Variations of the IMF and of the SFE:

Physics or Random Sampling?

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Collaborators

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Fundamental Issues in Star Formation

- Formation and statistical properties of dense molecular cloud cores

(mass function of cores, scaling relations, gravitational boundedness, rotational properties)

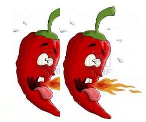
- Role of gravity: coalescence of cores, gas accretion

- Role of the initial conditions: chemical composition, turbulence, magnetic fields

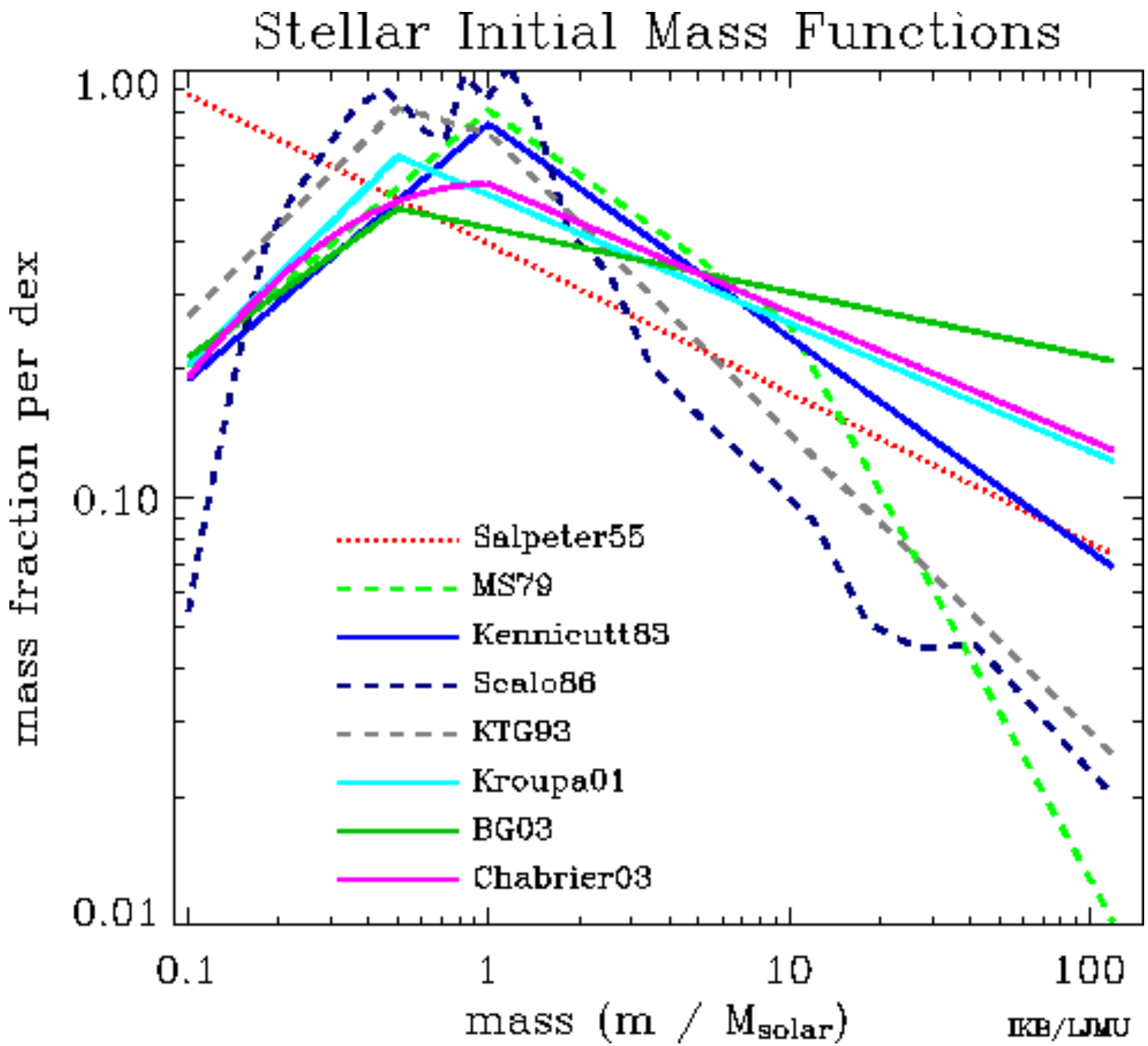
- Role of feedback: stellar outflows, radiation, winds

- The relationship between CMF and the IMF

- How do these processes regulate the SFE ?



The field IMF

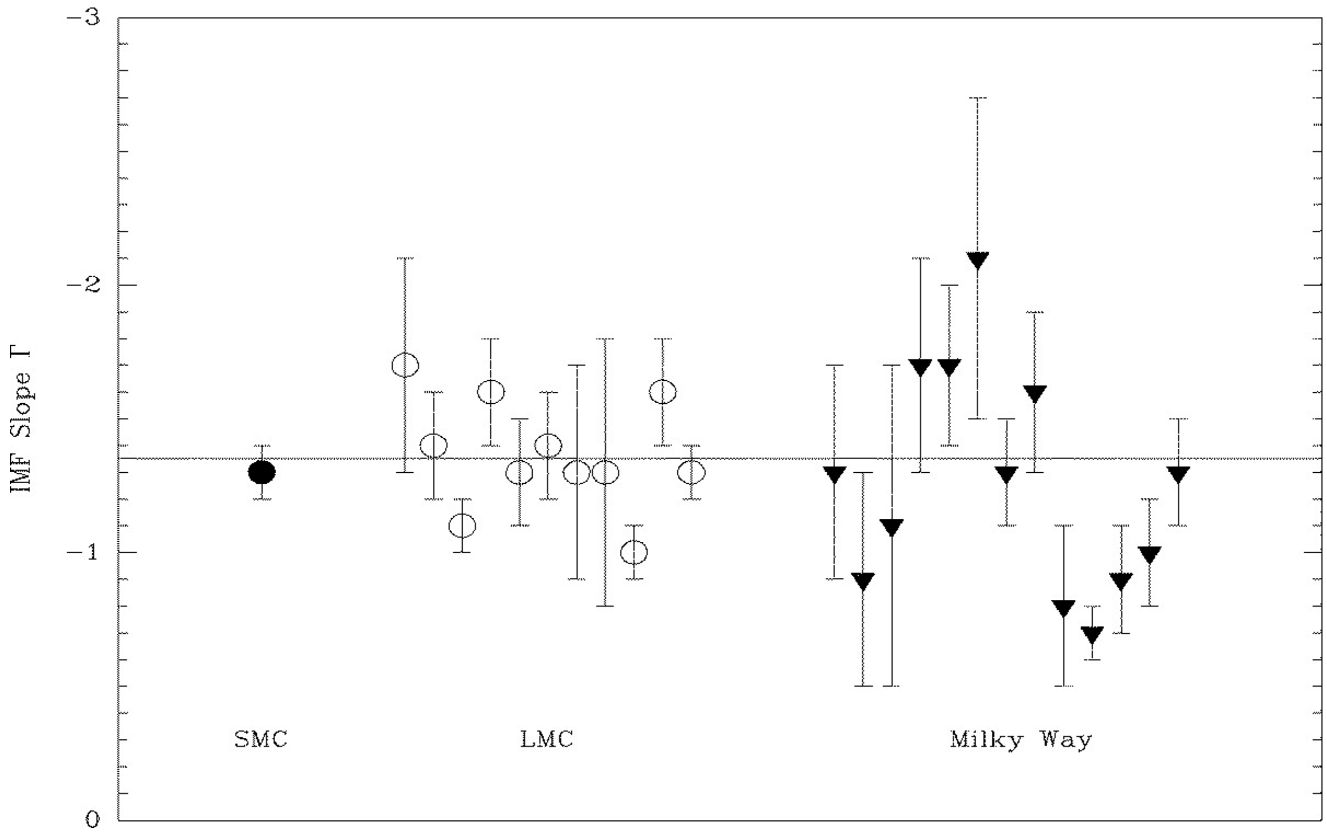


Salpeter IMF

$$\frac{dN}{dM} = M^{-\alpha} = M^{-2.35}$$

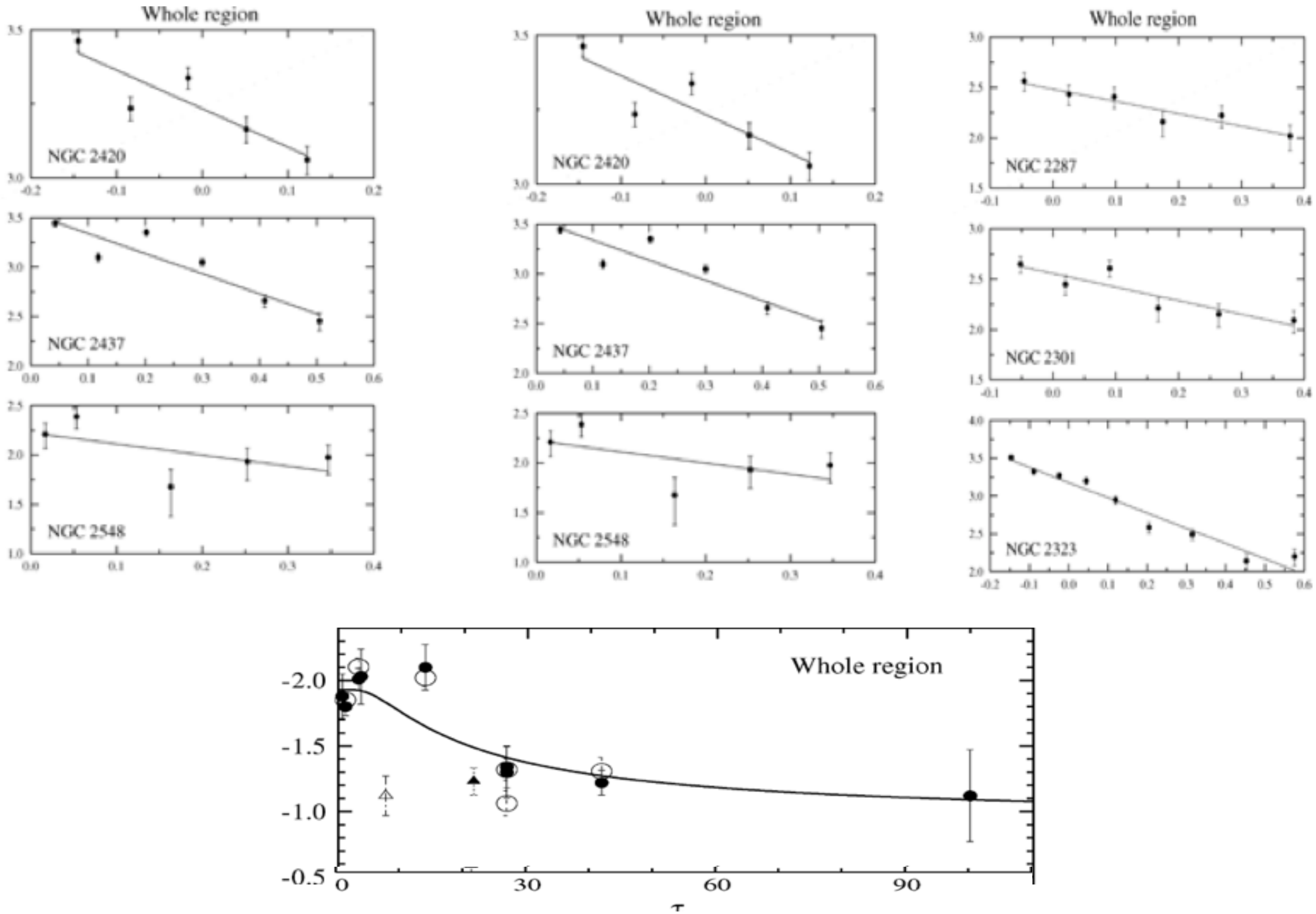
$$\frac{dN}{d\log M} = M^{-\Gamma} = M^{-1.35}$$

