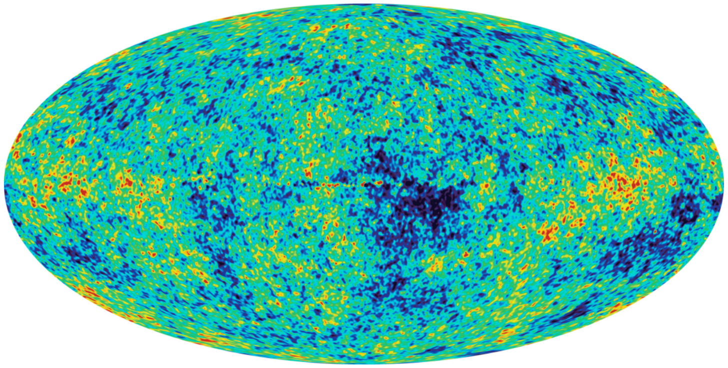
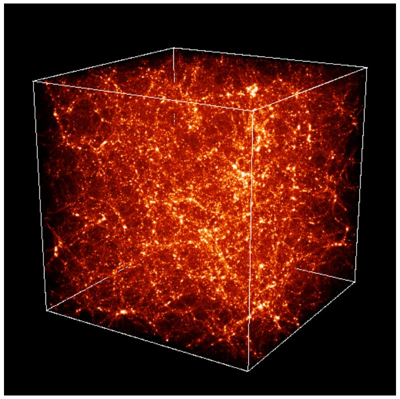
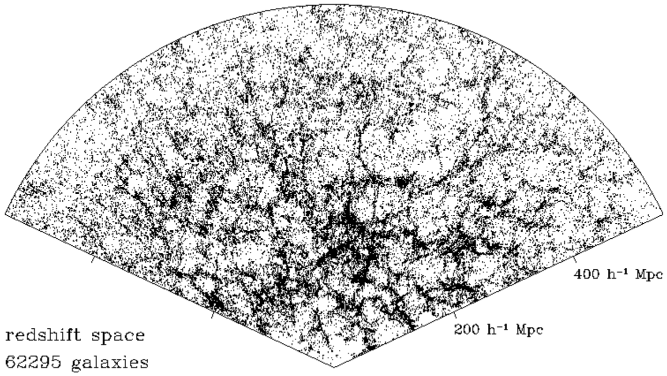
Disc formation in cosmological simulations using AMR

Romain Teyssier

University of Zurich







Outline

- MW-like disc galaxy formation with RAMSES
- Towards resolving the clumpy ISM
- Cold stream accretion and high-redshift galaxies

Stephanie Courty, Brad Gibson (UCLan)
Pierre Ocvirk (Potsdam)
Avishai Dekel (Jerusalem)
Oscar Agertz, Ben Moore (UniZH)

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 $\rho_{\rm g} > \rho_0$

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

Star formation recipes: $\dot{\rho}_* = \dfrac{\rho_{\rm g}}{t_*(\rho_{\rm g})}$

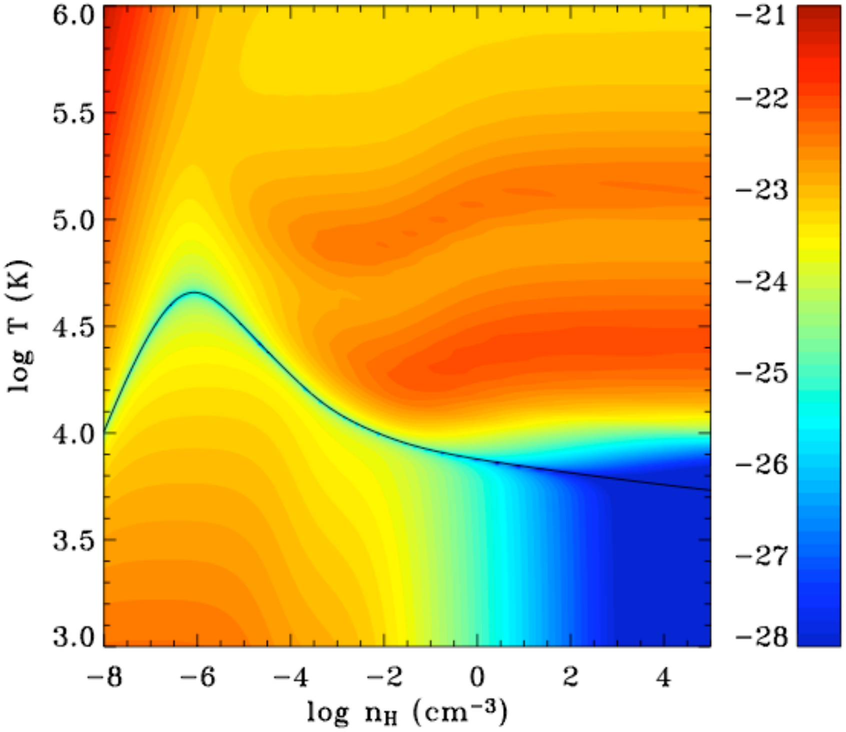
$$t_* = t_0 \left(\frac{\rho_{\rm g}}{\rho_0}\right)^{-1/2}$$

- 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

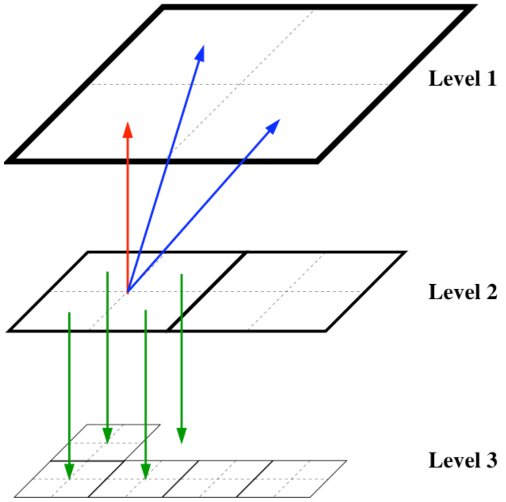
Numerical issues:

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



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.

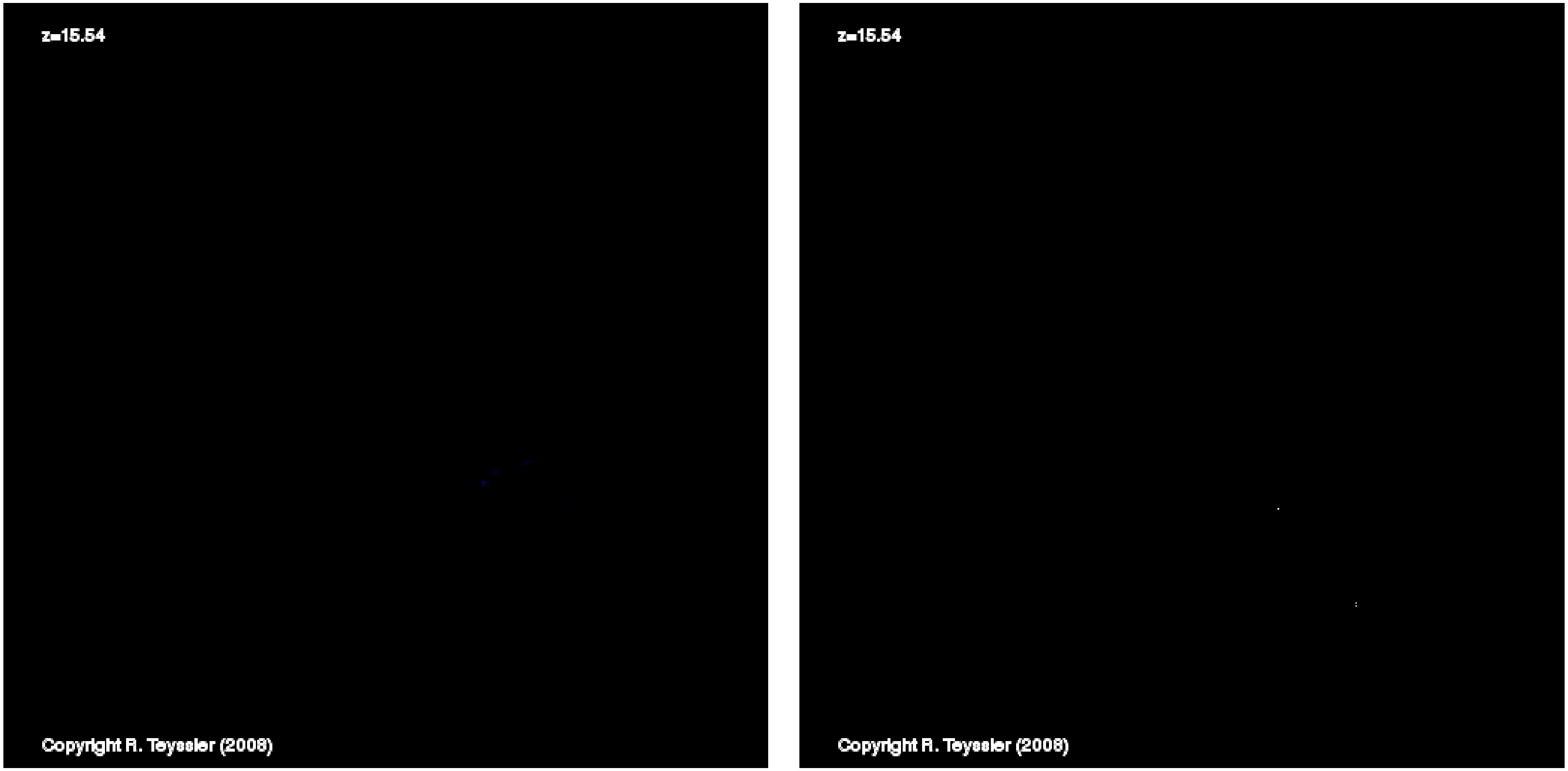
Hydro module: unsplit second order Godunov method (MUSCL) with various Riemann solvers and slope limiters. New CT based MHD solver.

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.

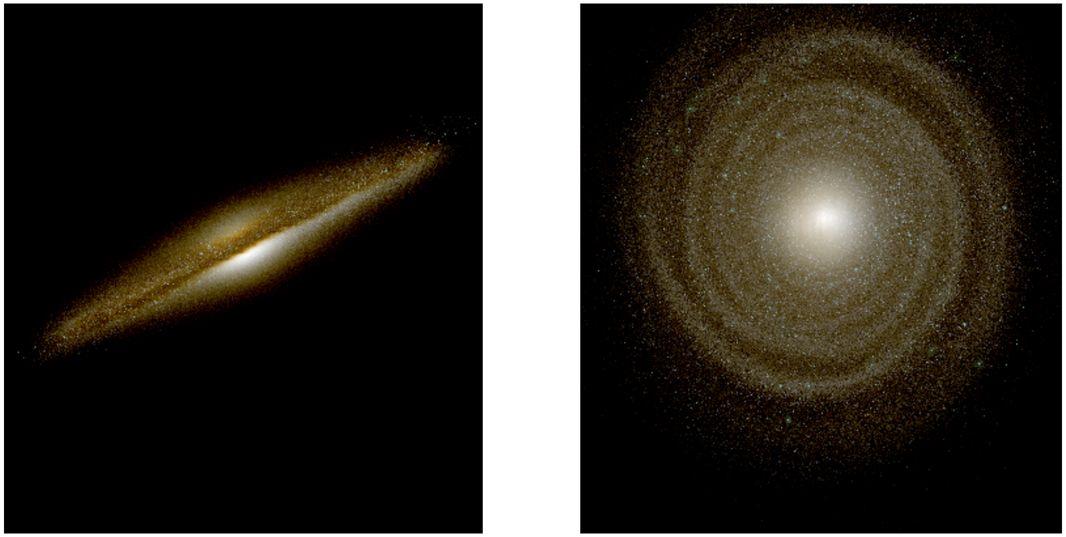
Simulating disc galaxies with AMR



RAMSES (AMR) simulation of a spiral disc at z=0.
200 pc spatial resolution (sub-grid model)
8×10^5 dark matter particles in R_{200} and $M_{200}=7 \times 10^{11}$ M_{sol}
Collaboration with Brad Gibson and Stéphanie Courty
(University of Central Lancashire)

A realistic spiral galaxy ?

