Dynamical Feedback in Star Formation

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Question from *Star formation then & now:*

Is stellar feedback important in current star formation?

When and how?

Why feedback?

Stars are deep potential wells (v_{esc} ~ hundreds of km s^{-1}) with very high nuclear energy budgets.

They interact with gas for which v_{esc} ~ a few km s^{-1}.

The interaction is radiative and inefficient, but cannot be less efficient than pure momentum conservation.

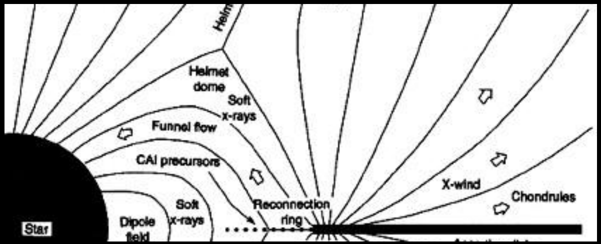
For dense gas, their effect is strong enough to replenish turbulence and influence any ongoing star formation.

Star formation is inefficient (not just slow).

Part 1 – protostellar outflows Part 2 – HII regions

Dynamical feedback by protostellar outflows

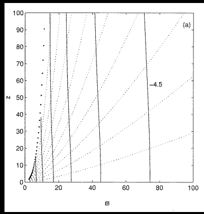
Step 1: Magnetic fields channel a fraction *f* of accretion into wind



Shang et al 97

Wind velocity ~ stellar escape speed
Low-mass stars: wind momentum is
($f\ v_w$ ~ 40 km/s) times M_*

Step 2: Magnetic fields collimate wind into an asymptotically universal structure.



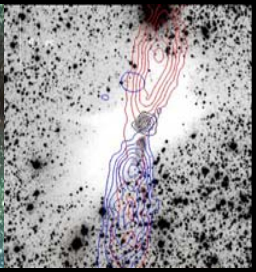
Shu et al 96

Toroidal fields relax to force-free state $B_\phi \sim 1/(r \sin\theta)$
Poloidal fields and mass flux are collimated this way
Alfven Mach number varies slowly, so $\rho v_w^2 \sim 1/(r \sin\theta)^2$
NOTE: Momentum evenly distributed across log(θ) or log(ram pressure)
Significant wide-angle component

Shu et al 98 / Ostriker 98 / Matzner & McKee 99

Step 3: Radiative interaction with ambient gas
Radial momentum is approximately conserved

Alves et al.



Garay et al.

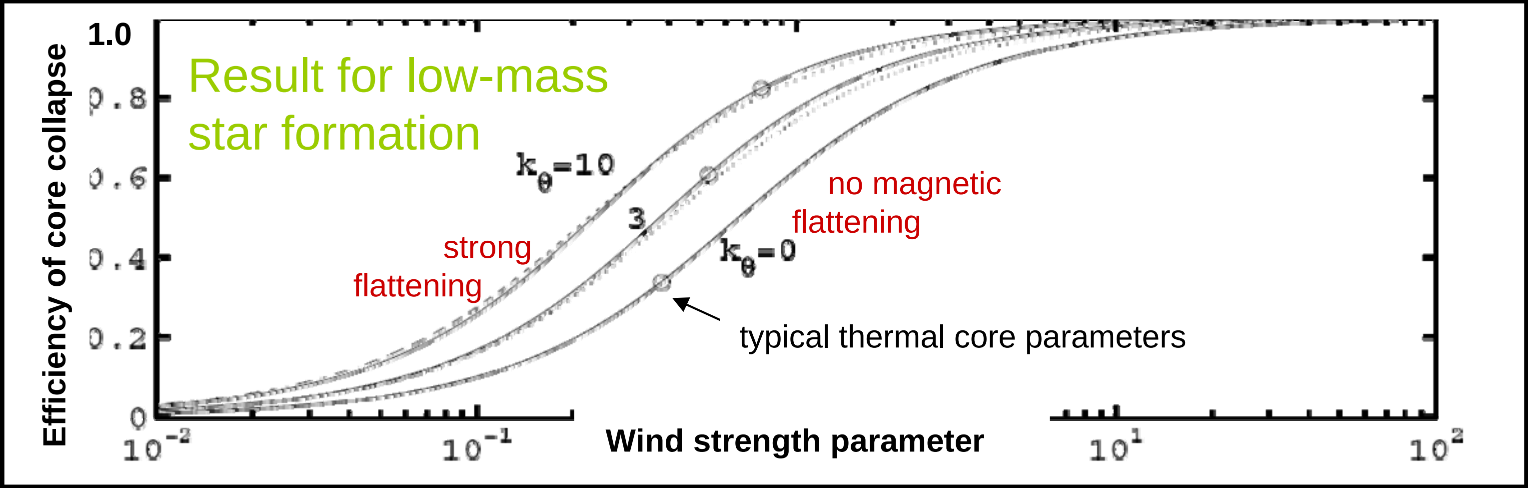
Dynamical feedback by protostellar outflows

