The (Non?) Universality of the IMF

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Overview

- A crash course in IMF models
  - The isothermal conundrum and two solutions
- The IMF from Non-Isothermal Fragmentation
- Implications

Isothermal 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

$$\mathcal{M} = \frac{\sigma}{c_s} \quad \propto \quad \sigma$$

$$\beta = \frac{8\pi\rho c_s^2}{B^2} \quad \propto \quad \rho B^{-2}$$

$$n_J = \frac{\rho L^3}{c_s^3/\sqrt{G^3\rho}} \quad \propto \quad \rho^{3/2} L^3$$

$$\mathcal{M}_A = \mathcal{M}\sqrt{\frac{\beta}{2}}$$

$$\mu_\Phi = \frac{M}{M_\Phi} = \sqrt{\frac{\pi\beta}{2}} n_J^{1/3}$$

$$n_{J,\mathrm{turb}} = \frac{n_J}{\mathcal{M}^3}$$

$$\alpha_{\mathrm{vir}} = \frac{5\sigma^2 L}{2GM} = \frac{5}{6\pi}\left(\frac{\mathcal{M}}{n_J}\right)^2$$

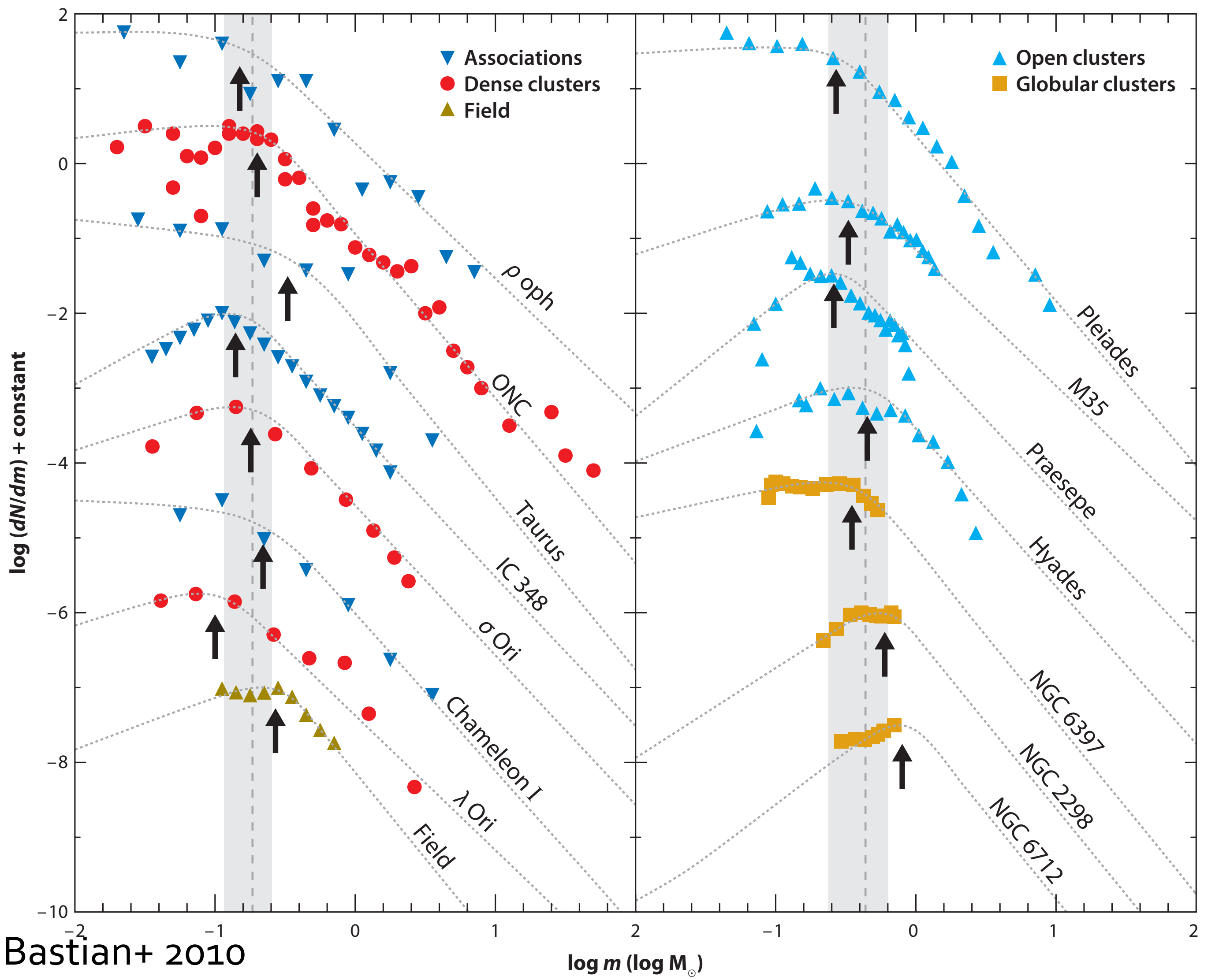
All dimensionless numbers invariant under $\rho \rightarrow x\rho$, $L \rightarrow x^{-1/2}L$, $B \rightarrow x^{1/2}B$, but $M \rightarrow x^{-1/2}M$

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

Option 1: Galactic Properties

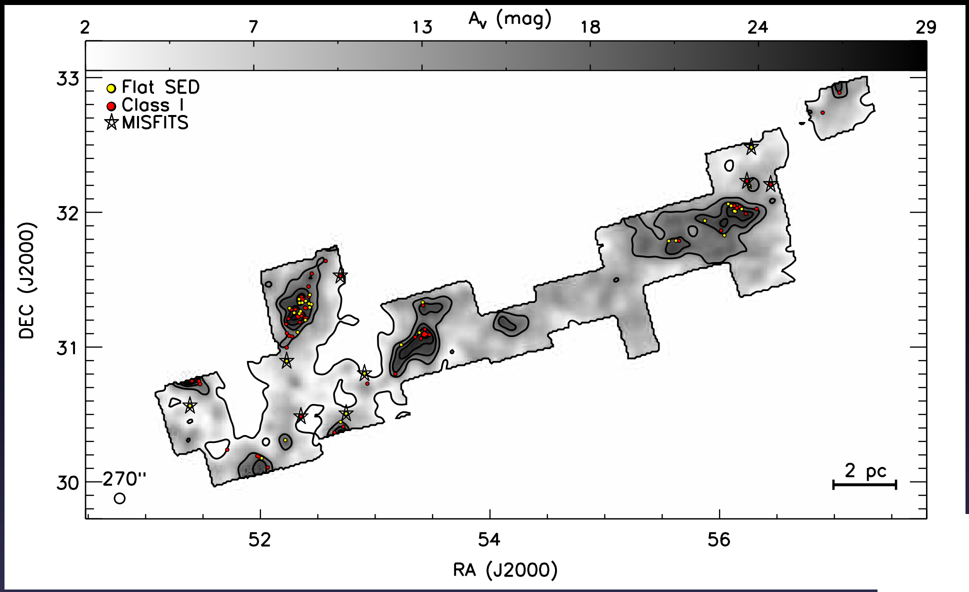
- GMCs embedded in a galaxy-scale non-isothermal medium
- Set IMF peak from Jeans mass at mean density (e.g. Padoan & Nordlund 2002, Hopkins 2012, Narayanan & Dave 2012)
- … or from linewidth-size relation (e.g. Hennebelle & Chabrier 2008, 2009; Hopkins 2012)

