Formation of massive stars: a review

Patrick Hennebelle

Thanks to: Benoît Commerçon, Marc Joos, Andrea Ciardi

Gilles Chabrier, Romain Teyssier

How massive stars form ?

-Can we form massive stars in spite of the radiative pressure ?
  - -1D: grain solution
  - -2D: flashlight solution
  - -3D: radiative instability solution
  - -collision model

-Can we prevent the gas to fragment in many objects ?
  - -isothermal
  - -radiative feedback
  - -magnetized non-radiative
  - -radiative and magnetized

-Where the gas is coming from ?
  - -competitive accretion
  - -gravitational well based theory
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Thermal Support

Consider a cloud of initial radius R

If γ<4/3, when R decreases, Etherm/Egrav decreases:
=> heating/cooling processes

$$\frac{E_{therm}}{E_{grav}} = \frac{PV}{GM^2/R} \propto \rho^{\gamma} R^4 \propto R^{4-3\gamma}$$

Centrifugal Support and Angular Momentum Conservation

When R decreases, Erot/Egrav increases:
=>(magnetic) braking process

$$j = R^2 \omega(t) = R_0{}^2 \omega_0$$

$$\frac{E_{rot}}{E_{grav}} = \frac{MR^2\omega^2}{GM^2/R} \propto \frac{1}{R}$$

Magnetic Support and Flux Conservation

$$\phi \propto BR^2$$

When R decreases, Emag/Egrav is constant:
Typically one infers $\mu = (M/\phi)/(M/\phi)_c = 1\text{-}4$
(Crutcher et al. 1999, 2004)

$$\frac{E_{mag}}{E_{grav}} = \frac{B^2R^3}{M^2/R} \propto (\phi/M)^2$$

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The Issue of Radiative Pressure

The coupling occurs through the coupling of the radiation to the dust
=> Treating well the radiative transfer and the micro-physics

Larson & Starrfield 1971 (Kahn 1974) :

\+ Collapse conditions =>
Radiation Pressure / Dynamical Pressure = 1

$$\Rightarrow \frac{L/4\pi r^2 c}{\rho u^2} \approx 1$$

$$+ u^2 = 2GM/r \Rightarrow \frac{L/4\pi r^2 c}{\rho u^2} \approx 1.3\times 10^{-11} \frac{L/L_S}{(M/M_S)^{1/2}} r^{1/2}$$

\+ the radius where grains vaporize corresponds to => T=1500 K

\+ Estimate of T using simple radiative transfer

=>Radiative Pressure / Dynamical Pressure = $2\times 10^{-5} \frac{(L/L_S)^{6/5}}{(M/M_S)^{3/5}}$

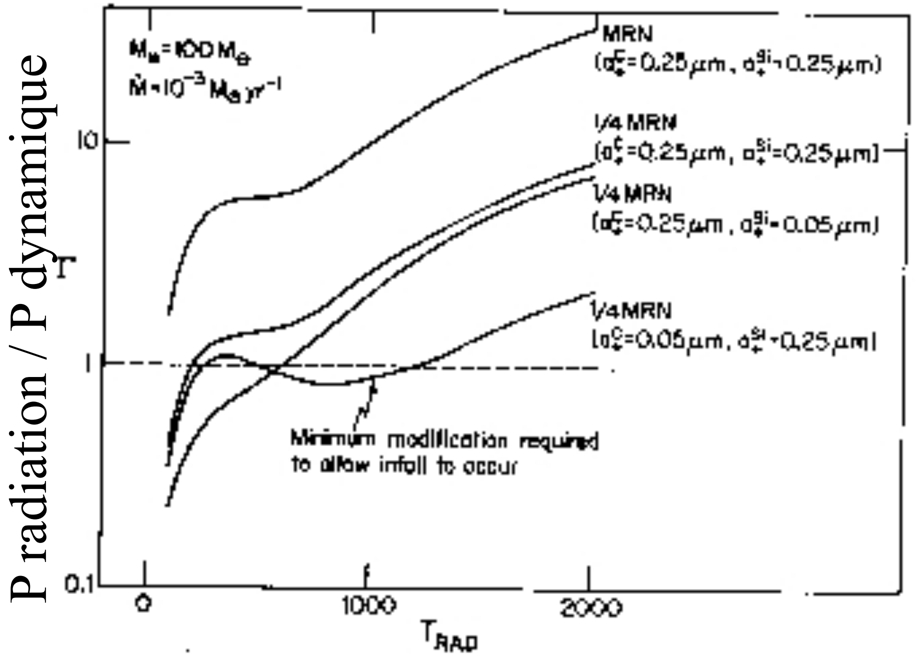
leads to M~20 M$_s$

Wolfire and Cassinelli (1985):

-assume a constant accretion rate of $10^{-3}M_s$/an

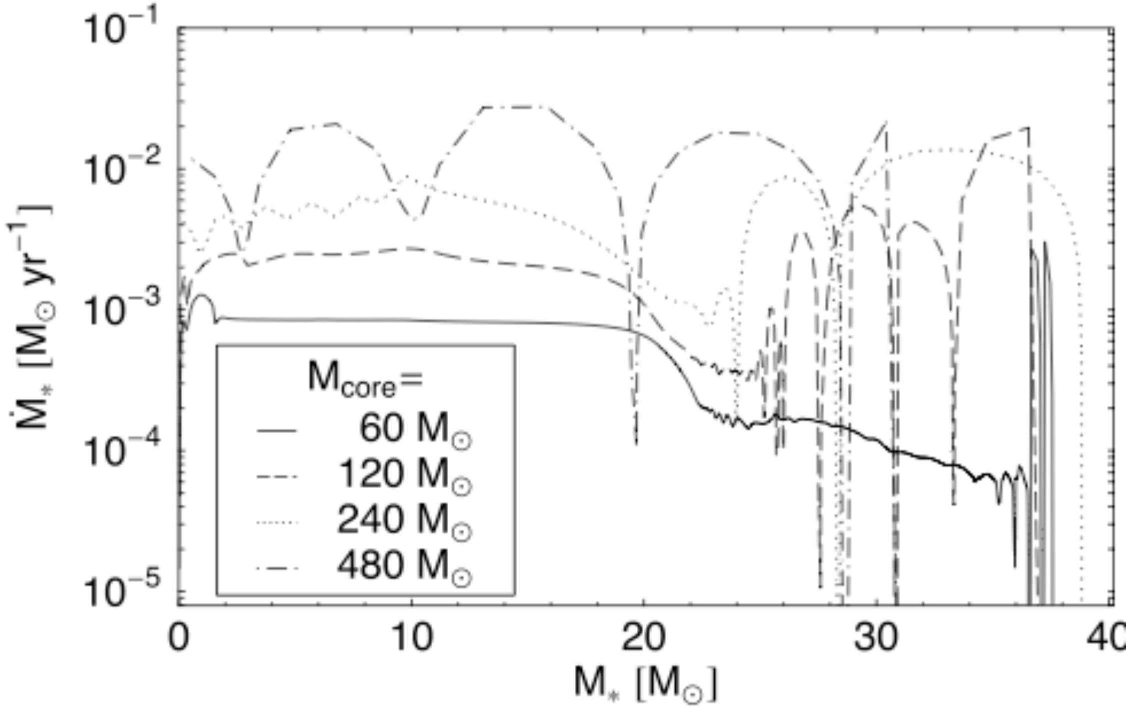
-consider a classical (Matthis et al. 1977) grains distribution

-explore the influence of a grain deficit



A 100 Ms stars cannot form with a standard grain abundance (1/4 is required)

Solution:
weak abundance of grains



1D results by Kuiper et al. (2010)

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The Multi-D approach

(e.g. Yorke & Sonnhalter 2002, Krumholz et al. 2009, Kuiper et al. 2010)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla P - \rho \nabla \phi,$$

$$\frac{\partial (\rho e)}{\partial t} + \nabla \cdot [(\rho e + P)\mathbf{v}] = \rho \mathbf{v} \nabla \phi - \kappa_R \rho (4\pi B - cE),$$

$$\nabla^2 \phi = 4\pi G \left[\rho + \sum_n m_n \delta(\mathbf{x} - \mathbf{x}_n) \right],$$

$$\frac{\partial E}{\partial t} - \nabla \cdot \left(\frac{c\lambda}{\kappa_R \rho} \nabla E \right) = \kappa_P \rho (4\pi B - cE) + \sum_n L_n W(\mathbf{x} - \mathbf{x}_n)$$

$$L_n = \frac{G\dot{M}M}{R} + L_*$$

$$\kappa_R = 0.1 + 4.4(T_g/350)\ \mathrm{cm}^2\ \mathrm{g}^{-1},$$

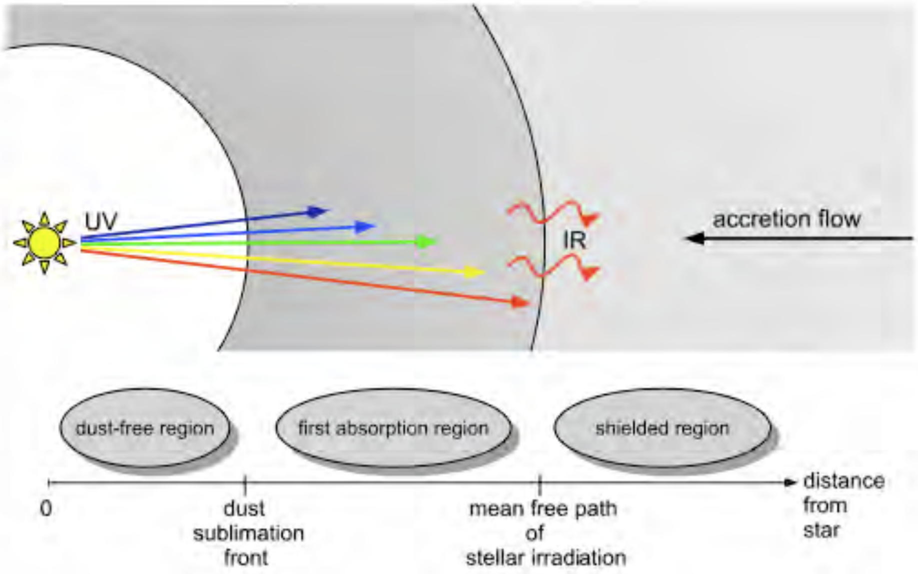
$$\kappa_P = 0.3 + 7.0(T_g/375)\ \mathrm{cm}^2\ \mathrm{g}^{-1}.$$

Flux limited diffusion method:

-implicit methods : expensive

-usually assume grey-body except Yorke & Sonnhalter who do multi-frequency

-Kuiper et al. use an hydrib scheme, treating FLD as grey but also include the direct illumination from central stars (multi-wavelength)



2D results by Yorke & Sonnhalter (2002)

Solution of the radiative pressure problem:
the anisotropy due to the disk, ***The flashlight effect***
(Yorke & Bodenheimer 99)

-due to centrifugal force, matter piles up in the equatorial plan

-bigger optical depth in the equatorial plan than along the pole

-the photons escape in this direction and the radiative pressure is reduced

Yorke & Sonnhalter
(2D, 64 wavelengths)

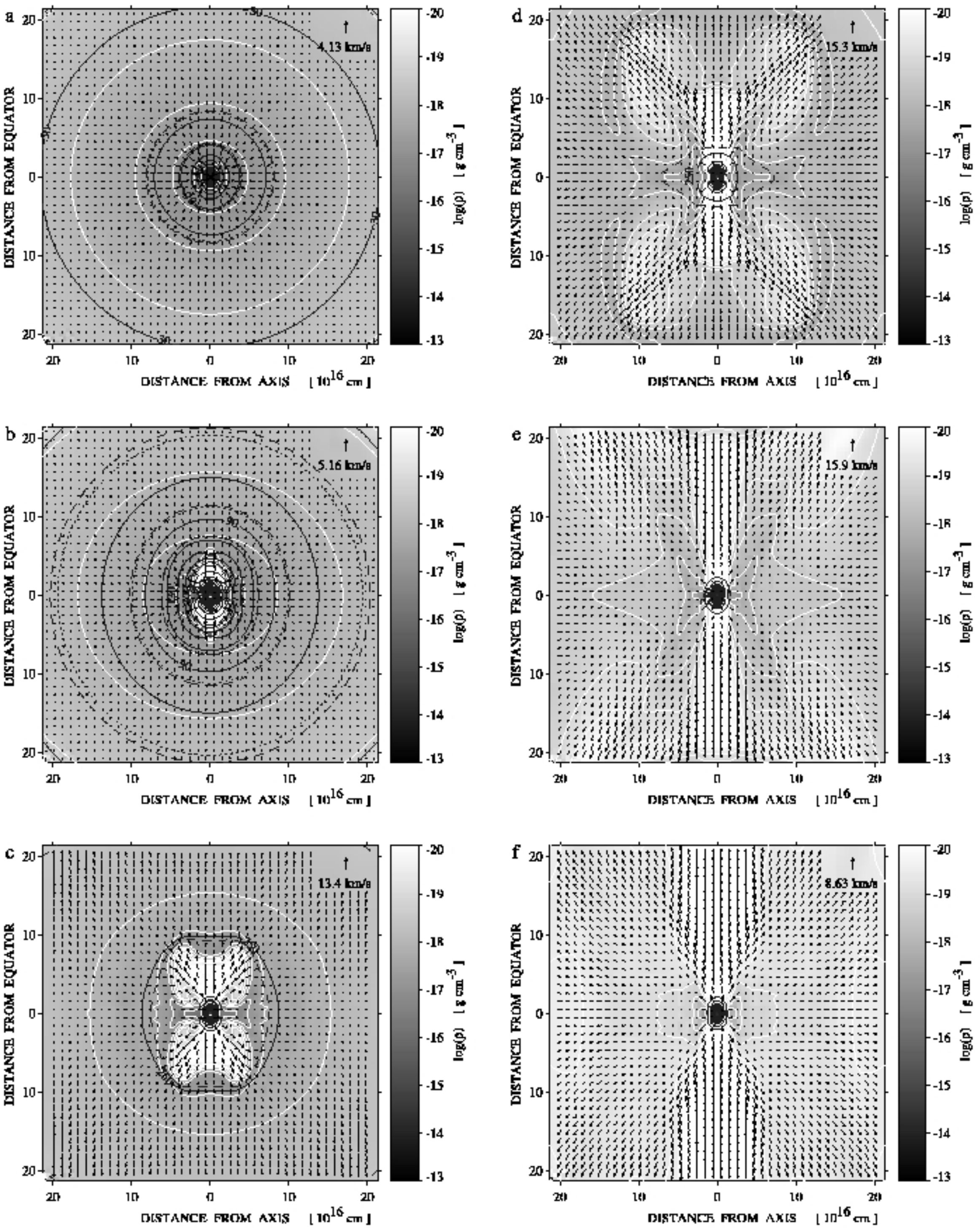
+collapse nearly spherical

+flattening in the equatorial plan

+formation of outflows along the pole

+eventually expansion even along the equatorial plan

Formation of 33 Ms star
(total mass 60).



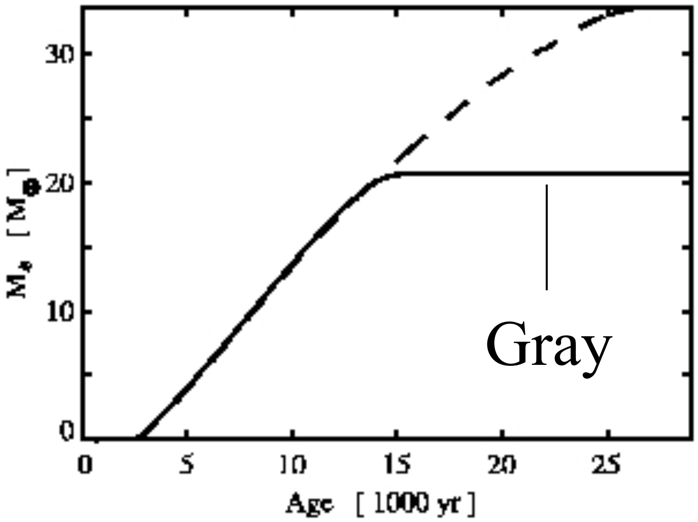
Yorke & Sonnhalter

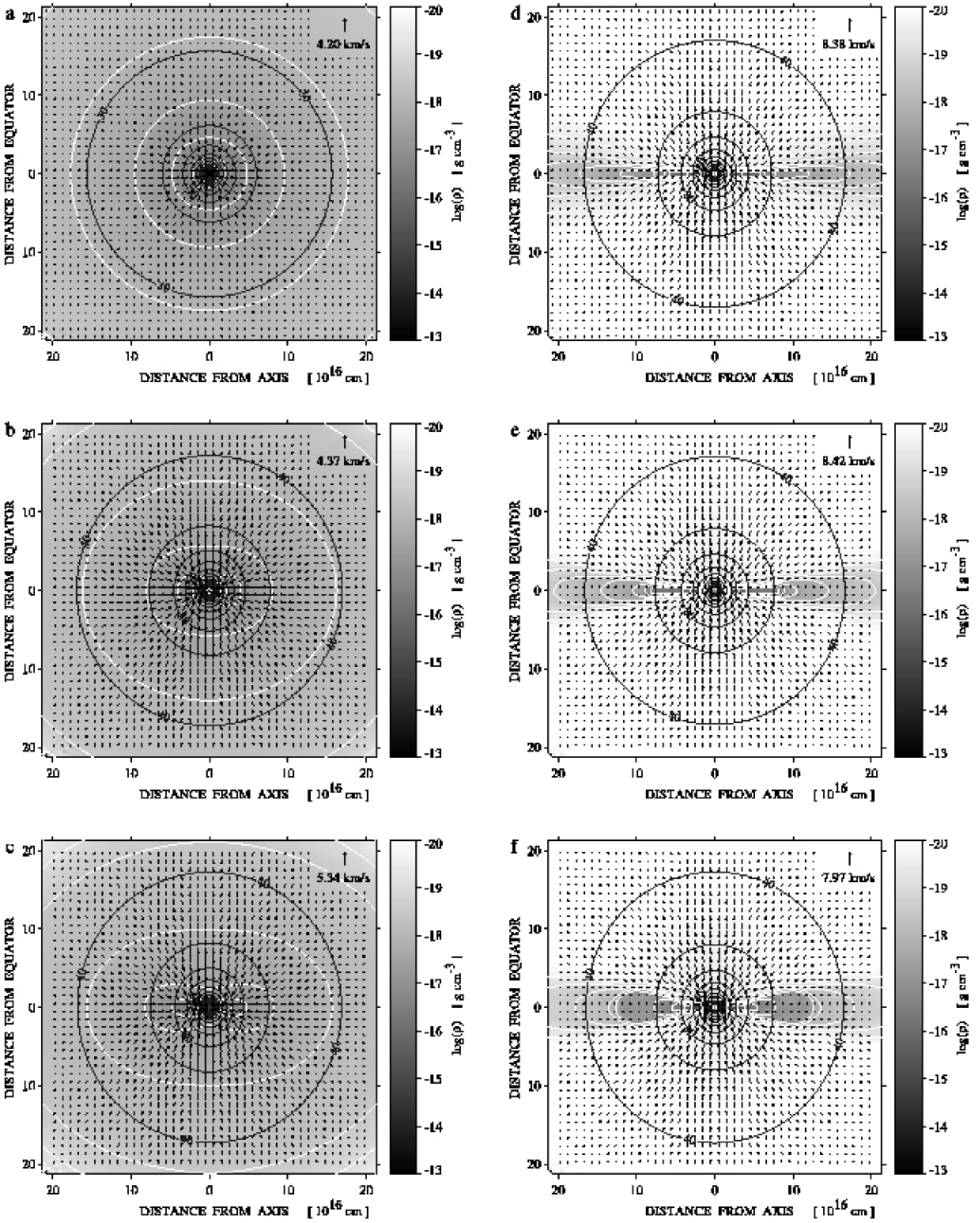
Identical but grey treatment

Important differences :

