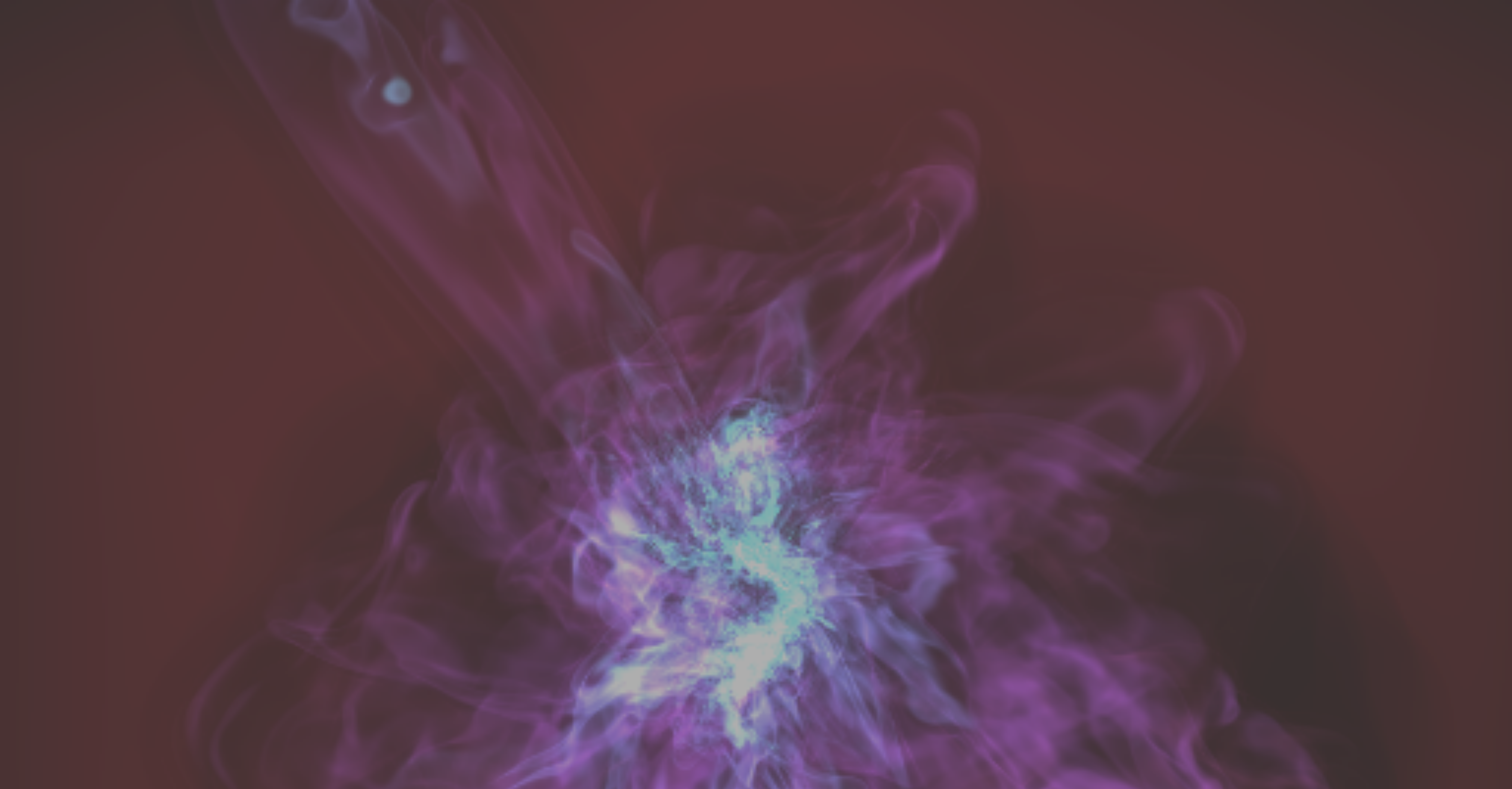


HOW OUTFLOWS AND RADIATIVE FEEDBACK LIMIT ACCRETION ONTO MASSIVE STARS

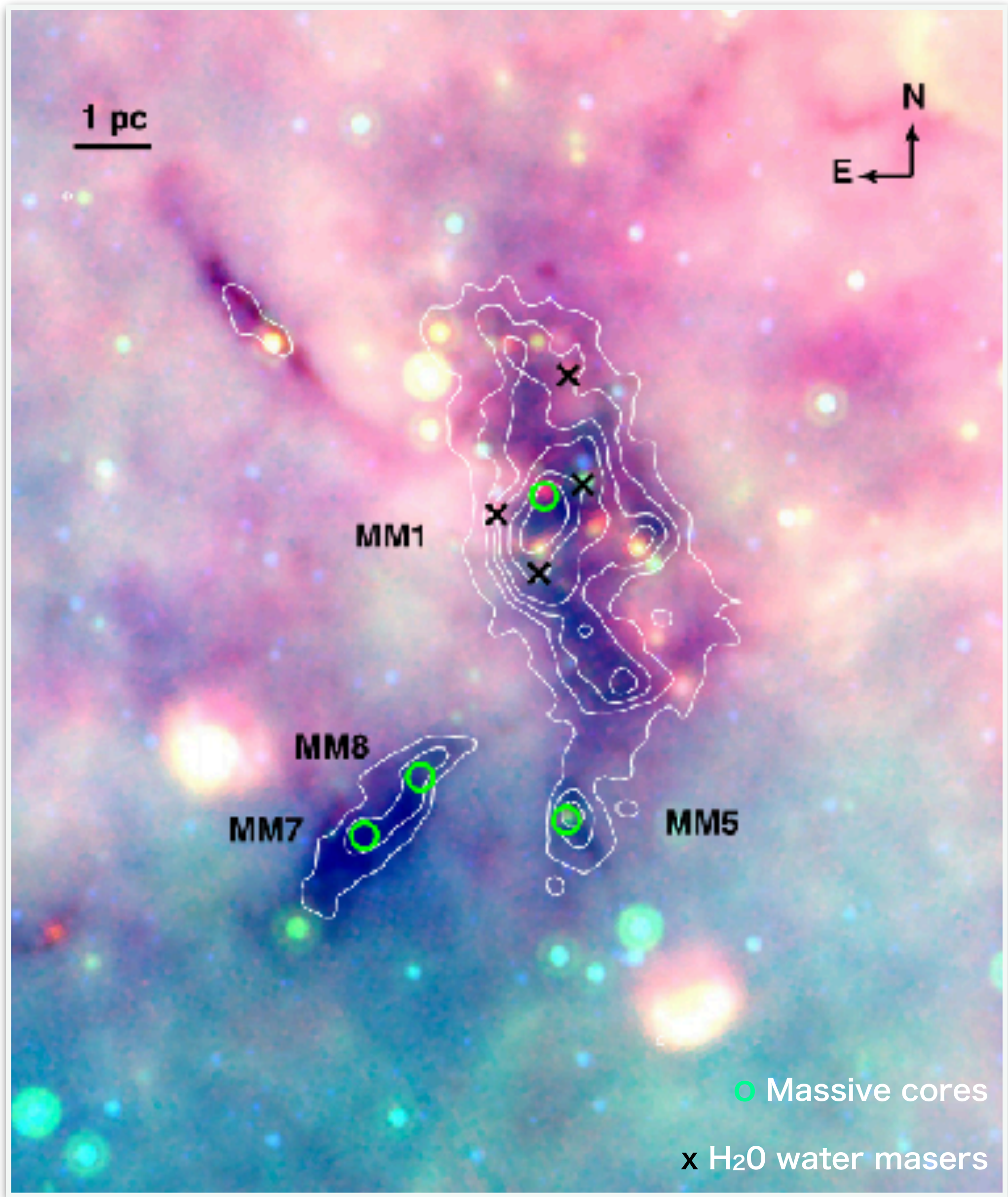
Anna Rosen
NASA Einstein Fellow
Harvard-Smithsonian Center for Astrophysics

In collaboration with: Alyssa Goodman (CfA), Richard Klein (UCB/LLNL), Mark Krumholz (ANU), Aaron Lee (UT Austin), Chris McKee (UCB), Jeff Oishi (Bates College)

Harvard-Smithsonian Center for Astrophysics

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 supported by turbulent pressure
  $$P_{\rm Turb} \gg P_{\rm Th}$$
- Observations suggest massive cores have $\alpha_{\rm vir} \lesssim 1$

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

(e.g., Pillai+2011, Tan+2013, Battersby+2014, Lu+2015, Zhang+2015, Ohashi+2015)

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:

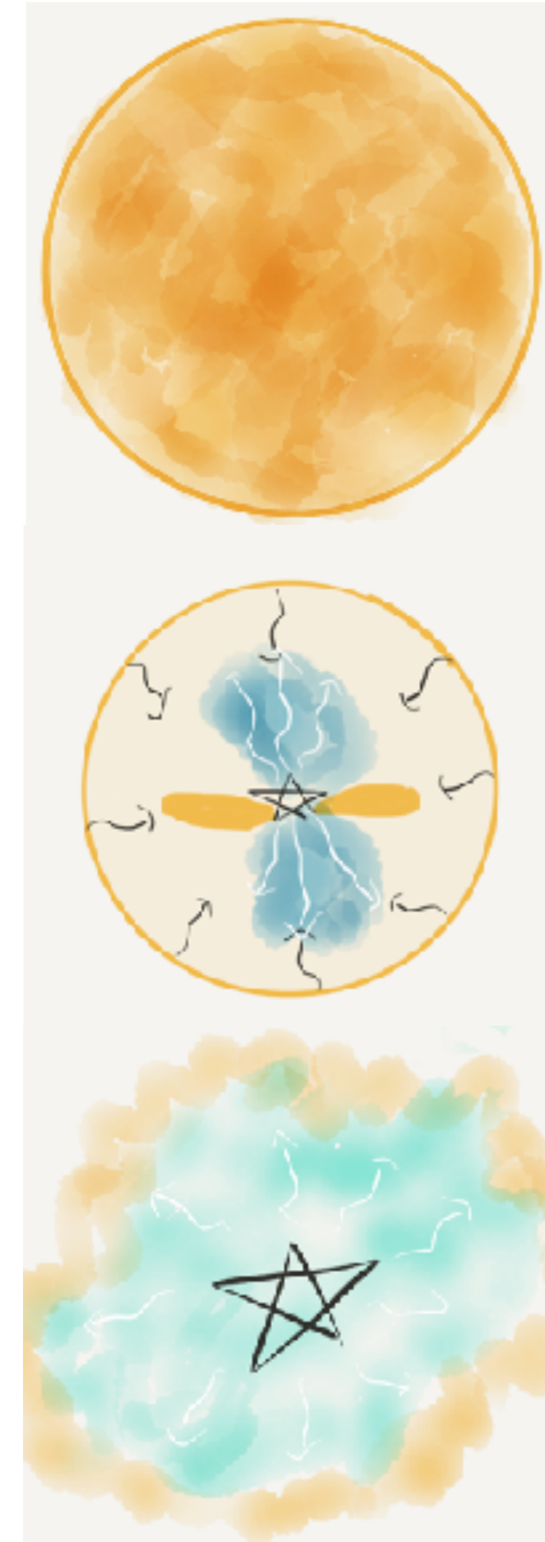
$$f_{\rm rad} = \frac{L_\star}{4\pi r^2 c}(1 + f_{\rm trap})$$

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

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

Radiation halts isotropic accretion when $f_{\rm edd} \gtrsim 1$

for $M_\star \gtrsim 20\ M_\odot$

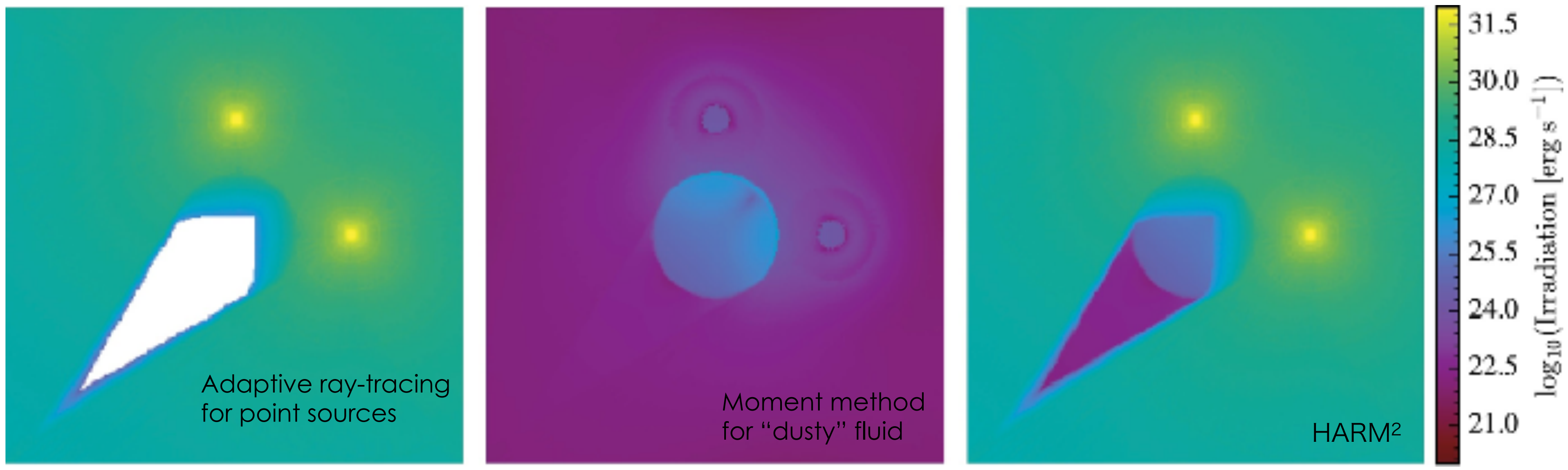


(e.g., Larson & Starrfield 1971, Kahn 1974, Yorke 1979, Yorke+1995, Wolfire & Cassinelli 1986, 1987; Yorke & Bodenheimer 1999)

Modeling massive star formation requires **multi**-dimensional **radiation**-hydrodynamic simulations

Modeling radiation pressure in (massive) star formation simulations

Hybrid Adaptive Ray-Moment Method (HARM²):



Direct radiation pressure | Dust-reprocessed radiation pressure

Rosen+2017

Absorption of (multi-frequency) stellar radiation field:

Radiative Transfer Equation along ray:

$$\frac{\partial L_{\mathrm{ray},j}}{\partial r} = -\kappa_j \rho L_{\mathrm{ray},j},$$