Problem 1: MW Cluster IMFs

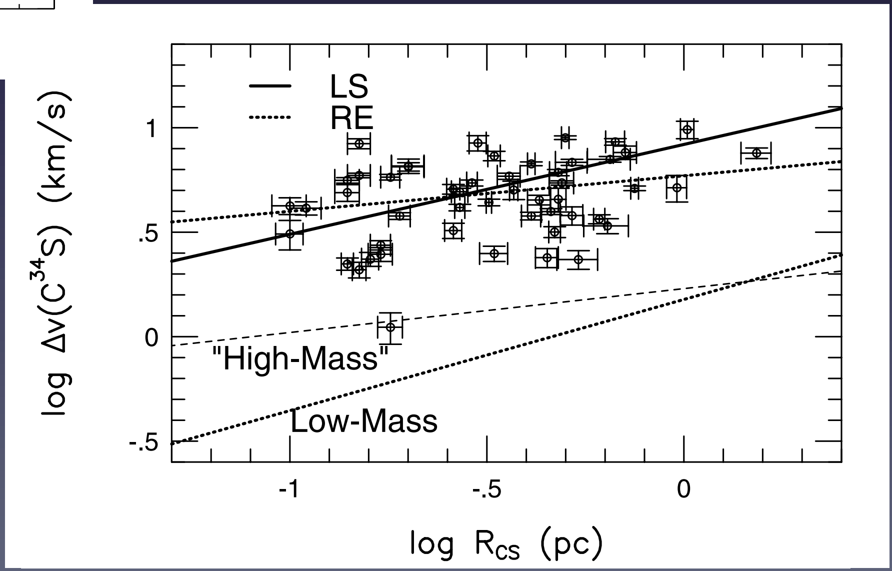


Bastian+ 2010

Problem 2: Choice of Scale

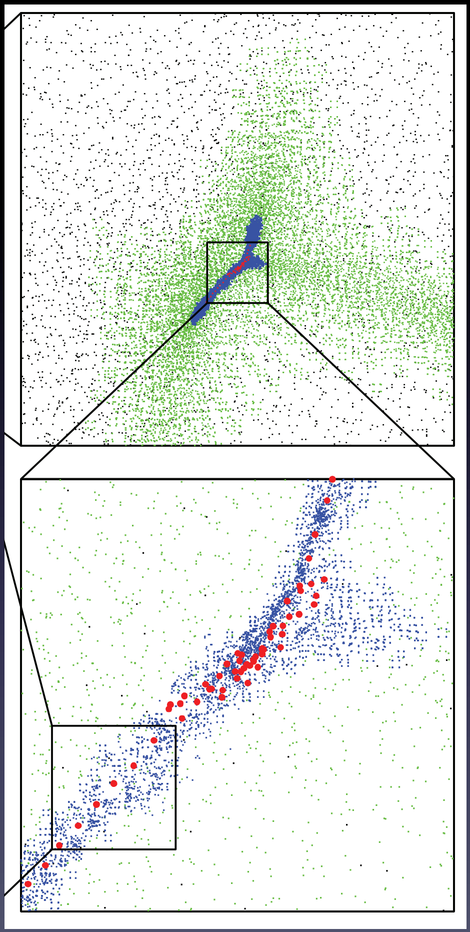


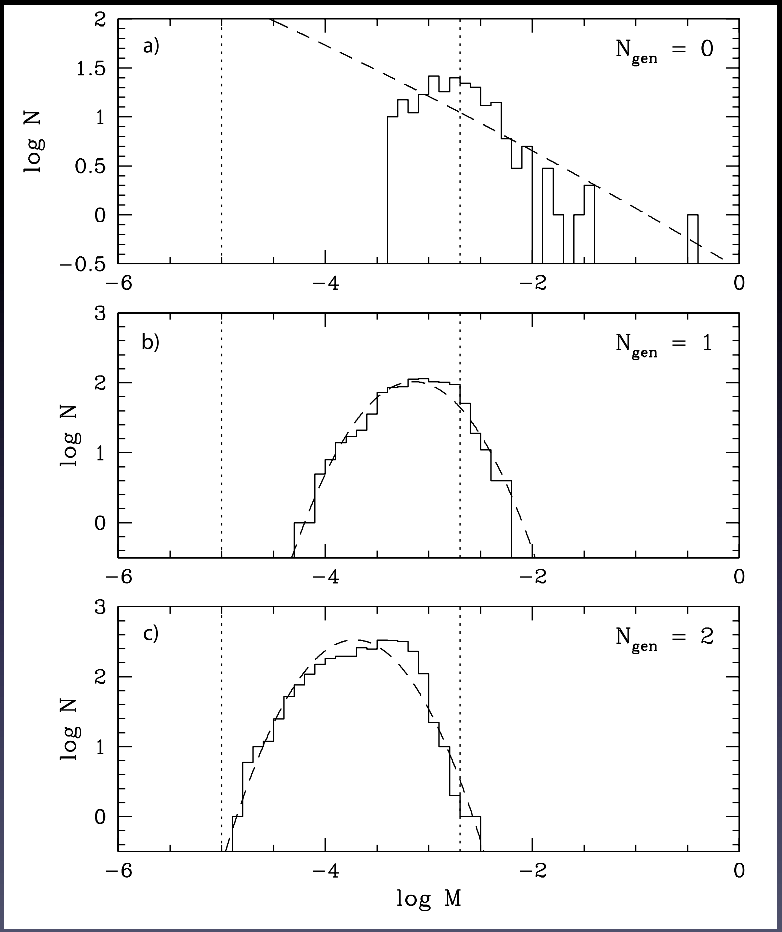
Map of the Perseus molecular cloud (Heiderman+ 2010)



