Is the stellar IMF universal ?

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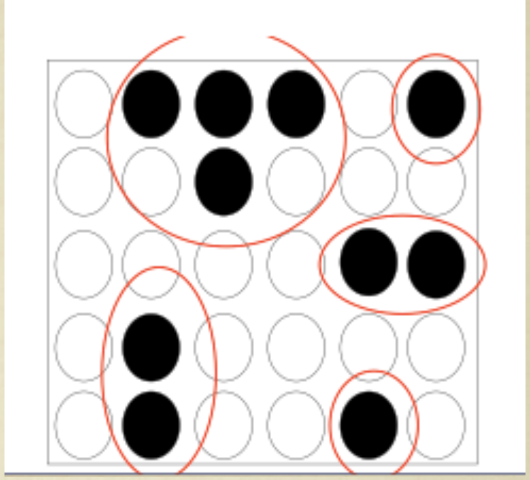
Star formation accross space and time, november 2014

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, $\delta = \dfrac{\rho - \bar{\rho}}{\bar{\rho}}$,

$$\mathcal{P}(\delta_M)\,\mathrm{d}\delta_M = \frac{1}{\sqrt{2\pi}\,\sigma_M}\exp\left[-\frac{\delta_M^2}{2\sigma_M^2}\right]\mathrm{d}\delta_M$$

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

$$\mathcal{P}(\delta_M > \delta_\mathrm{c}) = \frac{1}{\sqrt{2\pi}\,\sigma_M}\int_{\delta_\mathrm{c}}^{\infty}\exp\left[-\frac{\delta_M^2}{2\sigma_M^2}\right]\mathrm{d}\delta_M = \frac{1}{2}\mathrm{erfc}\left[\frac{\delta_\mathrm{c}}{2\sigma_M}\right]$$

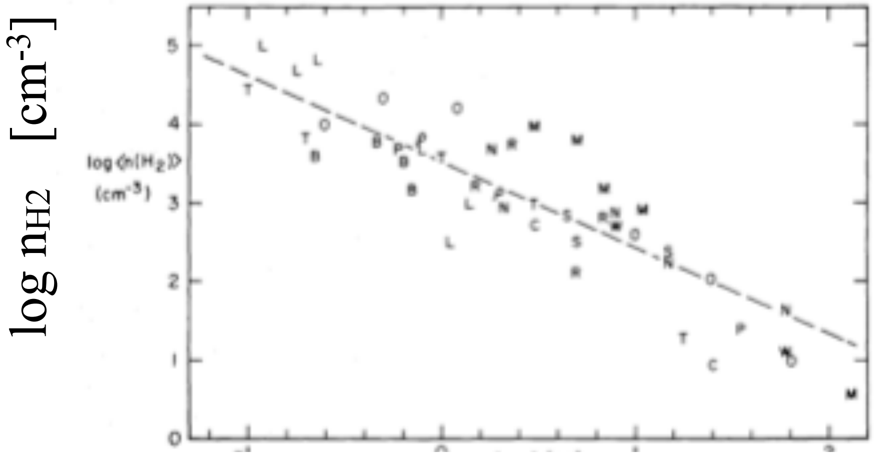
- sum over all the corresponding fluctuations

$$n(M,t)\,\mathrm{d}M = 2\frac{\bar{\rho}}{M}\frac{\partial\mathcal{P}(>\delta_\mathrm{c})}{\partial M}\mathrm{d}M = \sqrt{\frac{2}{\pi}}\frac{\bar{\rho}}{M^2}\frac{\delta_\mathrm{c}}{\sigma_M}\exp\left(-\frac{\delta_\mathrm{c}^2}{2\sigma_M^2}\right)\left|\frac{\mathrm{d}\ln\sigma_M}{\mathrm{d}\ln M}\right|\mathrm{d}M$$

Which density fluctuation statistics for molecular clouds ?

