HOW STELLAR FEEDBACK LIMITS ACCRETION ONTO MASSIVE STARS

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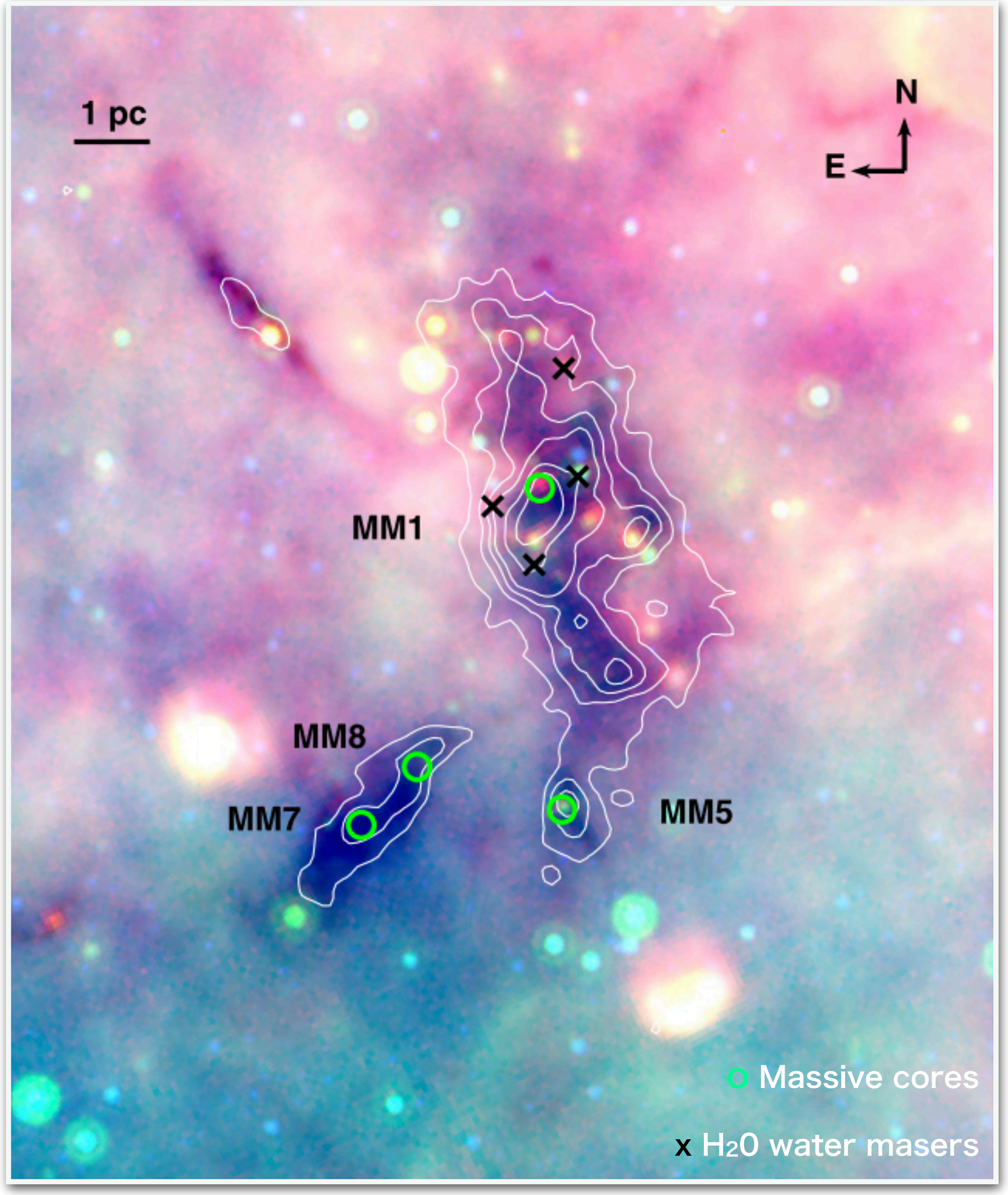
Massive star formation is [likely] a scaled up version of low-mass star formation

Infrared dark cloud (IRDC) G28.53



Lu+2015

- IRDCs can fragment into dense, massive clumps which then fragment into massive pre-stellar cores.

- Massive pre-stellar cores are supersonic.

$$P_{\rm Turb} \gg P_{\rm Th}$$

- Observations suggest massive cores have $\alpha_{\rm vir} \lesssim 1$

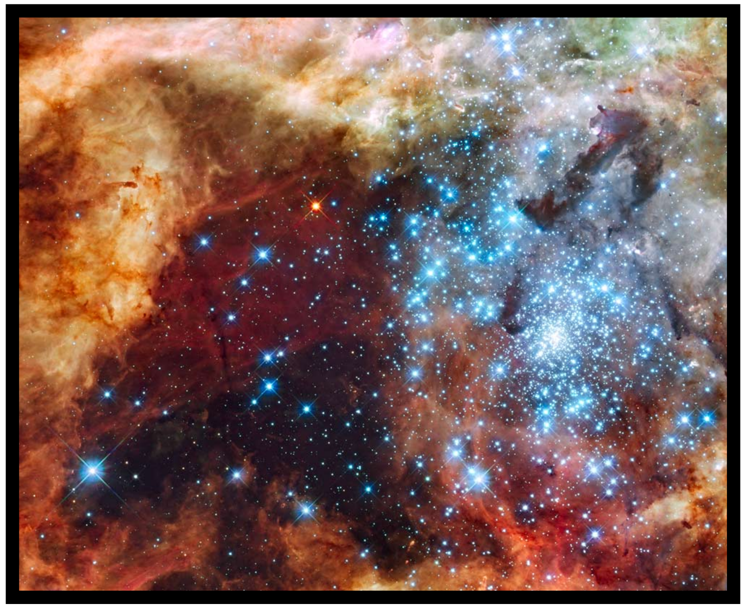
$$\alpha_{\rm vir} = \frac{2E_{\rm KE}}{E_{\rm G}} = \frac{5\sigma^2 R_{\rm c}}{GM_{\rm c}}$$

- Possibly supported by magnetic fields?

(e.g., Pillai+2011, Lu+2015, Zhang+2015, Ohashi+2015)

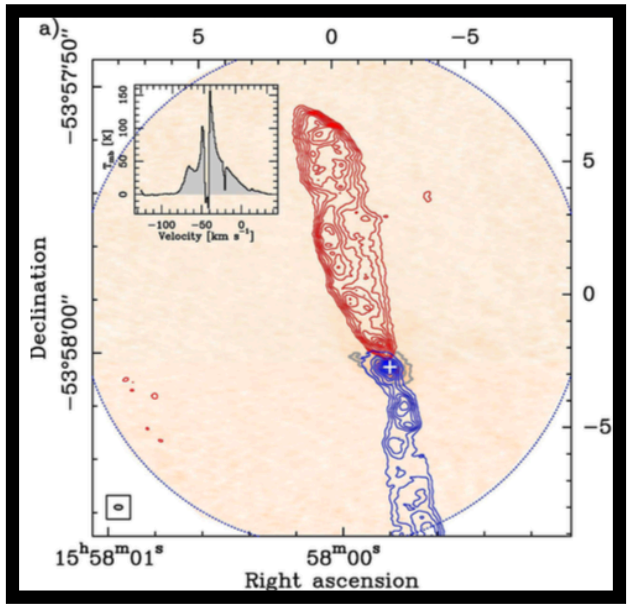
Massive star formation up close:
Stellar feedback processes

Radiation



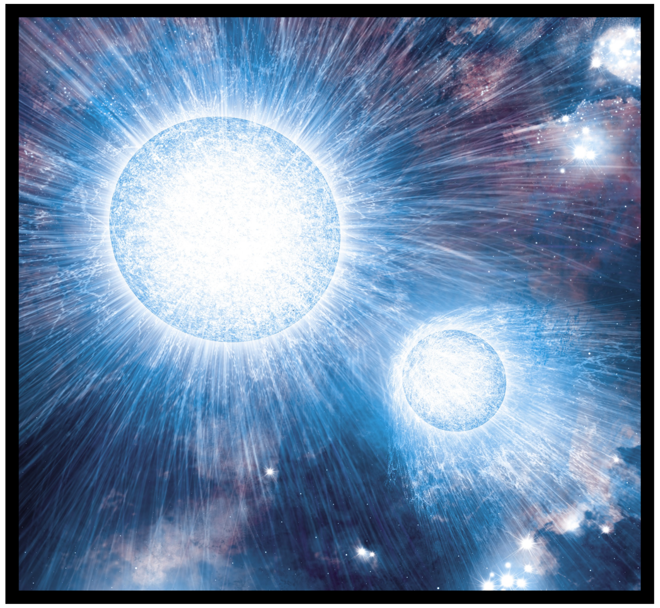
R136 in the LMC (NASA)

Protostellar Outflows



Csengari+2018

Stellar winds



NASA (Artist rendition)

Stellar feedback — the injection of energy and momentum by stars into the ISM — can halt accretion, possibly limiting stellar masses.

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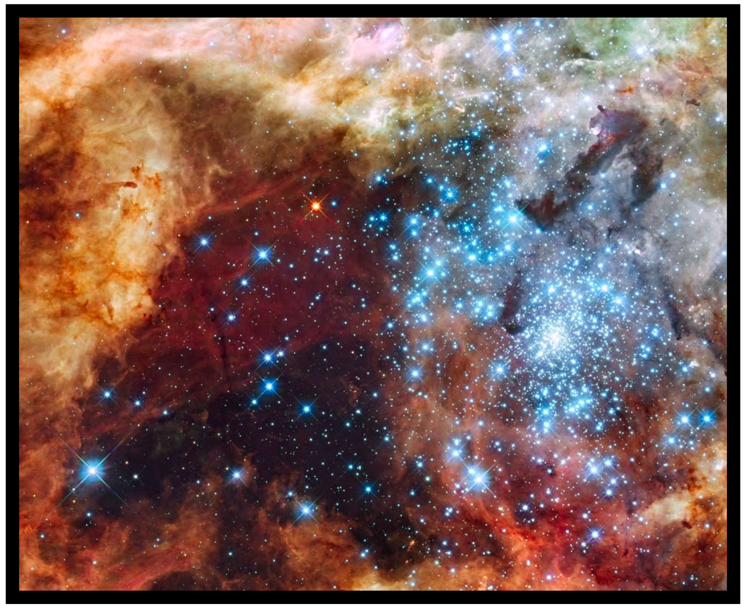

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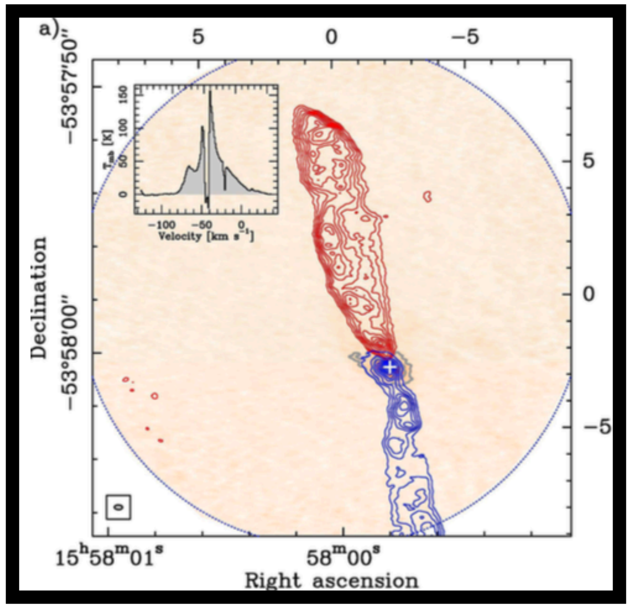

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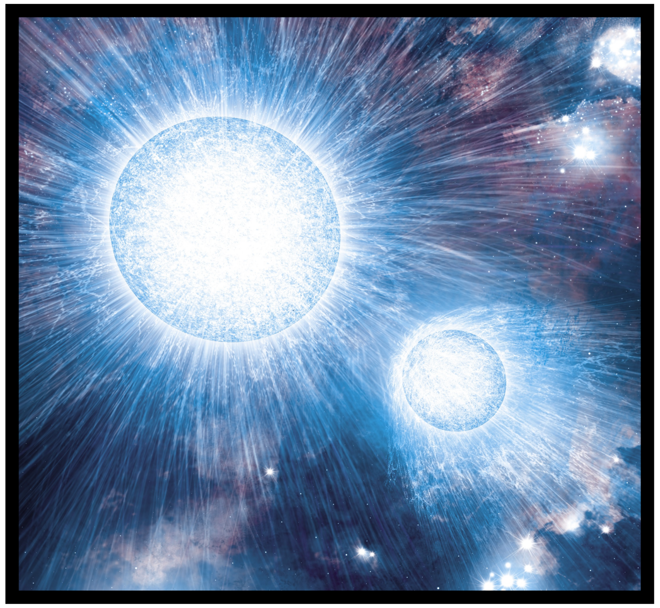

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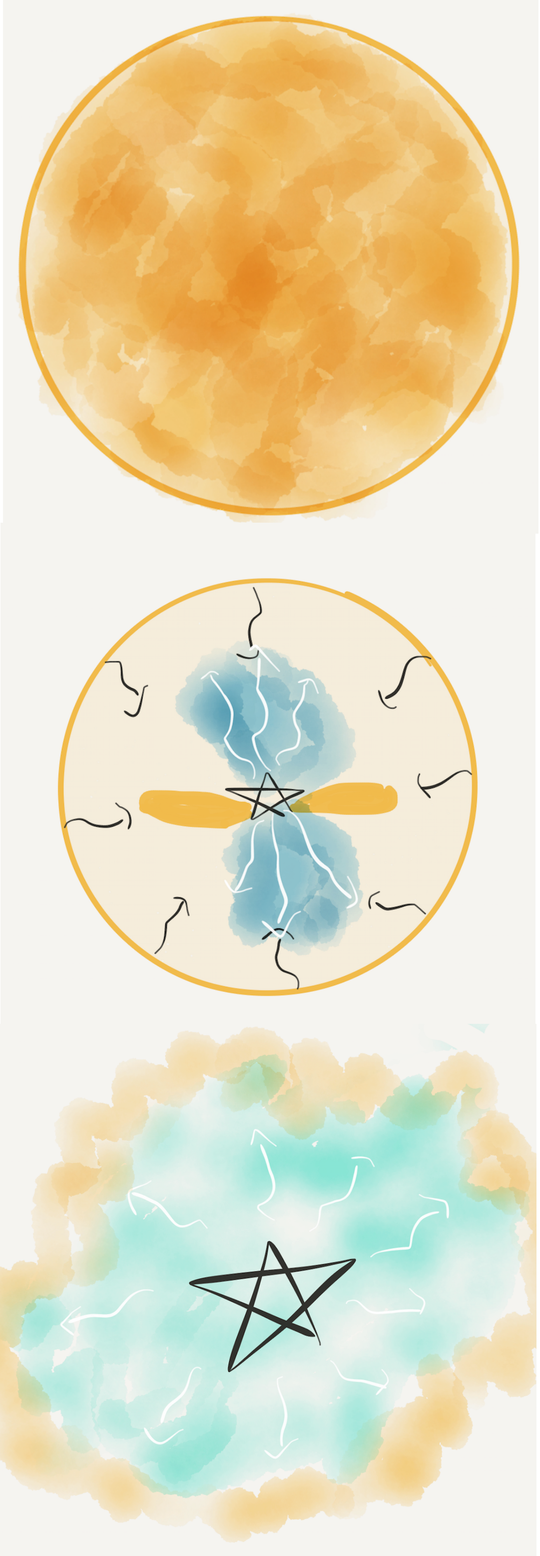
Isotropic accretion leads to the radiation pressure barrier problem in massive star formation



Formation of massive stars is a competition between gravity and (direct+indirect) radiation pressure

Gravitational Force:

$$f_{\rm grav}(r) = \frac{GM_\star \Sigma}{r^2}$$

$$\Sigma(r) = \int_0^r \rho(r')dr'$$

Radiative Force:

$$f_{\rm rad} = \frac{L_\star}{4\pi r^2 c}(1 + f_{\rm trap})$$

$$L_\star \propto M_\star^3$$

$$f_{\rm edd} = 7.7 \times 10^{-5}\,(1 + f_{\rm trap})\left(\frac{L_\star}{M_\star}\right)_\odot \left(\frac{\Sigma}{1\ {\rm g\ cm^{-2}}}\right)^{-1}$$

Radiation halts isotropic accretion when $f_{\rm edd} \gtrsim 1$ for $M_\star \gtrsim 20\ M_\odot$

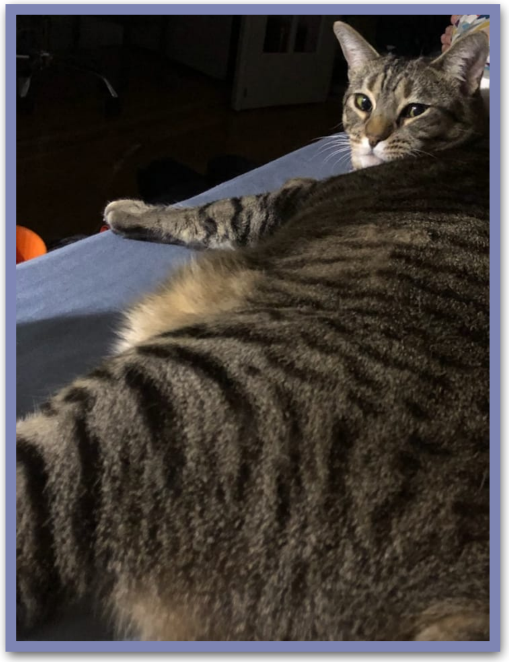
(e.g., Larson & Starrfield 1971, Kahn 1974, Yorke 1979, Yorke+1995, Wolfire & Cassinelli 1986, 1987; Yorke & Bodenheimer 1999)

Challenges in Observing Massive Star Formation (MSF) — need to turn to (3D radiation-hydrodynamics) simulations

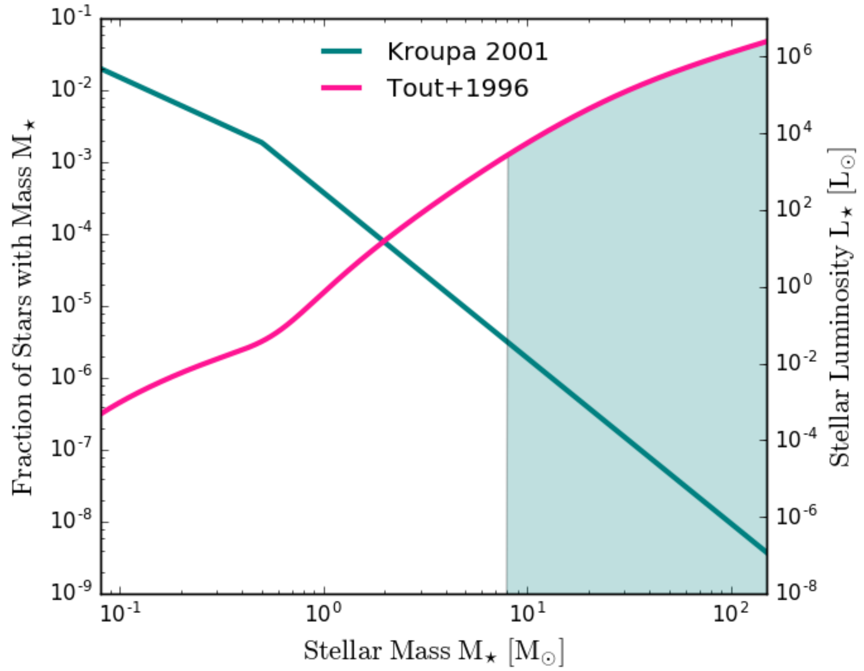
How do we go from this?

