Thermal Evolution of Giant and Rocky Planets

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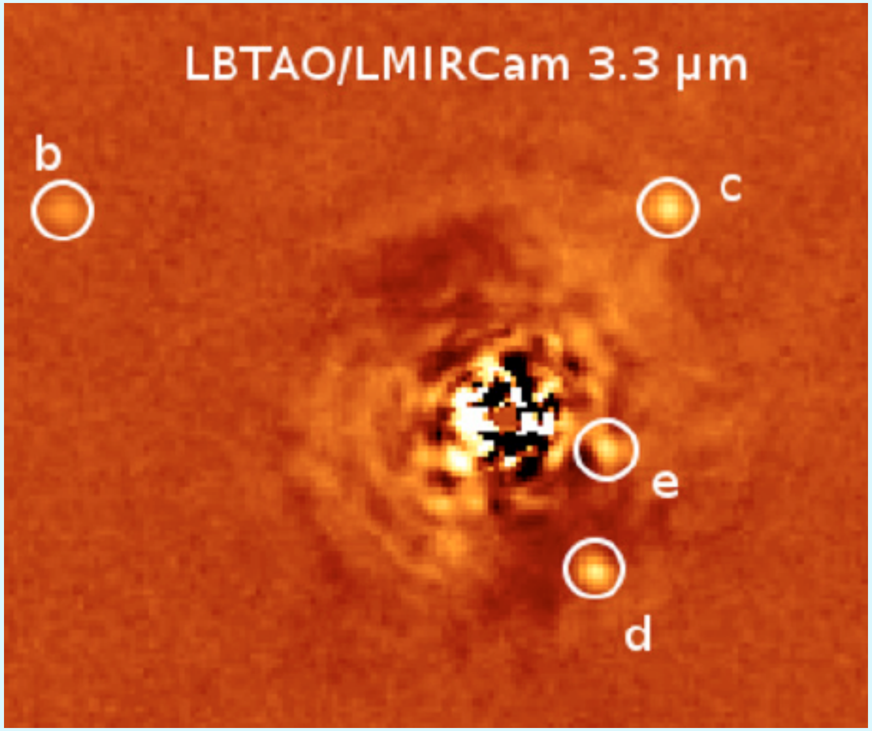
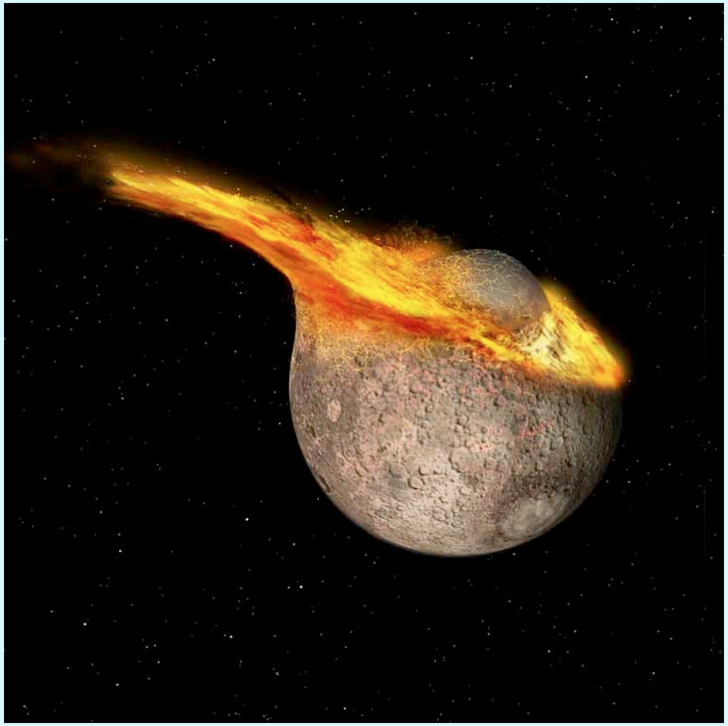
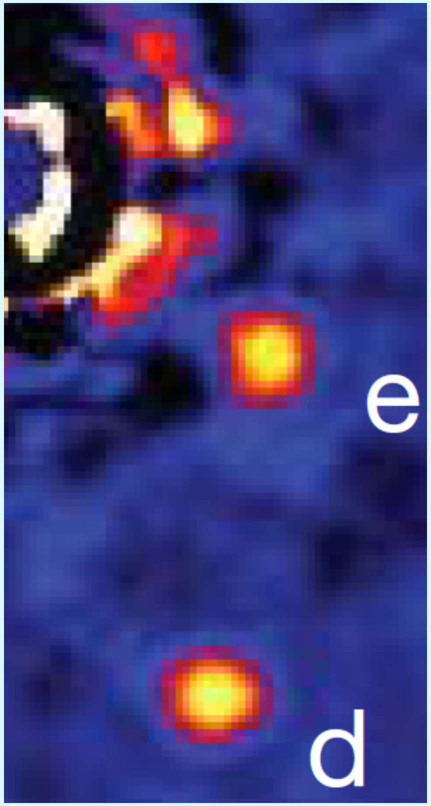




Why are Evolution Models Important?

- For imaged planets, masses are rarely dynamically constrained
- Mass estimates come from measuring the magnitude in 1 (or several) bands (or determining T_{eff}) + *the estimated age*
- Model tracks aim to understand T_{eff} vs. age, for a grid of masses



Example: Baraffe et al. (2003) grid of cloud-free models

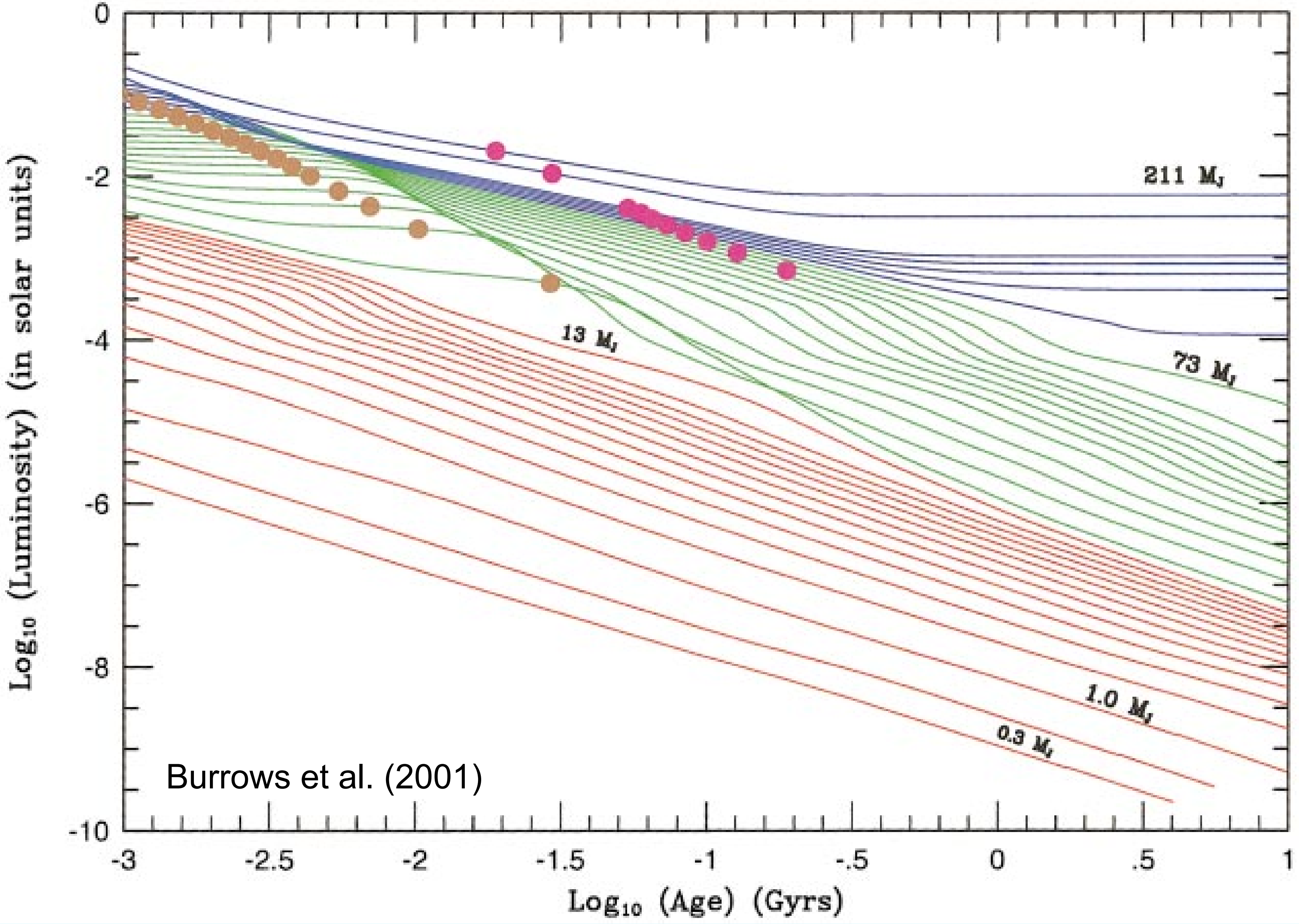
perso.ens-lyon.fr/isabelle.baraffe/COND03_models