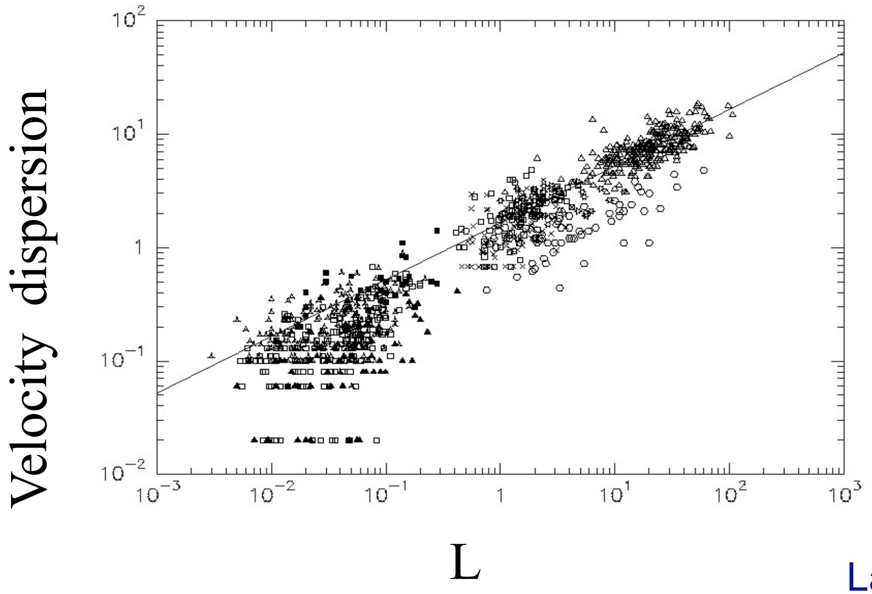
At large scale, molecular clouds dominated by supersonic turbulence

Density versus size of CO clumps



$\langle n \rangle\ \alpha\ L^{-0.7\ \ -1}$

Velocity dispersion versus size of CO clumps



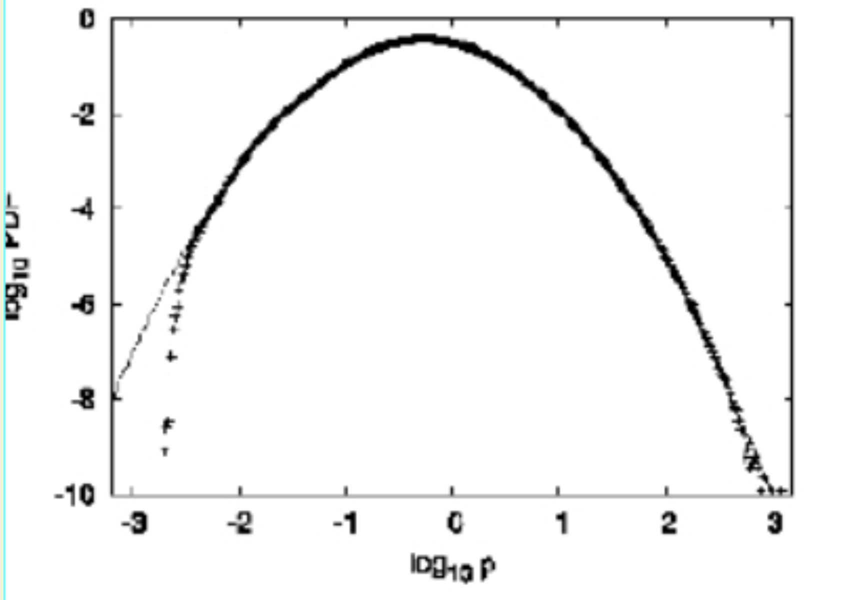
$V_{rms}\ \alpha\ L^{0.4\ -\ 0.5}$

Larson '81;
Hennebelle & Falgarone '12

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

PDF of compressible turbulence

PDF of density field
(Kritsuk et al. 2007)



$$\delta = \ln(\rho/\overline{\rho})$$

A lognormal distribution:

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

$$\sigma^2 = \frac{1}{V}\int_V \delta_R^2 dV = \left(\frac{1}{2\pi}\right)^3 \int \tilde{\delta}^2(k) W_k^2(R) d^3k$$

$$\langle V_{rms}^2(R)\rangle = \int_{2\pi/R}^{\infty} k^{-n} d^3k$$

$$\mathcal{P}_{\log\rho} \propto k^{n'}$$

$$\mathcal{P}_V \propto k^n$$

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

Beresnyak et al. '04, Kritsuk et al. '07, Federrath et al. '08

Step 1: we ignore gravity

<u>structures due to turbulence-induced fluct'ns</u> (scale free)

Clumps are defined as <u>unbound</u> structures having <u>a</u> density above some **<u>constant</u>** density threshold $\delta_c = \ln(\varrho_c / \varrho)$

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

power law

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

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

Compatible with the observed CO clump distribution

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

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

X $$M = R(1+\mathcal{M}_\star^2 R^{2\eta})$$

(see Schmidt et al. 2010)

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

$\mathcal{M}_\star$ = 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)

