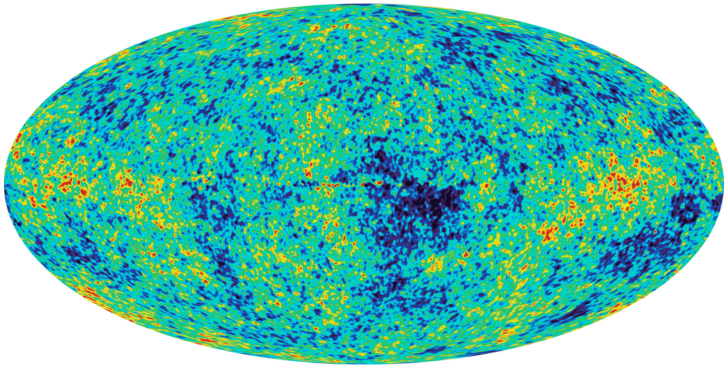
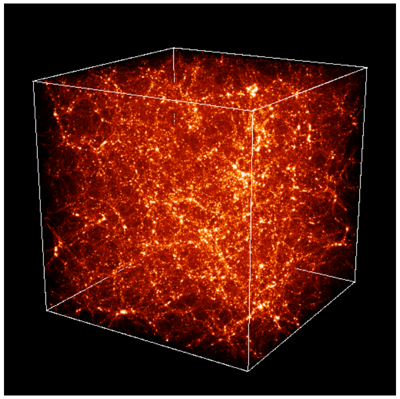
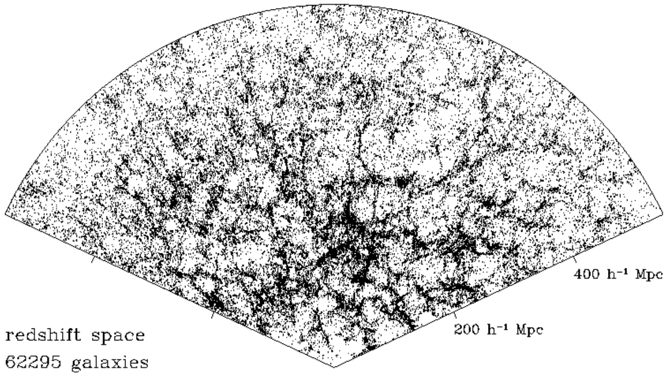
Computational Cosmology: from large scale structure to galaxy formation

Romain Teyssier
Universität Zürich







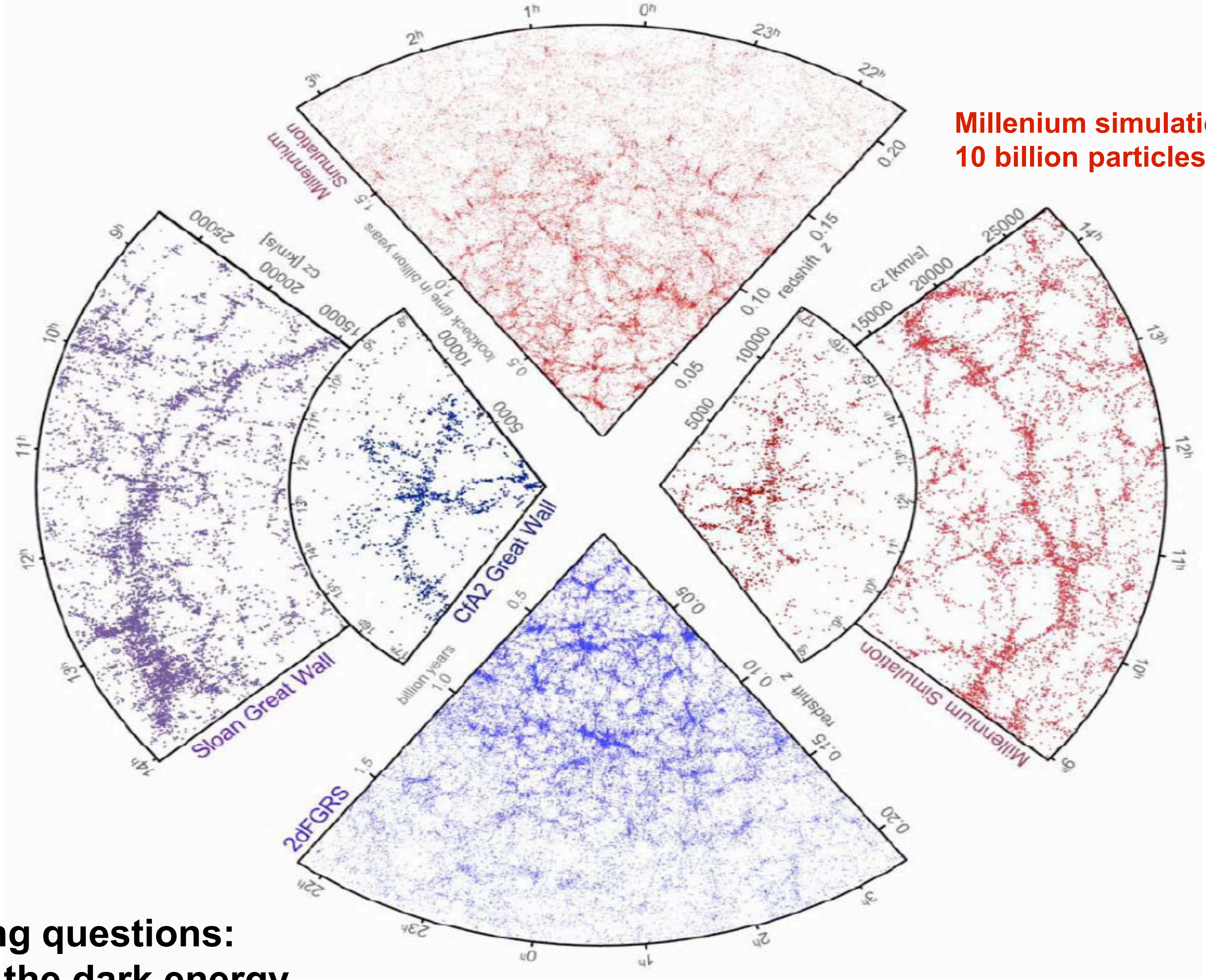
Outline

- Large scale structures and the role of baryons
- Cold streams around high-redshift galaxies
- Galaxy formation from cosmological simulations
- Cosmic magnetism: a hierarchical dynamo ?

Thomas Guillet, Damien Chapon (Saclay)
Stephanie Courty, Brad Gibson (UCLan)
Avishai Dekel (Jerusalem)
Oscar Agertz, Ben Moore (UniZH)
Marie Martig, Frédéric Bournaud (Saclay)
Yohan Dubois, Julien Devriendt (Oxford)

The Horizon Project (www.projet-horizon.fr)

Success of the Cold Dark Matter model

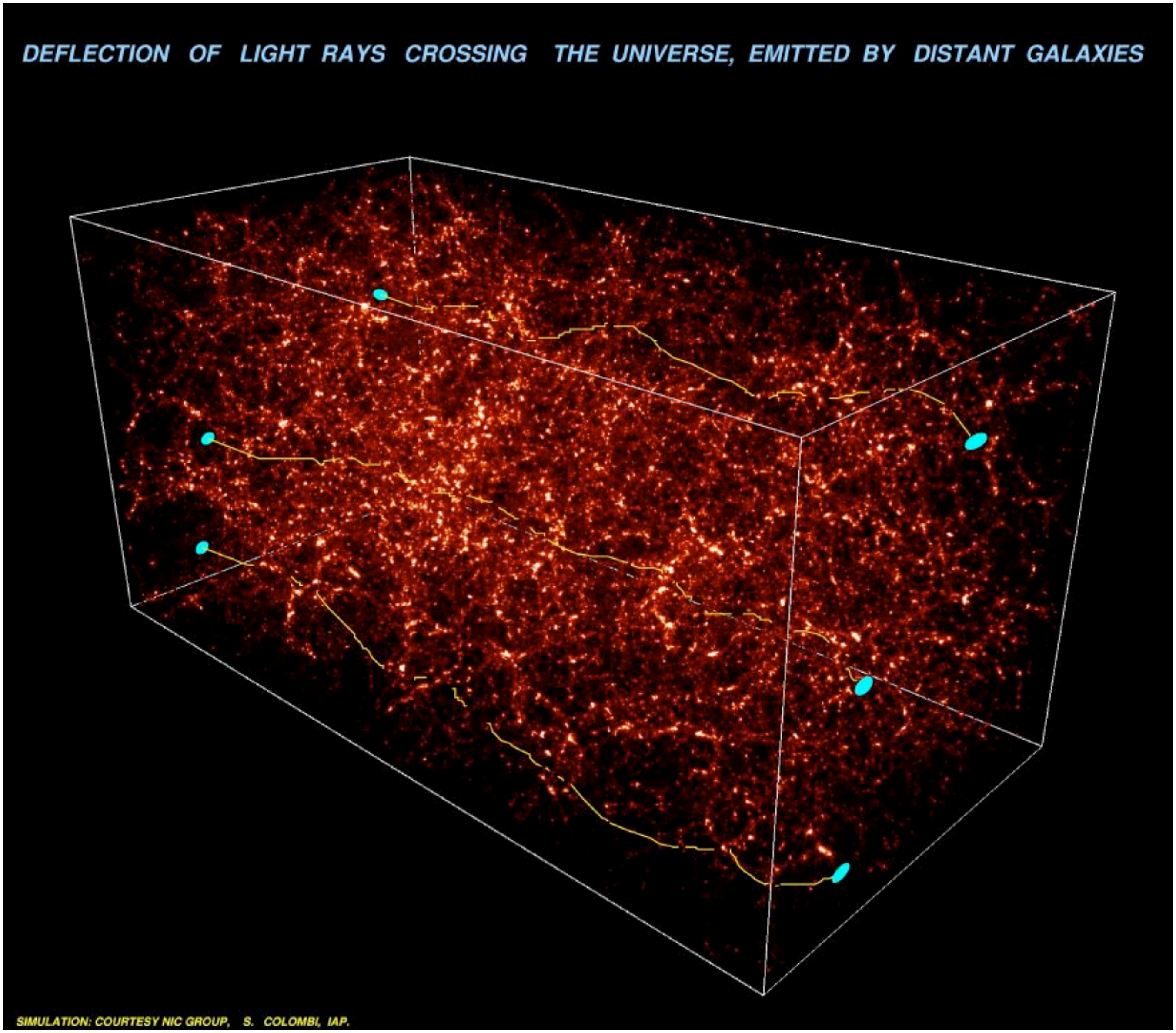


Millenium simulation:
10 billion particles run

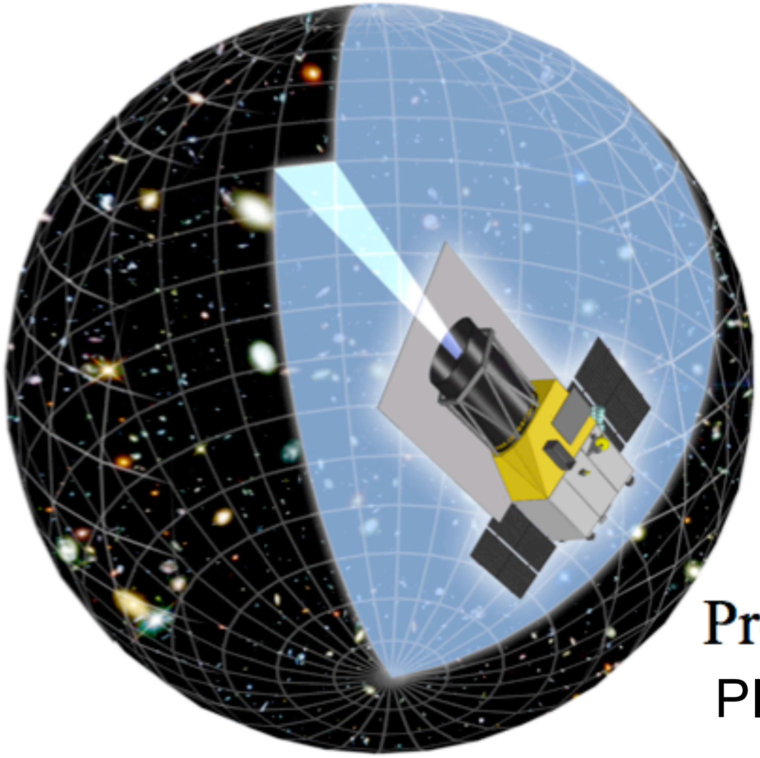
Outstanding questions:
- nature of the dark energy
- nature of the dark matter
- origin of the initial conditions (inflation ?)

How do galaxies form ?

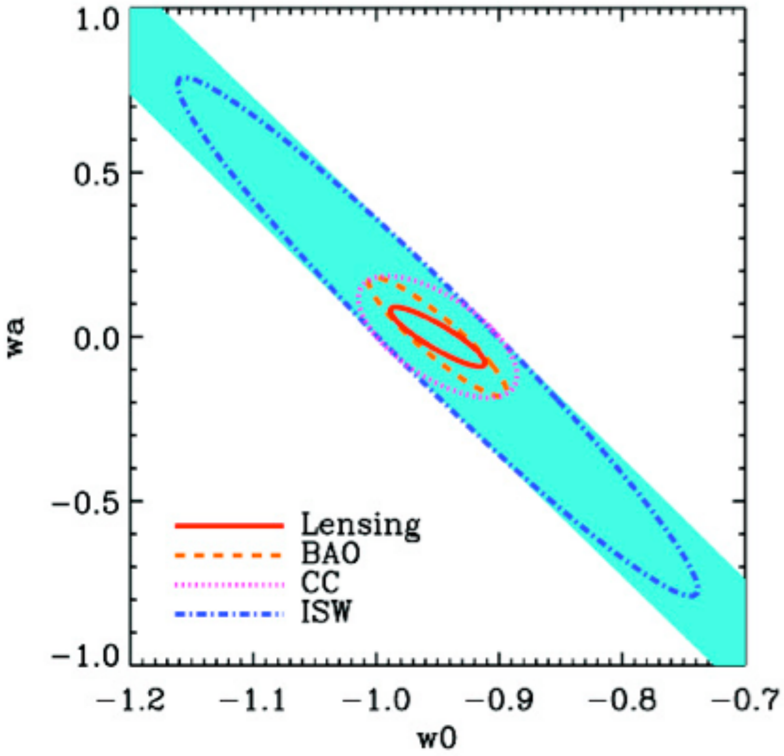
Weak-lensing by large-scale structure



DUNE: the Dark UNiverse Explorer



Dark energy parameters



Proposed to ESA's Cosmic vision

PI: Alexandre Refregier (CEA Saclay)

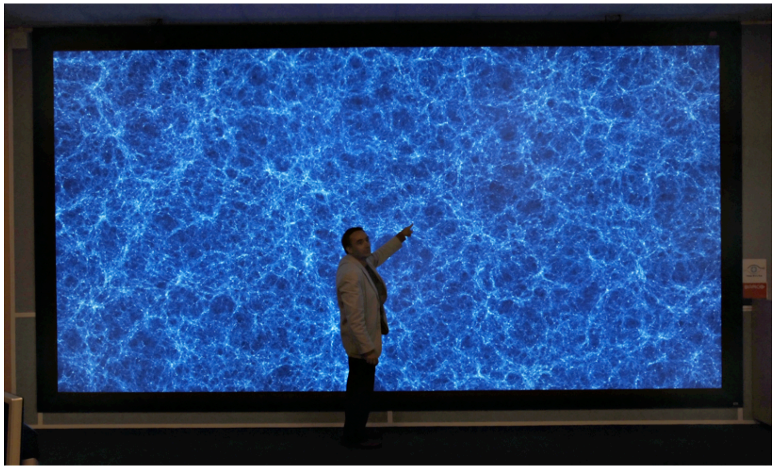
The Horizon 4Pi Simulation

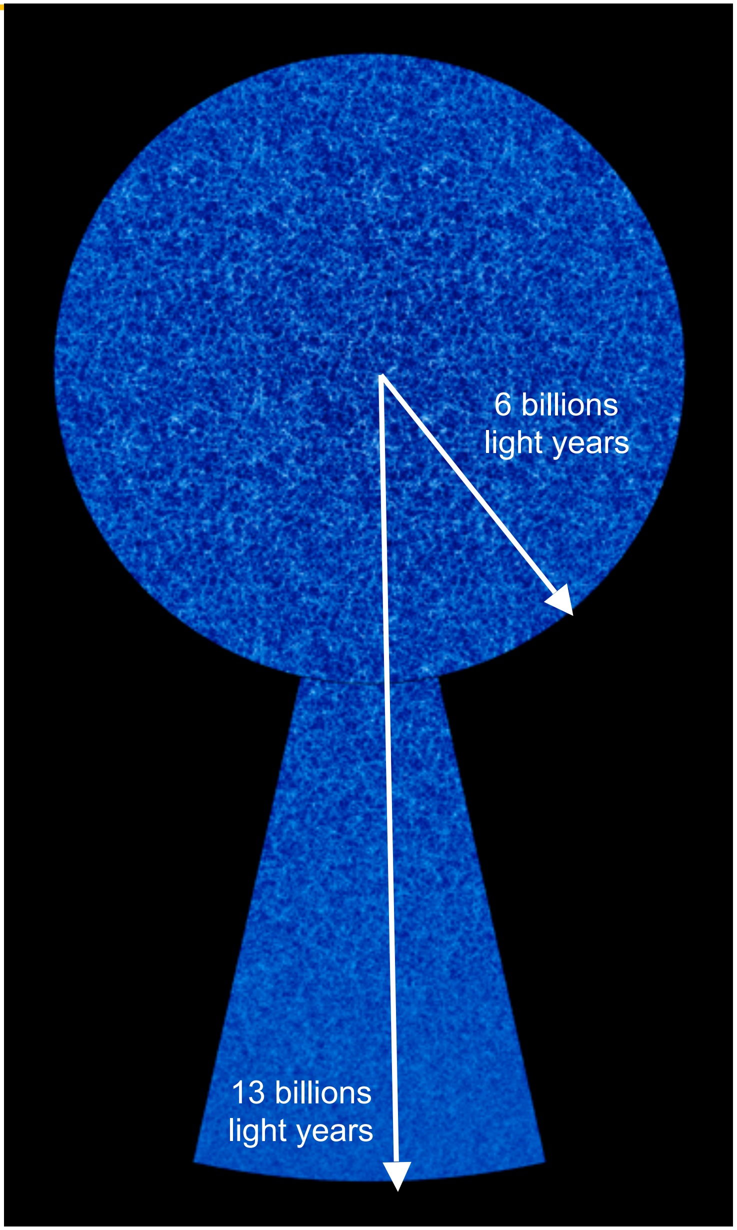
We report on a 70 billions particles N-body simulation with 140 billions AMR cells for a 2 Gpc/h periodic box in a LCDM universe.

We use a new French supercomputer BULL Novascale 3045 recently commissioned at CCRT (Centre de Calcul Recherche et Technologie, CEA).

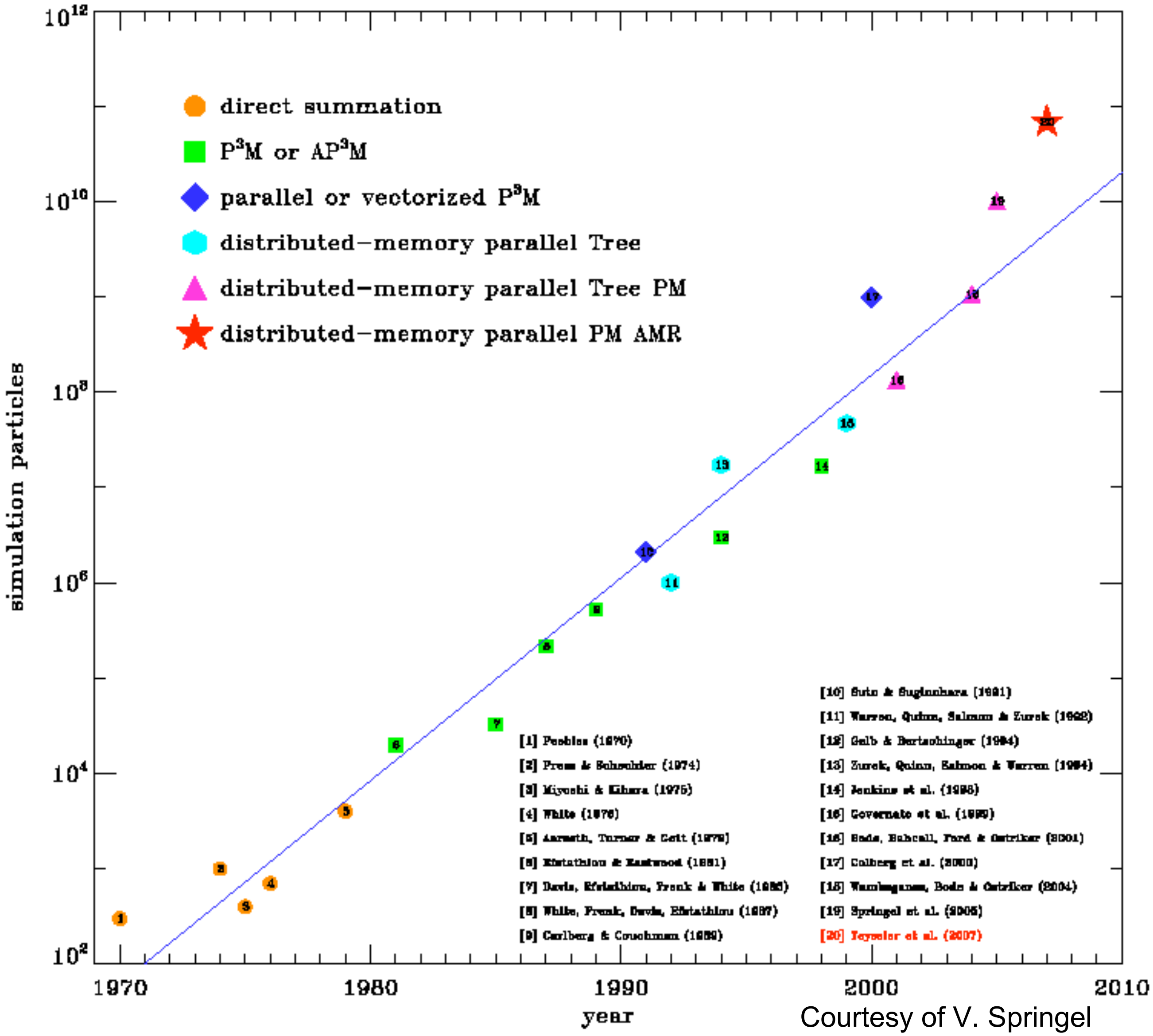
We ran RAMSES in pure N-body mode with 6144 processors for 2 months. Starting with a base grid of 4096^3 cells, we used 6 additional level of refinements for a formal resolution of 262144^3.

