Radiative Feedback and the Origin of the IMF

Mark Krumholz (UC Santa Cruz)

Fire Down Below, Kavli Institute for Theoretical Physics
April 18, 2014

Overview

- Introduction
- Models
  - The powerlaw tail
  - The characteristic stellar mass
- Summary

Brief plug: parts of this talk discussed in much more detail in the review "The Big Problems in Star Formation", *Physics Reports*, in press, arXiv:1402.0867

Historical Aside

until its absence is proved. For many years interstellar matter has figured in astronomical investigations, but chiefly with a *negative* importance. Three examples

(1) In

clusters

there is

(2) St

diminish

compens

(3) In

if the controlling gravitational field

Diffuse Matter in Interstellar Space.

Systematic Distribution of Activity-areas on the Sun.

Nov. 1926.] *Correspondence.* 335

it may be possible to argue that the explorer's temperature must be 1500° when the fire is going, but am I bound to believe that it must have been 1500° before the fire was lighted? The absence of stars from the primæval mass of diffuse matter robs Prof. Eddington's figure of 10,000° of all significance.

Prof. Eddington's case that the condensations are nebulæ is, I suppose, that he calculated that their mass must be between 470,000 ☉ and 730,000 ☉. But he obtained these masses merely by calculating what masses of his assumed medium would lie within spheres of radii 136 and 158 parsecs. He has since admitted that these distances were "a pre-arranged adjustment" and "not a prediction from theory." In the light of this admission, his only argument in favour of the condensations being nebulæ is seen to be that he made them so by a "pre-arranged adjustment" at the beginning of his lecture. For him to try, after making this admission, to pretend that I "fell into a trap" in supposing the condensations to be stars (not nebulæ) seems extraordinarily naïve.

The extract from Prof. Eddington's letter which I have already quoted further charges me with having in 1905 "obtained a density 10,000 times too great." Feeling pretty confident that he could not substantiate this charge, I wrote to him (privately, but warning him I might quote his reply) asking him for chapter and verse. In reply he refers me to a paragraph in my 1905 paper (p. 99, "To examine . . ."), which contains no calculation of density at all, and adds (italics mine): "I think that the sentence in my letter states correctly what *would have been the result of my falling* into the same trap." He here drops in private the charge he had made in public that *I had made* a 10,000 miscalculation, and replaces it by the entirely irrelevant statement that *he himself might have made* a 10,000 miscalculation.

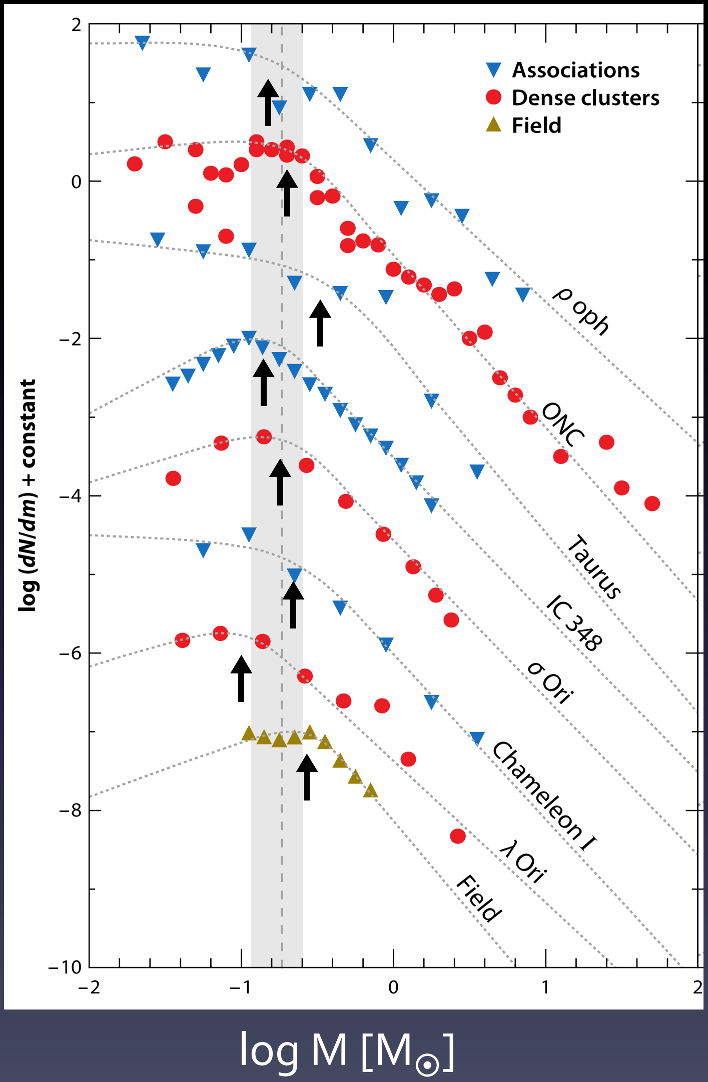
May I conclude by assuring Prof. Eddington it would give me great pleasure if he could remove a long-standing source of friction between us by abstaining in future from making wild attacks on my work which he cannot substantiate, and by making the usual acknowledgments whenever he finds that my previous work is of use to him? I attach all the more importance to the second part of the request, because I find that some of the most fruitful ideas which I have introduced into astronomical physics—*e.g.*, the annihilation of matter as a source of stellar energy, and highly dissociated atoms and free electrons as the substance of the stars—are by now fairly generally attributed to Prof. Eddington.

With apologies for so long a letter,

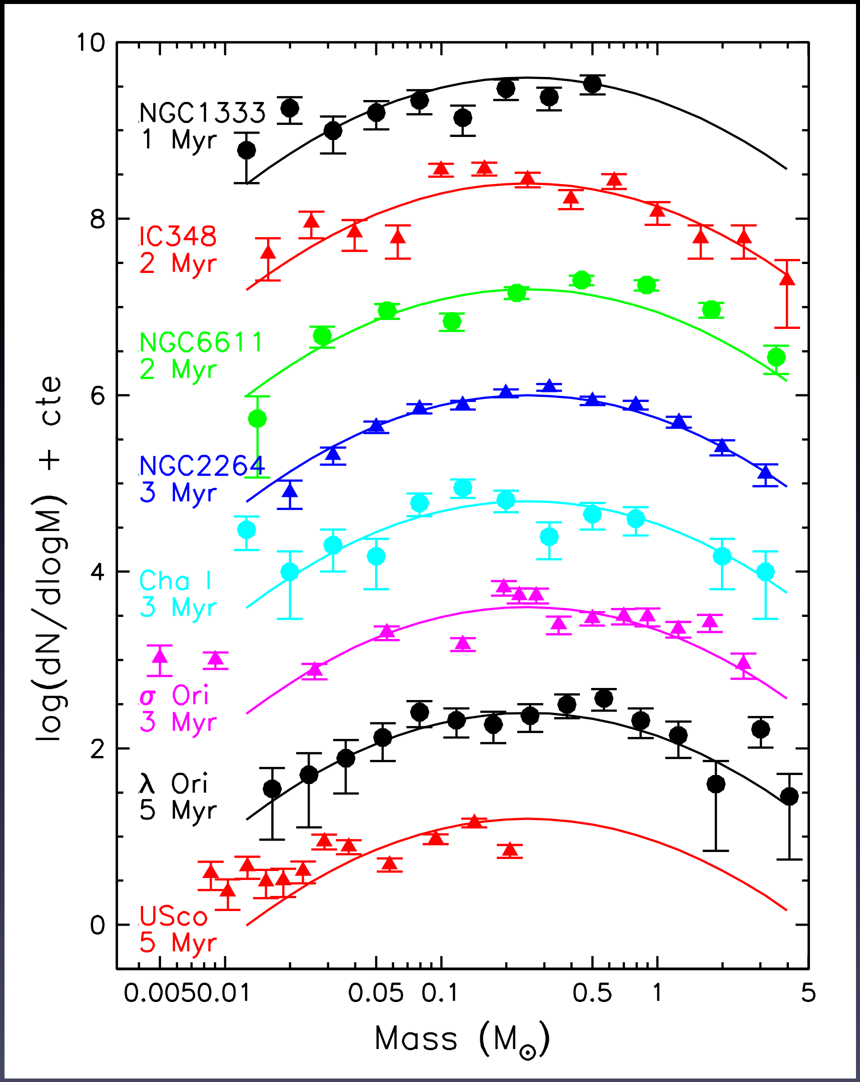
I am, Gentlemen,
Yours faithfully,
J. H. Jeans.