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

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

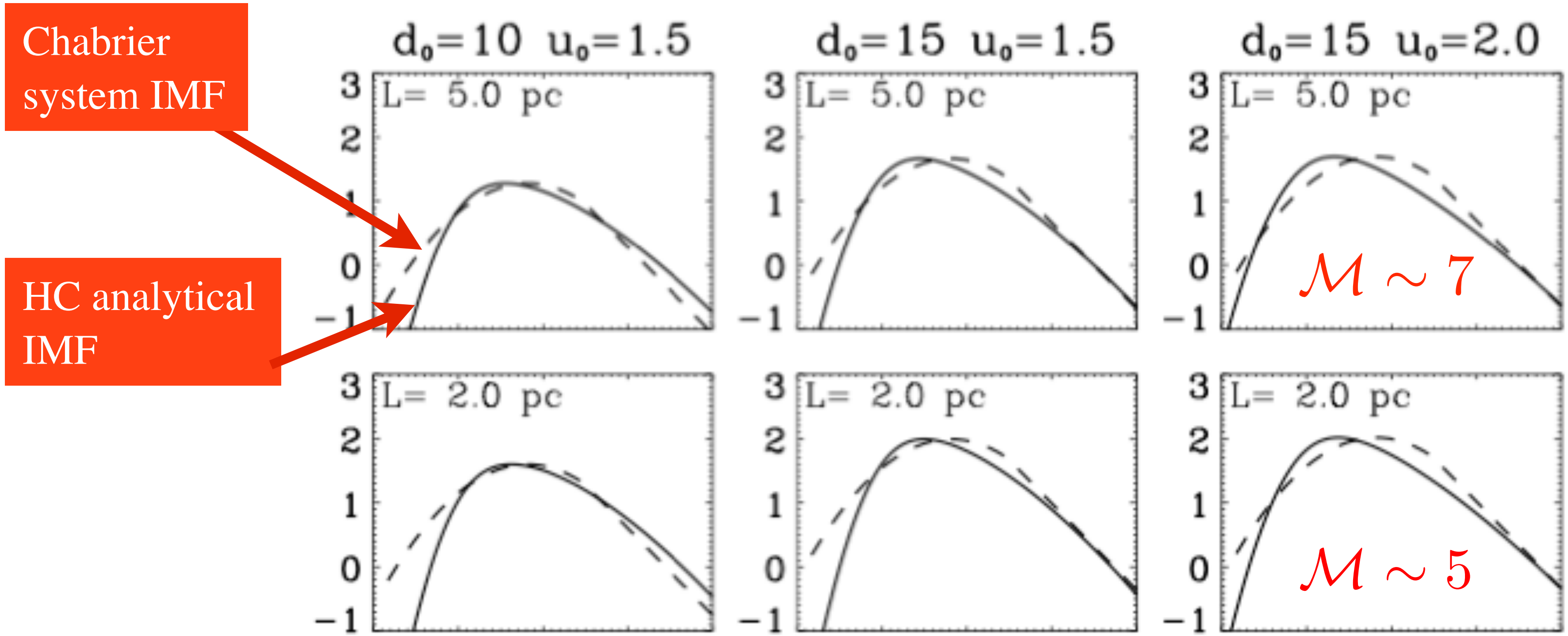
For n=3.8 dN/dM ~ $M^{-2.33}$

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

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

Hennebelle & Chabrier '08; Chabrier & Hennebelle '11

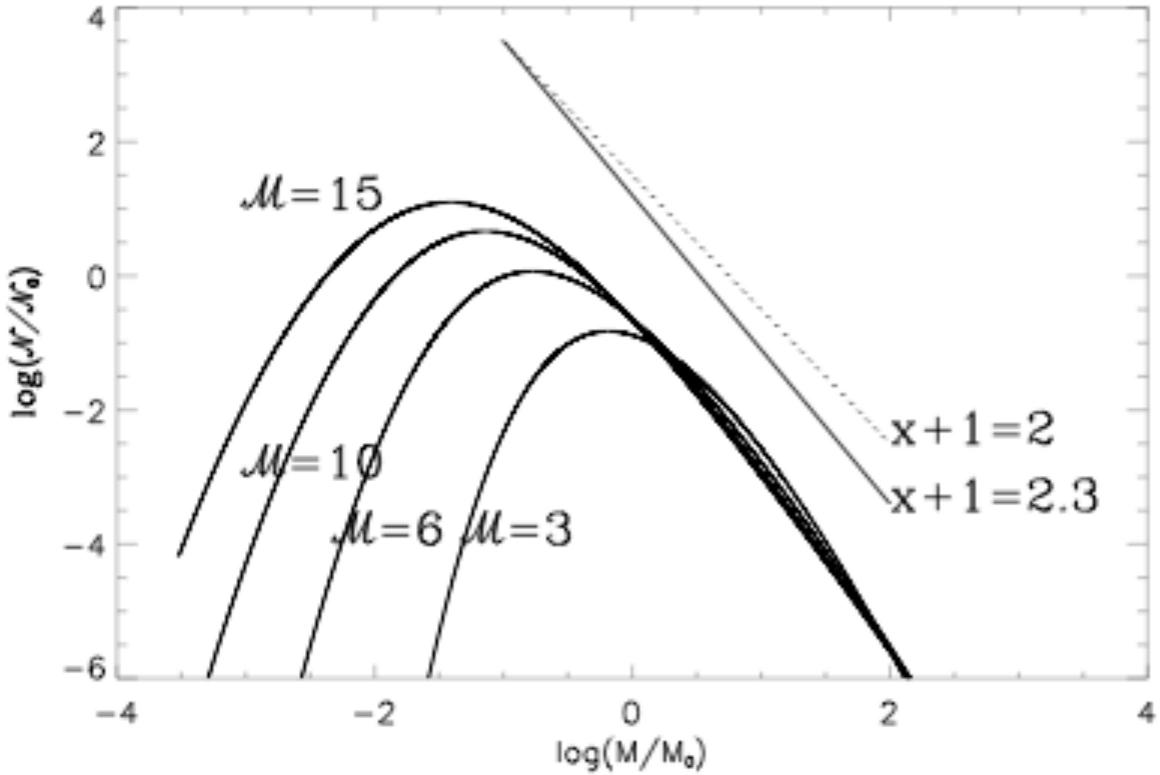
$$\bar{n} = (d_0 \times 10^3 \text{ cm}^{-3}) \left(\frac{L}{1\text{pc}}\right)^{-0.7}, \quad V_{\text{rms}} = (u_0 \times 0.8 \text{ km s}^{-1}) \left(\frac{L}{1\text{pc}}\right)^{\eta}.$$