1. Blowout of mass: maximum efficiency Matzner & McKee 2000

Convert a fraction ε of the cloud into stars

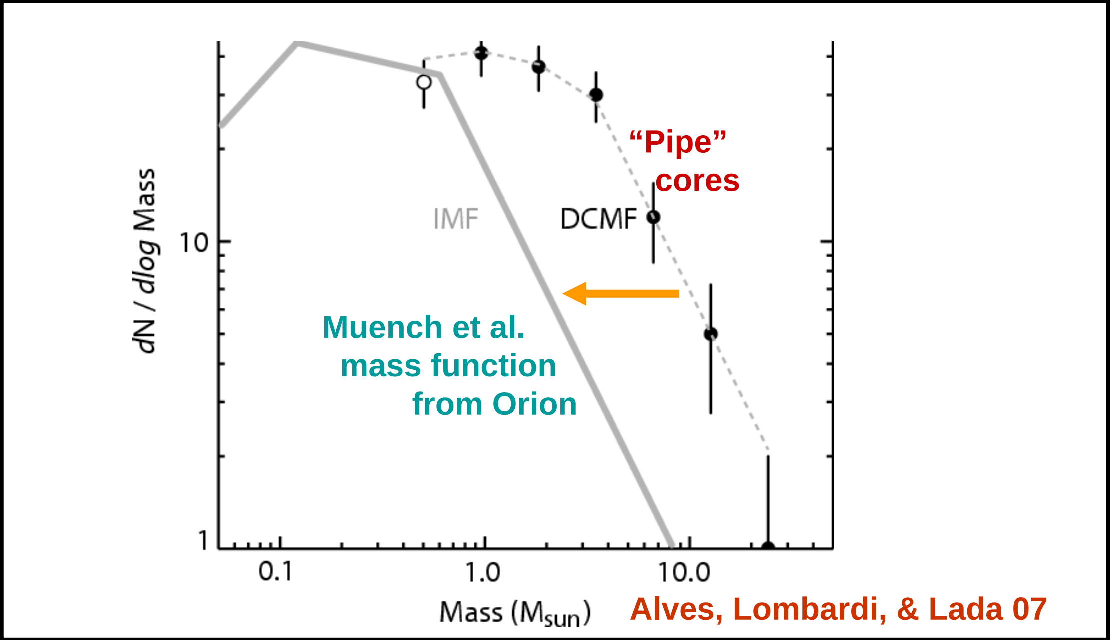
$$\frac{\text{Momentum output}}{\text{Binding momentum}} = \frac{(M_* = \varepsilon M_{cl})\,(f\, v_w)}{M_{cl}\, v_{esc}} \sim 1 * (\text{logarithmic correction})$$

$$\text{so} \quad \varepsilon \sim \frac{v_{esc}}{f\, v_w} * (\text{log.corr.})$$



Is there evidence?

A hint of mass loss in the core-to-star transition



And, low star formation efficiency in cluster formation, and a prevalence of unbound associations

Dynamical feedback by protostellar outflows

2. Reinvigoration of turbulence

Back-of-envelope version
see Norman & Silk 1980

depends on collimation

Catch a fraction $\varphi \sim 0.5$ of the outflow momentum $M_* f v_w$

Outflows degenerate into turbulent motions when $v_{shell} \sim \sigma_v$

By momentum conservation, each sweeps up a mass

$$M_{swept} = \frac{\varphi f v_w}{\sigma_v} M_* \sim \frac{40\ \varphi\ \mathrm{km\ s^{-1}}}{\sigma_v} M_*$$

The fraction of the mass per free-fall time touched by outflows traveling faster than σ_v is therefore

$$\frac{40\ \varphi\ \mathrm{km\ s^{-1}}}{\sigma_v}\ SFR_{ff}$$

But this should not exceed ~1 or σ_v was incorrect, so

$$\sigma_v \sim 40\ \varphi\, SFR_{ff}\ \mathrm{km\ s^{-1}} \sim 1\text{-}2\ \mathrm{km/s}$$

