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MASSIVE STAR FORMATION

(A PRIMER FOR PEOPLE WHO DON'T CARE ABOUT THE ISM)

MOTIVATION FOR THIS TALK

- Massive stars are the ultimate sources of many of the multi-messenger signals of interest to most at this meeting
- The demographics of massive stars are therefore a crucial input to efforts to model source populations; conversely, these demographics can be constrained by observations
- Many demographic features matter: IMF, binary statistics, spin; we care about how these depend on environment
- My goal: tell you what is known theoretically (and a little observationally) about these demographics

OUTLINE

- Observational background on massive star formation

- Key physical processes for massive star formation
  - Fragmentation
  - Feedback and the upper mass limit
  - Disks: fragmentation and braking

- Variations: what changes with environment, and why?
  - The initial mass function
  - Binarity / multiplicity
  - Rotation

- Implications and questions


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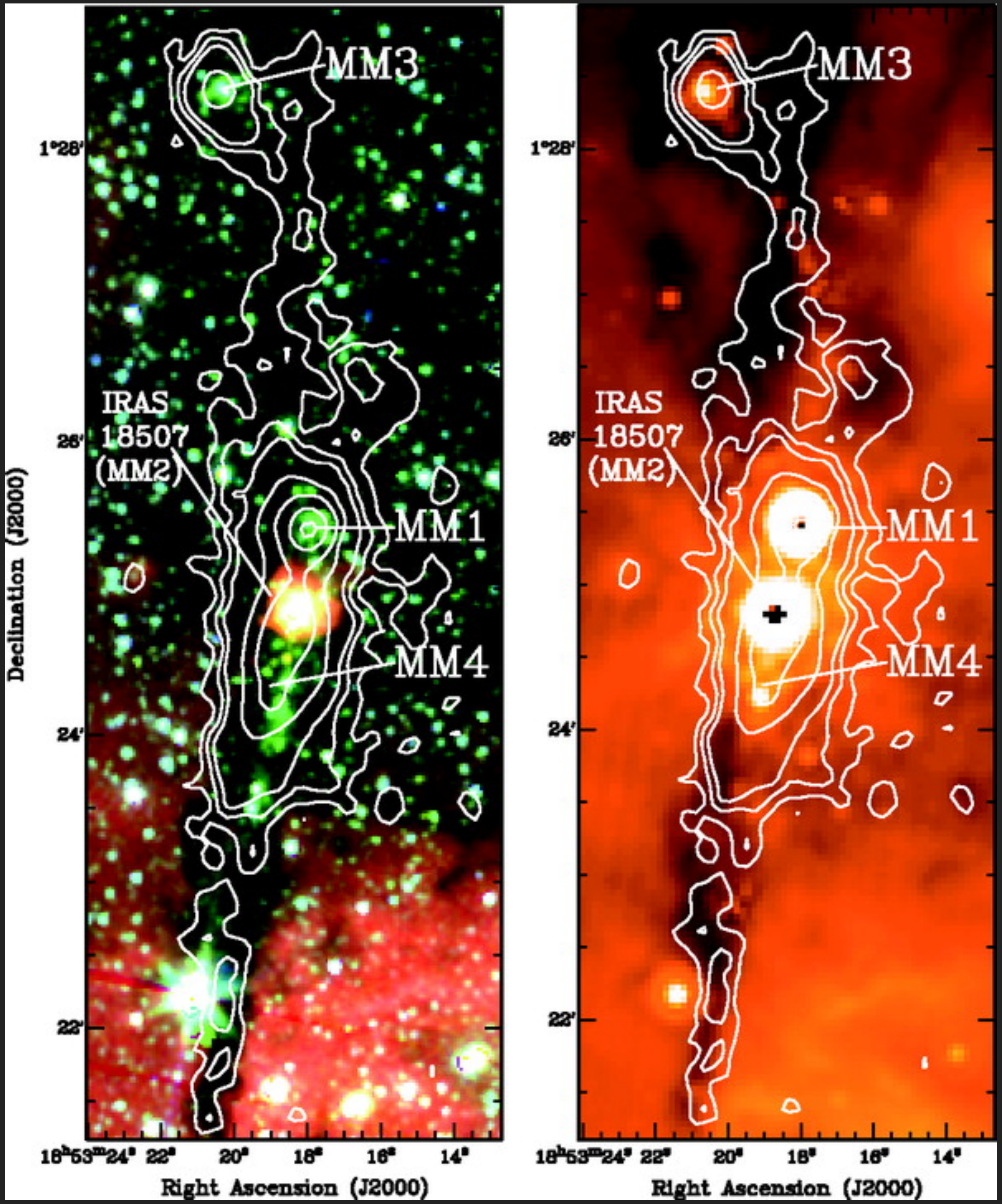
OBSERVATIONAL BACKGROUND

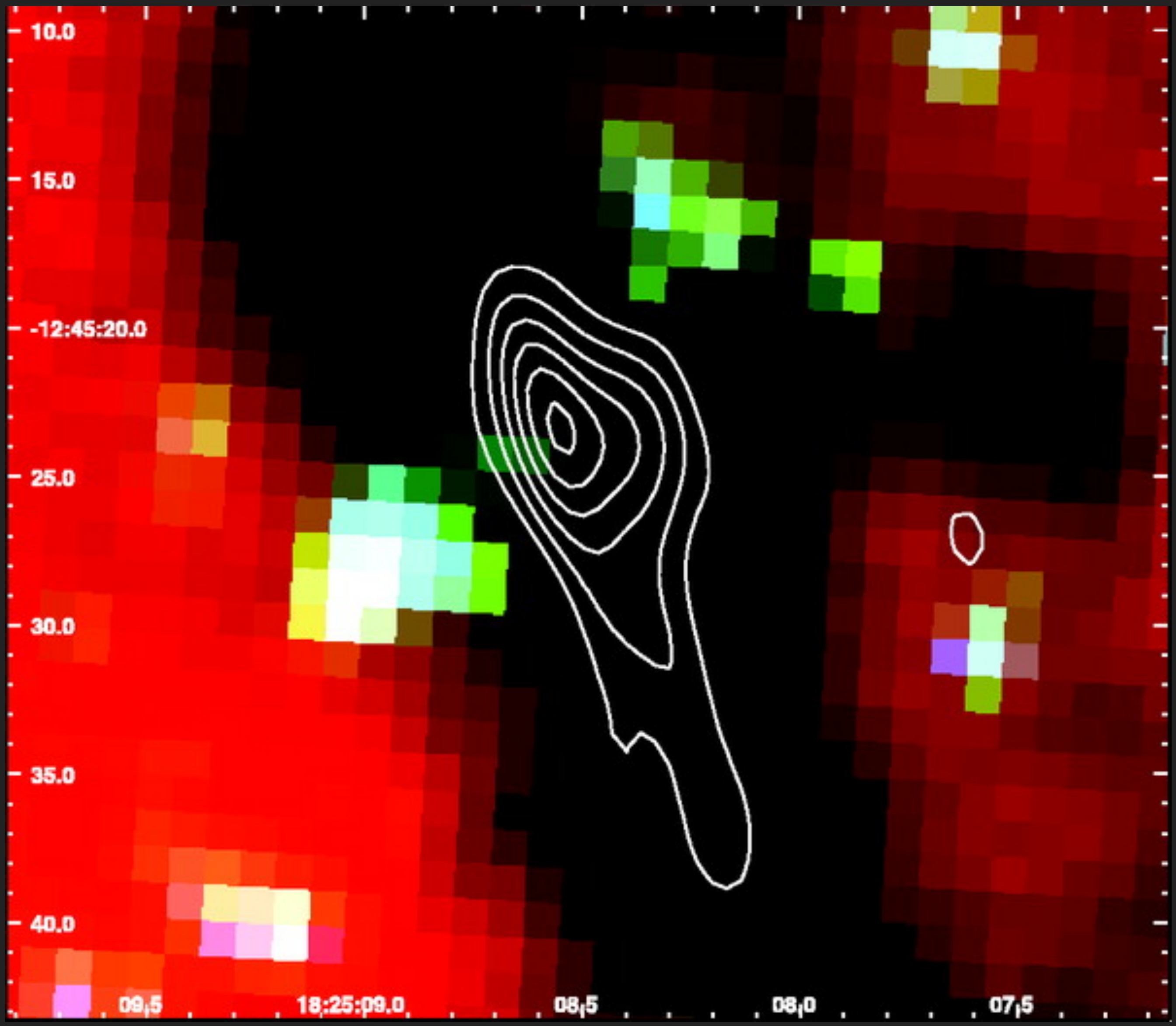
For no reason whatsoever, here is a baby wombat

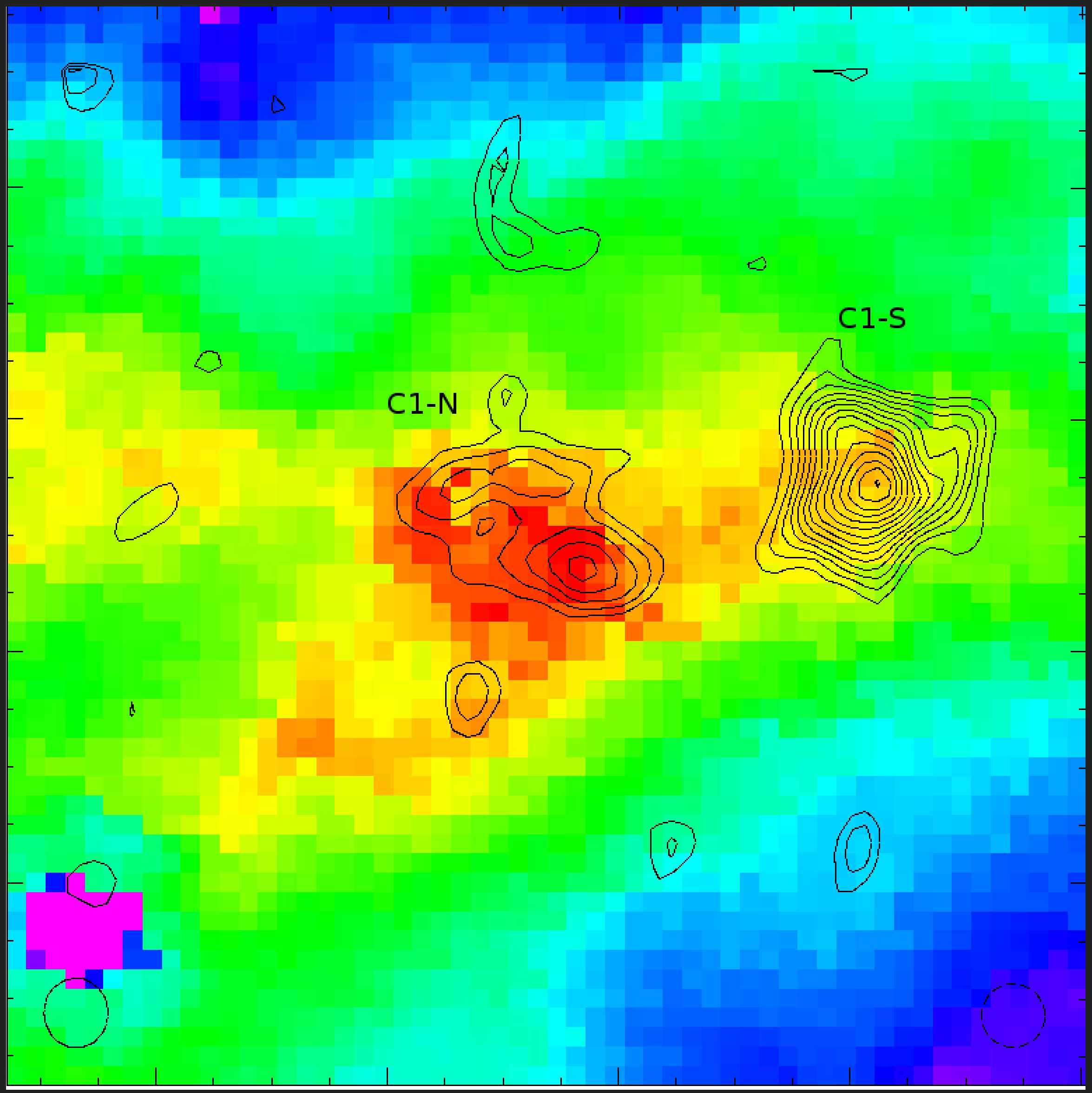
SITES OF MASSIVE STAR FORMATION

- Massive stars form in cold, dense, dusty interstellar clouds
- Detect massive protostars in clouds by mid-IR emission
- Detect clouds by near- or mid-IR absorption, FIR or mm emission
- Typical surface density $\Sigma \sim 0.1 - 1$ g cm^{-2}, temperature $T \sim 10$ K
- Contain MIR-dark cores with $M \sim 100\ M_\odot$, $\Sigma \sim 1$ g cm^{-2}, $\sigma \sim 1$ km s^{-1}



