The substellar mass function of open clusters

Variability or Dynamical Evolution ?

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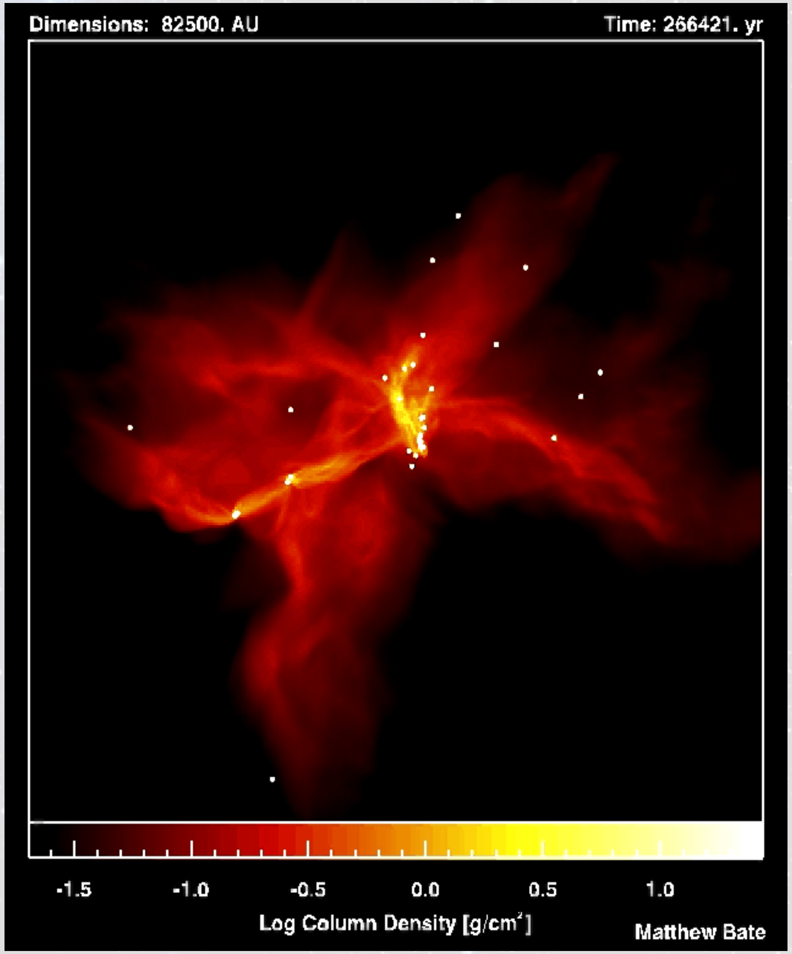
Stellar formation

- Most of the stars form in groups / clusters (N=10-10^5)
- How do clusters form ?
  - Quasi-equilibrium and slow contraction scenarios
  - Highly dynamic: fragmentation driven by supersonic MHD turbulence (e.g. Bate et al. 2009)



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- Different scenarios -> different predictions
- **What are the cluster statistical properties at birth ?**
  - **Initial Mass Function**
  - Spatial distribution
  - Multiplicity properties
  - Disk properties
  - Kinematics

Motivation

The IMF

What is the origin of the initial mass function (IMF) ?

Is the IMF universal ?

How early is the mass distribution set ?

Is the shape of the IMF tracing different formation processes ?

The substellar domain

Do brown dwarfs form like H-burning stars ?

Are the formation mechanisms different for low mass BD and planets ?

I. The substellar MF

Young open clusters (30-100 Myr): down to 30 Mjup

Star forming regions (1-5 Myr): the lowest mass objects

Determination of the mass function

- **Young open clusters and star forming regions :** homogeneous populations from low mass to high mass stars (same distance, age, [Fe/H], initial conditions)

- **Wide field imaging surveys** to identify the very low mass stars and brown dwarfs in the cluster

(e.g. CFHT/MegaCam: 1°x1°, 36 CCD, 0.187''/pixel)

Optical	Near Infrared
30 Mjup – 3 Msun In open clusters	**3 Mjup – 30 Mjup** **In SFR**

Pleiades : a benchmark cluster

Distance = 120-130 pc

Lithium age = 125 +/- 8 Myr
(Stauffer et al. 1998)

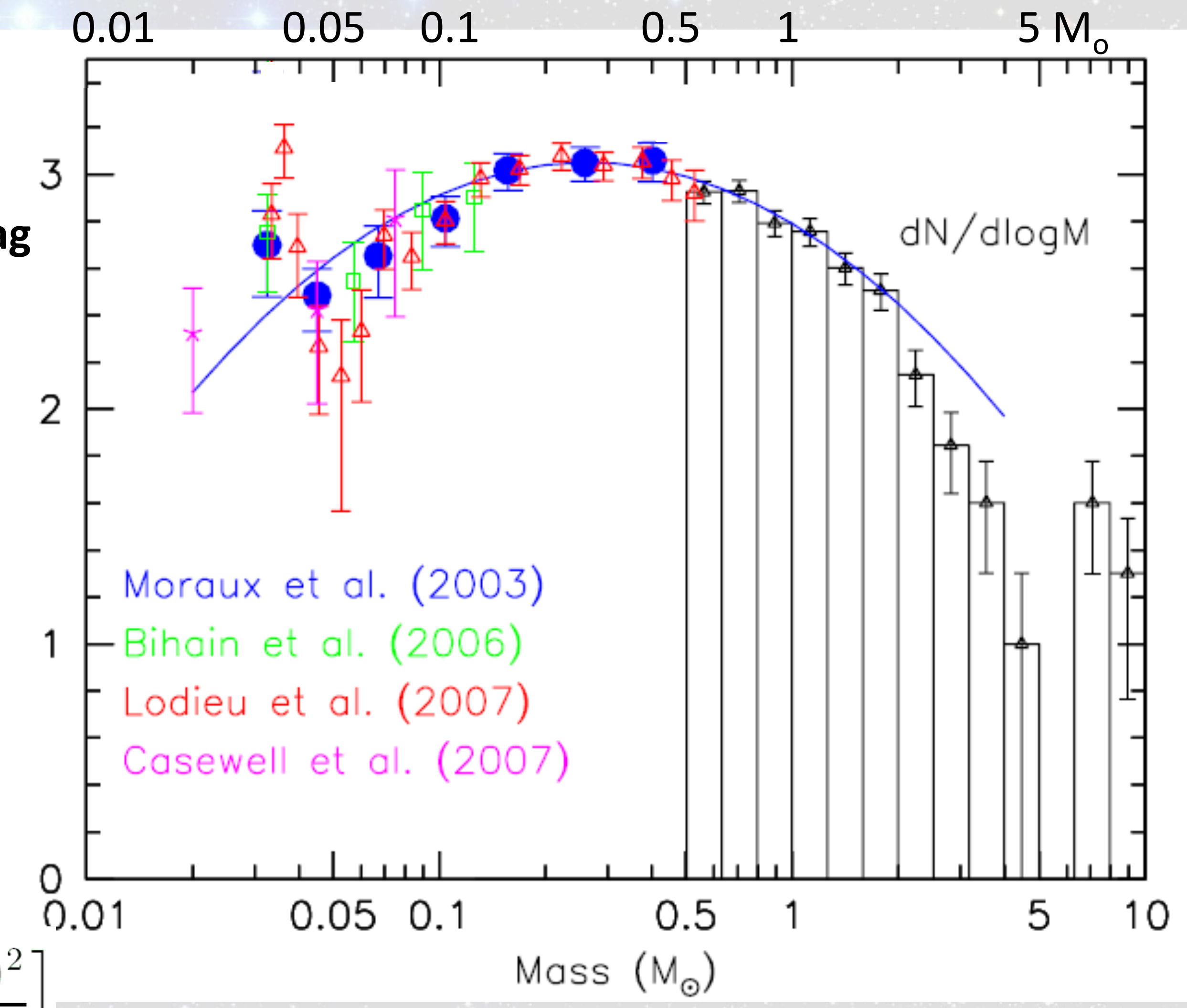
Star / BD boundary @ I ~ 17.8 mag
(Bouvier et al. 1998)

