The Formation of Massive Stars

Mark Krumholz

UC Santa Cruz

Collaborators:
Richard Klein, Chris McKee, Stella Offner (UC Berkeley)
Andrew Cunningham (LLNL)
Kaitlin Kratter, Chris Matzner (U. Toronto)
Jim Stone (Princeton)
Todd Thompson (Ohio State)

FLASH seminar
January 9, 2008

Talk Outline

- What we know about massive stars
- Massive cores: an initial condition?
- From core to star
  - Fragmentation
  - Disks and binaries
  - Stellar feedback
- Prospects and problems for the future

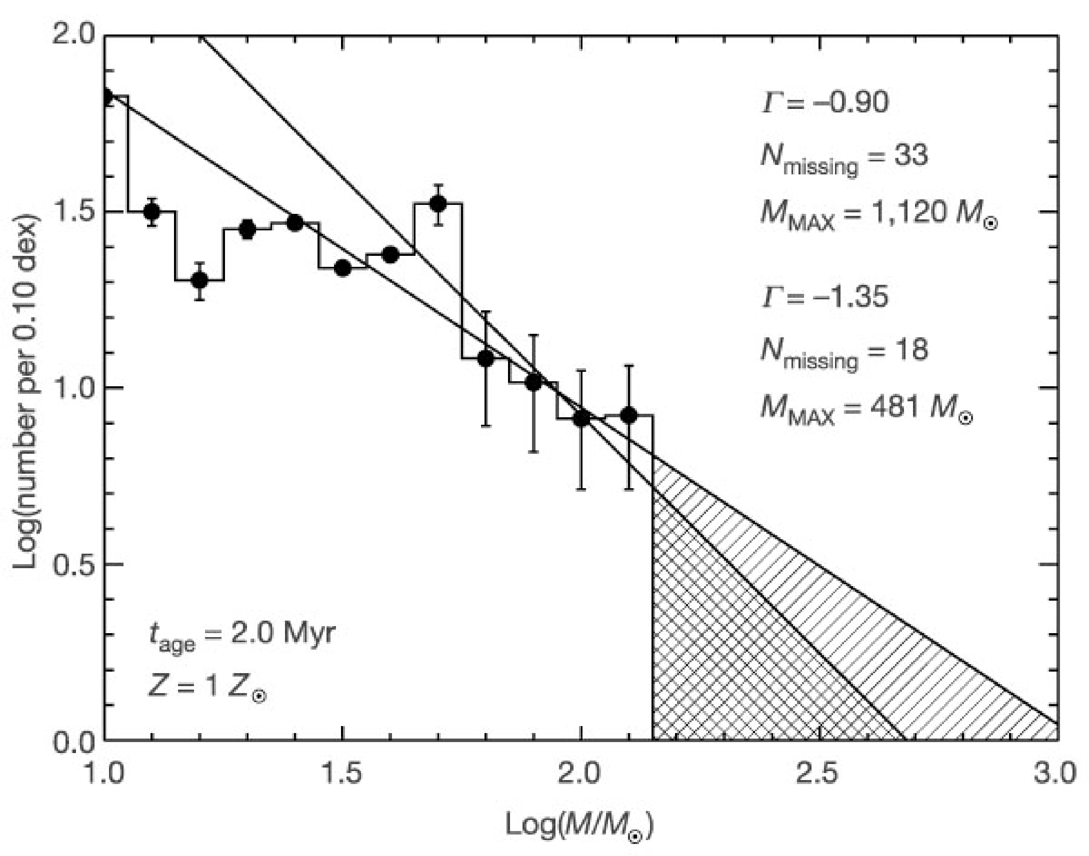
Why Do We Care About Massive Stars?

Massive stars…

- dominate the total energy output of galaxies in the present epoch
- dominate energy injection into the interstellar medium (HII regions, SNe)
- produce most of the metals in the universe
- shape the formation of planets and low mass stars

The High End of the IMF

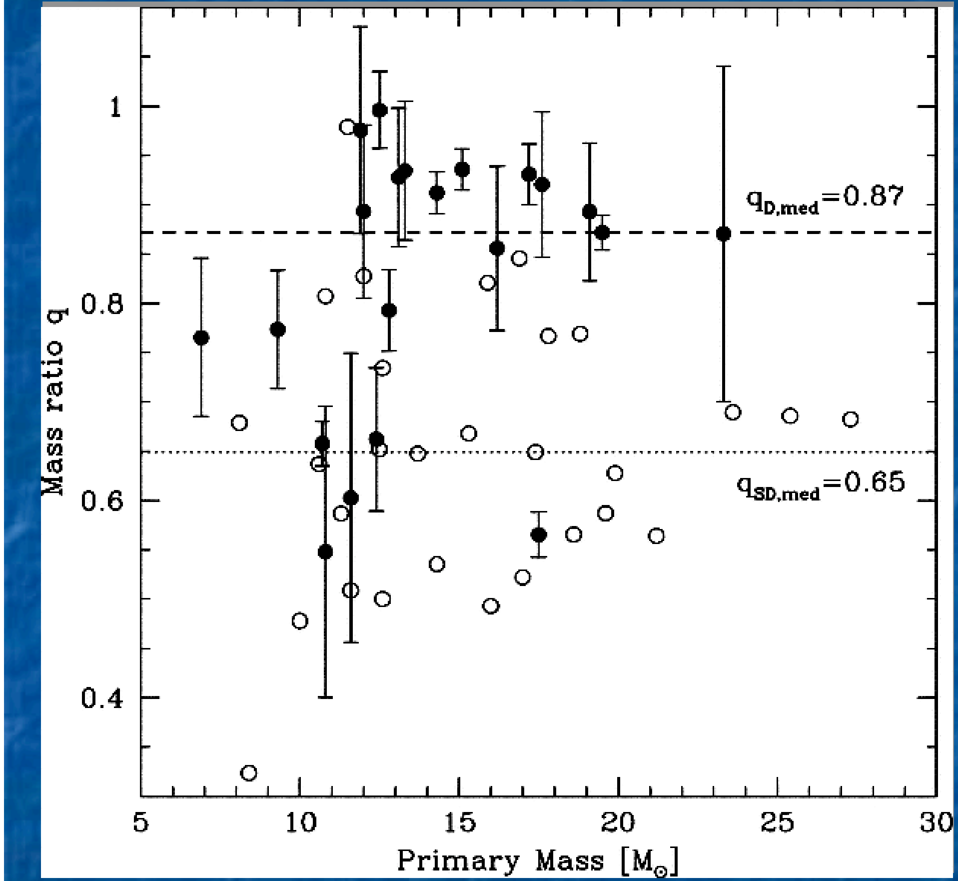
- The IMF is a power-law from ~1-150 $M_{\odot}$; stars >150 $M_{\odot}$ are very rare or non-existent (Elmegreen 2000, Figer 2005)
- No solid evidence for variations with environment, though hints seen



IMF of the Arches cluster (Figer 2005)

- Caveat: binary correction extremely difficult

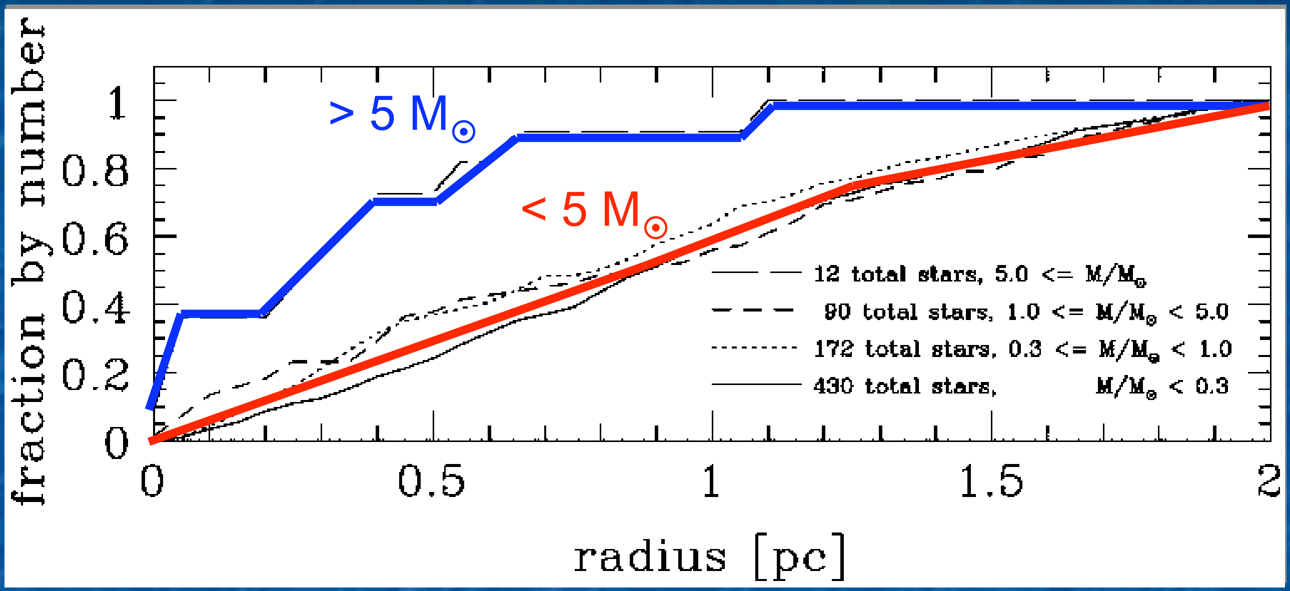
Massive Binaries



Mass ratio for 26 detached eclipsing binaries in the SMC (Pinsonneault & Stanek 2006)

- Most O stars (>70%) have OB companions
  (Sana et al. 2008)
- For close companions, mass ratios near unity ("twins") common
  (Pinsonneault & Stanek 2006)
- Most massive known binary is WR20a: M_{tot} = 165 $M_\odot$, q = 0.99 ± 0.05
  (Rauw et al. 2005)
- Caveat: selection bias

Clustering

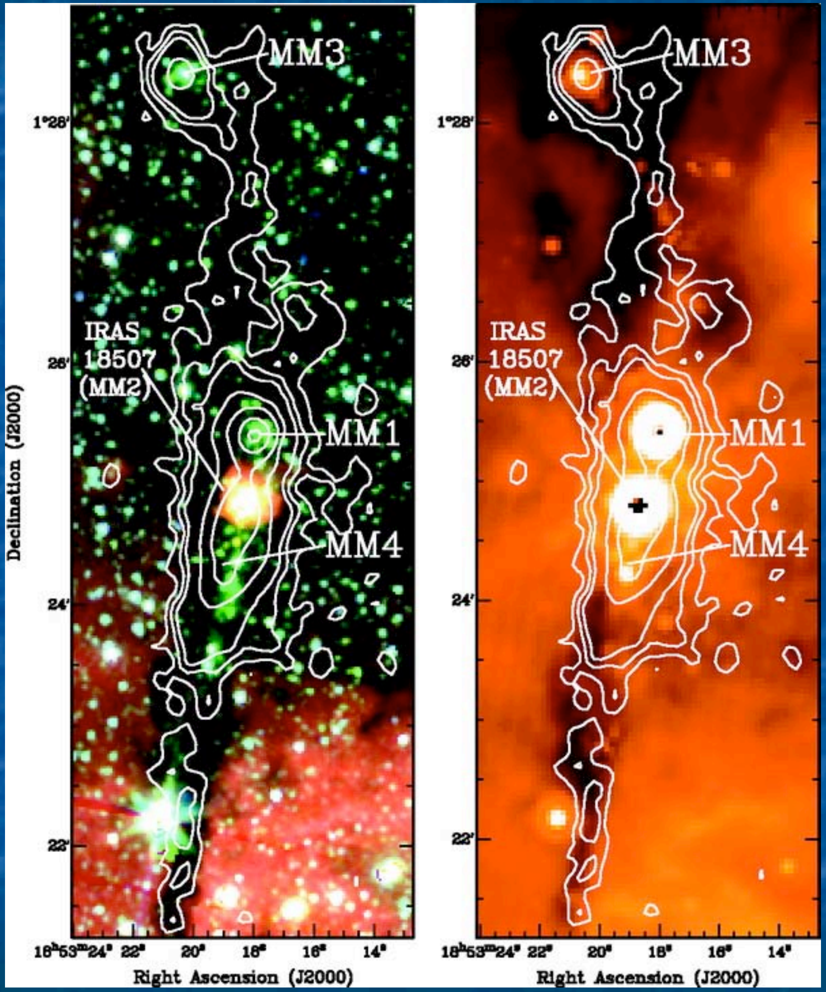


Fraction of stars vs. radius for stars of different masses in the ONC (Hillenbrand & Hartmann 1998)