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

Problem 3: Simulations

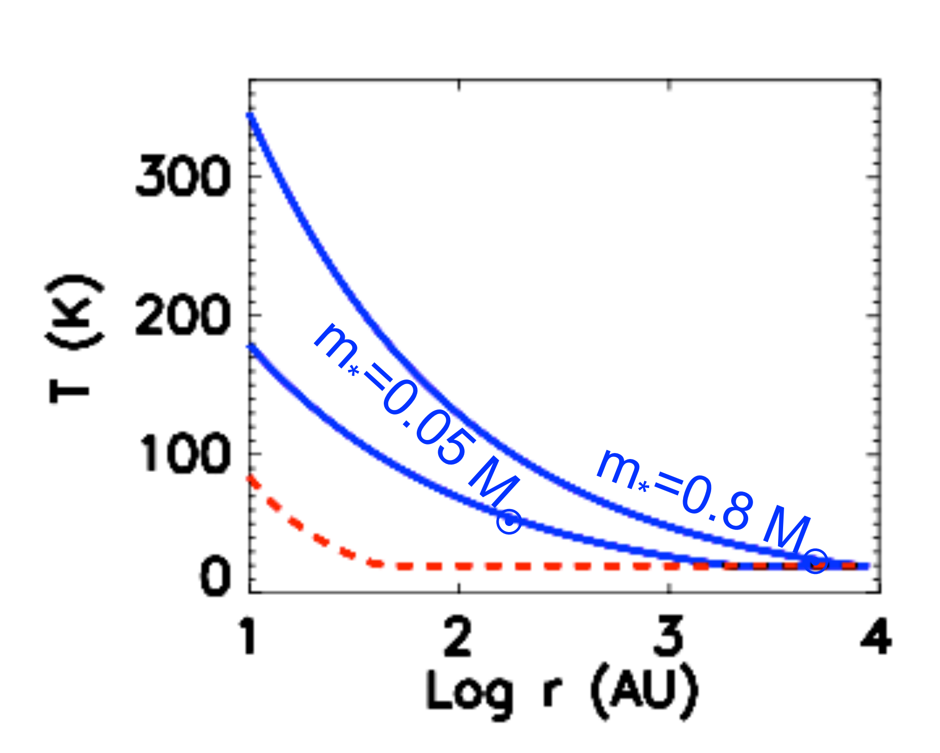




Left: fragmentation in an isothermal simulation (Martel+ 2006)
Right: IMF at 3 different resolutions for isothermal simulations

Option 2: Small Scale Non-Isothermality

- Fragmentation by small-scale non-isothermality (e.g. Larson 2005, Jappsen+2005, Elmegreen+ 2008)
- Most important source: stellar accretion luminosity



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

Setting the IMF Peak

(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 $T_{core} \sim 10^6$ K; calculable from fundamental constants
- Fixed T_{core} → fixed M_*/R_*
- No metall

