Class 19: Massive star formation

ASTR 4008 / 8008, Semester 2, 2020

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Outline

- Observational phenomenology
  - Challenges
  - Massive clumps
  - Massive cores
- Fragmentation and binarity
- Feedback and barriers to accretion
  - Winds
  - Ionisation
  - Direct radiation pressure
  - Indirect (dust-reprocessed) radiation pressure

Challenges

Why we know less about massive star formation

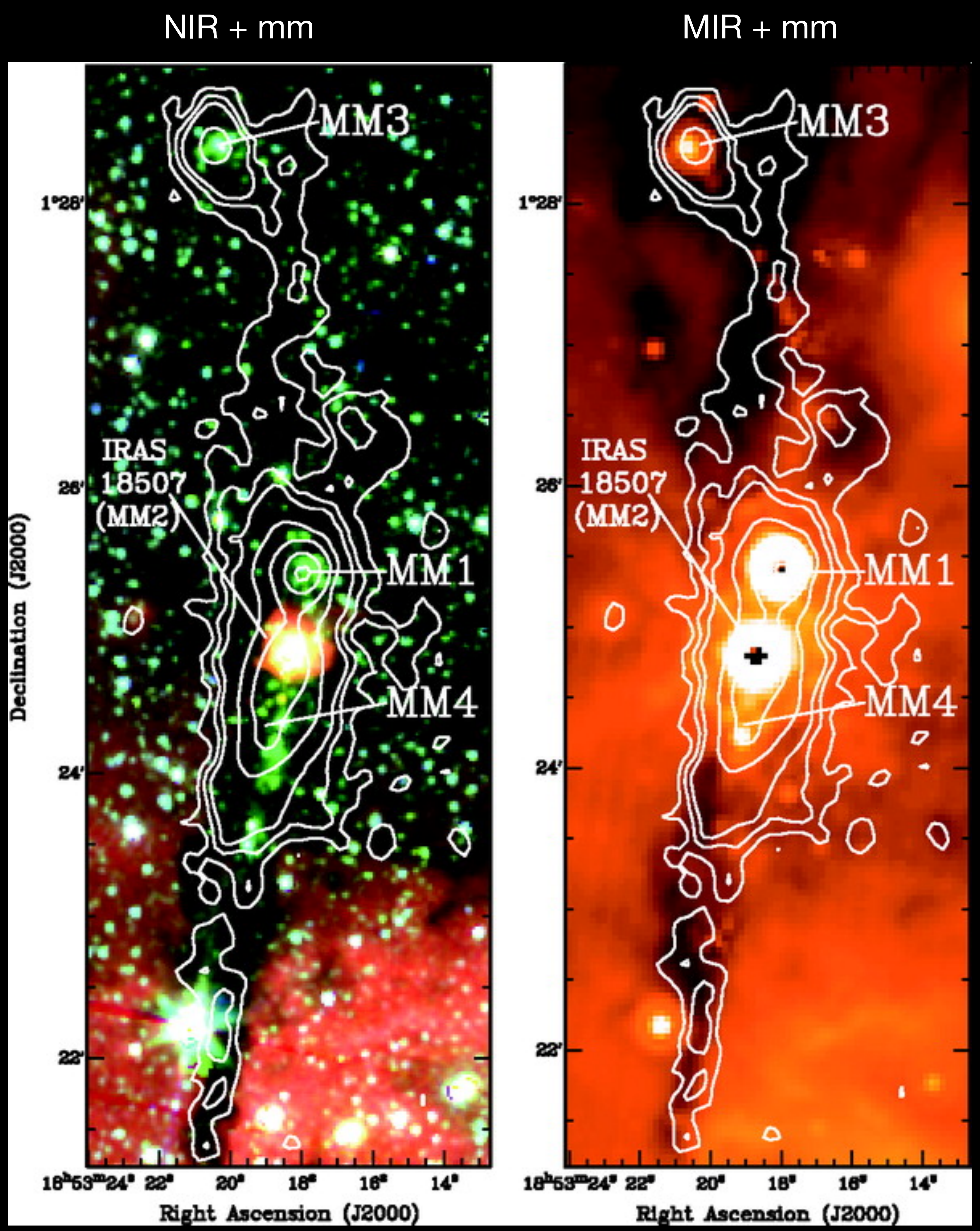
- Massive stars rare compared to low-mass stars, so closest sites further from Earth — closest is Orion (400 pc), next closest regions are all > 1 kpc away
- Confusion: massive stars tend to be at dense centres of clusters, e.g., central density of ONC is 10^5 pc^{-3} → mean interstellar distance ~5000 AU
- Obscuration: mean central density in massive star forming regions ~0.1 - 1 g cm^{-2}, corresponds to 5 - 50 mag at K band
- Timescales: high density and strong feedback means very fast evolution, so we go straight from class 0 or I to main sequence; no class II or III phase

Class exercise: given column density, at what wavelengths would you expect to see massive clumps in emission vs absorption? Does this depend on whether they have an embedded massive star?

