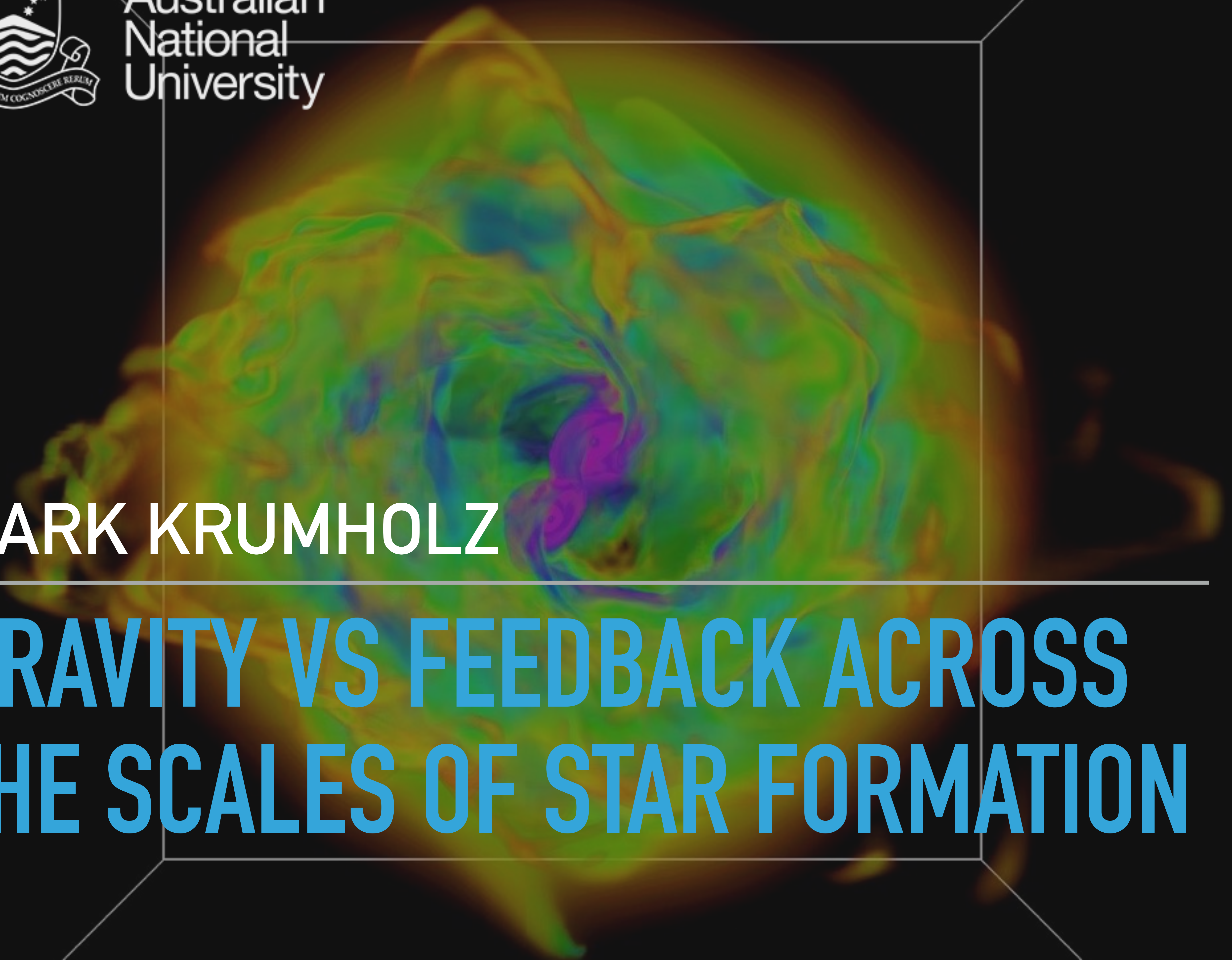
Australian National University



MARK KRUMHOLZ

GRAVITY VS FEEDBACK ACROSS THE SCALES OF STAR FORMATION

OUTLINE

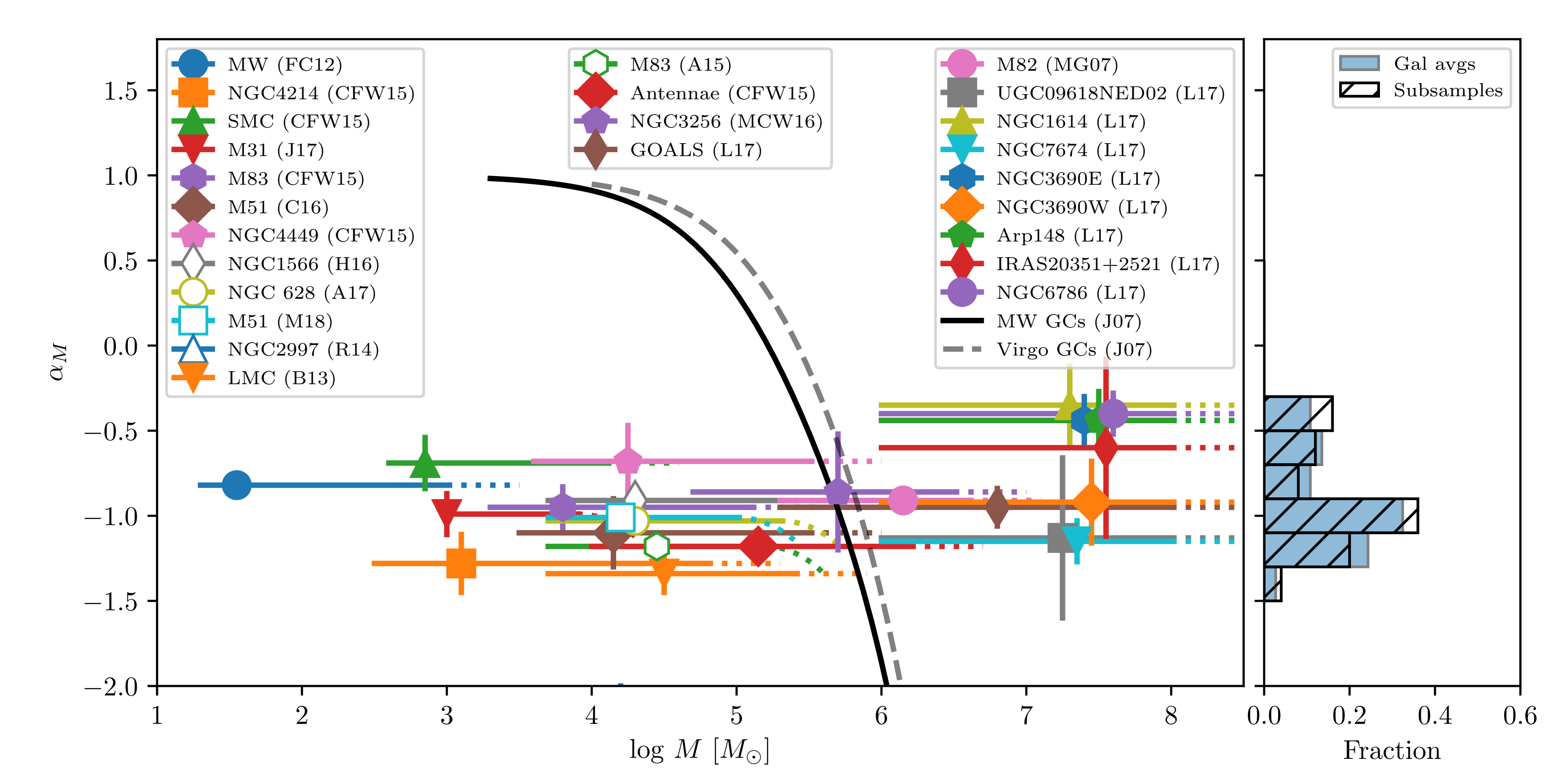
- Massive star clusters
  - Demographic considerations
  - Feedback and regulation of star formation
- Individual massive stars
  - Linking the cluster and stellar scales
  - Fragmentation
  - The upper mass limit

MASSIVE STAR CLUSTERS: DEMOGRAPHICS

For no reason whatsoever, here is a baby wombat

THE STAR CLUSTER MASS FUNCTION

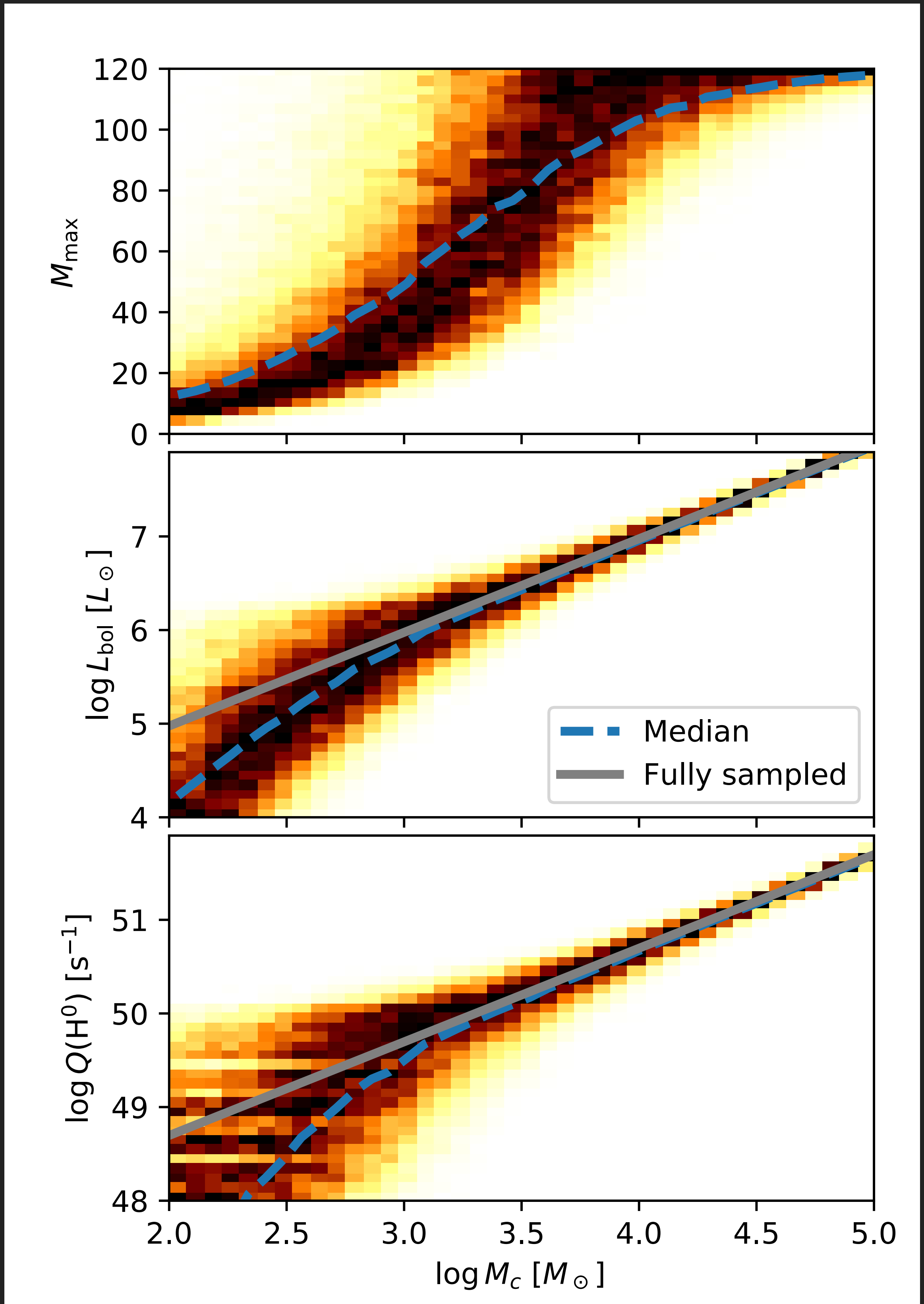
- Cluster mass function is dN / dlogM ~ M^{α} with $\alpha \approx -1$ in all galaxies, probably due to turbulence (e.g., Dobbs+ 2017, Hopkins+ 2018)
- On low mass end, power law continues to < 100 $M_\odot$; possible high mass truncation



Krumholz, McKee, & Bland-Hawthorn, ARA&A, 2018, in prep

WHAT IS A MASSIVE STAR CLUSTER?