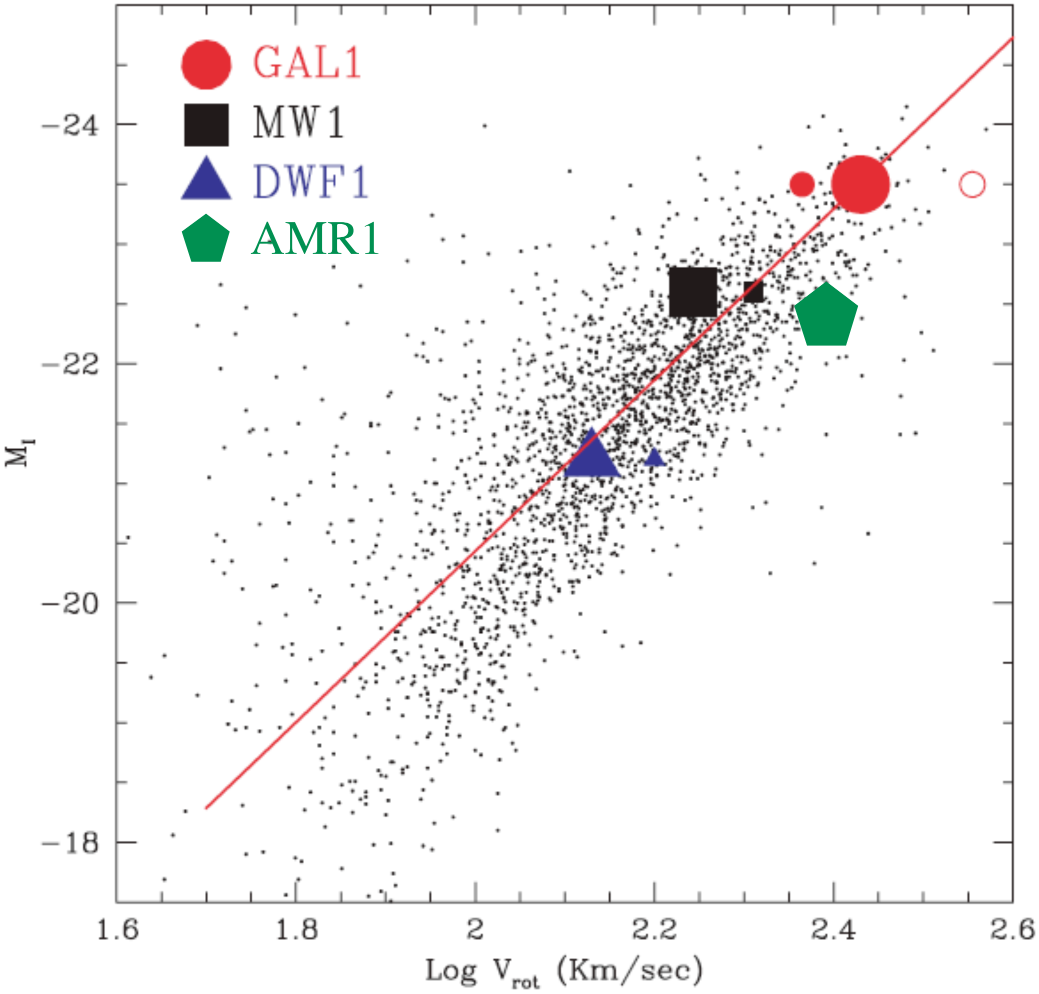
B/D ~ 1



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)

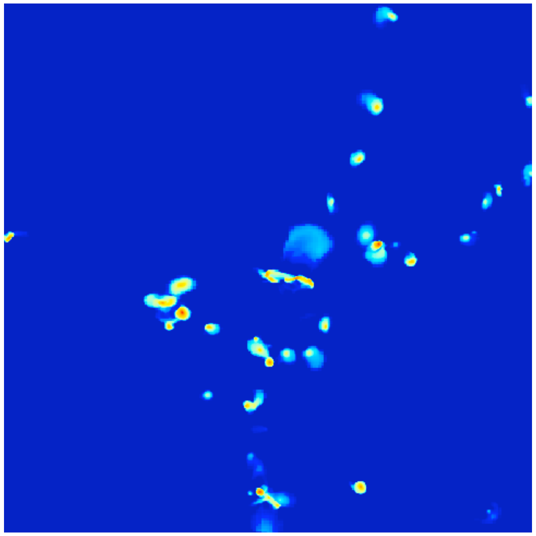
Kinetic feedback:
For each new stellar particle, create another collisionless particle to account for a companion Giant Molecular Cloud. After 10 Myr, release the GMC mass together with the supernova ejecta in a Sedov blast wave.

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)

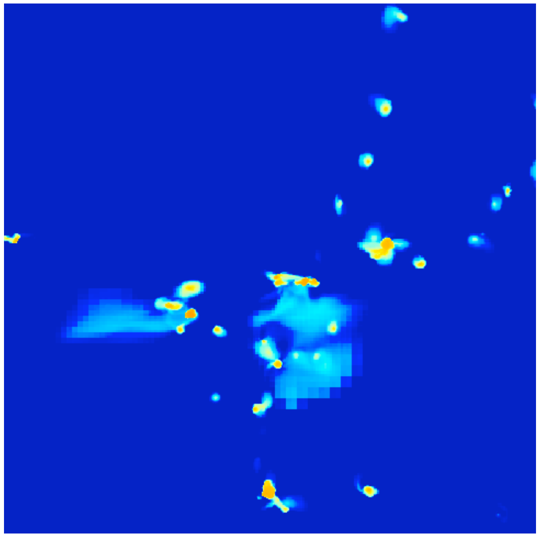
4- Kinetic feedback with $M_{GMC}=M_{gas}/2$ in the parent cell: blast wave with maximum momentum kick but $v_{SN} < 35$ km/s

