The Feedback Effects of Radiation and Protostellar Outflows on 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

$\Rightarrow$ ORION: AMR Magneto-Rad-Hydro; self-gravity,sink particles, stellar evolutionary models, 2nd order Godunov, multi-grid solves

Radiation transport formulated in mixed frame to order v/c in all regimes (static diffusion, dynamic diffusion, free streaming)

Theoretical Challenges of High Mass Star Formation

1. Effects of Strong Radiation Pressure and Radiative Heating

– Massive stars M ≥ 20 $M_\odot$ have $t_K < t_{form}$ (Shu et al. 1987) and begin nuclear burning during accretion phase

Radiates enormous energy

For M ≥ 100 $M_\odot$

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

however σ >> σ

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

But, observations show M ~ 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?

Do radiation pressure and radiation heating provide a natural limit to the formation of high mass stars?

Theoretical Challenges of High Mass Star Formation (cont.)

2. Effects of Protostellar outflows

- Contemporary 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)

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)

Fundamental Problem: 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?

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 $R \geq 150$AU for $M_* \geq 4\ M_\odot$ (Kratter & Matzner 2006)
- Radiation driven Rayleigh-Taylor instability breaks Eddington Barrier(KKM ‘05, ‘09)
- Gravitational instability in disk $\Rightarrow$ massive binary system

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

- Radiative feedback from massive binary results in highly asymmetric bubble formation and radiative heating supressing small scale frag.

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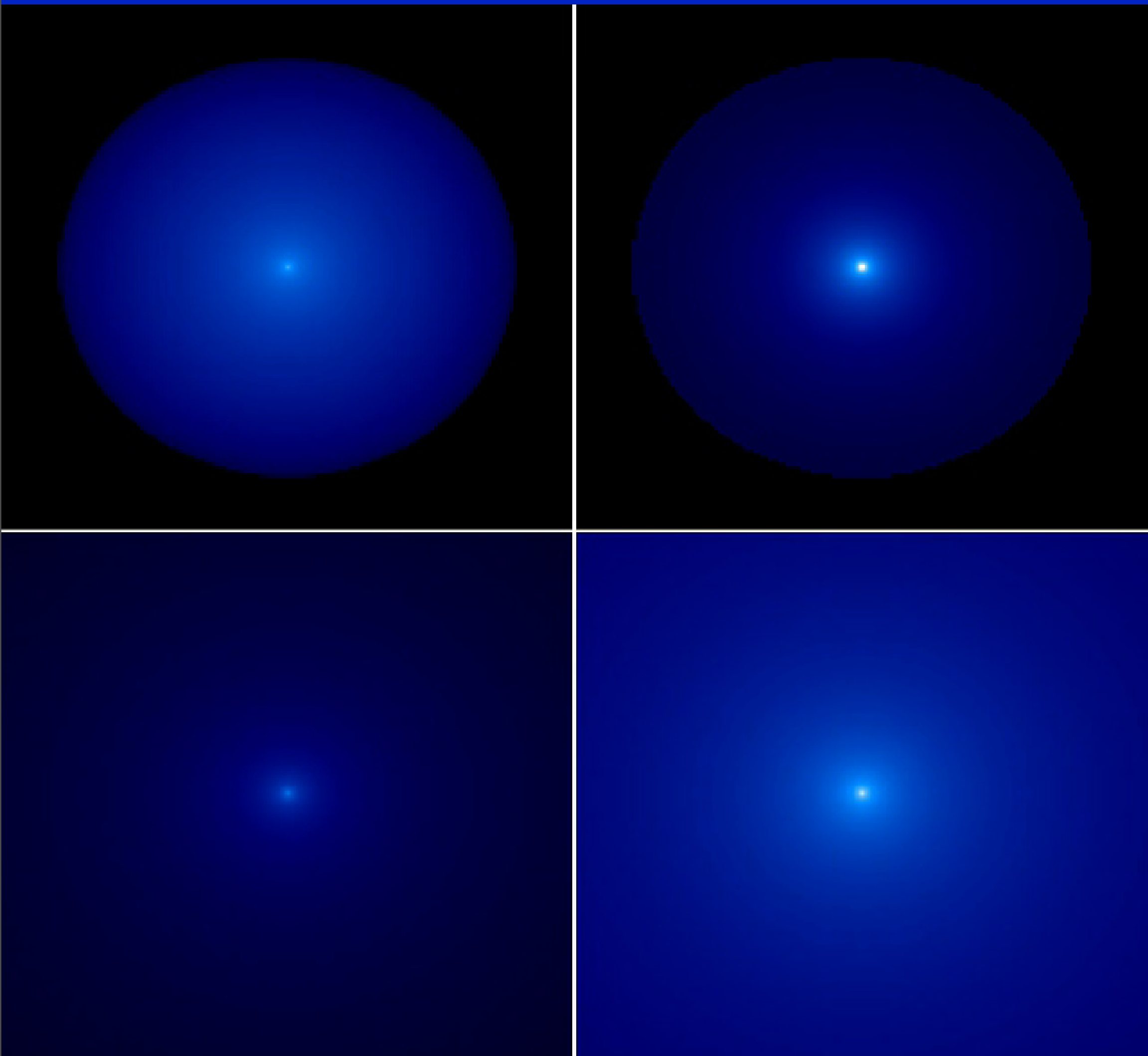

