Brown Dwarfs from Turbulent Fragmentation

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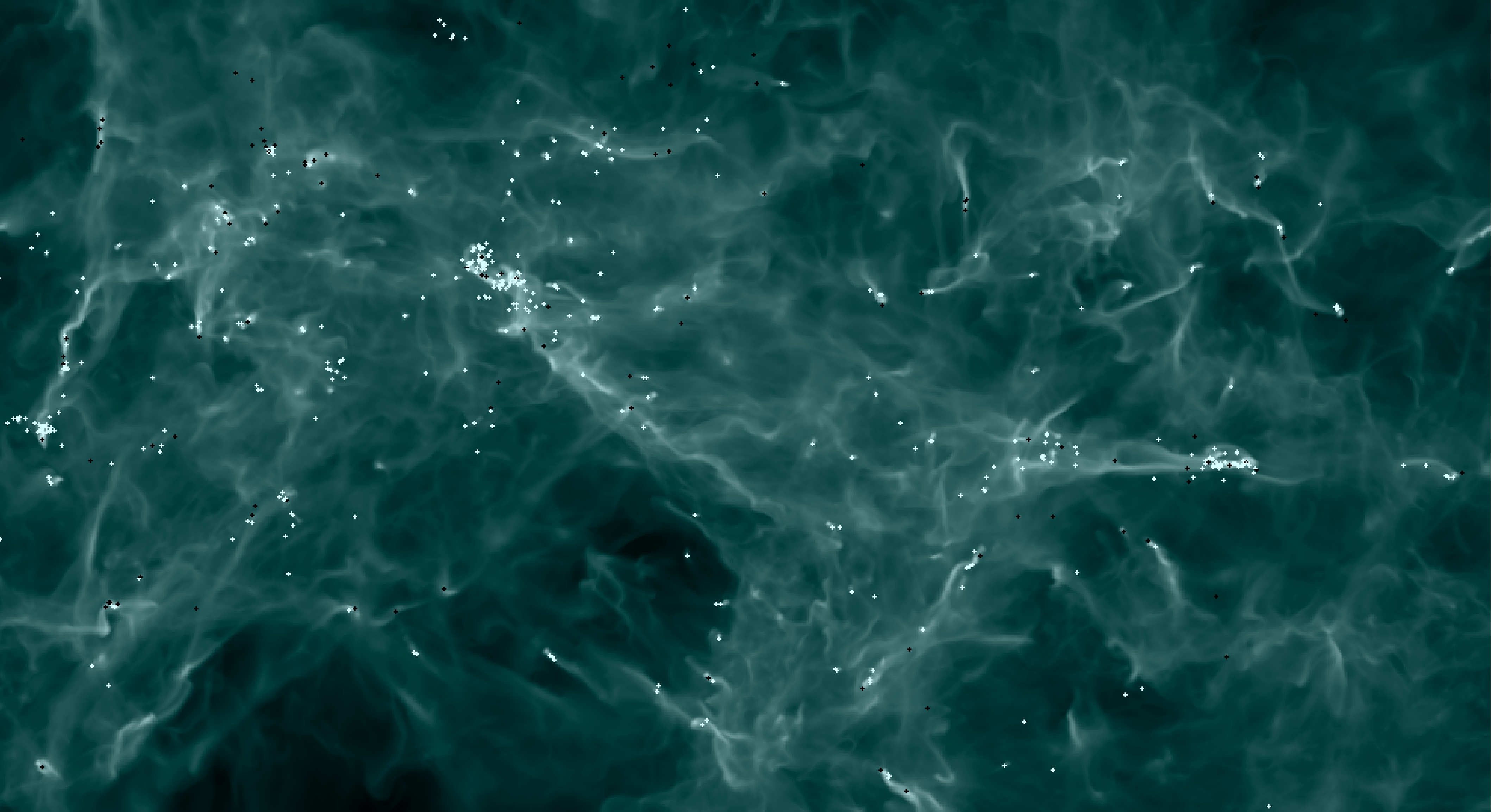

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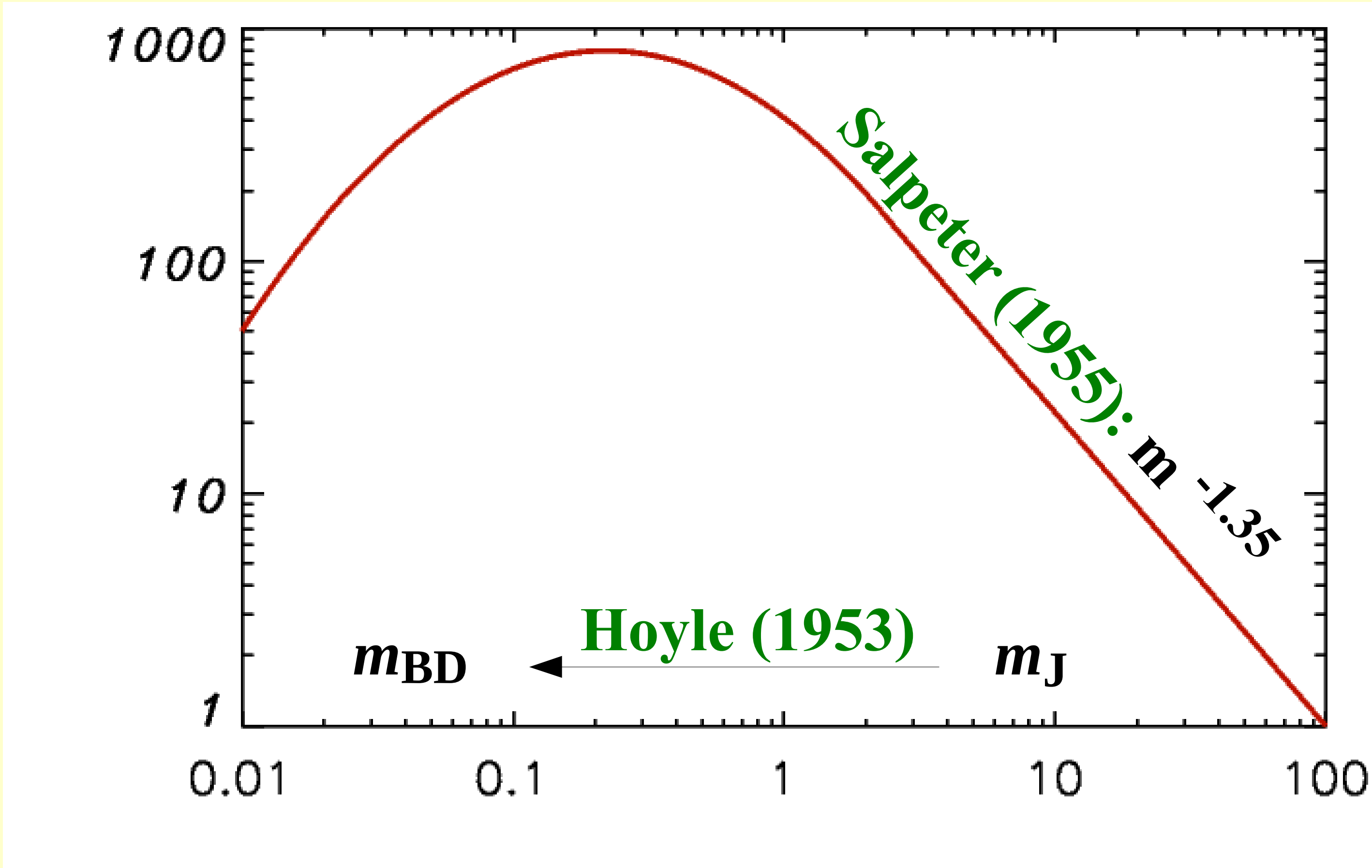
1. The IMF and BD Basic Problems



1. Why such a huge mass range (0.01-100 m) and a peak << m_J?

2. What is the origin of BD masses << m_J ?

The problem is not forming BDs, it is forming stars! (Kevin Luhman)

→ Why looking for a special mechanism for BD origin?