1926, Oct. 26.

Many IMFs, One IMF

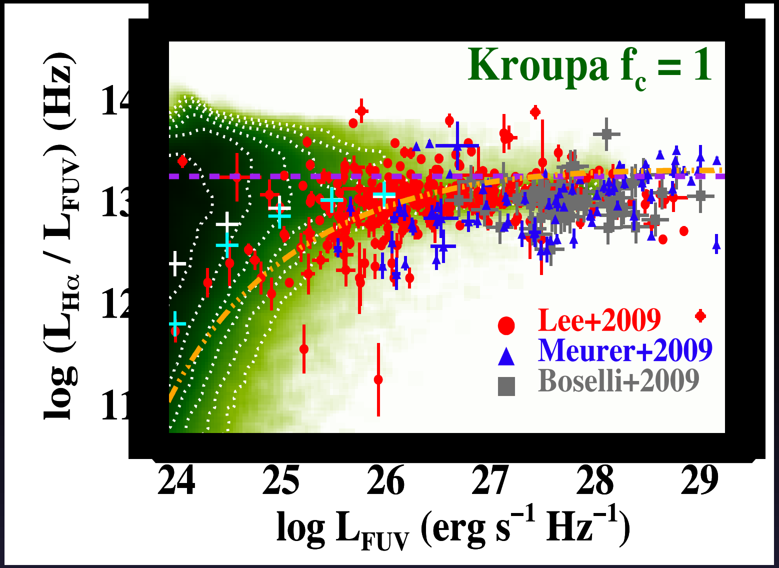


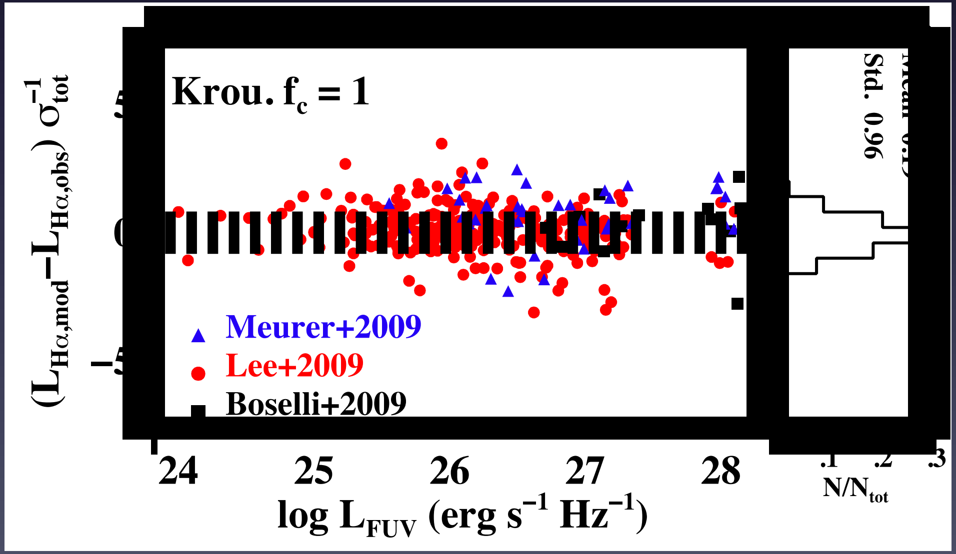
Bastian+ (2010)



Offner+ (2014)

Dwarfs: Hα Emission





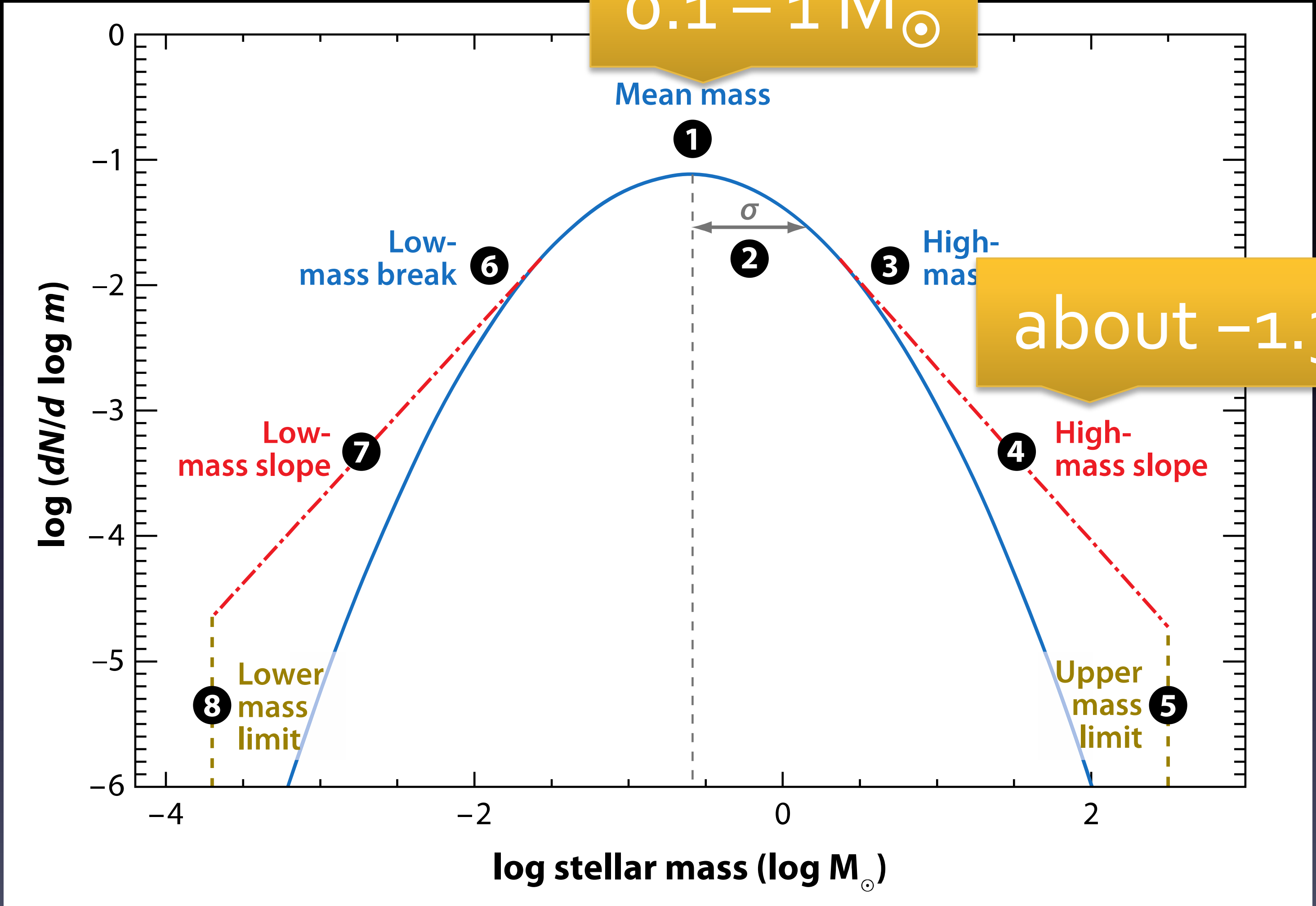
- Hα/FUV and Hα EW: proxies for upper IMF
- Dwarfs are Hα-deficient: IMF variation? (Hoversten & Glazebrook 2008; Lee+ 2009; Meurer+ 2009; Boselli+ 2009)
- No! Turns out to be a normal IMF, coupled to low SFR + clustering

