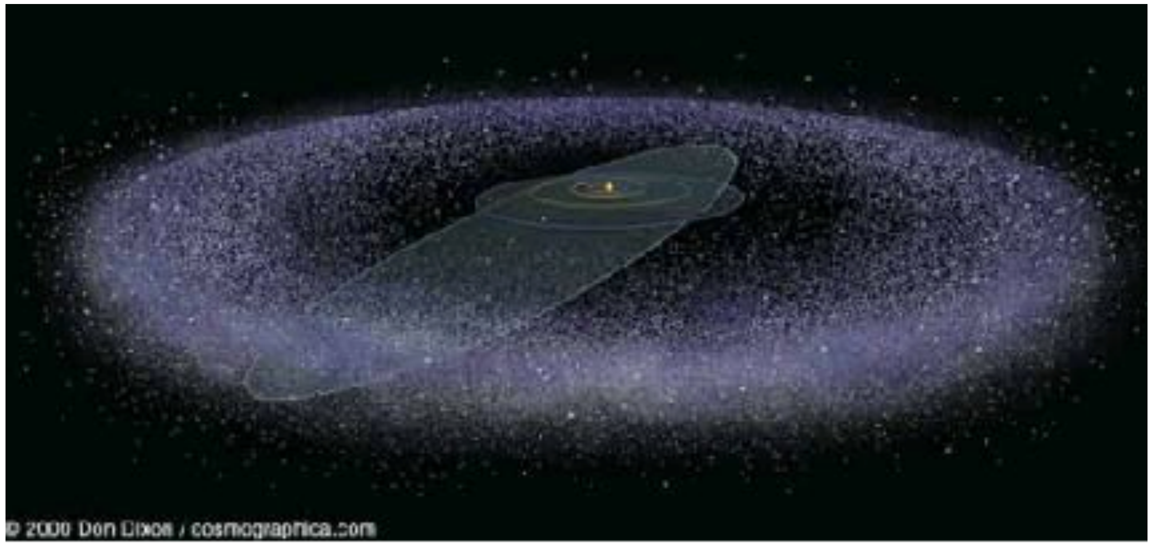
Outward migration

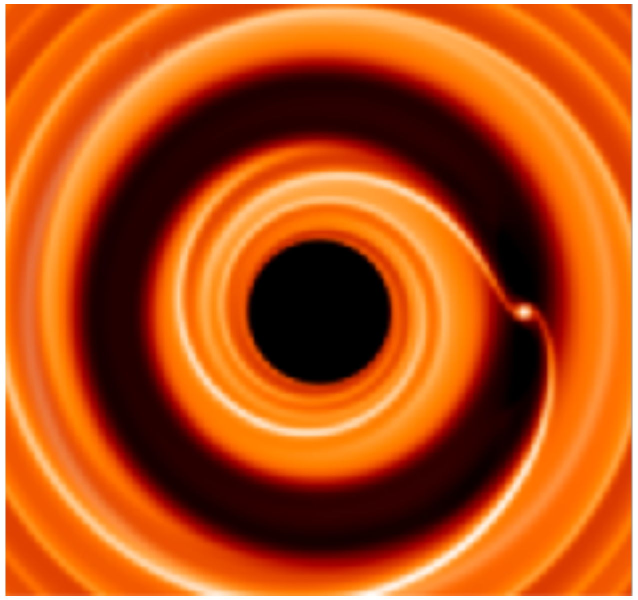
Neptune mass planets should be found at 5 AU and 16 AU !!

Bitsch et al. 2012

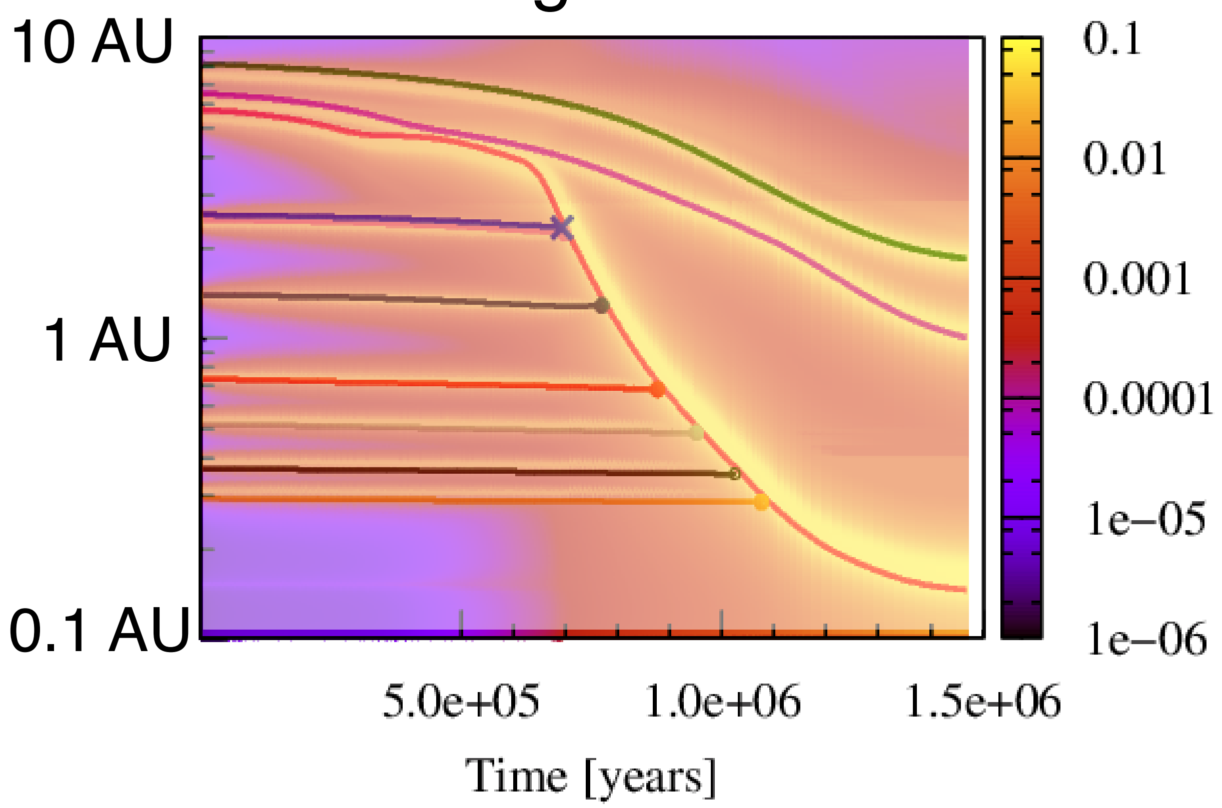
Planet formation: full numerical or integrated models?

the full numerical approach





the integrated models



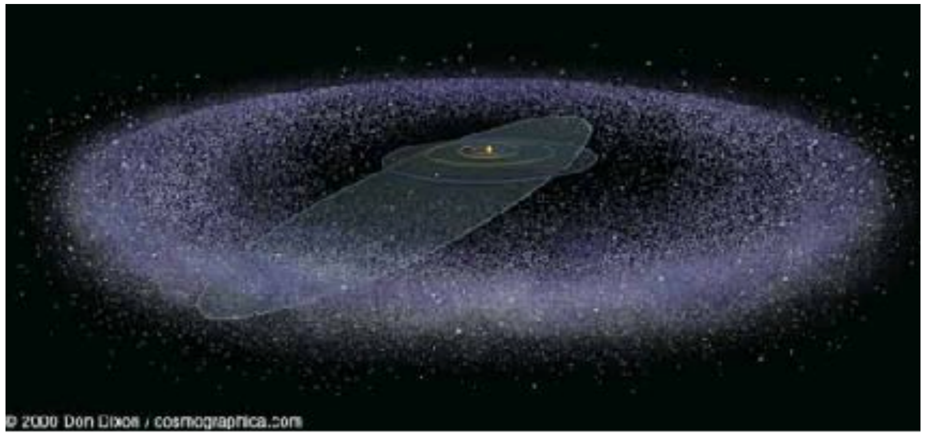
$$\frac{de}{dt} = \left.\frac{de}{dt}\right|_{GD} + \left.\frac{de}{dt}\right|_{VS,E} + \left.\frac{de}{dt}\right|_{VS,p}$$

$$\tau_{\rm mig1} = \frac{a}{\dot{a}} = \frac{1}{C_1}\frac{1}{3.81}\left(\frac{c_s}{a\Omega_{\rm K}}\right)^2 \frac{M_*}{M_{\rm planet}}\frac{M_*}{a^2\Sigma_g}\Omega_{\rm K}^{-1}$$

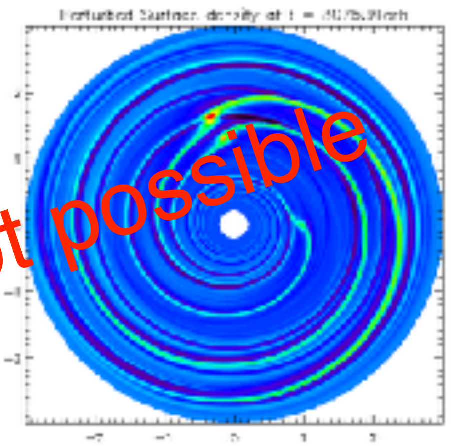
Different integrated models

full numerical model

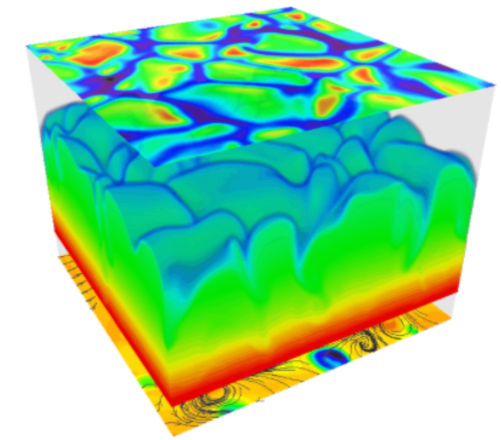
Nbody (incl. planetesimals)



hydrodynamical disk

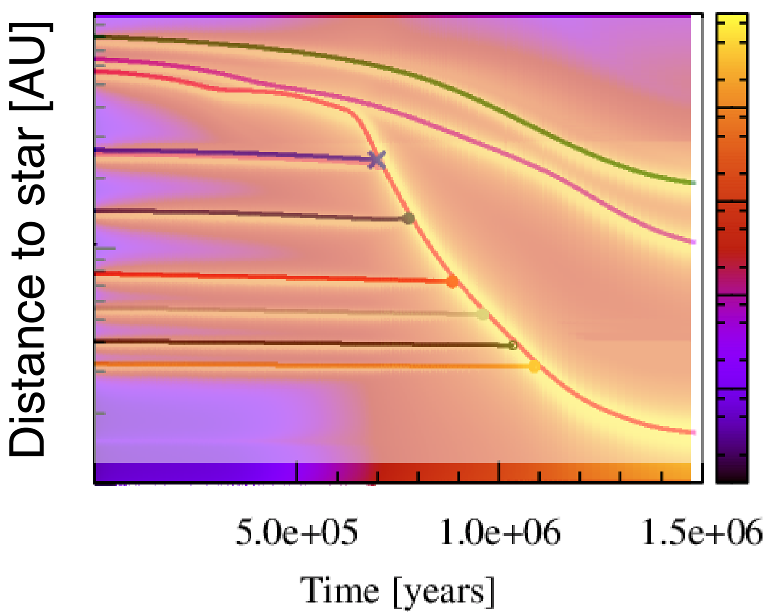


3D interior structure

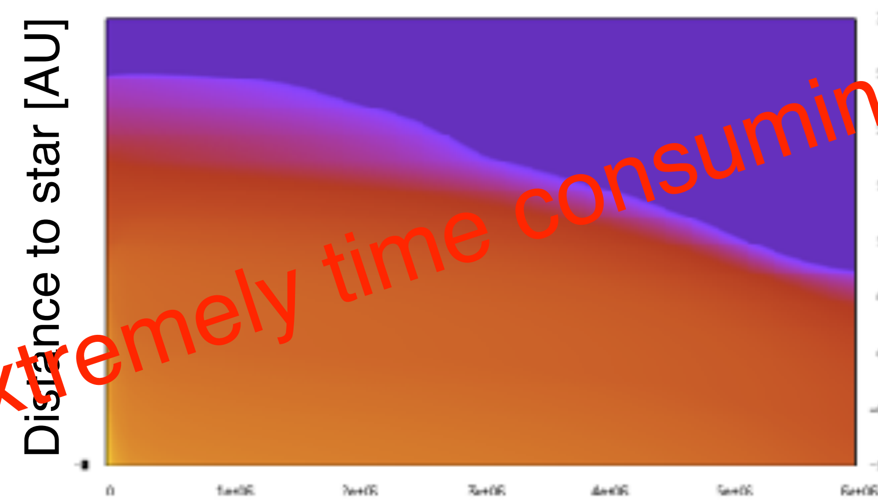


Bern model

Nbody + statistics of planetesimals



semi-analytical disk



1D interior structure

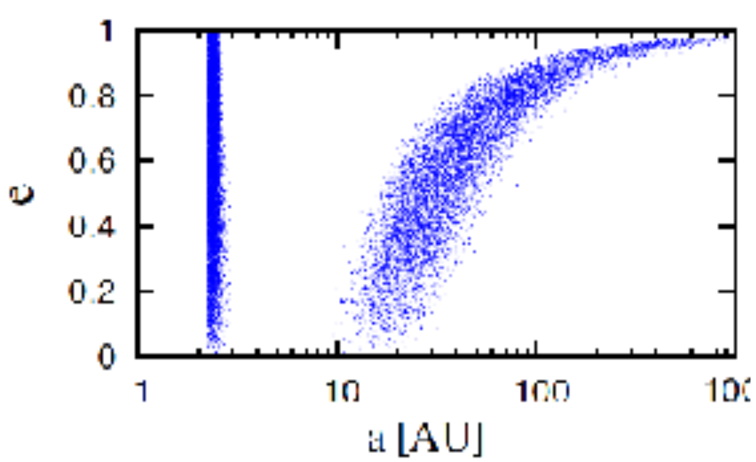
$$\frac{dr}{dM_r} = \frac{1}{4\pi\rho r^2}$$

$$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4}$$

$$\frac{dT}{dP} = \nabla_{ad} \text{ or } \nabla_{rad}$$

IL model

statistical Nbody (planets)



parametrized disk

extremely fast

$$\Sigma = \Sigma_{10} f_g (r/10\text{AU})^{-q}$$

$$f_g = f_{g,0} \exp(-t/\tau_{\text{dep}})$$

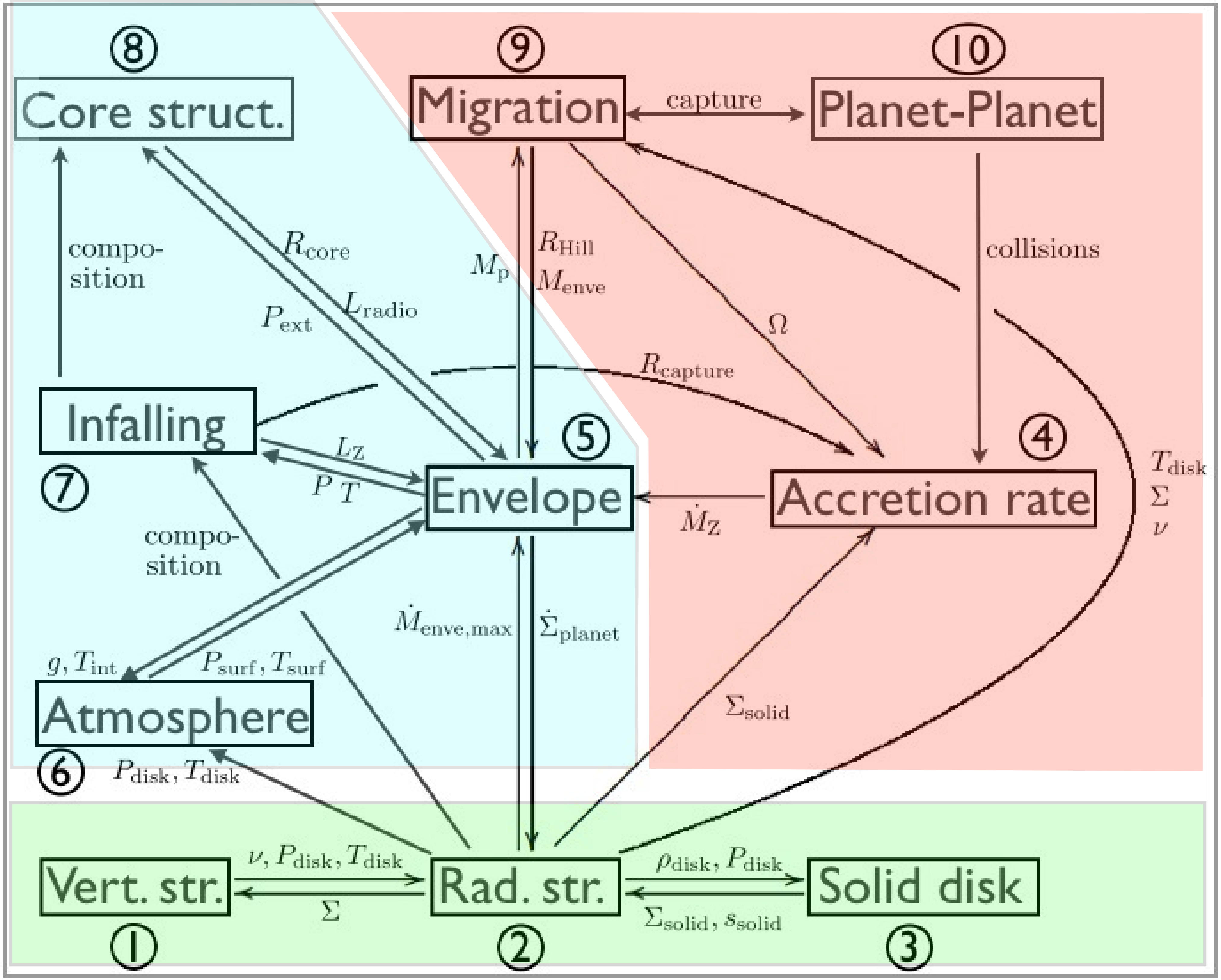
rate equations

$$\frac{dM_{\text{planet}}}{dt} \simeq \frac{M_{\text{planet}}}{\tau_{\text{KH}}}$$

$$\tau_{\text{KH}} \simeq \tau_{\text{KH1}} \left(\frac{M_{\text{planet}}}{M_\oplus}\right)^{-k2}$$

