Giant planets vs Brown Dwarfs: who’s who ?

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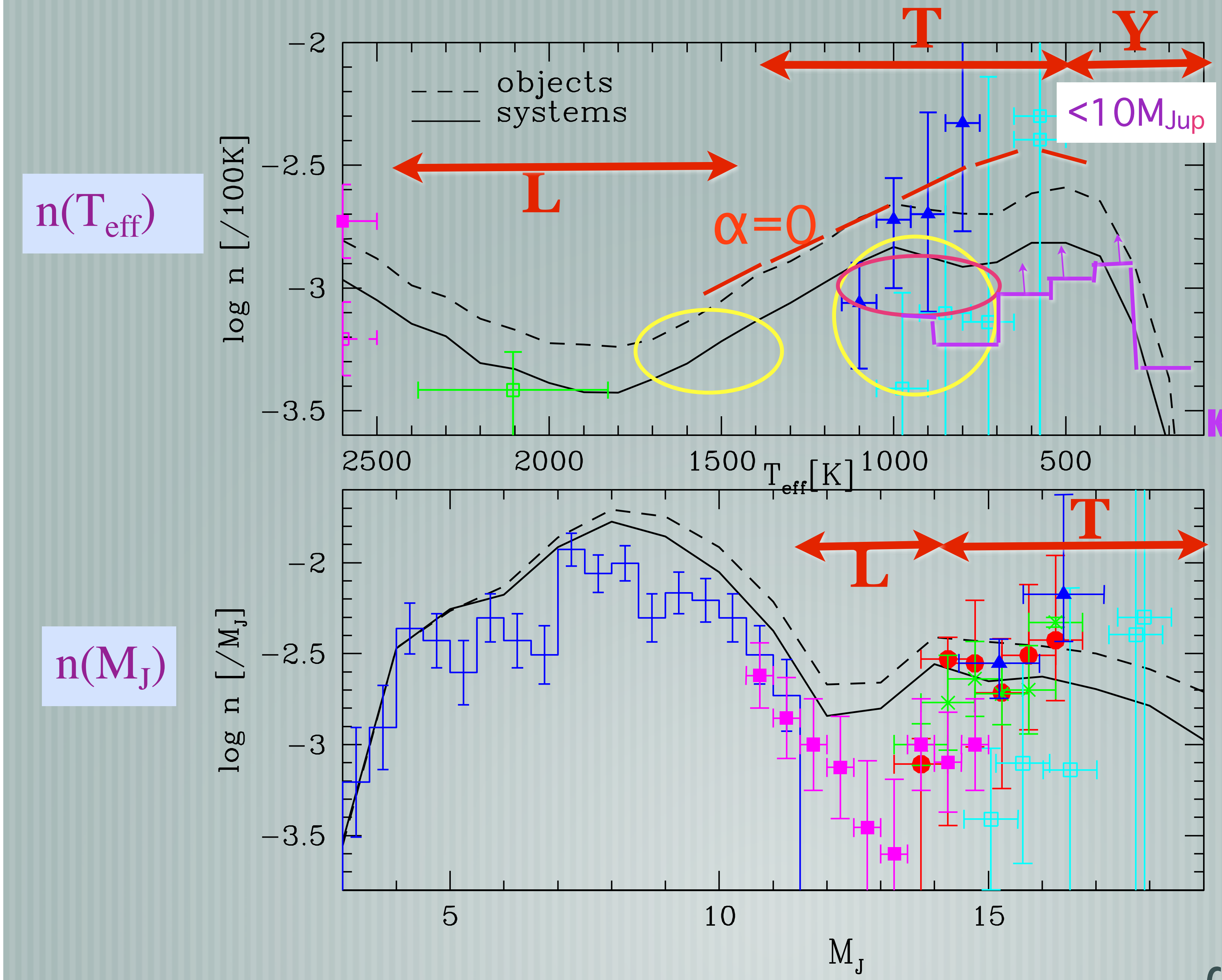
European
Research
Council

1) THE MASS FUNCTION

Brown dwarf mass function



Reid et al. '04
+ Cruz et al. '07
Burgasser '04
Burningham et al. '10
Gizis et al. '00
Metchev et al. '08
Reylé et al. '10
Kirkpatrick et al.'12

Reylé et al. '10 CFHBS

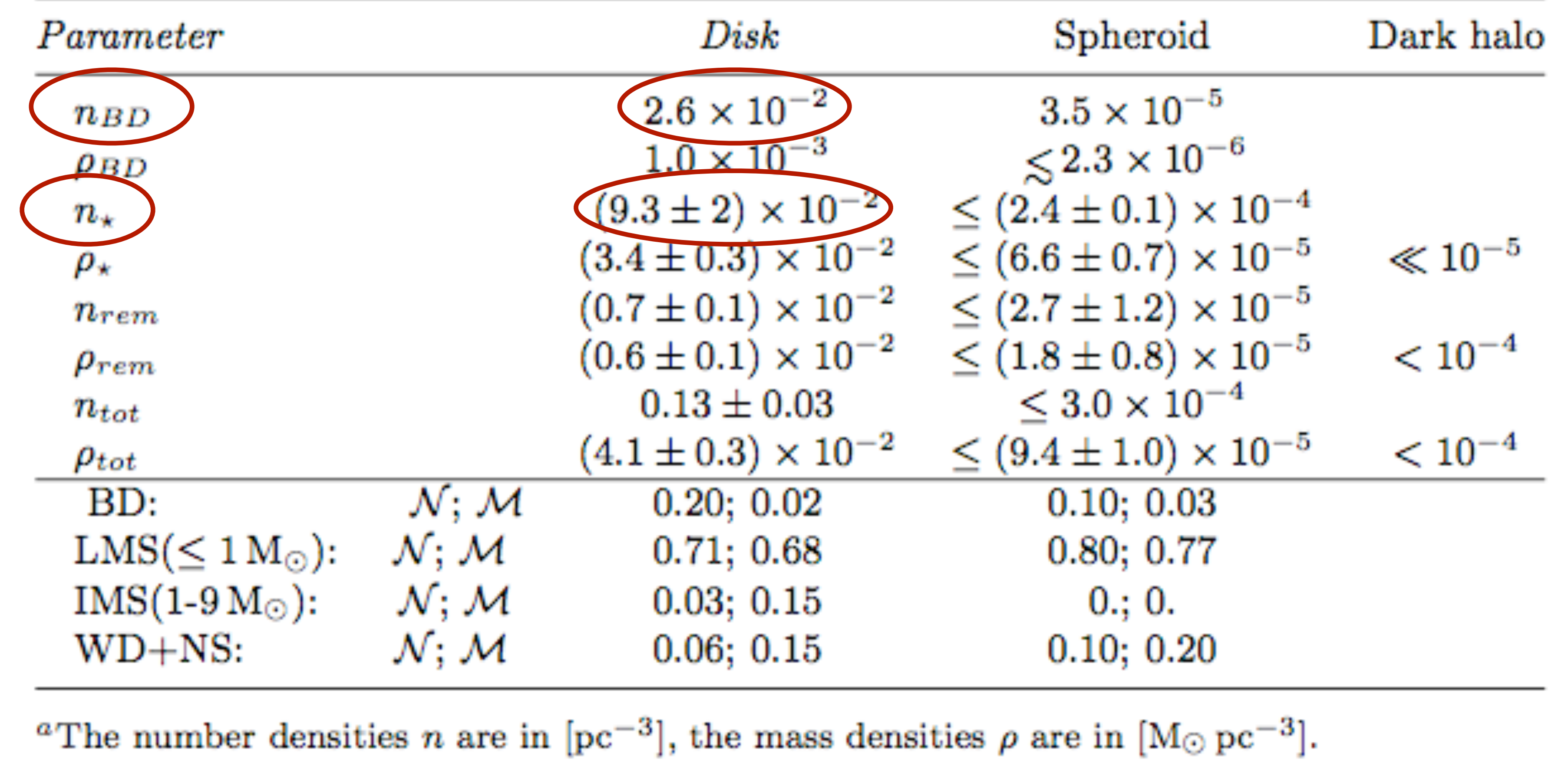
Allen et al. '05

Reid et al. '04
+ Cruz et al. '07

Burgasser '04

Burningham et al. '10

Chabrier, ASSL 2005



Parameter		*Disk*	Spheroid	Dark halo
n_{BD}		2.6×10^{-2}	3.5×10^{-5}	
ρ_{BD}		1.0×10^{-3}	$\lesssim 2.3 \times 10^{-6}$	
$n_\star$		$(9.3 \pm 2) \times 10^{-2}$	$\le (2.4 \pm 0.1) \times 10^{-4}$	
$\rho_\star$		$(3.4 \pm 0.3) \times 10^{-2}$	$\le (6.6 \pm 0.7) \times 10^{-5}$	$\ll 10^{-5}$
n_{rem}		$(0.7 \pm 0.1) \times 10^{-2}$	$\le (2.7 \pm 1.2) \times 10^{-5}$	
ρ_{rem}		$(0.6 \pm 0.1) \times 10^{-2}$	$\le (1.8 \pm 0.8) \times 10^{-5}$	$< 10^{-4}$
n_{tot}		0.13 ± 0.03	$\lesssim 3.0 \times 10^{-4}$	
ρ_{tot}		$(4.1 \pm 0.3) \times 10^{-2}$	$\le (9.4 \pm 1.0) \times 10^{-5}$	$< 10^{-4}$
BD:	$\mathcal{N}$; $\mathcal{M}$	0.20; 0.02	0.10; 0.03	
LMS($\le 1\,M_\odot$):	$\mathcal{N}$; $\mathcal{M}$	0.71; 0.68	0.80; 0.77	
IMS(1-9 $M_\odot$):	$\mathcal{N}$; $\mathcal{M}$	0.03; 0.15	0.; 0.	
WD+NS:	$\mathcal{N}$; $\mathcal{M}$	0.06; 0.15	0.10; 0.20	

