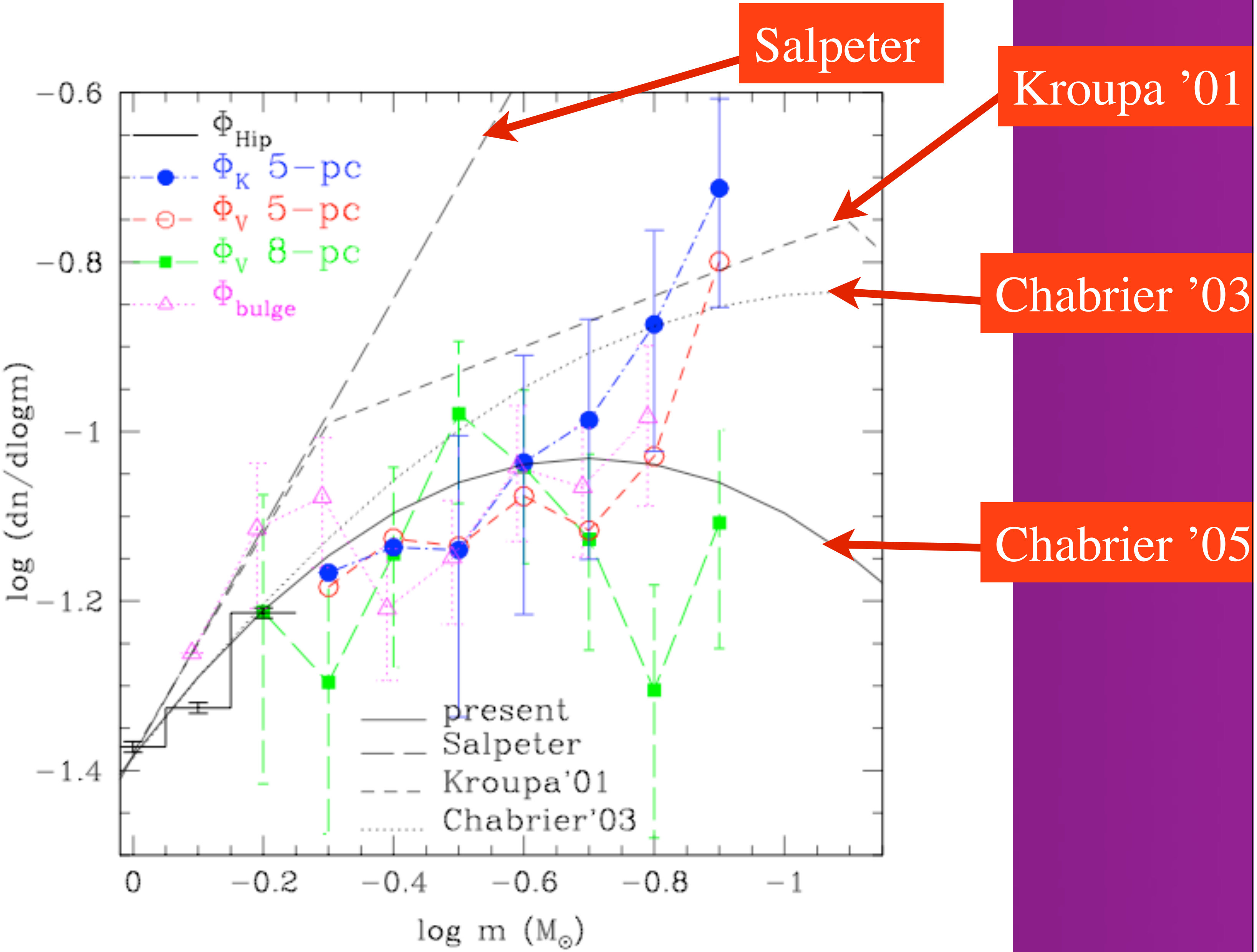
Revealing and understanding the low-mass end of the IMF

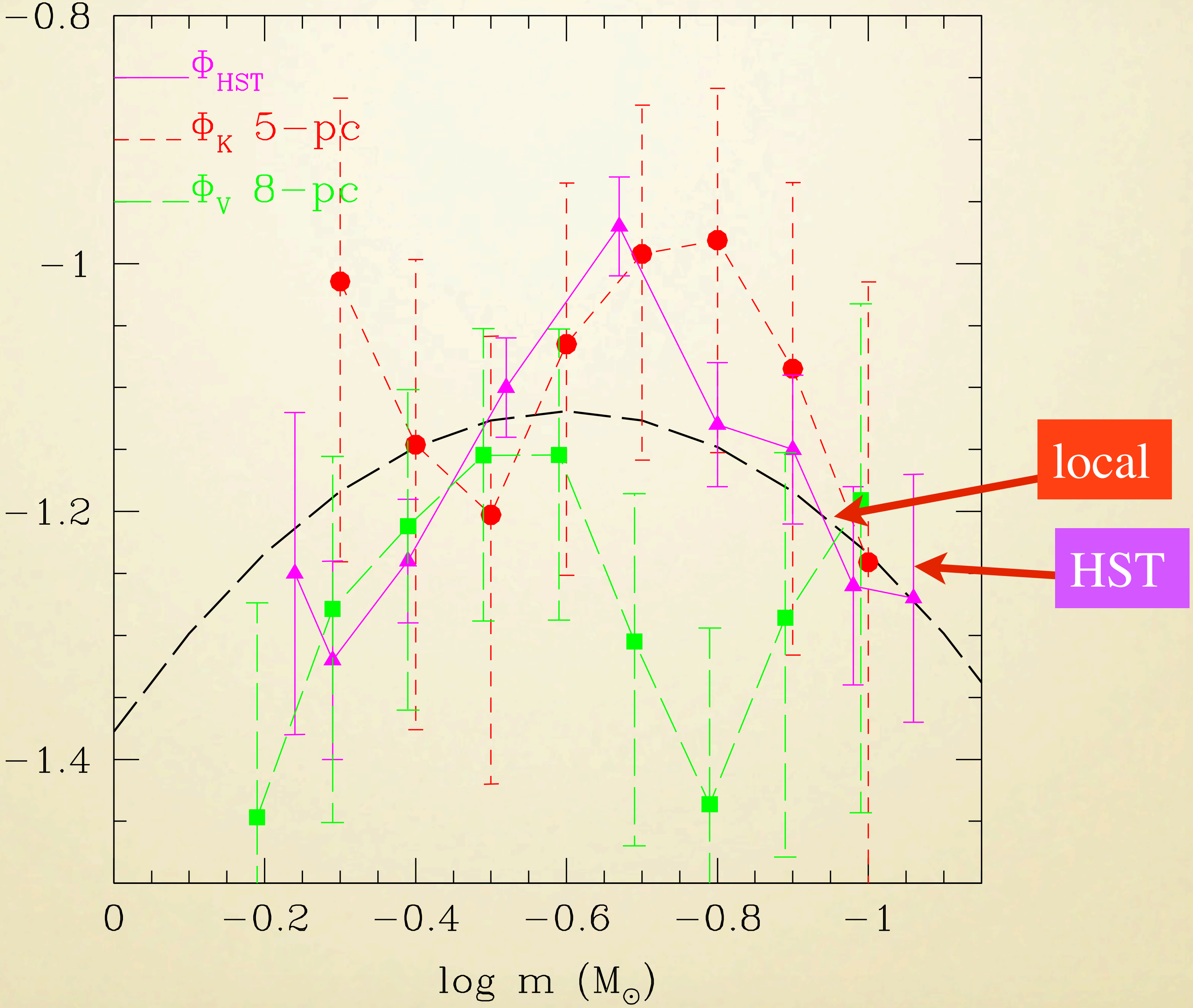
Low-mass part of the Initial Mass Function
Star, brown dwarf formation

