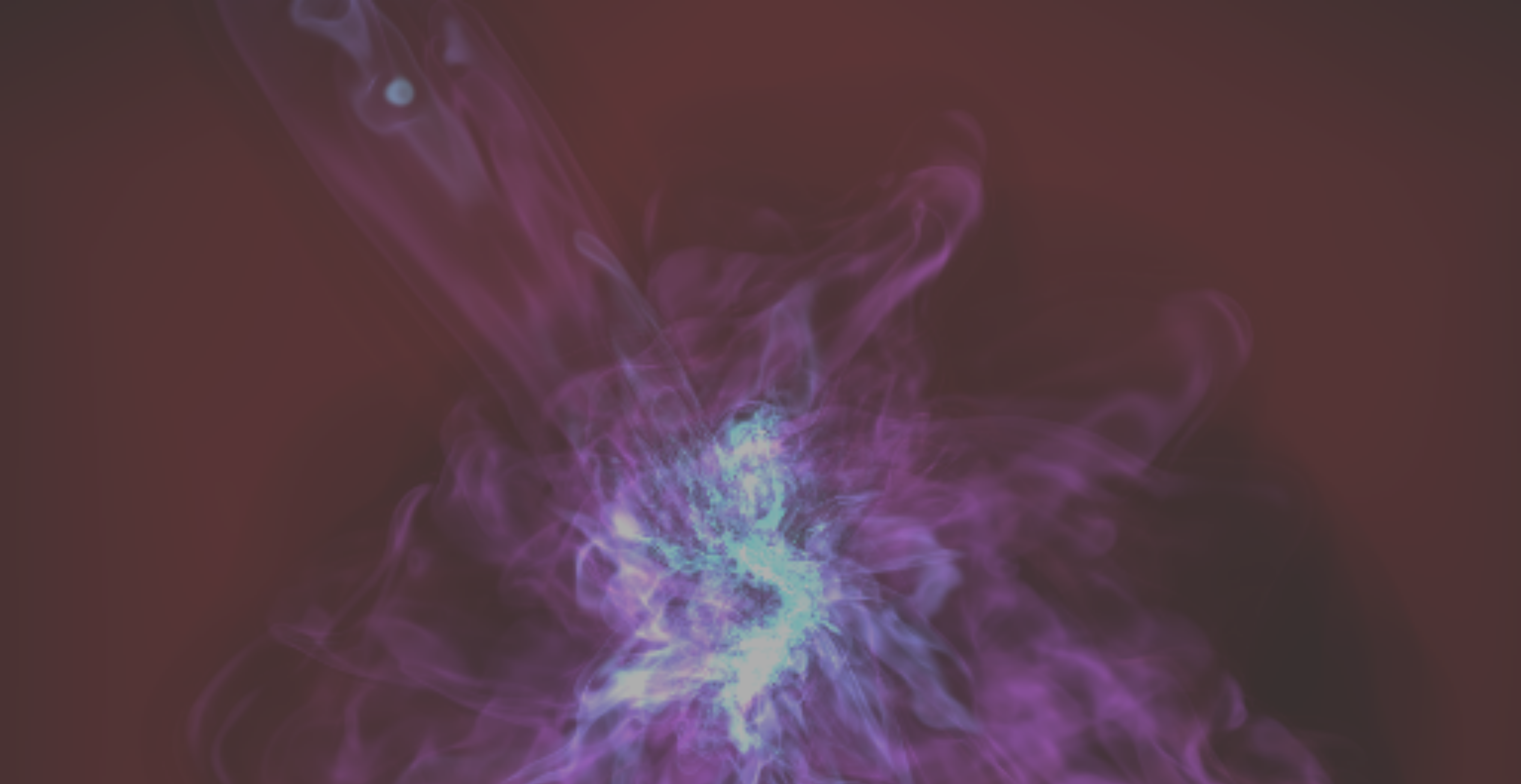


HOW OUTFLOWS AND RADIATIVE FEEDBACK LIMIT ACCRETION ONTO MASSIVE STARS

Anna Rosen

NASA Einstein Fellow

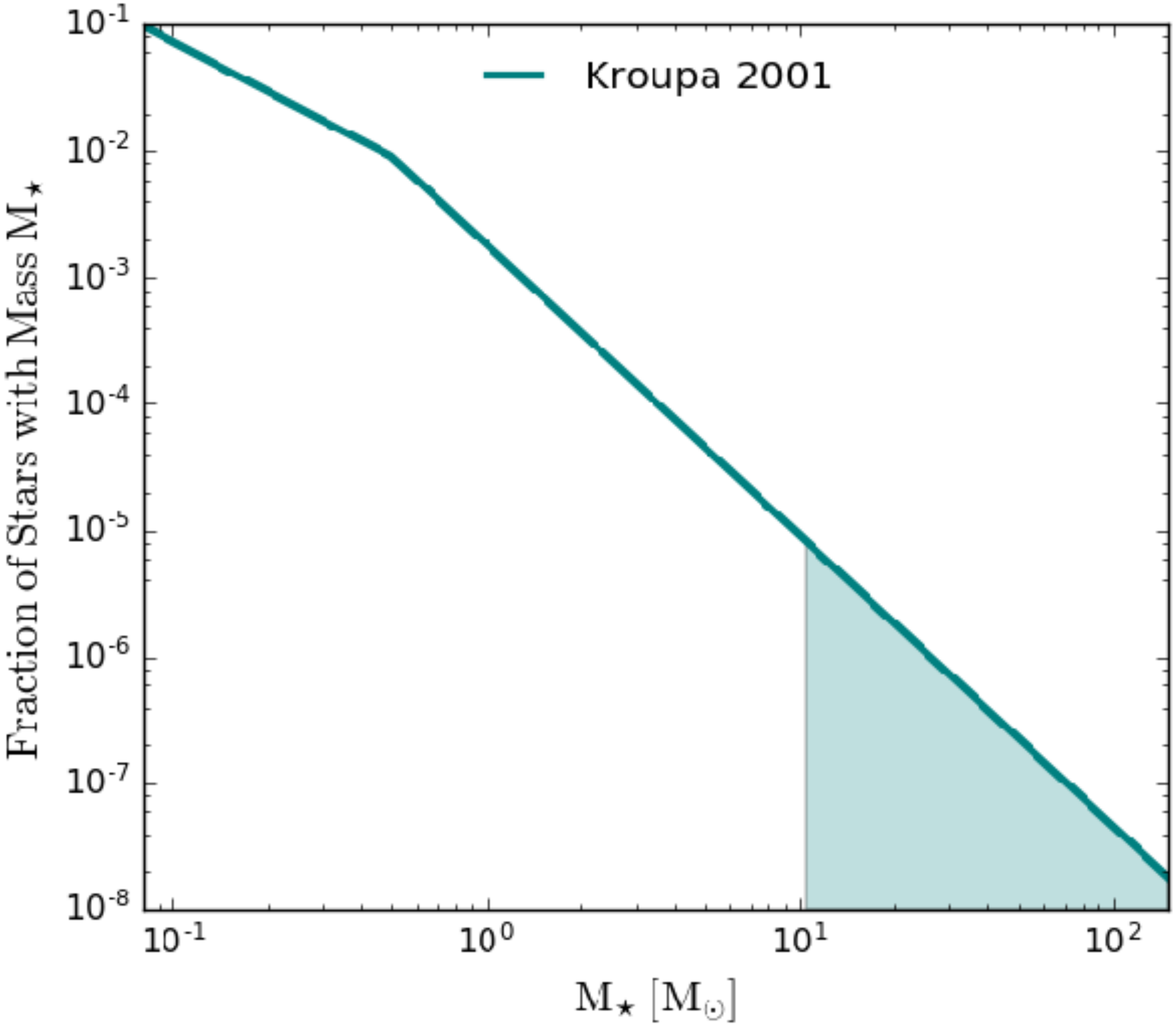
Harvard-Smithsonian Center for Astrophysics

<u>In collaboration with:</u> Alyssa Goodman (CfA), Mark Krumholz (ANU)

CfA NASA

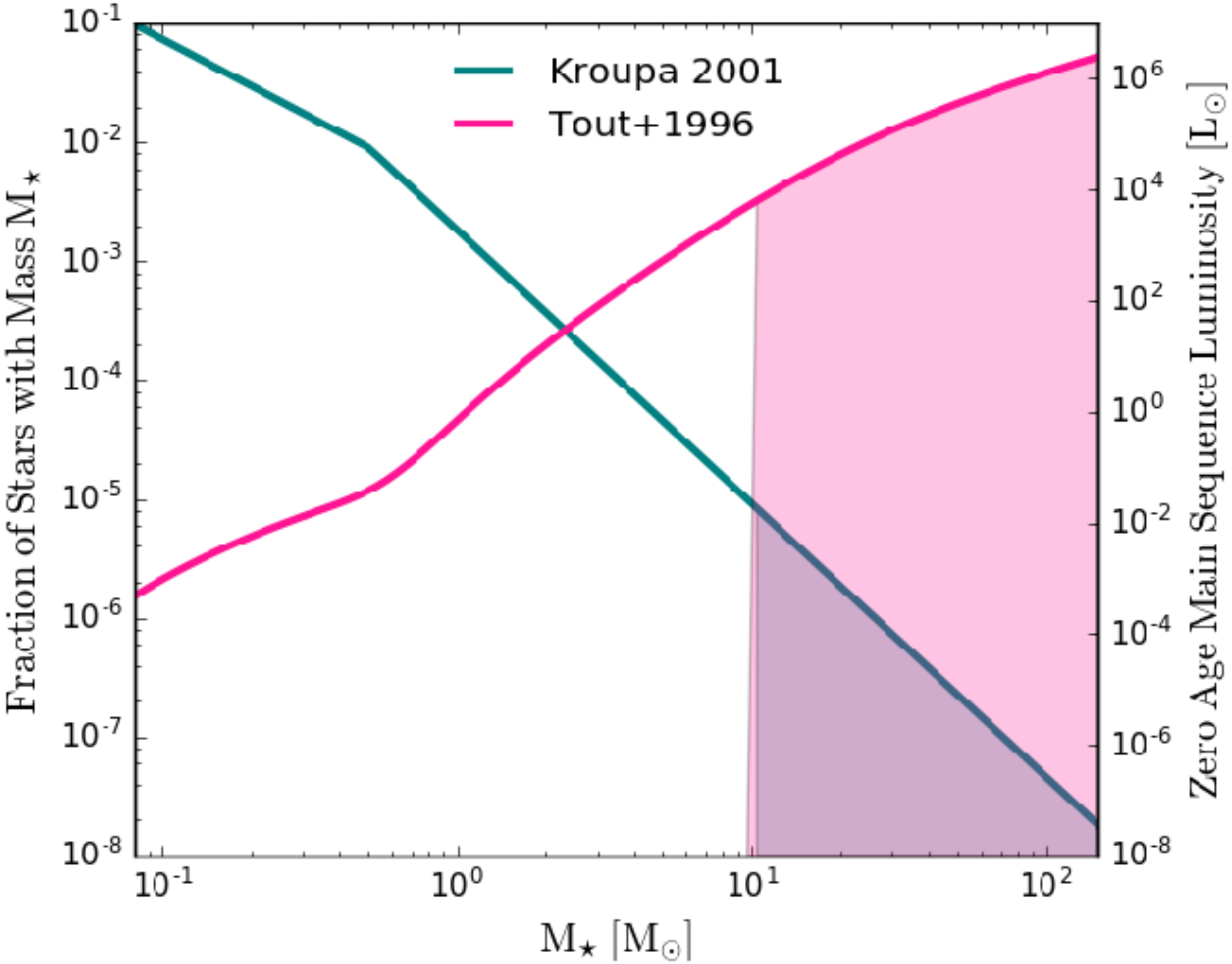
Harvard-Smithsonian Center for Astrophysics

Massive stars are rare



~1% of stars are massive

Massive stars are rare but they dominate the energy budget of the Milky Way and other star-forming galaxies



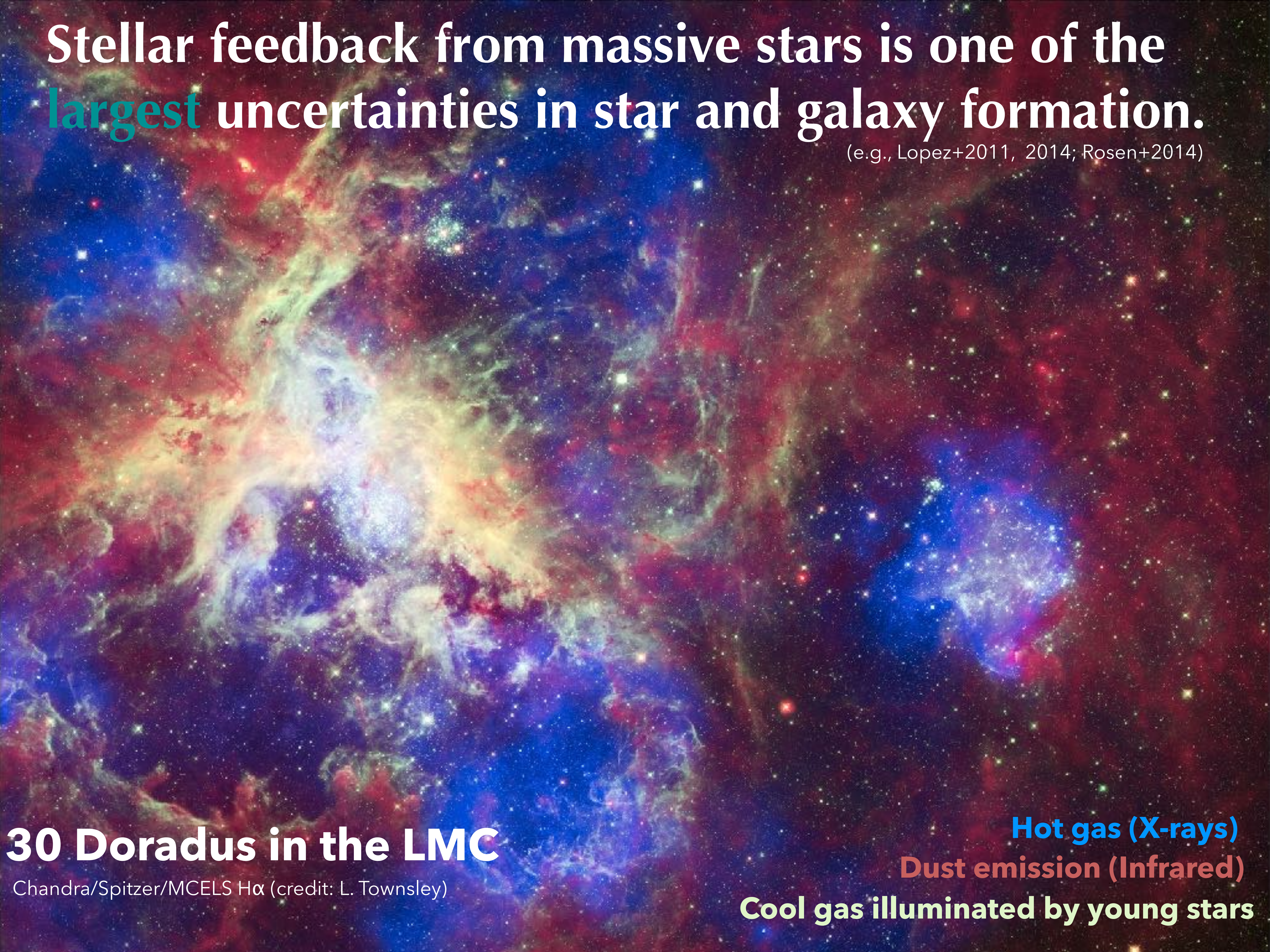
~1% of stars are massive

~97% of stellar radiation energy comes from massive stars

Massive stars are the 1% of the Universe.

Stellar feedback from massive stars is one of the largest uncertainties in star and galaxy formation.

(e.g., Lopez+2011, 2014; Rosen+2014)

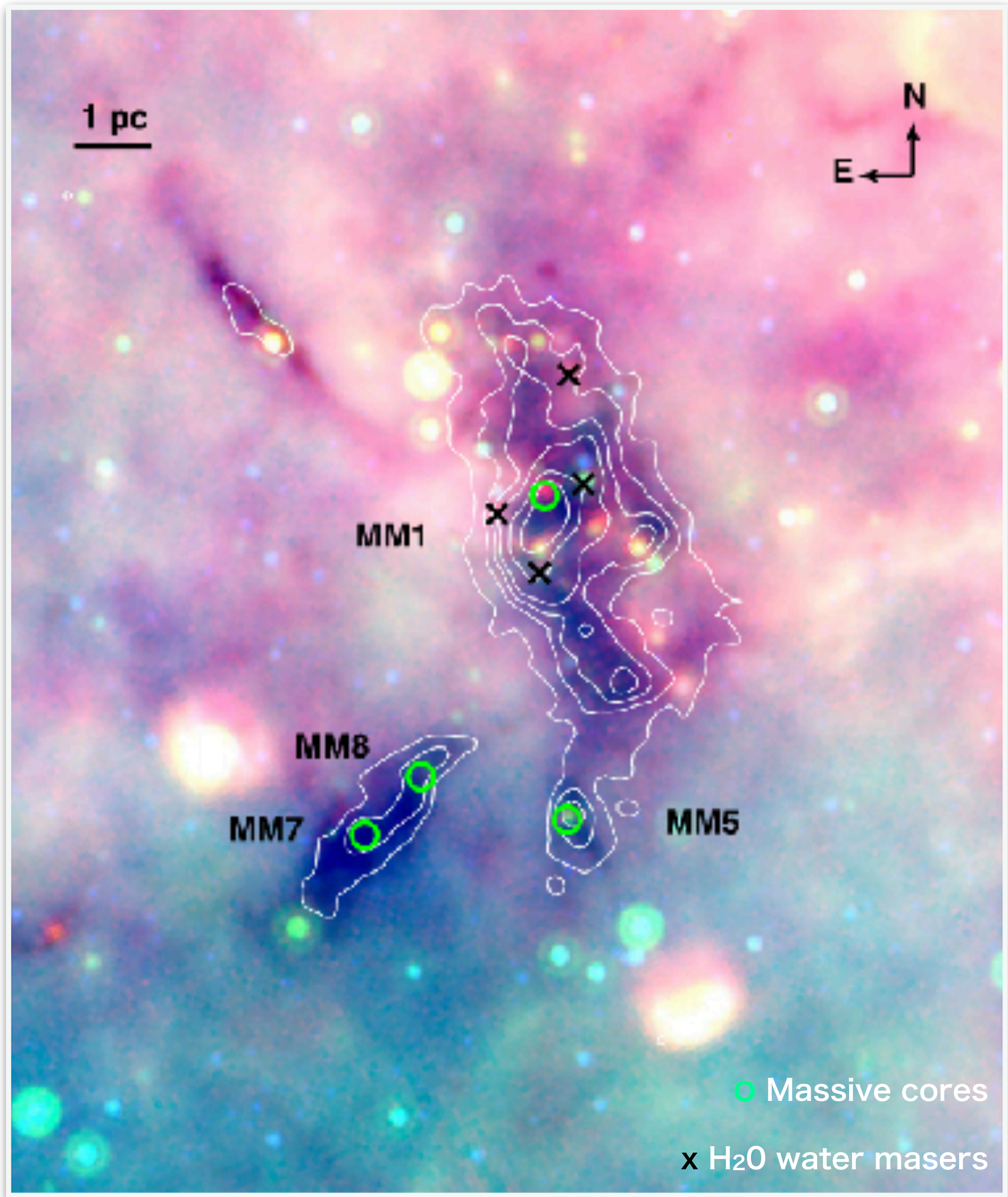


30 Doradus in the LMC

Chandra/Spitzer/MCELS Hα (credit: L. Townsley)

