The lower mass function of young open clusters: clues to (sub)stellar formation

E. Moraux (IoA)
J. Bouvier (LAOG)
C. Clarke (IoA)

T. Kendall, G. Meeus, J.C. Cuillandre,
J. Stauffer, D. Barrado, L. Testi

(Sub)Stellar Formation

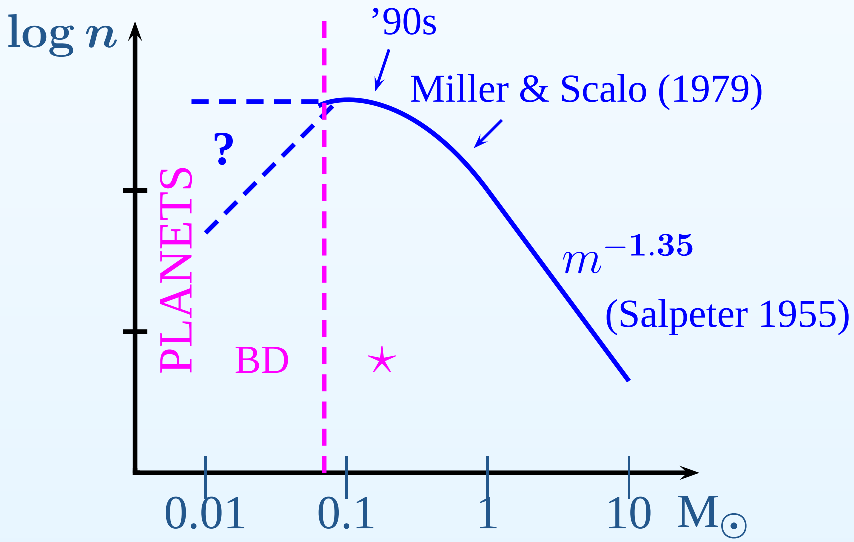
- ⋆ **'isolated' gravitational core collapse**
- ⋆ **dynamical ejection** (Reipurth & Clarke 2001)
  core fragmentation → instable proto-stellar multiple systems
  dynamical decay → ejection of fragments which remain substellar
- ⋆ gravitational instabilities of massive circumstellar disks
- ⋆ photo-erosion of pre-stellar cores in HII regions

Which process is the dominant one ? Does it depend on the environment ?

⇒ Combination of various observational studies to discriminate (IMF, dynamical evolution)

Initial Mass Function (IMF)

$$\xi(\log m) = \frac{dn}{d \log m}$$



Substellar domain ?

IMF still poorly constrained

Dependency to initial conditions ?

some stellar formation models predict variations in the BD domain

Lower mass limit to the IMF ?

Young open clusters

- ⋆ large samples over 2-3 decades of masses
- ⋆ homogeneous population (same age, distance, metallicity)
- ⋆ star formation is terminated
- ⋆ young populations (BDs still bright enough to be detected)

cluster	age	[Fe/H]	richness
Blanco 1	100 Myr	+0.1/0.2	$>$ 200 stars
Pleiades	120 Myr	0.0	$\sim$ 1200 stars
NGC 2516	150 Myr	-0.3/0.0	$\sim$ 2000 stars
Hyades	625 Myr	+0.14	$>$ 300 stars

Determination of the mass function

1. deep wide-field photometric surveys (CFH12K,ESO2.2m/WFI)

   $\longrightarrow$ candidates selection

2. follow-up observations : proper motion, surface gravity, infrared photometry, spectral type (CFHTIR, SOFI, FORS2, NICS)

   $\longrightarrow$ confirmation

3. then utilisation of mass-magnitude relationship (Baraffe et al. 1998, Chabrier et al. 2000)

   luminosity function $\longrightarrow$ mass function

$$\frac{dn}{dm} = \left[\frac{dn}{dM_\lambda}\right] \left[\frac{dm}{dM_\lambda}\right]^{-1}$$