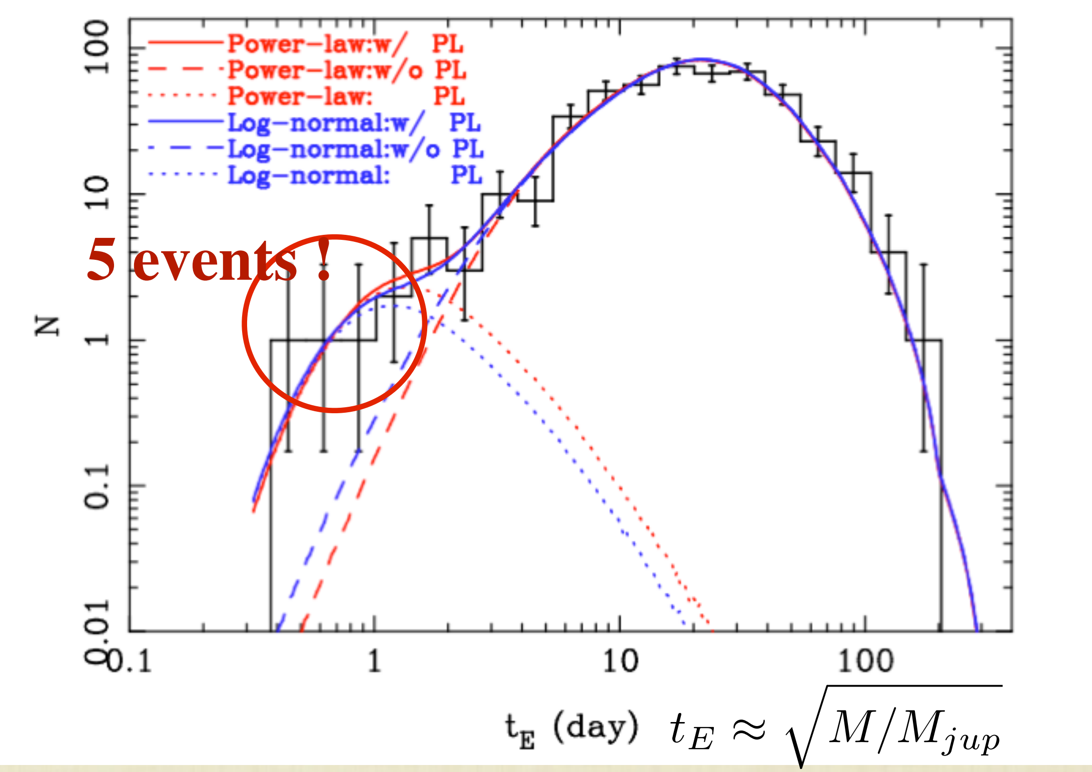
^{a}The number densities n are in [pc^{-3}], the mass densities ρ are in [$M_\odot$ pc^{-3}].

$N_{BD}/N_* = 1/4 - 1/3$ WISE (now !)~1/5

Chabrier '05

Excess of very-low-mass objects ?

Sumi et al. ’11



$t_E \approx \sqrt{M/M_{jup}}$

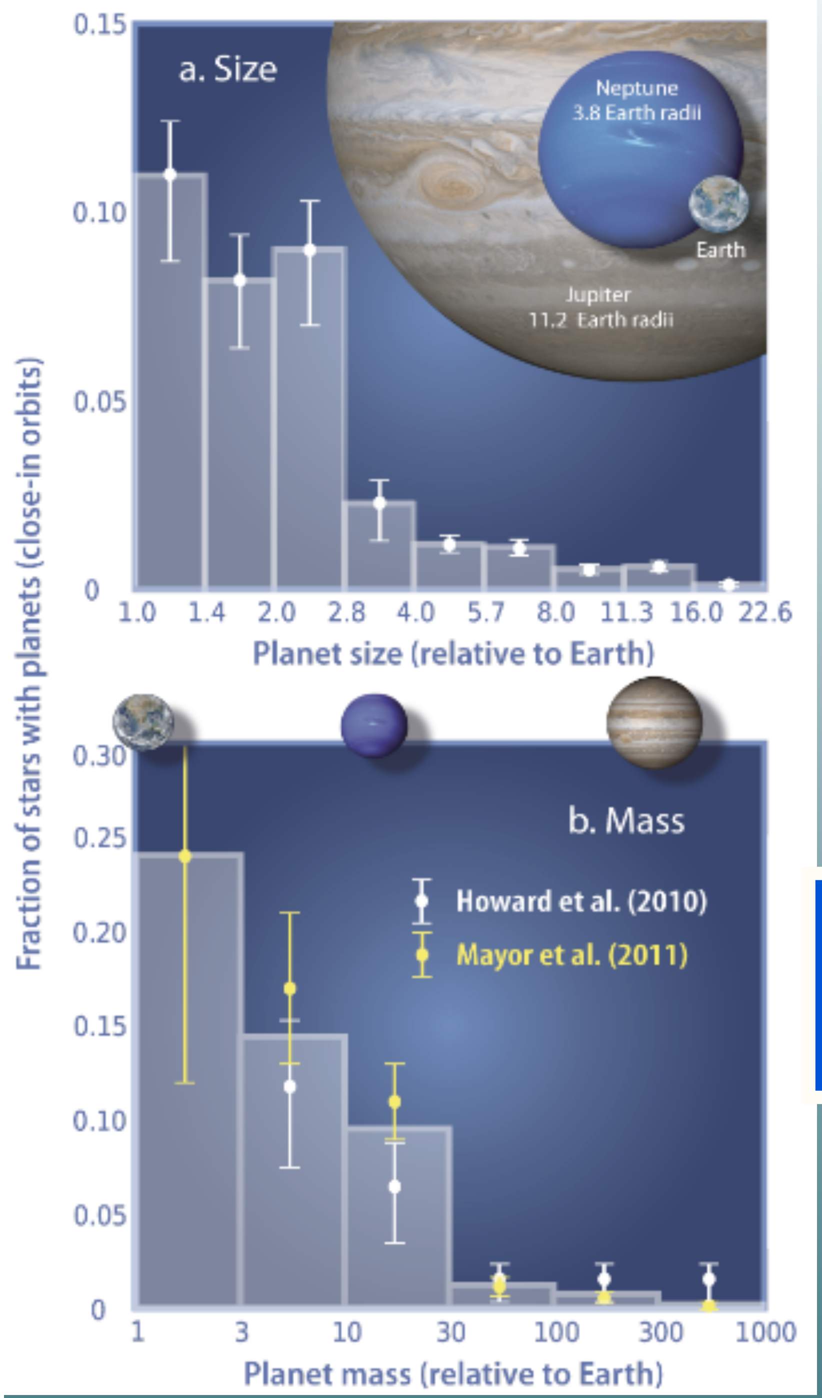
- 5 « anomalous » events: no statistical significance
- $n_{jup} \sim 2 \times n_\star$ $dN/dM \propto M^{-1.3}$ $(M < 10\, M_{jup})$

excluded by observations in SFRs (Scholz et al ’12, Caballero et al. ’07,…). See also Quanz et al. ‘12

- when observing a short duration isolated event with low S/N and non-complete coverage, the symmetry of the event, a characteristic property of lensing events, is very difficult to assess properly, in contrast to the case when the planetary event occurs as a caustic during a stellar lensing event.
- **Free-floating planet candidate events are thus much more uncertain than star-planet candidate events and should be considered with extreme caution.**

Planet mass function

Mayor et al. (2011),
Howard et al. (2013)



<u>Planets</u> INCREASE
with **<u>decreasing</u>** size/mass

<u>Brown dwarfs</u> DECREASE
with **<u>decreasing</u>** mass

in the same mass range

- **Expected from core-accretion**
- **GP Mass dist’n ≠ BD Mass dist’n**

2) THE FORMATION

GRAVOTURBULENT FRAGMENTATION

Padoan & Nordlund; Hennebelle & Chabrier; Hopkins

(see Chabrier, Johansen, Janson & Rafikov 2014 for more details)

- Large-scale turbulence (density PDF lognormal) sets up a lognormal distribution of overdense regions at all scales in the cloud

- Virial: regions M(R) with $|E_{grav}(R)| > (E_{th}+E_{rms}(R)+E_{mag})$ grav. collapse

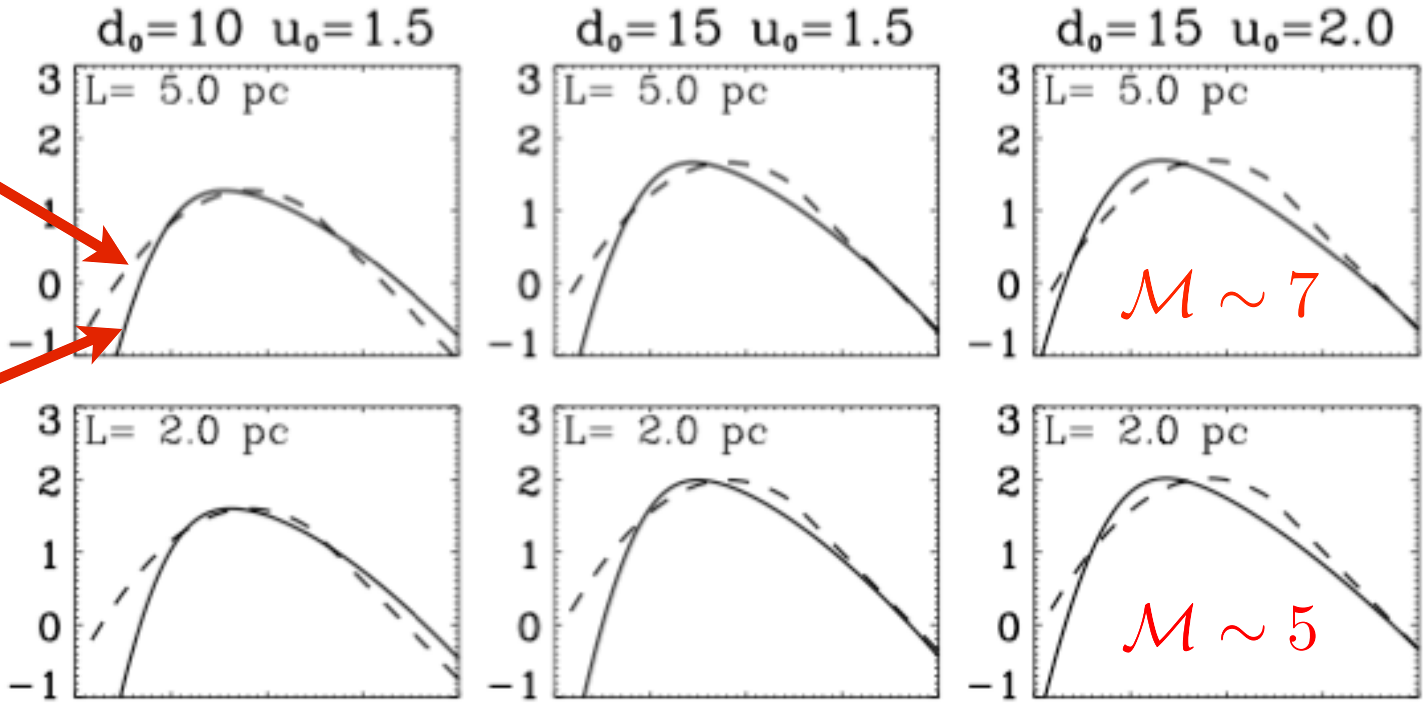
  -> leads to the prestellar **core** mass function (**CMF**)