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, Lu+2015, Zhang+2015, Ohashi+2015)

Stellar feedback can limit accretion onto massive stars

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

Gravitational Force:

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

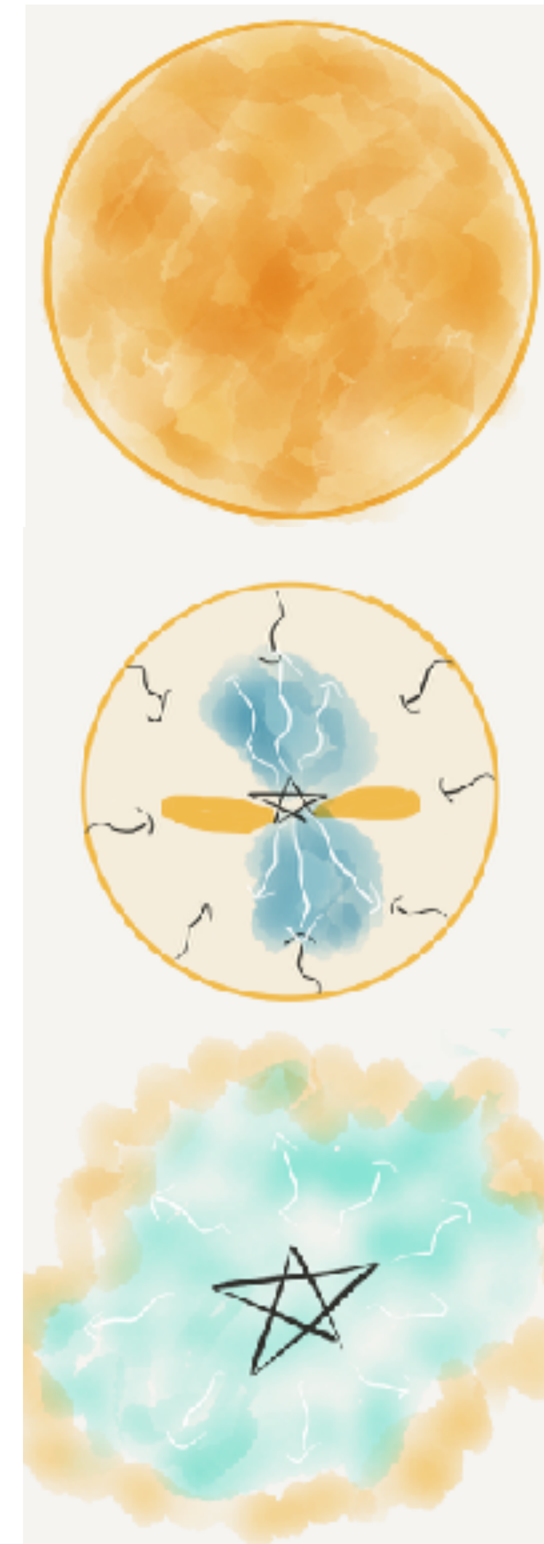
$$\Sigma(r) = \int_0^r \rho(r')dr'$$

Radiative Force:

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

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

$$f_{\rm edd} = 7.7\times10^{-5}\,(1+f_{\rm trap})\left(\frac{L_\star}{M_\star}\right)_\odot\left(\frac{\Sigma}{1\ {\rm g\ cm^{-2}}}\right)^{-1}$$



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

$$f_{\rm edd} \gtrsim 1$$

when

$$\left(\frac{L_\star}{M_\star}\right)_\odot \gtrsim 2500$$

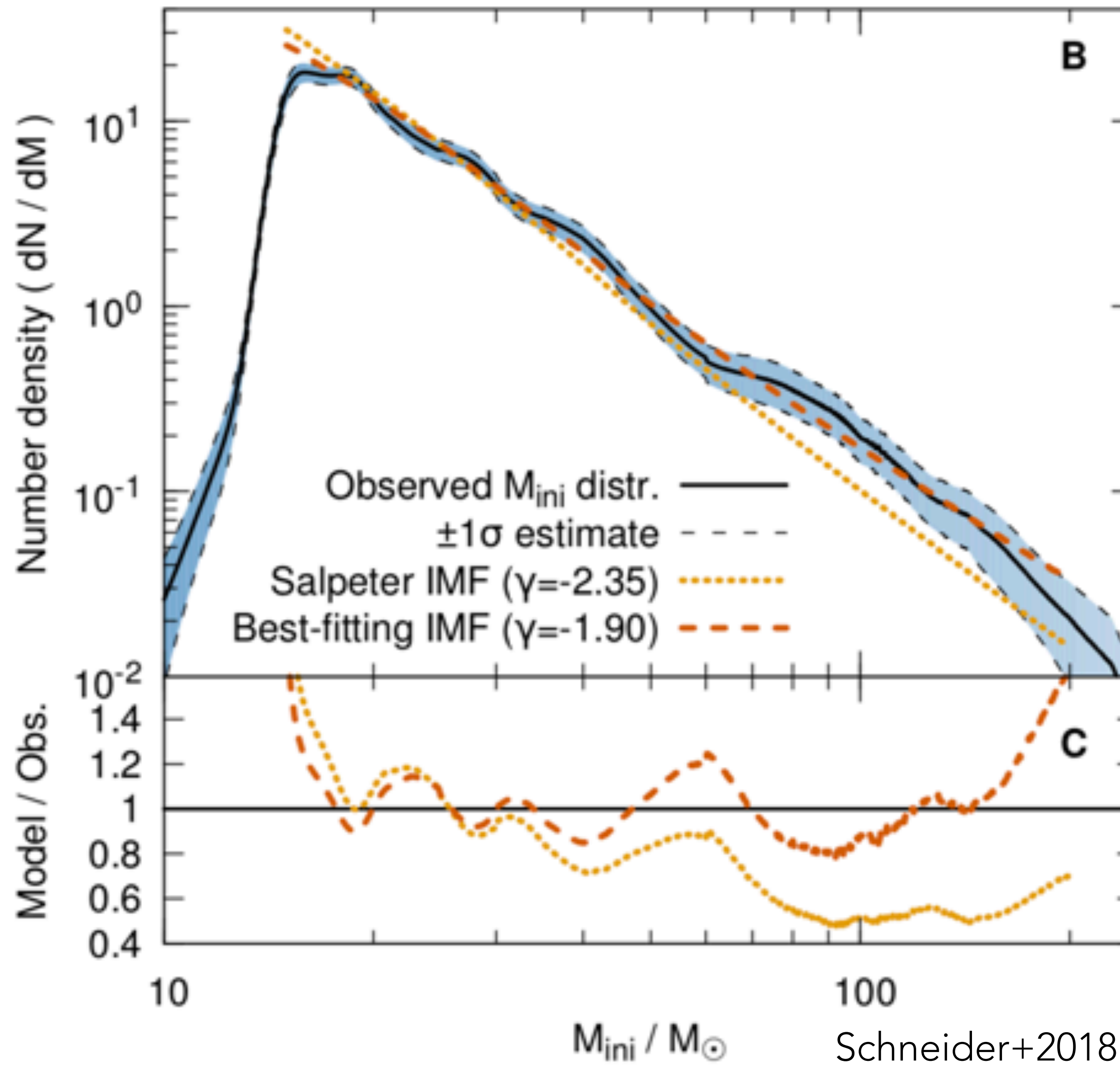
Larson & Starrfield 1971, Kahn 1974, Yorke 1979, Yorke+1995, Wolfire & Cassinelli 1986, 1987; Yorke & Bodenheimer 1999, Krumholz+2009

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

…but stars with masses well in excess of this limit exist

30 Doradus in the LMC

Chandra/Spitzer/MCELS Hα (credit: L. Townsley)



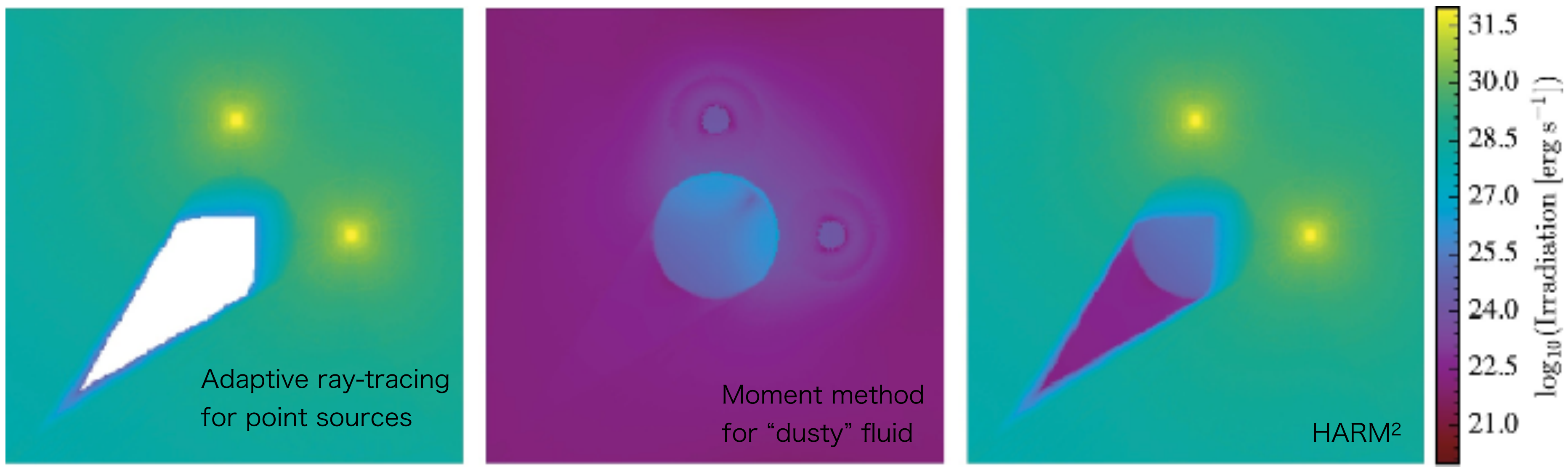
Schneider+2018

How do these very massive stars form?

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

Modeling radiation pressure in 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:

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

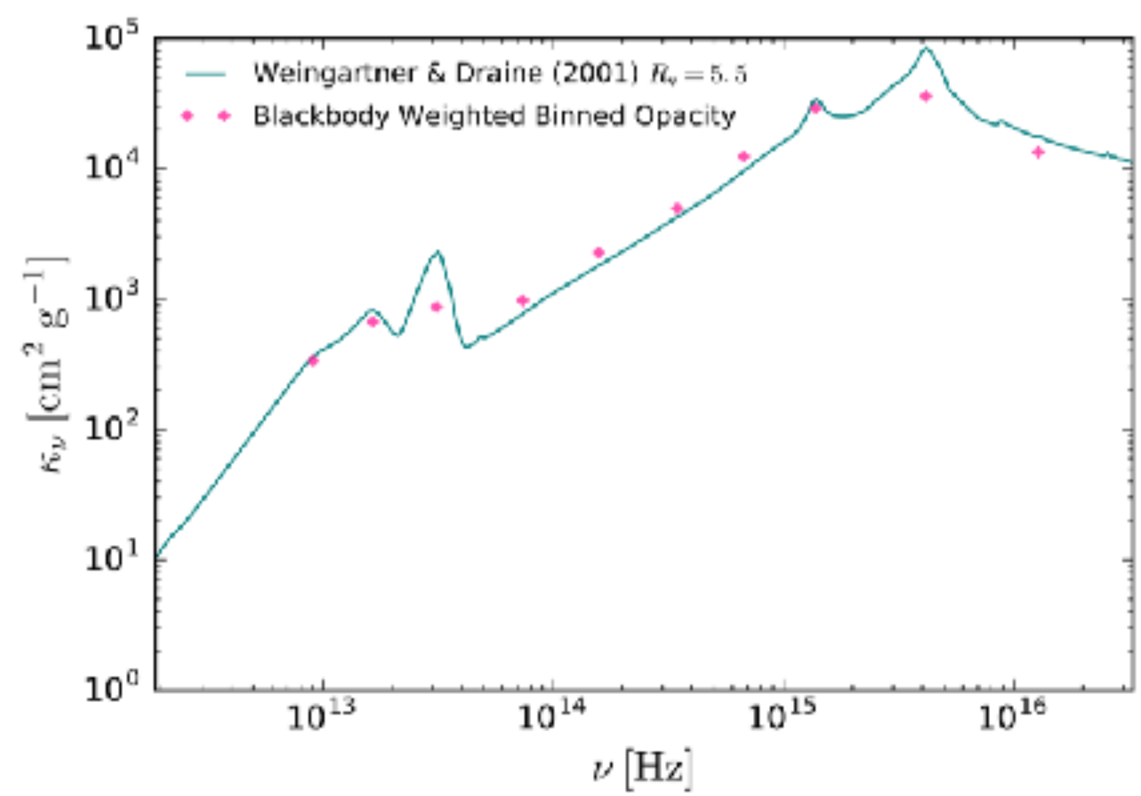
Luminosity absorbed ($\tau_j = \rho_d \kappa_j\, dl$):

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

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

ORION solves RHD equations and evolves accreting Lagrangian sink particles on adaptive grids

RHD equations describe conservation of:

Mass:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + \sum_i \dot{M}_i W(\mathbf{x} - \mathbf{x}_i)$$

Momentum:

$$\frac{\partial (\rho \mathbf{v})}{\partial t} = -\nabla \cdot (\rho \mathbf{v}\mathbf{v}) - \nabla P - \rho \nabla \phi - \lambda \nabla E_{\mathrm{R}} + \sum_i \left[\dot{\mathbf{p}}_{\mathrm{rad},i} - \dot{\mathbf{p}}_i W(\mathbf{x} - \mathbf{x}_i)\right]$$

Energy:

$$\frac{\partial (\rho e)}{\partial t} = -\nabla \cdot [(\rho e + P)\mathbf{v}] - \rho \mathbf{v} \cdot \nabla \phi - \kappa_{0\mathrm{P}} \rho (4\pi B - c E_{\mathrm{R}}) + \lambda \left(2 \frac{\kappa_{0\mathrm{P}}}{\kappa_{0\mathrm{R}}} - 1\right) \mathbf{v} \cdot \nabla E_{\mathrm{R}} - \left(\frac{\rho}{m_{\mathrm{p}}}\right)^2 \Lambda(T_{\mathrm{g}}) + \sum_i \left[\dot{\varepsilon}_{\mathrm{rad},i} - \dot{\varepsilon}_i W(\mathbf{x} - \mathbf{x}_i)\right]$$

Radiation Energy:

$$\frac{\partial E_{\mathrm{R}}}{\partial t} = \nabla \cdot \left(\frac{c\lambda}{\kappa_{0\mathrm{R}} \rho} \nabla E_{\mathrm{R}}\right) + \kappa_{0\mathrm{P}} \rho (4\pi B - c E_{\mathrm{R}}) - \lambda \left(2 \frac{\kappa_{0\mathrm{P}}}{\kappa_{0\mathrm{R}}} - 1\right) \mathbf{v} \cdot \nabla E_{\mathrm{R}} - \nabla \cdot \left(\frac{3 - R_2}{2} \mathbf{v} E_{\mathrm{R}}\right) + \left(\frac{\rho}{m_{\mathrm{p}}}\right)^2 \Lambda(T_{\mathrm{g}})$$

Star particles updated via:

$$\frac{dM_{\mathrm{i}}}{dt} = \dot{M}$$

$$\frac{d\mathbf{x}_{\mathrm{i}}}{dt} = \frac{\mathbf{p}_{\mathrm{i}}}{M_{\mathrm{i}}}$$

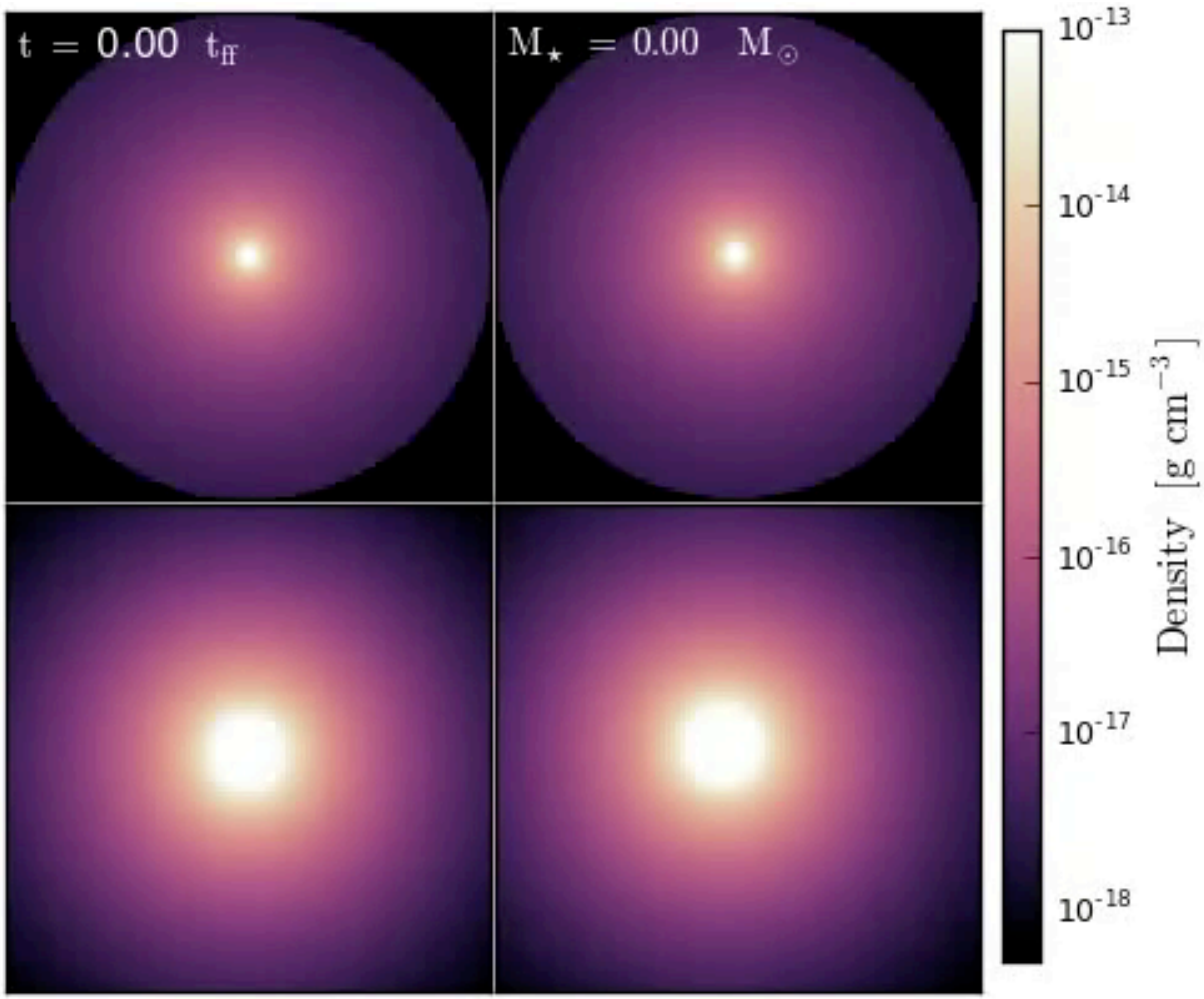
$$\frac{d\mathbf{p}_{\mathrm{i}}}{dt} = -M_i \nabla \phi + \dot{\mathbf{p}}_i,$$

