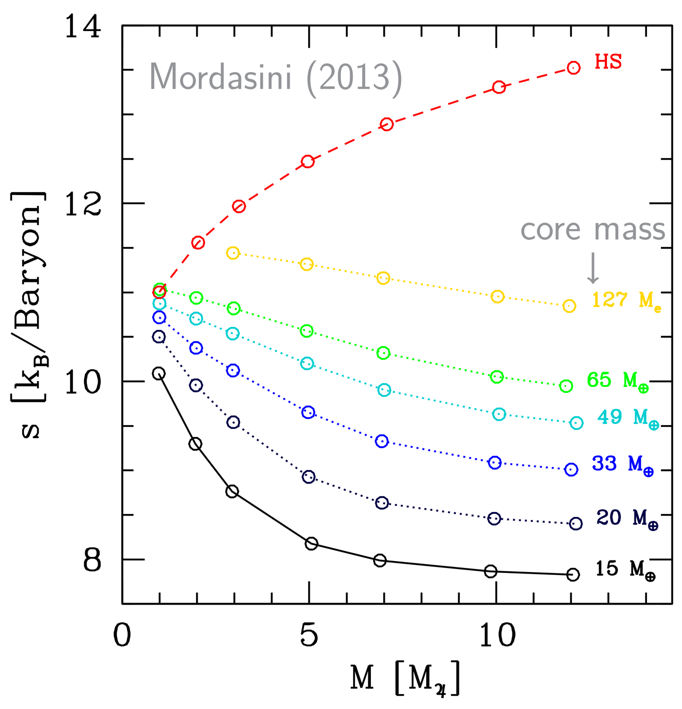
Constraining the initial entropy of directly-detected exoplanets

Gabriel-Dominique Marleau[1,2] & Andrew Cumming[2]

[1] Max-Planck-Institut für Astronomie, Heidelberg, Germany
[2] McGill University, Montréal, Québec, Canada

Context: Hot start or cold start?

- Formation models (CA, GI) **cannot predict** post-formation, **initial entropies** (yet)
  - ▷ Shock details, $\Sigma_{\rm solids}$, etc. $\rightarrow$ range of S_i
  - ▷ Core accretion $\not\Leftrightarrow$ cold start
    Gravitational instability $\not\Leftrightarrow$ hot start



- … hence **cannot assume** S_i's when inferring M
  $\Rightarrow$ Need to consider cooling tracks with arbitrary S_i

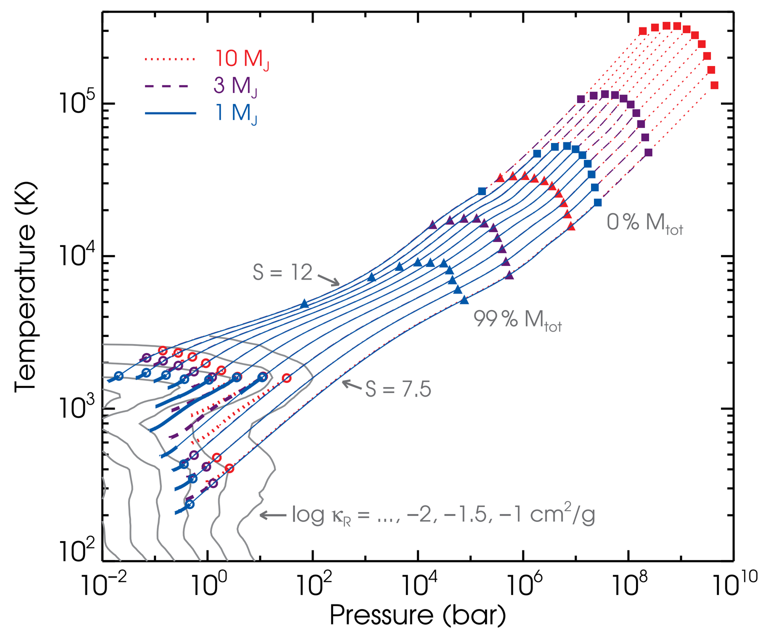
In a nutshell

Use current brightness and age to **constrain M and S_i jointly**:
- ▶ Make planet models with arbitrary entropy $\rightarrow L = L(M, S(t))$
- ▶ Find needed S_i at each M to match L and age
- ⋆ Independent of formation process