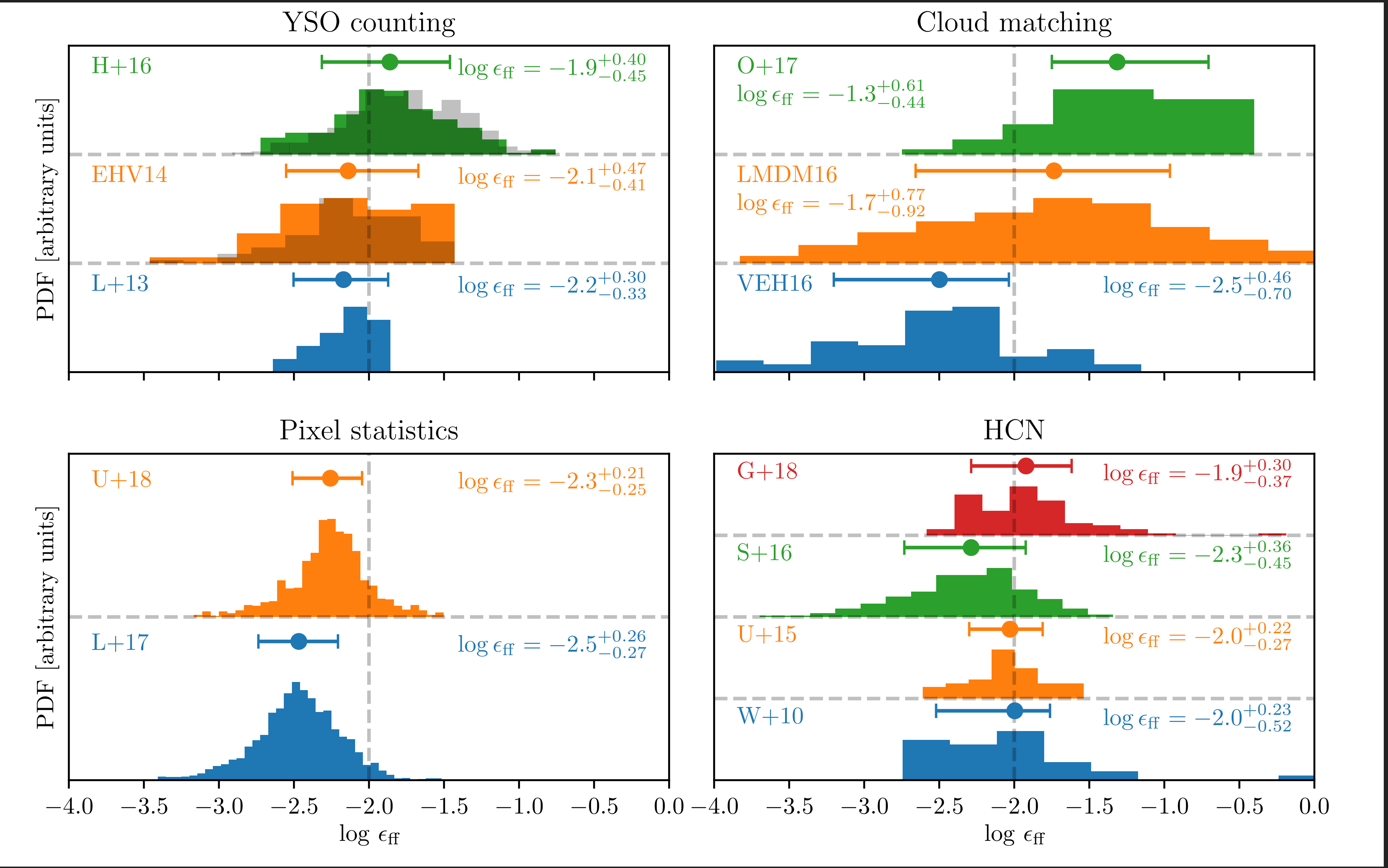
- For stellar masses drawn from a Chabrier or Kroupa IMF, only clusters with masses ≳ 3000 $M_\odot$ likely to produce stars ≳ 60 $M_\odot$
- Since feedback heavily depends on the most massive stars, this motivates a definition of massive cluster: one with mass ≳ 3000 $M_\odot$
- For observed CMF, ≳ 1/2 of star formation is in massive clusters



STAR FORMATION EFFICIENCY

- Two types of star formation efficiency:
  - ε_{ff} = fraction of mass turned into stars per free-fall time
  - $\varepsilon_\star$ = mass fraction turned into stars over full cloud lifetime
- First type can be measured directly by comparing SF tracers to tracers of gas mass using several methods
- Second type harder to measure; constrained to be $\lesssim 0.3$ in most regions by the fact that most star clusters do not survive past ~10 Myr, indicating they were unbound

CONSTRAINTS ON EFFICIENCY



Compilation: Krumholz, McKee, & Bland-Hawthorn, ARAA 2018, in prep

Data:
H+16 = Heyer+ 2016
EHV14 = Evans+ 2014
L+13 = Lada+ 2013
O+17 = Ochsendorf+ 2017
LMDM16 = Lee+ 2016
VEH16 = Vutisalchavakul+ 2016
U+18 = Utomo+ 2018
L+17 = Leroy+ 2017
G+18 = Gallagher+ 2018
S+16 = Stephens+ 2016
U+15 = Usero+ 2015
W+10 = Wu+ 2010

HCN calibration: Onus+ 2018

Summary: $\varepsilon_{ff} \approx 0.01$, $\sigma_{\varepsilon ff} \approx 0.5$ dex, 0.5 dex systematic error.
No obvious variation with SF-region mass.

MASSIVE STAR CLUSTERS: FEEDBACK

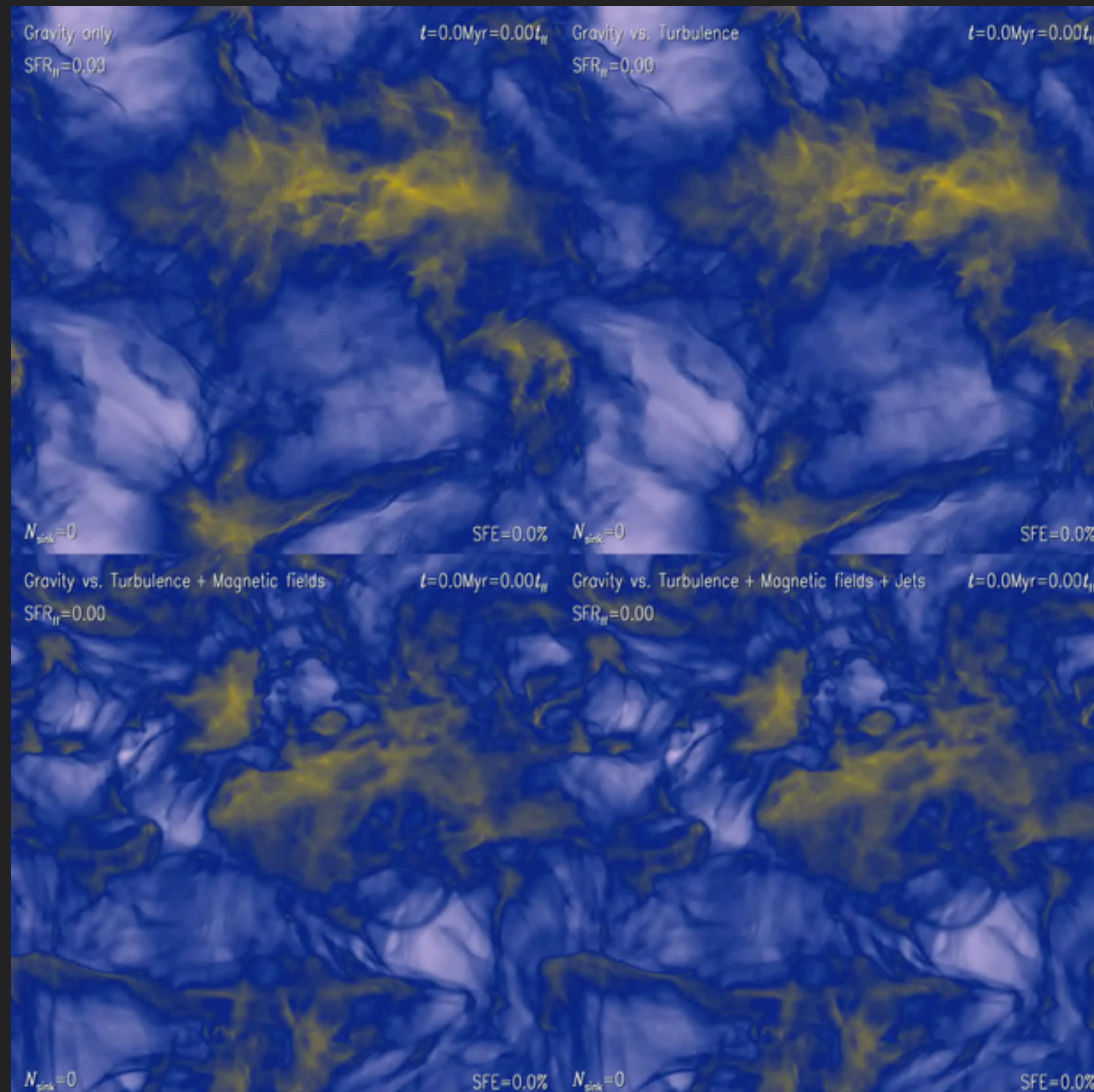
For no reason whatsoever, here is a baby echidna

INVENTORY OF FEEDBACK MECHANISMS

- Feedback needed to explain low ϵ_{ff} and $\epsilon_\star$; these are NOT the same, and may not be explained by the same mechanism
  - ϵ_{ff} mostly depends on inhibiting star formation (e.g., by turbulence)
  - $\epsilon_\star$ mostly depends on ejecting mass
- Mechanisms to think about:
  - Protostellar outflows
  - Photoionization
  - Direct radiation pressure
  - Dust-reprocessed IR radiation pressure
  - Massive star winds
  - Supernovae

OUTFLOWS

- Most likely to explain low ϵ_{ff}: they start immediately, drive turbulence, and eject mass from cores
- Need B fields to work
- Modern simulations have ϵ_{ff} ~ few percent
- Outflows do not lower $\epsilon_\star$ unless escape speed is $\lesssim$ few km s^{-1}

