Feedback and **Accretion** in **Star Cluster Formation**

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Motivating questions:

Where does star cluster formation (SCF) fit in the continuum of formation phenomena?

What parameters characterize SCF?

What are the relative roles of feedback and accretion in star cluster formation (SCF)?

Which GMC properties control the outcome?

What terminates star cluster formation?

Single SF

Binary/Multiple SF

Star Cluster Formation

Molecular cloud formation

Galaxy formation

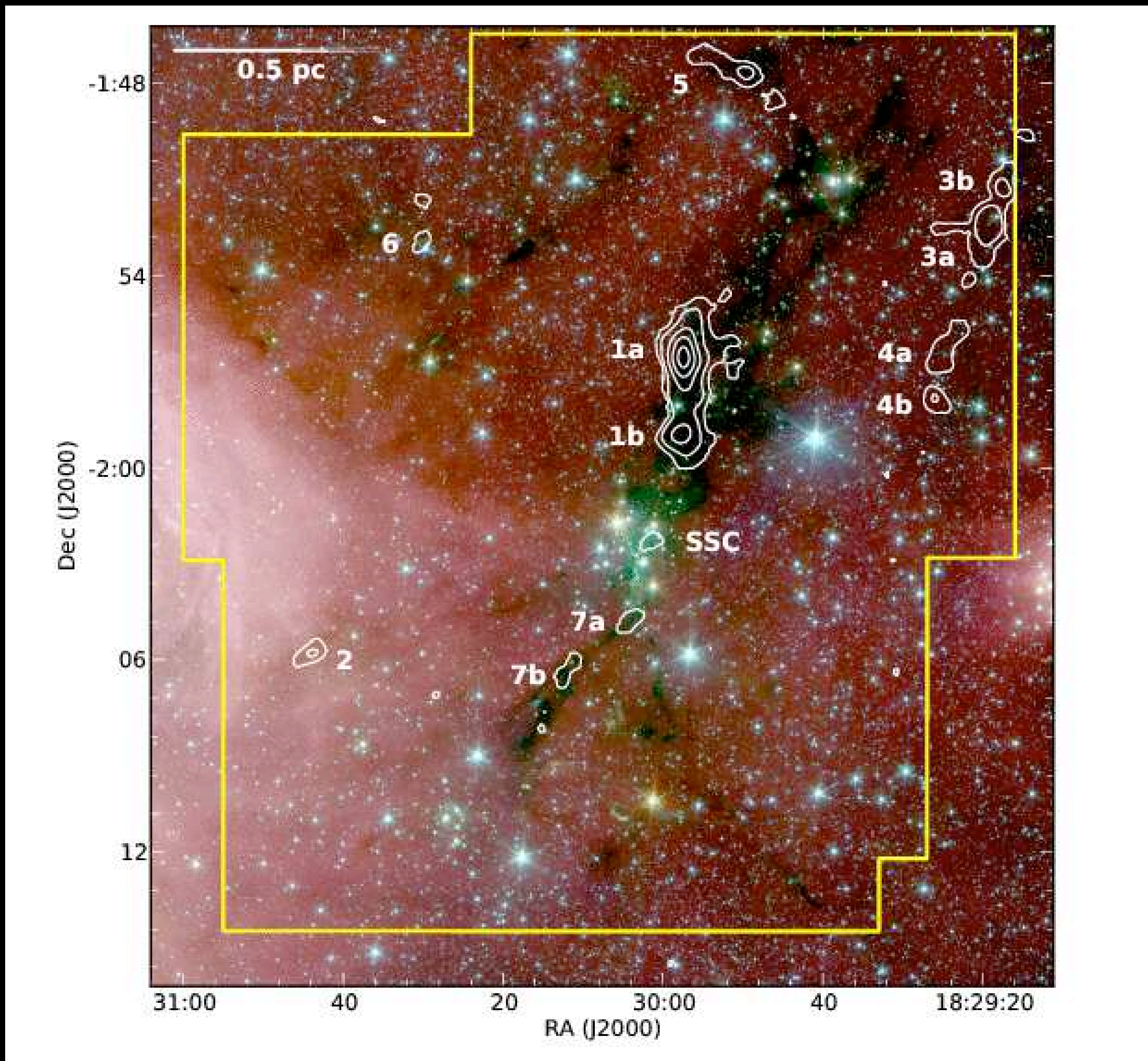
Single SF

Binary/Multiple SF

Star Cluster Formation

Molecular cloud formation

Galaxy formation



Serpens South protocluster

Spitzer: Gutermuth + 08 HC$_7$N: Friessen + 13

Parameters for rapid inflow in SCF

Dimensional: M_c R_c σ_c $\dot{M}_{\rm in}$ $|\langle \mathbf{j}_{\rm in} \rangle|$

$\dot{M}_c$ M_g $\dot{M}_*$ c_s t + magenetization + feedback

Dimensionless:

Virial	Inflow	Rotation	Effic.	Gas fcn.	SFR	Mach	Growth
$\frac{5\sigma_c^2 R_c}{G M_c} = \alpha_c$	$\frac{G\dot{M}_{\rm in}}{\sigma_c^3} = \xi_c$	$\frac{\dot{M}_{\rm in} j_{\rm in}^3}{G^2 M_c^3} = \Gamma_{\rm rot}$	$\frac{\dot{M}_c}{\dot{M}_{\rm in}} = \varepsilon_{\rm in}$	$\frac{M_g}{M_c} = f_g$	$\frac{\dot{M}_* t_{\rm ff}}{M_g} = {\rm SFR}_{\rm ff}$	$\frac{\sigma_c}{c_s} = \mathcal{M}$	$\frac{\dot{M}_c t}{M_c} = \eta_M$

