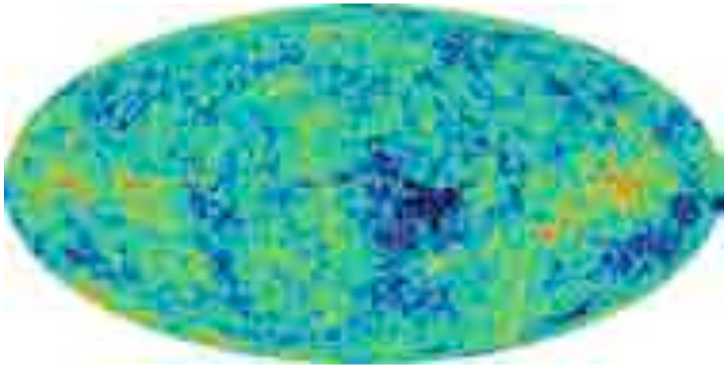
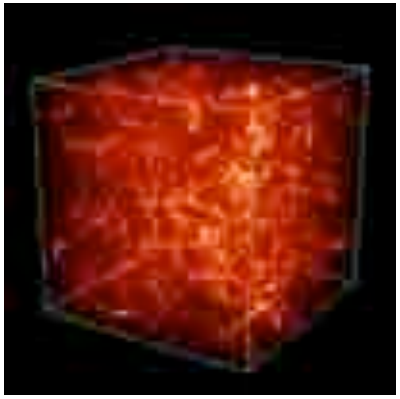
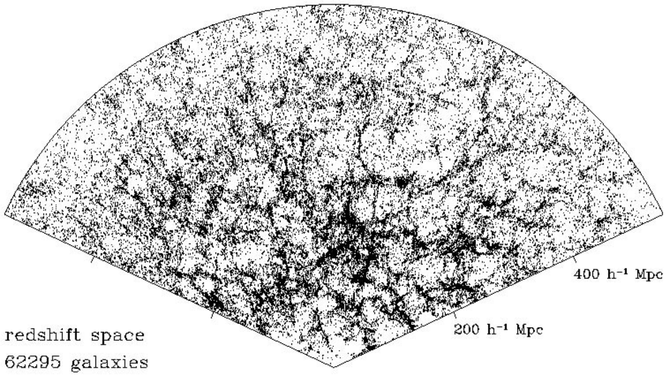
Cosmological simulations of galaxy formation

Romain Teyssier







Outline

- Cosmological disc formation with RAMSES
- Towards resolving the clumpy ISM ?
- Cold streams and clumpy galaxies
- The cosmic dynamo

Stephanie Courty, Brad Gibson (Preston)

Oscar Agertz, Ben Moore (Zurich)

Damien Chapon, Frédéric Bournaud (Saclay)

Tobias Goerdt, Avishai Dekel (Jerusalem)

Yohan Dubois (Oxford)

Galaxy formation theory: a minimal model

Dark matter is collisionless: Vlasov-Poisson equations with a PIC or Tree code
Baryons are collisional: Euler-Poisson equations with a grid or SPH code
Gravitational collapse and shock heating (gas temperature increases with halo mass).
Cooling by H, He, metals and heating by Haardt & Madau UV background
Multiphase interstellar medium as a "sub-grid" model $\rho_g > \rho_0$

- Polytropic equation of state
- Phenomenological star formation model
- Supernova driven winds and metal enrichment

Star formation recipes: $\dot{\rho}_* = \frac{\rho_g}{t_*(\rho_g)}$

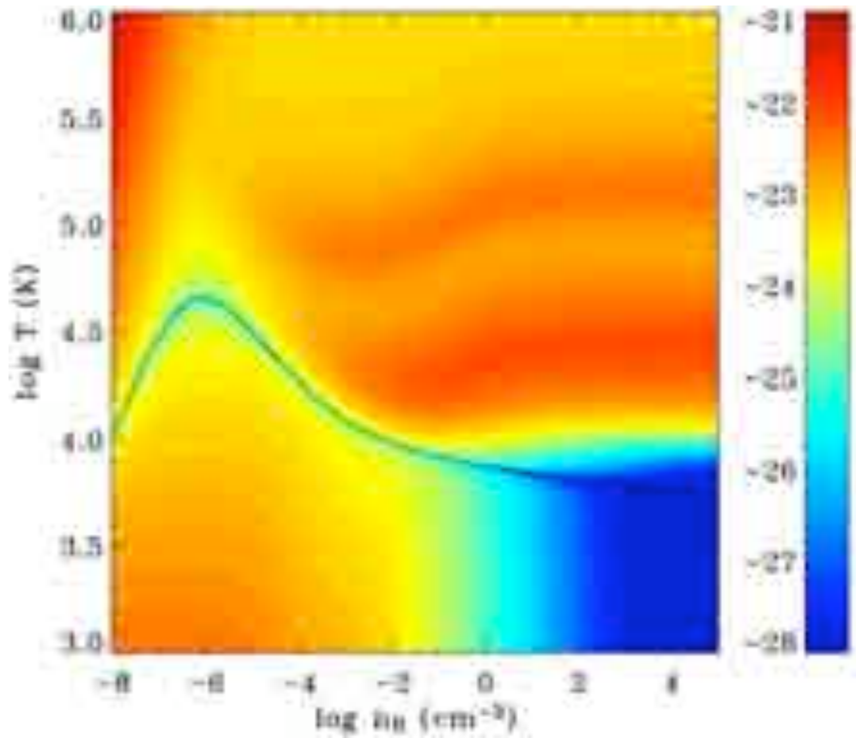
$$t_* = t_0\left(\frac{\rho_g}{\rho_0}\right)^{-1/2}$$

- t_0= 1-10 Gyr (Kennicutt 1998)
- α = 0.02-0.05 (Krumholz & Tan 2007)
- n_0= 0.1-100 H/cm^3

Parameters depend on physical resolution

Numerical issues:

- SPH/Tree versus PM/AMR
- Resolution in mass
- Resolution in space and time



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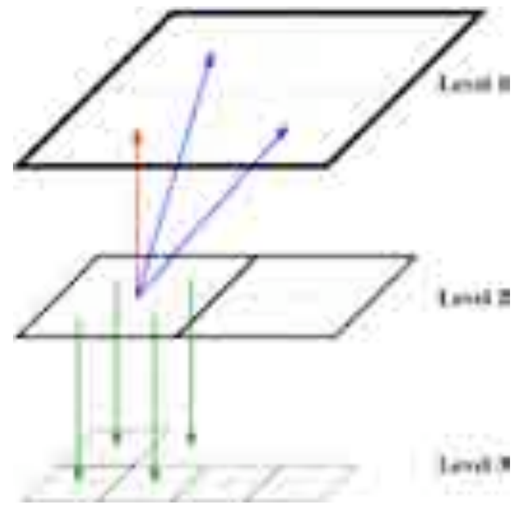
RAMSES: a parallel AMR code

- Graded octree structure: the cartesian mesh is refined on a cell by cell basis
- Full connectivity: each oct have direct access to neighboring parent cells and to children octs (memory overhead 2 integers per cell).
- Optimize the mesh adaptivity to complex geometry but CPU overhead can be as large as 50%.



N body module: Particle-Mesh method on AMR grid (similar to the ART code). Poisson equation solved using a multigrid solver.

Hydro module: unsplit second order Godunov method (MUSCL) with various Riemann solvers and slope limiters. New CT based MHD solver.

Time integration: single time step or fine levels sub-cycling.

Other: Radiative cooling and heating, star formation and feedback.

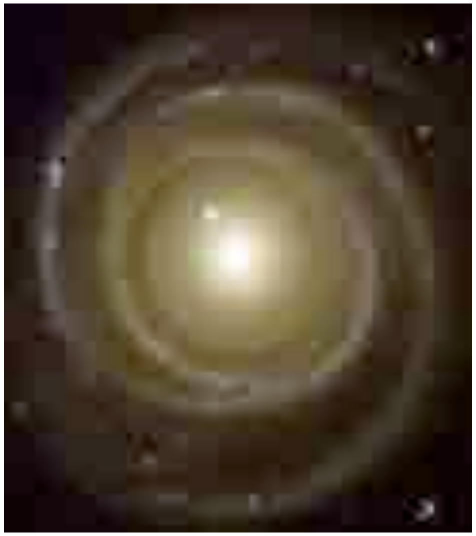
MPI-based parallel computing using time-dependant domain decomposition based on Peano-Hilbert cell ordering.

Simulating disc galaxies with AMR

RAMSES (AMR) simulation of a spiral disc at z=0.
200 pc spatial resolution (sub-grid model)
$8x10^5$ dark matter particles in R_{200} and $M_{200}=7x10^{11}$ M_{sol}
Collaboration with Brad Gibson and Stéphanie Courty
(University of Central Lancashire)

A realistic spiral galaxy ?

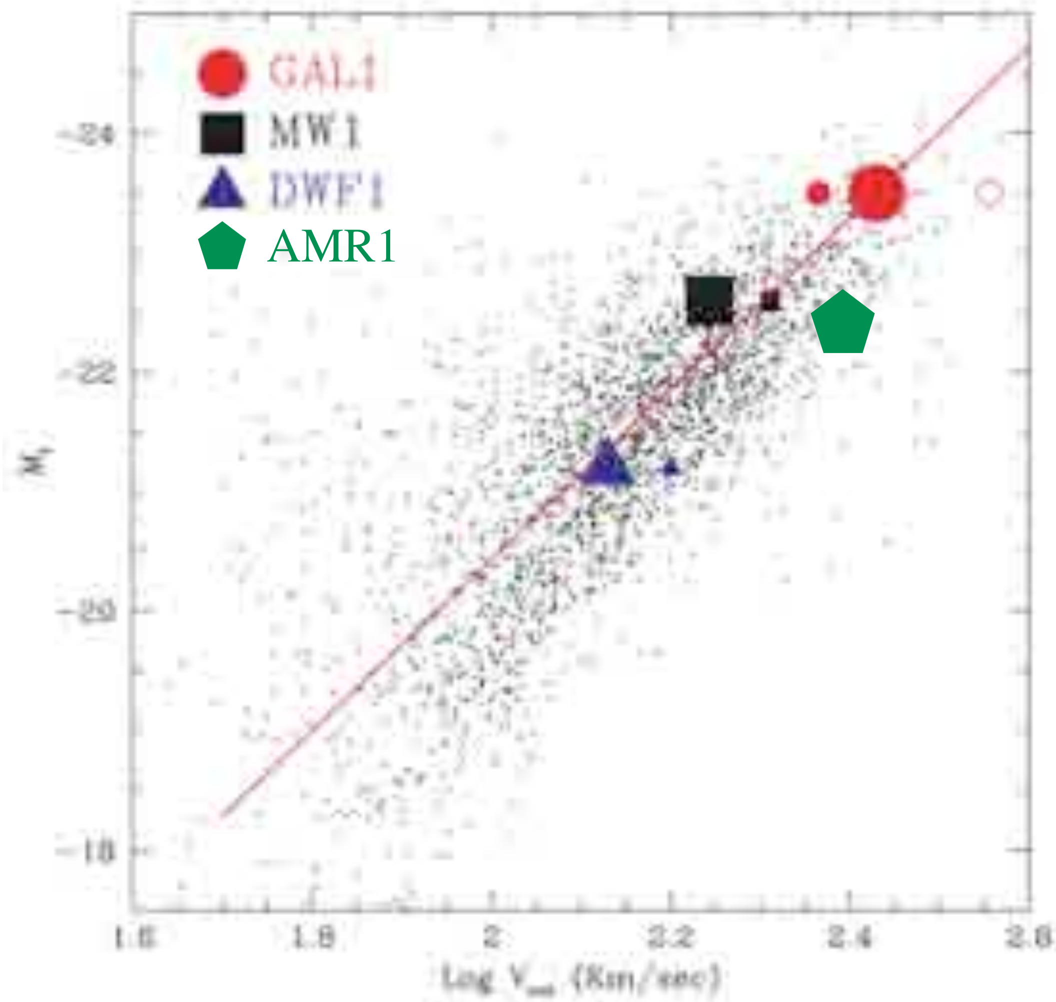
B/D ~ 1



Mock gri SDSS composite image with dust absorption based on Draine opacity model.

NGC4622 as seen from HST

A realistic spiral galaxy ?



I Band Tully-Fisher relation
GASOLINE data from Governato et al. 2007, Mayer et al. 2008

Different implementation of supernovae feedback

1- Thermal feedback: 10^{51} erg per supernova (10 M_{sol}) after 10 Myr.

2- Thermal feedback with delayed cooling: cooling turned-off during 50 Myr after last star formation episode (Governato *et al.* in GASOLINE)

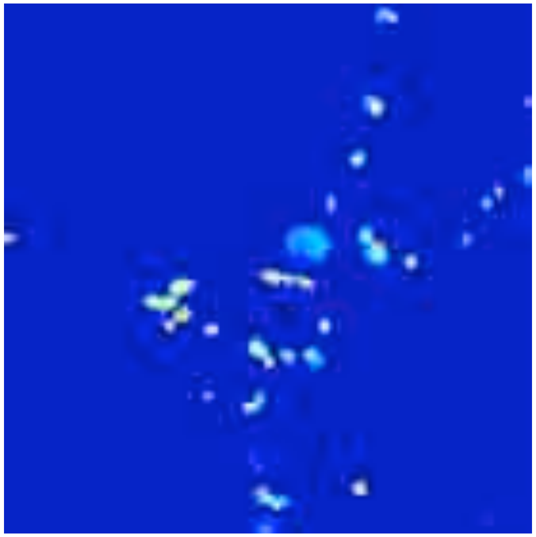
Kinetic feedback:
For each new stellar particle, create another collisionless particle to account for a companion Giant Molecular Cloud. After 10 Myr, release the GMC mass together with the supernova ejecta in a Sedov blast wave.