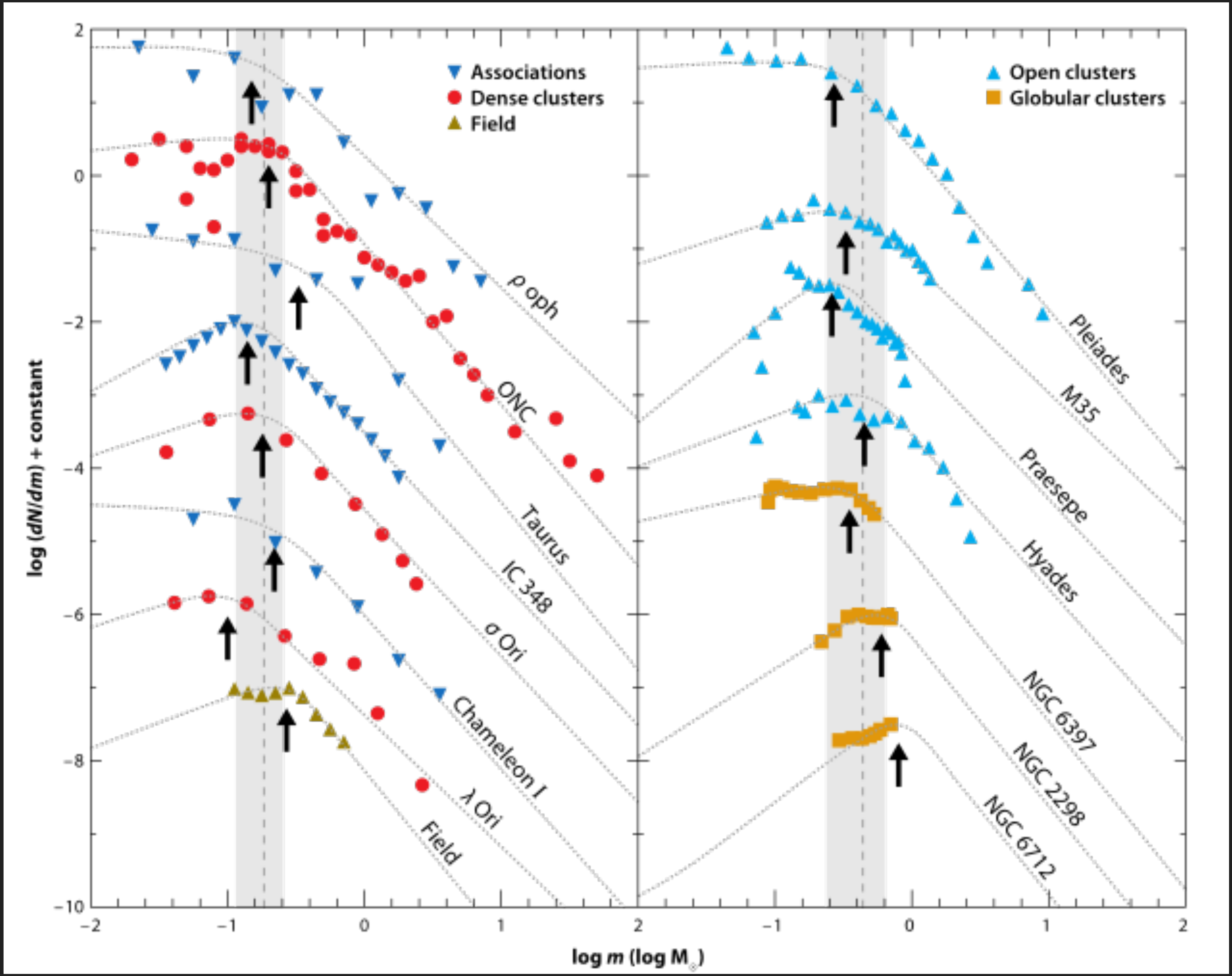
Rathborne+ 2005
Left: Spitzer NIR + IRAM mm
Right: Spitzer MIR + IRAM mm





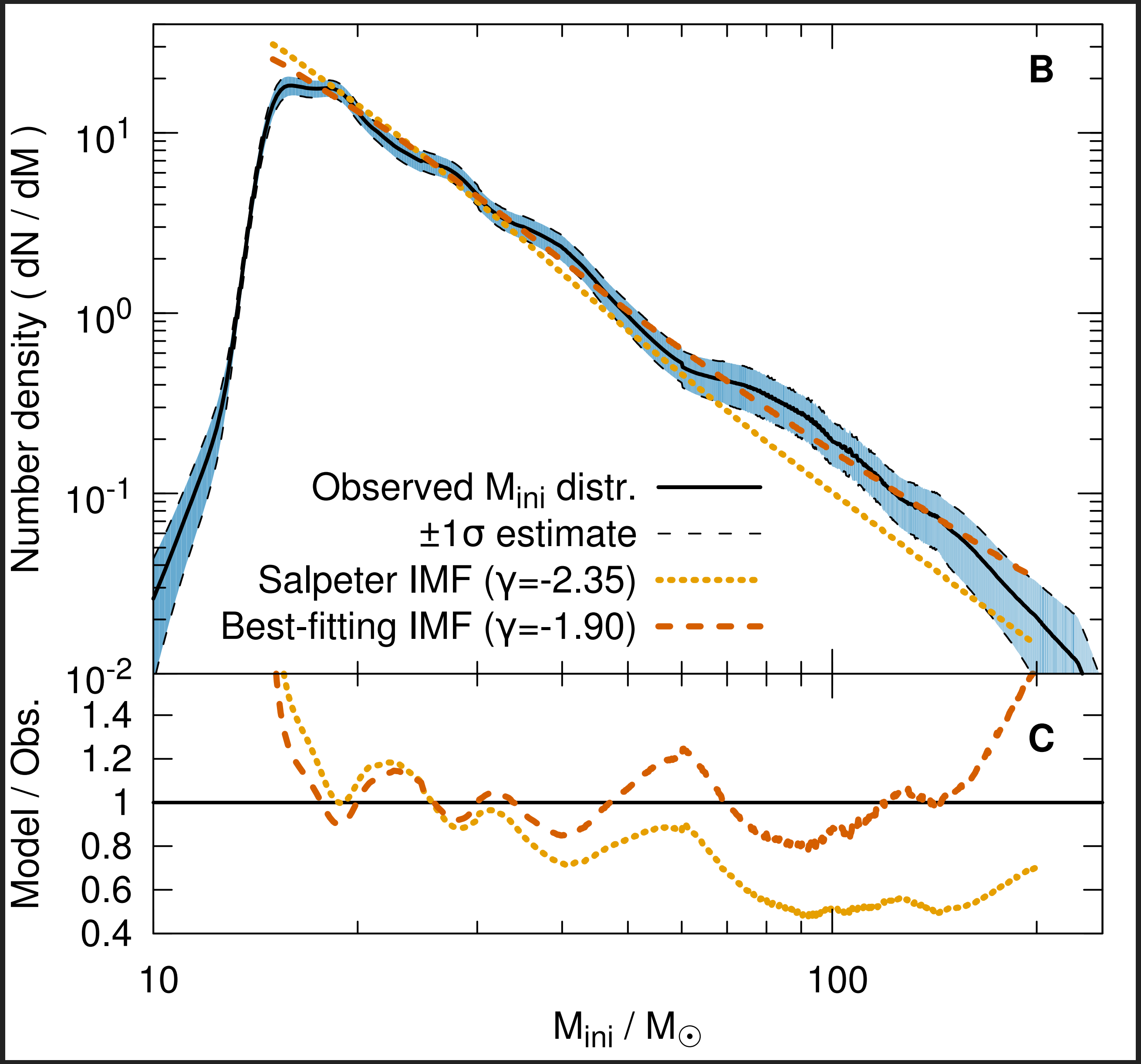
MASSIVE CORES

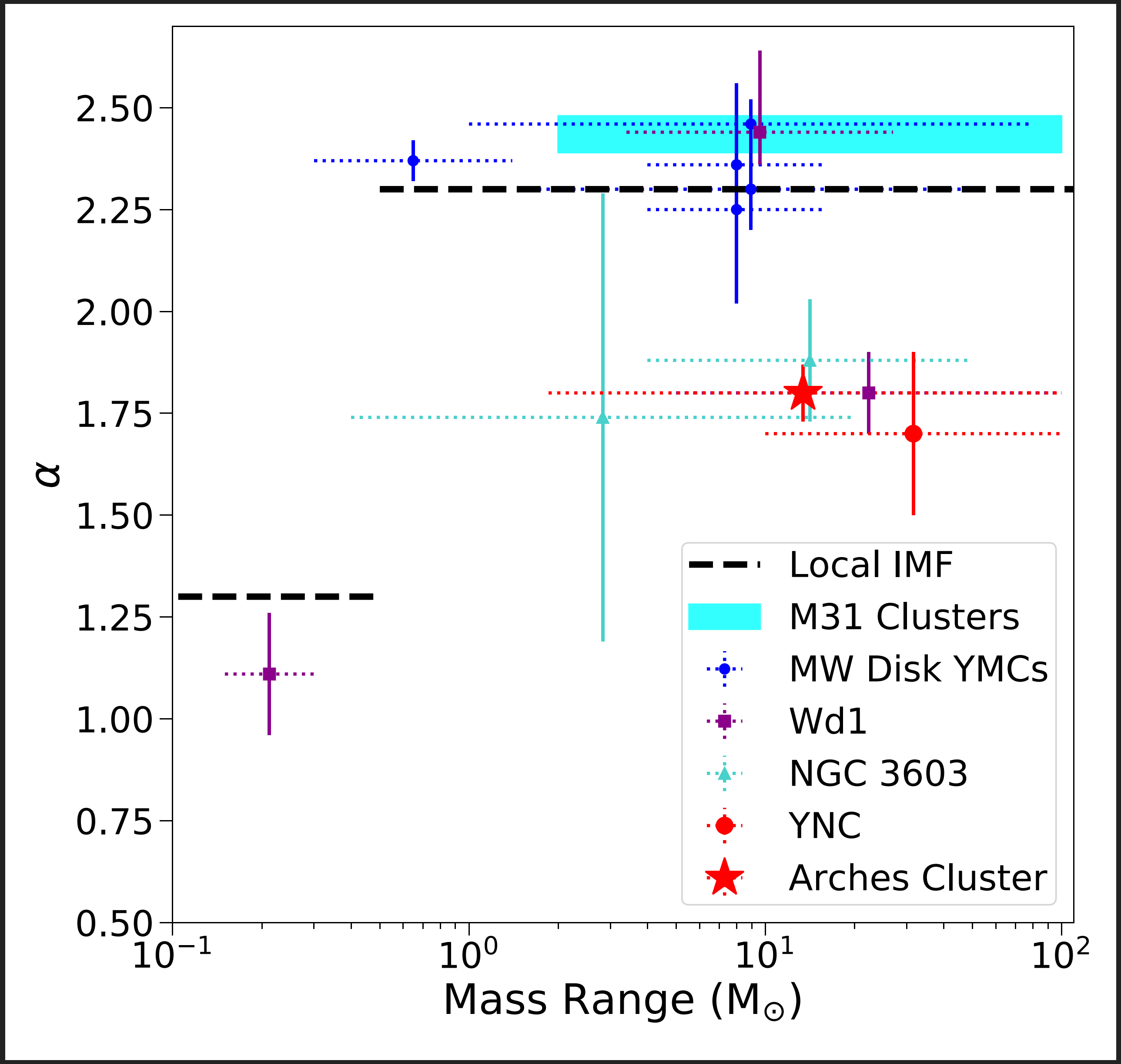
Left: Beuther+ 2005, Spitzer MIR + IRAM mm
Right: Tan+ 2014, Herschel MIR + ALMA mm



THE OBSERVED IMF

Bastian+ 2012



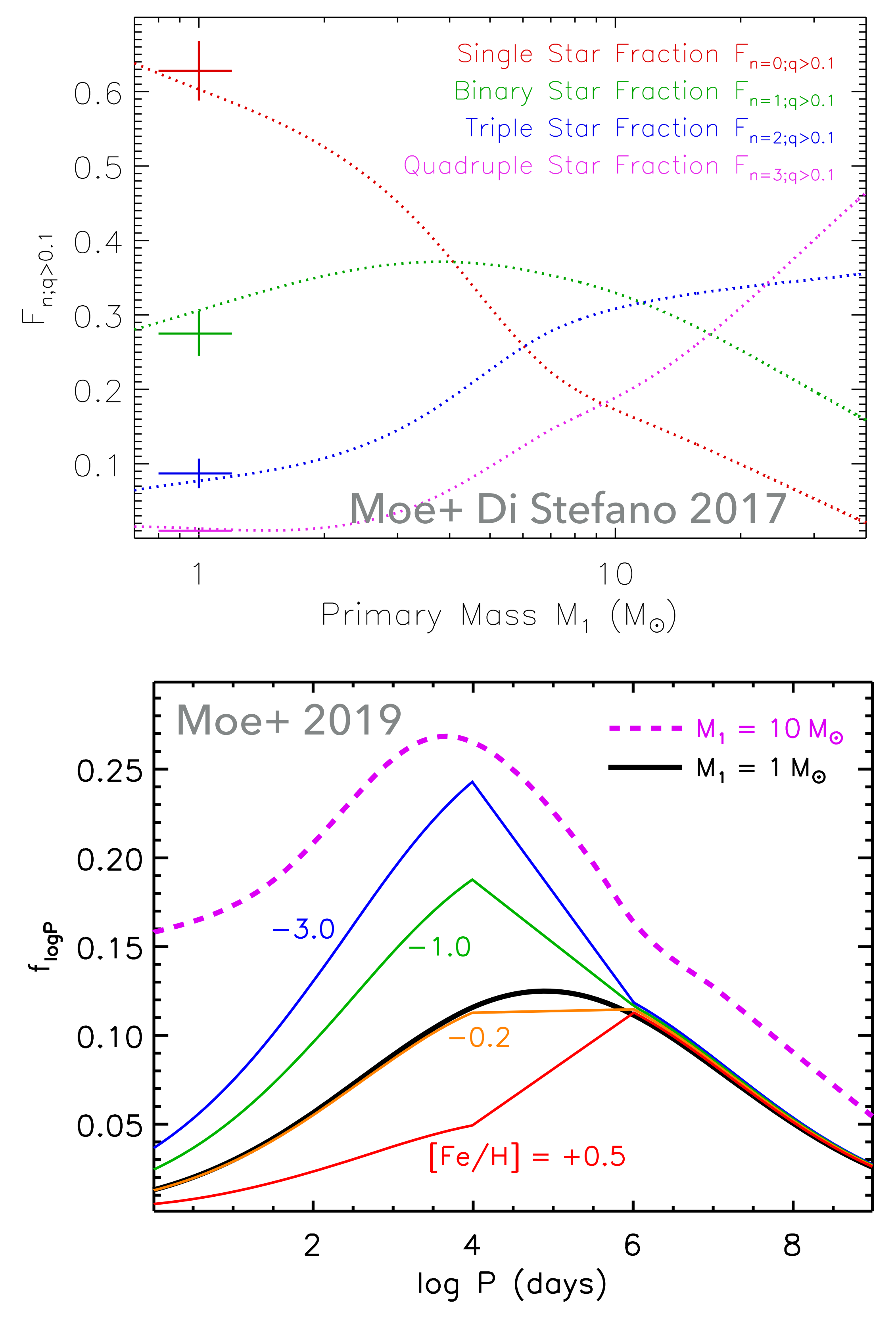


IMF VARIATIONS

Left: IMF in 30 Doradus, Schneider+ 2018
Right: IMF in MW center clusters, Hosek+ 2019