The IMF of Open Stellar Clusters



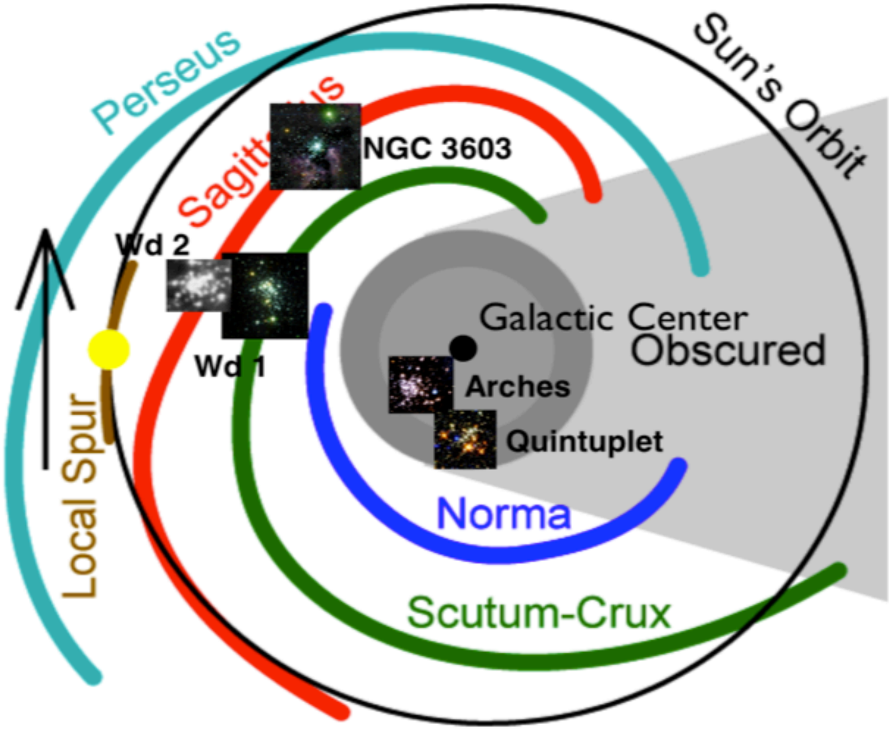
Massey et al. 1995a,b
Massey 2003

The IMF of open stellar clusters



Sharma et al. 2008

Starburst Clusters

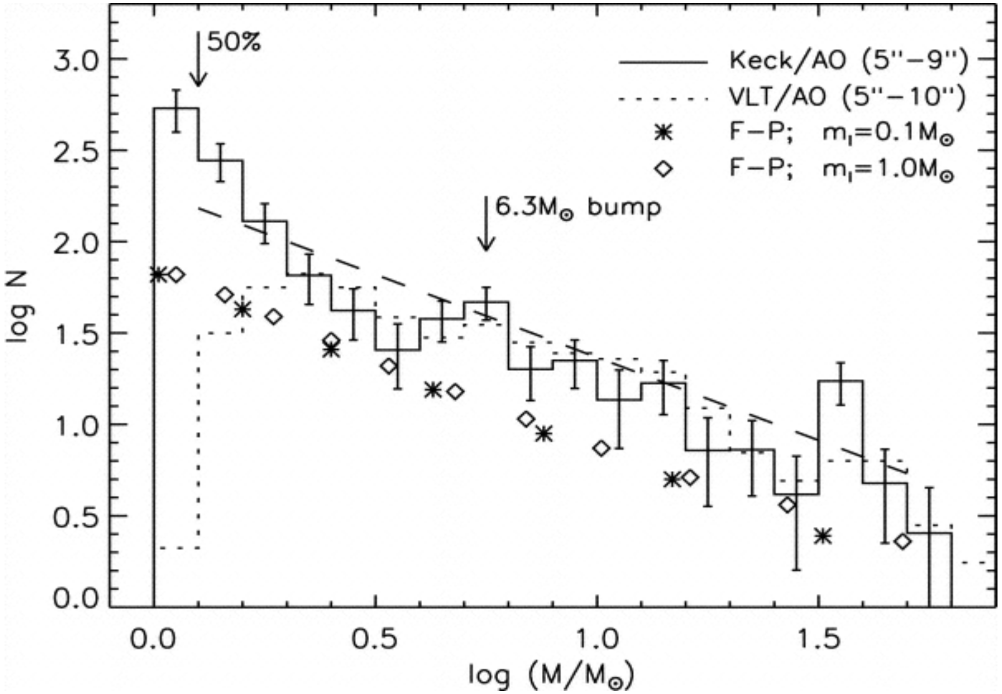


They are:

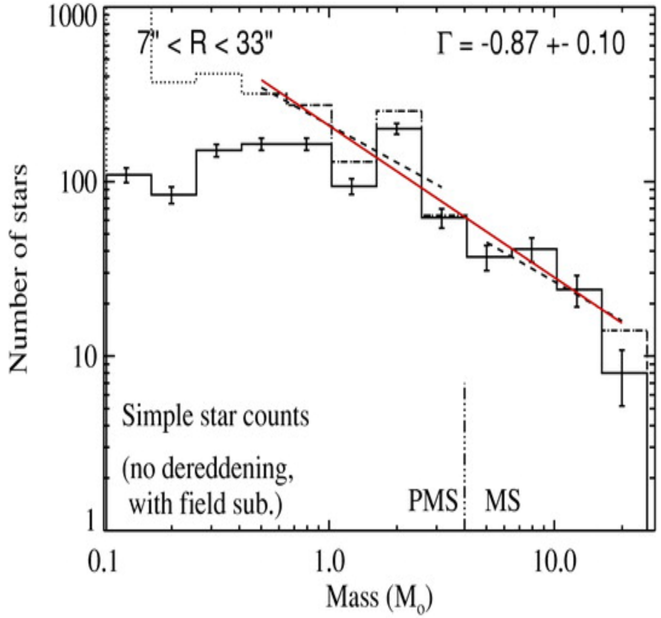
Massive: ~10^4-10^5 Msol

Dense ~ 10^4-10^5 Msol pc^{-2}

The IMF of Starburst Stellar Clusters

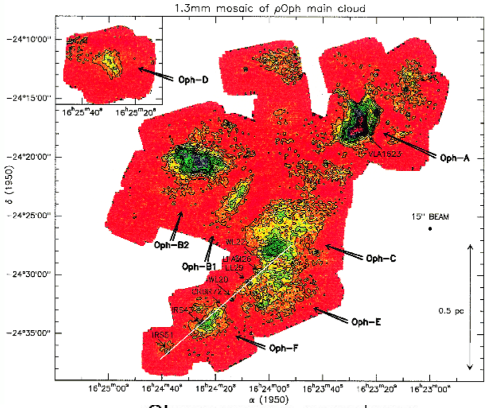


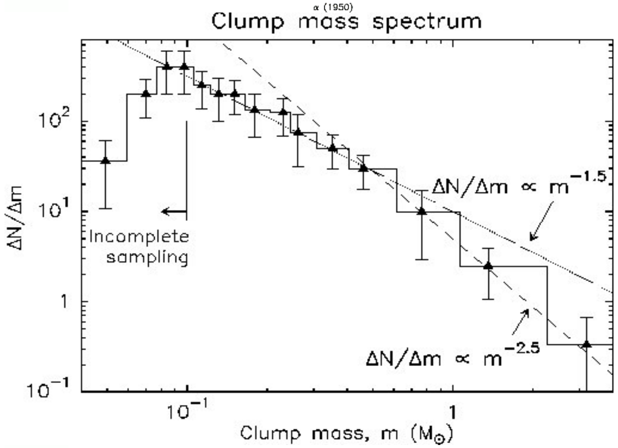
Arches: Stolte et al. 2005, Kim et al. 2006



NGC 3603: Stolte et al. 2006; Eisenhauer et al. 1998, Harayama et al. 2007

The imprint of the gaseous phase: CMF-IMF relation ?



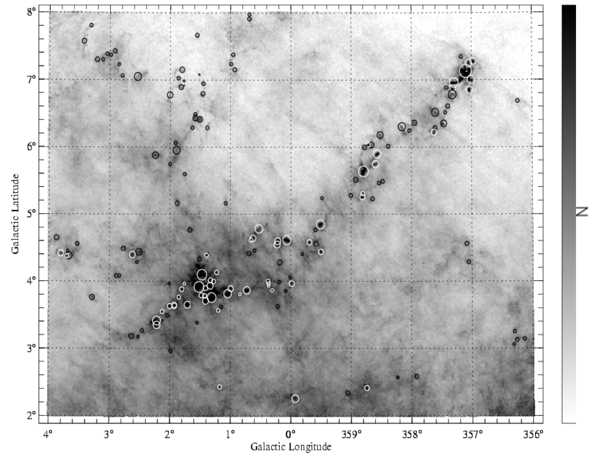


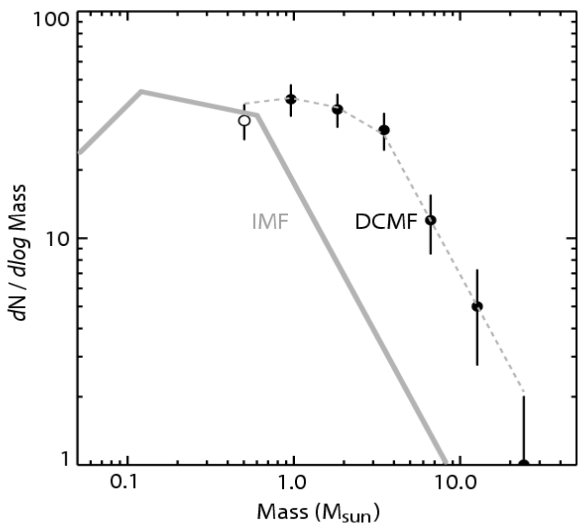
rho Ophiucus cloud

Motte, André & Neri 1998

André et al. 2007

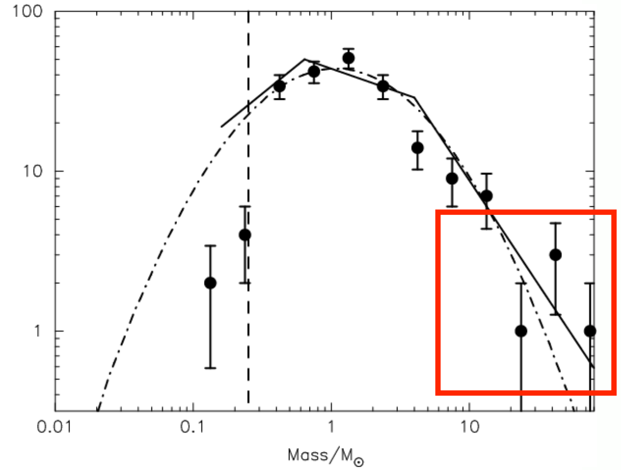
Johnstone et al. (2001,2002, 2006)





Pipe nebula cloud

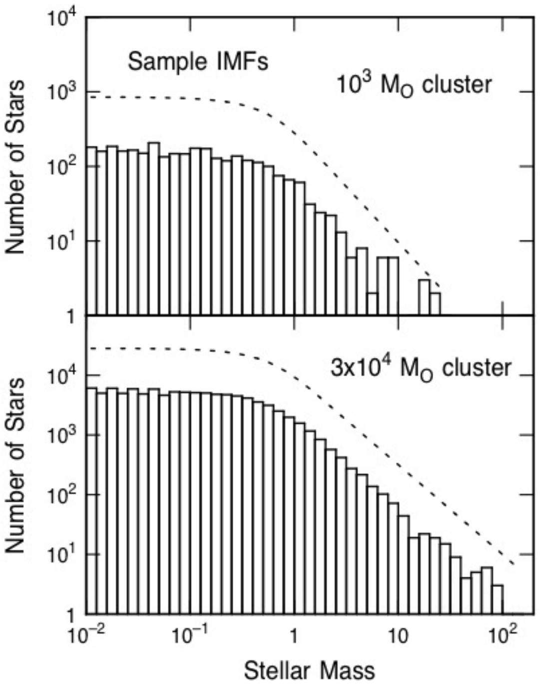
Alves, Lombardi & Lada 2007



Orion AN+ BN

Nutter & Ward-Thompson 2007

Random Sampling the IMF



$$N(M)dM = M^{-(\Gamma+1)}\left(1-\exp^{-\left(M/M_t\right)^{\Gamma}}\right)dM$$

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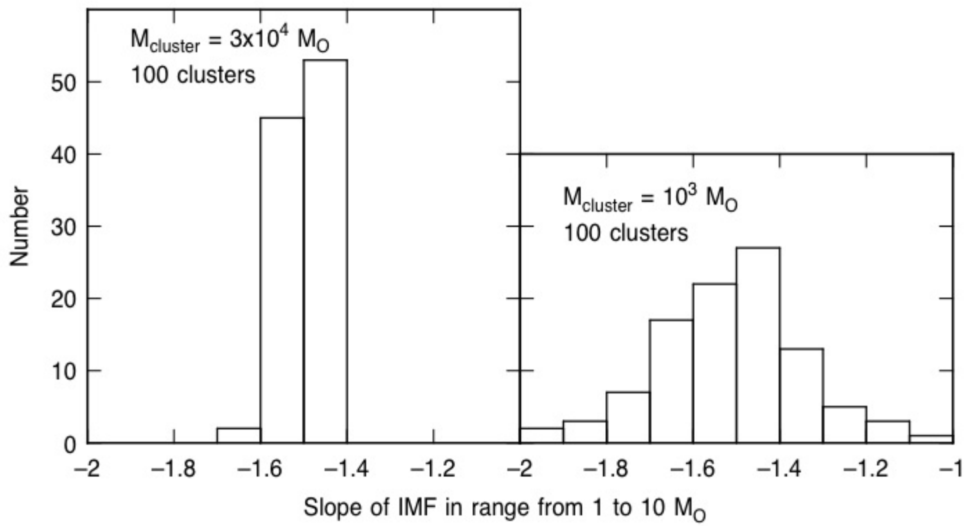
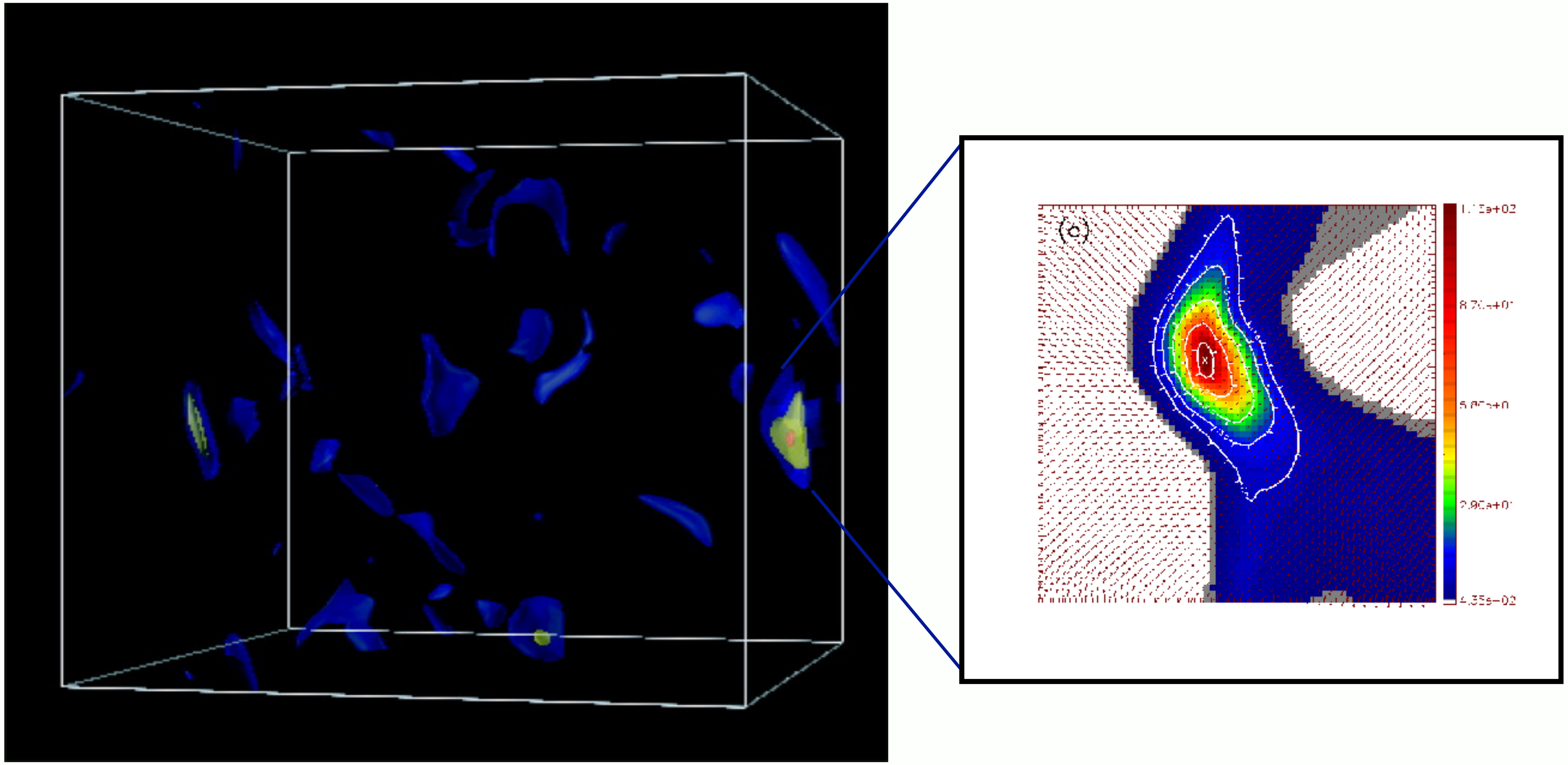