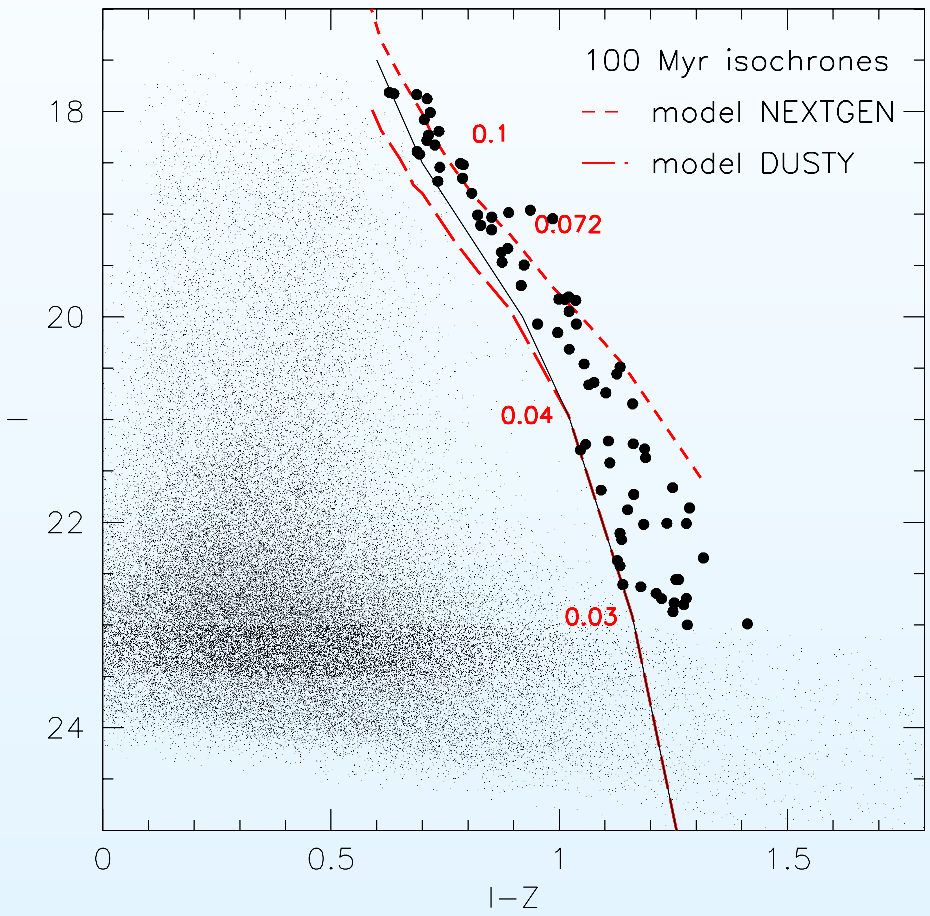
m : mass

M_λ : magnitude in λ-band

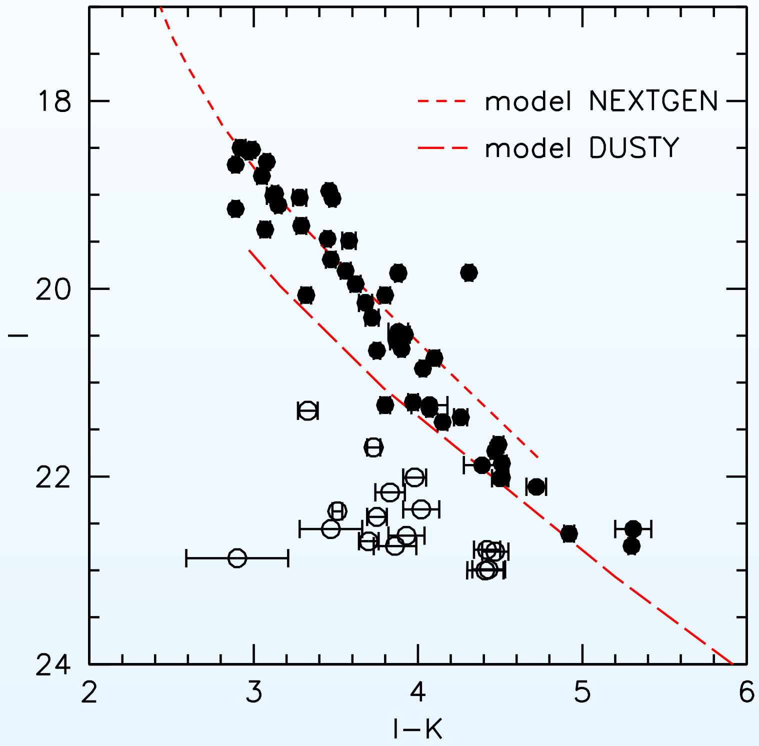
Blanco 1

56 BD candidates down to 30M_{Jup}

optical CMD ($I, I - z$)



near-infrared CMD ($I, I - K$)

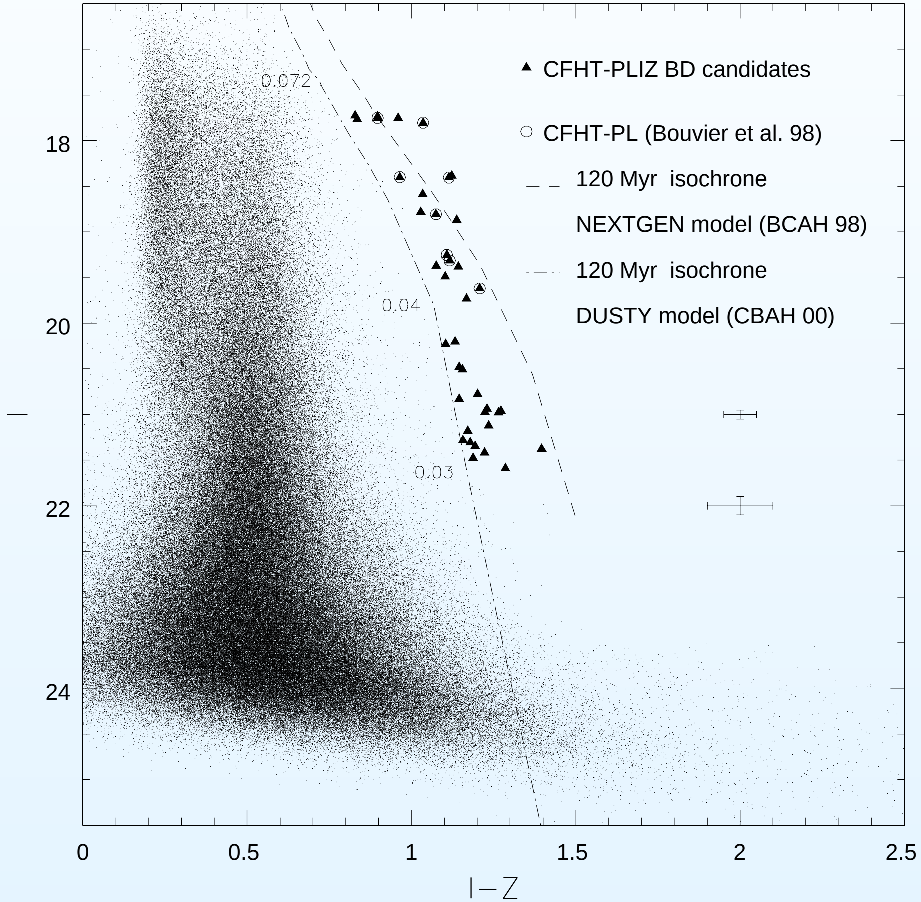


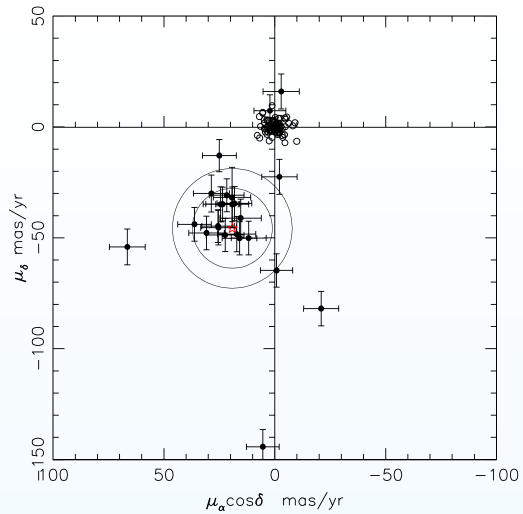
+ Optical spectroscopy

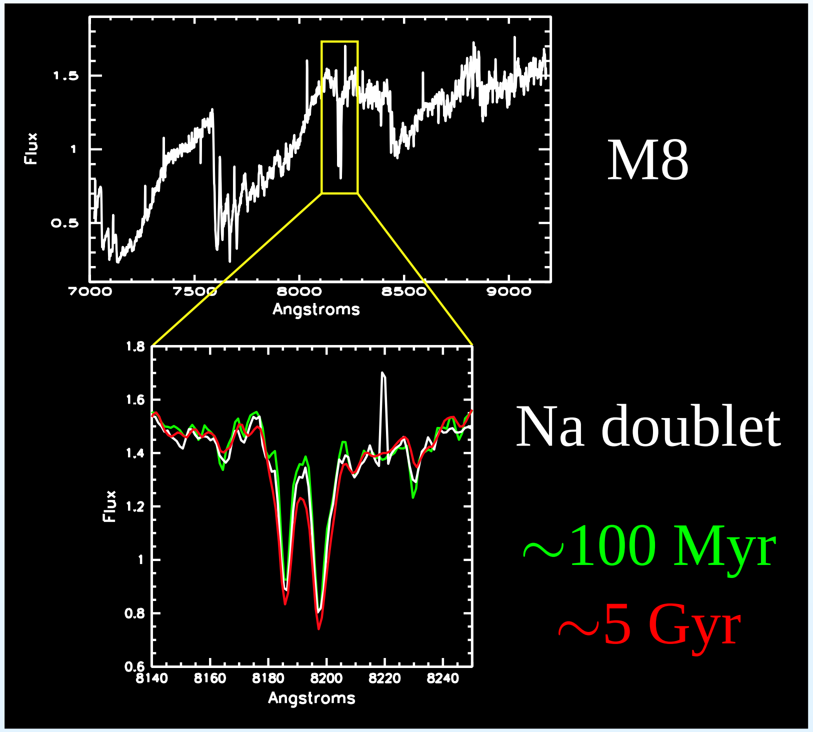
(Moraux et al. 2005)