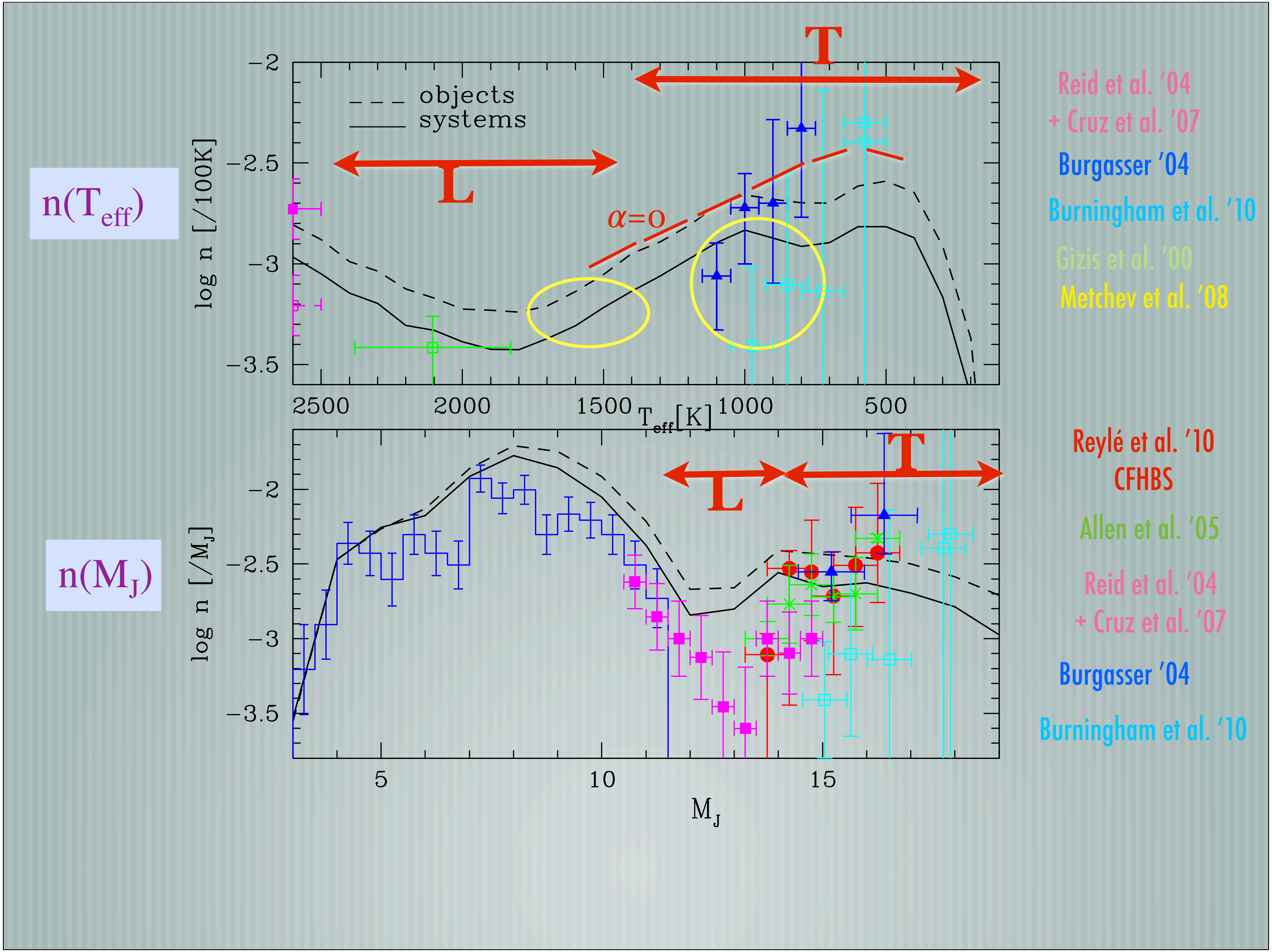
G. Chabrier

Field: ***Resolved objects*** IMF down to the HB limit



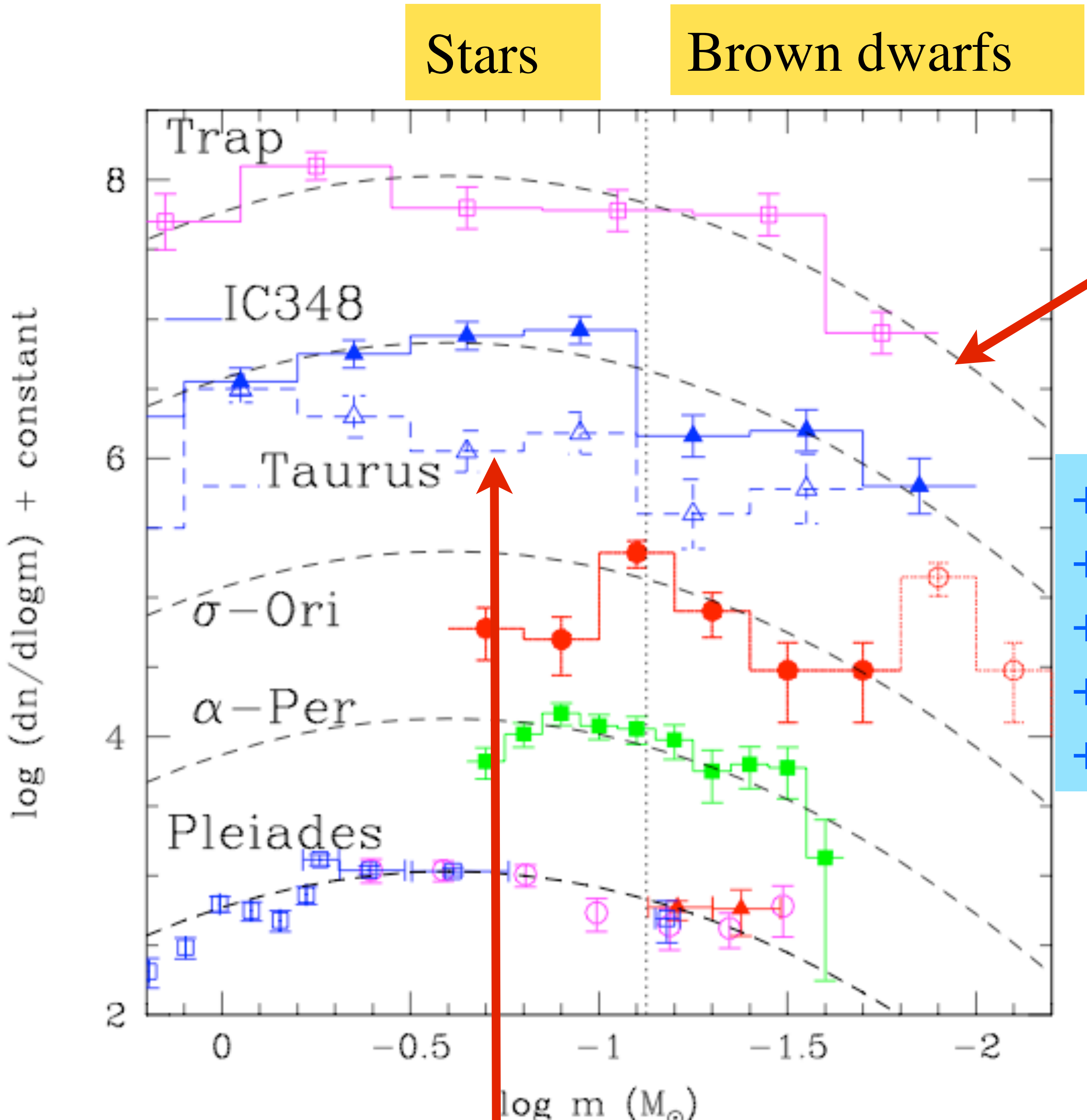
Field: ***Unresolved systems*** IMF down to the HB limit





n(T_eff)
n(M_J)
objects
systems
L
T
α=0
log n [/100K]
T_eff[K]
2500
2000
1500
1000
500
−2
−2.5
−3
−3.5
log n [/M_J]
M_J
5
10
15
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
CFHBS
Allen et al. '05
Reid et al. '04
+ Cruz et al. '07
Burgasser '04
Burningham et al. '10

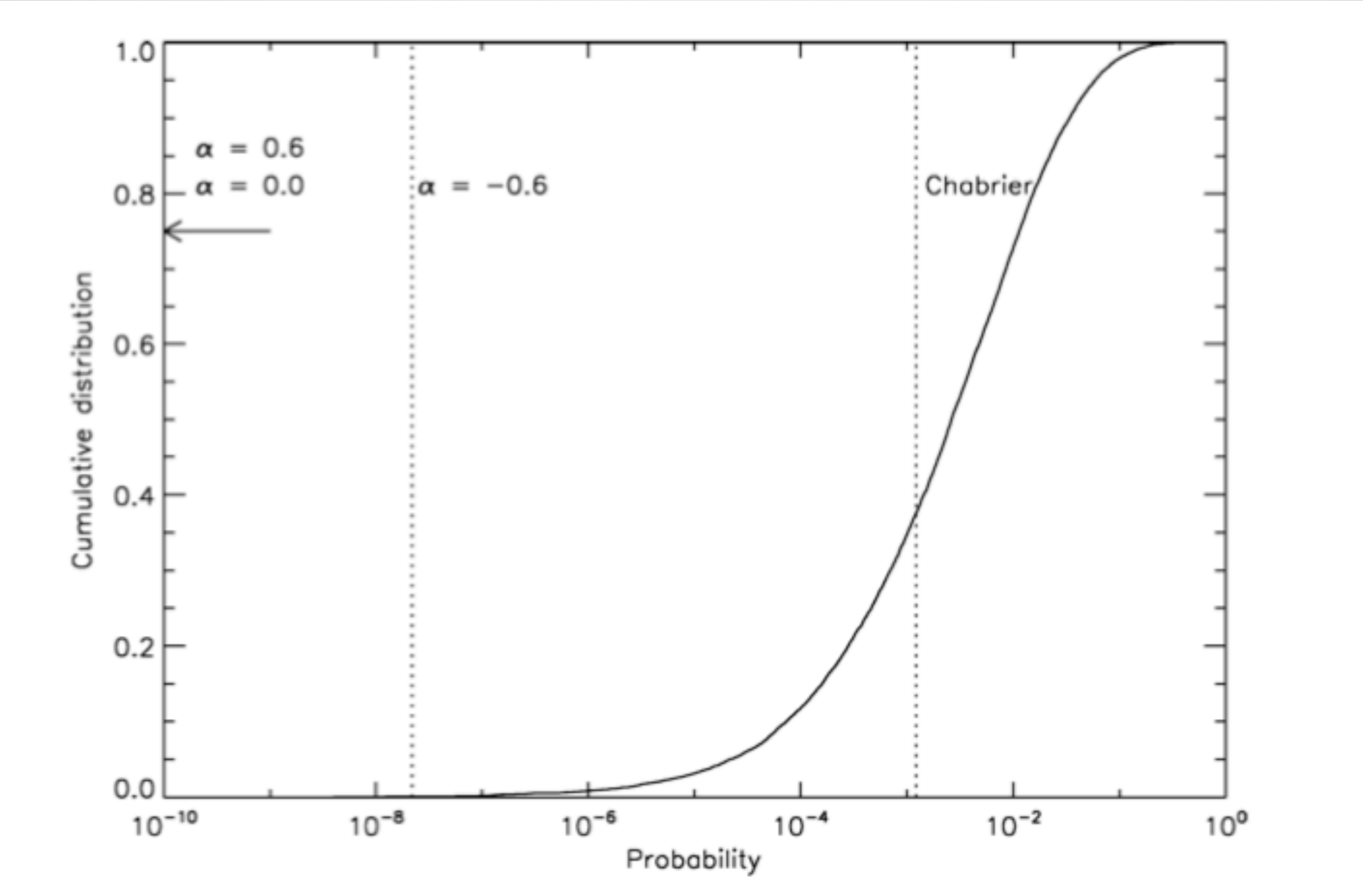
Young clusters and SFR: *system* IMF across the HB limit



+ **IC4665** (Lodieu et al. ’11)
+ **Blanco I** (Moraux et al. ’07
+ **ONC** (Weights et al. ’09)
+ **Chameleon** (Luhman ’07)
+ **Lambda Ori** (Bayo et al. ’1

