# THE LOW MASS IMF IN CLUSTERS

## VARIATION OR DYNAMICAL EVOLUTION ?

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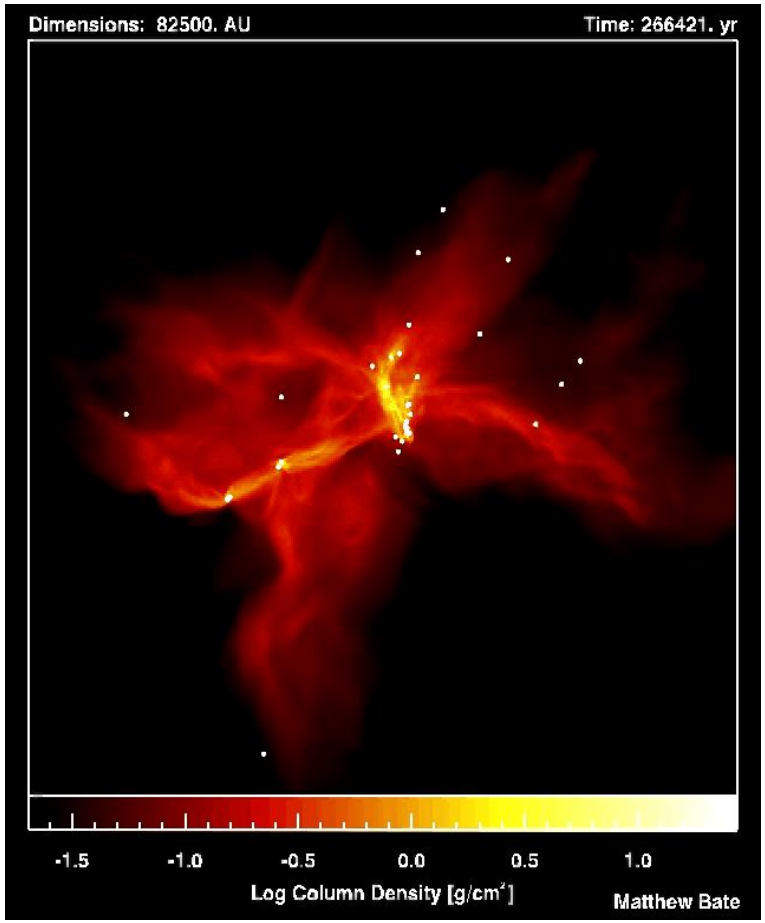
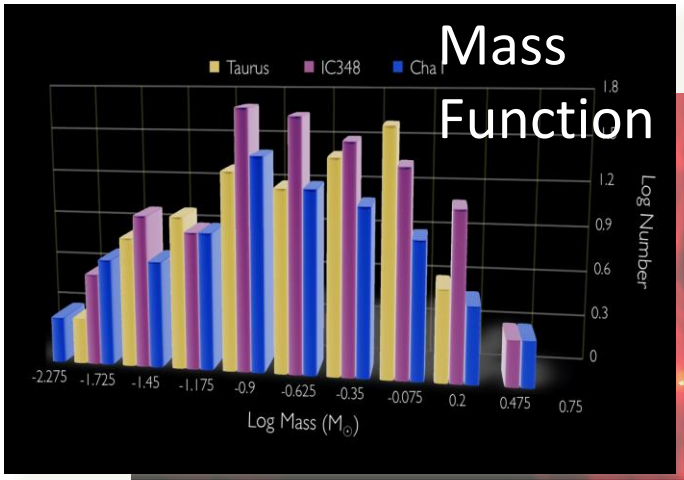
# Star formation

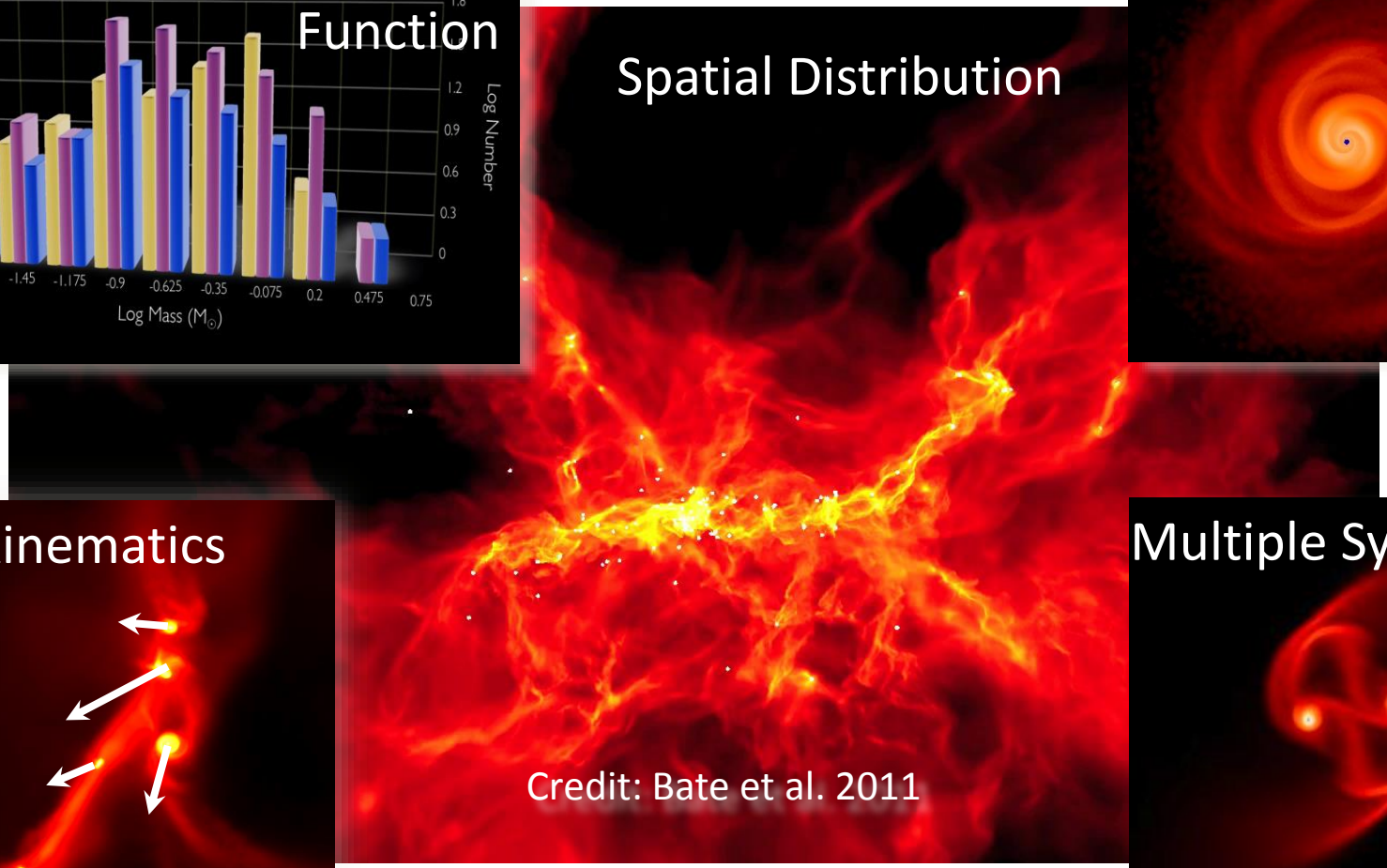
- Most of the stars form in groups / clusters (N=10-$10^5$)
- How do clusters form ?
  - Quasi-equilibrium and slow contraction scenarios
  - Highly dynamic: fragmentation driven by supersonic MHD turbulence (e.g. Bate et al. 2009)
- Different scenarios

