Feedback Regulated Star Formation: From Star Clusters to Galaxies

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SFEs in clusters

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

Final value of the SFE

$$SFE_{\exp} = SFE(t_{\exp}) \approx \frac{M_{cluster}(t_{\exp})}{M_{gas,i} + M_{gas,acc}\left(t_{\exp}\right)}$$

For an isolated clump

$$SFE_{\exp} \approx \frac{M_{cluster}\left(t_{\exp}\right)}{M_{clump}}$$

Derived SFEs in clusters

$$SFE_{cluster,obs} \sim 0.1\text{-}0.5$$

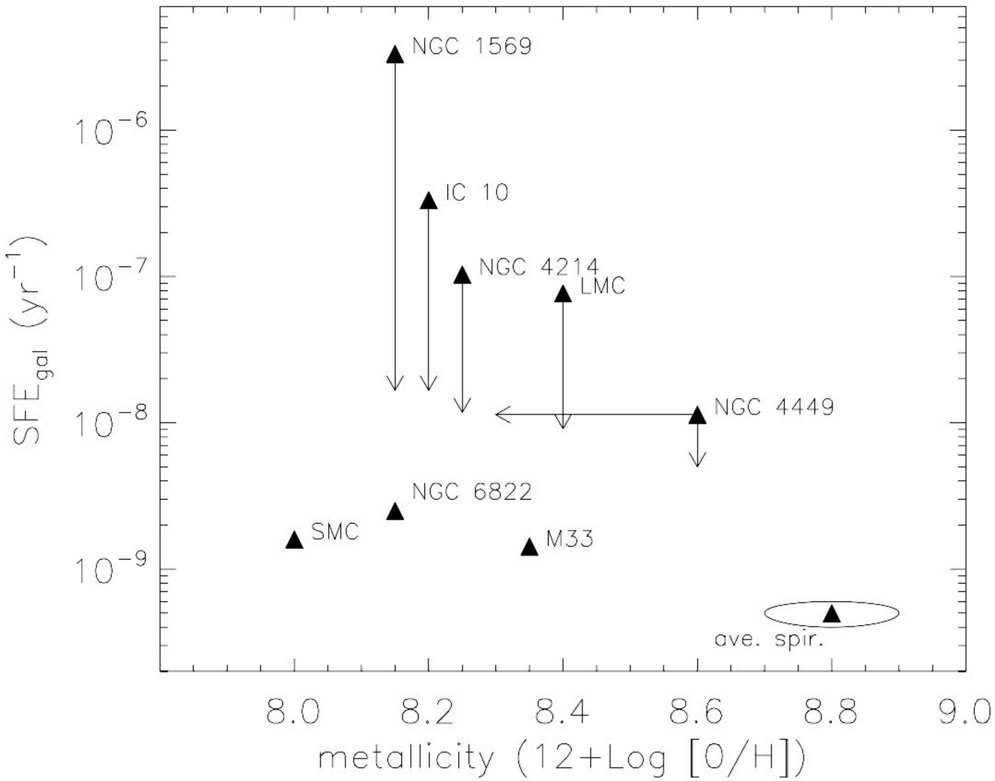
$$SFE_{cluster,obs} \approx \frac{M_{cluster}}{M_{cluster} + M_{gas}}$$

e.g. Lada & Lada (2003) and references therein

No established dependences on mass, metallicity, environment.

Derived SFEs in Galaxies

$$SFE_{gal} \approx \frac{SFR_{gal}}{M_{H_2}}$$



Dib et al. (2011)

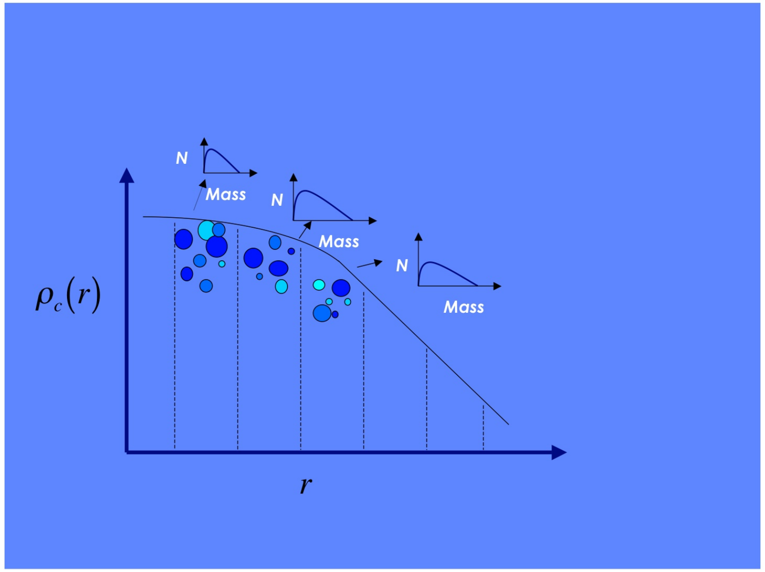
Data compiled from:

average spirals (Murgia et al. 2002)

M33 and NGC6822 (Gratier et al. 2010a,b)

SMC (Leroy et al. 2006)

Star formation in a protocluster clump



General properties

A) Fraction of the mass of the clump converted into dense cores per free fall time CFE_{ff}

Clump properties

C) Protocluster cloud mass-radius relation, M_cl-R_cl (constrained by the observations)

D) Clump core Radius, R_c0 (0.02 pc)

E) exponent of density profile in outer regions (-2)

F) Larson relation exponent α, or exponent of turbulent vel. field power spectra β (constrained by the observations)

Core properties

G) Contration timescale t_cont = ν t_ff; ν =1-10 (constrained by the observations and theory)

H) Cores peak density with respect to clump background density as a function ρ_{p0} (constrained by the observations and theory)

I) Core to star efficiency 1/3

Feedback from massive stars (M > 5 M_{sol})