The Taurus case (Luhman et al. ’09, Ghieu et al. ’06, Rebull et al. ’10)

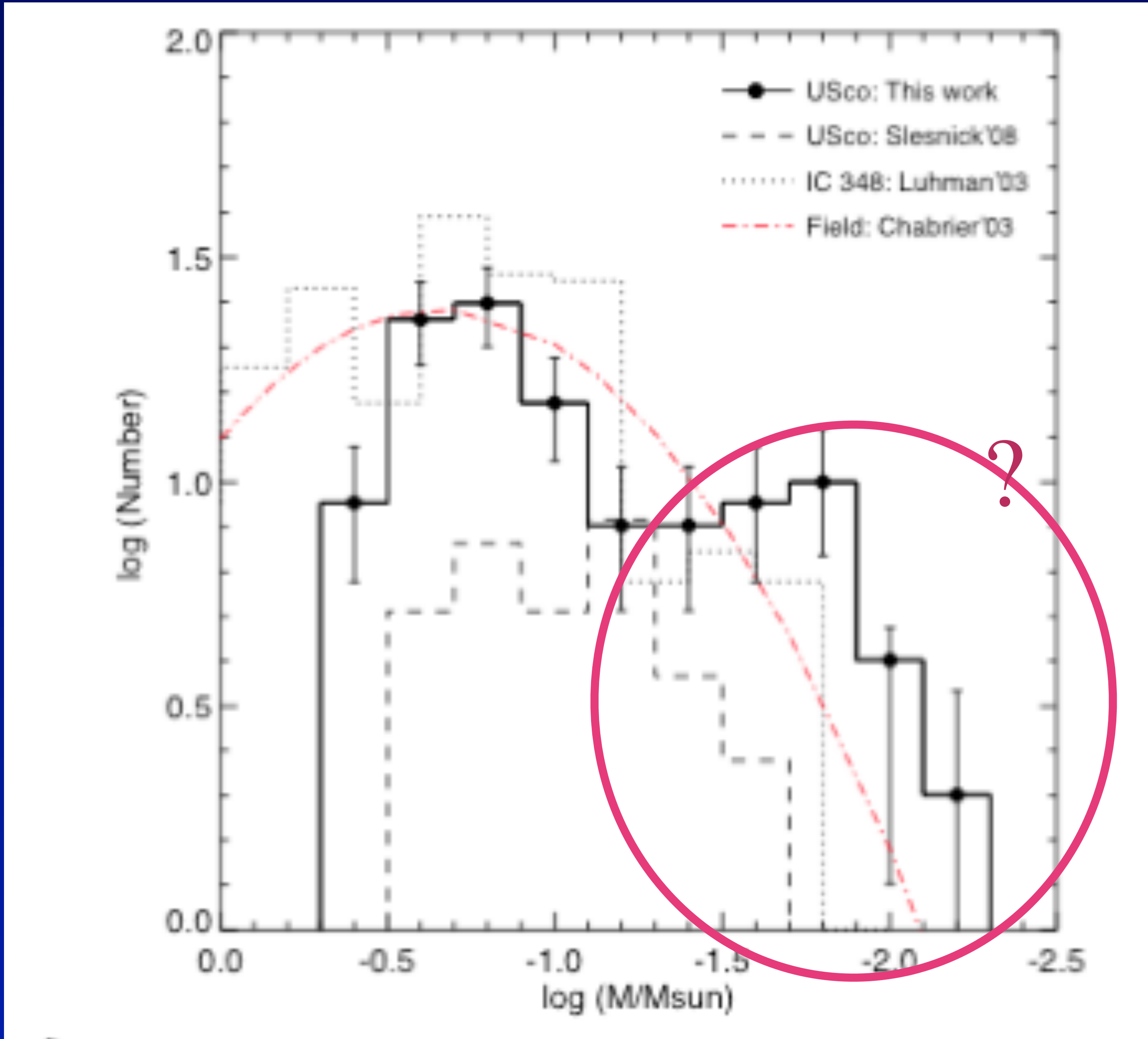
Andersen et al. 2008



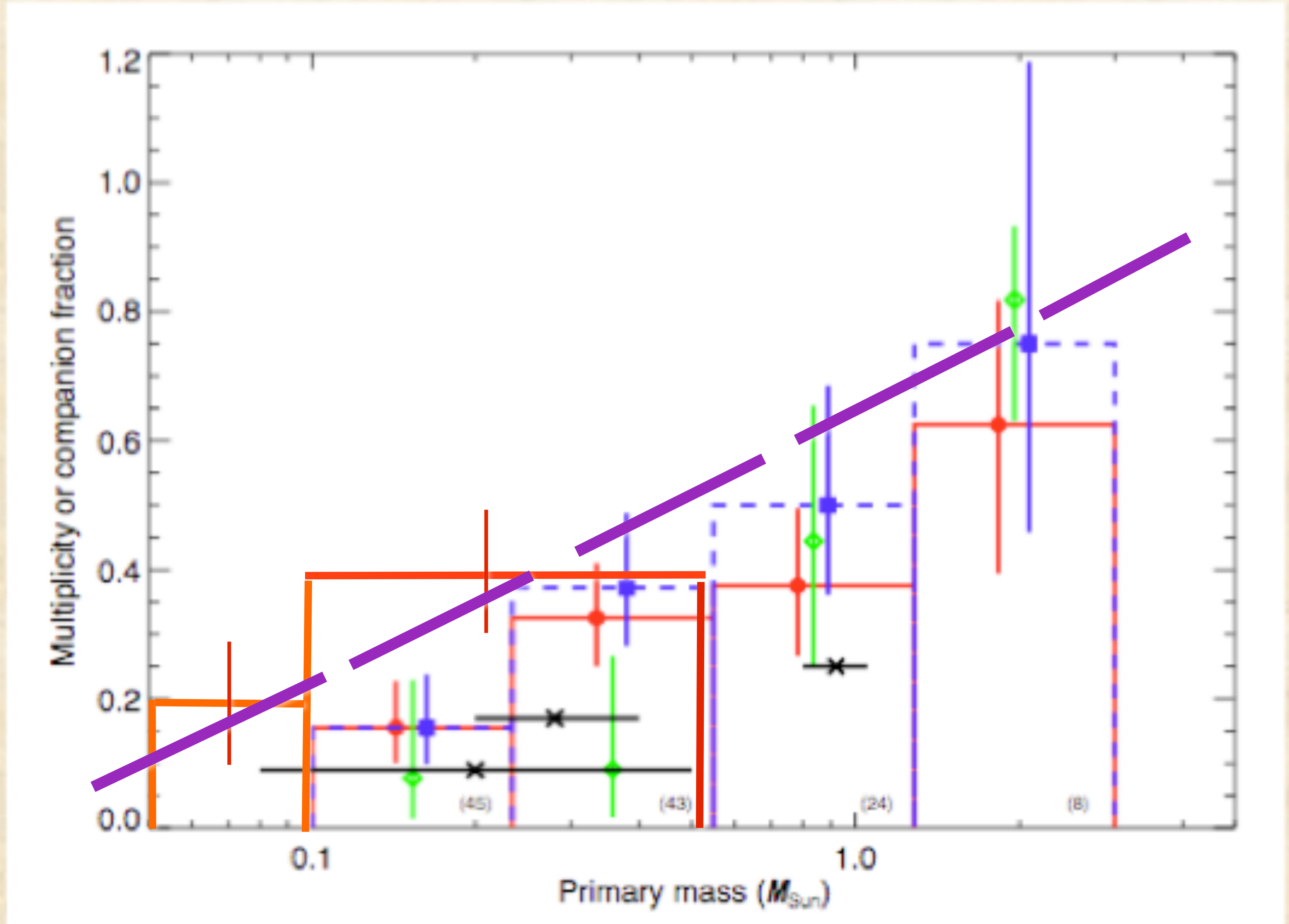
Combined analysis of 7 SFR's

star/BD ratio in the 7 clusters ***consistent w/ the same underlying IMF***

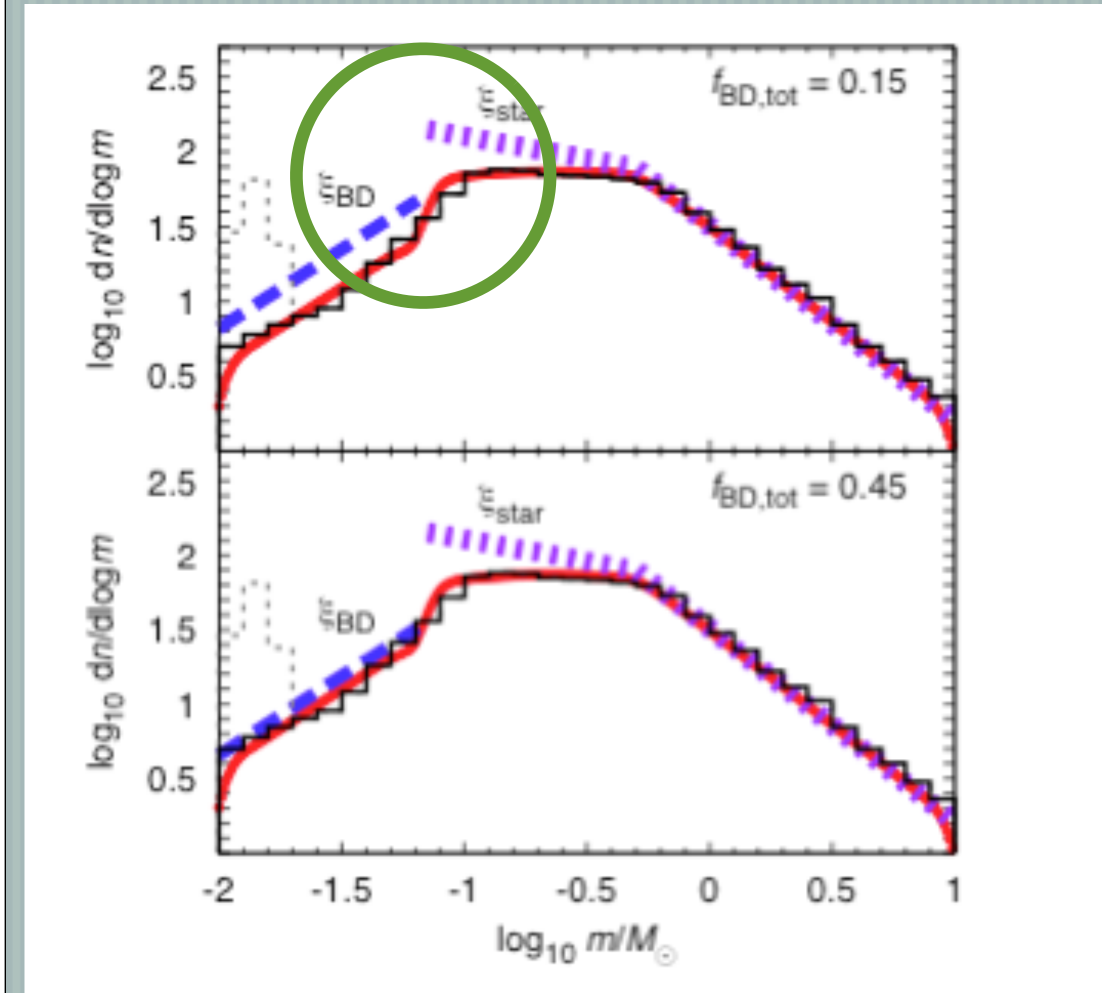
Lodieu et al. '11 : Upper Sco : excess of BD's wrt field ?