Pleiades

40 BD candidates down to 30M_{Jup}







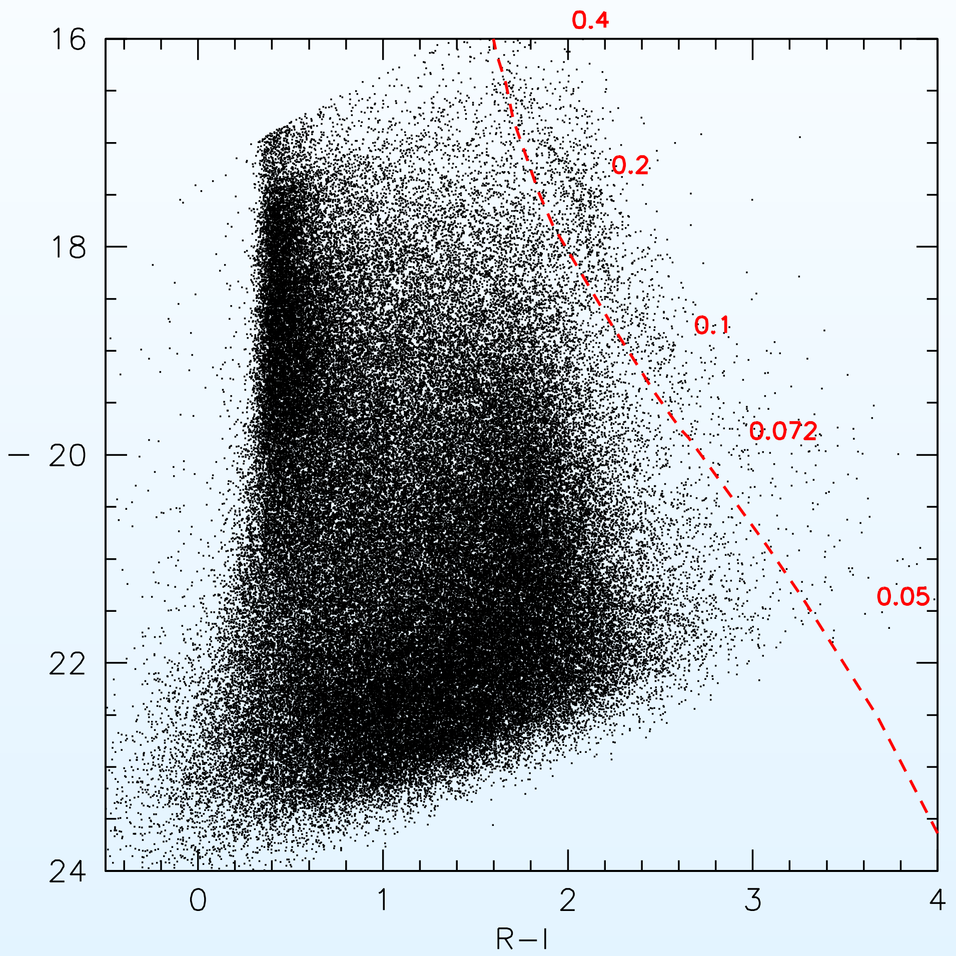
(Moraux et al. 2003)

