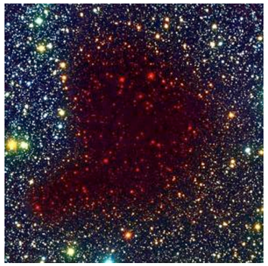
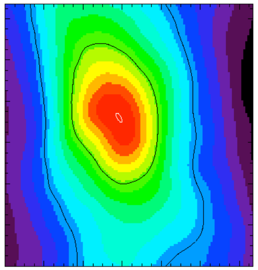
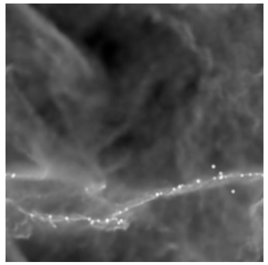
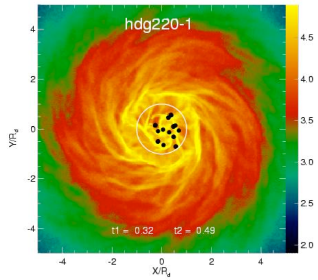
Is the IMF universal?
influence of thermal properties





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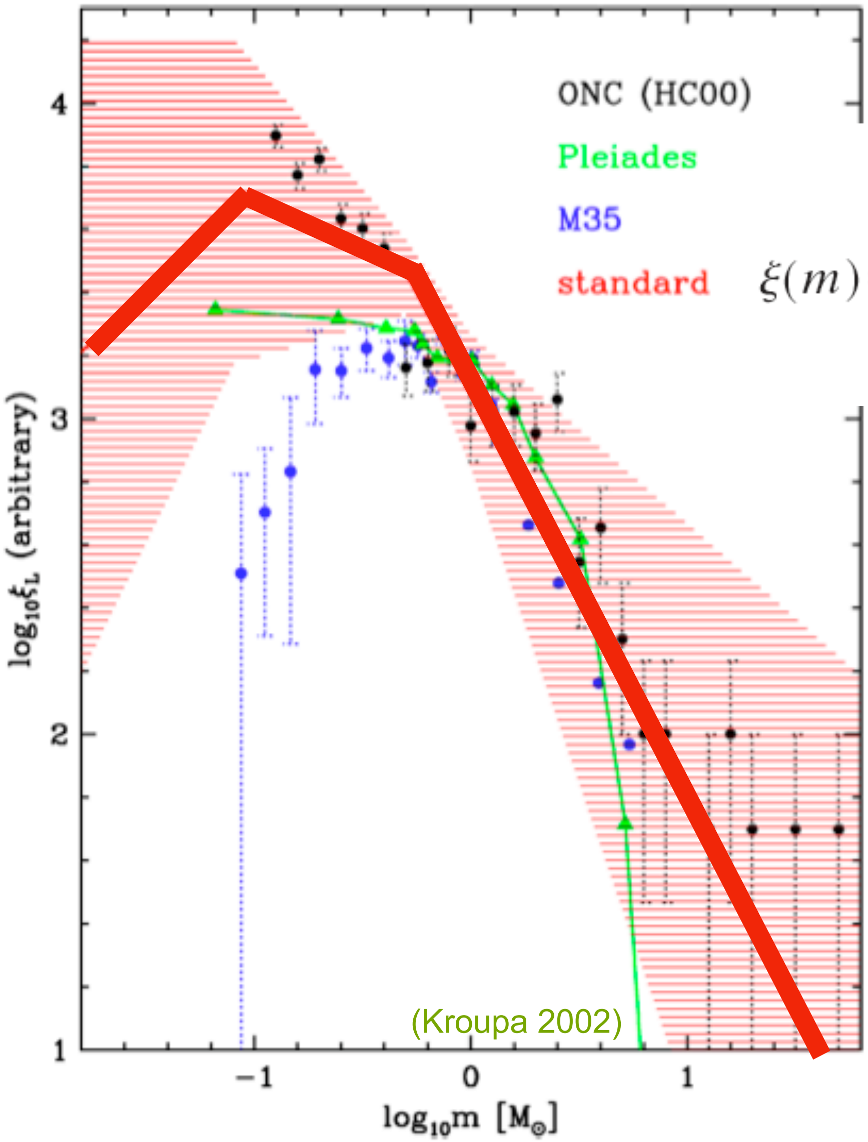
observed IMF



triple power-law description:

$$\xi(m) = \begin{cases} 0.26 \quad m^{-0.3} & \text{for} \quad 0.01 \leqslant m < 0.08 \\ 0.035 \quad m^{-1.3} & \text{for} \quad 0.08 \leqslant m < 0.5 \\ 0.019 \quad m^{-2.3} & \text{for} \quad 0.5 \leqslant m < \infty. \end{cases}$$

observed IMF

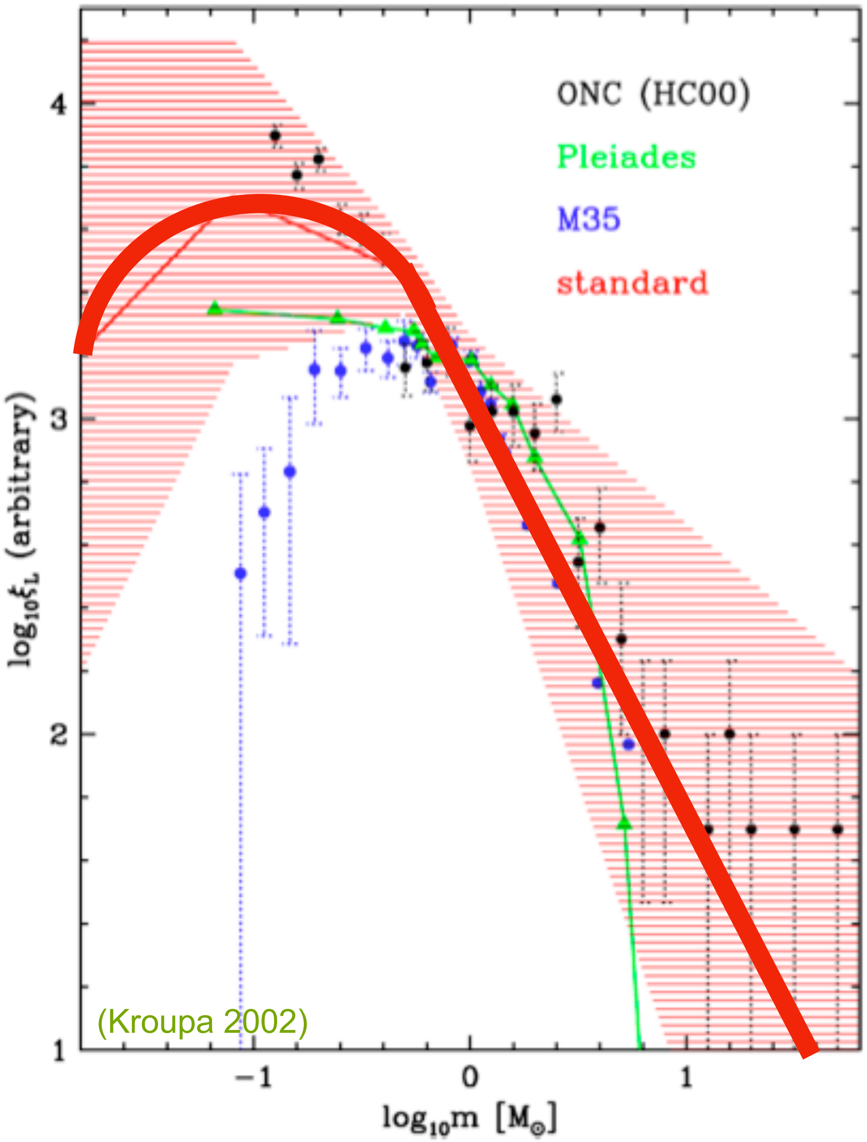
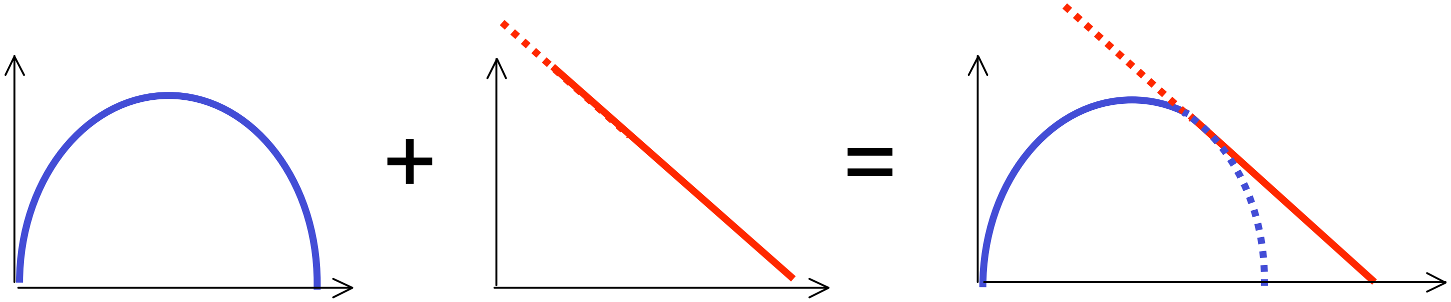