Galactic winds at redshift 3

Thermal

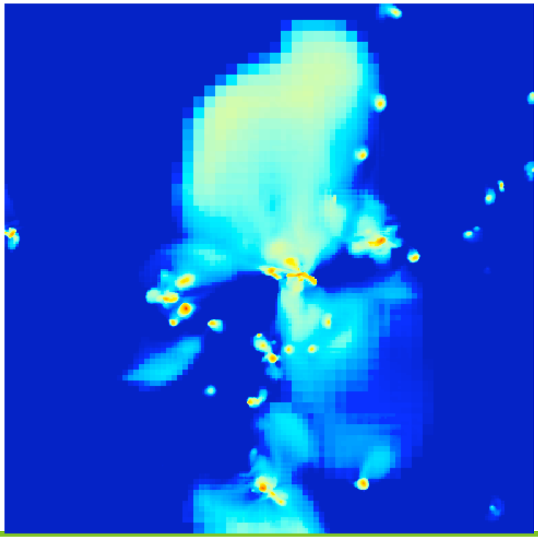


Delayed 50 Myr

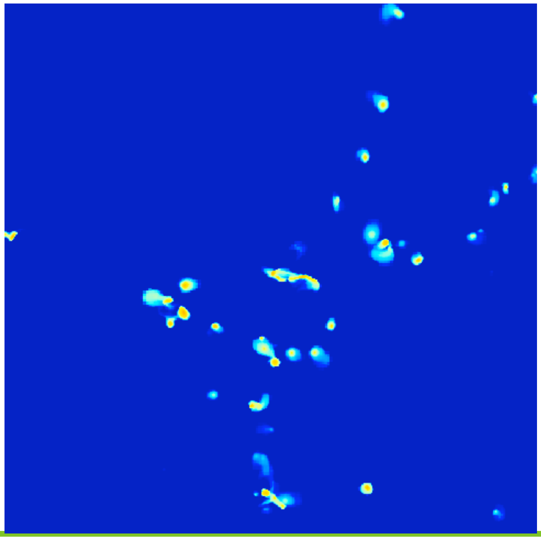


Metal maps:
Size 200 kpc/h physical
Max. resolution 200 pc physical

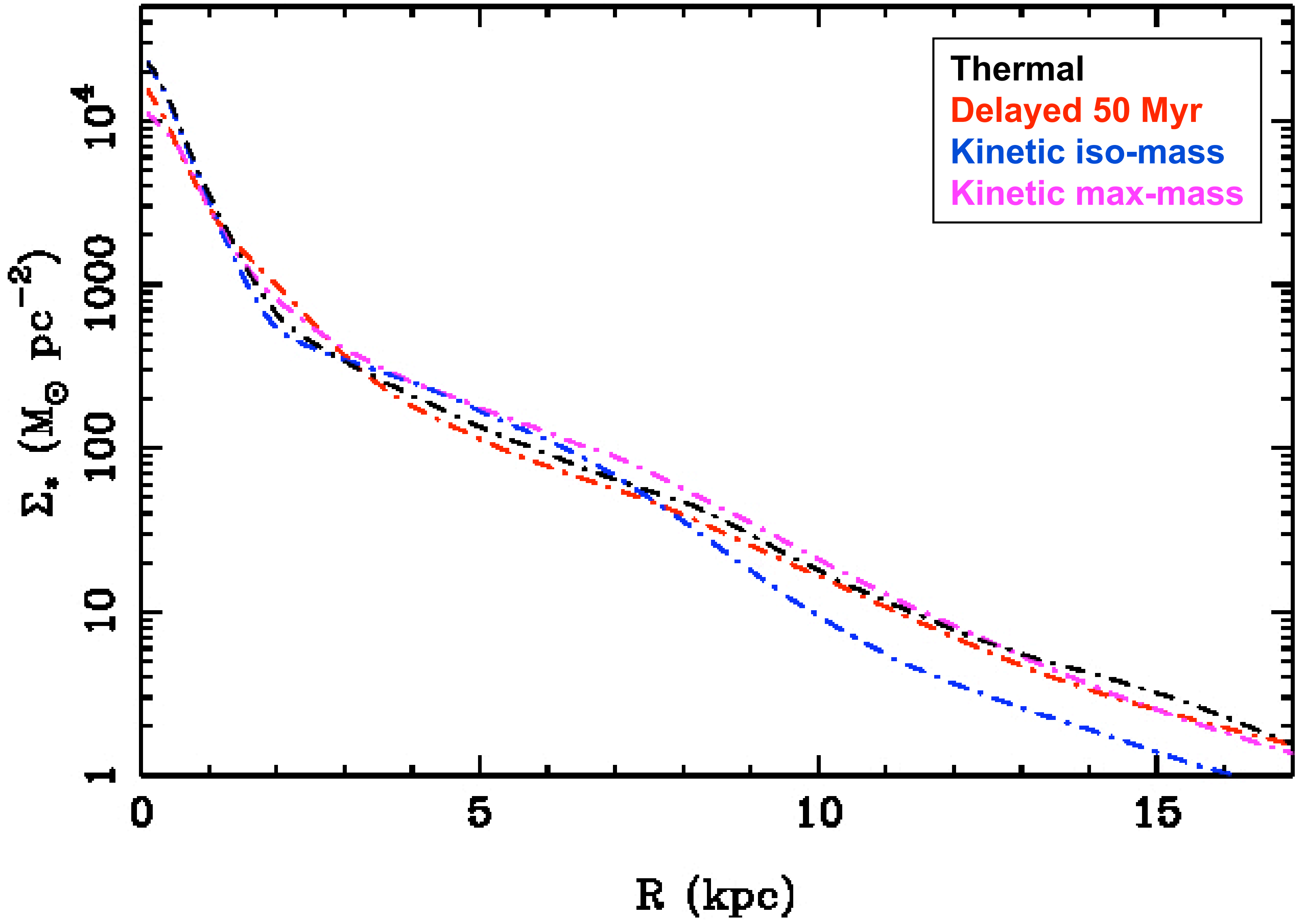
Kinetic iso-mass



Kinetic max-mass



Stellar surface densities



Baryon budget

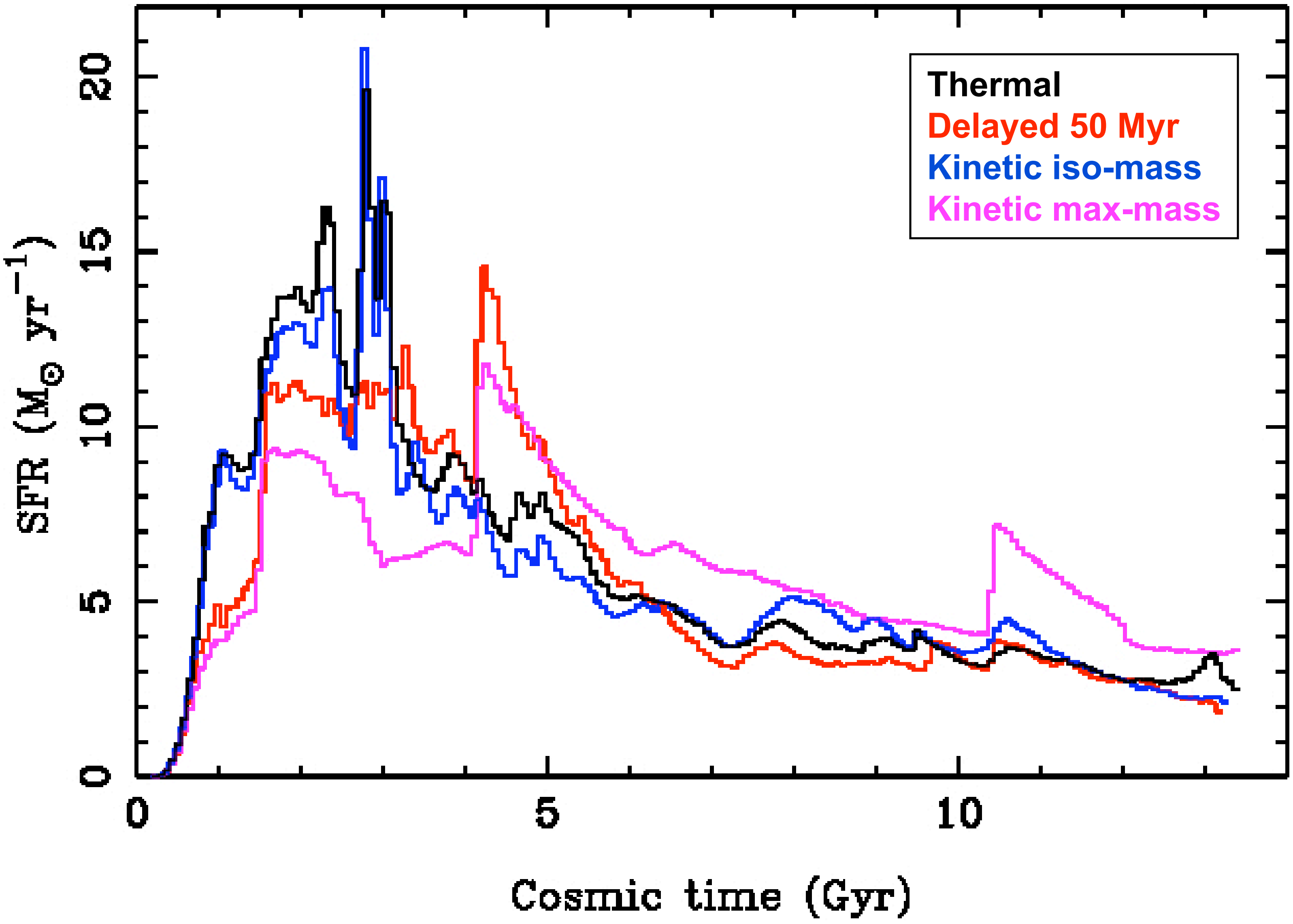
$M_{vir} = 7 \times 10^{11}\ M_{sol}$

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

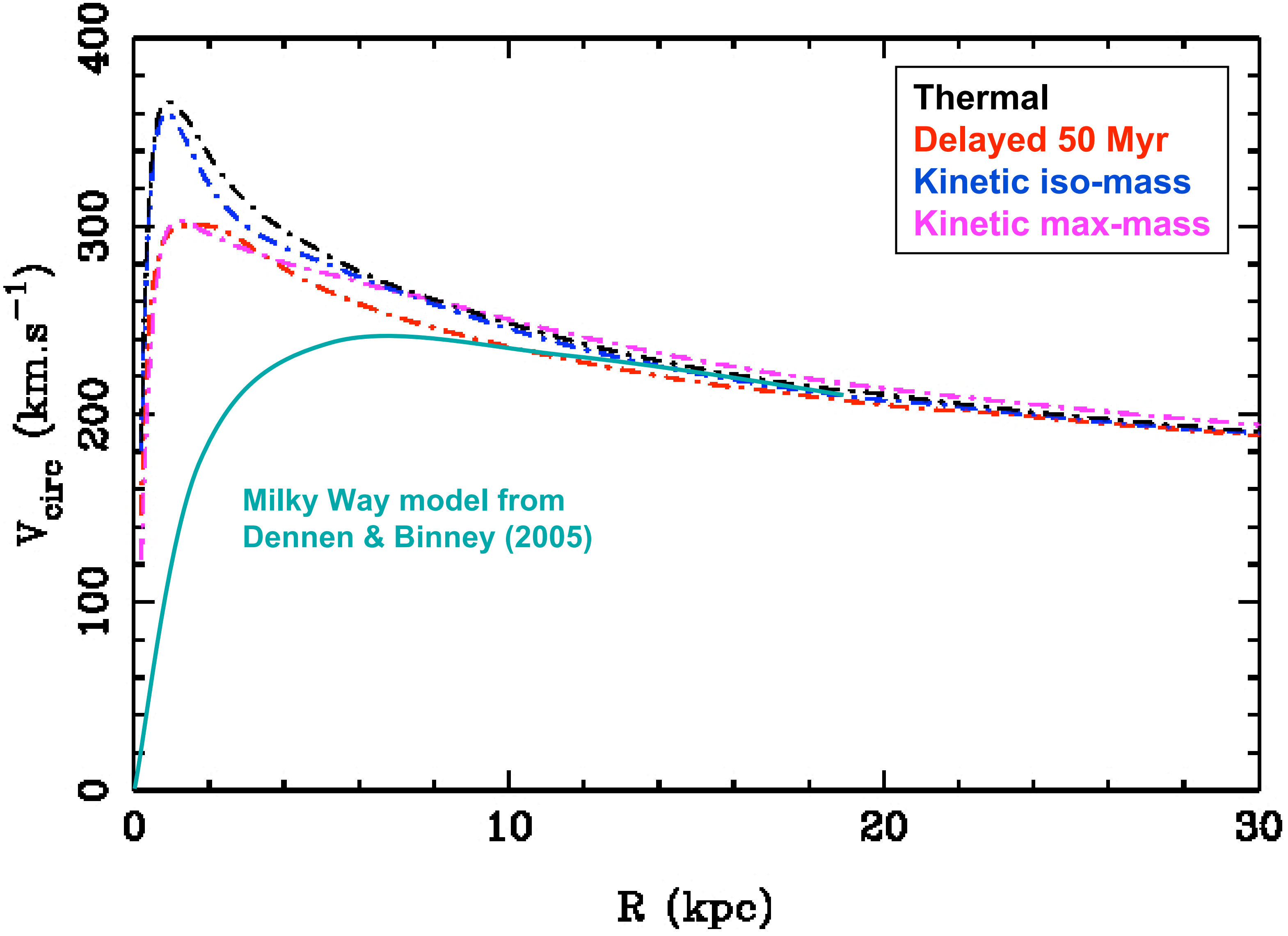
Bulbe: r < 3 kpc

$\times 10^{10}\ M_{sol}$	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%

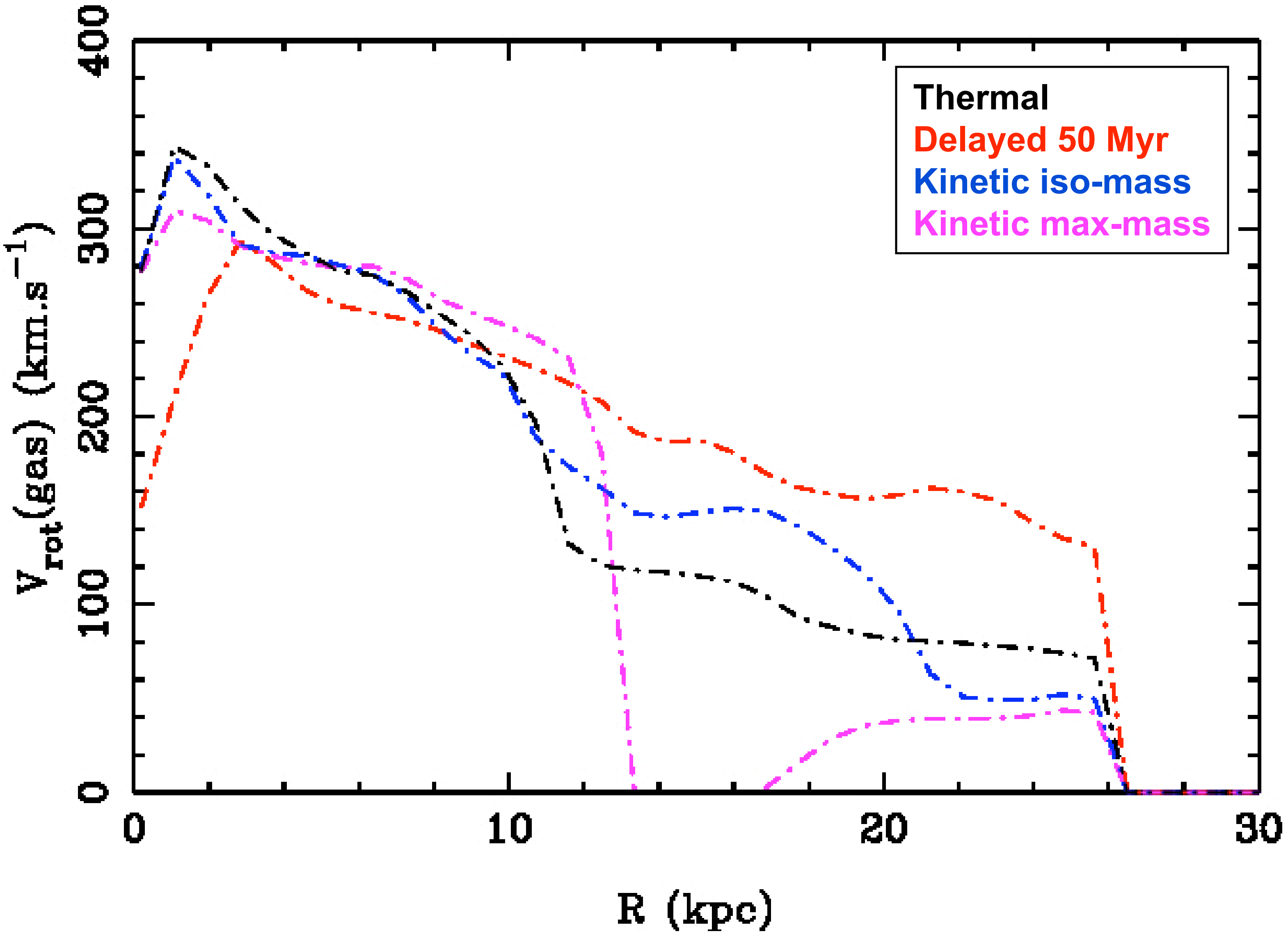
Star formation histories



Circular velocities

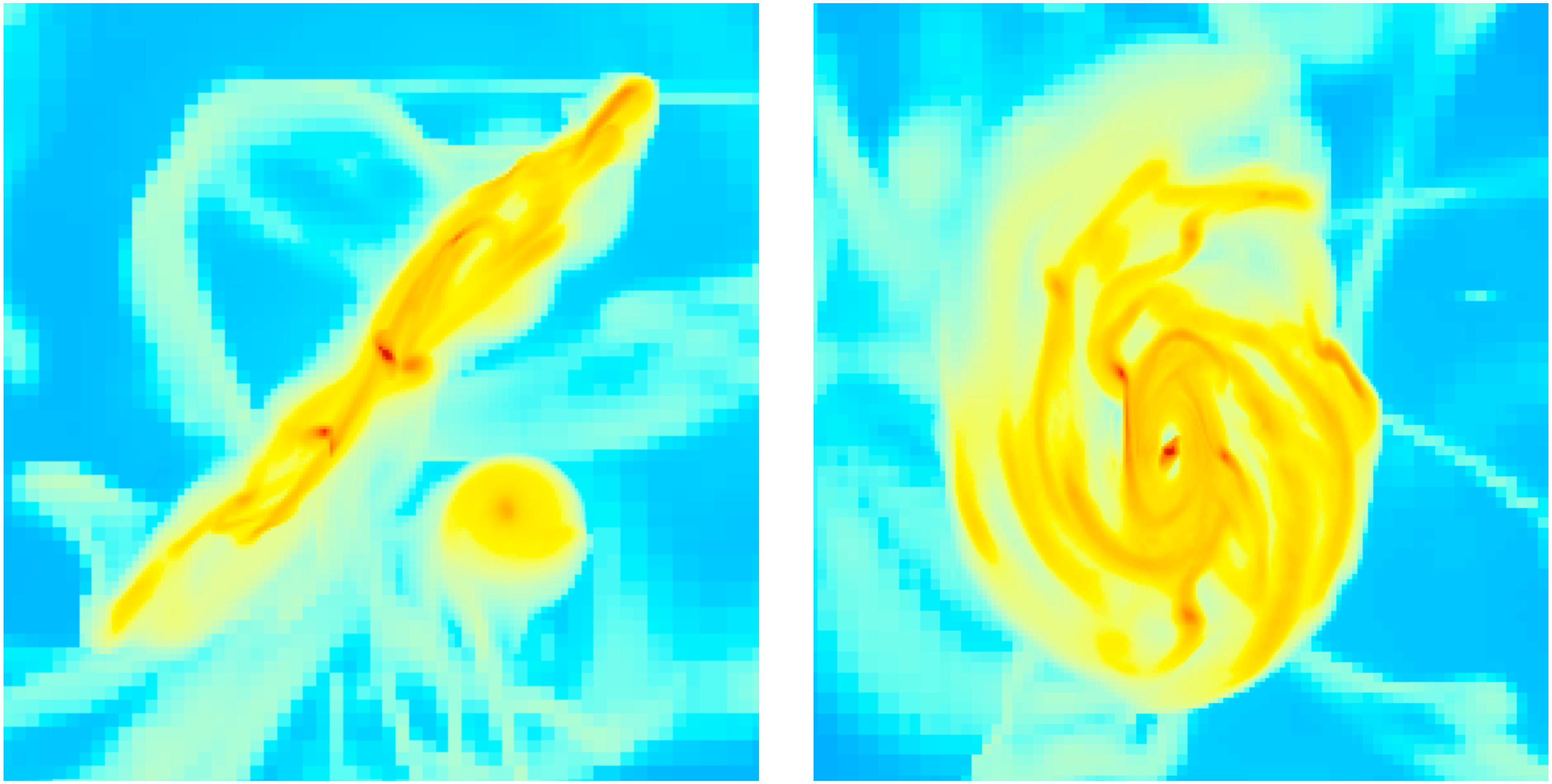


Gas rotational velocities



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

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

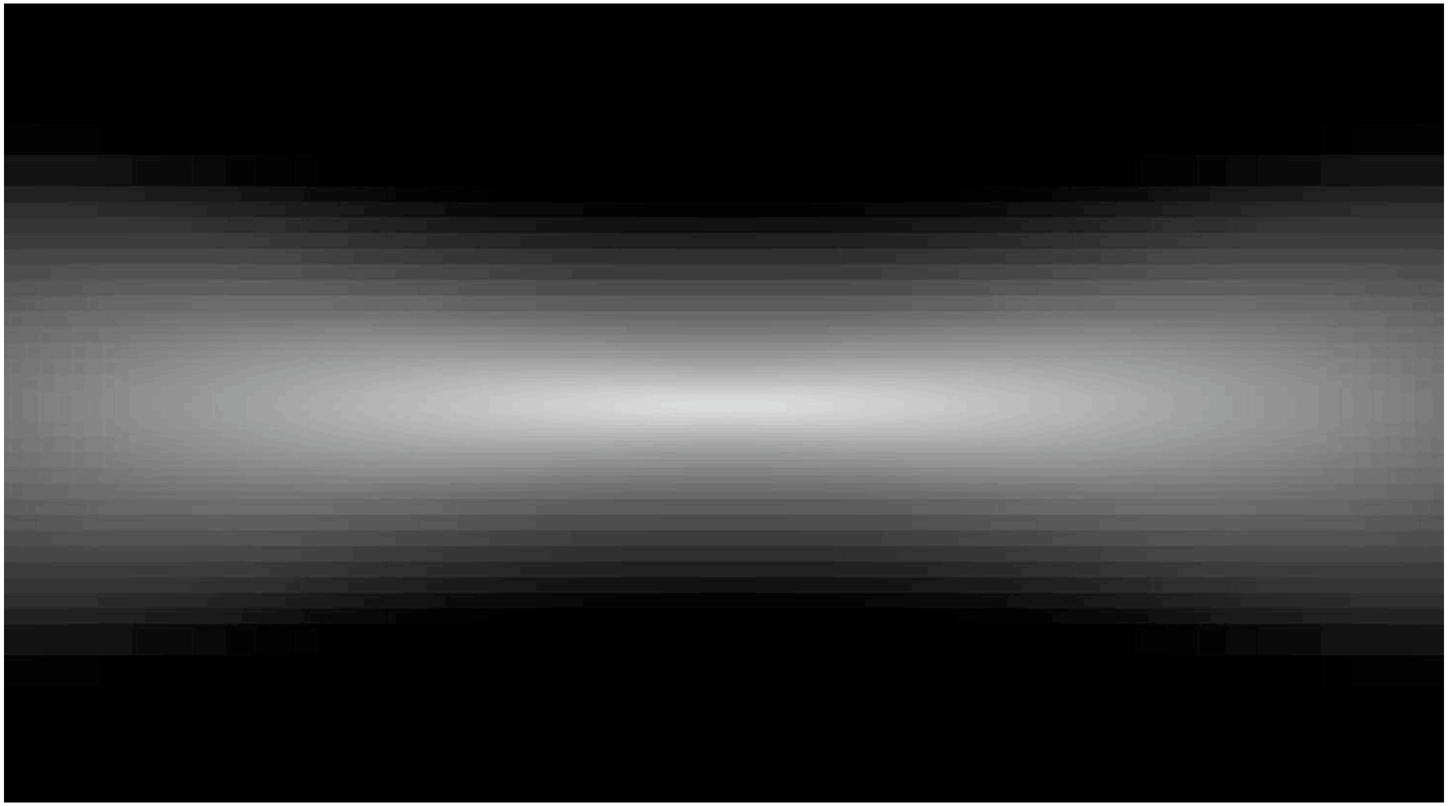
Few pc resolution !