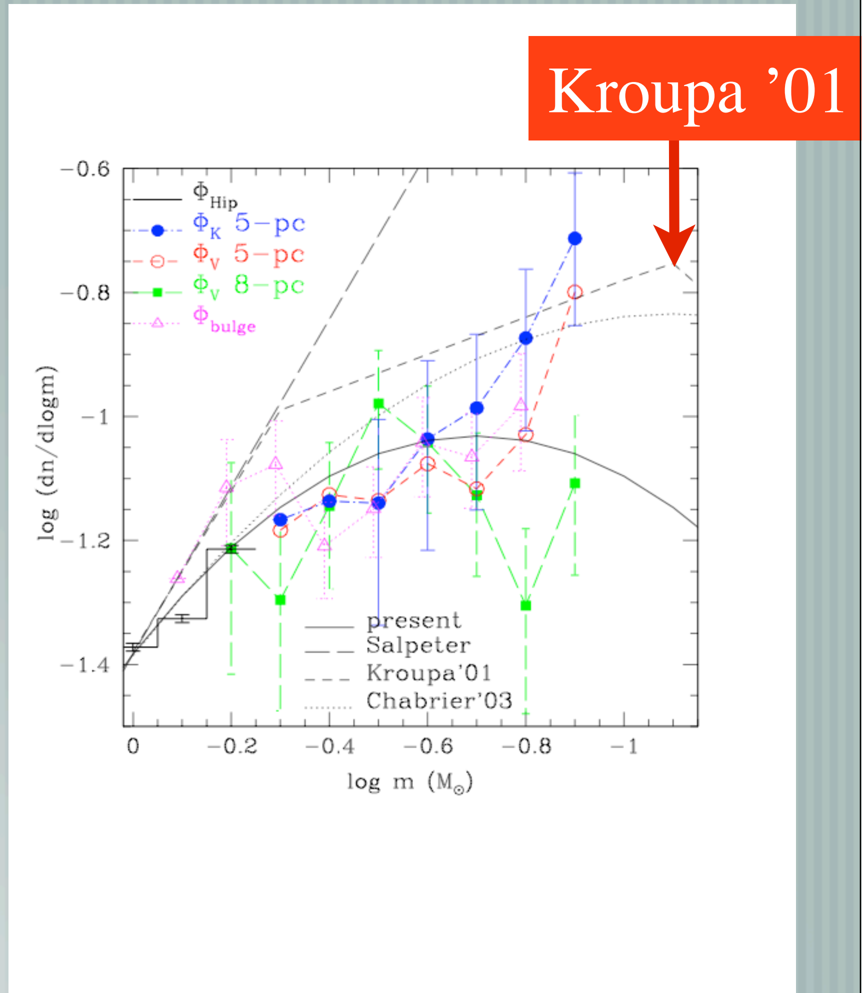


Multiplicity frequency in the stellar and substellar regime



Thies & Kroupa 2008 :
discontinuity between the stellar and the BD IMF





$$\frac{dn}{dm} \propto m^{-\alpha} \quad \alpha = 0.3 - 1$$

- IMF similar between the field and young clusters/SFR's (with some scatter <3σ)
  consistent w/ the same underlying IMF

- No obvious discontinuity near the HB limit

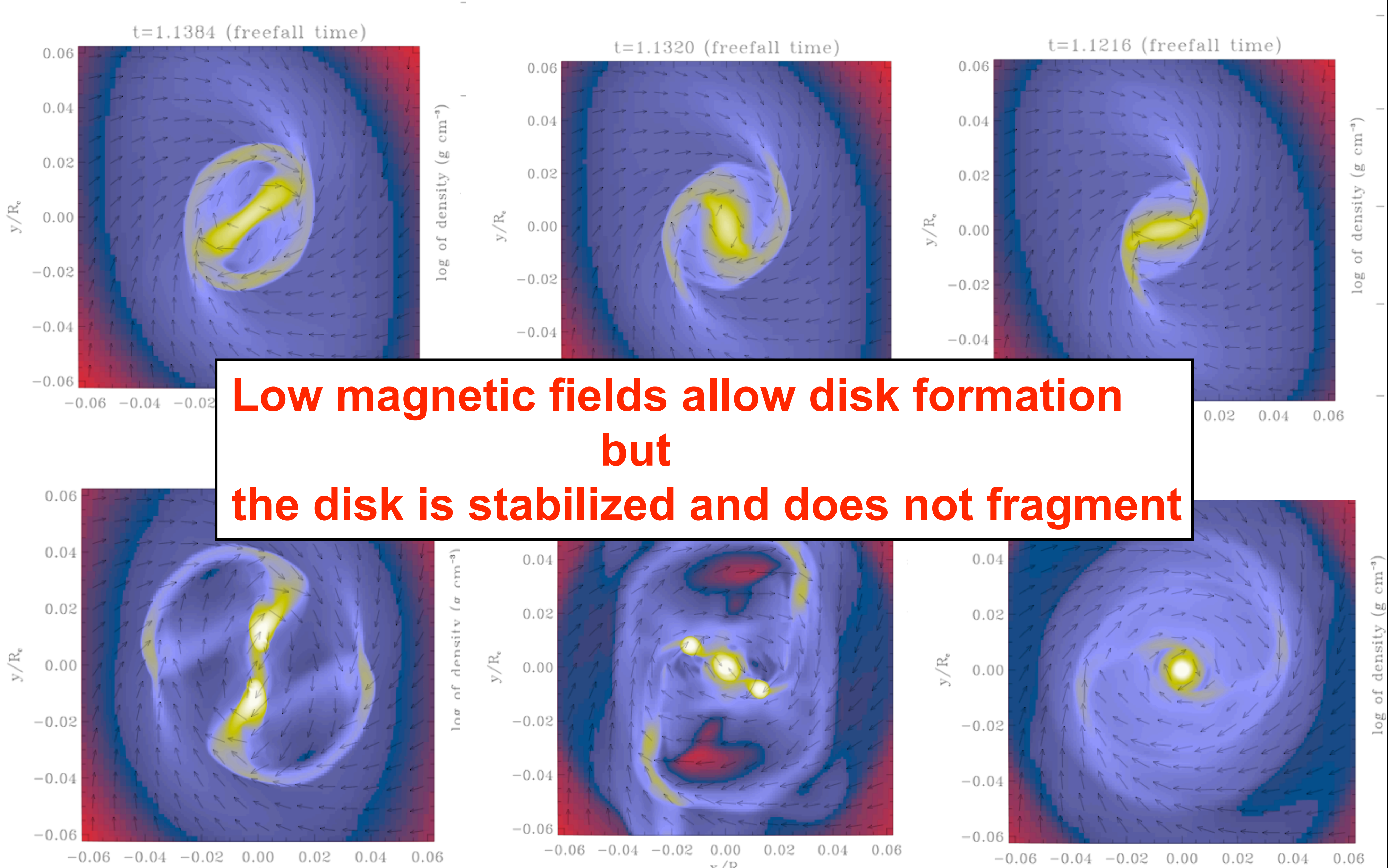
- No (or at least very weak) dependence on the environment / $N_{BD}/N_{*} \sim$ 1/4 - 1/5

Brown dwarf formation

- Disk fragmentation
  Vorobyov & Basu; Stamatellos & Whitworth; Bate
- Accretion - ejection
  Reipurth & Clarke; Bate, Bonnell

