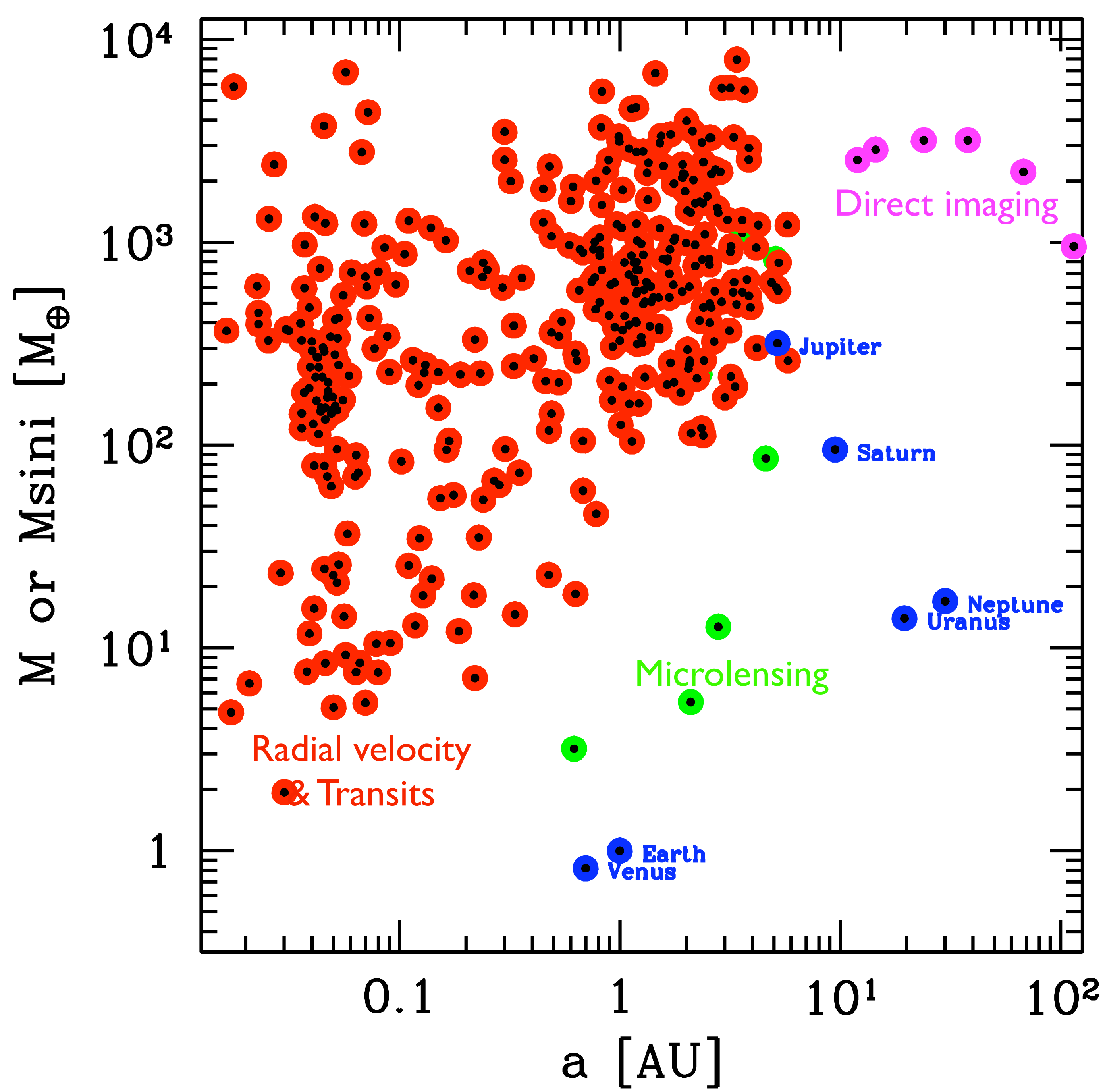
Architecture of planetary systems 0.1-100 AU

Christoph Mordasini

Fellow of the A. v. Humboldt Foundation

Flagstaff, 5.5.2011



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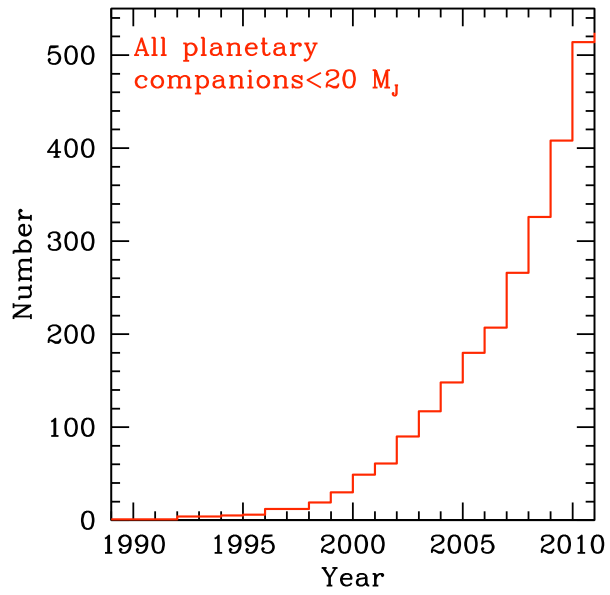
A new situation



and 1235 KEPLER candidates

- Phase of major change in exoplanet research.
- Incredible wealth of data provided by already flying space mission (e.g. CoRoT and Kepler). More to come (e.g. Gaia, PLATO).
- Field observationally driven. Formation theory struggles to keep up... Observation and theory often don't match well.
- Common characteristic: provide observations of a large number of exoplanets. This data should therefore be treated as a statistical ensemble. This could help.

Architectures of planetary systems

- Extrasolar planets exhibit a very large diversity (all techniques).
- Frequencies
  - -Low mass close-in planets: approx. 30 % (radial velocity)
  - -Jovian planets inside a few AU: approx. 10 % (rv)
  - -Hot Jupiters: 0.5-1% (rv, transits)
  - -Cold Neptunes are common (microlensing)
- The mass function is strongly rising towards small masses. There might be local minimum in the planetary mass function around 30-100 M_{earth} (rv).
- The radius distribution is strongly increasing towards small radii (transits).
- The semimajor axis distribution of giant planets consists of a pile up at a period of about 3 days, a period valley, and an upturn at about 1 AU. (rv)
- Close-in low mass (or small radius) planets are found somewhat further out than Hot Jupiters (rv, transits).
- Hot Jupiters are lonely (rv, transits).
- Low mass close-in planets are in multiple systems (rv, transits).
- Massive giants planets at large distances are rare, at least around solar like stars (direct imaging).
- Giant planet frequency and host star [Fe/H] are positively correlated.

Architectures of planetary systems

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✴ The radius distri...).

✴ The se... up at a period of ab... (rv)

✴ ... somewhat further out than Hot J...

✴ Ho...

✴ Low ... in multiple systems (rv, transits).

✴ Massive ... at large distances are rare, at least around solar like stars (direct imag...

✴ Giant planet frequency and host star [Fe/H] are positively correlated.

Today, formation theory cannot explain all these observed characteristics in one coherent picture.
But at least for some observations, theory can give us ideas about possible mechanisms responsible for them.

Talk structure

1. Planet formation model: core accretion

2. Planetary population synthesis to understand statistics

3. Architecture of planetary systems: selected points, moving from the star outwards.

4.1 ✳ The radius distribution is strongly increasing towards small radii (transits).

4.2 ✳ Close-in low mass (or small radius) planets are found somewhat further out than Hot Jupiters (rv, transits).

4.3 ✳ Low mass close-in planets are in multiple systems (rv, transits).

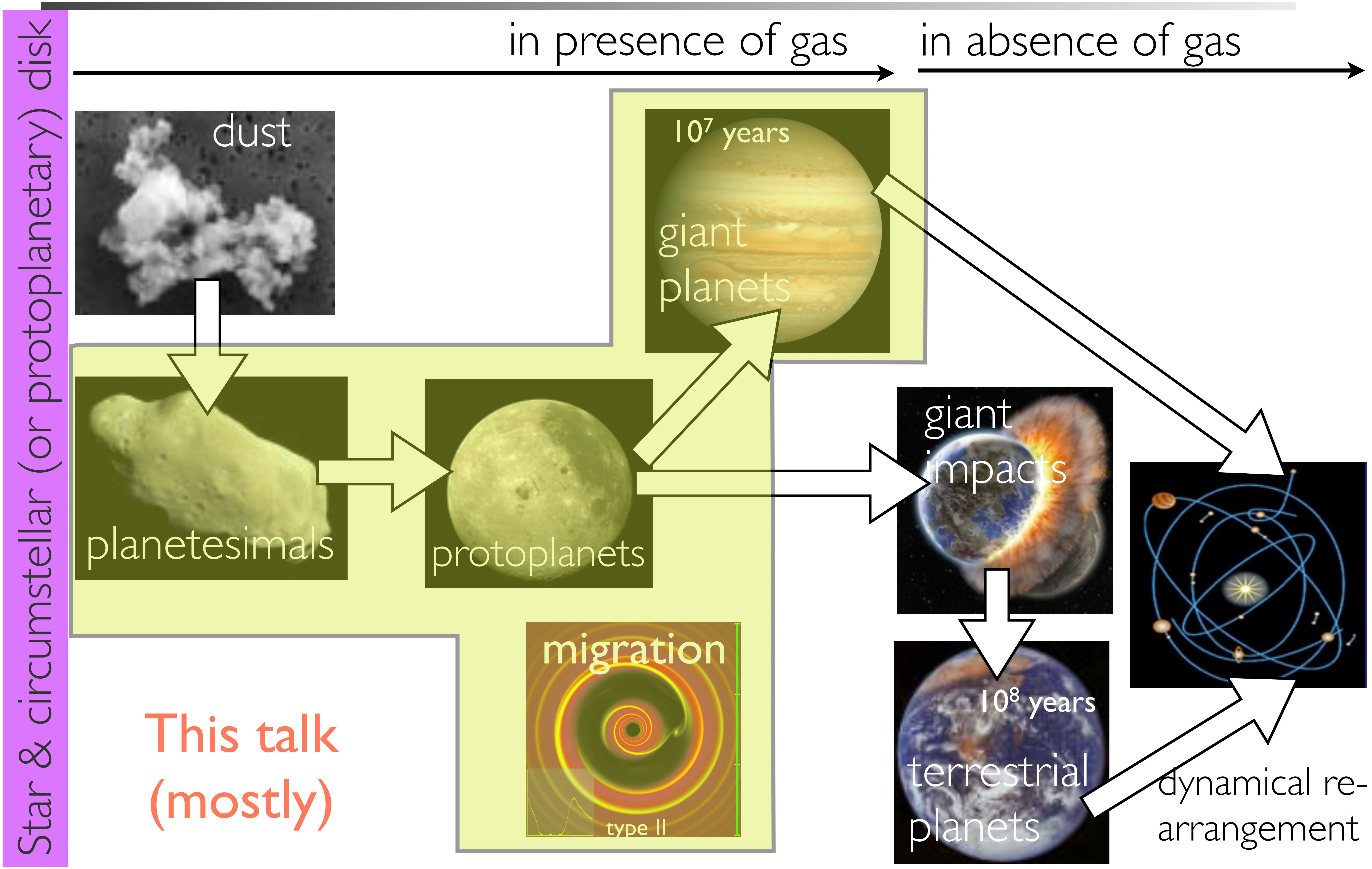
4.4 ✳ The semimajor axis distribution of giant planets consists of a pile up at a period of about 3 days, a period valley, and an upturn at about 1 AU. (rv)

4.5 ✳ Massive giants planets at large distances are rare, at least around solar like stars (direct imaging).

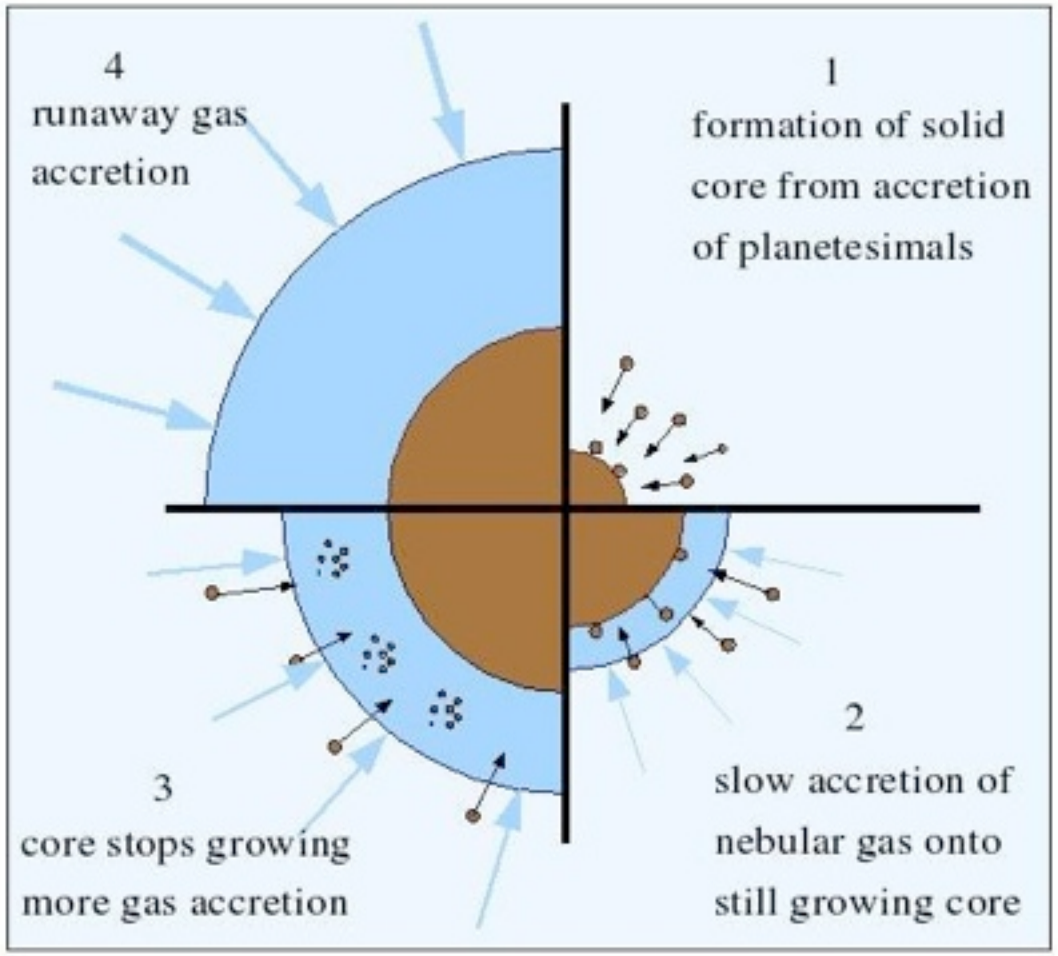
I Planet formation modelling:

Core accretion planet formation model

Planet Formation: stages



Core Accretion Paradigm



Perri & Cameron 1974, Mizuno et al. 1978, Mizuno 1980, Bodenheimer & Pollack 1986, Pollack et al. 1996

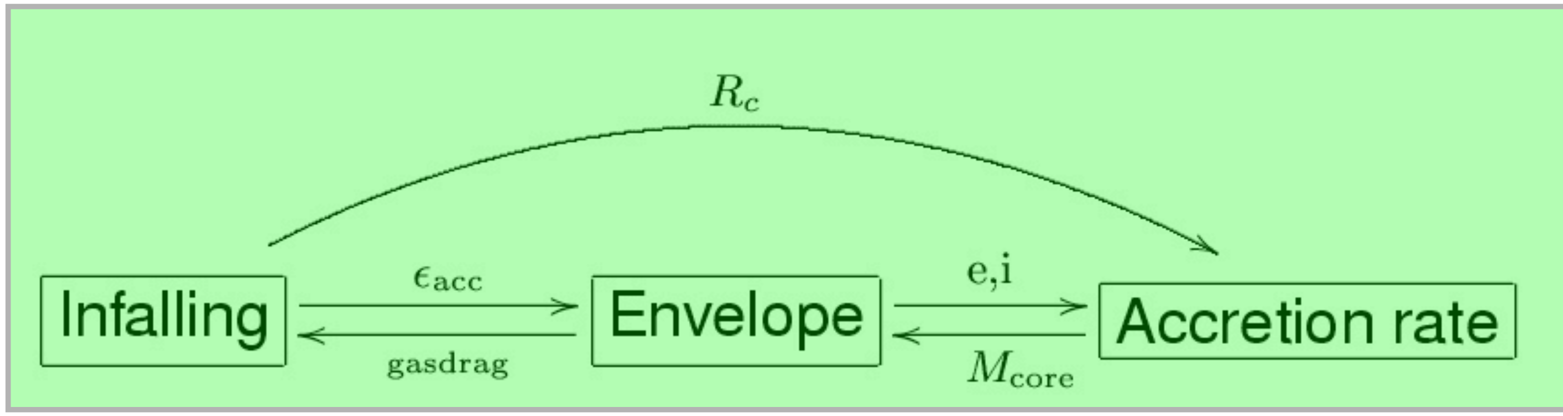
1)Build up critical core
2)Accrete gas

A timing issue!

Follow gas and solid accretion of an initially small solid core (ice, rock) surrounded by a gaseous envelope (H2 & He) in the protoplanetary disk consisting itself of gas and planetesimals.

Divide problem in three modules

- *Planetesimal accretion rate*
- *Gas accretion (envelope)*
- *Planetesimal-envelope interaction (infalling)*

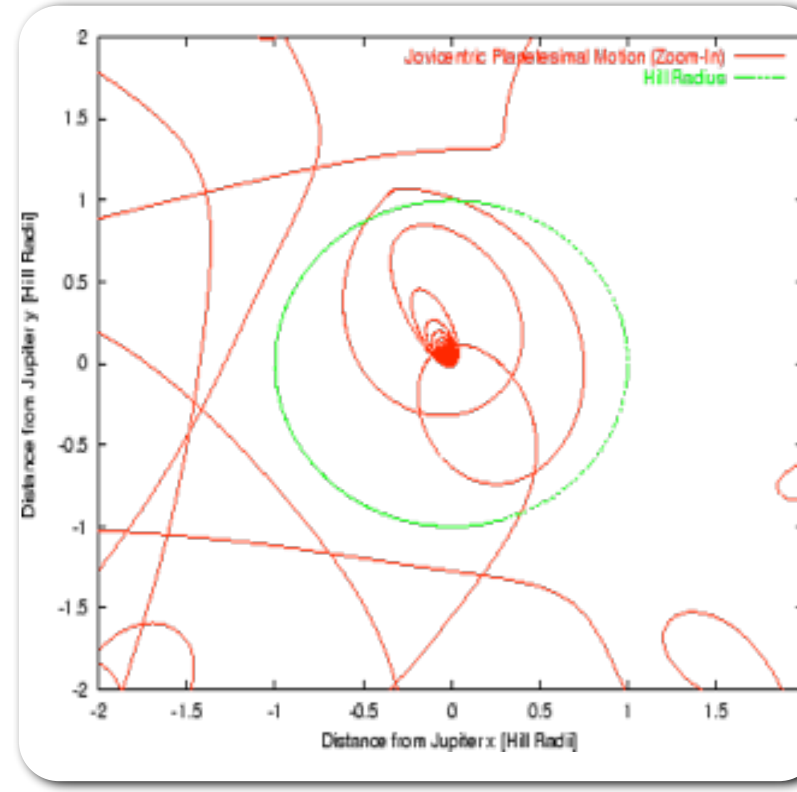


Accretion of *planetesimals*

- *Collisional growth of one big body from small background planetesimals (100 km)*
- *Safronov-type rate equation for* ***dM_Z/dt***

$$\frac{dM_Z}{dt} = \Omega \Sigma_p \pi R_{capt}^2 F_G(e,i)$$

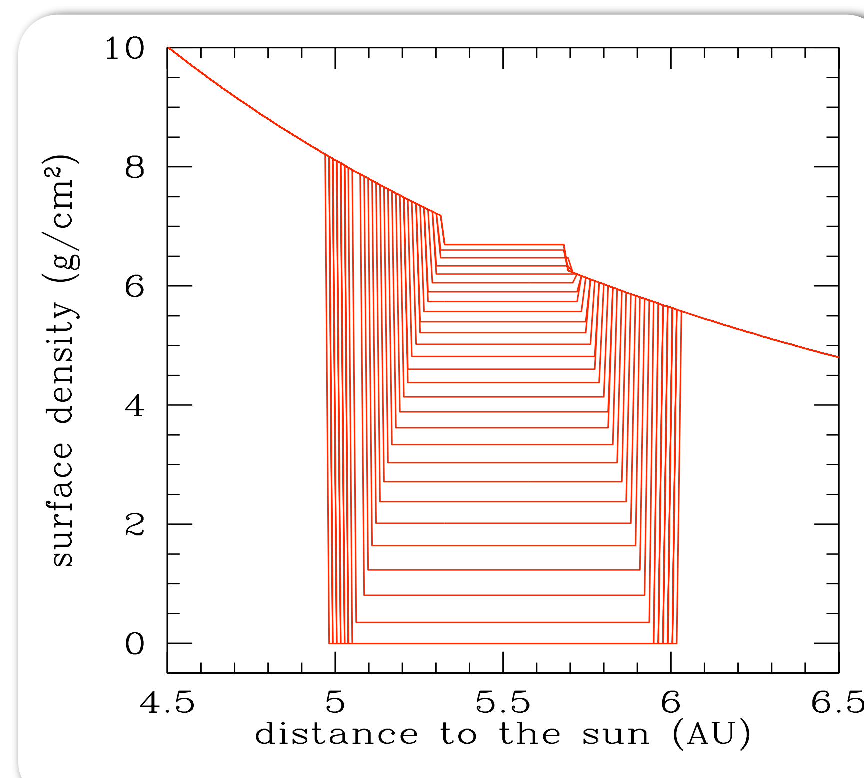
Safronov 1969, Ida & Nakazawa 1989, Greenzweig & Lissauer 1992, ..