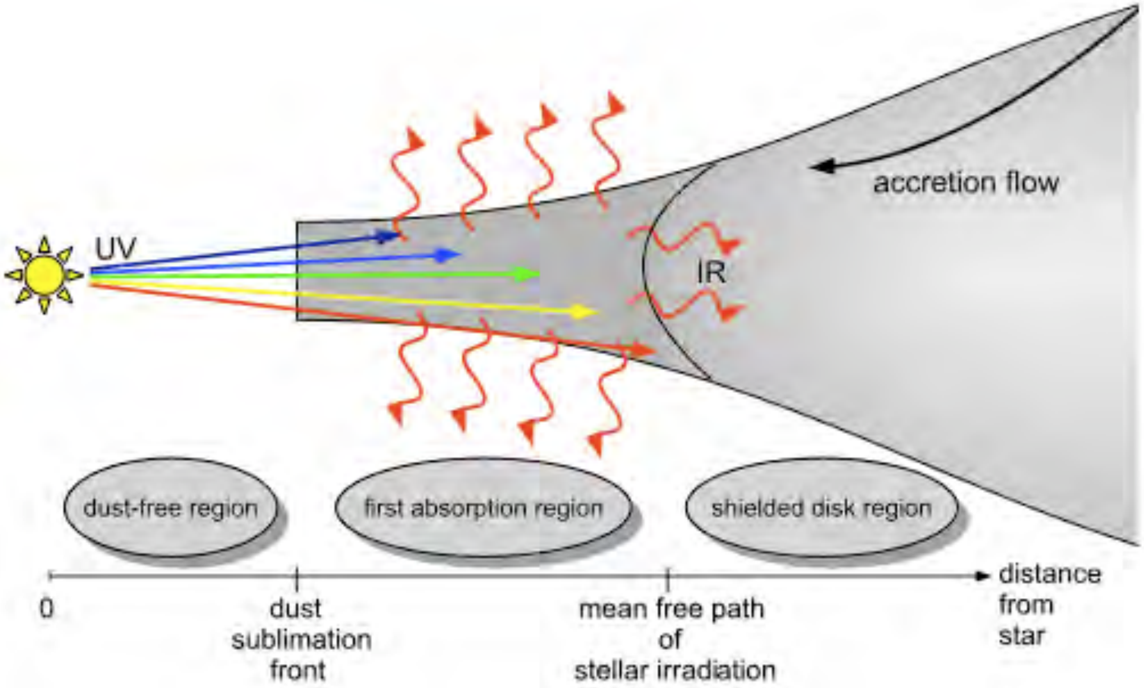
-no outflow

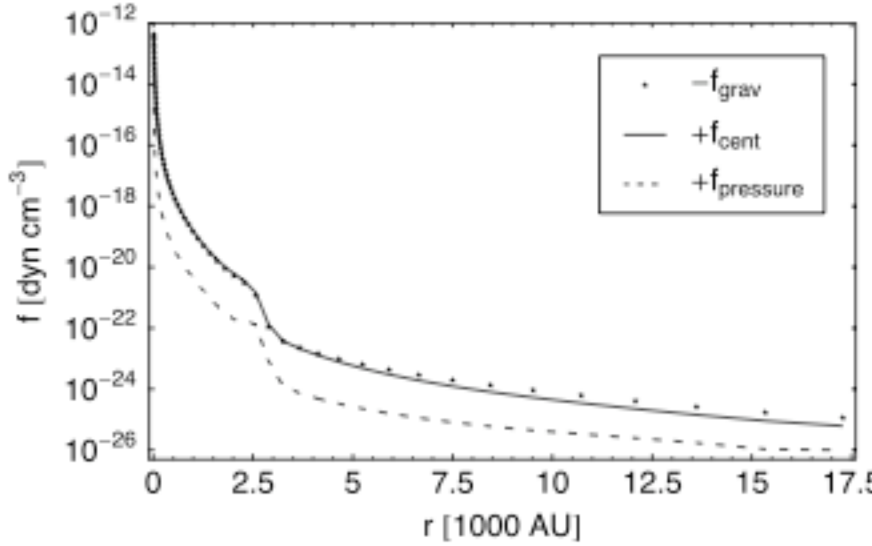
-Final Mass : 20 Ms
(total mass 60 Ms).

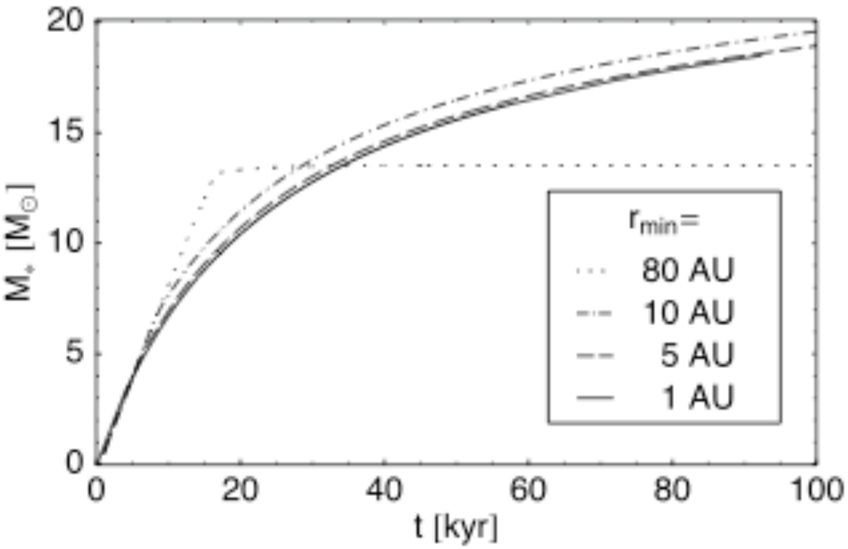


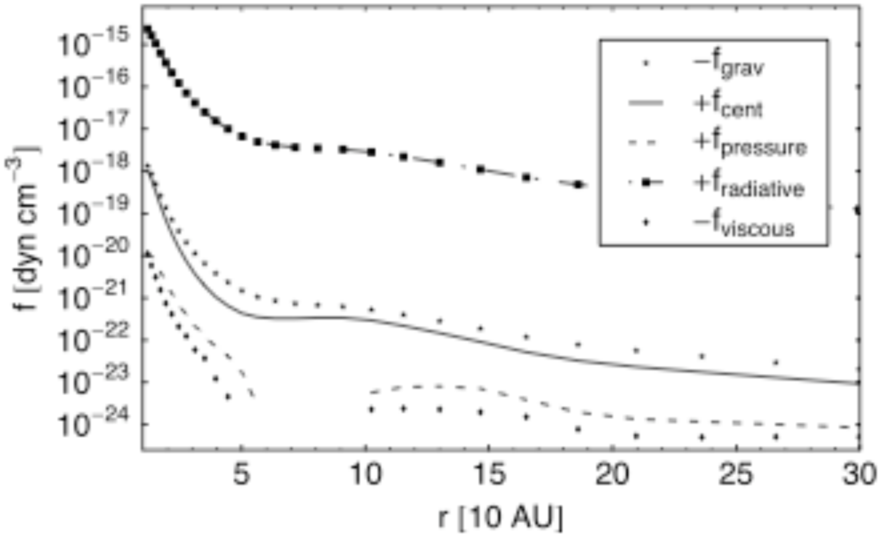


Results of Kuiper et al. 2010
Importance of solving the dust free regions
(otherwise the radiation is too isotropic and this stops the Flashlight effect)









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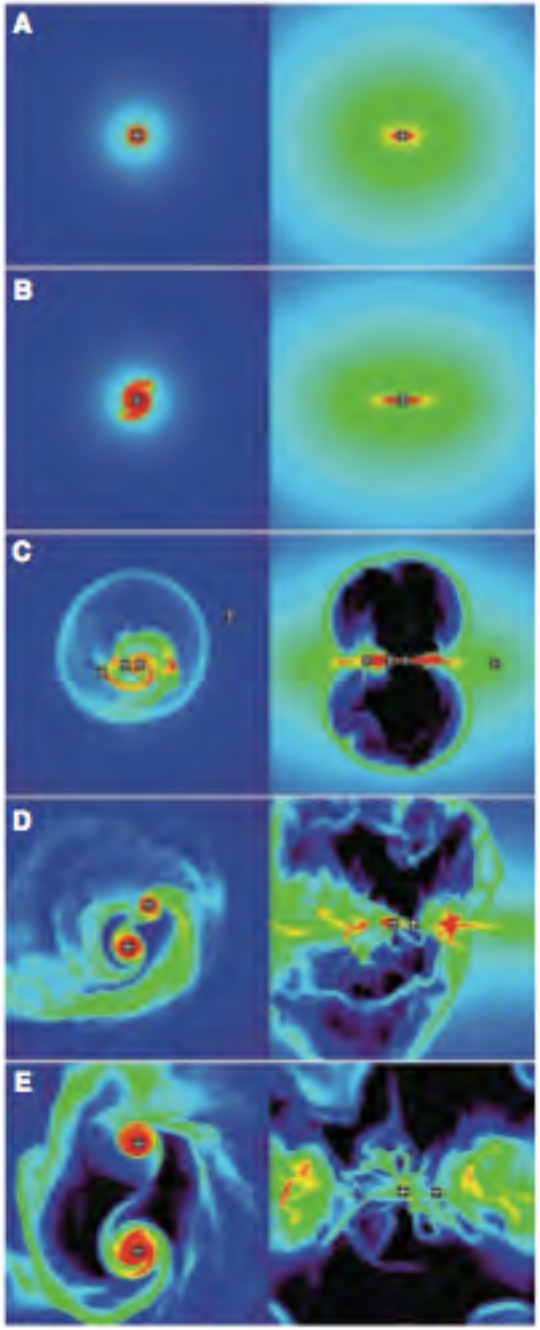
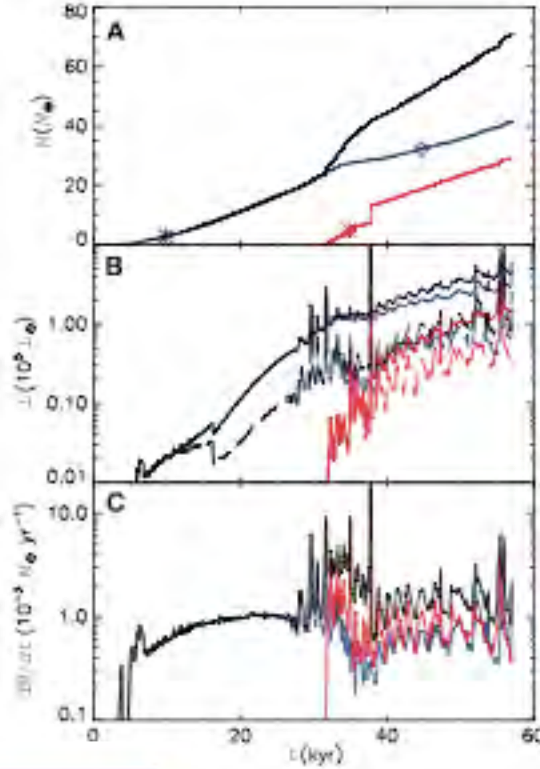
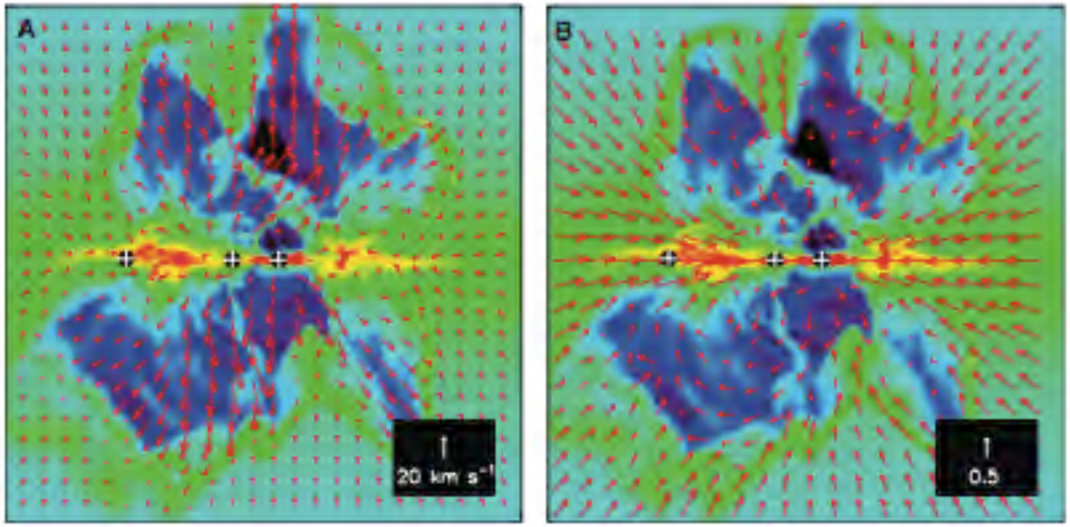
3D results by Krumholz et al. 2009
The cavity becomes unstable to Rayleigh-Taylor instability and more gas is accreted



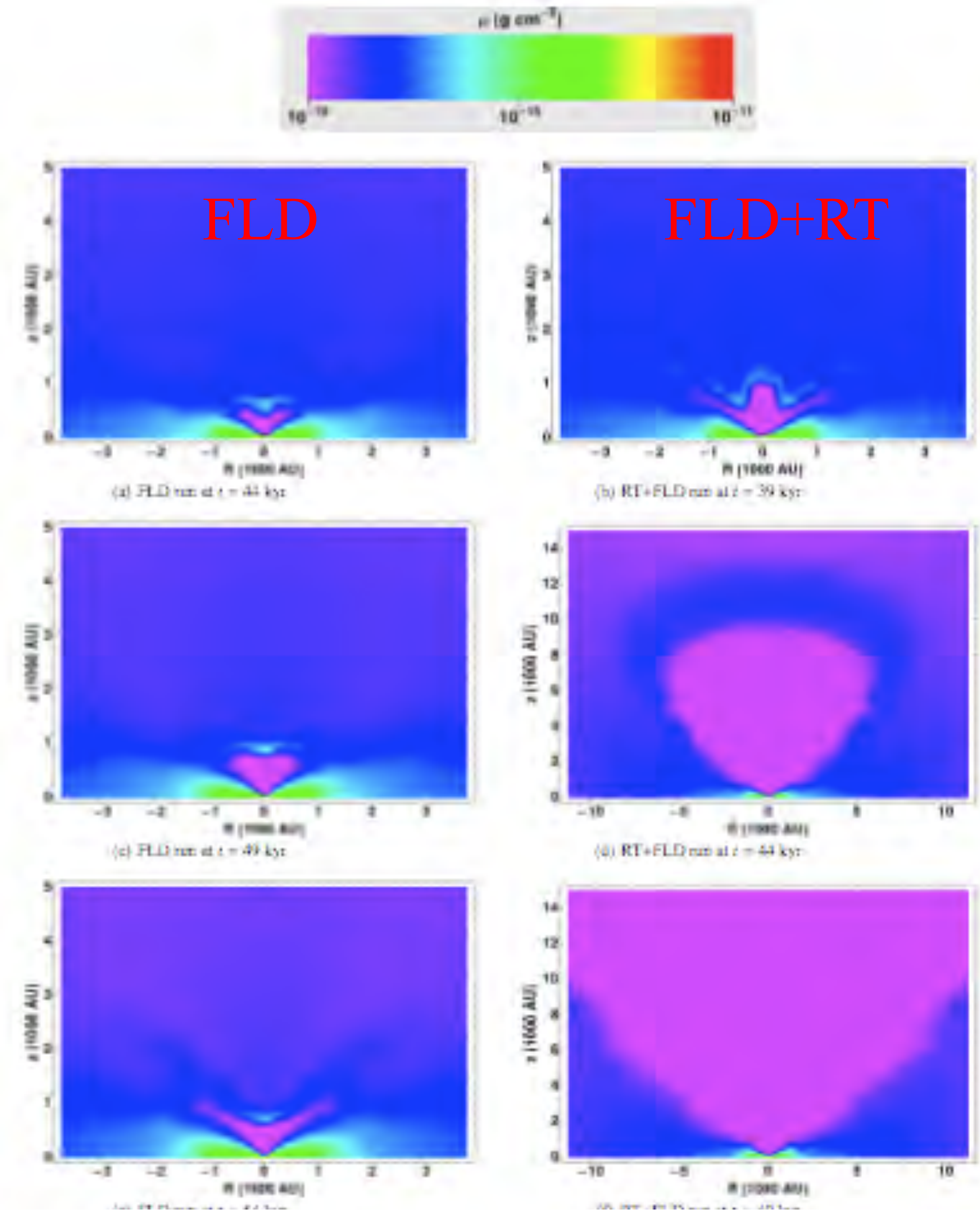




Results of Kuiper et al. 2011

The instability of the cavity is due to the FLD scheme

The hydrid scheme (FLD+ray tracing) leads to higher radiative pressure and no instability