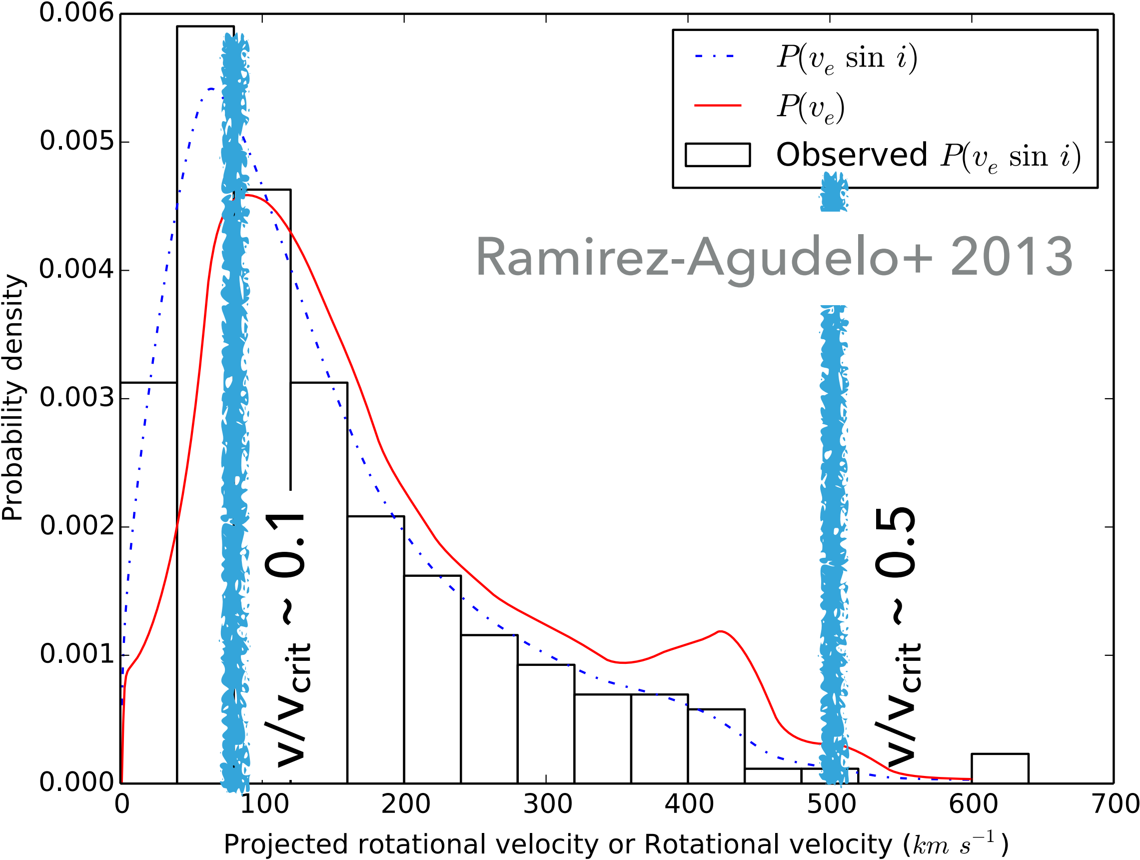
MASSIVE STAR MULTIPLICITY

- Essentially all massive stars form in multiple systems, many with multiple companions
- Compared to lower mass stars at Solar metallicity, significant excess of close companions
- Mass ratios mostly moderate at most separations, q ~ 0.3 - 0.5, with 10% excess of “twin” binaries (q > 0.95) at small separation

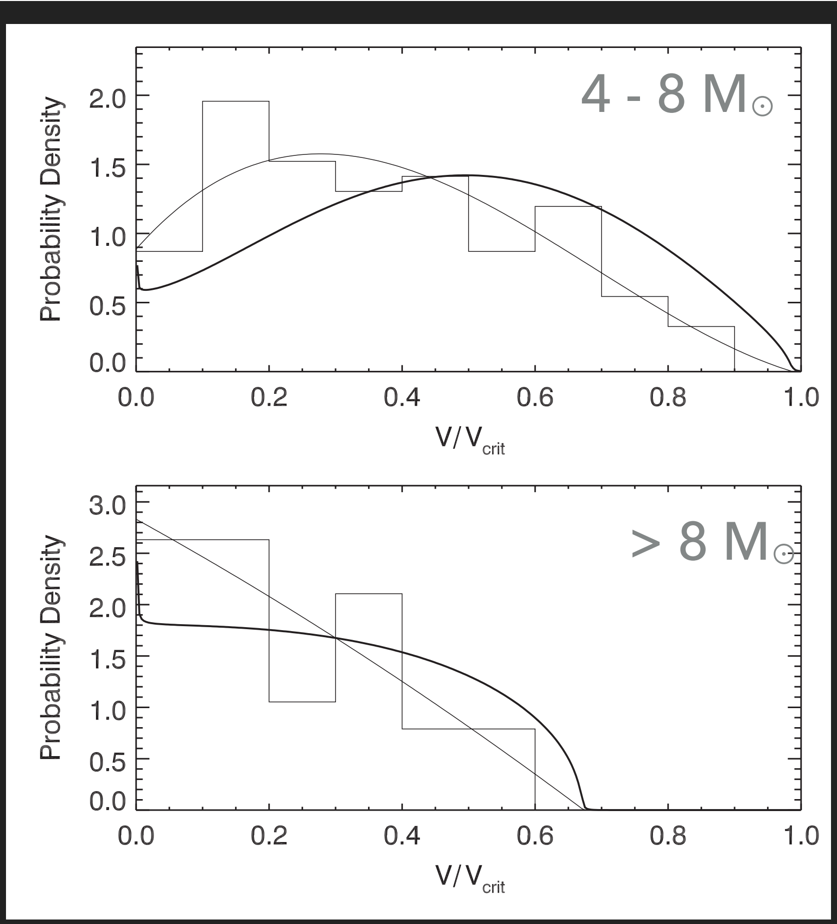


MASSIVE STAR ROTATION

- Observed massive stars mostly rotating at ~10-20% of breakup, but with tail to up ~50% of breakup
- Rotation speed at birth very likely higher, close to ~50% – stars spin down due to magnetised winds
- Evidence for wind spin-down: B stars with weak winds typically at ~50% of breakup



Ramirez-Agudelo+ 2013



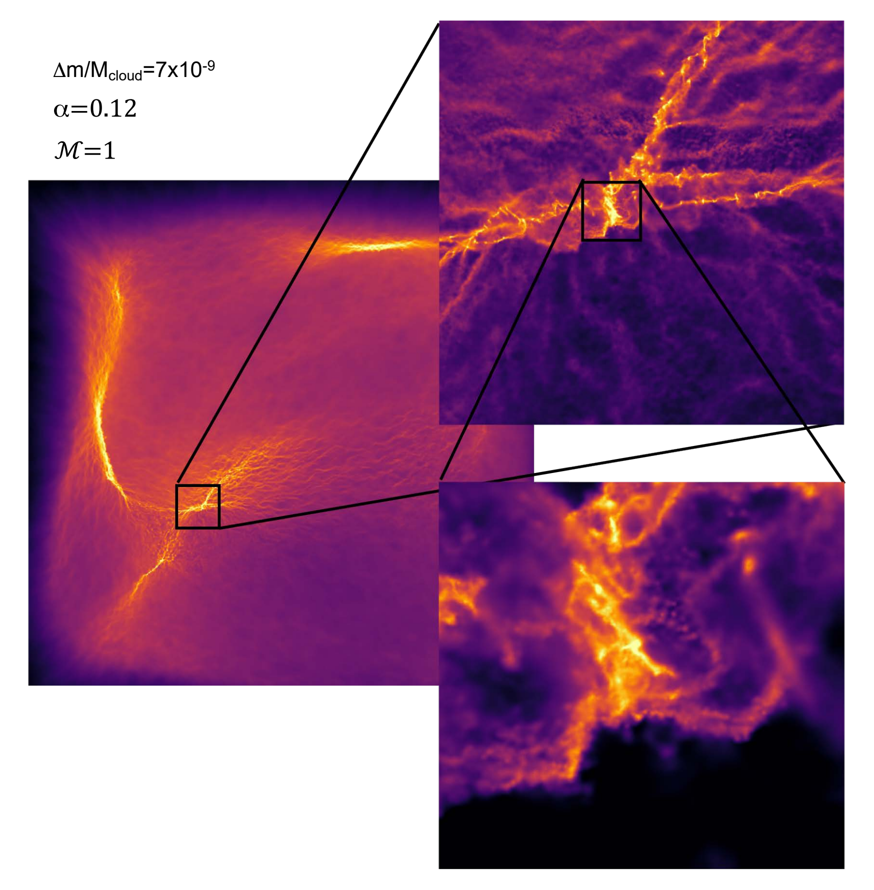
Huang+ 2010

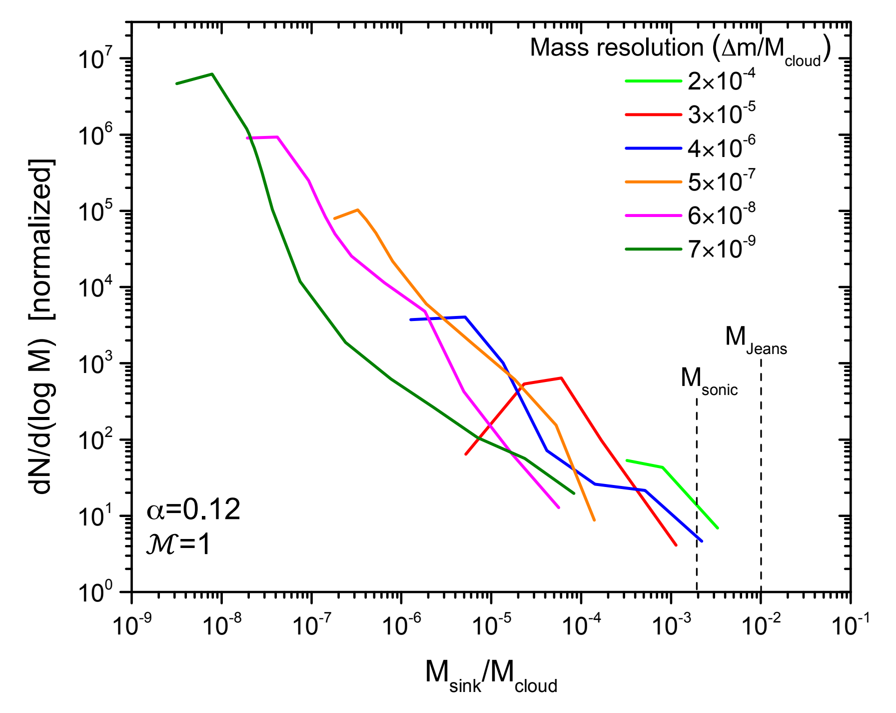
MASSIVE STAR FORMATION PHYSICS

For no reason whatsoever, here is a baby quokka

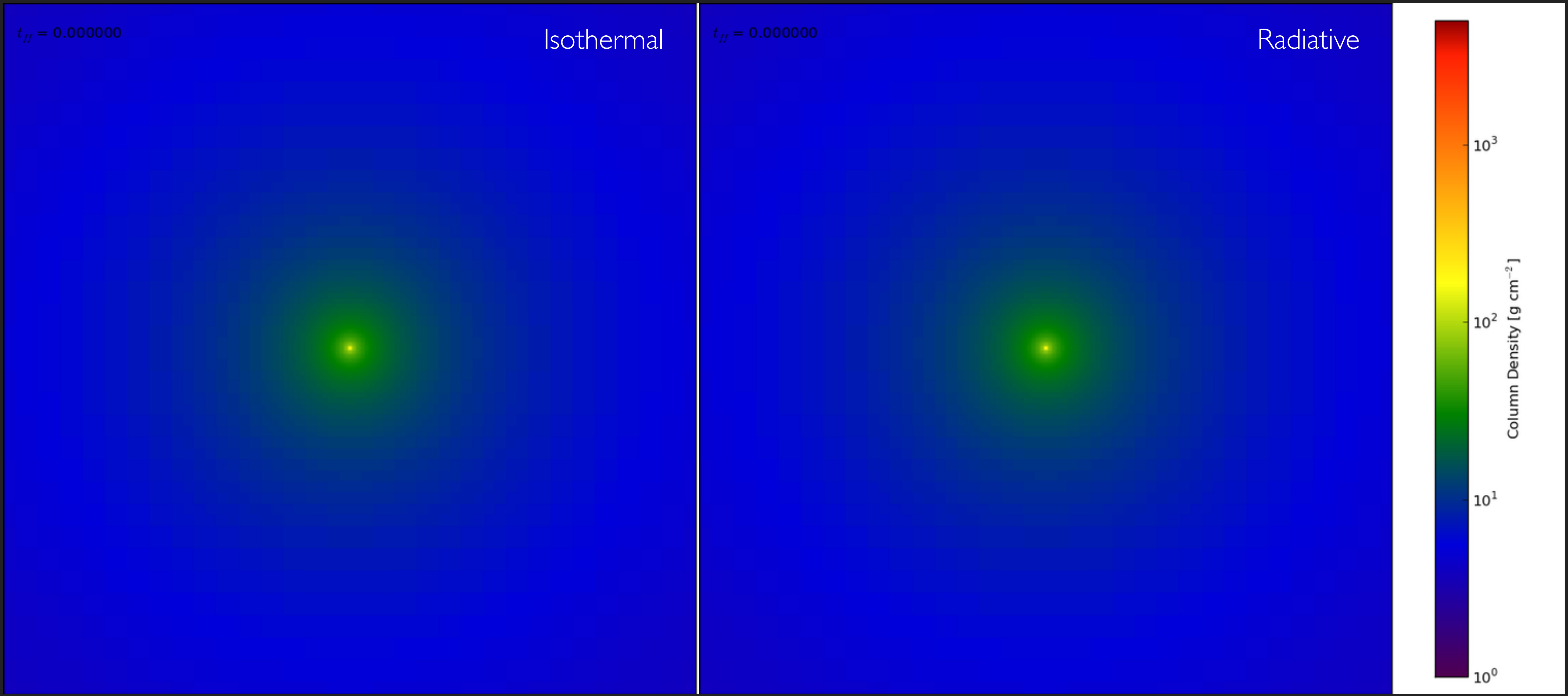
ISOTHERMAL FRAGMENTATION

- Jeans mass $M_J \sim \rho^{-1/2}$, so as collapse occurs, mass that is able to fragment goes to zero
- Numerical experiments show that this produces fragmentation to infinitely small scales
- To form a massive star, the fragmentation cascade must be halted
- Likely agent: radiative feedback