NGC 2516

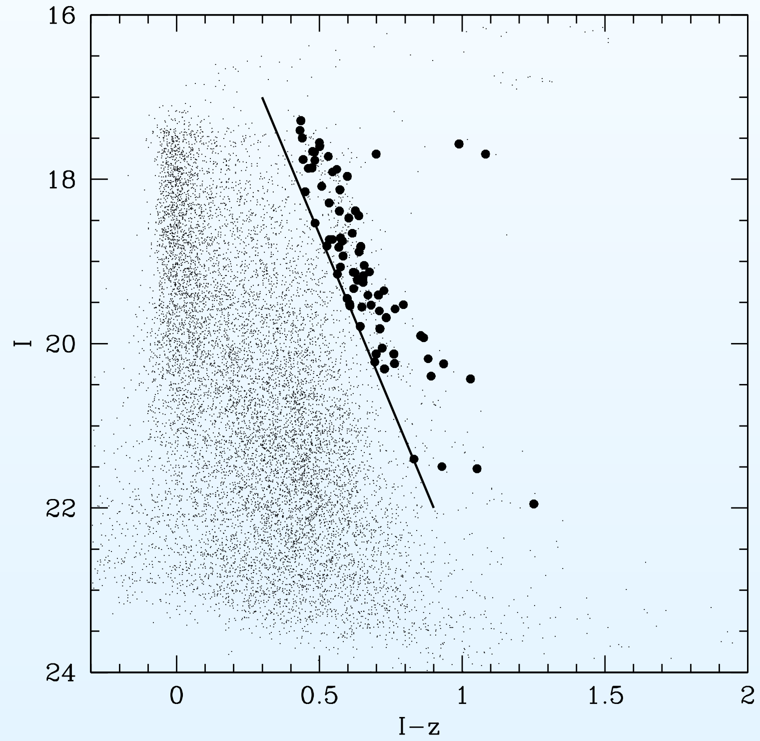
hundreds of VLM & BD candidates

down to 50M_{Jup}

$(I, R - I)$ CMD

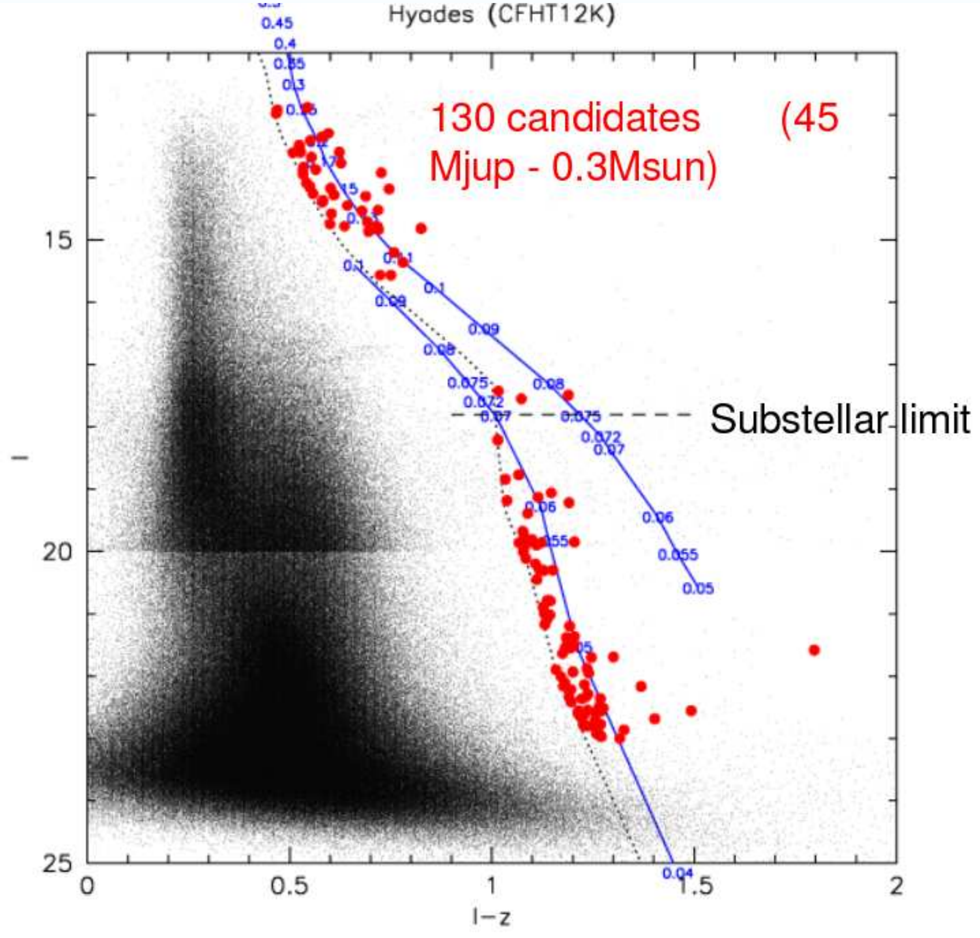


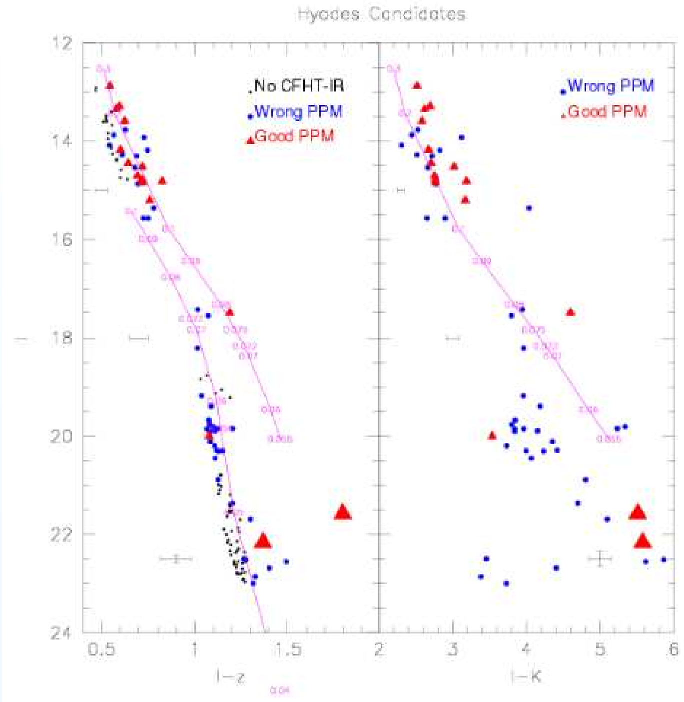
$(I, I - z)$ CMD

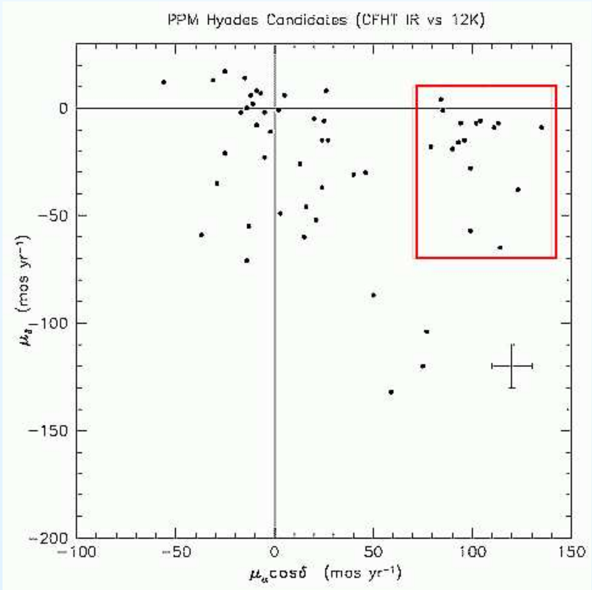


Hyades

11 VLM, 1 VLM/BD, 2 BDs

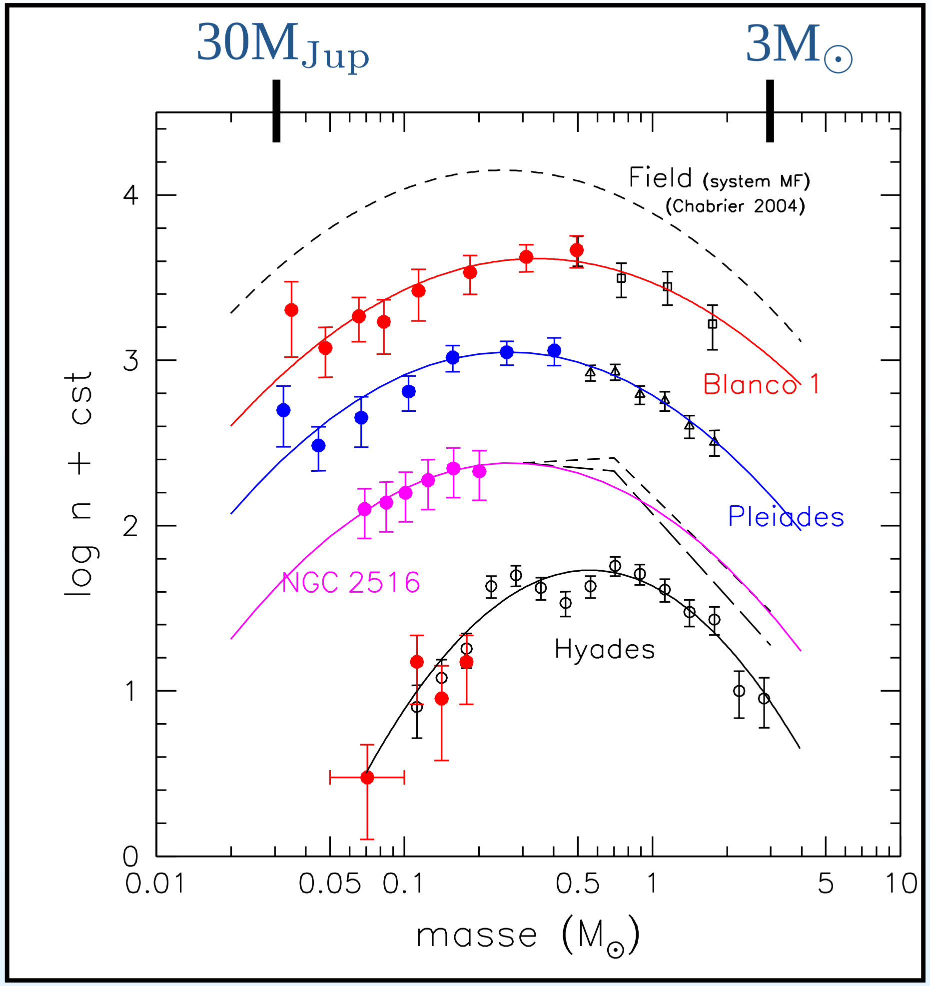






(Bouvier, Kendall, Meeus, Moraux, in prep.)

