What Does it Take to Make a Massive Star?

Mark Krumholz
UC Santa Cruz

Collaborators:
Richard Klein, Chris McKee, Stella Offner (UC Berkeley)
Andrew Cunningham (LLNL)
Kaitlin Kratter, Chris Matzner (U. Toronto)

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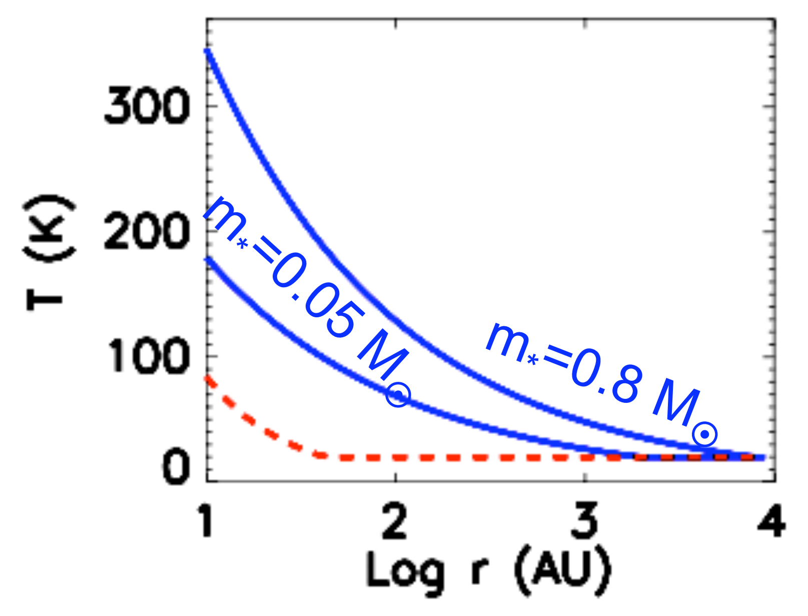
Recipe for a Massive Star

1) Start with a massive core.
2) Keep the gas from fragmenting too much – we want a few big stars, not a cluster of small ones.
3) Get rid of most of angular momentum, and put the rest into companions. Most massive stars have them.
4) Keep accreting, even though radiation pressure opposes it.

Fragmentation and Heating

(Krumholz 2006)

- Massive cores are many Jeans masses
- Hydro simulations find they fragment down to ~0.5 $M_\odot$ – no big stars
- However, accretion can produce > 100 $L_\odot$ even for 0.1 $M_\odot$ stars
- This will produce rapid heating, suppressing fragmentation



Temperature vs. radius computed with accretion luminosity and radiative transfer (blue) and estimated with a barotropic EOS (red) in a 50 $M_\odot$, 1 g cm^{-2} core