- *Random velocity* ***σ(e,i)*** *of planetesimals is key parameter (runaway, oligarchic, orderly)*

- *Accretion from a feeding zone with spatially constant planetesimal surface density* ***Σ_P***

$$\frac{d\Sigma_P}{dt} = -\frac{(3M_\star)^{1/3}}{6\pi a^2 B_L M^{1/3}} \frac{dM_Z}{dt}$$



e,g, Thommes et al. 2003

Gas accretion

- 1-D structure equations (similar to stellar structure, e.g. Bodenheimer & Pollack 1986)

$$\frac{dm}{dr} = 4\pi r^2 \rho \qquad \frac{dP}{dr} = -\frac{Gm}{r^2}\rho$$

$$\frac{dl}{dr} = 4\pi r^2 \rho \left(\epsilon - T\frac{\partial S}{\partial t}\right) \qquad \frac{dT}{dr} = \frac{T}{P}\frac{dP}{dr}\nabla$$

Mass conservation
Hydrostat. equilibrium
Energy conservation
Energy transport

$$\nabla = \frac{d\ln T}{d\ln P} = \min(\nabla_{\rm ad}, \nabla_{\rm rad}) \qquad \nabla_{\rm rad} = \frac{3}{64\pi\sigma G}\frac{\kappa l P}{T^4 m}$$

Additional energy source: impacting planetesimals

Gas accretion rate given by ability to radiate away energy (T_{KH})

- *Accretion rate in the disk*

  (flow of gas usually towards the star)

$$\dot{M}_{disk} = 3\pi\tilde{\nu}\Sigma + 6\pi r\frac{\partial \tilde{\nu}\Sigma}{\partial r}$$

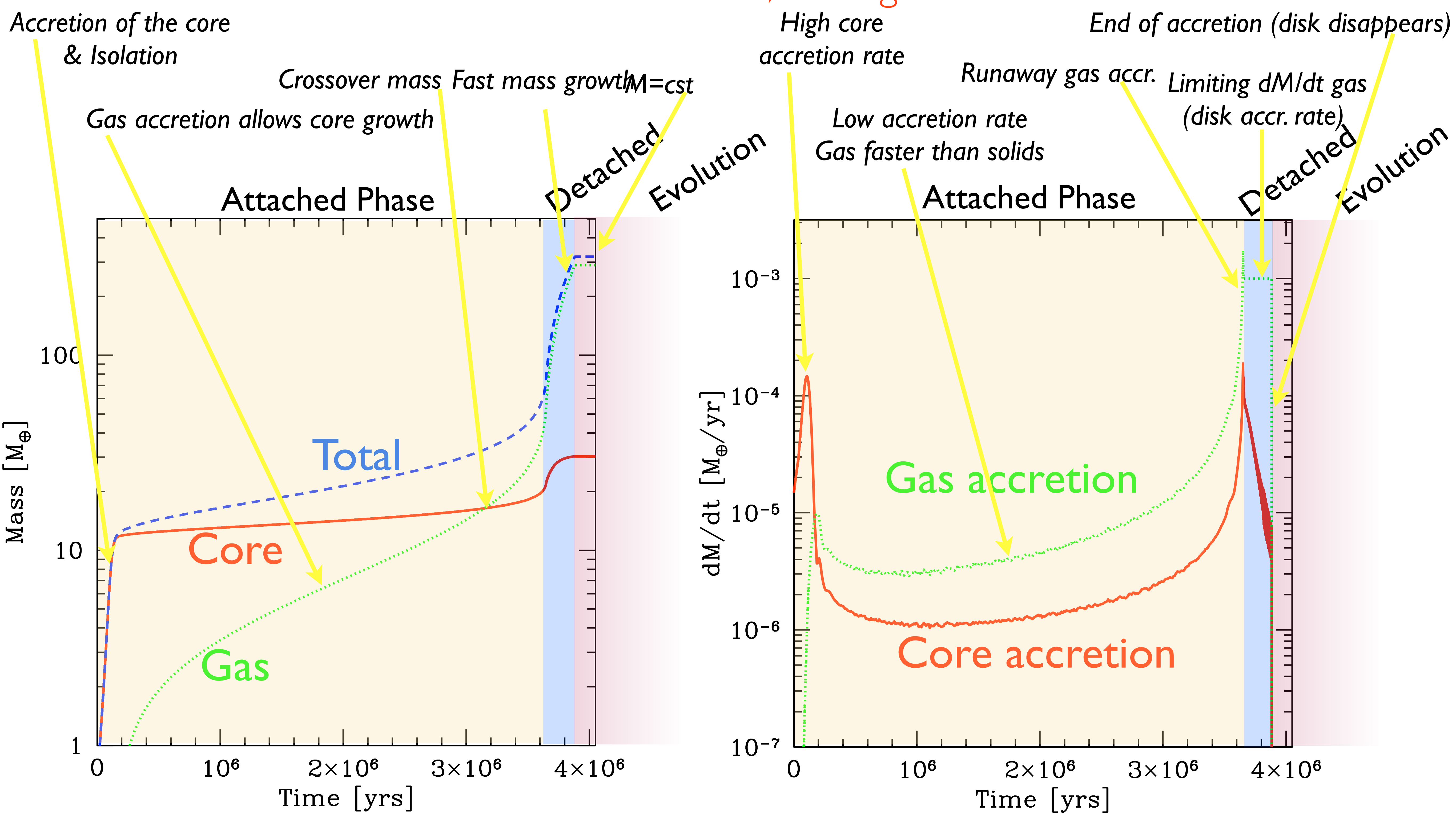
- *Planet cannot accrete more than disk gives*

$$\frac{dM_{XY}}{dt} = Min\left[\frac{dM_{struct}}{dt}, k_{\rm Lub}\dot{M}_{disk}\right]$$

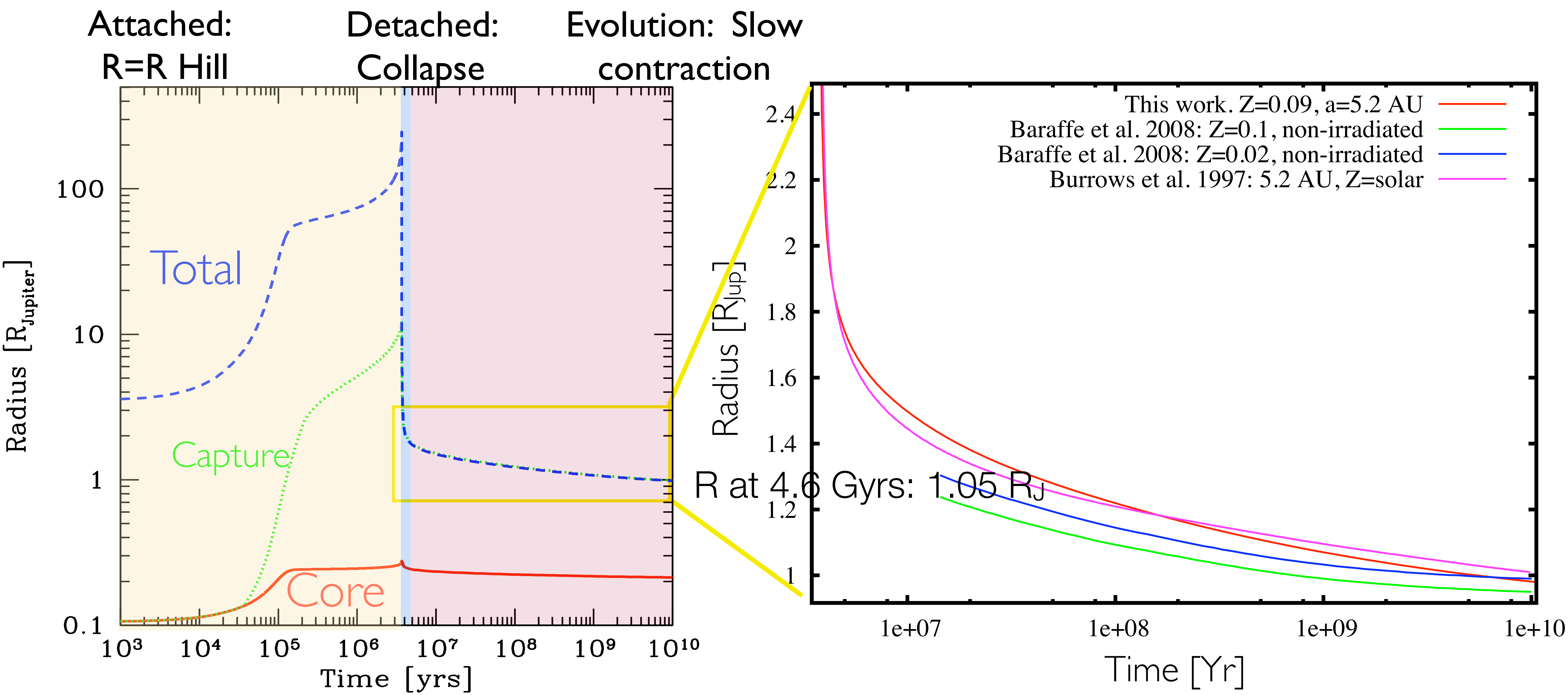
Example: Jupiter *in situ* formation I

Initial contions: 4 x MMSN, 2% grain opacity, 5.2 AU (cf. Pollack et al. 1996)

No disk evolution, no migration

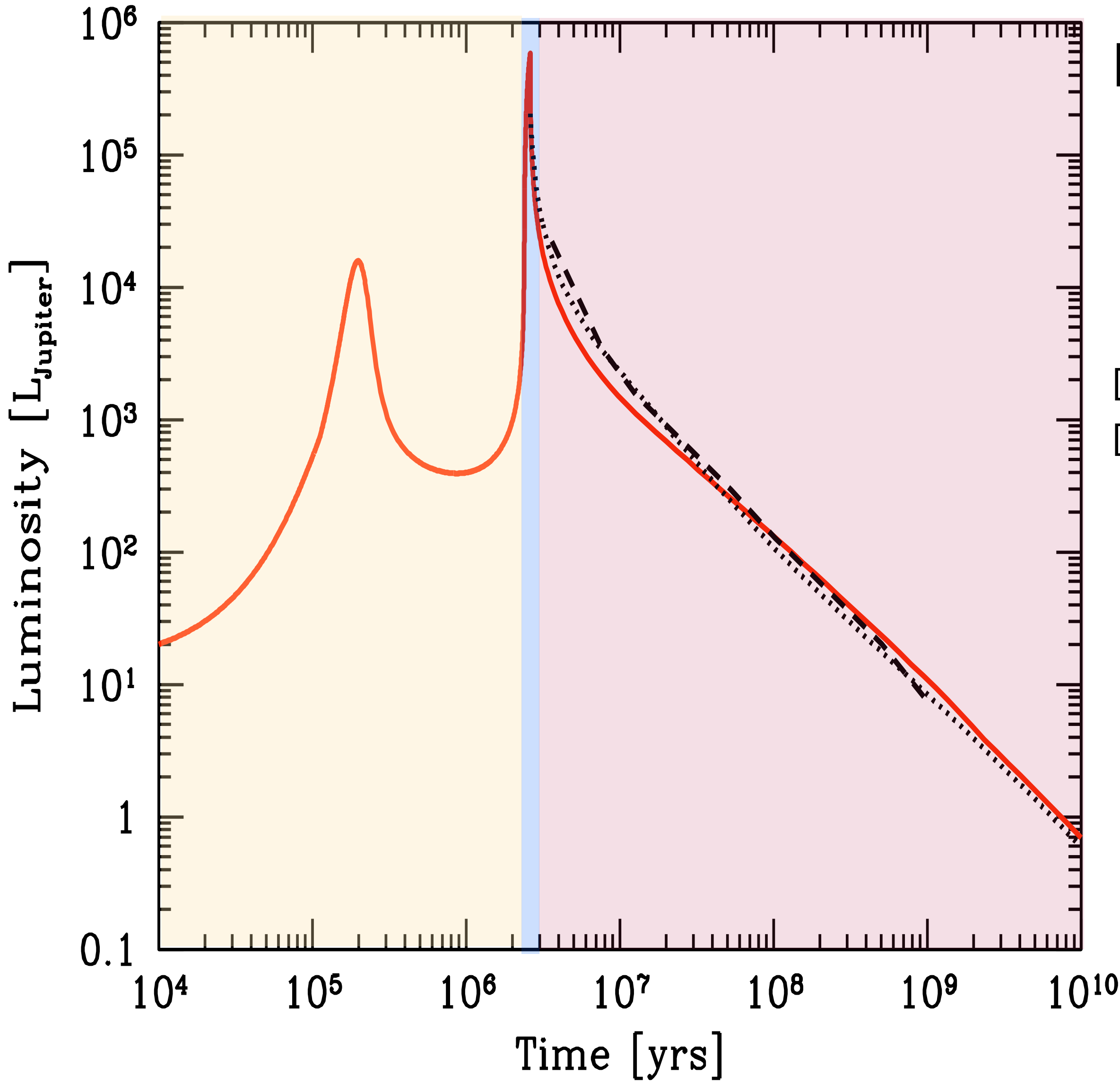


Jupiter in situ formation II: Radius



- Attached & detached (collapse) phase: Very similar to Lissauer et al. 2009 & Broeg et al. in prep.
- Long term evolution of radii agree to typically 10 % compared to more complex Baraffe et al. or Burrows et al. models which have e.g. non-gray boundary conditions.

Jupiter in situ formation III: Luminosity



L_{max} ca 5×10^{-4} L_{sun}

Dotted: Burrows et al. 97
Dashed: Baraffe et al. 03

L at 4.6 Gyrs: 1.8 L_J
M_{tot}: 320 M_{Earth}
M_Z: 31 M_{Earth}
T_{eff}: 133 K
T_{cent}: 17300 K
Mean core density: 12.1 g/cm^2

Model planet fullfils the most important observational constraints

- Agreement for luminosities of factor ca. 2 during long term evolution compared to Baraffe et al. or Burrows et al. models. Differences at early times (hot vs cold start).

1 b *Planet formation modelling:*
Extended Core accretion planet formation models

Extended model

Similar timescales of various processes:

$\tau_{migration} \leq \tau_{formation} \approx \tau_{disk\ evolution}$

→ *extend model to include in a self consistent way (Alibert, Mordasini, Benz 2004)*

1) *disk evolution*

(1+1 D) **α***-disk with photoevaporation + irradiation (Papaloizou & Terquem 1999, Chiang & Goldreich 1997, Matsuyama et al. 2003, Clarke et al. 2001)*

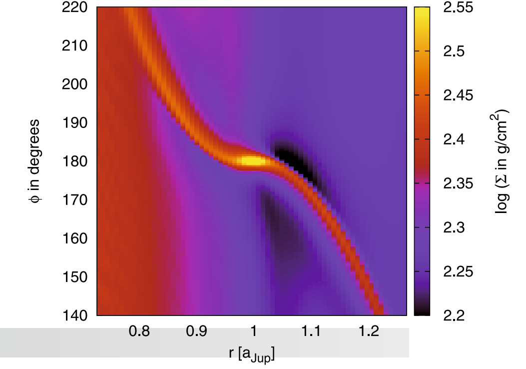
2) *type I and type II planetary migration*

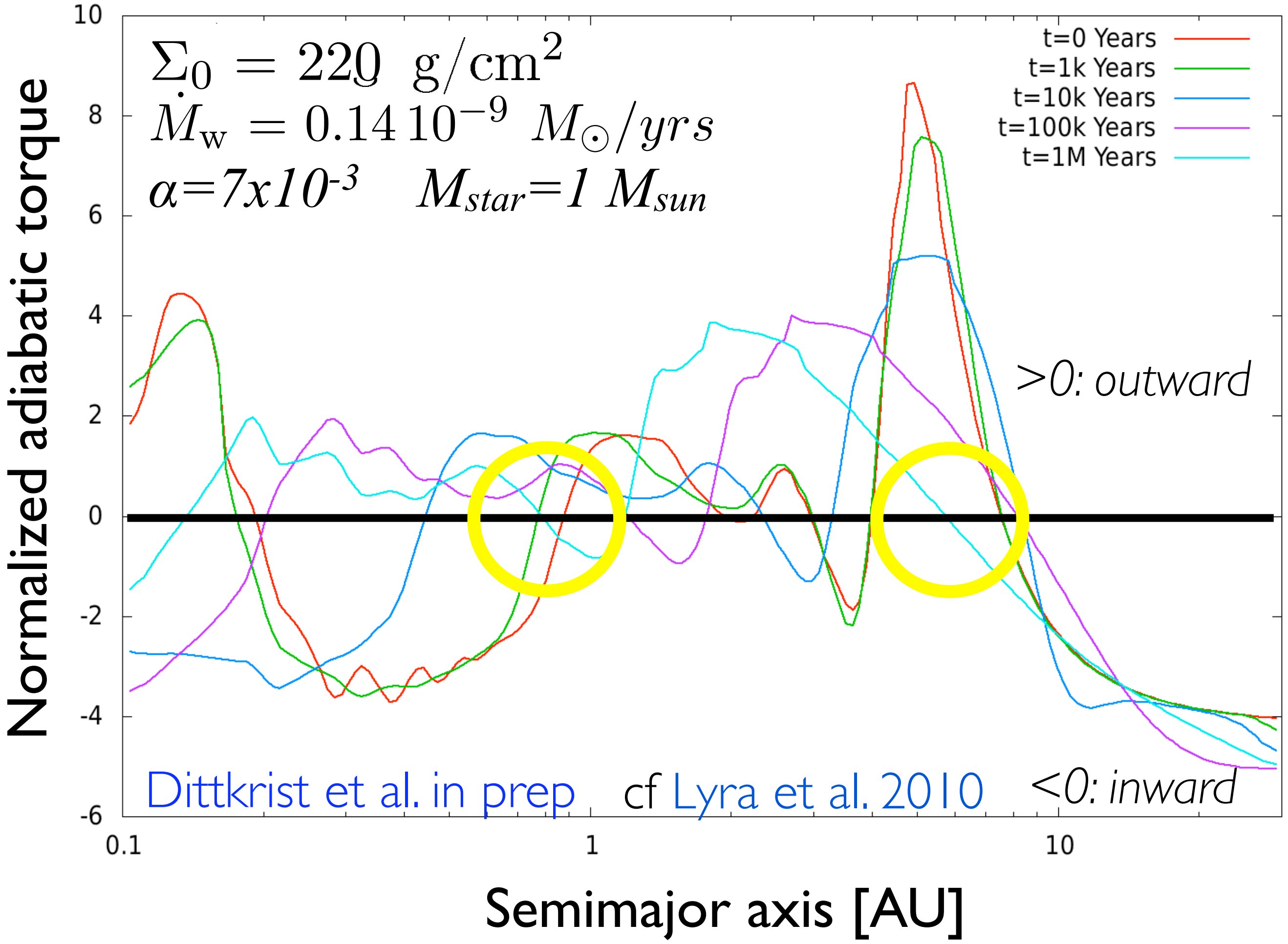
(Lin & Papaloizou 86; Tanaka et al. 02). Isothermal Type I reduced by constant factor f_1 (free parameter). Updated recently (Paardekooper et al 2010, Dittkrist et al in prep).