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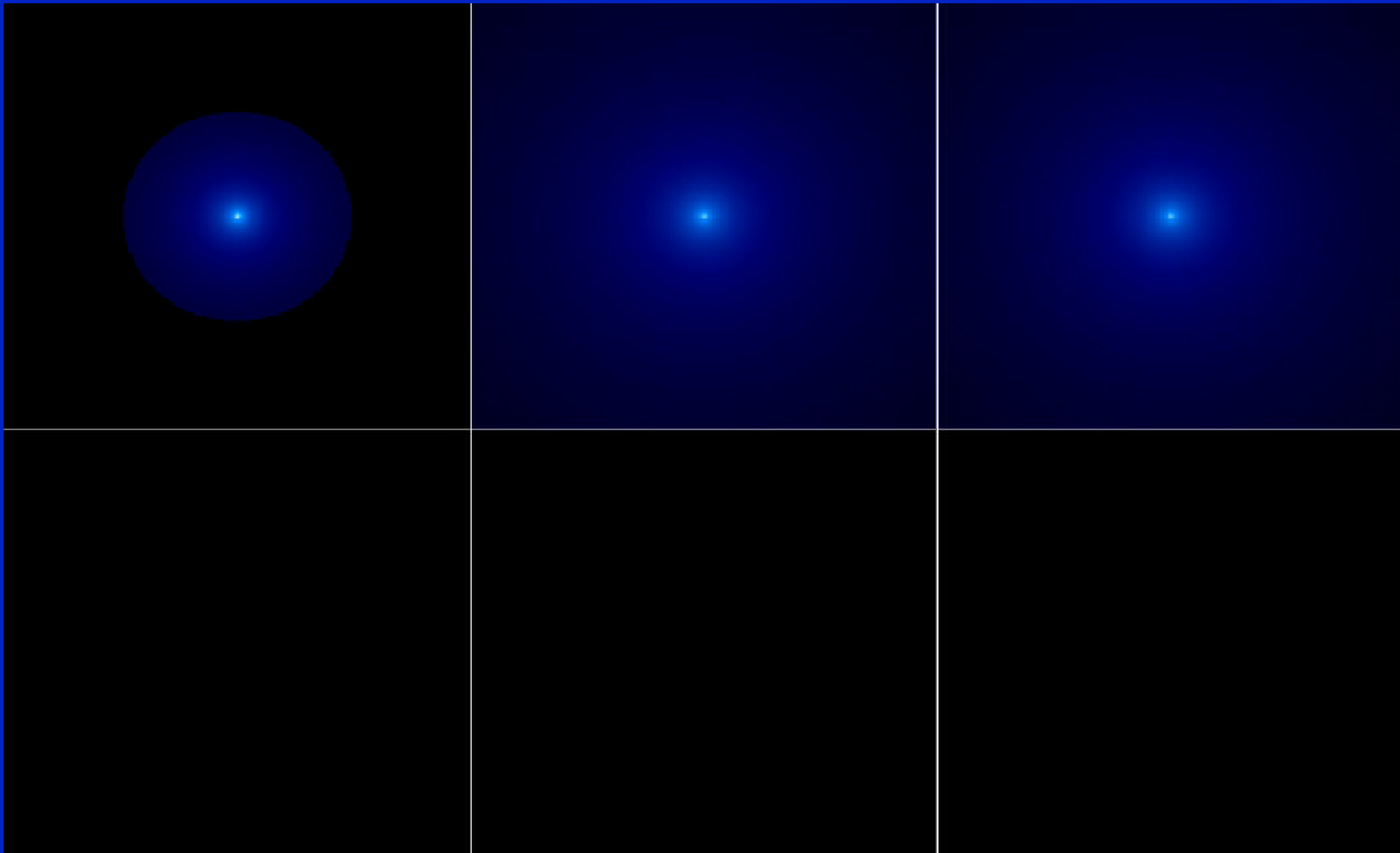
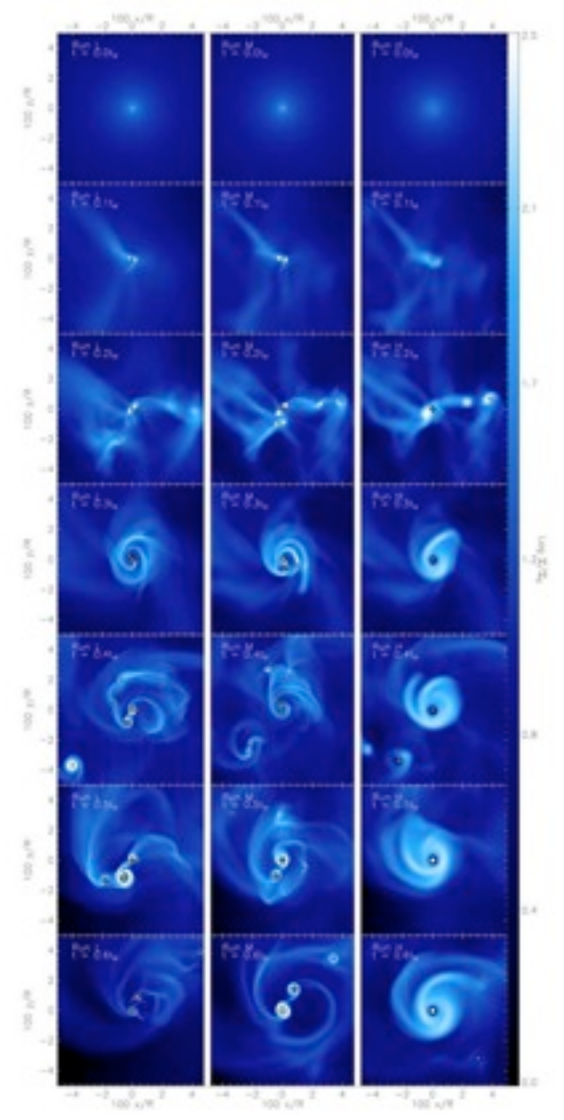