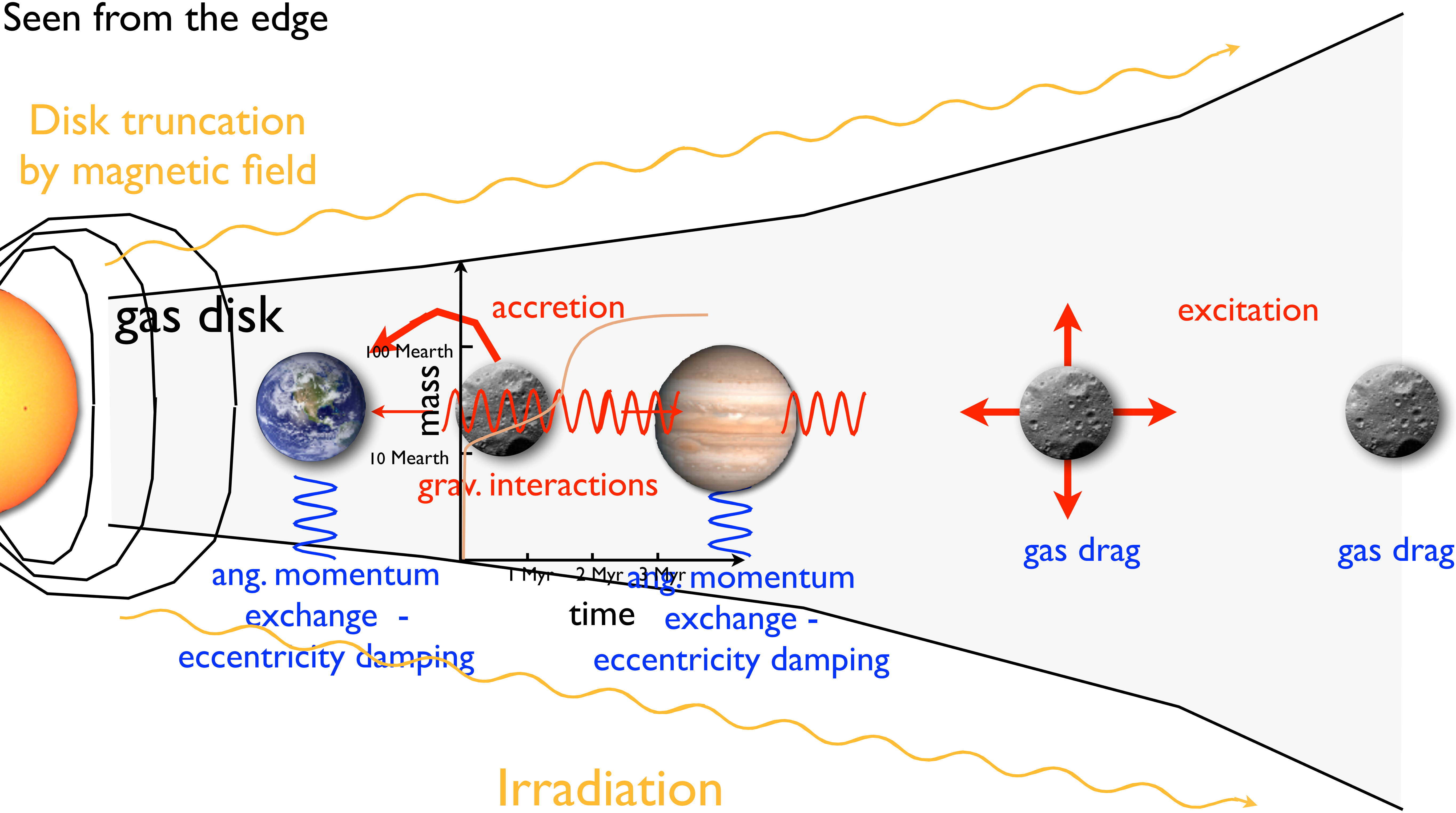
Ida, Lin & Nagasawa 2013 Fortier et al. 2013

Formation & evolution model: Bern model

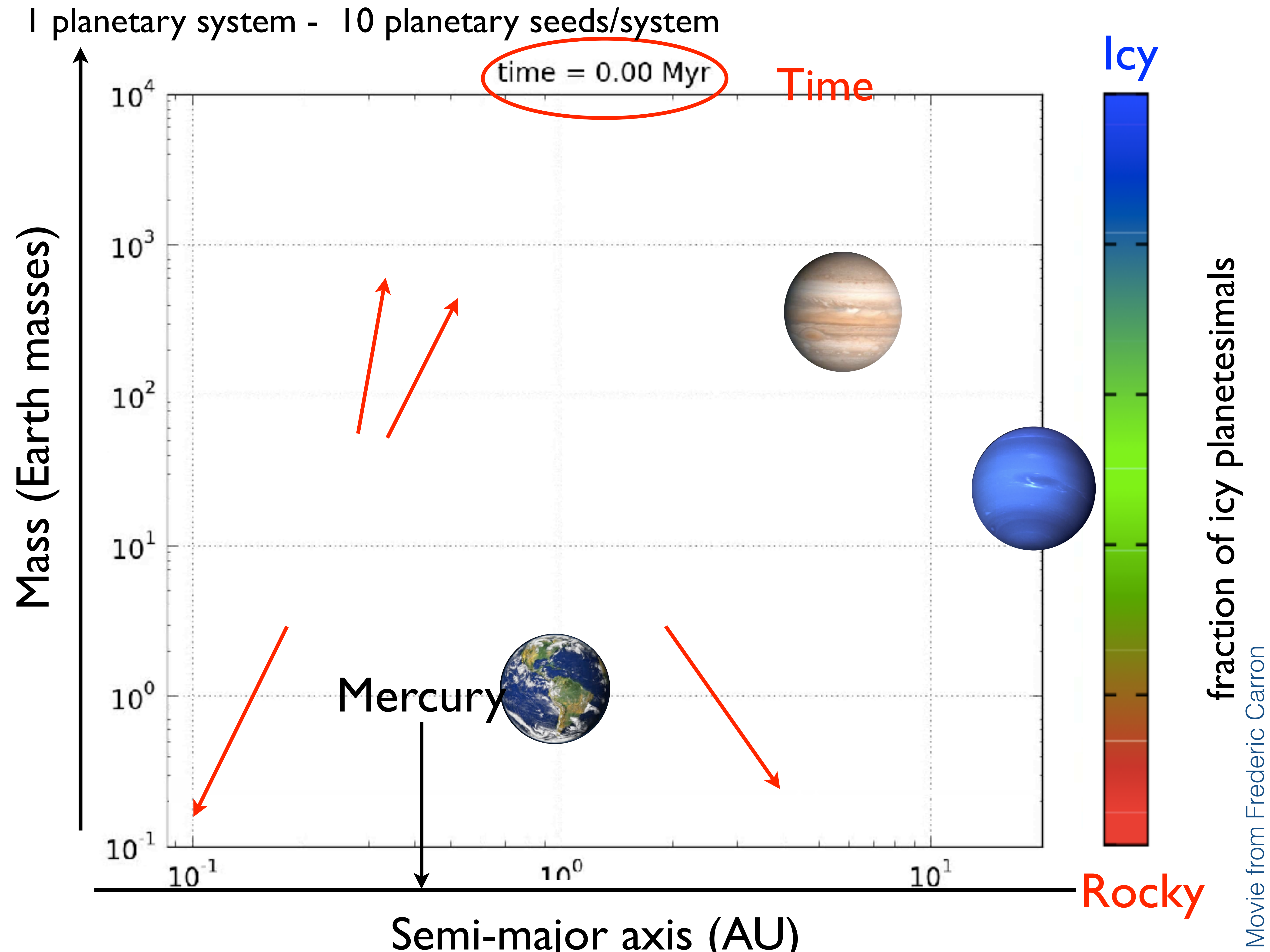


Formation & evolution model: Bern model

Seen from the edge

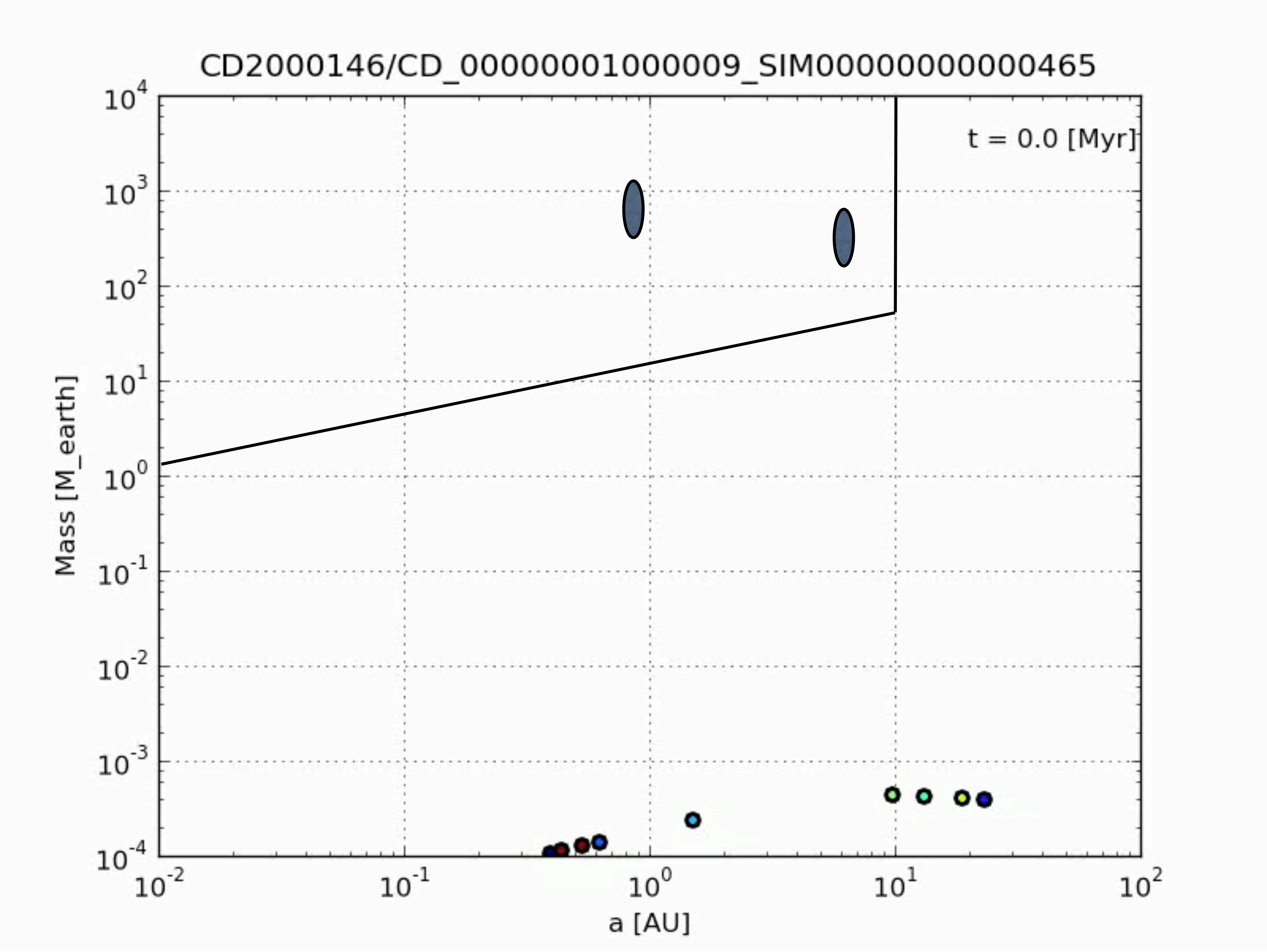


protoplanetary disk = gas disk + solids



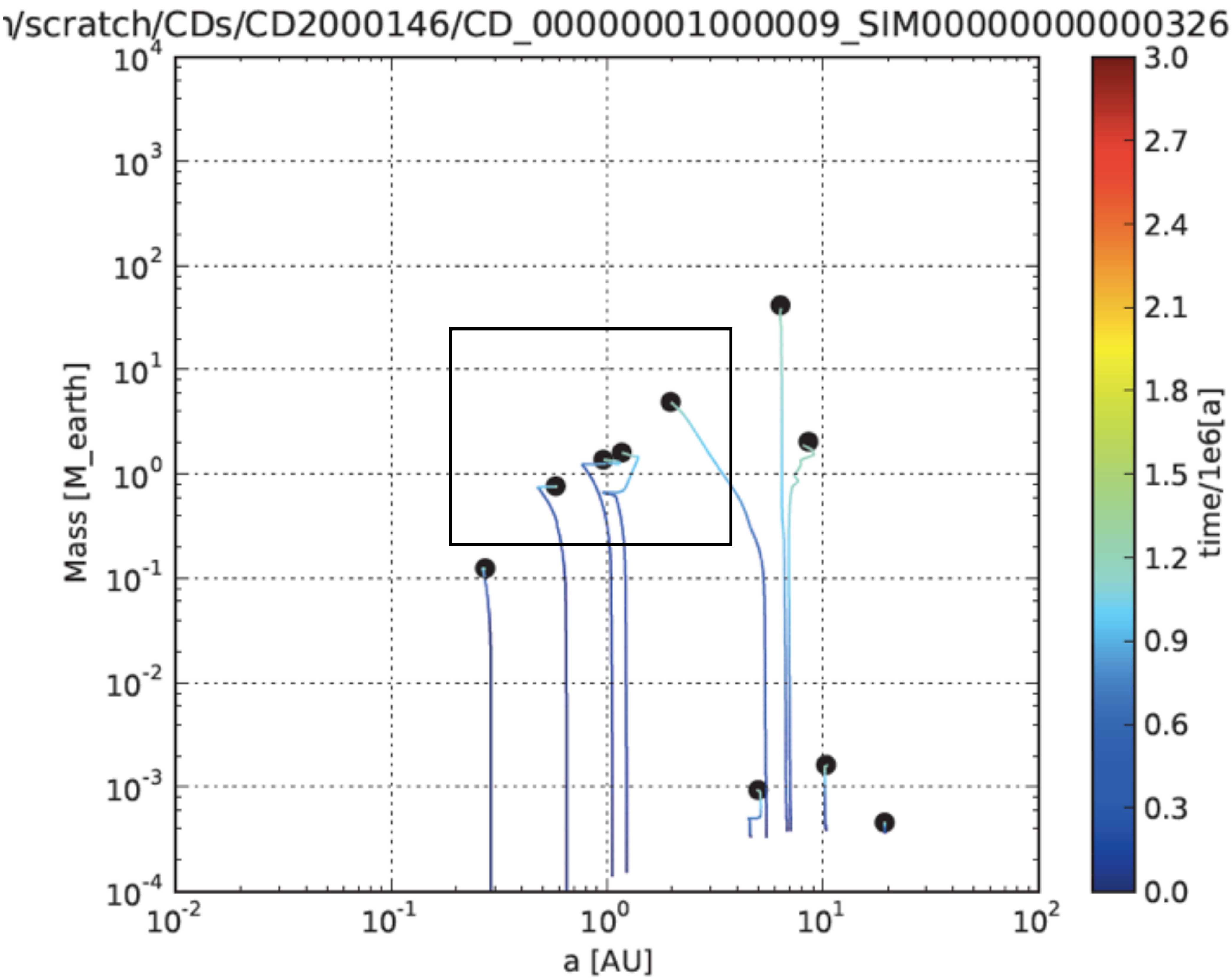
1 planetary system - 10 planetary seeds/system
time = 0.00 Myr
Time
Icy
Mass (Earth masses)
10^4
10^3
10^2
10^1
10^0
10^{-1}
Mercury
10^{-1}
10^0
10^1
Rocky
Semi-major axis (AU)
fraction of icy planetesimals
Movie from Frederic Carron