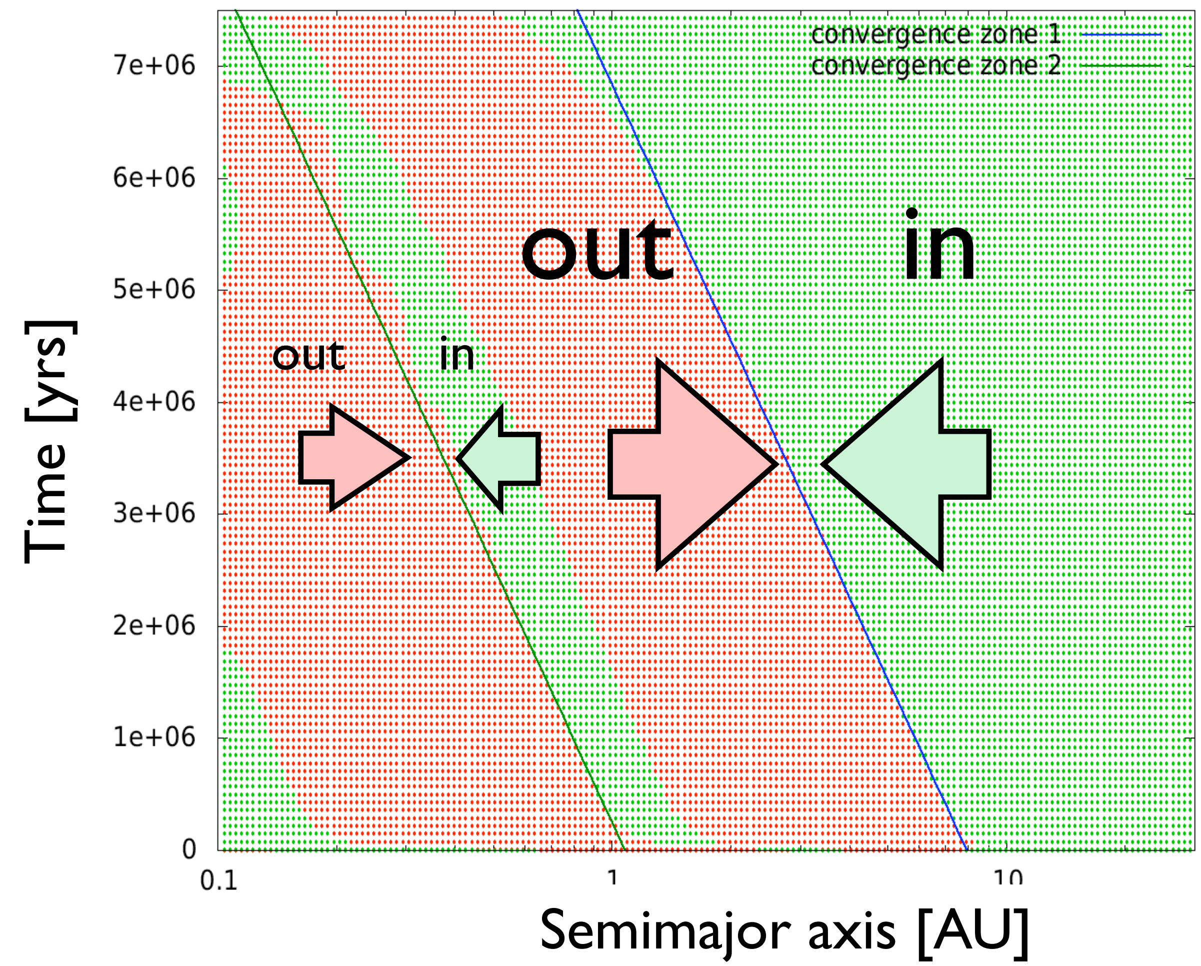
Simplifications (most important)

- *One embryo per disk, no systems (work in progress)*
- *Accretion only until the gas disk disappears: No mass growth/loss after disk dispersal (Terrestrial planets, Ice giants, evaporating planets) Work in progress.*
- *No eccentricity, planets on circular orbits. Work in progress.*
- *No particular stopping mechanism, a_{min}=0.1 AU. Work in progress, too.*

Convergence zones

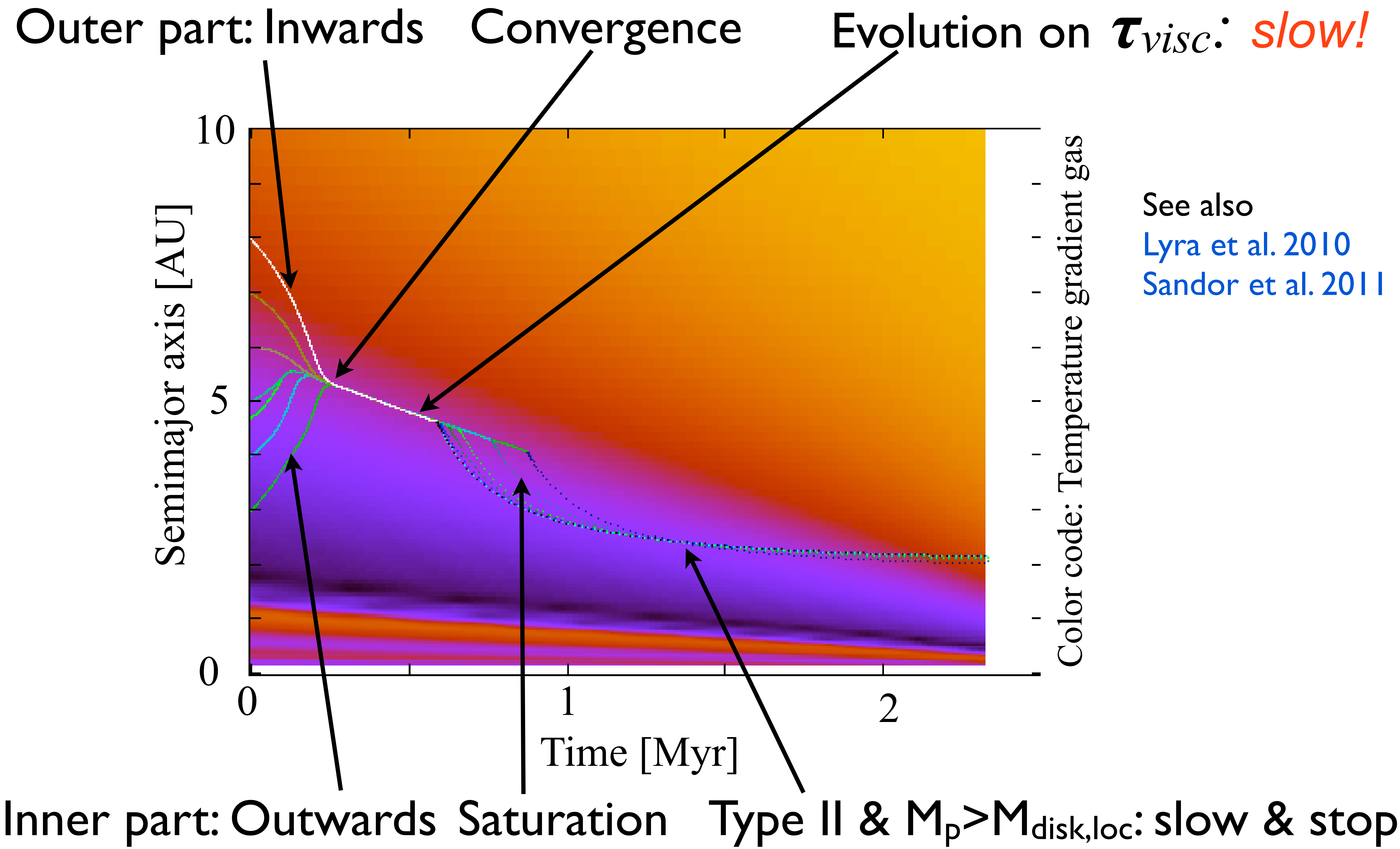






- Original Type I migration (linear, isothermal, Tanaka et al. 2002) so fast that many embryos fall into star.
- Recent progress in type I modeling: different sub-regimes (isothermal, adiabatic, saturation). In & outward migration. Paardekooper et al. 2010, Kley, Bitsch, Klahr 2009...
- Set up semi-analytical model based on these results. Regimes found by timescale arguments.
- Migration in alpha disk model. Opacity transitions lead to changes in the radial slopes of Σ and T.
- Therefore, special zones, with zero torque, and dΓ/dr<0: Migration trap.
- All protoplanets migrate towards these convergence zones. Two zones.
- Several AU wide. Concentrate a lot of matter. Birth place of massive cores?
- Converge zones themselves move inwards on a viscous timescale.

Convergent migration



See also
Lyra et al. 2010
Sandor et al. 2011

Concentrating all matter in one place

Isn't that *crazy*? Well:

2009 **Formation of the Terrestrial Planets from a Narrow Annulus**

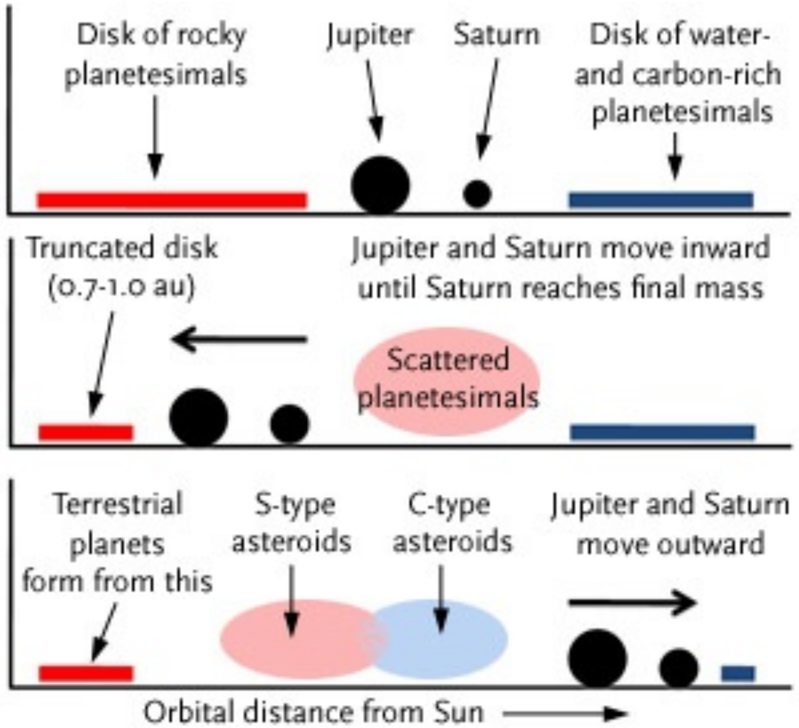
Brad M. S. Hansen[1]

ABSTRACT

We show that the assembly of the Solar System terrestrial planets can be successfully modelled with all of the mass initially confined to a narrow annulus between 0.7 and 1.0 AU. With this configuration, analogues of Mercury and Mars

Remember also "Jupiter's Grand Tack" down to 1.5 AU, also truncating the disk. (Hal Levisson's talk on Monday)

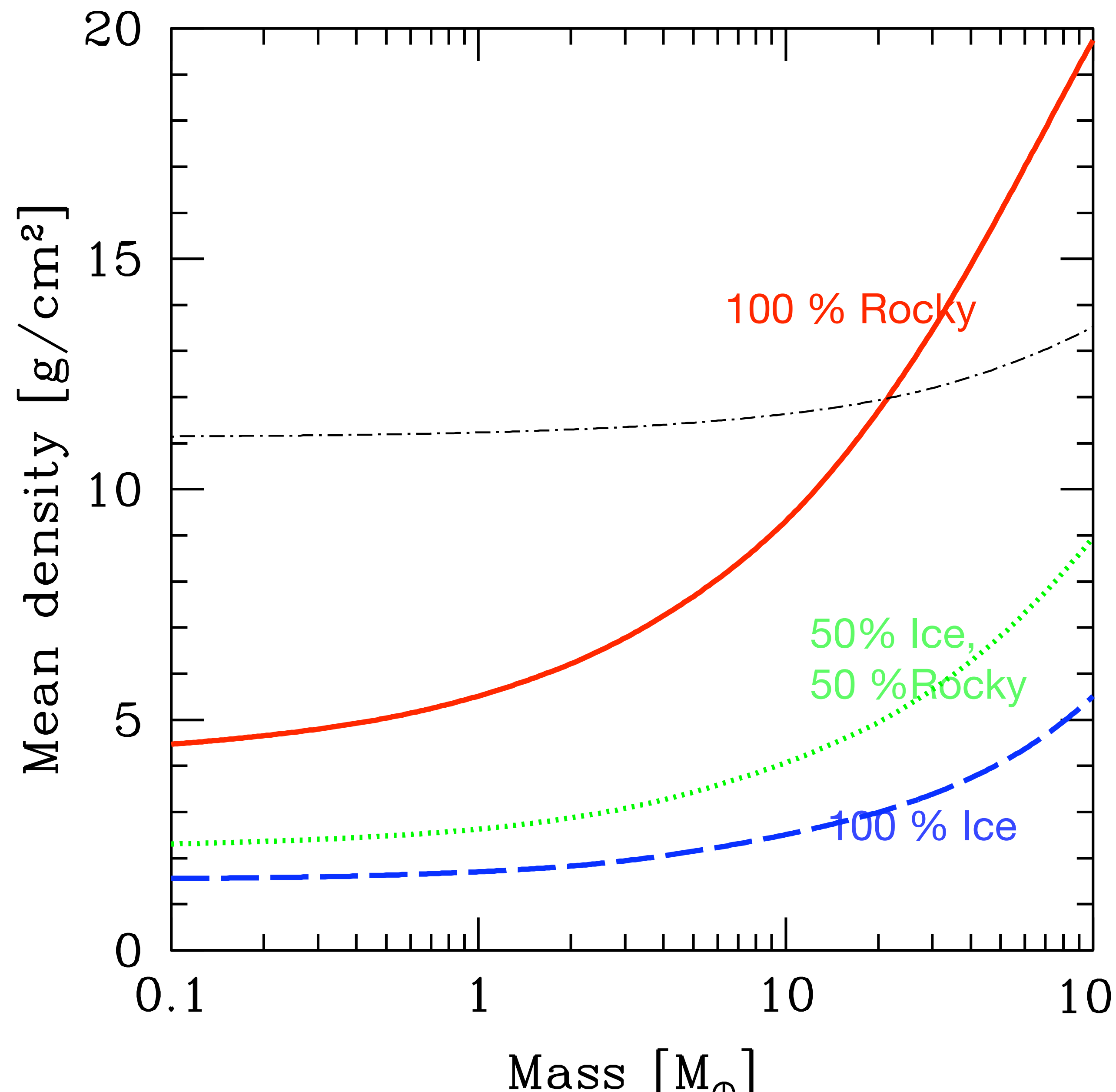
But it also makes clear that the dynamical rearrangement phase must be included...



Radii for the solid core

- Formation models (Bodenheimer, Alibert..) typically assume inert core with constant density (3.2 g/cm^3).
- Replaced with internal structure model for the core
- Three layer differentiated planet model (iron&nickel, silicates, ices).
- Ice fraction: from formation model (accretion in or outside ice line).
- Include effect of external pressure on the surface (giant planets), $R(M, P_{ext}, f_{ice})$

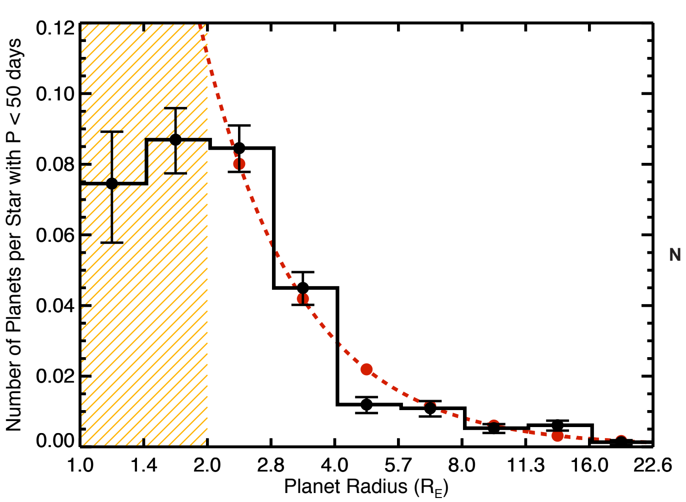
External pressures P_{ext}=0

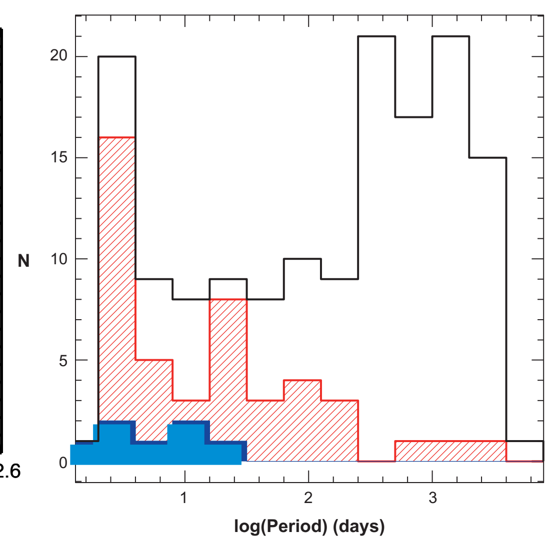


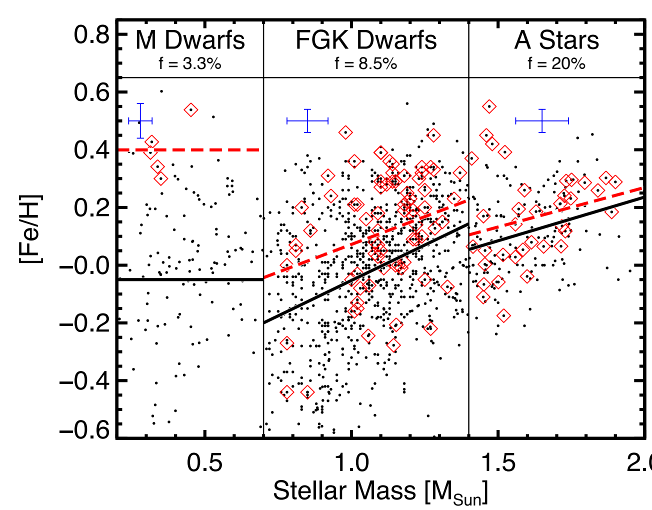
Dash-dotted line: Jupiter core conditions today with 75% ice, 25% rocky and P_{ext}=4000 GPa

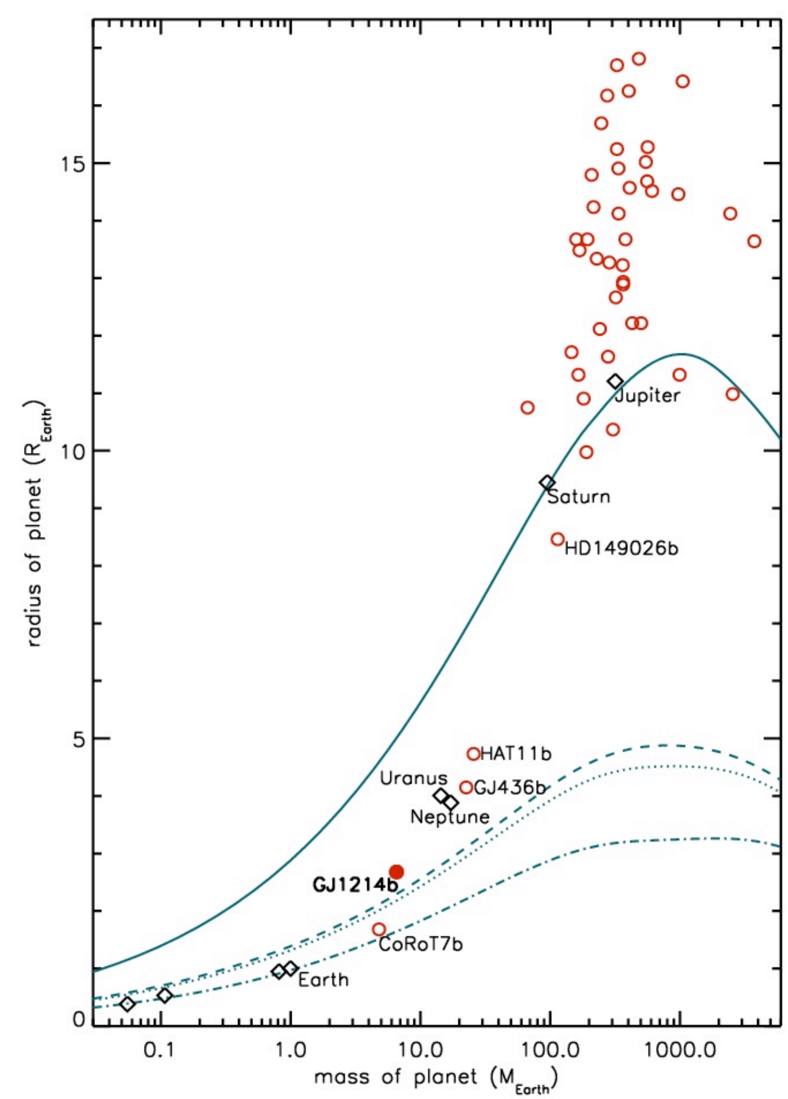
See Seager et al. 2007, Fortney et al. 2007, Valencia et al. 2006-2011

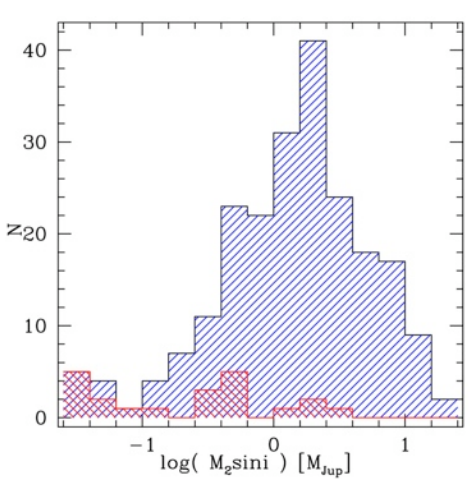
3 *Planetary population synthesis* or *How to deal with statistical information*