Nova

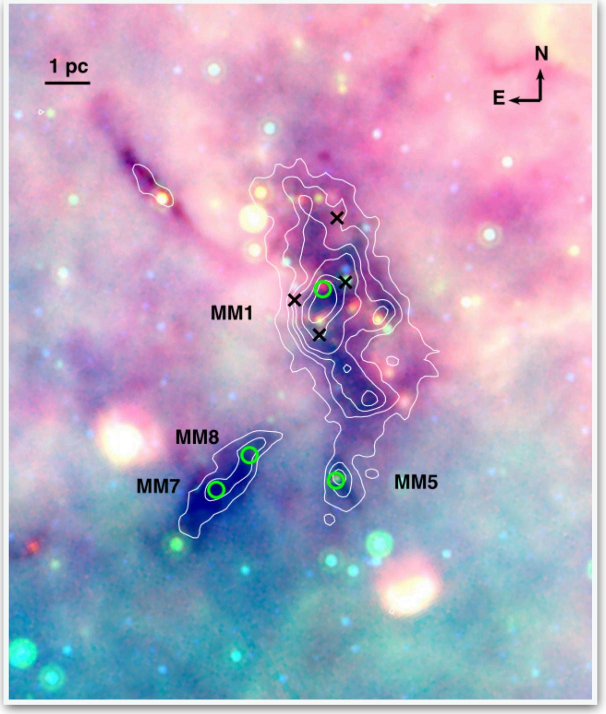
To this?



(super)Nova



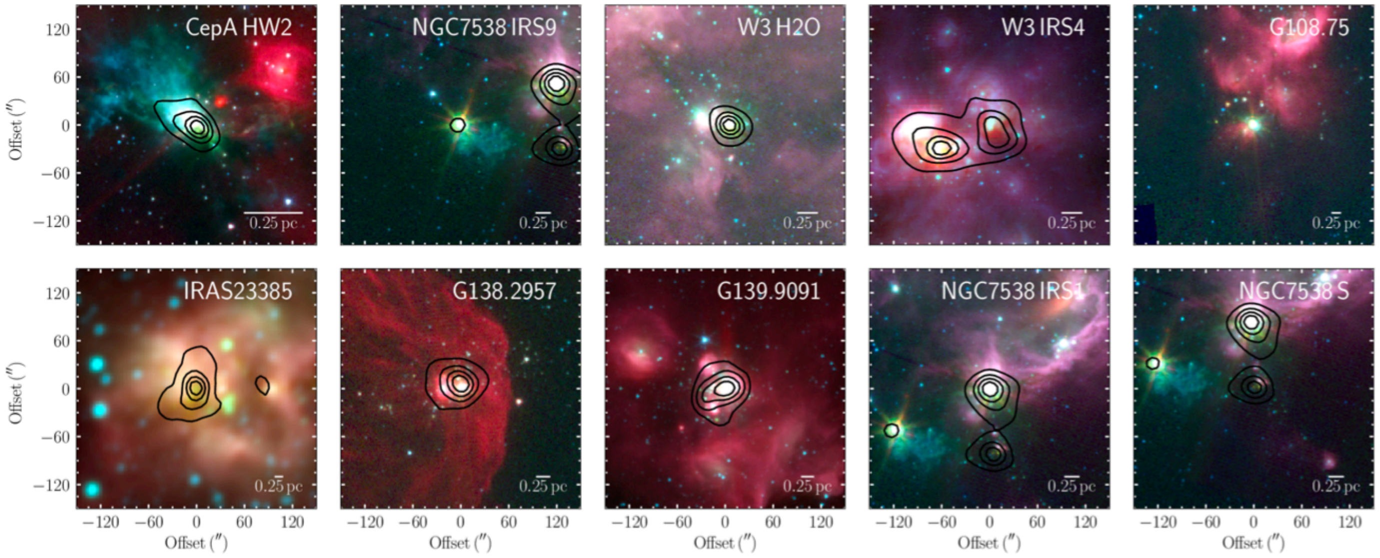
Massive stars are rare, representing only ~1% of stars by number but they dominate the energy budget.



Lu+2015

NOEMA CORE Program

Massive protostellar cores with $L>10^4\ L_\odot$ and d<6 kpc



Infrared — WiSE and Spitzer multi-λ images, contours = SCUBA 850μm
Beuther+2018b, CORE program

MSF regions are rare, far away (d ≳few kpc), and highly-embedded and obscured throughout their short formation

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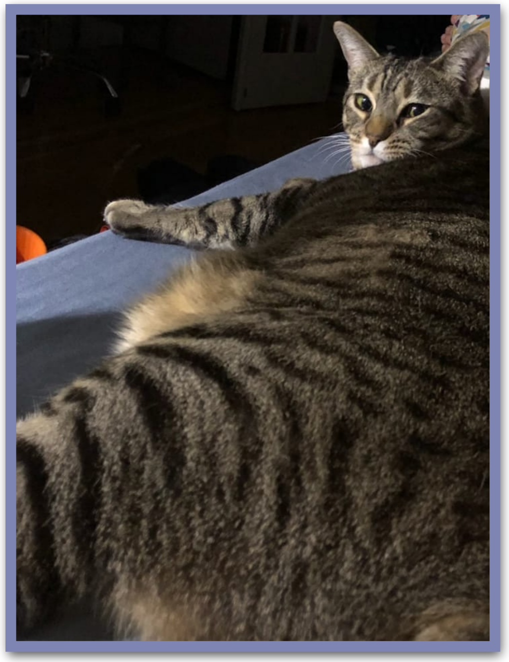

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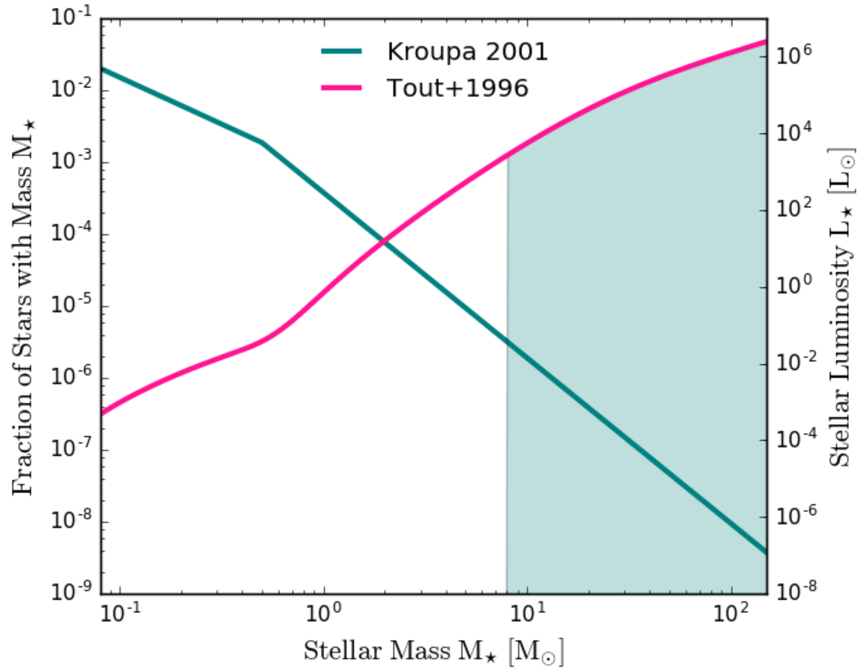

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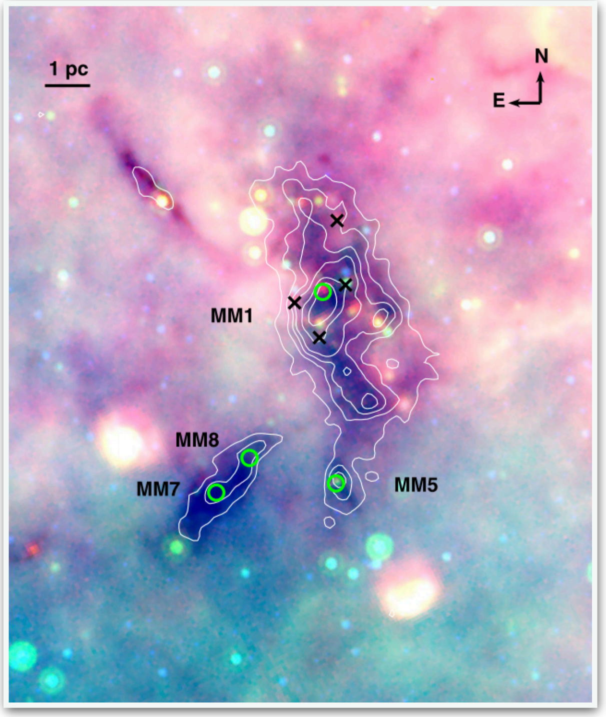

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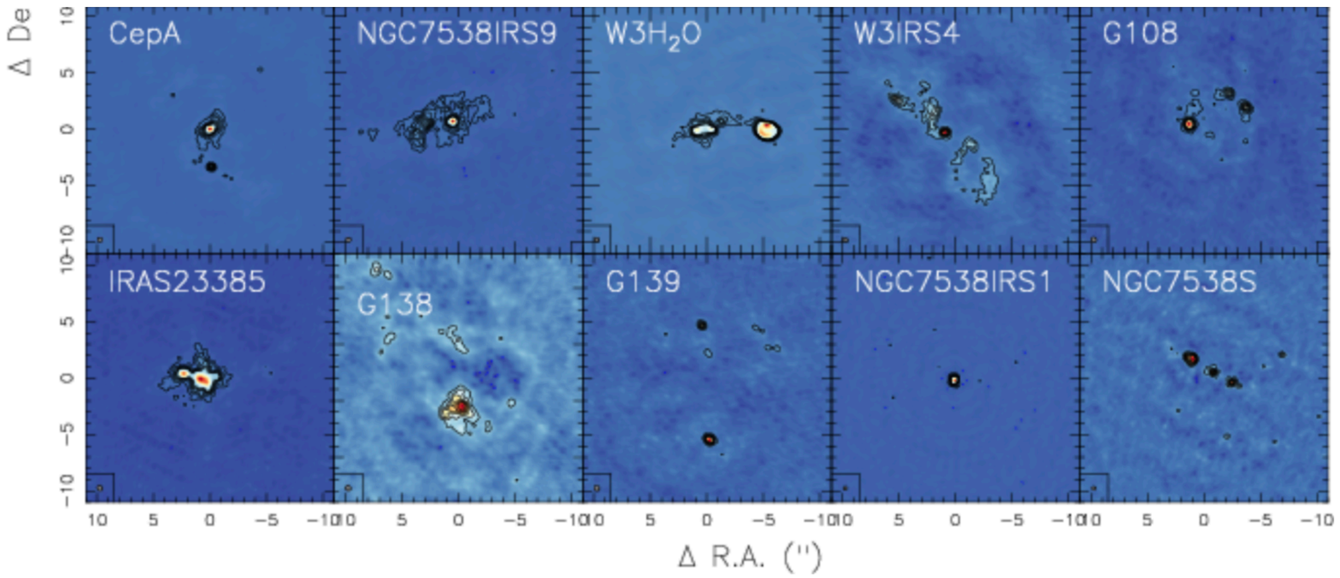

NOEMA 1.3 mm dust continuum
Beuther+2018b, CORE program

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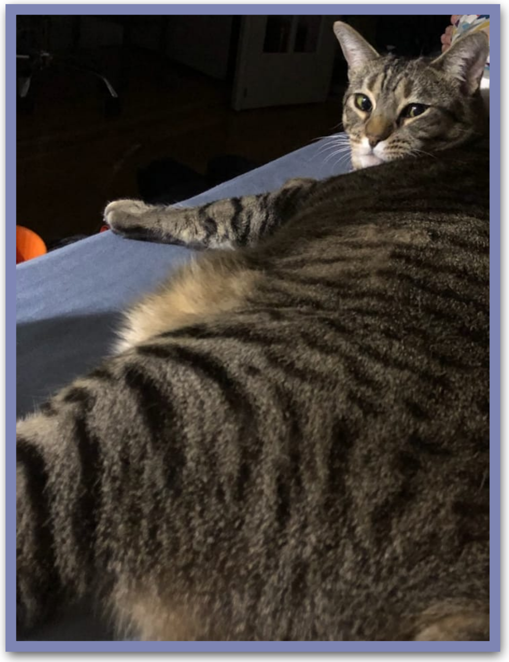
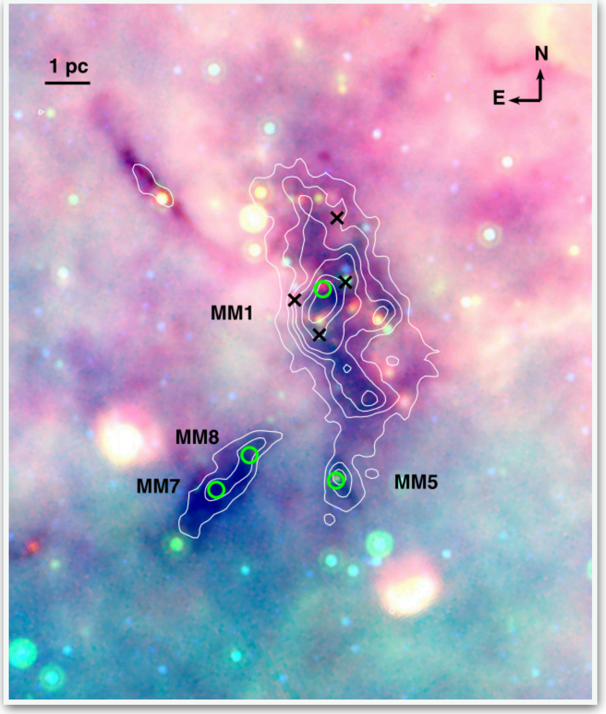


(super)Nova

Viewing angles make all the difference



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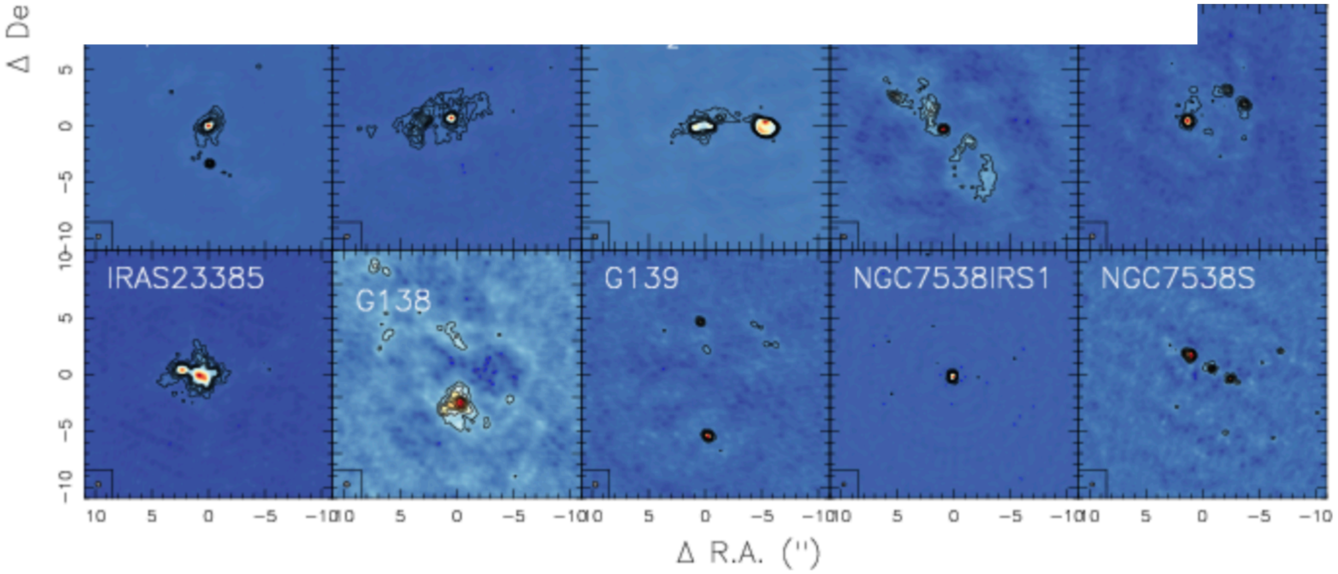

