AN UNSTABLE TRUTH: HOW MASSIVE STARS GET THEIR MASS

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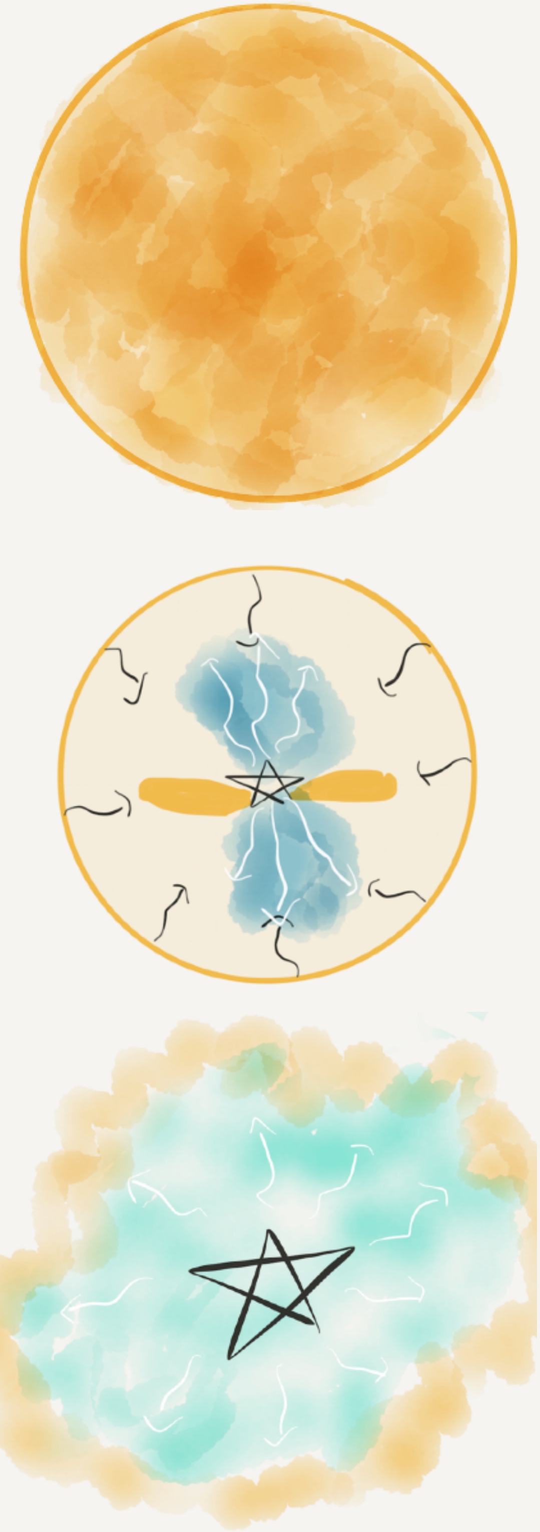
How do massive stars get their mass?

Massive star formation 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:

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

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

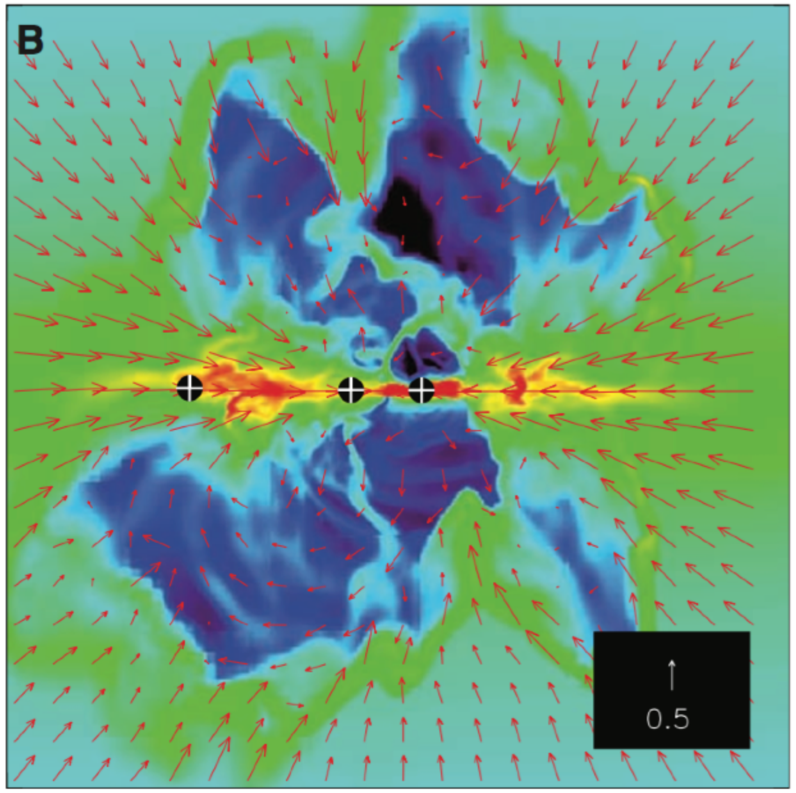
$$f_{\rm edd} = 7.7\times10^{-5}\,(1+f_{\rm trap})\left(\frac{L_\star}{M_\star}\right)_\odot\left(\frac{\Sigma}{1\ {\rm g\ cm^{-2}}}\right)^{-1}$$

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

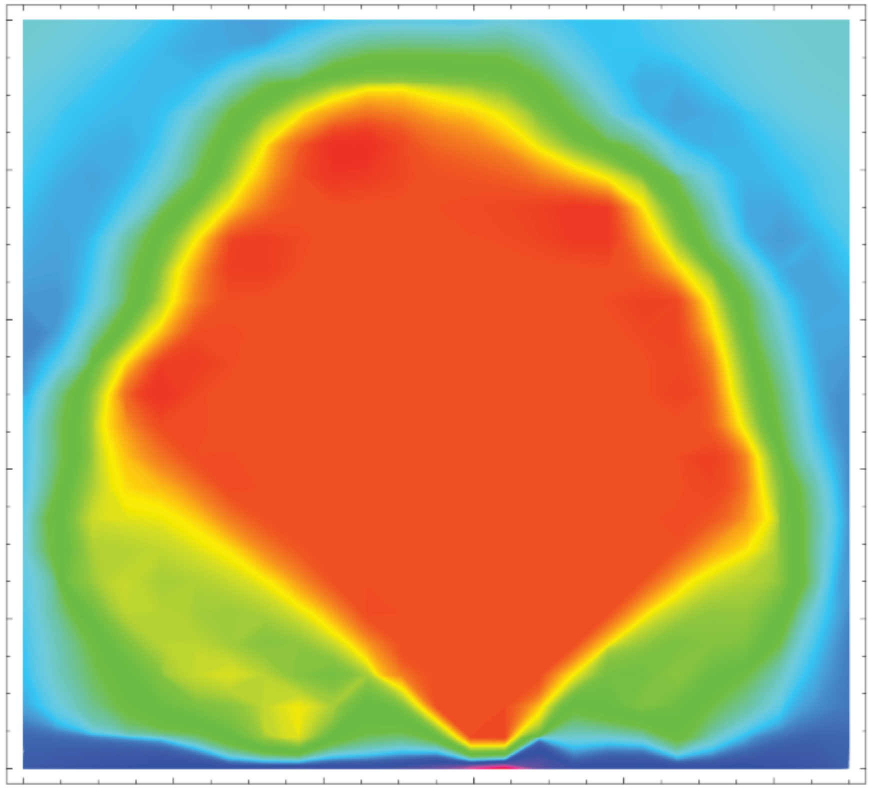
Larson & Starrfield 1971, Kahn 1974, Yorke 1979, Yorke+1995, Wolfire & Cassinelli 1986, 1987; Yorke & Bodenheimer 1999, Krumholz+2009

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

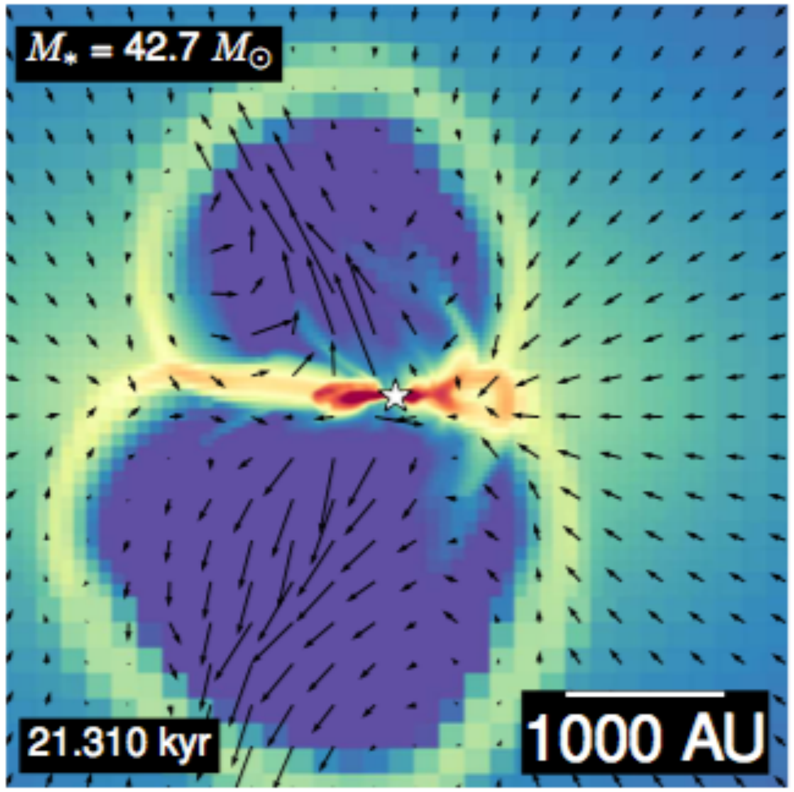
How do massive stars get their mass?



