How do galaxies get their magnetic fields ?

(from theory / simulations)

Alexander Beck

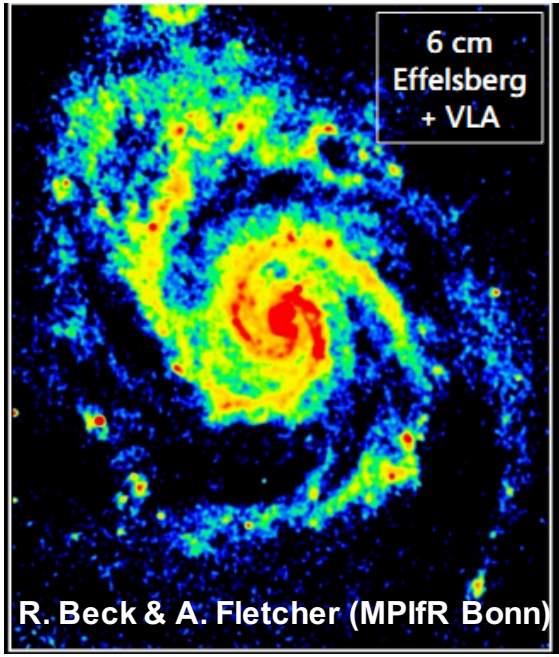
University Observatory Munich

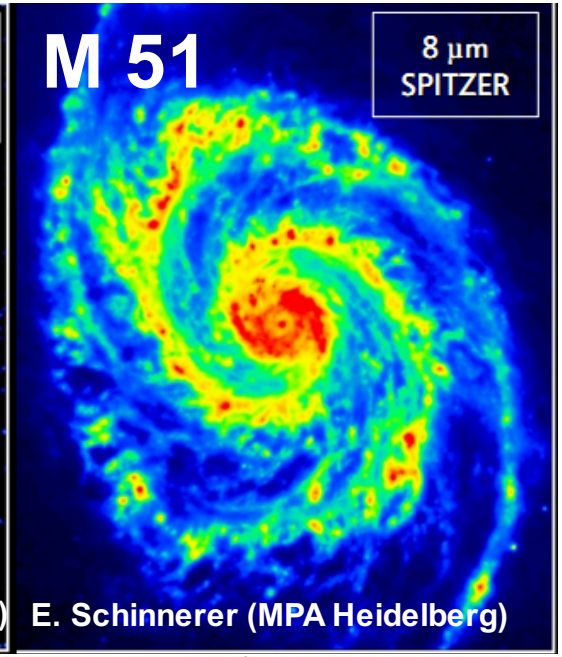
In collaboration with:

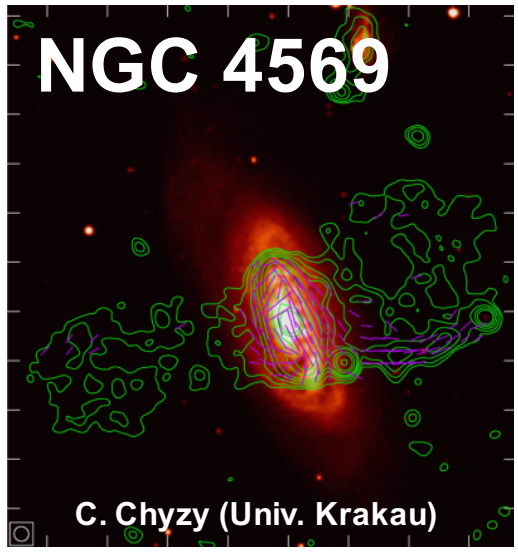
Harald Lesch, Klaus Dolag
Phil Kronberg & Stefano Borgani

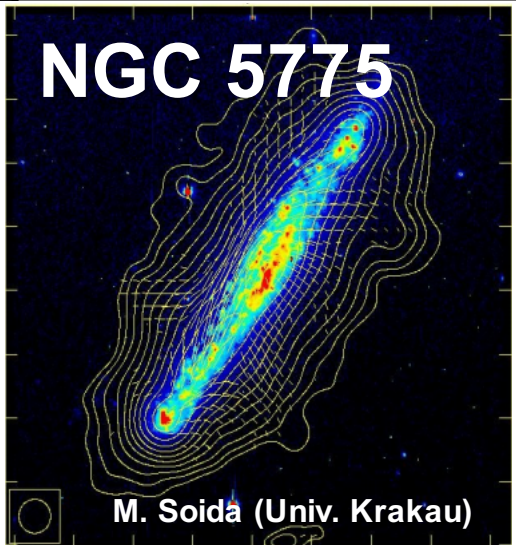
MAGNETICUM

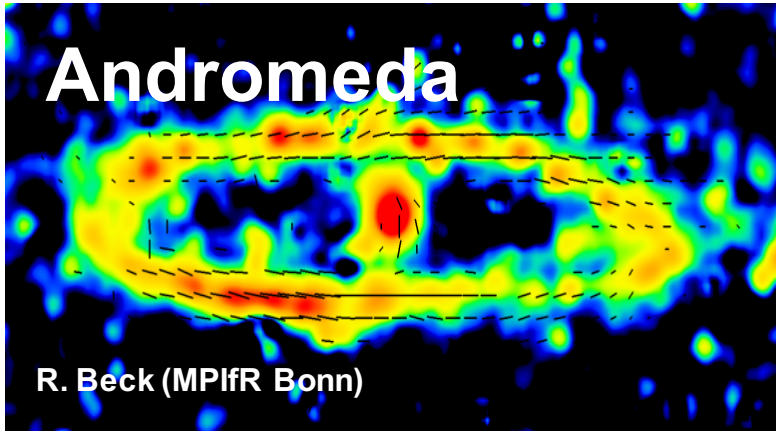
Magnetic fields in galaxies











Magnetic field theory

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \eta \Delta B + \left.\frac{\partial B}{\partial t}\right|_{\text{Seed}}$$

Plasma motions are the only source of magnetic field amplification!

