The Effects of Radiative Transfer on Low-Mass Star Formation

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Dense Cores in Dark Clouds
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Molecular Clouds

Summary

- **Clouds are turbulent**

(Myers 1983, Myers & Khersonsky 1995, Myers & Gammie 1999...)

- **Gravitational Instability causes local collapse:**

(Myers & Fuller 1993, Myers et al 1995, Myers & Zweible 2001, Myers 2005...)

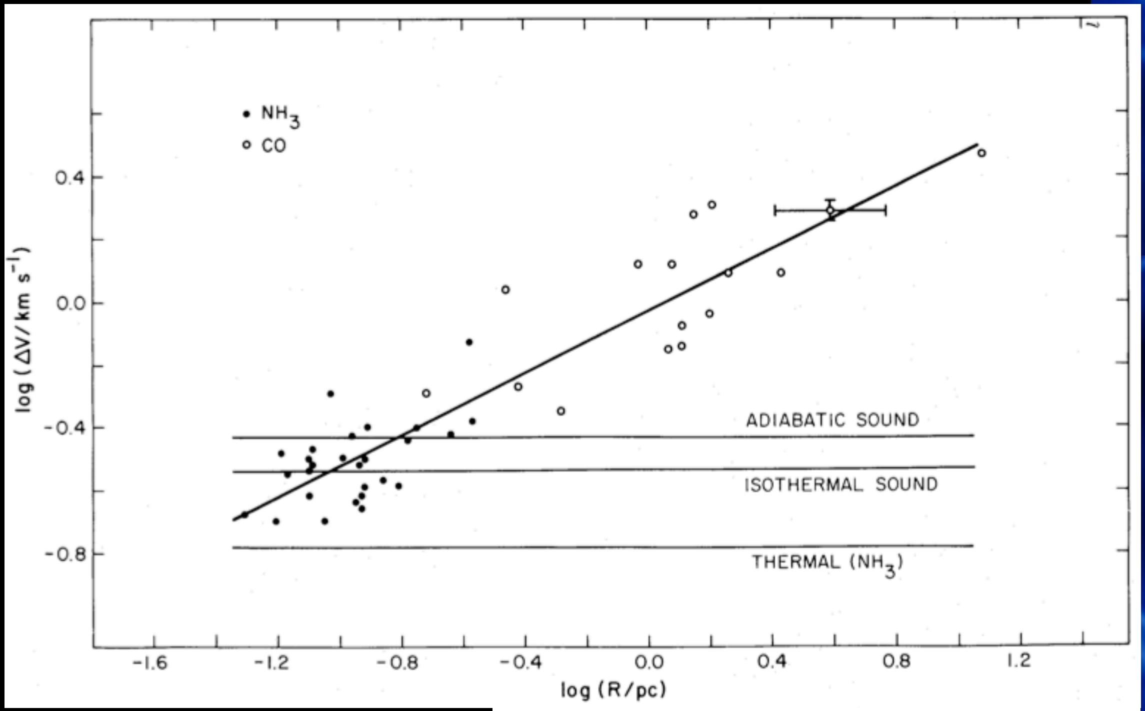
$$\lambda_J = 2\,\pi/k_J = (\pi\, c_s^2 /\ G\,\rho\,)^{1/2}$$

- **Star formation is inefficient; clouds are ~ virialized**

(Myers 1982, Myers et al. 1986, Myers & Goodman 1988, Myers 2000)

- **On large scales clouds are ~ isothermal**

(Myers & Fuller 92, Myers 2008)



Linewidth vs. Cloud Size (Myers 1983)

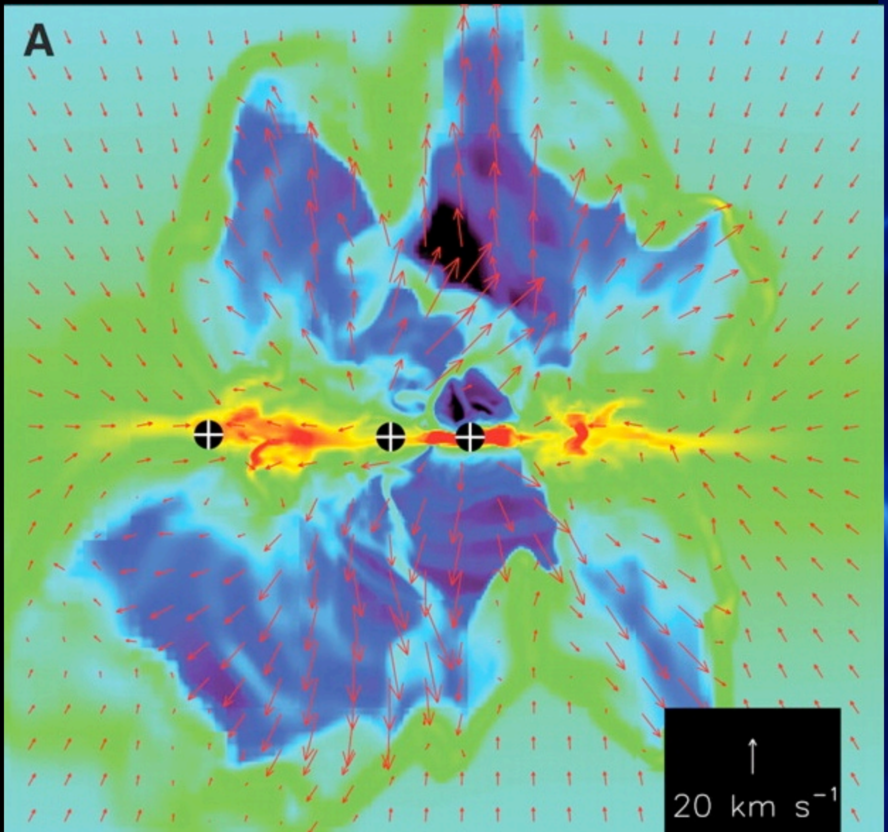
Stellar Feedback

Stars serve as important sources of thermal and kinetic energy....