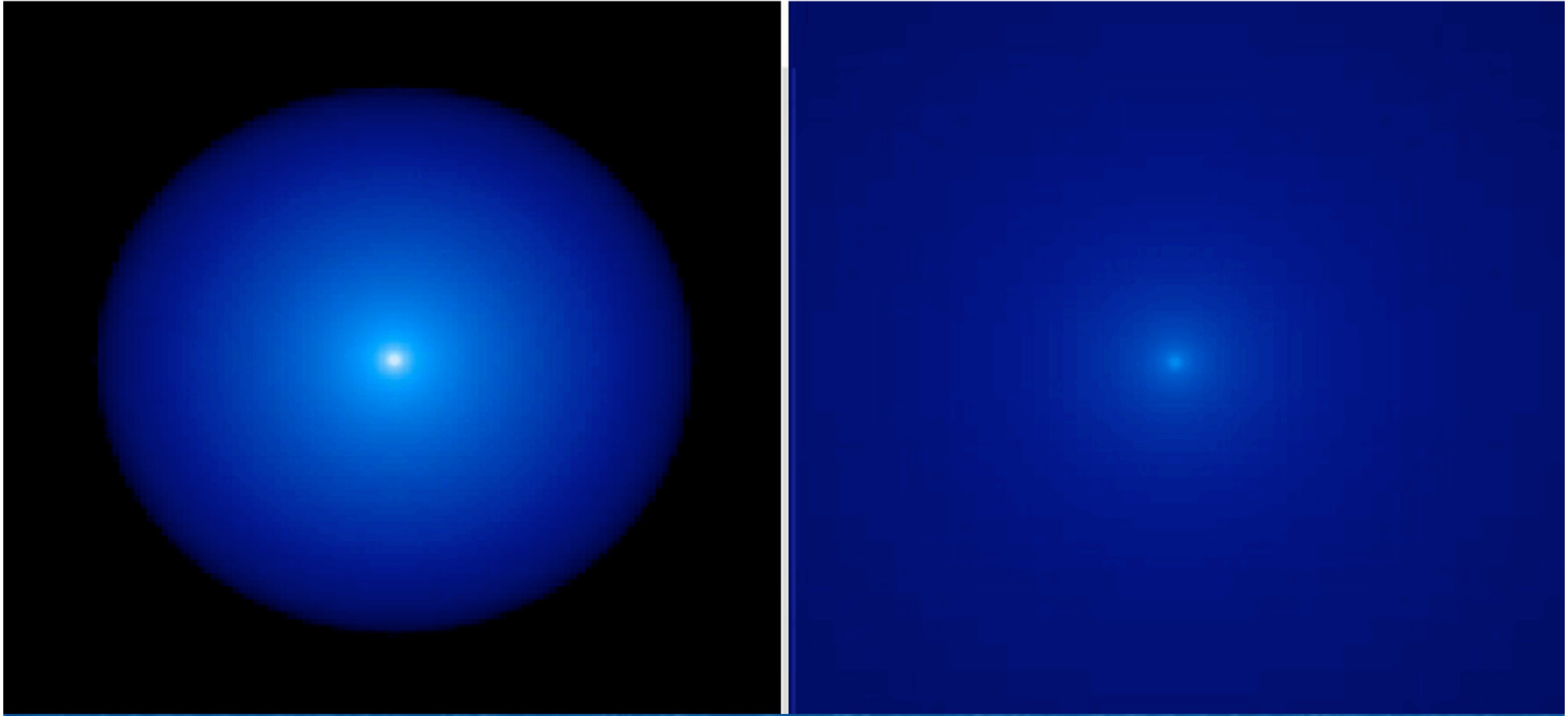
Radiation-Hydro Simulations

- To study this effect, do simulations
- Use the Orion code adaptive mesh refinement code, including (Krumholz, Klein, & McKee 2007a, 2007b)
  - Hydrodynamics
  - Gravity
  - Radiation (gray FLD)
  - Radiating sink particles

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) &= 0 \\
\frac{\partial}{\partial t}(\rho\mathbf{v}) + \nabla\cdot(\rho\mathbf{v}\mathbf{v}) &= -\nabla P - \rho\nabla\phi - \lambda\nabla E \\
\frac{\partial}{\partial t}(\rho e) + \nabla\cdot[(\rho e + P)\,\mathbf{v}] &= -\rho\mathbf{v}\cdot\nabla\phi - \kappa_{\mathrm{P}}\rho(4\pi B - cE) + \lambda\mathbf{v}\cdot\nabla E \\
\frac{\partial E}{\partial t} + \nabla\cdot(\mathbf{v}E + \mathbf{v}\cdot\mathcal{P}) &= \kappa_{\mathrm{P}}\rho(4\pi B - cE) - \lambda\mathbf{v}\cdot\nabla E + \nabla\cdot\left(\frac{c\lambda}{\kappa_{\mathrm{R}}}\nabla E\right) \\
\nabla^2\phi &= 4\pi G\rho
\end{aligned}
$$

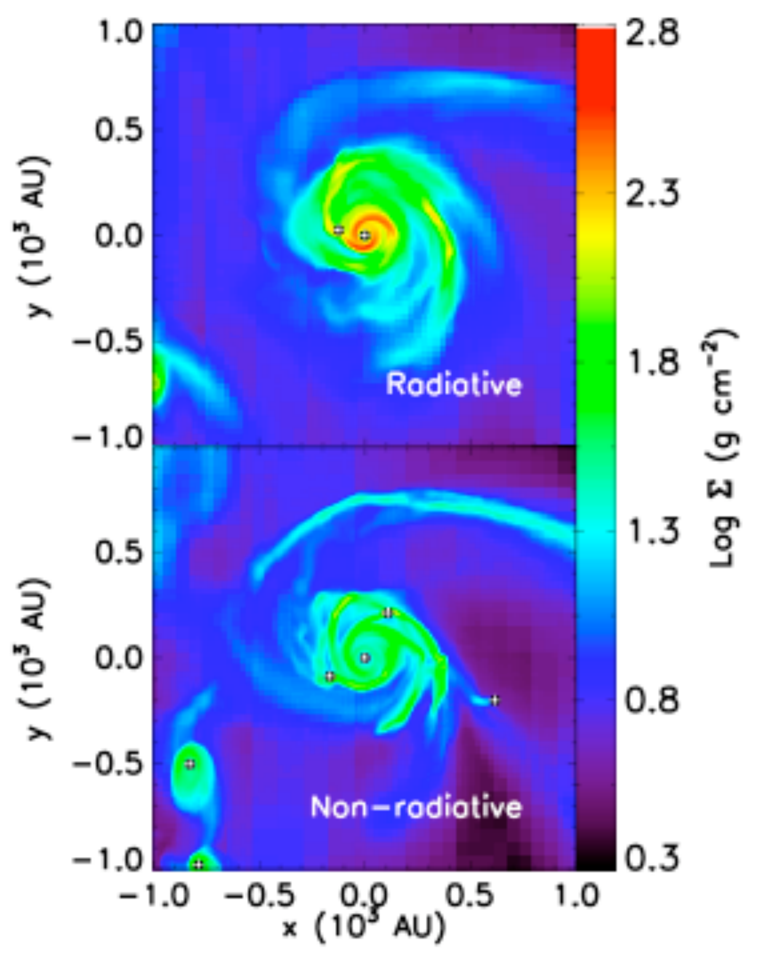
Mass conservation
Momentum conservation
Gas energy conservation
Rad. energy conservation
Self-gravity

Simulation of a Massive Core



- Column density from simulation of a core with M = 100 $M_\odot$, r = 0.1 pc, σ = 1.7 km s^{-1}
- Left: whole core; right: central $(2000\ \mathrm{AU})^2$