Elmegreen 2008

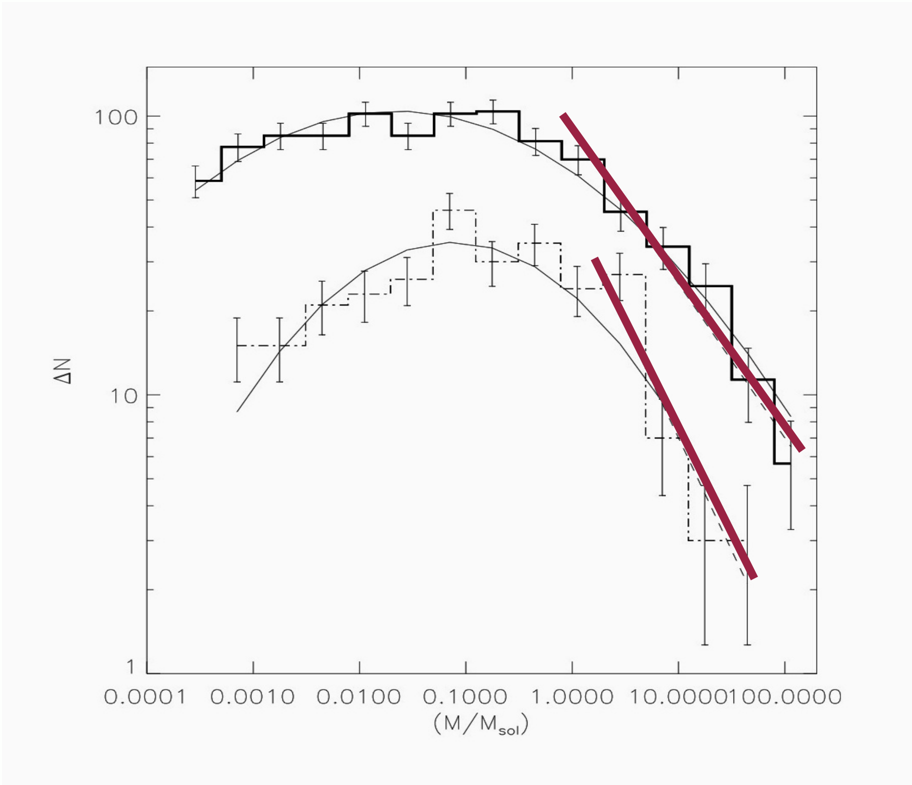
The input of numerical Simulations

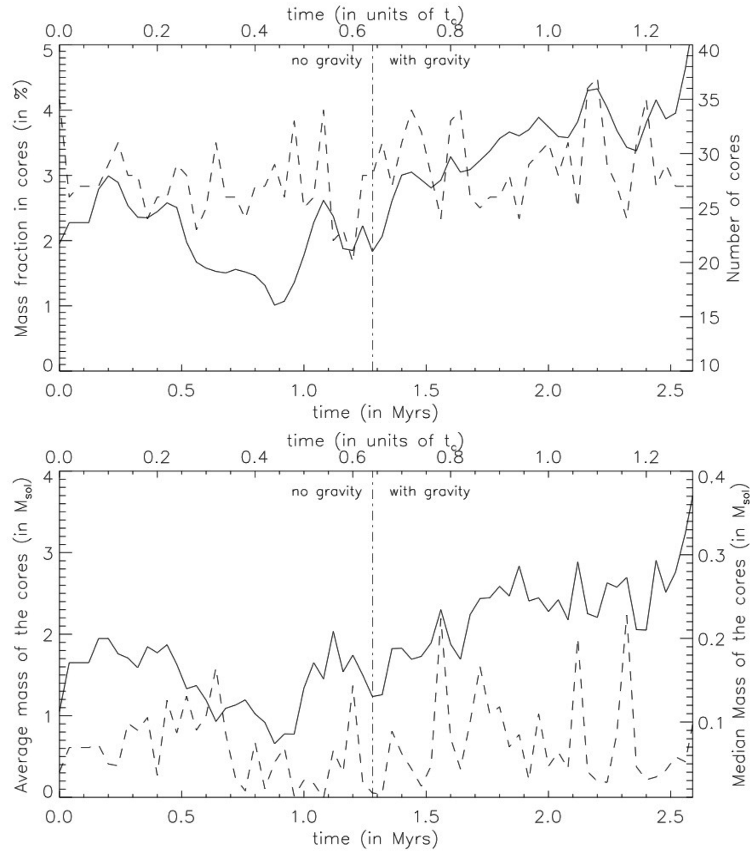
Simulations of turbulent, magnetized, and self-gravitating clouds

with grid codes: ZEUS, TVD (256^3 and 512^3), and the AMR code RAMSES (effective resolution of 4096^3)



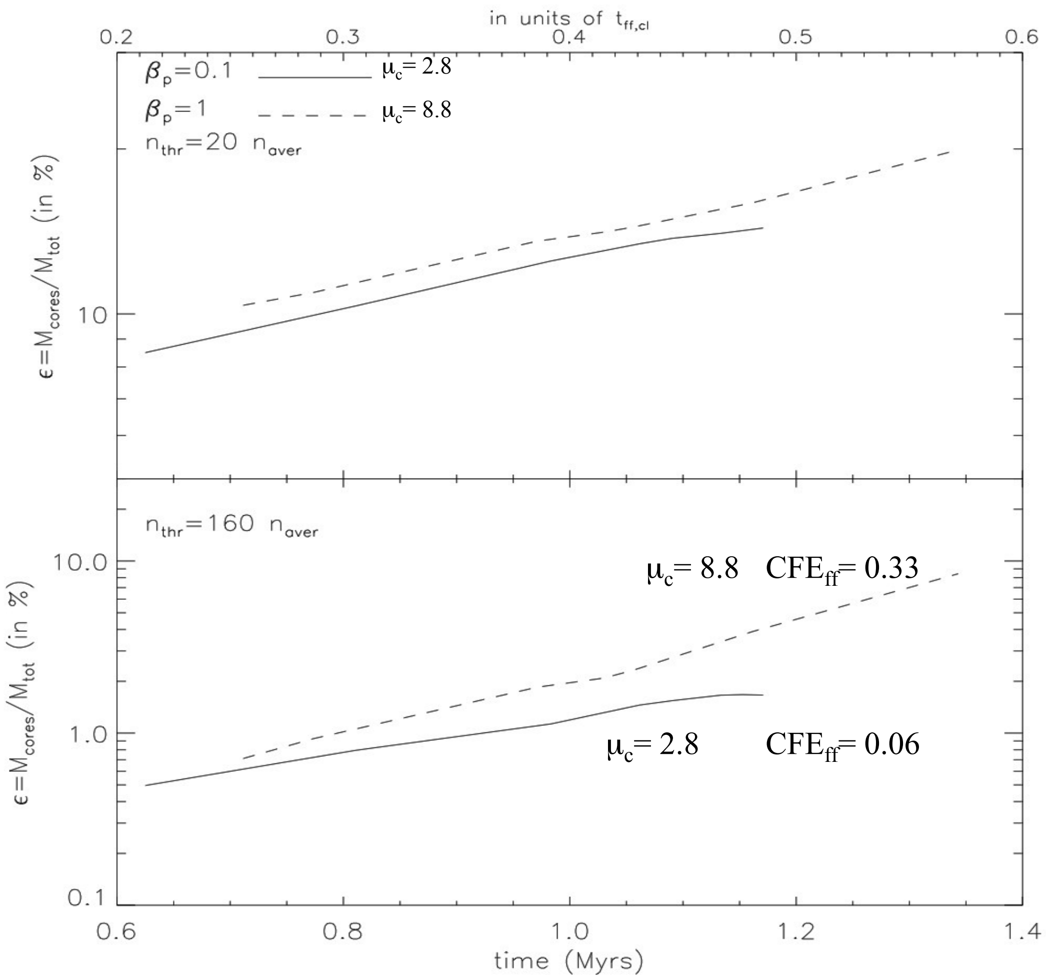
CMF: Lognormal …but with ongoing accretion





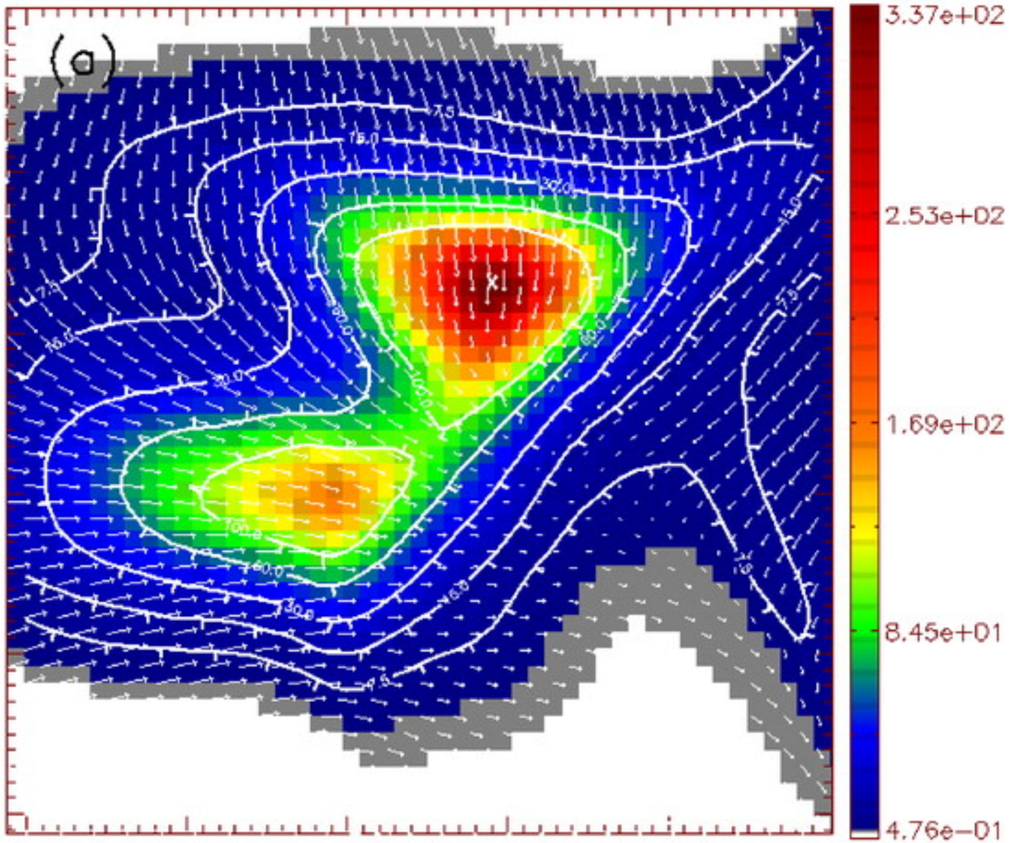
Dib et al. (2007a), Dib et al. (2008a,b)