- Massive stars output ionizing radiation
- Radiation pressure becomes significant for large luminosities (Krumholz et al. 2009)
- Thermal feedback may affect the fragmentation scale (Krumholz et al. 2007)

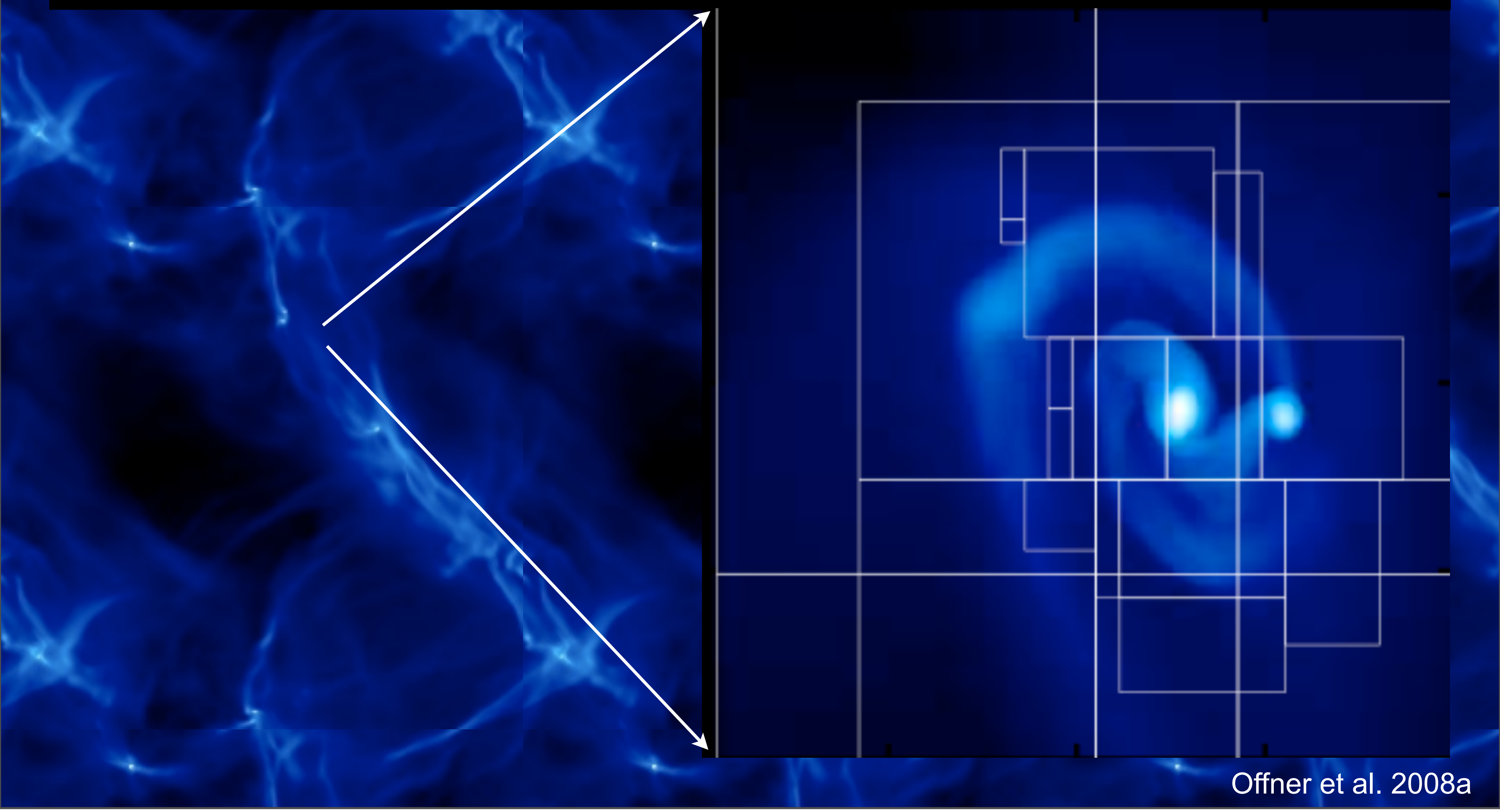
$$\lambda_J = 2\pi/k_J = (\pi c_s^2 / G\rho)^{1/2} \sim T^{1/2}$$

- Radiation has been largely neglected in low-mass star formation (e.g. Offner et al. 2009, Bate et al. 2009)



Krumholz et al 2009

Adaptive Mesh Refinement



Offner et al. 2008a

Adaptive Mesh Refinement

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

Conservation of Mass

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

Conservation of Momentum

$$\frac{\partial (\rho e)}{\partial t} + \nabla \cdot [(\rho e + P)\mathbf{v}] = \rho \mathbf{v} \nabla \phi - \kappa_R \rho (4\pi B - cE)$$

Conservation of Energy

$$\nabla^2 \phi = 4\pi G \left[\rho + \sum_n m_n \delta(\mathbf{x} - \mathbf{x}_n) \right]$$

Poisson Equation

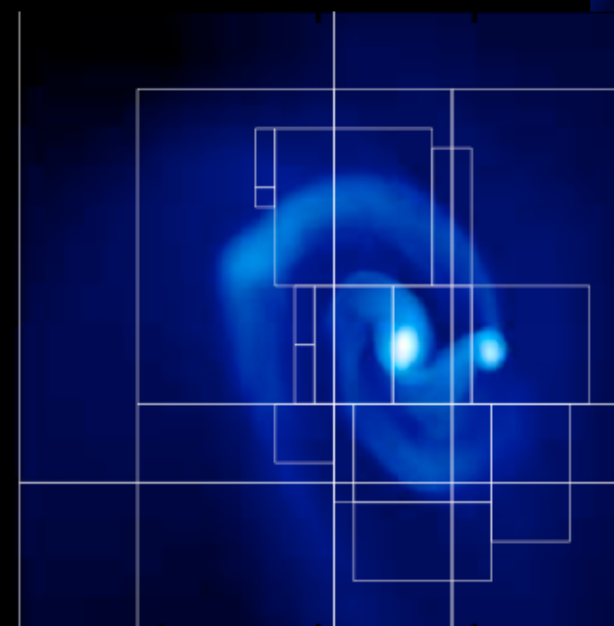
Radiation Diffusion Equation

Source Terms

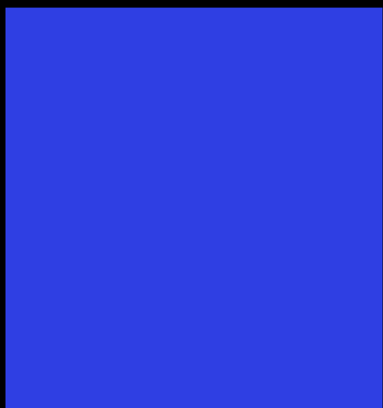
$$\frac{\partial E}{\partial t} - \nabla \cdot \left(\frac{c\lambda}{\kappa_R \rho} \nabla E \right) = \kappa_P \rho (4\pi B - cE) + \sum_n L_n W(\mathbf{x} - \mathbf{x}_n),$$