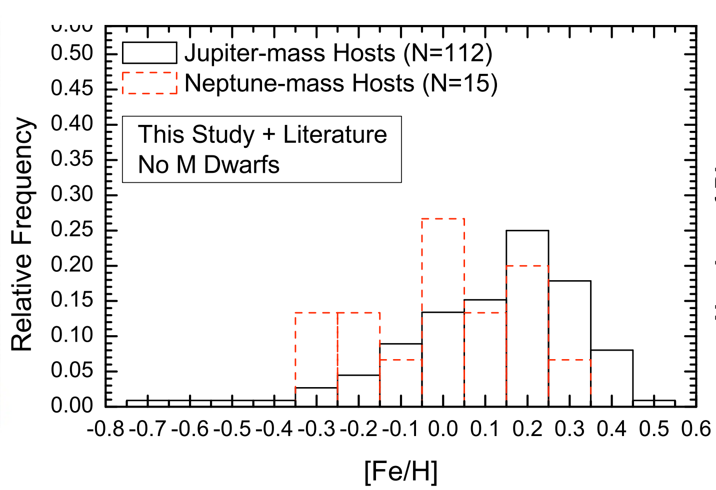


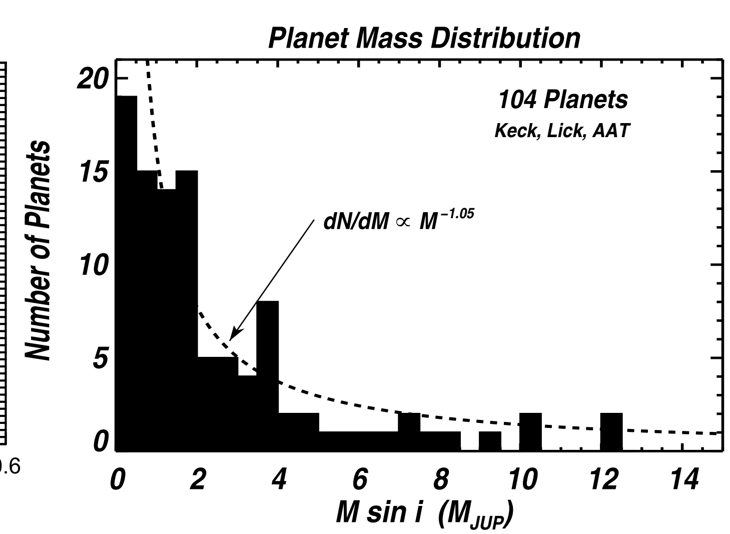












Marcy et al. 2005, Udry & Santos 2007, Charbonneau et al. 2009, Howard et al. 2011, Ghezzi et al. 2010, Johnson et al. 2010

The essence of population synthesis

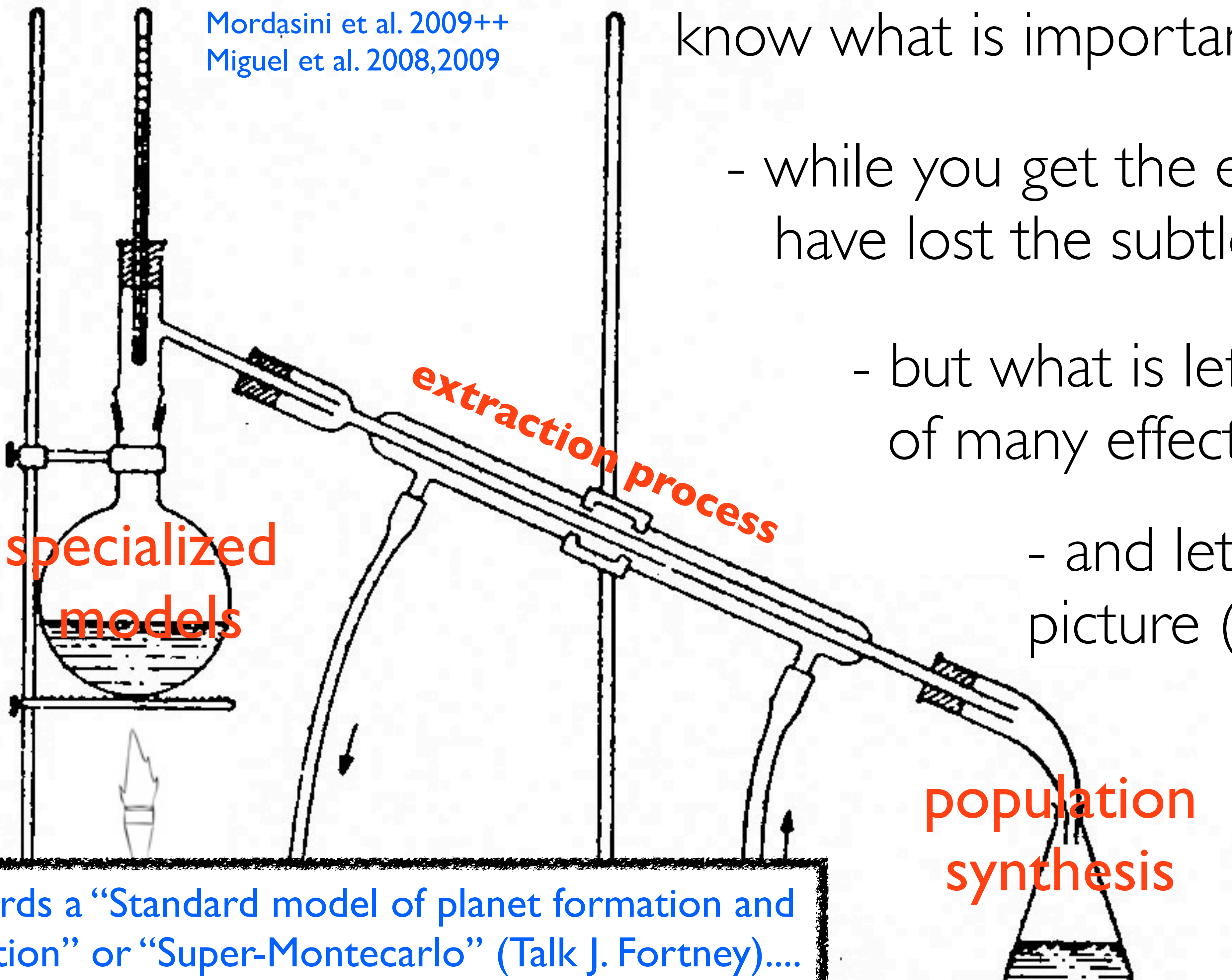
Ida & Lin 2004++
Thomes et al. 2008
Mordasini et al. 2009++
Miguel et al. 2008,2009

- you need specialized models to know what is important

- while you get the essence, you have lost the subtlety of the original

- but what is left is a concentrate of many effects

- and lets you see the big picture (hopefully)



Run the formation model with many different initial conditions

Towards a "Standard model of planet formation and evolution" or "Super-Montecarlo" (Talk J. Fortney)....

Population Synthesis Principle

Formation model

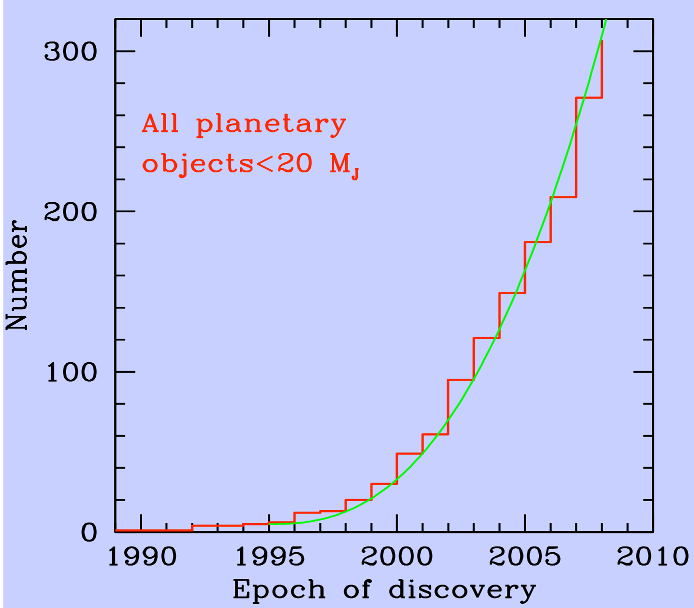
Initial Conditions: Probability distributions & parameters

Disk gas mass
Disk dust mass
Disk lifetime

From observations

Draw and compute synthetic planet population

Apply observational detection bias



Observed population

Comparison:

Observable sub-population
- Distribution of semi-major axis
- Distribution of masses
- Fraction of hot/cold Jupiters
- Distribution of radii

No match: improve, change parameters

Match

Model solution found!

Predictions
(going back to the full synthetic population)

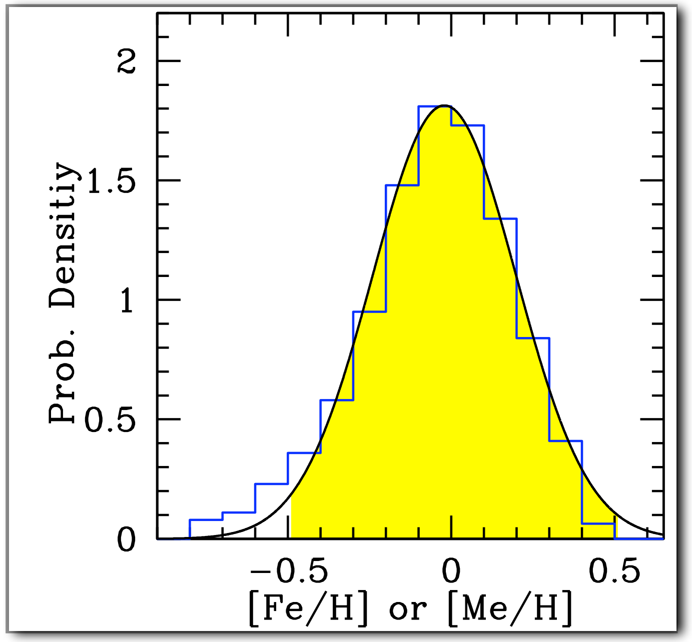
Mordasini et al. 2009a
Mordasini et al. 2009b

Constraints on the initial conditions

1 Metallicity

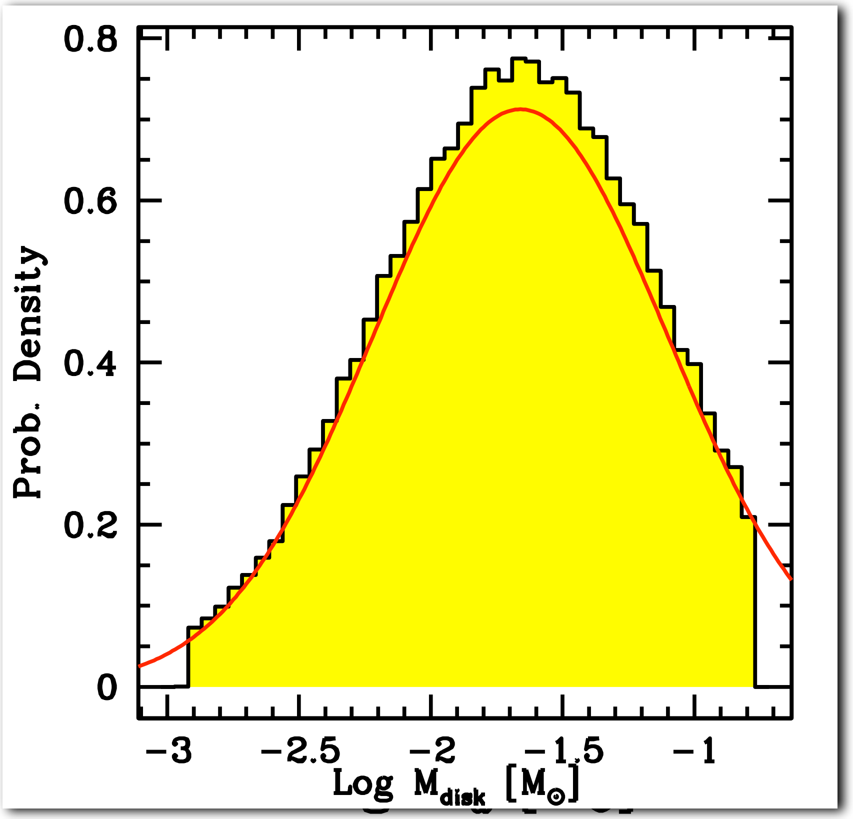
assume same in star and disk

Stellar [Fe/H] from spectroscopy. Gaussian distribution for [Fe/H] with μ ~0.0, σ~ 0.2. (e.g. Santos et al. 2003)



2 Disk (gas) masses

Thermal continuum emission from cold dust at mm and submm wavelengths (Ophiuchus nebula).



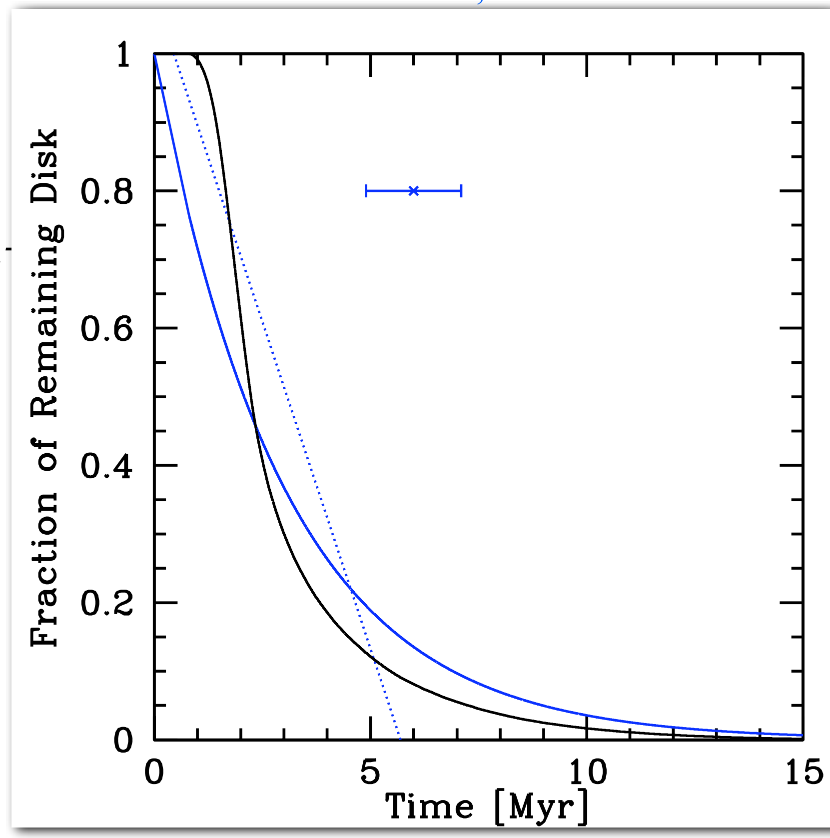
3 Disk lifetime

L-band (3.4 μm) photometry:

- excess caused by μ-sized dust @ ~900K

... ok to < 10 AU

Haisch et al. 2001, Fedele et al. 2010



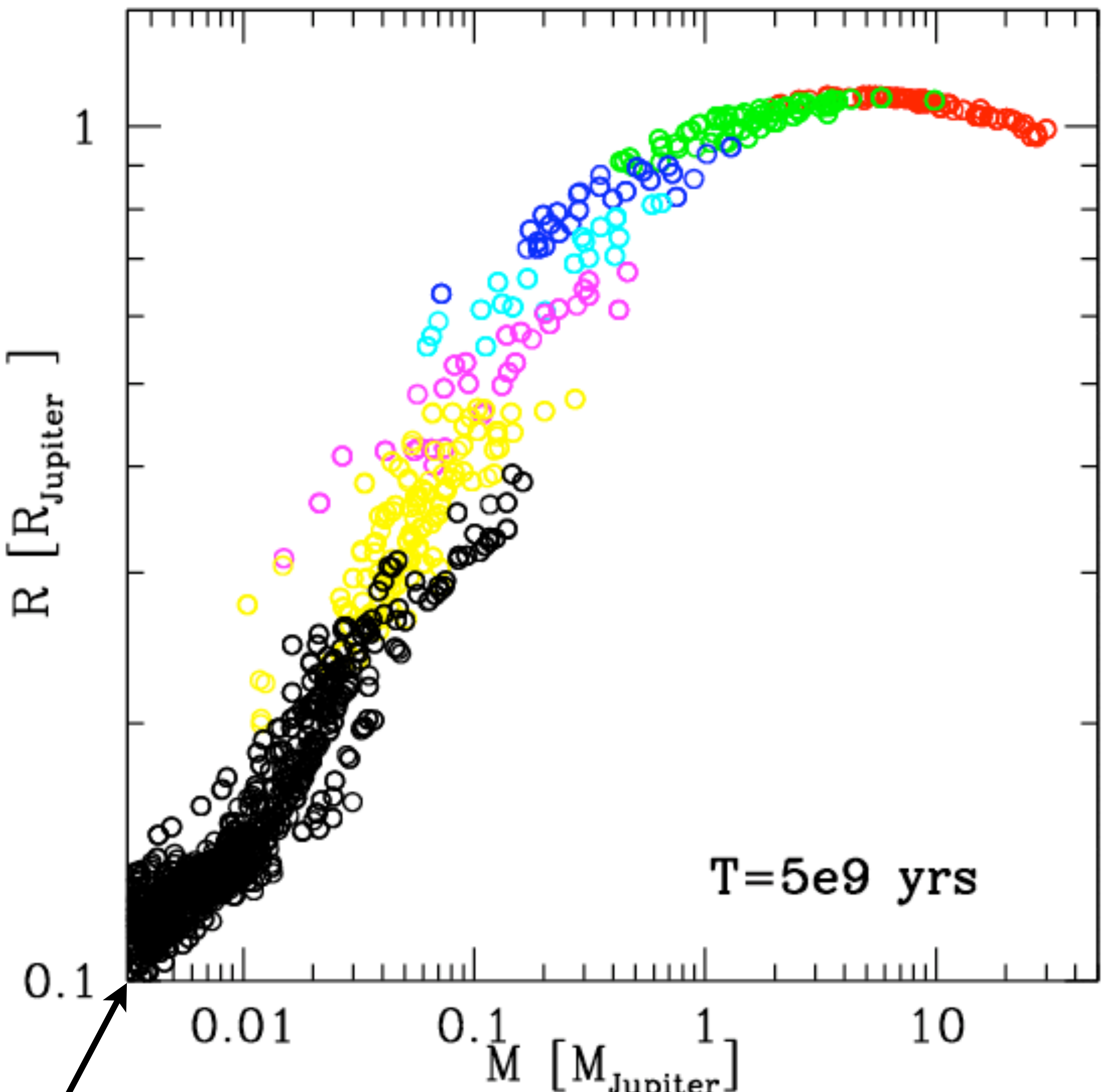
4 Initial semimajor axis of the seed embryo: not observationally constrained

Analytical work (Lissauer & Steward 1992) and numerical simulations (Kokubo & Ida 2000): spacing between bodies $\Delta \propto a$

$$p(a)da \propto \frac{da}{\Delta} \propto \frac{da}{a} = dlog(a) \propto const.$$

i.e. uniform in log(a) (Ida & Lin 2004)

Formation of mass-radius diagram



1 Earth Mass

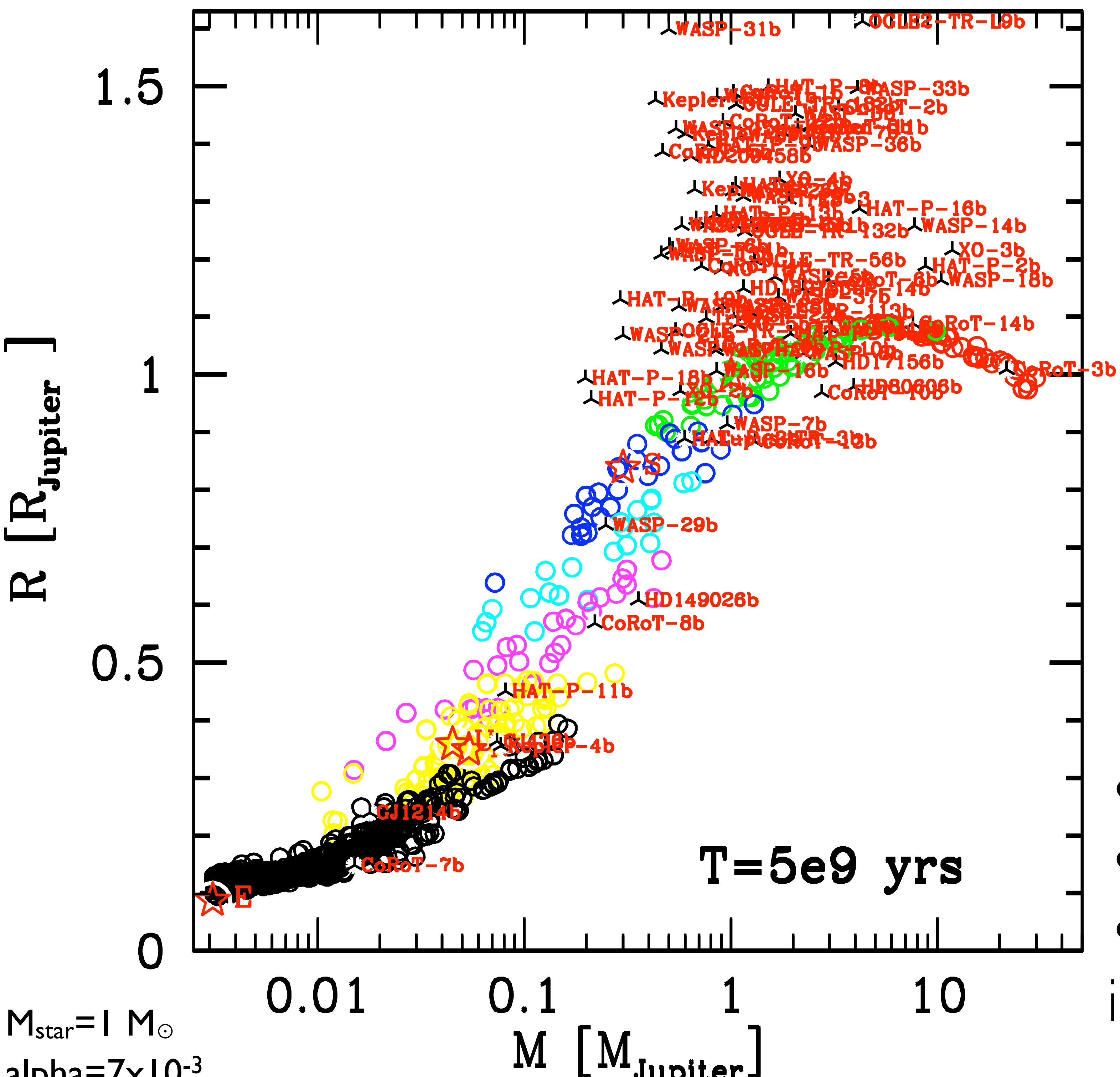
M_{star}=1 $M_\odot$
alpha=7×10^{-3}

Fraction Z of heavy elements

Z<5%
5 < Z < 20 %
20 < Z < 40 %
40 < Z < 60 %
60 < Z < 80 %
80 < Z < 95 %
Z > 95 %

- Rapid collapse at about 0.2 M_J
- when Z≈ 0.5
- Two groups for R (pre/post collapse) during formation.
- After disk dispersal (T>10 Myrs), slow contraction.
- At late times, characteristic maximum at about 4 M_J (degeneracy).
- Z decreasing with total mass.
- At given mass, high Z planets have smaller radius.