Theoretical Models of BD Formation

Like H-burning stars:

Turbulent fragmentation of molecular clouds

(Padoan & Nordlund 2002, 2004)

Gravitational fragmentation of molecular clouds

(Bonnell, Clark & Bate 2008)

Different from H-burning stars:

Disk gravitational fragmentation

(Bate et al. 2002; Whitworth & Stamatellos 2006, Stamatellos et al. 2007)

Embryo ejection

(Reipurth & Clarke 2001; Bate et al. 2002)

Core photo-erosion

(Whitworth & Zinnecker 2004)

Numerics:

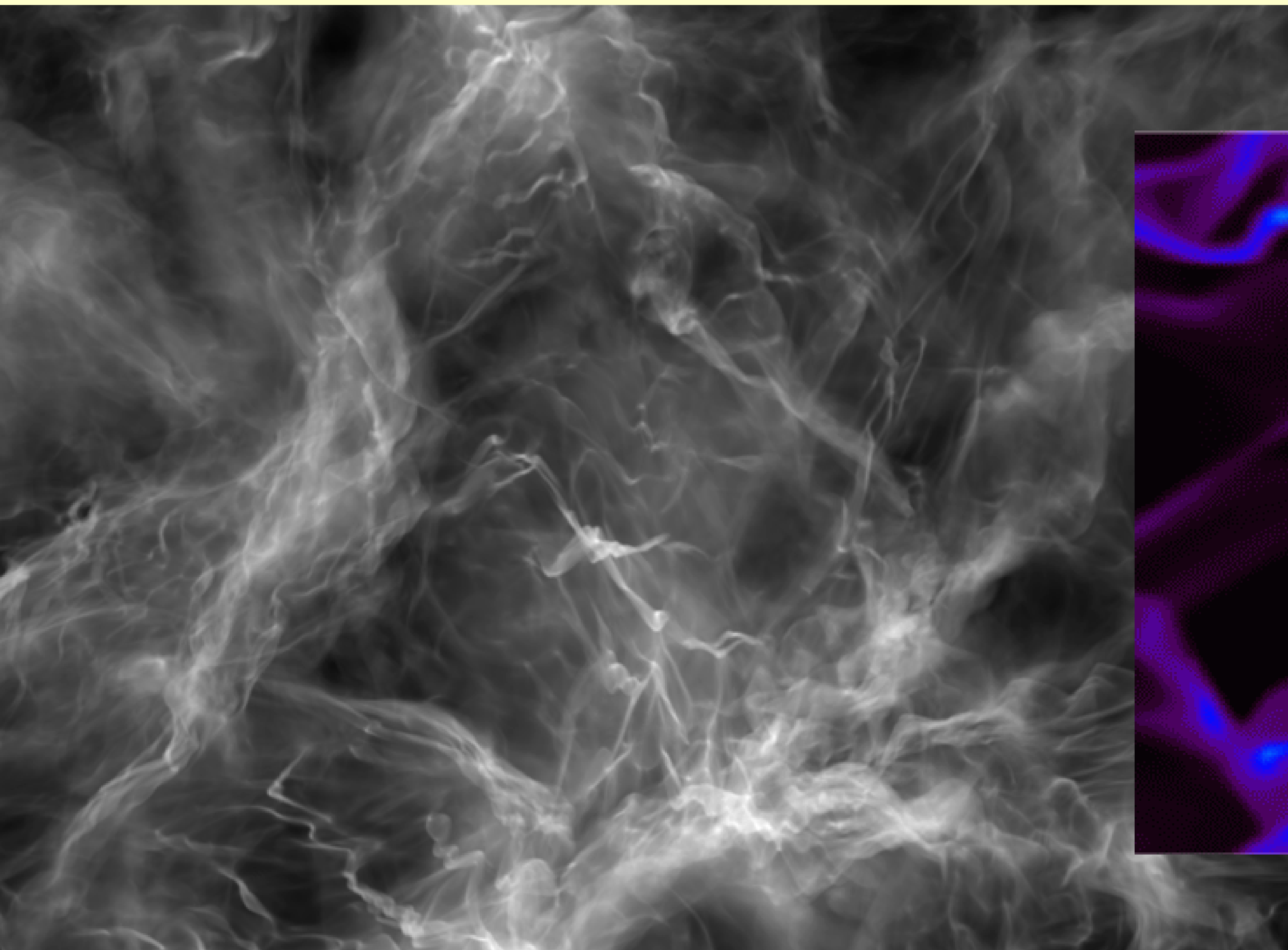
Turbulent fragmentation: unigrid MHD (needs $N \geq 1{,}000^3$ zones)

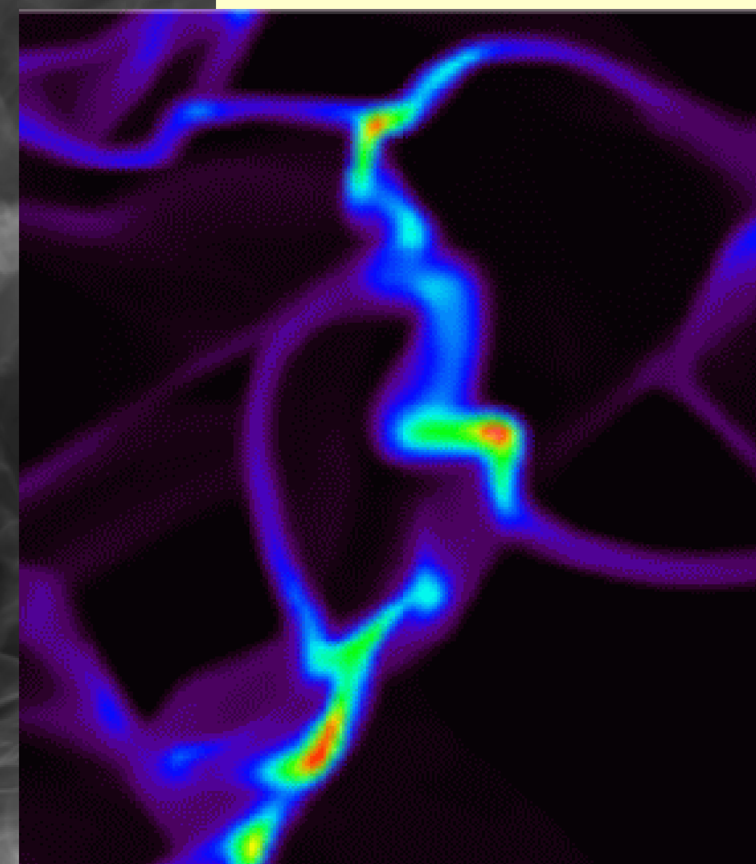
Everything else: SPH ($N \leq 170^3$ particles → *no scale-free turbulence*)