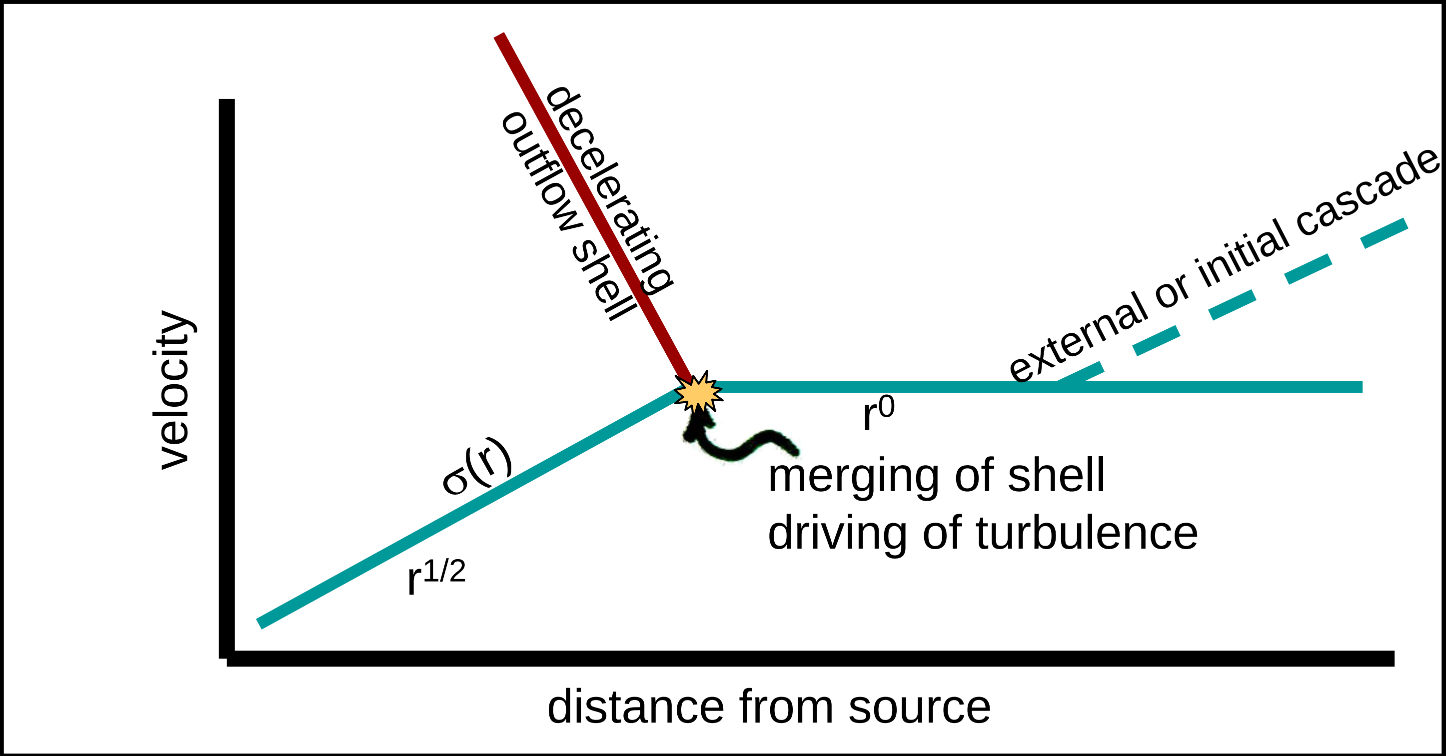
for *slow* star formation

@ $SFR_{ff} \sim 1/30$

Dynamical feedback by protostellar outflows

2. Reinvigoration of turbulence

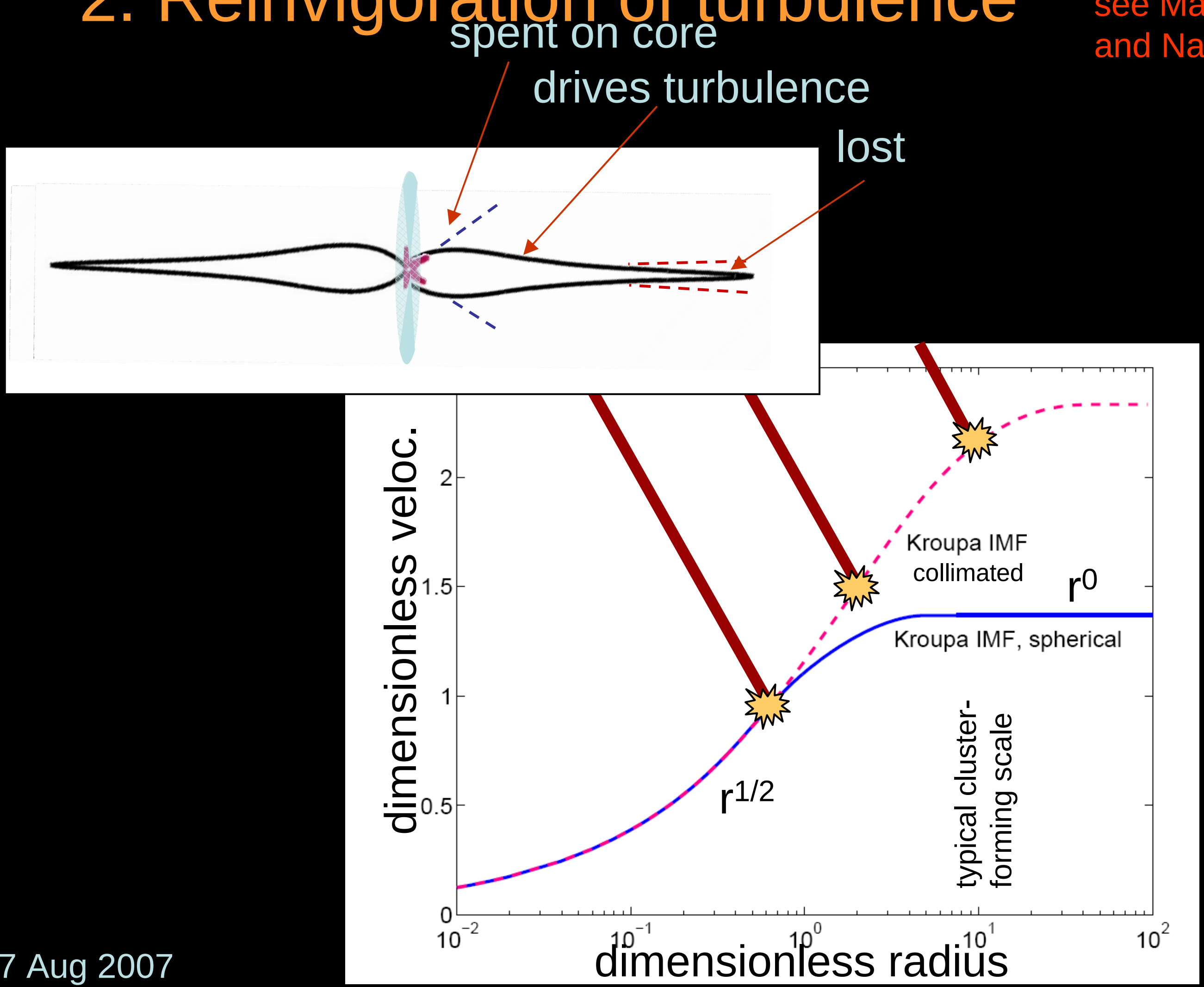
Back-of-a-big-envelope version
see Matzner 2007



Dynamical feedback by protostellar outflows

2. Reinvigoration of turbulence

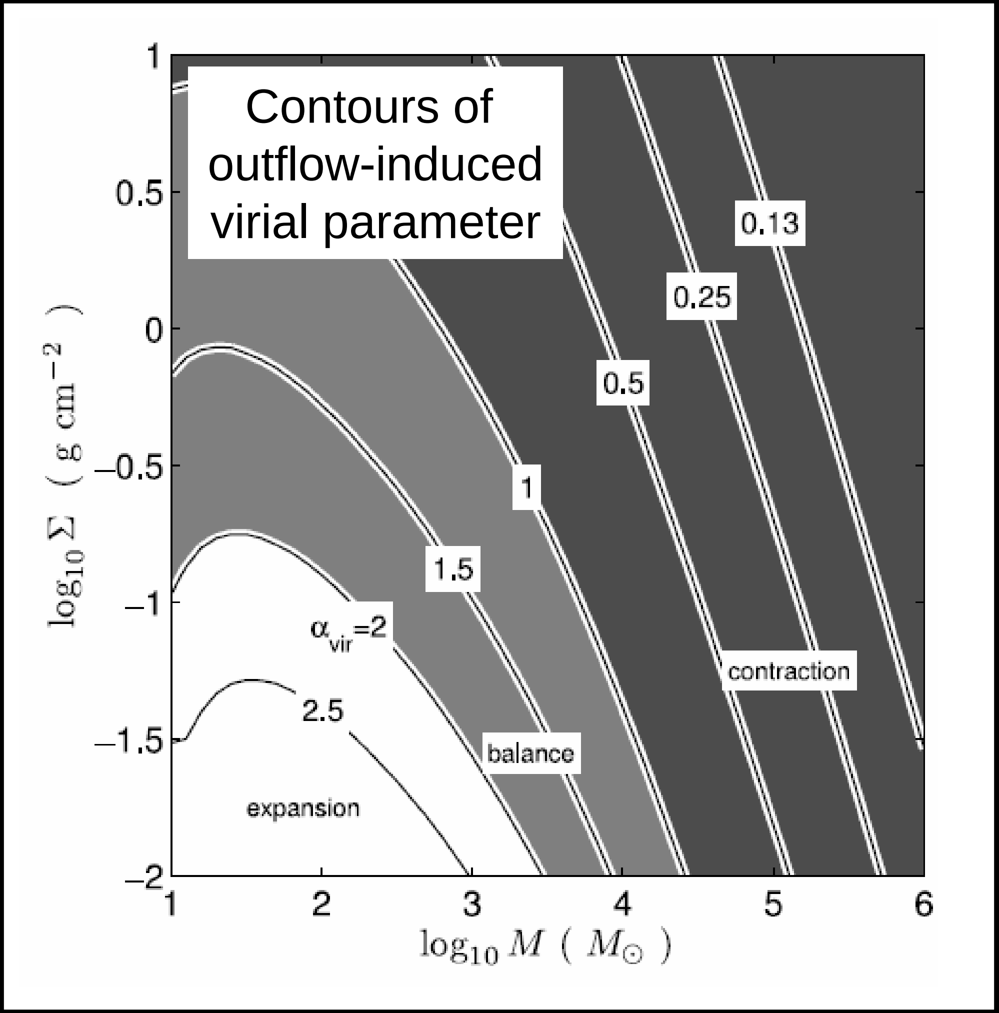
Back-of-a-big-envelope version
see Matzner 2007
and Nakamura & Li 2007