Massive Cores Fragment Weakly



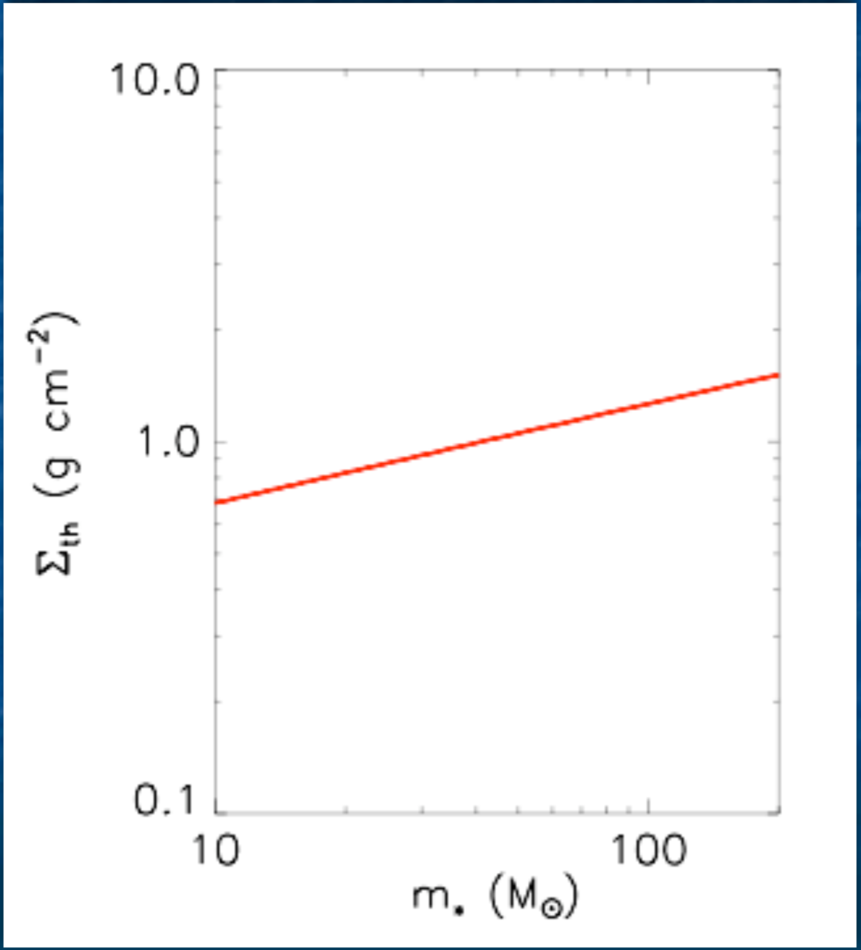
Column density with (upper) and without (lower) RT, for identical times and initial conditions

- With RT: 6 fragments, most mass accretes onto single largest star through a massive disk
- Without RT: 23 fragments, stars gain mass by collisions, disk less massive
- Barotropic or optically-thin cooling EOS fails
- Conclusion: radiation inhibits fragmentation

Halting Fragmentation: A Condition for Massive SF?

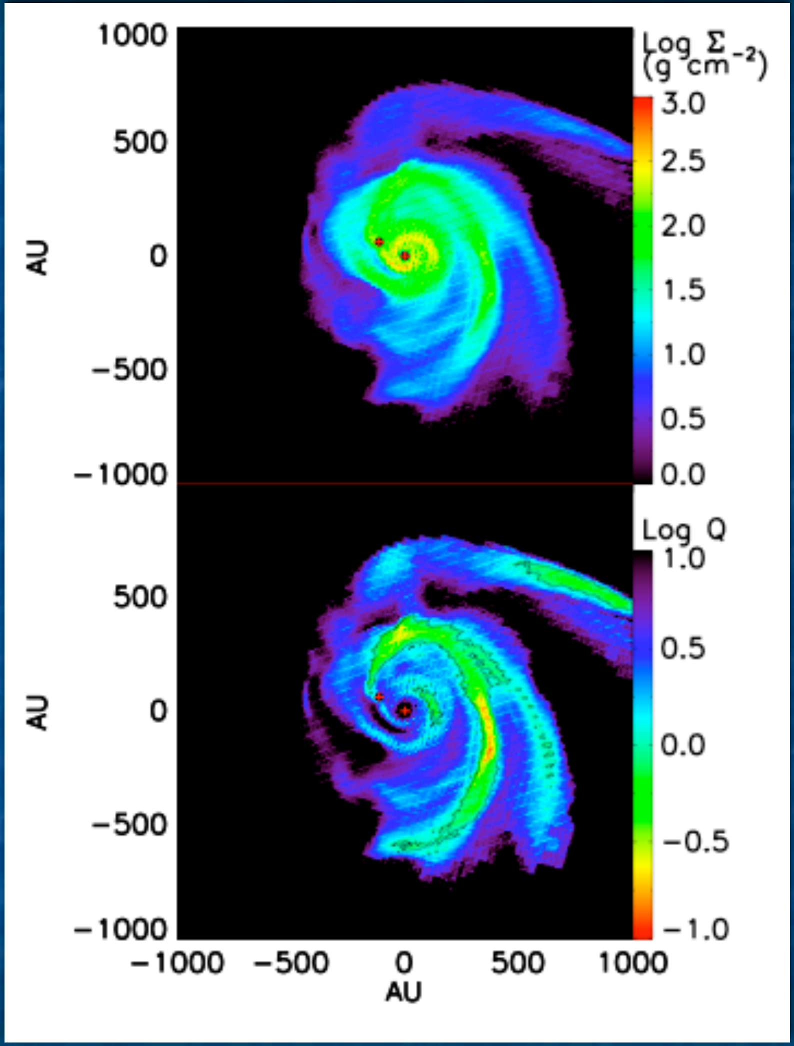
(Krumholz & McKee 2008)

