The control of the star formation efficiency in molecular clouds

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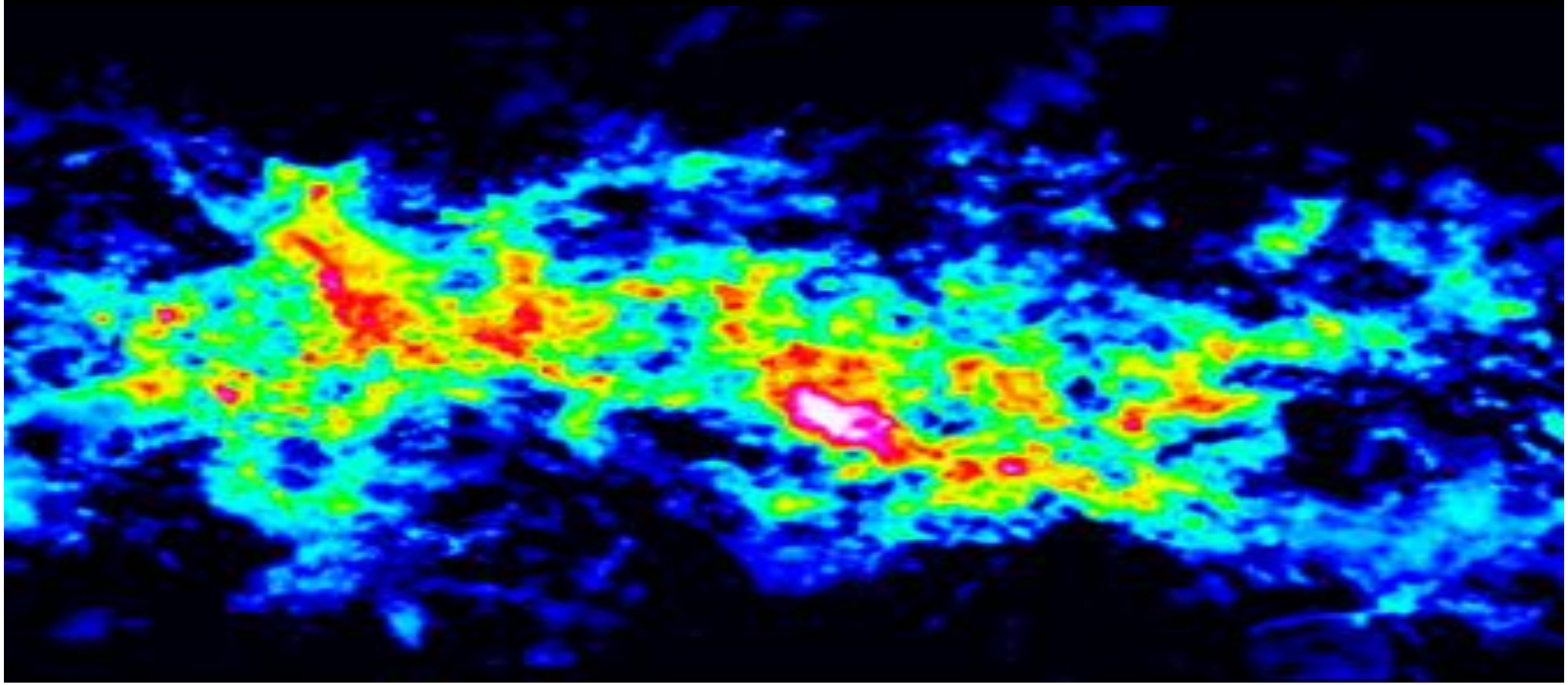
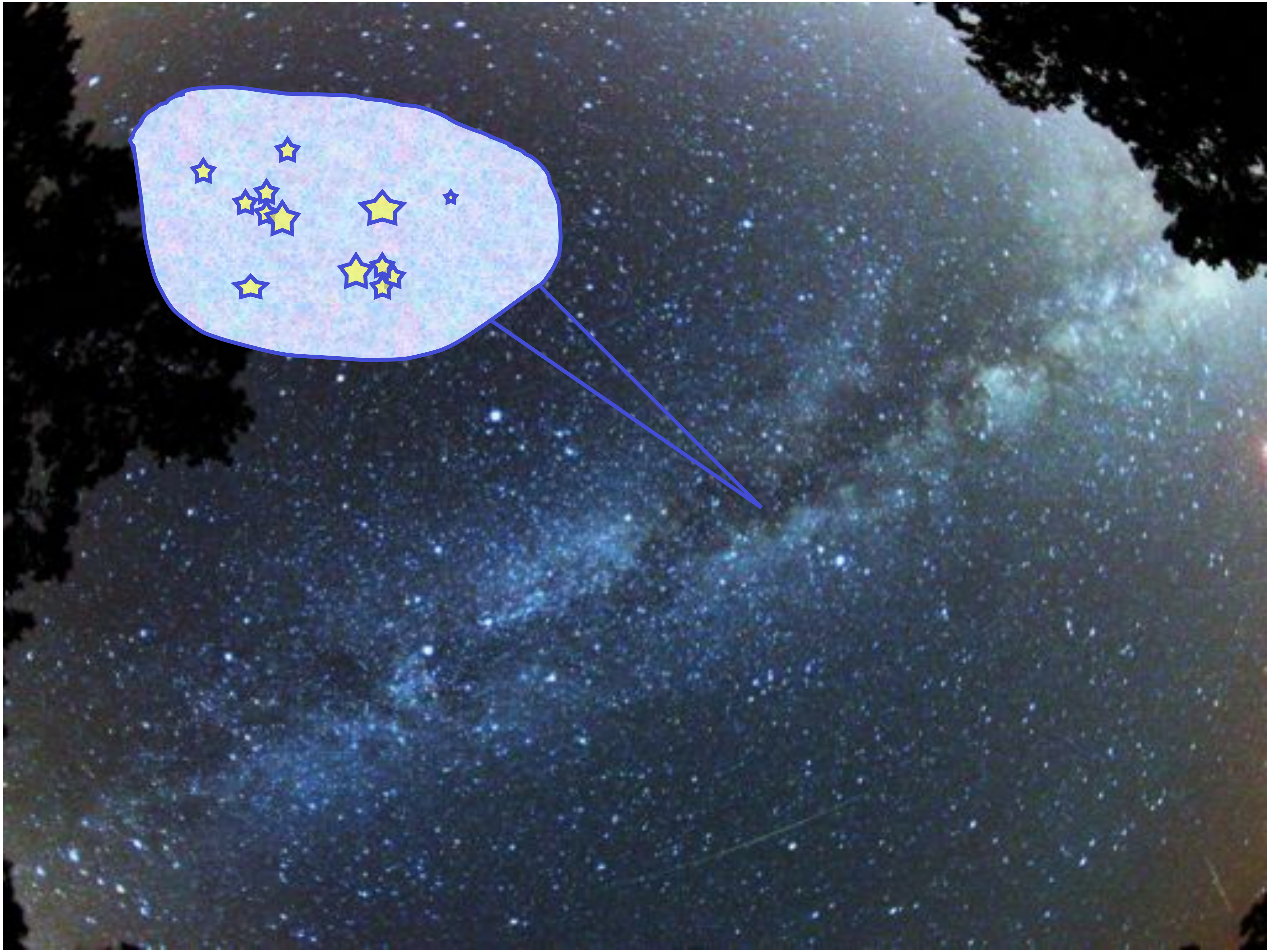
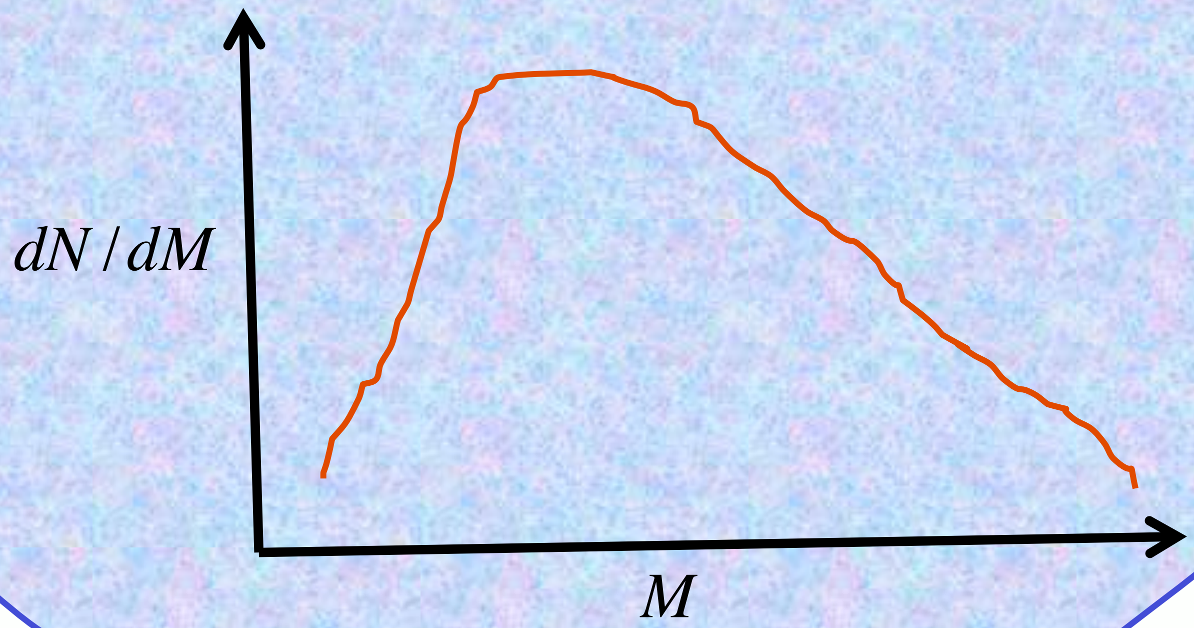


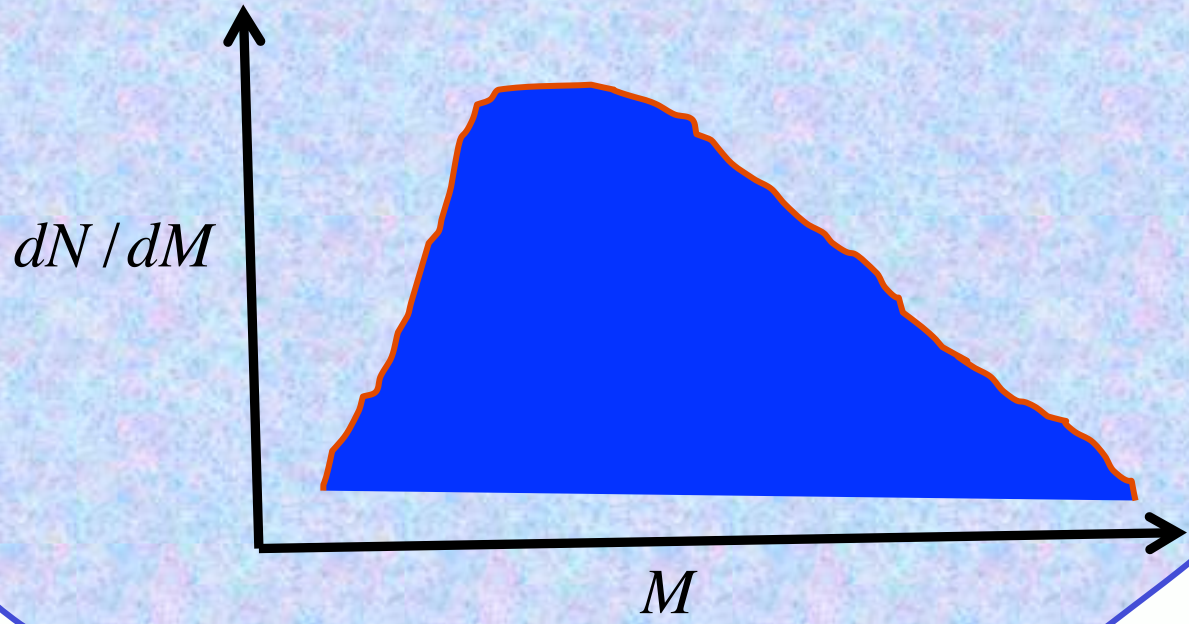


⊙ what determines the initial mass function of stars (IMF) ?



⊙ what determines the initial mass function of stars (IMF) ?

⊙ What determines the total mass of stars that can form in the cloud ?



- ⊙ What determines the total mass of stars that can form in the cloud ?
- ⊙ Do they form in a single cluster (monolitically) or from the coalescence of sub-clusters ?
- ⊙ what is the fraction of stars that are in binary/triple/multiple systems ?