Synthetic *mass-radius* diagram: Comparison with observations



M_{star}=1 $M_{\odot}$

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Fraction Z of heavy elements

- Z<5%
- 5 < Z < 20 %
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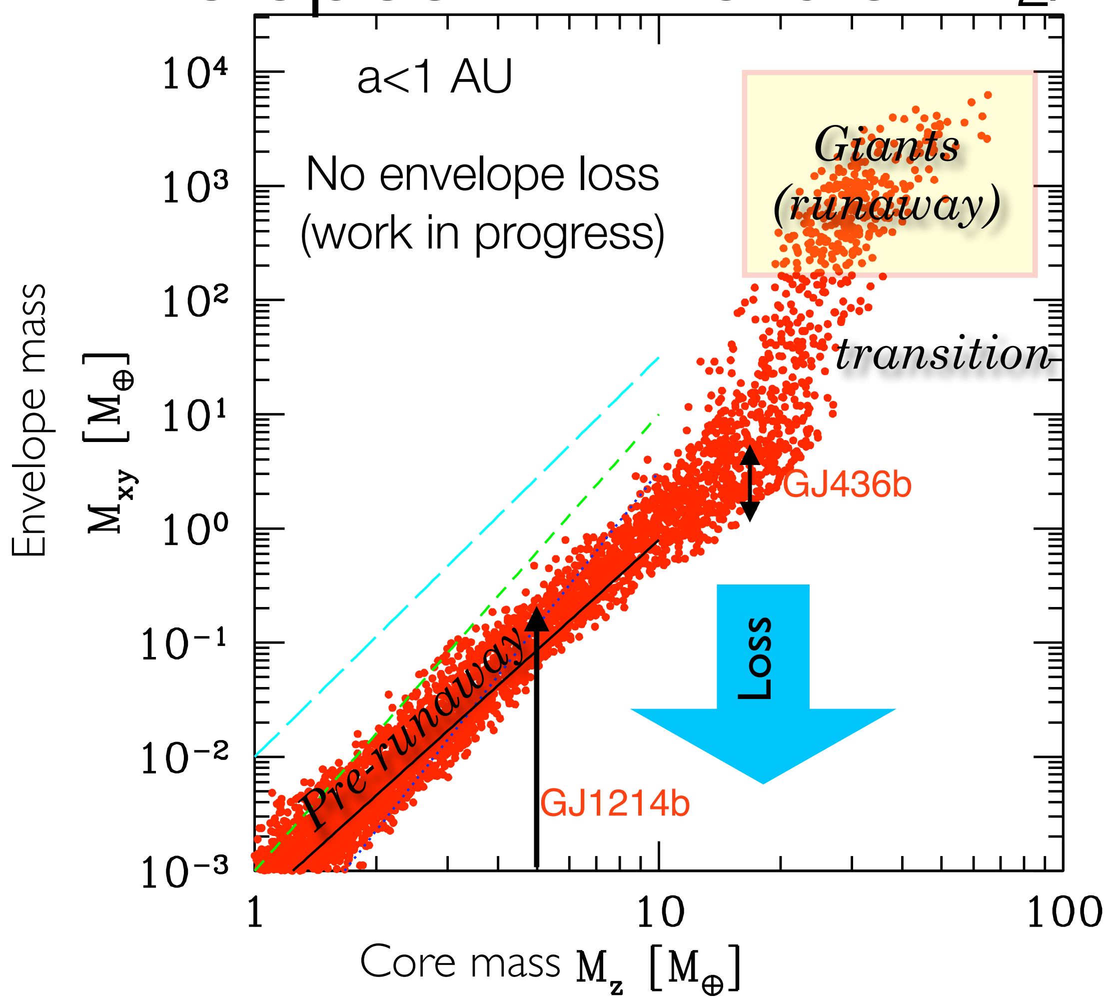
- 40 < Z < 60 %
- 60 < Z < 80 %
- 80 < Z < 95 %
- Z > 95 %

- Synthetic planets: all semi. axes, but a>0.1 AU.
- No (nearly) pure gas balls with low M. No nearly pure rock/ice giants.
- Solar system well reproduced (M-R & composition)
- Bloated R cannot be reproduced.
- Low M: Good agreement.
- Large spread in R (factor 2) at intermediate M (ca. 0.1 M_J).

Composition

Envelopes: Primordial H_2/He

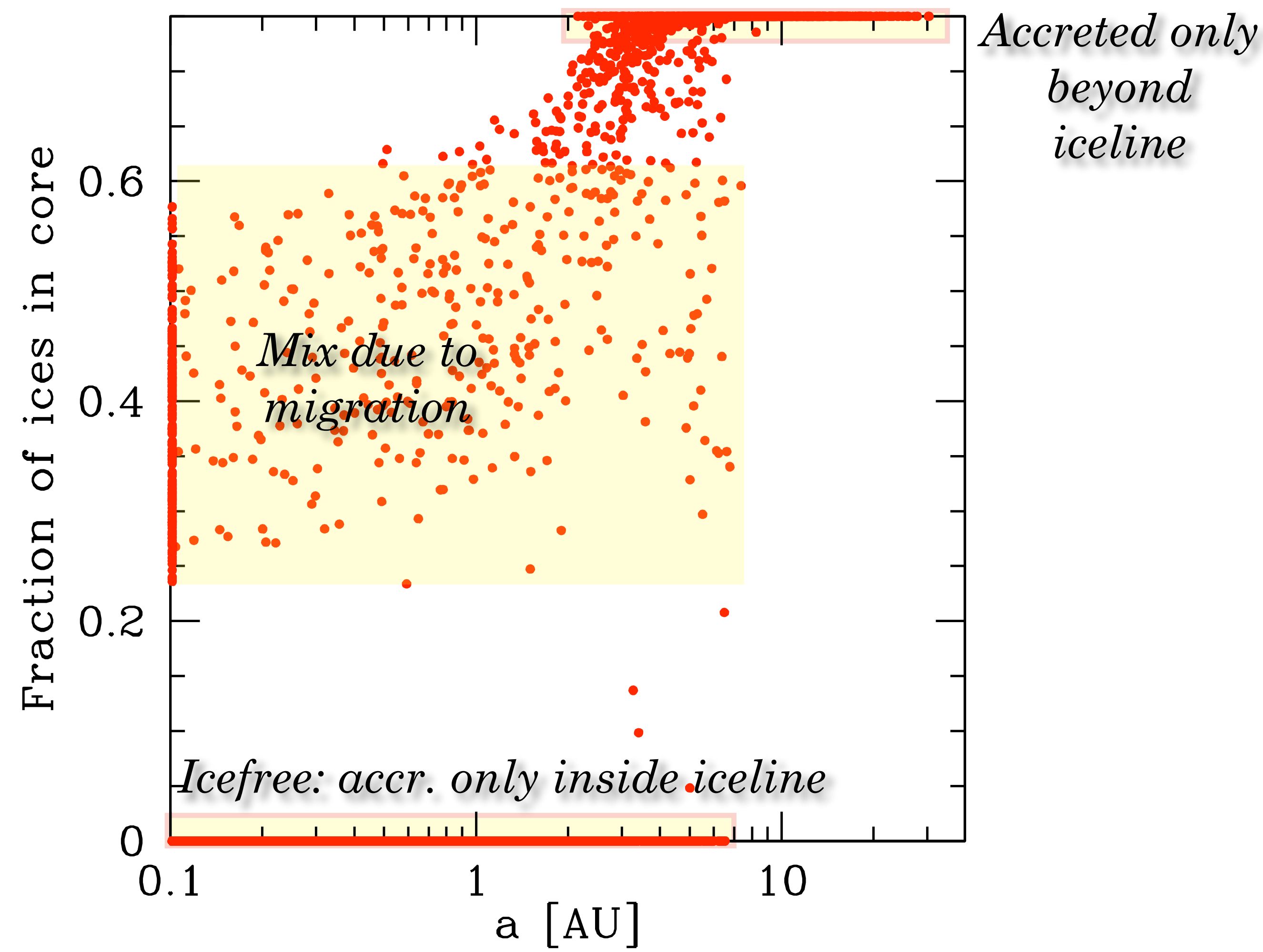


- Pre runaway (M_z <10-20)

$$\tau_{\mathrm{KH}} \simeq 10^b \left(\frac{M_p}{M_\oplus}\right)^{-c} \left(\frac{\kappa}{1 \text{ g cm}^{-2}}\right) \text{ yr} \quad \frac{dM_{p,g}}{dt} \simeq \frac{M_p}{\tau_{\mathrm{KH}}}$$

- Grain growth => more massive H_2/He envelopes.
- Starting point for evolution.

Cores: Ice fraction



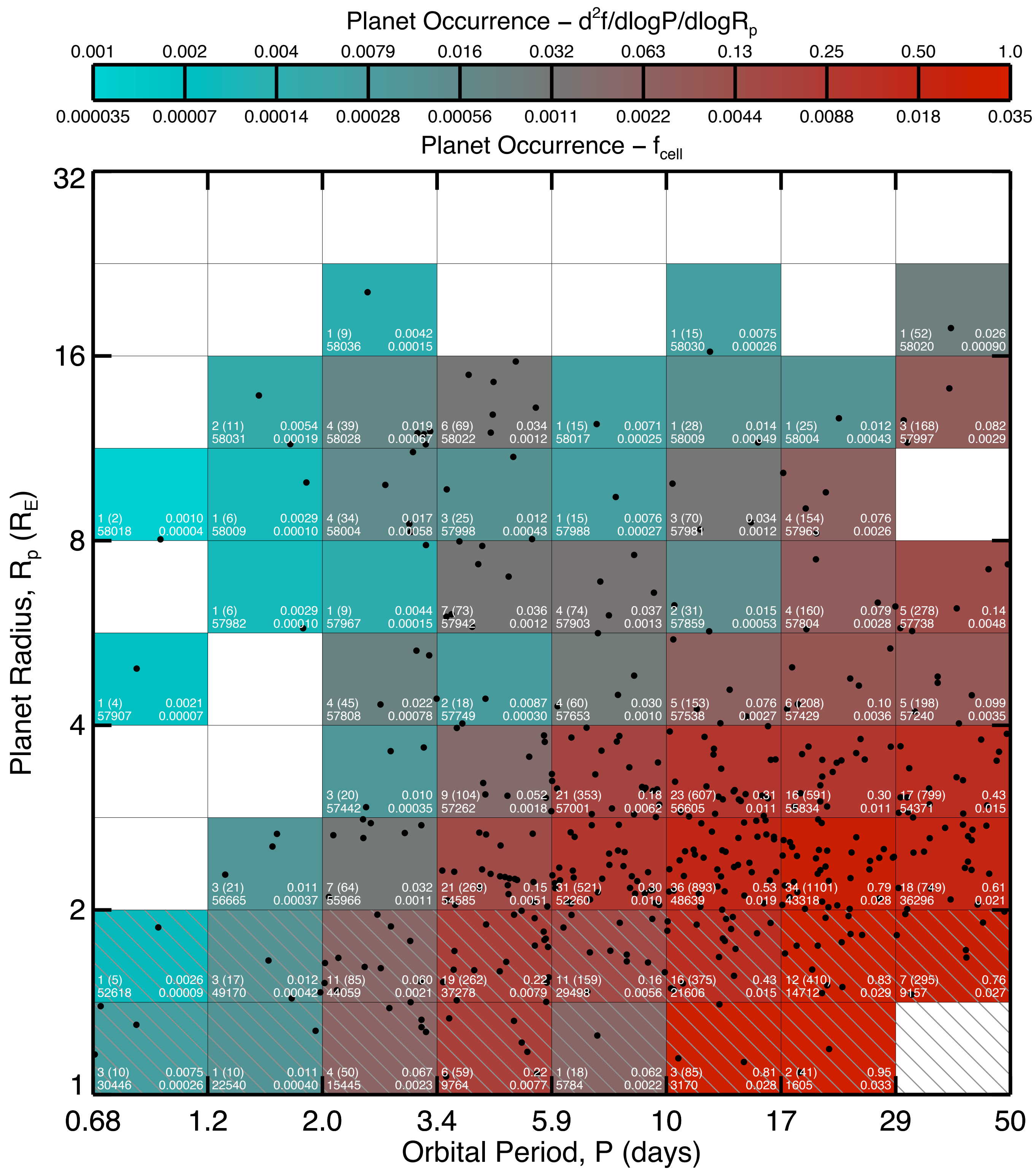
- Know where in disk how much accreted. (in/outside iceline)
- Planets inside 2 AU:
  - Either no ices at all, or 30-60 %
- Sensitive to migration=>constrain models!
- Input for outgassing.

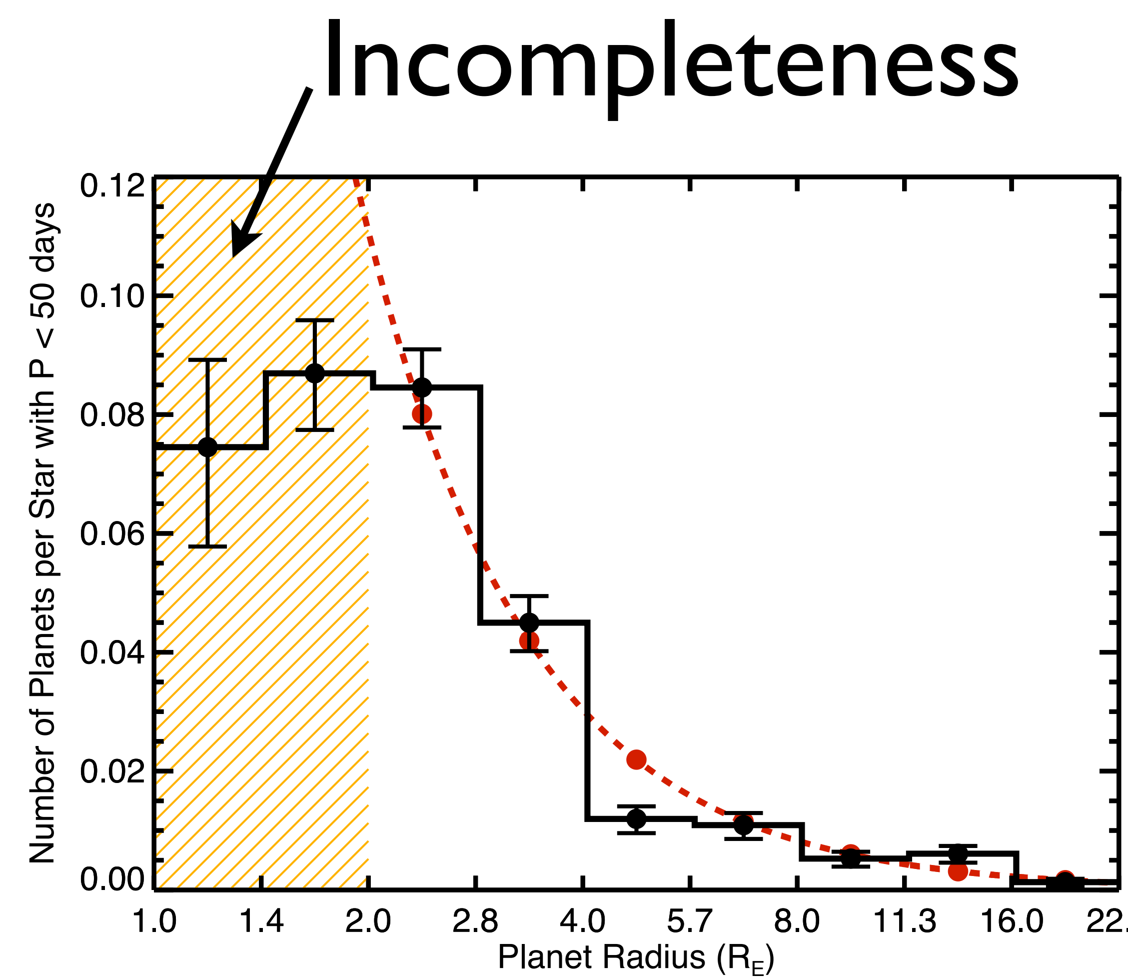
On the way to the Super-Montecarlo (Talk J. Fortney)....

3.1 The radius distribution is strongly increasing towards small radii (transits).

Comparison: KEPLER data

Howard et al. 2011





Only reliable KEPLER candidates around bright, main sequence GK stars.