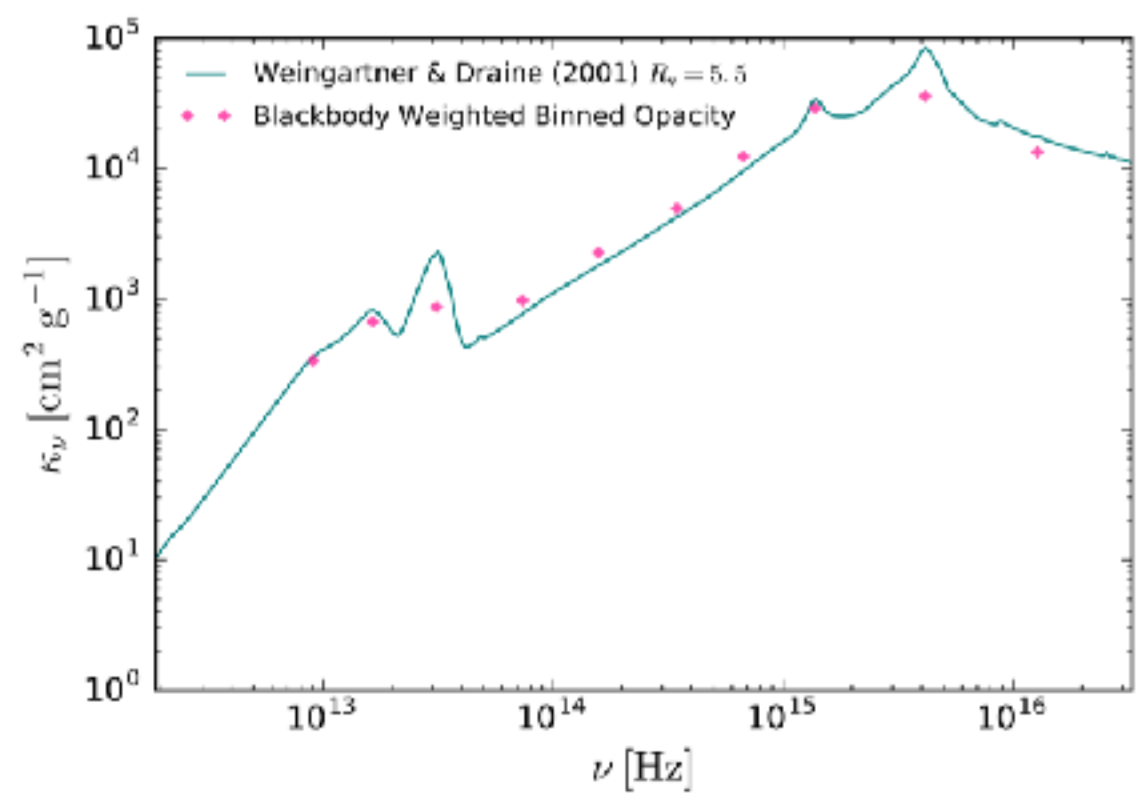
Luminosity absorbed ($\tau_j = \rho_d \kappa_j\, dl$):

$$dL_{\mathrm{ray},j} = L_{\mathrm{ray},j}\left(1 - e^{-\tau_j}\right)$$

Energy and momentum deposition:

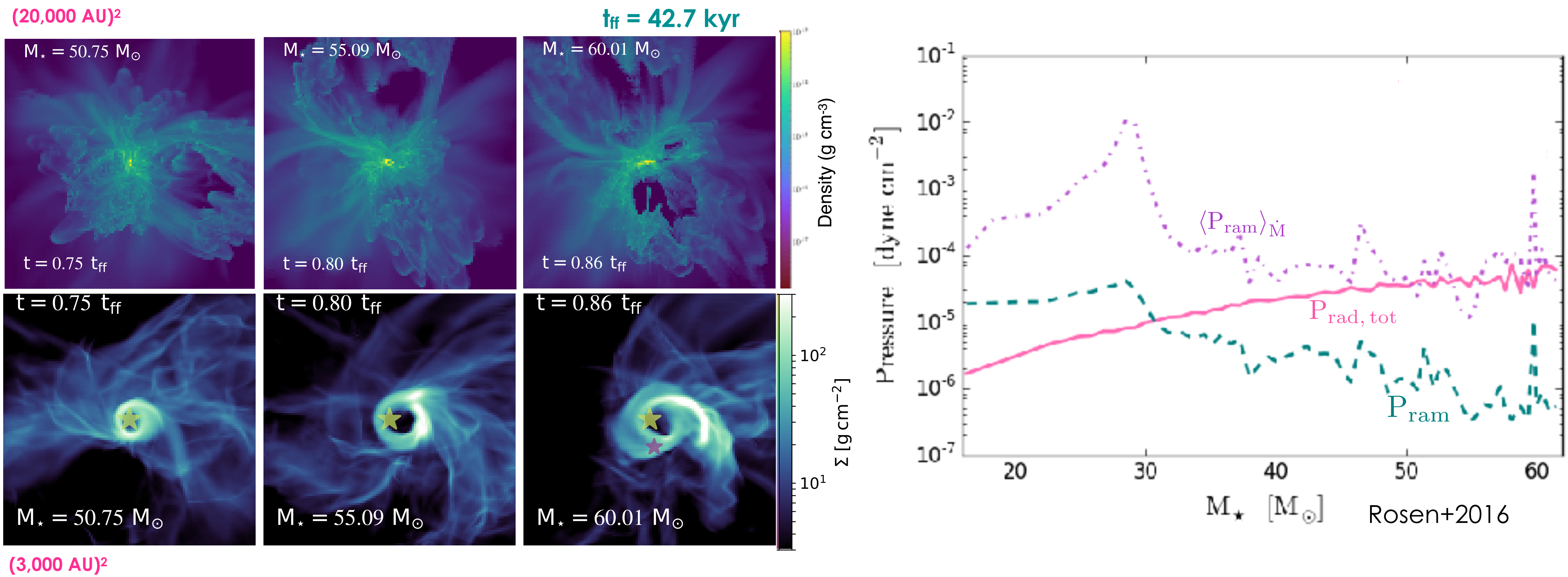
$$\dot{\varepsilon}_{\mathrm{rad,ray}} = \sum_{j=1}^{N_\nu} dL_{\mathrm{ray},j}$$

$$\dot{\mathbf{p}}_{\mathrm{rad,ray}} = \sum_{j=1}^{N_\nu} \frac{dL_{\mathrm{ray},j}}{c}\mathbf{n}.$$



Rosen+2016

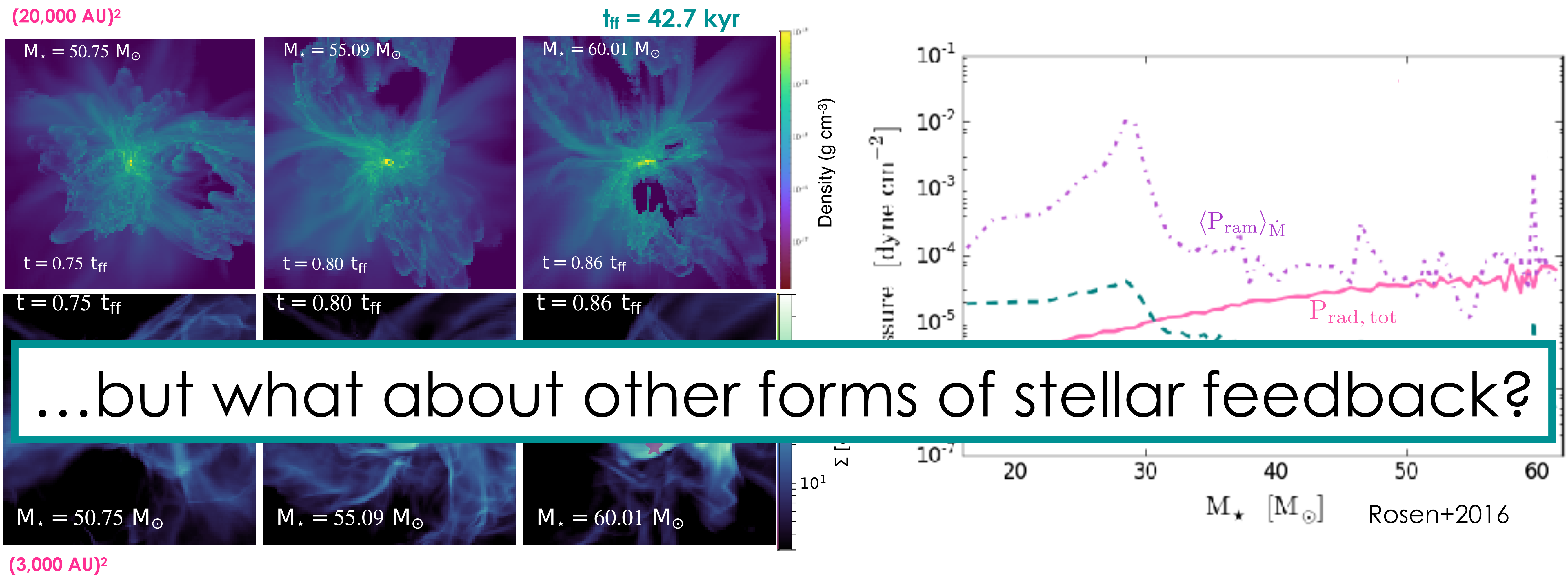
Overcoming the radiation pressure barrier



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.

Overcoming the radiation pressure barrier

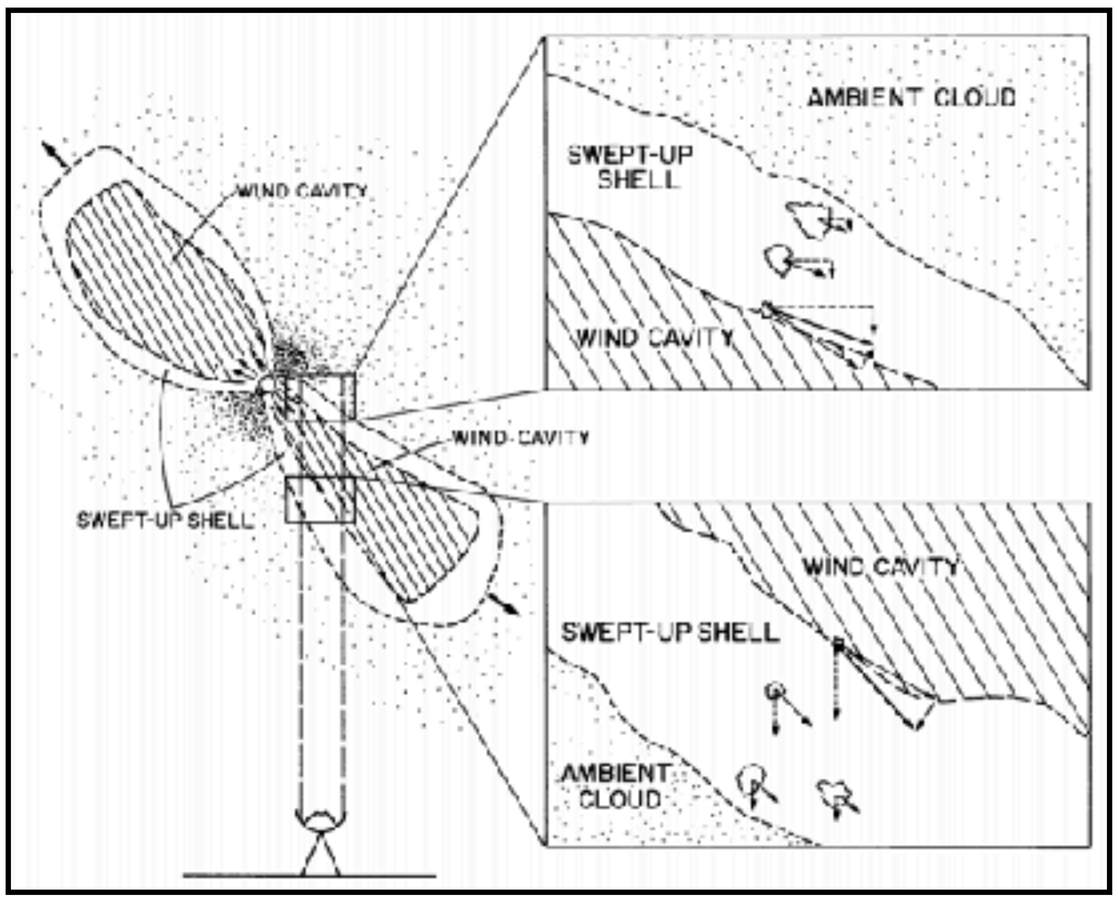


…but what about other forms of stellar feedback?

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

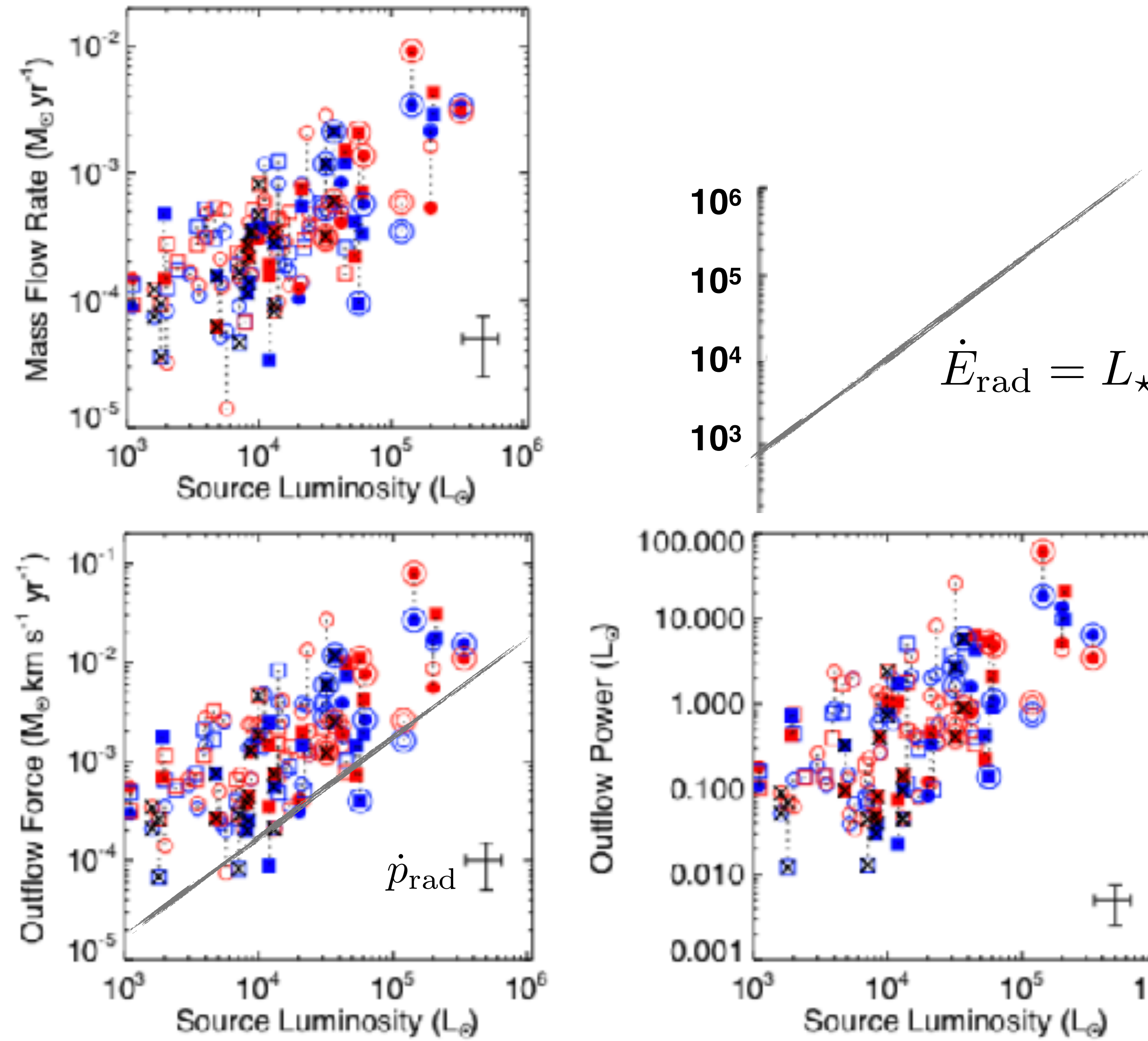
High accretion rates and infalling filaments provide sufficient ram pressure to overcome radiation pressure.