I) Mass loss rate of massive stars and the terminal velocity of the wind

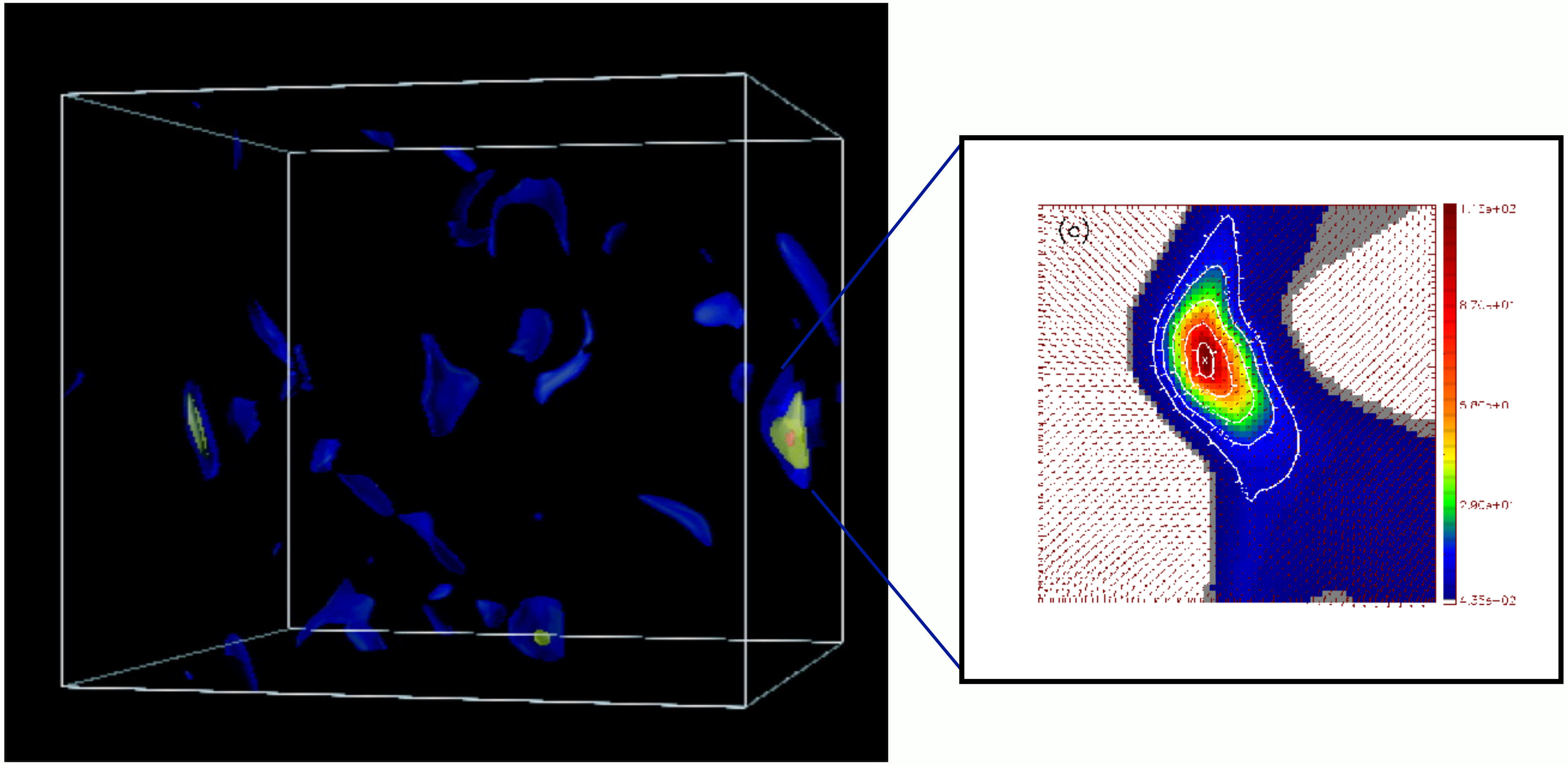
J) Fraction of wind energy that disperses the gas from the clump

(unknown, we take 0.1)

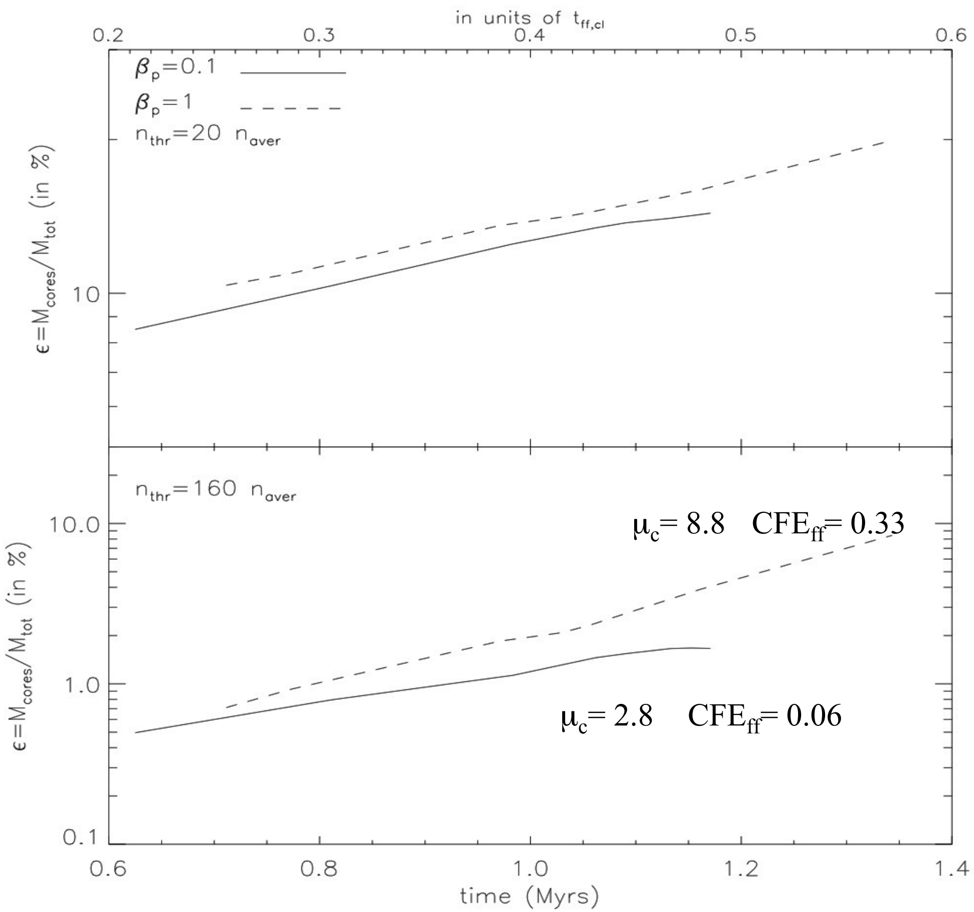
Variation of the CFE: The input of numerical simulations

Simulations of Turbulent, magnetized, and self-gravitating clouds

with the AMR code RAMSES (resolution of 4096^3)



Influence of the magnetic field



Dib et al. in 2010a

Feedback: Stellar Winds

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

Terminal wind velocity v_∞

Energy cumulated in winds

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

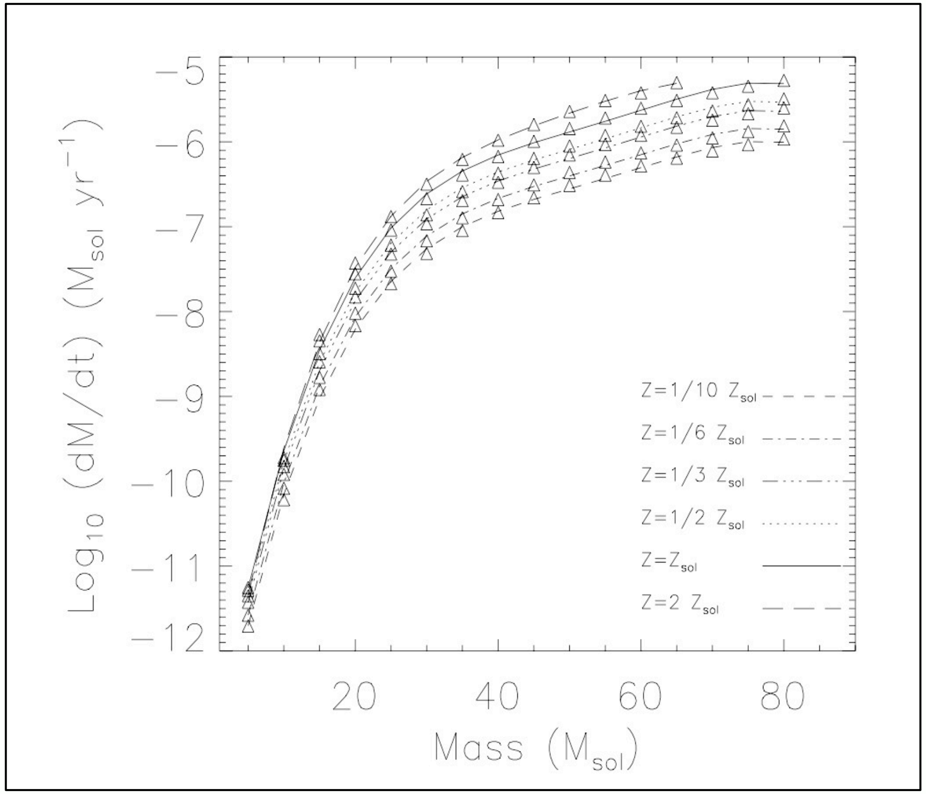
Fraction of wind energy that counters gravity $E_{k,wind} = \kappa E_{wind}$