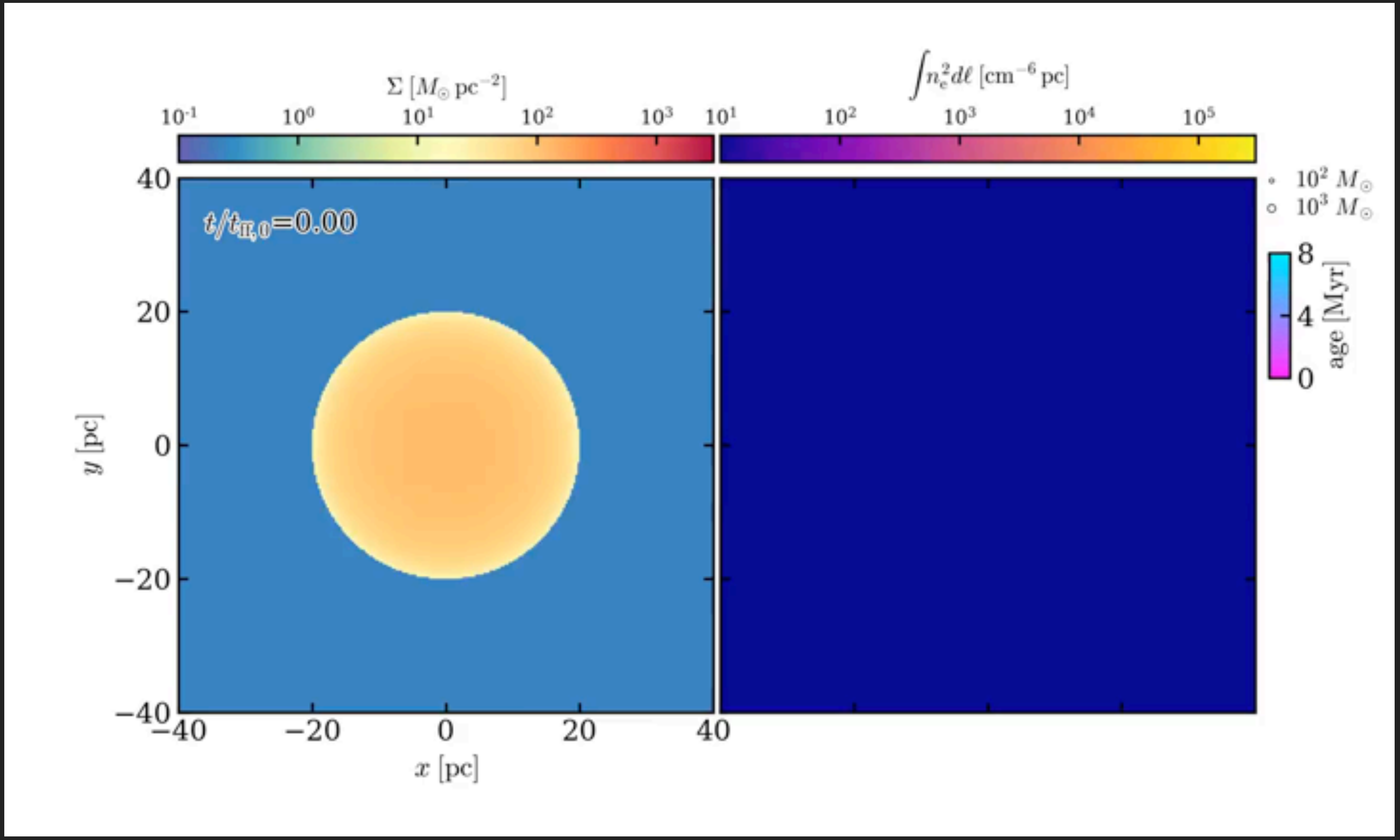


Federrath 2015

PHOTOIONIZATION

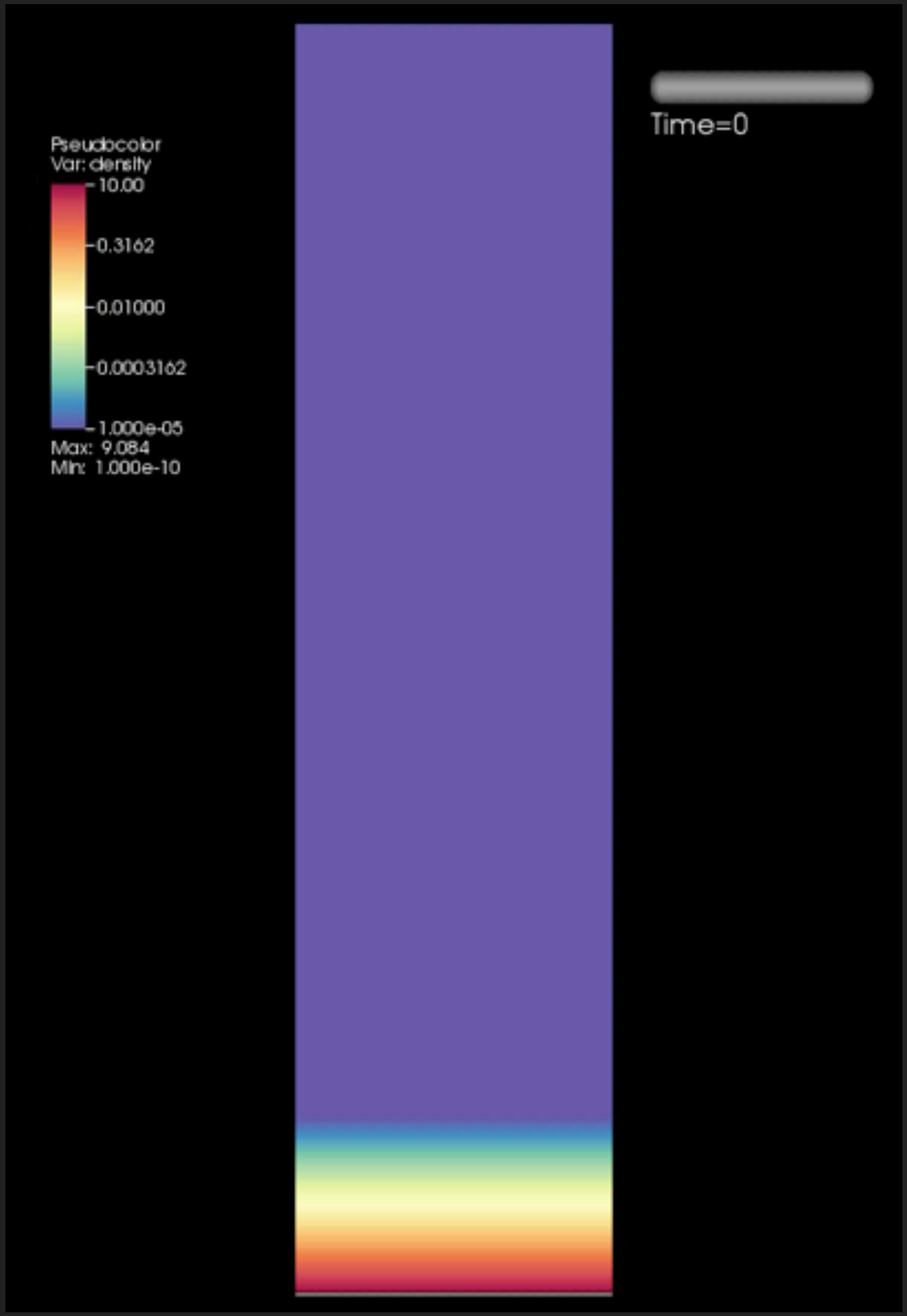
- Ionization heats gas to 10^4 K, producing pressure-driven wind
- Able to limit $\varepsilon_\star$ to ~0.3 as long as $v_{esc} \lesssim 10$ km s^{-1}

Kim, Kim, & Ostriker 2018



DIRECT RADIATION PRESSURE

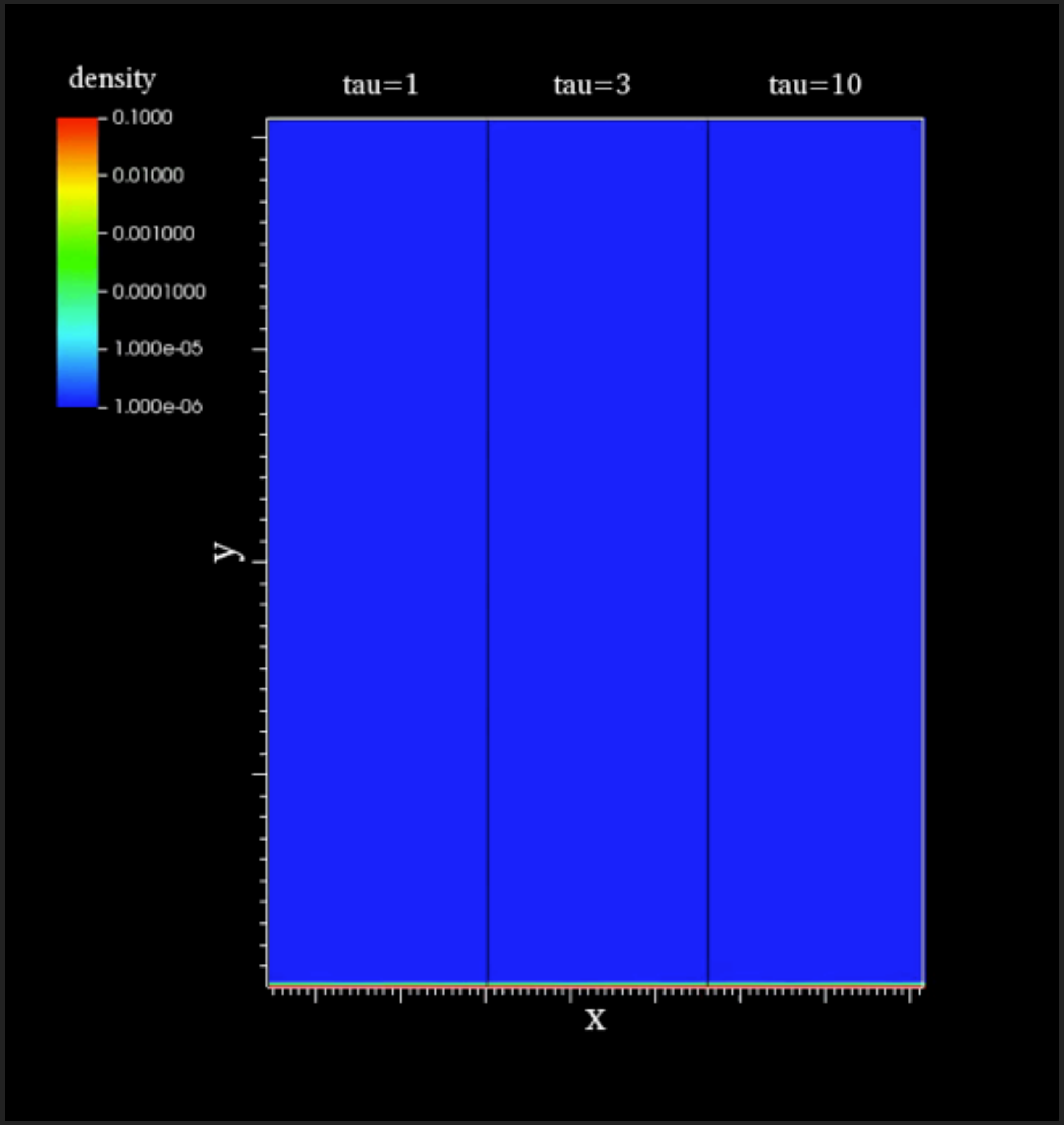
- Radiation force > gravitational force on any gas column with $\Sigma < \Sigma_{crit} = (L/M) / 4\pi Gc \sim 300\ M_\odot\ pc^{-2}$ (Fall+ 2010)
- In a turbulent medium with a PDF of Σ's, low Σ regions ejected even if mean $\Sigma > \Sigma_{crit}$ (Thompson & Krumholz 2016)
- Net effect is to limit $\varepsilon_\star$ to ~50% for $\Sigma \lesssim 10\ \Sigma_{crit}$