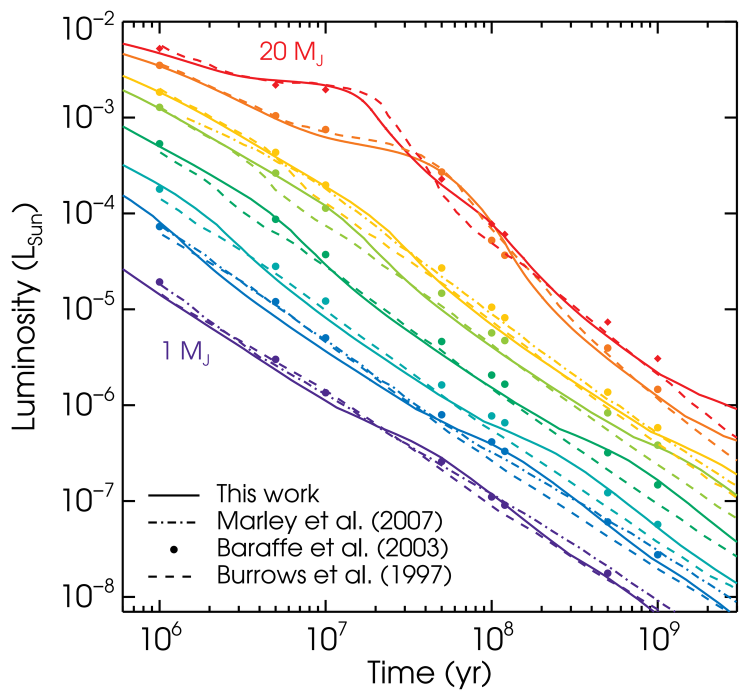
- Many CA candidates expected soon (SPHERE, GPI, etc.)
  $\rightarrow$ Statistical constraints on formation models

Planetary models

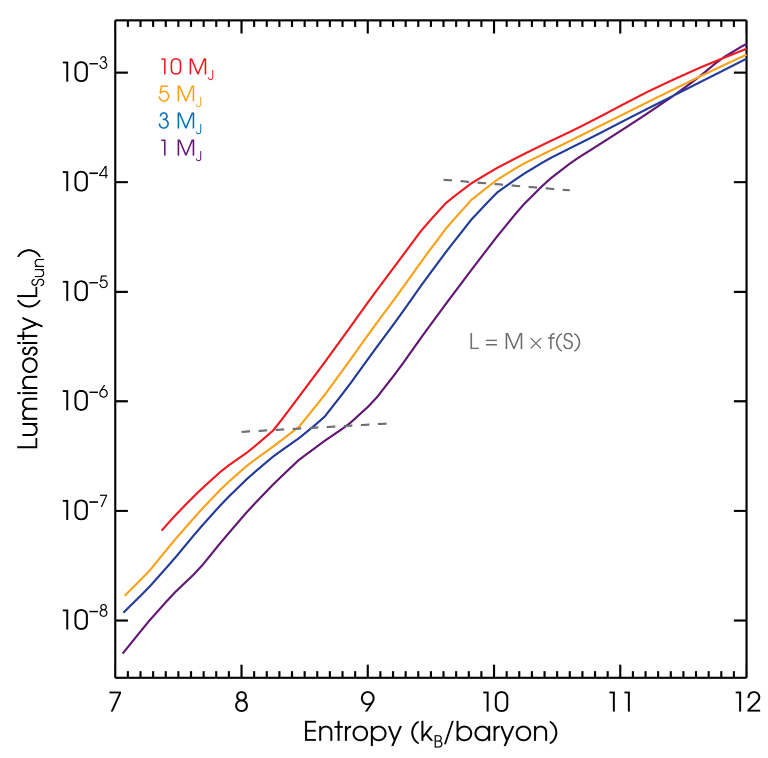
- Interior models:
  - ▷ Usual equations of stellar structure
  - ▷ Schwarzschild criterion for convection
  - ▷ Simple grey Eddington outer b.c.
  - ▷ No solid core by default



- Cooling by "following the adiabats":
  (Hubbard 1977, Arras & Bildsten 2006)
  - ▷ Given Δt, find ΔS with dS/dt from
  $$L = -M\langle T\rangle \frac{dS}{dt} + L_{\rm D}$$
  $\Rightarrow$ Rapidly move in S at given M
  - ⋆ Excellent agreement with classics