$\Theta_c \approx 12.4$

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

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

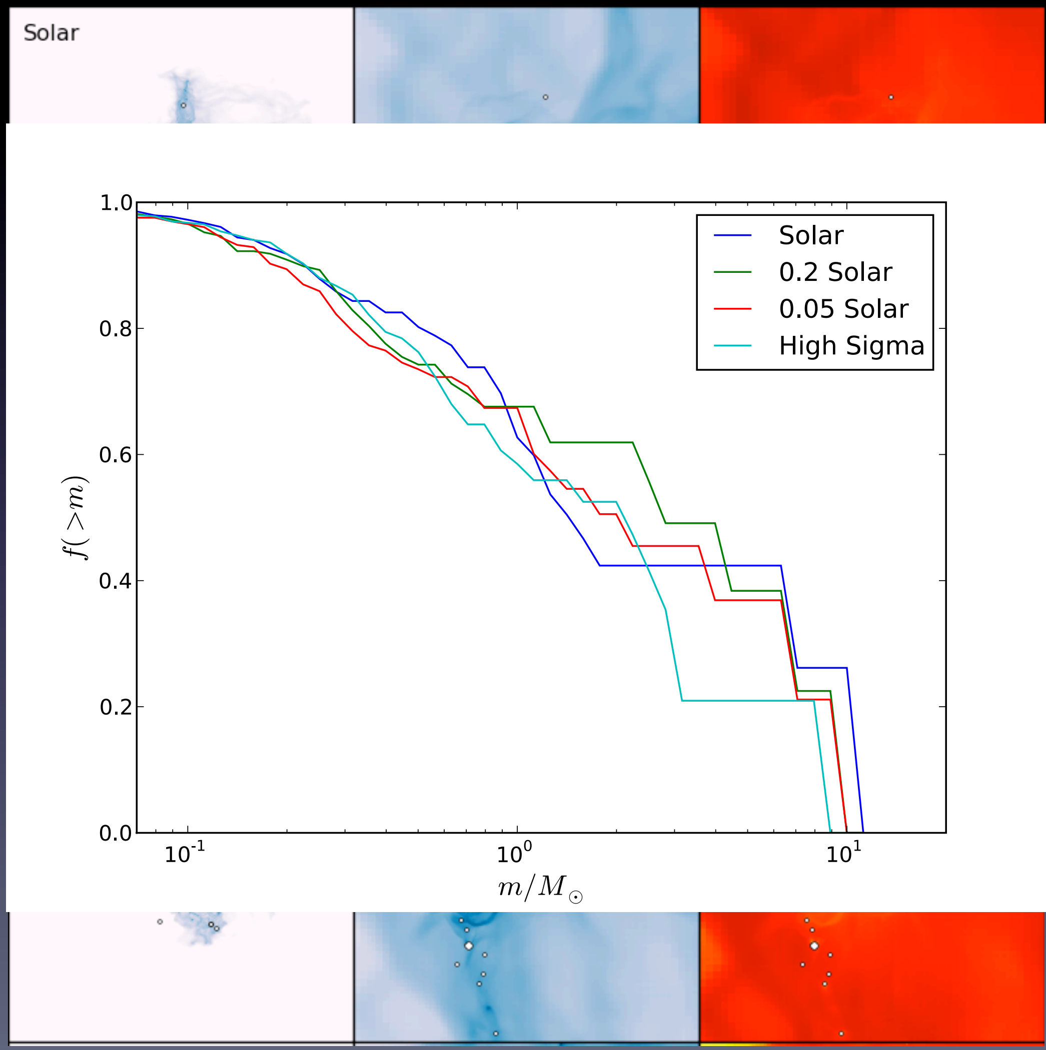
$P_{Pl} = c^7 / \hbar G^2$

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

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

Checking this Story

Check Metallicity Independence

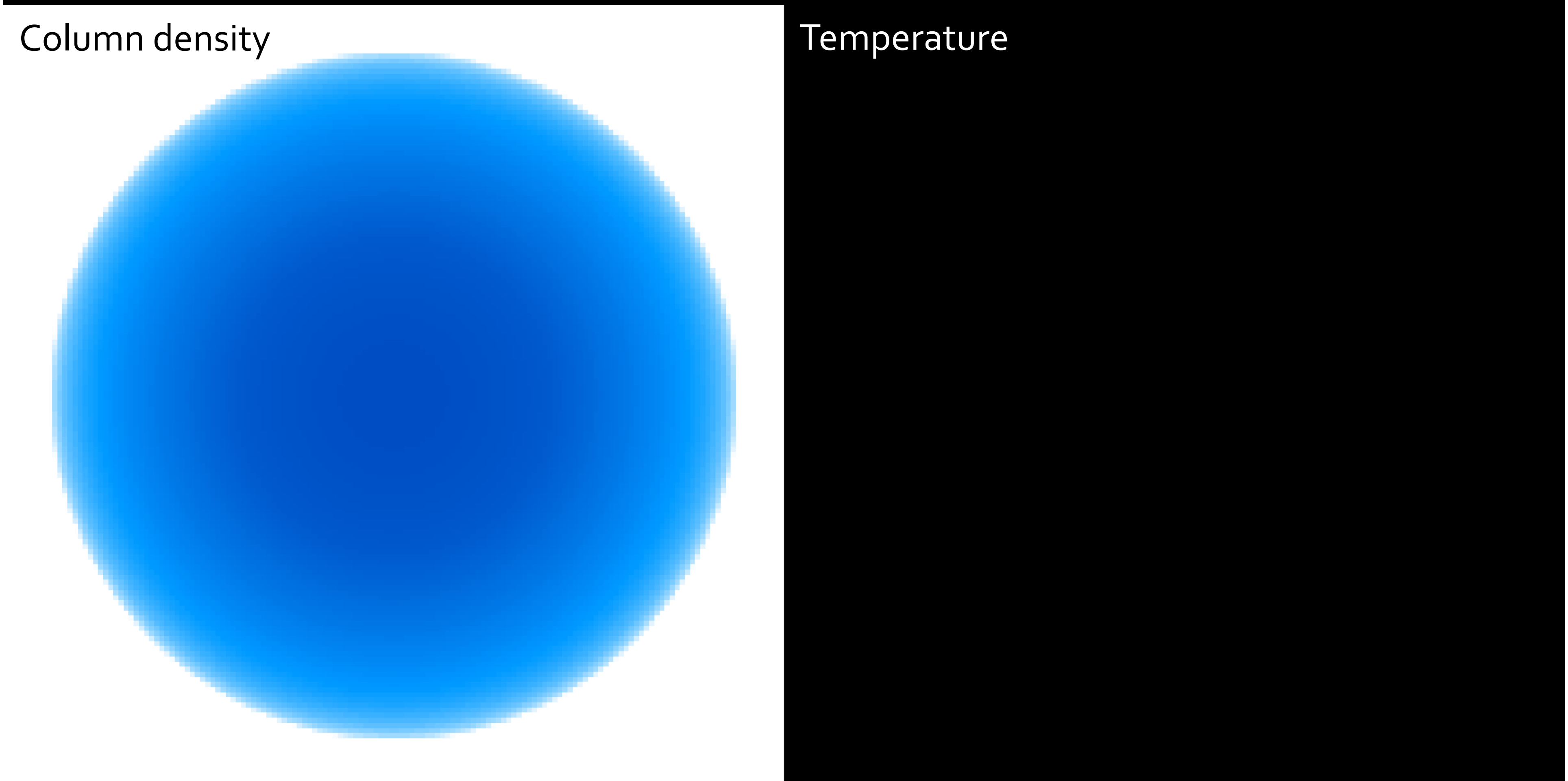


Simulations with varying metallicity show very little change in fragmentation, as long as the gas remains optically thick

(Myers+ 2011)

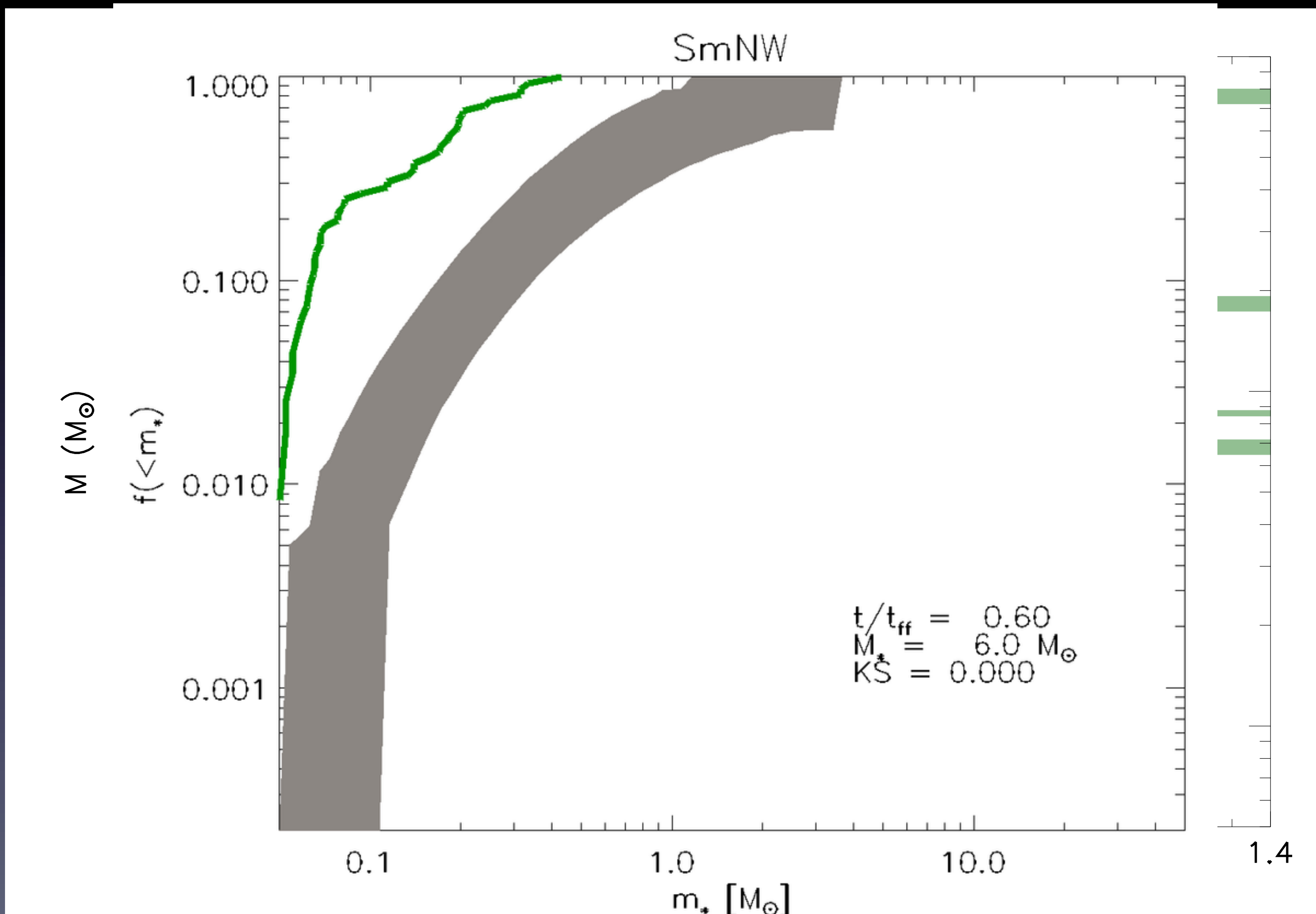
Simple Collapsing Cluster Simulation

(Krumholz+ 2011)