- Most but not all massive stars are born in clusters (de Wit et al. 2004, 2005)
- Young clusters are strongly mass-segregated (Hillenbrand & Hartmann 1998, Huff & Stahler 2006)
- Unknown if segregation is dynamical or primordial (Bonnell & Davis 1998, Tan et al. 2006, McMillan et al. 2007)

Sites of Massive Star Formation

(Plume et al. 1997; Shirley et al. 2003; Rathbone et al. 2005; Yonekura et al. 2005)



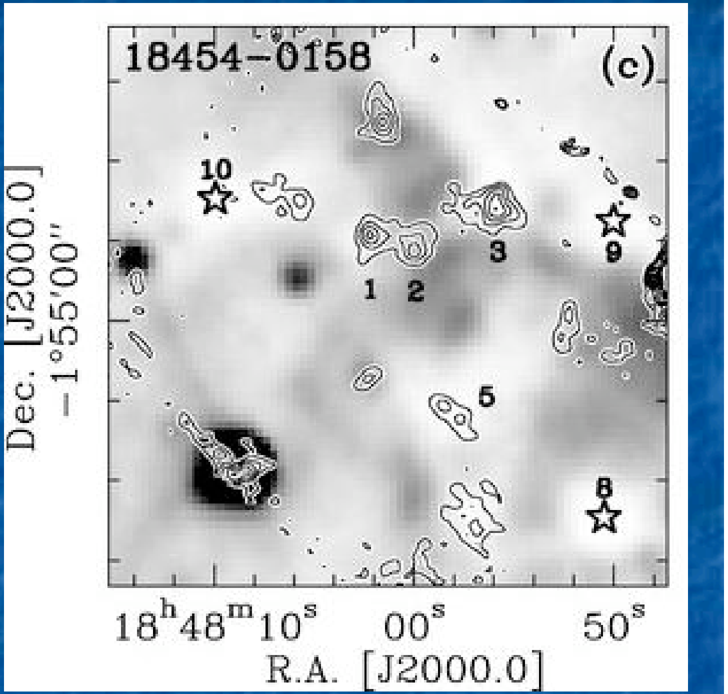
Spitzer/IRAC (left) and Spitzer/MIPS (right), Rathbone et al. (2005)

- Massive stars form in clumps observed in mm continuum or lines, or in IR absorption (IRDCs)
- Clumps have high surface densities (Σ ~1 g cm^{-2}), similar to Σ in rich clusters
- Clumps are very turbulent, σ ~ 4 km s^{-1}, off ordinary linewidth-size relation
- Virial parameter α_{vir} ~ 1

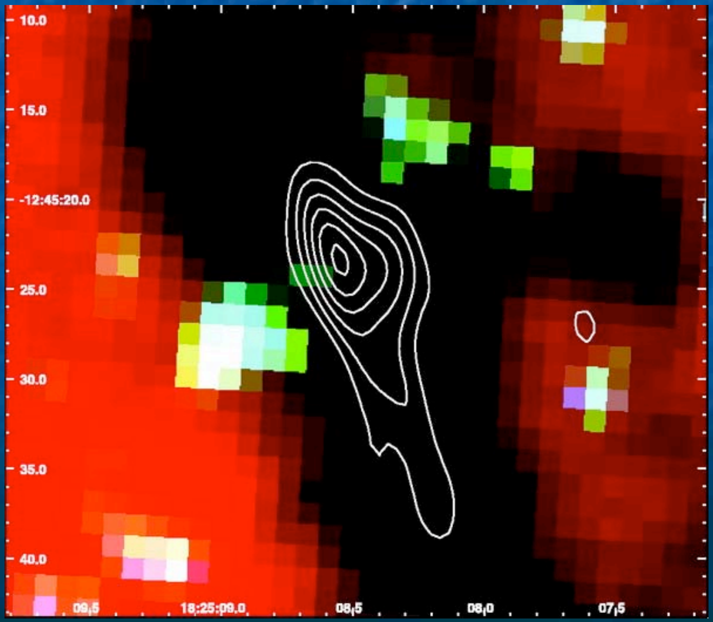
Massive Cores in Clumps

(Beuther & Shilke 2004, Sridharan et al. 2005,
Beuther, Sridharan, & Saito 2005, Garay 2005)

- Largest cores in clumps: M ~ 100 $M_\odot$, R ~ 0.1 pc, $\Sigma \sim 1$ g cm^{-2}, centrally condensed
- Some examples show no MIR emission ⇒ mostly starless



Cores in IRDC 18454-0158, MSX 8 μm (grayscale), 1.2 mm IRAM 30m (contours), Sridharan et al. (2005)

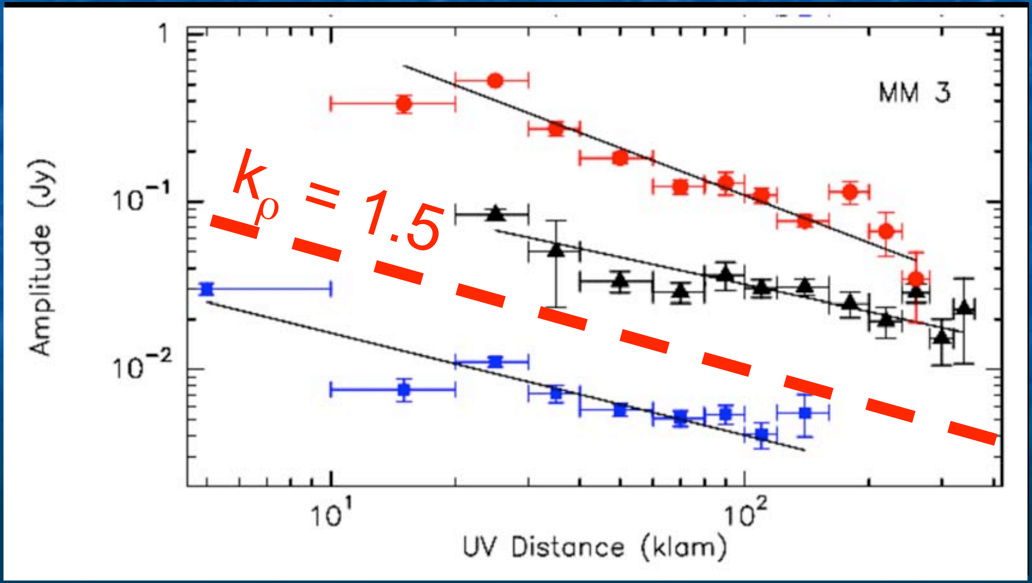


Core in IRDC 18223-3, Spitzer/IRAC (color) and PdBI 93 GHz continuum (contours), Beuther, Sridharan, & Saito (2005)

Turbulent Core Model

(McKee & Tan 2002, 2003)

- Observed cores appear to be bound, roughly virialized structures that move coherently
- Approximate as polytropic sphere with $\rho \propto r^{-1.5}$
- High pressure and density gives free-fall time ~10^5 yr ⇒ fast accretion, 10^{-4} - 10^{-2} $M_\odot$ / yr

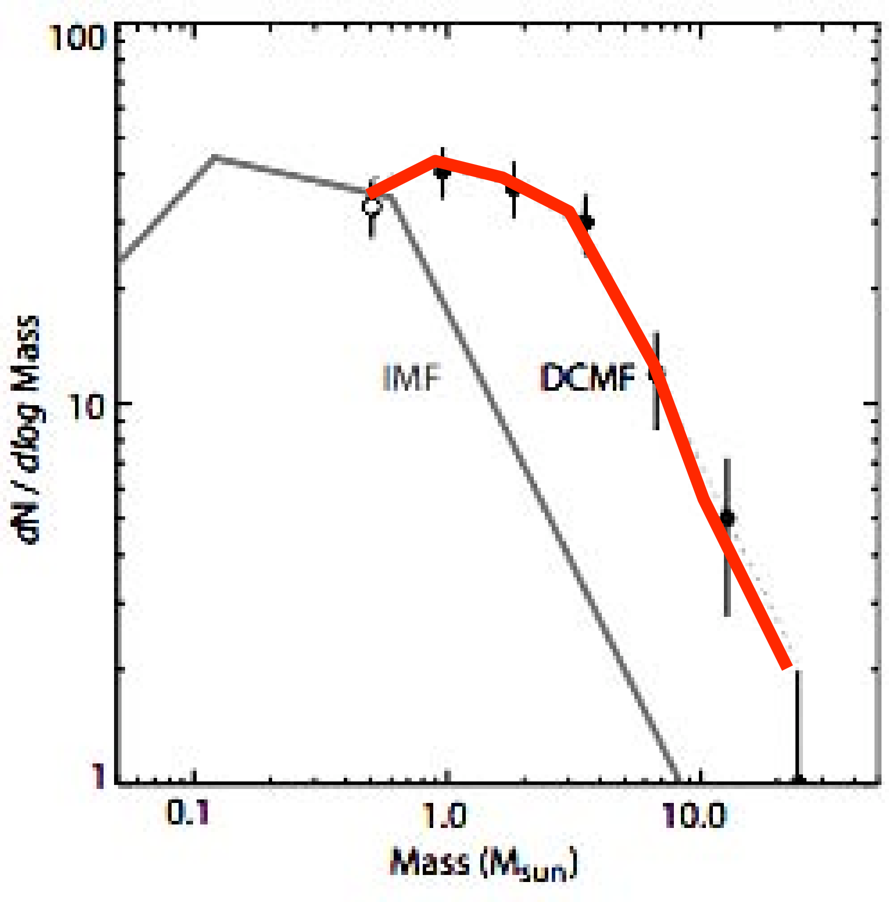


Density profile of a massive core in the different wavelengths (Beuther et al. 2007), overlayed with expected line for $\rho \propto r^{-1.5}$ density profile

The Core Mass Function

(Motte, Andre, & Neri 1998, Testi & Sargent 1998, Johnstone et al. 2001, Onishi et al. 2002, Reid & Wilson 2005, 2006, Alves et al. 2007)