Using our light cone, we have computed a full sky convergence map for simulating future weak-lensing surveys like DUNE or LSST.



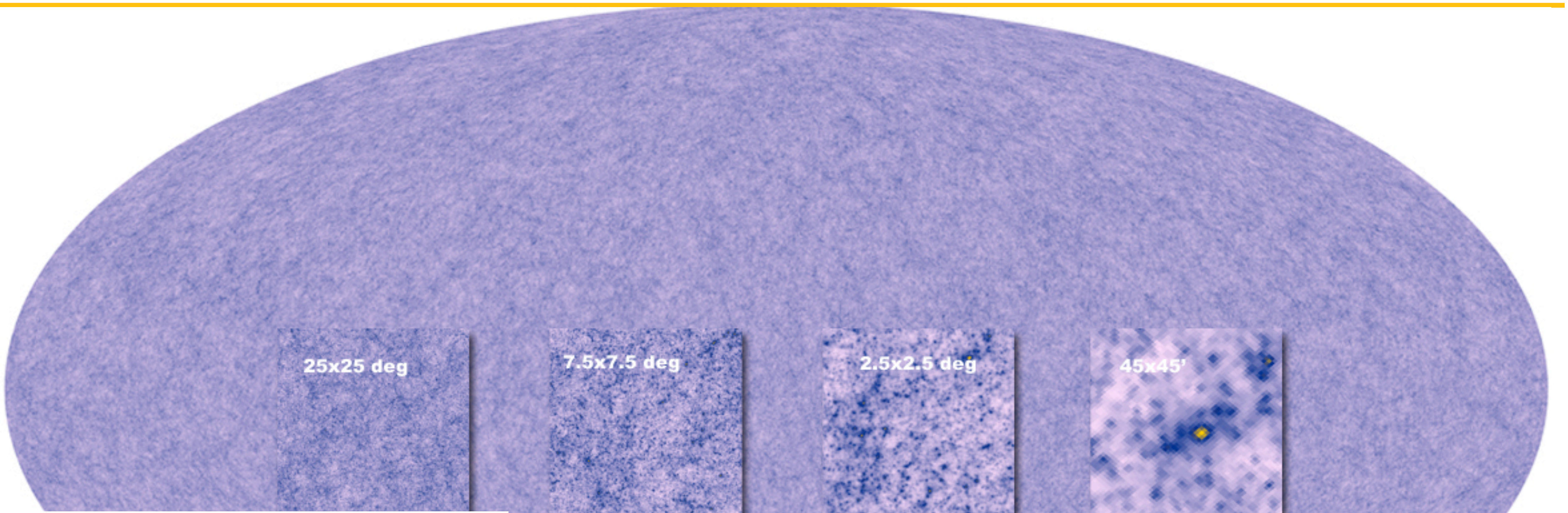


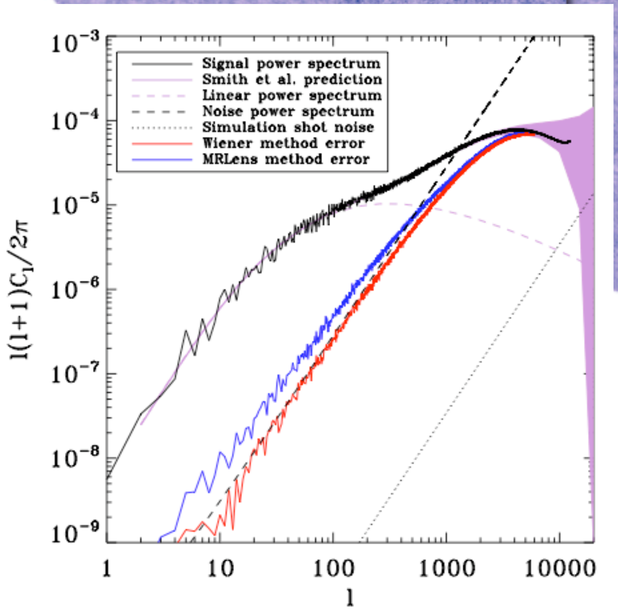
The Horizon 4Pi Simulation



Courtesy of V. Springel

The Horizon 4Pi Simulation





The first Full-Sky weak-lensing map with 0.9 arcmin^2 resolution : 4 decade in angular scales !!!

Preparation for cosmology surveys using wide field imaging in space

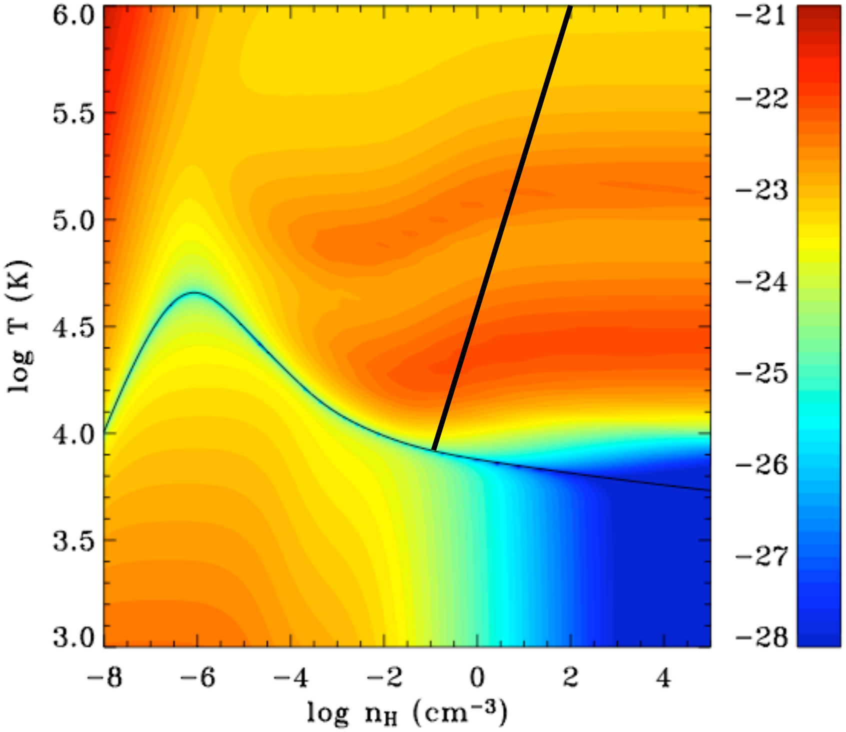
Teyssier et al., 2009, in press

Galaxy formation theory: model « a minima »

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

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

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



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

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

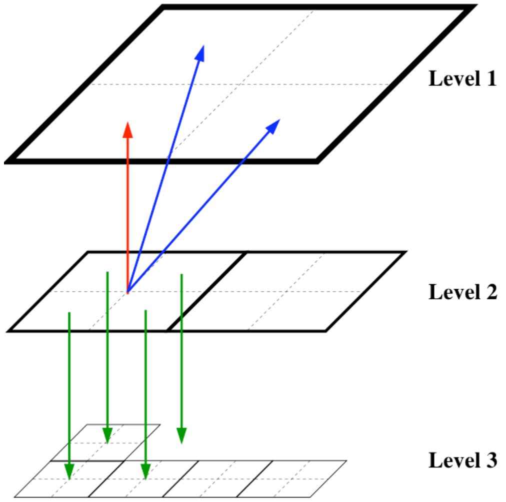
- t_0= 1-10 Gyr (Kennicutt 1998)
- α = 0.01-0.02 (Krumholz & Tan 2007)
- n_0= 0.1 H/cm^3

Parameters depend on physical resolution

Numerical issues:

- SPH versus 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.

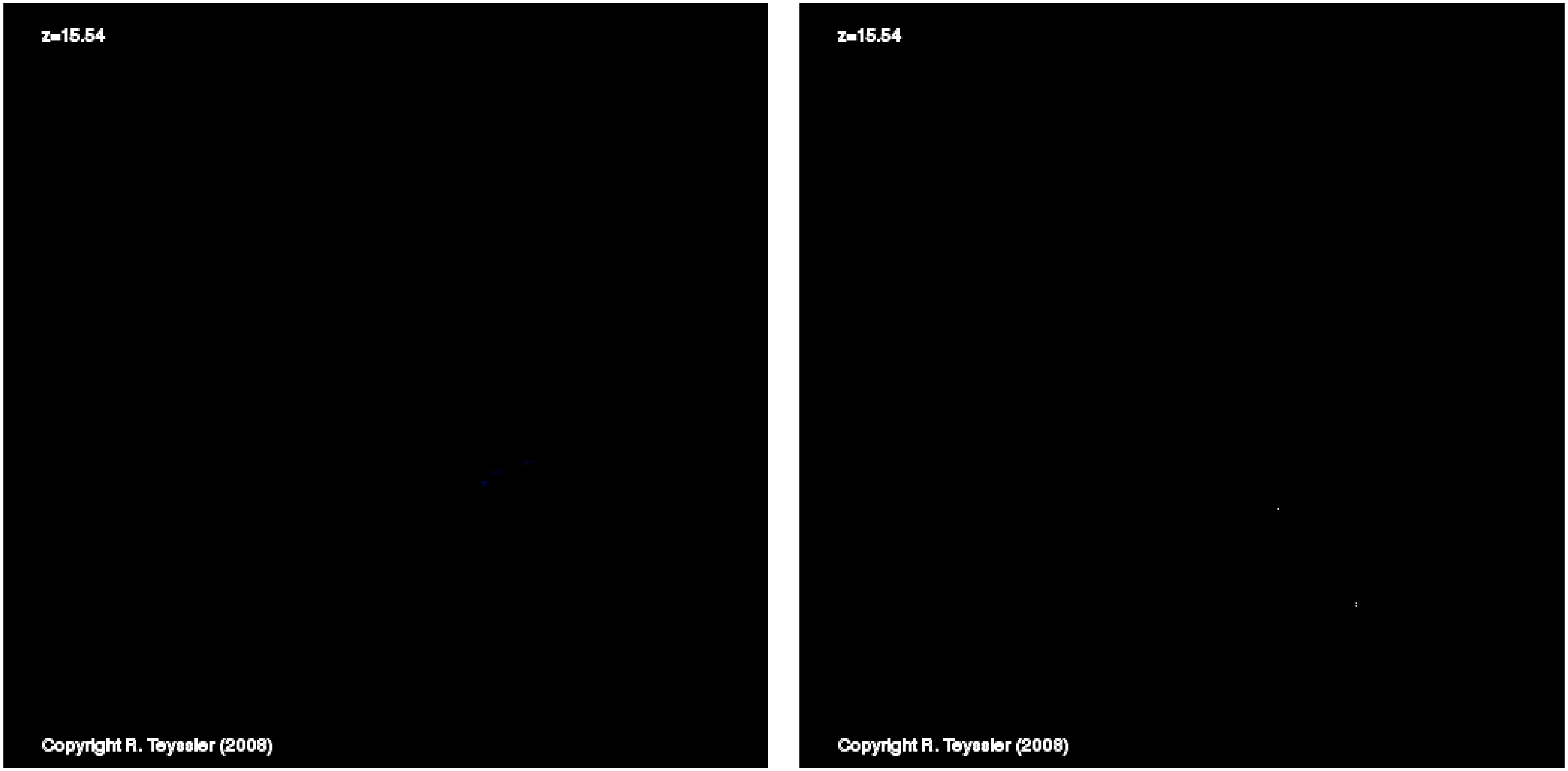
Hydro module: unsplit second order Godunov method (MUSCL) with various Riemann solvers and slope limiters. New CT based MHD solver.

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

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

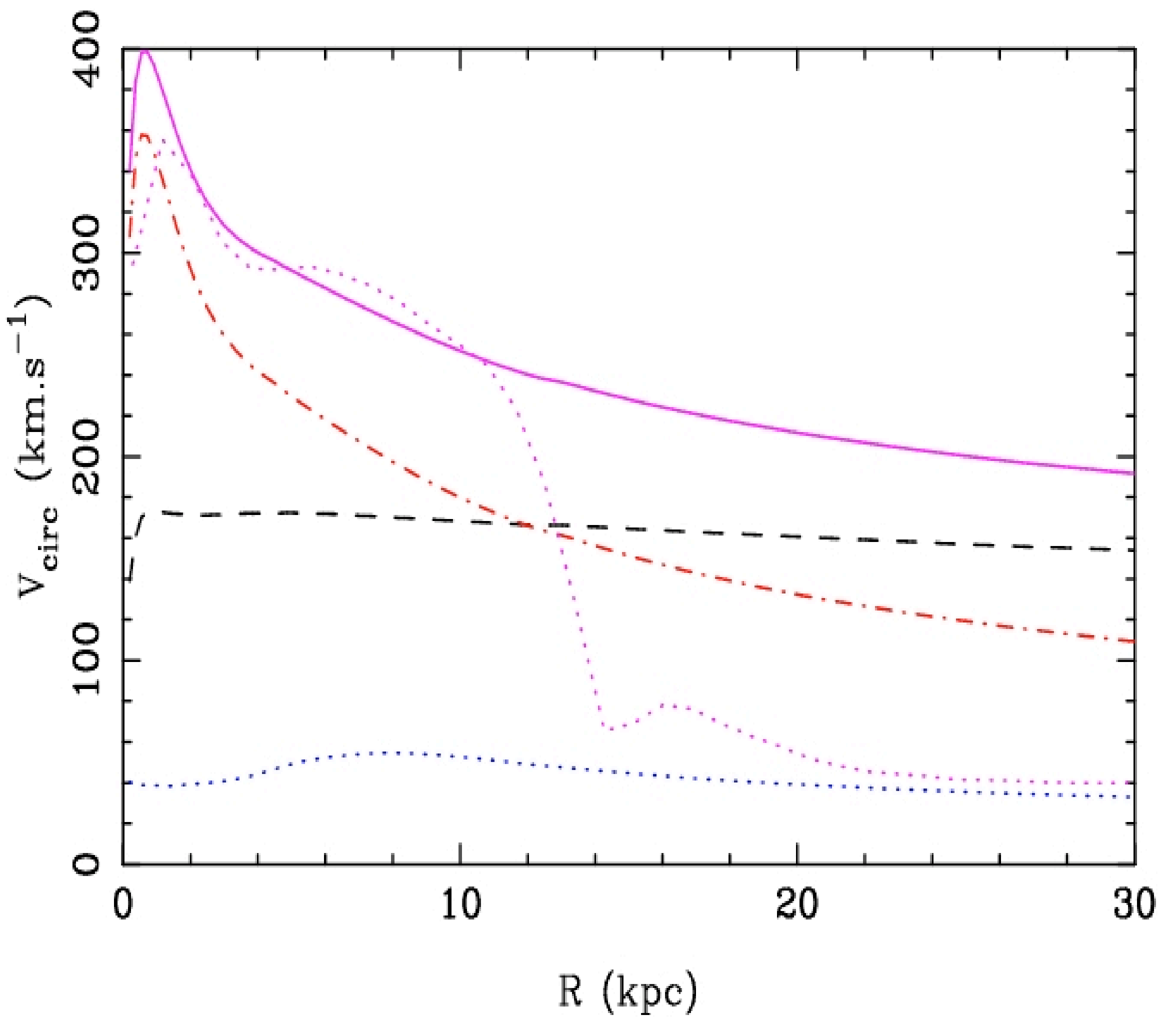
MPI-based parallel computing using time-dependant domain decomposition based on Peano-Hilbert cell ordering.

Simulating disc galaxies in a computer



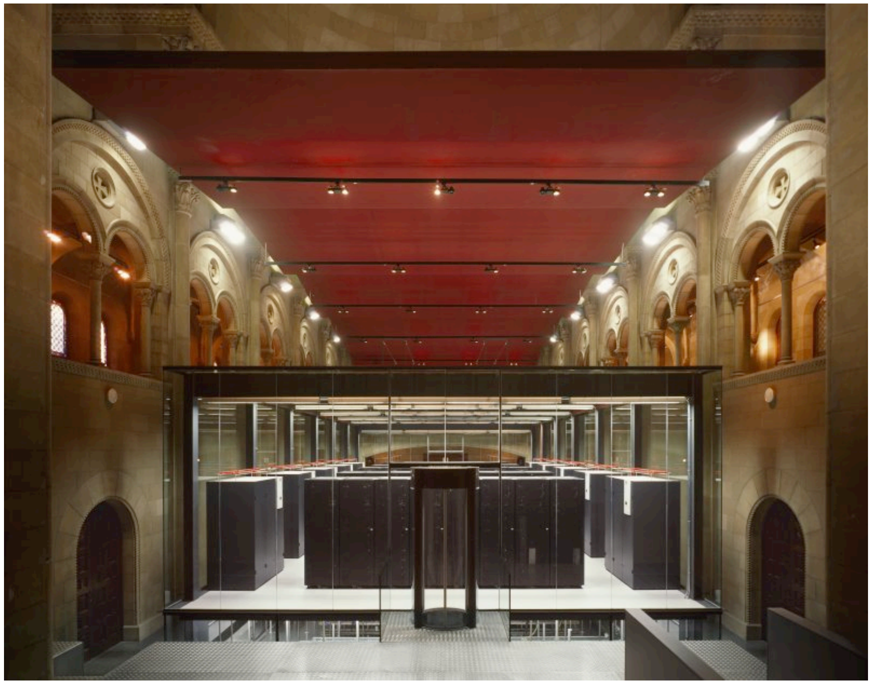
RAMSES (AMR) simulation of a spiral disc at z=0.
200 pc spatial resolution (sub-grid model)
10^6 dark matter particles in R_{200}.
Collaboration with Brad Gibson and Stéphanie Courty
(University of Central Lancashire)

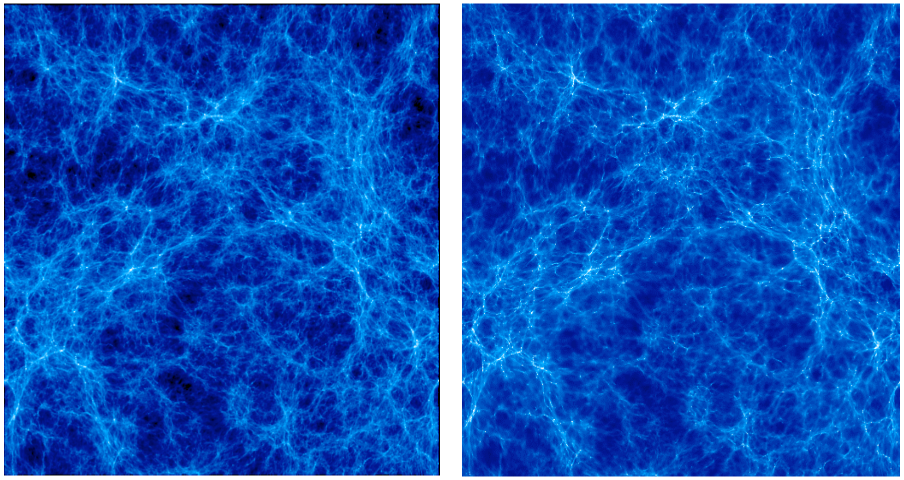
A realistic spiral galaxy ?