TABLE 1
DISK IMF AND PDMF FOR SINGLE OBJECTS

Parameter	IMF	PDMF
$m \le 1.0\ M_\odot$, $\xi(\log m) = A \exp[-(\log m - \log m_c)^2/2\sigma^2]$		
A	$0.158^{+0.051}_{-0.046}$	
m_c	$0.079^{-0.016}_{+0.021}$	
σ	$0.69^{-0.01}_{+0.05}$	
$m > 1.0\ M_\odot$, $\xi(\log m) = Am^{-x}$		
A	4.43×10^{-2}	
x	1.3 ± 0.3	

(Chabrier 2003)

Plausibility argument for shape

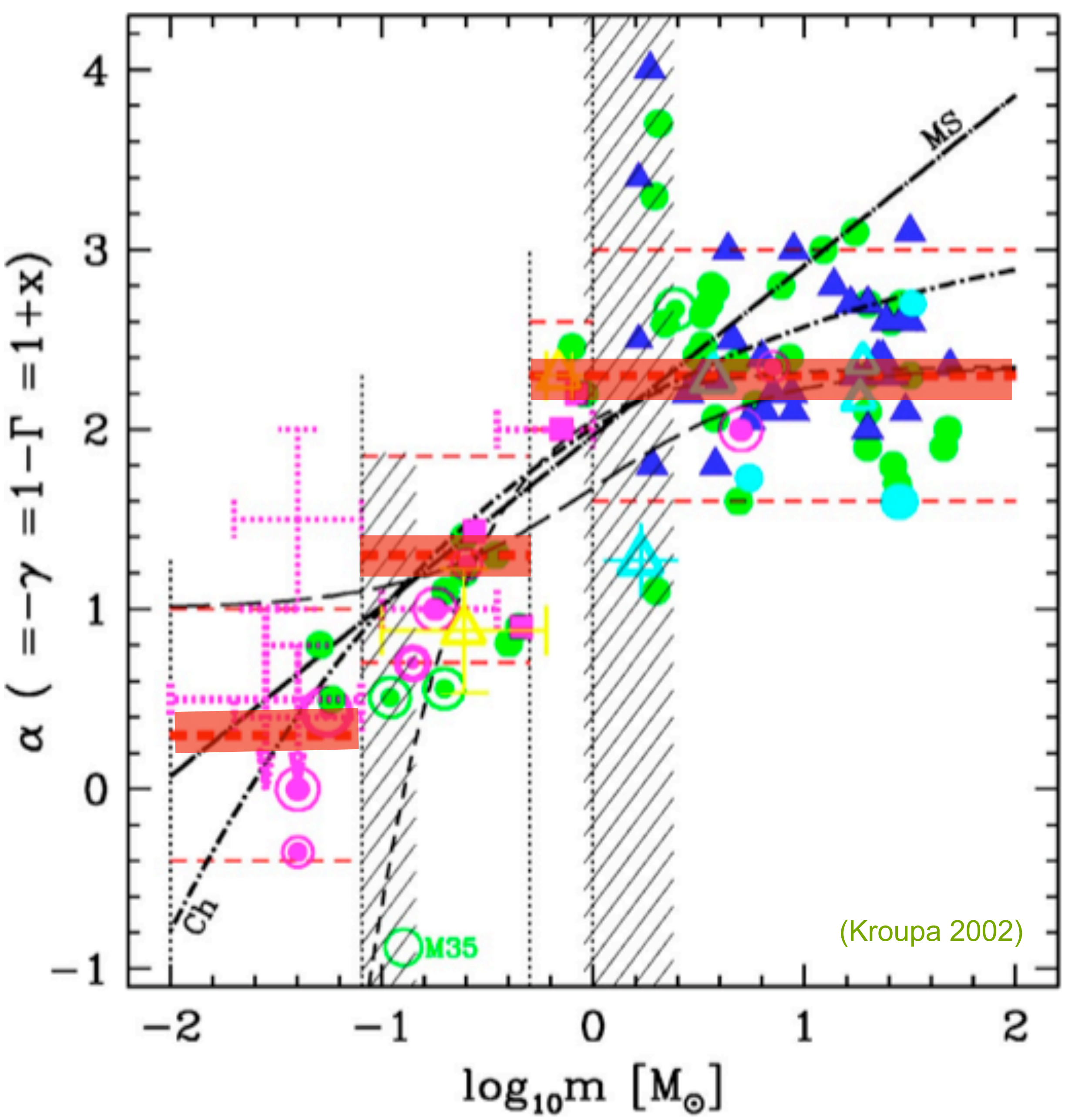


- Supersonic turbulence is scale free process

  → *POWER LAW BEHAVIOR*

- *But also:* turbulence and fragmentation are highly stochastic processes → central limit theorem

  → *GAUSSIAN DISTRIBUTION*



IMF variations in clusters in solar neighborhood can be explained by dynamical processes....

(Kroupa 2001, 2002)

initial mass function

- IMF variations in clusters in solar neighborhood are consistent with stellar dynamical effects.
  ⇒ **IMF in solar neighborhood appears universal!**
- 2 QUESTIONS:
  - **Why is that?**
    (Given the diversity of star forming regions)
  - **Is it really true?**
    (What about truely extreme environments?)

IMF: role of gravo-turbulence

- IMF determined interplay between supersonic turbulence and self-gravity in star-forming gas.
  - interstellar gas is highly *inhomogeneous* --> rapid formation of *molecular clouds* (at stagnation points of convergent flows)
    - *gravitational instability*
    - *thermal instability*
    - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
  - inside *cold clouds:* turbulence is highly supersonic ($\mathcal{M} \approx 1...20$)
    → *turbulence* creates large density contrast,
    gravity selects for collapse
    ⟶ ***GRAVOTUBULENT FRAGMENTATION***
  - *turbulent cascade:* local compression *within* a cloud provokes collapse → formation of individual *stars* and *star clusters*

(e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194
Ballesteros-Paredes et al. 2007, PPV)

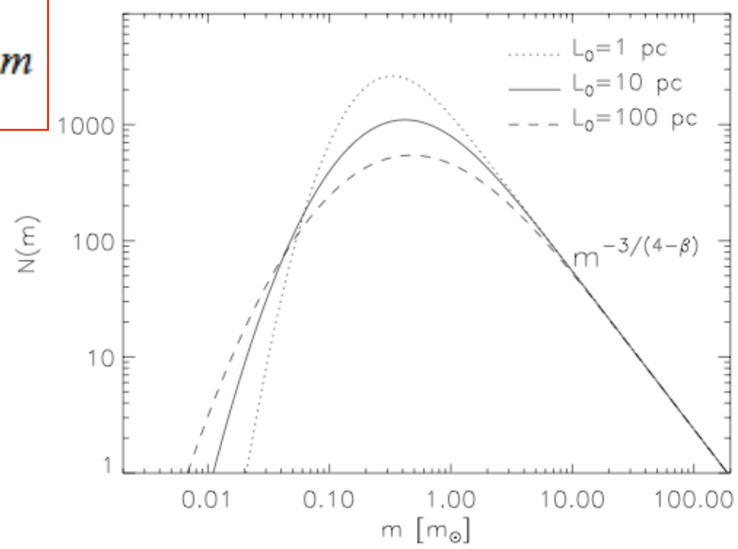
IMF: role of gravo-turbulence

- first analytic theory (based on turbulence, still neglect of effects of gravity on dynamics)
  MHD jump conditions, clumps have constant density, density independent of clump mass, supercritical clumps from convolution with density pdf (Jeans)

$$N(m)\,d\log m \propto m^{-3/(4-\beta)} \left[\int_0^m p(m_J)\,dm_J \right] d\log m$$

$$p(m_J)\,d\ln m_J = \frac{1}{\sqrt{2\pi}\sigma/2} \left(\frac{m_J}{m_{J,0}} \right)^{-2} \times \exp\left[-\frac{1}{2} \left(\frac{\ln m_J - A}{\sigma/2} \right)^2 \right] d\ln m_J$$

$$A = \ln m_{J,0}^2 - \overline{\ln n'} \,.$$



(Padoan & Nordlund 2002, Padoan et al. 2007)