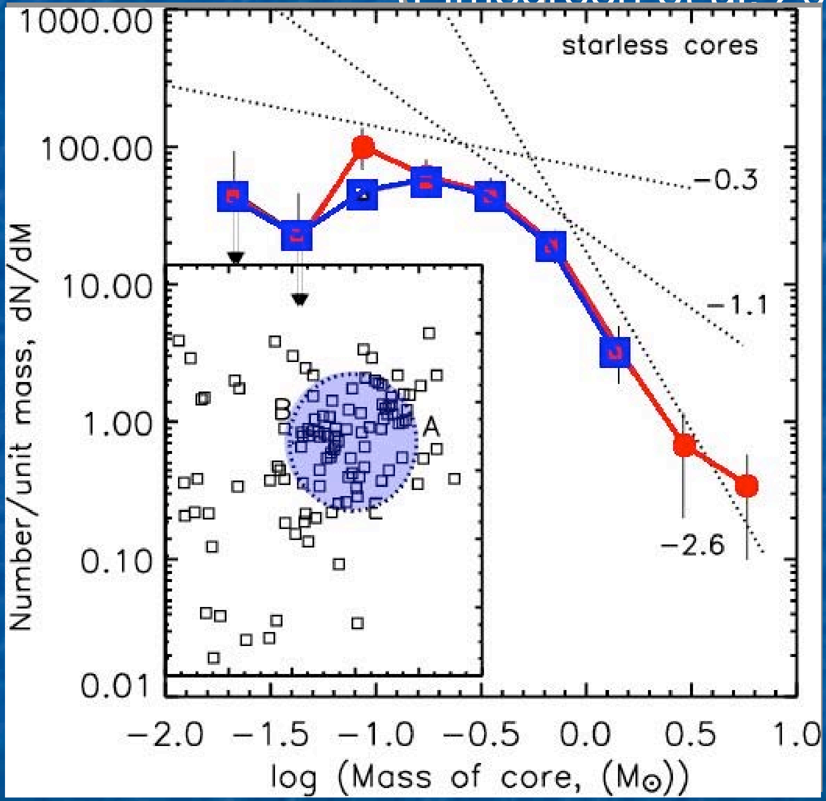
- The CMF looks like the IMF, shifted to higher masses a factor of 2 – 3
- Result is independent of region and mass tracer
- Caveat: distant, massive regions may be affected by poor resolution



Core mass function in the Pipe Nebula (red), compared to stellar IMF (gray), Alves et al. (2007)

The Spatial Distribution of Cores

(Elmegreen et al. 2001, Stanke et al. 2006)



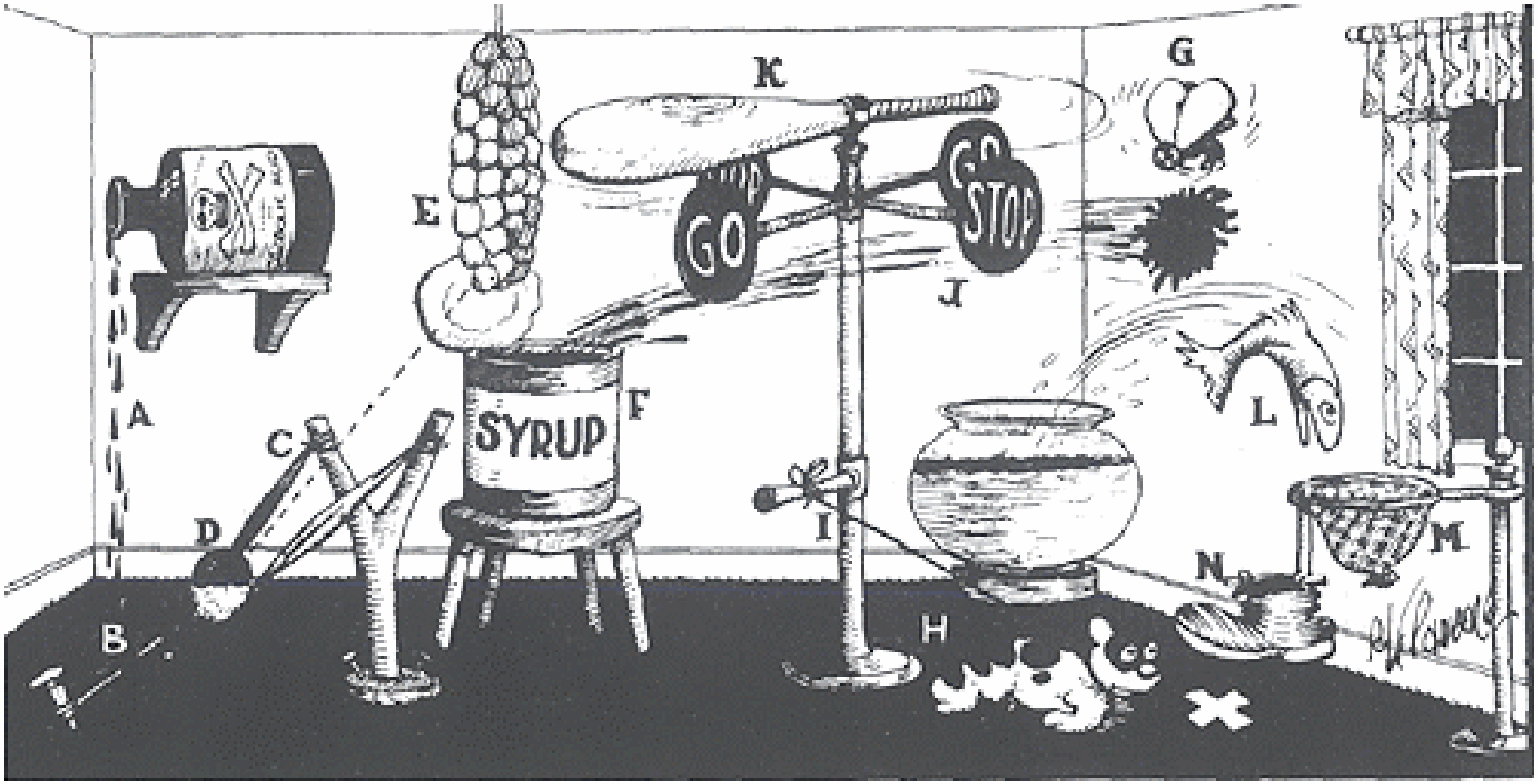
Core mass function for inner (red) and outer (blue) parts of ρ Oph, Stanke et al. (2006)

- Cores in clumps are mass segregated just like stars in clusters
- Similar type of segregation: MF below ~ 5 $M_\odot$ is the same everywhere; cores above ~5 $M_\odot$ are only found in clump centers

A Direct Core to Star Mapping?

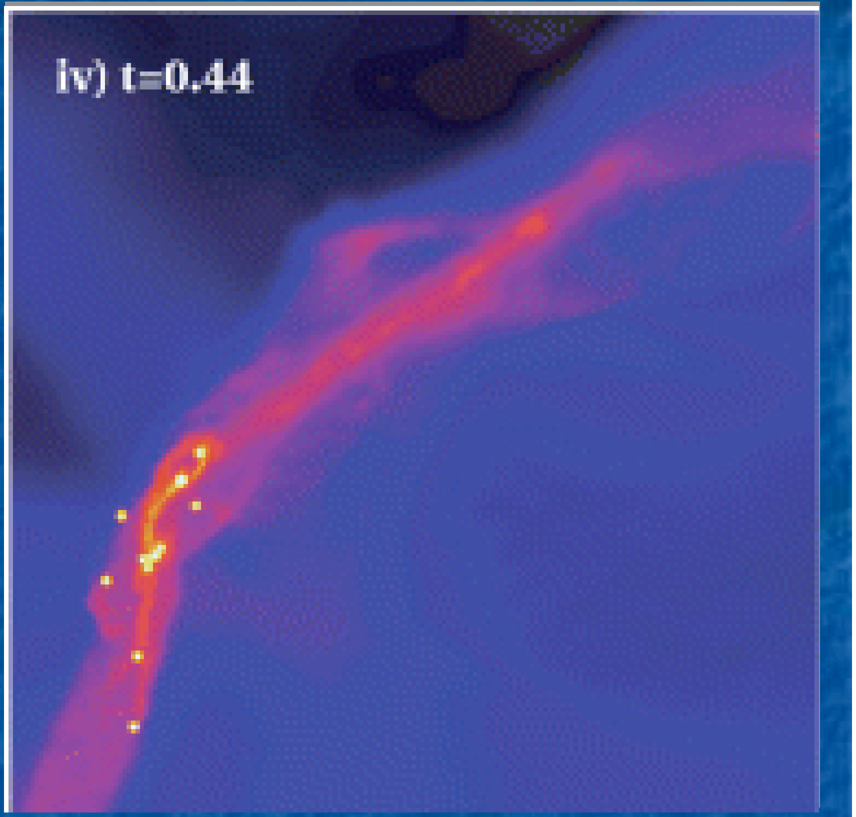
- Cores and young stars have similar mass and spatial distributions
- It is tempting to explain star properties as arising simply from core properties
- This only works if
  - One core forms one star or a small multiple system, not a cluster of low mass stars
  - Can explain high binary fraction, twin binaries
  - ~ 30 – 50% of the mass of a core accretes onto that one system

Assembling a Massive Star



Step 1: Initial Fragmentation

- The Jeans mass in star-forming clouds is ~1 $M_\odot$, so massive cores contain many M_J
- Some simulations find massive cores make ~30 stars (Dobbs et al. 2005)
- How strongly do massive cores fragment?

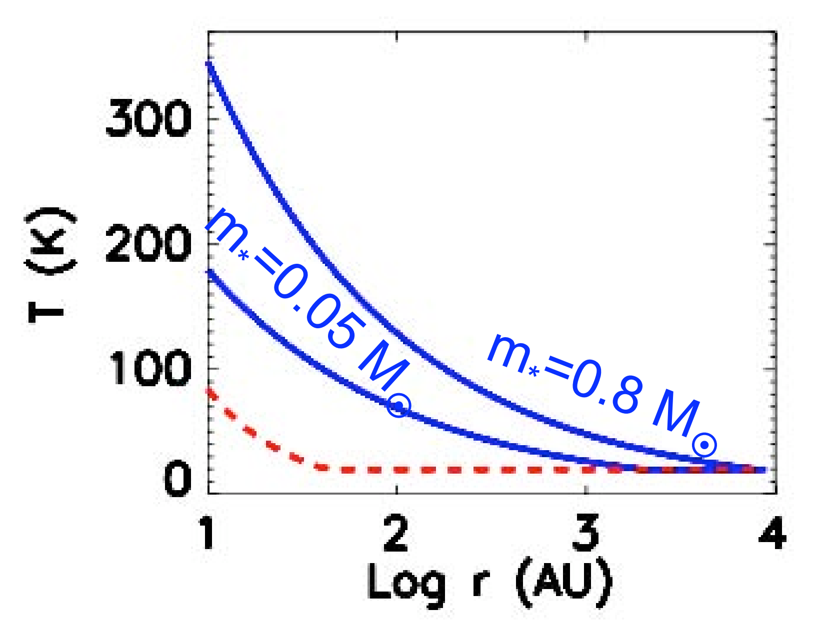


Simulation of the fragmentation of a massive core to many objects (Dobbs et al. 2005)

Fragmentation and Heating

(Krumholz 2006)

- Pure hydro simulations find many small fragments, but these neglect radiation
- 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 $50\ M_\odot$, $1\ \mathrm{g\ cm^{-2}}$ core