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



Lada 1985, ARAA

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

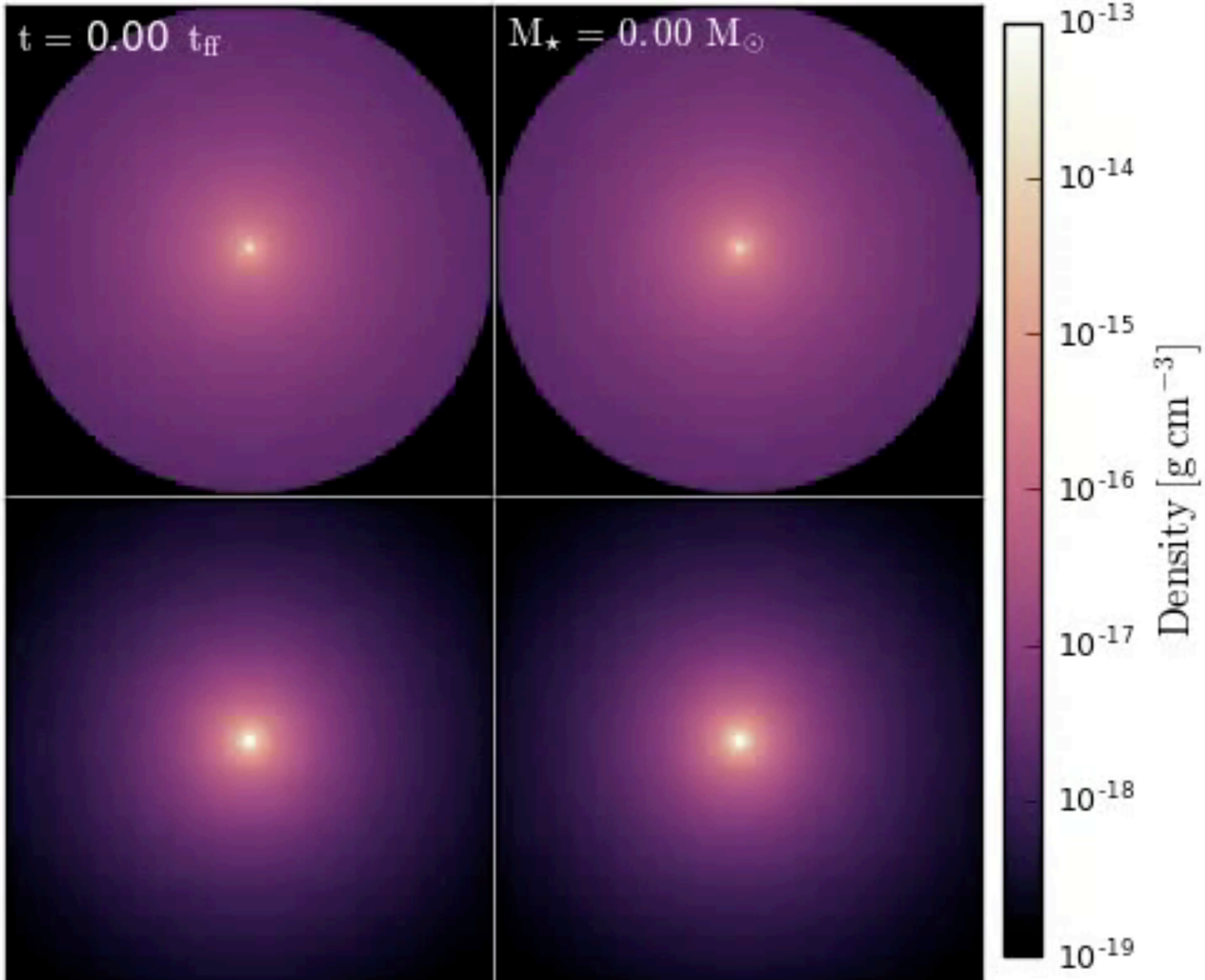


Maud+2015

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

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}

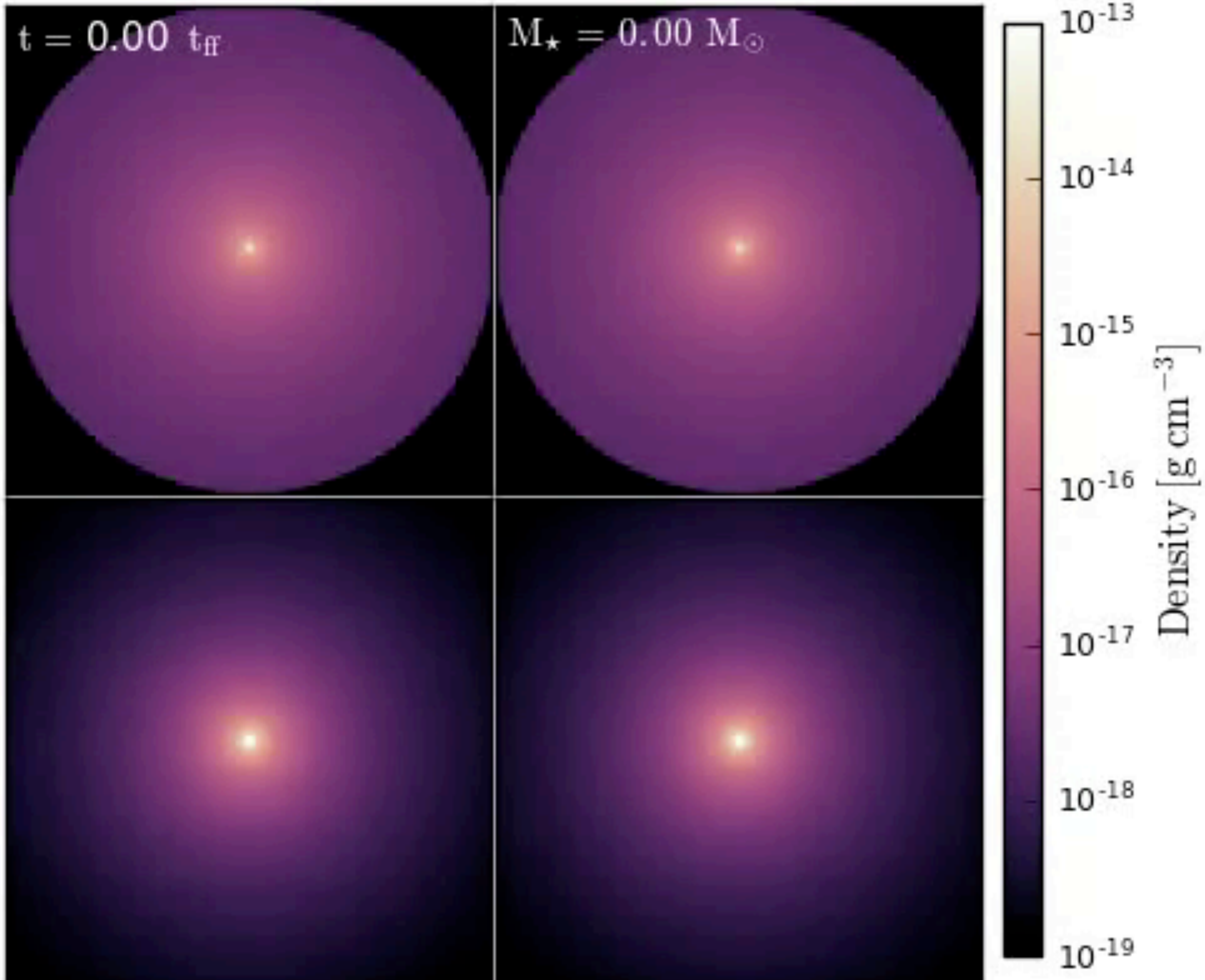
$\alpha_{vir} \sim 1$

Δx_{min}=20 AU

t_{ff}=42,710 yrs

$$p_{\rm OF} = \dot{M}_{\rm OF} v_{\rm OF}$$
$$\dot{M}_{\rm OF} = 0.21 \times \dot{M}_{\rm acc}$$
$$v_{\rm OF} = 0.3 \times v_{\rm esc}$$

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}

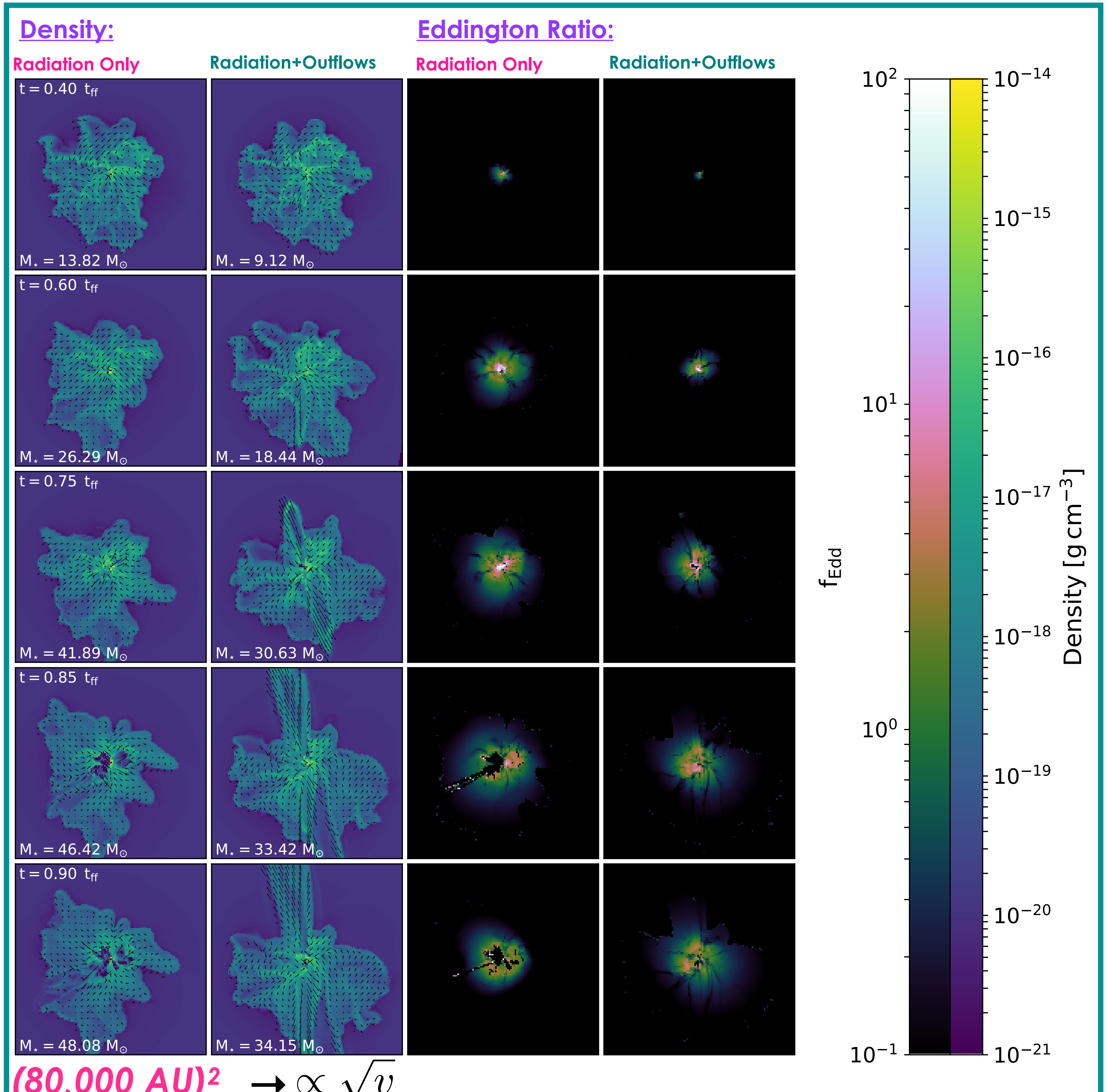
$\alpha_{vir} \sim 1$

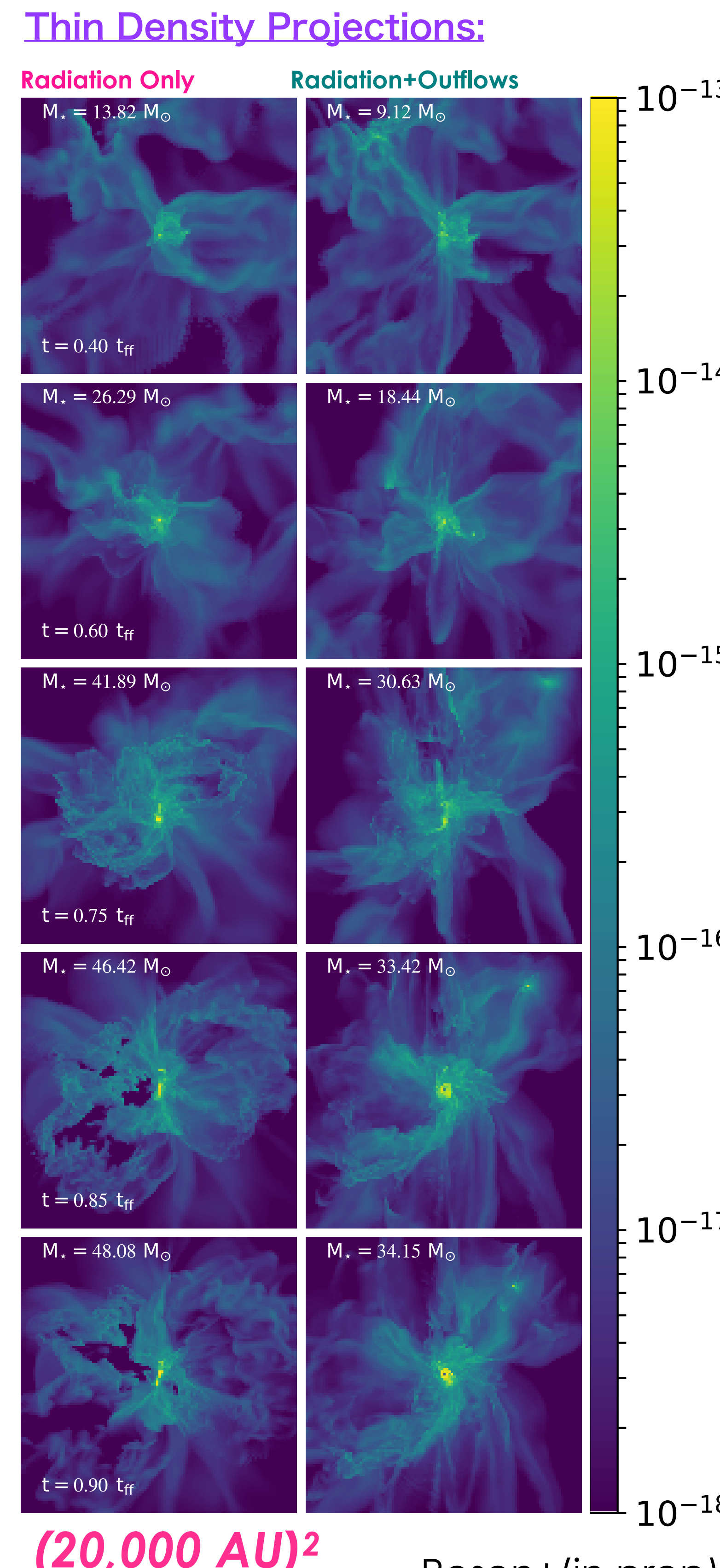
Δx_{min}=20 AU

t_{ff}=42,710 yrs

$$p_{\rm OF} = \dot{M}_{\rm OF} v_{\rm OF}$$
$$\dot{M}_{\rm OF} = 0.21 \times \dot{M}_{\rm acc}$$
$$v_{\rm OF} = 0.3 \times v_{\rm esc}$$

