Feedback Effects in the Formation of High Mass and Low Mass Star Formation

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Outstanding Challenges of Massive Star Formation

- What is the formation Mechanism: Gravitational collapse of an unstable cloud; Competitive Bondi-Hoyle accretion; Collisional Coalescence?
- How can gravitationally collapsing clouds overcome the Eddington limit due to radiation pressure?
- What determines the upper limit for High Mass Stars? ($120M_{sun} \rightarrow 150M_{sun}$)
- How do feedback mechanisms such as protostellar outflows and radiation affect protostellar evolution? These mechanisms can also have a dramatic effect on cluster formation
- How do the systems in which massive stars are present form?

Theoretical Challenges of High Mass Star Formation

1. **Effects of Strong Radiation Pressure and Radiative Heating**
   - Massive stars $M \geq 20\ M_\odot$ have $t_K < t_{form}$ (Shu et al. 1987) and begin nuclear burning during accretion phase
     - ⇒ Radiates enormous energy
     - ⇒ For $M \geq 100\ M_\odot$

$$L_* \sim L_{edd} = \frac{4\pi G m_p c M}{\sigma_T} \sim 3\times10^6\, L_\odot$$

however $\sigma_{dust} >> \sigma_T$

$$\Rightarrow f_{rad} > f_{grav} \quad for\ M > 10\ M_\odot$$

But, observations show $M \sim 100\ M_\odot$ (Massey 1998, 2003)

<u>Fundamental Problem:</u> How is it possible to sustain a sufficiently high-mass accretion rate onto protostellar core despite "Eddington" barrier?

Does radiation pressure provide a natural limit to the formation of high mass stars?

Theoretical Challenges of High Mass Star Formation (cont.)

2. Effects of Protostellar outflows

- Massive stars produce strong radiation driven stellar winds with momentum fluxes $\dot{M}v \leq L/c$
- Massive YSO have observed (CO) protostellar outflows where $\dot{M}v \sim 100 L/c$ (Richer et al. 2000; Cesaroni 2004)

$\Rightarrow$ If outflows where spherically symmetric this would create a greater obstacle to massive star formation than radiation pressure

but, flows are found to be collimated with collimation factors 2-10 (Beuther 2002, 2003, 2004)

<u>Fundamental Problem:</u> How do outflows effect the formation of Massive stars? How do outflows interact with radiation from the protostar? Do outflows limit the mass of a star?

Physical Effects in High-Mass Star Formation

- Dust
  - Critical role in massive star formation → couples gas to radiation flux from central star
- Photostellar outflows
  - Molecular outflows in neighborhood of massive stars $\sim 10^{-4} - 10^{-2}\ M_{\odot}/yr$. Force required to drive such outflows $F_{co} > 10 - 100\ L_{BOL}/c$
  - ⇒ Outflows may be important to protostellar evolution
- Three-Dimensional Effects
  - Interaction of radiation with infalling envelope subject to radiation driven instabilities
  - Interaction of protostellar outflow with infalling envelope possibly unstable
  - Accretion disks develop non-axisymmetric structures in turbulent flows
  - ⇒ Three dimensional simulations are crucial

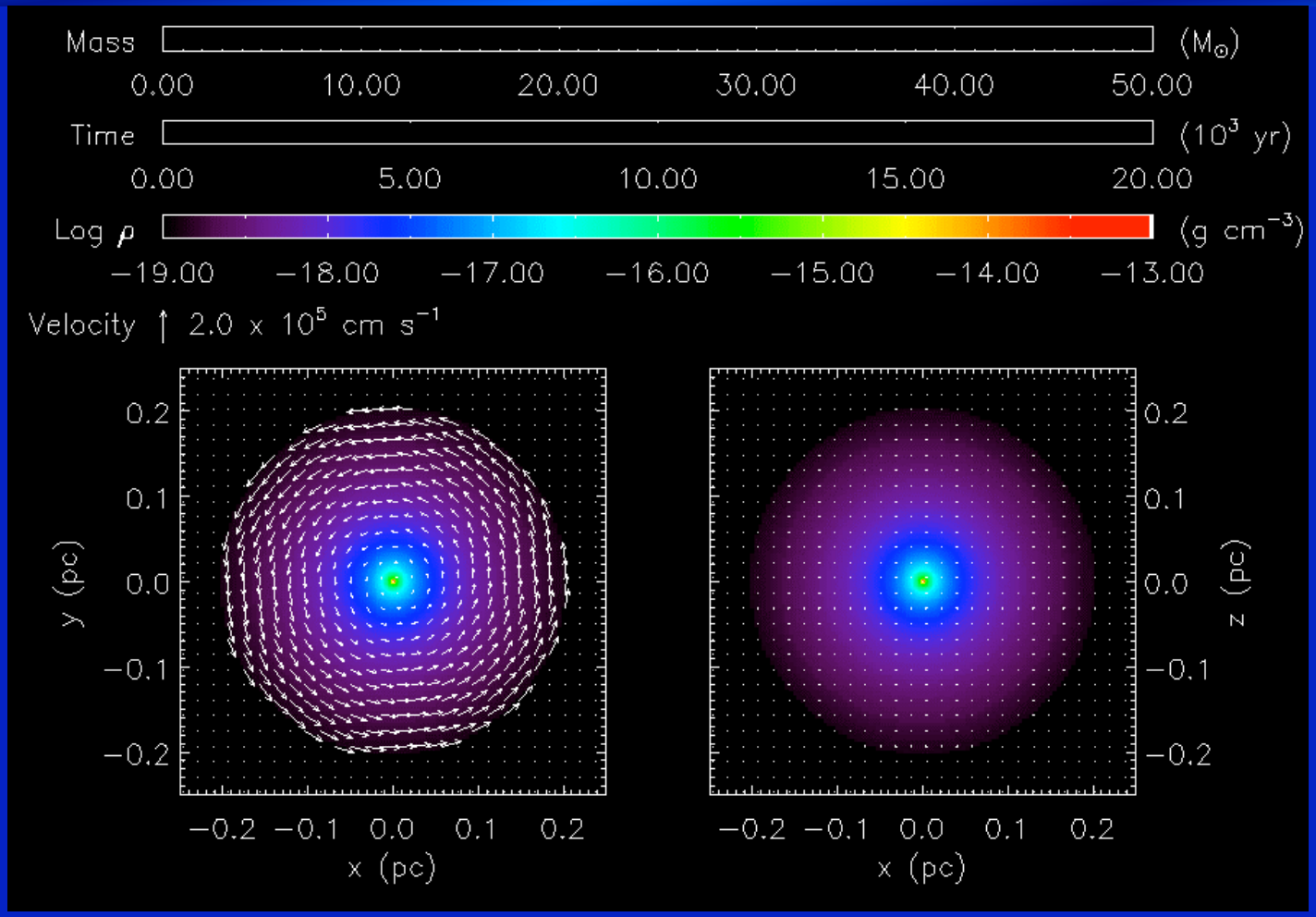
High Mass Star Formation Simulation Physics:ORION-AMR

- Multi-fluid Euler equations of compressible gas dynamics with gravity
- Radiative transfer and radiation pressure in the gray, flux-limited diffusion approximation ⇒ Radiative Feedback
- Model of dust opacity based on Pollack et al. (1994) (6 species)
- Outflows: hydromagnetic outflow using x-wind model (Shu et al. 2000) or Matzner and McKee 2000

  ⇒ Dynamical Feedback
- Eulerian sink particles: (Krumholz, McKee, & Klein 2004)
  - Created when the density in a cell exceeds the local Jeans density
  - Free to move through the grid and continue to accrete gas
  - Sink particles feed radiation and winds back into the grid based on a protostellar evolution model model
  - Model includes accretion, KH contraction, deuterium and hydrogen burning (McKee & Tan 2003), x-winds
- Capability to handle the enormous range of scales involved ⇒ ORION AMR

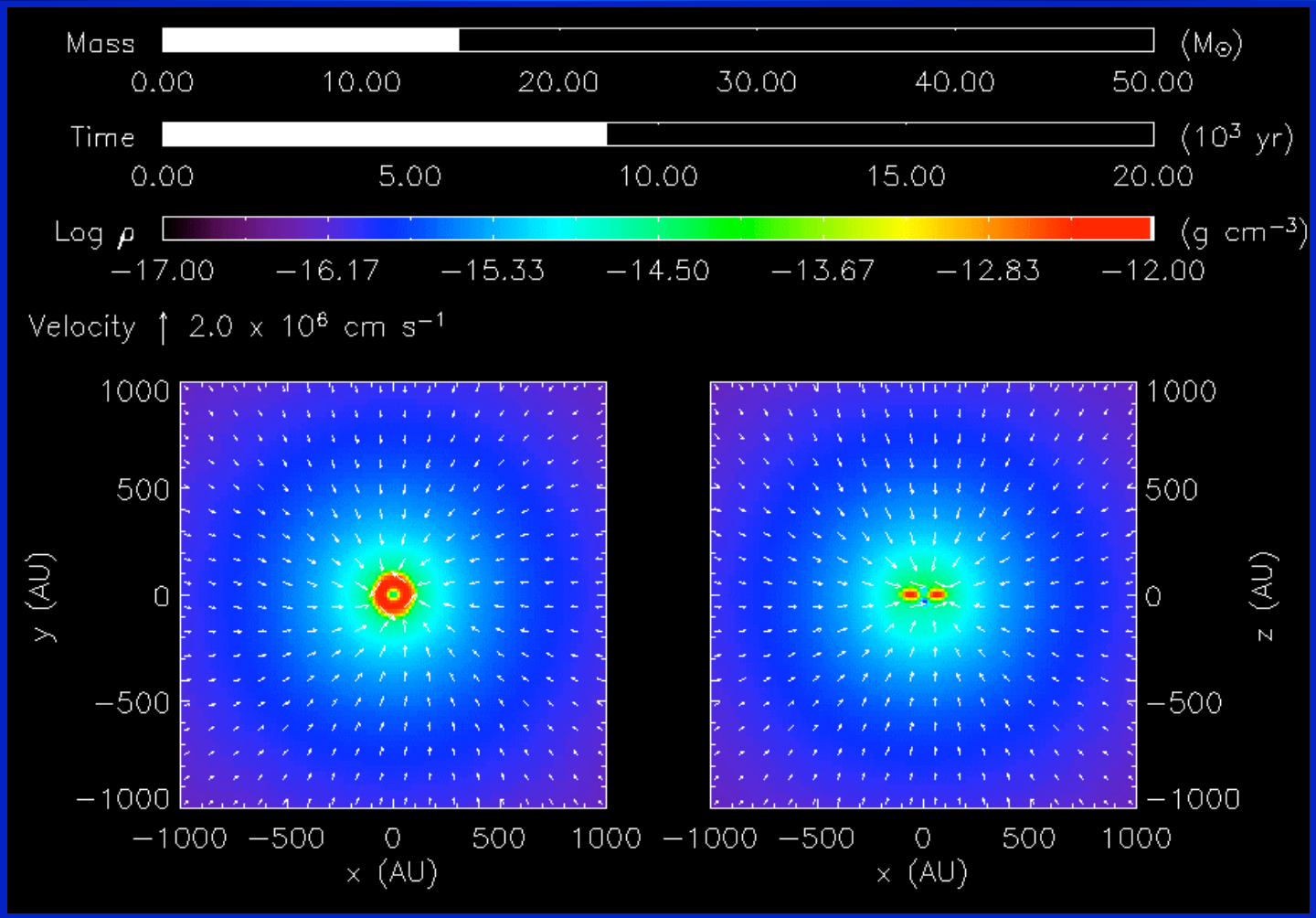
  (Truelove, Klein, McKee et al. 1997; Klein 1999)