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

Agertz et al. 2008
Tasker et al. 2008

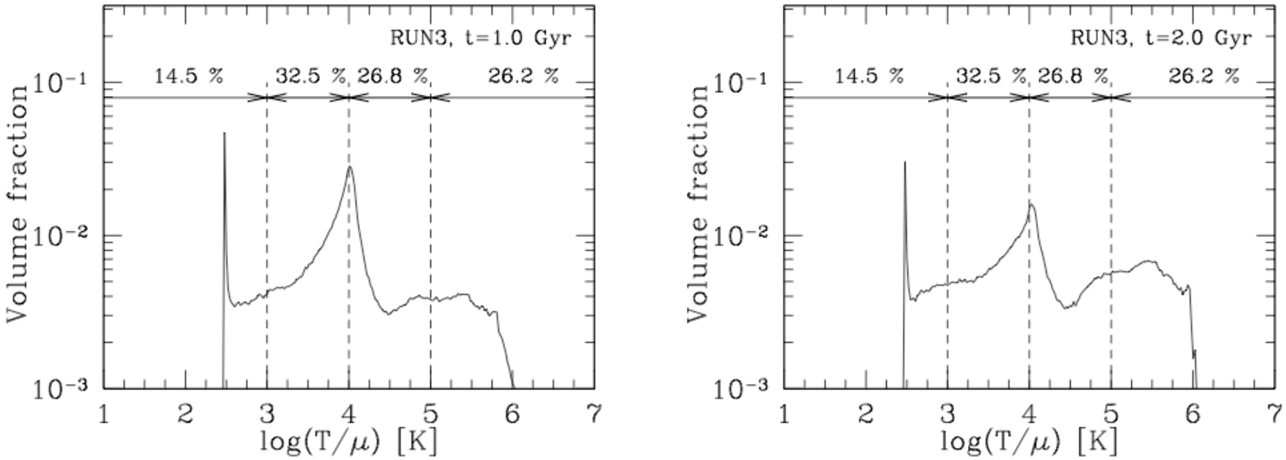
Disc edge on (gas column density)

Agertz et al. 2008



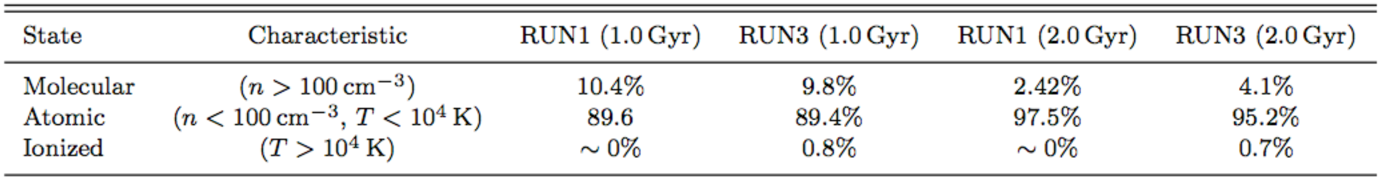
If the density exceeds ρ_0=100 H/cc, we form stars with 2% efficiency, and we impose a temperature floor around 300 K (polytrope with γ=2).
Supernovae feedback with a thermal dump after 10 Myr.
Refinement strategy: 100 pc initially, then Lagrangian evolution augmented by 4 cells per Jeans length criterion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



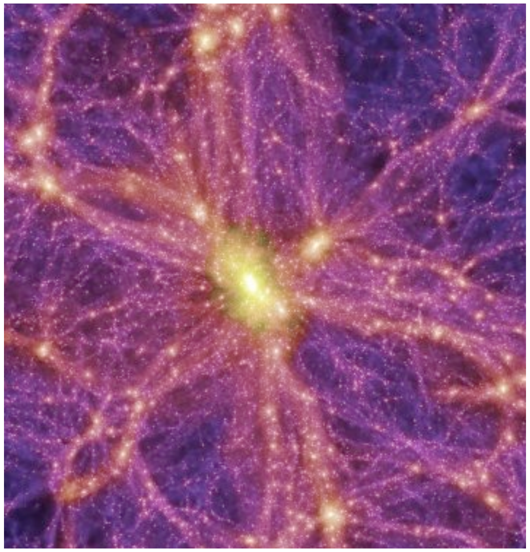
State	Characteristic	RUN1 (1.0 Gyr)	RUN3 (1.0 Gyr)	RUN1 (2.0 Gyr)	RUN3 (2.0 Gyr)
Molecular	$(n > 100\,\mathrm{cm}^{-3})$	10.4%	9.8%	2.42%	4.1%
Atomic	$(n < 100\,\mathrm{cm}^{-3},\ T < 10^4\,\mathrm{K})$	89.6	89.4%	97.5%	95.2%
Ionized	$(T > 10^4\,\mathrm{K})$	$\sim 0\%$	0.8%	$\sim 0\%$	0.7%

Accretion: cold streams or hot shocks?