SFE in a molecular cloud

$$SFE(t) \approx \frac{M_{cluster}(t)}{M_{gas,i} + M_{gas,acc}(t)}$$

Final value of the SFE

$$SFE_f = [SFE(t_{\exp}),1] \approx \left[\frac{M_{cluster}\left(t_{\exp}\right)}{M_{gas,initial + M_{gas,acc}}\left(t_{\exp}\right)},1\right]$$

In real observations

$$SFE_f \approx \left[\frac{M_{cluster}}{M_{gas,present} + M_{cluster}}\right] \approx [0.01 - 0.5]$$

Lada & Lada (2003)

Molecular Cloud Properties

M~10^4-10^6 $M_\odot$

R ~10-30 parsecs

T ~10-30 K, c_s~0.2-0.3 km s^{-1}

Number densities n ~100 cm^{-3}

Ma=σ/c_s ~ 5-10

B ~10^{-5}-10^{-4} Gauss

Free-fall time:

t_{ff}~$(3\pi/32 G \rho)^{1/2}$

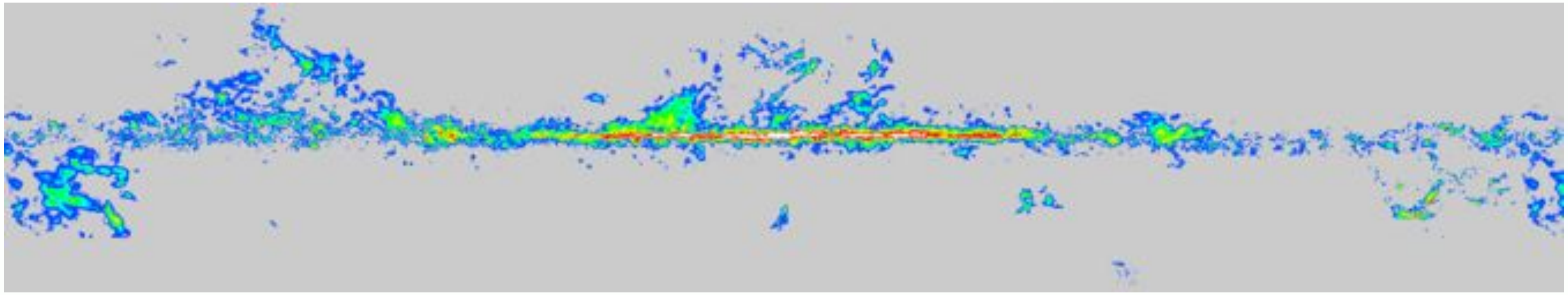
$=(3\pi N_A/ 32 G \mu n)^{1/2}$~1-5*$10^6$ yrs

t_{cr}~R/σ~5*10^6 yrs

The Star Formation Paradigm

The star formation rate: $SFR = SFE\left(\frac{M_{H_2}}{\tau_{SF}}\right)$

Mass of molecular hydrogen in the Galaxy (CO map converted to H_2): $M_{H_2} = 2 \times 10^9 M_{sol}$



Dame et al. (1987, 2001)

If : $\tau_{SF} \approx \tau_{ff}$ **then** $SFR \approx 1000 M_{sol} yr^{-1}$ **or** $SFR \approx 10 - 100 M_{sol} yr^{-1}$ **with** $SFE \approx 0.01 - 0.1$

Observations, from counting protostars (with the Spitzer space telescope) indicate that the Galactic value is $SFR \approx 1.5 M_{sol} yr^{-1}$

Robitaille & Whitney (2010)

The Star Formation Paradigm

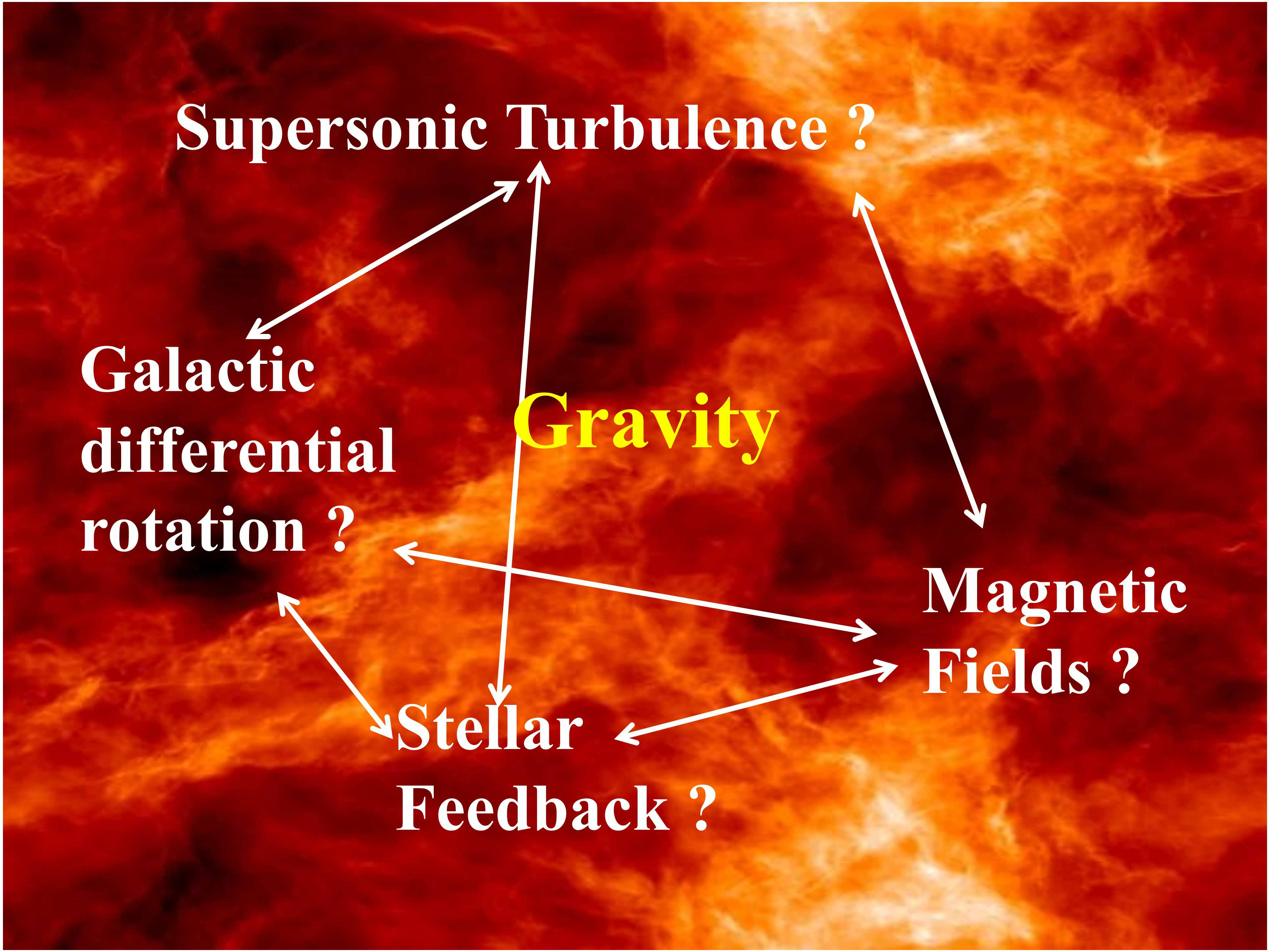
Galactic SFR value is $SFR \approx 1.5 M_{sol}$

This implies that molecular clouds are long lived $\tau_{SF} \approx 20\tau_{ff}$

And that the SFE is low ~0.01

It also implies that turbulence in the clouds must be replenished.

What controls the low galactic star formation rates & efficiencies ?


Supersonic Turbulence ?
Galactic
differential
rotation ?
Gravity
Magnetic
Fields ?
Stellar
Feedback ?

The role of supersonic turbulence

- **Supersonic in molecular clouds**
- **Possesses a certain injection scale, (or a multitude of them)**
- **Decays on a crossing time**
- **Cascades towards smaller scales following a given power spectrum**

Main Consequences

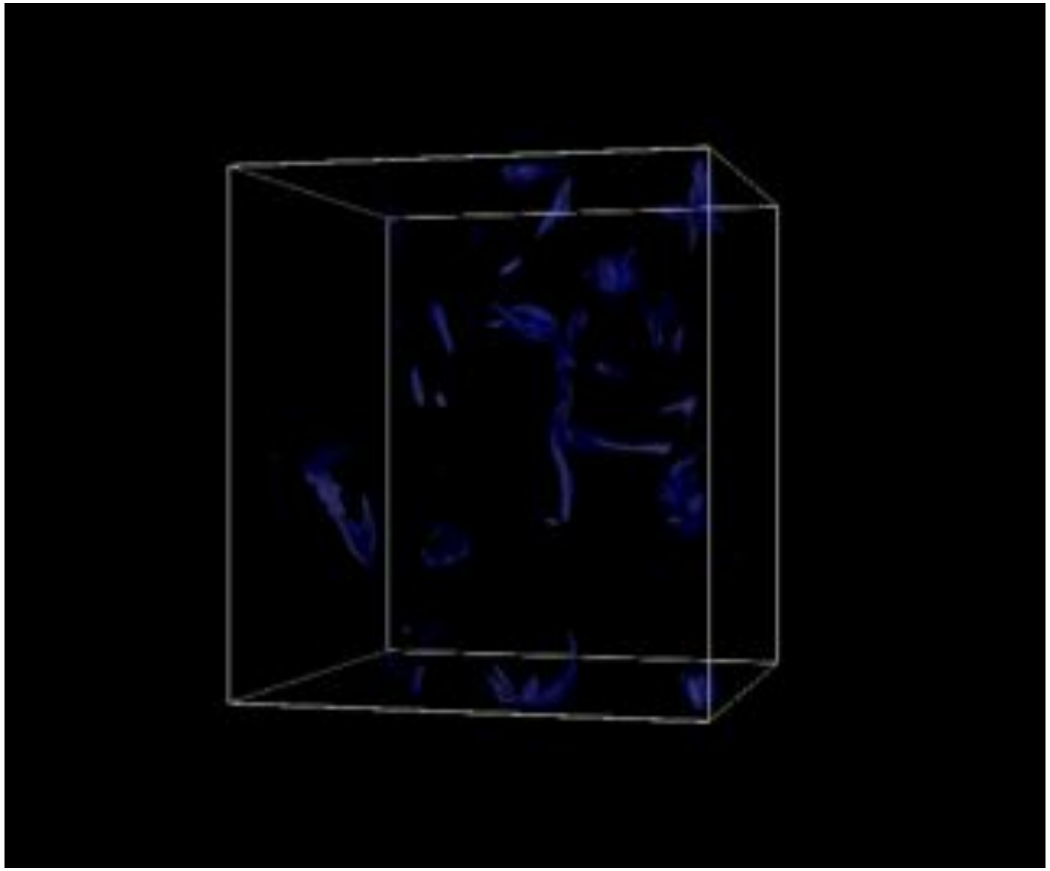
*** without gravity: generates the a lognormal distrubution of the density field. In the presence of gravity: lognormal + power at the high density end**

*** Localized star formation sites in the overdensities in which $t_{ff,local} << t_{ff,cloud}$**

The role of supersonic turbulence

Simulations

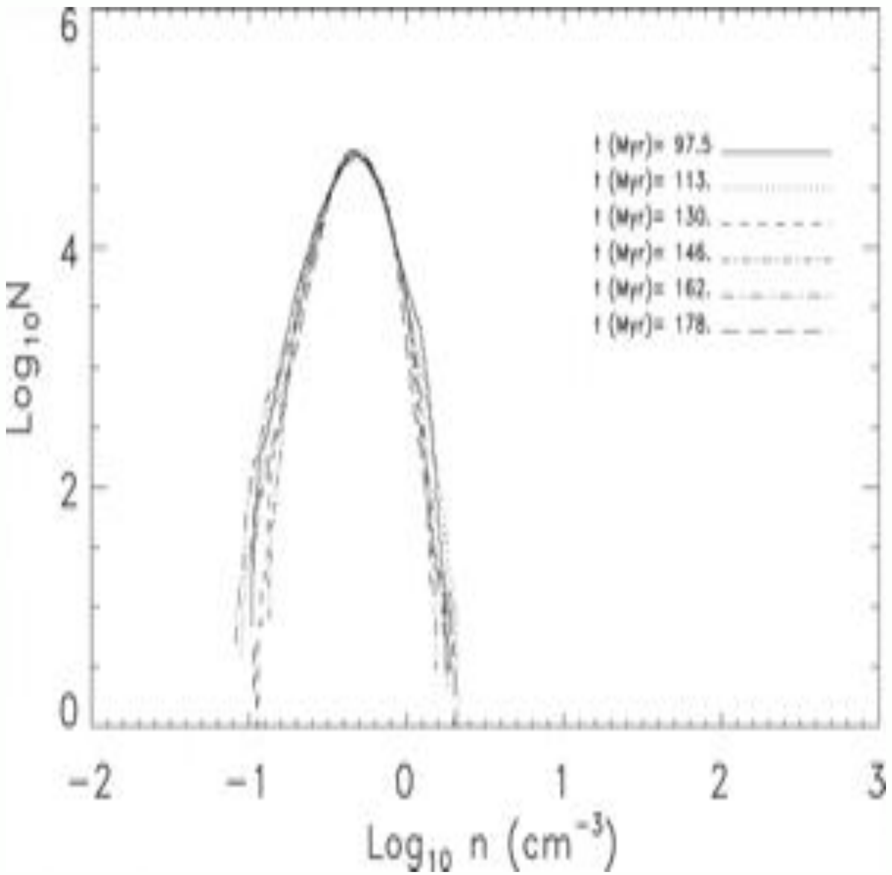
- 3D grids: 256^3, 512^3, 4096^3 resolutions
- Periodic boundary conditions
- MHD, Isothermal
- self-gravity
- driven turbulence (or decaying) on large scales (perturbation with wav numbers in the range k=1-2)
- Ma= 10, $J=L_0/L_J=4$
- L_0= 4pc, n_0= 500 cm^{-3}, T=11.4 K, c_s=0.2 km s^{-1}