Magnetic diffusion: Topological changes

Magnetic seeding term

This equation has to be solved in the context of a galaxy.

Magnetic field theory

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \eta \Delta B + \left.\frac{\partial B}{\partial t}\right|_{\text{Seed}}$$

Plasma motions are the only source of magnetic field amplification!

Magnetic diffusion: Topological changes

Magnetic seeding term

This equation has to be solved in the context of a galaxy.

Galaxy formation ? **Magnetic fields**

Do the first structures form within (un)magnetized gas ?
(Primordial seed fields, Supernova / AGN seed fields, ...)

Can a high-redshift generation of protogalaxies magnetized the IGM?

Protogalactic magnetic fields

THE PROTOGALACTIC ORIGIN FOR COSMIC MAGNETIC FIELDS

RUSSELL M. KULSRUD,[1] RENYUE CEN,[1] JEREMIAH P. OSTRIKER,[1] AND DONGSU RYU[2]

Received 1996 July 29; accepted 1996 December 5

ABSTRACT

It is demonstrated that strong magnetic fields are produced from a zero initial magnetic field during the pregalactic era, when the galaxy is first forming. Their development proceeds in three phases. In the first phase, weak magnetic fields are created by the Biermann battery mechanism. During the second phase, results from a numerical simulation make it appear likely that homogenous isotropic Kolmogorov turbulence develops that is associated with gravitational structure formation of galaxies. Assuming that this turbulence is real, then these weak magnetic fields will be amplified to strong magnetic fields by this Kolmogorov turbulence. During this second phase, the magnetic fields reach saturation with the turbulent power, but they are coherent only on the scale of the smallest eddy. During the third phase, which follows this saturation, it is expected that the magnetic field strength will increase to equipartition with the turbulent energy and that the coherence length of the magnetic fields will increase to the scale of the largest turbulent eddy, comparable to the scale of the entire galaxy. The resulting magnetic field represents a galactic magnetic field of primordial origin. No further dynamo action after the galaxy forms is necessary to explain the origin of magnetic fields. However, the magnetic field will certainly be altered by dynamo action once the galaxy and the galactic disk have formed.

Galactic magnetic fields are a result of the galaxy *formation* process

(Arshakian et al., 2009; Beck A. et al., 2012; Pakmor & Springel 2014, etc …)

Beck et al. 2013

Magnetic fields of stellar origin

Extend induction equation

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \Delta \boldsymbol{B} + \left.\frac{\partial \boldsymbol{B}}{\partial t}\right|_{\rm Seed}$$

Seeding term

$$\left.\frac{\partial \boldsymbol{B}}{\partial t}\right|_{\rm Seed} = \sqrt{N_{\rm SN}^{\rm eff}}\,\frac{B_{\rm Inj}}{\Delta t}\,\boldsymbol{e}_{\rm B}$$

Supernova events

$$N_{\rm SN}^{\rm eff} = \alpha \frac{m_{\rm SN}}{M_\odot}$$

α,β from IMF (Salpeter 1955)

Supernova mass

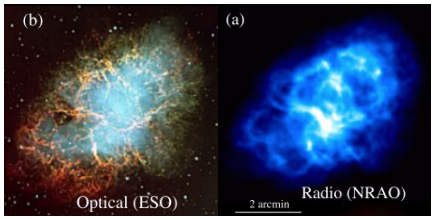
$$m_{\rm SN} = \beta \frac{\Delta t}{t_*} m_{\rm c}$$

Global:
(primordial, …)

$$\vec{B}_0(\vec{x}_0) = \varphi(\vec{x}, \rho, T \ldots)$$

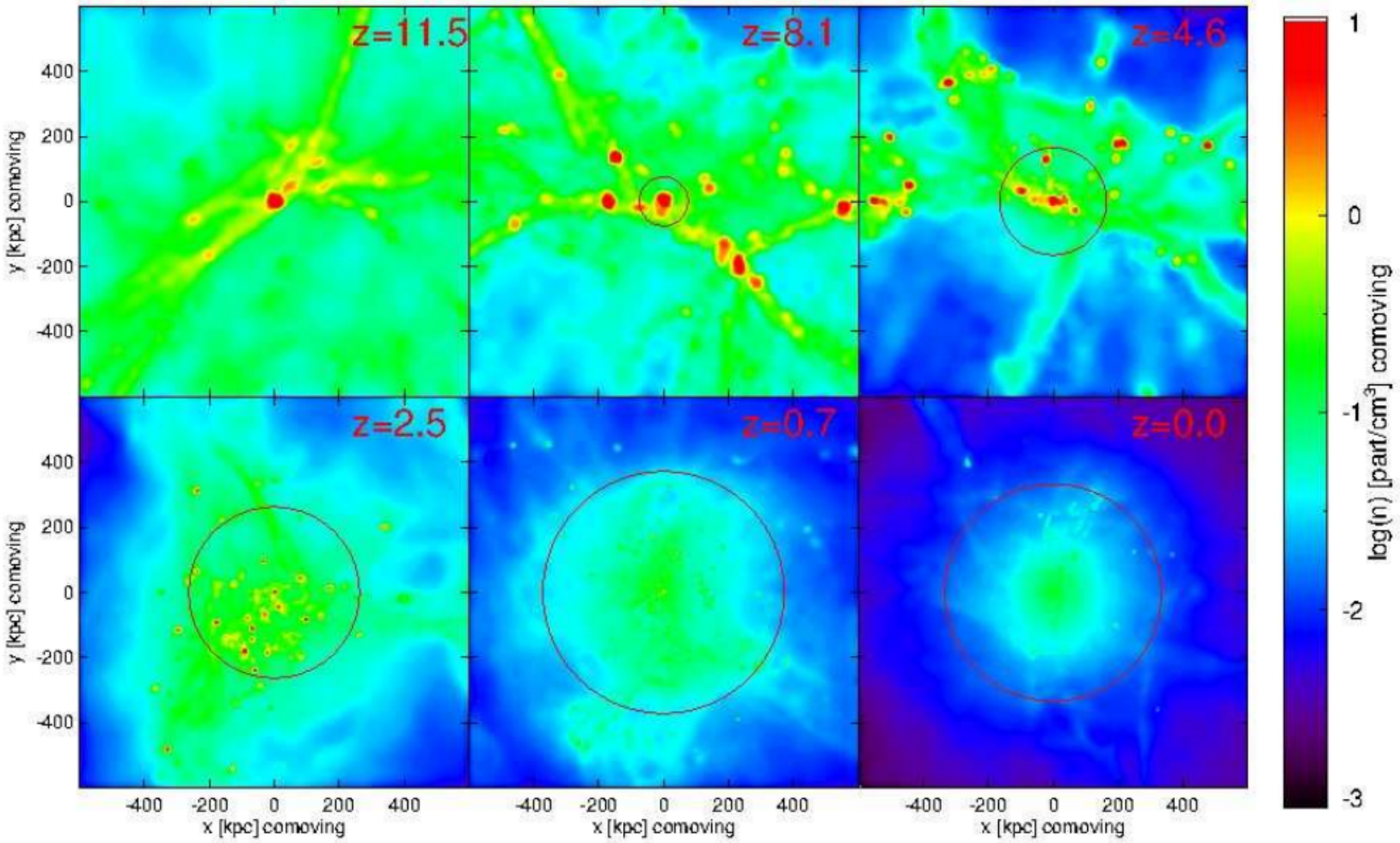
Local:
(SN, AGN, …)

