Planetary Population Synthesis

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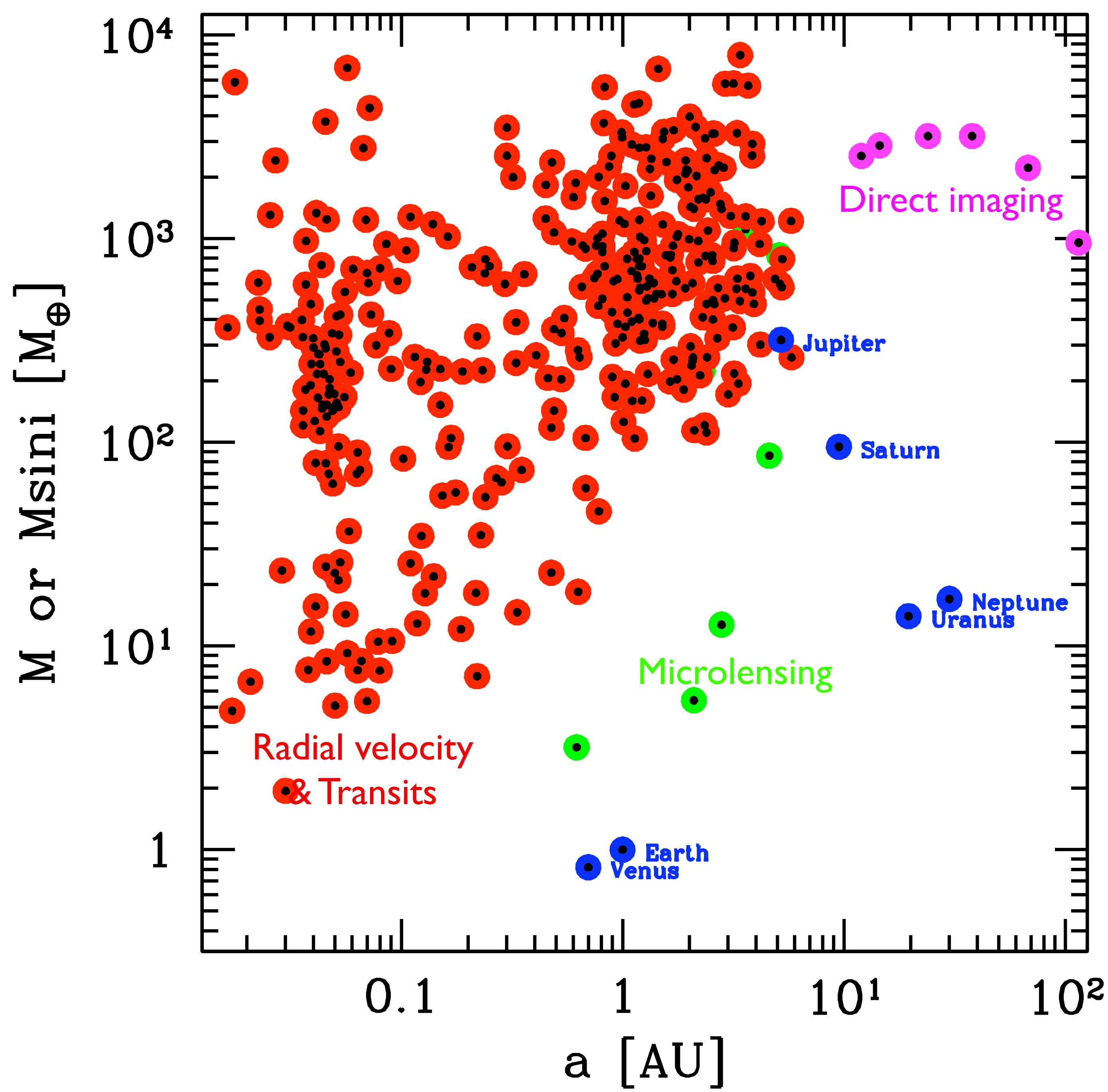
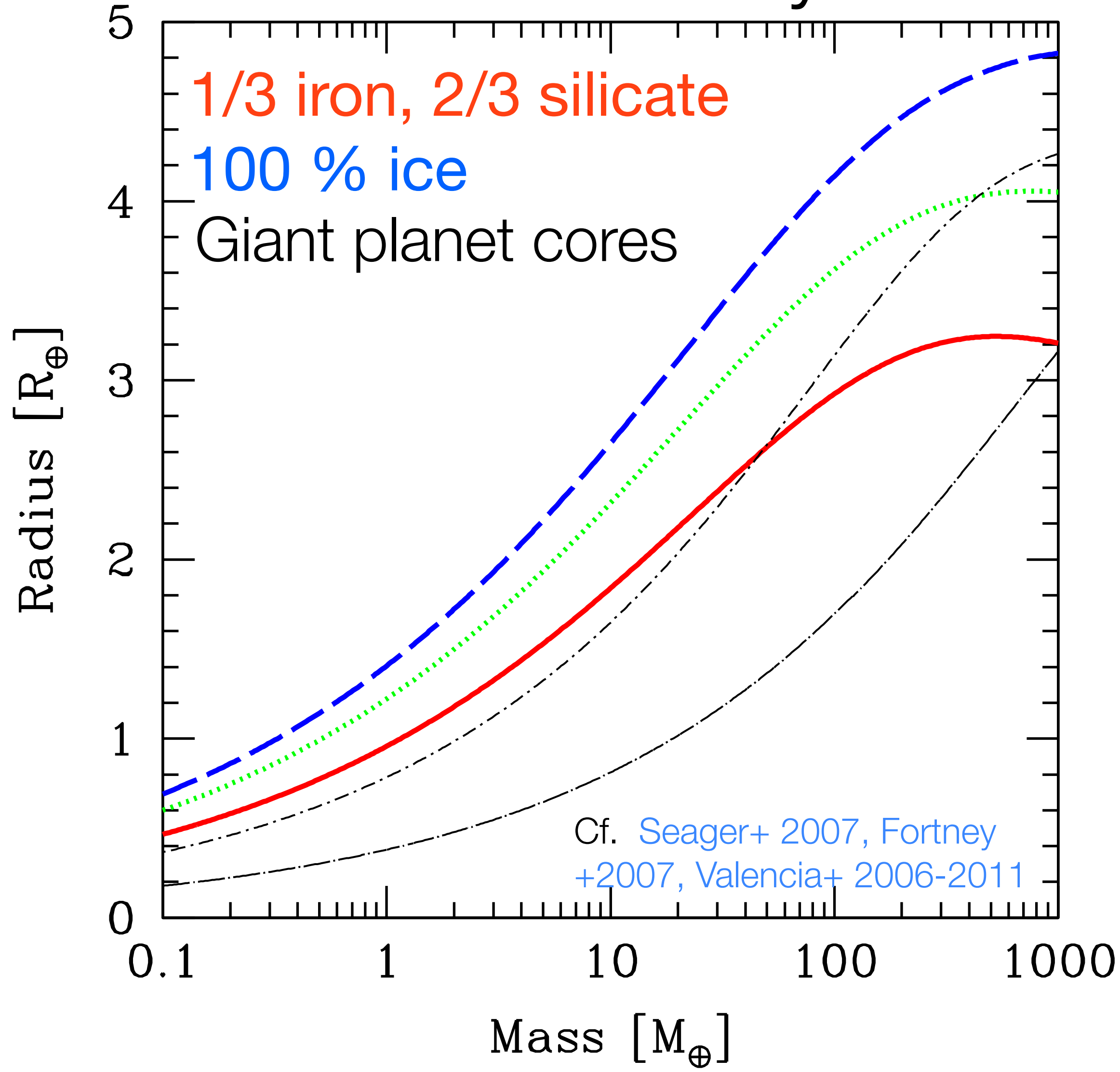