3- Kinetic feedback with $M_{GMC}=M_*$: blast wave velocity v_{SN} = 600 km/s with shock radius of 400 pc (Springel & Hernquist 2005; Dubois & Teyssier 2008)

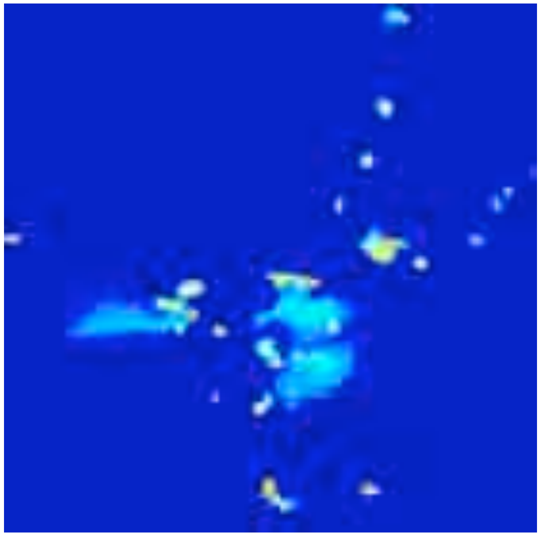
4- Kinetic feedback with $M_{GMC}=M_{gas}/2$ in the parent cell: blast wave with maximum momentum kick but v_{SN} < 35 km/s

Galactic winds at redshift 3

Thermal

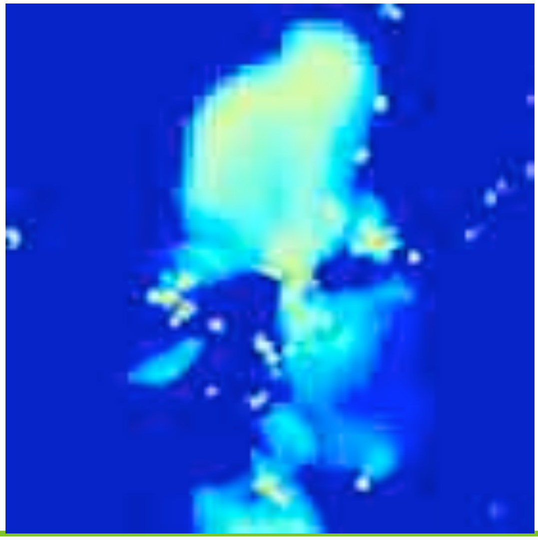


Delayed 50 Myr

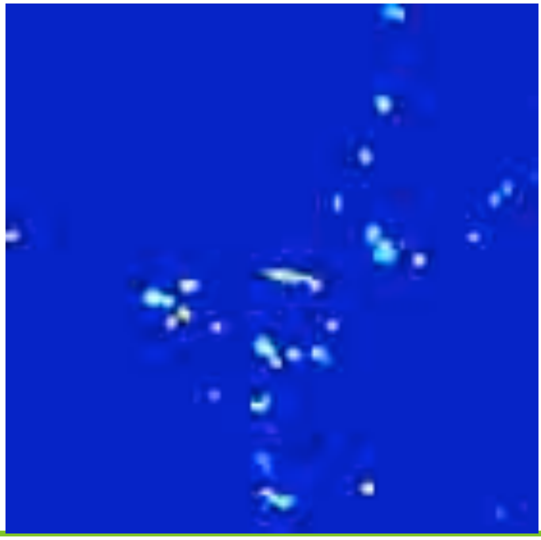


Metal maps:
Size 200 kpc/h physical
Max. resolution 200 pc physical

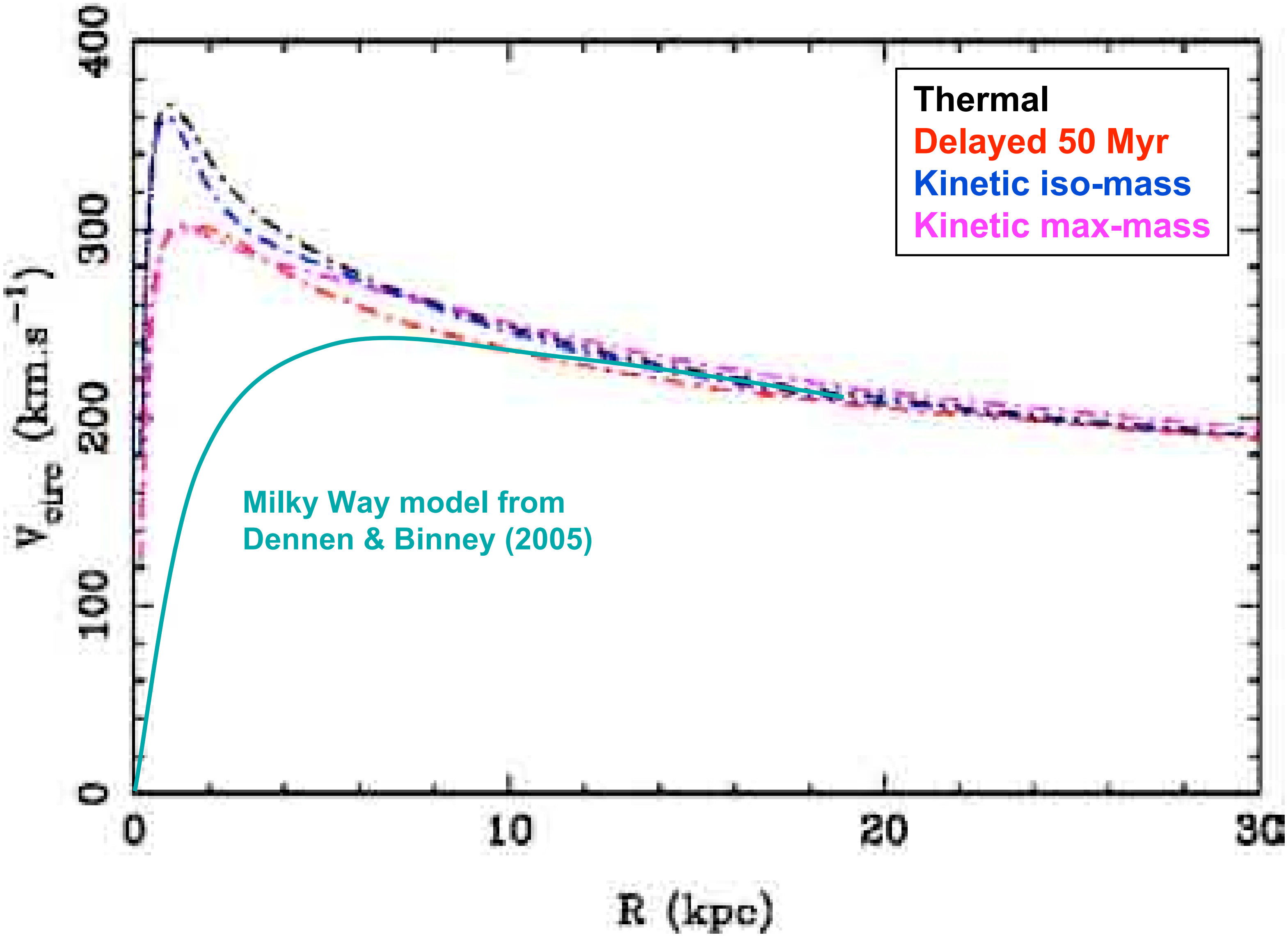
Kinetic iso-mass



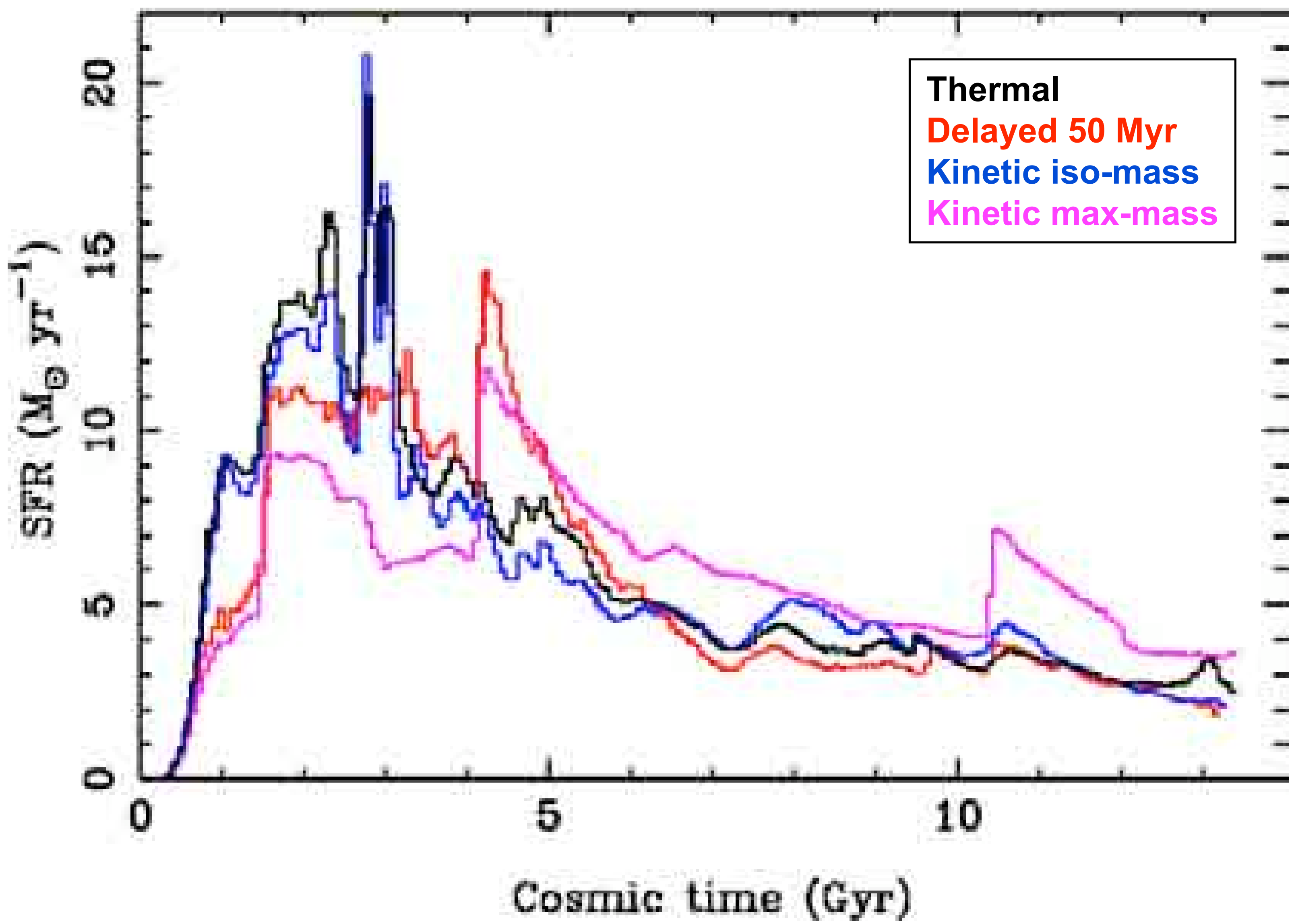
Kinetic max-mass



Circular velocities



Star formation histories



Baryon budget

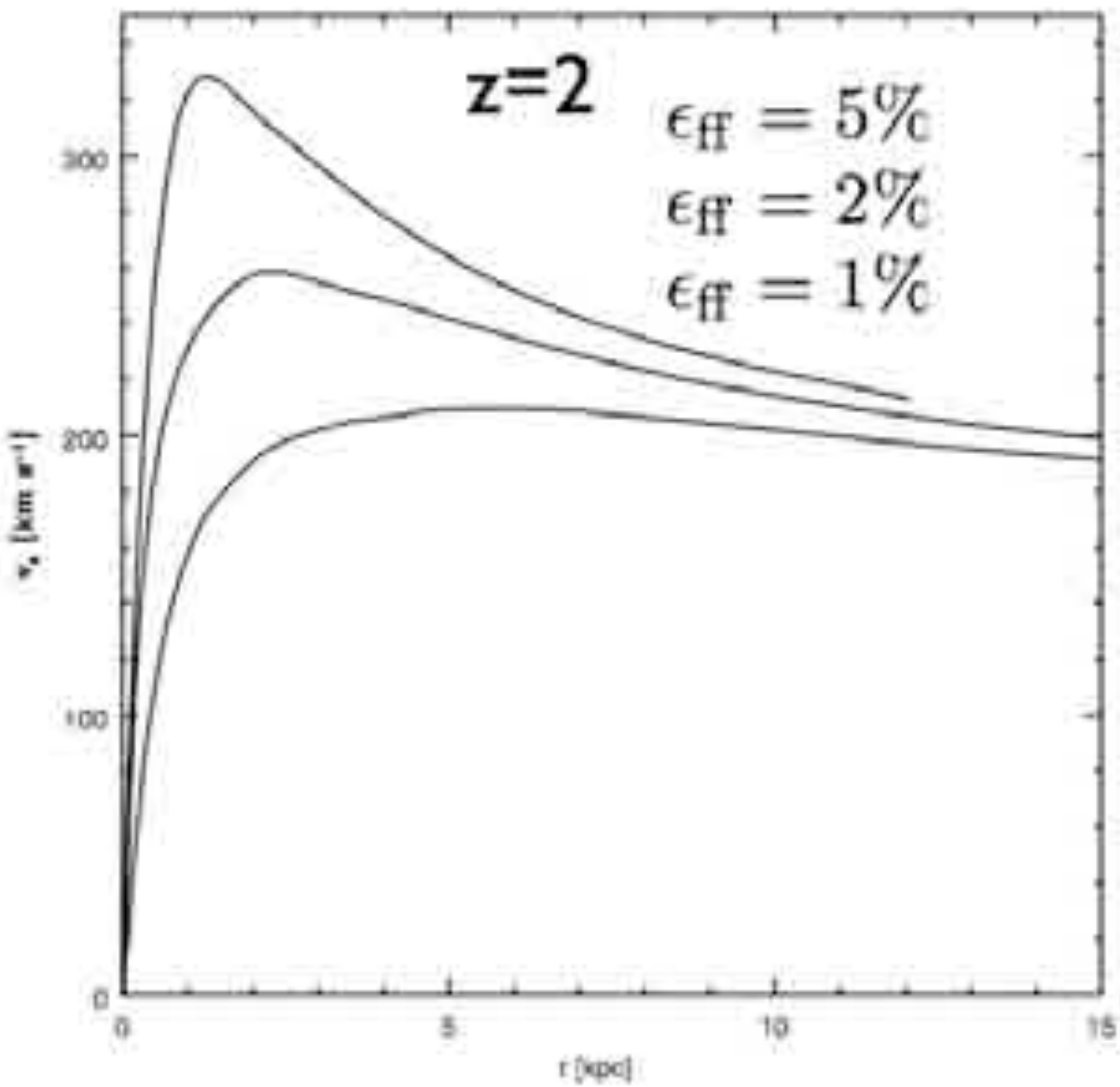
$M_{vir} = 7x10^{11}\ M_{sol}$

Galaxy: R < 15 kpc and |z| < 3 kpc

Bulge: r < 3 kpc

$x10^{10}\ M_{sol}$	Thermal	Delayed 50 Myr	Kinetic iso-mass	Kinetic max-mass	f_{gas}
M_D+M_B	7.9	7.4	7.6	8.1	10%
M_B	4.8	4.6	4.5	4.1	2.5%
M_D	3.1	2.8	3.1	4.0	20%

Circular velocities



Modelling the turbulent ISM in low z galactic disc

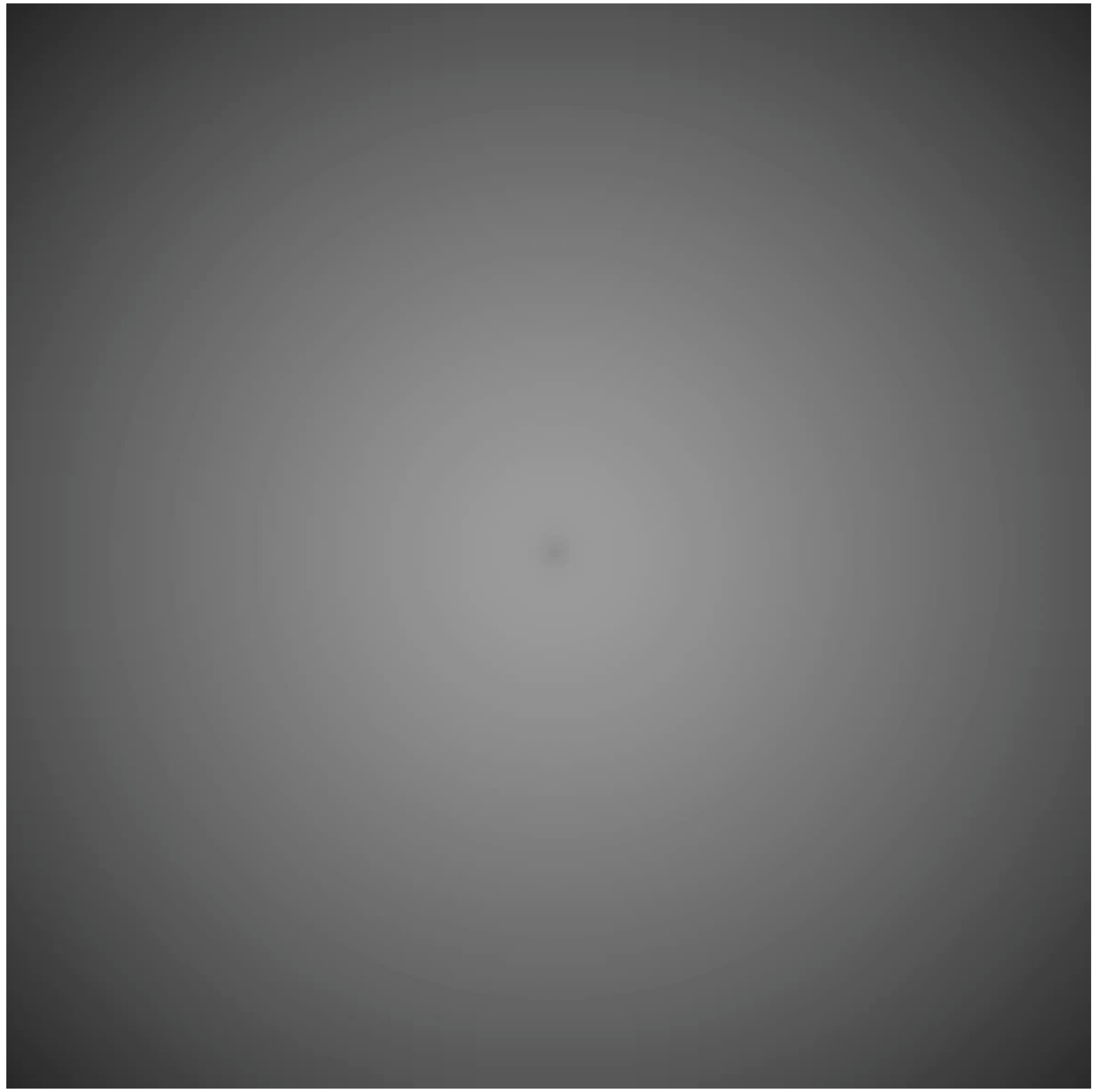
Isolated disc within a static NFW halo.