$$\frac{\partial \vec{B}}{\partial t} = \psi(\vec{x}, t, \rho, T, SFR, \ldots)$$



Beck et al. 2013

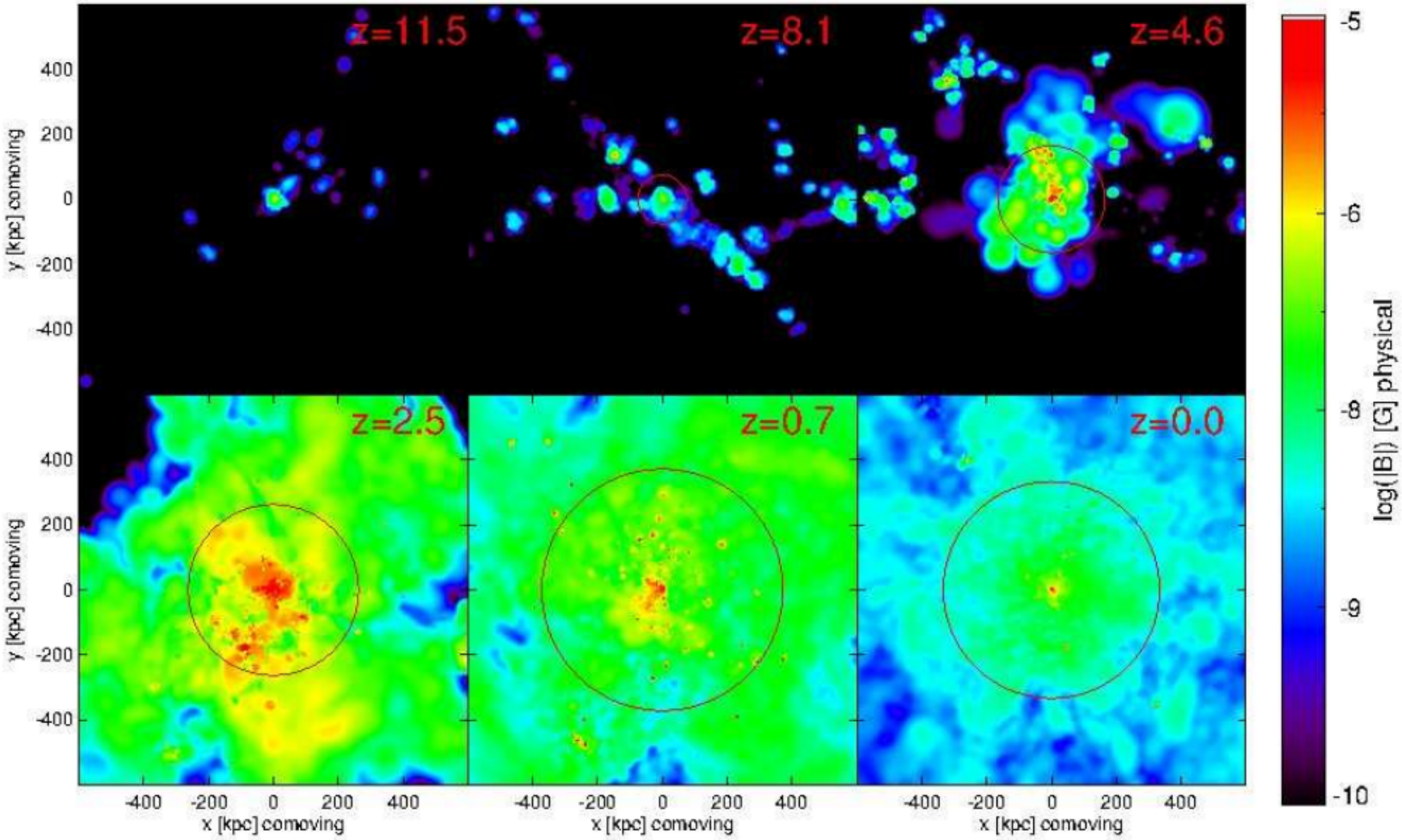
MW halo gas density



Cosmological simulation with GADGET: gas density

Beck et al. 2013