HD 134987



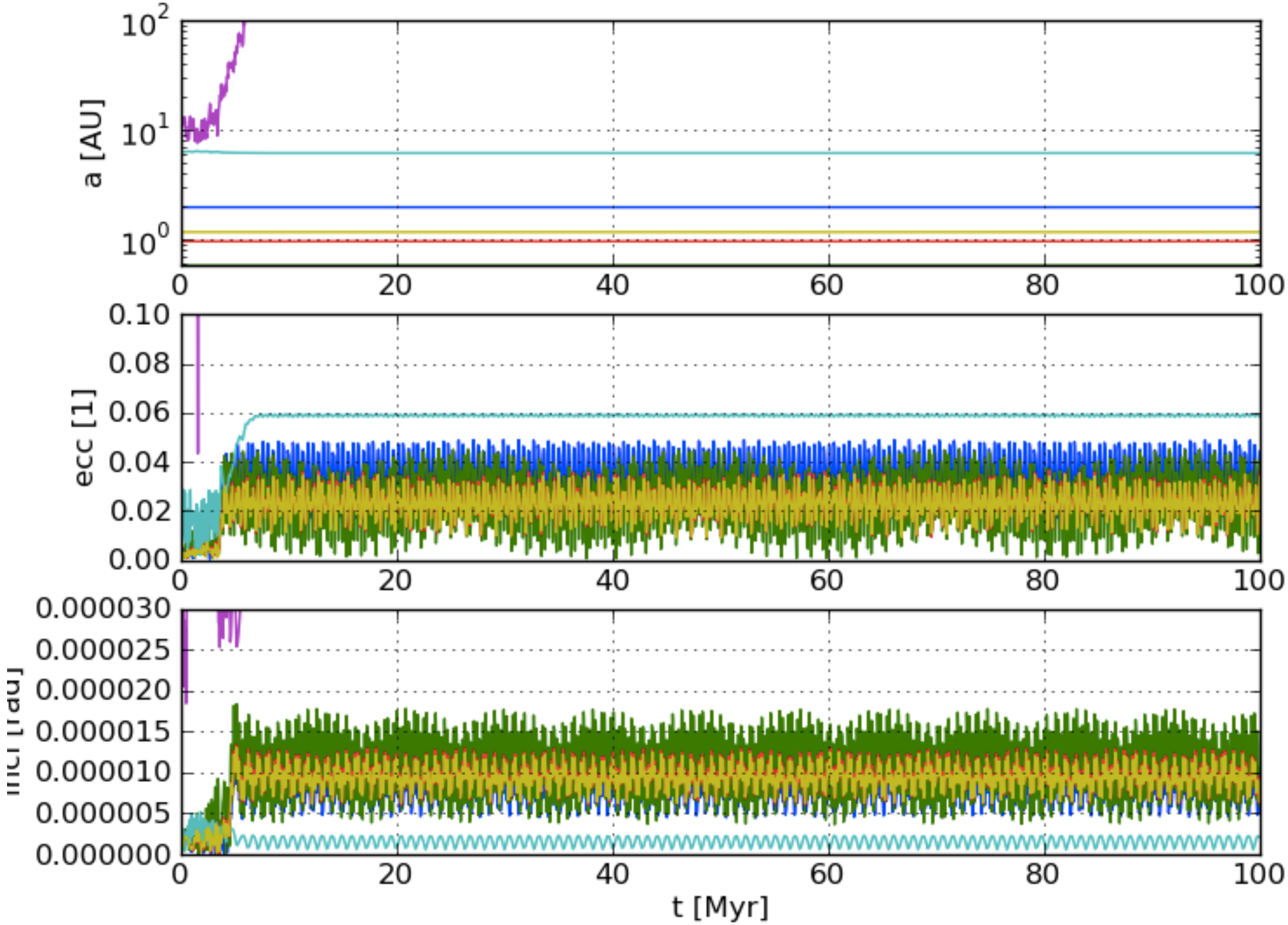
CD2000146/CD_000000010000009_SIM000000000000465
t = 0.0 [Myr]
Mass [M_earth]
a [AU]
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-2
10^-1
10^0
10^1
10^2

a system with TWO Earths at 1 AU



Plot from Frederic Carron

long term stability



Plot from Frederic Carron

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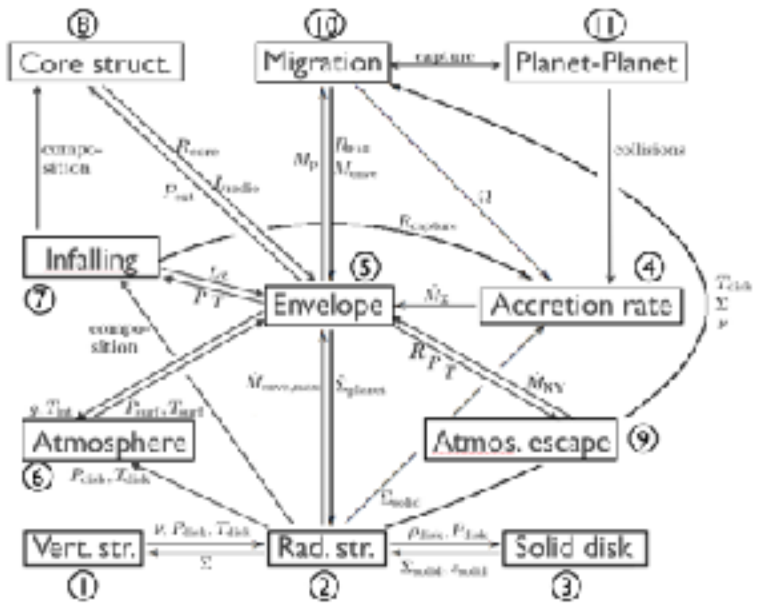
Population synthesis

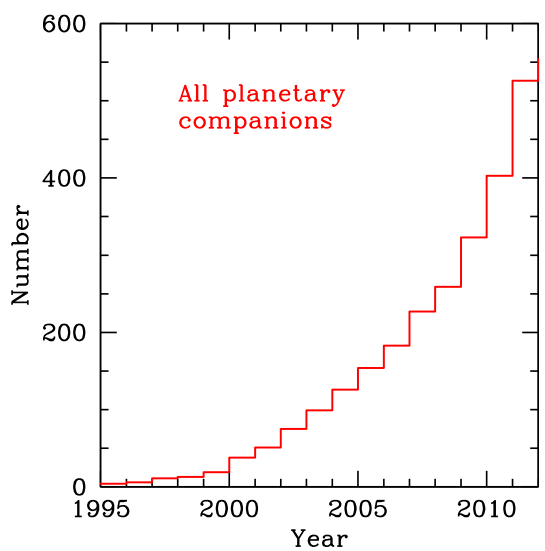
Formation & evolution model



Initial Conditions

Compute synthetic planet population

Apply observational detection bias



Observed population

Predictions

(going back to the full synthetic population)

Comparison:

Observable sub-population

- Distribution of semi-major axis
- Distribution of masses
- Distribution of luminosities
- Distribution of radii

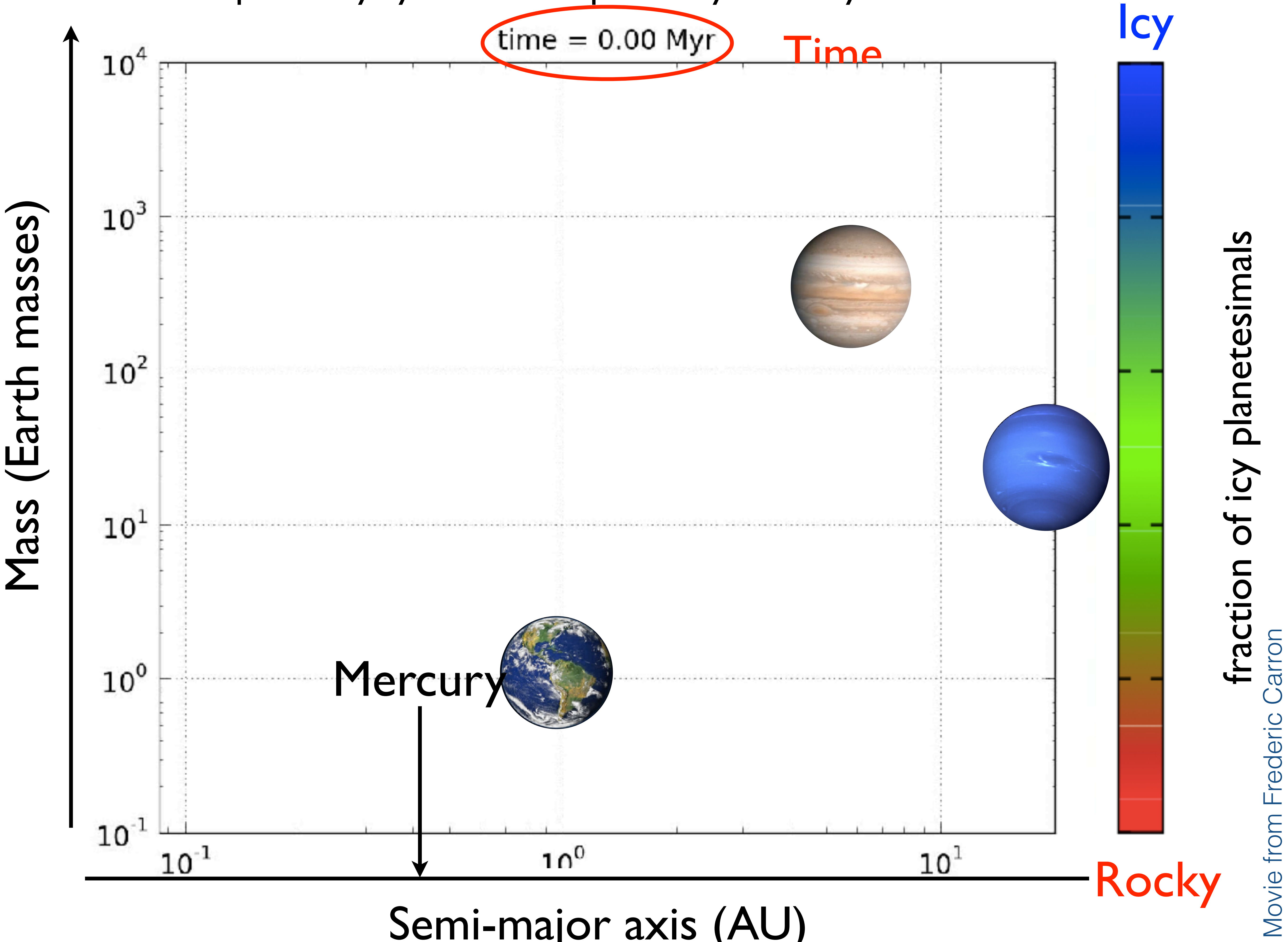
No match

Match

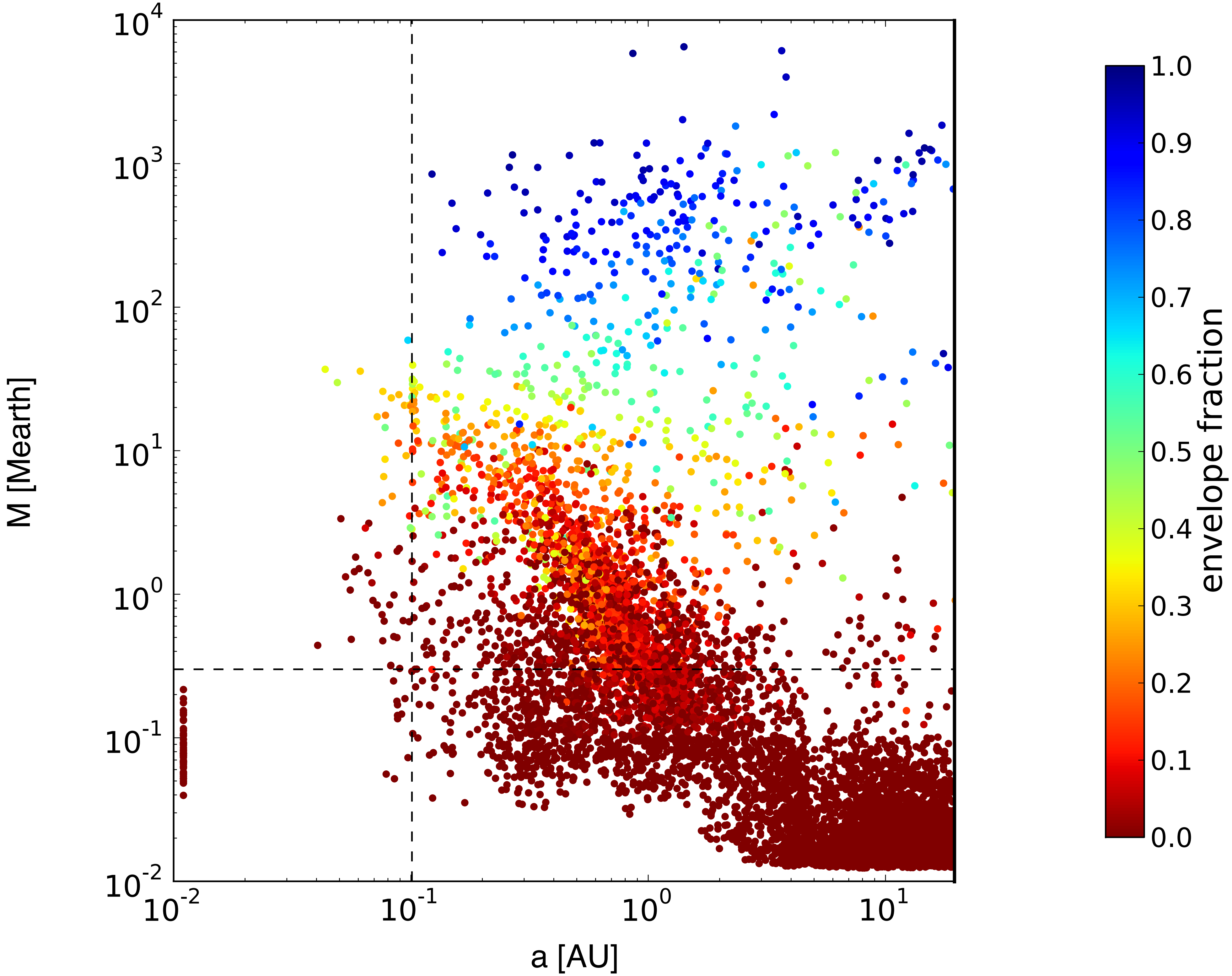
Model solution found

Ida & Lin 2004-2013, Thommes et al. 2008, Mordasini et al. 2009-2012, Miguel et al. 2011, Hellary & Nelson 2012, Alibert et al. 2013, Pfyffer et al. 2014