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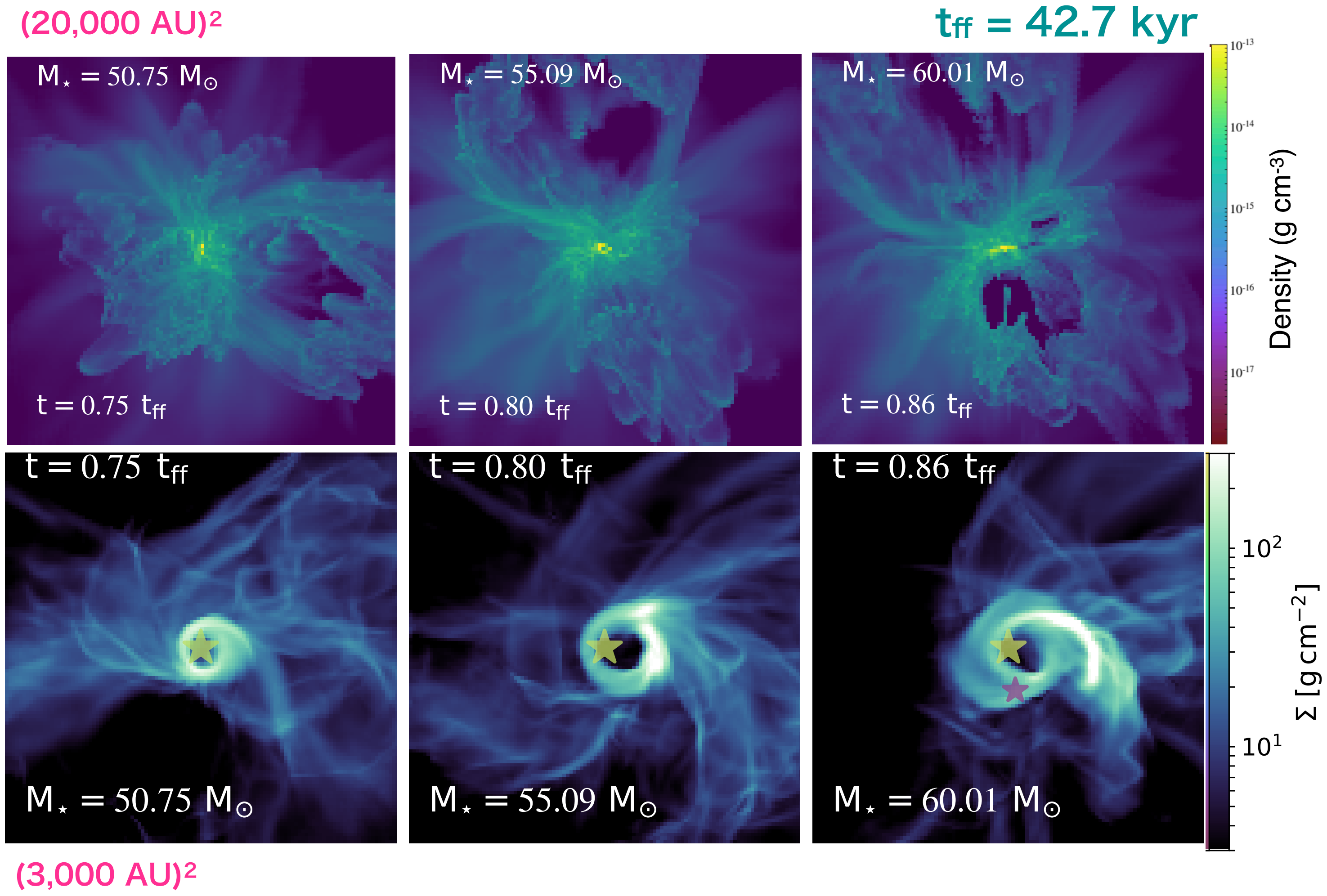
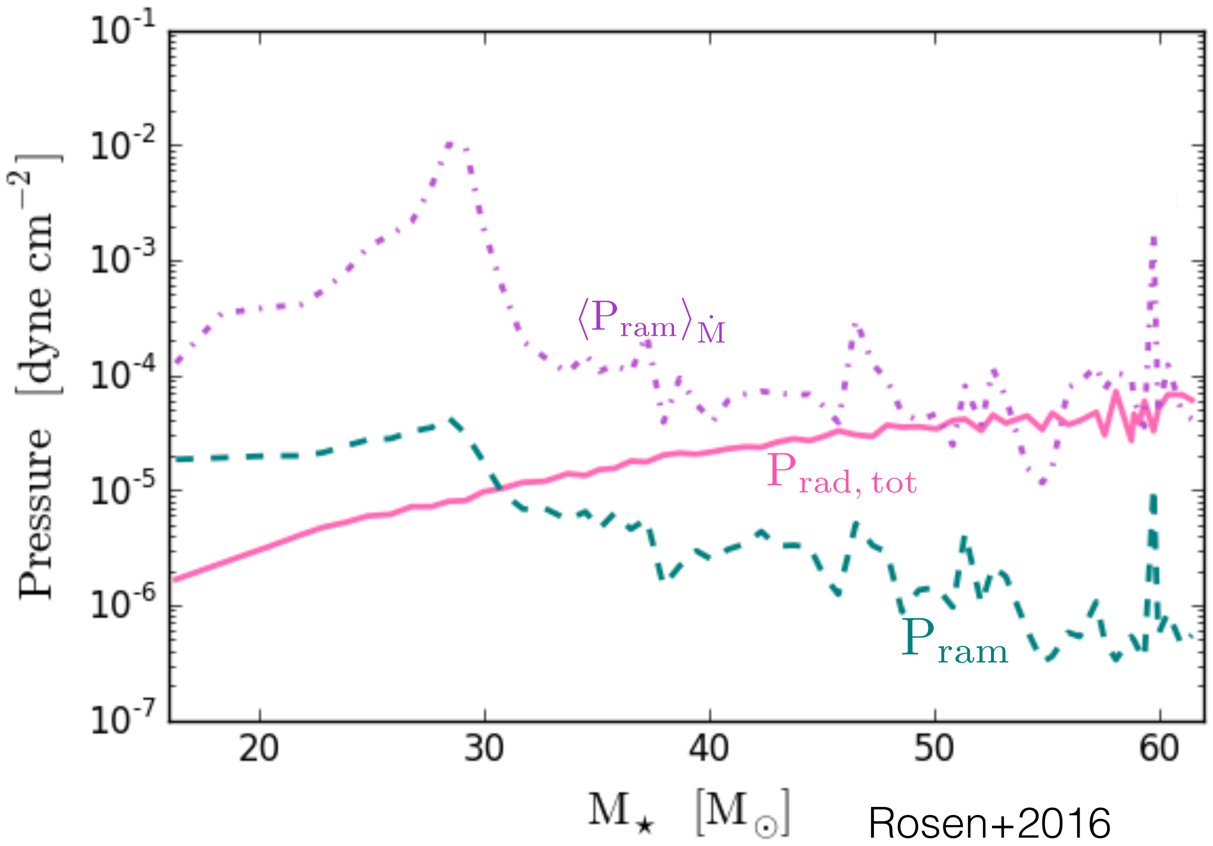
Overcoming the radiation pressure barrier





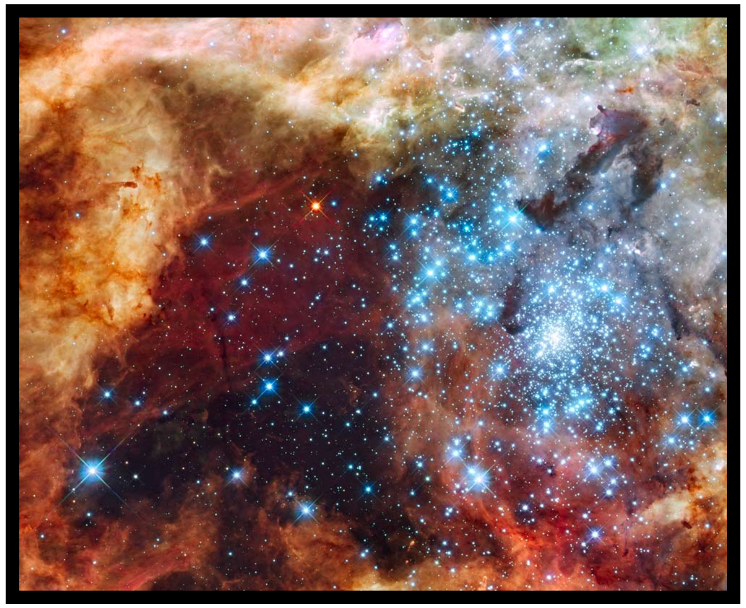
Rosen+2016

Mass delivered to star via infalling dense filaments, radiative Rayleigh Taylor (RT) instabilities, and disk accretion.

High accretion rates and infalling filaments provide sufficient ram pressure to overcome radiation pressure.

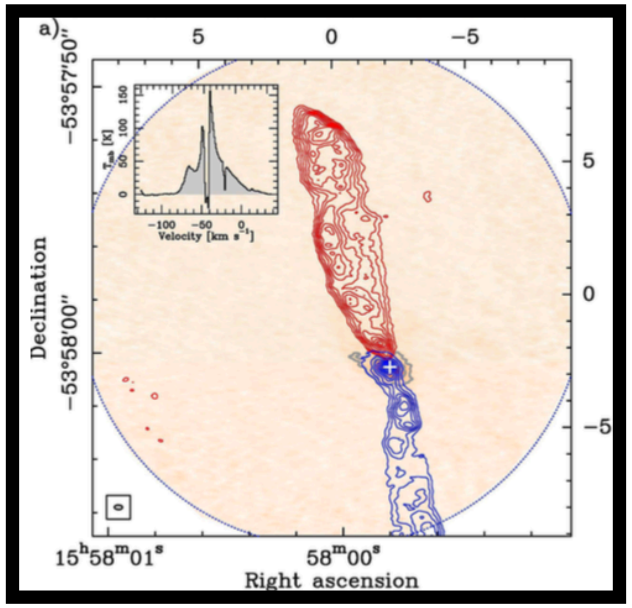
Massive Star Formation up close:
Stellar feedback processes

Radiation



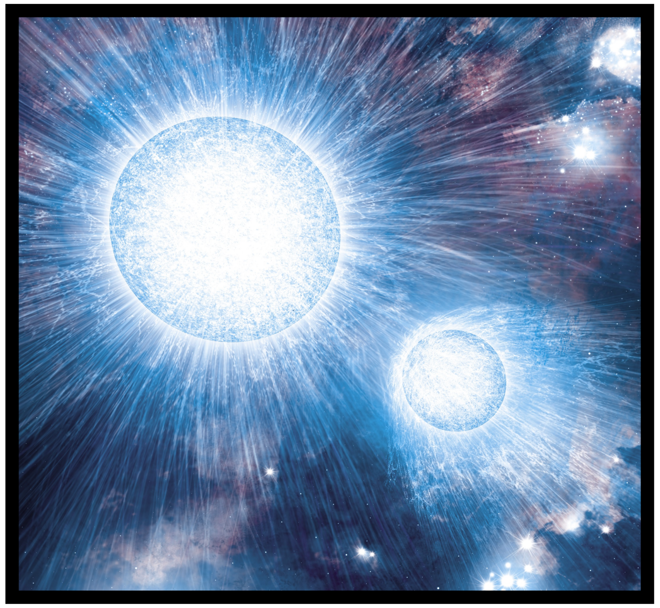
R136 in the LMC (NASA)

Protostellar Outflows



Csengari+2018

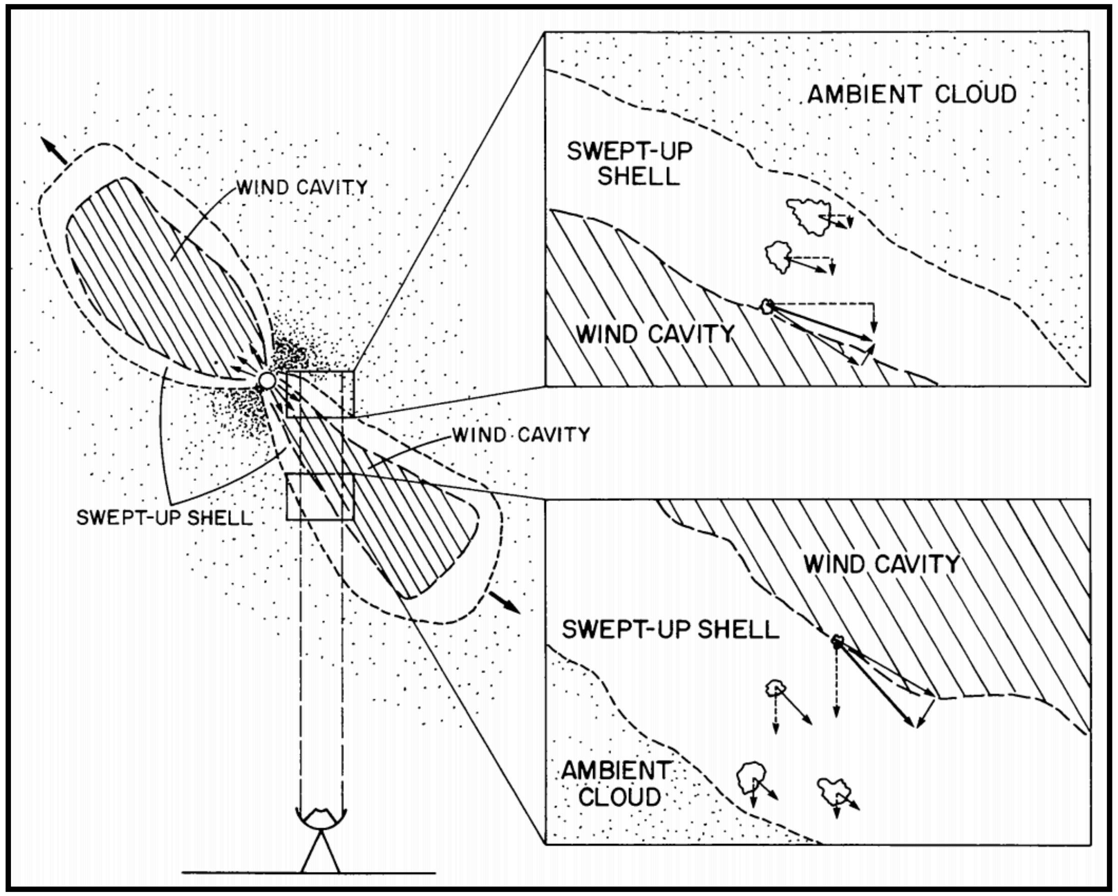
Stellar winds



NASA (Artist rendition)

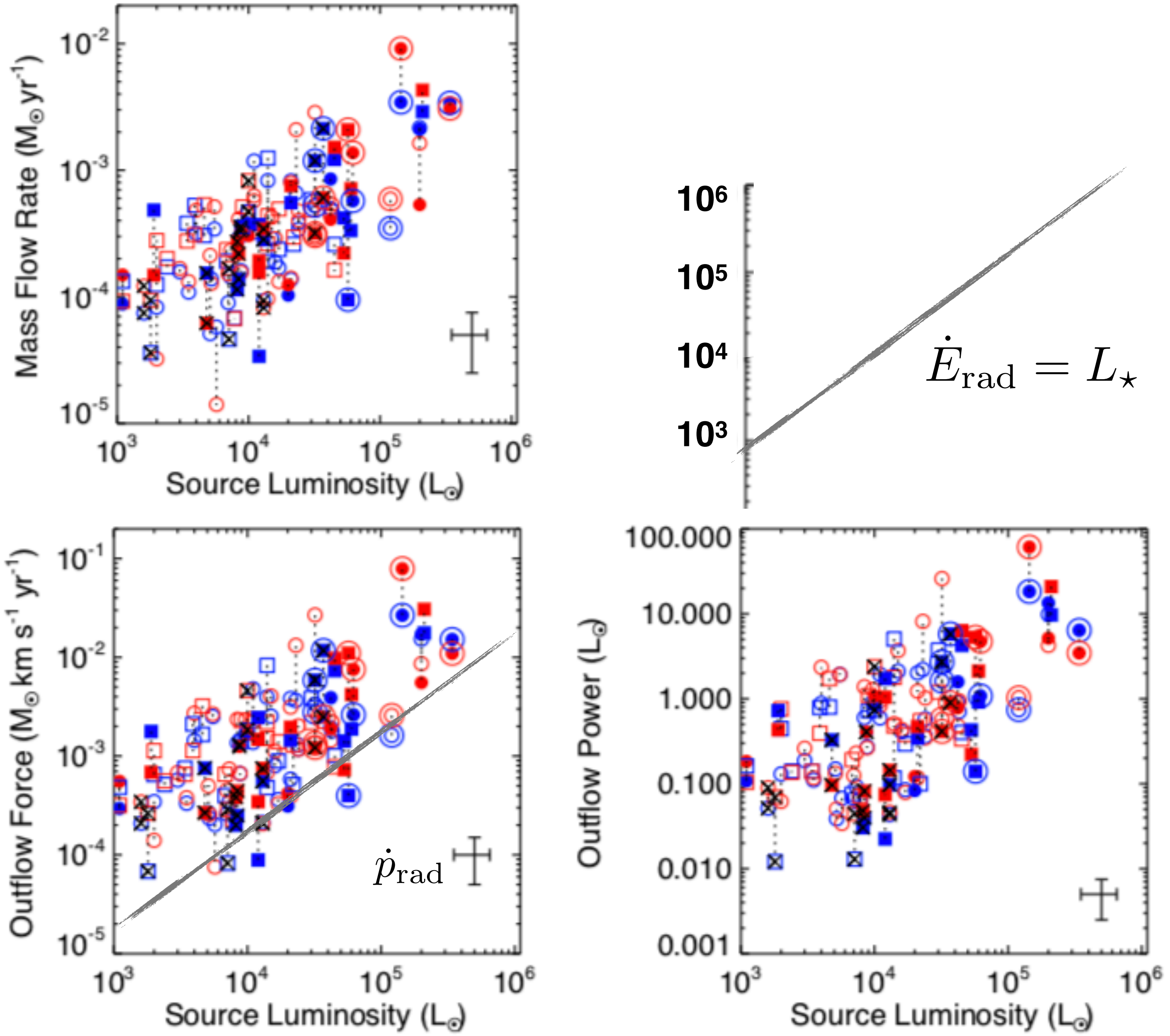
Stellar feedback — the injection of energy and momentum by stars into the ISM — can halt accretion, possibly limiting stellar masses.