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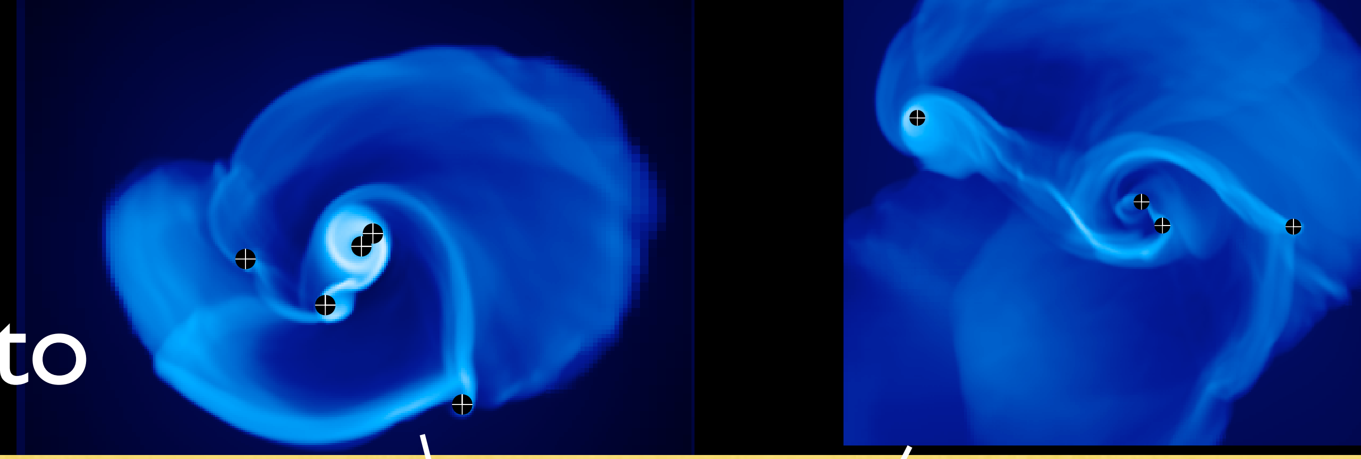
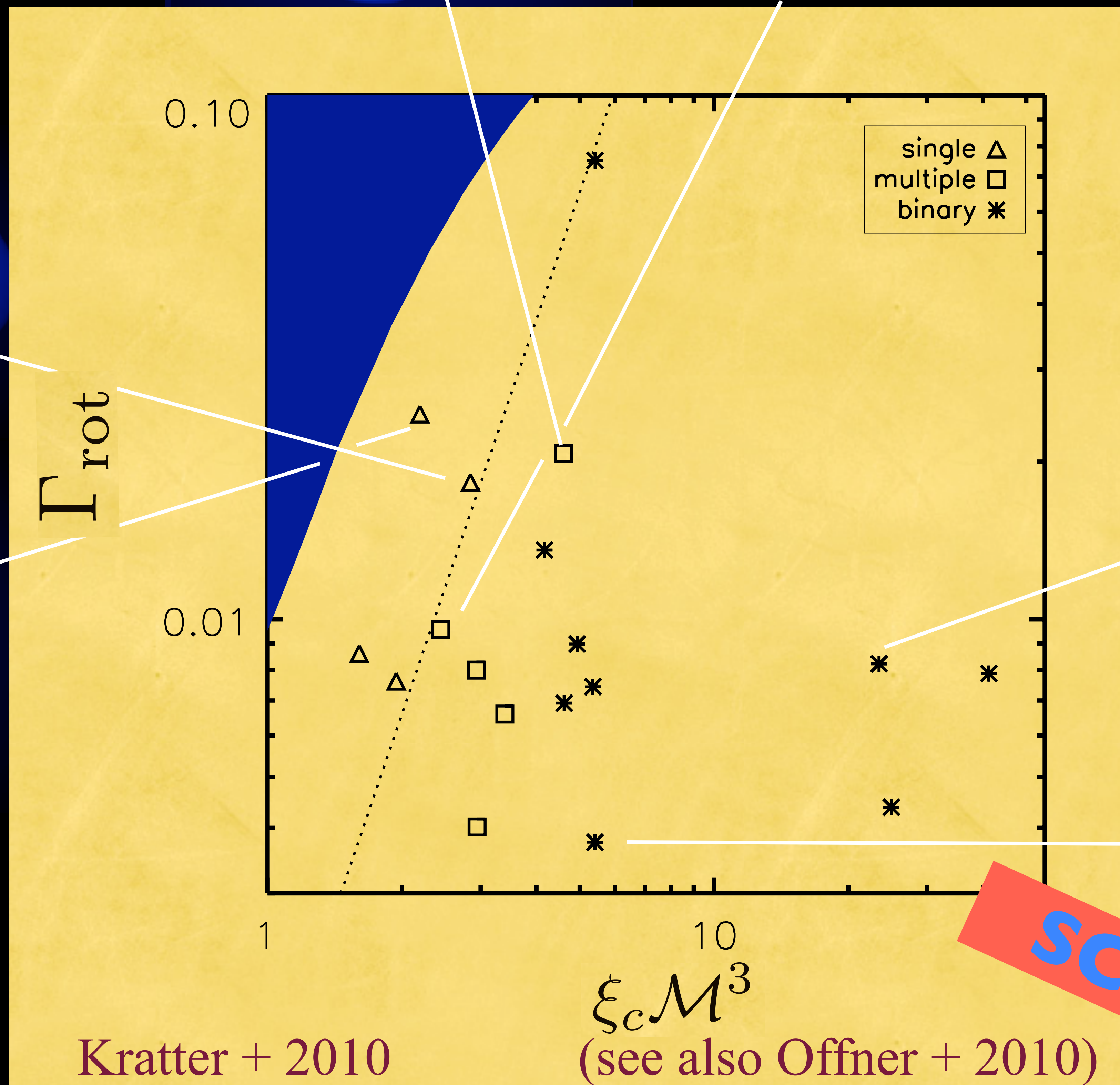
$$\dot{M}_{\rm in} :: \dot{M}_* :: \frac{M_c}{t_{\rm ff}} = \frac{{\alpha_c}^{3/2}\xi_c}{10.1} :: f_g {\rm SFR}_{\rm ff} :: 1$$

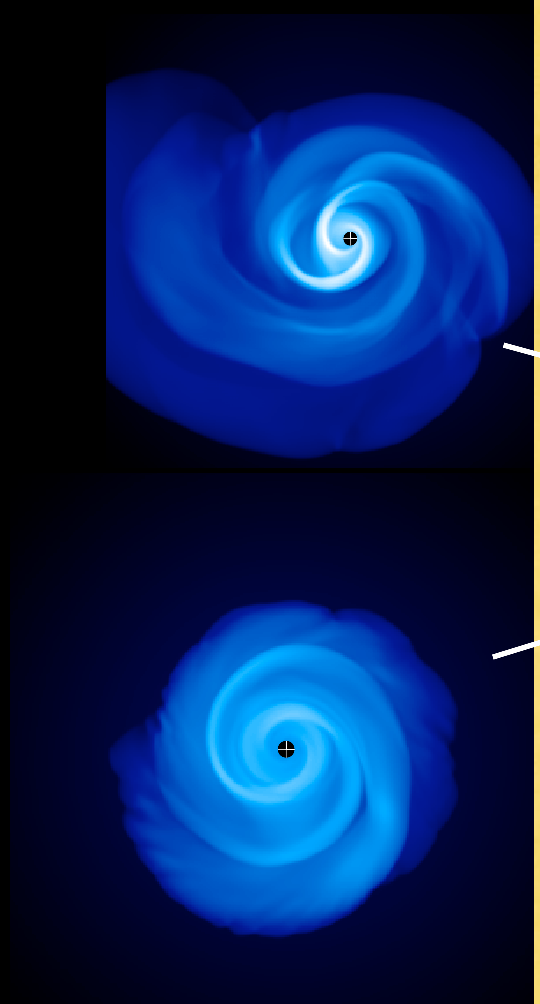
$$\frac{R_{\rm Kep}}{R_c} = \frac{5}{\alpha_c}\left(\frac{\Gamma}{\xi_c}\right)^{2/3}$$