100 planetary systems - 10 planetary seeds/system

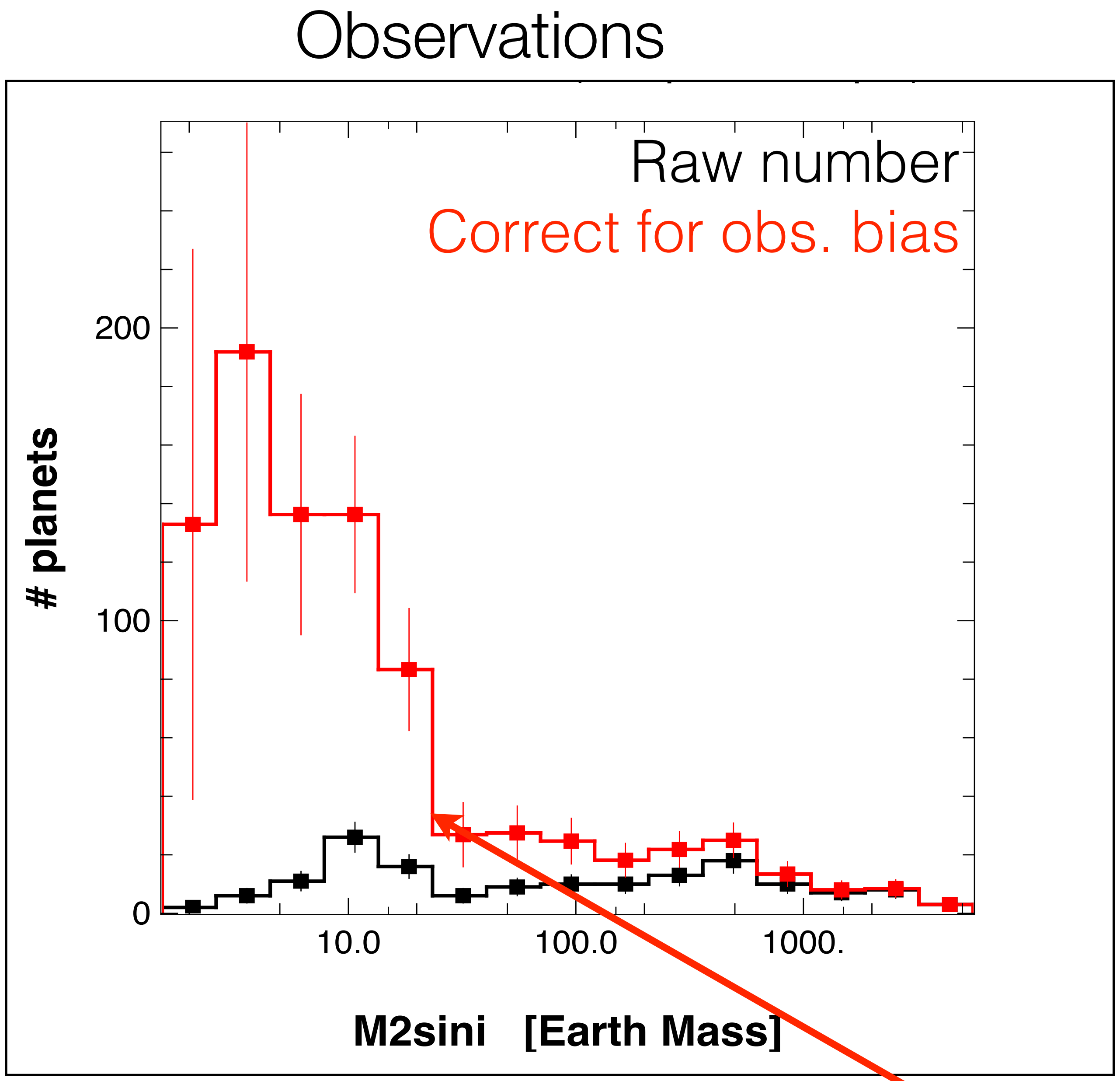


Planetesimal based: gas fraction

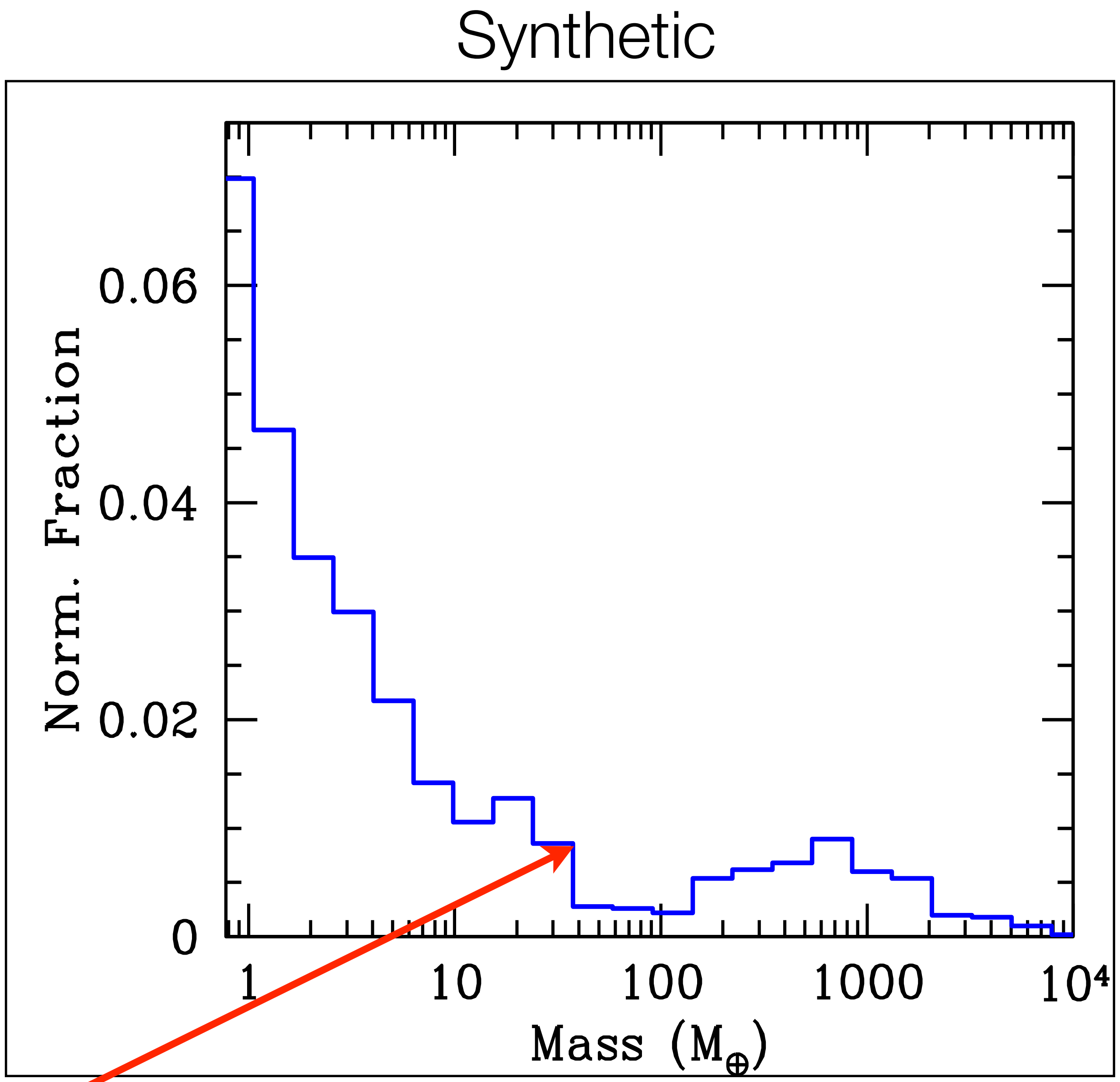


Swoboda et al. in prep

Planetesimal based: mass function



Mayor et al. 2011



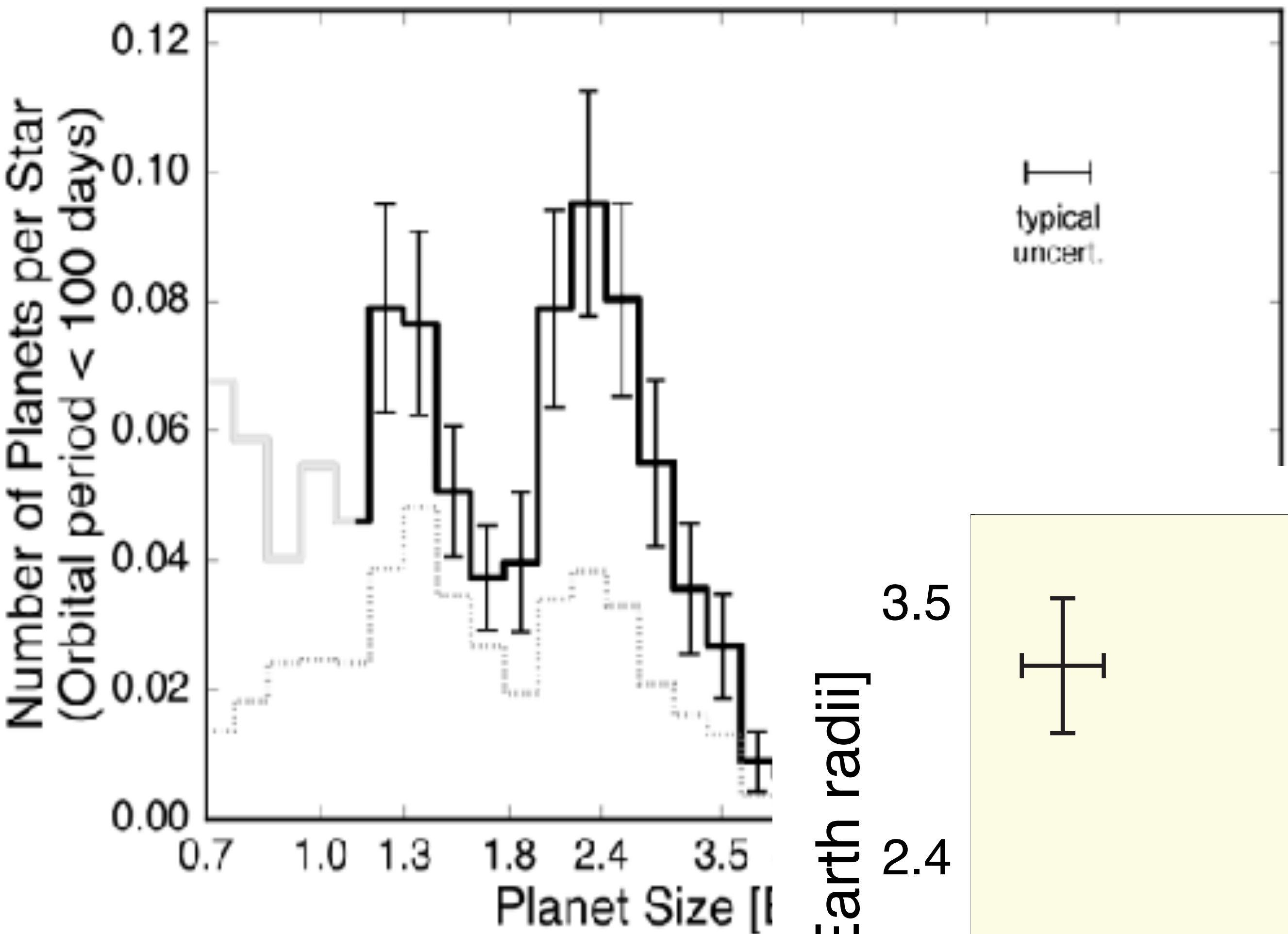
Benz et al. 2014

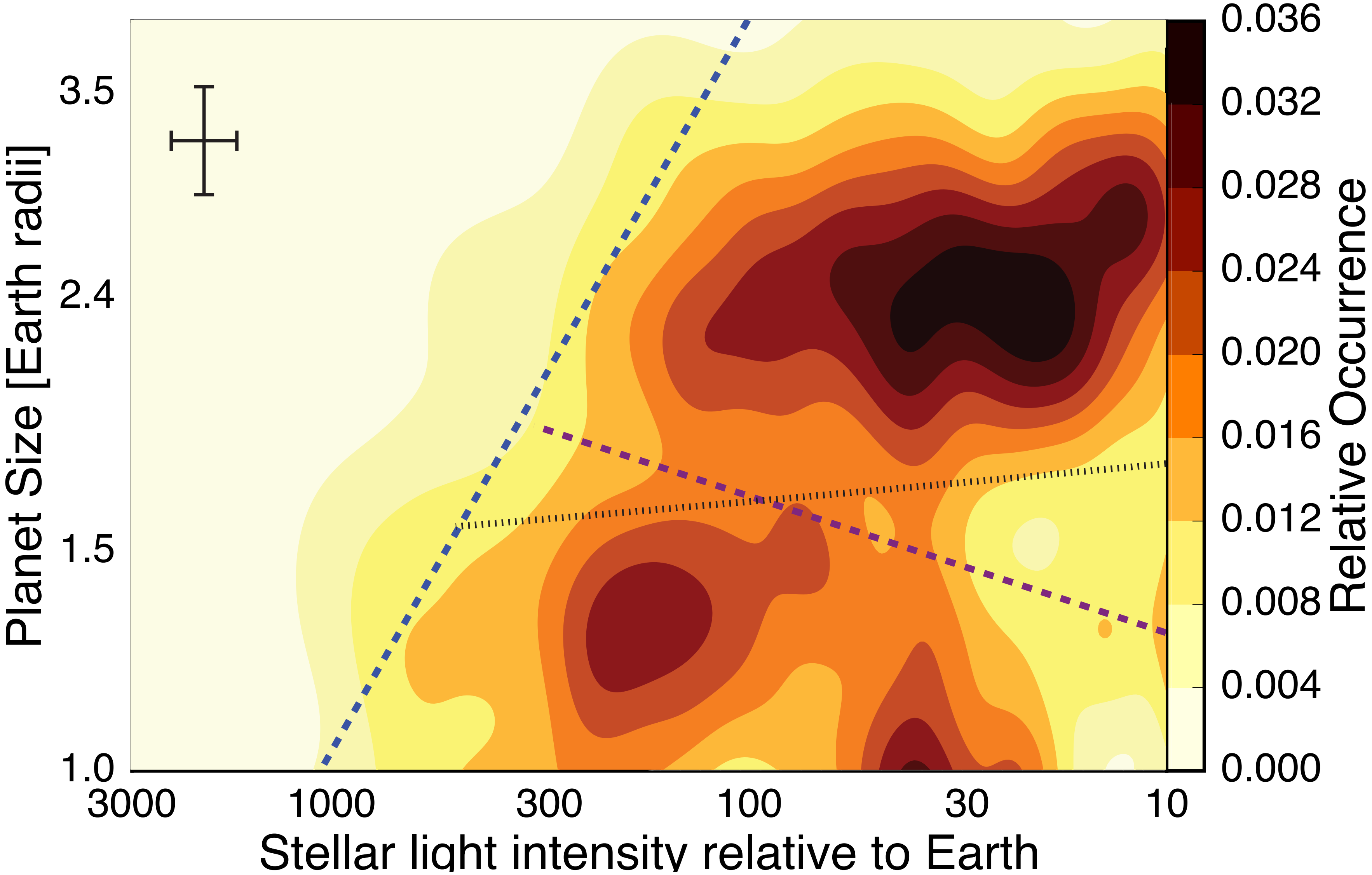
Sudden increase

Typical for core accretion. Constraint on M_{crit} & gas accretion rate .

Testing models with transit observations

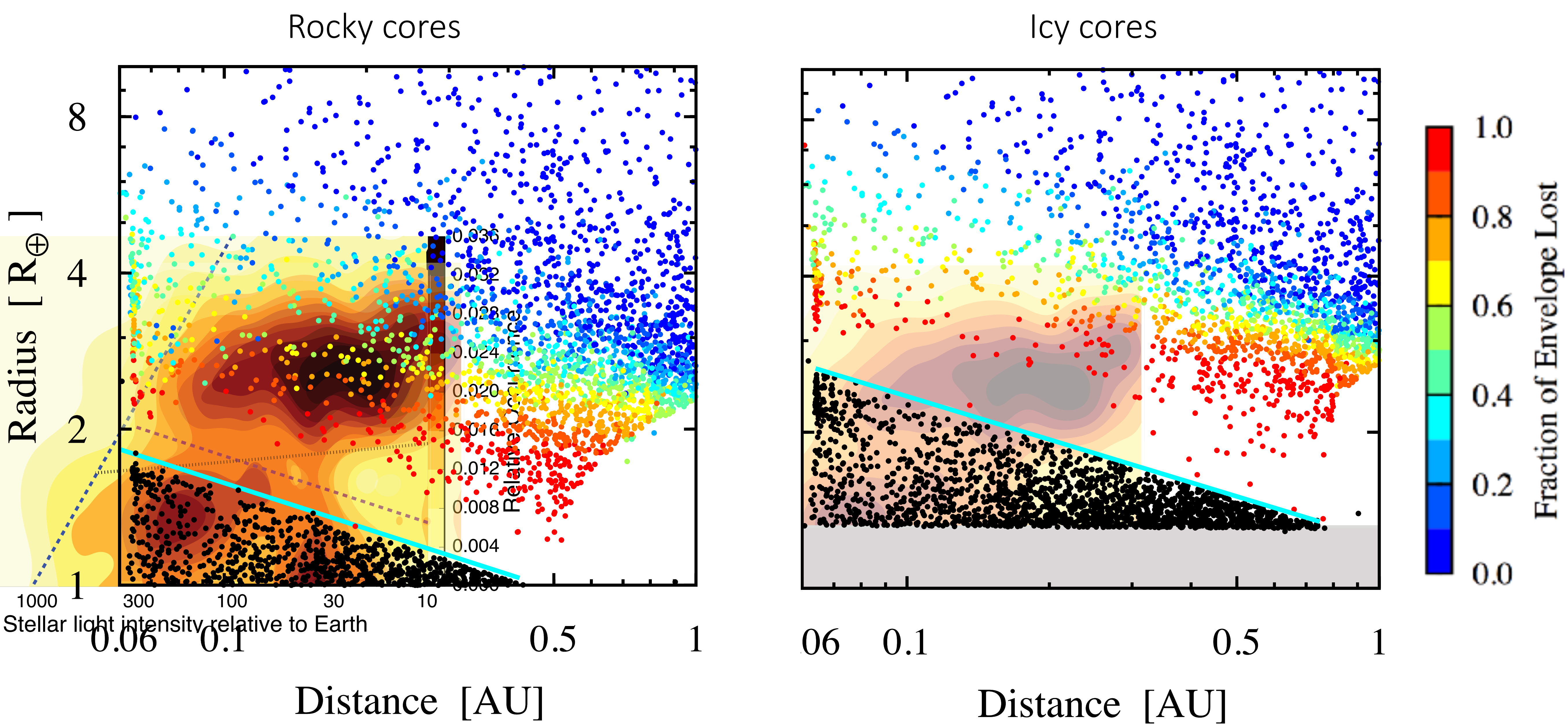
Kepler - bias corrected Fulton et al. 2017





Testing models with transit observations

Jin & Mordasini, astroph-170600251J



Observed locus of the valley agrees with evaporation

-*consistent* with mainly *rocky* composition

-*inconsistent* with mainly *icy* composition

Planetesimal based: sucesses and problems

1- Predicted mass function is similar to observed one

2- Disk size similar to observations / masses in the higher end of the distribution

3- Works better with low mass planetesimals (~km)

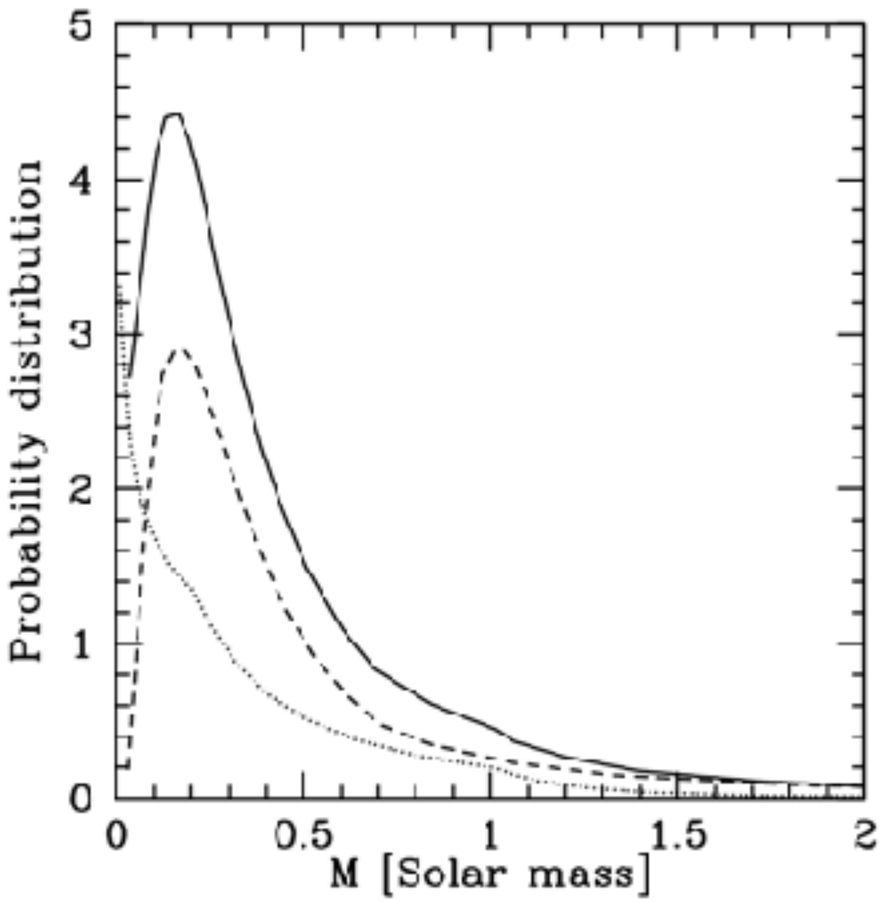
4- Formation of planets at large distance - timescale problem

-> ejection?