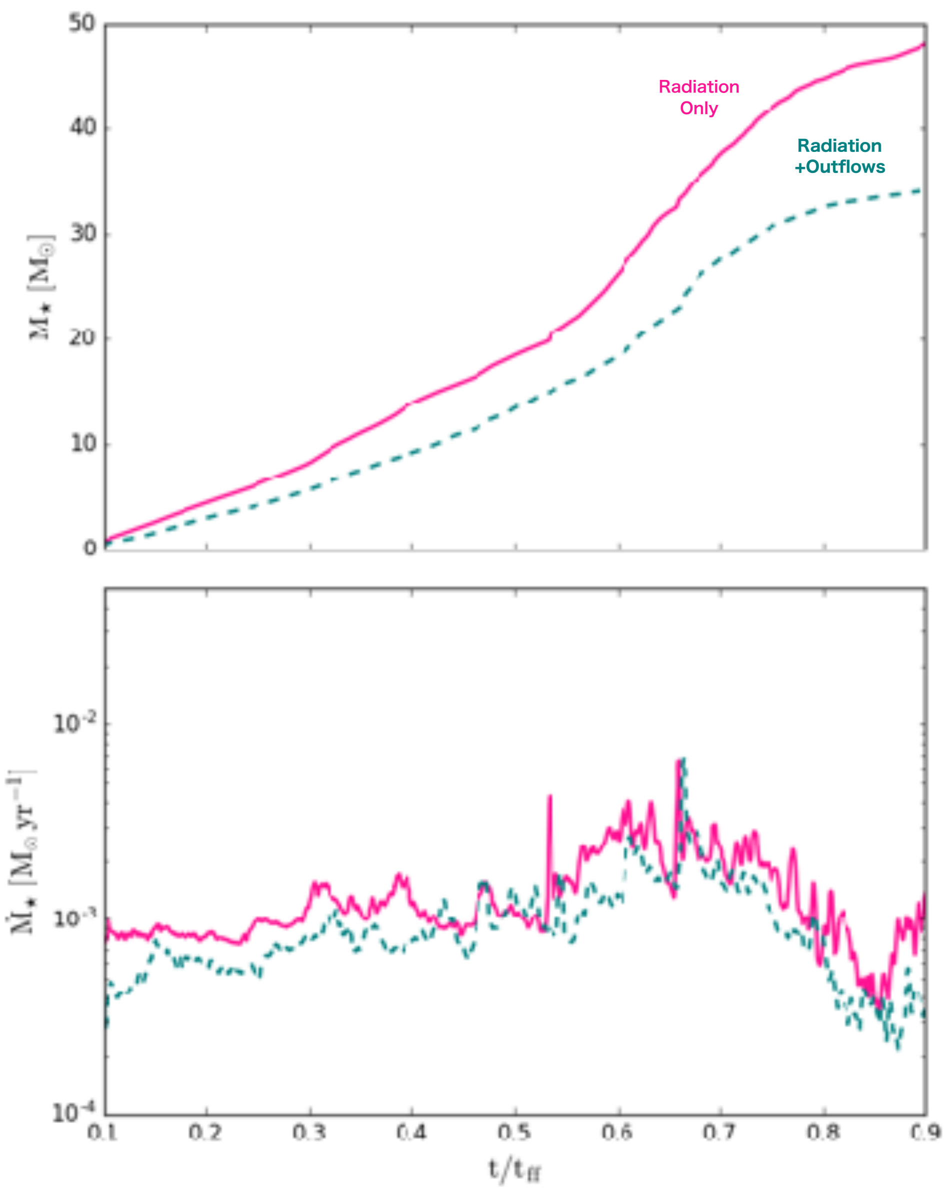
Outflows punch holes in ISM along the star's polar directions allowing radiation to escape, thereby reducing the development of RT instabilities.



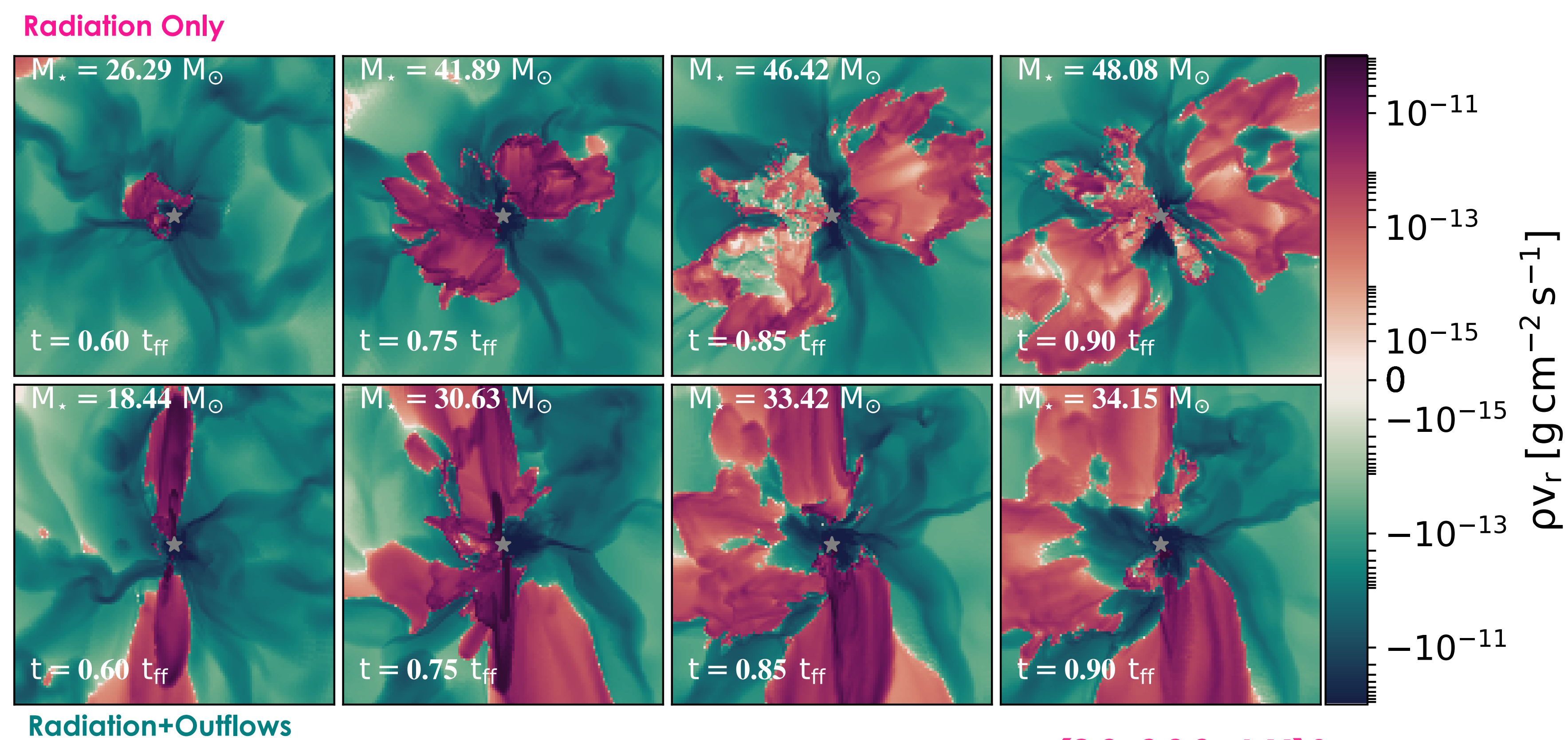


Rosen+(in prep)

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

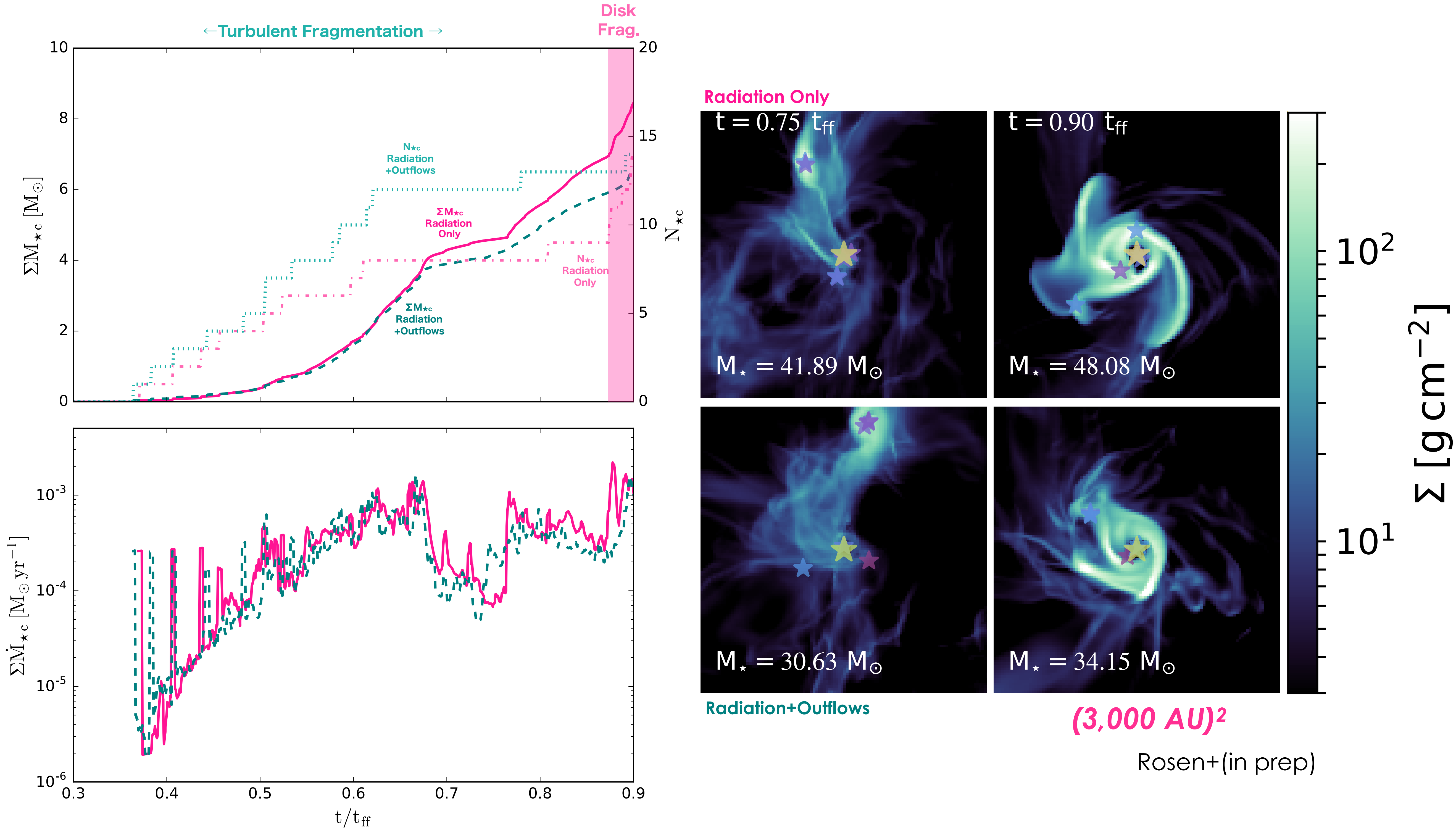


Rosen+(in prep)



21% of accreted mass ejected by outflows
→ only ~8% difference!

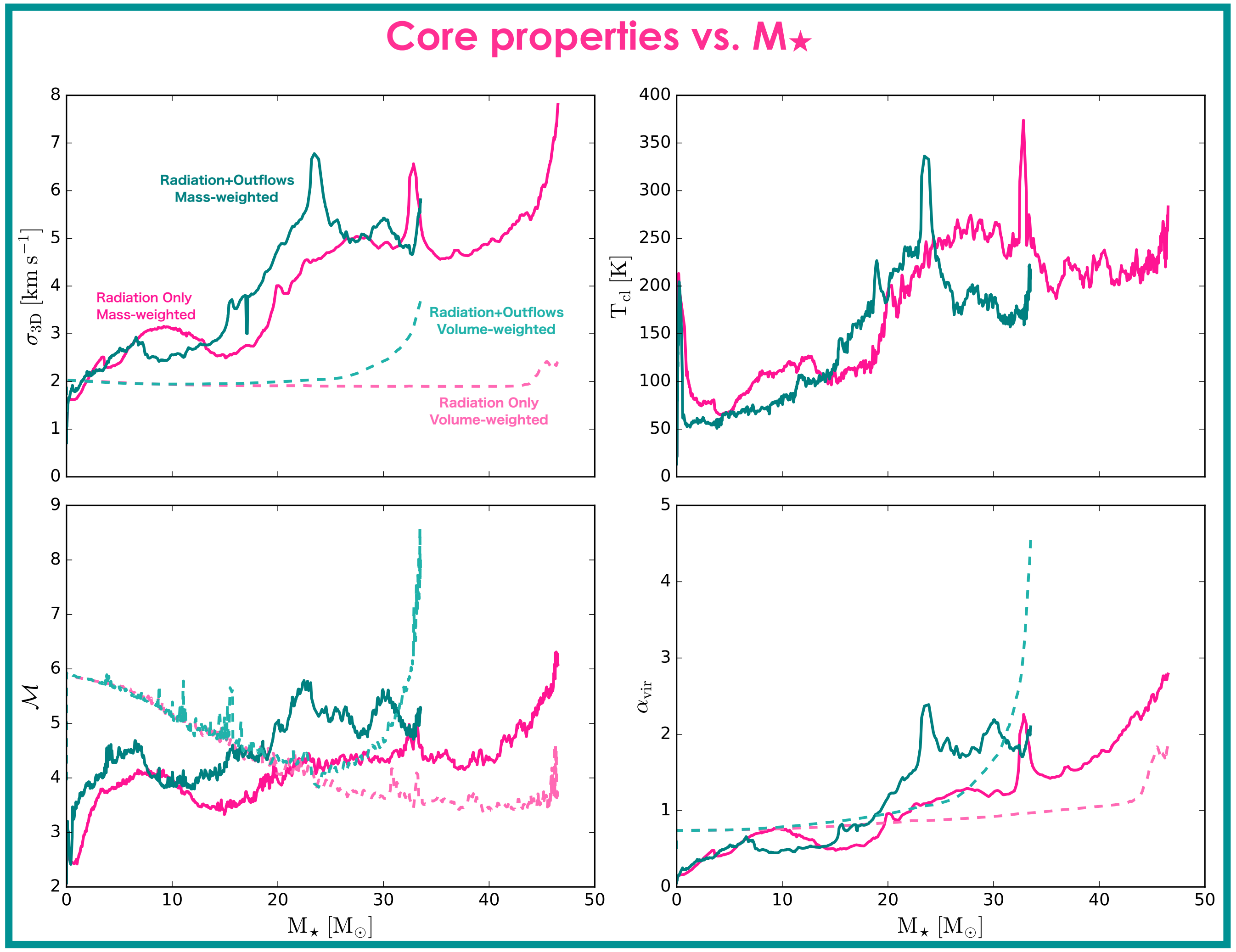
Disks are crucial to massive star formation, especially at late times.