Both fluid density and particles contribute to gravity:

$$\nabla^2 \phi = 4\pi G \left[\rho + \sum_i M_i \delta(\mathbf{x} - \mathbf{x}_{\mathrm{i}})\right]$$

Klein+1999, Mignone+2012 (Hydro); Krumholz+2004 (Lagrangian sink particles), Offner+2009 (protostellar evolution model); Truelove+1998 (self-gravity); Krumholz+2007, Shestakov & Offner 2008, Rosen+2017 (Radiation)

Formation of a massive stellar system from the collapse of a subvirial turbulent pre-stellar core with radiative feedback



Rosen+2016

Initial Conditions:

M_{core}=150 $M_\odot$

R_{core}=0.1 pc

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

σ_{1D}=0.4 km s^{-1}

α_{vir} = 0.12

Δx_{min}=20 AU

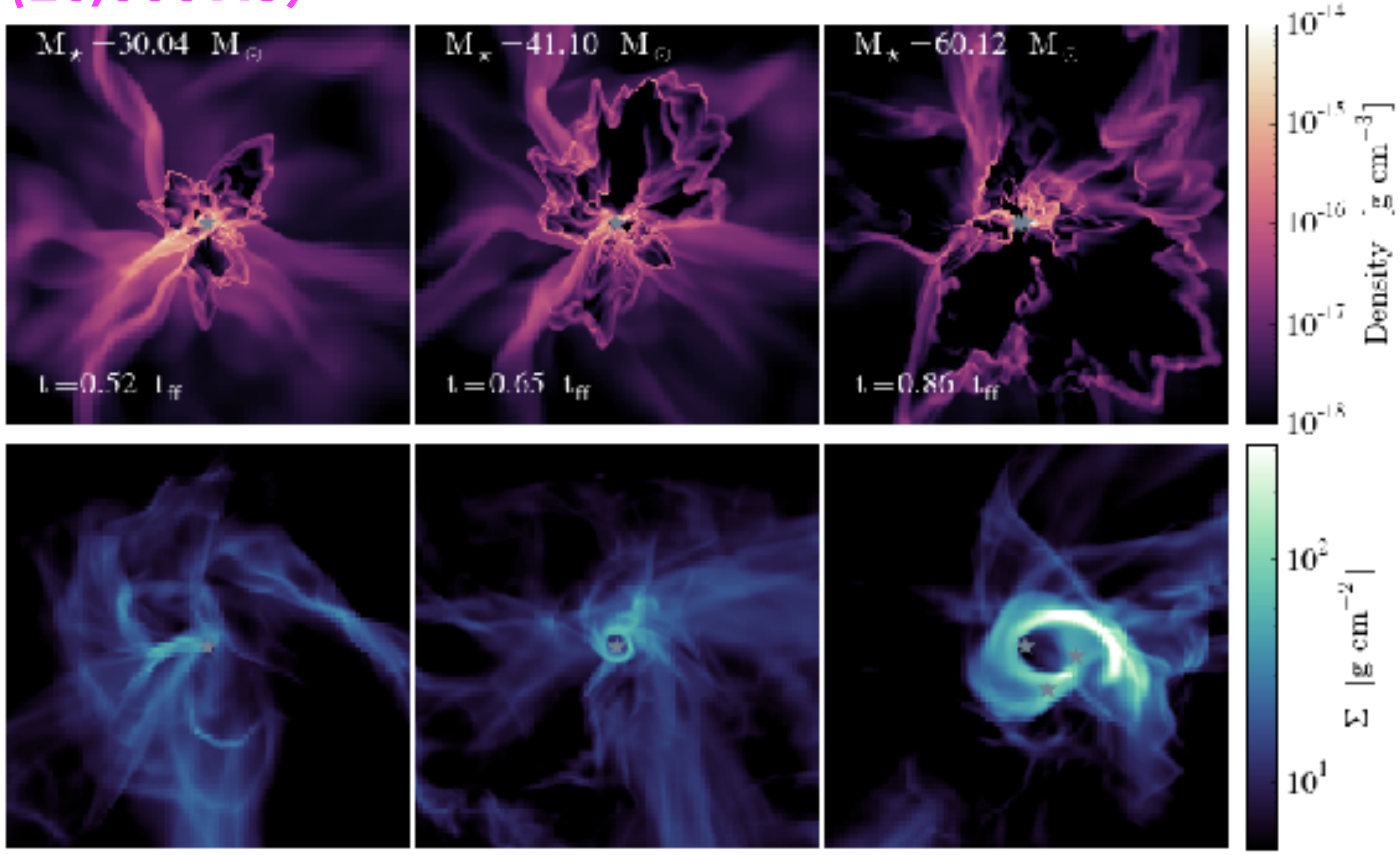
t_{ff}=42,710 yrs

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

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

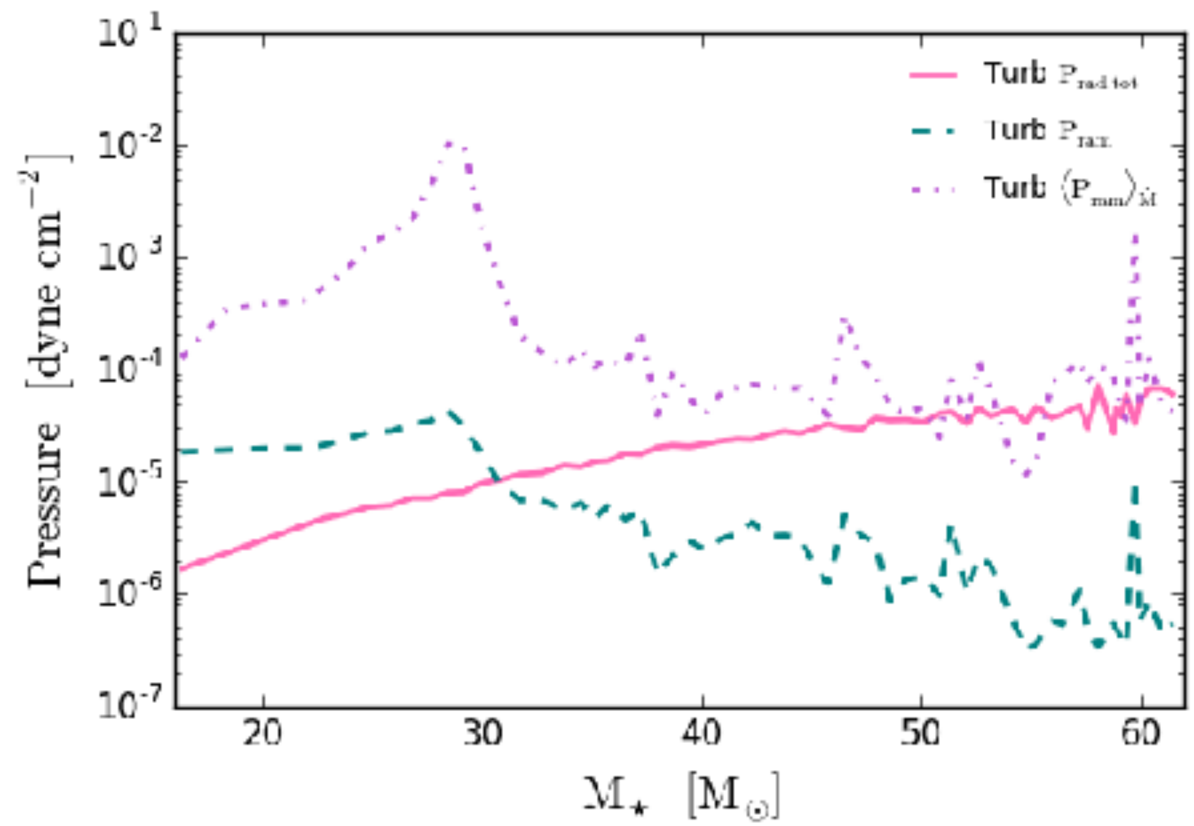
Mass delivered to star via infalling dense filaments, radiative Rayleigh Taylor instabilities, and disk accretion.

(20,000 AU)²



(3,000 AU)²

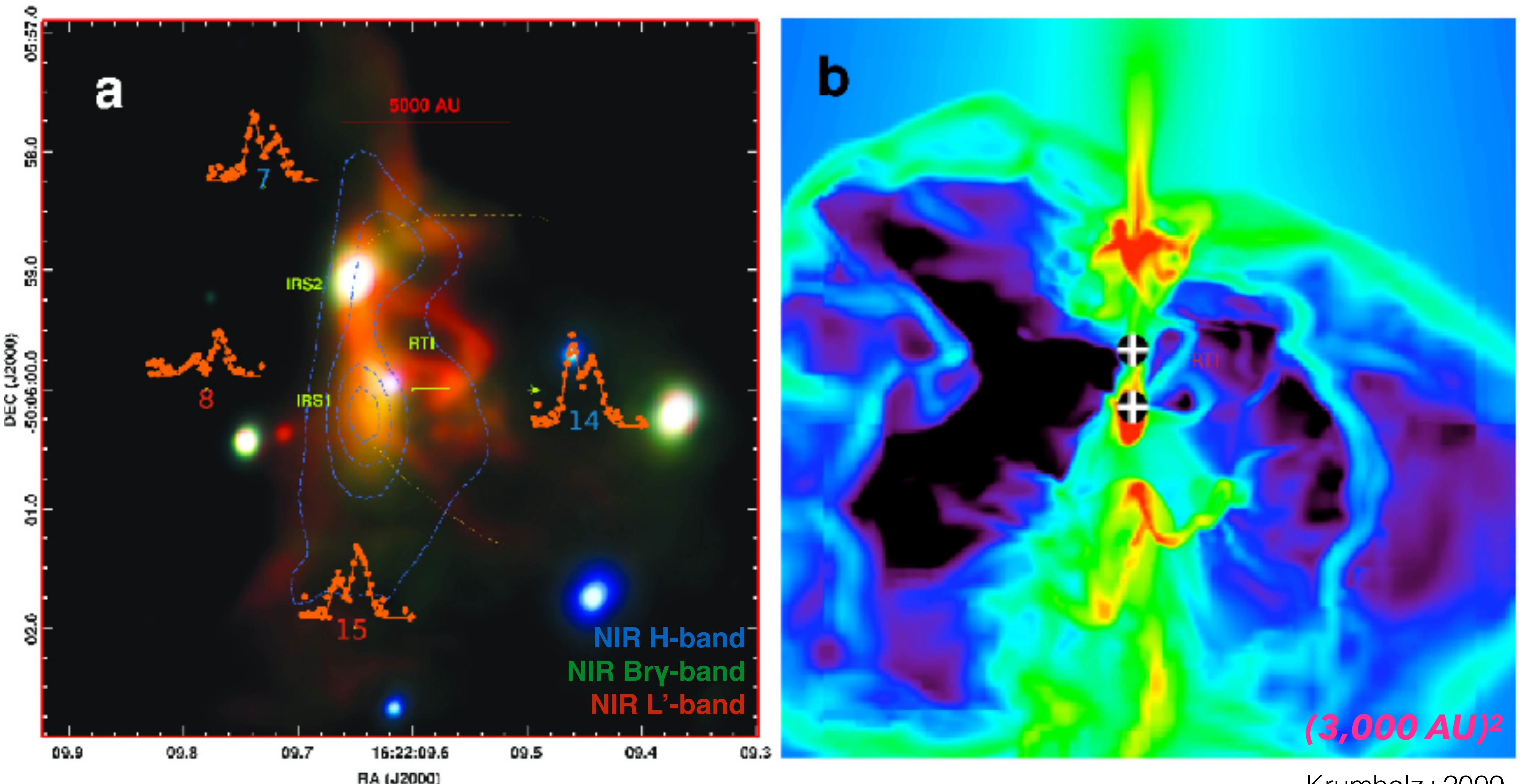
Rosen+2016



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

Radiation pressure barrier is no longer a barrier!

In agreement, Rayleigh Taylor Instabilities (RTI) have been observed in massive star formation.

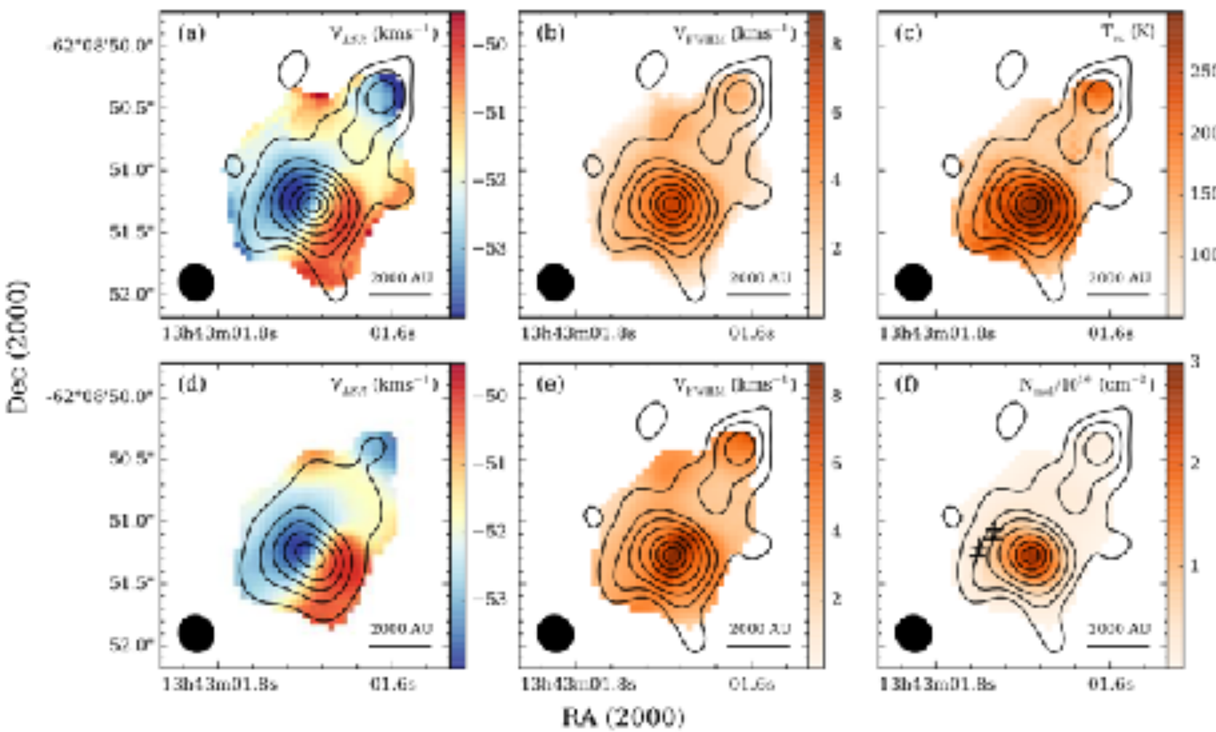


Kumar 2013

Krumholz+2009

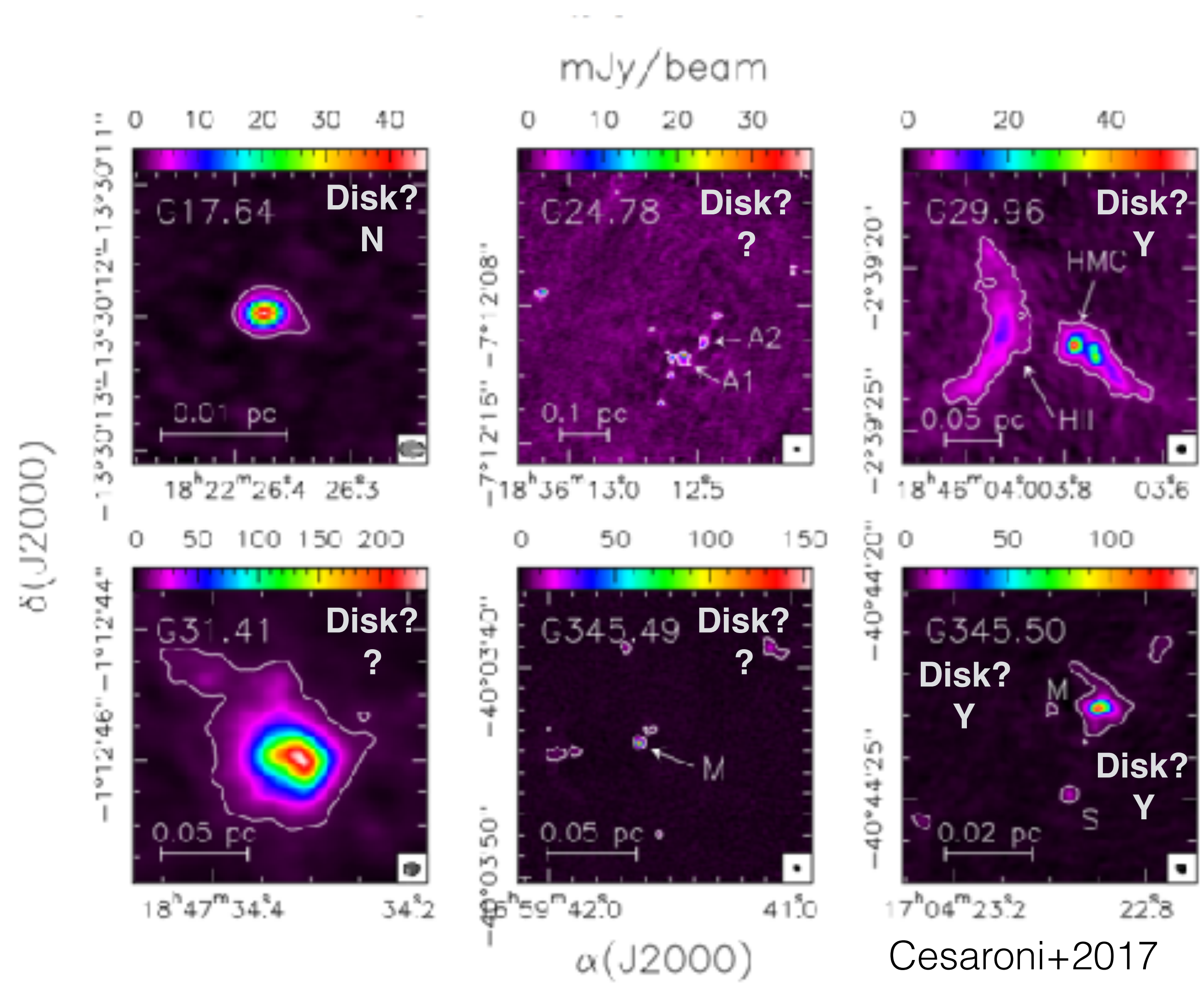
RT filaments mean length ~2000 AU, mean width ~500 AU