System MF
(unresolved binaries)
~70 substellar members

Lognormal fit :

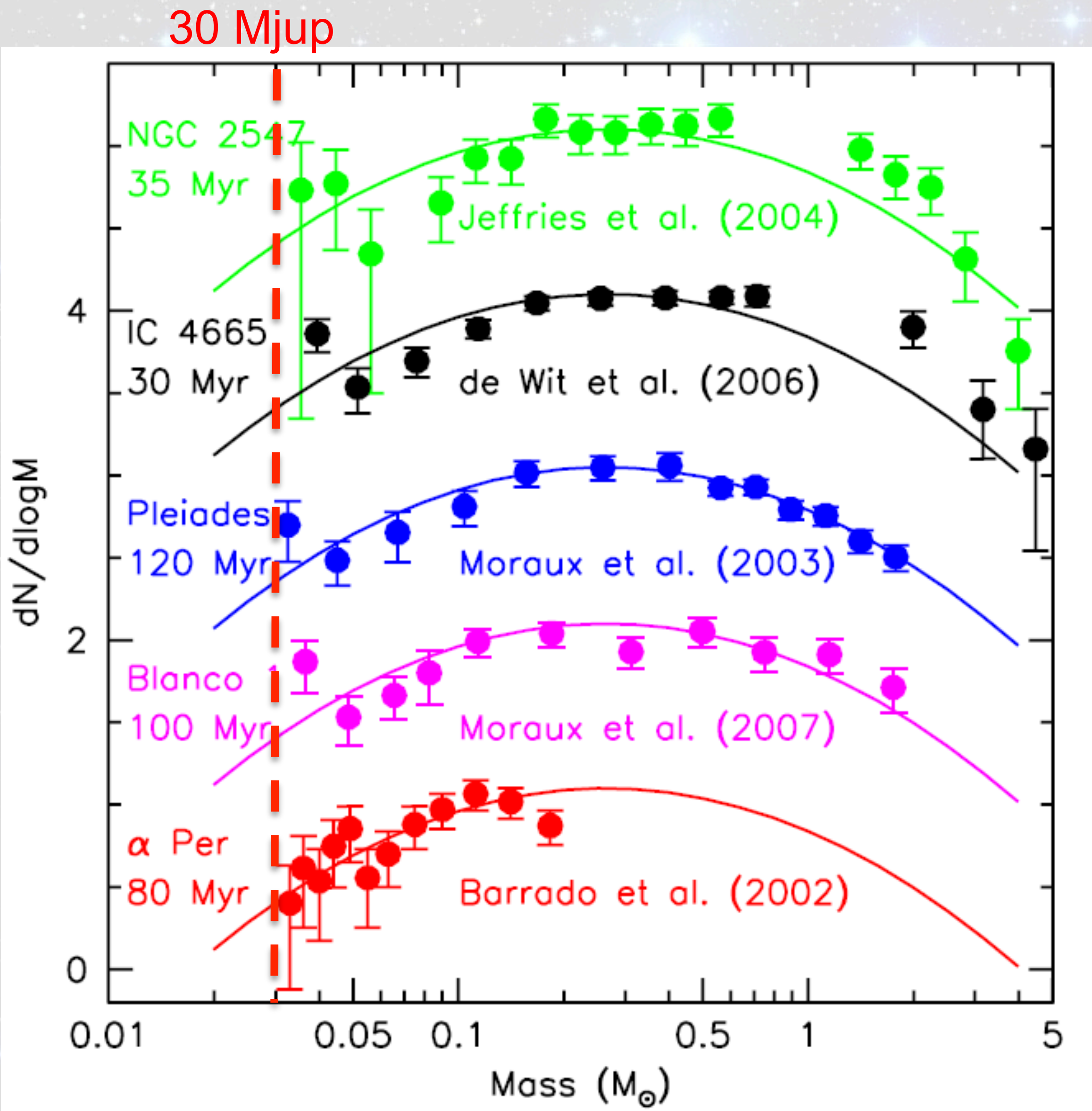
m_0 = 0.25 Mo
σ = 0.52

$$\frac{dn}{d\log m} \propto \exp\left[-\frac{(\log m - \log m_0)^2}{2\sigma^2}\right]$$



(note the "M7 gap" at ~0.05Mo; cf. Dobbie et al. 2002, Moraux et al. 2007)

The observed MF of open clusters



System MF (unresolved binaries)

All observed YOC MFs consistent within errors with Pleiades lognormal fit in the mass range **~0.03-3.0 Msun**

$$\frac{dn}{d\log m} \propto \exp\left[-\frac{(\log m - \log m_0)^2}{2\sigma^2}\right]$$