Guszejnov+ 2018



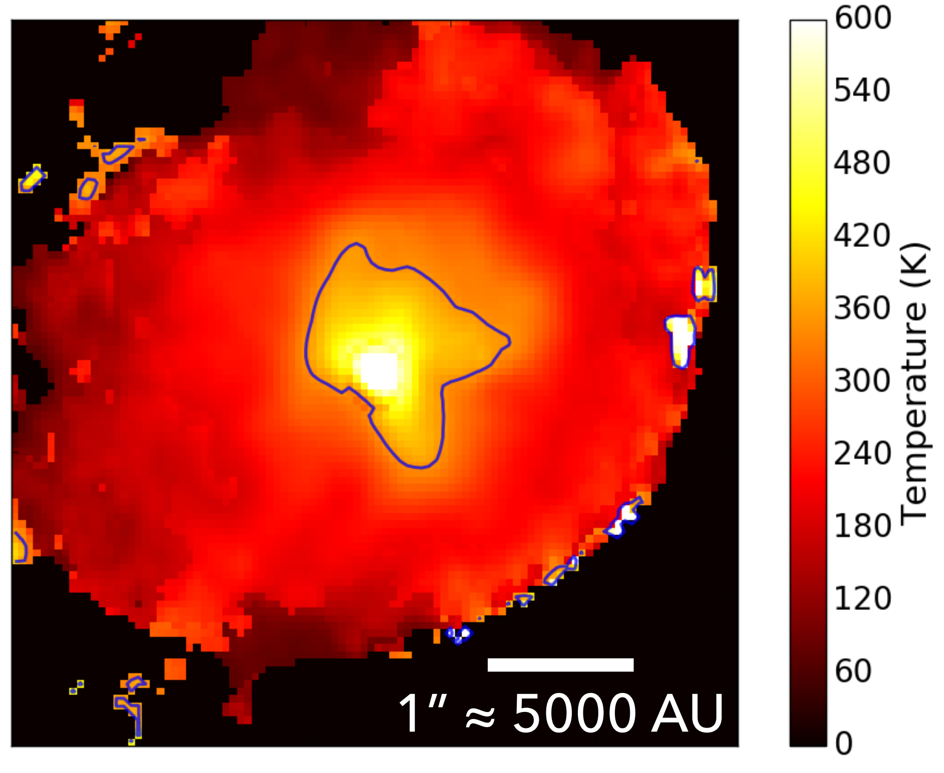
RMHD SIMULATIONS

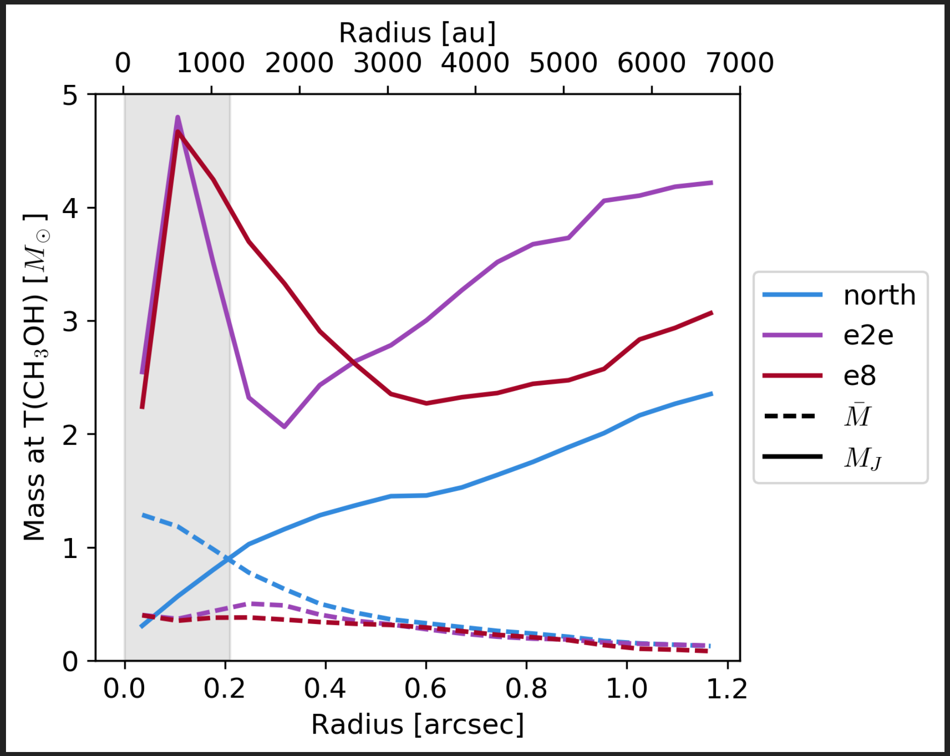
Myers+ 2013

200 $M_{\odot}$ centrally-condensed core

OBSERVATIONAL EVIDENCE

- Observations of temperature structure around massive protostars shows warm gas
- Observed heating sufficient to suppress fragmentation on >1000 AU scales
- Supports the idea that radiative feedback is key to allowing massive star formation





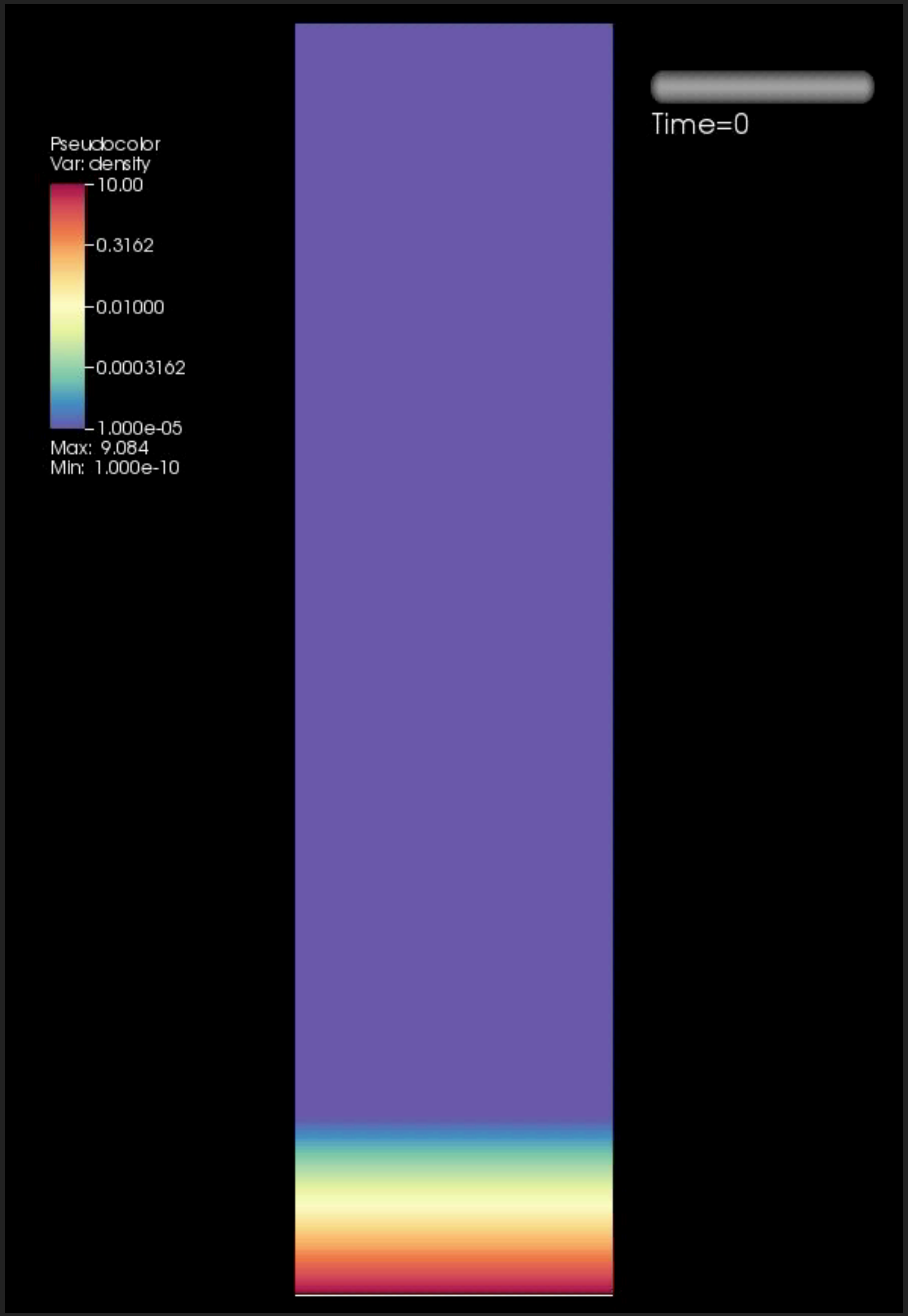
W51, Ginsburg+ 2017

LIMITING STELLAR MASSES: WINDS AND PHOTOIONIZATION

- Photoionization feedback mostly ineffective because dM/dt ~ 10^{-4} sufficient to keep ionized region trapped near star (Walmsley 1995, Keto+ 2002, 2003, 2007)
- Main sequence winds can only become important at masses above ~40 $M_\odot$ – otherwise star is bloated and has T_{eff} too low to drive wind
- Winds conceivably important after that, but only if they become trapped; otherwise too little momentum

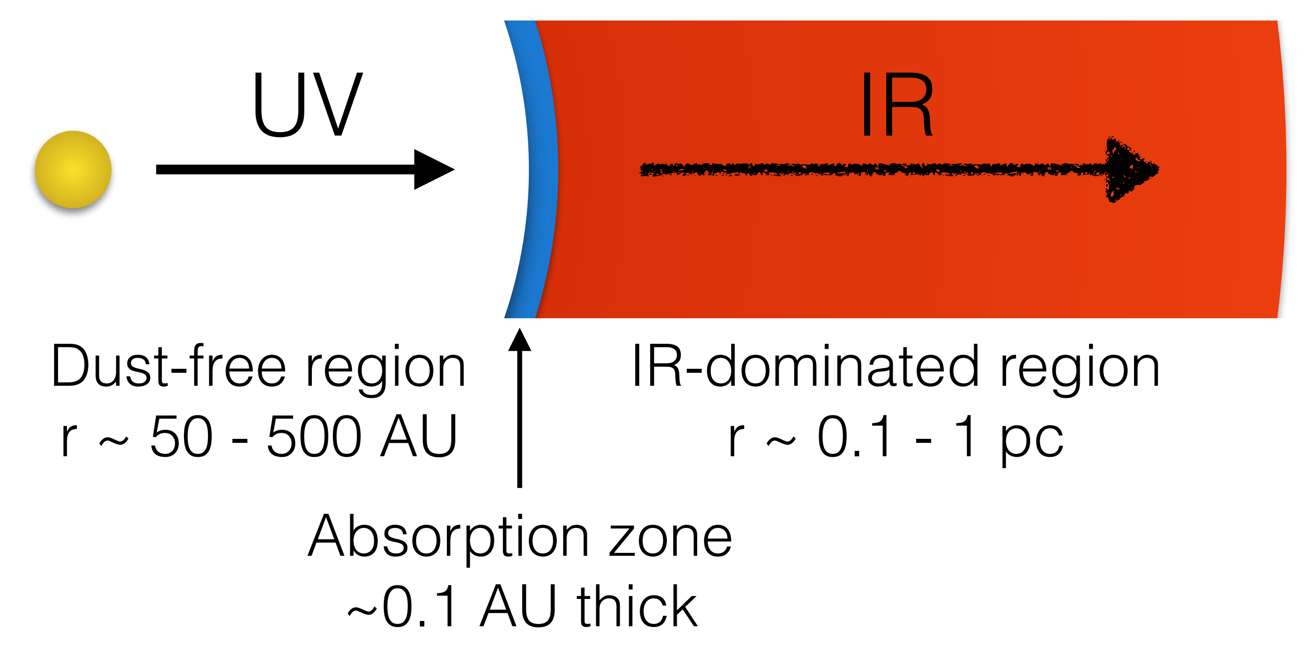
DIRECT RADIATION PRESSURE

- Radiation force > gravitational force on any gas column with $\Sigma < \Sigma_{\rm crit} = (L/M) / 4\pi G c \sim 300\ M_\odot\ {\rm pc}^{-2}$ (Fall, Krumholz, & Matzner 2010)
- In a turbulent medium with a PDF of Σ's, low Σ regions unstable to ejection even if mean $\Sigma > \Sigma_{\rm crit}$ (Thompson & Krumholz 2016)
- However, most massive stars have $L/M \approx 10^4\ L_\odot/M_\odot \rightarrow \Sigma_{\rm crit} \approx 0.8$ g cm^{-2}; direct radiation pressure cannot set a mass limit in cores of higher Σ

