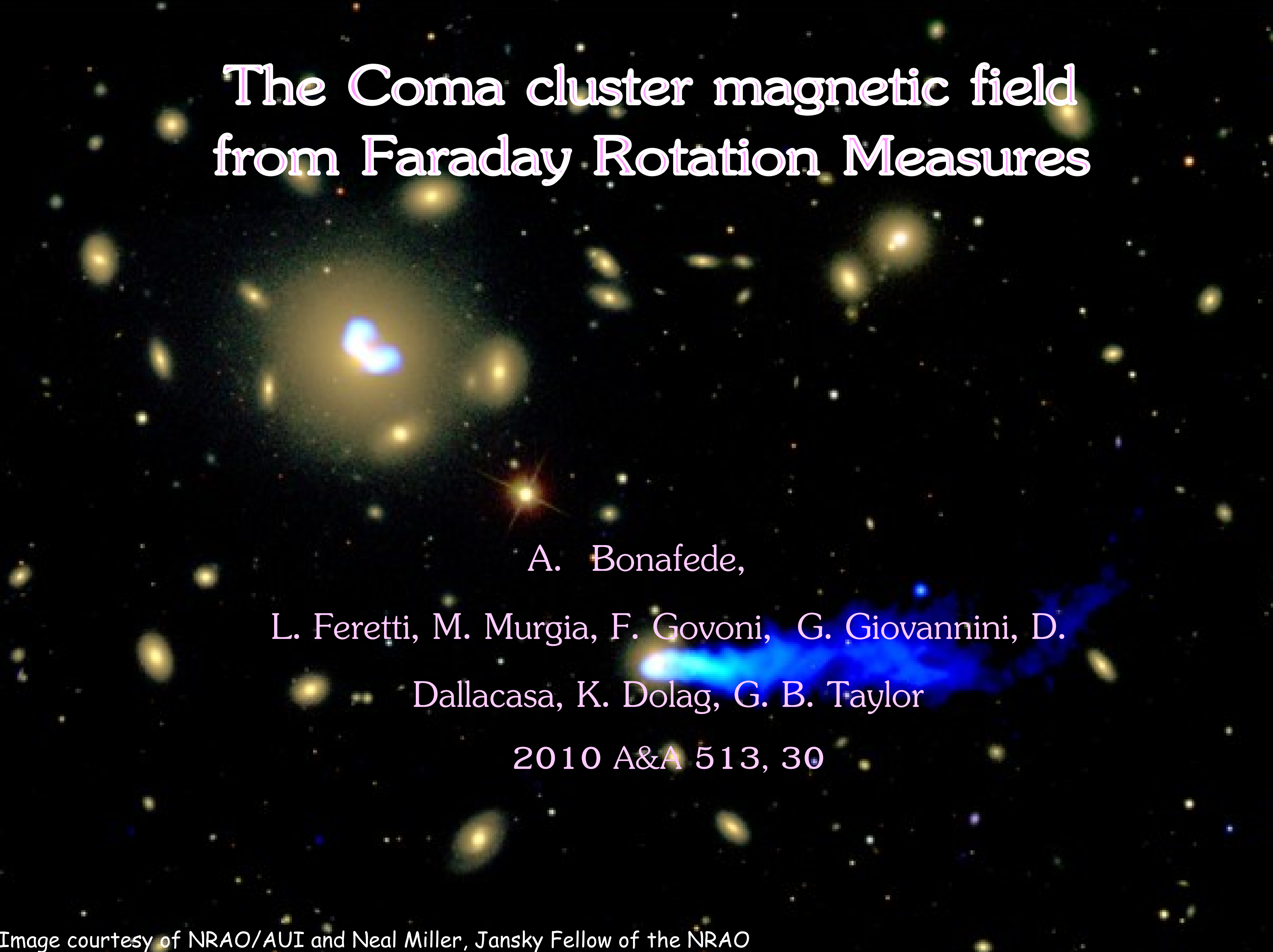
# The Coma cluster magnetic field from Faraday Rotation Measures



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L. Feretti, M. Murgia, F. Govoni, G. Giovannini, D. Dallacasa, K. Dolag, G. B. Taylor