GMail GCal NYTimes ESPN WPost SI ADS Fb YMail Exo.eu Mint Bay

t (Gyr) =   0.100

M/Ms	Teff	L/Ls	g	R	Mv	Mr	Mi	Mj	Mh	Mk	Mll	Mm
0.0005	240.	-7.418	3.020	0.114	41.98	37.51	34.00	28.42	26.59	37.66	19.57	17.64
0.0010	309.	-6.957	3.300	0.117	32.58	28.68	25.89	22.43	22.38	29.11	17.41	15.69
0.0020	425.	-6.383	3.580	0.120	29.69	25.62	22.79	20.05	19.76	23.13	15.94	14.55
0.0030	493.	-6.112	3.746	0.121	28.71	24.48	21.66	18.88	18.57	20.88	15.21	13.93
0.0040	563.	-5.880	3.869	0.122	28.09	23.77	20.95	17.95	17.71	19.35	14.59	13.50
0.0050	630.	-5.686	3.965	0.122	27.65	23.25	20.44	17.23	17.02	18.15	14.06	13.14
0.0060	688.	-5.534	4.048	0.121	27.36	22.92	20.09	16.71	16.51	17.26	13.67	12.83
0.0070	760.	-5.365	4.117	0.121	27.03	22.55	19.74	16.16	16.01	16.38	13.26	12.55
0.0080	816.	-5.246	4.180	0.120	26.77	22.28	19.49	15.76	15.65	15.79	12.97	12.35
0.0090	886.	-5.103	4.232	0.120	26.45	21.96	19.19	15.32	15.23	15.16	12.63	12.13
0.0100	953.	-4.978	4.279	0.120	26.10	21.66	18.92	14.94	14.86	14.69	12.34	11.96
0.0120	1335.	-4.332	4.297	0.129	23.53	19.44	16.79	13.20	12.97	12.76	10.90	11.17
0.0150	1399.	-4.281	4.424	0.124	23.30	19.24	16.46	13.05	12.82	12.65	10.83	11.15
0.0200	1561.	-4.110	4.569	0.122	22.30	18.55	16.08	12.60	12.34	12.17	10.53	10.99
0.0300	1979.	-3.668	4.715	0.126	19.96	16.80	14.48	11.52	11.20	10.90	9.82	10.38
0.0400	2270.	-3.386	4.797	0.132	18.46	15.63	13.31	10.89	10.52	10.19	9.39	9.84
0.0500	2493.	-3.167	4.837	0.141	17.09	14.77	12.53	10.43	10.02	9.71	9.04	9.37
0.0600	2648.	-3.008	4.863	0.150	16.08	14.12	12.01	10.10	9.68	9.37	8.78	9.03
0.0700	2762.	-2.879	4.874	0.160	15.33	13.59	11.60	9.82	9.39	9.10	8.55	8.75
0.0720	2782.	-2.856	4.875	0.162	15.20	13.50	11.53	9.77	9.34	9.05	8.51	8.70
0.0750	2809.	-2.821	4.875	0.166	15.01	13.36	11.42	9.69	9.26	8.97	8.44	8.63
0.0800	2846.	-2.776	4.880	0.170	14.77	13.18	11.29	9.60	9.16	8.87	8.36	8.53
0.0900	2910.	-2.689	4.884	0.180	14.34	12.85	11.03	9.40	8.96	8.68	8.19	8.35
0.1000	2960.	-2.617	4.887	0.189	14.02	12.58	10.82	9.24	8.80	8.52	8.05	8.19

Atmosphere models are essential, because they tell you T_{eff} of a given internal structure



Log10 (Luminosity) (in solar units)
Log10 (Age) (Gyrs)
211 MJ
73 MJ
13 MJ
1.0 MJ
0.3 MJ
Burrows et al. (2001)

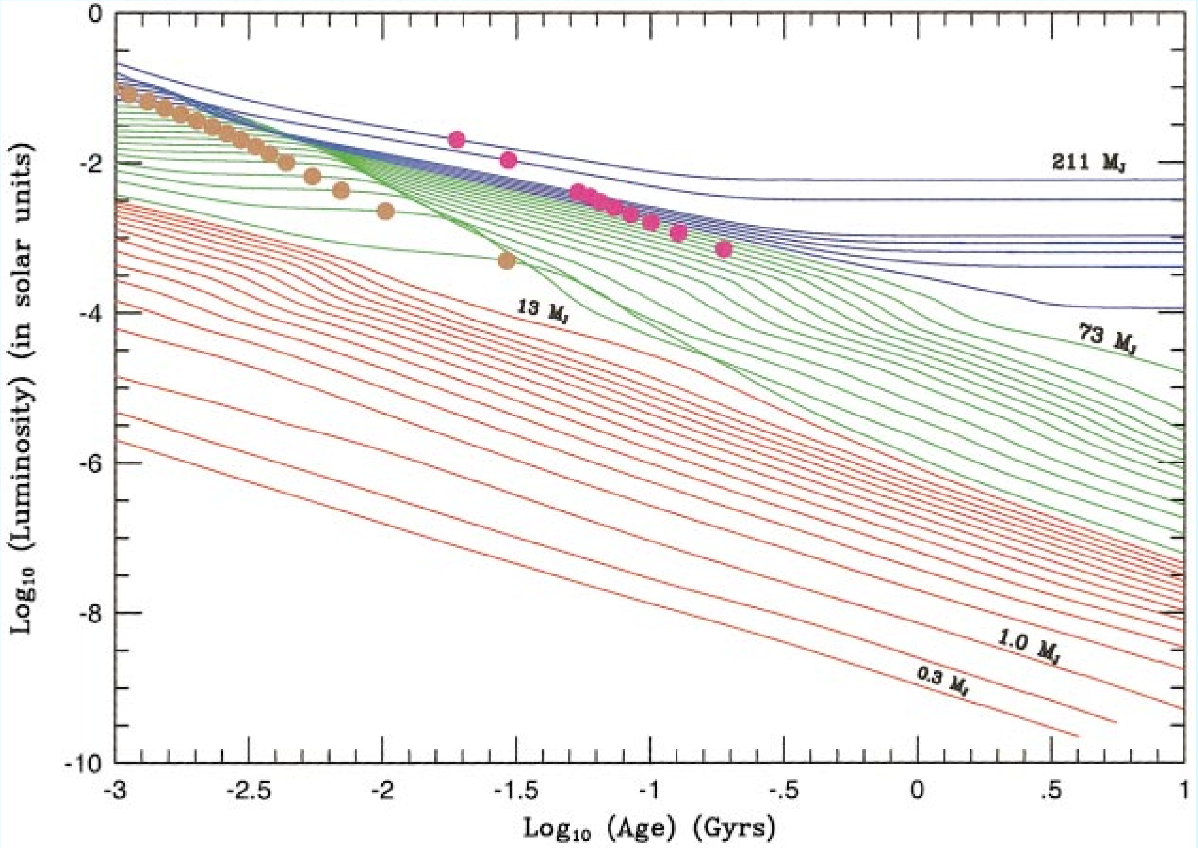
$$\frac{\partial P}{\partial M_r} = -\frac{GM_r}{4\pi r^4} - \frac{1}{4\pi r^2}\frac{\partial^2 r}{\partial t^2},$$

$$\frac{\partial r}{\partial M_r} = \frac{1}{4\pi r^2 \rho},$$

$$\frac{\partial T}{\partial M_r} = -\frac{3\kappa L_r}{64\pi^2 ac T^3 r^4},$$

$$\frac{\partial L_r}{\partial M_r} = \epsilon - T\frac{\partial S}{\partial t}.$$

TdS=dQ=dU+PdV



- Upper boundary condition is quite important
  - For fully convective objects, the radiative atmosphere dictates cooling
  - *Stellar tie in*: Analytic models of the Hayashi track show location depends entirely on atmospheric opacities (e.g. Kippenhahn et al. Section 24.2)

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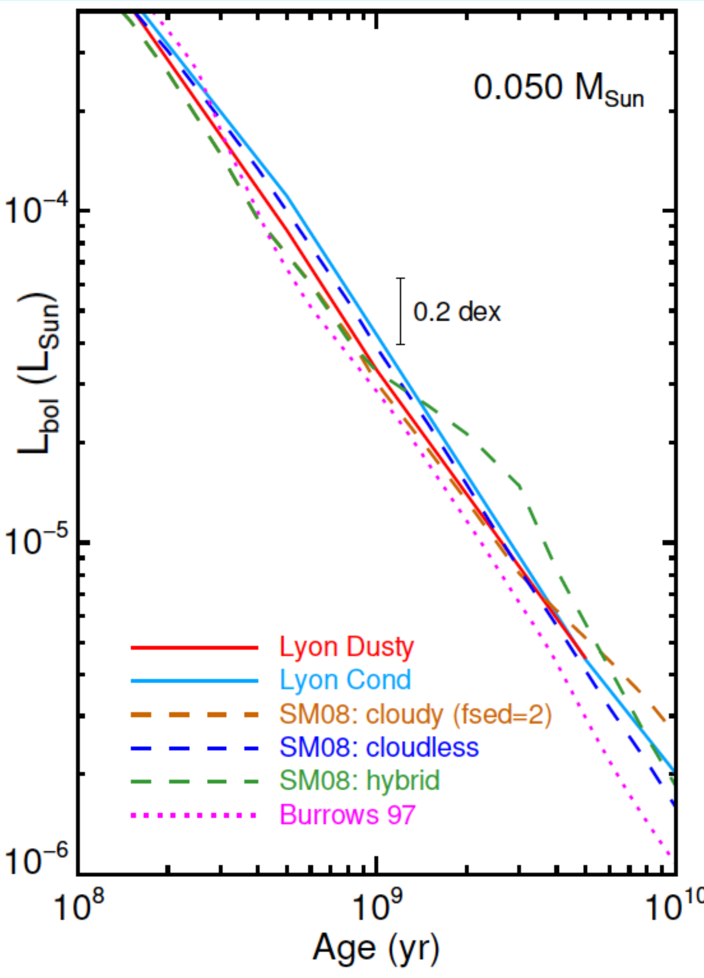
Most widely used:

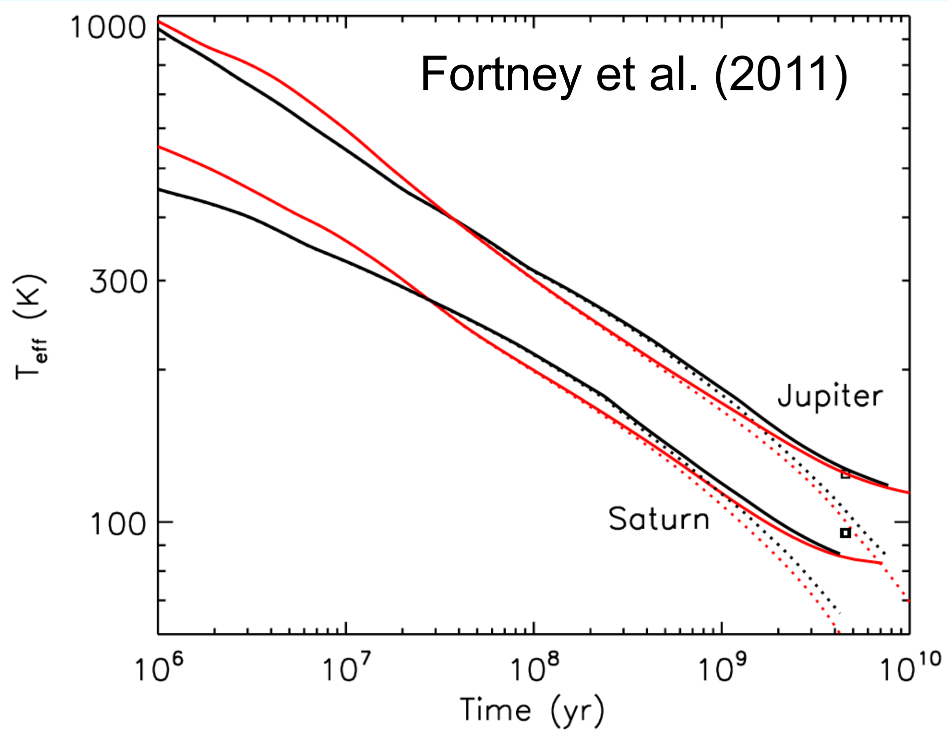
- Burrows et al. (1997), classic, but "showing their age," partially updated in Spiegel & Burrows (2012) below 10 M_J
- Chabrier et al. (2000), maximally DUSTY case
- Baraffe et al. (2003), same chemistry as DUSTY, but dust opacity removed
  - Both are approximations in terms of real chemistry
- Saumon & Marley (2008)
  - Include a transition from cloudy to cloud-free at a T_{eff} that matches observations. Also Fortney et al. (2008)

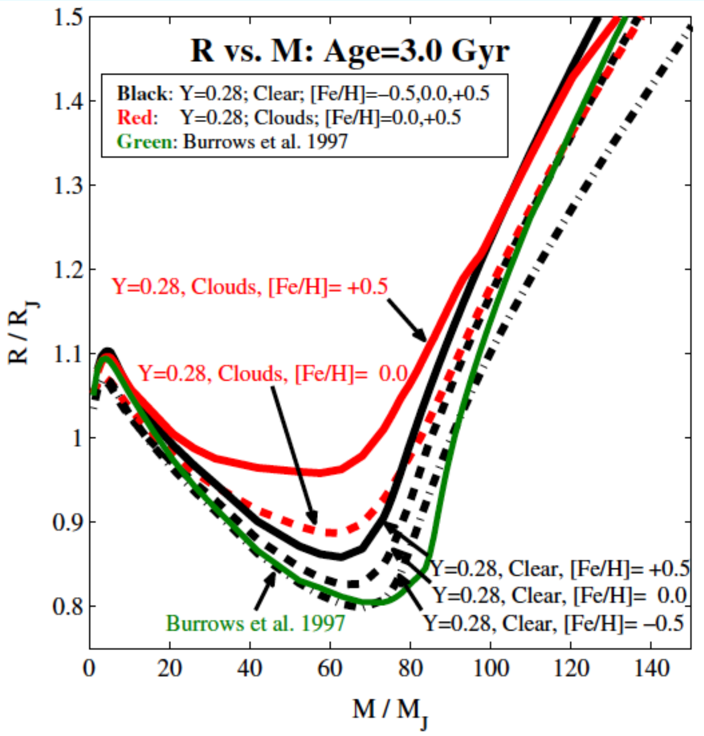


Dupuy et al. (2014)

- All the models use the same H/He EOS. Most of the "free parameters" (so far) are really in the atmosphere

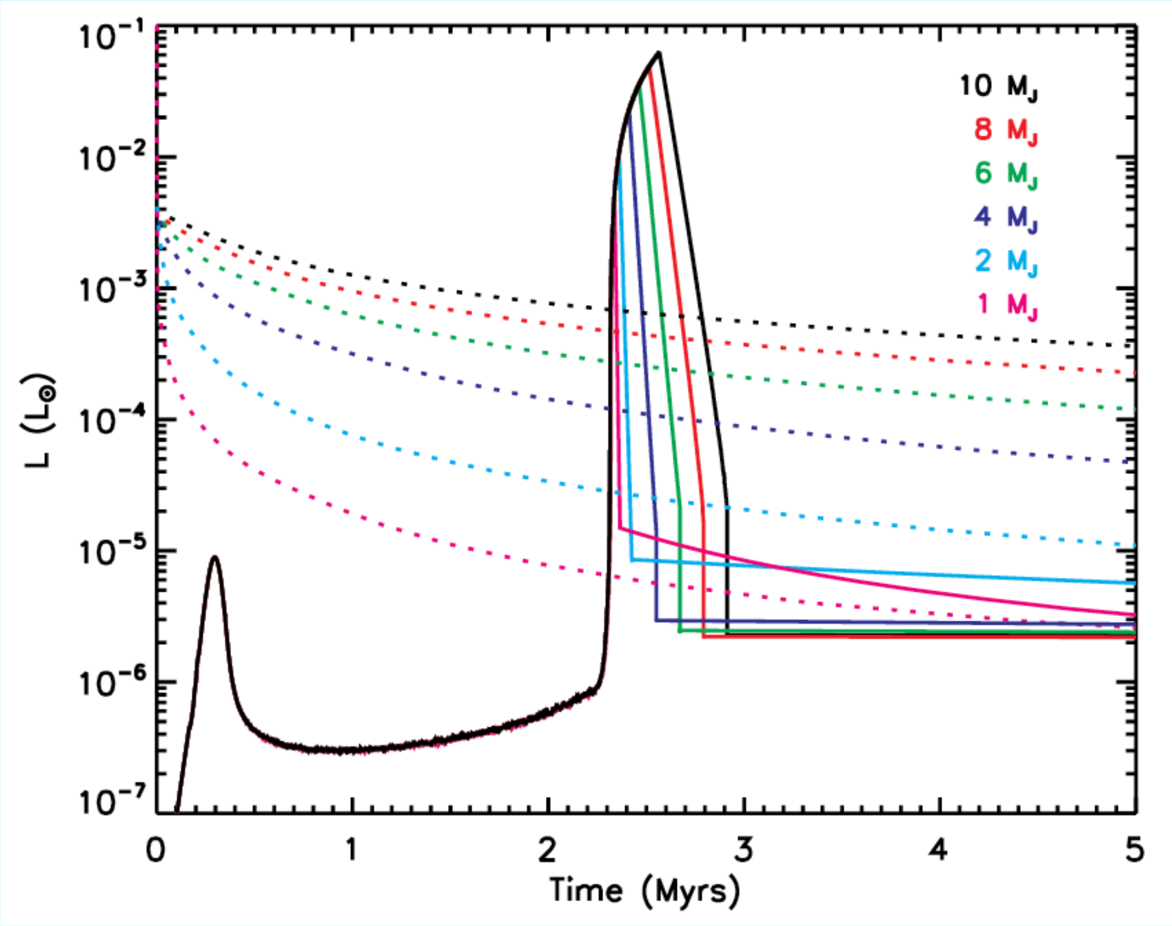
- **Do the models "work?"**
- Yes, for Jupiter
  - Jupiter is old and "low mass", and directly imaged planets are generally young (and more massive)
- "Benchmark" brown dwarfs with well-determined masses and ages suggest that models under-predict the luminosity of cloudy L dwarfs by ~2x (e.g. Dupuy et al. 2014). This is a ~30% mass error.
- Strongly irradiated objects are an imperfect test





Burrows et al. (2013)