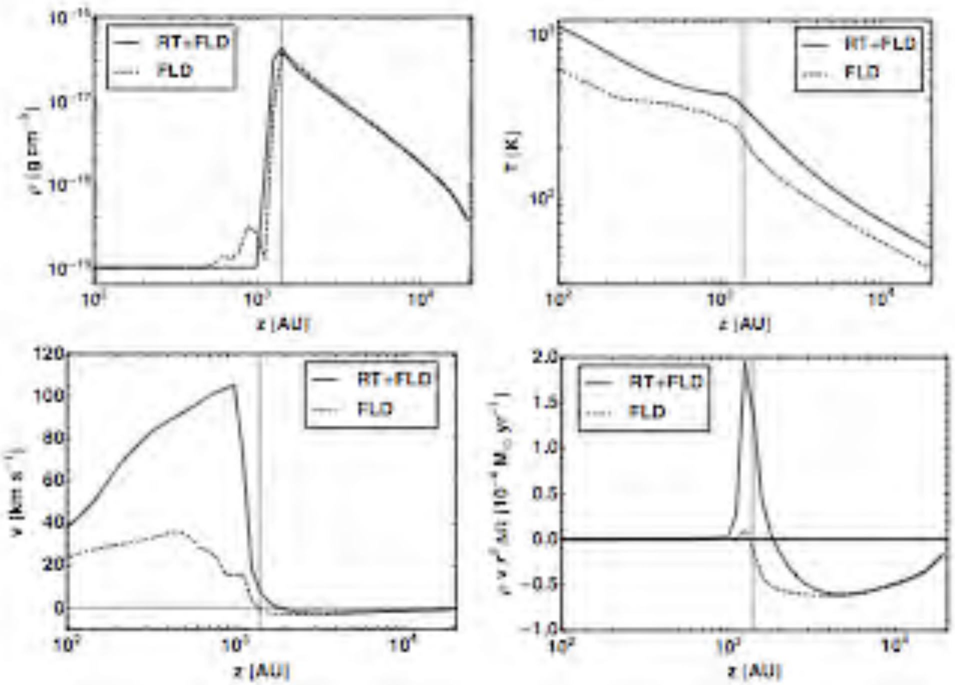


(a) FLD run at t = 44 kyr

(b) RT+FLD run at t = 39 kyr

(c) FLD run at t = 49 kyr

(d) RT+FLD run at t = 44 kyr



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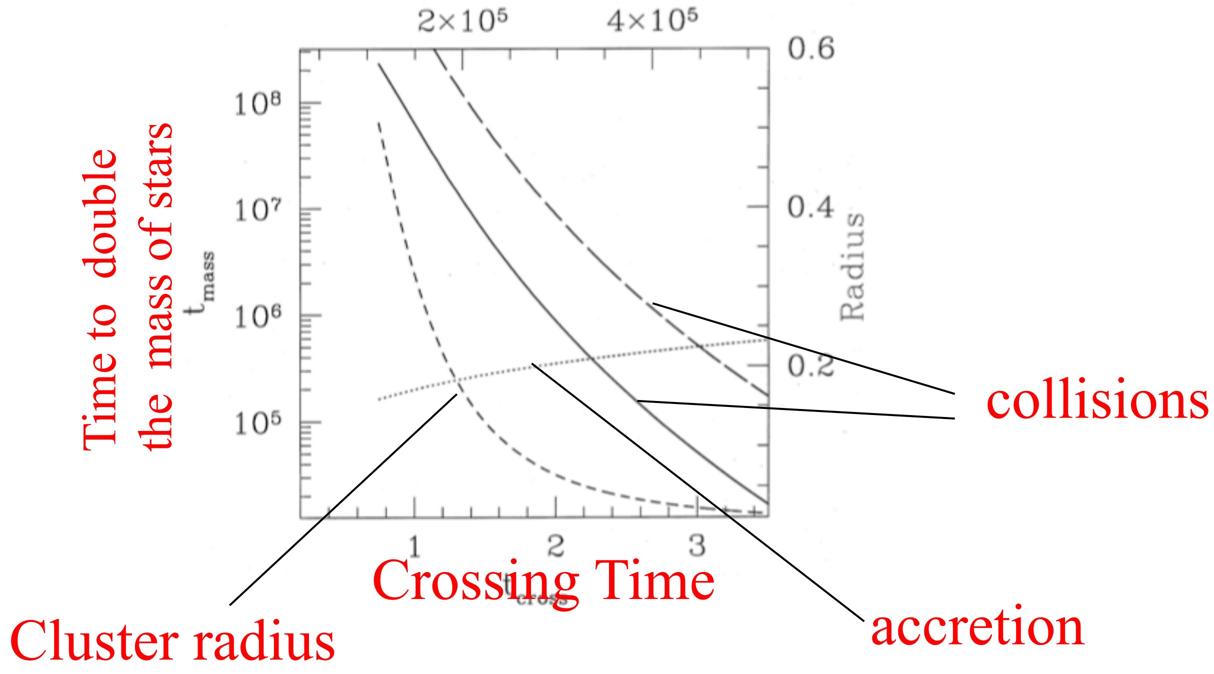
The collision model

Alternative Scenario (Bonnell et al. 98, 02, 04):
Formation of massive stars by « merging » of low mass stars

The radiative pressure has no influence on the collisions between stars

Bonnell et al. 98 develop a Toy model that takes into account accretion, merging by collision and cluster dynamics.



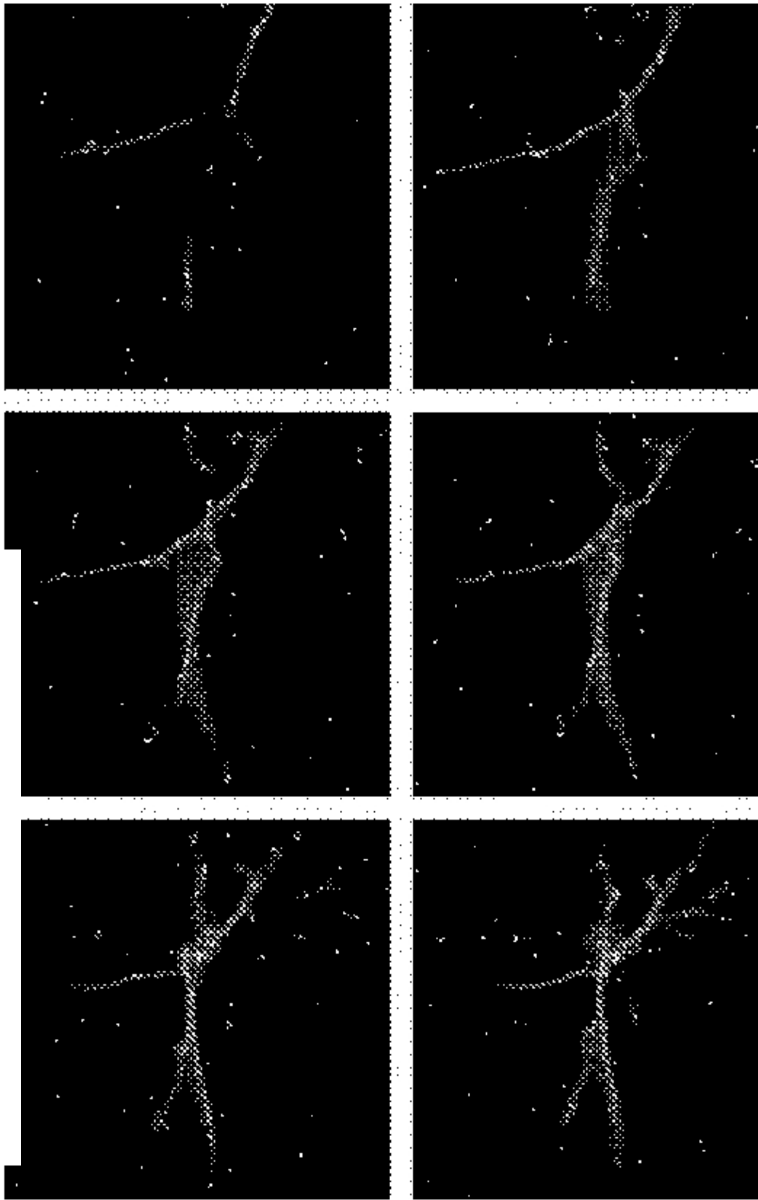
=>efficiency requiered 10^8 stars/pc^2

Estimate using direct simulations

(Bonnell & Bate 02,05)

SPH with 1,000,000 of particules, use sink particles

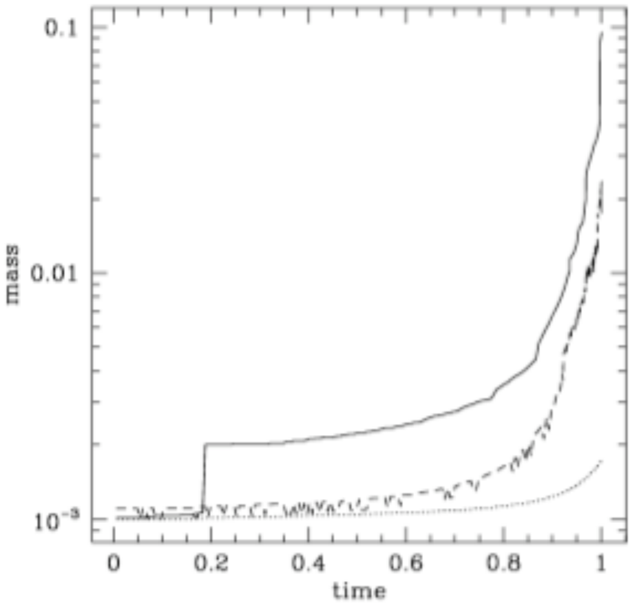
Possible to merge the sinks (distance threshold)



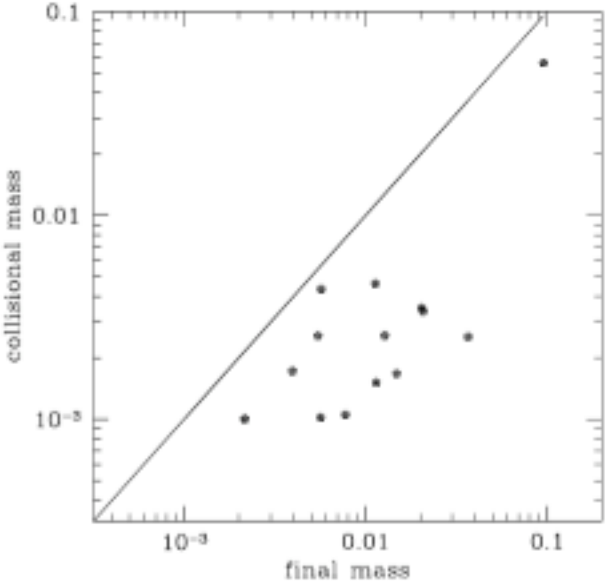
+Mass of most massive stars

+Mean mass in the cluster core

+Mean mass



Mass due to collisions as a function of the final mass



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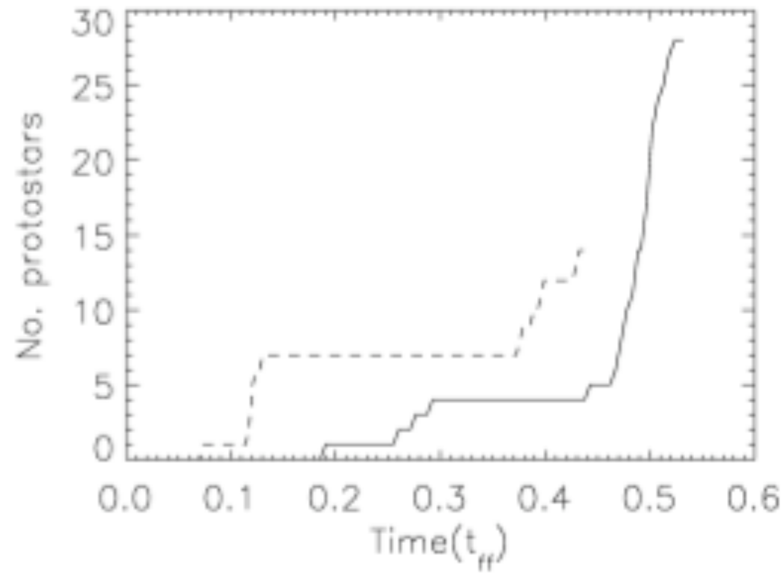
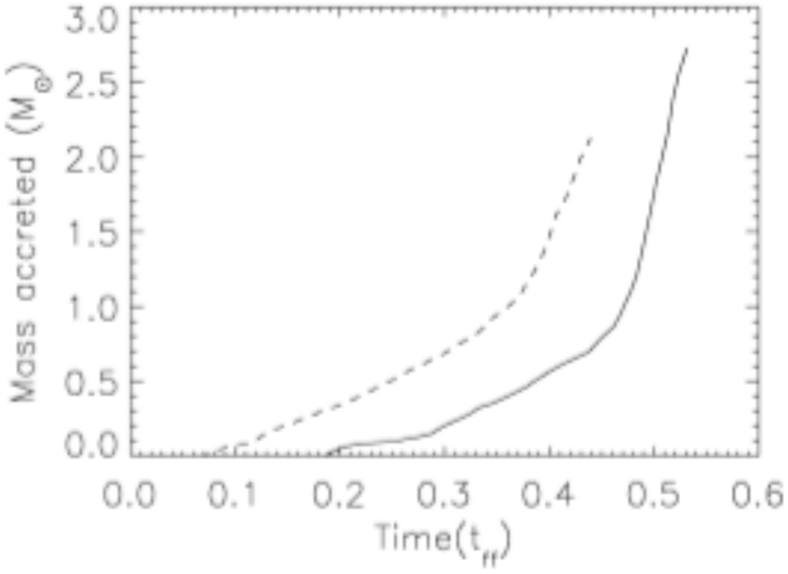
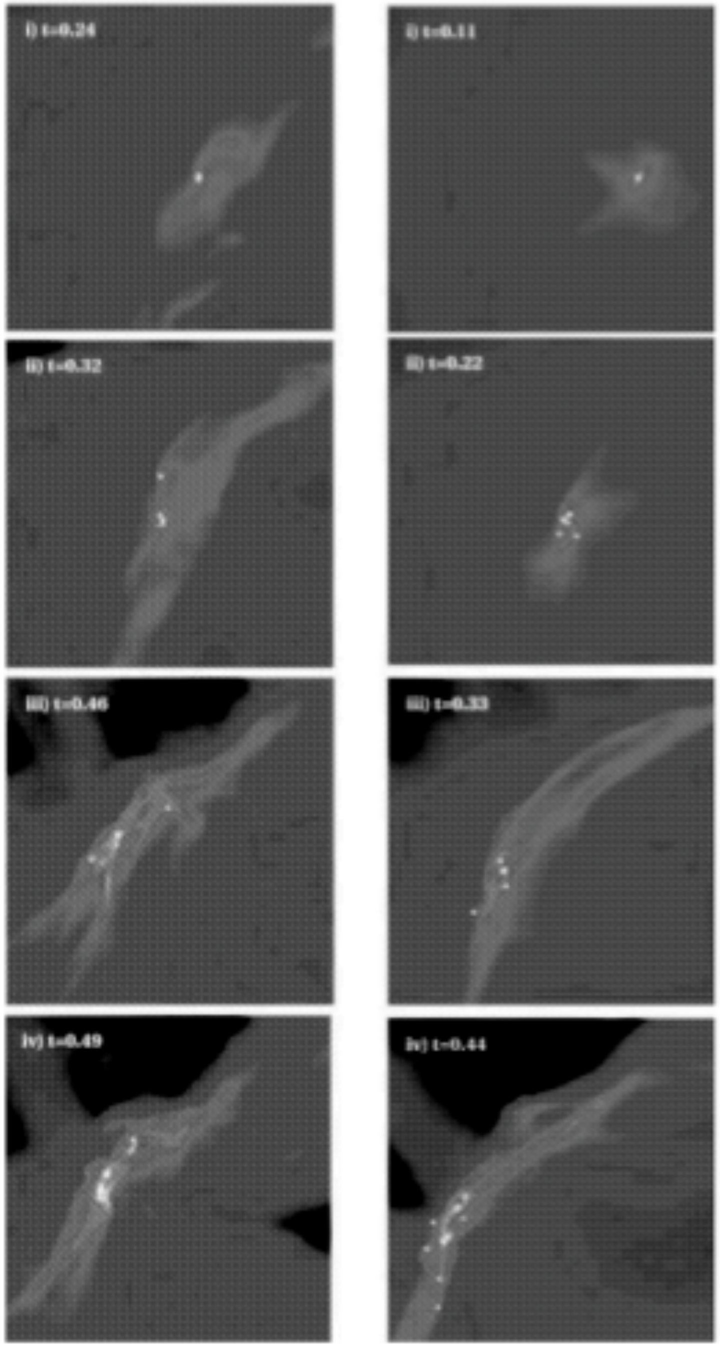
Fragmentation of a collapsing unmagnetized isothermal Massive core (Dobbs et al. 2005)







The core fragments in many objects therefore limiting the mass of stars.

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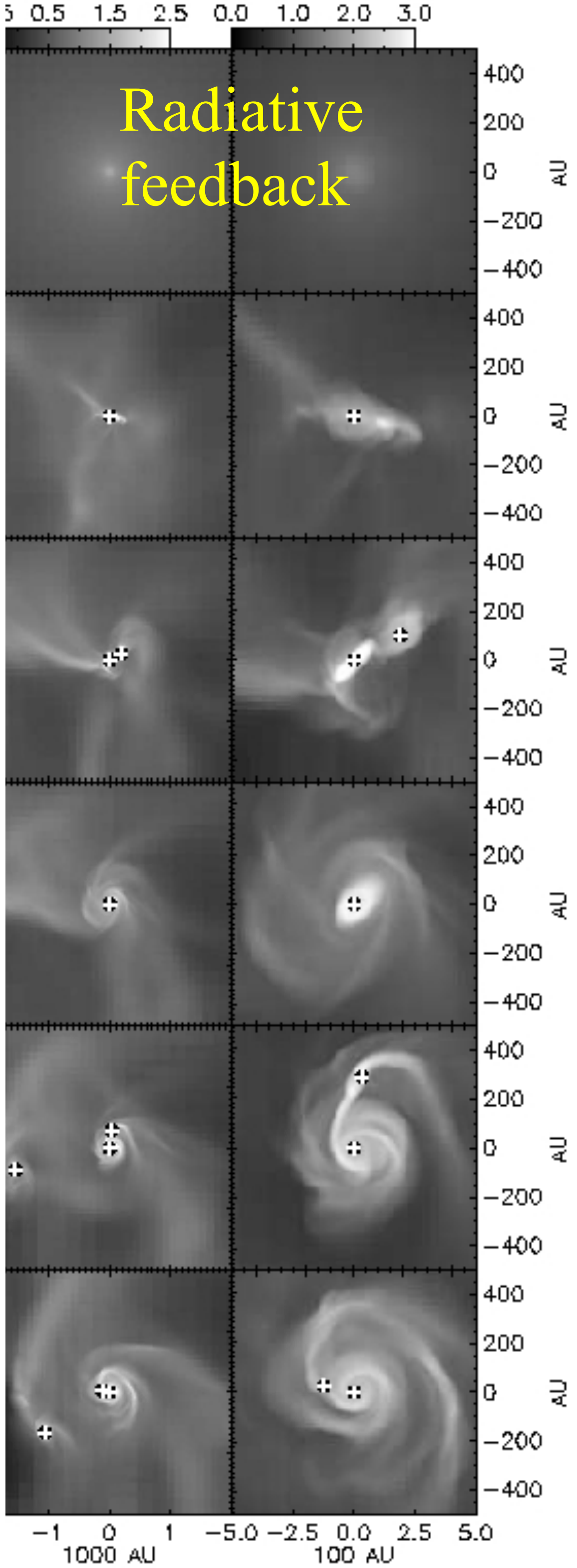
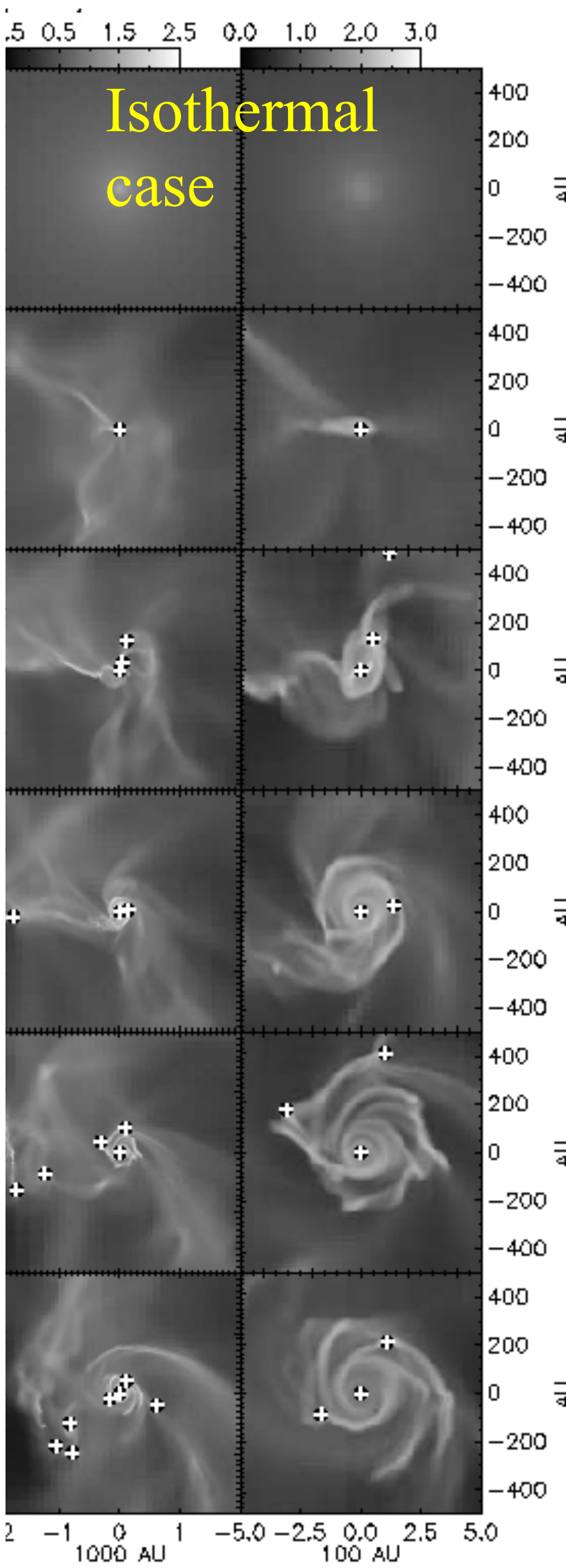
Influence of the radiative feedback on a massive core