Radiation Feedback, Fragmentation and Environmental Dependence of the IMF (Krumholz,Cunningham, Klein & McKee ApJ, 2010)

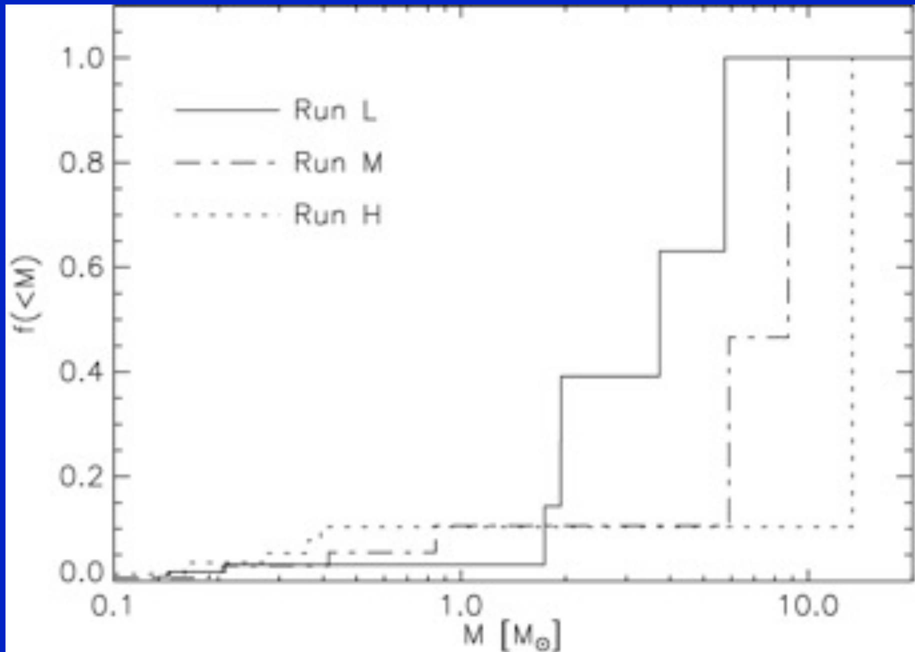


- Column densities L= 0.1, M=1.0, H=10.0 g cm^{-2} (Diffuse clouds such as Taurus, Perseus and Ophiuchus; typical galactic massive star forming regions; extra-galactic super star clusters)
- Surface density determines effectiveness of trapping radiation and accretion luminosities of forming stars (Krumholz, McKee 2008)
- As surface density increases, the suppression of fragmentation increases ⇒ (L) small cluster, no massive stars, depleted disks; (M) massive binary with 2 circumstellar disks and large circumbinary disk; (H) single large disk with single massive star

⇒Higher surface density environments produce higher accretion rates and thus higher accretion luminosities from embedded protostars.