Linewidth-size relation
Derive $\sigma_v \sim r^q$ with
$0<q<1/2$

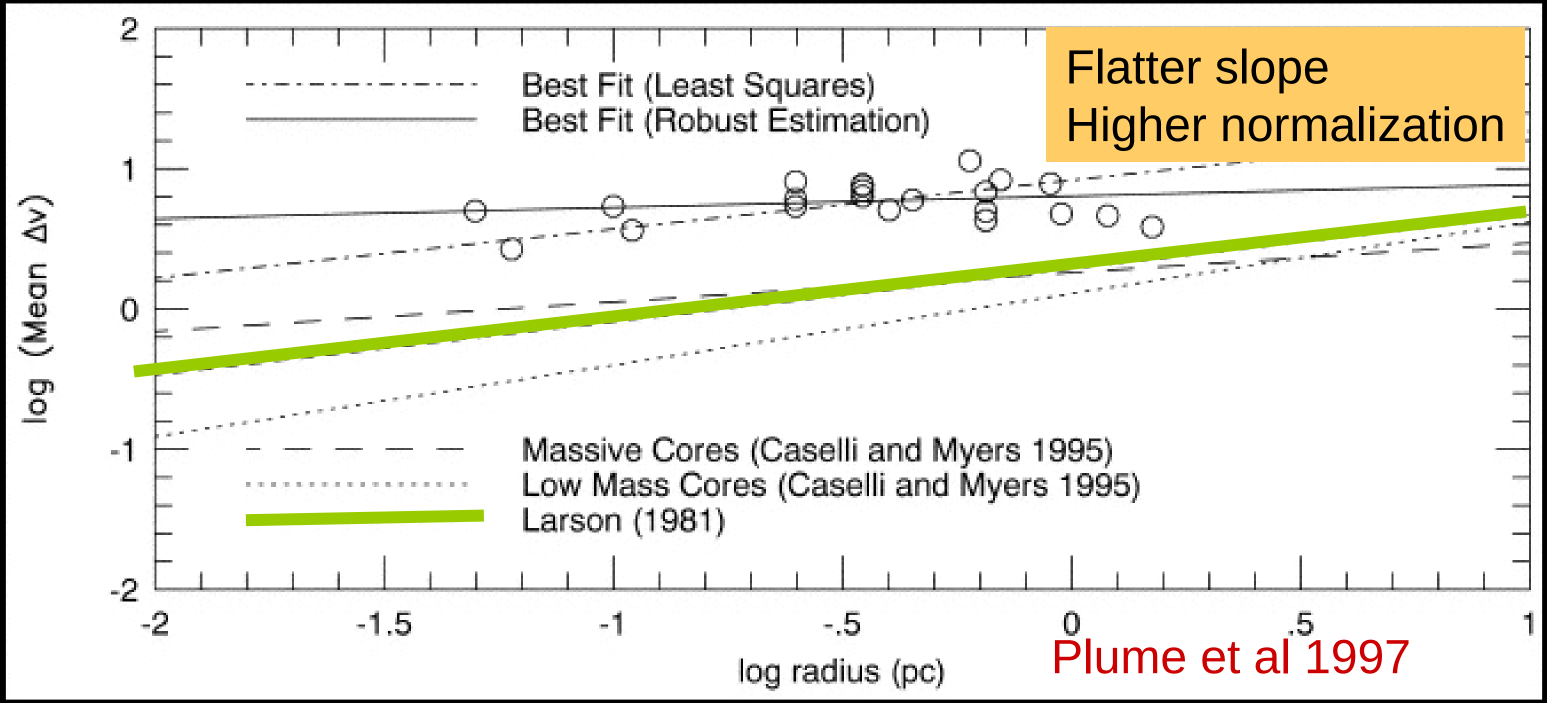
Virial balance:
Expect $\rho \sim r^{-p}$ with
$1<p<2$

Can outflows slow or halt collapse? This depends on scale:



Evidence?

Deviations from a universal line width-size relation *among* cores:



Massive-Star Outflows?

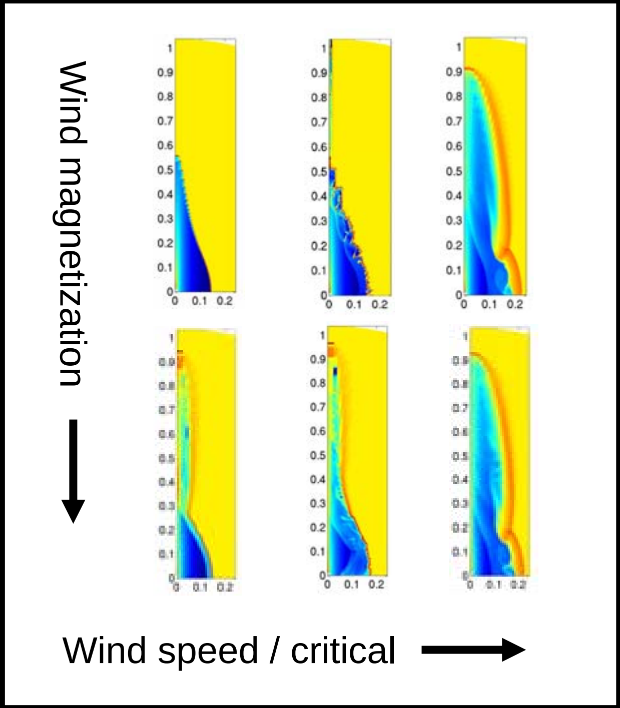
Momentum content is significant
Tan & McKee 2002