IMF: role of thermodynamics

- IMF determined thermodynamic properties of gas (in addition to turbulence)

Richard Larson in MNRAS, 359, 211 - 222 (2005)

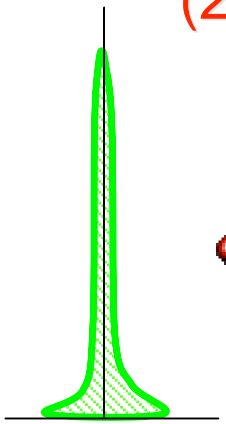
The thermal properties of star-forming clouds have an important influence on how they fragment into stars, and it is suggested in this paper that the low-mass stellar initial mass function (IMF), which appears to be almost universal, is determined largely by the thermal physics of these clouds. In particular, it is suggested that the characteristic stellar mass, a little below one solar mass, is determined by the transition from an initial cooling phase of collapse to a later phase of slowly rising temperature that occurs when the gas becomes thermally coupled to the dust. Numerical simulations support the hypothesis that the Jeans mass at this transition point plays an important role in determining the peak mass of the IMF.

(see also Y. Li et al. 2003, Jappsen et al. 2005, Bonnell et al. 2006)

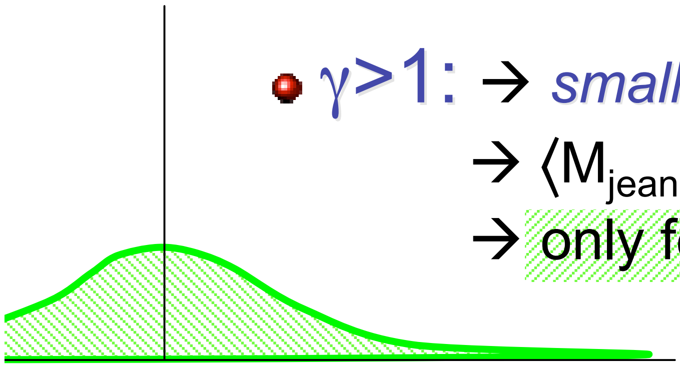
fragmentation depends on EOS

(1) $p \propto \rho^{\gamma} \rightarrow \rho \propto p^{1/\gamma}$

(2) $M_{jeans} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}$

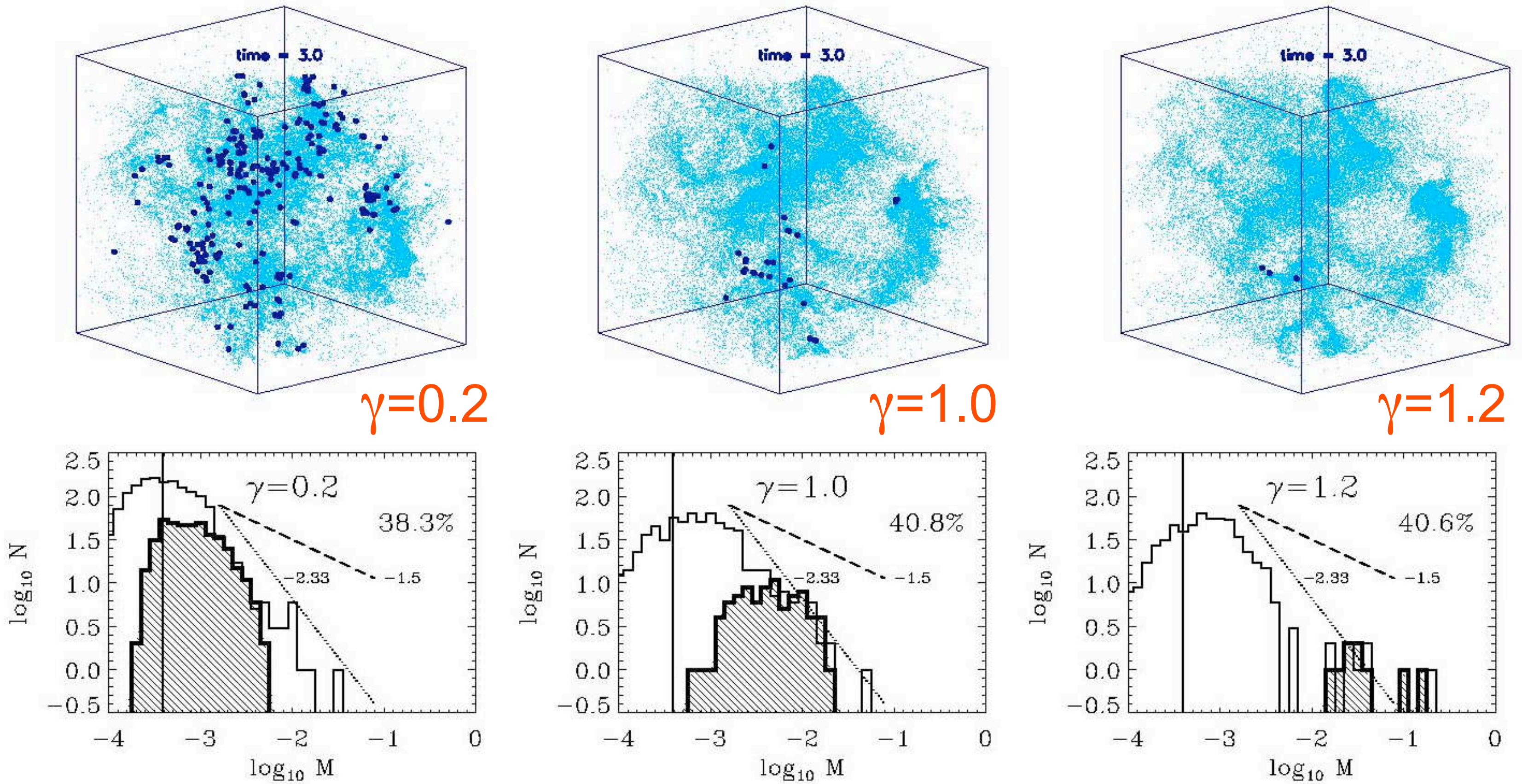


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

fragmentation depends on EOS



for γ<1 fragmentation is enhanced → *cluster of low-mass stars*

for γ>1 it is suppressed → formation of *isolated massive stars*

(from Li, Klessen, & Mac Low 2003, ApJ, 592, 975)

possible implications

- degree of fragmentation depends on *EOS!*

- polytropic EOS: $p \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars

(see Li, Klessen, & Mac Low 2003, ApJ, 592, 975; Kawachi & Hanawa 1998; Larson 2003; also Jappsen, Klessen, Larson, Li, Mac Low, 2005, 435, 611)

- implications for extreme environmental conditions

  - expect Pop III stars to be massive and form in isolation
    but when is the transition from Pop III to “normal” Pop II/2 *???*