Wibking+ 2018

IR RADIATION PRESSURE

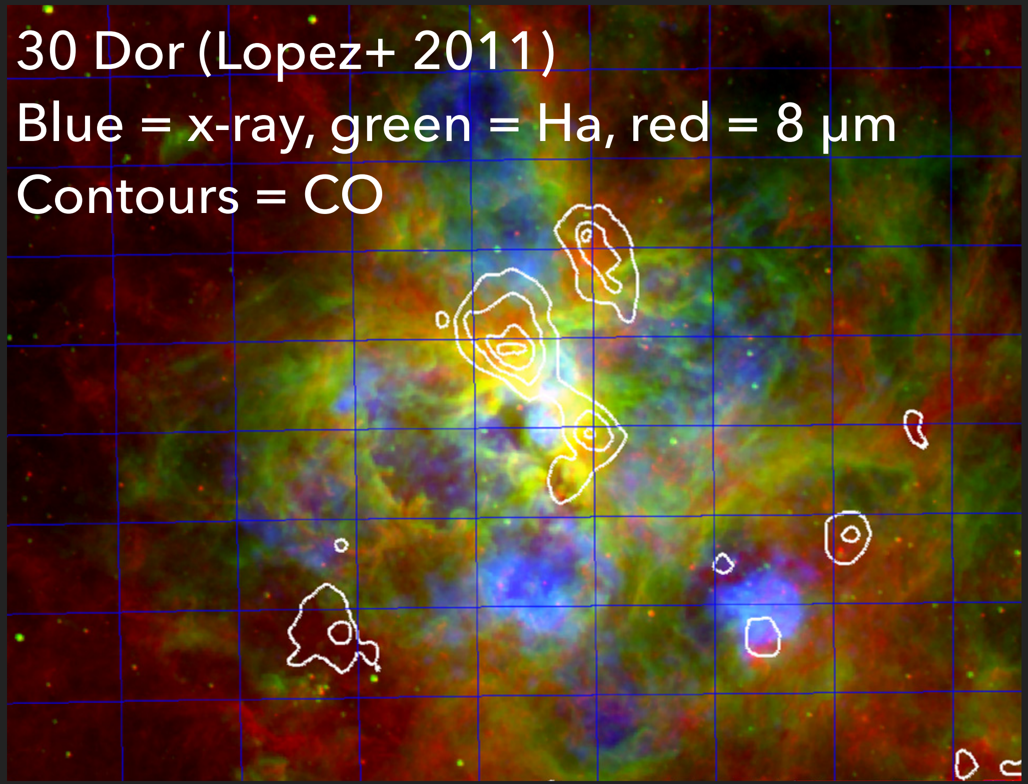
- If column is high enough, re-radiated IR can be trapped
- Force can be ≫ direct radiation force, ejecting gas in bulk
- Ejection rate limited by radiation RT instability
- Only happens if $\tau > 1$ even for opacity at dust photosphere: needs $\Sigma \gtrsim 10^5\ M_\odot\ pc^{-2}$

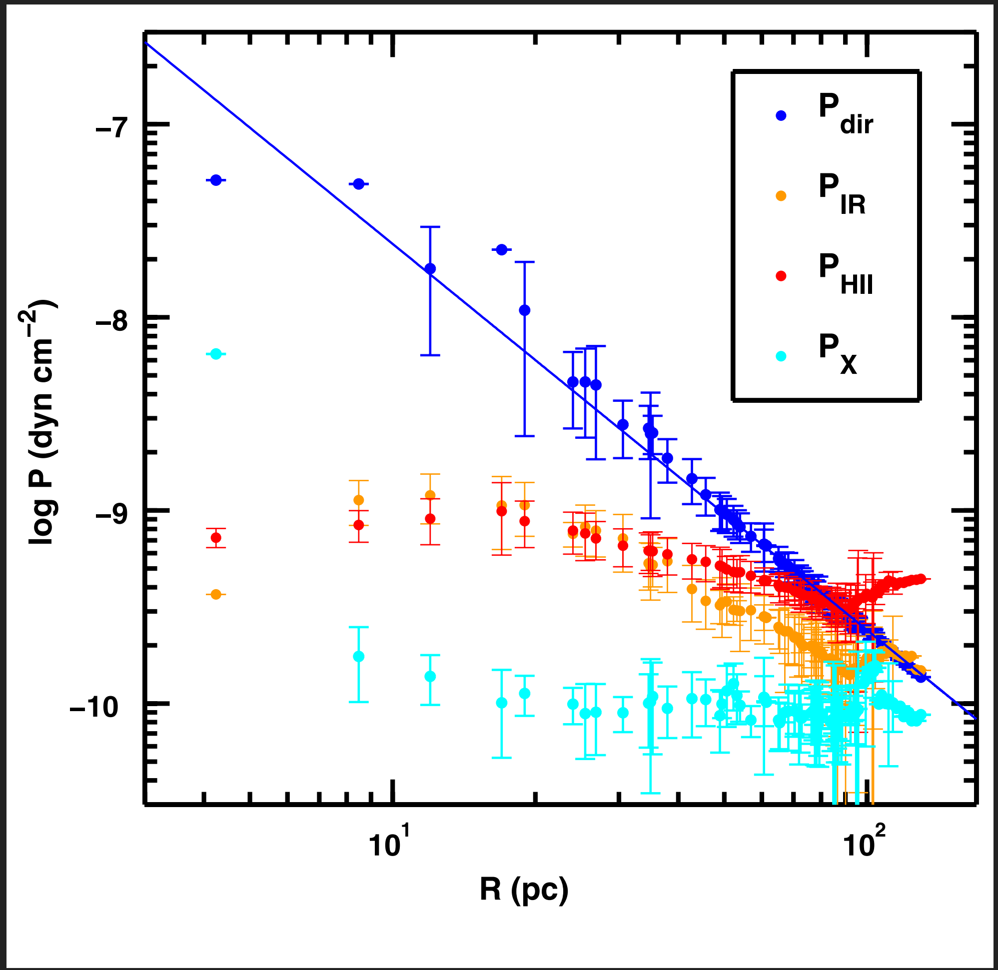


Davis, Jiang, Stone, & Murray 2014

MASSIVE STAR WINDS

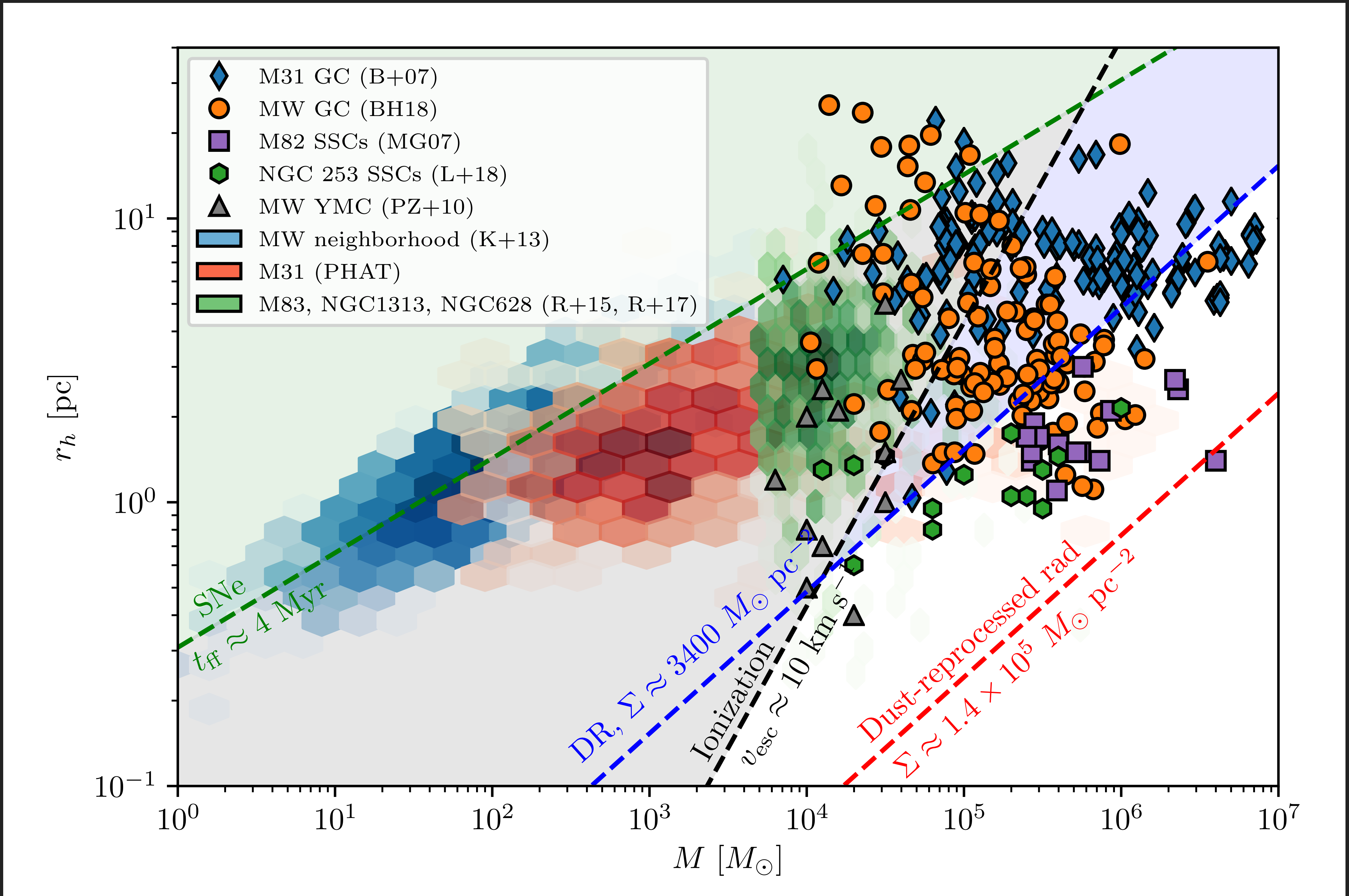
- Key issue with winds is leakage: how much hot gas escapes without exerting significant forces?
- Can measure directly by x-rays
- Compare to other pressures: photoionized gas (from radio free-free), direct radiation (from bolometric luminosity), IR radiation (from dust SED)
- Winds not observed to be dominant





SUPERNOVA FEEDBACK

- First SNe do not explode until $\gtrsim$ 4 Myr after star formation
- Dynamical time is 4 Myr for densities $n \approx 100$ cm^{-3}; at ε_{ff} = 1%, $\varepsilon_\star$ reaches 50% before first SN if $n \gtrsim 3 \times 10^5$ cm^{-3}
- Thus SNe probably only important for SF regulation in low-density regions
- However, a significant fraction of stars may form in such regions, and this may ultimately be the reason that $\varepsilon_\star$ is limited to small values (Kruijssen 2012)



Data:
Barmby+ 2007
Baumgardt & Hilker 2018
McCrady & Graham 2007
Portegies-Zwart+ 2010
Kharchenko+ 2013
Johnson+ 2012 / Fouesneau+ 2014
Ryon+ 2015, 2017
Leroy+ 2018