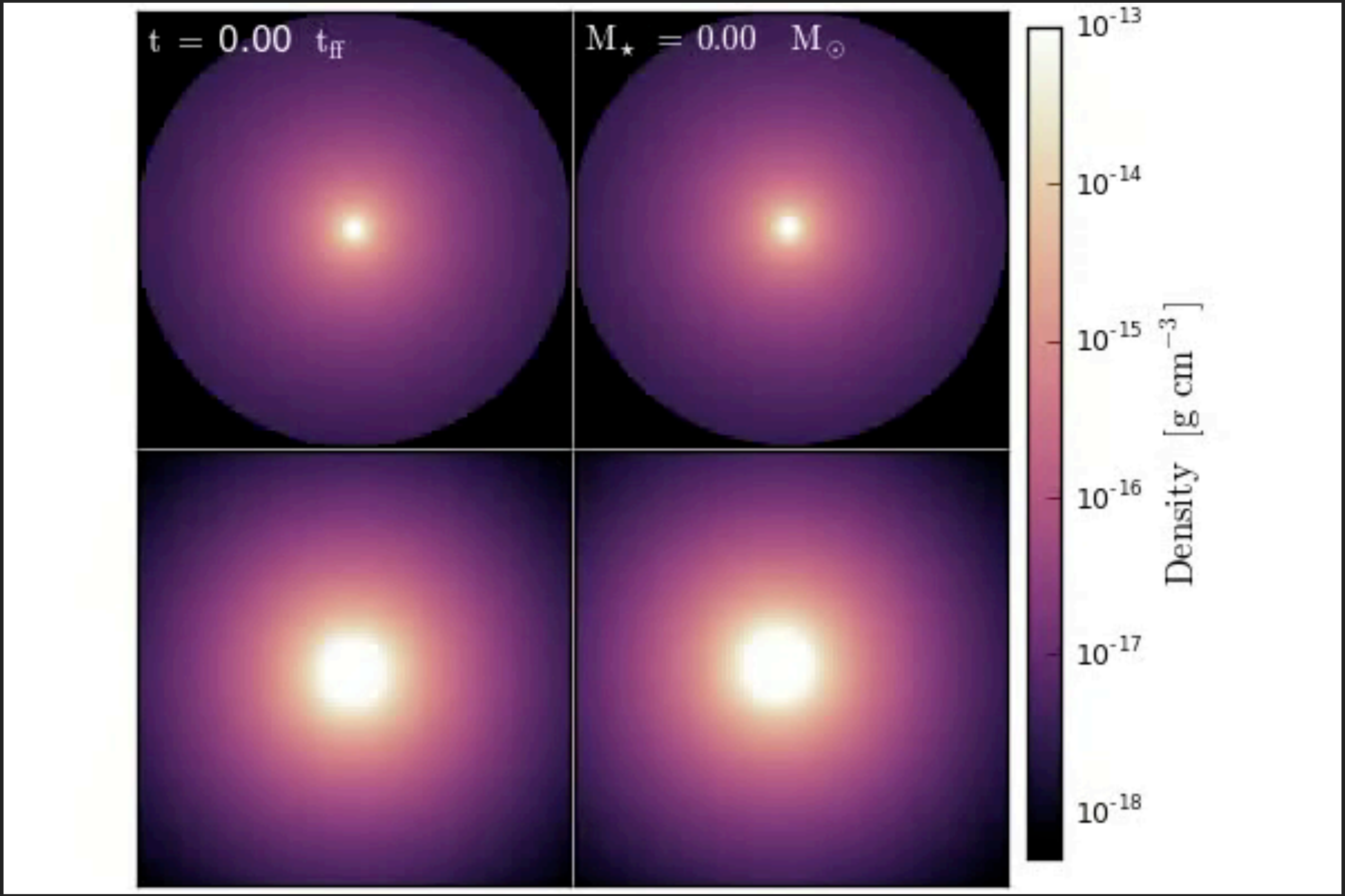


Wibking, Thompson & Krumholz 2018

INDIRECT RADIATION PRESSURE

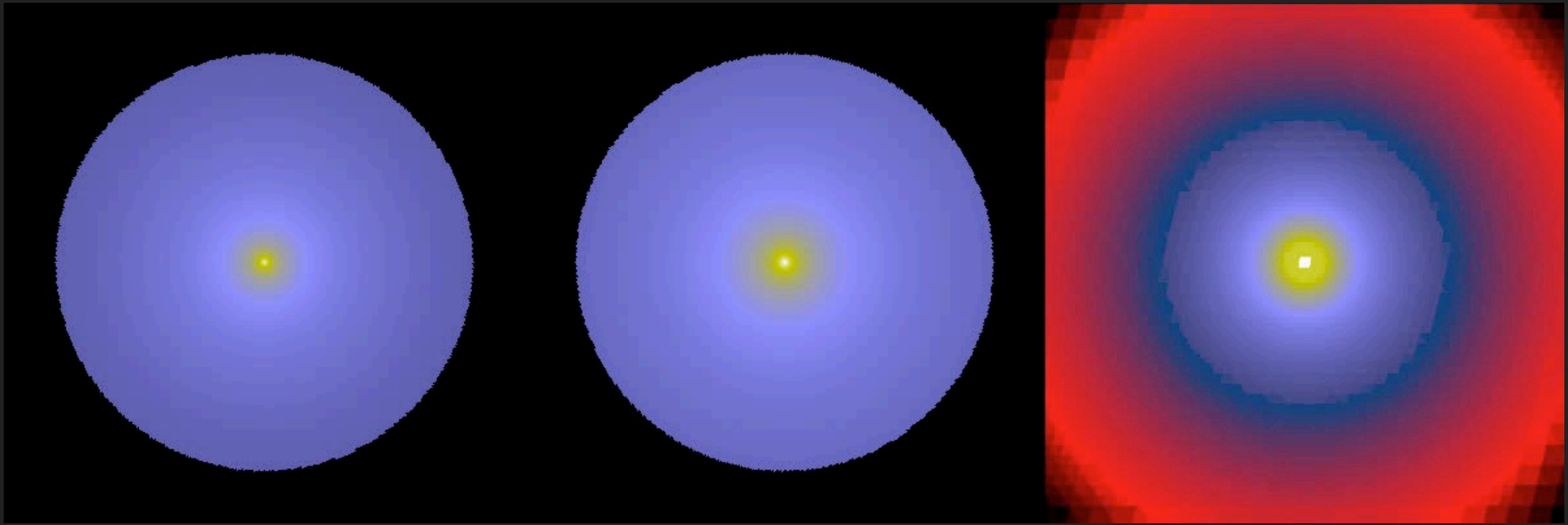


- Near massive star, radiation creates a dust-free zone with low opacity
- Radiation free-streams to dust destruction front, is reprocessed into IR
- In IR-dominated region, Eddington ratio is for isotropic radiation flux is $f_{Edd} = \kappa_{IR} L / 4\pi GMc \approx 8 (\kappa_{IR}/10 \text{ cm}^2 \text{ g}^{-1})$
- Thus accretion is possible only if some mechanism makes the radiation flux anisotropic



BEATING RP: THE RRT INSTABILITY

Rosen+ 2016, 2017

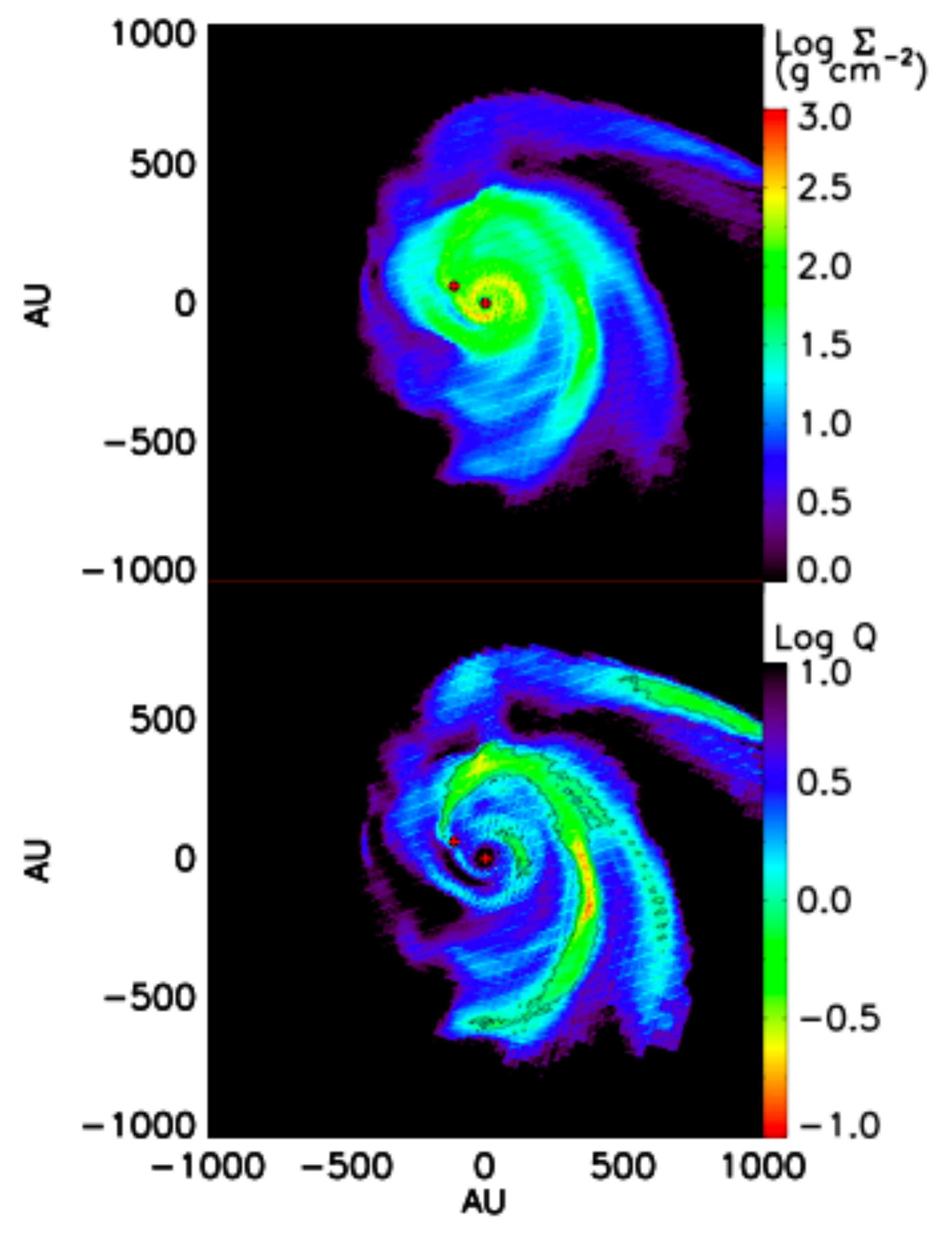


BEATING RP: OUTFLOWS

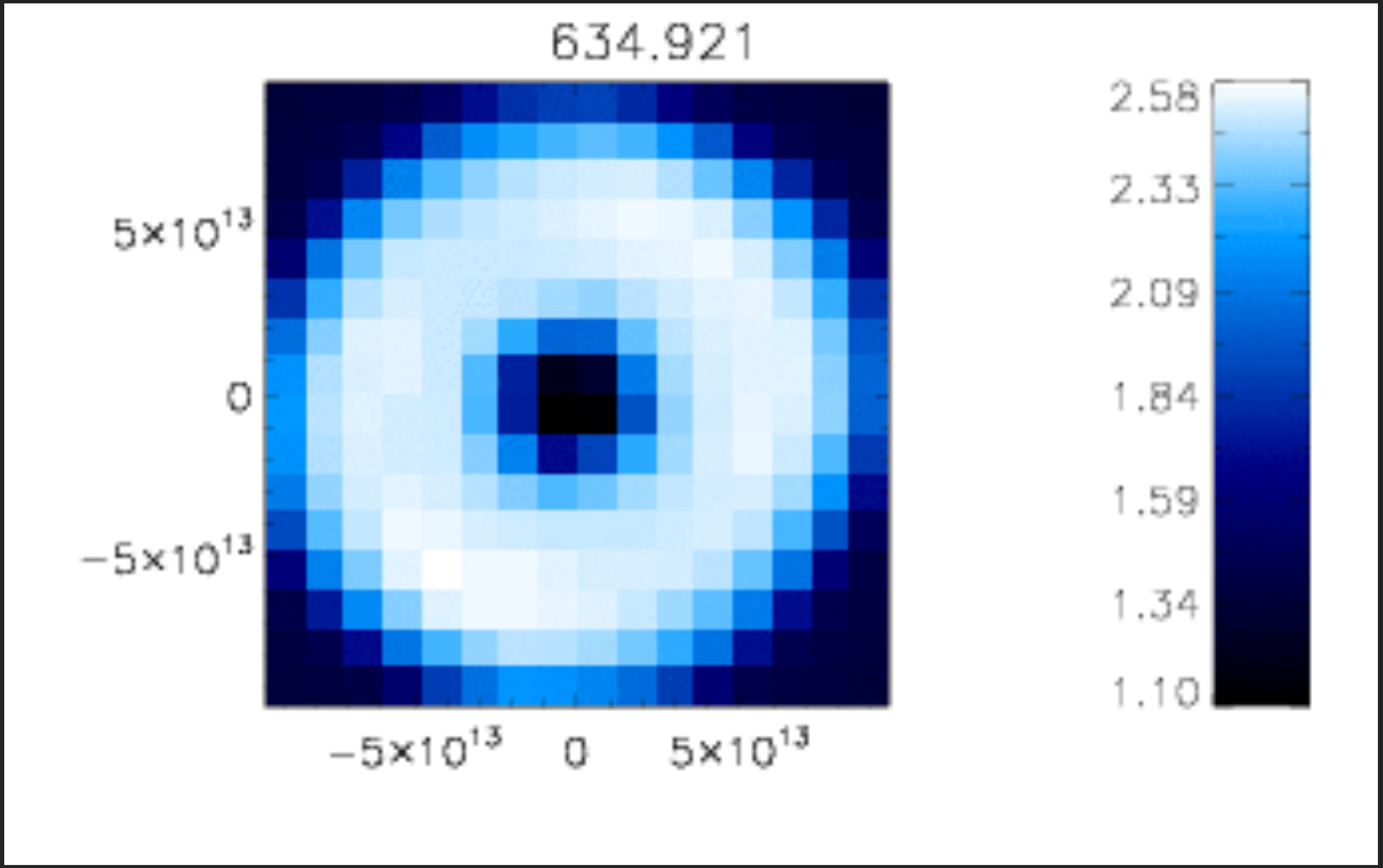
Cunningham+ 2011

MASSIVE STAR DISKS

- Accretion rate onto disk $\dot{M} \sim \sigma^3 / G \sim \text{few} \times 10^{-4}\, M_\odot\, \text{yr}^{-1}$
- Disk accretion rate $\dot{M} = 3\alpha c_s^3 / GQ = 1.5 \times 10^{-4}\, T_2^{3/2}\, (\alpha/Q)\, M_\odot\, \text{yr}^{-1}$
- Implication: disk can only deposit material on star as quickly as it accretes if $\alpha \approx 1$ AND $Q \approx 1$
- Disk likely to be gravitationally unstable (Kratter & Matzner 2006; Kratter+ 2008, 2010)



