From density fluctuations to prestellar cores: assembling the stellar mass

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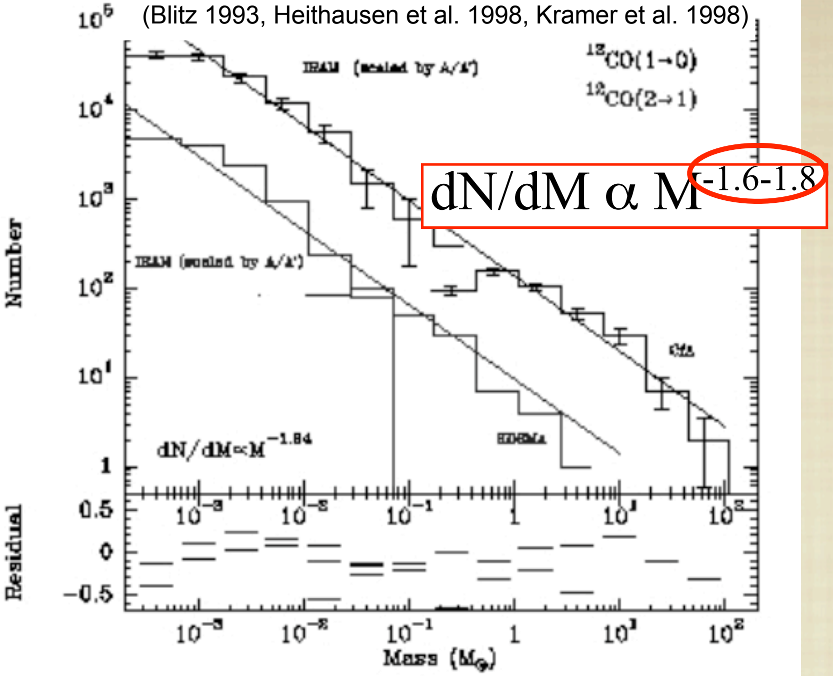
A **strongly** biased point of view !!

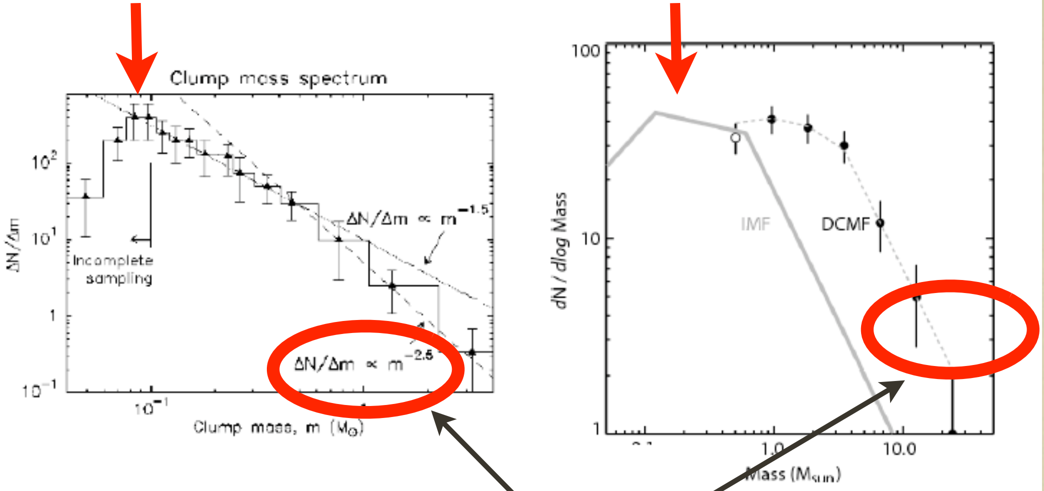
Universal Mass Spectrum of the CO clumps

(Blitz 1993, Heithausen et al. 1998, Kramer et al. 1998)



Prestellar core mass function

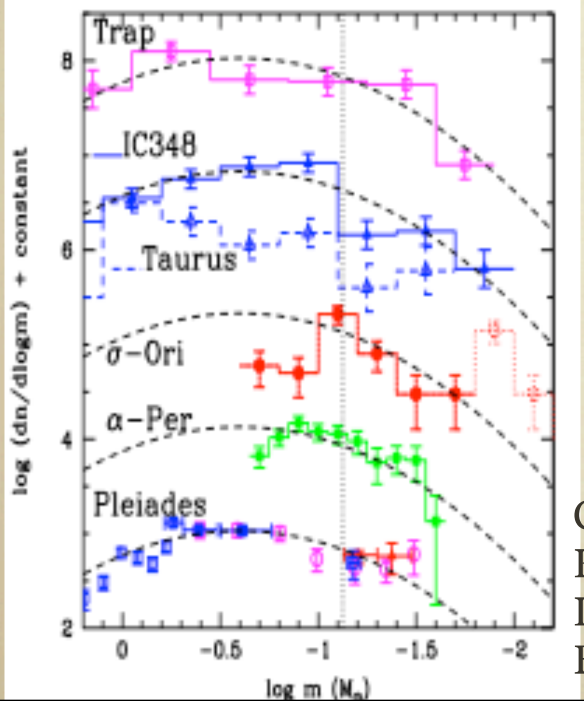
(Motte et al. 1998, Alves et al. 2007 , Johnstone et al. 2002)