2. A Simple Solution from Supersonic Turbulence

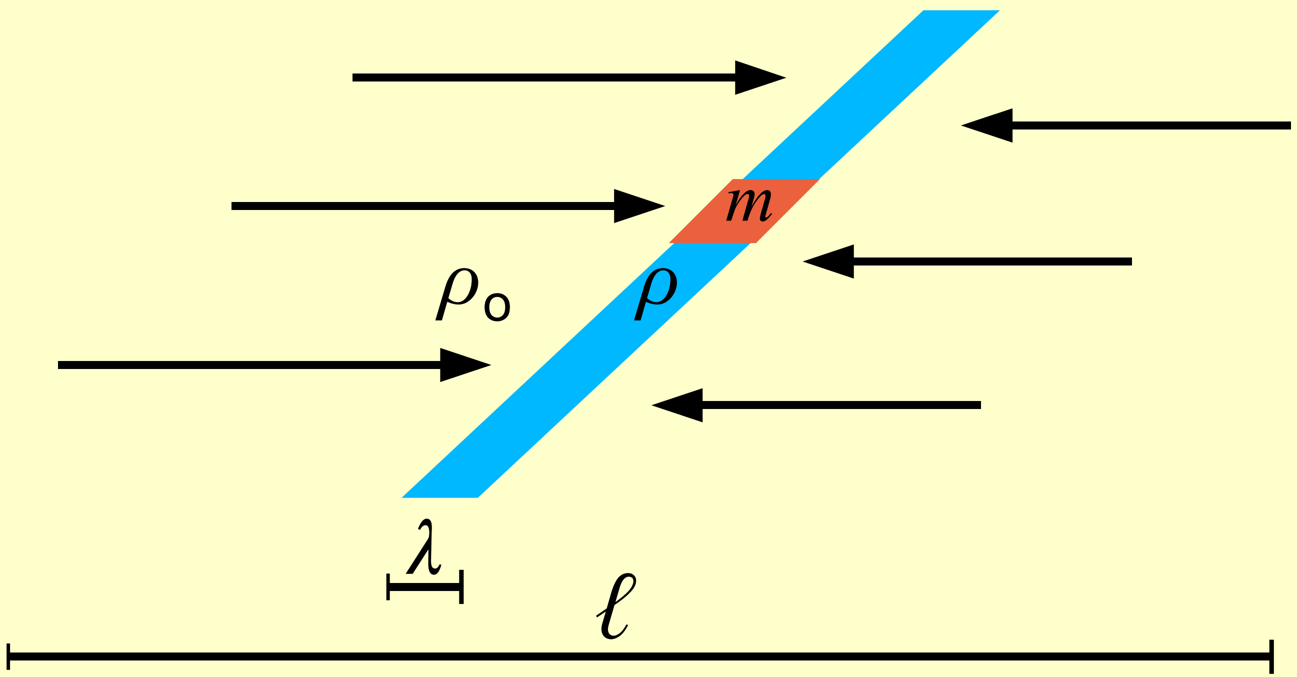
The cold ISM is highly turbulent: $Re = U\,L\,/\,\nu \sim 10^8$

The turbulence is highly supersonic: $\mathcal{M} = \sigma_v\,/\,c_s \sim 20$





Idealized MHD shock: $\lambda = \ell \,/\, \mathcal{M}_\ell \qquad \rho = \rho_o \, \mathcal{M}_\ell$



Mass: $m \sim \rho \, \lambda^3 \sim \rho_o \, \ell^{\,3} \,/\, \mathcal{M}_\ell^{\;2}$

Turbulence: $\mathcal{M}_A(\ell) \sim u(\ell) \sim \ell^{\,1/2} \quad \rightarrow \quad m \sim \ell^{\,2}$

Mass range: $m_{max} \,/\, m_{min} = (L \,/\, \ell_s)^2 \sim \mathcal{M}_o^{\;4} \sim 10^4$

This explains the range of masses, 0.01-100 $m_\odot$

But what is the chance that a very small core collapses?

It must be larger than the critical m_{BE} in the postshock gas:

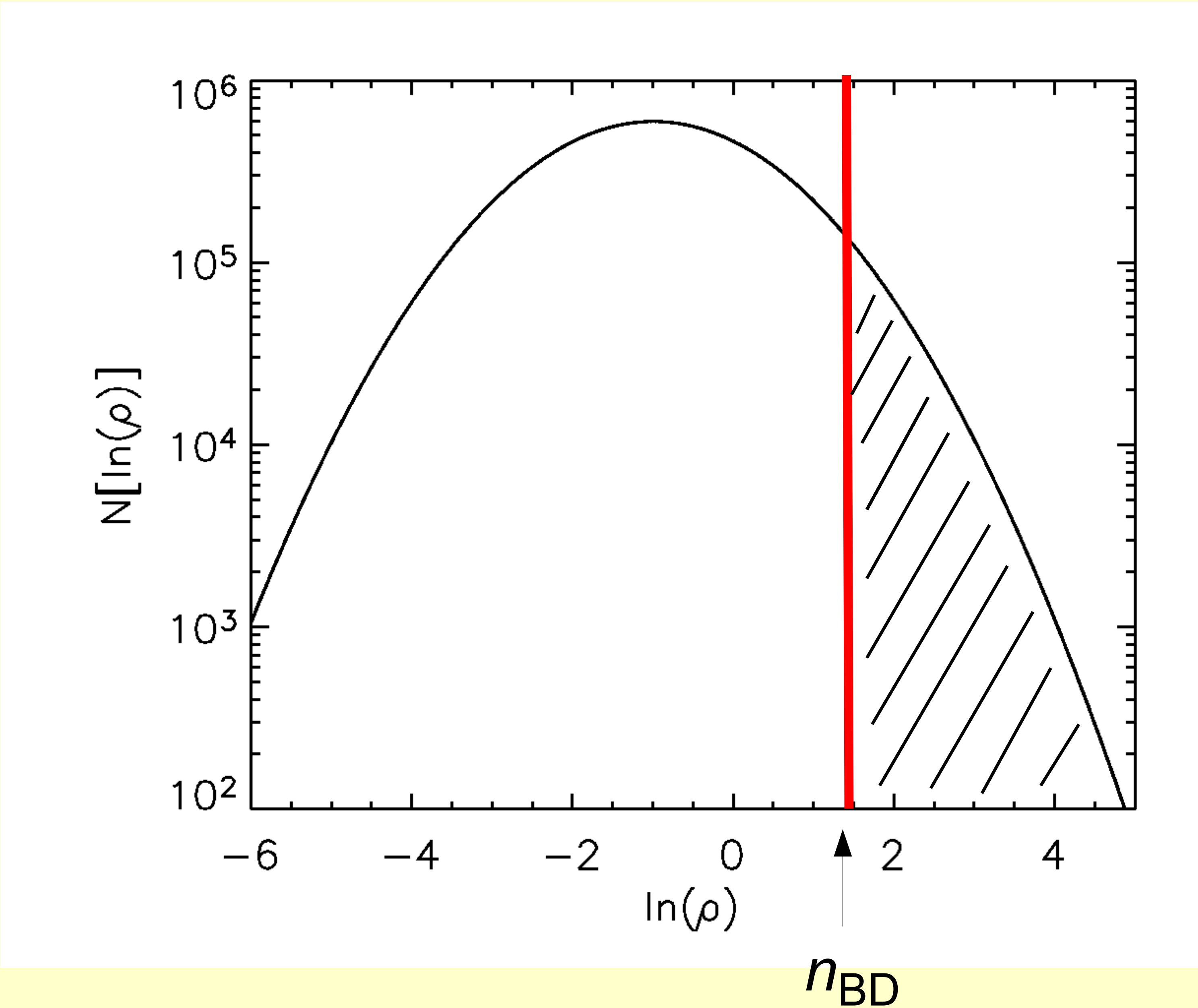
$$m_{\mathrm{BD}} \geq m_{\mathrm{BE}} = 3.3\,\mathrm{m}_{\mathrm{SUN}} \left(\frac{T}{10\,\mathrm{K}} \right)^{3/2} \left(\frac{n_{\mathrm{BD}}}{10^3\,\mathrm{cm}^{-3}} \right)^{-1/2}$$