HMSF Initial Conditions: Non-Turbulent



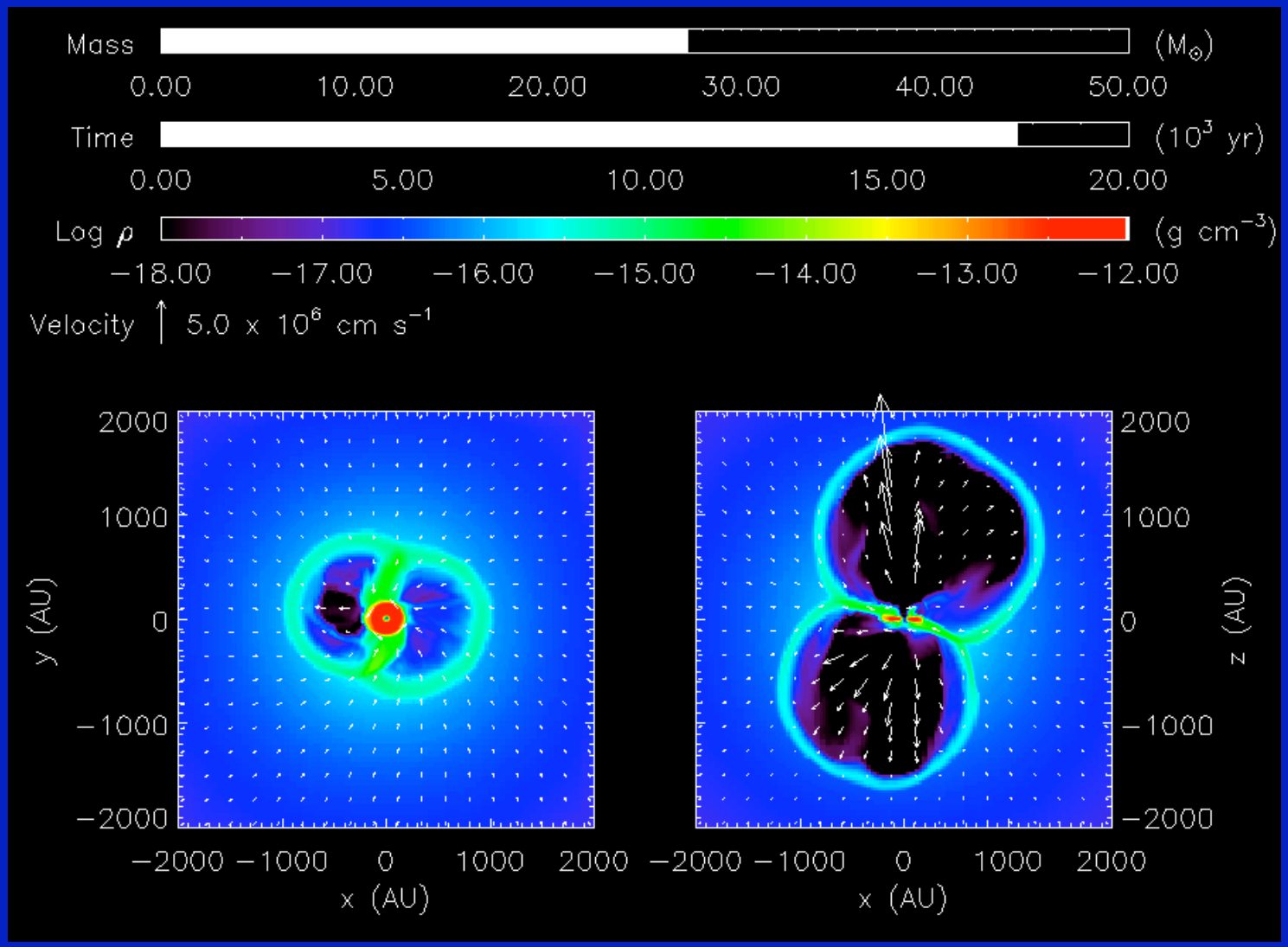
r^{-2} density profile, r = 0.1–0.2 pc, M = 100–200 M_{sun}, slow solid-body rotation: β = 0.02, dynamic range = 8192

Non-Turbulent IC: Early Evolution

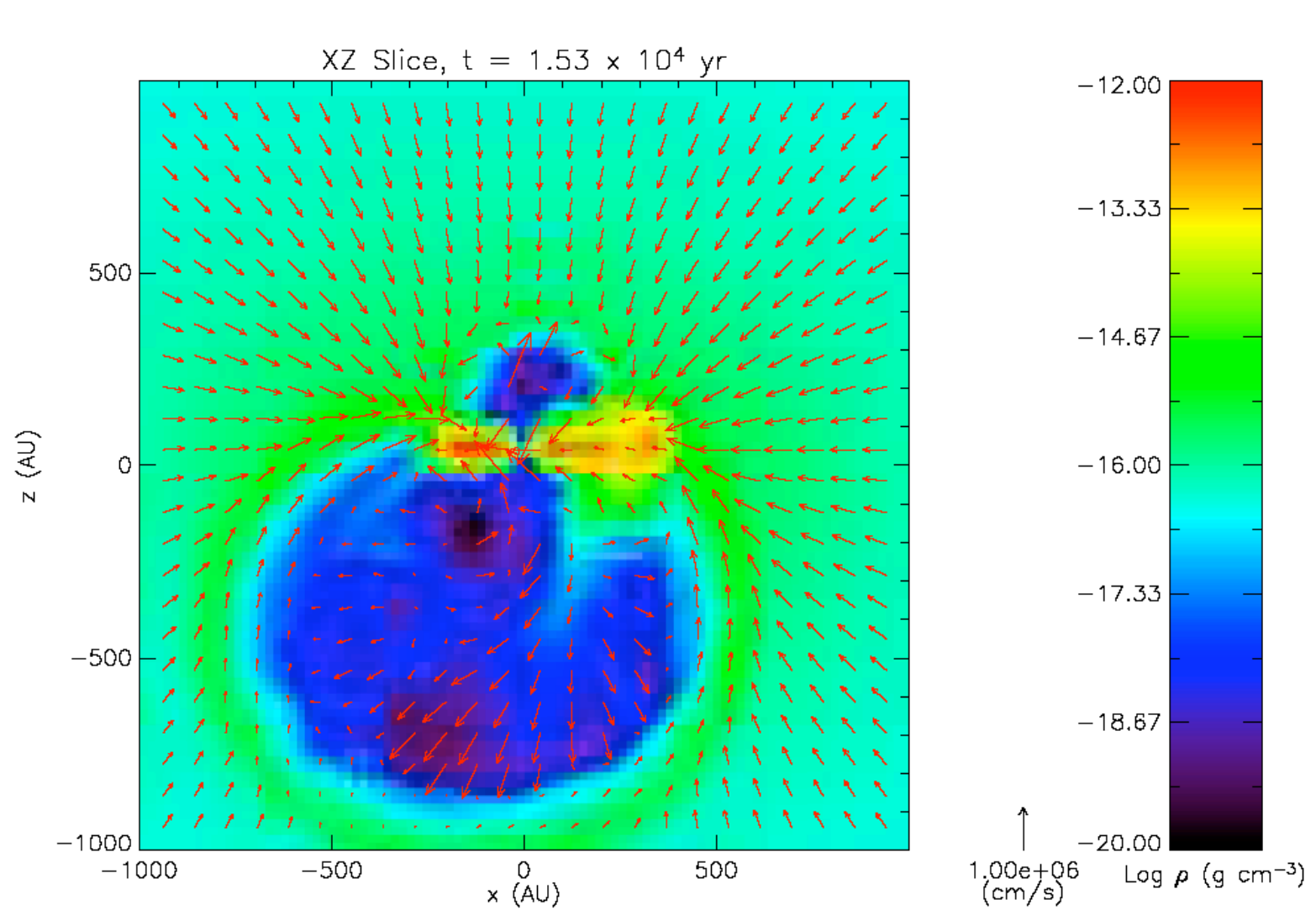


At early stages the star accretes steadily and a Keplerian disk forms. Cylindrical symmetry is maintained.