Higher Σ environments lead to higher optical depths which trap resulting radiation more effectively

Cumulative Distribution Function of Stellar Mass t= 0.6 t_{ff}

(Krumholz, Cunningham, Klein & McKee ApJ 2010)



- **(L) system consists of several low mass stars of roughly comparable mass; (M) most of mass in 2 stars forming binary; (H) comparable fraction of mass in single massive star**

⇒ **Stellar IMF need not be universal between regions of low surface density ($\Sigma \ll 1$ g cm^{-2}) and those of high surface density ($\Sigma \gg 1$ g cm^{-2})**

Feedback 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 2010, ApJ in Prep)

52 $M_\odot$ accreted through disk to protostellar system; 30% ejected into outflow wind
$\Rightarrow$ 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 $M_\odot$ and 2.9 $M_\odot$ respectively

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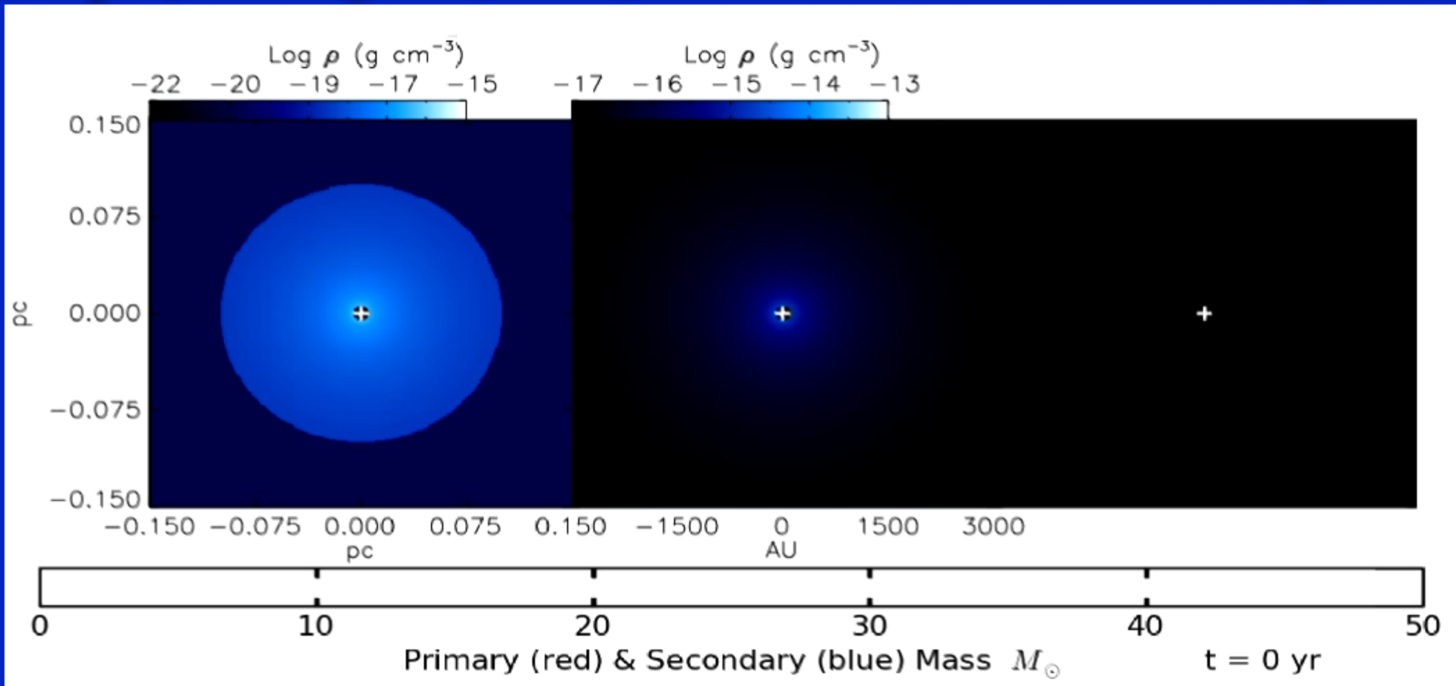