Fumagalli+ (2011); also see da Silva+ (2012), Weisz+ (2012), Andrews+ (2013)

IMF Observations: Summary

- IMF is a powerlaw at high masses, with a turnover or plateau at lower masses
- In resolved stellar populations, both slope and turnover (at ~0.1 - 1 $M_\odot$) consistent with being universal
- Tentative evidence for lower turnover mass in giant ellipticals (P. van Dokkum's talk)
- Weaker evidence for dwarfs at low mass end (Geha et al. 2013)

Theory: What is to be Explained

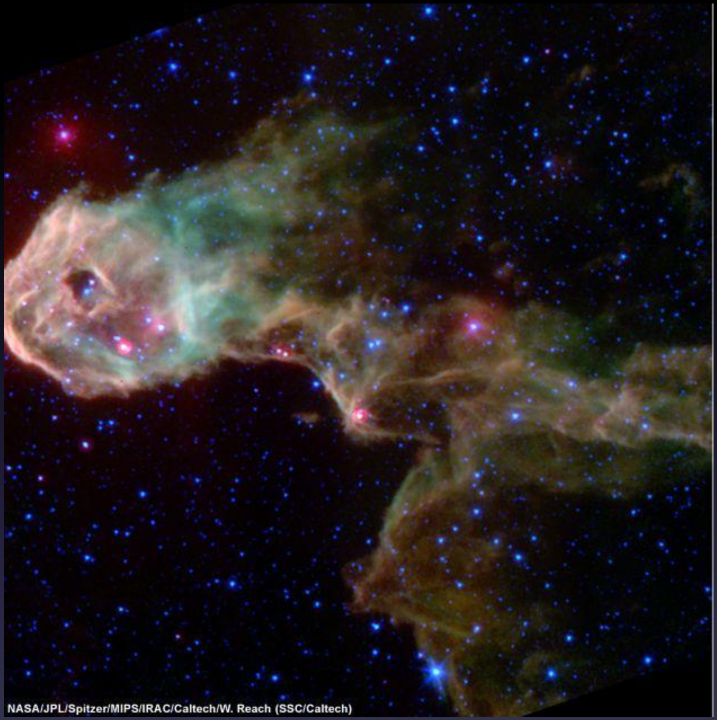


$0.1 - 1\, M_\odot$

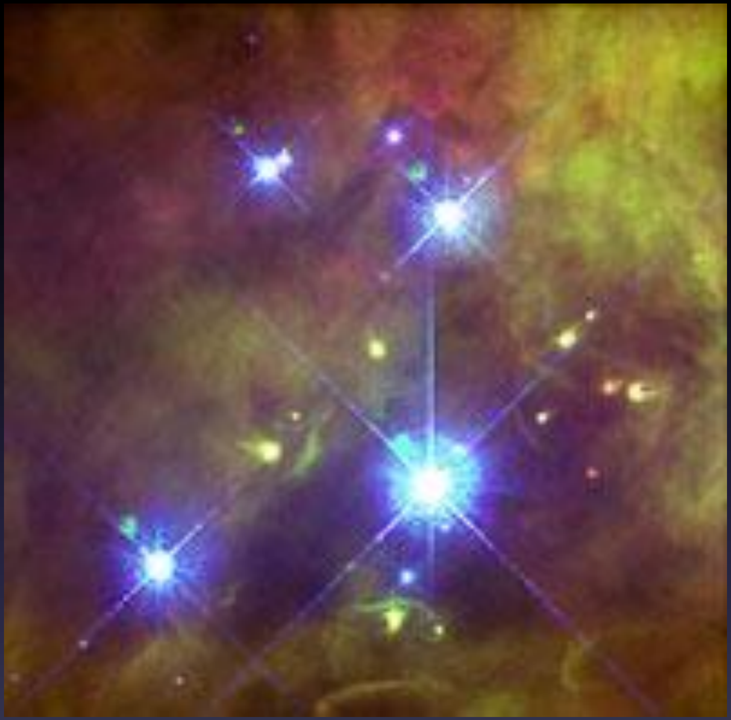
about −1.3

Schematic of the IMF (Bastian+ 2010)

Assembling the IMF



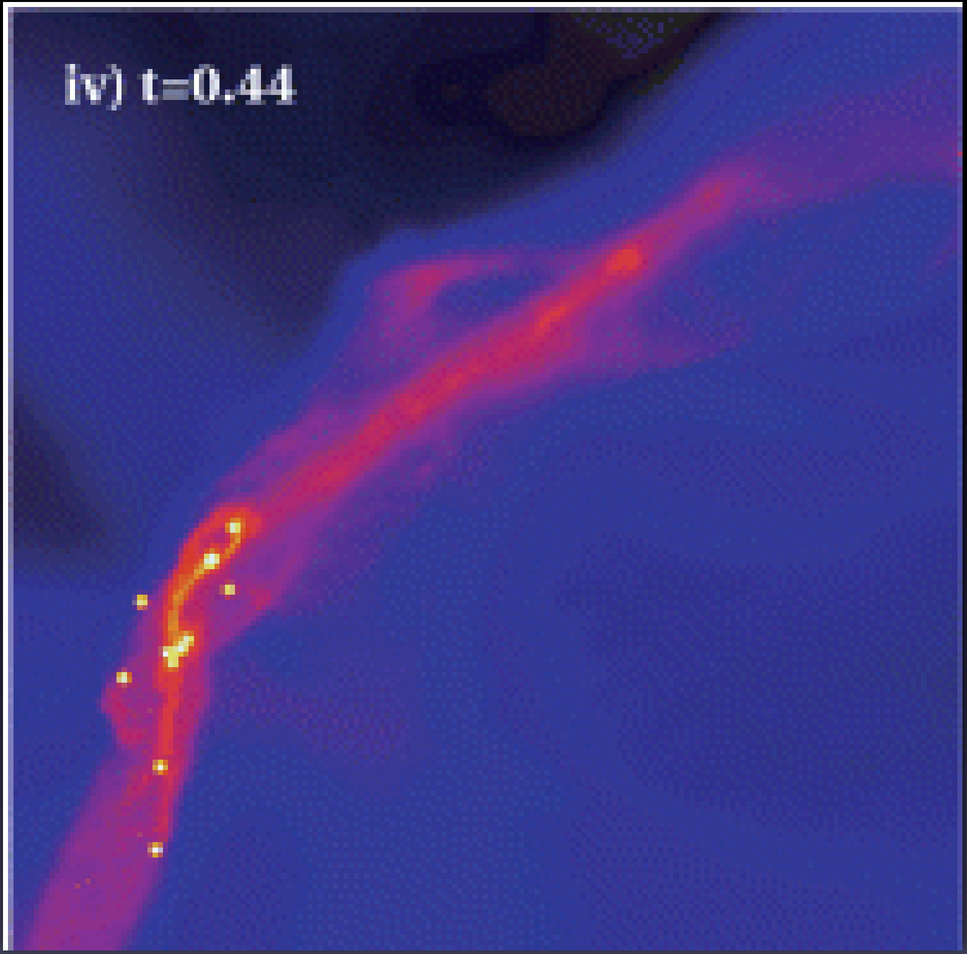
NASA/JPL/Spitzer/MIPS/IRAC/Caltech/W. Reach (SSC/Caltech)