Collimated bipolar outflows are ubiquitous in (low-mass and) high-mass star formation



Lada 1985, ARAA

$$v_{\rm jet} \sim \sqrt{\frac{GM_\star}{R_{\rm star}}} \sim 100 \ {\rm km\ s^{-1}}$$

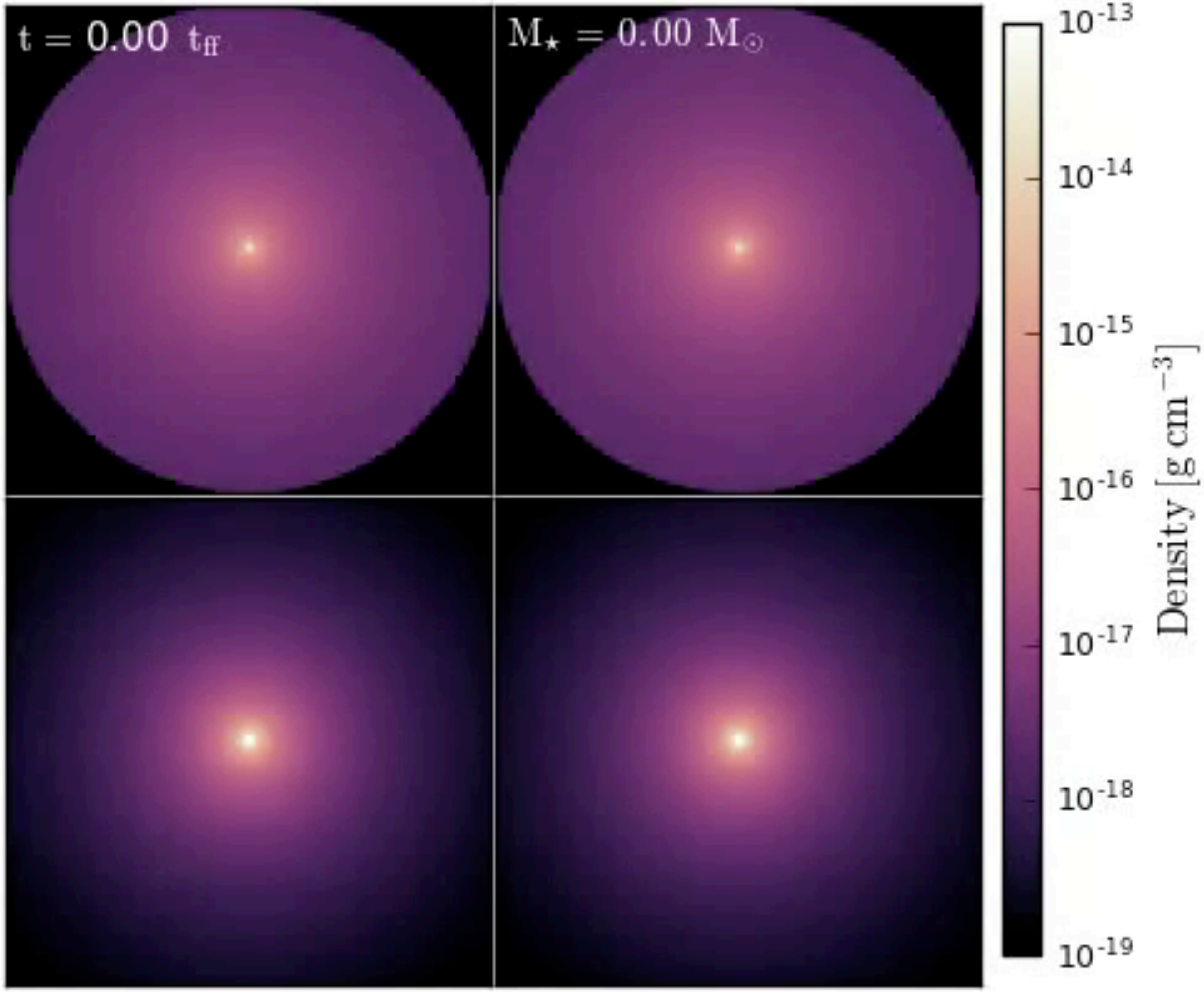


Maud+2015

$$\dot{p}_{\rm rad} = \frac{L_\star}{c} = 2 \times 10^{-8} \left(\frac{L_{\rm star}}{L_\odot}\right) {\rm M_\odot\ km\ s^{-1}\ yr^{-1}}$$

Powerful jets from accreting stars can drive wide angle molecular outflows from star-forming cores and eject core material

Massive star formation with radiative *and* outflow feedback



Rosen+(in prep)

Top panel: (40,000 AU x 40,000 AU)

Bottom panel: (8,000 AU x 8,000 AU)

Initial Conditions:

M_{core}=150 $M_\odot$

R_{core}=0.1 pc

$\rho(r) \propto r^{-3/2}$

σ_{1D}=1.2 km s^{-1}

$\alpha_{vir} \sim 1$

Δx_{min}=20 AU

t_{ff}=42,710 yrs

Subgrid outflow model:

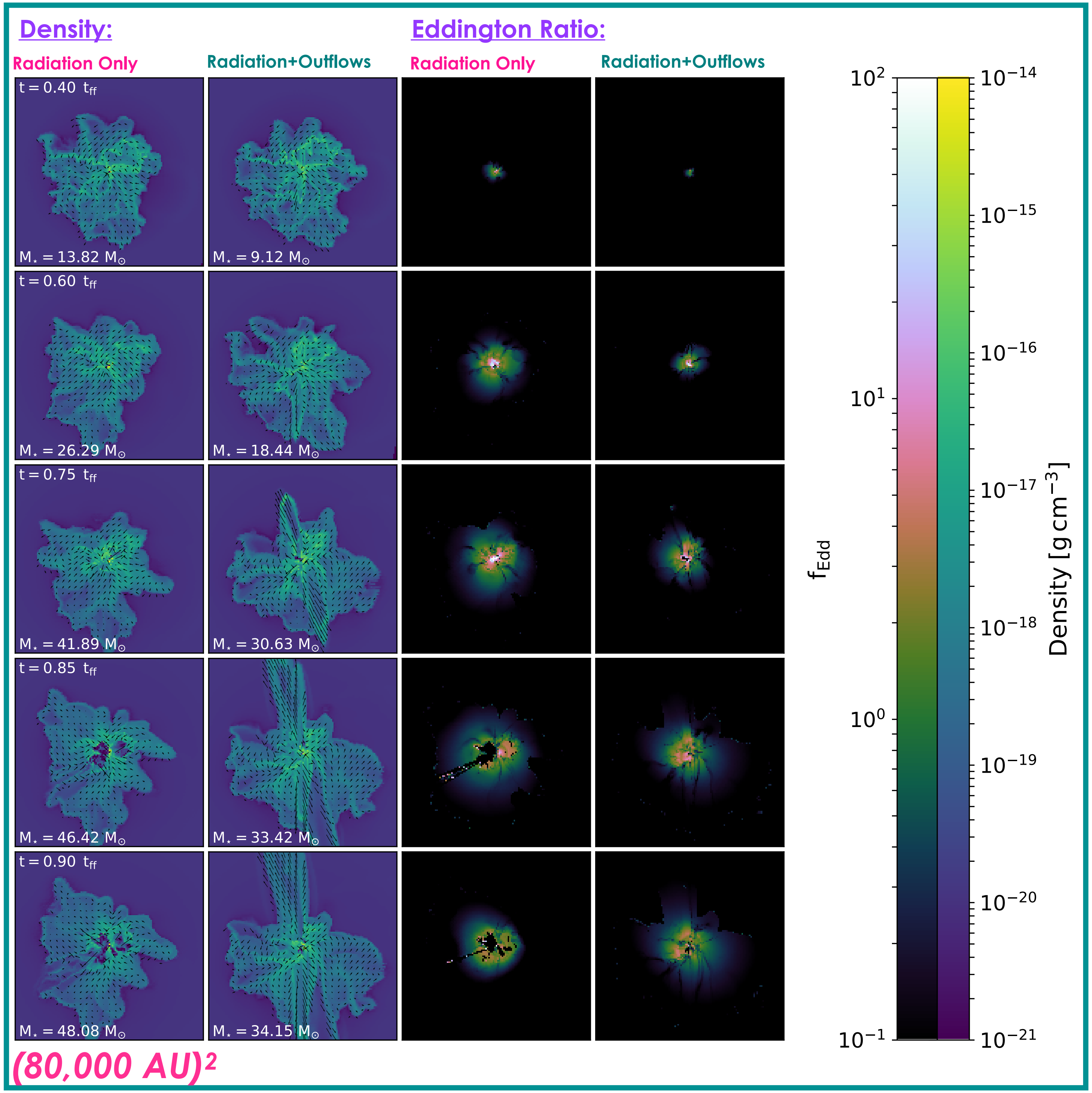
$$p_{\rm OF} = \dot{M}_{\rm OF} v_{\rm OF}$$

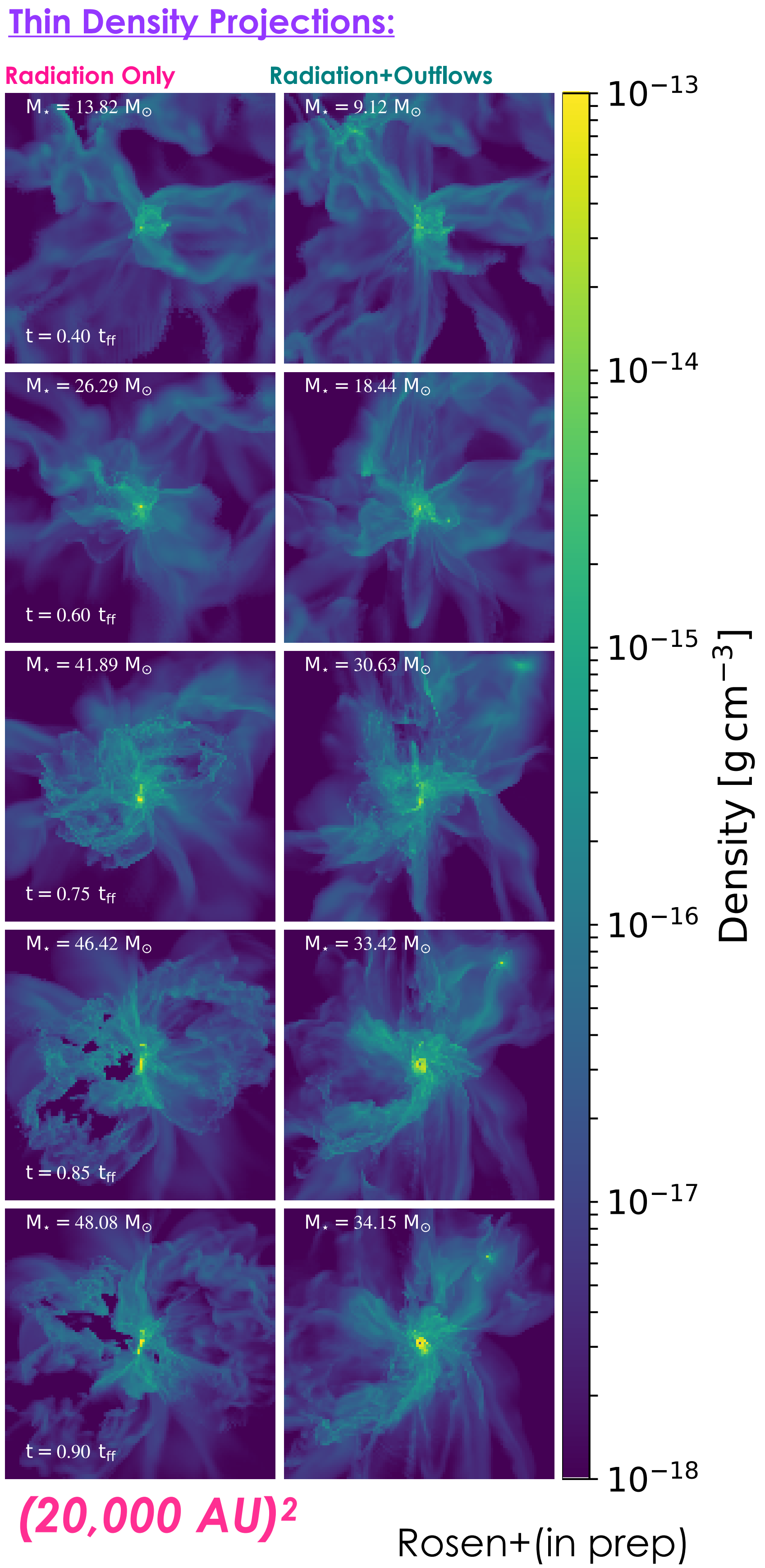
$$\dot{M}_{\rm OF} = 0.21 \times \dot{M}_{\rm acc}$$

$$v_{\rm OF} = 0.3 \times v_{\rm esc}$$

(e.g., Matzner & McKee 1999, Cunningham+2011)

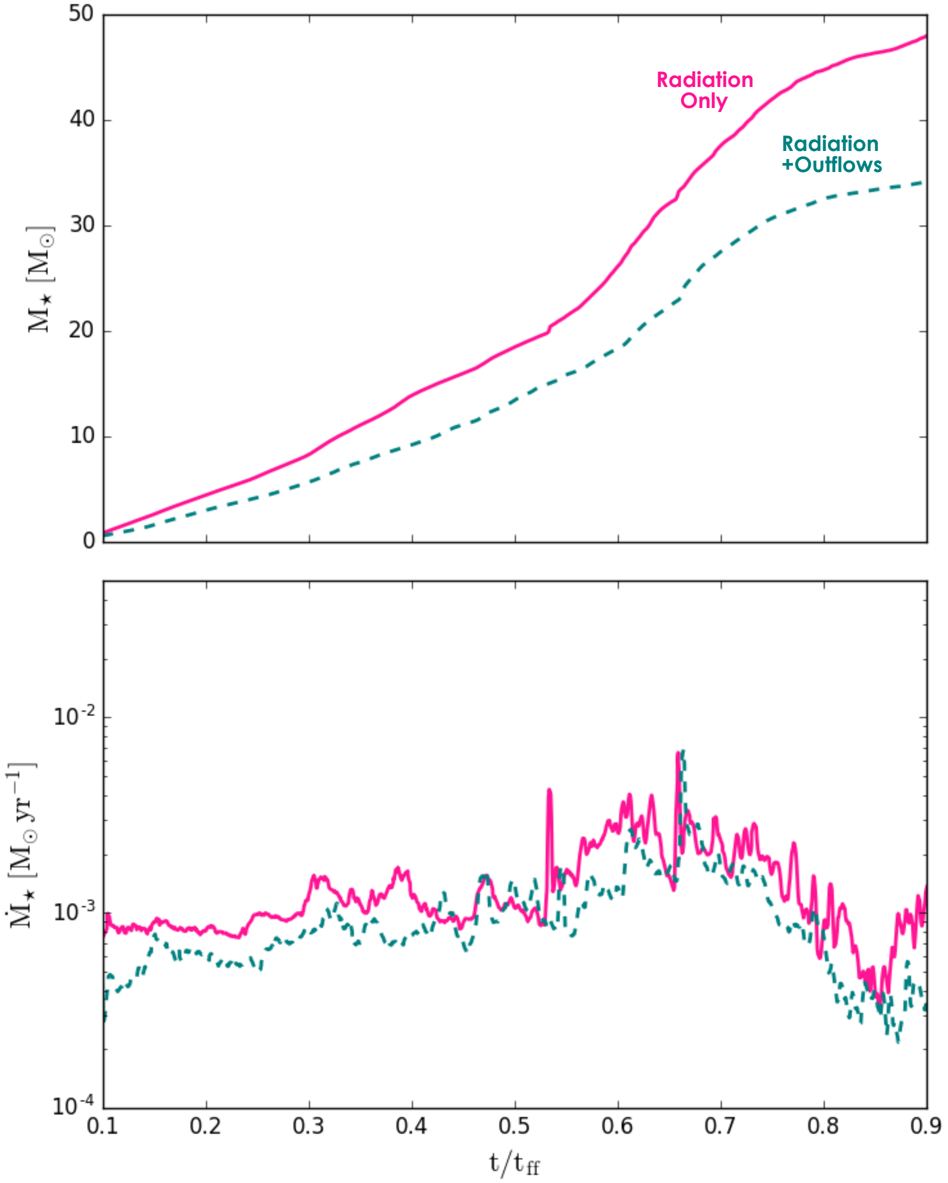
Outflows punch holes in core along the star's polar directions allowing radiation to escape, thereby reducing the development of RT instabilities.



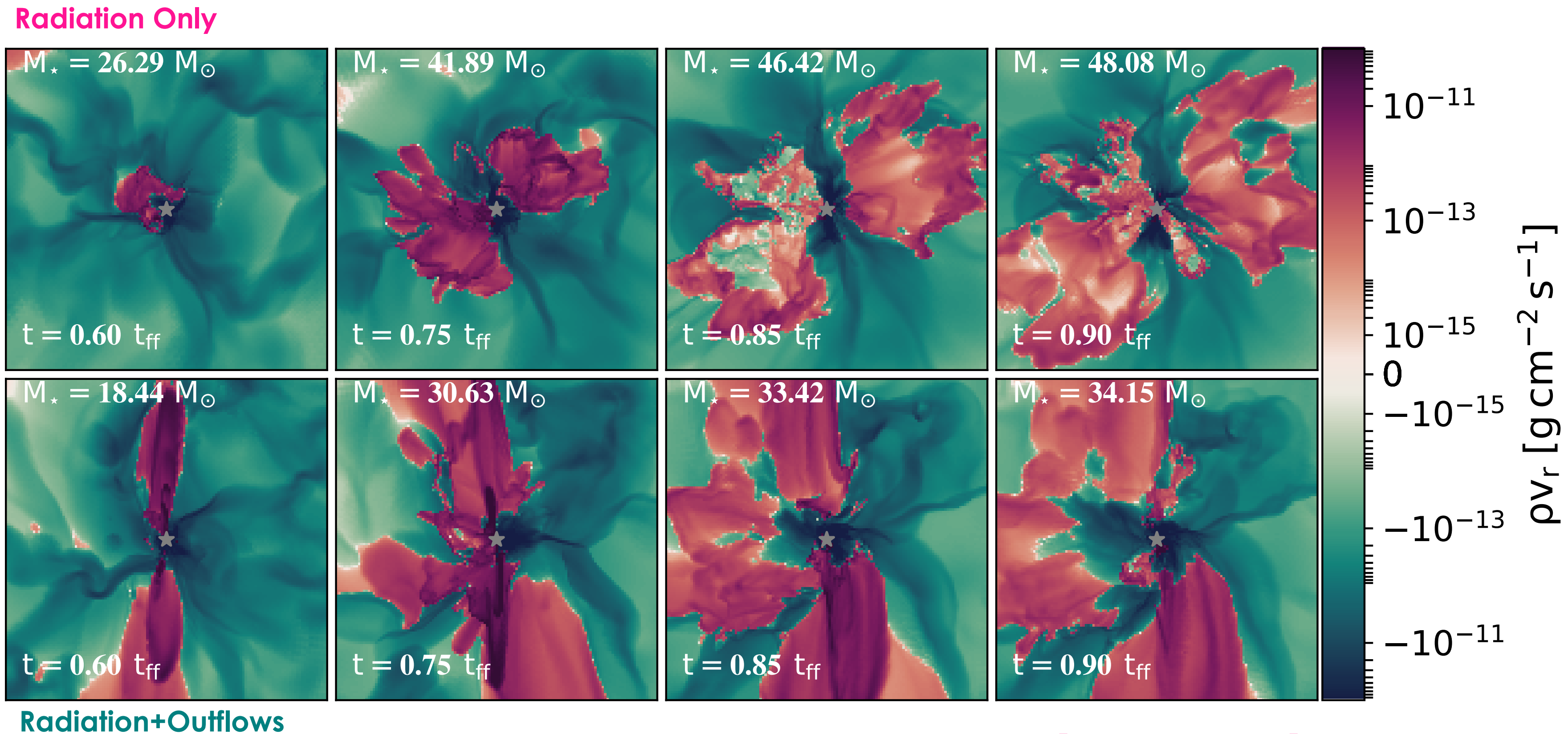


Rosen+(in prep)

Outflows+radiation pressure efficient at ejecting material away from the star than radiation pressure alone.