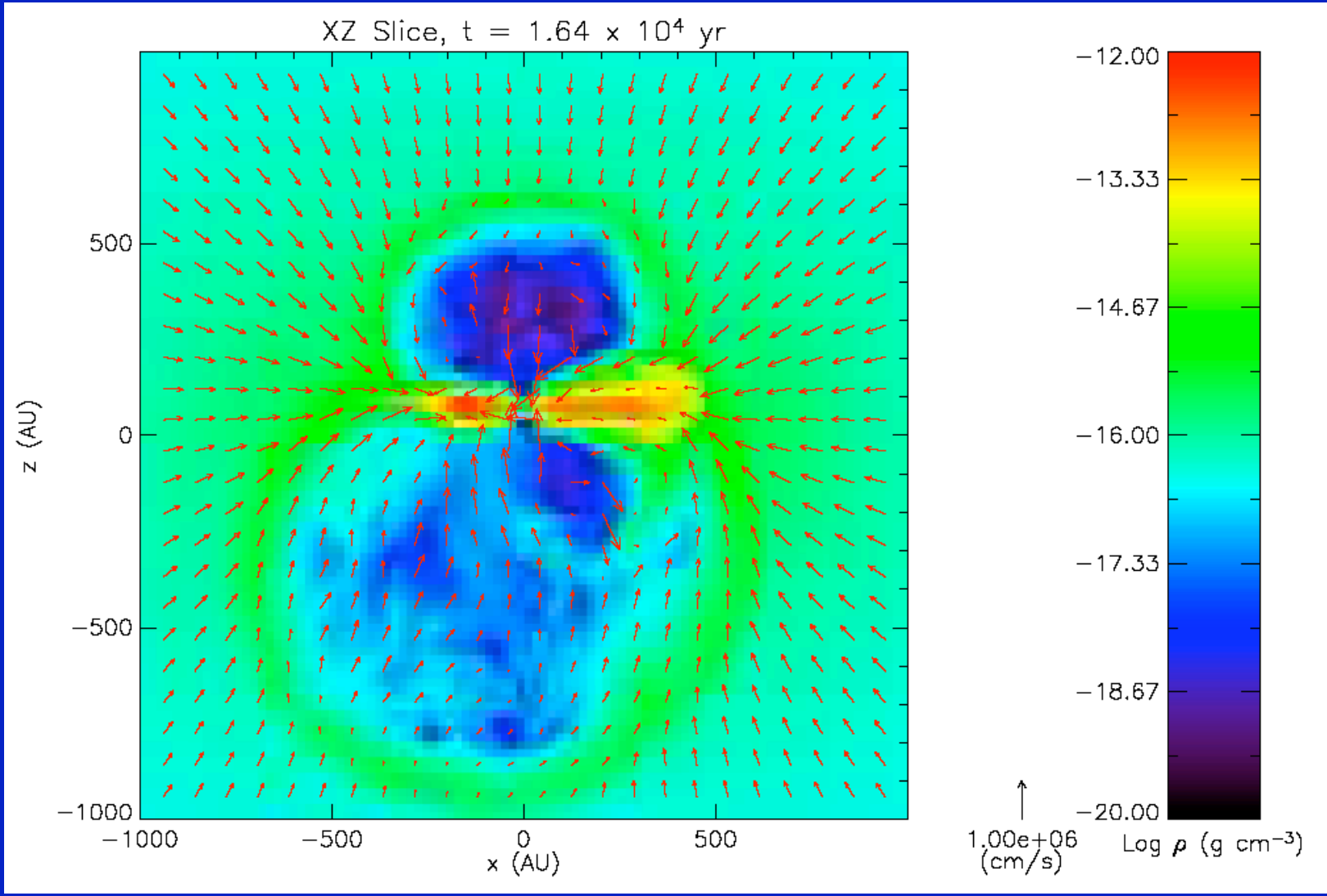
Expansion of Radiation Driven Bubble



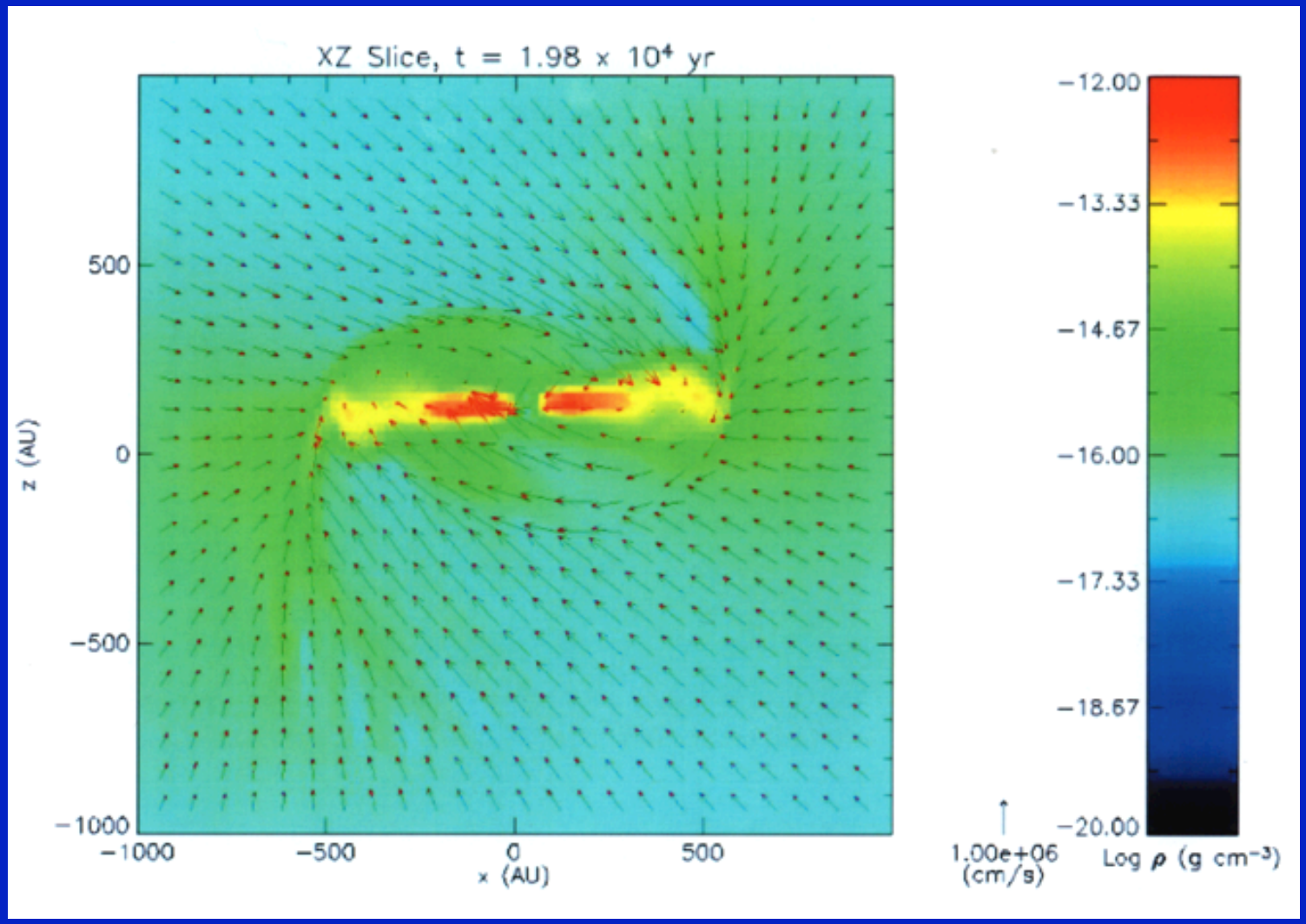
High Mass Disk and Formation of Expanding Radiation Driven Bubble



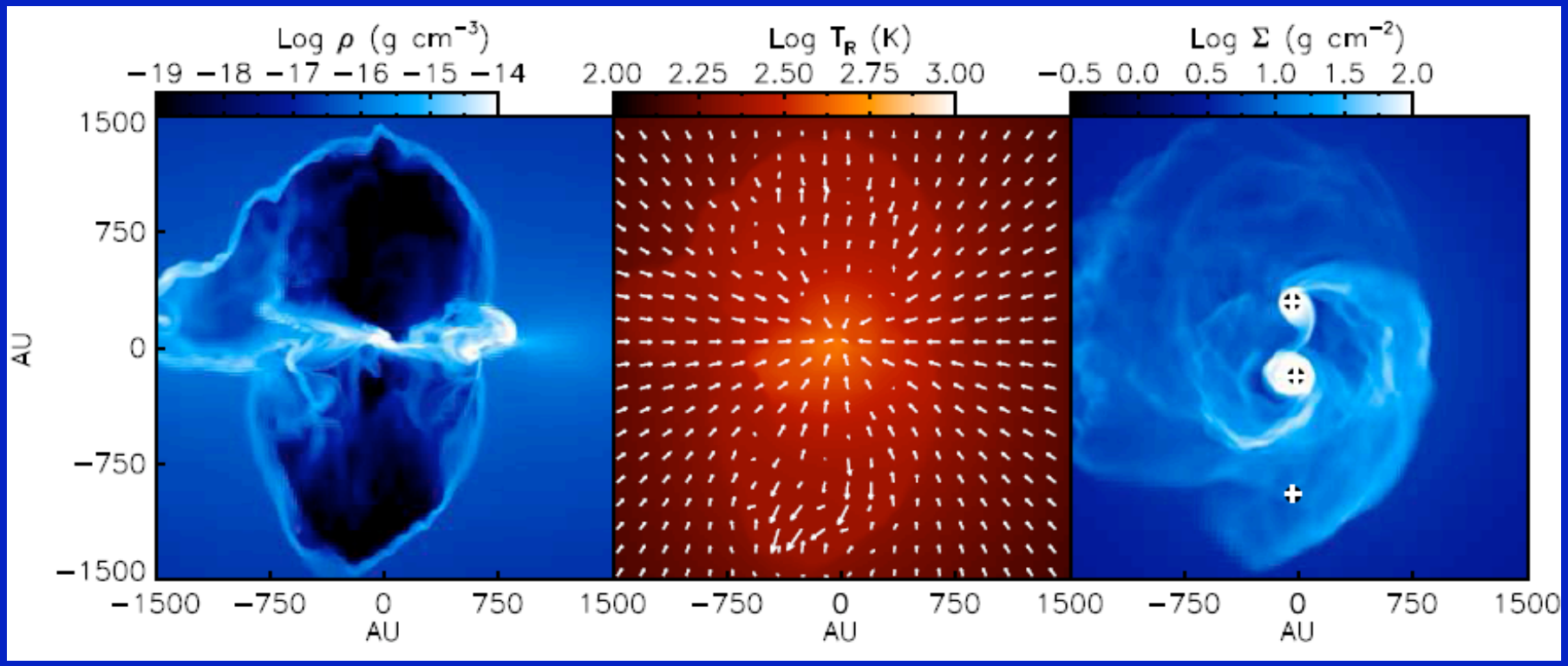
Rayleigh-Taylor Instability in Radiation Driven Bubble