The collapse of a BD mass cores requires $n \geq n_{\mathrm{BD}}$,

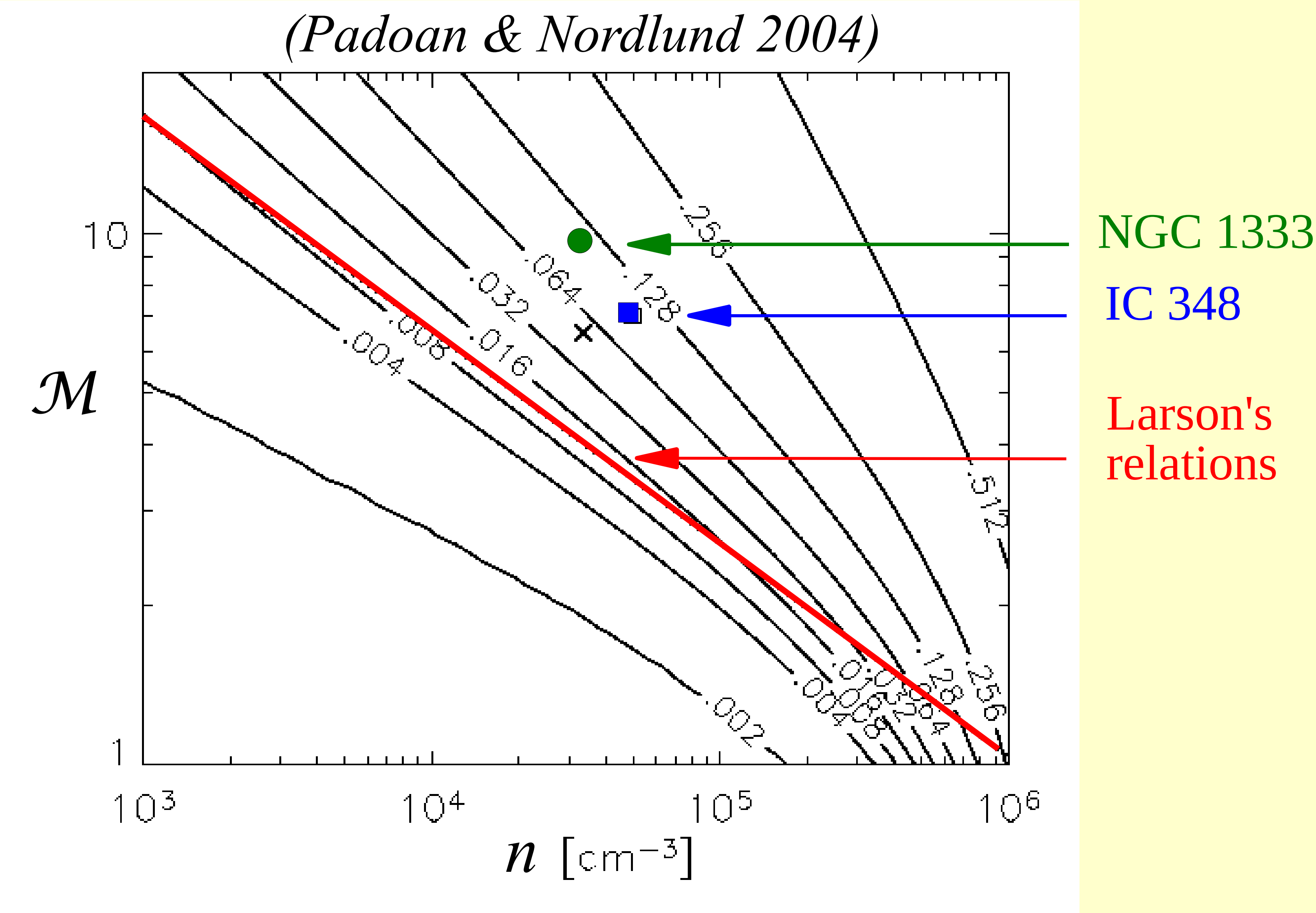
$$n_{\mathrm{BD}} = 2 \times 10^6\,\mathrm{cm}^{-3} \left(\frac{T}{10\,\mathrm{K}} \right)^3$$

Turbulence → Log-Normal density pdf

$\sigma_\rho = \mathcal{M} / 2 \qquad \sigma_{\ln\rho}{}^2 = \ln(1 + \mathcal{M}^2 / 4)$



Mass fraction ***available*** to form BDs:
1% in molecular clouds, 10% in clusters (T~10K)



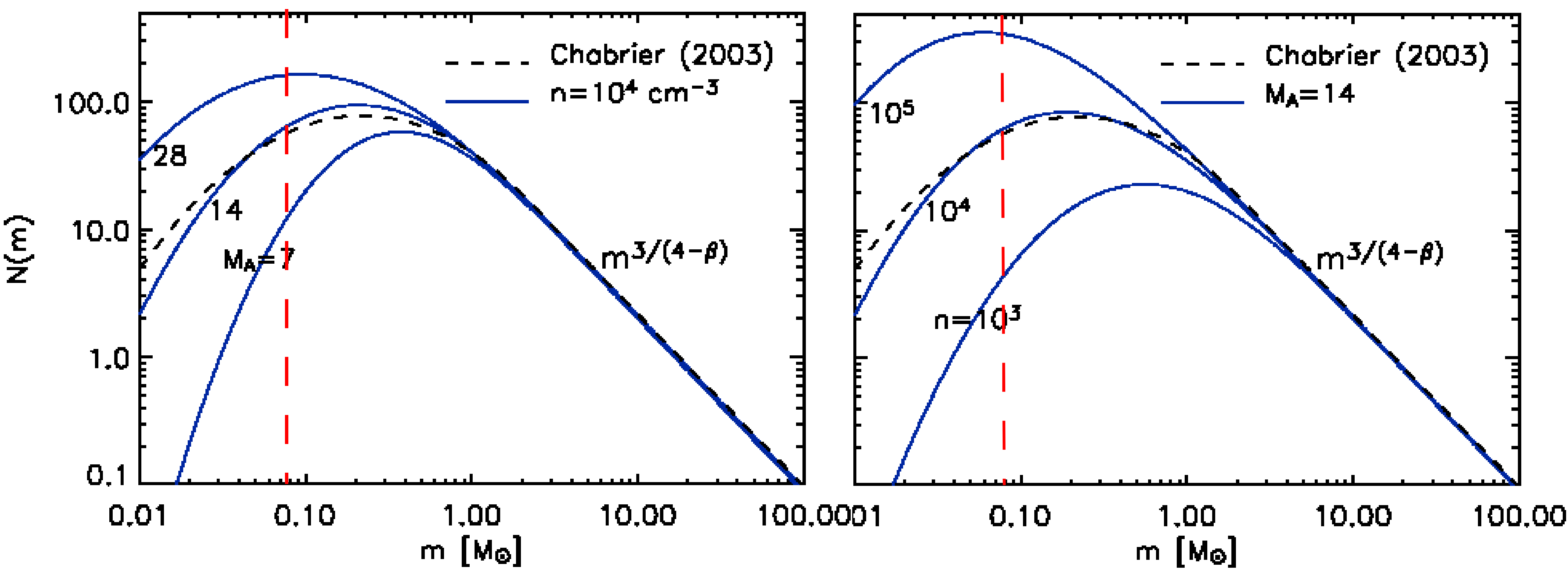
Pretty good chance that shocked filaments are dense enough to form BDs, especially in cluster-forming regions of large average density.