m_0 **~ 0.25 Msun**

σ **~ 0.5-0.6**

Consistent with the field MF down to $0.1M_0$

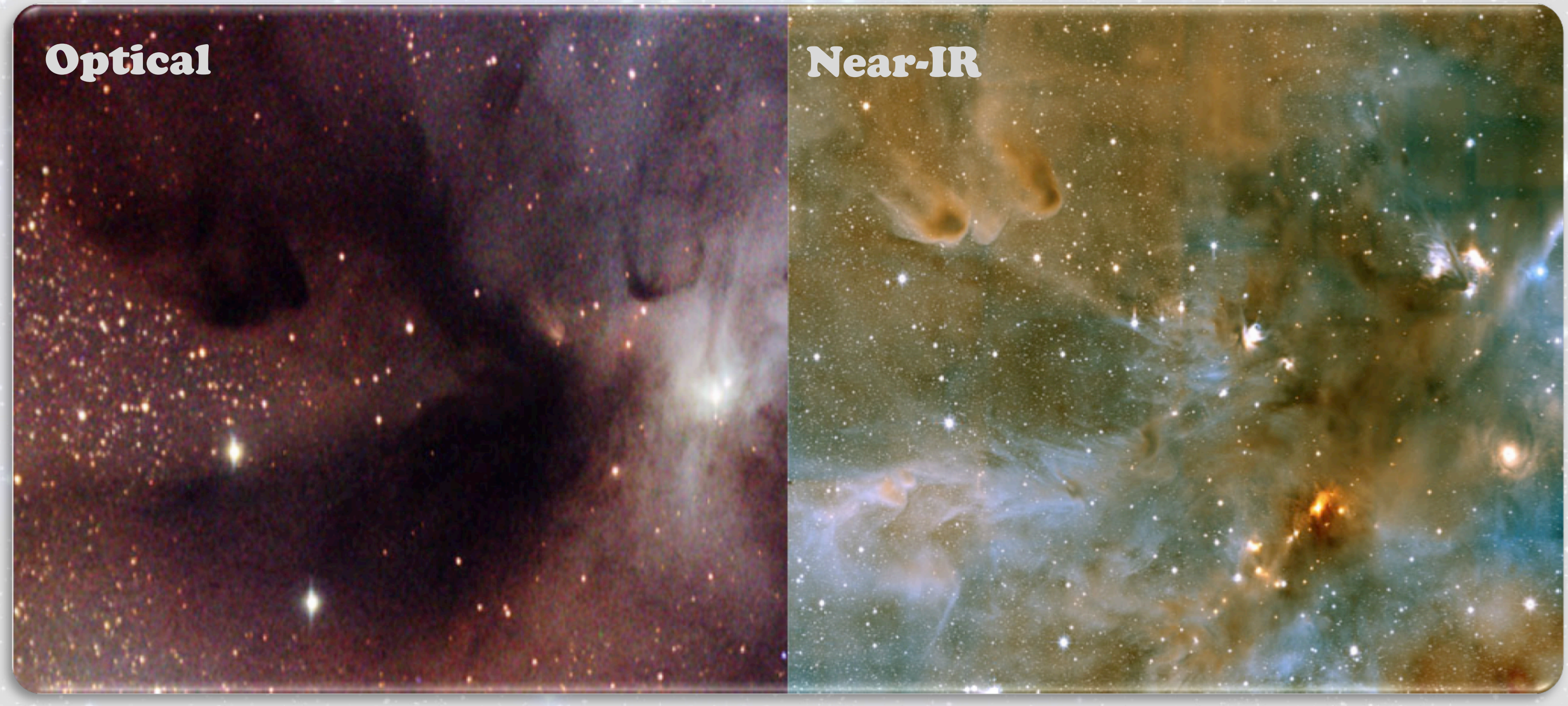
→ a universal IMF ?

The CFHT/WIRCAM survey

Low mass brown dwarfs: the younger the brighter, in the NIR

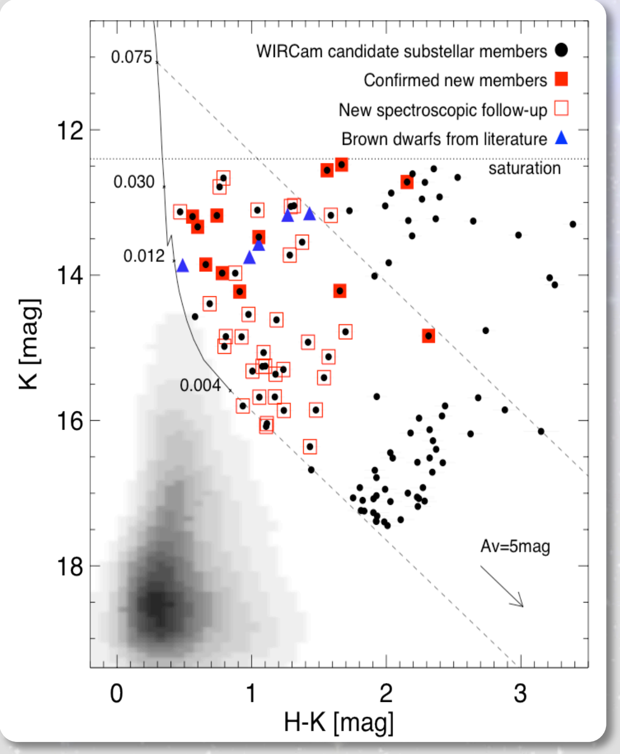
WIRCam near-IR deep imaging: Y J H Ks, and CH4 filters

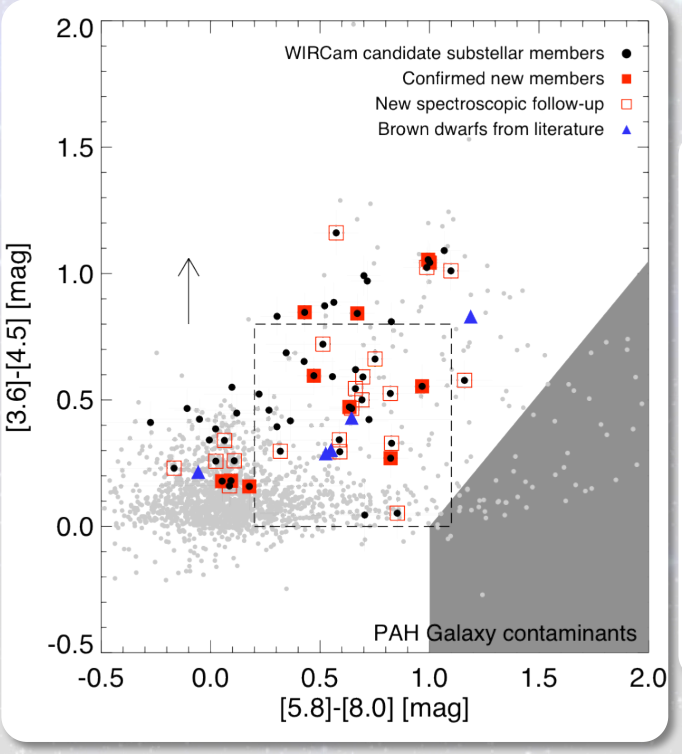
Nearby star-forming regions: Ophiuchus, IC348, NGC1333, Serpens, NGC2464, and Lambda Ori