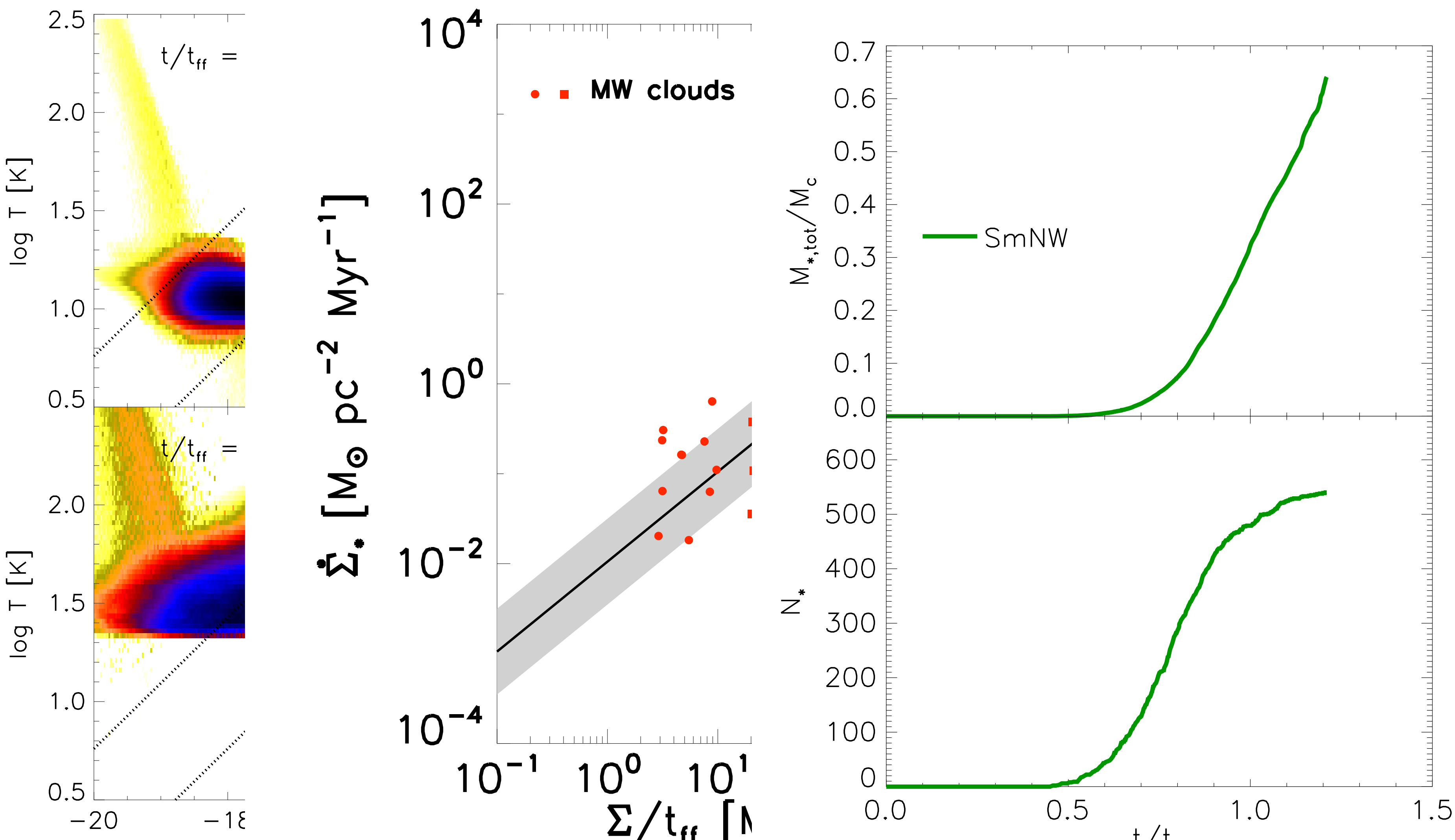


1000 $M_\odot$ cloud (roughly the size of the ONC), isolated, no protostellar outflows

Doesn't Work!


SmNW
1.000
0.100
0.010
0.001
f(<m*)
M (M⊙)
0.1
1.0
10.0
m* [M⊙]
t/tff = 0.60
M* = 6.0 M⊙
KS = 0.000
1.4