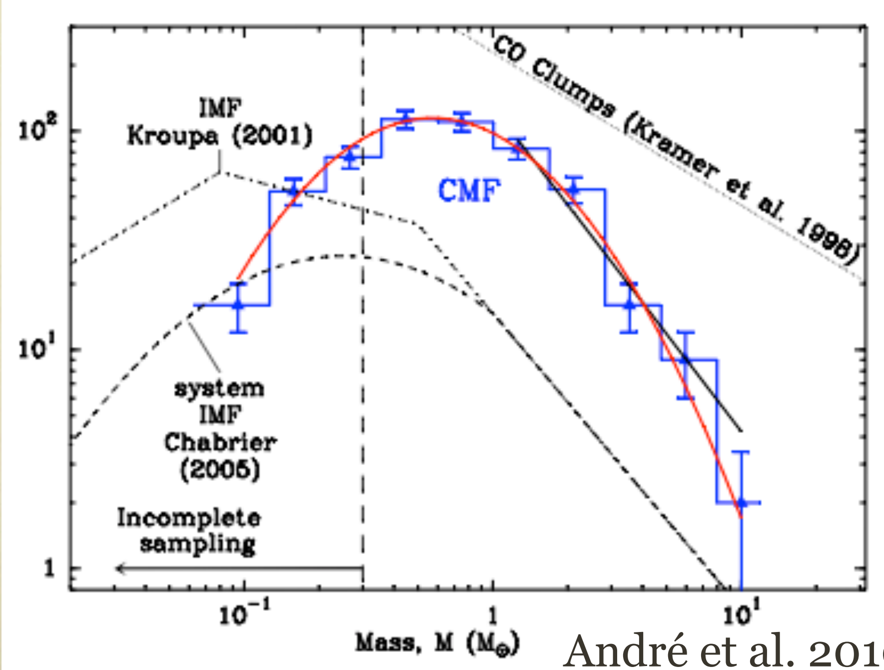
Motte et al. 1998

Alves et al. 2007

$$dN/dM \propto M^{-2.35}$$



Chabrier 2003, 2005
Kroupa 2002
Luhman et al 07 (PPV)
Bastian et al. 2010



André et al. 2010

MAIN SCENARIOS

- **Competitive accretion**
  (Bonnell, Bate and collaborators)
- **gravo-turbulent collapse**
  (Padoan & Nordlund; Hennebelle & Chabrier)
- (**stopped acretion**)
  (S. Basu; Ph. Meyers)

Competitive accretion

$$\dot{M}_\star = \pi \rho V_{rel} R_{acc}^2$$

Case 1: potential dominated by the gas

$$n_\star \propto R^{-2}$$

$$R_{acc} = R_{tide} \simeq 0.5 (\frac{M_\star}{M_{<R}})^{1/3} R$$

$$V_{rel} = V_{infall} = \sqrt{GM(R)/R}$$

$$dN = n_\star(R) \times 4\pi R^2 dR \Rightarrow \boxed{dN/dM \propto M^{-1.5}}$$

Case 2: potential dominated by the stars

$$n_\star \propto R^{-3/2}$$

$$R_{acc} = R_{BH} \propto M_\star / V_{rel}^2$$

$$V_{rel} = V_{infall} \propto R^{-1/2}$$

$$\boxed{\Rightarrow dN/dM \propto M^{-2}}$$

Neither turbulence nor Jeans mass enter explicitely !

Issues

- *Difficult to obtain the proper (Salpeter) exponent*
- $\dot{M}_{obs} \gtrsim 3 \times \dot{M}_{BH}$ => *too long accretion time at the class-O, class-I stage compared w/ observations (eg André et al. '07, '09)*
- $t_{core} \ll t_{coll}$ => *cores are likely to evolve individually (eg André et al. '07, '09)*
- *how to explain the invariance of the IMF (and its peak) ? (see however Bate '09 for the peak)*
- what about non-clustered SRF (too small gas density) ?

DIFFICULT TO EXPLAIN THE BULK (~ <M_{JEANS}>) OF THE IMF.

MIGHT APPLY TO MASSIVE STAR FORM'N

Extending Press-Schechter (1974) statistical approach to the domain of (turbulence driven) star formation

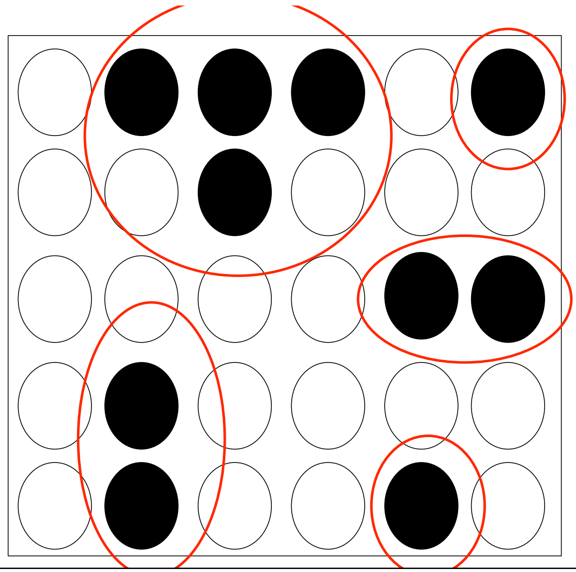
Principles of Press-Schechter formalism (used in cosmology to predict the mass spectrum of primordial collapsing structures (galaxies)). Very successful !

- consider a density field, $\delta(\vec{x})$, of density fluctuations, $\delta = \dfrac{\rho - \bar{\rho}}{\bar{\rho}}$,
  w/ statistical properties, $\mathcal{P}(\delta)$, characterized by its power spectrum, $|\tilde{\delta_k}|^2 \propto k^n$

  smoothed at scale *R*

- setup a density threshold, δ_c, to determine which perturbations should be considered (collapse time < Hubble time in cosmology)

- sum over all the corresponding fluctuations



$$\boxed{\frac{dN}{dM} \propto M^{\frac{n}{6}-\frac{3}{2}} \times \exp\left(-\frac{\delta_c^2}{2\,\sigma^2}\right)}$$

PDF of compressible turbulence

PDF of density field

(Kritsuk et al. 2007)

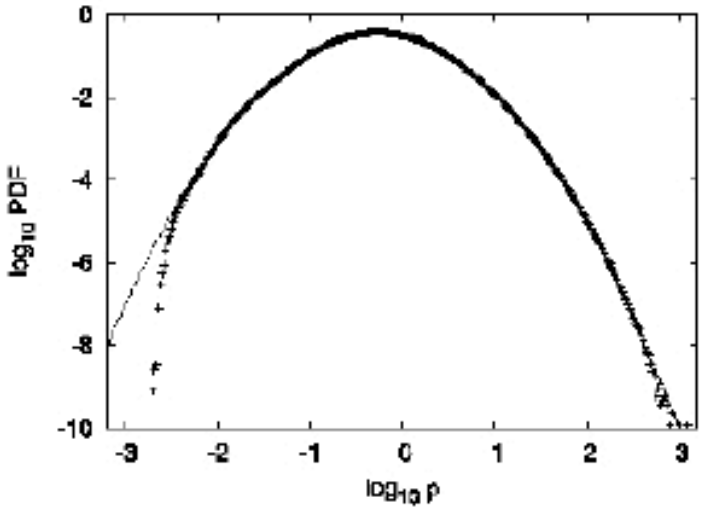


Fig. 3.—Probability density function for the gas density and the best-fit lognormal approximation. Note the excellent fit quality over eight decades in the probability along the high-density wing of the PDF. The sample size is 2×10^{11}. [*See the electronic edition of the Journal for a color version of this figure.*]