- magneto-centrifugally outflows expel ~30-50% of the mass

  -> leads to the **star** mass function (**IMF**)

- **turbulence sets up the density fluctuations at the very early stages of star formation**
- **the IMF is imprinted in the very cloud conditions (<n>, T, Mach)**

$$\bar{n} = (d_0 \times 10^3\ \mathrm{cm}^{-3}) \left(\frac{L}{1\mathrm{pc}}\right)^{-0.7}, \quad V_{\rm rms} = (u_0 \times 0.8\ \mathrm{km\ s}^{-1}) \left(\frac{L}{1\mathrm{pc}}\right)^{\eta}.$$

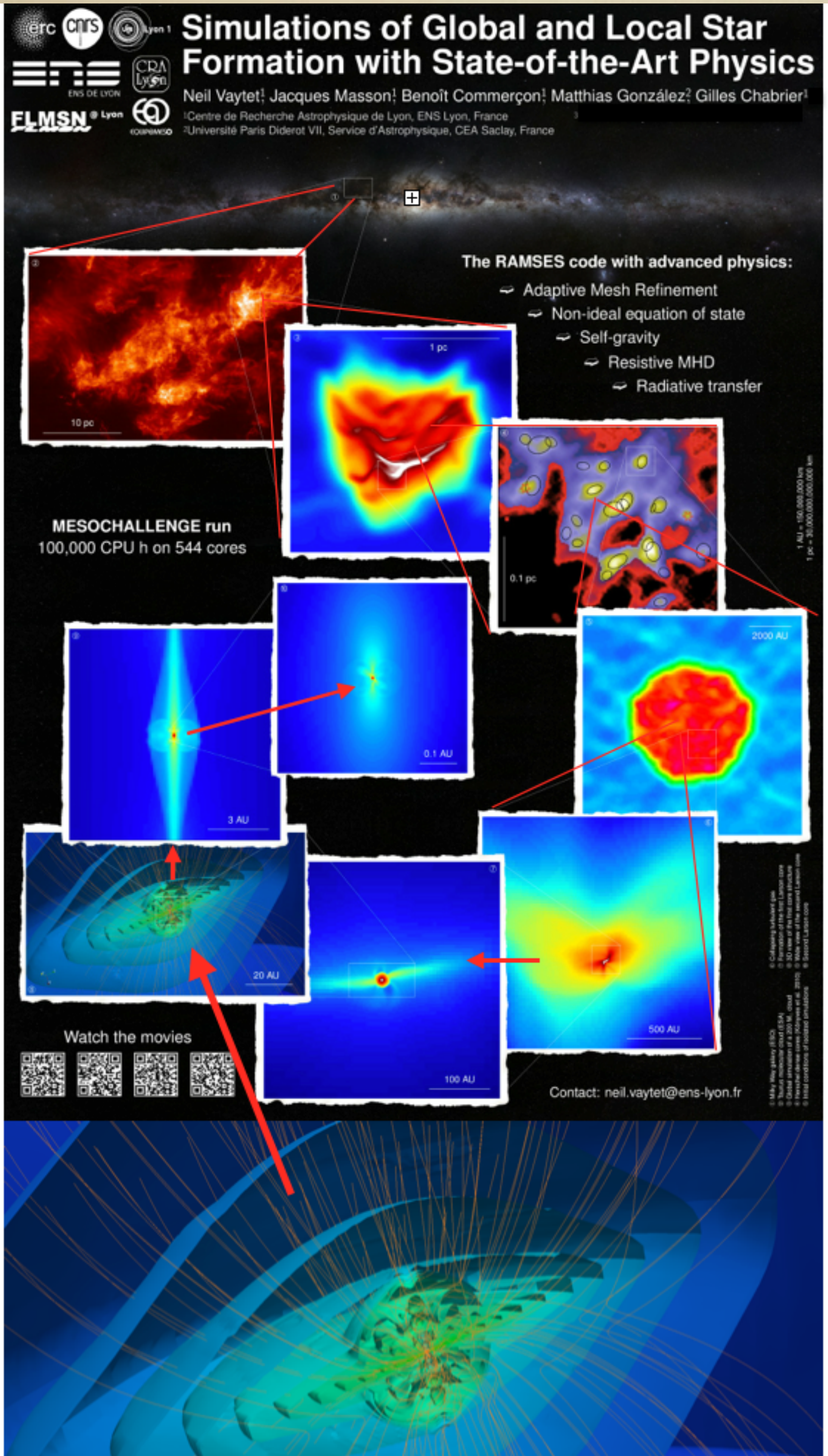


Chabrier system IMF

HC analytical IMF

Hennebelle & Chabrier ’09, ’13

Star/Brown dwarf formation



Simulations of Global and Local Star Formation with State-of-the-Art Physics

Neil Vaytet[1], Jacques Masson[1], Benoît Commerçon[1], Matthias González[2], Gilles Chabrier[1]

[1]Centre de Recherche Astrophysique de Lyon, ENS Lyon, France
[2]Université Paris Diderot VII, Service d'Astrophysique, CEA Saclay, France
[3] [redacted]

The RAMSES code with advanced physics:

- Adaptive Mesh Refinement
  - Non-ideal equation of state
    - Self-gravity
      - Resistive MHD
        - Radiative transfer

MESOCHALLENGE run
100,000 CPU h on 544 cores

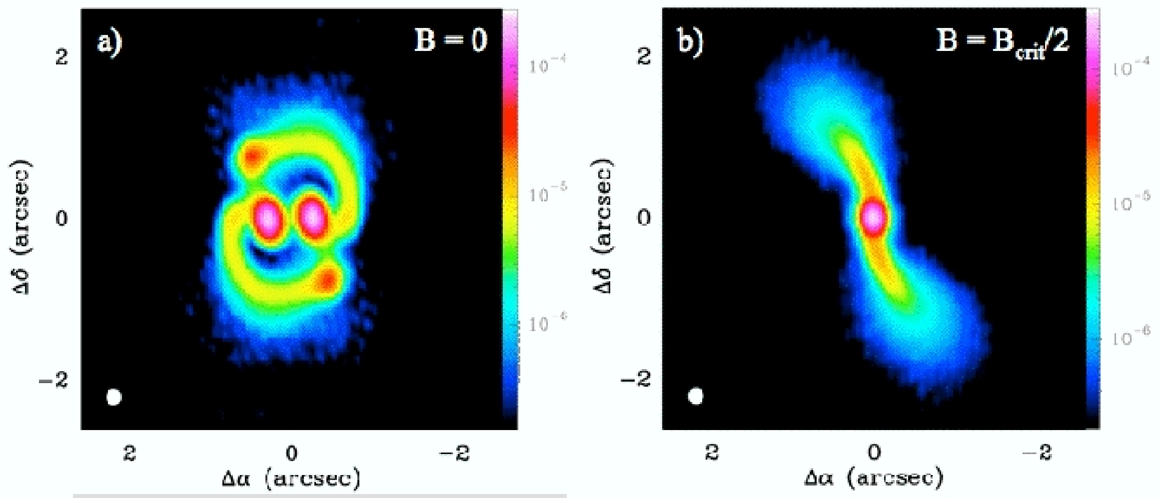
Watch the movies

Contact: neil.vaytet@ens-lyon.fr

Can we test these ideas ?

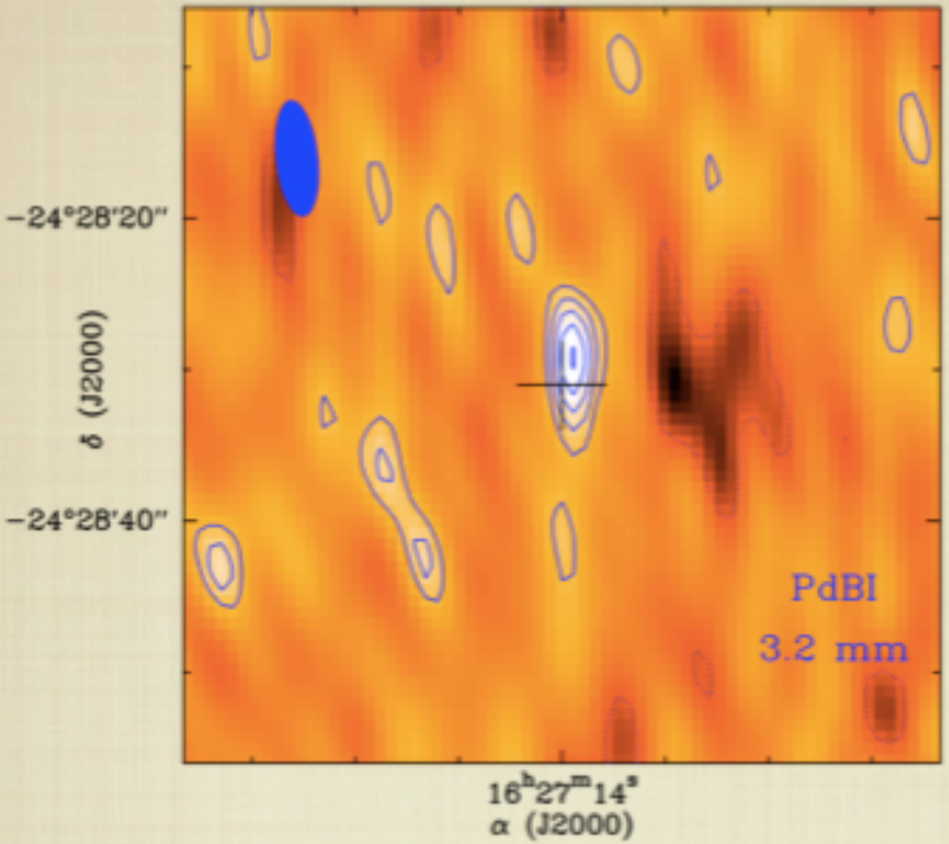
ALMA will offer the spatial resolution required