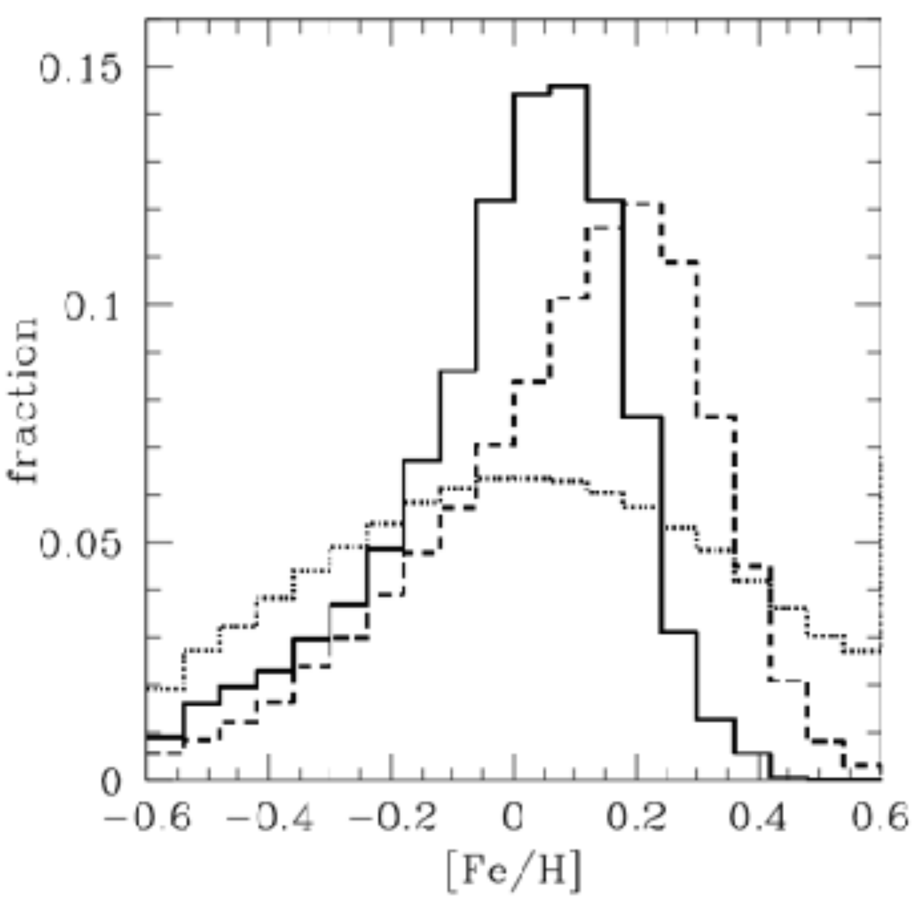
-> outwards migration?

-> another formation mechanism?

Testing models with microlensing observations



Dominik 2006



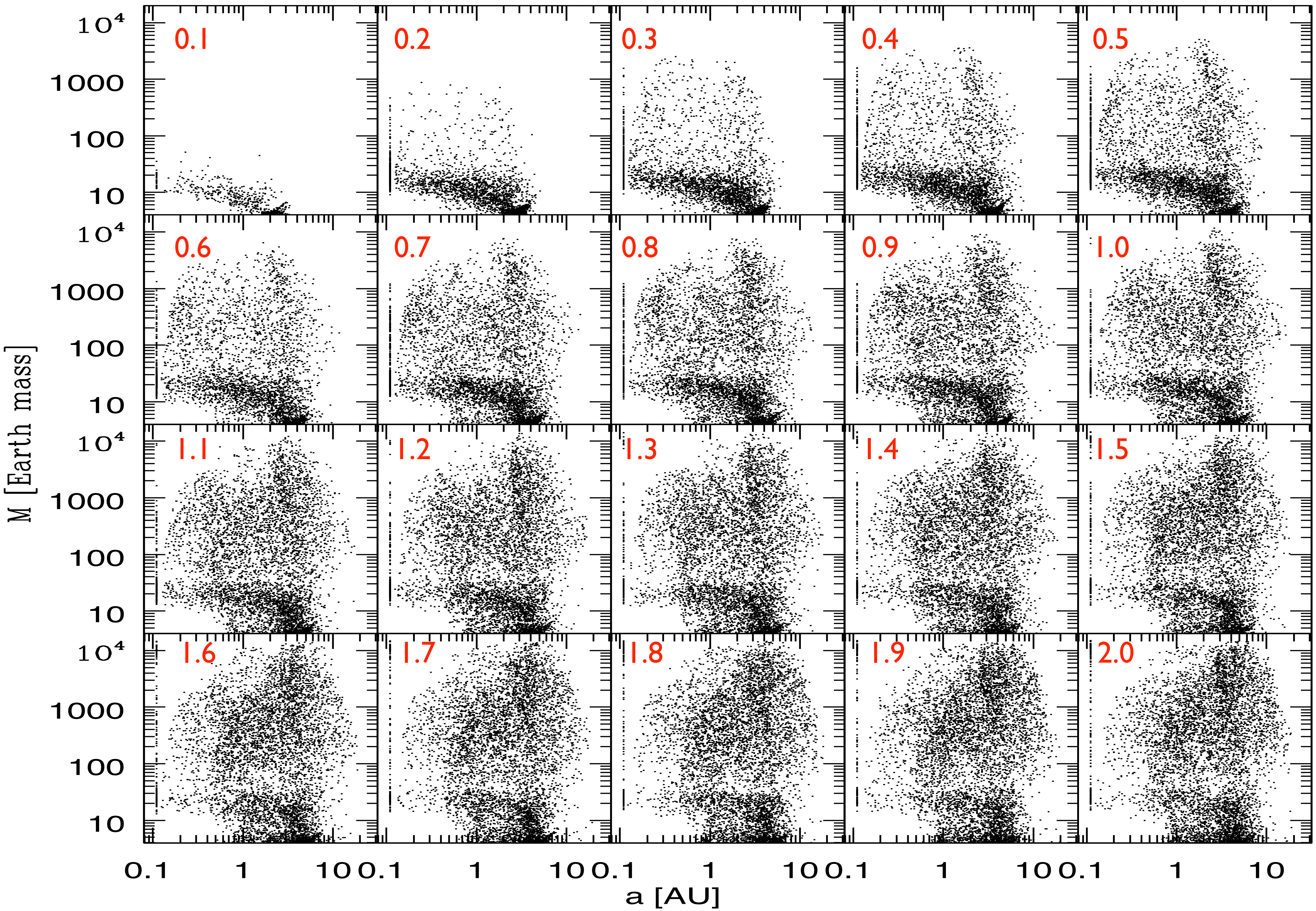
Besancon model
Robin et al. 2003

Theoretical lens population including mass and metallicity distributions

Alibert et al. 2011 (unpublished)

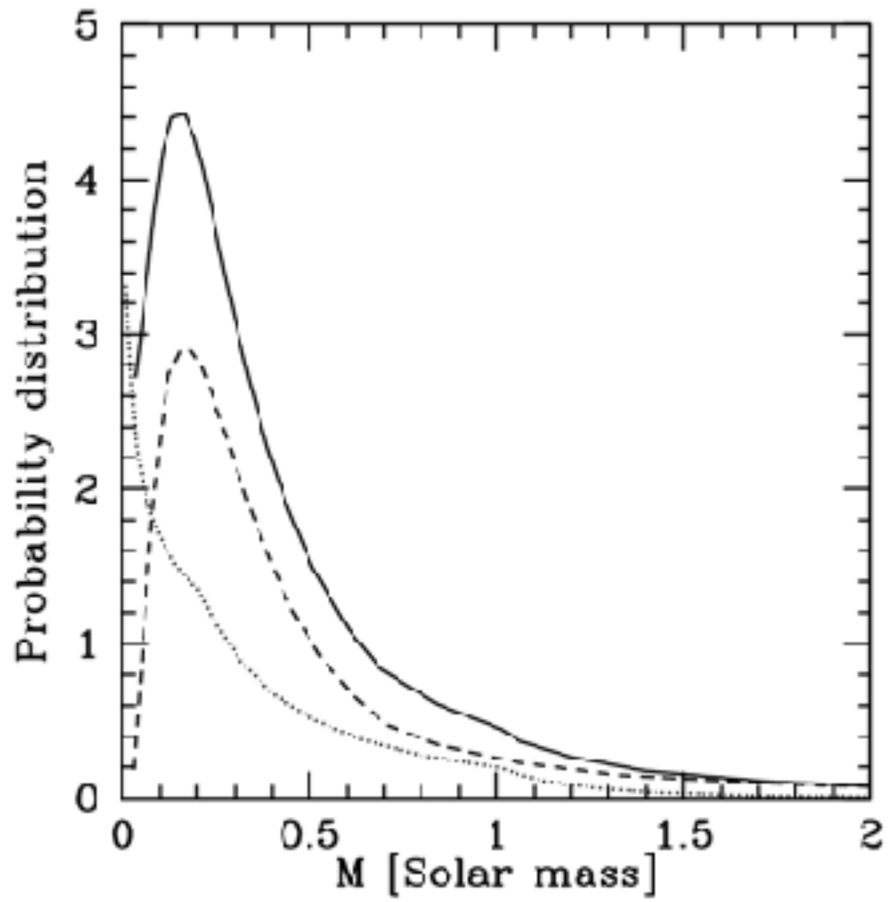
Testing models with microlensing observations

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

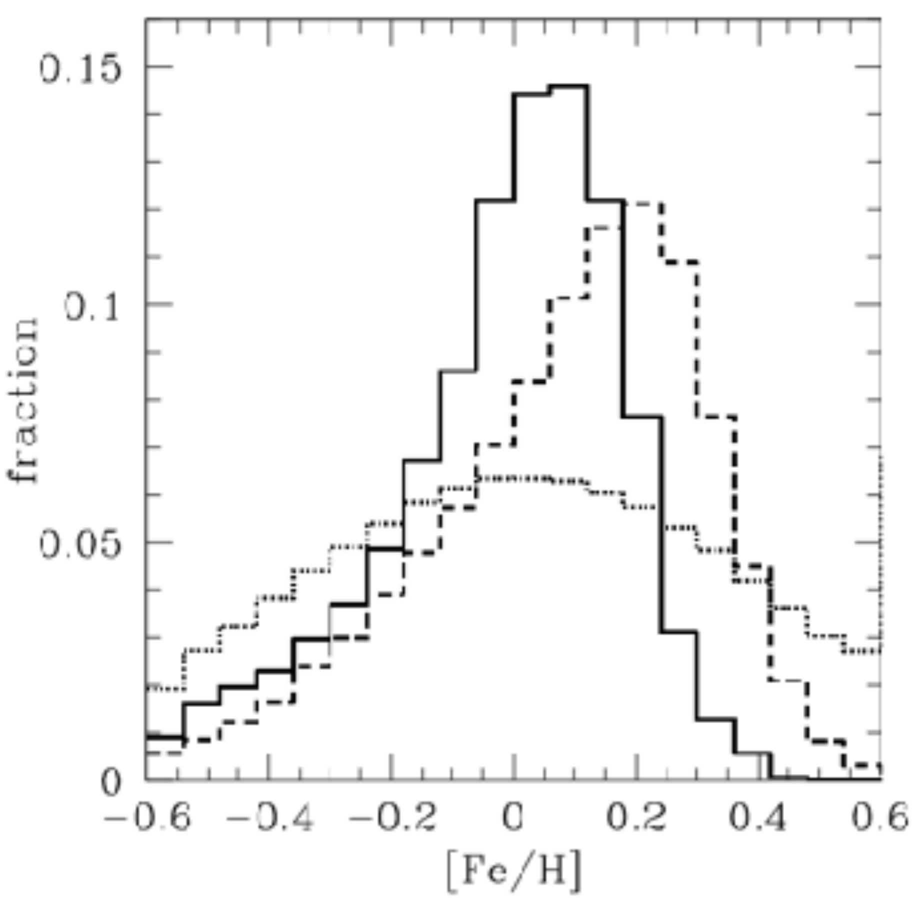


!! one-planet models !!

Testing models with microlensing observations



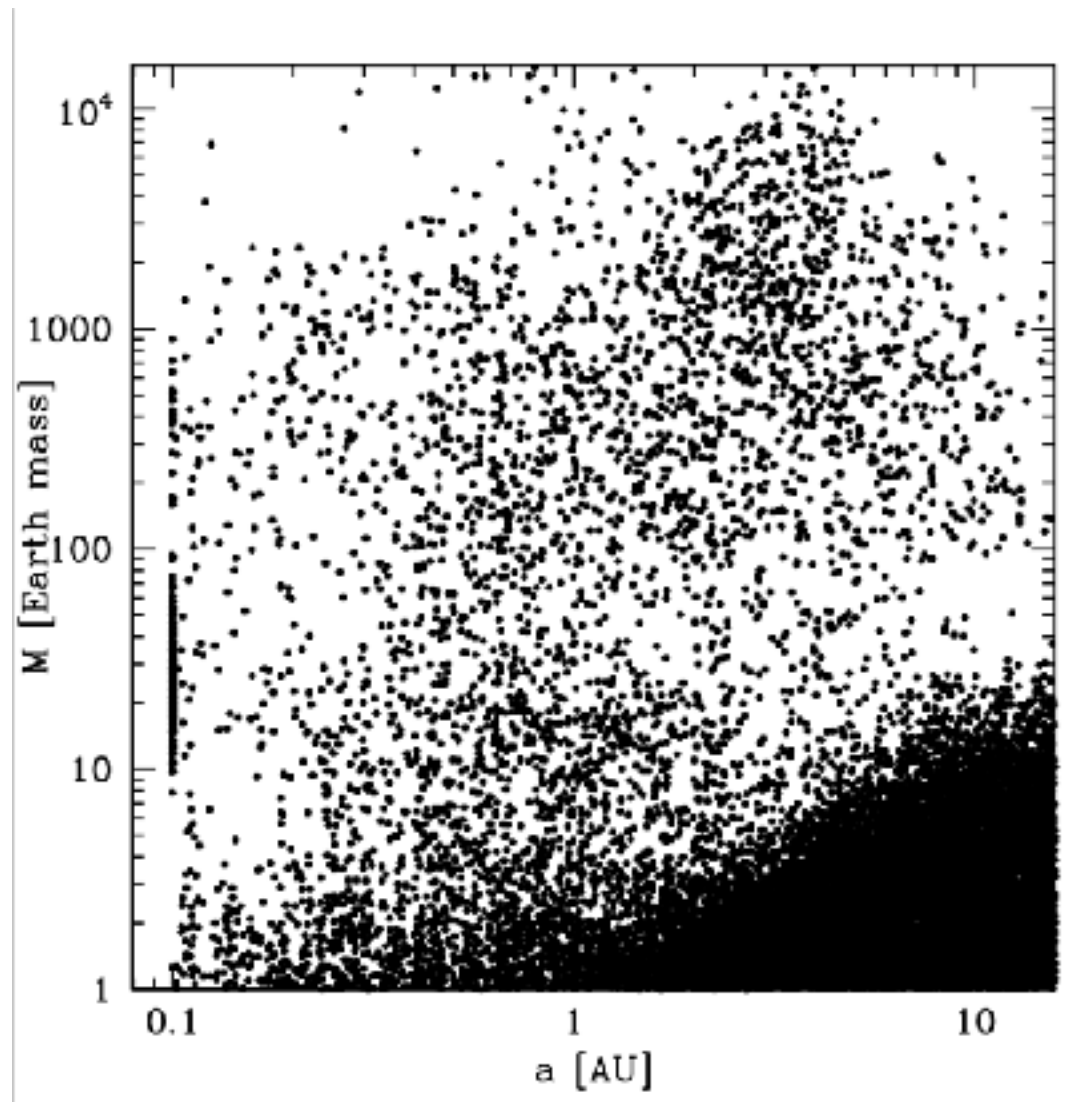
Dominik 2006



Besancon model
Robin et al. 2003

→

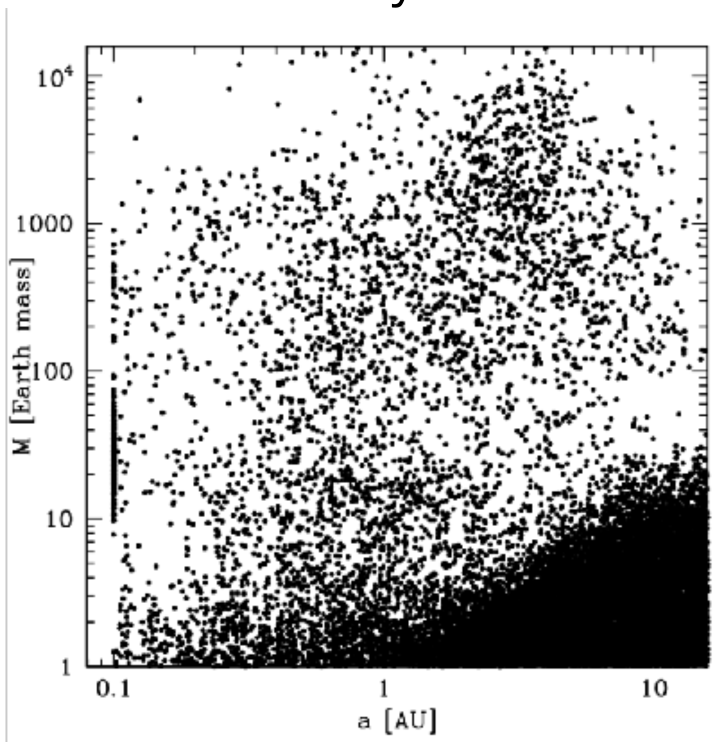
Theoretical lens population including mass and metallicity distributions