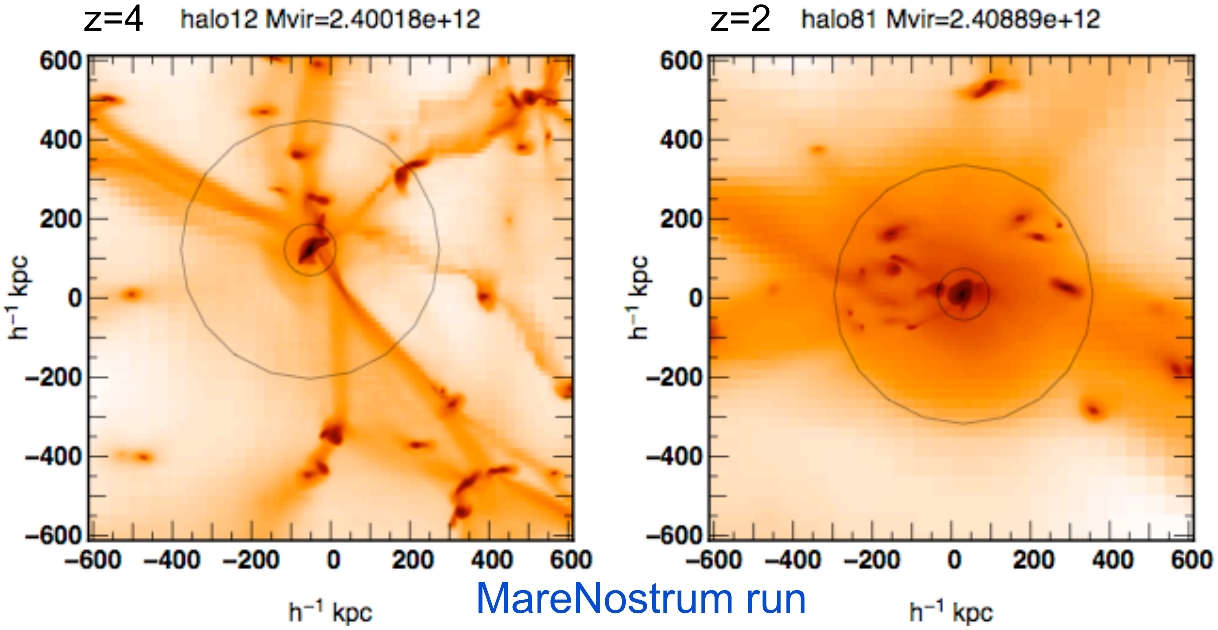
Standard model: gas is shock-heated at T_{vir}, then cools down and rains to the central disc.

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

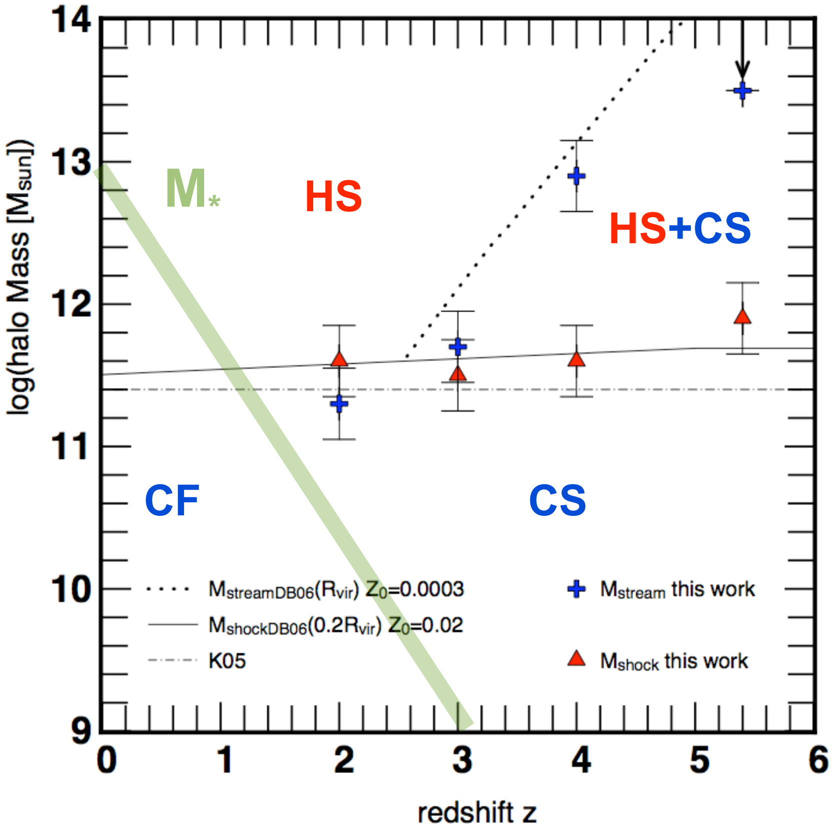


MareNostrum run

Kravtsov (2003)
Birnboim & Dekel (2003)
Keres et al. (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:

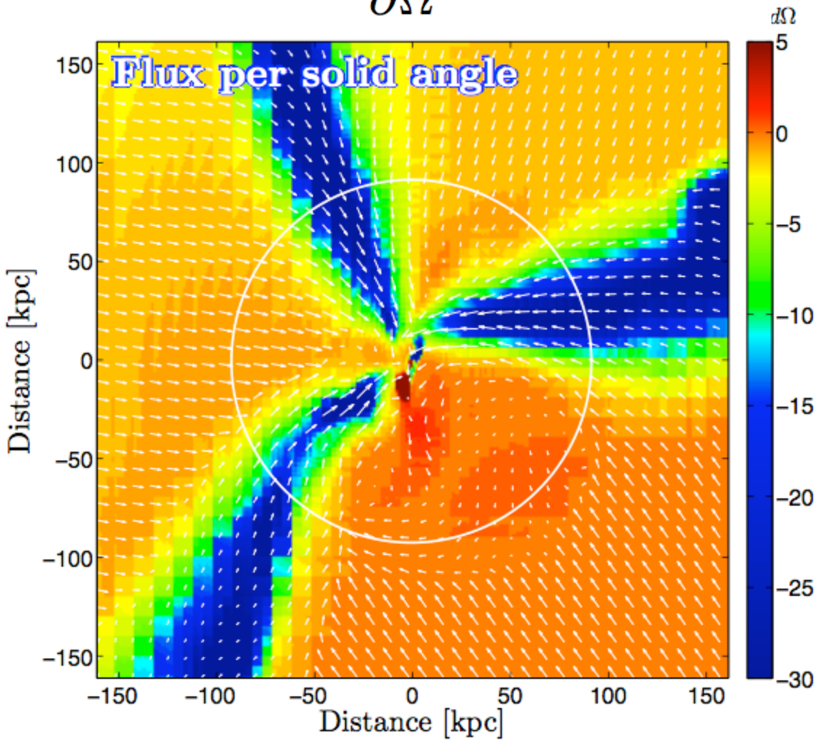
Shock stability: $t_{cool}(\rho_{vir}) \sim R_{vir}/V_{vir}$

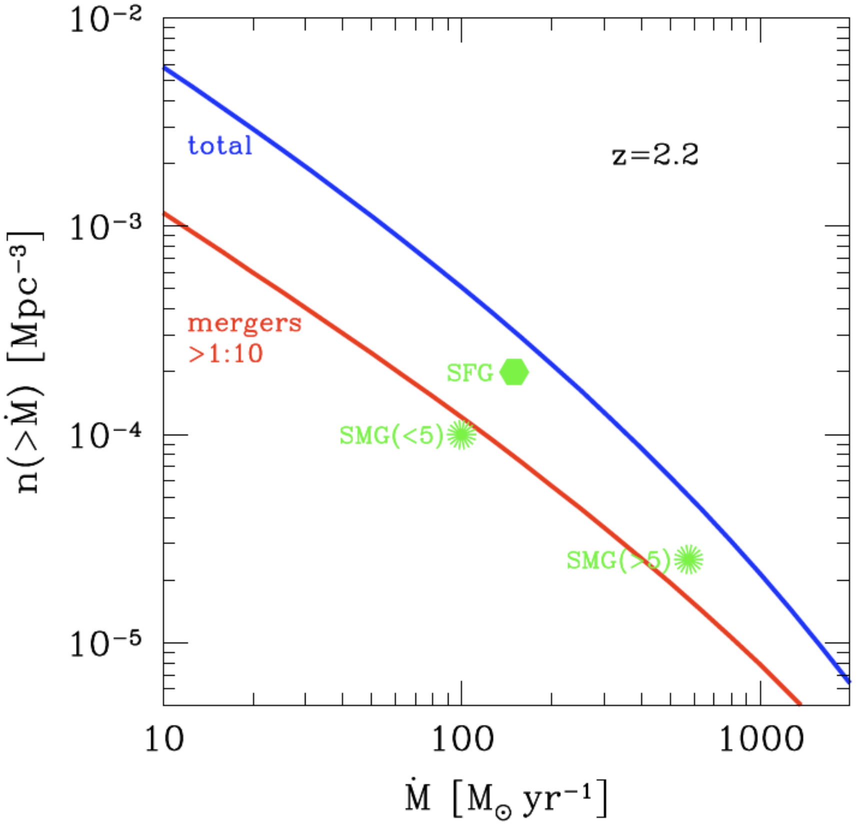
The MareNostrum simulation confirms Birnboim & Dekel (2006) analytical theory.

Data points from Ocvirk et al. 2008

Star formation and cold stream accretion

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



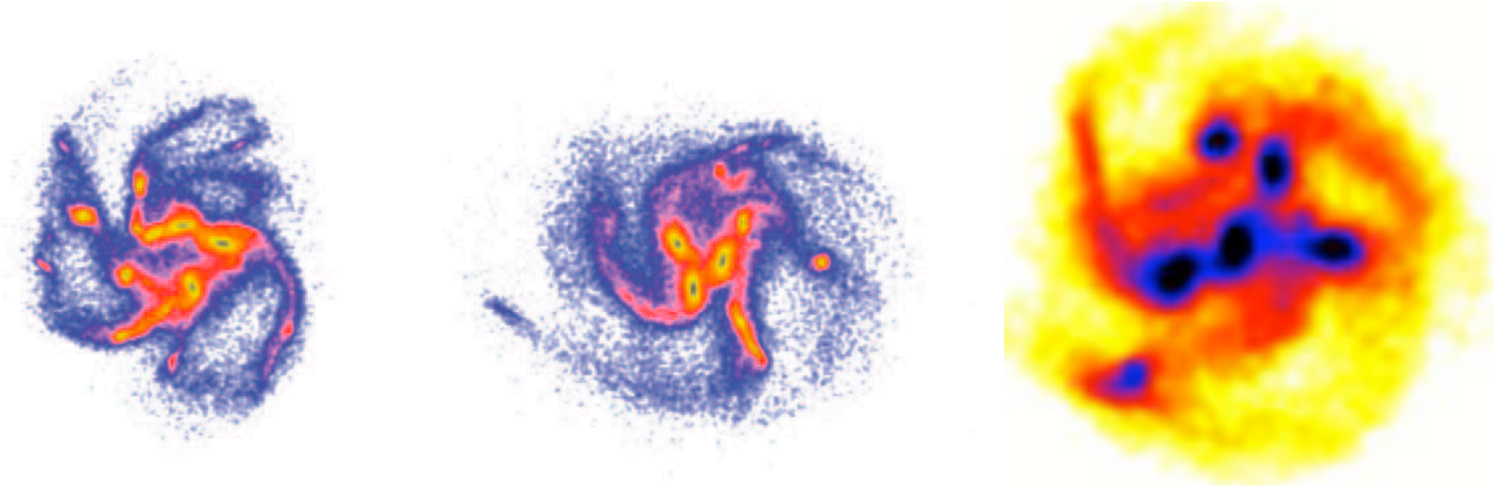


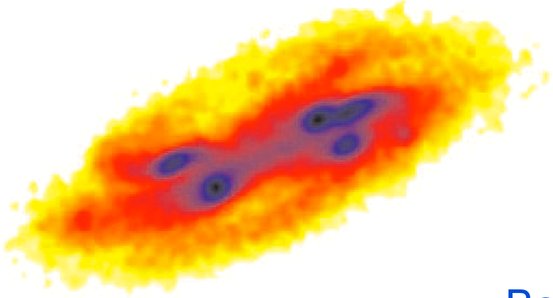
Star formation at high redshift (BzK galaxies ?) proceeds through efficient gas accretion via cold streams. Major mergers (sub-mm galaxies ?) are not frequent enough and cannot explain the disk-like morphologies.