Synthetic observations done with the ALMA simulator
Included in the Gildas software



Commerçon et al. 2012

Observed **isolated Pre**-Brown dwarf **core**



Oph B-11
M~30 M_{Jup}
R<460 AU
n~ 10^7-10^8 cm^{-3}

André et al., 2012, Science 337, 69

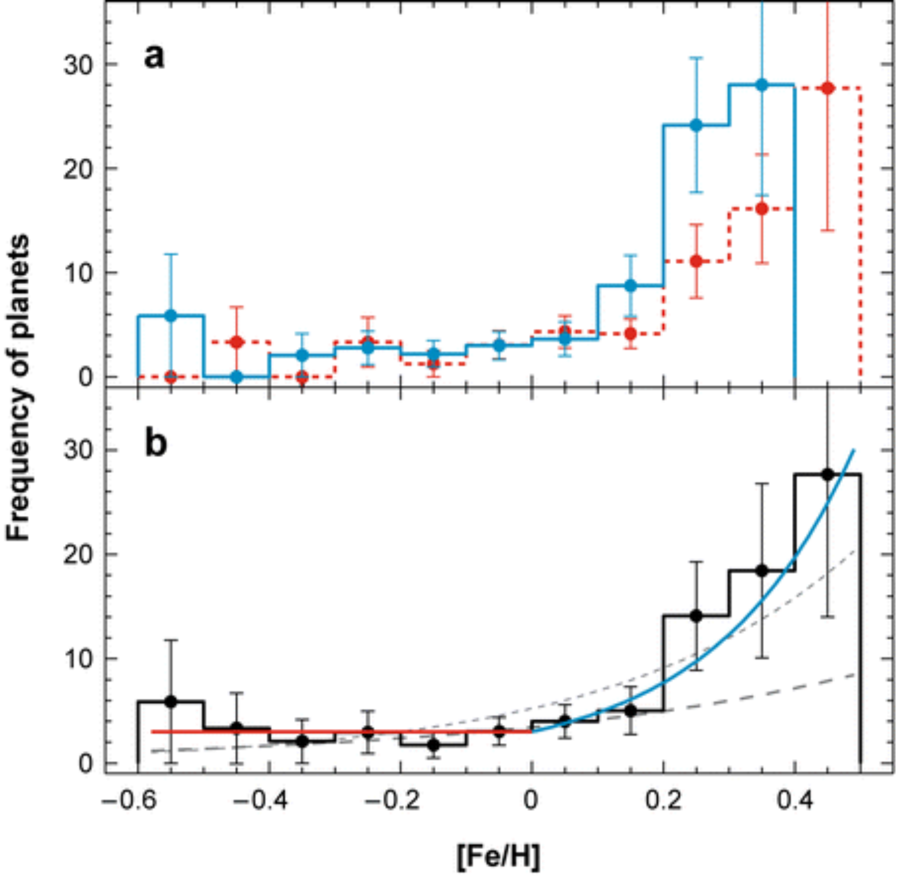
emerging observations of **isolated proto-brown dwarfs**

VeLLO L1148–IRS (Kauffmann et al. '11); **IRAS 16253-2429** (Wiseman et al.)
J042118 + J041757 1-5 M_{Jup} (Palau et al. '12); **L328-IRS <50 M_{Jup}** (C-W. Lee et al. '13)

Growing theoretical and observational evidence that BDs dominantly form like stars
(Luhman, ARA&A 2012, Chabrier et al., PPVI review 2014)

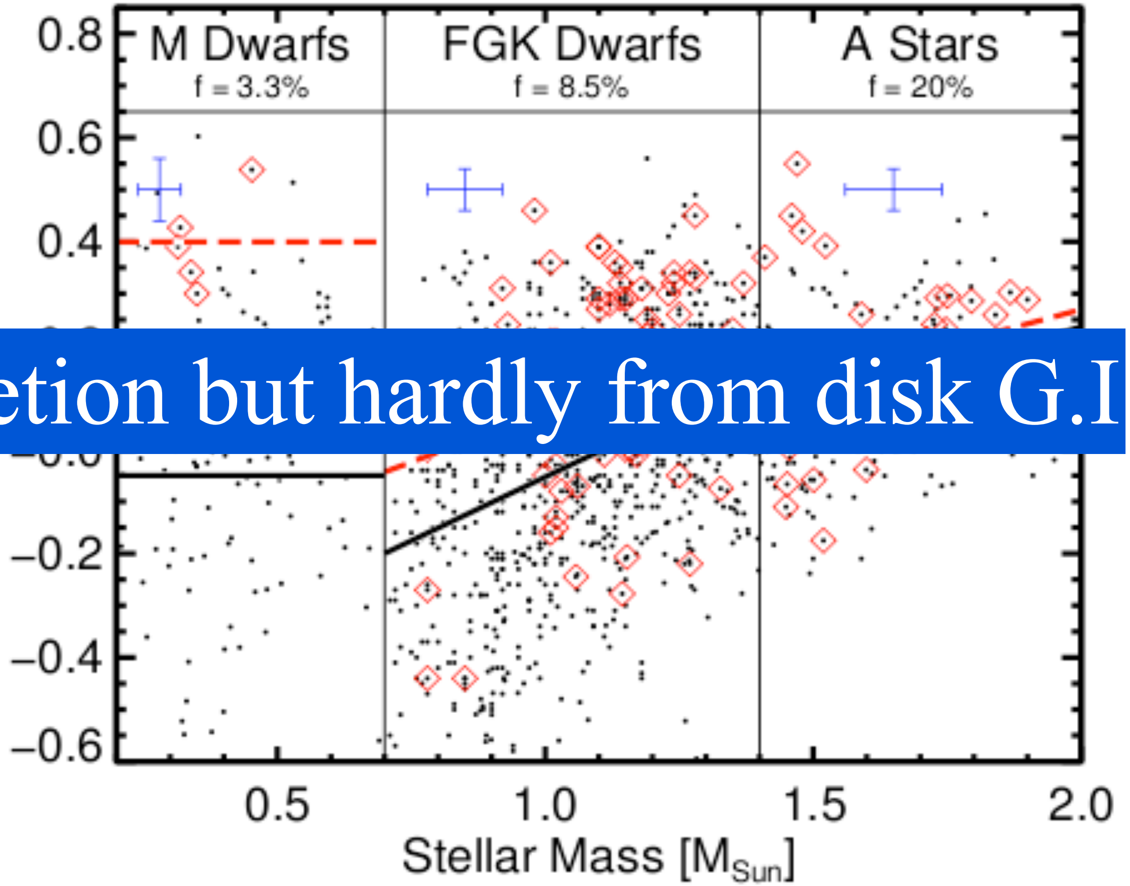
Metallicity

Giant planet frequency is strongly dependent on stellar host metallicity



Udry S, Santos NC. 2007.
Annu. Rev. Astron. Astrophys. 45:397–439

Johnson et al. (2010)



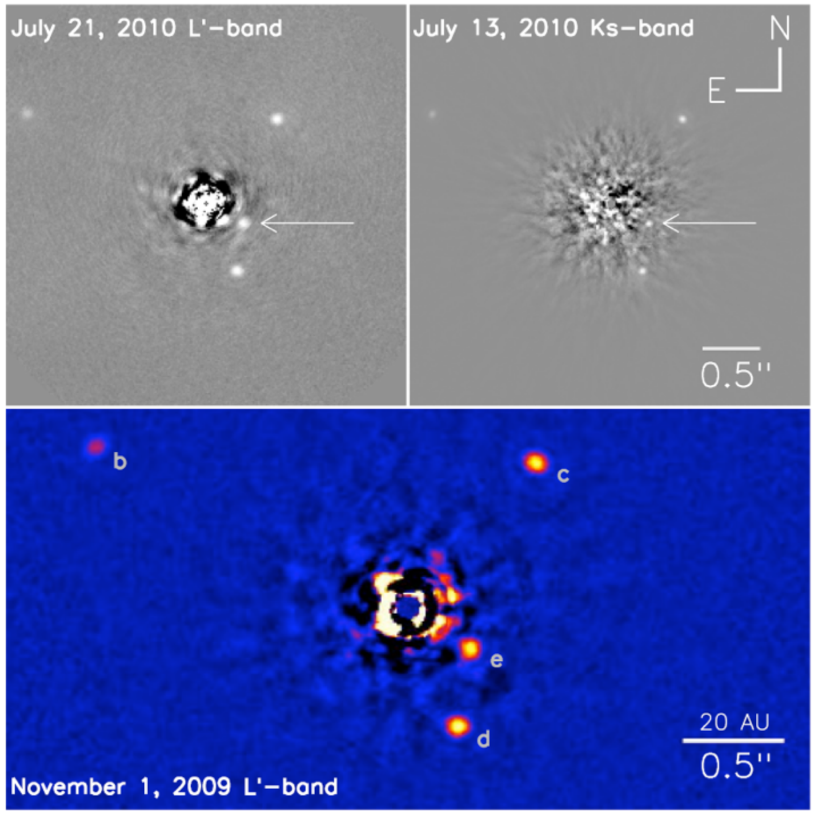
Expected from core-accretion but hardly from disk G.I