Collapse of radiation driven bubble

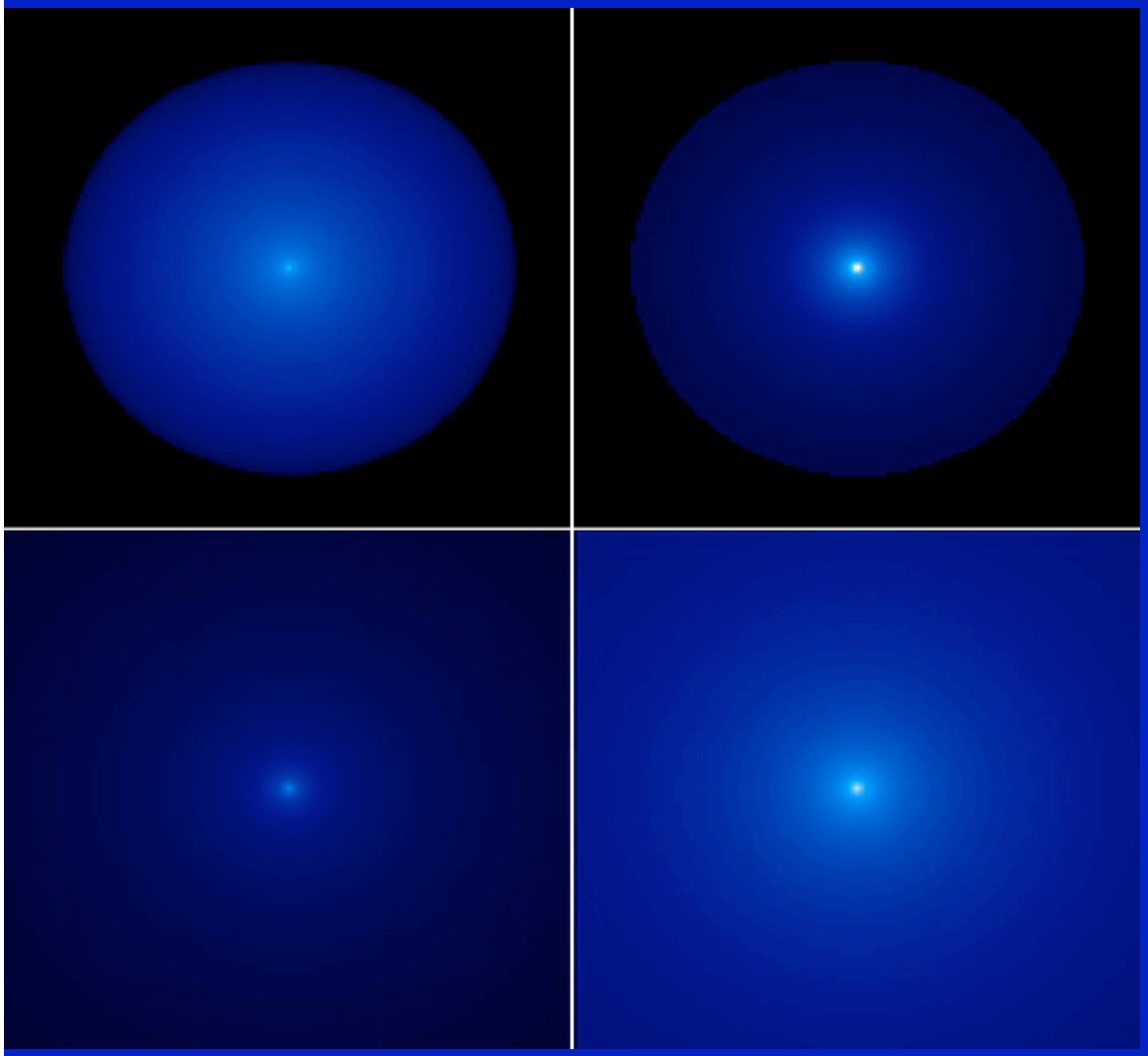


Formation of a Massive Binary (Krumholz, Klein, McKee, Offner and Cunningham Science, 2009)



- Gravitational instability in disk $\Rightarrow$ massive binary system 32 $M_\odot$ and 18$M_\odot$ and low mass star 0.1 $M_\odot$ at t= 44 Kyr
- Radiative feedback from massive binary results in highly asymmetric bubble formation

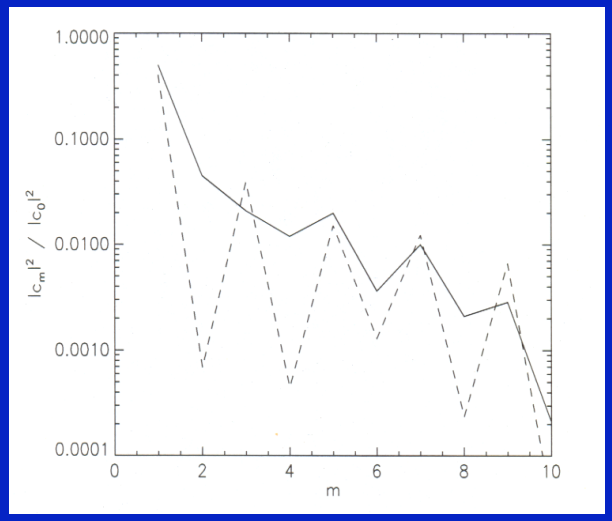
Formation of a Massive Binary System (Krumholz, Klein and McKee, Science, 2009)



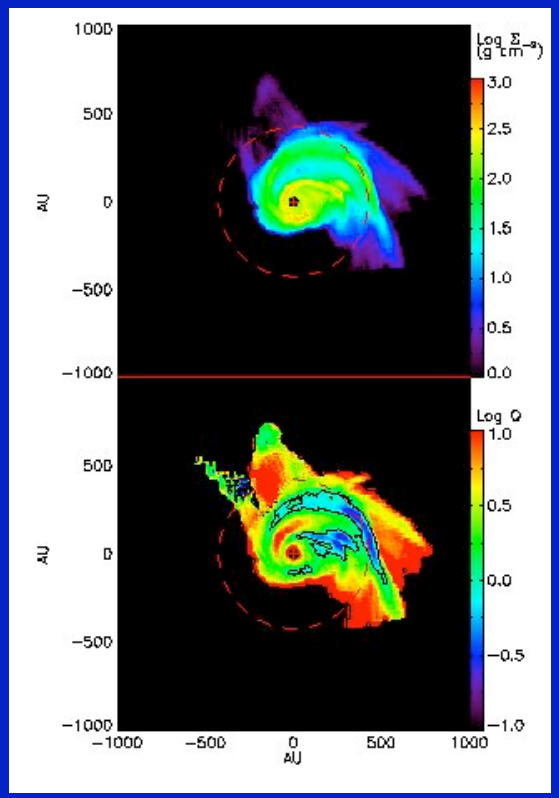
- Observations indicate most massive O-stars have one or more companions; binaries are common (> 59%) Gies 2008
- Massive protostellar disks are unstable to fragmentation at R≥ 150AU for $M_* \geq 4\ M_\odot$ (Kratter & Matzner 2006)
- Cores above ~ 20 $M_\odot$ will form a multiple through disk fragmentation. Higher mass systems form binaries earlier in their evolution (Kratter, Matzner and Krumholz 2008)
- Gravitational instability in disk ⇒ massive binary system

32 $M_\odot$ and 18 $M_\odot$ and low mass star 0.1 $M_\odot$

Angular Momentum Transport and Fragmentation properties of Massive Protostellar Disks (Krumholz, Klein, McKee 2007)