ORION

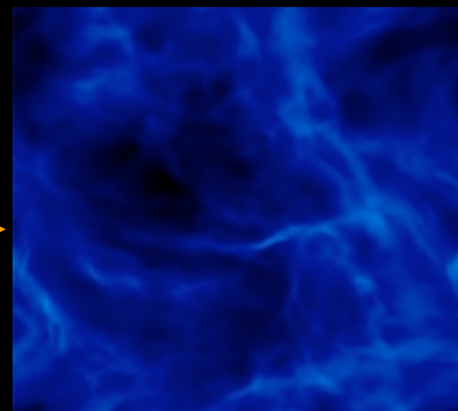
Offner et al. 2008a



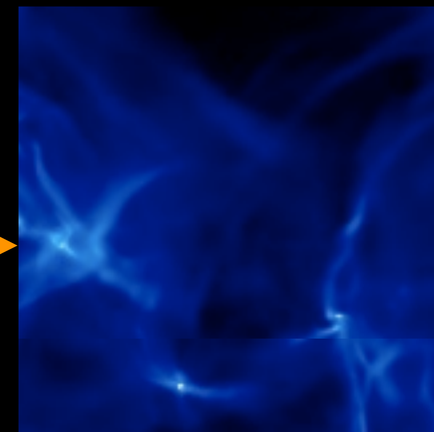
Methods



Initial time



Driving Phase



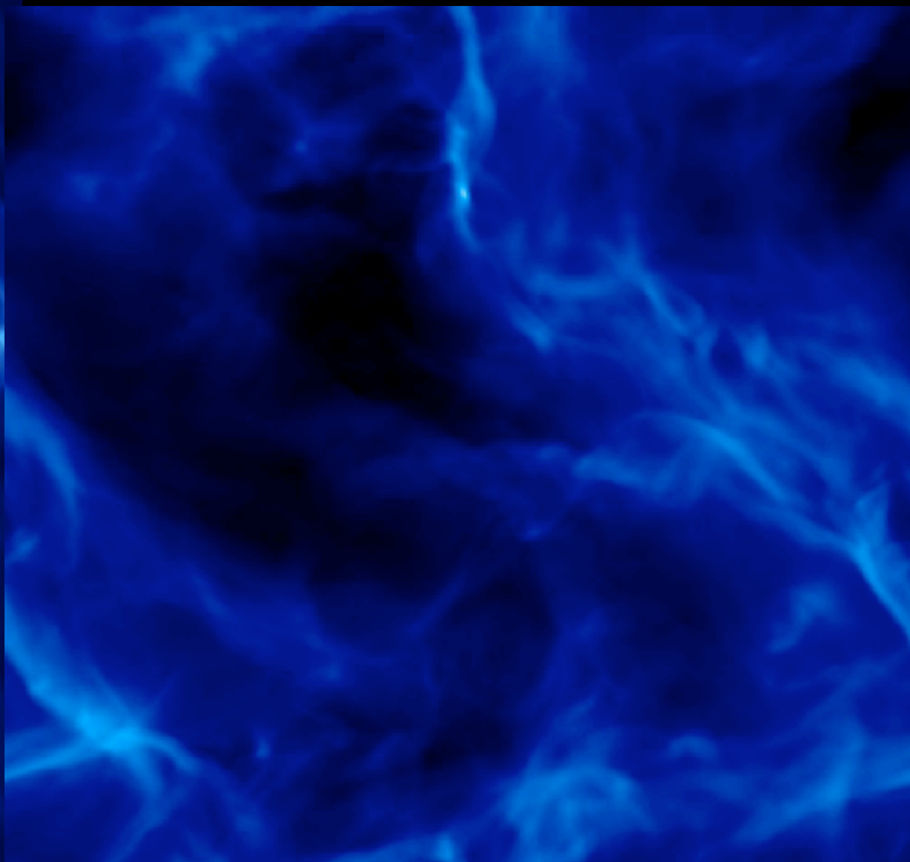
Collapse Phase

<u>Properties:</u>

- Mach~4, k=1..2 driving, M_J= 5.0 Msun
- T=10 K, L = 0.65 pc, M = 180 Msun
- 4096^3 Effective resolution

