Controlling the Star Formation Efficiency in Molecular Clouds

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With

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MARIE CURIE ACTIONS
The Niels Bohr International Academy
STARPLAN
CENTRE FOR STAR AND PLANET FORMATION
A research centre for cosmochemistry, astrophysics and astronomy

Products of the star formation process

- PDF of density, core mass function, scaling relations between mass, size, velocity dispersion of clumps cores, accretion rates, ect ... 🌶
- IMF 🌶🌶
- SFE 🌶🌶
- Age spread 🌶🌶🌶
- spatial distribution of stars, clustering, mass segregation 🌶
- dynamics of stars 🌶
- multiplicity 🌶🌶

Molecular Cloud Properties

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

$R \sim 10 - 30$ parsecs

$T \sim 10 - 30$ K, $c_s \sim 0.2 - 0.3$ km s^{-1}

Number densities $n \sim 100$ cm^{-3}

$Ma = \sigma / c_s \sim 5 - 10$

$B \sim 10^{-5} - 10^{-4}$ Gauss

Free-fall time:

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

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

$t_{cr} \sim R / \sigma \sim 5 * 10^6$ yrs

SFE in molecular clouds

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

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 the observations

$$SFE_f \approx \left[\frac{M_{cluster}}{M_{gas,present} + M_{cluster}}\right] \approx [0.05 - 0.6]$$

In protocluster forming regions: e.g., Lada & Lada (2003)

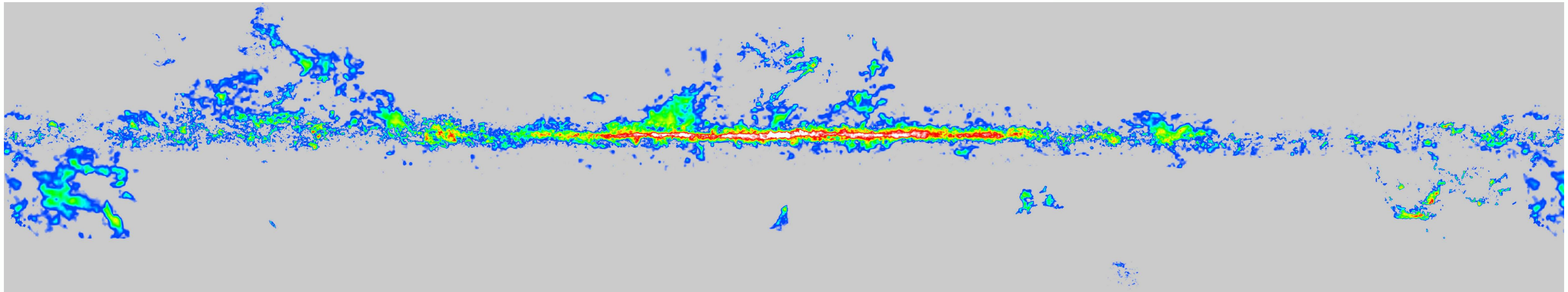
$$\approx [0.01 - 0.1]$$

On the scale of entire GMCs: Myers et al. (1986), Evans et al. (2009) Lada et al. (2010), Murray (2011)

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): $M_{H_2} = 2\times10^9 M_{sol}$



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)

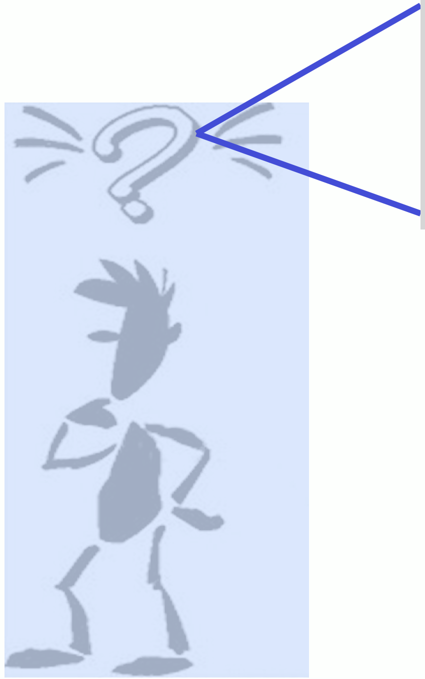
The Star Formation Paradigm

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

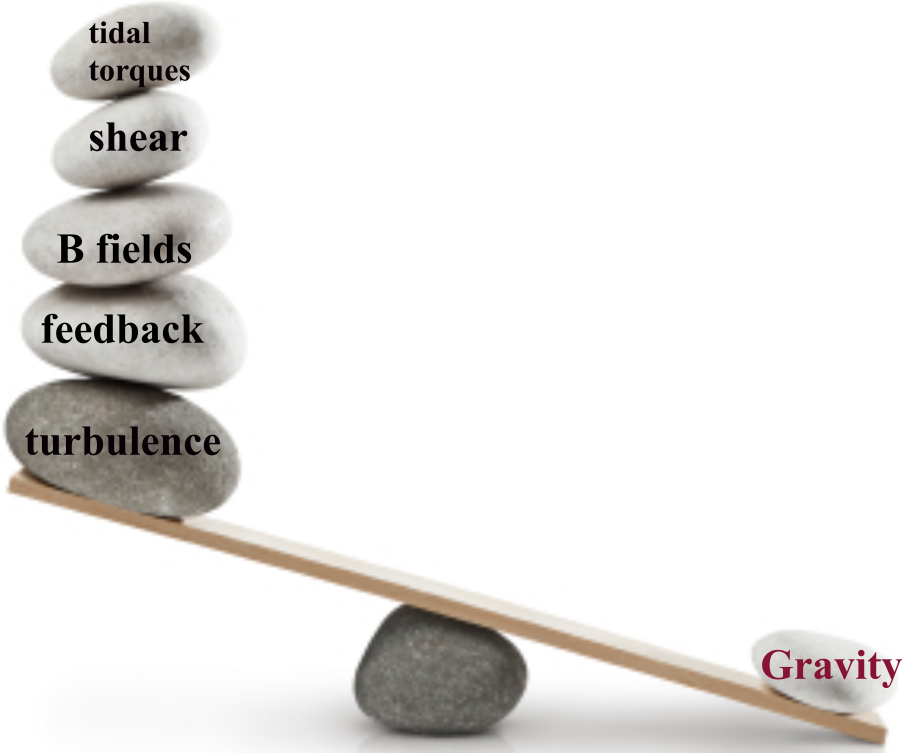
This implies that molecular clouds are long lived $\tau_{SF} \approx 20\tau_{ff}$

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 ?


tidal torques
shear
B fields
feedback
turbulence
Gravity

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

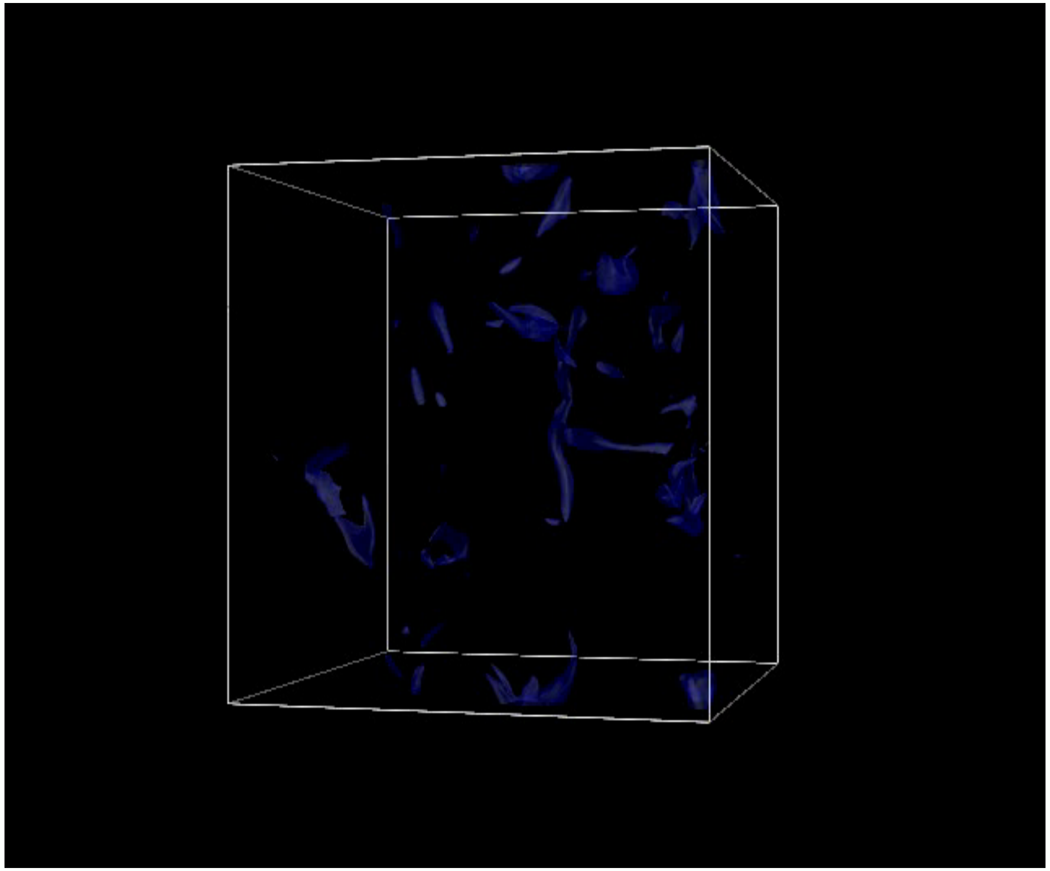
* without gravity: generates the a lognormal distrubution of the density field.
In the presence of gravity: lognormal + power at the high density end

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

The Role of Supersonic Turbulence

Simulations

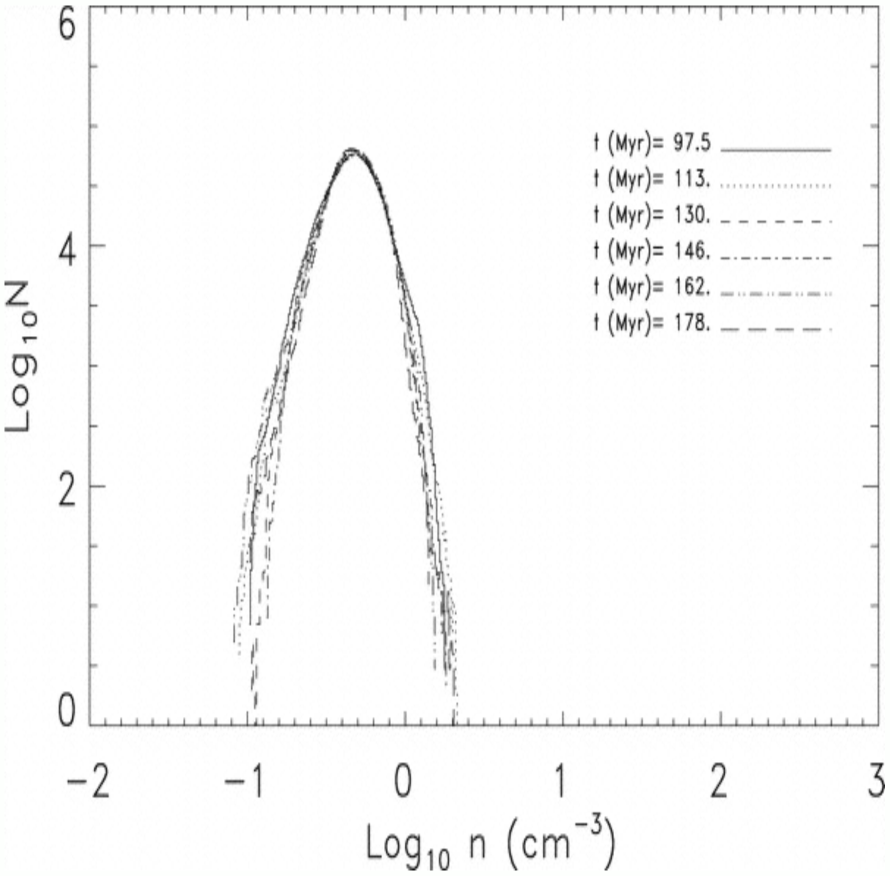
- 3D grids: 256^3, 512^3, 4096^3 resolutions
- Periodic boundary conditions
- MHD, Isothermal
- self-gravity
- driven turbulence (or decaying) on large scales (perturbation with wav numbers in the range k=1-2)
- Ma= 10, $J=L_0/L_J=4$
- L_0= 4pc, n_0= 500 cm^{-3}, T=11.4 K, c_s=0.2 km s^{-1}



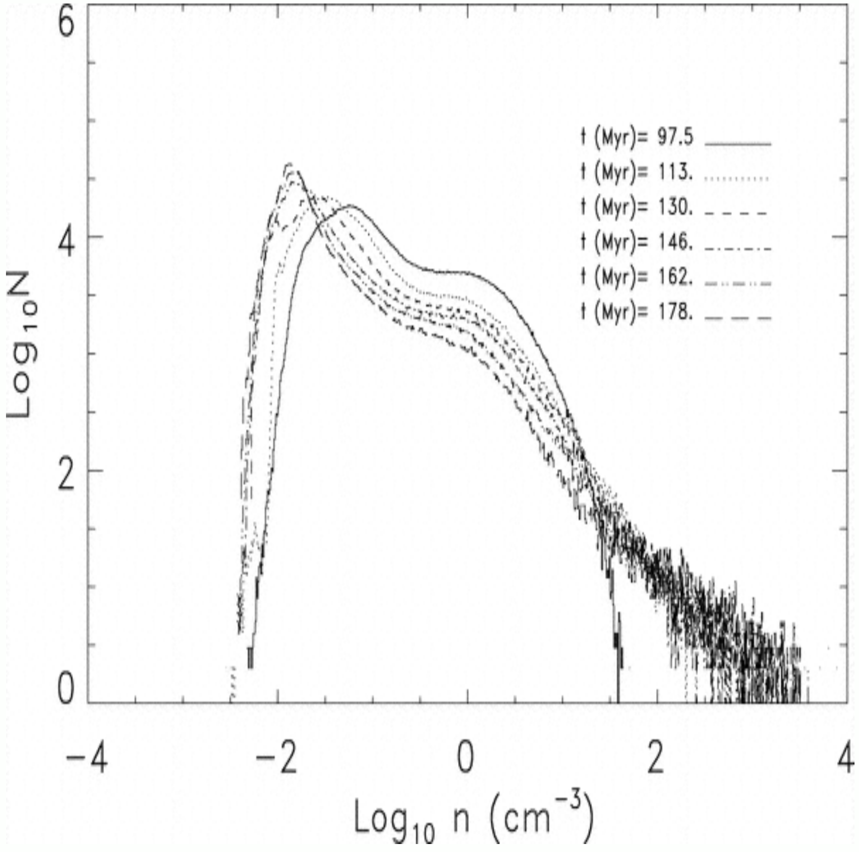
Vazquez-Semadeni et al. (2005), Dib et al. (2007,2008)