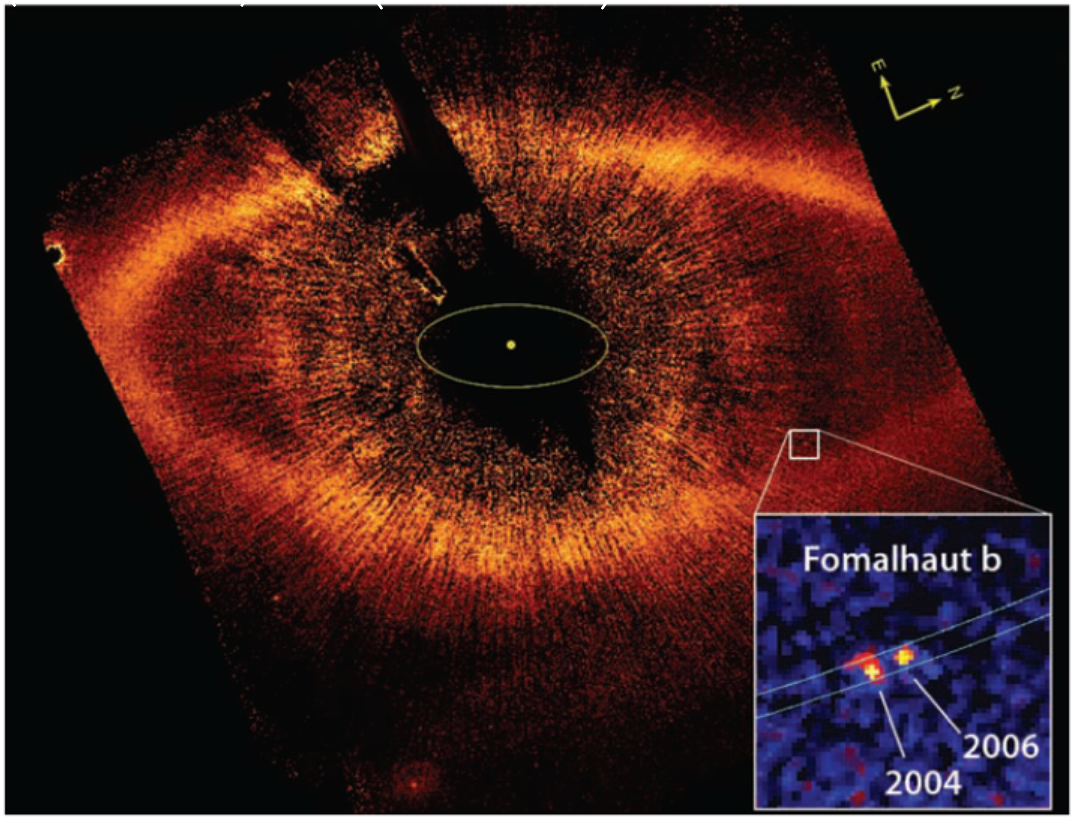
Correlation is weaker for lower-mass planets but stronger for lower-mass stars

Problem for C.A. : planets on wide orbits

$$a < 44\ AU\ \kappa_{0.1}^{-0.09}\left(\frac{\tau_{neb}}{3Myrs}\right)^{0.75}\left(\frac{\Sigma}{\Sigma_{MMSN}}\right)^{2/3}$$

(Rafikov 2010)



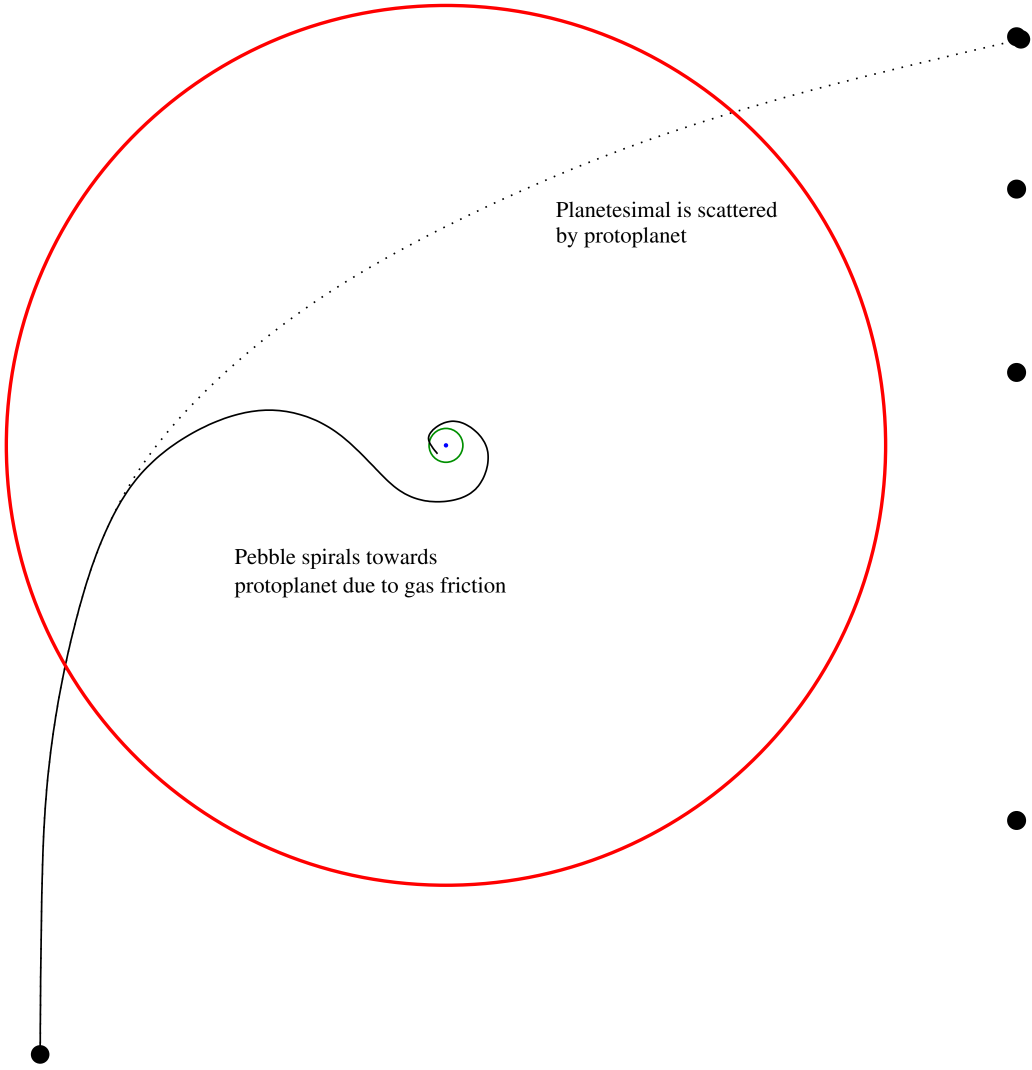


HR 8799 (4 planets at 14.5, 24, 38, 68 AU)

Fomalhaut (1 controversial planet at 113 AU)

No way to form the cores of these planets within the lifetime of the protoplanetary disc by standard core accretion

Pebble accretion



- Most planetesimals are simply scattered by the protoplanet
- Pebbles spiral in towards the protoplanet due to gas friction
- Pebbles are accreted from the entire Hill sphere

- Growth rate by planetesimal accretion :

$$\dot{M} = \alpha R_{\mathrm{H}}^2 \mathcal{F}_{\mathrm{H}}$$

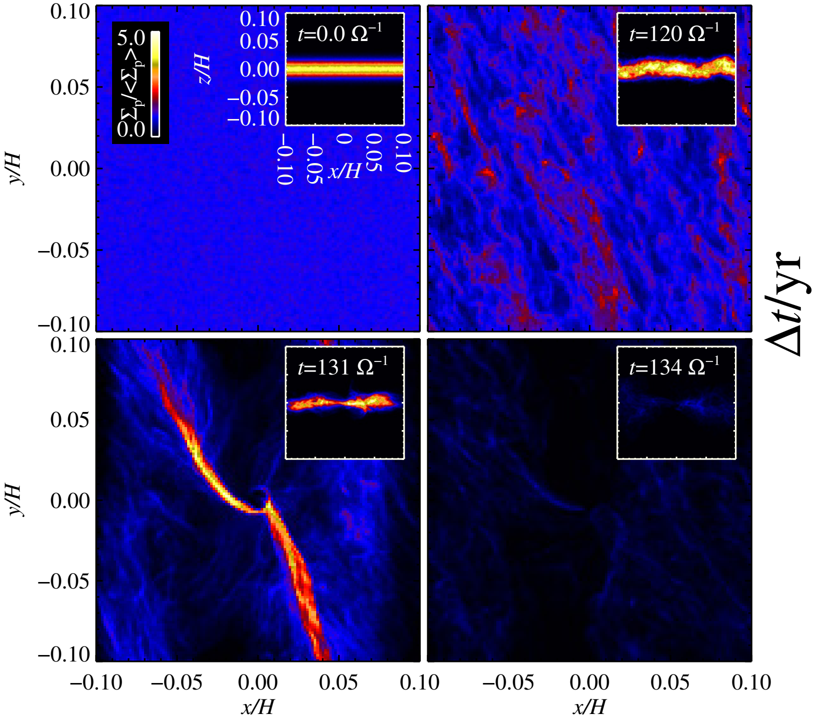
$$\frac{R_{\mathrm{p}}}{R_{\mathrm{H}}} \equiv \alpha \approx 0.001 \left(\frac{r}{5\,\mathrm{AU}}\right)^{-1}$$