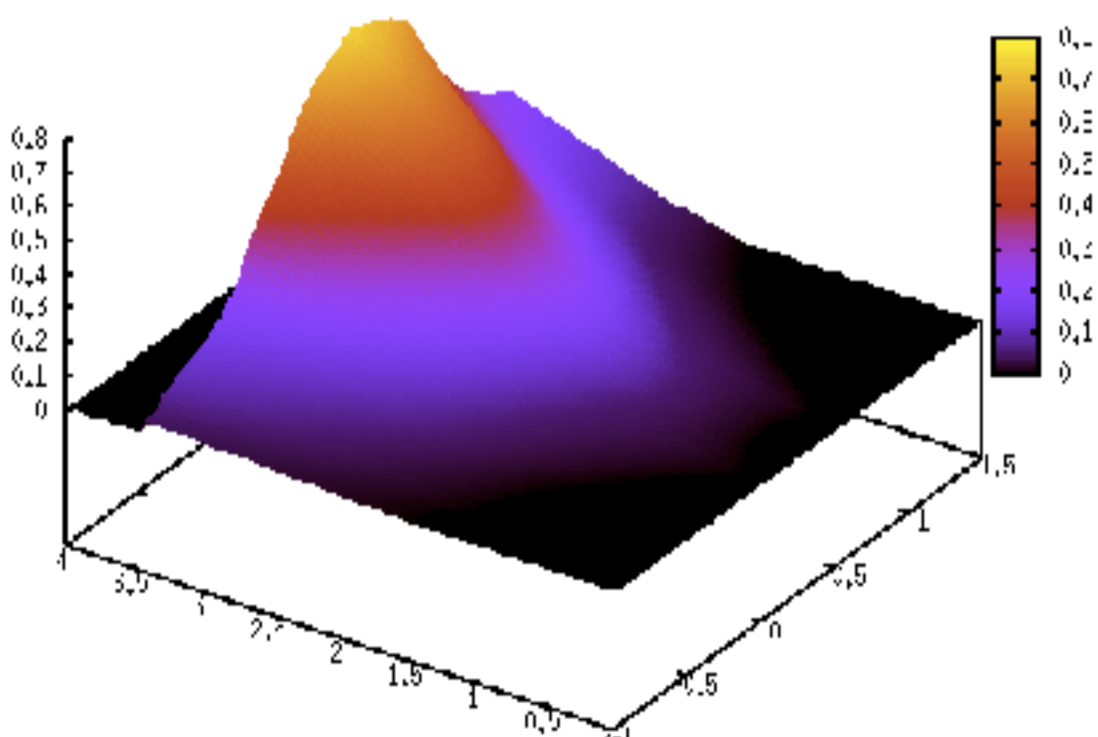


Alibert et al. 2011 (unpublished)

Testing models with microlensing observations

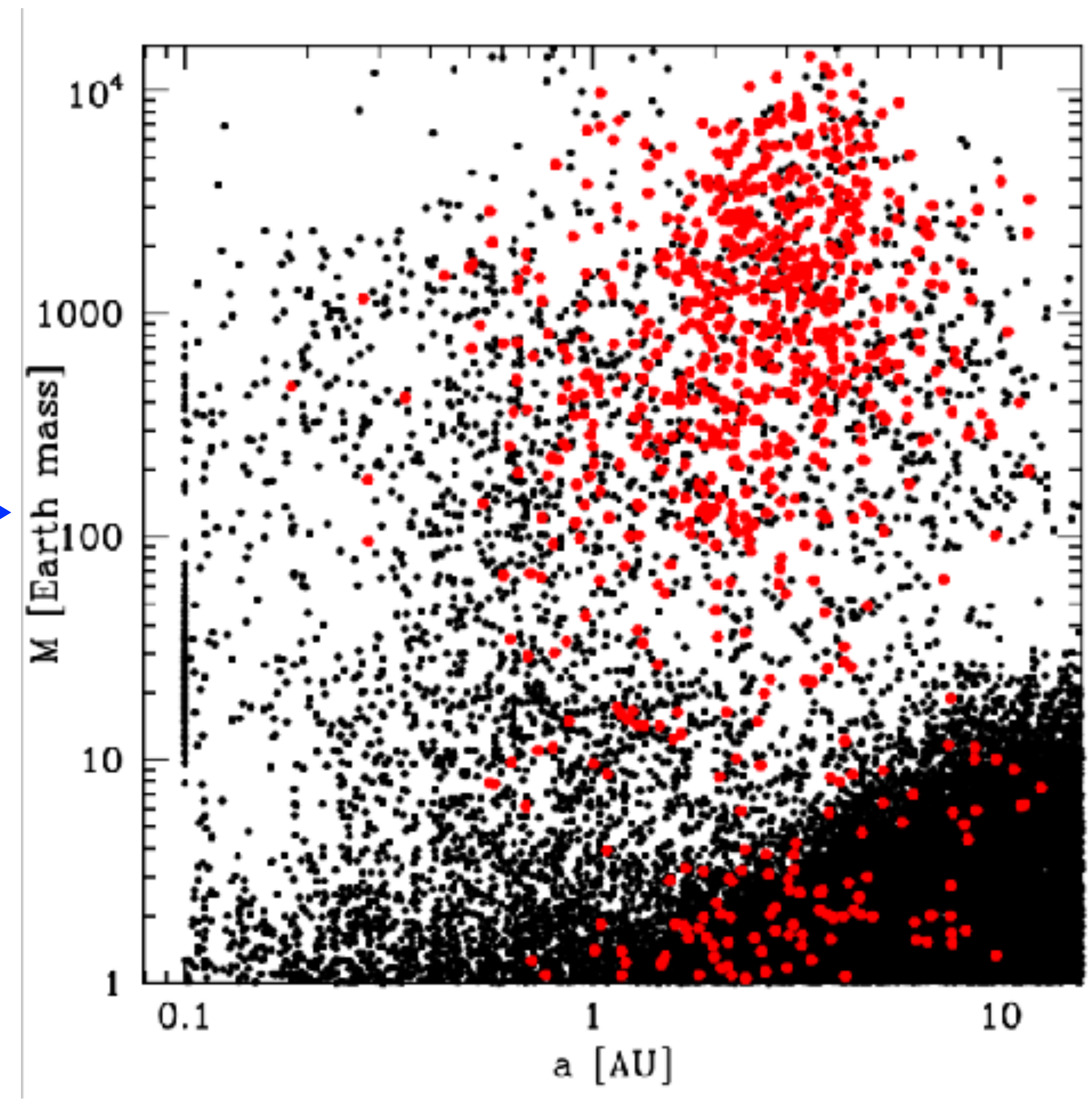
Theoretical lens population including mass and metallicity distributions





Cassan, Sumi & Kubas 2008

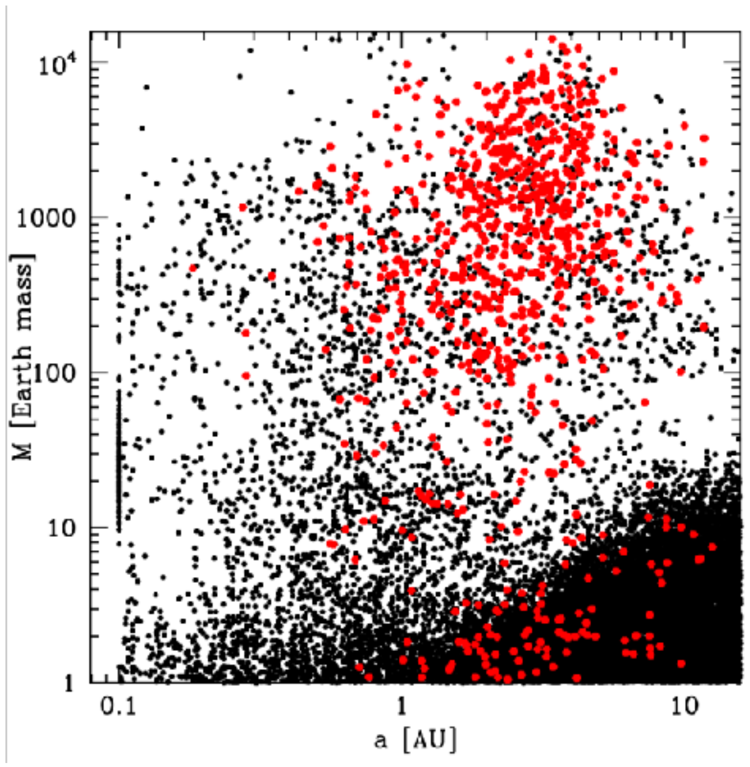
Theoretical observable lens population

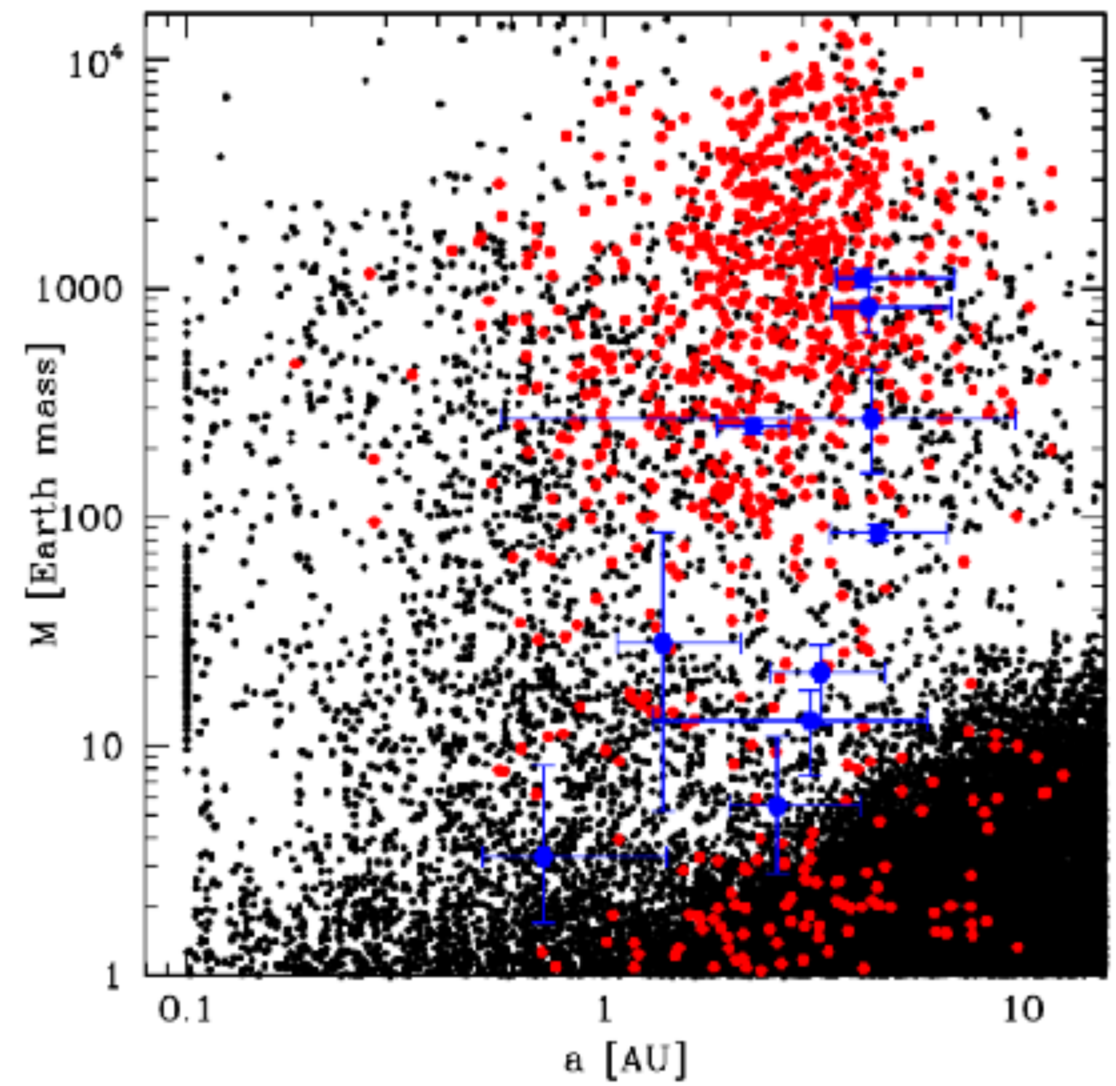


Alibert et al. 2011 (unpublished)