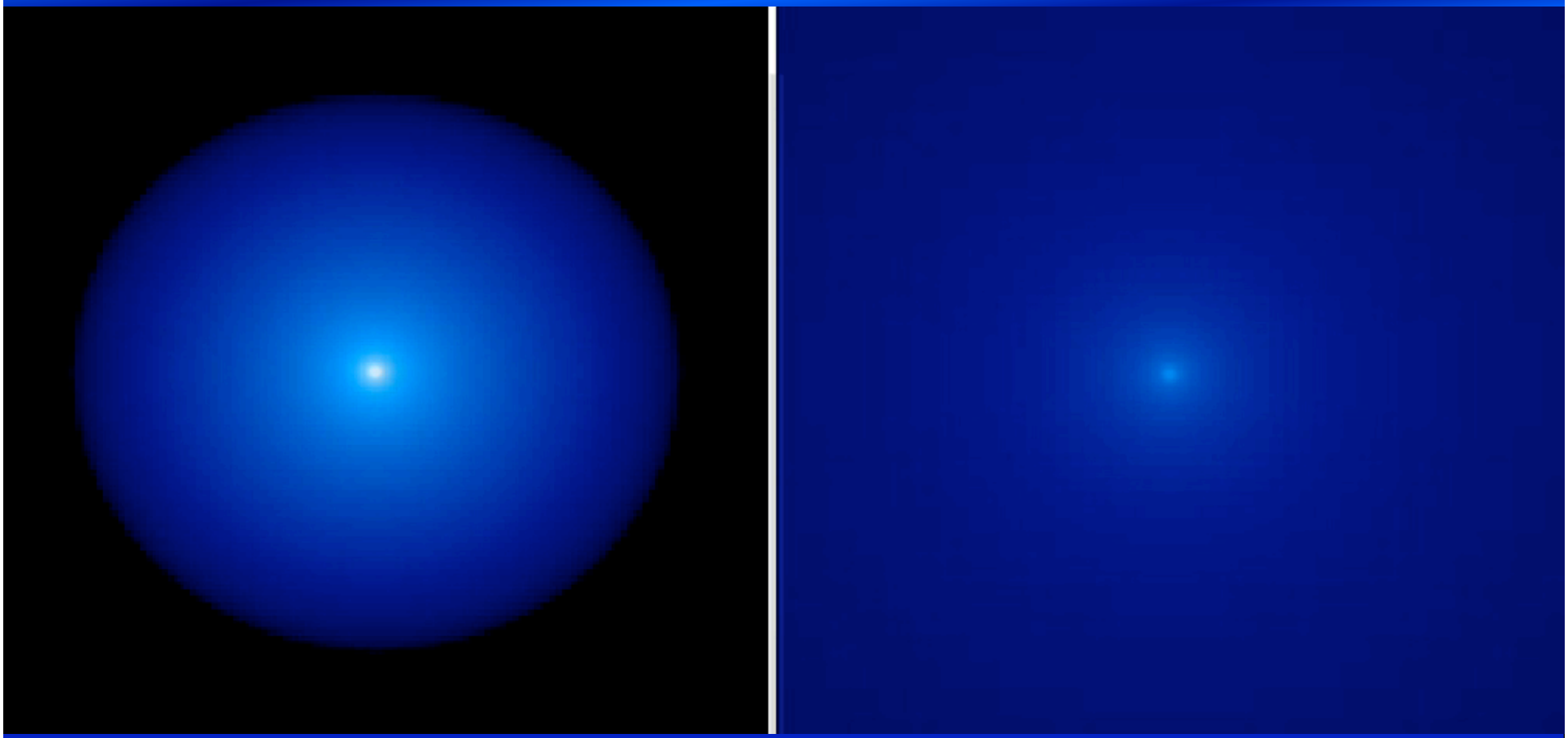


Normalized power $|c_m|^2/|c_0|^2$ in azimuthal mode *m* in the disk around the primary star at 17 kyr (*solid line*) and 20 kyr (*dashed line*)



- **Most of the power is in m=1 spiral mode ⇒ angular momentum transport and spiral arm formation in disk is primarily due to SLING instability which enables accretion on a disk dynamical time, rather than a viscous timescale ($\alpha \sim 1$)**
- **Angular momentum transport occurs via a global rather than a local instability**
- **Disk begins to fragment at 17 kyr as shown by calculation of Toomre $Q \approx \Omega c_s/\pi G\Sigma$**

Suppression of Small Scale Fragmentation in Massive Star Formation due to Radiative Feedback (KKM 2007)

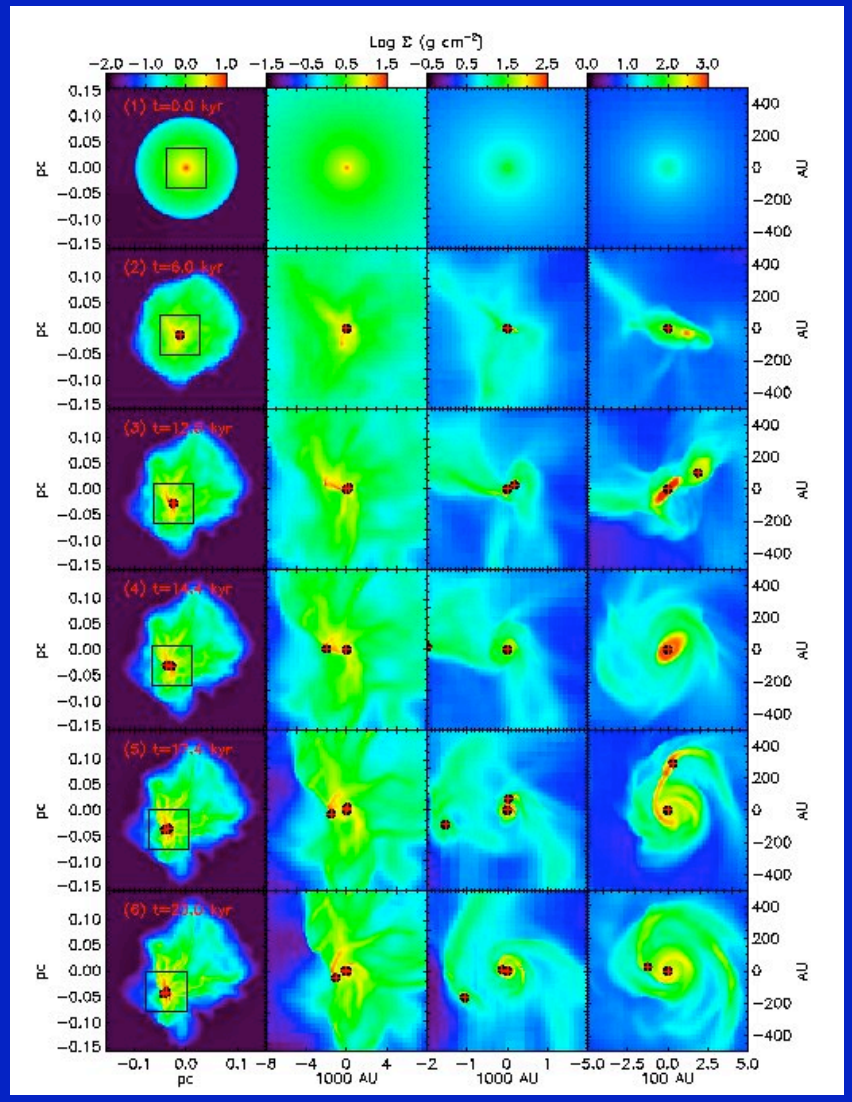


0.26 pc

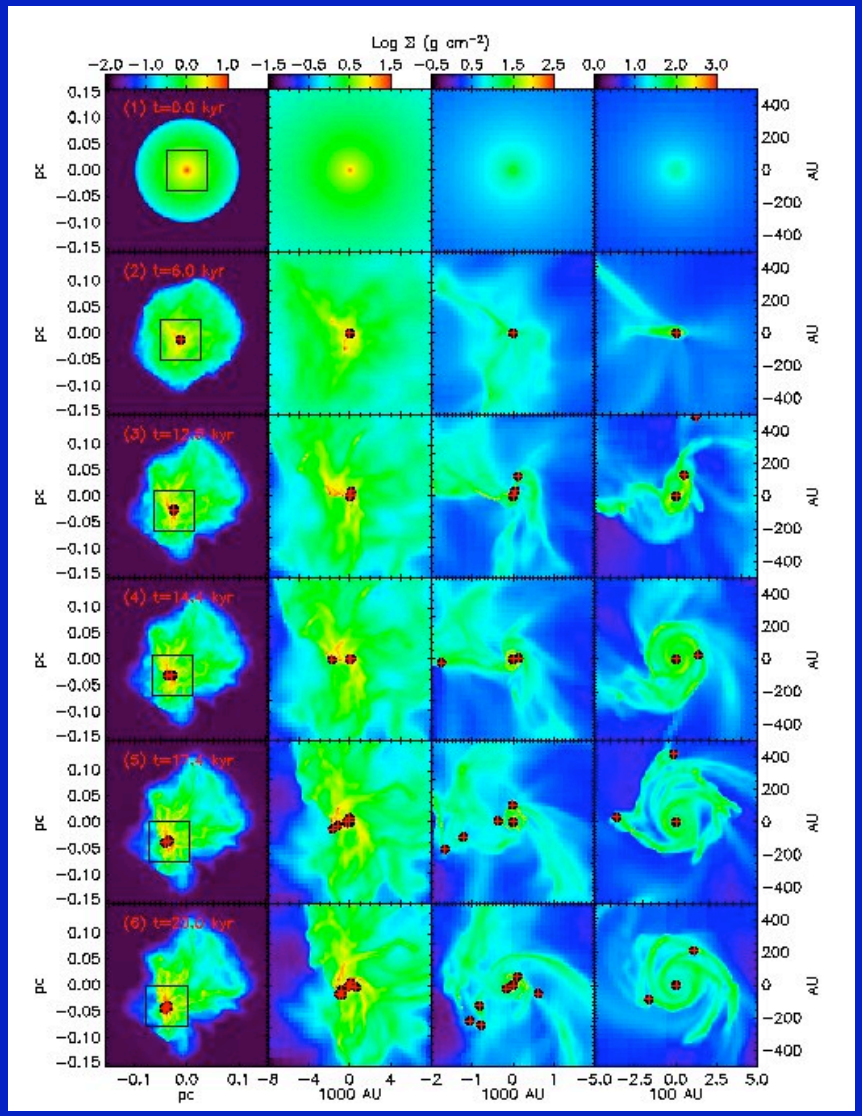
6700 AU

Most of the available mass in turbulent cloud goes into one massive star.