Also, a “handful” of disks have been found around young O-stars



Johnston+2015

O-type Star AFGL4176 (O7?)
R_{Disk}~ 2000 AU
M_{Disk}~ 12 $M_{\odot}$



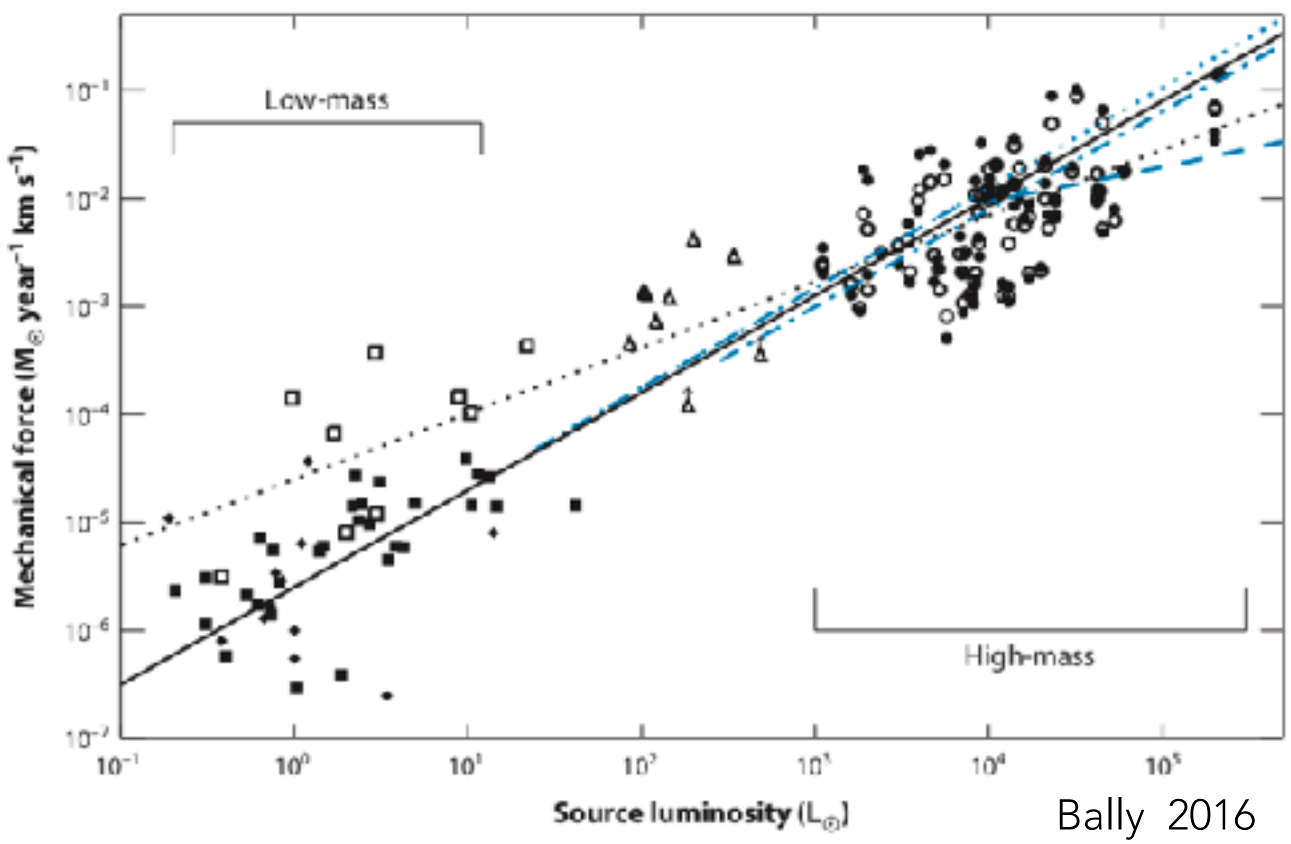
Cesaroni+2017

Criteria for Disk:

1) CH_3CN emission (dense gas) perpendicular to SiO emission (shocks produced by outflows)
2) Velocity increases with decreasing distance to star.

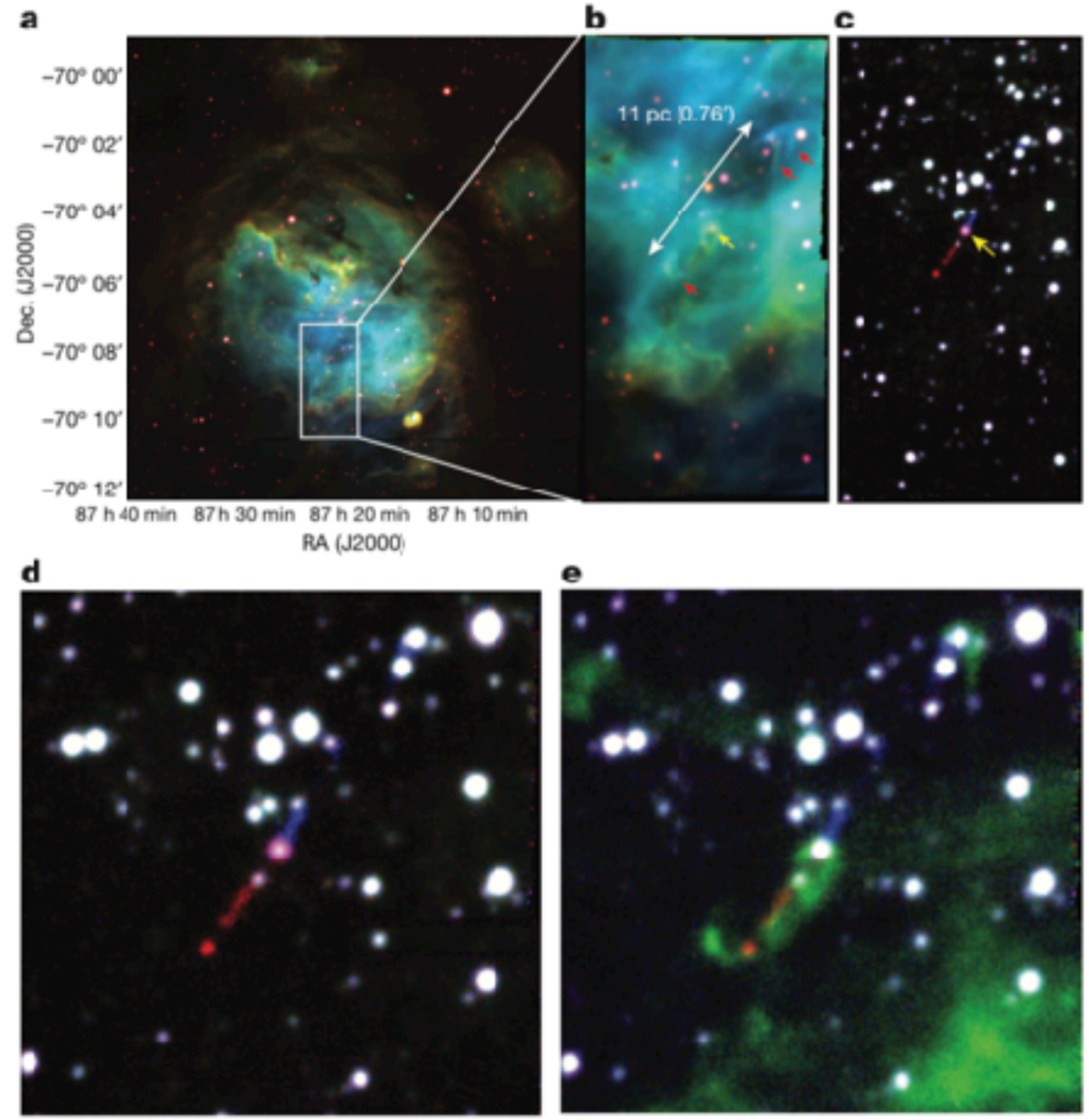
However, there are other feedback mechanisms also at play in massive star formation.

Collimated Outflows:



Bally 2016

Parsec scale jets from a massive star in the LMC (HH-1177)

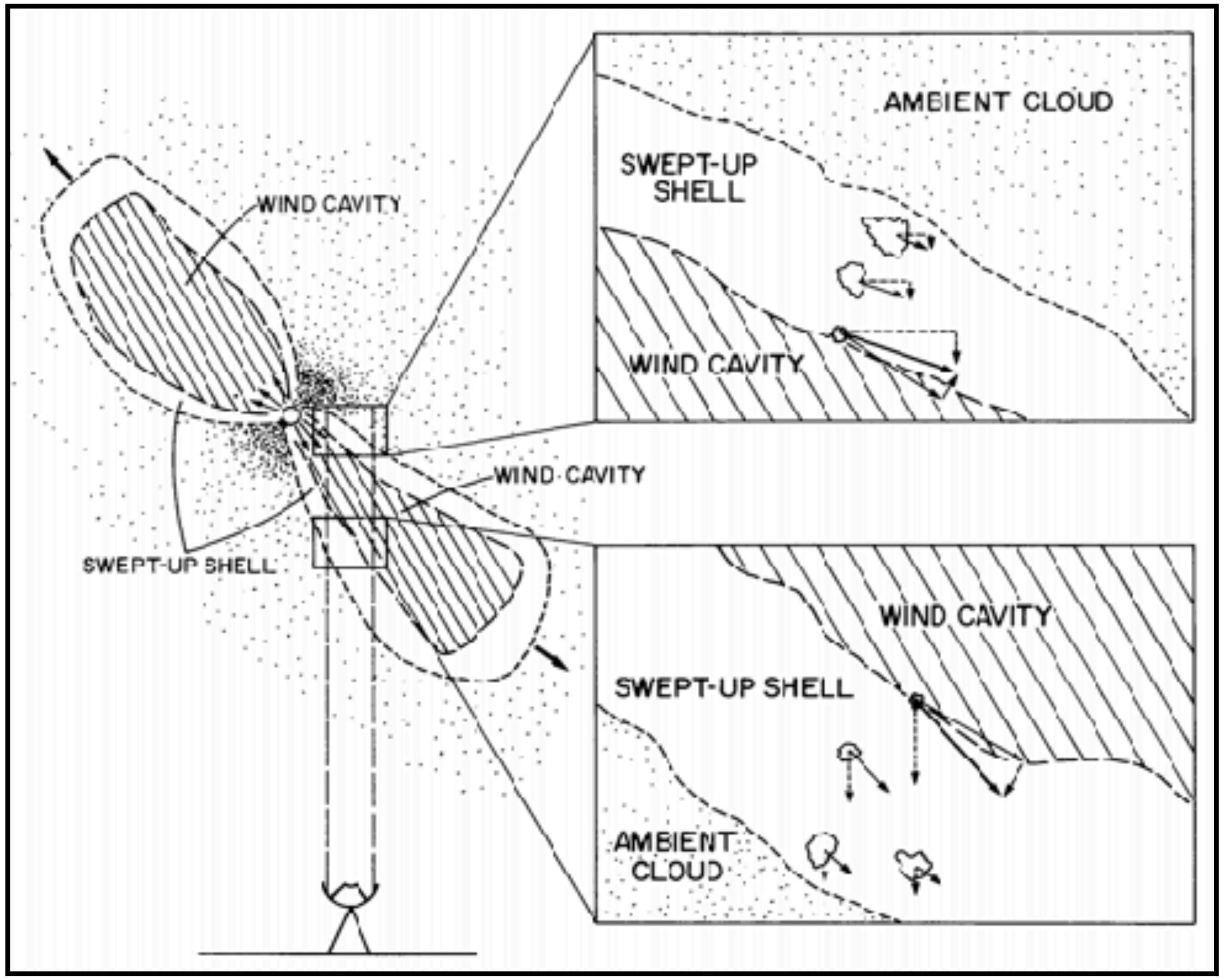


~12 M⊙ MYSO

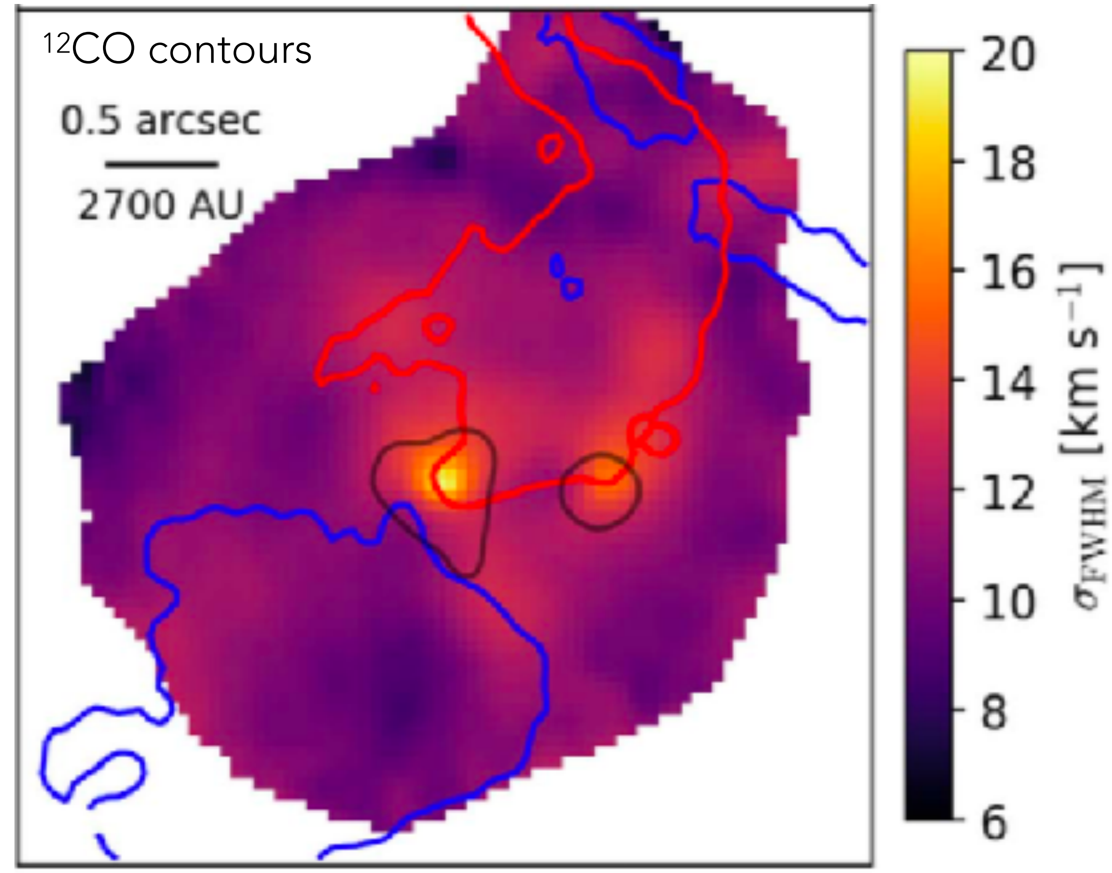
McLeod+2018

Disk mediated accreting massive stars have magnetically launched collimated bipolar outflows like low-mass stars.