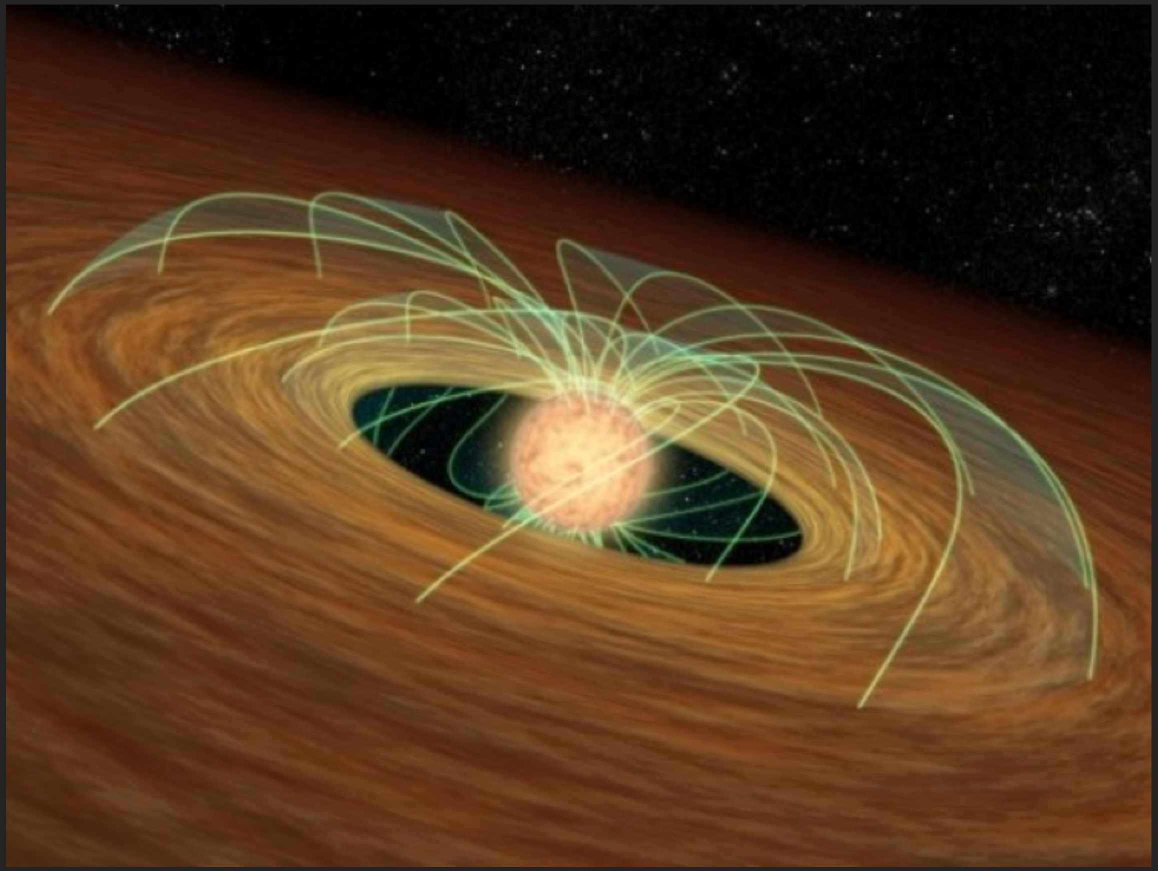
Krumholz+ 2007



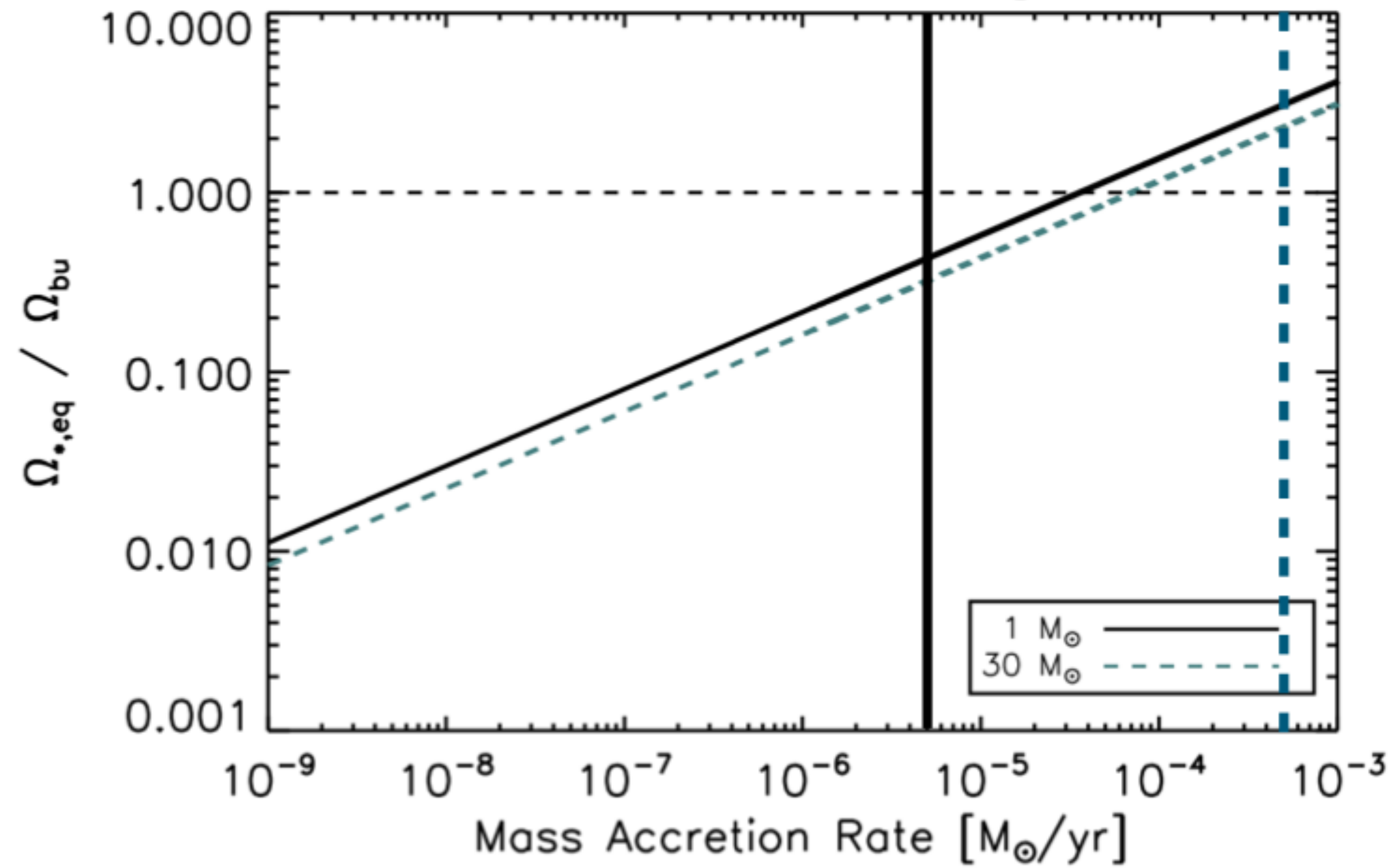
DISK FRAGMENTATION

Kratter+ 2010

MAGNETIC BRAKING BY DISKS

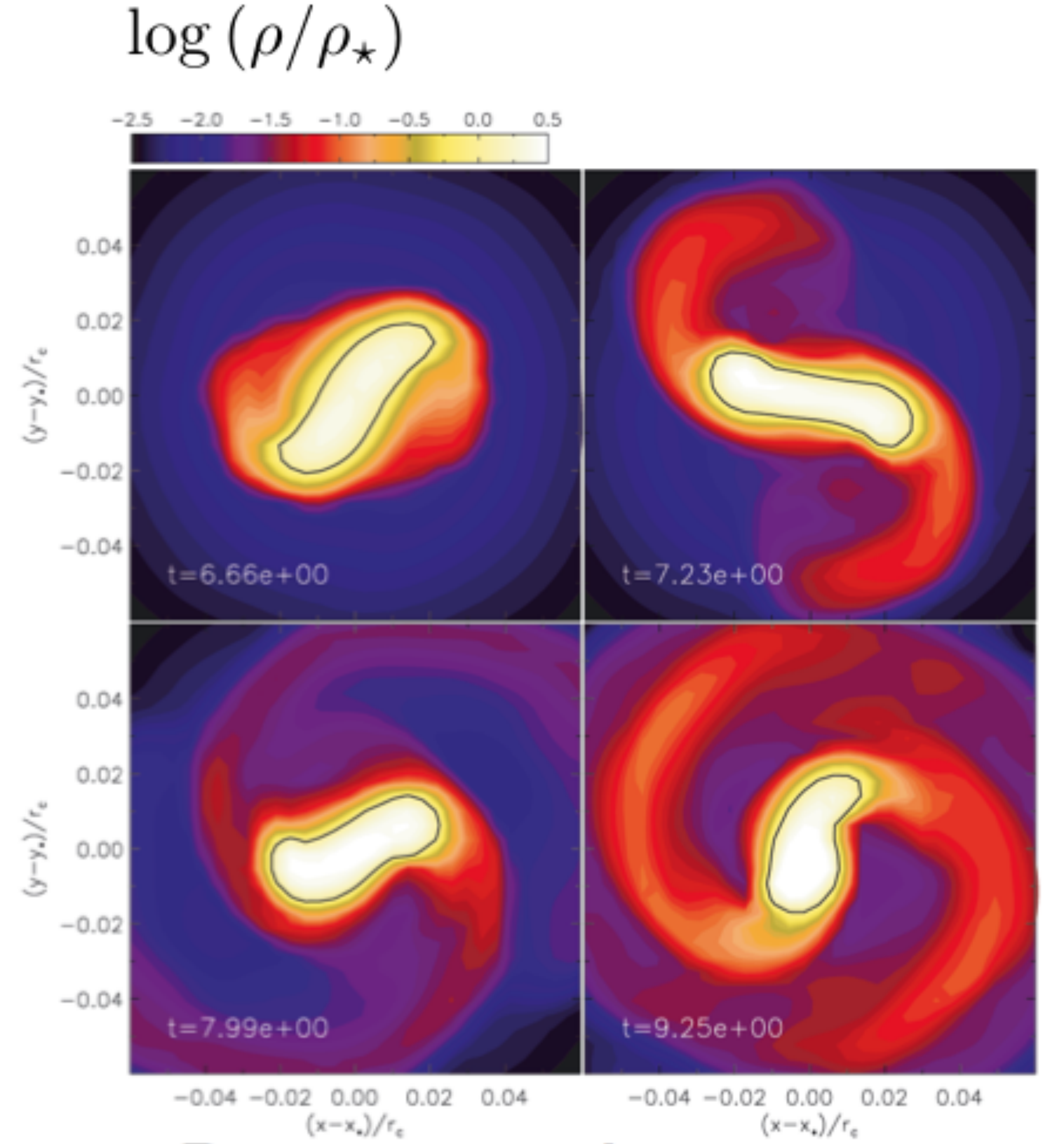


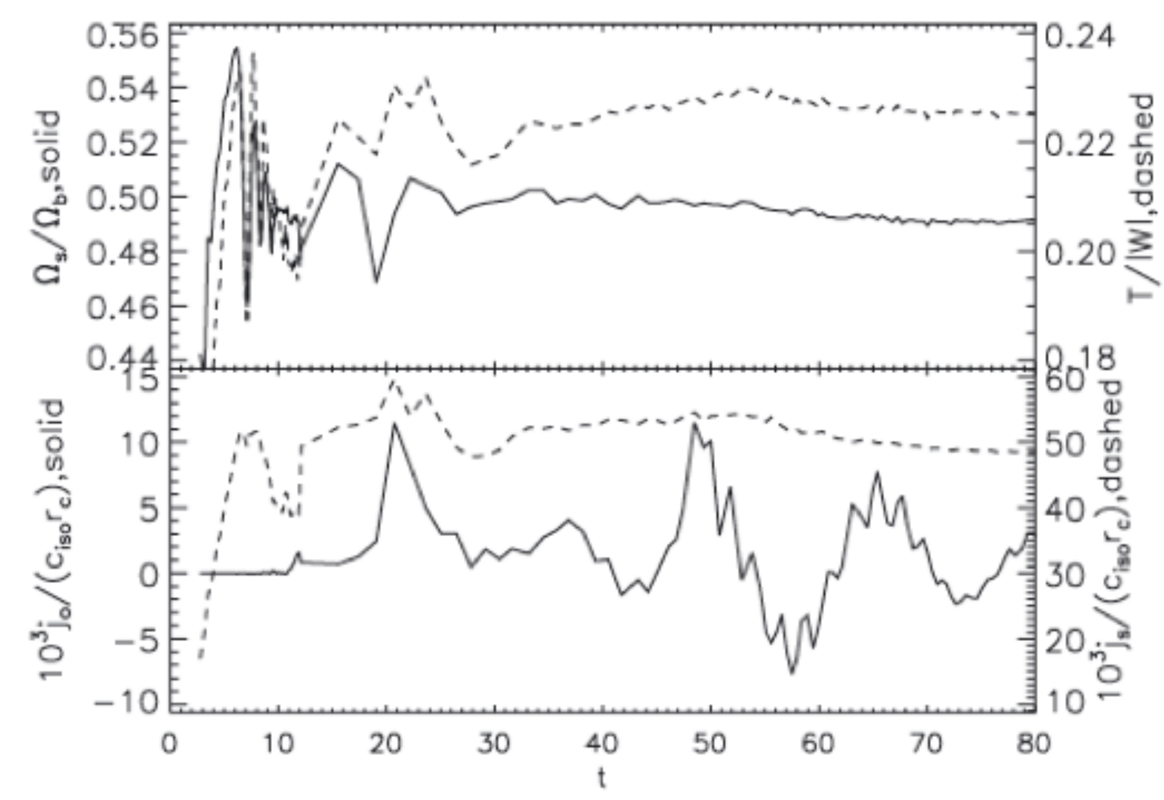
- Bipolar stellar B field:
  $B_z = B_* (r/R_*)^{-3}$
- Magnetic truncation of disk:
  $B^2 / 8\pi = \rho v^2$
  - Combining the above: $R_A/R_* \sim (B_*^4 R_*^5 / \dot{M}^2 M_*)^{1/7}$
- Accretion torque $\tau_A = \dot{M} (G M_* R_A)^{1/2}$
- Magnetic torque $\tau_M = (1/3)\, B_*^2 R_*^6 \,[R_A^{-3} - 2(R_{CO} R_A)^{-3/2}]$