Part I: The Tail

The Fragmentation Problem

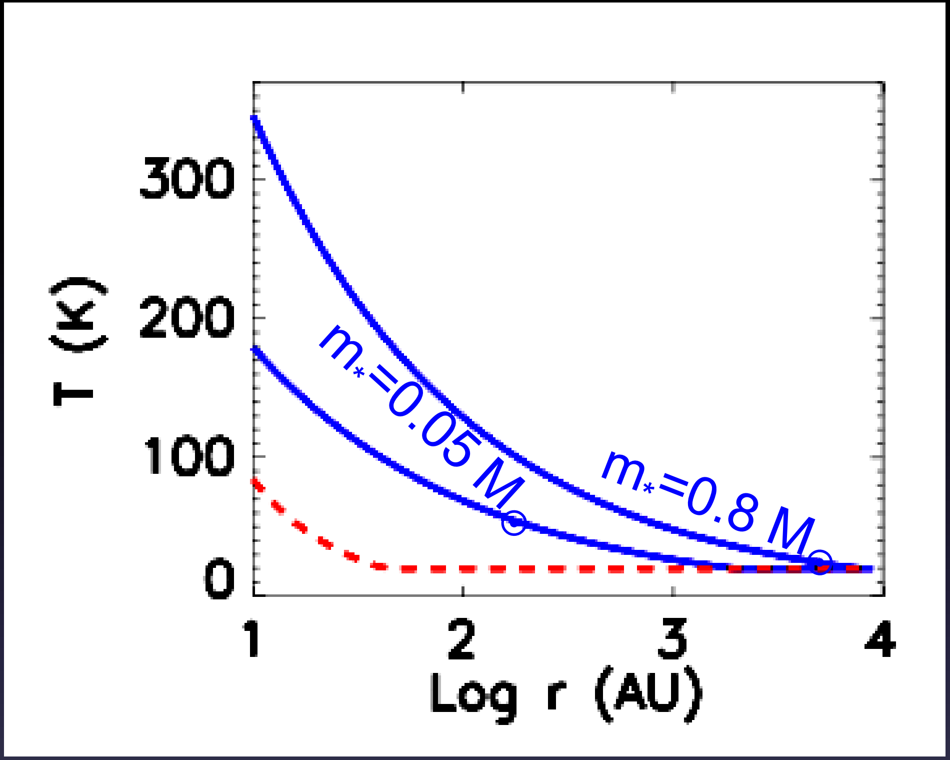
- Fragmentation scale is $M_J \sim c_s^3 / G^{3/2} \rho^{1/2} \sim 1\ M_\odot$
- Why don't ~100 M_J cores sub-fragment?



Hydrodynamic simulation of the fragmentation of a massive core (Dobbs et al. 2005)

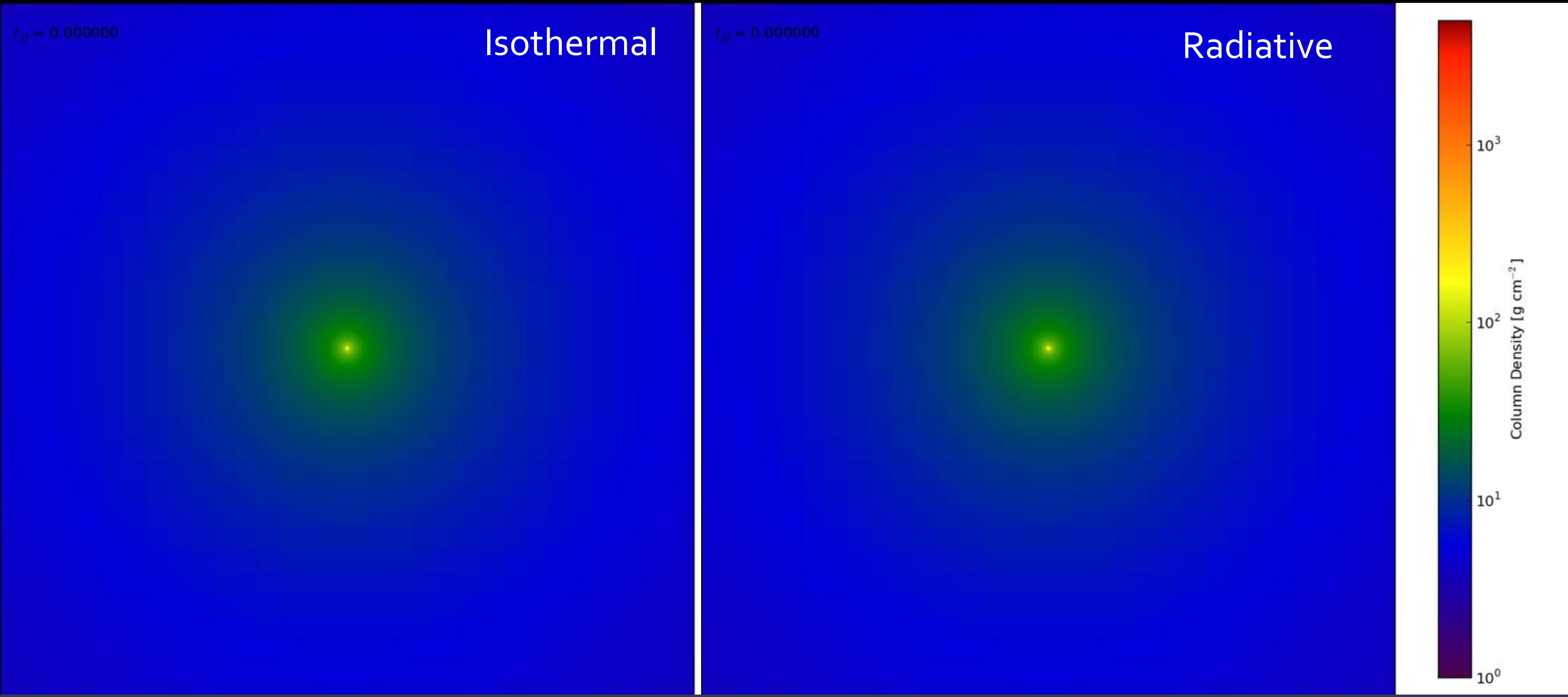
Fragmentation and Radiation

- Accretion can produce > 100 $L_\odot$ even for 0.1 $M_\odot$ stars
- Extra energy heats gas, raises Jeans mass, inhibiting fragmentation



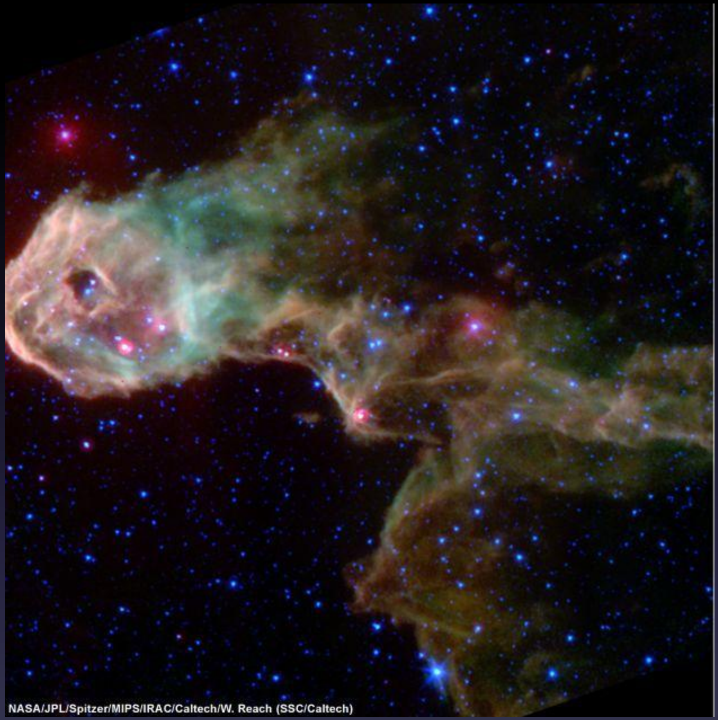
Temperature vs. radius before (red) and after (blue) star formation begins in a 50 $M_\odot$, 1 g cm^{-2} core (Krumholz 2006)

