Extragalactic Magnetic Fields

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Ginzburg Centennial Conference on Physics, May 29-June 3, Moscow

Outline

1. Why study extragalactic magnetic fields
2. How to diagnose magnetic fields
3. Current knowledge of magnetic fields in clusters and beyond
4. Summary and perspectives

Most matter in the Universe is magnetized on all scales

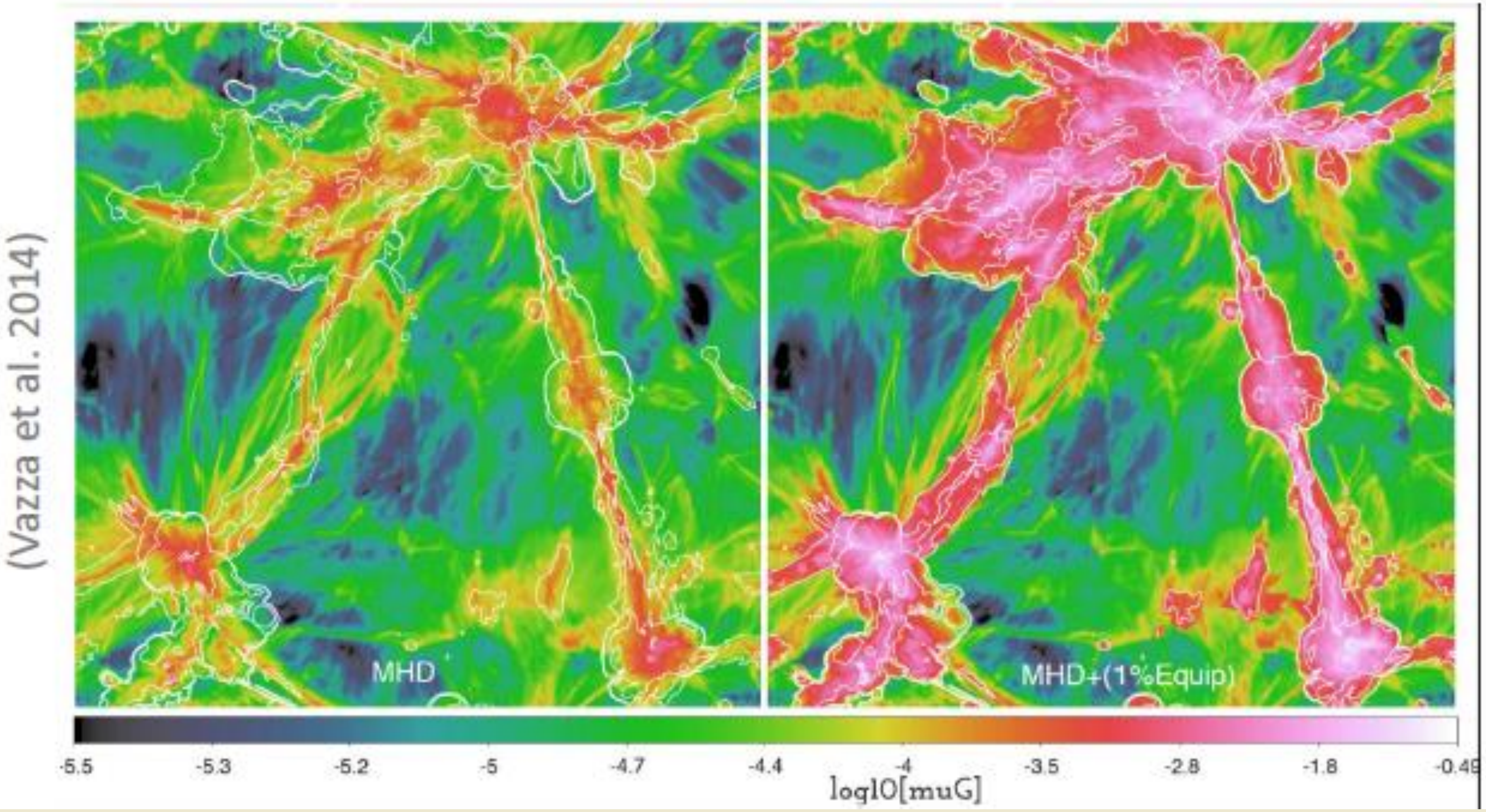
Earth: $\sim$ 0.5 G
Interplanetary Space: $\sim$ 50 μG
Sun: $\sim$ 10 G (poles) $\sim$ 1000 G (sunspots)
Protostars: $\sim$ 1 mG
White dwarfs: $\sim 10^6$ G
Neutron stars: $\sim 10^{12}$ G

Milky Way: $\sim$ 5 μG (widespread) $\sim$ 1 mG (nucleus)
Spiral galaxies: $\sim$ 10 μG (average) $\sim$ 30 μG (massive arms)
Starburst galaxies: $\sim$ 50 μG

Radio galaxies: $\sim$ μG

Clusters of galaxies: $\sim$ 0.1-1 μG
Filaments and Intergalactic space: $\lesssim 10^{-4}$ - 10^{-3} μG

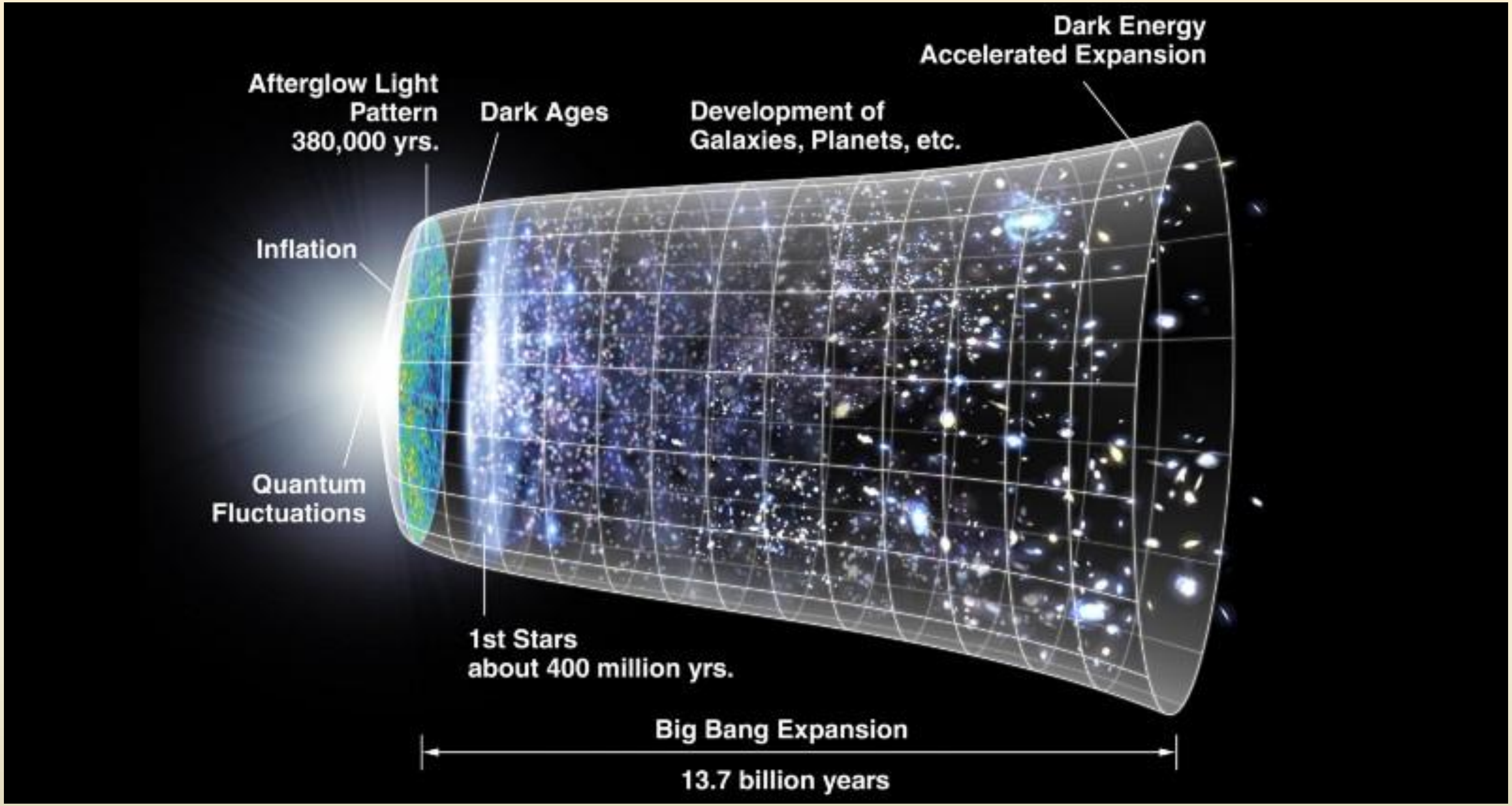
Understanding the origin and evolution of B fields



- how were first magnetic fields generated ?
- how did they evolve and how were presently observed magnetic fields obtained ?
- how are they maintained ?
- how do they regulate the evolution of large-scale structure and of galaxies/AGN ?