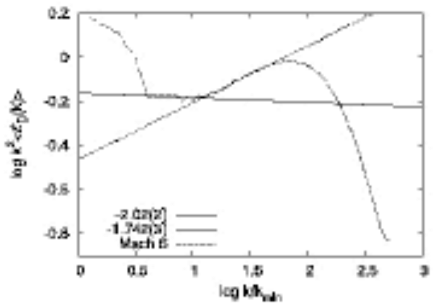
A lognormal distribution:

$$P(\delta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\delta + \sigma^2/2)^2}{2\sigma^2} \right)$$

$$\delta = \ln(\rho/\bar{\rho}), \quad \boxed{\sigma^2 \approx \ln\left(1 + 0.25 \times M^2\right)}$$

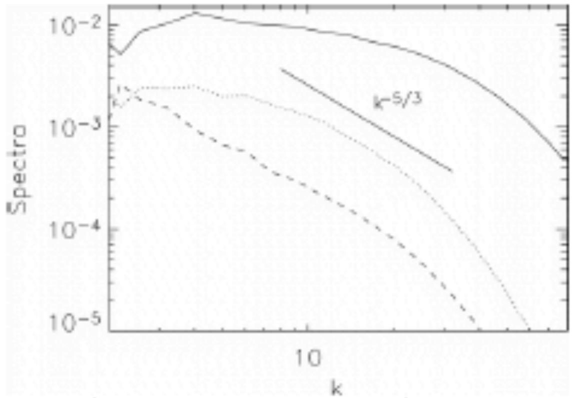
$$(\mathcal{M} = V_{rms}/C_s)$$

Obs: Kainulainen, J, Beuther, H et al. 2009, A&A, 508L, 35



Velocity power spectrum

Index between Kolmogorov (n=11/3) and Burgers (n=4). n of the order of 1.95



Logarithm of density power spectrum

(Beresnyak et al. 2005, Kritsuk 2007, Federath et al. 2008)

Index close to Kolmogorov

Kolmogorov (n=3.66) < **n ~ 3.8** < Burgers (n=4)

Step 1: we ignore gravity

structures due to turbulence-induced fluct'ns ***(scale free)***

Clumps are defined as unbound structures having a density above some **constant** density threshold $\delta_c = \ln(\rho_c / \rho)$

$$\frac{dN}{dM} \propto M^{-(2-\frac{n'-3}{3})} \times \exp\left(-\left(\frac{\delta_c - \frac{\sigma^2}{2}}{2\sigma^2}\right)^2\right)$$

power law

gaussian truncation at large scale
$(R \to L_i \Rightarrow \sigma \to 0)$

$$\boxed{n = 3.8 \Rightarrow \frac{dN}{dM} \propto M^{-1.7}}$$

Compatible with the observed CO clump distribution

Step 2: we include gravity

Virial theorem defines collapsing structures:

$$2(E_{therm} + E_{cin}) + E_{mag} \leq -E_{pot}$$

$$E_{therm} \propto kT, \;\; E_{cin} \propto \langle V_{rms} \rangle^2, \;\; E_{mag} \propto V_A^2 \qquad (\mathcal{M}_A \sim cte \Rightarrow V_A^2 \propto \langle V_{rms}^2 \rangle)$$

(Basu 00)

$$(\; \langle V_{rms} \rangle = V_0 \times (\frac{R}{1\,\mathrm{pc}})^\eta \;)$$

<u>*Condition for collapsing structures*</u> :

$$\boxed{M > M_J^{eff} = \frac{a_J^{2/3}}{G}(C_s^{eff})^2 R}$$

Now depends on the scale ***R***

$$(C_s^{eff})^2 = C_s^2 + \frac{\langle V_{rms}^2 \rangle}{3} + \frac{V_A^2}{6}$$

$$\boxed{\frac{dN}{dM} \propto \frac{1}{R^6}\frac{M}{R^3}^{-\frac{3}{2}-\frac{1}{2\sigma^2}\ln(M/R^3)} \times \exp(-\frac{\sigma^2}{8})}$$

Combination of *power law* and *lognormal* (dominant at small and large scales)

$$\boxed{M = R(1+\underline{\mathcal{M}_\star^2} R^{2\eta})} \qquad \mathcal{M}_\star = \frac{1}{\sqrt{3}}\frac{V_0}{C_s}\left(\frac{\lambda_J}{1\,\mathrm{pc}}\right)^\eta \quad (\mathcal{M}_\star \sim 1-2)$$

(see Schmidt et al. 2010)

$\mathcal{M}_\star$ = Mach number at the *Jeans scale* due to turbulent support
(transition thermal to turbulent support ($\mathcal{M}_\star R^\eta > 1$) around 1 M_J)

$$\mathcal{M}_\star \approx 0, \frac{dN}{d\log M} \propto M^{-3}$$

$$\mathcal{M}_\star \geq 1, \frac{dN}{d\log M} \propto M^{-\frac{n+1}{2n-4}} \propto M^{-x}$$