Much more sporadic

Higher wind speeds: less radiative
(dynamics more explosive)

Intensifying wind: outflows
dynamically unstable

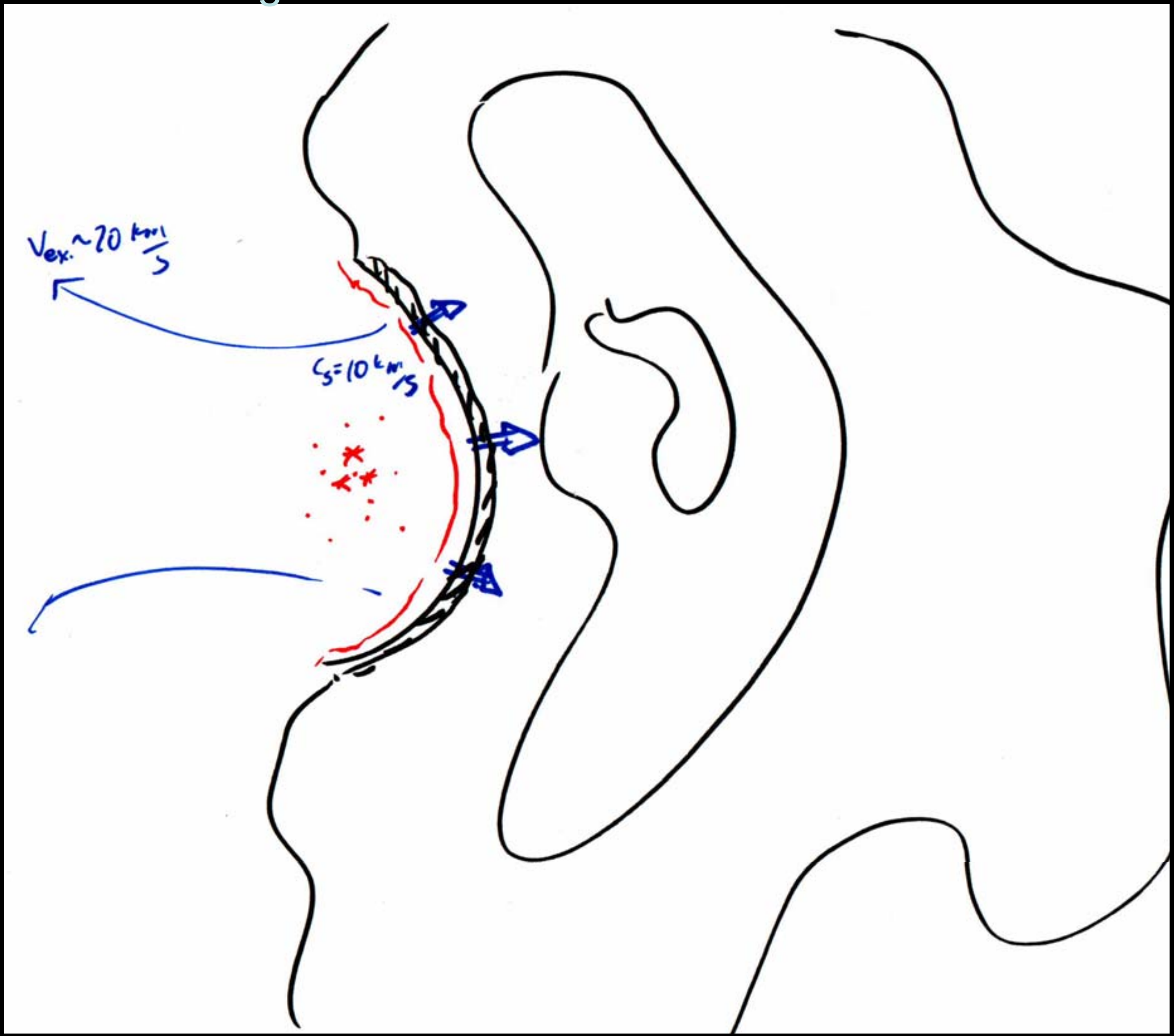
R. Krasnopolsky & CDM
2007 in prep.



How important is feedback on the molecular-cloud scale?

Photoionization, stellar winds, and supernovae

Clustering and correlation of star formation is critical



Whitworth 1979

Matzner 2002

Krumholz, Matzner, McKee 2006

Dynamical feedback by HII regions

Simple version:

Matzner 2002
Krumholz, Matzner, McKee 2006

Suppose HII regions destroy the cloud -- all but a small mass fraction.

Remainder spat out at 10-20 km s^{-1} which exceeds linewidth $\sigma_v \sim$ 5-8 km/s

Cloud destruction is therefore a strong source of energy, if the cloud is destroyed rapidly.

More detailed version:

Average momentum input from associations: ~ 260 km s^{-1} per stellar mass

Net energy input ~ $10^{-26.2}$ erg s^{-1} cm^{-3} comparable to dissipation rate $10^{-26.7}$ to 10^{-26} erg s^{-1} cm^{-3} (Stone, Ostriker & Gammie 98)

Galactic ionizing luminosity consistent with turbulent dissipation rate

Conclusions

Dynamical feedback cannot be less significant than momentum conservation would dictate.

Protostellar outflows have a significant impact on dense gas with $\sigma_v \sim 0.2\text{-}2$ km s^{-1}

Effects: mass ejection, stirring of turbulence

HII regions couple well to molecular clouds:

$\sigma_v \sim 5\text{-}8$ km s^{-1}, $n \sim$ few hundred cm^{-3}

Star formation is not dictated by *G*, *P*, and ***B*** alone.

Dynamical feedback by protostellar outflows

1. Blowout of mass: maximum efficiency

How does this scale with mass?