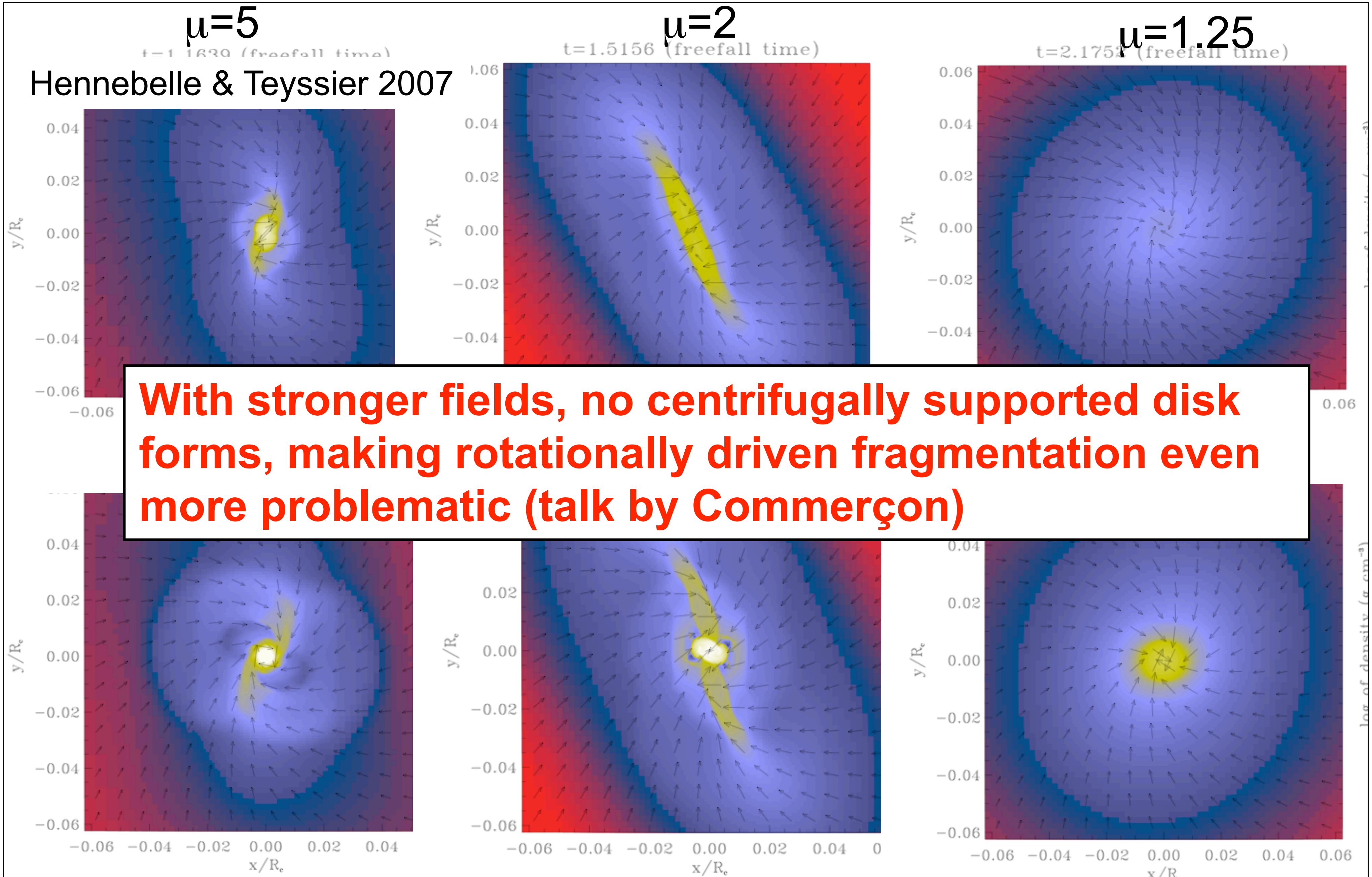
- Gravo-turbulent fragmentation
  Padoan & Nordlund; Hennebelle & Chabrier

μ=1000 (hydro) | μ=50 | μ=20



Low magnetic fields allow disk formation
but
the disk is stabilized and does not fragment

Machida et al. ’04; Vorobyov & Basu ’06; Hennebelle & Teyssier ’07; Price & Bate ’07; Hennebelle & Ciardi ’09; Commerçon et al. ’10



With stronger fields, no centrifugally supported disk forms, making rotationally driven fragmentation even more problematic (talk by Commerçon)

Li et al'11: resistive MHD => moderate B suppresses disk f'n/frag'n in the presence of ambipolar diffusion.

Sufficient resolution crucial to avoid numerical reconnection (spurious flux loss) !

Comparison of the PdBI maps with MHD simulations

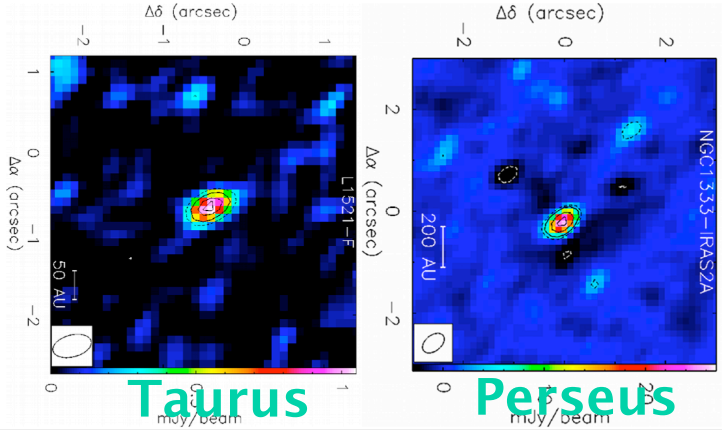
Maury et al. 2010; see also Stamatellos, Maury et al. '11

Hydrodynamical simulations produce too much extended (+ multiple) structures if compared to the observations.

→ MHD simulations ?

Taurus : L1521-F   Perseus : N1333-IRS2A

Obs



Hennebelle & Teyssier (2008) MHD simulations : produce PdB-A synthetic images with **typical FWHM ~ 0.2" - 0.6"**

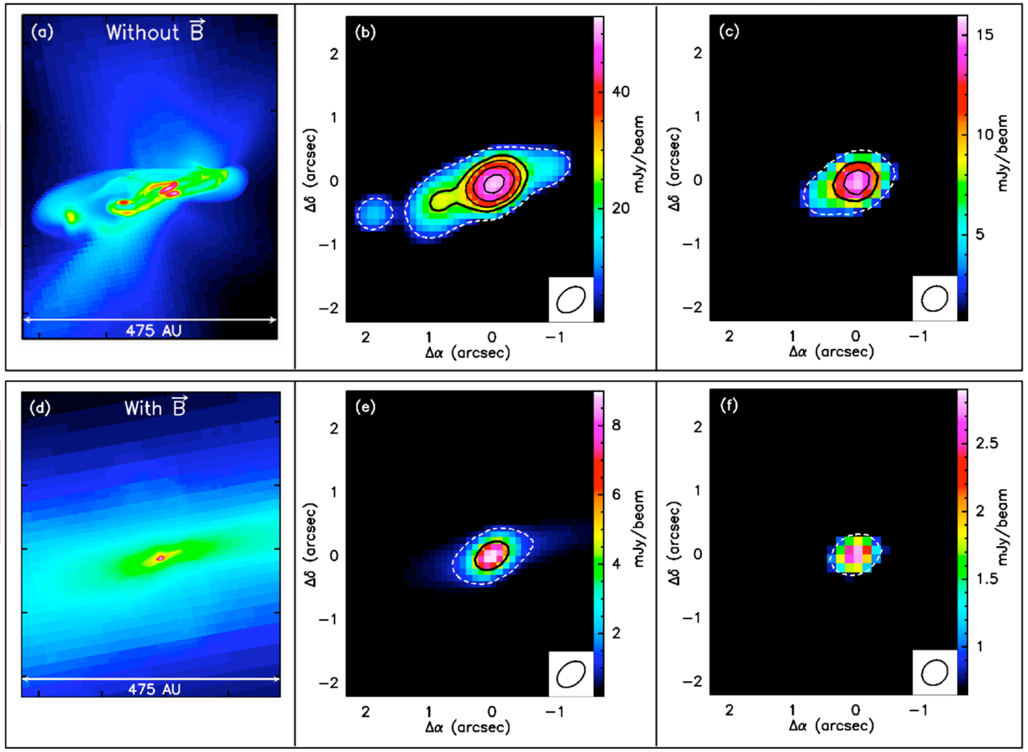
Similar to Class 0 PdB-A sources observed !

↓

need B to produce compact, single PdB-A sources.

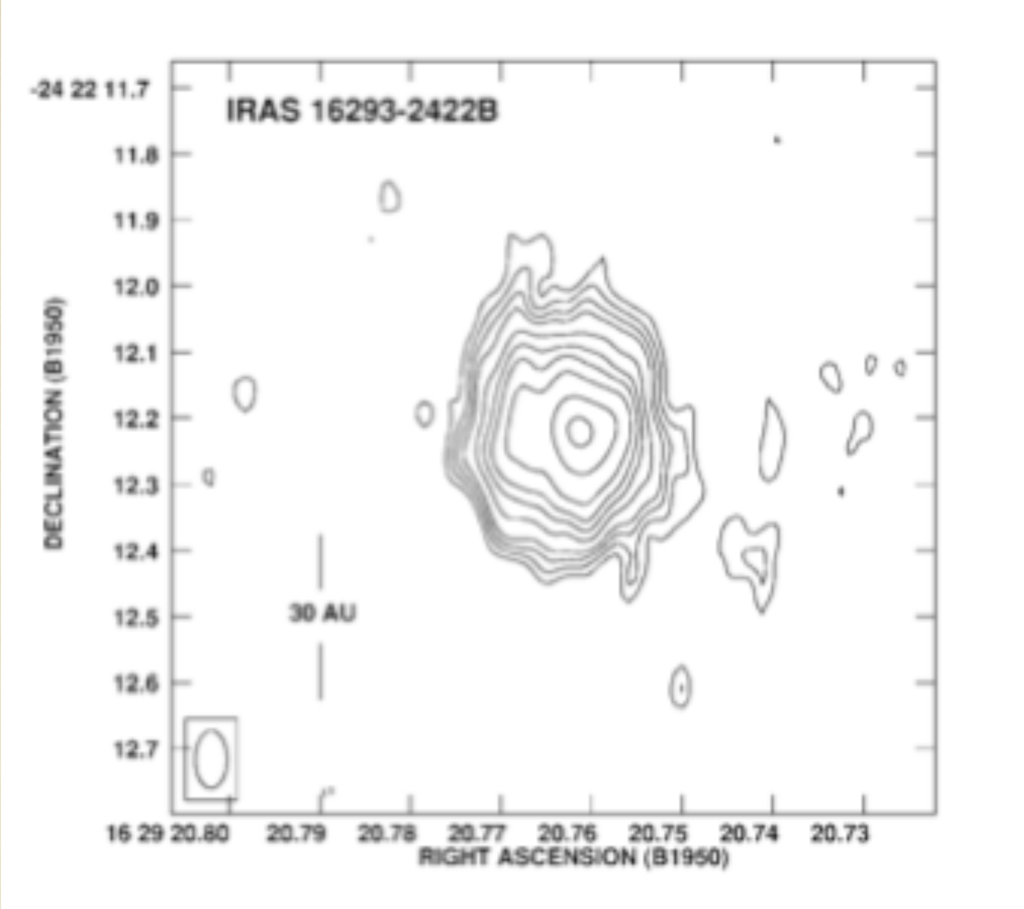
No B

w/ B



13 Oct. 2011: Massive disks prone to fragmentation not observed !

Rodriguez et al. ’05



Isolated, massive, compact (R_{out}~20 AU) disk around class 0

consistent w/ MHD disks !

