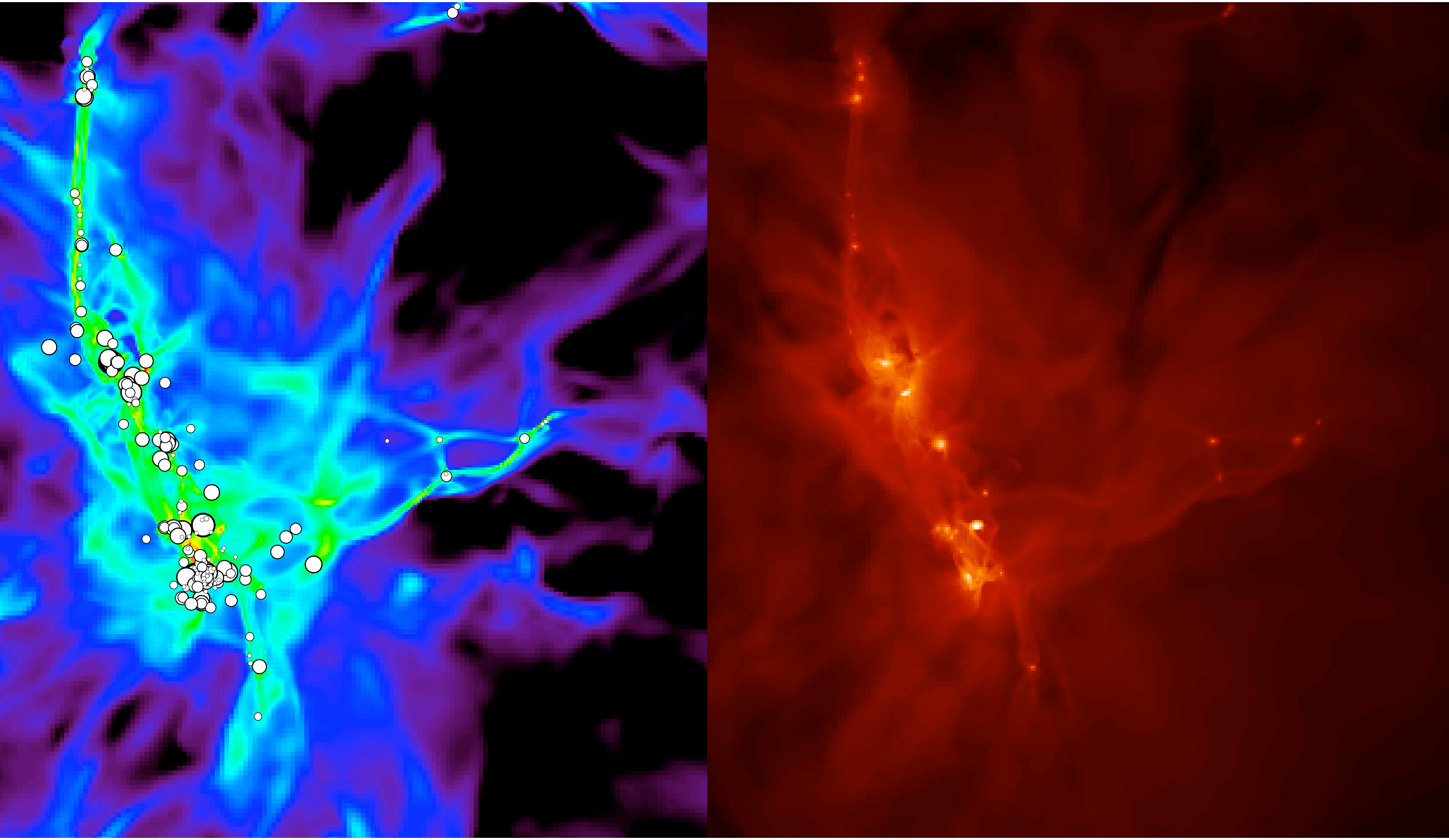


Progress Towards a Theory of the IMF

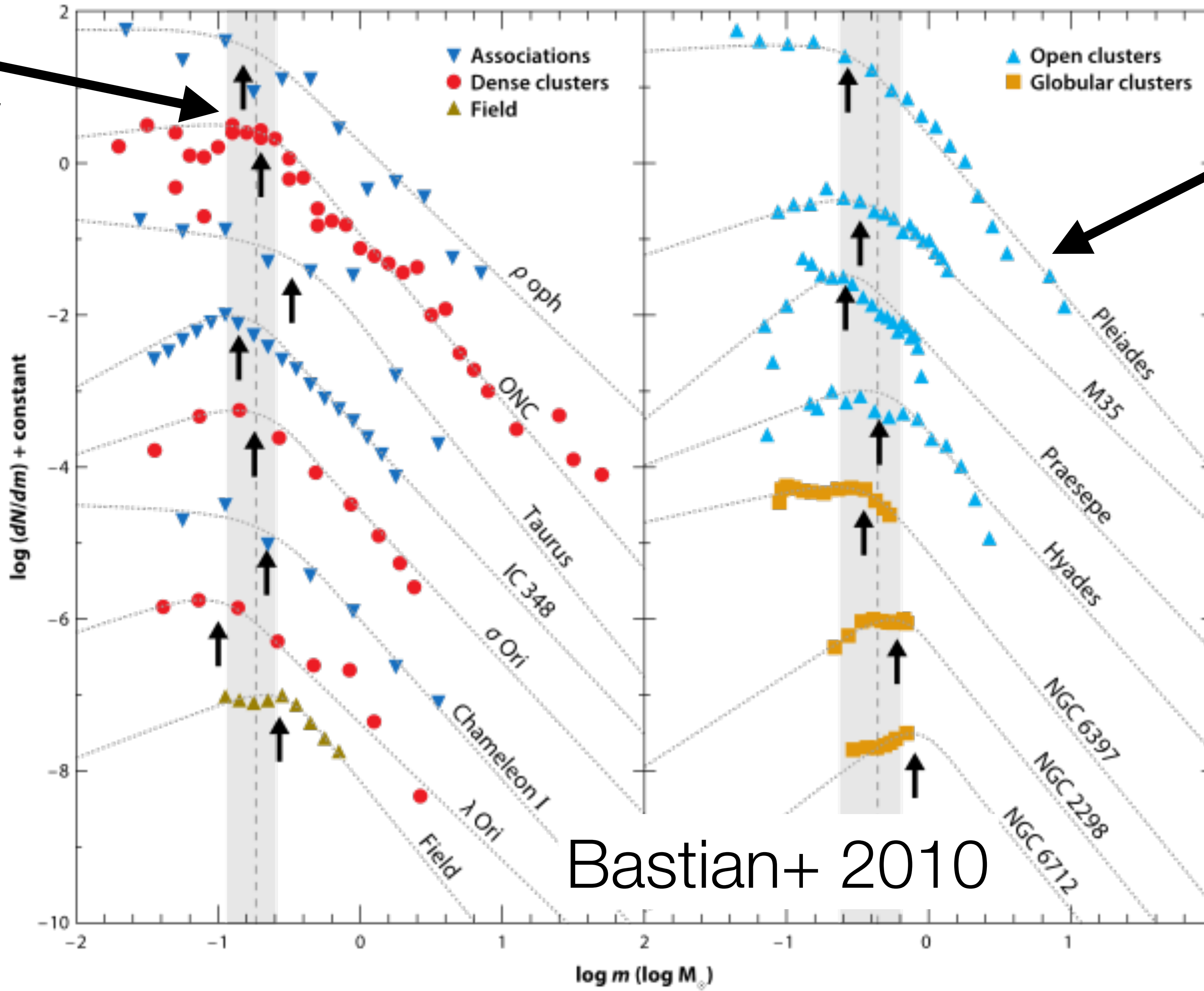
Mark Krumholz (ANU)

Explaining the Low-Mass IMF

- The isothermal conundrum
- Possible solutions
  - The galactic approach: ordinary or turbulent Jeans mass
  - The small-scale approach: equation of state and radiative feedback models
- Concluding thoughts

What We'd Like to Explain

Not a powerlaw



Powerlaw

Bastian+ 2010

Why This Matters

- Stars have a distinctive mass scale (few x 0.1 $M_\odot$)
- Classical explanation: this mass reflects the Jeans mass in the star-forming cloud

$$M_J \approx \frac{c_s^3}{\sqrt{G^3\rho}} \approx 0.3 M_\odot \left(\frac{T}{10\,\mathrm{K}}\right)^{3/2} \left(\frac{n}{10^5\,\mathrm{cm}^{-3}}\right)^{1/2}$$

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- Problem: Jeans mass depends on T and ρ; which ρ should we use?

The Isothermal Conundrum

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

The Isothermal Conundrum

- Isothermal self-gravitating ideal MHD described by:

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

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

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

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

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

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- Dimensionless numbers unchanged by $\rho_0 \rightarrow x\rho_0$, $L \rightarrow x^{-1/2}L$, $B_0 \rightarrow x^{-1/2}B_0$, but mass changes by $M \rightarrow x^{-1/2}M$

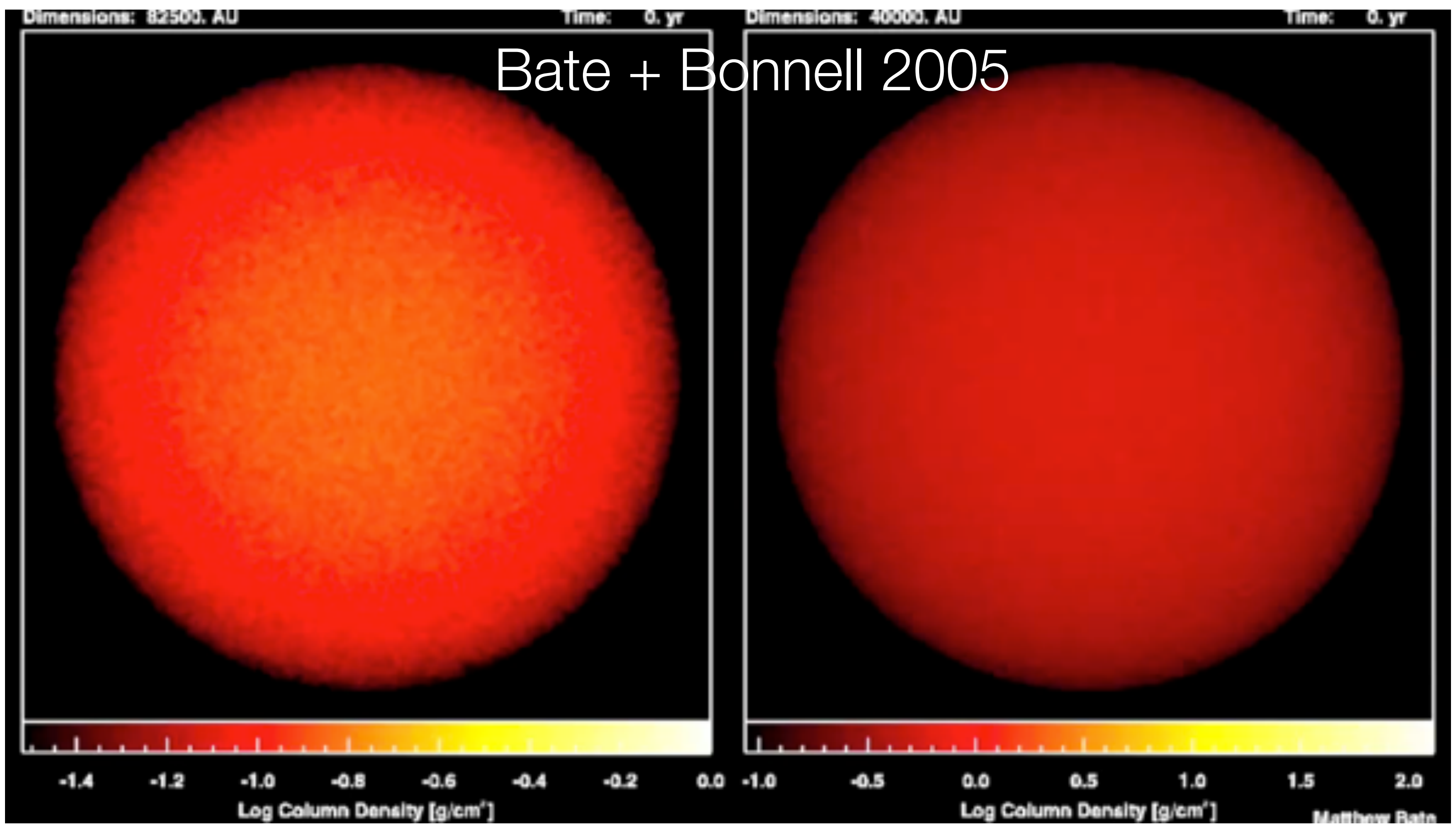
- Implication: isothermal gas has no mass scale!

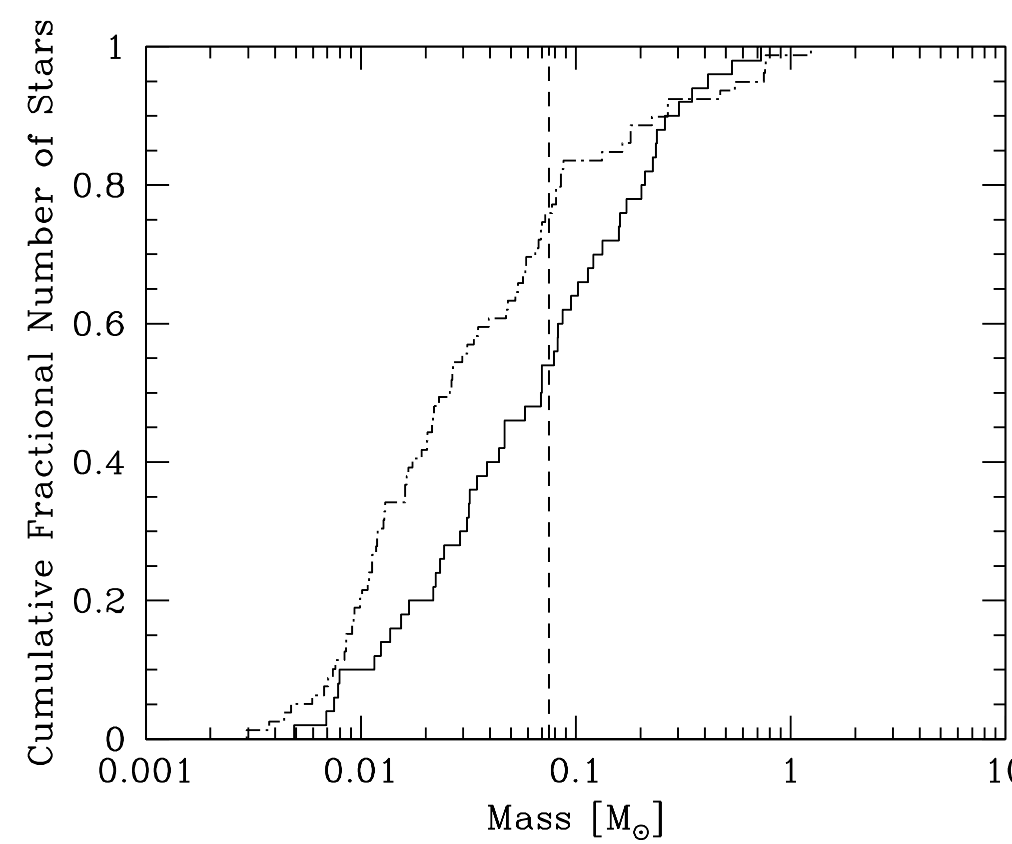
How Do We Get Out of This?