Initial Conditions: Particularly Important for Directly Imaged Planets



Initial Conditions: Particularly Important for Directly Imaged Planets

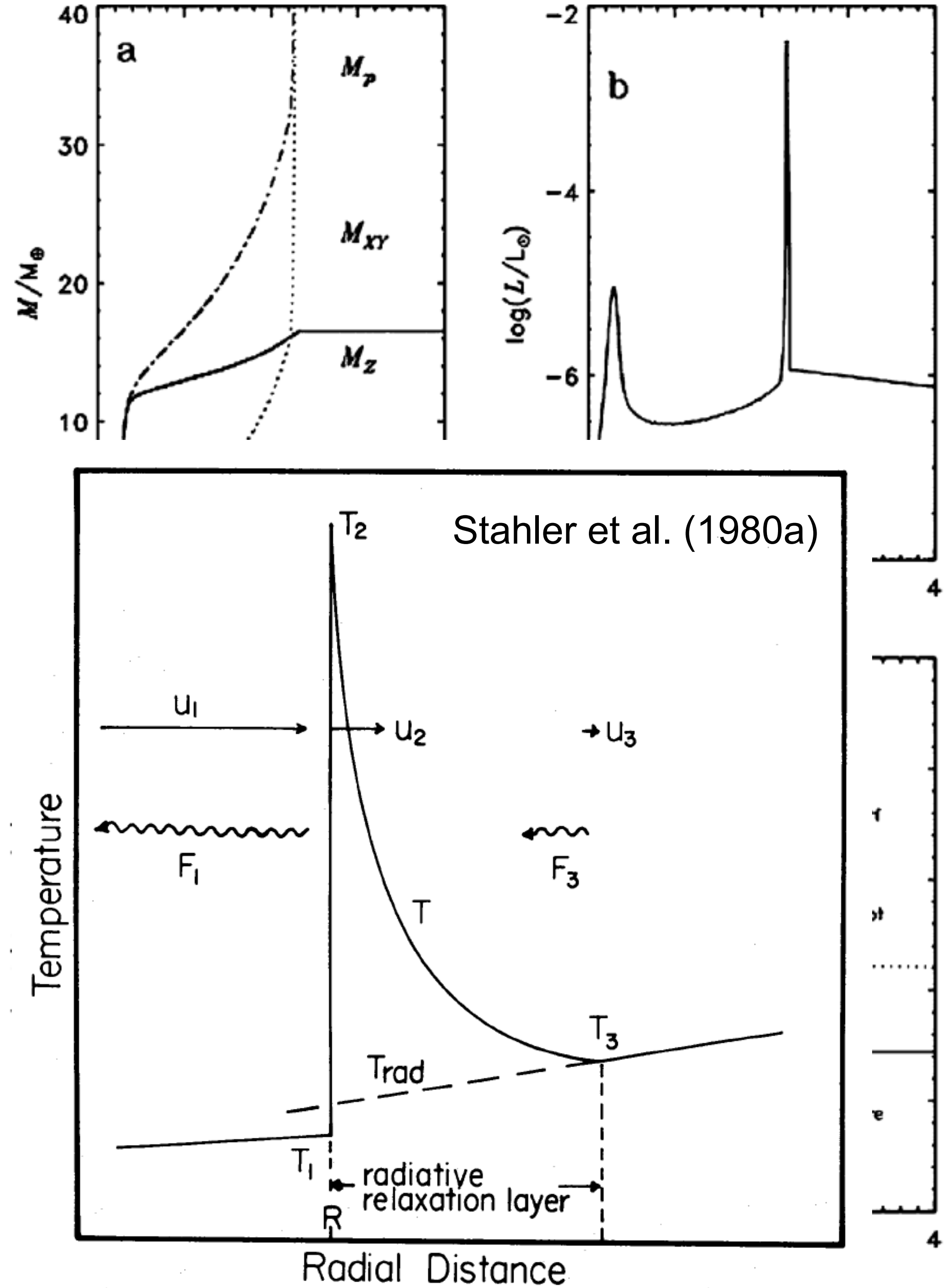
Standard cooling models for giant planets (and brown dwarfs) make simplifying assumptions:

- Planets begin evolution fully formed
- Planets are adiabatic at all ages
- Initially *arbitrarily large and hot*
- Initial model is unimportant as long as it is quite hot (t_{KH} is very short at large L and R), and models are only plotted for t >1 Myr

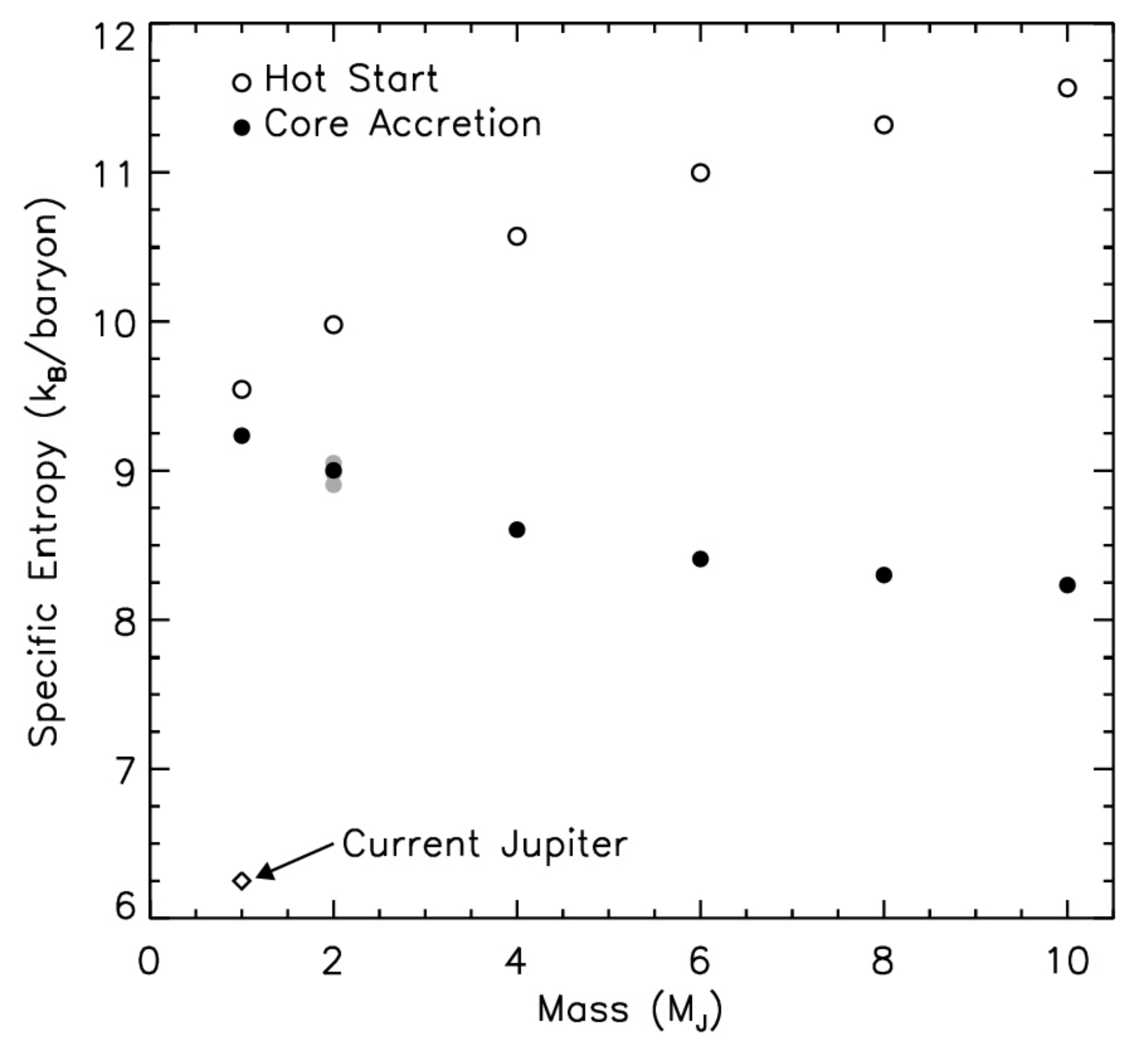
"Although all these calculations may reliably represent the degenerate cooling phase, they cannot be expected to provide accurate information on the first 10^5-10^8 years of evolution because of the artificiality of an initially adiabatic, homologously contracting state."   --Stevenson (1982, AREPS)

Bodenheimer & Lissauer (& Pollack) implementation of the core-accretion model

1. Planetesimals→core
2. Gas accretion rate grows and surpasses solid accretion rate
3. Runaway gas accretion
4. Limiting gas accretion→how fast can nebular gas be supplied? Gas arrives at a *shock interface*.
5. Accretion terminates→ isolation stage (cooling & contraction)



Post-Formation Entropy



Marley, Fortney, et al. (2007)

- Internal specific entropy 1 Myr after formation
- Entropy monotonically decreases with age
- Low post-formation entropy → small radii & low luminosity
- Quite dependent on the treatment of the accretion shock!
- At higher masses, a higher % of mass has passed through shock