I Model

Core accretion + disk evolution + migration

Upgraded planet model

Variable core density



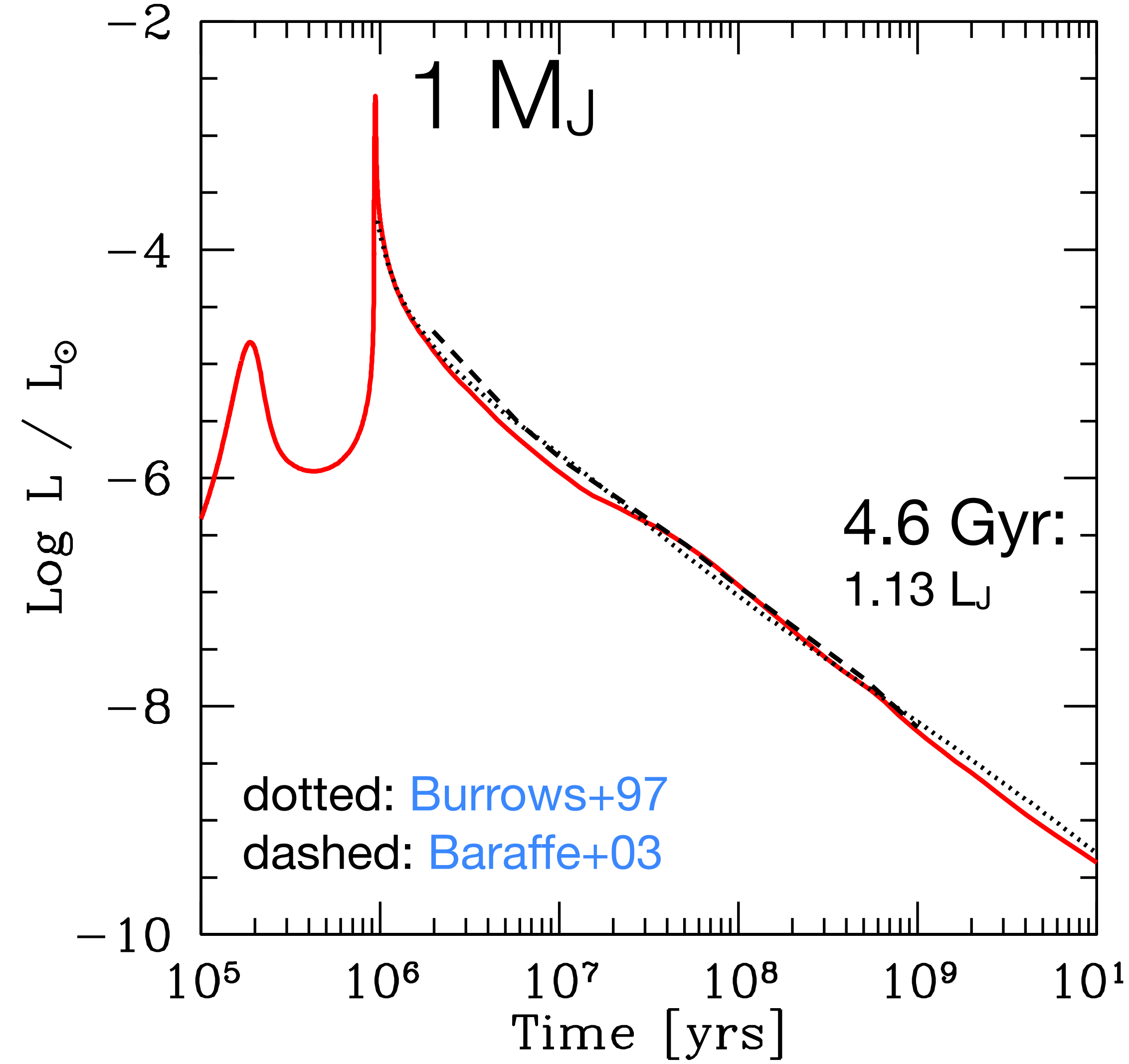
Simple three layer differentiated planet model:

-iron/nickel, silicates, and if accretion at $a > a_{snow}$ ices. EOS from Seager+ 2007

-Includes effect of external pressure (cores).

-Core luminosity from radioactive decay, assuming chondritic composition.

Coupled long term evolution



-Simple, grey atmosphere

$$P = \frac{2g}{3\kappa} \qquad T_{\rm int}^4 = \frac{L_{\rm int}}{4\pi\sigma R^2}$$

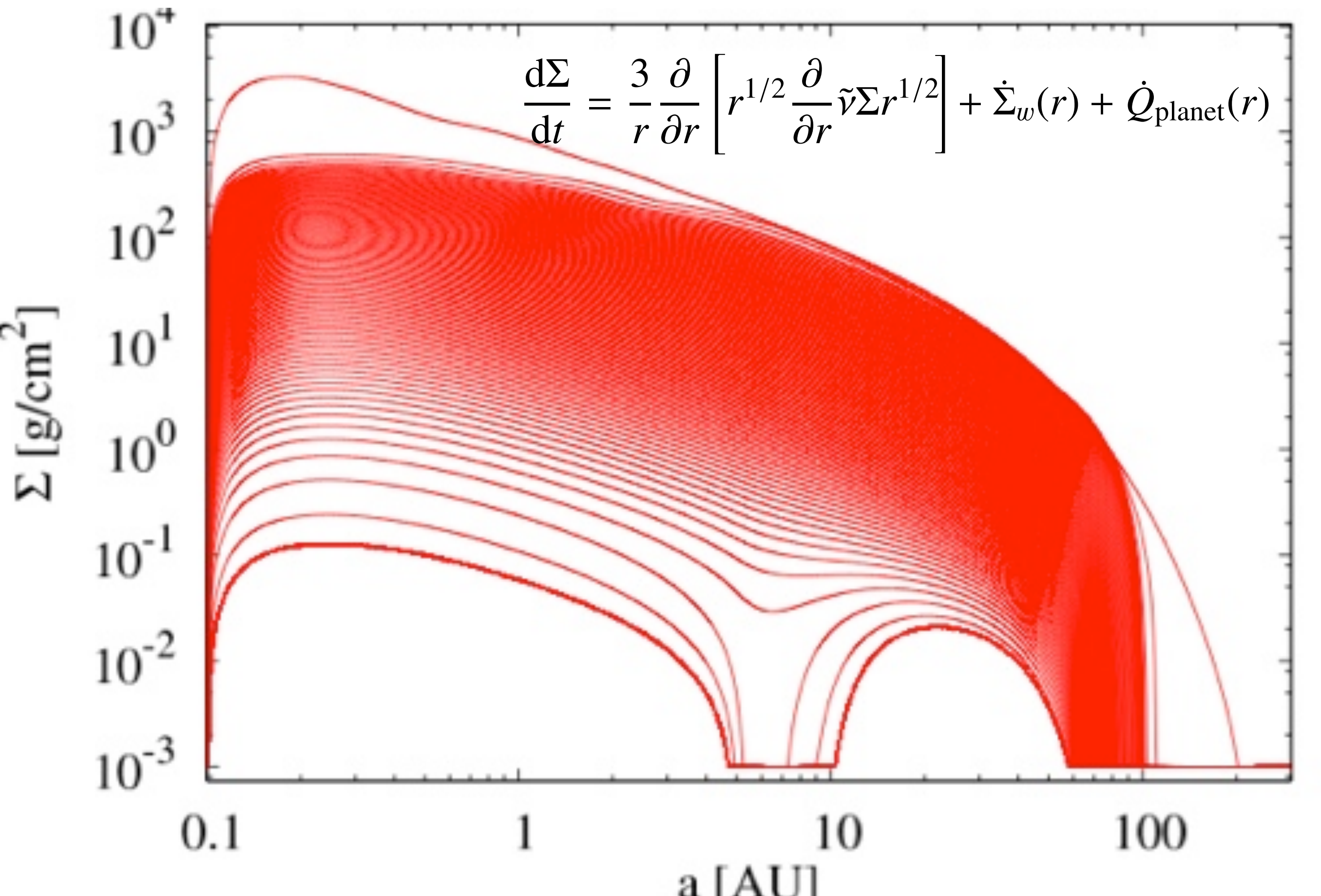
$$T_{\rm equi} = 280\,{\rm K}\left(\frac{a}{1{\rm AU}}\right)^{-\frac{1}{2}}\left(\frac{M_*}{M_\odot}\right) \qquad T^4 = (1-A)T_{\rm equi}^4 + T_{\rm int}^4$$

- Gas opacities from Freedman+ 2008

-Gives radius and luminosity at any moment, inkl. collapse (Lissauer+ 2009)

Upgraded disk & migration model

Disk gas surface density (1+1D α model)



Viscosity, photoevaporation, planet accretion.