- Need to bring in extra physics beyond self-gravitating isothermal MHD turbulence to explain low mass IMF
- Three basic approaches
  - IMF set by the large-scale properties of the galaxy
  - IMF set by deviations from isothermal behavior due to dust-gas coupling and/or opacity effects
  - IMF set by local radiative feedback processes

Galactic Hypothesis v1: The Jeans Mass

- Conjecture: IMF peak ~ Jeans mass at GMC mean density (Bate + Bonnell 2005; Tumlinson 2007; Narayanan & Dave 2012, 2013)
- Implies top-heavy IMF at high SFR, high z due to high gas temp





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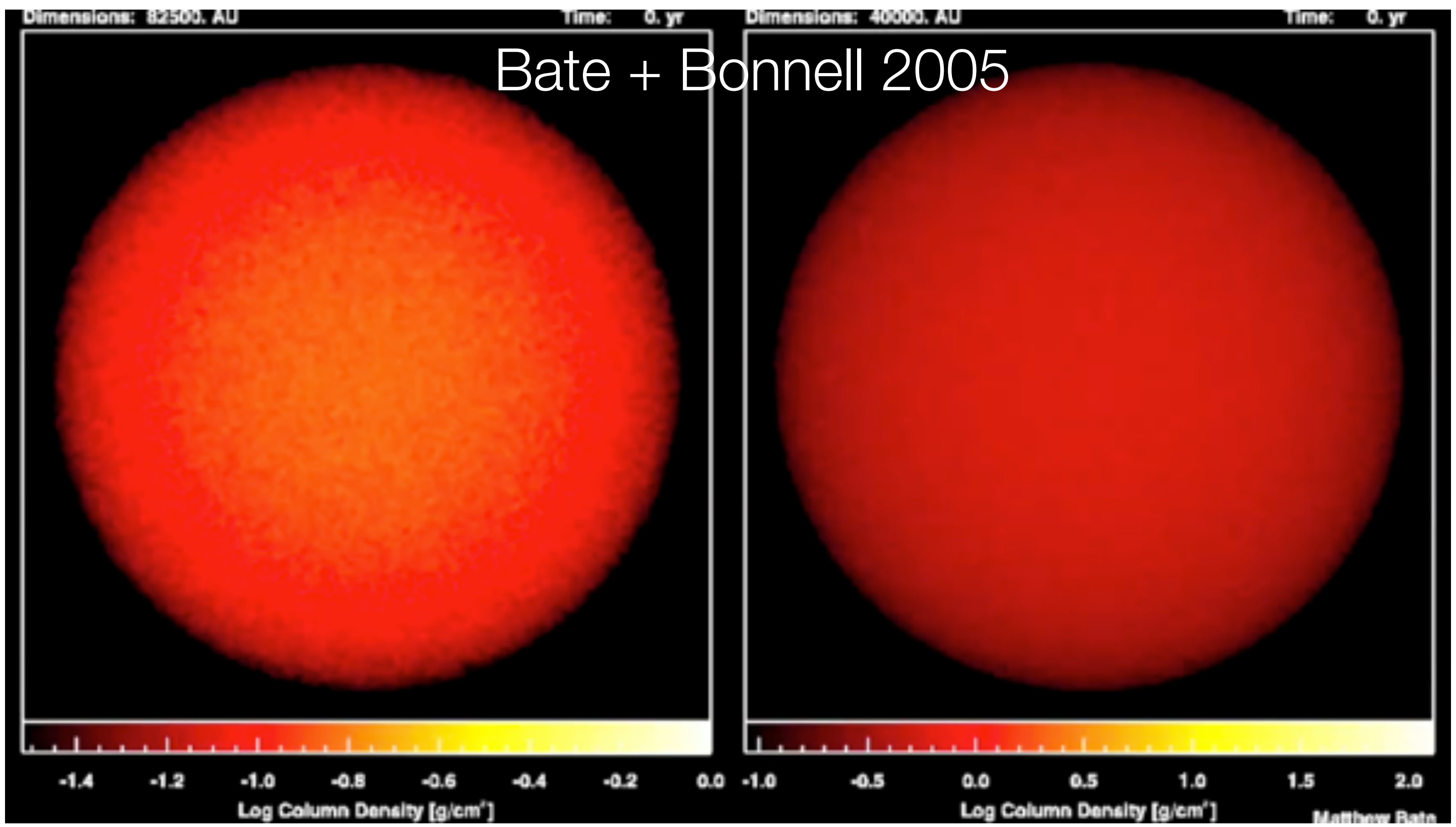
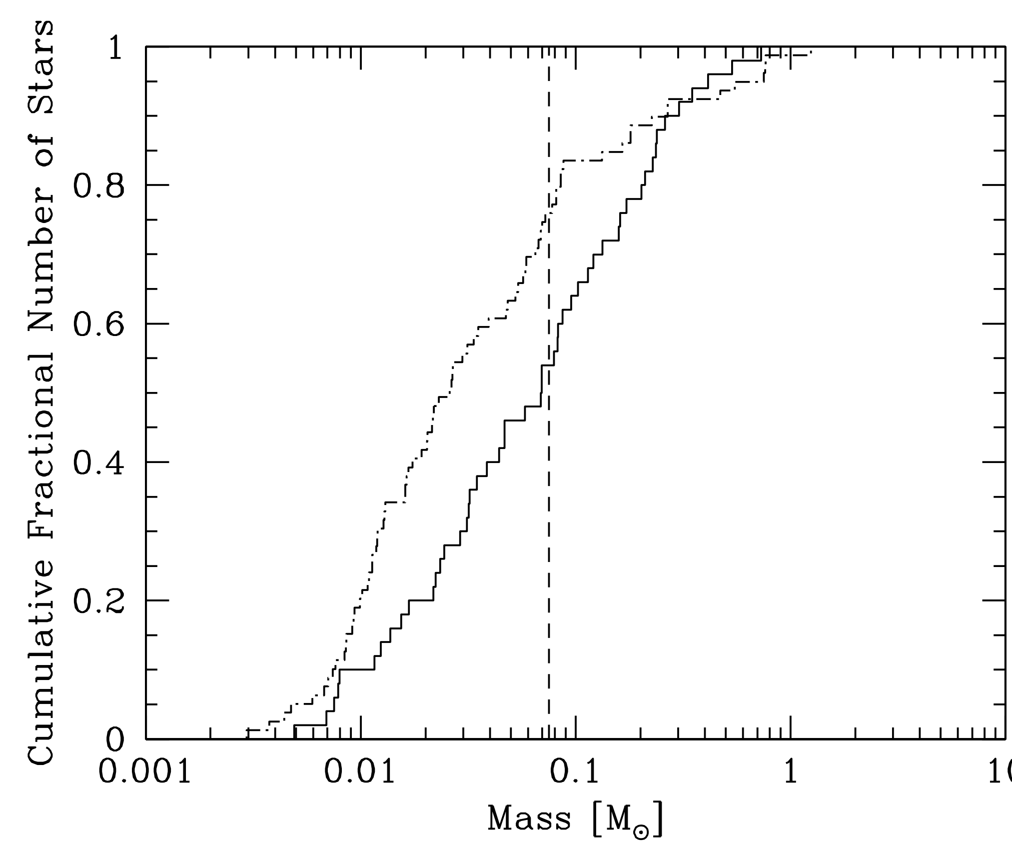
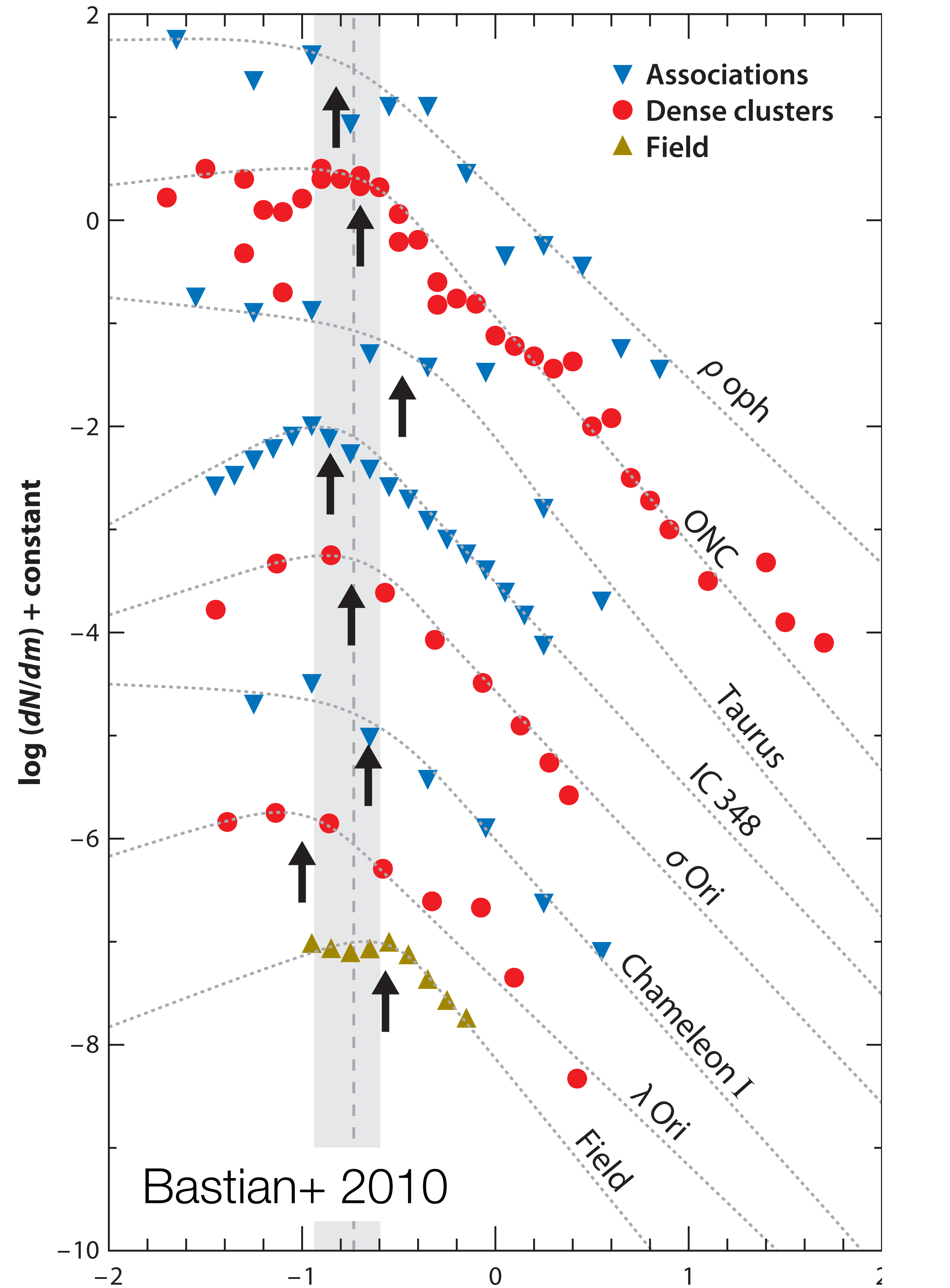




Problems with Jeans Mass Hypothesis

- Densities vary widely in local SF regions, e.g.,
  - Taurus: ≲ 60 stars pc^{-3} (Hartman 2002)
  - ONC: ~20,000 stars pc^{-3} (Hillenbrand + Hartmann 1998)
- Factor of ~300 density variation should produce factor of ~20 IMF variation
- NOT OBSERVED!