Rosen+(in prep)

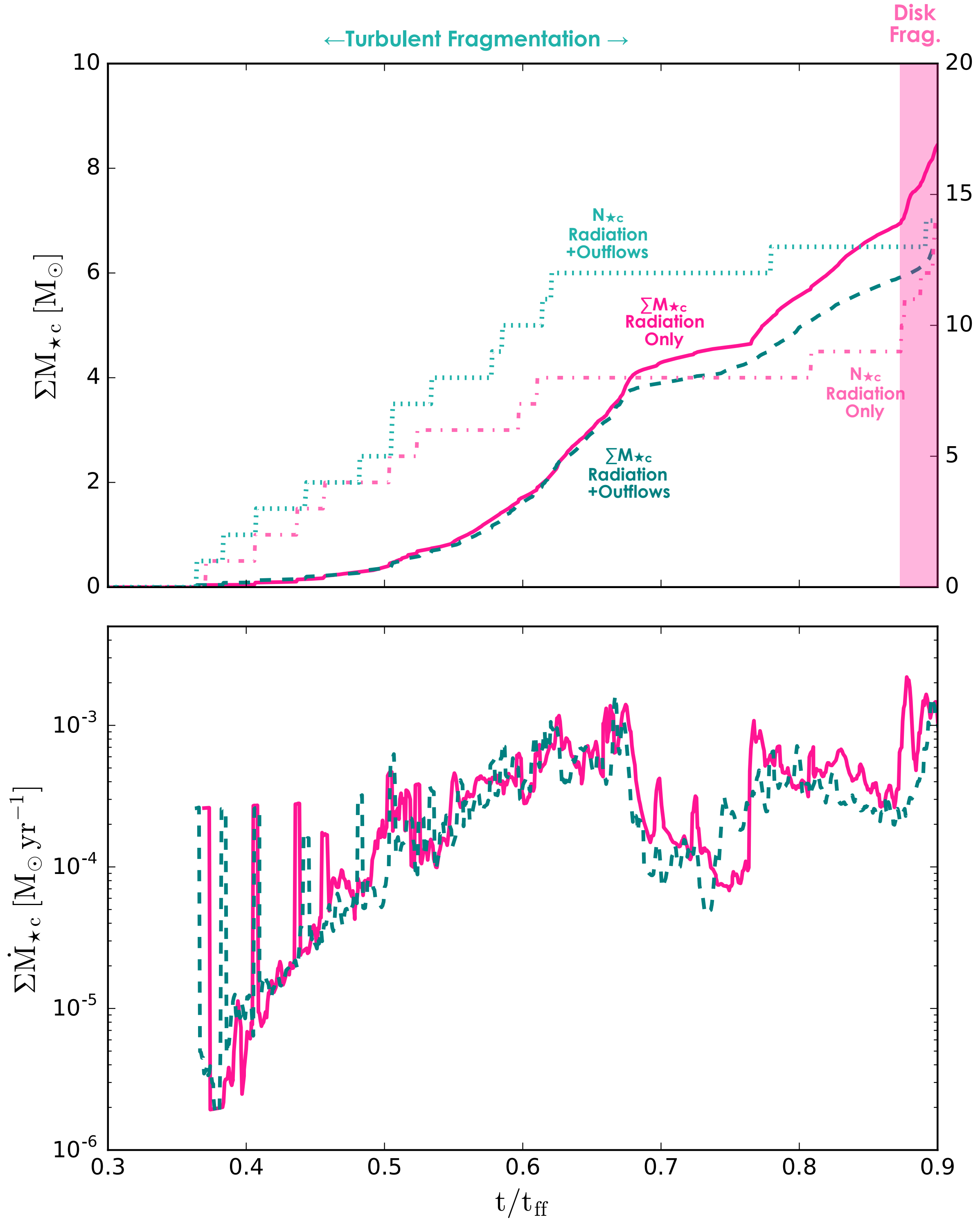


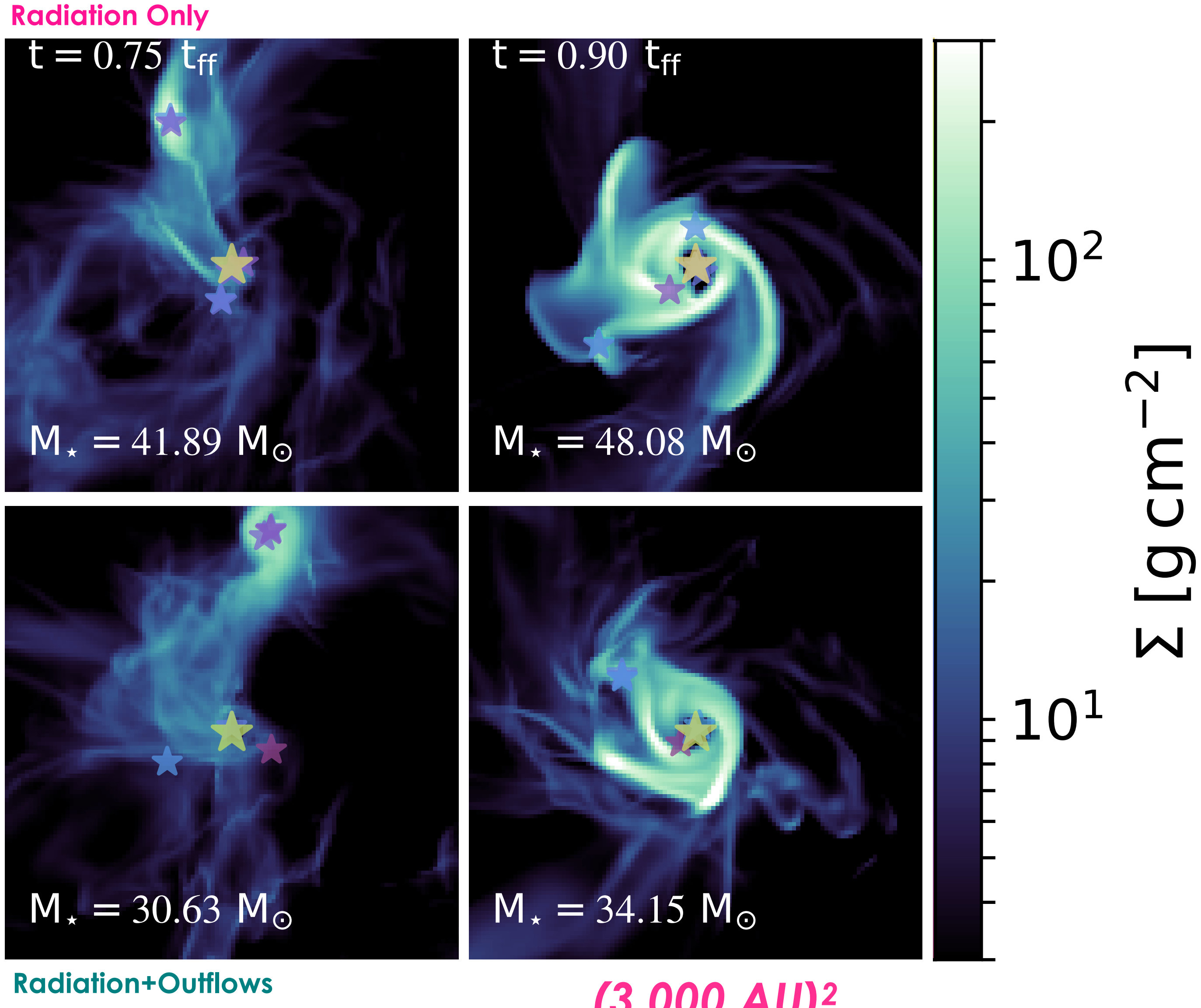
(20,000 AU)²

21% of accreted mass ejected by outflows

→ only ~8% difference!

Disks are crucial to massive star formation, especially at late times.



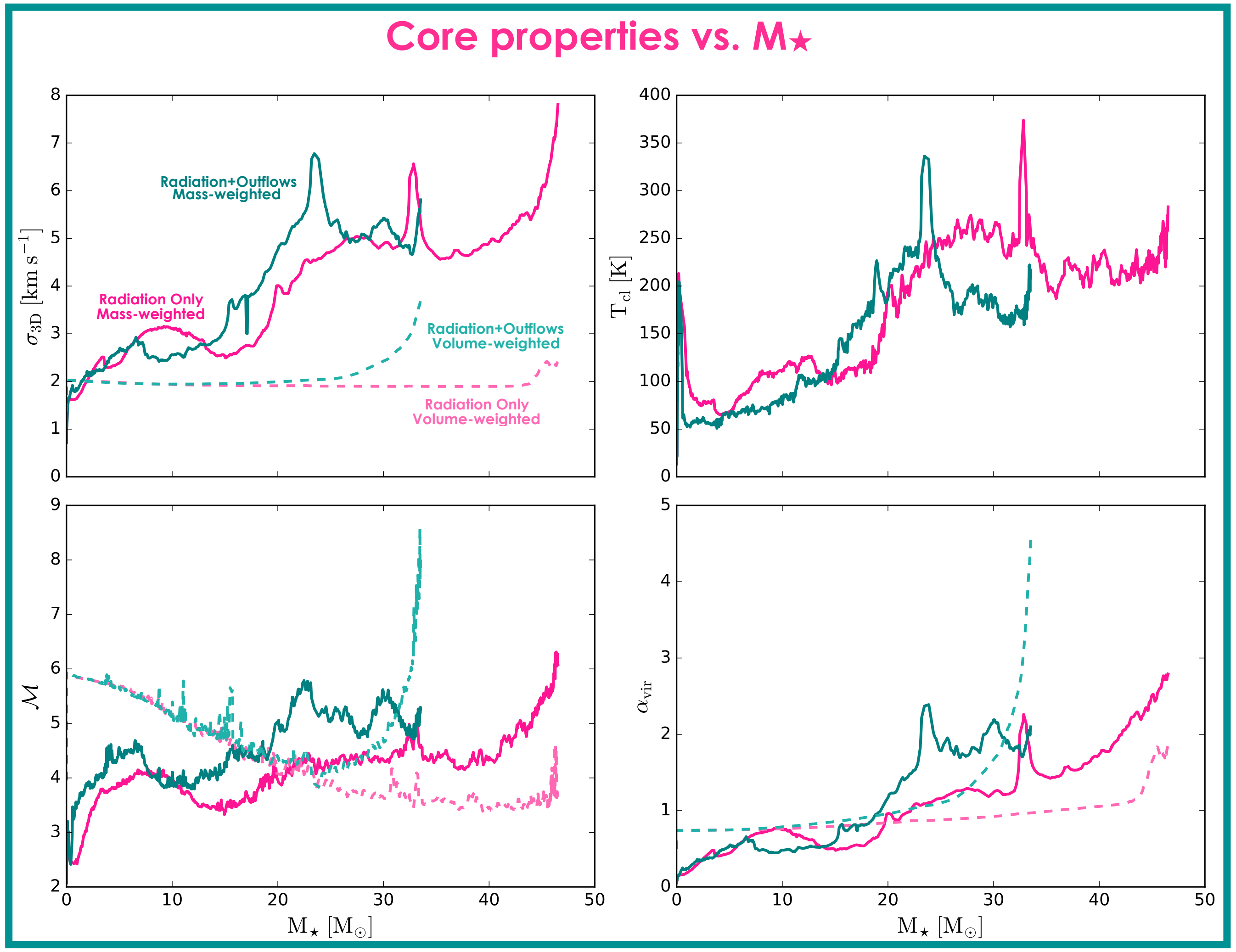


(3,000 AU)^2

Rosen+(in prep)

Companions formed via turbulent fragmentation at early times, disk fragmentation at late times

Outflows drive out entrained gas, eventually unbinding the core



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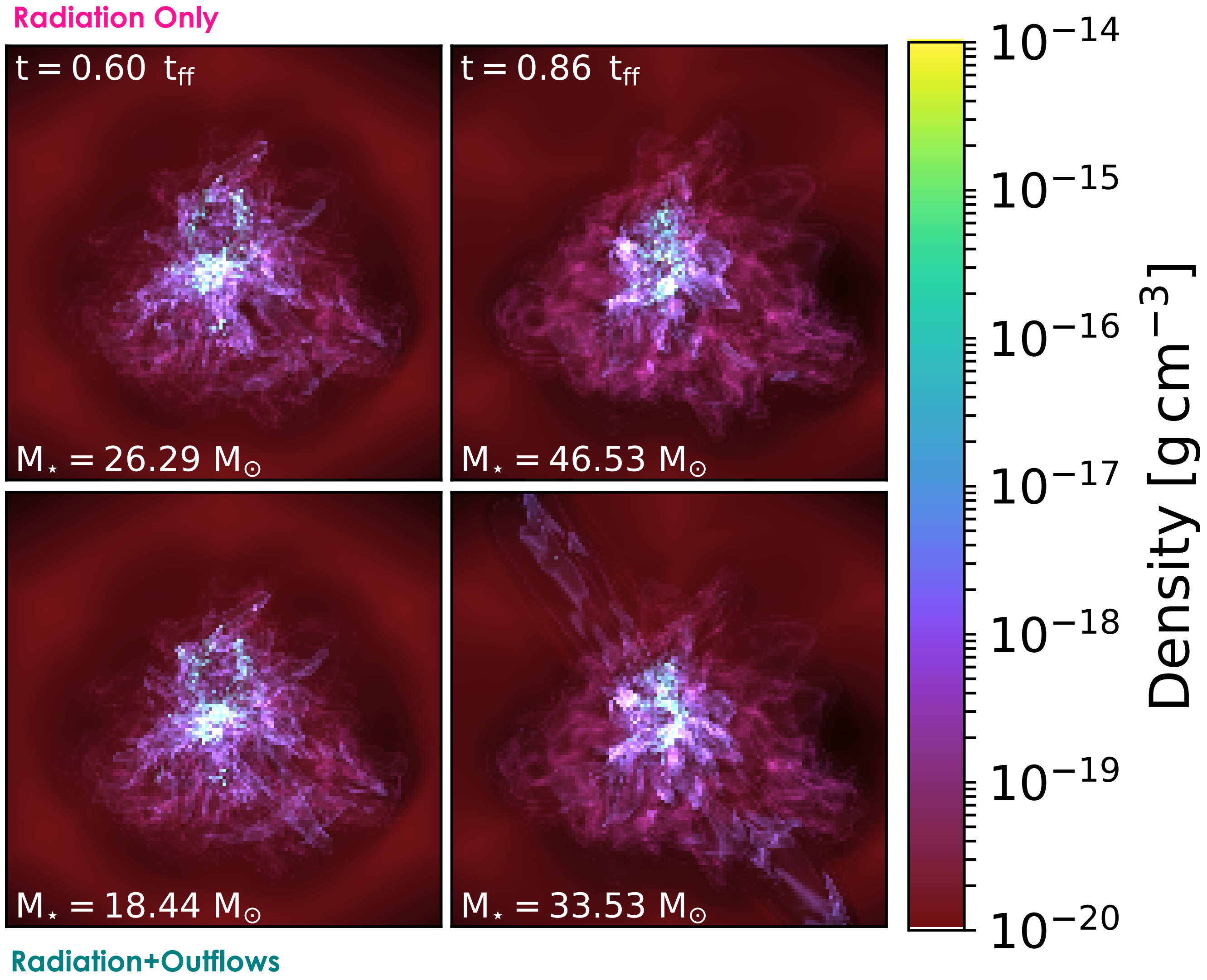
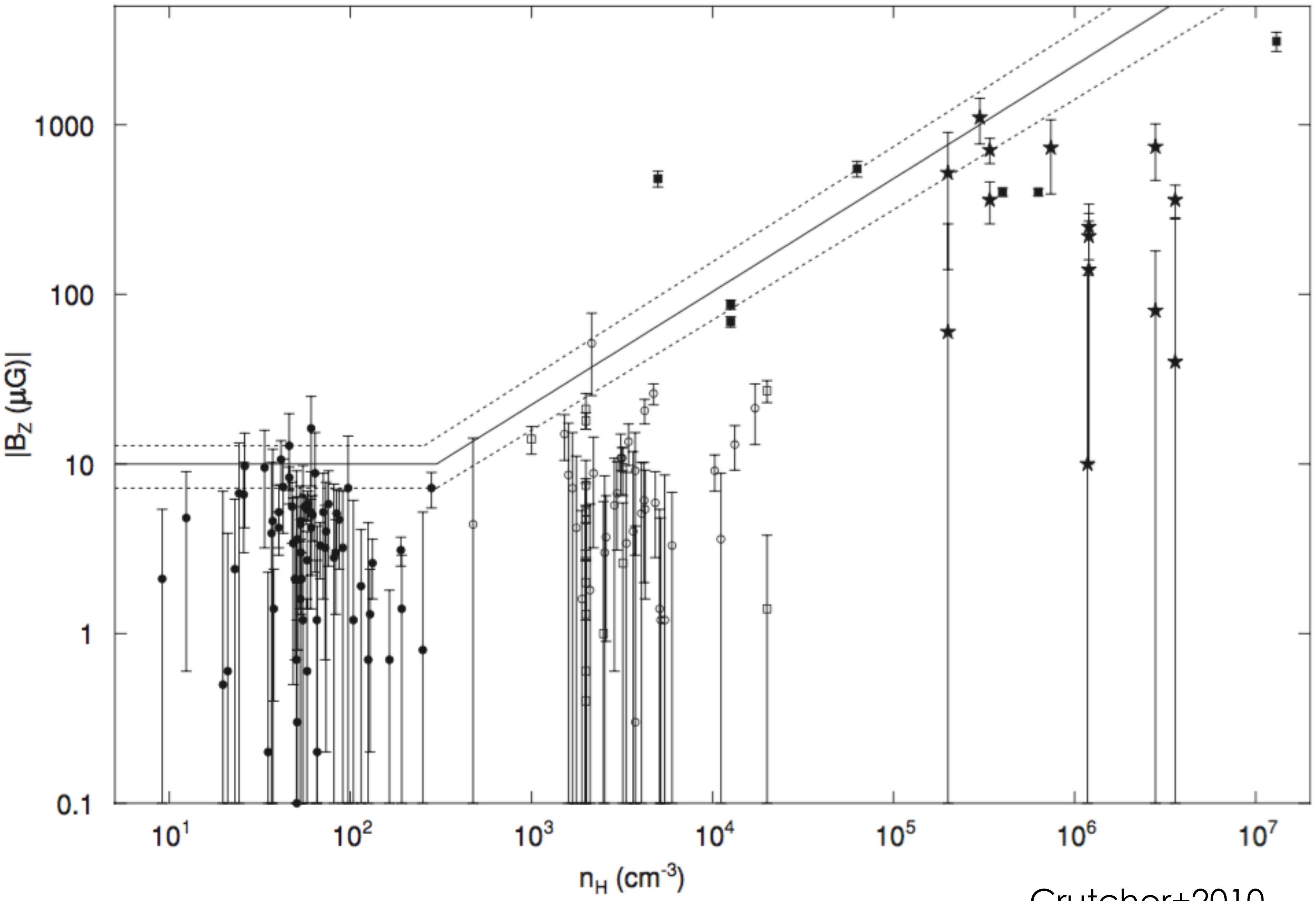


Feedback from outflows allows radiation to escape, thereby reducing radiative heating.