Krumholz et al. 2007



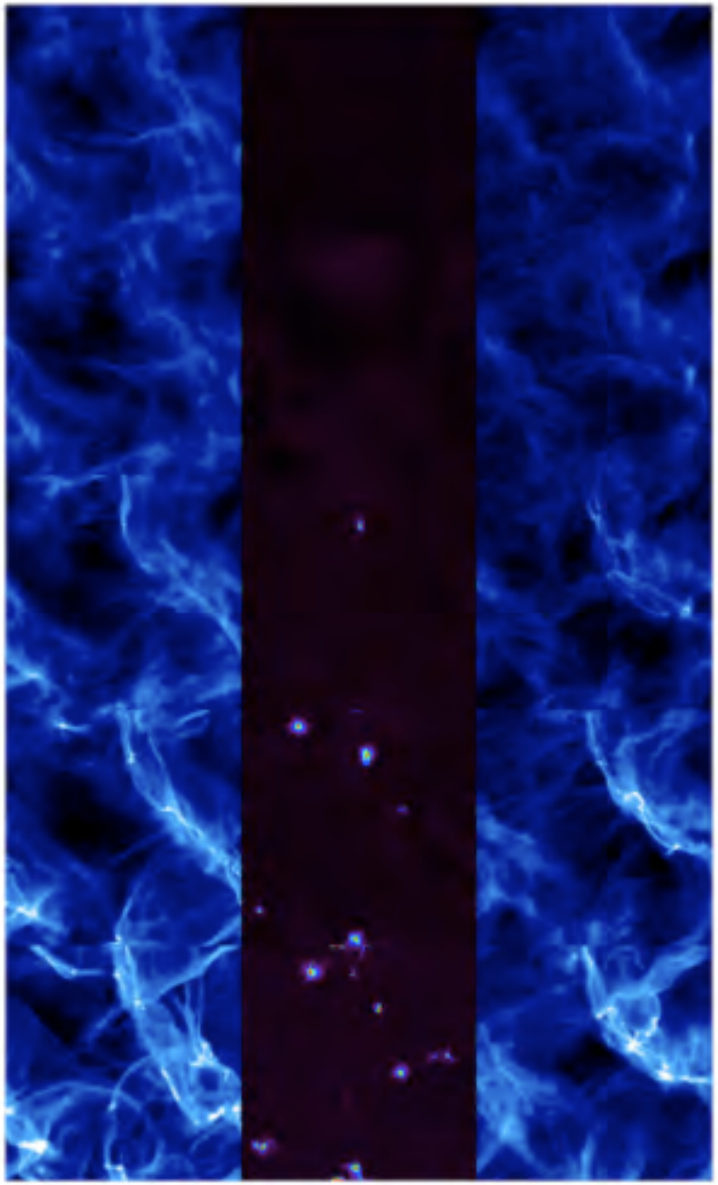
Radiative feedback reduces the number of fragments simply because it increases the temperature and increases the Jeans mass

Note however that the initial conditions are very peaked (singular isothermal sphere) and tend to prevent fragmentation Girichidis et al. 2010



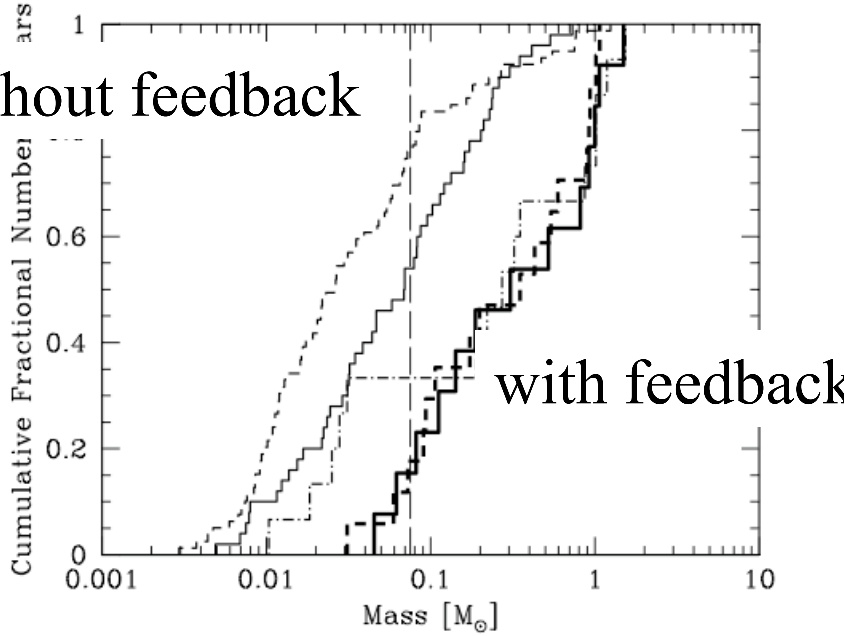
Influence of the protostellar feedback : further calculations

Bate 2009, Offner et al. 2009, Commerçon et al. 2010, Tomida et al. 2010, Krumholz et al. 2012



with feedback

Bate 2009, 2012

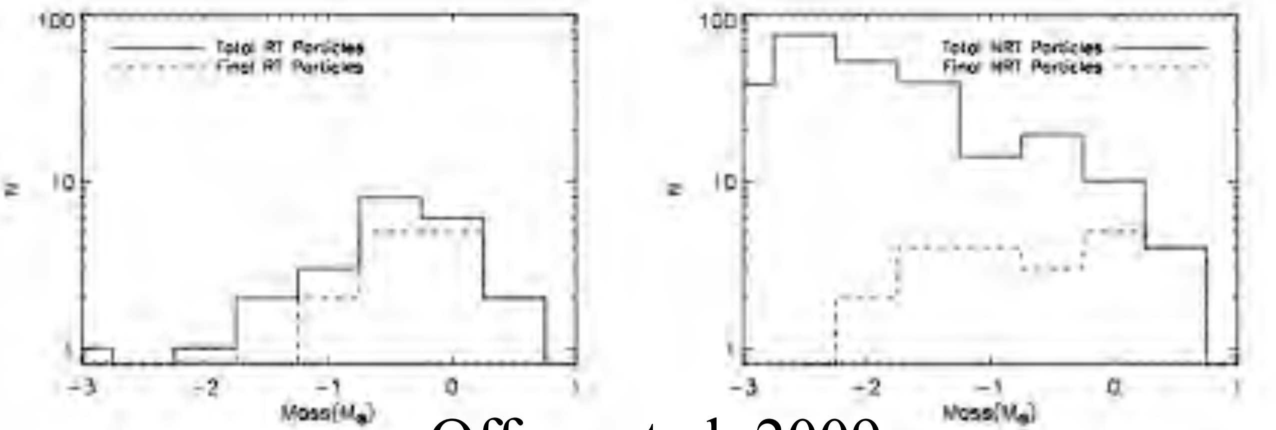


without feedback

with feedback

with feedback

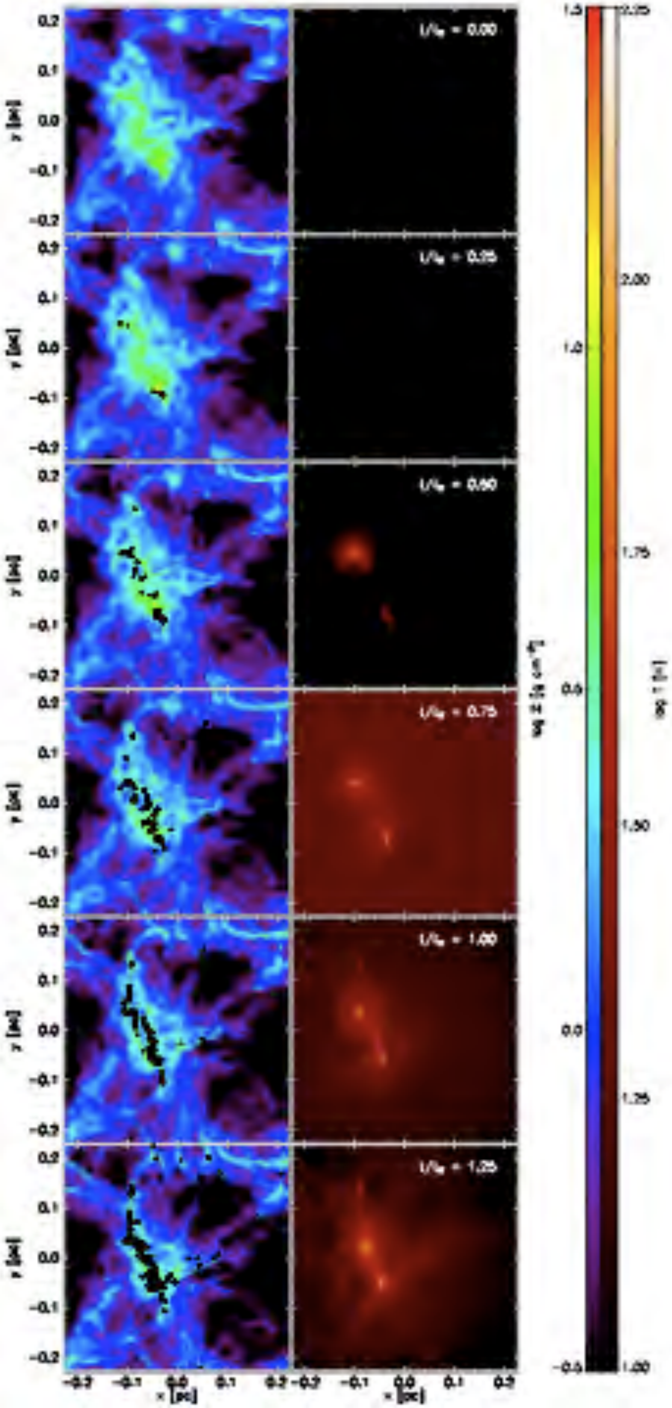
without feedback



Offner et al. 2009

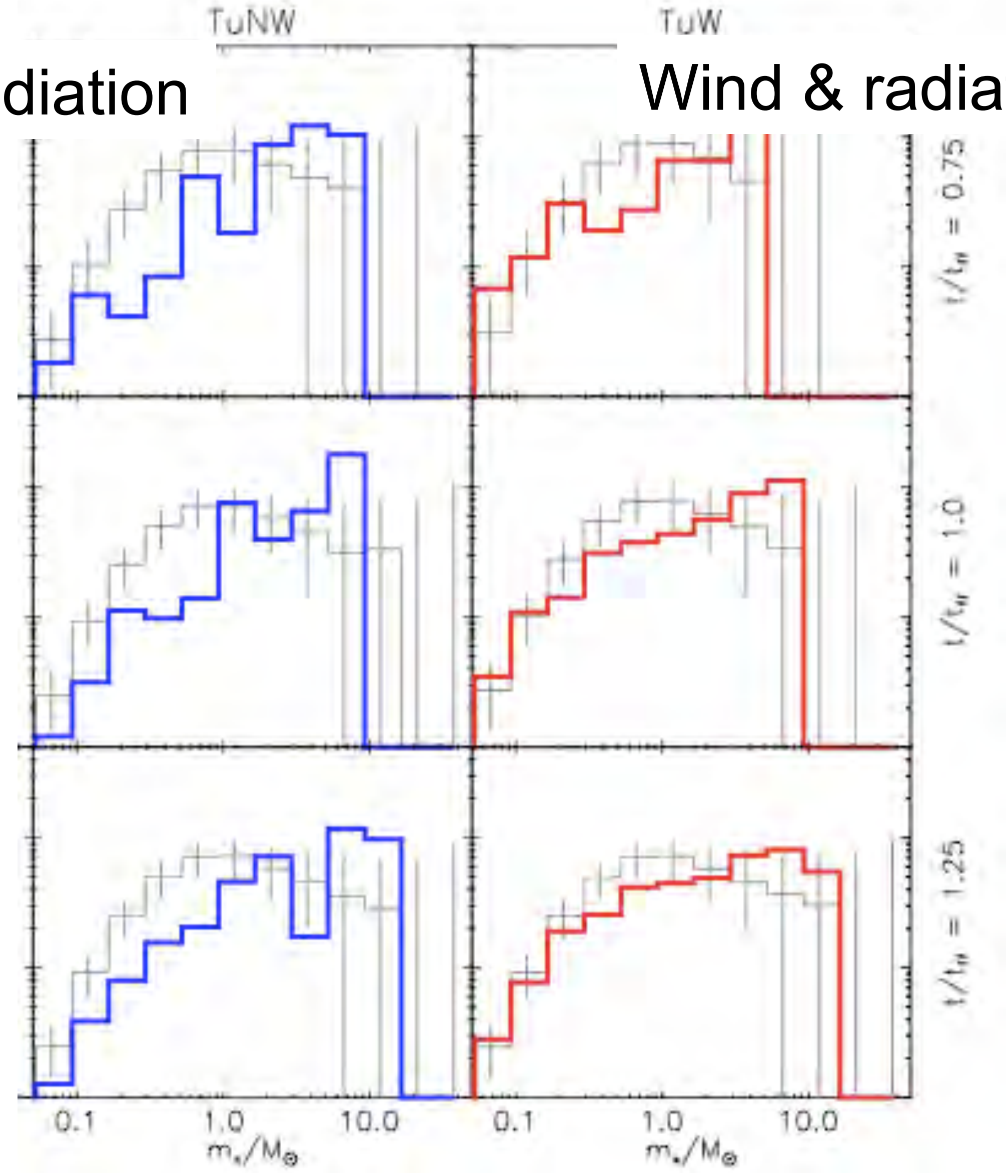
Wind and Radiative feedback

Krumholz et al. 2012



Pure radiation

Wind & radiation



=>Too few low mass objects with pure radiation, winds help to reduce feedback which escape along cavities

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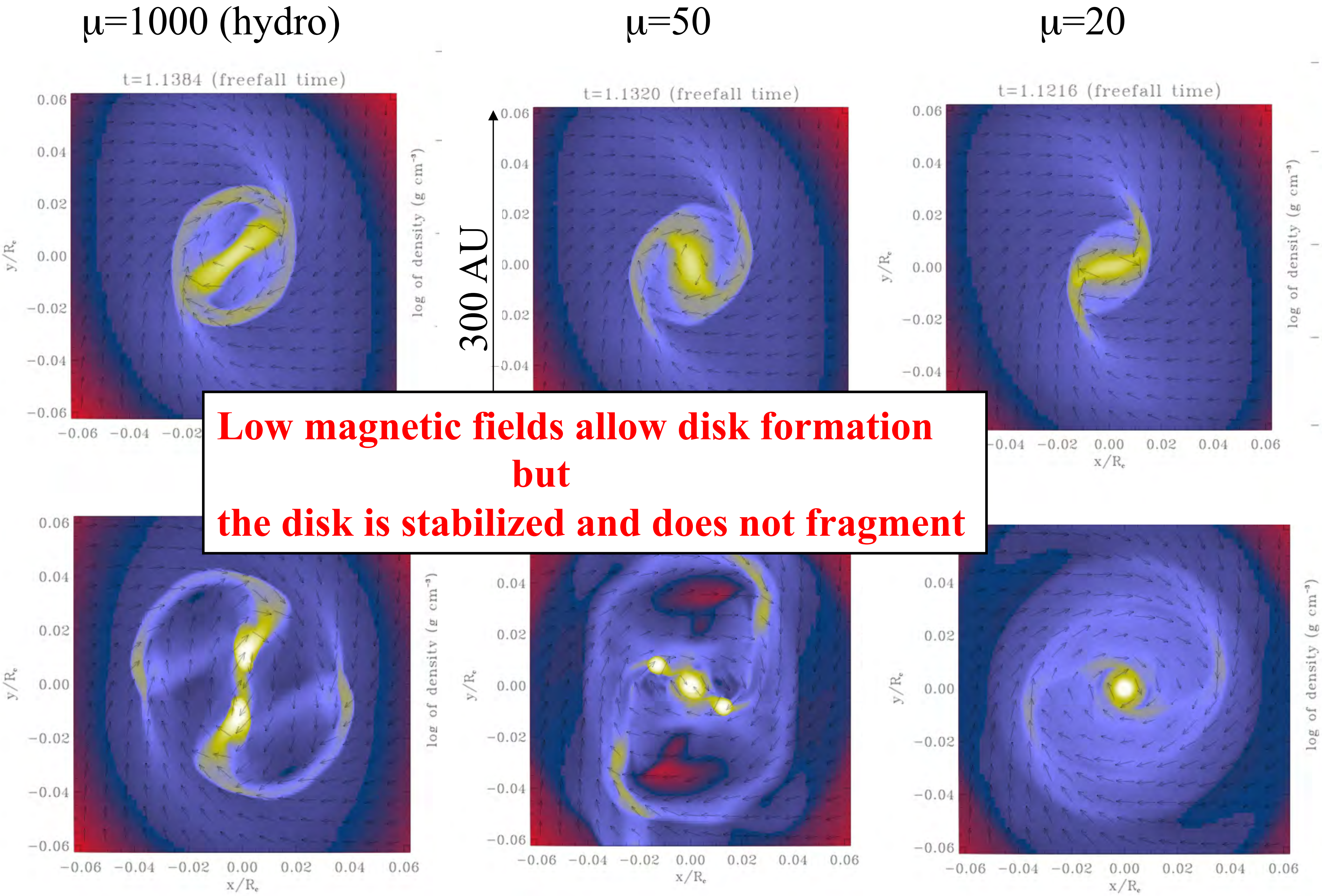
Influence of a weak magnetic field on the fragmentation of low mass core