Kim & Ostriker 2001
Wada et al 2002
Tasker & Bryan 2006
Wada & Norman 2007
Kim & Ostriker 2007

Few pc resolution !

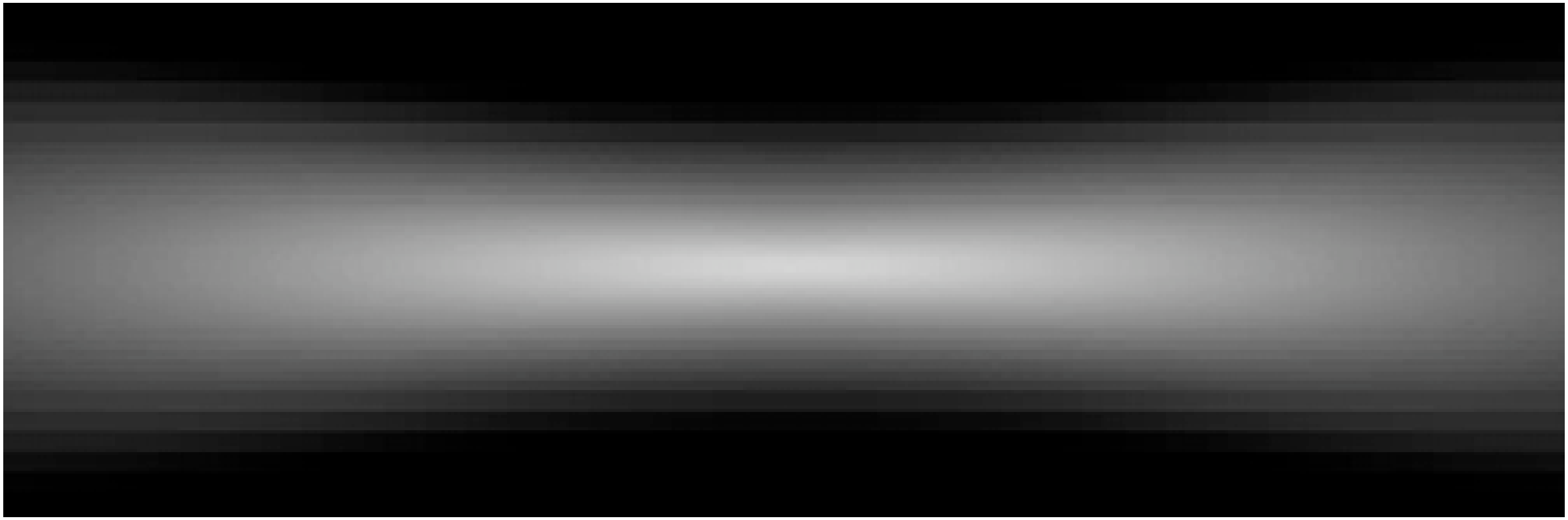
Formation of “clumpy” galaxies and turbulent HI gas discs through gravitational instability.

Agertz et al. 2008
Tasker et al. 2008



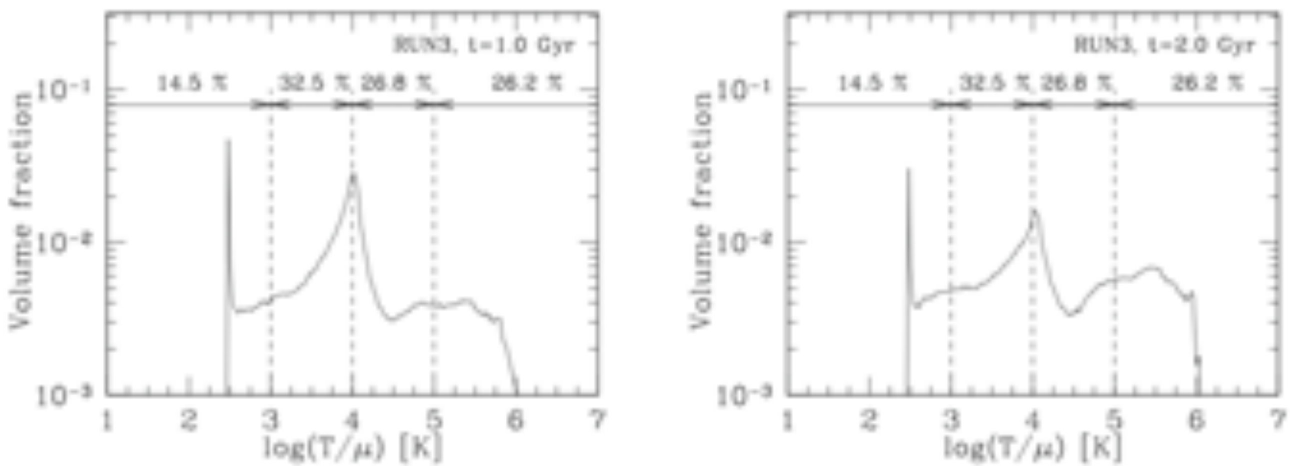
Disc edge on (gas column density)

Agertz et al. 2008



If the density exceeds ρ_0=100 H/cc, we form stars with 2% efficiency, and we impose a temperature floor around 300 K (polytrope with γ=2).
Supernovae feedback with a thermal dump after 10 Myr.
Refinement strategy: 100 pc initially, then Lagrangian evolution augmented by 4 cells per Jeans length criterion (Truelove et al. 1997) down to 6 pc !

Volume-weighted histograms

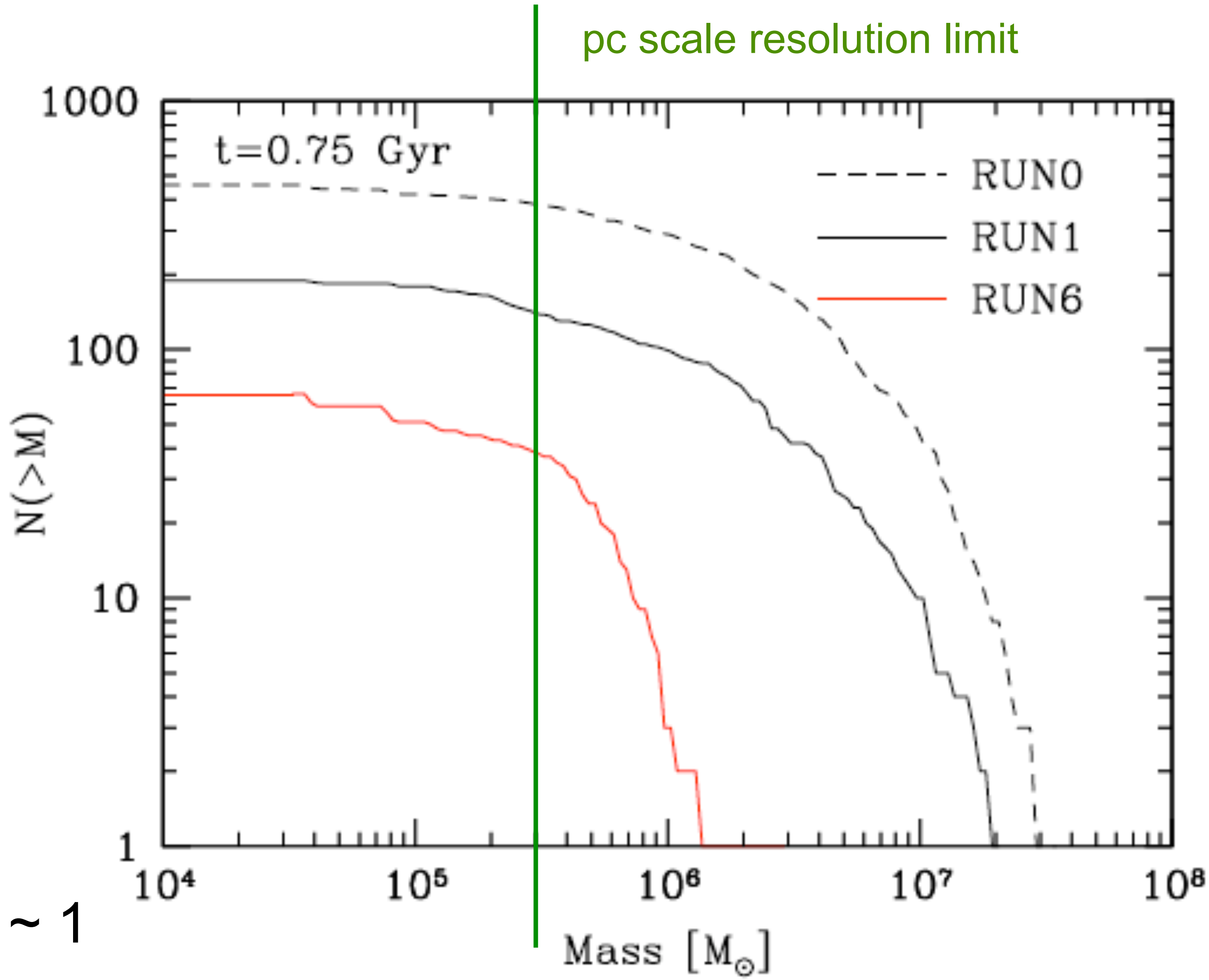


A multiphase ISM à la McKee & Ostriker (1977) with only gravitational instability, hydrodynamics, cooling and supernovae feedback ?

In mass:

State	Characteristic	RUN1 (1.0 Gyr)	RUN3 (1.0 Gyr)	RUN1 (2.0 Gyr)	RUN3 (2.0 Gyr)
Molecular	($n > 100\,\mathrm{cm}^{-3}$)	10.4%	9.8%	2.42%	4.1%
Atomic	($n < 100\,\mathrm{cm}^{-3}$, $T < 10^4$ K)	89.6	89.4%	97.5%	95.2%
Ionized	($T > 10^4$ K)	~0%	0.8%	~0%	0.7%

Clump mass function



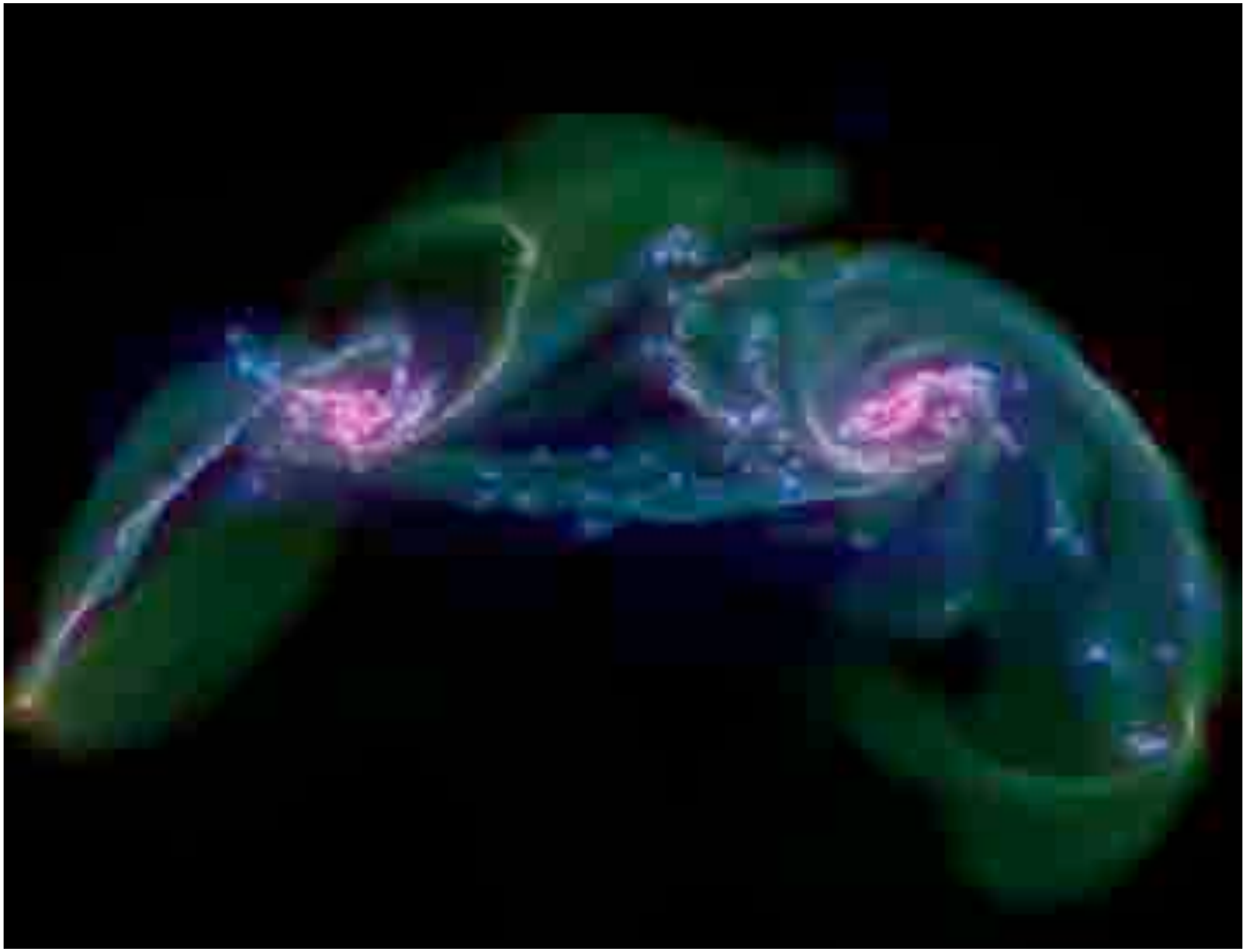
$$M_J \simeq \frac{\sigma^4}{G^2\Sigma}$$