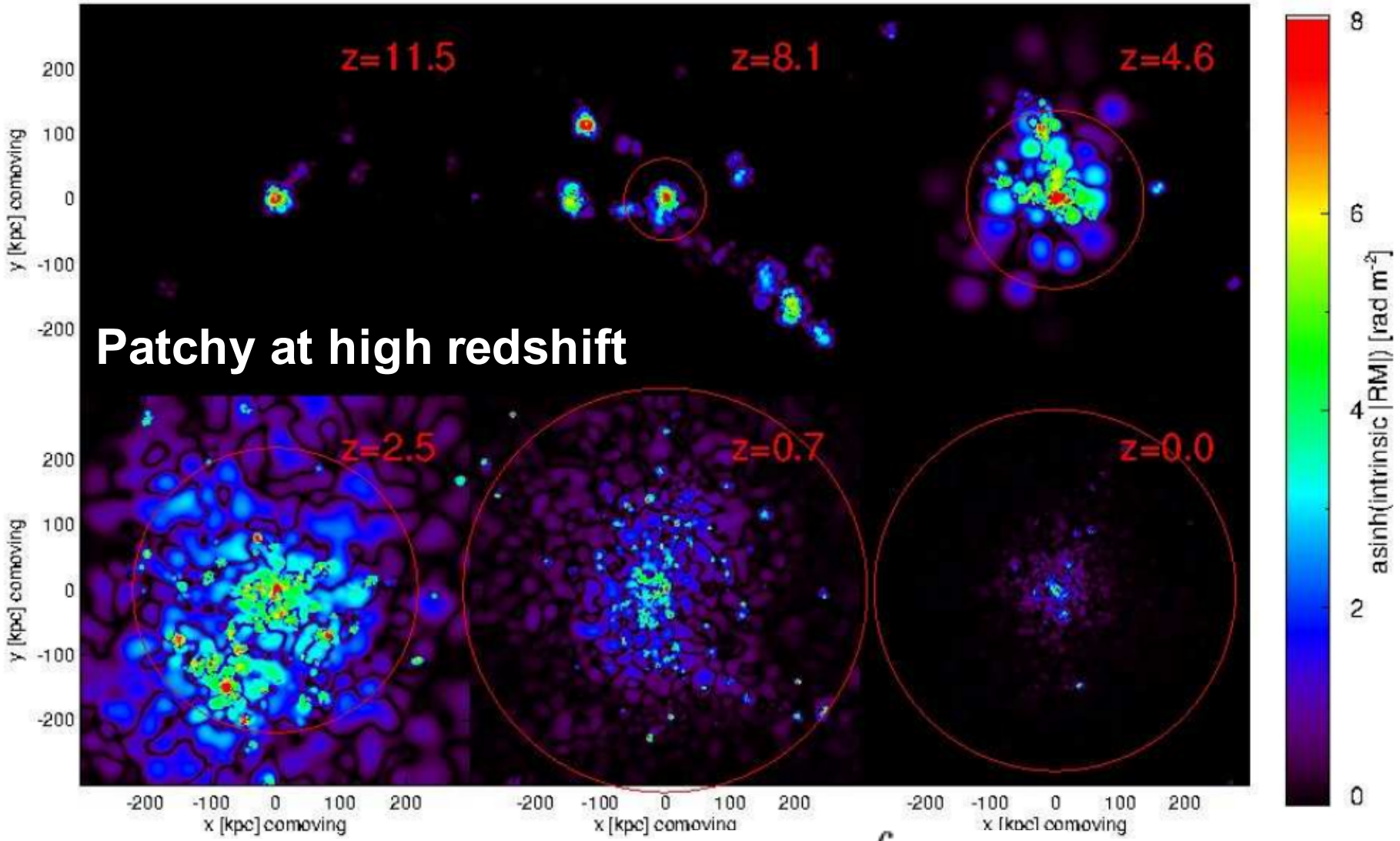
MW halo magnetic field



Cosmological simulation with GADGET: magnetic field

Beck et al. 2013

MW halo rotation measure

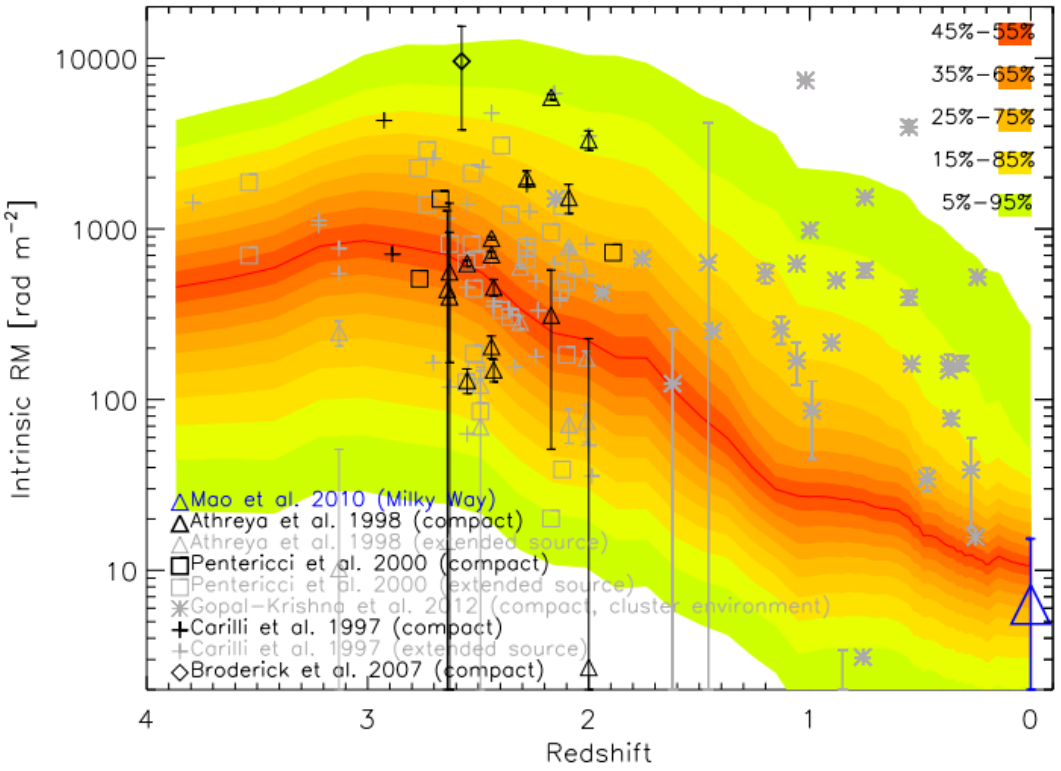


(Faraday) Rotation Measure:

$$\mathrm{RM} \sim \int n_e B_{\parallel} dl.$$

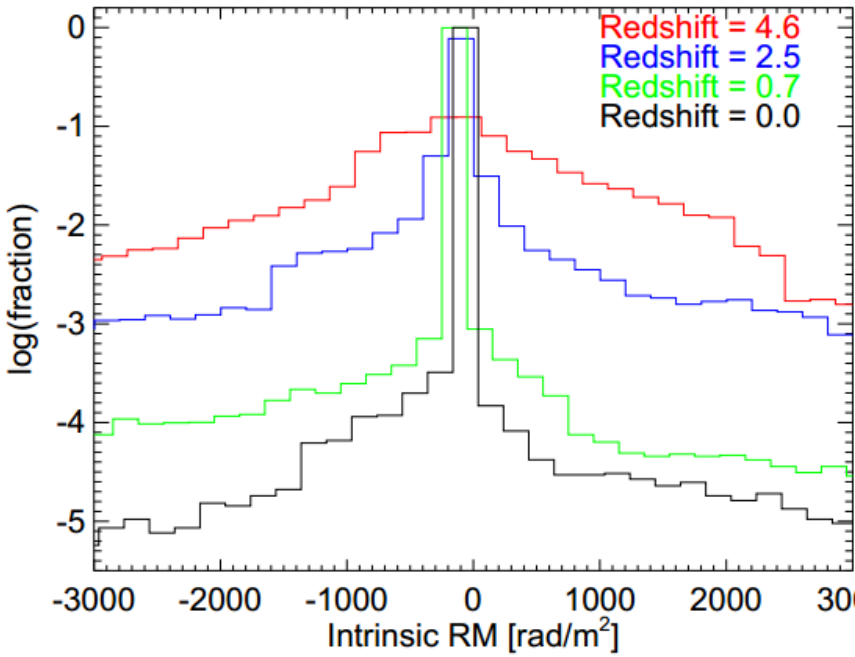
Beck et al. 2013
Beck & Dolag 2016

Comparison with observations



Rotation measure time evolution

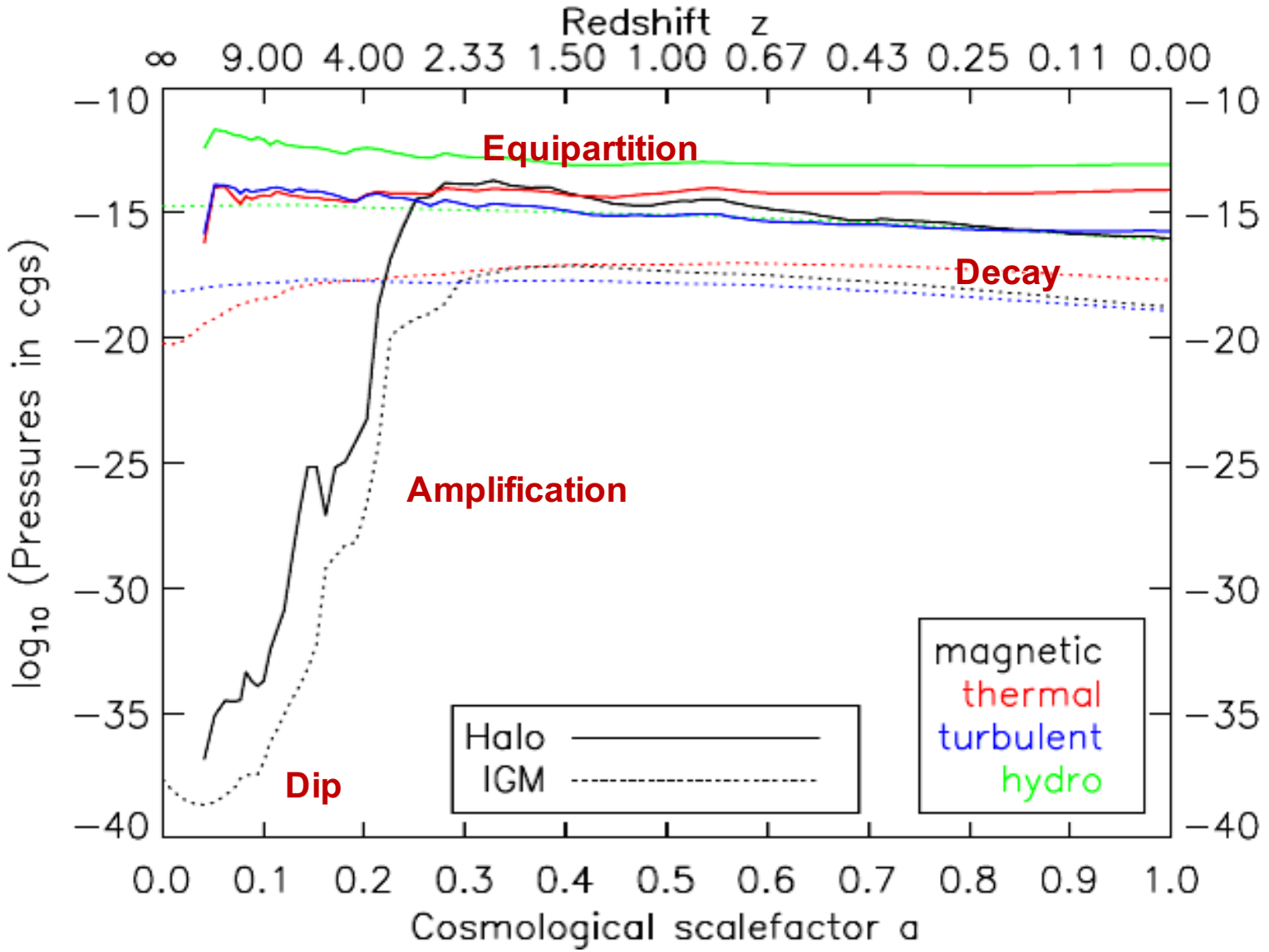
Rotation measure distribution



- **Can we compare the simulations to observed high –z RM's ?**
  → both at low and at high redshifts
- **What causes the observed RM's ?**
- **What causes the simulated RM's ?**

