Understanding Radiatively-Driven Dusty Winds

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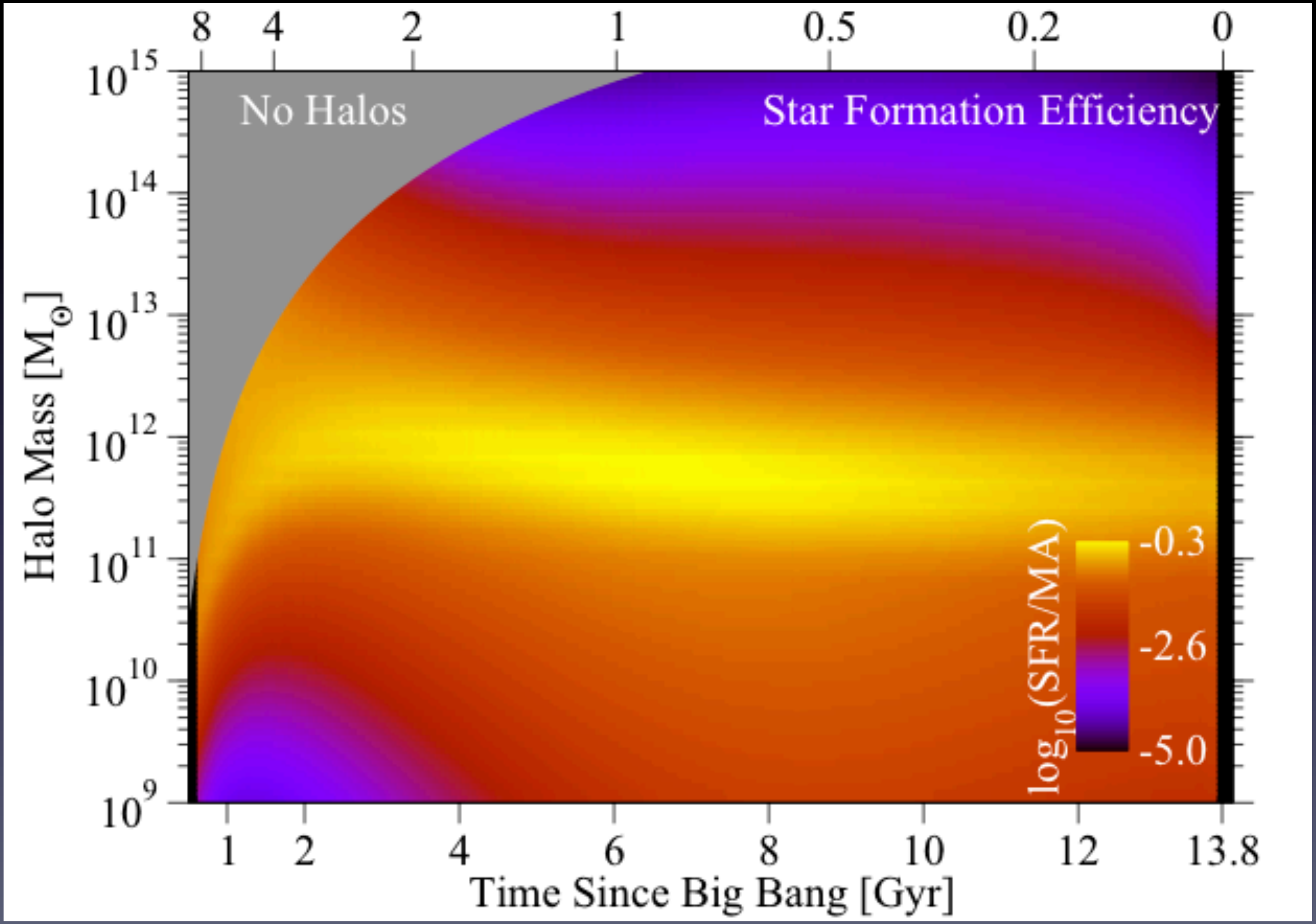
Outline

- Radiation pressure basics
- A simple model system
- Implications and observational signatures

Galaxy Formation Too Efficient



Behroozi+ (2013)

The Question…

What terminates star formation?

Feedback: What is Needed

- Consider an object with escape speed v_{esc}
- Momentum injection rate required to drive wind with $(dM/dt)_{wind} \sim (dM_*/dt)$ is

$$\left\langle \frac{p}{M} \right\rangle > v_{\rm esc}$$

- NB: this is a lower limit, assuming no losses
- SFE <~ 0.5 in galaxies with v_{esc} > 500 km s^{-1} ➔ need feedback <p/M> >> 500 km s^{-1}
- <p/M> ~ 100 km s^{-1} sufficient for clusters

Radiation Pressure Budget

- For a Kroupa IMF, instantaneous and total radiation production are (Dekel & Krumholz 2013)

$$\left\langle \frac{L}{M} \right\rangle = 1140\, L_\odot\, M_\odot^{-1} = 2200 \text{ erg g}^{-1}$$

$$\left\langle \frac{E_\mathrm{rad}}{M} \right\rangle = 1.1 \times 10^{51} \text{ erg}\, M_\odot^{-1} = 6.2 \times 10^{-4} c^2$$

- Corresponding radiation momenta:

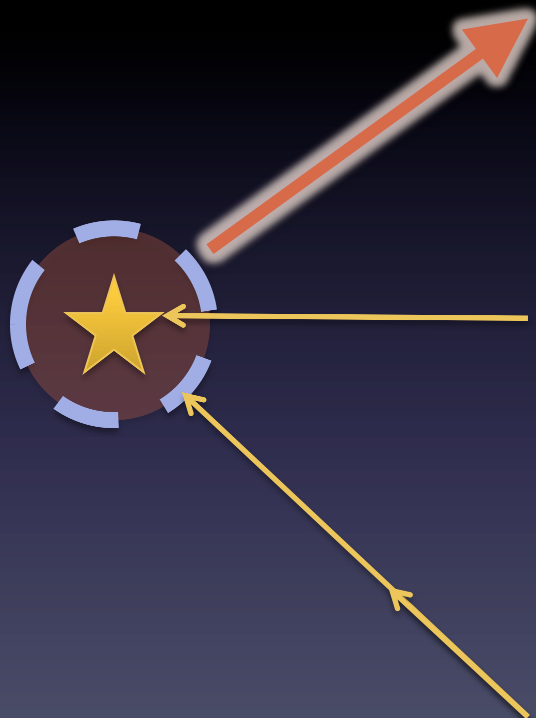
$$\left\langle \frac{\dot{p}_\mathrm{rad}}{M} \right\rangle = 23 \text{ km s}^{-1} \text{ Myr}^{-1}$$

$$\left\langle \frac{p_\mathrm{rad}}{M} \right\rangle = 190 \text{ km s}^{-1}$$

Tentative Conclusion…

- Radiation pressure may be important for individual clusters, probably not for galaxies
- …unless the true momentum input of the radiation is much larger than simply the direct momentum output of the starlight