PUTTING IT ALL TOGETHER

Krumholz, McKee, & Bland-Hawthorn, ARAA 2018, in prep

MASSIVE STARS: LINKS TO THE CLUSTER SCALE

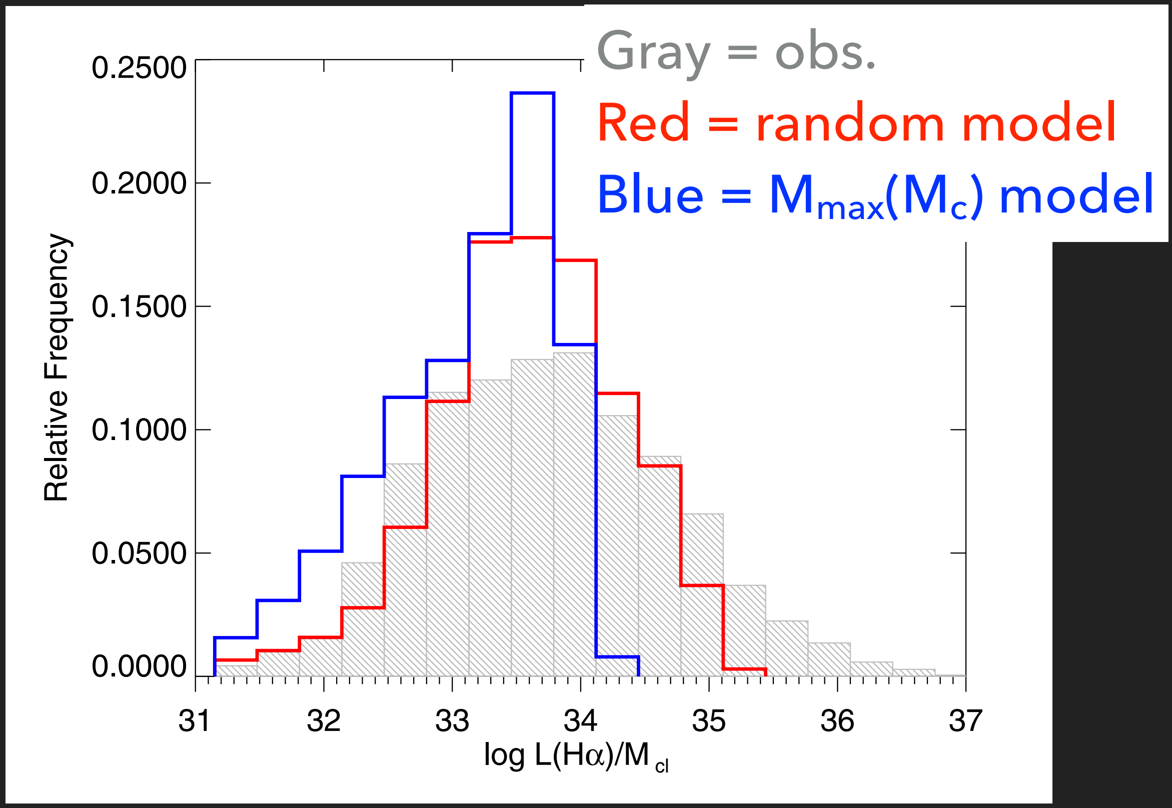
For no reason whatsoever, here is a baby quokka

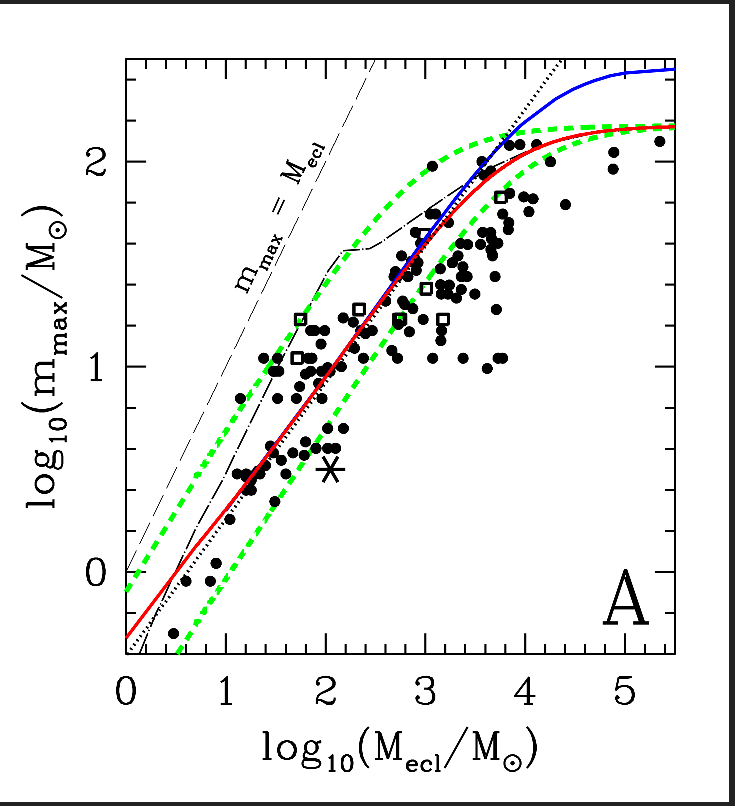
THE CLUSTER-STELLAR LINK

- Calculations discussed so far assumed that feedback in massive clusters comes from a fully-sampled IMF
- Is this necessarily the case? Is any star cluster with sufficient mass expected to be able to produce a massive star, or are there special conditions that a protocluster has to meet to make massive stars?
- How is mass assembled from cluster scale to form a massive star? Fast or slow? Global collapse or slow accumulation?

DOES CLUSTER MASS MATTER?

- Does cluster mass affect stellar mass, beyond size of sample effect?
- Extragalactic studies with uniform selection, analysis strongly indicate no, but these rely on proxies like ionizing luminosity
- Galactic studies less clear; results extremely sensitive to exact definition of cluster and means of sample selection, and systematic errors usually ignored



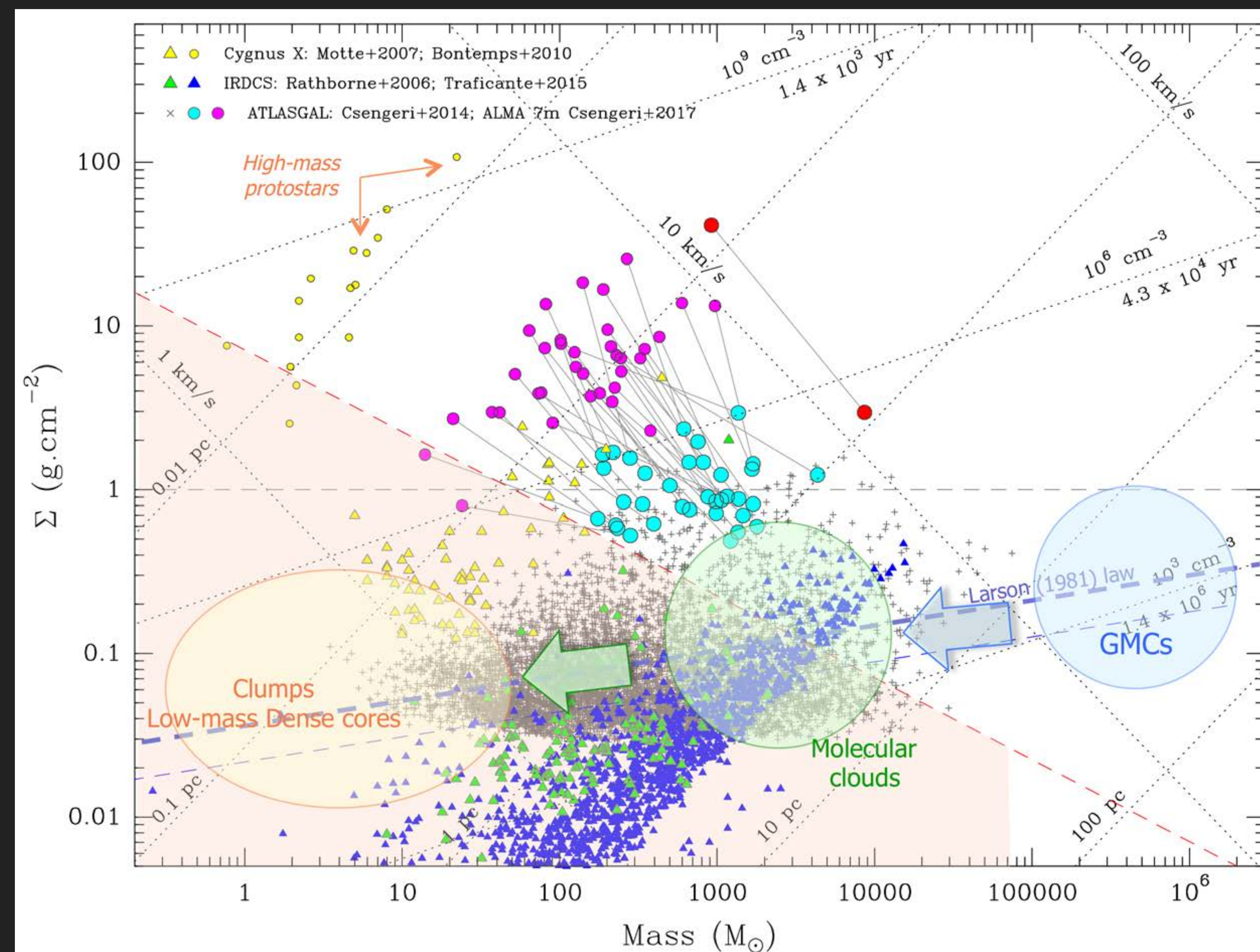


Top: Andrews, Calzetti, + 2014

Right: Weidner, Kroupa, & Pflamm-Altenburg 2014

DOES SURFACE DENSITY MATTER?

- High Σ regions more likely to show signs of massive star formation (e.g., Kauffmann & Pillai 2010, Lopez-Sepulcre+ 2010)
- IR-dark high Σ regions more likely to be close to monolithic when imaged with an interferometer (e.g., Csengeri+ 2017)
- Difficult to define scale on which Σ should be measured