Krumholz+2009



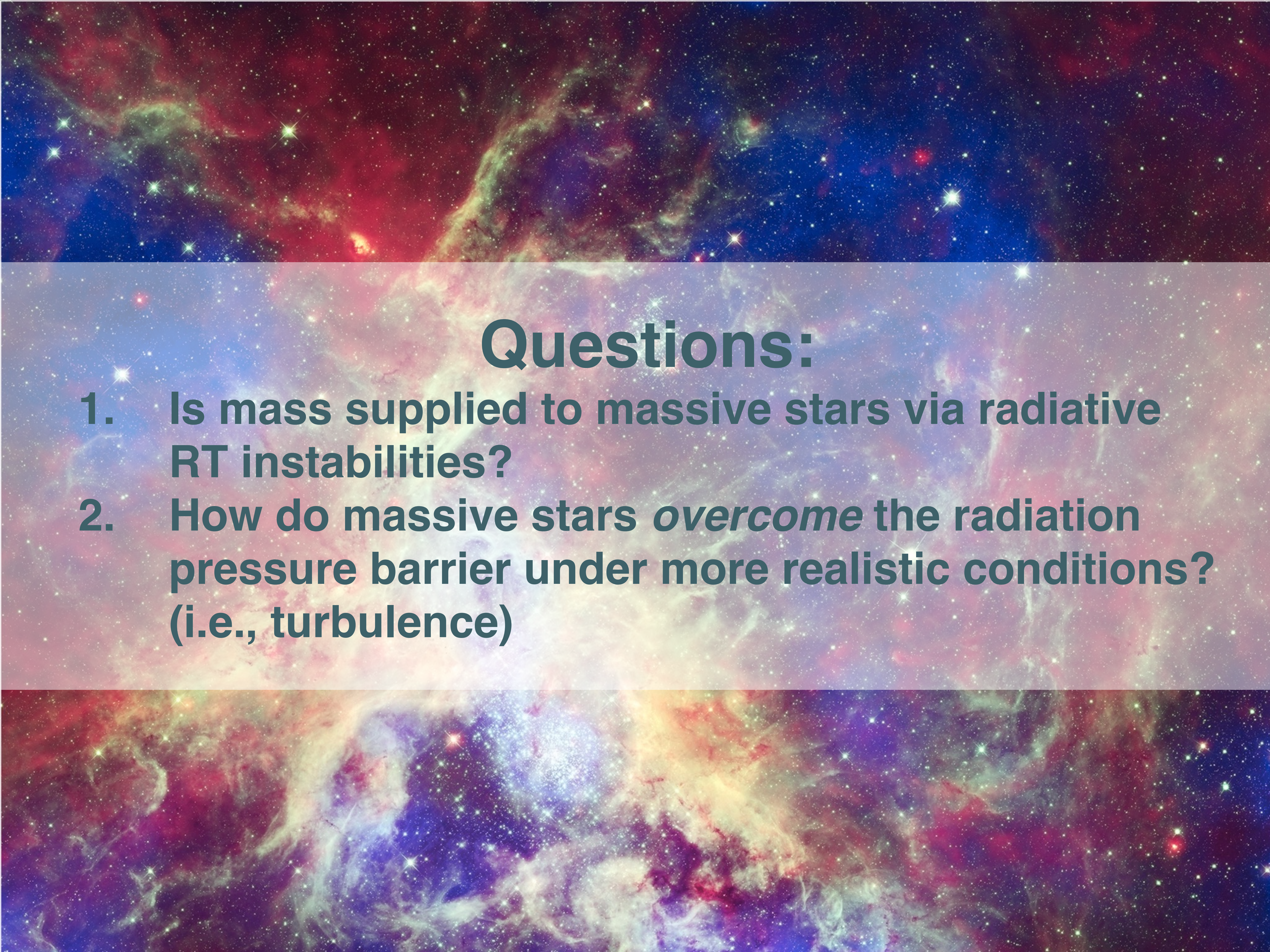
Kuiper+2011, 2012



Klassen+2016

- Star grows via disk accretion and radiative Rayleigh Taylor (RT) instabilities
- Only includes indirect $P_{\rm rad}$

- Star grows via disk accretion only.
- RT instabilities do not develop
- Includes both direct and indirect $P_{\rm rad}$

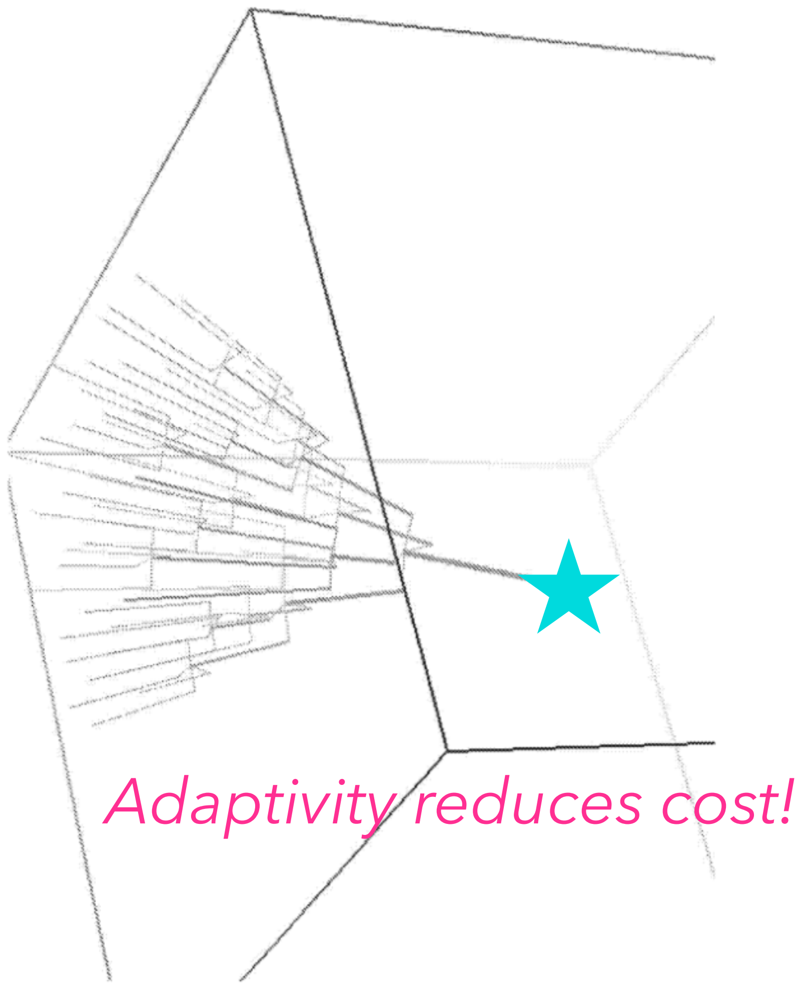


Questions:

1. Is mass supplied to massive stars via radiative RT instabilities?
2. How do massive stars *overcome* the radiation pressure barrier under more realistic conditions? (i.e., turbulence)

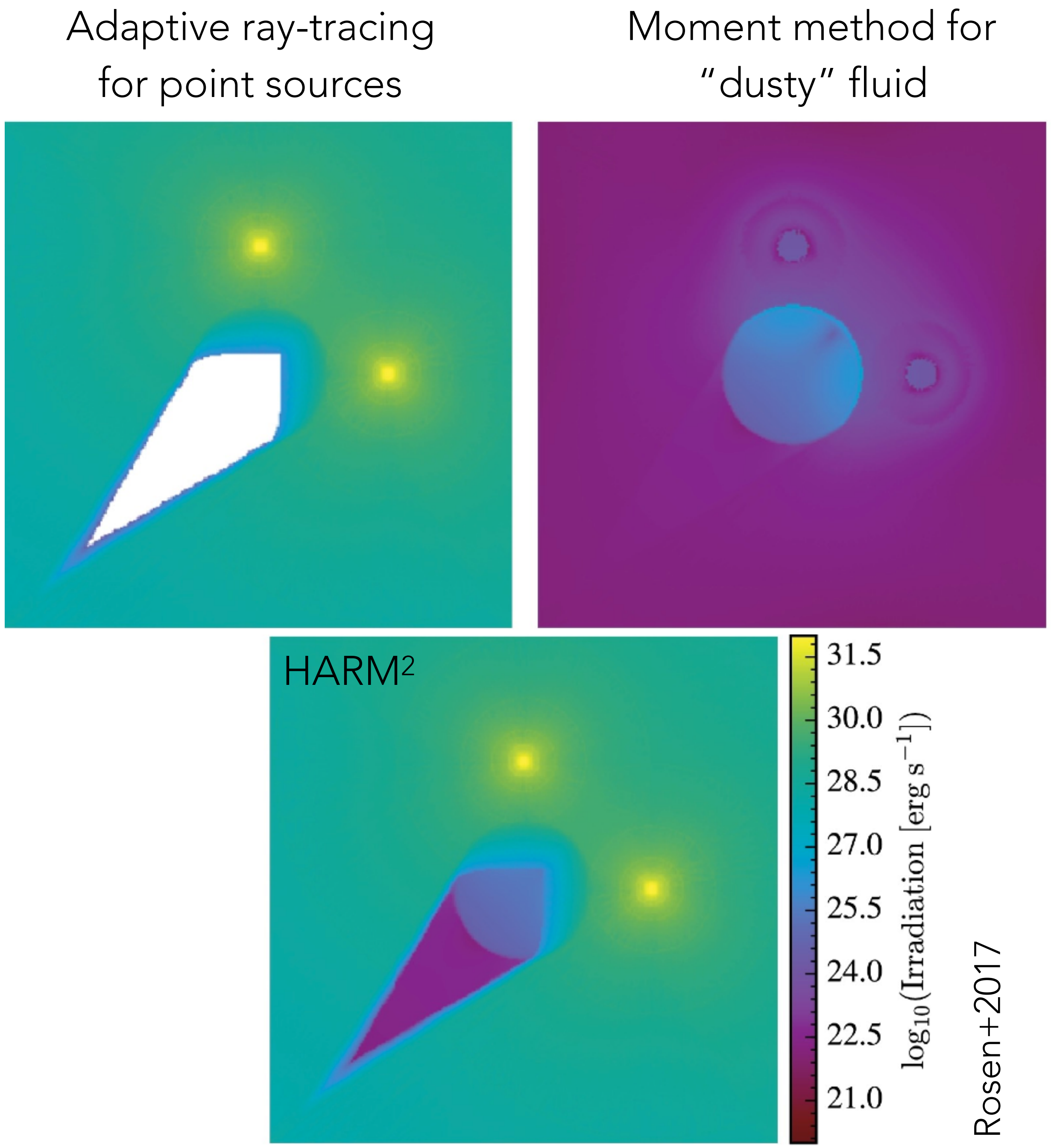
Hybrid Adaptive Ray-Moment Method (HARM^2):

New Hybrid Radiative Transfer Method for AMR RHD simulations



Adaptivity reduces cost!