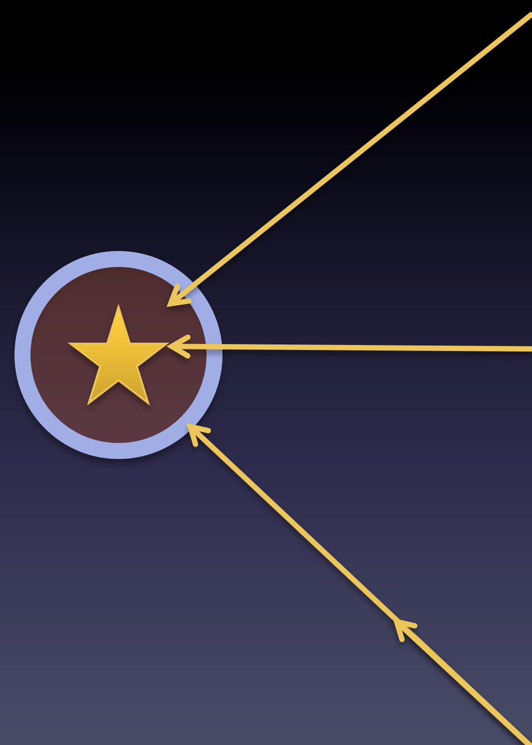
The Momentum-Conserving Limit



Shell radius set by momentum conservation:

$$\dot{p}t \sim M_{\rm sh}\dot{r}$$

The Energy-Conserving Limit



Shell radius set by energy conservation:

$$\dot{E}t \sim M_{\rm sh}\dot{r}^2 + (4\pi/3)U_{\rm IR}r^3 \sim 2M_{\rm sh}\dot{r}^2$$

What's the Difference?

- Consider a source w/luminosity L; after time t, shell has mass M, radius r
- Energy-conserving case: $M_E \dot{r}_E^2 \sim Lt$
- Momentum-conserving case: $M_p \dot{r}_p \sim (L/c)t$
- Ratio of energies, momenta at equal times:

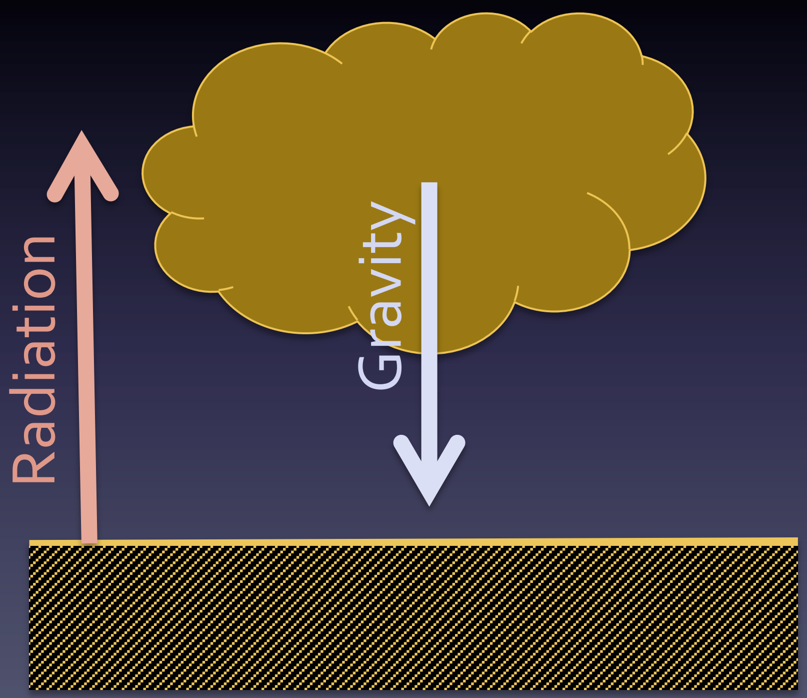
$$\frac{M_E \dot{r}_E^2}{M_p \dot{r}_p^2} \sim \frac{c}{\dot{r}_p} \qquad \frac{M_E \dot{r}_E}{M_p \dot{r}_p} \sim \sqrt{\frac{M_E c^2}{Lt}}$$

- Define $f_{\rm trap} = \dfrac{M\dot{r}}{(L/c)t} - 1$, i.e. $p_{sh}/p_* - 1$

What is f_{trap}?

- Hypothesis #1: if IR optical depth >> 1, photons absorbed and re-emitted many times while escaping, and $f_{trap} \sim \tau_{IR}$ (Thompson et al. 2005; Murray et al. 2010, 2011; Hopkins+ 2011, 2012)
- Hypothesis #2: instabilities and holes through which photons can leak make it hard to build up to $f_{trap} \gtrsim 1$ (Krumholz & Matzner 2009; Fall+ 2010; Krumholz & Dekel 2010, Dekel & Krumholz 2013)

Measuring f_{trap} in a Simple Model



- Slab of material of column density Σ
- Opacity function $\kappa_R \sim T^2$
- Radiation flux F_o in +z direction injected at $z = 0$
- Gravitational force g in –z direction