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

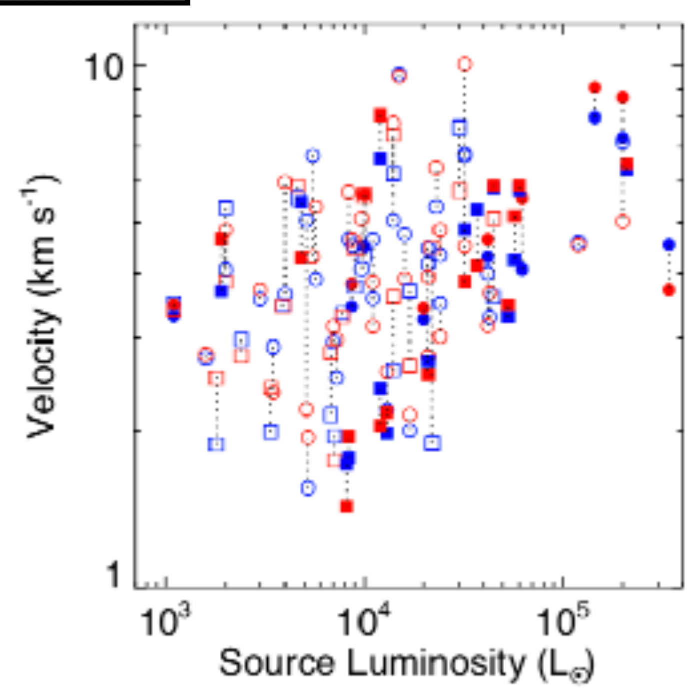


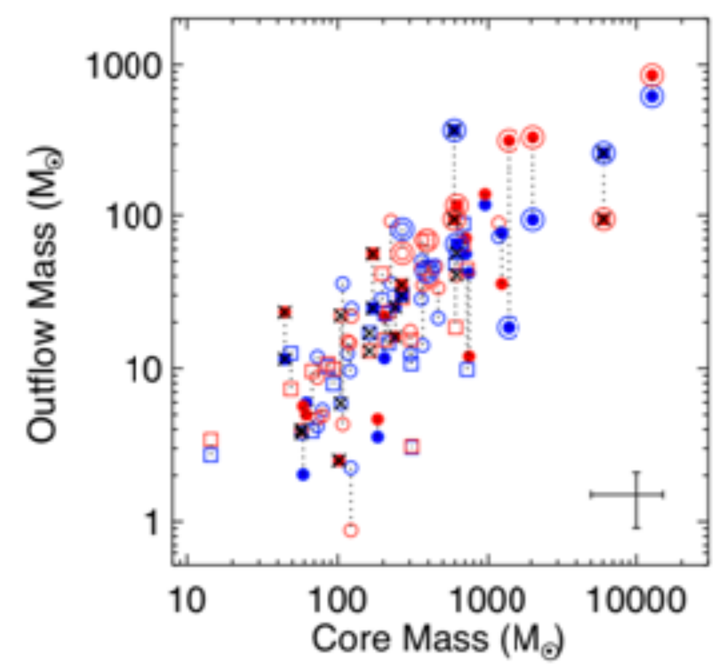
Lada 1985, ARAA



Ginsburg+2017

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



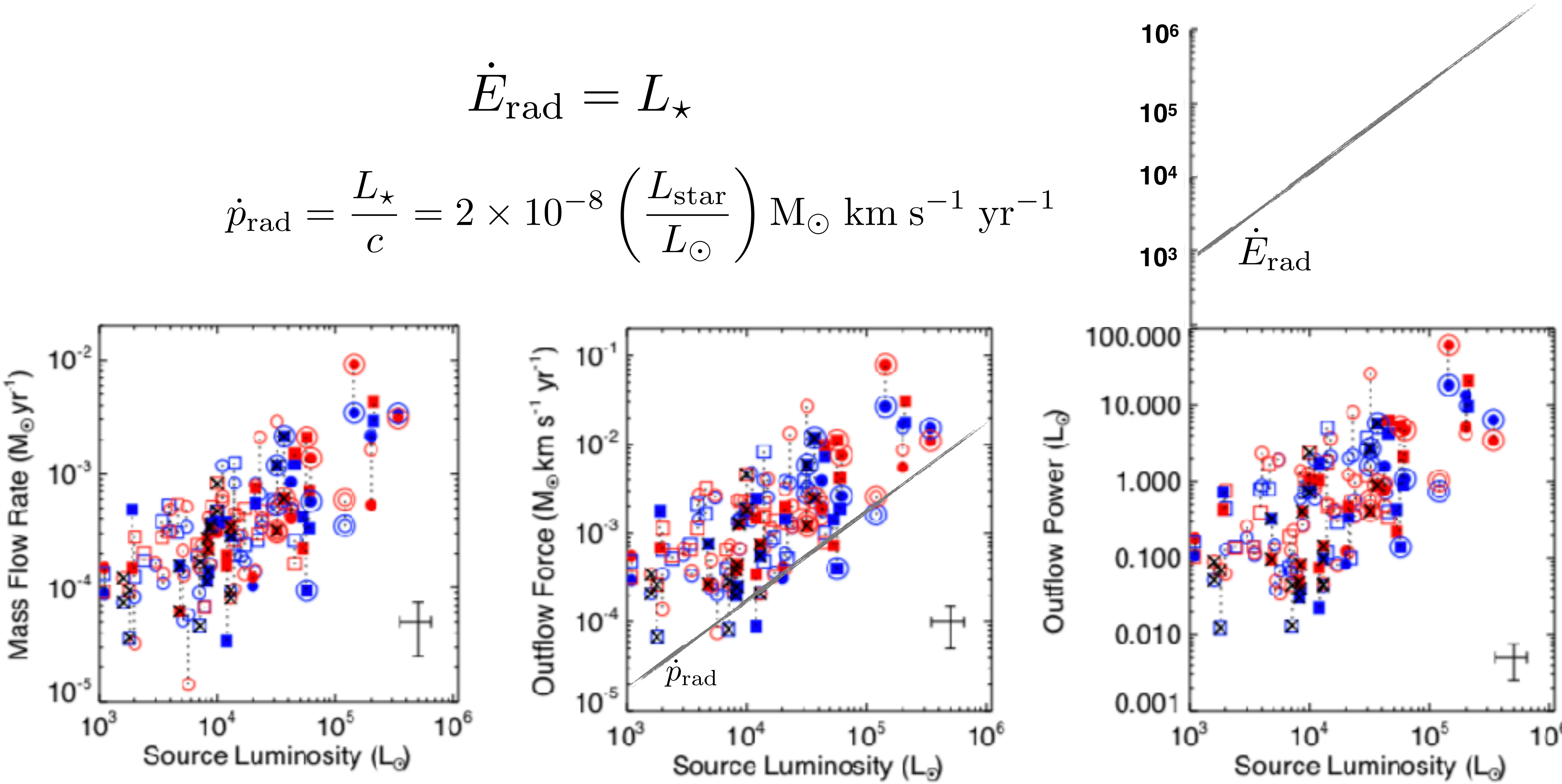


Maud+2015

Bipolar outflows are ubiquitous in massive star formation

$$\dot{E}_{\rm rad} = L_\star$$

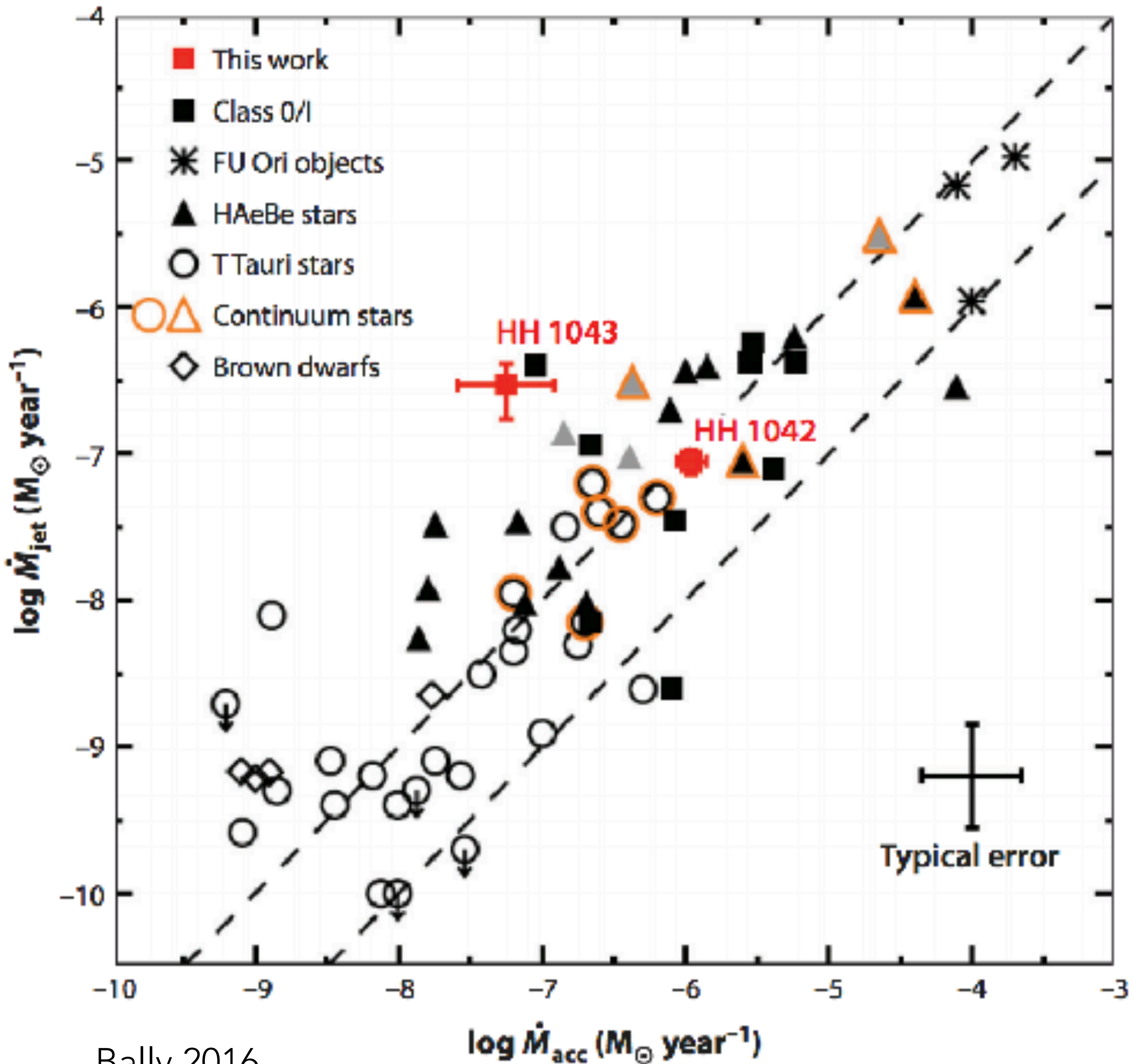
$$\dot{p}_{\rm rad} = \frac{L_\star}{c} = 2 \times 10^{-8} \left(\frac{L_{\rm star}}{L_\odot}\right) {\rm M_\odot\ km\ s^{-1}\ yr^{-1}}$$



Maud+2015

Momentum feedback from outflows > momentum feedback from radiation, whereas radiation dominates energy injection.

Collimated Outflows add mass, momentum, and energy to gas



Bally 2016

Subgrid outflow model in ORION:

$$\dot{M}_{w,i} = f_w \dot{M}_i$$

$$\left.\frac{d\rho}{dt}\right|_s = -\dot{M}_{w,i}\chi_w(|\mathbf{r}_i|)\bar{\xi}(\theta_i),$$

$$\left.\frac{d\rho\mathbf{v}}{dt}\right|_s = -f_v v_{k,i}\dot{M}_{w,i}\chi_w(|\mathbf{r}_i|)\bar{\xi}(\theta_i)\cdot\hat{\mathbf{r}}_i,$$

$$\left.\frac{d\rho e}{dt}\right|_s = -\dot{M}_{w,i}\chi_w(|\mathbf{r}_i|)\bar{\xi}(\theta_i)\frac{k_B T_w}{\mu(\gamma-1)},$$

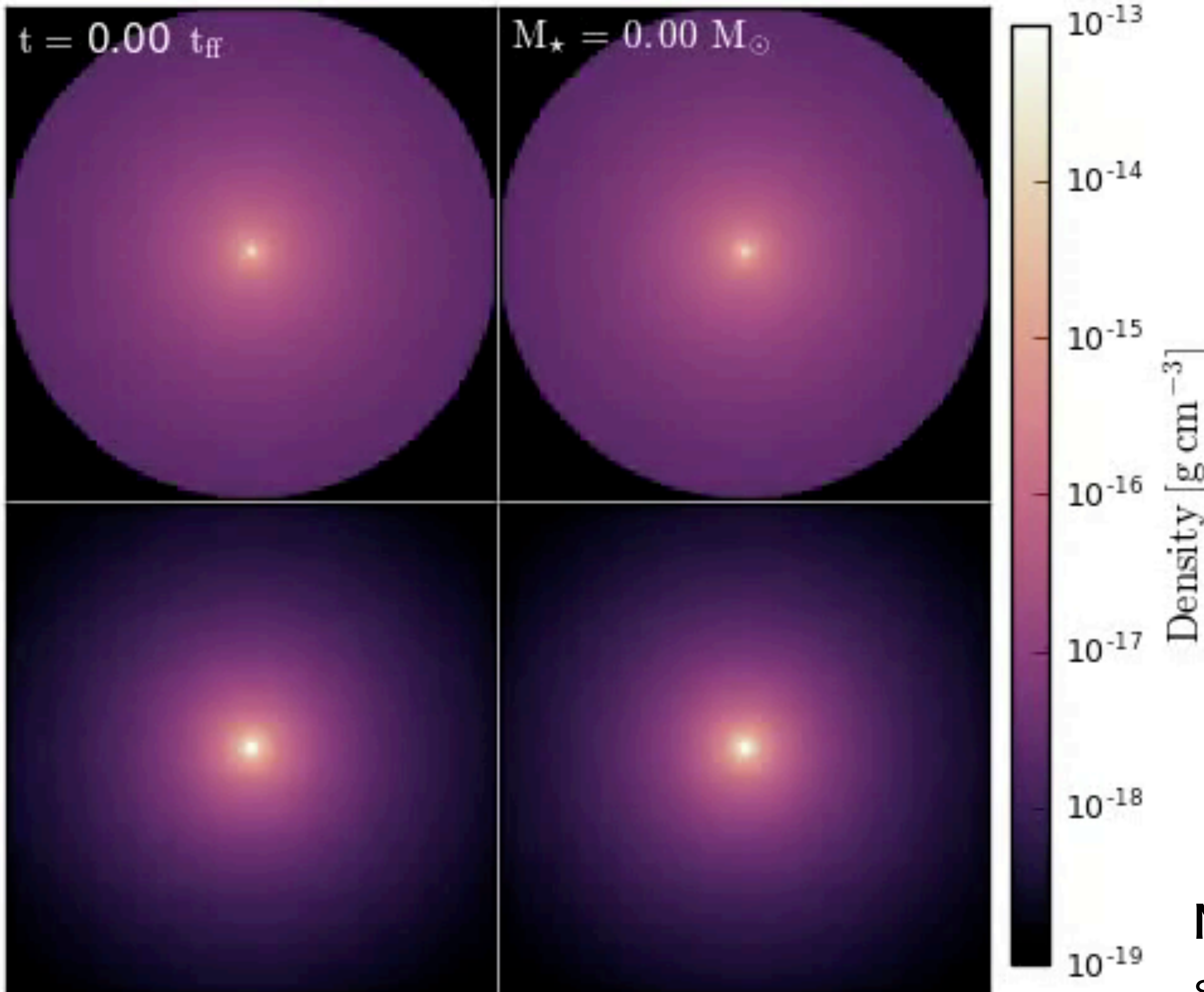
$$f_w f_v = \frac{P_w}{v_k M_*},$$

Observations yield values of $0.025 \lesssim f_w f_v \lesssim 0.38.$

We take: $f_w = 0.21, f_v = 0.3$

Cunningham+2011

Formation of a massive stellar system from the collapse of a ~virial turbulent pre-stellar core with radiative and outflow feedback



Rosen+(in prep)

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

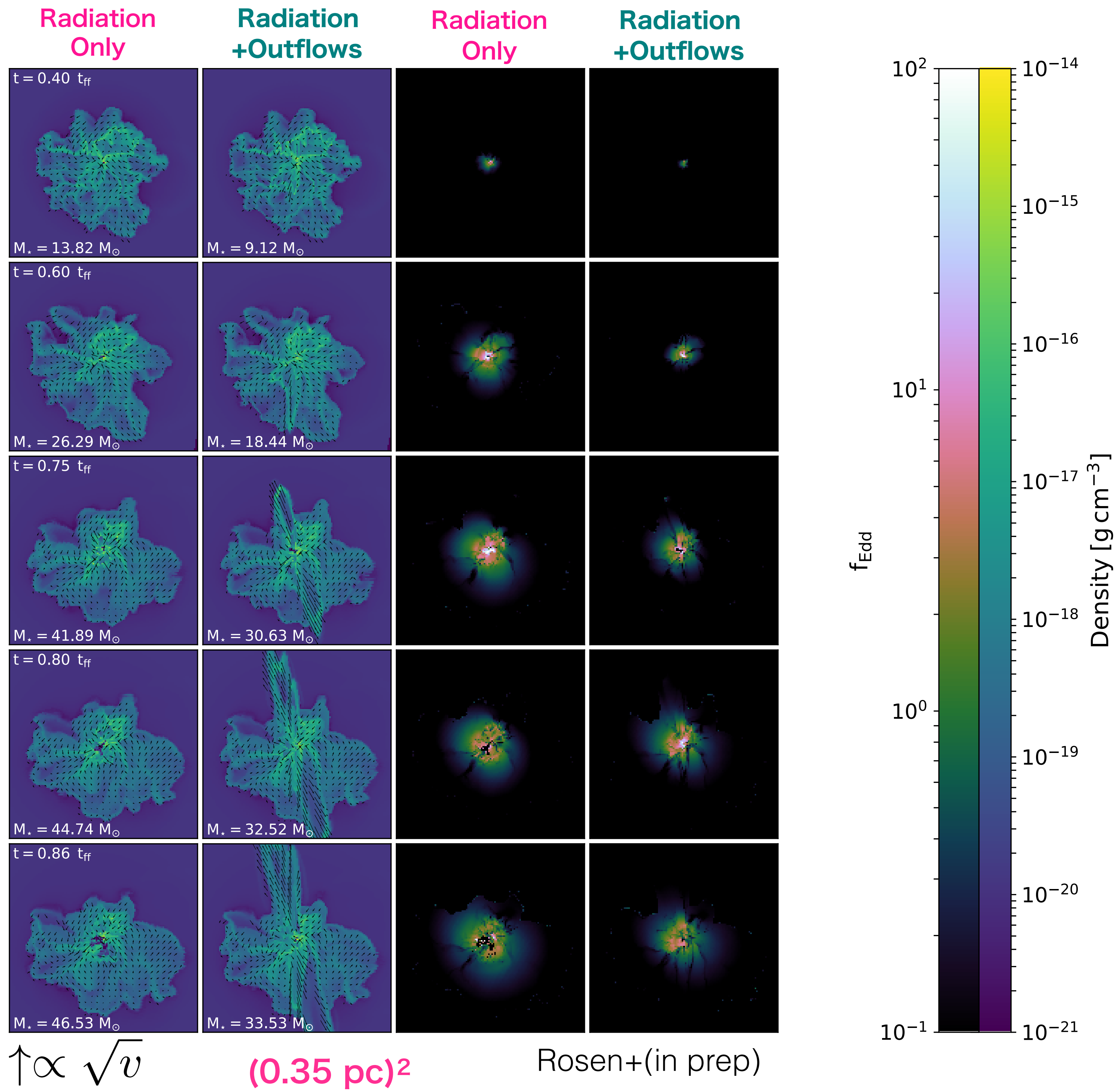
t_{ff}=42,710 yrs

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

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

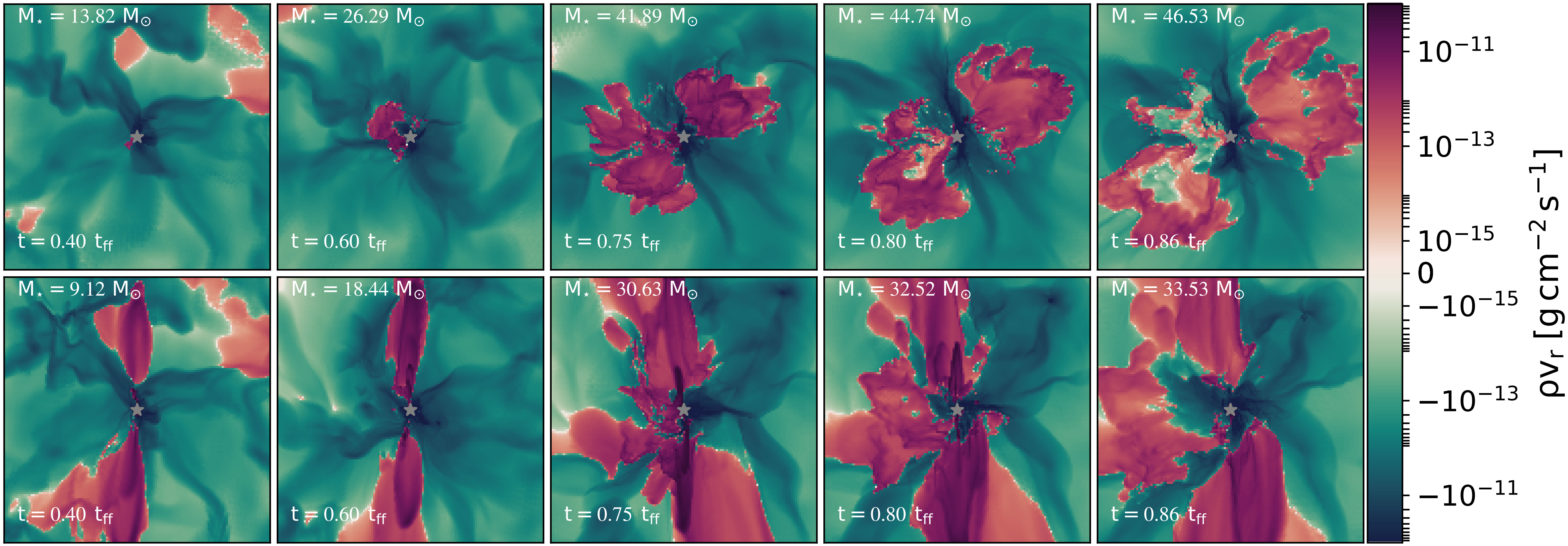
Note: we compare this simulation with same initial conditions, but no outflows (radiation pressure feedback only).

Momentum injection by outflows efficiently ejects material from massive star-forming cores at late times.



- Outflows can eject gas from core while massive stars are actively forming.
- Outflows likely responsible for observed low star formation efficiencies in cores.
- $f_{edd} > 1$ within inner regions of core
- Dense filaments collapse and attain $f_{edd} < 1$

Outflows+radiation pressure very efficient at ejecting material away from the (lower-mass) star than radiation pressure alone.