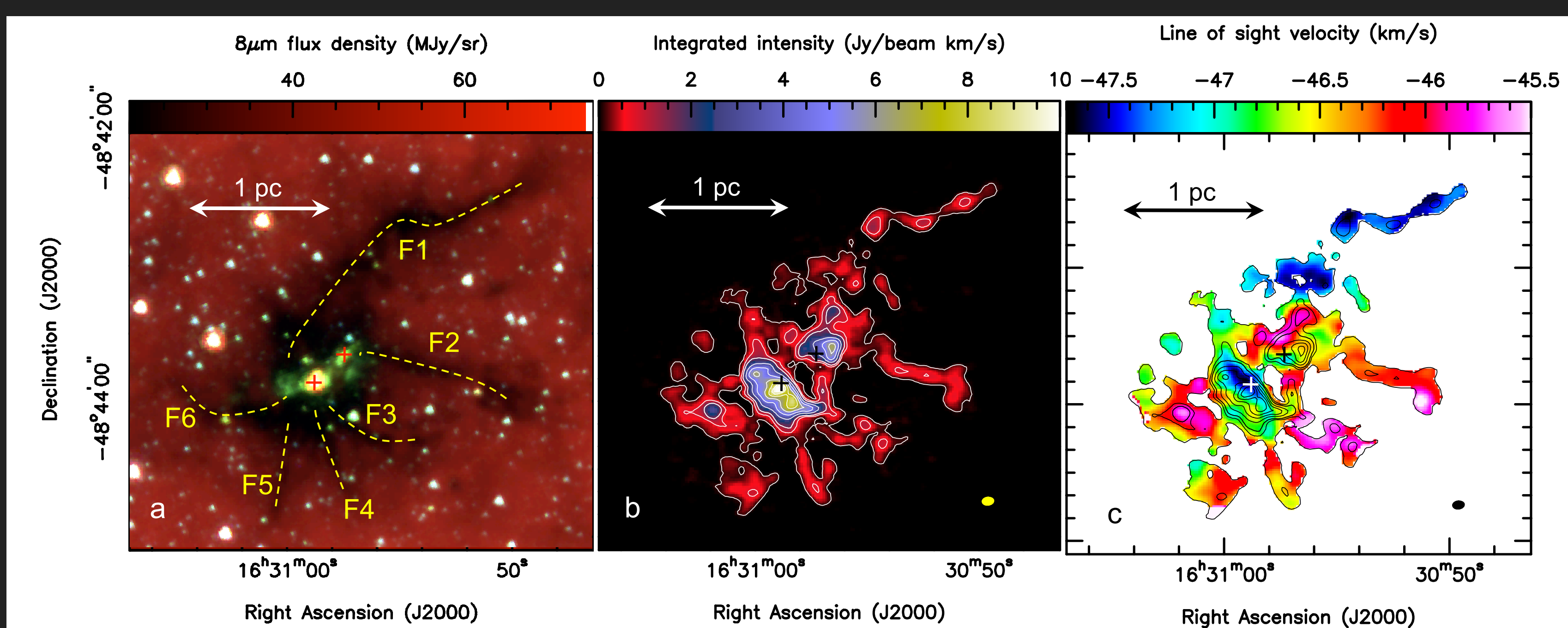
Motte, Bontemps, & Louvet 2018

MASS ASSEMBLY

- Timescales can be constrained by relative numbers of objects in different observed states
- Searches for “starless, massive cores” (defined as $M \gtrsim 100\ M_\odot$, $n \gtrsim 10^6\ \mathrm{cm}^{-3}$, IR-dark) show few candidates; inferred duration of this phase $\lesssim 10^5$ yr, comparable to t_{ff}
- This implies massive protostellar cores must begin star formation as they are assembled, rather than being assembled first (Motte, Bontemps, & Louvet 2018)

MASS ASSEMBLY II

- Inflow rates on larger scales imply lifetimes > t_{ff}
- E.g. SDSC335 has $dM/dt \approx 2 \times 10^{-3}\ M_\odot\ yr^{-1}$, $M \approx 2600\ M_\odot$, $r \approx 0.6$ pc, so $t_{acc} = M / (dM/dt) \approx 1$ Myr and $t_{ff} \approx 0.1$ Myr, so $t_{acc} / t_{ff} \approx 10$ (Tan+ 2014)
- Suggested picture: massive core collapse begins immediately, and core is fed while collapsing, but is itself quasi-virialized (e.g., Lee & Hennebelle 2016)