Mass Functions



log-normal distributions :

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

Blanco1, Pleiades, NGC2516 :

$m_0 \sim 0.25\text{-}0.30 M_\odot, \sigma \simeq 0.55$

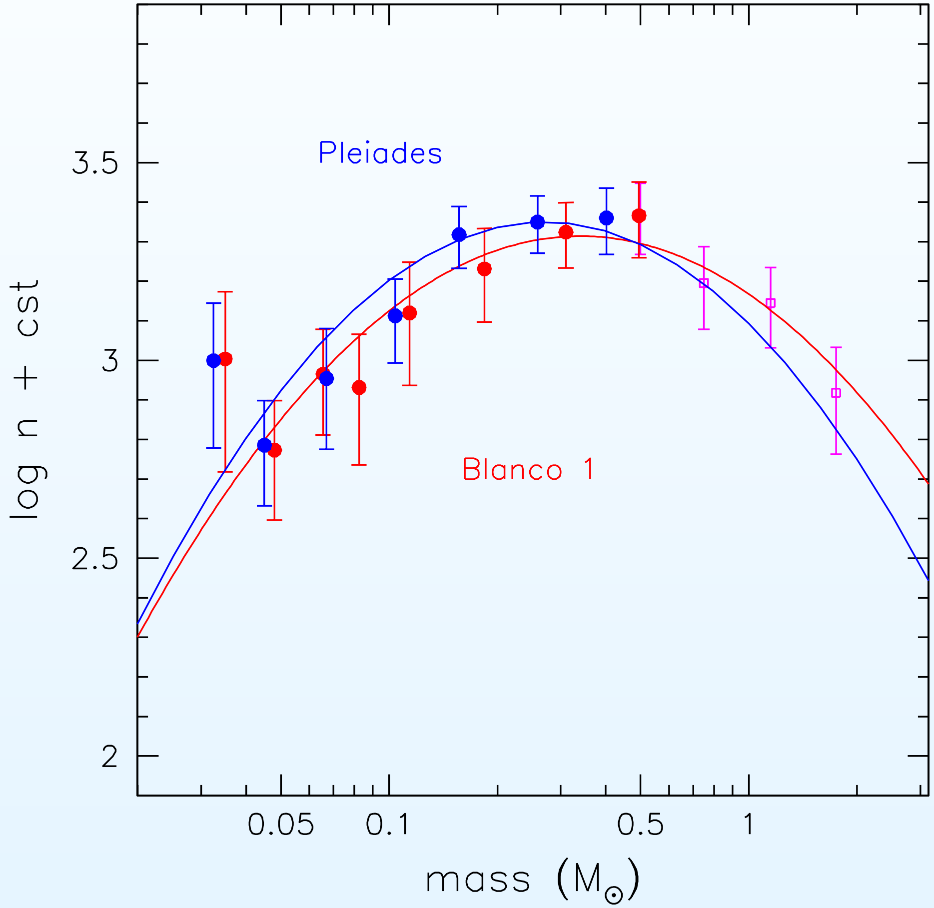
age $= 10\text{-}15 t_{cr}$

Hyades :

$m_0 \sim 0.56 M_\odot, \sigma \simeq 0.38$

age $= 43 t_{cr}$

Blanco1/Pleiades



Similar within the uncertainties

Pleiades :

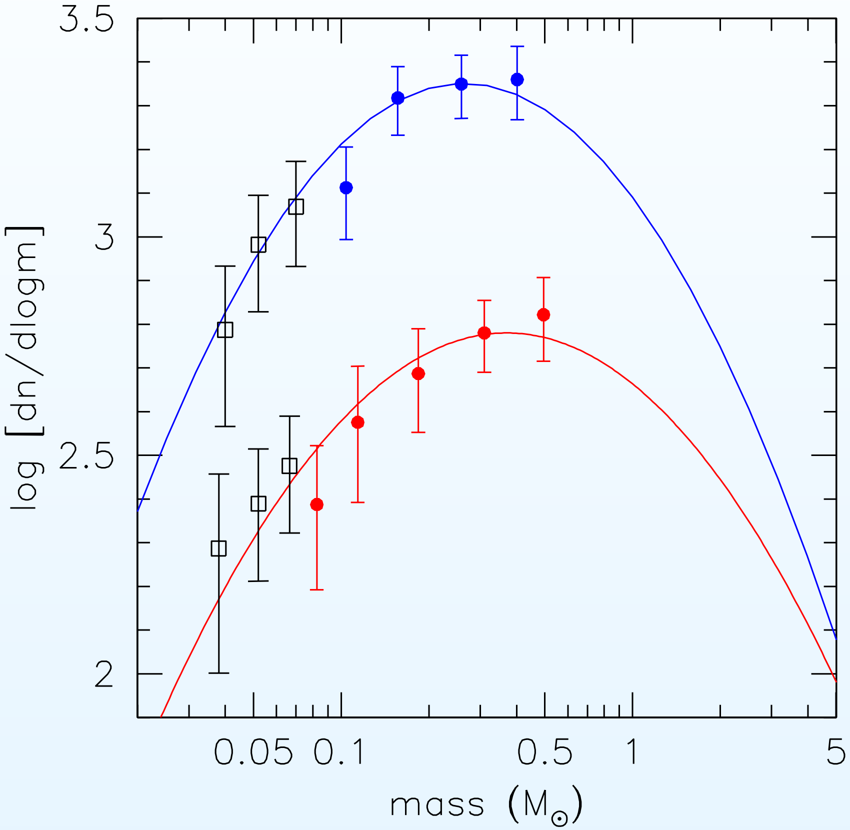
$m_0 \sim 0.26 M_\odot$, $\sigma \simeq 0.53$

Blanco 1 :

$m_0 \sim 0.34 M_\odot$, $\sigma \simeq 0.57$

	[Fe/H]	richness
Blanco 1	+0.1/0.2	$> 200\star$
Pleiades	0.0	$\sim 1200\star$

The "M7 gap"



masses underestimated by the models below $T_{eff} \sim 2700$K (Dobbie et al. 2002)

correction using empirical mass-magnitude relationship

model calibration for different ages is needed ($\rightarrow$ Monitor project)