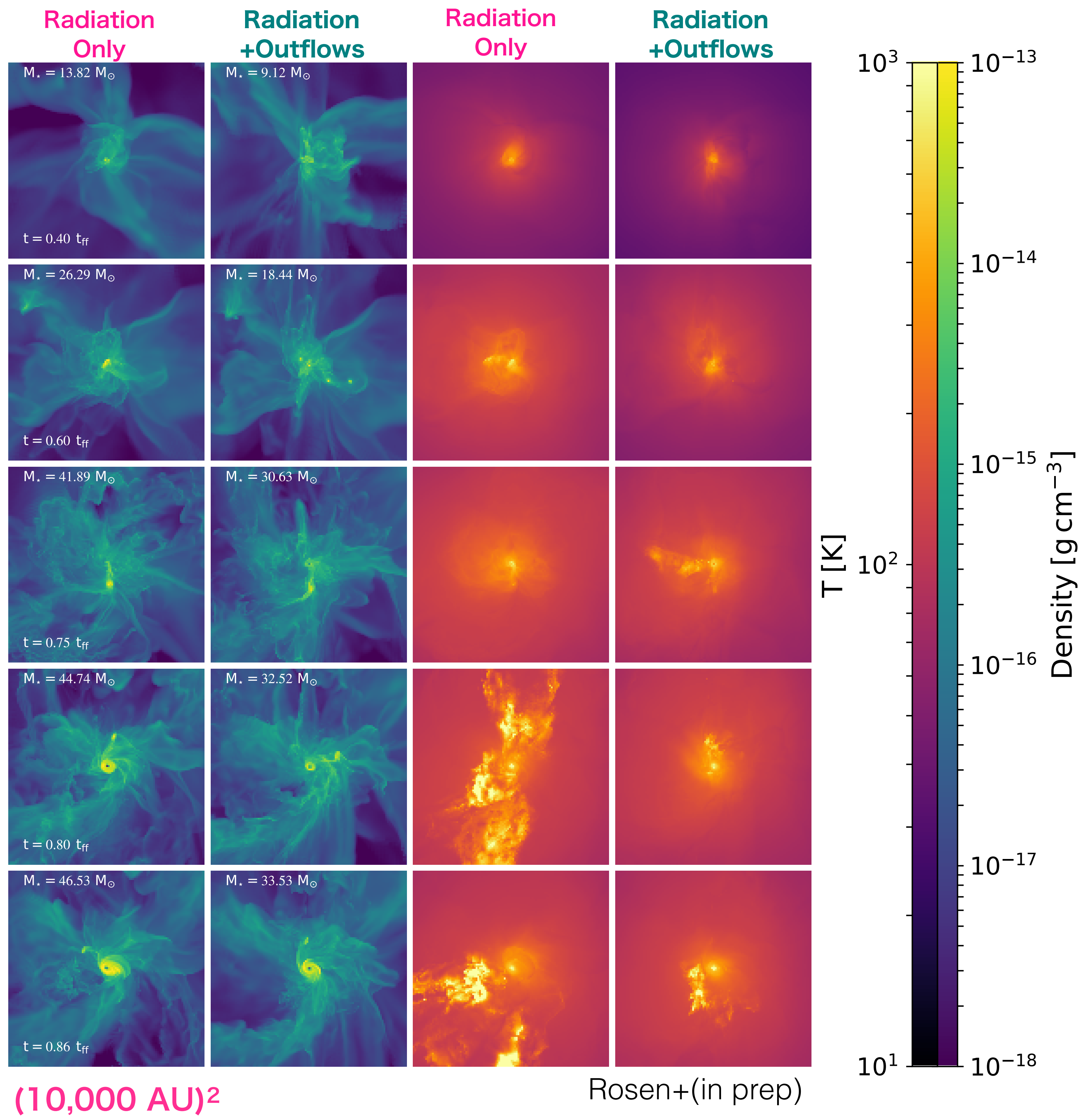
(20,000 AU)²

Rosen+(in prep)

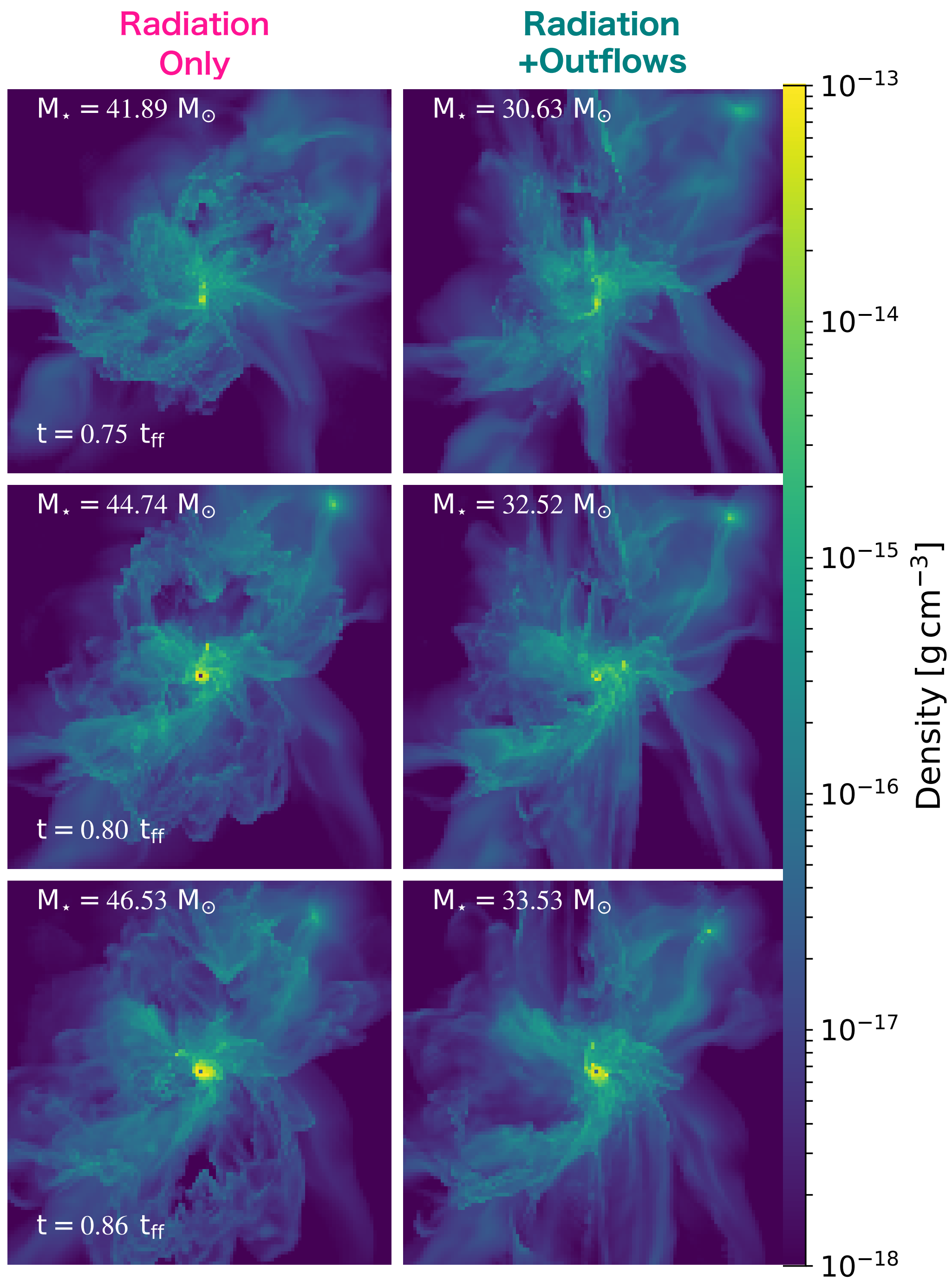
When only radiation pressure is considered, the radiation dominated bubbles can become radiative Rayleigh Taylor (RT) unstable.

Momentum injection from outflows are necessary to eject material from core.

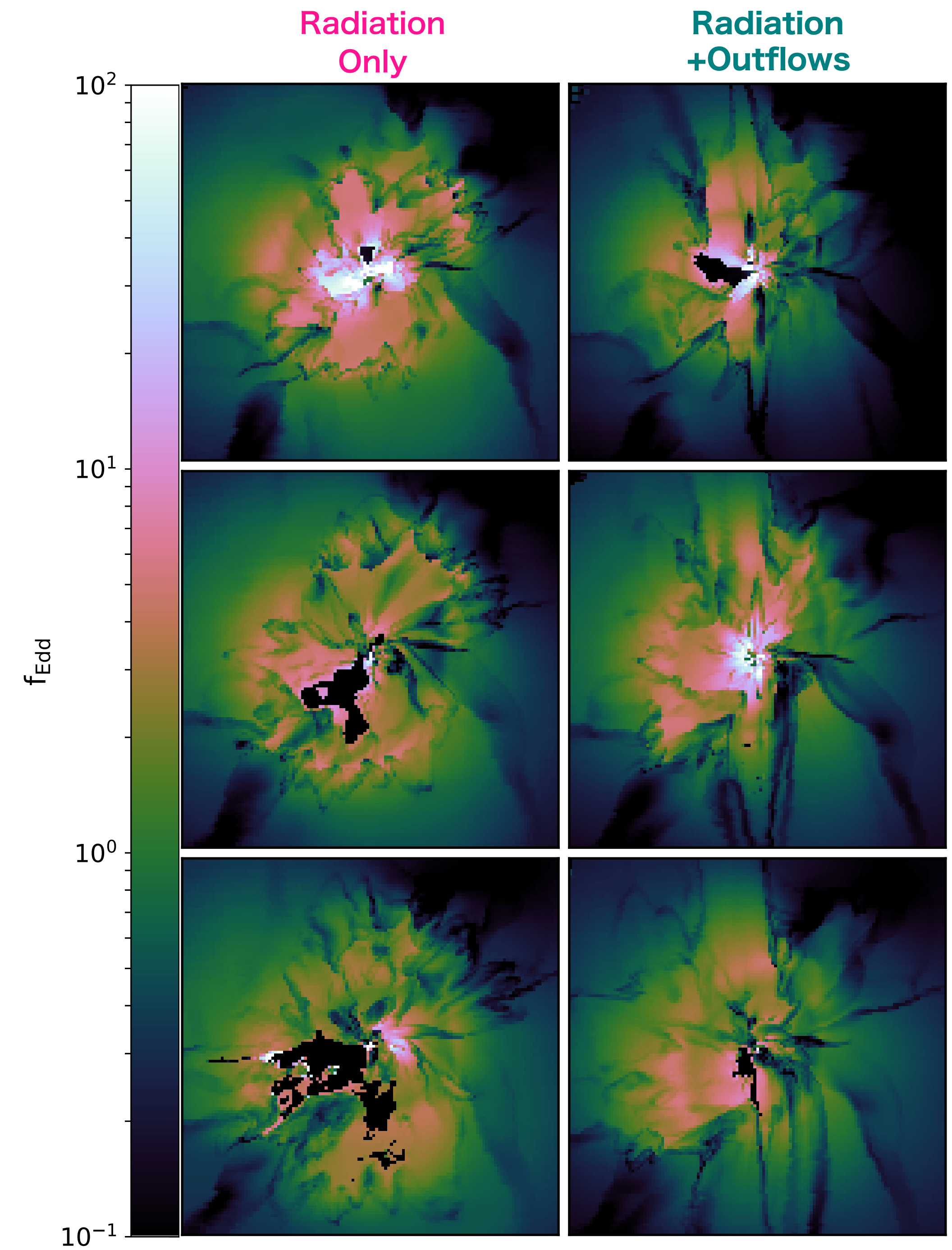
Shock heating by outflows and energy deposited by stellar radiation heats gas.



…but RT instabilities are less prominent when outflows are included.



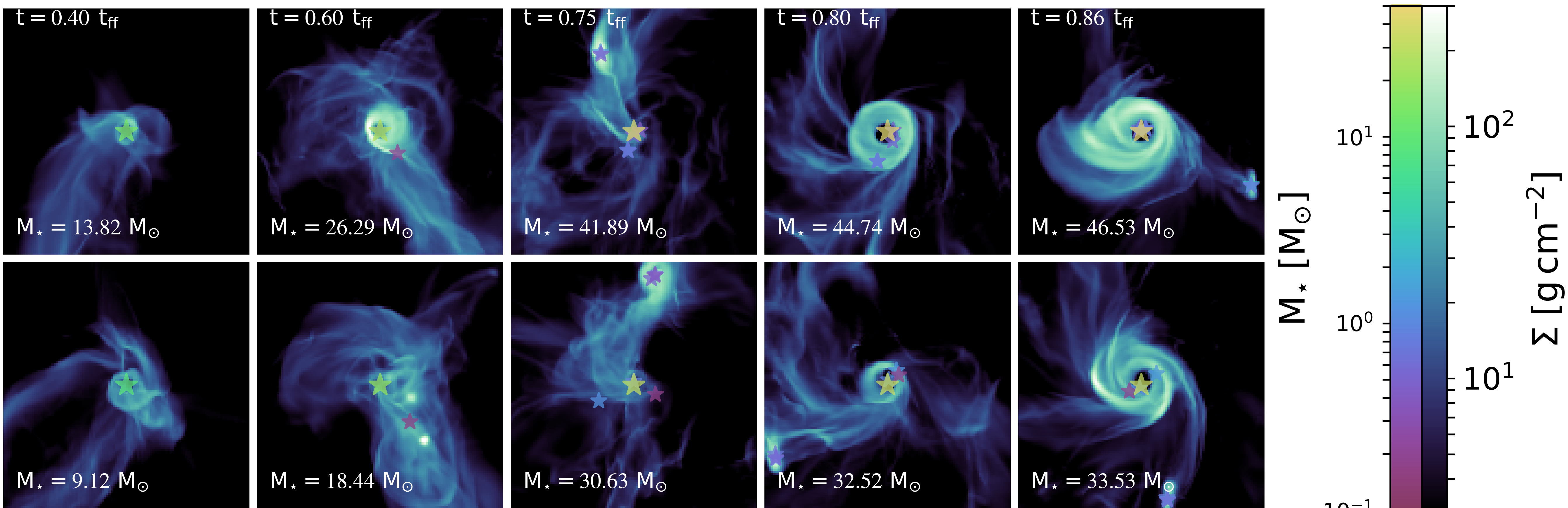
(20,000 AU)^2



Rosen+(in prep)

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

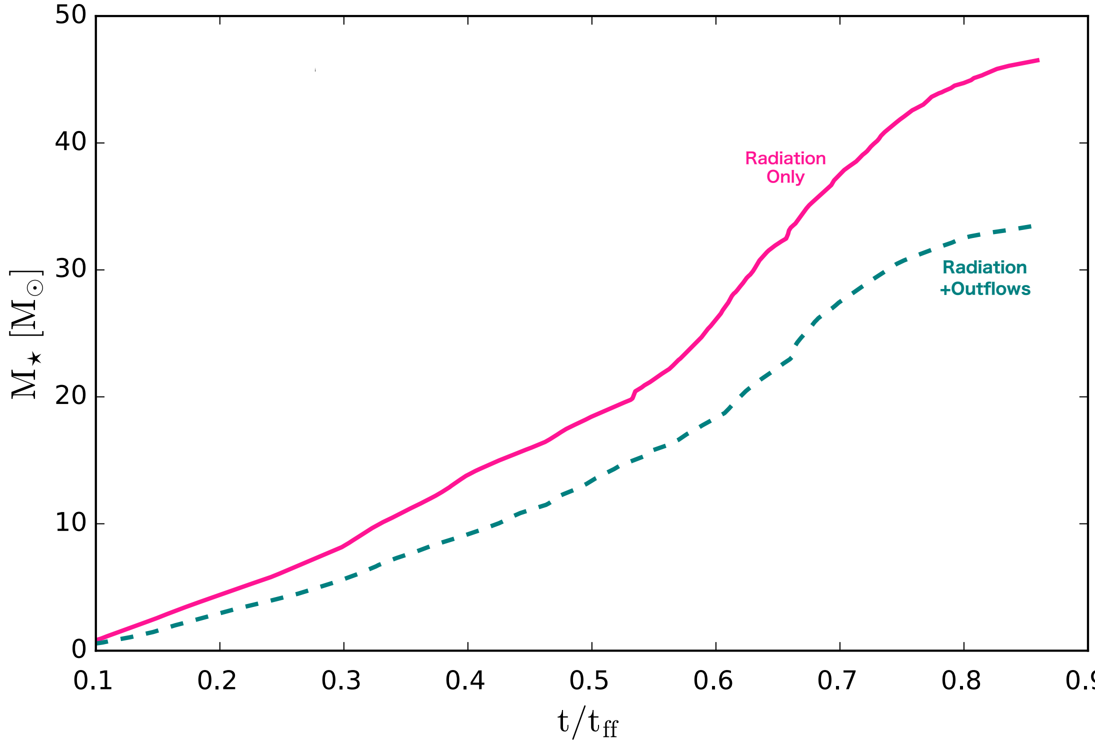
Disks are crucial to massive star formation, especially at late times.