- Halting fragmentation requires that a cloud be heated throughout
- This requires a light to mass ratio $\eta_{\mathrm{halt}}(\Sigma)$
- Accretion produces a maximum luminosity / unit mass $\eta_{\mathrm{acc}}(\Sigma, M_c)$
- Result: a threshold Σ for massive SF!



Massive Disks and Binaries

- $M_{disk} / M_* \approx 0.2 – 0.5$, $r_{disk} \sim 1000$ AU
- Global GI creates strong spiral pattern
- Spiral waves drive rapid accretion; $\alpha_{eff} \sim 1$
- Disks reach Q ~ 1, form stellar fragments
- Some fragments migrate inward with gas, likely producing close companions



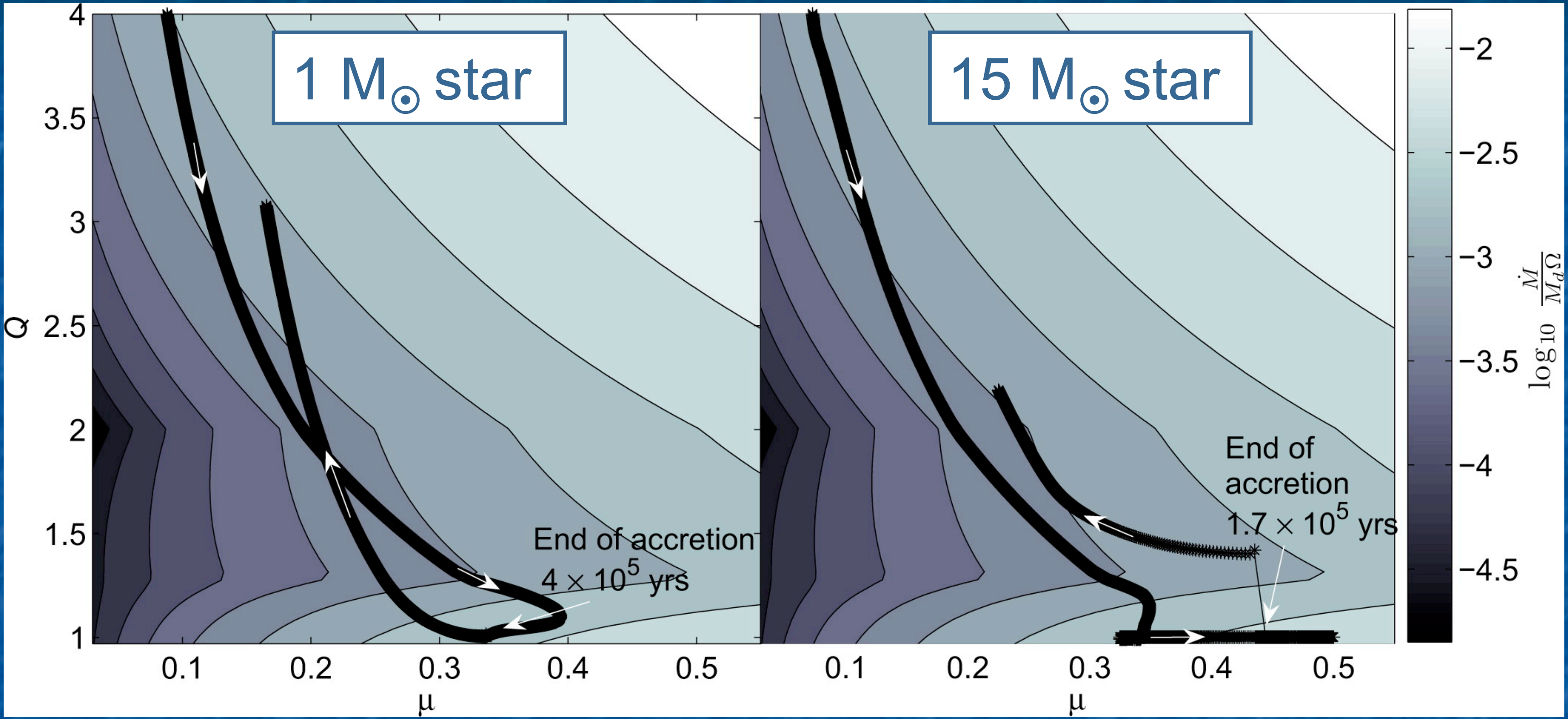
Surface density (upper) and Toomre Q (lower); striping is from projection

Understanding Massive Disks

(Kratter & Matzner 2006, Kratter, Matzner & Krumholz 2008)