Low magnetic fields allow disk formation
but
the disk is stabilized and does not fragment

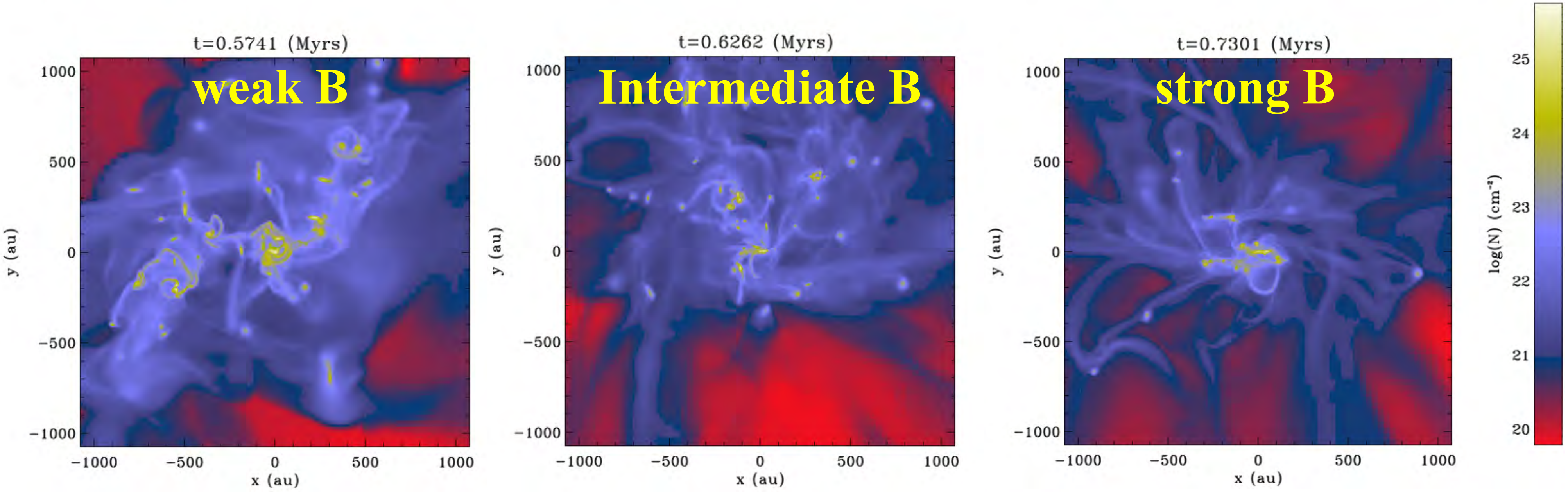
H & Teyssier 2008 (see also Machida et al. 2005)

100 $M_\odot$ magnetized, turbulent and dense barotropic core

(other related works : Peters et al. 2010, Seifried et al. 2012)

Turbulence is initially seeded. Eturb/Egrav ~20%

In the case of a massive turbulent core, magnetic field reduces, though, do not suppress fragmentation

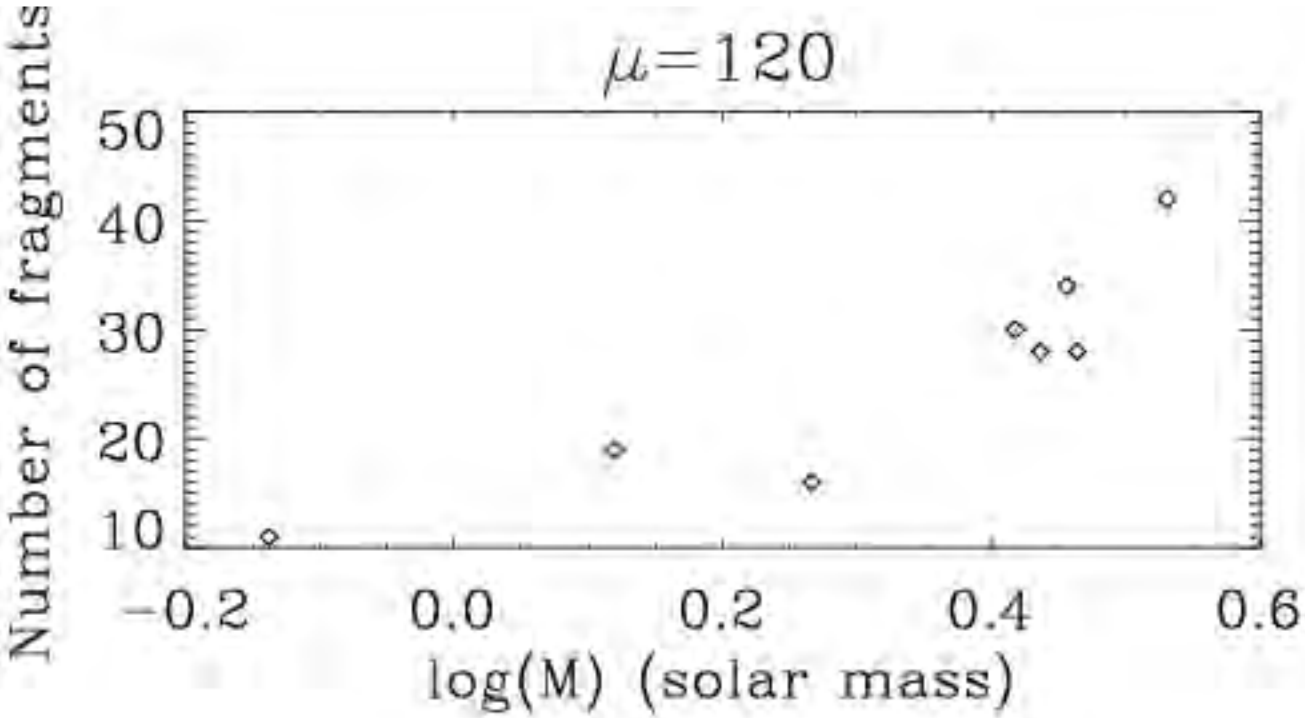


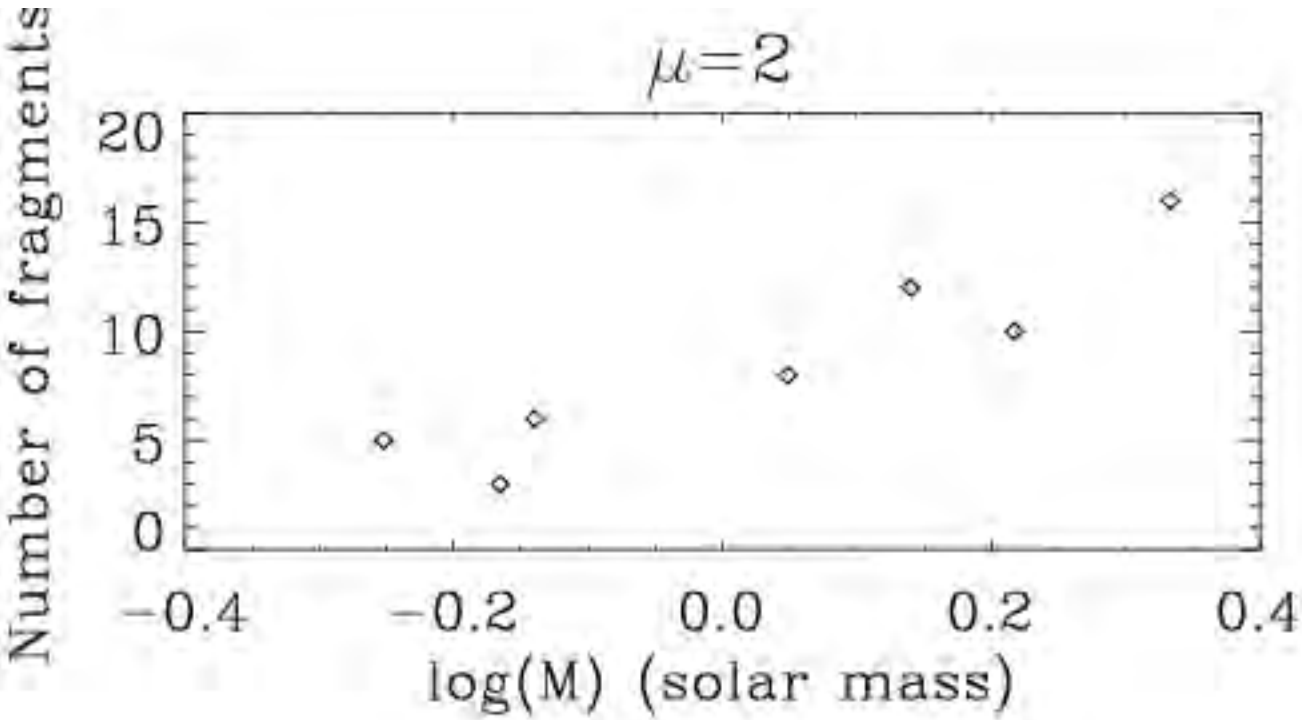
μ=120

μ=5

μ=2

H+2011


μ=120
Number of fragments
50
40
30
20
10
−0.2
0.0
0.2
0.4
0.6
log(M) (solar mass)

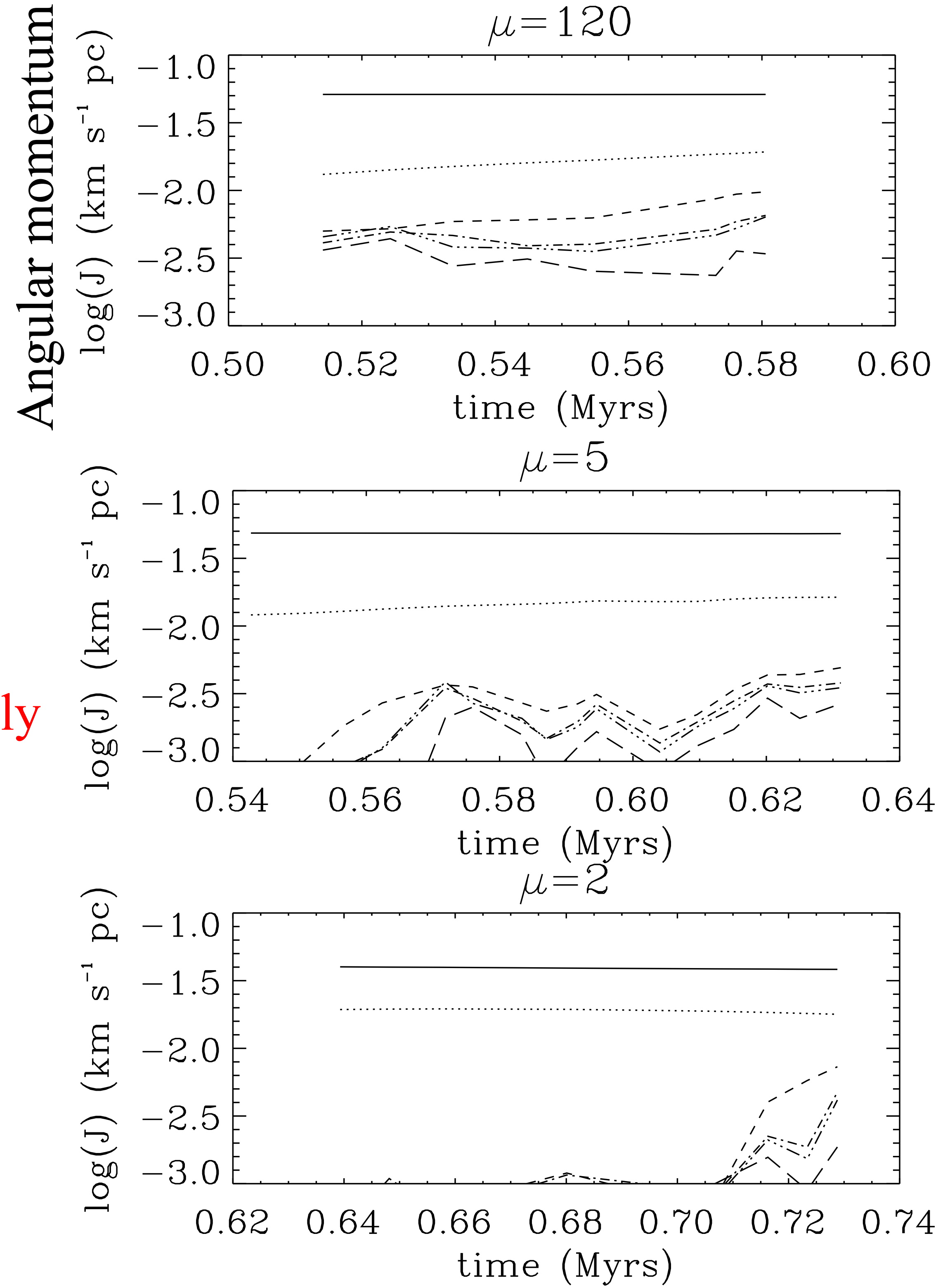

μ=2
Number of fragments
20
15
10
5
0
−0.4
−0.2
0.0
0.2
0.4
log(M) (solar mass)

Impact of the magnetic braking:

J is much reduced as B Increases

=>

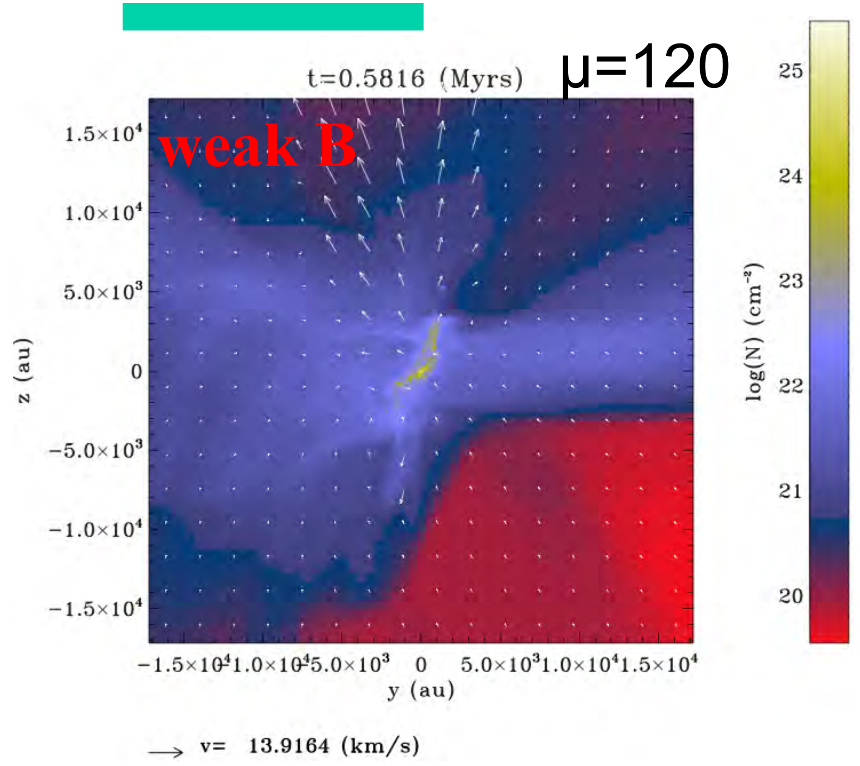
Magnetic braking is important even when the flow is significantly turbulent

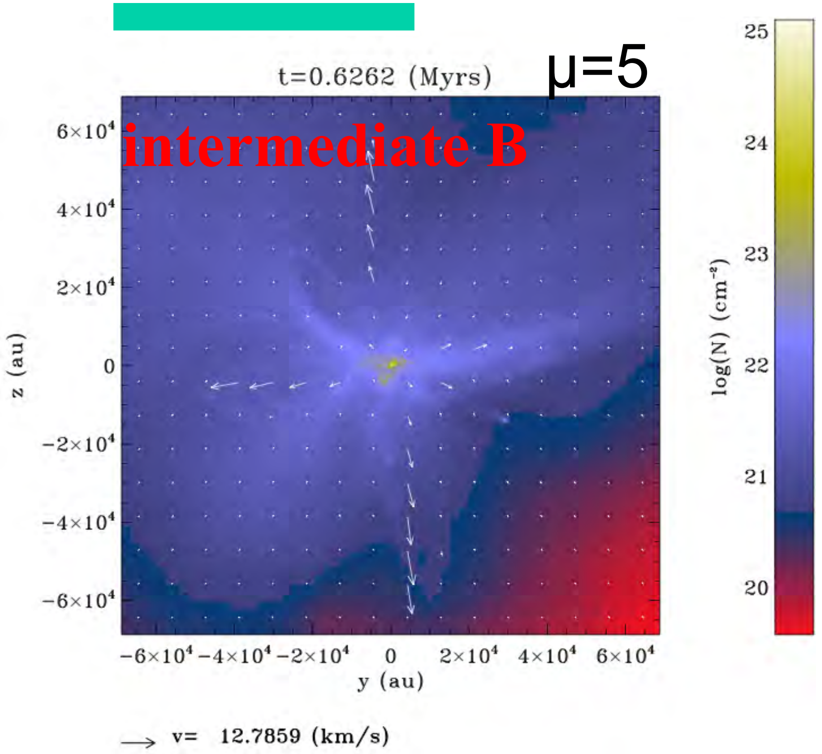


100 M⊙ magnetized, turbulent and dense barotropic core

Powerful outflows are launched even in turbulent cores

Faster flows appear with weaker fields





H et al. 2011

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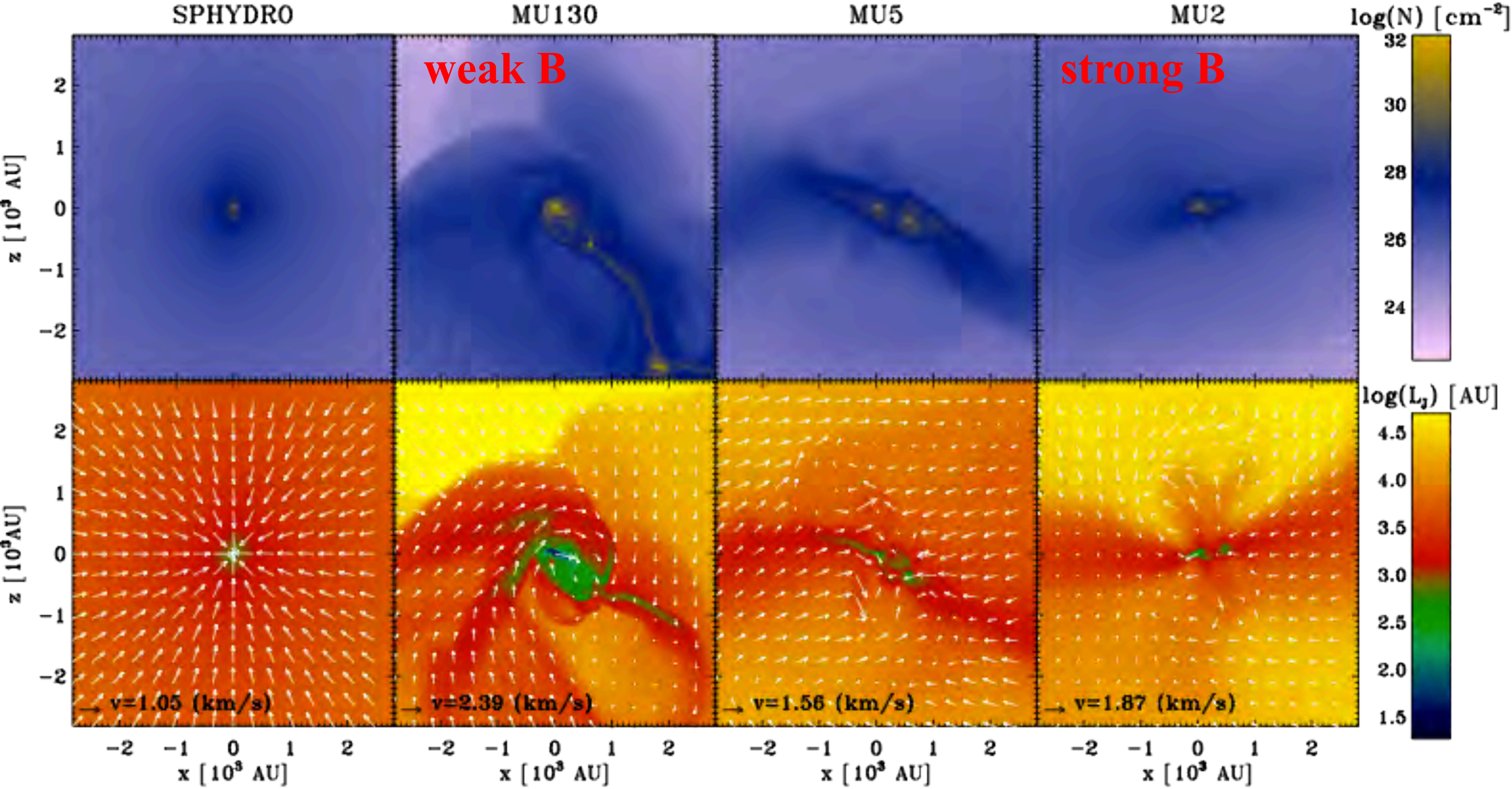
100 M⊙ turbulent dense core collapse