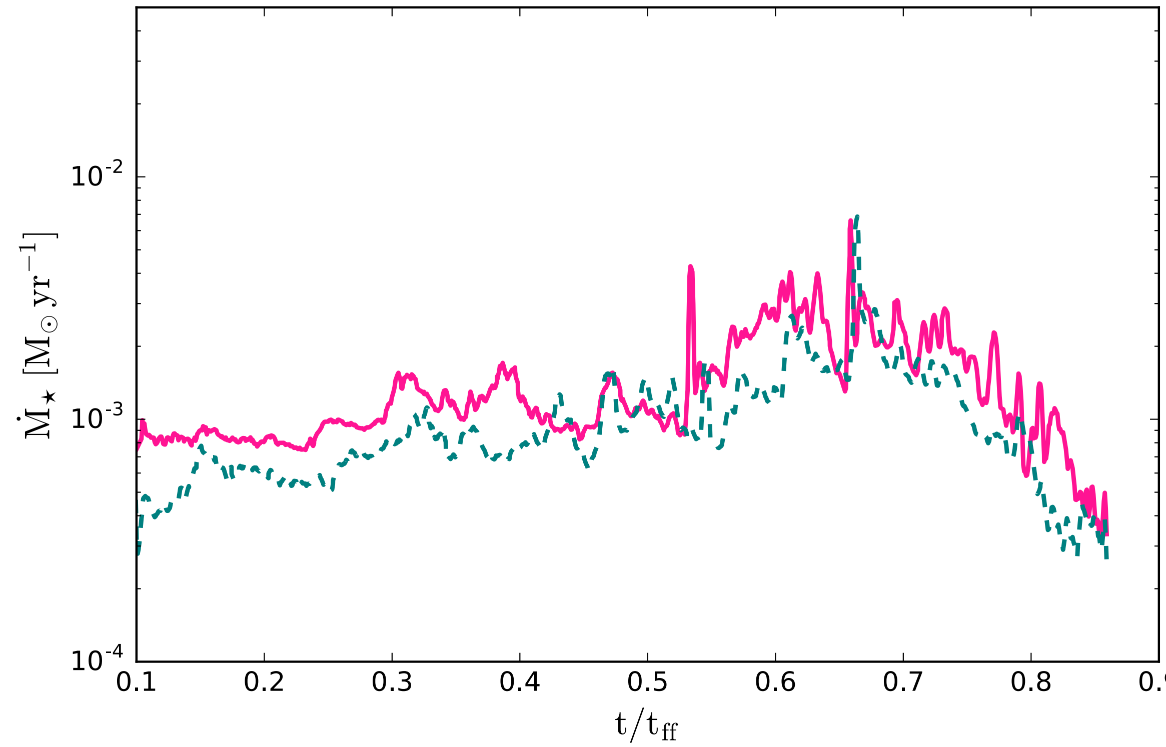


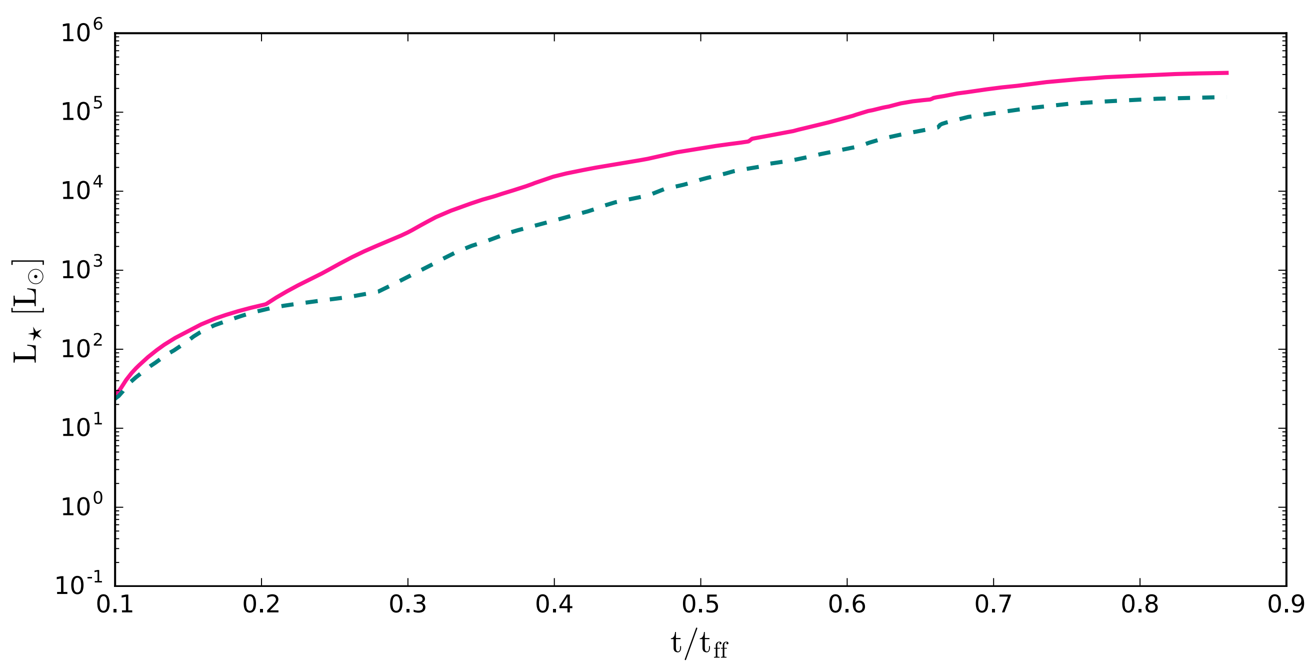
(3,000 AU)²

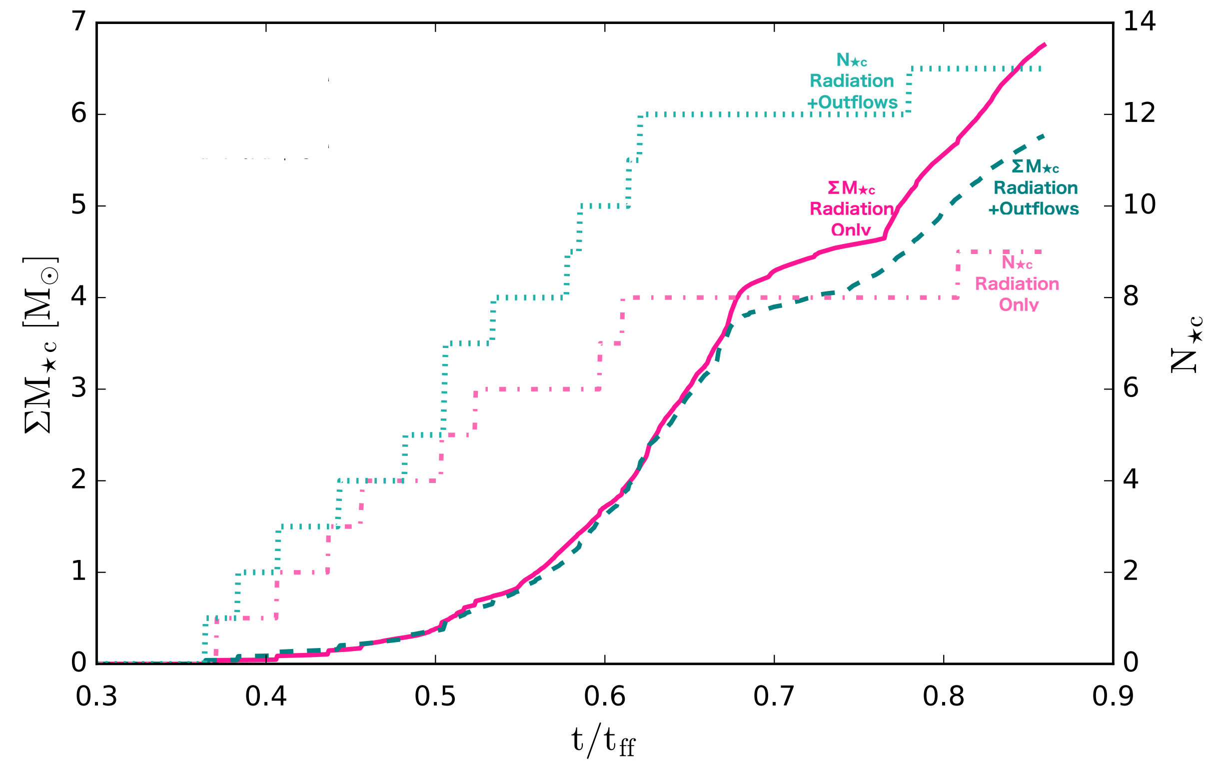
Disk is destroyed by dynamical effects (accretion of companions, filaments) but it re-emerges.

Feedback causes accretion rate onto massive star to decrease at late times ($t \gtrsim 0.7\ t_{ff}$)





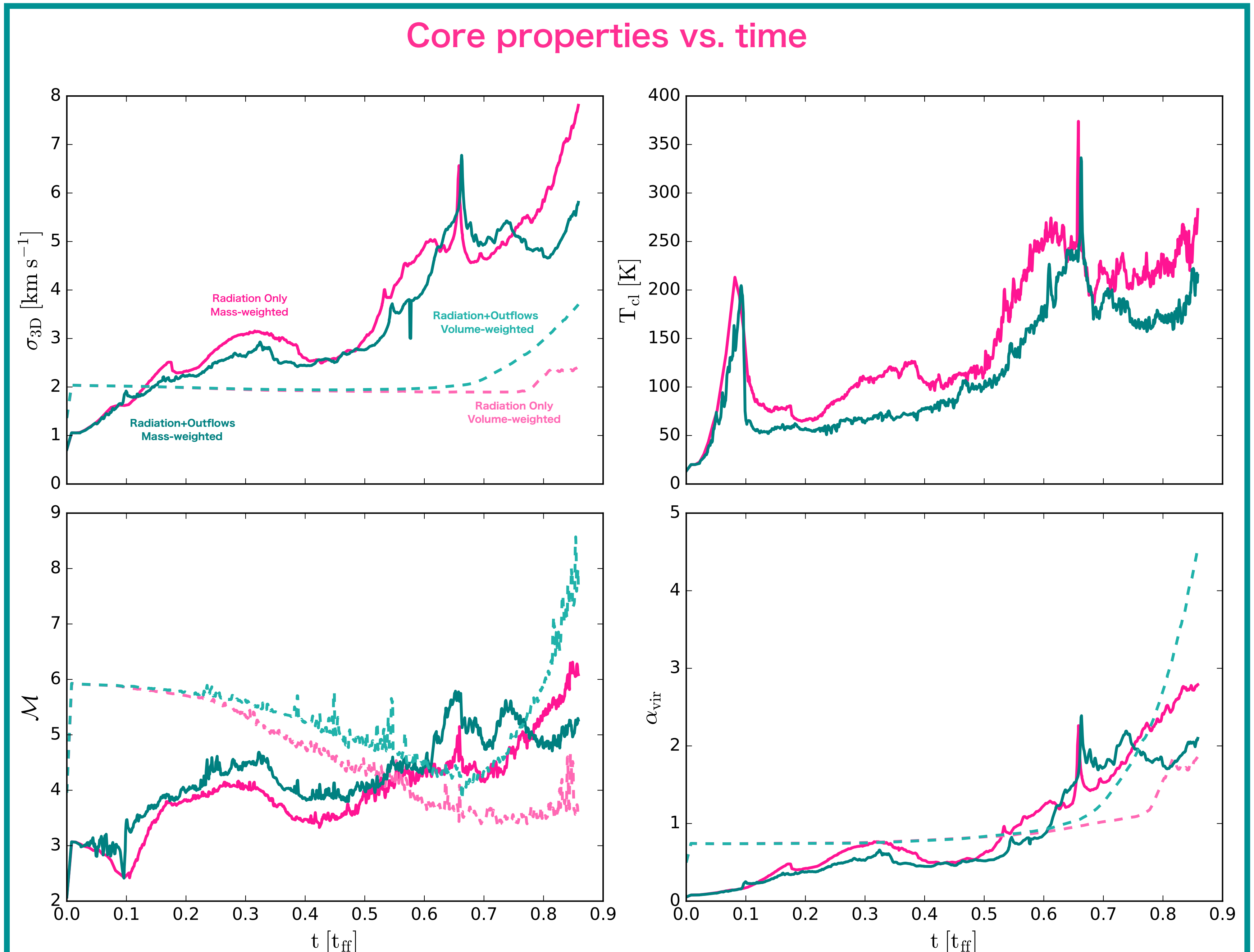




Fragmentation into companions is reduced when radiative heating is enhanced (e.g., no outflows case).

Rosen+(in prep)

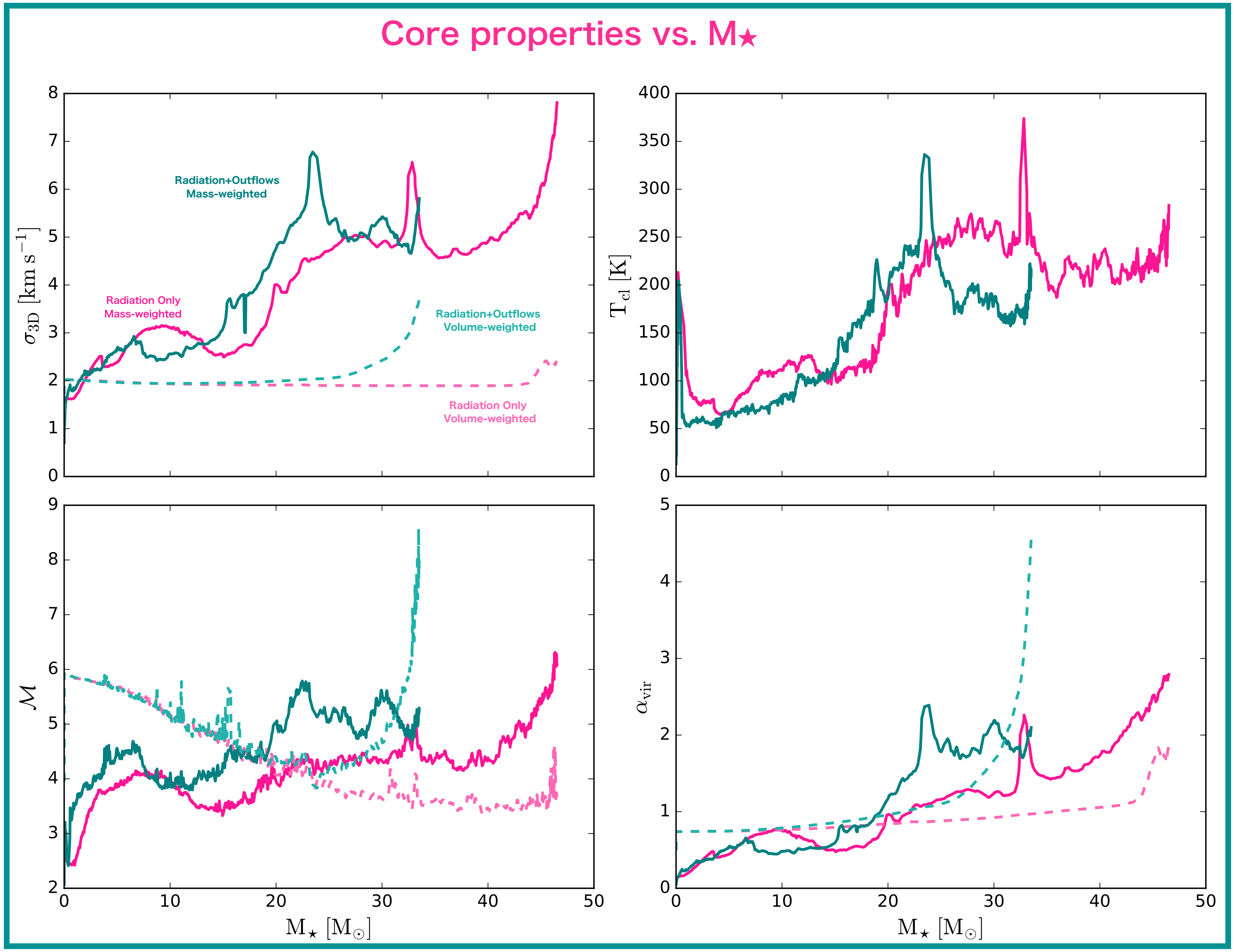
Reduced accretion rate onto primary is due to radiative heating and momentum injection by outflows, effectively making the core unbound at late times.



Rosen+(in prep)

Momentum feedback from outflows are more efficient than radiation to unbind star-forming cores (volume-weighted).

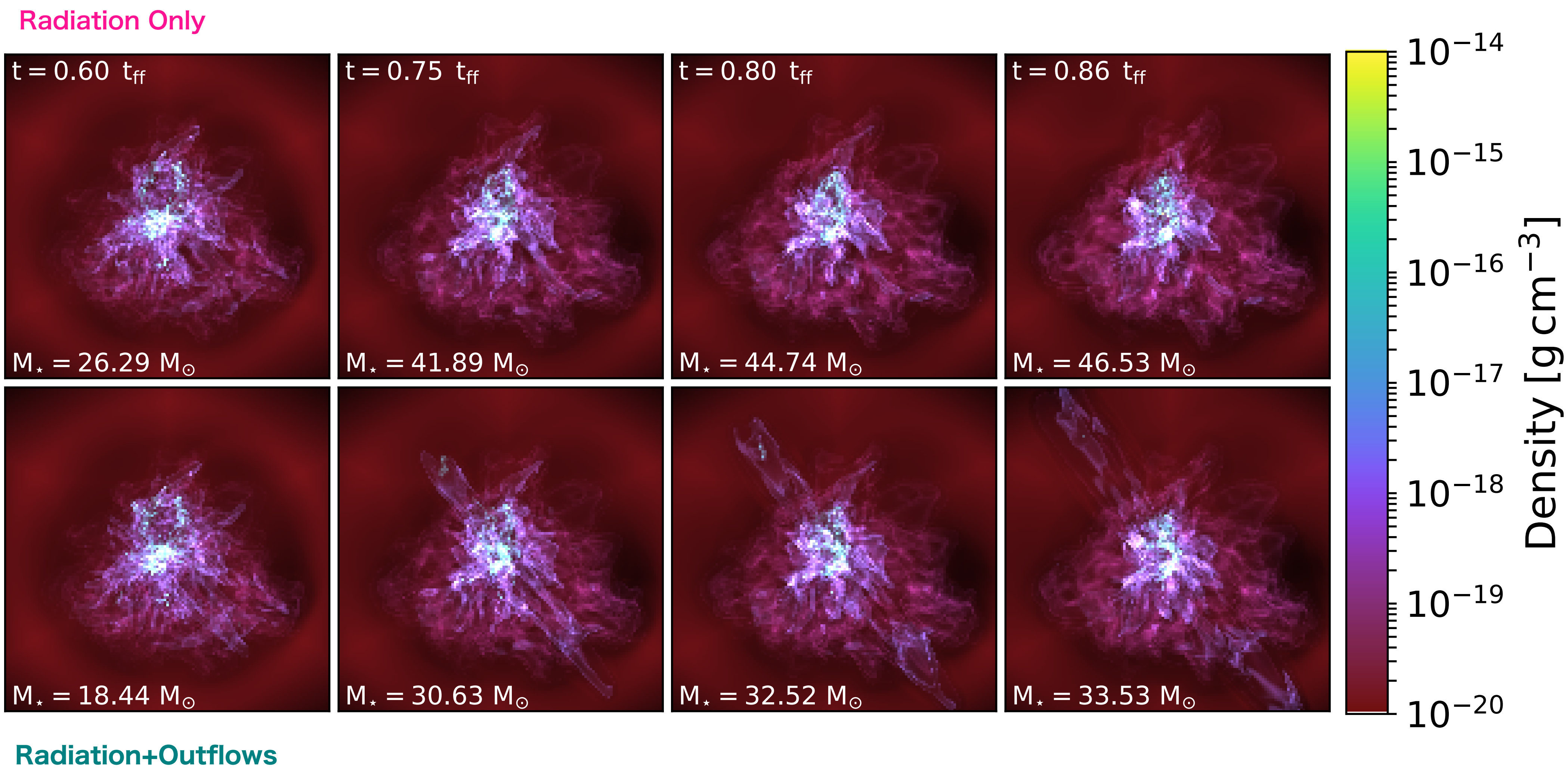
Reduced accretion rate onto primary is due to radiative heating and momentum injection by outflows, effectively making the core unbound at late times.



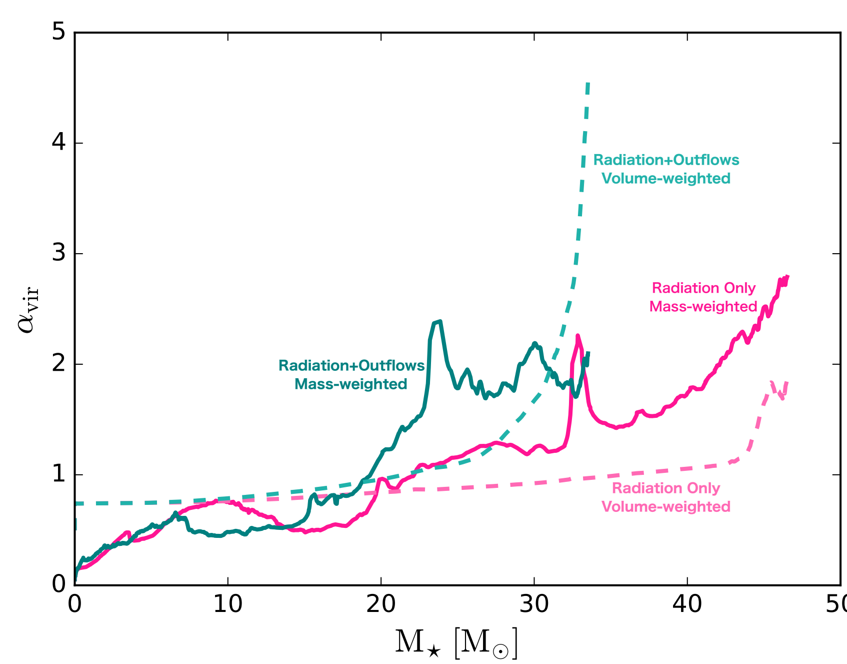
Rosen+(in prep)

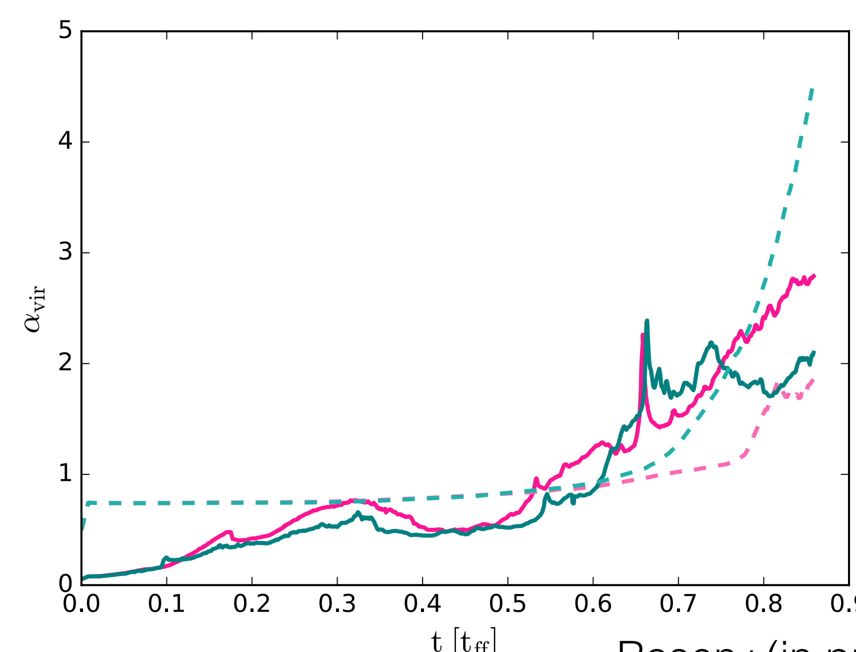
Rapid increase in α for Radiation+Outflows case likely due to outflows break out.