I Band Tully-Fisher relation (Governato et al. 2007, Mayer et al. 2008)

The MareNostrum galaxy formation project



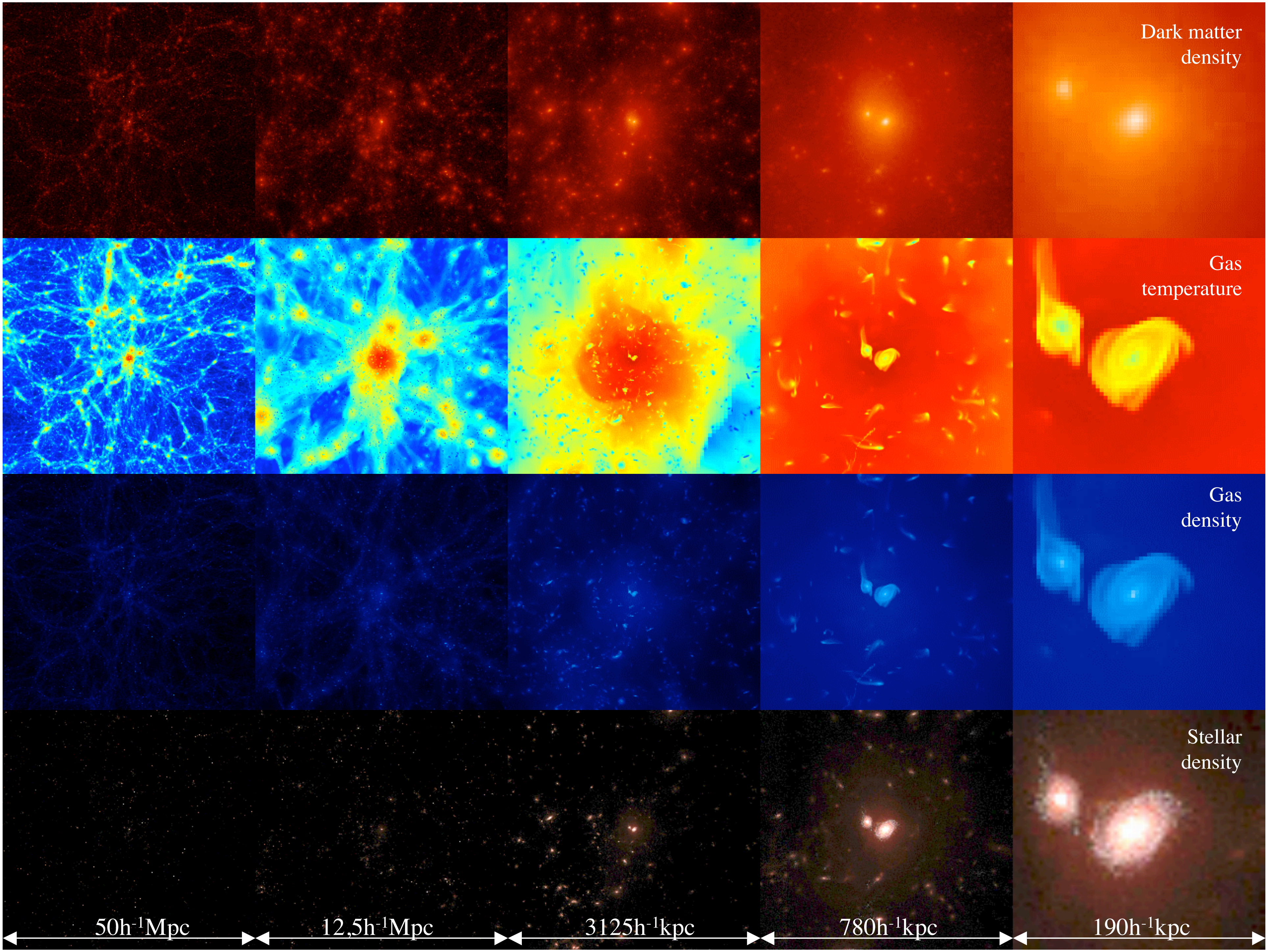


GADGET
SPH

z=5.7

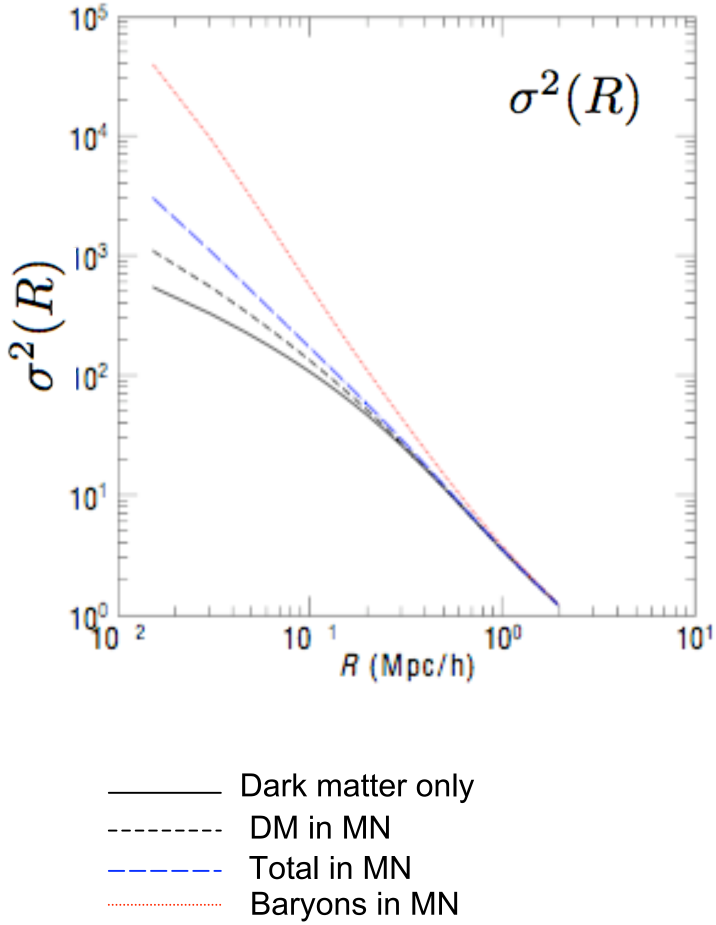
RAMSES
AMR

GADGET team: G. Yepes, R. Sevilla, L. Martinez (UAM), S. Gottloeber, C. Wagner, A. Khalatyan (AIP)
RAMSES team: R. Teyssier, D. Aubert, P. Ocvirk, E. Audit (CEA), J. Devriendt (Oxford), C. Pichon (IAP)
with strong support from DEISA, BSC (S. Girona and support) and IDRIS (P. Wautelet, P.-F. Lavallée).

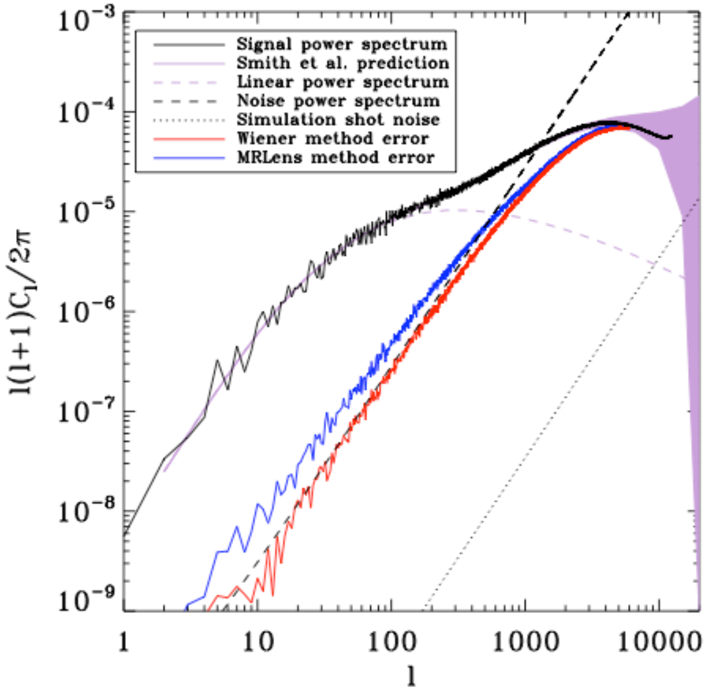

Dark matter density
Gas temperature
Gas density
Stellar density
50h-1Mpc
12,5h-1Mpc
3125h-1kpc
780h-1kpc
190h-1kpc

The impact of baryons on the matter power spectrum

The MareNostrum simulation
Matter power spectrum



The Horizon simulation
Full-sky kappa map

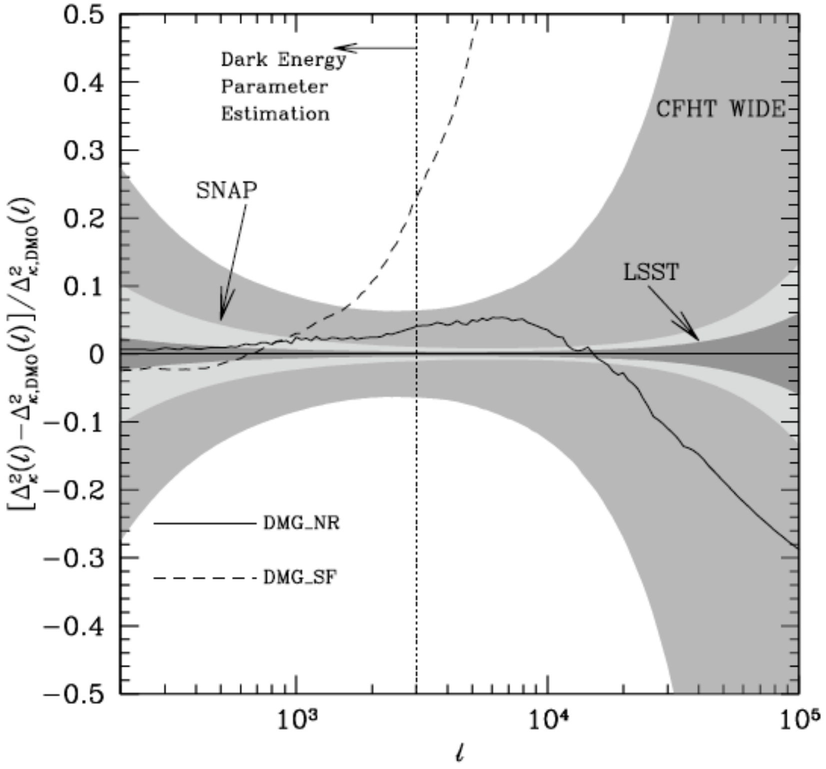


$$\sigma^2(R) = \frac{1}{2\pi^2}\int \frac{\mathrm{d}k}{k} k^3 P(k) \left|W(kR)\right|^2$$

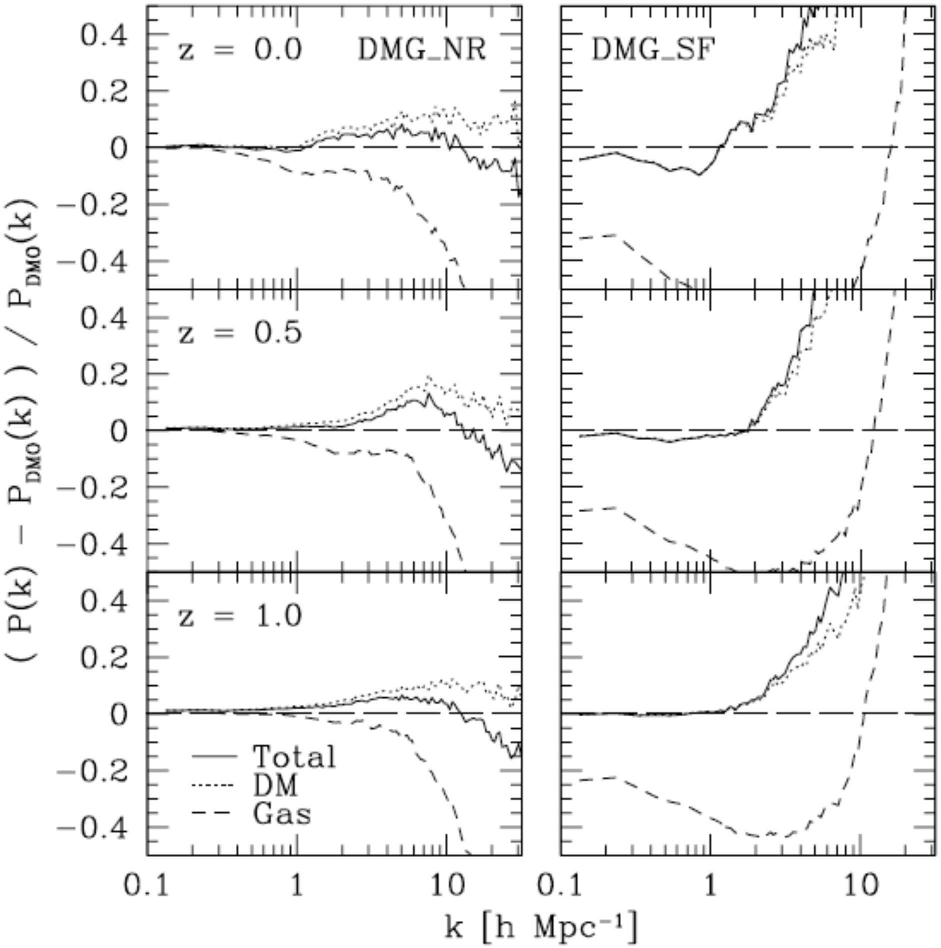
The impact of baryons on the matter power spectrum

Some history: Jing et al. 2006; Rudd et al. 2008
Modify the total power spectrum wrt pure DM spectrum up to 20 percent !
between l=10^3 and 10^4

Rudd et al. 2008



Rudd et al. 2008



Ideas:

- design halo models that account for baryons
- validate the halo model on numerical data (extreme models ?)
- use the halo model to fit real data

Modified halo models and high-order statistics

Assume a collection of NFW halos described by the PS mass function.

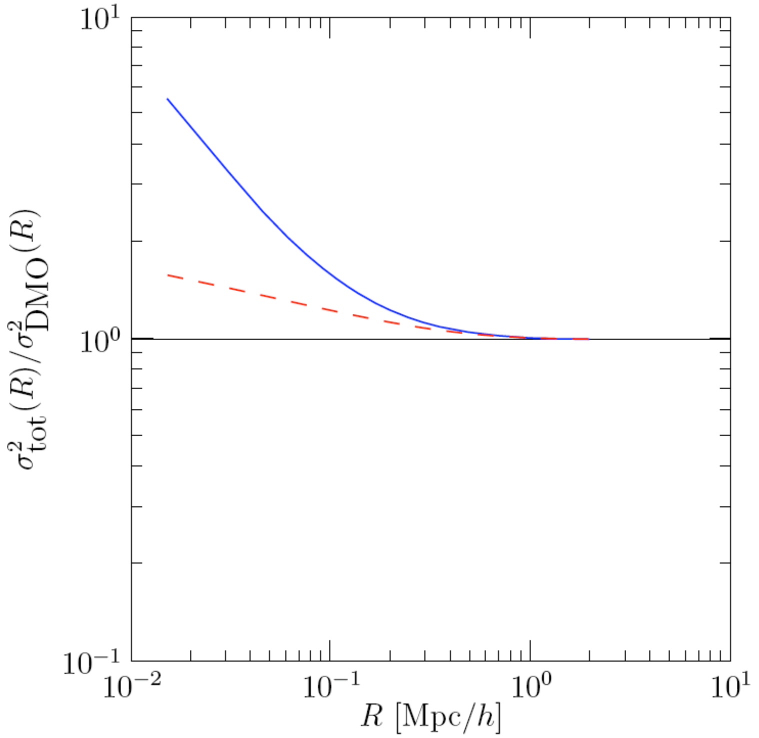
Concentration parameters $c=R_{200}/r_s$

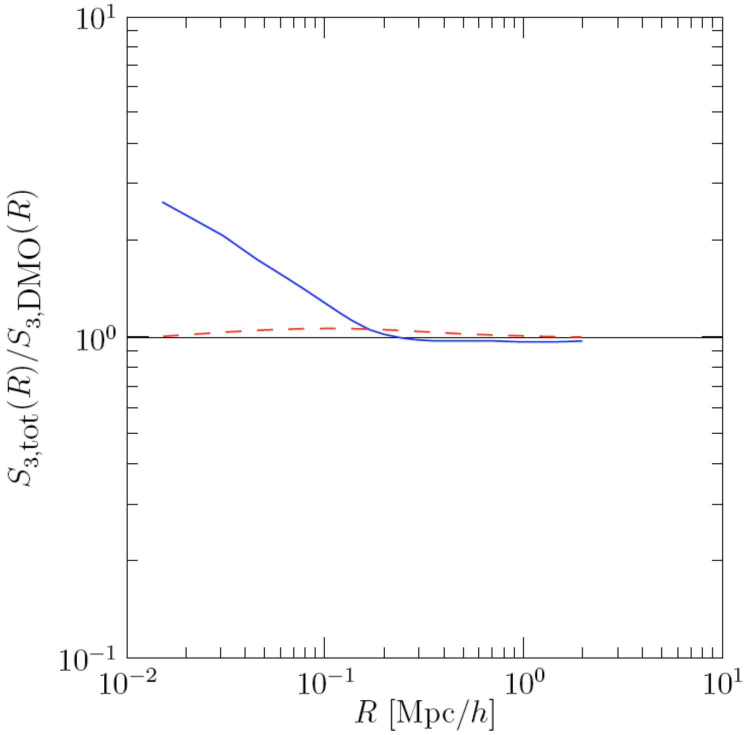
Use Rudd et al. 2008 model: $$c(M) = c_0\left(\frac{M}{M_*}\right)^b,$$ $c_0=9$, $b=-0.13$

Baryons collapse increase c by 70%:

$c_0=15$

$\sigma^2(R)$ $S_3(R)$

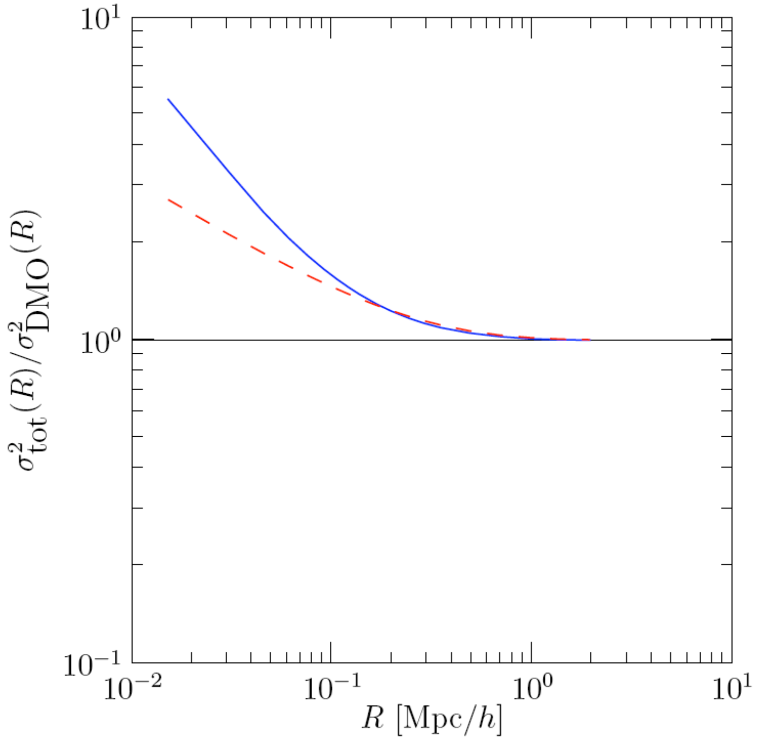




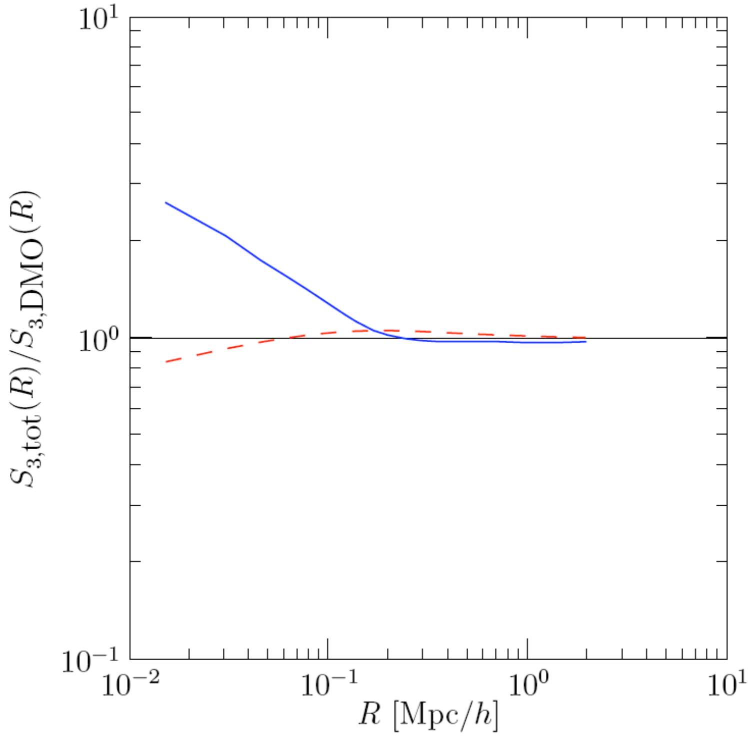
Modified halo models and high-order statistics

What about « best fit » concentration parameters ?
We tried c_0=35, b=-0.25.
Unphysical and not even working for high-order moments.

$\sigma^2(R)$



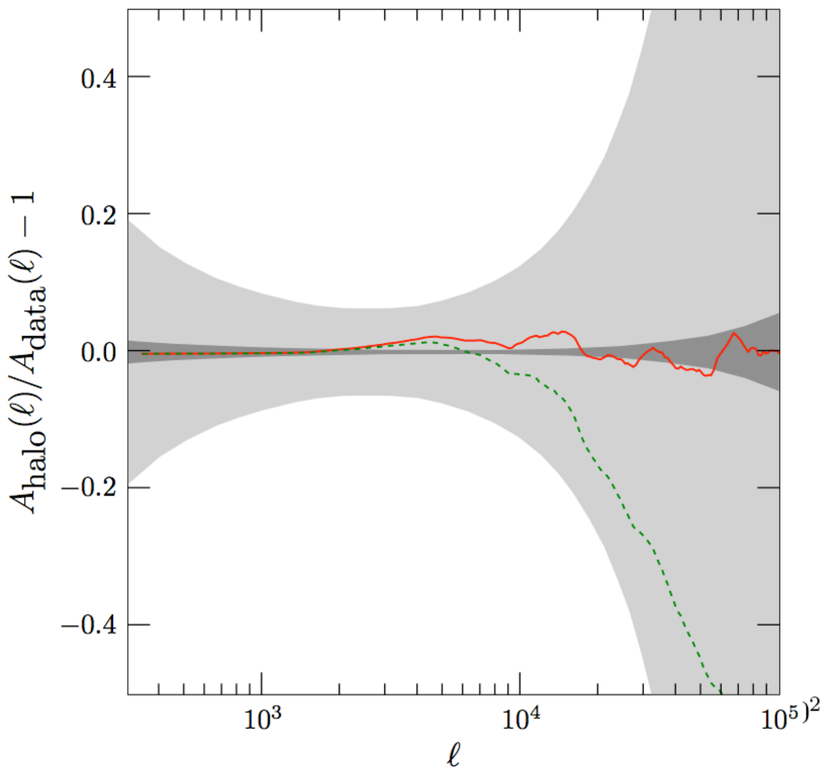
$S_3(R)$



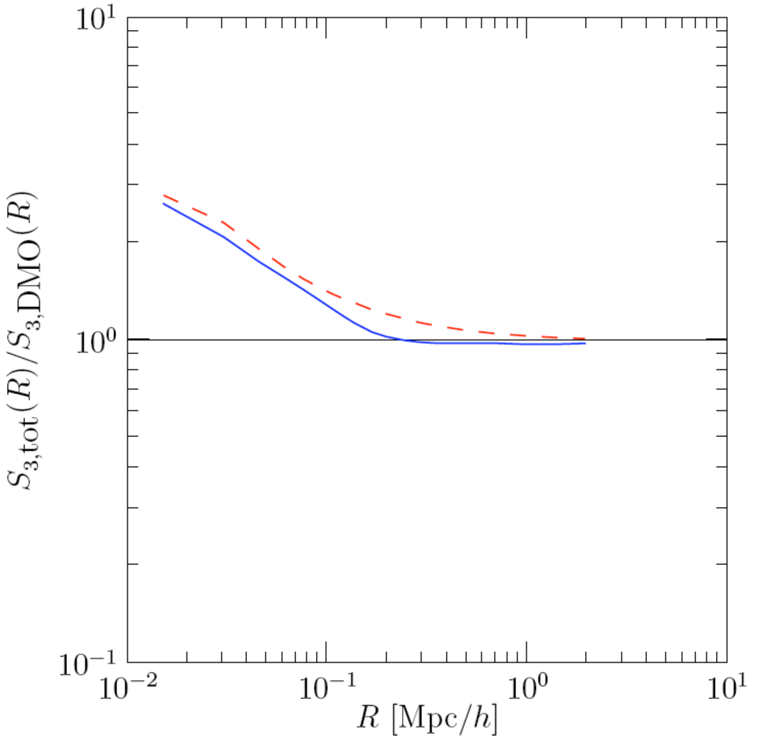
Modified halo models and high-order statistics

New model with 2 components:
9% of the mass in an exponential disk with r_d=0.03r_s
91% in a NFW halo with c_0=15 and b=-0.15

$\sigma^2(R)$



$S_3(R)$



Accretion: cold streams or hot shocks?