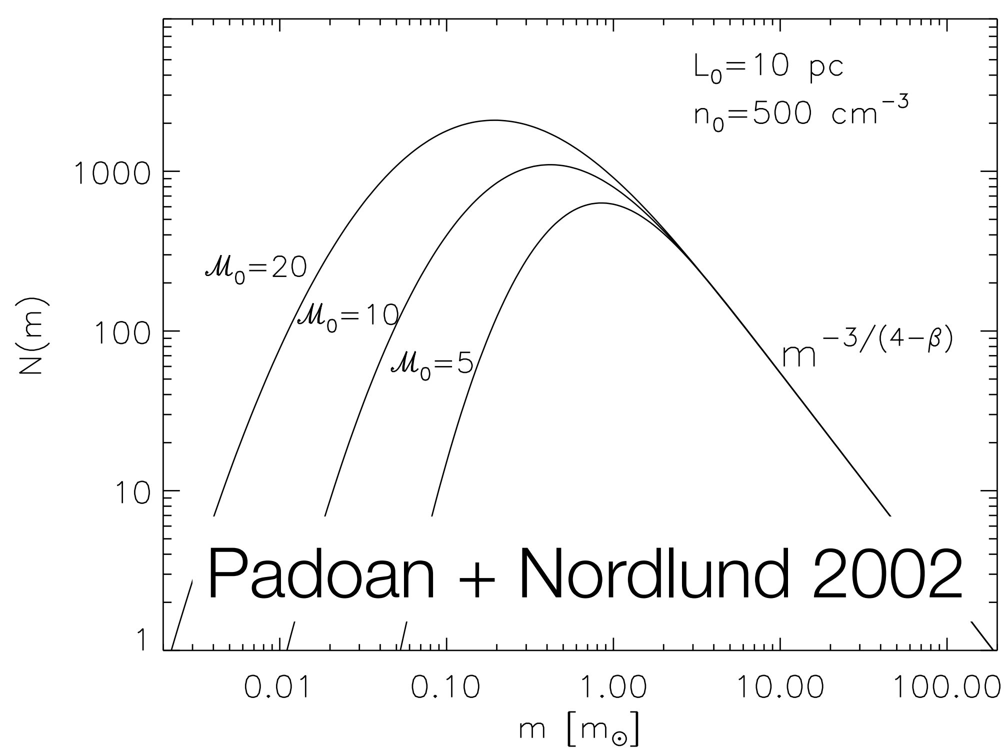
Galactic Hypothesis v2: Turbulent Jeans Mass

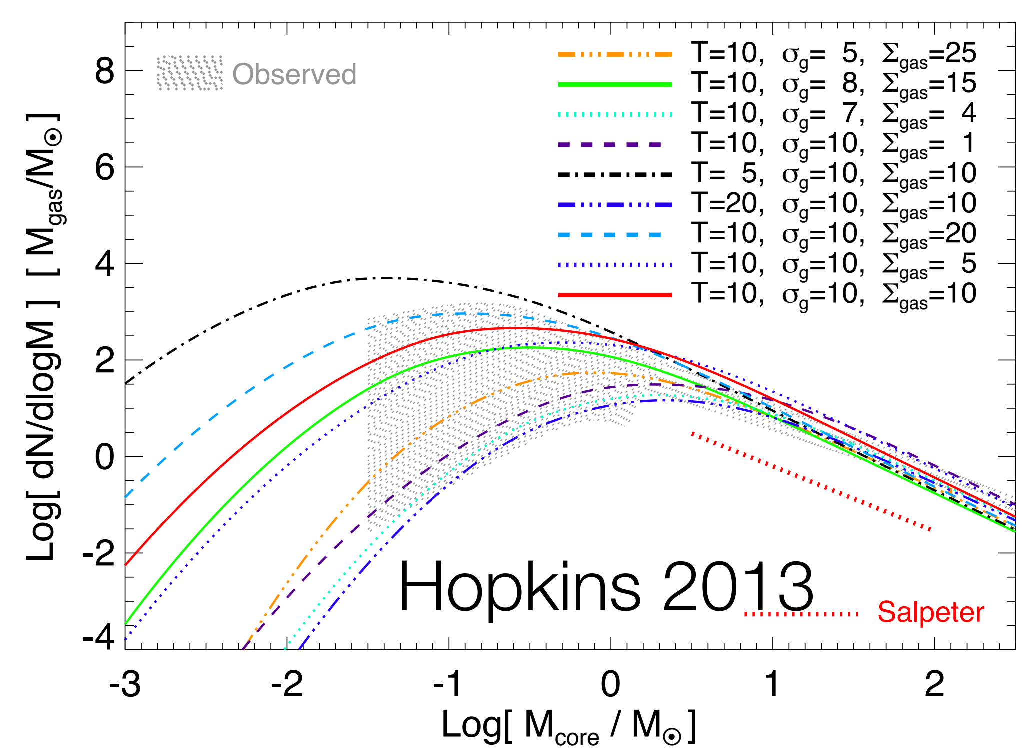
- Conjecture: IMF peak occurs because collapse suppressed by thermal pressure below a critical mass ~ Jeans mass at median density (Padoan + Nordlund 2002; Hennebelle + Chabrier 2008, 2009; Hopkins 2012, 2013)
- Critical mass is

$$M_{\rm crit} \approx \frac{M_J(\rho_0)}{\mathcal{M}} \approx \frac{c_s^2}{G\sigma_{\rm pc}} \approx \frac{c_s^2}{G^2\Sigma}$$

LWS normalization

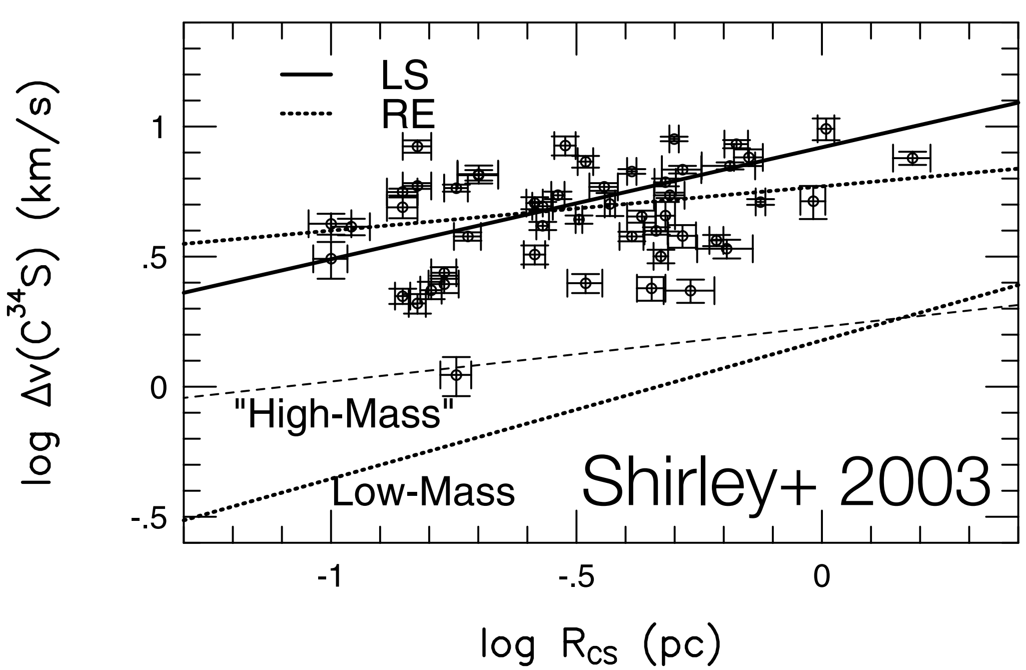
GMC surface density





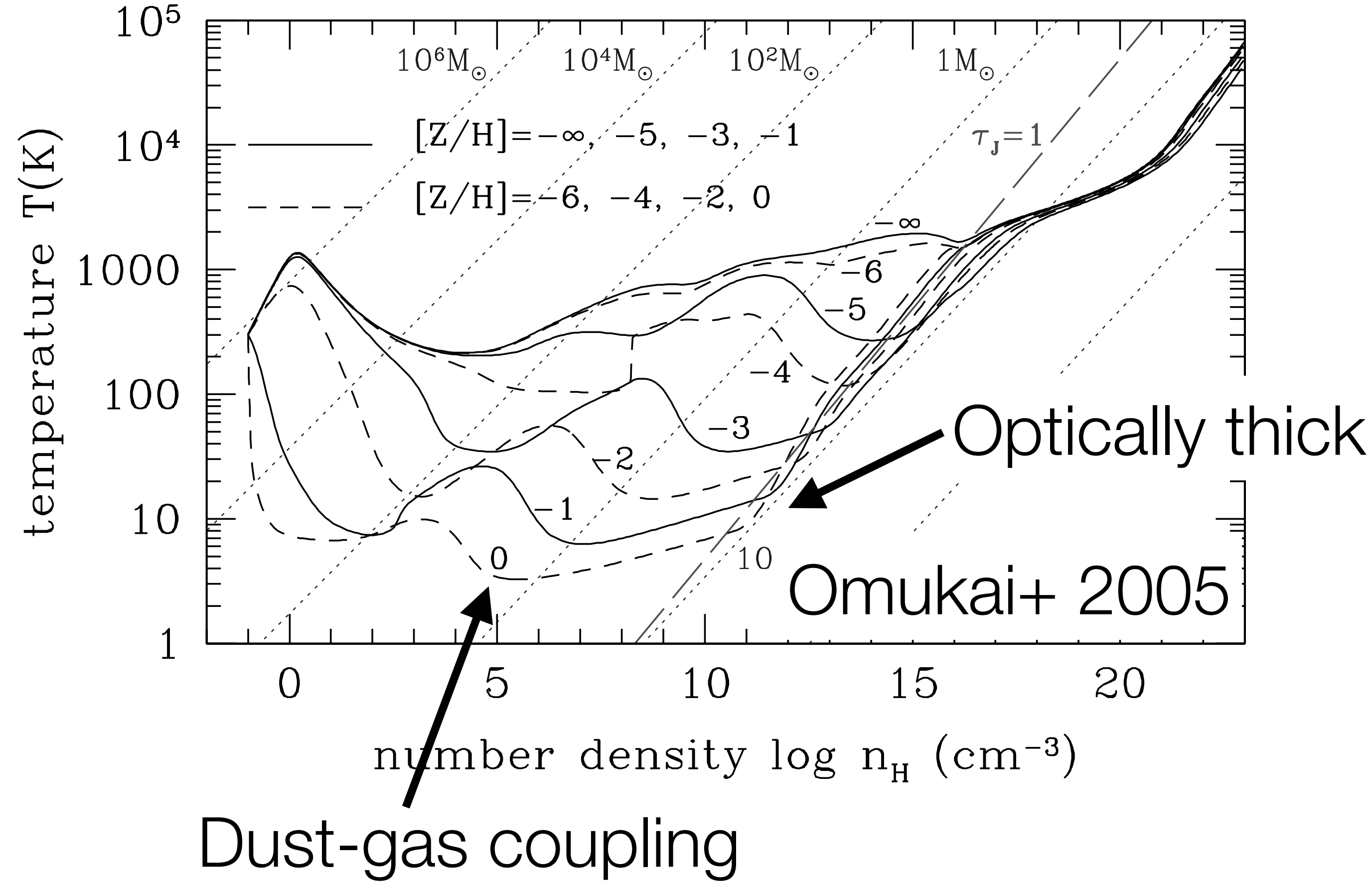
Turbulent Jeans Mass Predictions and Problems

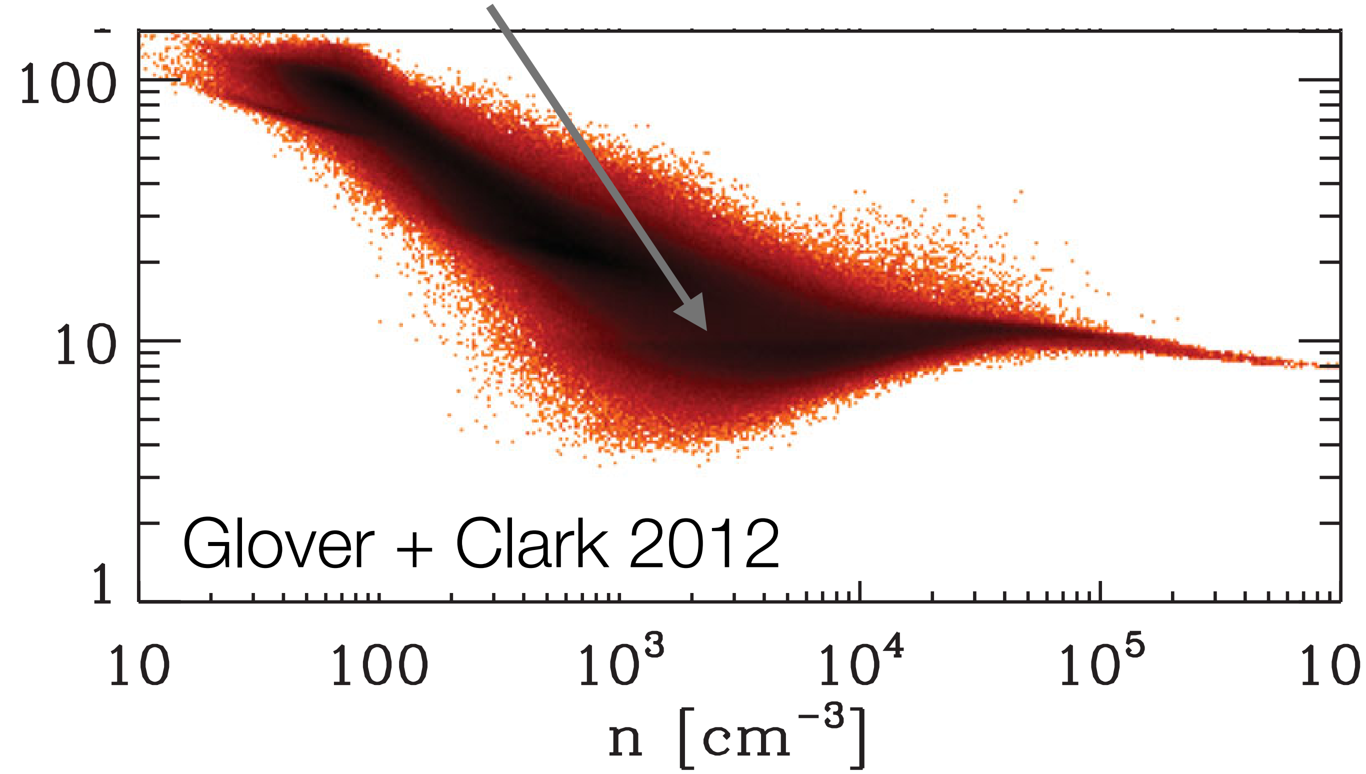
- Prediction: characteristic mass depends on temperature / linewidth-size normalization OR GMC surface density
- Predicts less variation than normal Jeans mass hypothesis due to cancellation: higher T ↔ higher σ_{pc}, Σ
- Biggest variation likely in starbursts, but not yet calculated in detail; depends on T vs. Σ
- May have problems in high-mass SF-regions: σ_{pc} higher by a factor of 10, T is not