Outflows drive out entrained gas, increasing overall (volume-weighted) velocity dispersion



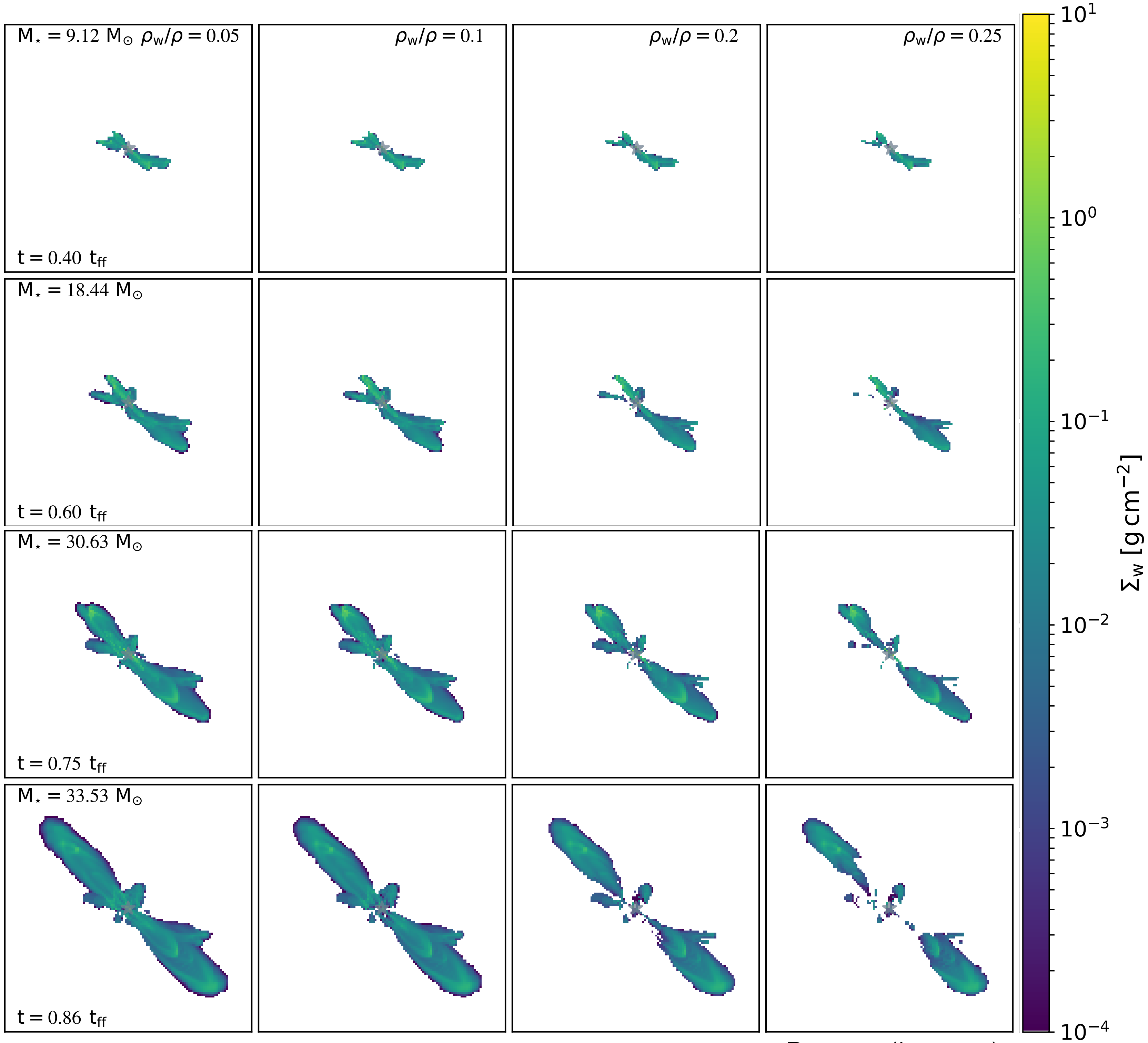
Core becomes unbound when the outflows breakout





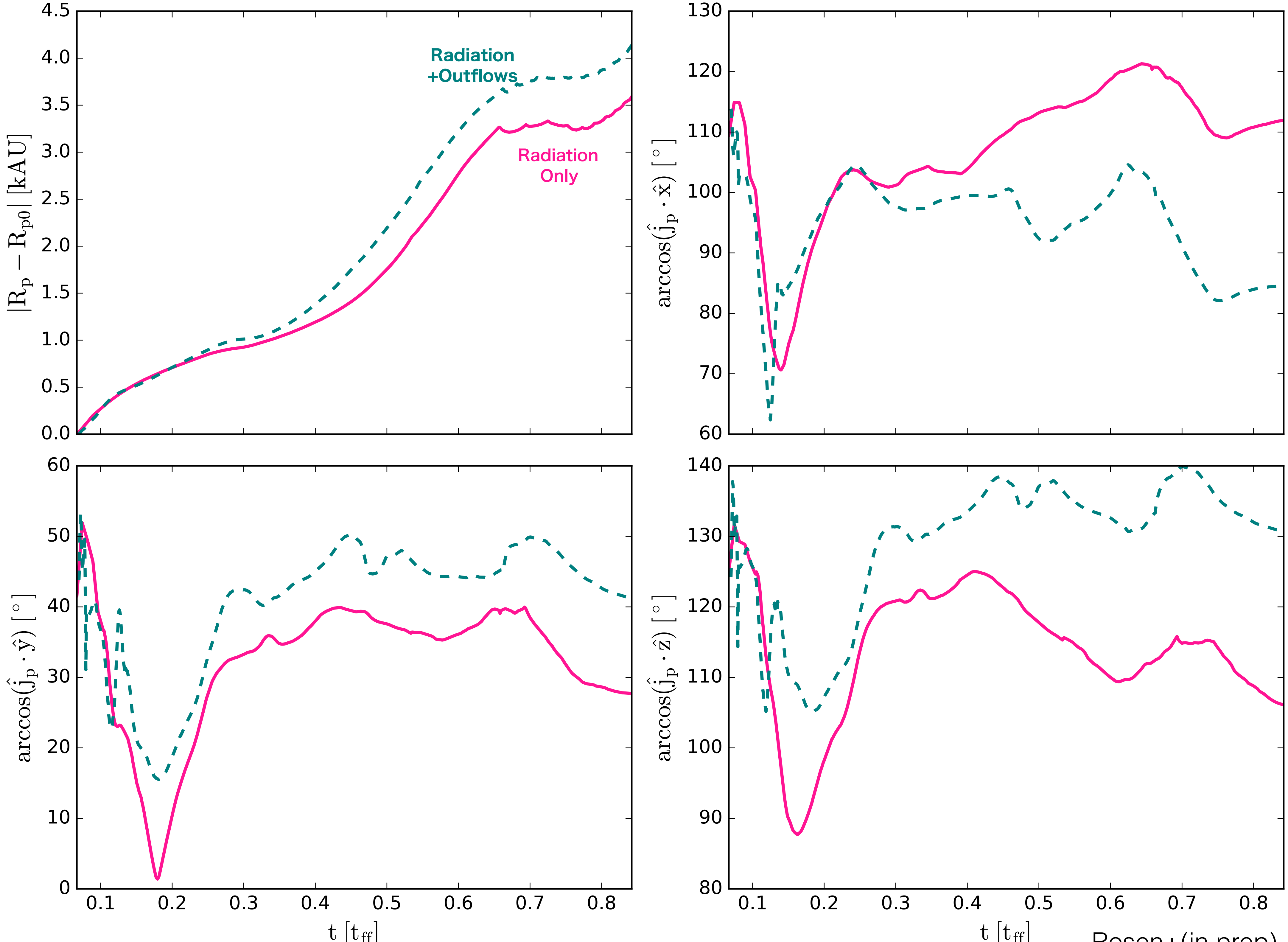
Rosen+(in prep)

Outflow structure and molecular gas entrainment from momentum injection by protostellar jets



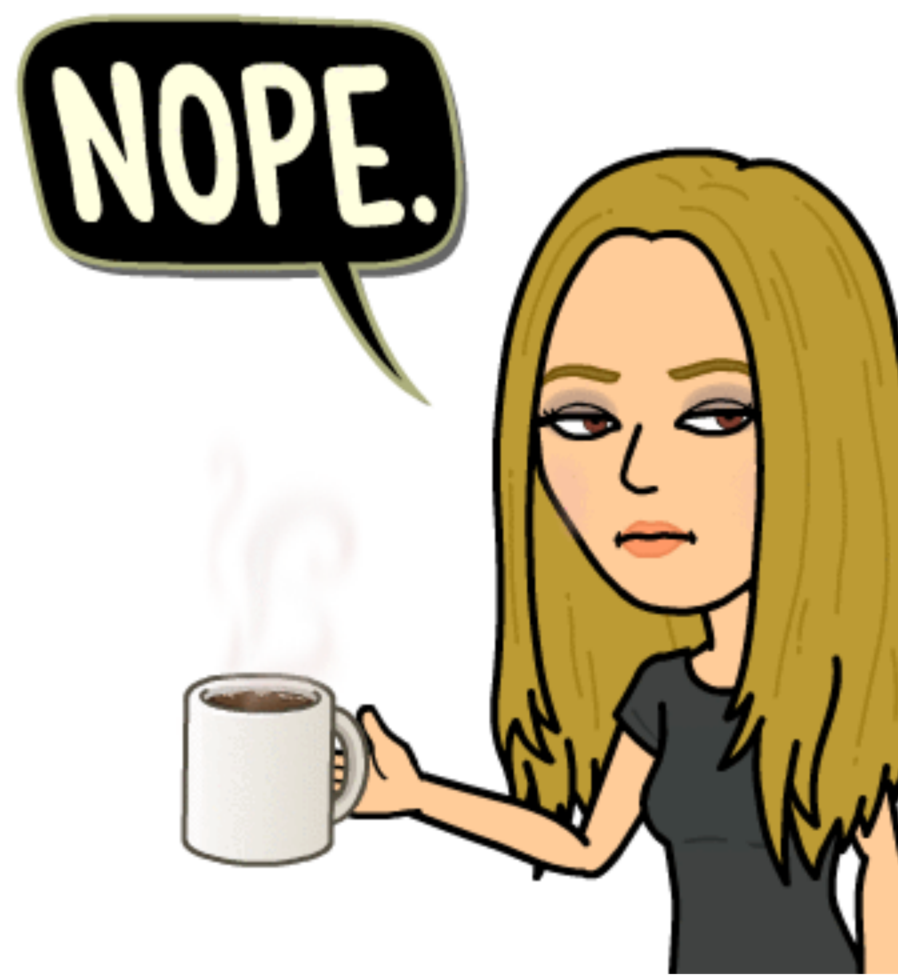
Rosen+(in prep)

Accretion from turbulent accretion pushes star around, widening the opening angles of the entrained material

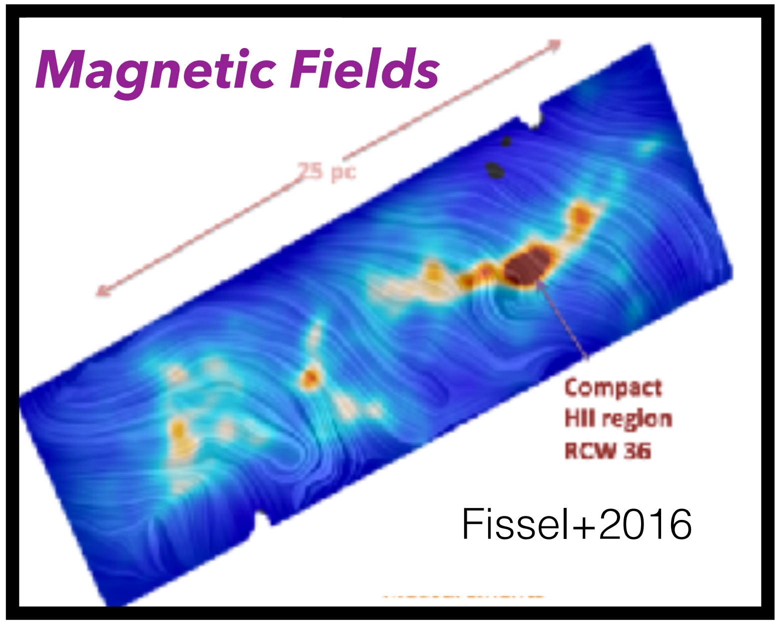


Rosen+(in prep)

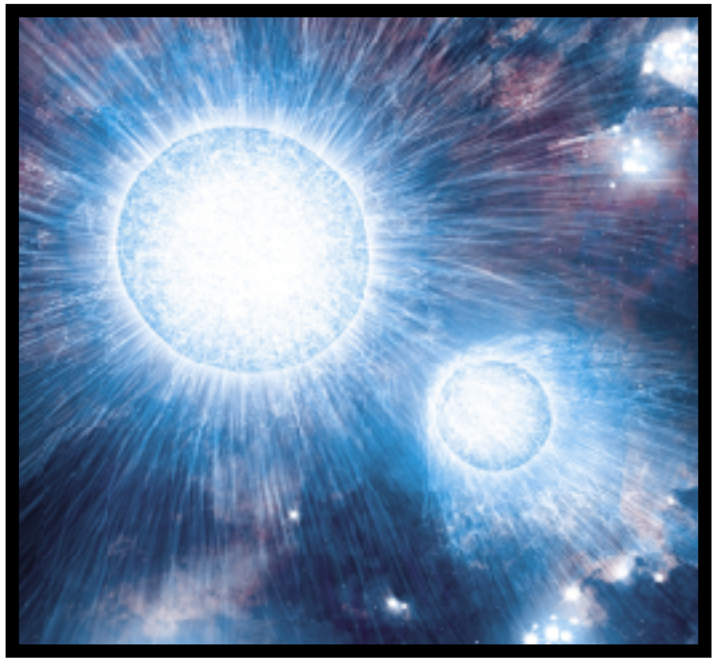
Did I solve all of massive star formation?



Important elements are still missing



Stellar Winds



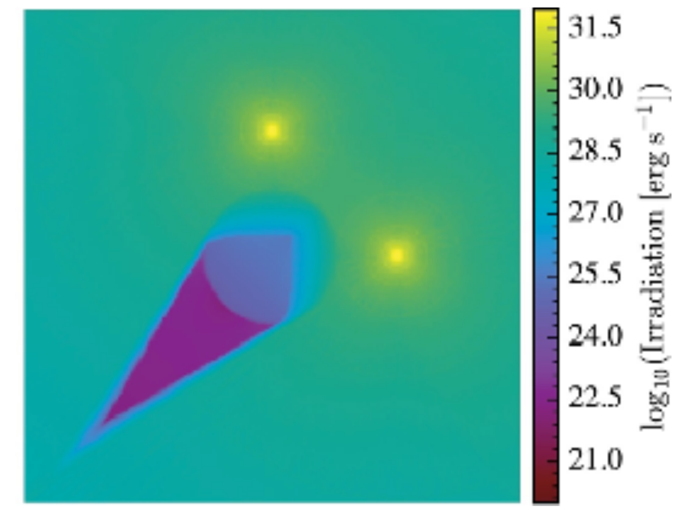
NASA (Artist rendition)

R136 in the LMC (NASA)

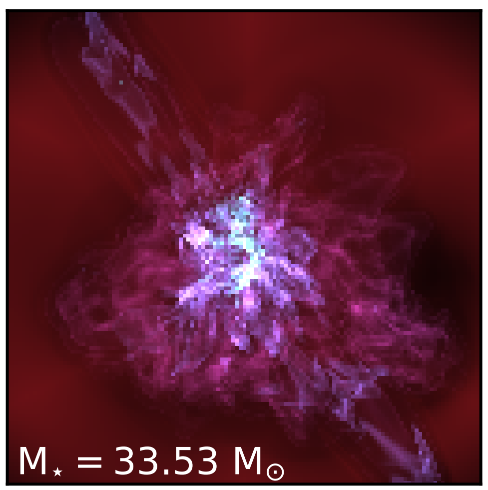
(How) Does feedback set the upper mass limit of the IMF?

… stay tuned.

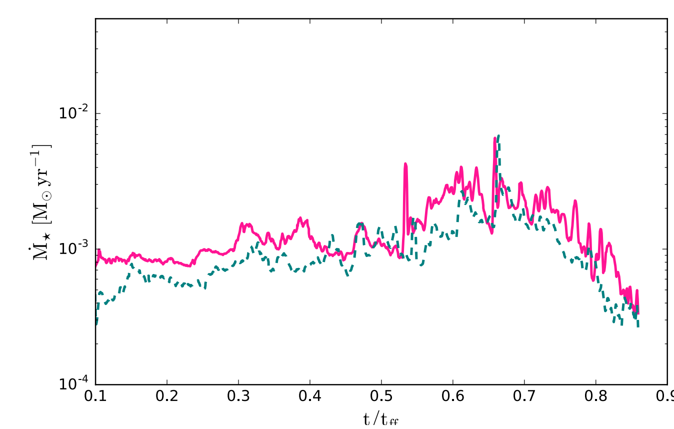
Summary

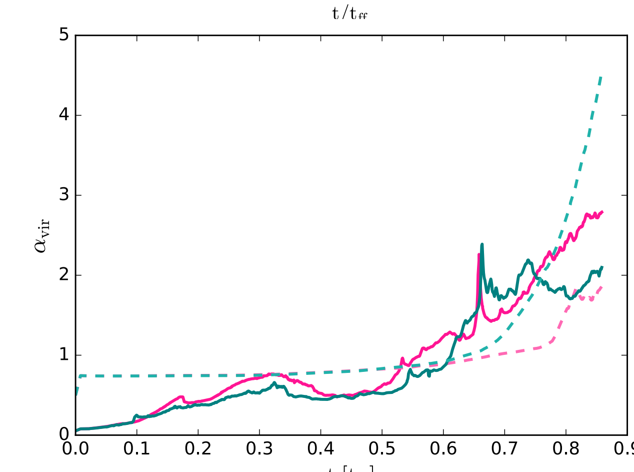


New hybrid radiative transfer method, HARM^2, models direct and dust-reprocessed radiation fields for RHD simulations



Performed 3D RHD 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 accretion rate unto massive star, significantly reducing stellar mass growth.
- Ejects jet and entrained material from core.
- Causes core to become unbound.