The Role of Supersonic Turbulence

PDF of density field: Isothermal gas



PDF of density field: multiphase gas

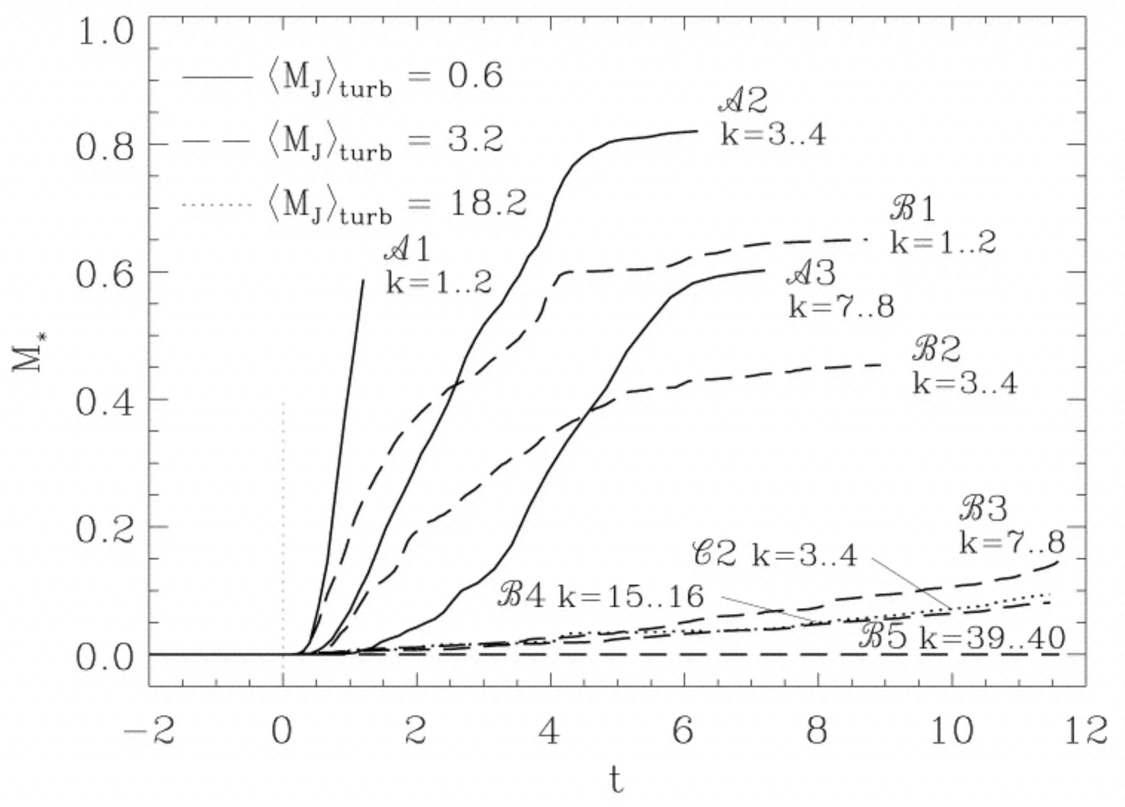


Dib & Burkert 2005

Kritsuk et al. 2001

The Role of Supersonic Turbulence

SFE dependence on the turbulence properties



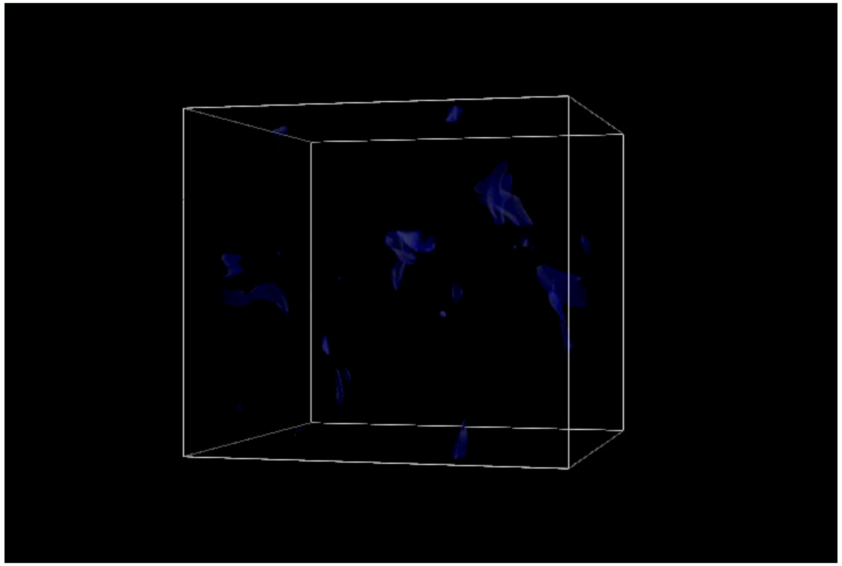
Klessen et al. 2000

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

Influence of the Magnetic Field



<u>Mass-to magnetic flux ratio</u>

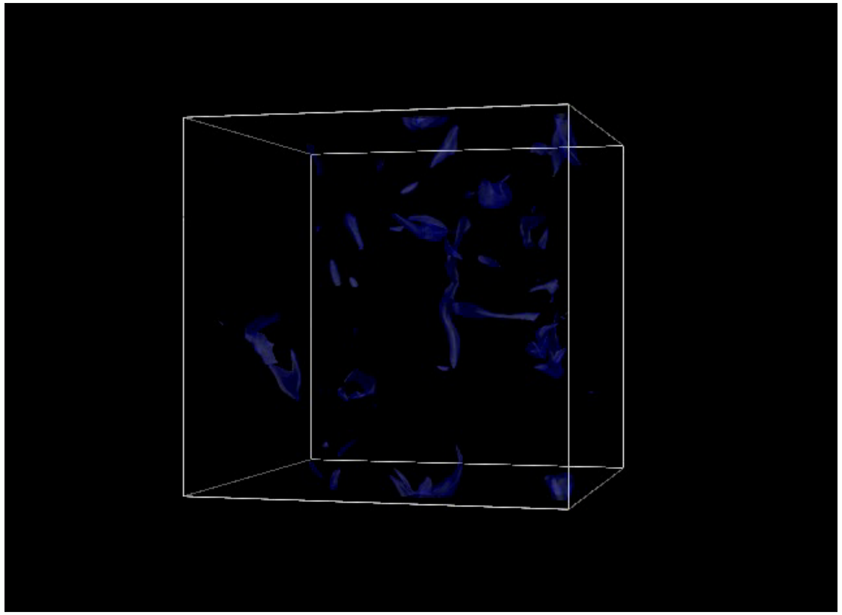
$\mu c = (M/\Phi)c / (M/\Phi)cr$

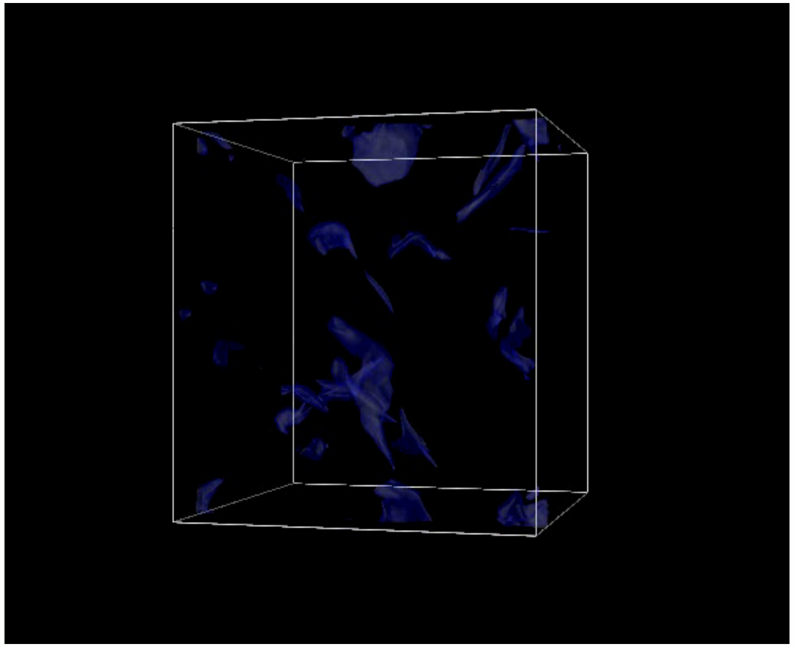
$\Phi c = \pi\ Bm\ Rc^2$

Bm is the the Mean Magnetic field

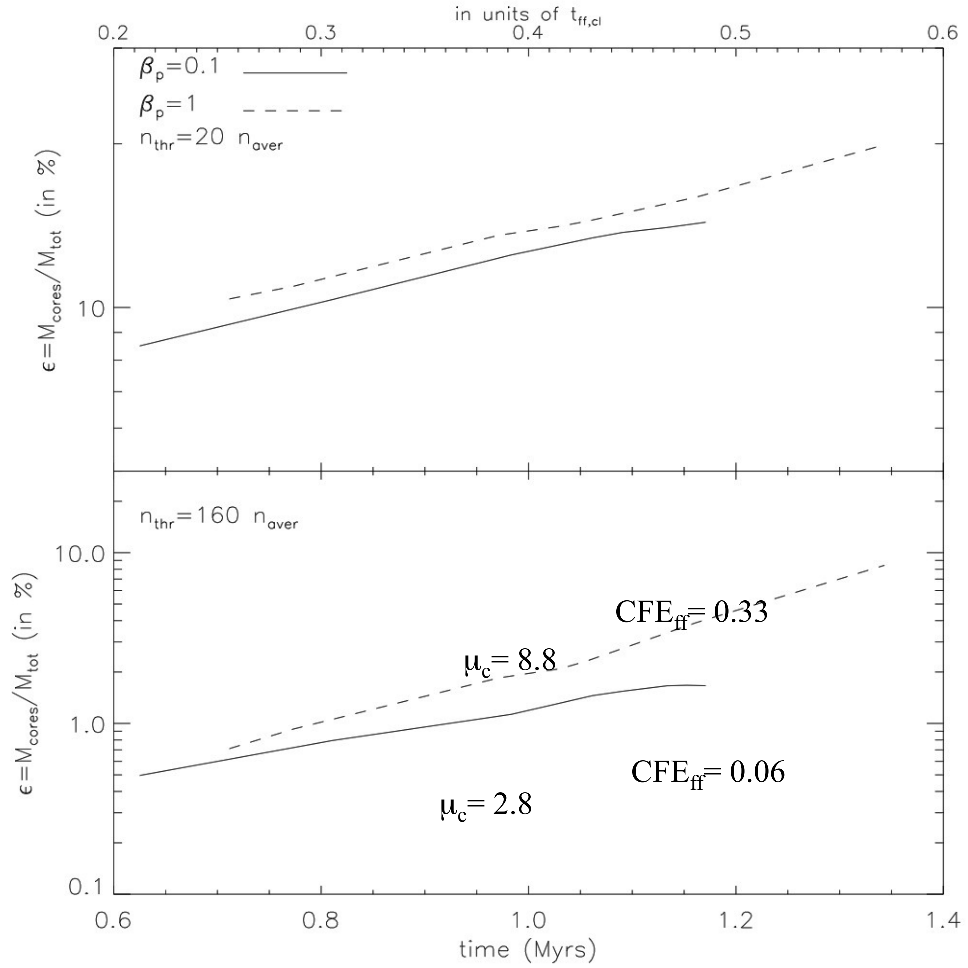
$\mu c < 1$: magnetic support, $\mu c > 1$ no magnetic support.

We used $\mu c=0.9$ (B=4.5 microG), 2.8 (B=14.5 microG), 8.8 (B=45 microG)