Simulation of a Massive Core

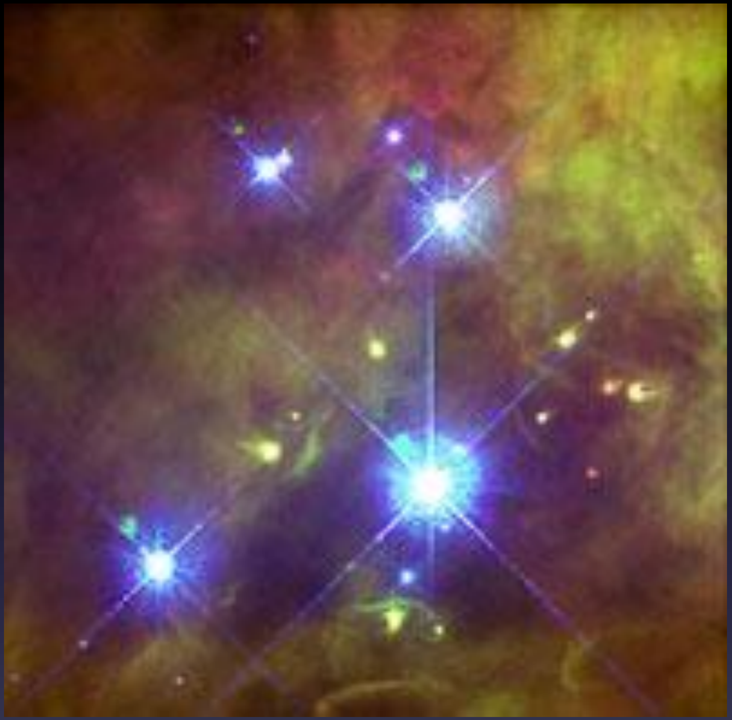


200 $M_\odot$ centrally-condensed core (Myers+ 2012)
Both simulations use MHD, sink particle, AMR

Assembling the IMF



NASA/JPL/Spitzer/MIPS/IRAC/Caltech/W. Reach (SSC/Caltech)



Part II: The Peak

Understanding Fragmentation

- Gas clouds fragment due to Jeans instability

$$M_J \approx \sqrt{\frac{c_s^3}{G^3 \rho}}$$

$$\approx 0.4 M_\odot \left(\frac{T}{10\,\mathrm{K}}\right)^{3/2} \left(\frac{n}{10^5\,\mathrm{cm}^{-3}}\right)^{-1/2}$$

- Problem: GMCs have T ~ constant, but n varies a lot

Isothermal Gas is Scale Free

$$\frac{\partial r}{\partial t'} = -\nabla' \cdot (r\mathbf{u})$$

$$\frac{\partial}{\partial t'}(r\mathbf{u}) = -\nabla' \cdot (r\mathbf{u}\mathbf{u}) - \frac{1}{\mathcal{M}^2}\nabla' r + \frac{1}{\mathcal{M}_A^2}(\nabla' \times \mathbf{b}) \times \mathbf{b} - \frac{1}{\alpha_{\rm vir}} r\nabla'\psi$$

$$\frac{\partial \mathbf{b}}{\partial t'} = -\nabla' \times (\mathbf{b} \times \mathbf{u})$$

$$\nabla'^2\psi = 4\pi r$$

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho\mathbf{v})$$

$$\frac{\partial}{\partial t}(\rho\mathbf{v}) = -\nabla \cdot (\rho\mathbf{v}\mathbf{v}) - c_s^2\nabla\rho + \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} - \rho\nabla\phi$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{B} \times \mathbf{v})$$

$$\nabla^2\phi = 4\pi G\rho$$

$$\mathcal{M} = \frac{V}{c_s}$$

$$\mathcal{M}_A = \frac{V}{V_A} = V\frac{\sqrt{4\pi\rho_0}}{B_0}$$

$$\alpha_{\rm vir} = \frac{V^2}{G\rho_0 L^2}$$

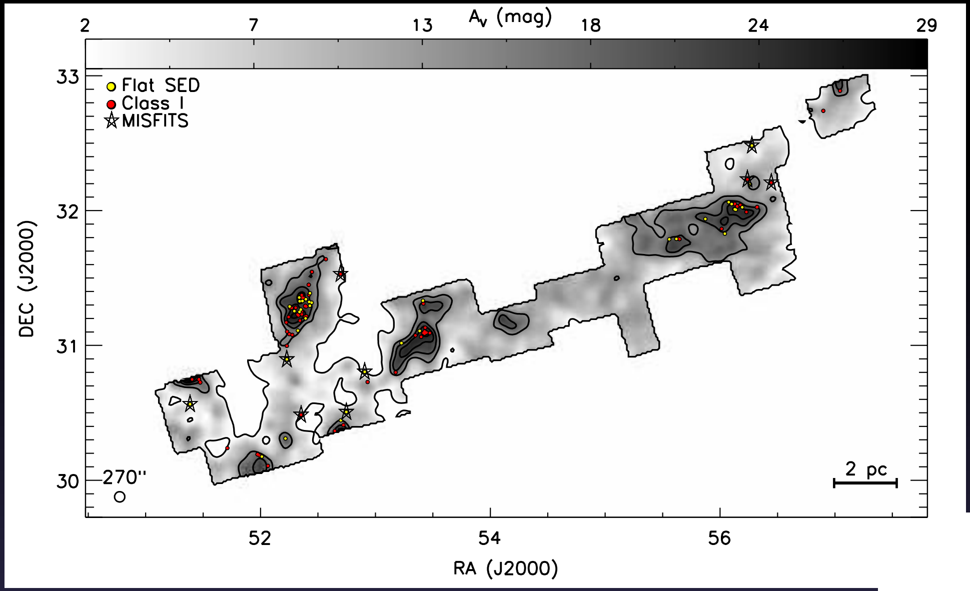
All dimensionless numbers invariant under $\rho_o \rightarrow x\rho_o$, $L \rightarrow x^{-1/2}L$, $B \rightarrow x^{1/2}B$, but $M \rightarrow x^{-1/2}M$

→ Non-isothermality **required** to explain IMF peak!

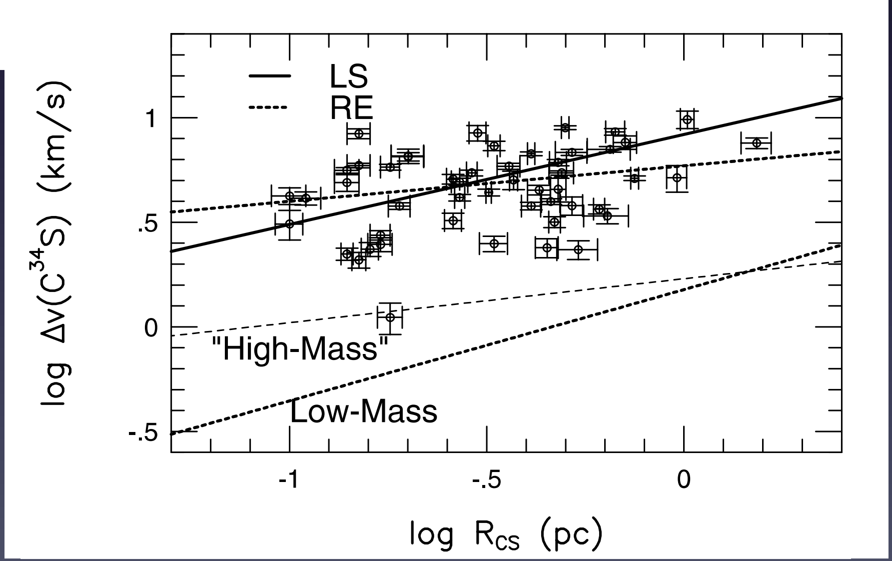
Option 1: Galactic Properties

- GMCs embedded in a galaxy-scale non-isothermal medium
- Set IMF peak from Jeans mass at volume-mean density (Larson 2005, Narayanan & Dave 2012)
- … or from mass-averaged density / linewidth-size relation (e.g. Padoan & Nordlund 2002, Hennebelle & Chabrier 2008, 2009; Hopkins 2012)