$$Q = \frac{\sigma_r \kappa}{\pi G \Sigma} \sim 1$$

Clump formation in the Antennae galaxy

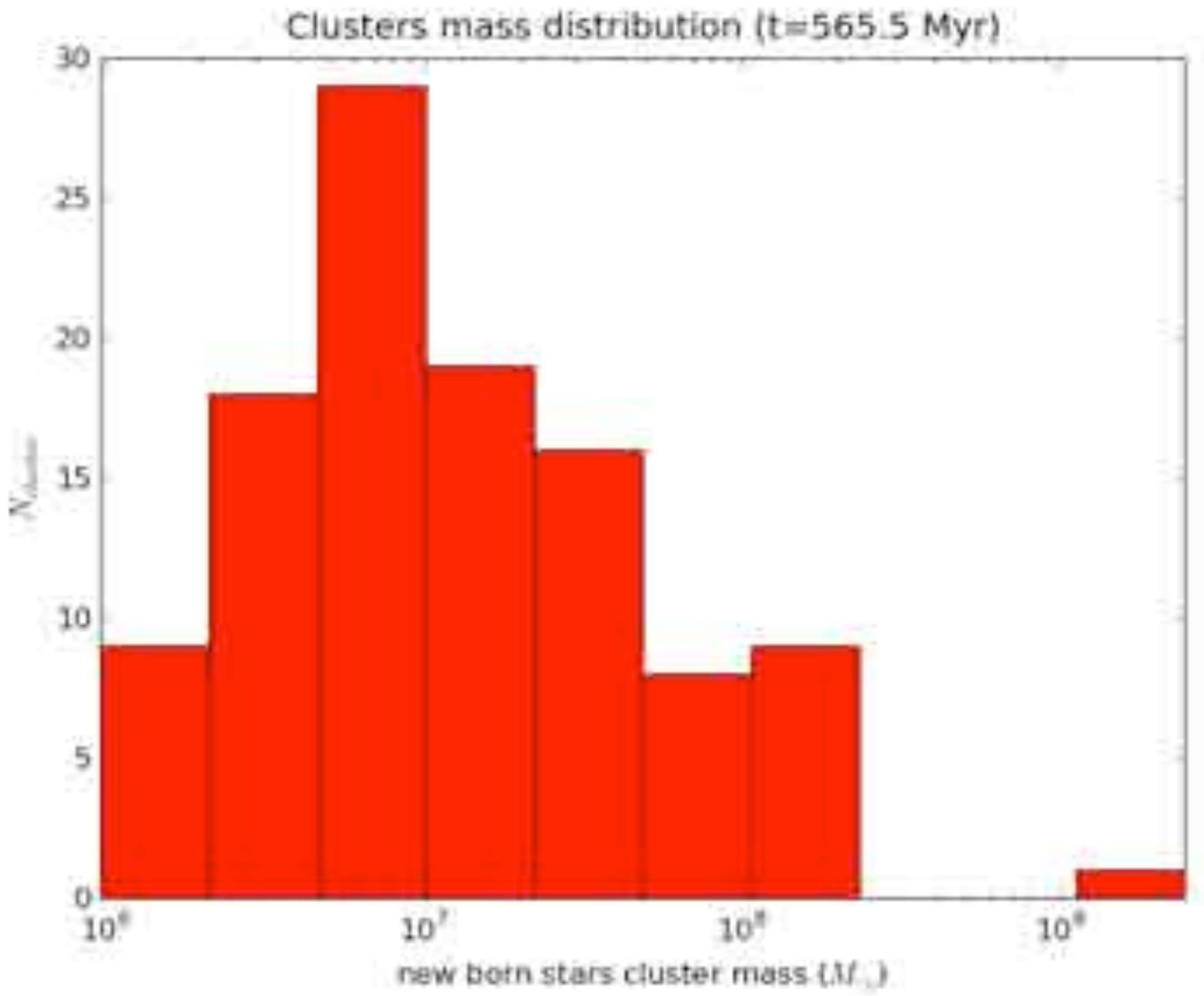
with D. Chapon and F. Bournaud, in collaboration with the Strasbourg group

Stellar cluster formation in the Antennae galaxy

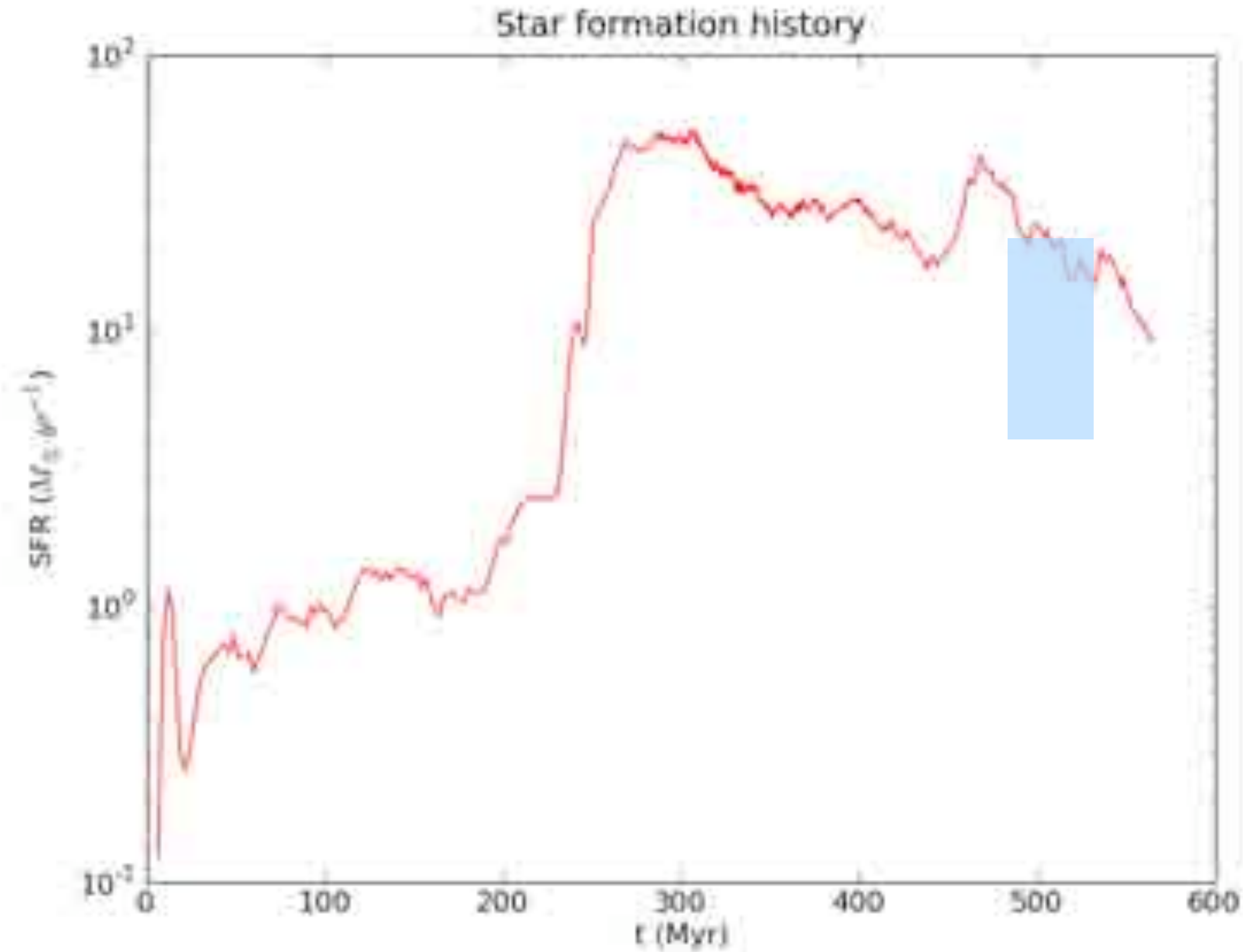


No feedback. Star formation with 1% efficiency for gas density above 10 H/cc.

Stellar cluster mass function



Associated star formation history

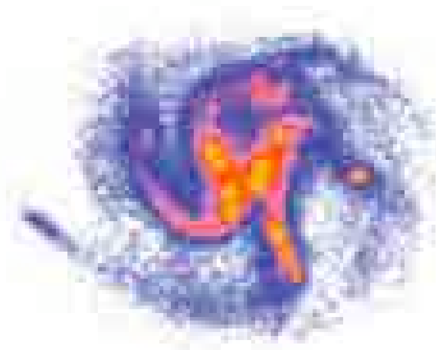


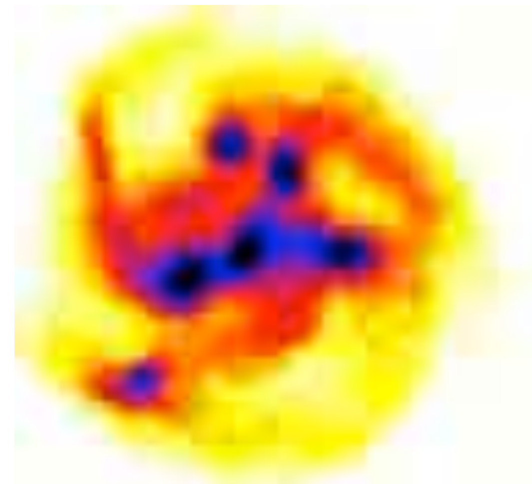
Smooth discs models find SFR ~ 2 Msol/yr (Mihos+ 93, Karl+ 09)


Young galaxies are more asymmetrical and more clumpy than present day galaxies

A model for high-redshift clumpy disks

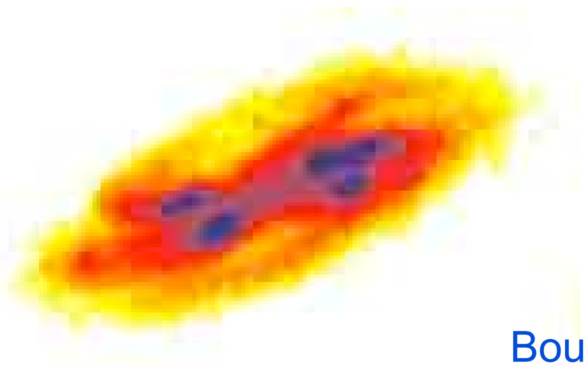
Starting with smooth unstable disks:





$$M_J \simeq \frac{\sigma^4}{G^2 \Sigma}$$

$$Q = \frac{\sigma_r \kappa}{\pi G \Sigma} \sim 1$$



Bournaud, Elmegreen & Elmegreen 2007

Fragmentation into realistic clump-clusters/chains in 100-300Myr

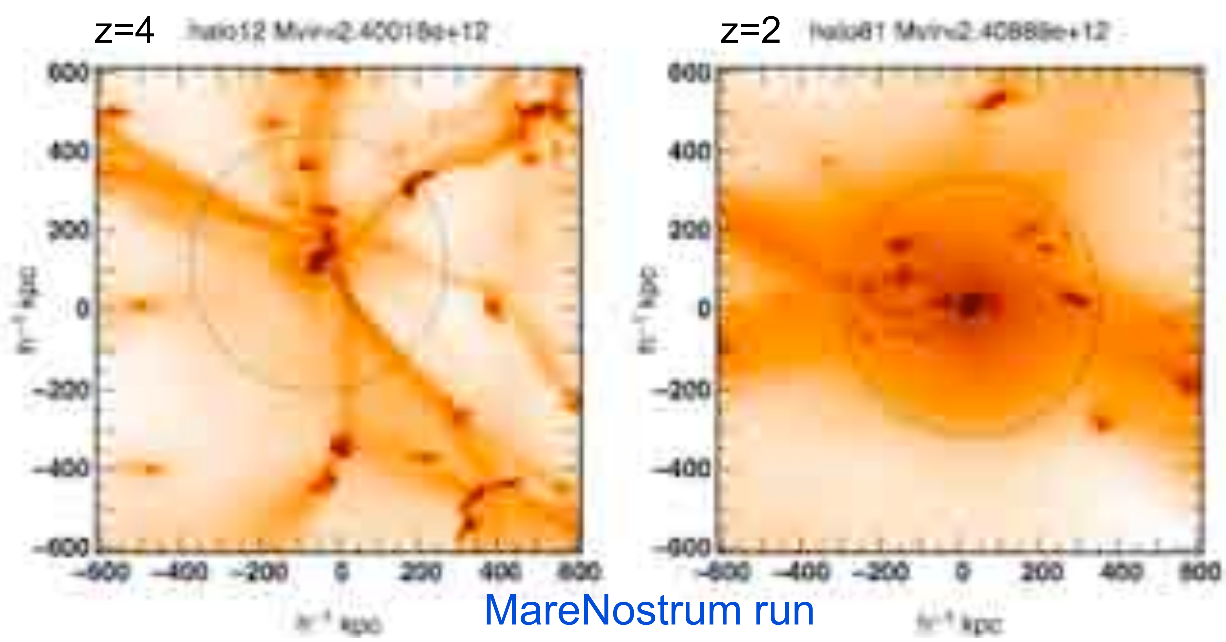
Accretion: cold streams or hot shocks?

Standard model: gas is shock-heated at T_{vir}, then cools down and rains to the central disc.

New model: large scale filaments feed directly fresh cold gas into the disc.

Cold streams accretion occurs at high redshift around high-sigma peaks

Galaxy cluster in the Millenium run



MareNostrum run

Kravtsov (2003)

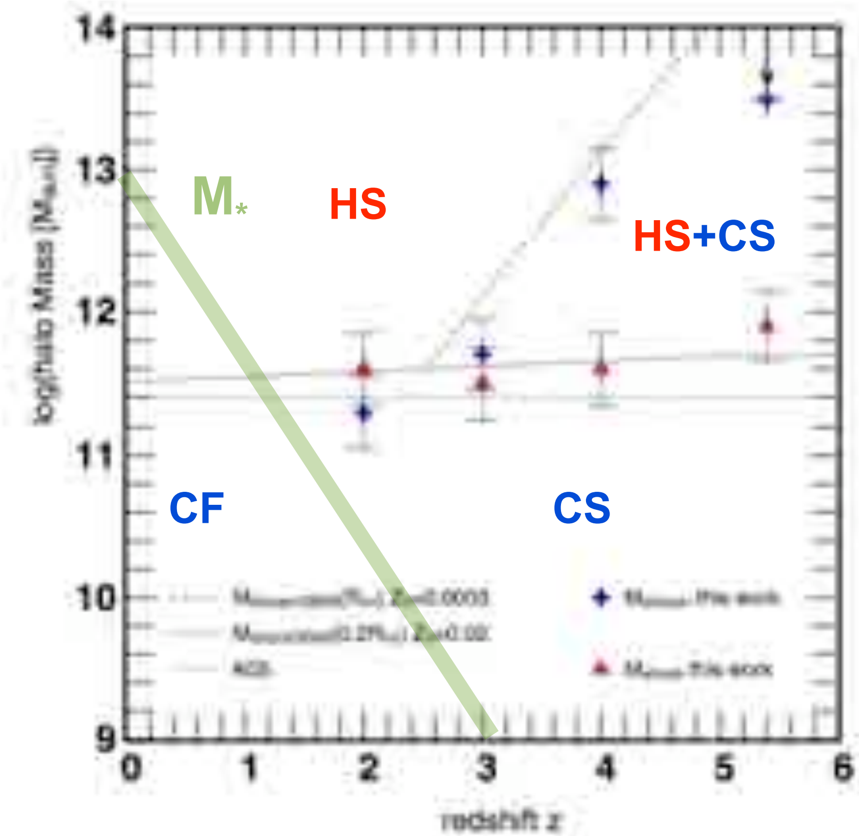
Birnboim & Dekel (2003)

Keres+ (2005)

Dekel & Birnboim (2006)

Smooth gas accretion flows

4 different accretion modes



CF: cold flows

CS: cold streams

HS: hot shocks

Cold stream critical mass:

Filament survival: $t_{cool}(\rho_f) \sim R_{vir}/V_{vir}$

Density enhancement: $\rho_f T_* \sim \rho_{vir} T_{vir}$

for $M_{vir} > M_*$

Hot shock critical mass:

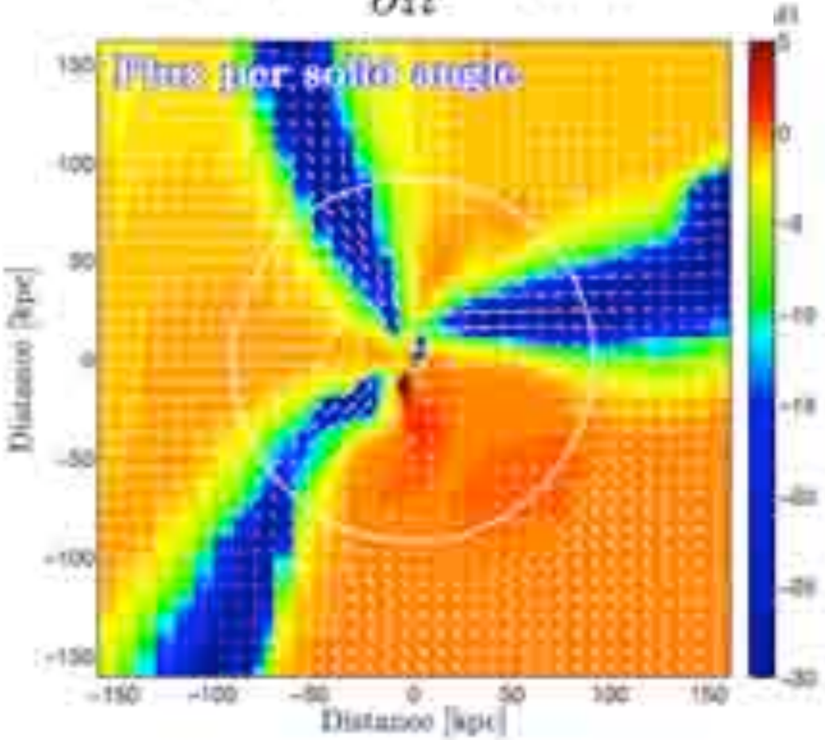
Shock stability: $t_{cool}(\rho_{vir}) \sim R_{vir}/V_{vir}$

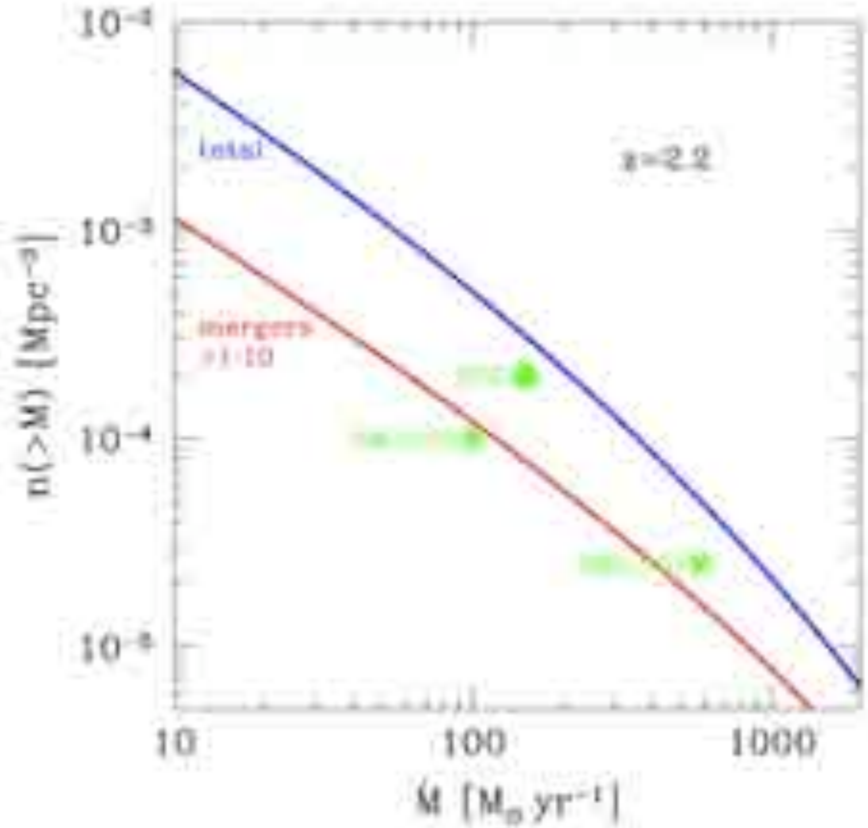
The MareNostrum simulation confirms Birnboim & Dekel (2006) analytical theory.

Data points from Ocvirk+ 2008

Star formation and cold stream accretion

$$\dot{m}_R(r,\Omega) = \frac{\partial \dot{M}}{\partial \Omega} = \rho_R \mathbf{v}_R \cdot \mathbf{n}\, r^2$$

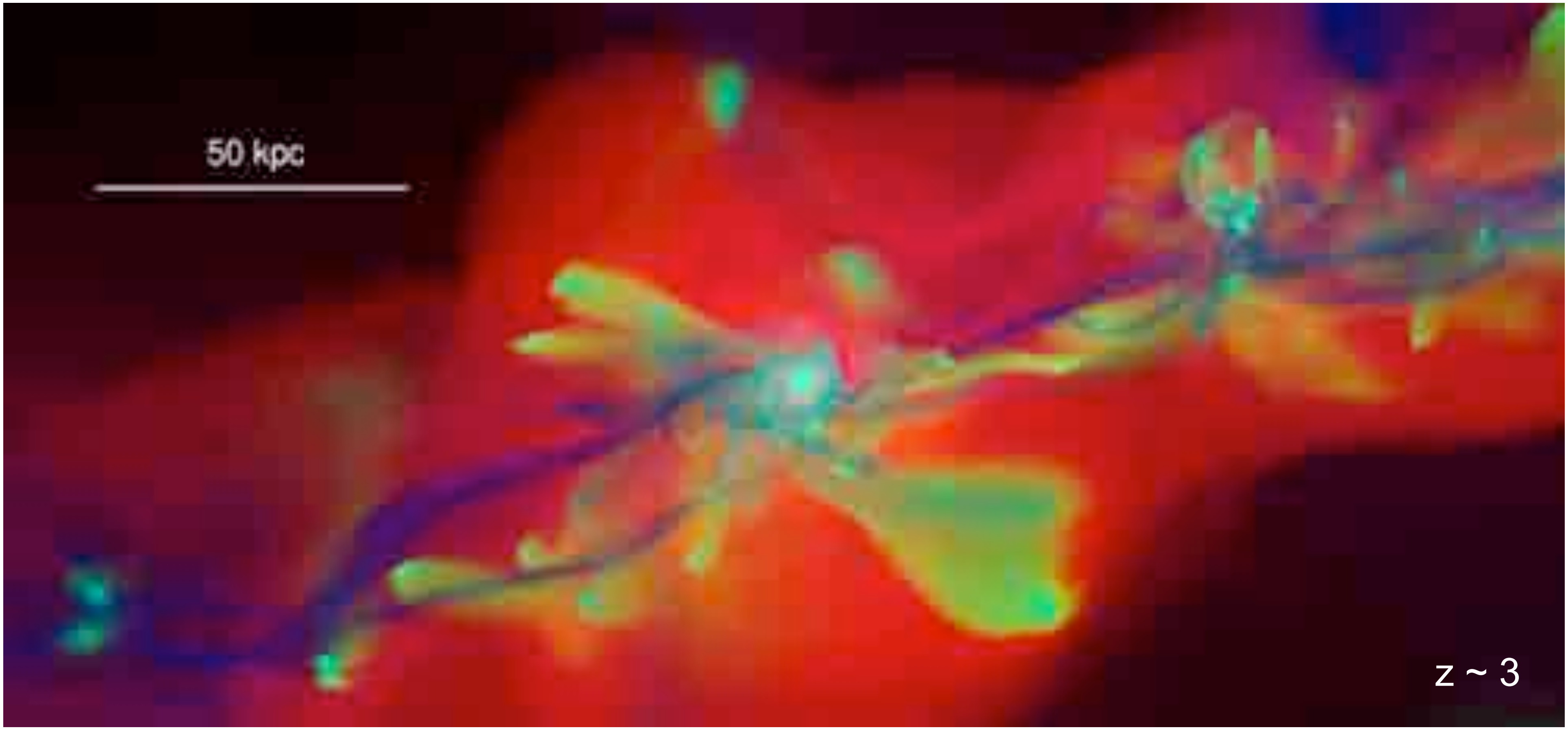




Star formation at high redshift (BzK galaxies ?) proceeds through efficient gas accretion via cold streams. Major mergers (sub-mm galaxies ?) are not frequent enough and cannot explain the disk-like morphologies.

Dekel+ 2009

Cold streams and the origin of clumpy galaxies at high z



Cosmological simulation with RAMSES: low T metal cooling and 40 pc resolution

10^{12} Msol halo from Via Lactea run (Diemand et al. 2006)

Artificial fragmentation suppressed using pressure floor (Truelove et al. 1997)

Agertz+ 2009; Dekel+ 2009; Ceverino+ 2009

Formation of an unstable disc at z=2.7

SFR ~ 20 Msol/yr

M_*~ $6x10^{10}$ Msol

R ~ 10 kpc

3 clumps M_b ~ 10^9 Msol

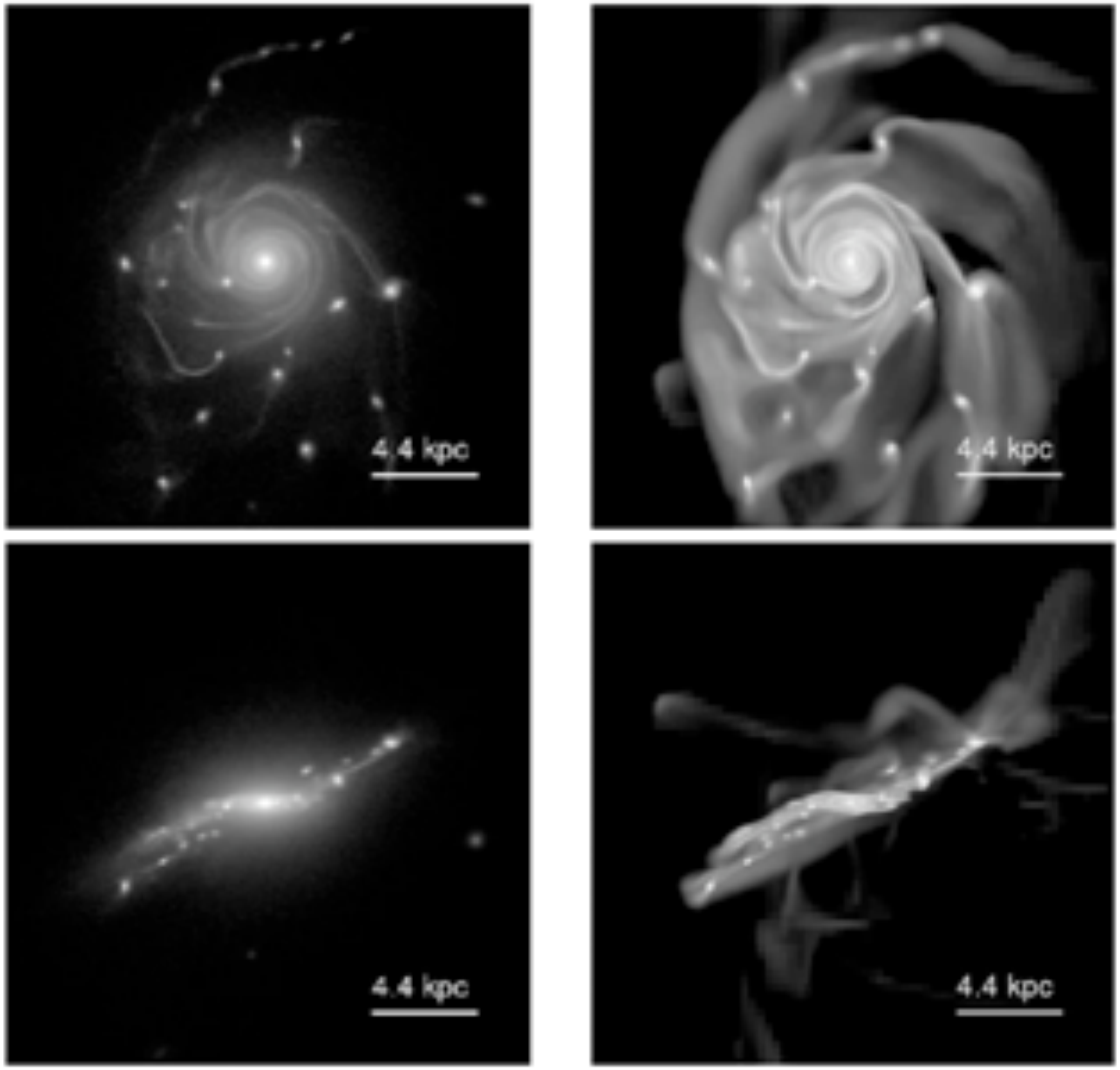
9 clumps M_b ~ 10^8 Msol

2 satellites

Misaligned inner and outer discs

Z/Z_o (inner) ~ 1

Z/Z_o (clumps) ~ 0.1



Cosmic evolution of the magnetic field

In order to explain the observed magnetic field in galaxy clusters, we need $B_{\rm IGM} = 10^{-4} - 10^{-5}\,\mu{\rm G}$

One possible scenario: gas and magnetic field stripping from galaxy satellites.

Where does this (yet undetected) IGM magnetic field comes from ?

Galactic dynamos can amplify the field and eject it in the IGM with galactic winds (Bertone et al. 2006)

Magnetic field evolution in dwarf galaxies is the key process in the cosmic history of the magnetic field.

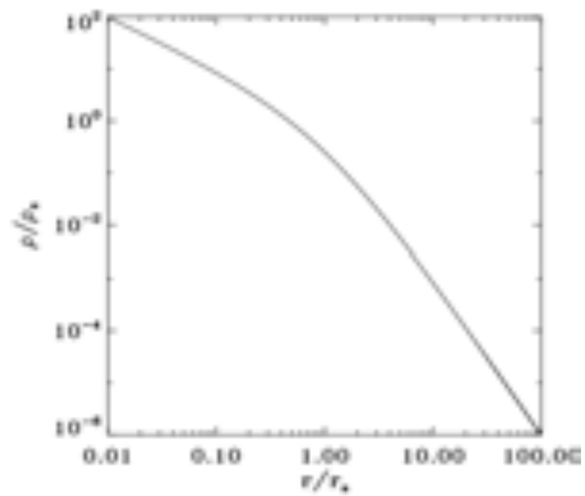
Perform MHD simulations of dwarf galaxies with supernovae-driven winds (Dubois & Teyssier submitted).