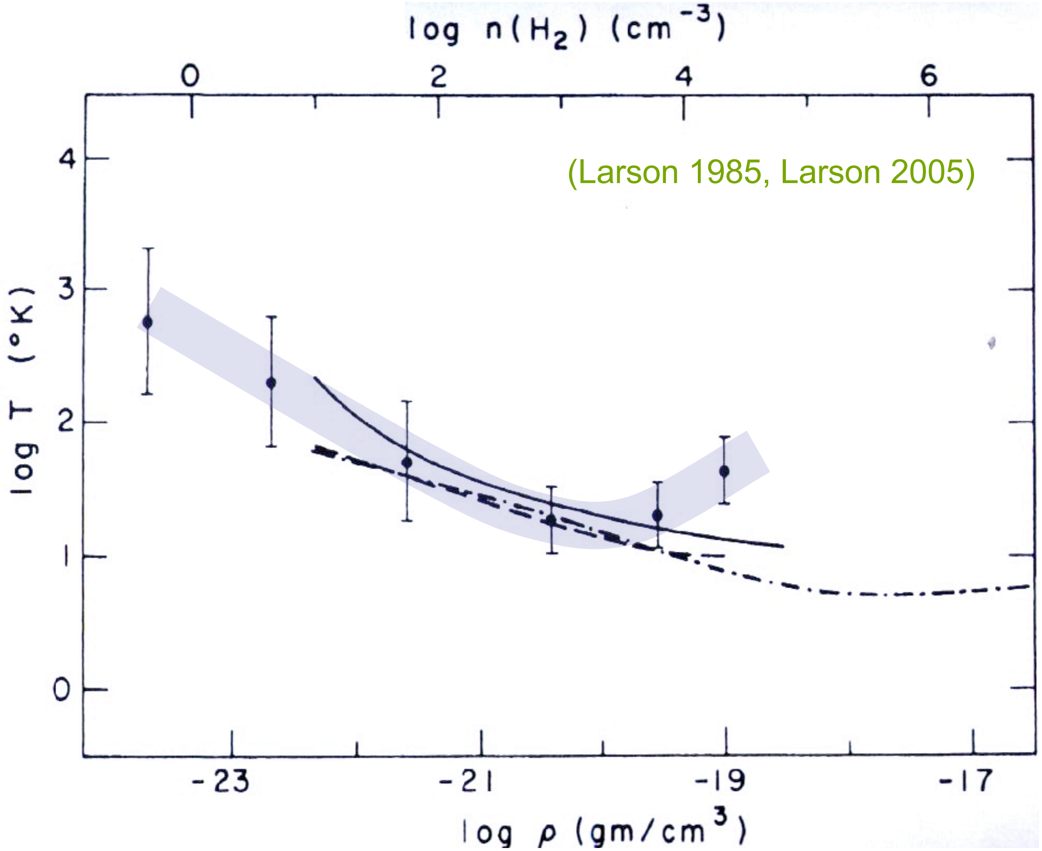
    (Bromm, Larson, Coppi 2002, Smith & Sigurdsson 2007, Omukai et al 2005, Schneider et al. 2006, Clark, Glover, Klessen 2007)

  - expect IMF variations in warm & dusty starburst regions
    (Spaans & Silk 2005; Klessen, Spaans, & Jappsen 2007)