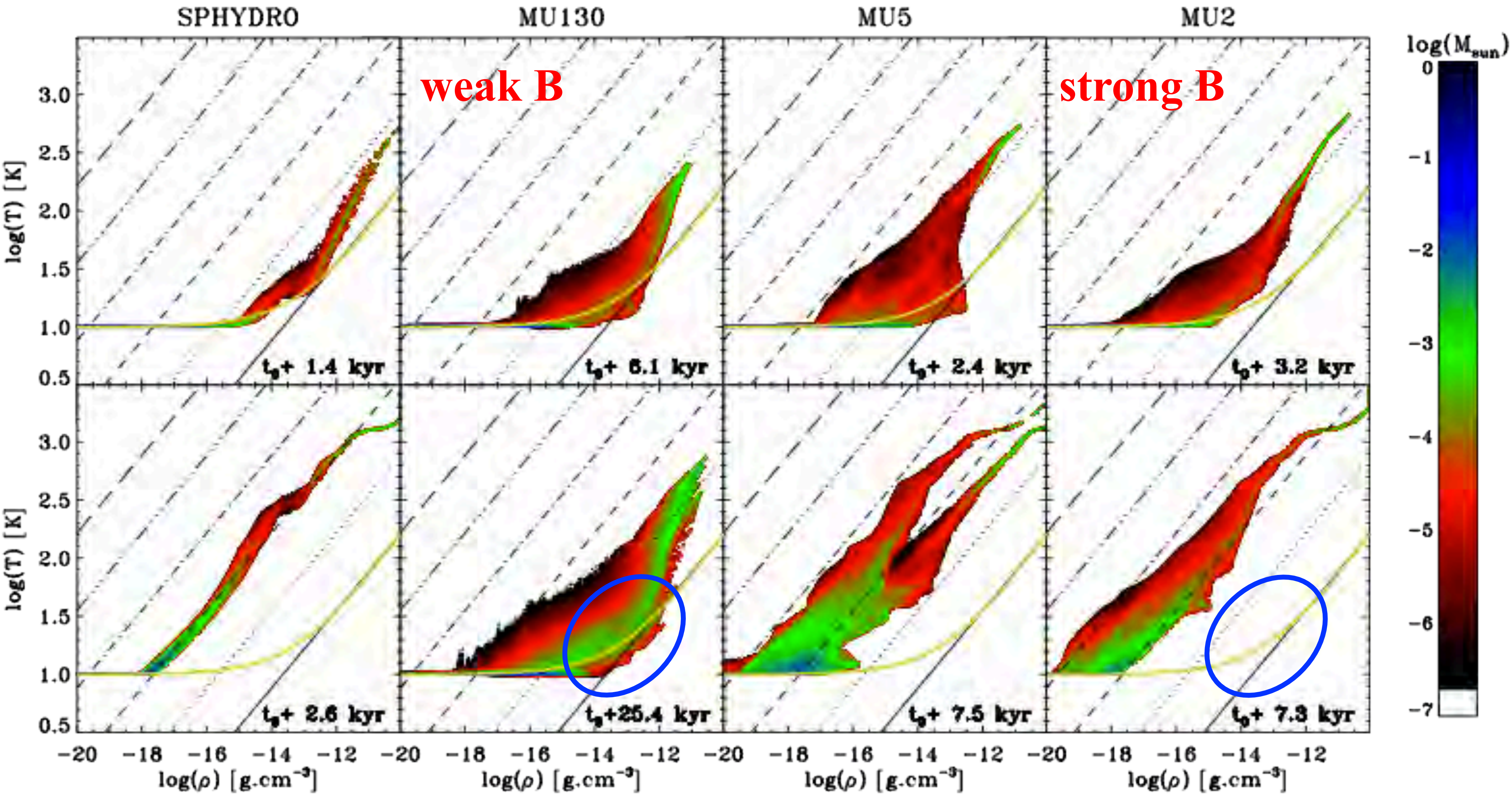
Eturb/Egrav=20% initially



Commerçon, H & Henning, ApJL 2011

(see also Price & Bate 2009 at larger scales, Myers et al. 2013, 2014)

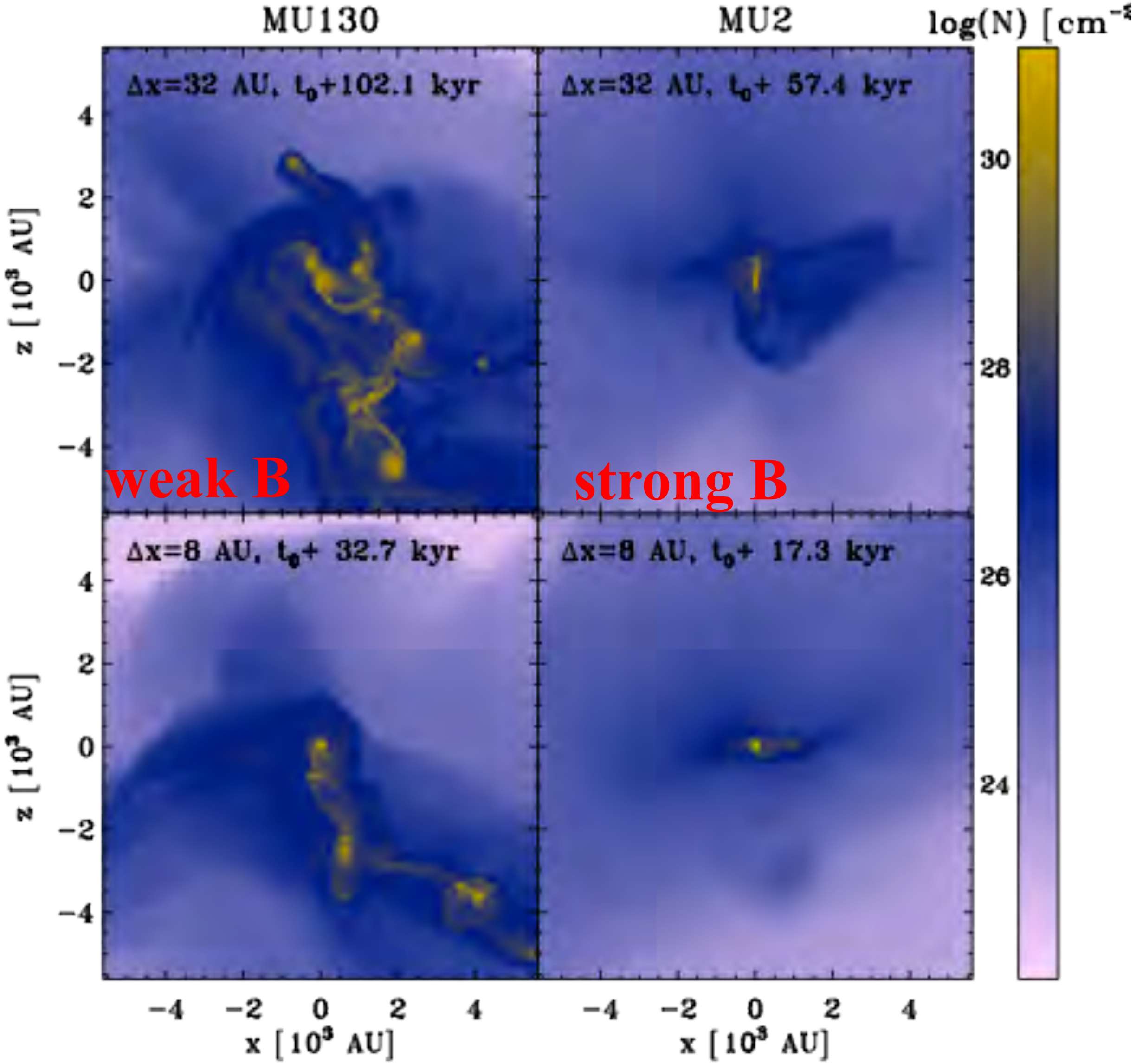
100 M⊙ turbulent dense core collapse



Commerçon, H & Henning, ApJL 2011

100 $M_\odot$ turbulent dense core collapse

Trend confirmed with lower resolution runs:

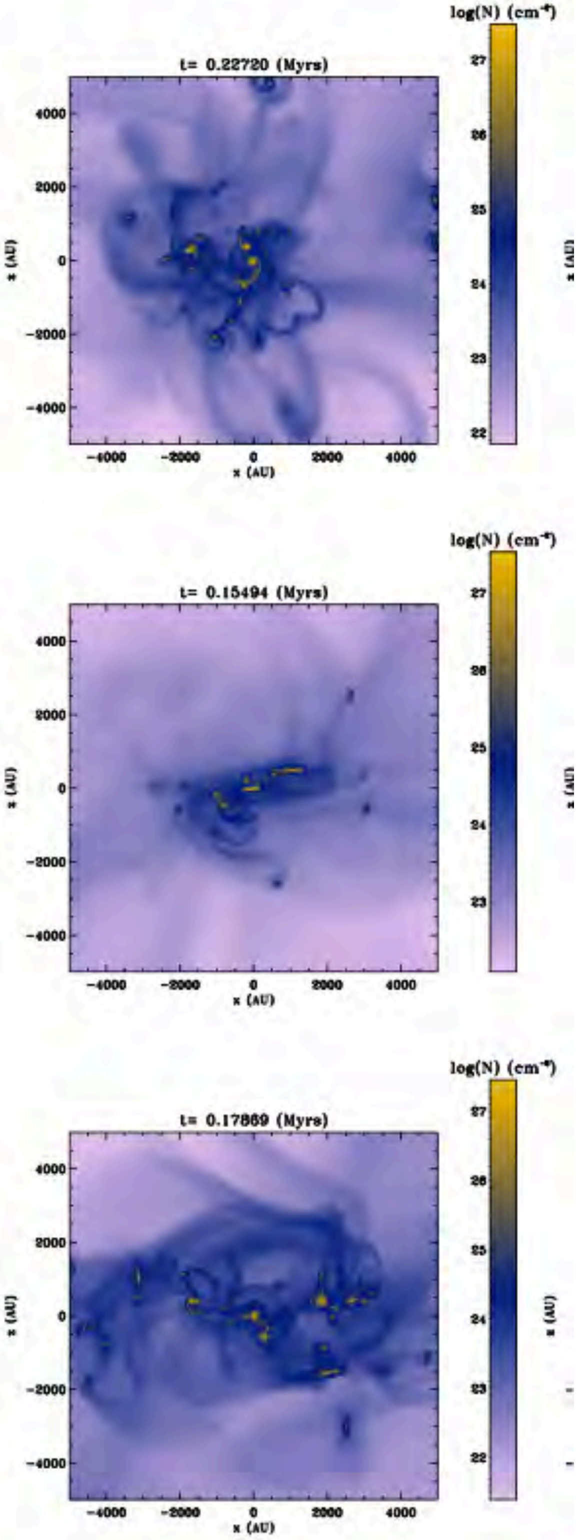


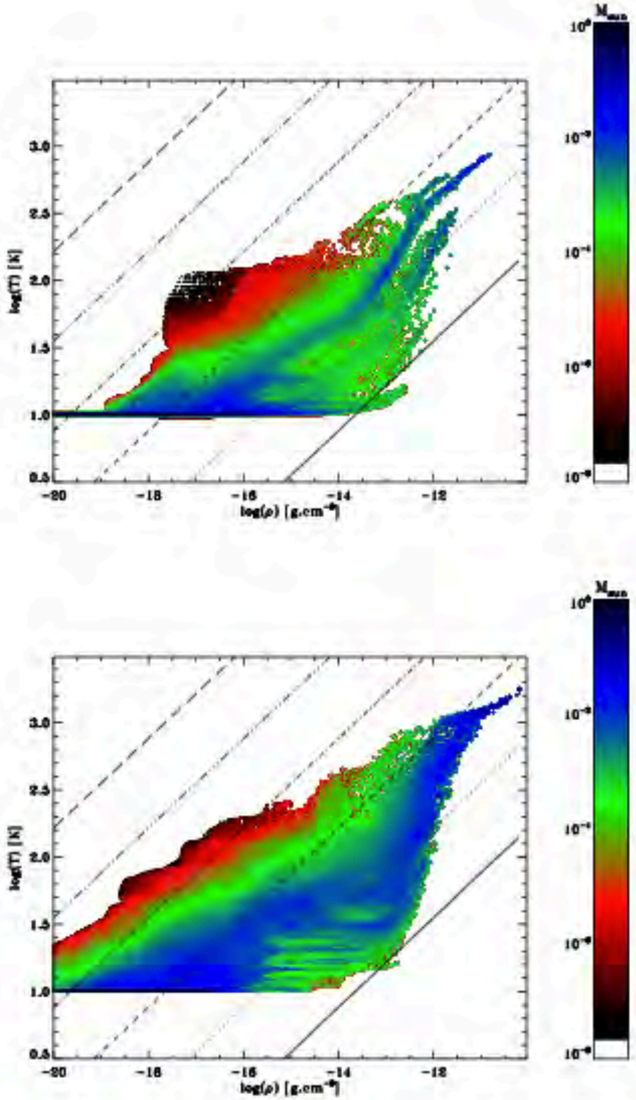
weak B

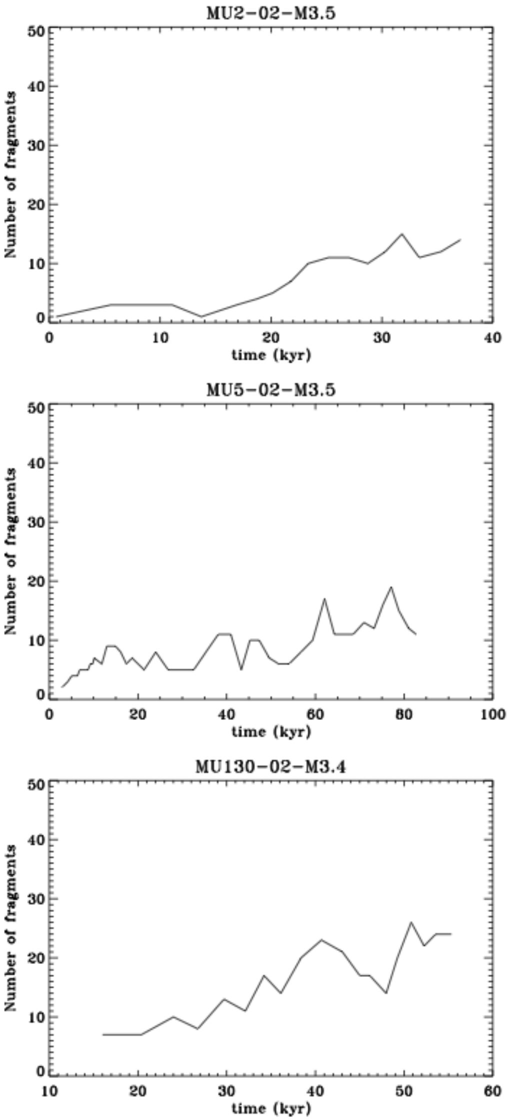
strong B

100 Ms cores with larger column densities

(Myers et al. 2014, Commercon & H 2015)



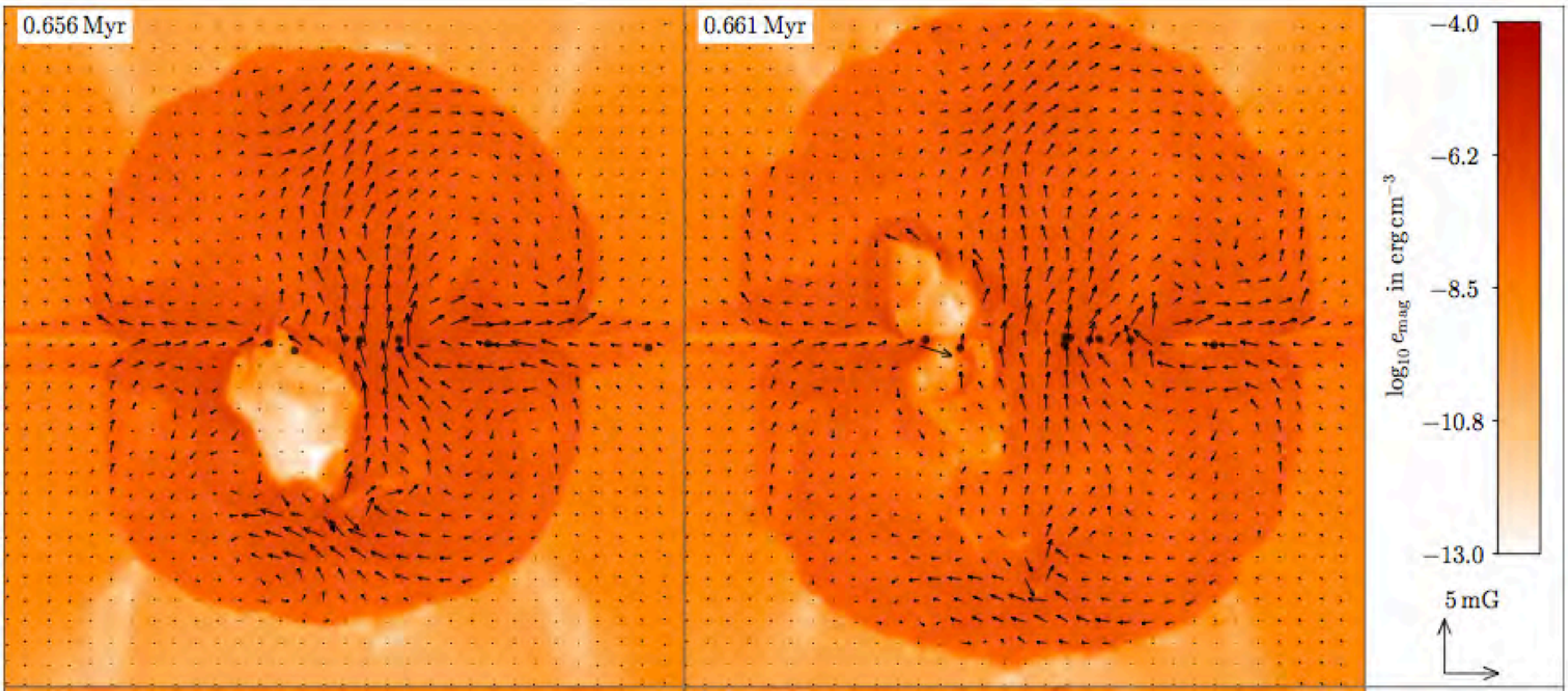




Similar effects still observed

Magnetized runs have about 2 times less fragments

Peters et al. 2010, 2011, 2012
take also into account **ionising radiation**



Ionising radiation tends to push further the gas outwards and may be important/dominant for outflows in massive stars

How massive stars form ?