Massive clumps

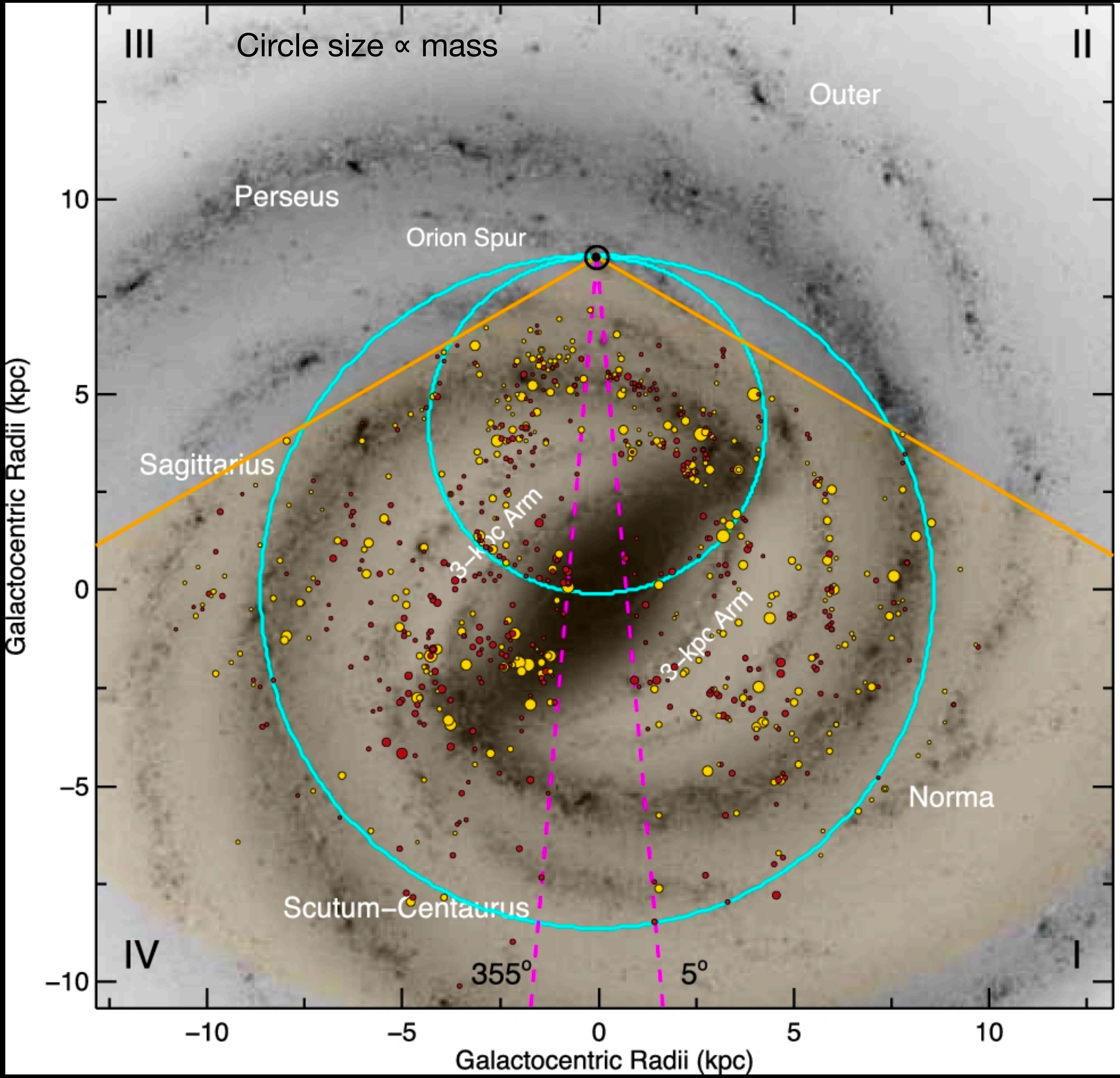
Sites of massive star formation

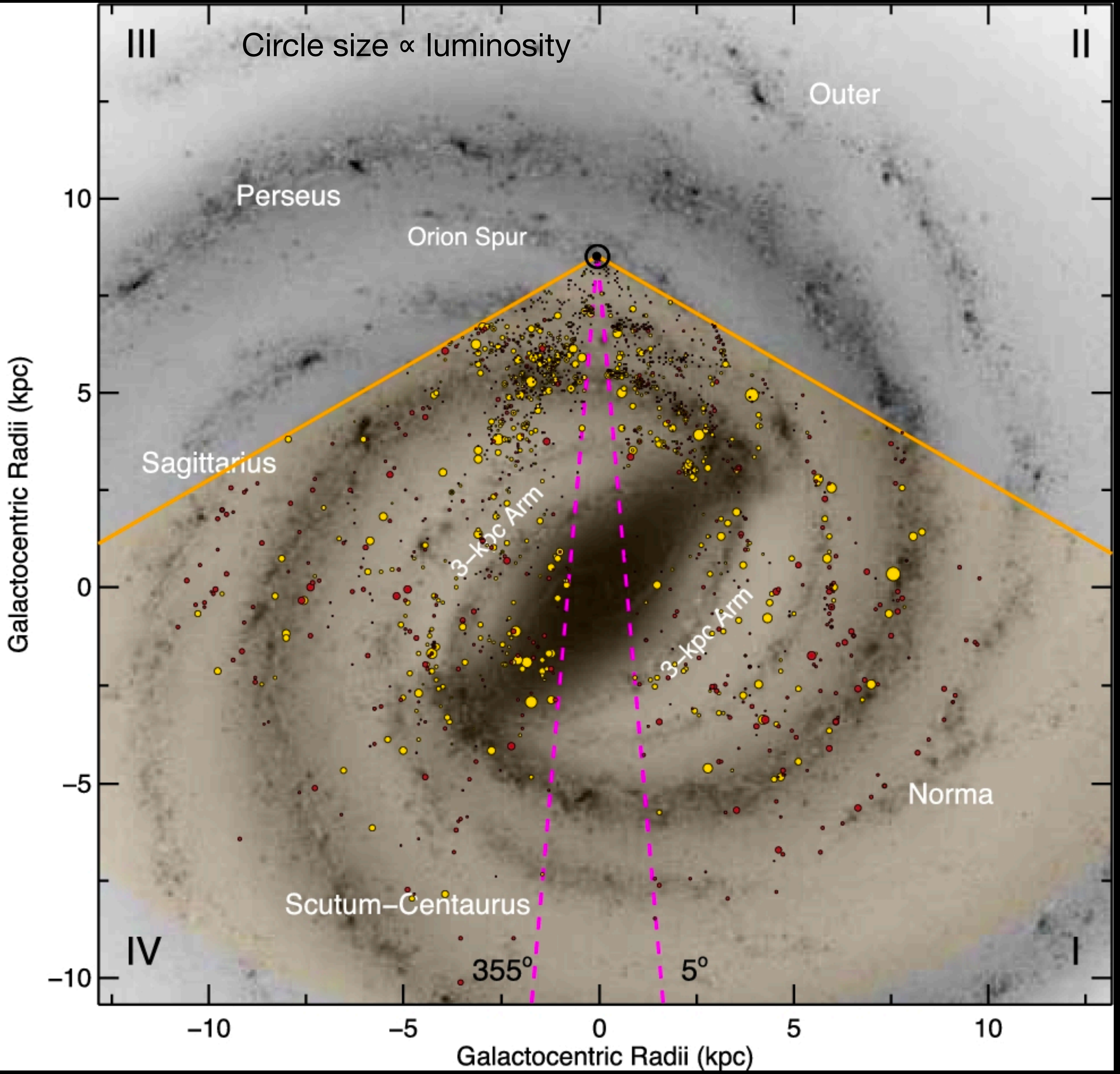
- High optical depth → massive SF sites often seen in NIR absorption: “infrared dark clouds” (IRDCs)
- Can be observed in emission in mm
- Can in in absorption or emission at MIR, depending on whether there is already an embedded massive star