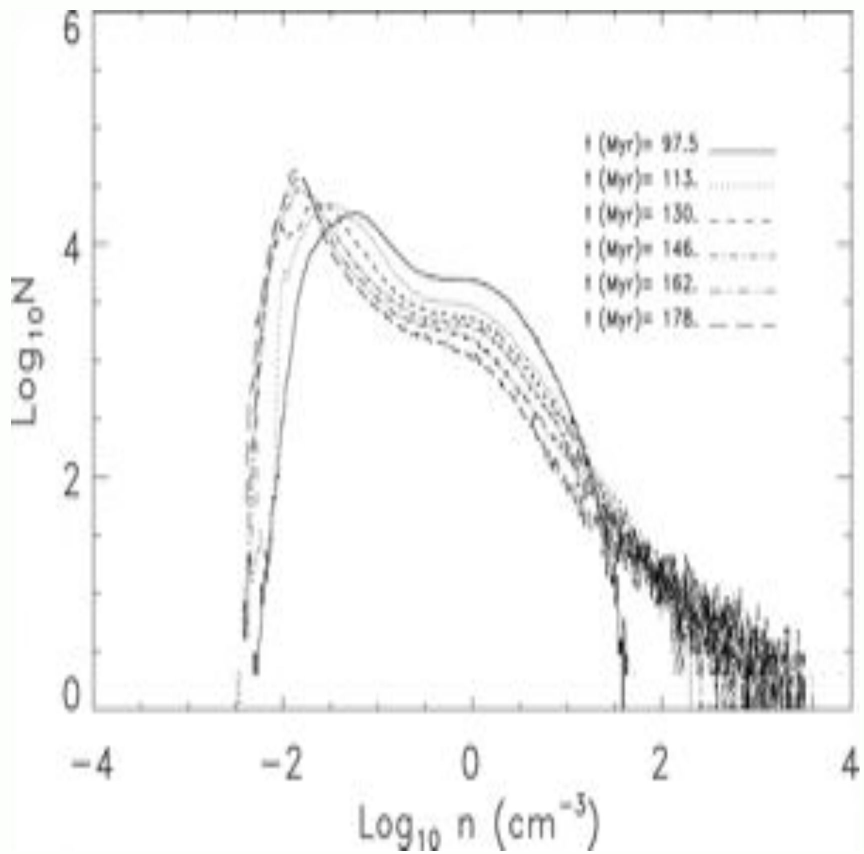
Vazquez-Semadeni et al. (2005), Dib et al. (2007,2008)

The role of supersonic turbulence

PDF of density field: Isothermal gas



PDF of density field: multiphase gas



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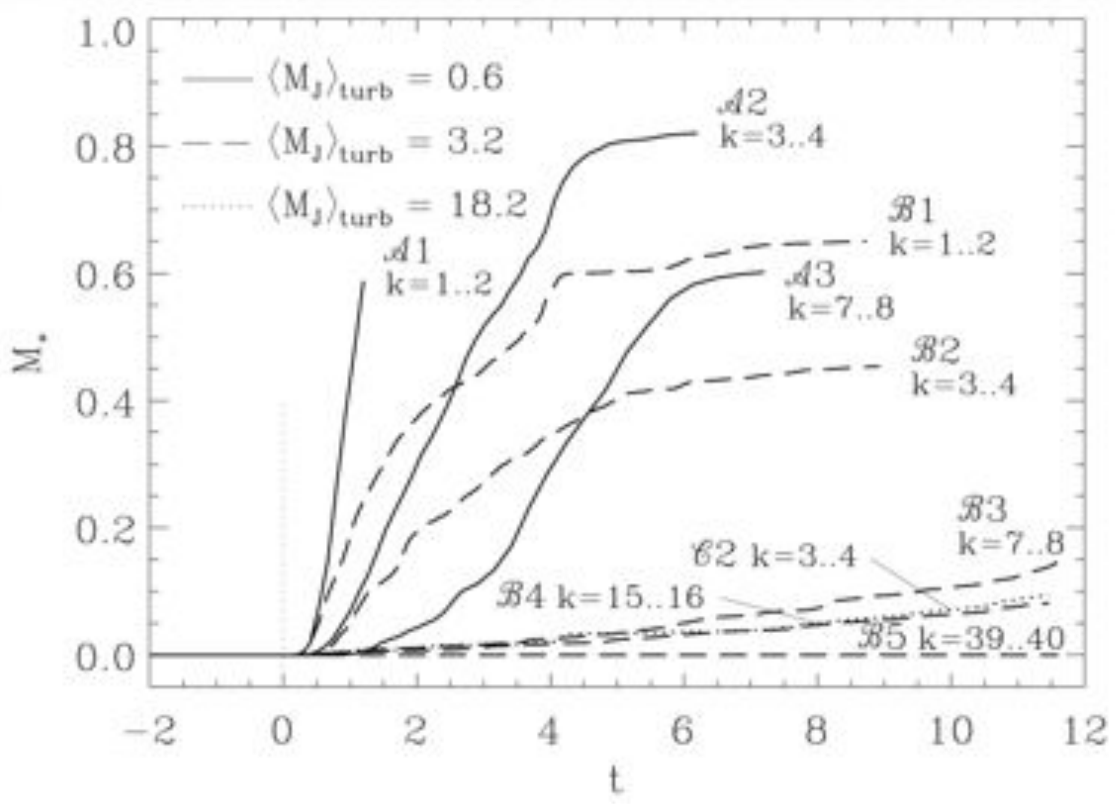
The role of supersonic turbulence