2010 A&A 513, 30

Image courtesy of NRAO/AUI and Neal Miller, Jansky Fellow of the NRAO

OUTLINE

- Why should we care about Magnetic Field in Galaxy Clusters

- how to estimate the Magnetic Field in Galaxy Clusters

## *The Coma cluster*:

- magnetic field in the Coma cluster from previous estimates

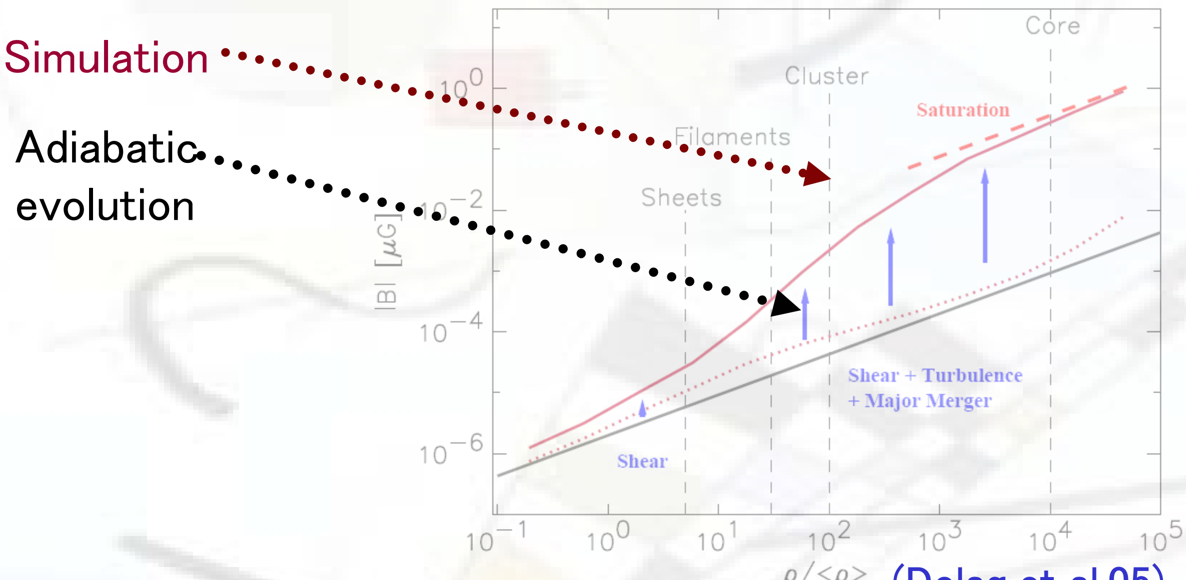
- new source sample: radio data and RM images

- Magnetic field simulations

- Results

- Comparison with previous estimates and discussion

· Origin of magnetic field in the universe still unknown:
magnetic field on large scales → dynamo processes too slow
other amplification mechanisms are required




(Dolag et al.05)