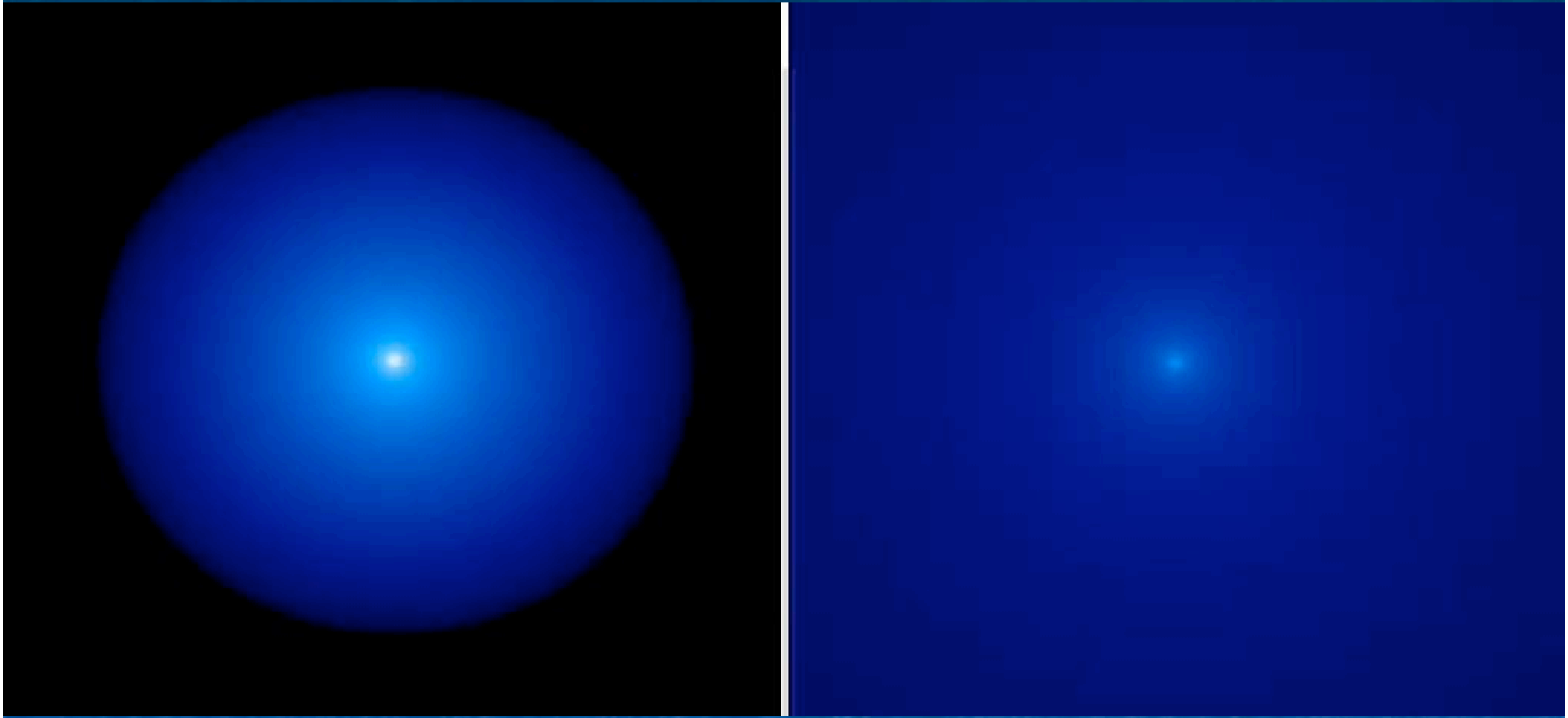
Radiation-Hydro Simulations

- 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

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

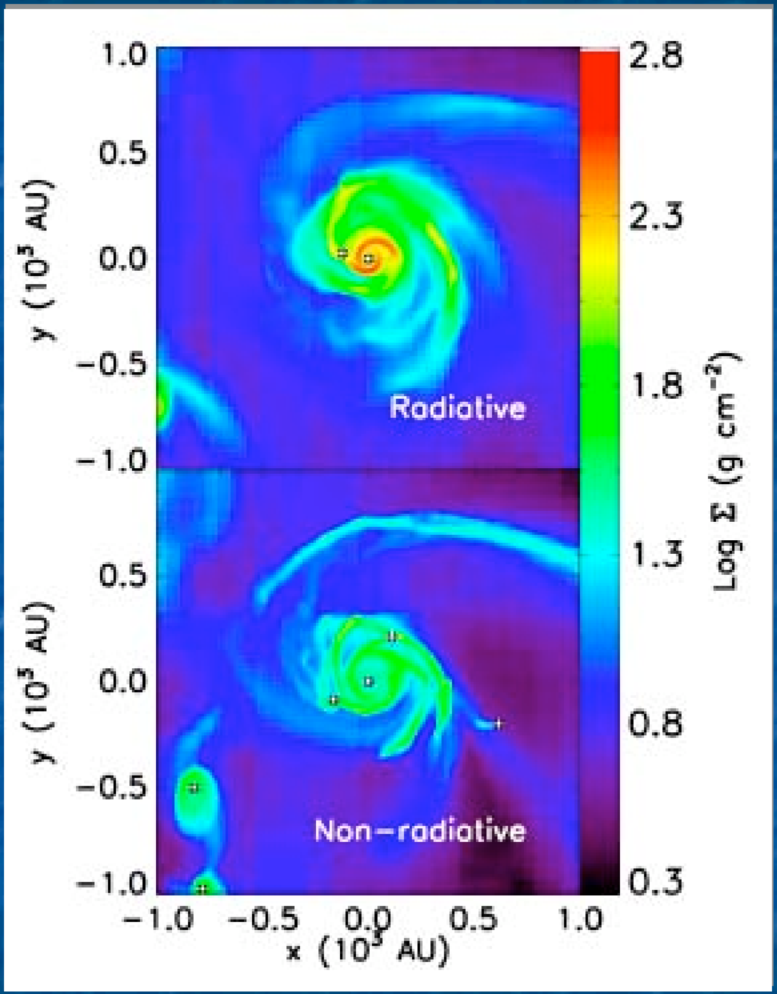
Mass conservation
Momentum conservation
Gas energy conservation
Rad. energy conservation
Self-gravity

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 $(2000\ AU)^2$

Massive Cores Fragment Weakly



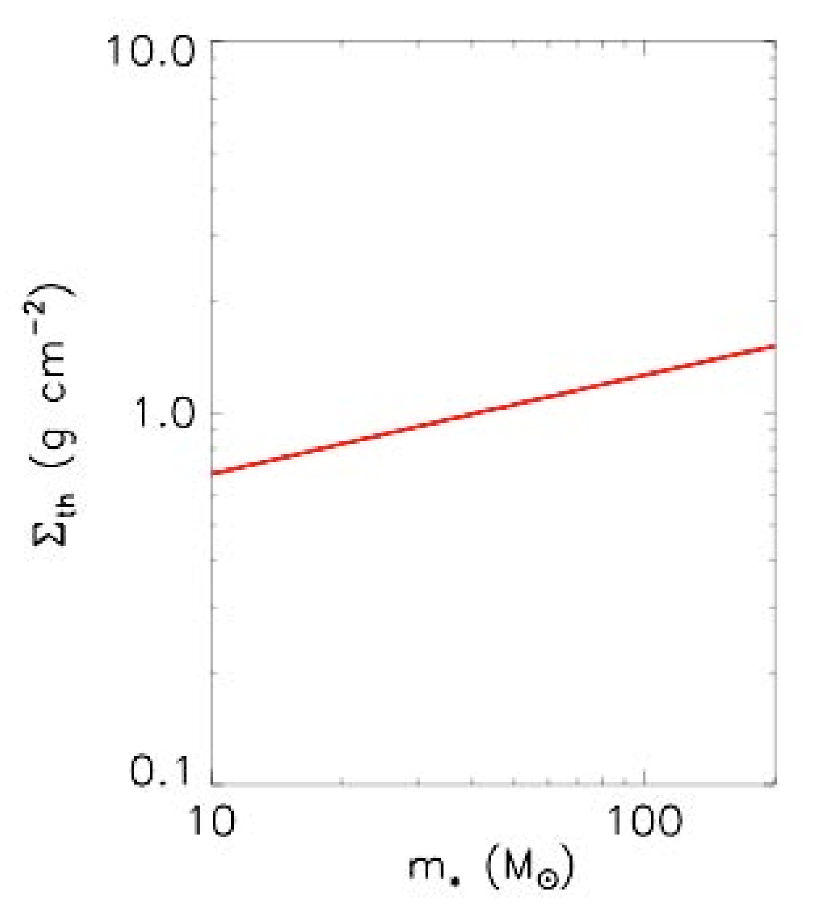
Column density with (upper) and without (lower) RT, for identical times and initial conditions

- 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 $\eta_{halt}(\Sigma)$
- Accretion produces a maximum luminosity / unit mass $\eta_{acc}(\Sigma, M_c)$
- Result: a threshold Σ for massive SF!

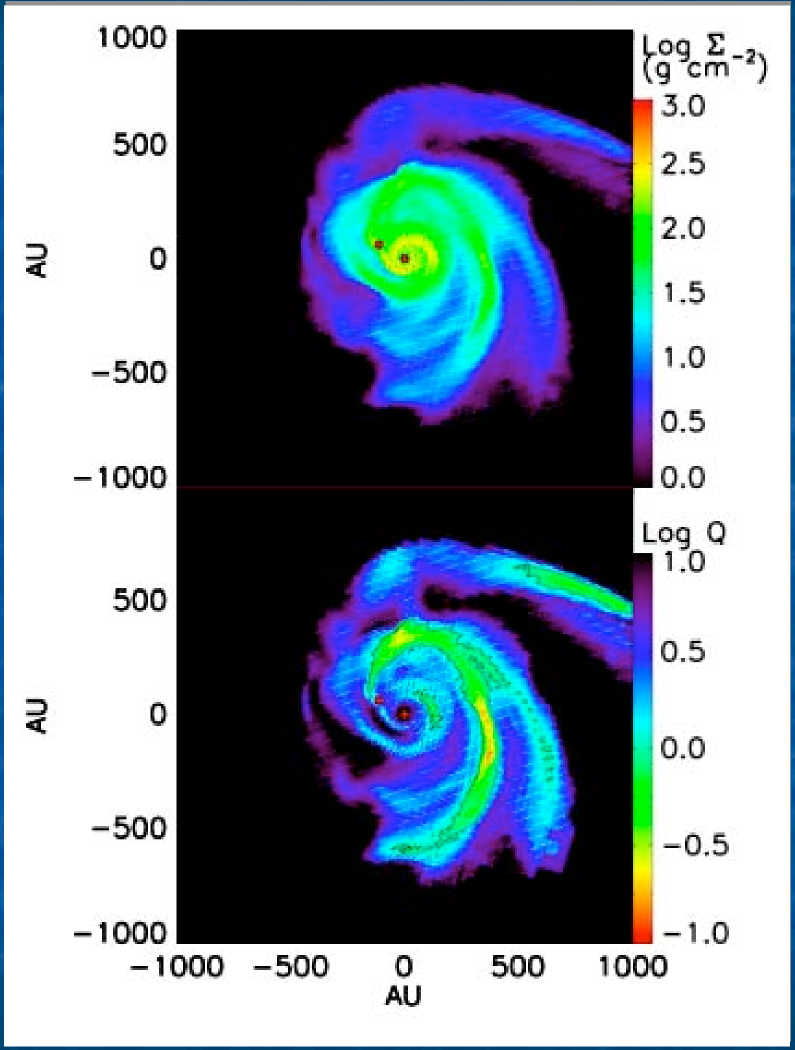


Step 2: Massive Disks and Massive Binaries

- Radiative heating seems to suppress fragmentation into many stars
- … but can we explain the high fraction of massive stars that are binaries?
- We would also like to be able to explain massive twins
- Start by looking at massive disks…