SFE dependence on the turbulence properties



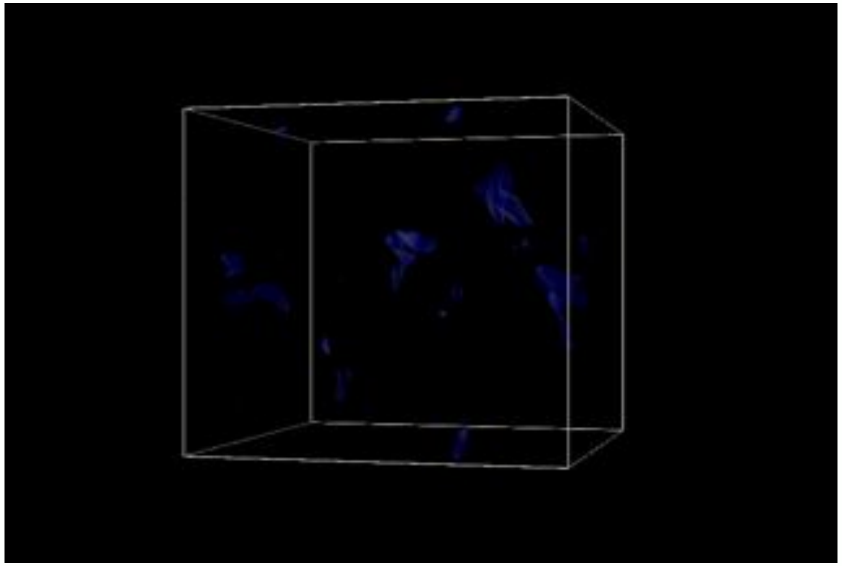
Klessen et al. 2000

Jeans Mass $M_J \propto c_s^3 n^{-1/2}$

Turbulent Jeans mass $M_J \propto c_{s,eff}^3 n^{-1/2}$

with $c_{s,eff}^2 = c_s^2 + \frac{\sigma^2}{3}$

Influence of the magnetic fields



Mass-to magnetic flux ratio

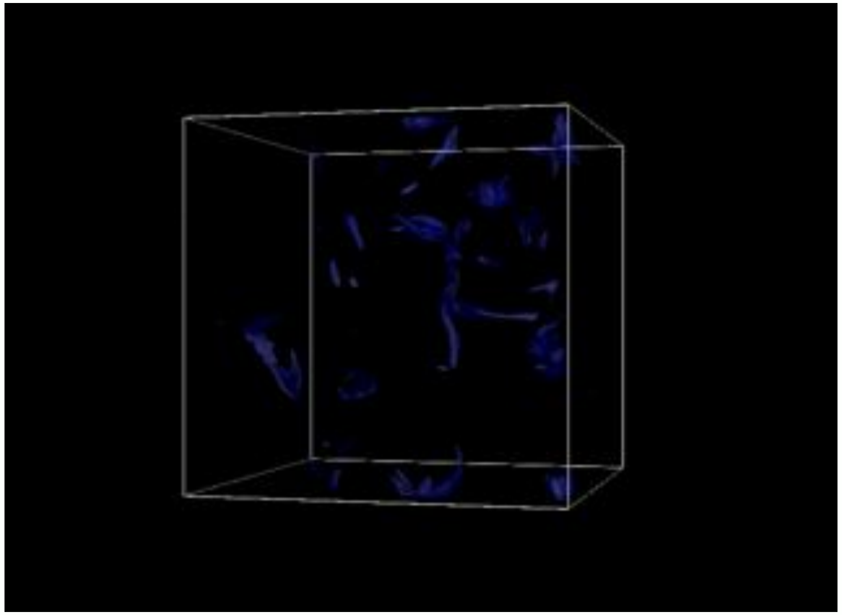
$\mu c = (M/\Phi)c / (M/\Phi)cr$

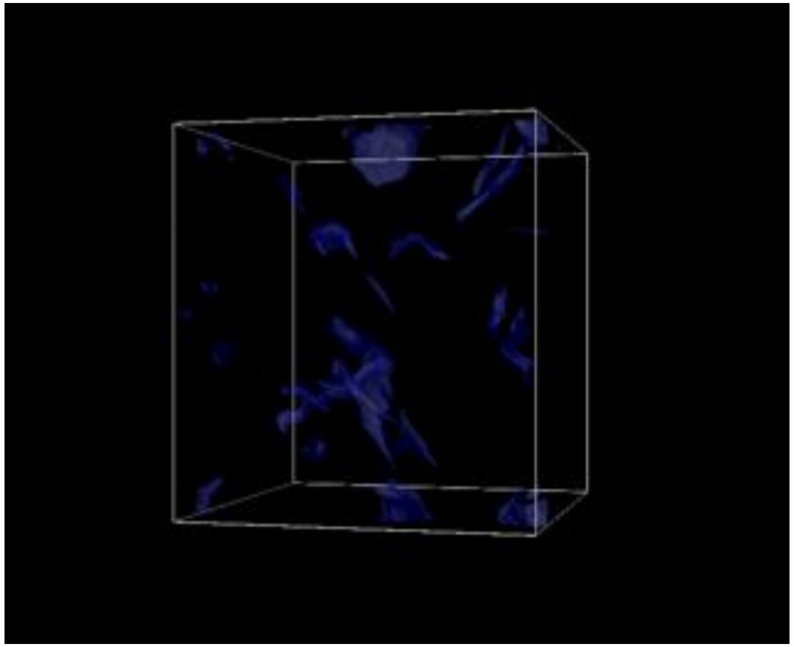
$\Phi c = \pi \, Bm \, Rc^2$

Bm is the the Mean Magnetic field

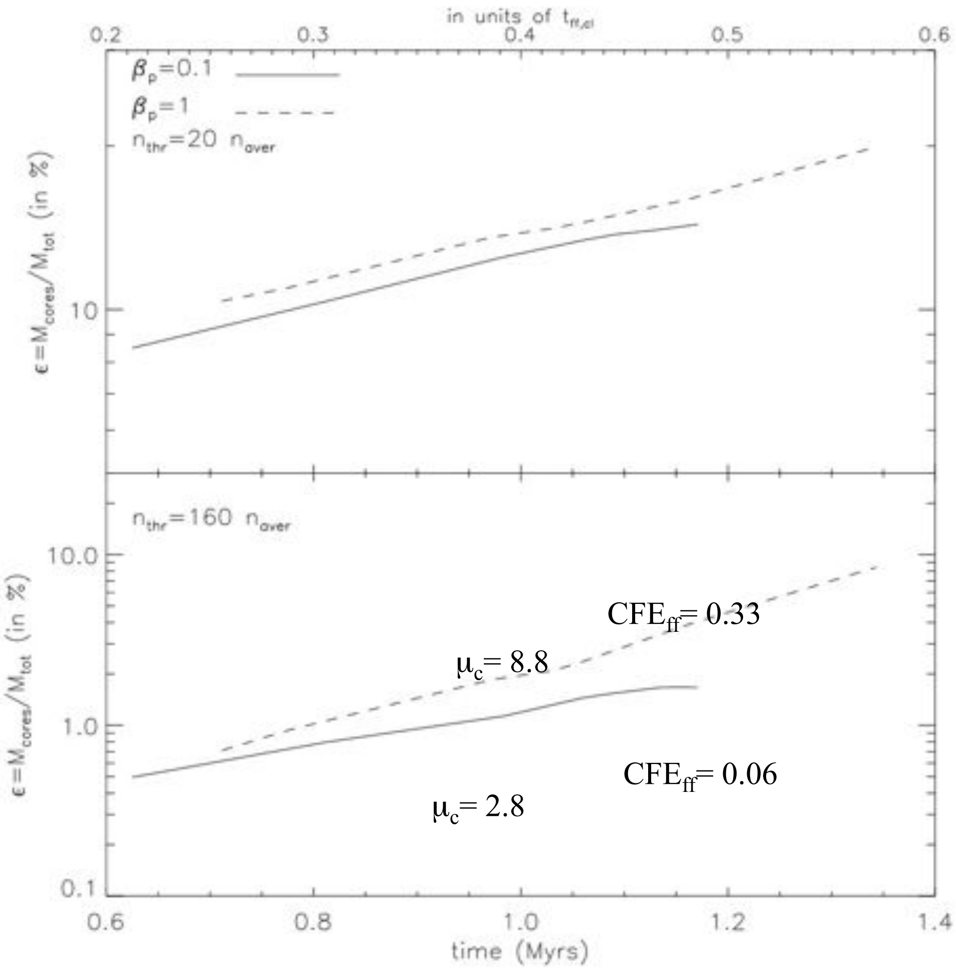
$\mu c < 1$: magnetic support, $\mu c > 1$ no magnetic support.

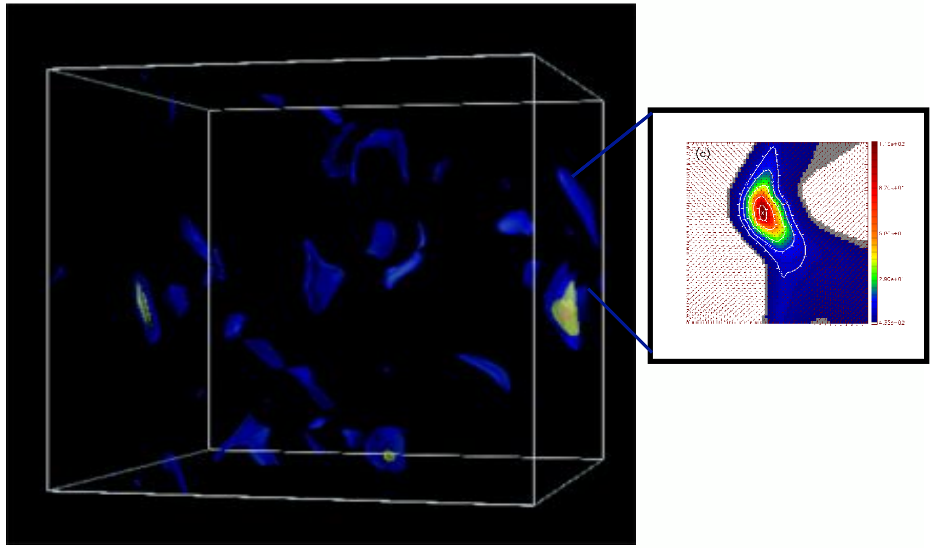
We used μc=0.9 (B=4.5 microG), 2.8 (B=14.5 microG), 8.8 (B=45 microG)