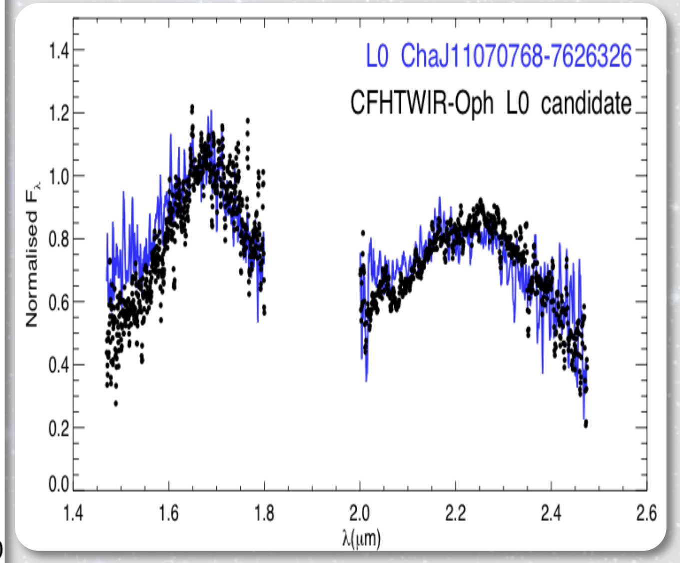
Selection of results: Rho Ophiuchus

- 110 substellar candidates, from which 80 were previously unknown
- 6 new BD confirmed spectroscopically, bringing to 21 the total number of substellar members (more to come… follow-up in progress)
- $R = N_{BD(0.01\text{-}0.08Msun)}/N_{star(0.1\text{-}1Msun)} \sim 0.25$ consistent with Pleiades MF

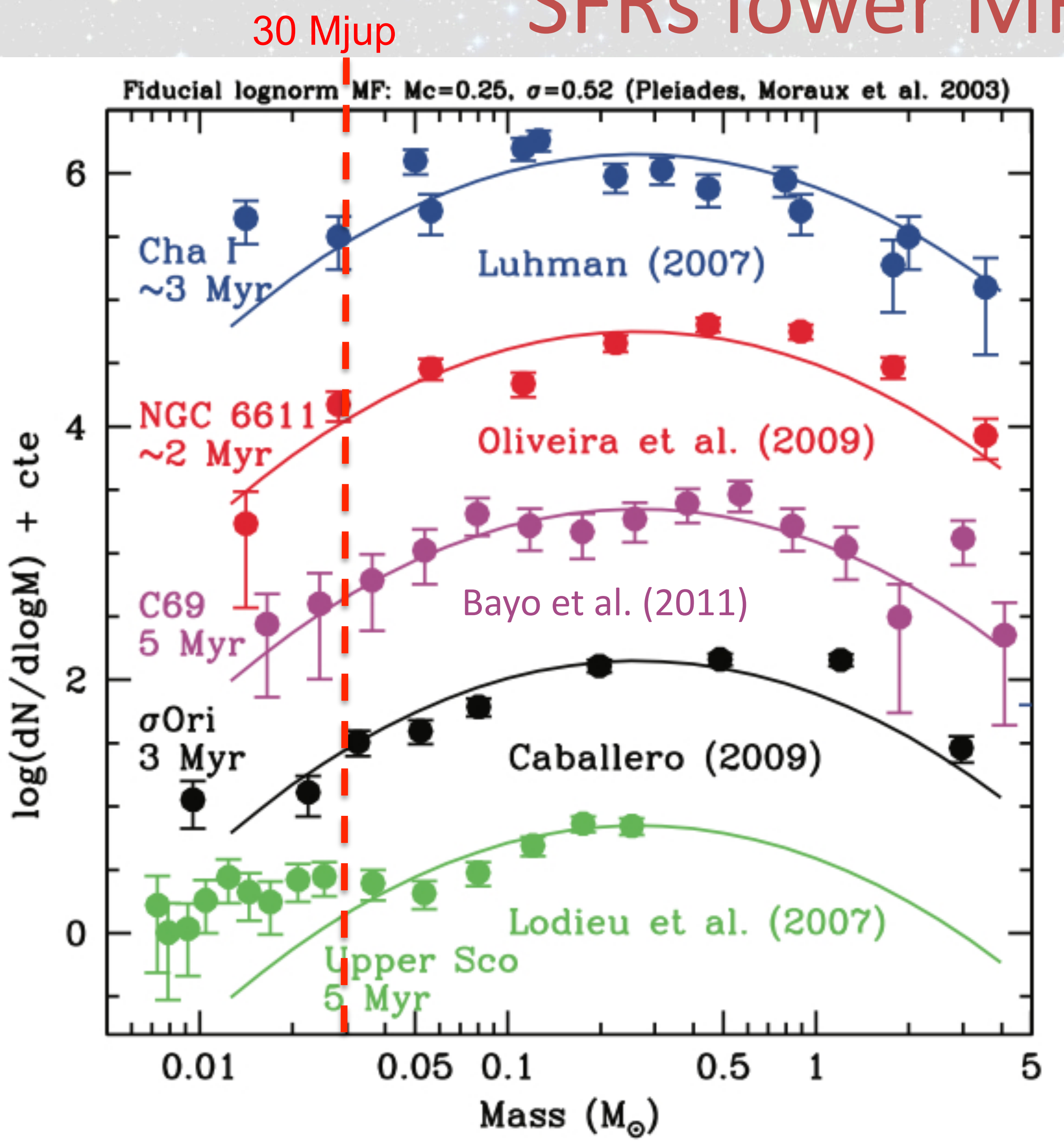




(Alves de Oliveira et al. 2010)



SFRs lower MF



System MF
(unresolved binaries)

- **Similar MF down to 30Mj** (consistent with the Pleiades)
- **Variation at lower masses ?**

Issues:

Residual contamination ?
Incompleteness?
Mass segregation ?

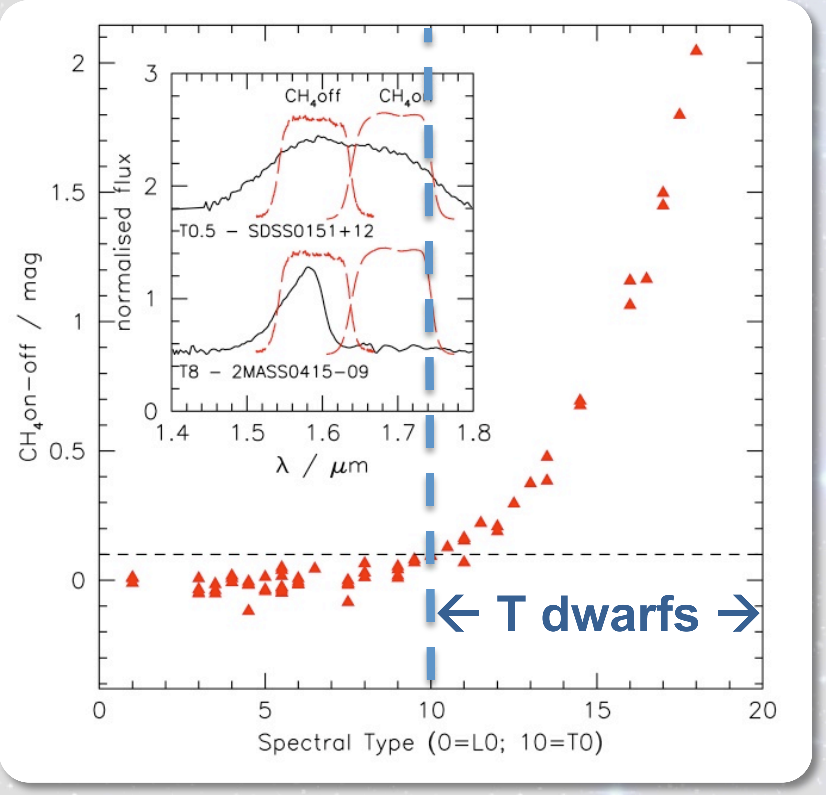
Uncertain mass-luminosity relationship at very low masses and young ages