The timescale argument (Stamatellos & Whitworth)

short-lived (~10^4 yr) -> low probability to be seen

but....

no accreting envelop in their simulations

e.g. Vorobyov-Basu $t_{disk} \sim 10^5$ yr

Class-0 lasts ~ 10^5 yr (Evans et al., Enoch et al.)

=> **most Class-0 objects should have massive disks**

way out: 1% of the Class-O pop. makes up the entire BD pop. !

\+ BD LHS6343c (Johnson et al. 2010)

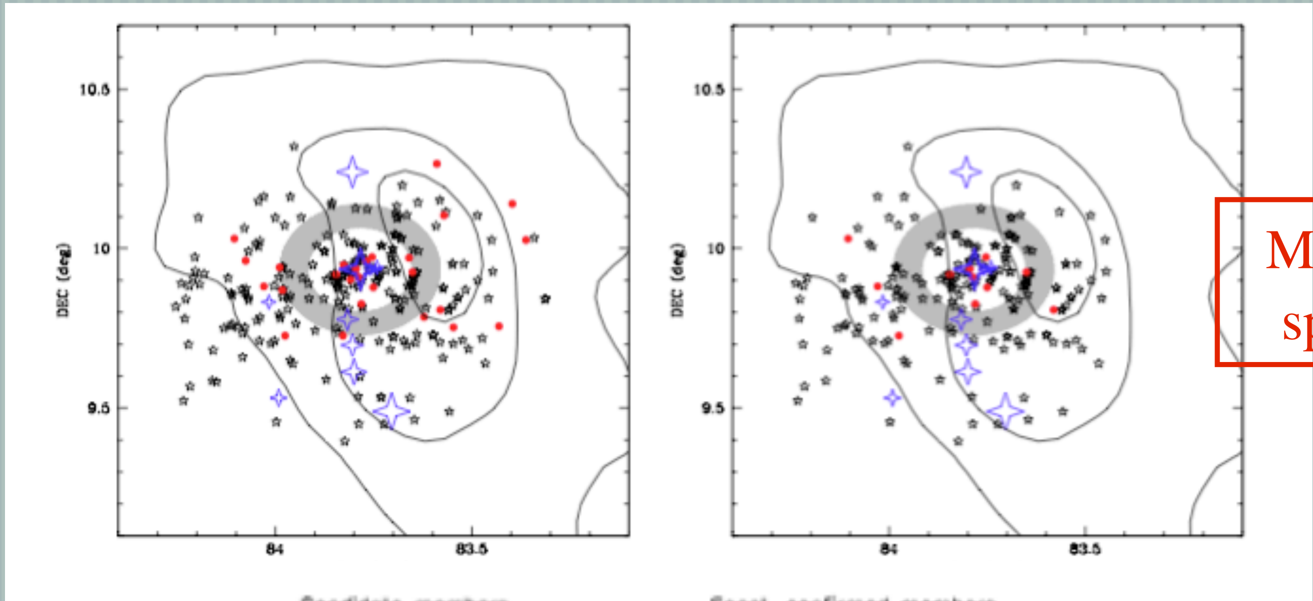
M_A=0.37 M_{sol}

M_C=0.063 M_{sol}

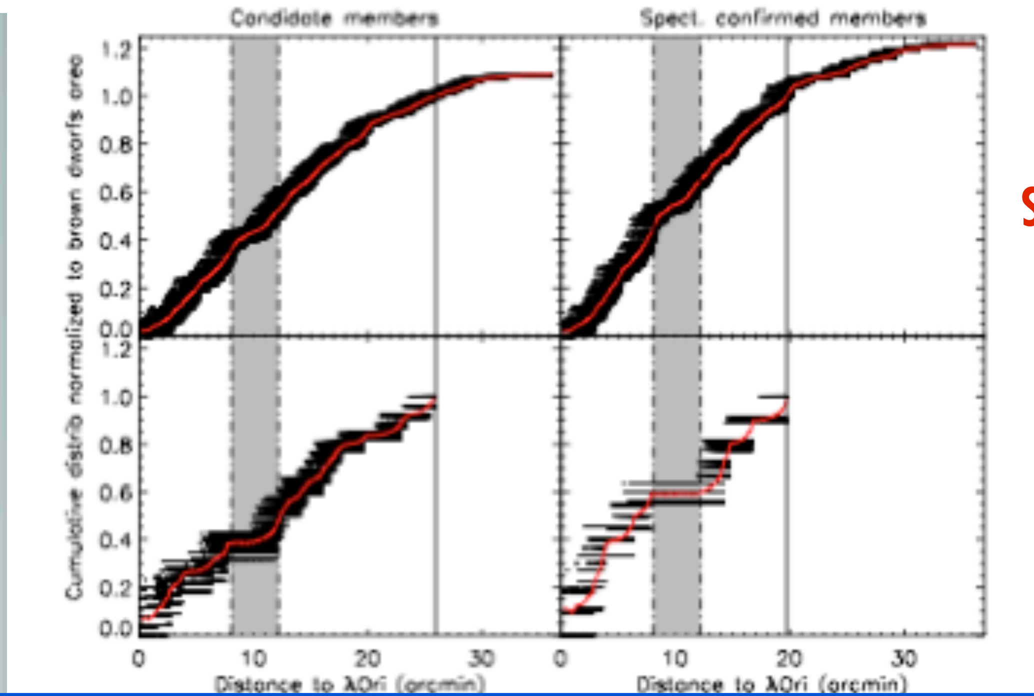
M_{disk} around M dwarfs not massive enough to form BD's !

Bayo et al. '11: radial dist'n of stars and BDs in Lambda-Ori

★ stars
* BD's



Members confirmed spectroscopically !