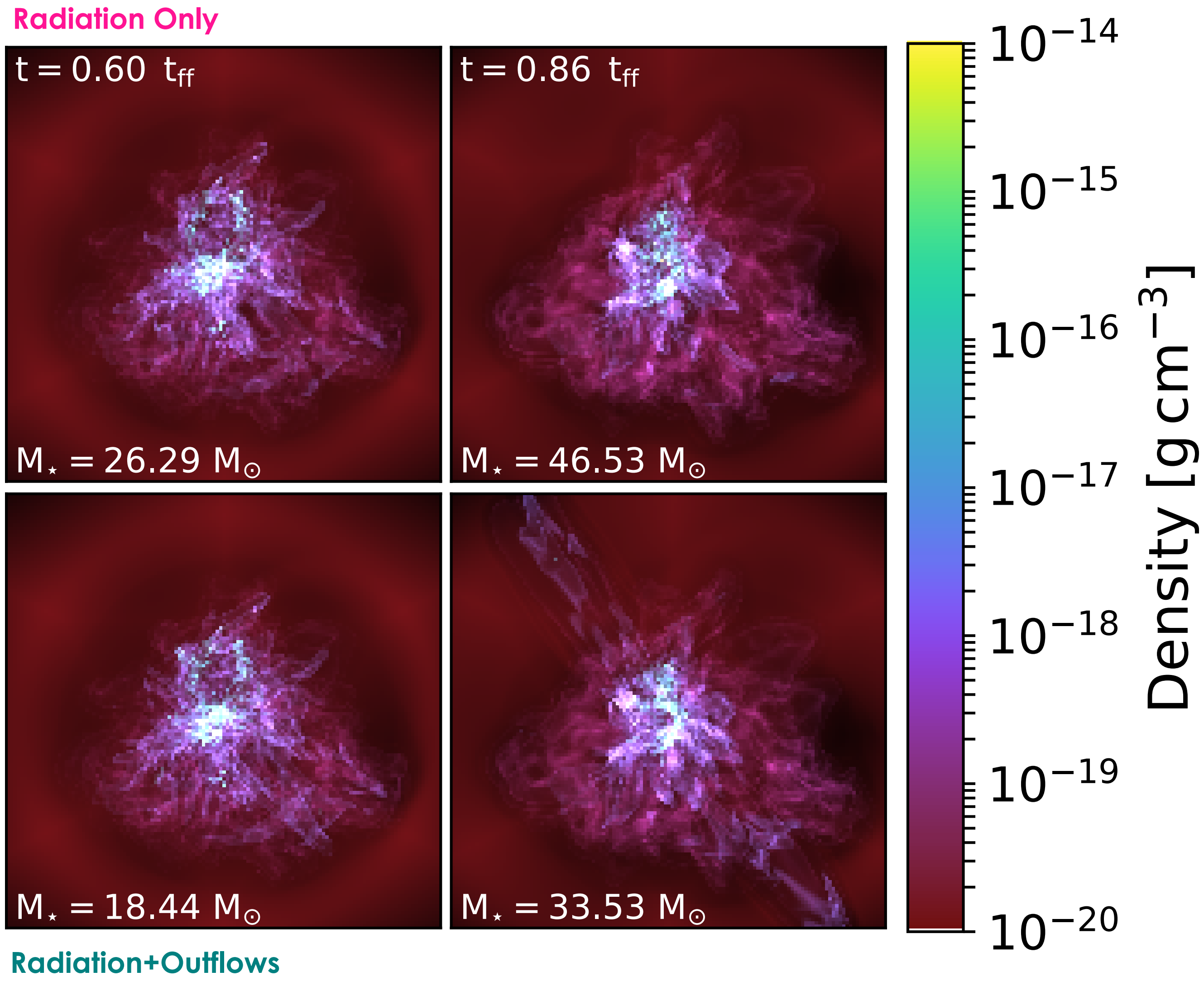
Rosen+(in prep)

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

Outflows drive out entrained gas, eventually unbinding the core

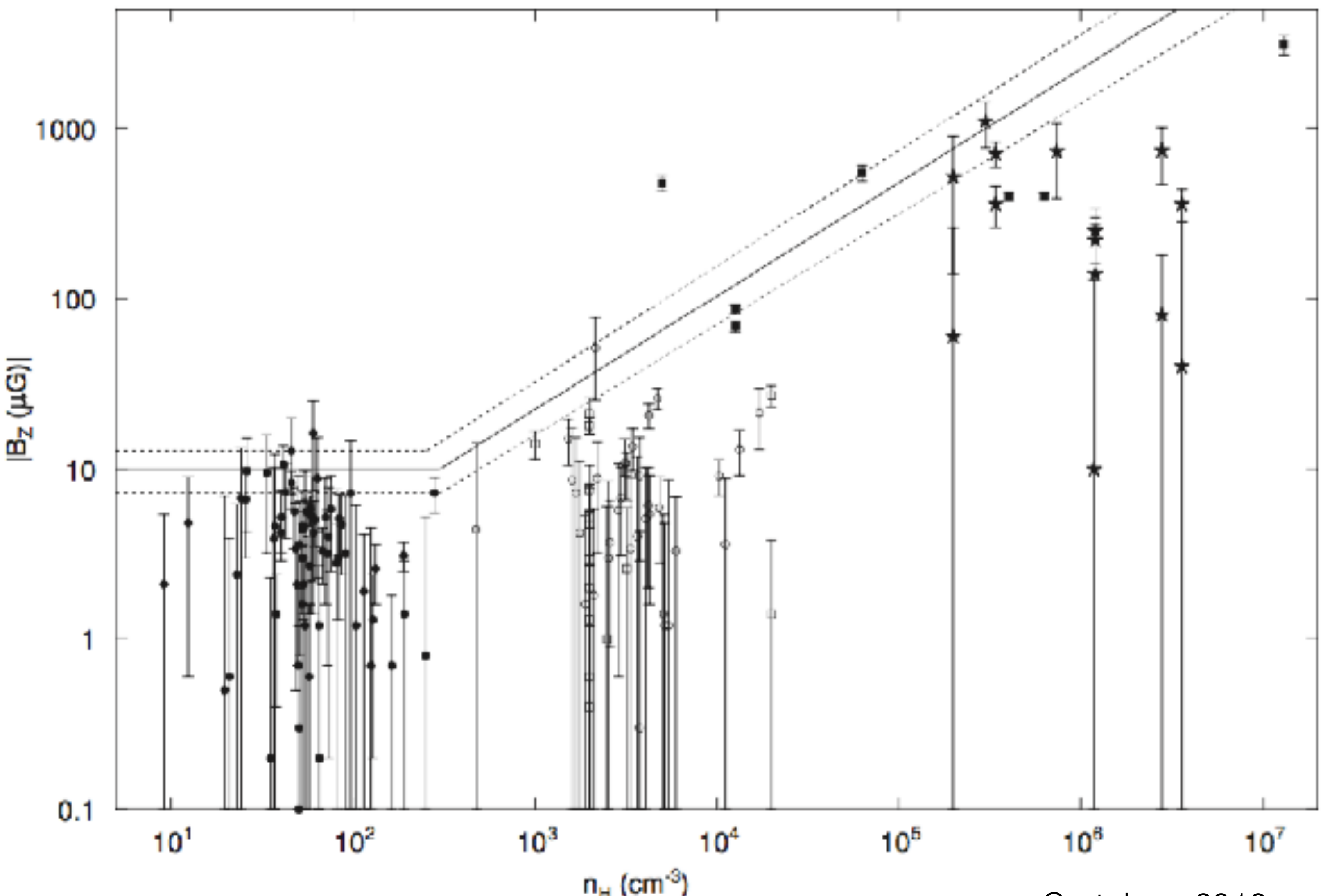


Rosen+(in prep)



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

$$\mu_\Phi > 1$$

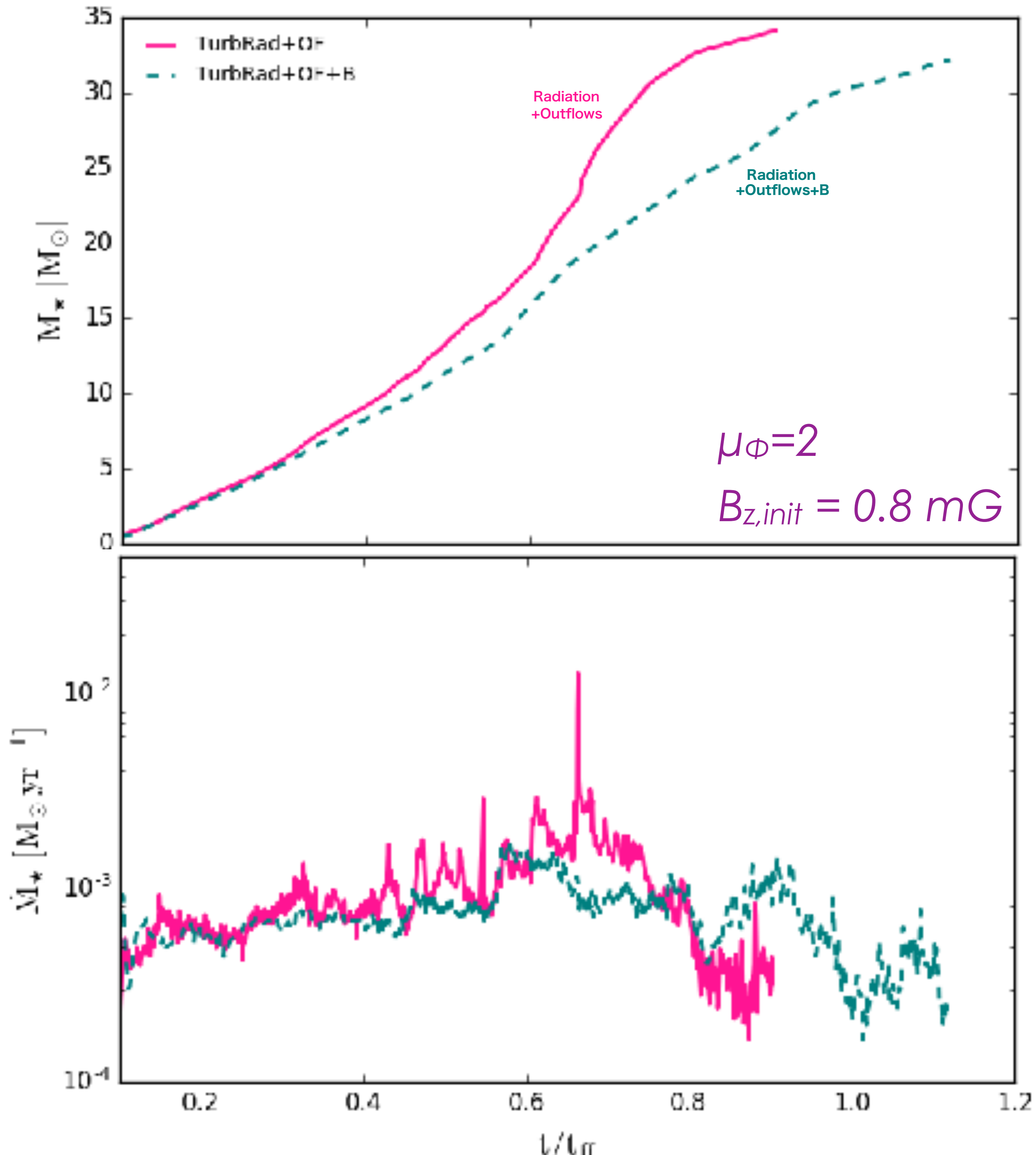
Subcritical

$$\mu_\Phi < 1$$

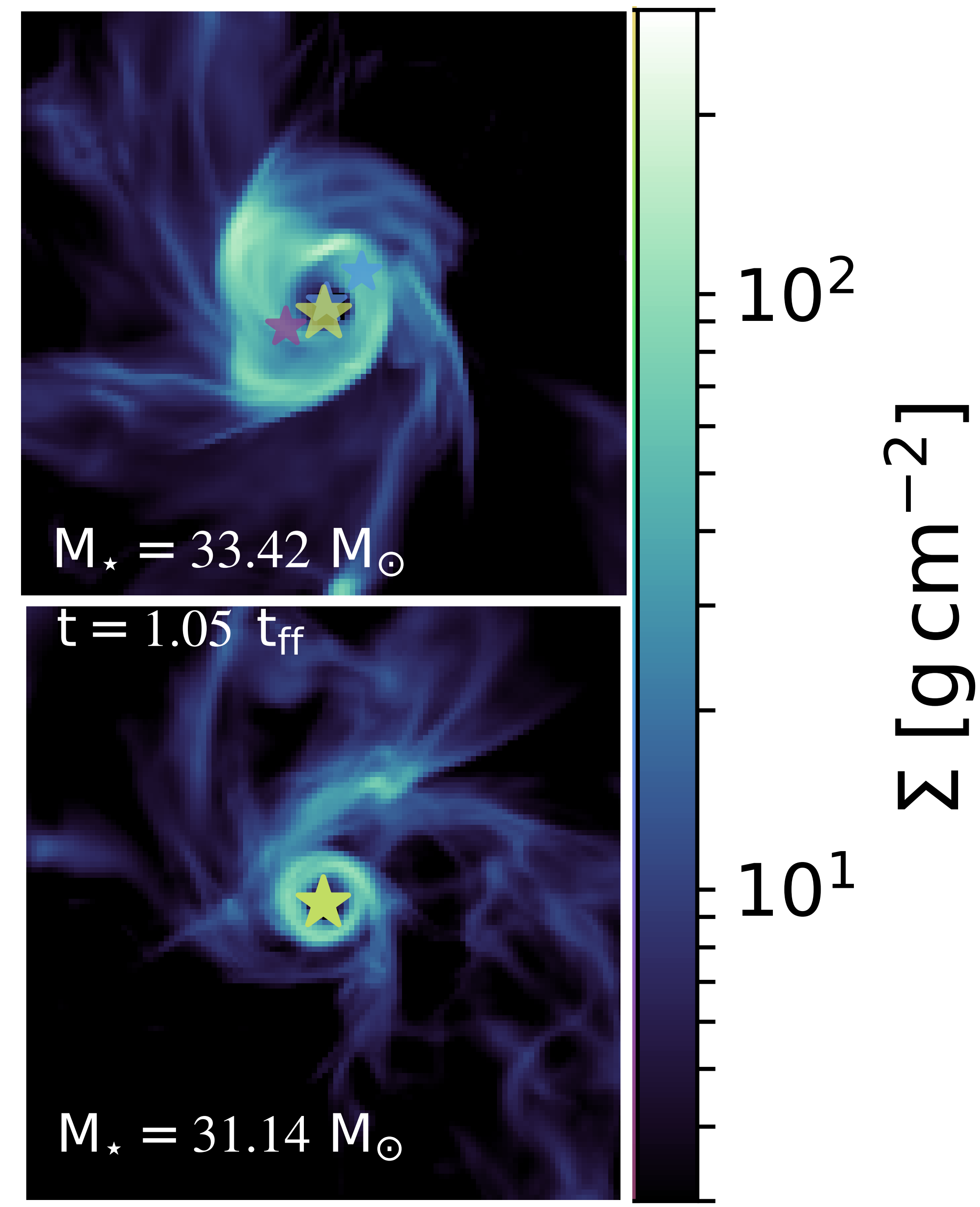
Observations suggest that dense molecular gas has $\mu_\Phi \sim 2$ (supercritical).

Magnetic pressure will slow down collapse and reduce fragmentation.