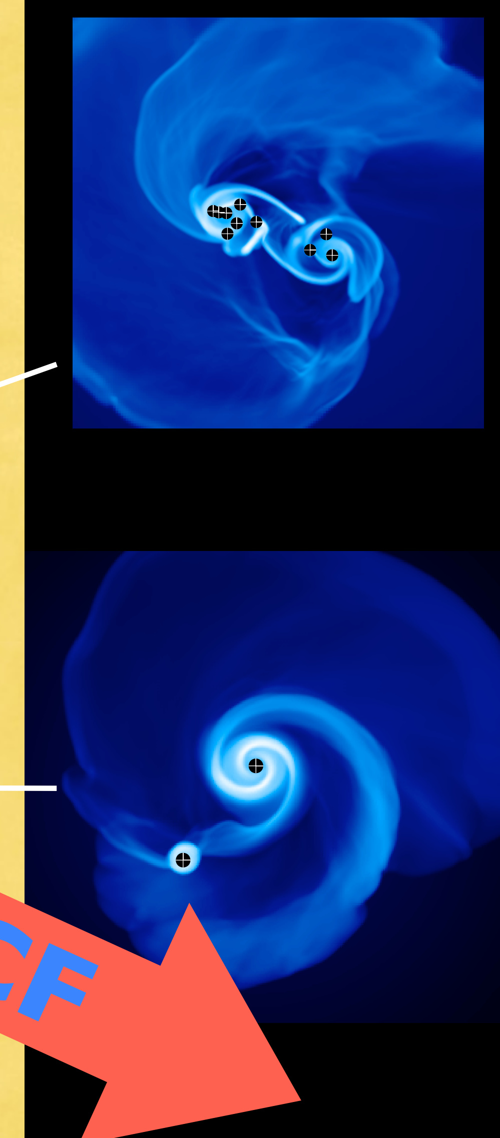
$$\frac{M_c}{M_{\rm BE}} = \frac{4.63 f_g^{1/2}}{{\alpha_c}^{3/2}}(\mathcal{M}^2+1)^2$$

Star formation: parameters map to multiplicity









Self-similar virialized growth?

$\eta_M \quad \alpha_c \quad \xi_c$ stay fixed

$\Gamma_{\rm rot} \quad P_{\rm ext}/(G\Sigma_c^2)$ negligible or const.

$\varepsilon_{\rm in} \quad f_g \quad {\rm SFR}_{\rm ff}$ vary slowly

$$\frac{1}{f_g} = 1 + \frac{10.1\,{\rm SFR}_{\rm ff}}{\varepsilon_{\rm in}\xi_c{\alpha_c}^{3/2}}$$

What would make this possible?

Accretion-driven turbulence?

Wise & Abel 07
Wang & Abel 08
Klessen & Hennebelle 10
Vazquez-Semandeni + 10
Goldbaum + 11
Hennebelle 2012

Goldblaum+ 11

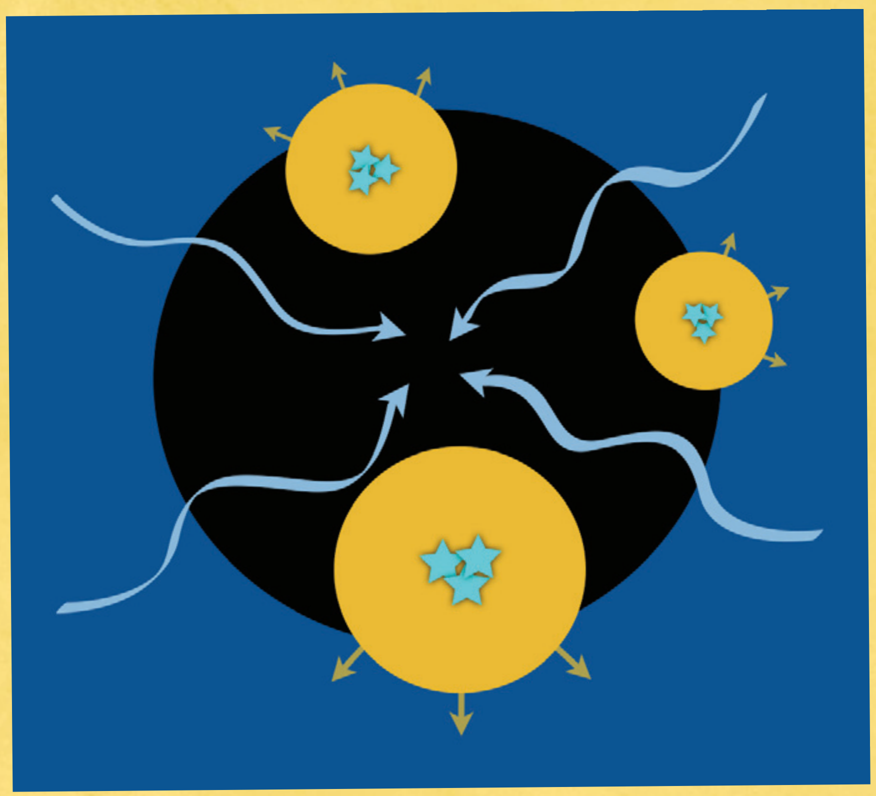
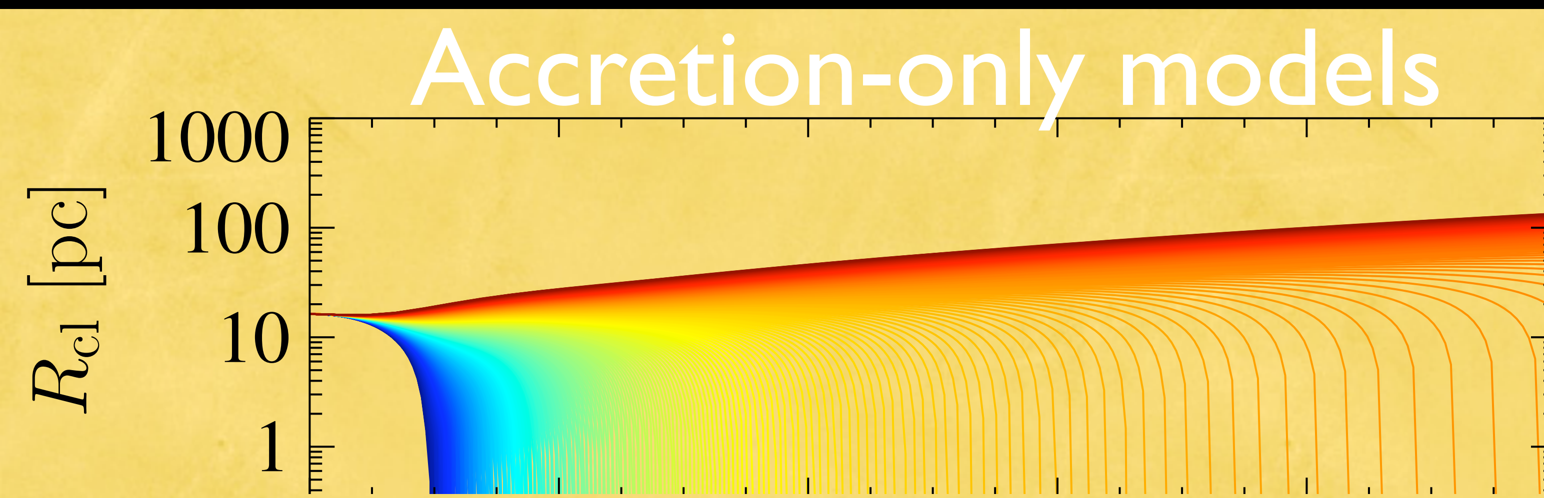