Equilibria, Dimensionless Numbers

- Equilibrium density, temp. profile obey

$$\frac{d}{d\xi_z}(b\Theta) = -(1 - f_{\mathrm{E},*}k_R)b$$

$$\frac{d}{d\xi_z}\Theta = -\frac{3\tau_* k_R b}{4\Theta^3}$$

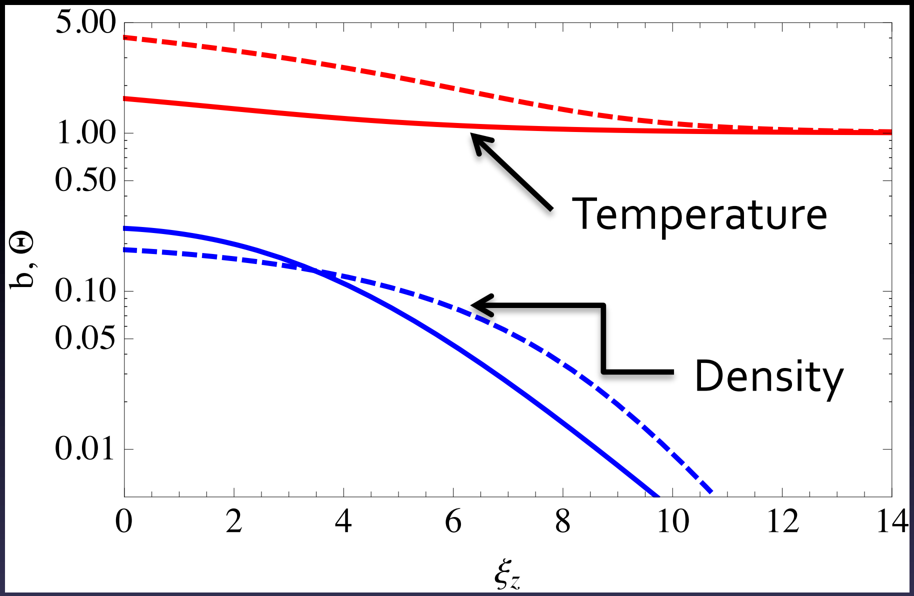
- Here

$$T_* = \left(\frac{F_0}{ca}\right)^{1/4} \qquad k_R = \frac{\kappa_R}{\kappa_R(T_*)}$$

$$\xi_z = \frac{z}{c_{s,*}^2/g} \qquad \Theta = \frac{T}{T_*}$$

- Key numbers:

$$f_{E,*} = \frac{\kappa_R(T_*)F_0}{gc} \qquad \tau_* = \Sigma\kappa_R(T_*)$$



Two equilibrium profiles: $f_{E,*} = 0.3$, $\tau_* = 1$ (solid) and $f_{E,*} = 0.03$, $\tau_* = 10$ (dashed) (Krumholz & Thompson 2012)