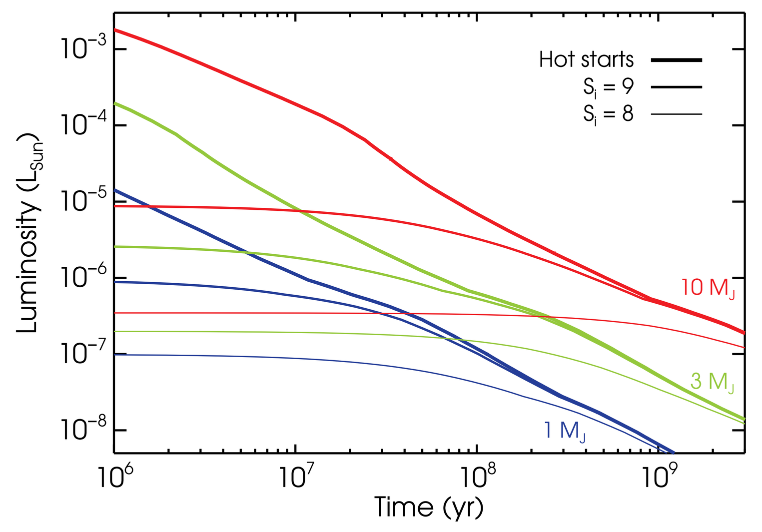
- Grid of models:
  - ▷ Consists of $L(M,S)$ and $\langle T\rangle(M,S)$
  - ▷ Shows simple luminosity scalings:
    - ▸ Low S:
    $$L_{\rm low} = 10^{-7.7} L_\odot \left(\frac{M}{M_{\rm J}}\right)^{0.7} 10^{1.3\,(S-7.5)}$$
    - ▸ **Intermediate S**:
    $$L_{\rm rz} = 10^{-5.1}\,L_\odot \frac{M}{M_{\rm J}}\,10^{1.5\,(S-9.6)}$$
    Deep atmosphere $\rightarrow$ radiative-zero solution
    $\rightarrow$ semi-analytically derivable $L_{\rm rz}(M,S)$
    - ▸ High S:
    $$L_{\rm high} = 10^{-3.9}\,L_\odot \left(\frac{M}{M_{\rm J}}\right)^{0.3} 10^{0.6\,(S-10.5)}$$



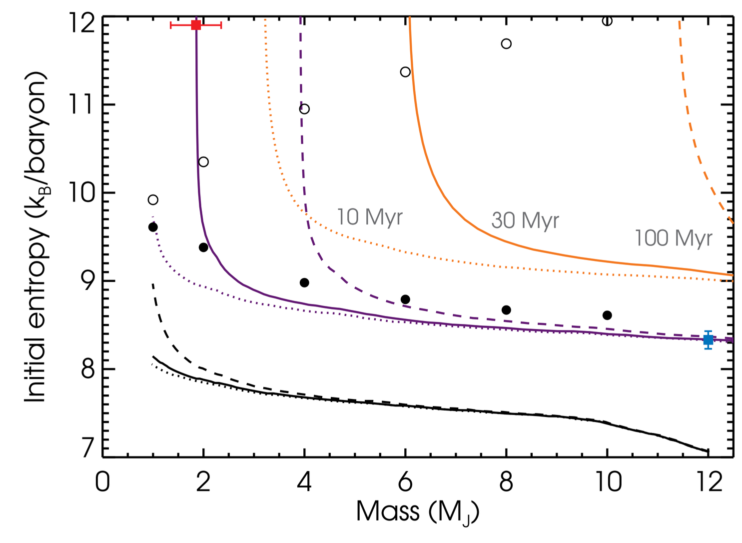
Please leave your name to receive a copy of work, or write a comment!