A dwarf galaxy in isolation

- Isolated gas and DM halo with average profile

$$\rho = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

Navarro, Frenk & White 1996



- Static potential for the dark halo $\frac{r_{vir}}{r_s} = c = 10$
- Average angular momentum profile

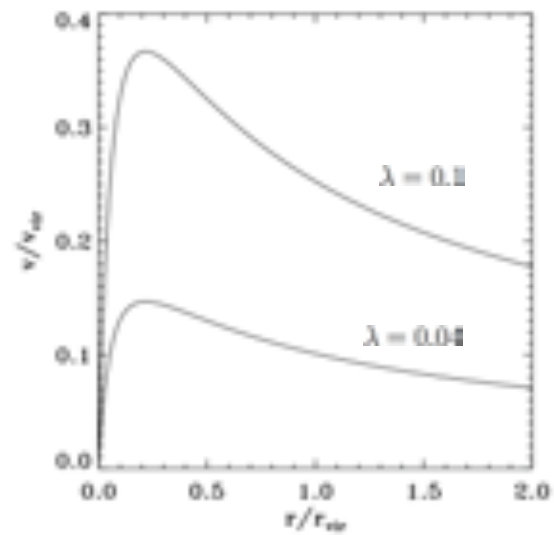
$$j(r) = j_{max}\left(\frac{M(r)}{M_{vir}}\right)^s, \; s = 1 \qquad \lambda = \frac{J|E|^{1/2}}{GM_{vir}^{5/2}}$$

Bullock et al. 2001

- High initial gas fraction:

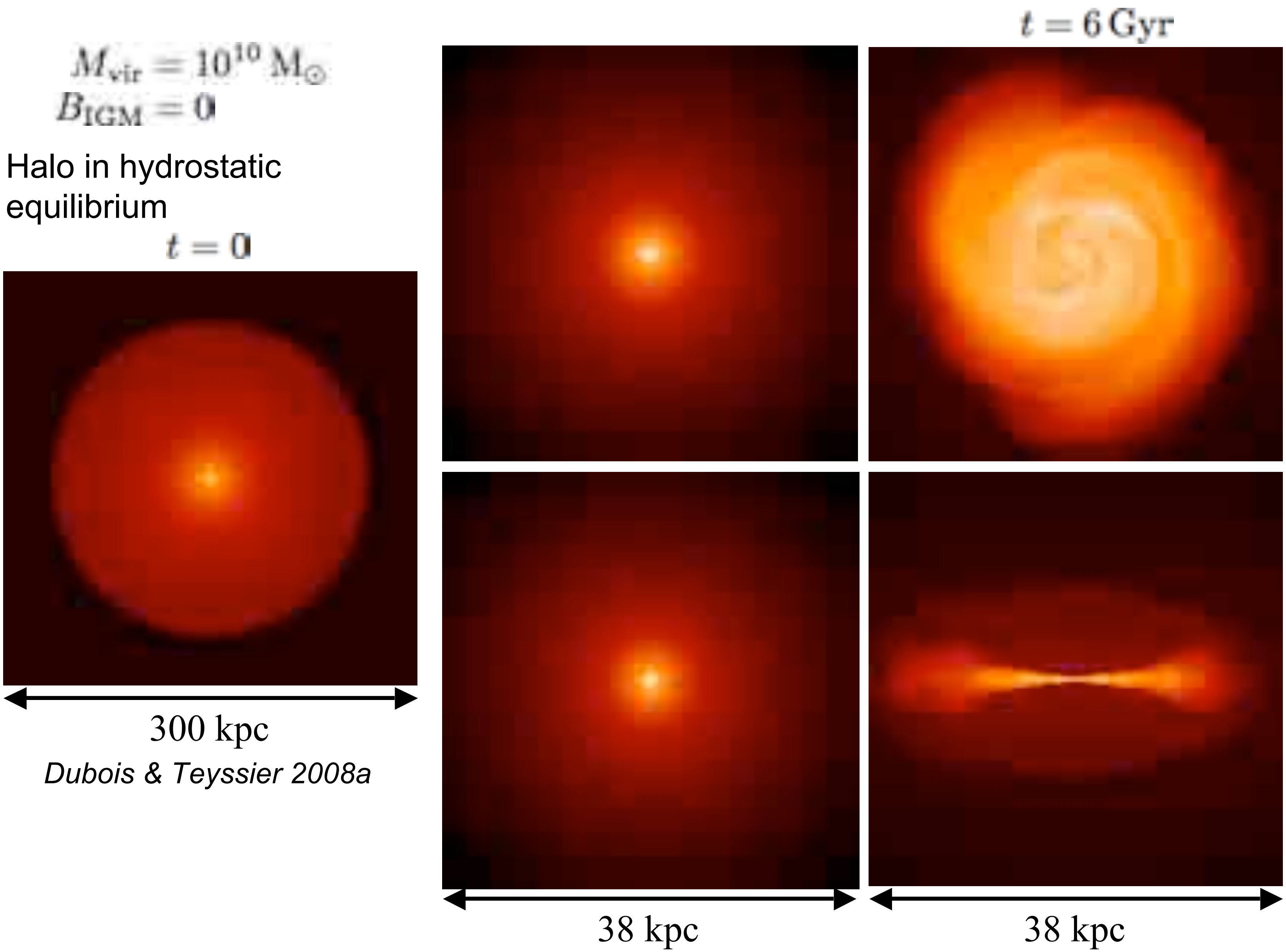
$$\frac{\Omega_b}{\Omega_m} = 15\%$$

- Boundary conditions :
  - Outflow (hydro and B fields)
  - Isolated for Poisson



- Physics : Radiative cooling and effective ISM Equation Of State, star formation and supernovae feedback

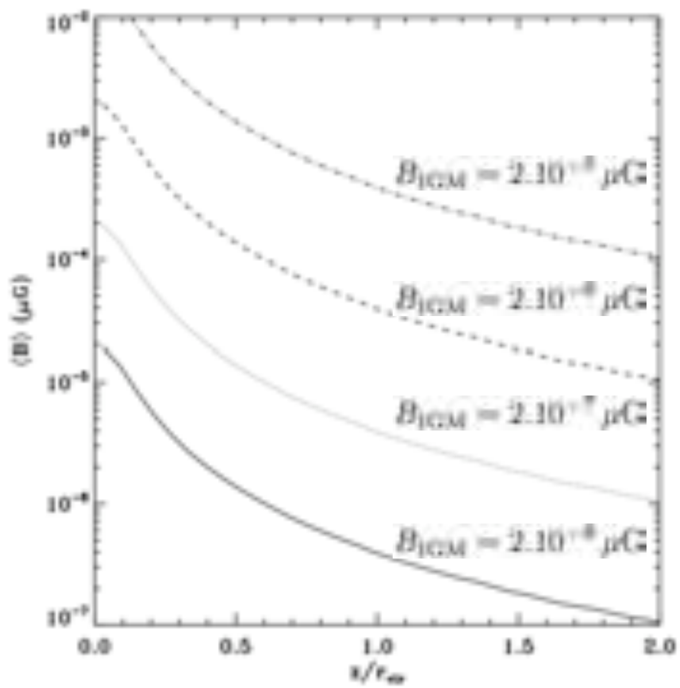
A dwarf galaxy in isolation



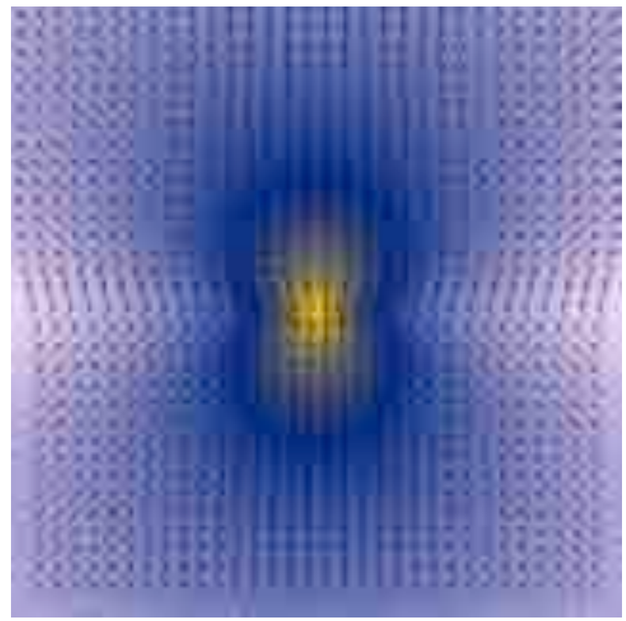
Dubois & Teyssier 2008a

Initial magnetic field in the hydrostatic halo

$$B \propto \rho^{2/3}$$



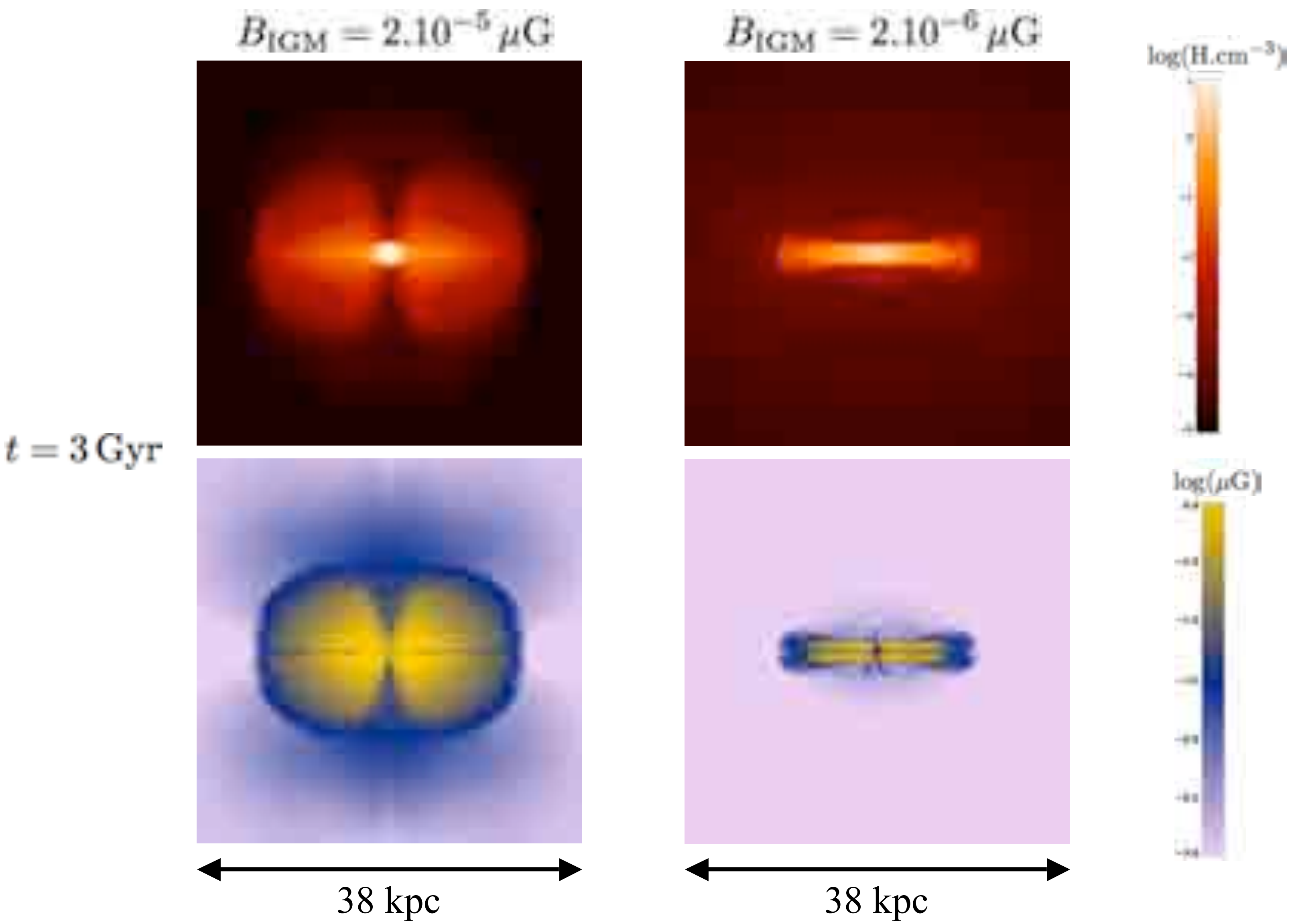
Magnetic field



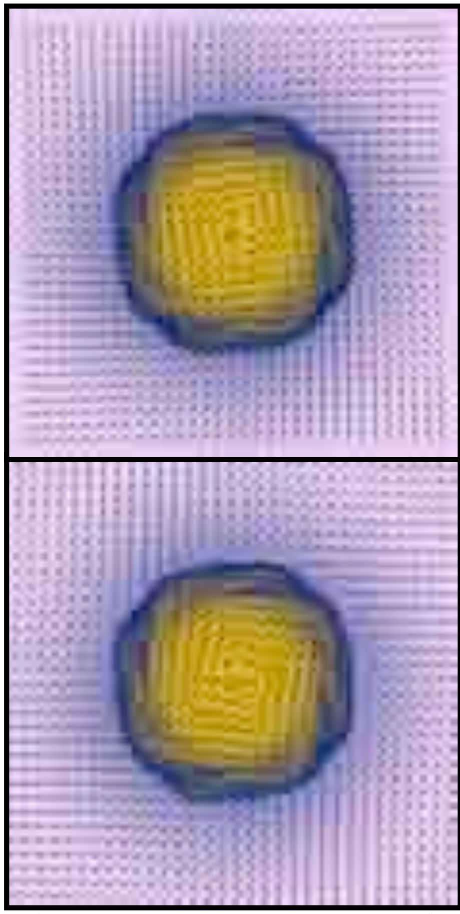
z

Dipole structure aligned with rotation axis

A critical magnetic field for dwarf galaxies ?



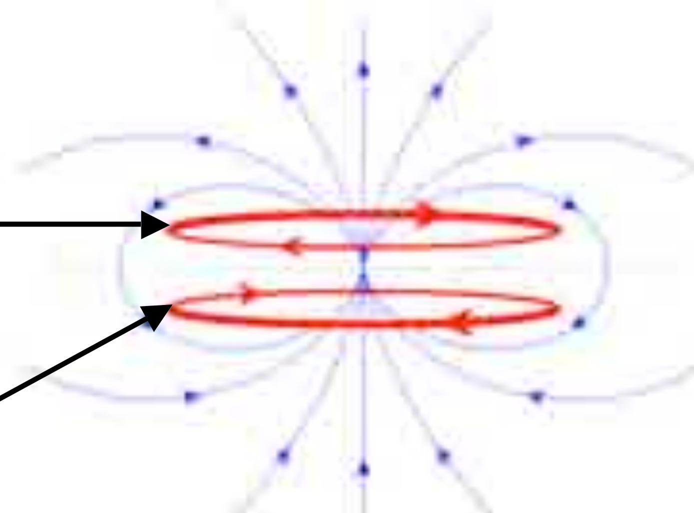
Topology of the galactic magnetic field



Above the plane

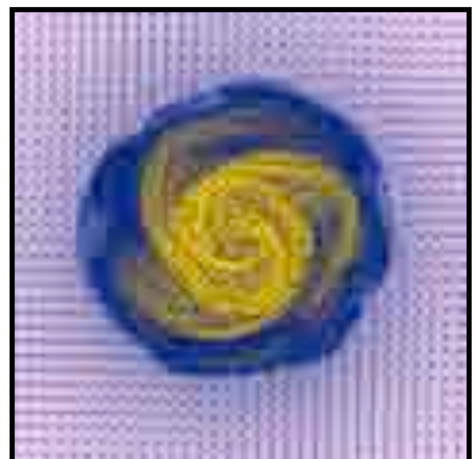
Below the plane

38 kpc



A0 : antisymetric mode with m=0

Spiral structure



38 kpc

Growth of magnetic energy in the disc

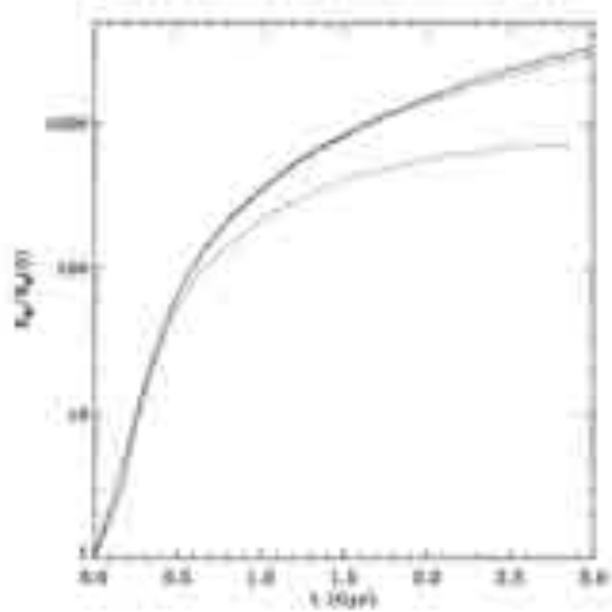


Fig. 3. Total magnetic energy amplification as a function of time for B_{IGM} = 2.10[illegible] μG (solid), B_{IGM} = 2.10[illegible] μG (dotted), B_{IGM} = 2.10[illegible] μG (dashed) et B_{IGM} = 2.10[illegible] μG (dash-dotted).