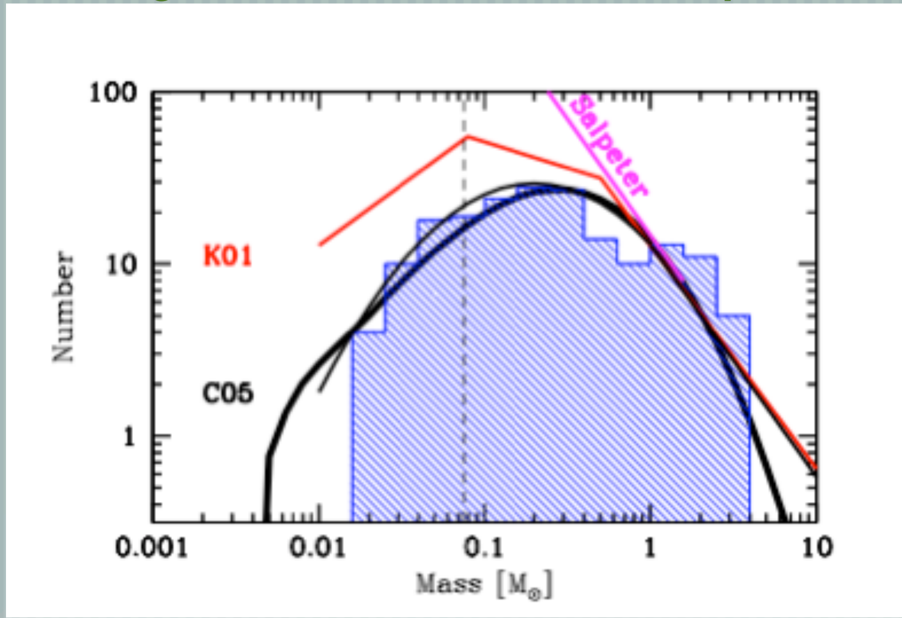


stars

BD's

No difference in the distributions of stellar and substellar members

Bate '11: fragmentation of a cloud w/ radiatove feedback



L=0.4 pc ; n ~ 10^5 pc^{-3} ; M=14

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

Falgarone et al. '00

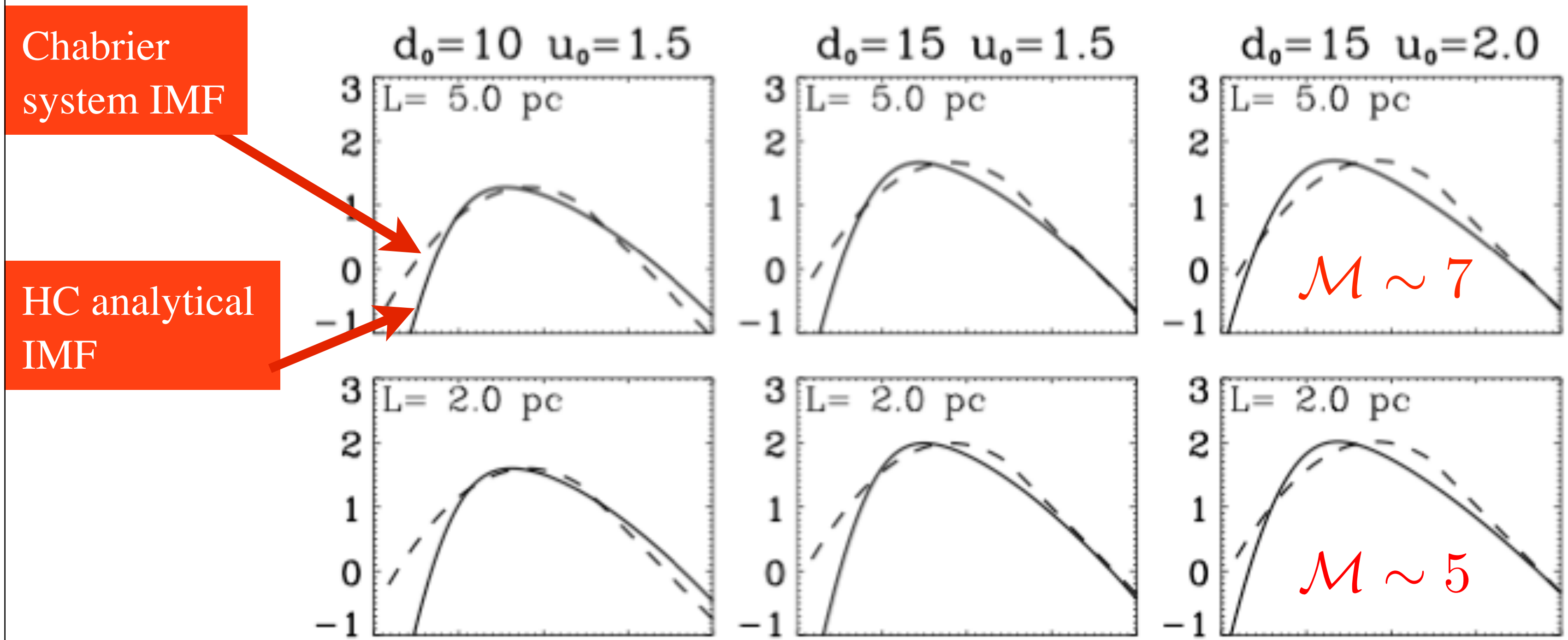
~ 50x denser and 5x more turbulent than (observed) Larson's relations ! => <u>overfavor dynamical int'ns</u> !!

idem NGC1333 : N_{*+BD} (simus) = 191 Msol N_{*+BD} (observed) ~ 50 M_{sol} (Scholz et al. '11)

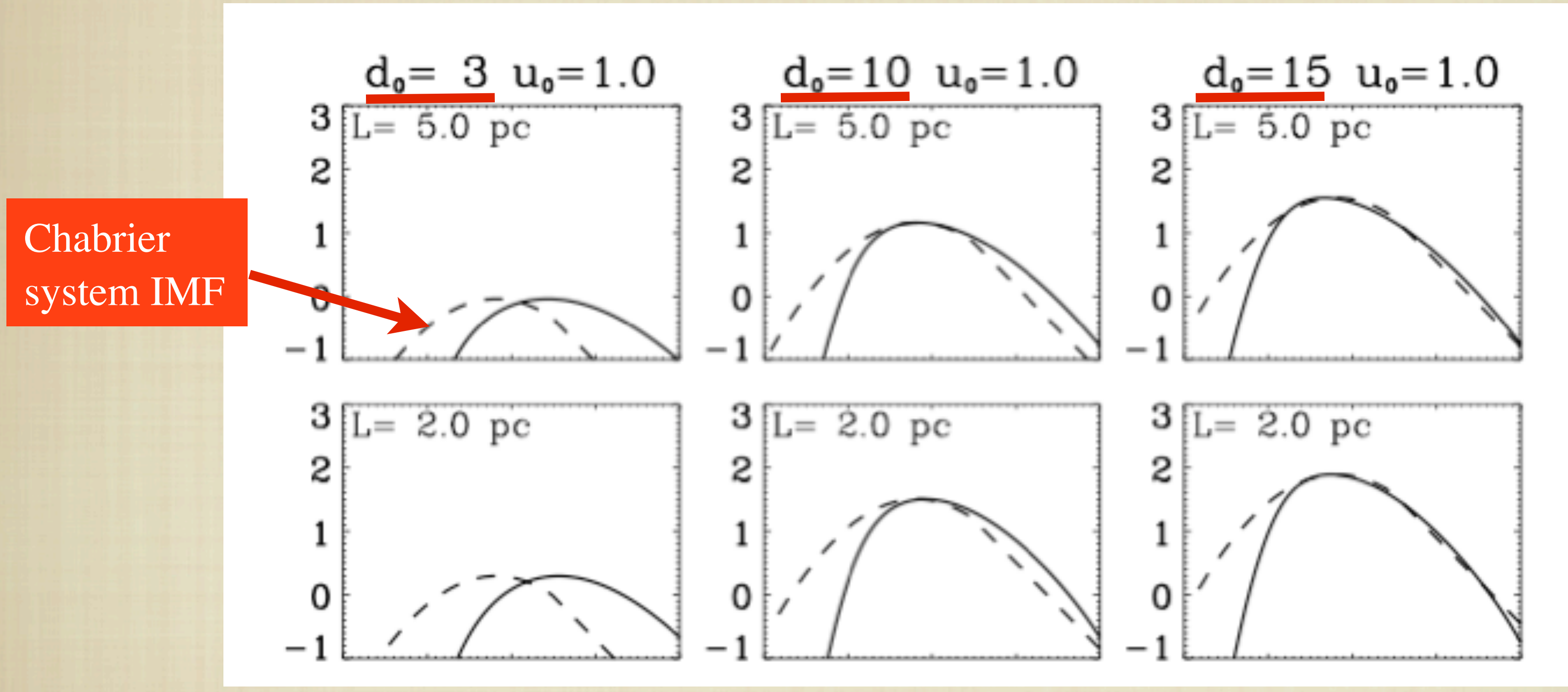
+ no turbulent compressive mode (Federath et al; Hennebelle & Chabrier '09)
uniform initial density (Girichidis et al.)
no B

Dependence upon I.C. (density, Mach,...) ? (Bonnell, Clarke, Bonnell '06: IMF peak depends upon I.C. ; Krumholtz et al.)
How can accretion/ejection explain «universality» of the IMF ?
What about more realistic I.C ?

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



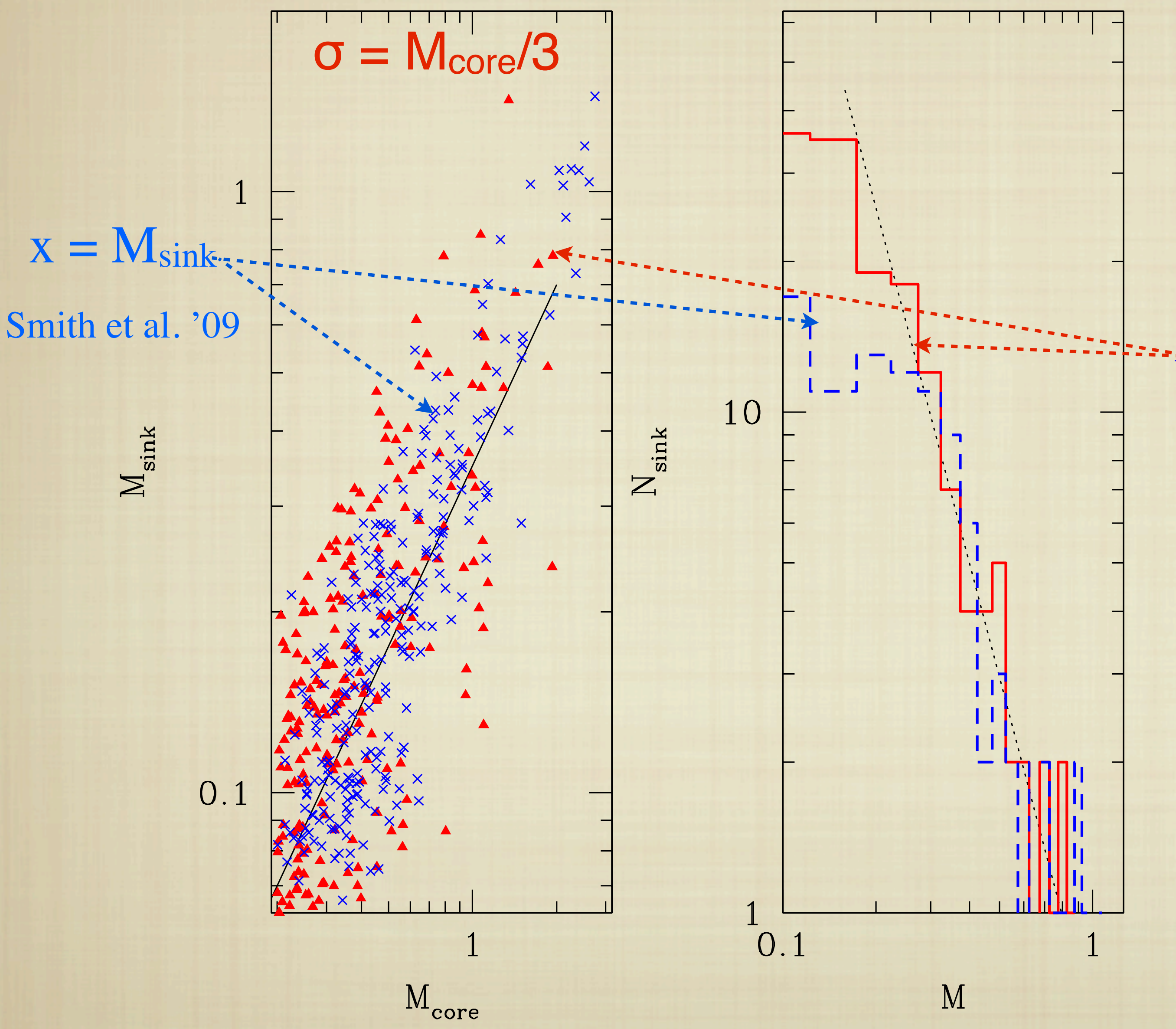
Hennebelle & Chabrier ’09



Chabrier system IMF
d₀= 3 u₀=1.0
d₀=10 u₀=1.0
d₀=15 u₀=1.0
L= 5.0 pc
L= 2.0 pc
3
2
1
0
−1

Smith et al. 2009: frag'n of a MC -> bound cores

-> sink particles (proxy of stellar masses)