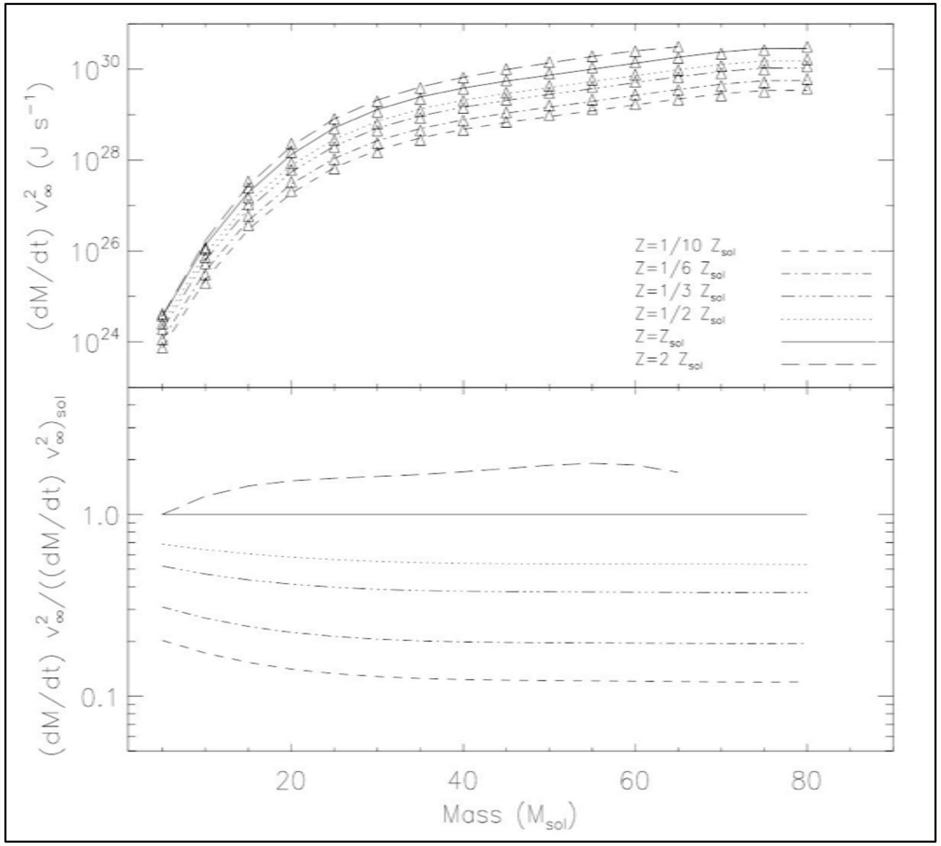
$$k < 1$$

Power of stellar wind

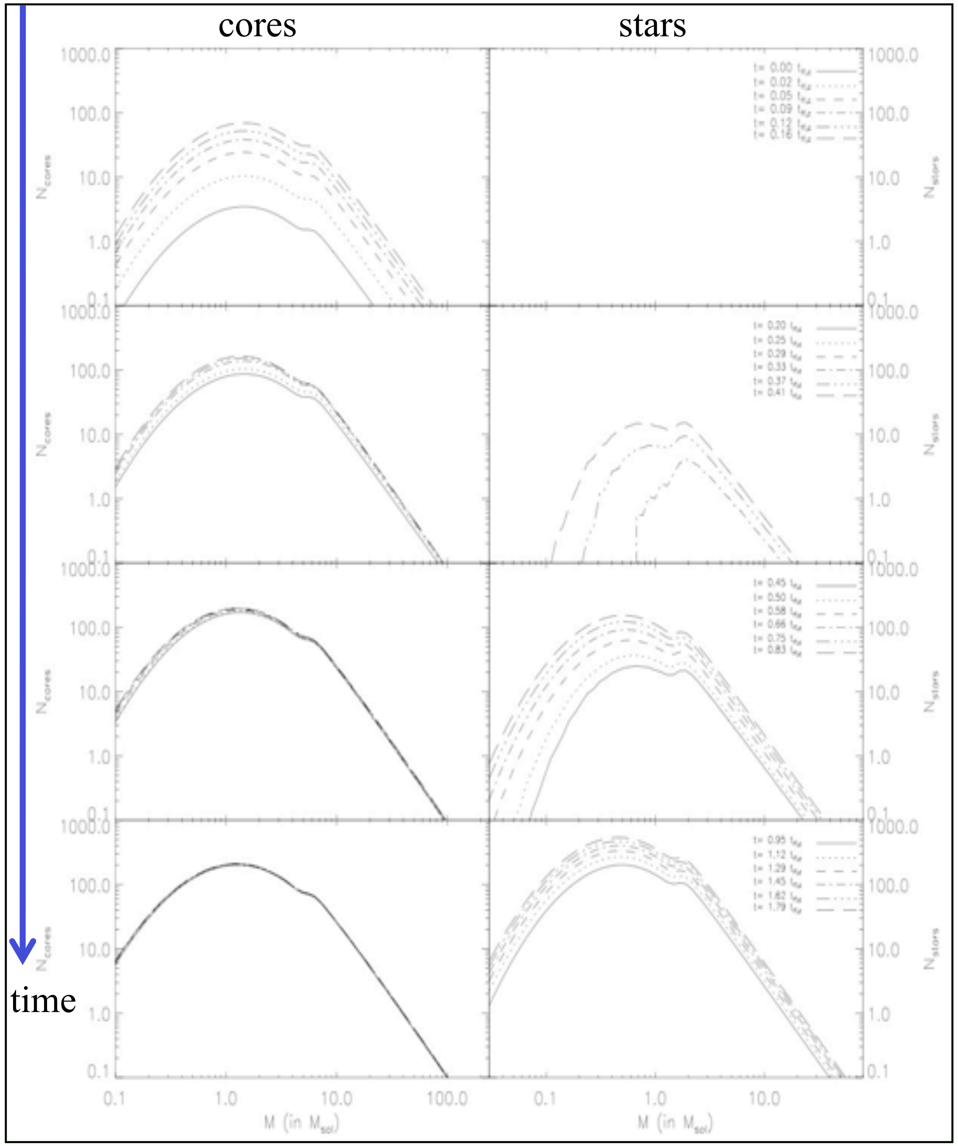
- Calculate main sequence models of OB stars (≥ 5 $M_{\odot}$) (using CESAM)

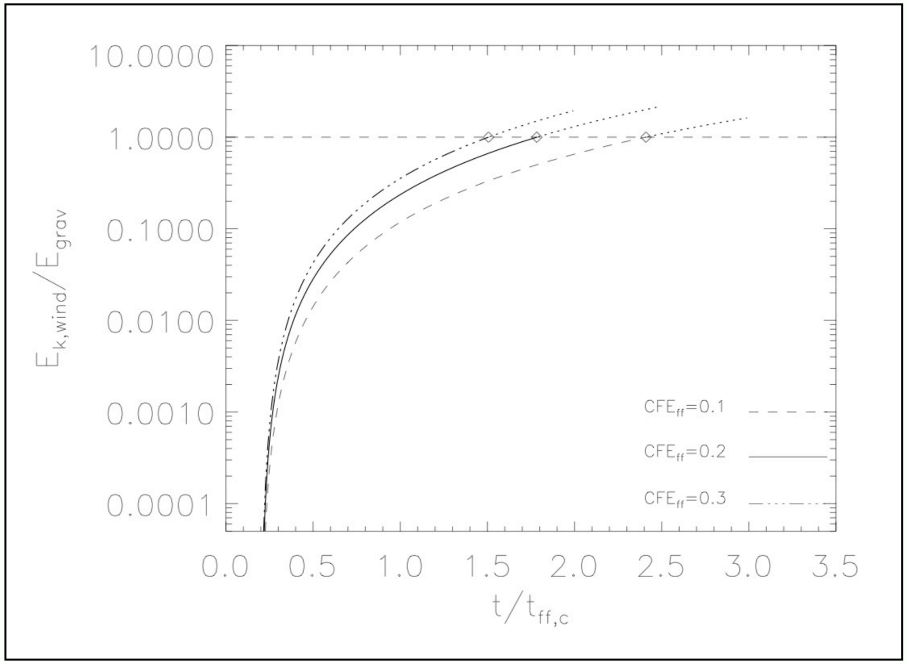
- (T_{eff}, L_*, R_*) ➔ Stellar atmosphere model (Vink et al.) ➔ $\dot{M}$ $\dot{M} v_\infty^2$