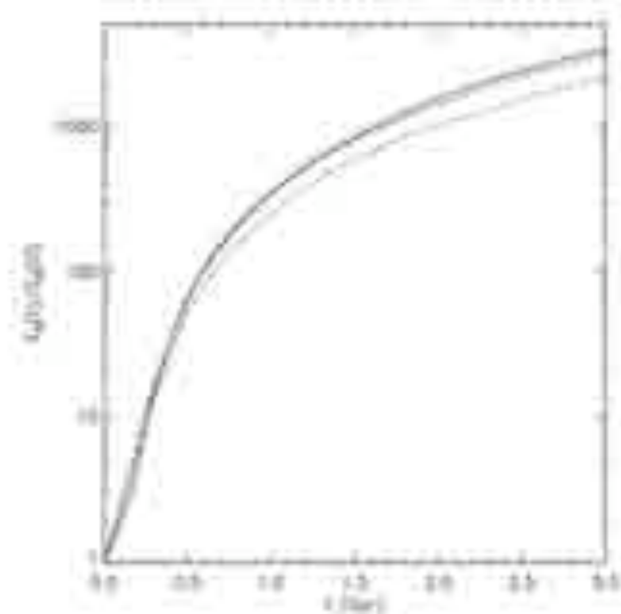


Fig. 5. Total magnetic energy amplification as a function of time during the halo collapse of M_{vir} = [illegible] $M_{\odot}$, λ = 0.1, and with an initial magnetic field B_{IGM} = 2.10[illegible] μG, for different values of the refinement criterion: [illegible] is the reference run (solid line), [illegible] = 5 × [illegible] (dotted line), [illegible] = 25 × [illegible] (dashed line) and [illegible] = 100 × [illegible] (dash-dotted line).

See also Wang & Abel (2008) with a clumpy ISM or Kotarba et al (2009) with an isolated disc

Galactic Dynamo Theory

Consider the induction equation $\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B})$

Decompose both velocity and magnetic field into:

- a mean field
- a fluctuating, small scale field

$$\vec{v} = \langle \vec{v} \rangle + \vec{v}' \qquad \vec{B} = \langle \vec{B} \rangle + \vec{B}'$$

The evolution of the mean field now writes:

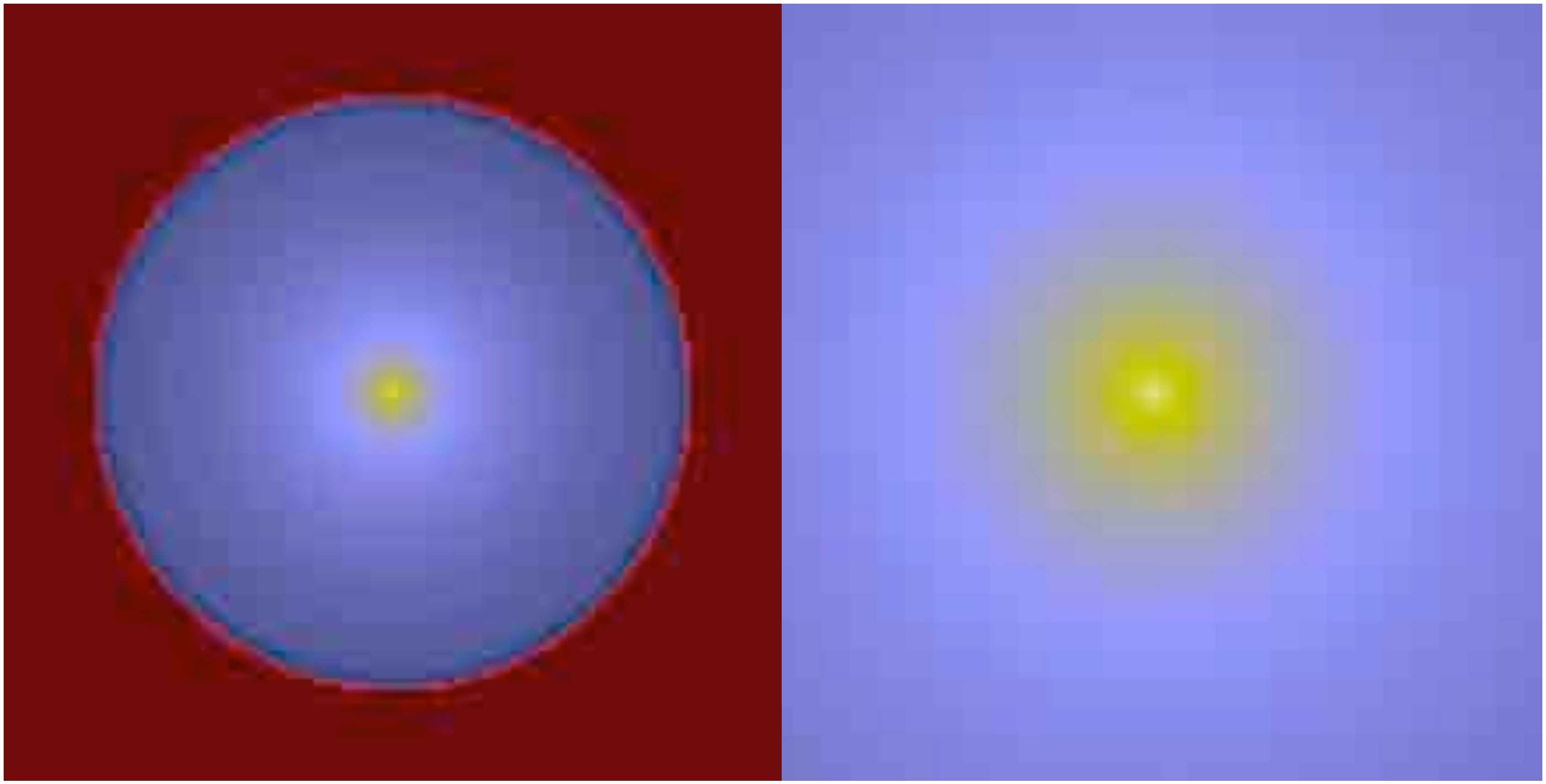
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) + \nabla \times \alpha \vec{B},$$

The parameter $\alpha = \frac{1}{3}\tau \langle \vec{v}' \cdot (\nabla \times \vec{v}') \rangle$ depends on small scale properties of the MHD turbulence that are poorly known.

Galactic winds

$M_{\rm vir} = 10^{10}\,{\rm M}_\odot$ $\lambda = 0.1$ $t_0 = 8\,{\rm Gyr}$ $\Delta x_{\rm min} = 75\,{\rm pc}$

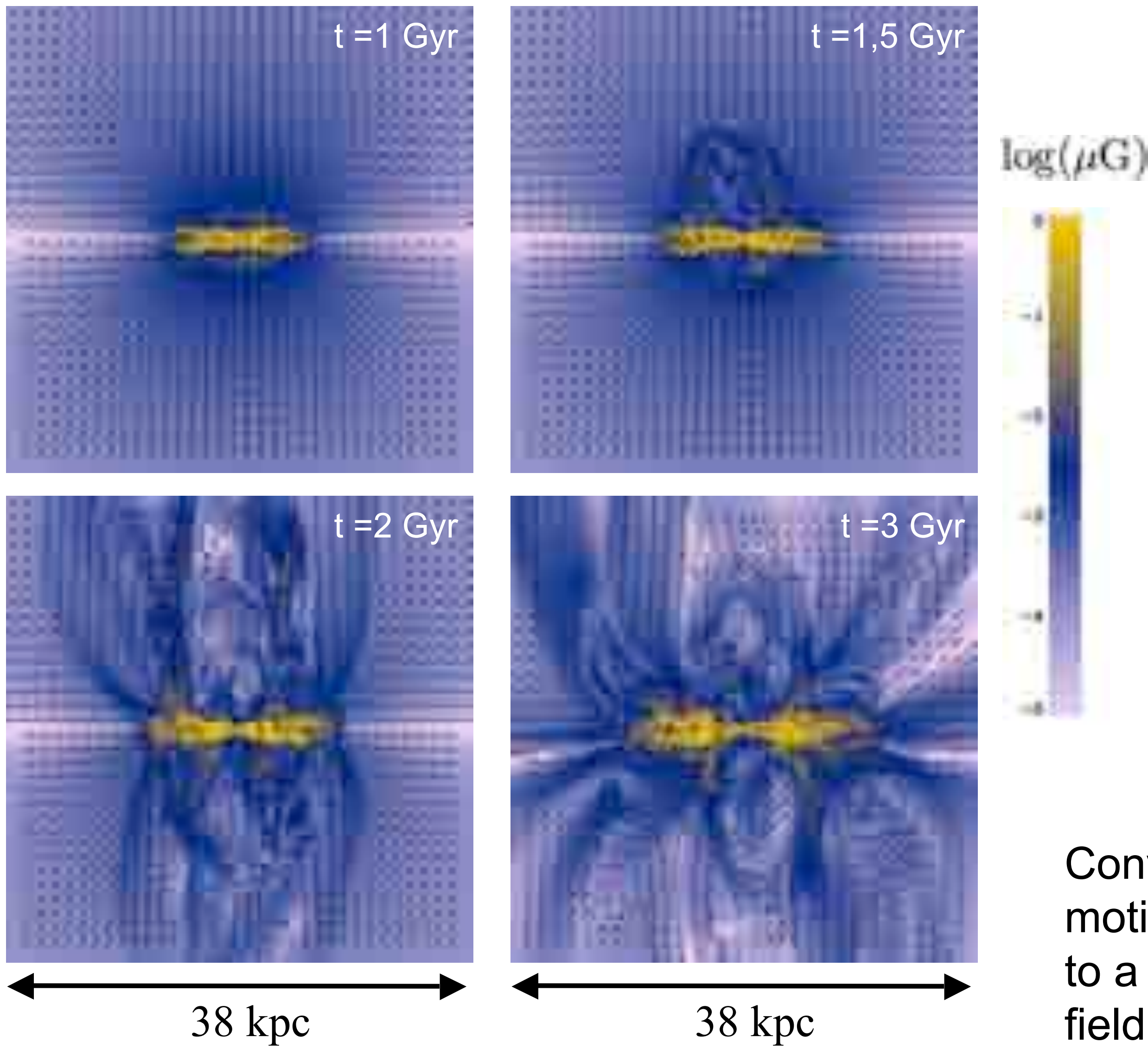
Density map



300 kpc 75 kpc

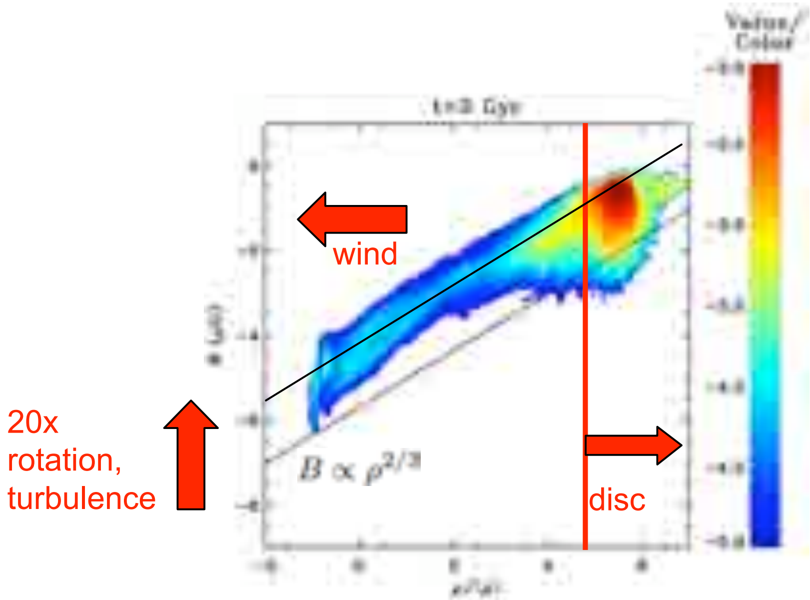
Building up a magnetized wind

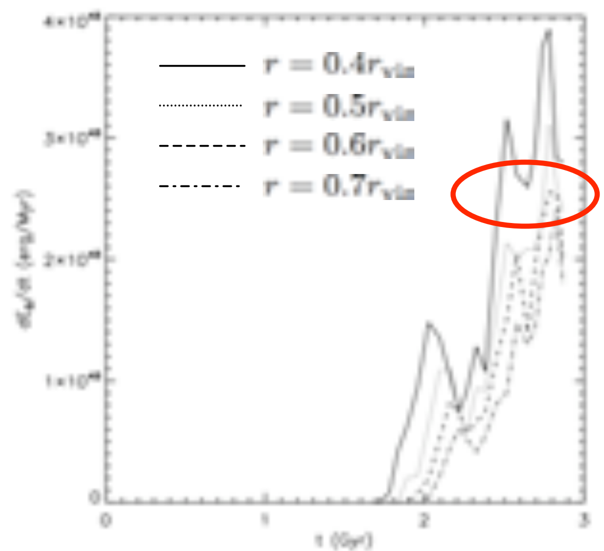
$$B_{IGM} = 2.10^{-6}\,\mu G$$



Convective motions lead to a turbulent field topology

Magnetic energy injection into the IGM





$$\frac{\mathrm{d}E_B}{\mathrm{d}t} = \dot{E}_{B,in} - \frac{1}{3}\frac{\dot{V}_W}{V_W}E_B$$

Bertone et al. 2006

$$\boxed{< B_{\rm bulle} > \simeq 3.10^{-5}\,\mu\mathrm{G}}$$

Magnetic energy injection at the base of the wind

Magnetic energy decrease due to flux conservation

$$B \propto \rho^{2/3} \propto R^{-2}$$

$$E_B \propto B^2 V \propto R^{-1}$$

The Euler equations with a gravity source term

$$\partial_t(\rho) + \partial_x(\rho u) = 0$$

$$\partial_t(\rho u) + \partial_x(\rho u^2 + P) = \rho \mathbf{g}$$

$$\partial_t(E) + \partial_x(E + P)u = \rho \mathbf{u} \cdot \mathbf{g}$$

Gravitational acceleration $\mathbf{g} = -\nabla\Phi$ from the Poisson equation $\Delta\Phi = 4\pi G\rho$

By analogy with the previous analysis, we can define the characteristic time scale for gravitational collapse as the isothermal free-fall time:

$$\tau_{ff} = \sqrt{\frac{\pi}{G\rho}}$$

We can define the gravitational Peclet number as: $\mathrm{Pe} = \dfrac{\Delta x}{c\tau_{ff}} = \dfrac{\Delta x}{\lambda_J}$

Homogeneous collapse

Consider the isothermal collapse of an self-gravitating gas sphere.