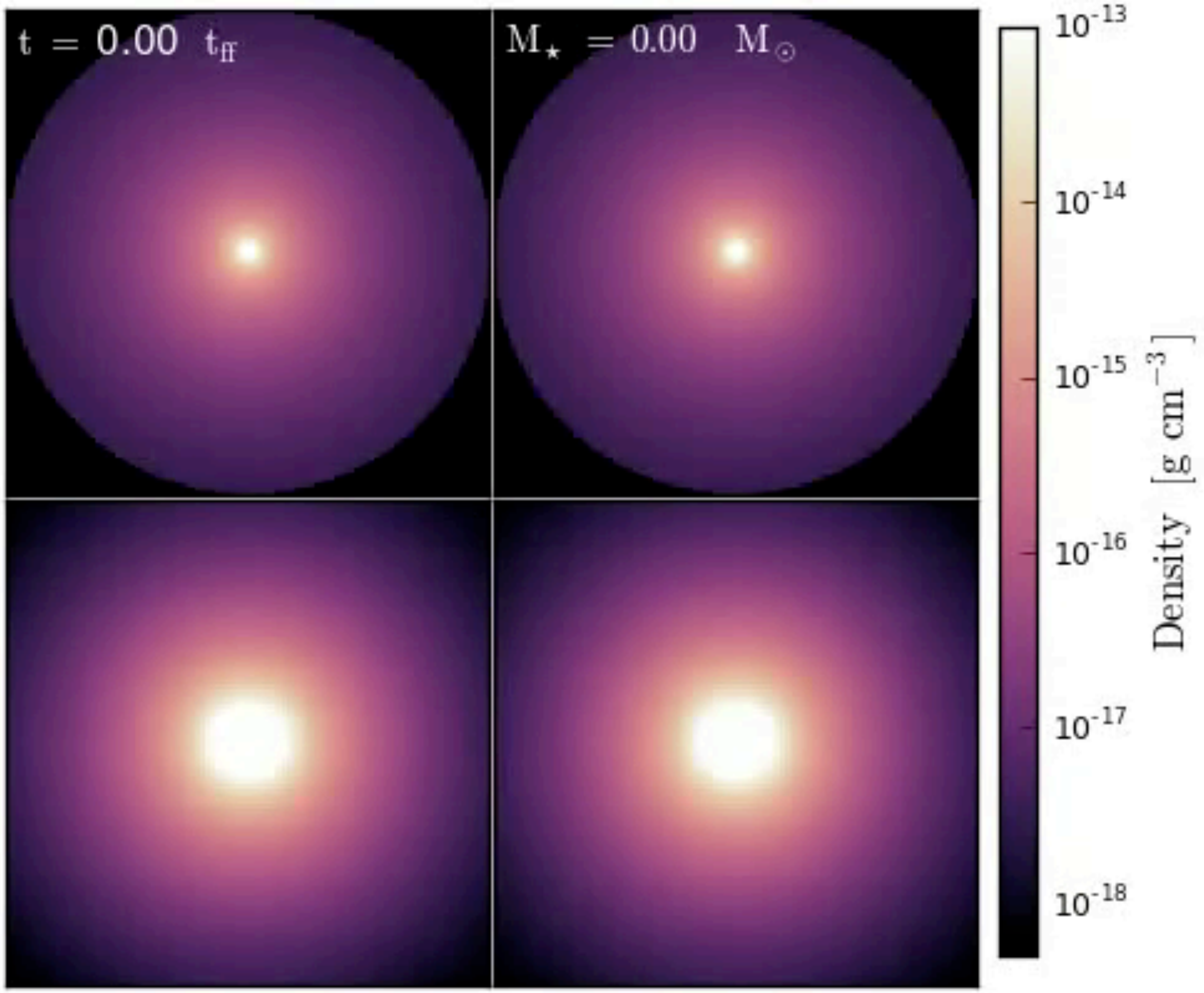
Abel & Wandelt 2002,
Wise & Abel 2011



Rosen+2017

HARM^2 models radiative heating and pressure from the direct (stellar) and indirect (dust-reprocessed) radiation fields

Revisiting radiative RT instabilities



Rosen+2016

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

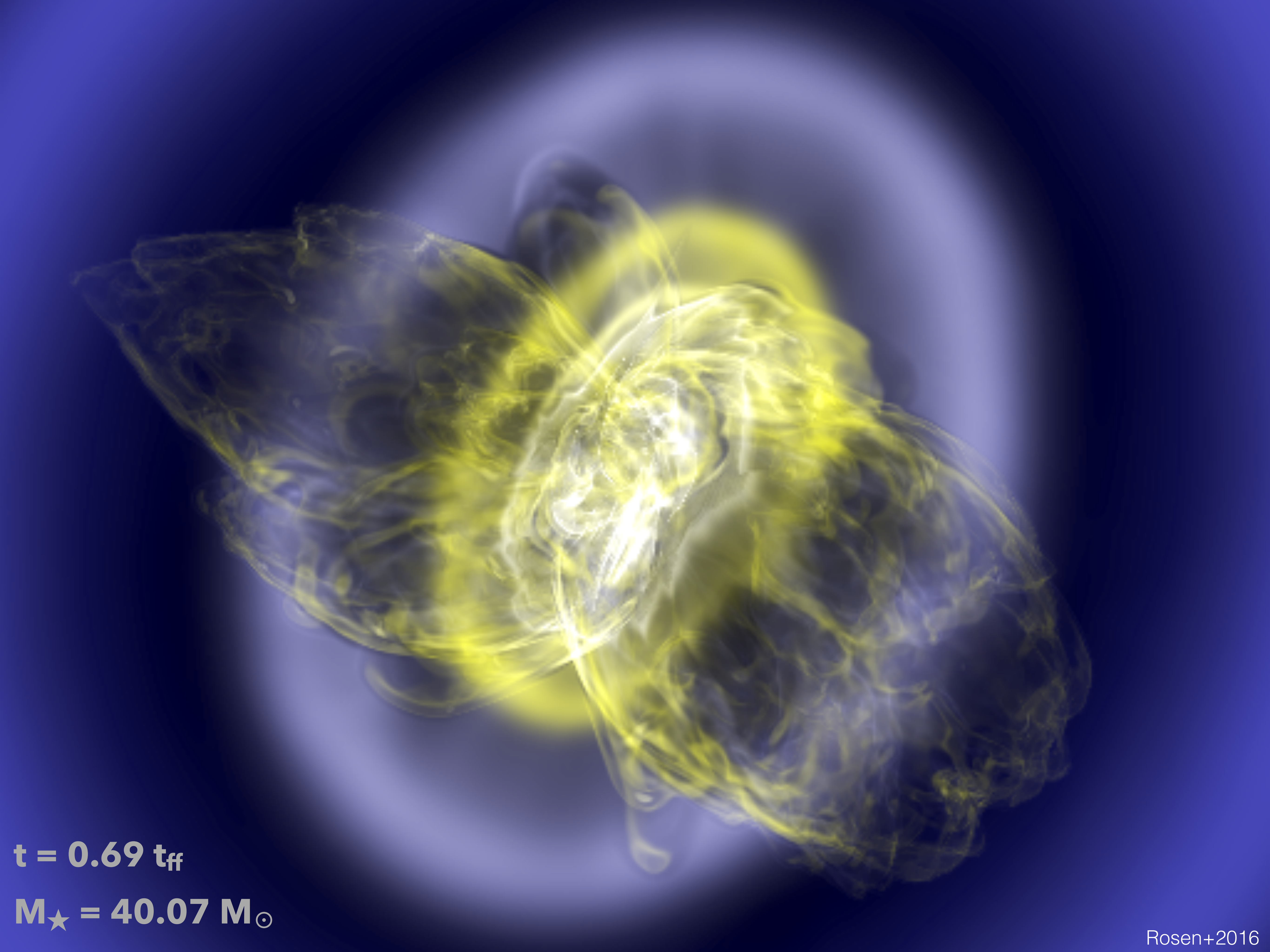
$\rho(r) \propto r^{-3/2}$

E_{rot}/E_{grav}=0.04

Δx_{min}=20 AU

t_{ff}=42,710 yrs

(★ = stars with masses>0.1$M_\odot$)