Massive Disk Properties

- $M_{disk} / M_* \approx 0.2 - 0.5$, $r_{disk} \sim 1000$ 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



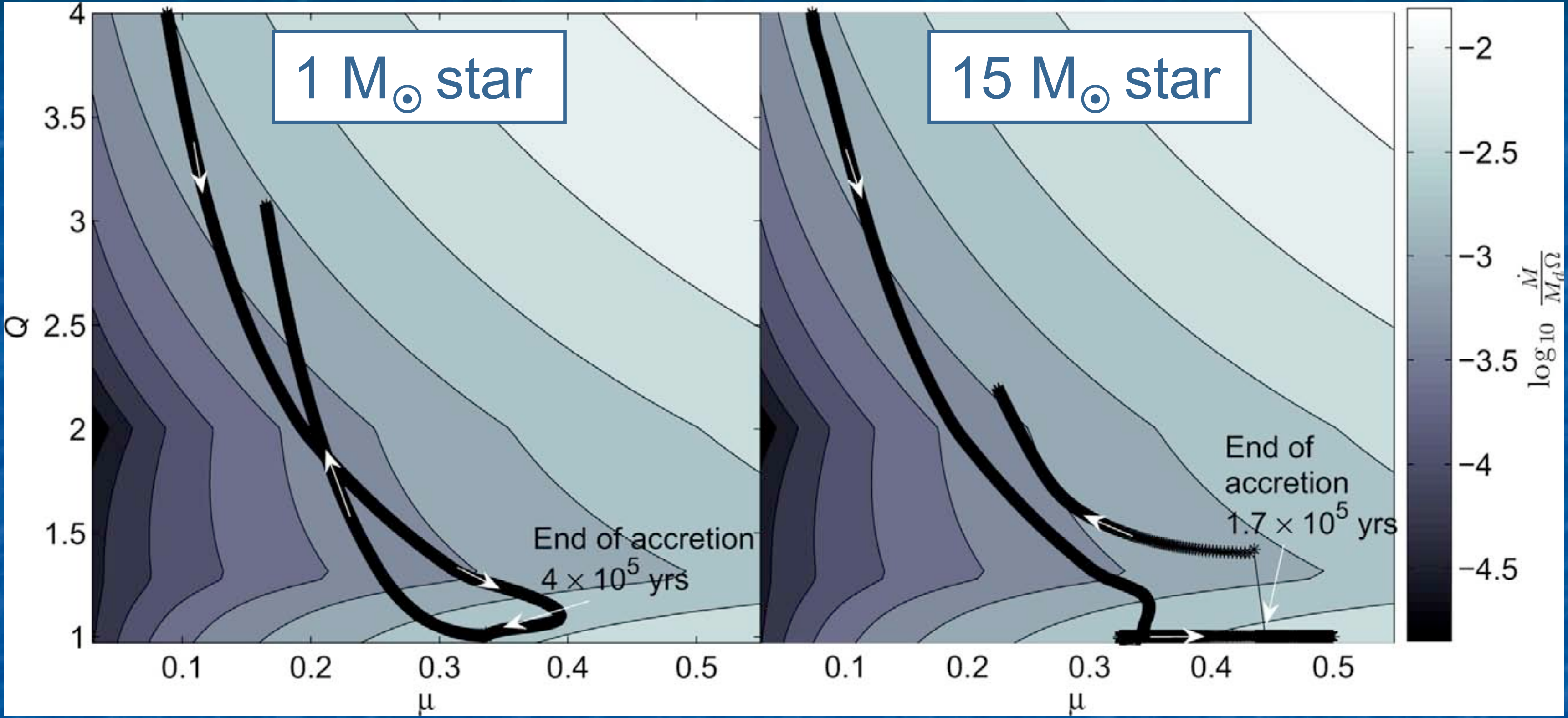
Surface density (upper) and Toomre Q (lower); striping is from projection

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 ($\alpha \ll 1$) 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 ⇒ massive, unstable disks
- Study disk evolution using semi-analytic core model, including accretion, radiative heating, parameterized treatment of angular momentum transport

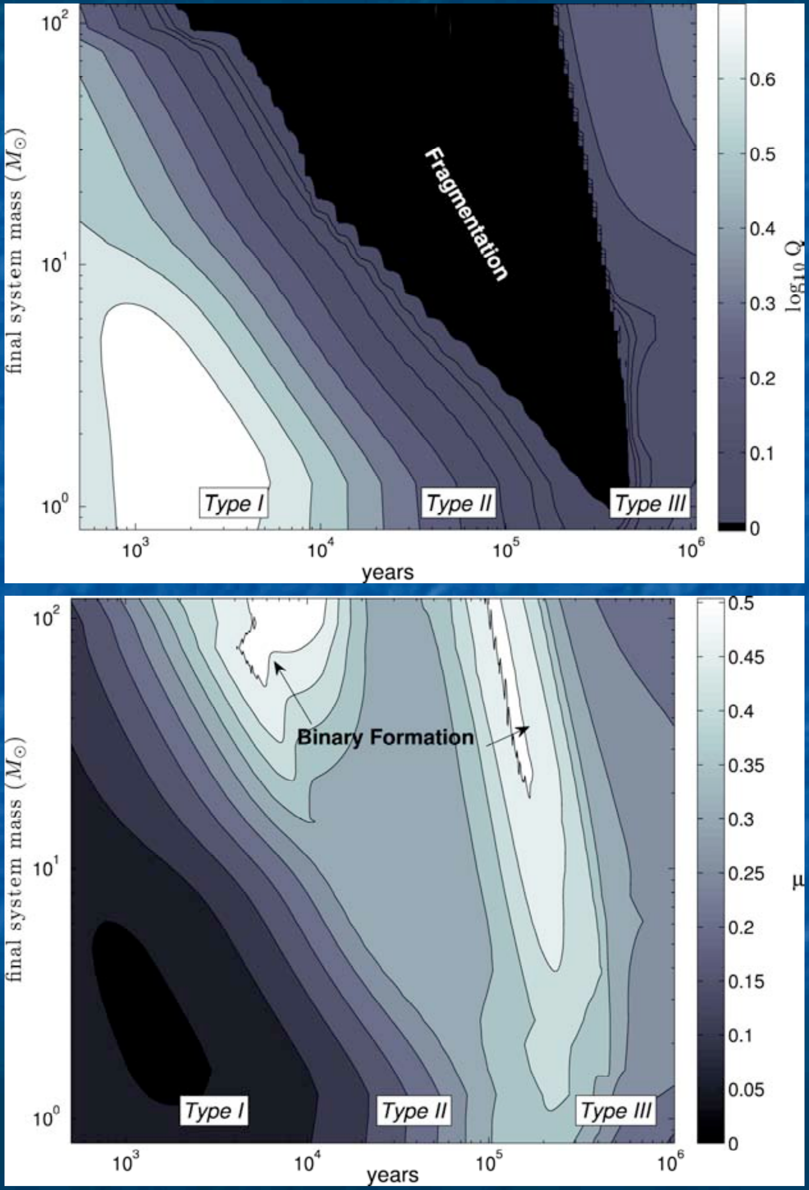
Model Disk Evolution



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

Prediction: μ increases and Q decreases as M_* increases

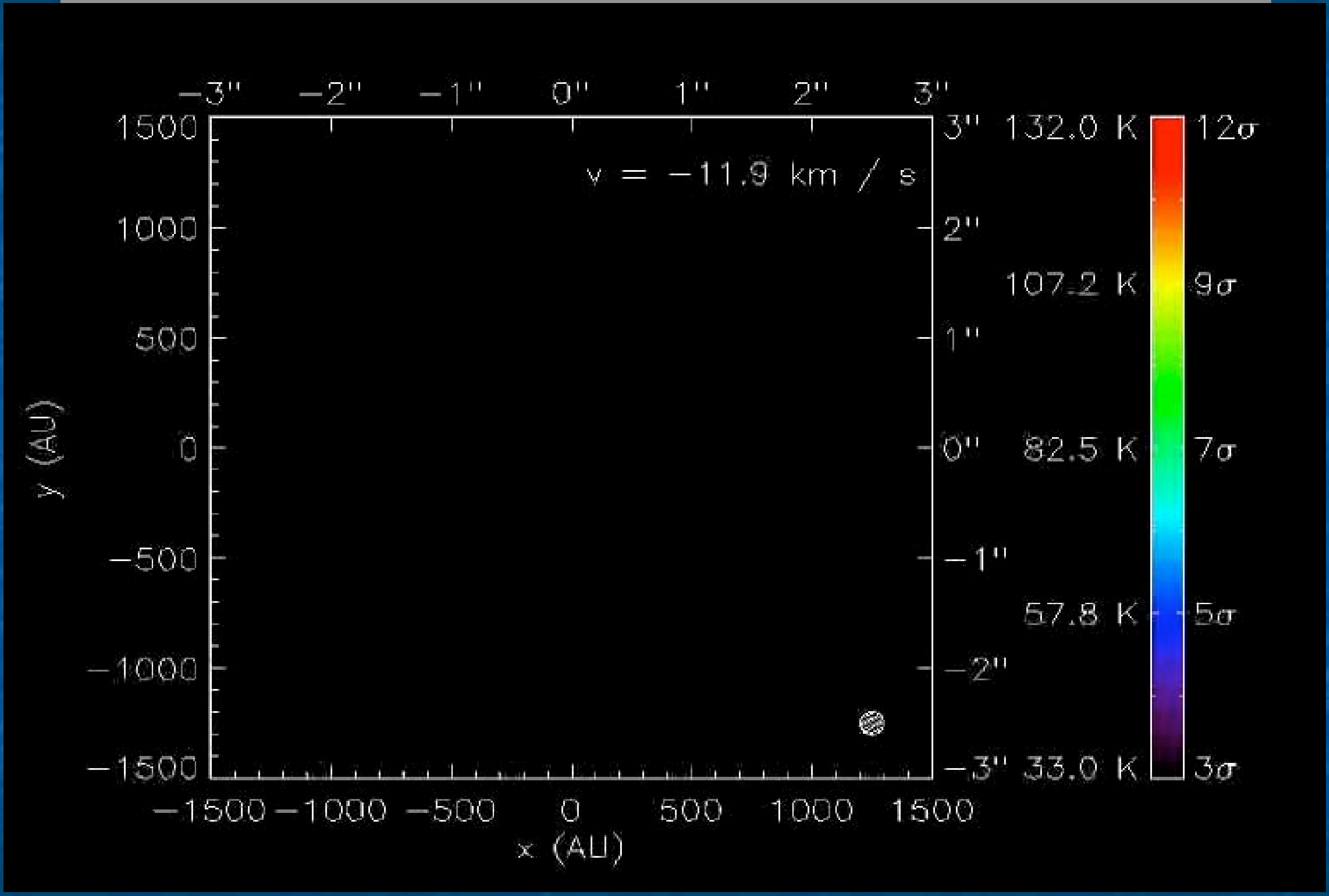
Disk Properties vs. Stellar Mass



- 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)

Step 3: Radiation Pressure

- Fragmentation and binary properties seem ok
- …but a protostar reaches the MS in a Kelvin time:

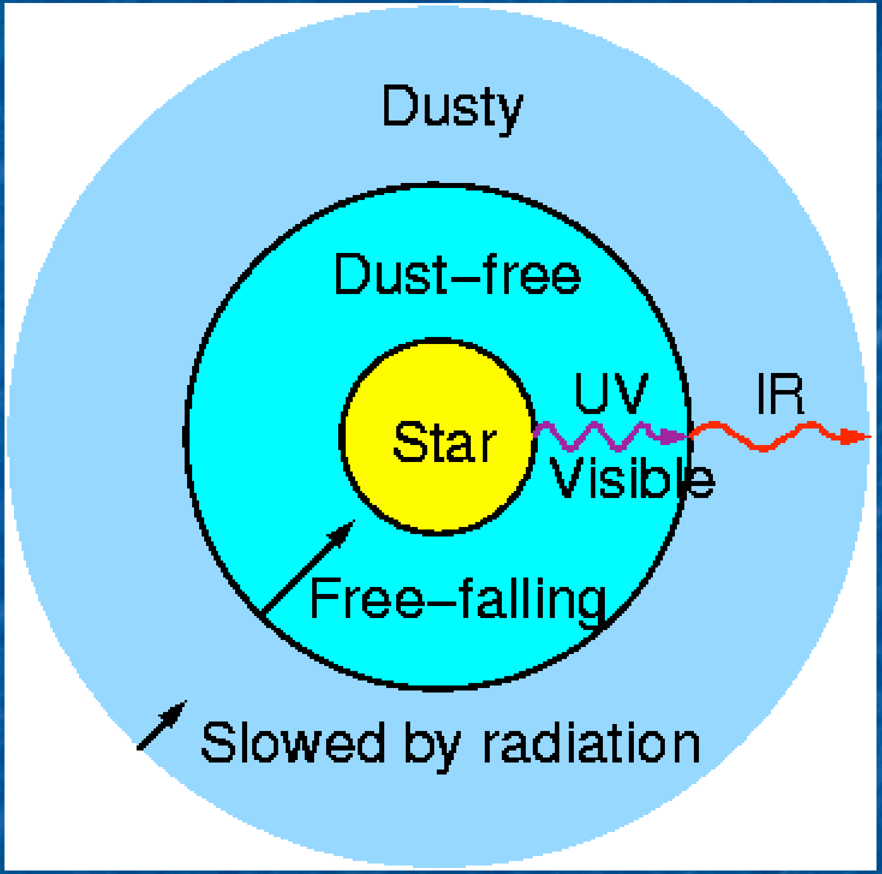
$$t_{\mathrm{KH}} = \frac{GM^2}{RL} \approx 2 \times 10^4 \ \mathrm{yr}$$

$$(\mathrm{for}\ M = 60 M_\odot)$$

- This is shorter than the formation time ⇒ accretion is opposed by huge radiation pressure
- If radiation pressure prevents most of the mass in a large core from accreting, then the core MF can’t produce the stellar IMF

Radiation Pressure in 1D

(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

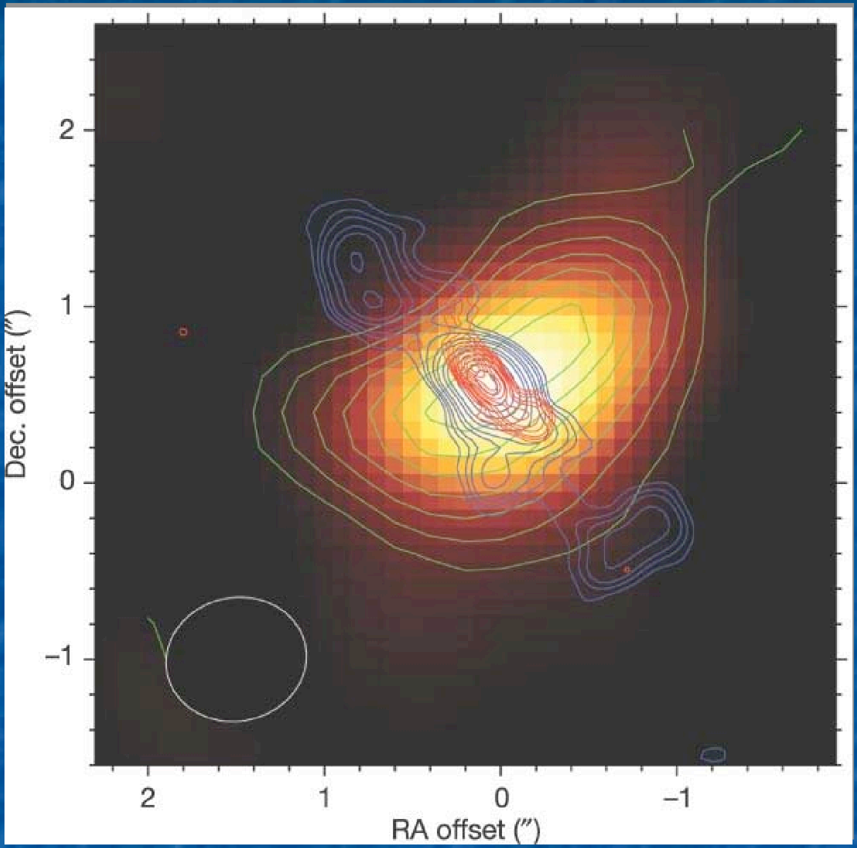
$$L > 4\pi GMc/\kappa$$

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

- For 50 $M_\odot$ ZAMS star, $L = 4 \times 10^5\ L_\odot$

⇒ Massive stars approach their Eddington limits while forming

Non-Spherical Accretion

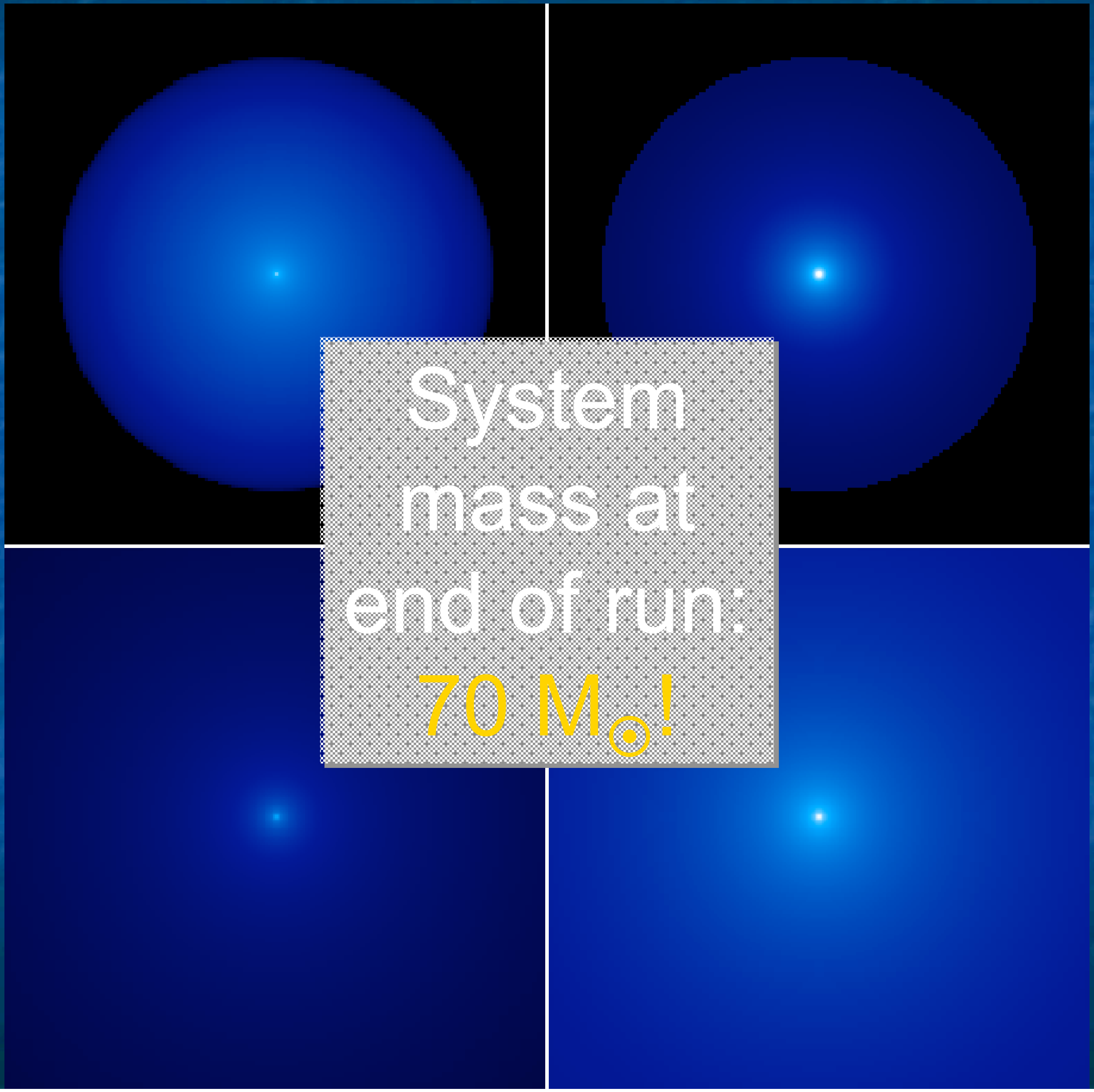


Disk (color image, dust continuum) and outflow (contours, CH_3CN) around massive protostar Ceph A HW2 (Patel et al. 2005)

- In reality, accretion is through a disk, and protostars have outflows
- These make envelope non-spherical, possibly an important effect
- Investigate with Orion simulations with simple initial conditions
- Follow stars to main sequence

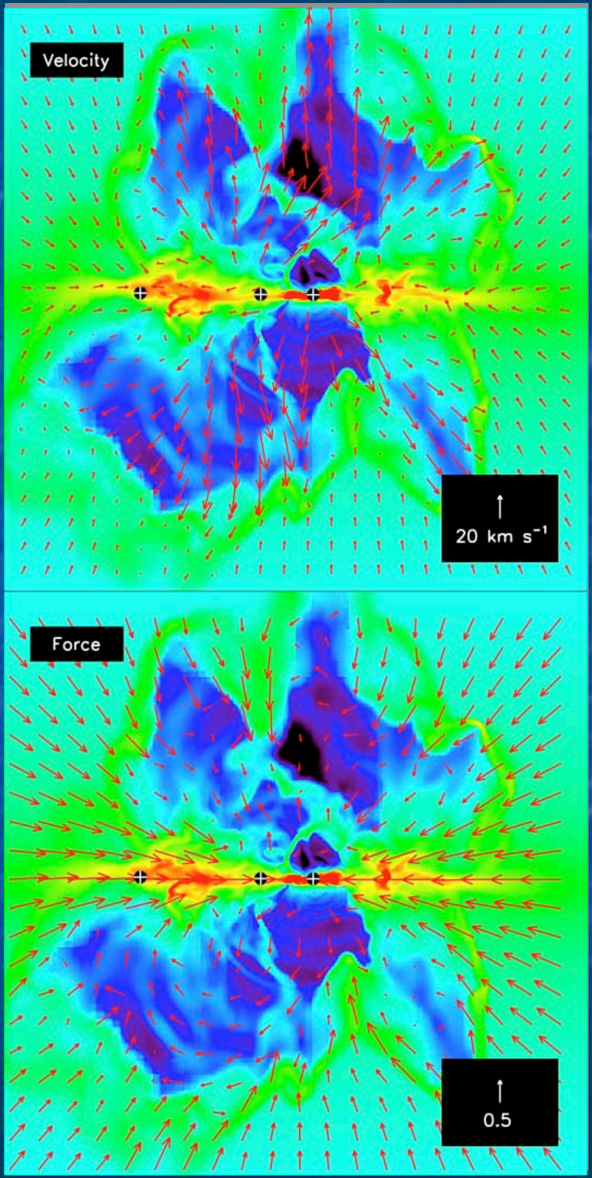
Simulations of Radiation Pressure

(Krumholz, Klein, McKee, Offner, & Cunningham, 2008, in press)