The Non-Isothermal EOS Hypothesis

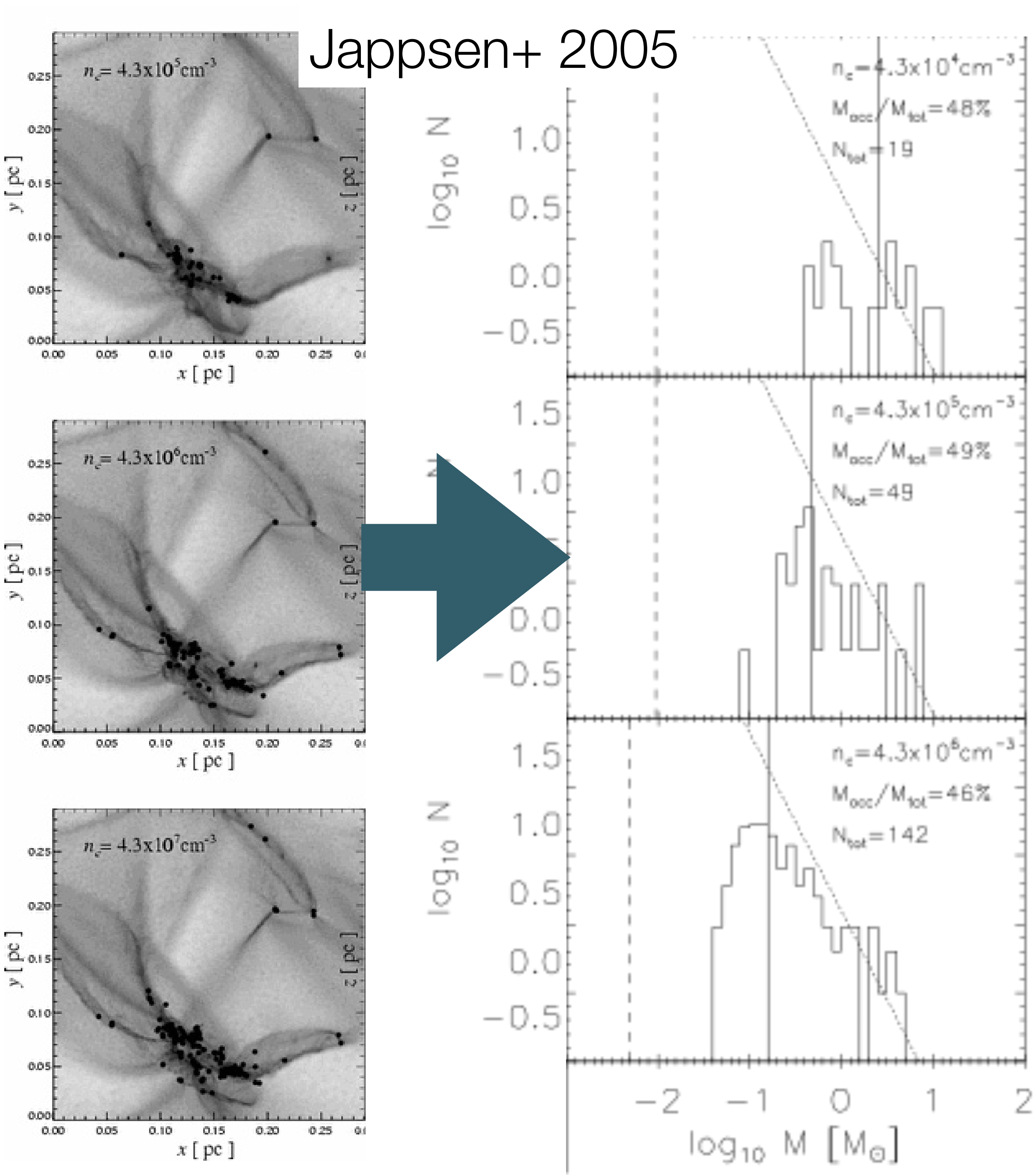
- Gas not perfectly isothermal:
  - Dust-gas coupling imperfect below ~10^5 pc^{-3}
  - Gas becomes optically thick at ~10^{10} pc^{-3}
- EOS has near-discontinuities in ɣ at these densities
- Conjecture: stellar mass scale set by M_J at such a discontinuity (Larson 2005; Omukai+ 2005; Bonnell+ 2006; Elmegreen+ 2008; Guszejnov & Hopkins 2015)



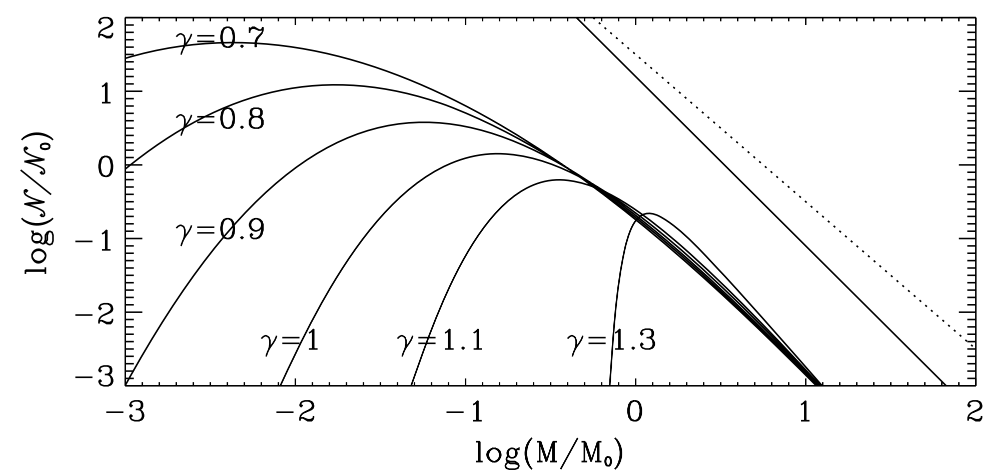


Simulations and Models for the Non-Isothermal EOS Hypothesis

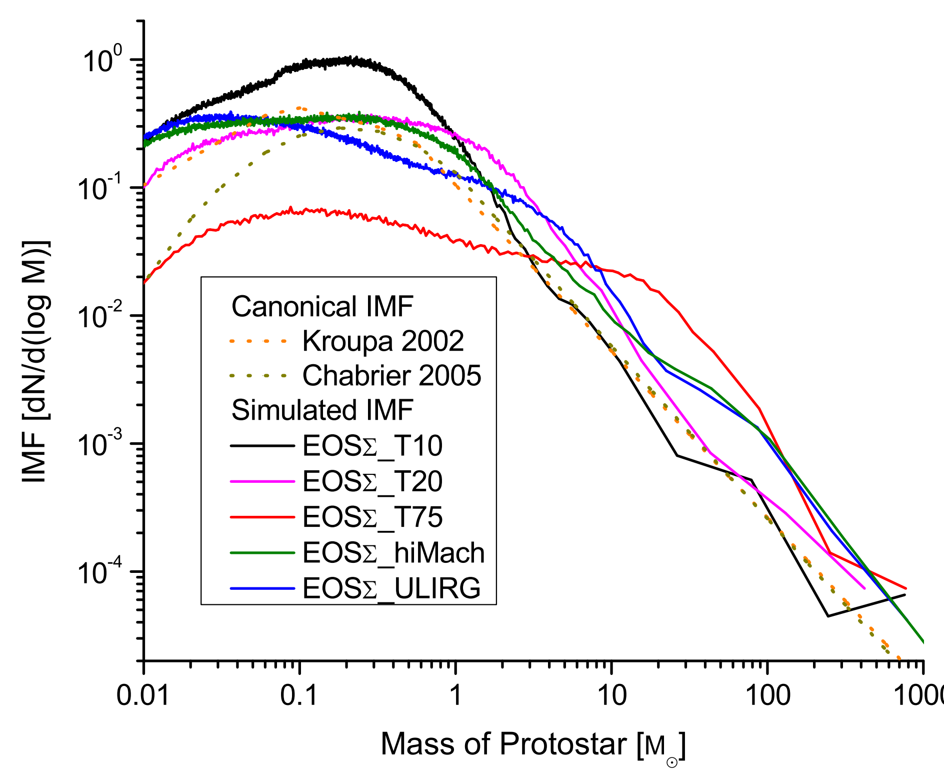
Jappsen+ 2005



Hennebelle + Chabrier 2008

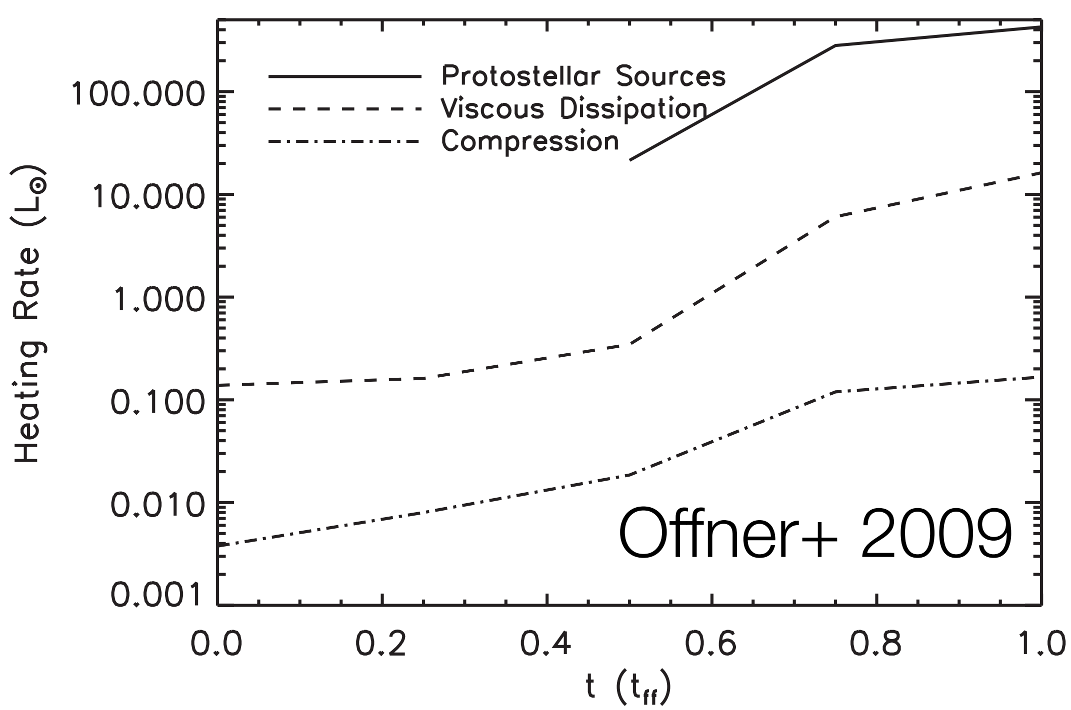


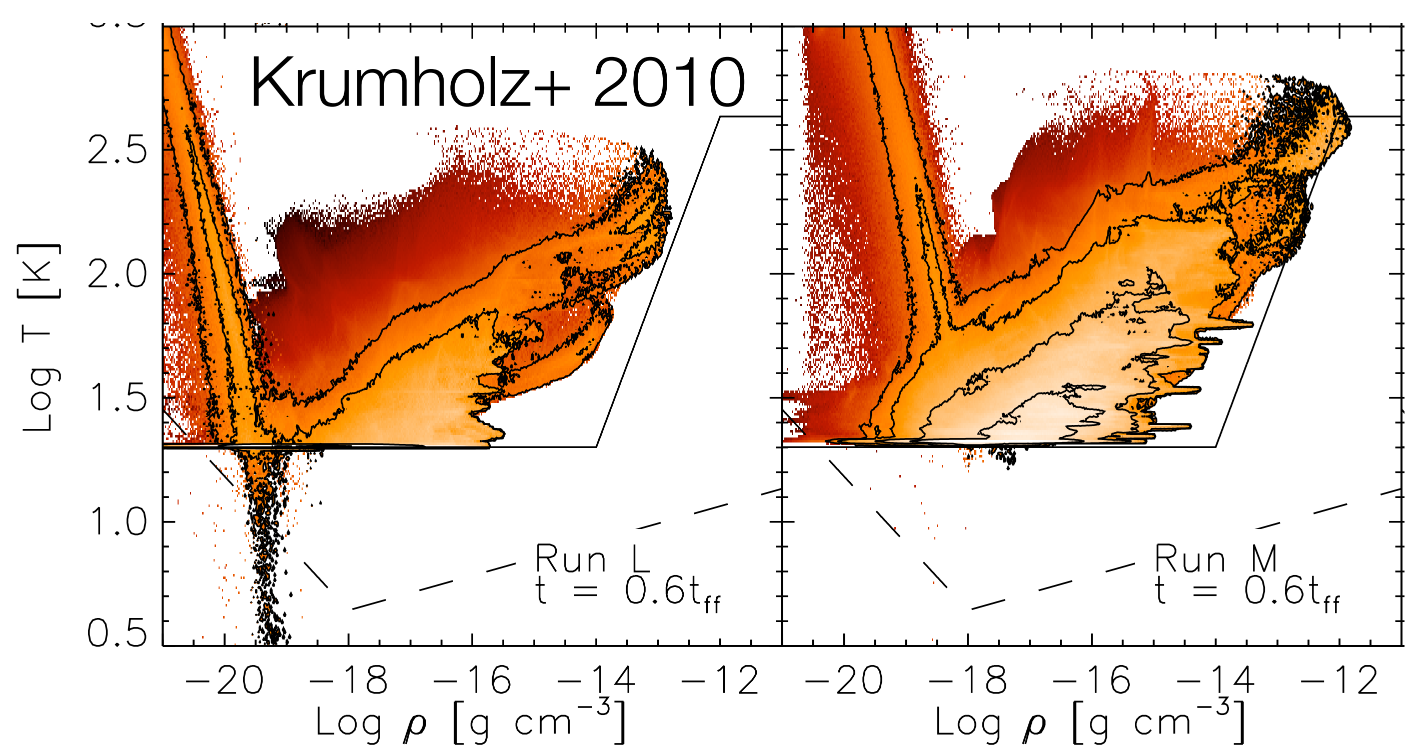
Guszejnov+ 2015



Problems with the Non-Isothermal EOS Hypothesis

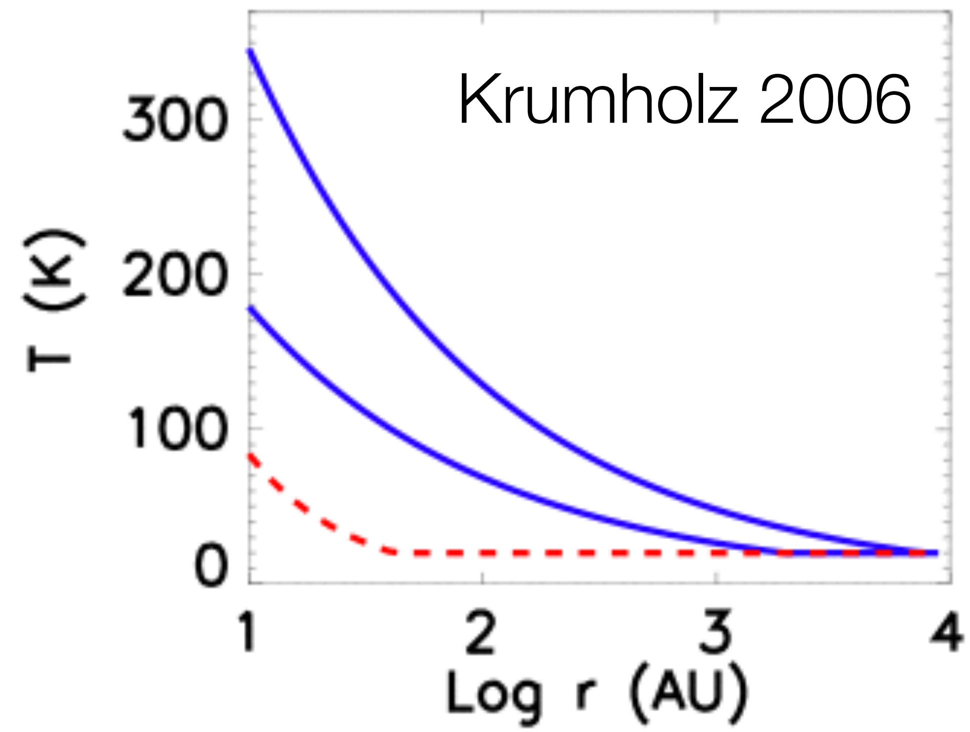
- IMF in BD regime exquisitely sensitive to assumed EOS
- Proposed EOS's not a good fit once stars turn on, since these dominate the energy budget
- Not possible to describe T vs. ρ with a single function once this happens