Figure 1. Schematic overview of the GMC model. A molecular cloud (black) is embedded in a warm atomic envelope (dark blue). Cool atomic gas (light blue) flows onto the cloud, where it condenses, recombines into molecules, and mixes with the cloud. Newborn OB associations (blue stars) drive H II regions (orange) and eject ionized winds back into the ambient medium.



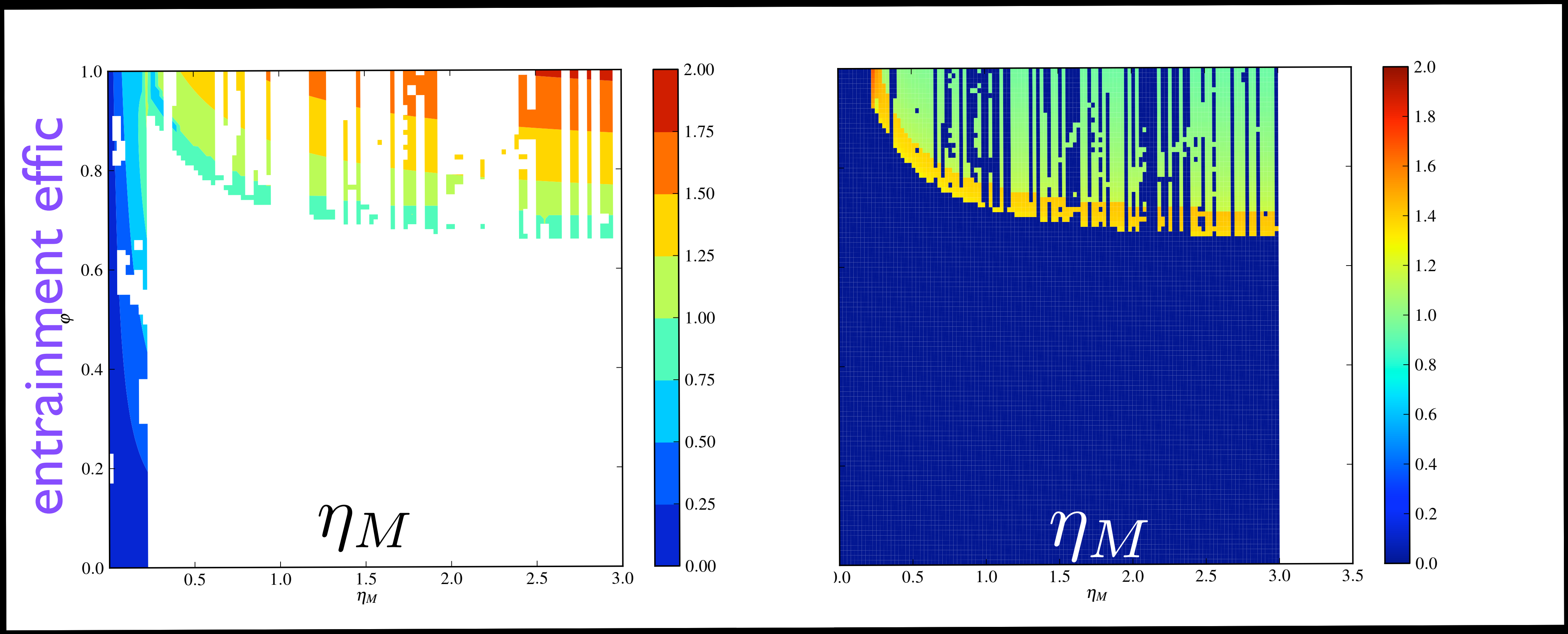
Turb. driving by HII rgns [Matzner 02, Krumholz&CDM 09] + Accretion

Evolution from dynamical virial theorem [Matzner 99, Krumholz+ 06]

What would make this possible?

Accretion-driven turbulence?

Search for self-similar growth solutions in G+11 eqs:



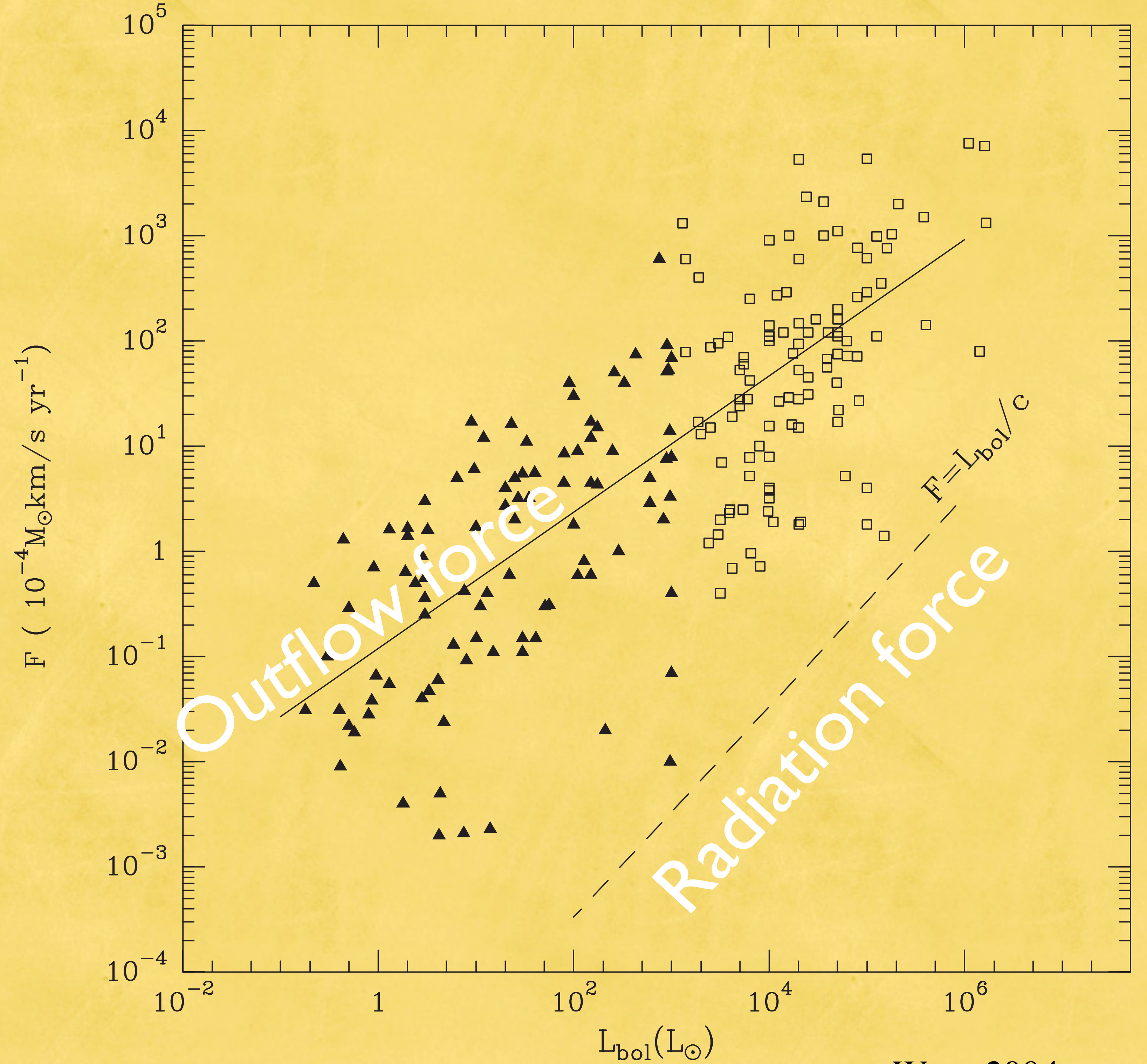
α_c ξ_c

Feedback vs. Inflow: Protostellar outflows

Theory: Norman & Silk 80; McKee 89; CDM & McKee 99, 00; Matzner 07 (but see Banerjee+ 07)
Simulations: Nakamura / Li 06,7,8; Cunningham+ 06; Frank 07; Carroll+ 09; Wang+ 10, Cunningham+ 09,11, Krumholz + 12, Hansen + 12, Klein 13, Offner & Arce 14, Myers + 14, Federrath+ 14 ...
Observations: Levrault 84; Myers 88; ... Bally+ 94; Quillen+ 05; Graves+ 10; Nakamura+ 11; Mottram & Brunt 12; Plunkett+ 13 *and many more*

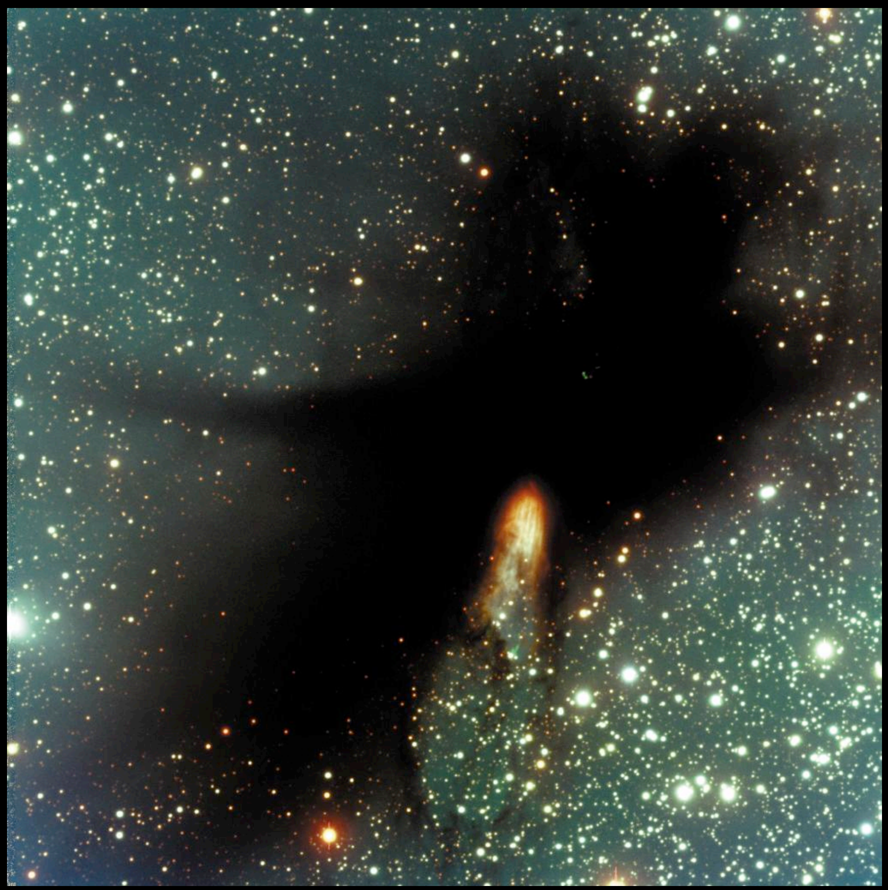
Outflows:

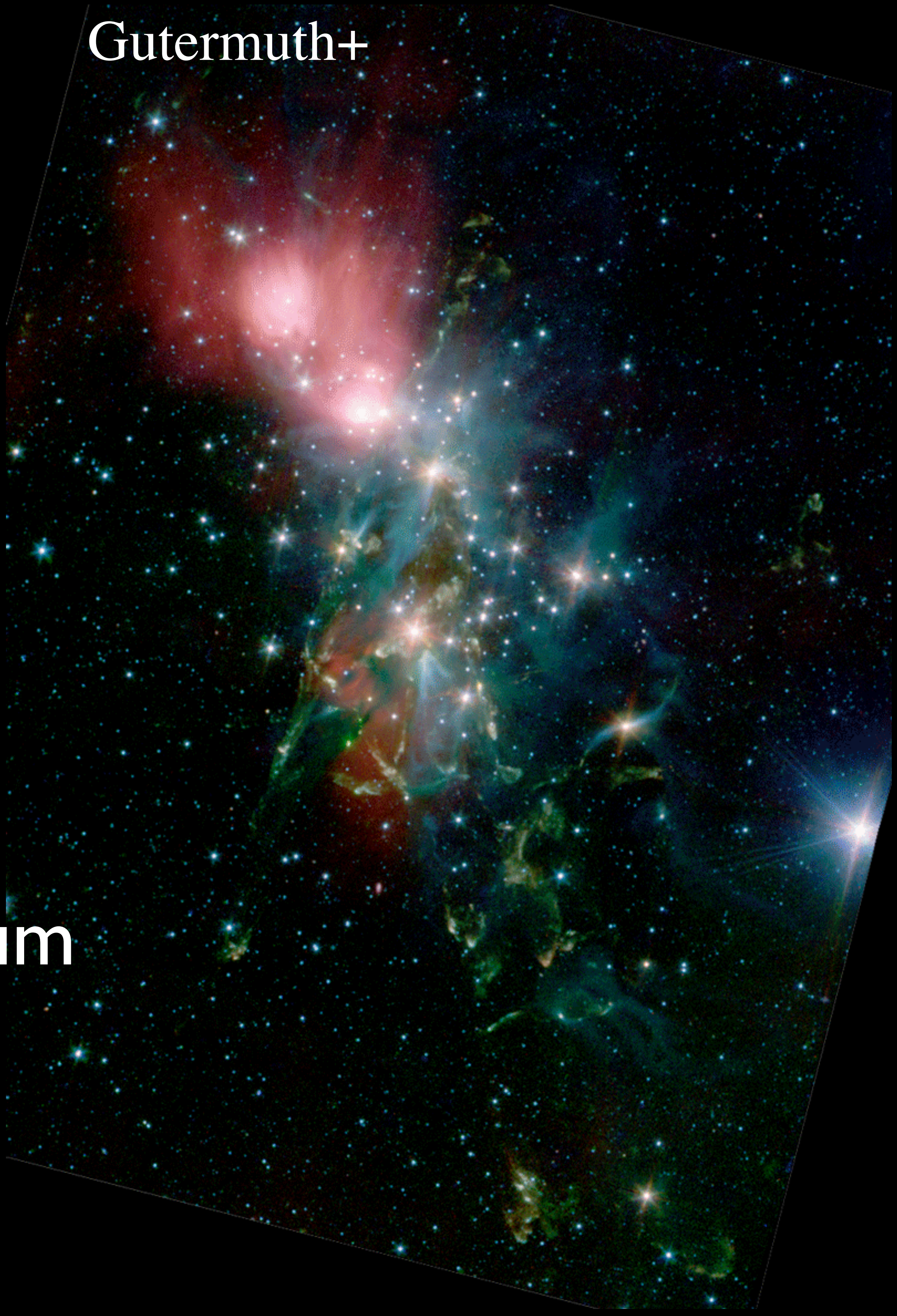
- Accompany all star formation
  - precede, outnumber massive stars' feedback
- Coincide in time with star cluster formation
- Emit far more momentum than starlight (while they last)
- Are highly collimated *but also* exert force at wide angles
  [Shu+ 05, CDM & McKee 99]
- Couple well with dense gas on 0.1 parsec scales



10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
$F\ (10^{-4} M_{\odot} km/s\ yr^{-1})$
$L_{bol}(L_{\odot})$
$F=L_{bol}/c$
Outflow force
Radiation force

Wu + 2004





Critical parameter:
mean outflow momentum per stellar mass, $v_{\rm of}$

Feedback vs. Inflow: Protostellar outflows

Simple force estimate

gravity :: inflow force/mass :: outflow force/mass

$$\frac{GM_c}{R_c^2} :: \frac{\dot{M}_{\rm in} v_{\rm esc}}{M_g} :: \frac{\dot{M}_* v_c}{M_g}$$

$$\left(\frac{4}{\alpha_c}\right)^{3/2} \frac{f_g}{\xi_c} :: 1 :: \frac{3.2 f_g}{\alpha_c} \frac{\mathrm{SFR}_{\rm ff} v_{\rm of}}{(\xi_c G \dot{M}_{\rm in})^{1/3}}$$

$$\gtrsim 1 \quad :: 1 :: \quad \sim 1$$

More complicated estimate: Matzner 07 model

- Couple outflows to turbulent cascade of momentum in self-consistent $\sigma(r)$
- Account for collimation & mass function
- Allow escape of momentum (& mass)
- Allow for externally driven cascade, i.e. accretion