- Accretion rate onto star + disk is $\sim \sigma^3 / G \sim 10^{-3}\ M_\odot / \mathrm{yr}$ in a massive core, but max transfer rate through a stable disk ($\alpha << 1$) is $\sim c_s^3 / G \sim 5 \times 10^{-5}\ M_\odot / \mathrm{yr}$ at $T = 100$ K
- Core accretes faster than stable disk can process $\Rightarrow$ massive, unstable disks
- Study disk evolution using semi-analytic core model, including accretion, radiative heating, parameterized treatment of angular momentum transport

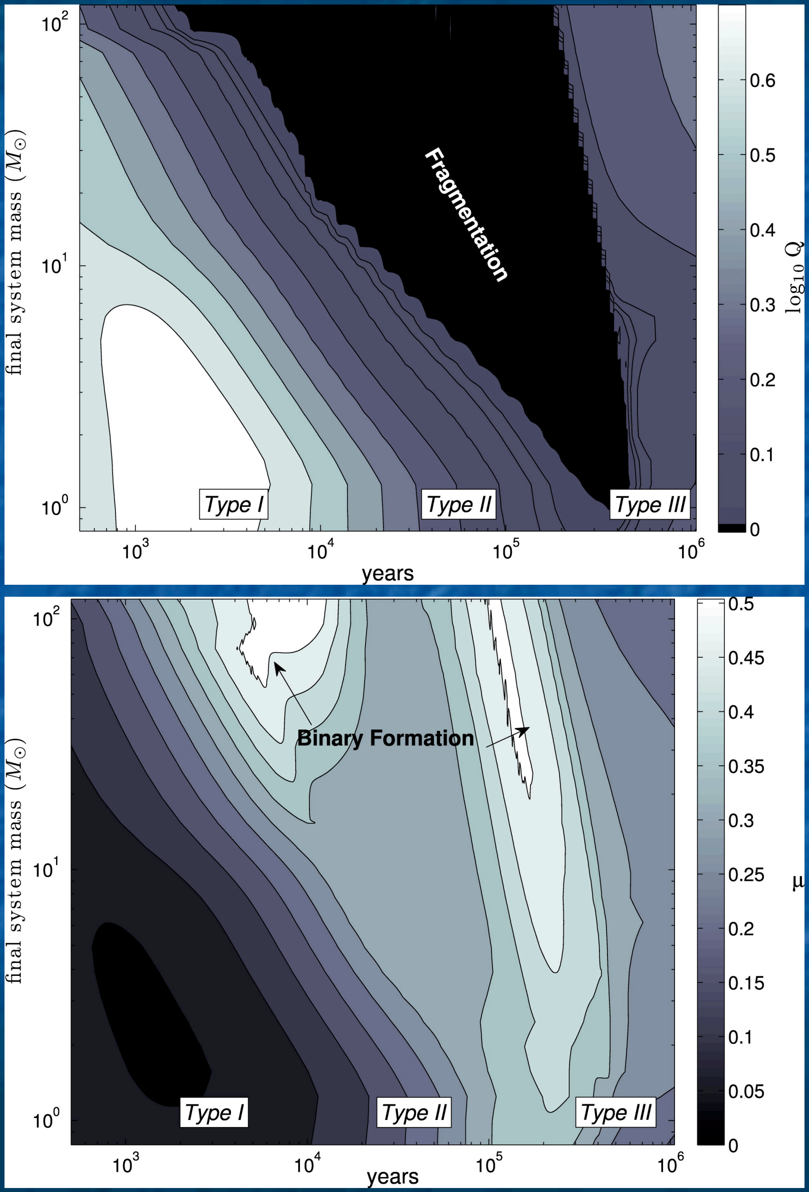
Model Disk Evolution



Evolutionary tracks for $1\ M_\odot$ and $15\ M_\odot$ stars in the plane of Toomre Q and disk mass fraction $\mu = M_{disk} / (M_{disk} + M_*)$