· Physical processes in the Intra Cluster Medium

Magnetic fields Affects the thermal conduction

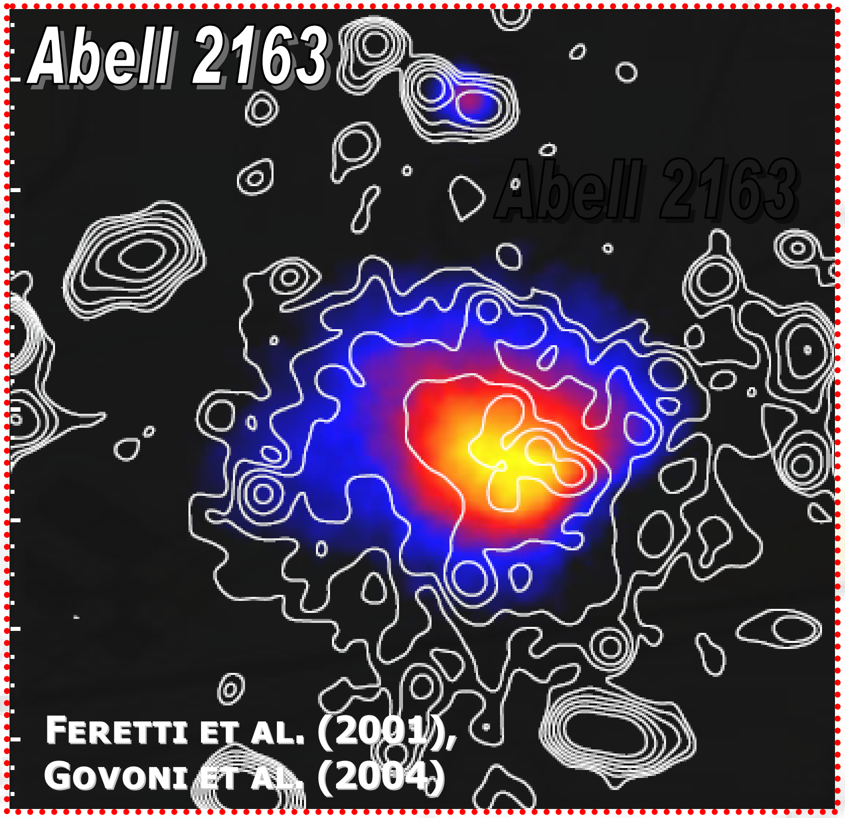
Implication on the origin of radio emission

## Radio halos:

Synchrotron emission on Mpc scale

Low surface brightness
~ 1 μJy/arcsec$^2$ at 1.4 GHz

Magnetic field estimate -> Equipartition



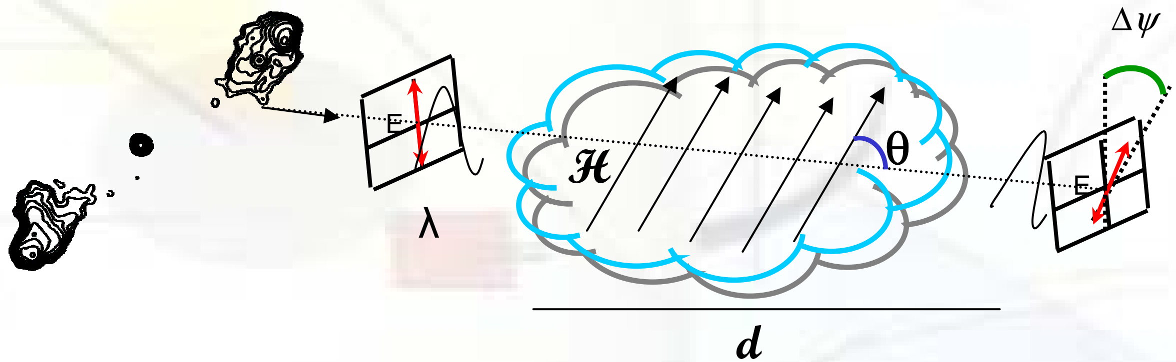

Origin of the emitting particles?

Particles generated or accelerated everywhere in the cluster

Turbulence? (e.g. Petrosian 2001, Brunetti 2001)

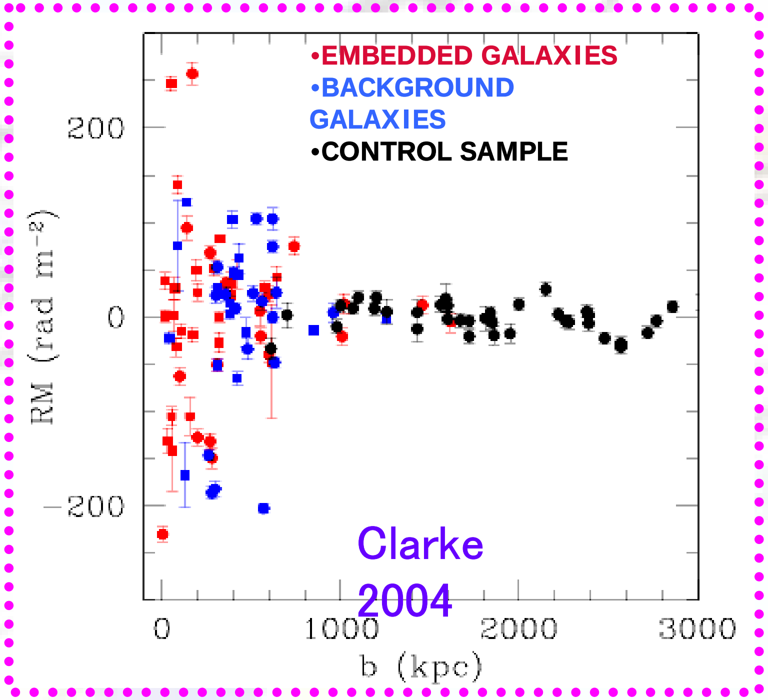
Secondary origin from p-p collisions?
(e.g. Dennison 1980, Blasi & Colafrancesco 1999)