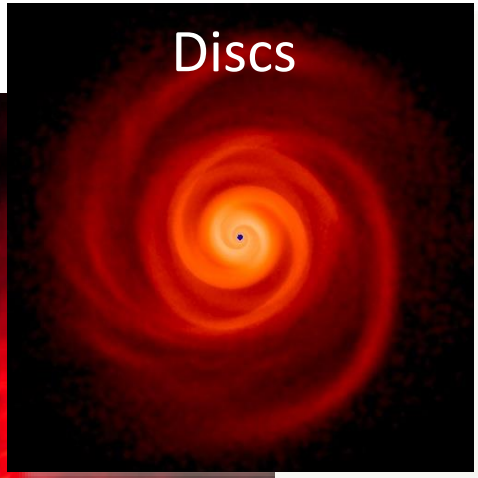
→ different predictions

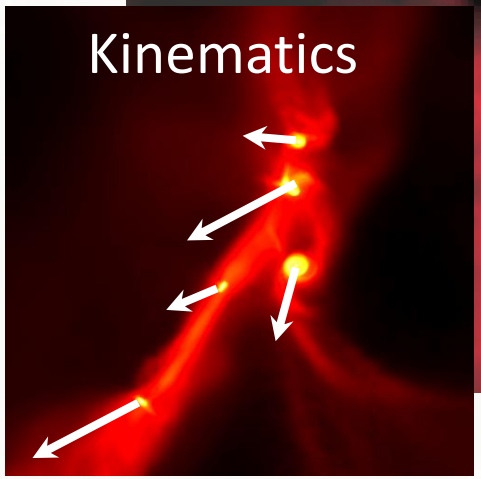


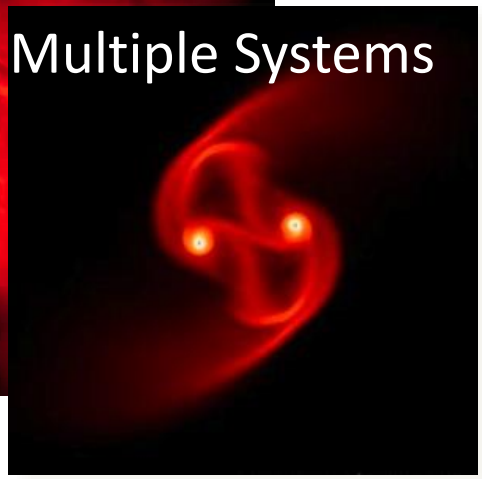
# Star Formation Products



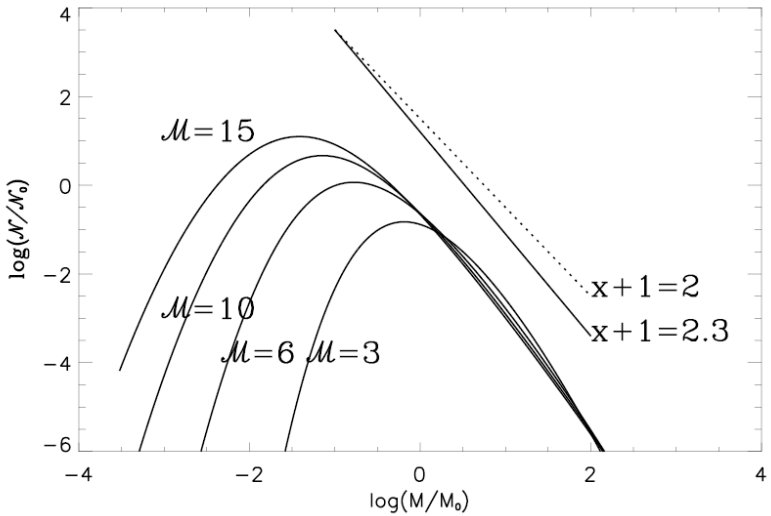




**What are the cluster statistical properties at birth ?**

# Theoretical predictions of the IMF

- Power-law at high masses (>1Msun)
- lognormal shape below 1Msun
- peak around the Jeans mass (0.1-0.5 Msun)
- lower limit due to opacity-limited fragmentation (~5 Mj)
- dependence on the local conditions in the substellar domain

e.g. Hennebelle & Chabrier 2008



# I. Determination of the IMF

Main uncertainties

# Methodology

1. Determination of the luminosity function (LF)
   - Surveys to uncover candidates: photometric, kinematic, youth indicators, spectroscopy
   - Assess contamination and completeness
   - Correct for extinction if necessary
2. Convert LF to Present Day Mass Function (PDMF)
   - Distance to cluster
   - Convert spectral type to temperature
   - Convert magnitudes to luminosity (with distance and BC correction)
   - Convert Teff and/or Luminosity (HR diagram) to mass
3. Convert PDMF to IMF
   - Correct for star formation history, stellar evolution, dynamical evolution
   - (Correct for binarity)

# Observational uncertainties on the luminosity function (LF)

- **Contamination** of photometric surveys by field stars (dwarfs, giants) and/or extragalactic objects (galaxies, quasars)
- **Uncompleteness** of magnitude- and/or volume-limited surveys, in particular when the extinction is spatially variable
- **Biases** (Malmquist, mass segregation) and **low number statistics** (Poisson, binning)
- **Multiplicity**, crowding, missed objects (e.g. near bright stars)

# Theoretical uncertainties on the present day mass function (PDMF)

- **Mass-luminosity relationship**: LF→PDMF (model-dependent, age-dependent)
- **Disk accretion** may affect the early evolution of young stars (cf. Baraffe et al. 2009)
- **Magnetic activity** impacts on the luminosity (hence, mass estimate) of low mass stars (cf. Jackson et al. 2009, Mohanty et al. 2009)

# Uncertainties

- Field (2-5 Gyr) issues: age, mass, [Fe/H], sample completeness
- Young open clusters (30-200 Myr) issues: contamination, dynamical evolution, mass segregation
- Star forming regions (1-10 Myr) issues: variable extinction, accretion, mass-luminosity relationship
- All: multiplicity, magnetic activity

# II. The low mass IMF in clusters

# Open clusters (30-200 Myr)

- **Advantages:**
  - ⟶ homogeneous population ([Fe/H], initial conditions)
  - ⟶ **Coeval**
  - ⟶ **Distance and age fairly constrained**
  - ⟶ Uniform (low) extinction
  - ⟶ Rich clusters
  - ⟶ Compact on sky

- **Limitations:**
  - ⟶ Contamination
  - ⟶ Mass segregation
  - ⟶ Dynamical evaporation of very low mass objects