Problem 1: Choice of Scale

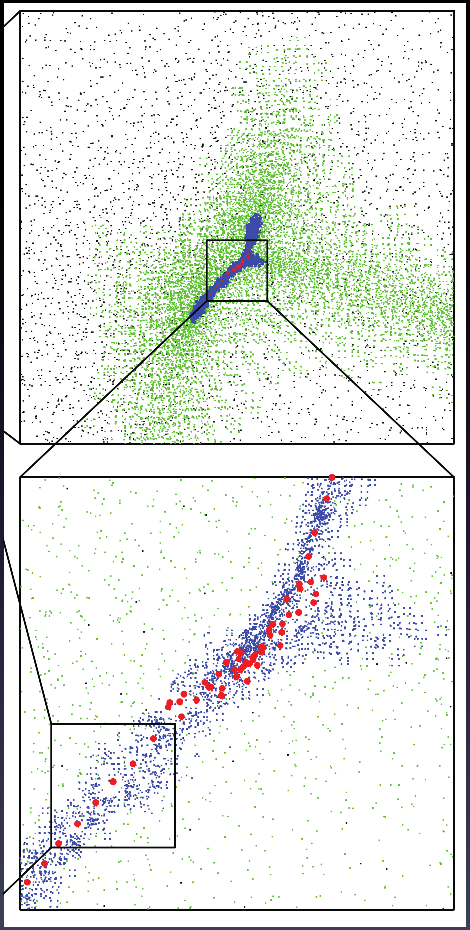


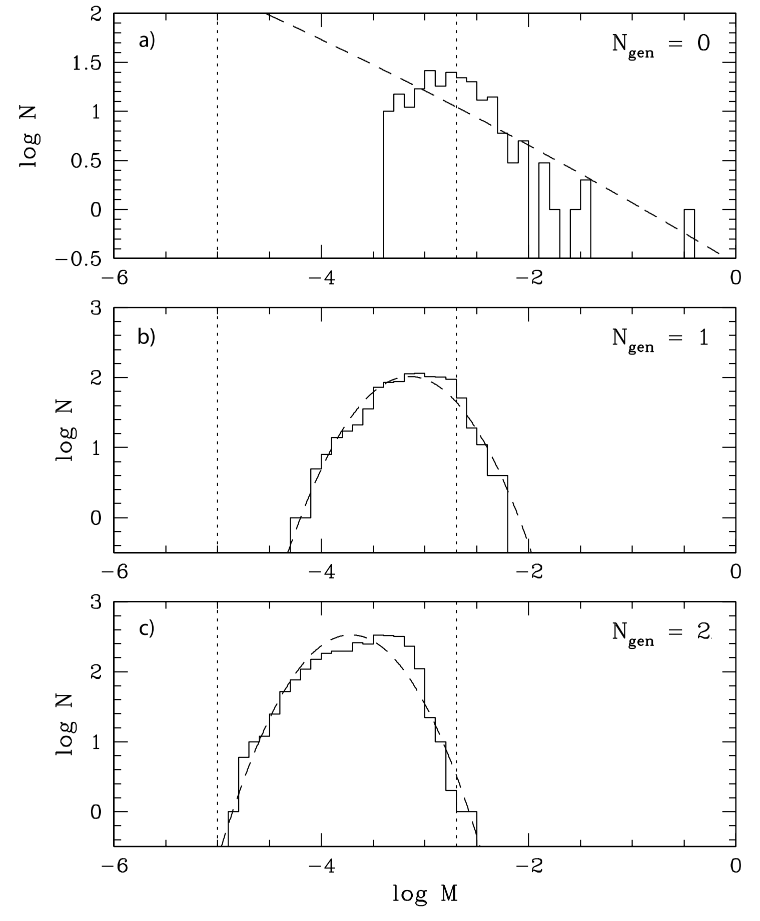
Map of the Perseus molecular cloud (Heiderman+ 2010)



Linewidth-size relation low and high mass star-forming regions (Shirley+ 2003)

Problem 2: Non-Convergence

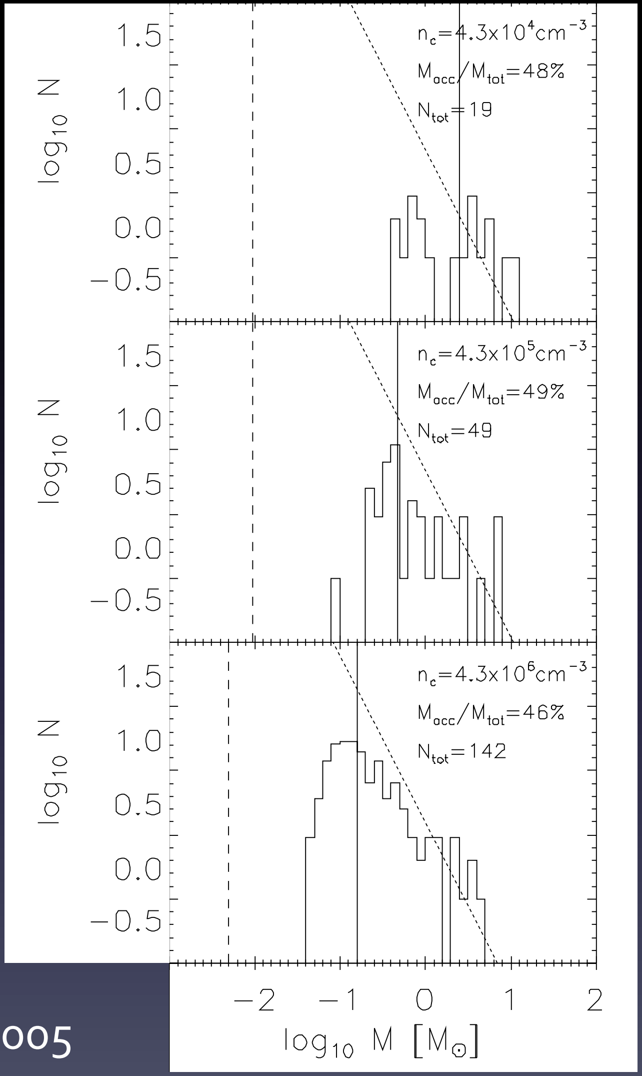




Left: fragmentation in an isothermal simulation (Martel+ 2006)
Right: IMF at 3 different resolutions for isothermal simulations