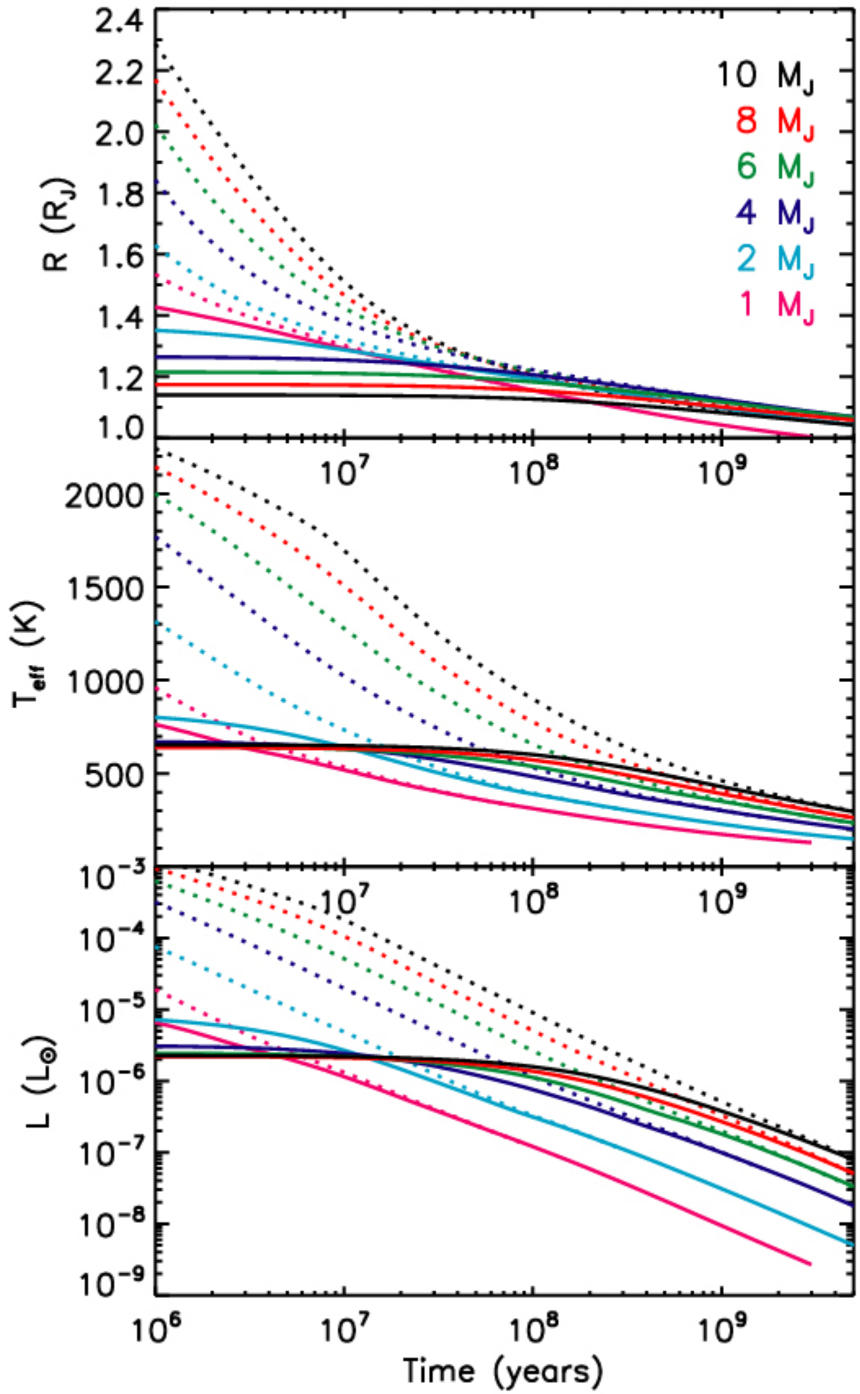
1. _Model_ core-accretion planets ("cold start") are formed with significantly smaller entropy and radii than "hot start"

2. $t_{KH} \propto 1/LR$, meaning evolution is initially much slower for the core-accretion planets

3. Initial conditions are not forgotten in "a few million years," but rather, 10 million to 1 billion.

4. Initial T_{eff} values cluster around 600-800 K

5. *Entire effect depends on the treatment of accretion*

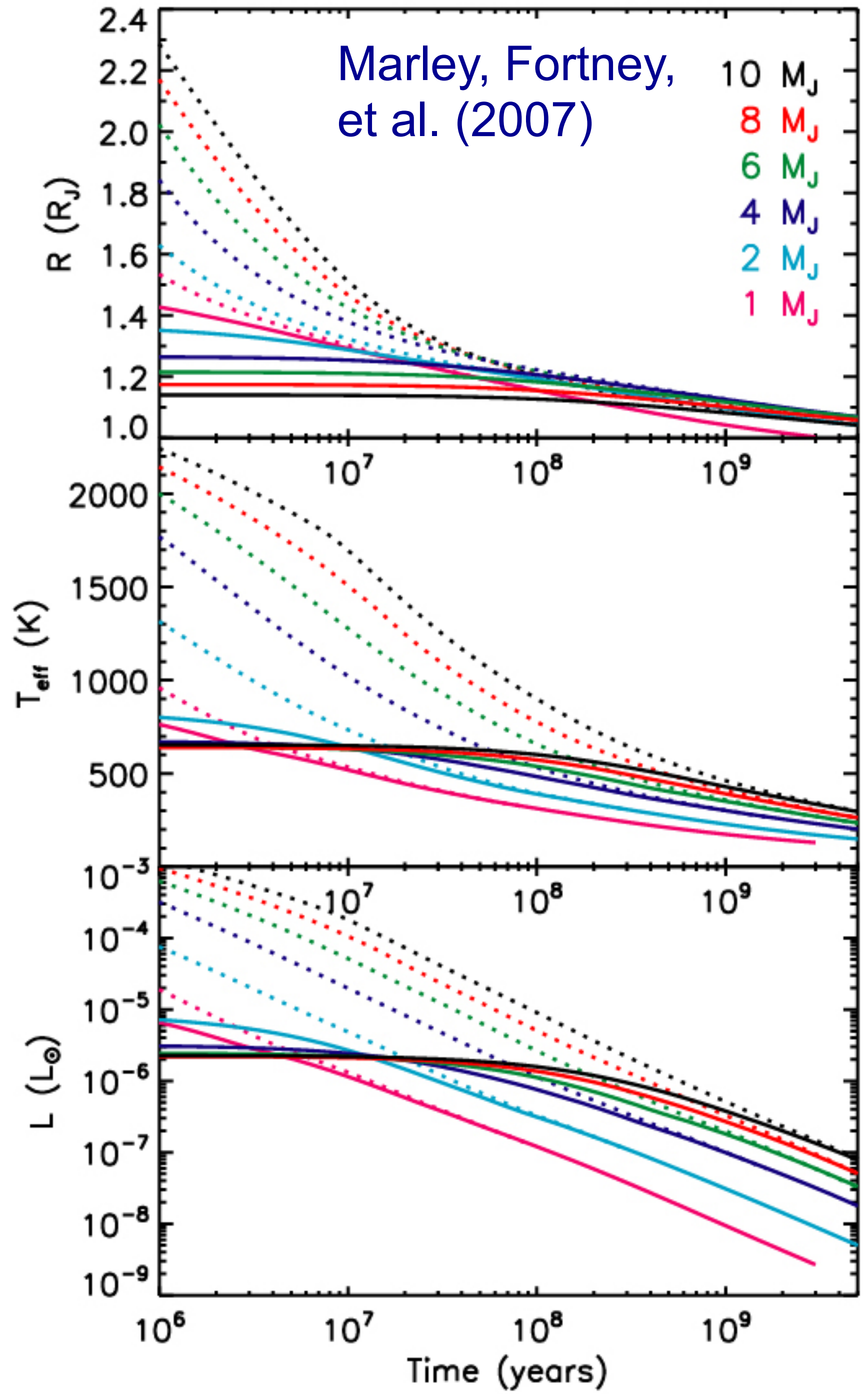


Initial Conditions:

Hot, Cold, and Warm Starts
Marley et al. (2007)
Fortney et al. (2008)
Spiegel & Burrows (2012)
Mordasini (2013)
Marleau & Cumming (2014)

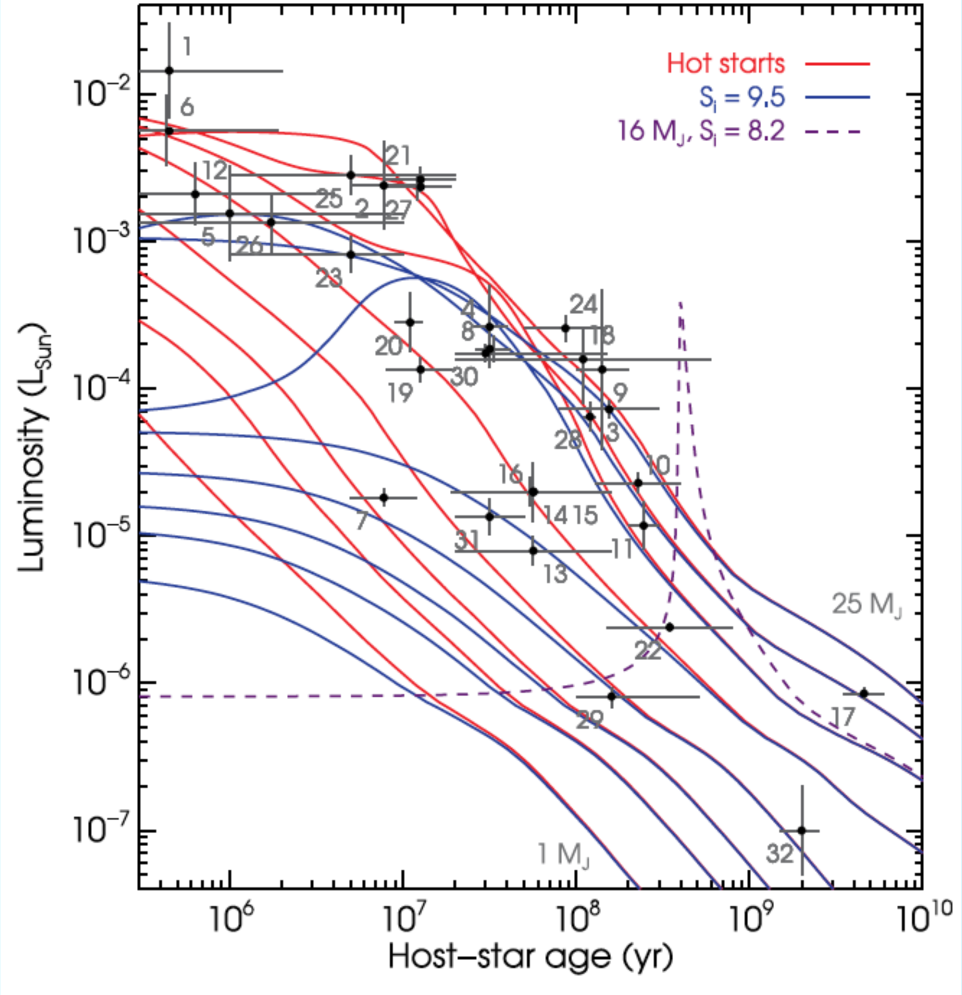
Effects of D-burning
Mollière & Mordasini (2012)
Bodenheimer et al. (2013)