Dekel *et al.* 2009

A model for high-redshift clumpy disks

Starting with smooth unstable disks:

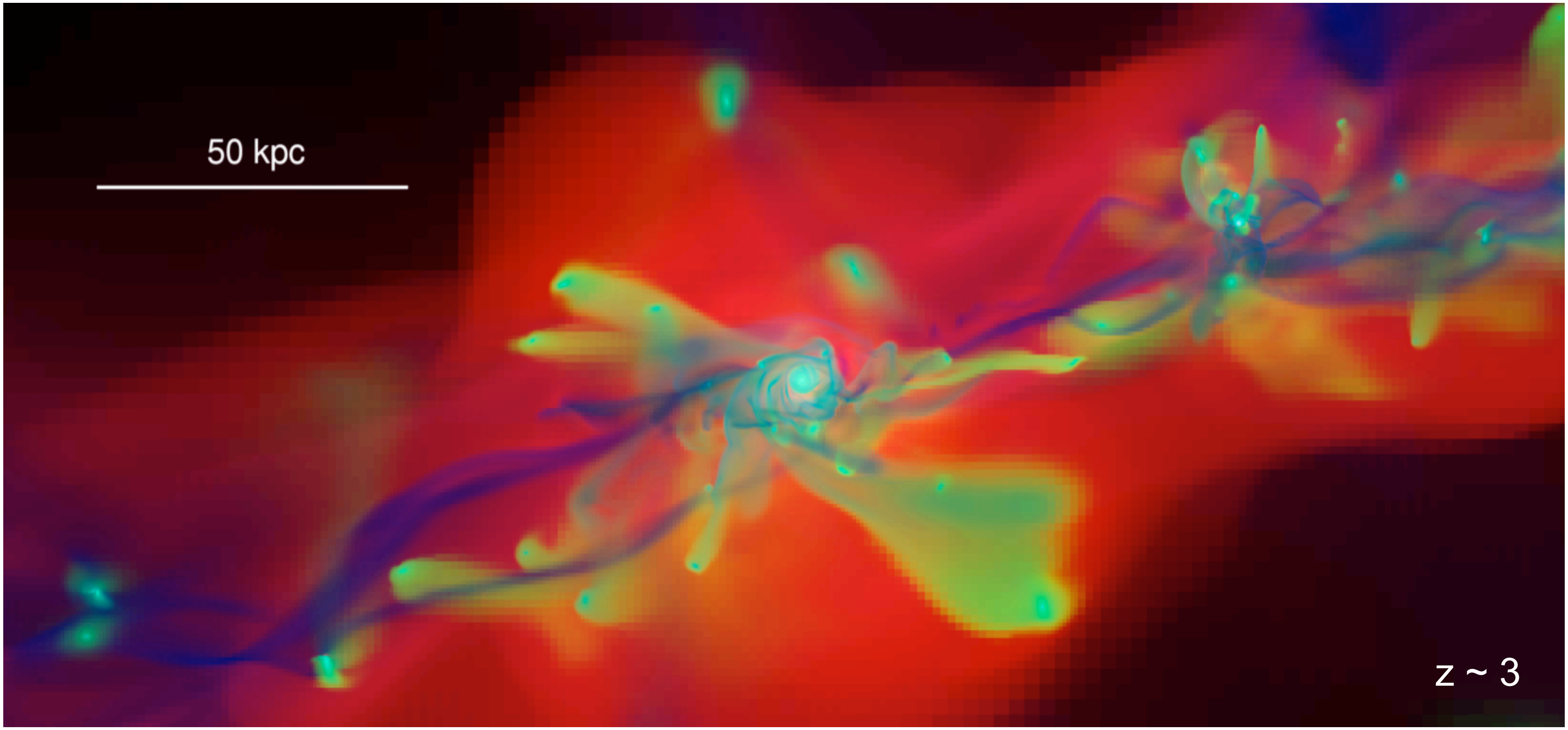




Bournaud, Elmegreen & Elmegreen 2007

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

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 et al. 2009 (astro-ph/0901-2635); Dekel et al. 2009 (astro-ph/0901-2458)

Formation of an unstable disc at z=2.7

SFR ~ 20 Msol/yr

M_*~ 6×10^{10} Msol

R ~ 10 kpc

3 clumps M_b ~ 10^9 Msol

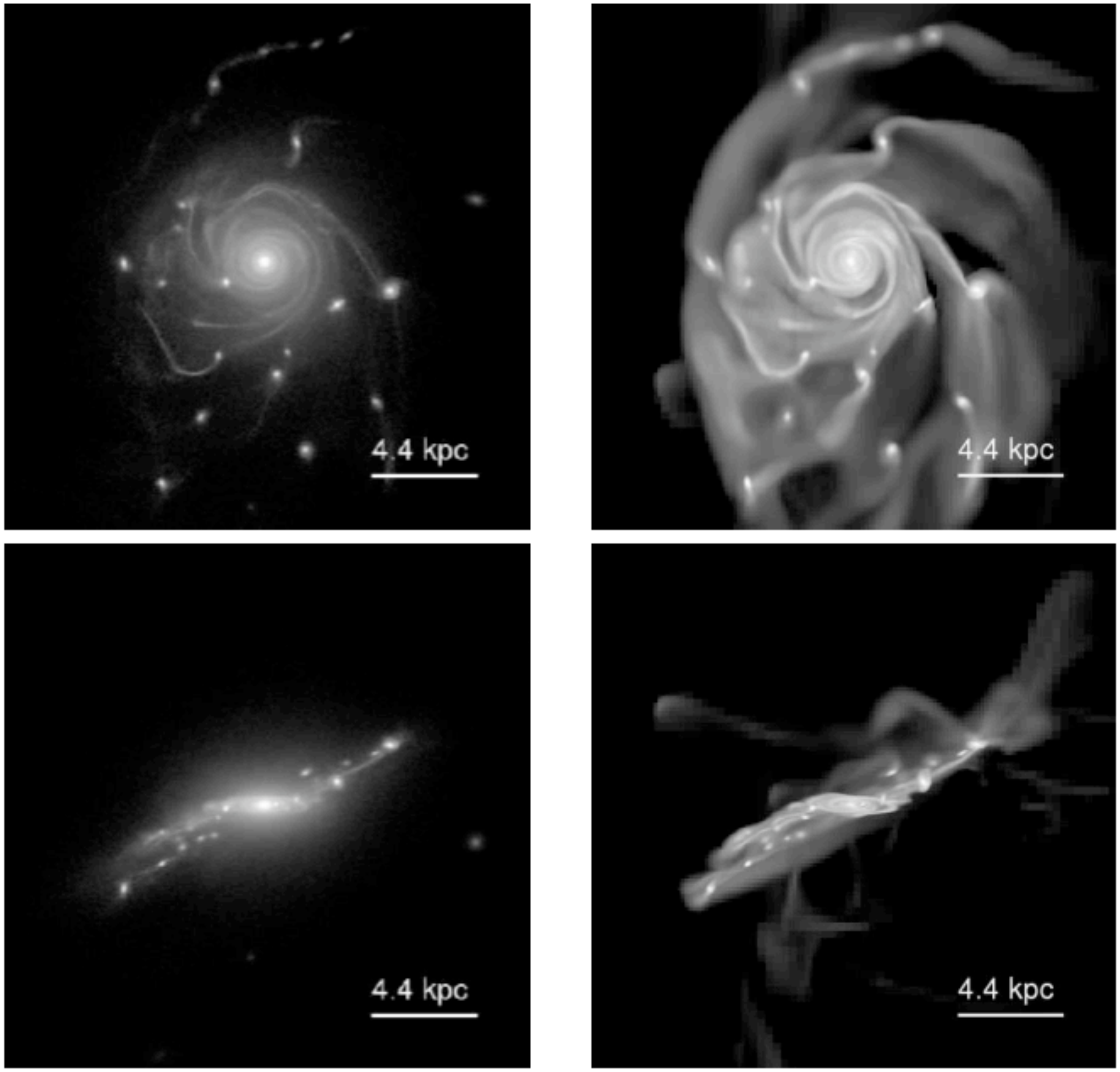
9 clumps M_b ~ 10^8 Msol

2 satellites

Misaligned inner and outer discs

Z/Z_o (inner) ~ 1

Z/Z_o (clumps) ~ 0.1



Fragmentation in the outer disc

Tidal debris and cold streams interact with the inner disc

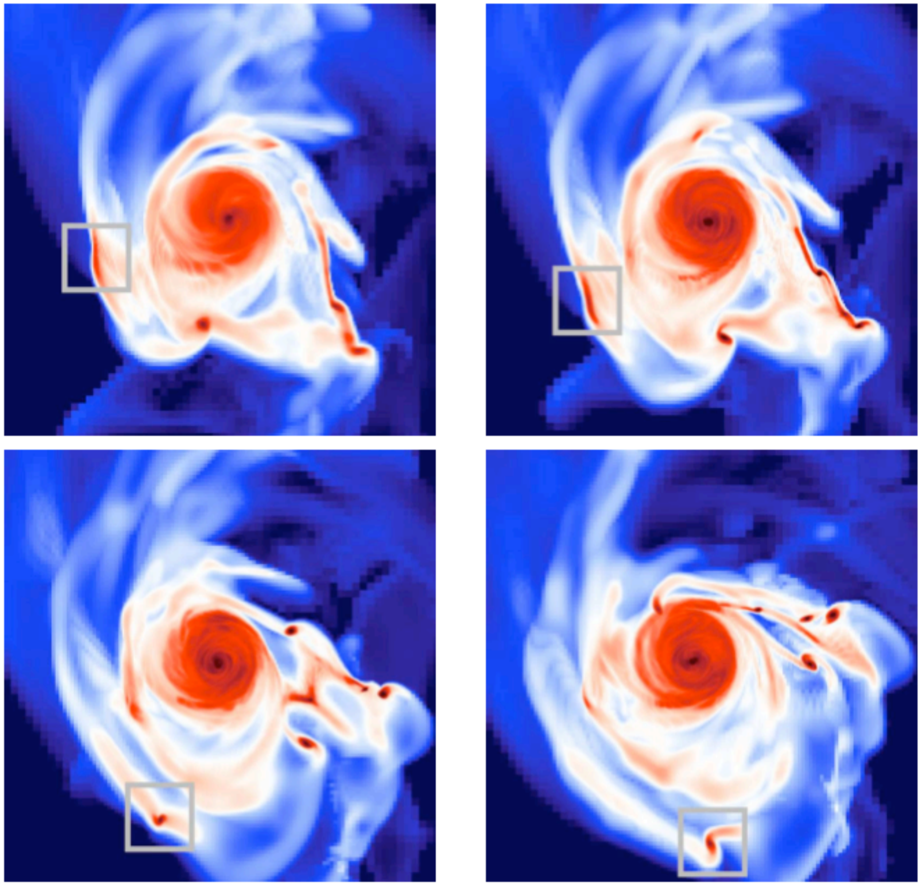
Gravitational instability in the arm

$$M_{\mathrm{J}} \simeq \frac{\sigma^4}{G^2\Sigma}$$

Shear and compression give rise to large velocity dispersions

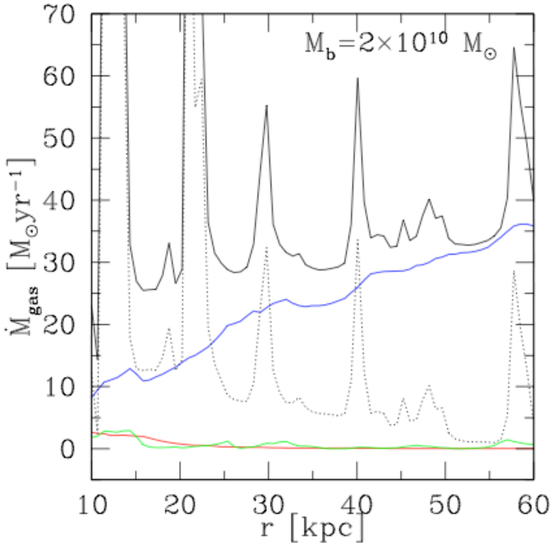
$$\sigma \simeq \frac{\lambda}{\mathcal{R}_{\mathrm{c}}} v_{\mathrm{orb}}$$