…BUT WAIT! What about magnetic fields?



Crutcher+2010

$$\mu_\Phi = \frac{M}{M_\Phi} \simeq \frac{2\pi\sqrt{G}M}{\pi B^2}$$

Supercritical

$$\mu_\Phi > 1$$

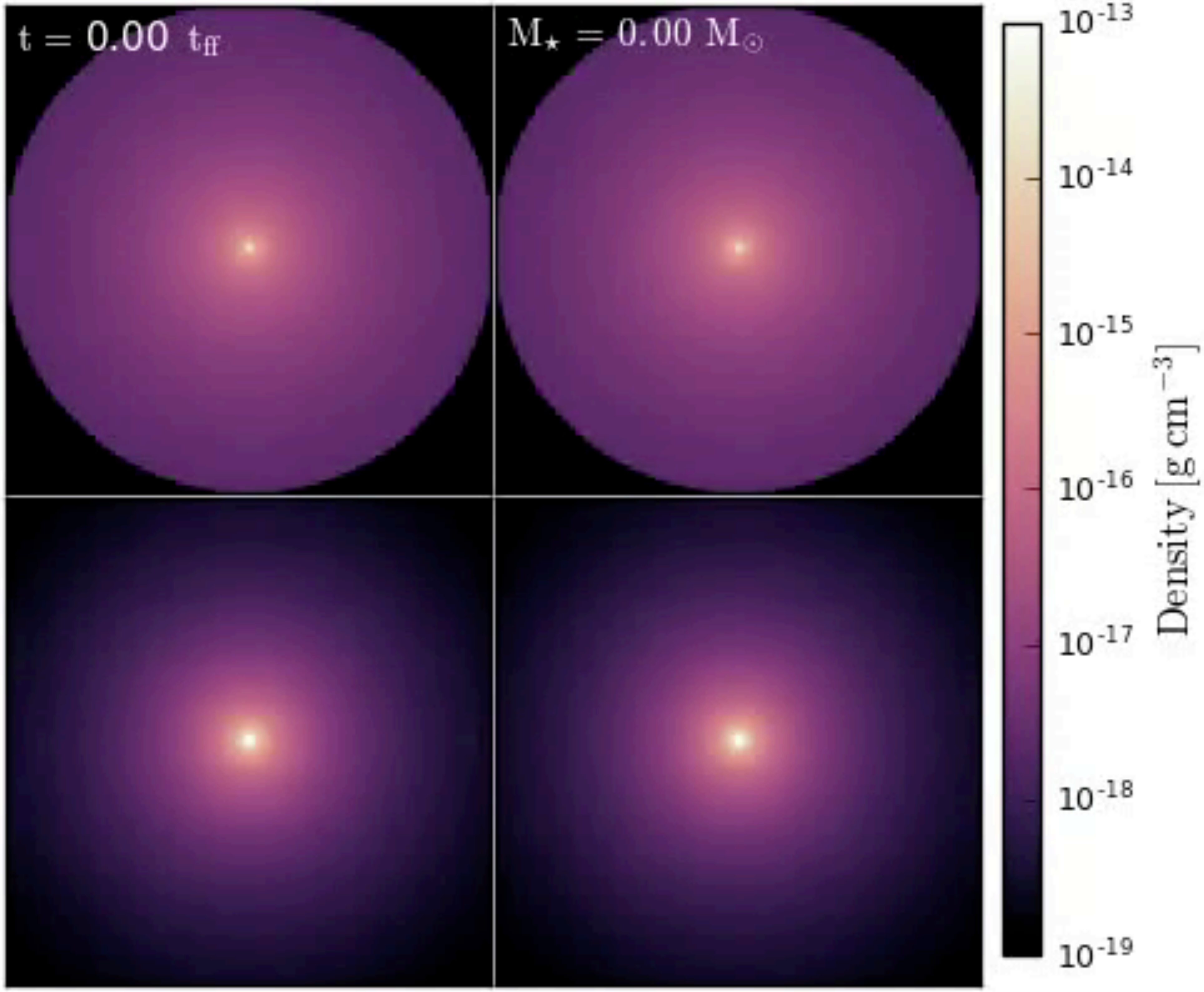
Subcritical

$$\mu_\Phi < 1$$

Observations suggest that dense molecular gas has μ_Φ~2 (supercritical).

Magnetic pressure will slow down collapse and reduce fragmentation.

Massive star formation with B-fields *and* radiative *and* outflow feedback



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$R_{core}=0.1$ pc

$\rho(r) \propto r^{-3/2}$

$\sigma_{1D}=1.2$ km s^{-1}

$\alpha_{vir} \sim 1$

$\Delta x_{min}=20$ AU

$t_{ff}=42{,}710$ yrs

$\mu_\Phi=2$

$B_{z,init} = 0.8$ mG

Subgrid outflow model:

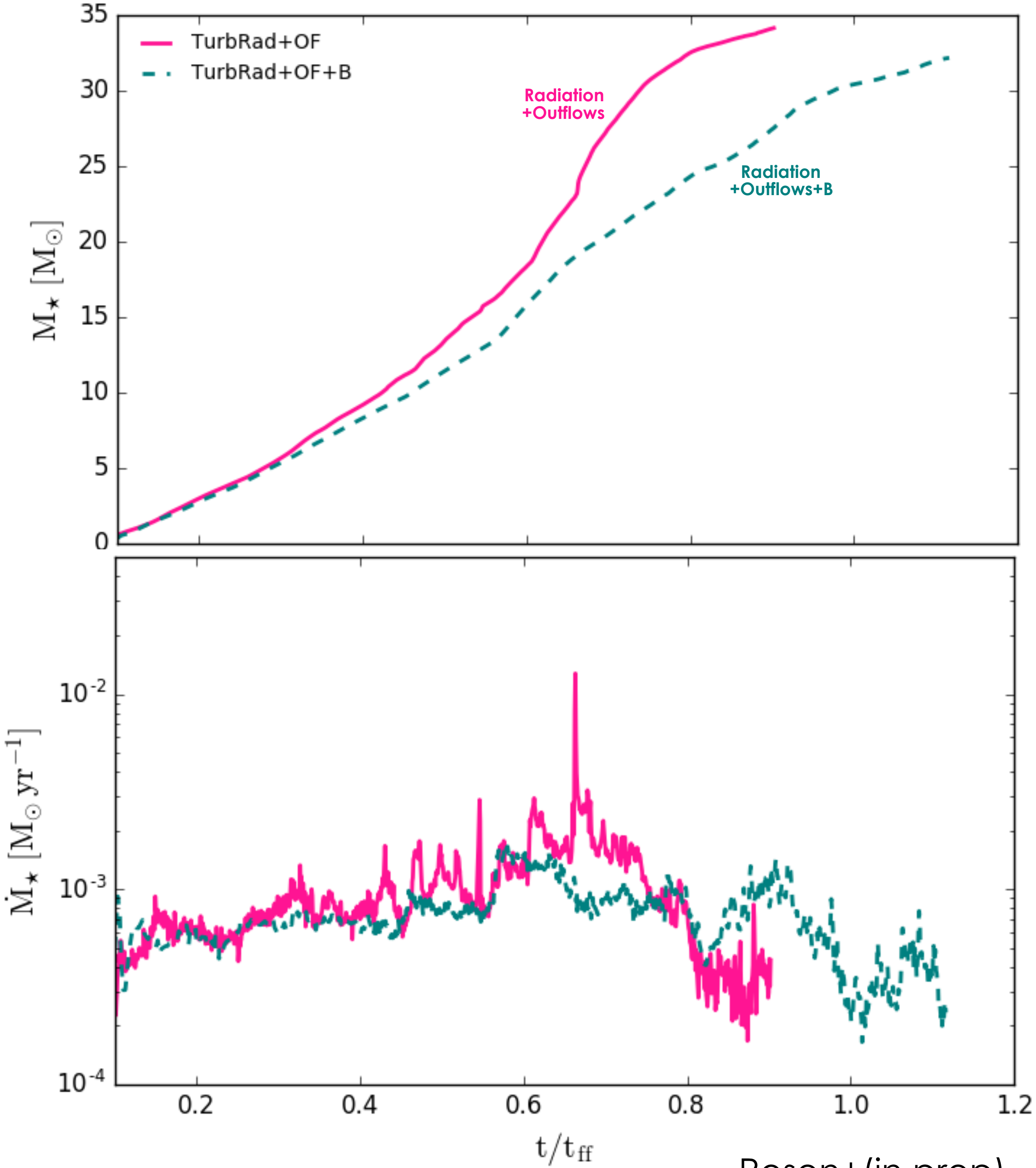
$$p_{\rm OF} = \dot{M}_{\rm OF} v_{\rm OF}$$

$$\dot{M}_{\rm OF} = 0.21 \times \dot{M}_{\rm acc}$$

$$v_{\rm OF} = 0.3 \times v_{\rm esc}$$

(e.g., Matzner & McKee 1999, Cunningham+2011)

Magnetic braking removes angular momentum resulting in a smaller disk. Fragmentation is highly suppressed.



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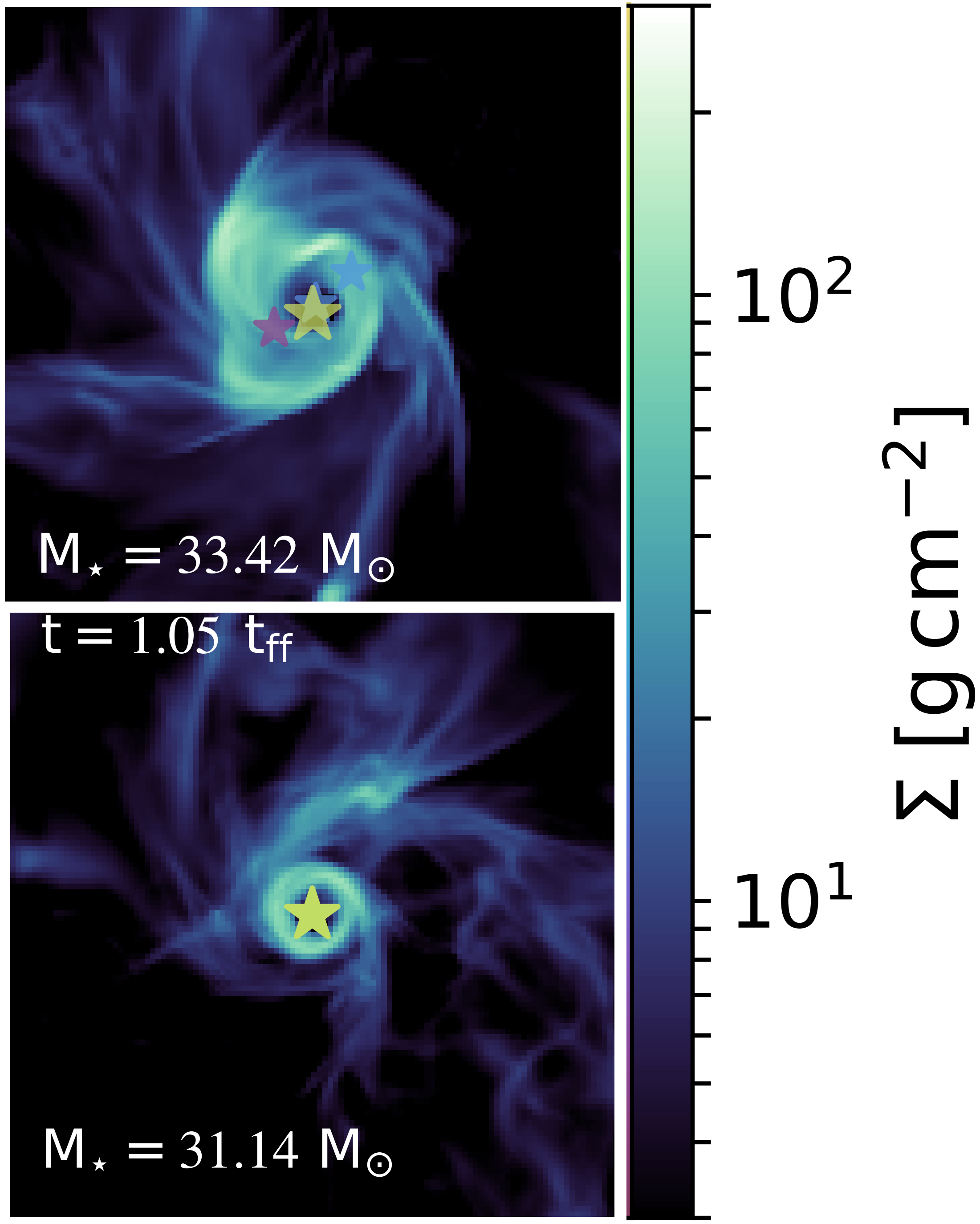
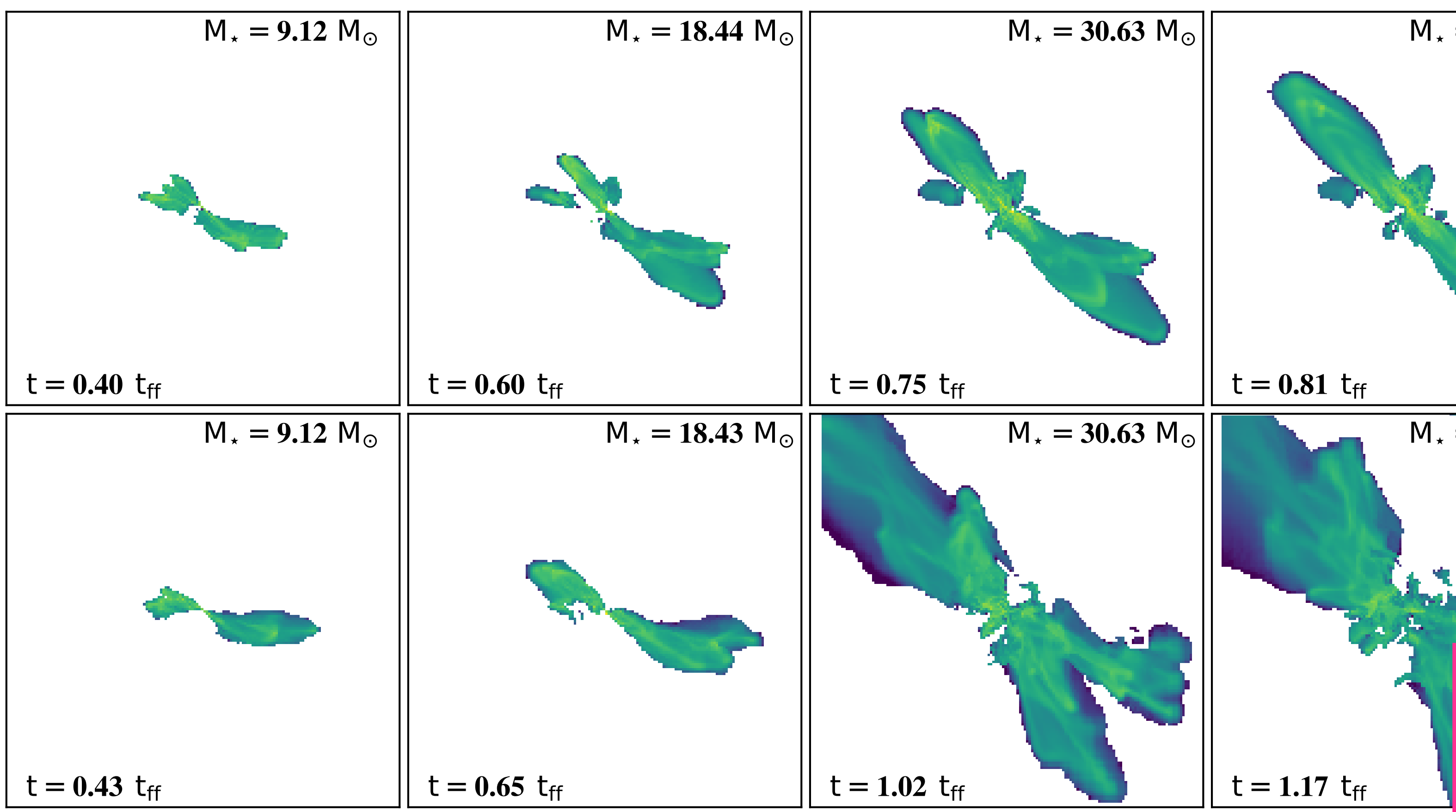


(3,000 AU)²

Inclusion of magnetic fields reduces final stellar mass by ~20% @ t=0.9 t_{ff}

Entrained molecular outflows are collimated, but have wider opening angles when magnetic fields are included

Radiation+Outflows



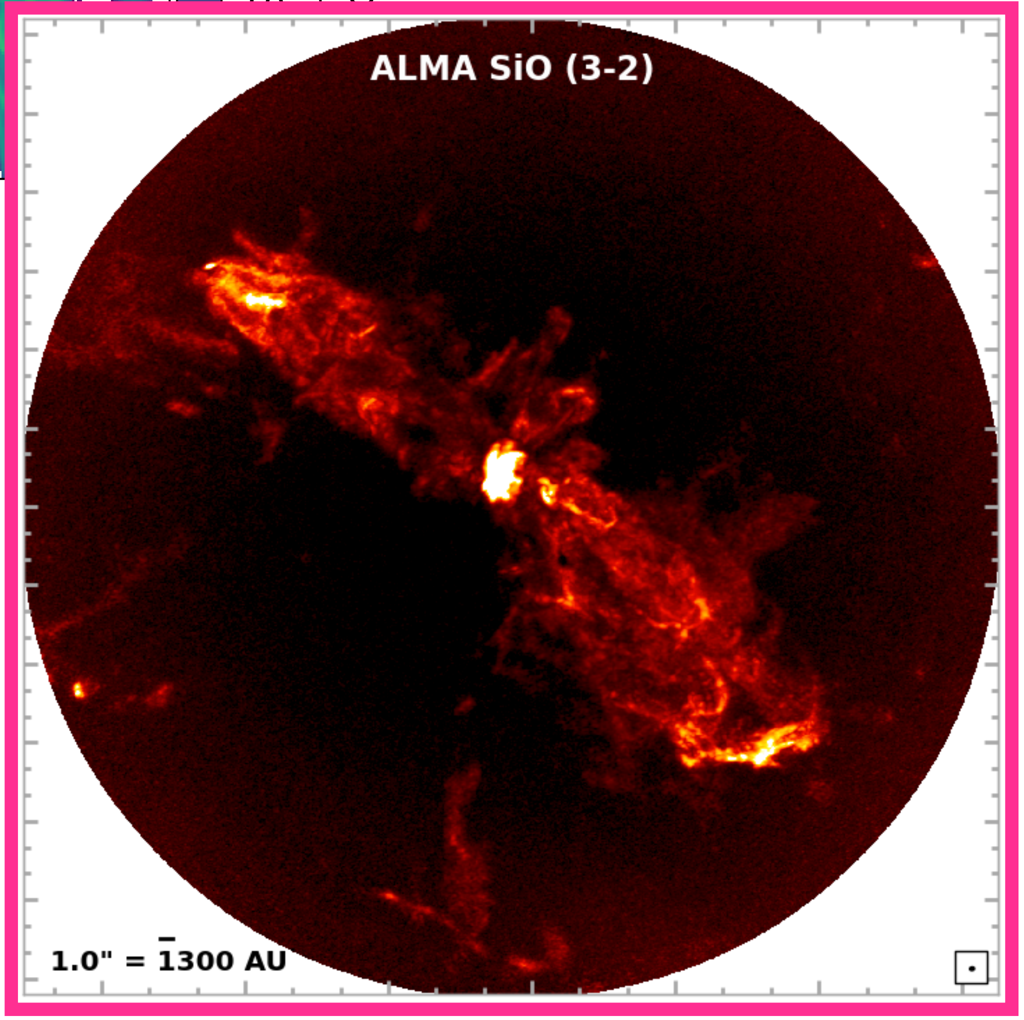
Radiation+Outflows+B

Rosen+(in prep)

$$\rho_w/\rho \gtrsim 5\%$$

$$v_{r,\star} > 0\ \mathrm{km\,s^{-1}}$$

…but how does this compare to observations?