# Pleiades : a benchmark cluster

**Distance = 120-130 pc**

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

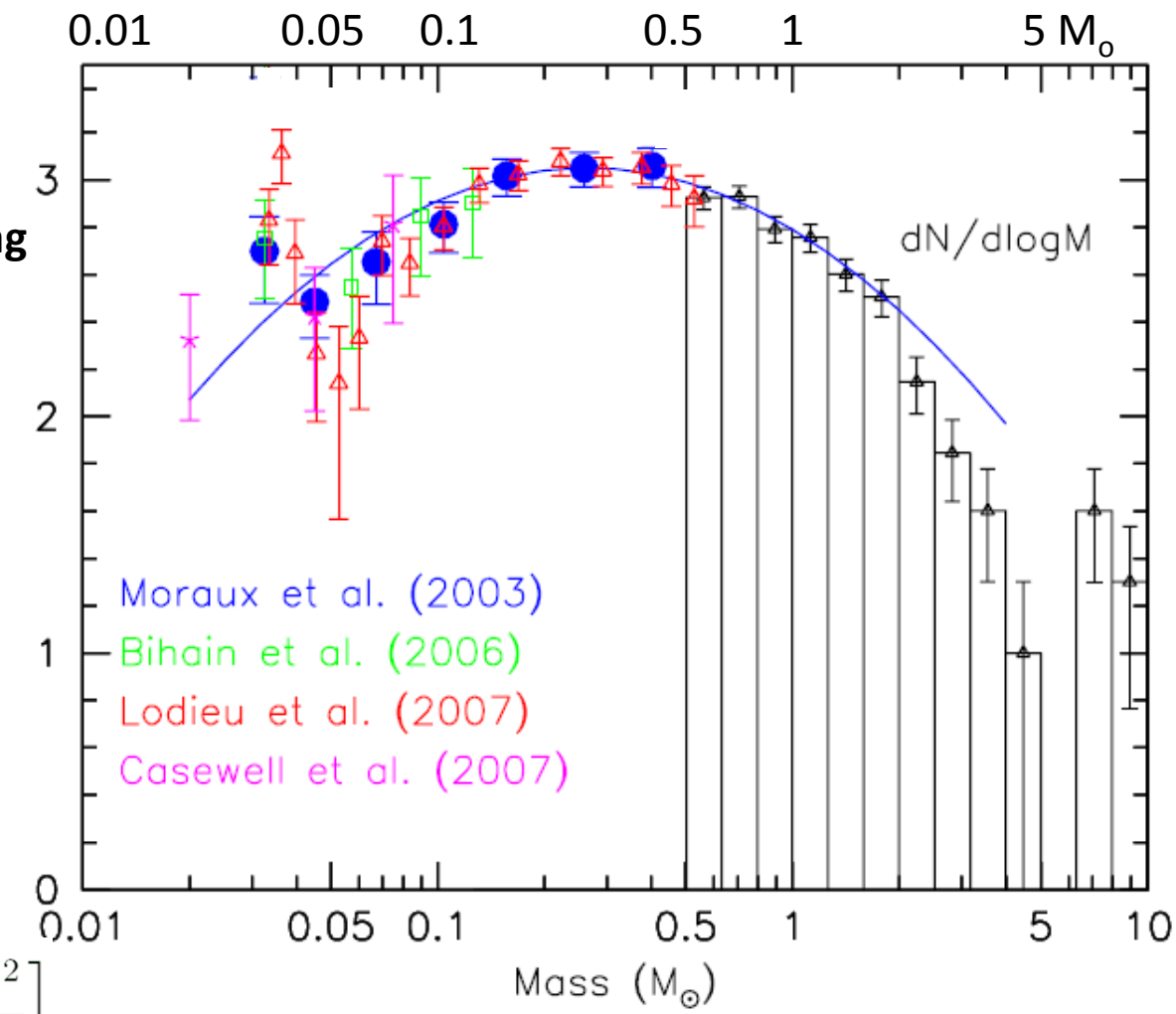
**Star / BD boundary @ I ~ 17.8 mag**
(Bouvier et al. 1998)

**System MF**
(unresolved binaries)
**~70 substellar members**

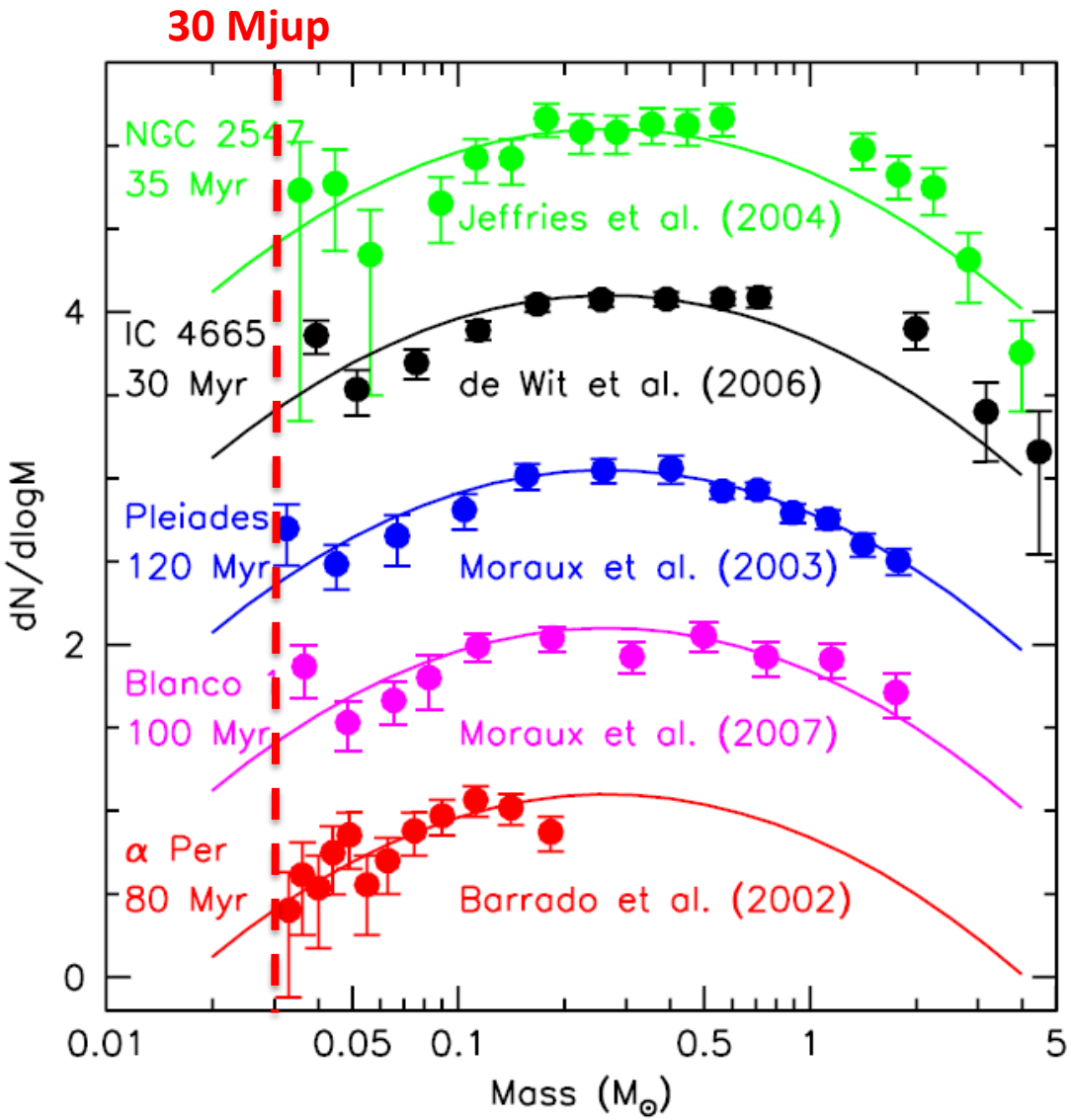
Lognormal fit :