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

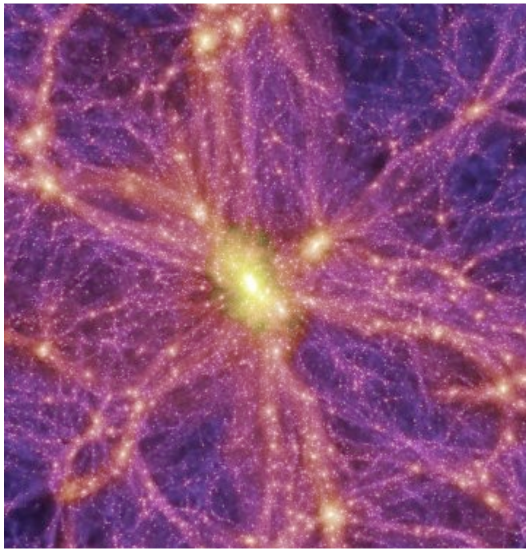
New model: large scale filaments feed directly fresh cold gas into the disc.

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

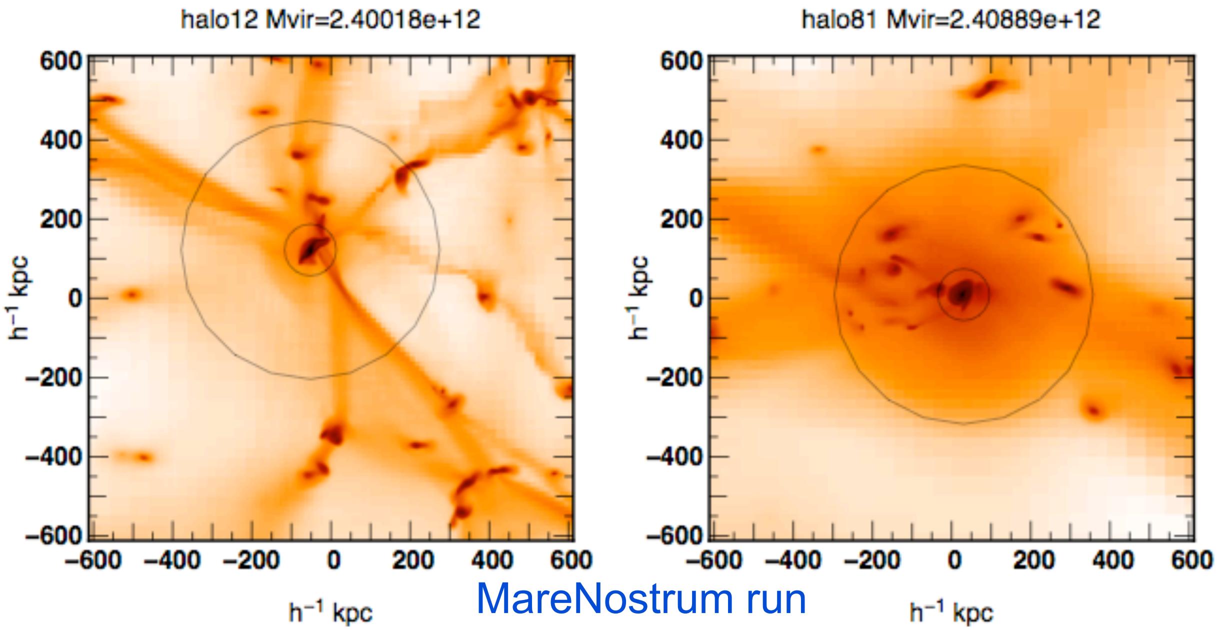
Density enhancement: $\rho_f T_* \sim \rho_{vir} T_{vir}$ for $M>M_*$

Only for large enough halo mass do we have hot shocks.

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



Galaxy cluster from the Millenium run



MareNostrum run

Kravtsov (2003)

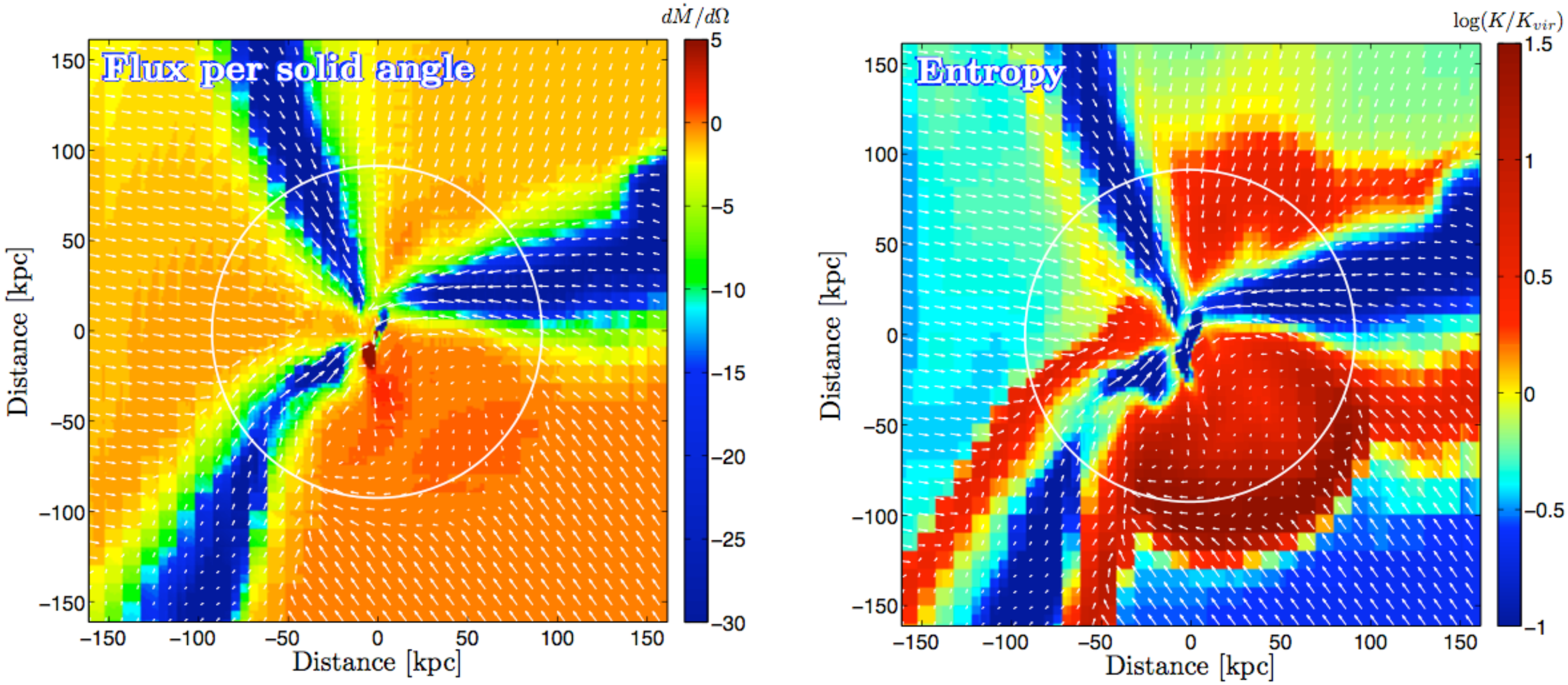
Birnboim & Dekel (2003)

Keres et al. (2005)

Dekel & Birnboim (2006)

An Eulerian view of gas accretion

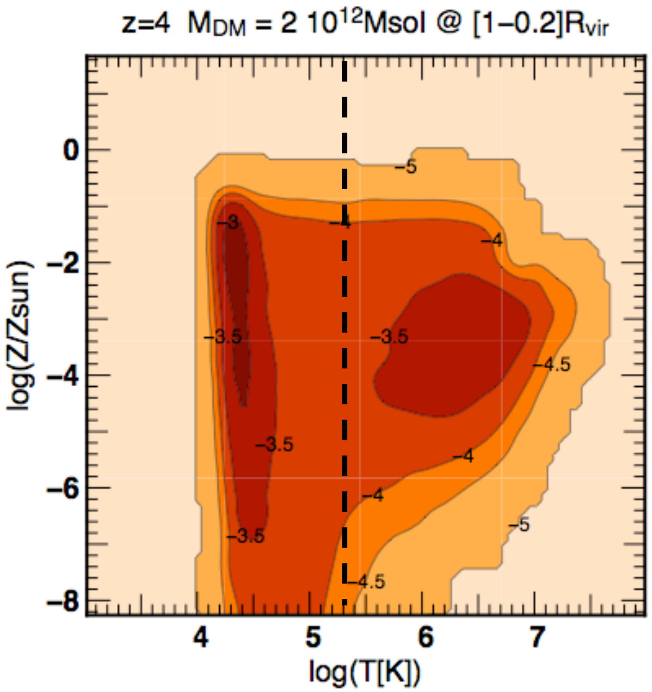
$$\dot{m}_R(r,\Omega) = \frac{\partial \dot{\mathrm{M}}}{\partial \Omega} = \rho_R \, \mathbf{v}_R \cdot \mathbf{n} \, r^2$$

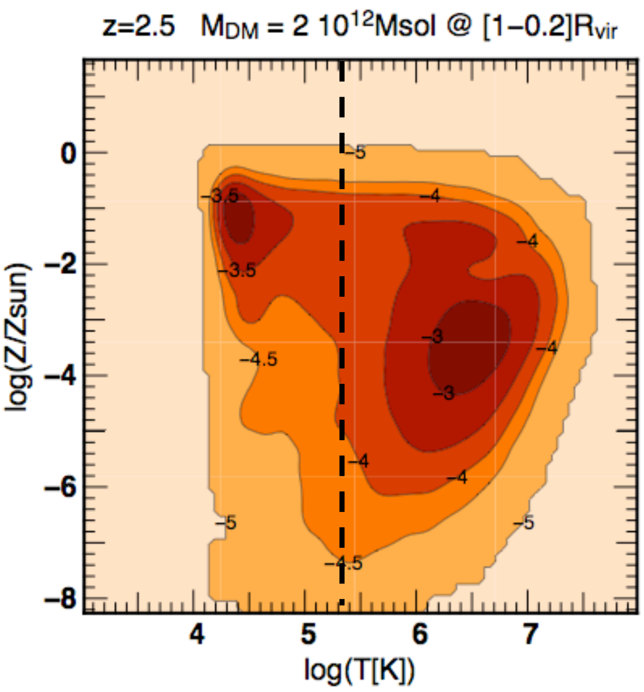


$$\dot{m}_R(r,T) = \int \delta_{\mathrm{D}}(T - T(\Omega)) \, \dot{m}_R \, \mathrm{d}\Omega = \frac{\partial \dot{\mathrm{M}}}{\partial T}$$

Accretion-weighted histograms

A proxy for detecting hot shocks: accretion-weighted histogram @ 0.2xRvir
A proxy for detecting cold streams: accretion-weighted histogram in [0.2-1]xRvir
Critical temperature T_0=2.5x10^5 K (as in Keres et al. 2005)





60% of accretion in cold phase **40% of accretion in hot phase**

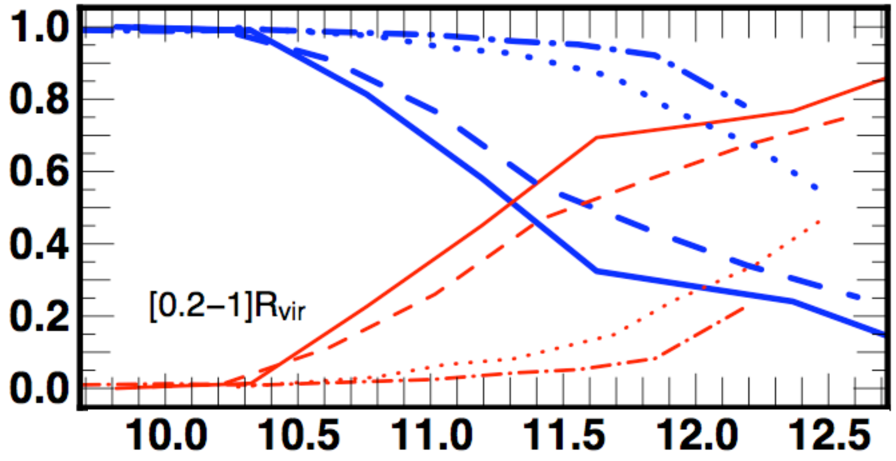
20% of accretion in cold phase **80% of accretion in hot phase**

Ocvirk et al., 2008, MNRAS

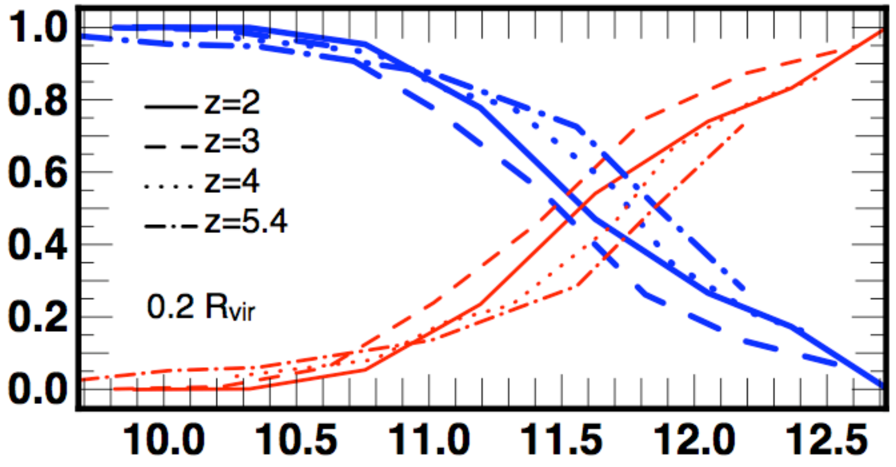
Bimodality in smooth accretion flows

Is star formation in a galaxy related to the properties of diffuse gas accretion ?

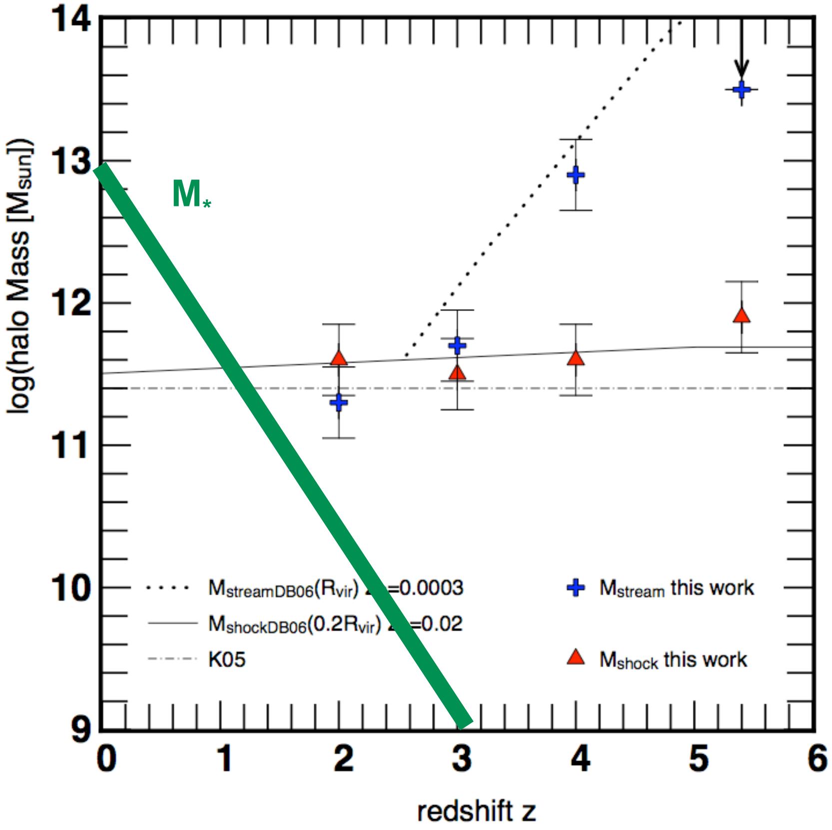
Transition masses for cold streams



Transition masses for hot shocks

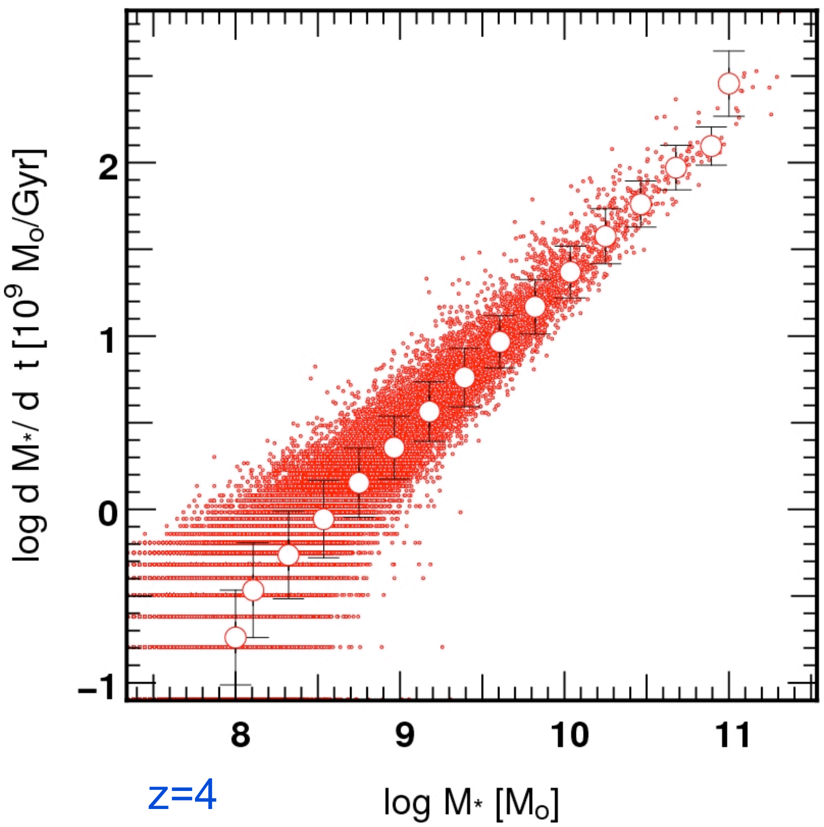


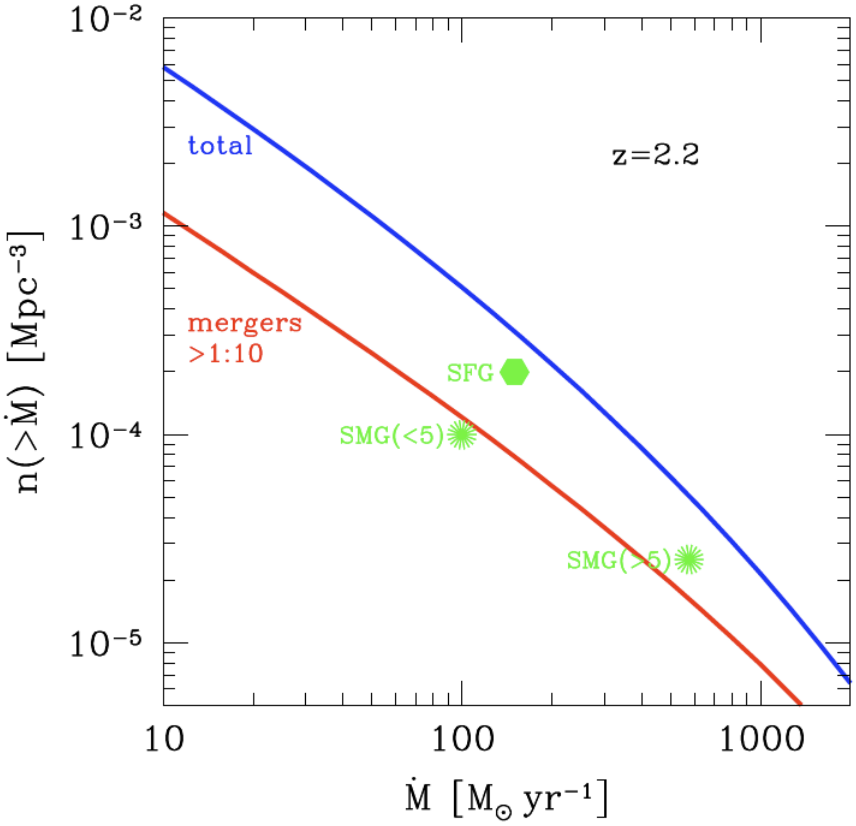
Metallicity of filaments/shocks is
the key parameter !