Density effect

peak $\sim M_{Jeans} \propto T^{3/2}\rho^{-1/2}$

lower density $\longrightarrow$ peak at higher mass

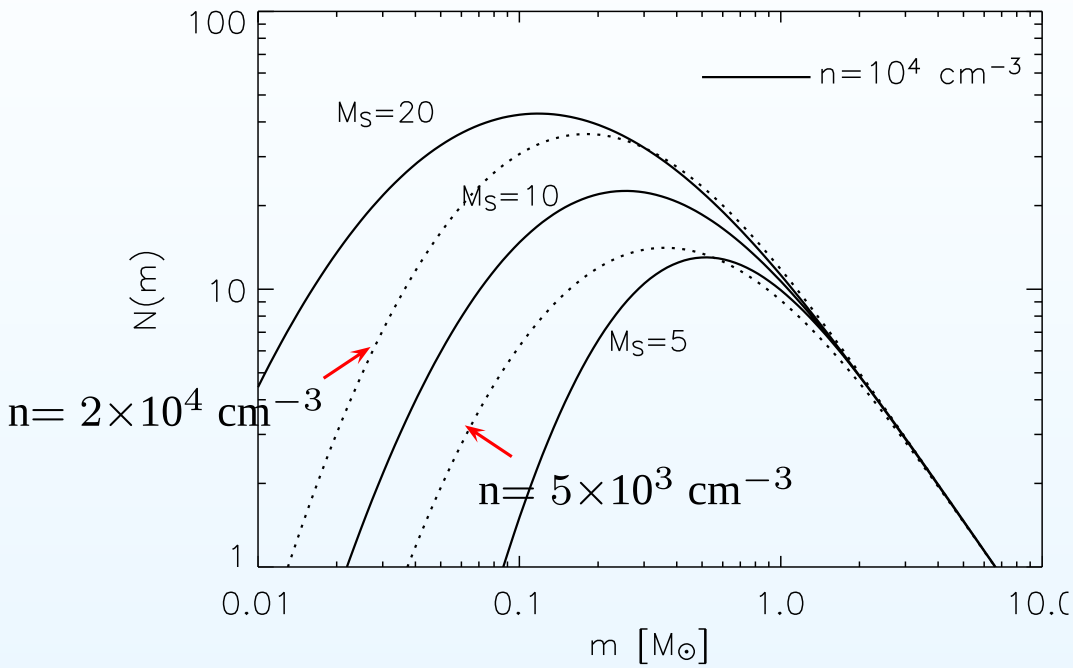
supersonic turbulence :

same sonic rms Mach number

but lower density

$\longrightarrow$ peak at higher mass

$\longrightarrow$ slightly broader mass function



(Padoan & Nordlund 2002)

model predictions :

$$m_{0\,Blanco1} \geq m_{0\,Pleiades} \qquad \sigma_{Blanco1} \geq \sigma_{Pleiades}$$

Metallicity effect

mass characteristic of the IMF $\sim M_{Jeans} \propto T^{3/2}\rho^{-1/2}$

higher metallicity $\rightarrow$ smaller T $\rightarrow$ peak at lower mass

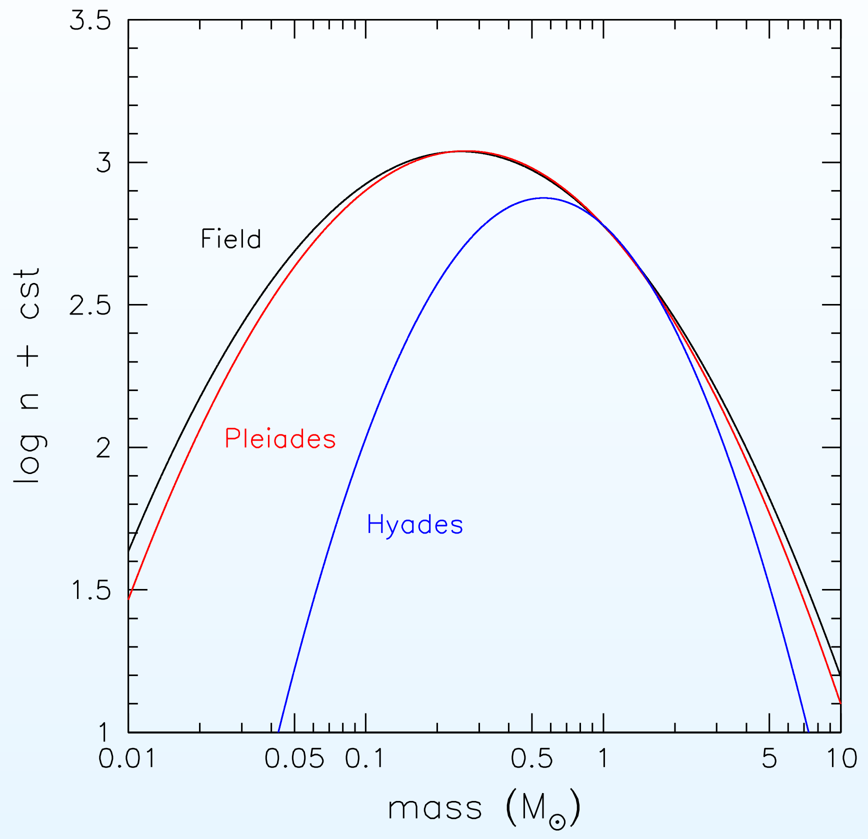
but $T = f(\rho)$ (Larson 2005)
peak corresponds to the minimum of T
$T_0, \rho_0 \rightarrow M_{Jeans} \sim 0.3\mathrm{M}_\odot$

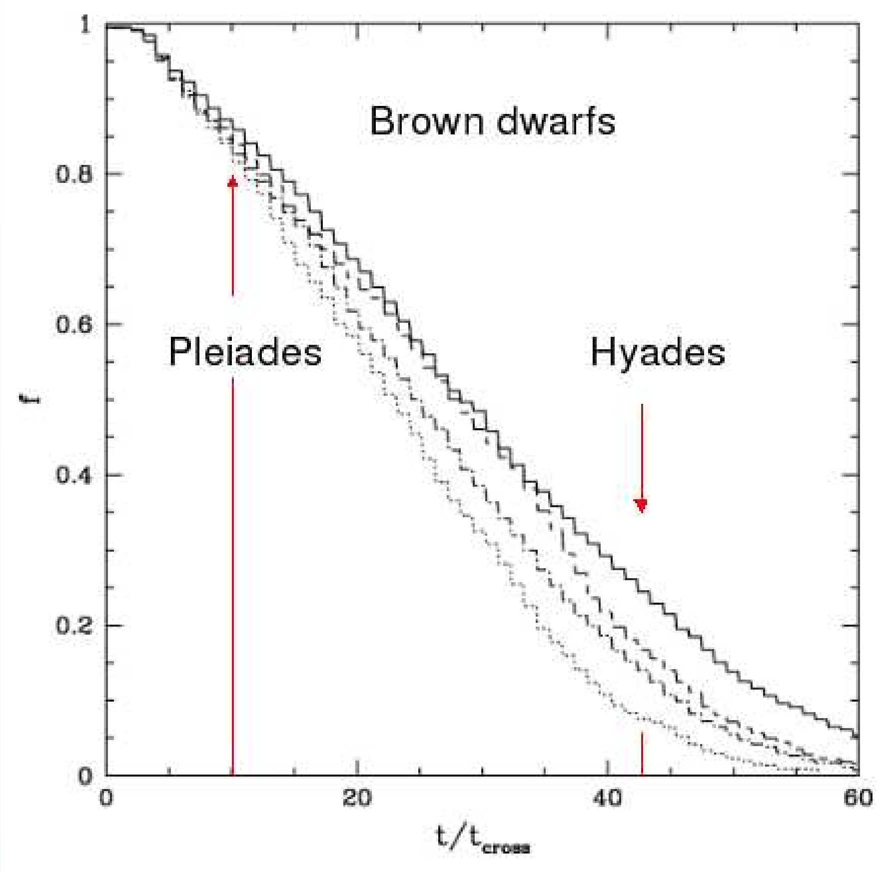
higher metallicity $\rightarrow T < T_0$ but minimum occurs at $\rho(T) < \rho_0$
so what about M_{Jeans} ?