Influence of the Magnetic Field

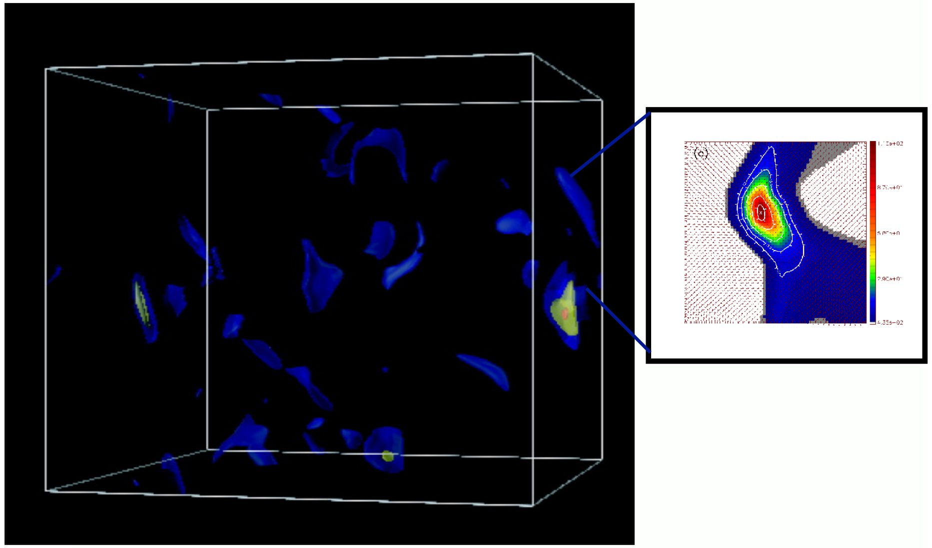


$CFE_{ff}= 0.33$

$\mu_c= 8.8$

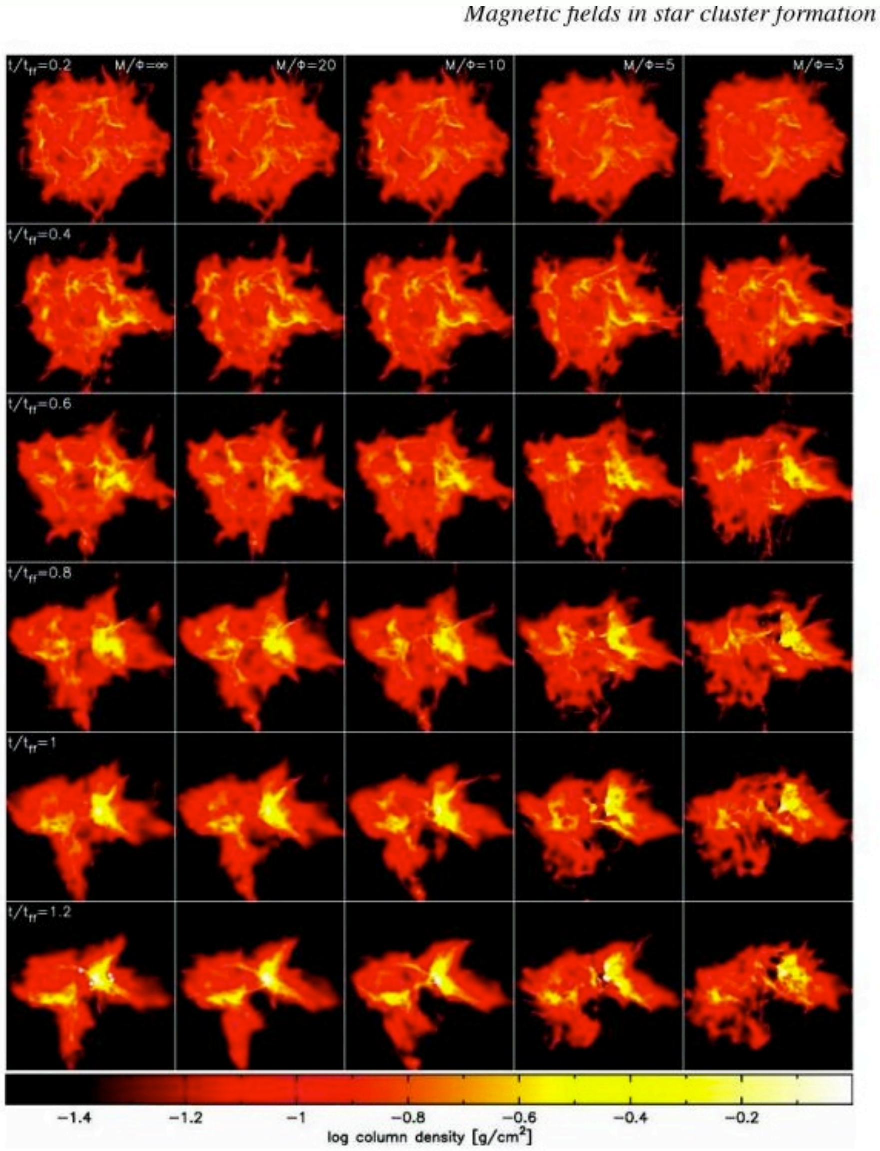
$CFE_{ff}= 0.06$

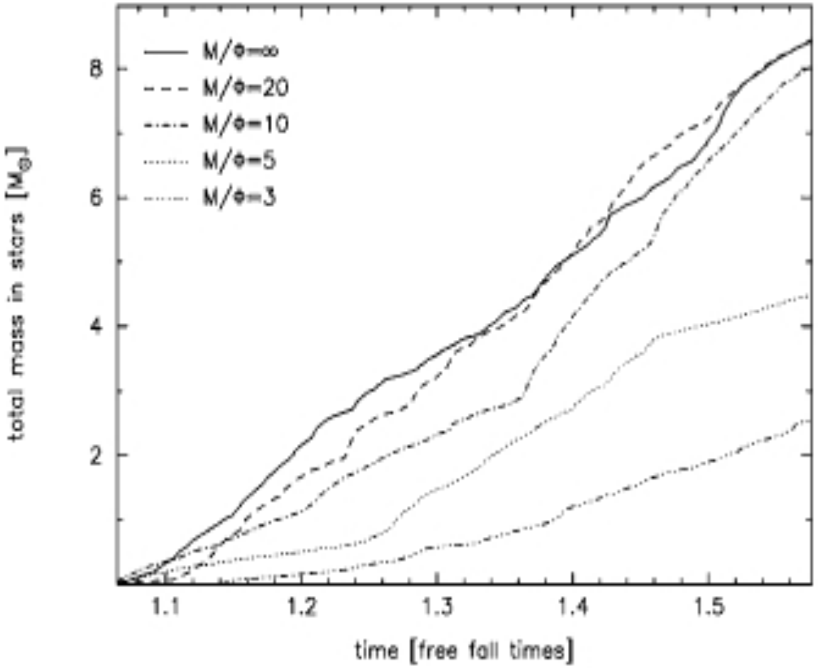
$\mu_c= 2.8$



Dib et al. 2010

Influence of the Magnetic Field





Price & Bate 2008

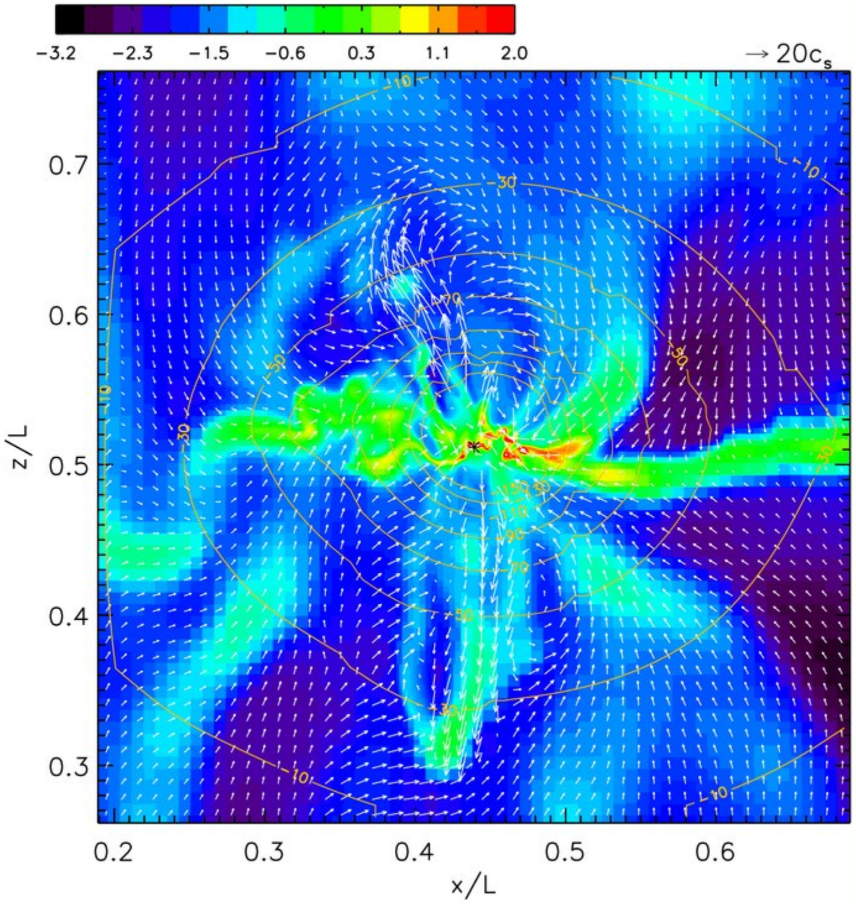
Influence of Stellar Feedback

Effects of feedback on the clouds evolution

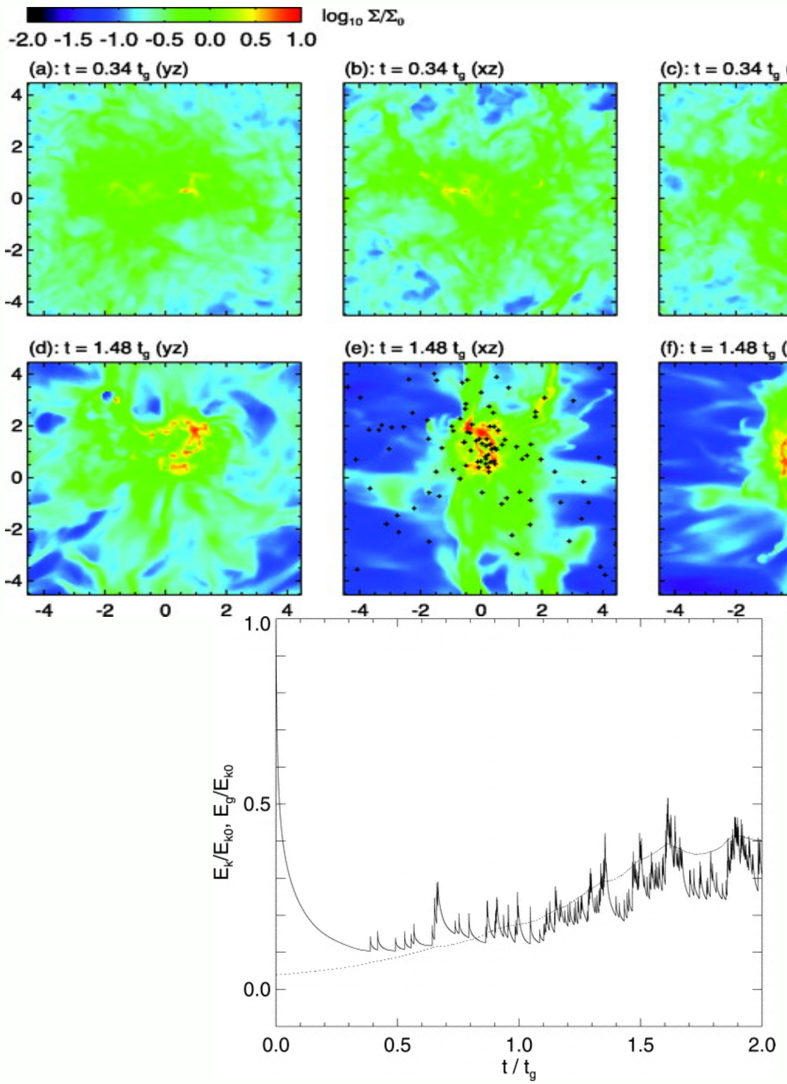
- Injects energy and momentum into the cloud
- Re-distributes matter in the cloud
- Maintains the turbulence
- Heats the gas → change the Jeans mass
- Eventually disperses the gas and destroys the clouds