$$\boxed{x = \frac{n+1}{2n-4}}$$

For n=3.8 dN/dM ~ $M^{-2.33}$

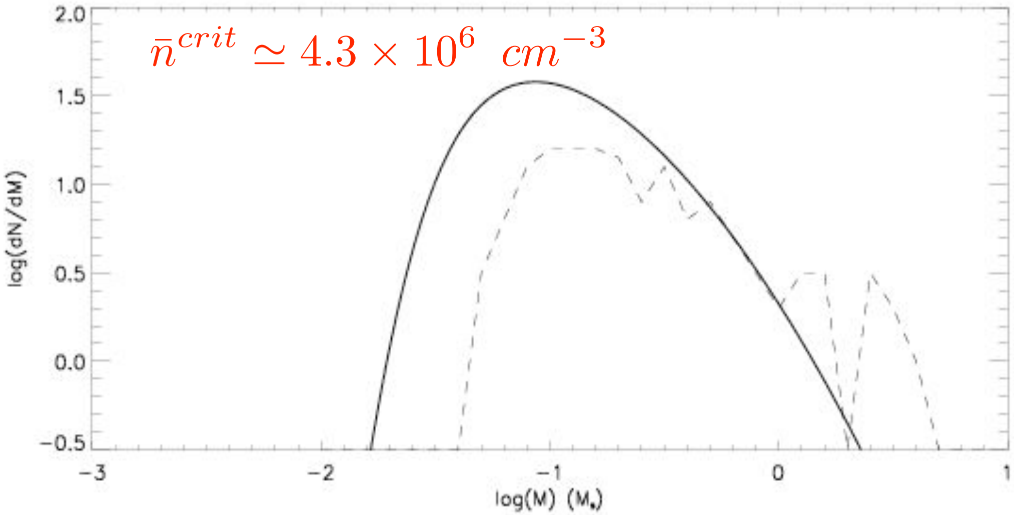
$$\boxed{\eta = \frac{n-3}{2}}$$

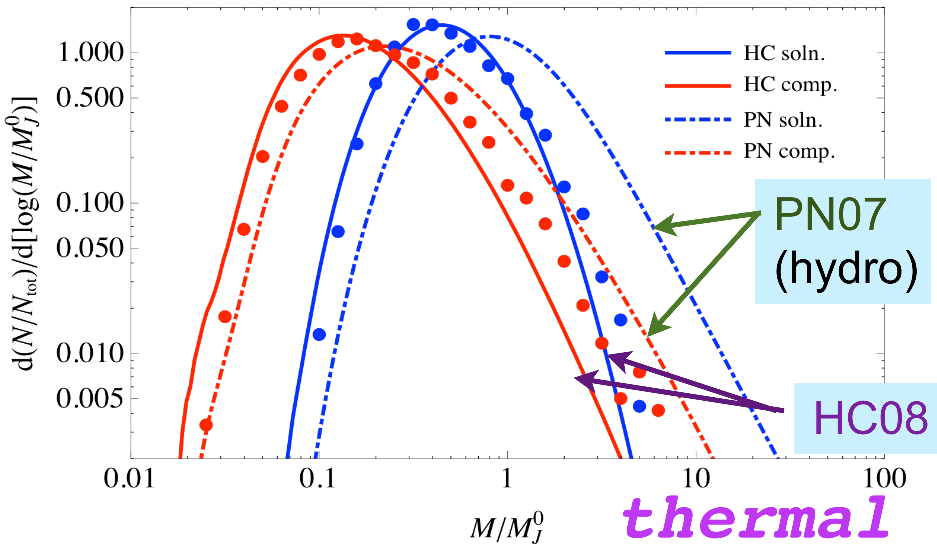
$n \simeq 3.8 \Rightarrow \eta = 0.4$

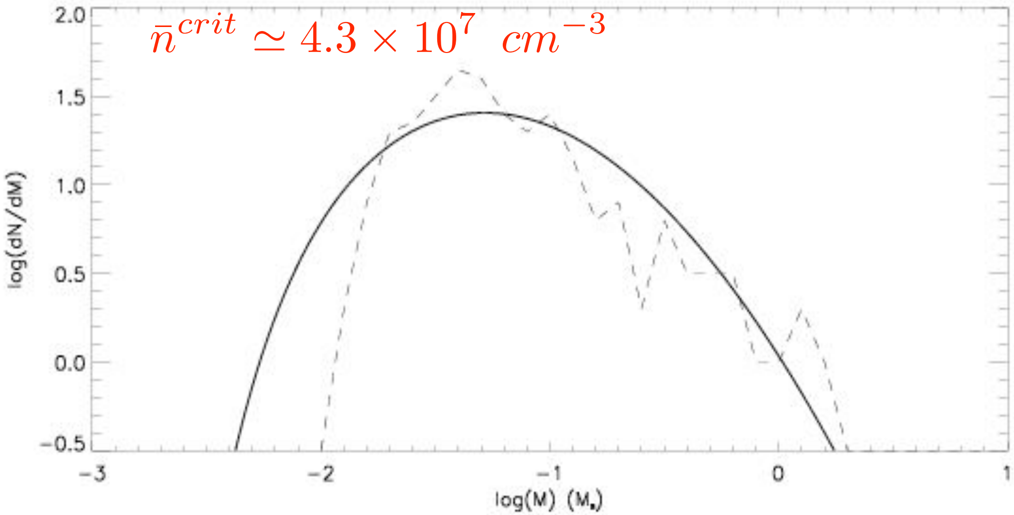
Comparisons with numerical simulations

Jappsen et al. '05

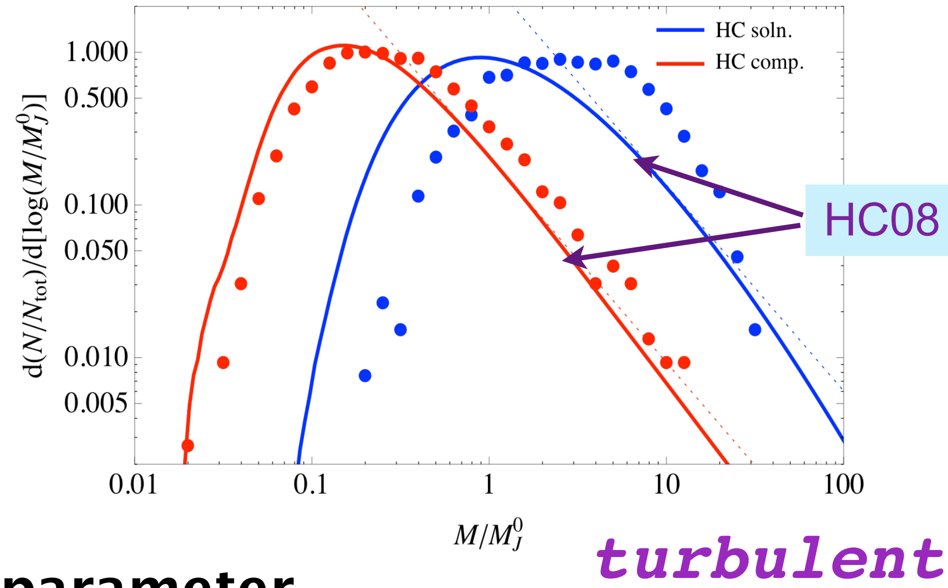
Schmidt et al. '10





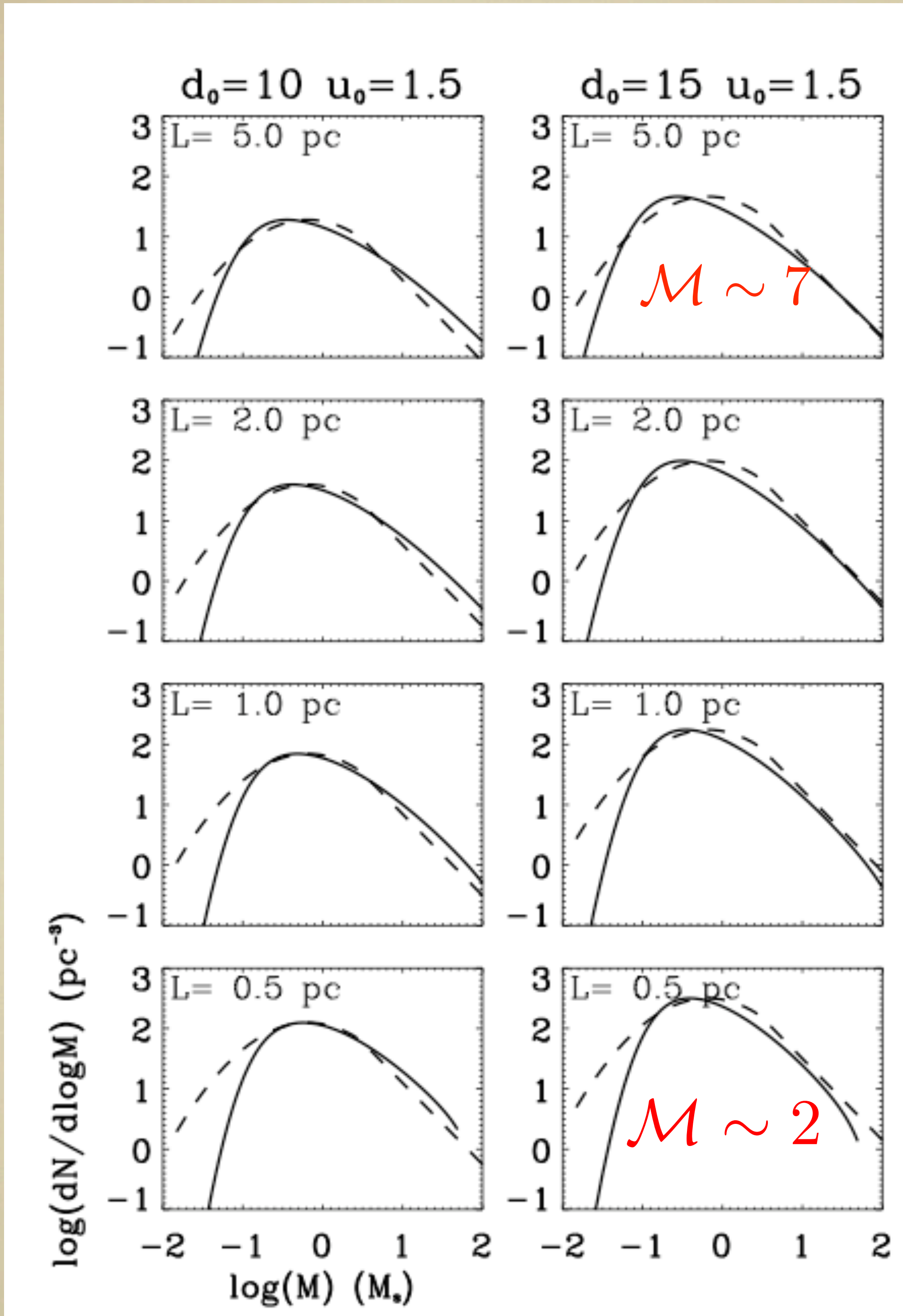


Hennebelle & Chabrier, '09



<u>No free parameter</u>

Comparisons with observations



$$d_0 = \left(\frac{\rho}{10^3\,\mathrm{cm}^{-3}}\right)\left(\frac{L}{1\,\mathrm{pc}}\right)^{0.7}$$

$$u_0 = \left(\frac{V_{rms}}{0.8\,\mathrm{kms}^{-1}}\right)\left(\frac{L}{1\,\mathrm{pc}}\right)^{-0.5}$$

suggests that prestellar cores form in regions ~ 3-5 times denser than predicted by the standard Larson relations