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



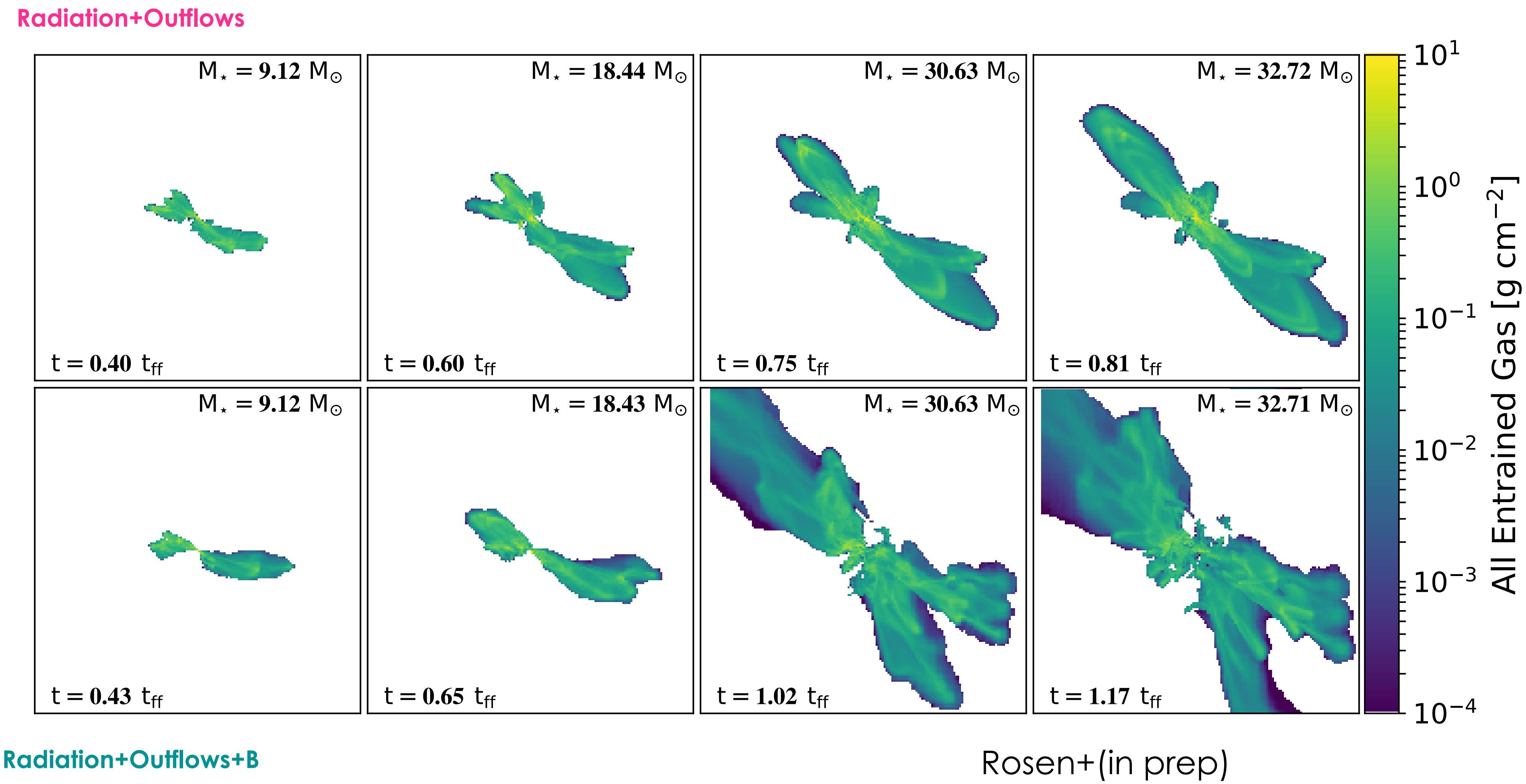
Rosen+(in prep)



$(3{,}000\ AU)^2$

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

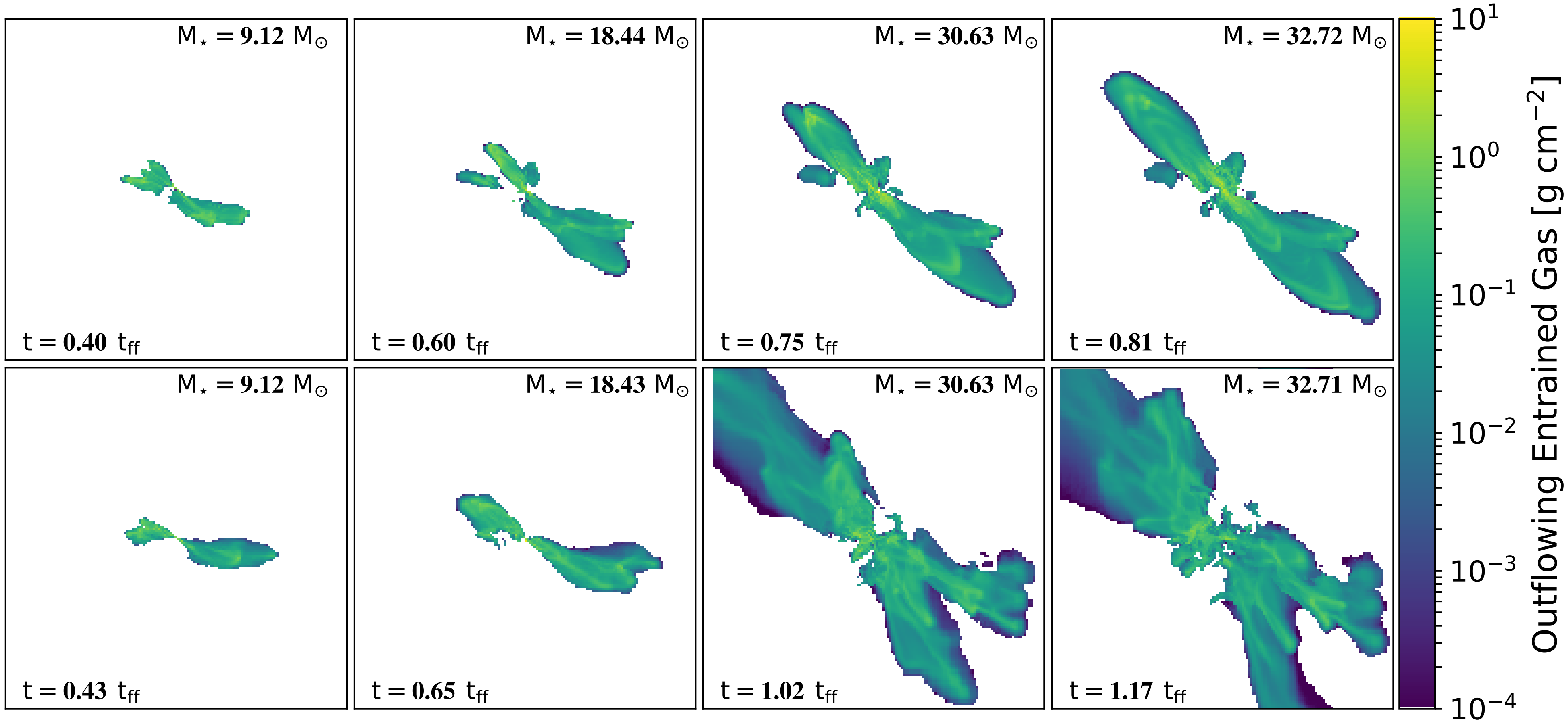


$$\rho_{\rm OF}/\rho \gtrsim 5\%$$

Rosen+(in prep)

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

Radiation+Outflows



$$\rho_{\rm OF}/\rho \gtrsim 5\%$$

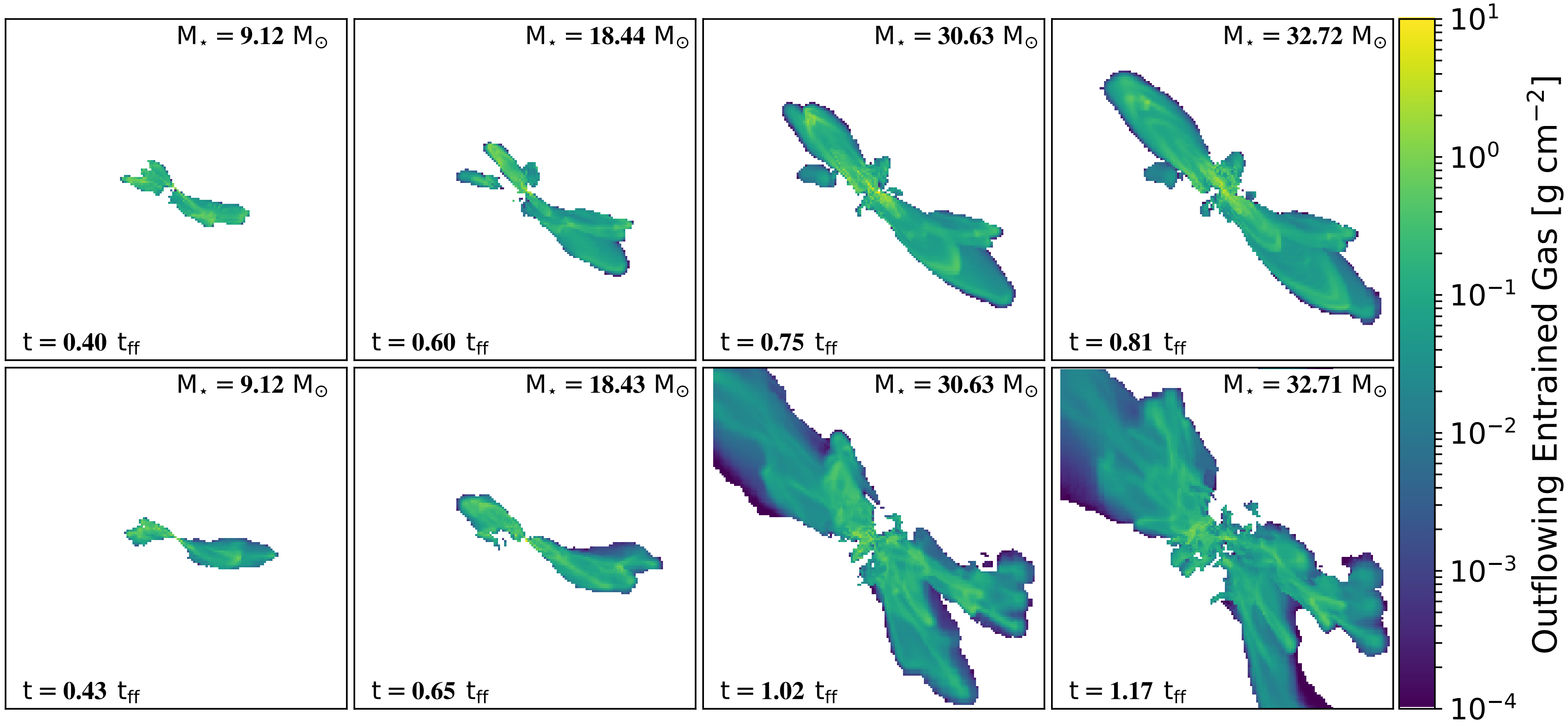
$$v_{\rm r,\star} > 0\ {\rm km\,s^{-1}}$$

Radiation+Outflows+B

Rosen+(in prep)

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

Radiation+Outflows



Radiation+Outflows+B

Rosen+(in prep)

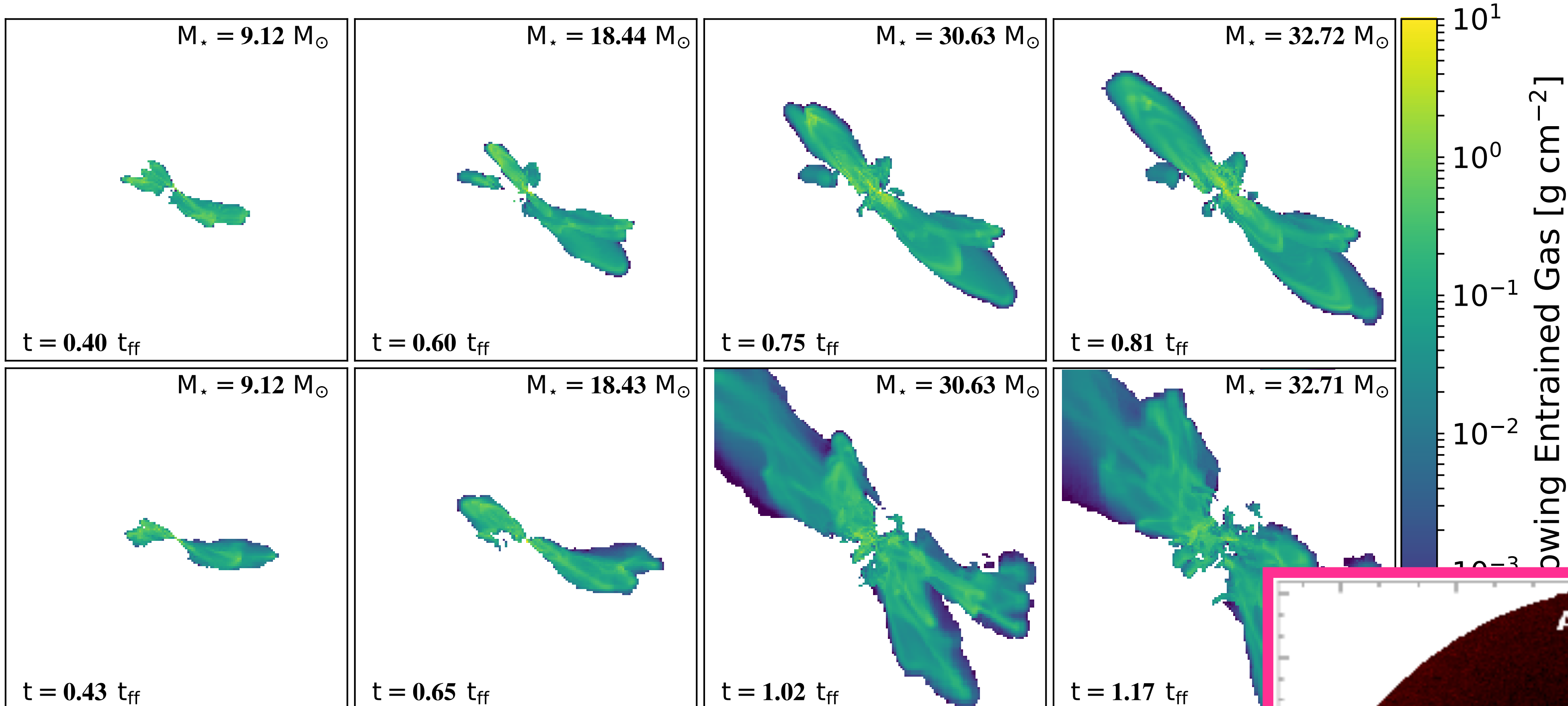
$$\rho_{\rm OF}/\rho \gtrsim 5\%$$

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

...but how does this compare to observations?

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

Radiation+Outflows



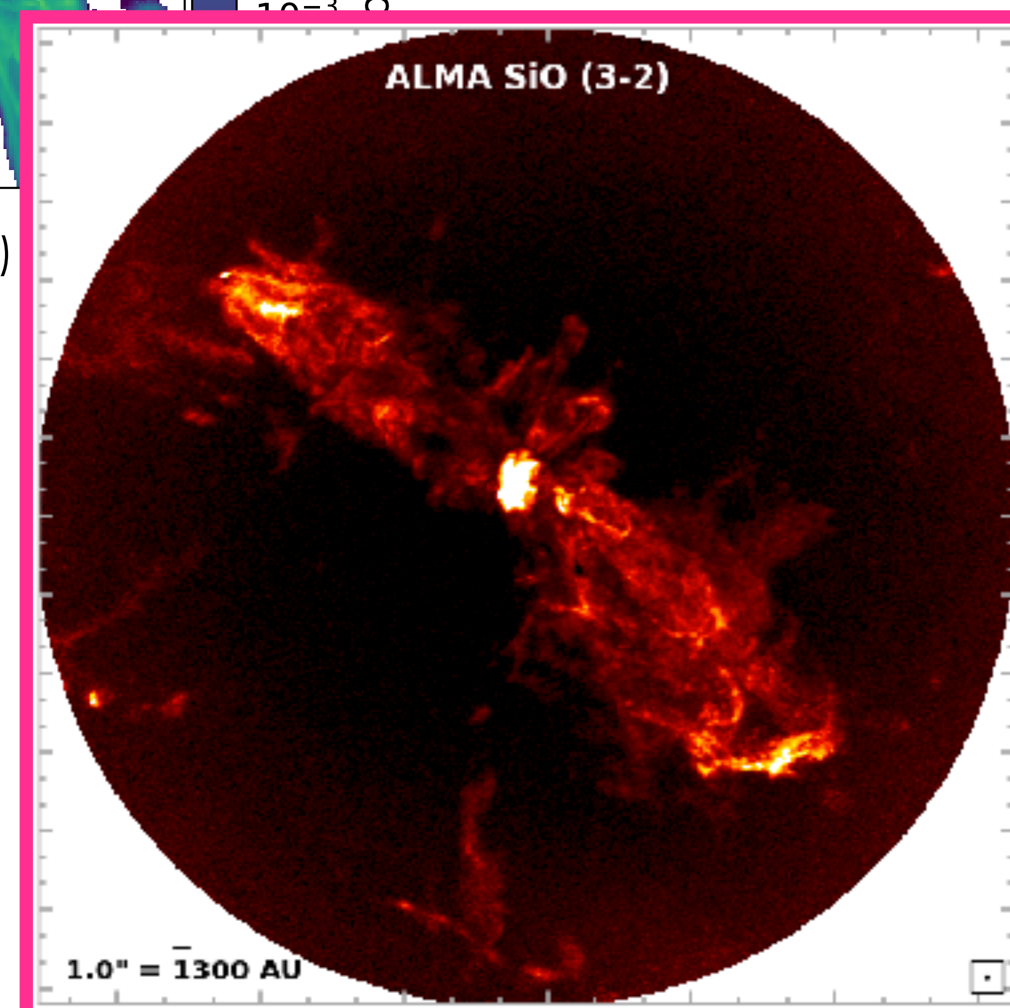
Radiation+Outflows+B

Rosen+(in prep)