Influence of Stellar Feedback

Effects of protostellar outflows



Wang et al. 2010

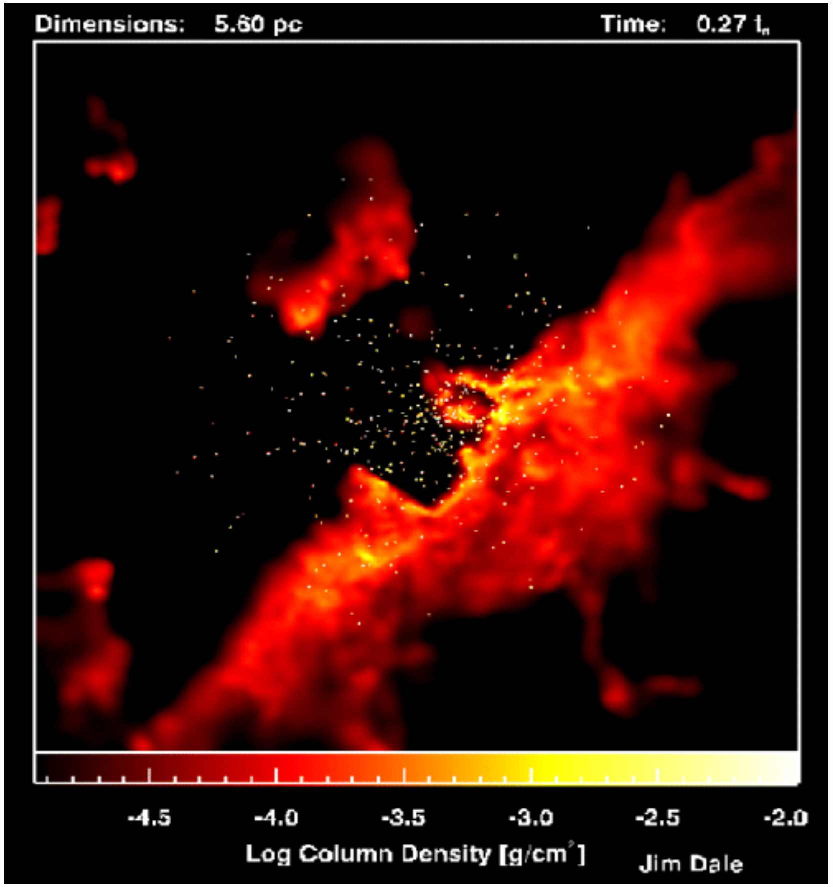


Li & Nakamura 2007

Influence of Stellar Feedback

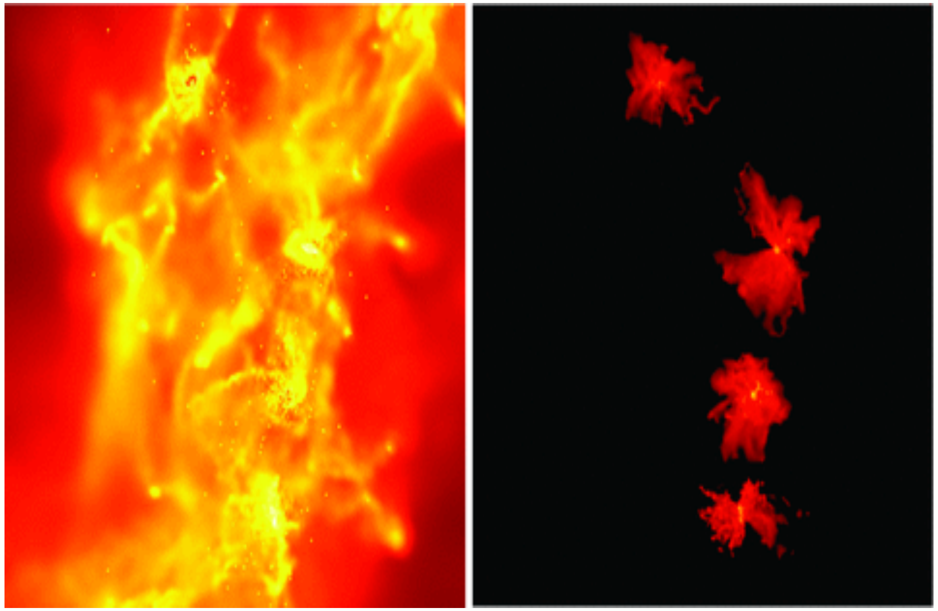
Feedback from massive stars

Ionization and heating of the gas



Dale et al 2005

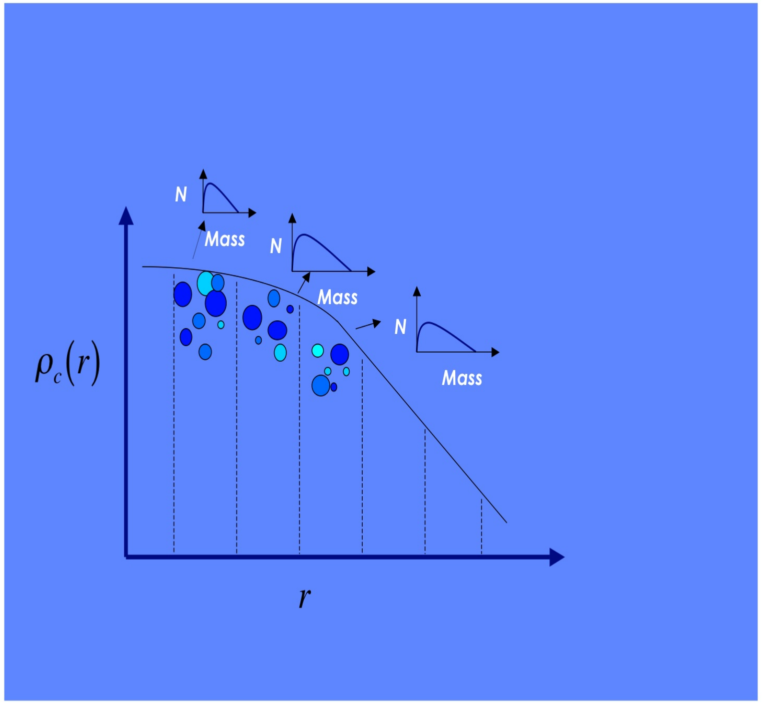
Stellar winds



Dale & Bonnell 2008

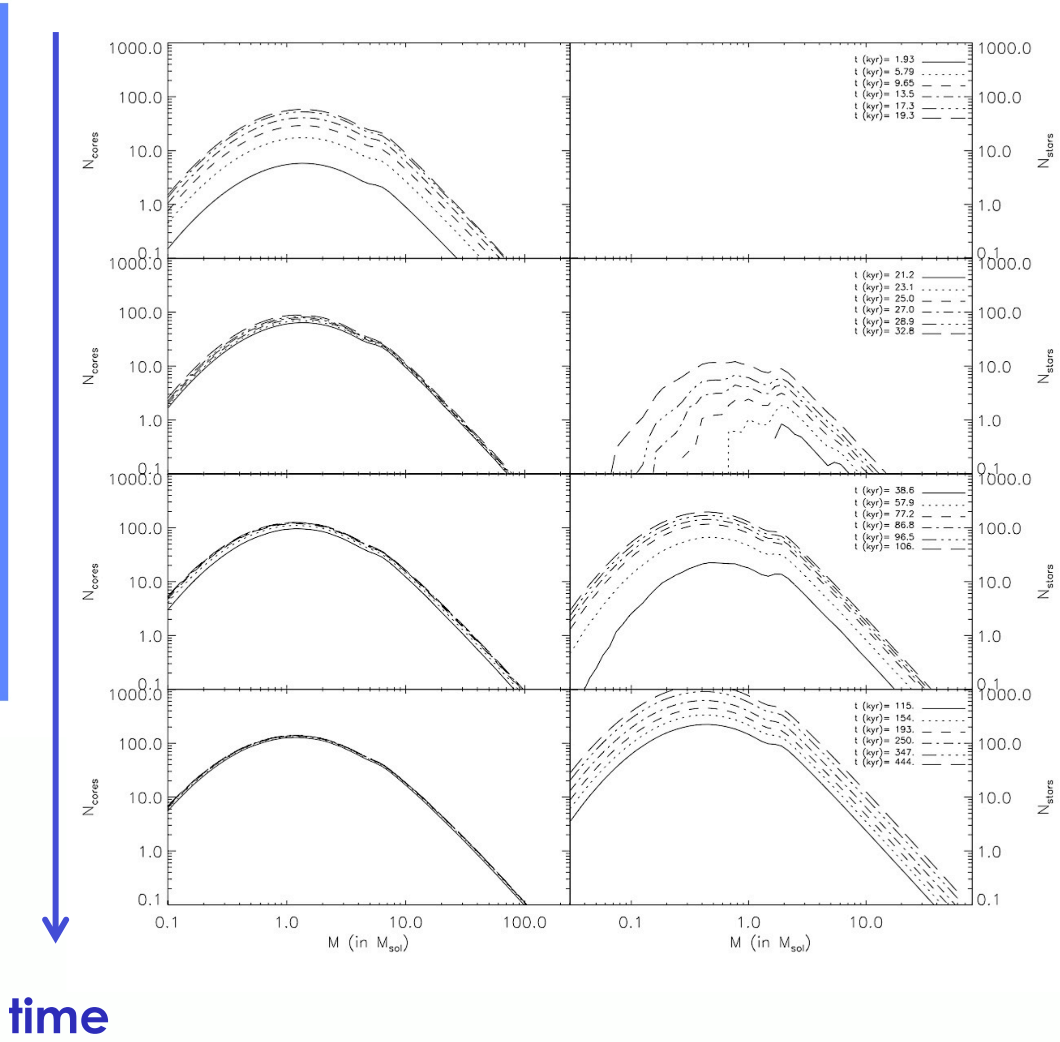
Influence of Stellar Feedback

A semi-analytical model for feedback from massive stars



Protocluster forming molecular cloud

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



Feedback model: Stellar Winds

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

Terminal wind velocity v_∞

Energy cumulated in winds

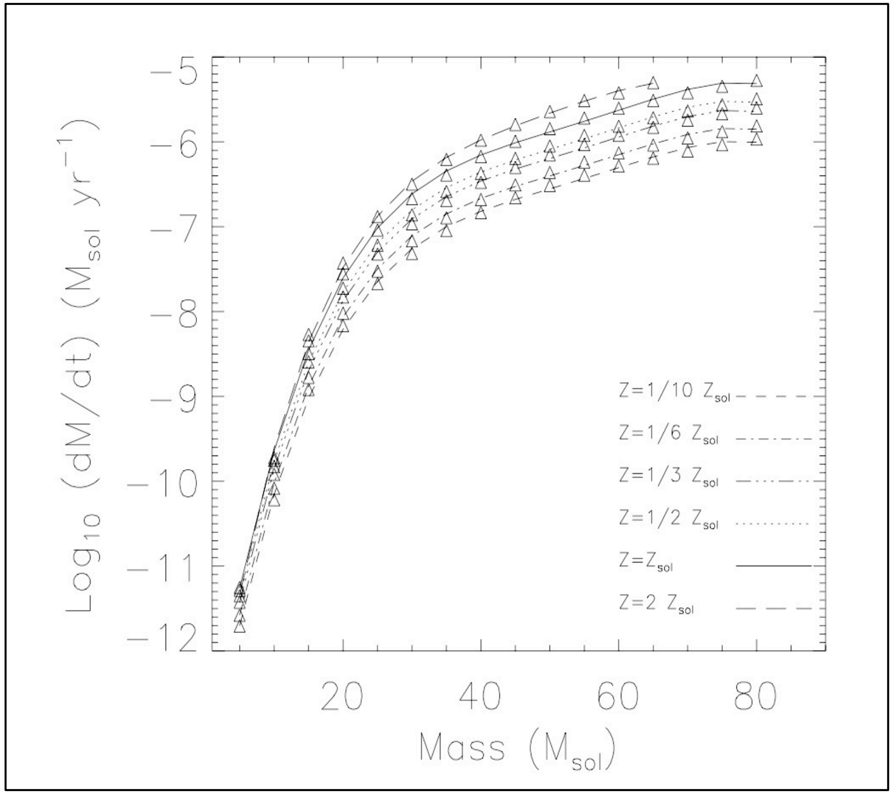
$$E_{wind} = \int_{t''=0}^{t''=t} \int_{m=5M_{sol}}^{m=80M_{sol}} \left(\frac{N(m)(dM/dt)_*(m)v_\infty^2}{2} dm \right) dt''$$

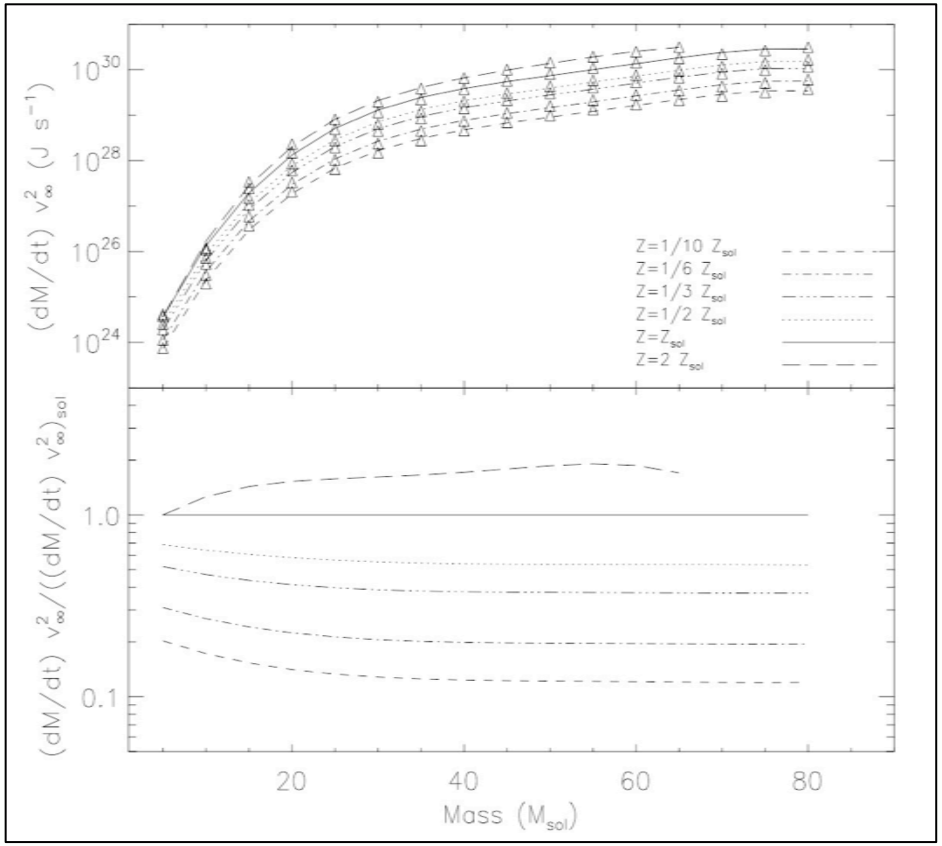
Fraction of wind energy that counters gravity $E_{k,wind} = \kappa E_{wind}$

$k < 1$

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.) ➔ $\dot{M}$ $\dot{M} v_\infty^2$



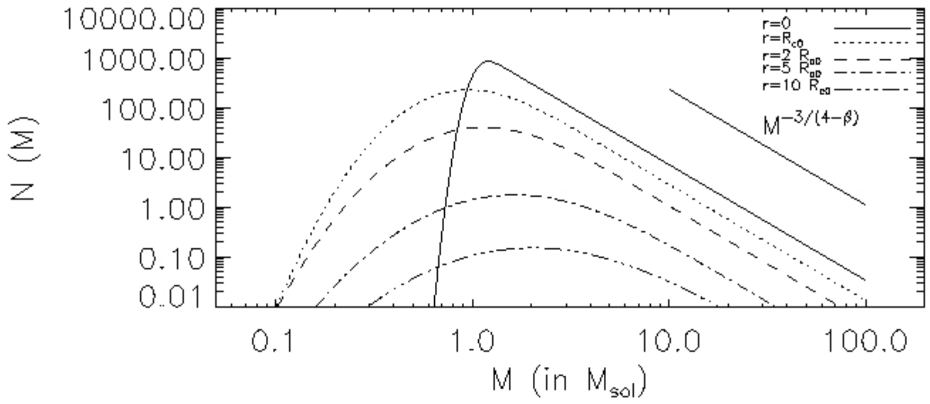


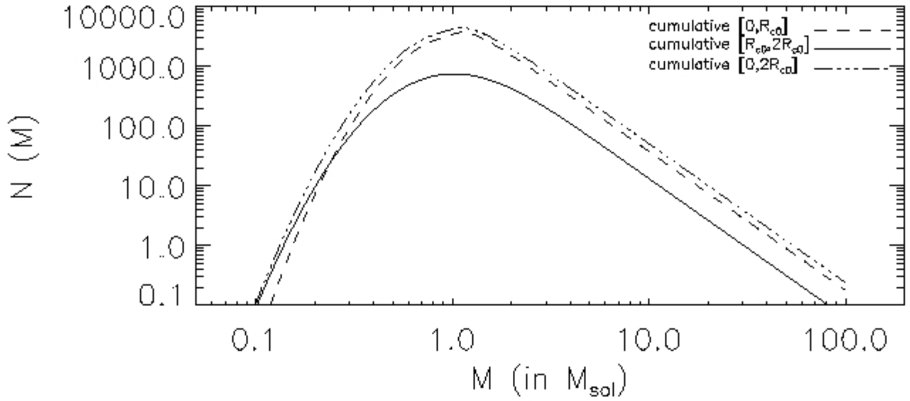
Dib et al. 2011

initial core population: Turbulent fragmentation of the clump

Initial CMFs

(Padoan & Nordlund 2002)