coupling coeff

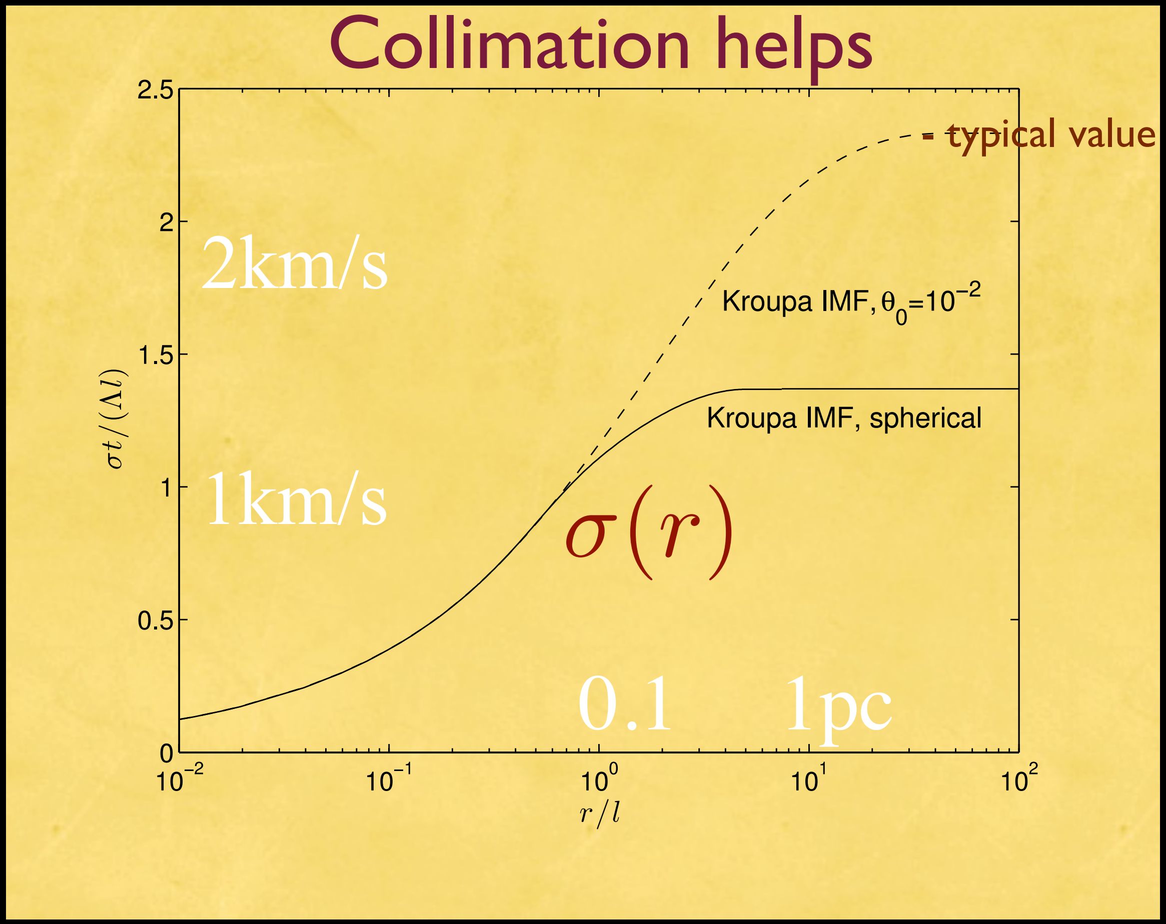
escape of finite region

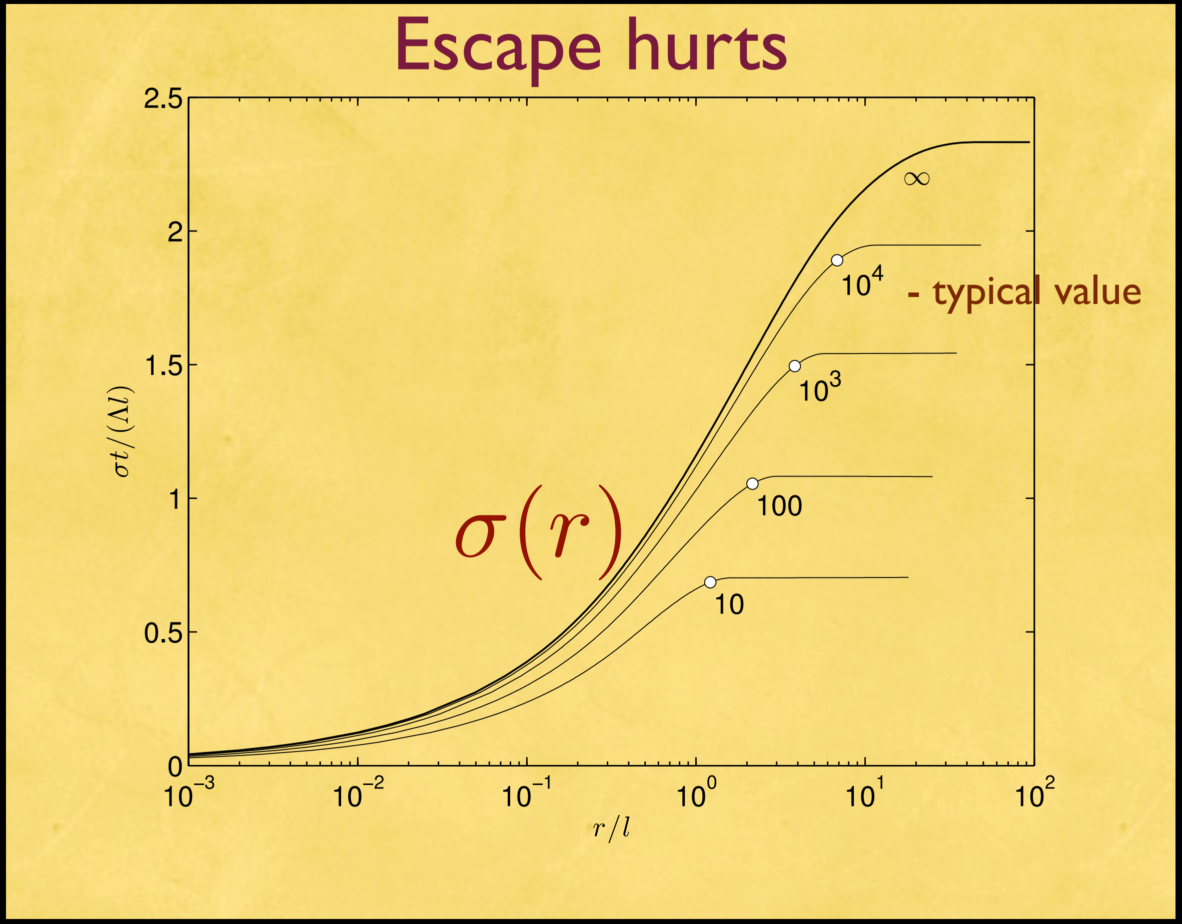
$$\frac{d\sigma^2}{dr} = a_{\rm ext} + \frac{\Lambda^2}{\rho_g} \int_{\hat{S}(\hat{\mathcal{I}}(r))}^{\hat{S}(\mathcal{I}_{\rm esc})} \hat{\mathcal{I}}' \, d\hat{S}'$$

inflow

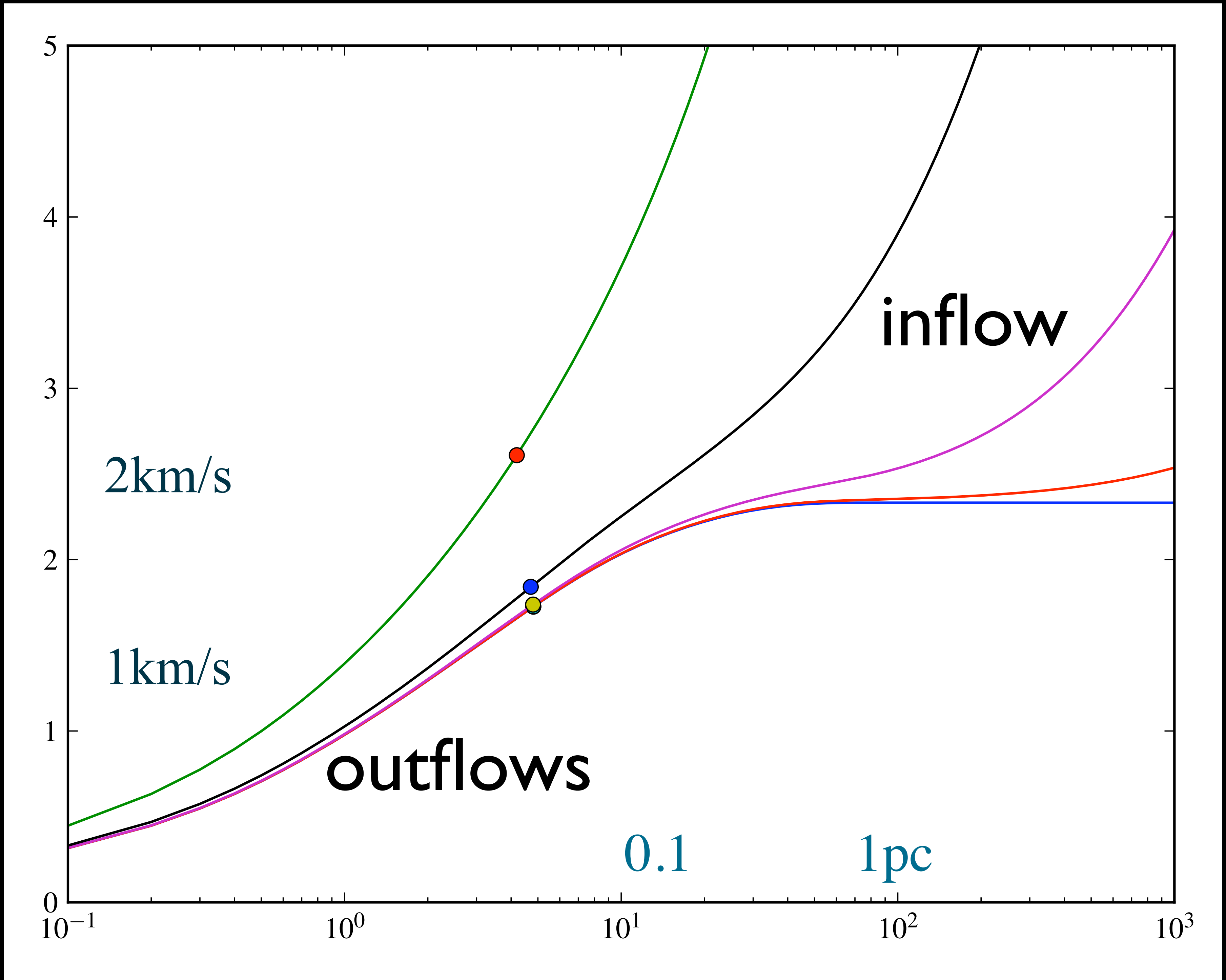
impulse distribution

Outflow driving [Matzner 07]





Thanks to collimation, simple estimate is pretty good.