Compare cases with (RT) and without (NRT) radiative transfer

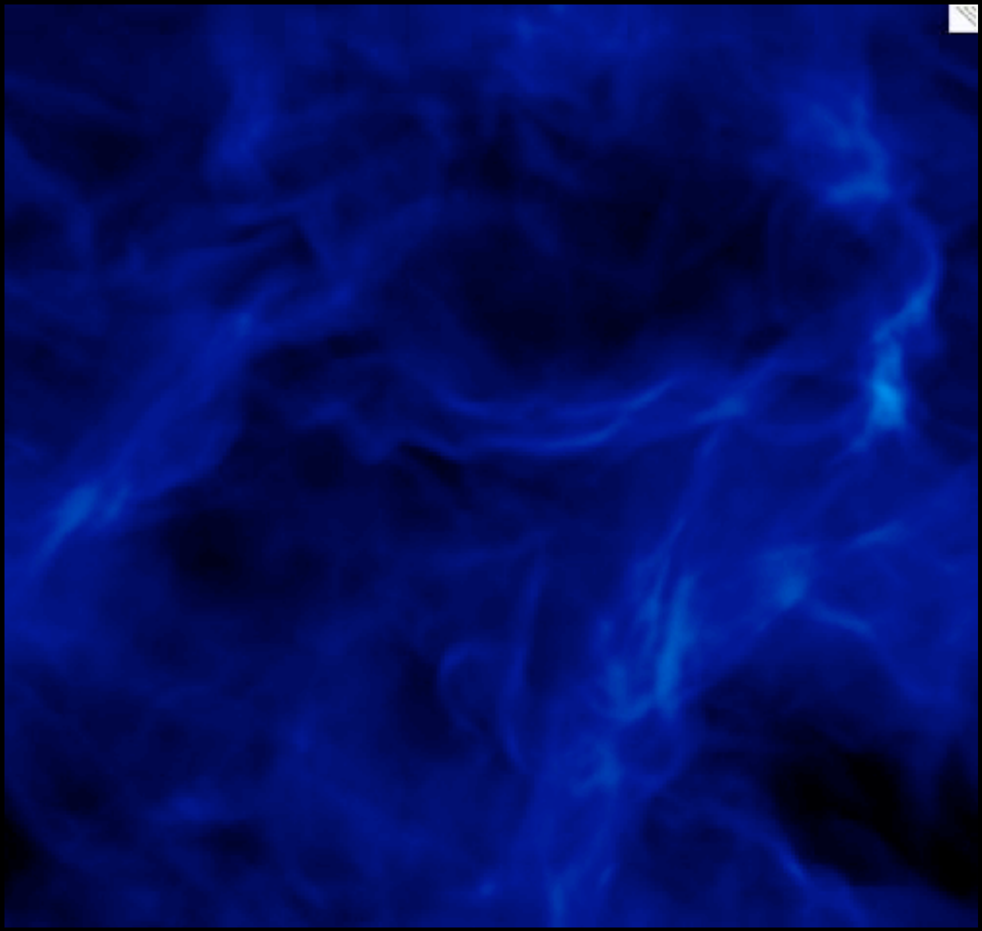
Radiation



Gas Column Density

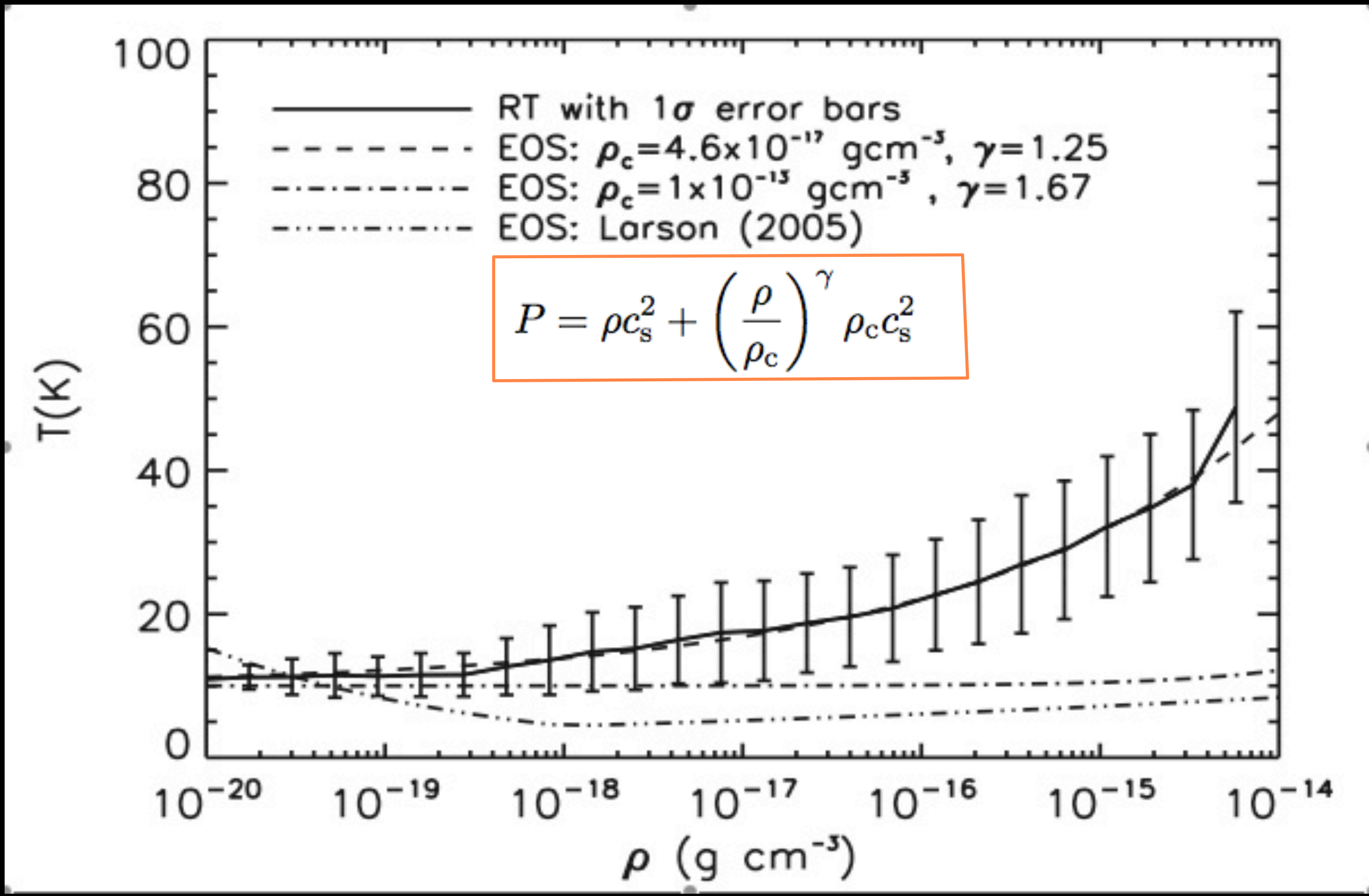
Density Weighted Gas Temperature

No Radiation



Gas Column Density

Heating is not Barotropic



Offner et al. 2009

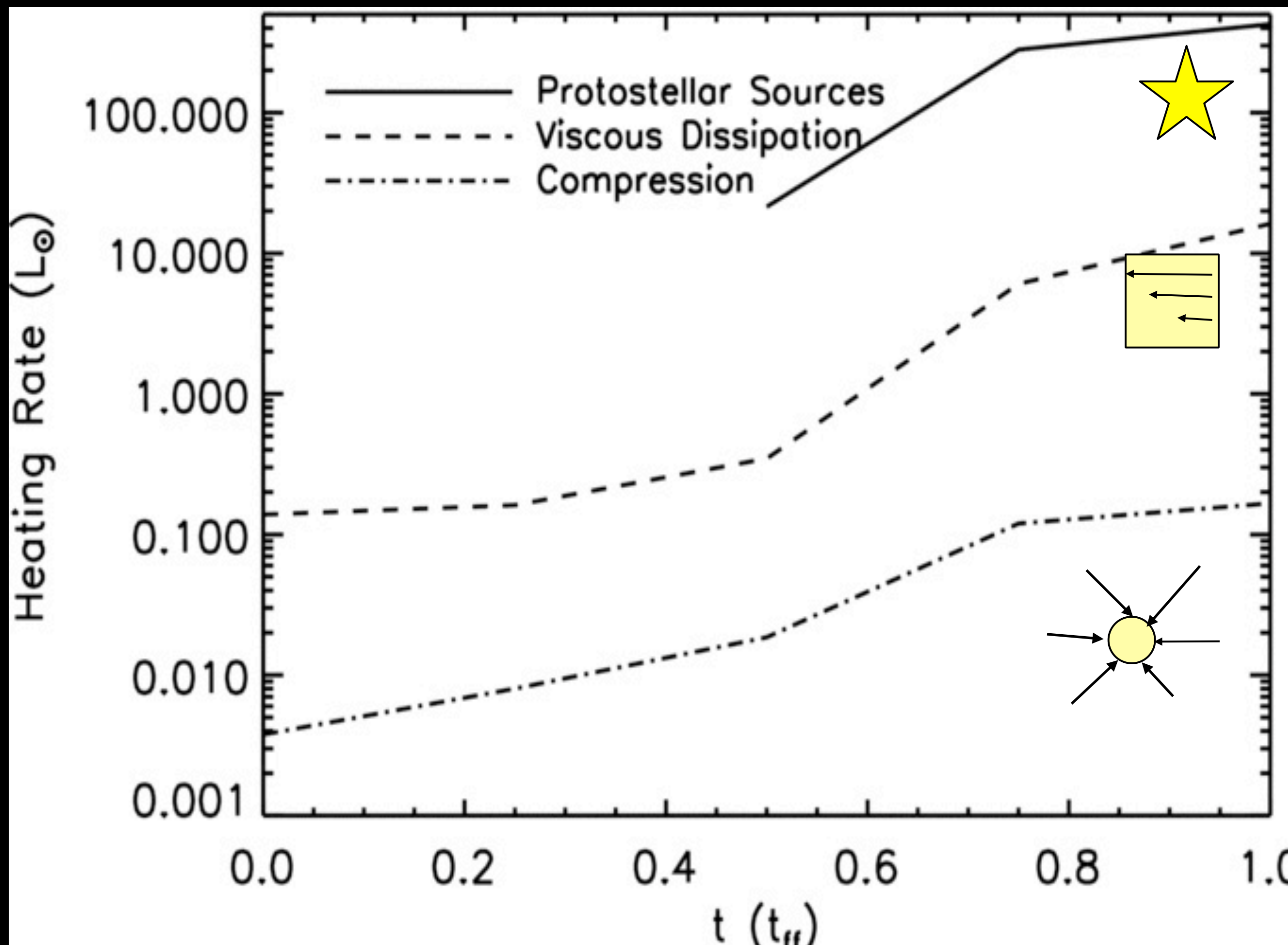
Sources of Heating

$de/dt = L_\star$