**$m_0$ = 0.25 Mo**
**σ = 0.52**

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



# The PDMF 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**

**$\sigma$ ~ 0.5-0.6**

Consistent with the field MF down to $0.1M_0$

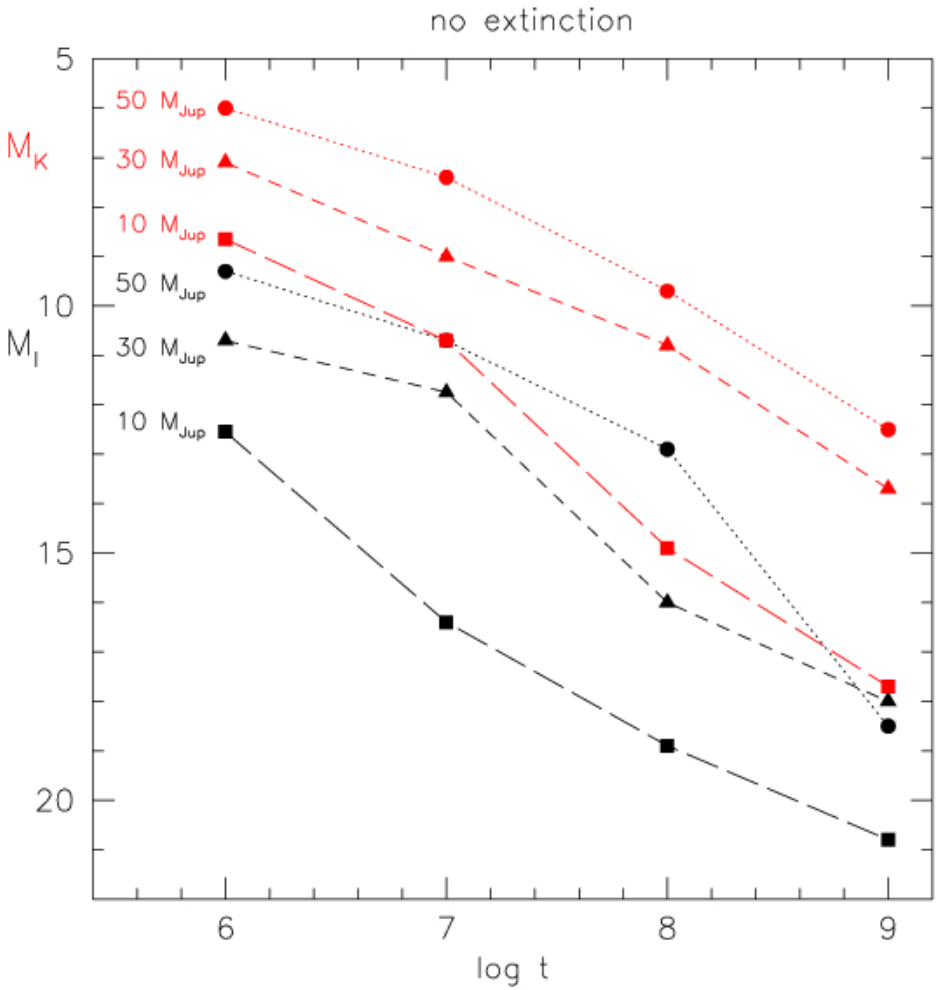
→ **a universal IMF ?**

# Looking for the lowest mass objects

- More luminous in the NIR
- Fade with mass and age
  - 10 Mjup @ 1 Myr : $M_K$~ 8.7
  - 10 Mjup @ 1 Gyr : $M_K$ ~ 17.7

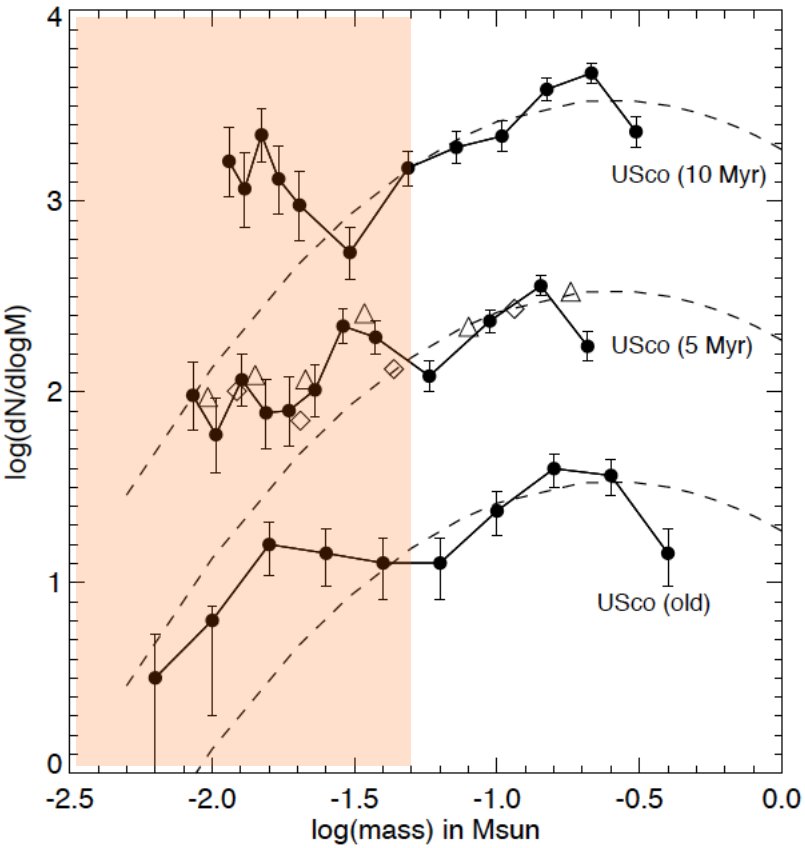
| Optical | Near Infrared |
|---|---|
| 30 Mjup – 3 Msun in open clusters | **3 Mjup – 30 Mjup in SFR** |