5
4
3
2
1
0
inflow
2km/s
1km/s
outflows
0.1
1pc
10^{-1}
10^0
10^1
10^2
10^3

Feedback vs. Inflow: Important points

1. Accretion-driven turbulence should be strongly modified by the presence of accretion

2. Outflow driving may not be strong enough on its own.

3. Even if it is, outflow-driven equilibrium states are unstable! (*)

4. Quite possibly, they need each other.

What is the nature of proto-cluster accretion?

Colliding flows

[Vazquez-Semadeni + 96]

?

Inside-out collapse

[Myers & Fuller 92, McLaughlin & Pudritz 97, McKee & Tan 03]

$$2 \lesssim \eta_M \lesssim 4$$

Murray+ (today):

Bondi accretion

[Naiman+ 11, Murray & Chang 12]

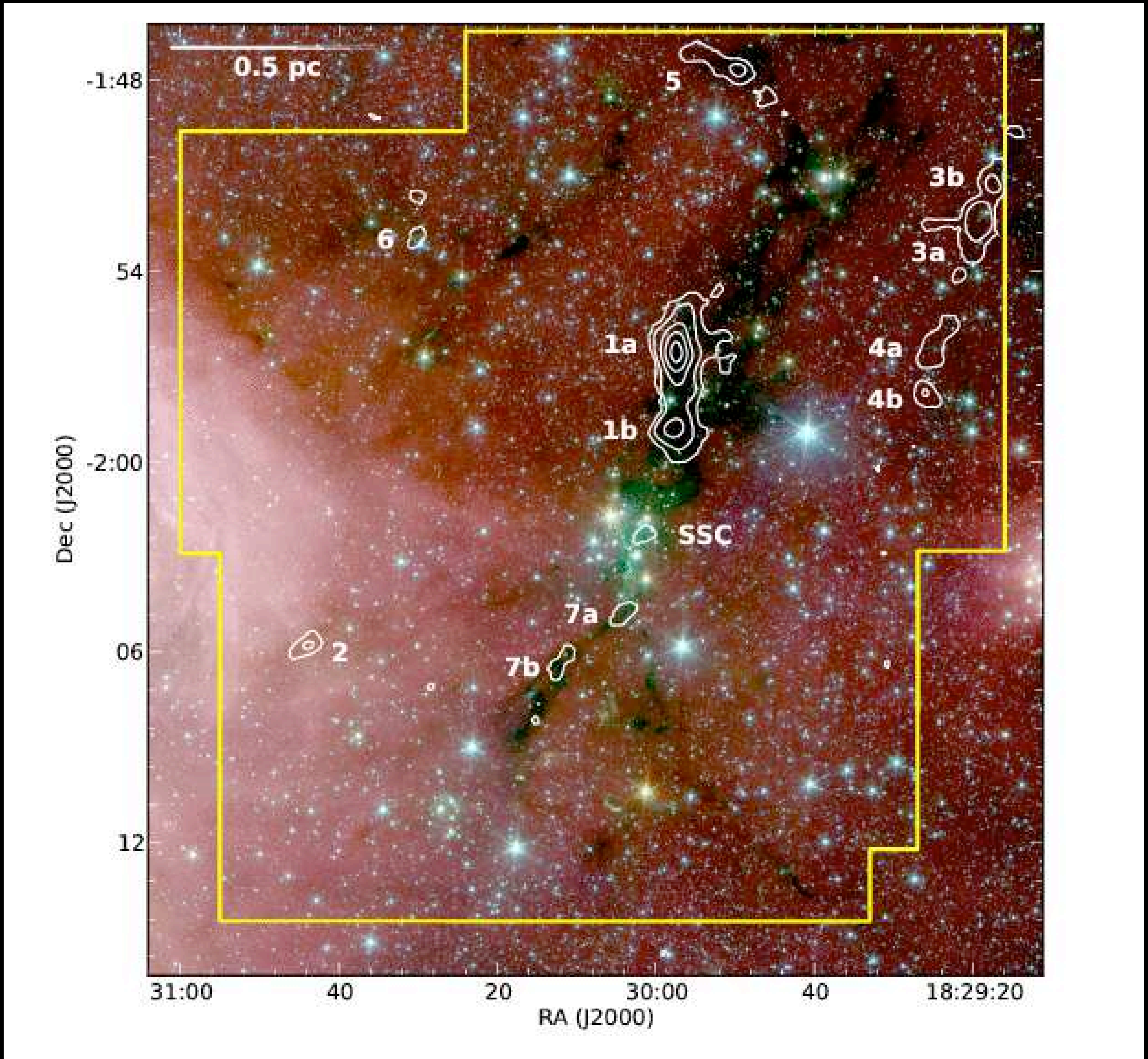
Filamentary infall

[Pon + 11]

$$\eta_M \gtrsim 1$$

← **Virial parameter of environment**

Kauffmann + 13 →



Filamentary infall

Filament *initial* mass/ length

$$2\lambda_{\rm fil}\frac{\sigma_{\rm fil}^2}{G}$$

$$\rightarrow 180\lambda_{\rm fil} M_\odot {\rm pc}^{-1}$$

Infall rate

$$2.5(N_{\rm fil}\lambda_{\rm fil})^{3/2}\frac{\sigma_{\rm fil}^3}{G}$$

$$\rightarrow 400\lambda_{\rm fil}^{3/2} M_\odot {\rm Myr}^{-1}$$

Protocluster

$$\sigma_c = 1.4\frac{(N_{\rm fil}\lambda_{\rm fil})^{1/2}}{\xi_c^{1/3}}\sigma_{\rm fil}$$

$$\rightarrow 1.3\lambda^{1/2}\xi_c^{-1/3}{\rm km/s}$$

Conclusions & further questions

Clusters inherit their properties from GMCs primarily via the accretion history.

Feedback and accretion conspire to create a stable protocluster.

Outflows dominate feedback (up to some cluster mass)

What ends cluster formation?

Why are GMC and cluster formation not disky?