Clump masses 10^8-10^9 M_{sol}

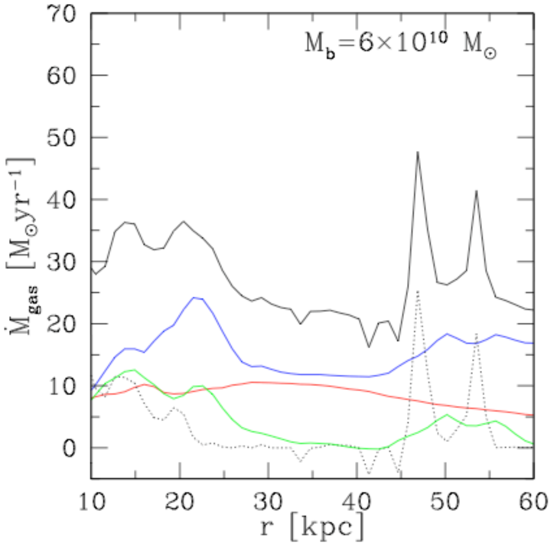


Similar scenario in major mergers for tidal dwarf galaxy formation
Elmegreen et al. 1993

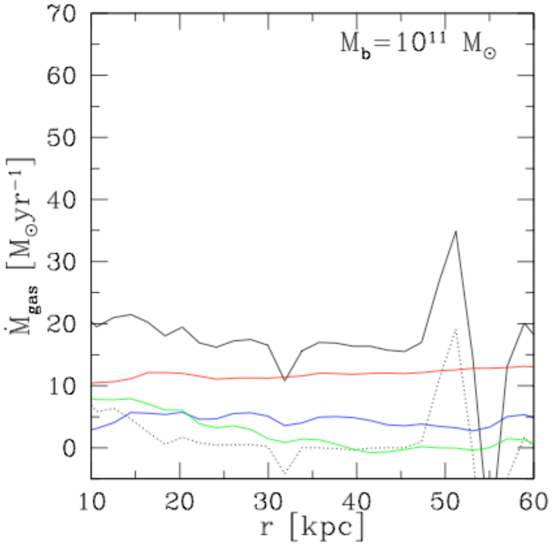
Cold streams accretion and massive clumps formation



z=5

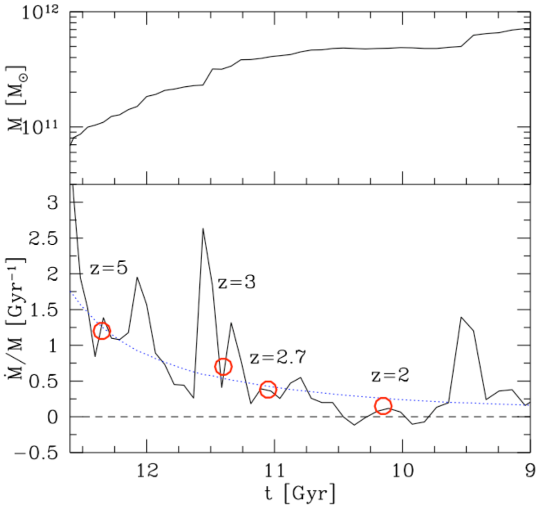


z=3



z=2

Intensive cold stream accretion and/or mergers drive massive clump formation

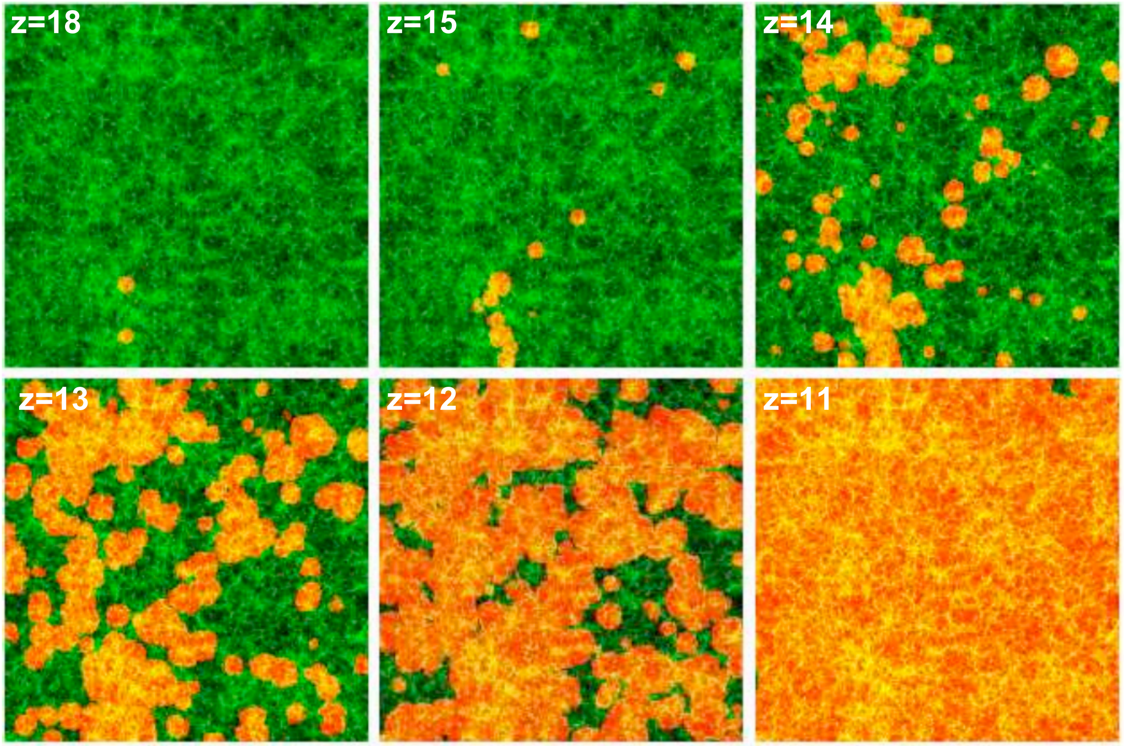


Small mass accretion rates result in quiescent disc (low redshift regime)

Romain Teyssier

Magnetic field generation by Biermann battery

During the reionization epoch, young stars photo-ionize their surroundings.
Green is neutral hydrogen; orange is ionized hydrogen and electrons.



At the microscopic level, pressure gradients move electrons away from ions.
This generates microscopic currents, and therefore magnetic fields.
Biermann used the term “battery” in analogy to chemical charge decoupling.

$$\frac{\partial \vec{B}}{\partial t} = \frac{c}{n_e^2 e} \nabla P_e \times \nabla n_e$$

This generates magnetic fields of 10^{-20} to 10^{-18} G.

Romain Teyssier

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:

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

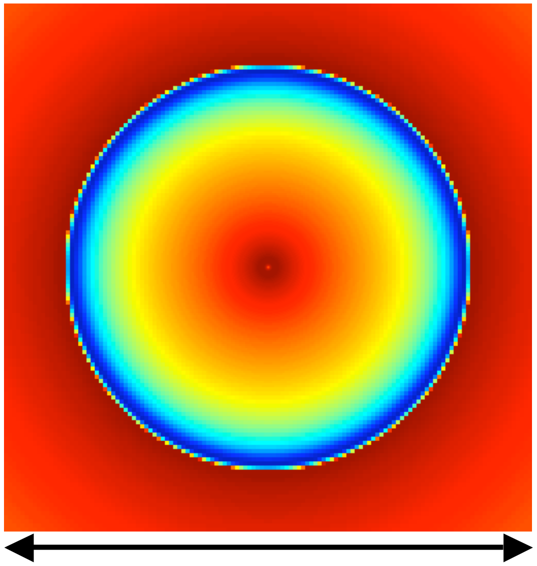
The parameter $\alpha = \frac{1}{3}\tau \langle \vec{v}' \cdot (\nabla \times \vec{v}') \rangle$ depends on small scale properties of the MHD turbulence that are poorly known.

An idealized dwarf galaxy in isolation

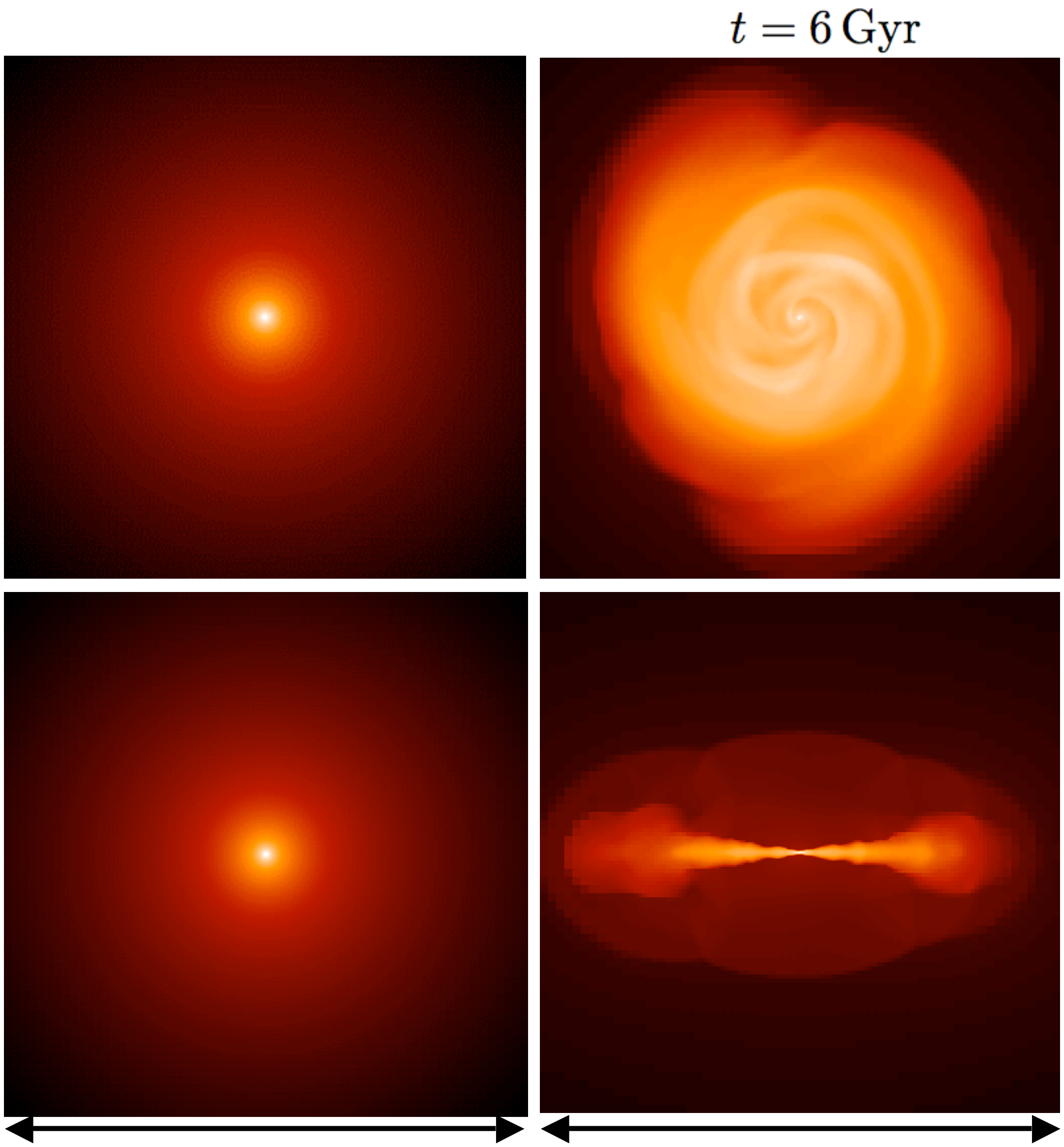
$$M_{\rm vir} = 10^{10}\,{\rm M}_\odot$$
$$B_{\rm IGM} = 0$$