➔ both observational and theoretical work

ORIGIN OF MAGNETIC FIELDS



PRIMORDIAL

EARLY STARS

PROTOGALXIES

GALAXIES/AGN

Origin:

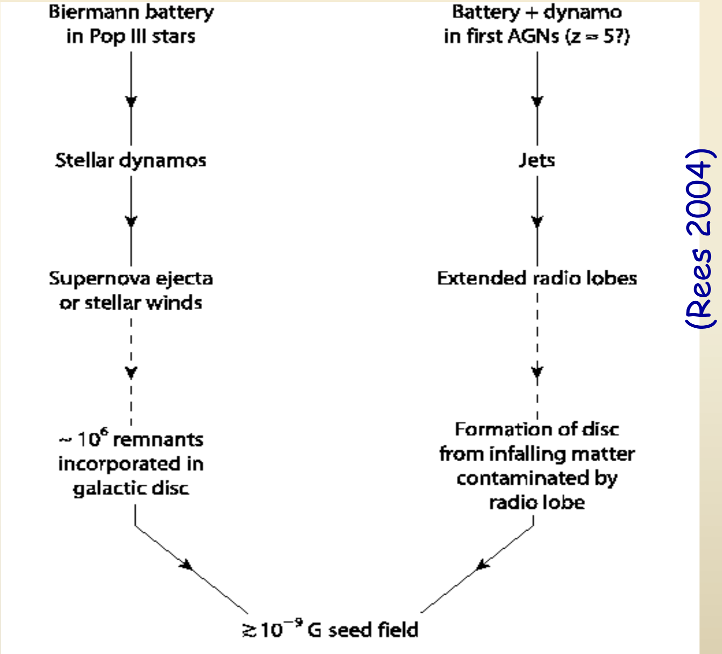
1 – Primordial: Phase transitions (GUT, EW, QH), Inflation (Subramanian 2016)

signatures on anisotropy and polarization of CMB, constraints from Planck : < few 10^{-9} G

2 – Produced locally and Injected by Stars, Supernovae, Galactic winds, AGN/Jets (Kronberg et al.1999, Völk & Atoyan 1999)

lower limit from Tev Blazars : > 10^{-16} G, coherent on Mpc scale

➔ «Seed» field



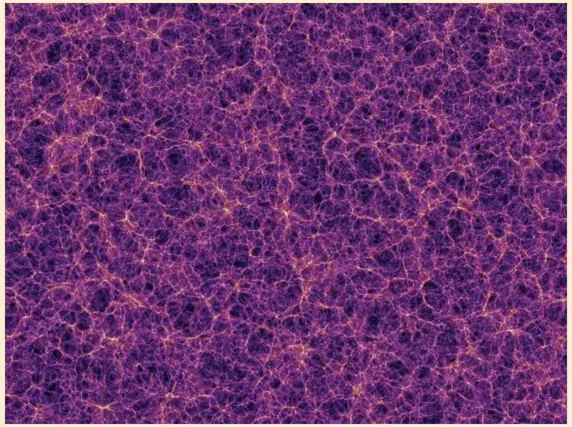
(Rees 2004)

Amplification:

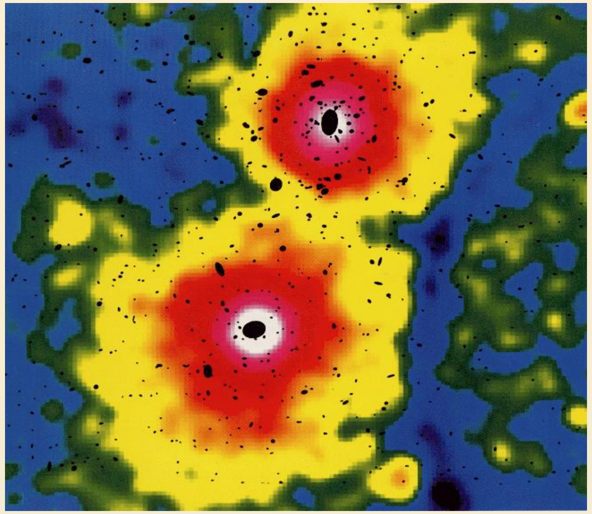
Dynamo
Turbulence
Shocks

Magnetic field in Clusters :

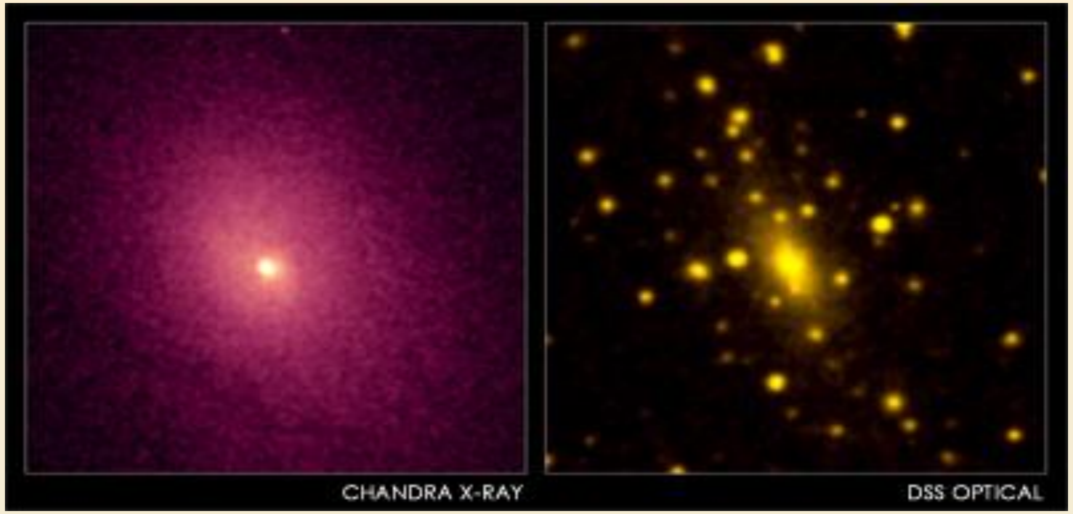
(Springel 2005)



(Schindler 1998)



A3528 - MERGING



(Lewis et al 2003)

A2029 - RELAXED

A cluster is a gravitationally bound system of galaxies, associated with deep gravitational potential well. Radius ~ 3-5 Mpc

➔ need amplification mechanism acting with large efficiency on 100s kpc ÷ Mpc scales

Magnetic fields affect structure formation (e.g. turbulence, cloud collapse, large scale motions, thermal conduction, heat and momentum transport, convection, viscous dissipation, cosmic ray propagation, …)

Interplay between thermal gas and non-thermal components

➔ constraints on the "seed" fields and their evolution and amplification

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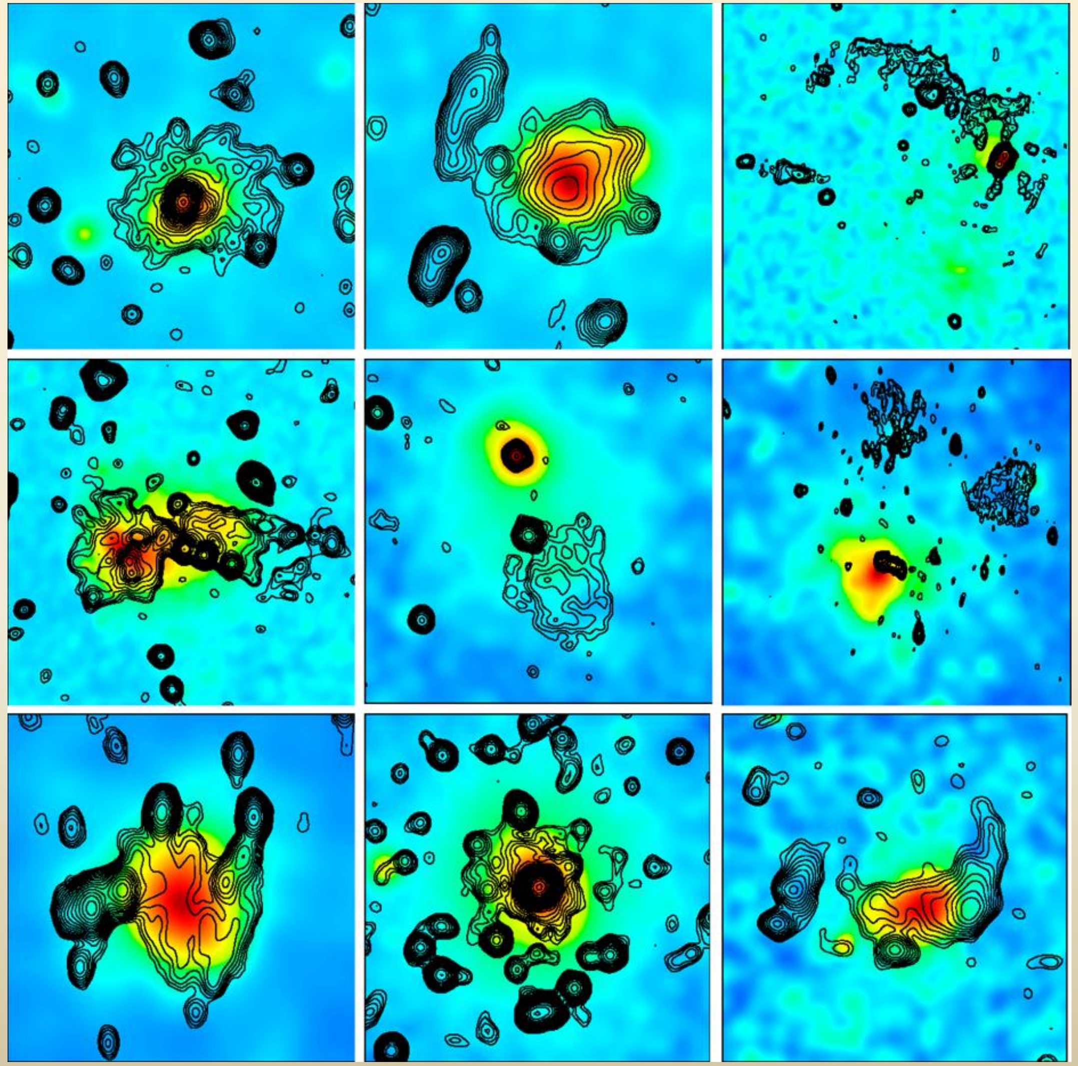
Measuring Magnetic fields in clusters