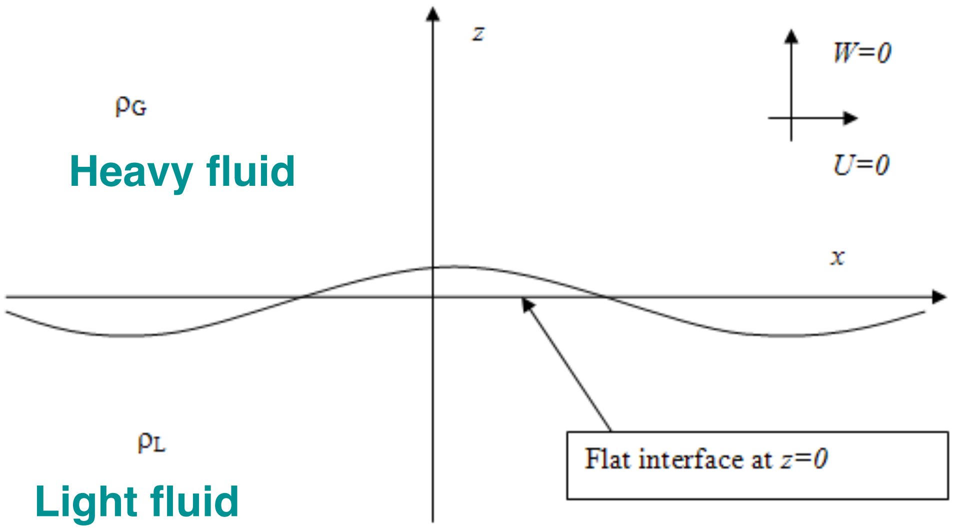


$t = 0.69\ t_{ff}$

$M_\star = 40.07\ M_\odot$

Rosen+2016

RT instability growth is sensitive to resolution



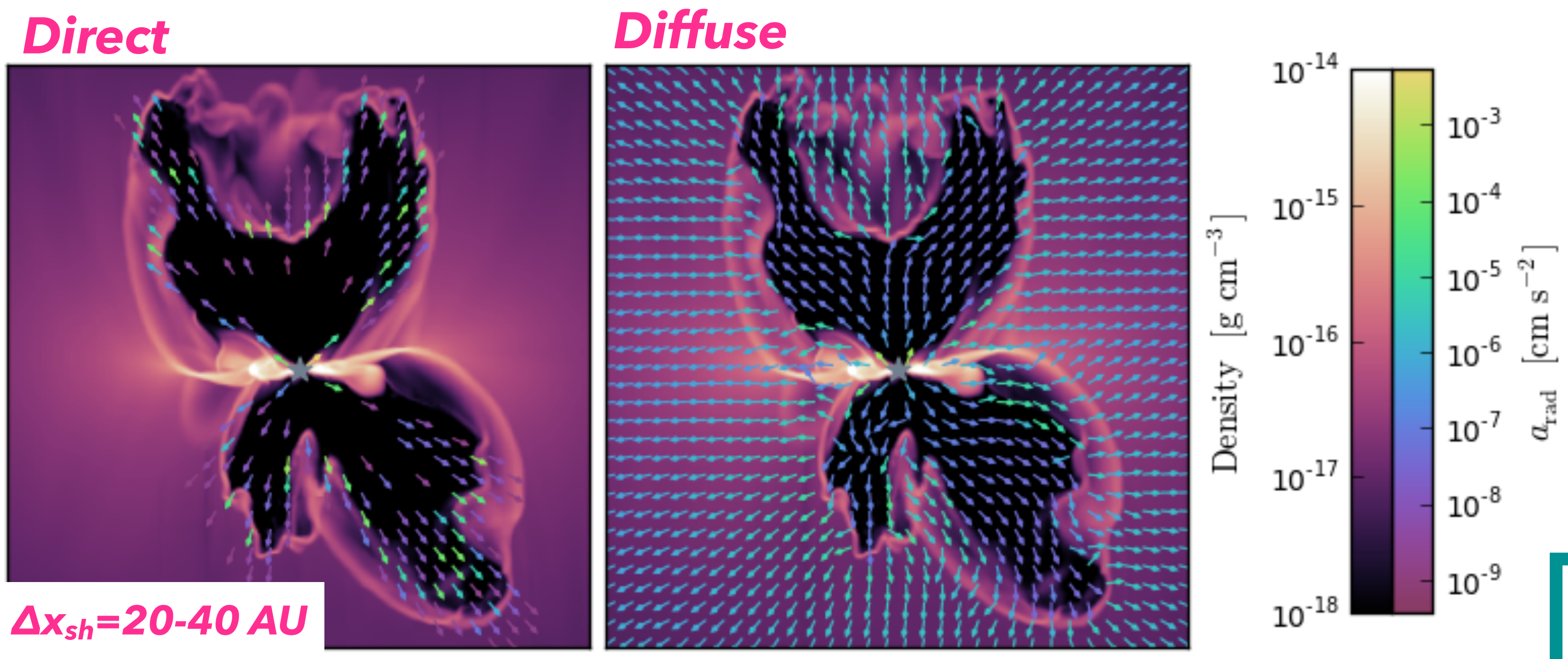
Wikipedia

Classical RT instabilities grow exponentially.

$$\eta(t) \propto \exp\left(\omega t\right) \text{ where } \omega \propto \sqrt{\lambda}$$

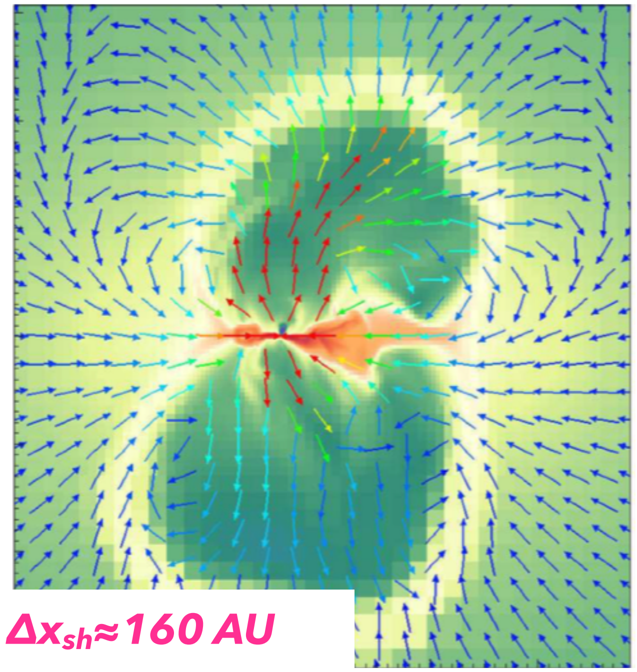
Growth rate faster for smaller modes.

$$\tau_{\mathrm{RT}} \propto \sqrt{\lambda}$$



Δx_{sh}=20-40 AU

Rosen+2016

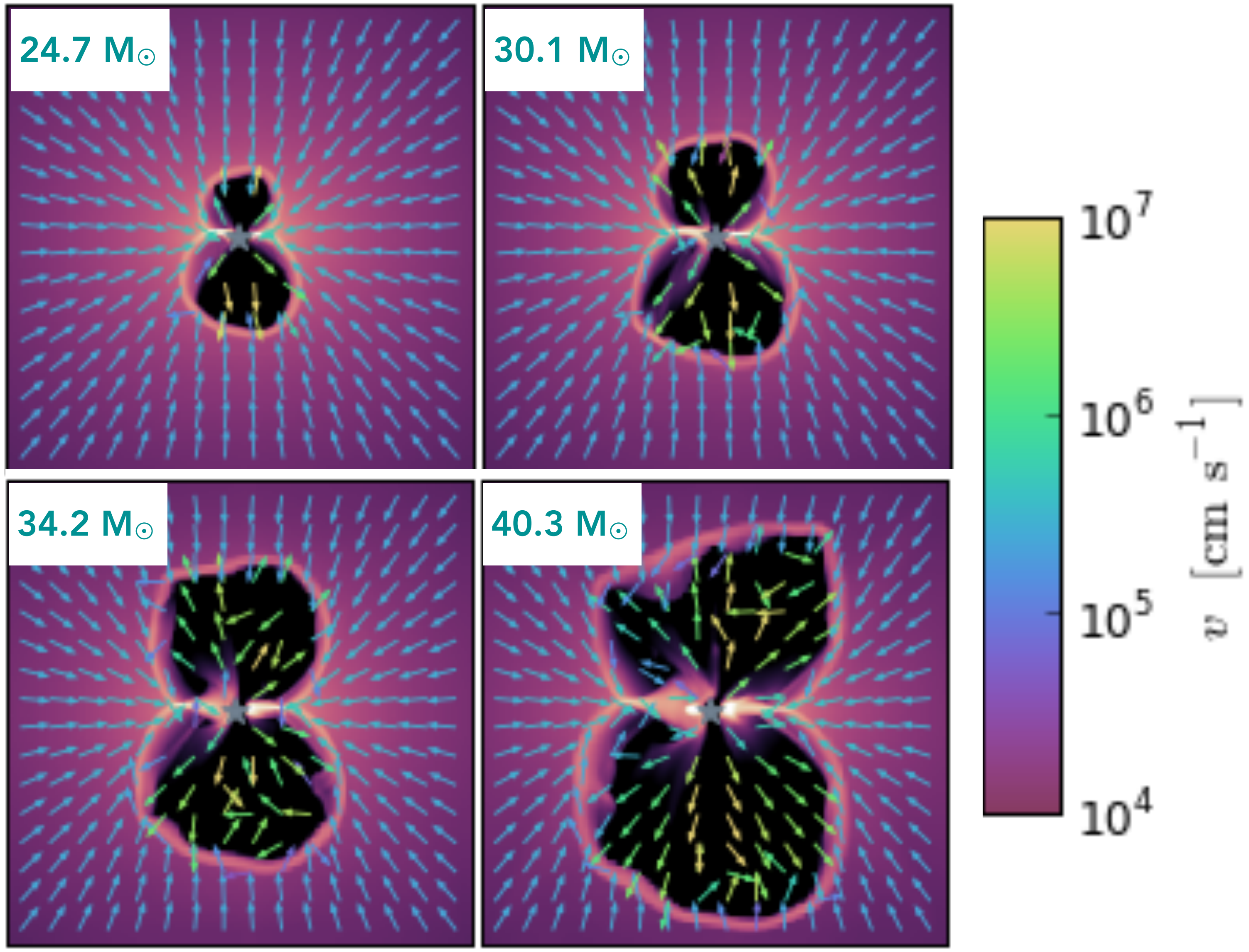


$\Delta x_{sh}\approx$160 AU

Klassen+2016

$P_{\rm dir}$ may suppress initial non-linear growth of RT instabilities but… Asymmetry drives instability!

Testing our hypothesis: Low-Res Run



Rosen+2016b

(8,000 AU)^2

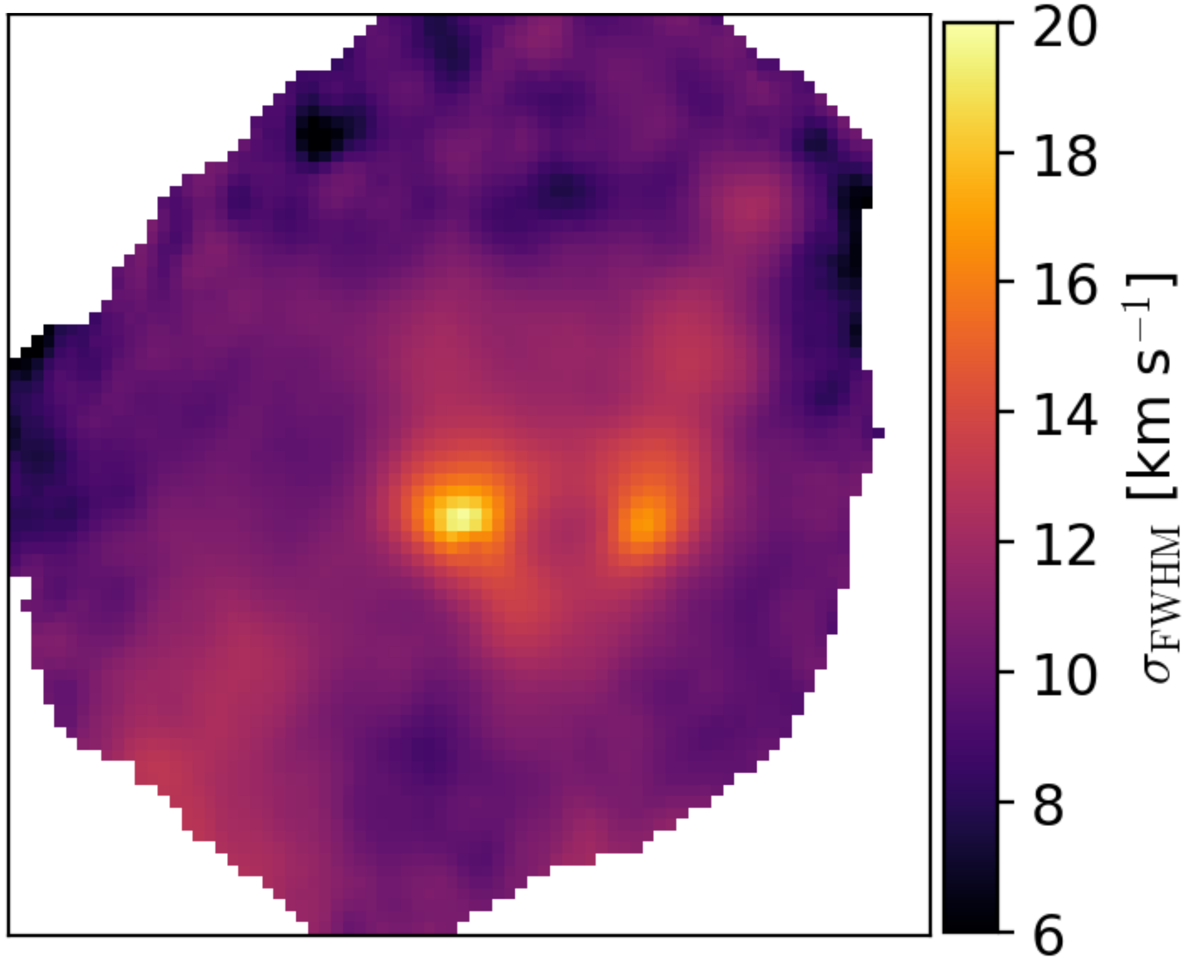
No refinement on ∇E_R!