Halo in hydrostatic equilibrium

$t = 0$

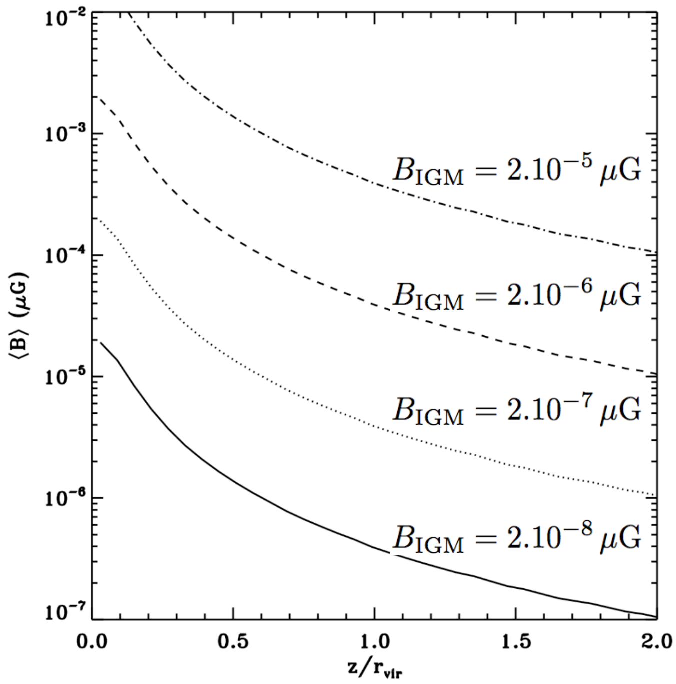


Dubois & Teyssier 2008a

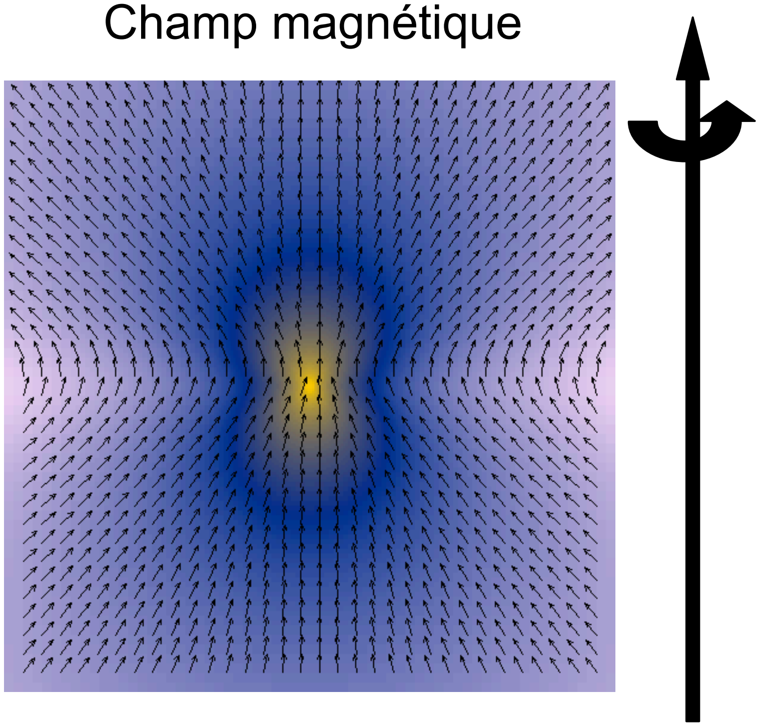

$t = 6\,{\rm Gyr}$

« Frozen-in » magnetic field in the initial halo

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



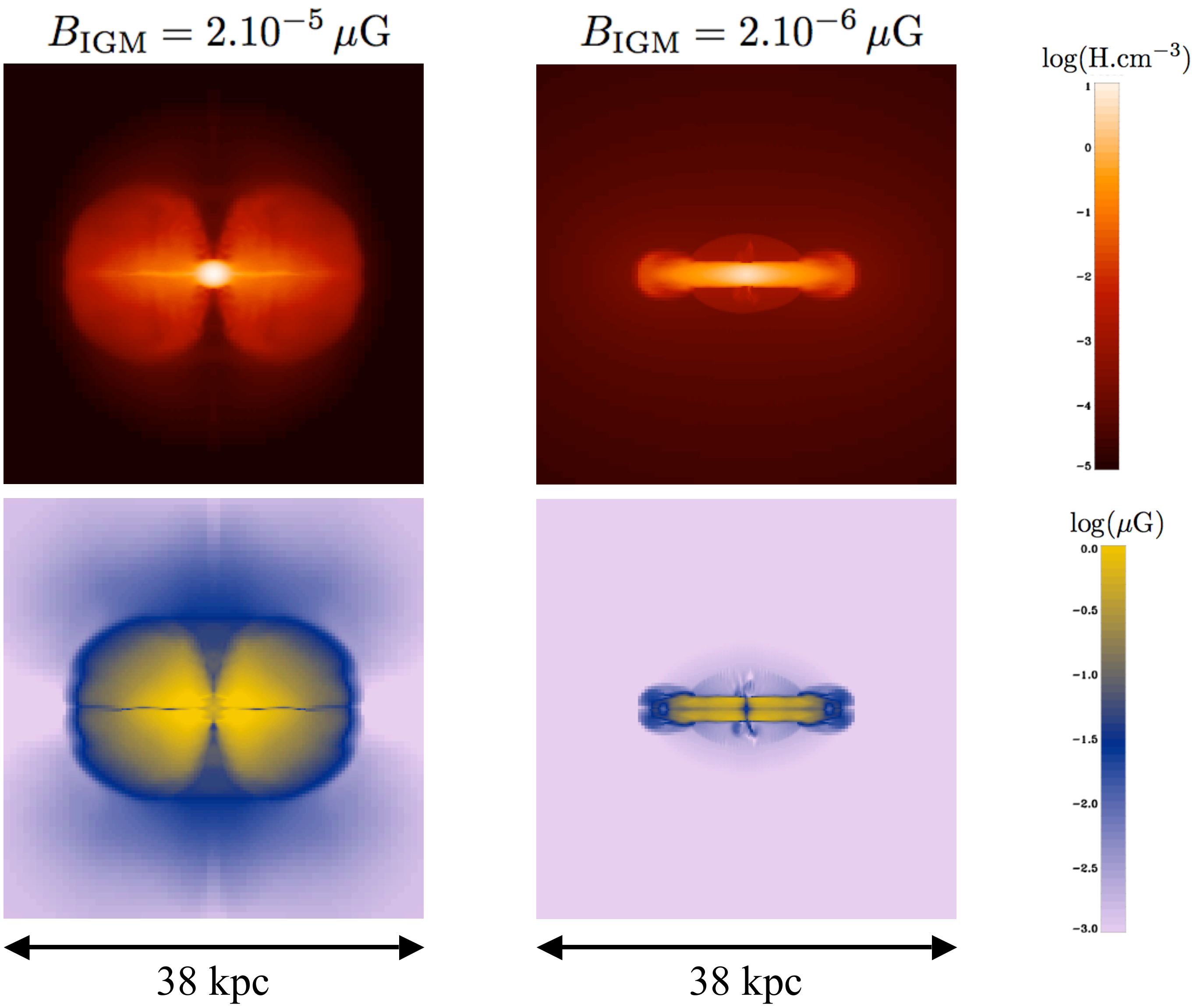
Champ magnétique



Dipole structure aligned with rotation axis

Magnetic fields in dwarf galaxies

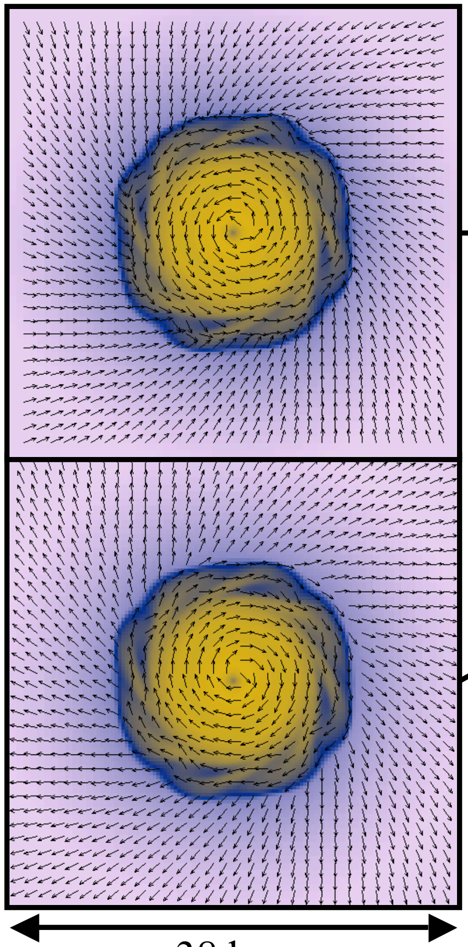
$t = 3\,\mathrm{Gyr}$



$B_{\mathrm{IGM}} = 2.10^{-5}\,\mu\mathrm{G}$

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

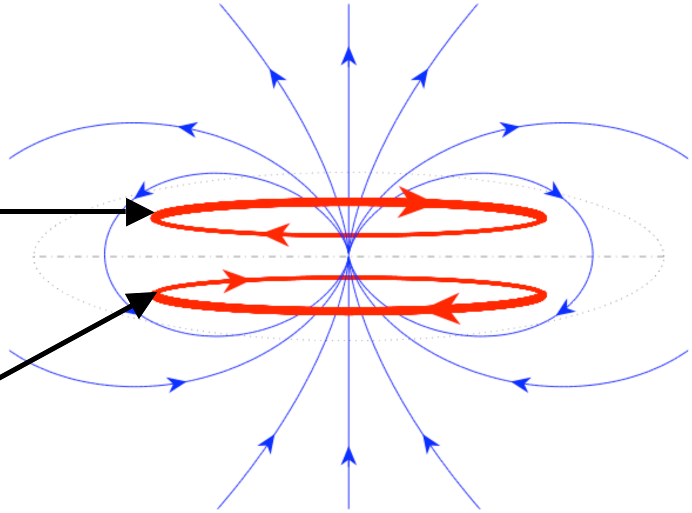
Topology of the galactic magnetic field



38 kpc

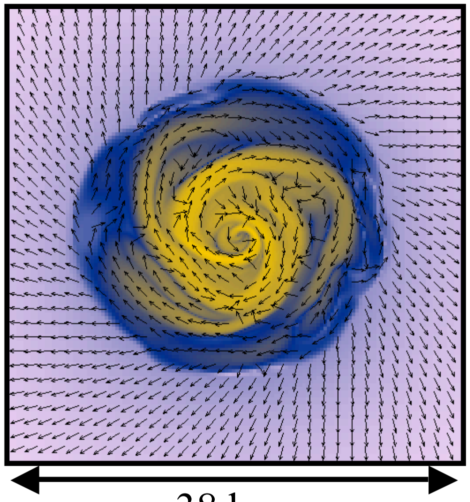
Above the plane

Below the plane



A0 : antisymetric mode with m=0

Spiral structure



38 kpc

Thank you !