1 • synchrotron emission: cosmic rays illuminate m.f. in the intracluster medium (ICM).
B info from total intensity and from polarization degree



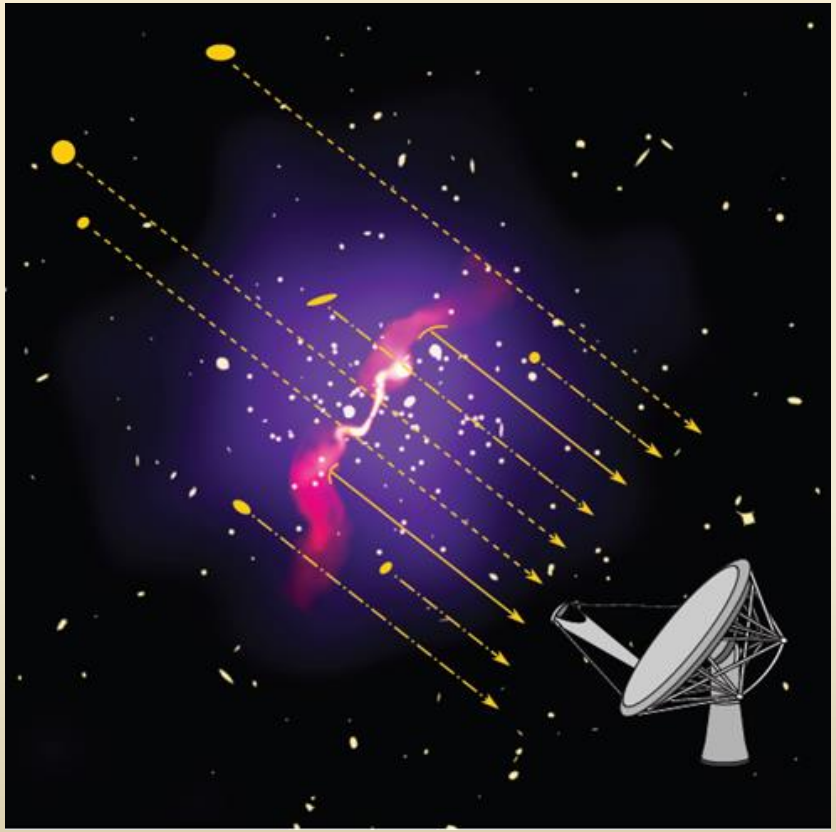
Halos (merging clusters)
Relics (merging clusters)
Minihalos (cool core)

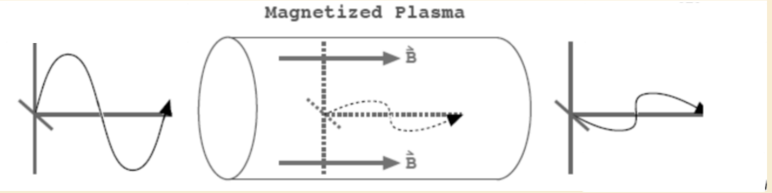
(Feretti et al. 2012)

Measuring Magnetic fields in clusters

2 • Faraday effect: rotation of the wave polarization plan when crossing magnetoionic medium (ICM)

Johnston-Hollitt et al. 2015





$$\chi = \chi_o + RM\lambda^2$$

RM = Rotation Measure

- from observations at many wavelenghts -

$$RM = 812 \int_0^L n_e B_z \, dl \; (\mathrm{rad\,m^{-2}})$$

$$RM = 812 \int_0^L n_e B_z \, dl \; (\mathrm{rad\,m^{-2}})$$

Values derived for B are model dependent :
Analytical solutions only for **simplest model of the Faraday screen**

Complications : - complicated geometries of the screen
- B field multiple components, ordered/random, profile,
- rotation not only in front of the emission, but also from thermal plasma mixed with the relativistic plasma internal to the source
- field fluctuations within the observing beam

➔ developments using semianalytical approaches, numerical techniques, RM synthesis (Ensslin & Vogt 2003, Vogt & Ensslin 2003,2005, Murgia et al. 2004, Brentjens & De Bruyn 2005, Laing et al. 2008)

Parameters to derive:

Magnetic field intensity at the cluster center

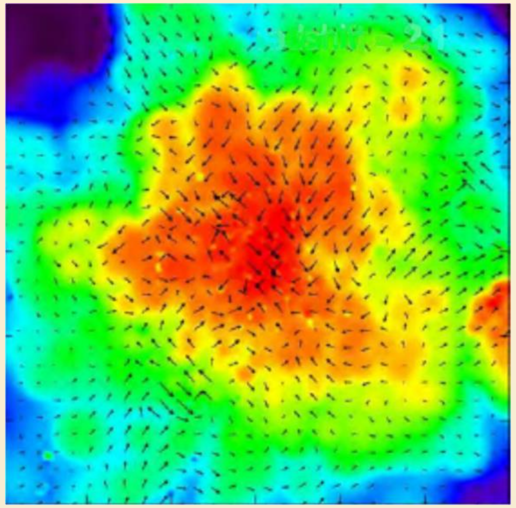
Structure

min and max scales

coherence lenght

power spectrum $|B_k|^2 \propto k^{-n}$

Kolmogorov spectrum, index =11/3



Adapted from Dolag 2013

Radial profile $B \propto n_{gas}^{\eta}$

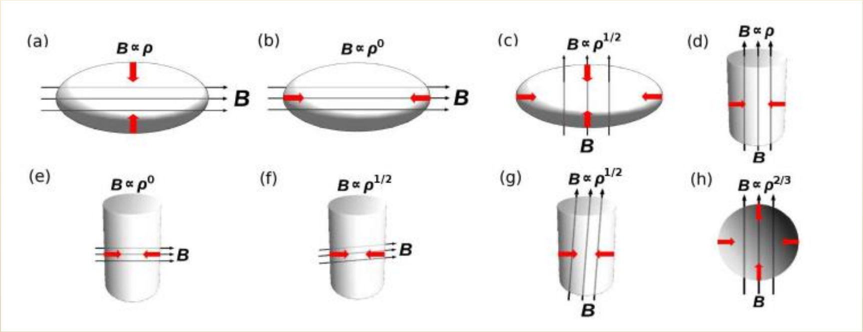
➔ Information on gas cloud collapse

η = 1/2 if B field energy scales as thermal energy

η = 2/3 if B field frozen-in during compression

η = 1 for perpendicular shocks

η = 0 for flow along the field lines



(Tritsis et al. 2015)

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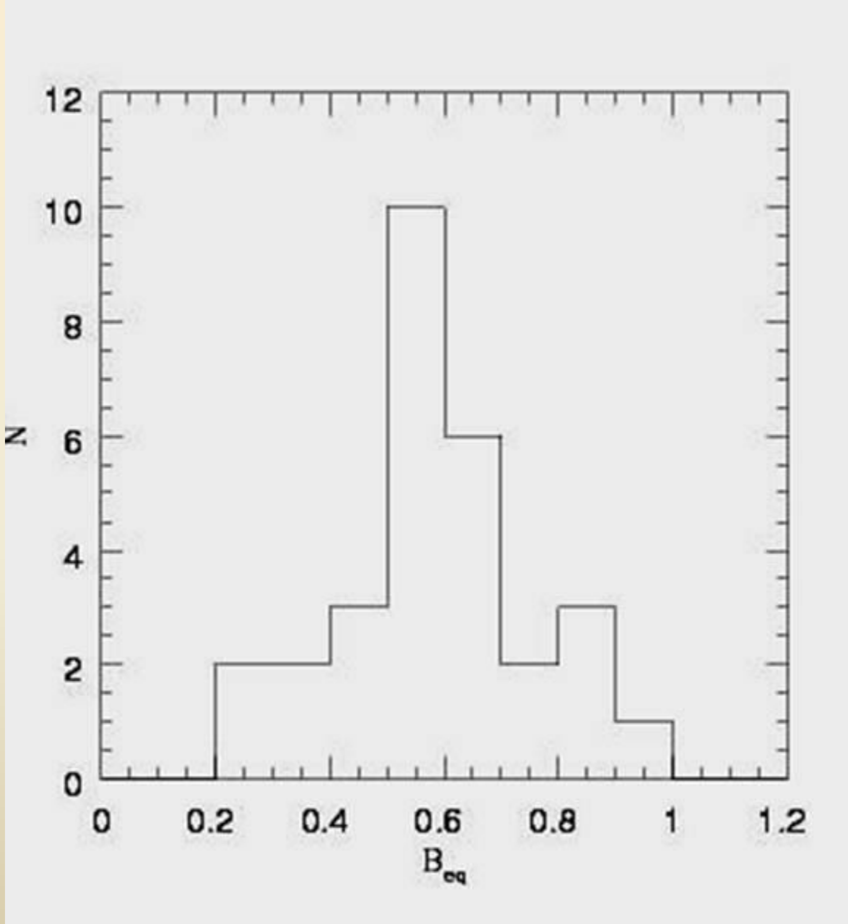
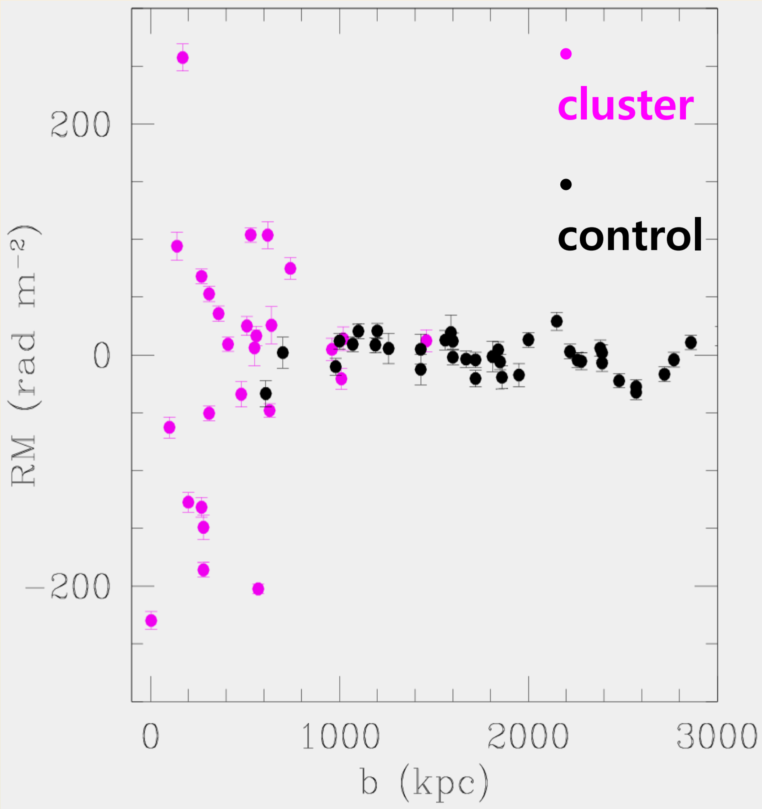
Magnetic field values from radio Halos under <u>Equipartition Conditions</u>