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HMSF with Protostellar Outflows in Turbulent Core:

(Cunningham, Klein, McKee and Krumholz 2010, ApJ in Prep)

- M_{core} = 300 $M_\odot$; T_i = 20K; $\sum$ = 2 g cm^{-2} ; R_{core} = 0.1pc; $\mathcal{M}_{turb}$ = 13.5; $<\rho>$ = 4.84x10^{-18} g cm^{-3}
- Early evolution t= 12.8 Kyr results in a massive primary with 13.5 $M_\odot$ and a secondary with 2.3 $M_\odot$ forming in a highly asymmetric turbulent disk
- Outflow has large dynamical affect in sweeping out wide region of turbulent core as wind becomes entrained in turbulent filaments

$\Longrightarrow$ Outflow cools core relieving radiation pressure resulting in formation of high mass

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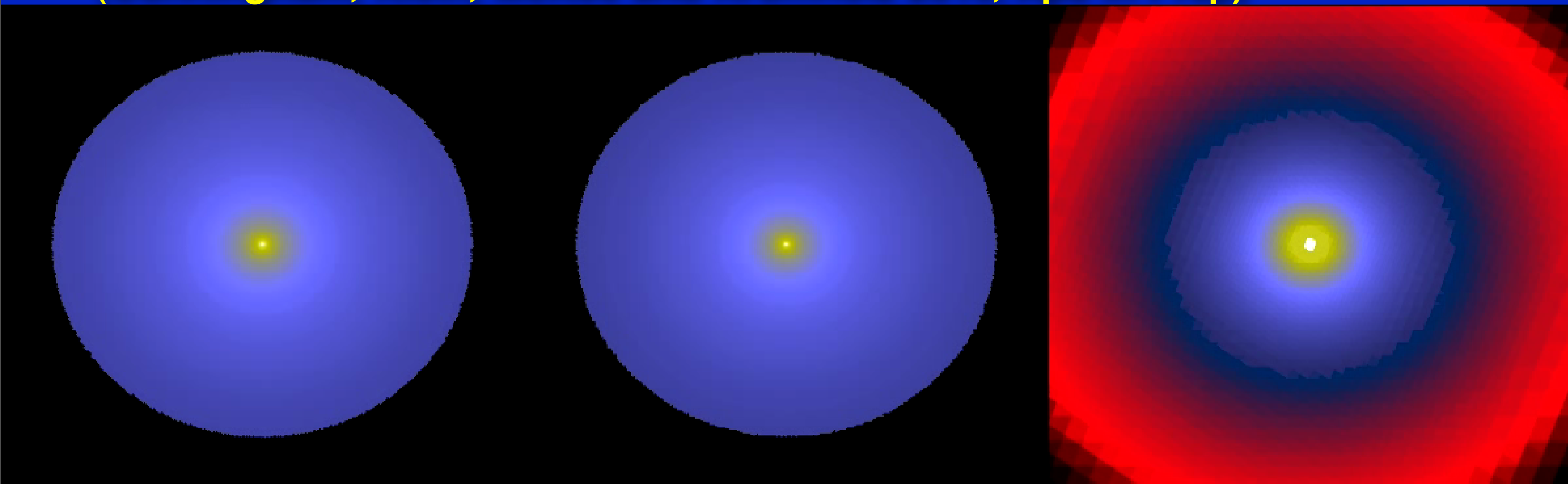