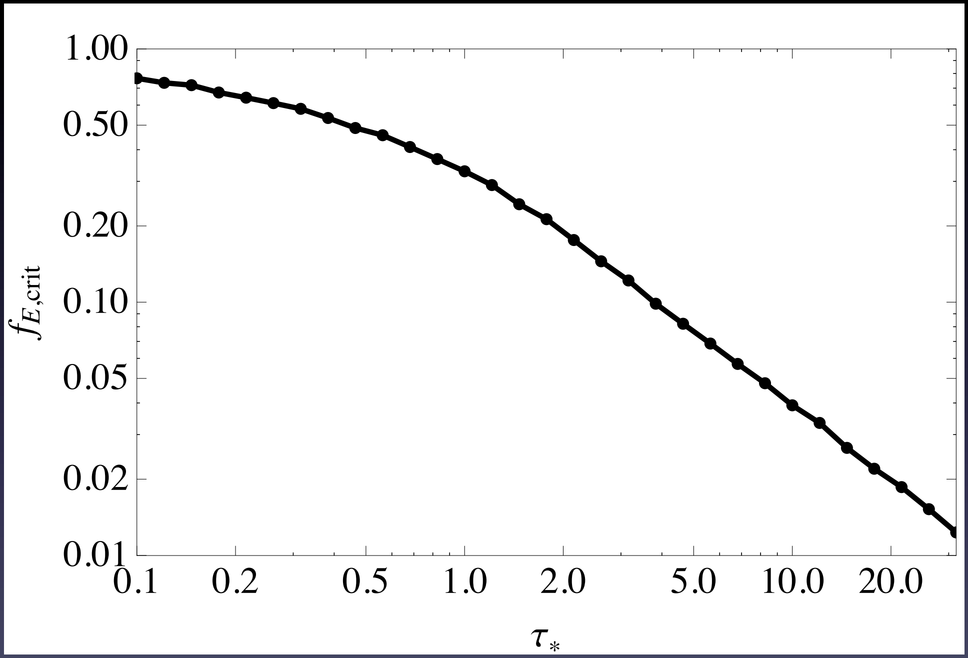
NB: $\tau_* << \tau_{IR}$

The Unstable Regime

- Hydrostatic solutions exist only for

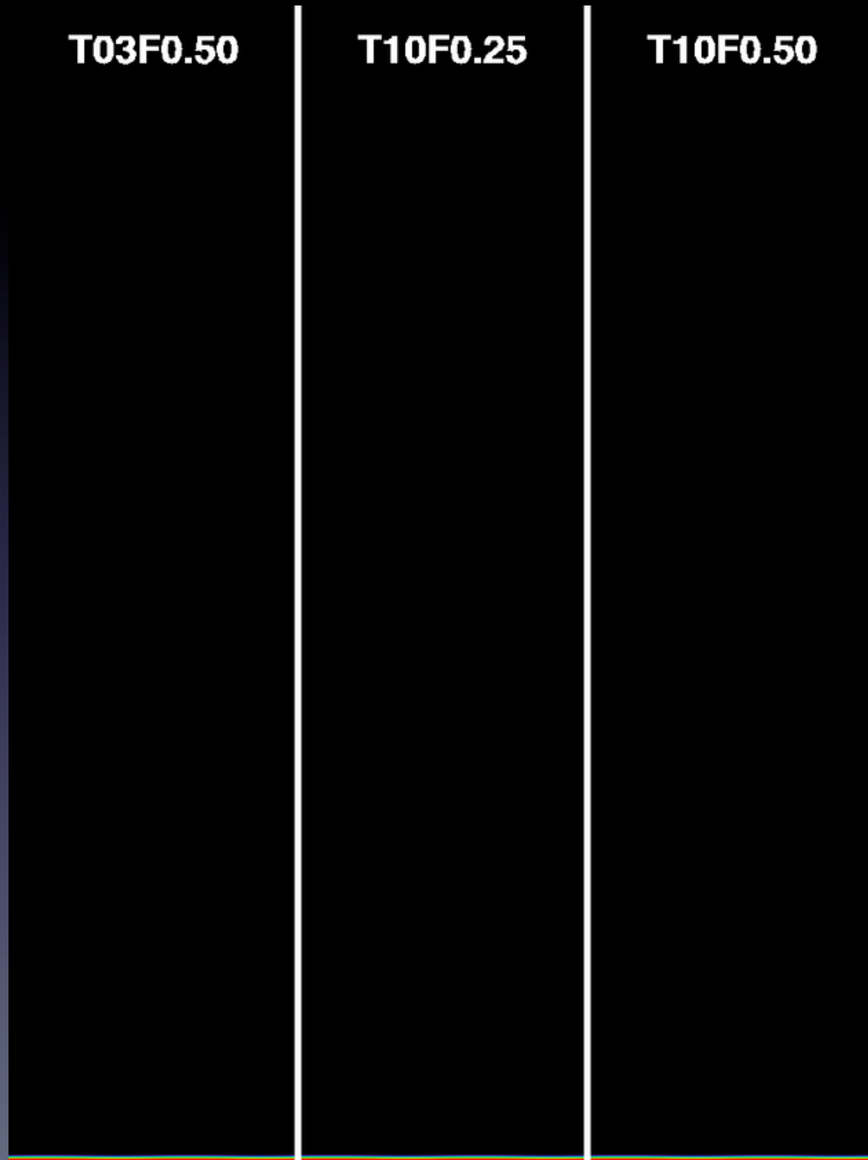
  $f_{E,*} < f_{E,crit}(\tau_*)$

- ULIRGs, massive star clusters indicates they can exceed this limit



Maximum possible $f_{E,*}$ for a hydrostatic atmosphere to exist (Krumholz & Thompson 2012)

Simulations: $f_{E,crit} < f_{E,*} < 1$



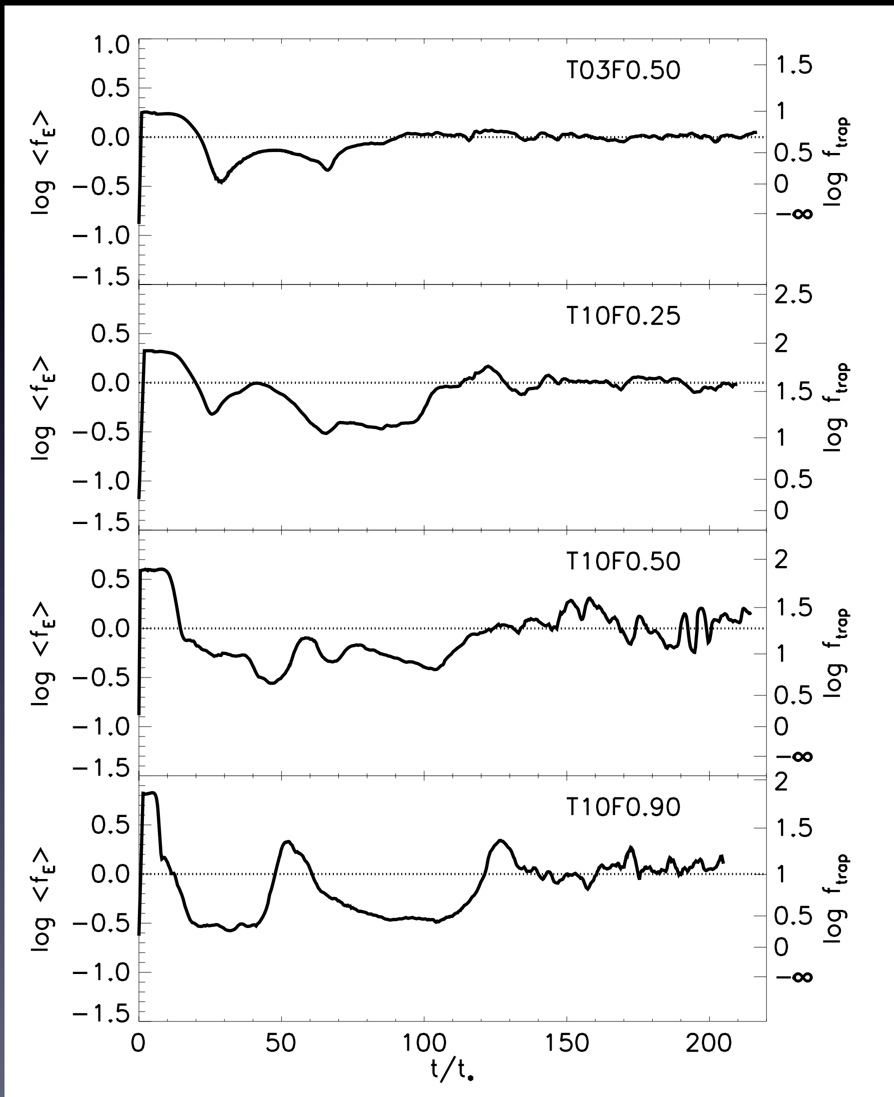
Simulations done with the ORION radiation-hydro code.

Models shown:

- $\tau_* = 3$, $f_{E,*} = 0.5$
- $\tau_* = 10$, $f_{E,*} = 0.25$
- $\tau_* = 10$, $f_{E,*} = 0.5$

(Krumholz & Thompson 2012)