RM : Statistical studies



Clarke et al. (2001,2003)

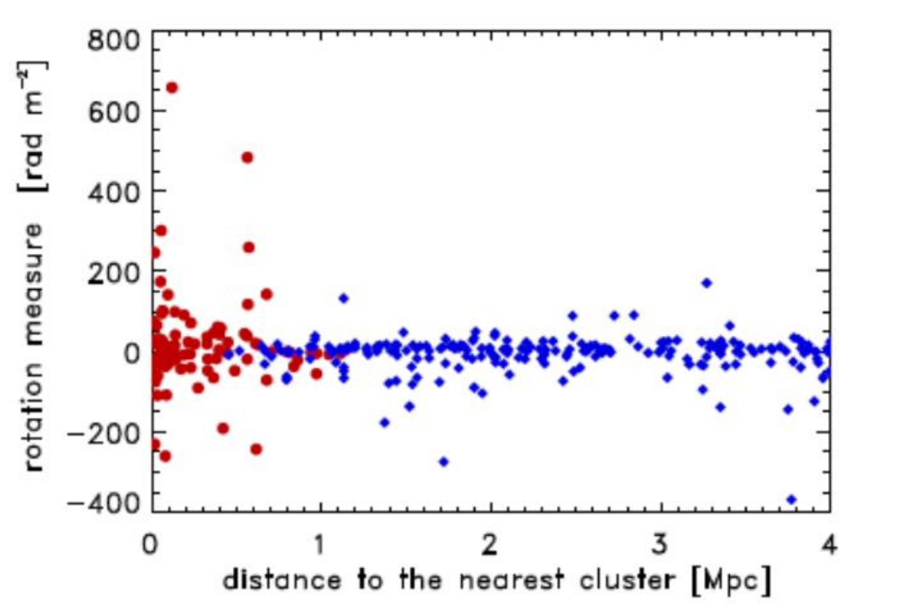
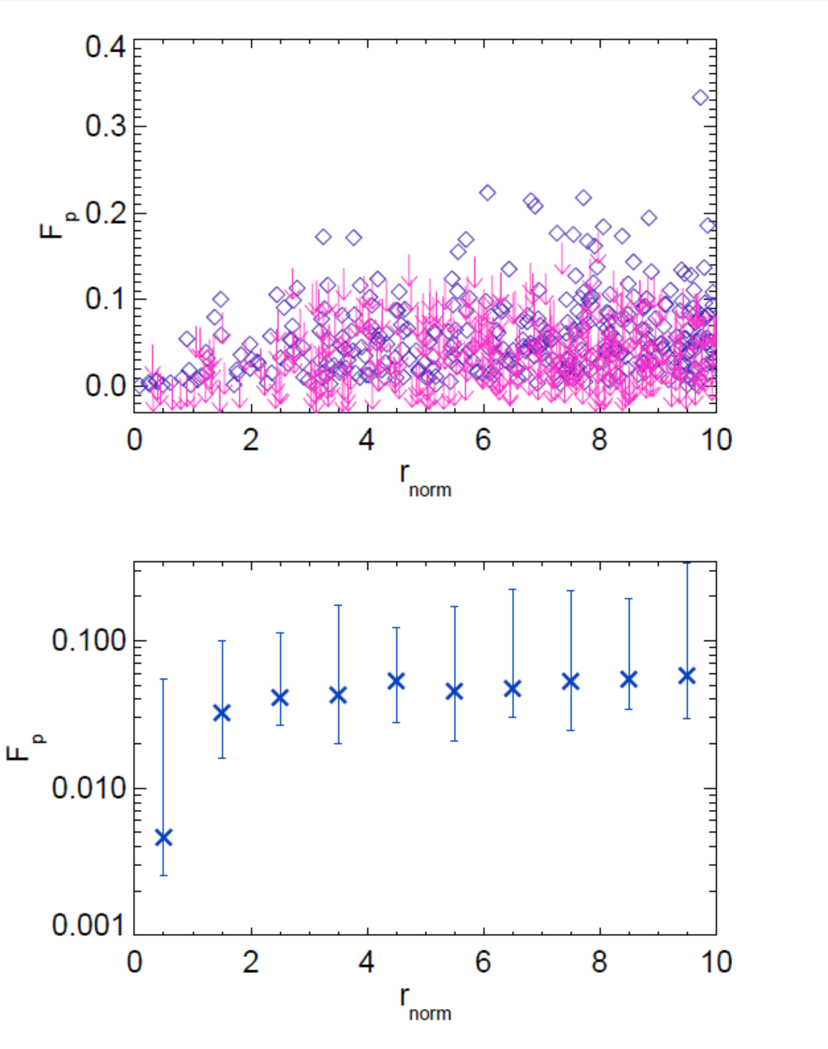


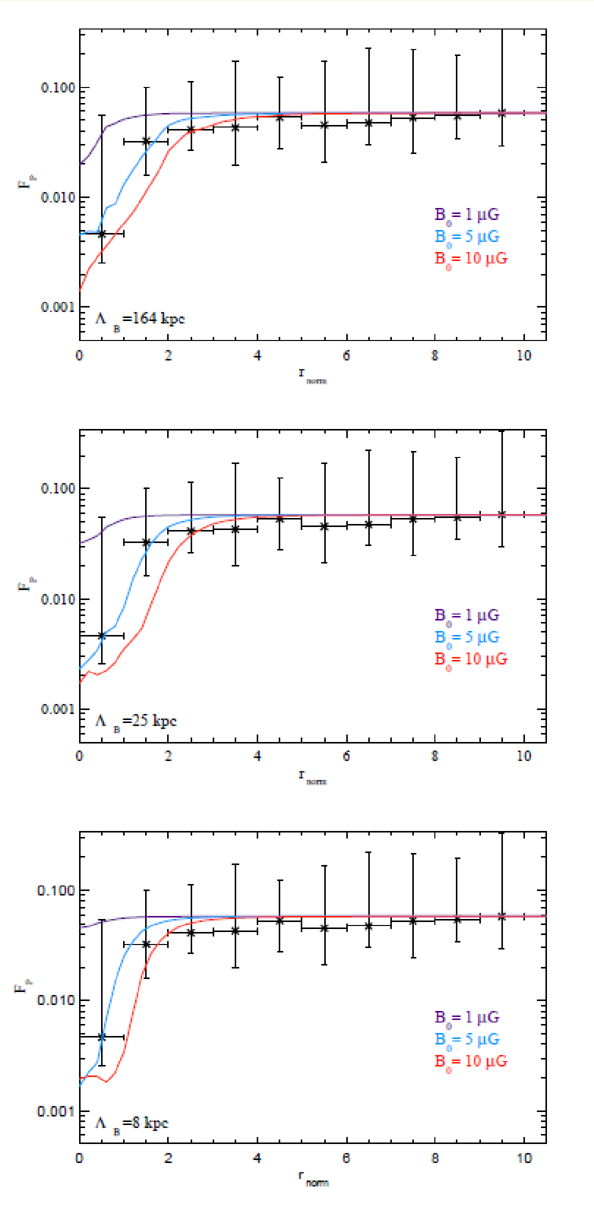
Fig. 2. Rotation measures as a function of cluster-centric distance in physical units (Mpc). The rotation measures inside r_{500} are marked by red circles and those outside by blue diamonds.