→ **NIR wide field surveys of star forming regions**



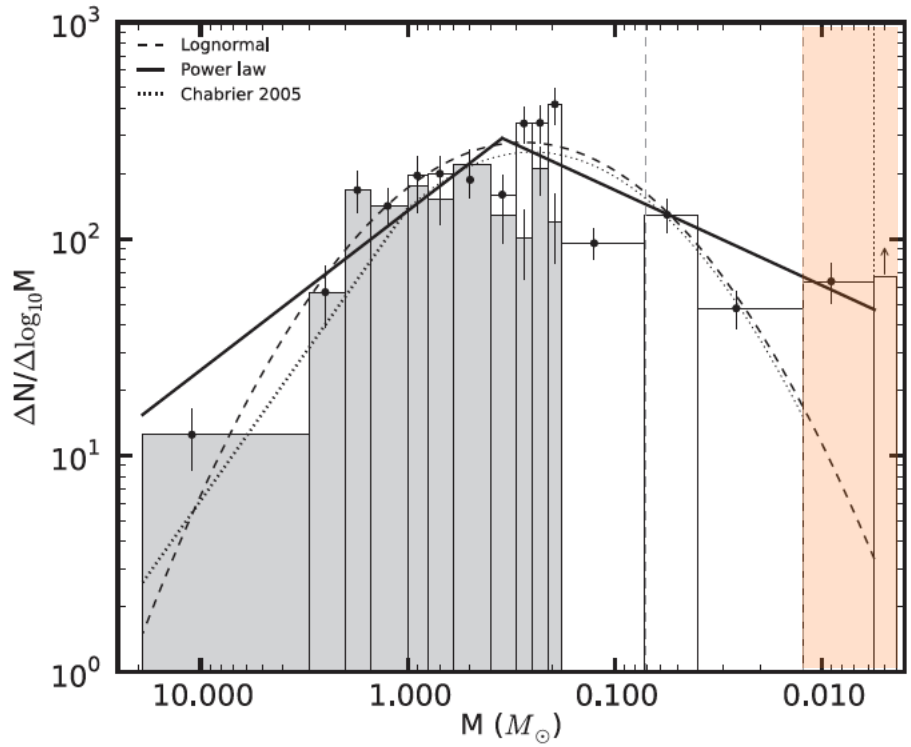
# Hint for variations below 0.03M$_\odot$?