Influence of the magnetic fields

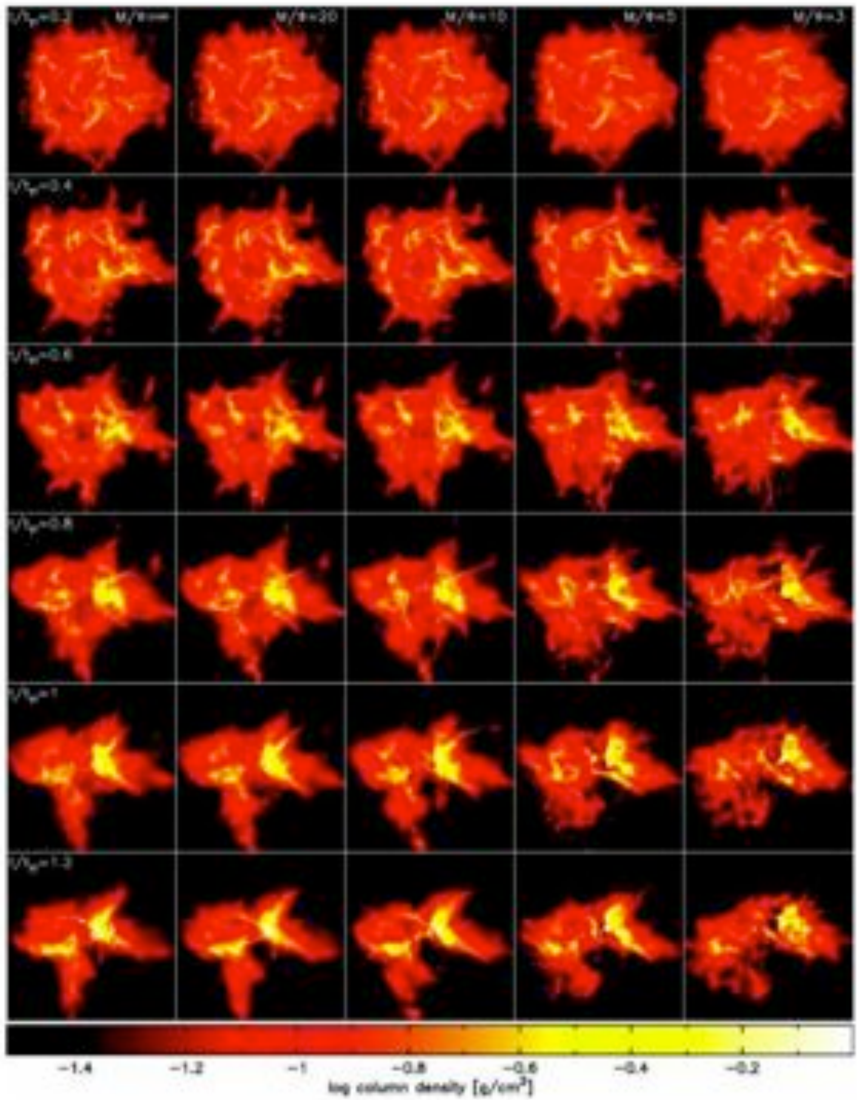


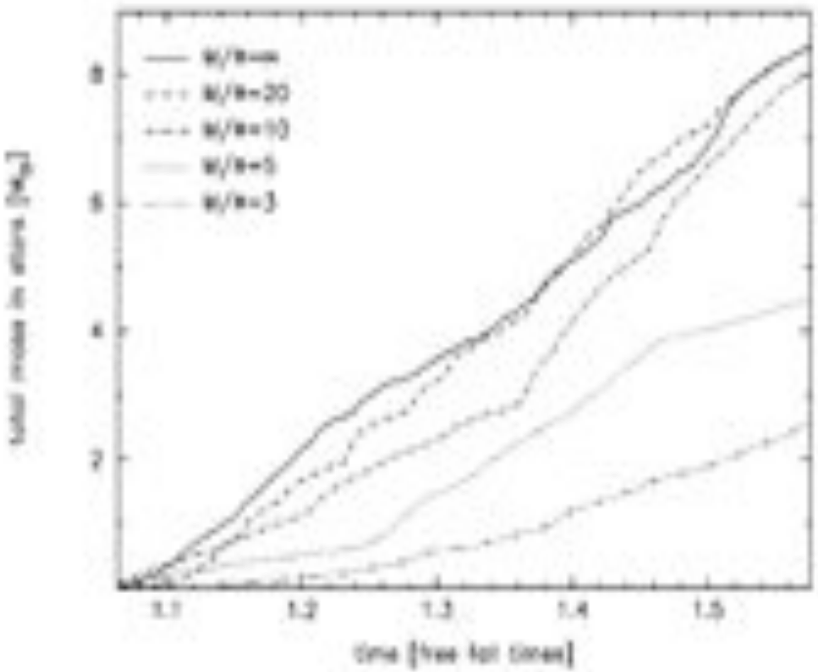


Dib et al. 2010

Influence of the magnetic fields

Magnetic fields in star cluster formation





Price & Bate 2008

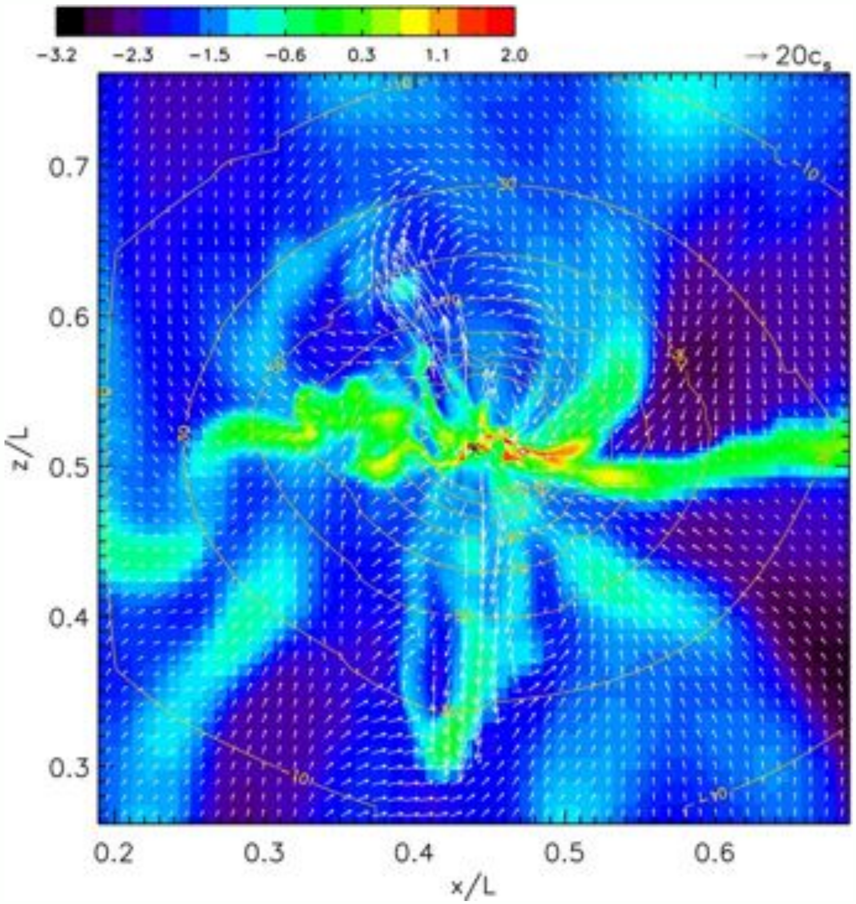
Influence of Stellar Feedback

Effects of feedback on the clouds evolution

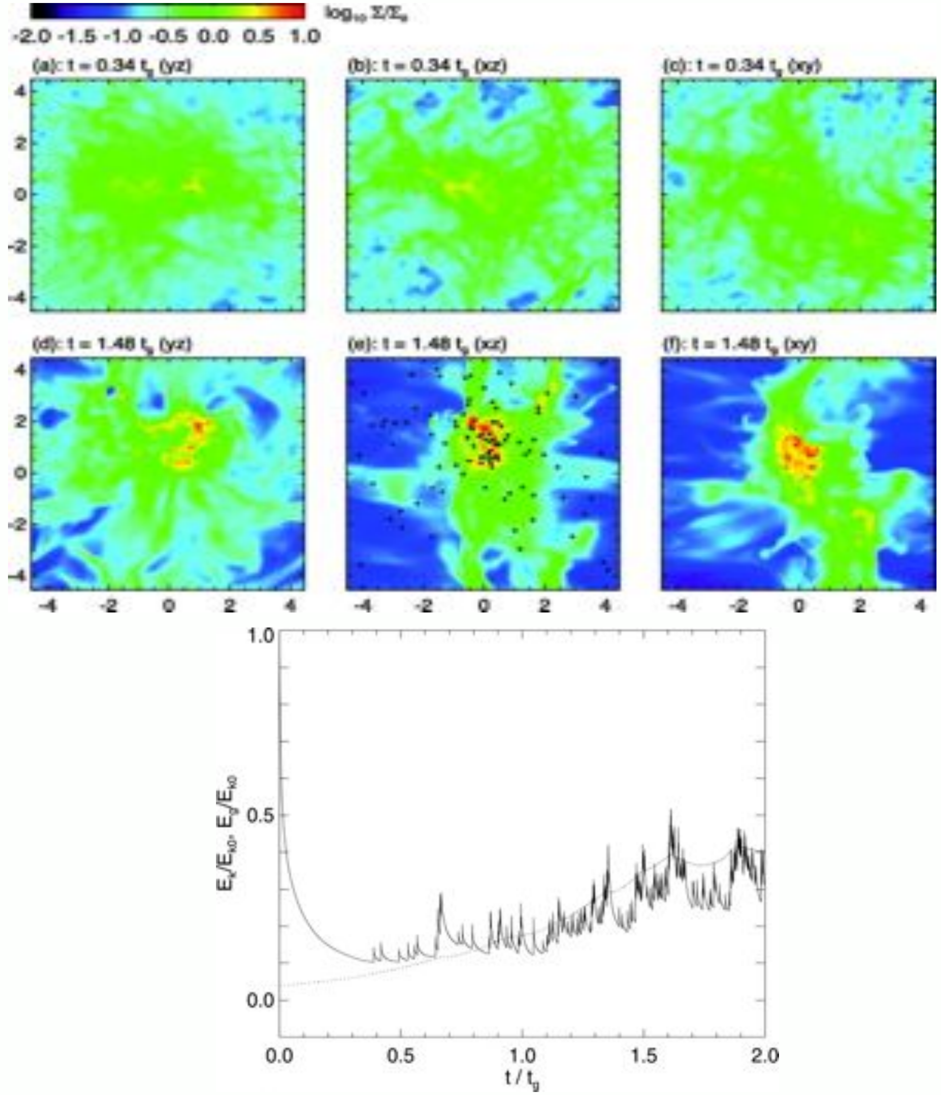
- Injects energy and momentum into the cloud
- Re-distributes matter in the cloud
- Maintains the turbulence
- Heats the gas → change the Jeans mass
- Eventually disperses the gas and destroys the clouds

Influence of Stellar Feedback

Effects of protostellar outflows



Wang et al. 2010

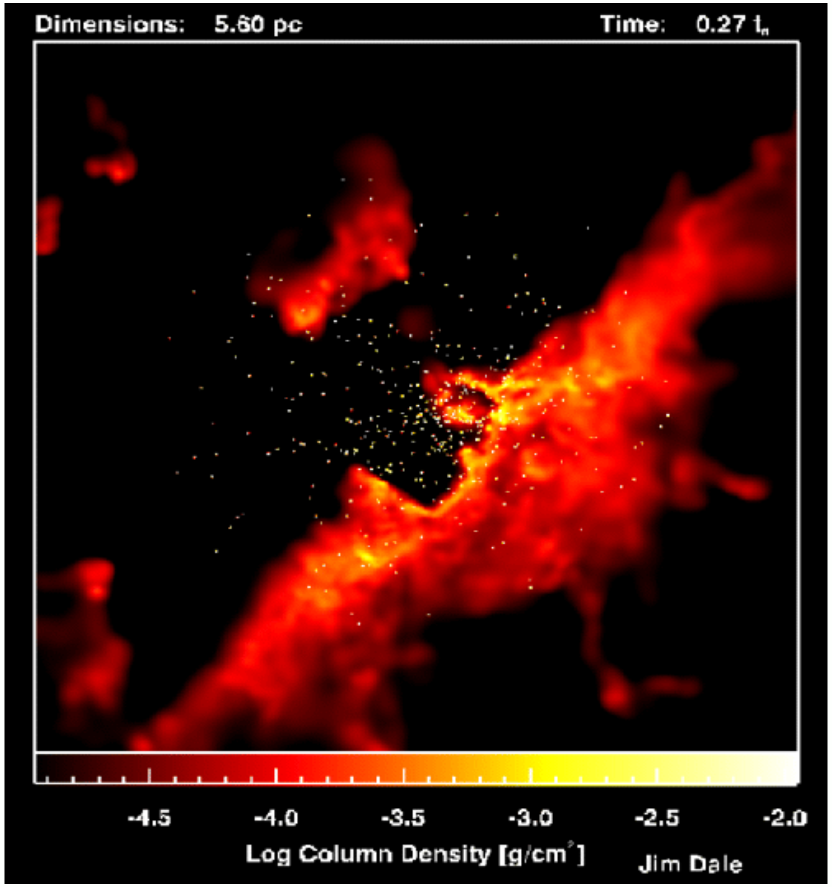


Li & Nakamura 2007

Influence of Stellar Feedback

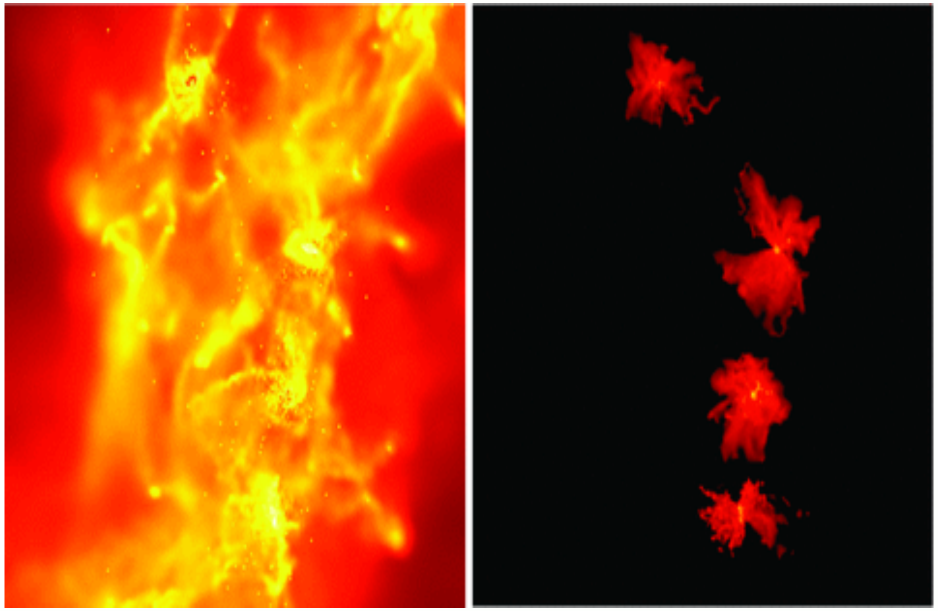
Feedback from massive stars

Ionization and heating of the gas



Dale et al 2005

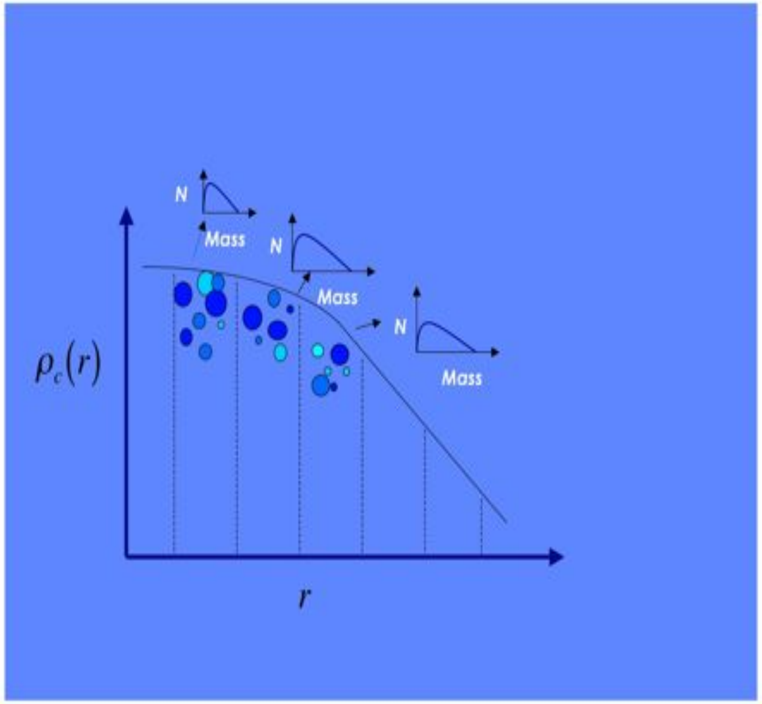
Stellar winds

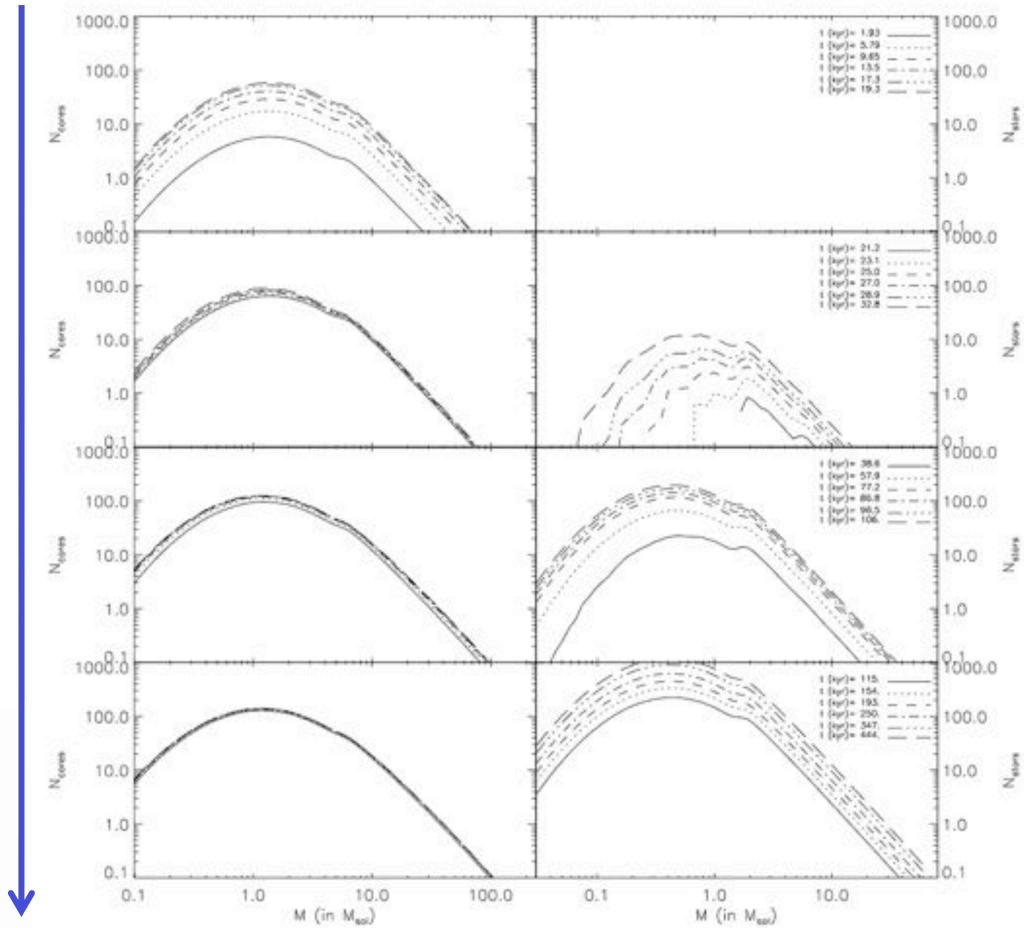


Dale & Bonnell 2008

Influence of Stellar Feedback

A semi-analytical model for feedback from massive stars





time

Protocluster forming molecular cloud

Mass~10^4-10^6 M_{sol}

Influence of Stellar Feedback

Feedback model: Stellar Winds

Stellar mass loss rate $\left(\frac{dM}{dt}\right)_*$

Terminal wind velocity v_∞

Energy cumulated in winds

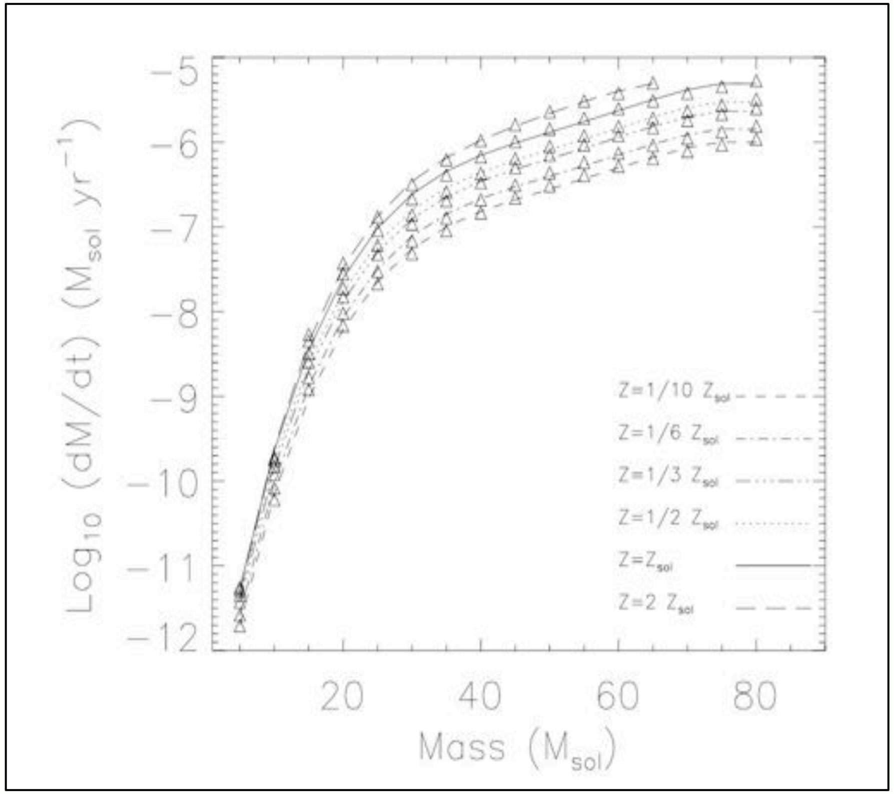
$$E_{wind} = \int_{t''=0}^{t''=t} \int_{m=5M_{sol}}^{m=80M_{sol}} \left(\frac{N(m)(dM/dt)_*(m)v_\infty^2}{2} dm \right) dt''$$