Boehringer et al. 2016

Faraday excess is due to presence of magnetic fields in the foreground intracluster medium ➔ $B_{clus} \sim \mu G$

Polarization percentage: statistical studies





Bonafede et al 2013

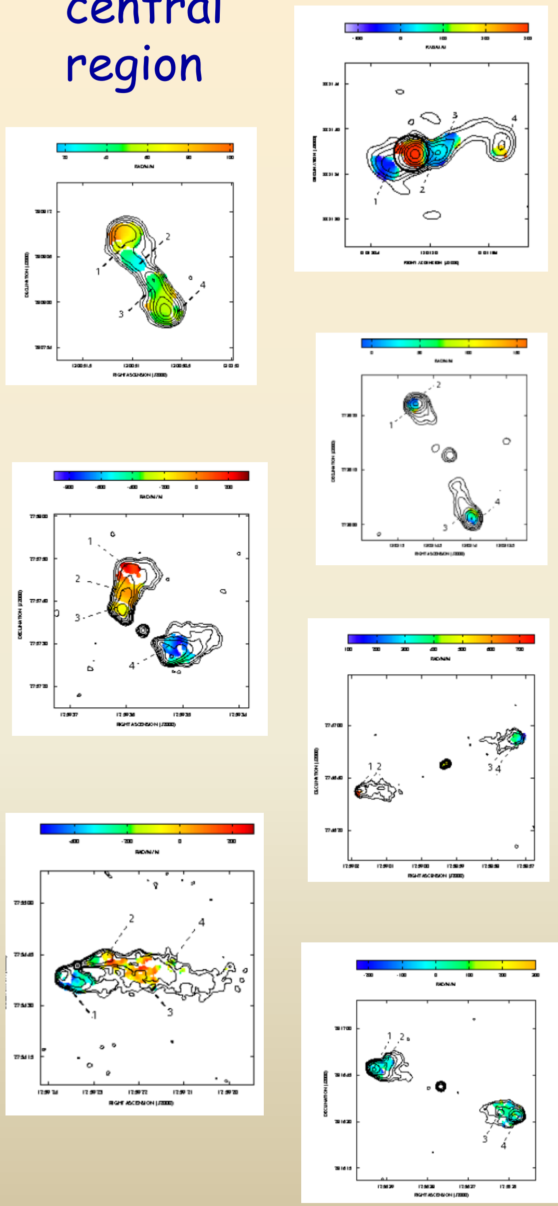
Consistent with ~ μG field
Differerence between merging and relaxed clusters