- In molecular lines, very high line width, ~1 - 2 km/s



Rathborne+ 2006

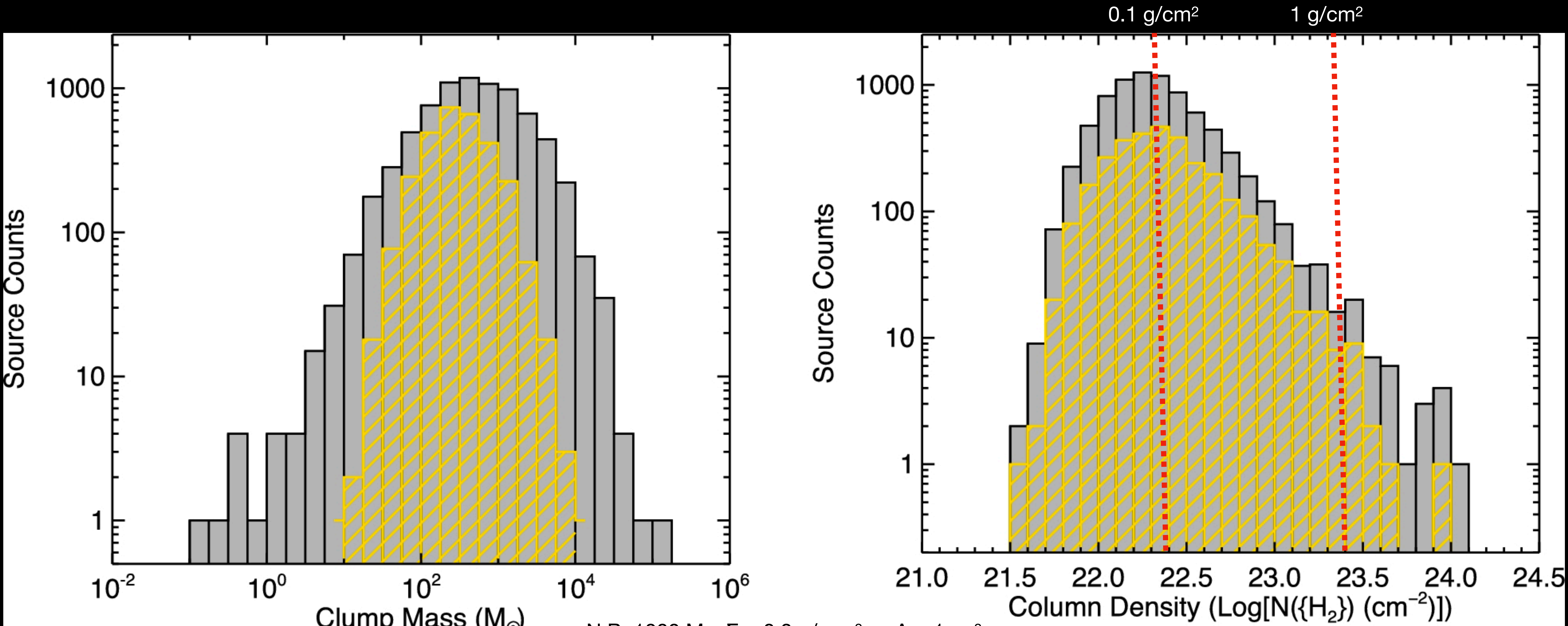
Galactic distribution of massive clumps





ATLASGAL — Urquhart+ 2018

Clump properties



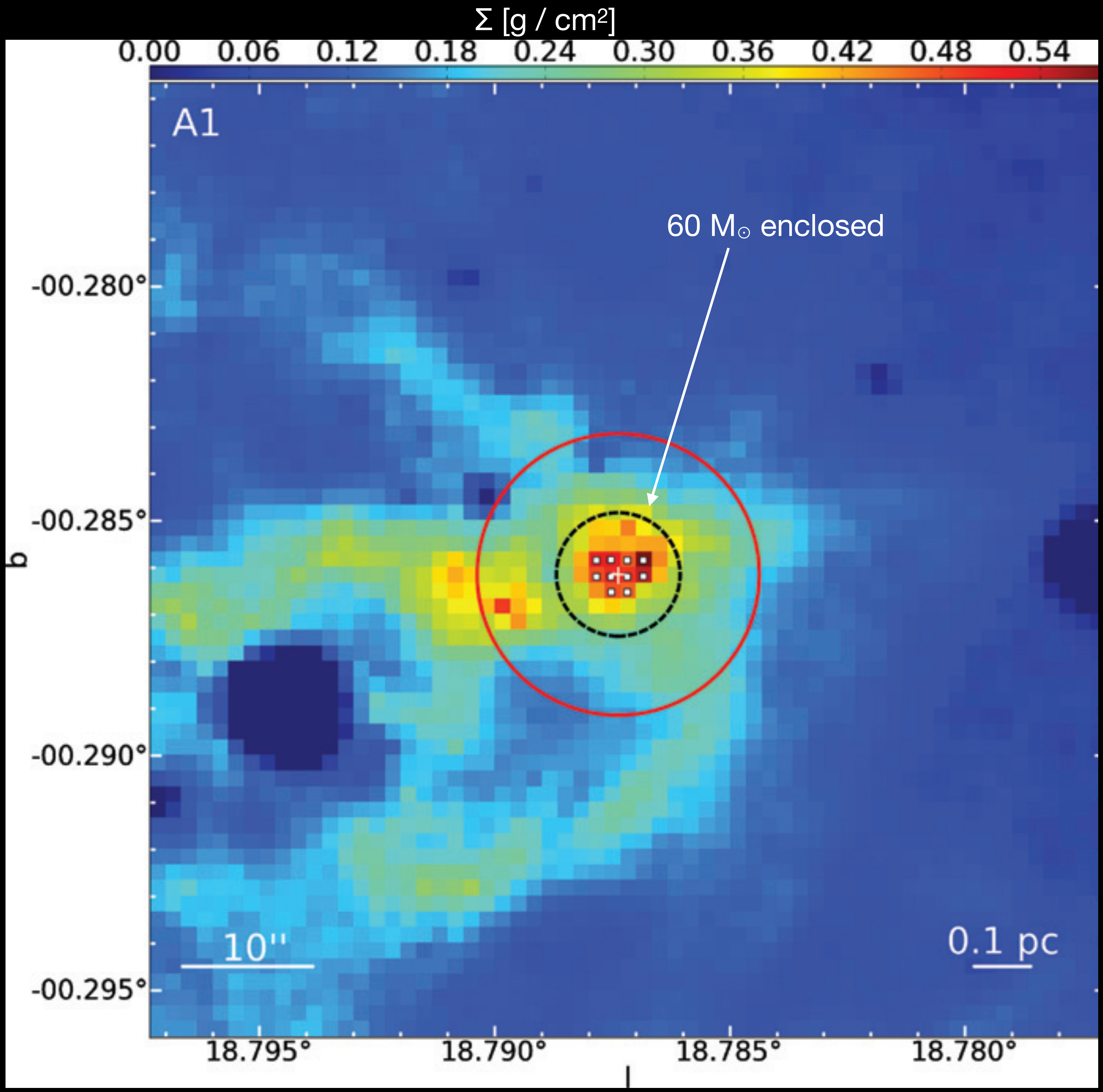
N.B. 1000 M☉, $\Sigma = 0.3$ g/cm^{-2} → A ~ 1 pc^2