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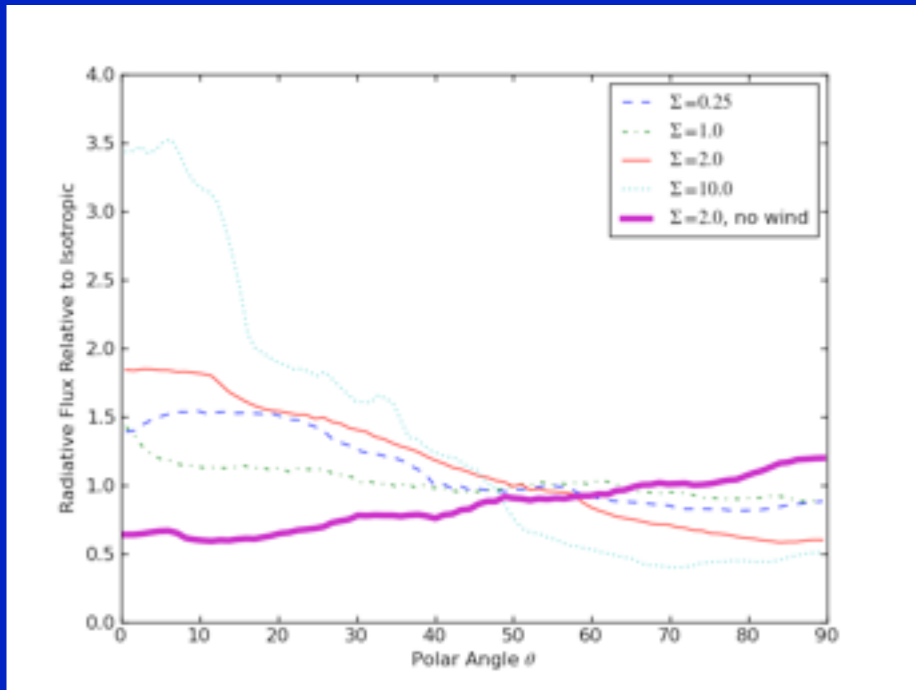
Environmental Effects on Radiation Beaming in HMSF with Protostellar Outflows in a Turbulent Core



- Radiation beaming is most collimated for Σ = 10 g cm^{-2} where cavity is well confined $\Longrightarrow$ pole to equator contrast ≈ 7 (consistent with KKM 2005)
- For less dense cores, beaming effect is diminished.
- Flashlight effect is destroyed as core becomes more depleted by strong dynamical effects of winds in low density environments

Cluster Formation in Driven Turbulent Cloud with Radiation Feedback show Local Environs Affected within 0.05 pc (Offner, Klein, McKee, Krumholz ApJ '09)