RM Coma Cluster

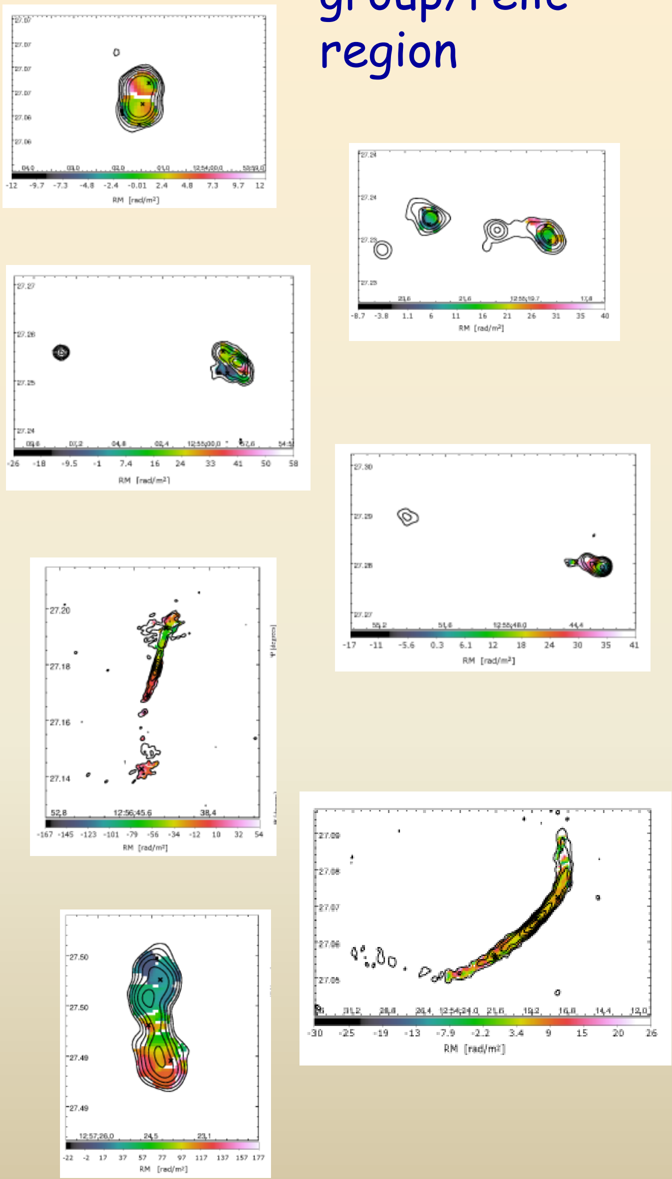
•Bonafede et al. 2010- center

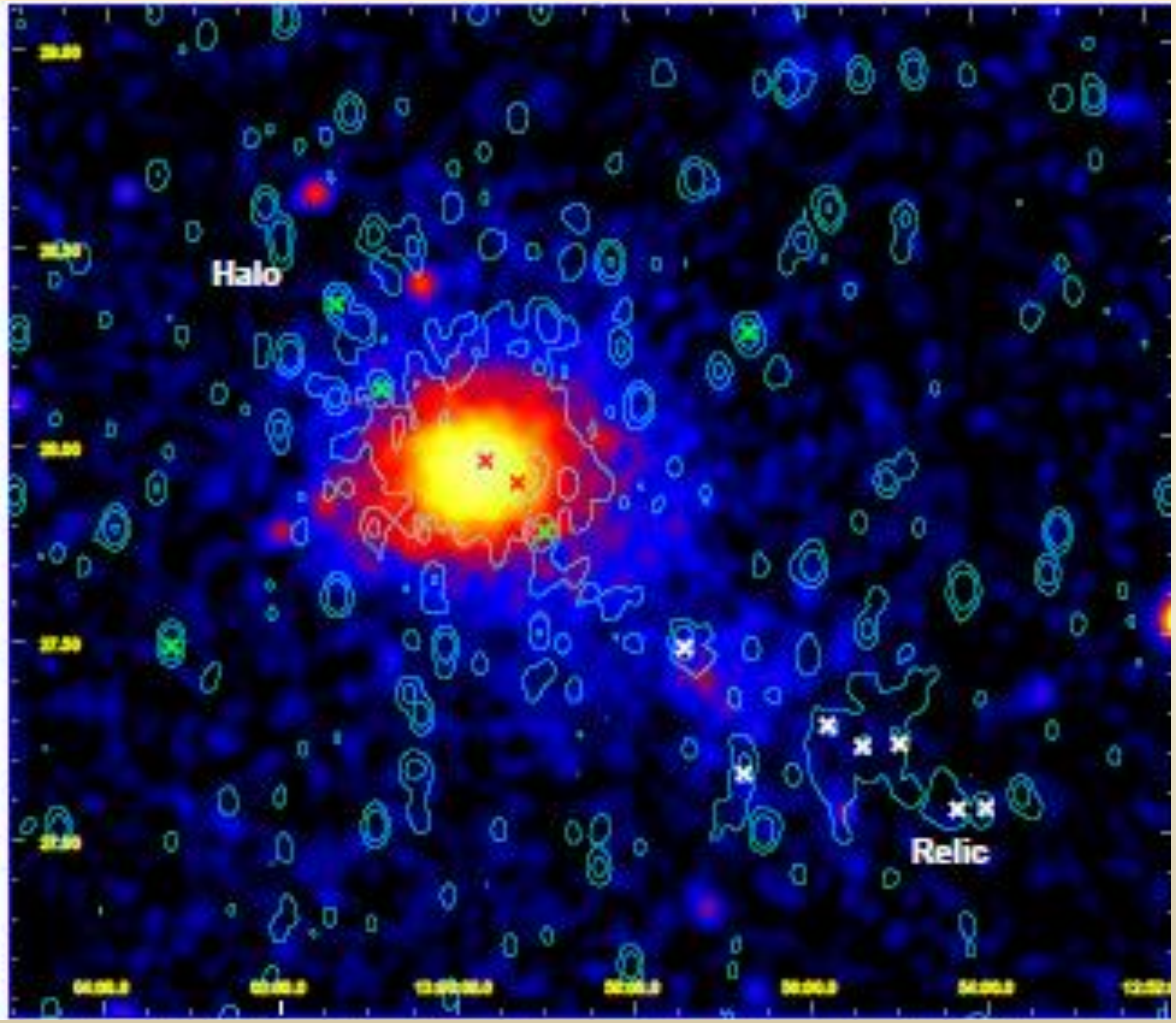
•Bonafede et al. 2013 - periphery

central region

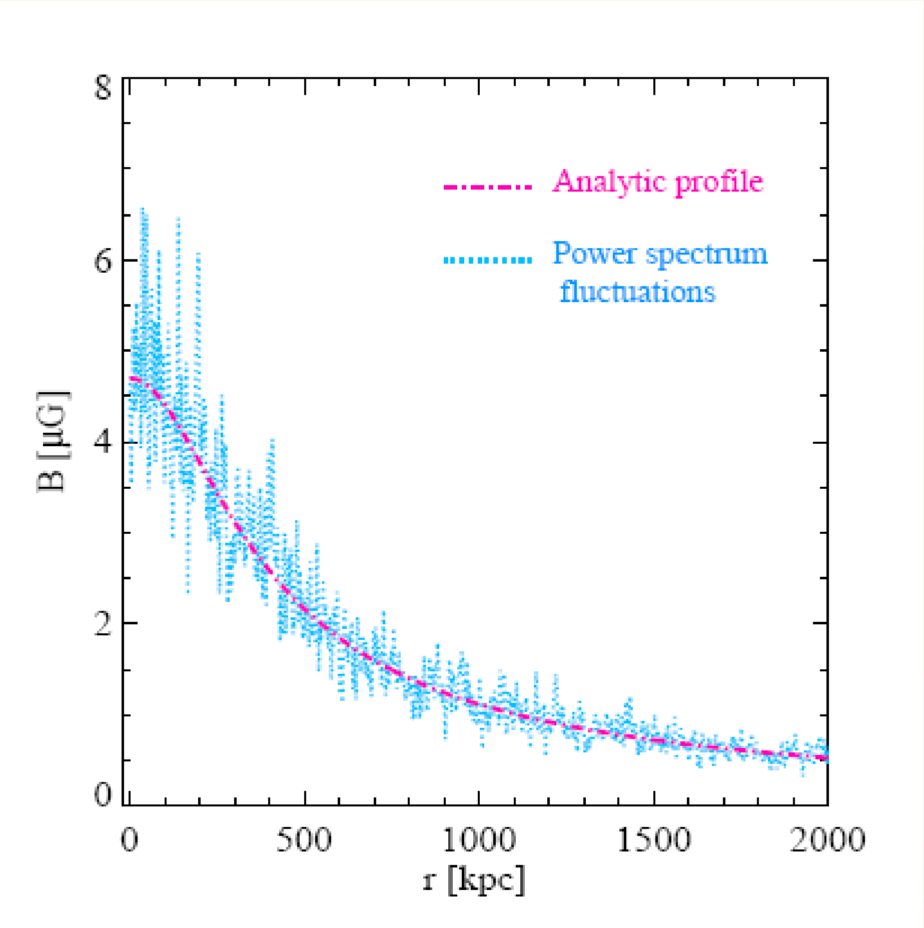


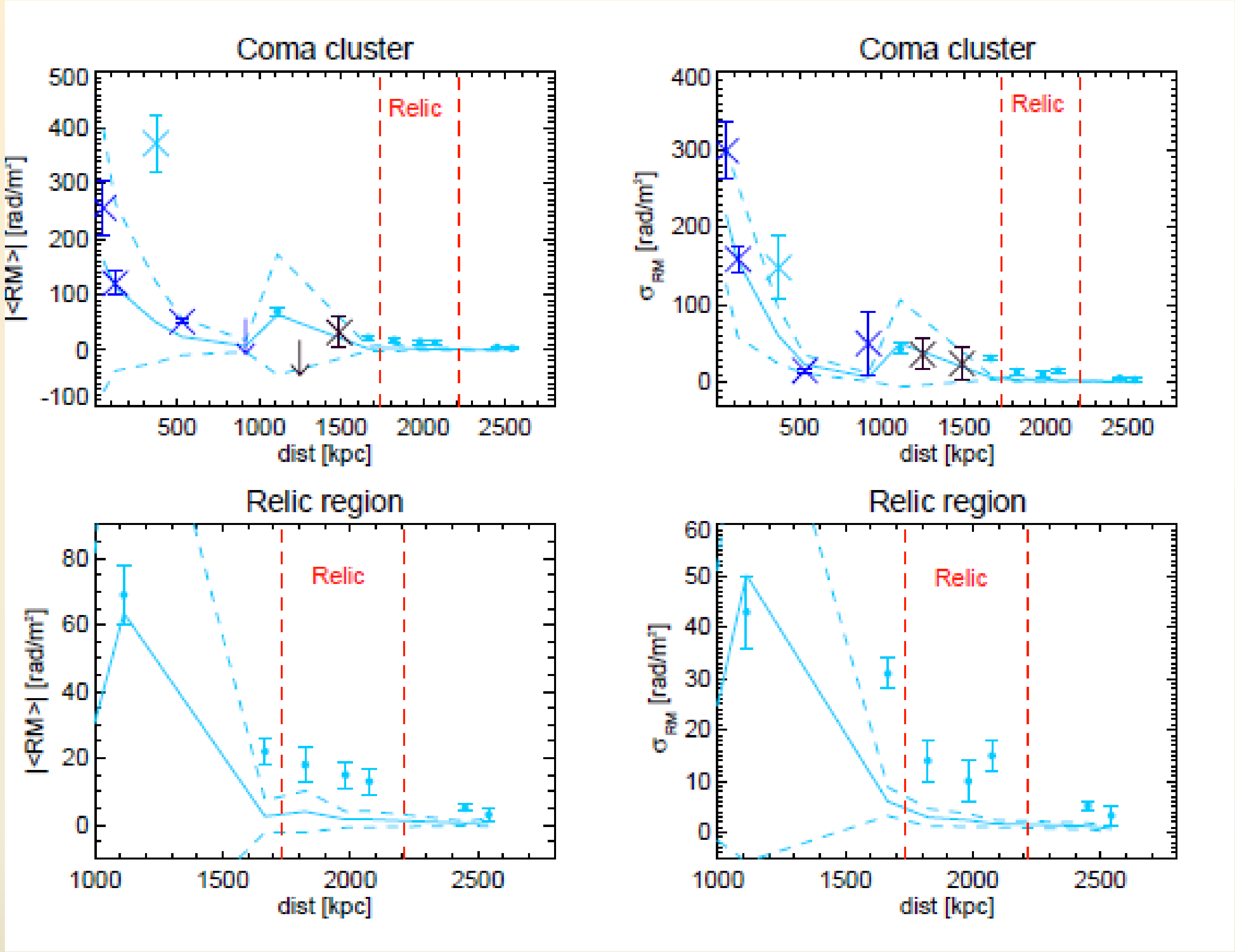
group/relic region





Coma



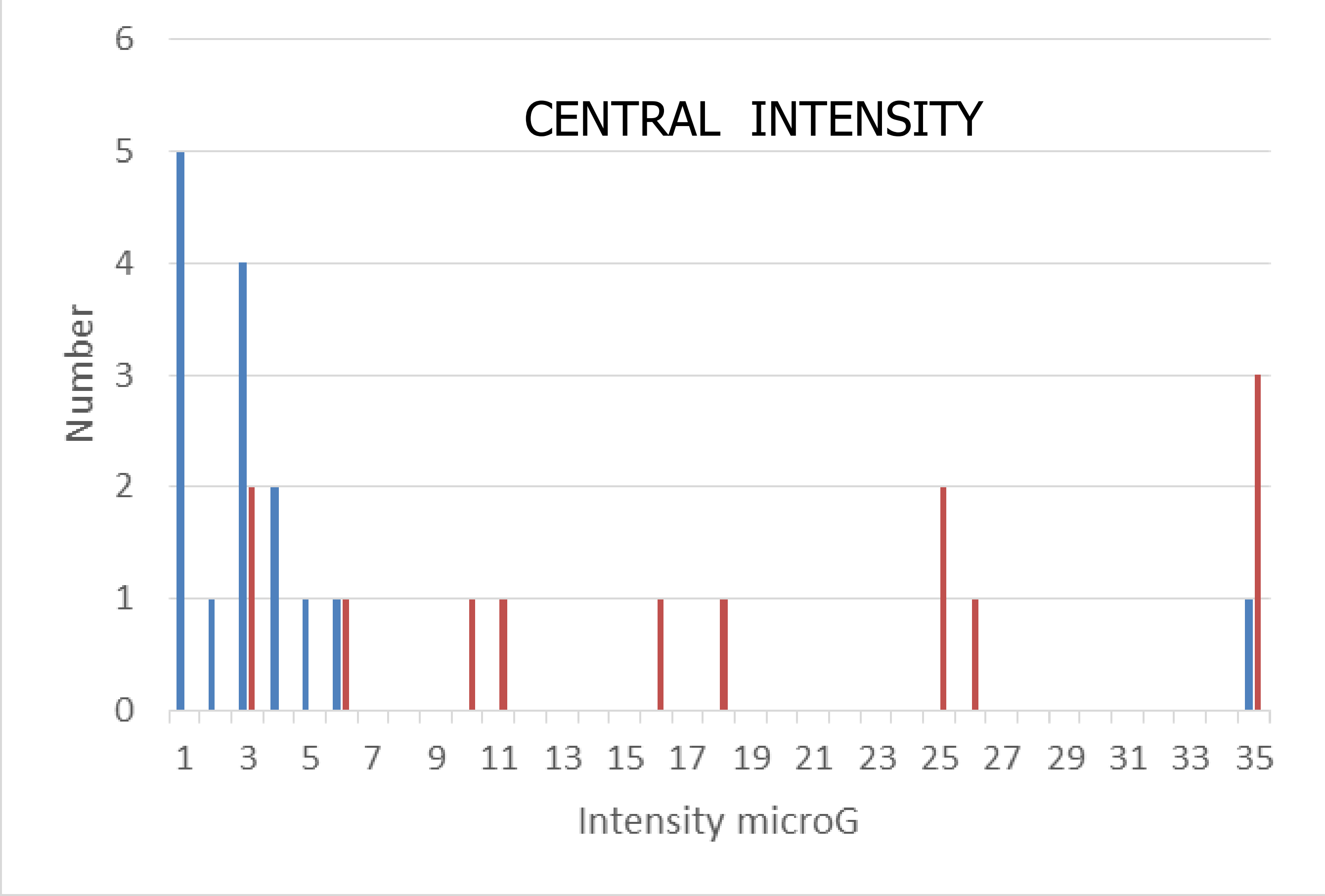


RM values reproduced by

$B_0 = 4.7_{-0.8}^{+0.7}$ μG
B profile scaling as $n^{0.5}$ $^{(-0.1, +0.2)}$
Kolmogorov power spectrum $|B_k|^2 \propto k^{-n}$
Coherence scales in the range 2 – 34 kpc