Beck et al. 2012

Energy densities (primordial run)



Analytical toy model

Ansatz $$B_t(t) = B_t(t_0) e^{\Gamma t} e^{-i\omega t}$$

Evolution equation $$\frac{\partial B_t^2(t)}{\partial t} = 2\Gamma B_t^2(t)$$

Kulsrud & Anderson, 1992
Malyshkin & Kulsrud, 2002
Beck et al. 2012

Truncation $$\Gamma = \gamma \left[1 - \frac{B_t^2(t)}{B_{\rm sat}^2} \right]$$

Belyanin, Sokoloff & Shukurov, 1993

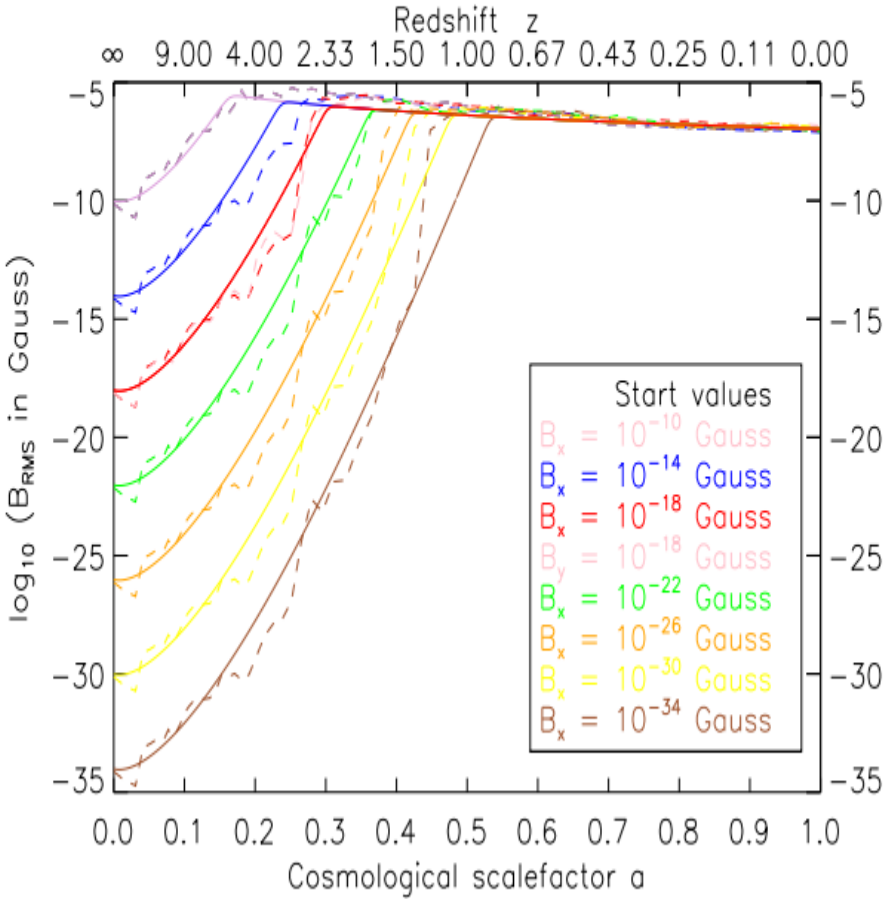
Growth rate $$\gamma = 2.050 \frac{v_{\rm turb}^{3/2} k_{\rm turb}^{1/2}}{\eta_{\rm turb}^{1/2}}$$

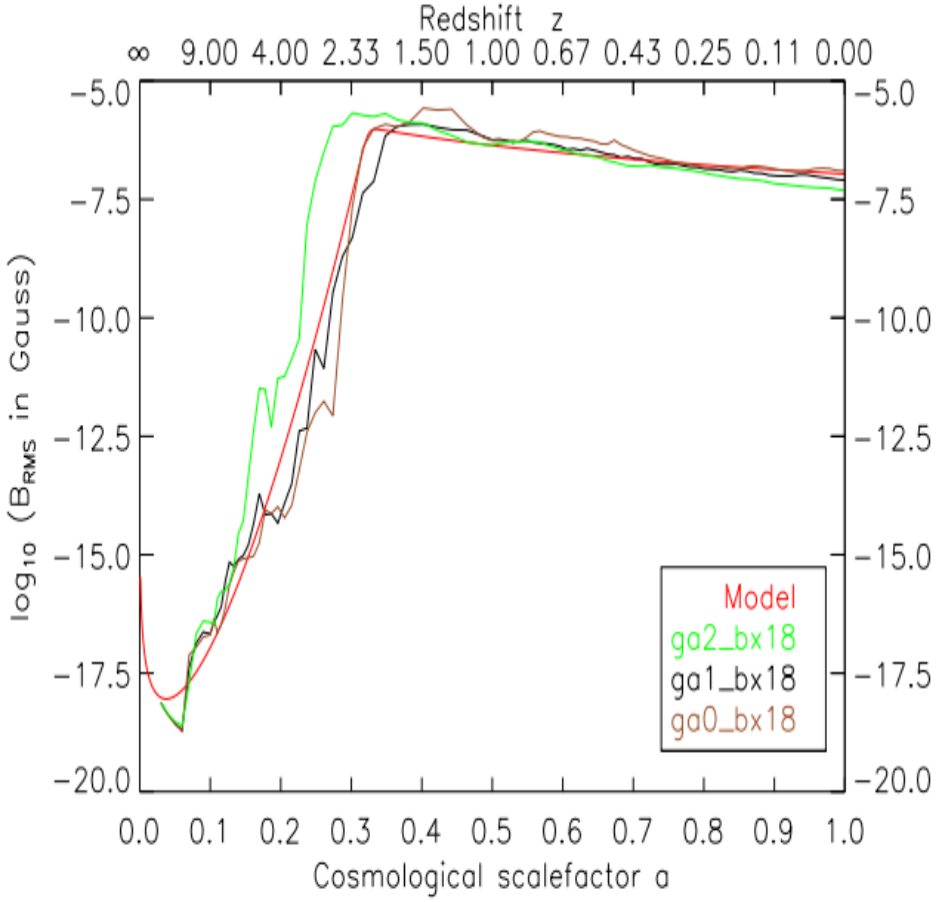
Kulsrud et al., 1997 (Kolmogorov turbulence)