3. Quantitative Predictions of the IMF Model

$$N(m) \propto m^{-3/(4-\beta)}$$

$$\text{for } \beta = 1.8 \quad \Rightarrow \quad N(m) \propto m^{-1.36}$$

Physical parameters: $\mathcal{M}$, *n*, *T*, *B* → IMF and BD abundance:



The "Universal" Peak of the IMF, m_p

Padoan et al. 2007: $m_\mathrm{p} = 3.0\, m_{\mathrm{BE},0}\, \mathcal{M}_0^{-1.1} \sim n^{-1/2} \sigma_v^{-1.1}$

Larson's relations: $\sigma_v \sim \ell^{\,0.42} \qquad n \sim \ell^{\,-1}$

$$\rightarrow\; m_\mathrm{p} \sim \ell^{\,0.5}\, \ell^{\,-0.46} = \ell^{\,0.04} \approx \text{constant}$$

Don't believe in Larson's density-size relation? Then just assume

Virial velocities: $\sigma_v^2 / (n\, \ell^{\,2}) = \text{constant}$

$$\rightarrow\; m_\mathrm{p} \sim n^{-1/2}\, n^{-0.55}\, \ell^{\,-1.1} \sim n^{0.05} N_\mathrm{col}^{-1.1}$$

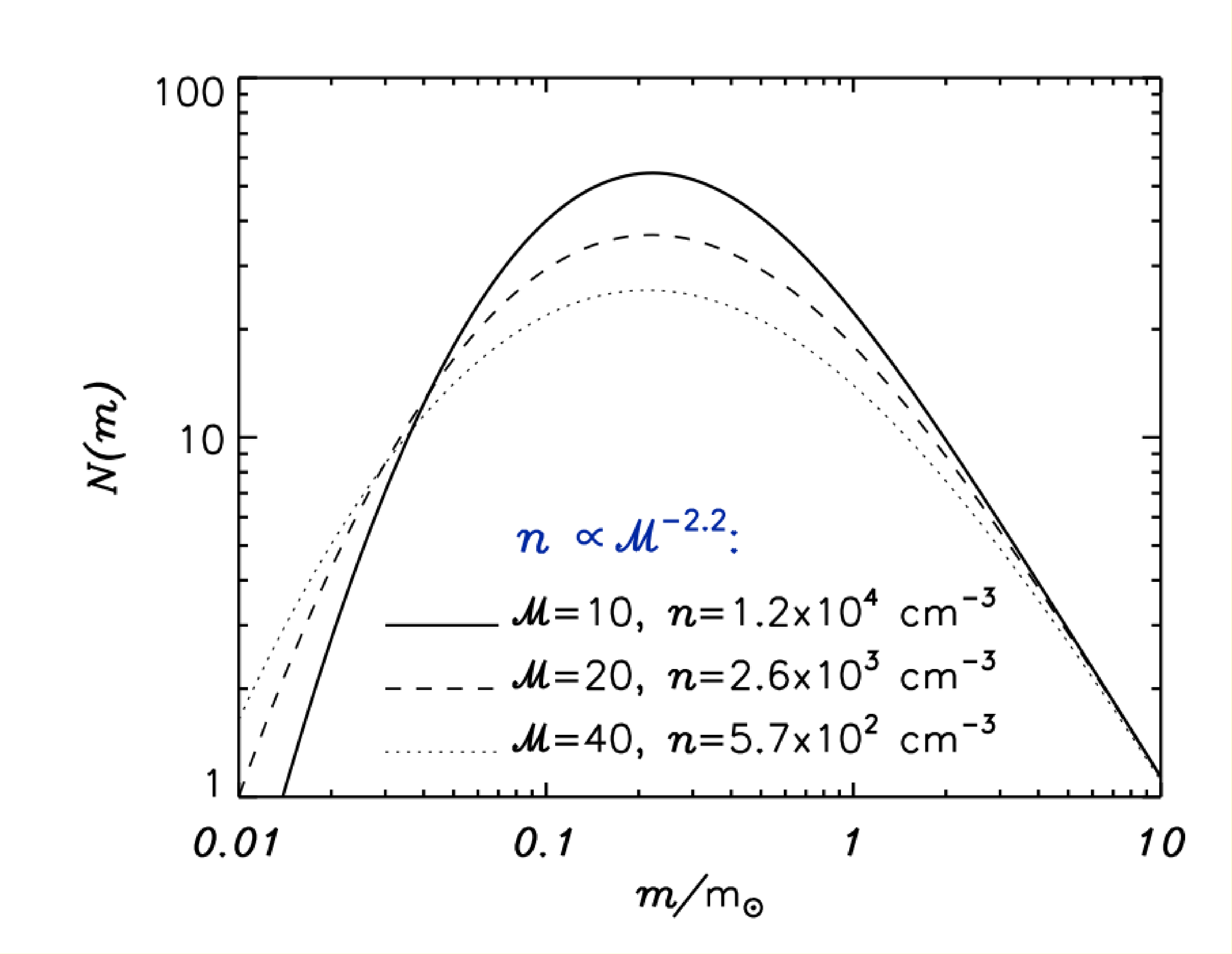
Do we see this column density effect?

Luhman 2004-2007: $m_\mathrm{p} = 0.25$ m in clusters; $m_\mathrm{p} = 1.0$ m in Taurus.

Cluster-forming regions have n ~10 times larger than Larson's relation at equal rms Mach $\rightarrow N_\mathrm{col} \sim 10^{2/3} \sim 4$ times larger $\rightarrow m_\mathrm{p} \sim 4$ times smaller.

Pretty decent prediction of the only known IMF variation!

Following Larson's relation the IMF peak is fixed:



4. Unigrid turbulence simulations + self-gravity + sinks

What is the role of the turbulence in setting the initial conditions?

We first tested the turbulent fragmentation model with simulations of supersonic MHD turbulence without self-gravity.

We selected "gravitationally unstable" density peaks and confirmed the model predictions *(Padoan et al. 2007)*.

Useful, but VERY idealized scenario:

Phase 1: Turbulence sets initial conditions with no help from gravity
Phase 2: Gravity selects the densest peaks, with no effect from turbulence

Clearly turbulence and gravity are somewhere coupled, and we also need to follow further the evolution of our turbulent peaks.