Hennebelle & Chabrier ’09

①

Influence of the global Mach number on the CMF



The larger the Mach number, the larger the number of small cores (brown dwarfs)

$$\sigma^2 = \mathrm{Ln}[1 + (b\mathcal{M})^2]$$

II

$$\frac{dn}{dM} \propto \left(\frac{M_R}{R^3}\right)^{-1-\frac{1}{2\sigma^2}\ln(M_R/R^3)}$$

$$\mathcal{M}_\star^2 \widetilde{R}^{2\eta} \gg 1 \;:\; \frac{dn}{dM} \propto M^{-\alpha}$$

$$\alpha = \alpha_1 + \alpha_2$$

$$\begin{cases} \alpha_1 = \frac{n+1}{n-2} \simeq \underline{2.66} \\ \alpha_2 = 3\frac{n-5}{(n-2)^2}\frac{\ln(\mathcal{M}_*)}{\sigma^2} \simeq \underline{-1.11\,(\ln \mathcal{M}_*)/\sigma^2} \end{cases}$$

MW : $\mathcal{M} \sim 3-8,\; \mathcal{M}_*^2 \sim 2 \Rightarrow \alpha_2 \simeq -0.15\;-\;-0.3$

$$\bar{n} \gtrsim (4.0\times10^3)\left(\frac{T}{10\,\mathrm{K}}\right)\left(\frac{L_c}{10\,\mathrm{pc}}\right)^{-2}\left(\frac{\mathcal{M}}{10}\right)^{4.8}\,\mathrm{cm}^{-3}$$

$$\alpha_2 \ll \alpha_1 \Rightarrow \alpha \simeq \alpha_1 \simeq 2.7$$

$$T = 60K, L_c = 100\mathrm{pc}, \mathcal{M} = 60, \rightarrow \bar{n} \gtrsim 10^6\,\mathrm{cm}^{-3}$$

Chabrier, Hennebelle & Charlot, ApJ, in press.

III

Characteristic mass (=peak) of the IMF

$$M_{peak} = \frac{M_J}{1+(b\mathcal{M})^2} \propto \bar{\rho}^{-1/2}\mathcal{M}^{-2}$$

$$\bar{\rho} \propto d_0 \times L^{-\eta_d} \qquad V_{rms} \propto V_0 \times L^{+\eta}$$