$$\rho_{\rm OF}/\rho \gtrsim 5\%$$

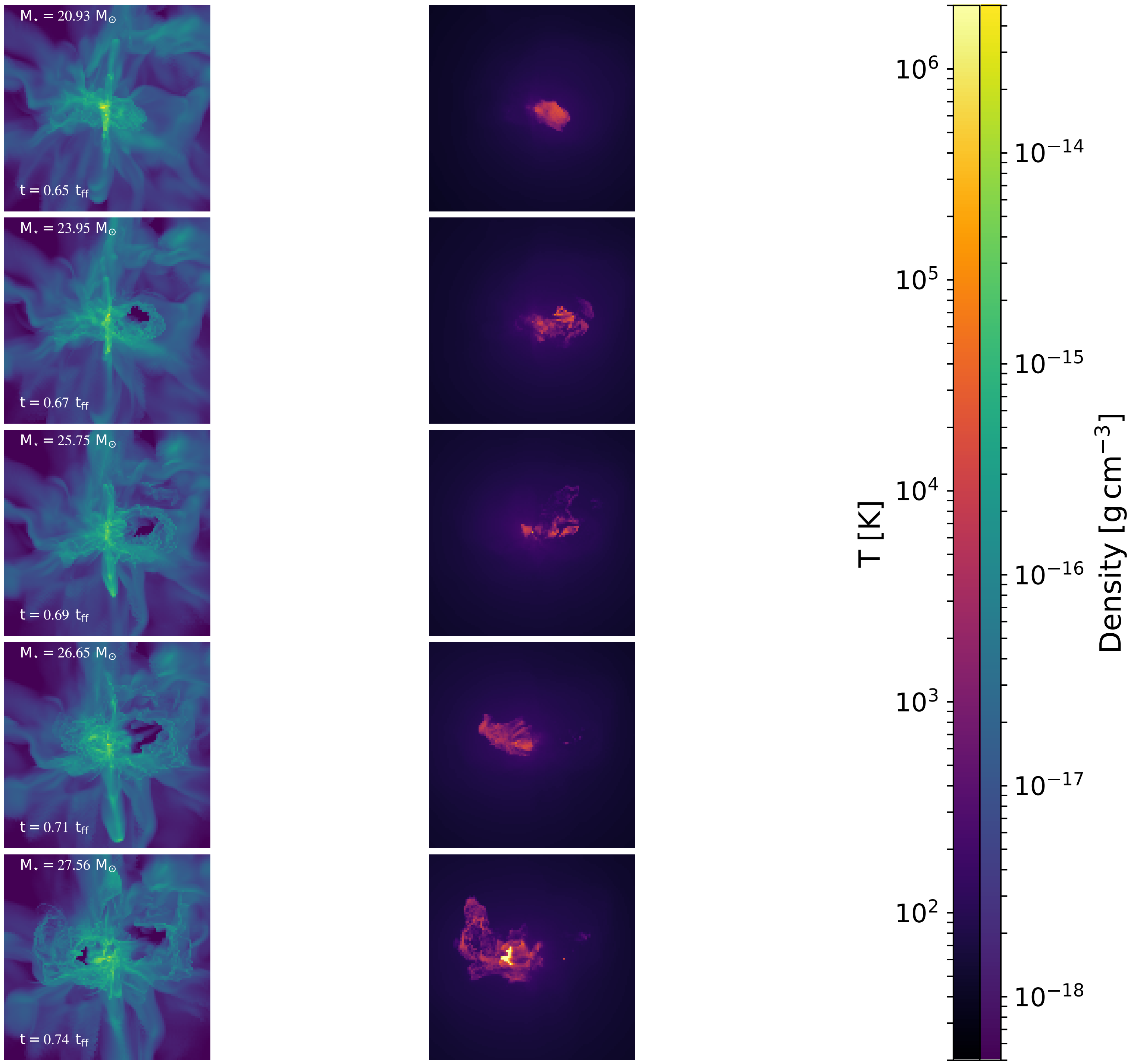
$$v_{\rm r,\star} > 0\ {\rm km\,s^{-1}}$$

...but how does this compare to observations?

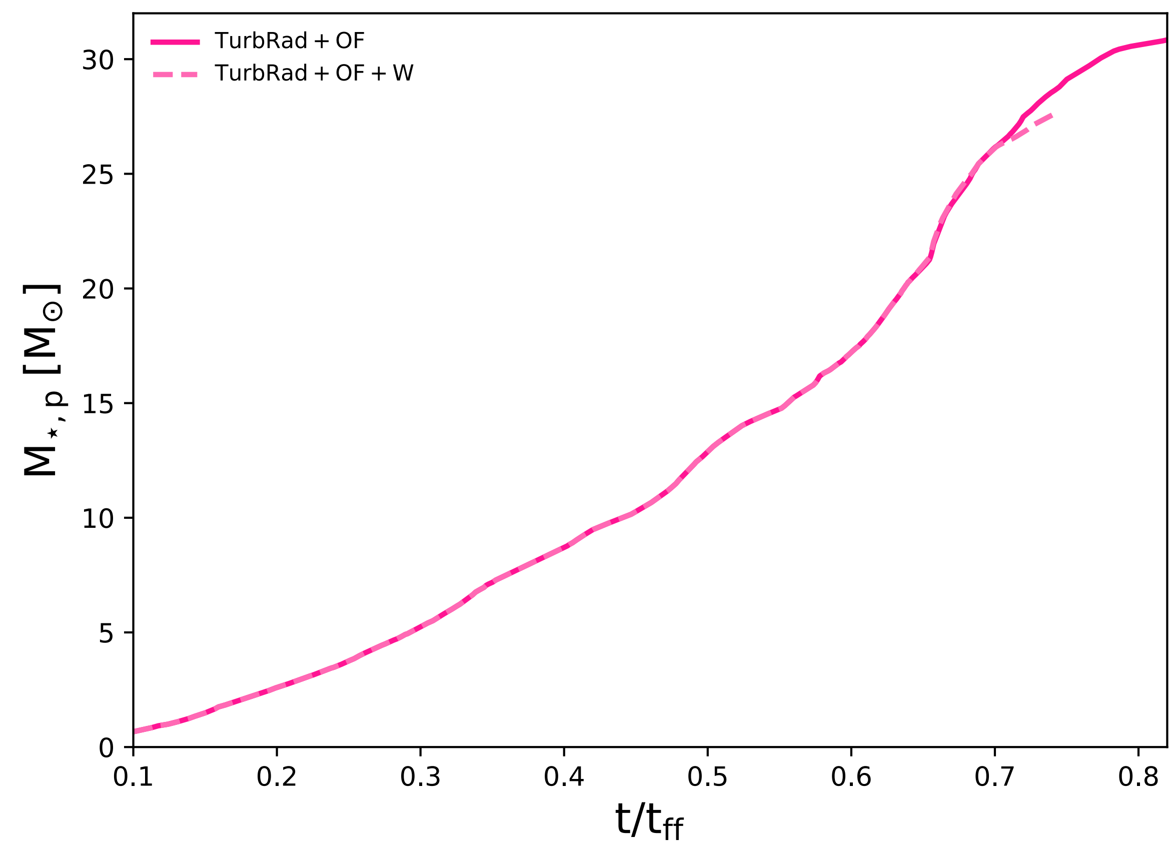


Courtesy of Crystal Brogan

…BUT WAIT! What about fast, isotropic radiatively driven winds? Caution: Preliminary results …. Stay tuned!



(20,000 AU)²



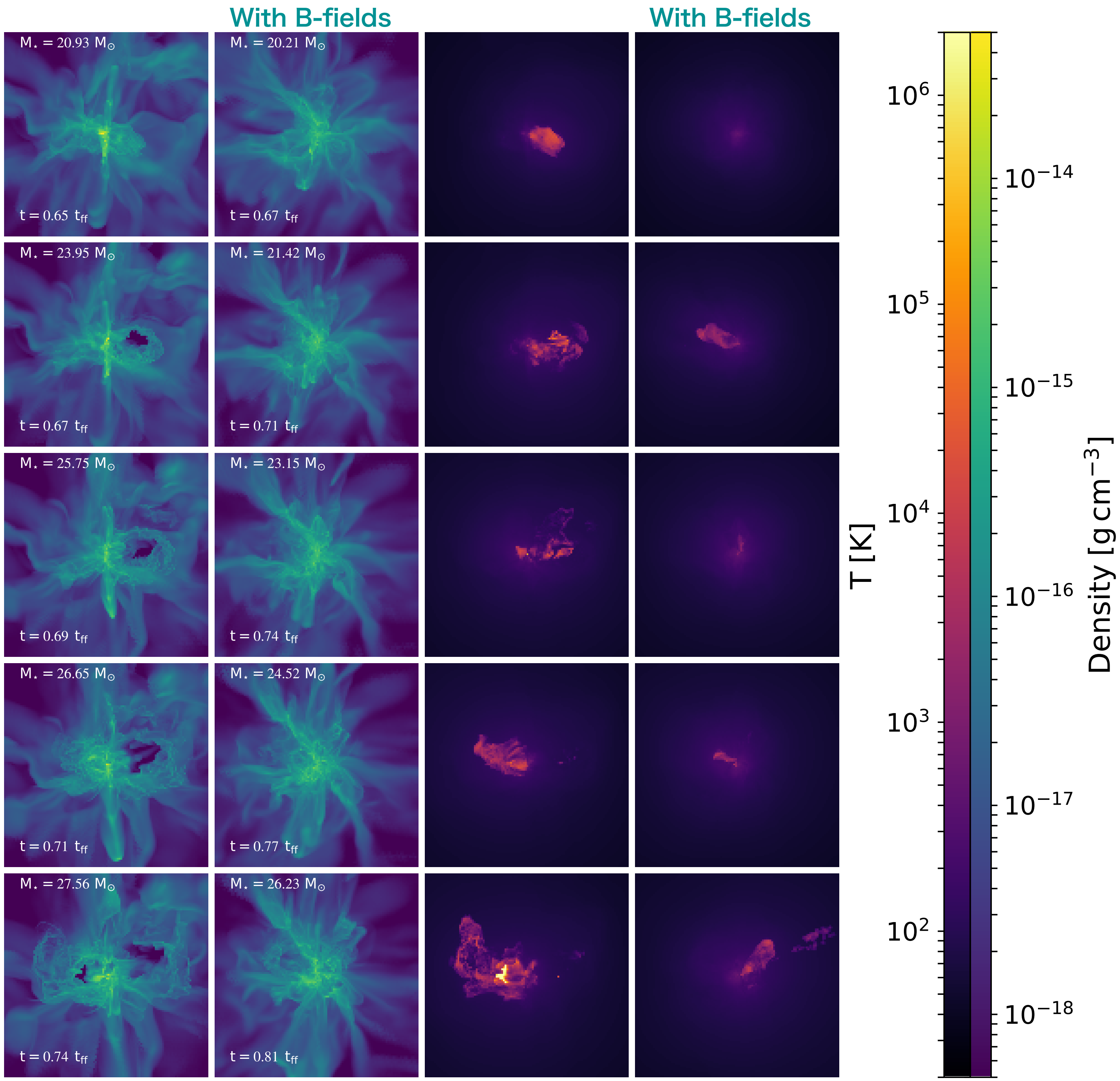
$$\dot{M}_w \sim 10^{-7} - 10^{-6}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$$

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

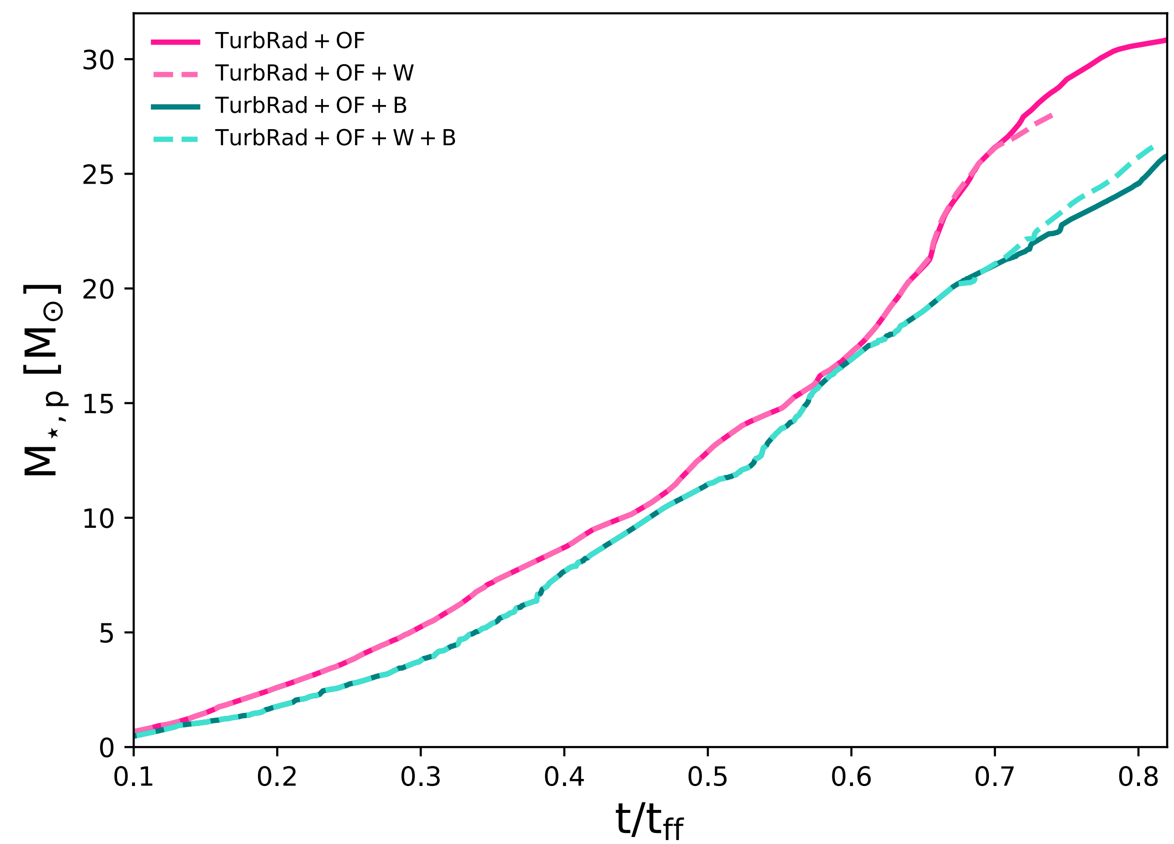
(Turn on winds when T_{eff} > 12.5 kK following Vink+2001 and Leitherer+1992)

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

…BUT WAIT! What about fast, isotropic radiatively driven winds? Caution: Preliminary results …. Stay tuned!