Hennebelle & Chabrier, '09

Position of the peak of the IMF

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

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

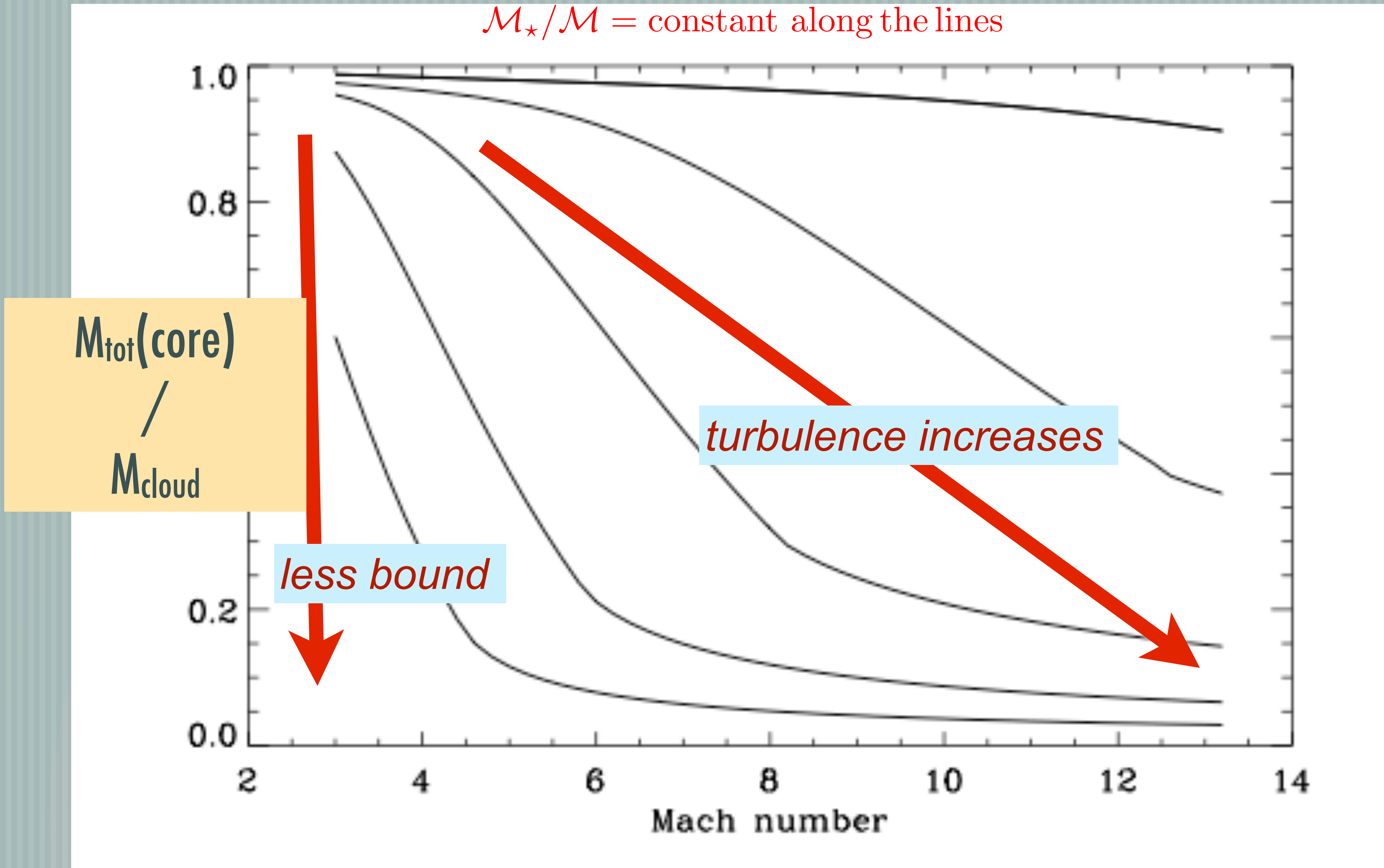
Mach   Jeans

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

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

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

Global effect of turbulence on star formation : negative !



Pros

- No adjustable parameter. IMF (and Larson's laws) entirely determined by turbulence power spectrum index n -> «universality» of the IMF

- Same theory explains unbound CO clumps (constant density threshold) and bound prestellar cores (scale dependence for gravitational collapse from virial condition)

- Provides a «simple» explanation for the invariance of the peak.

- Turbulent support included. Yields Salpeter slope for $M \gtrsim M_J$

- Direct counting of the fluctuations (including the ones embedded into larger ones) (see HC08)

$$M_{tot}(R) = L^3 \int_{\delta_c(R)}^{\infty} \bar{\rho}\, e^{\delta}\, \mathcal{P}_R(\delta)\, d\delta$$

Most massive star : $M_\star^{max} = M_{clump} - M_{tot}(R)$

indeed accretes from the limits of the clump <-> «competitive accretion» model

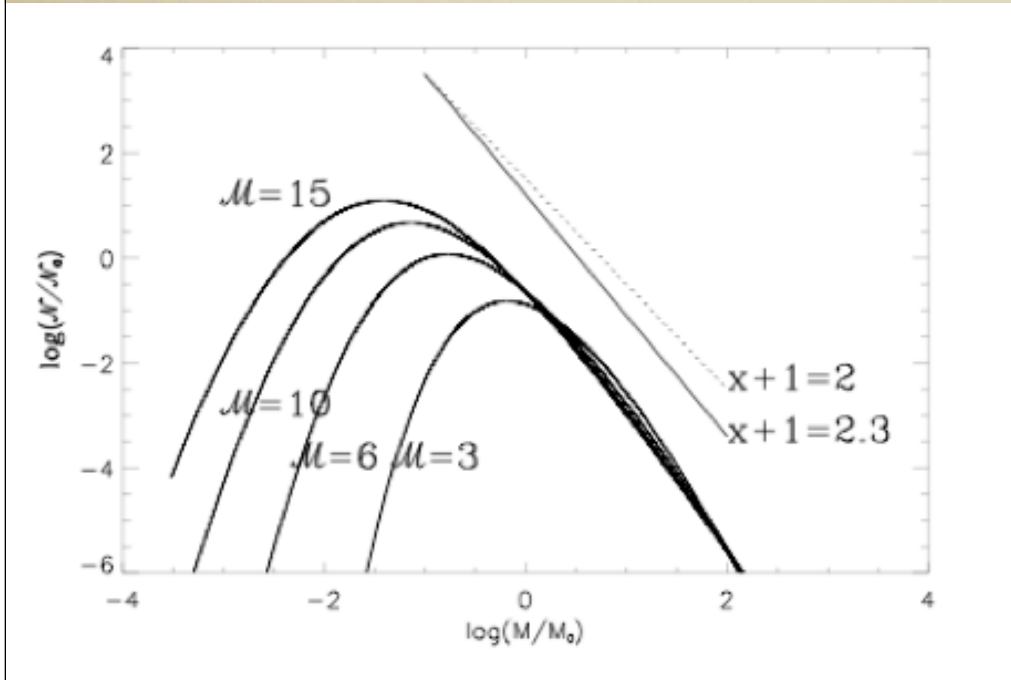
Cons

- Possibility that massive turbulent Jeans Mass fragment into many pieces ?
However, unlikely due to radiative feedback (eg Bate 2009, Offner et al. 2009) and B (eg Machida et al. 2005, Hennebelle & Teyssier 2008)

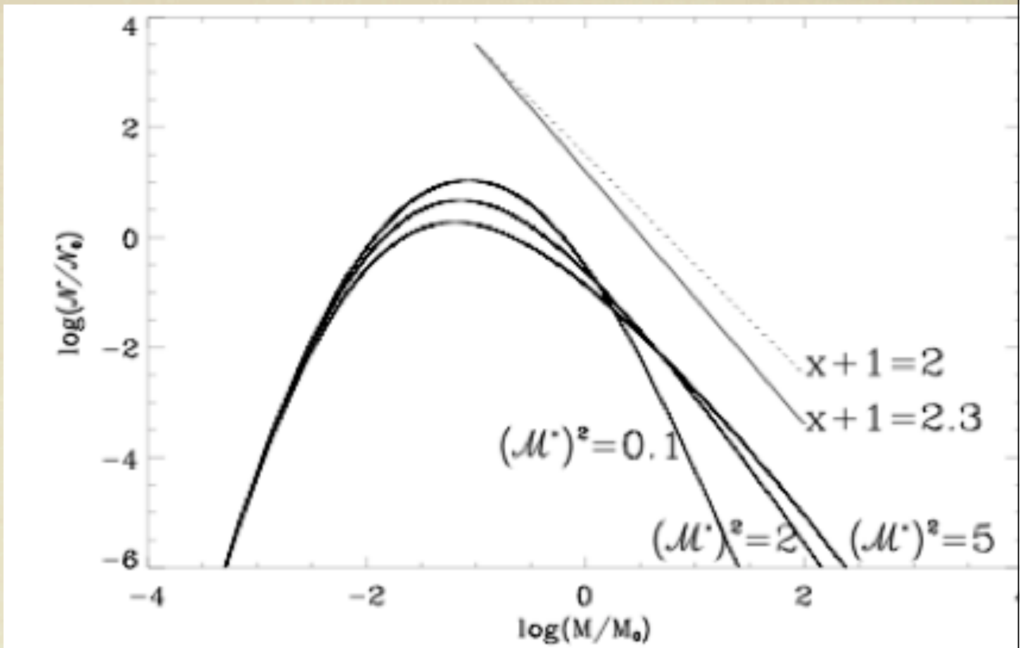
- No time dependence (under work !)