Core collapse models: accretion rate ~ v_{esc}^3/G ~ M_*/t_{acc}
So, expect v_{esc} to vary roughly as $M_*^{1/3}$

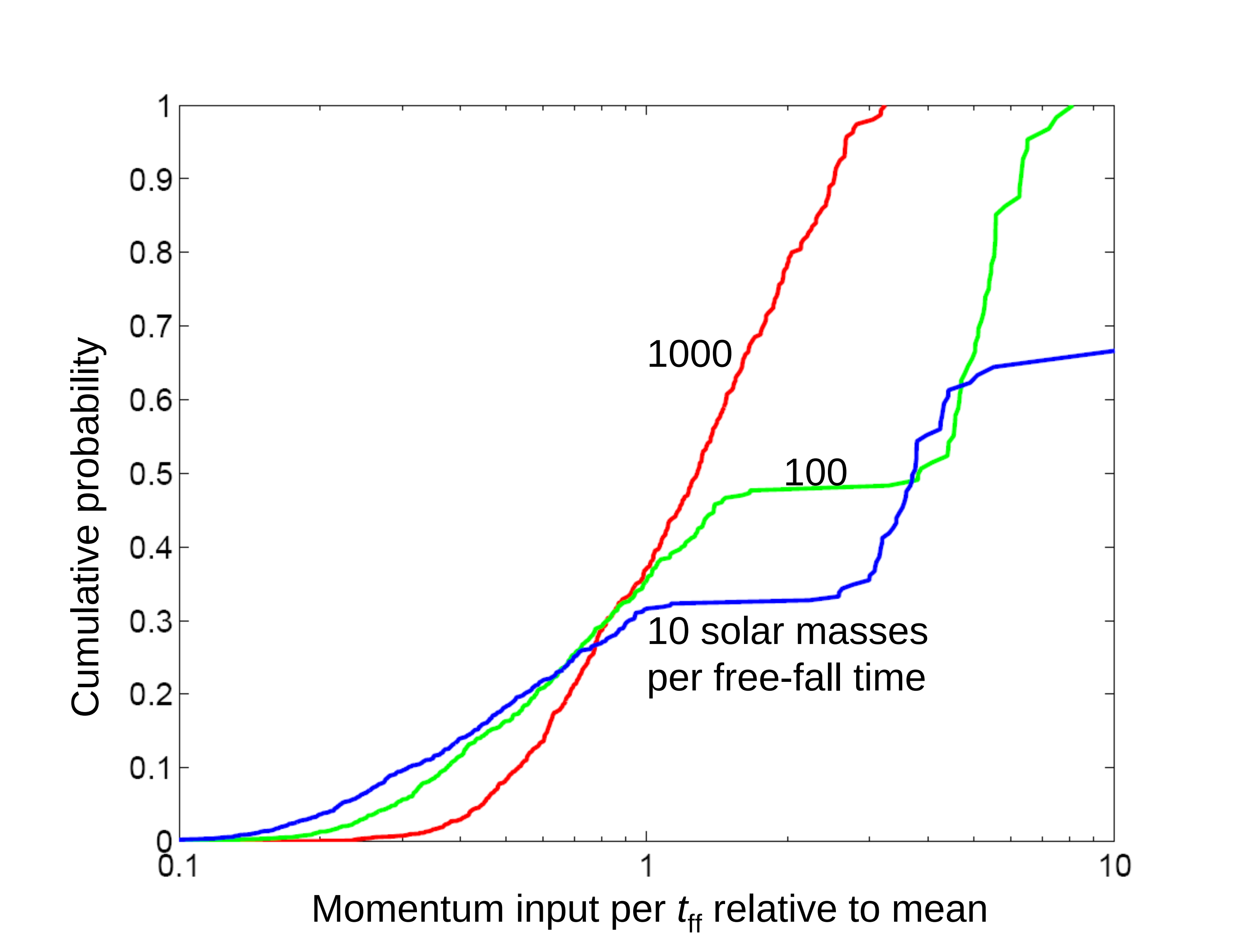
The wind speed v_w is expected to vary like the Kepler speed at the stellar surface
~ $M_*^{1/2}$ for $M_*<10M_o$ turning over to $M_*^{1/5}$ for $M_*>10M_o$ (for accretion at this rate)

The ejection fraction f is either (*a*) roughly constant or (*b*) declining slowly as $M_*^{-1/6}$

Net result:

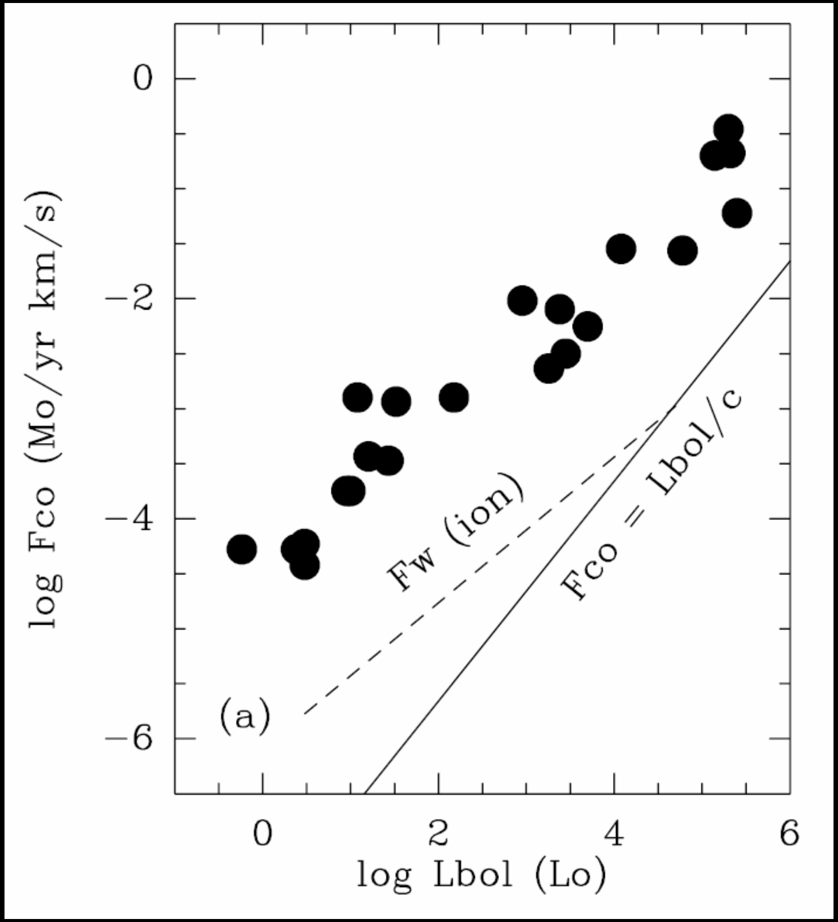
Either (*a*) ~10 M_o is a minimum of the accretion efficiency

or (b) the efficiency increases slowly with mass, more so for $M_*>10M_o$



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
1
10
Cumulative probability
Momentum input per t_{ff} relative to mean
1000
100
10 solar masses
per free-fall time

What about massive outflows?