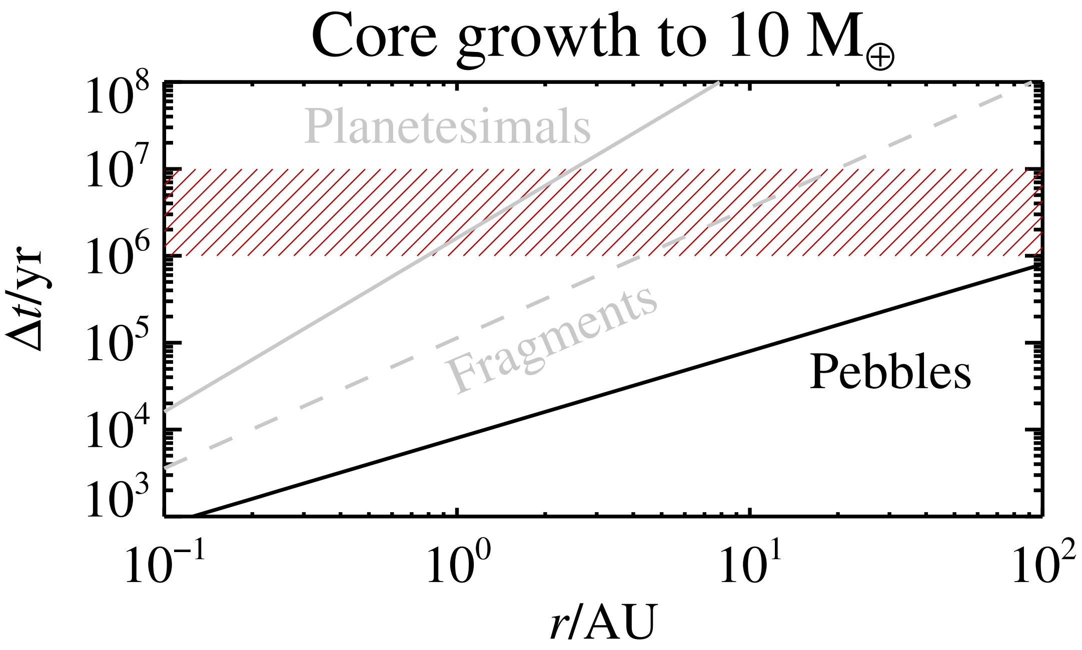
- Growth rate by pebble accretion :

$$\boxed{\dot{M} = R_{\mathrm{H}}^2 \mathcal{F}_{\mathrm{H}}}$$

Ormel & Klahr 2010; Lambrechts & Johansen 2012

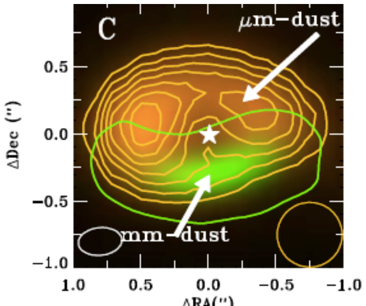
Time-scale of pebble accretion




Core growth to 10 $M_\oplus$

- **Pebble accretion speeds up core formation** by a factor 1,000 at 5 AU and 10,000 at 50 AU (Lambrechts & Johansen 2012; Ormel & Klahr 2010; Morbidelli & Nesvorny 2012)
- Cores form well within the lifetime of the protoplanetary gas disc, even at large orbital distances
- Requires large planetesimal seeds, consistent with turbulence-aided planetesimal formation (see e.g. A. Johansen et al. 2014, PPVI)

Observations of a «dust trap» in a disk between 45-90 AU
(Van der Marel et al., Science '13)



- **HD100546 b** (Quanz et al. 2011)

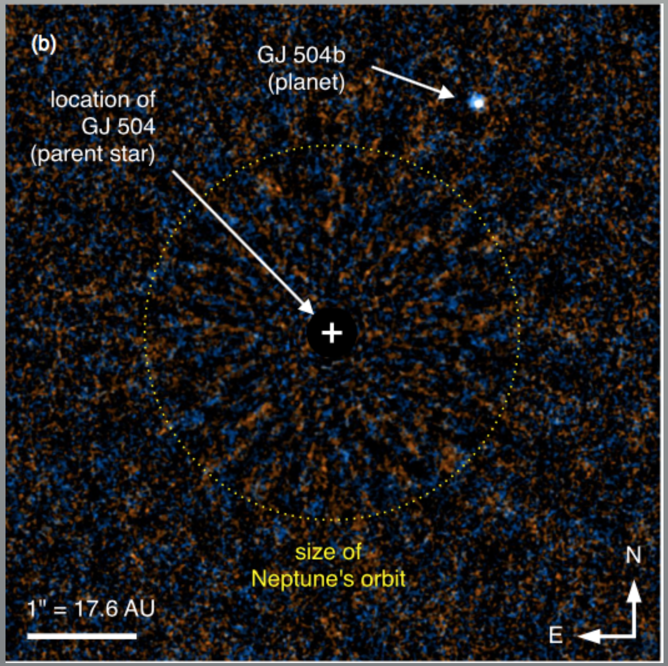
$M_\star$=2.4 M_{sol} M_p~5-12 M_{jup} @ 50 AU

Disk not massive enough (~0.4% $M_\star$) for GI.
Could be explained by cm-size pebble acc’n

- **GJ504b** (Kuzuhar et al. 2013)

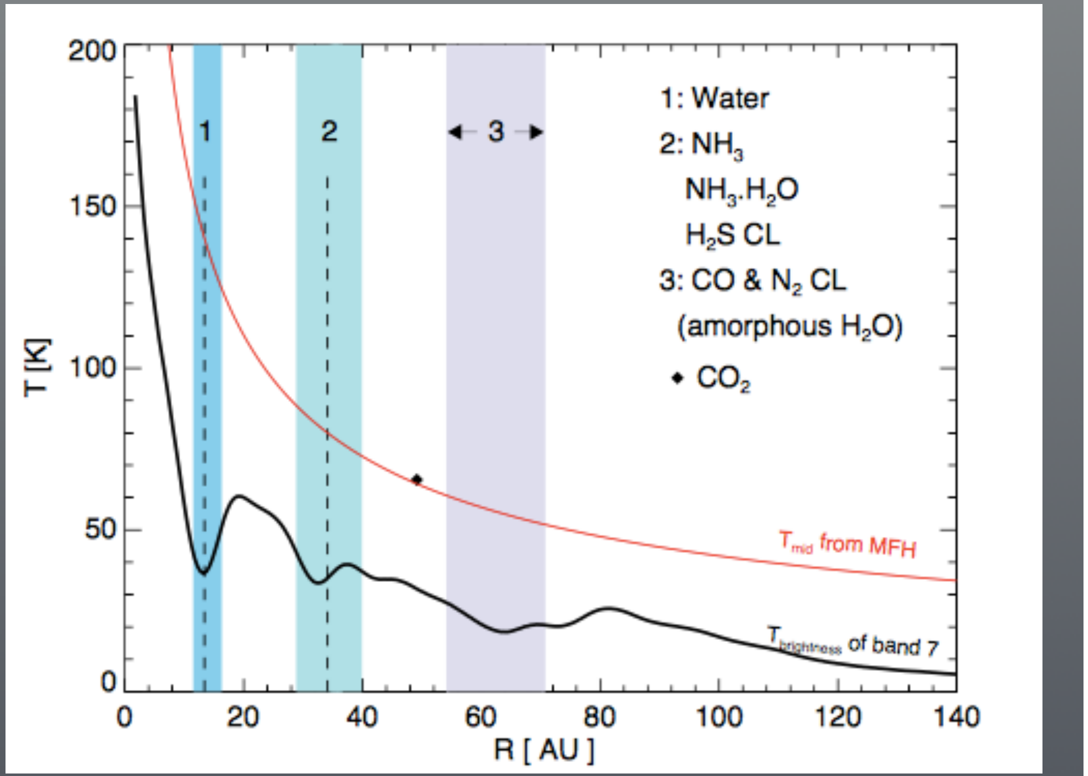
$M_\star$=1.2 M_{sol}, [M/H]=0.28 M_p~1-8 M_{jup} @ 44 AU

Could be explained by cm-size pebble acc’n

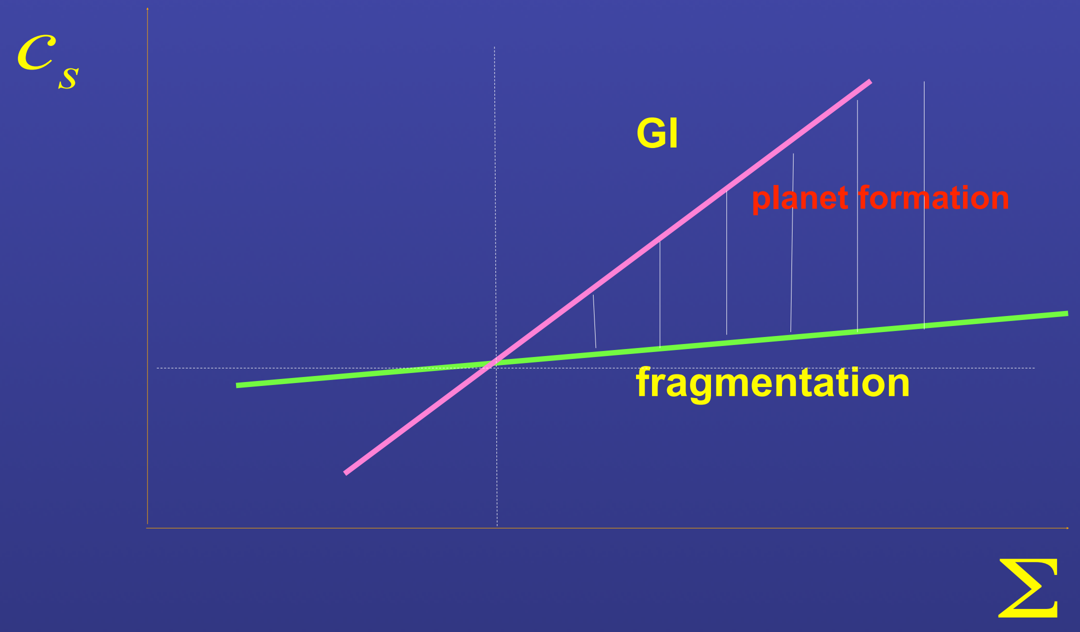


- Zhang et al. 2015

13 AU dip: cond’n H2O
32 AU dip: cond’n NH3+hydrates
dcm-size pebbles (Ros & Johansen ’13)
-> >km-size planetesimals by streaming instabilities (Johansen et al. 2014)



Gravitational Instability in a disk: Thermodynamical constraints



Rafikov 2005

As a result, giant planet formation by GI requires

$$\Sigma > \left[\frac{\Omega^7}{3\sigma(\pi G)^6} \left(\frac{k}{\mu} \right)^4 \right]^{1/5} = 3\times10^5 g\ cm^{-2} a_{AU}^{-21/10}$$

(~ 100 MMSN) !

$$T > \left[\frac{\Omega^2}{3\pi\sigma G} \left(\frac{k}{\mu} \right)^{3/2} \right]^{2/5} = 2200\ \ K\ a_{AU}^{-6/5}$$

$\left(\sim T_{Sun} \right)$!!!