Regulation of the CFE by B



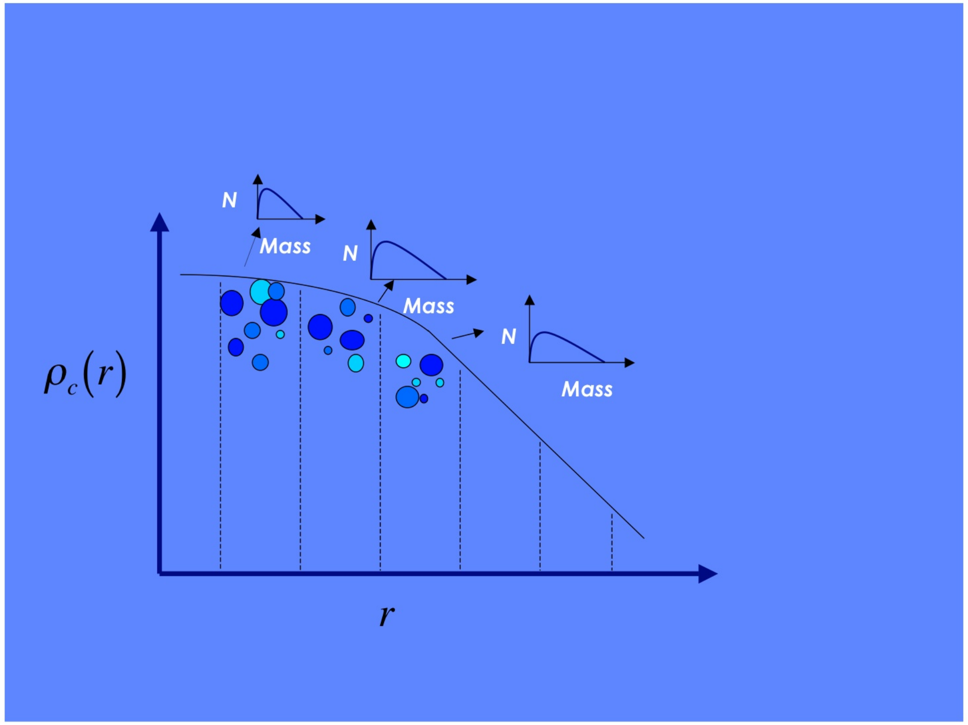
Dib et al. in 2010b

core coalescence



Dib et al. 2007a

A model for core coalescence in a protocluster clump



coalescence efficiency η; in principle η (r)

contration timescale t_cont = n t_ff; n=1-10

Protocluster cloud mass, Mcl

Radius and core Radius R_c, R_c0

fraction of mass in clumps ε

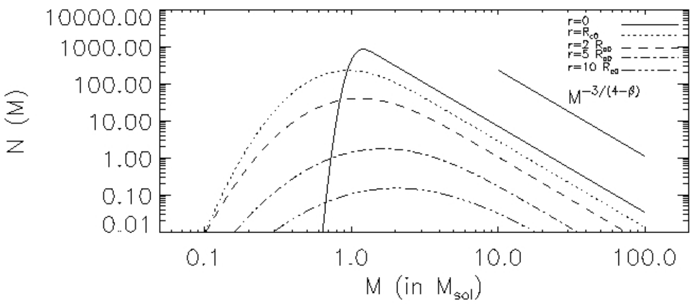
Larson relation exponent α, or exponent of turbulent vel. field power spectra β

Cores initial peak density n_p0

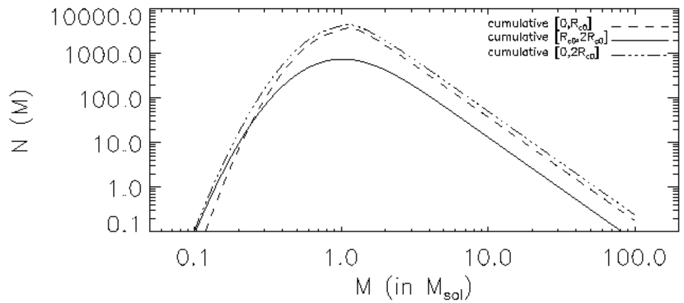
Mass fraction lost in outflows Ψ, in principle $=\Psi(M)$ (Matzner & McKee 2000)

Flowchart of the model

Initial conditions (Padoan & Nordlund 2002) → **calculate instanteneous cross section of collision between contracting objects of Masses M_i and M_j and integrate over the mass spectrum.**



$$\sigma(M_i, M_j, r, t) = \pi\left(R_i(t) + R_j(t)\right)^2 \left[1 + \frac{2G\left(M_i + M_j\right)}{2v^2\left(R_i(t) + R_j(t)\right)}\right]$$



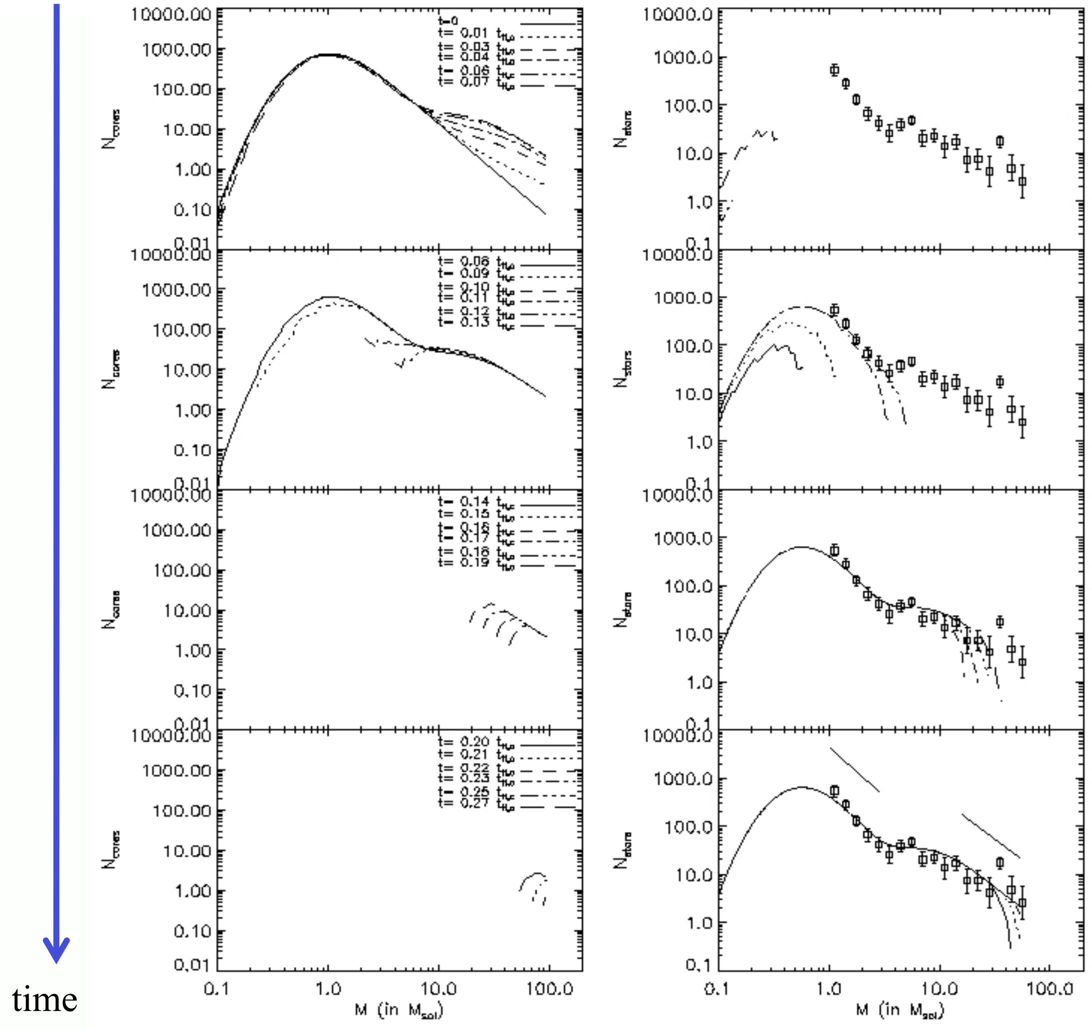
$$\frac{dN(r,M,t)_{coal}}{dt} = \frac{1}{2}\eta(r)\int_{M_{min}}^{M-M_{min}} N(r,m,t)N(r,M-m,t)\sigma(m,M-m,r,t)v(r)\,dm - \eta(r)N(r,M,t)\int_{M_{min}}^{M_{max}} N(r,m,t)\sigma(m,M-m,r,t)v(r)\,dm$$

α=0.4

β=1.8

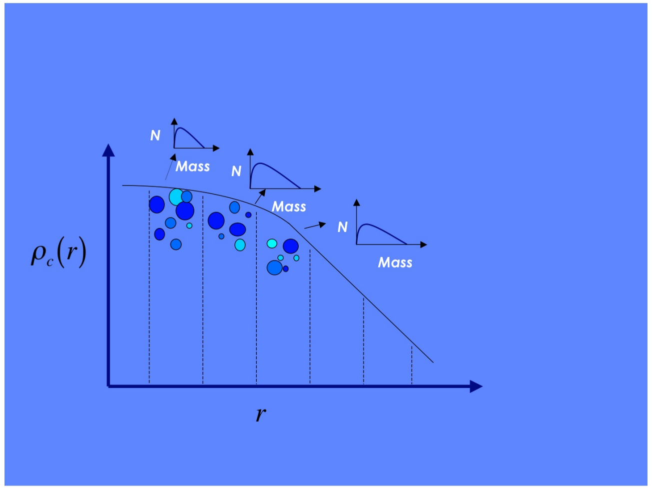
Slope= -3/(4-β)-1=-2.33

Coalescence-Collapse: Application to Starburst Clusters



Dib et al. 2007b

An Accretion-Collapse-Feedaback model in a protocluster clump



General properties

A) Accretion model (constrained by simulations) ; e.g. What is the form of $\dot{M}$

B) Fraction of the mass of the clumps converted into dense cores per free fall time ε (a few percent)

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, b. (between 1.4-2.2)

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)

Feedback from massive stars (M > 10 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)

then we evolve the population of cores and stars

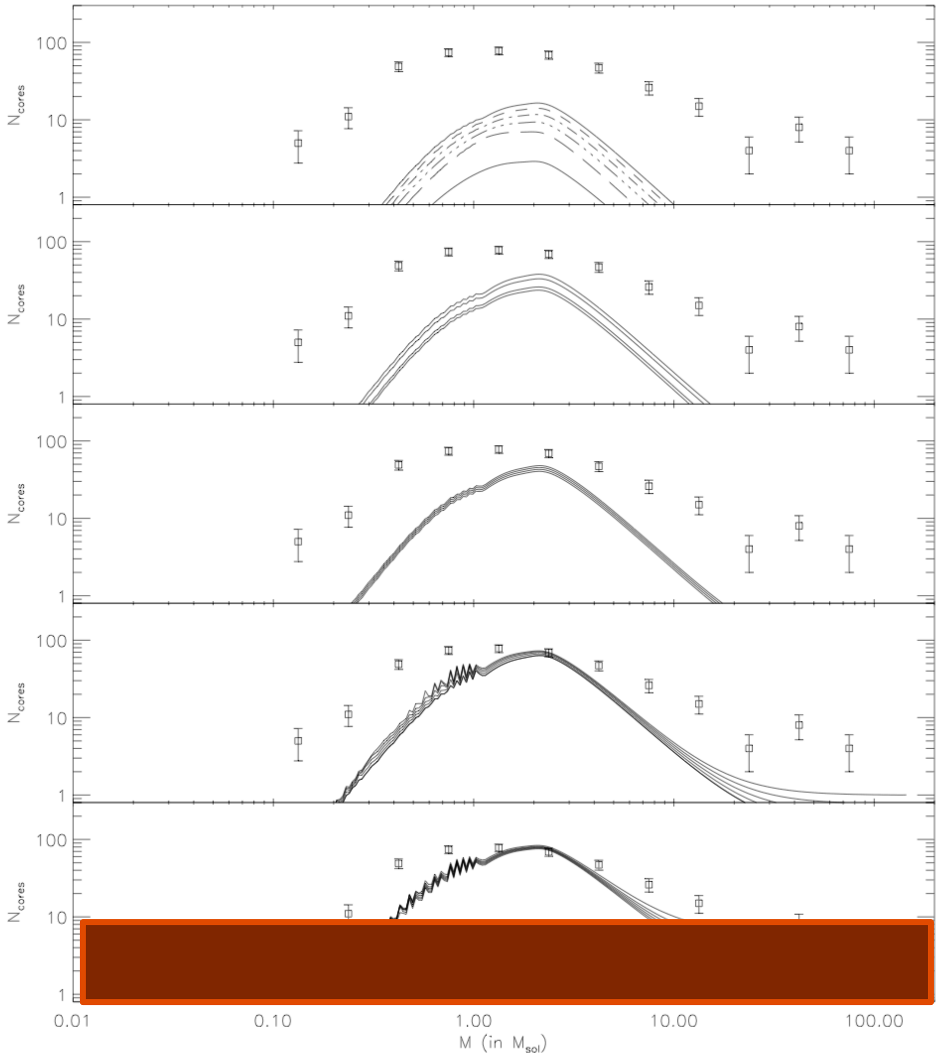
Populations of cores evolve by accretion