New:

-stellar irradiation

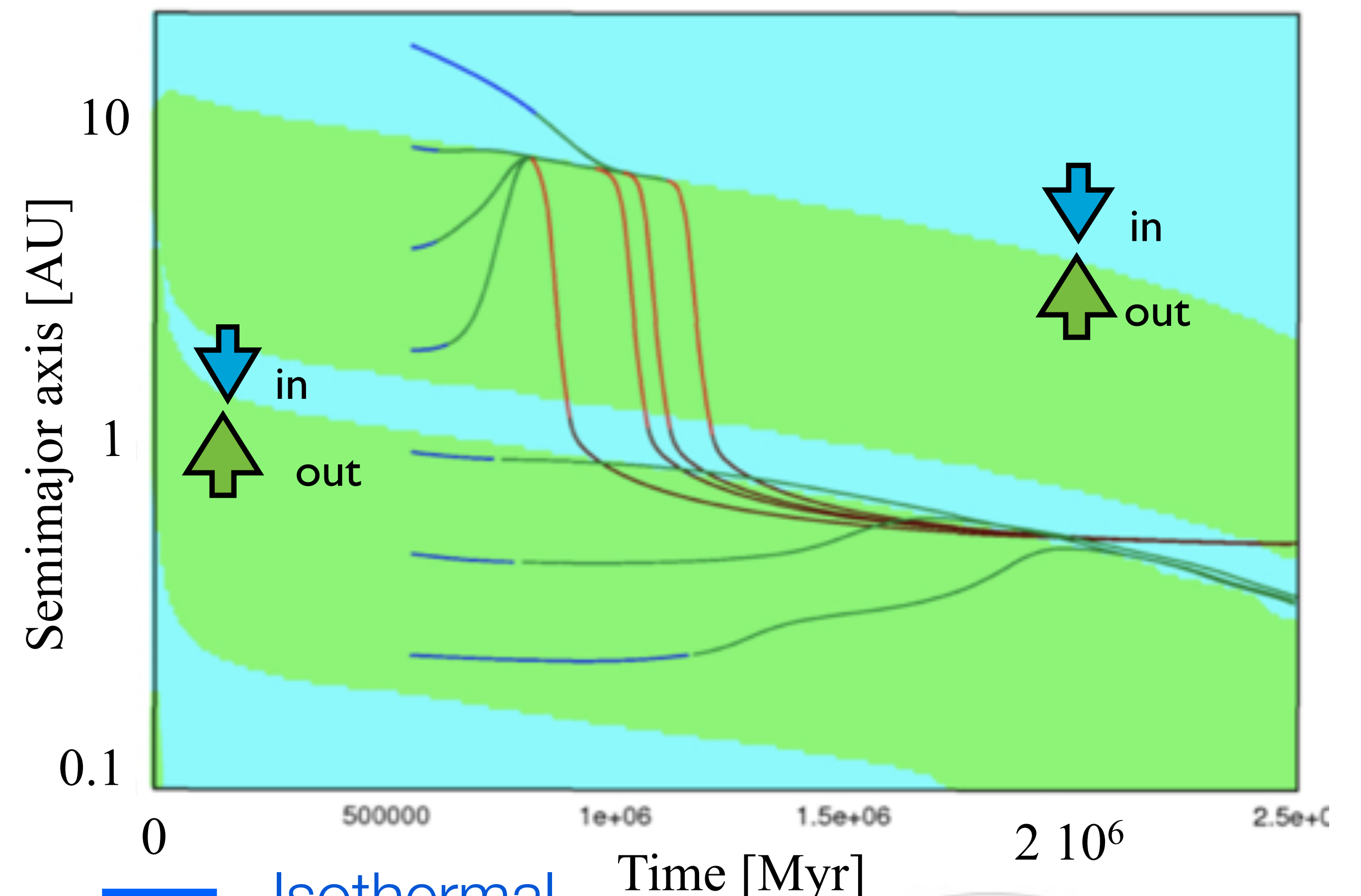
-external photoevaporation Matsuyama+ 2003

-internal photoevaporation Clarke+ 2001

-updated initial profile Andrews+ 2009

$$\Sigma(r, t=0) = \Sigma_0 \left(\frac{r}{R_0}\right)^{-\gamma} \exp\left[-\left(\frac{r}{R_c}\right)^{2-\gamma}\right]$$

Non-isothermal type I migration

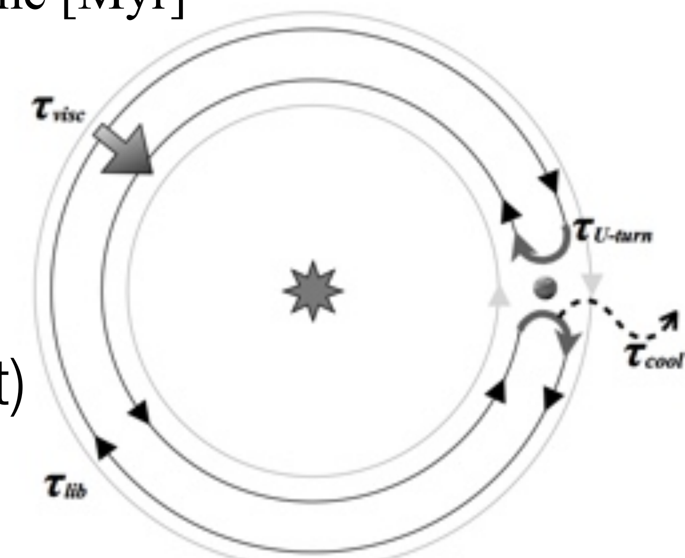


Isothermal

Adiabatic

Ad. saturated

Type II



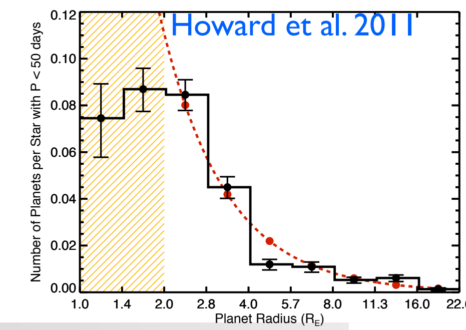
Different regimes (in/out) found w. timescales

(Kley & Crida 2008, Kley et al. 2009, Paardekooper et al. 2010, Baruteau & Lin 2010, Bitsch et al. 2011...)