Star formation and diffuse accretion

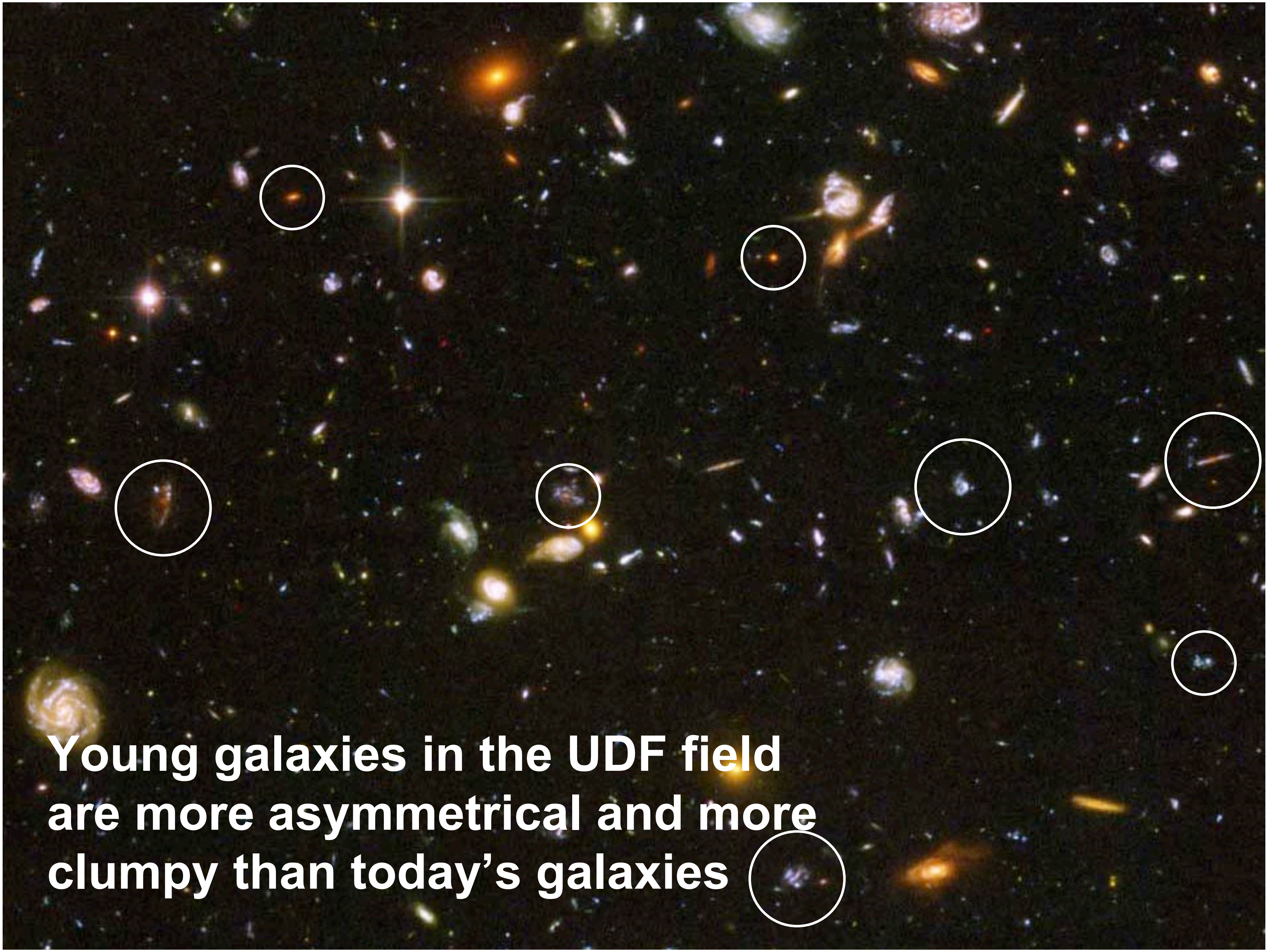
cosmic SFR vz mass





High star formation at high redshift (BzK galaxies) proceeds through efficient gas accretion via cold streams.

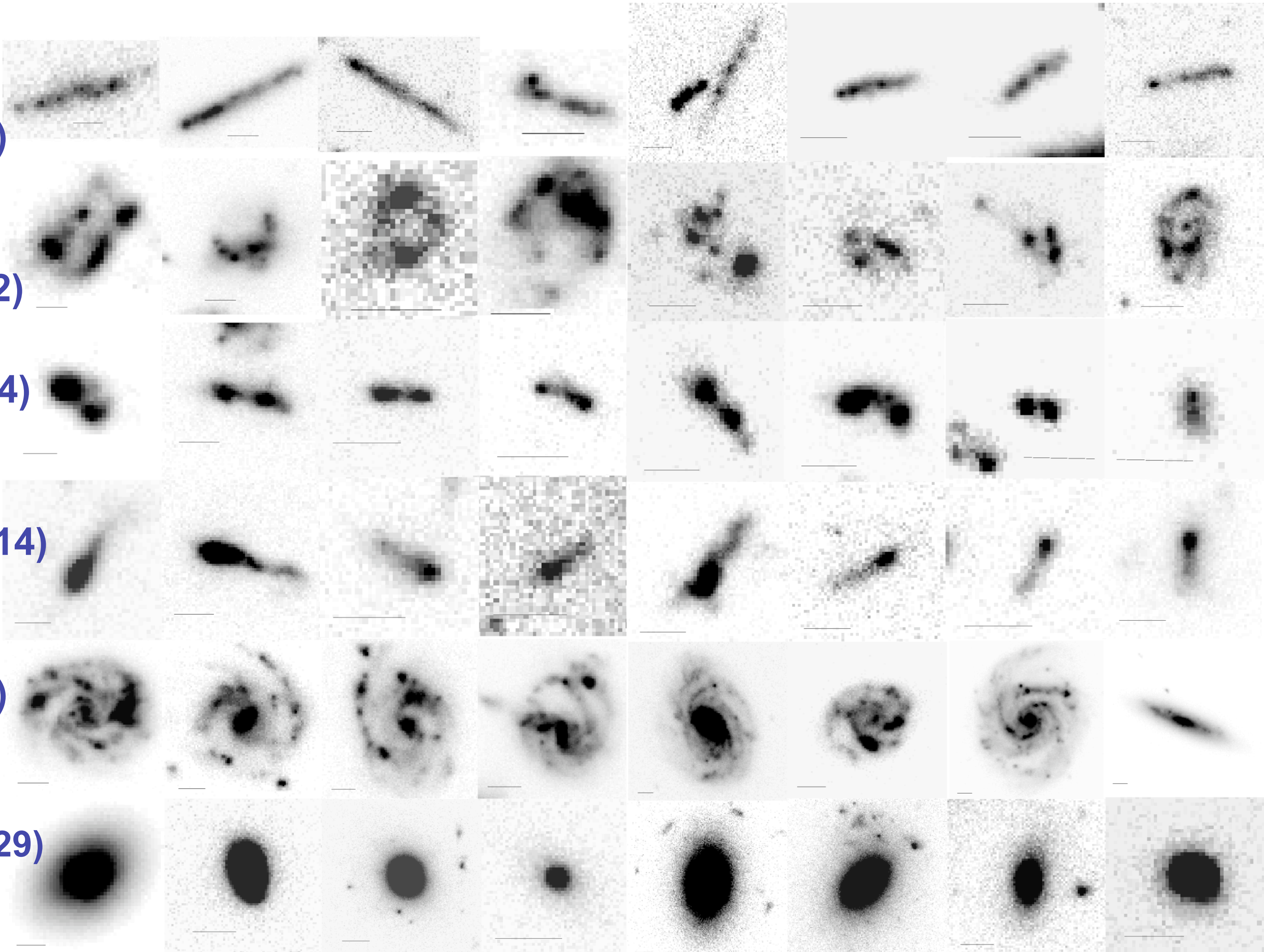
Dekel et al., 2009, Nature



Young galaxies in the UDF field are more asymmetrical and more clumpy than today’s galaxies

Chains, clump-clusters, and others

- **Chain (121)**
- **Clump cluster (192)**
- **Double (134)**
- **Tadpole (114)**
- **Spiral (313)**
- **Elliptical (129)**



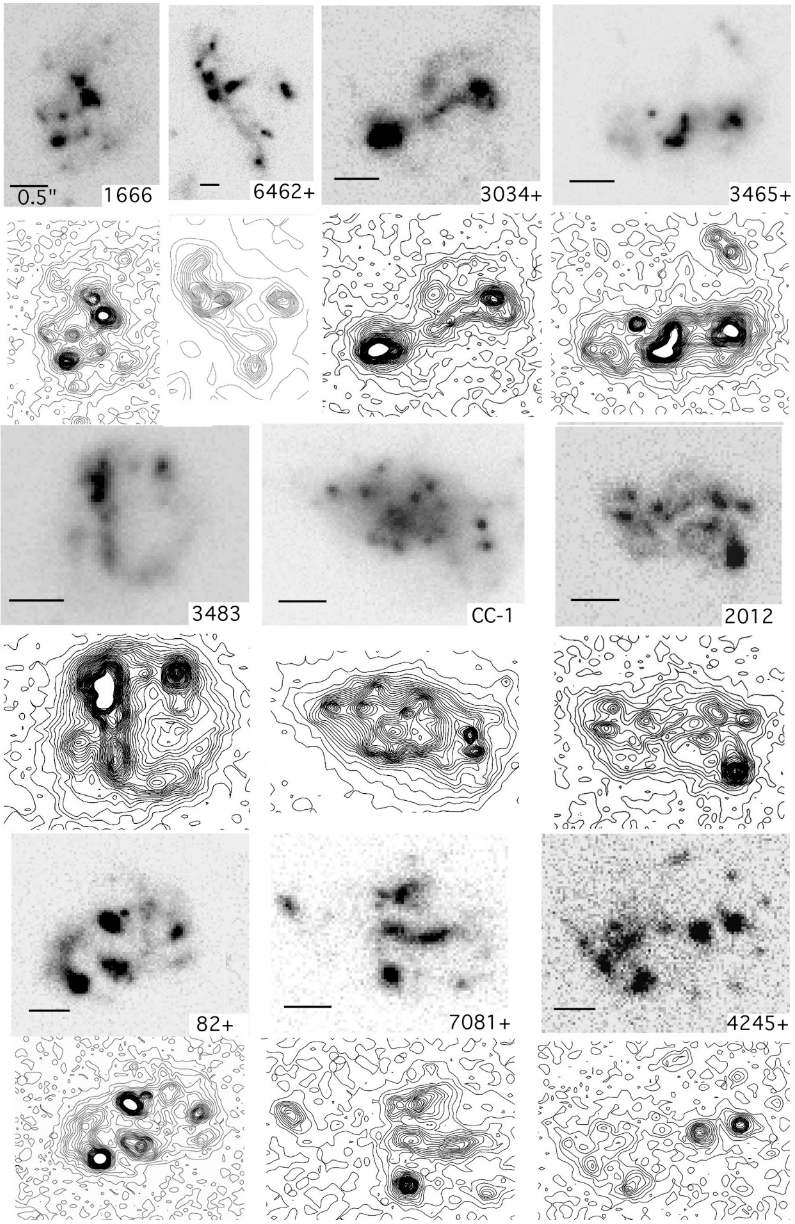
—— = 0.5”

(Elmegreen,Elmegreen, Rubin, Schaffer 05)

High redshift galaxies are clumpy

- Photometric z ($<z>\sim2.3$)
  - Bruzual & Charlot ‘03
  - Rowan-Robinson dust (and x2, x4)
  - Madau ’95 intergalactic H absorption
  - Calzetti/Leitherer extinction

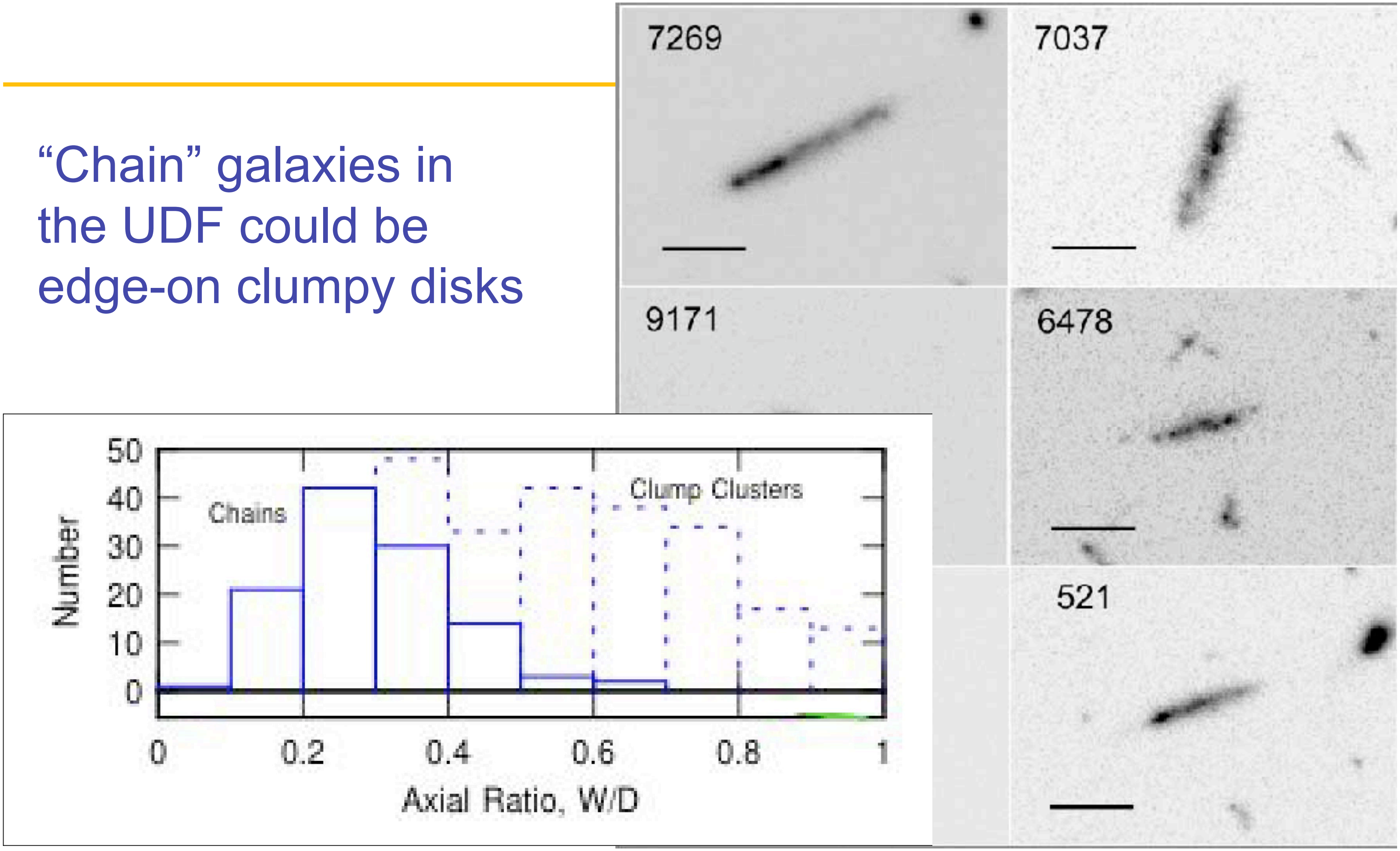
- Average clump:
  - Mass ~ $6x10^{8} M_O$
  - Diameter ~ 1.8 kpc,
  - age ~ 300 Myr, τ_{decay}~100 Myr
  - SFR ~ 20 M_O/yr(peak), 2 M_O/yr(ave)
- Average galaxy:
  - M_{gal} ~ $6x10^{10} M_O$,
  - D_{gal} ~ 20 kpc, V_{rot} ~ 150 km s^{-1}



—— =0.5”

(Elmegreen & Elmegreen 05)

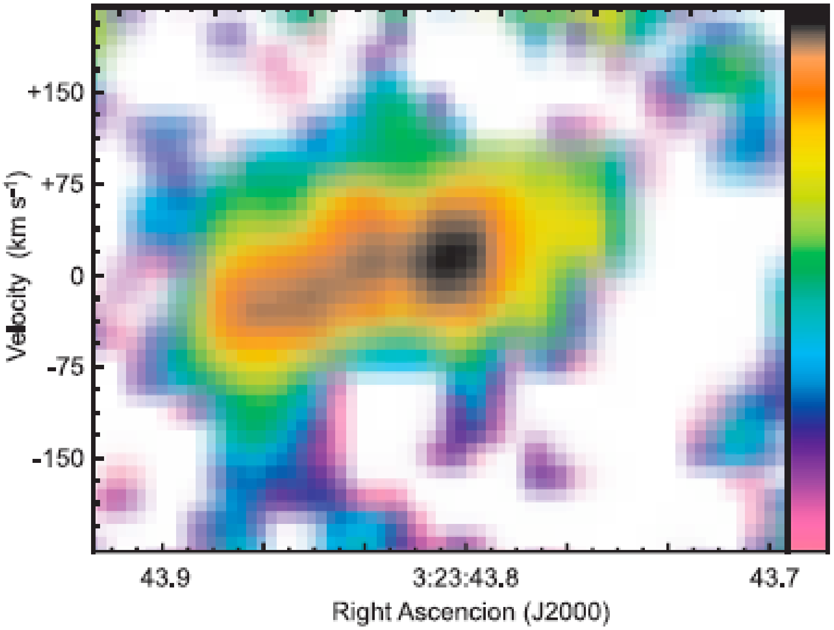
"Chain" galaxies in the UDF could be edge-on clumpy disks



Axial ratio distribution is ~ <u>constant</u>, as it is for randomly oriented circles

Elmegreen et al. 05, 06

UDF6999: a bent chain ?



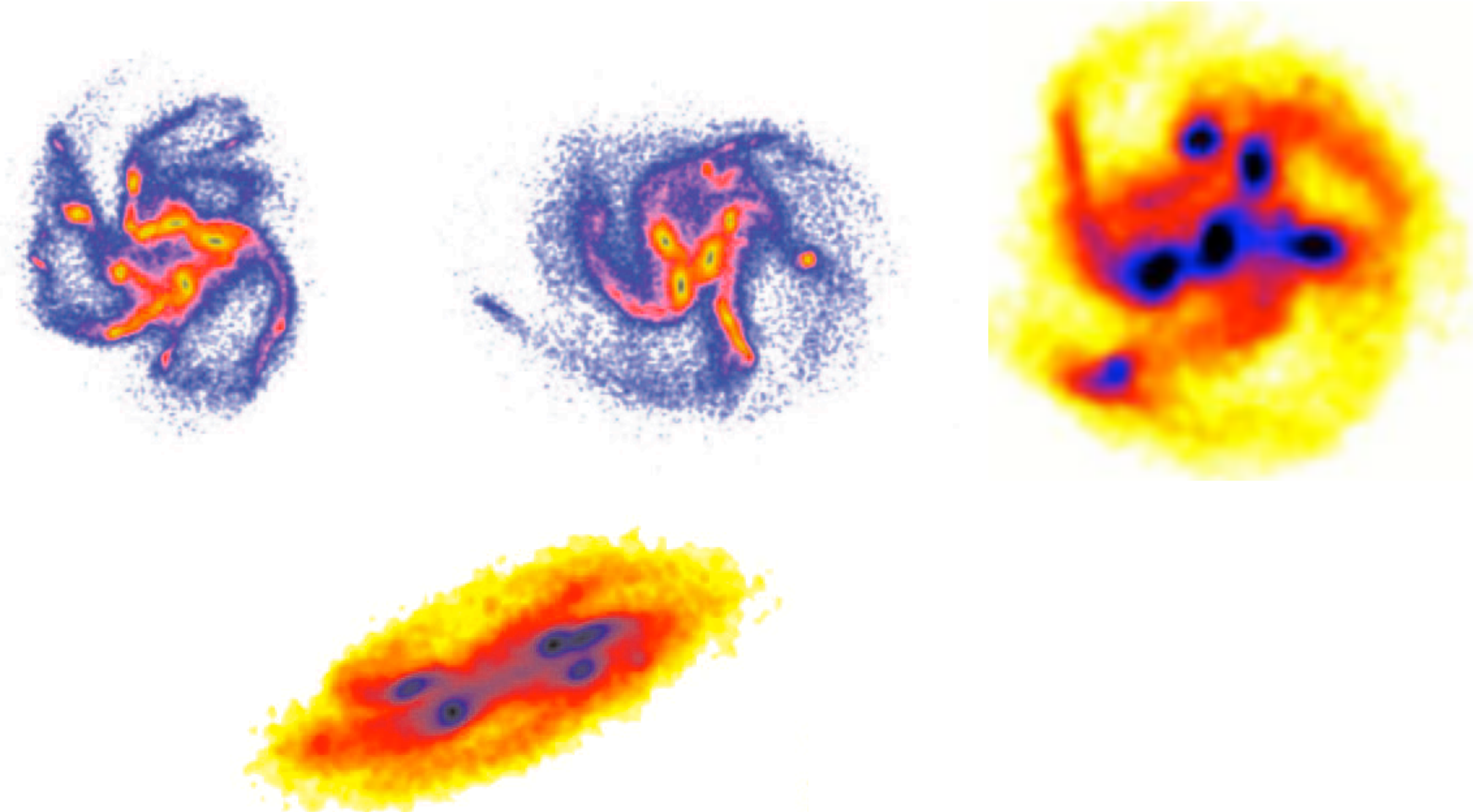
Disk-like rotation curve ?