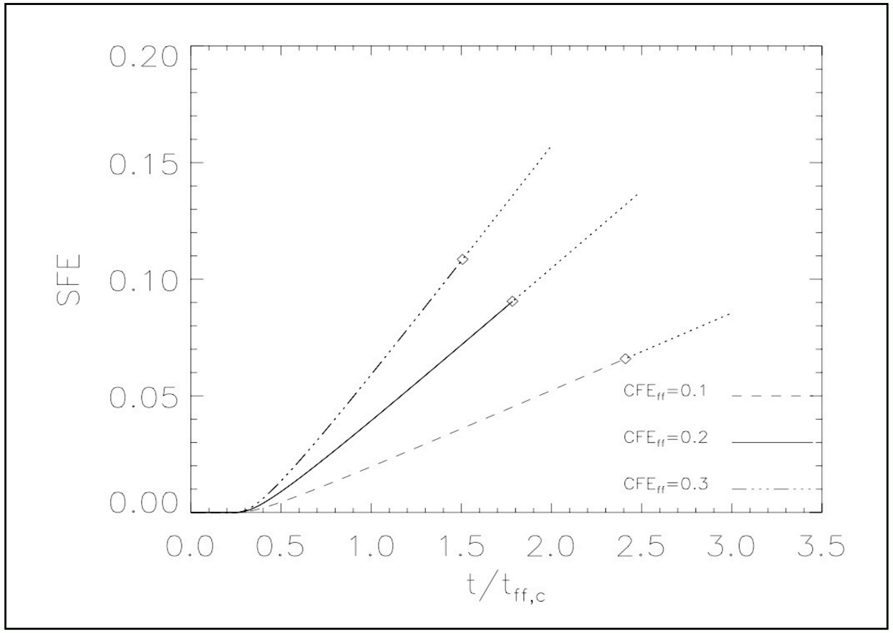




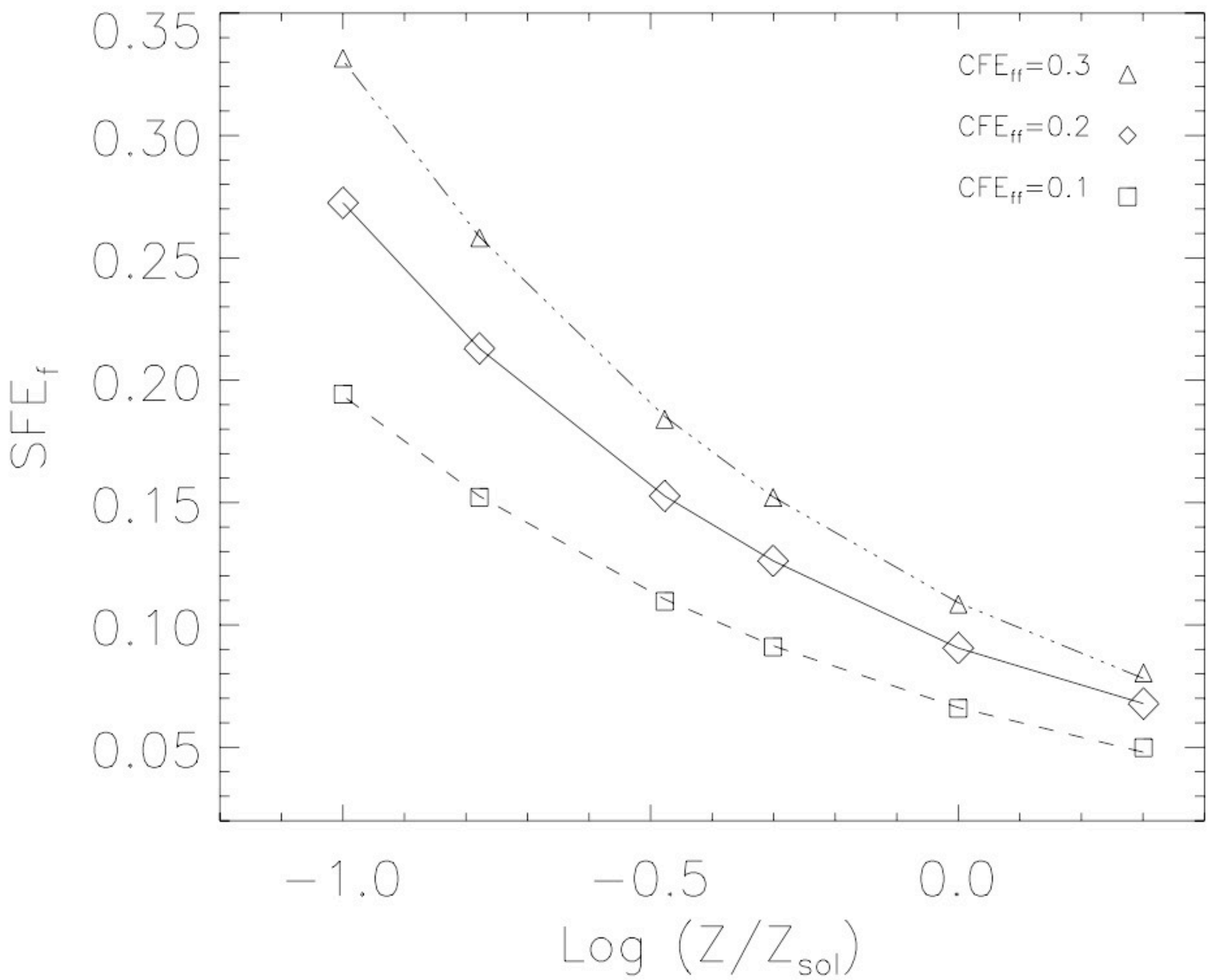
Model with solar metallicity







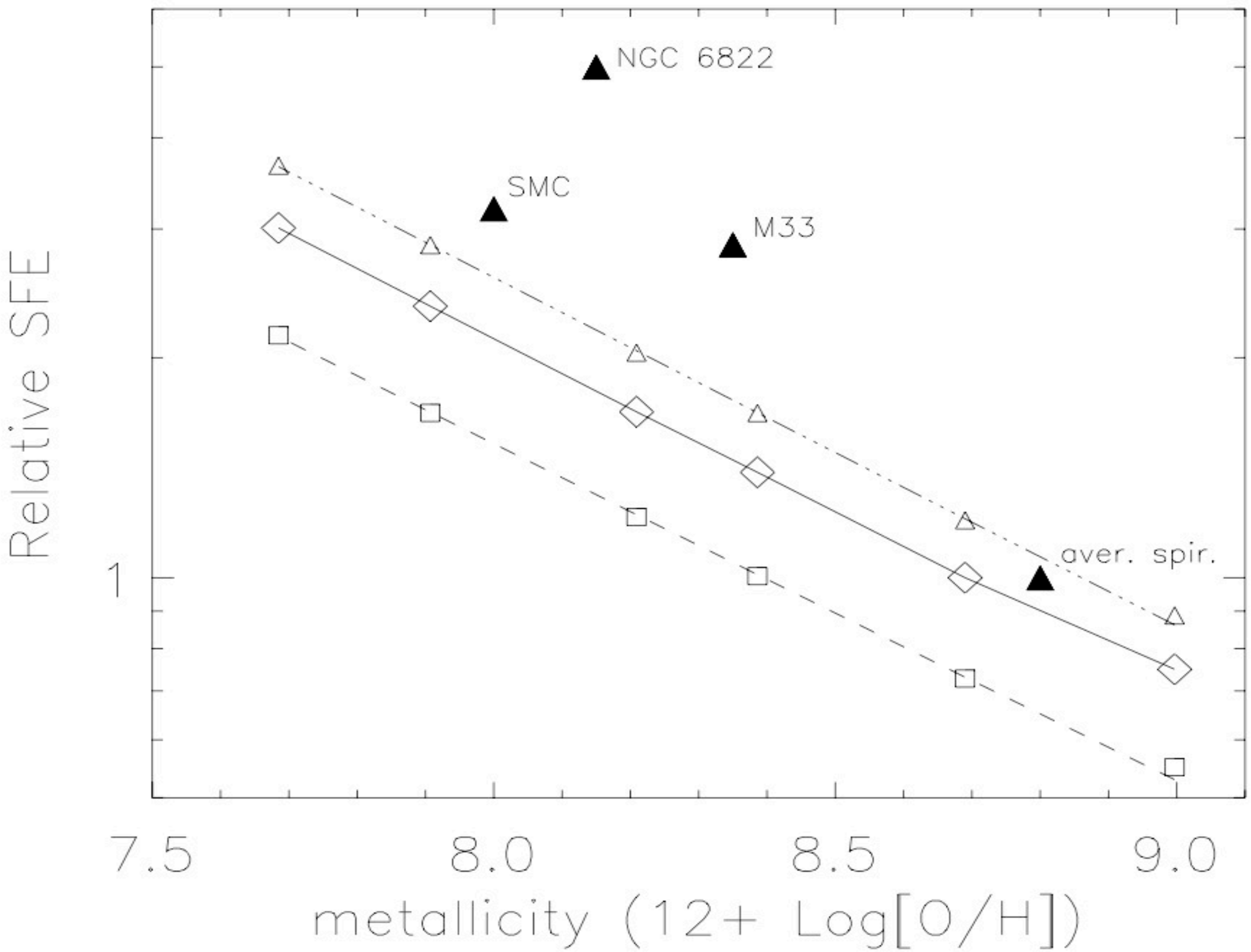
SFE_{exp} on metallicity



$$SFE_{\exp} = Ce^{-Log(Z/Z_{\Theta})/\tau}$$

Dib et al. (2011)

Galactic SFEs

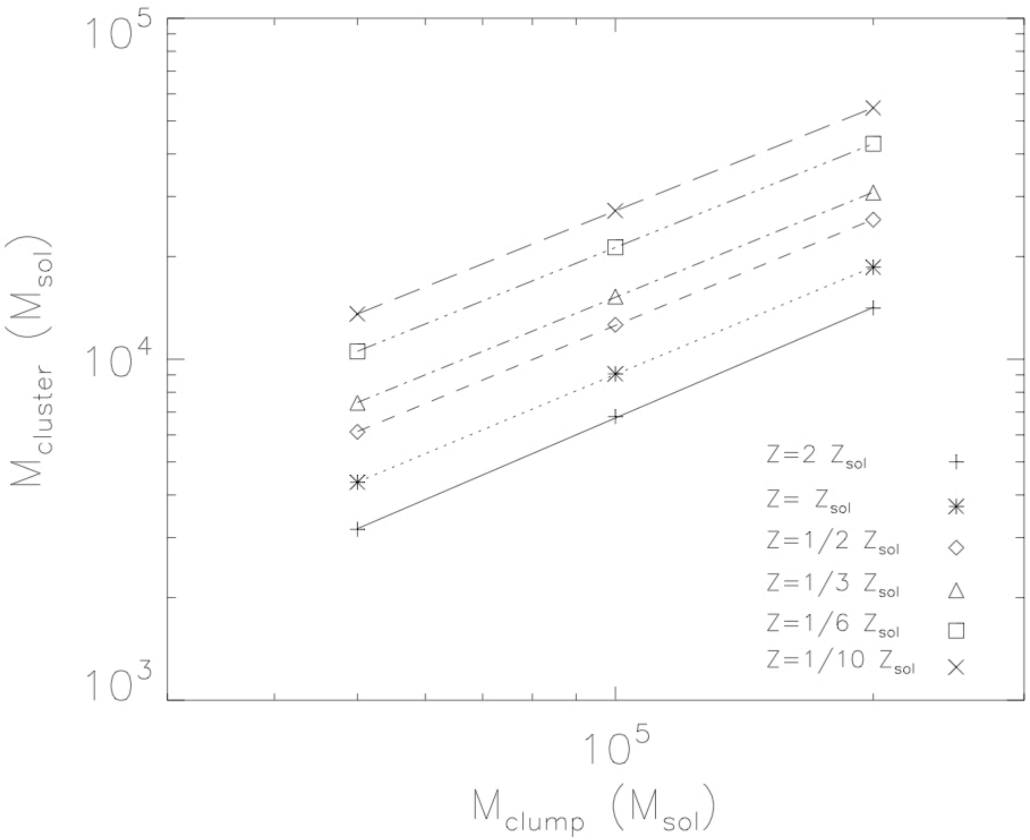


Dib et al. (2011)

Stellar clusters mass function vs. Protocluster clumps mass function

$$\left(\frac{dN}{dM}\right)_{clusters} \propto M^{\eta}_{emb,clusters}$$

$$\left(\frac{dN}{dM}\right)_{protocluster,clump} \propto M^{\delta}_{protocluster,clumps}$$



$$M_{cluster} \propto M^{\gamma}_{protocluster,clumps}$$