Brown Dwarfs
Baraffe et al. (2002, for brown dwarfs)

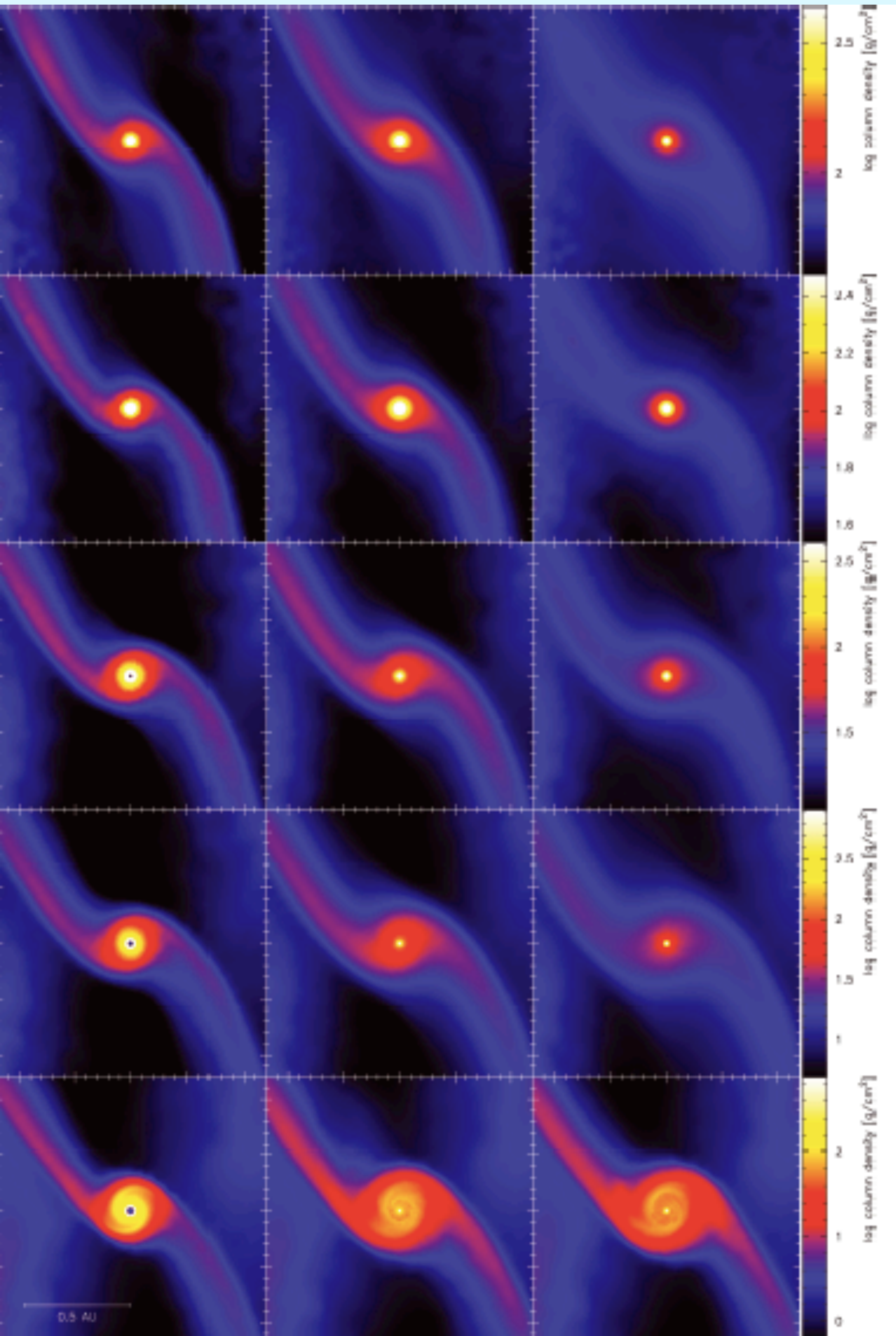


What is the Status of Models vs. Reality?

- "Hot Start" is really an upper limit on luminosity
- "Cold Start" is really a lower limit, and was not really a "prediction" of core-accretion
- Hot start appears to be closer to reality, at least for relatively massive objects found so far (which likely didn't form by core accretion!)
- How "warm" the start is is an important clue regarding the energetics of accretion



Marleau & Cumming (2014)