Testing models with microlensing observations

Theoretical observable lens population

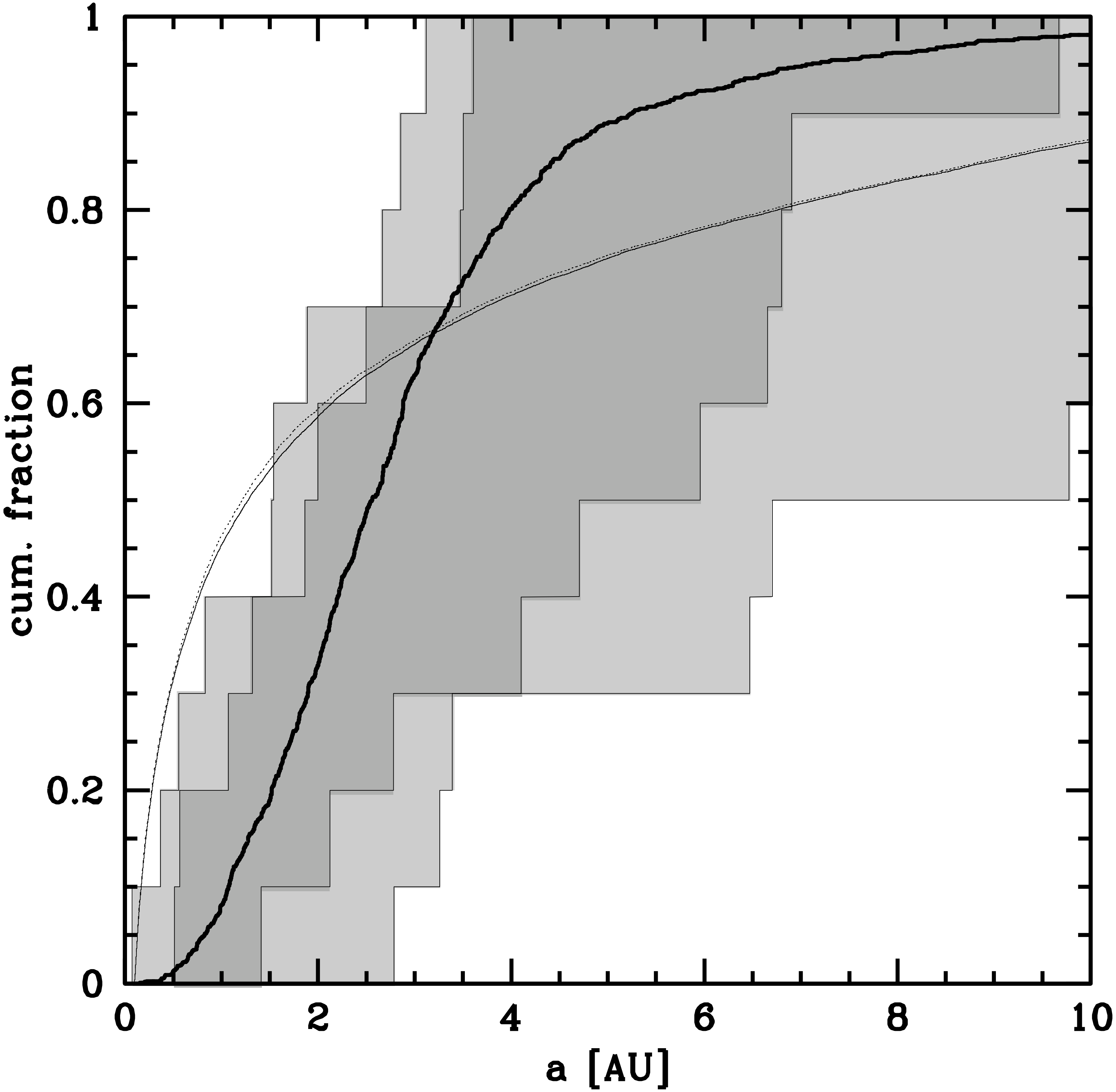




Name	$M_{star}/M_{\odot}$	$M_{planet}/M_{\oplus}$	a_{planet}/AU	$\log(\sigma_M^-)$	$\log(\sigma_M^+)$	$\log(\sigma_a^-)$	$\log(\sigma_a^+)$	Distance (kpc)
OGLE 235b/MOA 53b	0.63	2.6	5.1	0.8	0.8	1.6	1.6	5.2
OGLE 71b	0.46	3.5	3.6	0.3	0.3	0.2	0.2	3.3
OGLE 109b	0.51	0.727	2.3	0.06	0.06	0.5	0.5	1.51
OGLE 109c	0.51	0.271	4.5	0.022	0.022	1.0	1.0	1.51
MOA 192b	0.06	0.01	0.66	0.005	0.015	0.14	0.19	0.7
MOA 400b	0.35	0.9	0.85	0.4	0.4	0.25	0.25	6
OGLE 390b	0.22	0.017	2.1	0.0085	0.017	0.6	1.5	6.5
OGLE 169b	0.49	0.04	2.8	0.020	0.021	1.42	1.94	2.7
MOA 310b	0.67	0.23	1.25	0.05	0.05	0.1	0.1	>6
OGLE 368b	0.64	0.0694	3.3	0.025	0.022	0.8	1.4	5.9
MOA 319b	0.38	0.157	2.0	0.075	0.138	0.4	0.4	6.1
MOA 387b	0.19	2.6	1.8	1.6	4.1	0.7	0.9	5.7

Alibert et al. 2011 (unpublished)

Semi-major axis

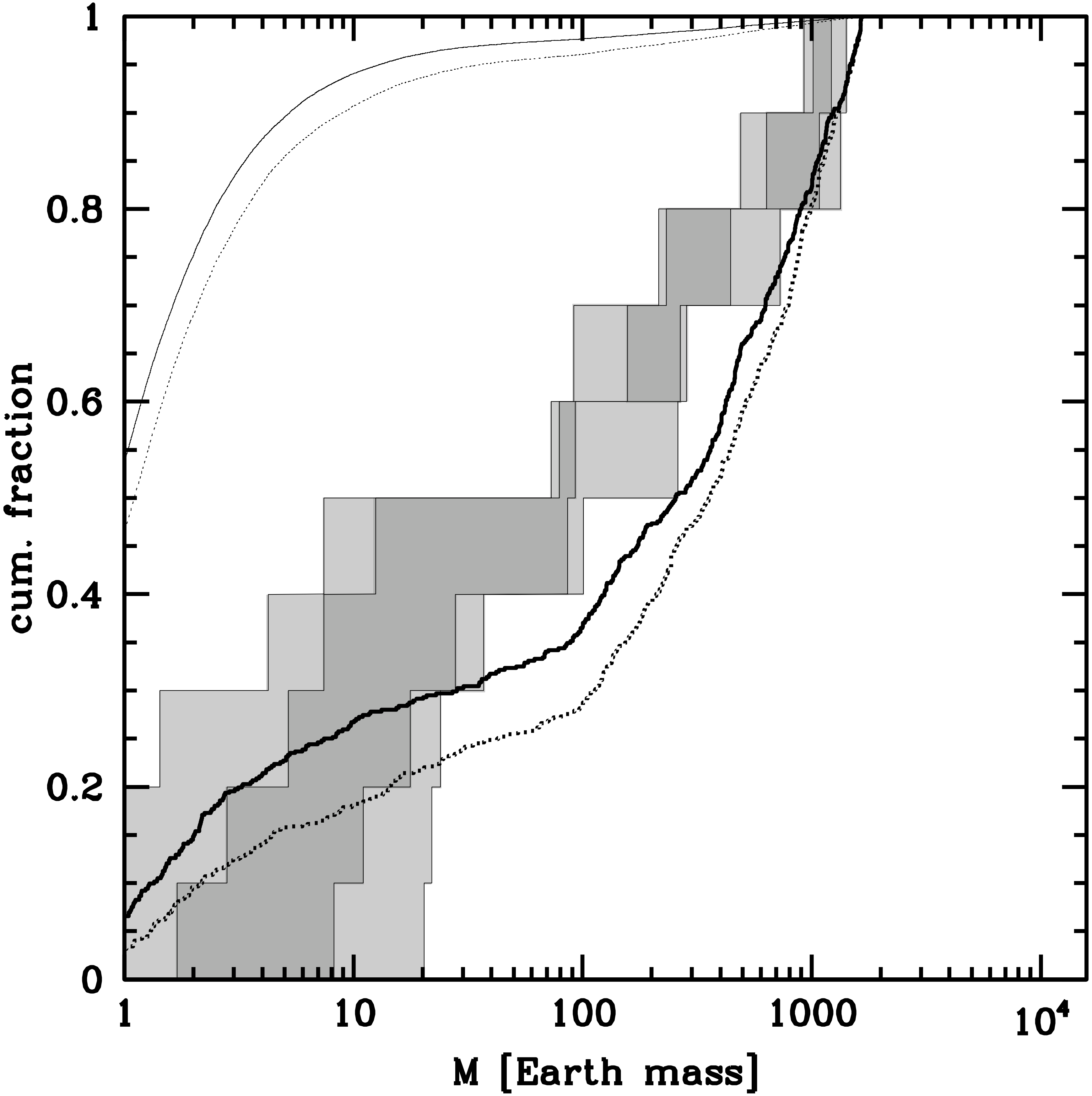


Lenses at 0.5 kpc

Lenses at 6 kpc

Alibert et al. 2011 (unpublished)

Mass



Lenses at 0.5 kpc

Lenses at 6 kpc

Alibert et al. 2011 (unpublished)

Outlines

1- Exoplanets and population synthesis

2- From disks to planets: integrated models

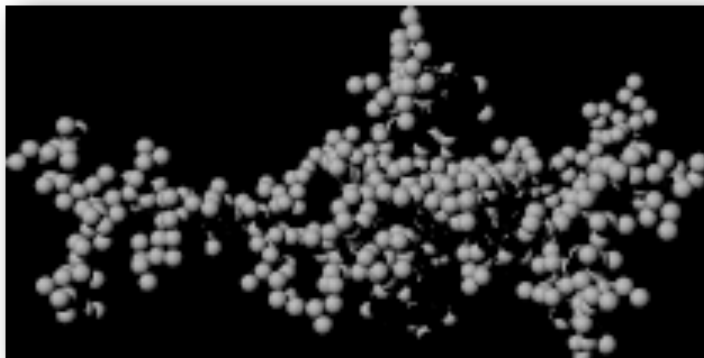
3- Population synthesis: comparison and results

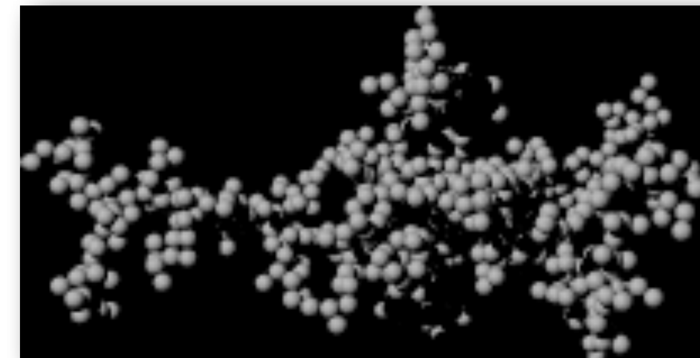
4- Pebbles *versus* planetesimals

What is the mass of core's building blocks?

Planetesimals-based model

Pebbles-based model





dust ~ microns

pebbles ~ cm

high efficiency

low efficiency

planetesimals ~ km

Planetesimal based: Integrated model

1- protoplanetary disk evolution

2- planet internal structure (core & envelope)

3- orbital migration

4- planet-planet interactions (gravity & competition)

Alibert, Mordasini, Benz 2004; Alibert et al. 2005, Mordasini et al. 2012, Alibert et al. 2013, Pfyffer et al. 2014, Alibert & Benz 2016, Swoboda et al. in prep…

Planetesimal based: sucesses and problems

1- Predicted mass function is similar to observed one

2- Disk size similar to observations / masses in the higher end of the distribution

3- Works better with low mass planetesimals (~km)

4- Formation of planets at large distance - timescale problem

-> ejection?

-> outwards migration?

-> another formation mechanism?

Pebble based: Integrated model

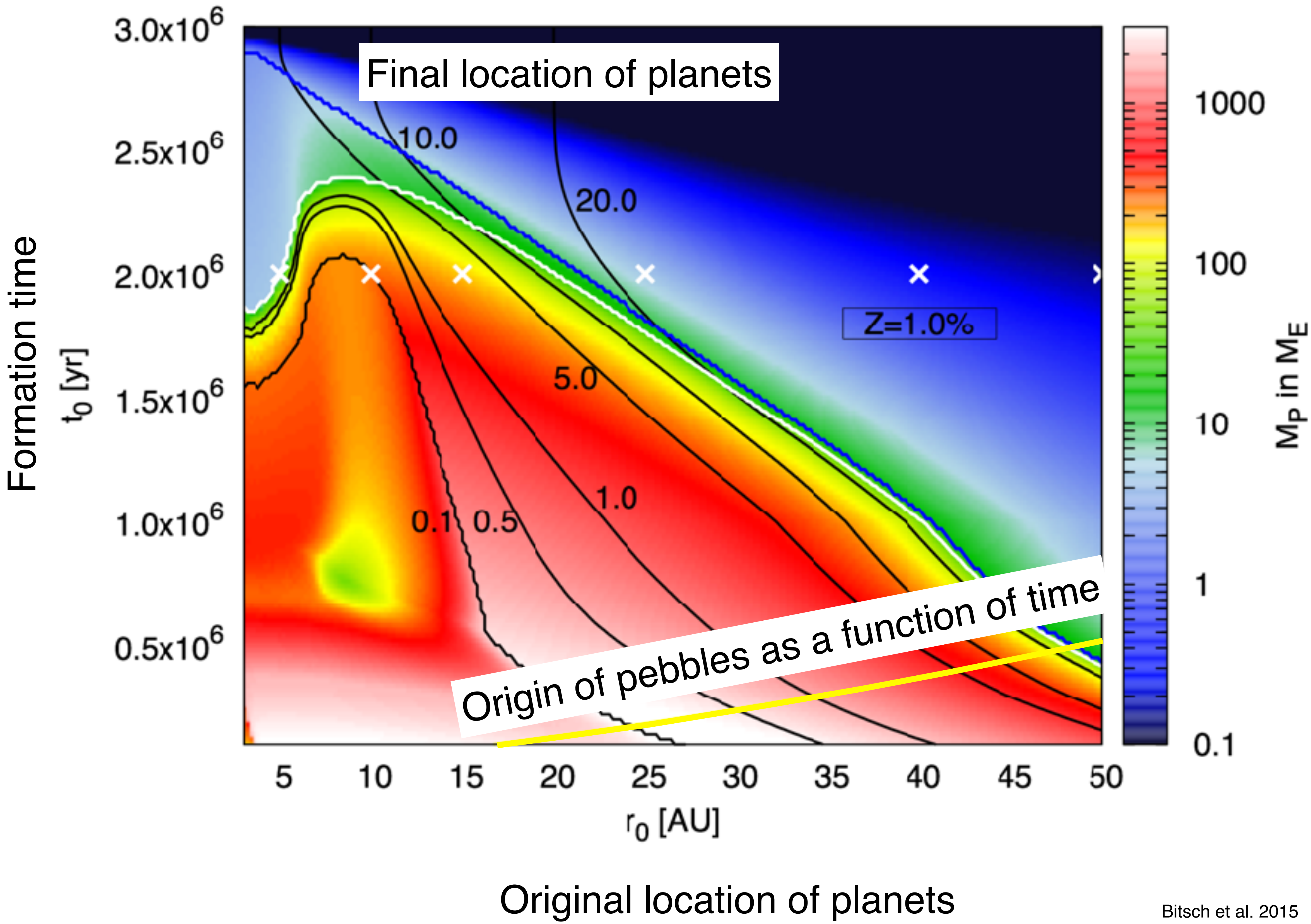
1- protoplanetary disk evolution

2- **no** planet internal structure

3- orbital migration

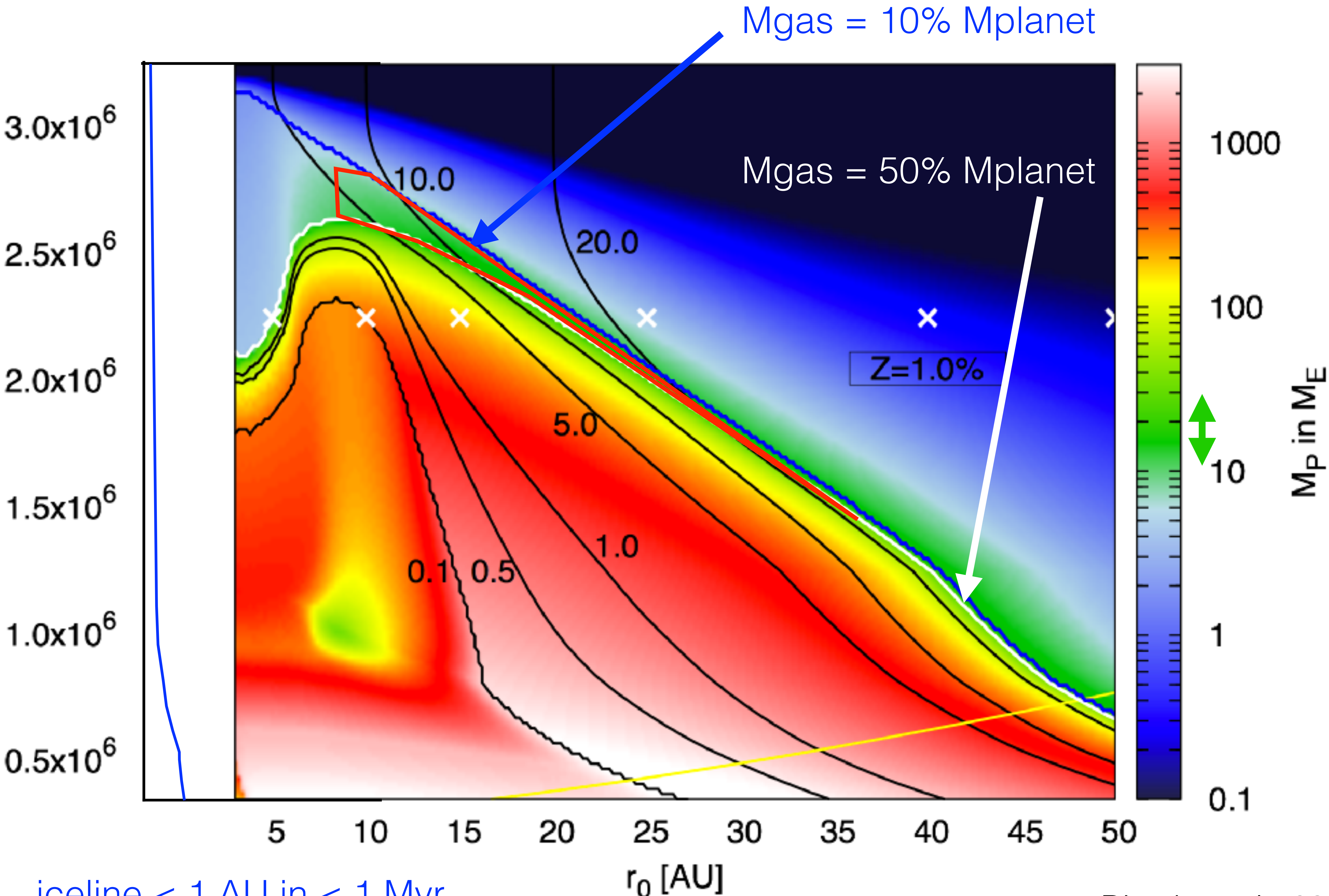
4- **no** planet-planet interactions (one planet per system)

Pebble-based model: rapid formation of planetary cores



Bitsch et al. 2015

Pebble-based model: few Neptune mass planets - no HN



iceline < 1 AU in < 1 Myr

Bitsch et al., 2015

Pebble based: sucesses and problems

1- No timescale problem (even *inversed* timescale problem)

2- All disks are observed with pebbles, but they should drift to the star and disappear very rapidly -> recycling process?