$\sim GM_\star dM_\star/dt / r_\star$

$de_{vis}/dt = (\sigma \cdot \nabla) v$

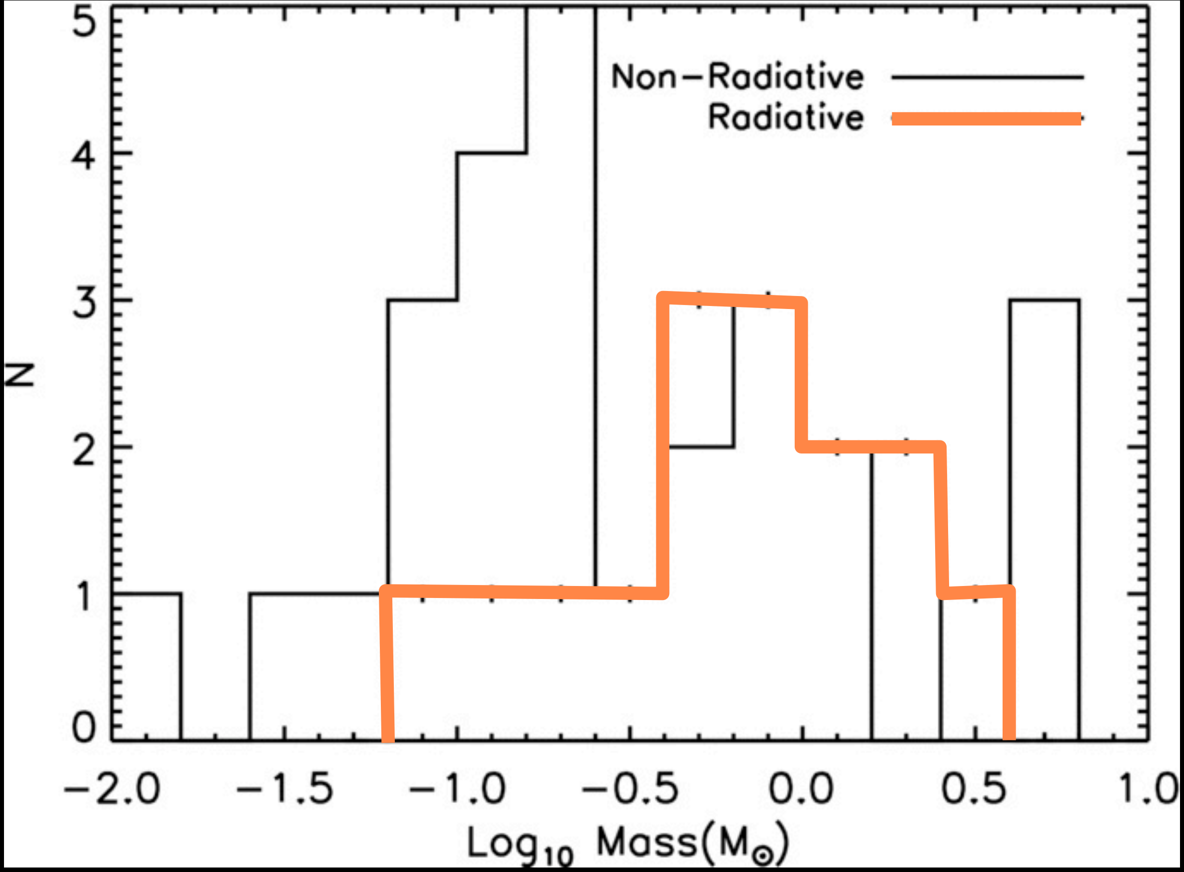
$de_{comp}/dt = P(\nabla \cdot v)$



Offner et al. 2009

3 main contributions to heating

Mass Distribution



Offner et al. 2009

- Radiation suppresses disk fragmentation (no BDs formed in disks)
- Accretion rates are lower with radiation (SFR is 4% vs 9%)