RT instabilities take longer to grow in lower-resolution shells.

RT instabilities still develop (later*) due to shielding/shadowing of direct radiation field.

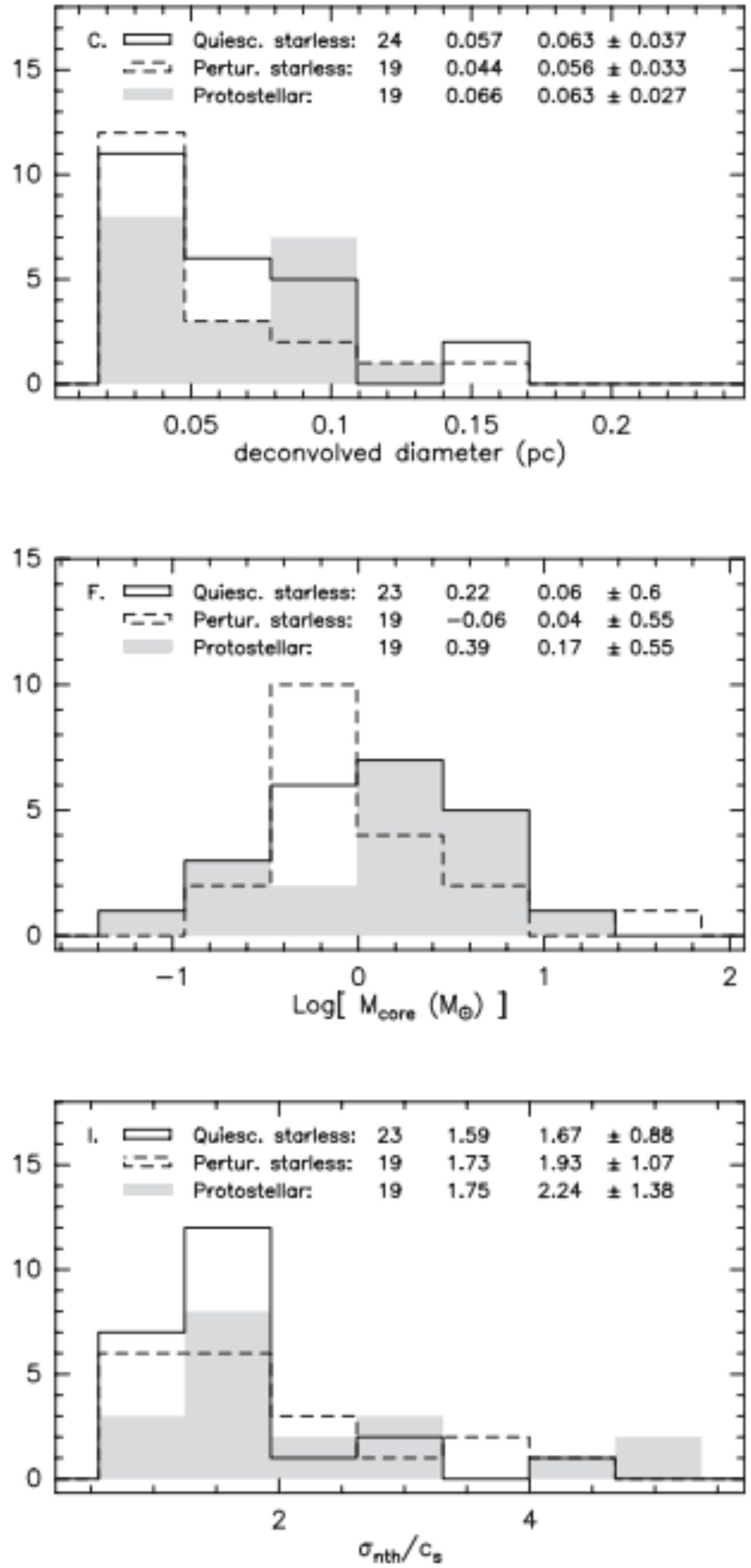
*For comparison: Shells start to become unstable when $M_\star \approx 25\text{-}30\ M_\odot$ in higher resolution simulation.

…but star forming cores are turbulent



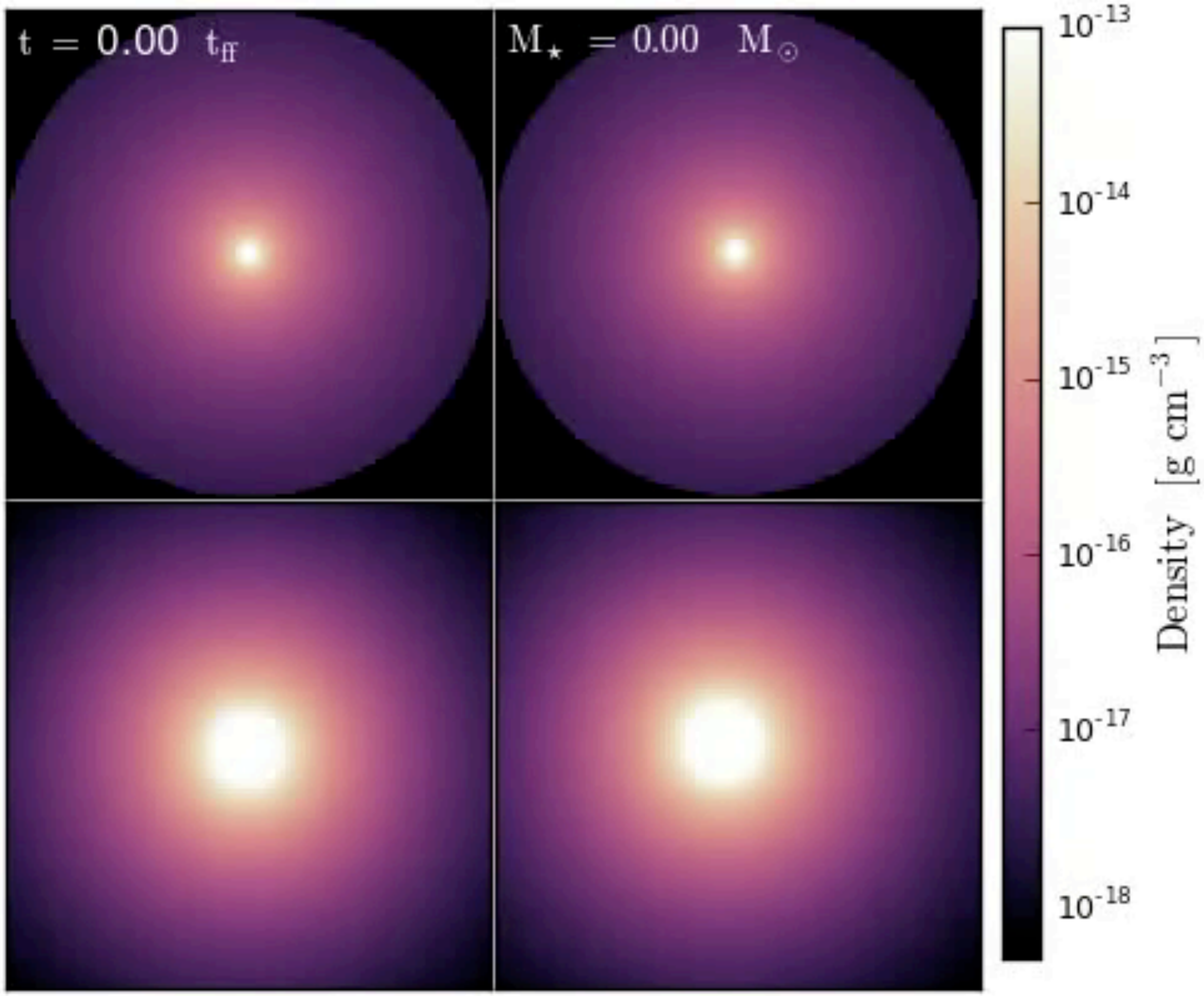
Ginsburg+2017

Turbulence should be initial seeds for RT instabilities.