- -Can we form massive stars in spite of the radiative pressure ?
  - -1D : grain solution
  - -2D : flashlight solution
  - -3D : radiative instability solution
  - -collision model

- -Can we prevent the gas to fragment in many objects ?
  - -isothermal
  - -radiative feedback
  - -magnetized non-radiative
  - -radiative and magnetized

- -Where the gas is coming from ?
  - -competitive accretion
  - -gravitational well based theory
  - -tracing the gas in simulations

Competitive accretion : individual wells are unimportant

(Zinnecker 1982, Bonnell et al. 2001, Bate et al. 2003,…)

Stellar dominated Potential: $\frac{dN}{dM} \propto M^{-2}$

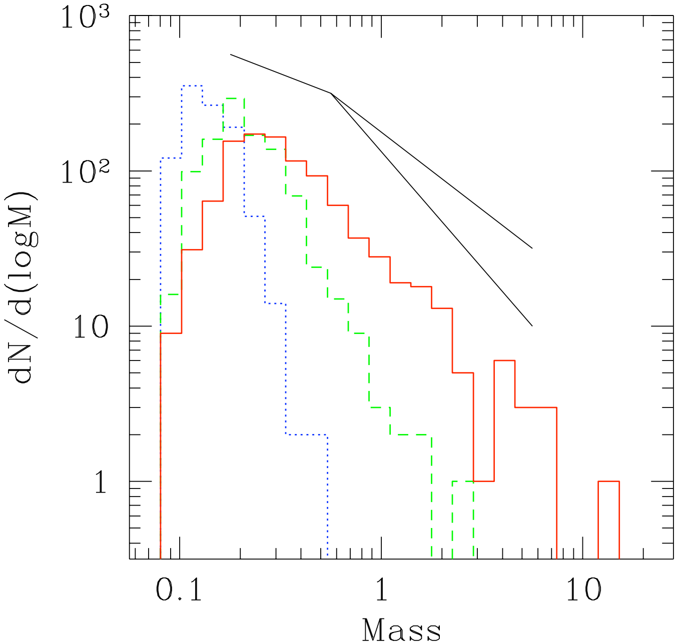
Assume $\rho_{gas} \propto R^{-3/2}$: typical after rarefaction wave propagates away

(Shu 1977) $\dot{M}_* = \pi \rho V_{rel} R_{acc}^2$

$$R_{acc} \approx R_{BH} \approx \frac{GM_*}{V_{rel}^2}, \qquad V_{rel} \approx \sqrt{GM_{cluster}/R} \approx R^{-1/2}$$

$\Rightarrow \dot{M}_* \propto M_*^2$ (accretion independent on the position in the cluster)

$\Rightarrow dN \propto M_*^{-2} dM_*$ (under reasonable assumptions…)



Mass spectrum from Bonnell et al. (2001)

1000 stars initially of mass 0.1 Ms, 10% of the total Mass

The mass spectrum develops and lead to a Salpeter type Slope

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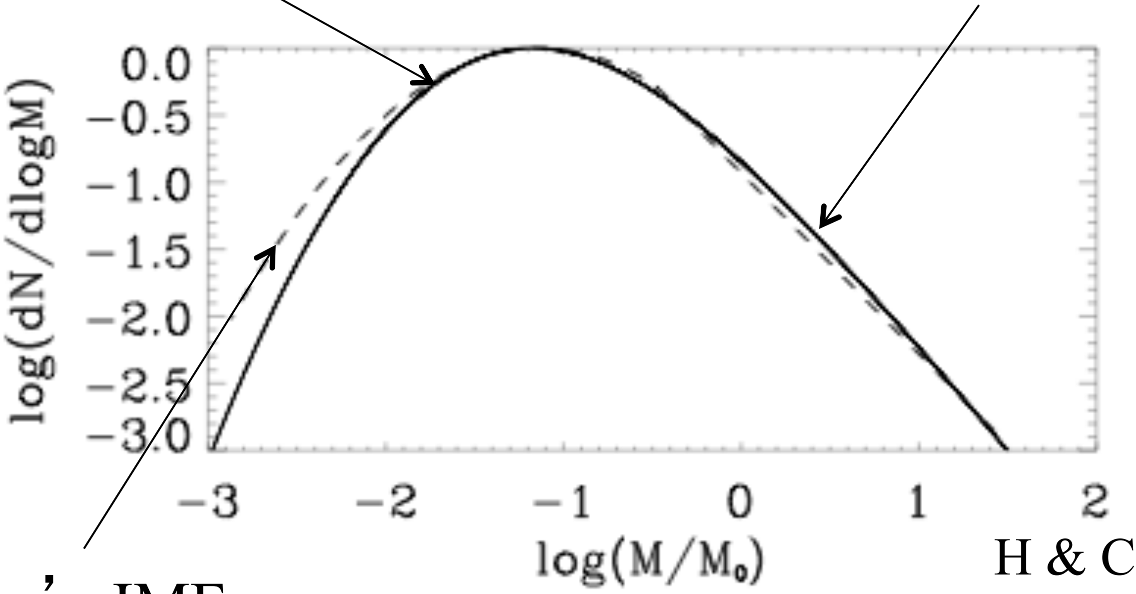
Theories assuming that individual wells are determinant

(Padoan et al. 97, McKee & Tan 2003, H & Chabrier 2008, Hopkins 2012)



Thermal support
Turbulent compression
+ gravity

Turbulent dispersion
Turbulent compression
+ gravity

Chabrier’ s IMF

H & Chabrier 08

$$\mathcal{N}(\tilde{M}) = 2\mathcal{N}_0 \frac{1}{\tilde{R}^3} \frac{1}{1+(2\eta+1)\mathcal{M}_*^2\tilde{R}^{2\eta}} \left[\frac{1+(1-\eta)\mathcal{M}_*^2\tilde{R}^{2\eta}}{(1+\mathcal{M}_*^2\tilde{R}^{2\eta})^{3/2}} - \frac{\delta_{\tilde{R}}^c + \sigma^2/2}{(1+\mathcal{M}_*^2\tilde{R}^{2\eta})^{1/2}} \frac{n'-3}{4} \frac{\sigma_0^2}{\sigma^2} \left(\frac{\tilde{R}}{\tilde{L}_i}\right)^{n'-3} \right]$$

$$\times \exp\left\{ -\frac{\left[\ln(\tilde{M}/\tilde{R}^3)\right]^2}{2\sigma^2} \right\} \frac{\exp(-\sigma^2/8)}{\sqrt{2\pi}\sigma},$$

How massive stars form ?

- Can we form massive stars in spite of the radiative pressure ?
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  - collision model

- Can we prevent the gas to fragment in many objects ?
  - isothermal
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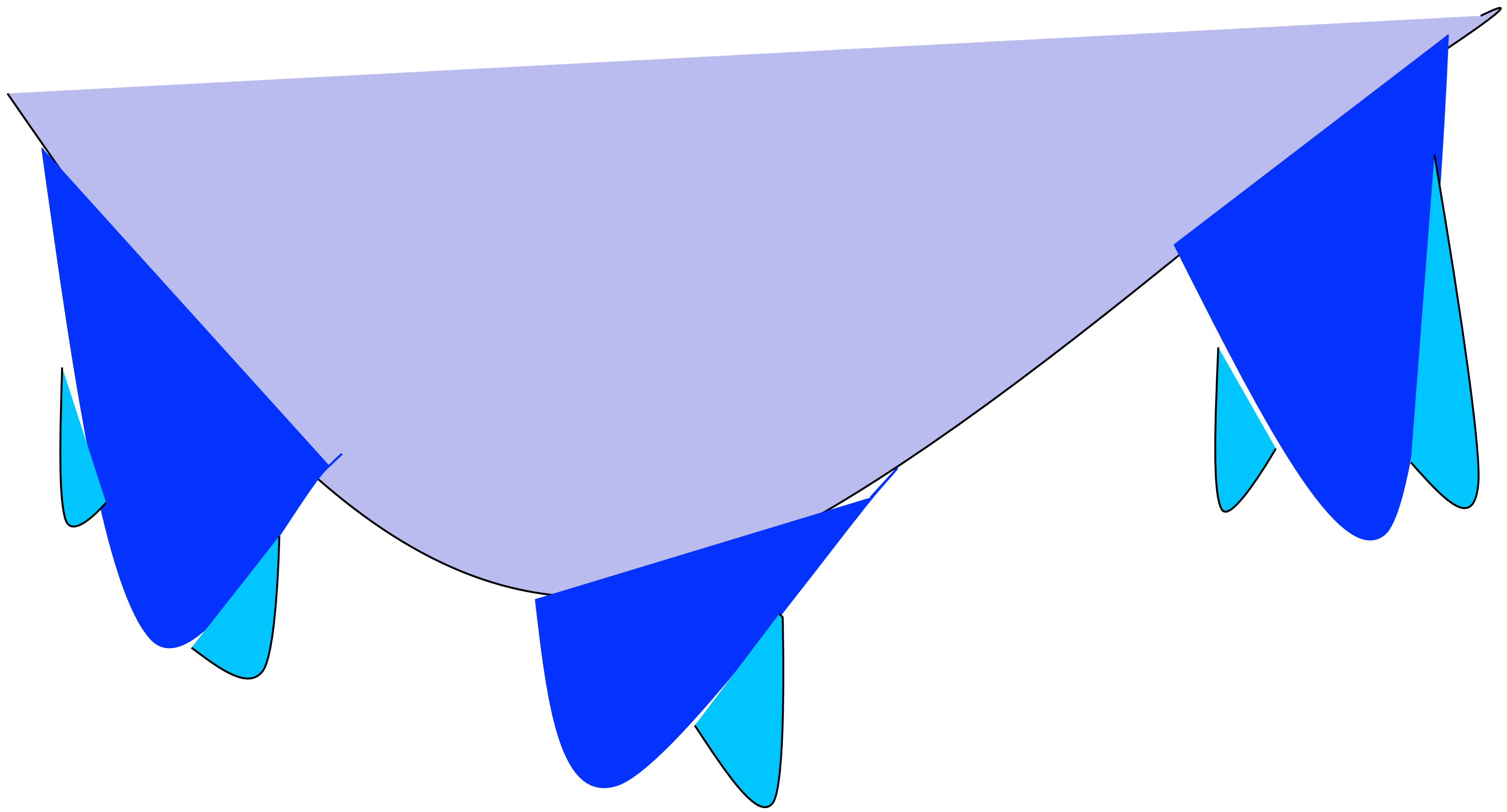
A hierarchy of wells:



Direct mapping between the wells and the stars ?
Exchange between the wells ?
Likely both ! But how much ?

Which mechanism is at play in gravo-turbulent simulations ?

Competitive accretion or core formation ?

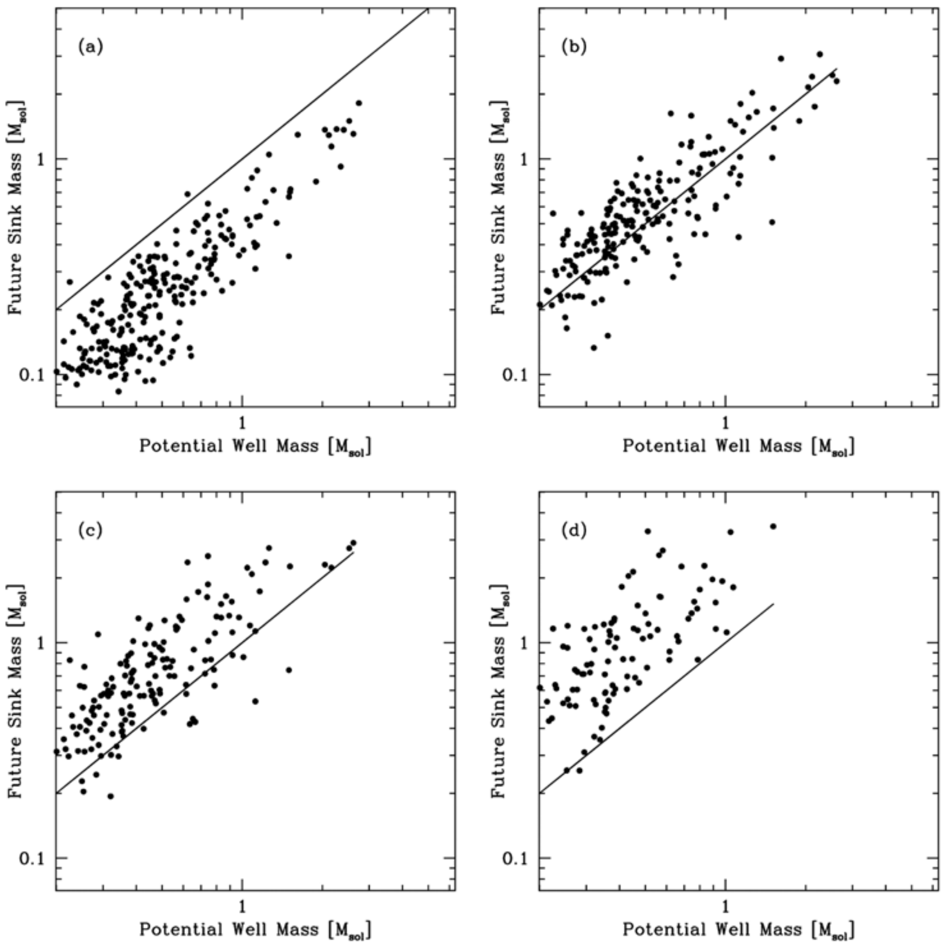
Smith et al. have run SPH simulations with gravity and sink particles

They identify cores and look at the correlation between the core masses and the sink masses.

The correlation is very good initially (few freefall times) and becomes progressively less good.

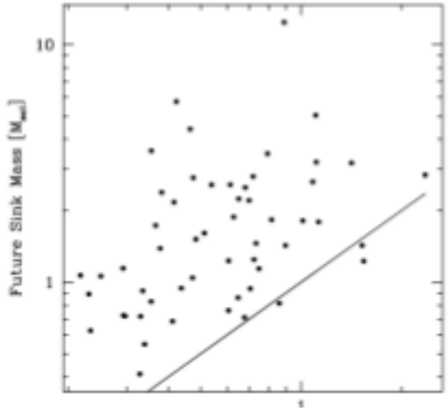
=>This is compatible with the core mass function being able to produce a reasonable IMF (Chabrier & H 2010).

Smith et al. 2008



Until how many freefall times are the cores accreting ?

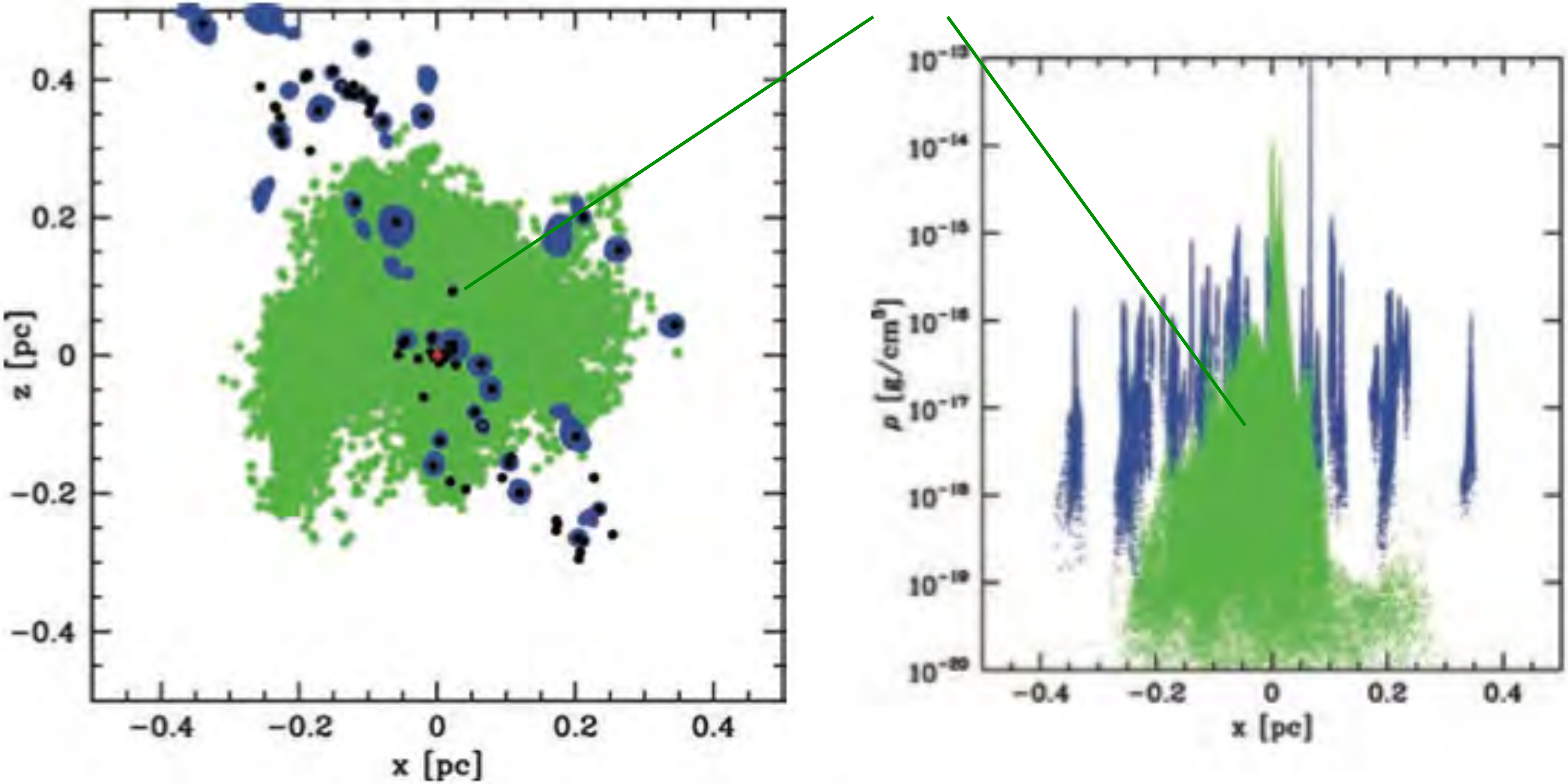
At the end of the simulation



The most massive stars is more massive than the mass contains in its initial well.
Where this mass comes from ?