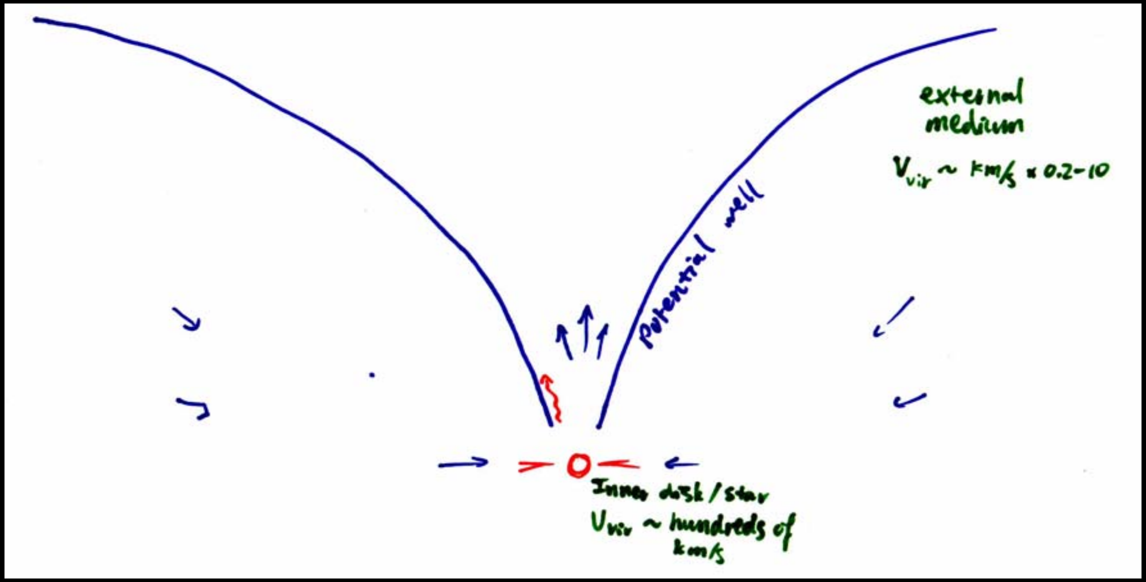


Outflow force far exceeds radiation force.

Still magnetically launched and collimated.

Richer et al 2000

Why feedback?



1. Tap high specific energy content of stars, set for instance by temperature thresholds in nuclear reaction rates
2. Momentum conservation dictates the effect on dense, radiative gas

Protostellar wind:	high inner disk speed
Photoionization, stellar wind, radiation pressure:	nuclear energy
Supernova:	even deeper potential well

Dynamical feedback by protostellar outflows

2. Reinvigoration of turbulence

Back-of-a-big-envelope version
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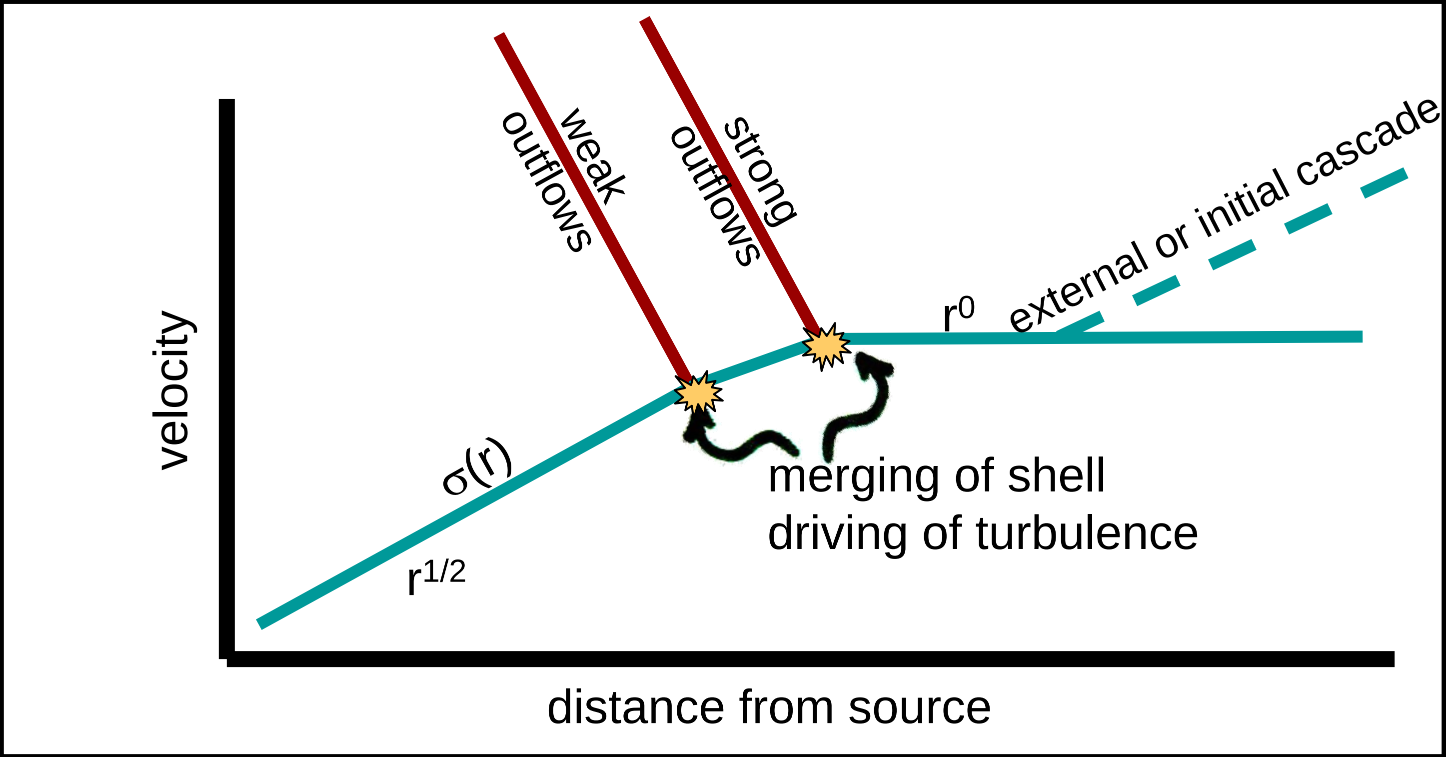
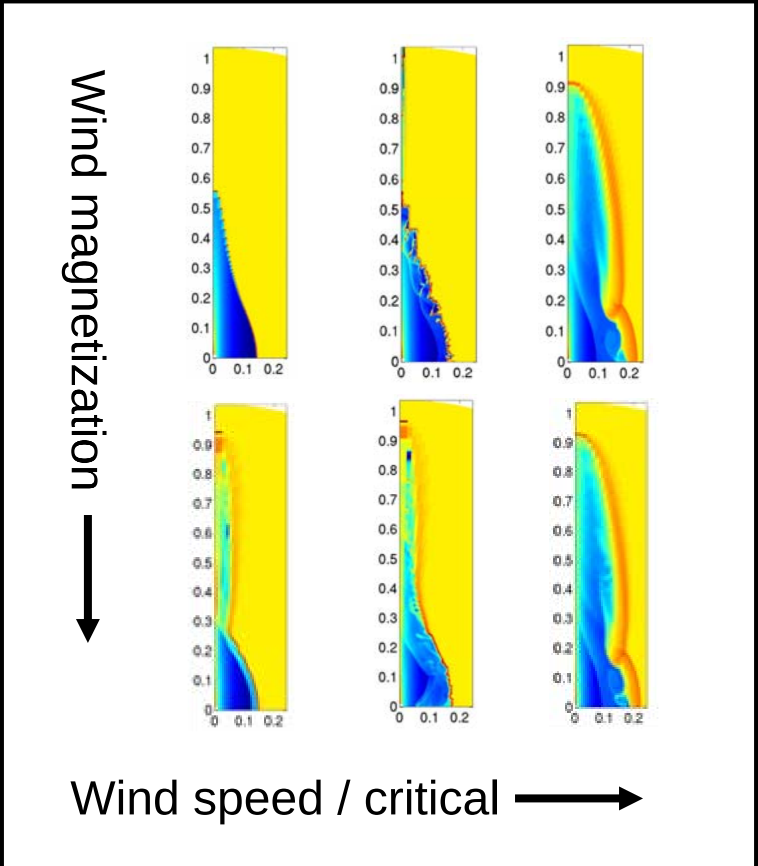