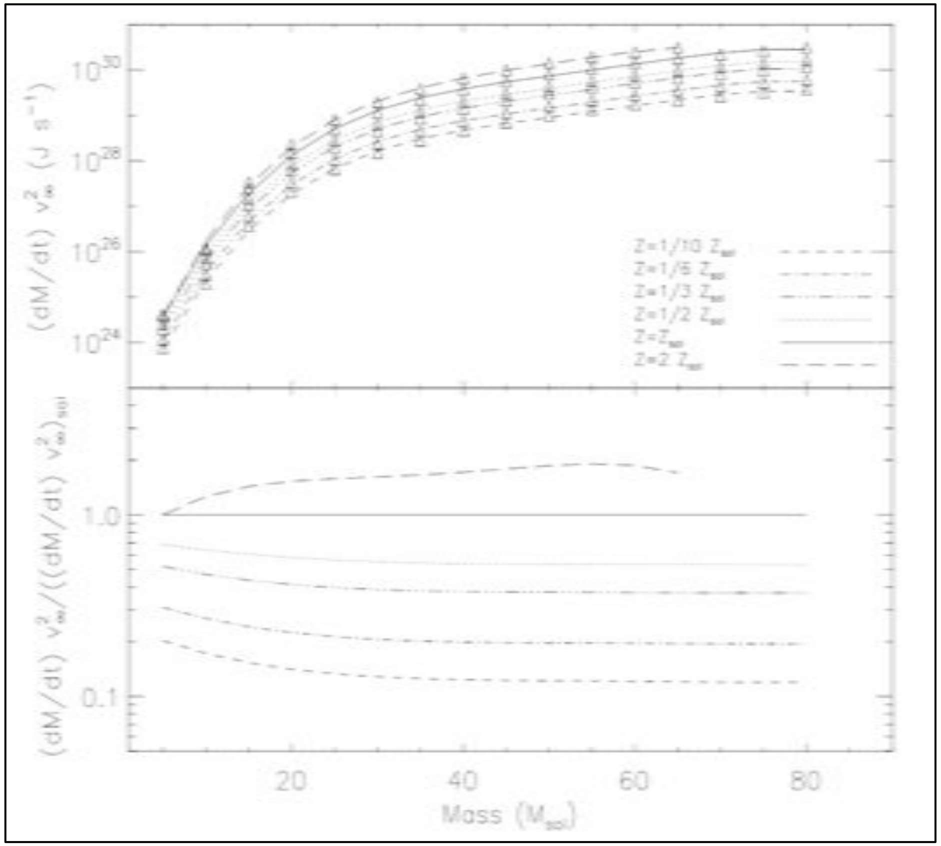
Fraction of wind energy that counters gravity $E_{k,wind} = \kappa E_{wind}$

$k < 1$

Power of stellar wind

- Calculate main sequence models of OB stars (≥ 5 $M_{\odot}$) (using CESAM)
- (T_{eff}, L_*, R_*) ➔ Stellar atmosphere model (Vink et al.) ➔ $\dot{M}$ $\dot{M} v_{\infty}^2$