$$\delta = \gamma(\eta + 1) - 1$$

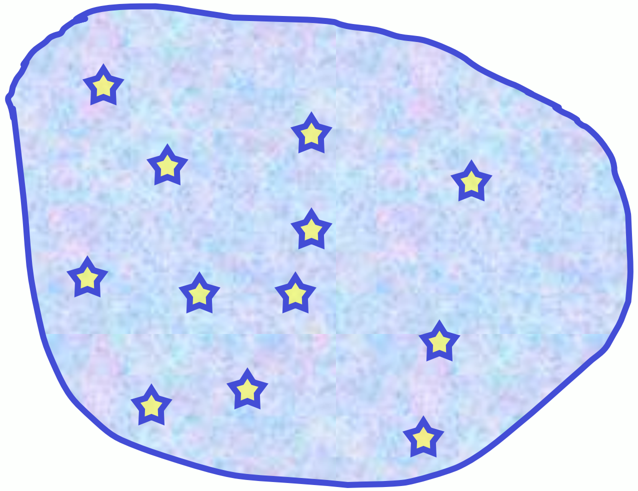
We find $\gamma = 1$

Then, if $\eta \approx -2$

$$\delta \approx -2$$

The Star Formation Laws in Galaxies in the pure Gravo-Turbulent Star Formation Model

$$\Sigma_{SFR} = \Sigma_g f_{H_2} \frac{SFE_{ff}}{t_{ff}}$$



* Star Formation occurs in GMCs

* The characteritic mass is $M_{char} = M_{GMC}$

M_{char} is set by the gravitational instability in the disk

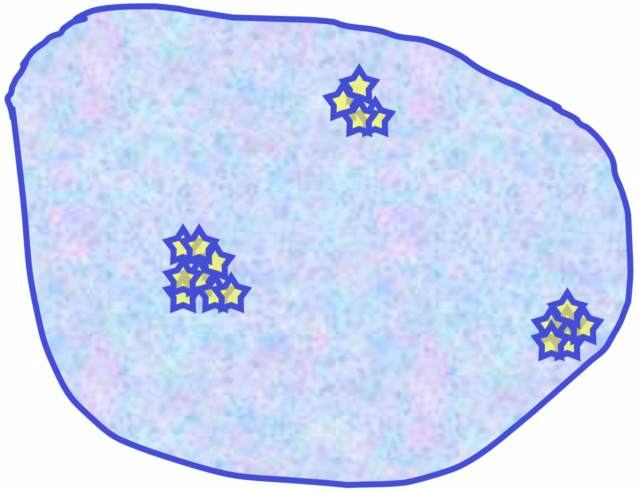
*A description of $f_{H_2}(Z^{'})$

(Krumholz, McKee, Tumlinson 2009;
Gnedin & Kravtsov 2010,2011 and others)