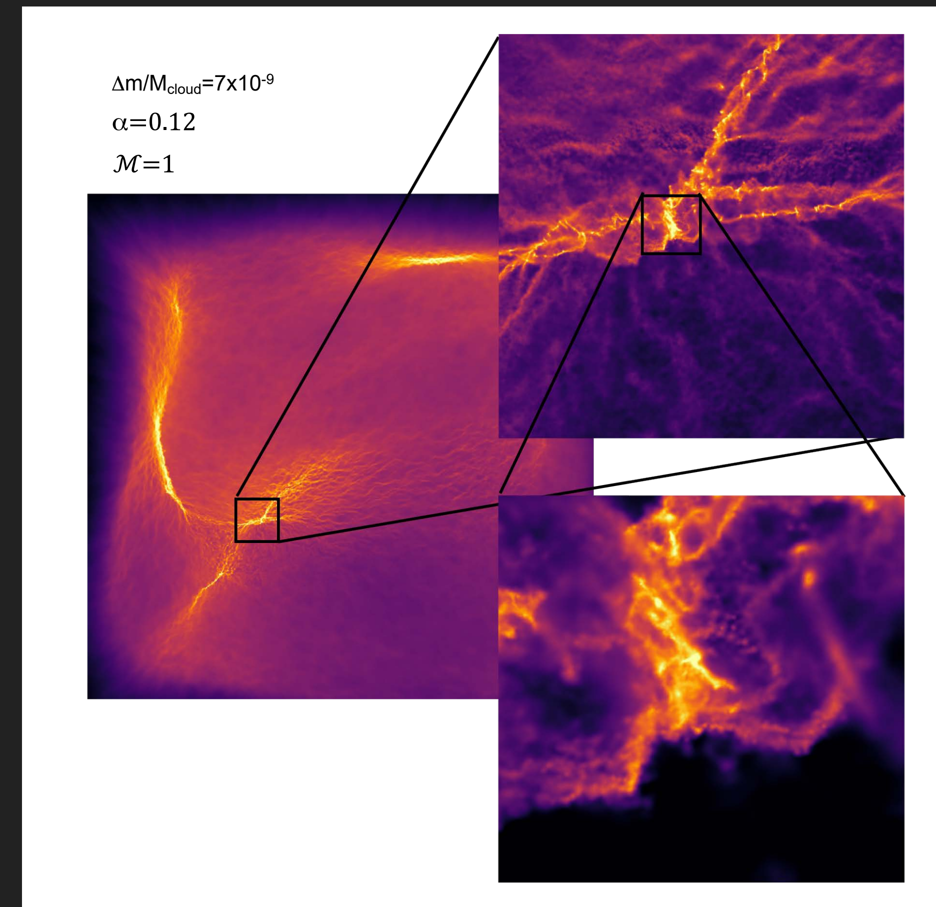
SDSC335; Peretto+ 2013

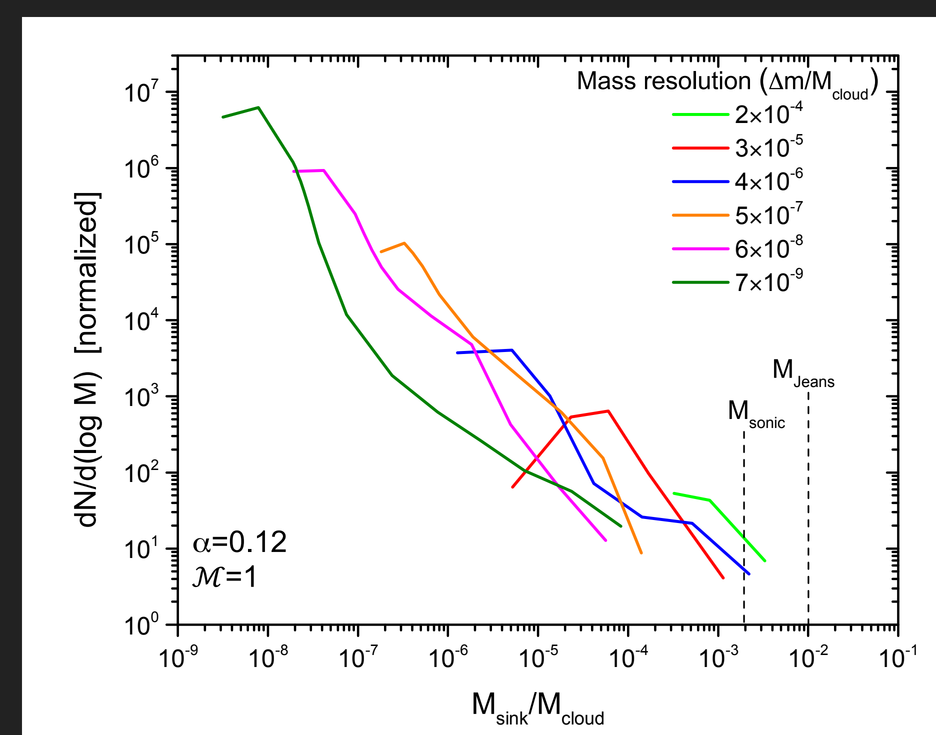
MASSIVE STARS: FRAGMENTATION

For no reason whatsoever, here are baby platypuses

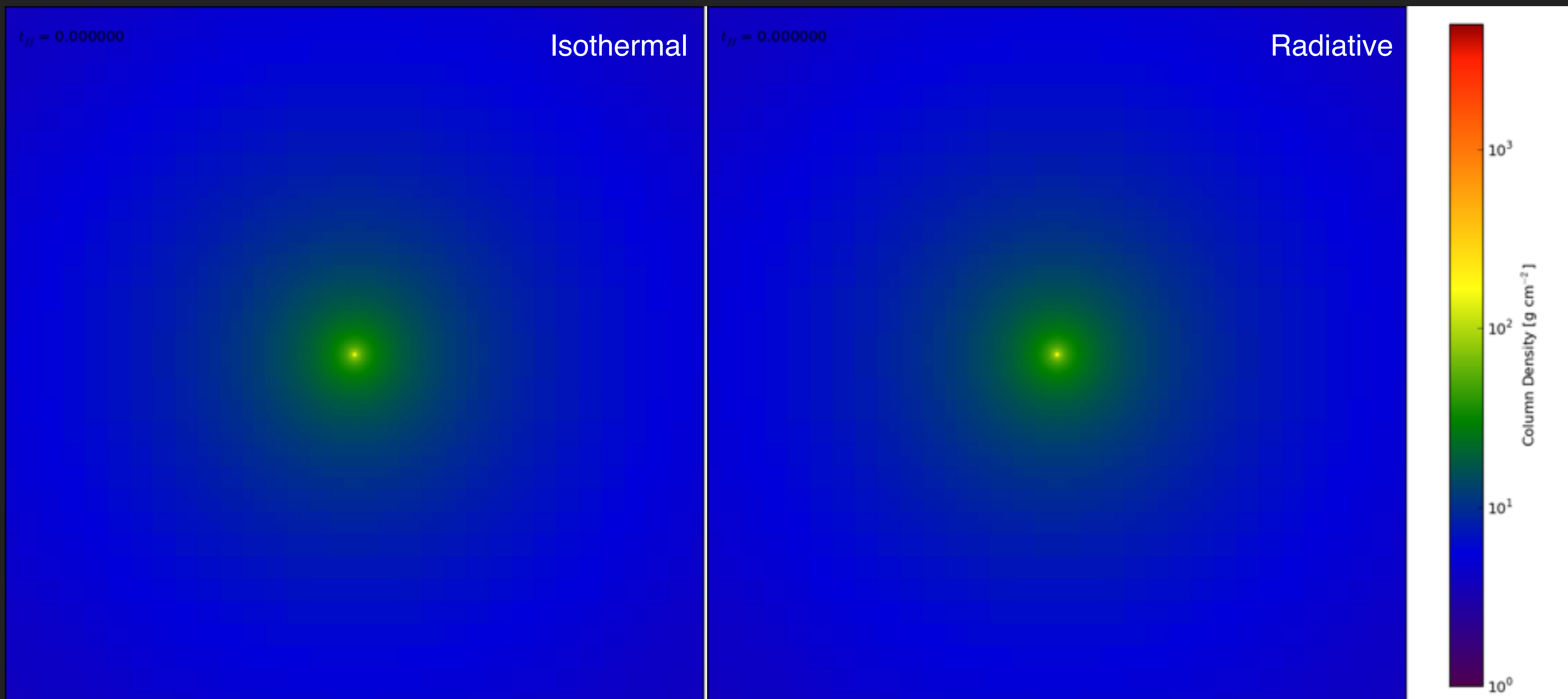
ISOTHERMAL FRAGMENTATION

- 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

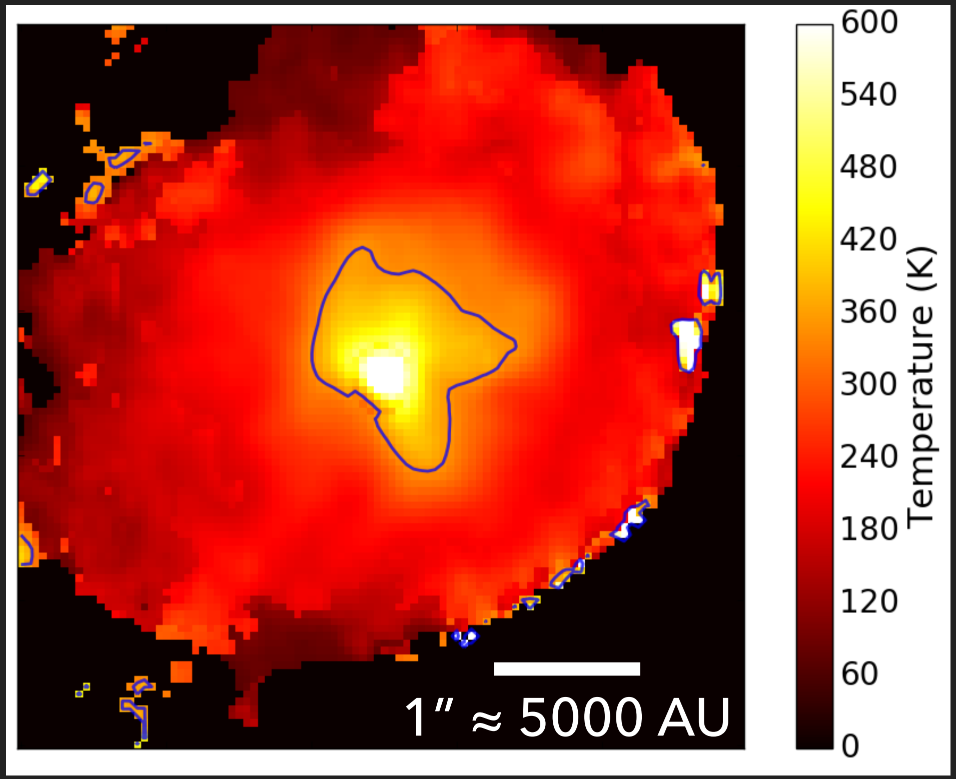


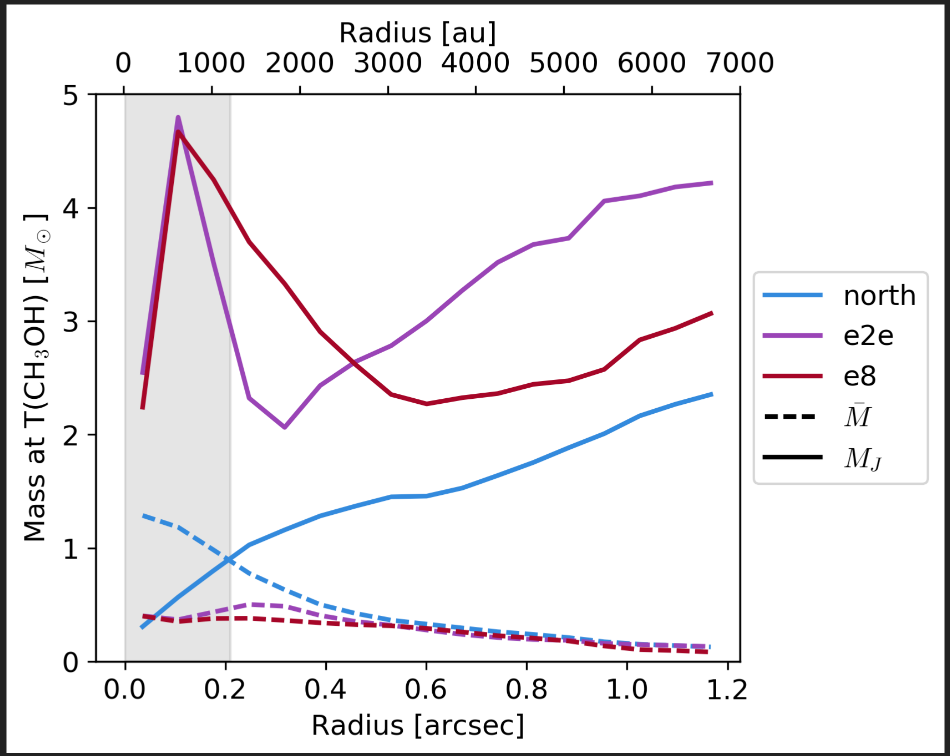
RMHD SIMULATIONS

Myers+ 2013

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

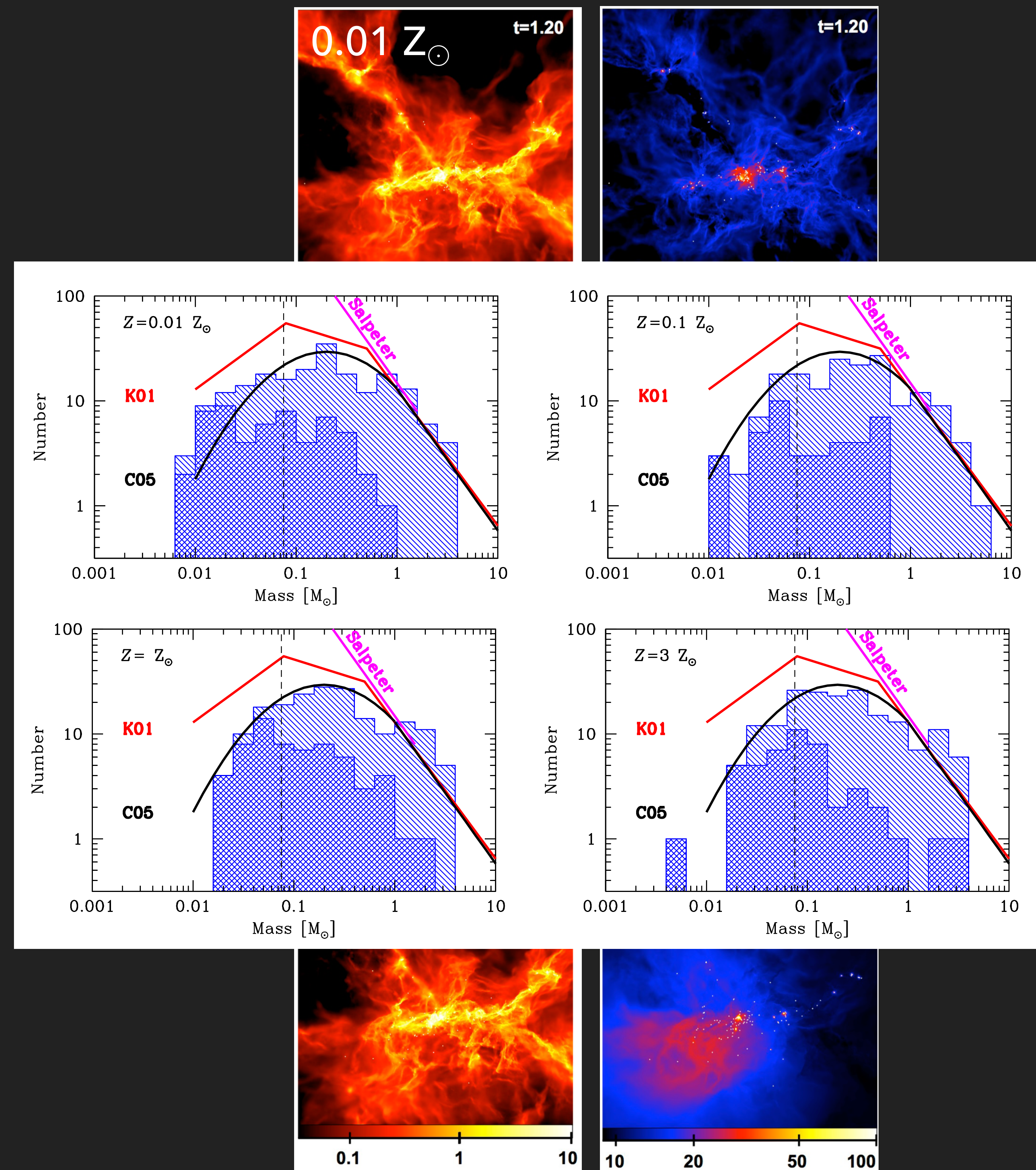




W51, Ginsburg+ 2017

DEPENDENCE ON Σ AND Z

- Radiation coupled to gas by dust, so metallicity might matter
- Turns out it doesn't, because at Σ ~ 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 Σ ~ 1 g cm^{-2} (Krumholz & McKee 2008)
  - Value with B fields unknown



Σ [g cm^{-2}]   T [K]

MASSIVE STARS: THE UPPER LIMIT

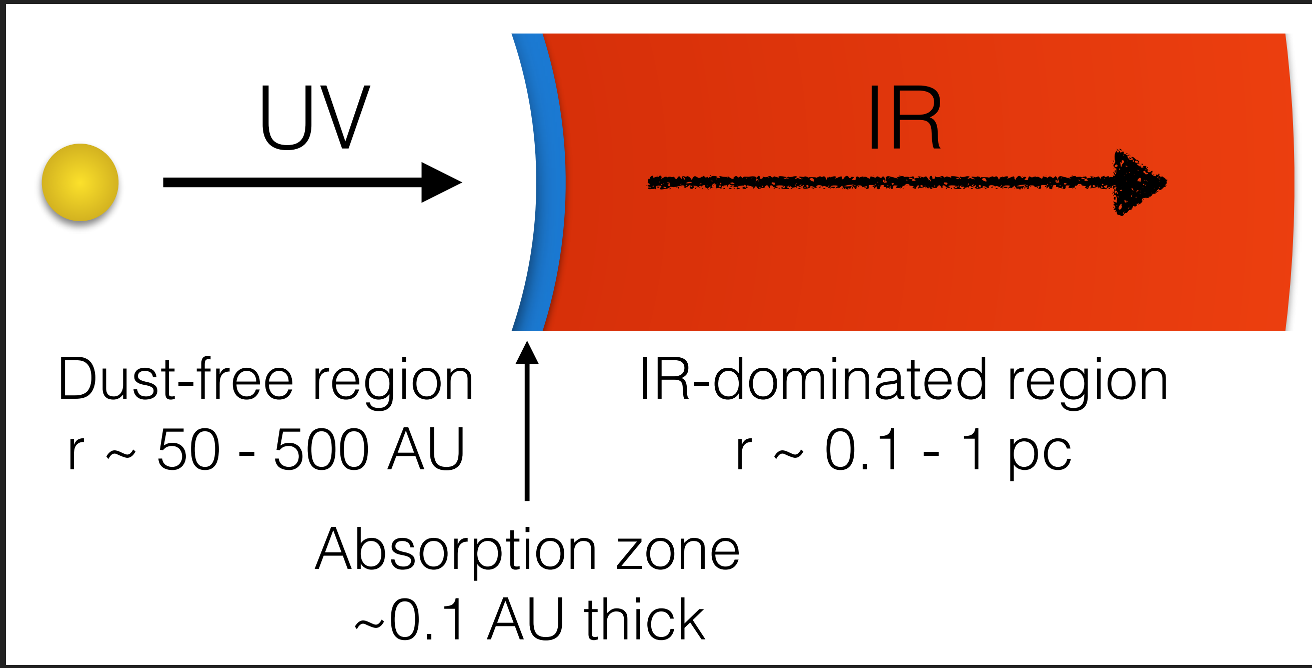
For no reason whatsoever, here is a baby sugar glider

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

LIMITING STELLAR MASSES: RADIATION PRESSURE

- Near massive star, radiation creates a dust-free zone with low opacity (except perhaps in the disk)
- UV radiation free-streams outward, delivers $\Delta p = L/c$ at dust destruction front
- IR diffuses out from DDF
- Accretion must overcome both UV and IR forces