Jeans Mach

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

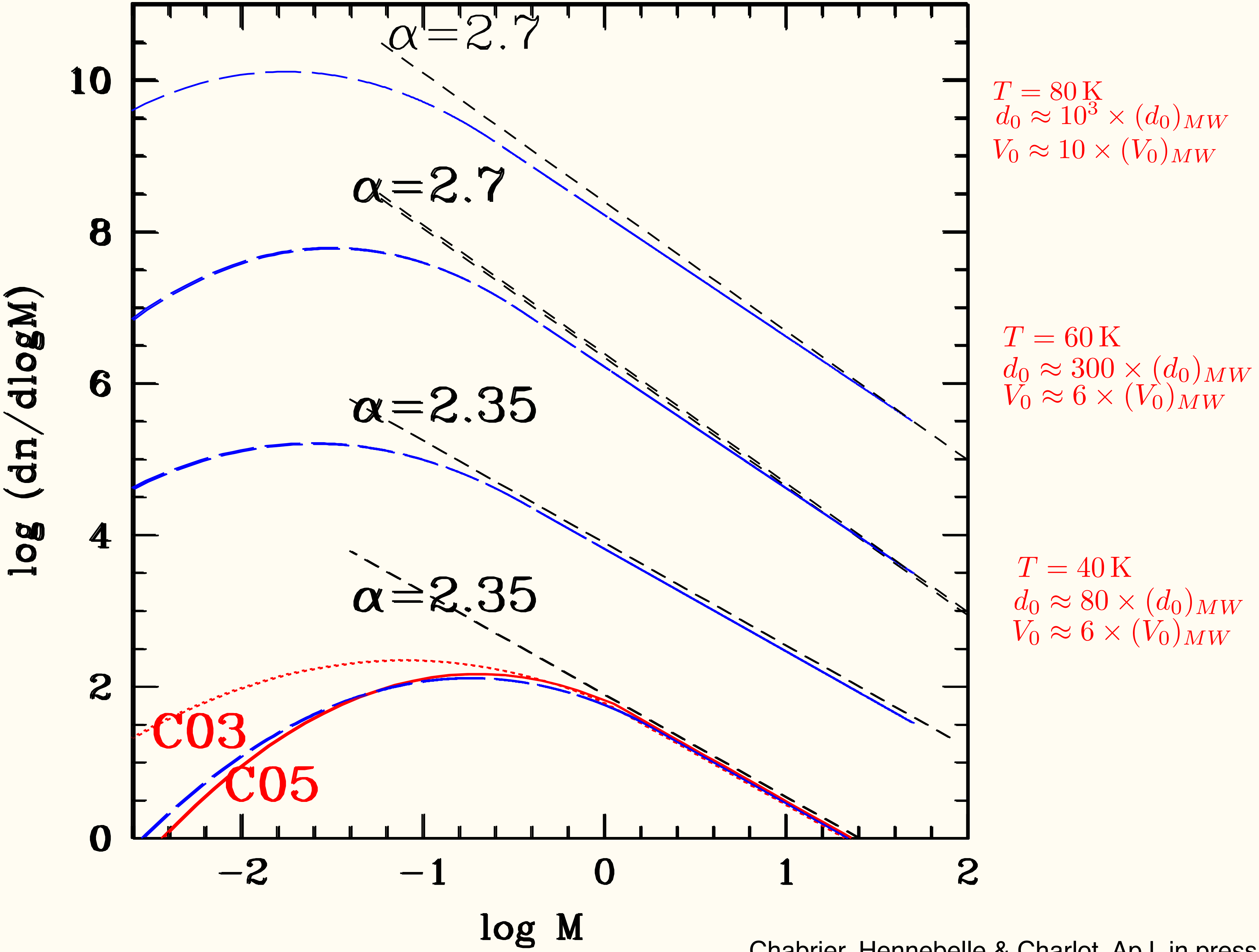
$$\Rightarrow M_{peak} \propto [d_0^{-0.7} V_0^{-2}] \times \quad M_c^{-0.15} - M_c^{-0.20}$$

Weak variation of the IMF for given cloud characteristic conditions (gas mean density, large scale velocity dispersion) !