11 Population synthesis

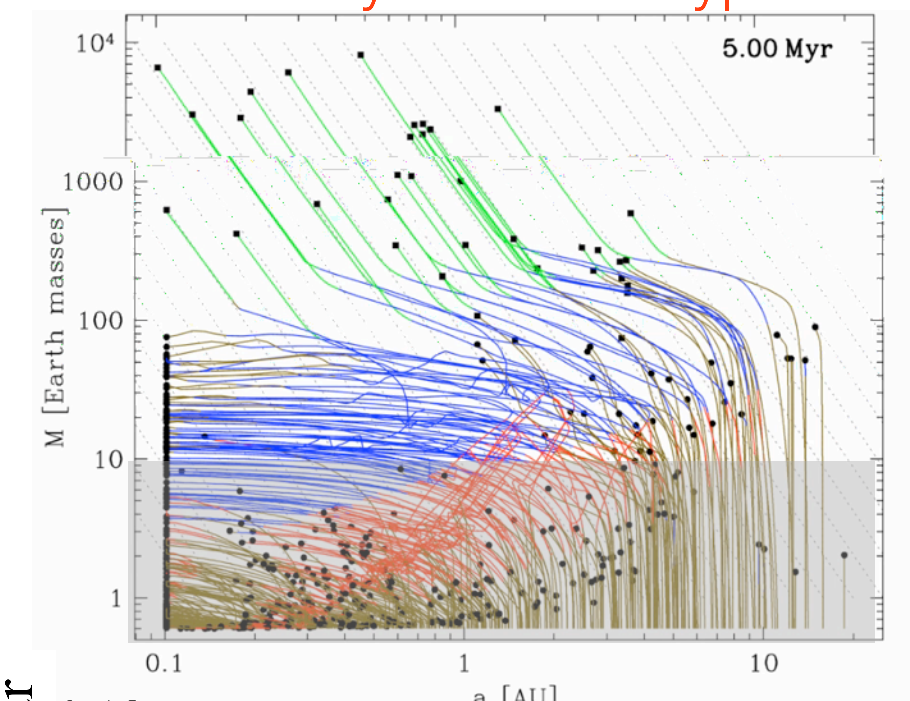
Vary initial conditions of formation model according to observed distributions of metallicity, disk mass and disk lifetime.

Formation tracks - Kepler comparison



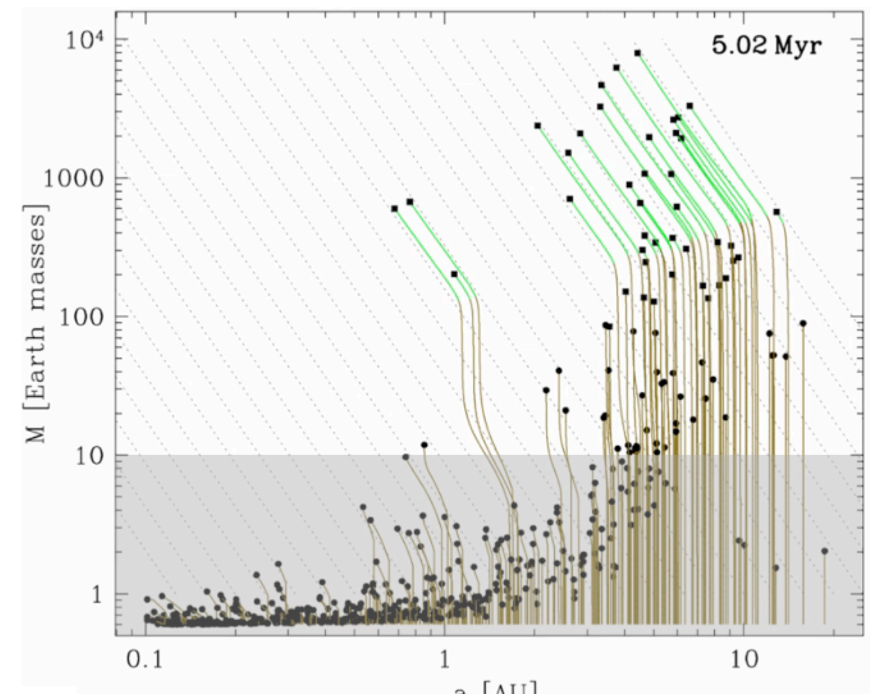
Mstar=1Msun, Memb,0=0.6 Mearth, irradiated disk, viscosity alpha=7×10^{-3}

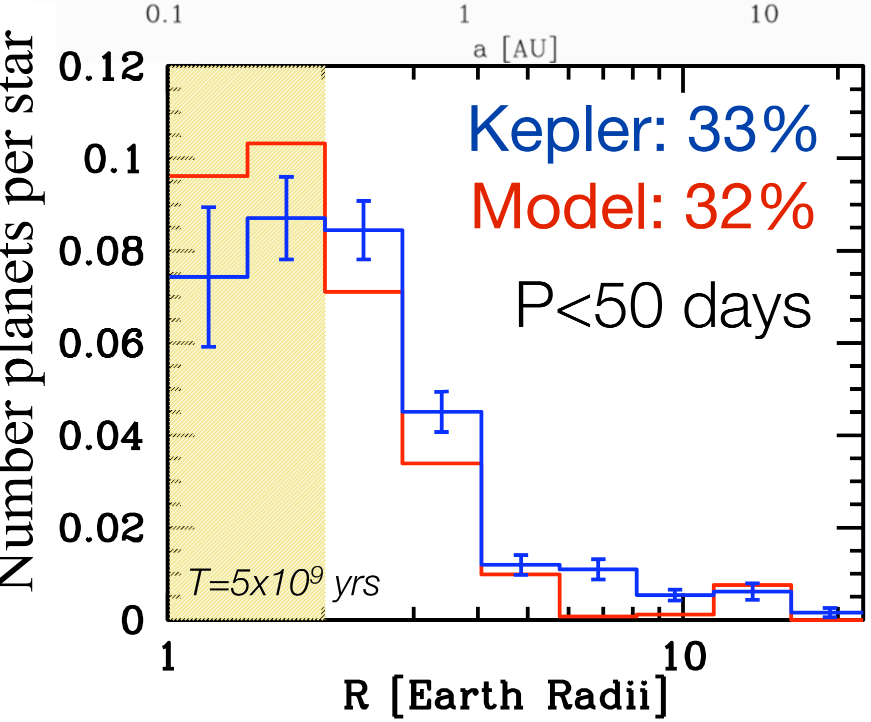
Nominal Model.
Updated Type I.
No efficiency factor for type I !



- Diversity!
- Can form both giant planets and close-in low mass planets.
- Migration still too rapid (giants).
- Imprint of convergence zones.

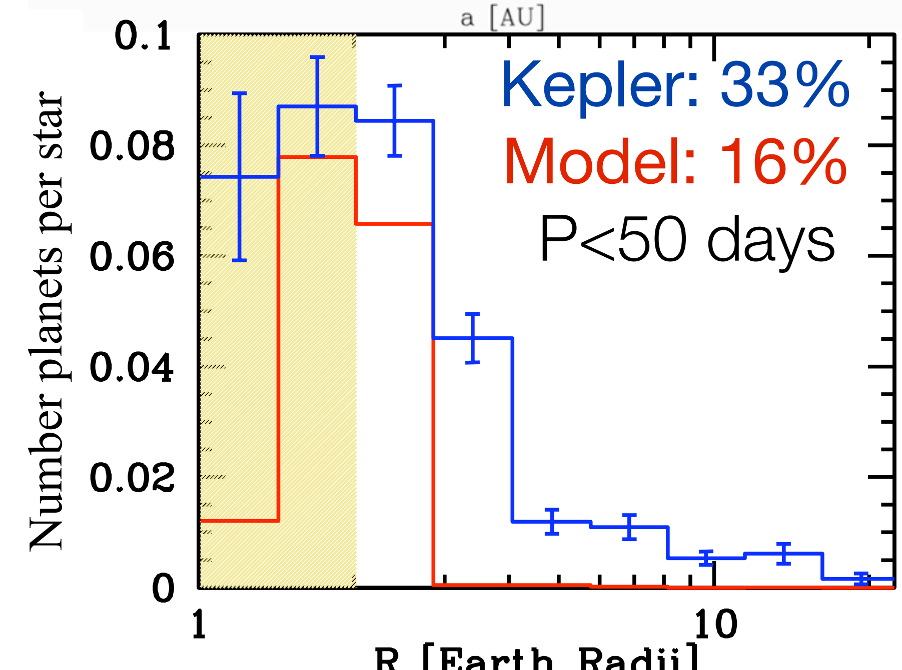
Isothermal Type I.
Tanaka f_1=0.01
Almost no type I migration.