$$m_{0\,Blanco1} \sim m_{0\,Pleiades}$$

Dynamical evolution

(Adams et al. 2002)





- dynamical relaxation : ⇒ evaporation of the low mass members
- ejection scenario : if $V_{ej} > V_{esc}$ ⇒ quick loss of primordial BDs

Pleiades-like clusters (100 Myr)

MF(Pleiades)$\sim$ MF(SFR, Field)

$\rightarrow$ **no** significant evaporation of BDs in 100 Myr

NBody simulations

toy model with $\sigma_{V_{\rm BD}} = k\,\sigma_{V_\star}$

$\sigma_{V_{\rm BD}}$	$\sigma_{V_\star}$	$1.5\sigma_{V_\star}$	$2\sigma_{V_\star}$
evaporation	10%	20%	40%

(Moraux & Clarke 2005)

$\Rightarrow$ $\boldsymbol{\sigma_{V_{\rm NB}} < 2\sigma_{V_\star}}$ **($\sim$ a few km/s) at birth**

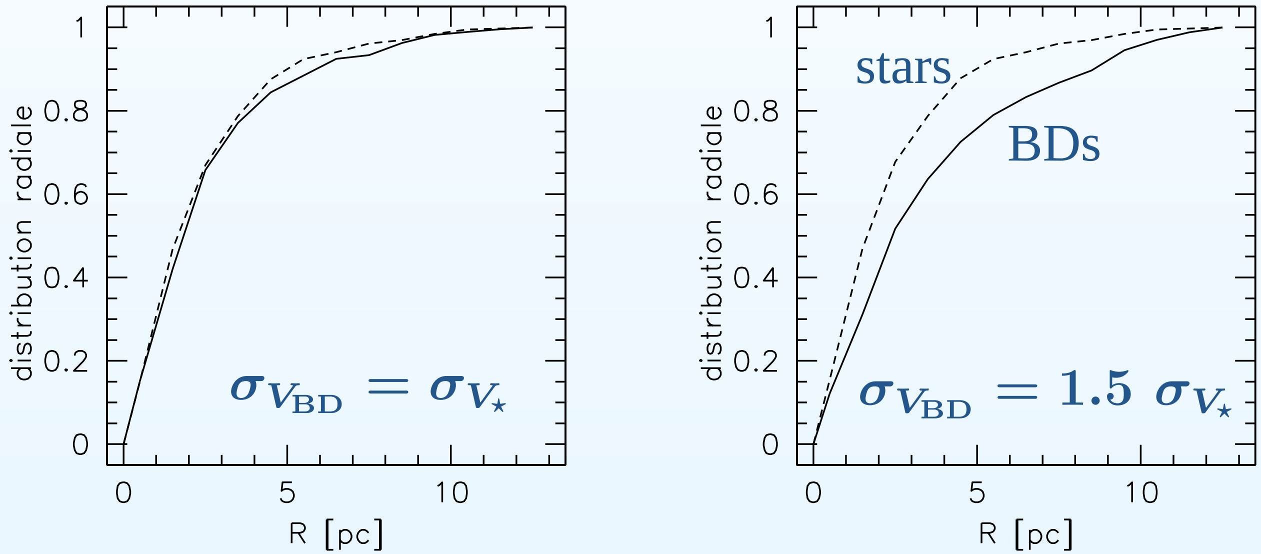
ejection velocity cannot be more than ~ 1 km/s

no (or very small) distribution tail with large $V_{\rm ej}$

Radial distribution

comparison BDs/very low mass stars

radial distributions in the cluster at $1t_{cr}$:



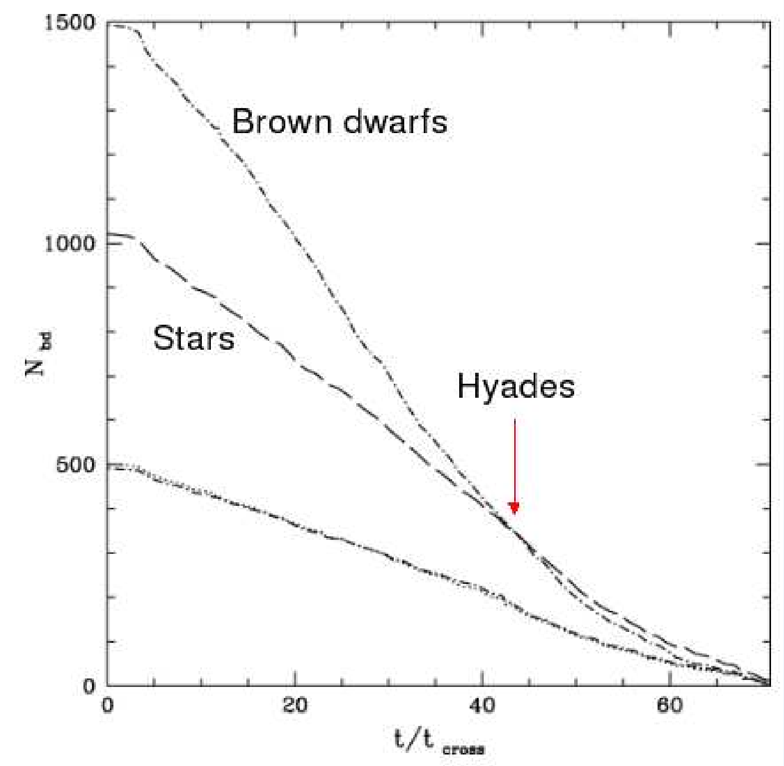
(Moraux & Clarke 2005)

Imprint of the initial kinematic at ∼10 Myr

age $\leq 2t_{cr} \quad (t_{cr} = 2R/\sigma_{V_\star})$

Hyades (625 Myr)

	model predictions	observations
% of BDs lost	∼85%	> 95%
% of stars lost	70%	55%



(Adams et al. 2002)