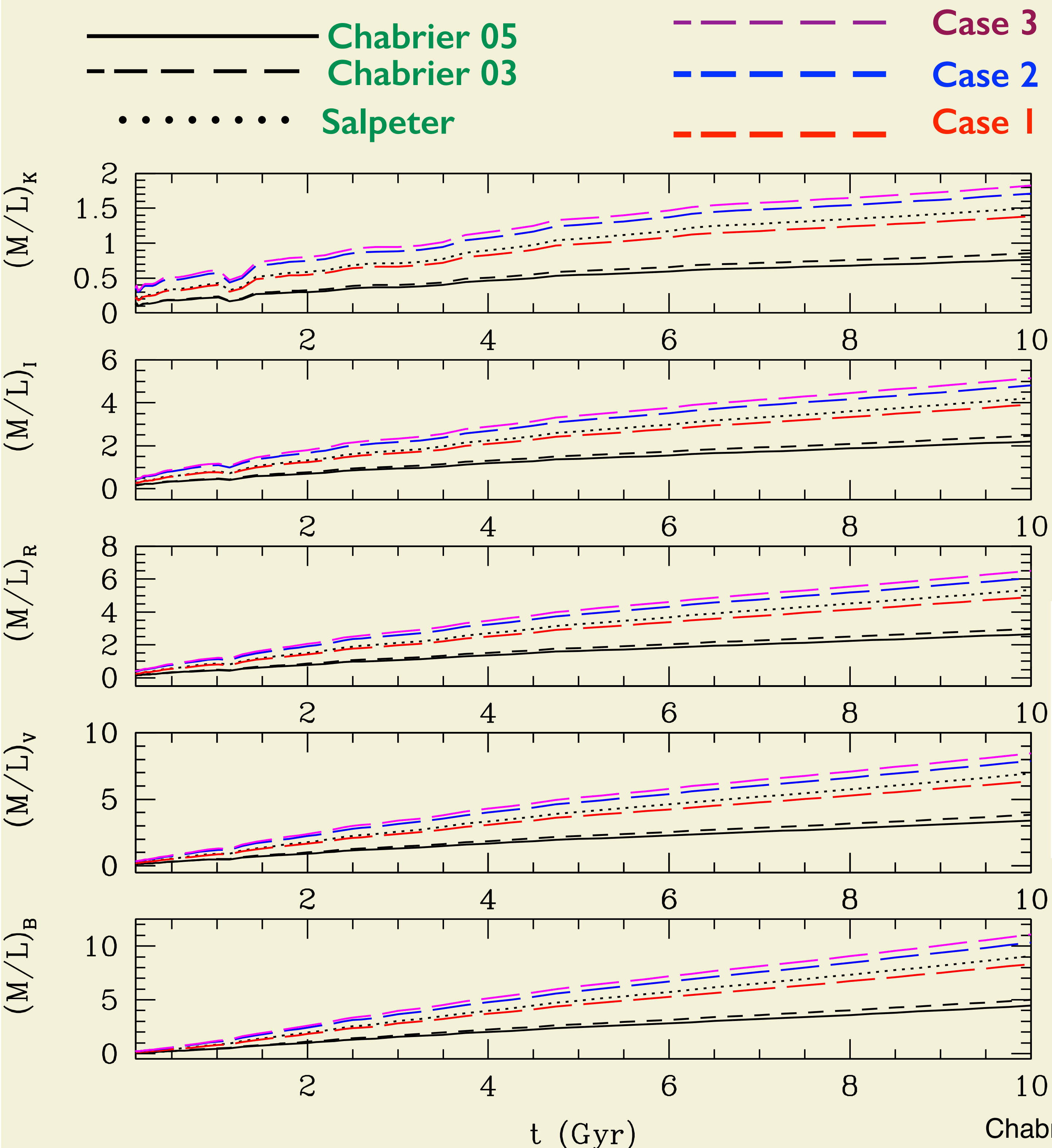
$$d_0 \approx 10^3 \left(\frac{\Sigma_0}{10\, M_\odot \mathrm{pc}^{-2}}\right) \approx 1.8 \times 10^3 \left(\frac{P/k_B}{10^4\, \mathrm{K\, cm}^{-3}}\right)^{1/2} \mathrm{km\, s}^{-1}$$

$$V_0 \approx 0.82 \left(\frac{\Sigma_0}{10\, M_\odot \mathrm{pc}^{-2}}\right)^{1/2} \approx 1.1 \left(\frac{P/k_B}{10^4\, \mathrm{K\, cm}^{-3}}\right)^{1/4} \mathrm{km\, s}^{-1}$$