Bent chain ?

Bournaud, Daddi, Elmegreen et al. 2008

Models of clumpy disks

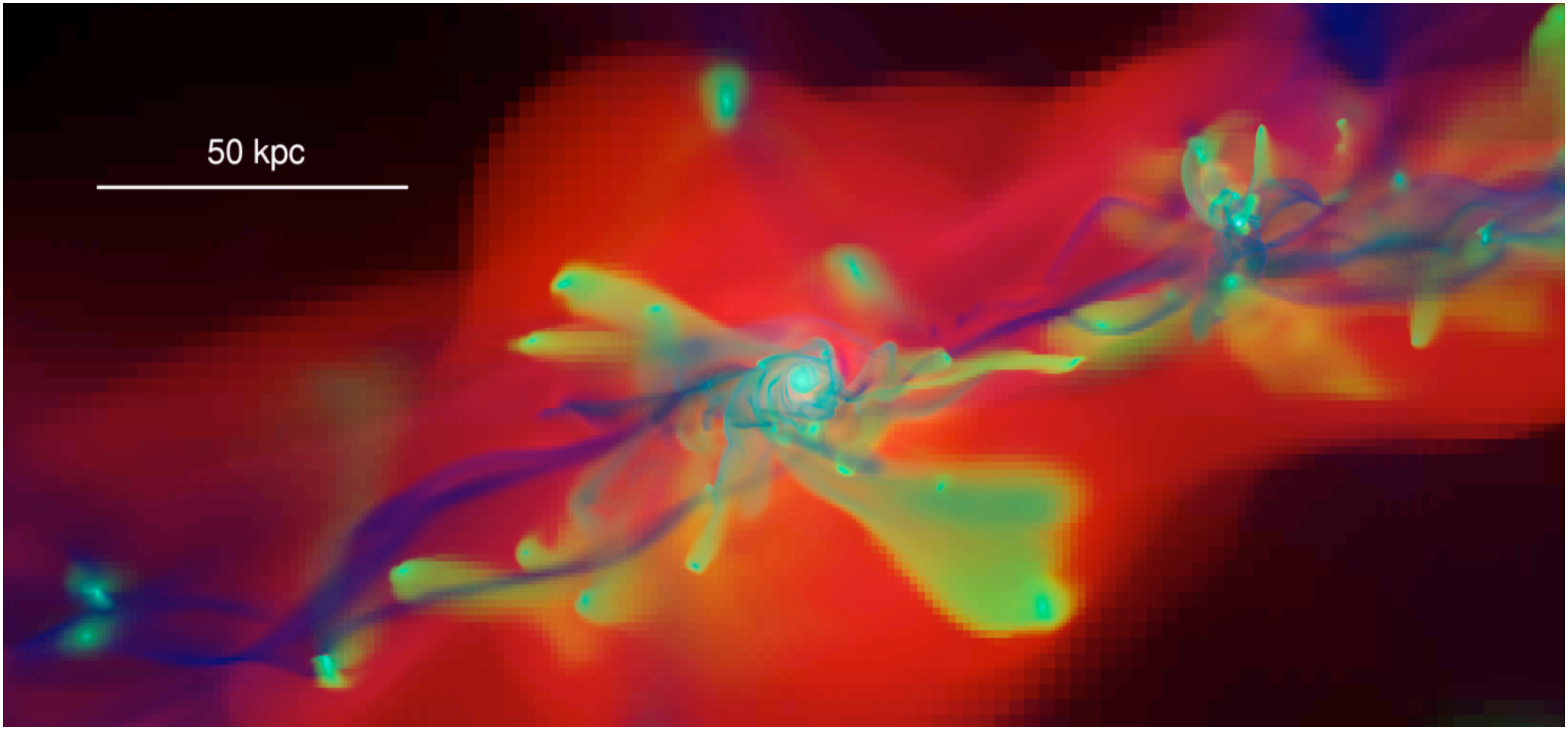
Starting with smooth unstable disks:



(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

SFR ~ 20 Msol/yr

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

R ~ 10 kpc

3 clumps Mcl ~ 10^9 Msol

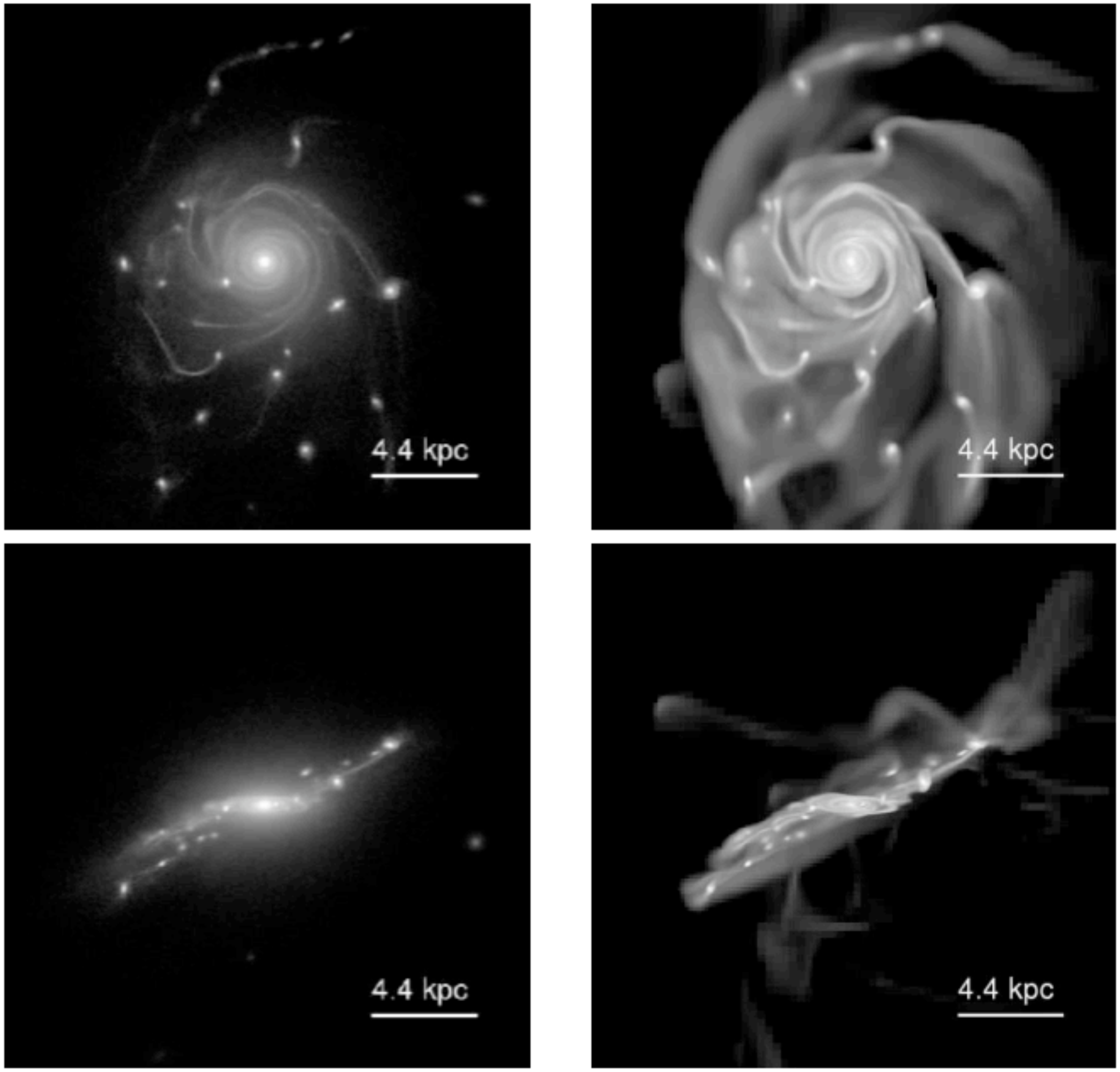
9 clumps Mcl ~ 10^8 Msol

2 satellites

Misaligned inner and outer discs

Z/Zsol (inner) ~ 1

Z/Zsol (clumps) ~ 0.1



Fragmentation of material arms

Tidal debris and cold streams interact with the inner disc

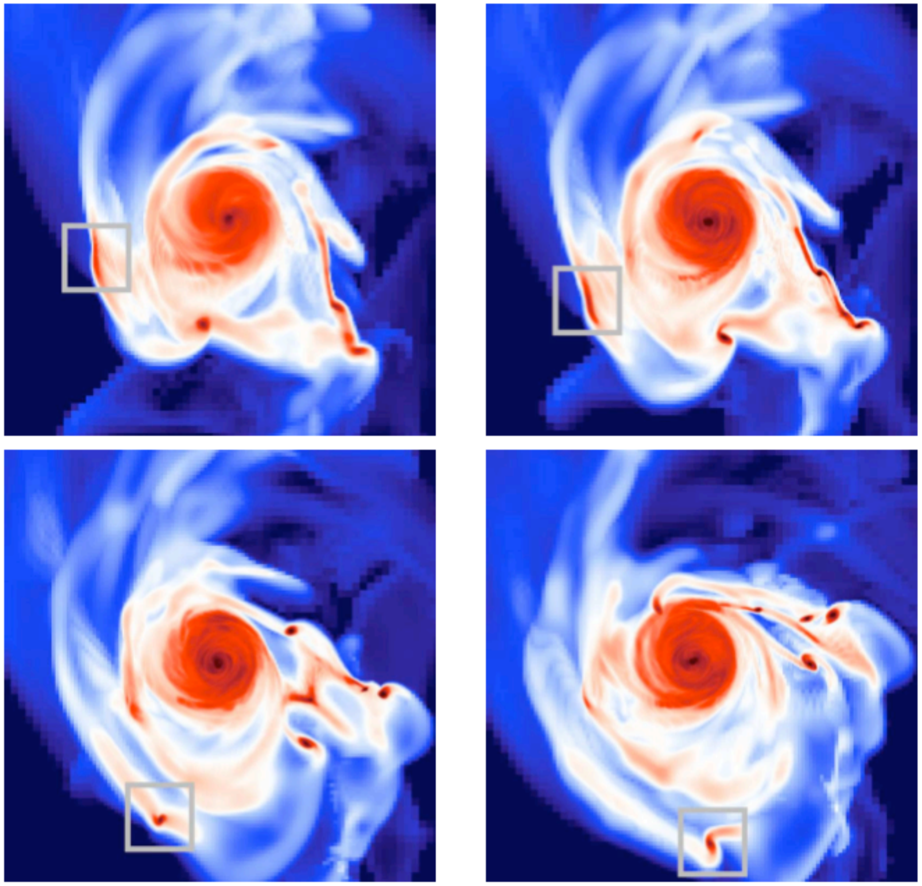
Gravitational instability in the arm

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

Shear and compression give rise to large velocity dispersions

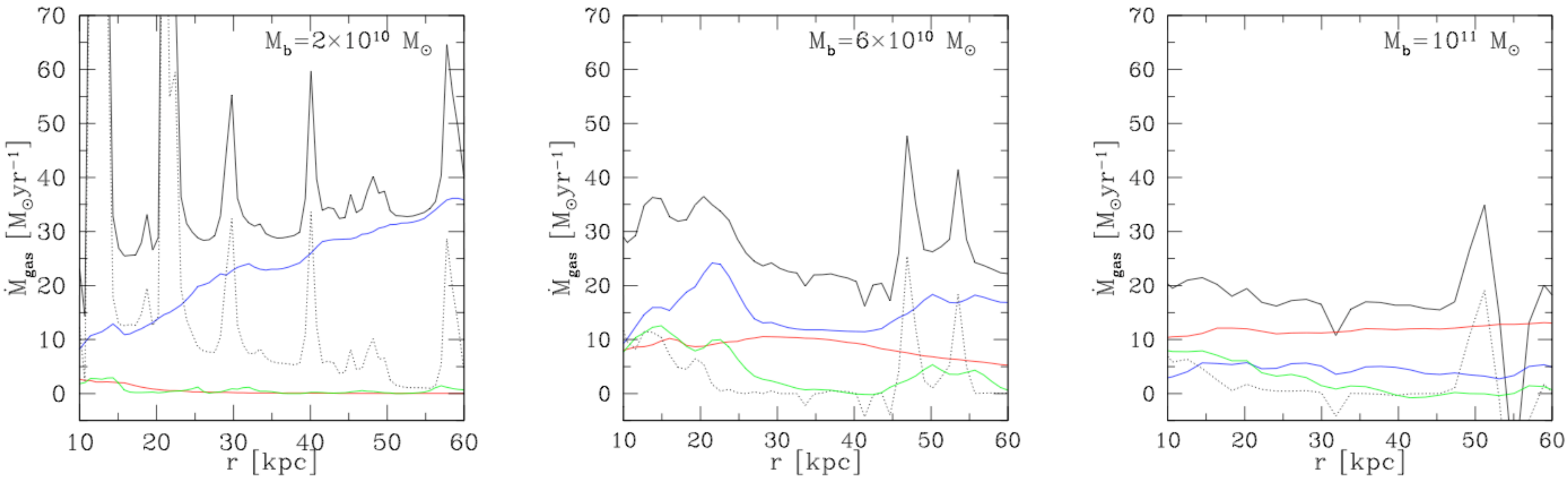
$$\sigma \simeq \frac{\lambda}{\mathcal{R}_{\rm c}} v_{\rm orb}$$

Clump masses 10^8-10^9 $M_{\rm sol}$

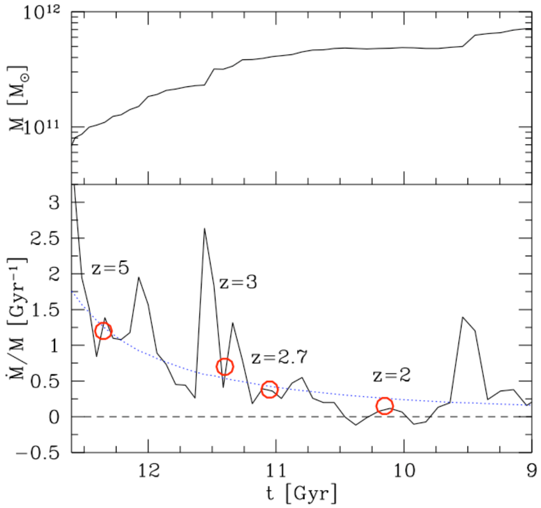


Similar scenario in major mergers for tidal dwarf formation at low redshift (Elmegreen et al. 1993)

Cold streams accretion and massive clumps formation



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



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

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

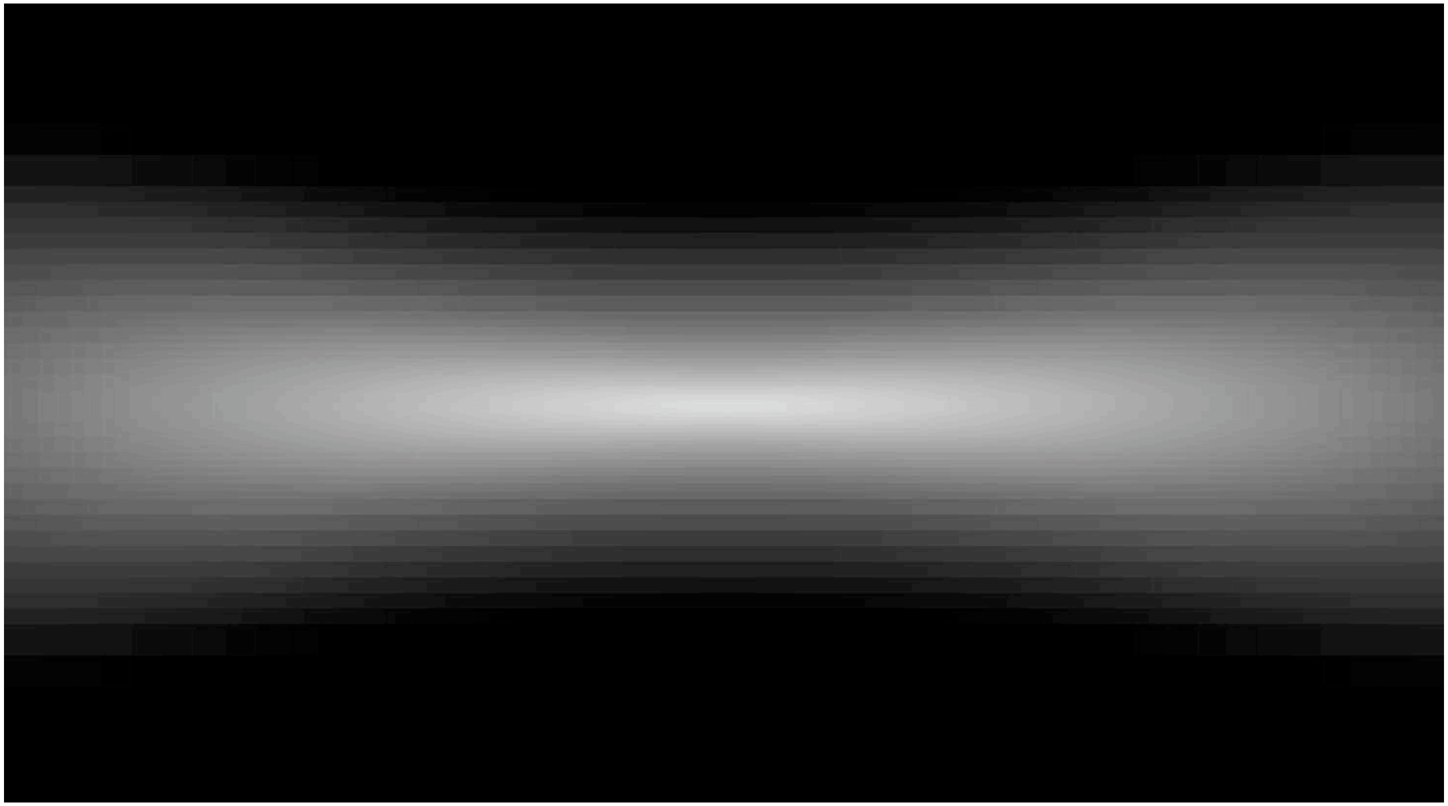
Few pc resolution !

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

Agertz et al. 2008
Tasker et al. 2008

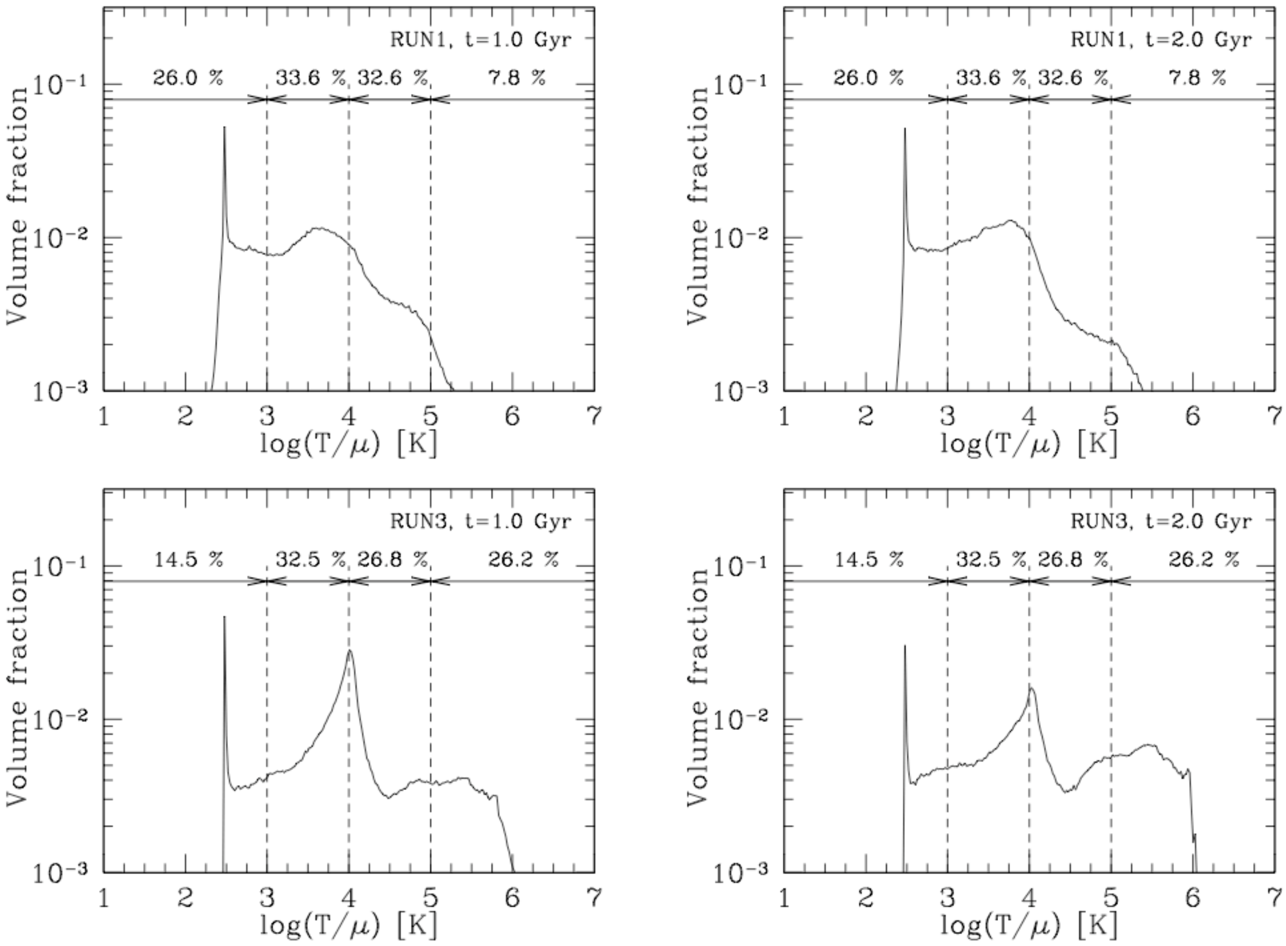
Disc edge on (gas column density)

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) ?