- Generally good agreement:
  - Increase towards small radii.
  - Many low radii.
  - Hot Jupiter 0.5-1%
  - Even in absolute fraction.

But no bimodality...!

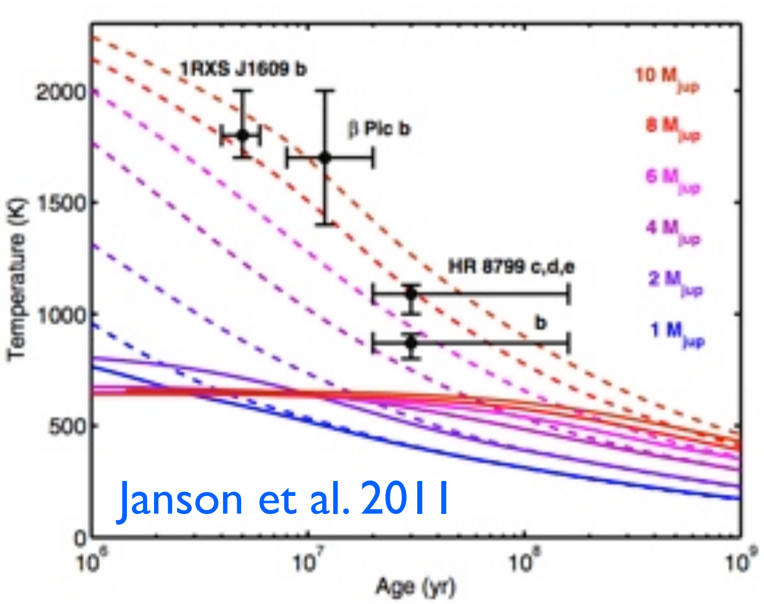


Luminosity of young Jupiters revisited

Use updated model to revisit luminosity of young Jupiters. Same model as normally used for population synthesis. Also as illustration that population synthesis formation model contains quite some physics.

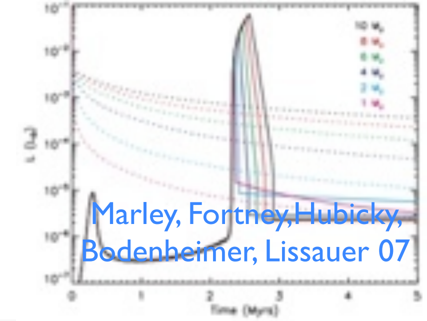
- Hot start: Start with fully formed planet, at (arbitrarily) large luminosity (entropy) and radius. Outcome of direct collapse / disk instability (?).

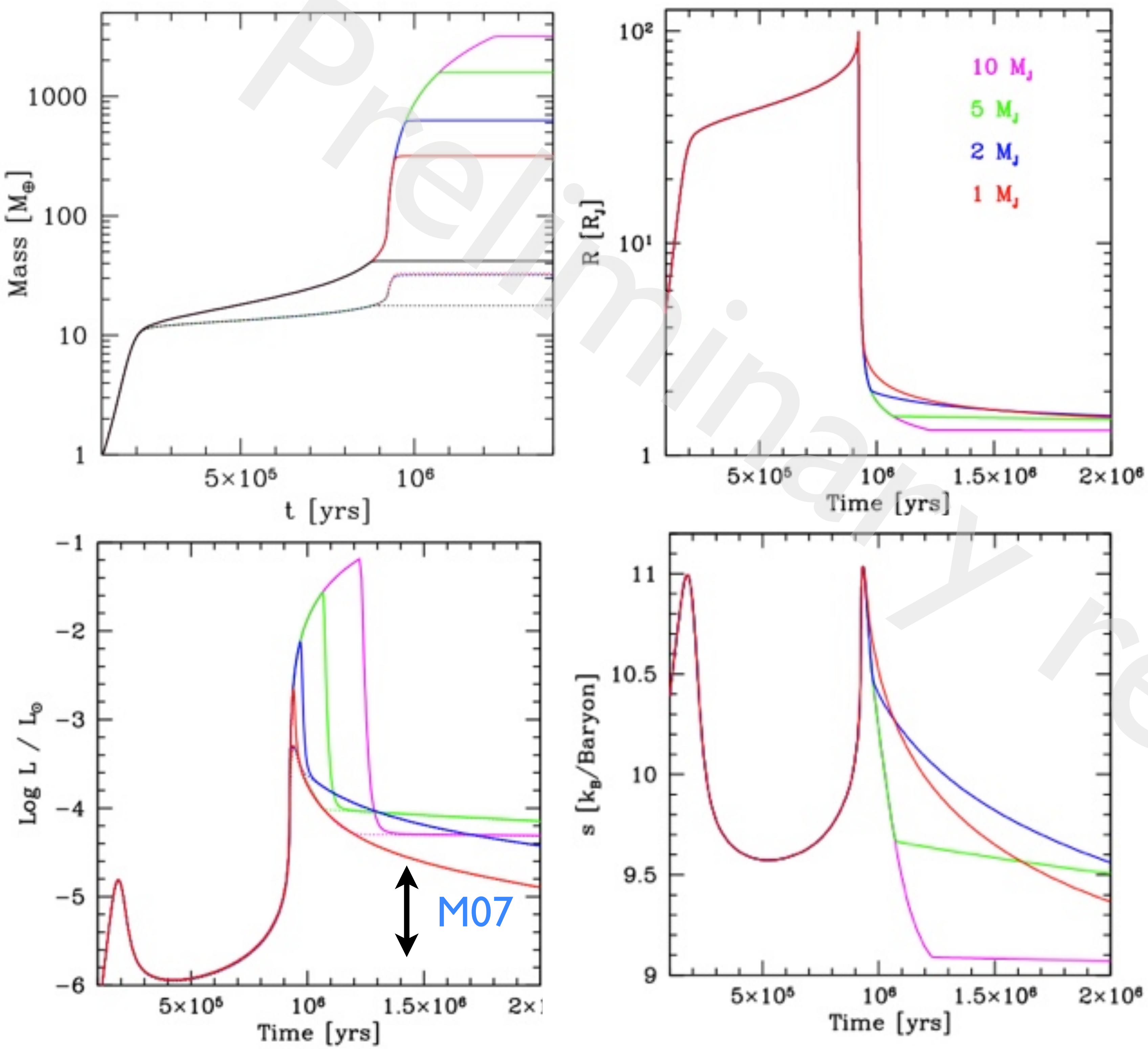
- Cold start: Gradually build up planet (core accretion). Accrete gas through accretion shock. Radiative loss of gravitational potential energy liberated at the shock. Lower initial luminosity and radius.



Currently known direct imaging planets are better reproduced by hot start models.