ATLASGAL — Urquhart+ 2018

Massive cores

Zooming in

- Zooming in to ~0.1 pc scales, one sees compact dust sources with mass ~100 $M_\odot$, $n \sim 10^6$ cm^{-3}, $\sigma \sim 1$ km/s
- Free-fall time ~50 kyr → $M / t_{ff} \sim 10^{-3}$ $M_\odot$ / yr ~ 10-100 c_s^3 / G
- Virial parameter ≲ 1, supported by combination of turbulence and magnetic fields

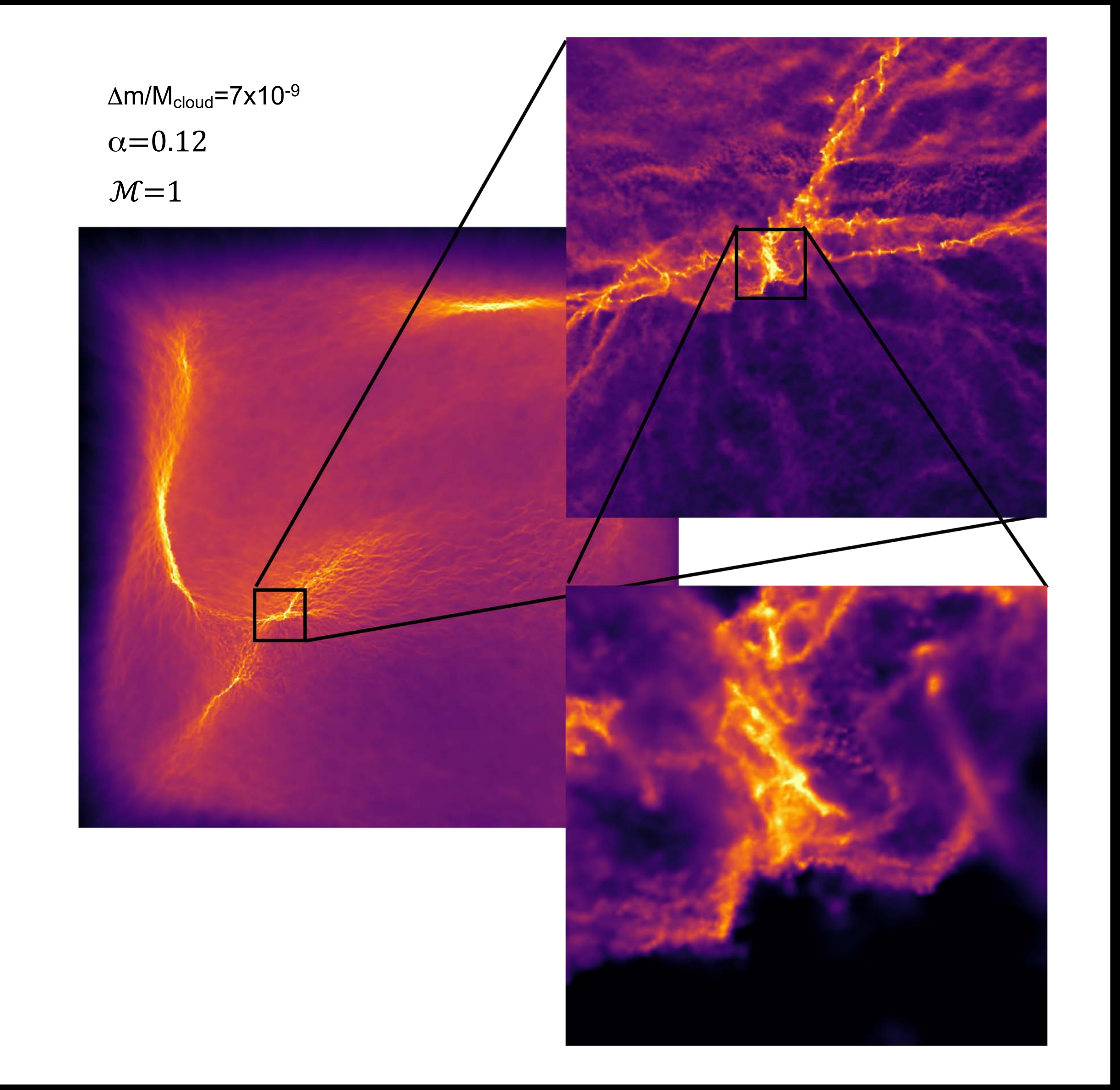


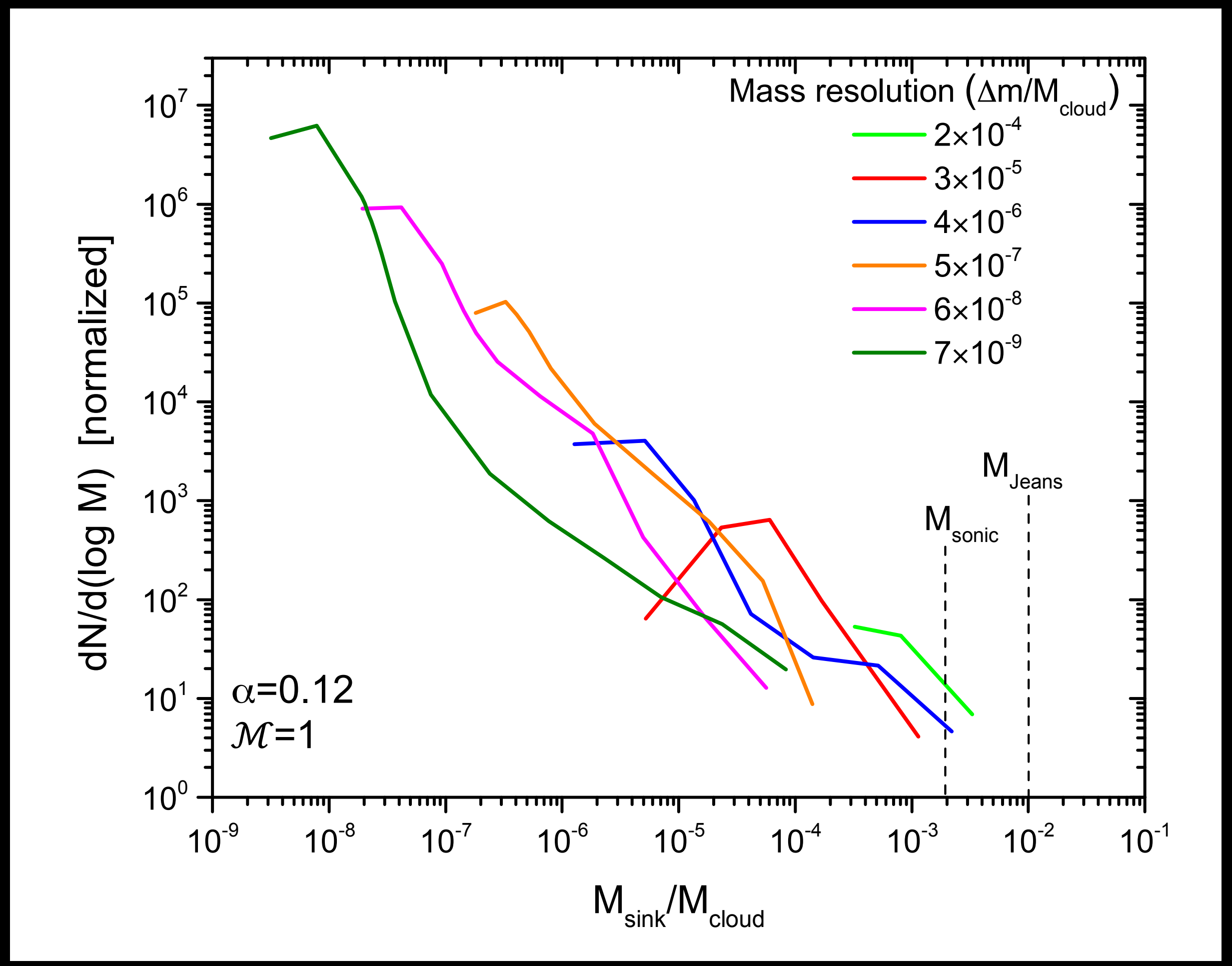
Butler & Tan 2012

Fragmentation of massive cores

The first barrier

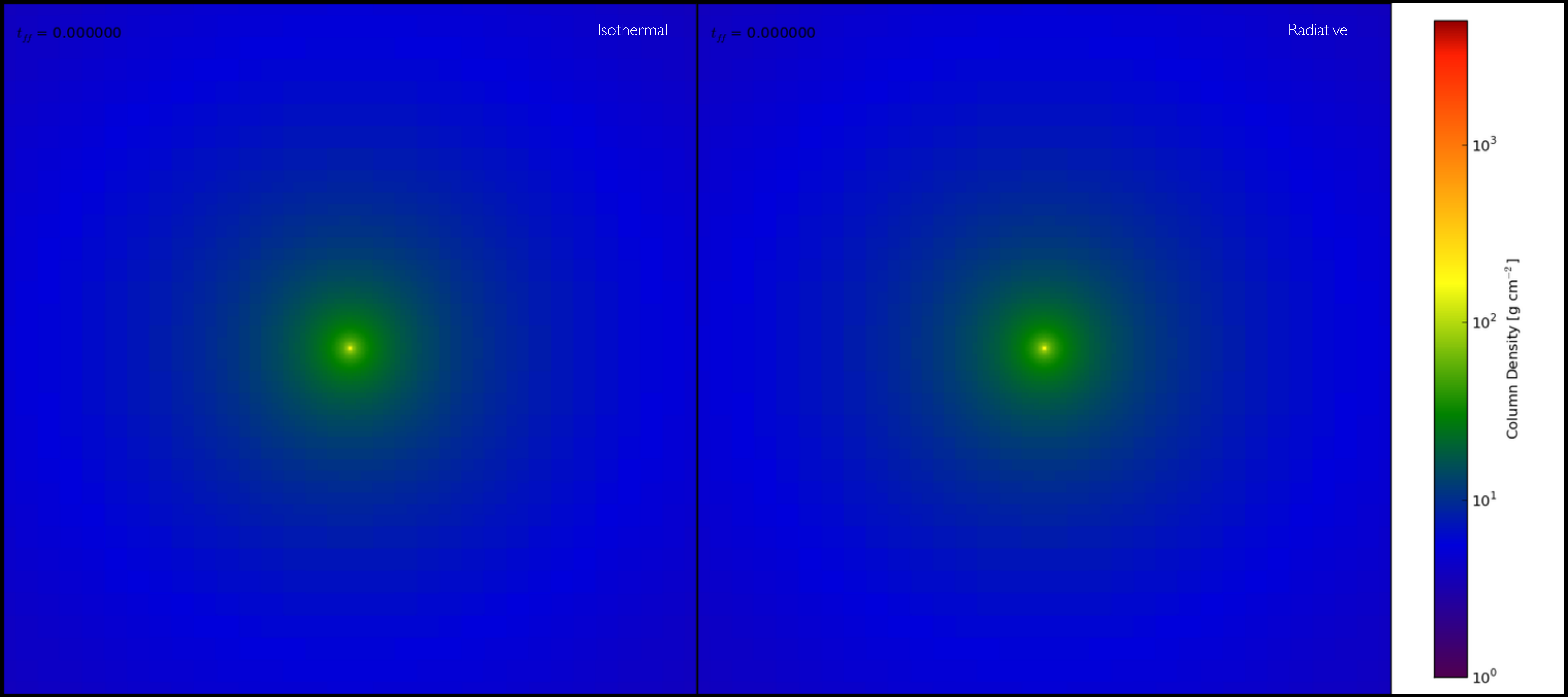
- A ~100 $M_\odot$ is much more massive than any plausible estimate of Jeans mass
- Consequently, expect it to fragment; simulations of isothermal turbulence show that this happens
- Basic question: why would you ever get one star of ~100 $M_\odot$ rather than 100 stars of ~1 $M_\odot$?
- Likely related to radiative feedback and magnetic fields, both of which suppress fragmentation