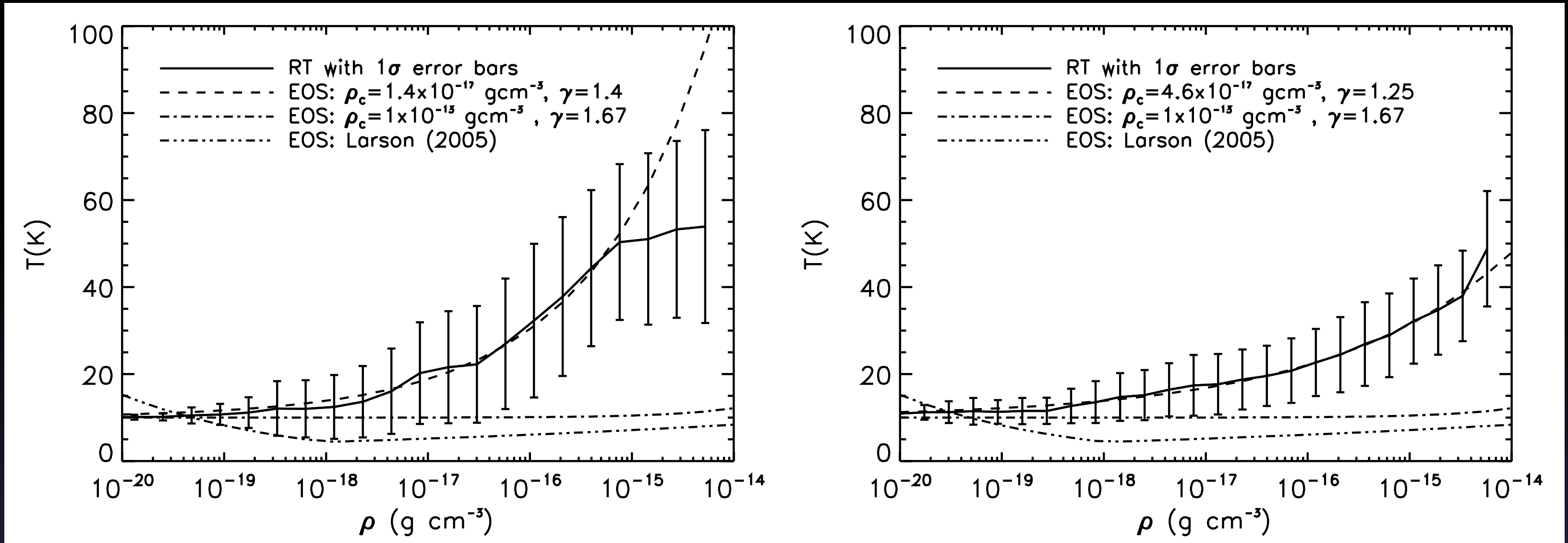
Option 2: Non-Isothermal EOS

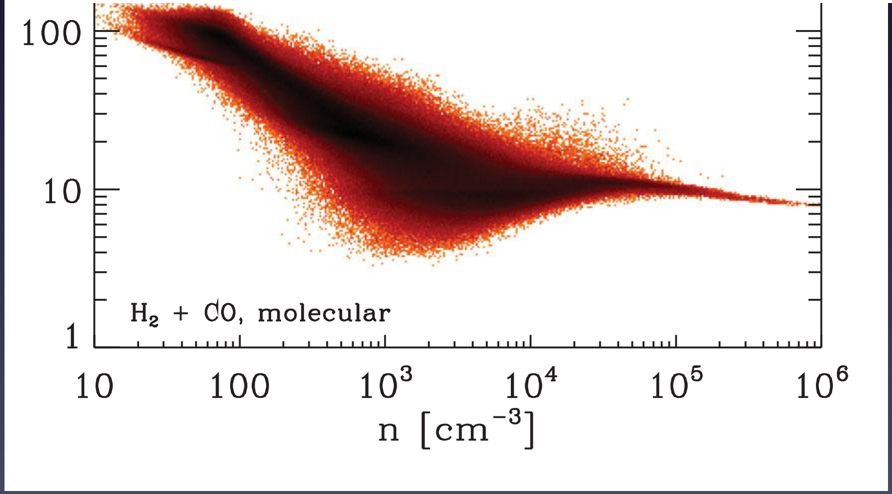
- Non-isothermal EOS does have a mass scale
- Model: gas fragments to the lowest Jeans mass for which γ < 1
  (Larson 2005; Jappsen+ 2005)
- Related to opacity limit for fragmentation



Jappsen+ 2005

Problem: EOS’s Are a Bad Fit





Top: Offner+ 2009

Left: Glover & Clark 2012

Option 3: Radiation

(Krumholz 2011)

$$P \approx GM^2/R^4$$

$$T = \left(\frac{3^{2/3} L}{\pi^{1/3} (\rho M)^{2/3} \sigma_{\rm SB}} \right)^{1/4}$$

$$L = \epsilon_L \epsilon_M \sqrt{2G\rho M} \sqrt{\frac{GM_*}{R_*}}$$

$$M_{\rm BE} = 1.18 \sqrt{\left(\frac{k_B T}{\mu m_{\rm H} G} \right)^3 \frac{1}{\rho}}$$

Mass-Radius Relation and the IMF

- Accreting stars burn D: D + 2 H → He
- Burning keeps $T_{\text{core}} \sim 10^6$ K; calculable from fundamental constants
- Fixed T_{cor}

$\Theta_c \approx 12.4$

$\alpha = e^2 / \hbar c$

$\alpha_G = G m_H^2 / \hbar c$

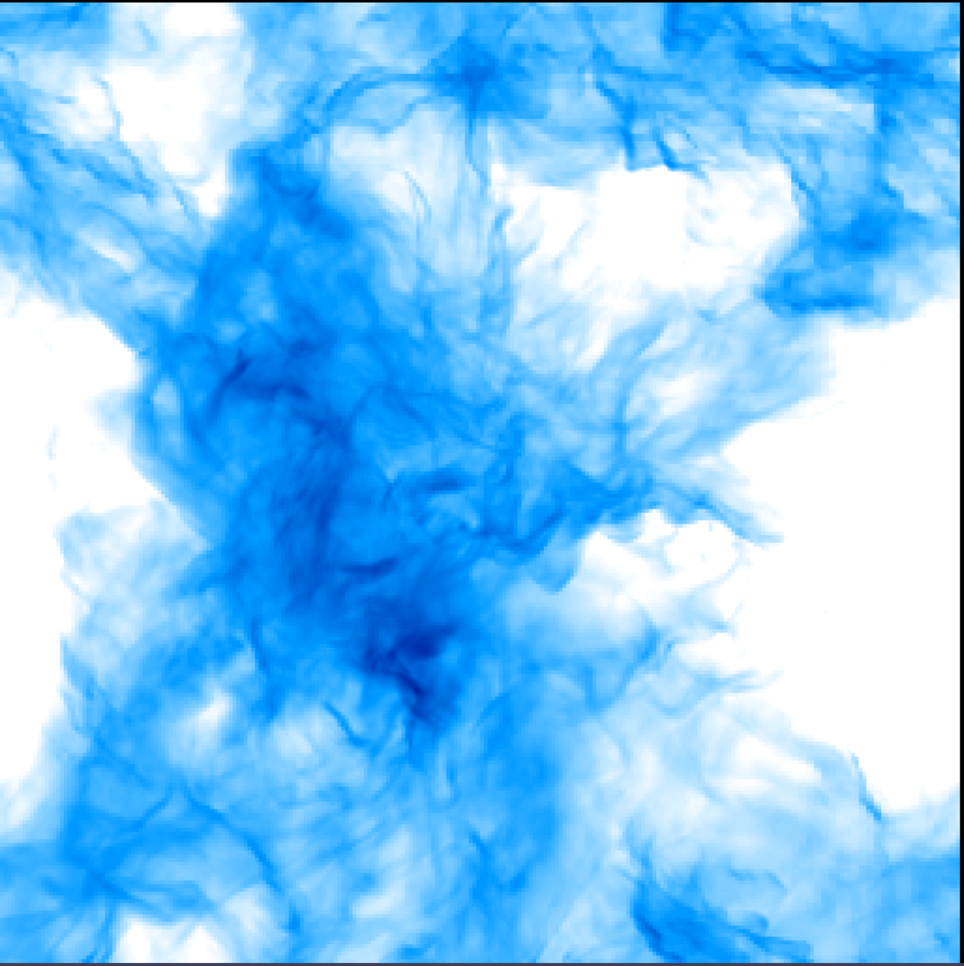
$P_{\text{Pl}} = c^7 / \hbar G^2$

$$M_* = 0.4 m_{\text{H}} \Theta_c^{-4/3} \quad {}^{8} \left(\quad \alpha_G^{25} \right) \quad \left(\quad P_{\text{Pl}} \right)^{/18}$$