The lowest mass objects

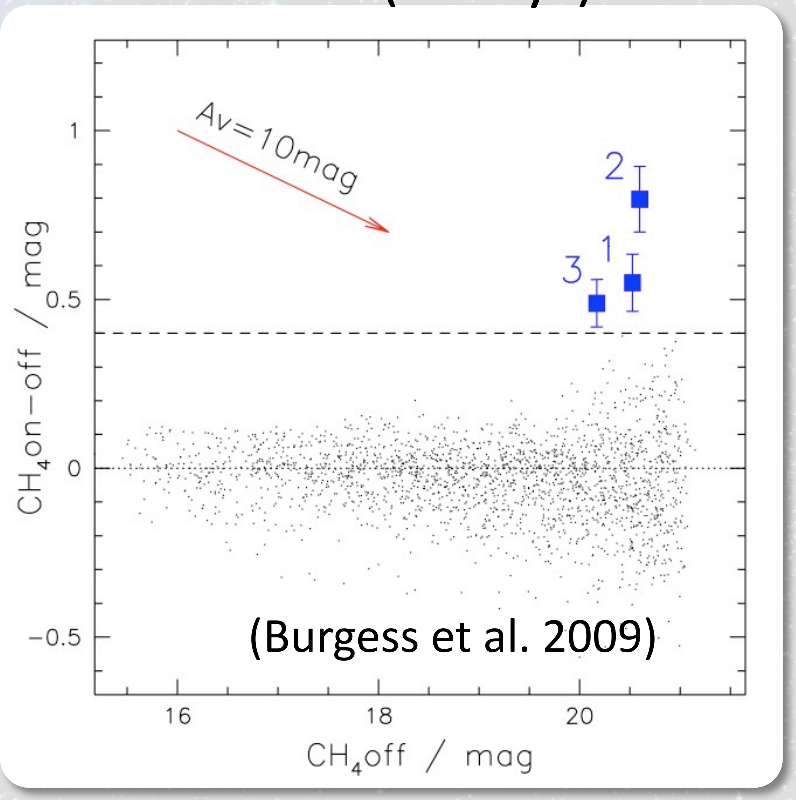
- **Isolated Planetary Mass Objects (<13 Mjup):**

T dwarfs (T_{eff}<1500K) are presumably below the D-burning limit (~13 Mjup) at an age of a few Myr *(models predict ≤5 Mjup)*

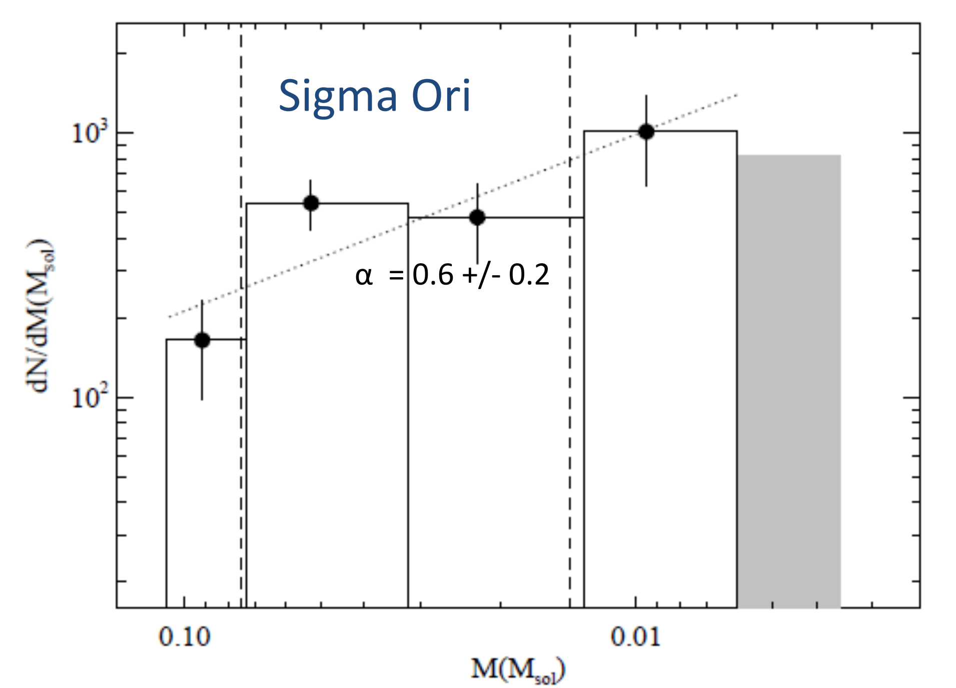
Methane colour



IC348 (~3Myr)



The end of the mass function ?



Caballero et al. (2007)
Bihain et al. (2009)
Lodieu et al. (2009)

Sigma Ori (~3 Myr):

S Ori 70: a T6 dwarf (Zapatero Osorio et al. 2002)

S Ori J053813.2−024910: >T8 candidate (Pena Ramirez et al. 2011)

IC348 (~3 Myr):

IC348_CH4_2 : ~ T6 candidate (Burgess et al. 2009)

Rho-Oph (~1 Myr):

#4450 : early T (Marsch et al. 2010)