Trapping and Winds at $f_{E,*} < 1$

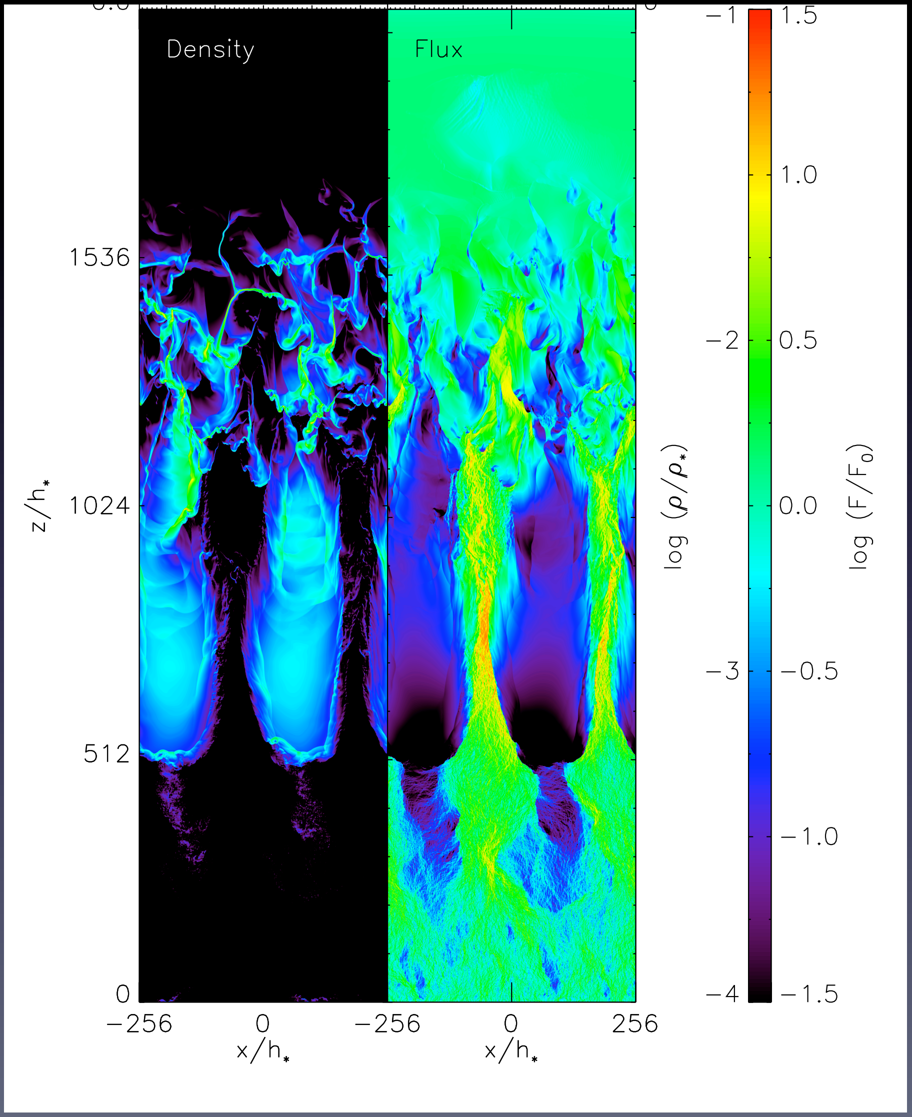


Conclusions:

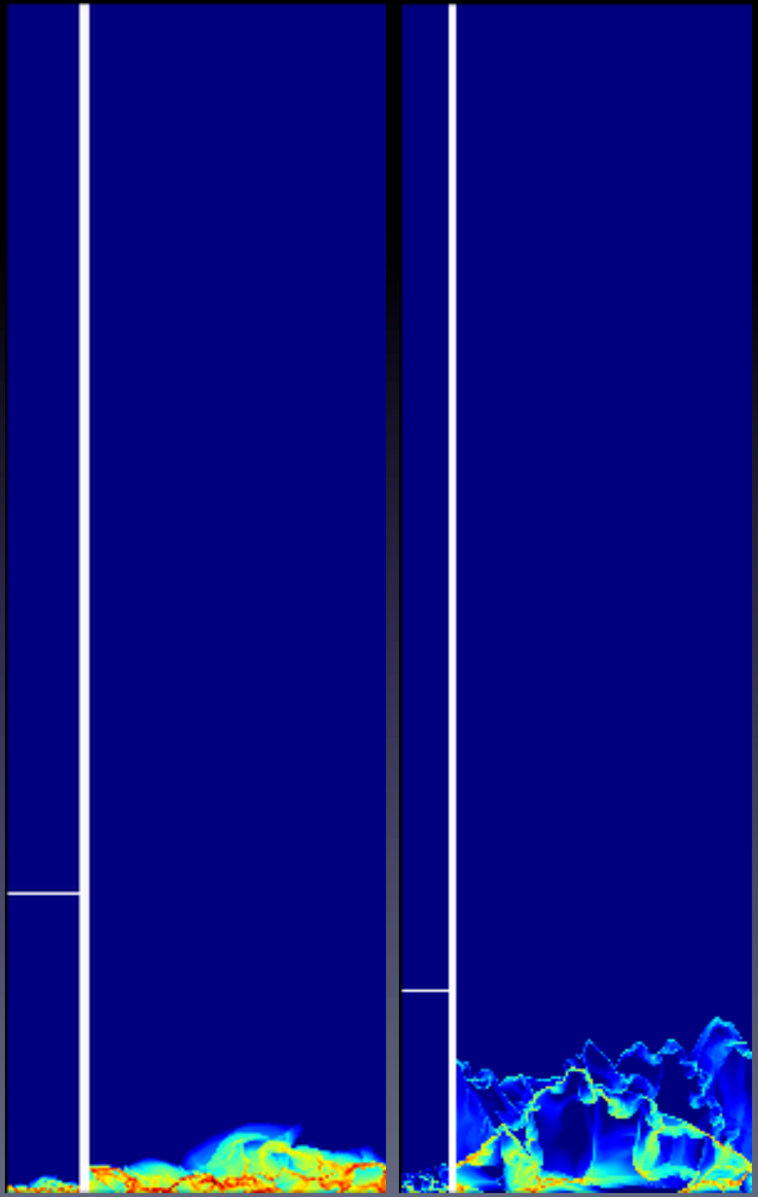
1. No wind is driven when $f_{E,*} < 1$
2. Radiation drives gas to supersonically turbulent state
3. f_{trap} self-adjusts so mass-weighted Eddington ratio = 1
4. $f_{trap} << \tau_{IR}$

Radiation RT Instability

- Radiation force small due to radiation RT instability ➔ density-flux anti-correlation (Jacquet & Krumholz 2011; Jiang et al. 2013)
- This is missed in simple 1D models