Prediction: μ increases and Q decreases as M_* increases

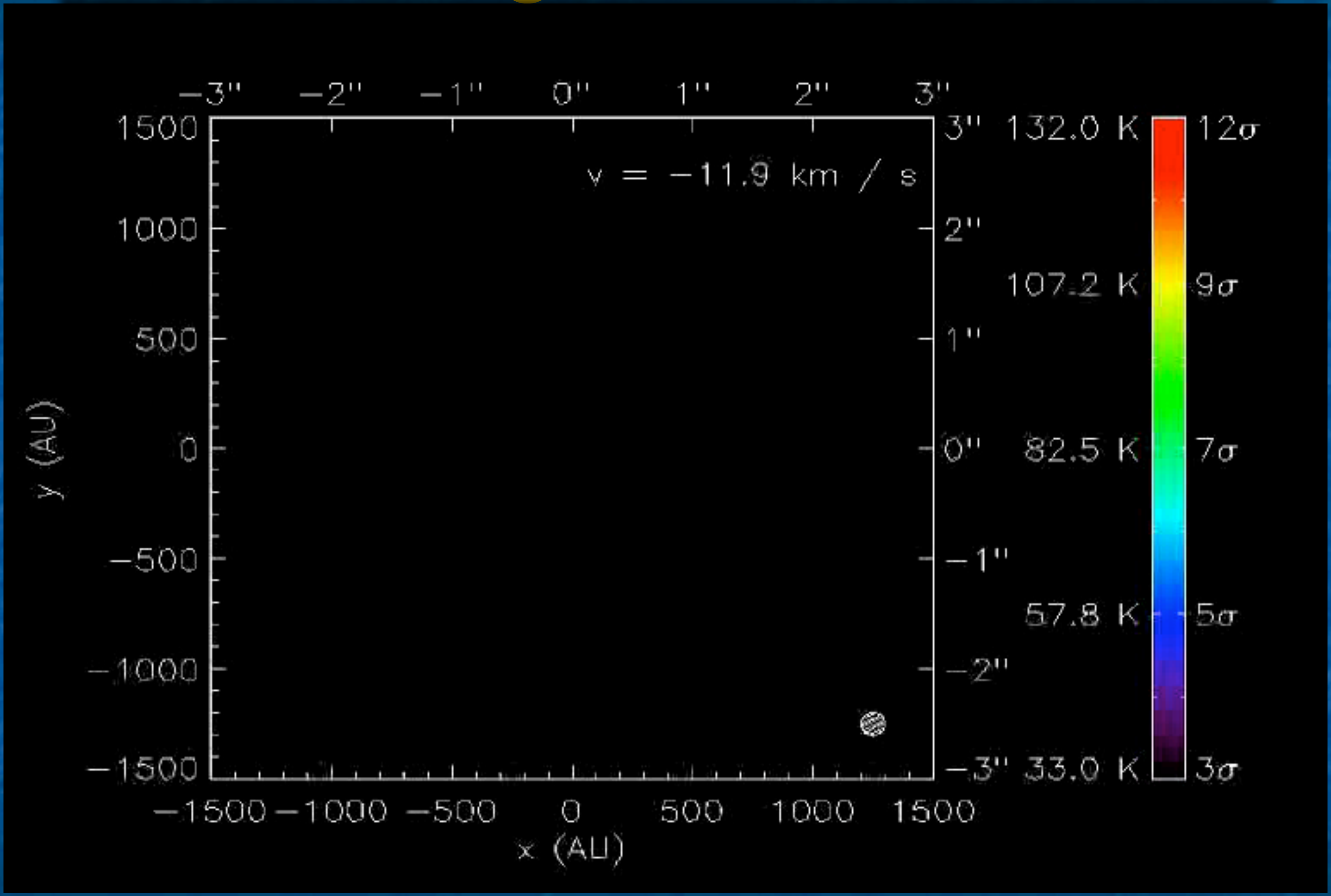
Disk Properties vs. Stellar Mass



- Disks reach Q = 1 for stars ~2 $M_\odot$ or larger
- Disks reach μ = 0.5 for stars ~20 $M_\odot$ or larger
- Explains:
  - why companion fraction increases with mass
  - why O stars preferentially have OB star companions

Q and μ as a function of final system mass and time since the onset of collapse

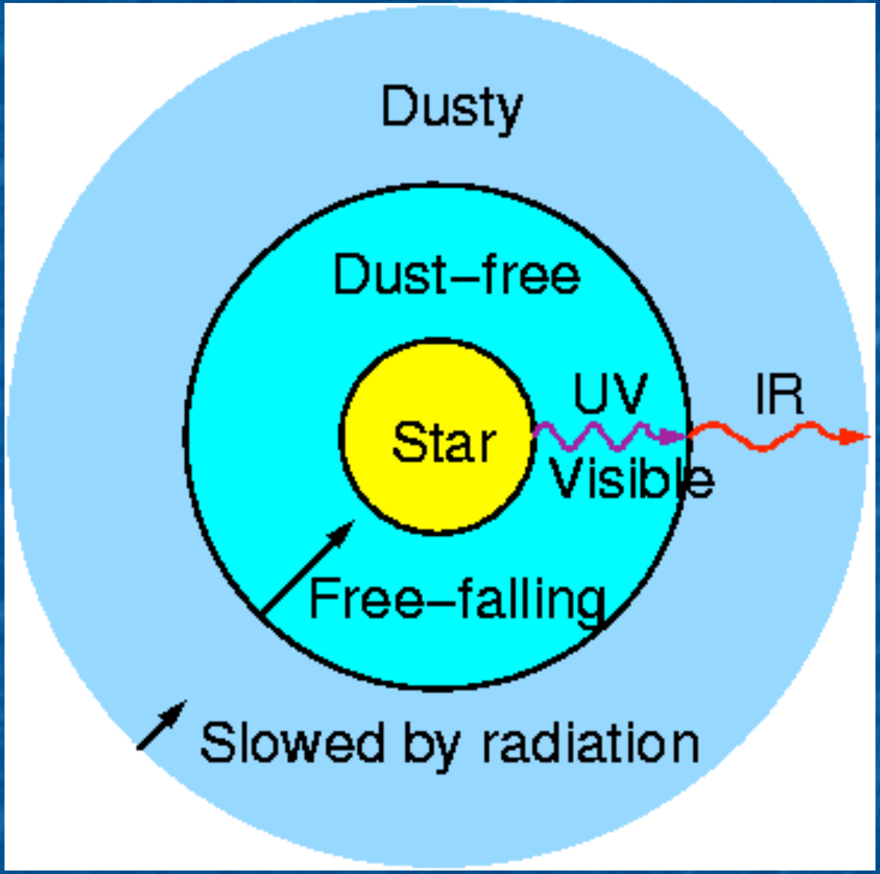
Observing Massive Disks



Integrated T_B in simulated 1000 s / pointing ALMA observation of disk at 0.5 kpc in CH_3CN 220.7472 GHz (Krumholz, Klein, & McKee 2007c)