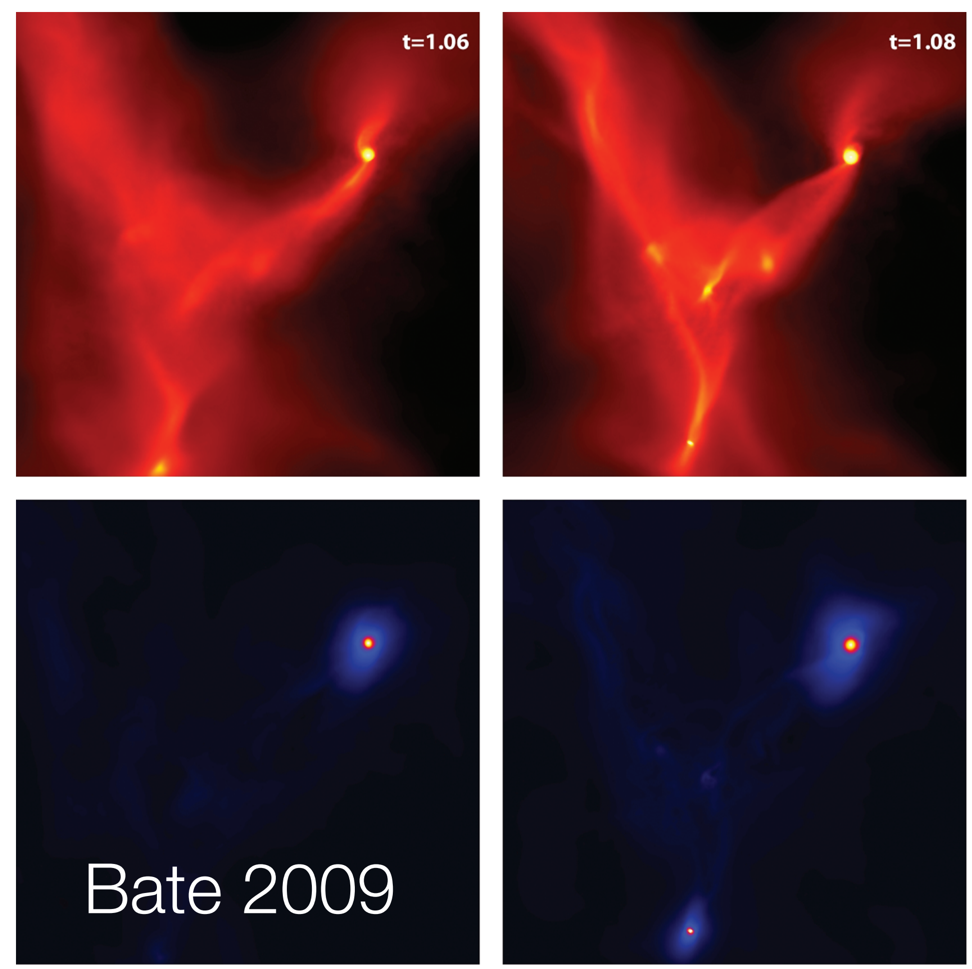




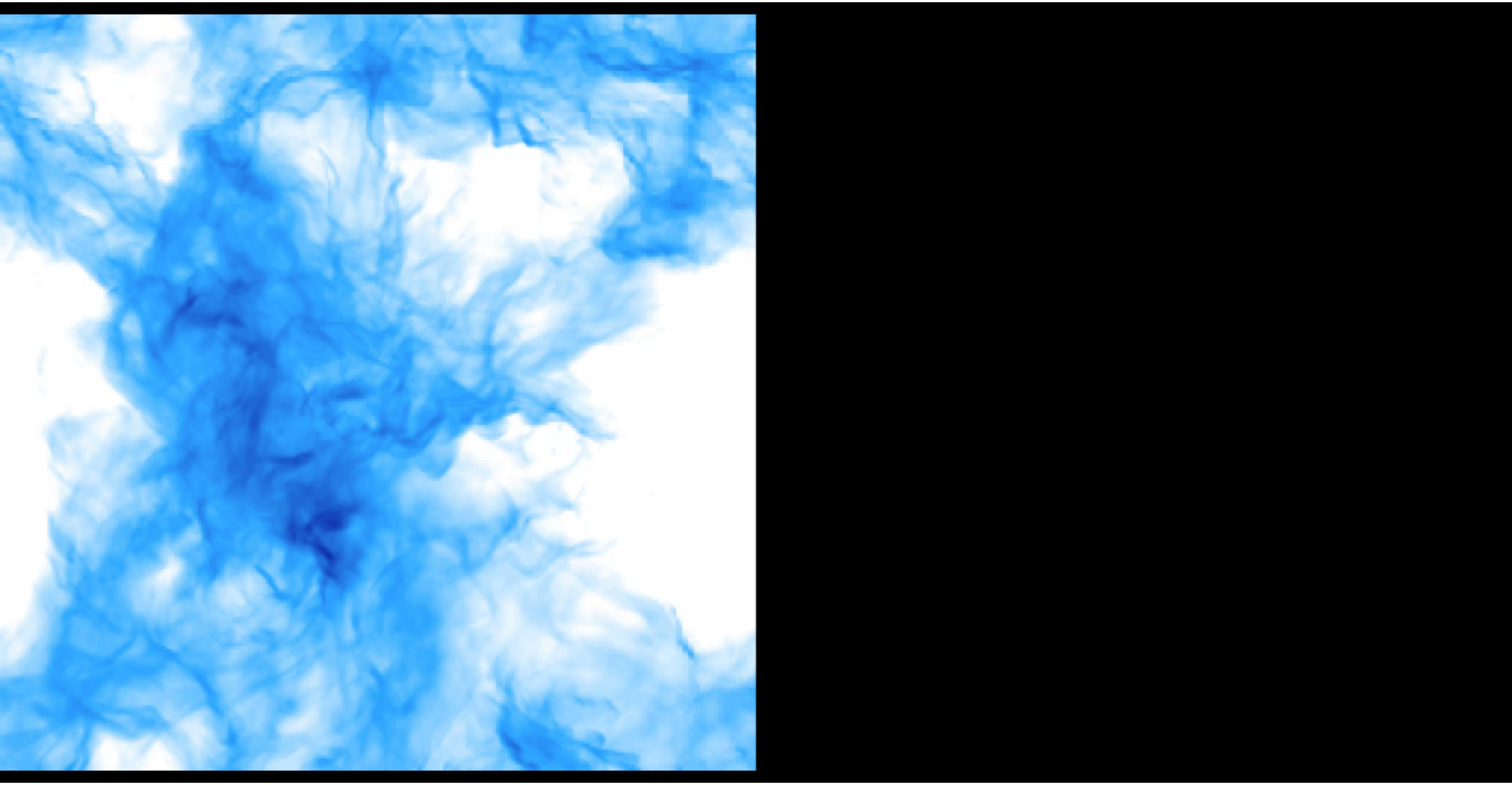
The Radiation Hypothesis

- Stars heat up the gas around them via accretion luminosity
- Heating is immediate, as soon as a collapse object forms
- Heating raises Jeans mass, chokes off fragmentation in a region around each star
- Conjecture: mass of heated region determines characteristic mass of IMF (Krumholz 2006, 2011; Offner+ 2009; Bate 2009, 2014)





Testing the Radiation Hypothesis



Krumholz+ 2012

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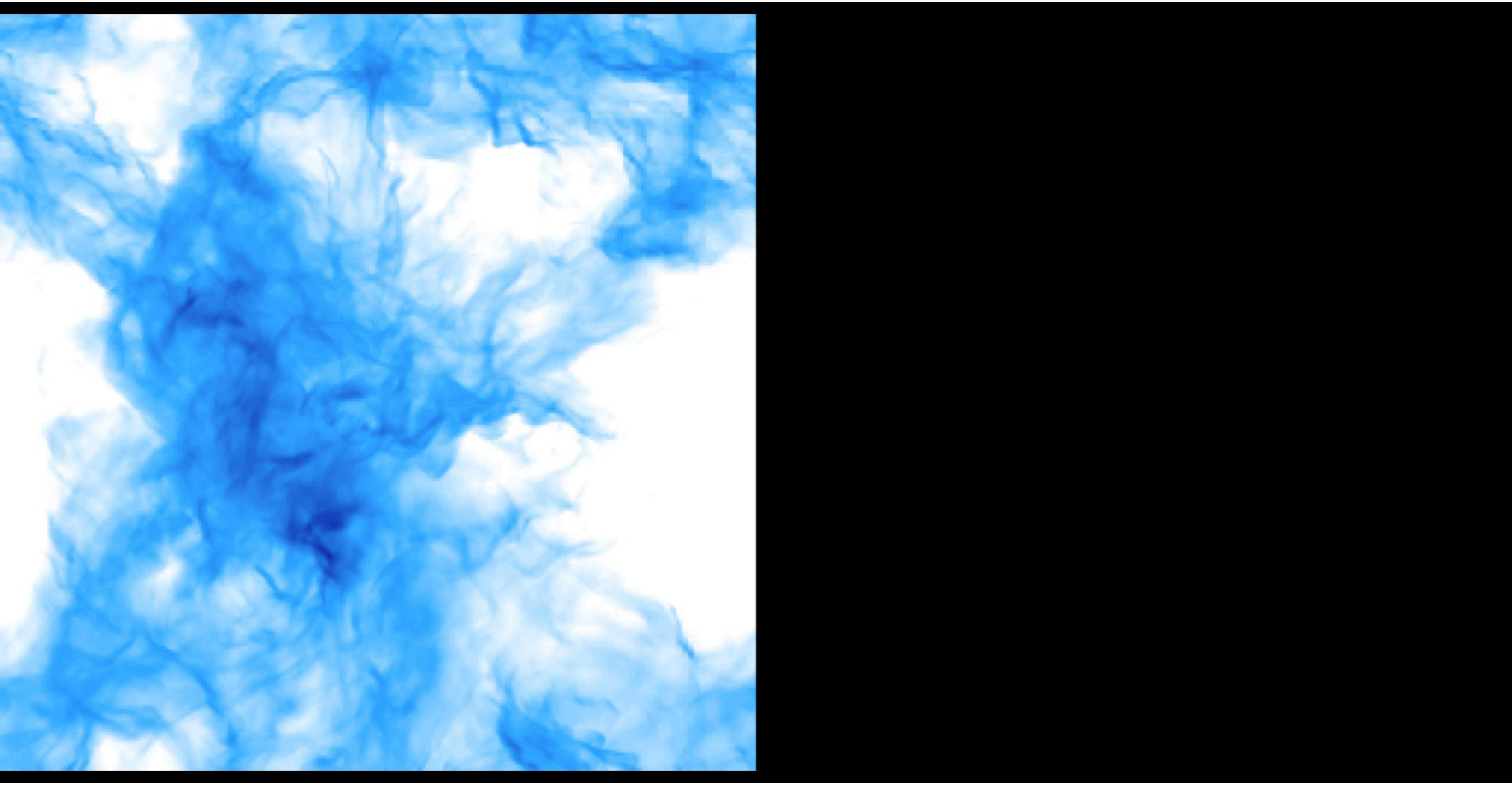

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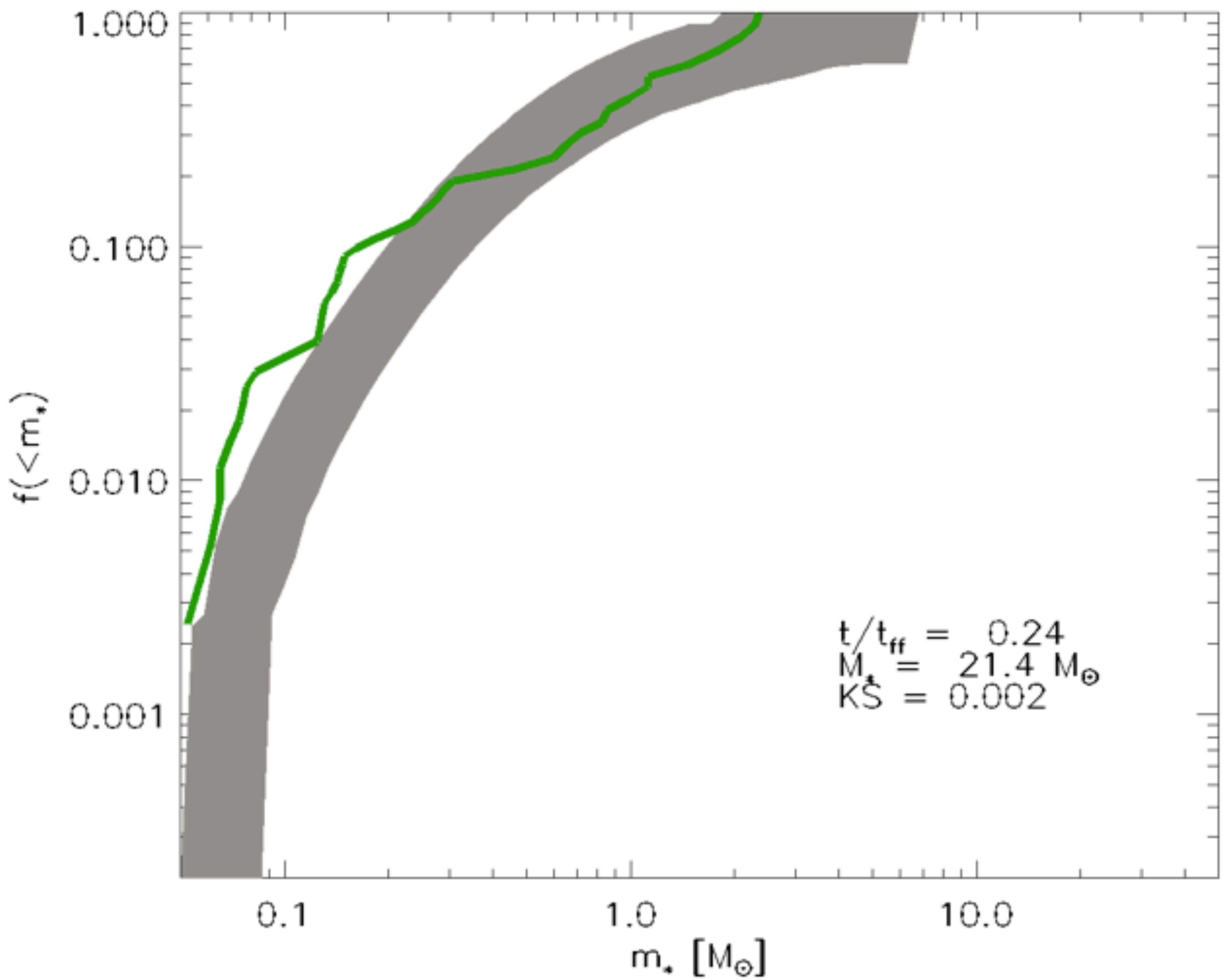