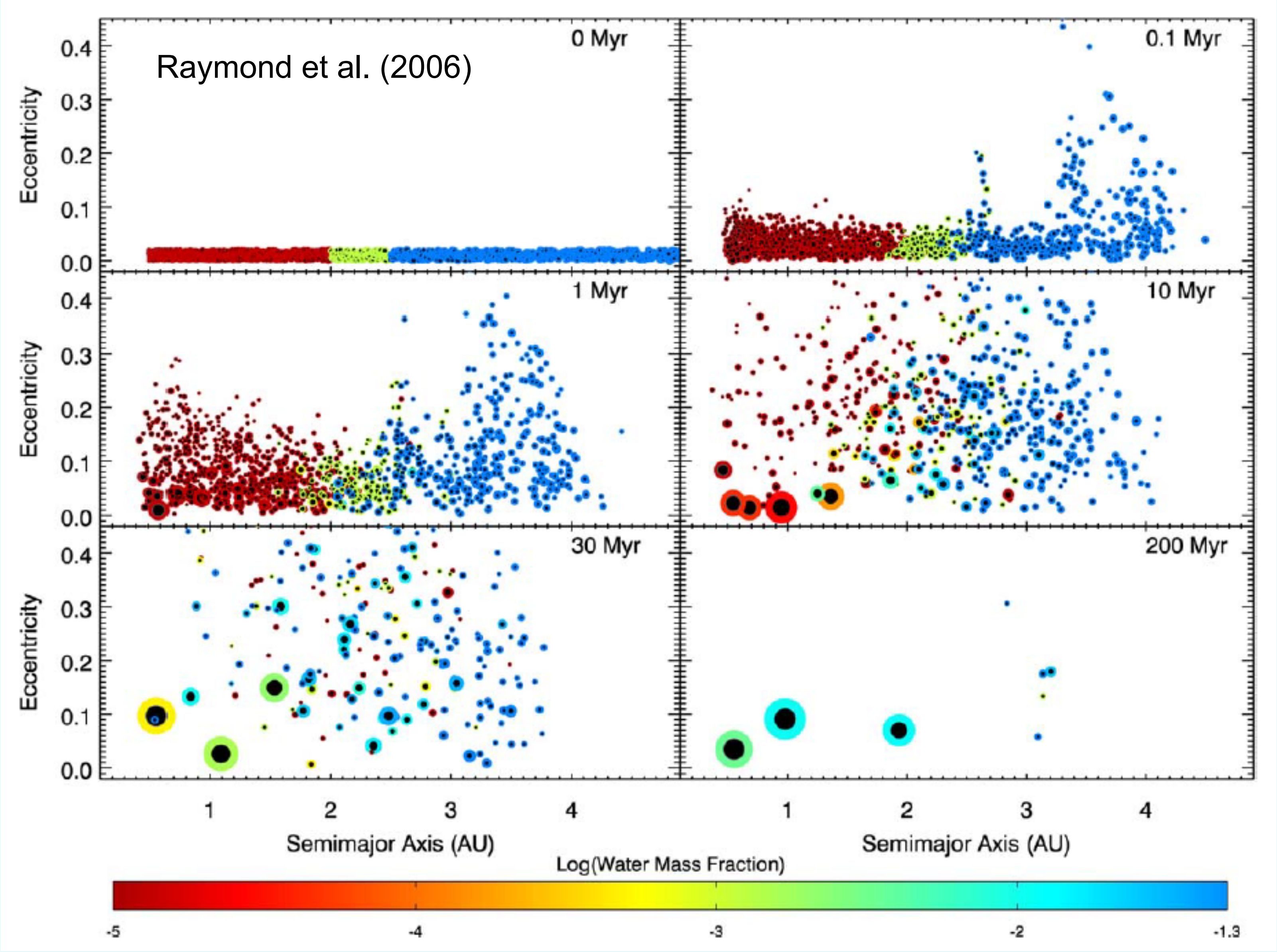
Energetics of Accretion: Hard

SPH radiation hydrodynamics

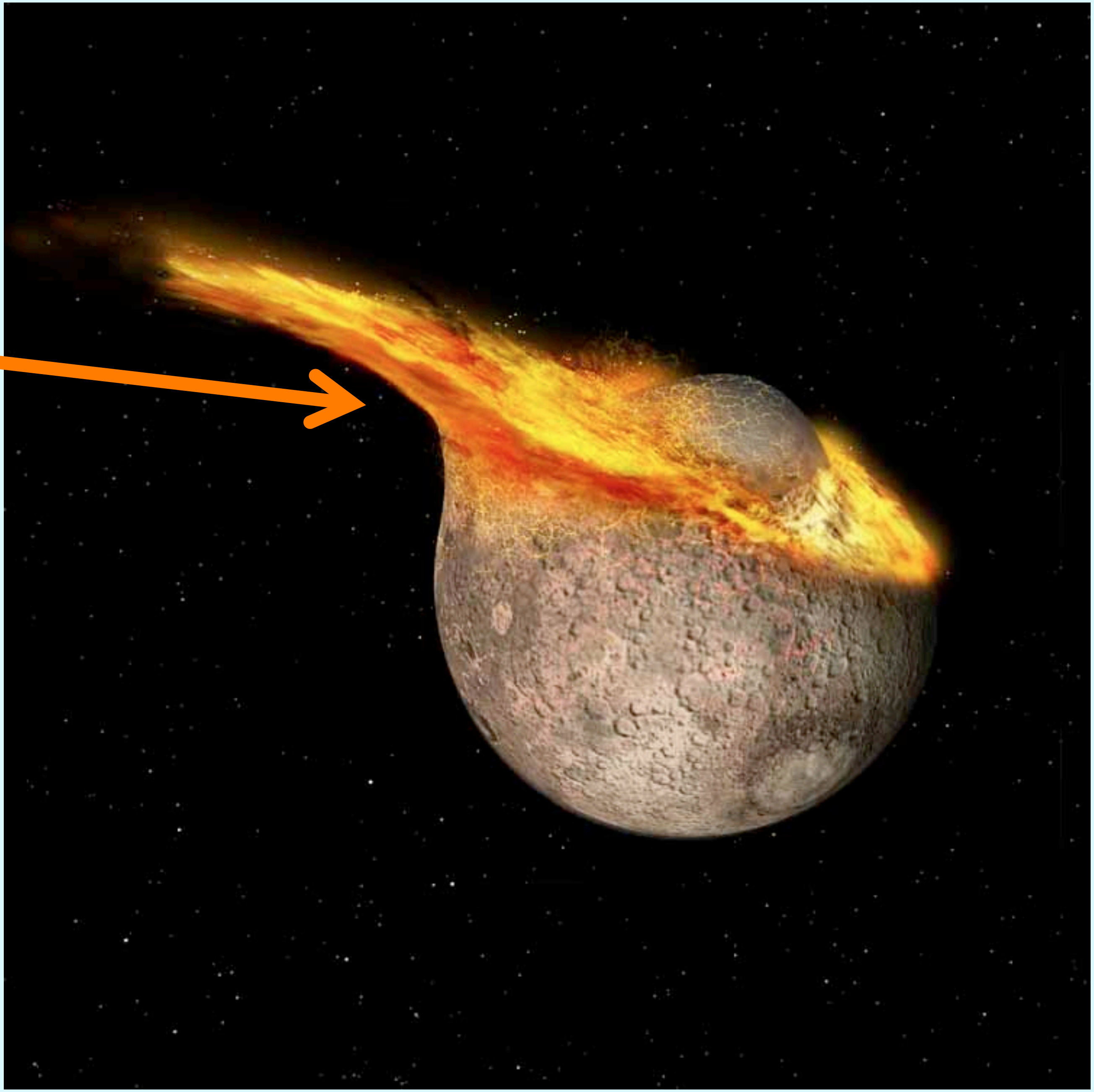
Must look at gas accretion for a few million years—lots of computing time

Ayliffe & Bate (2009)

Giant impacts are the generic end of rocky planet formation!

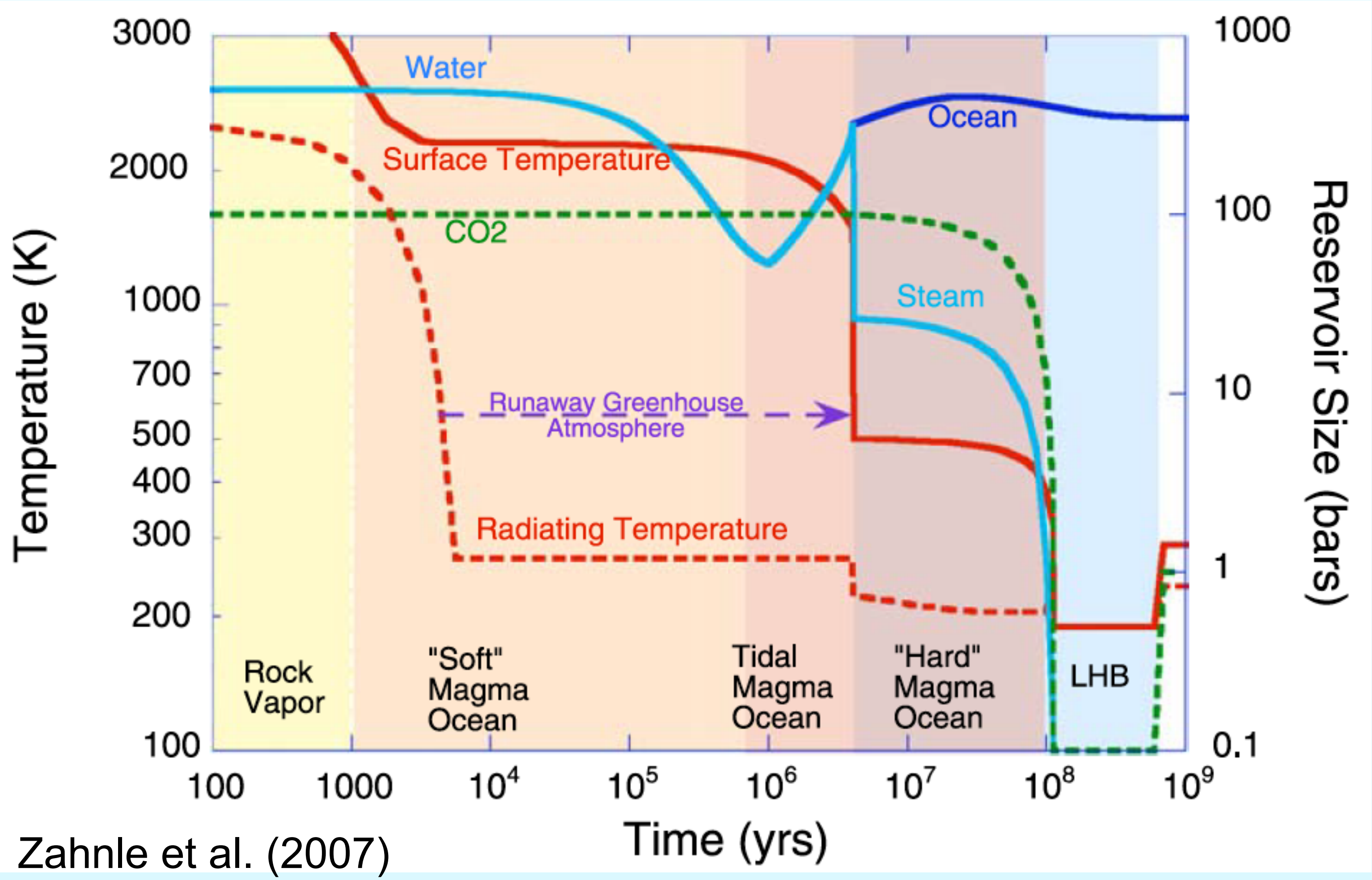


Hot,
Glowy



There has been a fair amount of work done to model what Earth was like after the Moon-forming impact

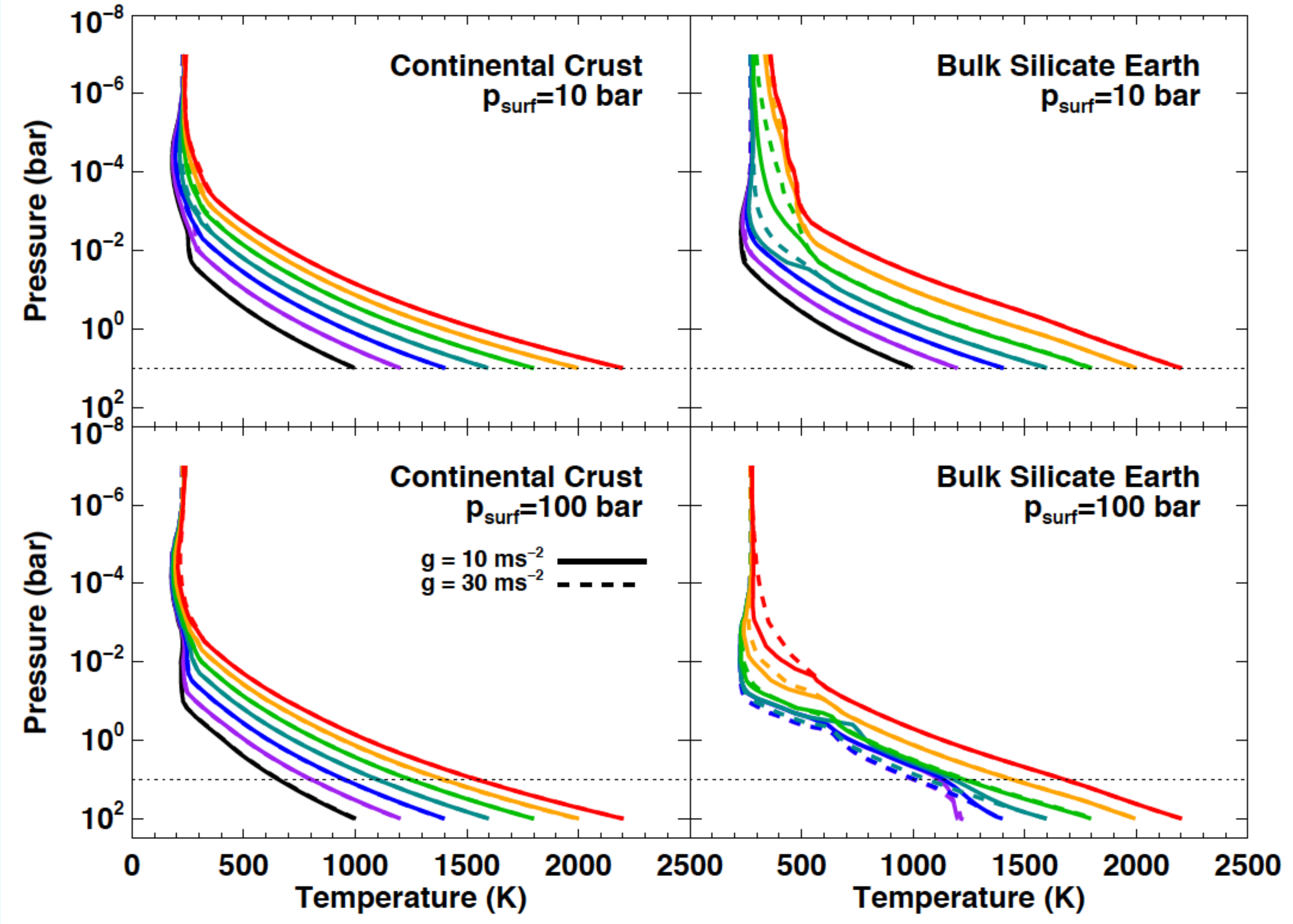
Such giant impacts are the generic end of planet formation