Radiation Pressure Feedback

(Larson & Starrfield 1971; Kahn 1974;
Yorke & Krügel 1977; Wolfire & Cassinelli 1987)



- Dust absorbs UV & visible, re-radiates IR
- Dust sublimes at T ~ 1200 K, r ~ 30 AU
- Radiation > gravity for

$$L > 4\pi GMc/\kappa$$

$$= 1.3 \times 10^5\ L_\odot\ M_{10}\kappa_1^{-1}$$

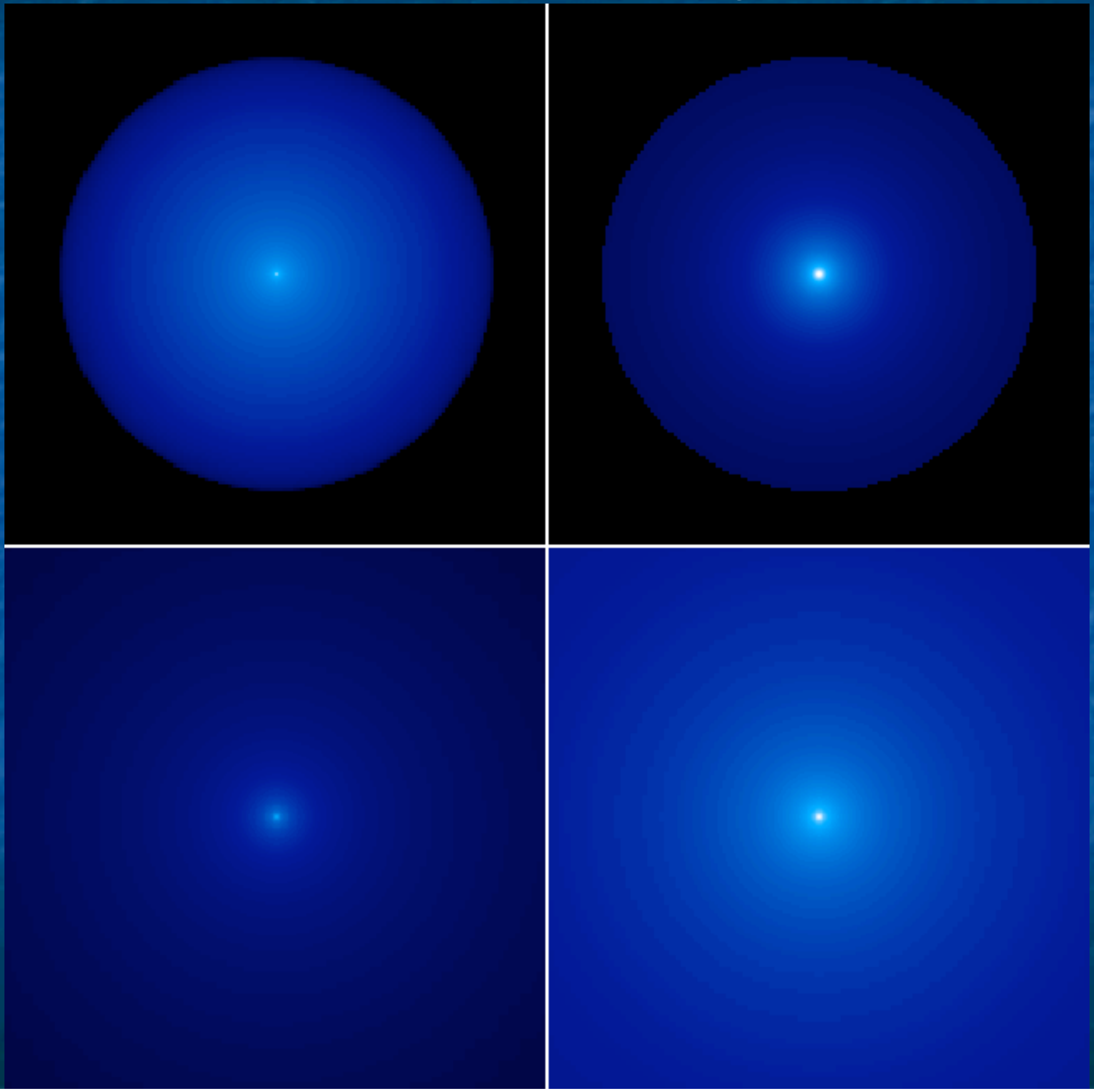
- For 50 $M_\odot$ ZAMS star,

$$L = 4 \times 10^5\ L_\odot$$

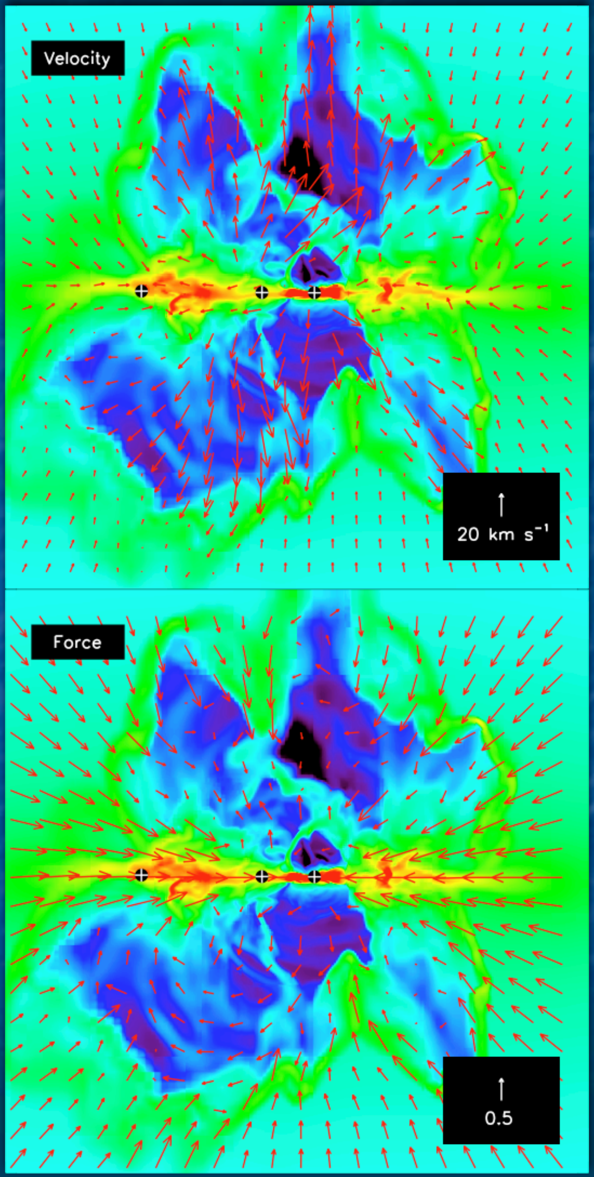
$\Rightarrow$ Massive stars approach their Eddington limits while forming

Simulations of Radiation Pressure