Courtesy of Crystal Brogan

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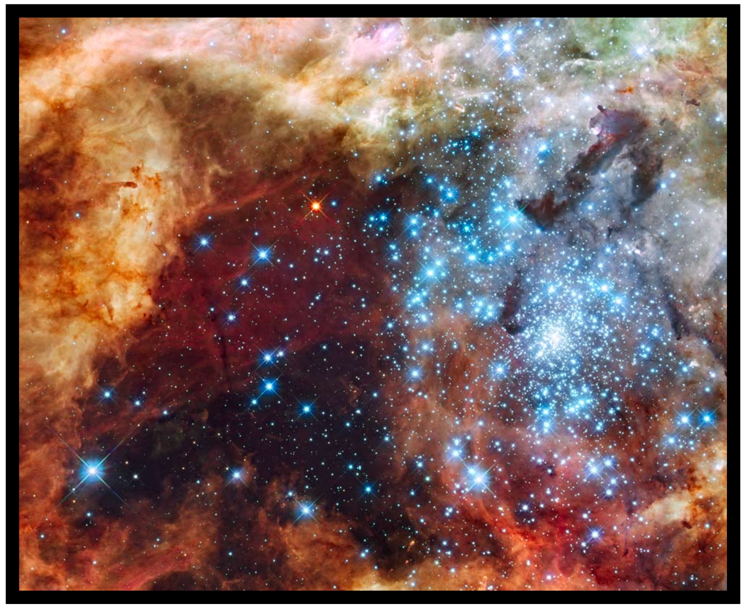

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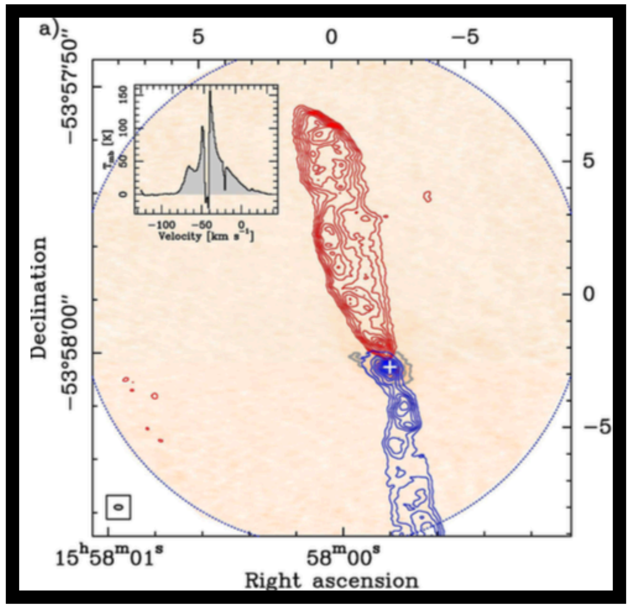
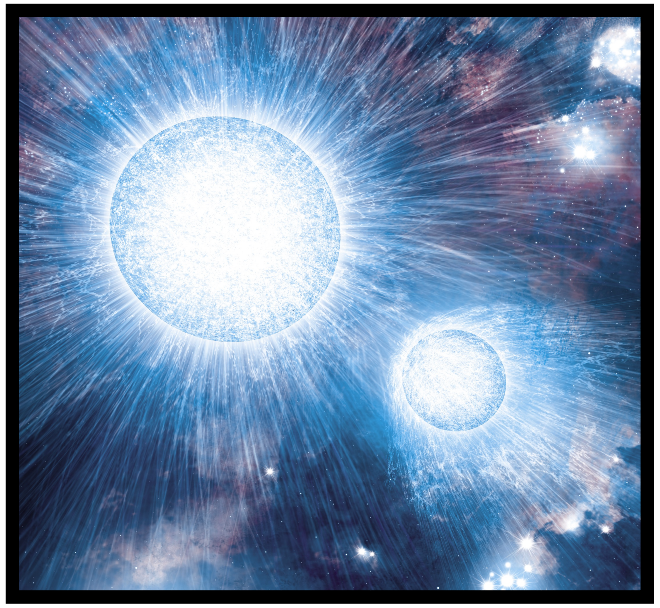


Csengari+2018

Stellar winds



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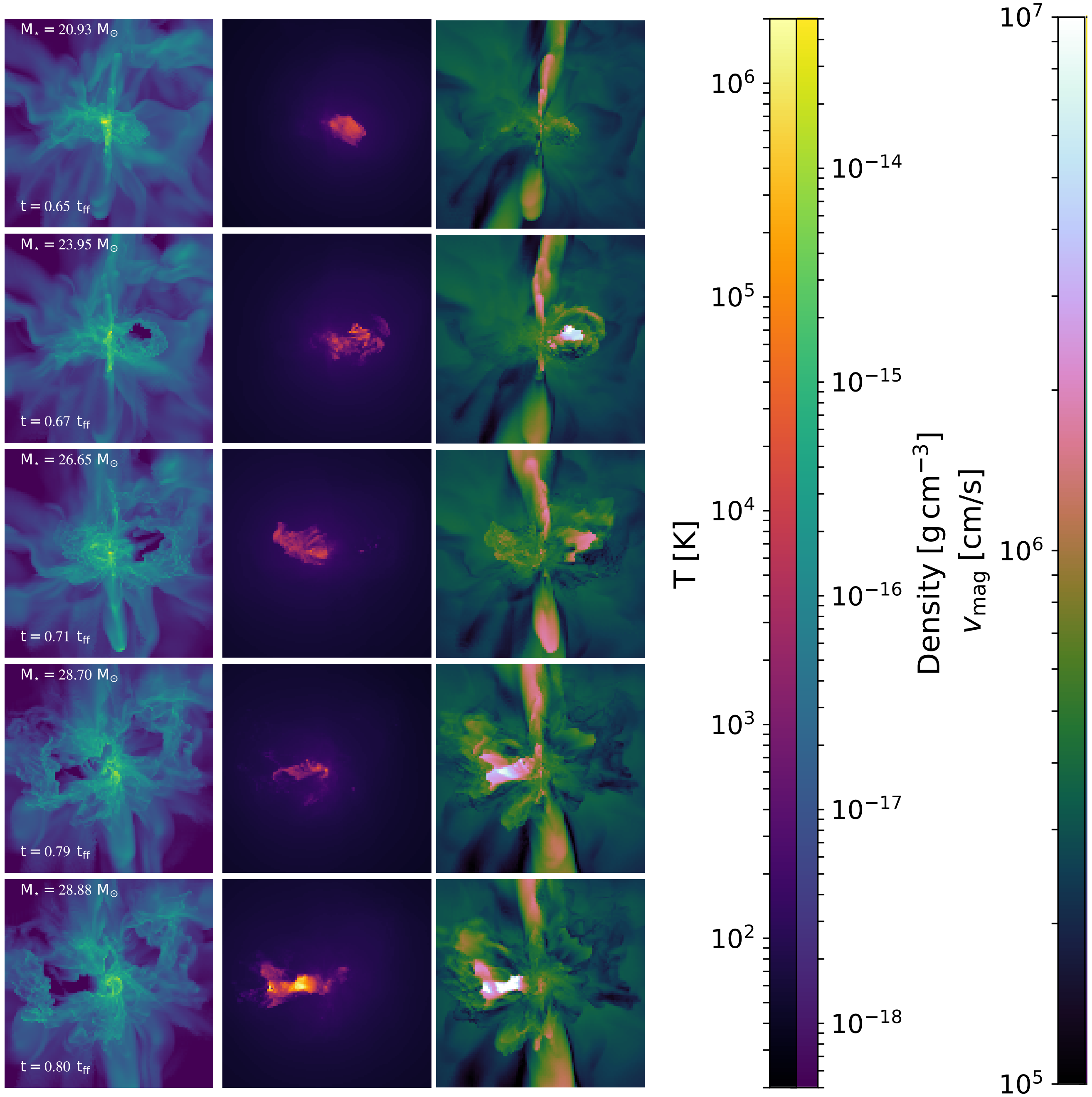
Fast, Isotropic winds should shock heat gas yielding $T_{\rm gas} \gtrsim 10^6$ K, gas adiabatically expands reducing dM/dt

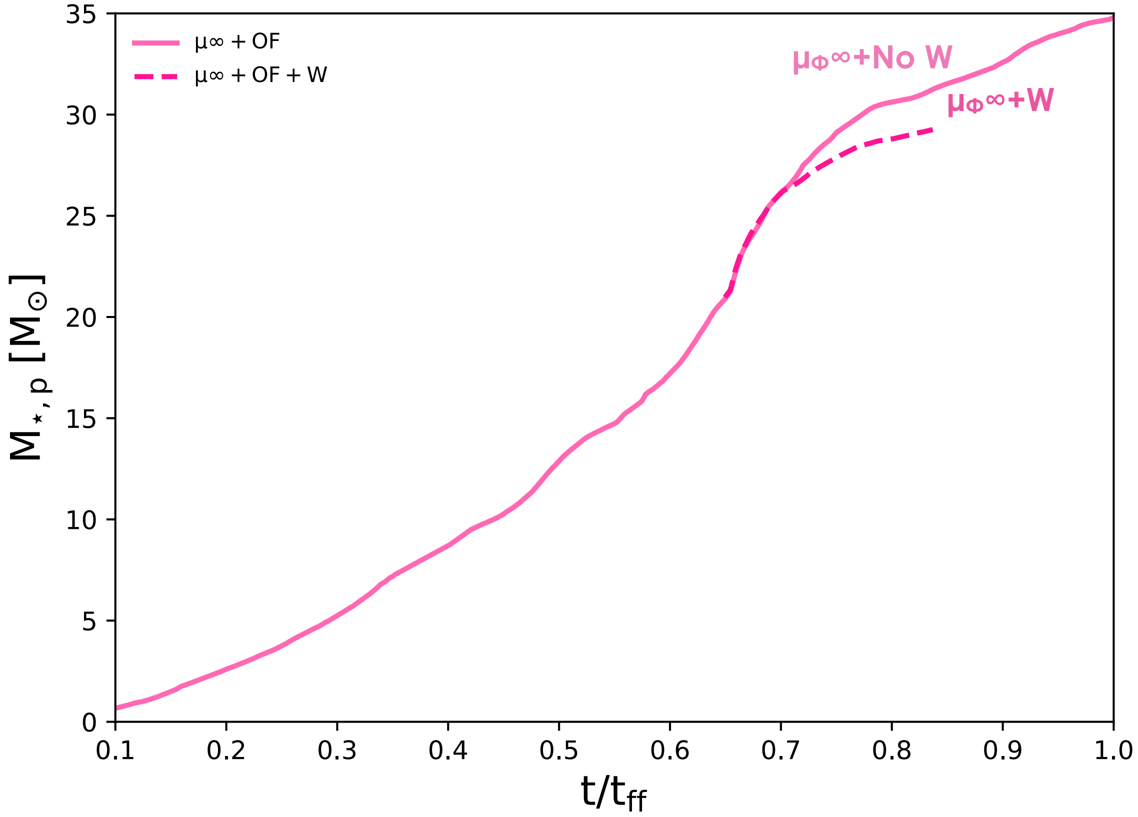
Rad+Outflows+Winds



<Density>$_M$ **<Temperature>$_M$** **<Velocity>$_M$**

(20,000 AU)^2

Rosen+(in progress)



$$\dot{M}_w \sim 10^{-7} - 10^{-6}\ \mathrm{M_\odot\ yr^{-1}}$$

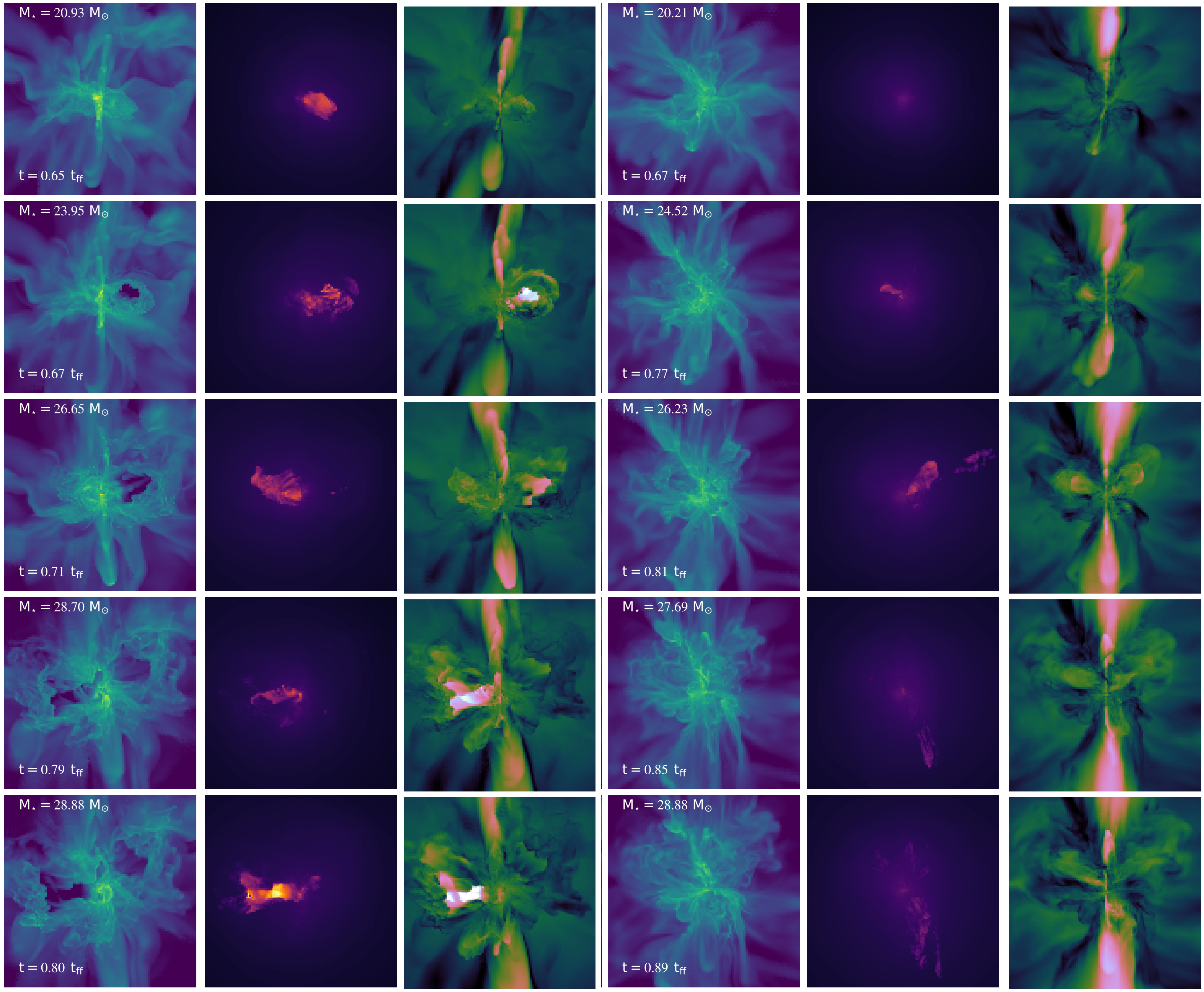
$$v_{\rm w} > 10^3\ \mathrm{km\ s^{-1}}$$

(Turn on winds when $T_{\rm eff}$ > 12.5 kK
following Vink+2001 and Leitherer+1992)

Fast, Isotropic winds should shock heat gas yielding $T_{gas} \gtrsim 10^6$ K, gas adiabatically expands reducing dM/dt

Rad+Outflows+Winds

Rad+Outflows+Winds+ B-Fields



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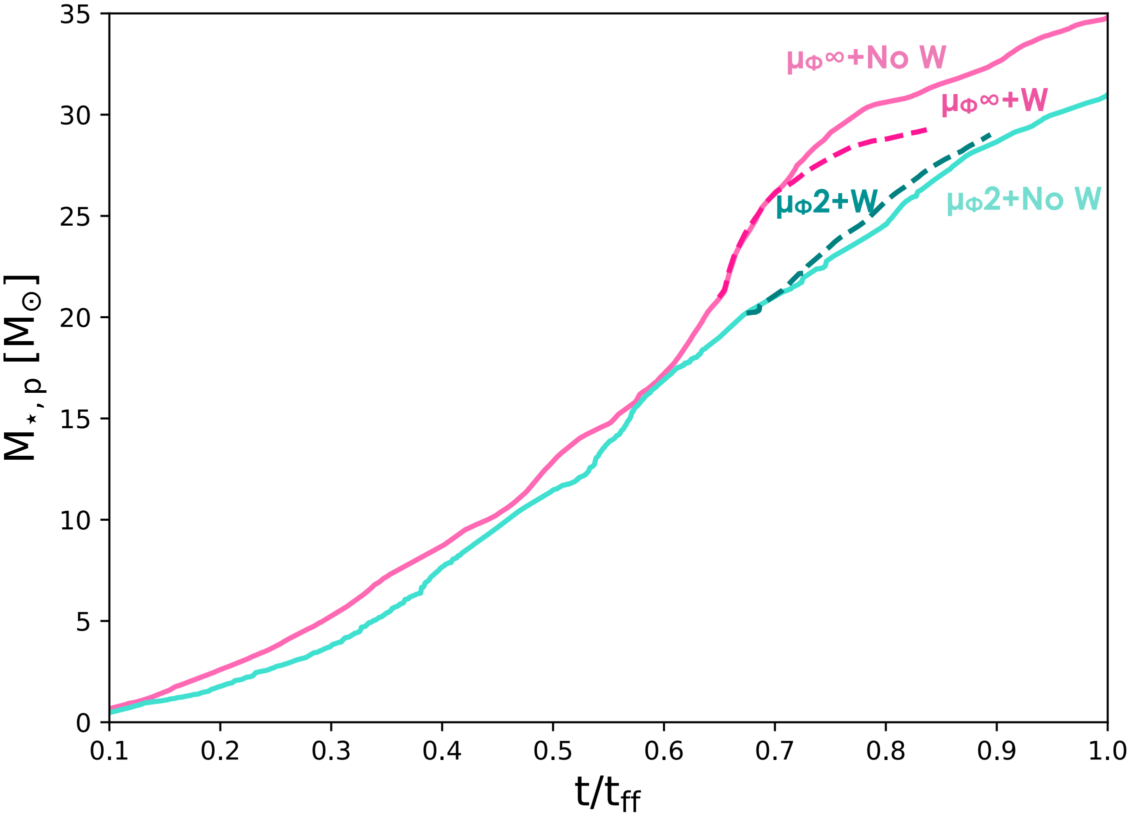