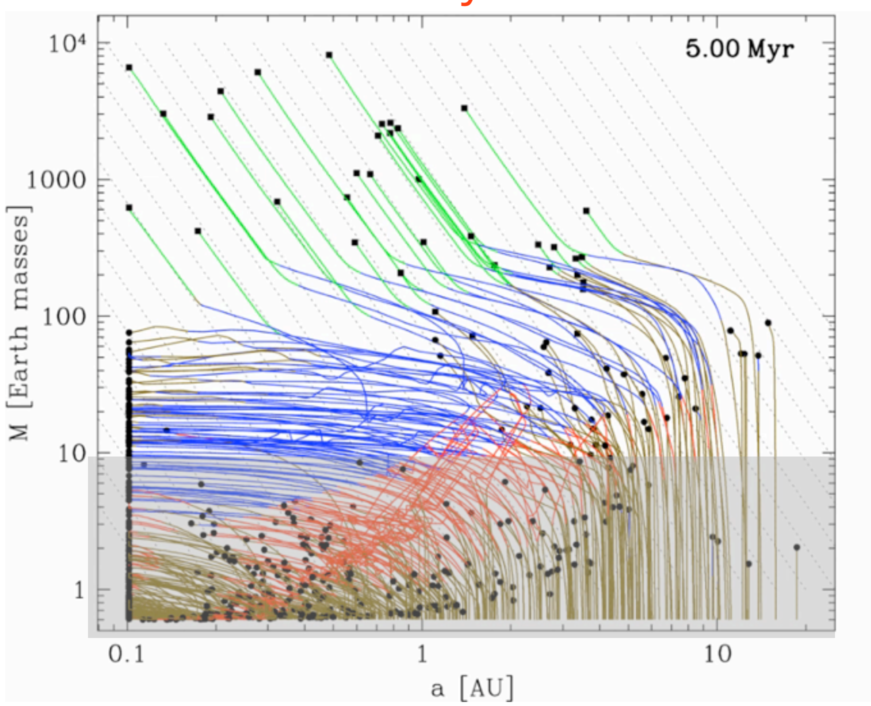
Correct for observational bias

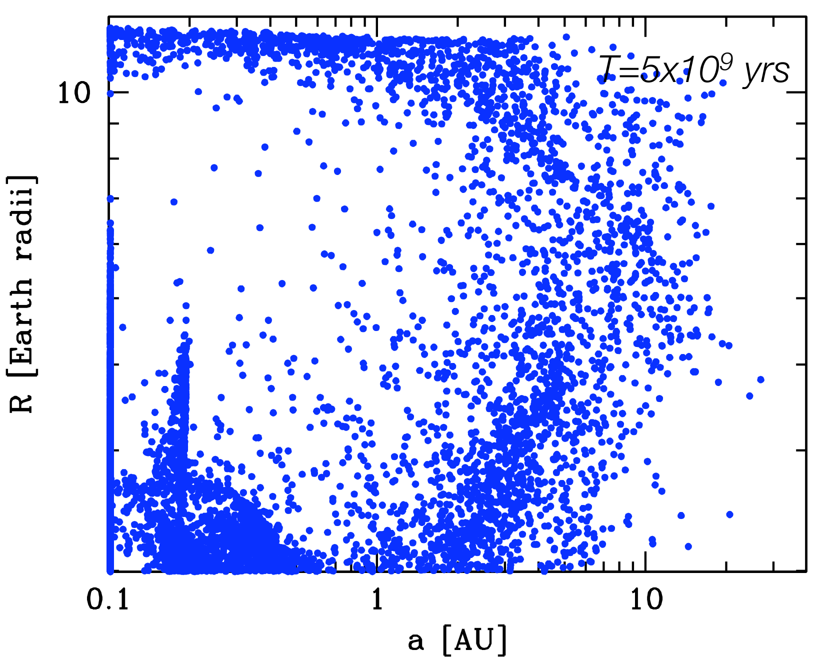
- -decrease with period
- -decrease with size (S/N)

Formation tracks - distance radius plot

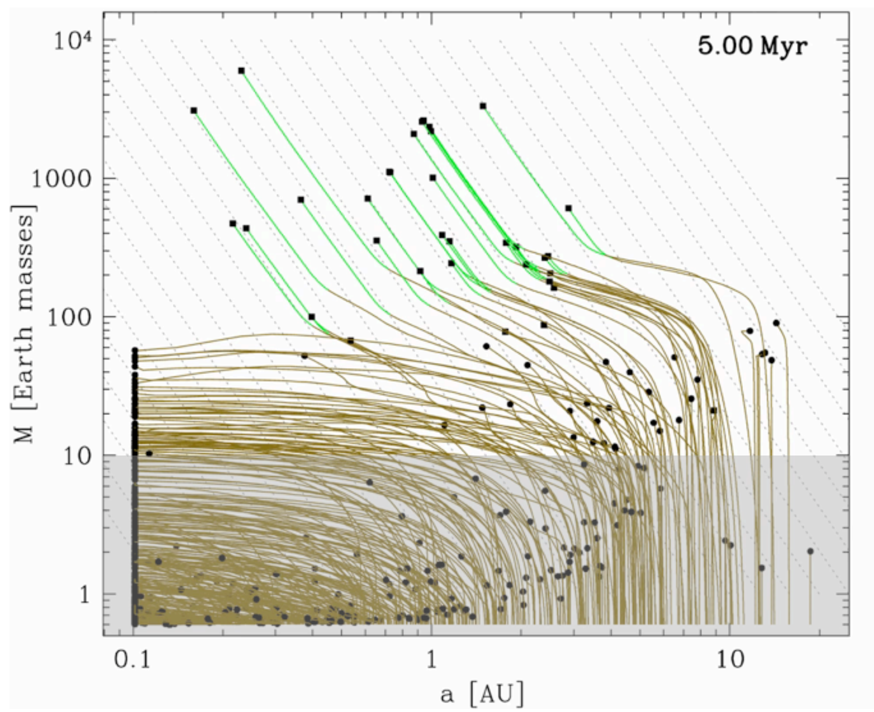
Mstar=1Msun, Memb,0=0.6 Mearth, irradiated disk, viscosity alpha=7×10^{-3}

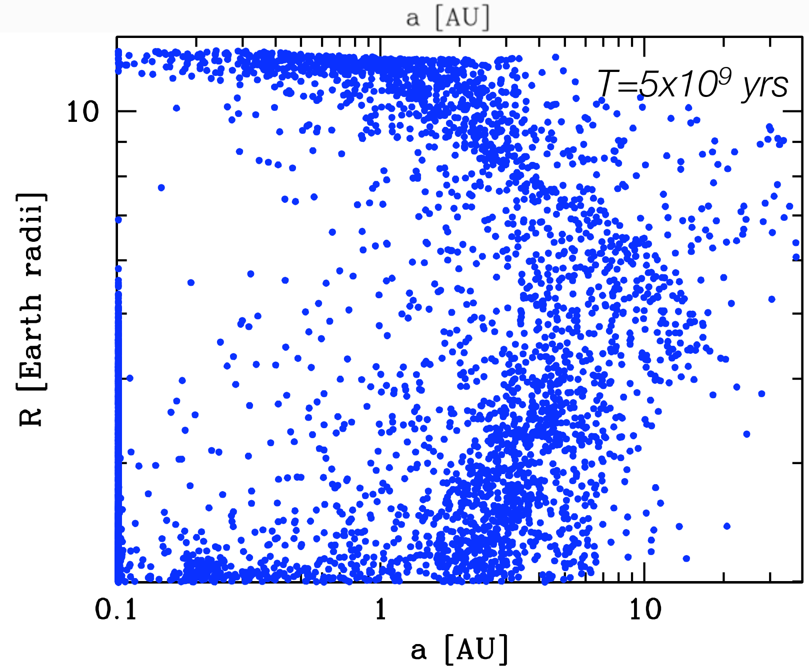
Nominal Model.
Updated Type I.
No efficiency factor!



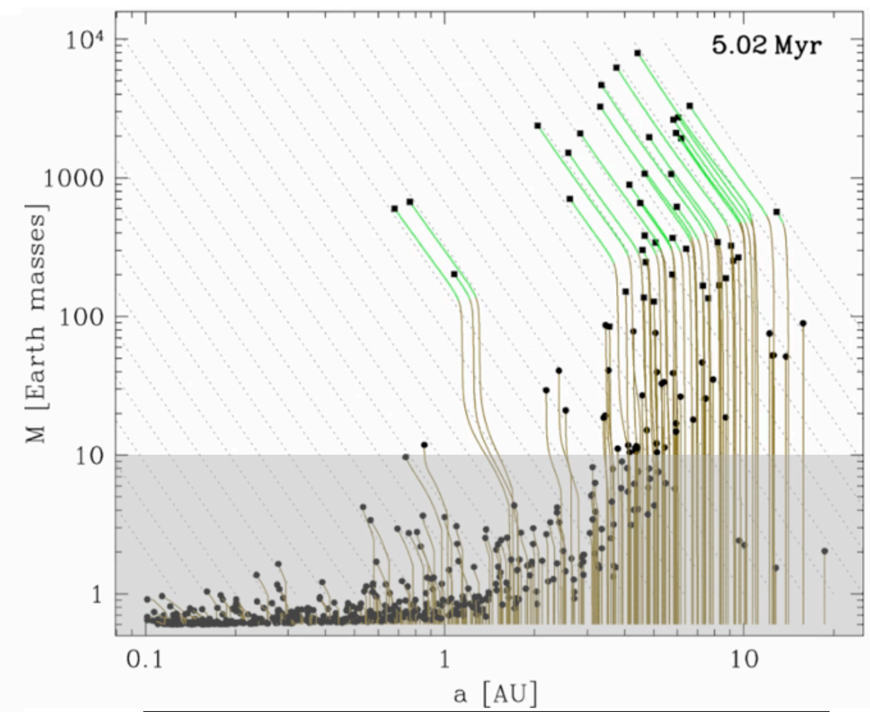


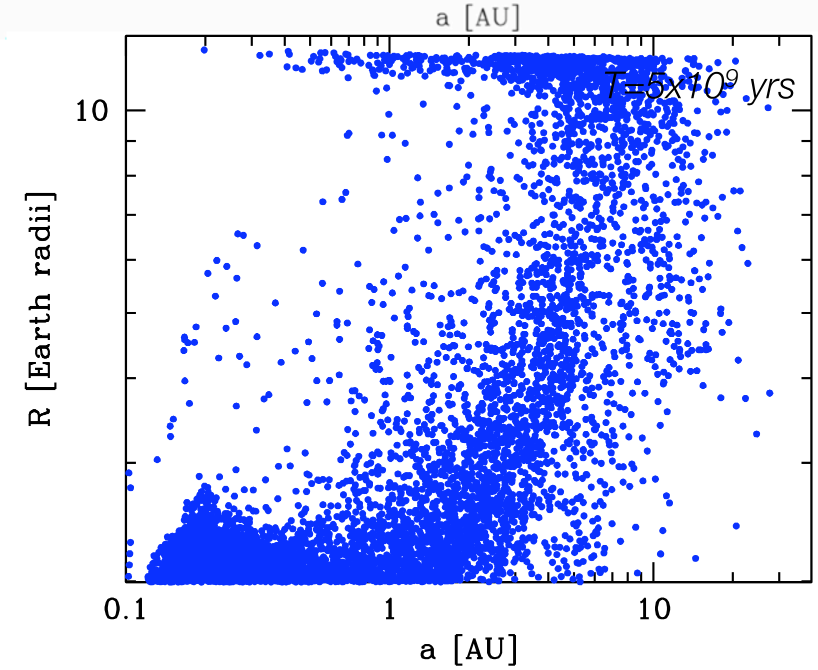
Isothermal Type I.
Tanaka f_1=1
(full migration rate)



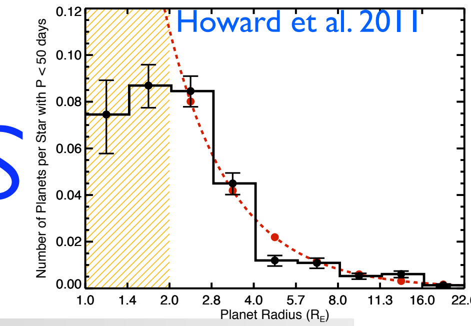


Isothermal Type I.
Tanaka f_1=0.01
Almost no type I migration.

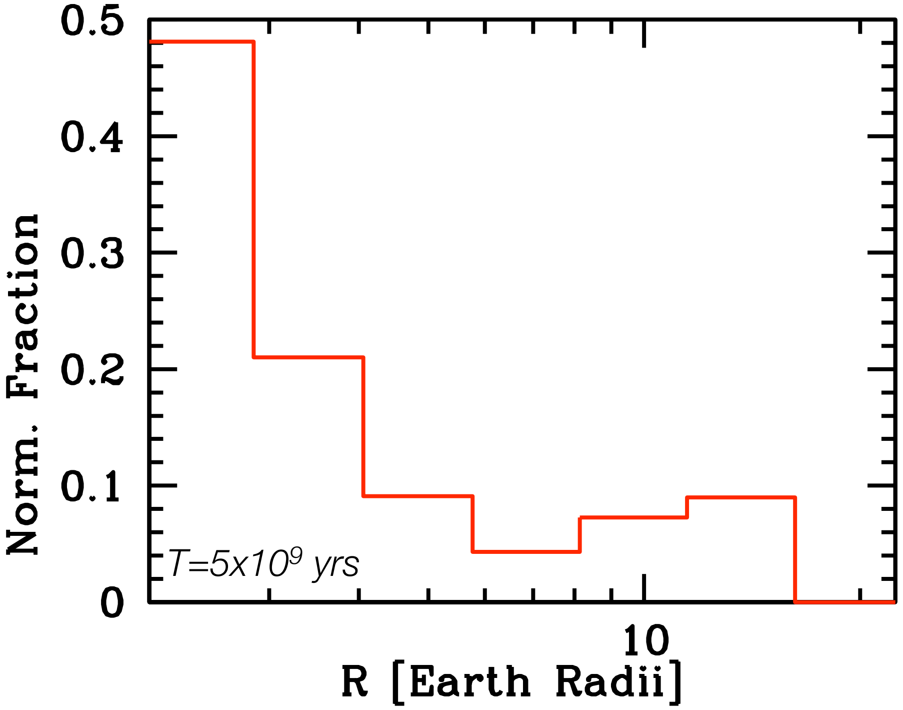




Radius distribution of KEPLER planets



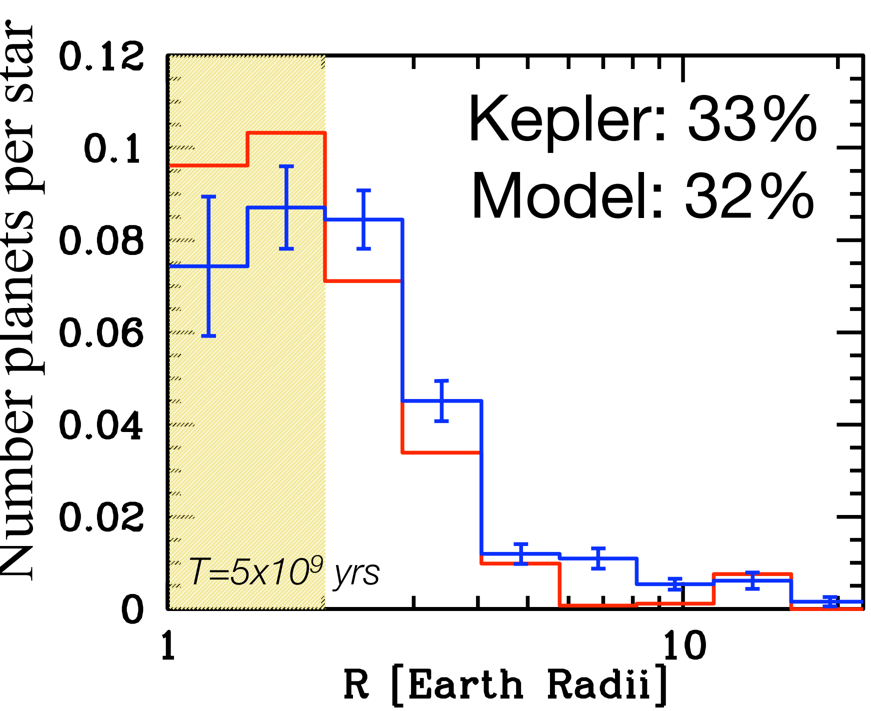
Nominal Model: all a



- Total radius distribution is *bimodal*: high peak at lowest radii, second peak at about 1 Jupiter radius.

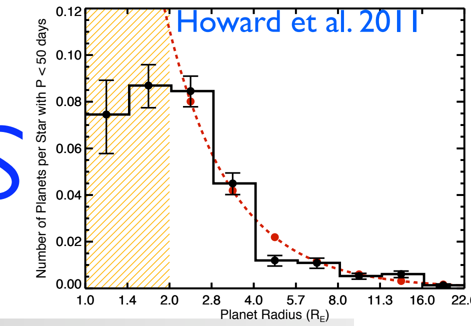
=>Giant planets contain much low density material (gas) and have all approx. *the same radius independent of mass* (degeneracy!)

Nominal Model: P<50 days

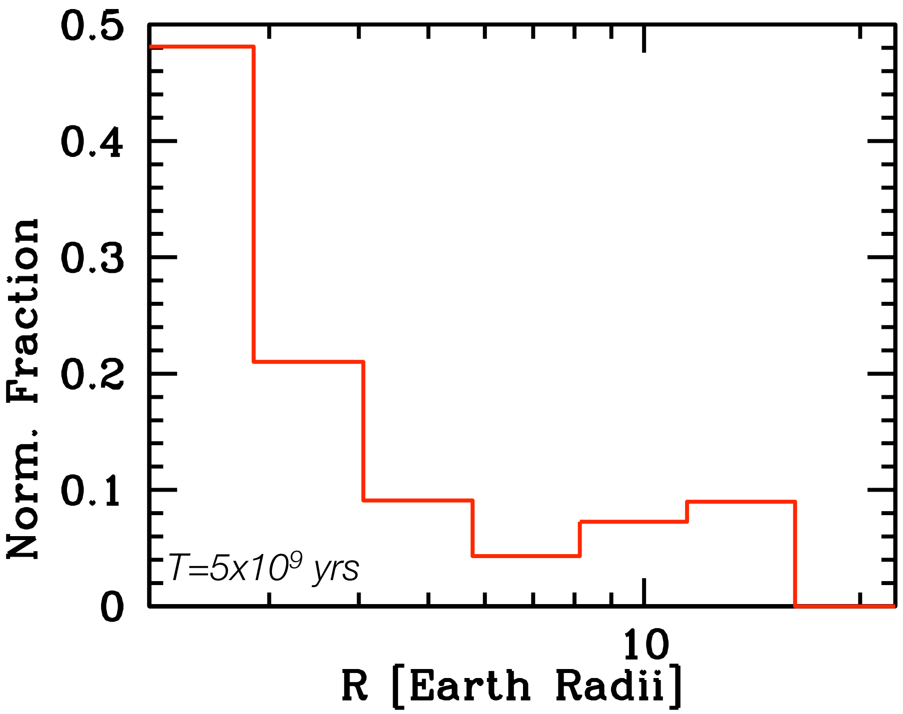


- Generally good agreement:
  - Increase towards small masses.
  - Many low radii.
  - Hot Jupiter 0.5-1%
  - Even in absolute fraction.
- But no bimodality...!