Are massive outflows dynamically different?

Yes: higher wind speeds, higher amb. density,
possibly lower collimation, accelerating injection

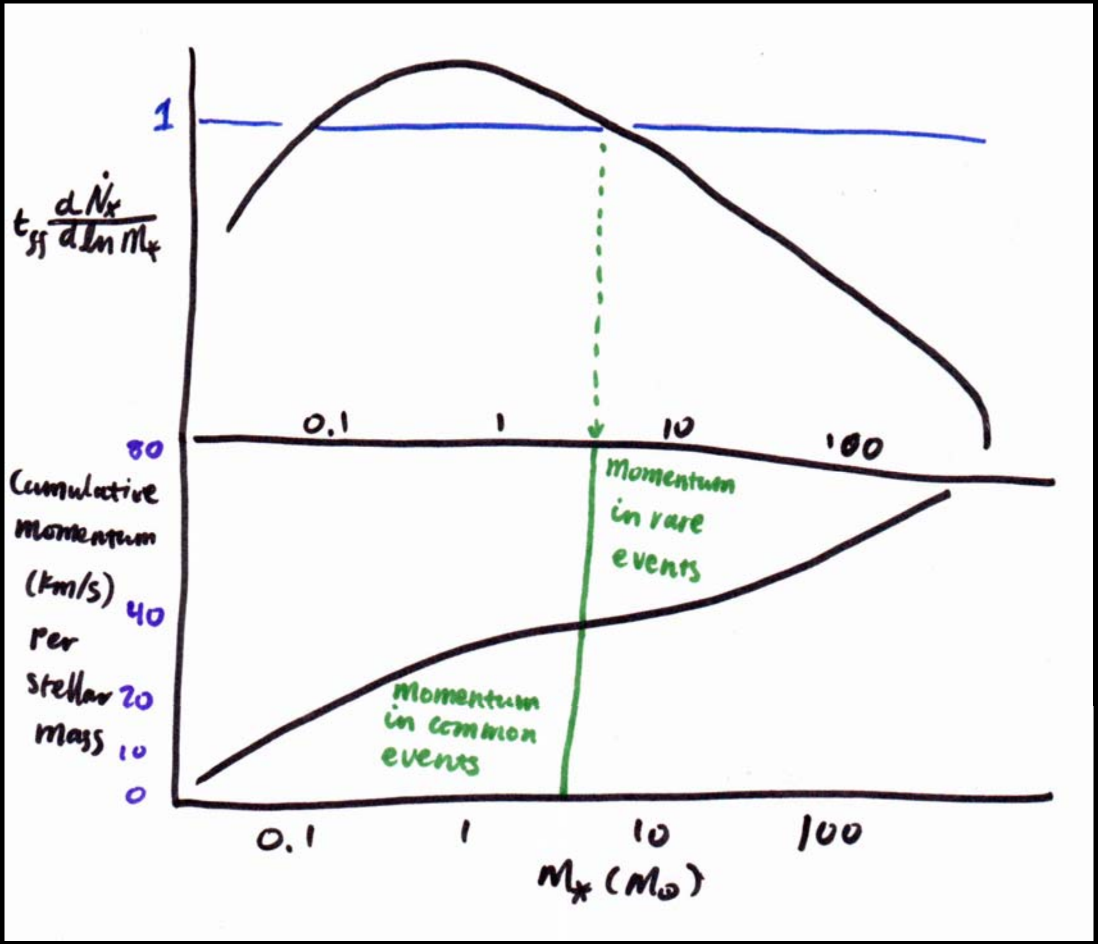
Implications? Less radiative flow
More explosive interaction, unstable pressurized cocoons
Outflow momentum exceeds wind momentum scale



R. Krasnopolsky & CDM
2007 in prep.

Massive-star outflows:

More massive stars do not dominate the momentum budget, but they are more sporadic and therefore more disruptive…



See also
Tan & McKee 04