HC08, HC13, CHC14

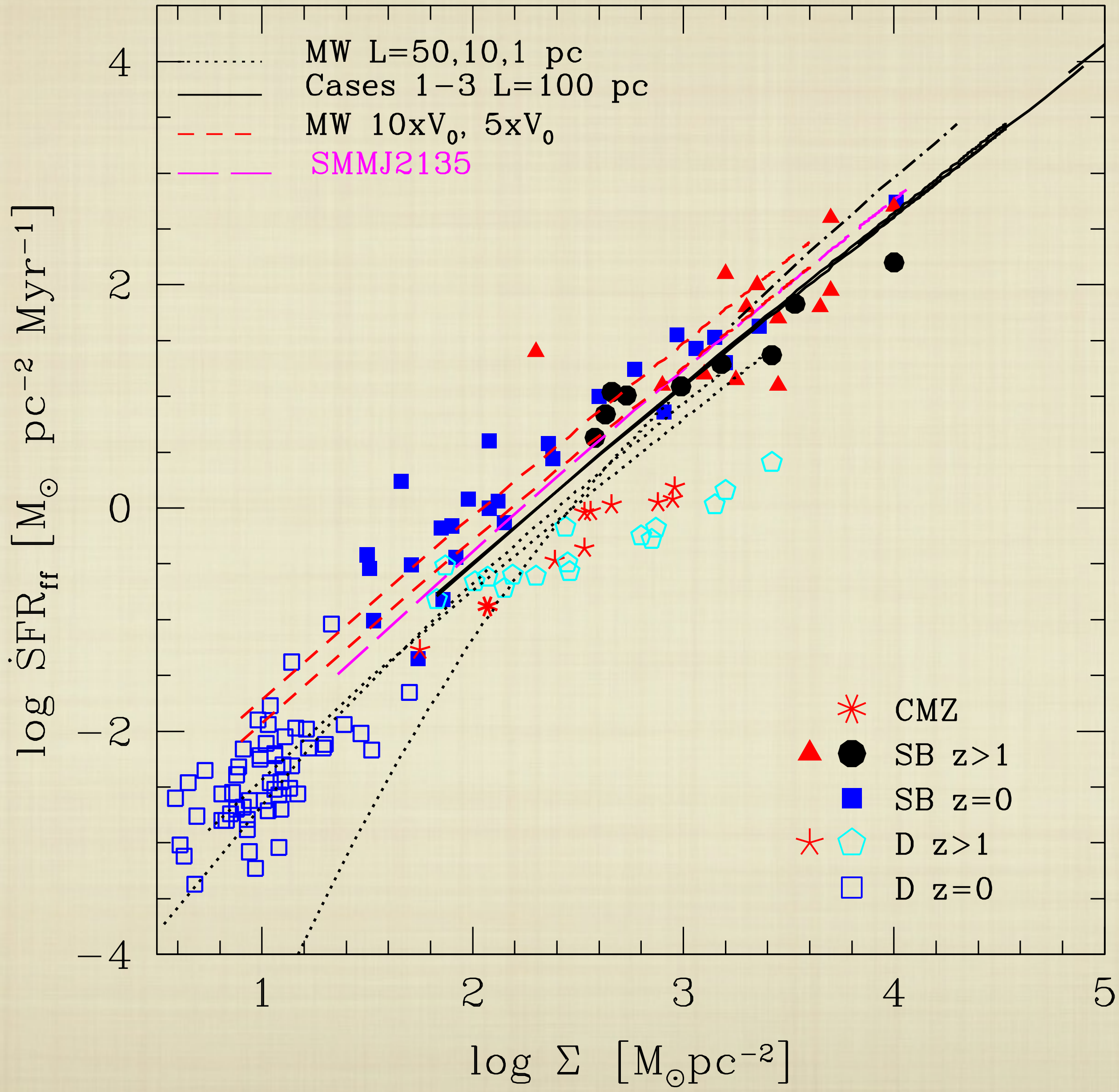


Chabrier, Hennebelle & Charlot, ApJ, in press.



	B	V	R	I	K	$\Upsilon/\Upsilon_{*,MW}$
MW	4.7	3.6	2.8	2.3	0.8	
Salpeter	9.1	6.9	5.4	4.2	1.5	~ 1.9
Case 1	8.3	6.4	4.9	3.9	1.4	~ 1.7
Case 2	10.3	7.9	6.1	4.8	1.7	~ 2.1-2.2
Case 3	11.1	8.5	6.5	5.1	1.8	~ 2.3

Chabrier, Hennebelle & Charlot, ApJ, in press.



Chabrier, Hennebelle & Charlot, ApJ, in press.

Conclusion

- IMF well described by a gravo-turbulent picture of star formation (HC, Hopkins):
  - turbulence sets up the **initial field of density fluctuations**
  - gravity selects those **dense enough to collapse** in a **turbulent medium** (virial cond'n)

  (collapsing structures can be filamentary (Inutsuka '01))

  « **universal process** » (only depends on turbulence $P_{\log\rho}$ and P_V)