General $M(S_i)$ constraints

- ▶ Cooling tracks, schematically:
  - ▷ Stay at initial S until $t \sim \tau_{\rm cool}$
  - ▷ Follow hot-start track for $t > \tau_{\rm cool}$
  - ⋆ $\tau_{\rm cool} \sim 10^8$ **yr** for low S

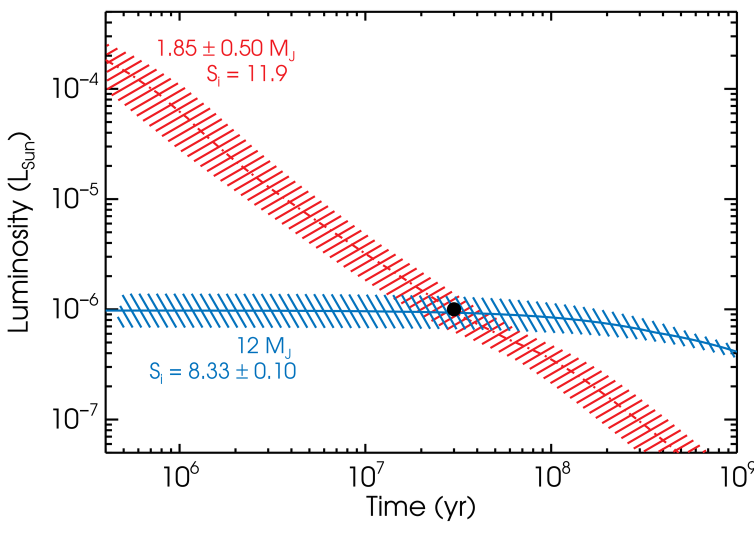


- ▶ Given L and t, get two $M(S_i)$ branches:
  - ▷ Unique **hot-start mass** $M_{\rm hs}$, high S_i
    - ▸ Usual fitting of hot-start tracks
    - ▸ Uncertainty in $M_{\rm hs}$: mainly from t
      $(\Delta M/M \simeq \frac{1}{2}\Delta t/t)$
  - ▷ Higher masses, $\sim$ constant S_i
    - ▸ **Lower bound on S_i**
    - ▸ Almost flat because $L_{\rm rz} \sim M\,10^{1.5\,S}$
    - ▸ Age uncertainties unimportant
      (Rather, $\Delta S_i \simeq 0.7\Delta \log_{10} L \sim 0.2$)
  - $\Rightarrow$ Mass **not constrained** from only L



Groups: $L = 10^{-7}, 10^{-6}, 10^{-5}\ L_\odot$

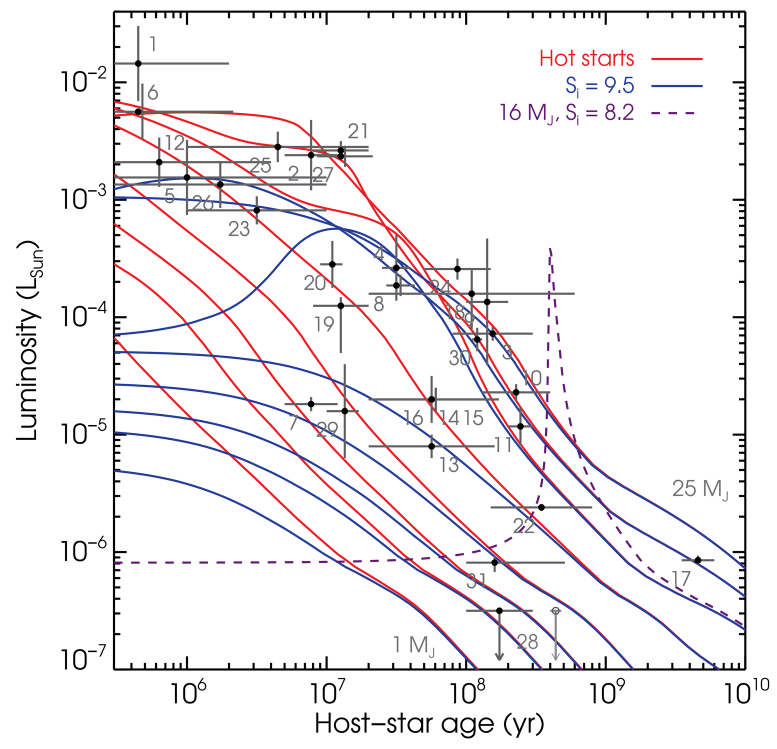
- ▶ Possible mass information:
  - ▷ Upper limit to $\log g$: somewhat rough
  - ▷ Dynamical stability: rare, difficult (many sensitive parameters)
  - ▷ Radial velocity: rare (weak signal)
  - ⋆ If $M_{\rm min} > M_{\rm hs}$: very tight S_i constraints



Two solutions for $10^{-7}\ L_\odot$ at 30 Myr

Directly-imaged objects so far

- ▶ Currently only few with low $M_{\rm hs}$
- ▶ Tentative features in t–L distribution:
  - ▷ Faintest detected L drops with t
  - ▷ 'Gap' at $10^{-4}\ L_\odot$, ~ 50 Myr: predicted by cooling tracks?
  - ⋆ Need to assess statiscal significance
    $\rightarrow$ Easier with uniform surveys
- ▶ Some consistent with D '**flashes**'…
  $\rightarrow$ Marleau & Cumming, in prep.