Sanchez-Monge+2013

Collapse of turbulent core with *HARM*^{2}



Rosen+2016

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

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

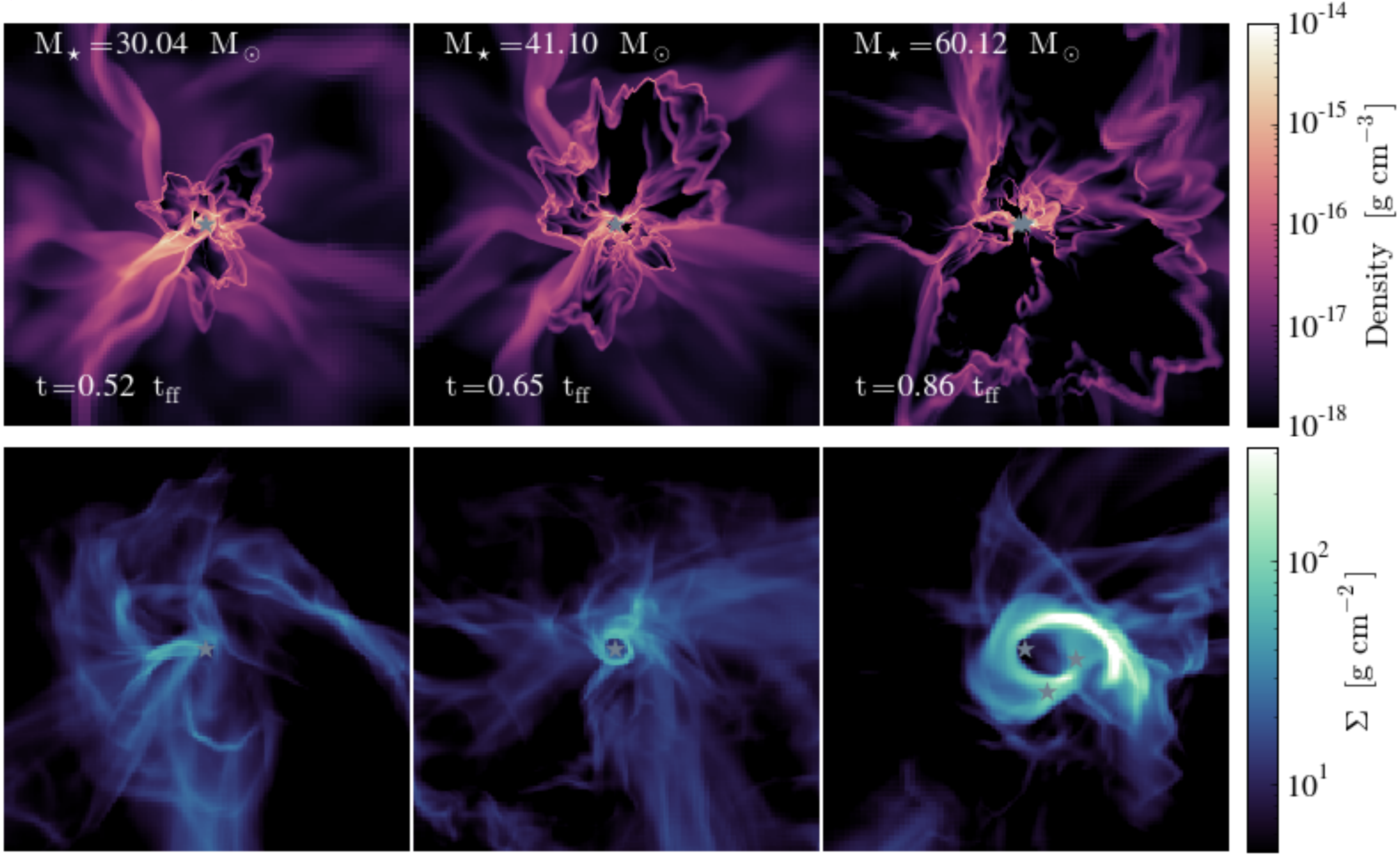
σ_{1D}=0.4 km s^{-1}

Δx_{min}=20 AU

t_{ff}=42,710 yrs

Mass delivered to star via infalling dense filaments, RT instabilities, and disk accretion.