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

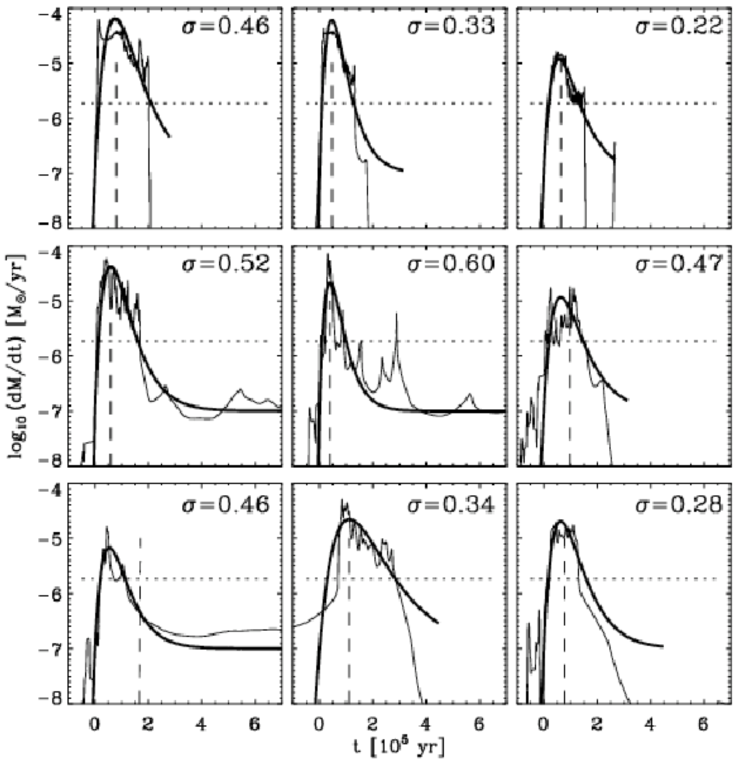
Populations of stars evolve under mass loss

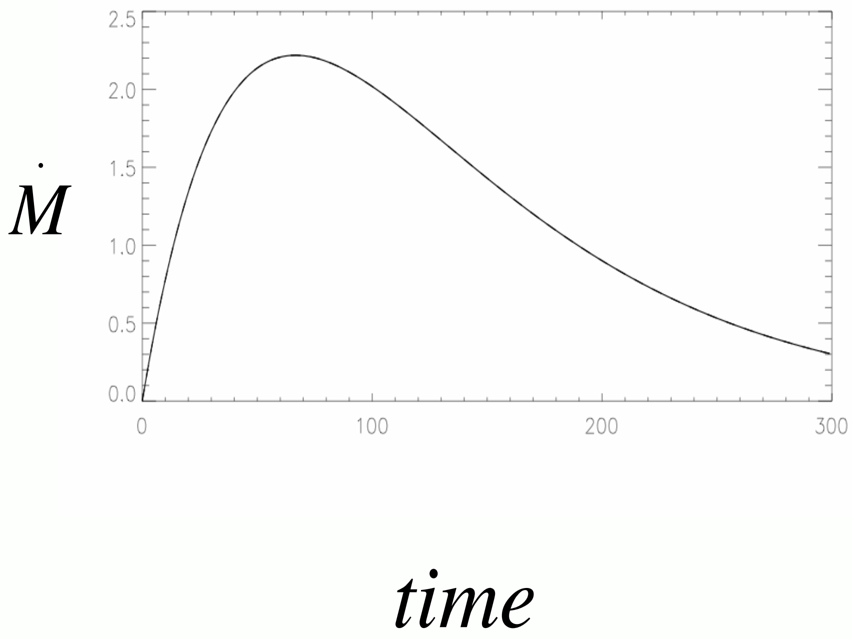
$$\frac{dN(r,M,t)_{*}}{dt} = \left(+\frac{\partial N_{*}}{\partial M_{*}}\dot{M}_{*} + \frac{\partial \dot{M}_{*}}{\partial M_{*}} N_{*} \right)(r,M,t)$$

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



The accretion model: accretion in a turbulent medium





Schmeja & Klessen 2004

$$\log \dot{M}_{SK04} = \left(\frac{n(cm^{-3})}{10^5} \right) \log \dot{M}_{SK04,0} \frac{e}{\tau} t e^{-t/\tau}$$

Feedback in the model

Stellar mass loss rate

$$\left(\frac{dM}{dt}\right)_* = 10^{-5}\left(\frac{M_*}{30 M_{sol}}\right)^4 M_{sol}\, yr^{-1}$$

Terminal wind velocity $v_{inf} = 10^3$ km s^{-1}

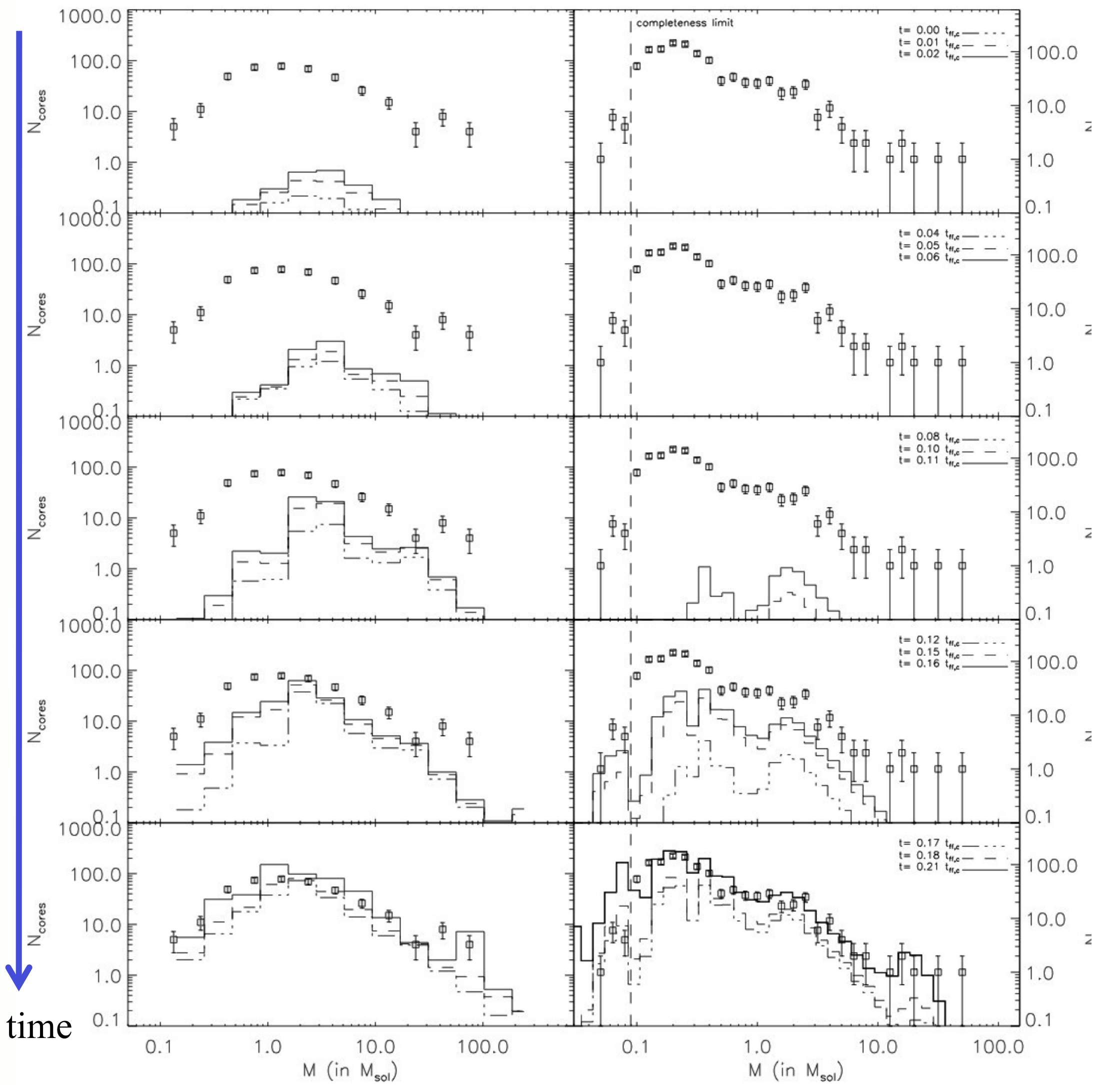
Energy cumulated in winds

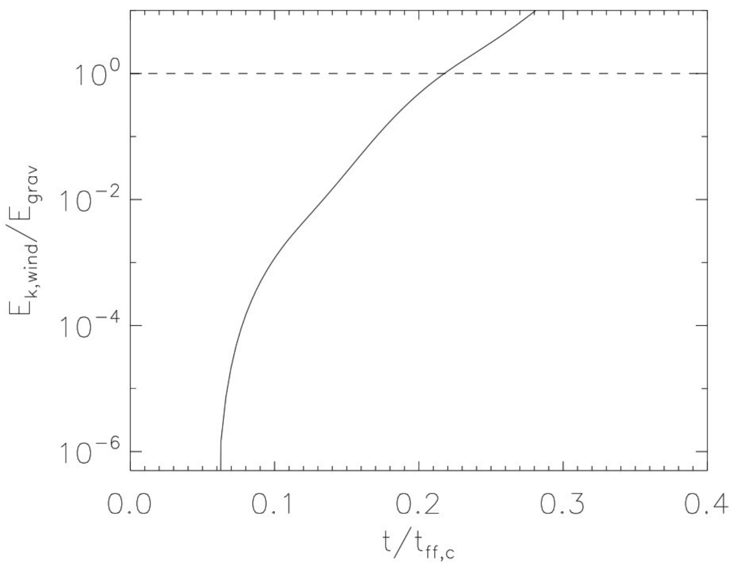
$$E_{wind} = \int_{t''=0}^{t''=t} \int_{m=10M_{sol}}^{m=120M_{sol}} \left(\frac{N(m)(dM/dt)_*(m) v_{\inf}^2}{2} dm \right) dt''$$

Fraction of wind energy that counters gravity

$E_{k,wind} = \kappa E_{wind}$ with $\kappa \le 1$

ACF model: fiducial model: Application to the ONC

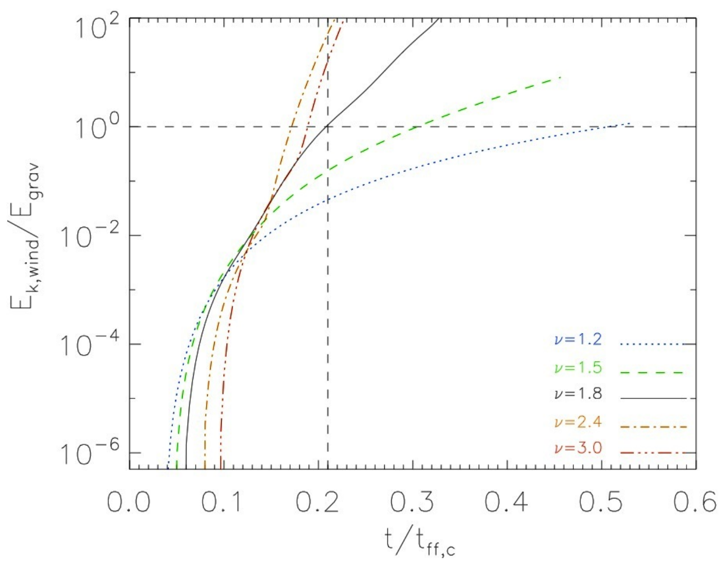


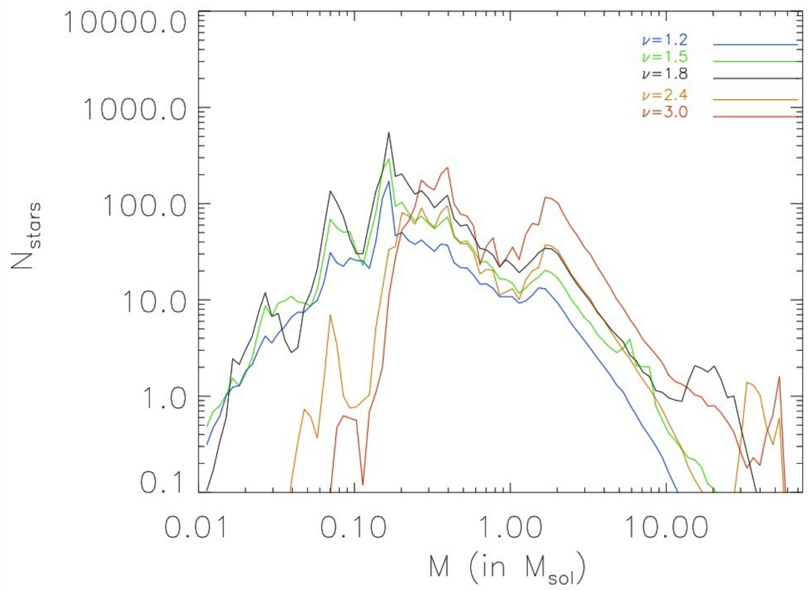


Dib et al. 2010a

Variations with the cores properties

Effect of the contraction timescale of the cores (parameter ν)





Dib et al. 2010a

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

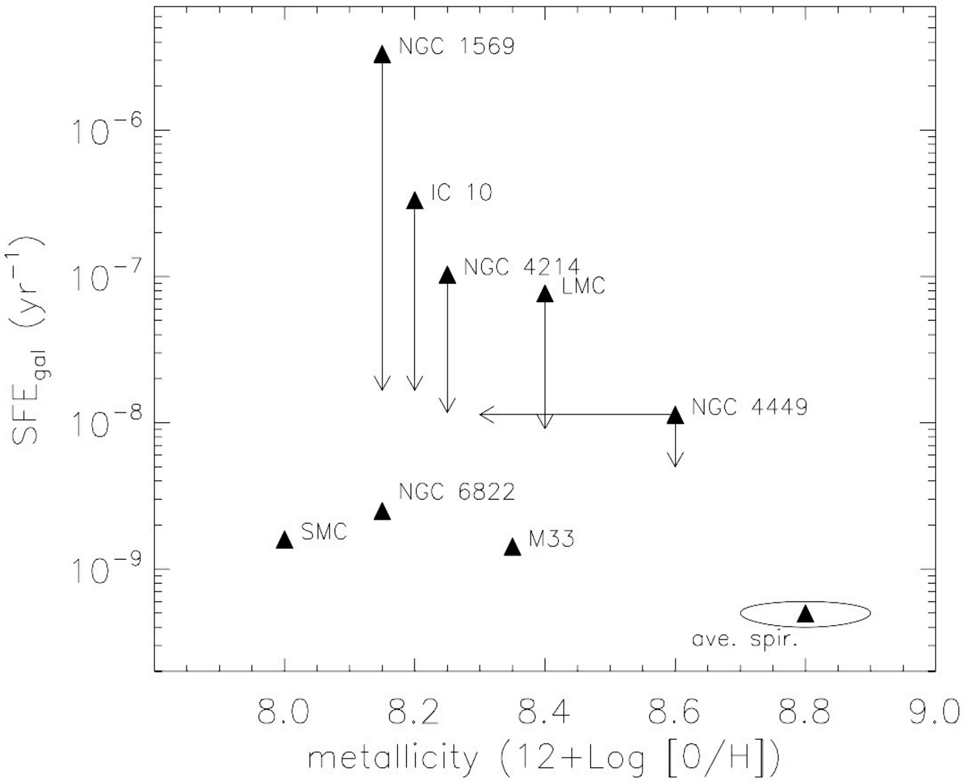
In the observations: $$SFE_{cluster,obs} \approx \frac{M_{cluster}}{M_{cluster} + M_{gas}}$$