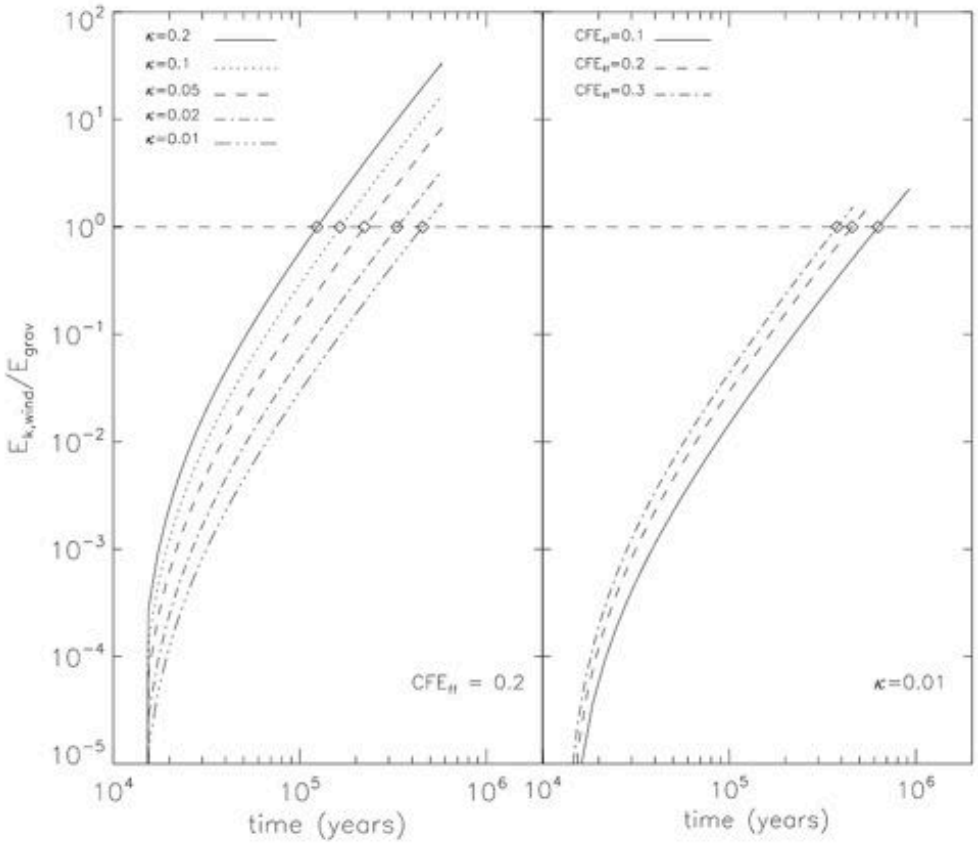


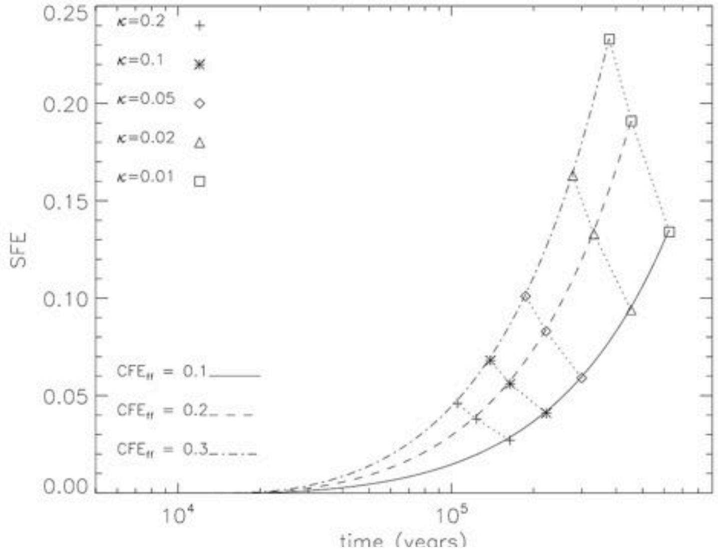


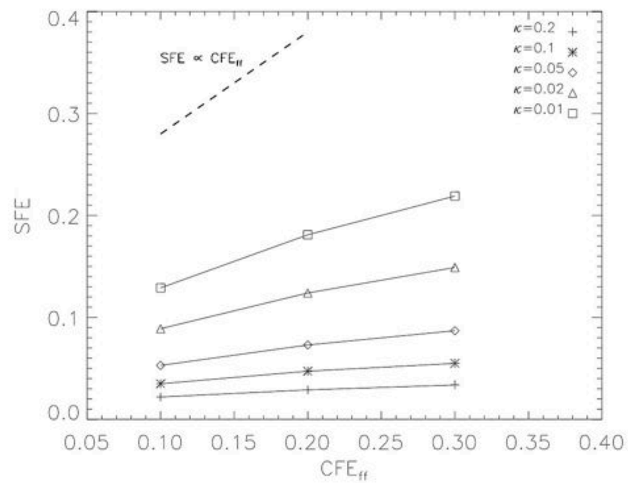
Dib et al. 2011

Influence of Stellar Feedback

Gas expulsion



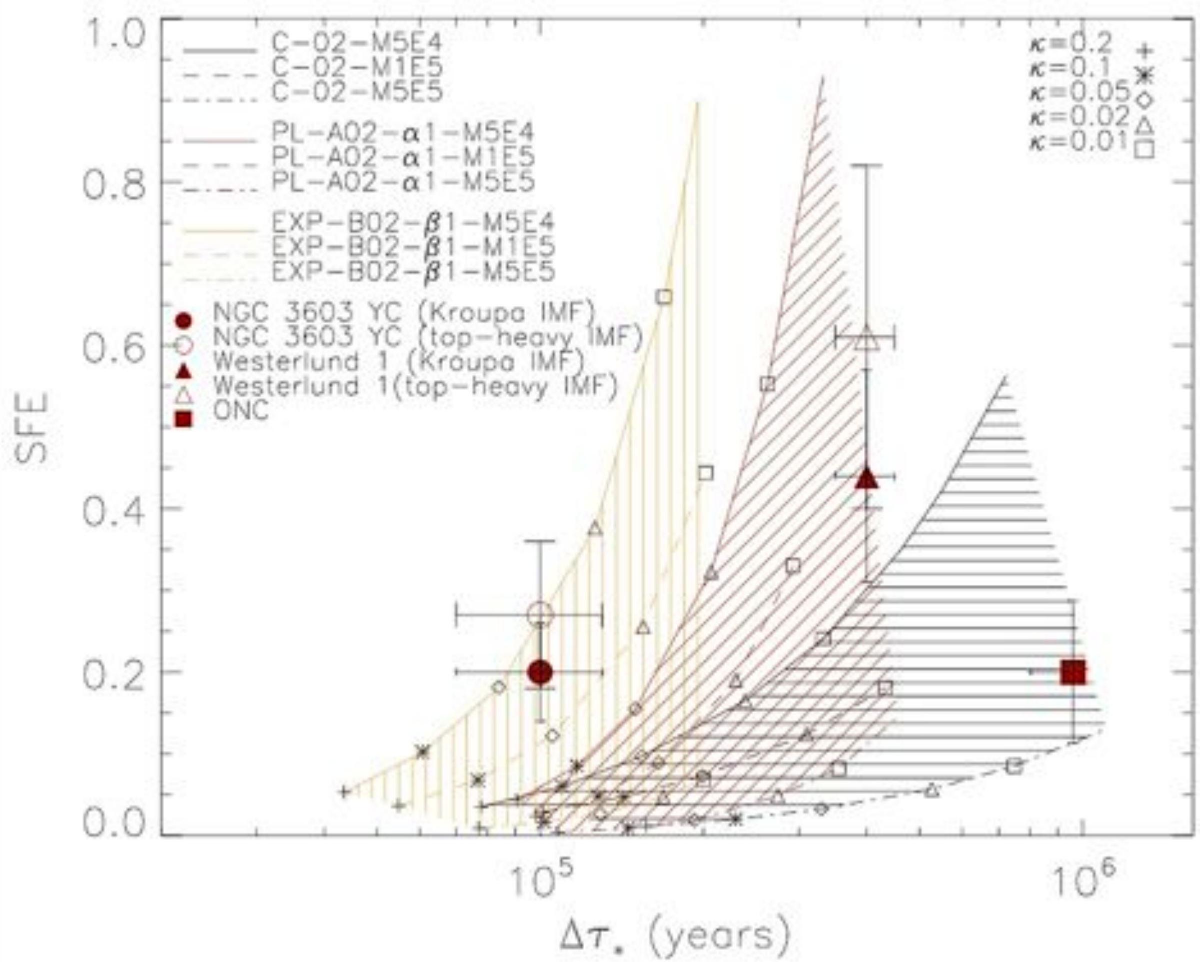




Dib et al. 2011,2013

Influence of Stellar Feedback

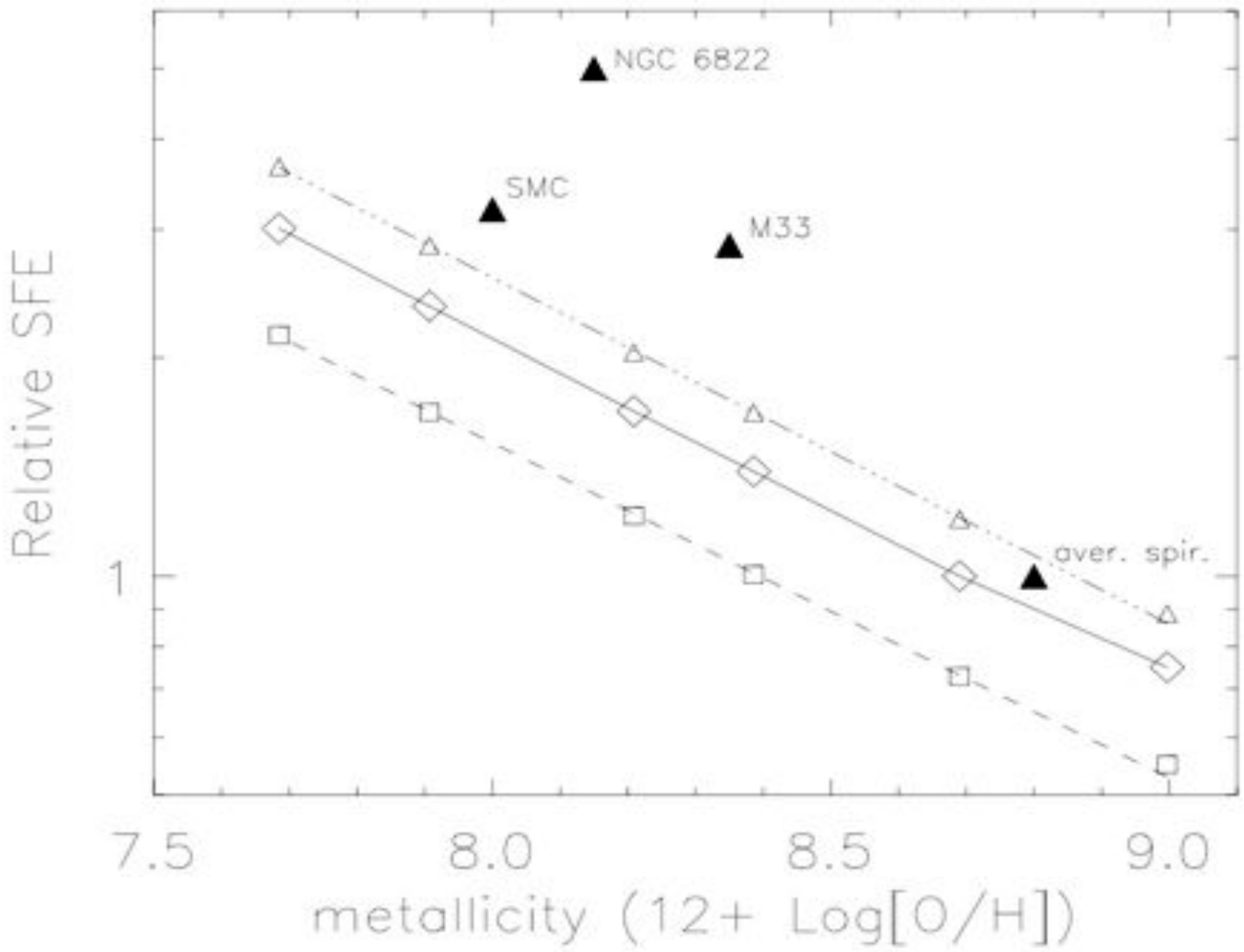
Comparison to observations: massive clusters



Dib et al. (2013)

Influence of Stellar Feedback

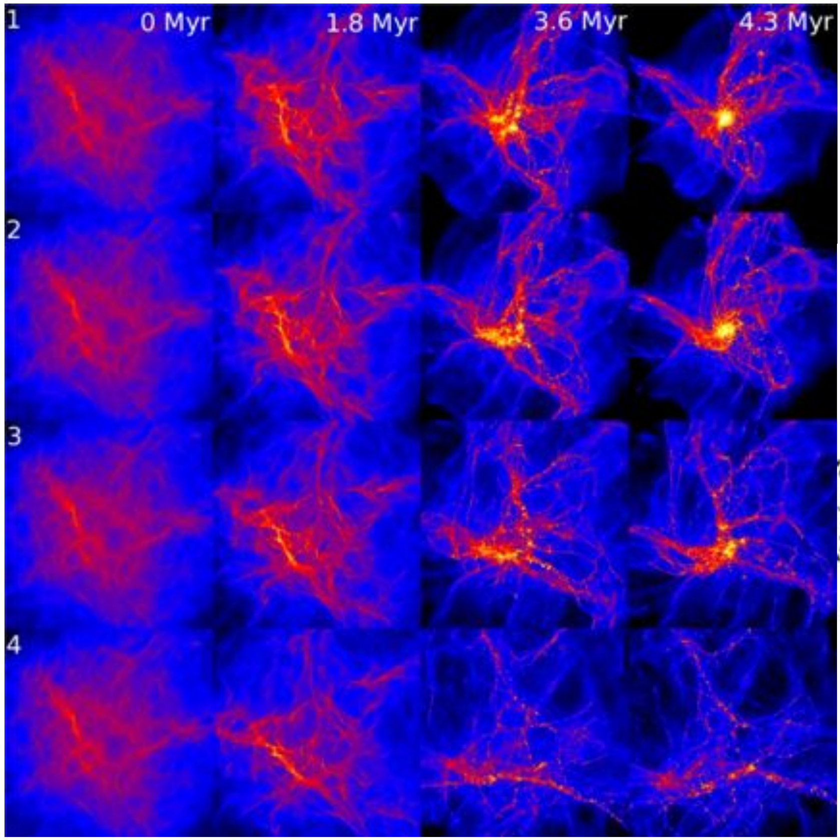
Dependence on metallicity: Galactic SFEs



Dib et al. (2011)

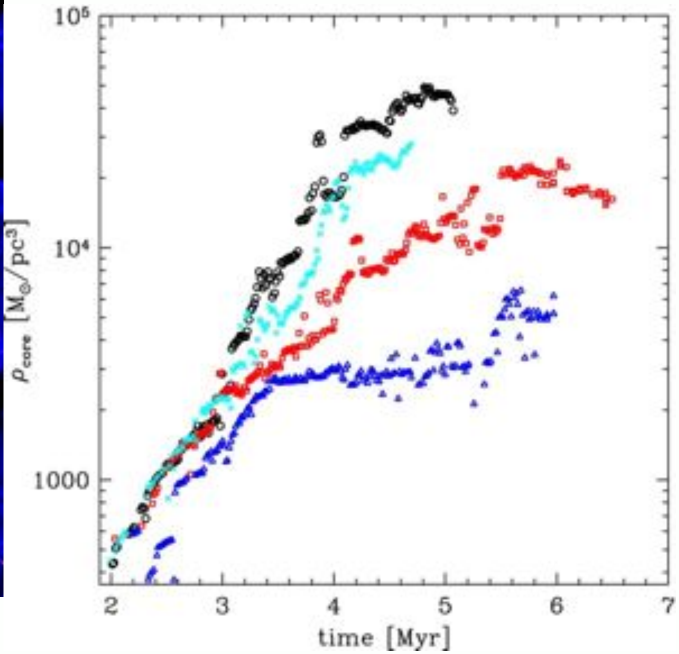
Influence of Shear

results from numerical simulations



Increasing shear

• Models of clouds with similar masses (10^6 M_{sol}), sizes (50 pc), but different angular velocities.



Weidner et al. (2010)

Influence of Shear

Correlation between shear and the distribution of molecular clouds and stars

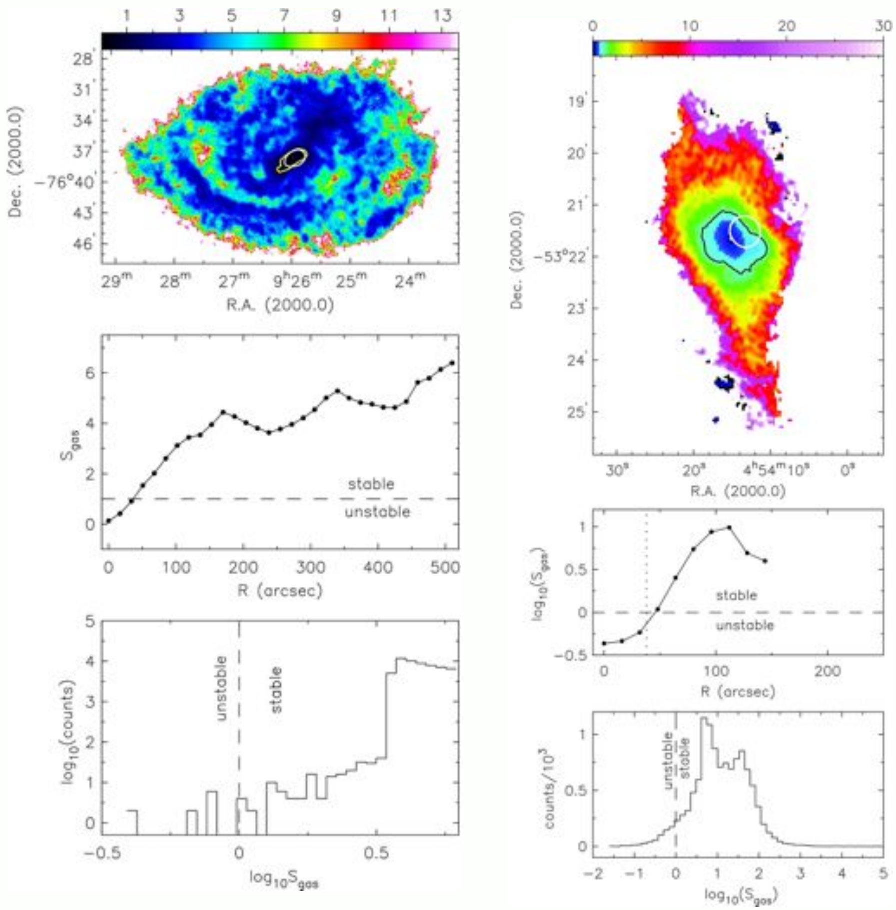
- Galaxies have differential rotation → shear
- Critial surface density beyong which shear is inefficient → gravity wins
- This defines a shear parameter

$$S = \frac{\Sigma_{cr}}{\Sigma} = \frac{\alpha_A A \sigma}{\pi G \Sigma}$$

with $$A = -\frac{1}{2} R \frac{d\Omega}{dR} = -\frac{1}{2}\left(\frac{V}{R} - \frac{dV}{dR}\right)$$