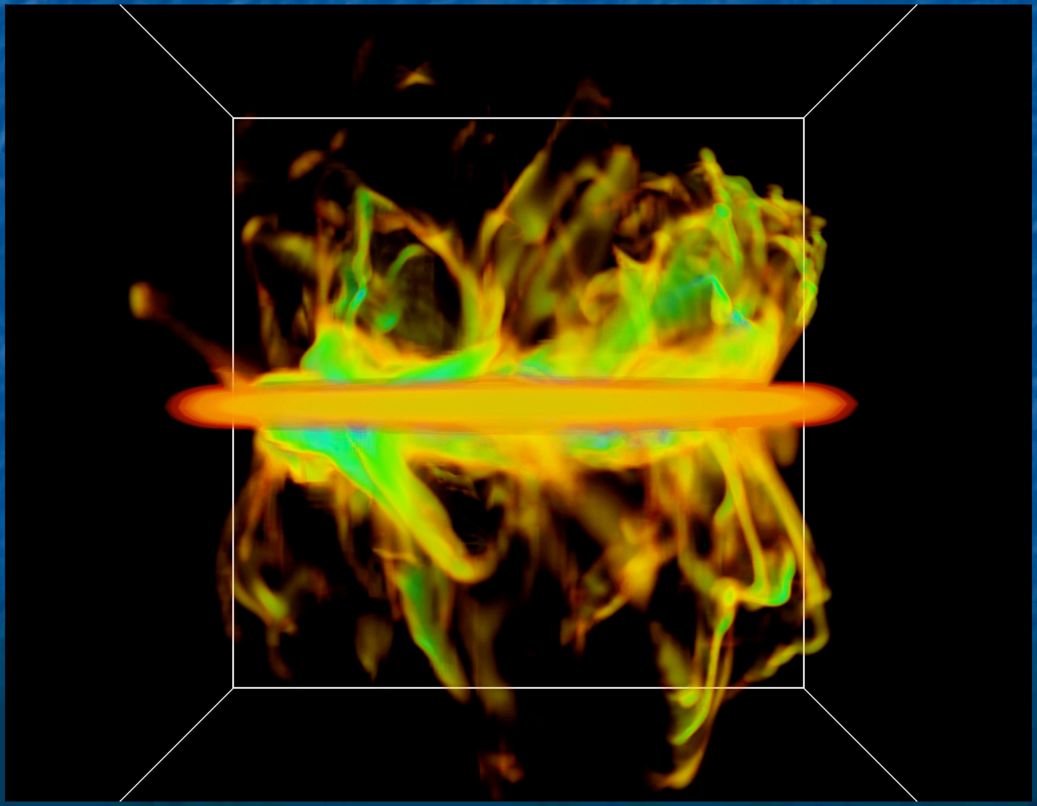
(Krumholz, Klein, McKee, Offner, & Cunningham, 2008, submitted)



Radiation Beaming



- RT instability allows accretion!
- Radiation leaves through transparent chimneys, mass accretes through opaque fingers



What Does it Take to Make a Massive Star?

- ✓ a dense core that resists fragmentation due to internal heating
- ✓ a massive, gravitationally unstable disk that can process incoming gas rapidly, and produce companions
- ✓ an optically thick core that gives rise to collimation of the radiation, allowing RT instability