Krumholz+ 2012

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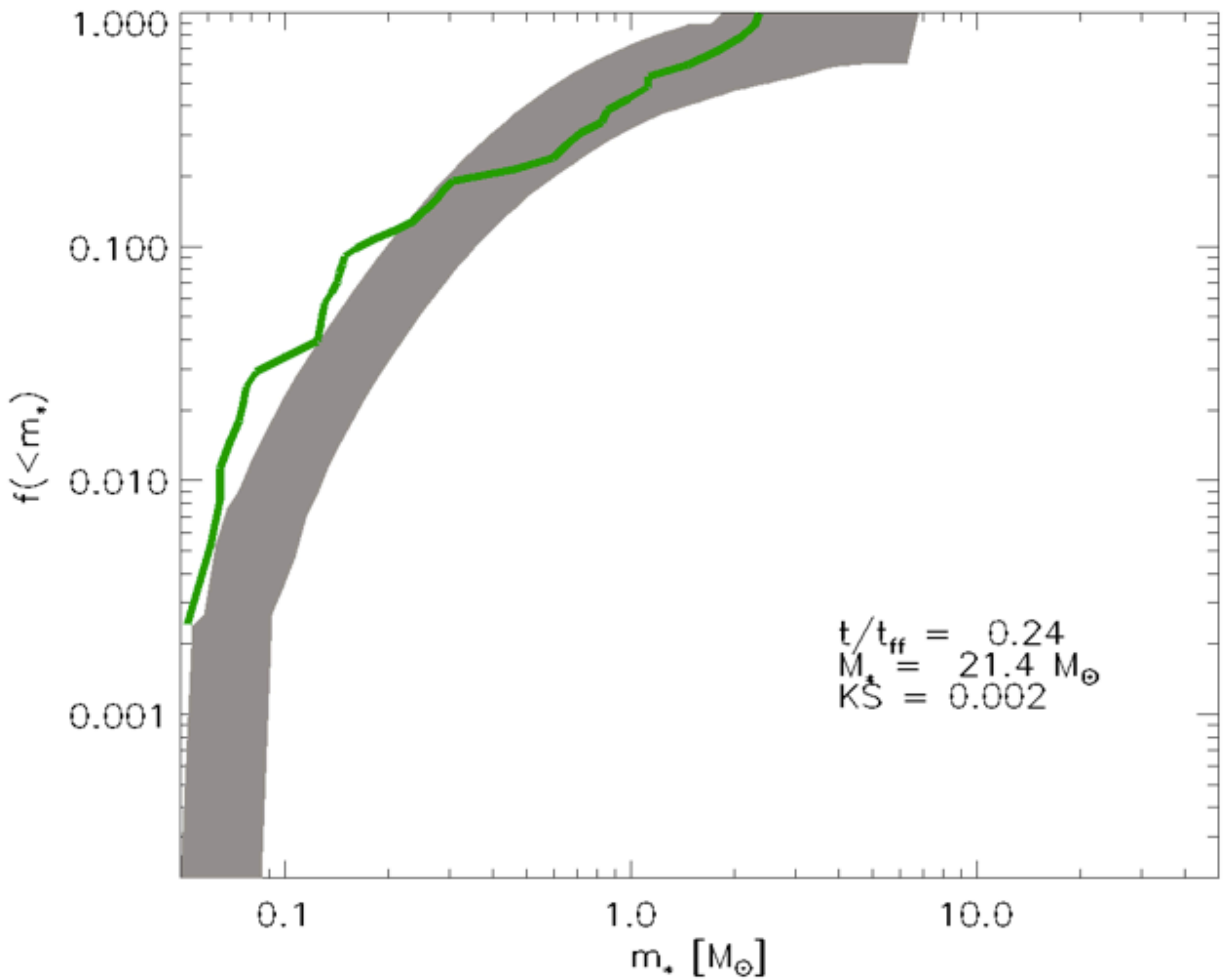
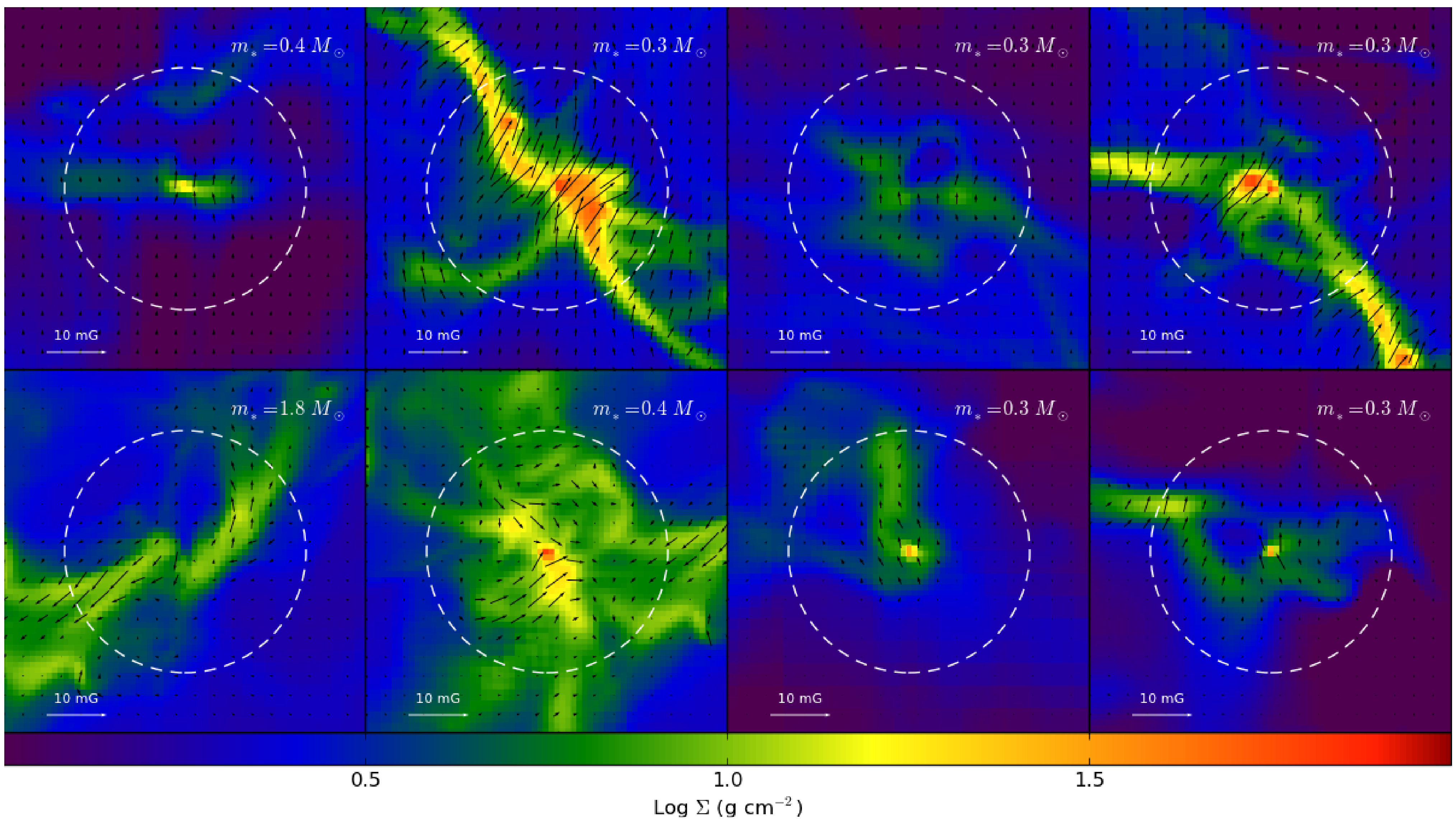


Krumholz+ 2012

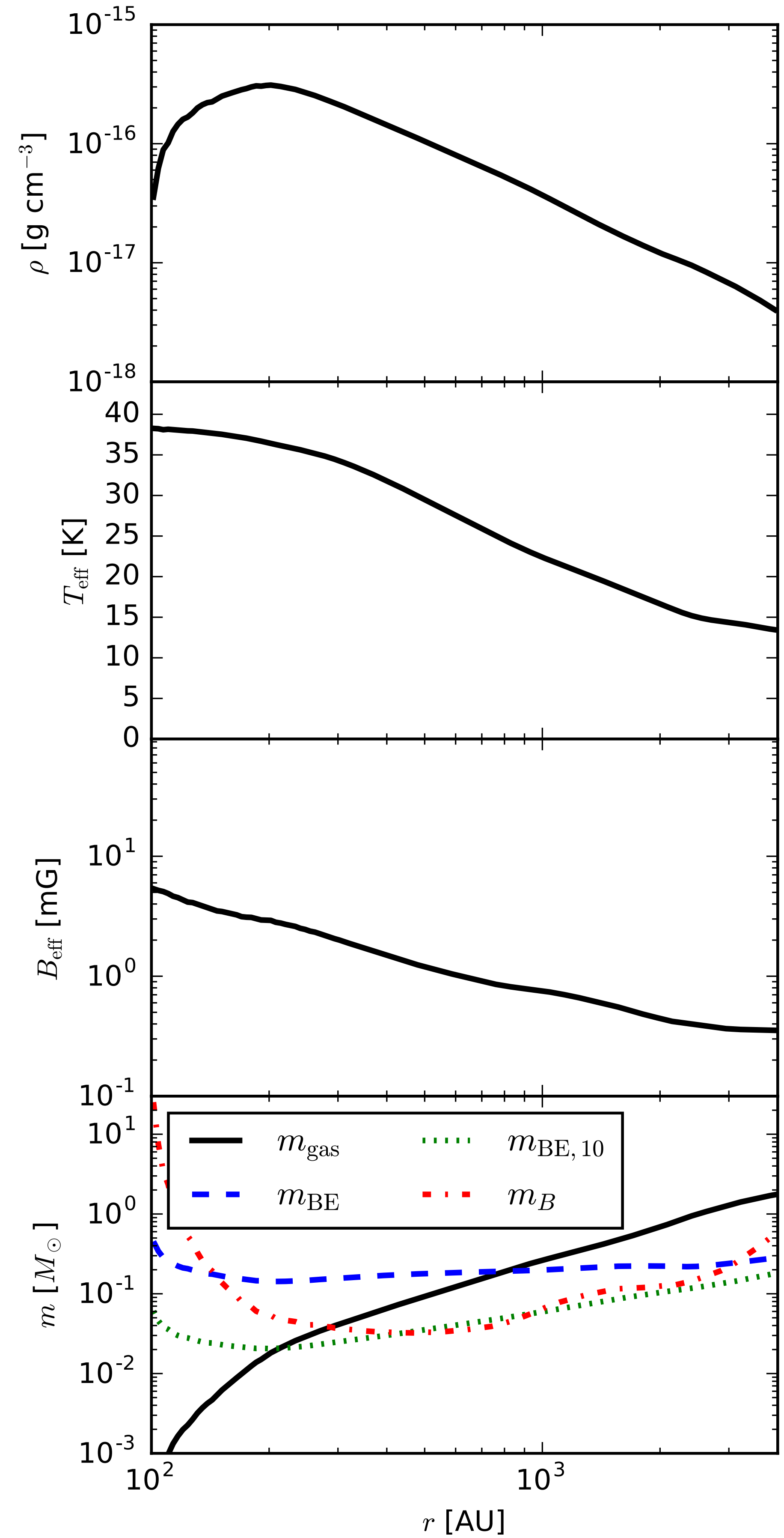
How Does Radiation Work? A Detailed View

- Examine all stars formed in radiation-MHD simulations so we can compare radiative and magnetic effects (Myers+ 2014, Cunningham+ 2016



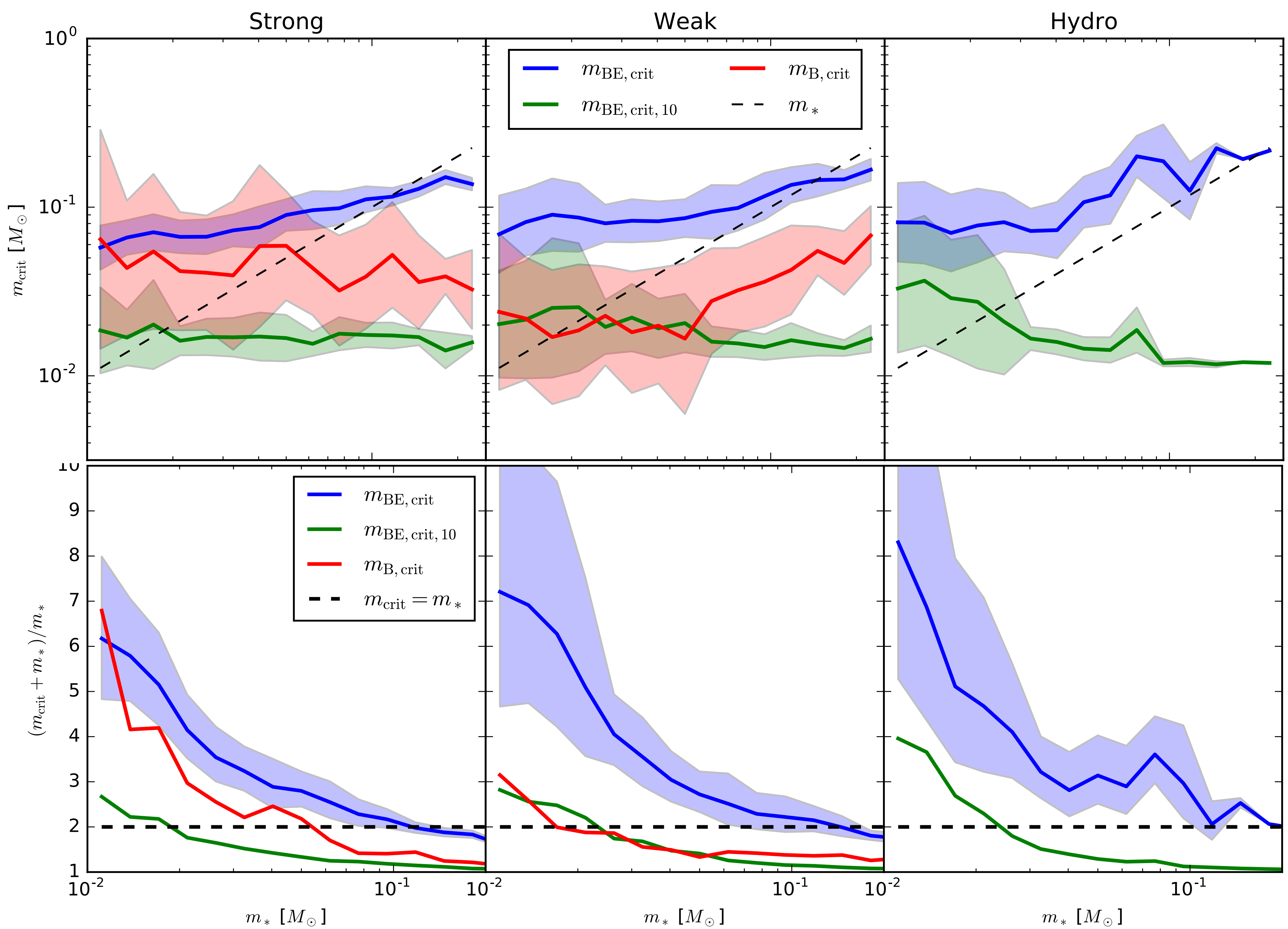
Dissecting Radiation Feedback

- Examine concentric shells around each star at each time
- Compare gas mass m_{gas} to:
  - m_{BE} — thermal pressure support
  - $m_{BE,10}$ — thermal pressure support we would have had without radiation feedback
  - m_B — magnetic support
- Mass of stabilized region set by $m_{gas} = \max(m_{BE}, m_B)$