Upper Sco



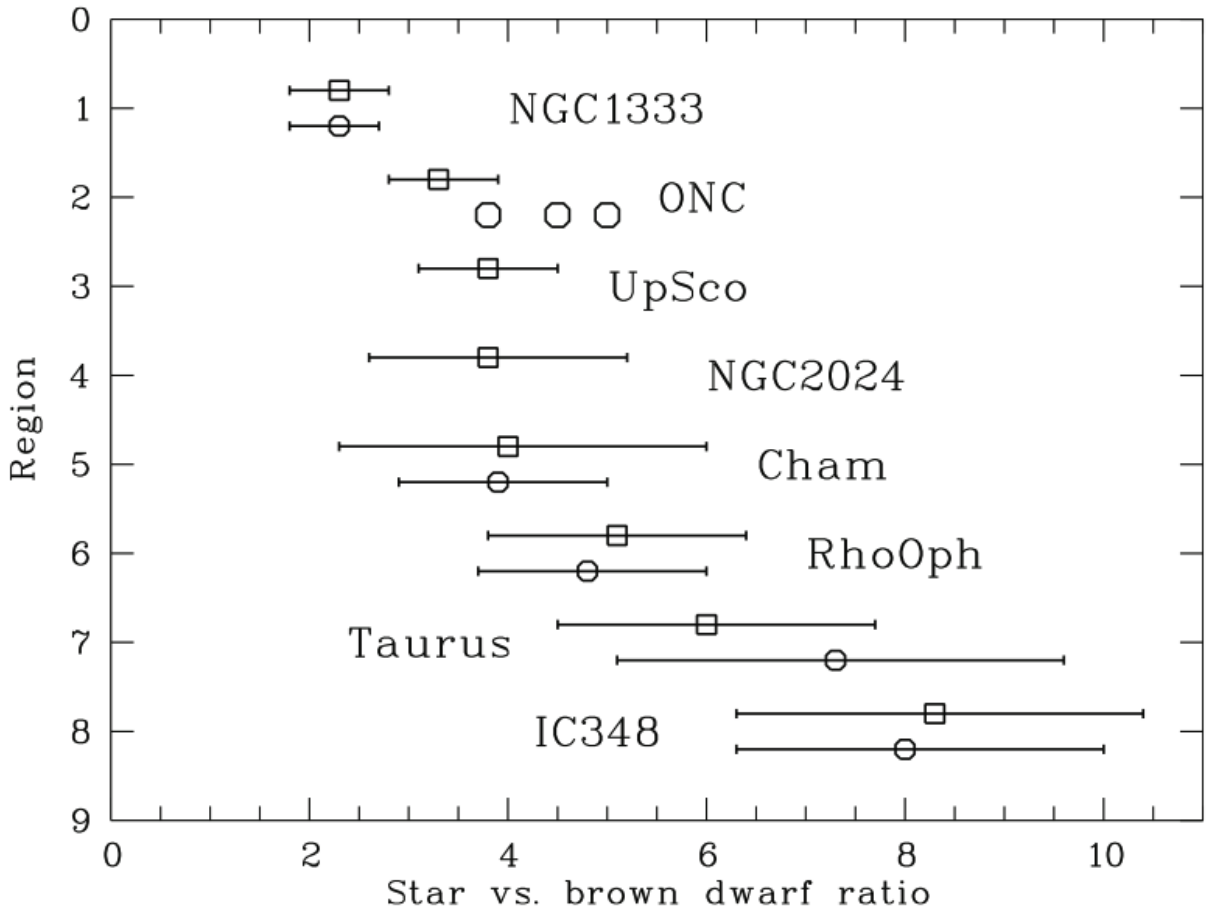

Lodieu 2013, MNRAS, 431, 3222

σ Ori




Peña Ramírez et al. 2012, ApJ, 754, 30

# Star to Brown Dwarf ratio

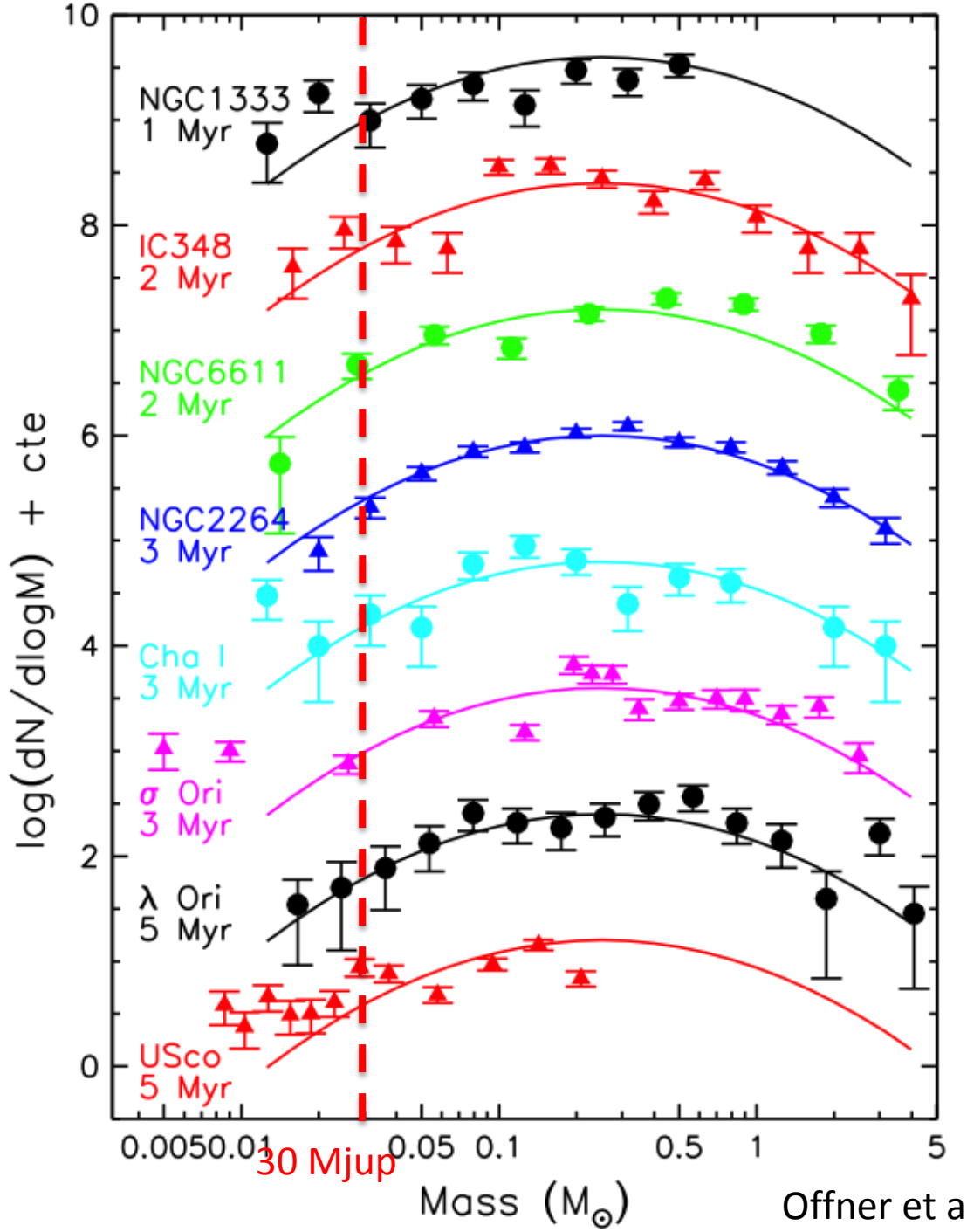



Scholz et al. (2012)

○ : $\frac{N(0.08 - 1\ M_\odot)}{N(0.03 - 0.08\ M_\odot)}$

□: $\frac{N(0.08 - 10\ M_\odot)}{N(0.02 - 0.08\ M_\odot)}$

# 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**

Offner et al. 2013, PPVI

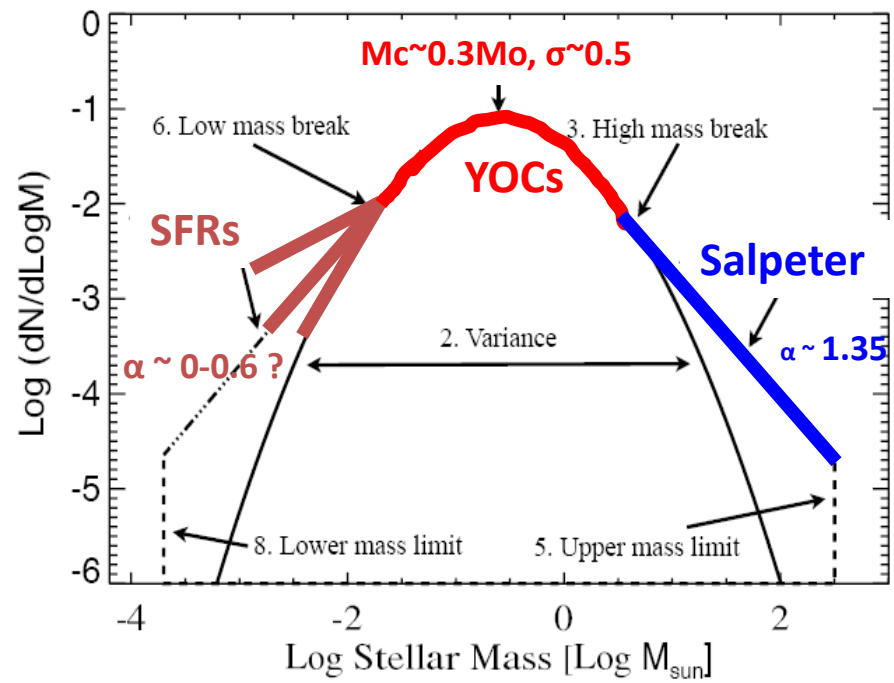
# Summary on the observed MF

- *Young open clusters:* **substellar MF** down to 30 Jupiter masses
  **Lognormal mass distribution with $M_c$~0.3$M_o$ 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 ?

→ Is it in agreement with star formation model predictions ??

adapted from Bastian, Covey, Meyer 2010



# III. Dynamical evolution of young open clusters

Effect on the shape of the MF ?

# Secular evolution

- 2-body interaction:

Cluster relaxation $(m\sigma_v^2 = cst)$ after $t_{rlx} = (N/8lnN)\ R/\sigma_v$

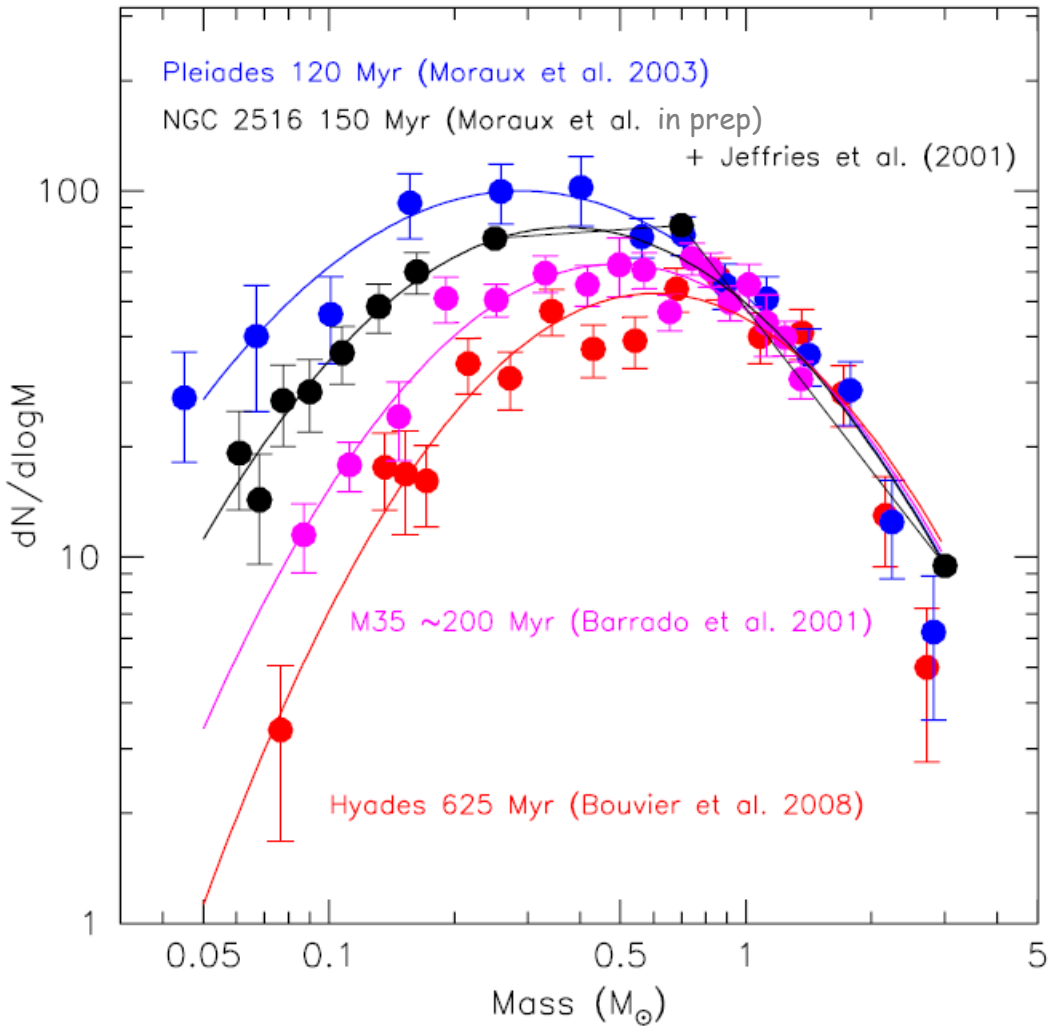
→ Mass segregation:

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:

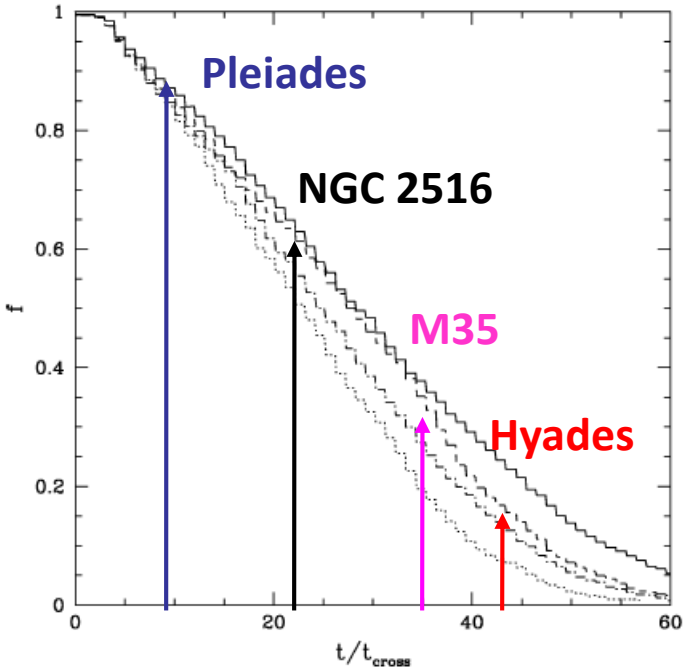
Deficit of BDs in dynamically relaxed clusters (age > $t_{dyn}$ )

# Evolution of the cluster MF



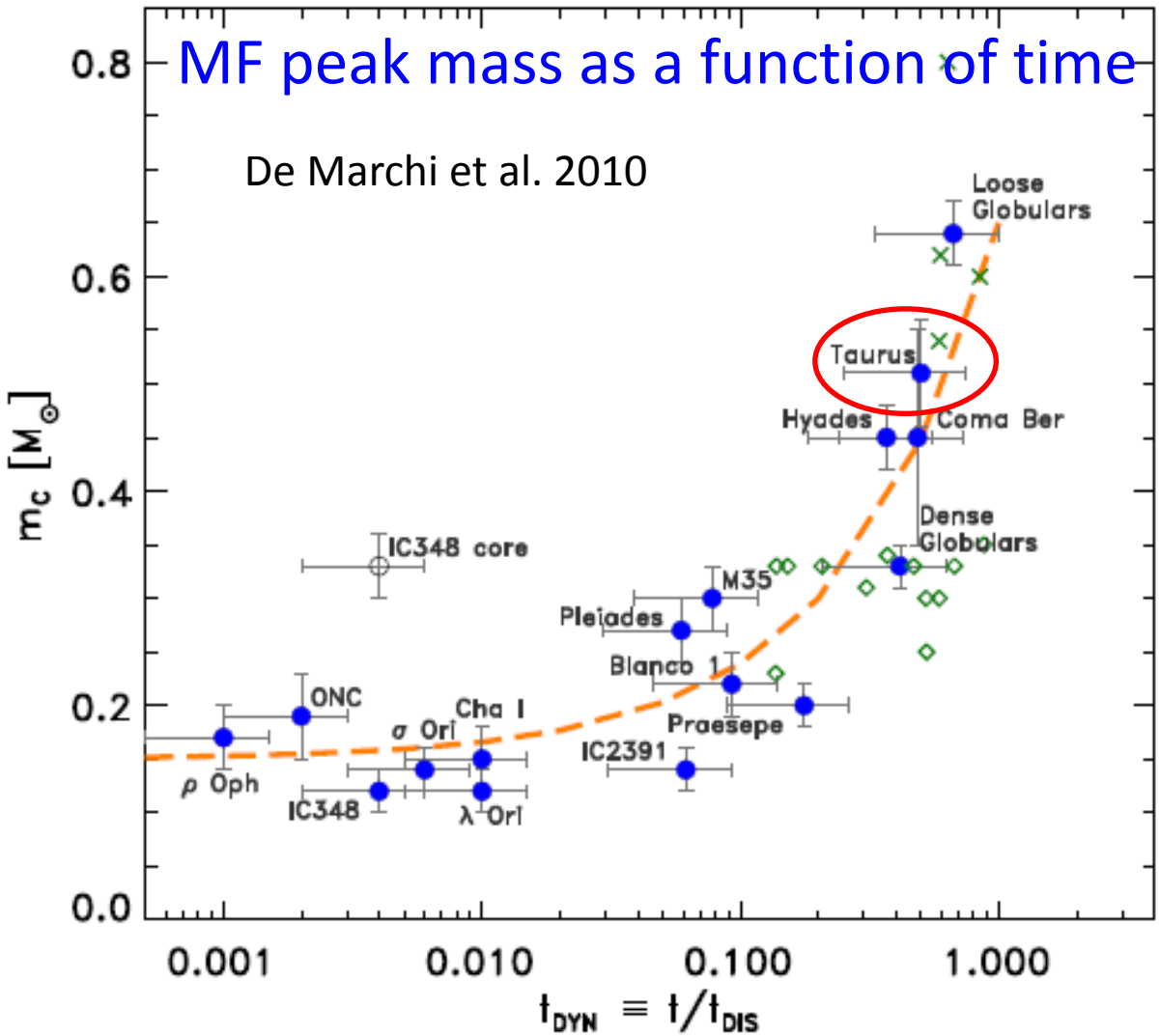

Dynamical evaporation of VLM stars and BD

Fraction of BD vs. time (Nbody models)