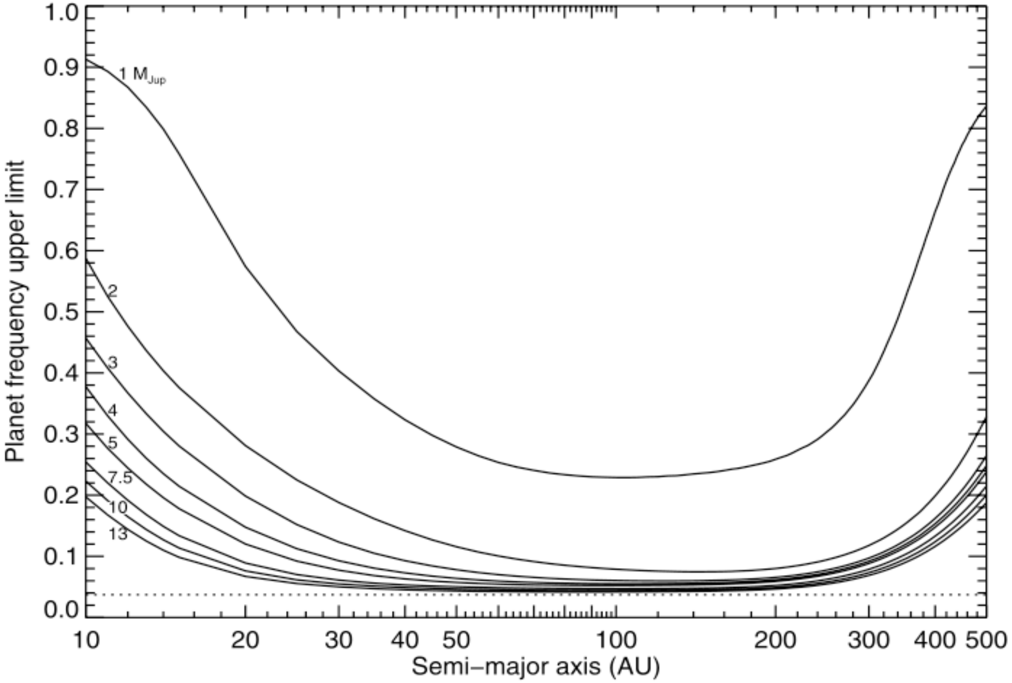
Requires rather extreme disk conditions

- Gravitational coupling to the massive disk quickly migrates them into the star

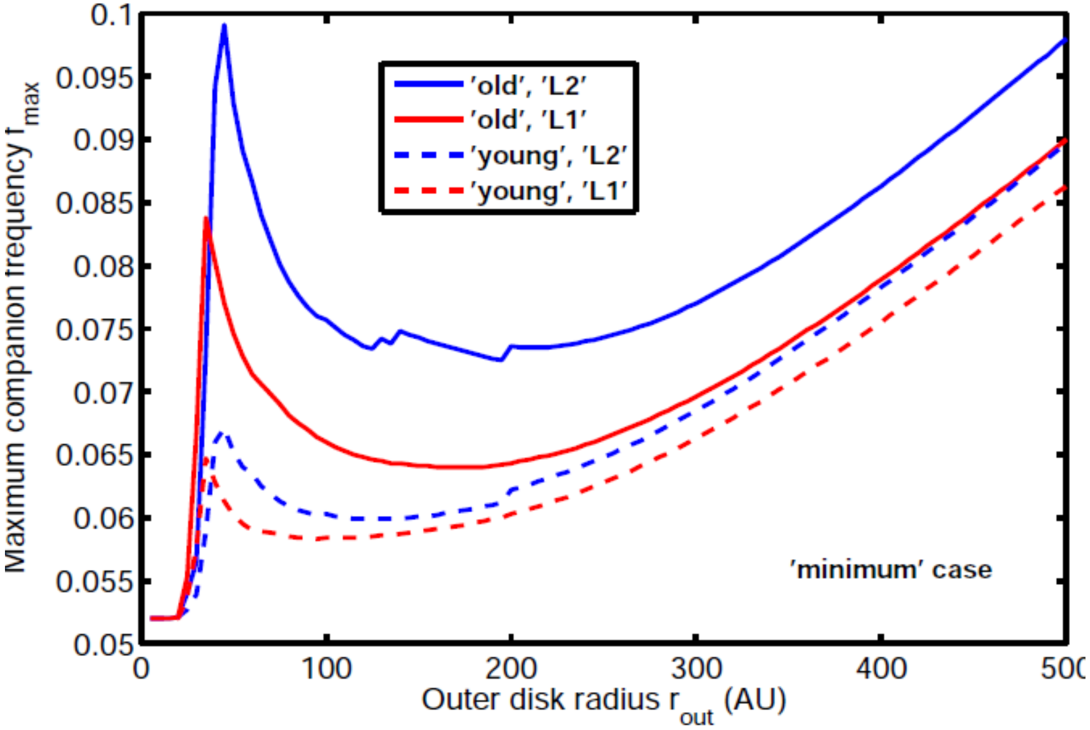
(Vorobyov & Basu 2005, Machida 2011, Baruteau et al. 2013)

Statistical constraints from Direct Imaging (with caveats!)

apply both to BD's and planets !



Lafreniere et al. (2007)



Janson et al. (2012)

<23% of stars have >2 M_J planets at 25-450 AU

<9% of stars have >5 M_J planets at 25-450 AU

<10% of stars host ~Jupiter-mass objects formed by disk instability

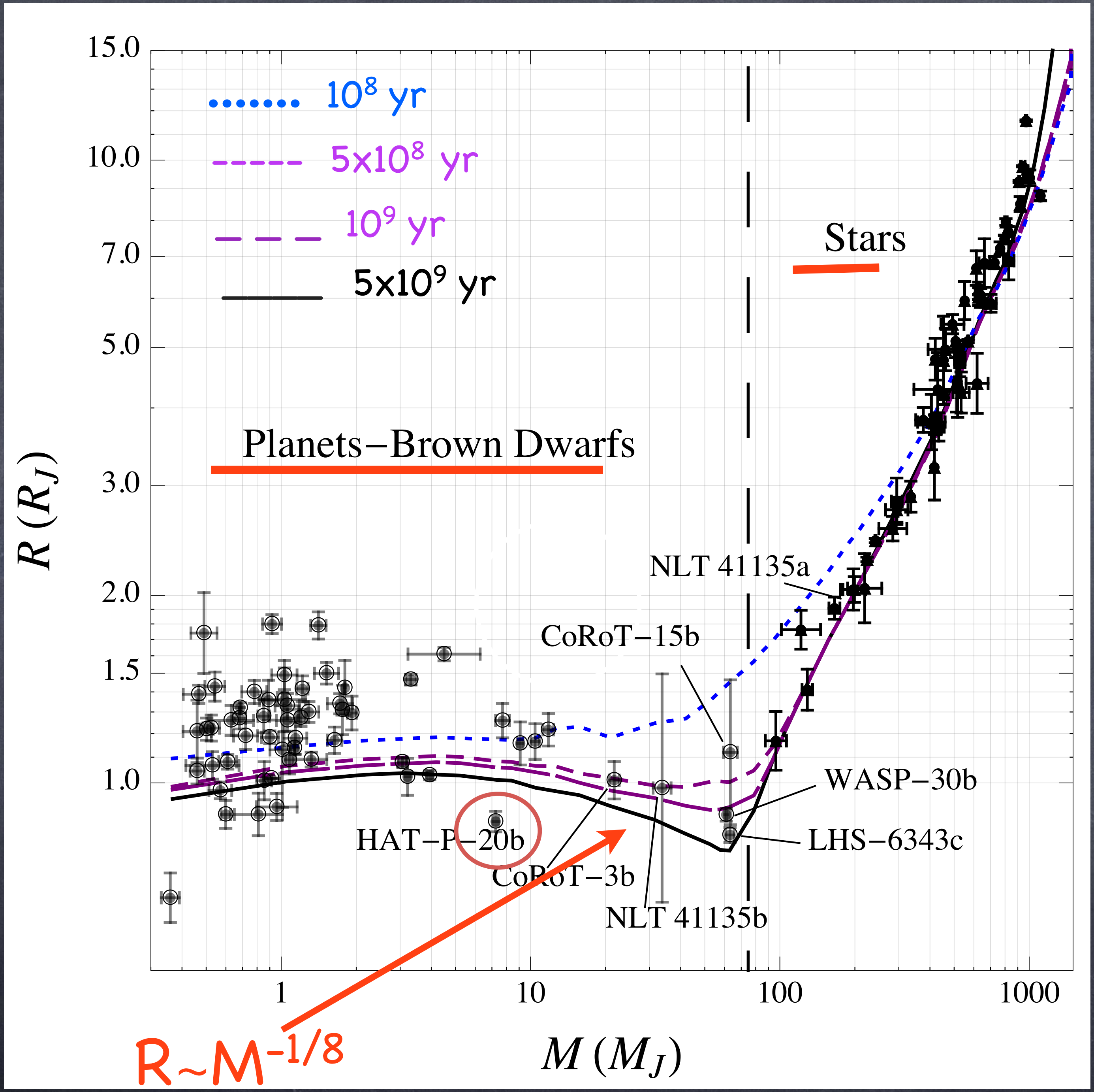
Brandt et al. (2015)

combined sample (SEEDS, GDPS, NICI MG) of 250 stars over a wide rand of ages and Sp

<5% of stars have substellar 5-70 Mjup comp'ns between 10-100 AU @ 95% C.L.

<11% of stars have substellar 10-70 Mjup comp'ns between 30-1600 AU @ 95% C.L.