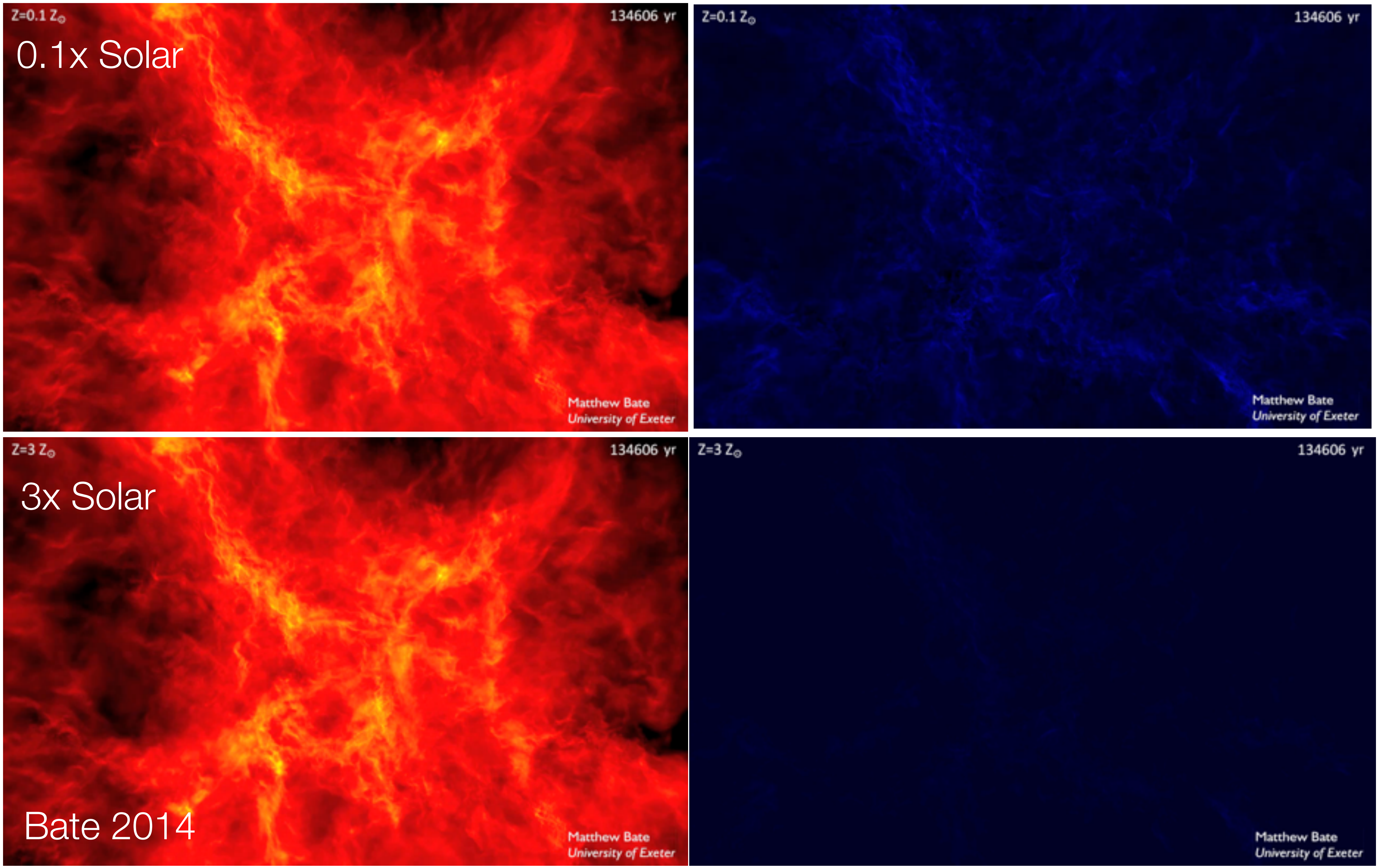


Krumholz+ 2016

Gas Stabilization by Radiative Feedback



Metallicity Doesn't Seem to Matter Much



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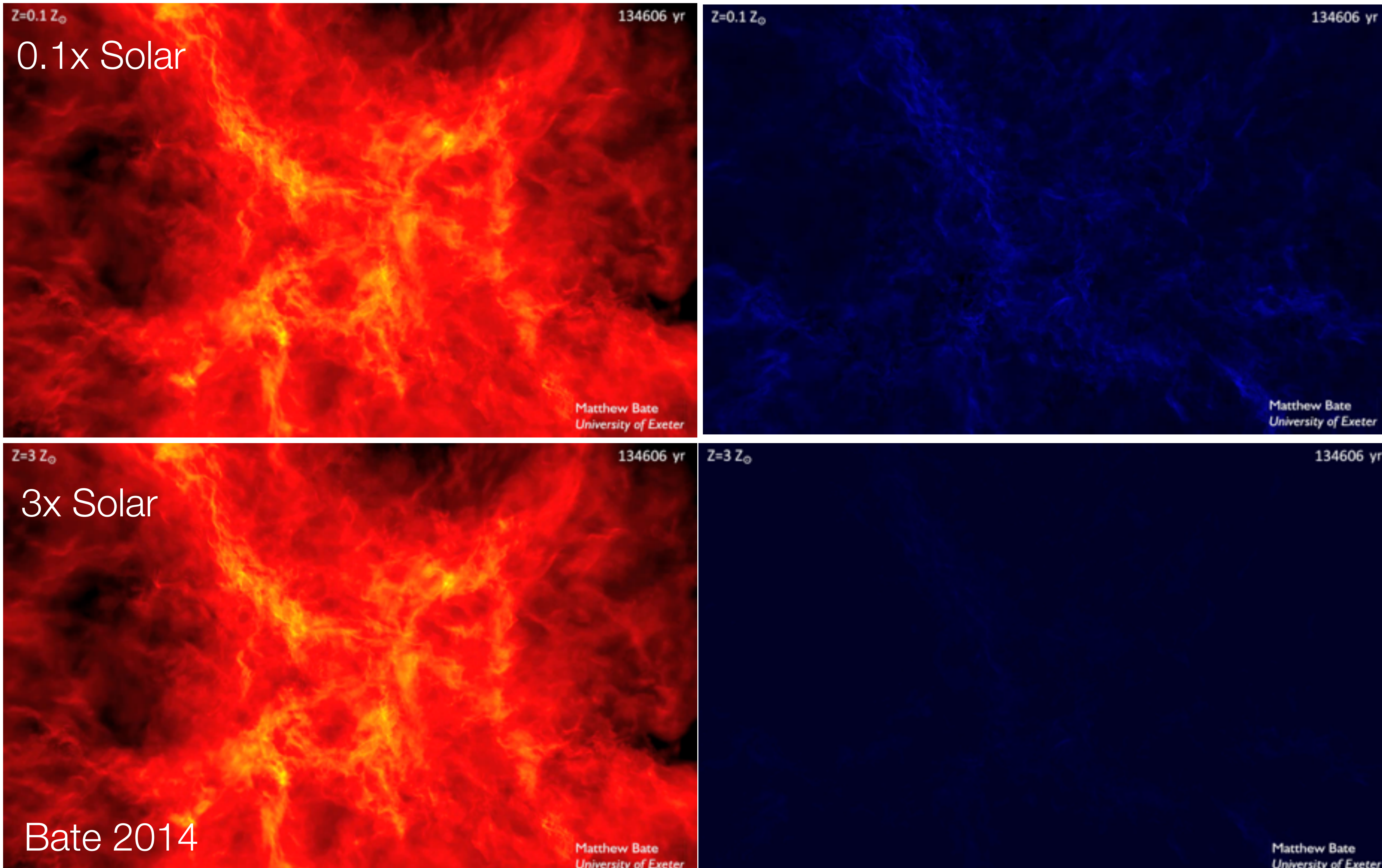

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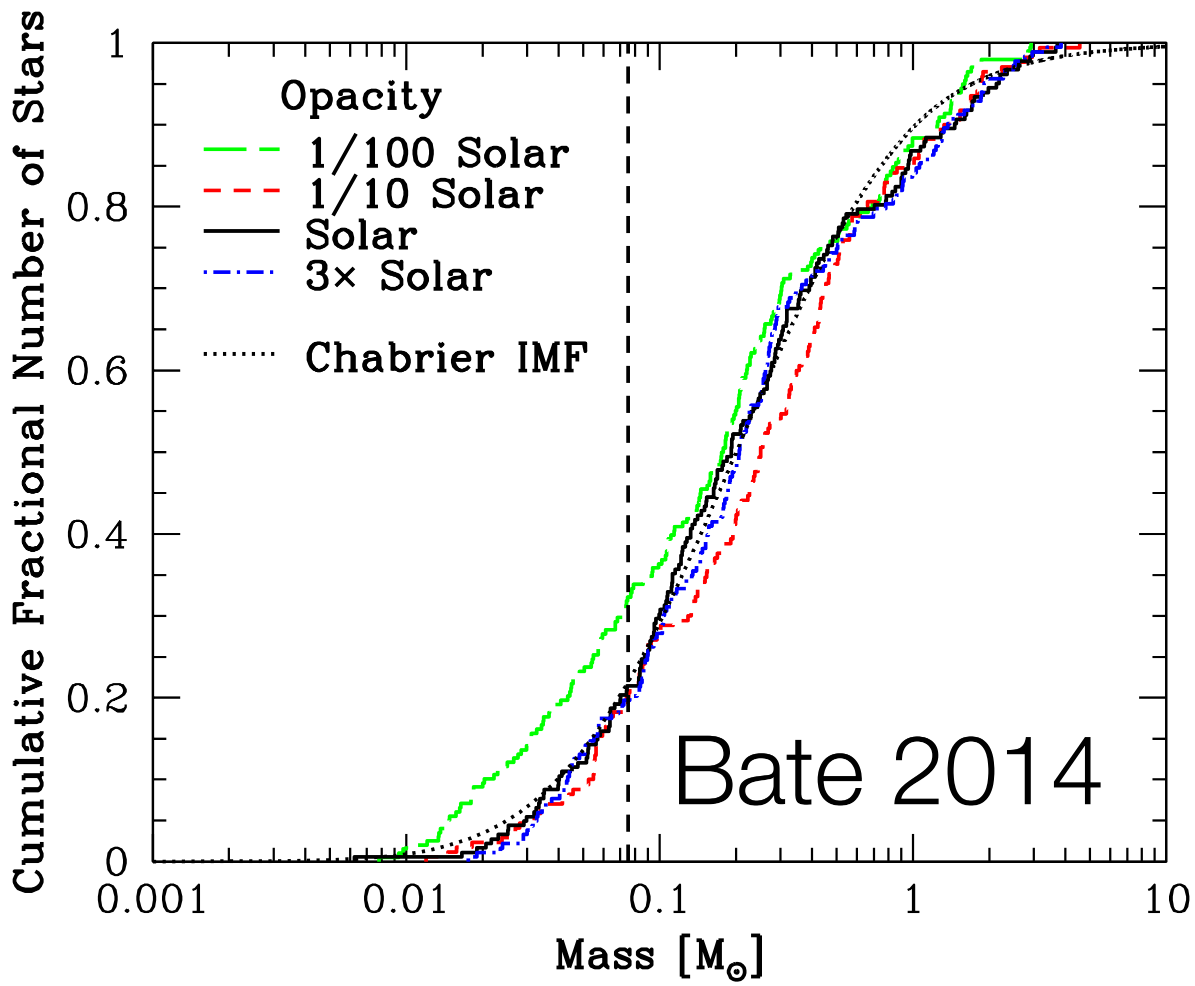
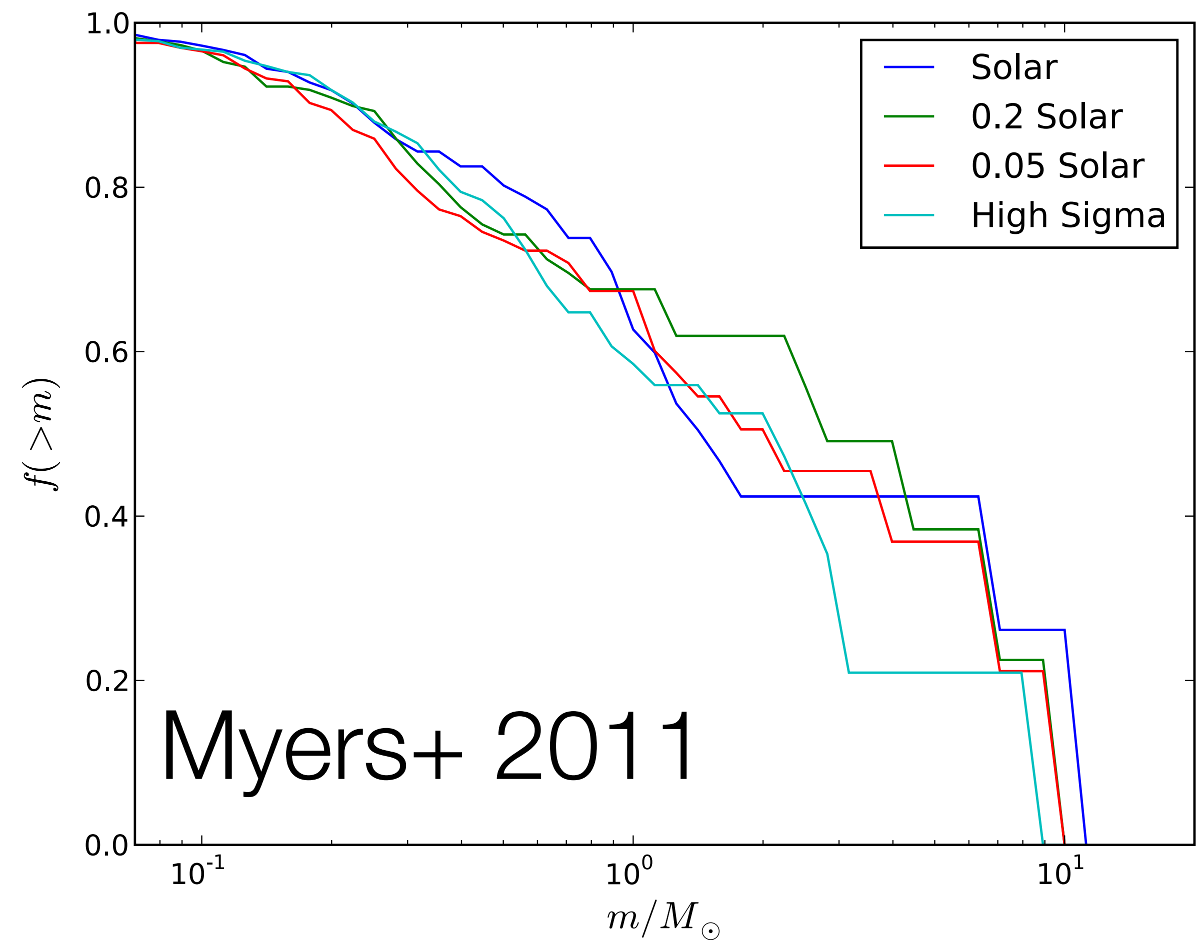