* A description of
(Krumholz & McKee 2005)

$$SFE_{ff} \approx 0.15 \varepsilon \alpha_{vir}^{-0.68} Ma^{-0.32}$$

The Star Formation Laws in Galaxies
in
The Feedback Regulated Star Formation Model



Star formation occurs in protostellar clumps (embedded in GMCs).

$$N(M_{clump}) \propto M_{clump}^{-2}$$

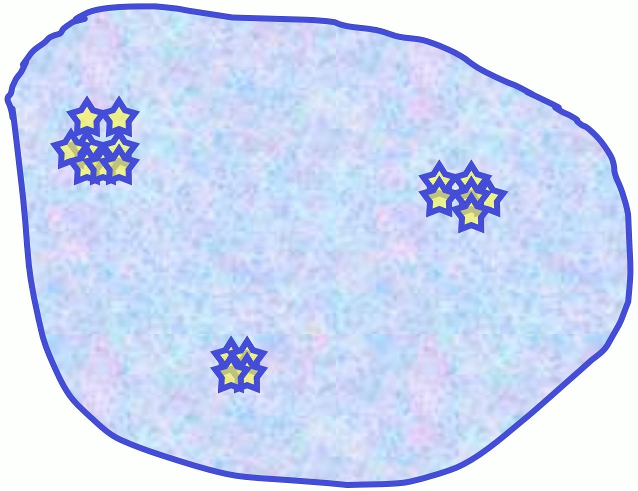
The characteristic mass is

$$M_{char} = \int_{M_{cl,\min}}^{Max(M_{cl,\max}, M_{GMC})} MN(M)dM$$

A description of $f_{H_2}(\Sigma_g, Z')$

The Star Formation Laws in Galaxies
in
The Feedback Regulated Star Formation Model

$$\Sigma_{SFR} = \Sigma_g f_{H_2}\left(\Sigma_g, Z'\right) \frac{\left\langle SFE_{\exp} \right\rangle}{\left\langle t_{\exp} \right\rangle}$$

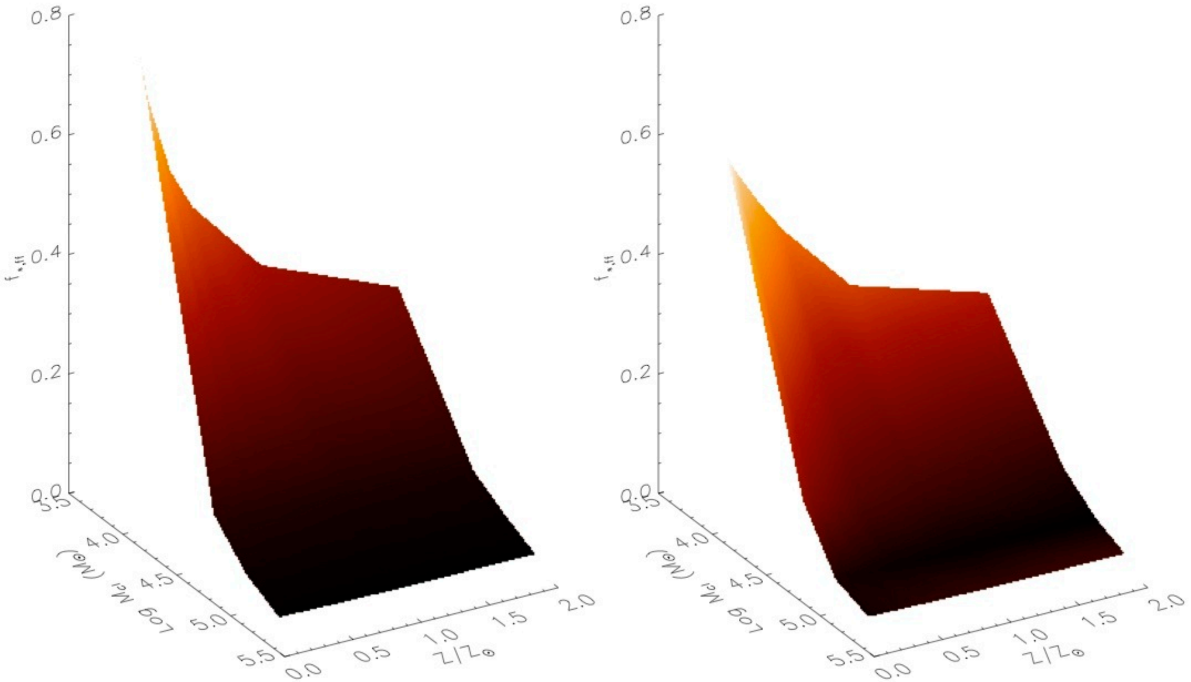


$$\Sigma_{SFR} = \Sigma_g f_{H_2}\left(\Sigma_g, Z'\right) \frac{\left\langle SFE_{\exp} \right\rangle}{\left\langle n_{\exp} t_{ff} \right\rangle}$$

$$\Sigma_{SFR} = \Sigma_g f_{H_2} \frac{\left\langle f_{*,ff} \right\rangle}{\left\langle t_{ff} \right\rangle}$$

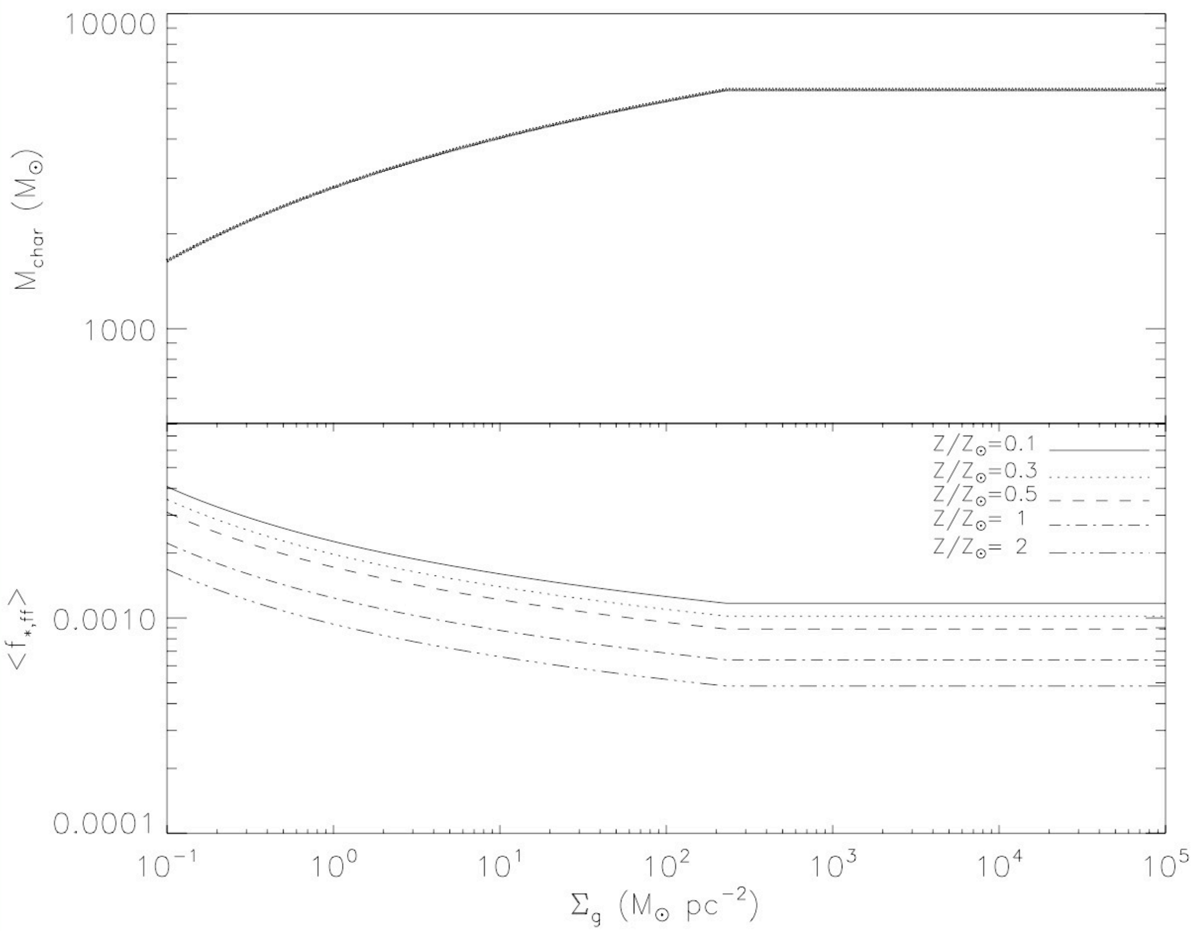
The Star Formation Efficiency per unit time in The Feedback Regulated Star Formation Model