EOS for solar neighborhood

below 10^{-18} gcm^{-3}: ρ ⬆ ⇨ T ⬇

above 10^{-18} gcm^{-3}: ρ ⬆ ⇨ T ⬆

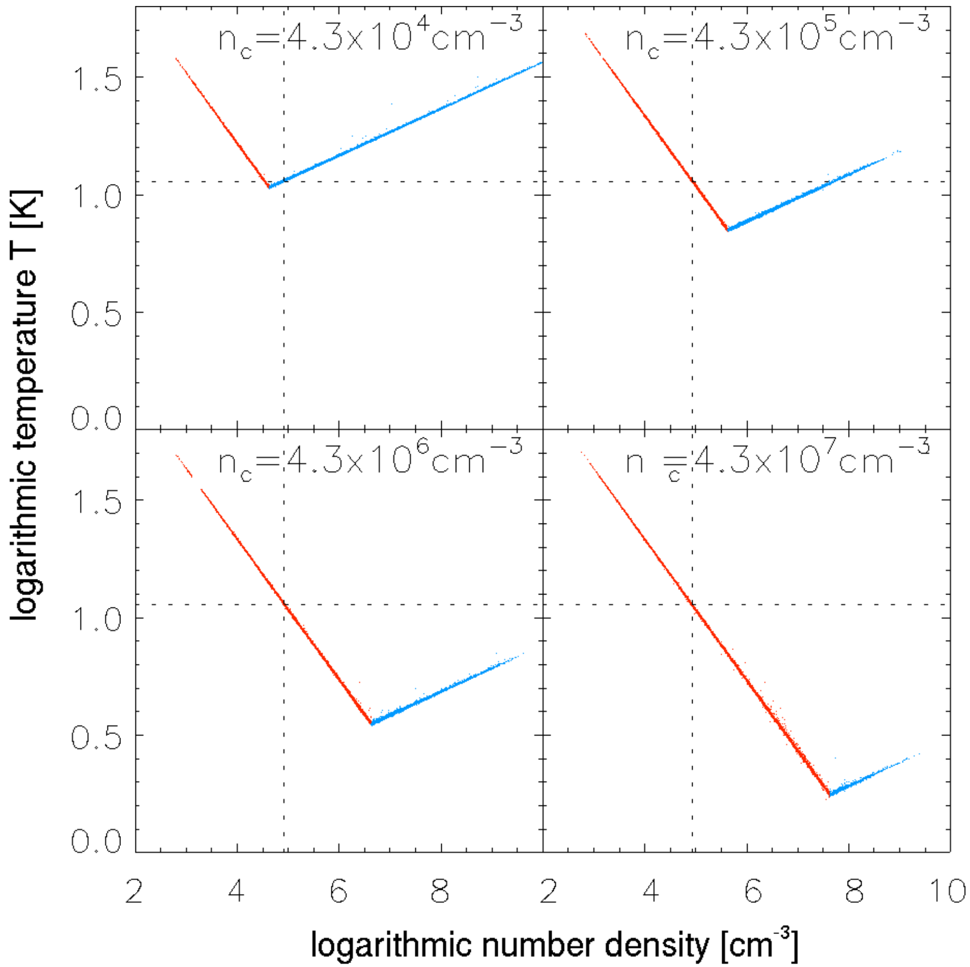


IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

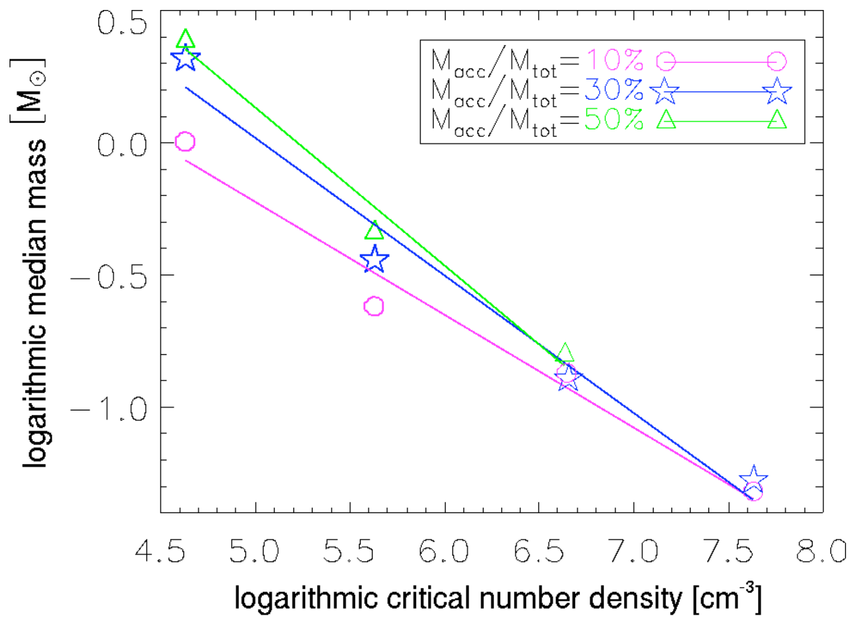
$$T \sim \rho^{\gamma-1}$$

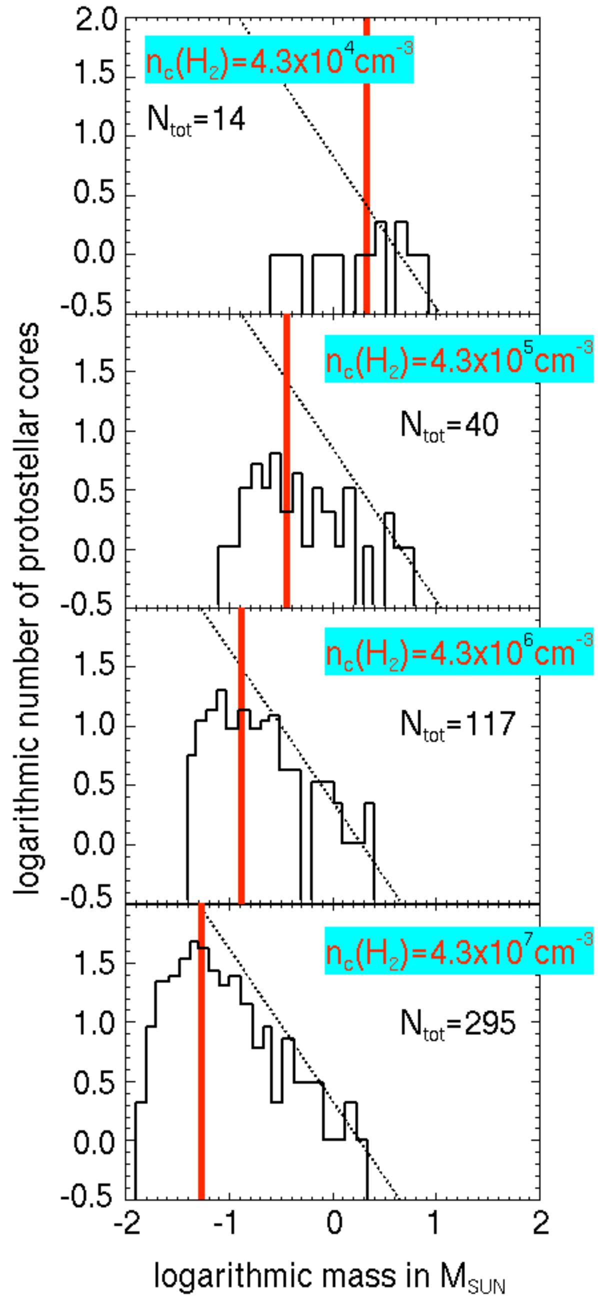


(Jappsen et al. 2005)

IMF from simple piece-wise polytropic EOS

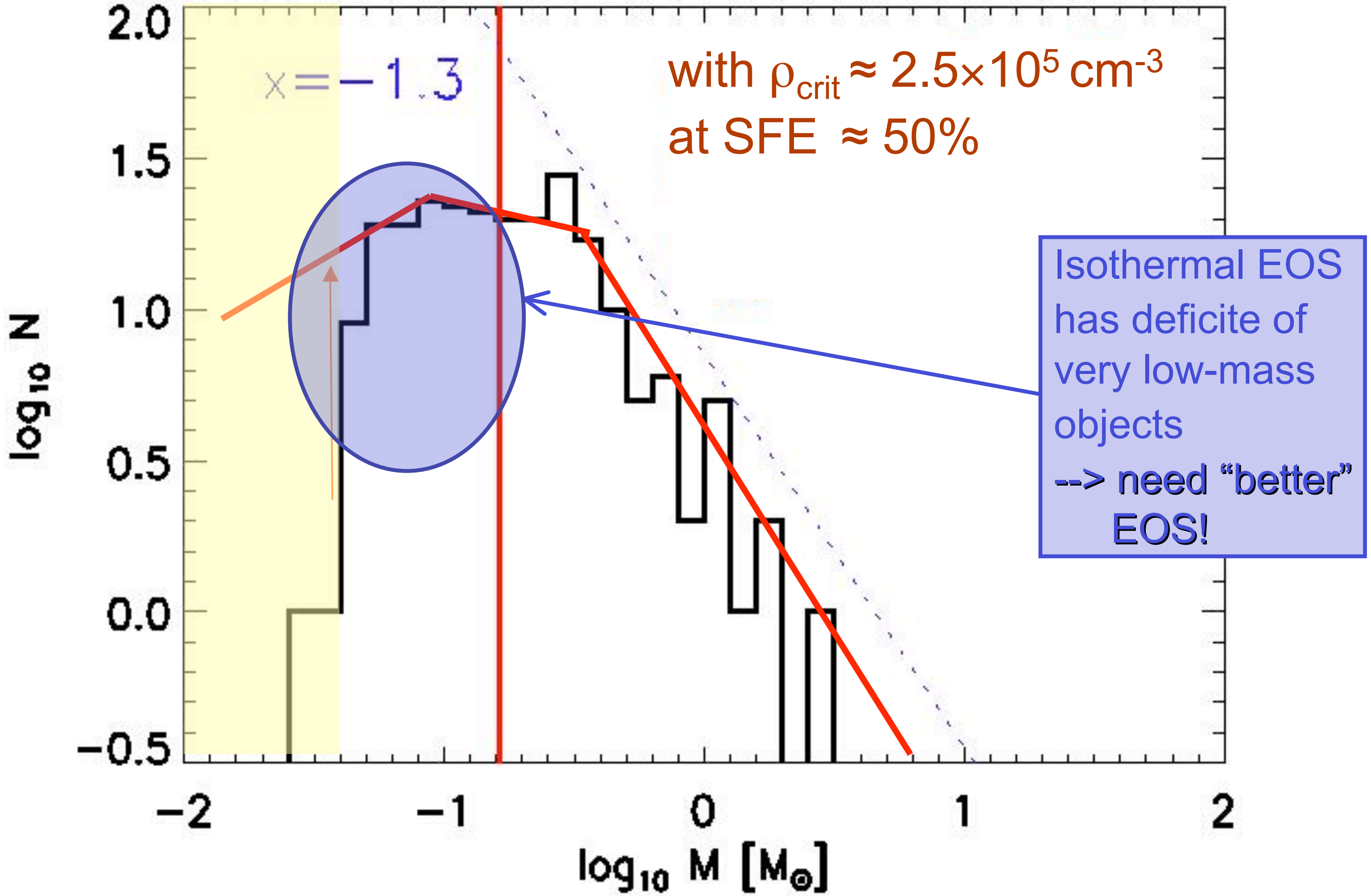
critical density ⬆ ⇨ median mass ⬇





(Jappsen et al. 2005)