Simulations: $f_{E,*} > 1$



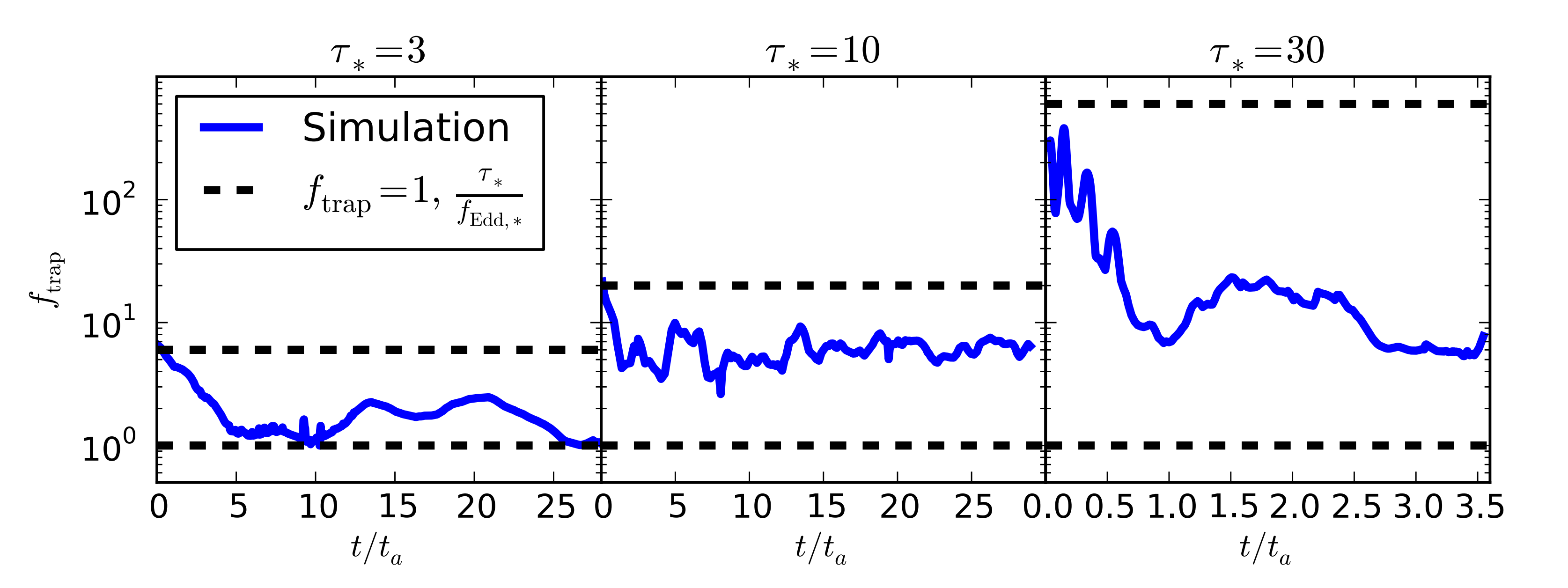
Turn off gravity in last set of simulations, so $f_{E,*} = \infty$ and wind develops

Models shown:

- $\tau_* = 3$
- $\tau_* = 10$

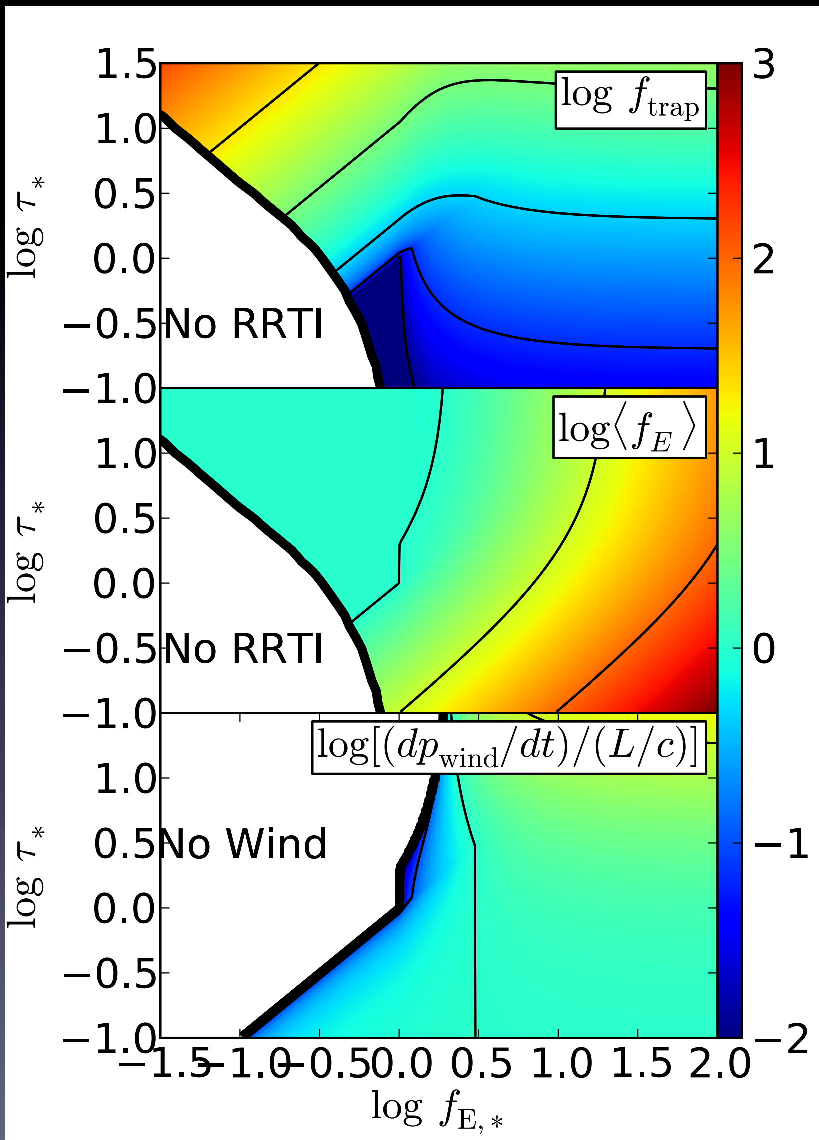
(Krumholz & Thompson 2013)

Trapping and Winds at $f_{E,*} >> 1$



- Wind is launched
- Without gravity, f_{trap} drops sharply
- $f_{trap} \sim \tau_*/2$ for $f_{E,*} >> 1$
- $f_{trap} << \tau_{IR}$, and does not scale lienarly in τ_{IR}

Interpolate Between Models



Identify three regimes:

- $f_{E,*} < f_{E,crit}$: hydrostatic
- $f_{E,crit} < f_{E,*} < 1$: no wind, turbulence, f_{trap} goes to value such that $\langle f_E \rangle = 1$
- $f_{E,*} > 1$: wind is driven, but f_{trap} small unless $\tau_* \gg 1$, so wind momentum flux ~ L/c

Krumholz & Thompson (2013)