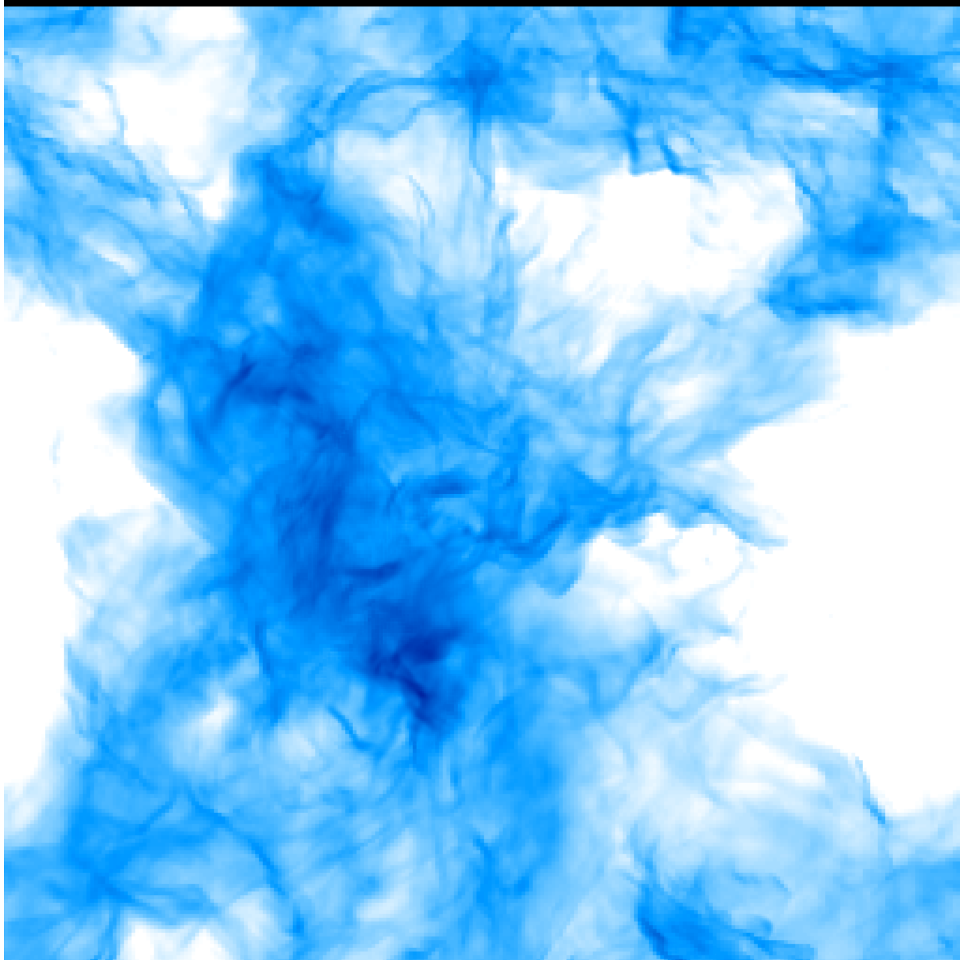
Why it Fails



Krumholz, Dekel, & McKee 2012

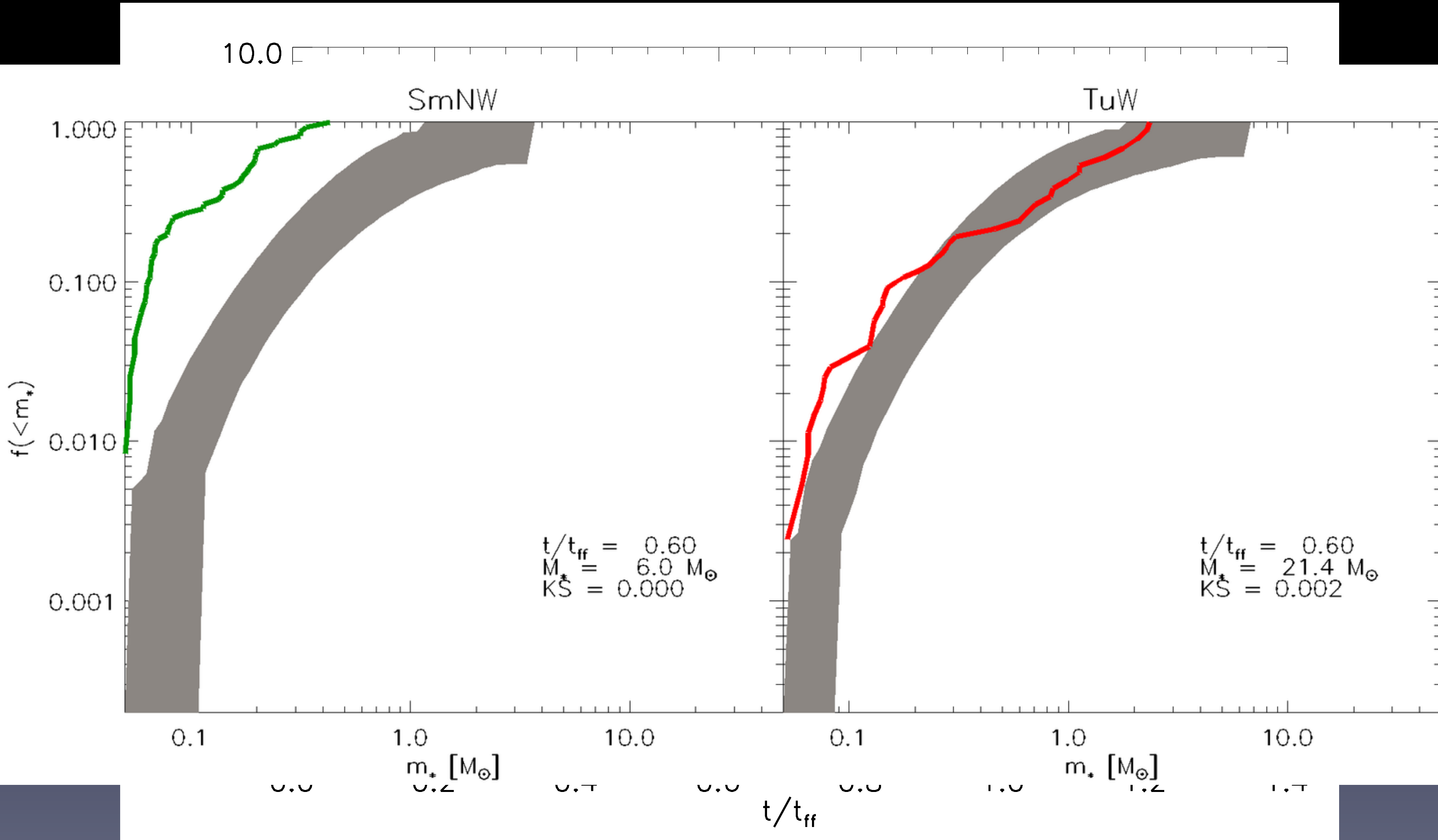
A More Realistic Simulation

(Krumholz+ 2012)