$$\langle f_{*,ff} \rangle (Z') = \int_{M_{cl,\min}}^{\max(M_{cl,\max}, M_{GMC})} f_{*,ff}(M, Z') N(M) dM$$

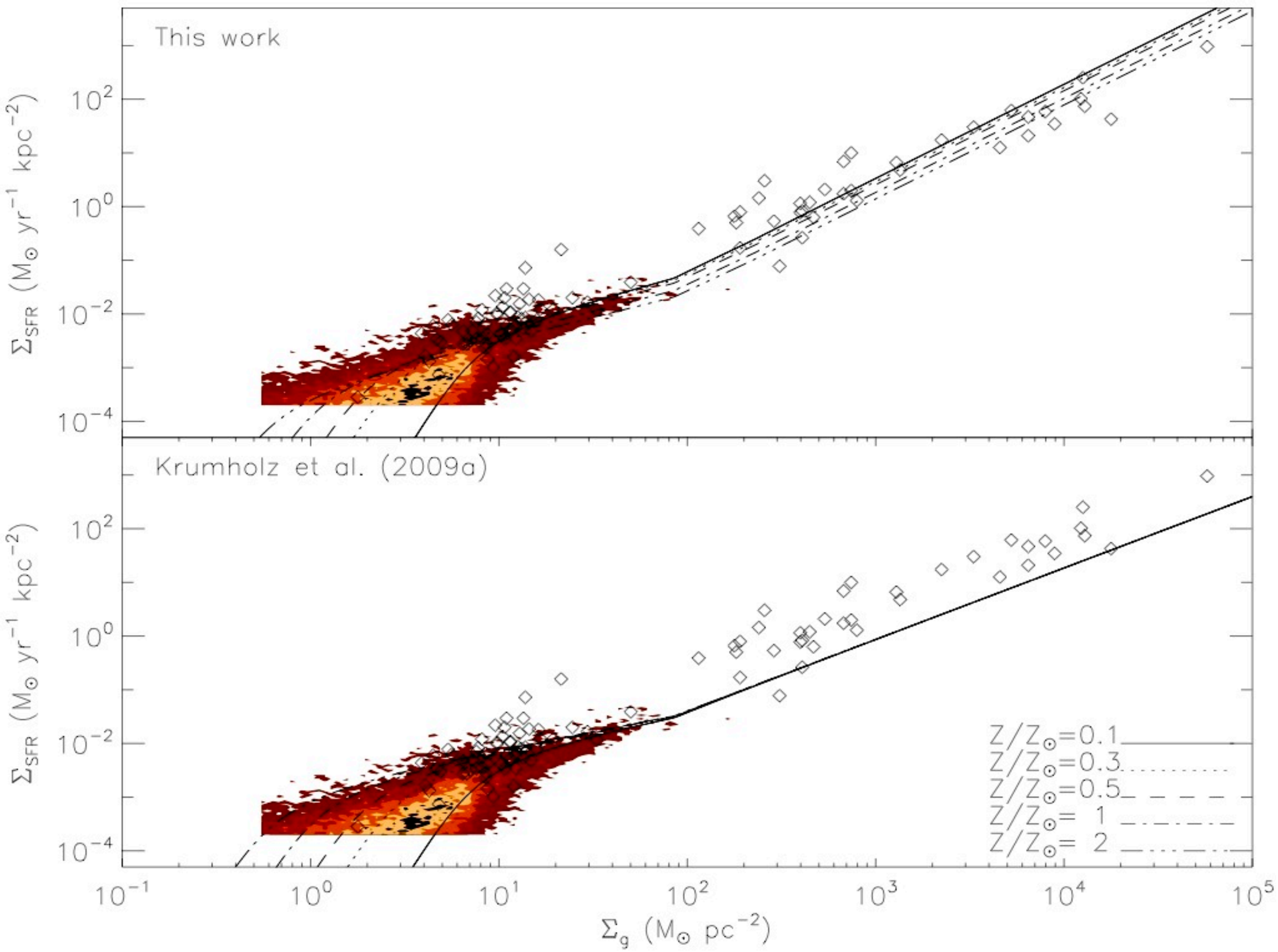


The Star Formation Efficiency per unit time in The Feedback Regulated Star Formation Model

$$\left\langle f_{*,ff}\right\rangle\left(Z'\right) = \int_{M_{cl,\min}}^{\max(M_{cl,\max},M_{GMC})} f_{*,ff}(M,Z')N\left(M\right)dM$$



The Star Formation Laws in Galaxies: Feedback regulated vs. Turbulence regulated



Observational data:

Kennicutt (1998), Bigiel et al. (2008, 2010)

Conclusions

* Turbulence, magnetic fields, geometry regulate the rate of core formation in a clump/cloud

* Feedback is a important regulator of the SFE in a protocluster clump.

* Stong metallicity dependence of the SFE. Decreases with increasing metallicity

Implications of the feedback regulated, metallicity dependent star formation

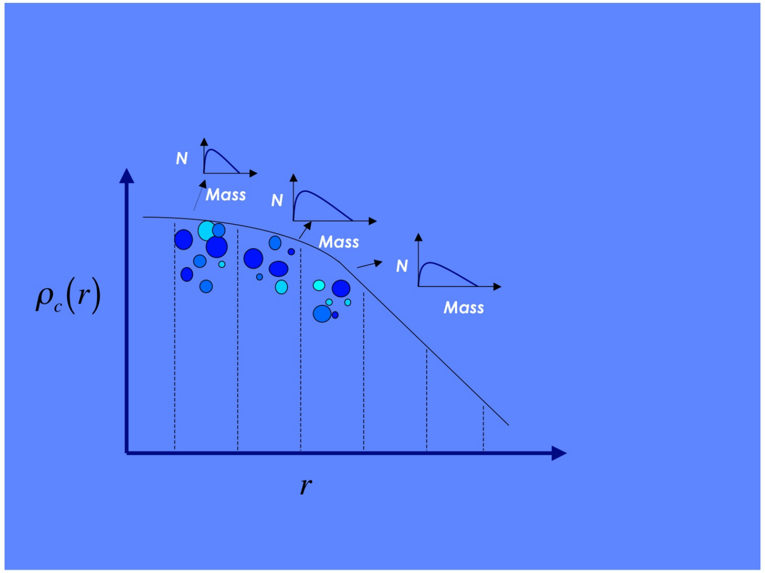
- Mass functions of protocluster clumps, and clusters (slopes of ≈ -2)