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%

Cosmic magnetism

Magnetic field is ubiquitous in the universe.

In the ISM, $P_{mag} \approx P_{CR} \approx P_{thermal}$.

Magnetic fields probably control star formation efficiency and the IMF.

In galaxy clusters, magnetic fields allow (or not) high-energy CR to escape.

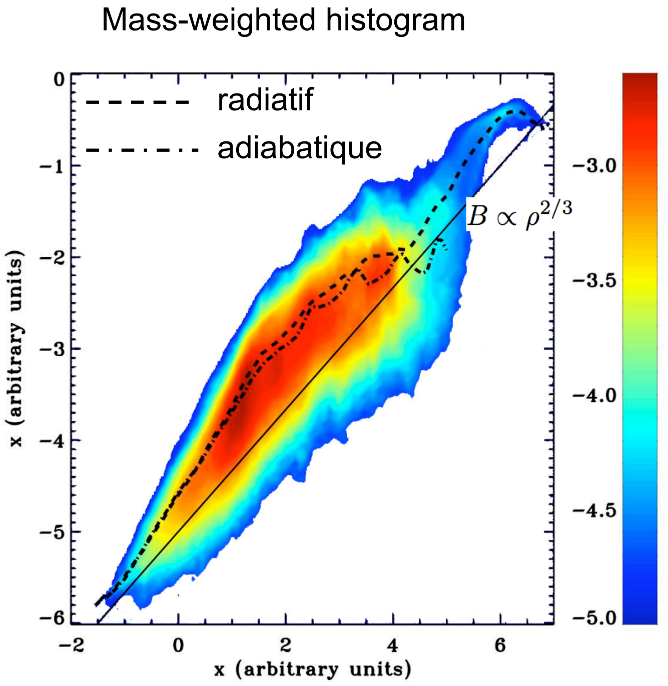
Magnetic fields might play a dominant dynamical role in high-density environments (cluster cooling flows, galactic centers, vicinity of AGN).

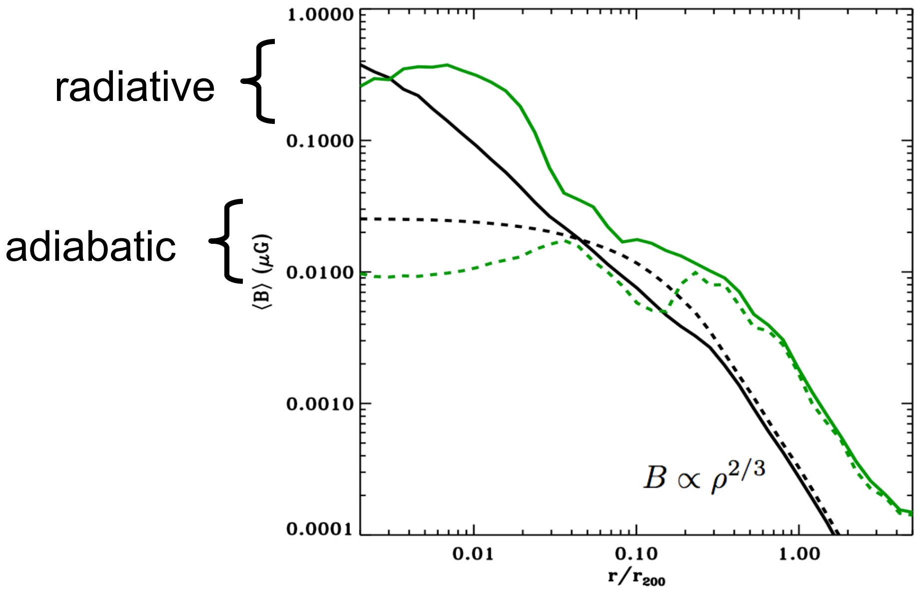
Questions:
- Where does it come from ?
- How does it get amplify at the present observed value (μG) ?

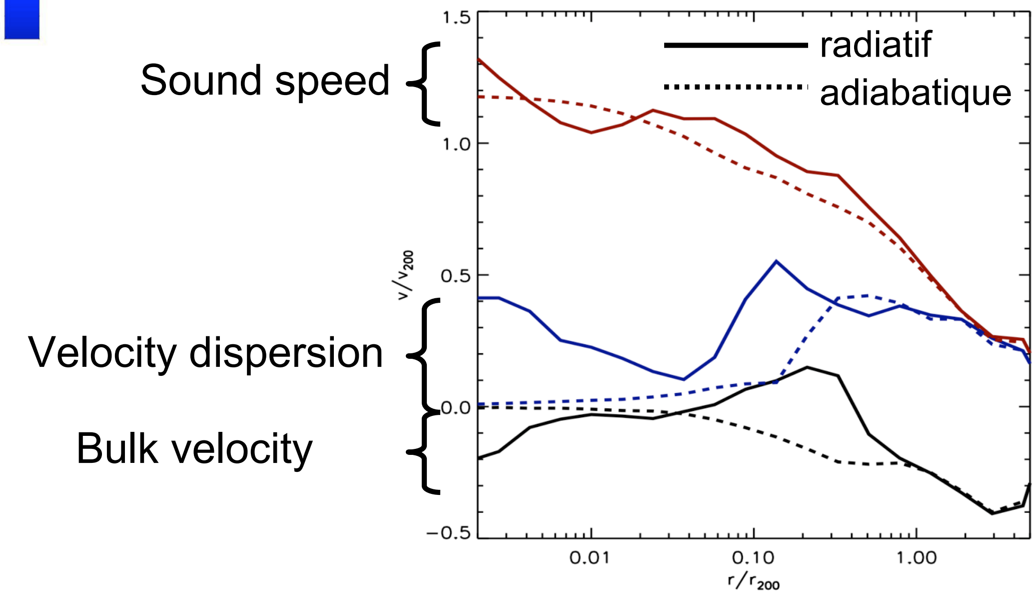
Classical theory:
- Biermann battery in the early universe
- Large-scale dynamos in (isolated) galactic discs.

How does this fit into the hierarchical clustering picture ?
What can we learn from MHD cosmological simulations ?

Magnetic field amplified by gravity and turbulence


Mass-weighted histogram



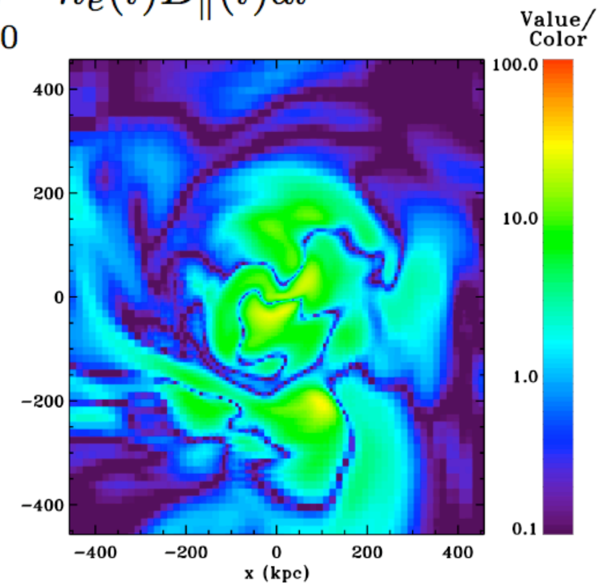


Dubois et Teyssier (200)

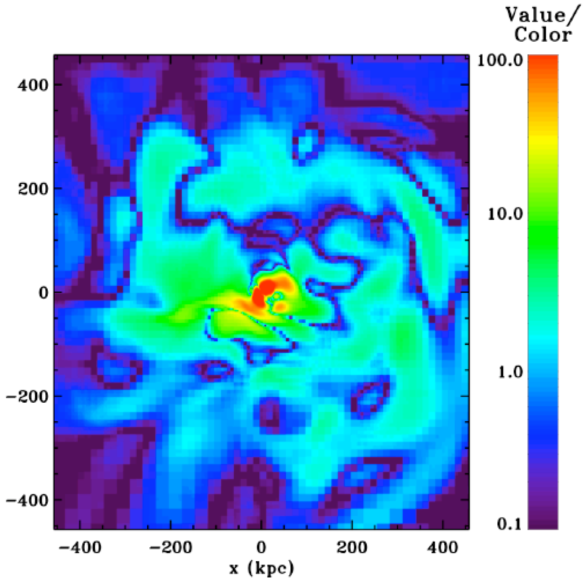
Faraday rotation measure in galaxy clusters

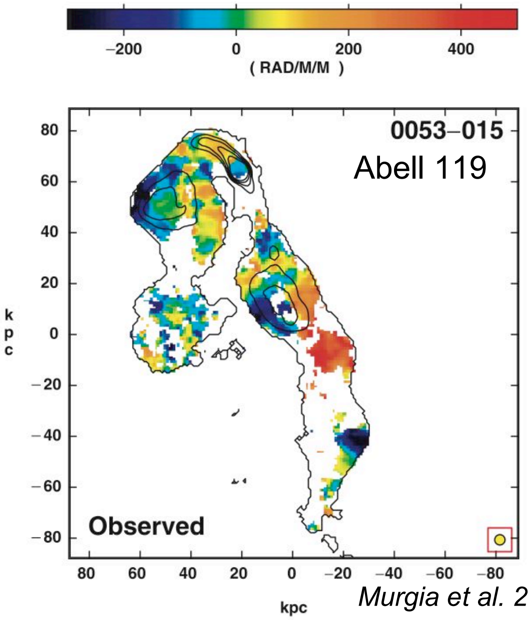
$$RM = \frac{e^3}{2\pi m_e^2 c^4}\int_0^L n_e(l)B_{\|}(l)dl$$

ADIABATIC

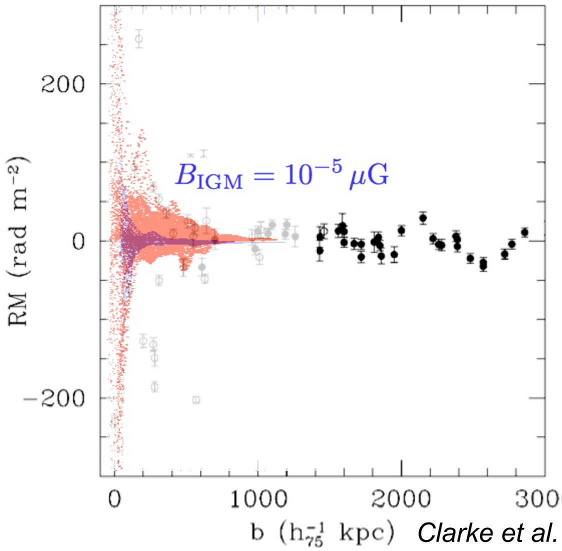


RADIATIVE





Murgia et al. 2004



Clarke et al. 2001

Origin of the magnetic field in the IGM ?

Starting with a background magnetic field of the order of $B_{\mathrm{IGM}} = 10^{-4} - 10^{-5}\,\mu\mathrm{G}$ we can reproduce the observed magnetic field in galaxy clusters.

Other 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 reject 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.

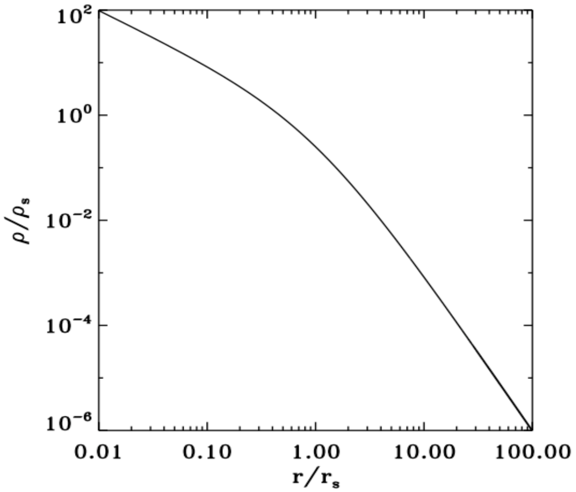
Perform MHD simulations of dwarf galaxies with supernovae-driven winds (Dubois & Teyssier in prep).

An idealized quiescent 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



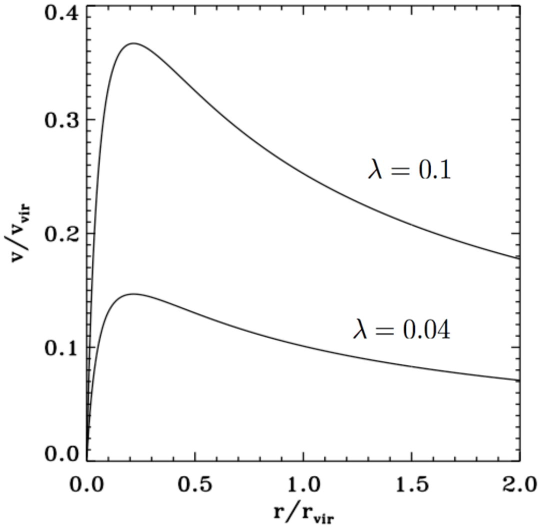
- Static potential for the dark halo $\frac{r_{vir}}{r_s} = c = 10$
- Average angular momentum profile

$$j(r) = j_{max}\left(\frac{M(r)}{M_{vir}}\right)^s, \ s = 1$$

Bullock et al. 2001

- High initial gas fraction: $\frac{\Omega_b}{\Omega_m} = 15\%$

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

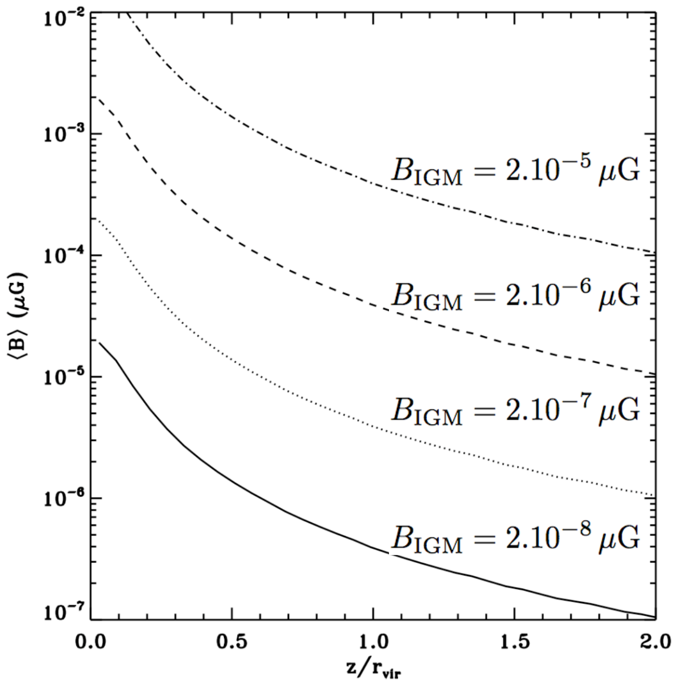


- Polytrope EOS

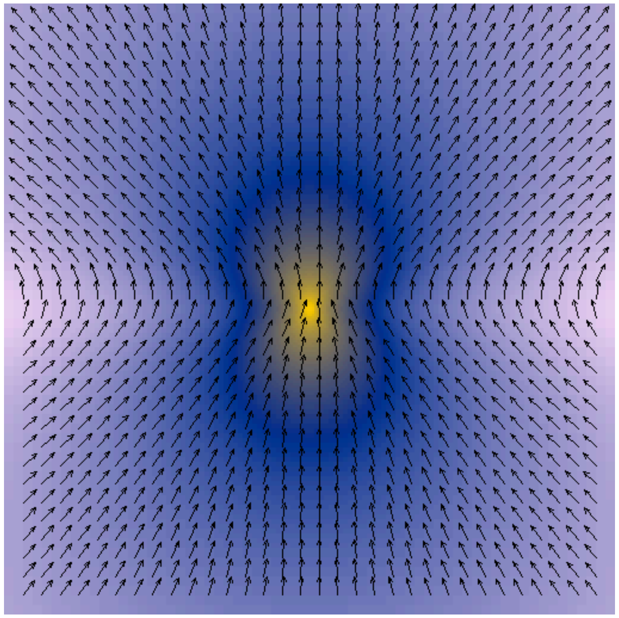
$$M_{\rm vir} = 10^{10}\, {\rm M}_\odot$$

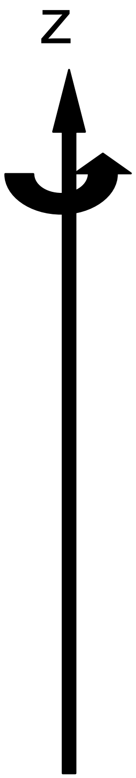
« Frozen-in » magnetic field in the initial halo

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



Champ magnétique

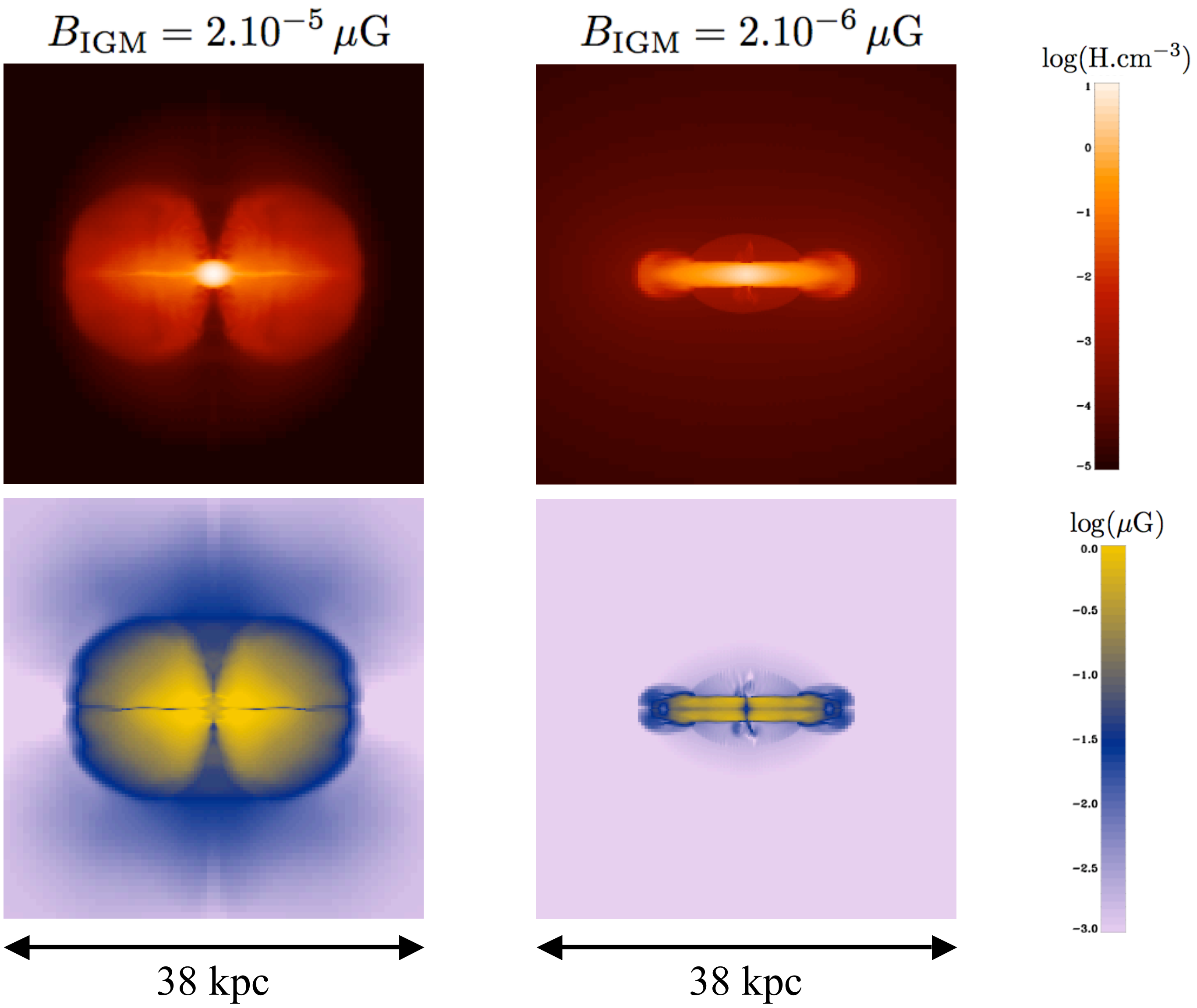




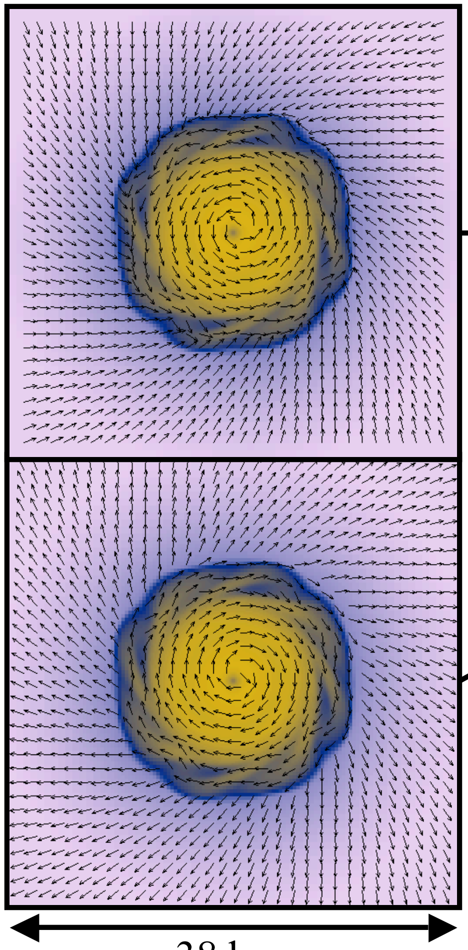
Dipole structure aligned with rotation axis