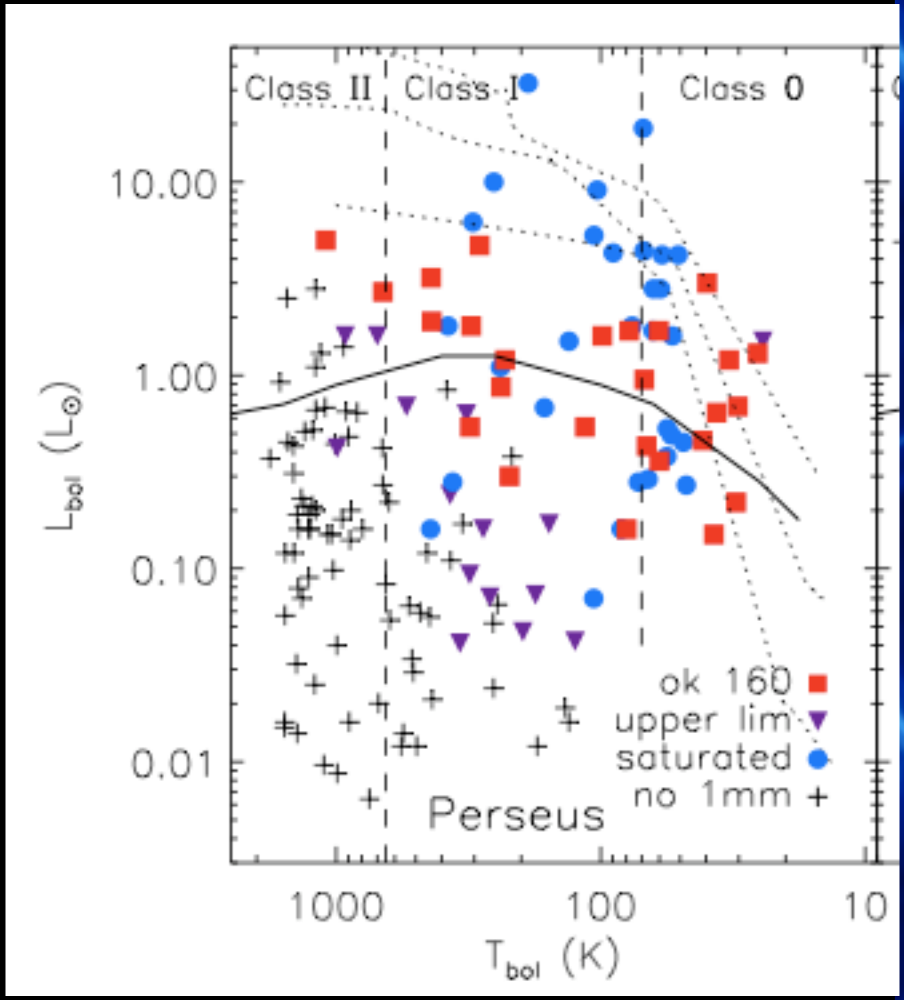
How is accretion affected?

- Accretion makes up an important part of the total luminosity
- Large range in bolometric luminosities could be explained by variability in accretion (e.g. Evans et al. 2009)
- Low-accretion protostars could explain the "luminosity problem" (Kenyon et al. 1990)

Typical Class 0-1 average luminosity ~ 1-2 Lsun (Enoch et al. 2008)

↓

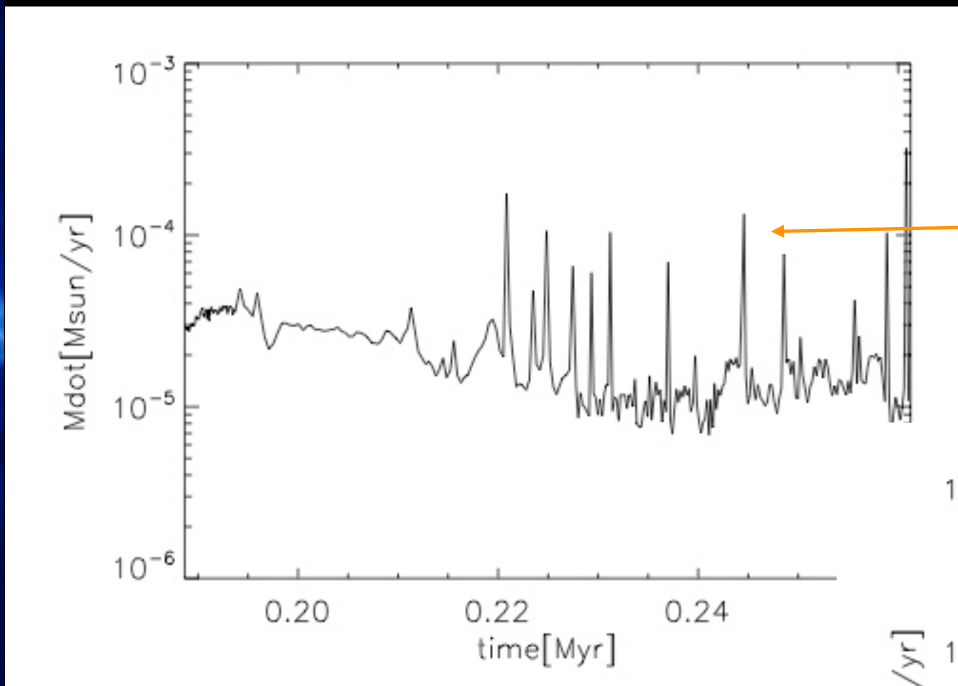
Typical Class 0-1 accretion rate = 2×10^{-6} Msun/yr