$$= 0.15 \left(\frac{P/k_B}{10^6 \text{ K cm}^{-3}} \right)^{-1/18} M_\odot$$

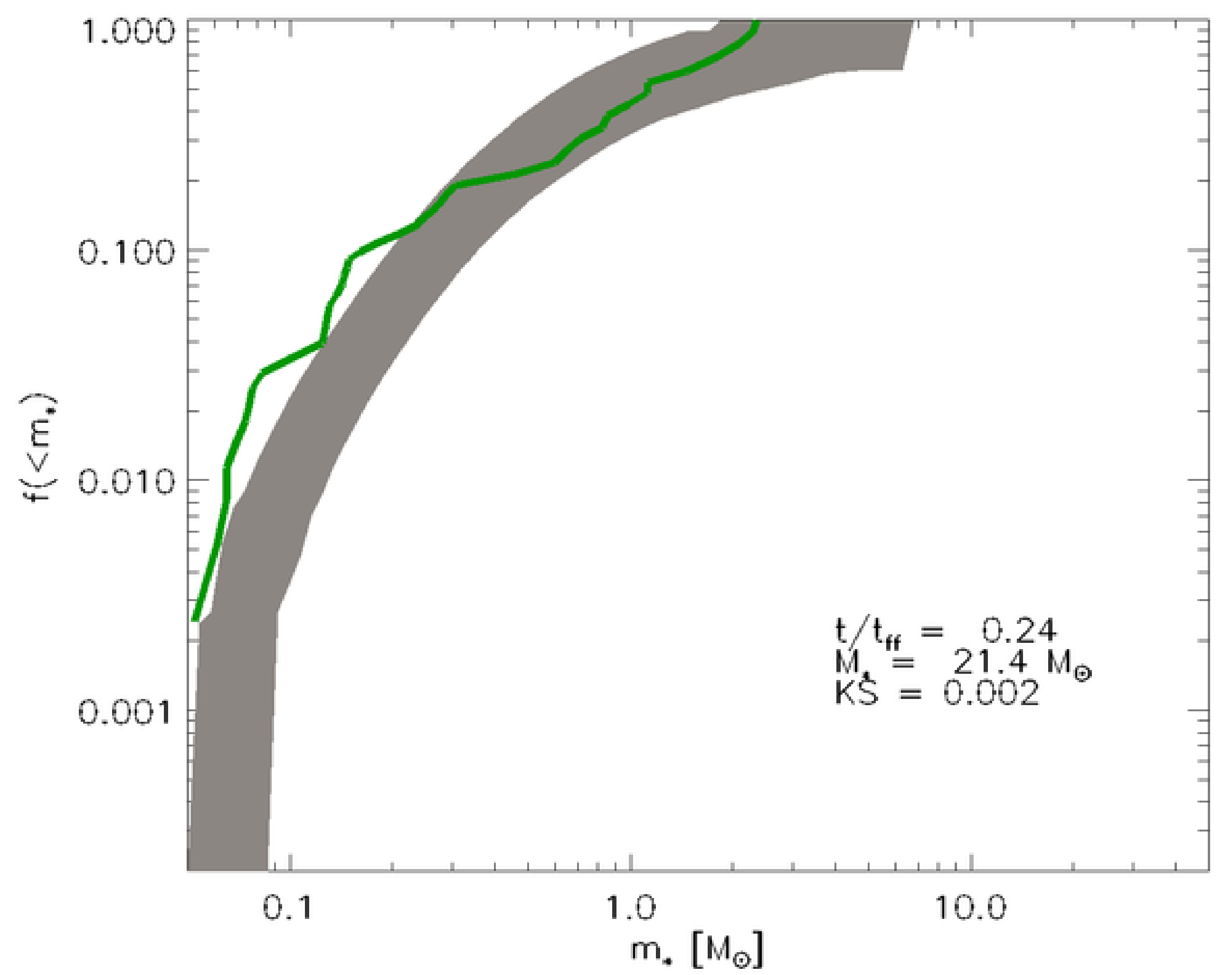
Pretty Movies

(Krumholz+ 2012)

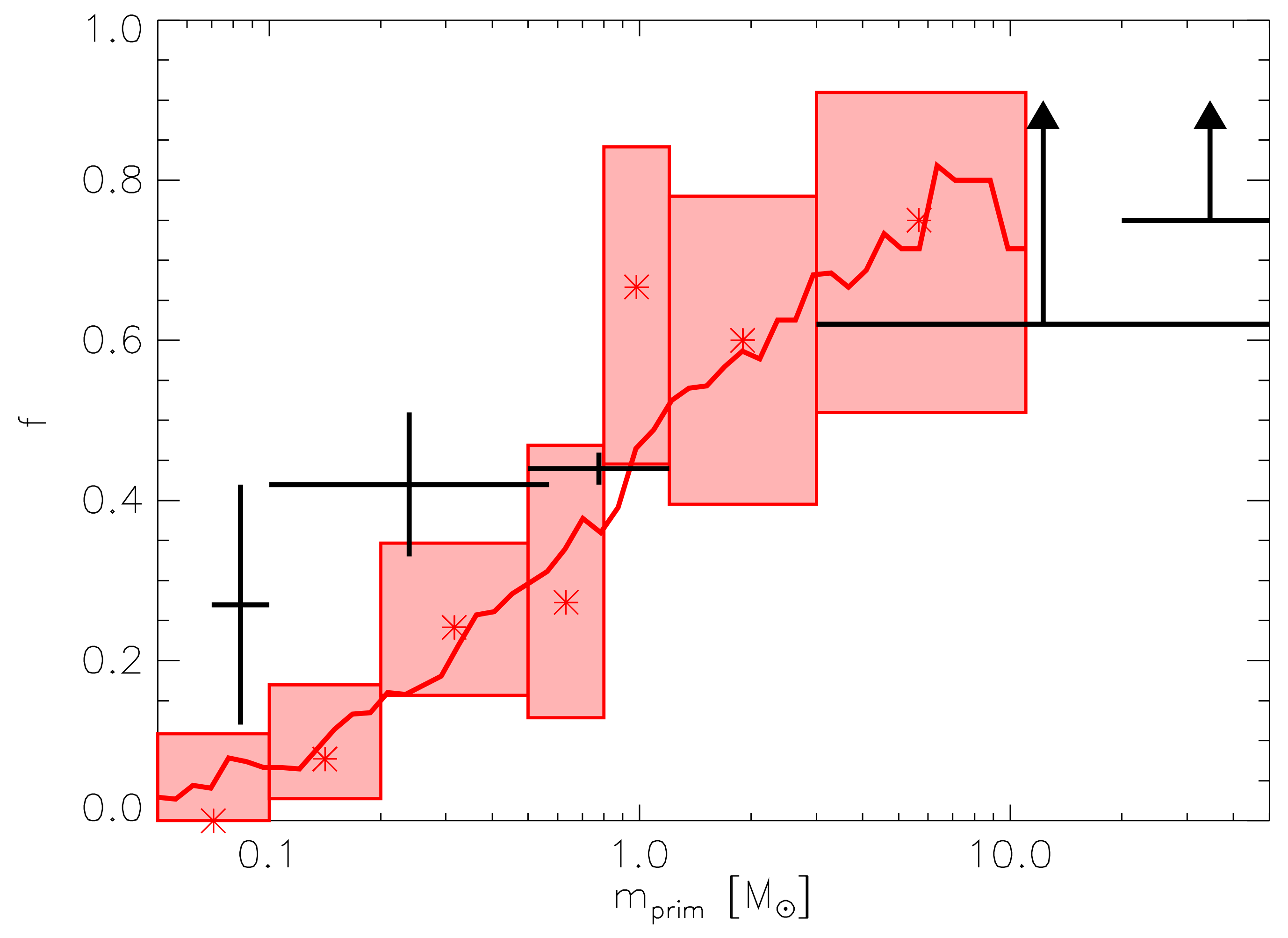


Cloud embedded in a larger, turbulent medium; simulation includes protostellar outflows

Comparison to Reality



Binaries from Cluster Simulation



Summary

- The IMF has two parts: a scale-free powerlaw at high masses, and a peak at low masses
- The powerlaw tail is plausibly produced by the statistics of supersonic turbulence, but radiation is required to avoid sub-fragmentation
- The characteristic peak mass likely comes from the effects of stellar heating