Zahnle et al. (2007)

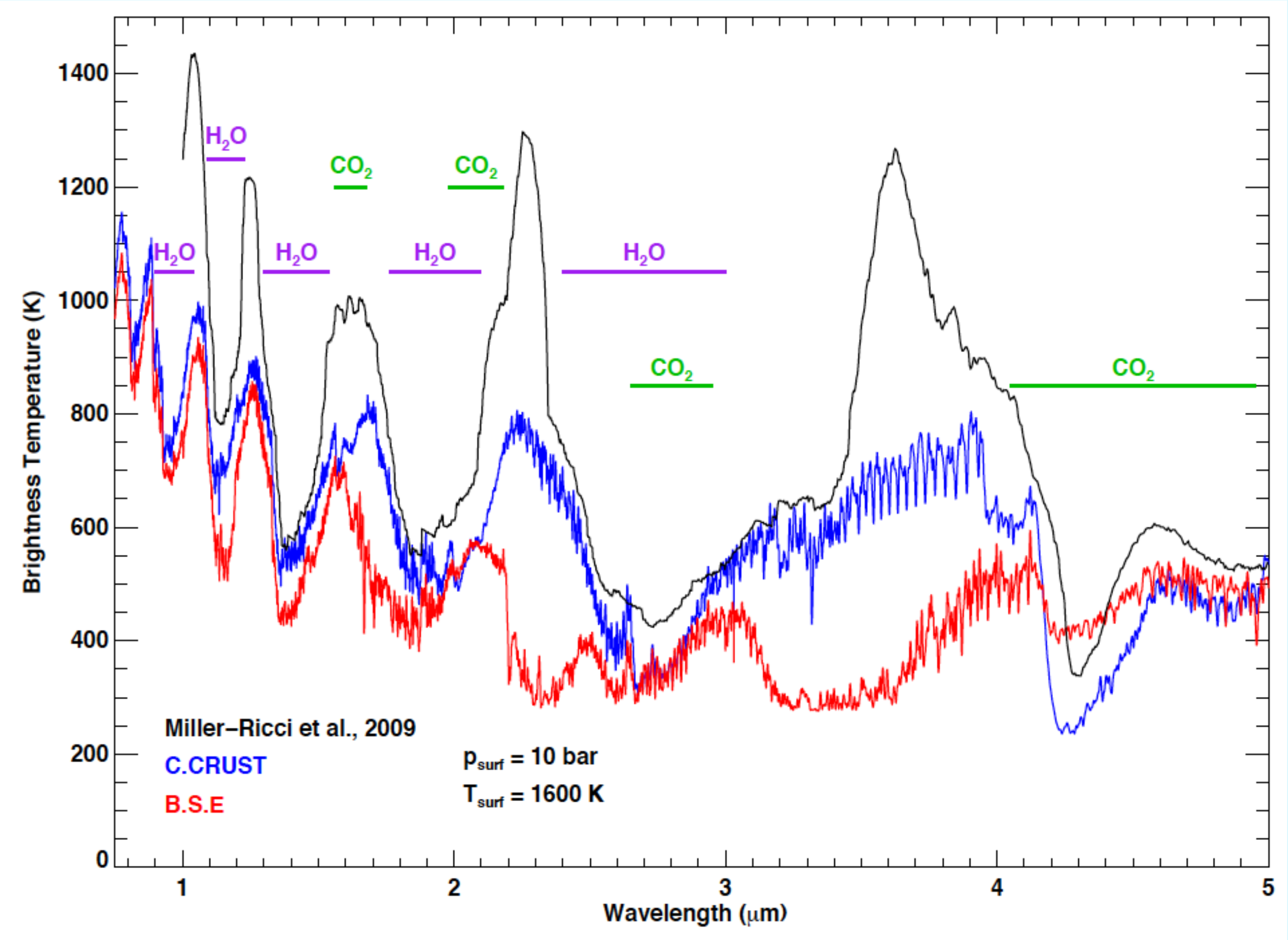
“Emergence of a Habitable Planet,” Space Science Review

Can’t see the hot surface: Giant impacts liberate volatiles that make thick atmospheres



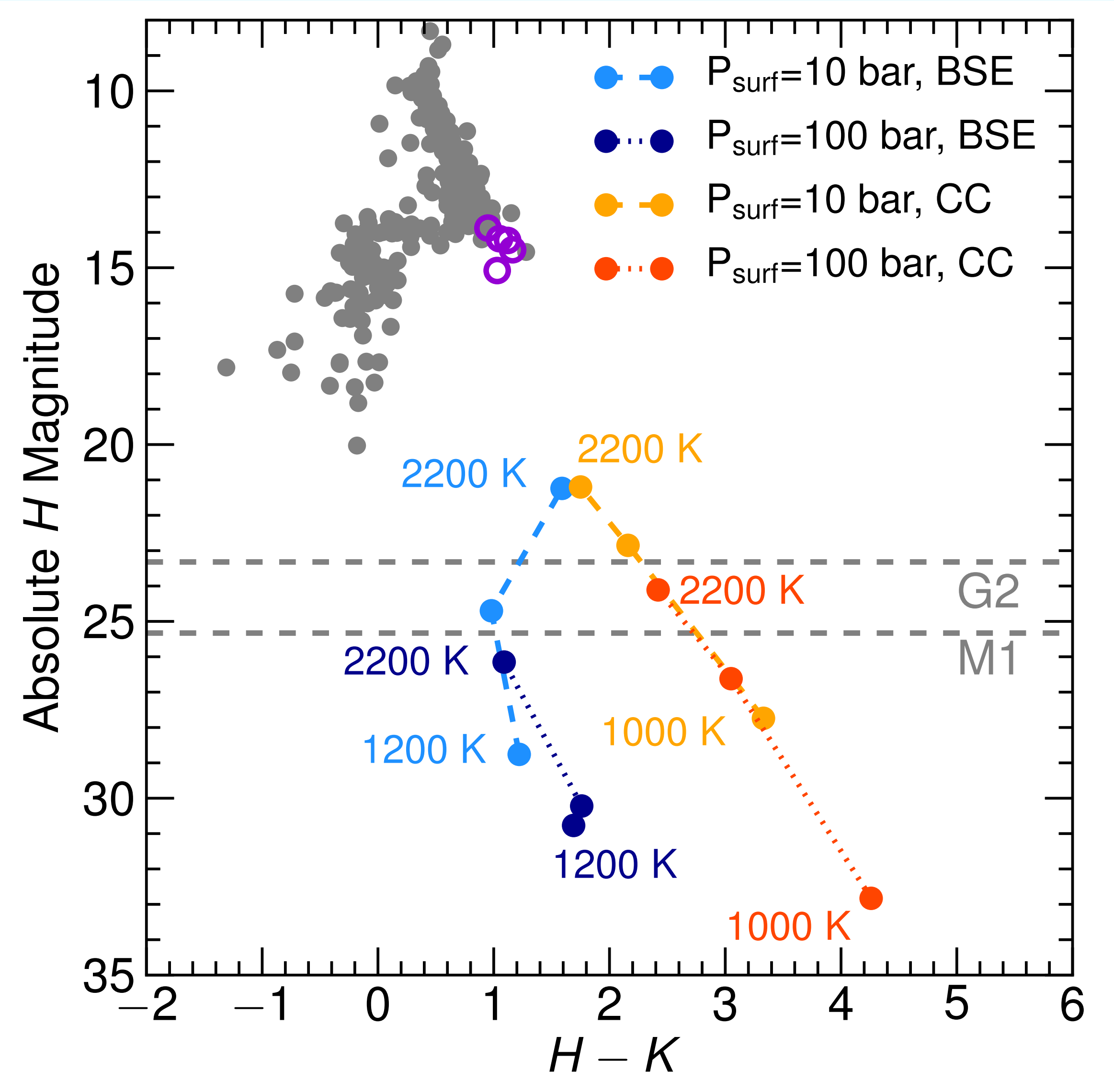
Lupu et al. (2014)

If the atmosphere is thick and the opacity is high, one can't see down near the hot surface



Lupu et al. (2014)

Due to their Small Size, and Cool T_{eff}, Hot Young Rocks are Faint



Lupu et al. (2014)

Conclusions

- Thermal evolution models of giant planets aim to understand the post-formation cooling history
- Free/unknown parameters mostly revolve around atmospheric boundary
- Model testing is just starting to progress and is coming from brown dwarfs with well-determined masses and ages
- For young planets, the role of initial conditions are still being investigated, but "cold start" does not always = core accretion
- Properties of "Hot Rocks" are still being explored. Unlikely to see the hot surface