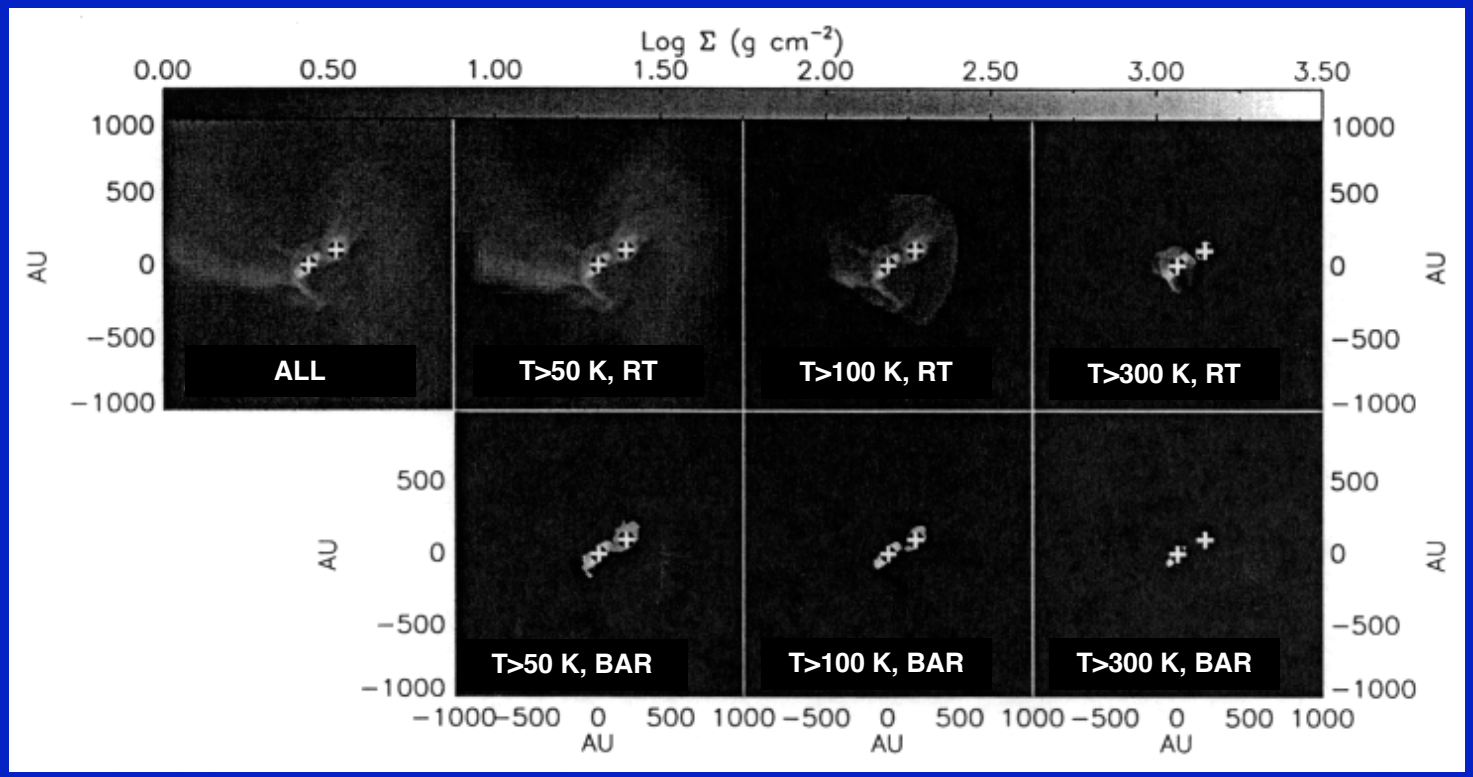
Evolution of 100 Solar Mass Turbulent Protostellar Core



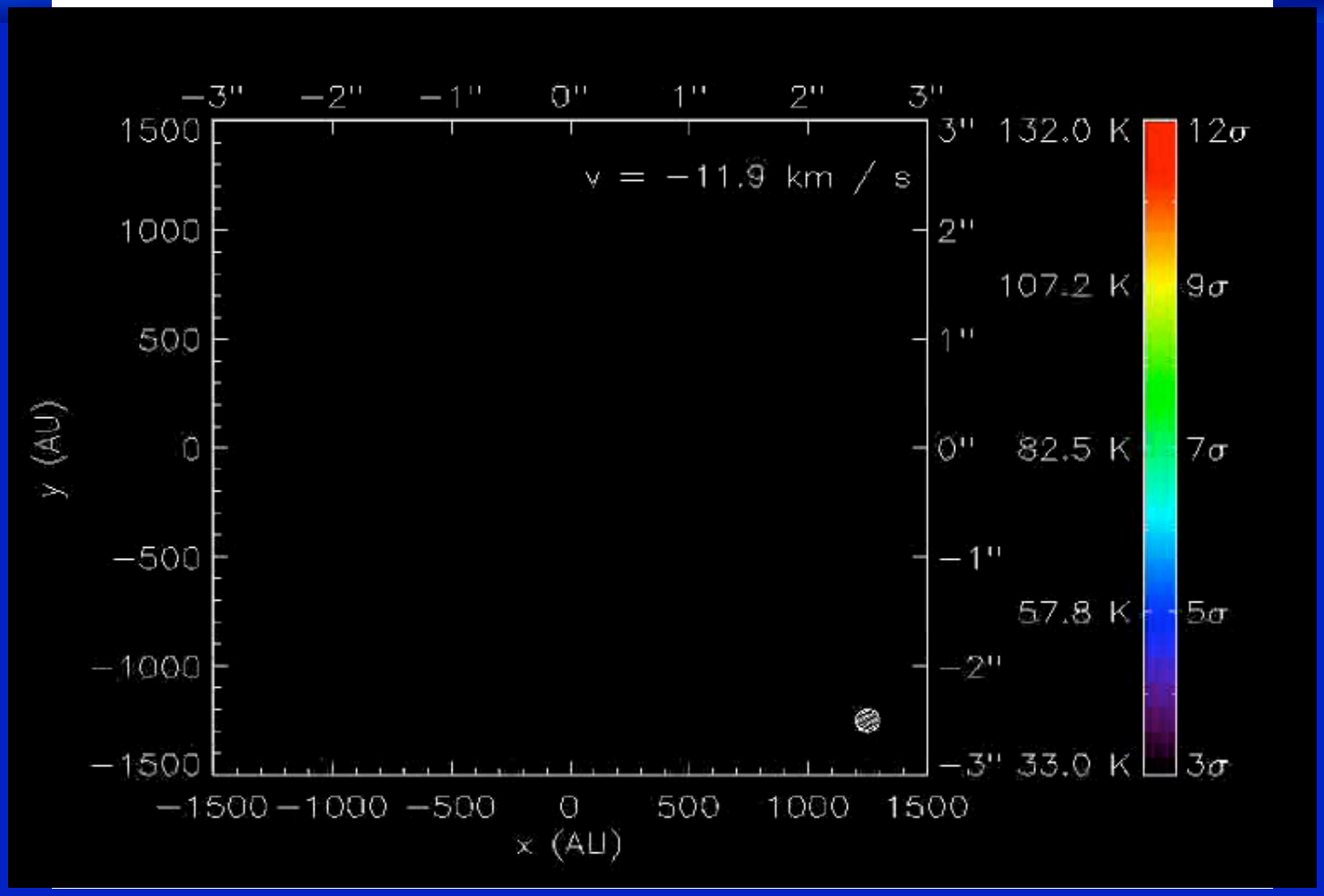
Evolution of 100 Solar Mass Turbulent Isothermal Protostellar Core



Temperature Distribution in 100 Solar Mass Core



Simulated Methyl Cyanide Emission Line ALMA Observation of High Mass Disk (Krumholz, Klein & McKee 2007c)

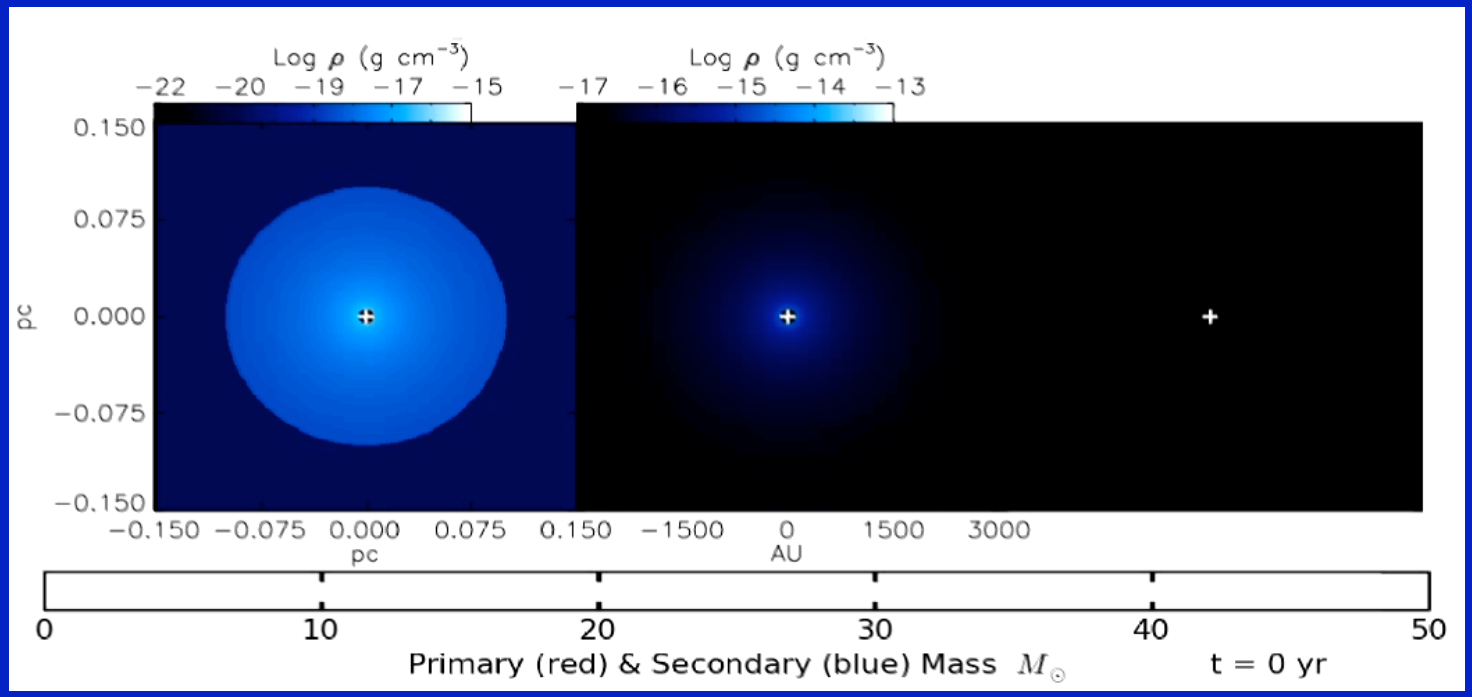


CH_3CN at 220.7472 GHz

Effects of Protostellar Outflows

- High mass protostars have outflows that look like larger versions of low mass protostellar outflows (Beuther et al. 2004)
- Outflows are launched inside star's dust destruction radius
- Due to high outflow velocities, there is no time for dust grains to regrow inside outflow cavities. Grains reach only ~$10^{-3}\mu$m by the time they escape the core.
- Because grains are small, outflow cavities are optically thin.
- Thin cavities can be very effective at collimating protostellar radiation, reducing the radiation pressure force in the equatorial plane
- Krumholz, McKee & Klein, (2005) using toy Monte-Carlo radiative transfer calculations find outflows cause a factor of 5 – 10 radiation pressure force reduction
- Outflows may be responsible for driving turbulence in clumps