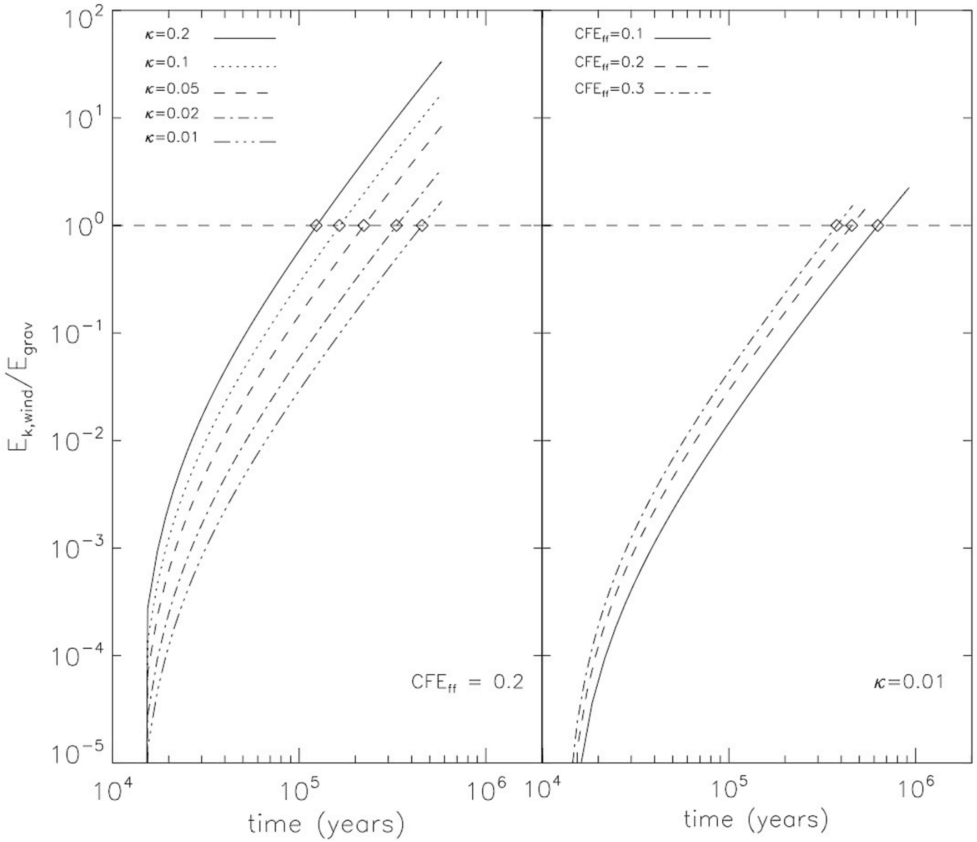


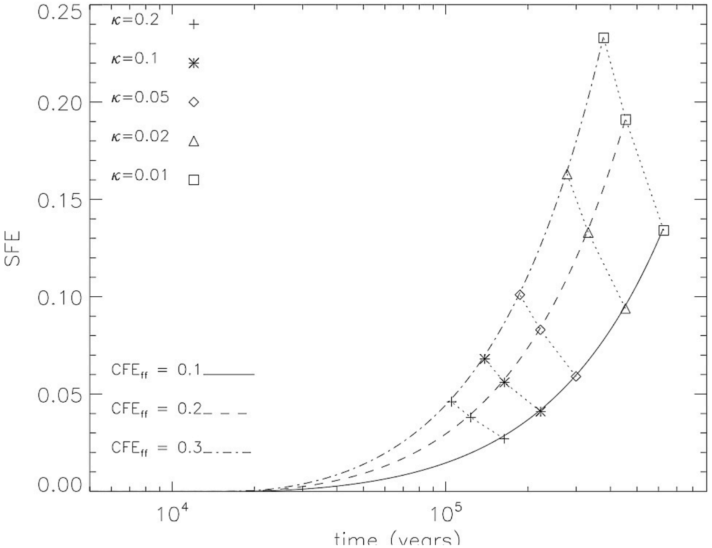
α=0.4

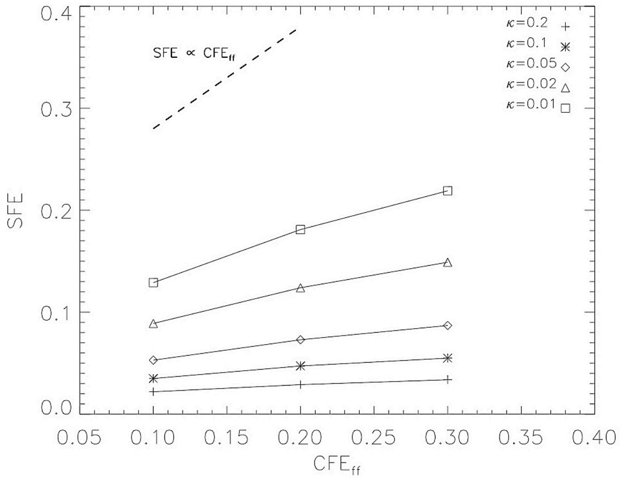
β=1.8

Slope= -3/(4-β)-1=-2.33

Gas expulsion

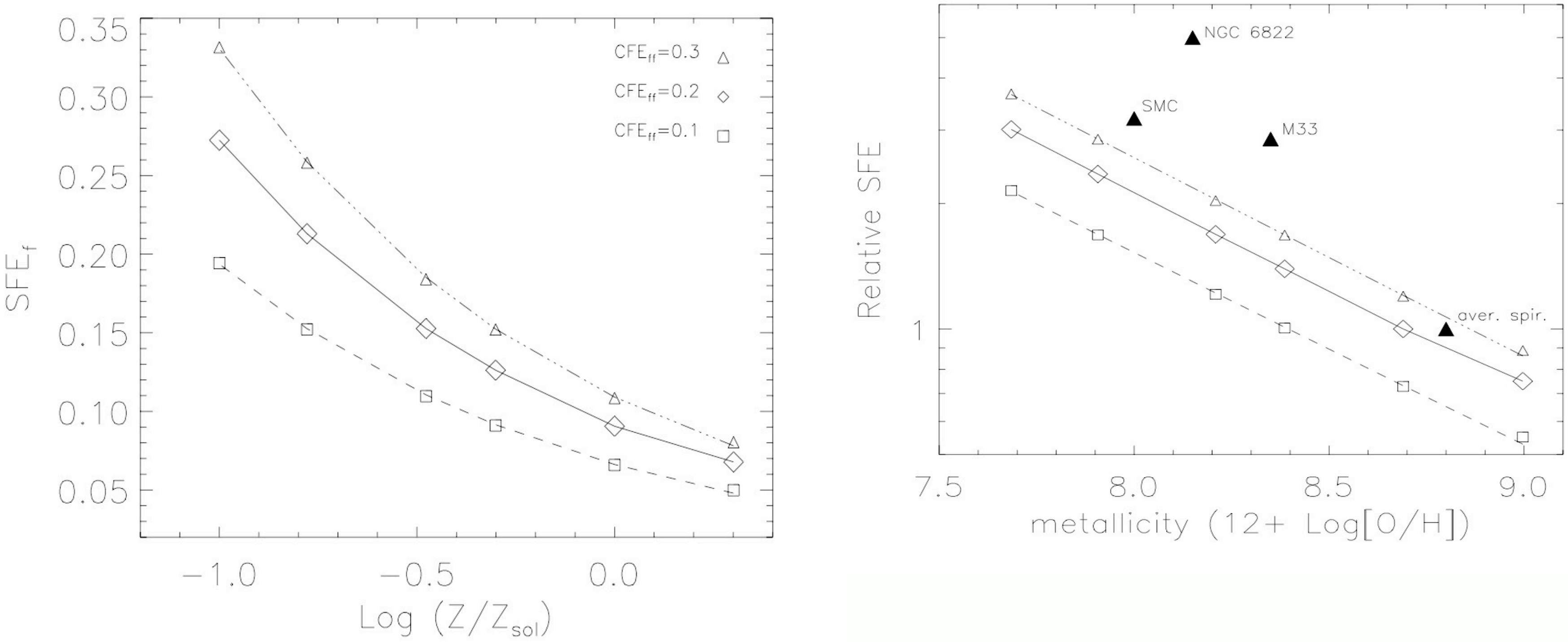






Dib et al. 2011,2013

Dependence of SFE_f on metallicity



Dib et al. (2011)

How did we measure the SFE in these clusters ?

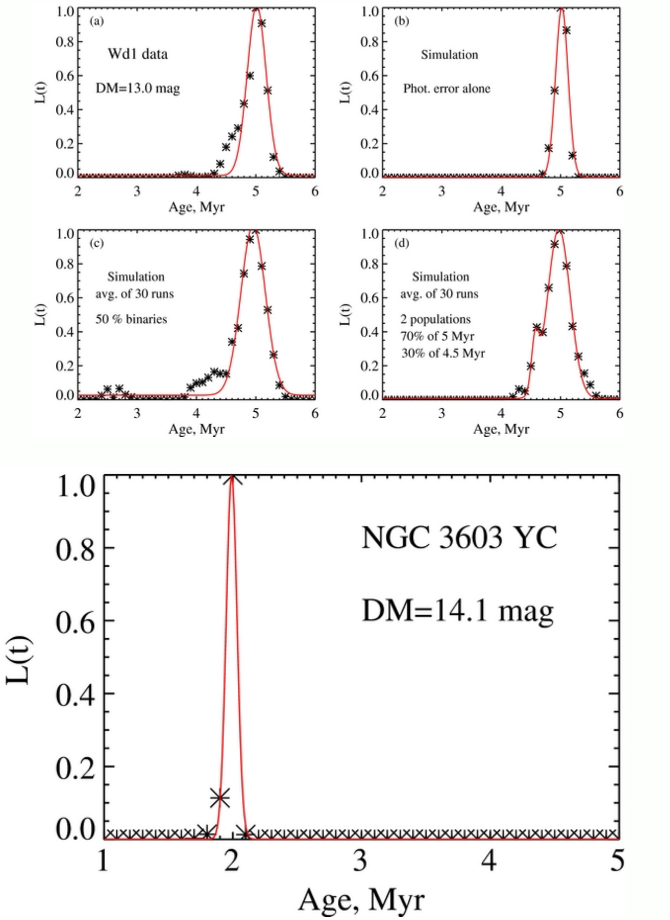
- Assume cluster is initially virialized, loses gas, and then re-virializes. Both are assumptions !!
- measure the dynamical mass of the cluster and then:

$$SFE = \frac{M_{phot}}{M_{dyn}} \qquad M_{dyn} = \frac{\eta r_{hm} \sigma_{*,3D}^{2}}{G}$$

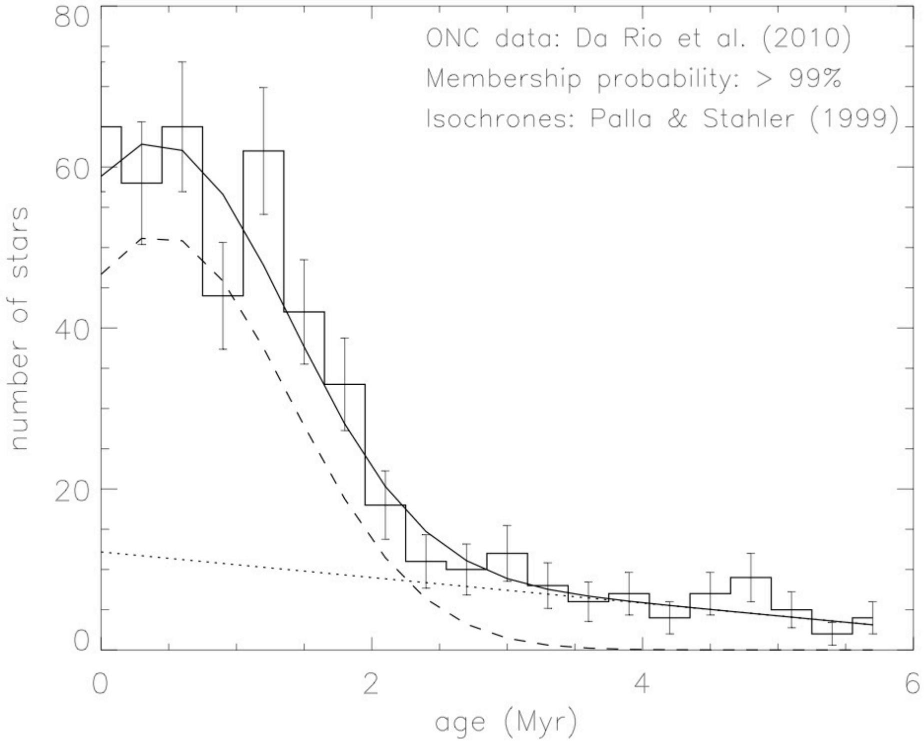
- stellar velocity dispersions of stars measured for intermediate mass stars from proper motions
- assume energy equipartition over all stellar masses and integrate over a selected IMF (Kroupa).

Dib et al. (2013)

Observed age spreads



Kudryavtseva, Brandner, et al. 2012



Dib et al. (2013)

Comparison to observations: massive clusters

- **clump masses [$5x10^4$-$5x10^5$] M_{sol}**

▪ **Models with uniform star formation: constant CFE_{ff}**

$$CFE_{ff} = 0.1,0.2,0.3$$

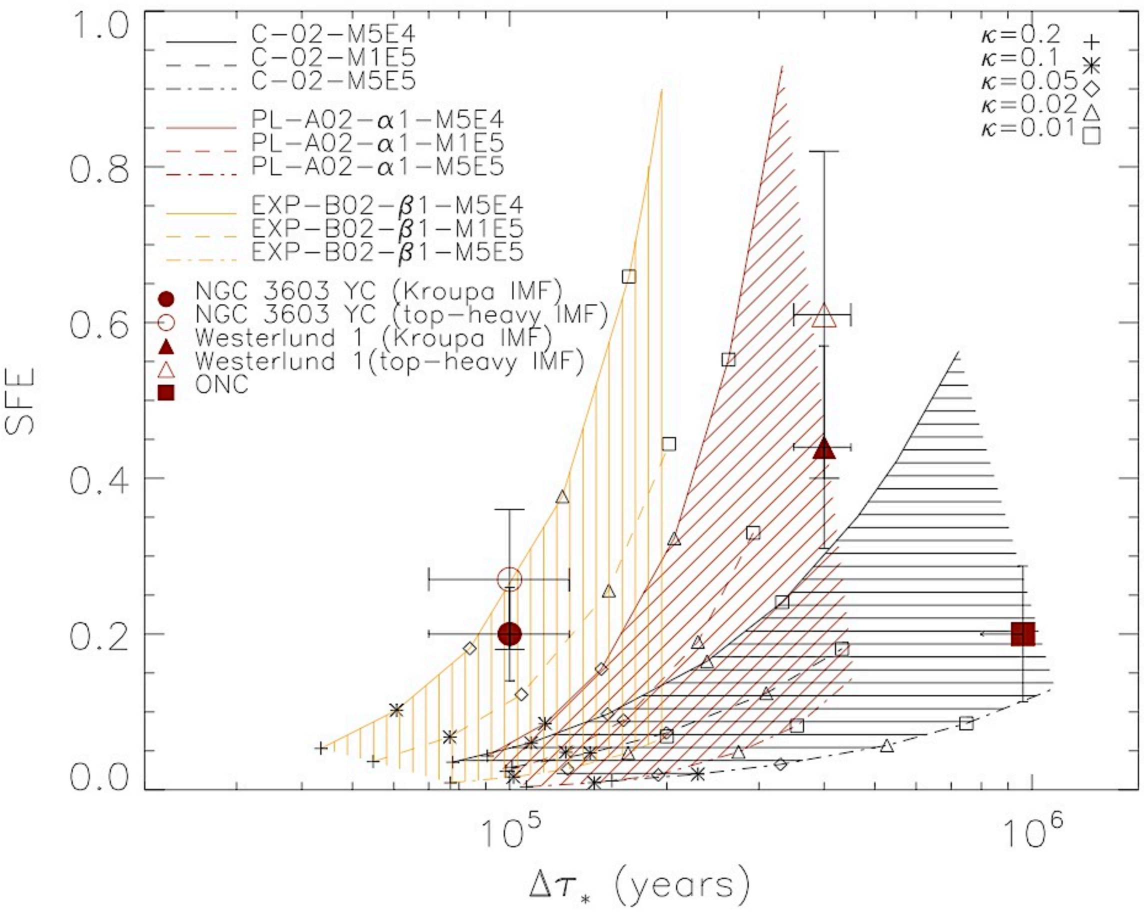
▪ **Models with accelerated star formation**