$$B_t(a) = \frac{1}{a^2} \left[(4\pi\rho v_{\rm turb}^2)^{-1} + B_0^{-2} e^{-2\gamma t(a)} \right]^{-\frac{1}{2}}$$

Beck et al. 2012

Agreement with analytical model





Length scale: 25 kpc
Turbulent velocity: 75 km/s

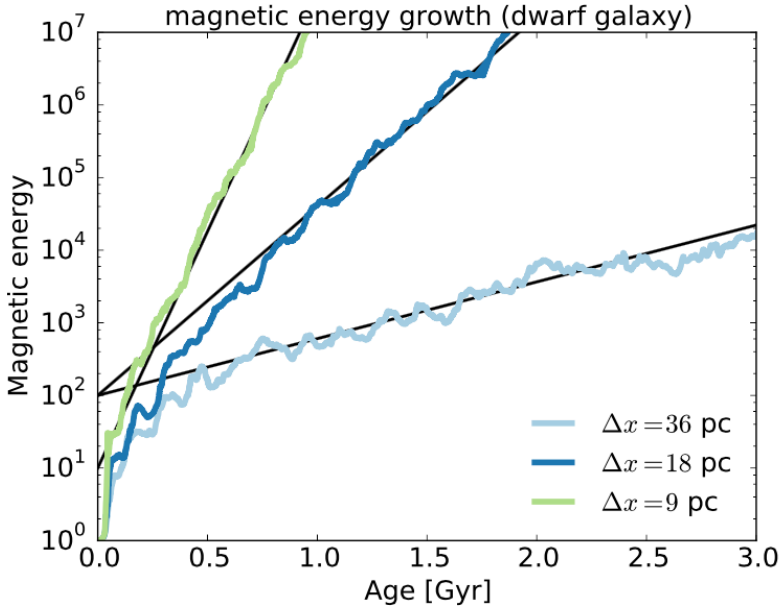
→ Excellent agreement !!!

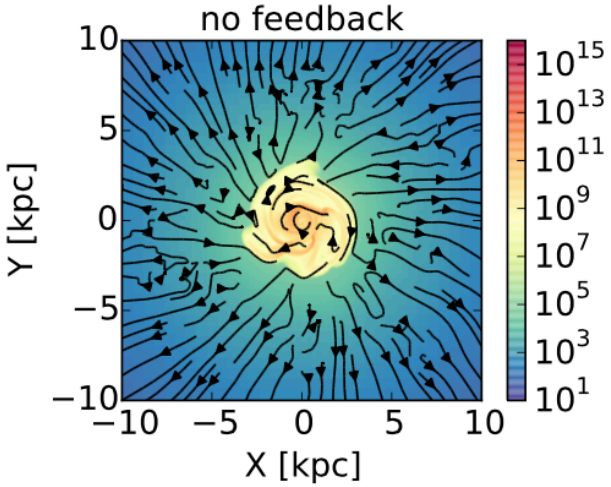
Later results with RAMSES

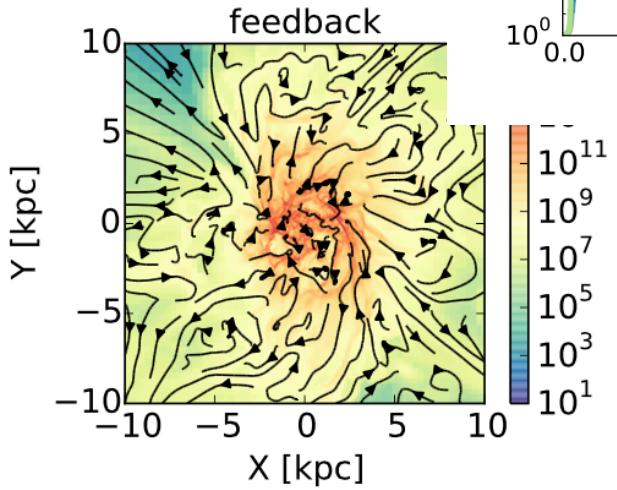
A small-scale dynamo in feedback-dominated galaxies as the origin of cosmic magnetic fields. I-the kinematic phase

Michael Rieder* and Romain Teyssier
Institute for Computational Science
Centre for Theoretical Astrophysics and Cosmology
Universität Zürich, 8057 Zürich, Switzerland