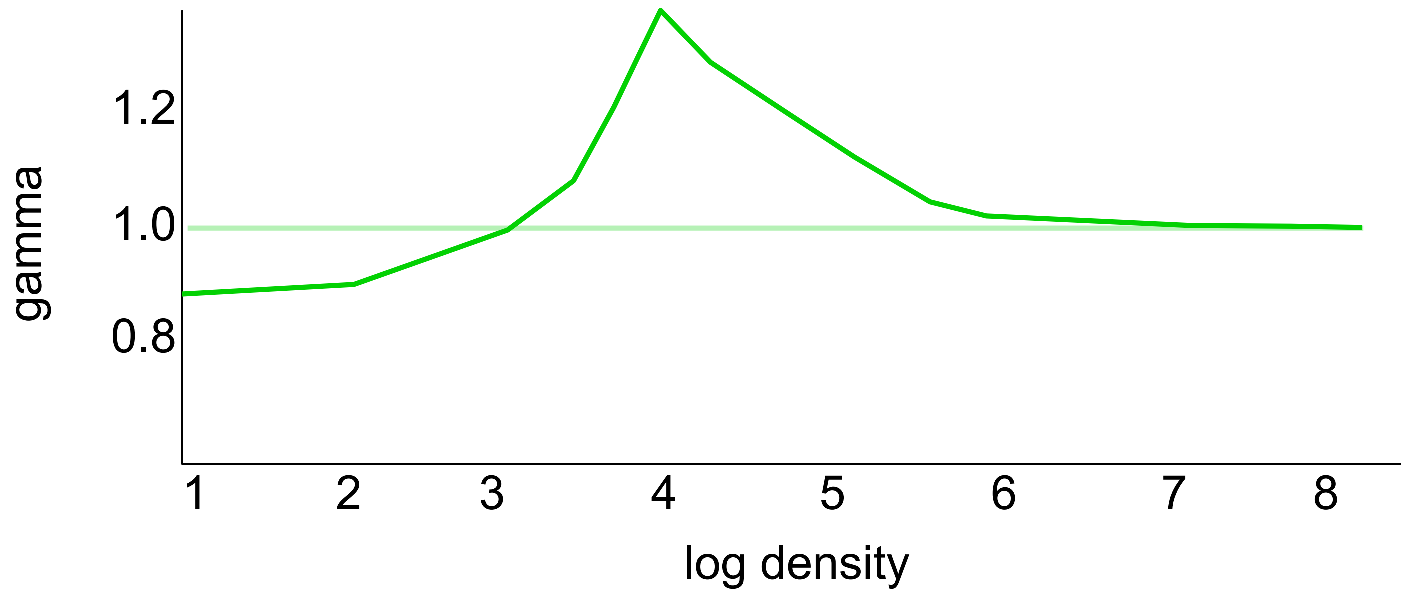
IMF in nearby molecular clouds



(Jappsen et al. 2005, A&A, 435, 611)c

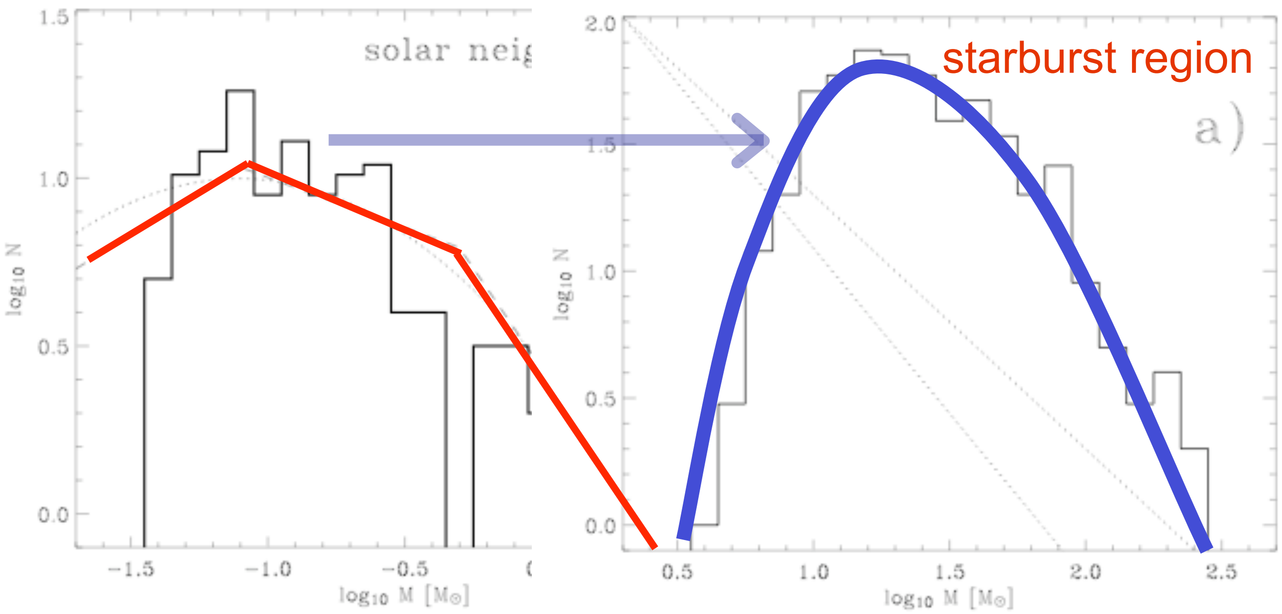
IMF in starburst galaxies

- Nuclear regions of starburst galaxies are extreme:
  - hot dust, large densities, strong radiation, etc.
- Thermodynamic properties of star-forming gas differ from Milky Way --> Different EOS!
  (see Spaans & Silk 2005)

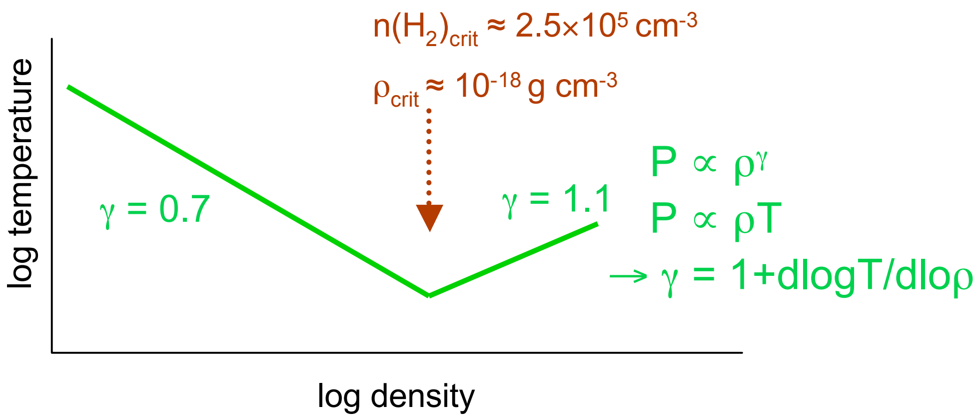


IMF in starburst galaxies

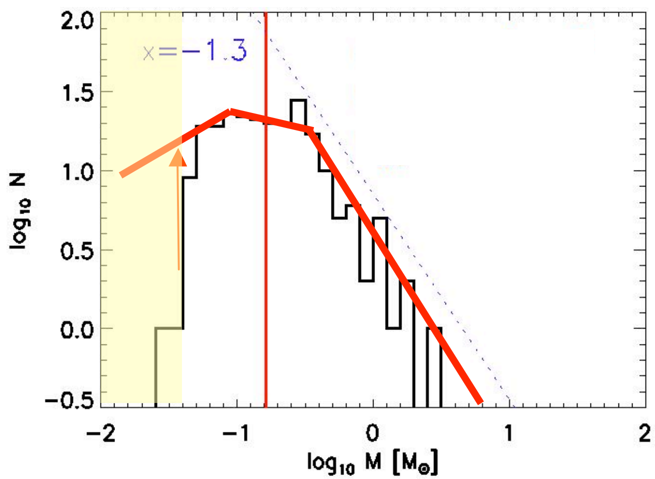
- Starburst EOS --> top-heavy IMF
  (Klessen, Spaans, Jappsen, 2007)



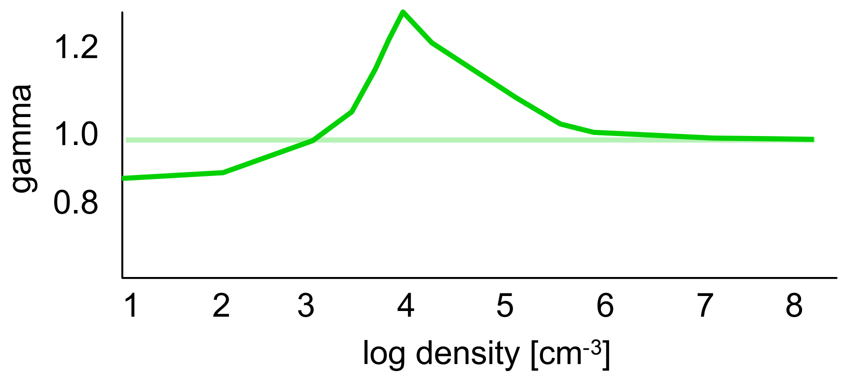
fragmentation depends on EOS



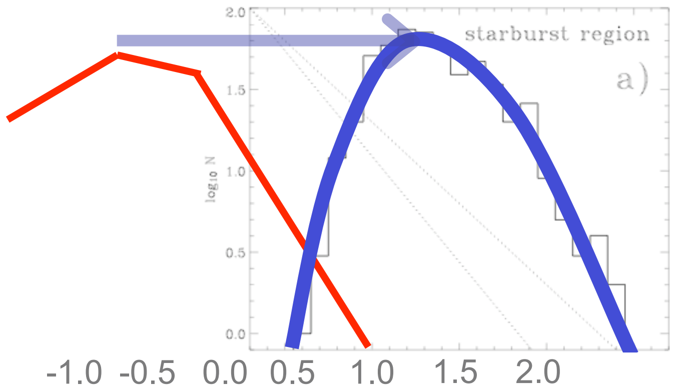
(Larson 2005)



(Jappsen et al. 2005)