Power laws:

$$CFE(t) = A\left(\frac{t}{f_{ff}}\right)^{\alpha}$$

Exponential laws:

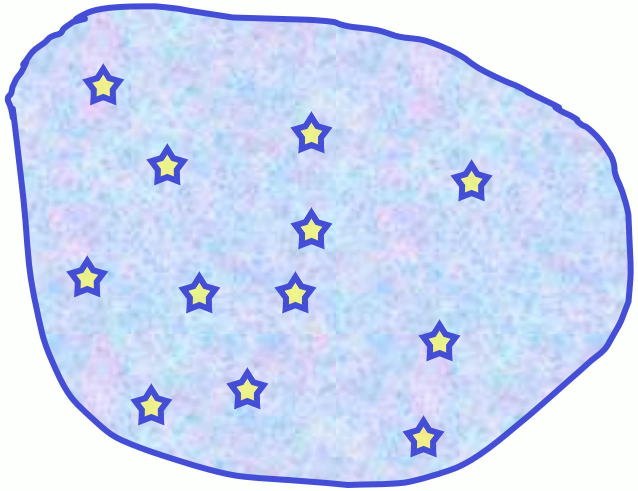
$$CFE(t) = B\exp\left(\frac{1}{\beta}\frac{t}{t_{ff,cl}}\right)$$



Dib et al. (2013)

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

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



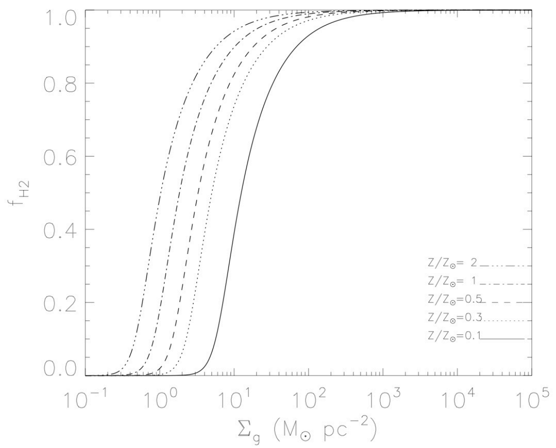
* Star Formation occurs in GMCs

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

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

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

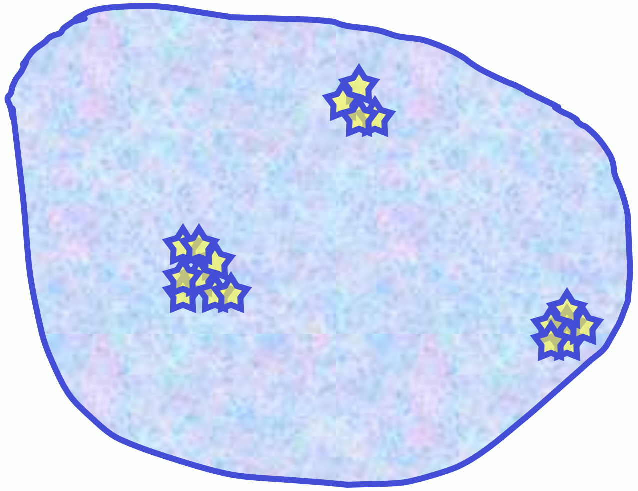
(Krumholz, McKee, Tumlinson 2009;
Gnedin & Kravtsov 2010,2011 and others)



* 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).

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

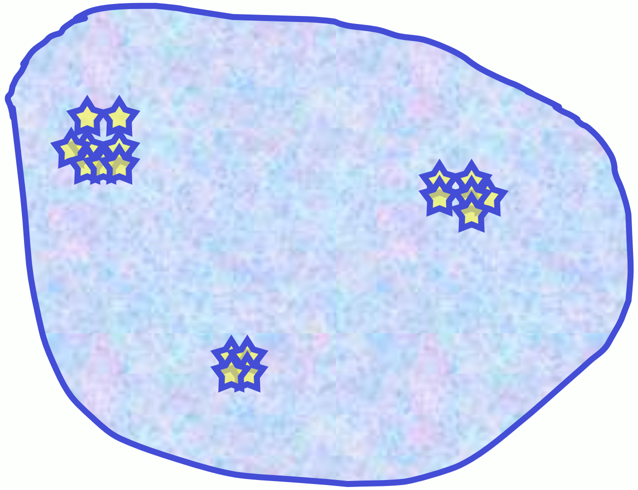
The characteristic mass is

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

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

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

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

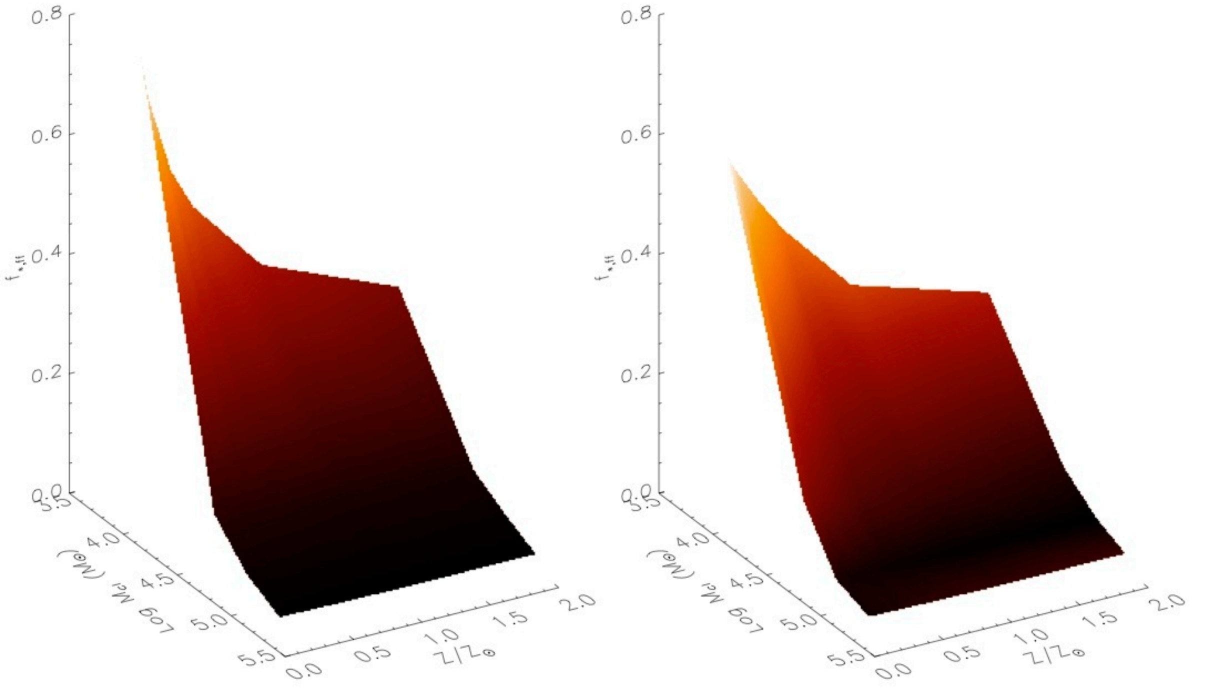


$$\Sigma_{SFR} = \Sigma_g f_{H_2}\left(\Sigma_g, Z'\right) \frac{\left\langle SFE_{\exp} \right\rangle}{\left\langle n_{\exp} t_{ff} \right\rangle}$$

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

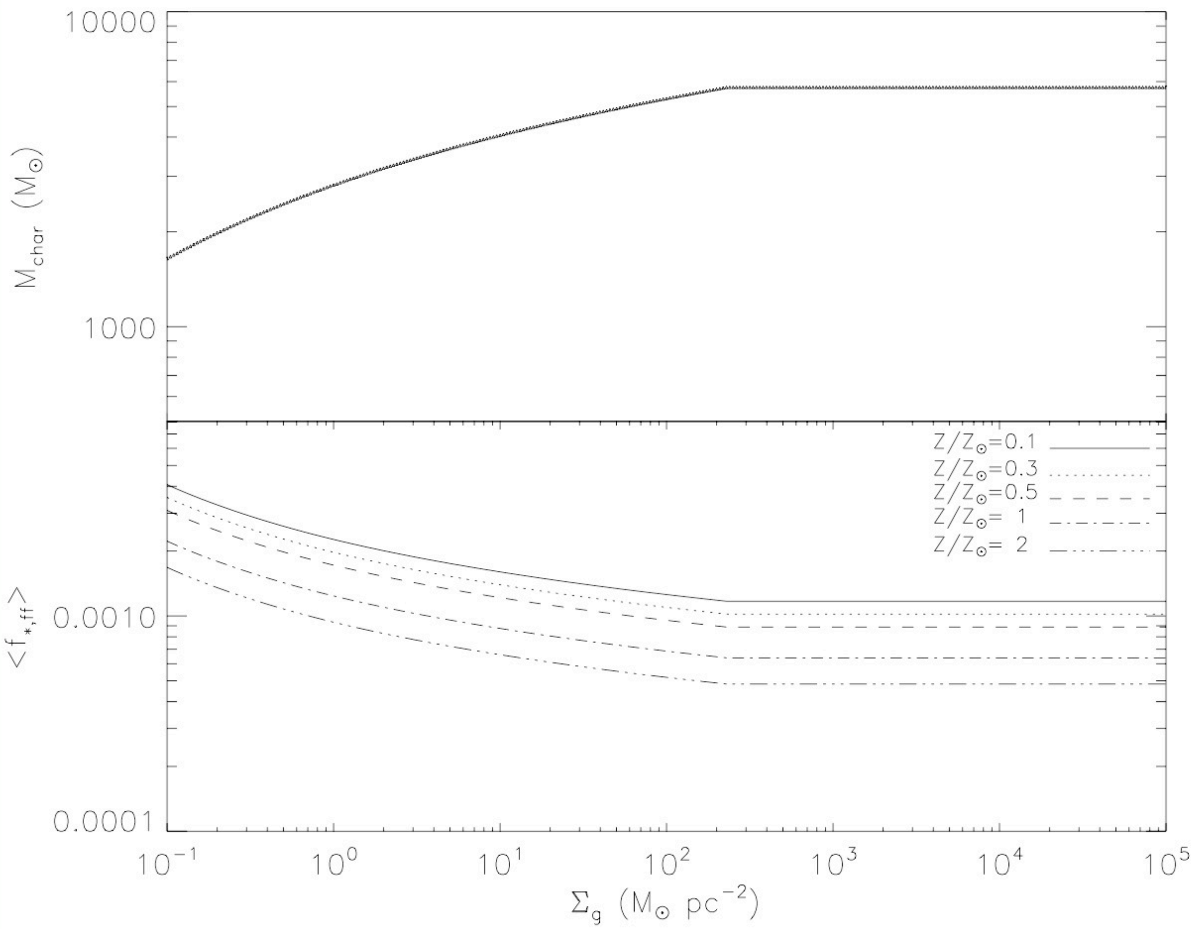
The Star Formation Efficiency per unit time in The Feedback Regulated Star Formation Model

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

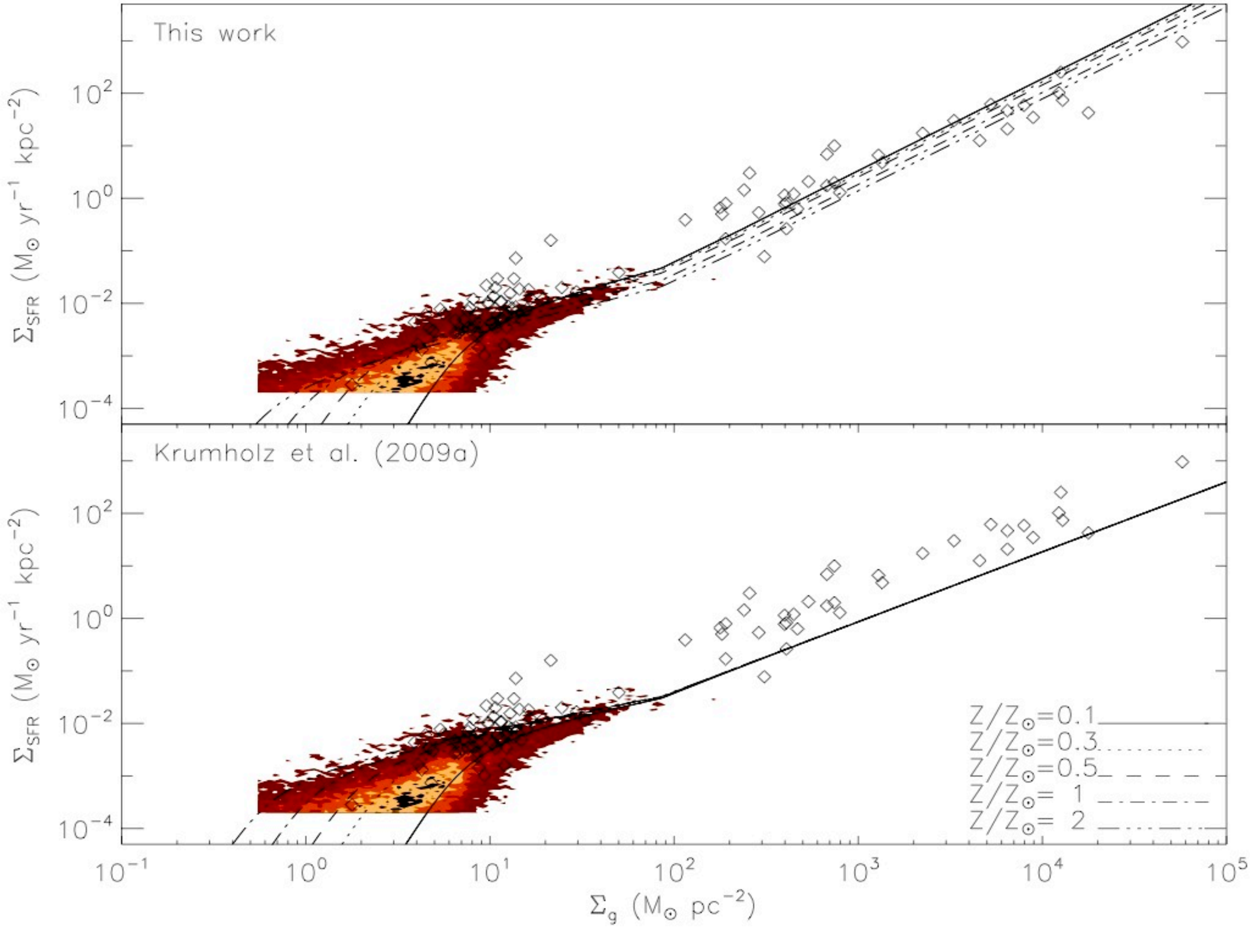


The Star Formation Efficiency per unit time in The Feedback Regulated Star Formation Model