Adams et al. 2002

# Evolution of the cluster MF



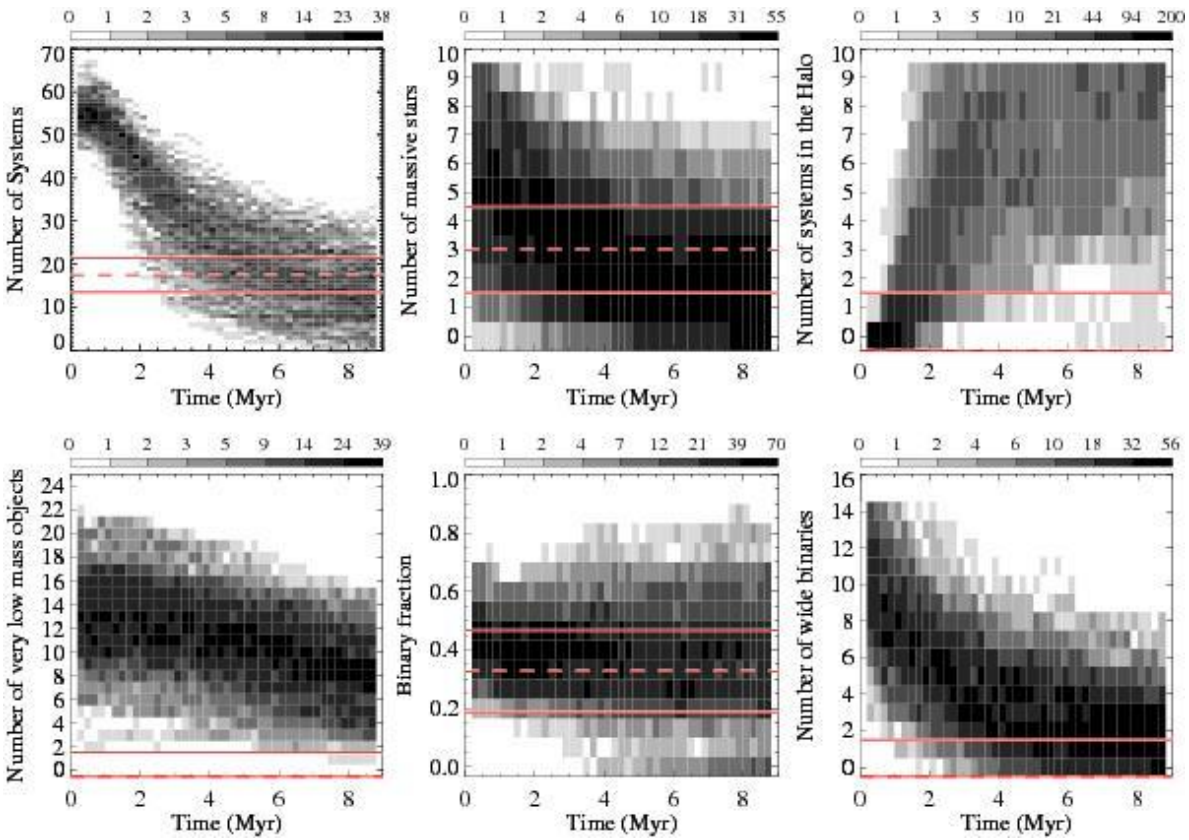

What matters is the cluster age **relative to its dynamical time**

# 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



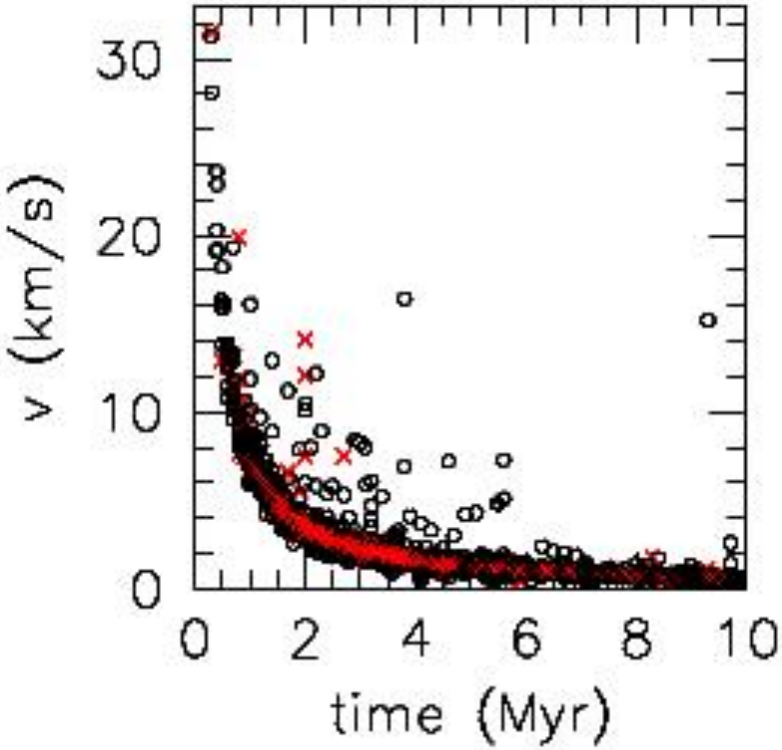

Could the IMF be lognormal ?

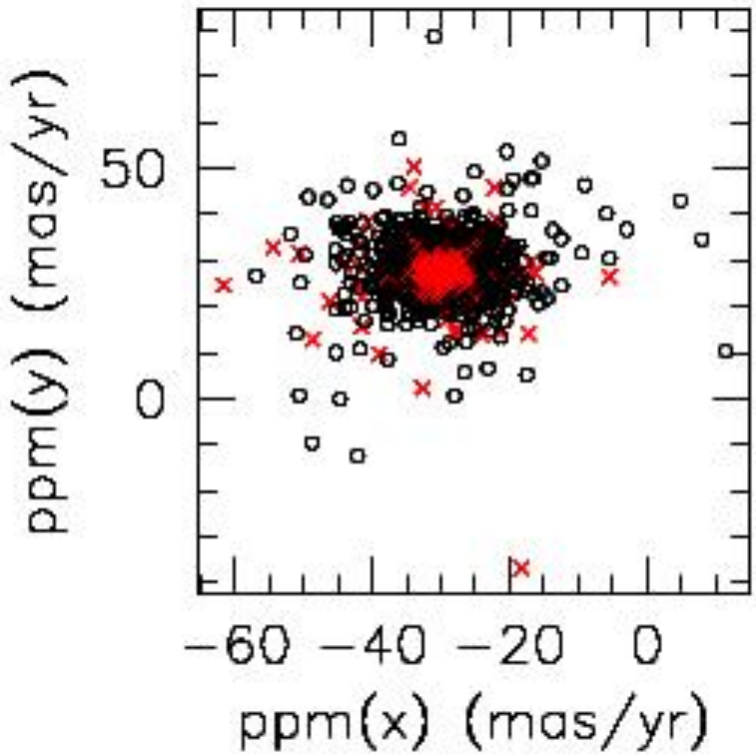
Probably not…

(Becker et al. 2013)

# 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 down to V~20
- GAIA-ESO public survey with FLAMES : ~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 (deeper and in the NIR to beat extinction)

Cf. H. Bouy's talk tomorrow

# 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