Gas is supported by shear if $S > 1$

Application to HI gas

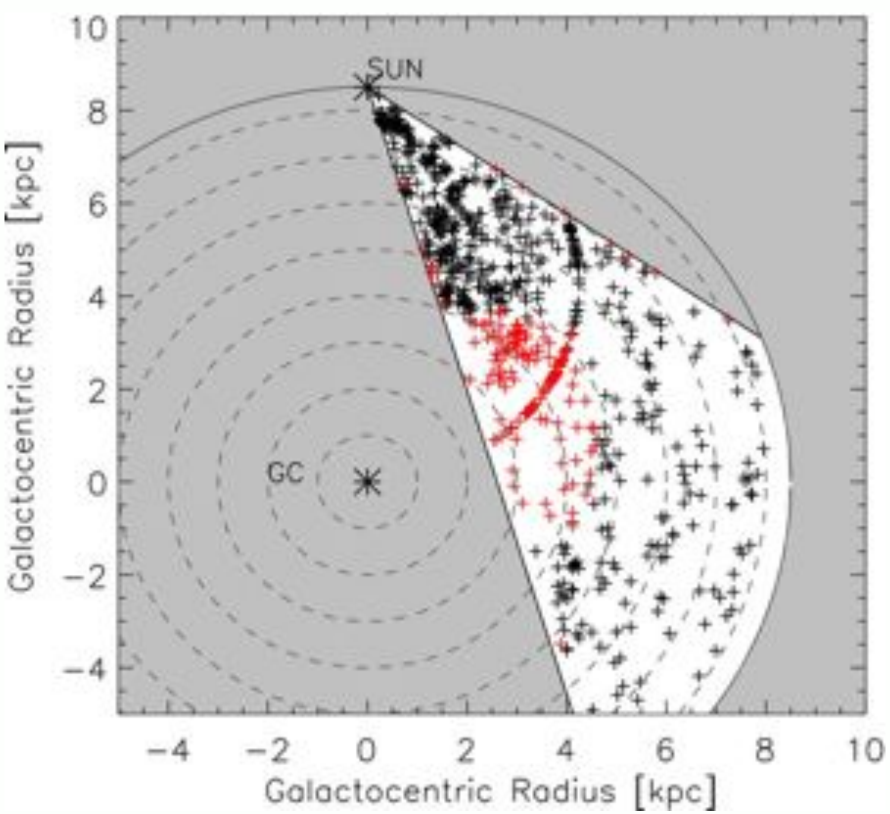


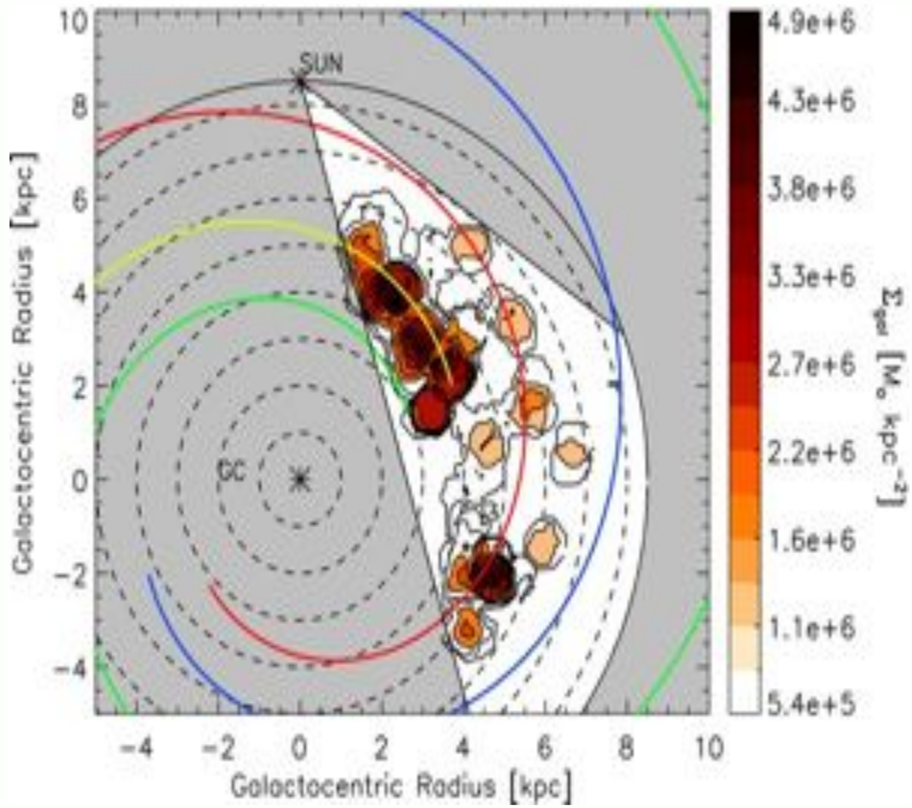
Elson et al. (2012)

Influence of Shear

Is shear (really) regulating the SFE on cloud scales ?

- Data from the Galactic Ring Survey (^{13}CO 1-0 line)
- masses [10-10^6] M_{sol}, sizes [0.5-70] pc



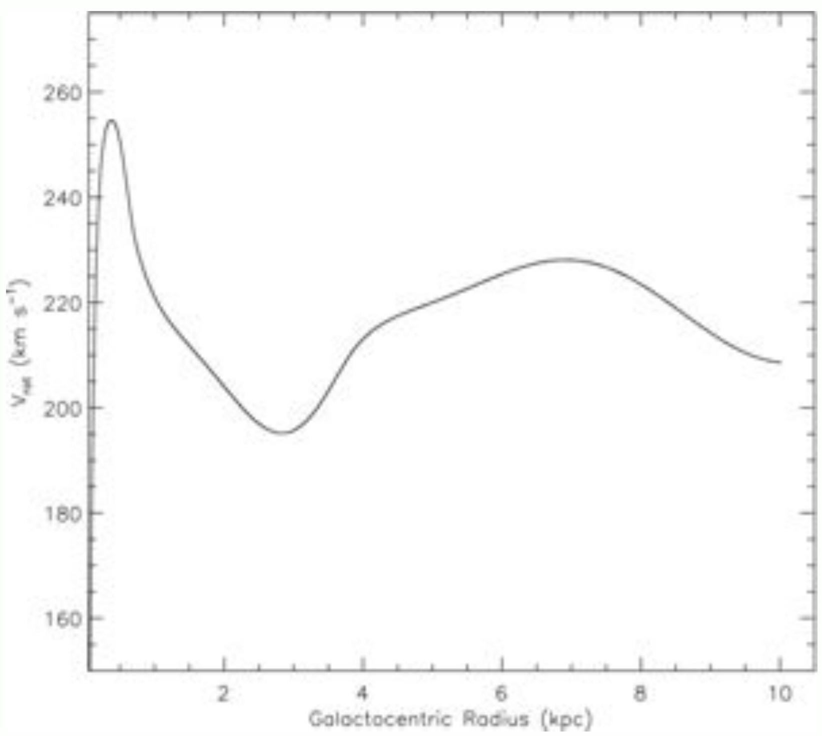


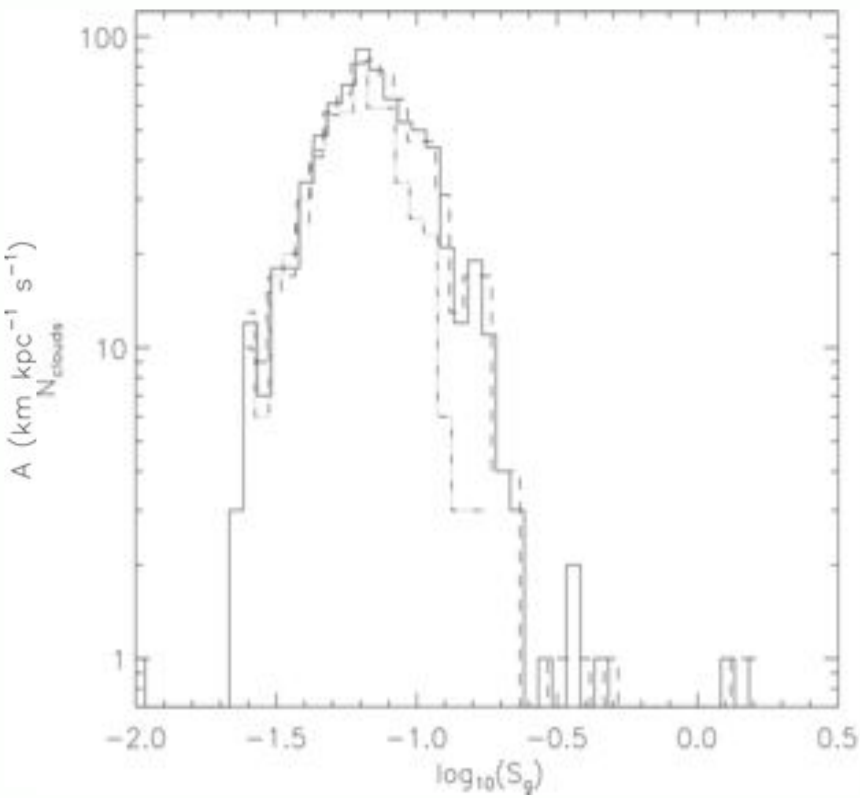
Roman-Duval et al. (2012)

Influence of Shear

Is shear (really) regulating the SFE on cloud scales ?

- **Measuring the shear parameter on molecular cloud scales**



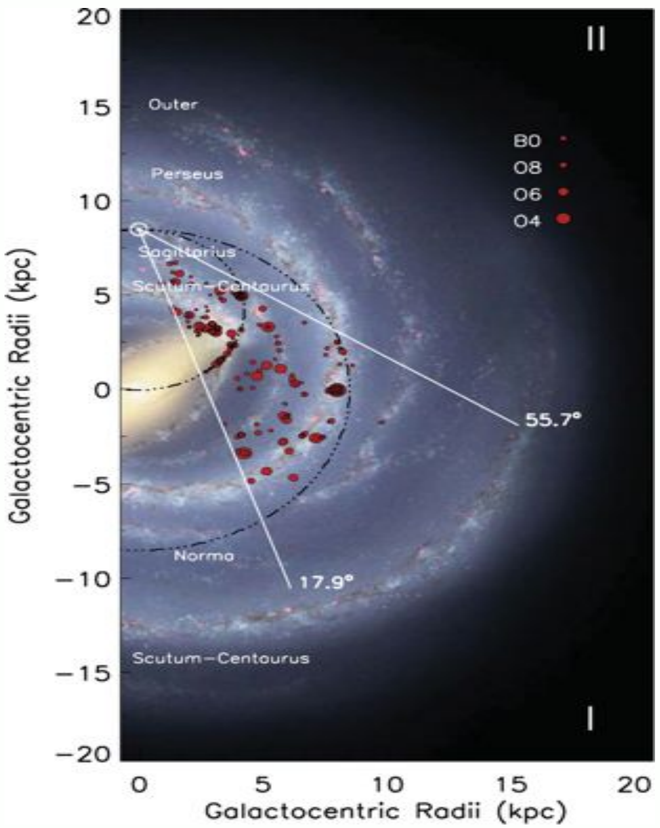


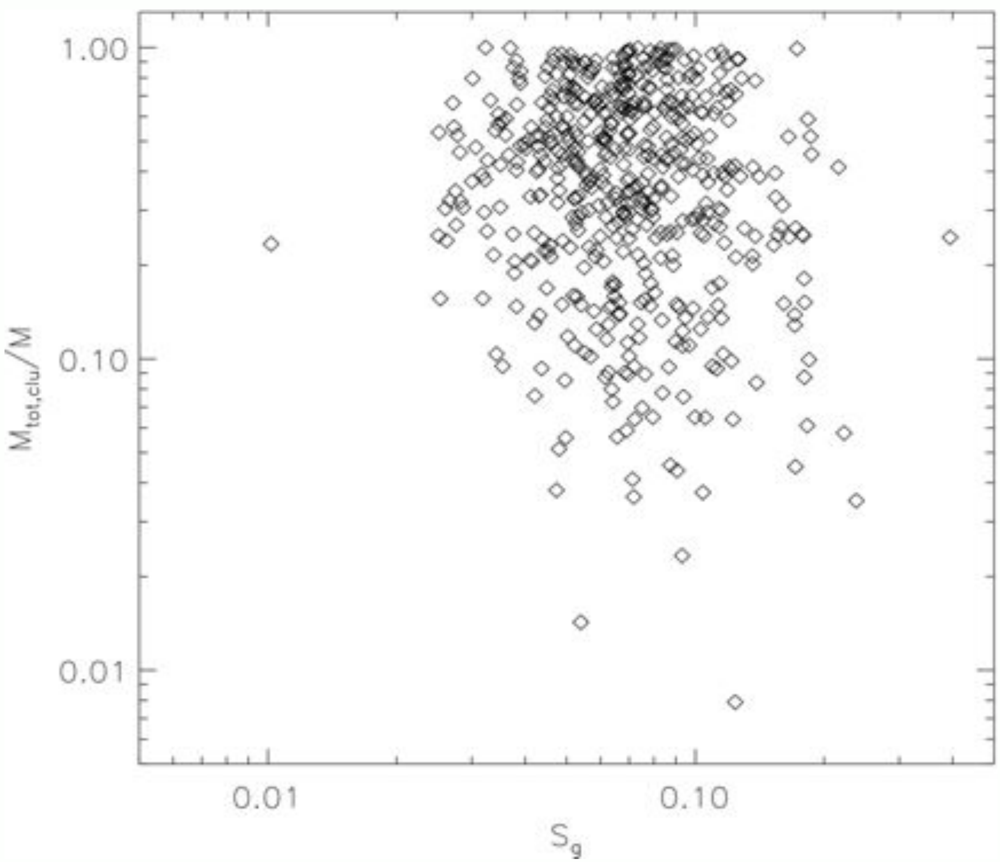
Dib et al. (2012)

Influence of Shear

Is shear (really) regulating the SFE on cloud scales ?

- **correlation between S and the YSOs Luminosities (RMS survey)**





Dib et al. (2012)

Conclusions

⊙ The SFE in Giant Molecular clouds: ~ 1-10 %

⊙ In protocluster forming regions: ~ 5-70 %

⊙ Many processus participate & eventually compete in setting the SFE in molecular clouds

⊙ magnetic fields: ✓

⊙ turbulence: ✓

⊙ stellar feedback ✓

⊙ shear: X

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* Effet of external disruptions/compressions/triggering (e.g., interaction with a shock, cloud-cloud collisions, tidal effects)

با تشکر از توجه شما