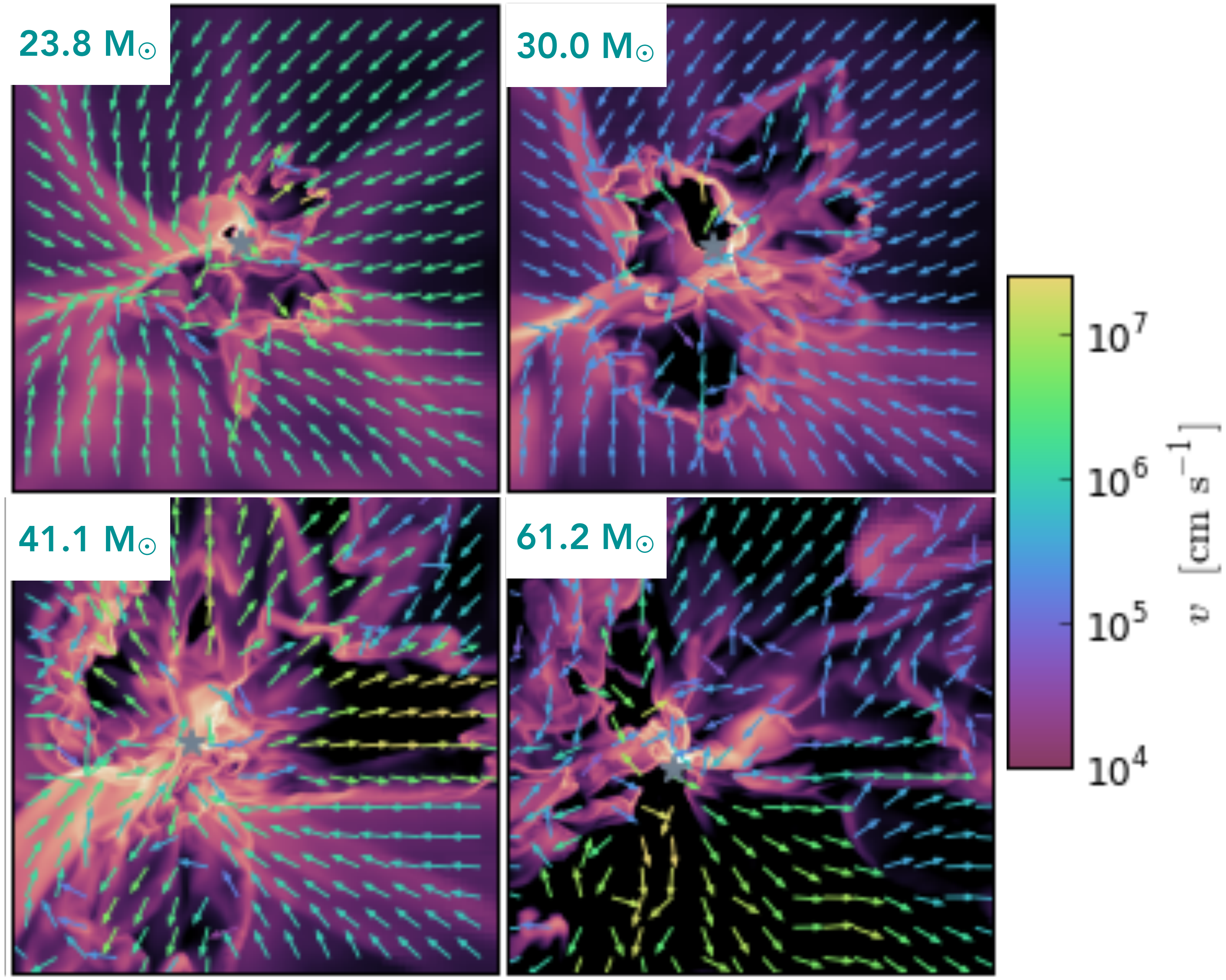
(20,000 AU)²



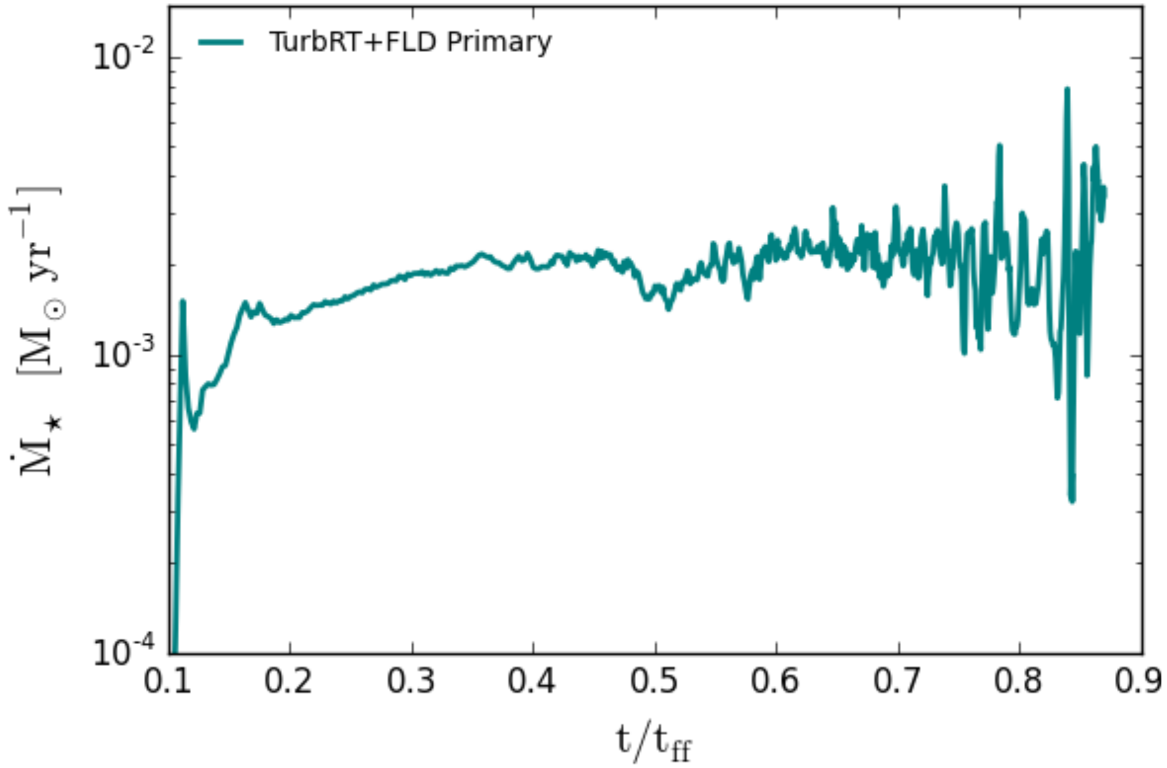
Rosen+2016

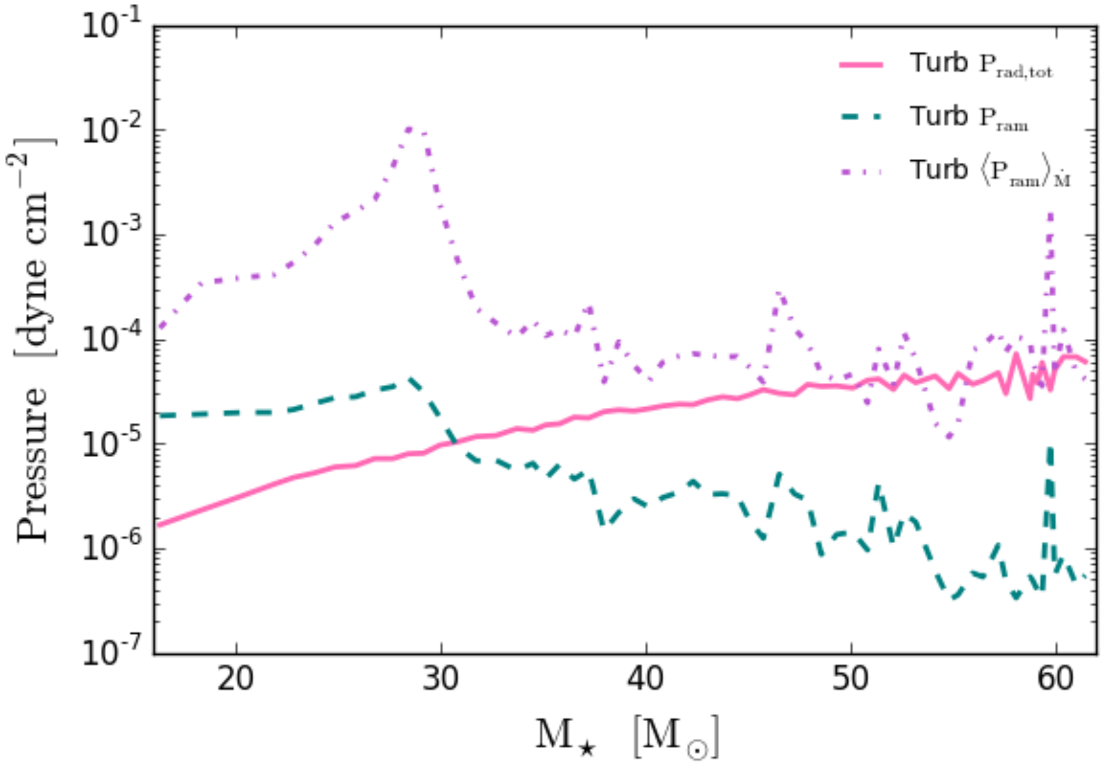
(3,000 AU)²

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



(10,000 AU)²



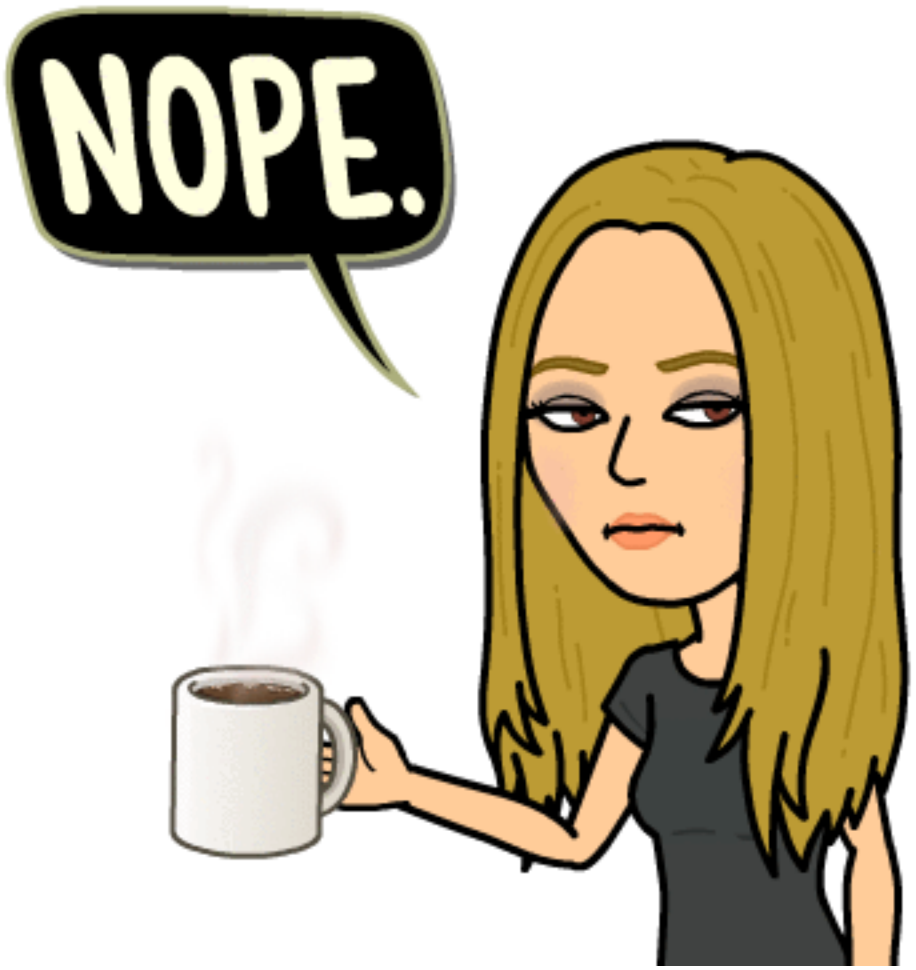


Rosen+2016

Agrees with turbulent core model for massive star formation

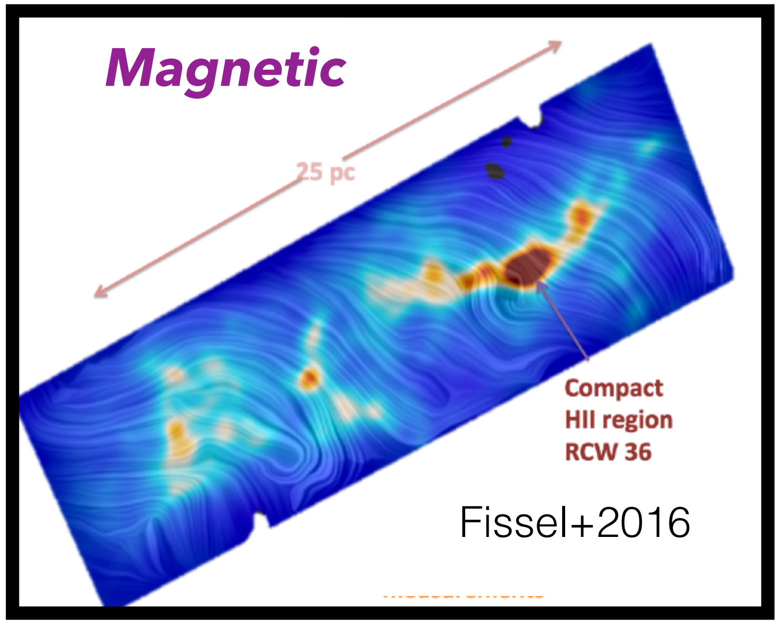
(McKee & Tan, 2003)

Did I solve all of massive star formation?