MAGNETIC BRAKING FAILS

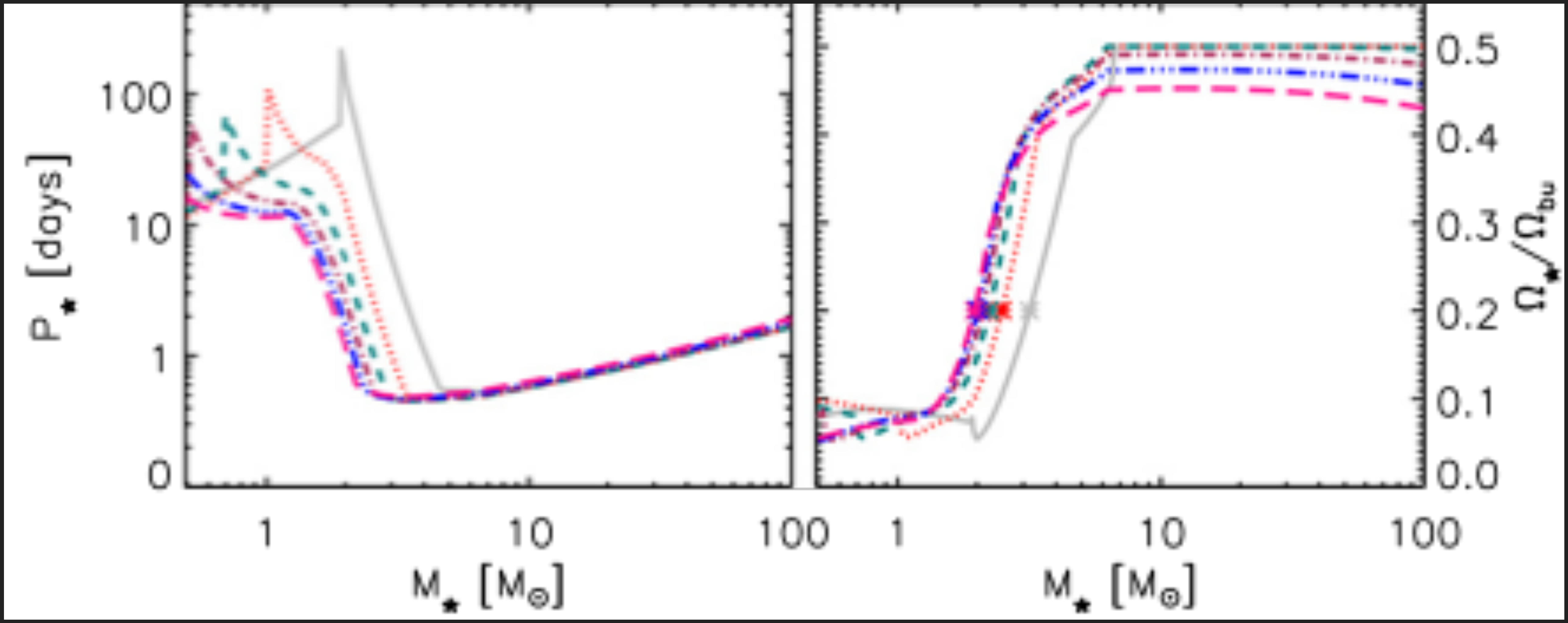
Rosen+ 2012





GRAVITATIONAL BRAKING

Lin+ 2011



MAGNETIC + GRAVITATIONAL BRAKING

Rosen+ 2012

VARIATION WITH ENVIRONMENT

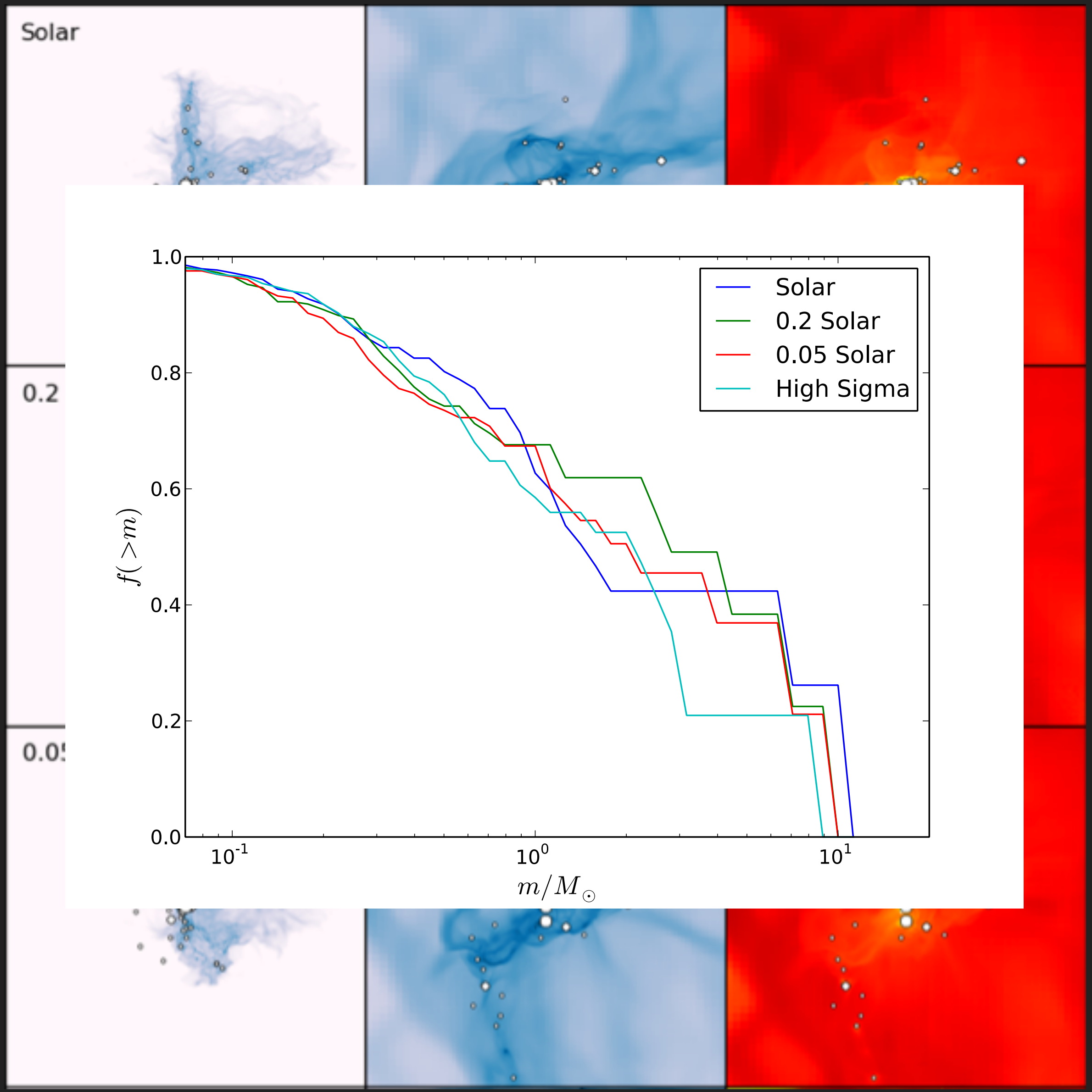
For no reason whatsoever, here are baby platypuses

POSSIBLE SOURCES OF IMF VARIATION

- IMF affected by two main factors:
    - Upper mass limit shaped by radiation pressure
    - Slope of upper IMF affected by fragmentation
- Radiation pressure problem appears to be overcome by RRT instability and outflows – seems unlikely that this depends on environment
- Fragmentation more likely to vary, since this depends on how effectively radiation is able to heat the gas

DEPENDENCE ON Σ AND Z

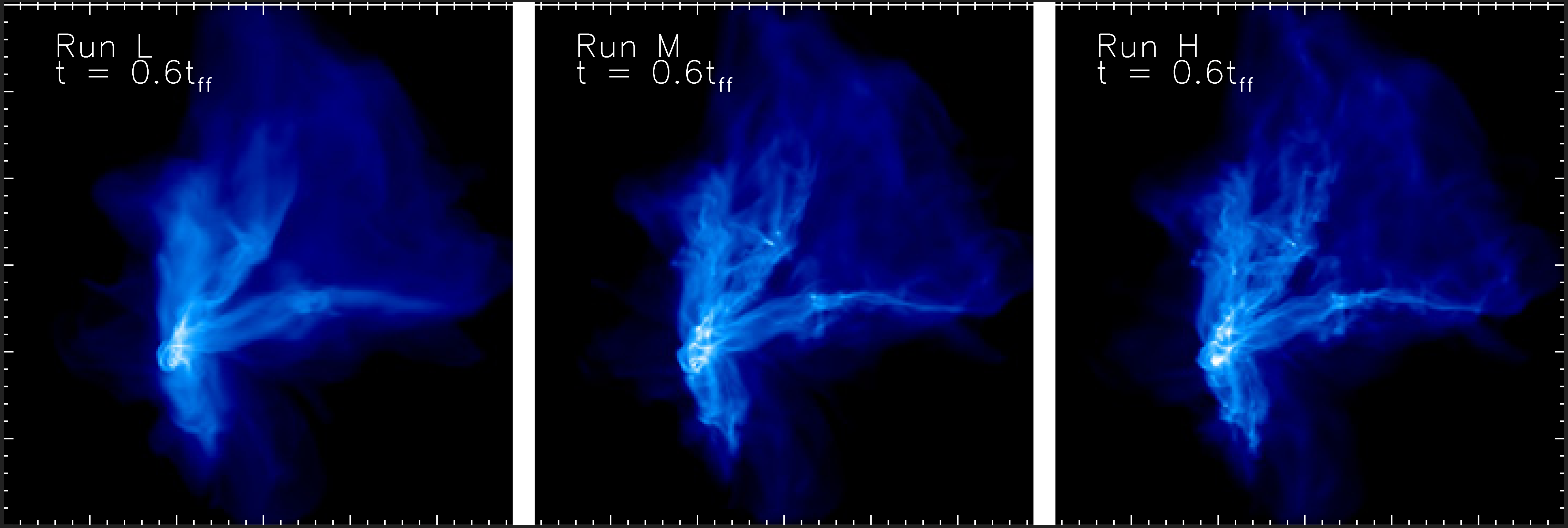
- Radiation coupled to gas by dust, so metallicity might matter
- Turns out it doesn't, because at $\Sigma \sim 1$ g cm^{-2}, even opacity 1% of Milky Way is sufficient to render gas optically thick to stellar photons
- However, Σ needs to be high enough to trap the radiation
    - For no B fields, "high enough" is $\Sigma \sim 1$ g cm^{-2} (Krumholz & McKee 2008)
    - Value with B fields unknown