Application to Clusters, Galaxies

For clusters (young stars) with $M_* = M_{gas}$:

$$\tau_* = 0.8 \left(\frac{\Sigma}{1 \text{ g cm}^{-2}} \right)^{3/2}$$

$$f_{E,*} = 0.02 \left(\frac{\Sigma}{1 \text{ g cm}^{-2}} \right)^{1/2}$$

For galactic disks (old stars) with $f_{gas} = 0.5$:

$$\tau_* = 0.7 \left(\frac{\dot{\Sigma}_*}{10^3 \, M_\odot \text{ pc}^{-2} \text{ Myr}^{-1}} \right)^{1/2} \left(\frac{\Sigma}{1 \text{ g cm}^{-2}} \right)$$

$$f_{E,*} = 0.4 \left(\frac{\dot{\Sigma}_*}{10^3 \, M_\odot \text{ pc}^{-2} \text{ Myr}^{-1}} \right)^{3/2} \left(\frac{\Sigma}{1 \text{ g cm}^{-2}} \right)^{-1}$$

Implications

- Galaxies have $\tau_* <\sim 1$ and $f_{E,*} <\sim 1$ ➔ $f_{trap} < 1$, so radiation pressure cannot drive galactic winds
- Star clusters also have $\tau_* <\sim 1$ and $f_{E,*} <\sim 1$, so *trapped* radiation pressure is also unimportant for star clusters…
- … however, recall that for $v_{esc} < 100$ km s^{-1}, *direct* radiation pressure can be significant

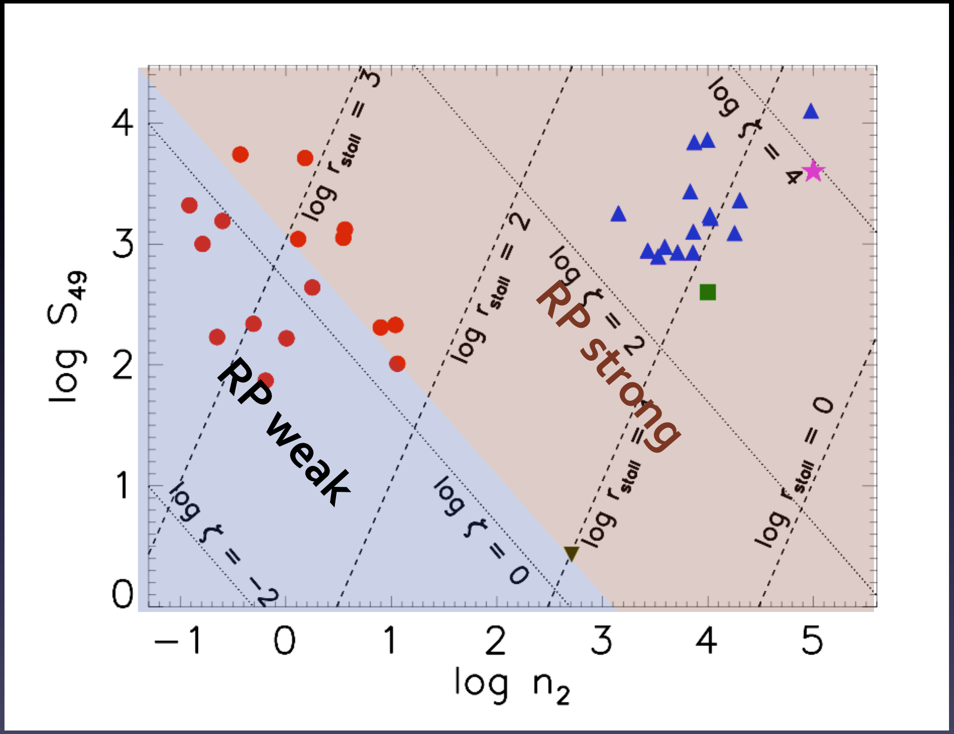
Direct Radiation Pressure Driving

- In an HII region, $P_{gas} < P_{rad}$ at radius (Krumholz & Matzner 2009; Yeh+ 2013)

$$r_{\rm ch} \approx \frac{\alpha_{\rm B} L^2}{12\pi(2.2k_B T c)^2 S}$$

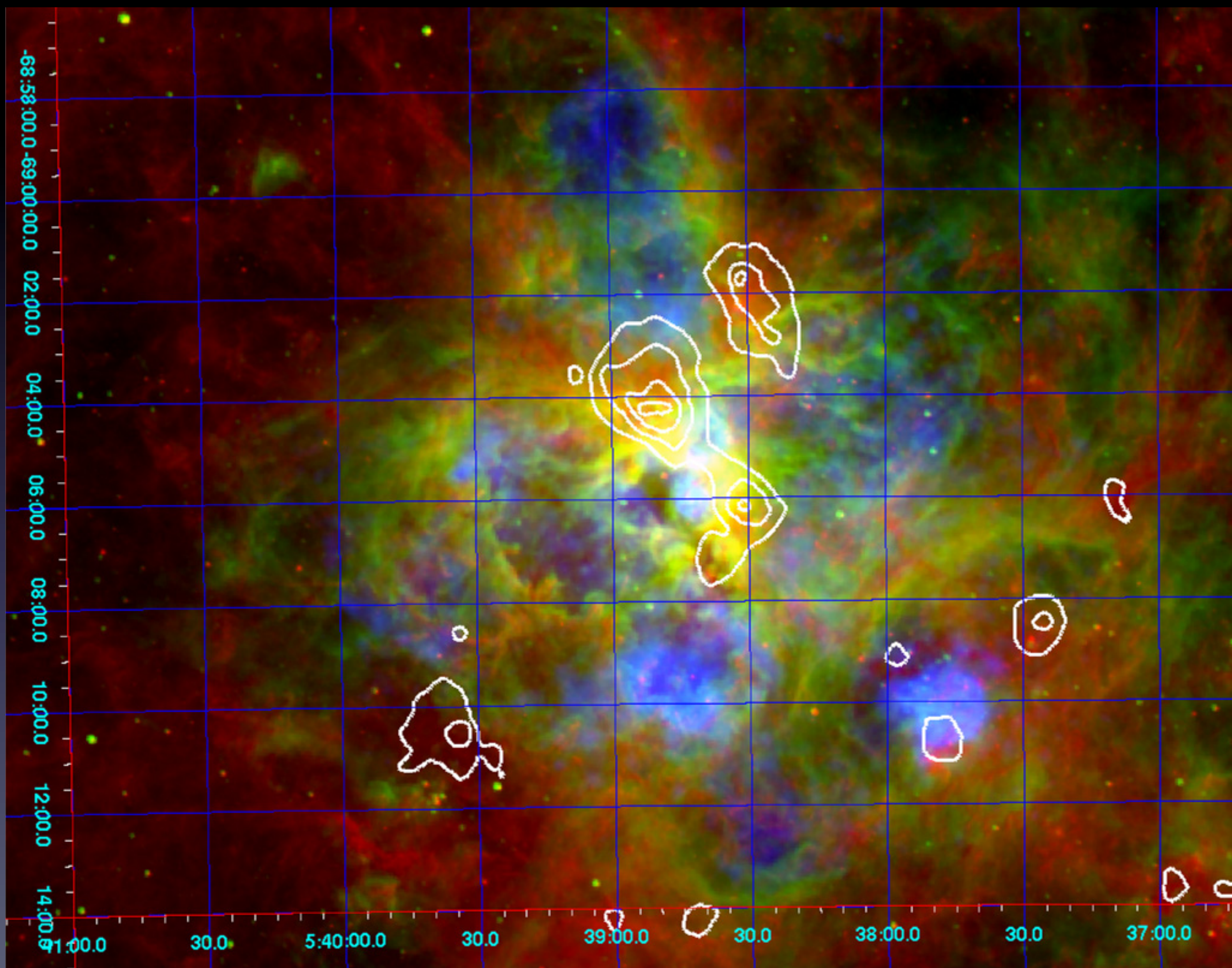
$$\approx 0.9 \left(\frac{L}{10^7\,L_\odot}\right)\ \rm pc$$