Guszejnov+ 2018

Fragmentation with and without radiation

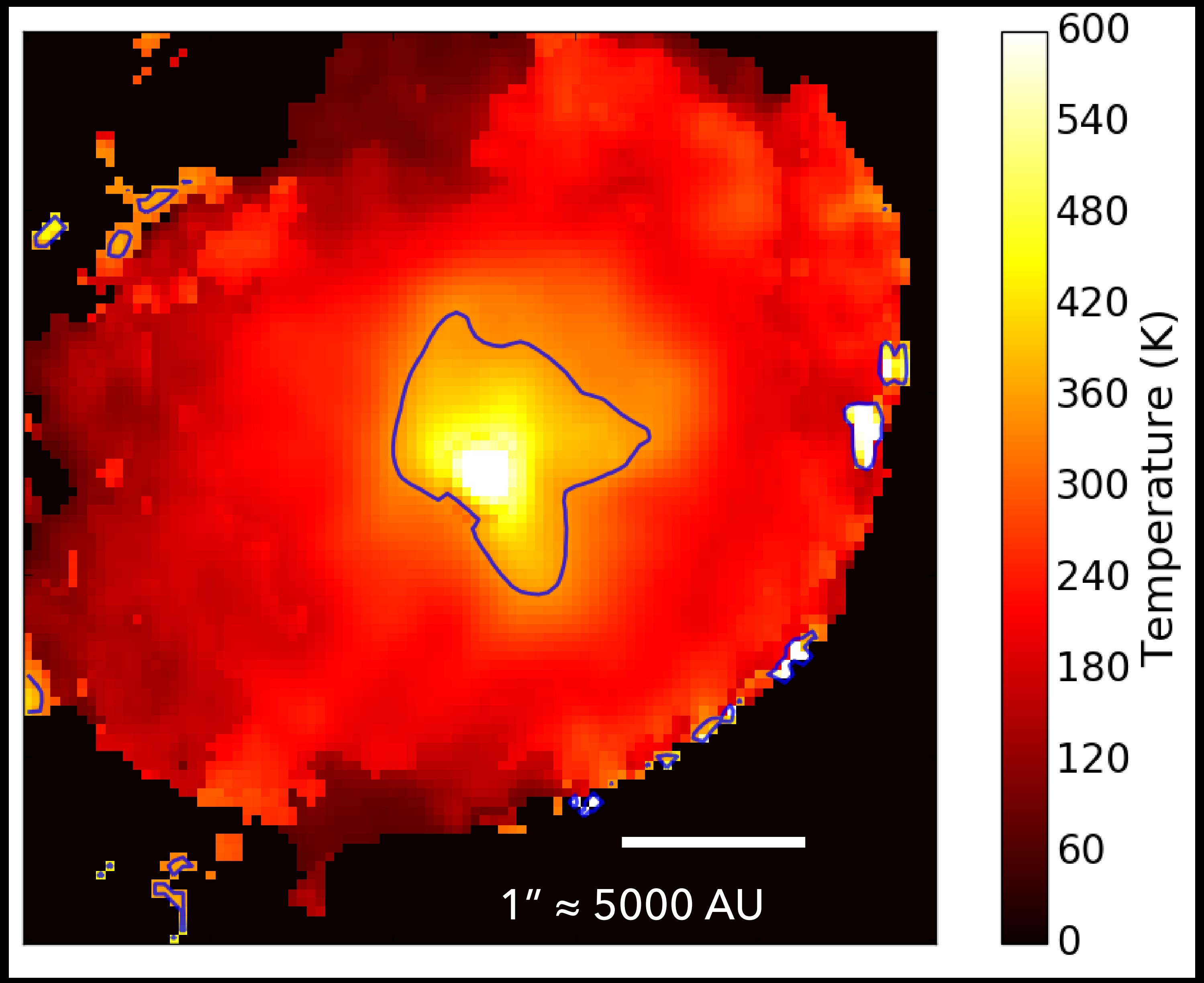


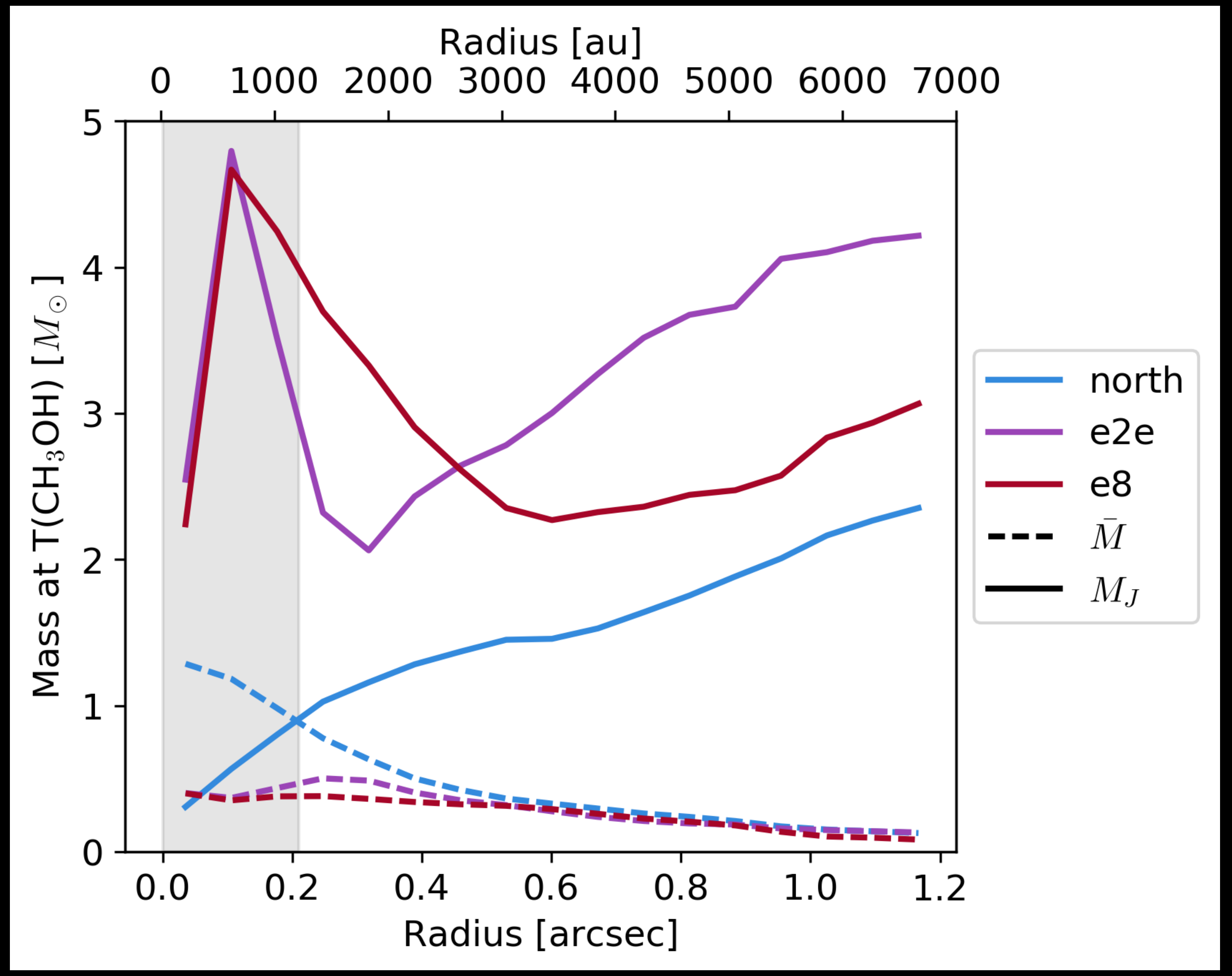
Myers+ 2013

Observational evidence

For the effects of heating

- Direct temperature diagnostics (e.g., NH_3) show heating around embedded protostars
- Observed heating sufficient to suppress fragmentation out to ~1000 AU scales
- Suggests radiative feedback from accretion onto low-mass stars helps them grow to higher mass, if they're in the right environment



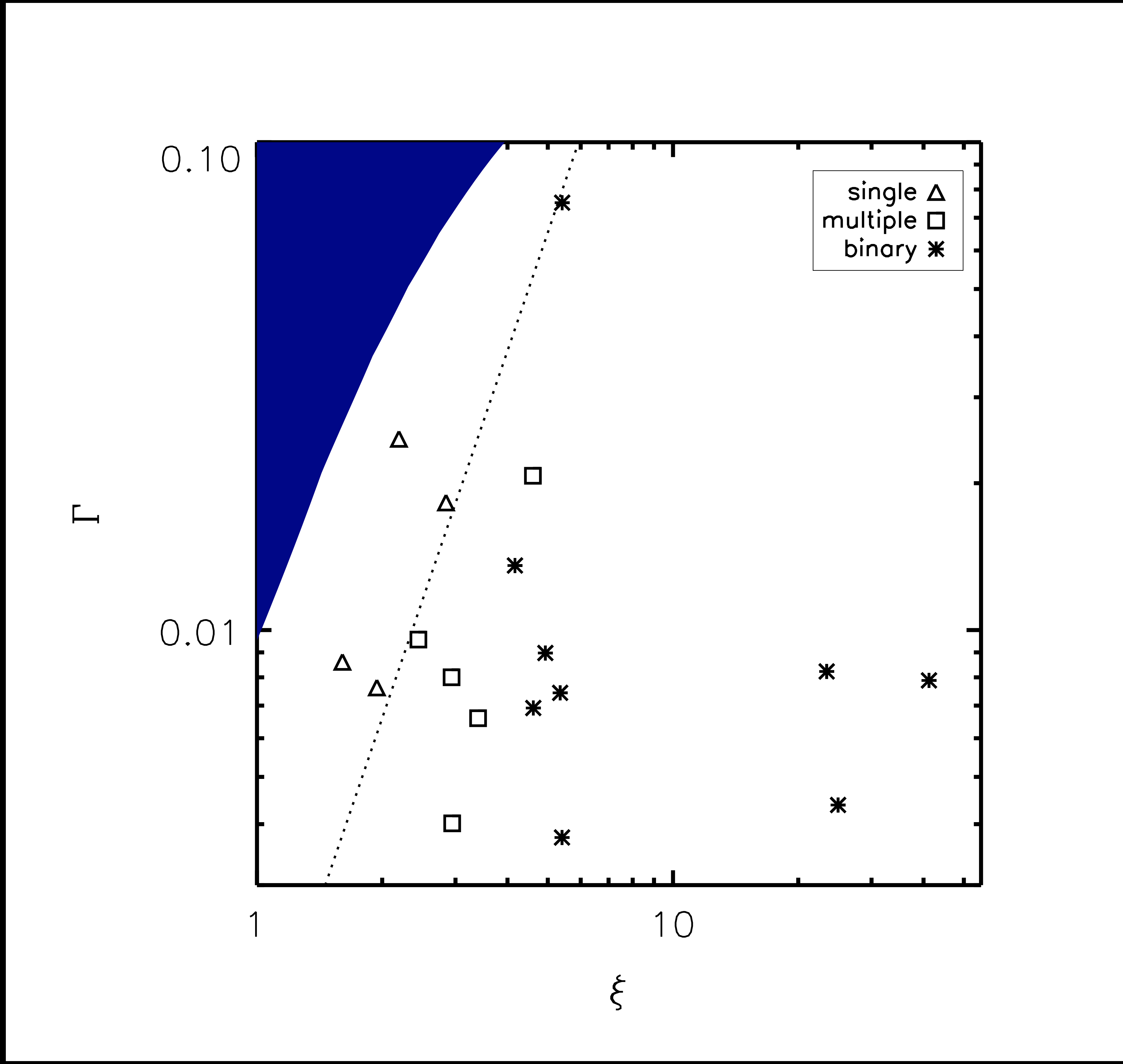


Ginsburg+ 2017

Massive binaries

Where there is fragmentation

- Fragmentation governed mostly by $\xi = G\,(dM/dt)\,/\,c_s^3$
- We previously showed that massive cores should accrete at ~10 - 100 c_s^3 / G, so $\xi \sim 10 - 100$
- Implication: massive discs should always be unstable, fragment to form binaries (at least)