Enoch et al. 2008

Accretion Rates

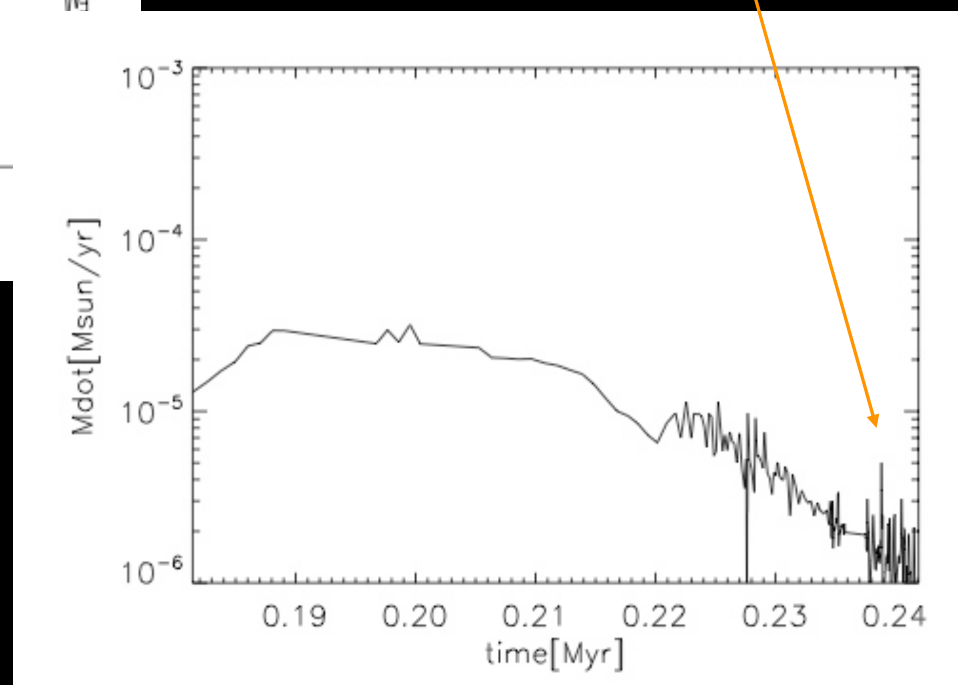
No Feedback



Offner et al. 2009

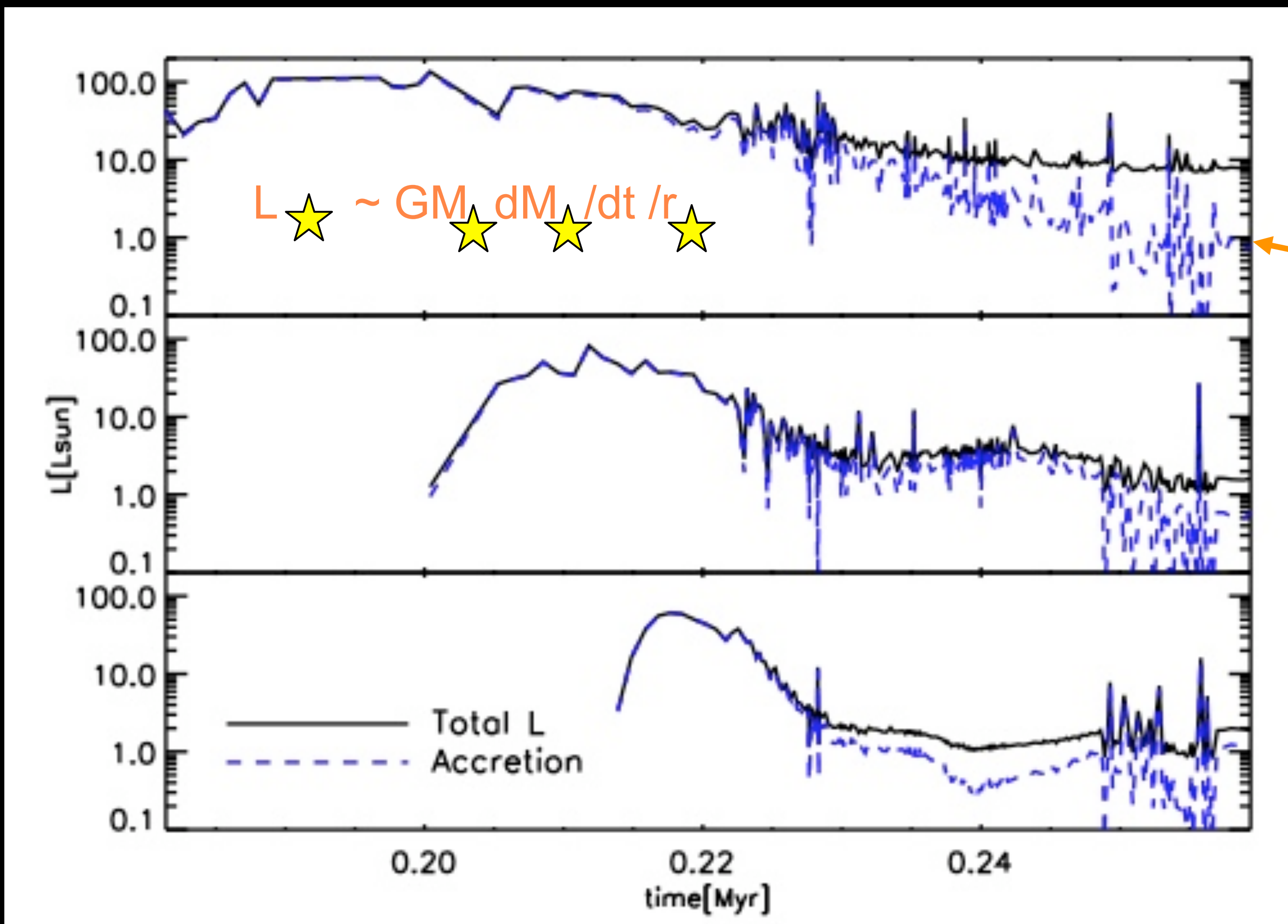
Episodic Accretion

Radiation Feedback



Typical Class 0-1 accretion rate = 2×10^{-6} Msun/yr (Enoch et al. 2008)

Luminosity



L(t) for three different protostars.

Accretion dominates L until late times.

Offner et al. 2009

Conclusions

- The temperature distribution is not well represented by a barotropic EOS
- Heating from protostellar sources dominates over compressional and viscous heating
- Heating due to radiative feedback suppresses local disk fragmentation and smooths accretion