New cold start models



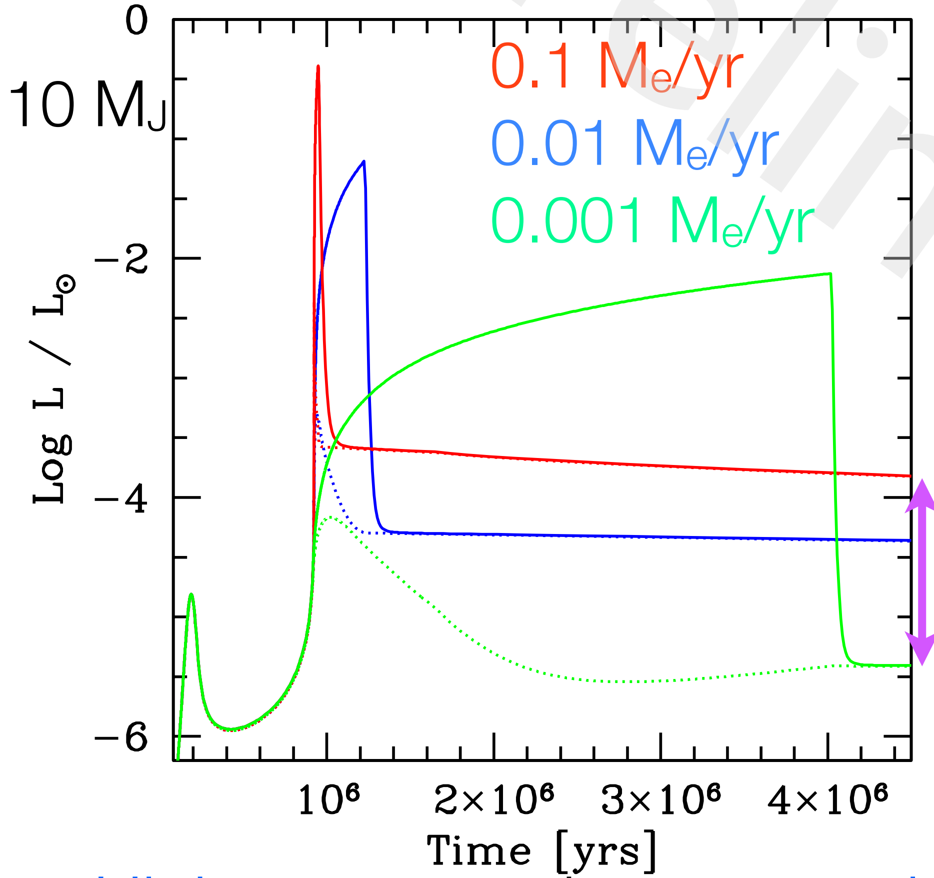


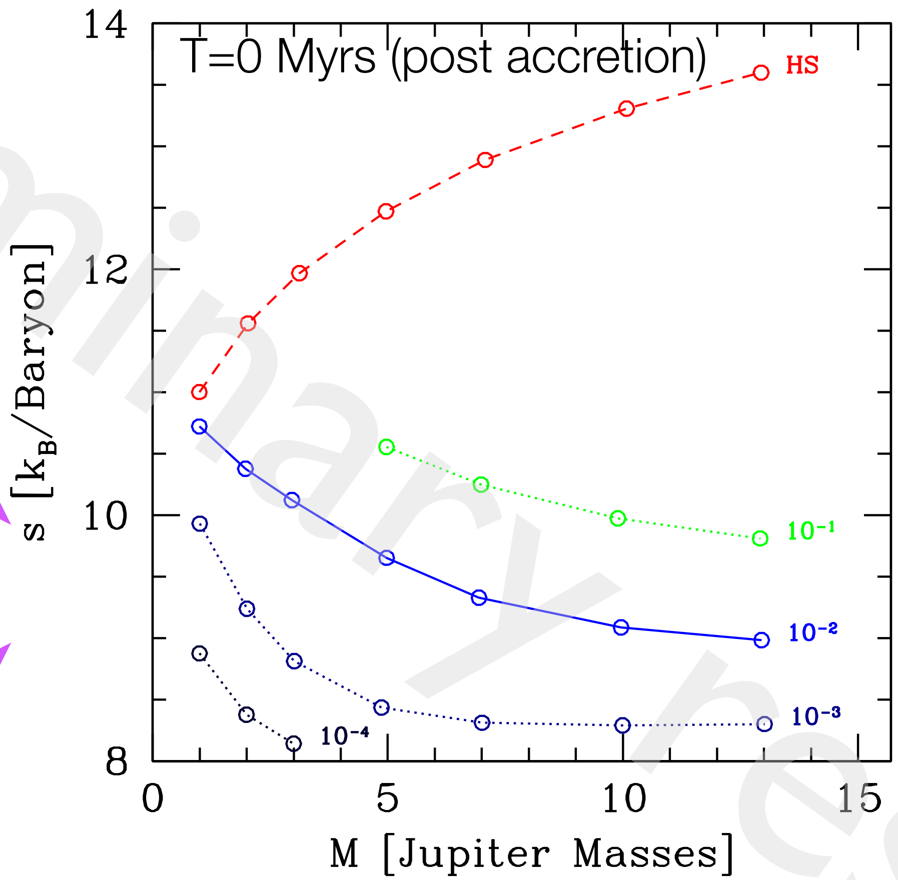
- Initial conditions like J1 in Pollack+ 1996. 1, 2, 5, 10 M_J. In situ. $\dot{M}_{max}$=0.01 M_e/yr. Low grain opacity.
- ALL accretional luminosity radiated away at the shock.
- As in Marley+ 2007, low L at end of formation. But somewhat higher L => see below.
- Accretion of low entropy material.

Unique? Dependence on parameters?

Luminosity is a strong function of the gas accretion rate

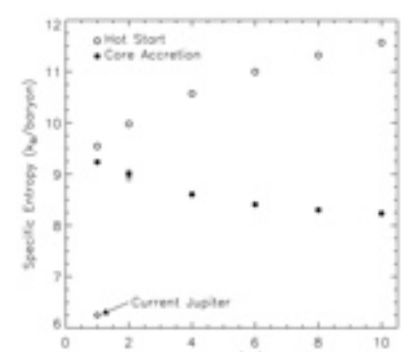
Gas accretion rate in runaway phase: given by disk (no more planet). Can vary!
In full model, $\dot{M}_{max}$ calculated self consistently from disk model.
Here: Consider planet with final mass 10 M_J, with $\dot{M}_{max}$ 0.1, 0.01 and 0.001 M_e/yr.

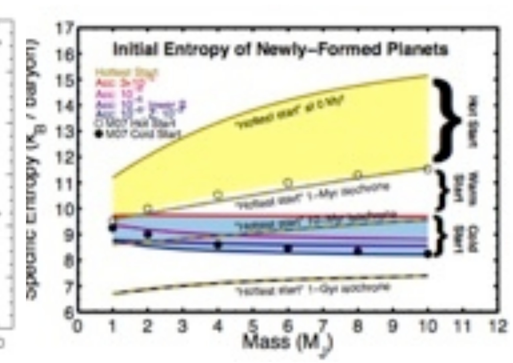




"Fork" diagram of initial specific entropies. High s => high L.

Clear $\dot{M}_{max}$ dependence.