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



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



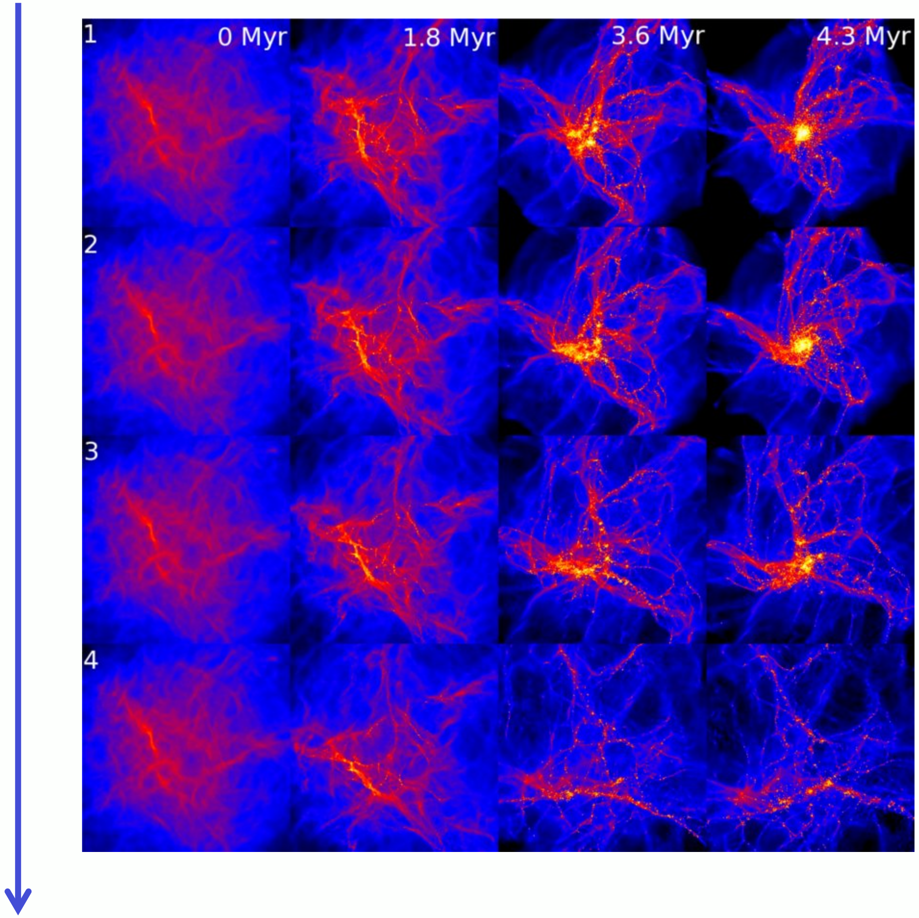
Dib (2011)

Observational data:

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

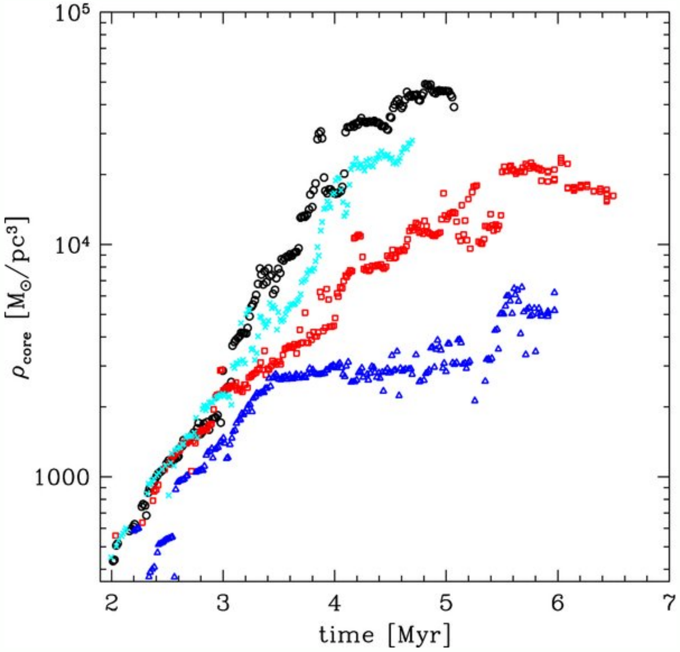
Influence of Shear

results from numerical simulations



Increasing ~~shear~~ rotation

- **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

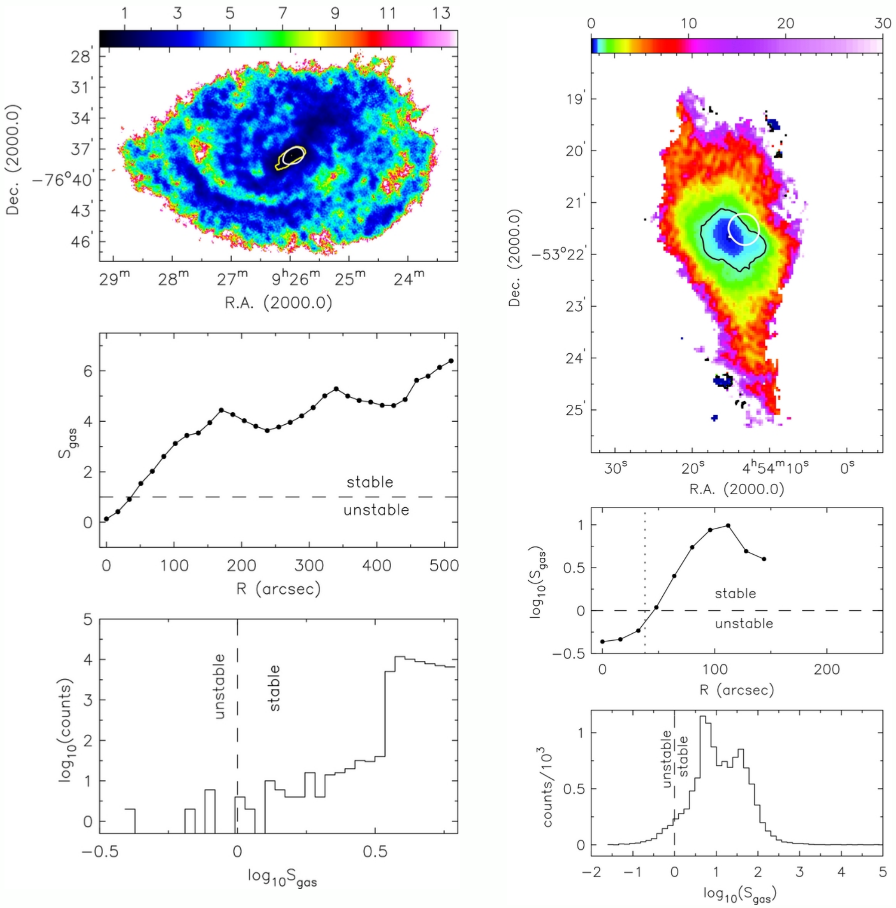
- Galaxies have differential rotation → shear
- Critial surface density above which shear is inefficient → gravity wins
- This defines a shear parameter

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

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

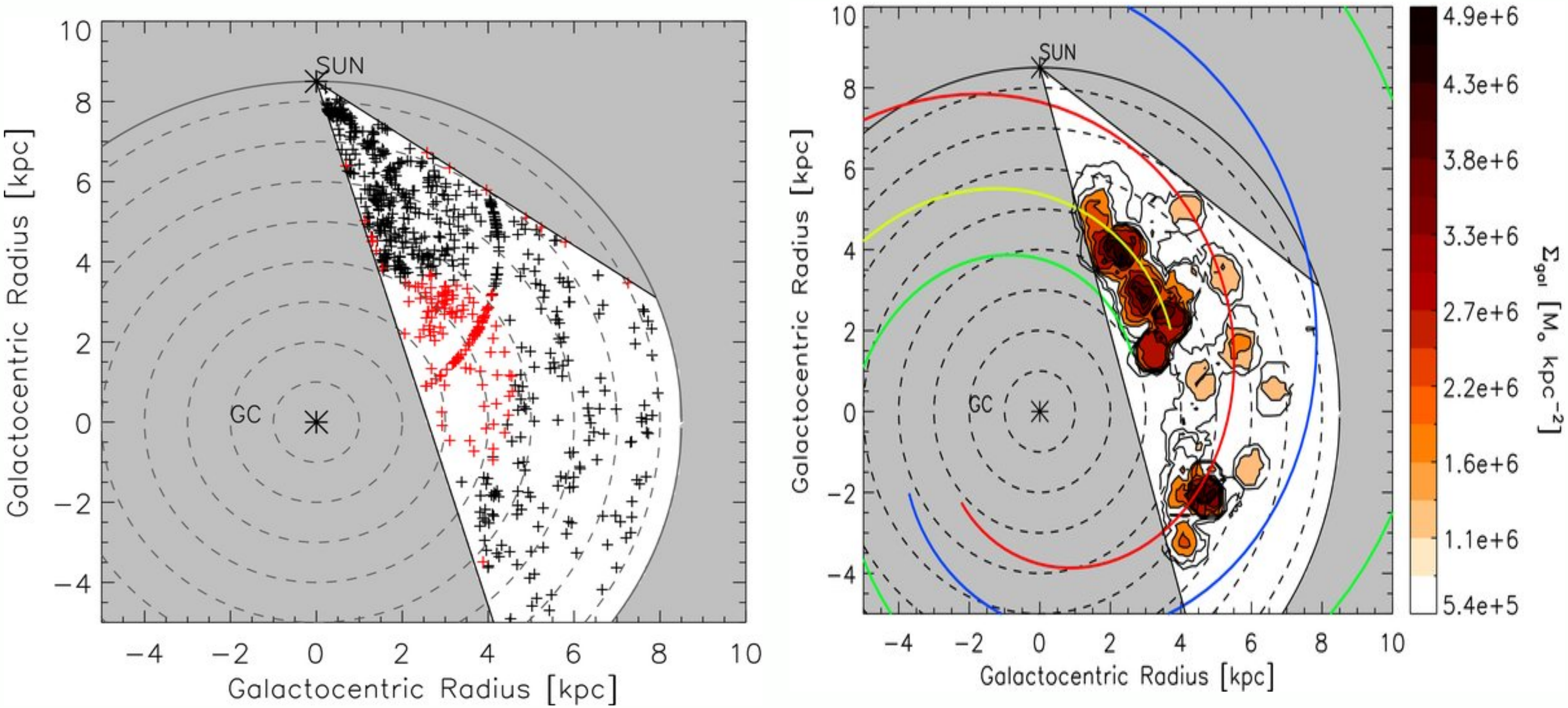


Elson et al. (2012)

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**

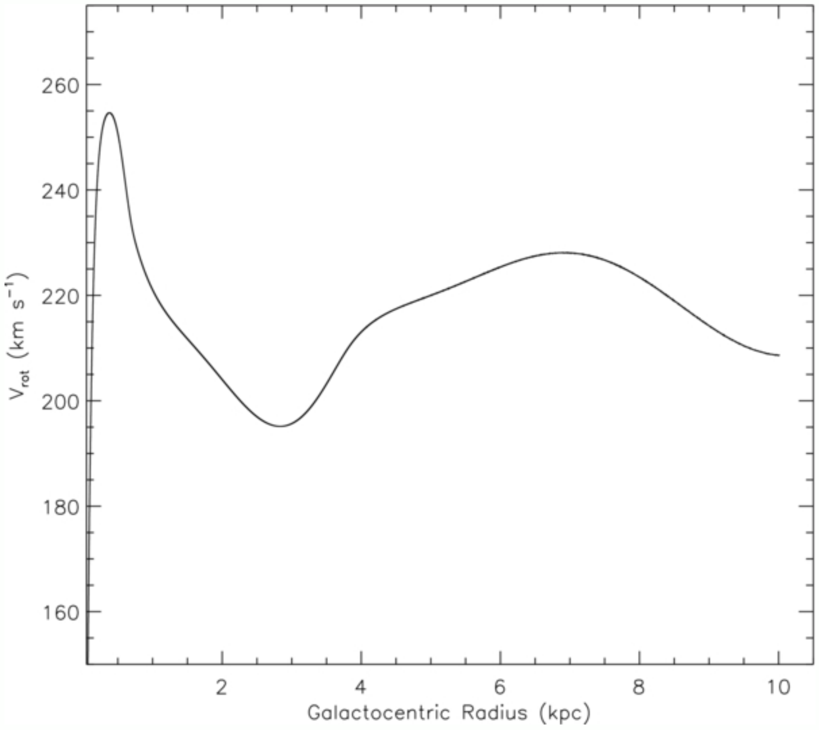


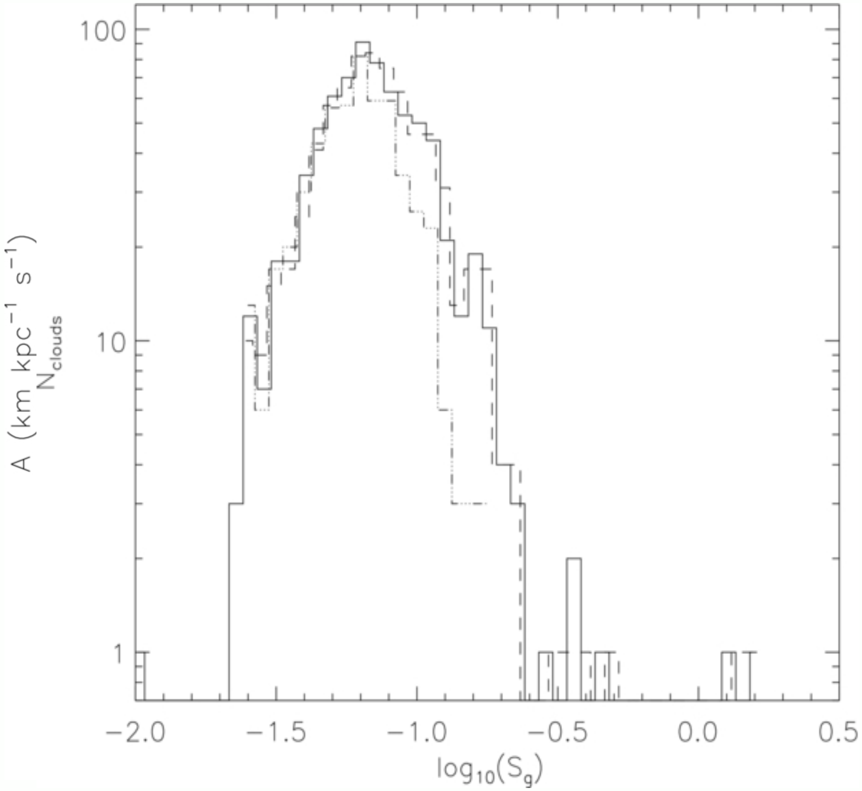
Roman-Duval et al. (2012)