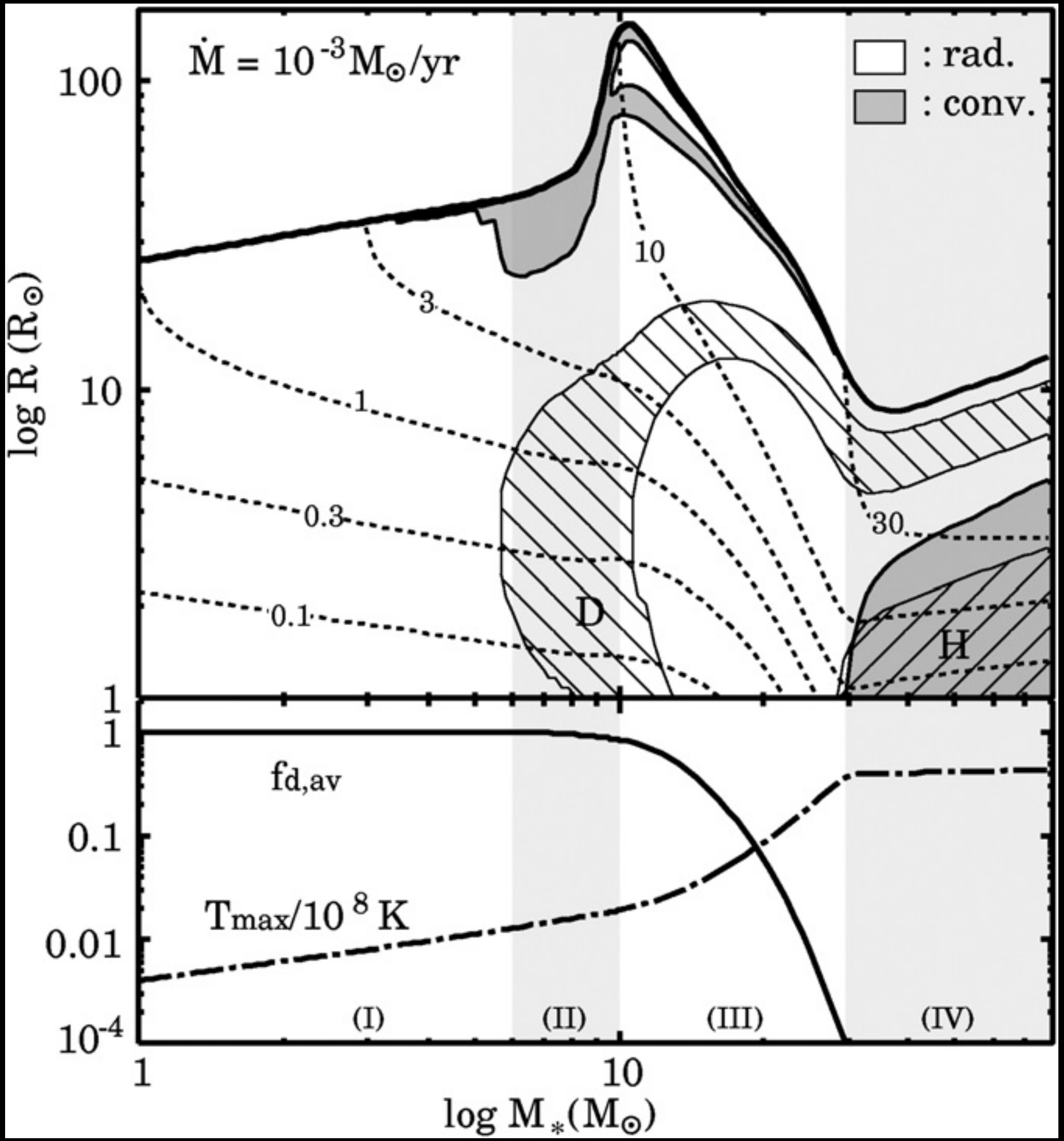


Kratter+ 2010

Massive star feedback

General considerations

- KH time for massive stars is short: $t_{KH} = GM^2 / RL = 0.3$ Myr for $M = 100\ M_\odot$, $R = 10\ R_\odot$, $L = 10^5\ L_\odot$
- Implication: massive stars reach main sequence and thus high T_{eff} while still accreting, produce winds and ionising radiation like a MS massive star
- Thus accretion must be able to continue despite these effects



Hosokawa + Omukai (2009)

Physics question: why is t_{KH} so much smaller for massive stars than for low-mass ones? (Hint: what does Kramers opacity have to do with this question?)

Winds vs accretion

Feedback mechanism I

- O stars launch strong winds driven by radiation pressure: mass flux ~10^{-7} $M_\odot$ / yr, speed ~ 1000 km/s (comparable to v_{ff} at stellar surface)
- Wind density given implicitly by $\dot{M}_{\rm wind} = 4\pi r^2 \rho v_{\rm wind}$
- Ram pressure of wind is therefore $P_{\rm wind} = \rho v_{\rm wind}^2 = \frac{\dot{M}_{\rm wind} v_{\rm wind}}{4\pi r^2}$
- By comparison, ram pressure of infall is $P_{\rm in} = \frac{\dot{M}_{\rm in} v_{\rm in}}{4\pi r^2}$
- Infall mass flux ≳ 1000 × wind mass flux, so infall wins unless infall speed ≲ 1 km/s — implausible, since this is less than turbulent speed in core
- Thus infall wins, as long as shocked wind gas escapes so *P* doesn't build up

Ionisation vs accretion

Feedback mechanism II

- Ionisation will heat gas near star to ~10^4 K, sound speed c_s ~ 10 km/s
- If $c_s > v_{esc}$, gas will not escape rather than accretion, so accretion flow stops
- To check if this happens, consider constant accretion flow at free-fall, so density given implicitly by $\dot{M} = 4\pi r^2 \rho v_{\mathrm{ff}} = 4\pi r^{3/2} \rho \sqrt{2GM}$
- Consider point source of ionising luminosity Q at centre of infall
- Compute radiation of ionised region by setting ionisation = recombination:

Ionisation front radius

$$Q = \int_{R_*}^{r_i} 4\pi r^2 \alpha_{\mathrm{B}} f_e \left(\frac{\rho}{\mu m_{\mathrm{H}}} \right)^2 dr$$

Mean mass per H

Stellar radius

Recombination rate coefficient

Free electrons per H

Ionisation vs accretion
Part II

- Result: $r_i = R_* \exp\left(\frac{8\pi G M \mu^2 m_{\rm H}^2 Q}{f_e \alpha_B \dot{M}^2}\right)$
- If factor inside exponential is ≲ 1, ionised region is confined close to stellar surface, while if it is ≫ ionised region is far from surface
- Condition $(2GM / r_\mathrm{i})^{1/2} > c_s$ met if $\dot{M} > \left[\frac{4\pi G M \mu^2 m_{\rm H}^2 S}{f_e \alpha_B \ln\left(v_{\rm esc}/c_s\right)}\right]^{1/2}$ Stellar surface escape speed
- Plugging in typical massive star numbers ($S \sim 10^{49}$ / s, $M \sim 100\ M_\odot$, $v_{\rm esc} \sim$ 1000 km/s), required accretion rate is few x $10^{-5}\ M_\odot$ / yr — easily satisfied in massive star-forming regions
- Conclusion: ionisation unlikely to halt accretion as long as accretion is rapid

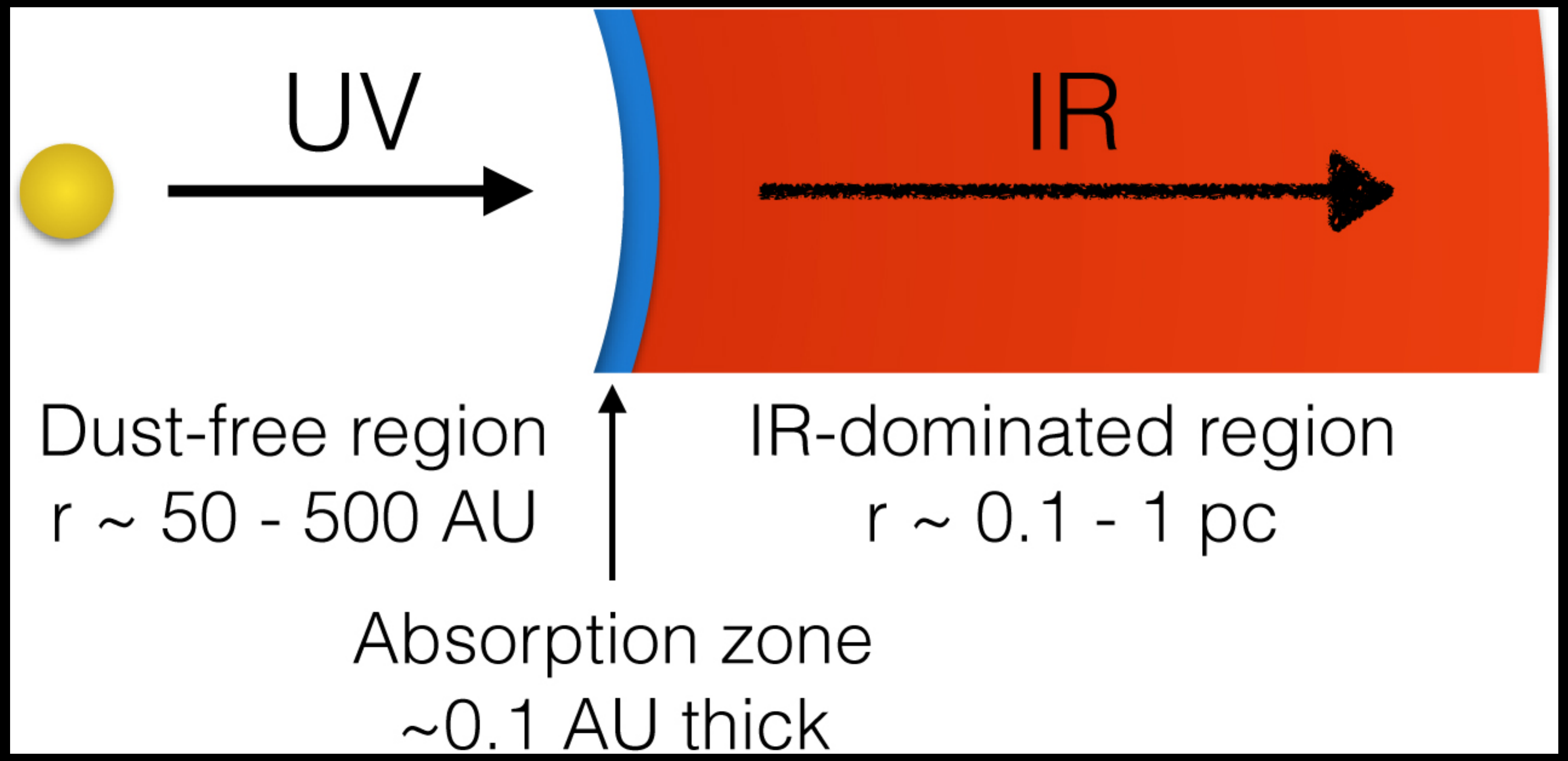
Direct radiation pressure

Feedback mechanism III

- Dust destruction radius given by

$$\frac{L}{4\pi r_d^2}\pi a^2 = 4\pi a^2 Q\sigma_{\rm SB}T_d^4 \quad \Longrightarrow \quad r_d = \sqrt{\frac{L}{16\pi Q\sigma_{\rm SB}T_d^4}}$$