3) THE DIAGNOSTIC(S)



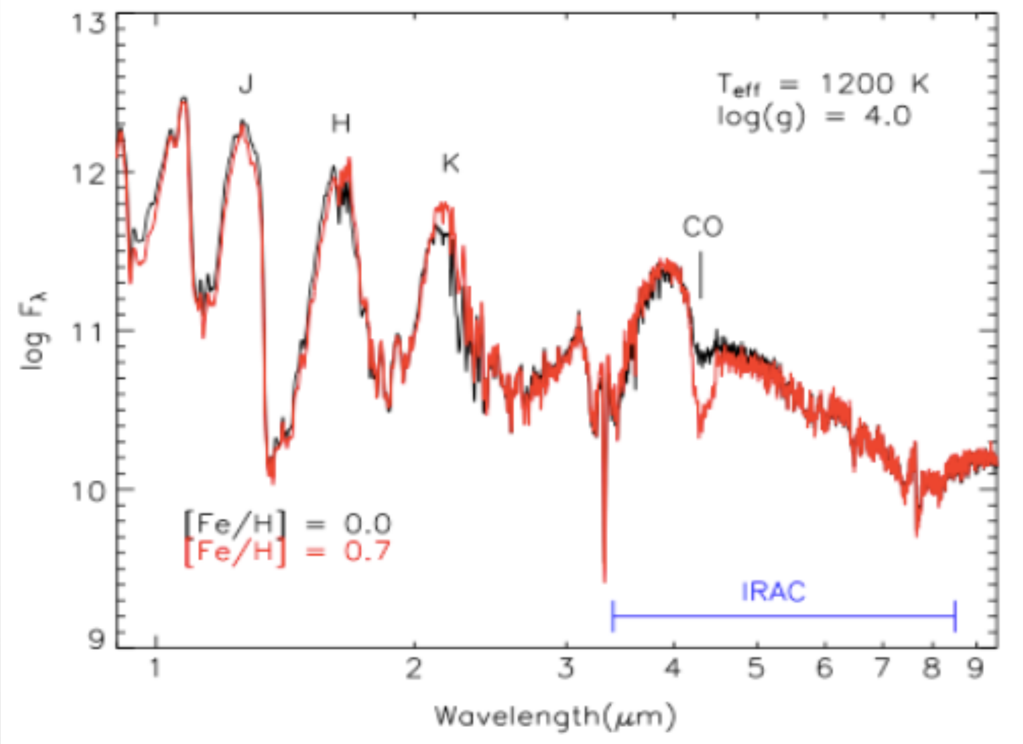
$R \sim M^{-1/8}$

(Chabrier & Baraffe 2000)

Chabrier, Leconte & Baraffe 2010

Distinguishing (low-mass) BDs from (massive) GPs

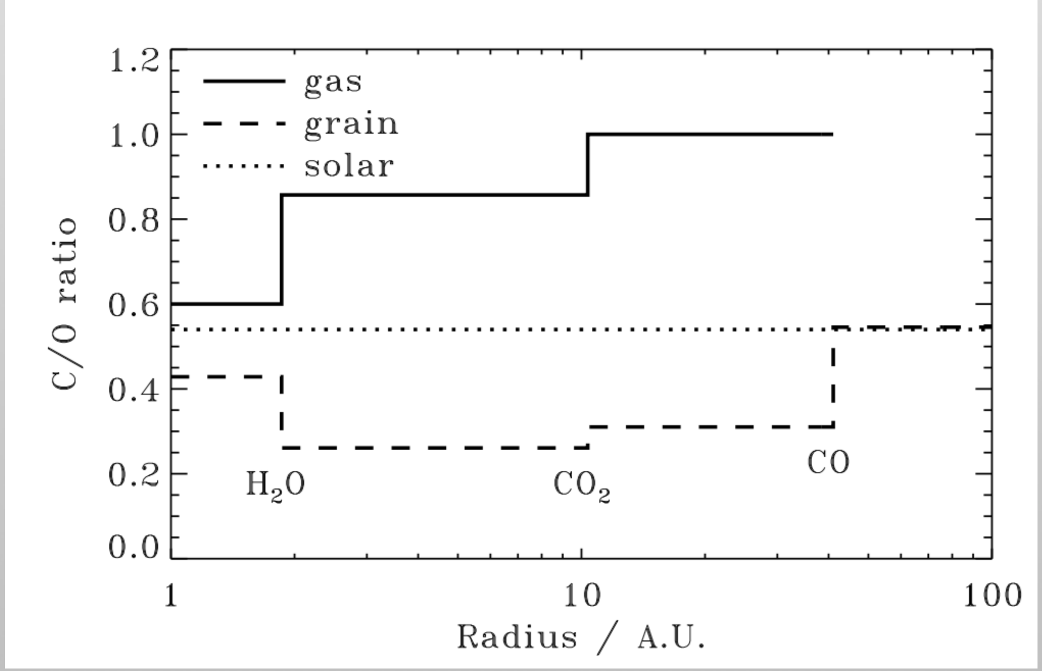
Effect of an increase of metallicity (factor 5) on spectra *(Chabrier et al. 2007)*



- deeper CO absorption
- enhanced K-band flux

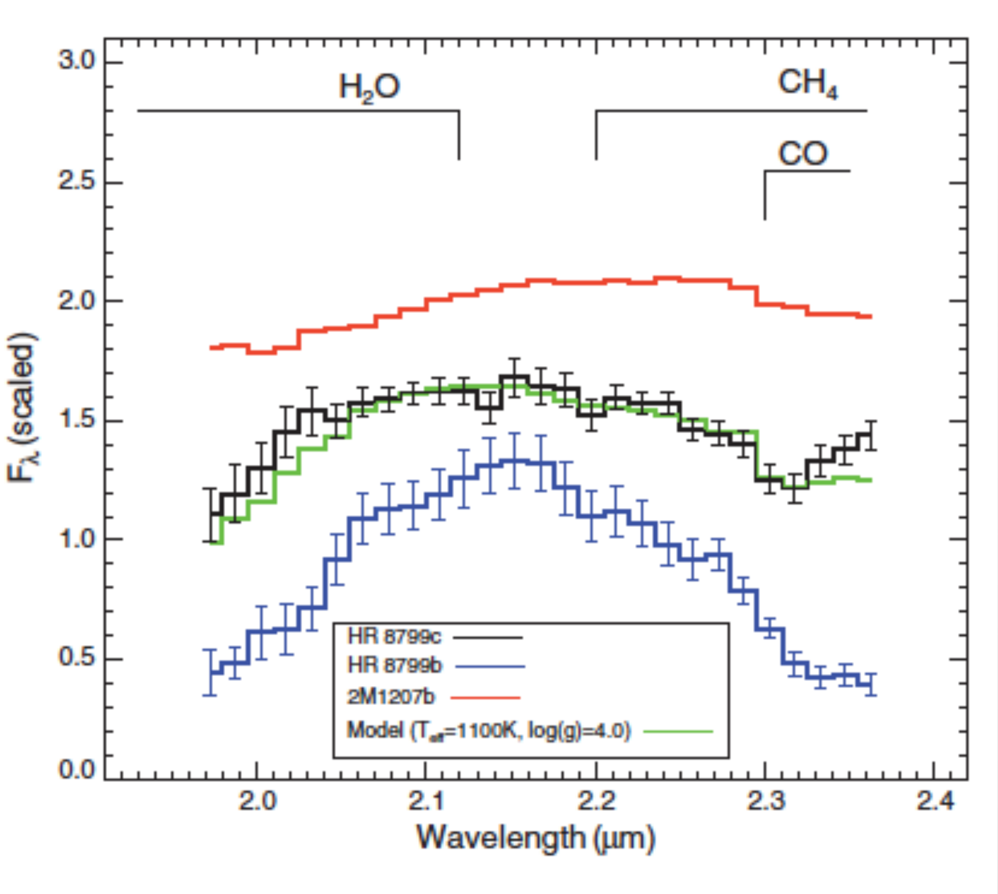
Fortney et al. 2008

spectrum calculated by T. Barman



C/O enhanced in regions of gas giant formation

Öberg et al. 2008



HR 8799c: enhanced C/O ratio and depleted C and O levels tend to favor a formation by C.A. *(Konopacky et al. 2013)*

Not so simple!….

- non-equilibrium chemistry (see talk by P. Tremblin)
- depends on the region of formation (different condensation lines)
- migration ….
- HOWEVER, **stellar C/O expected for planets formed by G.I.**

Conclusion 1

- Brown dwarfs form <u>**dominantly**</u> like stars, by gravoturbulent frag'n of a parent cloud/core (emerging population of <u>isolated</u> pre- and proto-BD cores)

- Overwhelming majority of discovered **exoplanets** consistent w/ predictions from **Core Accretion**

- Formation by **G.I. requires very peculiar (extreme ?) conditions**
  Adding migration makes the problem even more accute (requires some «fine tuning»).
  Even if G.I. occurs, survival of the fragment is still en issue

- G.I. might be operational at large orbital distances.
  However:
  * scarcity of objects at such distances (constraints from direct imaging)
  * C.A. might work («pebble» accretion)
  * other possibilities (outward migration, planet scattering,....)
  ... stay tuned ! Future projects (SPHERE, GPI, CHARIS) will help
  - G.I. might produce <u>some objects</u> (eg Delorme et al. '13)

- **Diagnostics to distinguish BDs from GPs**:
  - **M-R** ex.: Hat P 2b (9 M_{Jup}), Hat P 20b (7 M_{Jup}), $M_{core} > 200\ M_{Earth}$ (Leconte et al. '09, '11)
  - **spectro** : C/O, C/H expected to be non-stellar if formation by C.A.

Conclusion 2

- **BD f'n extends down to the opacity limit fragmentation (~1-5 Mjup)**
  (D-burning and non D-burning BDs, the same way PP and CNO stars)
- **GP f'n seems to extend at least to ~ 7-9 Mjup (Hat P 2b, Hat P 20b)**

* K And b : **$\sim$10-20 M_{Jup}**, 40 AU companion to a B9 star w/ **$q=M2/M1<1\%$**
* 2M 1207 b : **$\sim$4 M_{Jup}**, $\geq$ 55 AU companion to a BD w/ **$q=20\%$**
=> **existence of non D-burning BD's**
/ **D-burning planets not unlikely** (Baraffe et al. '08, Mollière & Mordasini '12)

*The very definition of a brown dwarf or a giant planet is intrinsically, tightly linked to its **formation mechanism**.*

- Free floating objects down to a few M_{jup} can rather unambiguously be identified as genuine (non D-burning) **brown dwarfs**
- **planets** are necessarily companions of a central, significantly more massive object. Should have a non-stellar mean metal abundance

? {
- genuine (ejected) free floating planets
- ~M_{jup} objects formed by G.I.

BD and GP mass domain overlap
Deuterium burning plays no role
IAU definition scientificallY meaningless