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

No established dependences on mass, metallicity, environment

SFEs in Galaxies

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



Dib et al. (2011)

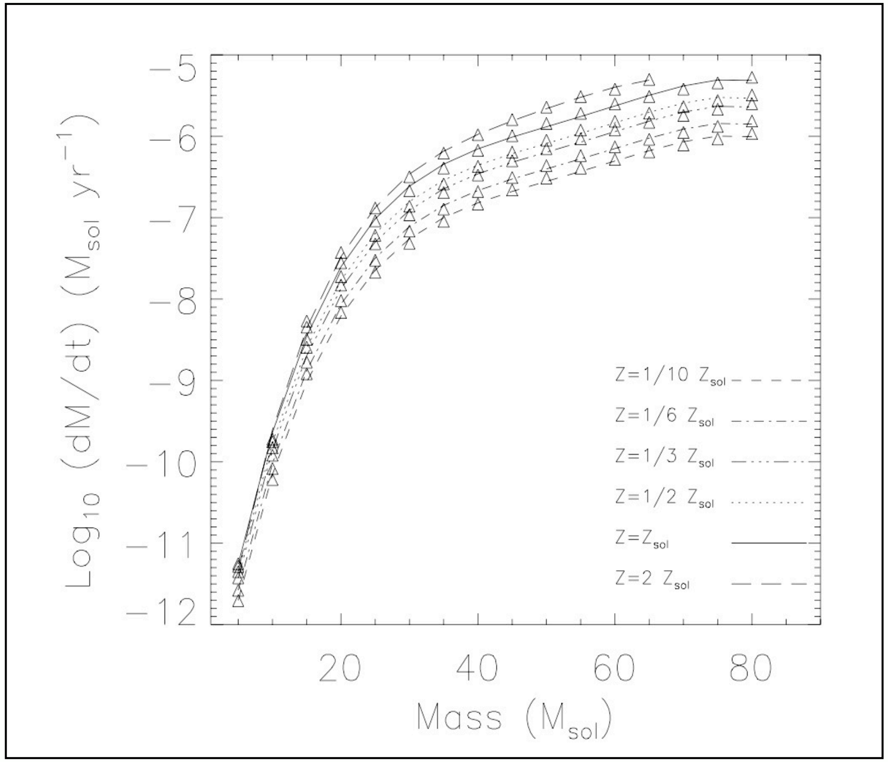
Data compiled from:

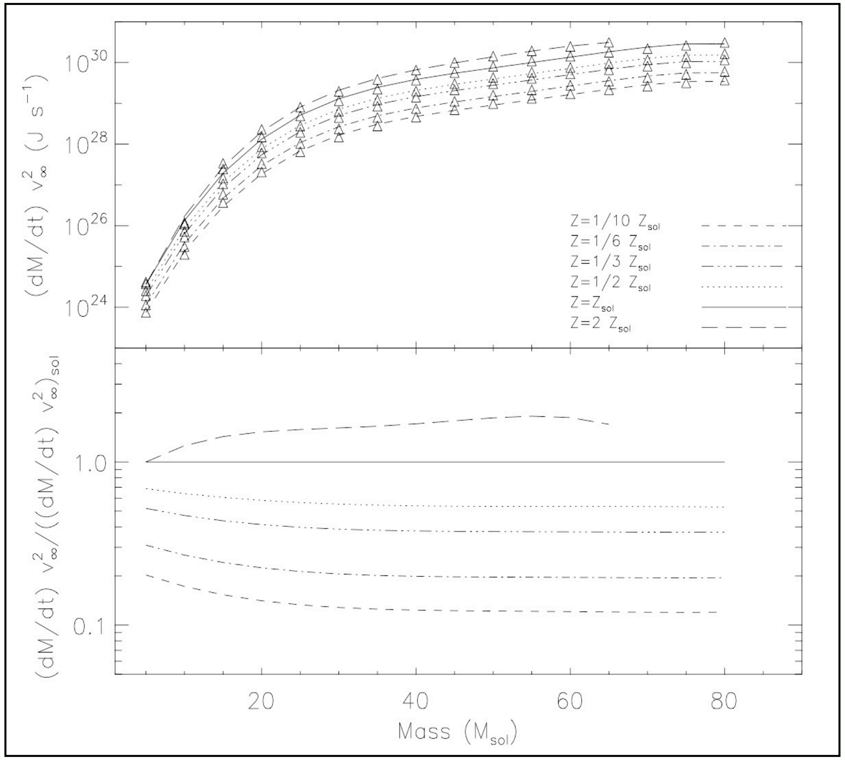
- **average spirals (Murgia et al. 2002)**
- **M33 and NGC6822 (Gratier et al. 2010a,b)**
- **SMC (Leroy et al. 2006)**

Power of stellar Winds of various metallicities In the range $Z/Z_{\odot}$=[0.1, 2]

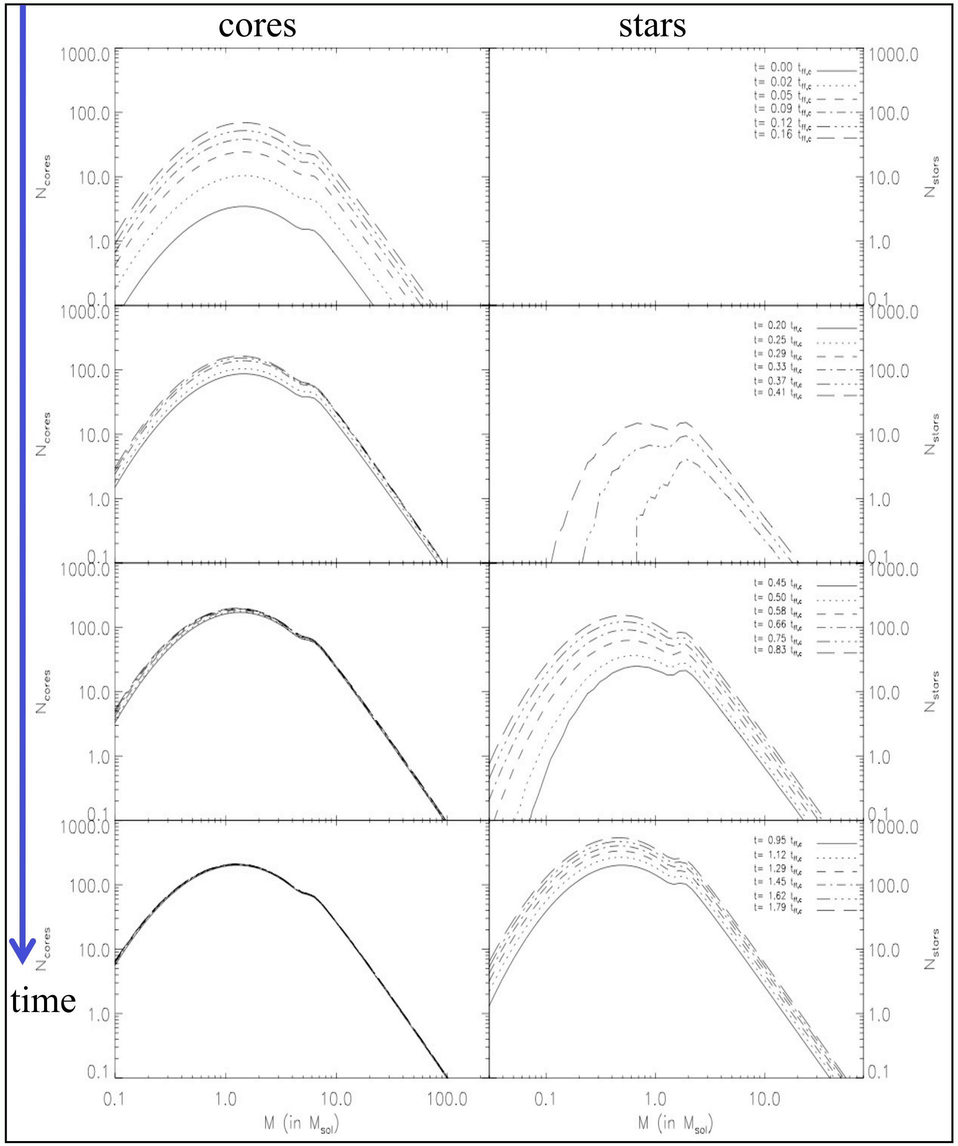
- Calculate main sequence models of OB stars ($\geq 5\ M_{\odot}$) (using CESAM)

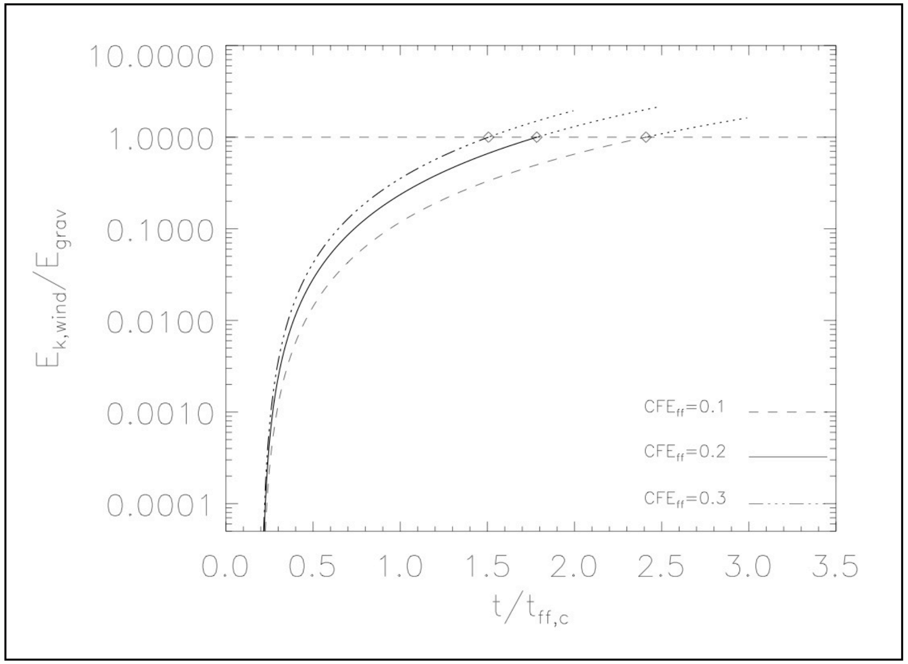
- (T_{eff}, L, Radius) ➔ Stellar atmosphere model (Vink et al.) ➔ $\dot{M}$ $\dot{M} v_{\infty}^2$