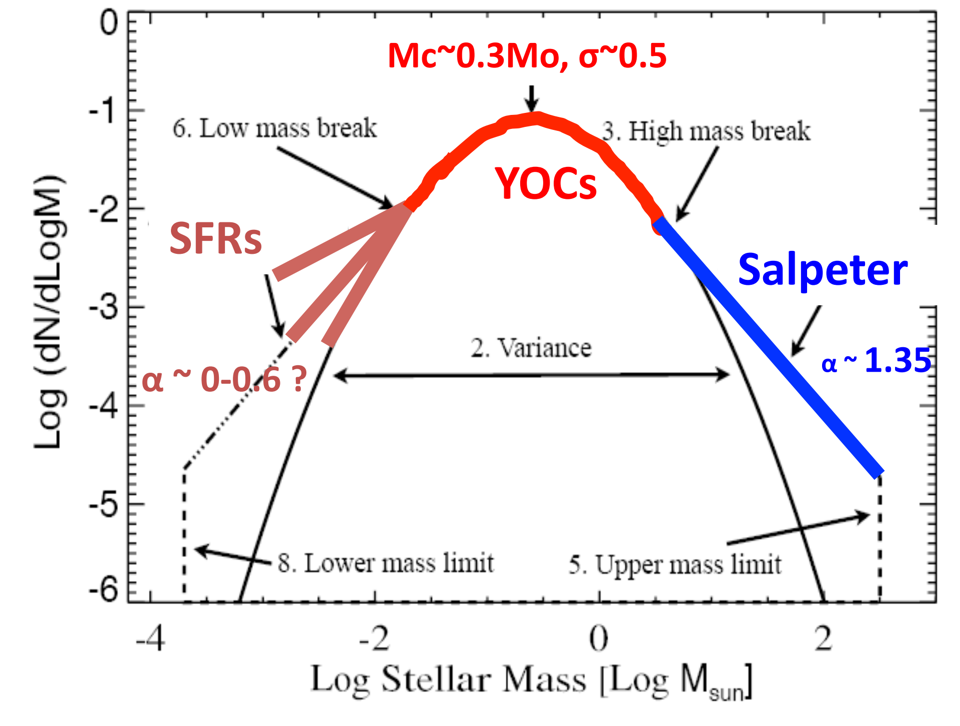
Consistent with the Pleiades MF extrapolation down to 1Mjup

Summary

- *Young open clusters:* **substellar MF** down to 30 Jupiter masses
  Lognormal mass distribution with M_c~0.3M_o and σ~0.5 over the mass range 0.03-1.0 M_o

- *Star forming regions:* **lower end of the IMF** down a few Mjup?
  Evidence for variations ?

adapted from Bastian, Covey, Meyer 2010



II. Dynamical evolution of young open clusters

Effect on the shape of the MF ?

Gas expulsion (after a few Myrs)

- Quick loss of a large fraction of cluster members
  (preferentially with high velocity or located in the outskirt)

- But no cluster to cluster variation from ~1 to 100 Myr down to 30 Mjup
  - → Cluster MF (<100 Myr) still representative of the **initial** MF
  - → Early loss of members independent of mass (and binarity)
  - → no primordial mass segregation
  - → Similar velocity dispersion for stars and BD: $\sigma_{V_{BD}} \leq 2\sigma_{V_*}$
    (Moraux & Clarke 2005)

- Or "infant mortality" select 1 type of clusters ?

Secular evolution

- 2-body interaction: Cluster relaxation after ~1 t_{dyn} $(m\sigma_v^2 = cst)$

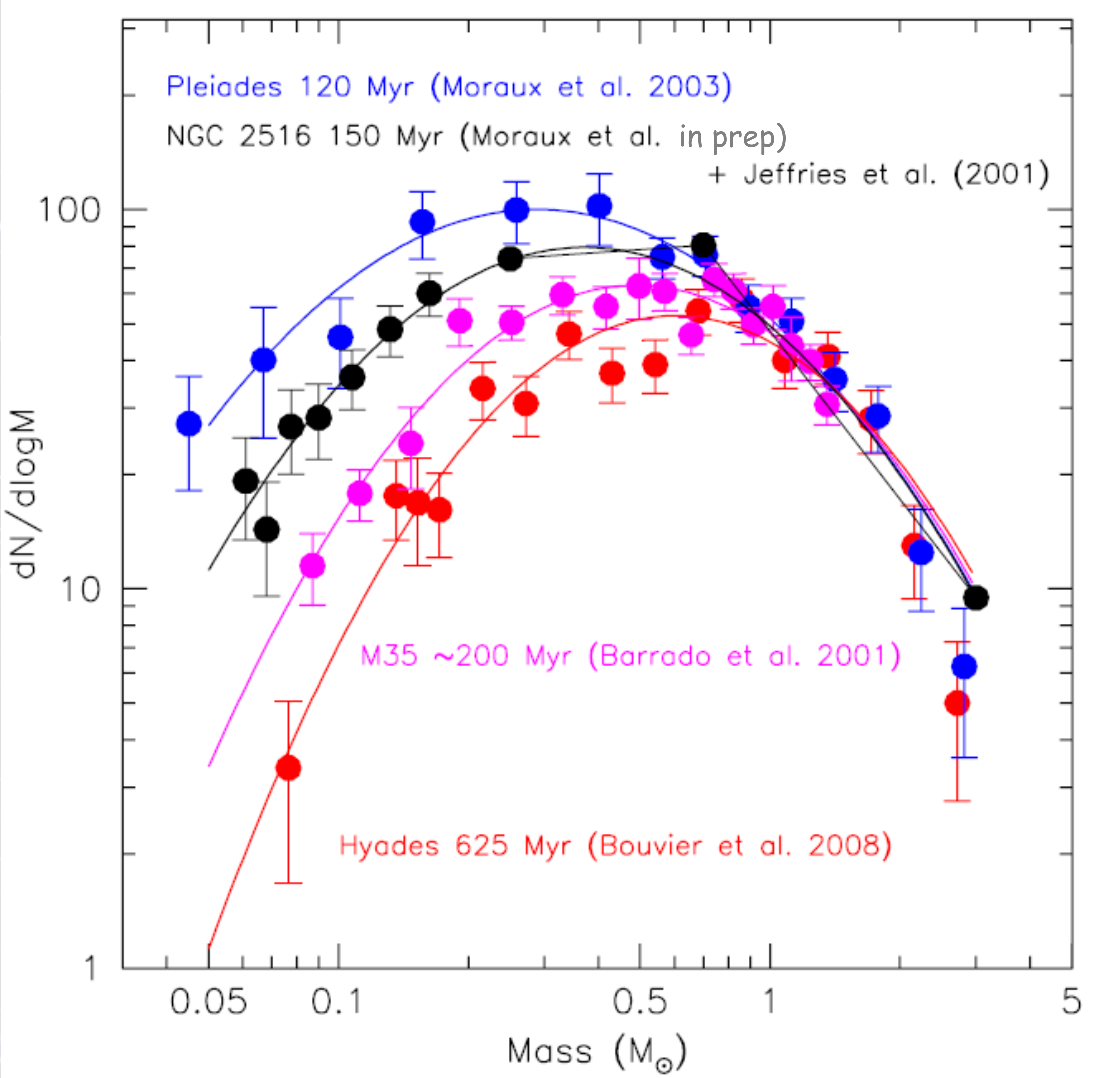
→ Mass segregation:

Deficit of low mass objects in cluster center compared to peripheric area (to be accounted for in the cluster MF)

→ Preferential loss of low mass members:

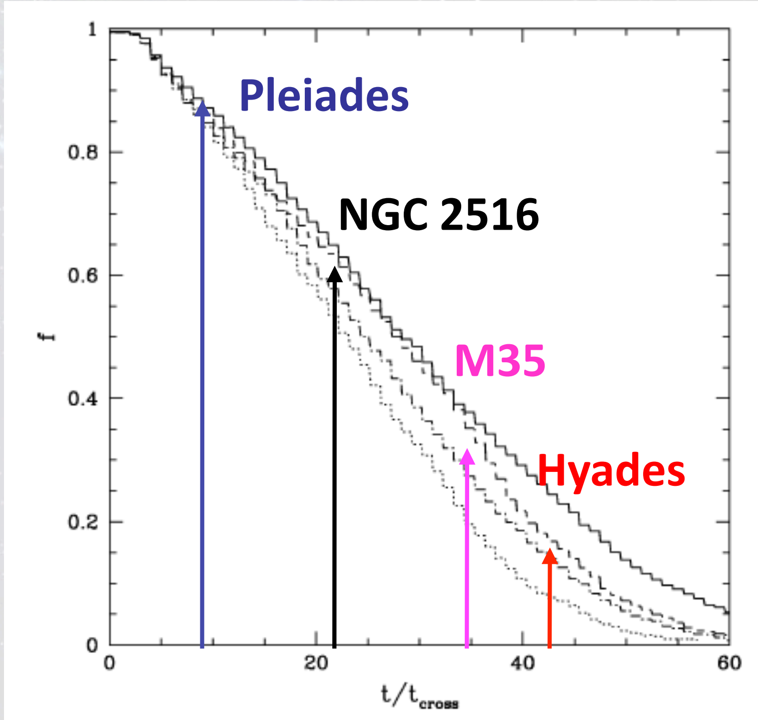
Deficit of BDs in dynamically relaxed clusters (age > t_{dyn})

Evolution of the cluster MF



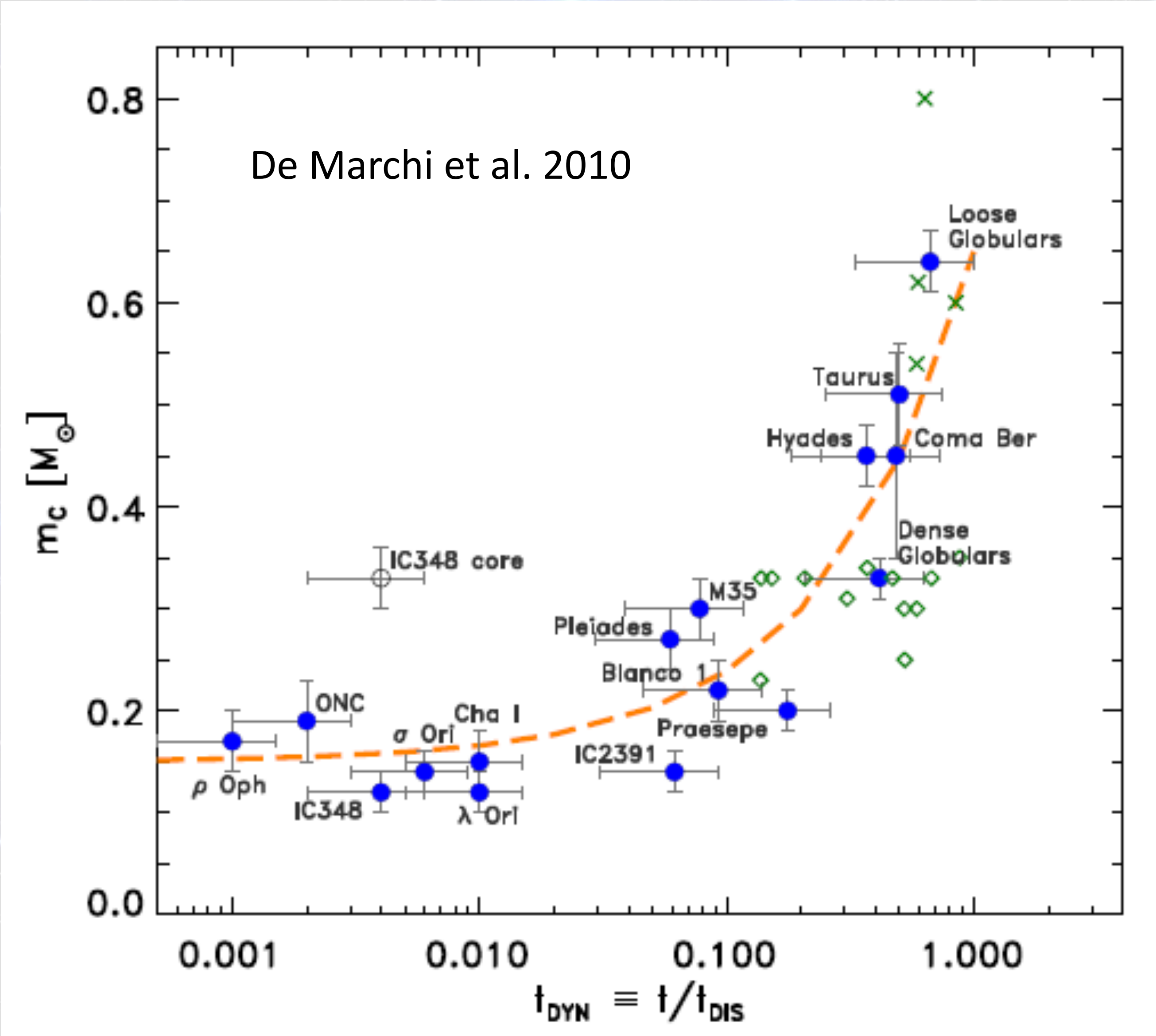
Dynamical evaporation of VLM stars and BD

Fraction of BD vs. time (Nbody models)



Adams et al. 2002

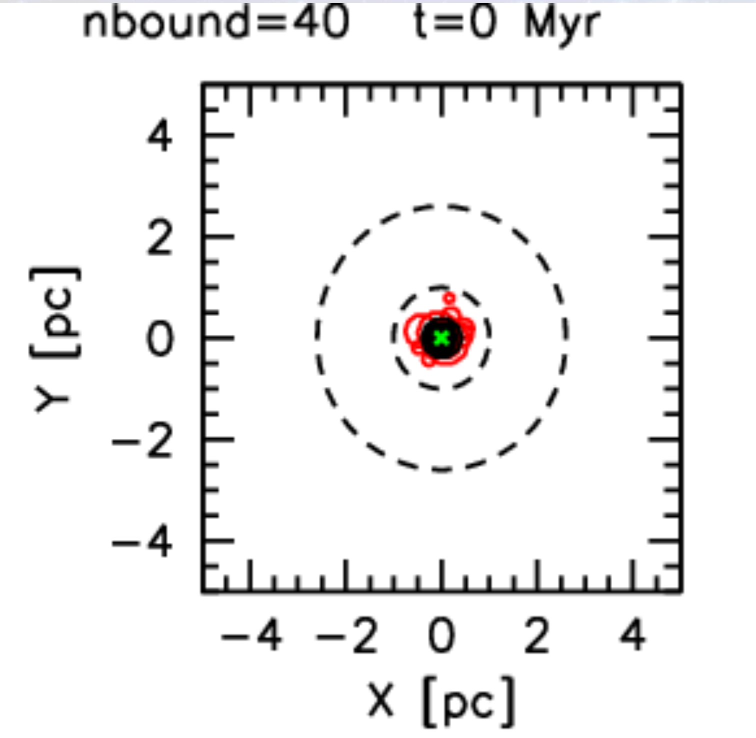
Evolution of the cluster MF



MF peak mass as a function of time

Eta Chamaeleontis (~9 Myr)