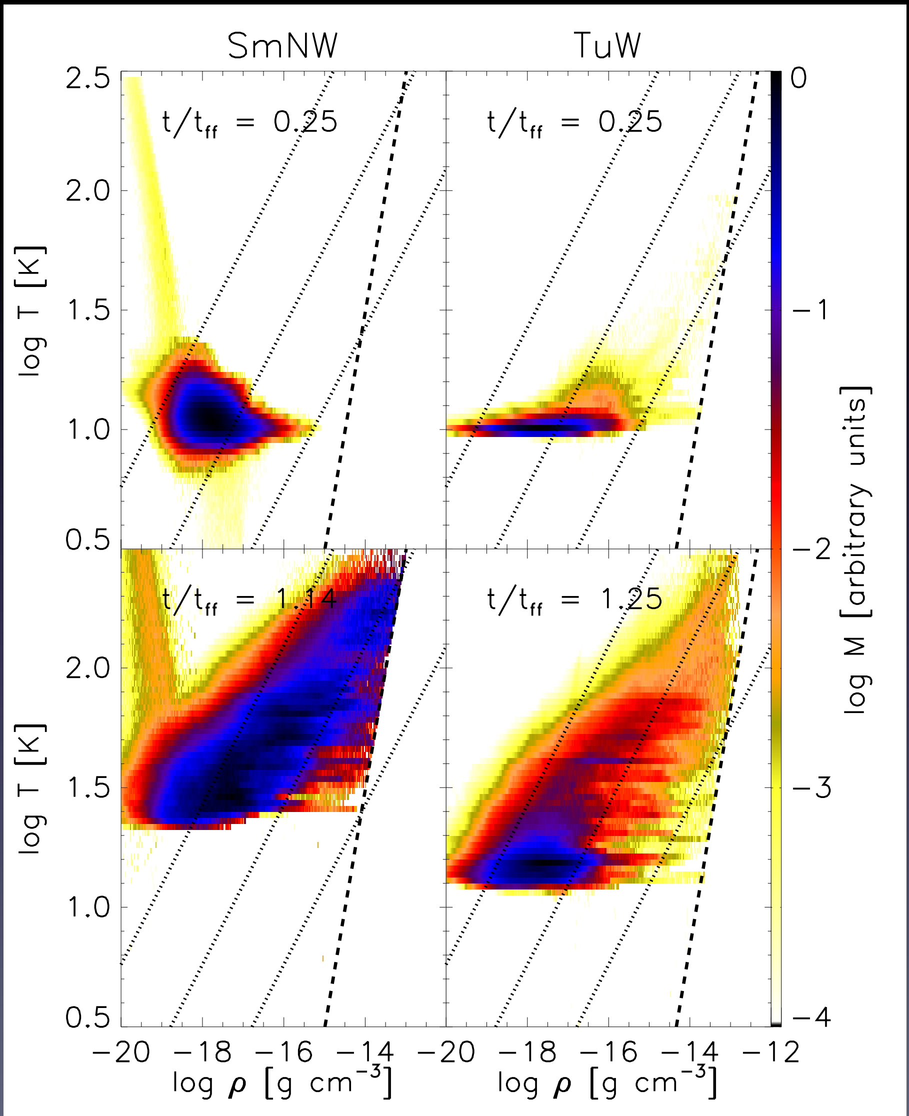


Cloud embedded in a larger, turbulent medium; simulation includes protostellar outflows