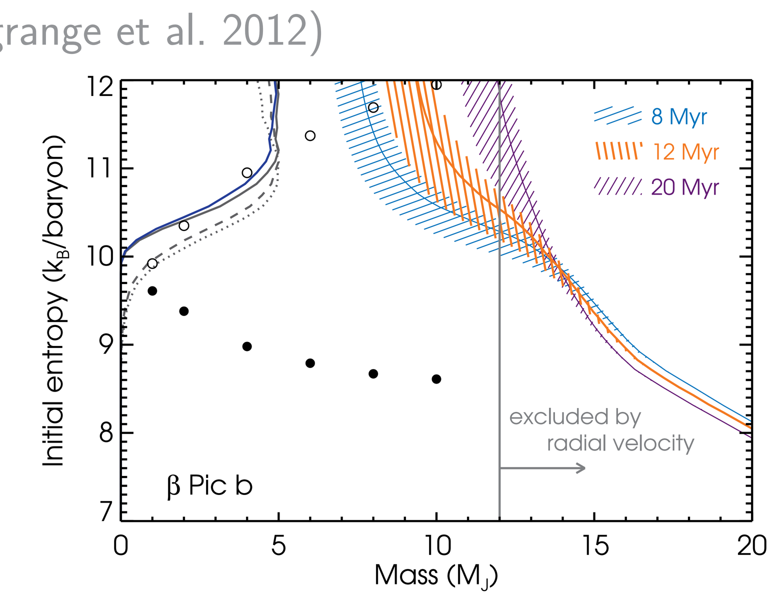


Based on Neuhäuser & Schmidt (2012): (1) GQ Tau Bb, (2) TWA 5 B, (3) GJ 417 BC, (4) GSC 8047 B/b, (5) DH Tau B/b, (6) GQ Lup b, **(7) 2M1207 b**, (8) AB Pic B/b, (9) LP 261-75 B/b, (10) HD 203030 B/b, (11) HN Peg B/b, (12) CT Cha b, **(13, 14, 15, 16) HR 8799 bcde**, (17) Wolf 940 B/b, (18) G 196-3 B/b, **(19)** β **Pic b**, (20) RXJ1609 B/b, (21) PZ Tel B/b, (22) Ross 458 C, (23) GSC 6214 B/b, (24) CD-35 2722 B/b, (25) HIP 78530 B/b, (26) SR 12 C, (27) HR 7329 B/b, (28) Fomalhaut b, (29) HD 95086 b, (30) 2M0122 b, (31) GJ 504 b

Application: β Pic b

Have $\log L/L_\odot = -3.87 \pm 0.08$, $t_{\rm host\ star} = 12^{+8}_{-4}$ Myr, $M \leqslant 12\ M_{\rm J}$
(Bonnefoy et al. 2013, Zuckerman et al. 2001, Lagrange et al. 2012)

- ▶ Recover hot-start mass: $9.5 \pm 2.5\ M_{\rm J}$
- ▶ Constrain $S_i \geqslant 9.8$ if no D burning…
- ▶ … and even $S_i \geqslant 10.2$ with RV
  - ▷ Coldest starts (Marley et al. 2007) ruled out **quantitatively** ($\Delta S \simeq 1.5$)
  - ▷ MCMC for σ_t and $\sigma_L \rightarrow S_i$ posterior



With own $\log L/L_\odot = -3.90^{+0.05}_{-0.12}$

Two-point (-and-one-star) summary

- ▶ Uncertain $S_i \Rightarrow$ need to **consider arbitrary S_i** to interpret direct detections
- ▶ Given L and t, find joint $M(S_i)$ constraints $\Rightarrow$ **lower bound** on S_i
- ⋆ Can use direct detections to constrain formation models

marleau@mpia.de