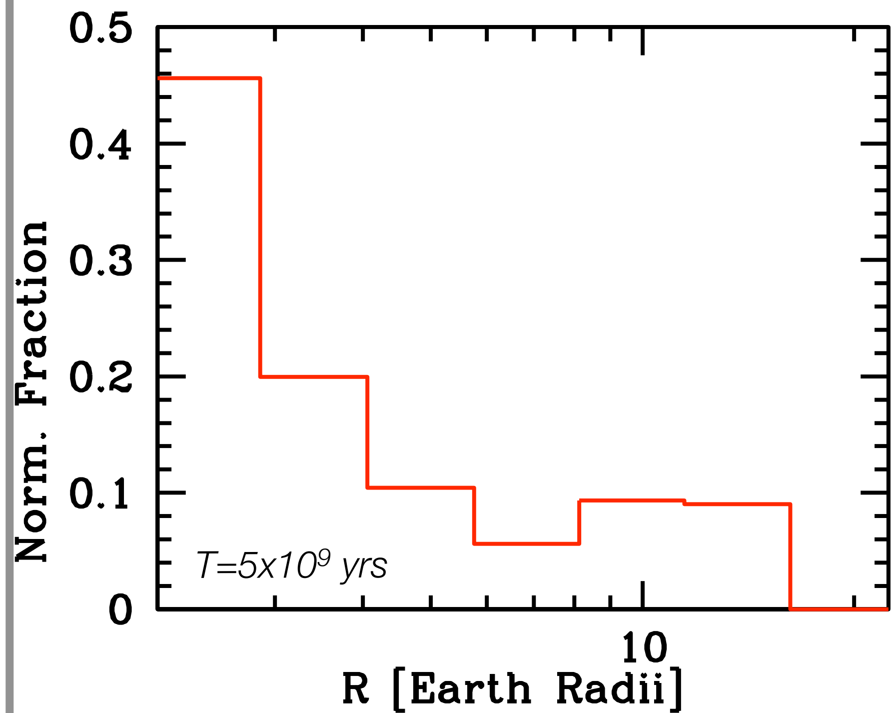
Radius distribution of KEPLER planets



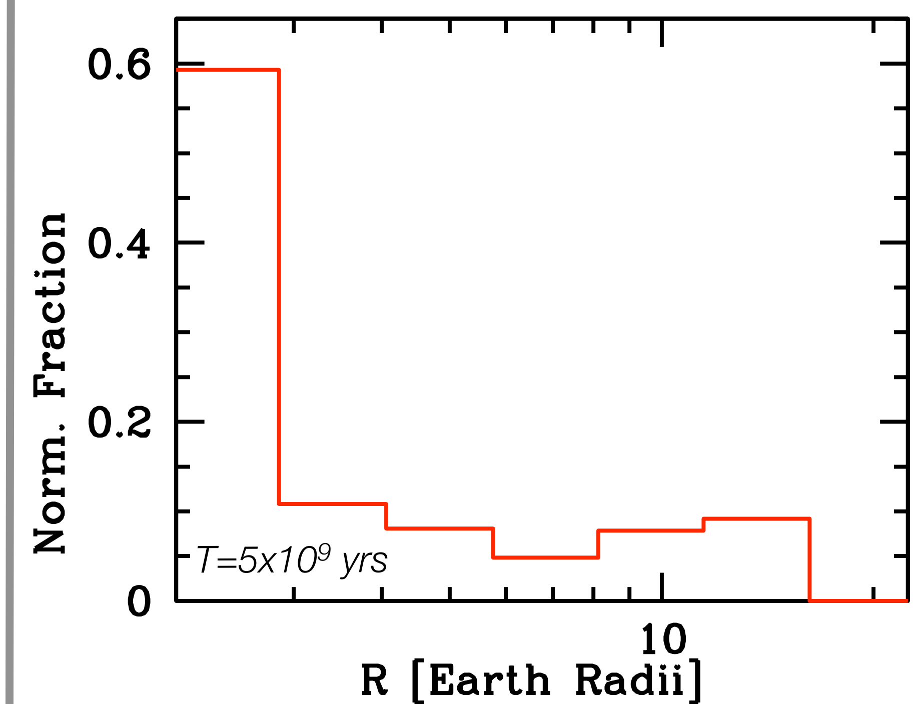
Nominal Model: all a



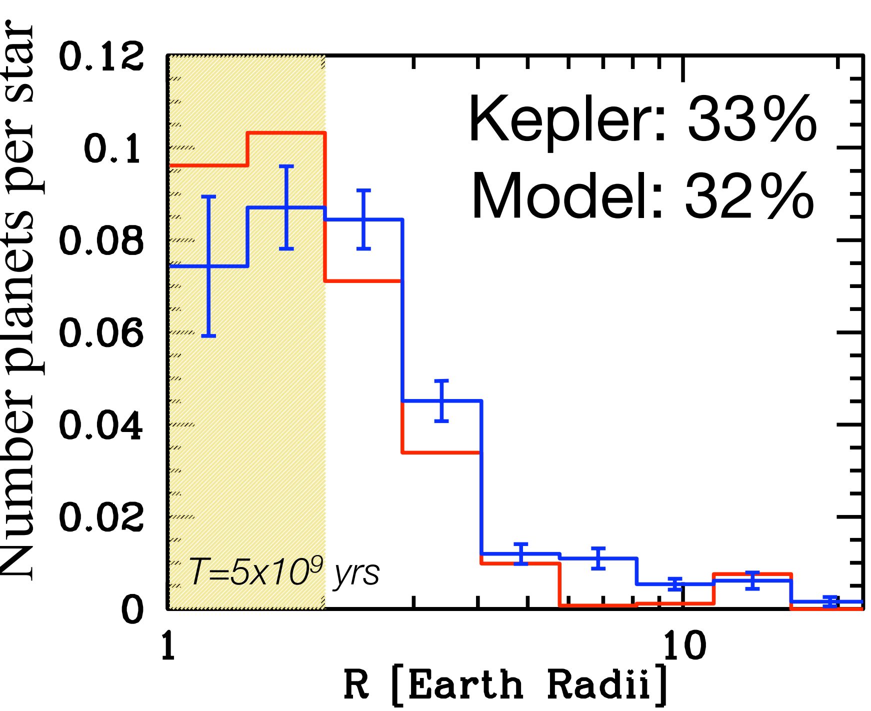
Full Tanaka: all a



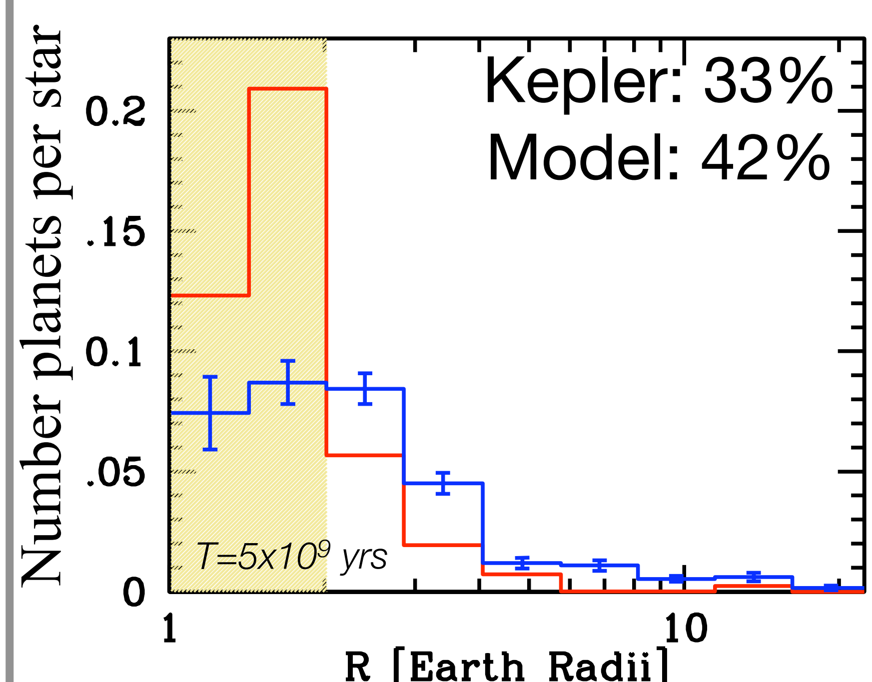
Nearly no type I: all a



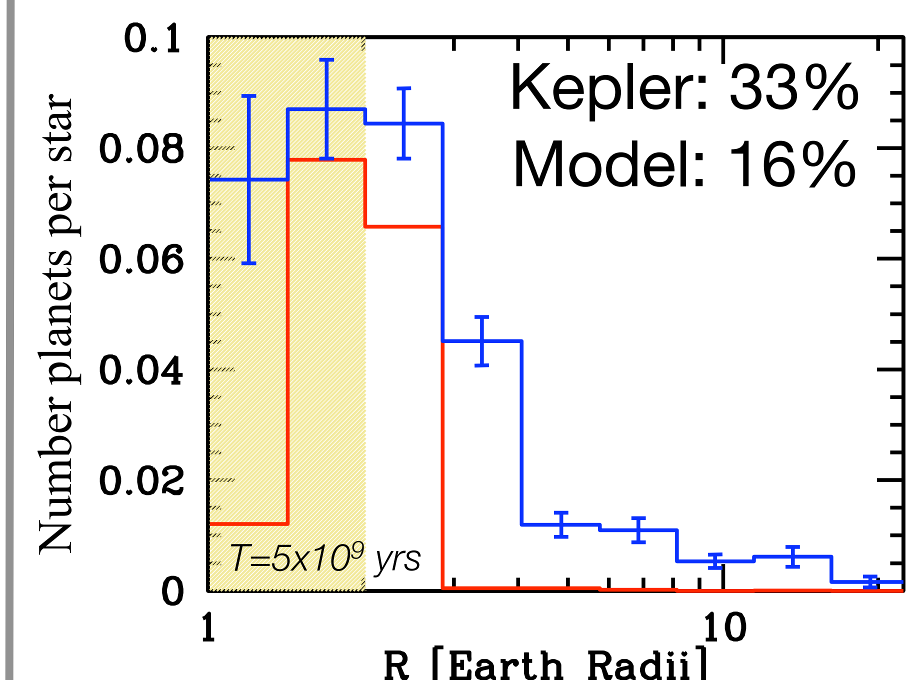
Nominal Model: P<50 days



Full isothermal: P<50 days



Nearly no type I: P<50 days

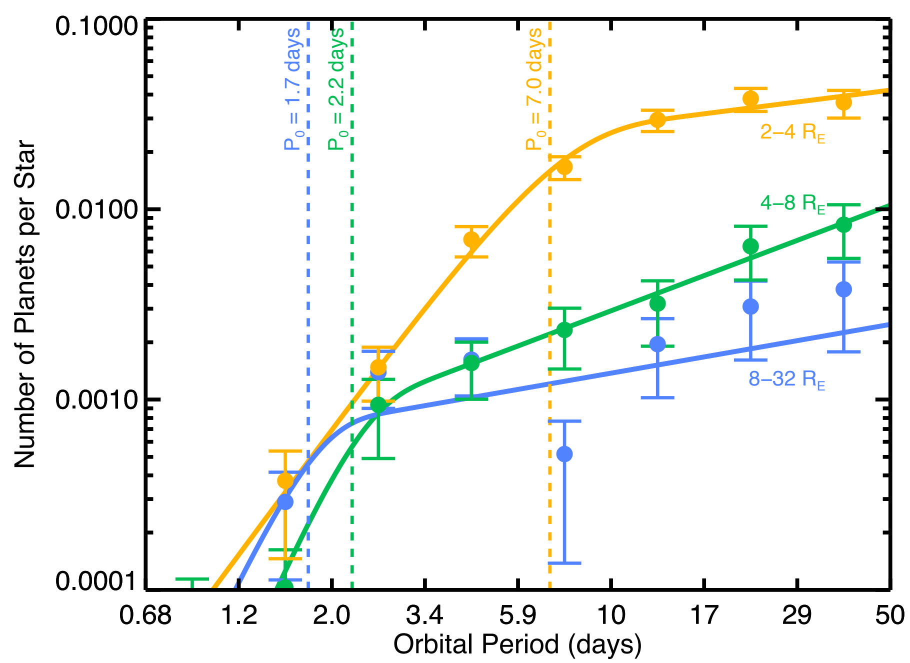


3.2 Close-in low mass (or small radius) planets are found somewhat further out than Hot Jupiters (rv, transits).

A qualitative explanation.

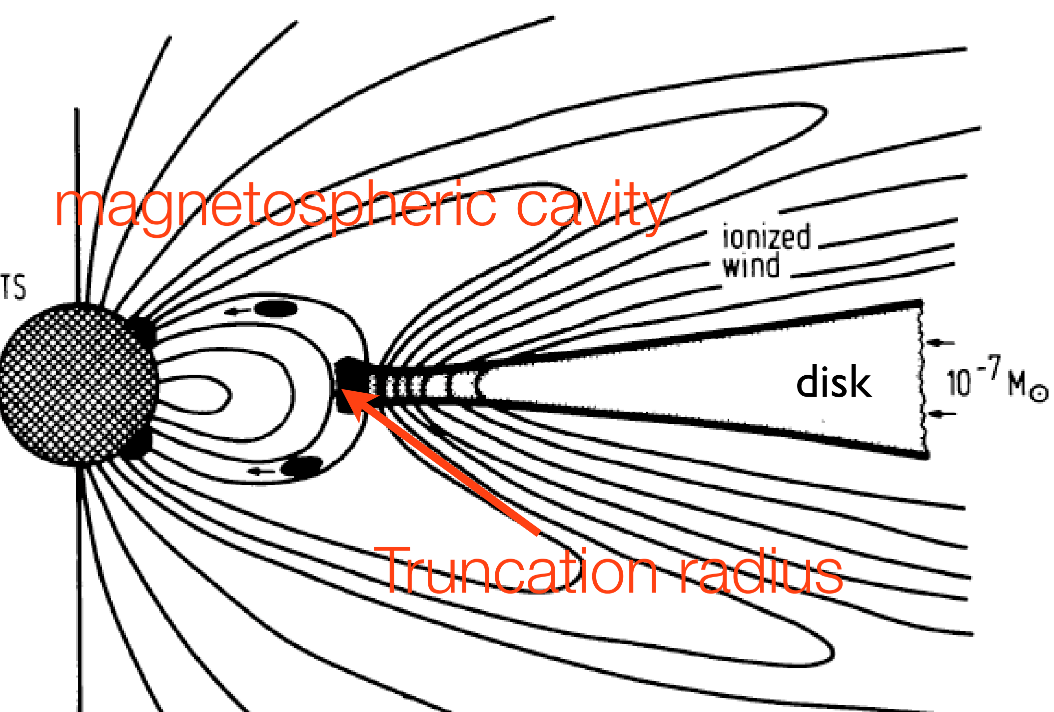
Semi-major axis in KEPLER data

Howard et al. 2011



Cut off below P_0:
-small radii 2-4 R_e: $P_0 = 7$ days
-large radii >4 R_e : $P_0 = 2$ days.

Neptunian and smaller sized further out. Consistent with earlier results from high precision RV. Lovis et al. 2009 estimated 10 days.



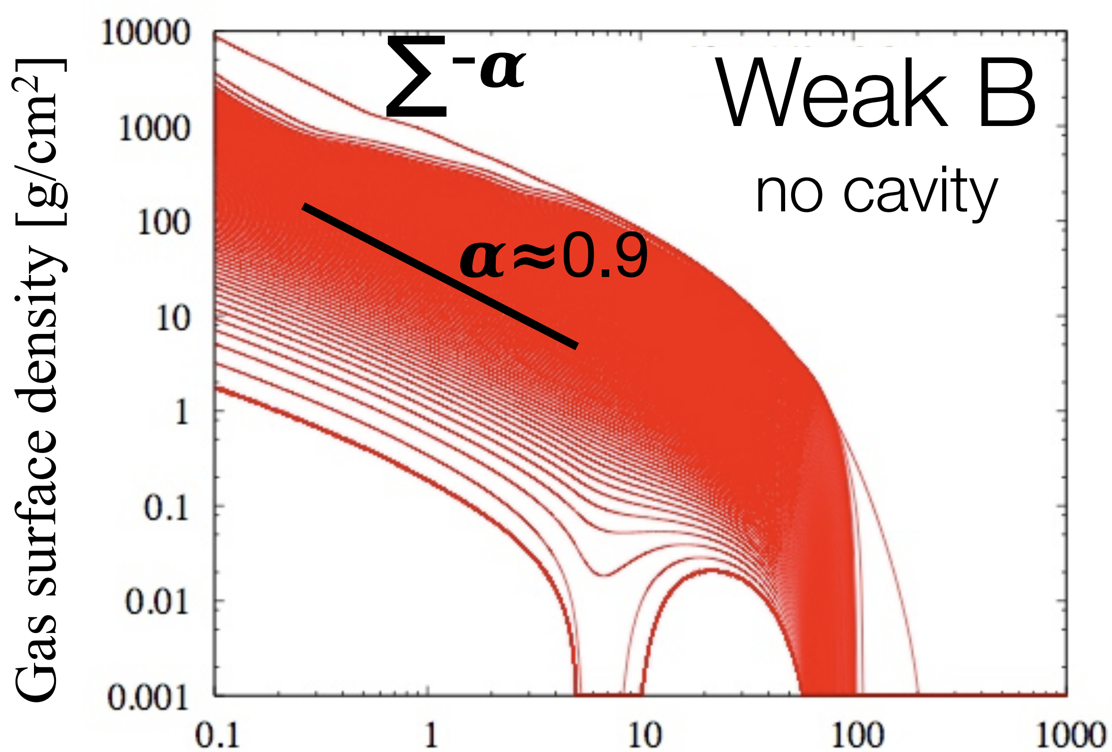
Camenzind 1999

Possible explanation: difference in stopping mechanism for disk migration of giant and low mass planets.

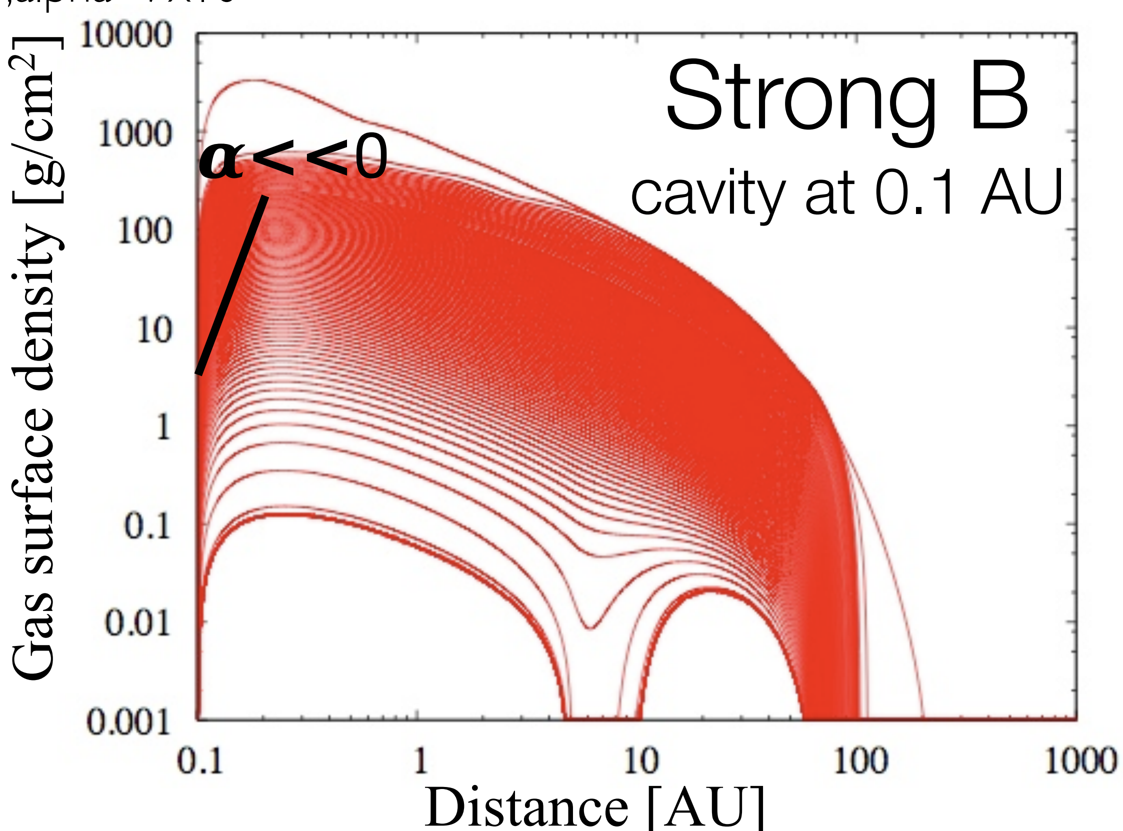
$$R_{mdisk} = \eta \left(\frac{B_*^4 R_*^{12}}{G M_* \dot{M}_{disk}^2} \right)^{1/7}$$

ca. 0.05 AU, but variable from star to star (magnetic field) and in time (disk accretion rate).

Two stopping distances



MMSN, irrad., $\Sigma_0 \propto a^{-0.9}$, ,alpha=7x$10^{-3}$



$$\Gamma_{\rm total}(3{\rm D}) = (1.364 + 0.541\alpha)\left(\frac{M_p}{M_c}\frac{r_p\Omega_p}{c}\right)^2 \sigma_p r_p^4 \Omega_p^2$$

$$\dot{r}_p = -2r_p \frac{\Gamma_{\rm total}}{L_p}$$

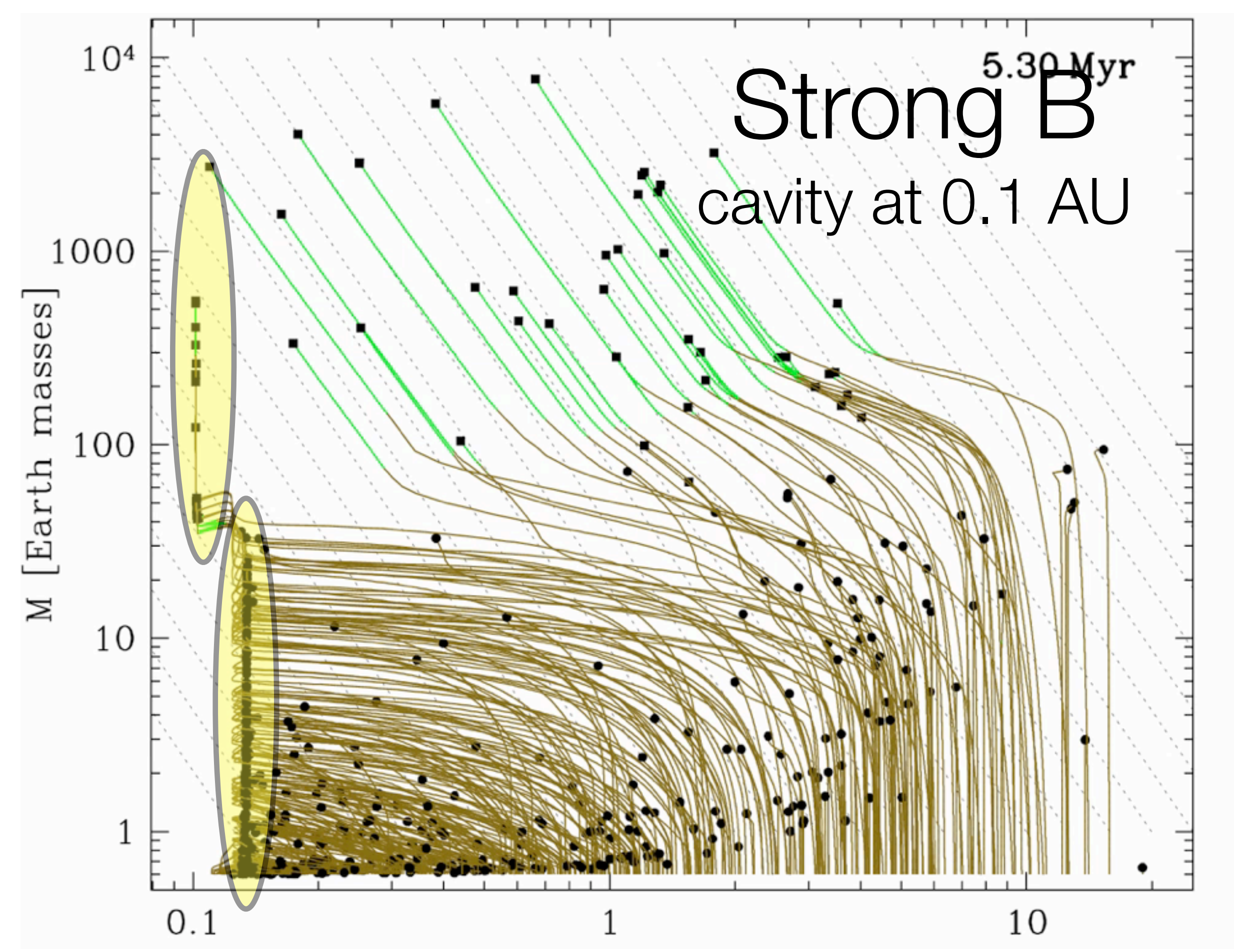
Tanaka et al. 2002

$$\frac{3}{4}\frac{H}{R_{\rm H}} + \frac{50}{q\mathcal{R}} \lesssim 1$$

Crida et al. 2006

Inner cavity is a strong stopping mechanism for low mass planets migrating in type I, but not for massive ones in type II.

cf. Masset et al. 2006



3.3 Low mass close-in planets are in multiple systems (rv, transits).

Close-in multiple planet system

- *HD10180 (Lovis et al. 2011), Kepler-11 (Lissauer et al. 2011)*

HD10180	a[AU]	Msini
(b)	0.02	1.4
c	0.06	13.2
d	0.13	11.9
e	0.27	25.4
f	0.49	23.6
g	1.4	21.4
h	3.4	65.3