Magnetic field in the SW Coma region is higher than predicted from the profile
B group = 3.6 *μG*
B relic = 2 *μG*

Individual cluster data obtained so far from RM:
16 merging, 13 cool core

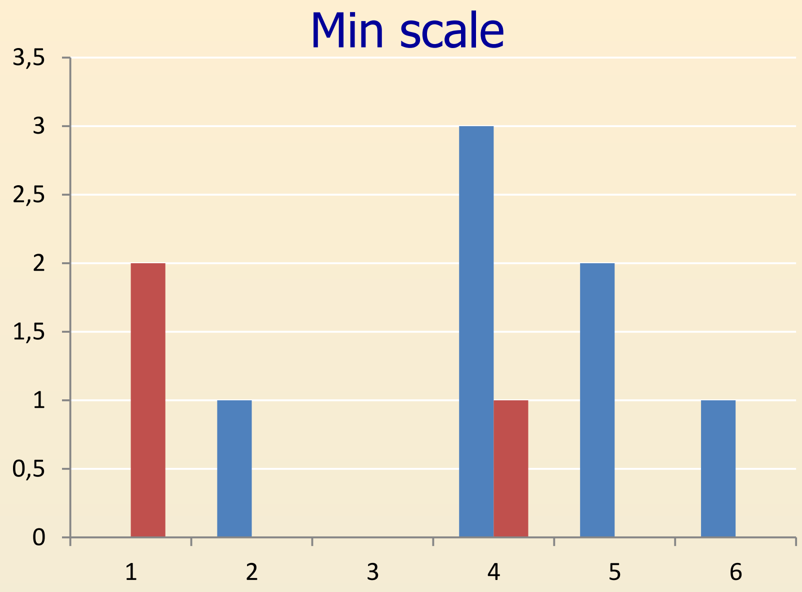


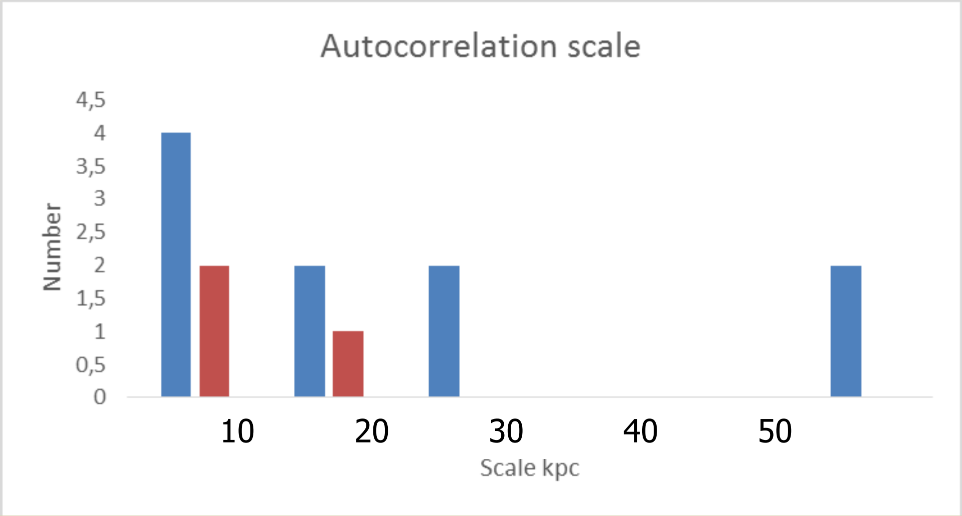
merging

cool core

a single-scale cell model is not appropriate ➔
field ordering + tangling

Power spectrum: Kolmogorov
on spatial scales 5 – 500 kpc





merging

cool core

$B \propto n^{1/2}$ if B field energy scales as thermal energy

$n^{2/3}$ if B field frozen-in during compression

n^{1} for perpendicular shocks

n^{0} for flow along the field lines

What we currently know:

Intensity : $\approx 1\ \mu G$ in merging clusters
$\approx 10\ \mu G$ in cooling core clusters

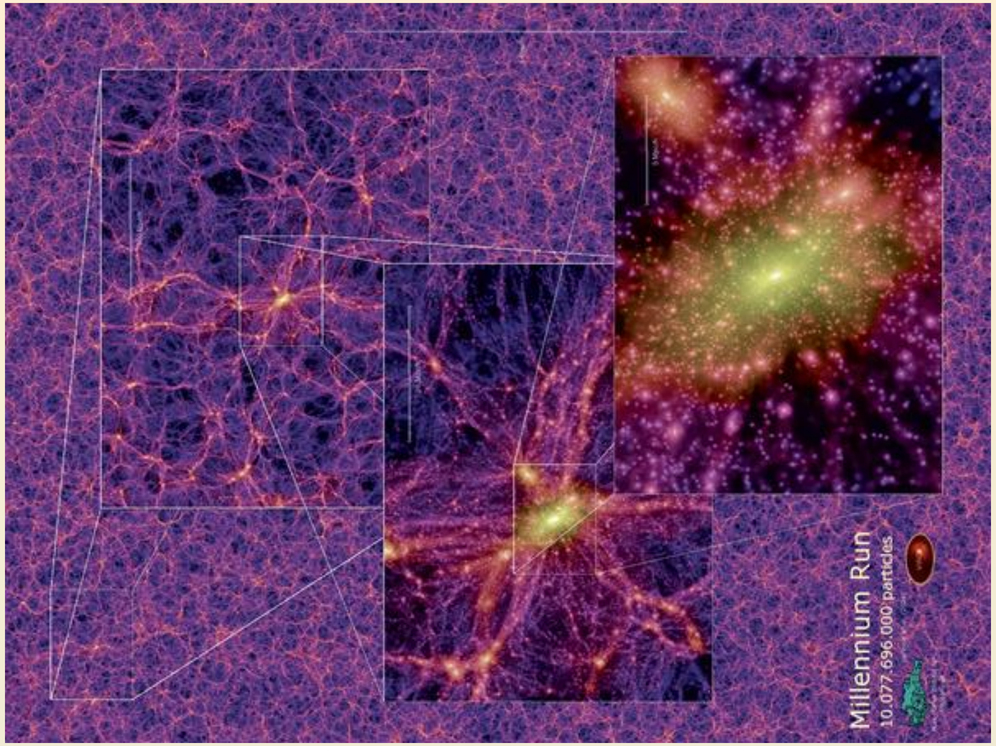
Structure :

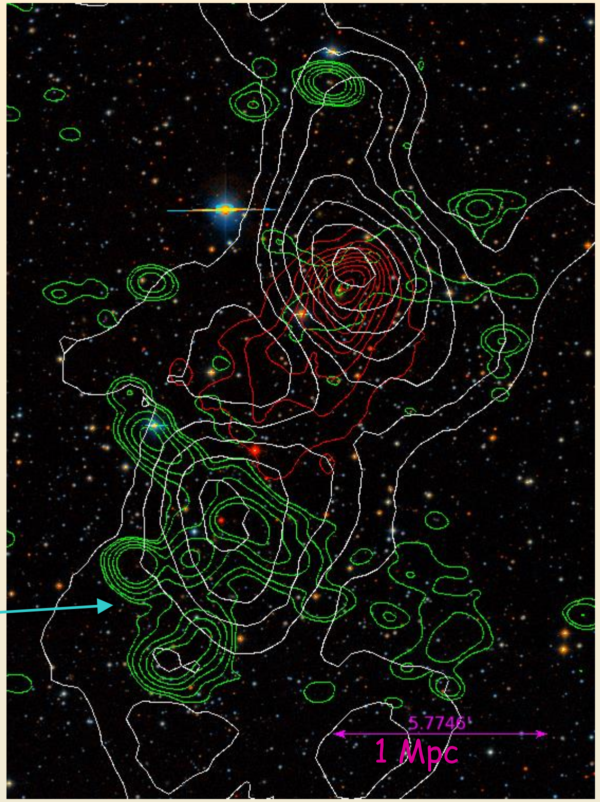
Coherence scale : a single-scale cell model is not suitable
(relation to cluster dynamical state ?)

Power spectrum: **$n = 2 \div 4$** with $|B_k|^2 \propto k^{-n}$
on **spatial scales 30 – 500 kpc**
but Kolmogorov often assumed

Radial profile: η **= 0.4 ÷ 1** with $B \propto n_{gas}^{\eta}$

Filaments





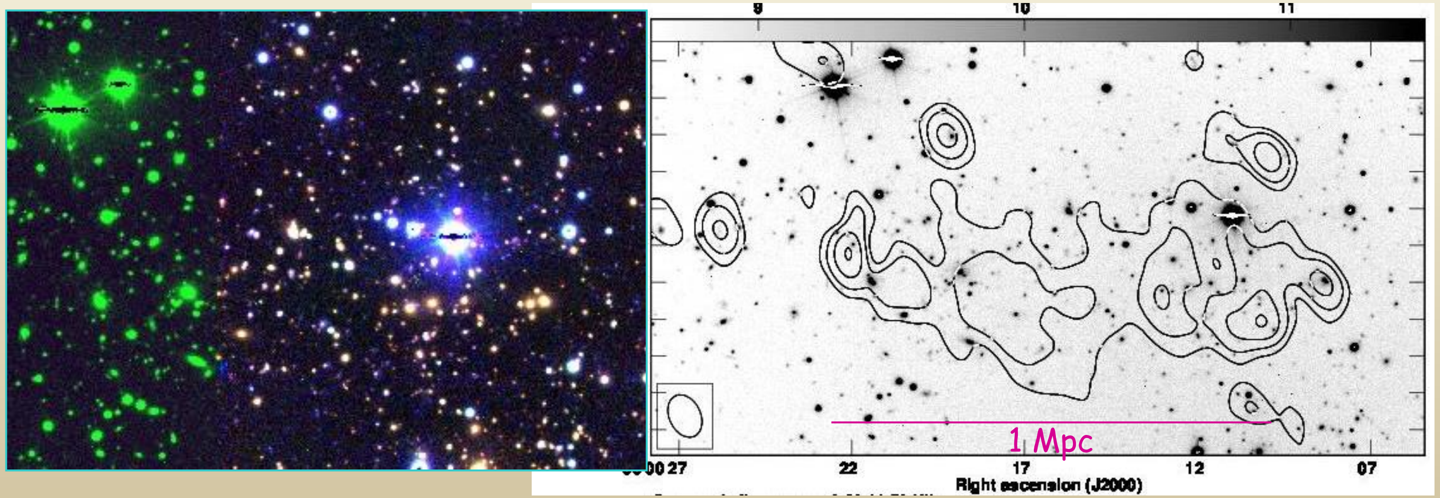
A3411+A3412
z=0.1687

(Giovannini et al. 2013,
Van Weeren et al. 2013)