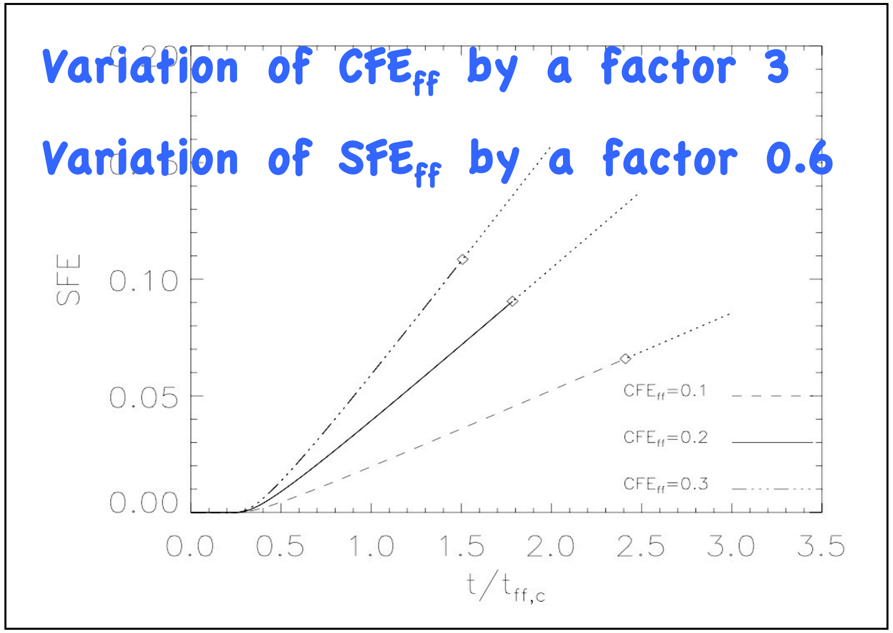




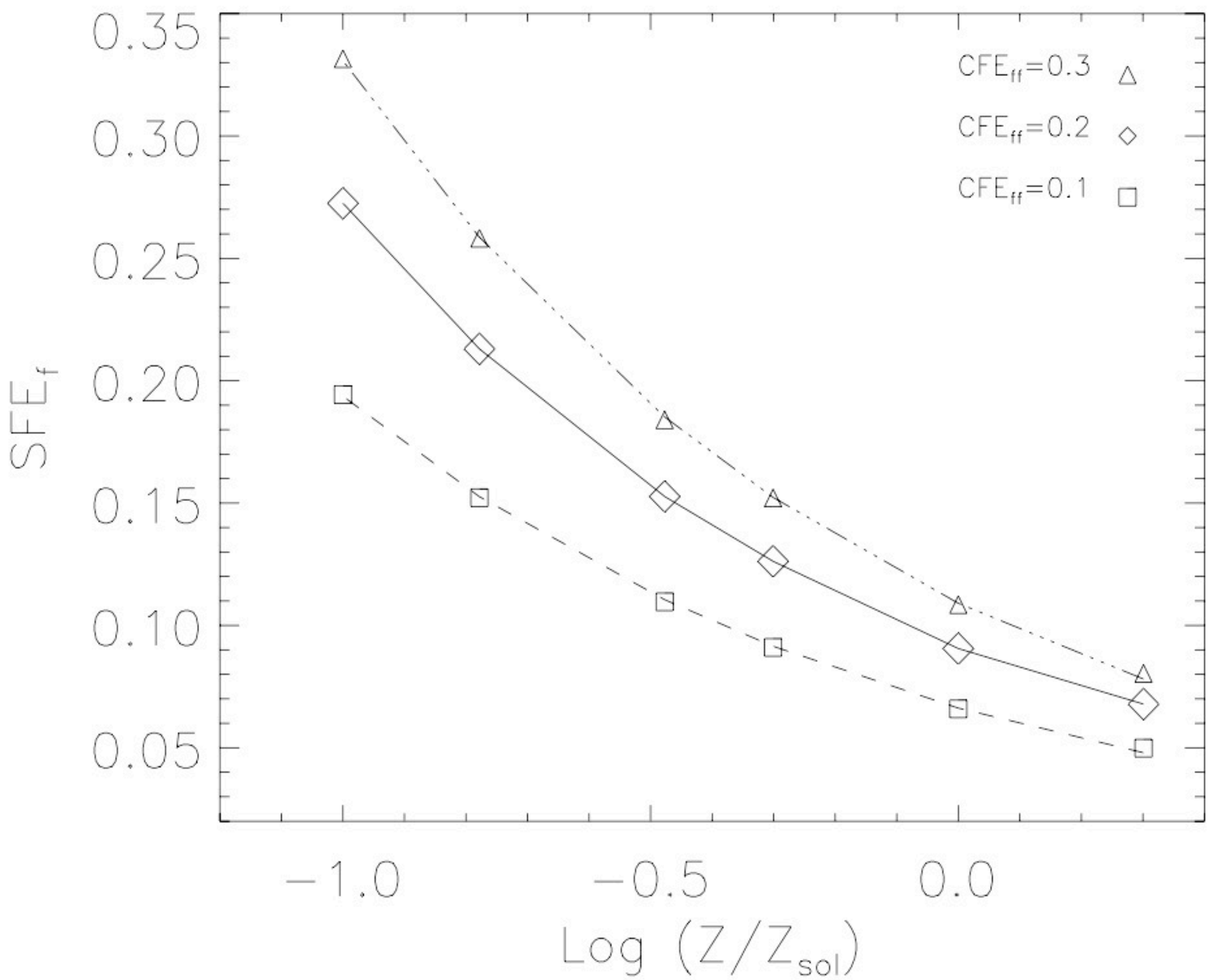
Model with solar metallicity







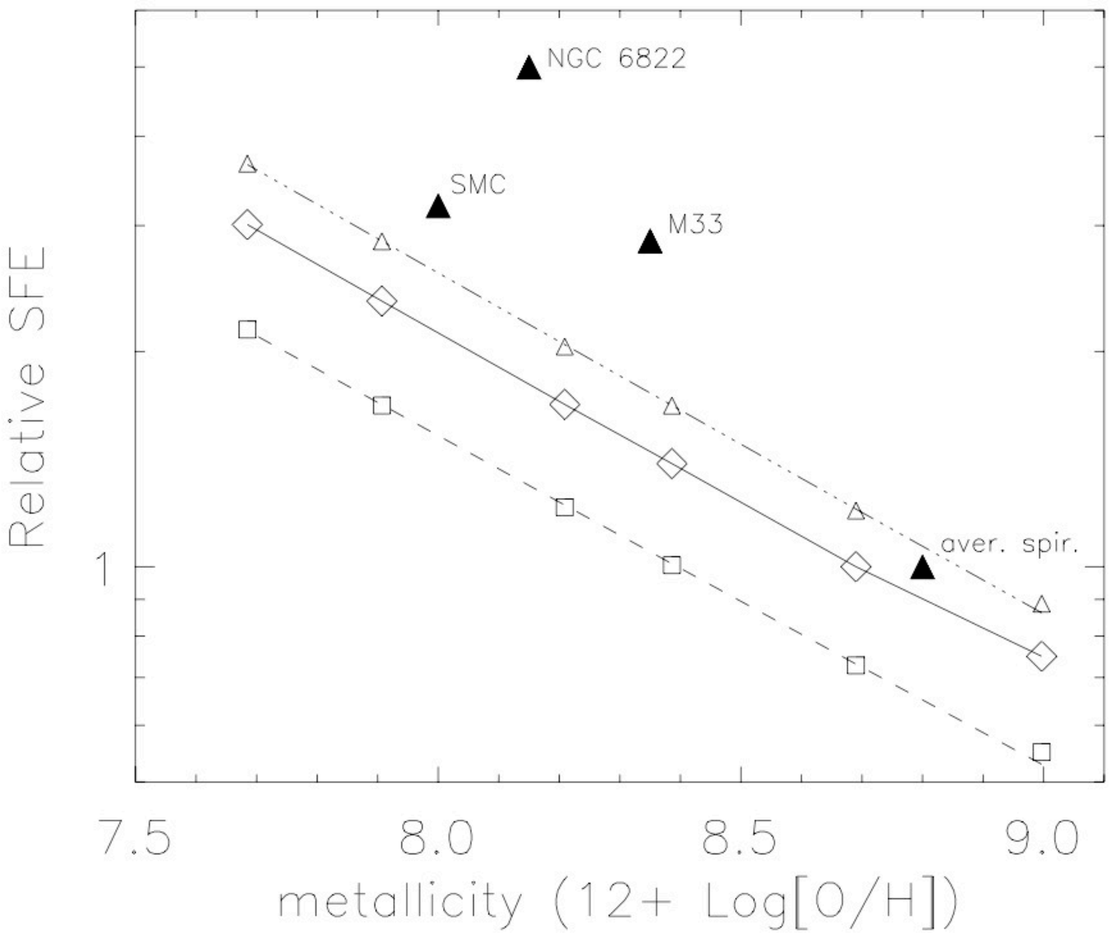
SFE_{exp}-metallicity relation



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

Dib et al. (2011)

Galatic SFEs

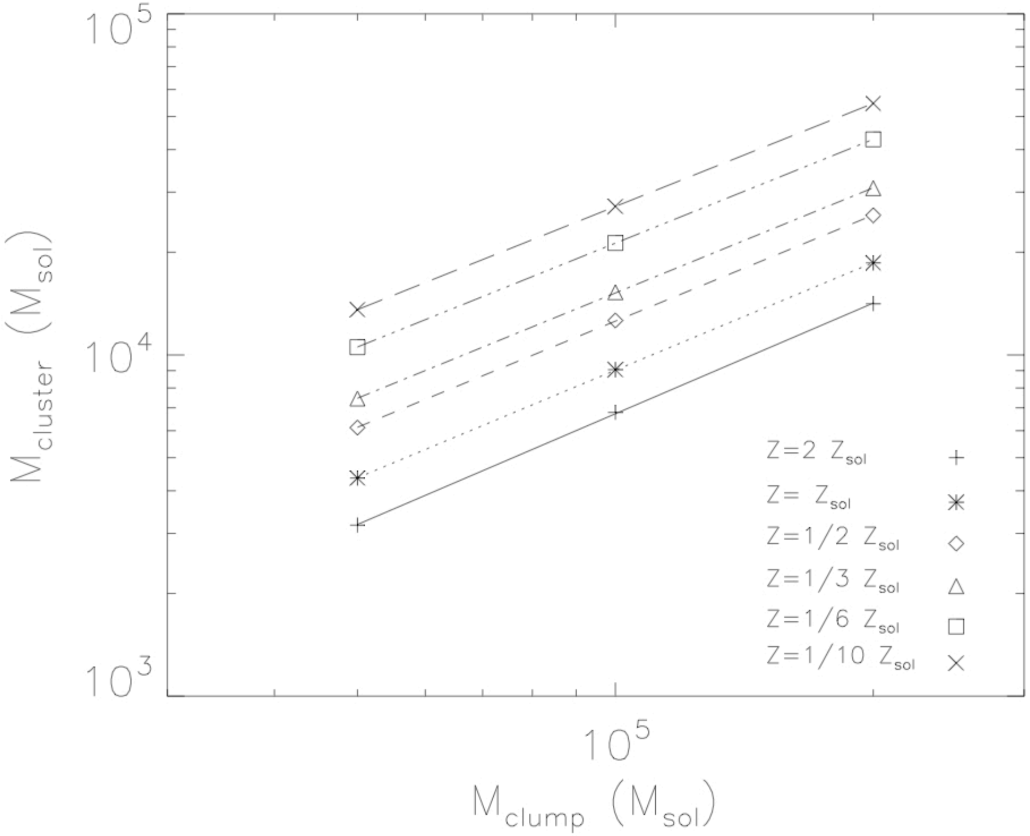


Dib et al. (2011)

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 $\gamma = 1$

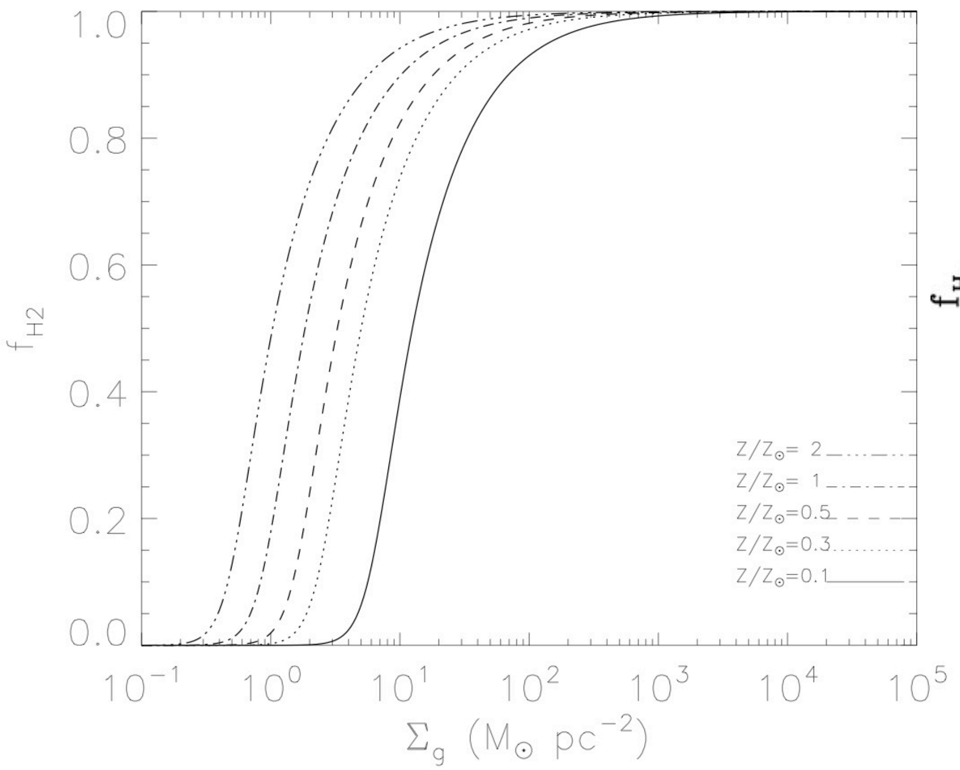
Then, if $\eta \approx -2$ **(as observed)**