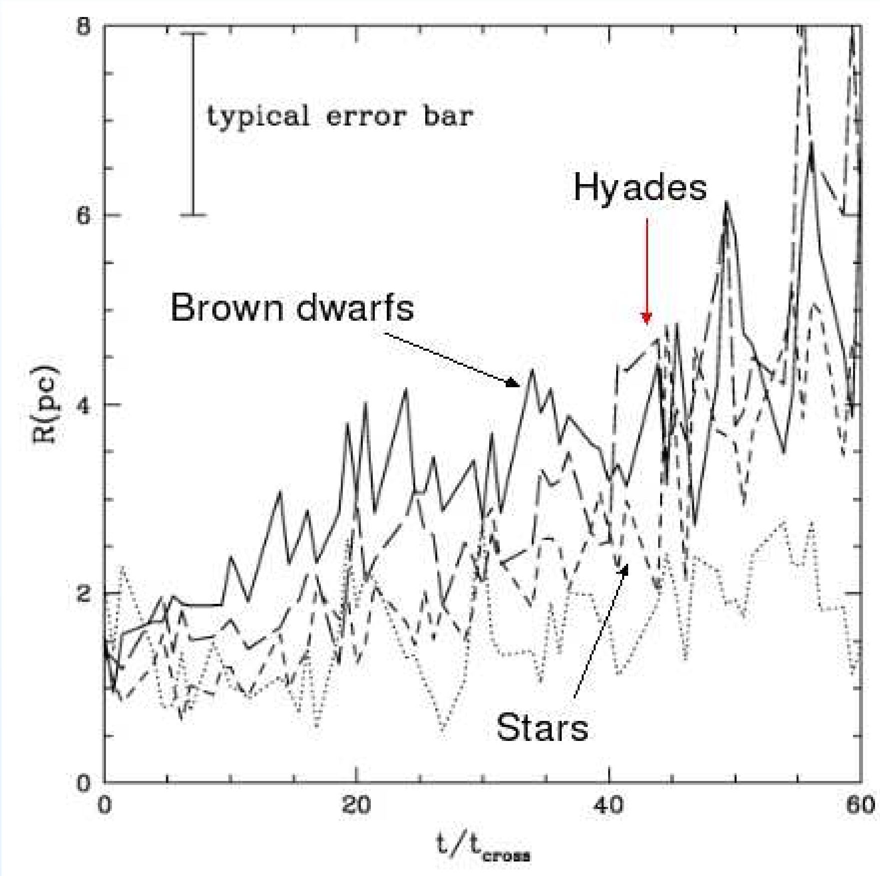
if we assume Hyades IMF = Field IMF

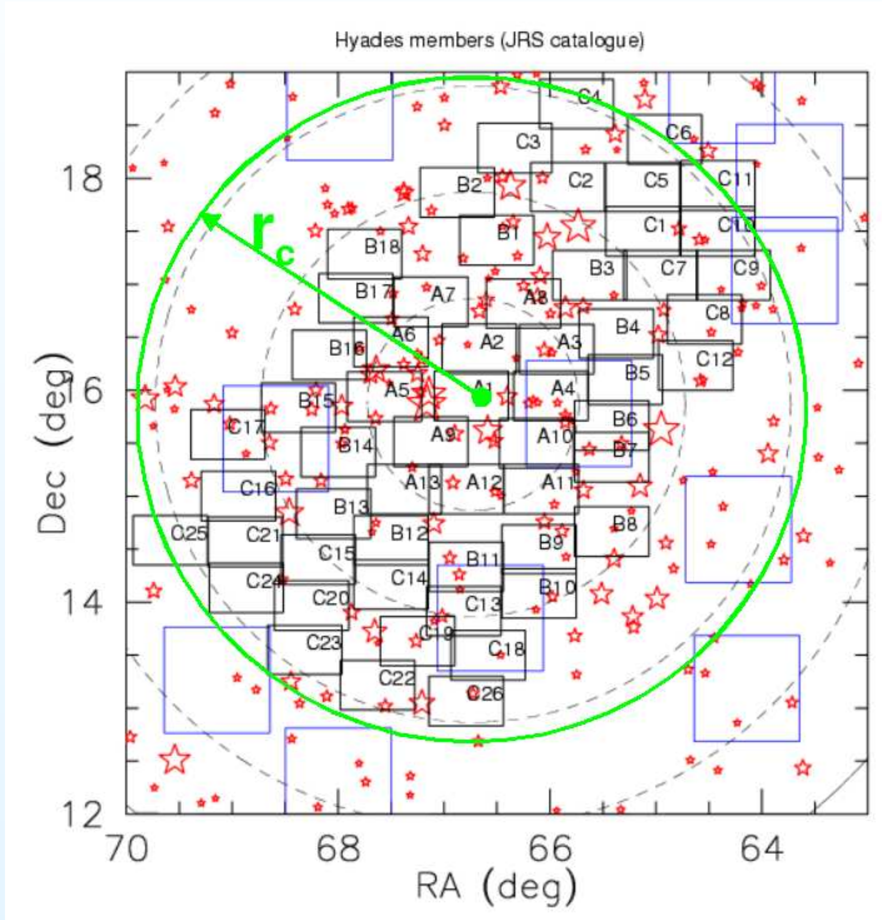
→ discrepancy between models and obs

too many BDs have been lost compared to stars

Hyades (625 Myr)

Mass segregation





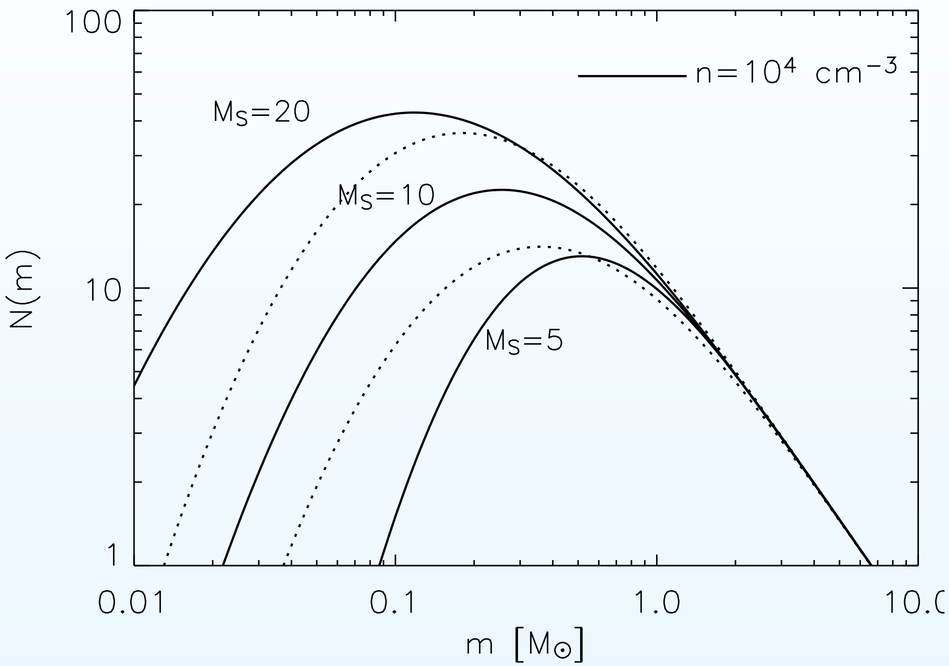
(Adams et al. 2002)

Hyades (625 Myr)

Dynamical evolution models do not explain the strong deficit of BDs

- additional loss of BDs due to ejection in the early stages ?
- BDs cool down more rapidly than evolutionary models predict ?
- different IMF due to different initial conditions (metallicity, turbulence, etc.) ?

Supersonic turbulence in molecular clouds



(Padoan & Nordlund 2002)

however IMF seems to be amazingly universal, even for Taurus...

star formation does not depend on global conditions ?

Conclusions

- ⋆ Cluster MF @100 Myr from 30M$_{Jup}$ to 3M$_{\odot}$
  log-normal with $m_0 \simeq 0.25$-0.30M$_{\odot}$, $\sigma \simeq 0.55$
- ⋆ Similar MF for all studied clusters in this age range
  "universal" IMF ?
- ⋆ Cluster MF similar to field MF
  Initial velocity of BDs less than escape speed
  Dynamical evaporation occurs past 150 Myr
- ⋆ Hyades strongly depleted in VLM stars and BDs
  dynamical evolution or different IMF ?