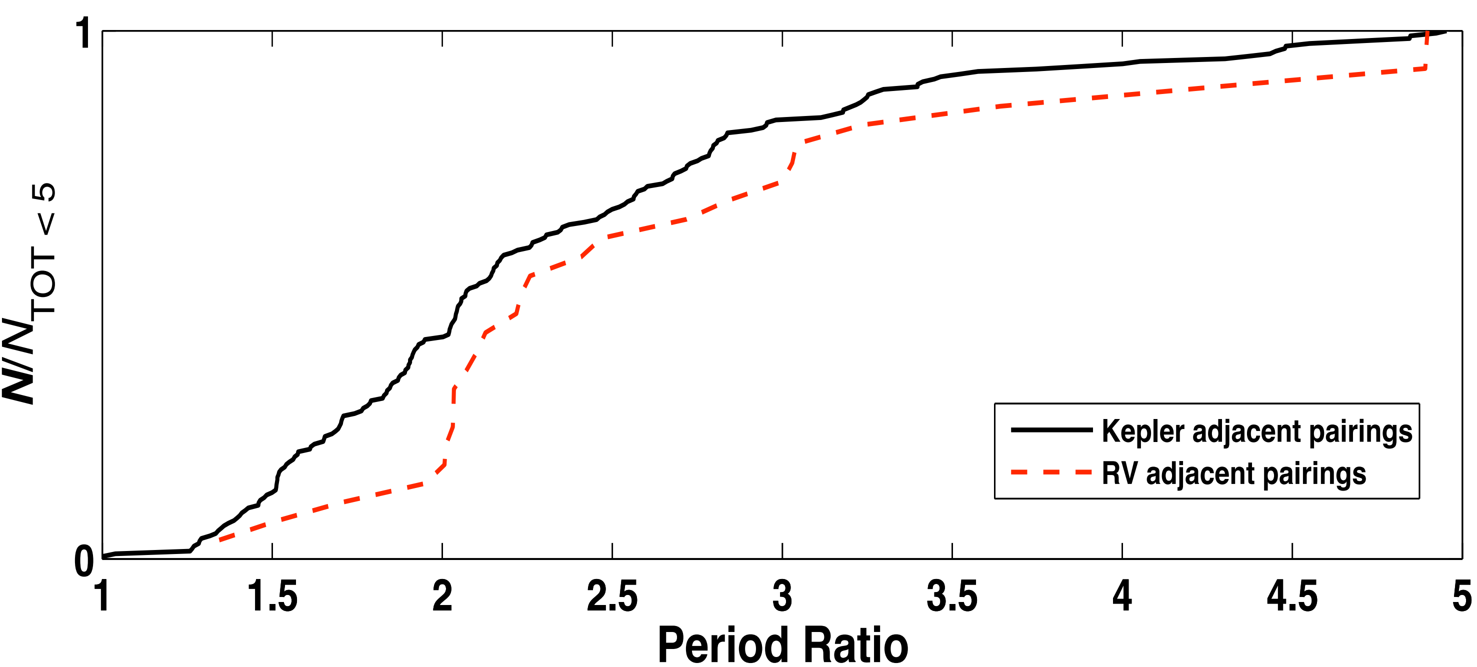
- Eccentricities 0-0.15
- Solar like star Fe/H=0.08, M=1.06 Msun
- Some period ratios are fairly close to integer or half-integer values, but no mean-motion resonances.
- Roughly regularly spaced on a logarithmic scale

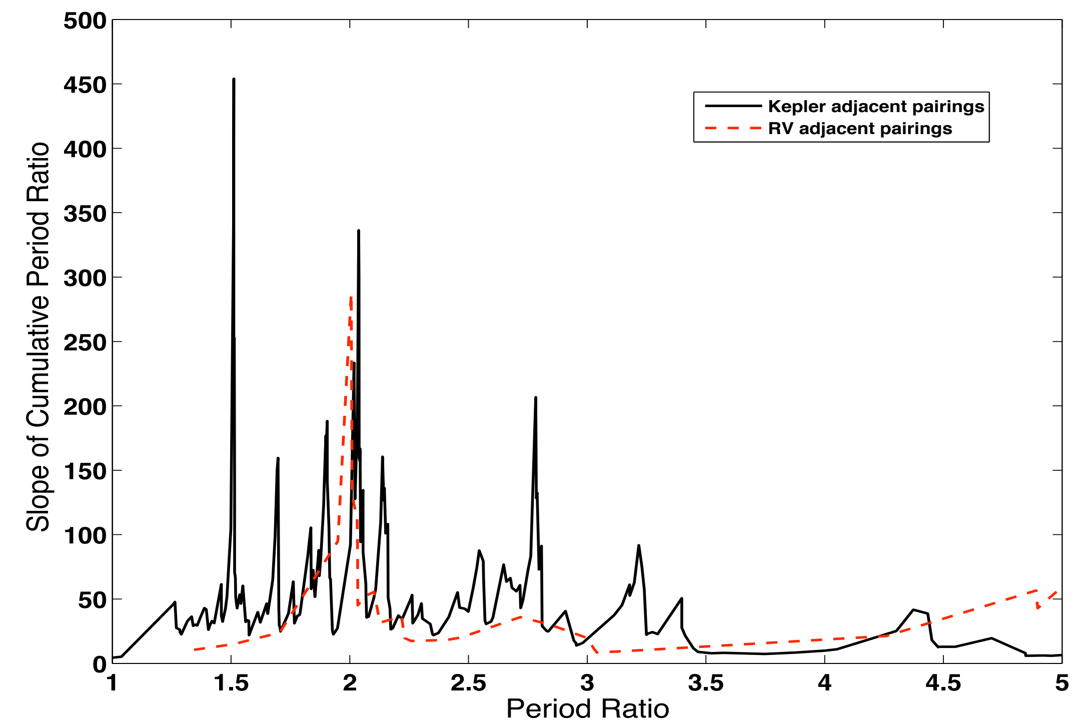
Kepler-11	a[AU]	Msini
b	0.09	4.3
c	0.11	13.5
d	0.15	6.1
e	0.19	8.4
f	0.25	2.3
g	0.46	<300

- all within i 1.5 deg. Very complanar.
- Solar like star Fe/H=0, M=0.95 Msun
- b, c close to 5:4 resonance, but otherwise not in resonances.
- Low densities
- Dynamically packed

Architectures of KEPLER systems

Lissauer et al. 2011

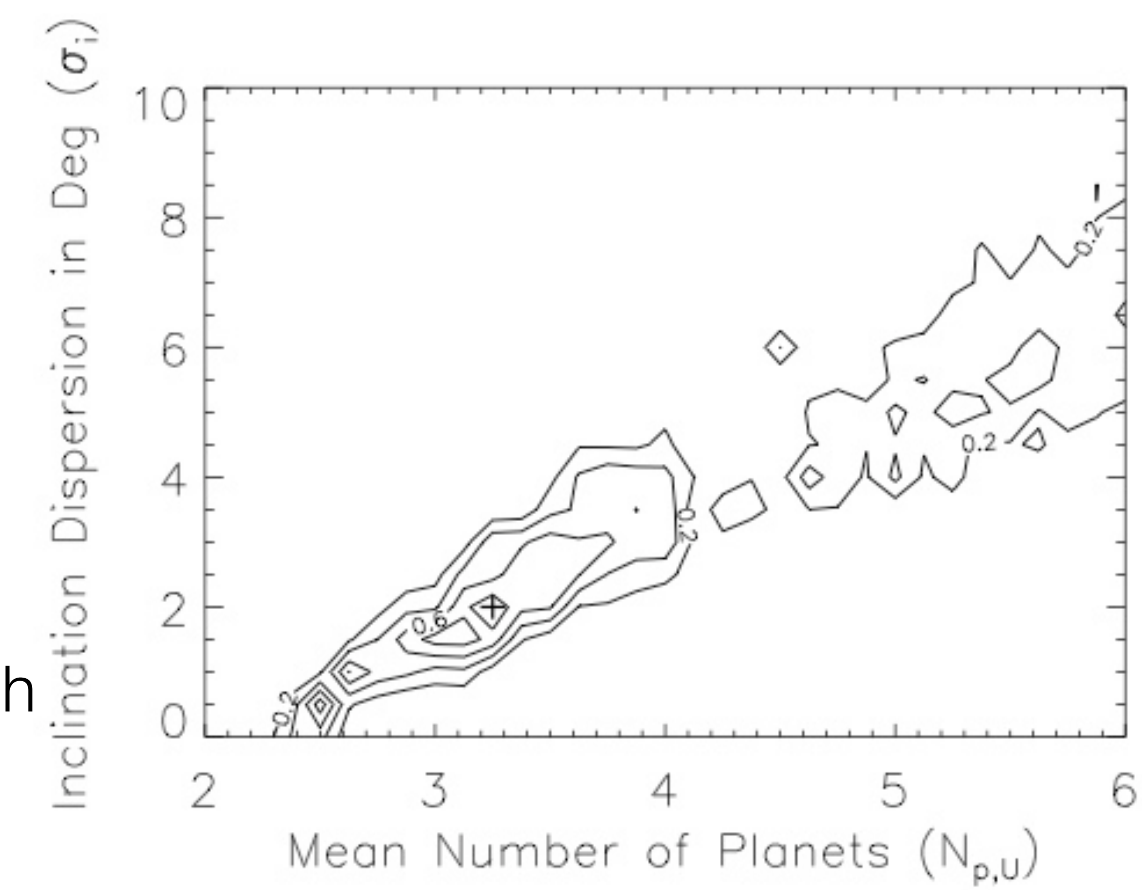




- The distribution of observed period ratios shows that the majority of candidate pairs are neither in nor near low-order mean motion resonances.

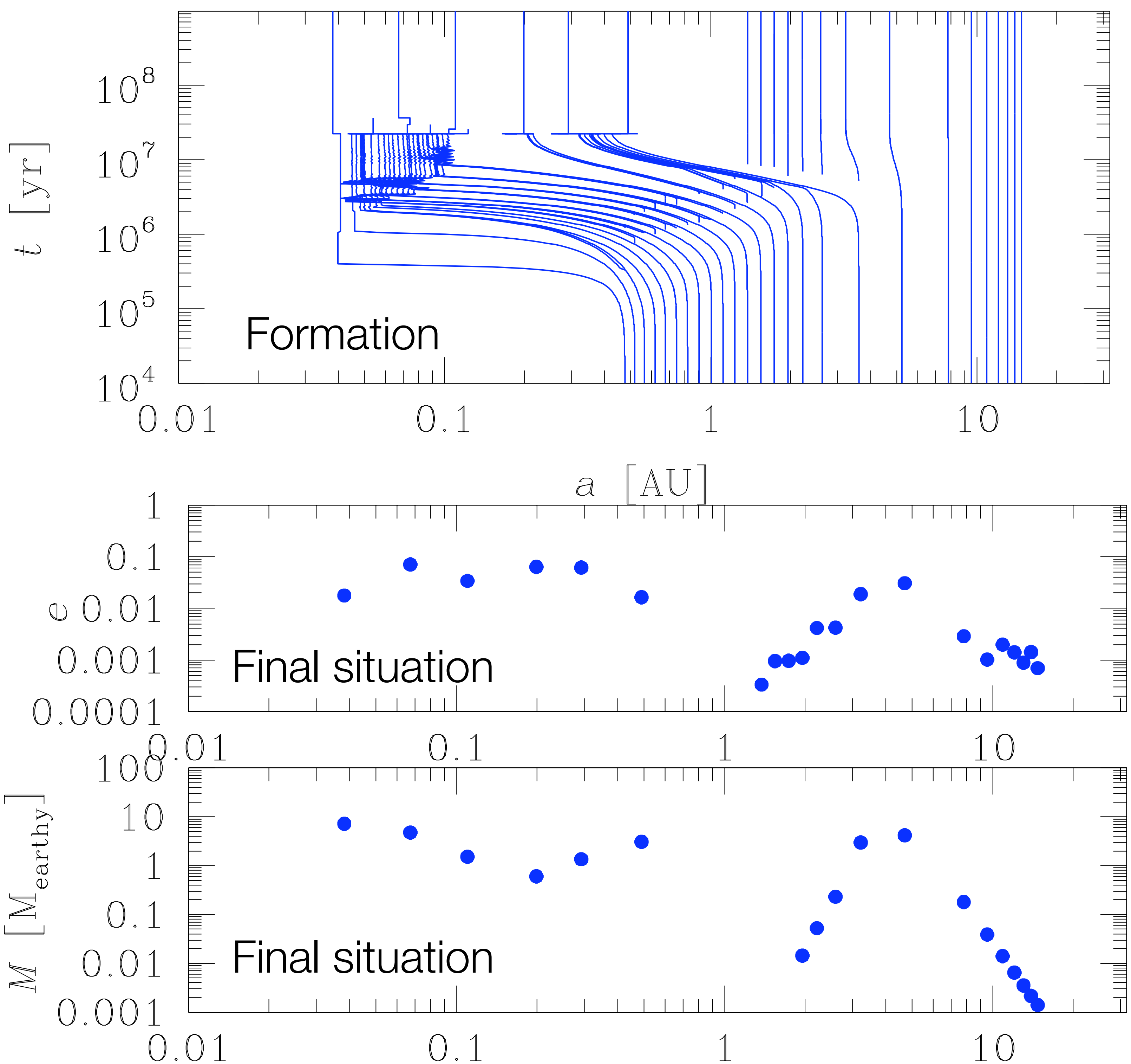
- Nonetheless, there is a small but statistically significant excesses of pairs both in resonance and spaced slightly further apart, particularly near 2:1.

- About 3-5% of the KEPLER stars have a system with a mean number of 3 small planets (R 1.5 to 6 R_{earth}, P<125 d).



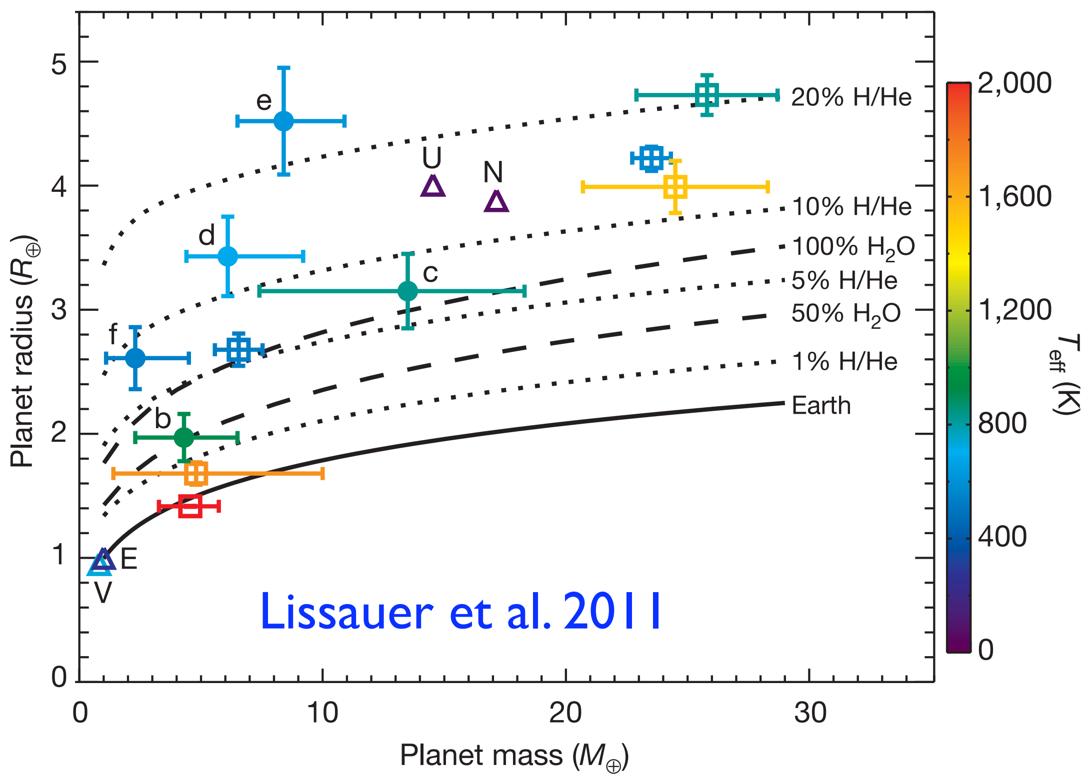
Formation scenario I

Ida & Lin 2010, Ogihara et al. 2010

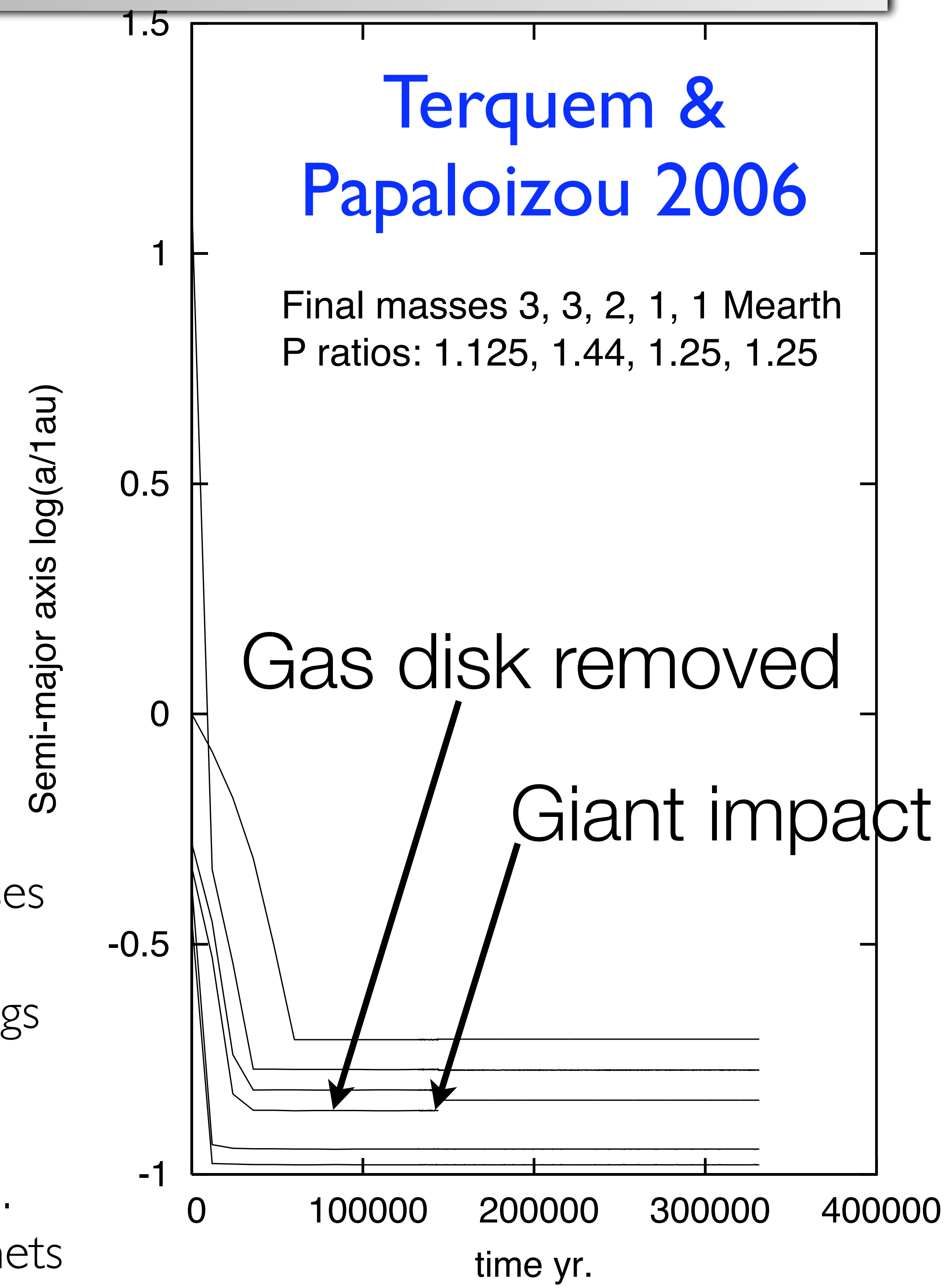


- Protoplanets grow to the isolation mass (Mars mass).
- Migrate inwards in resonant convoys.
- Get to inner disk edge, migration stalled.
- After disk depletion, start of eccentricity excitation.
- Giant impacts until long term stability. Resonances destroyed.
- Final Masses 1-10 M_{earth},Ecc. 0.01-0.1 (Earth current 0.017).
- No primordial H_2/He envelopes (Mars mass planets cannot accrete gas, and final masses reached only after disk dispersal).

Formation scenario II



- Kepler-11 d,e,f appear to require a H_2/He envelope.



- Again, different migration rates because of different masses & distances lead to capture in MMR.
- As the cores migrate inside the disk inner edge, scatterings and mergers of planets on unstable orbits, together with orbital circularization, causes strict commensurability to be lost. Near commensurability however is usually maintained.
- In this scenario, H_2/He rich atmospheres possible, as planets reach final masses (except for giant imacts) during disk life.

Conclusions

- We have entered an era in which different observational techniques yield a huge wealth of observational data describing many different aspects of the architectures of planetary systems.

- The discovery of a whole population of planets is providing important clues toward a better understanding of planet formation.
  -crucial to understand migration, accretion, internal structure
- A comprehensive picture of planet formation is still beyond present capabilities:
  - some key processes are identified, but models far from being complete

- Field still observationally driven but theory beginning to be able
  -to make quantitative statements for many different observational techniques
  -to interpretate the detections
  -to make testable predictions

But observations will remain the necessary guideline for theory.


Thanks!
HARDY