→ More realistic simulations including self-gravity and sink particles

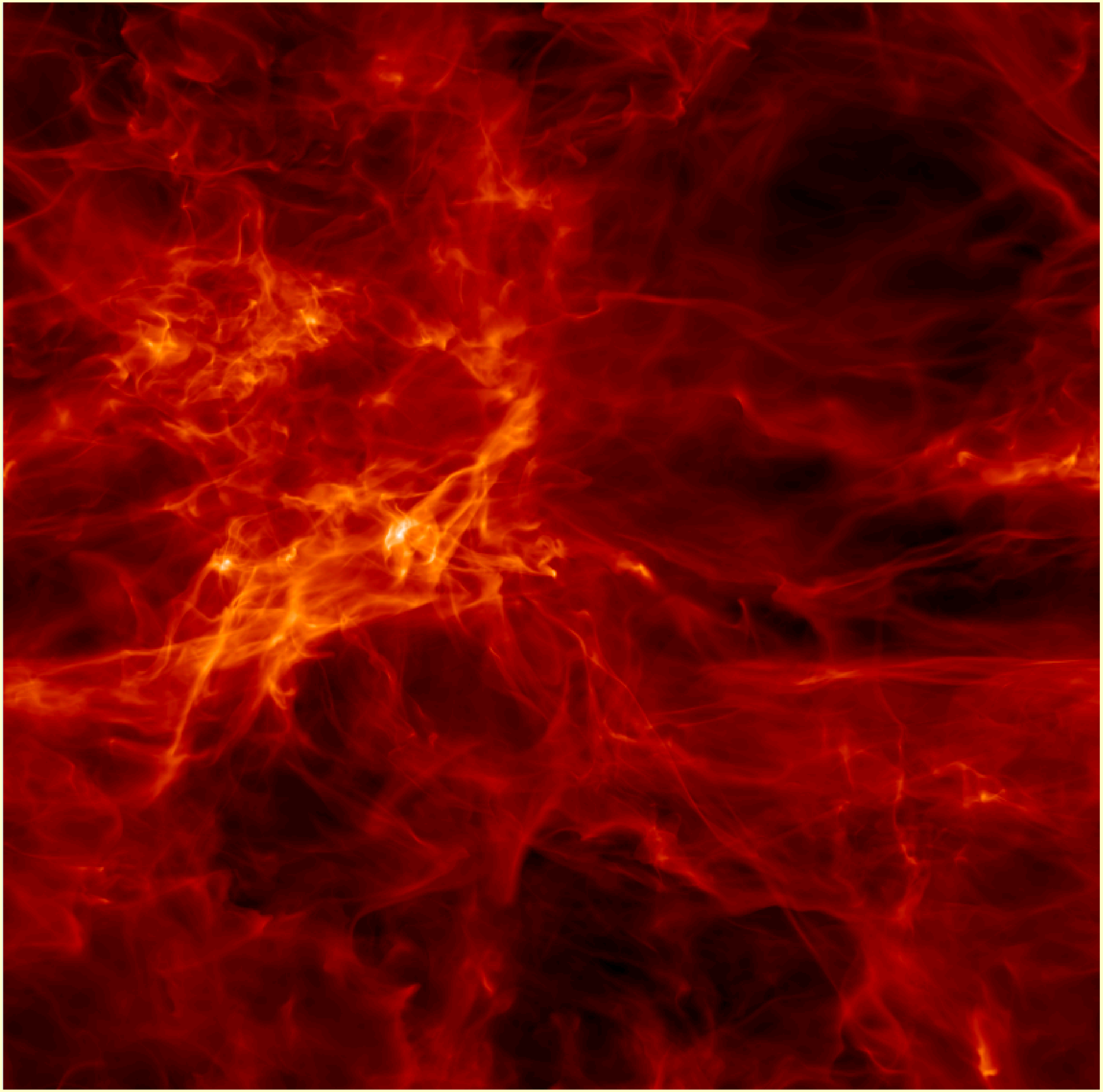
Unigrid Simulations + self-gravity + sinks

- Resolution up to **$1{,}600^3$** zones
- Periodic boundary conditions
- Isothermal equation of state
- Uniform initial magnetic and density fields
- Large scale ($1 \leq k \leq 2$), random, solenoidal initial velocity
- Random solenoidal force ($1 \leq k \leq 2$)

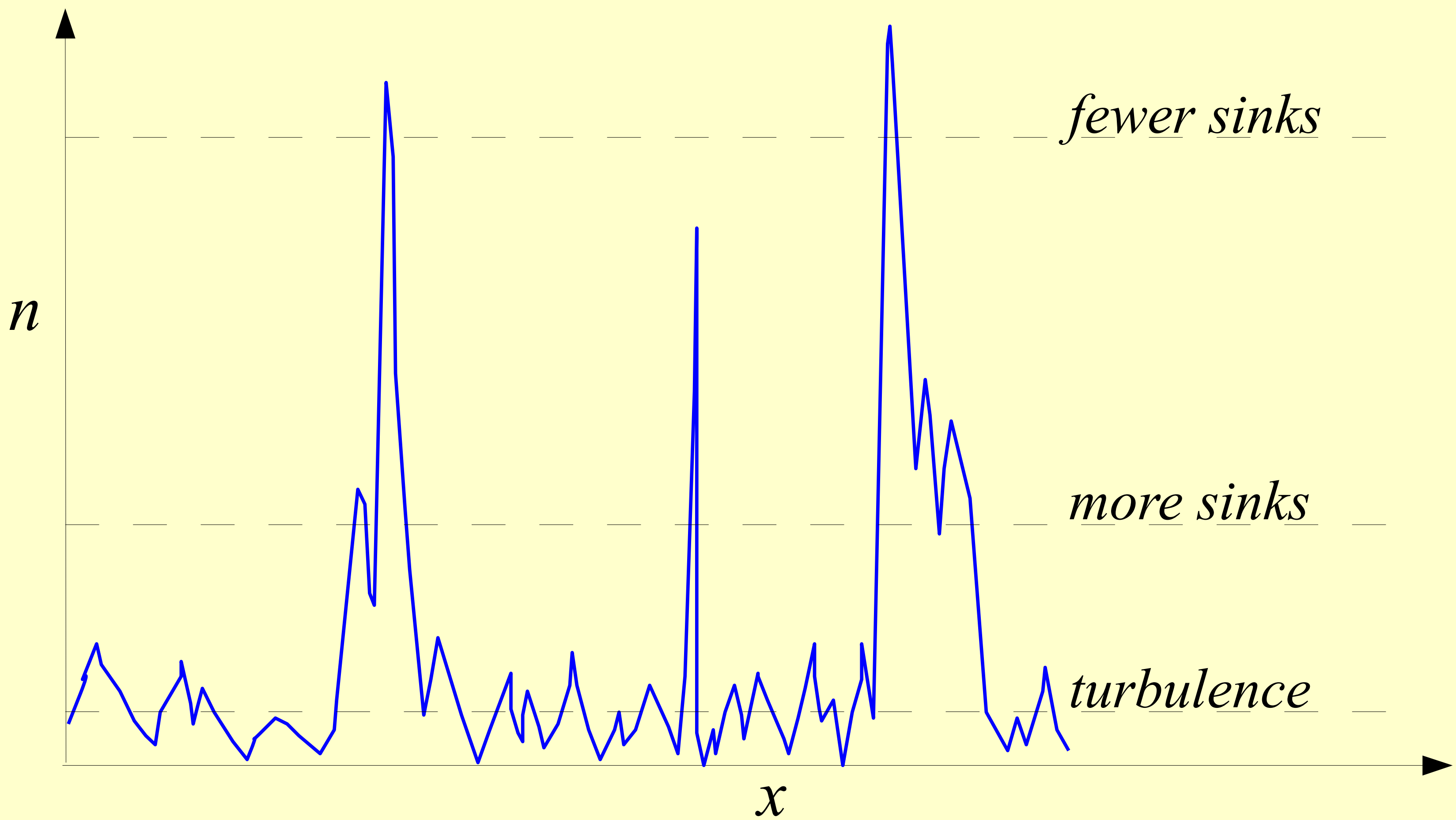
Fully developed turbulence $\rightarrow$ **Turn on self-gravity and sinks**

(See Padoan and Nordlund 2009 – arXiv:0907.0248)

The $1{,}600^3$ is still cooking....... Just $1{,}000^3$ for now.