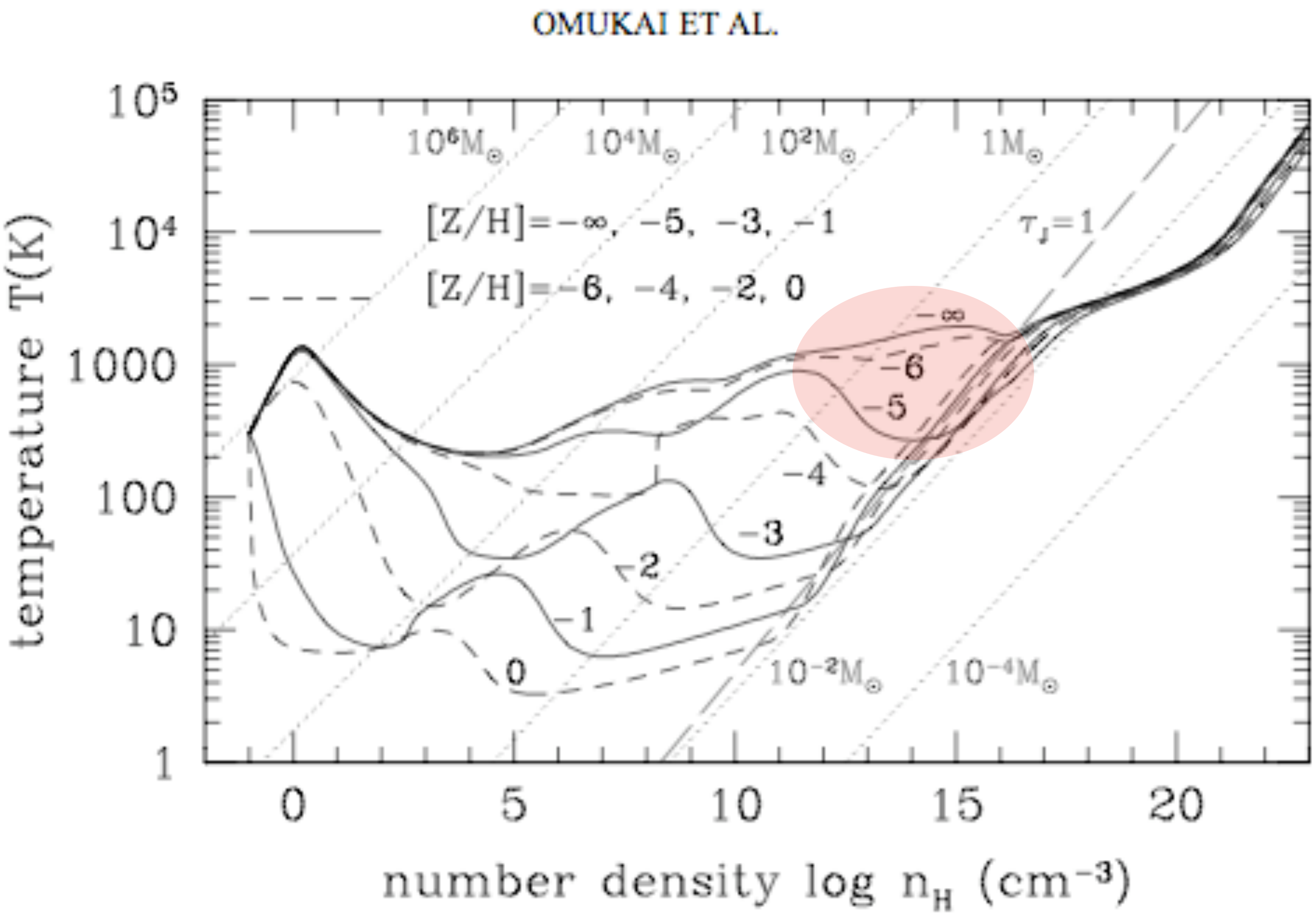


(Spaans & Silk 2005)



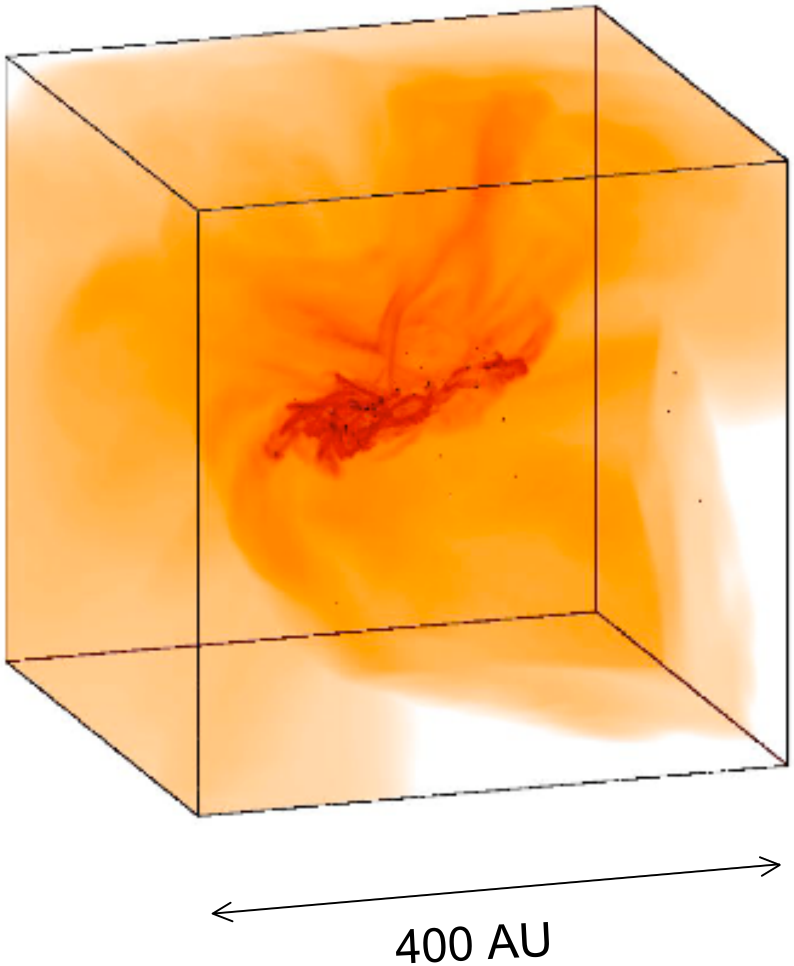
(Klessen et al. 2007)

transition: Pop III to Pop II/2



(Omukai et al. 2005, Clark et al. 2007)

dust induced fragmentation at $Z=10^{-5}$

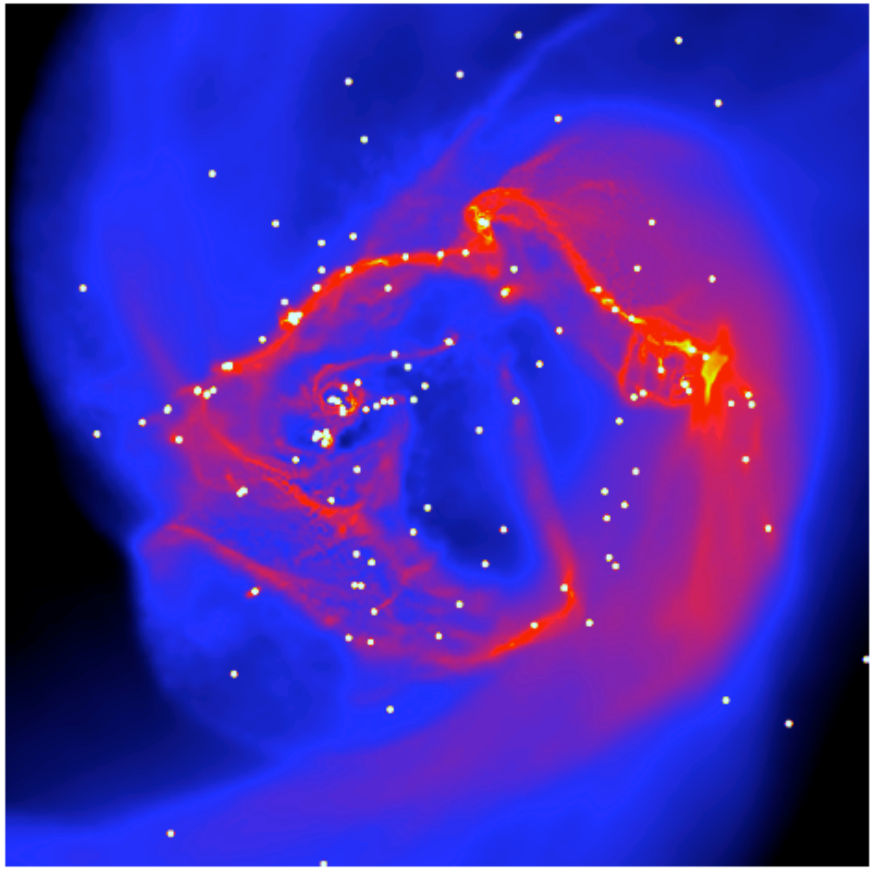


dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 M_{sun}
- cluster VERY dense $n_{stars} = 2.5 \times 10^9\ pc^{-3}$
- fragmentation at density $n_{gas} = 10^{12} - 10^{13}\ cm^{-3}$