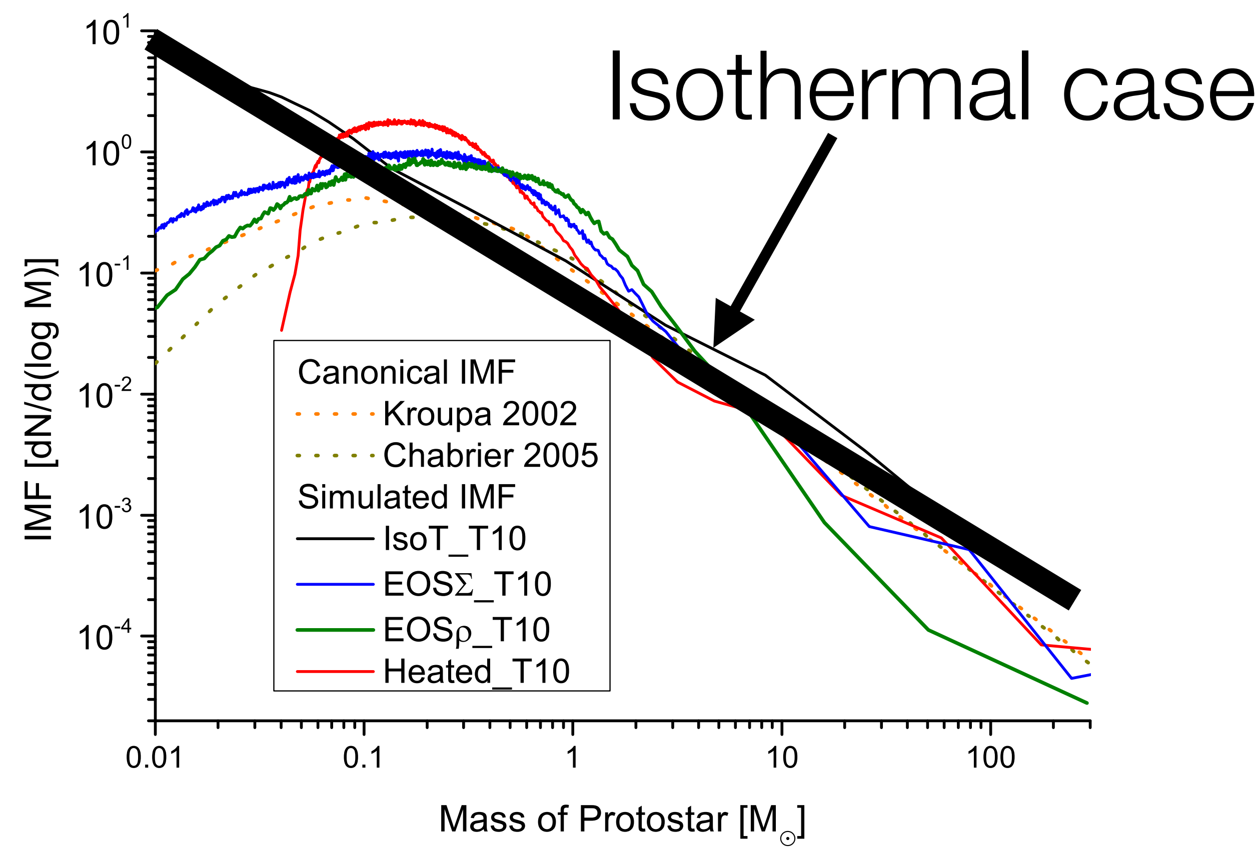
Extending the Radiation Hypothesis

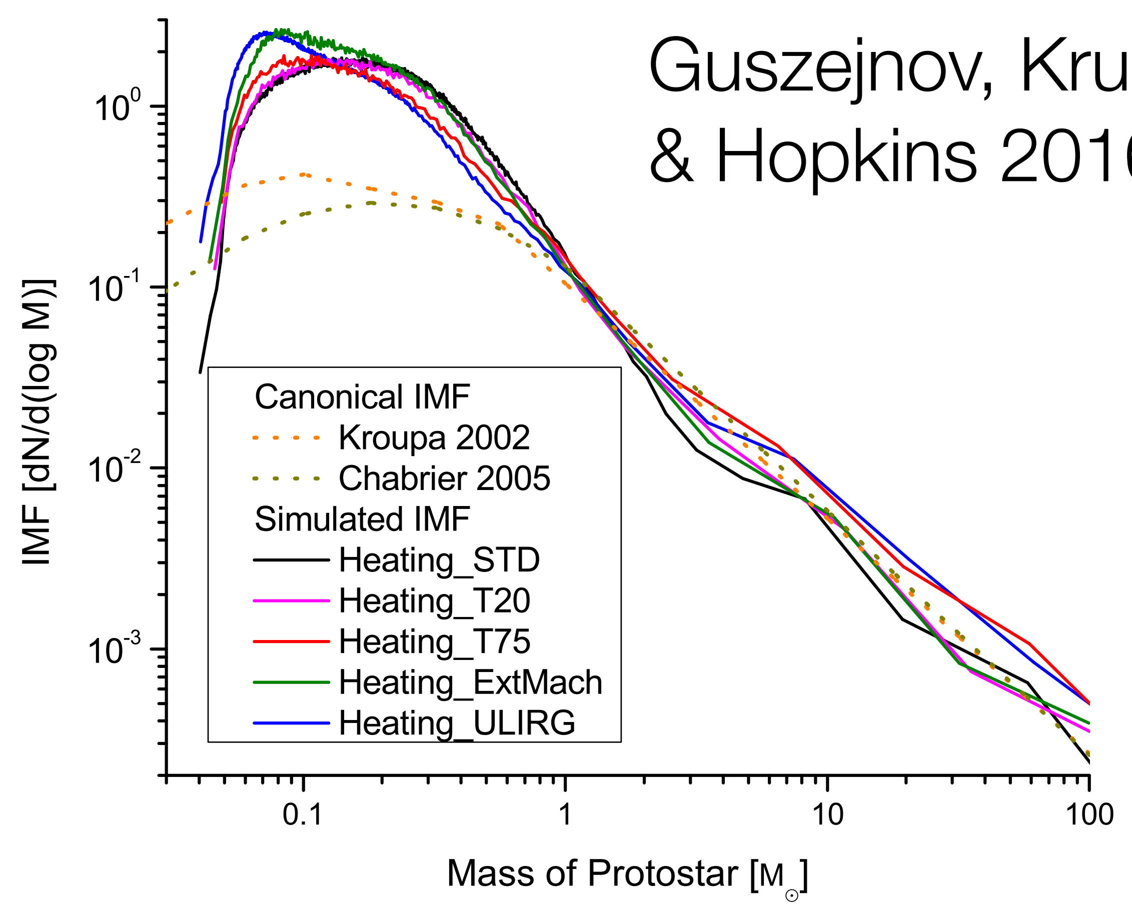
- Accretion luminosity set by surface escape speed, which in turn is set by T_{core}, which D burning fixes to ~ 10^6 K
- Escape speed can therefore be written approximately in terms of fundamental constants
- Analytically solve for size of heated region and characteristic mass, with almost no dependence in interstellar parameters (Krumholz 2011):

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

Radiation In a (Semi-)Analytic Model

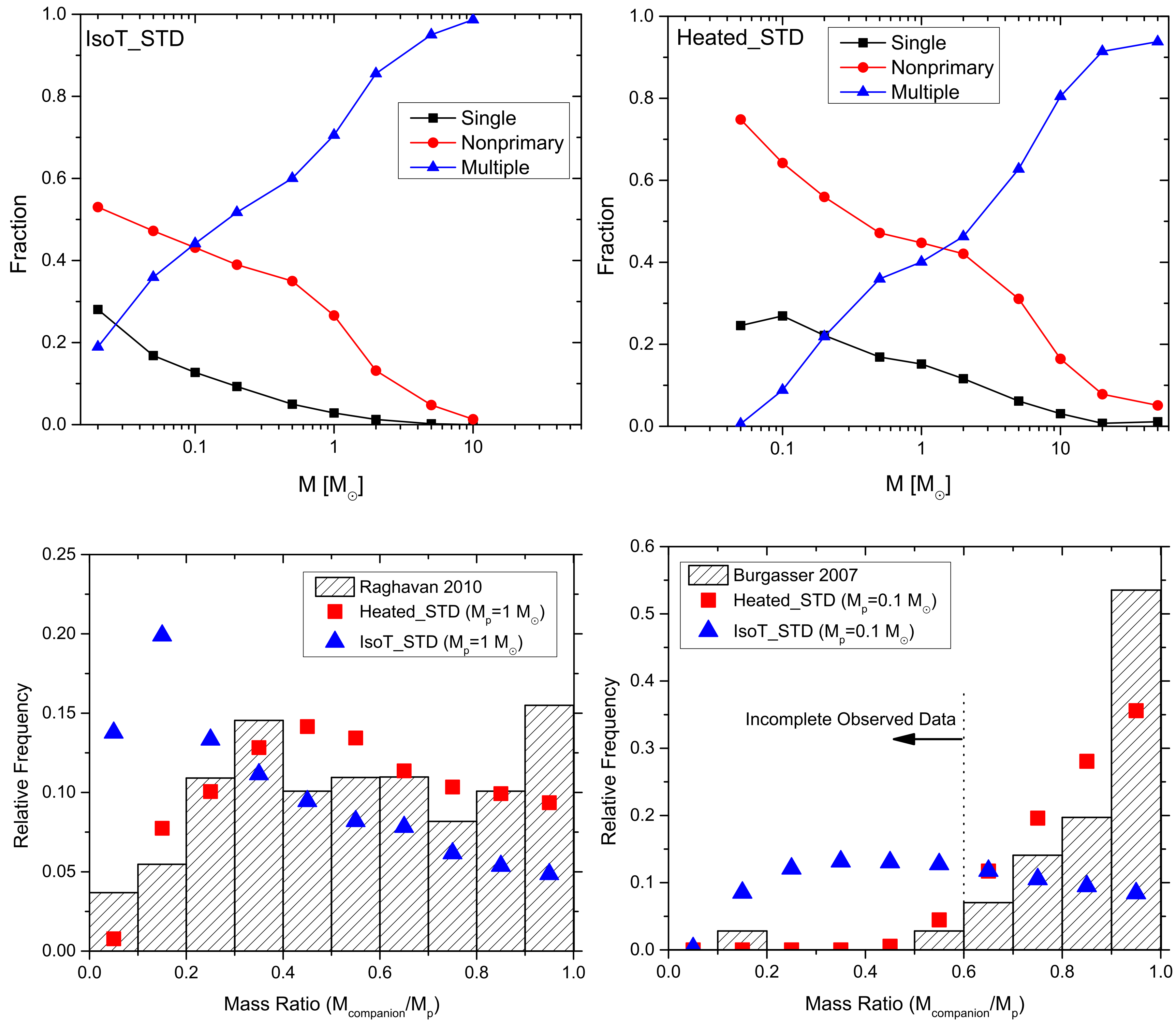
- Use excursion set-like model based on Hopkins+ fragmentation tree
- Add local radiative heating: in any collapsing region, use temperature computed from Krumholz+ 2011 formalism
- Vary environment:
  - Background T = 10, 20, 75 K
  - Mach number = 6 - 30
  - $\Sigma = 10 - 3000\ M_\odot\ pc^{-2}$
- Compare to isothermal, EOS not including radiation





Guszejnov, Krumholz, & Hopkins 2016

Semi-Analytic Model Also Gets Binaries Right



Implications and Possible Problems for the Radiation Hypothesis

- Suggests (very slightly) bottom-heavy IMF in the highest pressure star-forming environments

- Not clear yet what sets the shape of the IMF below the feedback break

- Probably need to extend models to include disk fragmentation — not currently captured, appear to have too few brown dwarfs in analytic model as compared to simulations

Summary

- Non-powerlaw part of the IMF must be controlled by deviations from isothermal behavior
- Two possibilities:
    - Important deviations are at galactic scale; apparent lack of IMF variation is due to convenient cancellation
    - Important deviations are at $\ll$ 1 pc scale, due to stellar feedback or dust-gas coupling; predicts at most weak IMF variation in very high pressure / density regions