Sink particle model: density threshold, n_{sp}



Sink accretion radius = $2.5\Delta x$ → Cannot form sinks closer than $2.5\Delta x$

Lower n_{sp} or higher resolution → more and smaller sinks

We set n_{sp} just above the critical collapse density of one Δx, and seek convergence with resolution

Dimensionless Simulation Parameters

Rms sonic Mach number: $\mathcal{M}_{\mathrm{s}} = \sigma_{\mathrm{v,3D}} / c_{\mathrm{s}} \approx 3 - 18,$

Virial parameter: $\boldsymbol{\alpha}_{\mathbf{vir}} = \dfrac{2E_{\mathrm{K}}}{E_{\mathrm{G}}} = \dfrac{5\sigma^2_{\mathrm{v,1D}} R}{G M} \approx 0.2 - 2.0 \quad \Rightarrow \quad n L^2 = \mathrm{const.}$

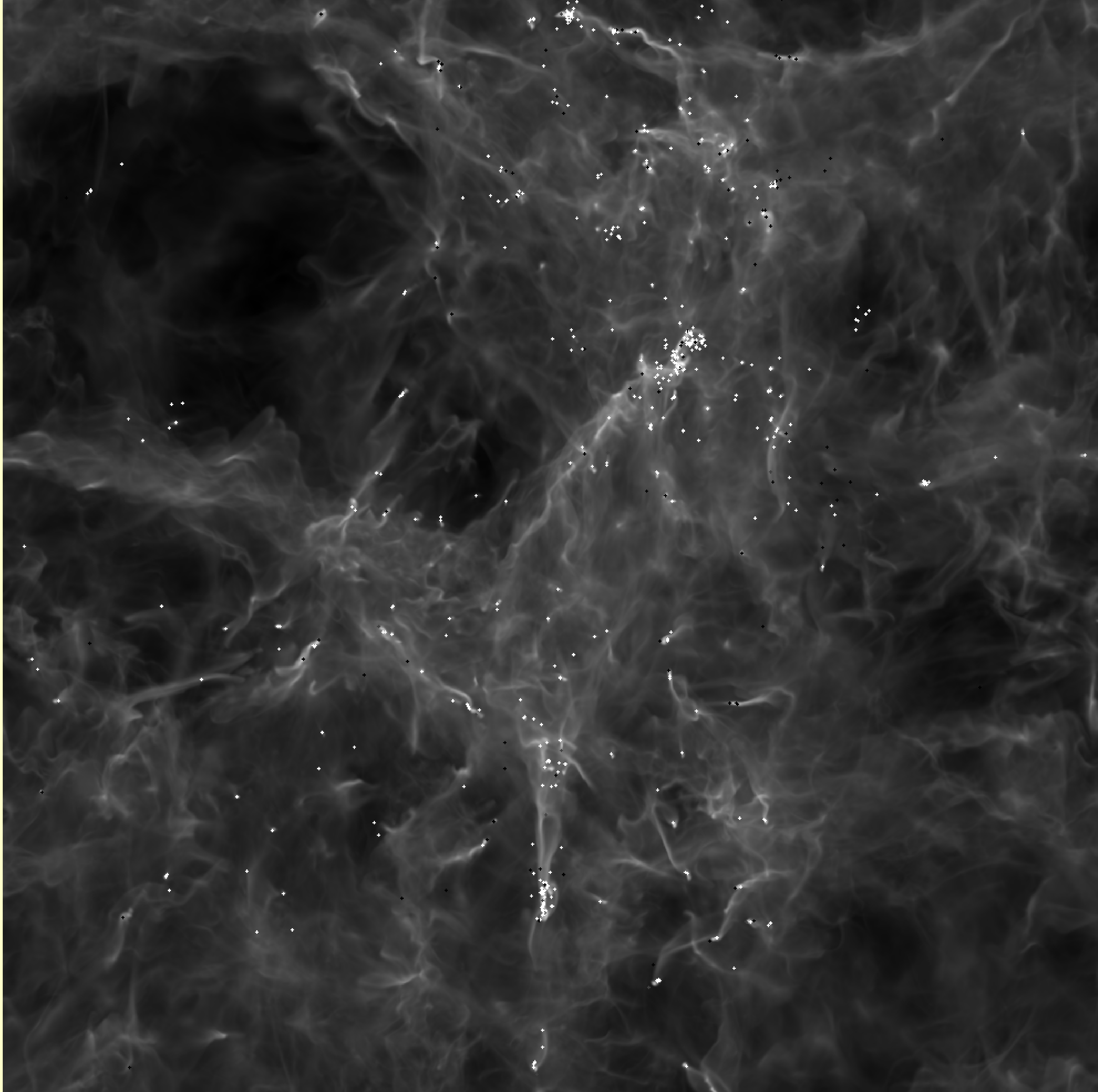
Init. gas to magnetic pressure: $\beta_{\mathrm{i}} = 22.2\,;$ turb. amplif. $\rightarrow \beta_{\mathrm{rms}} \approx 0.2$

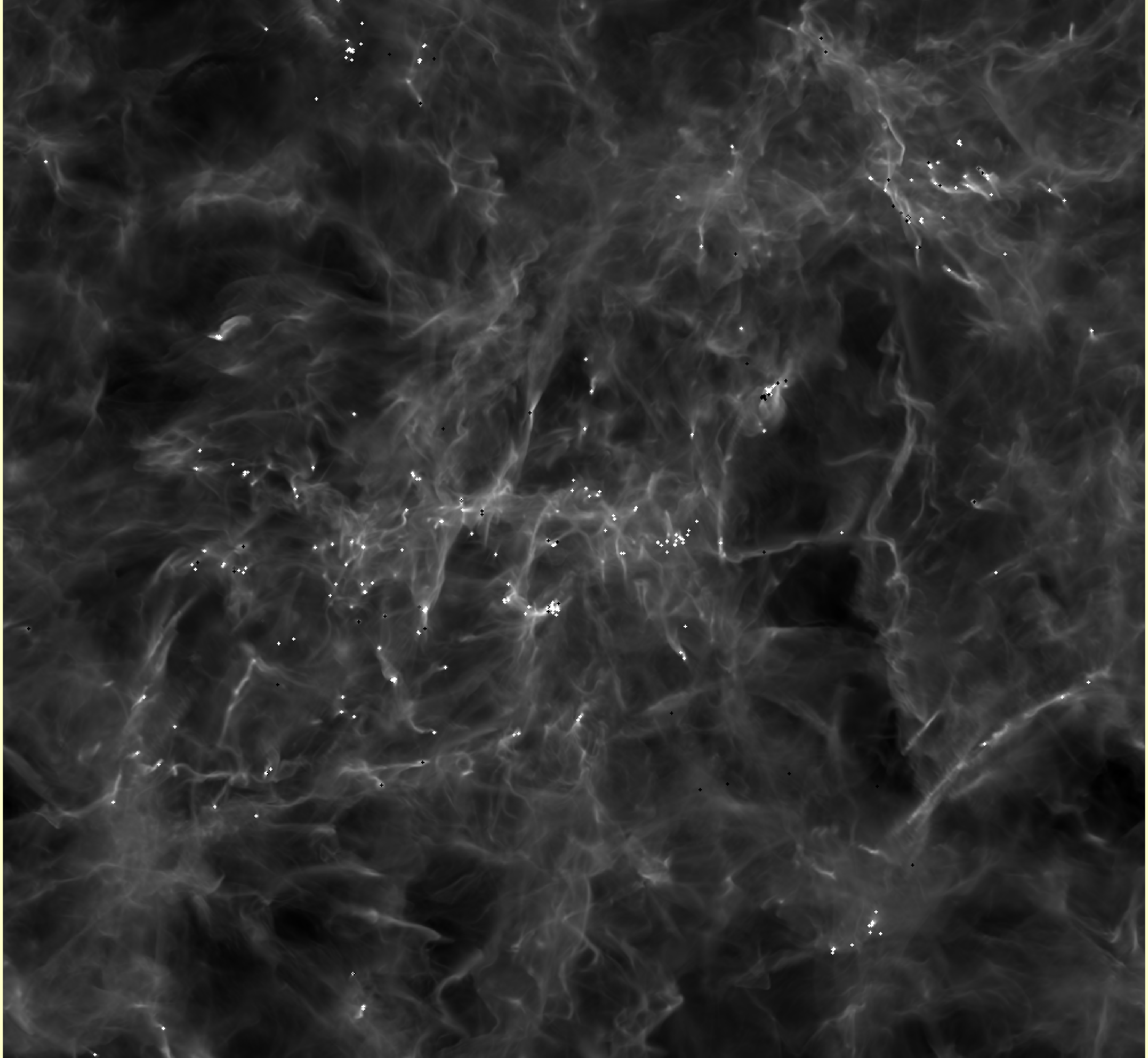
Example (cluster-forming region):