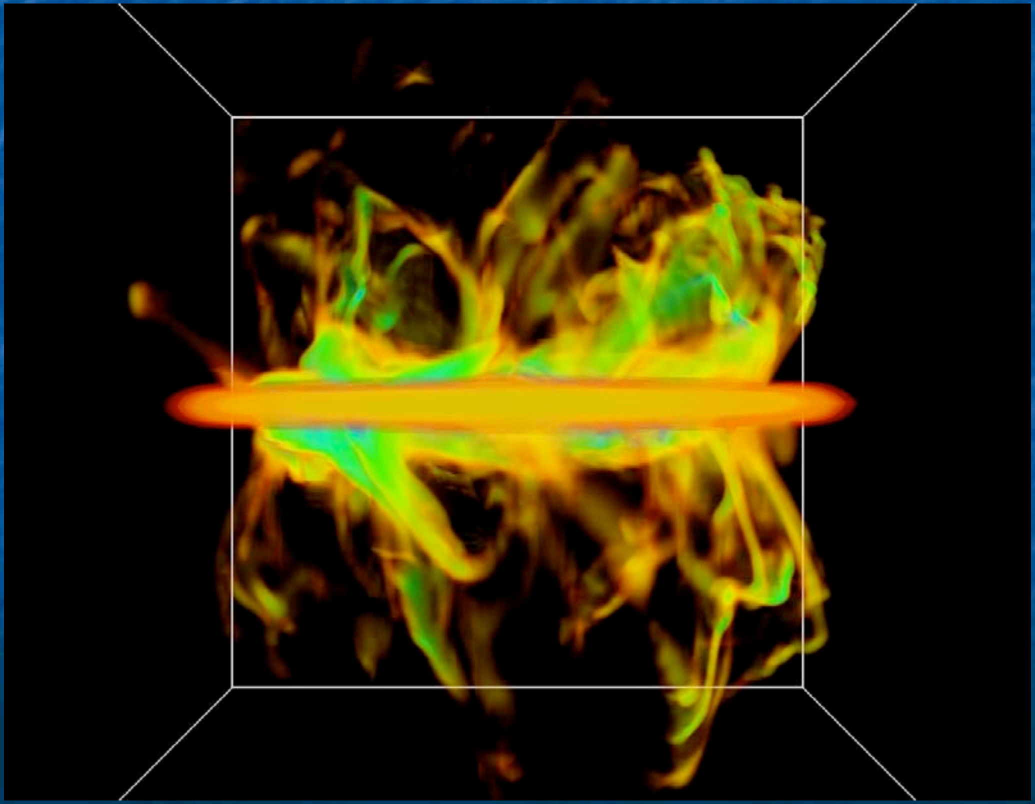


System mass at end of run: 70 $M_\odot$!

Radiation Beaming

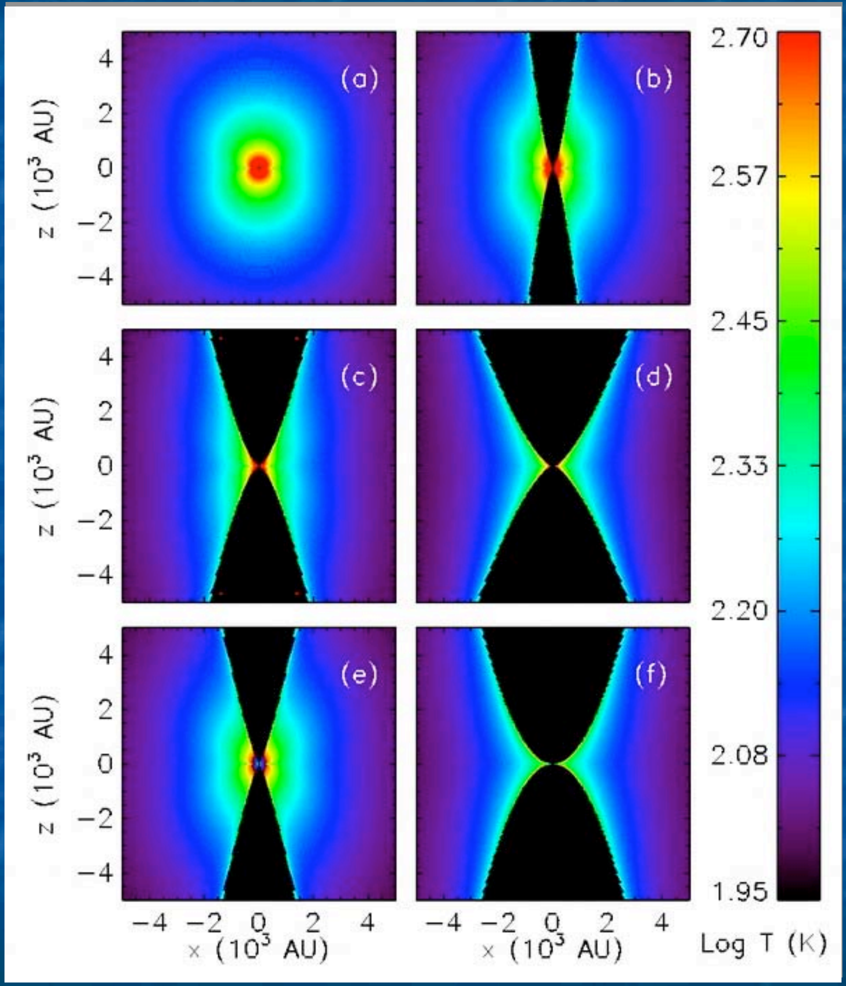


- RT instability allows accretion!
- Radiation leaves through transparent chimneys, mass accretes through opaque fingers



Beaming by Outflows

(Krumholz, McKee, & Klein 2005)

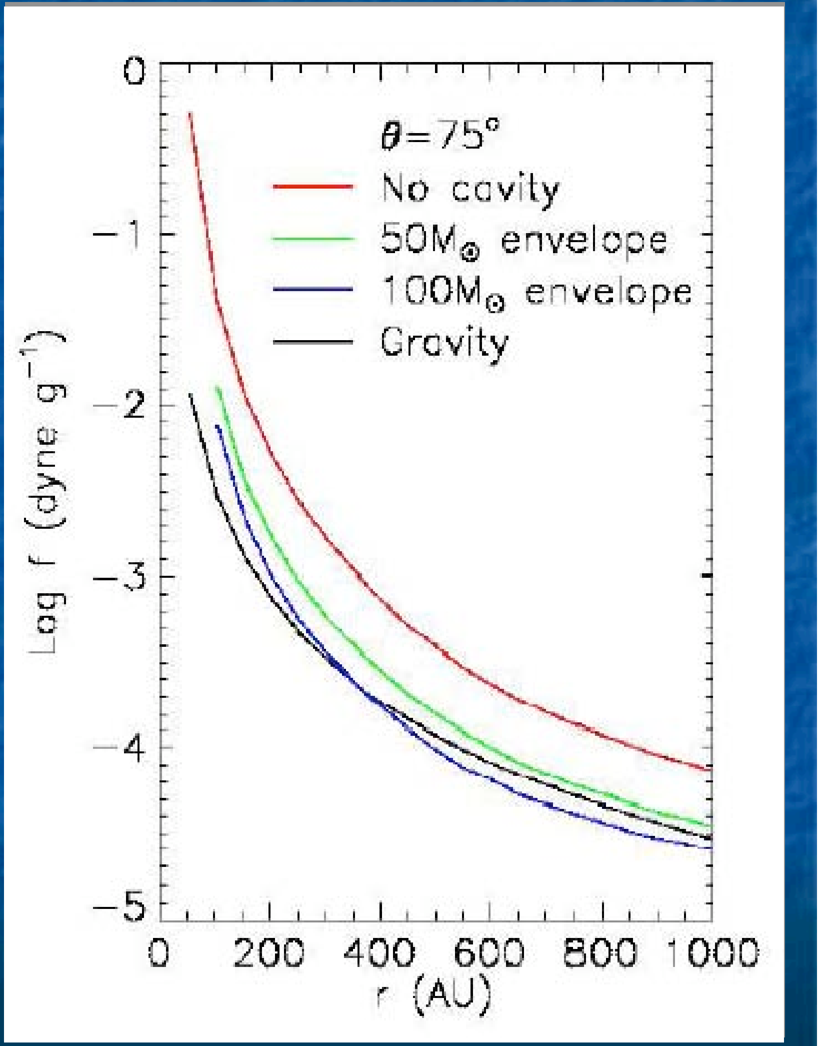


Gas temperature distributions with a 50 $M_\odot$ star, 50 $M_\odot$ envelope

- Massive stars have outflows launched from dust destruction zone
- Outflow velocity ~10^3 km s^{-1} ⇒ no time for grains to re-grow until gas is far from star
- Result: outflow cavities optically thin, radiation can leak out of them
- Simulate with MC radiative transfer code

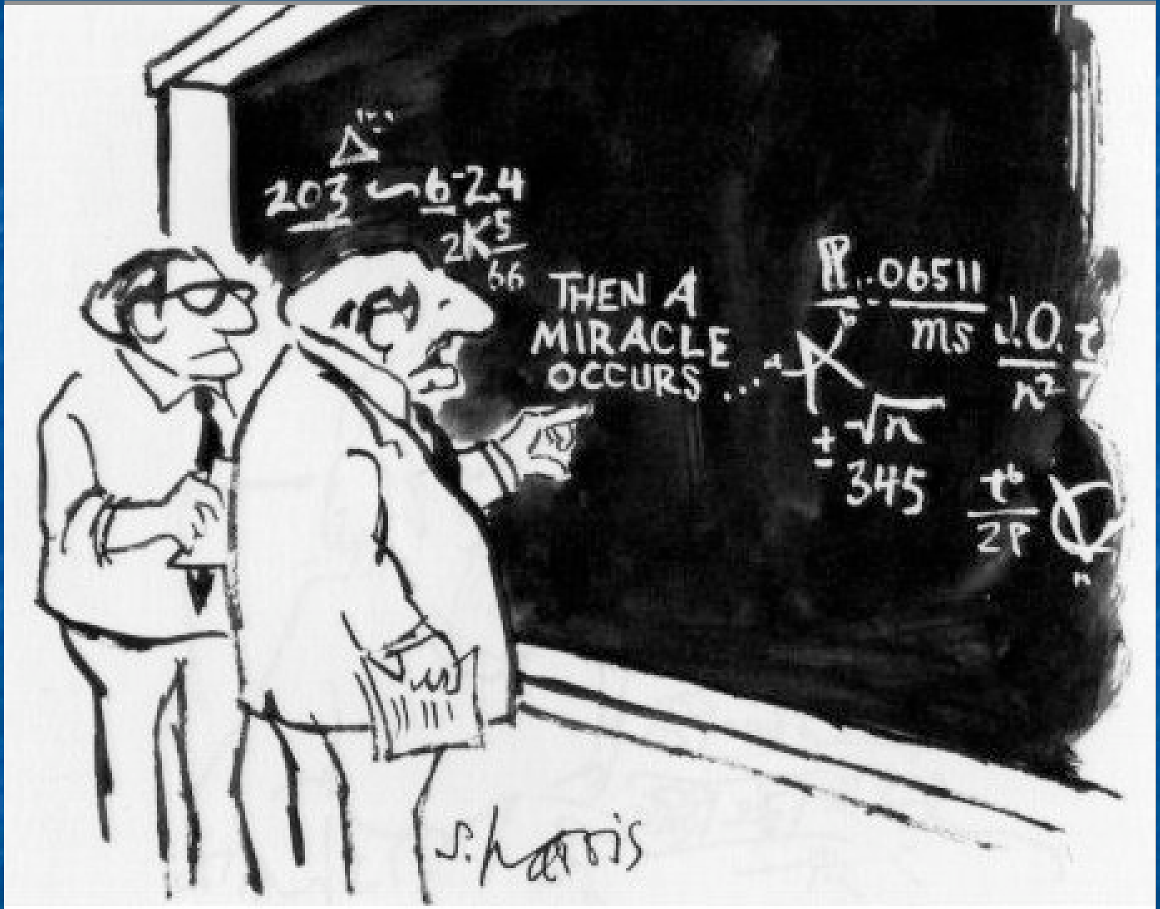
Outflows Help Accretion

- Simulations show that this effect can produce an order-of-magnitude reduction in radiation force
- This can move the system from radiation being stronger than gravity to weaker than gravity