Marley+07



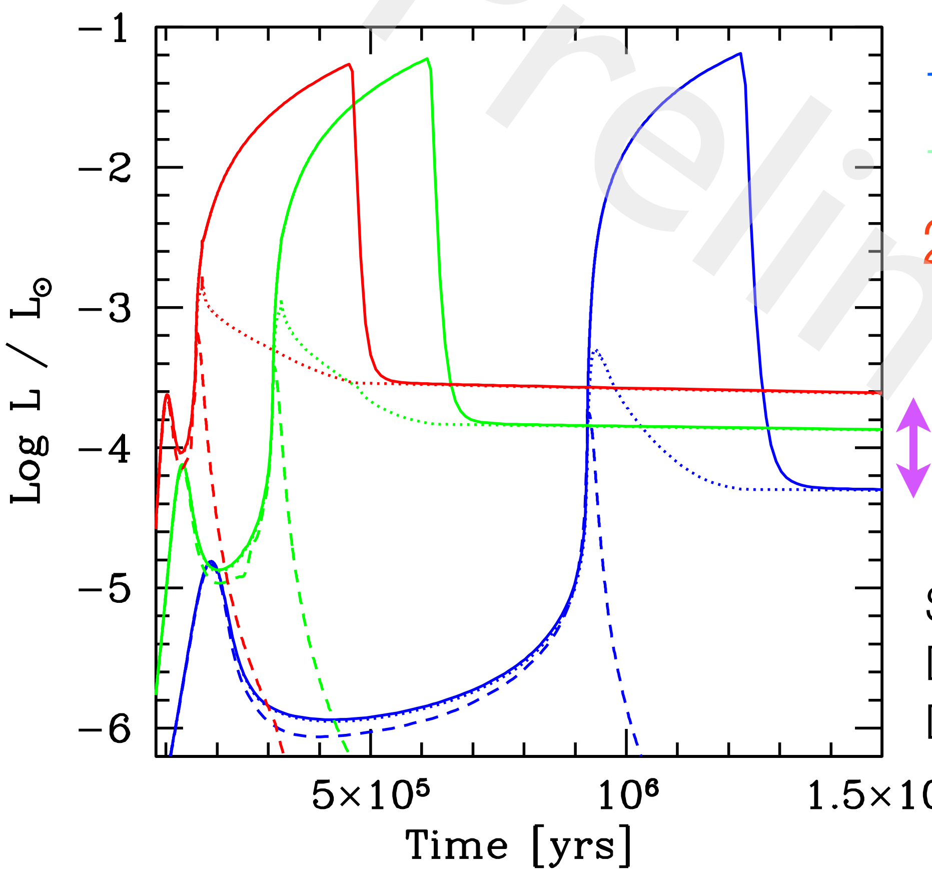
Spiegel & Burrows '11

- High gas accretion rate => high luminosity: almost 2 orders of magnitude difference.
- Accretion timescale vs. contraction timescale
- $t_{accr} \ll t_{cont}$ (high $\dot{M}_{max}$): high fraction of mass already accreted while the planet is still big. Less low entropy matter accreted through the shock.
- The higher $\dot{M}_{max}$, the closer we get to the hot start model which (formally) has a vanishing or very small t_{accr}.

Luminosity is a function of the core mass I

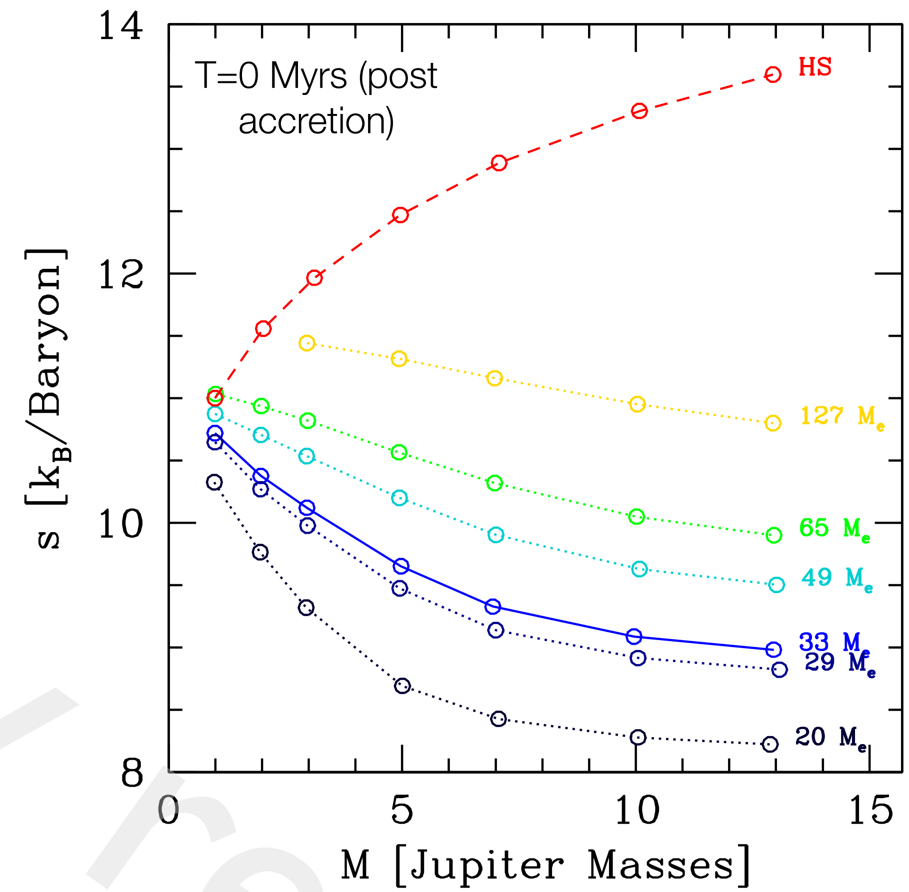
Planetesimal surface density: The higher, the shorter time till runaway and the larger M_{core}.