Magnetic fields in dwarf galaxies

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



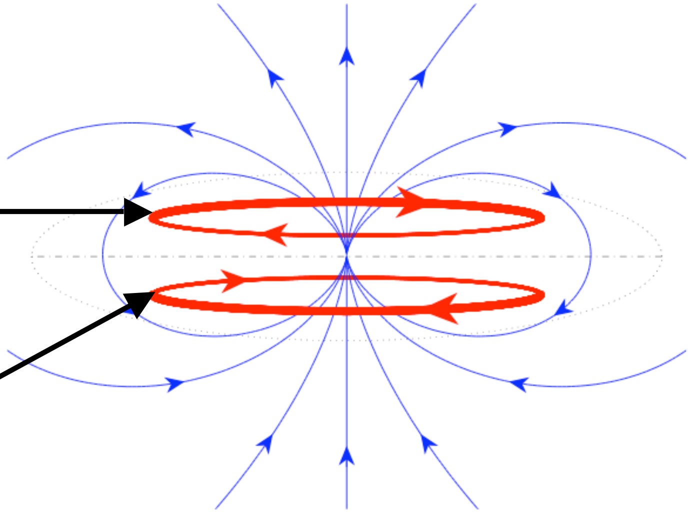
Topology of the galactic magnetic field



38 kpc

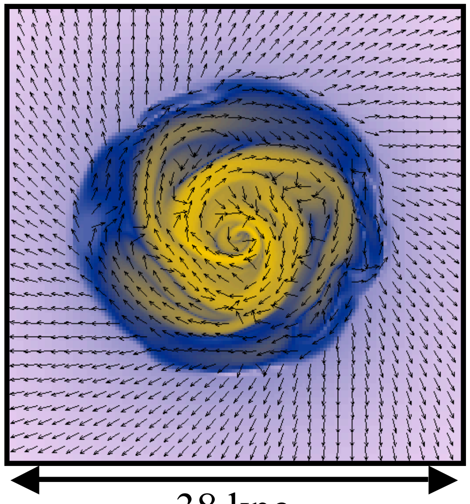
Above the plane

Below the plane



A0 : antisymetric mode with m=0

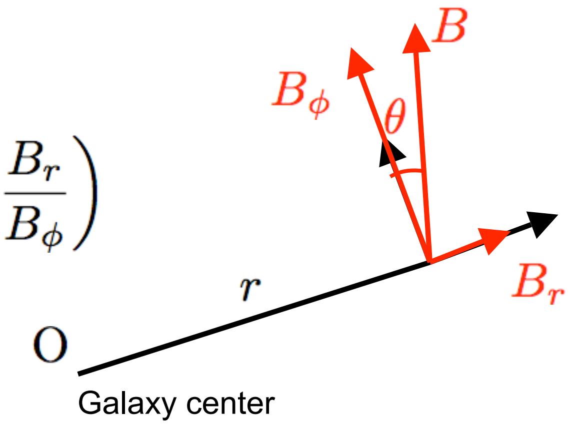
Spiral structure

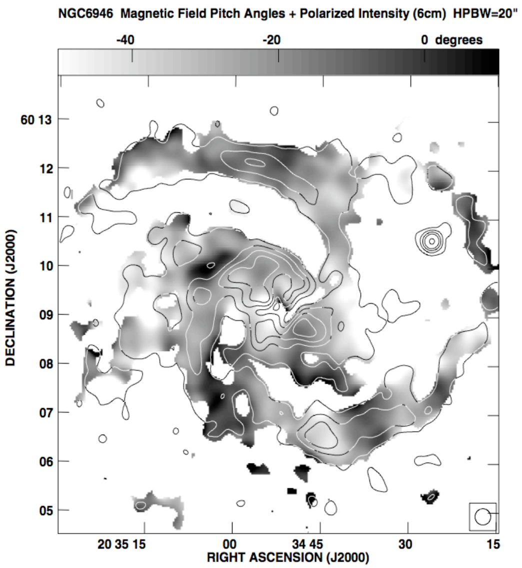


38 kpc

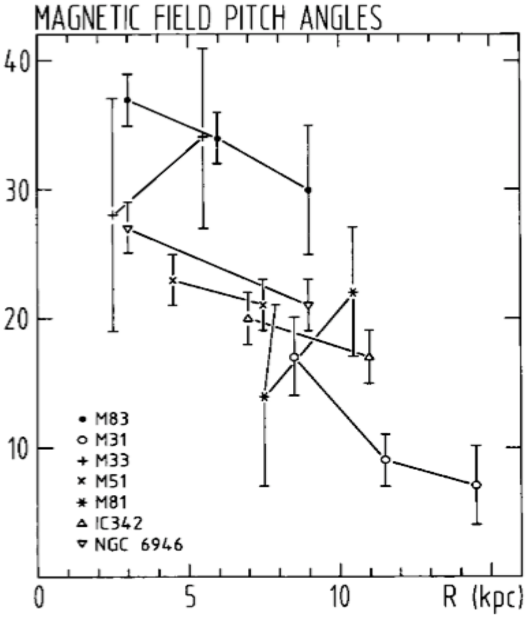
Observations of magnetic fields in galaxies

$$\theta = \mathrm{atan}\left(\frac{B_r}{B_\phi}\right)$$

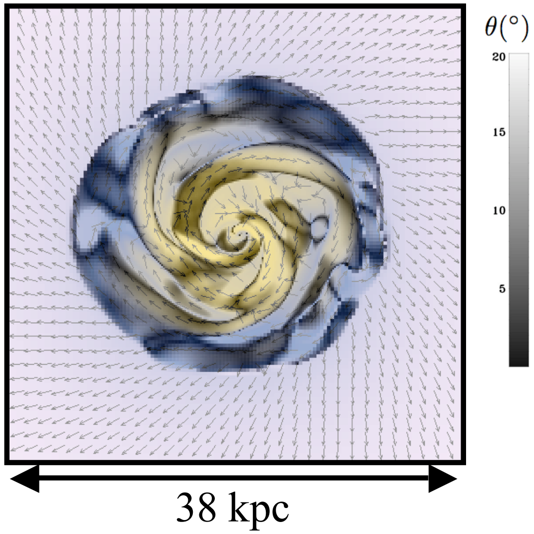




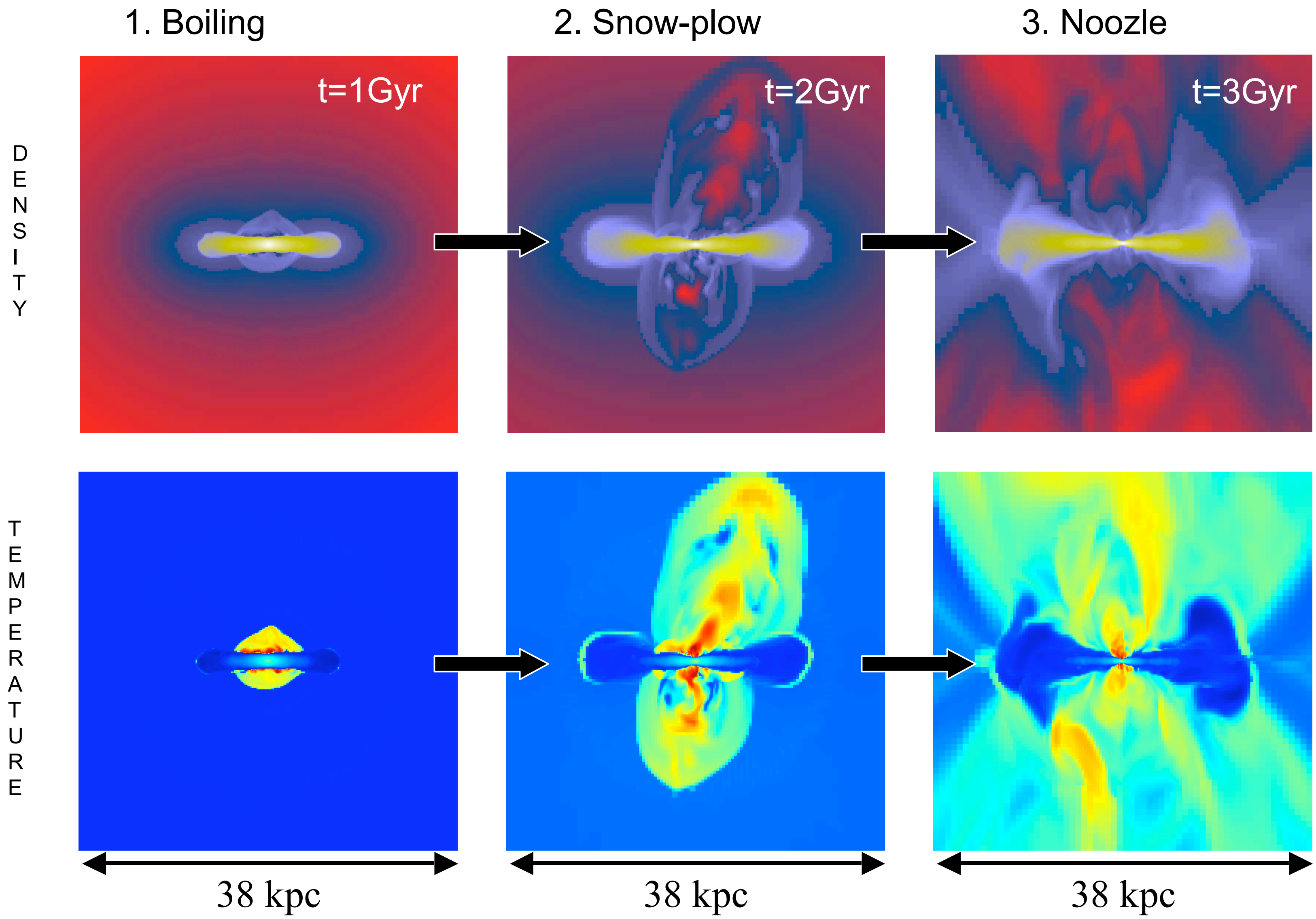
Beck 2007



Beck et al. 1996

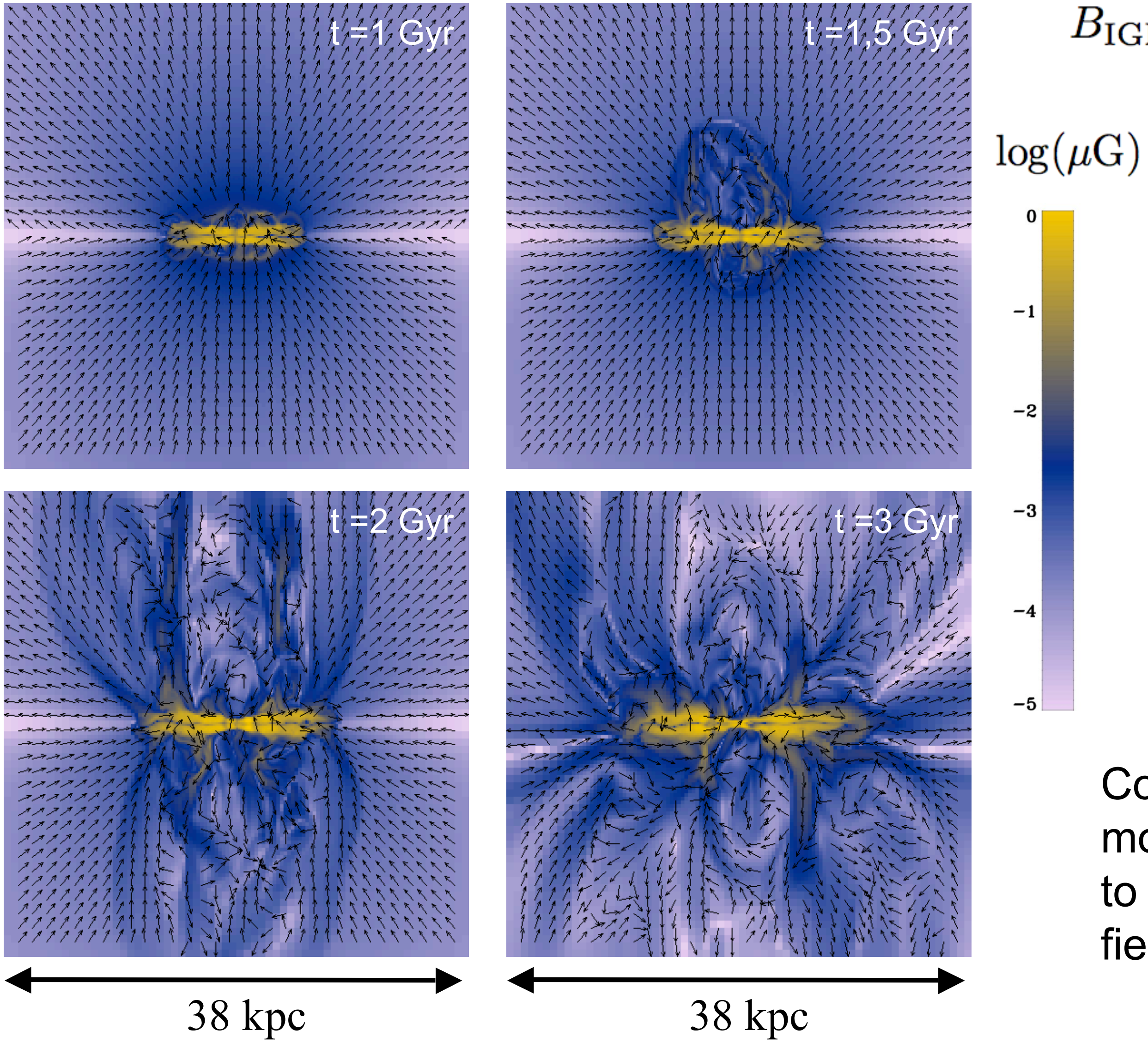


The build-up of a galactic wind



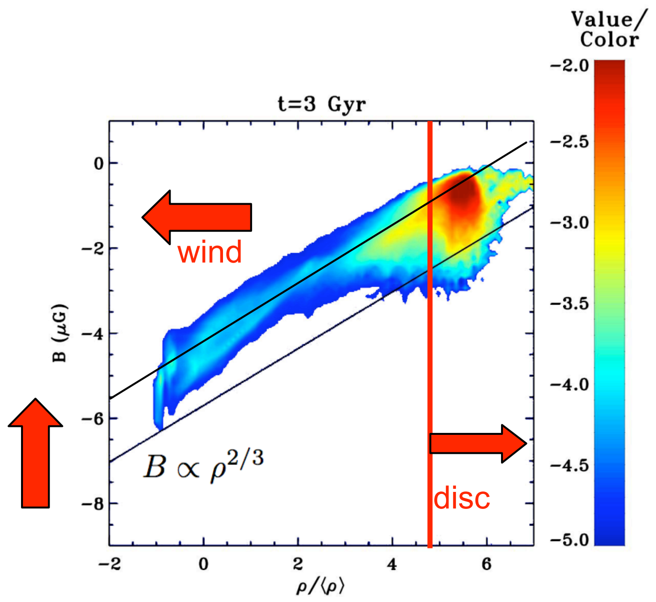
A strong magnetized wind

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

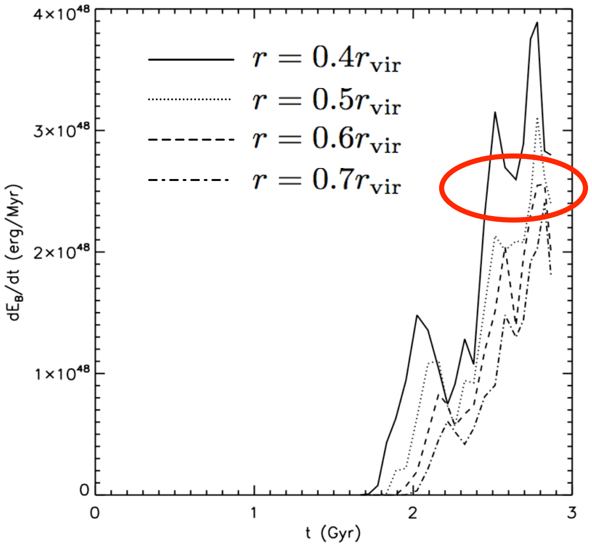


Convective motions lead to a turbulent field topology

Magnetic energy injection into the IGM



20x
rotation,
turbulence



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

Bertone et al. 2006

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

Magnetic energy injection at the base of the wind

Magnetic energy decrease due to flux conservation

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

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

A hierarchical dynamo ?

We have considered an initial field in the IGM $B_{IGM}=2x10^{-6}$ μG
We get a final field in the wind-driven bubble $B_{IGM}\sim3x10^{-5}$ μG
Amplification x10 of the magnetic field due large scale shearing motions

Wang & Abel (2008) obtained similar results with a clumpy ISM (low T cooling).

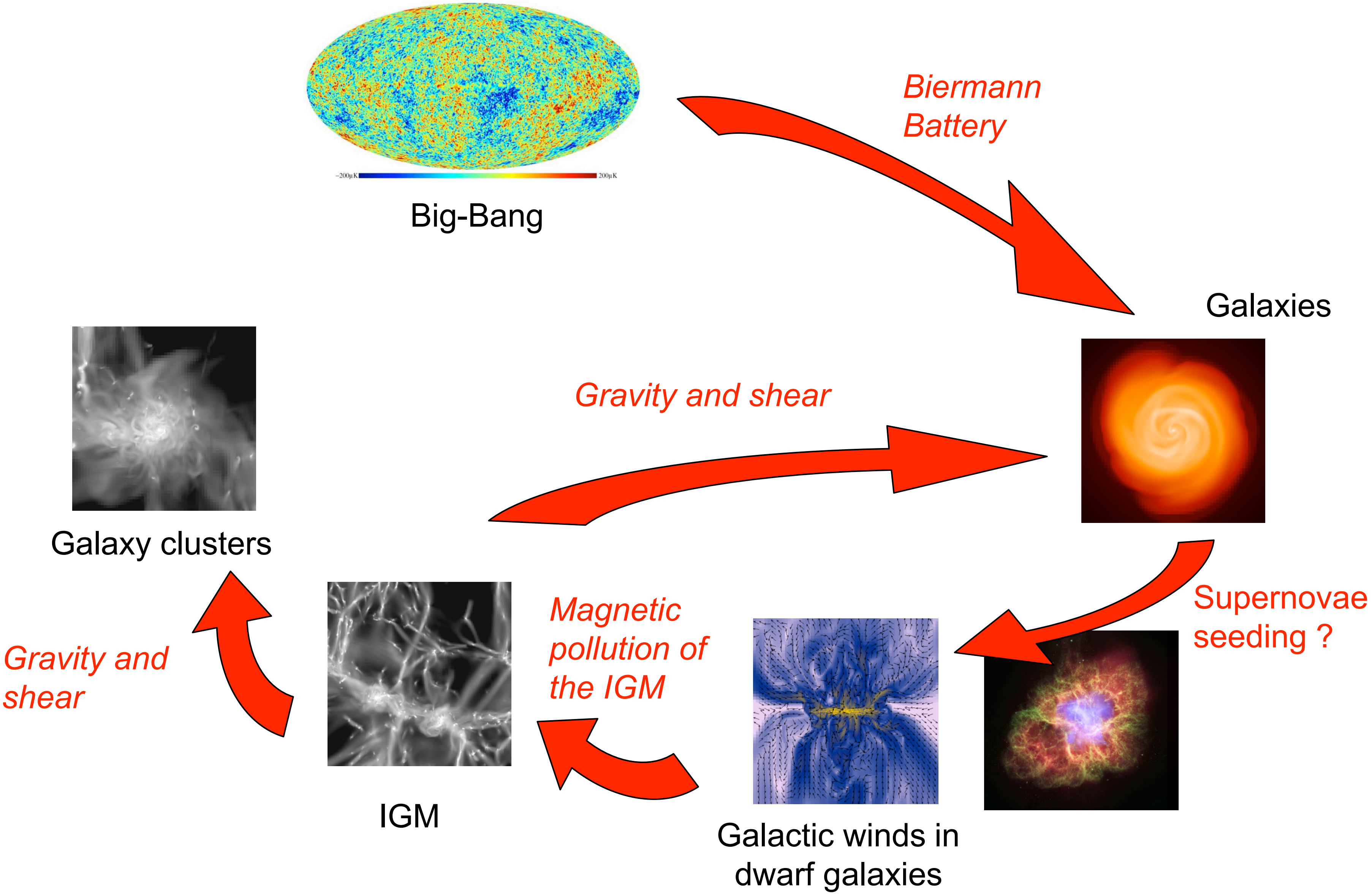
The big picture:

- $B_{primordial}\sim10^{-14}$ μG by Biermann batteries (around z=10)
- We need 10^{-4} - 10^{-5} μG in the IGM to account for X-ray clusters observations
- **10 generation of dwarf galaxies (from 10^{7} to 10^{10} Msun) amplify the field from 10^{-14} μG to 10^{-4} μG (in 10 mass doubling time)**
- **10^{-4} μG stops the formation of dwarf galaxies : « cosmic saturation »**

Alternative models for a cosmic dynamo

- Magneto-rotational instability ?
  (Balbus & Hawley 1991)
- Galactic dynamo with or without cosmic rays ?
  (Parker 1992 ; Kulsrud 1999 ; Hanasz 2004)
- Recent observations report μG at z=1.3 (5 Gyr after Big-Bang)
  (Bernet et al. 2008)
- Magnetic seeding by stellar remnants ?
  (Rees 1987, Kowalik & Hanasz 2007)

The Cosmic Dynamo



Big-Bang

Biermann Battery

Galaxies

Gravity and shear

Galaxy clusters

Supernovae seeding ?

Magnetic pollution of the IGM

Galactic winds in dwarf galaxies

IGM

Gravity and shear

Thank you !