HMSF with Protostellar Outflows: Late Time Evolution
t= 60 kyr (Cunningham, Klein, McKee and Krumholz 2009, ApJ in Prep)



- Wind properties characterized by $\dot{M}_w V_w = 0.3 \dot{M}_* V_k$ $V_w = f_w V_K$ $\dot{M}_w = f_m \dot{M}_*$
- Wind angular distribution $1/(r^2 \sin^2\theta + \chi)$

  52 $M_\odot$ accreted through disk to protostellar system; 30% ejected into outflow wind
  ⇒ reduction in radiation forces in disk results in protostar still building mass
- Final evolution results in a massive primary with 35 $M_\odot$ and a massive secondary with > 17 $M_\odot$ Each has a protostellar disk of 4.5 Msun and 2.9 Msun respectively

Radiative Feedback in Low Mass Star Formation (Offner, Klein, McKee, Krumholz ApJ 2009)

- To assess effects of radiation on the formation of low mass stars we perform comparative simulations with RT including radiative transfer and feedback from stellar sources and simulations with an EOS to describe thermal evolution of the gas
- Initial conditions: 3D turbulent cloud with $\mathcal{M} = 6.6$ and $\alpha \approx 1$

  $T_i = 10K$; $L = 0.65$ pc; $\langle\rho\rangle = 4.46 \times 10^{-20}$ g cm^{-3}; $M_{total} = 185\ M_\odot$

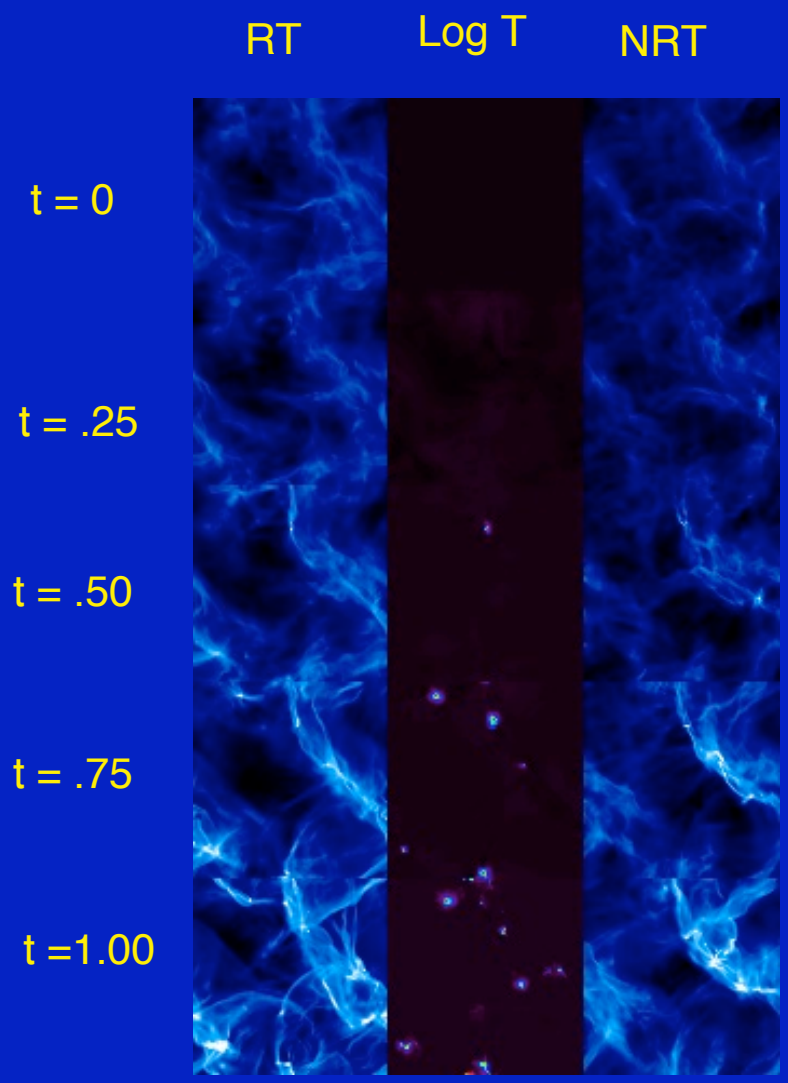
  Velocity perturbations initially applied corresponding to a Gaussian random field with flat power spectrum in range $1 \leq k \leq 2$

  after 3 cloud crossing times this follows $P(k) \propto k^{-2}$ Burgers power spectrum
- Turbulence continues to be driven with constant energy injection rate for one global free fall time ~ 0.315 Myr

  Calculations performed with 2 resolutions and multiple levels of grid refinement (AMR):

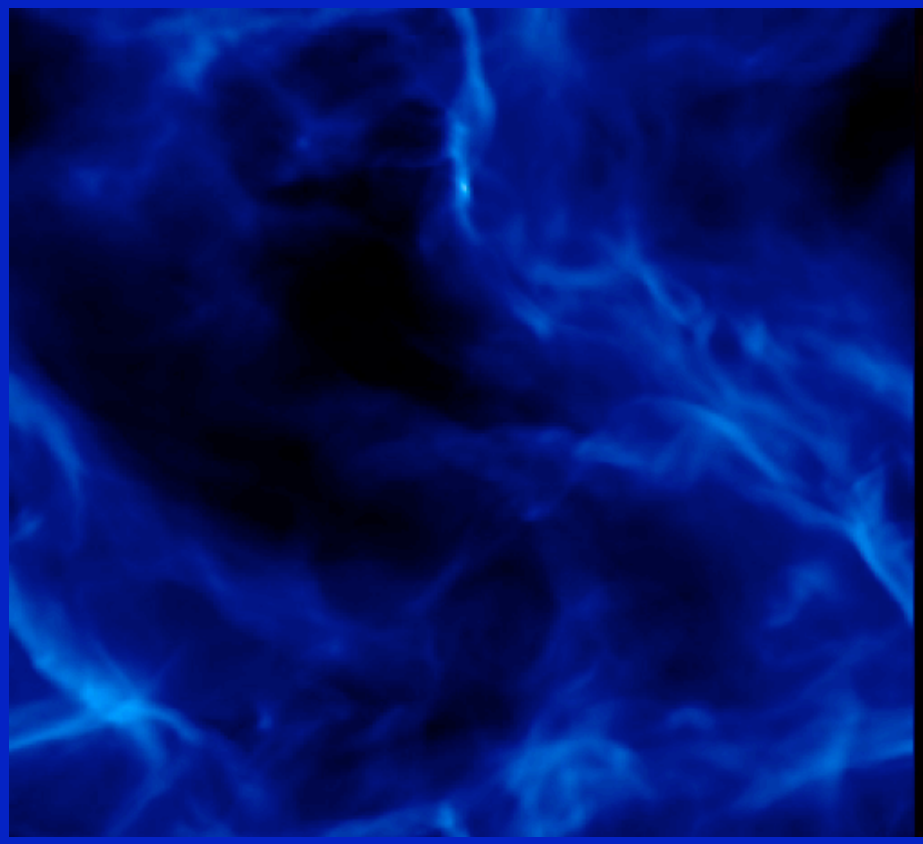
  effective resolution 4096^3 where $\Delta x = 32$ AU and $65{,}536^3$ with $\Delta x = 4$ AU

Log gas column density of radiative transfer and EOS simulations of Turbulent Cloud at different times



- Column density from $10^{-1.5}$ - $10^{0.5}$
- T = 10 - 50K variation in cloud
- Star formation commences at t~ .50 t_{ff}
- Radiation pressure effects not significant anywhere in cloud since advection of radiation enthalpy is small compared to rate of radiation diffusion

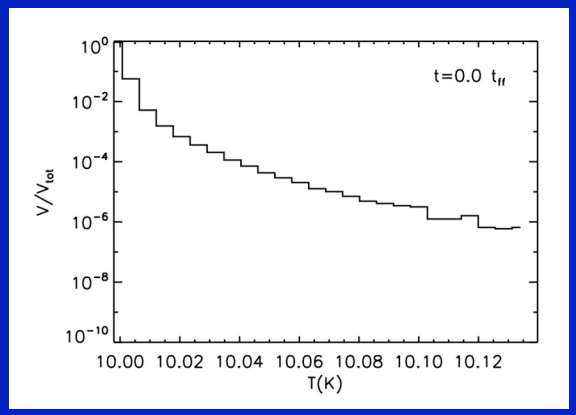
Cluster Formation in Driven Turbulent Cloud with Radiation Feedback