(20,000 AU)²



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

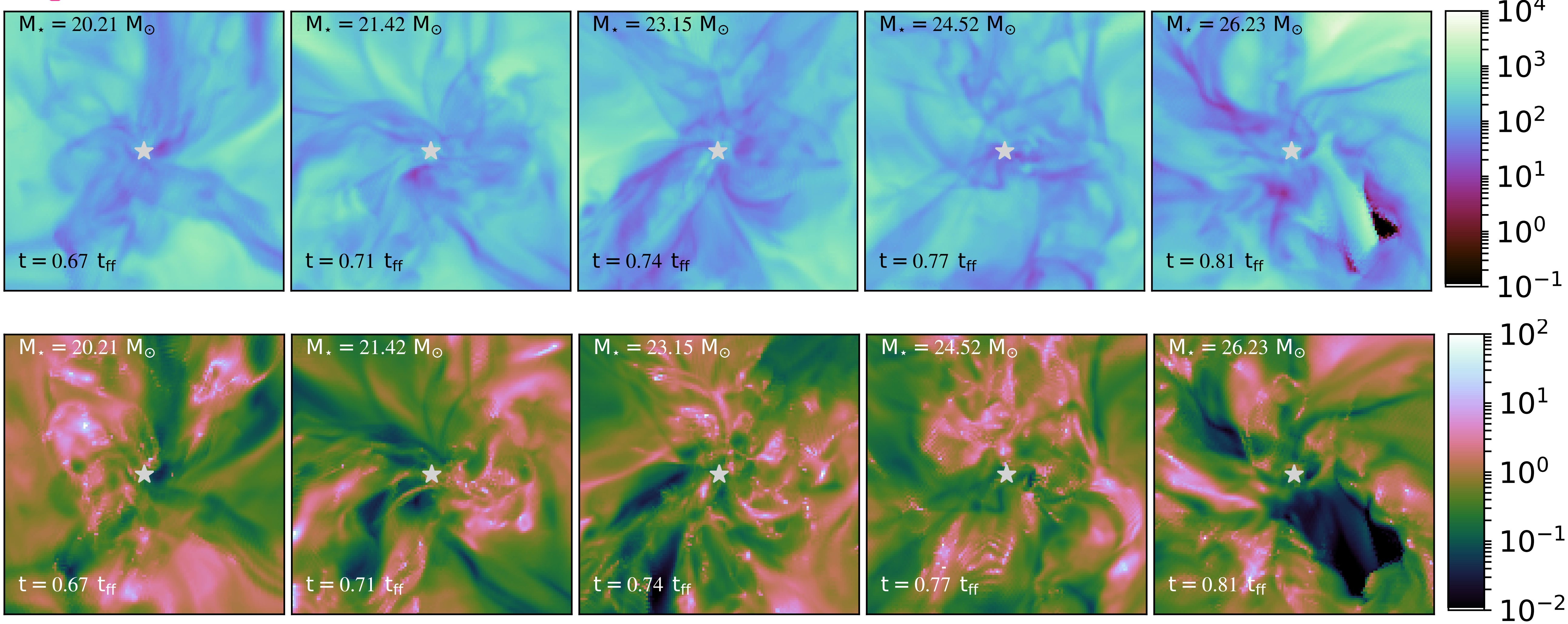
$$v_{\mathrm{w}} > 10^3\ \mathrm{km\ s^{-1}}$$

(Turn on winds when T_{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

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

Magnetic to Thermal Pressure



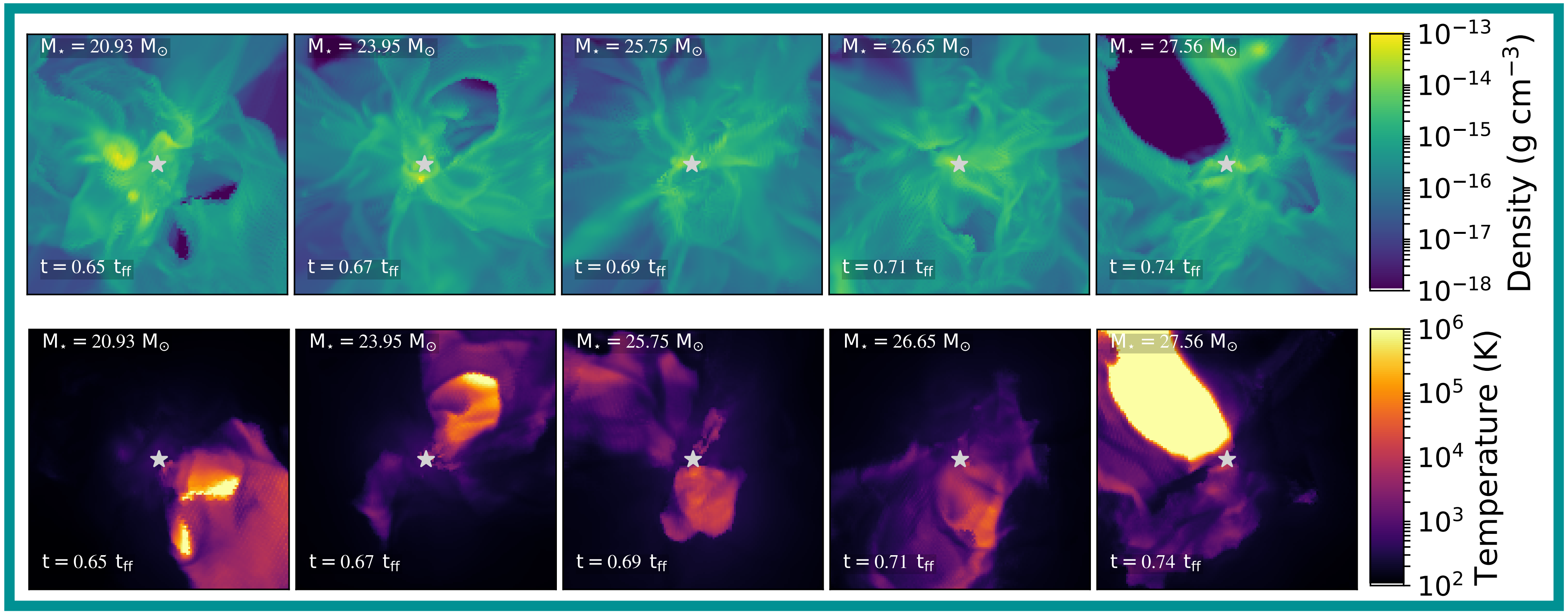
Magnetic to Ram Pressure
(P_{ram}= ρv^2)

(4,000 AU)²

Preliminary results …. Stay tuned!

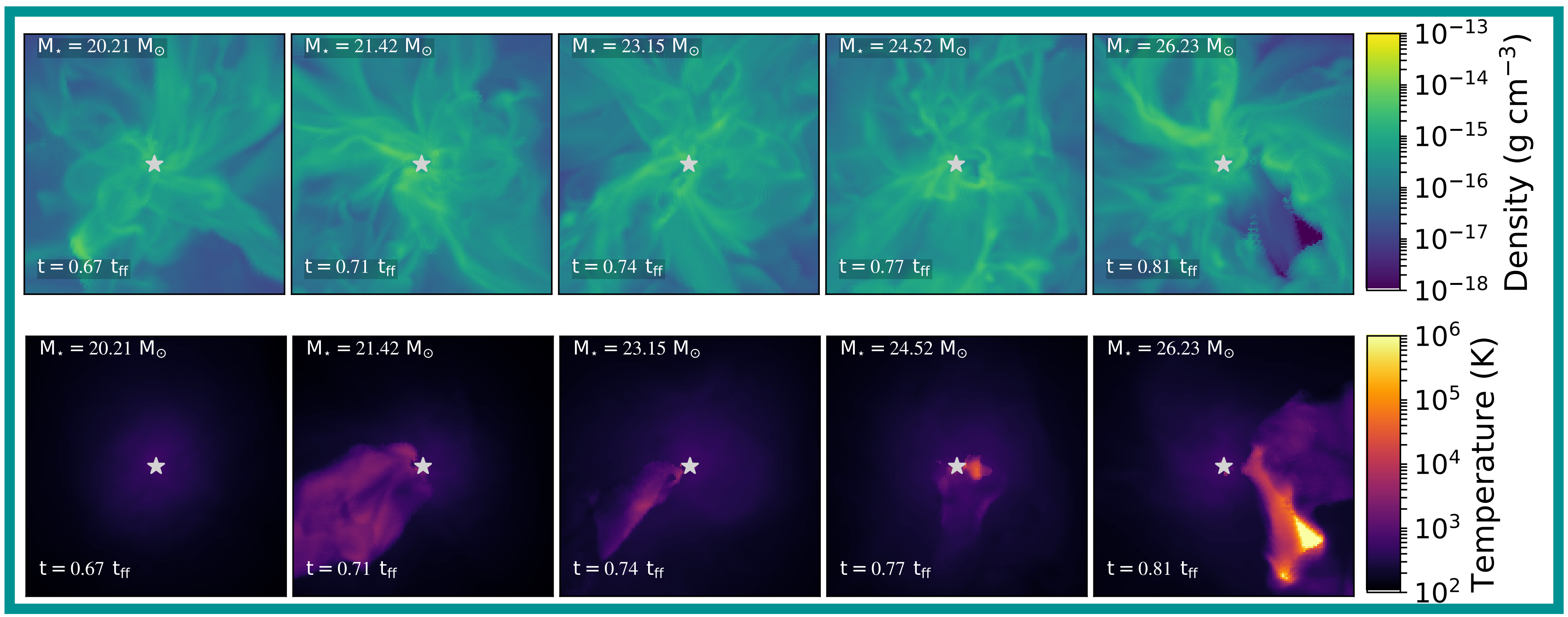
Magnetic pressure confines winds, reducing shock heating and adiabatic expansion → larger ρ and c_s such that dM/dt increases.

Winds+ No B



(4,000 AU)²

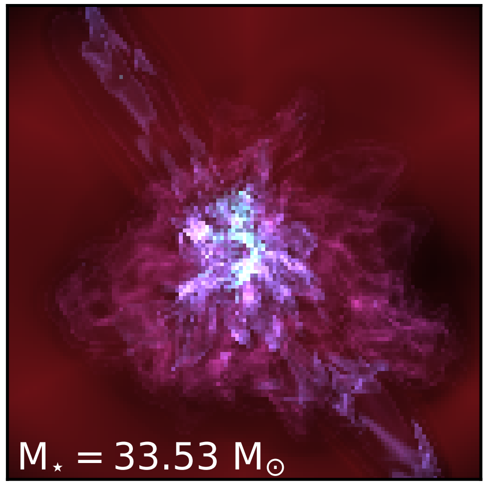
Winds+B



(4,000 AU)²

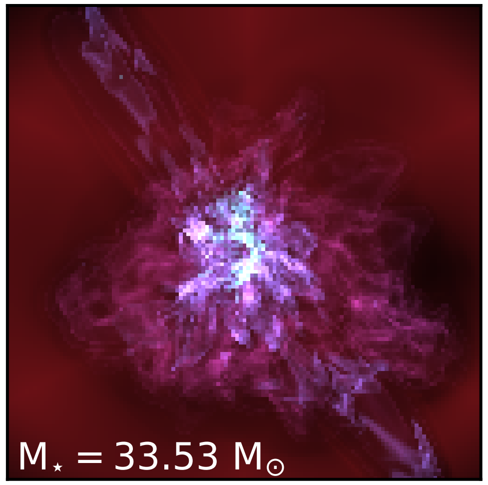
Preliminary results .... Stay tuned!

Summary

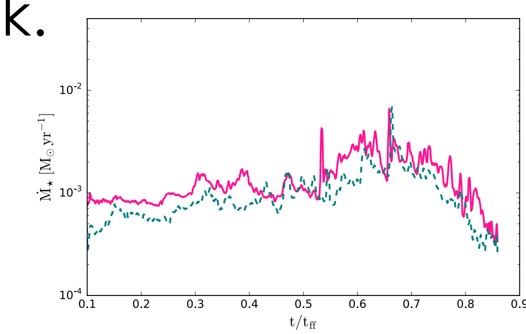


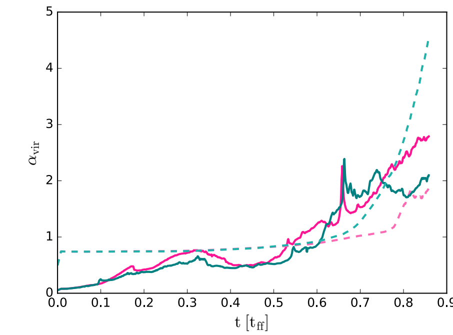
Performed 3D R(M)HD simulations of the formation of massive stellar systems from the collapse of turbulent massive pre-stellar cores with radiative and outflow feedback.

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 and outflow feedback.

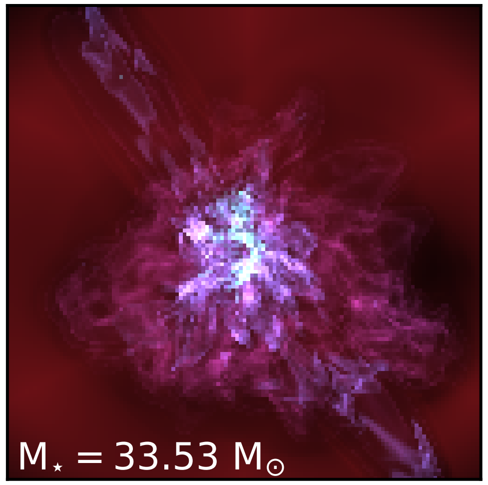




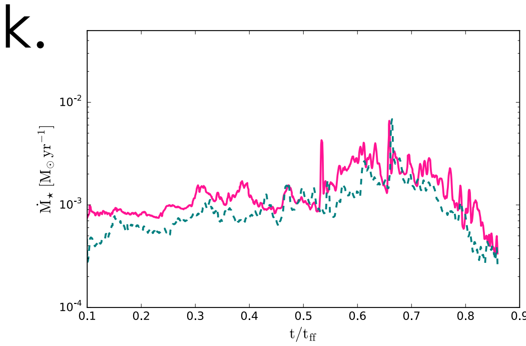
Inclusion of feedback by outflows in addition to radiation pressure:

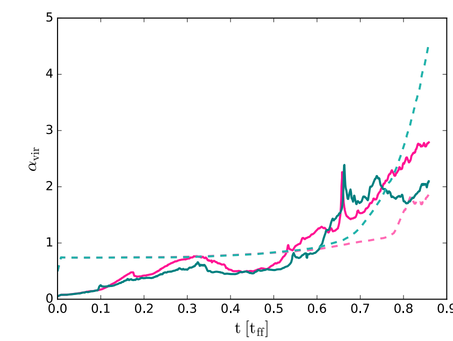
- Reduces effective mass growth by ~10% than radiation alone.
- Ejects jet and entrained material from core, results in unbinding core.

Summary



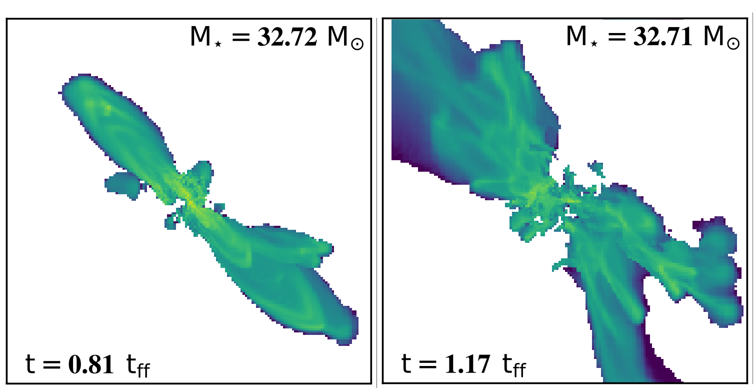
Performed 3D R(M)HD simulations of the formation of massive stellar systems from the collapse of turbulent massive pre-stellar cores with radiative and outflow feedback.

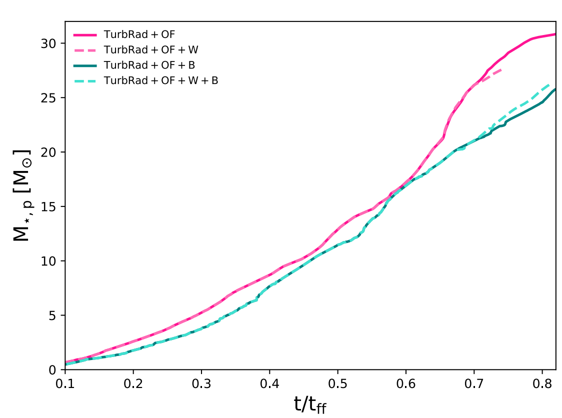




Inclusion of feedback by outflows in addition to radiation pressure:

- 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)