- Entails a **power law** + a **lognormal** contributions

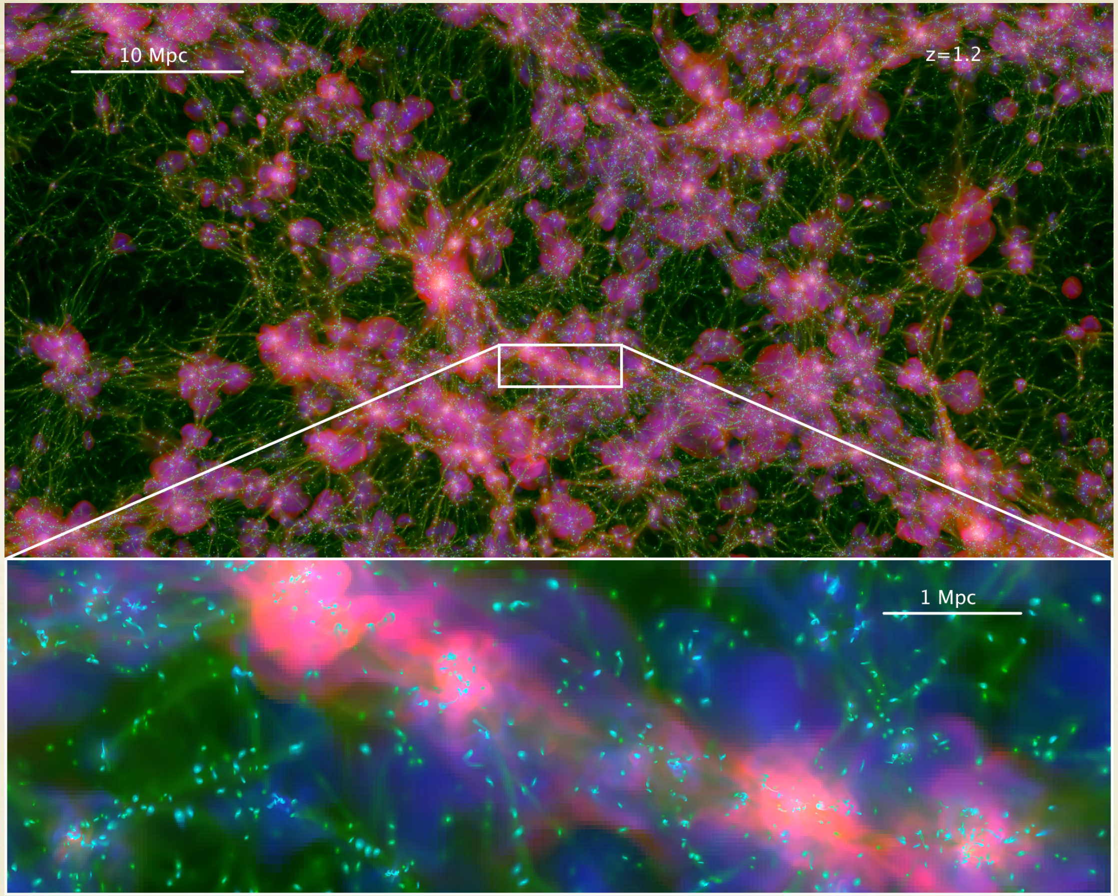
- Characteristics of the IMF (peak mass, width) DO **depend on the environment** (cloud, galaxy):

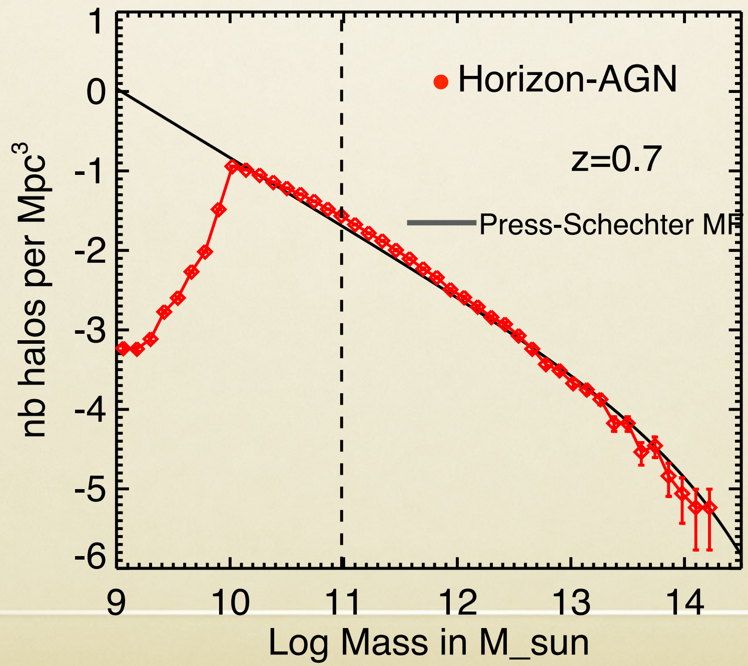
$$\mathbf{T,\ d_0, V_0 \ <\!\!-\!\!> \ \Sigma_0} \quad (\equiv \mathbf{P_{ext}}, \dot{M}_{acc})$$

- In **very dense** (compact⇒ **burst-like** star f'n) AND **turbulent** environments, the high-mass tail can reach

$$\alpha \sim 2.7$$

- Adequately reproduces M/L + SFR


10 Mpc
z=1.2
1 Mpc


Horizon-AGN
z=0.7
Press-Schechter MF
nb halos per Mpc^3
Log Mass in M_sun
1
0
-1
-2
-3
-4
-5
-6
9
10
11
12
13
14

Dubois et al.