(Clark et al. 2007)

dust induced fragmentation at $Z=10^{-5}$



400 AU

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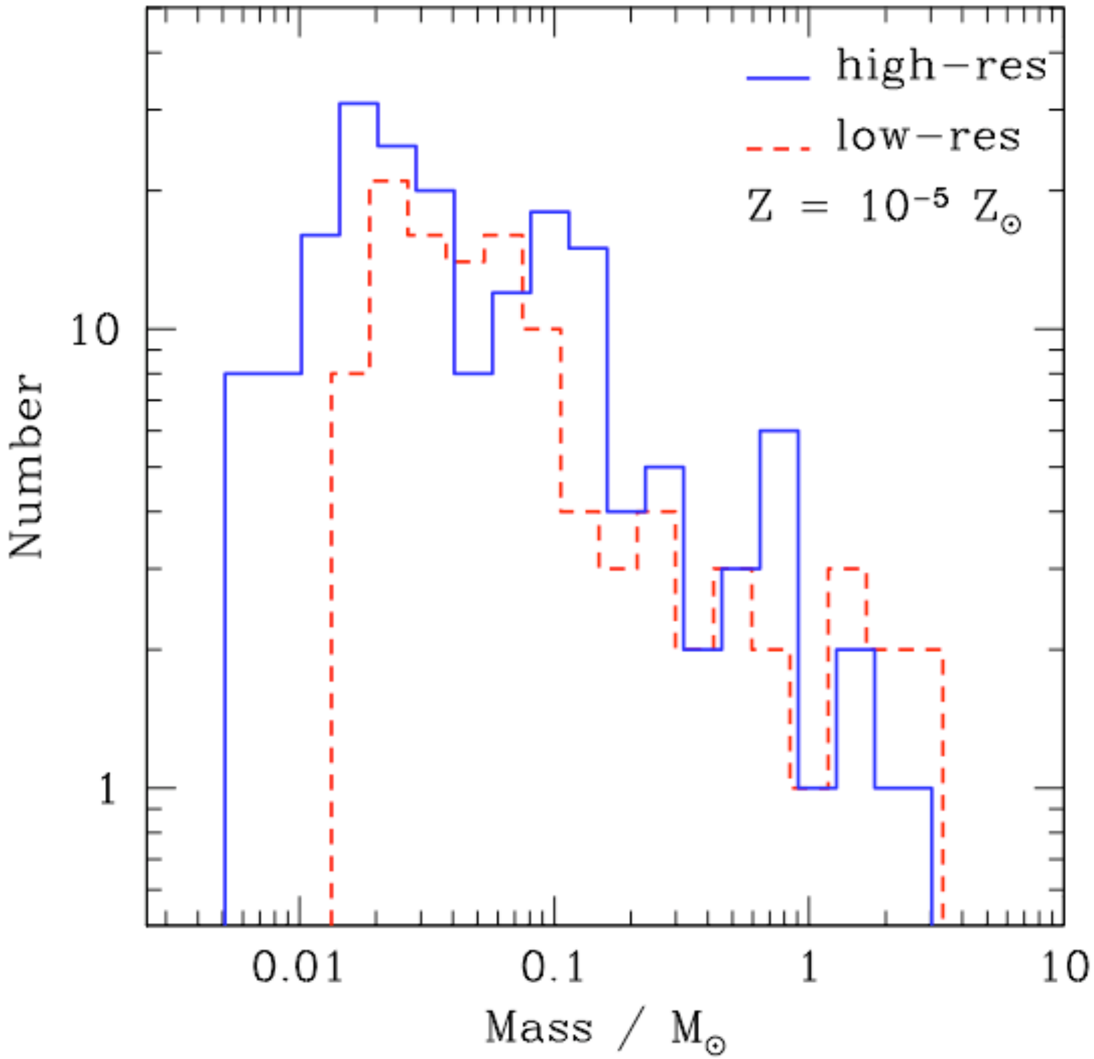

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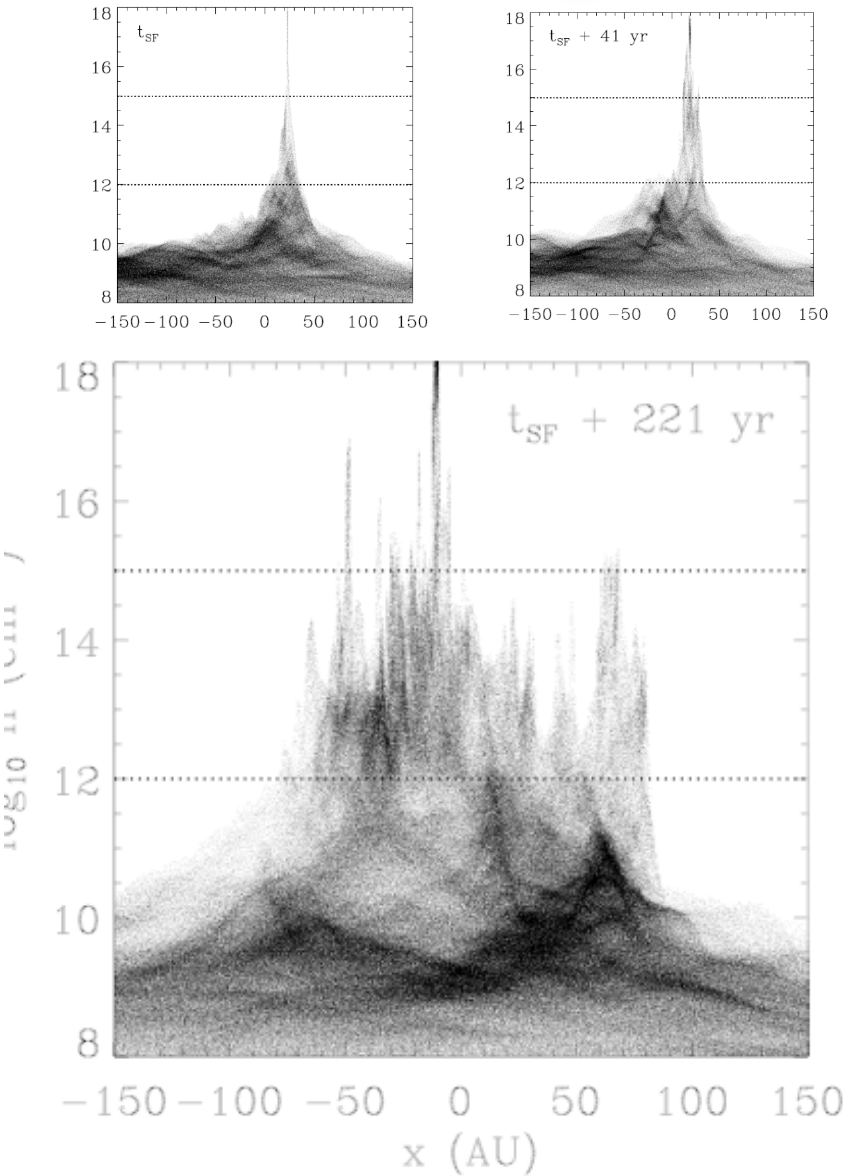

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(Clark et al. 2007)

summary

- basic parameters of IMF can be explained by interplay between gravity and turbulence

- thermodynamic properties of gas are very important (balance between heating and cooling determines compressibility of gas and, hence, probability for gravitational collapse)
  - universality in solar neighborhood
  - dependency on metallicity (transition Pop III -> Pop II/2)