Velocity field: $\mathbf{u} = -H(t)\mathbf{r}$ with $H(t)^2 = \frac{8\pi}{3} G\rho(t)\left(1 - \frac{R(t)}{R_0}\right)$

Using the Lax-Friedrich Riemann solver, we have the following flux:

$$(P + \rho u^2)^* \simeq \rho(t)\left(a^2 + H(t)^2 r^2 - \frac{(H(t)r + a)}{2}\Delta x H(t)\right)$$

At the origin, numerical diffusion is larger than thermal pressure if:

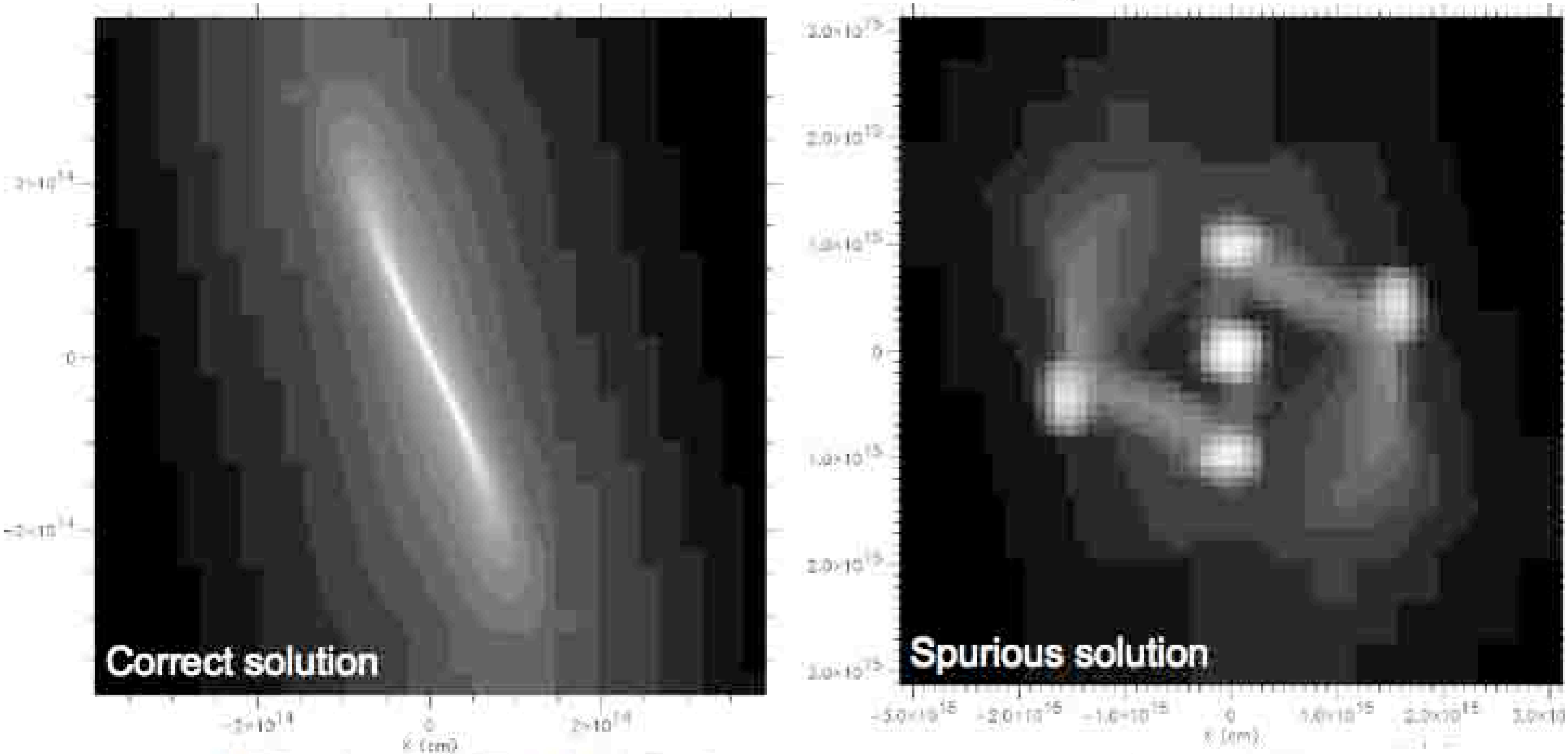
$$a < \frac{H(t)\Delta x}{2} \simeq \frac{12}{\tau_{ff}}\Delta x \quad \text{or} \quad \Delta x > \frac{\lambda_J}{12}$$

We need to resolve the Jeans length by at least ten cells in order to minimise numerical diffusion.

Otherwise, spurious fragmentation of the cloud occurs before collapse.

Numerical test with a collapsing cloud

Truelove *et al.* (1997) considered an initial m=2 perturbation for the spherical collapse of the homogeneous cloud. Using a PPM solver, they found that spurious fragmentation is avoided for $\Delta x < \frac{\lambda_J}{4}$



J. K. Truelove *et al.*, "The Jeans condition: a new constraint on spatial resolution in simulation of isothermal self-gravitational hydrodynamics", ApJ, 1997, 489, L179

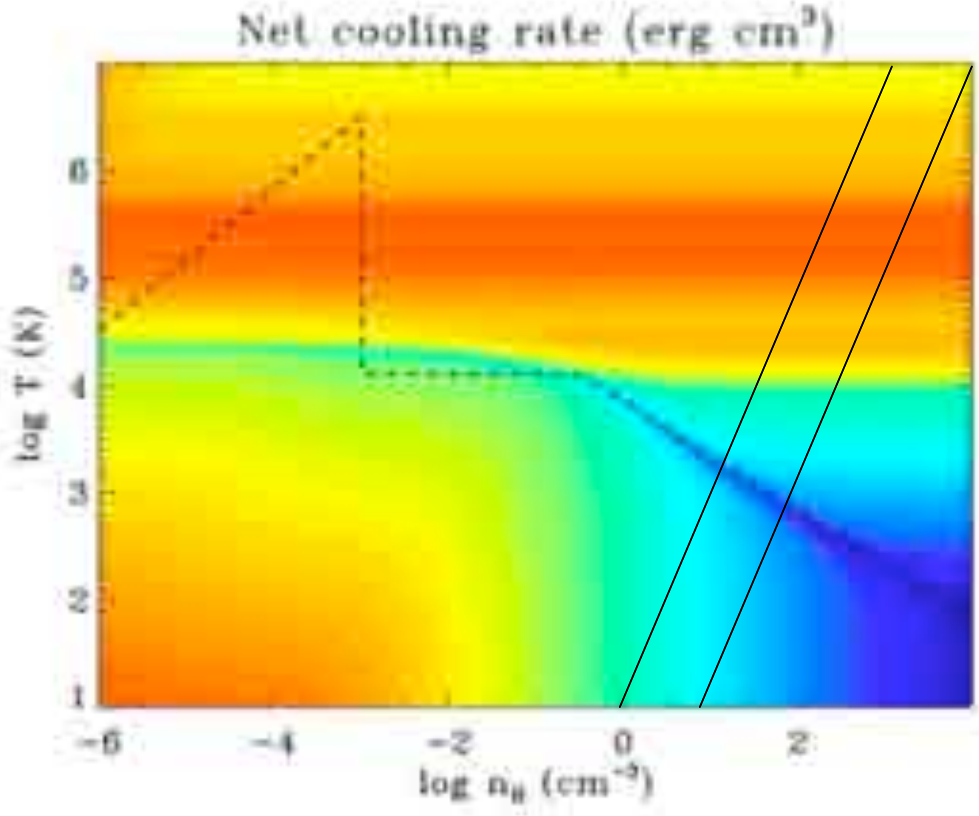
Artificial pressure support

In order to resolve the Jeans length, we add to the thermal pressure a dynamical, Jeans-length related, pressure floor defined as $P_J=16\Delta x^2 G\rho^2$

This sets an artificial thermal Jeans length in the problem.

Keeping a fixed artificial Jeans length, one can then refine the grid and check for convergence.

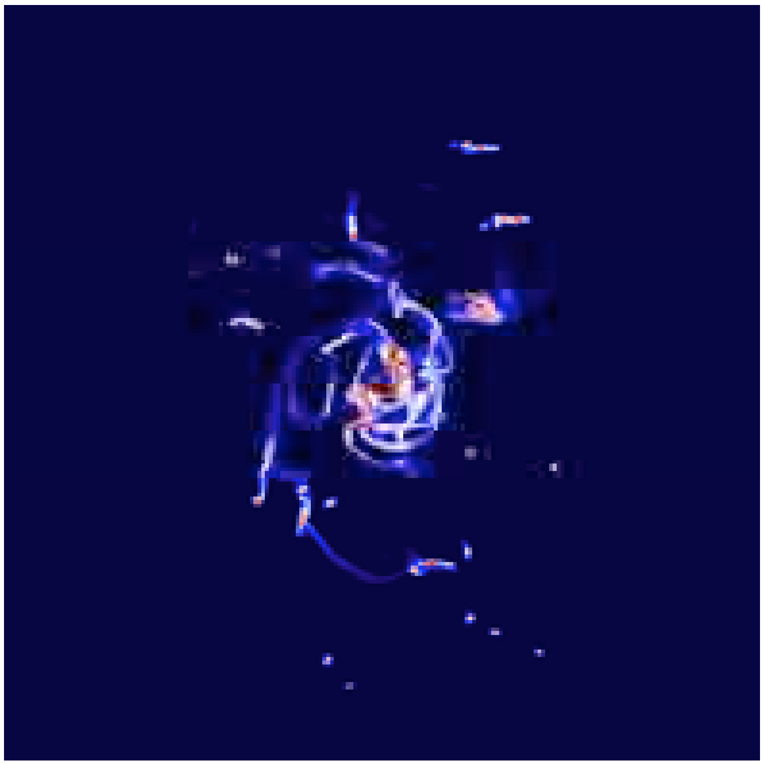
This artificial Jeans length sets the minimum cloud mass, equal to the thermal Jeans mass M_J.



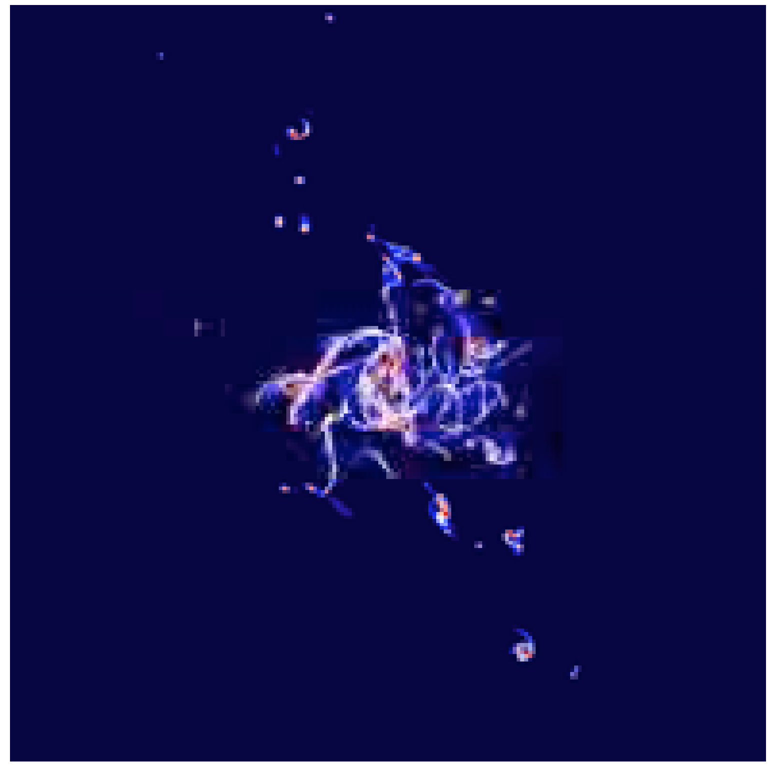
Truelove *et al.* 1997; Bates & Burkert 1997; Machacek *et al.* 2001, Robertson & Kravtsov 2008

Convergence study

High-redshift isolated clumpy disc



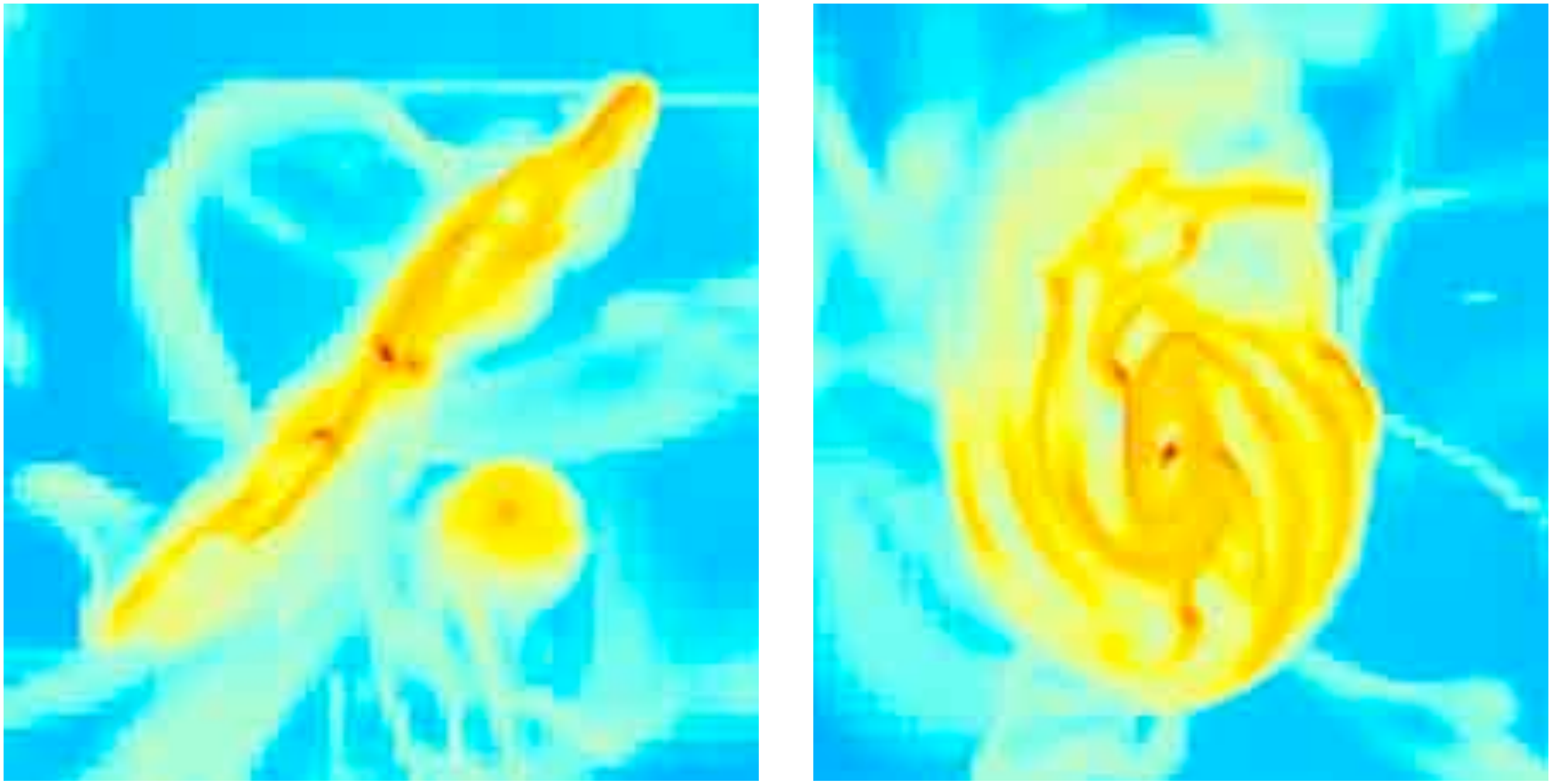
λ_J=80 pc with 4 cells



λ_J=80 pc with 8 cells

Higher resolution simulations in progress

Low T cooling with 50 pc resolution: formation of a clumpy ISM ?



Gas density maps 20 kpc physical at z ~ 1