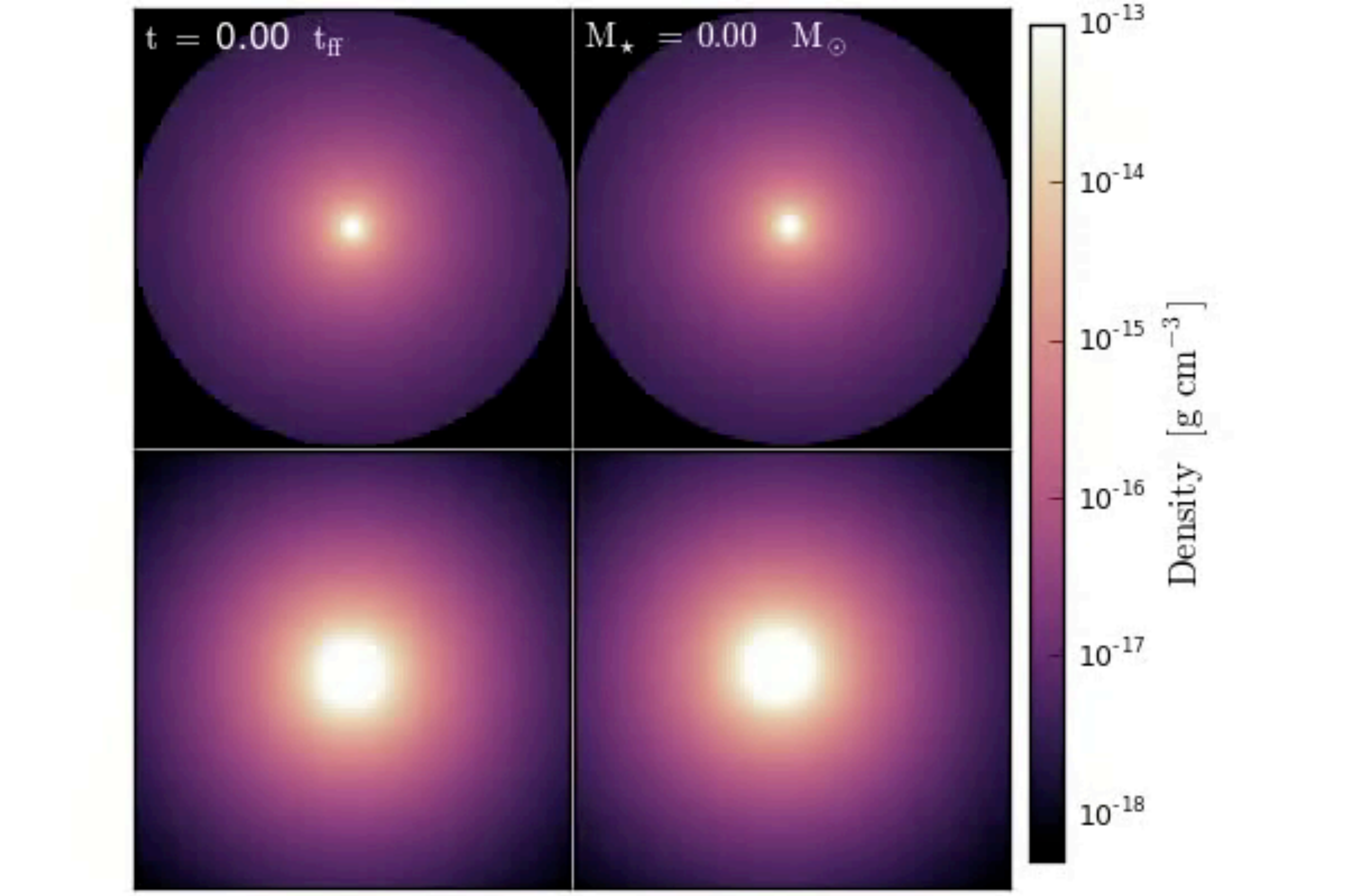


RADIATION FORCES: GENERAL CONSIDERATIONS

- Most massive stars have $L/M \approx 10^4\ L_\odot/M_\odot$, corresponding to $\Sigma_{crit} \approx 0.8$ g cm^{-2}; thus direct radiation pressure cannot set a mass limit in cores of higher Σ
- In IR-dominated region, Eddington ratio is for isotropic radiation flux is $f_{Edd} = \kappa_{IR}L\ /\ 4\pi GMc \approx 8\ (\kappa_{IR}/10\ \mathrm{cm}^2\ \mathrm{g}^{-1})$
- Thus accretion is possible only if some mechanism makes the radiation flux anisotropic

BEATING THE RADIATION PRESSURE LIMIT

- Many mechanisms available to make flux anisotropic
  - Disk collimation (Yorke & Sonnhalter+ 2002; Kuiper+ 2011, 2012, ...)
  - Radiation RT instability (Krumholz+ 2009; Rosen+ 2016)
  - Turbulence in the core + filamentary accretion (Rosen+ 2016)
  - Protostellar jet cavities (Krumholz+ 2005, Cunningham+ 2011, Kuiper+ 2015, 2016)
- Bottom line: all evidence suggests that the radiation pressure barrier is at most a minor nuisance to massive star formation



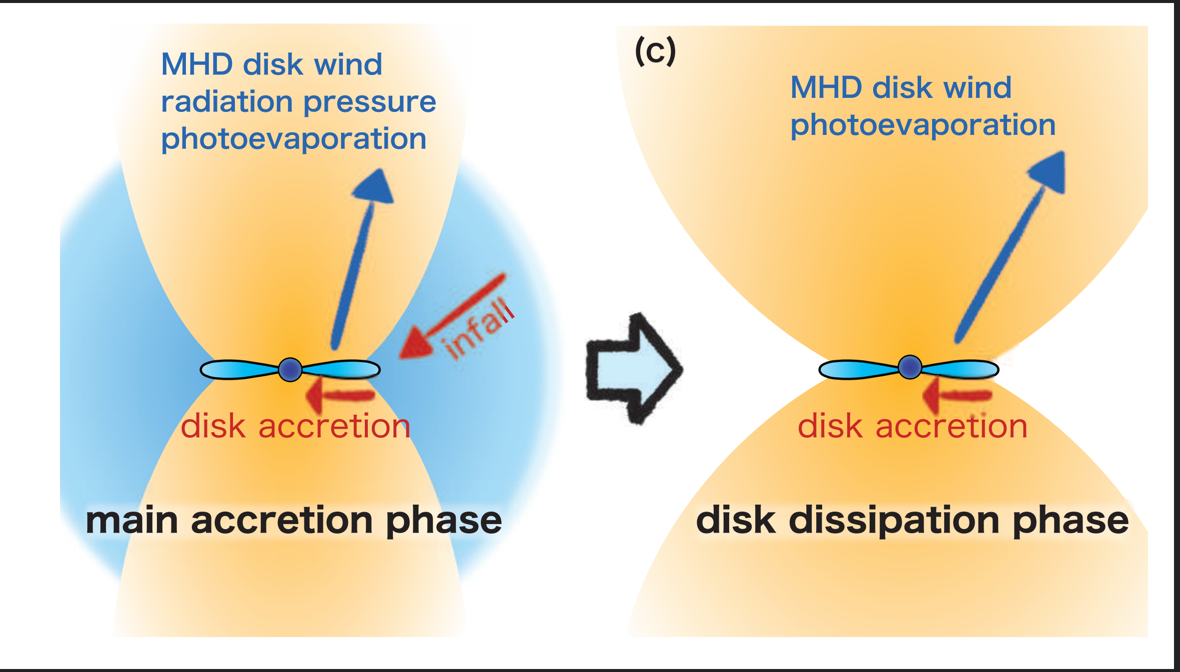
RADIATION PRESSURE SIMULATION

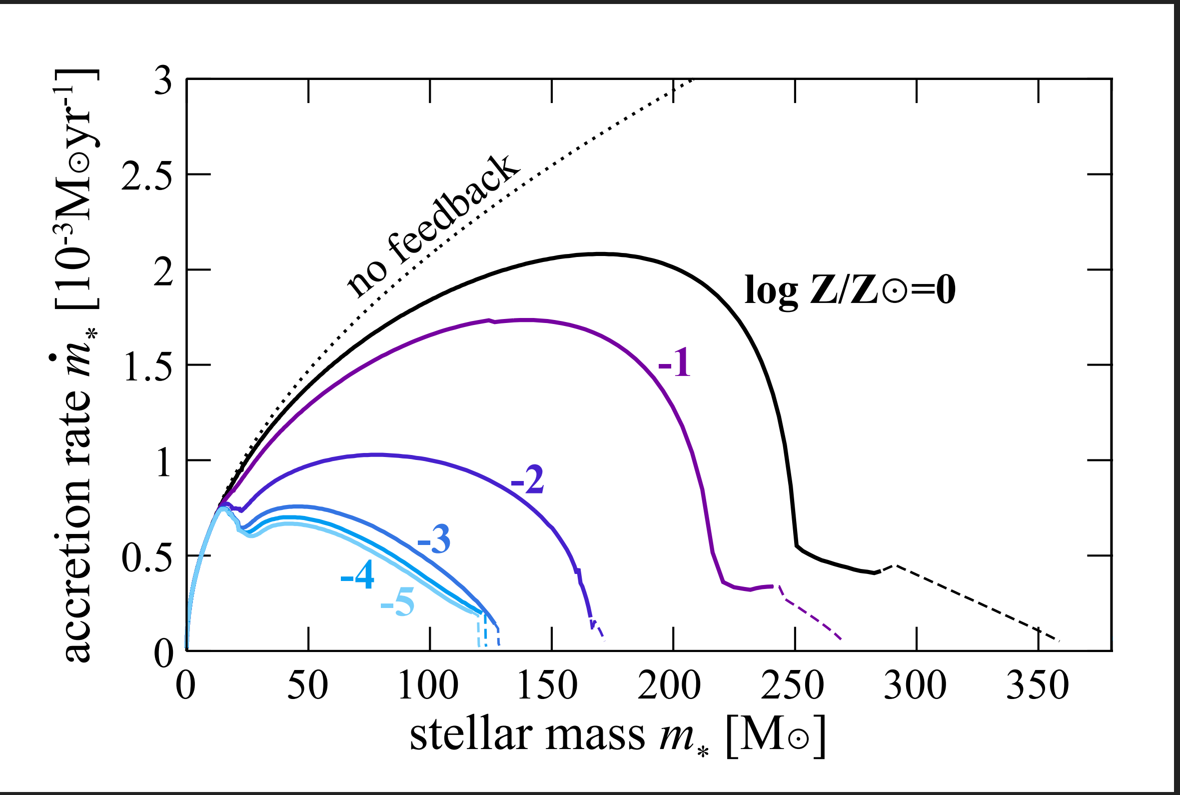
Rosen+ 2016

OTHER POSSIBLE MECHANISMS

- Disk photoevaporation: once outflow removes core, ionizing photons evaporate accretion disk (e.g., Hosokawa+ 2010, Tanaka+ 2018)
  - Only works at low Z, when dust shielding is weak

- Another possibility that has yet to be explored: instabilities in very massive stars that cause mass loss on the accretion time scale





Tanaka+ 2018

CLOSING THOUGHTS

For no reason whatsoever, here is a baby Tasmanian devil

CLOSING THOUGHT

- For both massive stars and massive clusters, the key question is feedback: balance of mass in and mass out
- Observations seem to demand that feedback keeps $\varepsilon_\star$ and ε_{ff} small at the scale of star clusters (e.g., in gas traced by HCN) but does not prevent formation of massive stars
- What are the key differences in scale: surface density (clusters have lower Σ), environment (external influence gets less important on smaller scales), something else?