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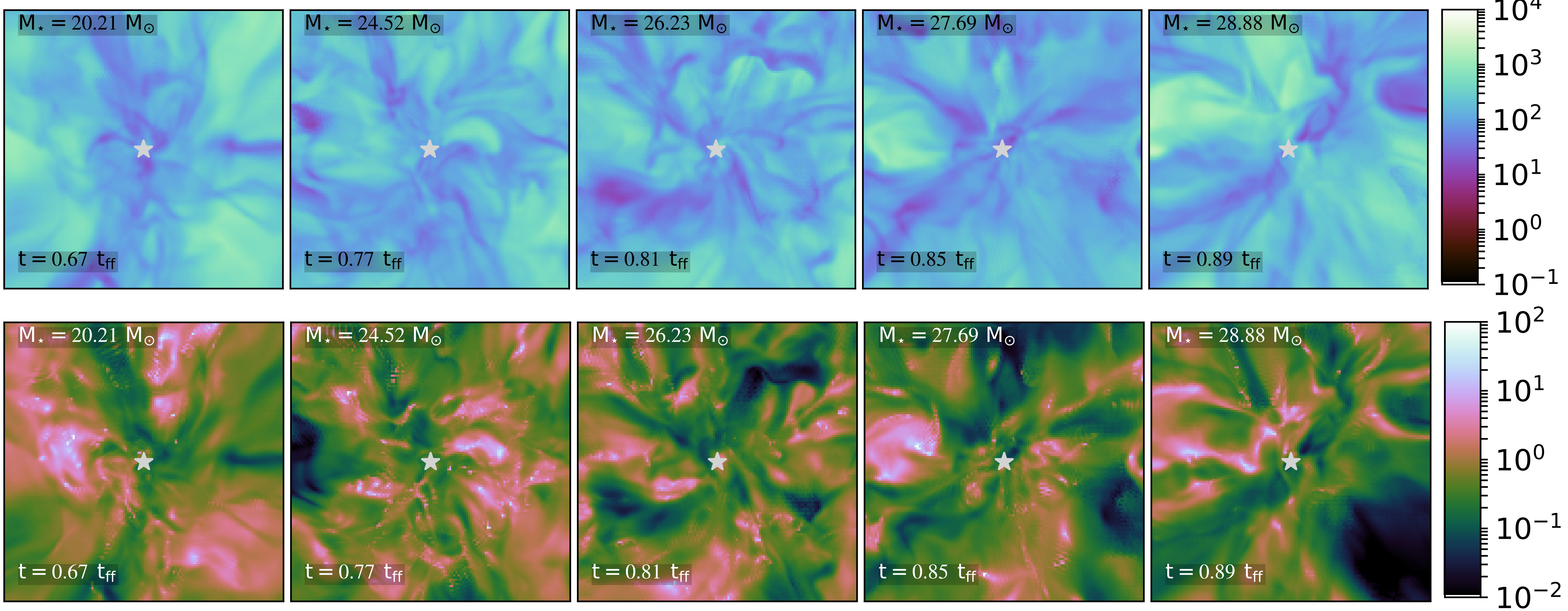
Preliminary results …. Stay tuned!

Magnetic pressure confines winds, reducing shock heating and adiabatic expansion → larger ρ and c_s such that dM/dt increases.

Magnetic Pressure/Thermal Pressure

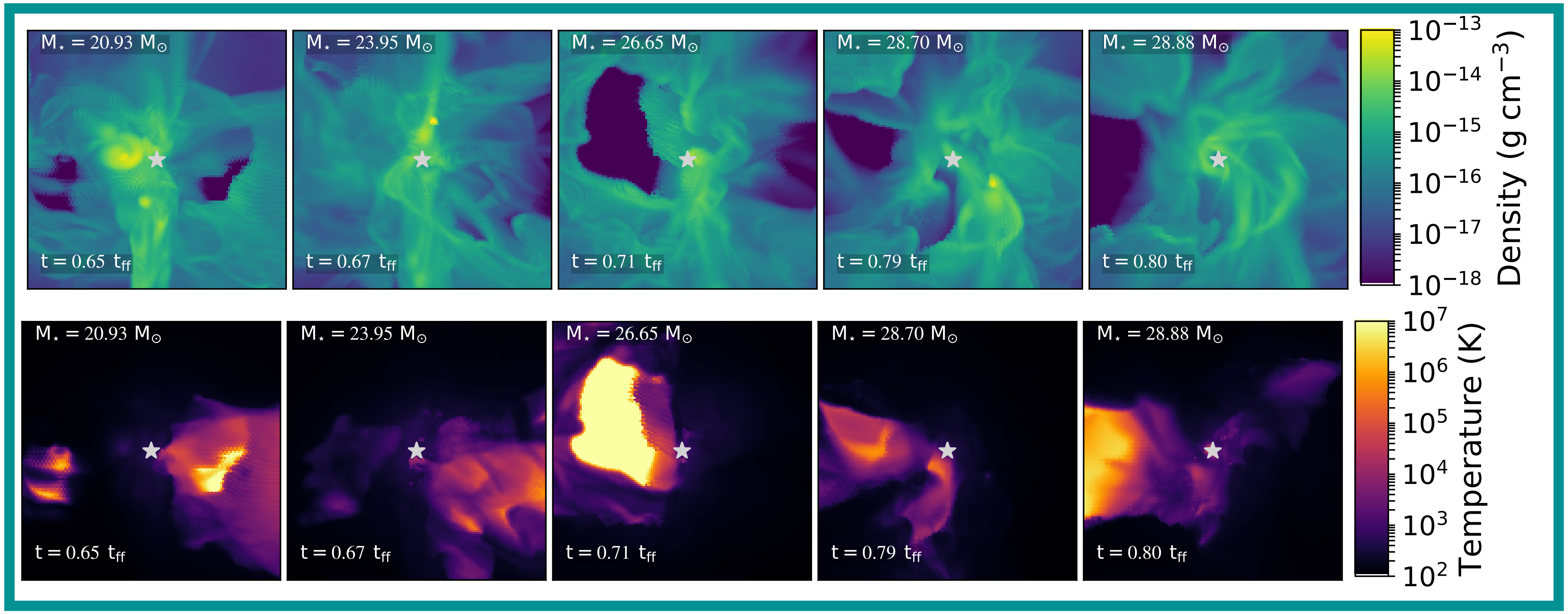


Magnetic Pressure/Ram Pressure
($P_{ram} = \rho v^2$)

Preliminary results …. Stay tuned!

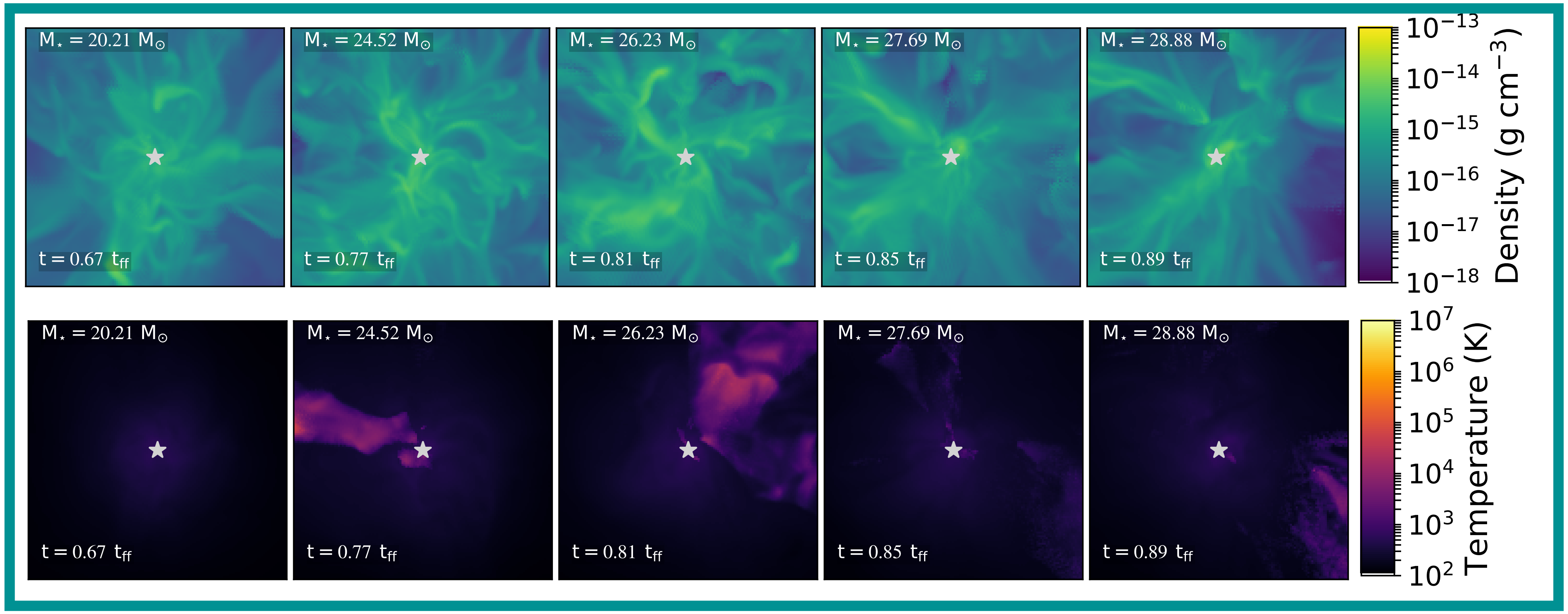
Magnetic pressure confines winds, reducing shock heating and adiabatic expansion → larger ρ and c_s such that dM/dt increases.

Winds+ No B



(4,000 AU)²

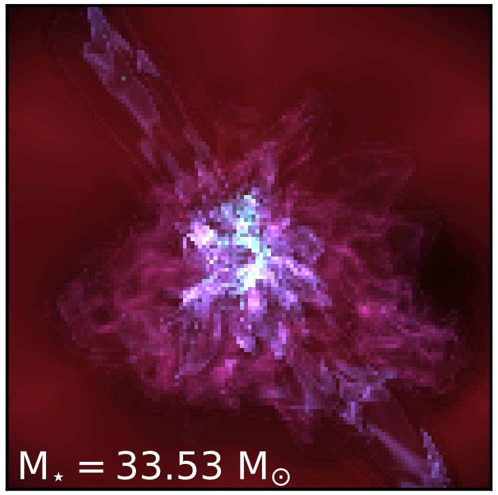
Winds+B



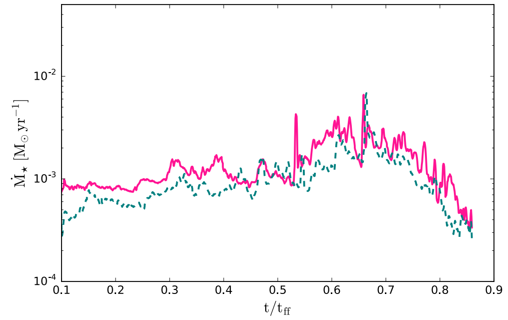
(4,000 AU)²

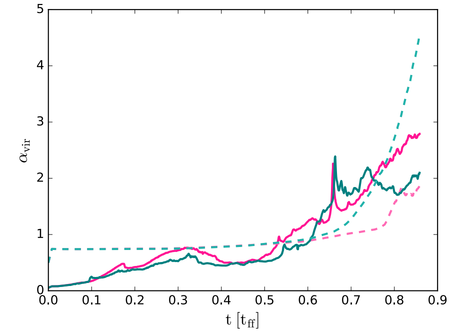
Preliminary results …. Stay tuned!

Summary



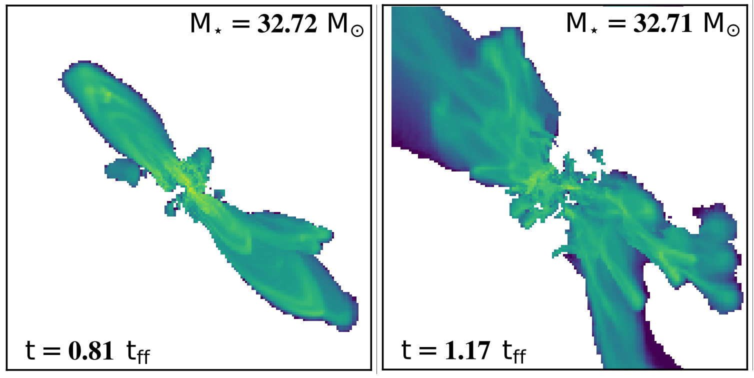
Performed 3D R(M)HD simulations of the formation of massive stellar systems from the collapse of turbulent massive pre-stellar cores with radiative, collimated outflow, and isotropic wind feedback.

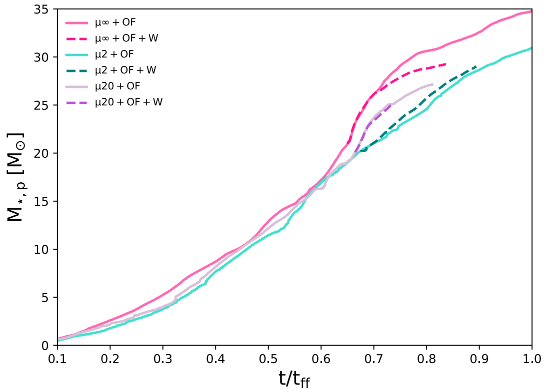




Inclusion of feedback by outflows in addition to radiation pressure:

- Reduces effective mass growth by ~10% than radiation alone.
- Ejects jet and entrained material from core, results in unbinding core.

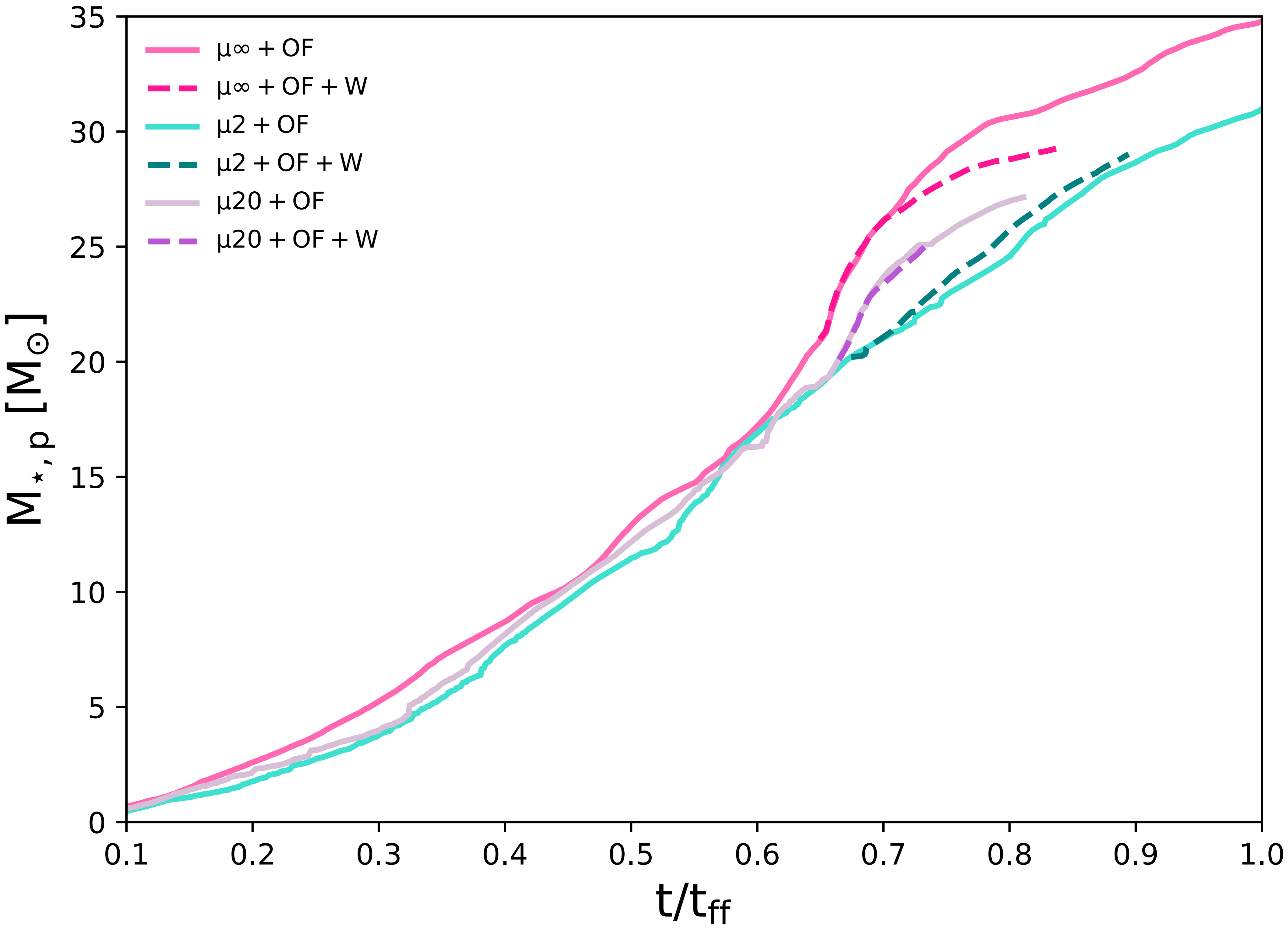




Inclusion of magnetic fields in MSF:

- Slows down the growth of massive stars
- Significantly reduces formation of companions via turbulent fragmentation.
- Leads to wider collimated molecular outflows.
- When winds are included, leads to a positive (?) feedback effect (at least at early times)

What about weak magnetic fields?



Preliminary results …. Stay tuned!