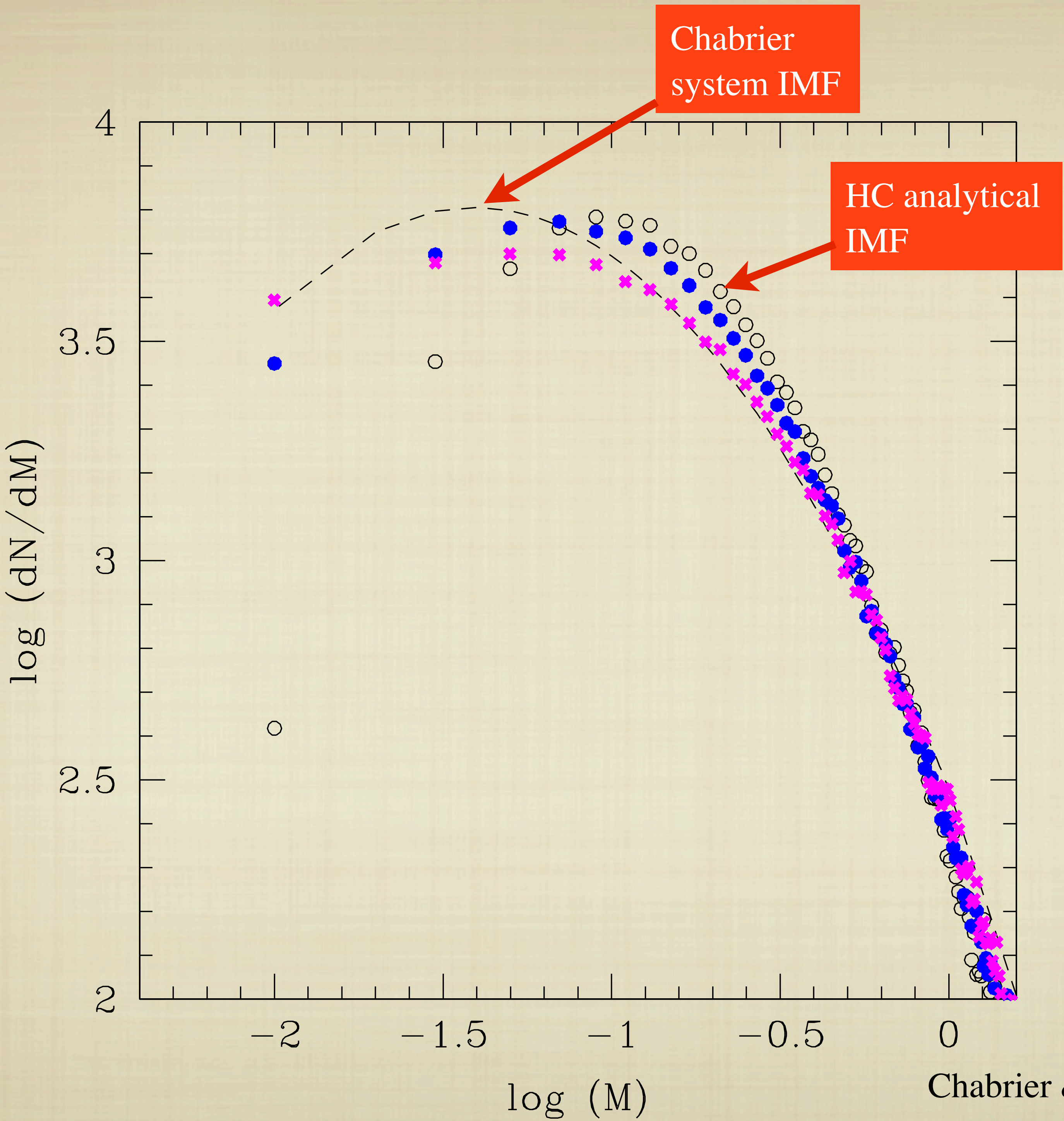
$p(M_{core}) \propto m^{-2.35}$

$p(M_{sink}) \propto \exp\left[-(x-\mu)^2/2\sigma^2\right]$

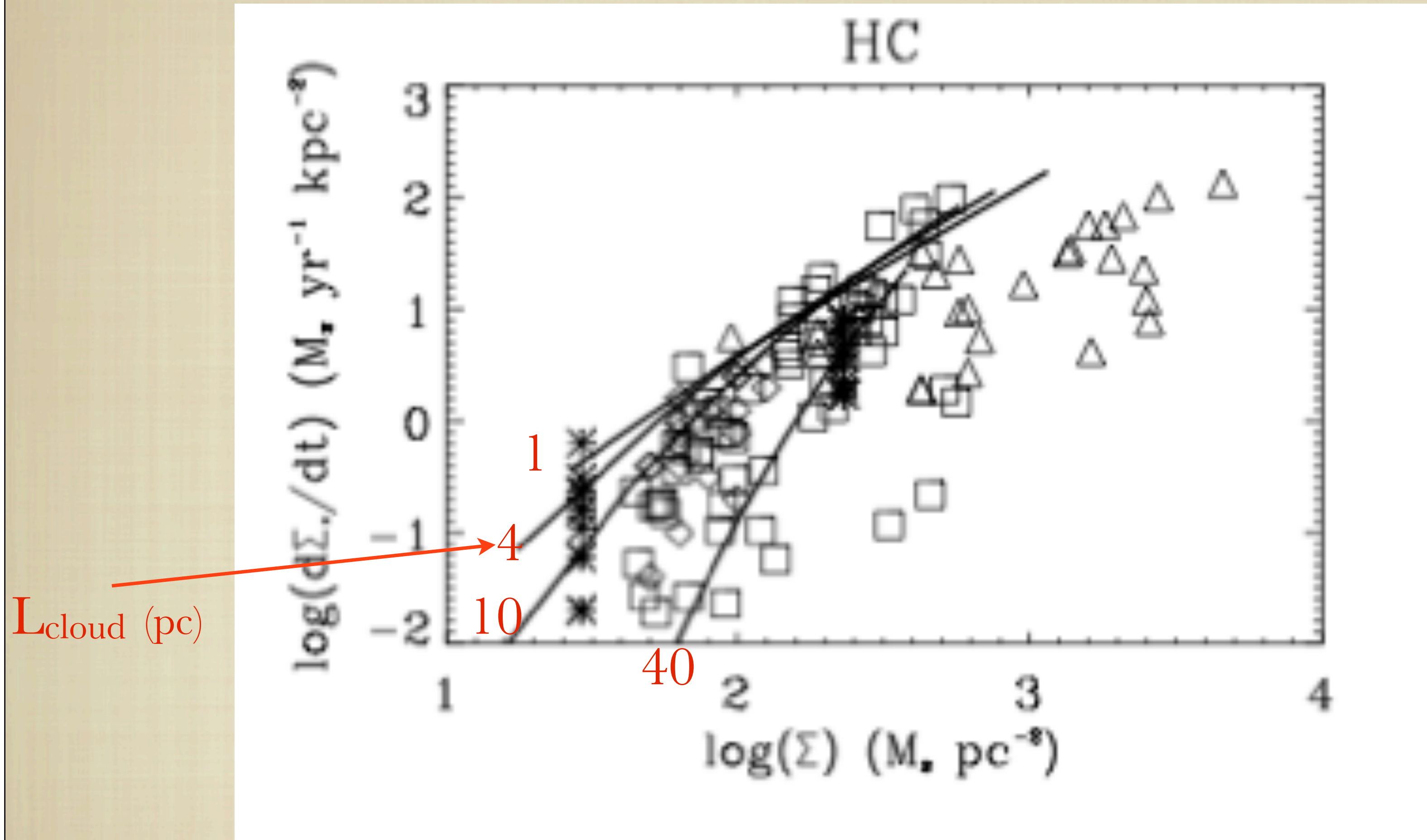
$\mu = \epsilon \cdot M_{core}$

$\sigma(M) = \langle M\rangle^2 - \langle M^2\rangle$

Chabrier & Hennebelle, 2010.



Chabrier & Hennebelle '10



* Lada et al. ’10

□ Evans et al. ’09
+ Heiderman et al. ’10

Hennebelle & Chabrier 2011

Position of the peak of the IMF

$$M_{peak} \propto M_J \times \frac{1}{(1+b\,\mathcal{M}^2)^{3/4}} \propto \rho^{-1/2}\,\mathcal{M}^{-3/2}$$

$$\langle V_{rms} \rangle \propto L^{\eta} \qquad \rho \propto L^{-a}$$

Mach   Jeans

$$M_{peak} \sim L^{-\frac{3}{2}\eta+\frac{a}{2}} \sim M_c^{\frac{1}{3-a}(-\frac{3}{2}\eta+\frac{a}{2})}$$

$$\eta \approx 0.4 \qquad a \approx 0.7 - 1.0$$

$$\Rightarrow M_{peak} \sim M_c^{0.1-0.2}$$

Brown dwarf formation

- Disk fragmentation
- Accretion - ejection

why not ? but
- not supported - so far - by observations
- IMF should vary appreciably w/ environment (however see Bate '09)
- need more realistic intial/physical conditions

- Gravo-turbulent fragmentation

still a (analytical) theory....
- need observations of isolated protoBD's
  (**VeLLO L1148–IRS ?** Kauffmann et al. '11; **IRAS 16253-2429** see poster by Wiseman et al.)
- IMF (at least partly) determined by the prestellar Core MF (André et al.,...)

Young BDs vs young star properties

see e.g. Luhman et al. '07

- same radial velocity dispersion
- same spatial distribution in young clusters
- [BDs as wide companions to stars] = [BDs/stars free floating]

  consistent with random choice from the same IMF
- wide binary BDs
- accretion + disk signature (large blue/UV excess, large asymetric emission lines, Hα

  => natural extension of CTTs
- disk fraction around BDs ~40-60% similar to stars
- timescales for accretion around BDs ~similar to stars ~1-10 Myrs
- presence of outflows

BD and star formation : common mechanism

ejection, disk frag'n, photoevaporation might play some rome but are not essential in making it possible for BDs to form