- Typical value for massive star ~100-200 AU
- Radiation absorbed at dust destruction front delivers impulse *L/c*
- Flow turned back unless $\dot{M} v_{\rm ff} > L/c \Longrightarrow \dot{M} > \frac{L}{c}\sqrt{\frac{r_d}{2GM}}$
- Condition generally met: for typical massive star parameters, requires $\dot{M} \gtrsim 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$



Physics question: how could you have figured out this answer just based on our discussion about winds, without doing any further calculations?

Indirect radiation pressure

Feedback mechanism IV

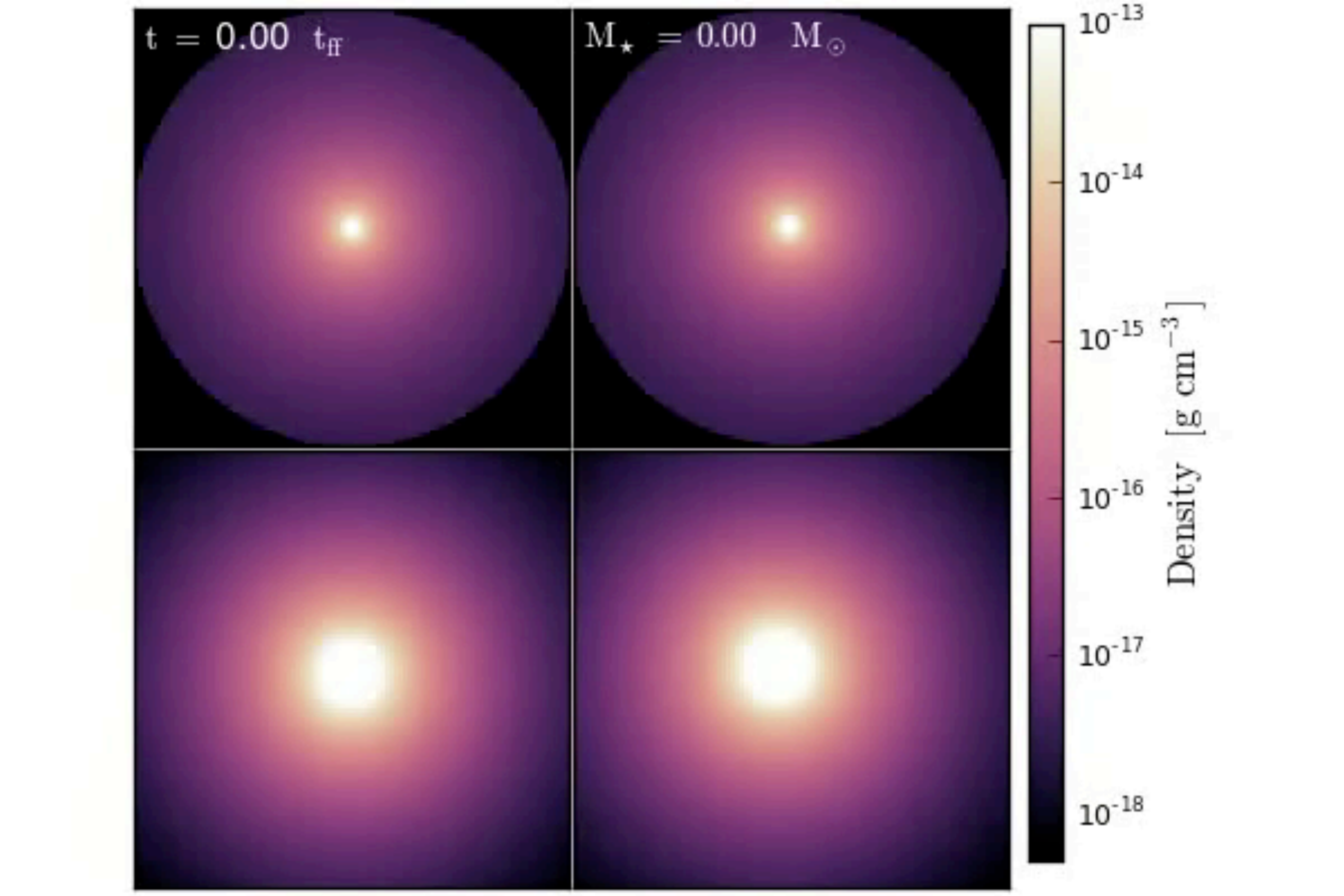
- Even if inflow carries enough momentum to crush UV radiation, IR radiation still exerts forces as it diffuses out
- Ratio of radiative to gravitational force is:

$$\frac{f_{\rm rad}}{f_{\rm grav}} = \frac{\kappa_{\rm IR} L/4\pi r^2 c}{GM/r^2} = \frac{\kappa_{\rm IR} L}{4\pi G M c} \approx 8 \left(\frac{\kappa_{\rm IR}}{10\ {\rm cm}^2\ {\rm g}^{-1}}\right)\left(\frac{L/M}{10^4\ L_\odot/M_\odot}\right)$$

- Conclusion: stars with $L/M \gtrsim 10^3\ \mathrm{L}_\odot/\mathrm{M}_\odot$ cannot form by spherical accretion — this is all stars larger than $\approx 20\ \mathrm{M}_\odot$
- Obviously something is wrong…