$\alpha_{\mathrm{vir}} = 0.9, \quad \mathcal{M}_{\mathrm{s}} = 18, \quad \beta_{\mathrm{i}} = 22.2$

$L = 1.3\,\mathrm{pc}\,, \quad \langle n \rangle = 3 \times 10^4\,\mathrm{cm}^{-3}, \quad m_{\mathrm{tot}} = 3{,}550\,\mathrm{m}_{\mathrm{sun}}\,, \quad T_{\mathrm{kin}} = 10\,\mathrm{K}$

$\Rightarrow \quad \langle B \rangle = 7.2\,\mu\mathrm{G}\,, \quad \langle B^2 \rangle^{1/2} = 64.5\,\mu\mathrm{G}$





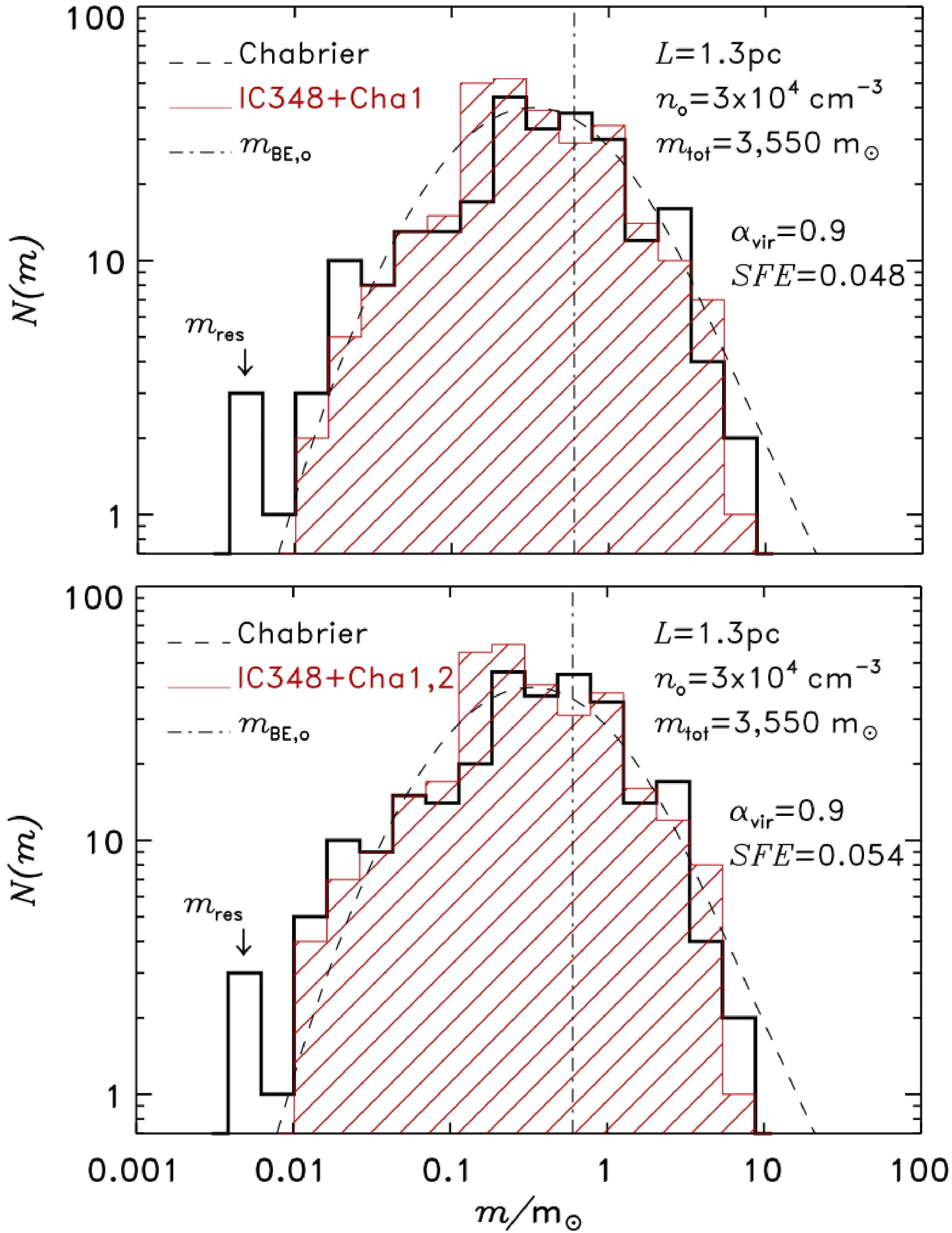
Mass function of sink particles that have stopped accreting

We compare with the combined IMFs of IC348, Cha1, and Cha2 (*Luhman 2003, 2007)* because:

1) **Each star** has been studied spectroscopically
2) They are complete in the wide range ~ 0.01-5.0 m
3) We have appropriate cluster-forming region parameters in this run

We choose a time in the simulation when the total stellar mass is the same as in the observational sample (170 and 190 m , which turns out to be *SFE*~ 5%).

We shift both the Chabrier and Luhman IMFs to larger masses by a factor of 5, $m \rightarrow 1.5m$, assuming that 50% of the sink mass should be lost in jets and outflows.


Chabrier
IC348+Cha1
$m_{BE,o}$
L=1.3pc
n_o=3x10^4 cm^{-3}
m_{tot}=3,550 m$_\odot$
α_{vir}=0.9
SFE=0.048
m_{res}
$N(m)$
Chabrier
IC348+Cha1,2
$m_{BE,o}$
L=1.3pc
n_o=3x10^4 cm^{-3}
m_{tot}=3,550 m$_\odot$
α_{vir}=0.9
SFE=0.054
m_{res}
$N(m)$
$m/m_\odot$

Conclusions

1. The turbulent fragmentation model of the IMF and BD origin *(Padoan and Nordlund 2002, 2004)* captures the fundamental physics:

Random turbulent compressions
→ initial **nonlinear** conditions for prestellar collapse

2. Simulations treating self-gravity ***without sacrificing the turbulence inertial range*** reproduce the observed IMF and BD abundance.

The initial conditions of local prestellar collapse in these simulations are set by the turbulent flow.

3. Significantly smaller numerical resolution results in larger stellar masses, and miss out completely this turbulent BD origin.