Column density

Density weighted temperature

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

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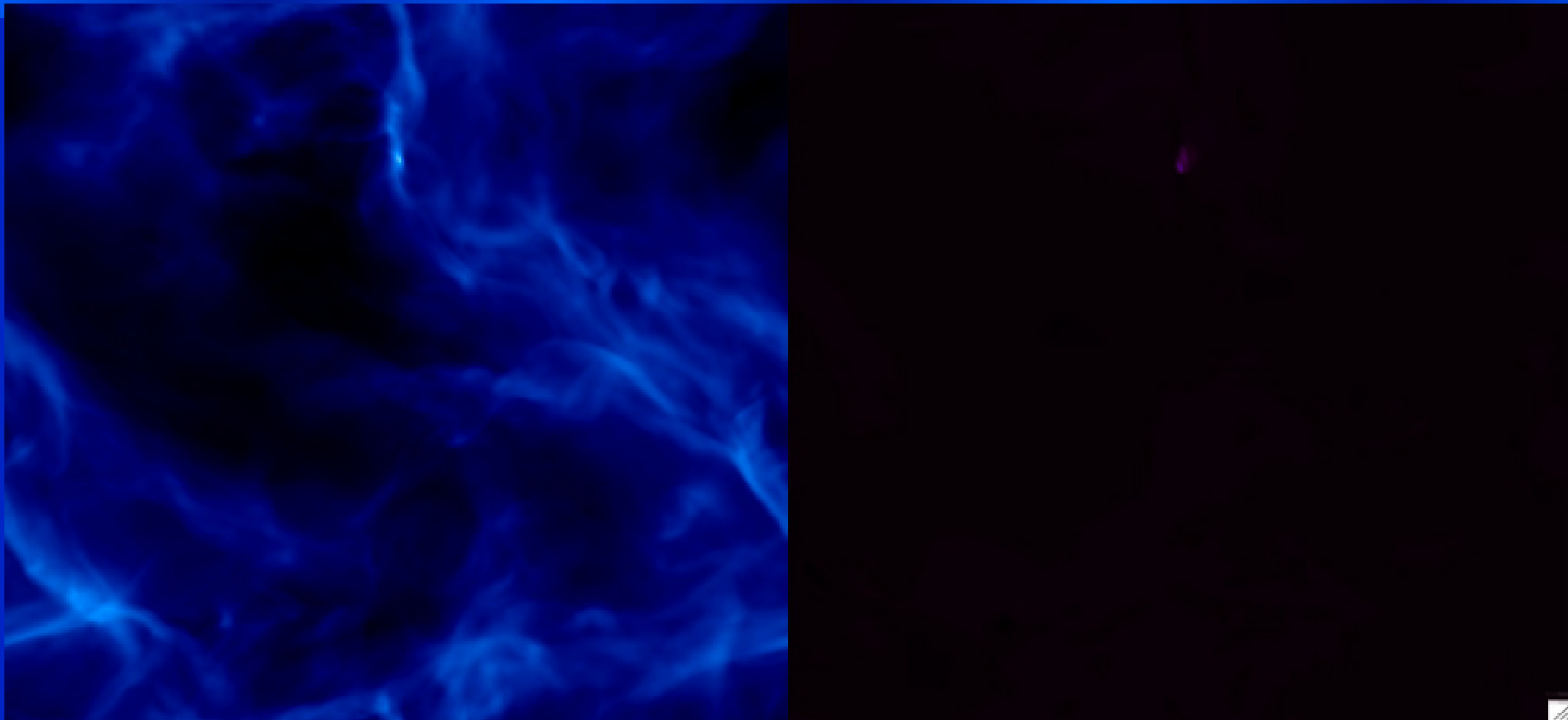

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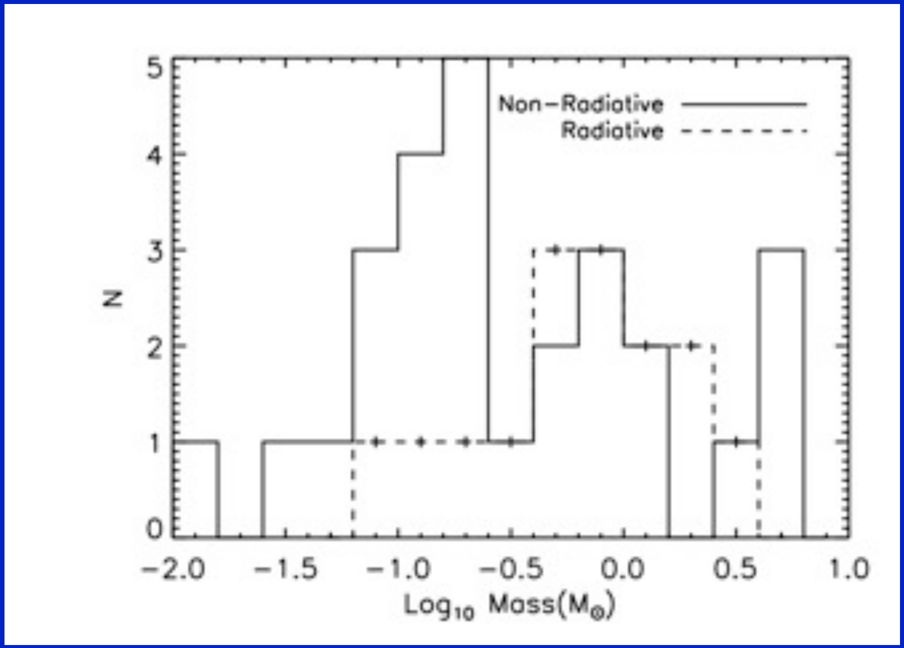
Stellar Mass Distribution of Star-disk System at $1t_{ff}$