When do we expect variations of the IMF ?

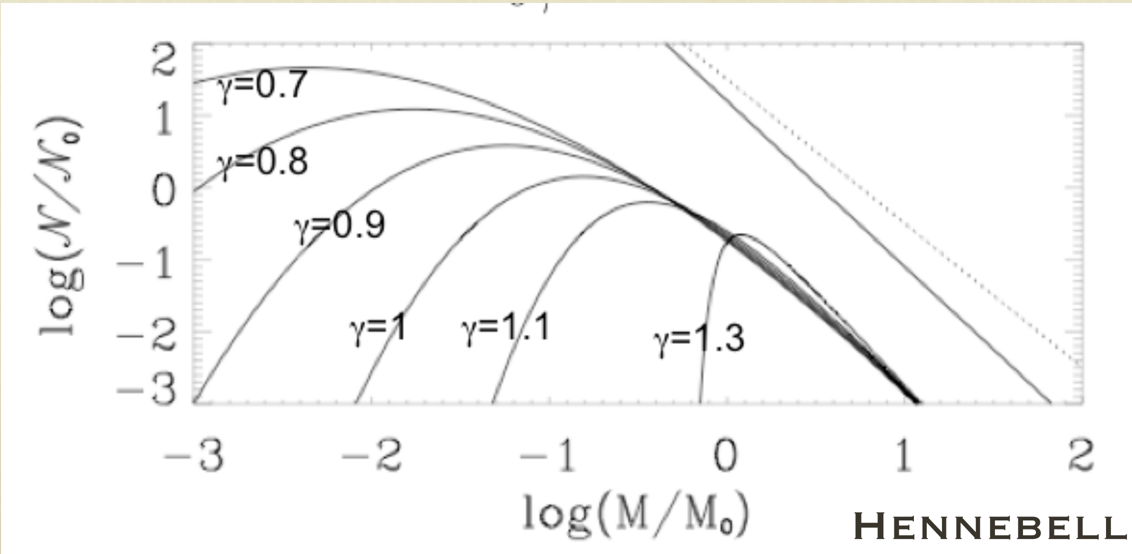
Global Mach number $\mathcal{M}$



Mach number at Jeans scale $\mathcal{M}_*$



Thermodynamics of the gas



Hennebelle & Chabrier 08, 09

CMF to IMF (1)

Clark et al. 2007:

$M_J \sim C_s^3 \varrho^{-1/2}$, $t_{ff} \sim \varrho^{-1/2} \Rightarrow t_{ff} \sim M_J$

$\Rightarrow$ high-mass stars collapse less rapidly

$\Rightarrow$ CMF must be shallower than IMF (Salpeter)

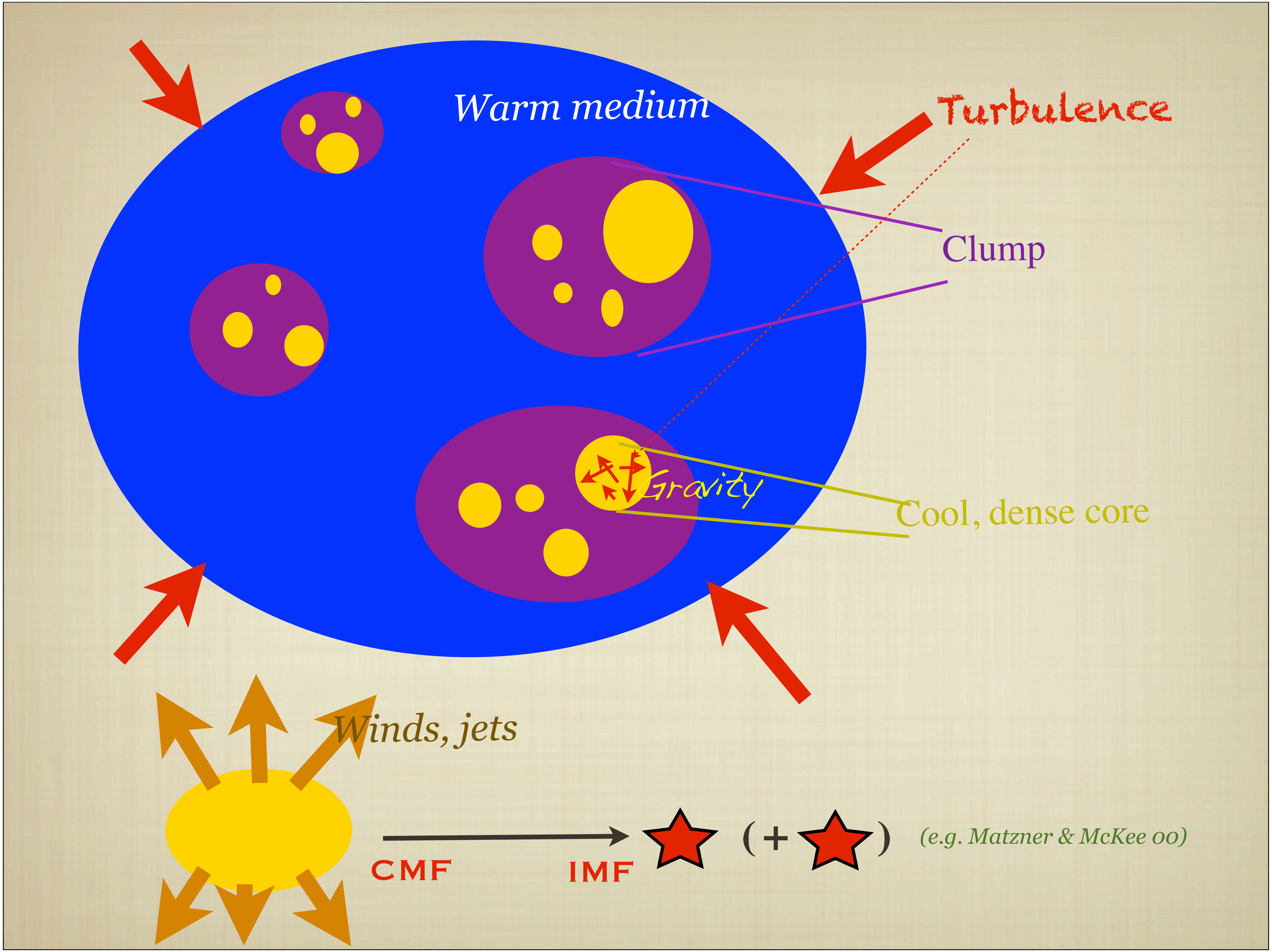
true if only thermal support !