Add Shapes, BDs, RT,
MGRD

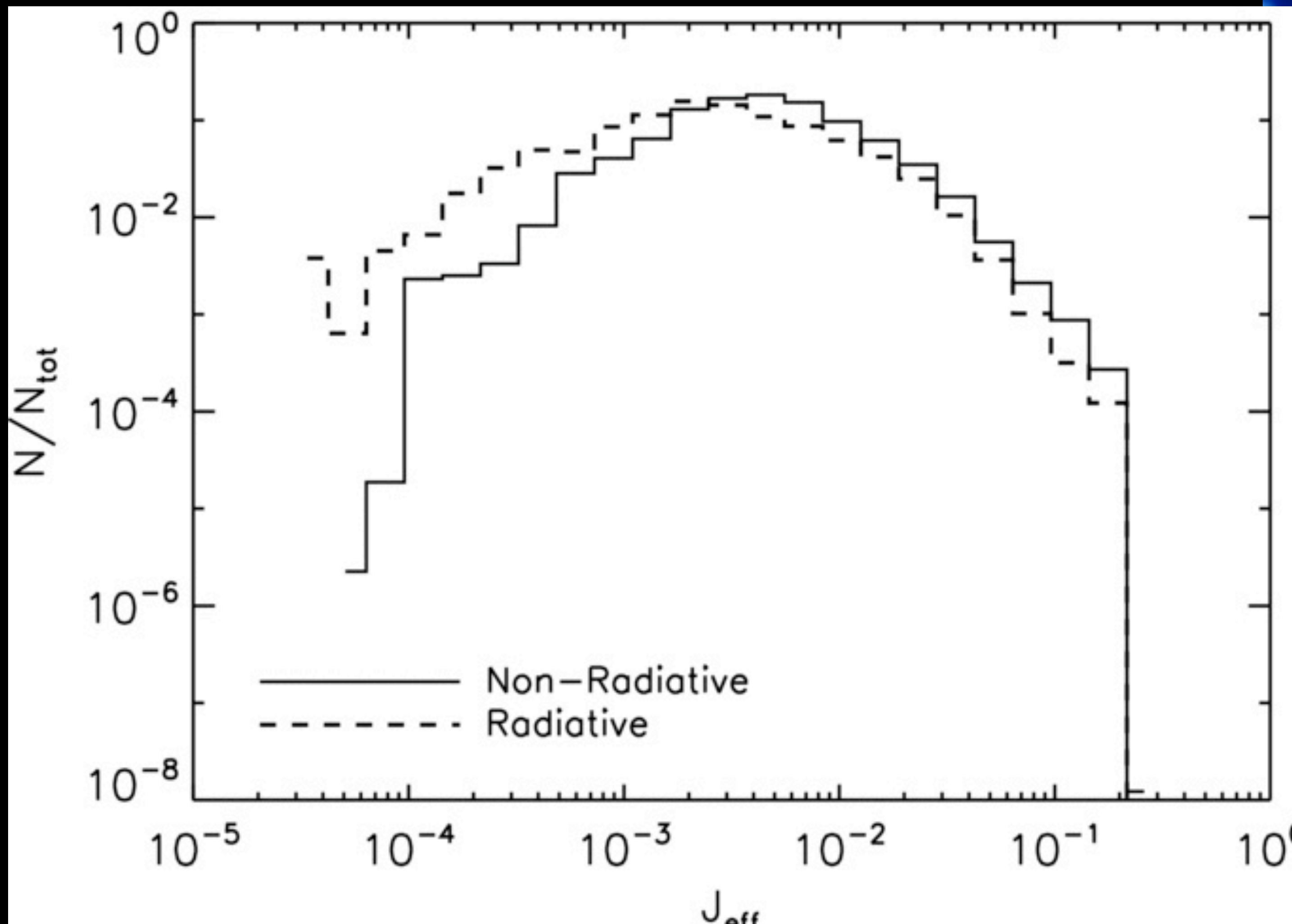
Wednesday, November 18, 2009

Add Shapes, BDs, RT,
MGRD

Resolution

To avoid artificial Fragmentation, we use a fiducial Jeans Number of 0.25
(Truelove et al. 1997)

Most cells are Very well resolved.



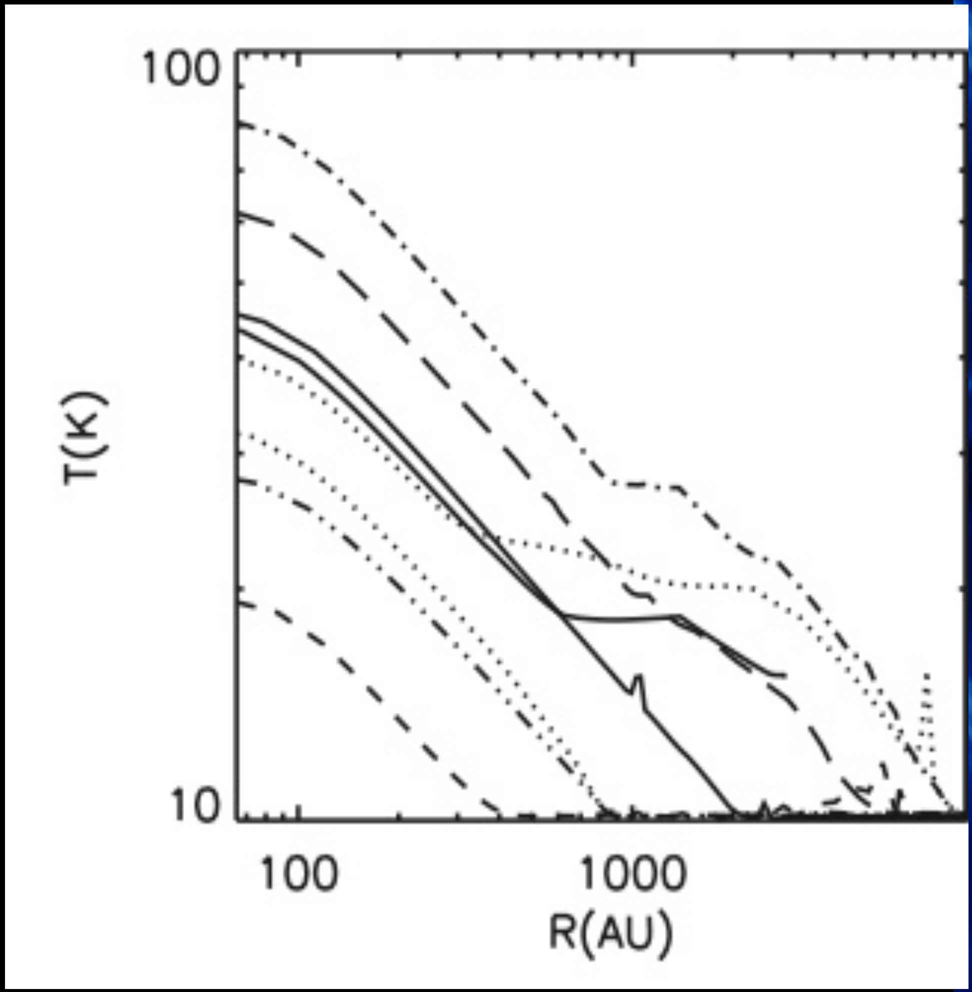
Add Shapes, BDs, RT,
MGRD

Gas Temperature vs. Radius

Gas and radiation are generally well coupled.

In this diffusion limit:

$$T \sim r^{-1/2}$$



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