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

  ⇒ SFR_{ff} (NRT) = 13% SFR_{ff} (RT) = 7%   good agreement observations (Krumholz and Tan 2007)

Low Mass Cluster Formation with Radiation and Protostellar Outflow Feedback (Hansen, Klein, McKee 2010)

- Winds interacting with filaments lead to enhanced star formation
- Lower mass stars form due to enhanced fragmentation and outflow loss results in lower luminosities and lower heating

$\Rightarrow$ less thermal support so higher fragmentation

$\Rightarrow \langle L \rangle = 6.5\ L_\odot$; Lmed = $1.7\ L_\odot$

Obser. $\langle L \rangle \sim 5.3\ L_\odot$; Lmed $\sim 1.5\ L_\odot$

C2D sample Dunham, Evans 2010

- If a weak wind shock interacts with an already fragmenting filament, it will lead to more fragmentation
- If it interacts with a marginally gravitationally bound filament, it can initiate collapse
- If it interacts with a low density filament, the extra compression can eventually lead to more fragmentation when that filament finally does collapse
- If a strong shock hits a filament, it can move a mass of gas away and then that can collapse.

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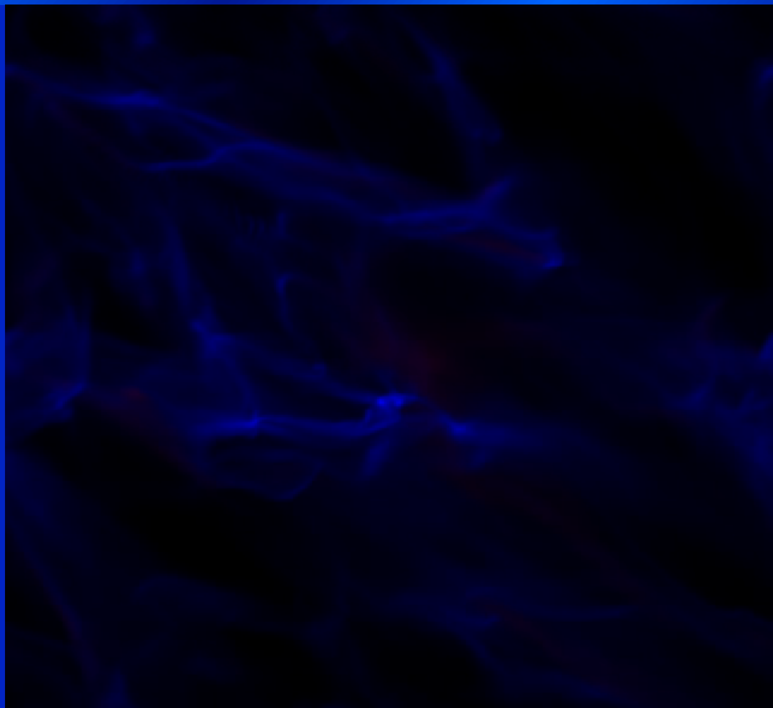

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Conclusions

High Mass Star Formation

3-D high resolution Rad-Hydro AMR simulations with ORION demonstrate:

- Two new mechanisms to overcome radiation pressure barrier to achieve high mass star formation $\Rightarrow$ 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 of radiation and reduction of radiation pressure $\rightarrow$ enhances accretion
  - Radiation feedback from accreting protostars inhibits fragmentation (KKM 2007)
  - Outflows dynamically effect larger volume of core and may result in lower $\Sigma_{threshold}$

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 small 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
- Outflows interact with filaments enhancing small scale multiplicity