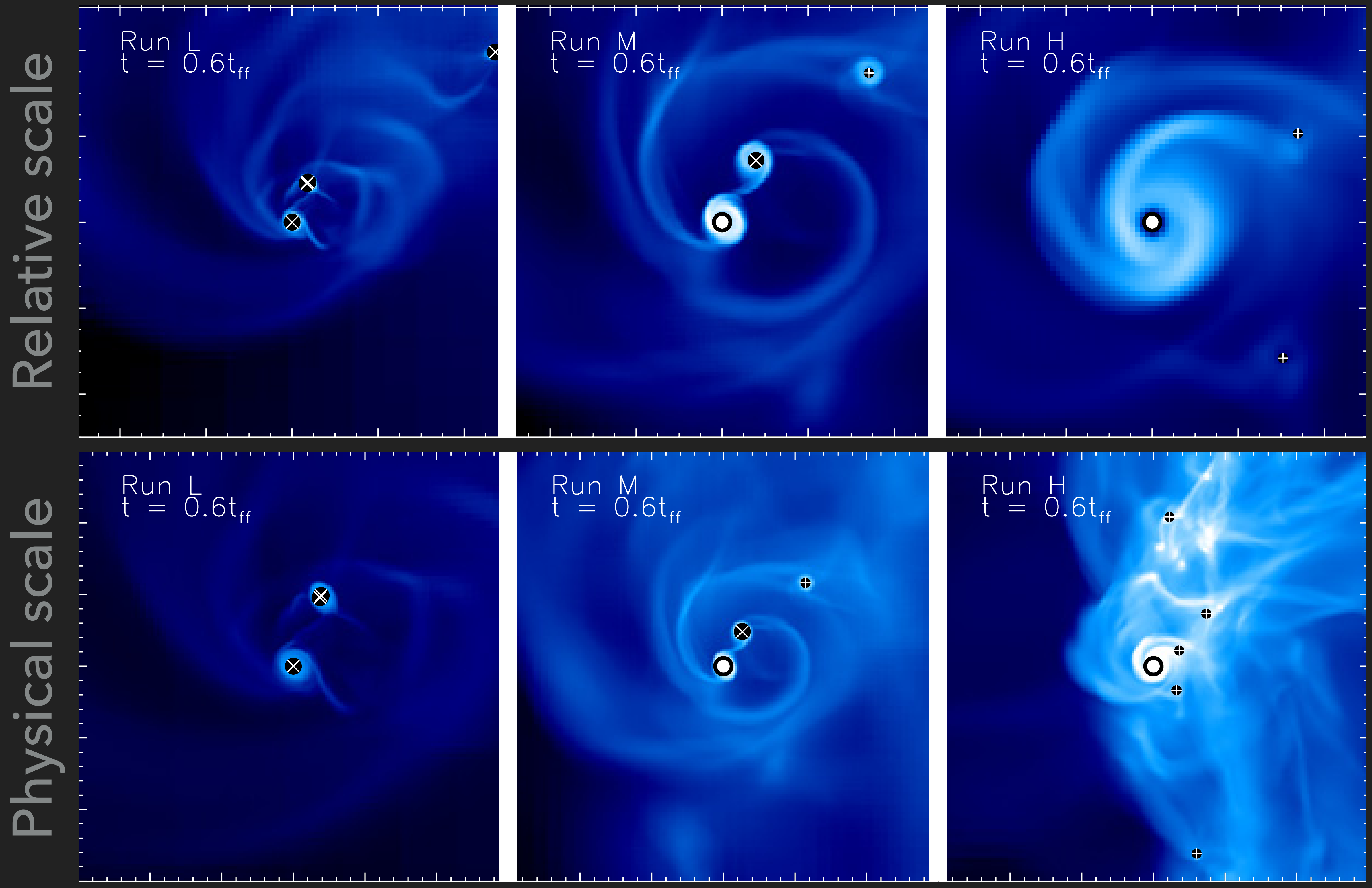


Myers+ 2011

NUMERICAL EXPERIMENTS: VARIATION WITH Σ

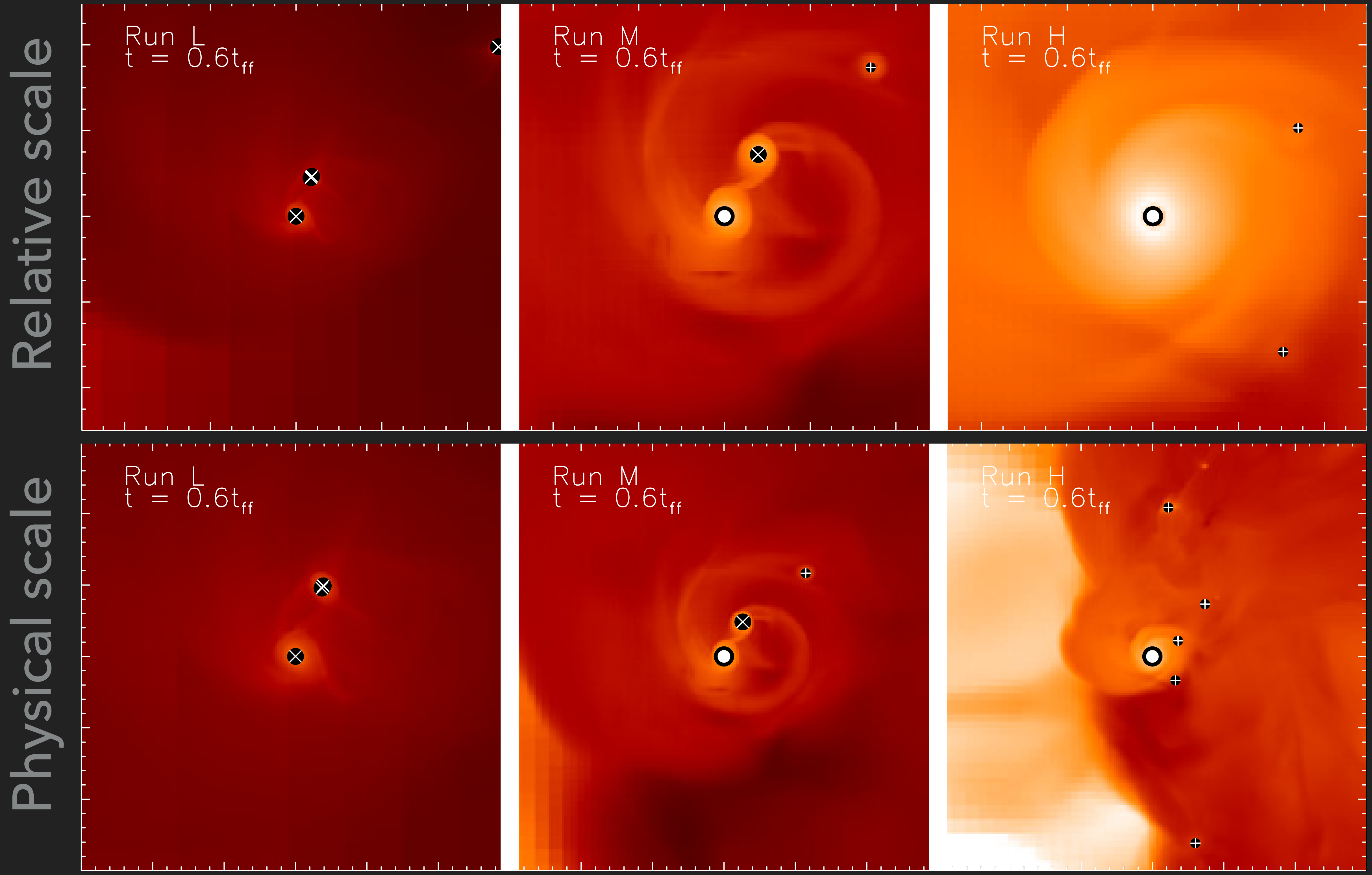
- Three simulations with identical mass, virial ratio, resolution, velocity field shape, but different column density (Krumholz+ 2010)





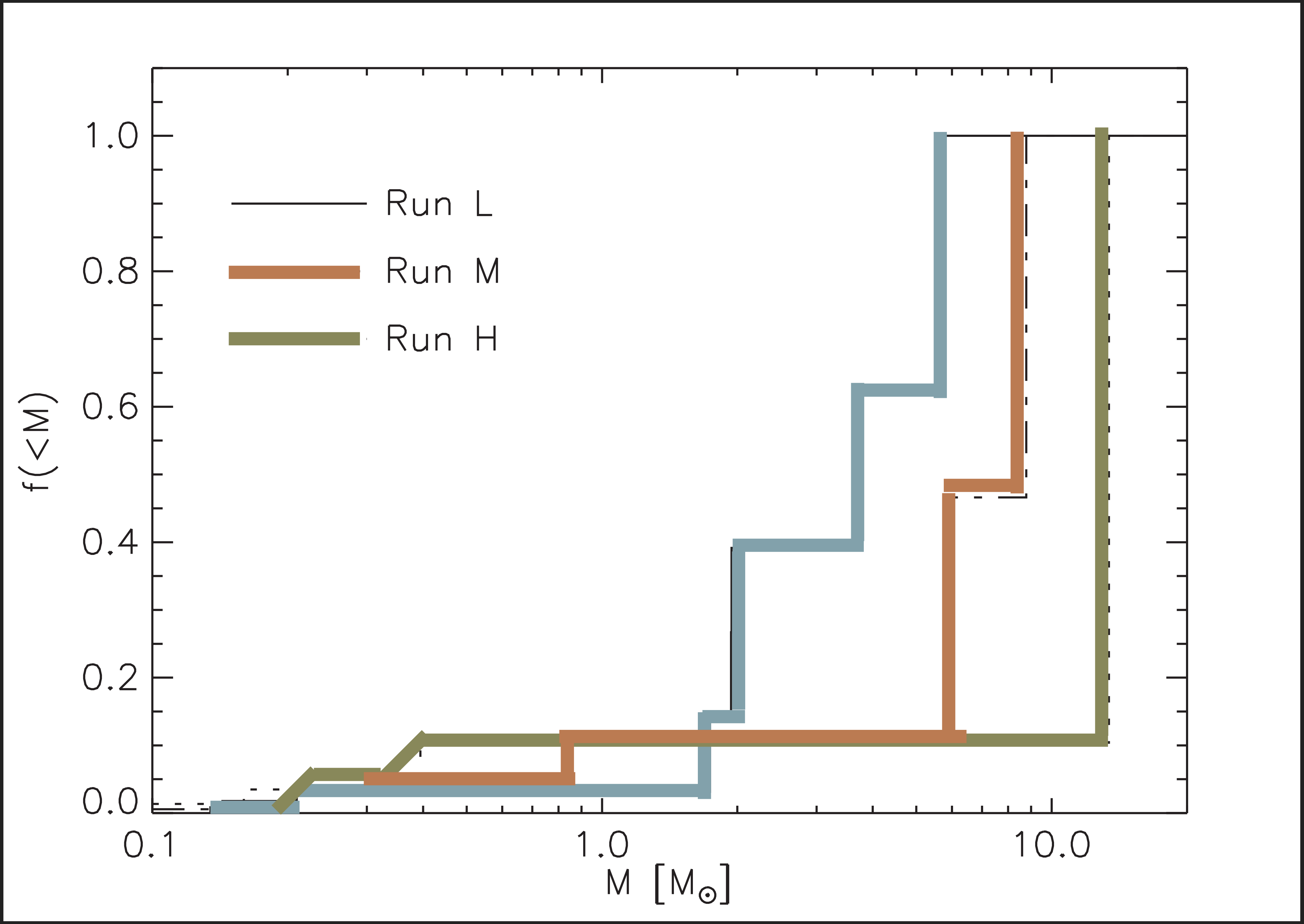
NUMERICAL EXPERIMENTS WITH Σ

Krumholz+ 2010



NUMERICAL EXPERIMENTS WITH Σ

Krumholz+ 2010

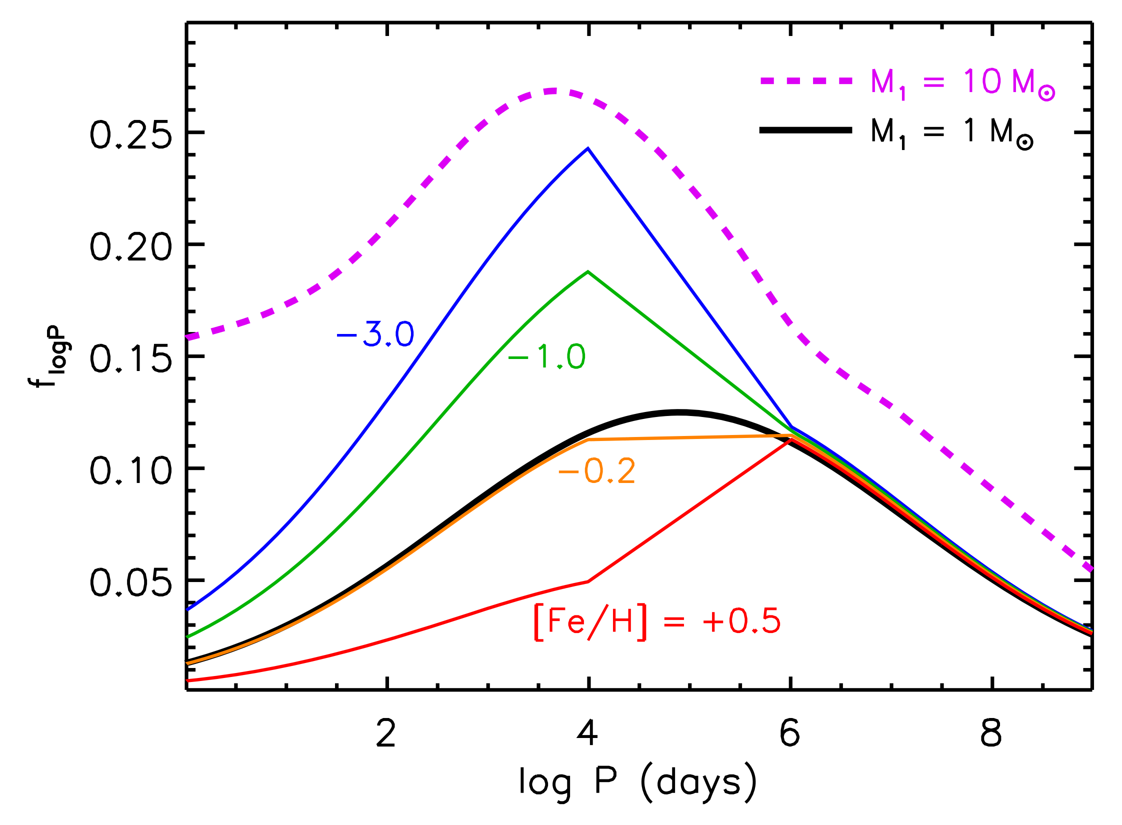


NUMERICAL EXPERIMENTS WITH Σ

Krumholz+ 2010

MULTIPLICITY VARIATION

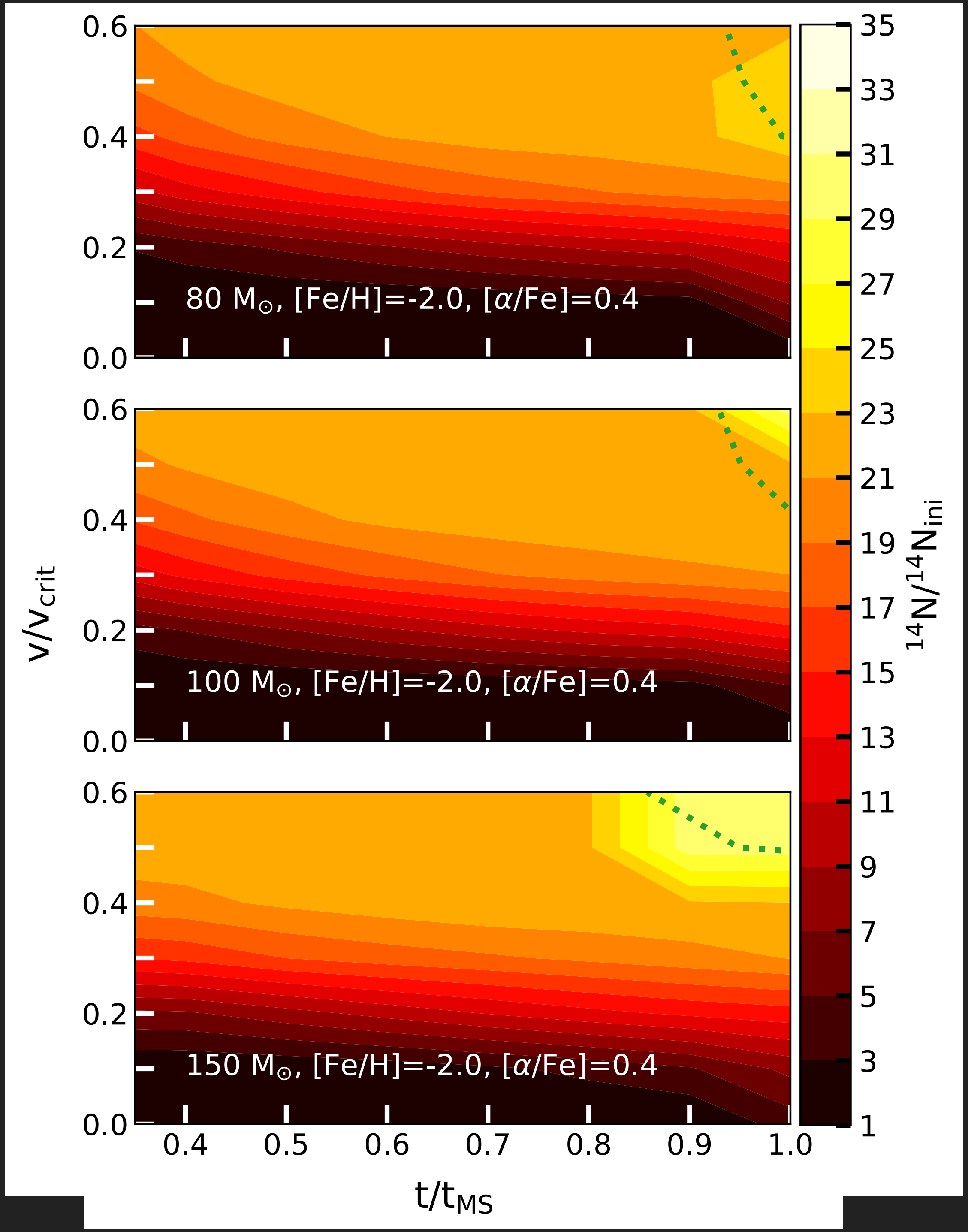
- Metallicity affects disk ability to absorb starlight and cool; big effect for solar-type stars
- For massive stars with high accretion rate, disk fragmentation unavailable even at $Z = Z_\odot$, so probably no big change with Z
- Changing Σ may affect accretion rate and thus fragmentation, but there have been no studies to date



Moe+ 2019

VARIATION IN ROTATION

- Gravitational torques independent of environment, so birth rotation distribution probably constant
- Post-birth spin down via winds depends on wind strength and therefore on metallicity
- Main effect: longer rapid rotation for low Z stars
- Probably affects WNL star frequency, maybe other things



Roy+ 2019

IMPLICATIONS AND QUESTIONS

For no reason whatsoever, here is a baby sugar glider

WHAT WE UNDERSTAND (MAYBE)

- Formation of massive stars controlled mostly by fragmentation; feedback probably ineffective
  - Fragmentation does not depend on Z, but does depend Σ – possibly less fragmentation at high Σ
- All massive stars are multiples due to disk fragmentation; no obvious reason this should vary with environment
- Massive stars born rotating fast in all environments, but spin-down weaker at lower metallicity

WHAT WE DEFINITELY DON'T UNDERSTAND

- How do any potential variations in demographics at birth interact with subsequent evolution (particularly in binaries) to affect rate of compact object production?
- How does variation with microscopic environment (for example local surface density) change the demographics averaged over galactic or cosmological scales? For example, do we have more high-Σ environments, and thus more massive stars, at higher redshift?