Influence of Shear

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

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



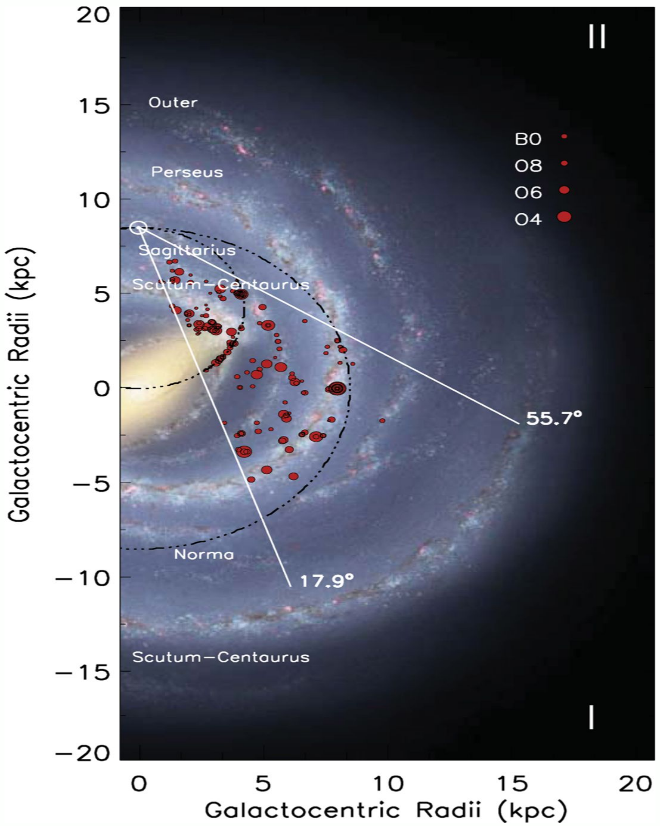


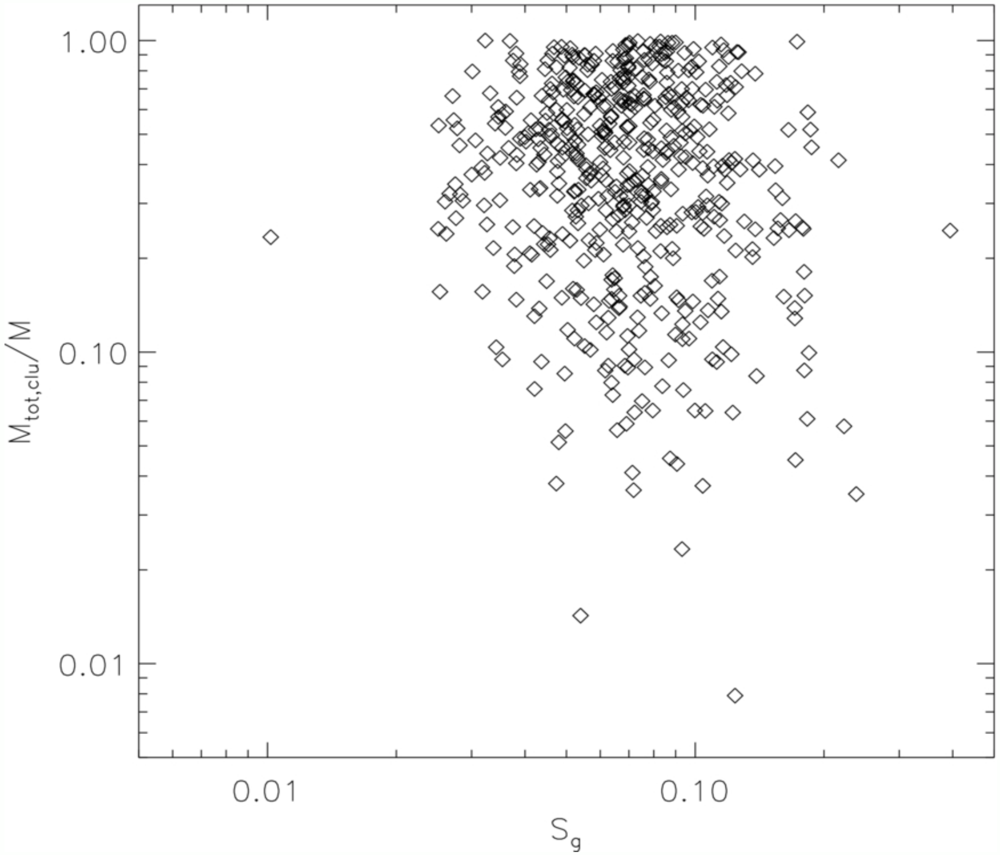
Dib et al. (2012)

Influence of Shear

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

- No correlation between S and the YSOs Luminosities (RMS survey)





Dib et al. (2012)

Take-home points

- ⊙ 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

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- magnetic fields: ✓
- turbulence: ✓
- stellar feedback ✓

Internal regulation

Take-home points

⊙ **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:** ✓

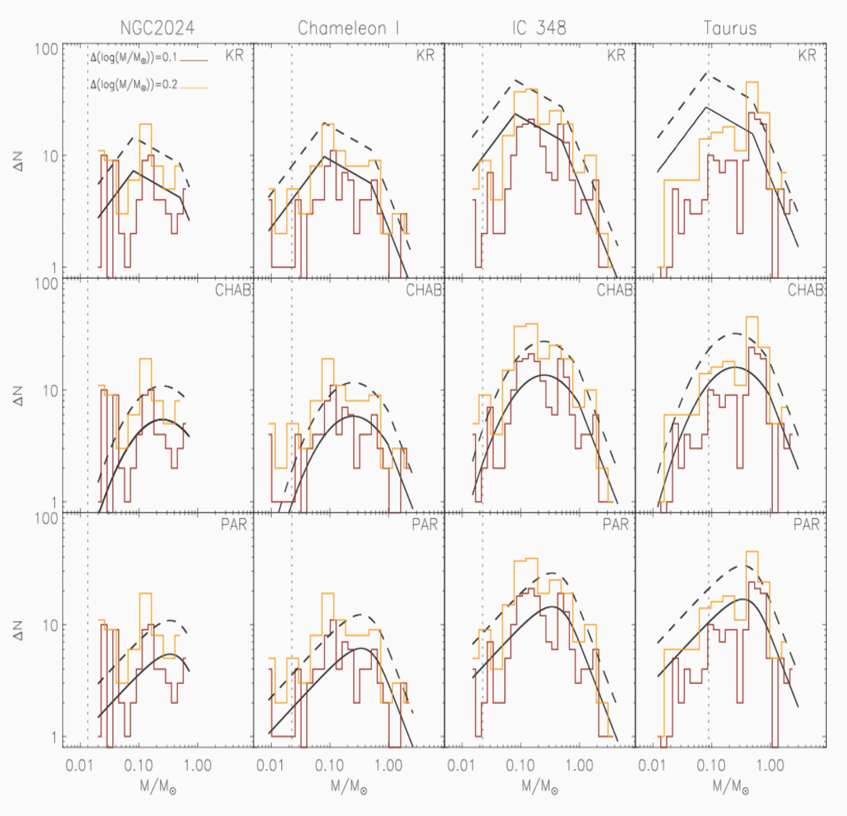
⊙ **stellar feedback** ✓

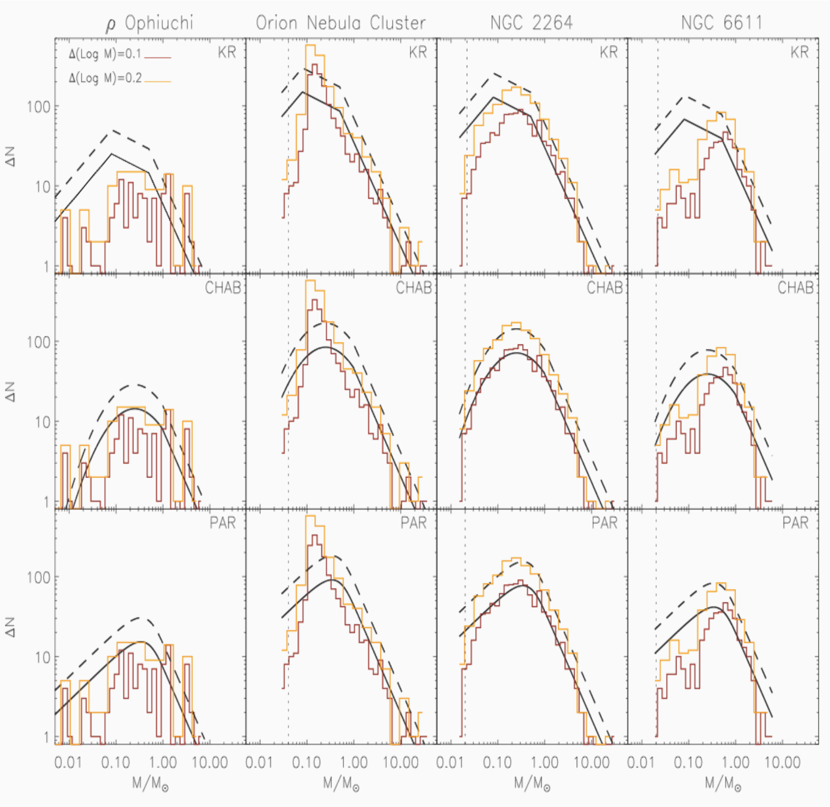
Internal regulation

⊙ **shear:** X

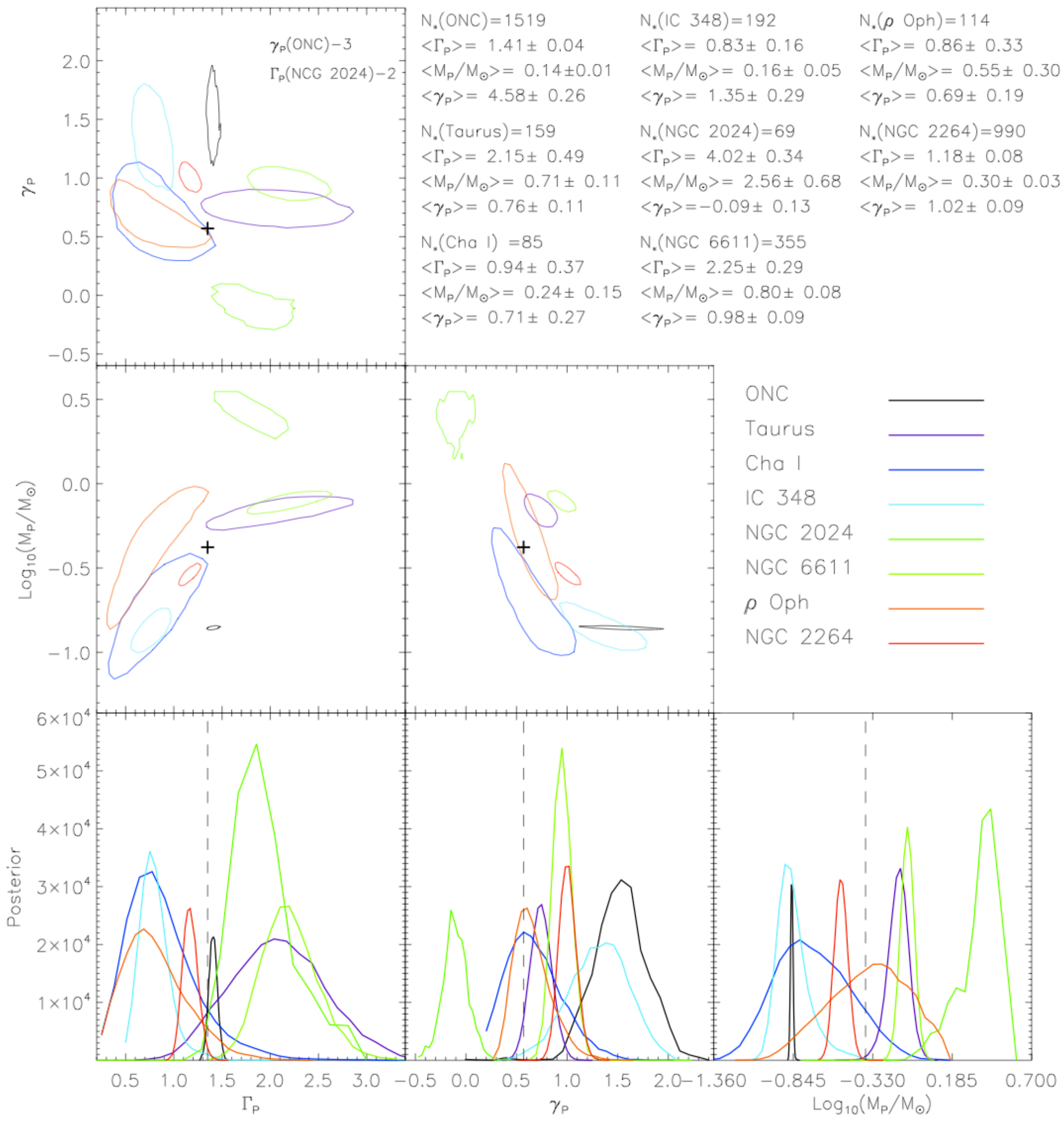
The IMF

"I'm right there in the room, and no one even acknowledges me."





The IMF



$$\psi(\log M) = A_P M^{-\Gamma_P}\left\{1-\exp\left[-\left(M/M_P\right)^{\gamma_P+\Gamma_P}\right]\right\}$$

The Early Life of Stellar Clusters: Formation and Dynamics

Copenhagen, Denmark, 3-7 November 2014

http://www.nbia.dk/nbia-clusters-2014

List of sessions

Observations of stellar clusters
The formation of stellar clusters
Dynamical evolution of stellar clusters
Impact of feedback on cluster formation and evolution
Numerical modeling of star cluster formation and dynamical evolution

Organisers

- Sami Dib (NBIA & StarPlan)
- Paolo Padoan (ICC, Barcelona)
- Simon Portegies Zwart (Leiden)
- Susanne Pfalzner (MPIfR, Bonn)
- Barbara Ercolano (USM, Munich)
- Inti Pelupessy (Leiden)
- Seyit Höçük (Groningen)
- Troels Haugbølle (StarPlan & NBI)

MARIE CURIE ACTIONS

The Niels Bohr International Academy

THE DANISH COUNCIL FOR INDEPENDENT RESEARCH
Sapere Aude

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