- For R136, r_{ch} = 6 pc; cluster core radius ~3 pc



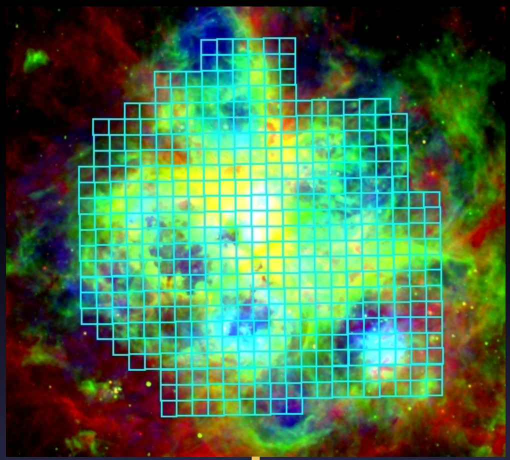
Sample of clusters: M82 (blue), Atennae (red), Arches (green), Orion (brown); ς is r_{ch} / $r_{Strömgren}$ (Krumholz & Matzner 2009)

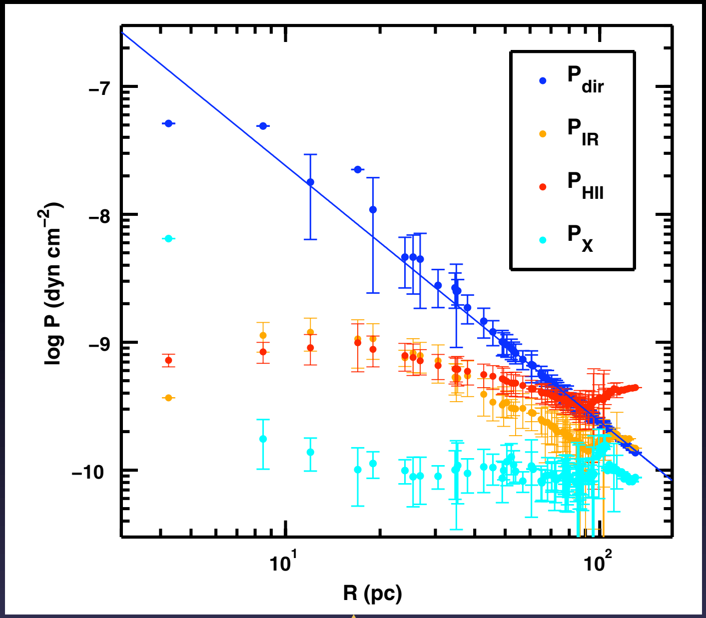
Observational Test: 30 Dor

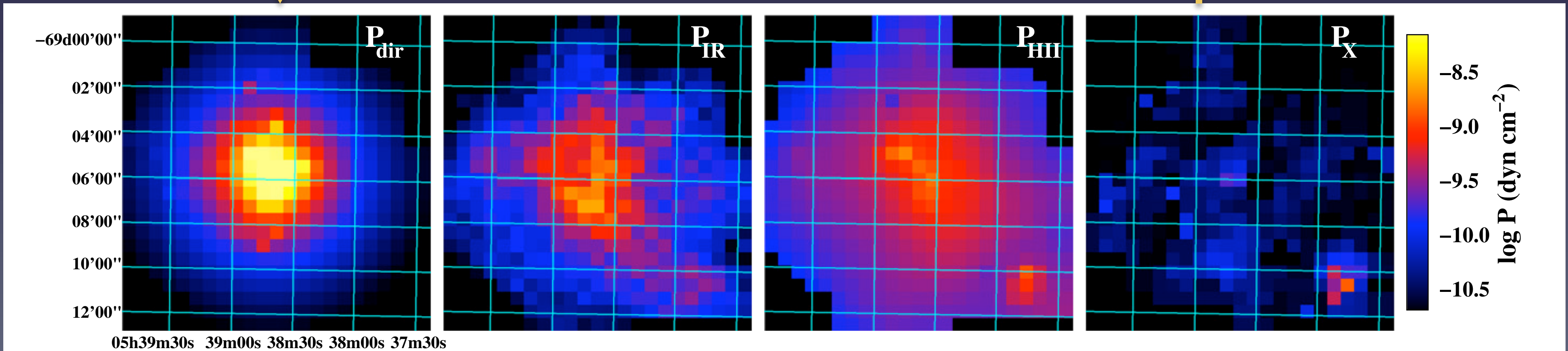


30 Dor in 8 μm (red), Hα (green), x-ray (blue), and CO (white contours) (Lopez+ 2011)

Pressures in 30 Dor







Summary

- Radiation drives dusty winds only if it is super-Eddington at the dust photosphere
- Wind momentum flux ~ $(\tau_*/2)$ $(L/c) << \tau_{IR}$ (L/c)
- Radiation pressure feedback unimportant on galaxy scales
- *Direct* radiation likely important for clusters; there is direct observational evidence for this