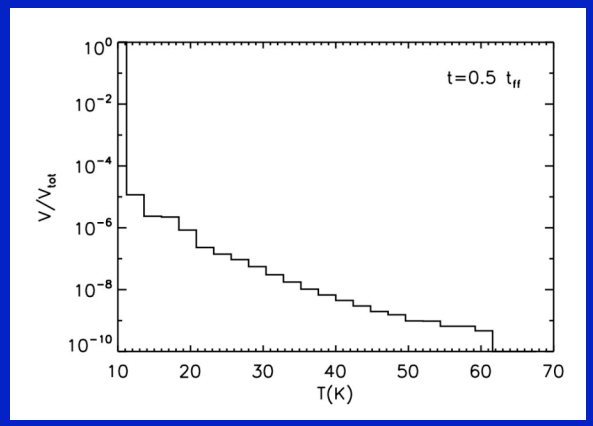


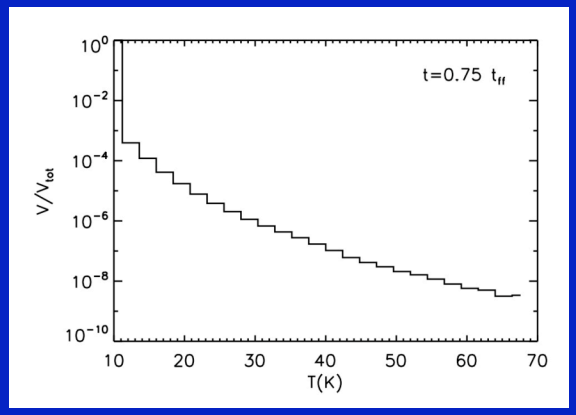
Column density

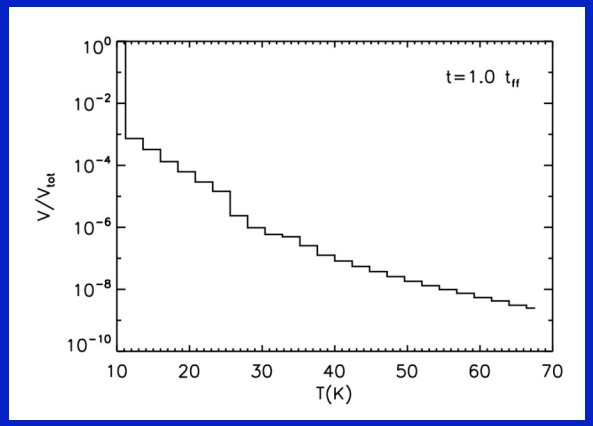
Density weighted temperature

Evolution of Gas Temperature Distribution



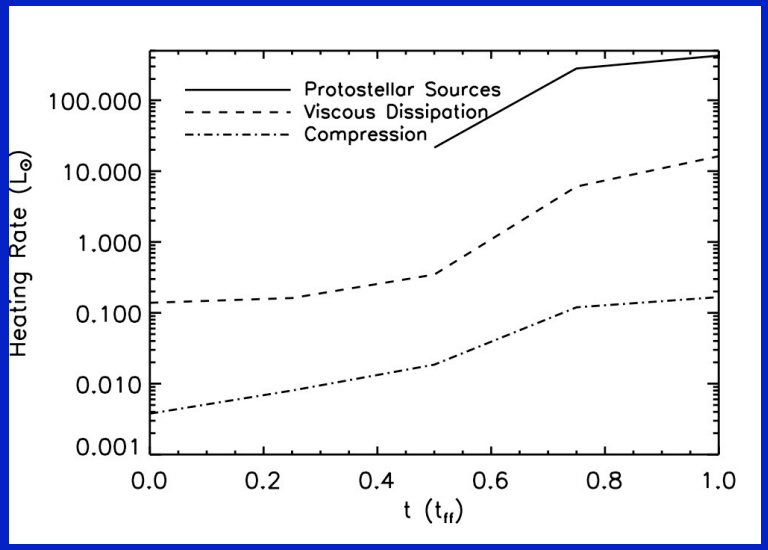






- 3 processes contribute to the heating: direct contribution from protostars;
- heating due to viscous dissipation
- net heating due to gas compression during collapse
- Heating is local and remains within ~0.05pc of protostars ⇒small volume filling fraction

Heating Rate due to Protostellar Sources, Viscous Dissipation and Compresion



- At t = 0 only source of heating is due to turbulent motions
- Viscous dissipation dominates heating prior to star formation
- After star formation commences protostellar output and accretion luminosity rather than compression and viscous diss. Is responsible for majority of radiative feedback

At $t \sim 1\ t_{ff}$ $H_{proto} > 10\ H_{visc}$; $H_{proto} \sim 10^4\ H_{comp}$

Accretion Luminosity Significant at Stellar Surface

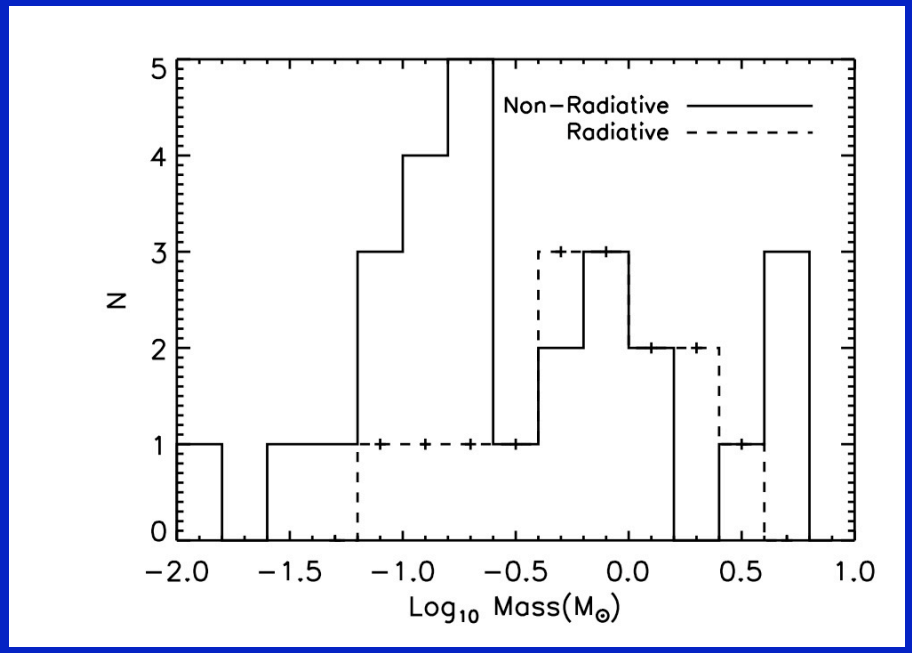
A low resolution simulation when not taking into account accretion luminosity predominantly emitted at R_* can significantly neglect a large component of the heating such as Bate 2009

→ If simulation has minimum resolution $R_{res} = 0.5$ AU and the accretion luminosity is emitted at $R_* = 5\ R_\odot$

$\Delta L \cong 20\ GMM_{dot} / R_{res}$ ⇒ Low resolution underestimates the luminosity by factor of 20 ⇒ ~ 2 underestimation of temperature

⇒ overestimation of small scale fragmentation and Brown Dwarf production

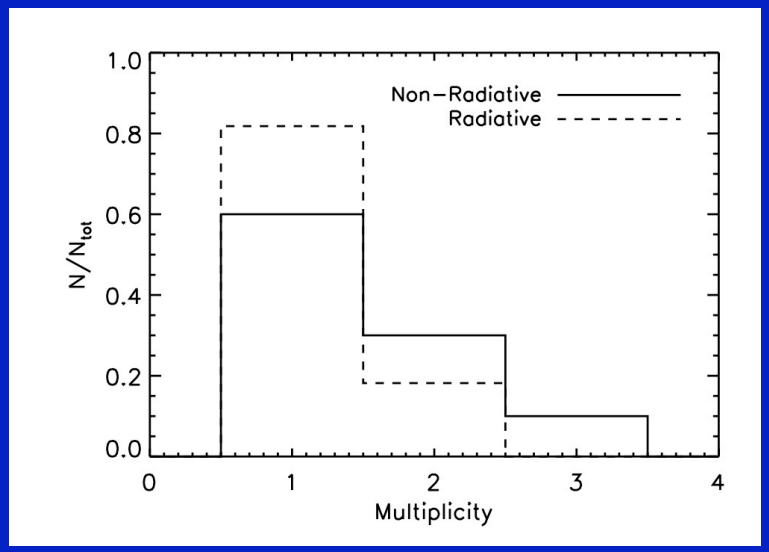
Stellar Mass Distribution of Star-disk System at $1t_{ff}$



- Large temperature range in the RT simulation has profound effect on stellar mass distribution
- Increased thermal support in protostellar disk acts to suppress disk instability and secondary fragmentation In the core
- Protostellar disks in the NRT simulation suffer high rates of fragmentation

  ⇒ SFR (RT) = 7% ~ .5 SFR (NRT) good agreement with Krumholz, Tan 2007 Observational SFR 3-6%

Initial Stellar System Multiplicity



- In RT simulations majority of stars formed are single stars
- In NRT majority of stars live in systems with 2 or more stars

⇒ Mainly due to continued disk fragmentation

Summary and Future Directions

High Mass Star Formation

- 3-D high resolution AMR simulations with ORION achieves protostellar masses considerably above previous 2-D axisymmetric gray simulations
- Two new mechanisms have been shown to overcome radiation pressure barrier to achieve high mass star formation ⇒ high mass binary system
  - 3-D Rayleigh-Taylor instabilities in radiation driven bubbles appear to be important in allowing accretion onto protostellar core
  - Protostellar outflows resulting in optically thin cavities promote focusing o f radiation and reduction of radiation pressure → enhances accretion
  - Radiation feedback from accreting protostars inhibits fragmentation (KKM 2007)
- ALMA observations will help distinguish between competing models of high mass star formation → gravitational core collapse predicts large scale disks

Low Mass Star Formation

- Inclusion of RT has a profound effect on temperature distribution, accretion and final stellar masses
- Heating by RT stabilizes protostellar disks and suppresses sm scale frag
- Vast majority of heating from protostellar Rad. Not comp or visc. dissipation
- For low mass SF, heating is local so, no inhibition of Turb. Frag. elsewhere

Future Directions

- Multi-frequency radiation-hydrodynamics: implemented
- Inclusion of MHD effects (CT AMR) in progress
- Improvement in flux limited diffusion $\Rightarrow$ Sn transport: future
- Self consistent evolution of high mass turbulent cores from large scale massive turbulent cloud in progress
- Scalability of fully coupled AMR self-gravitational magneto-radiation-hydrodynamics to 10s of thousands of processor cores to study full feedback in Giant Molecular Clouds : future
- $\Rightarrow$ Petascale capability: future