10 M_J, Initial planetesimal surface density $\Sigma_{p,0}$: 10, 15, 20 g/cm^2. $\dot{M}_{max} = 10^{-2}$ M_e/yr



10 => M_{core} 33 M_e
15 => M_{core} 49 M_e
20 => M_{core} 65 M_e

Solid: total L
Dotted: intrinsic L
Dashed: core L

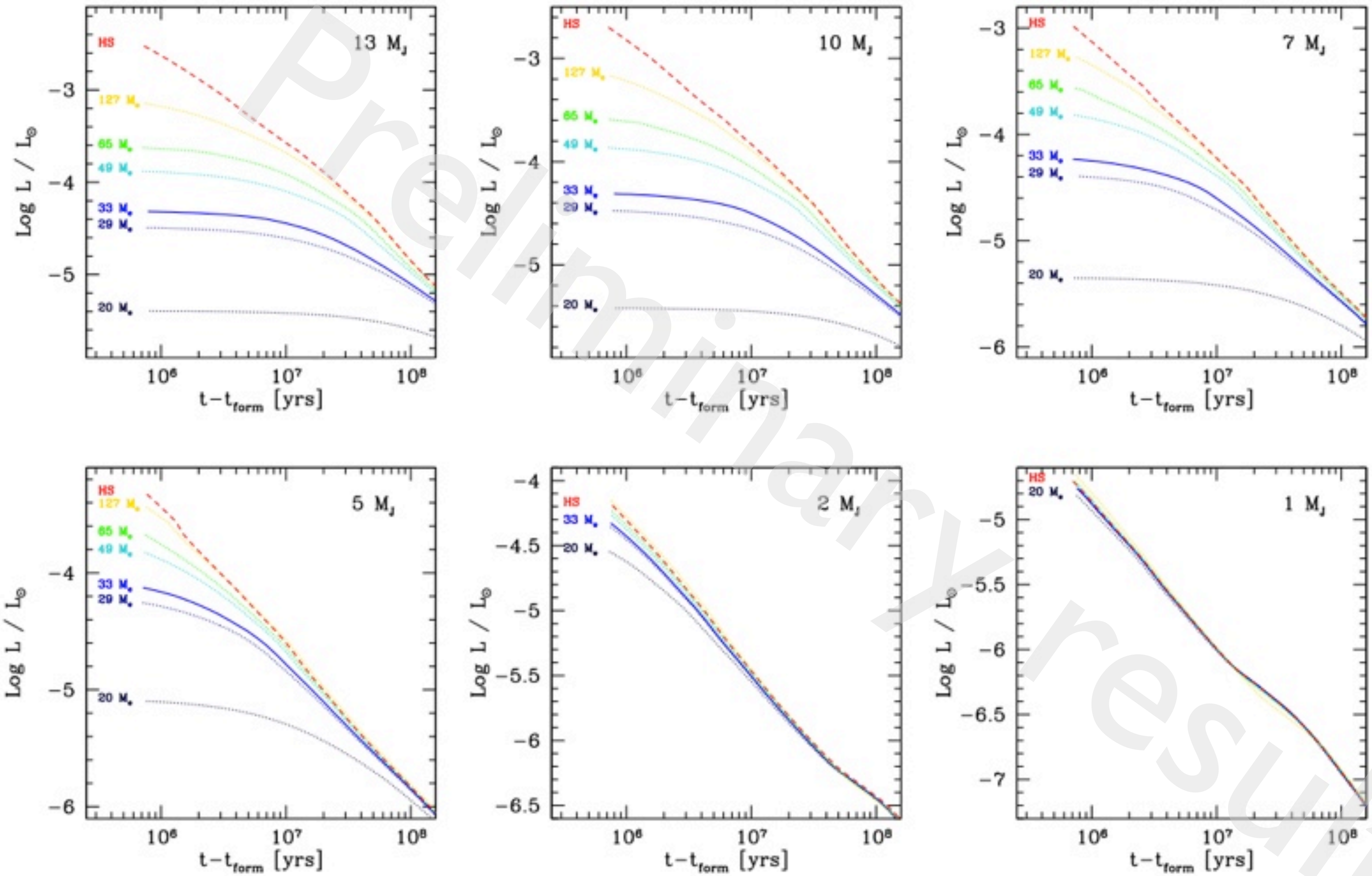


Initial specific entropy clearly depends on M_{core}.

New effect.

- During approach to runaway, L_{core} is a non-negligible contribution. Later decrease (R_{capt}).
- Matter contained in envelope when collapse starts is at higher entropy for higher L_{core}. Larger initial R => weaker shock => less radiative loss => difference gets bigger. (self sustaining process). Different M_{core} explains also difference to Marley+2007.
- Caveats: depends on planetesimal random velocity & planetesimal-protoplanetary envelope interaction. No dependence of opacity on $\Sigma_{p,0}$ included here (cf Spiegel & Burrows 2011).

Luminosity is a strong function of the core mass II: L (t, M, M_{core})



Red line: Hot start

Other lines, cold start with different $\Sigma_{p,0}$ and thus M_{core}

Hot start and cold start with massive core identical after 1 to 10 Myrs.

Planets with M_{core}>100 M_e do exist (Leconte et al. 2010).

Very large differences in luminosity for higher mass planets depending on core mass, remaining up to 10^8 years. Again, there is no such thing as one unique “cold start” luminosity.

(Preliminary) Conclusion

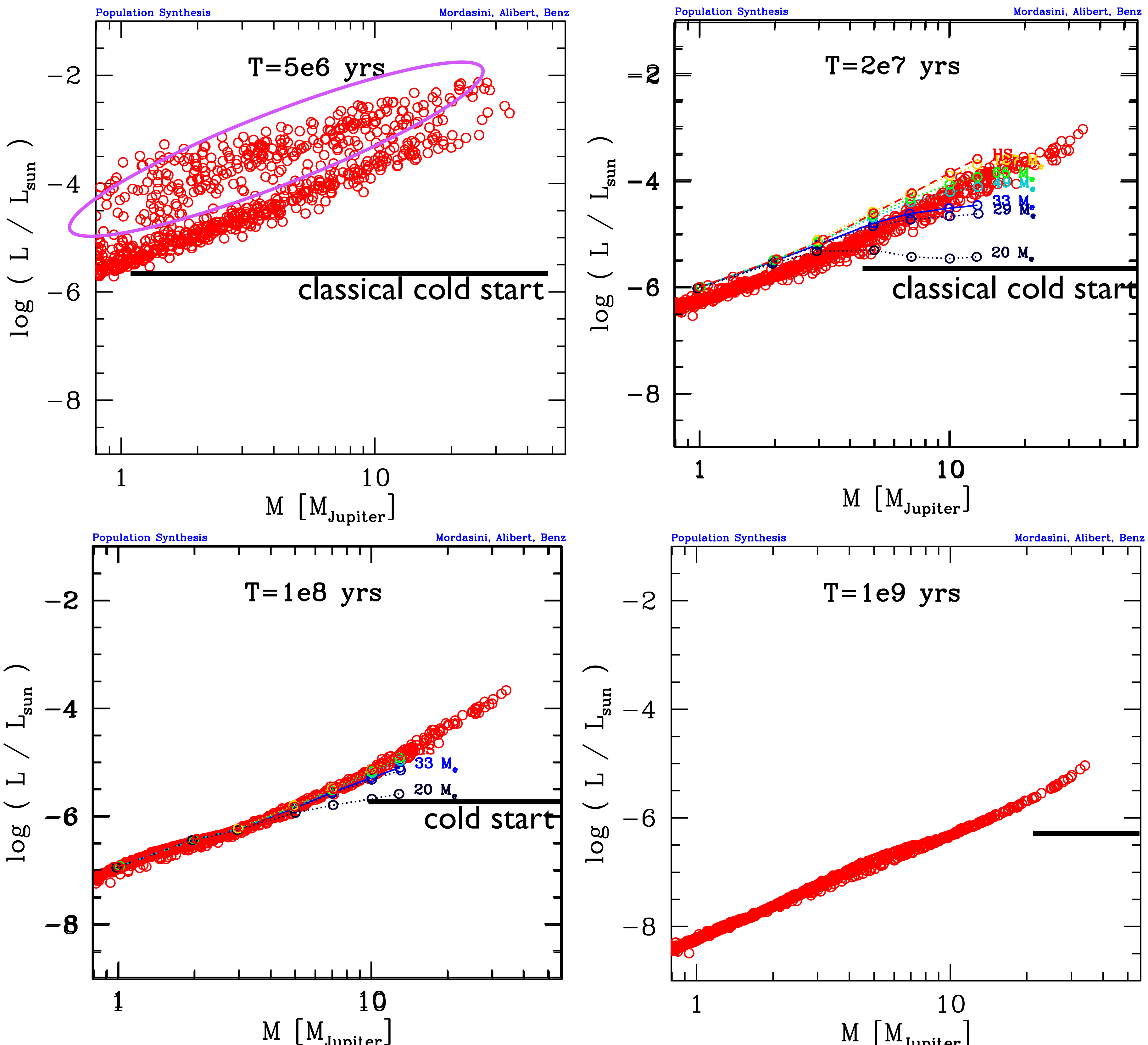
It is impossible to derive the formation mechanism or the mass from measuring the luminosity by direct imaging.

L can be anything.

Really?

Bring back in population synthesis!

Core Accretion is hot



Nominal population
M_{star}=1 $M_\odot$
alpha=7x10^{-3}
a>0.3 AU

Final conclusion from pop. synth.

Core accretion leads to L almost as high as Hot Start. $M_Z \geq 40\ M_e$. At least from this point, CA reproduces also planets at large distances. It leads to a relatively well defined M-L relation.

Summary

- Presented upgraded core accretion model combining self-consistently formation and evolution.
- Allows characterization of planets in mass, semimajor axis, composition, radius and luminosity from tiny embryo to Gyr old planet.
- Updated type I migration rates allow to obtain populations with a radius distribution similar as observed by Kepler without scaling factors. Giant planets however get still too close.
- Core accretion leads to post formation luminosities almost as high as in the "hot start" scenario. No clear difference to direct collapse model. On the other hand, L(M) is quite well defined.
- The model allows population synthesis results to be compared directly with RV, transits and direct imaging (and microlensing). This combination is the key to better understanding planet formation.