- Deficit of VLMS and BD, mass segregation, no wide binaries
  → a young, yet dynamically evolved ?
- NBody simulations to trace back the initial conditions



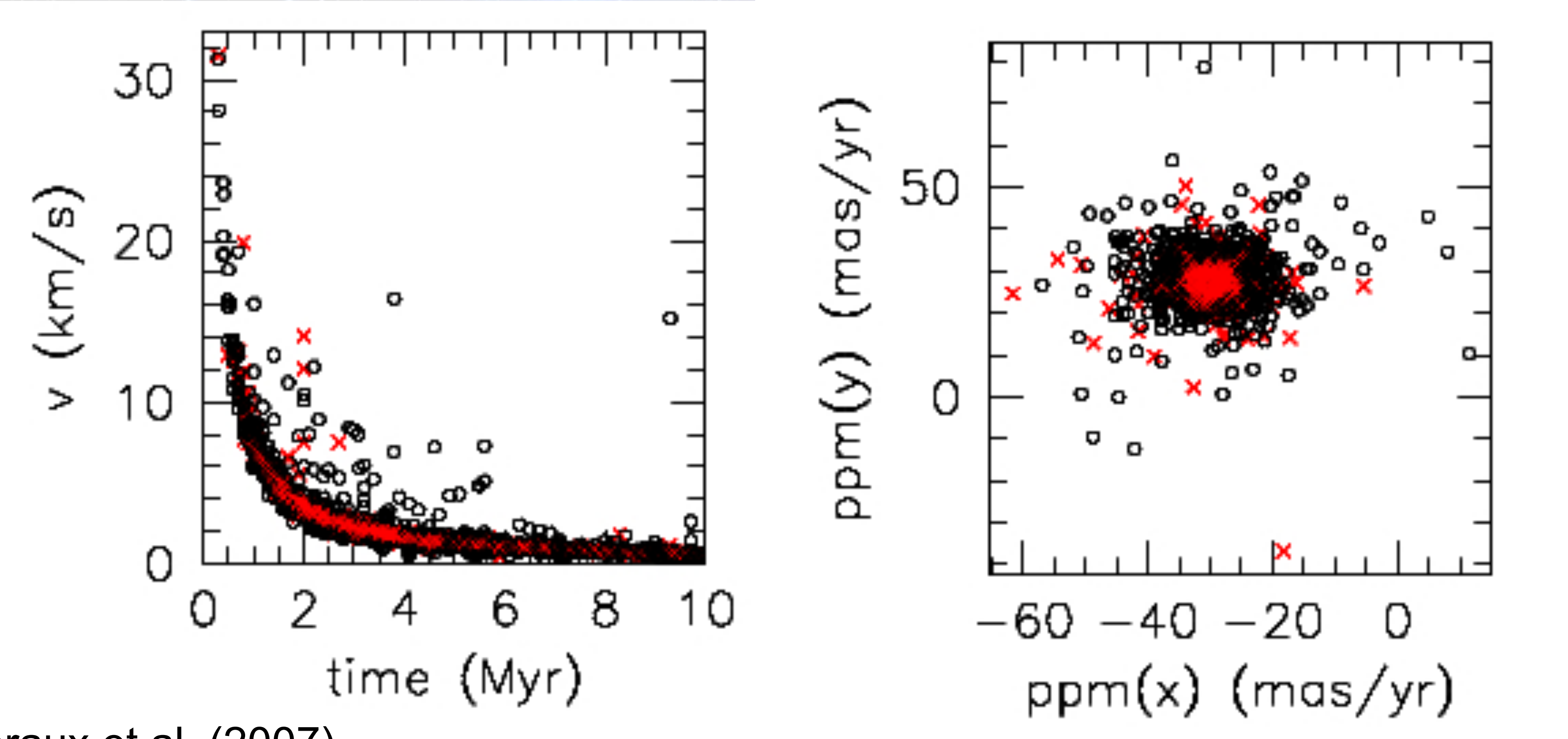
Could the IMF be lognormal ?

Maybe… (Moraux et al. 2007)

But see Becker et al. (in prep)

Proper motion and RV needed to find the escapers

+ investigate the dynamical state of the cluster



Moraux et al. (2007)

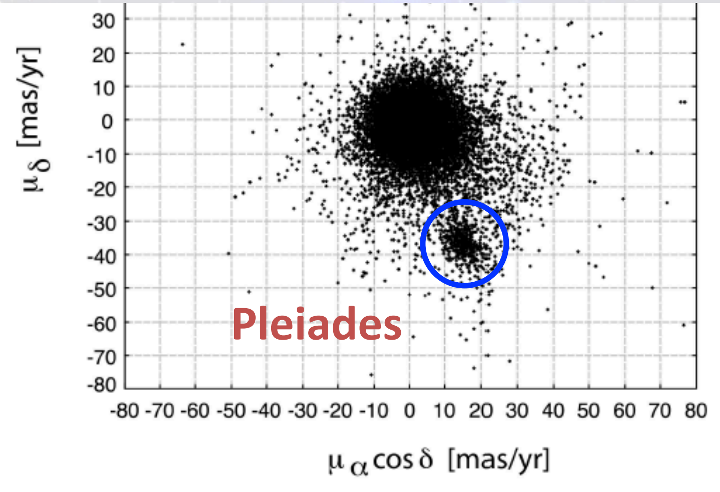
→ Requires very large coverage

→ Requires high precision 3D velocity (better than km/s) down to the substellar domain

GAIA + Spectroscopic follow-up

- GAIA: parallaxes + proper motion 0.3mas down to V~20
- ESO public survey with FLAMES (300 nights over 4-5 years): ~0.3 km/s down to V~19
  - 3D spatial structure + 3D kinematics
  - Relate field stars to their natal cluster → complete census
  - Internal dynamics

→ Need for complementary studies in the substellar domain



time baseline >10 yrs (archives)

~1mas/yr (~1km/s @200pc) down to I~22

See H. Bouy's talk

Prospects

→ to link theoretical predictions to observations

→ to constrain star formation theories

- Characterise the statistical properties of young cluster populations **down to planetary masses** at different ages

  (IMF, kinematics, spatial structure, multiplicity…)

- Simulations of the early dynamical evolution of clusters (Nbody + hydrodynamics) in order to trace back the initial conditions

→ ANR JC « DESC »