3- Formation of Neptune planets very unlikely - *no* Hot Neptunes

-> are they all formed by collision of smaller planets?

-> rotation axis of exo-Neptunes?

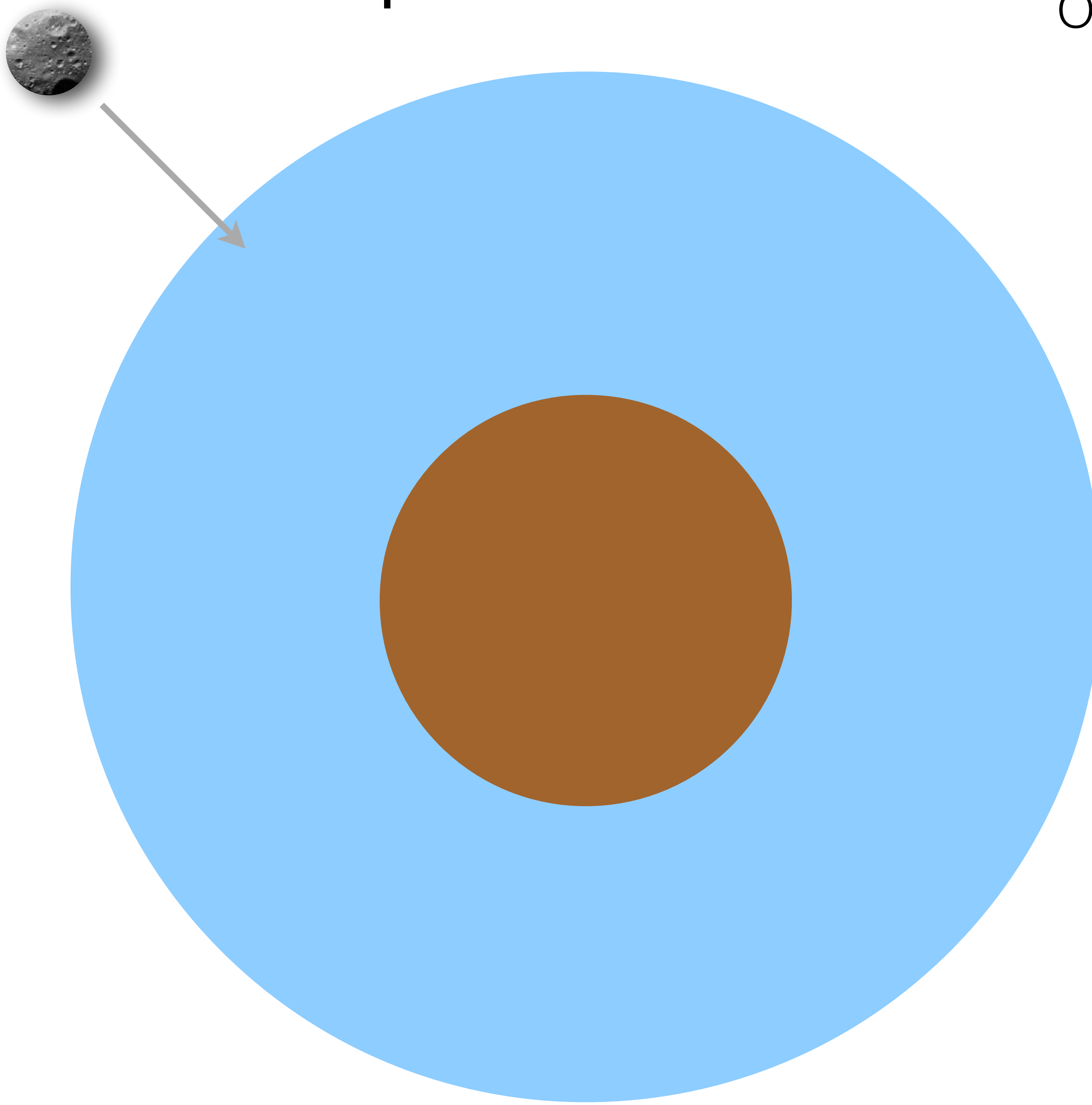
4- Pebbles are destroyed in the planetary envelope

Maximum mass of planets formed by pebble accretion

Alibert,astroph-1705.06008

Ormel et al. 2015

accreted pebble

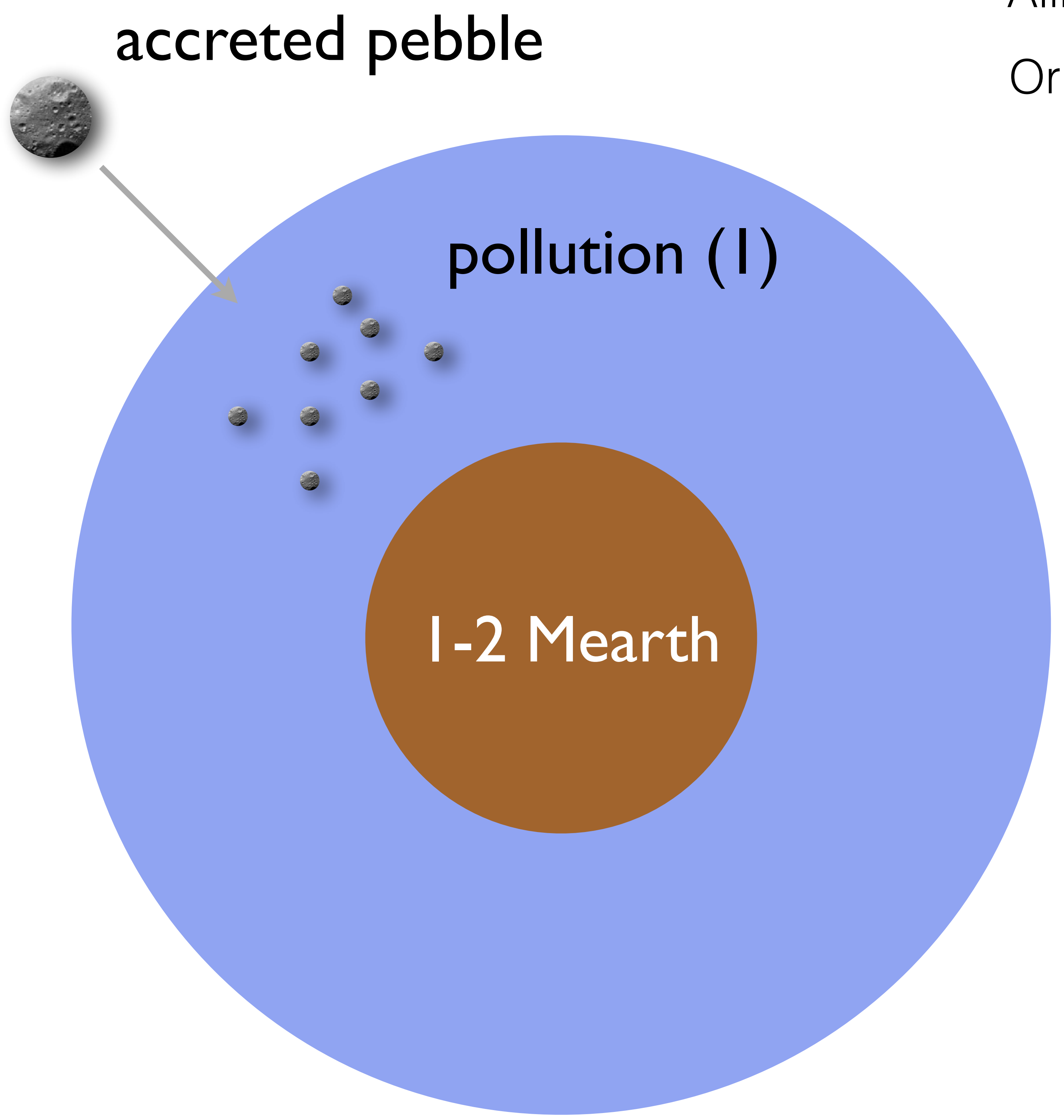


-> accreted pebbles interact with the envelope (gas drag)

Maximum mass of planets formed by pebble accretion

Alibert,astroph-1705.06008

Ormel et al. 2015

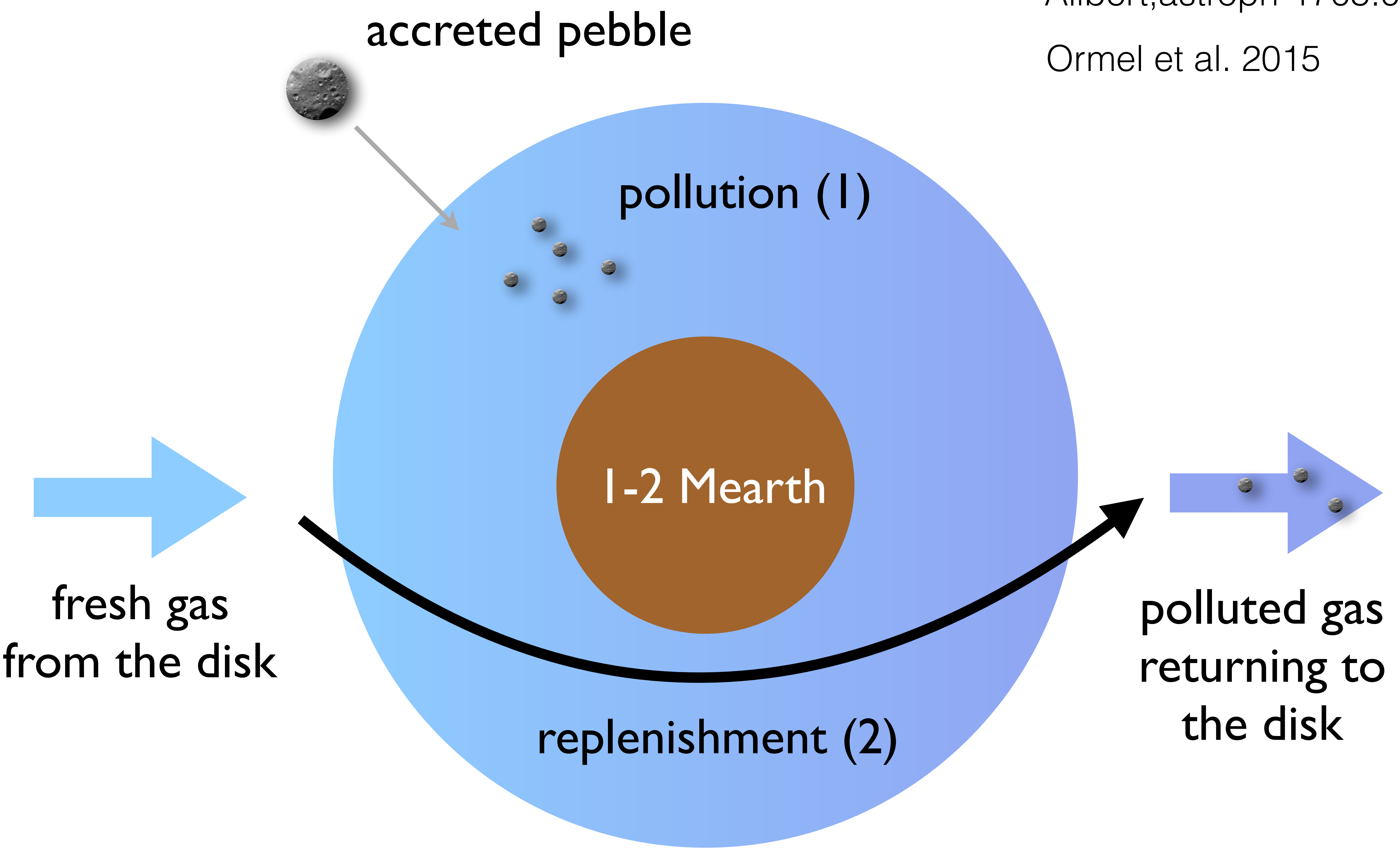


-> heavy material is dispersed and vaporized in the envelope
and *does not reach the core*

Maximum mass of planets formed by pebble accretion

Alibert, astroph-1705.06008

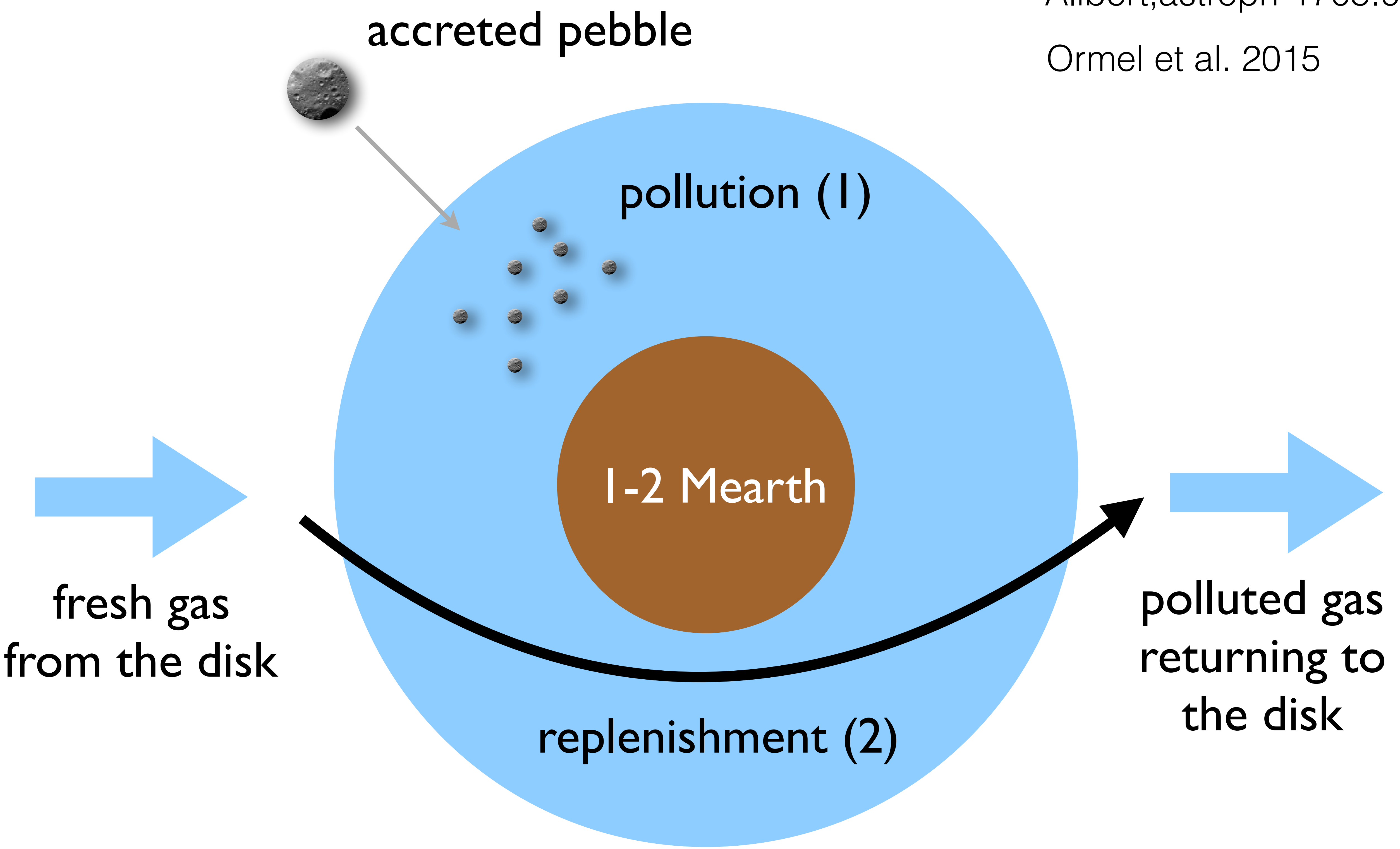
Ormel et al. 2015



Maximum mass of planets formed by pebble accretion

Alibert,astroph-1705.06008

Ormel et al. 2015



gas remains unpolluted if (2) is more rapid than (1), i.e. inside ~ 10 AU

Maximum mass of planets formed by pebble accretion

During core growth by pebble accretion, when the core is larger than ~ 1-2 Mearth:

-> heavy material is dispersed and vaporized in the envelope and ***does not reach the core***

-> the heavy elements ***cannot accumulate*** in the envelope because of mass exchange with the disk, inside ~10 AU

-> the total mass of heavy elements is limited to 1-2 Mearth

-> the planet ***cannot accrete gas*** because it is too small

heavy material cannot accumulate neither in the core nor in the envelope, gas cannot be accreted, the planetary growth stops at ~ 1-2 Mearth

-> no planet larger than ~1-2 Mearth can form directly by pebble accretion inside ~10 AU

Conclusions

Do not mix integrated models and population synthesis

1- integrated models = stellar evolution models

2- population synthesis = compute HR diagram

Population synthesis model can be used for:

1- get global picture of planetary formation

2- understand/predict planet statistics from different observation means

Population synthesis models require the knowledge of the bias - 'blind' observations better to avoir the 'observer bias'

Microlensing observations constraint a part of the aM diagram that is not probed by other means $\Rightarrow$ strong constraint on models