But if turbulent support (see HC09)

$M_J \sim V_{rms}^3 \varrho^{-1/2}$, $V_{rms} \sim R^\eta \sim R^{1/2}$, $t_{ff} \sim \varrho^{-1/2}$

$\Rightarrow \mathbf{t_{ff} \sim M_J^{1/4}}$

$\varrho \propto M/R^3 \propto M^{2\eta-2/2\eta+1} \sim M^{-1/2}$


Warm medium
Turbulence
Clump
Gravity
Cool, dense core
Winds, jets
CMF
IMF
(+)
(e.g. Matzner & McKee 00)

How do prestellar cores assemble their mass ?

- Large scale turbulence sets up initial density fluct'ns (mass seeds) (idem PN)

  Responsible for the «universality» of the IMF. Possible var'ns w/ $\mathcal{M}$, $\mathcal{M}_\star$, γ

- peak of the IMF nearly universal because of <u>compensating scale dependences between Mach and Jeans</u> => peak position depends very weakly on cloud properties (for *Larson clouds*)

- combination of a <u>**power-law**</u> + <u>**lognormal**</u> contributions (turbulence-gravity)

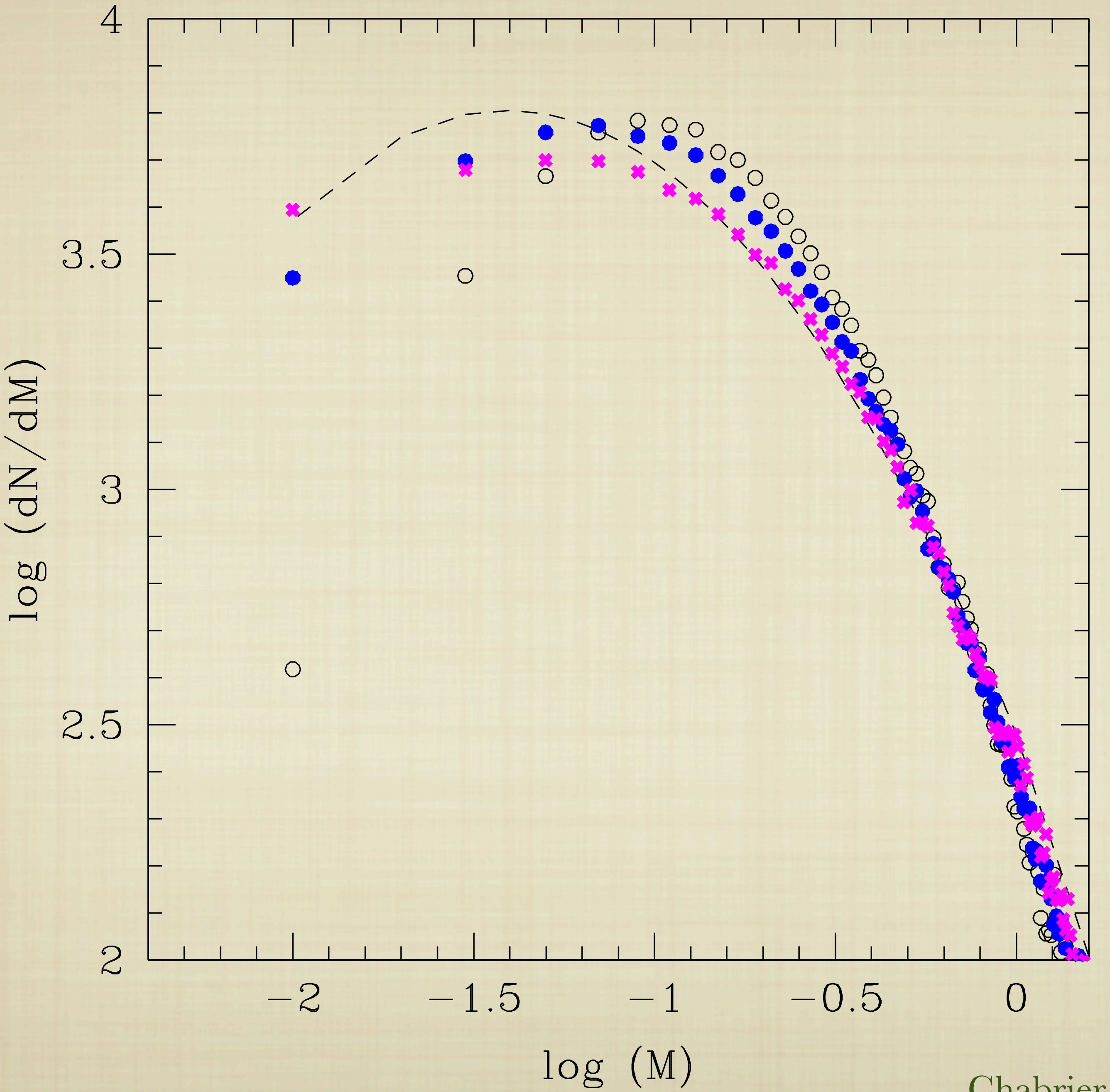
- <u>dual role of turbulence</u>:

  - <u>promotes</u> the f'n of overdense regions -> gravitational instability (BDs) and provides non-thermal support for $M_* \gtrsim M_J$ (<u>determines the Salpeter slope)</u>
  - globally ***inhibates*** star formation

- Star formation occurs in **denser (~5) regions than the Larson rel'ns** (triggering mech. ?)

- IMF seems to be strongly correlated with CMF

  stellar mass built primarily from its parent core ($\sigma = M_{core}/3$), i.e. from its <u>local environment</u> (parent cloud conditions rather than gas-to-star conversion processes) *(Chabrier & Hennebelle 2010, from simulations by Smith et al. 09)*



Chabrier & Hennebelle, 2010

Differences between Padoan & Nordlund (2002) and Hennebelle & Chabrier (2008)

<u>PN 2002</u>	<u>HC 2008</u>
-Assume $N(L) \propto L^{-3}$	-direct counting of the fluctuations
-Write magnetized shock condition (**assuming** $B \propto \rho$) =>determine the Salpeter slope, x	-No need to specify shock conditions
-no turbulent support	-turbulent support included ⇒determine the Salpeter slope, x
-predict different slopes in hydro and mhd cases	-x does not change with magnetic field
-obtain x=3/(6-n)	-obtain x=(n+1)/(2n-4)
CO clumps *a priori* follow Salpeter	CO clumps as in the observations