- Galactic SFEs depend on metallicity: cosmic chemical evolution

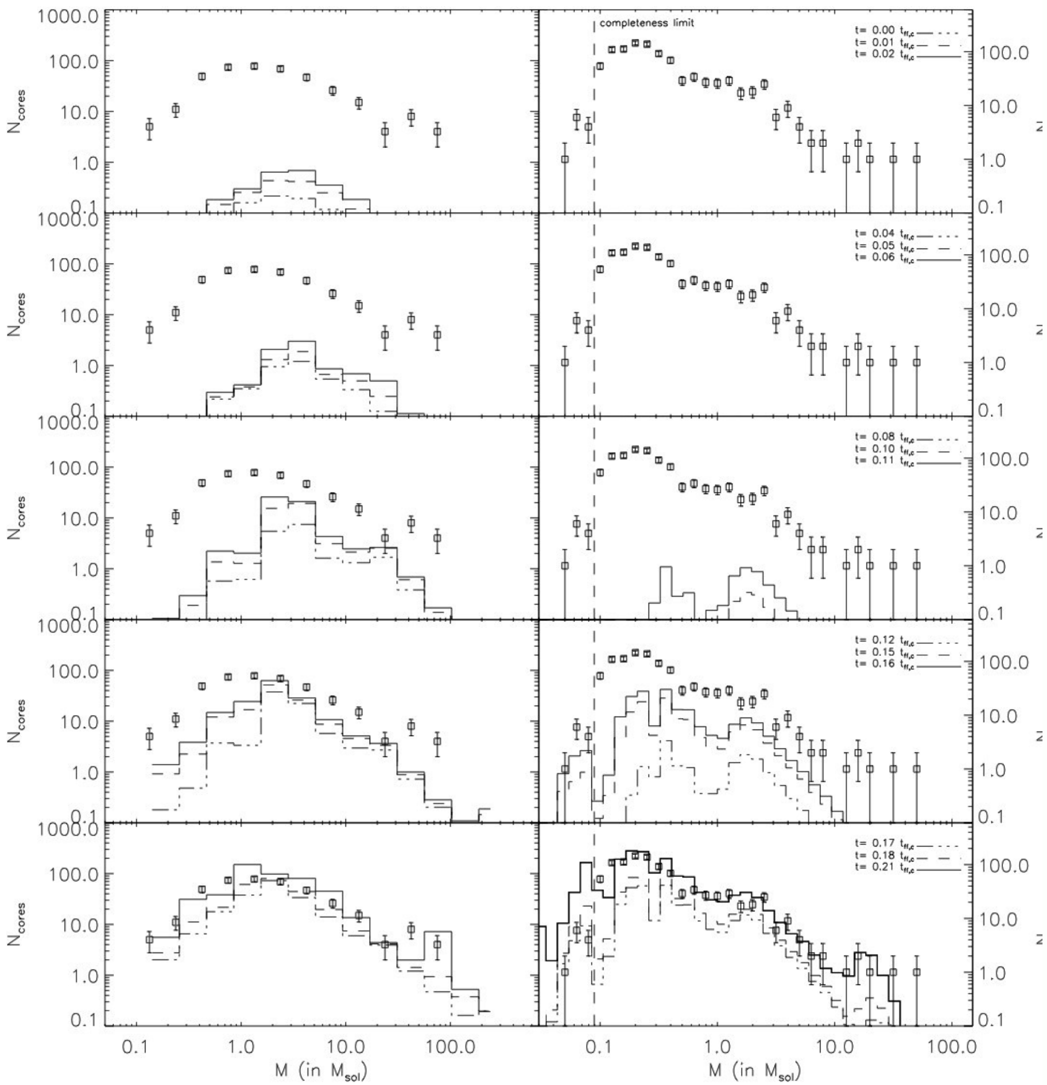
- Metallicty dependent Star Formation Laws in Galaxies over the entire surface density regime.

In the presence of accretion on cores
Variations of the SFE and IMF

$$\frac{dN(r,M,t)_{acc}}{dt} = \left(-\frac{\partial N}{\partial M}\dot{M} - \frac{\partial \dot{M}}{\partial M} N \right)(r,M,t)$$



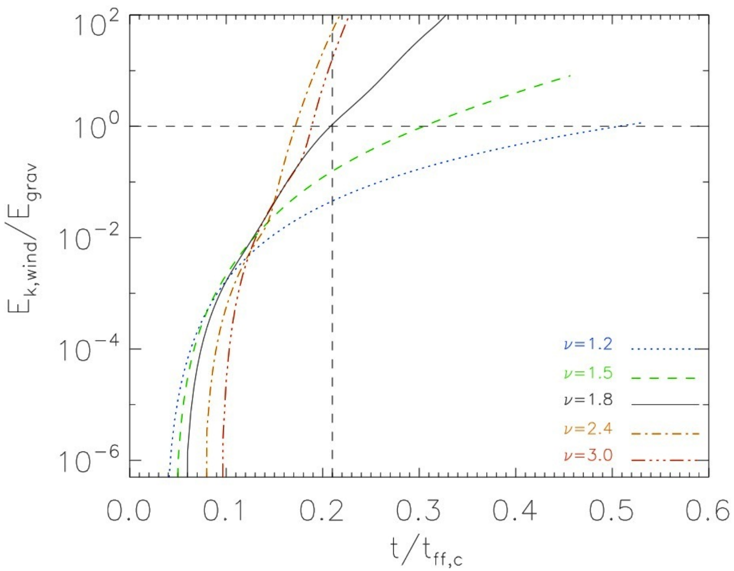
Application to the Orion Cloud and the ONC

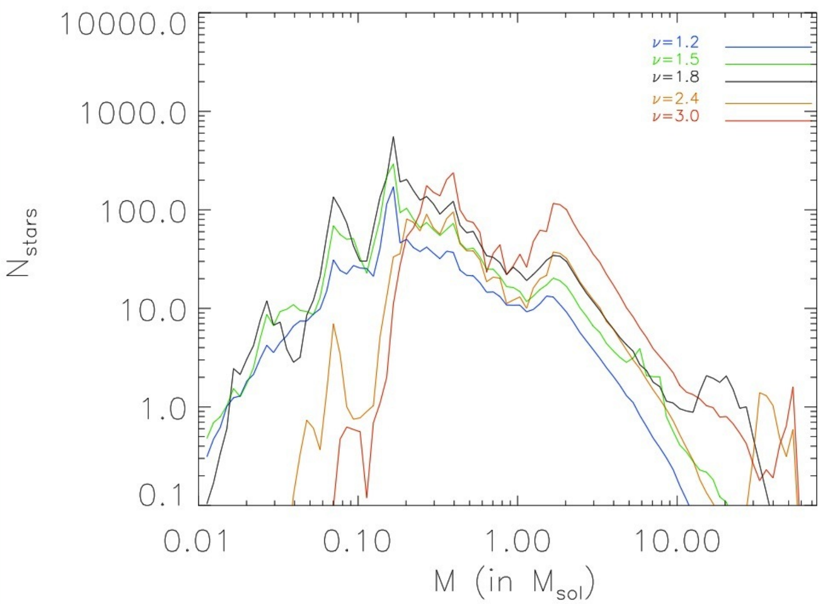


Dib et al. (2010b)

Variations with the cores properties

Effect of varying the lifetimes of the cores





Dib et al. 2010a