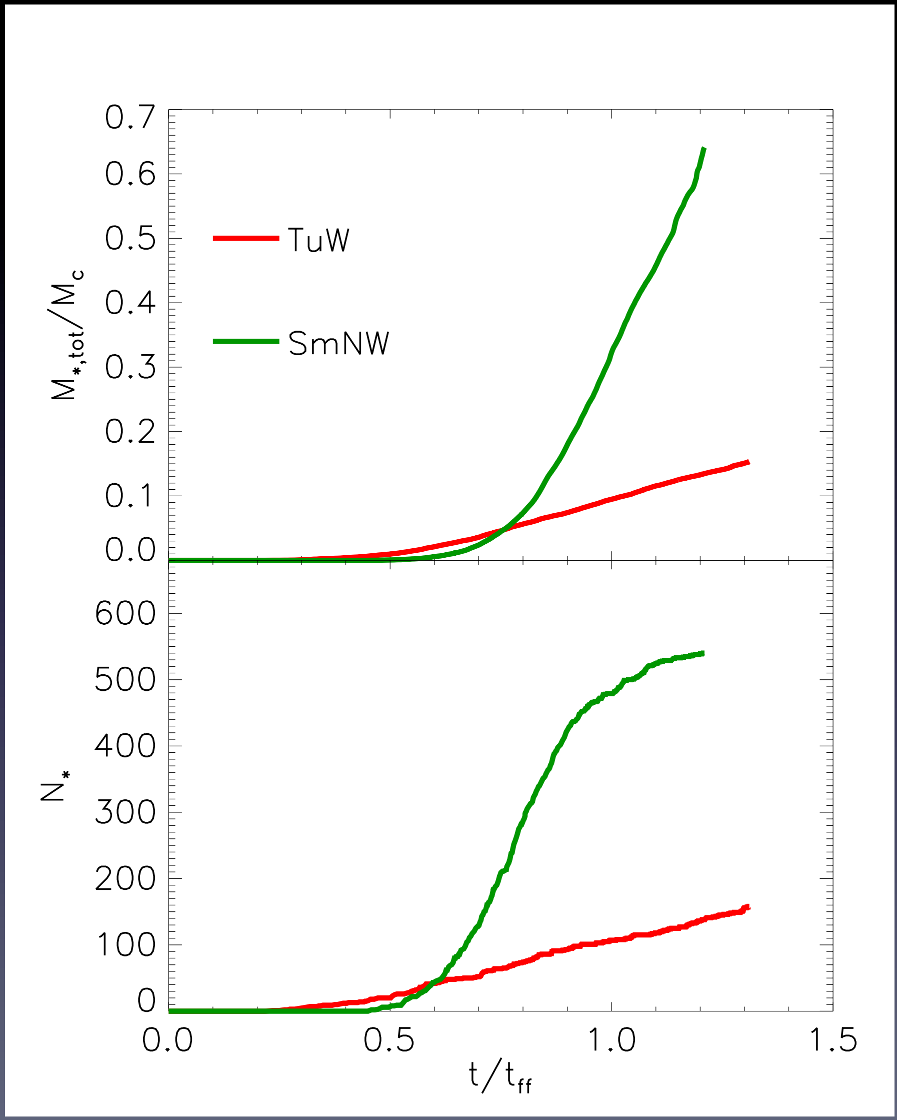
A Good IMF at Last



Why it Works

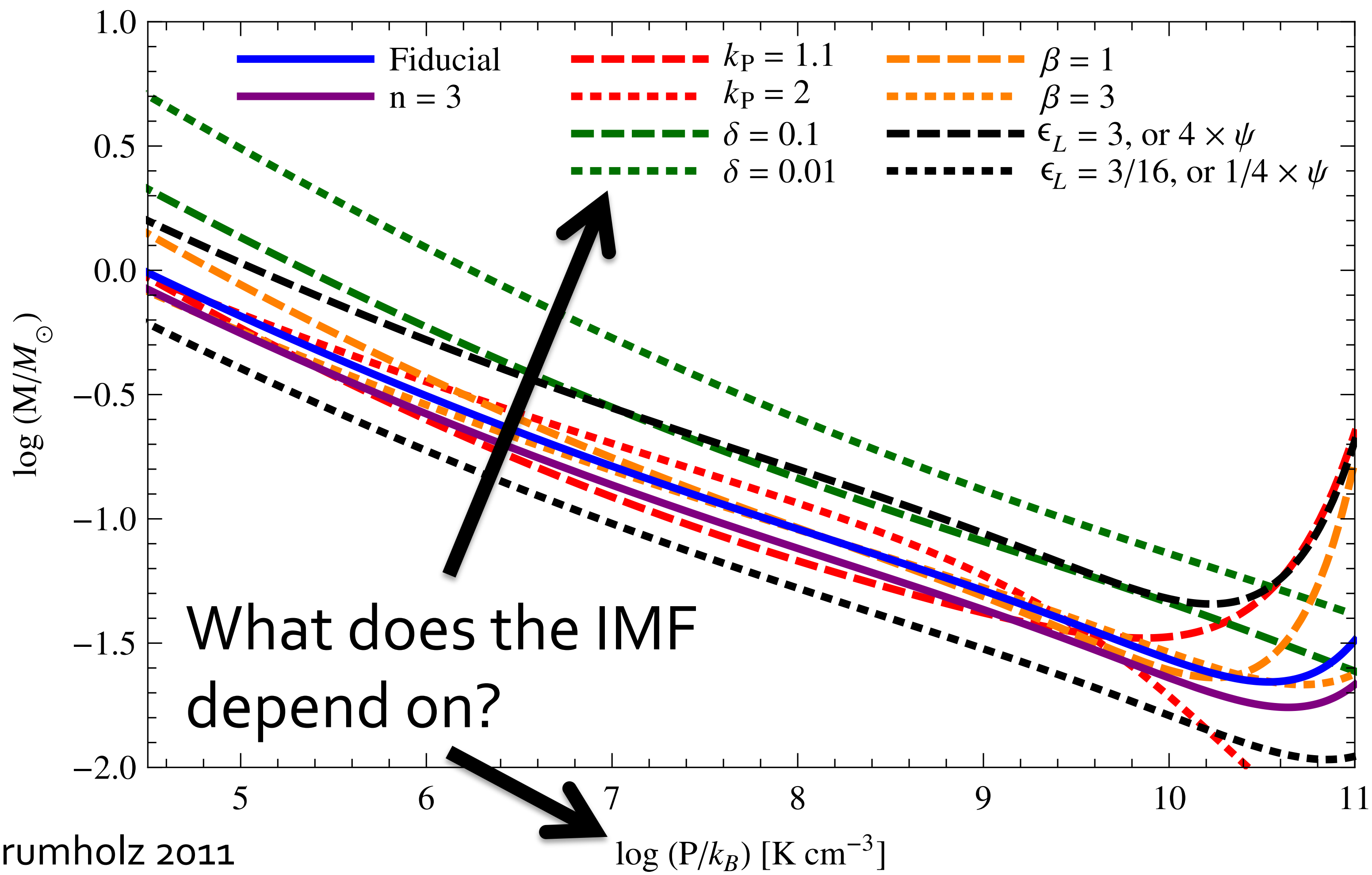


SmNW
TuW
t/t_{ff} = 0.25
t/t_{ff} = 0.25
t/t_{ff} = 1.14
t/t_{ff} = 1.25
log T [K]
log ρ [g cm^{-3}]
log M [arbitrary units]



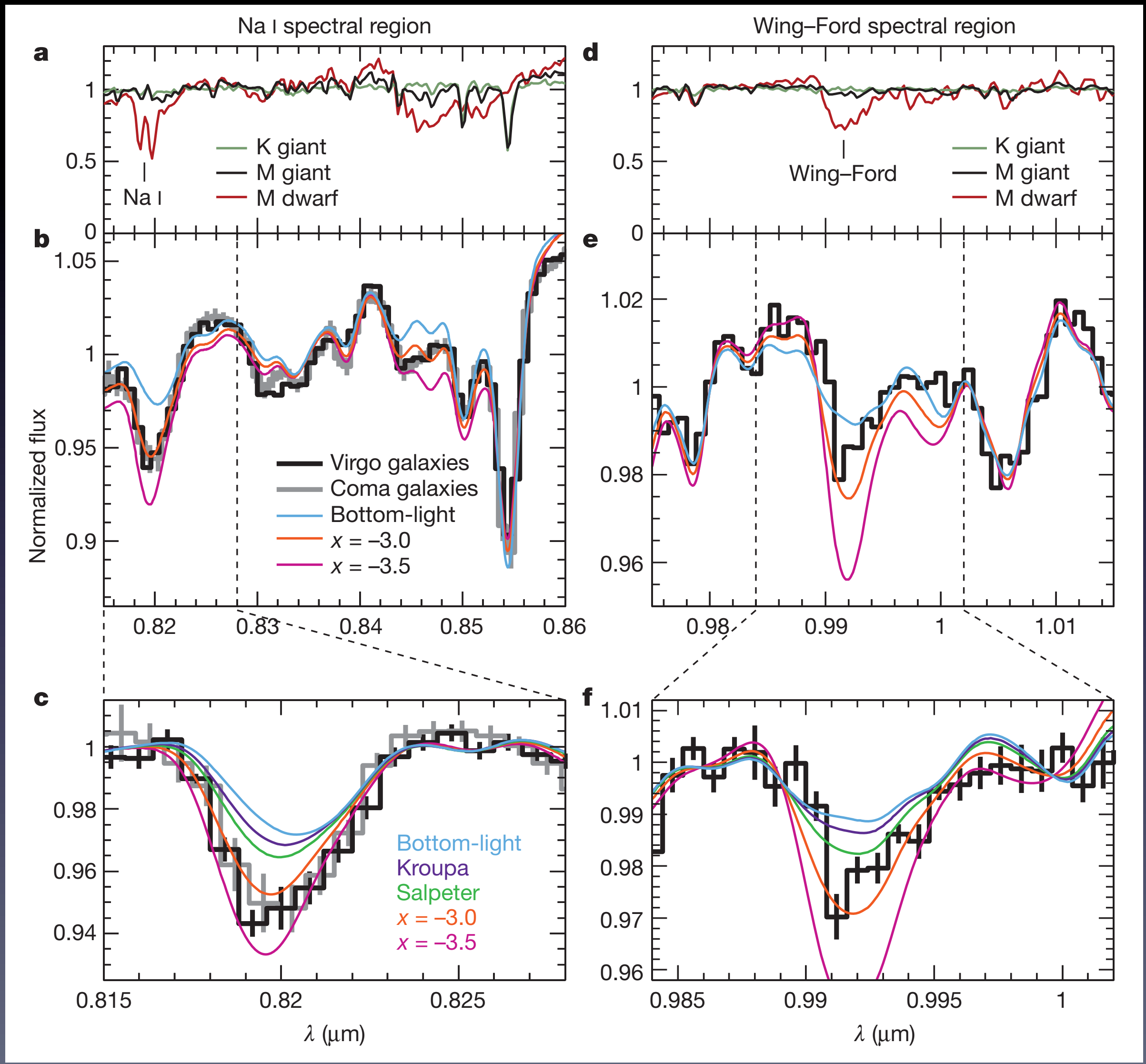
TuW
SmNW
$M_{*,tot}/M_c$
N_*
t/t_{ff}

Implications



Krumholz 2011

Possible Explanation for Ellipticals?



Giant elliptical galaxies have high pressure, high metallicity; NB: σ is a (rough) proxy for pressure

van Dokkum & Conroy (2010)

Summary

- IMF set by the thermodynamics of fragmenting gas on small scales, not galaxy scales
- The invariance of the peak comes from stellar feedback + fundamental physics
- Weak variation from radiation-matter coupling: peak moves to slightly lower mass at high P, Z. Simulations to test this are underway.