Indirect radiation pressure

Escape hatch I: radiation RT instability

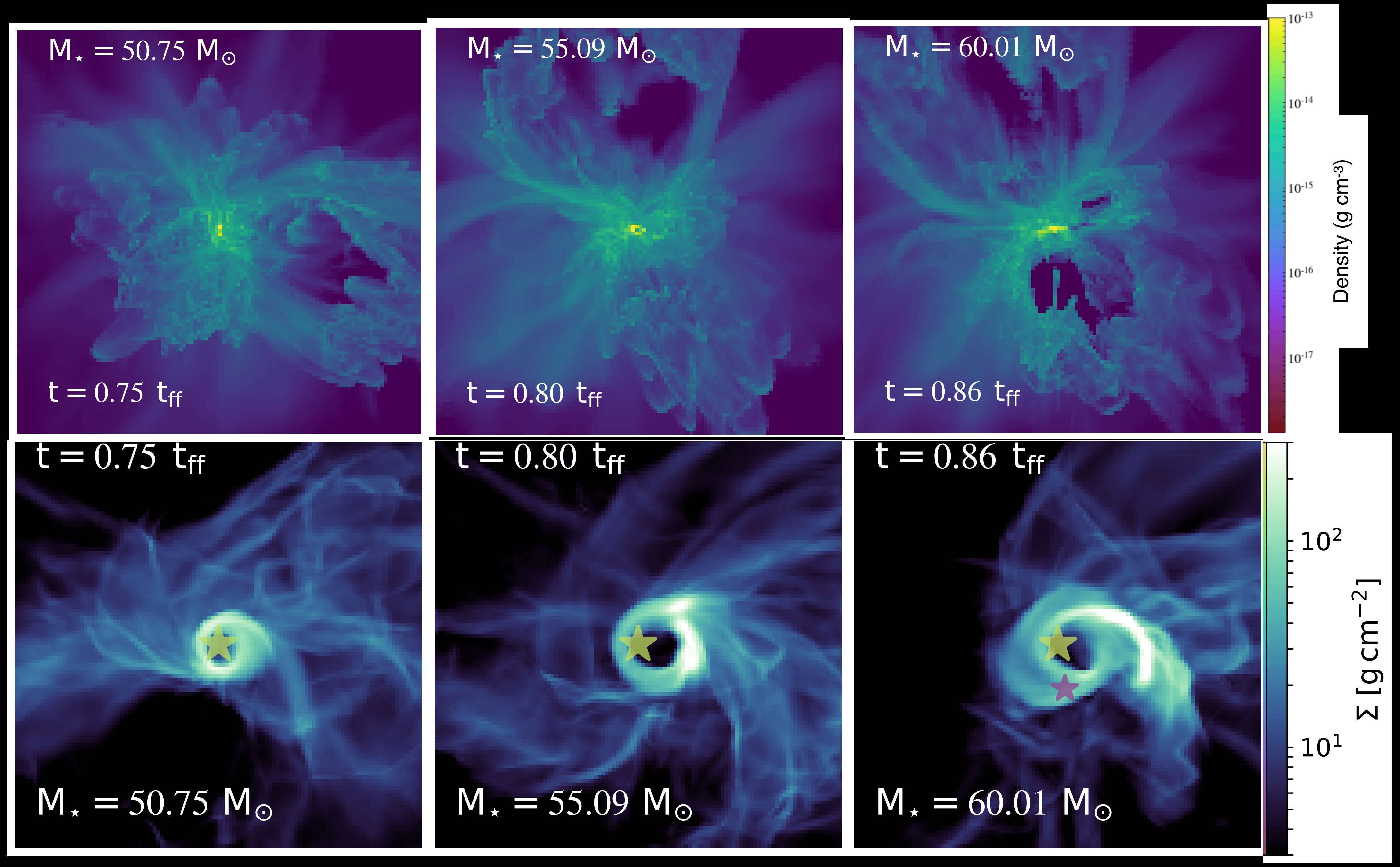


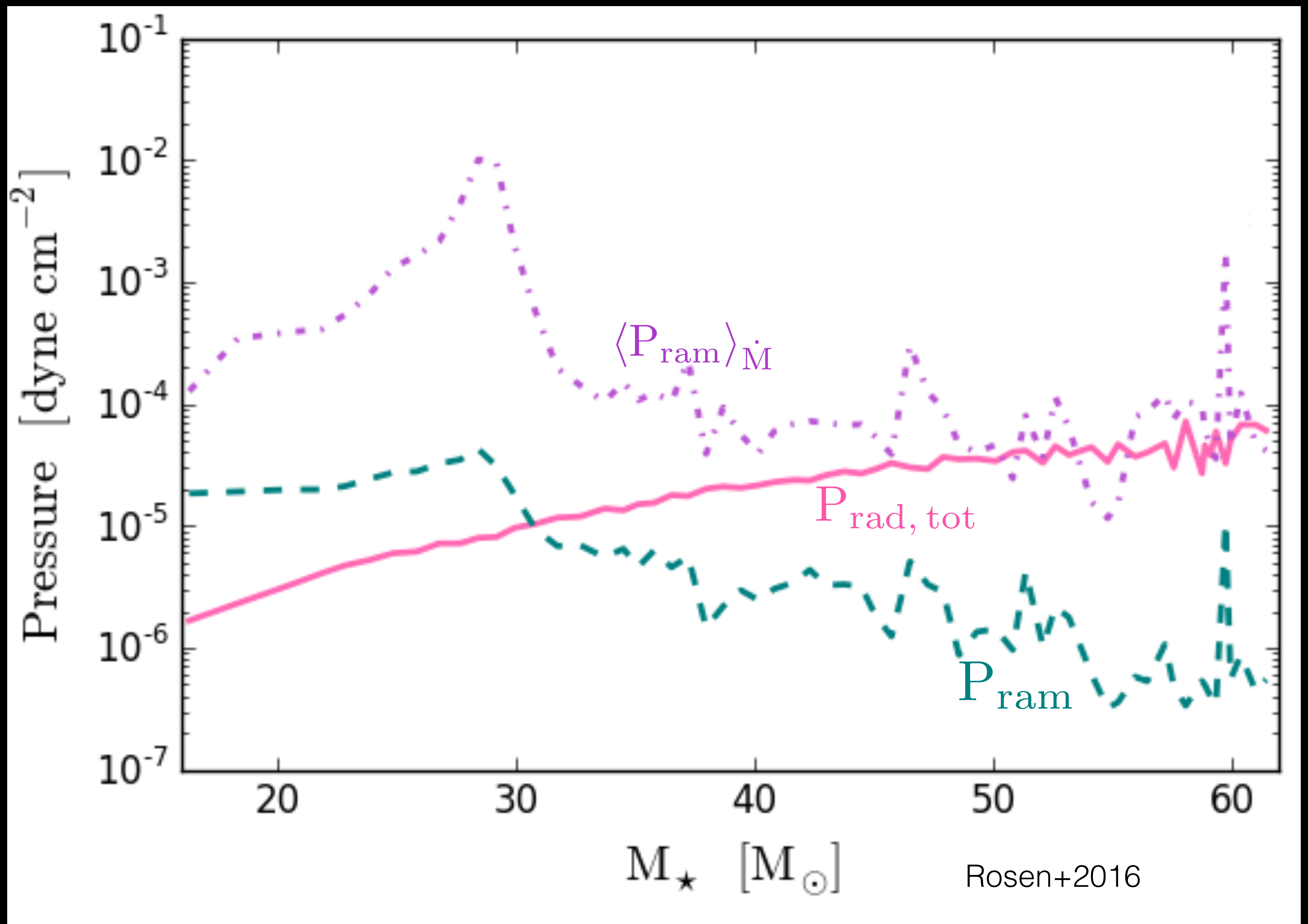
Rosen+ 2016

Anisotropic accretion

Why this works

- Key insight from simulations is that accretion is anisotropic: most mass arrives in a small solid angle (e.g., via a disc)
- This makes mass-averaged ram pressure ≫ spherically-averaged ram pressure, so mass can flow in even as most solid angle push outward

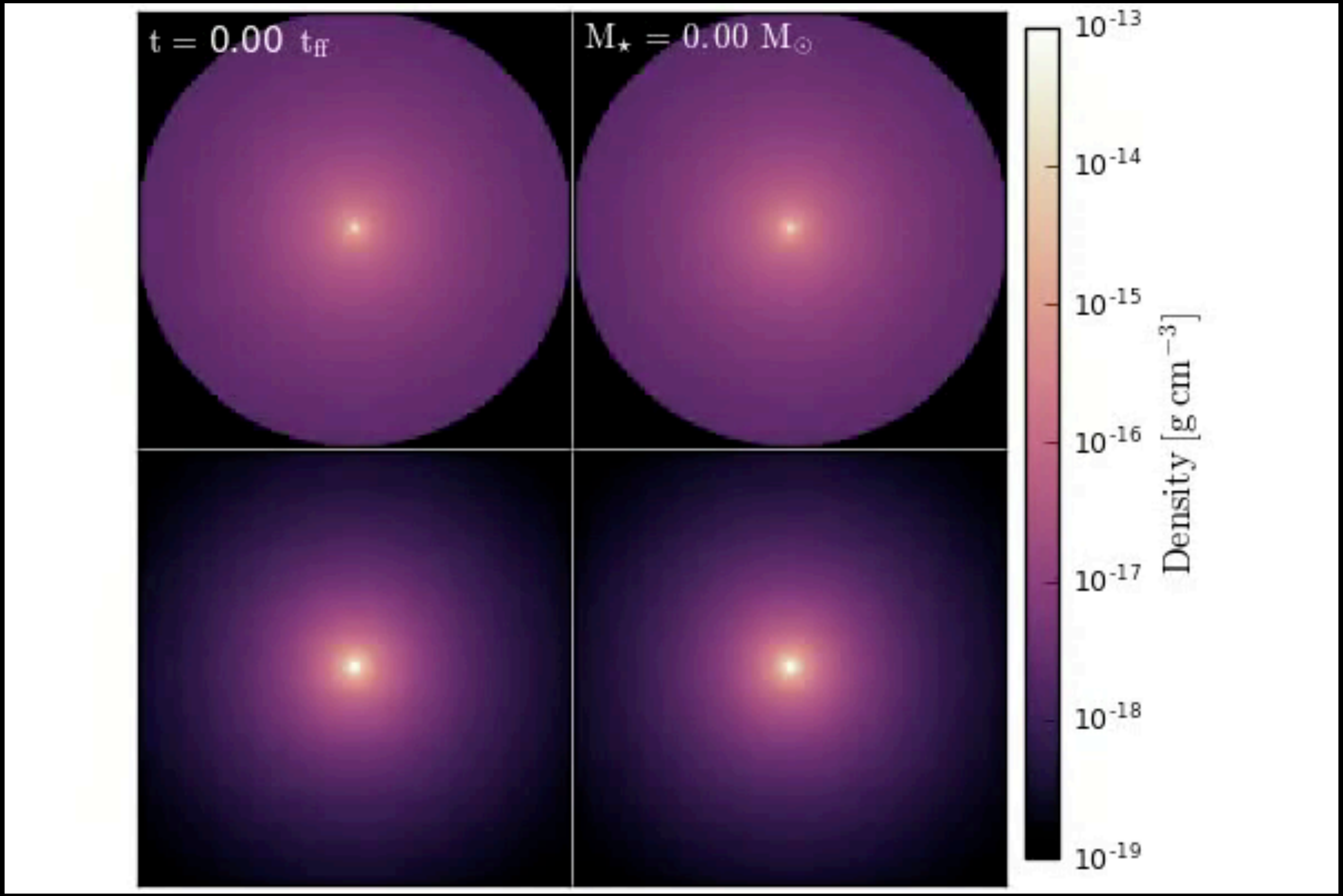




Rosen+2016

Indirect radiation pressure

Escape hatch II: outflows



Rosen+ 2020