$$\delta \approx -2$$

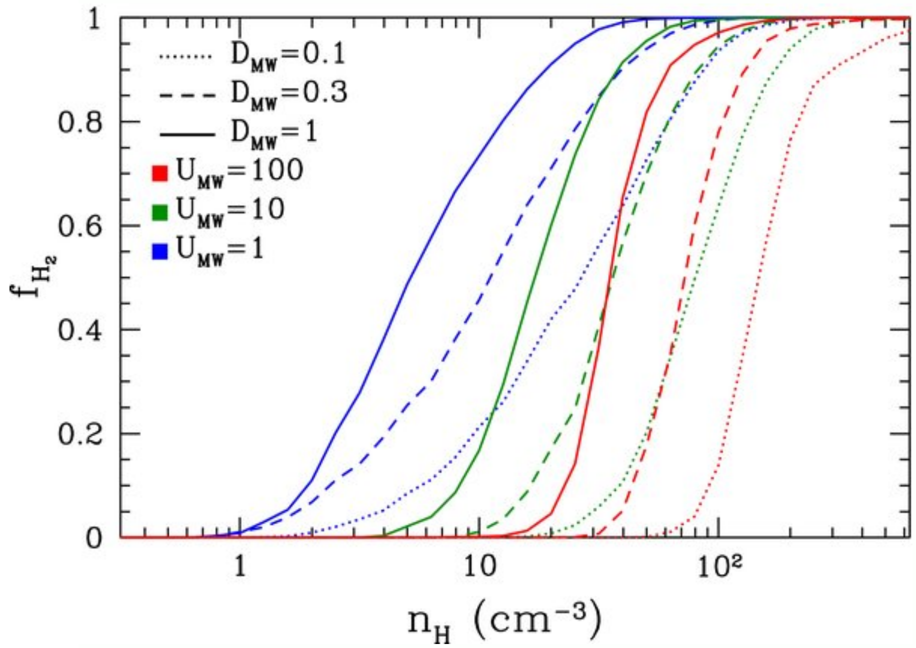
The Star Formation Law

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

The molecular fraction f_{H2}

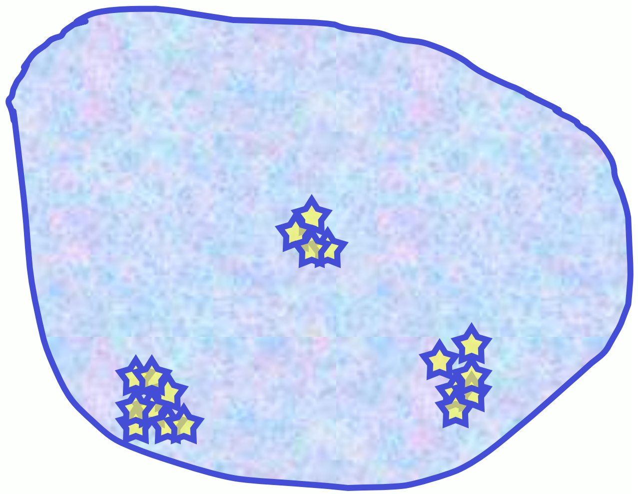


Krumholz, McKee & Tumlinson 2009



Gnedin & Kravtsov 2011

Regulation of the SFE by Feedback



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

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

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

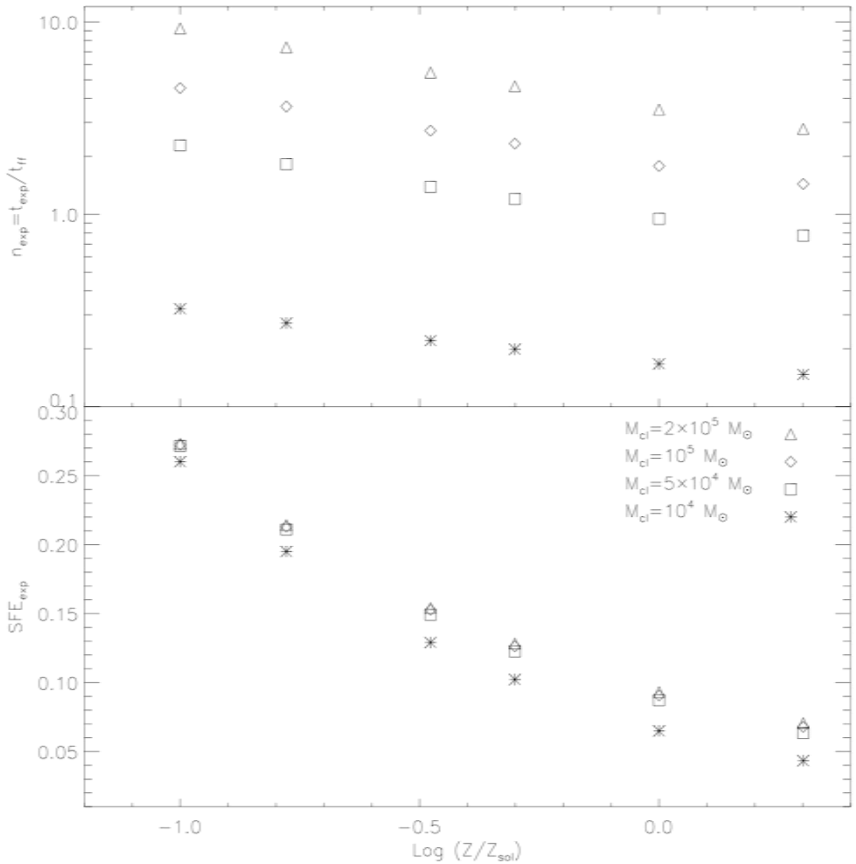
$$\Sigma_{SFR} = \Sigma_g f_{H_2} \frac{\langle f_{*,ff} \rangle}{\langle t_{ff} \rangle}$$

The characteristic mass is

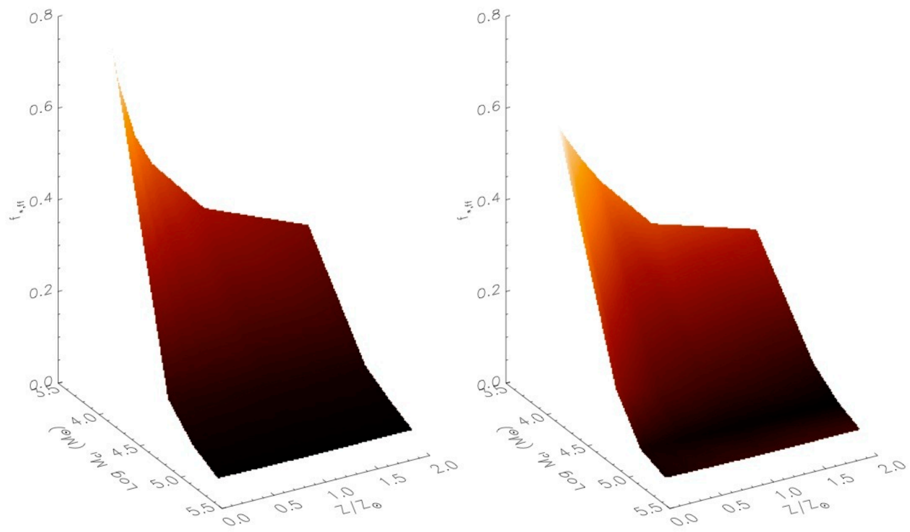
$$N(M_{clump}) \propto M_{clump}^{-\delta} \qquad M_{char} = \int_{M_{cl,\min}}^{Max(M_{cl,\max}, M_{GMC})} M N(M) dM$$

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

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

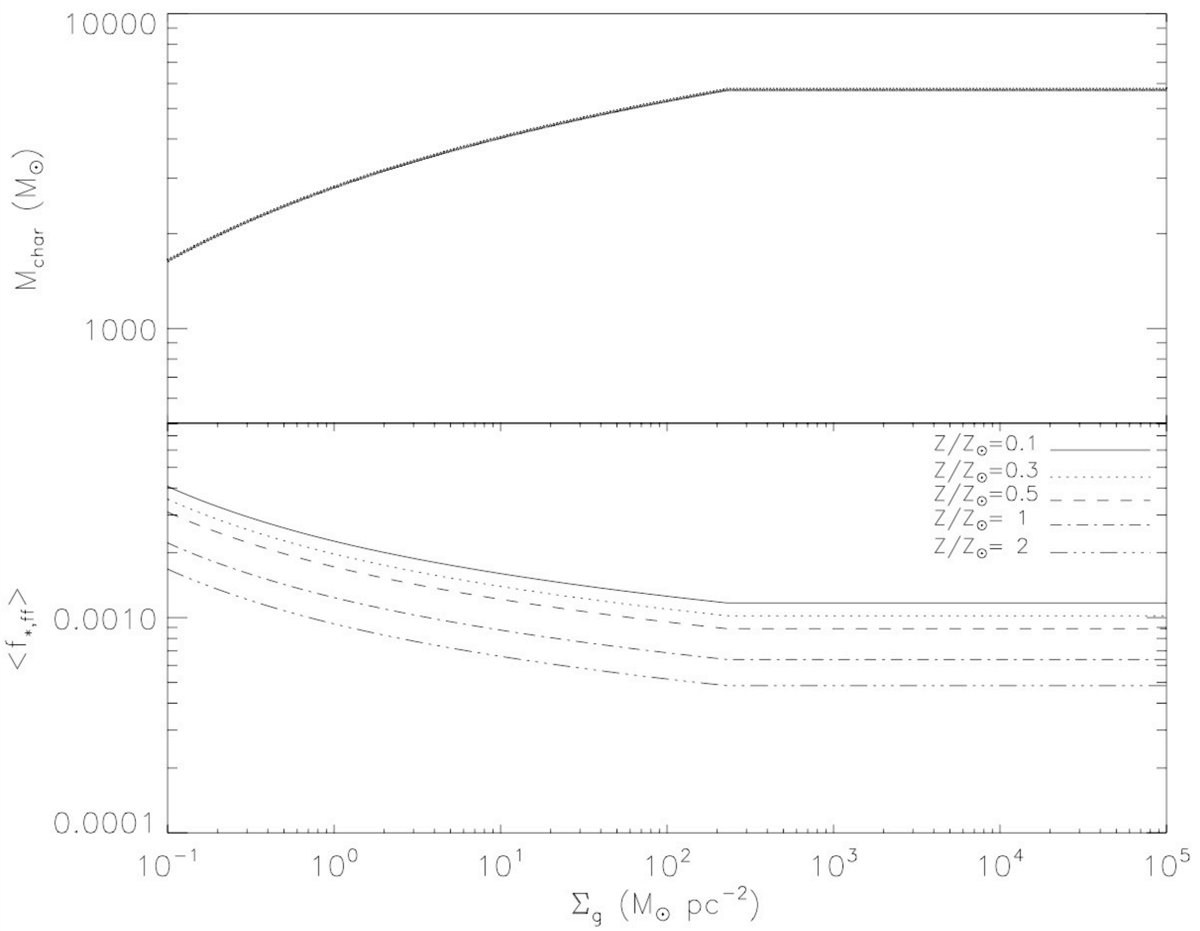


$$CFE_{ff} \approx 0.2$$

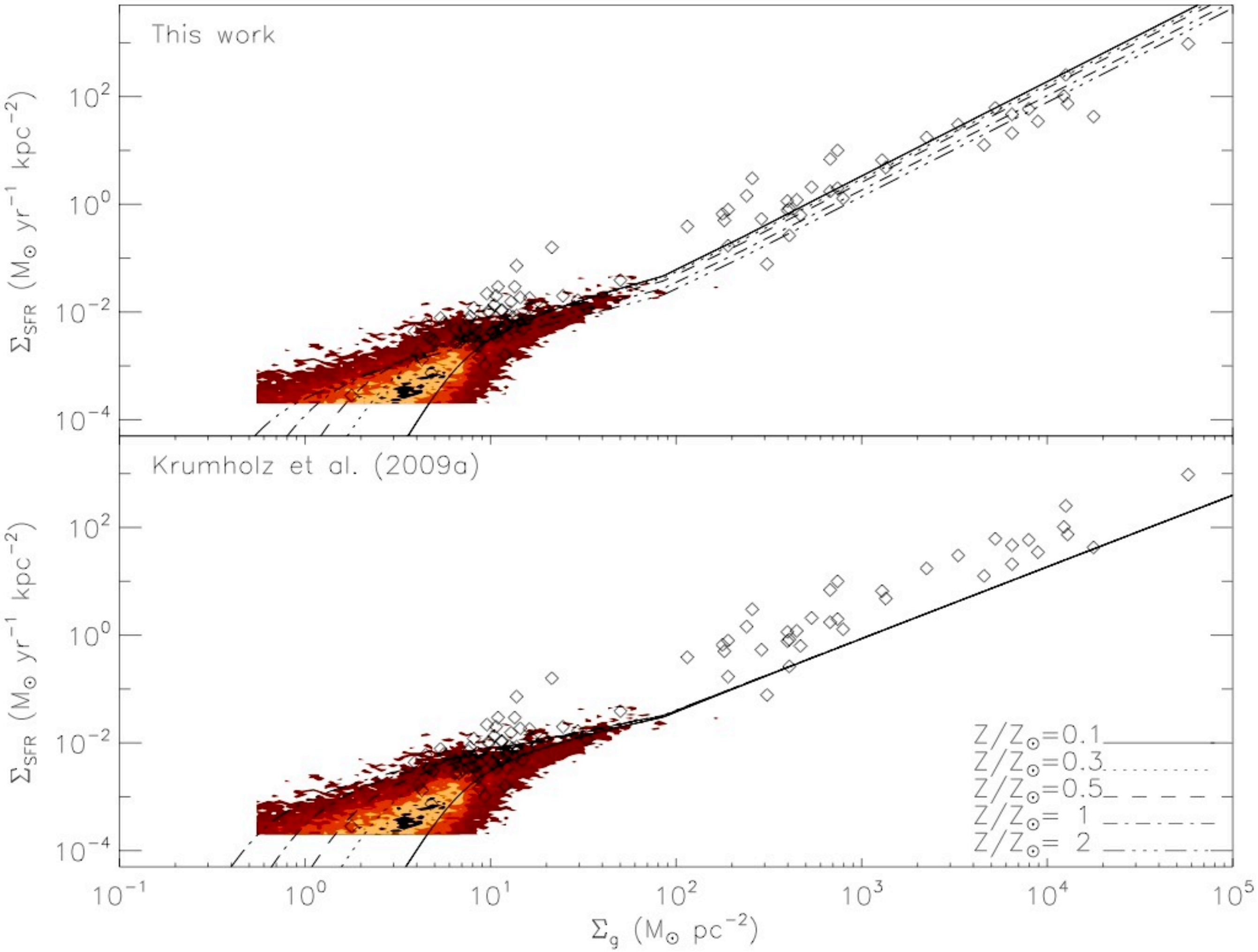


The Star Formation Efficiency per unit time in The Feedback Regulated Star Formation model

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



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



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

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

Observational data:

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

Conclusion

* Magnetic fields regulate the rate of core formation in a clump/cloud per unit time.

* Effiecent core coalescence can significantly flatten the CMF in the intermediate and high mass regimes

* Gas accretion affects all the CMF mass range

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

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

<u>Implications of the feedback regulated, metallicity dependent star formation</u>

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

- Galactic SFEs depend on metallicity

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