Red contours : X-ray
Green contours: radio
White contours: galaxy density

MACS J0600-2008
Z=0.46

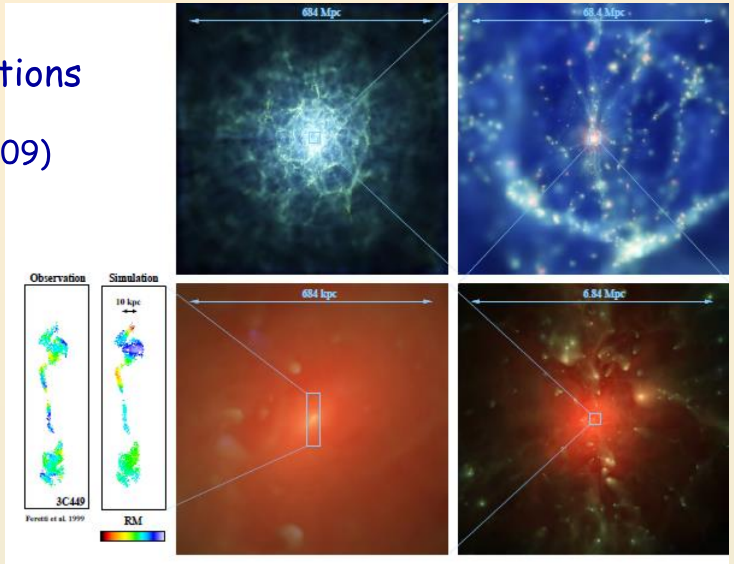
(Giovannini et al. in prep)



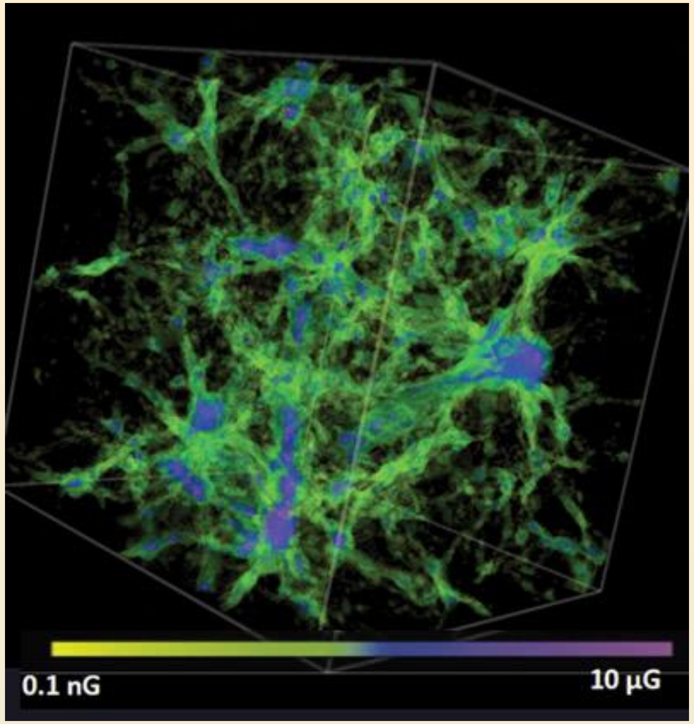
Contours: radio 1.4 GHz
JVLA (discrete sources
subtracted)

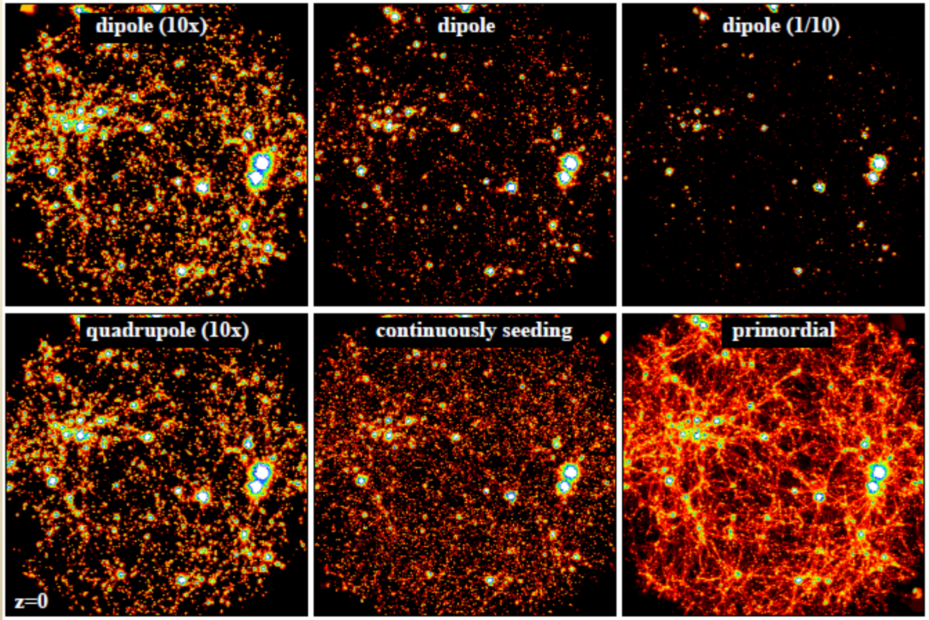
Magnetic field build up: simulations

MHD simulations
(Dolag & Stasyszyn 2009)

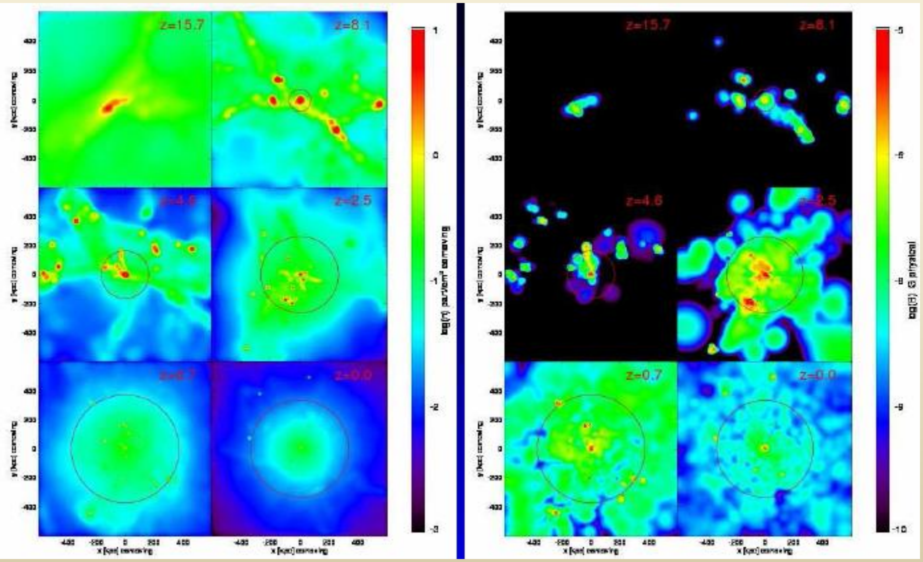


Growth of intergalactic magnetic fields through the turbulence in LSS formation
(Ryu et al. 2008)





Seeding from galactic outflows (different magnetic field models)
(Donnert et al. 2009)



Seeding from star-formation/SN (Beck A. et al. 2013)

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Fundamental Questions

- **STRUCTURE**
  - What are the strength and structure of the magnetic field in the intracluster and intergalactic medium ?
  - What is the **interplay** between the magnetic fields and the gas ?
- **EVOLUTION**
  - How were the present-day magnetic fields **amplified** and maintained ?
  - How did magnetic fields **evolve** as galaxies evolved ?
- **ORIGIN**
  - Were the **seed fields** in galaxies and clusters **primordial**, or were they ejected by stars, supernova remnants, or AGNs ?
  - Is there a connection between field formation and **structure formation** in the Early Universe ?
  - When and how were the **first magnetic fields** generated?

Future prospects

multivawelenght observations:

- radio ➔ cm/mm : SKA precursors/pathfinders, ALMA, SKA
- X-ray ➔ eRosita, Athena
- γ-ray ➔ Fermi, CTA
- CMB ➔ Planck

technical developments:

- techniques to image diffuse large scale emission,
- algorithms to extract information from RM data

theoretical developments:

- plasma simulations with realistic turbulent m.f.
- tests

Focus Meeting at XXX IAU GA, Vienna 2018 : Stay Tuned !

THANK YOU