Radiation and gravity forces vs. radius for a 50 M☉ star and a typical outflow cavity geometry

Problems for the Future



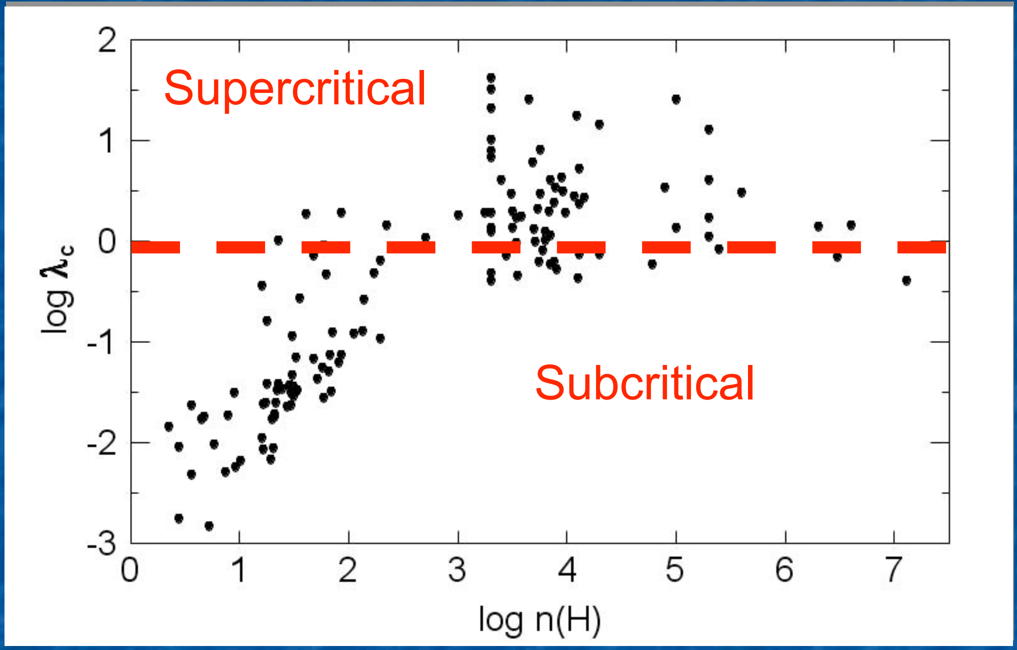
"I think you should be more explicit here in step two."

from *What's so Funny about Science?* by Sidney Harris (1977)

Magnetic Fields

(with Patrick Hennebelle, Romain Teyssier, and Jonathan Tan)

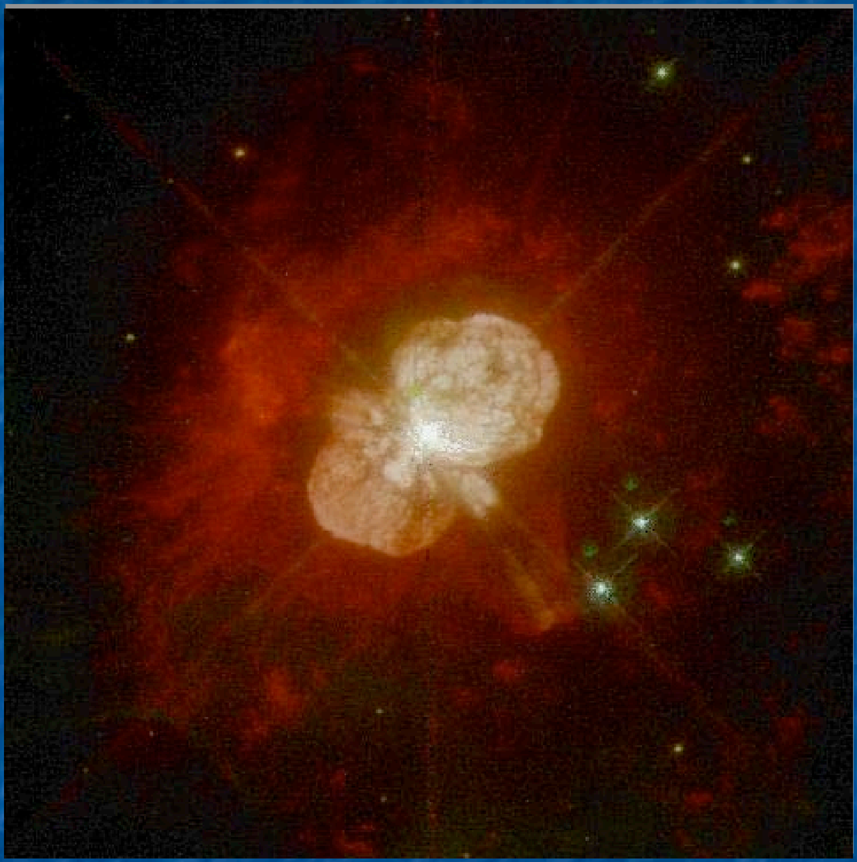
- Preliminary data: $M/M_\Phi \sim 1 - 2$, fields not dynamically dominant
- May reduce fragmentation, create photon bubble instability (Turner et al 2007)
- No large-scale MHD simulations done yet, but work in progress using Ramses AMR MHD code



M/M_Φ vs. density from Zeeman splitting measurements, Crutcher (2008)

The Origin of the IMF Cutoff

- Origin of ~150 $M_\odot$ limit hard to explain
  - L/M ~ constant above 75 $M_\odot$, so why 150 $M_\odot$?
  - Collisions should give a pure powerlaw
- Could be disk instability (Kratter & Matzner 2006)
- Limit may also come from mass loss driven by instabilities (e.g. Smith & Owocki 2006, Smith 2008)



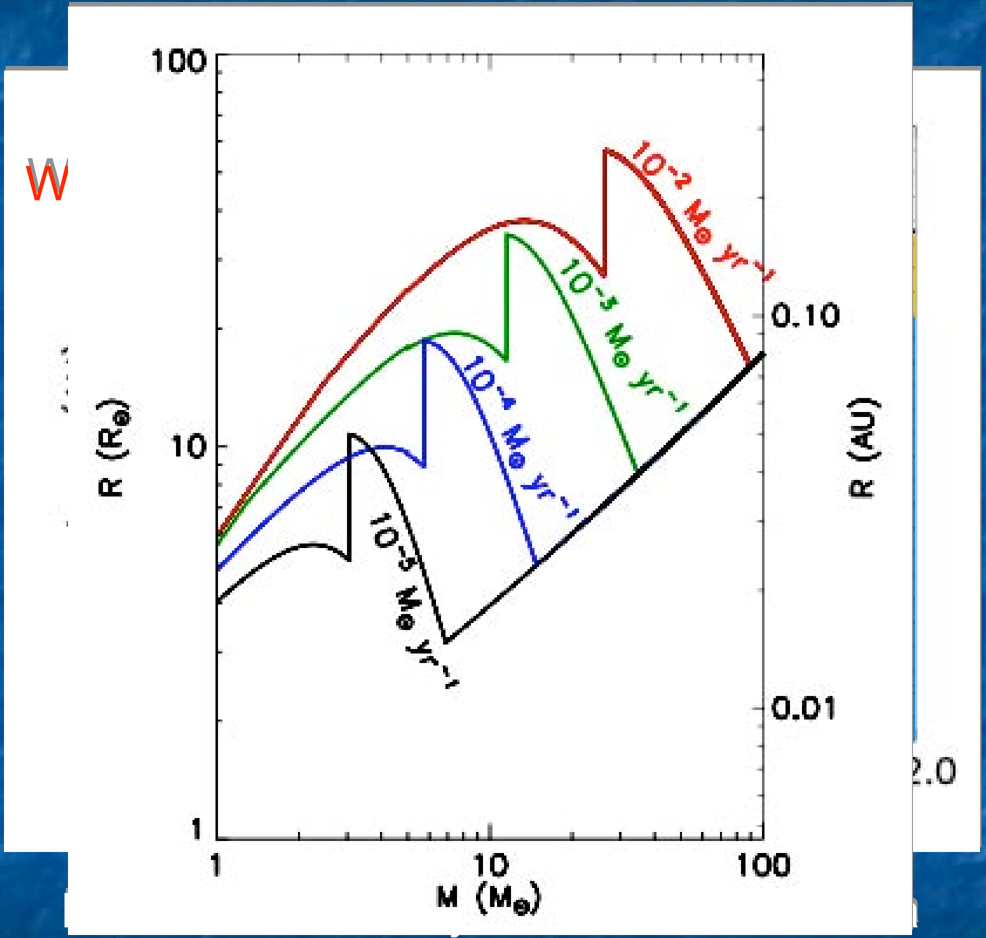
Gas shell around η Carinae produced by an eruption in the 1840s

Summary

- Massive stars form from massive cores
  - Massive cores fragment only weakly
  - Disk fragmentation explains high binary fraction; mass transfer explains twins
  - Radiation feedback cannot significantly inhibit accretion from cores onto stars
- Many properties of massive stars are inherited from their gas phase precursors
- However, every new bit of physics added has revealed something unexpected…

Massive “Twins”

(Krumholz & Thompson 2007)



Radius vs. mass for protostars of varying accretion rates

- Massive protostars reach radii ~ 0.1 AU due to convection driven by rapid accretion
- This produces RLOF in close binaries
- Transfer is from more to less massive ⇒ transfer unstable, stabilizes at $q \approx 1$
- Result: massive twin

HII Regions and Gas Clearing

(Krumholz, Stone, & Gardiner 2007; also with J. Oishi, R. Klein, C. McKee)

- Simulate HII region breakout to determine final SF efficiency, on star and cluster scale

Radiative Transfer Post-Process

(with Sukanya Chakrabarti)

- Post-process simulations using RADISHE radiative transfer code
- Purposes:
  - Produce IR continuum images of disks for comparison to observations
  - Test gray FLD radiative transfer against more sophisticated treatment
  - Potentially re-run using better RT, e.g. multi-frequency or SN-transport