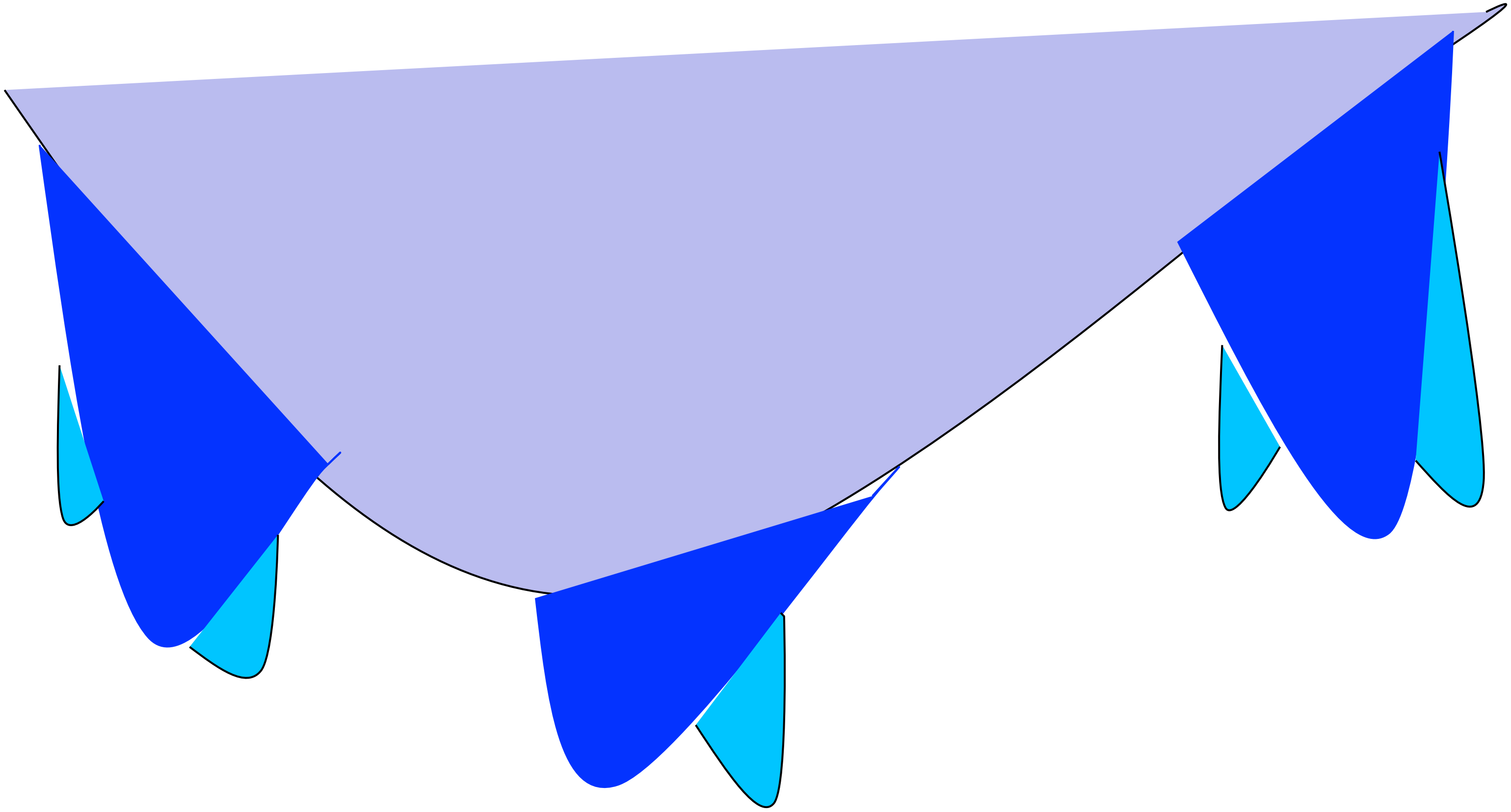
Where the gas comes from ?

Green gas eventually falls in the massive star



Smith et al. 2009

A hierarchy of wells:



Direct mapping between the wells and the stars ?
Exchange between the wells ?
Likely both ! But how much ?

Conclusions

Impact of radiative transfer and magnetic field are obviously drastic in:

- regulating the mass accretion (but not stopping it)
- limiting the fragmentation

Combination of magnetic field and radiative transfer is **more** than their **mere** juxtaposition.

Where the mass is coming from ? still unclear.
=> **Accretion is not a sufficiently clear statement**.
The salient questions are:

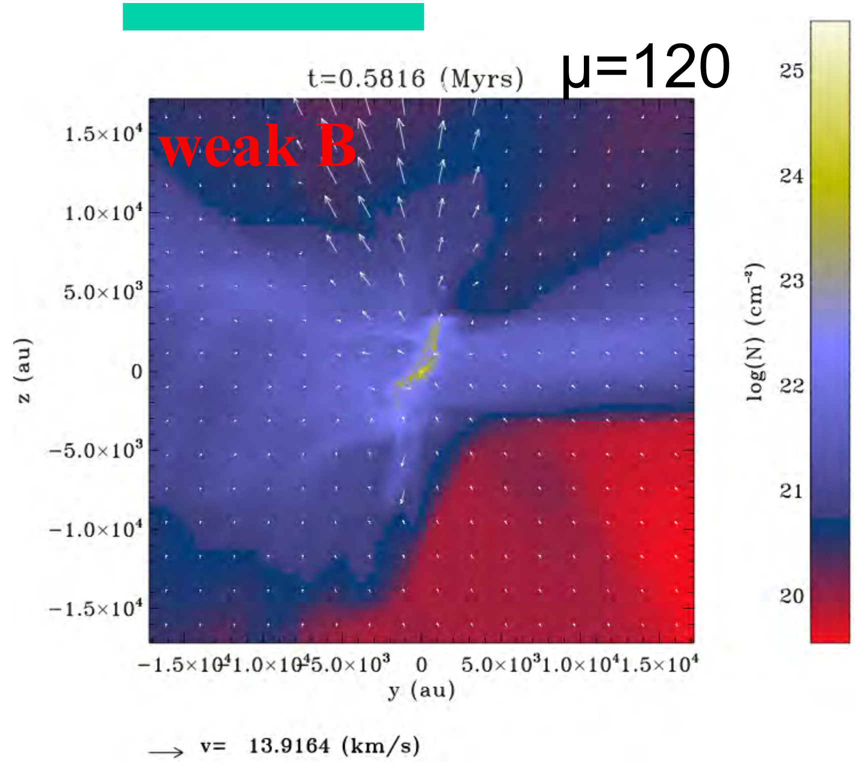
- -is accretion determined by the present mass object (compet. accret.) ?
- -is accretion determined by the initial well hierarchy ?

The feedback from massive stars is very non-linear. But predicting masses with an accuracy better than ~2 is a **huge challenge**.
=> a huge multi-scale, multi-physics problems

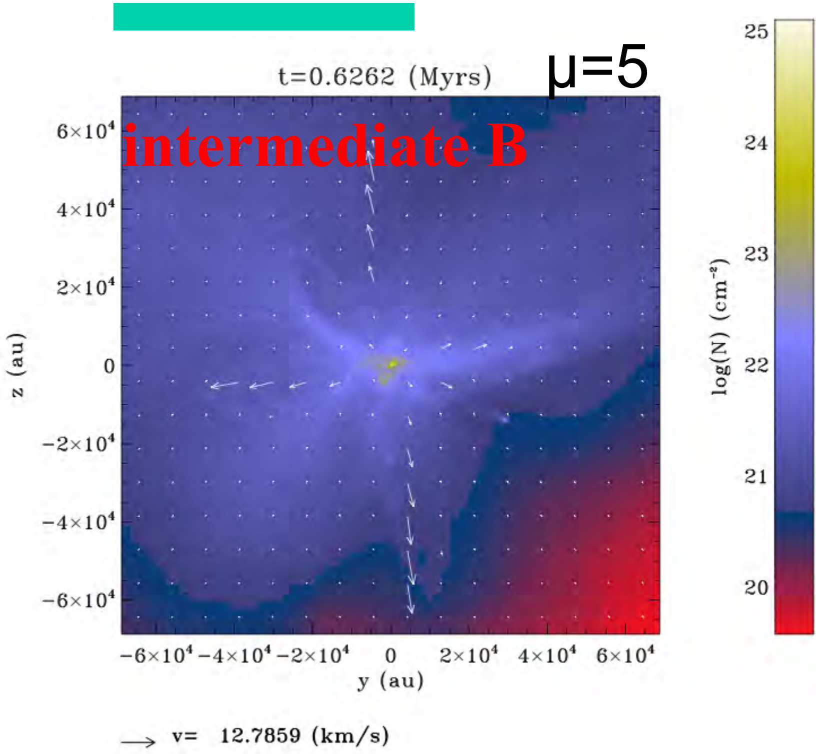
100 M⊙ magnetized, turbulent and dense barotropic core

Powerful outflows are launched even in turbulent cores

Faster flows appear with weaker fields



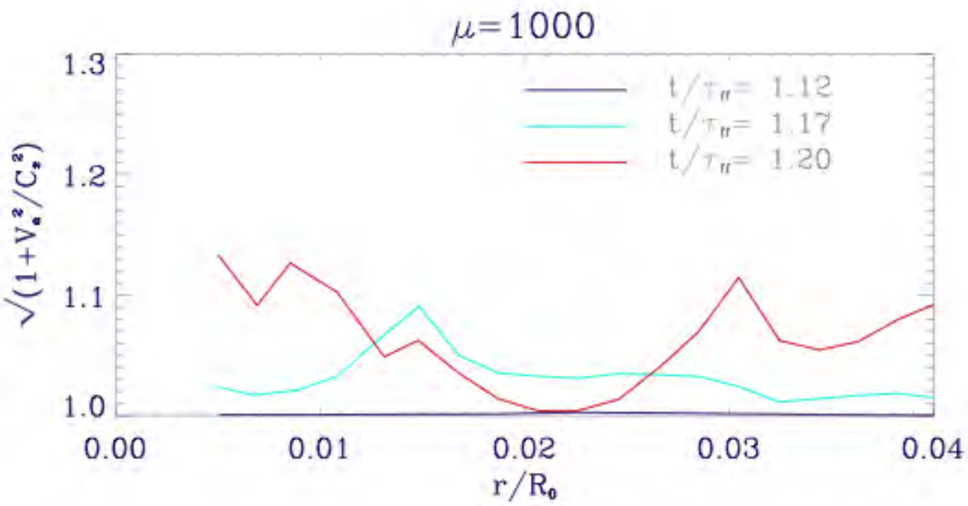
μ=120



μ=5

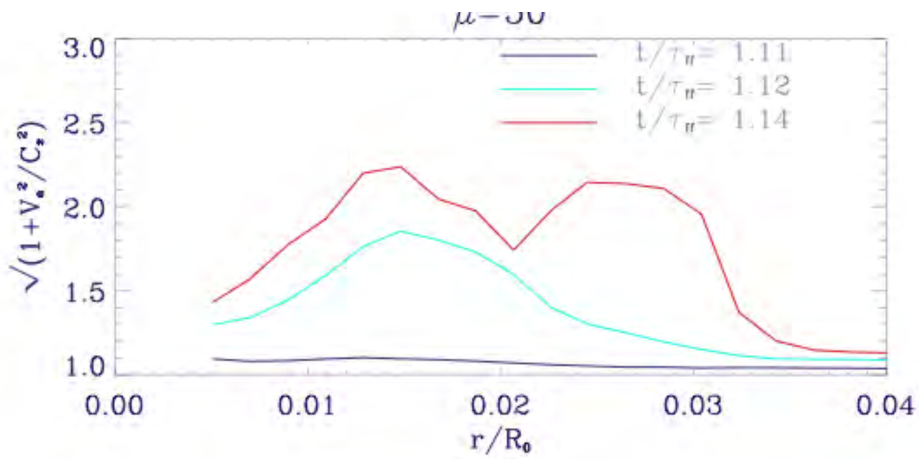
Hennebelle et al. 2011

Growth of the toroidal magnetic field within the disk

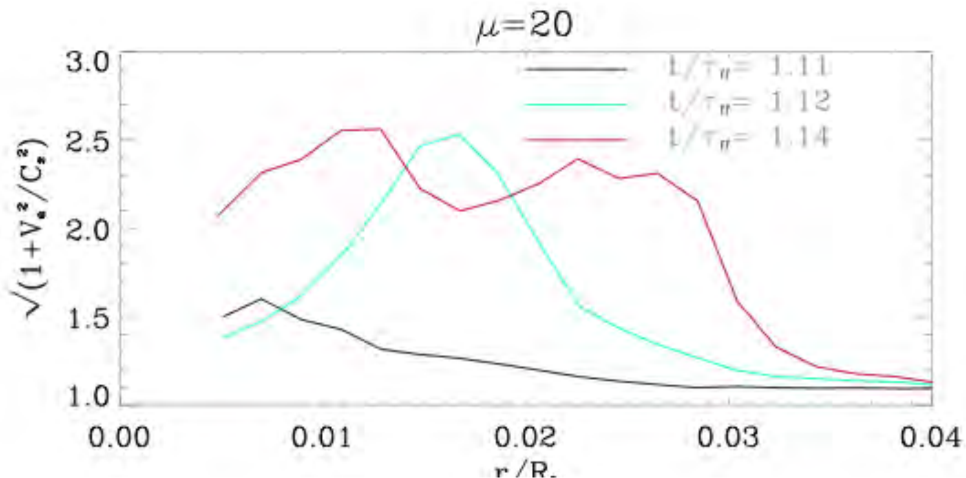

μ=1000

Importance of V_a/C_s

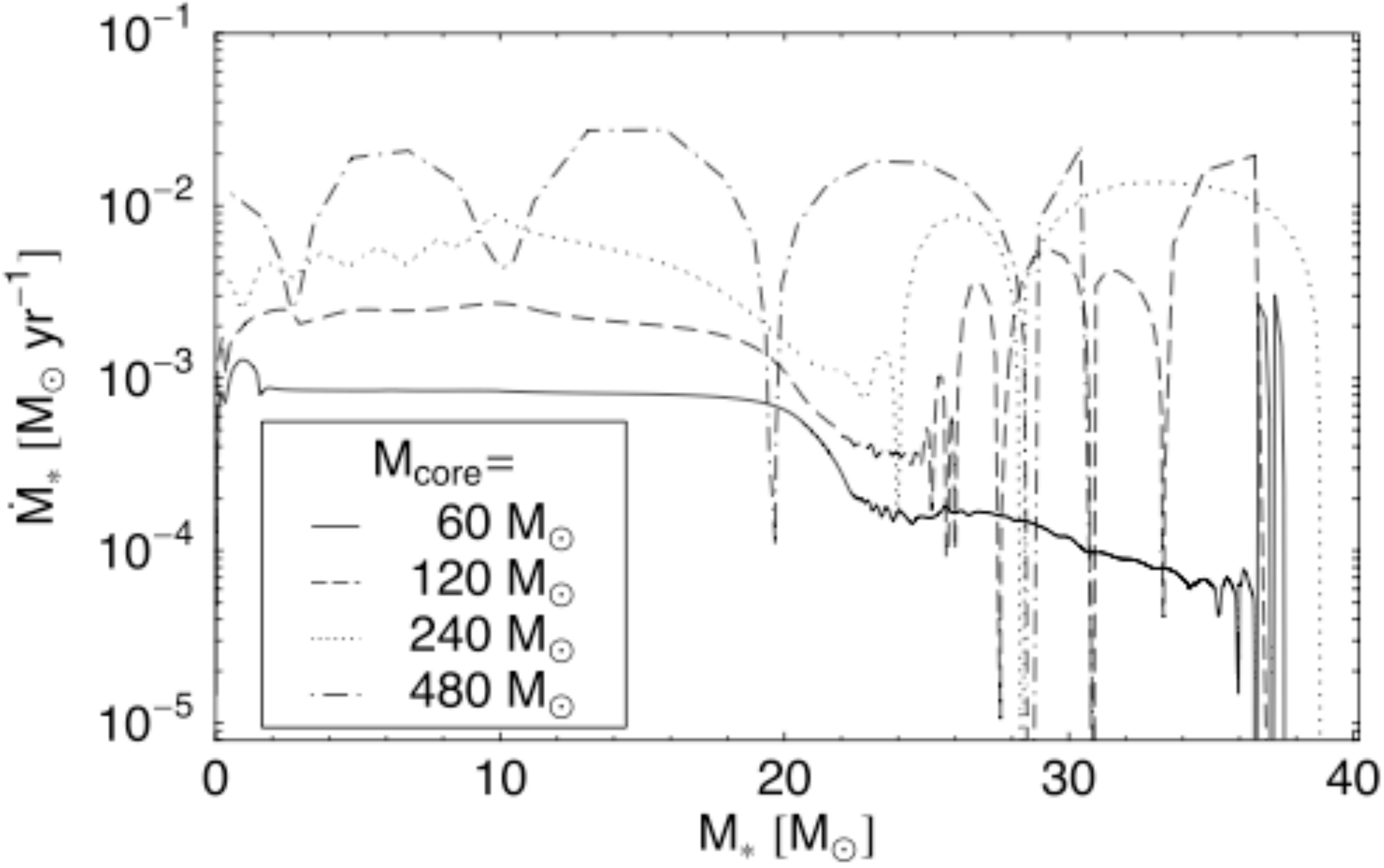
for various μ and various times


μ=50

=>Compatible with the assumption that the toroidal field, stabilizes the disk.


μ=20

1D results by Kuiper et al. (2010)



The final mass of the stars is about 35-37 Ms.
The history depends on the core mass.