3 June 2015





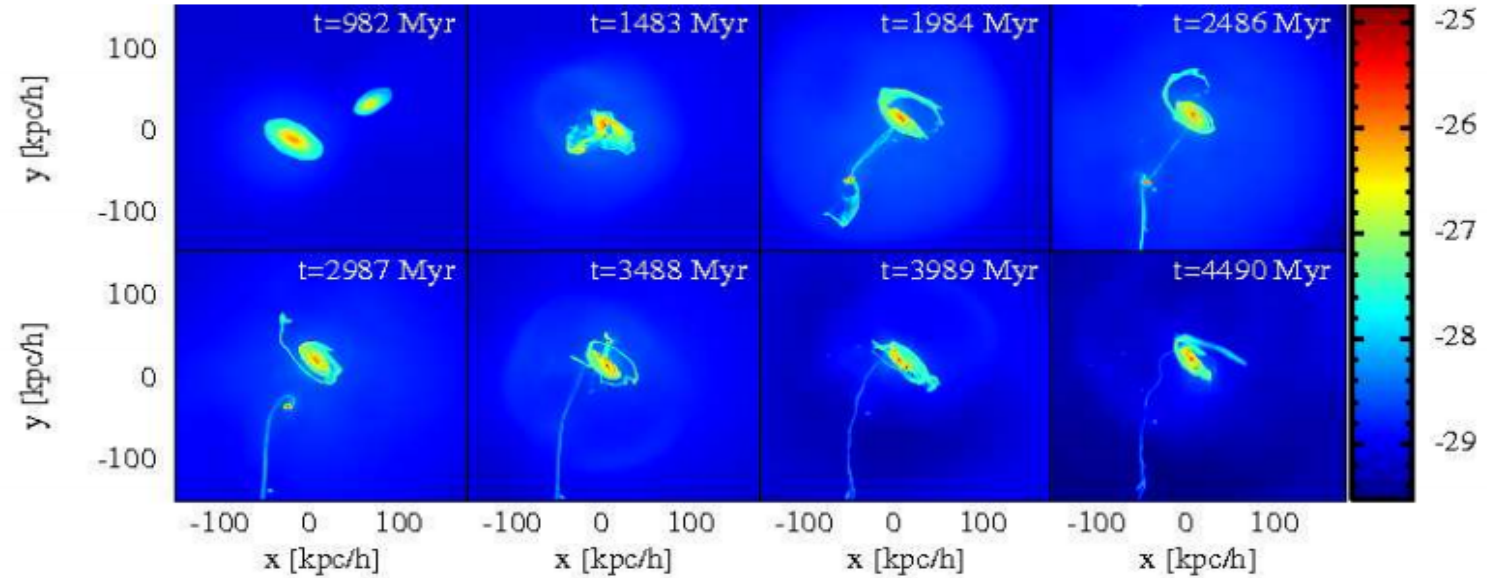


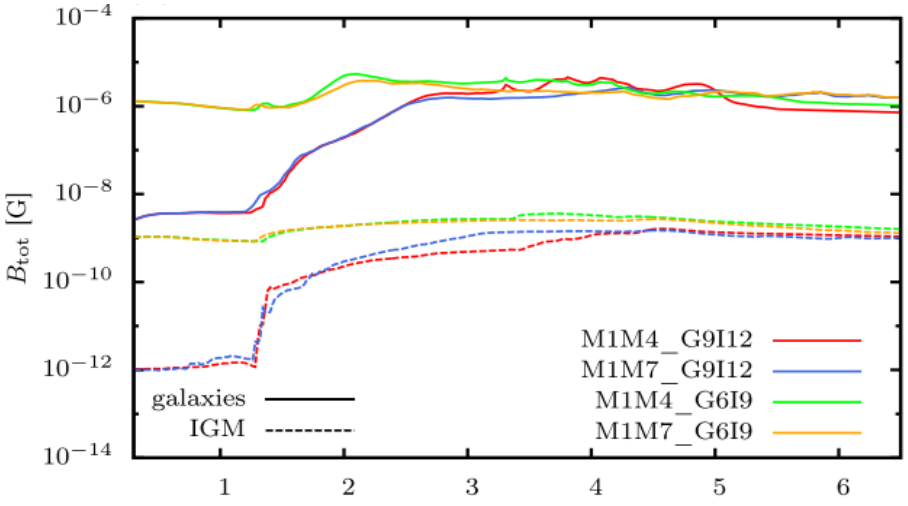
Summary & Conclusions

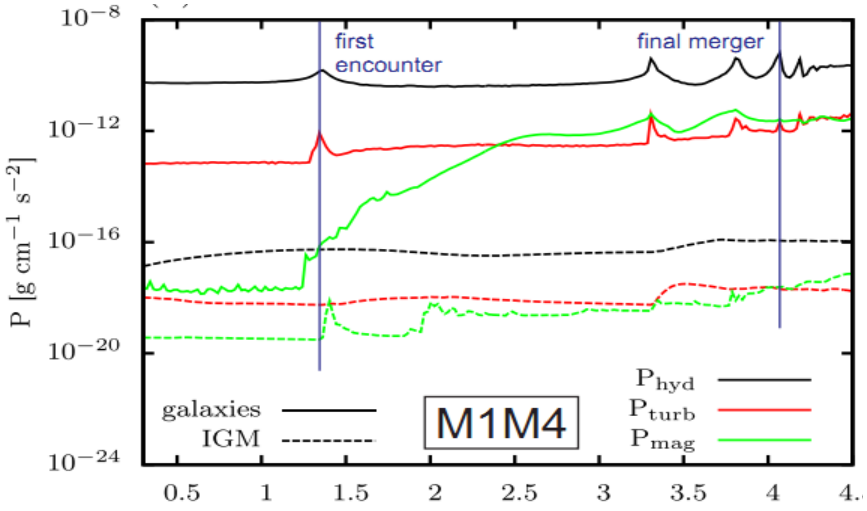
- **Galactic magnetic fields can origin from the galaxy formation process (with stellar seed fields)**
- **The origin/transport of IGM magnetic fields needs much more investigations**
- **We need to bring together the communities of galaxies and of radioastronomers**
- **Working on magnetic fields allows you to go to more conferences with top science and nice beaches**
- **We do not know the impact of the fields or related CR/non-thermal processes on galaxies well**

Geng, Beck et al. 2012

Field growth in minor mergers







Magnetic growth and saturation in galaxy minor mergers