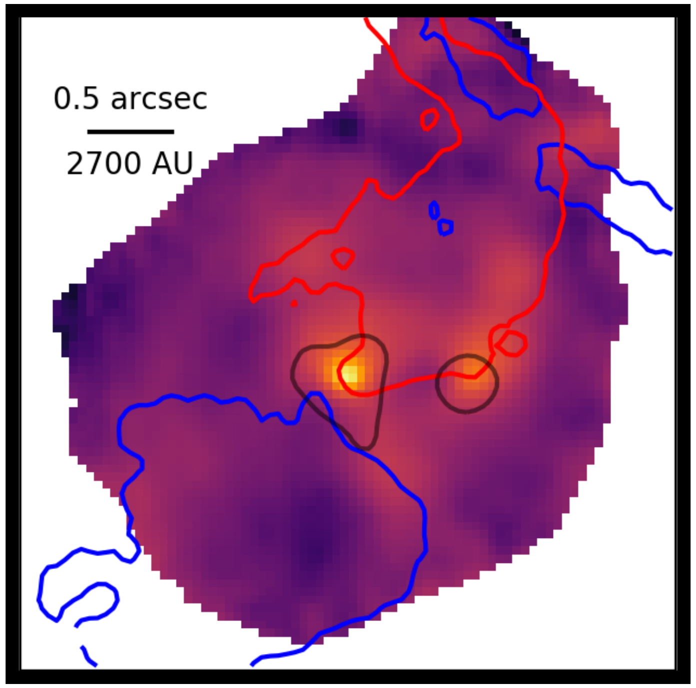
Many important elements are missing

Magnetic



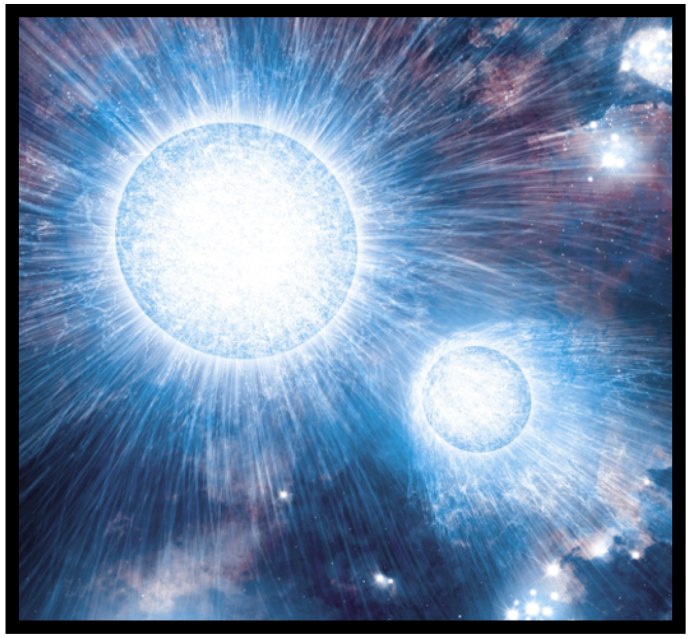
Fissel+2016

Outflows



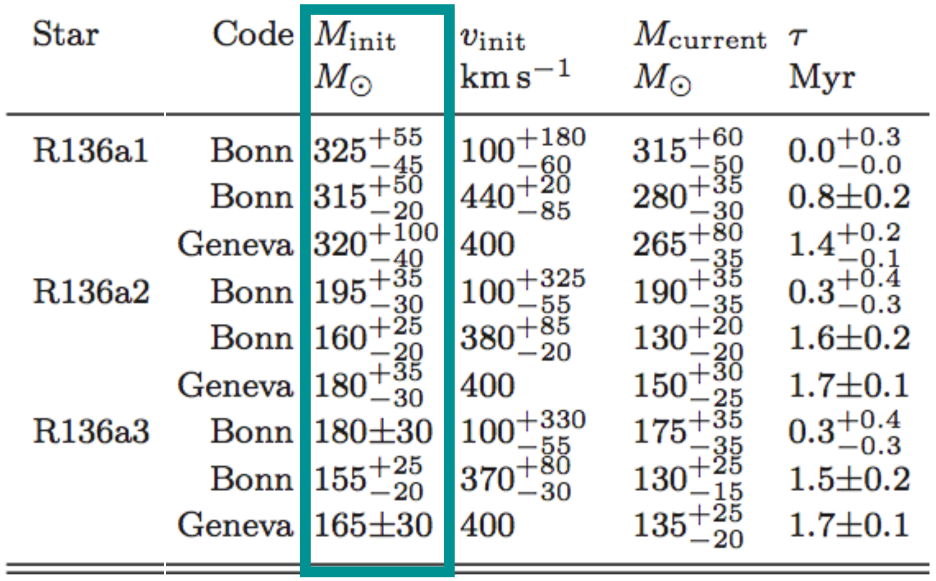
Ginsburg+2017

Stellar Winds



NASA (Artist rendition)

R136 in the LMC (NASA)

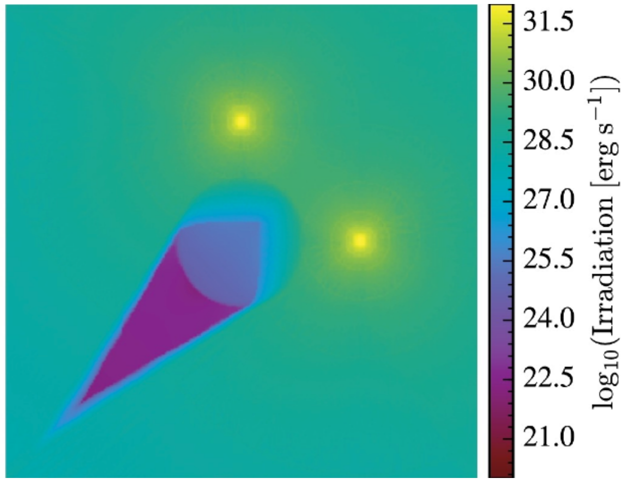


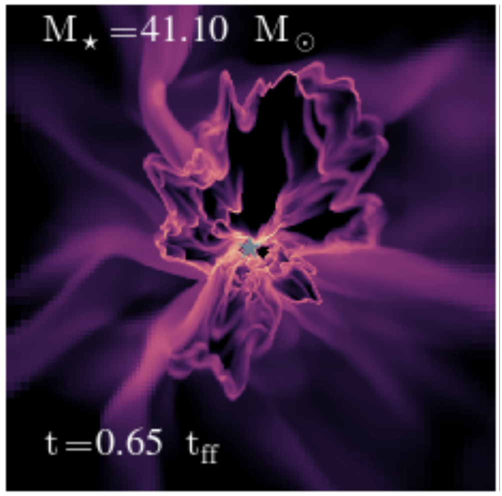
Star	Code	$M_{\rm init}$ $M_\odot$	$v_{\rm init}$ km s^{-1}	$M_{\rm current}$ $M_\odot$	τ Myr
R136a1	Bonn	325^{+55}_{-45}	100^{+180}_{-60}	315^{+60}_{-50}	$0.0^{+0.3}_{-0.0}$
	Bonn	315^{+50}_{-20}	440^{+20}_{-85}	280^{+35}_{-30}	0.8 ± 0.2
	Geneva	320^{+100}_{-40}	400	265^{+80}_{-35}	$1.4^{+0.2}_{-0.1}$
R136a2	Bonn	195^{+35}_{-30}	100^{+325}_{-55}	190^{+35}_{-35}	$0.3^{+0.4}_{-0.3}$
	Bonn	160^{+25}_{-20}	380^{+85}_{-20}	130^{+20}_{-20}	1.6 ± 0.2
	Geneva	180^{+35}_{-30}	400	150^{+30}_{-25}	1.7 ± 0.1
R136a3	Bonn	180 ± 30	100^{+330}_{-55}	175^{+35}_{-35}	$0.3^{+0.4}_{-0.3}$
	Bonn	155^{+25}_{-20}	370^{+80}_{-30}	130^{+25}_{-15}	1.5 ± 0.2
	Geneva	165 ± 30	400	135^{+25}_{-20}	1.7 ± 0.1

Does feedback set the upper mass limit of the IMF?

Summary

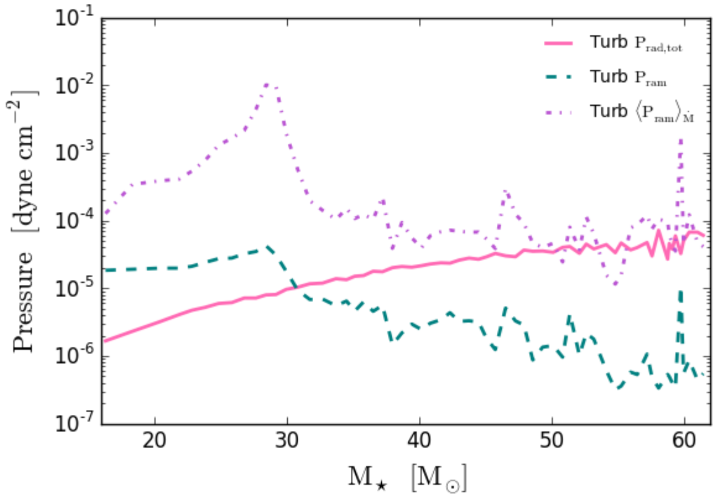
New hybrid radiative transfer method, HARM^2, models direct and dust-reprocessed radiation pressure for AMR RHD simulations



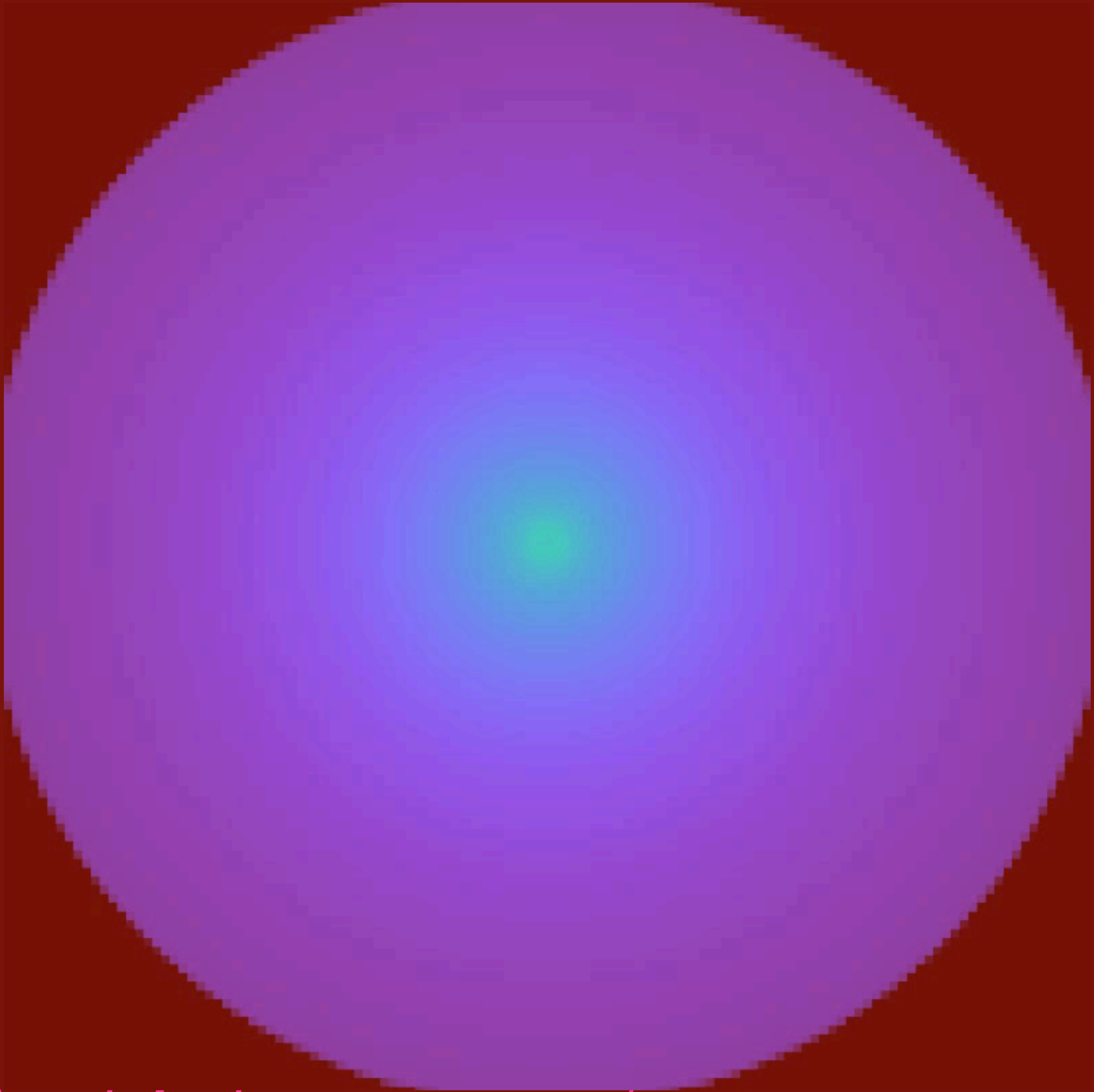


Performed 3D RHD simulations of the formation of massive stellar systems from the collapse of (laminar and turbulent) massive pre-stellar cores.

The "Radiation Pressure Barrier" is no longer a barrier. RT instabilities, dense filaments, and gravitational instabilities deliver mass to massive stars' during their formation.



Simulation movies can be found at www.anna-rosen.com/movies



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