Faraday Rotation




Ψ: Orientation of the polarization plane

$$RM \equiv \frac{\partial \psi}{\partial \lambda^2} \propto \int_0^d n_e H \cos \vartheta dl$$




RM distribution (mean and dispersion)
→ magnetic field strength and morphology

# Magnetic field in the Coma cluster: previous estimates

Observations of radio synchrotron emission on Mpc scale from the Intra Cluster Medium

Radio halos

Equipartition: B = 0.7 – 1.9 μG
over 1 $Mpc^3$ *(Thierback et al. 2003)*

Faraday Rotation Measure of sources inside/behind clusters

RM analysis of NGC4869 → B~ 6 μG
→ B=(0.2± 0.1) μG On larger scale
*(Feretti et al. 1995)*

Hard-X ray emission

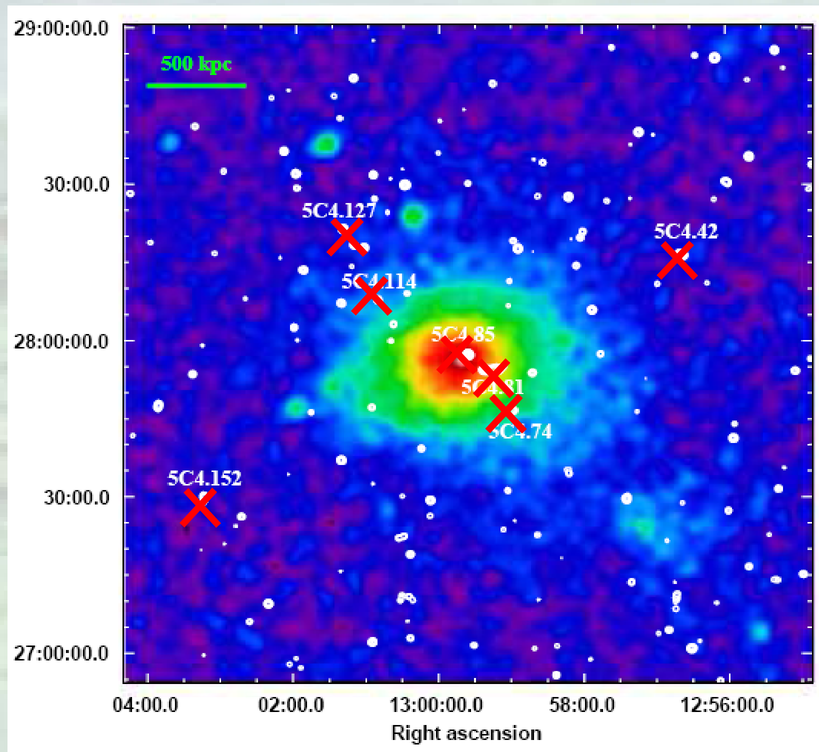
Inverse Compton → B ~ 0.2 μG
over 2.6°x 2.6°, *(Fusco Femiano et al. 2004)*

# Radio Data

Aim of the work: Constrain the magnetic field strength and structure

## Radio Data

- 7 extended sources observed in 2006 – 2009 at the VLA
  - At 4–5 frequencies in the range 1.4 –8.5 GHz
  - In B and C configuration
  - Time on source: 8 hour/source
  - Resolution 1.5'' (FWHM) – 0.7 kpc



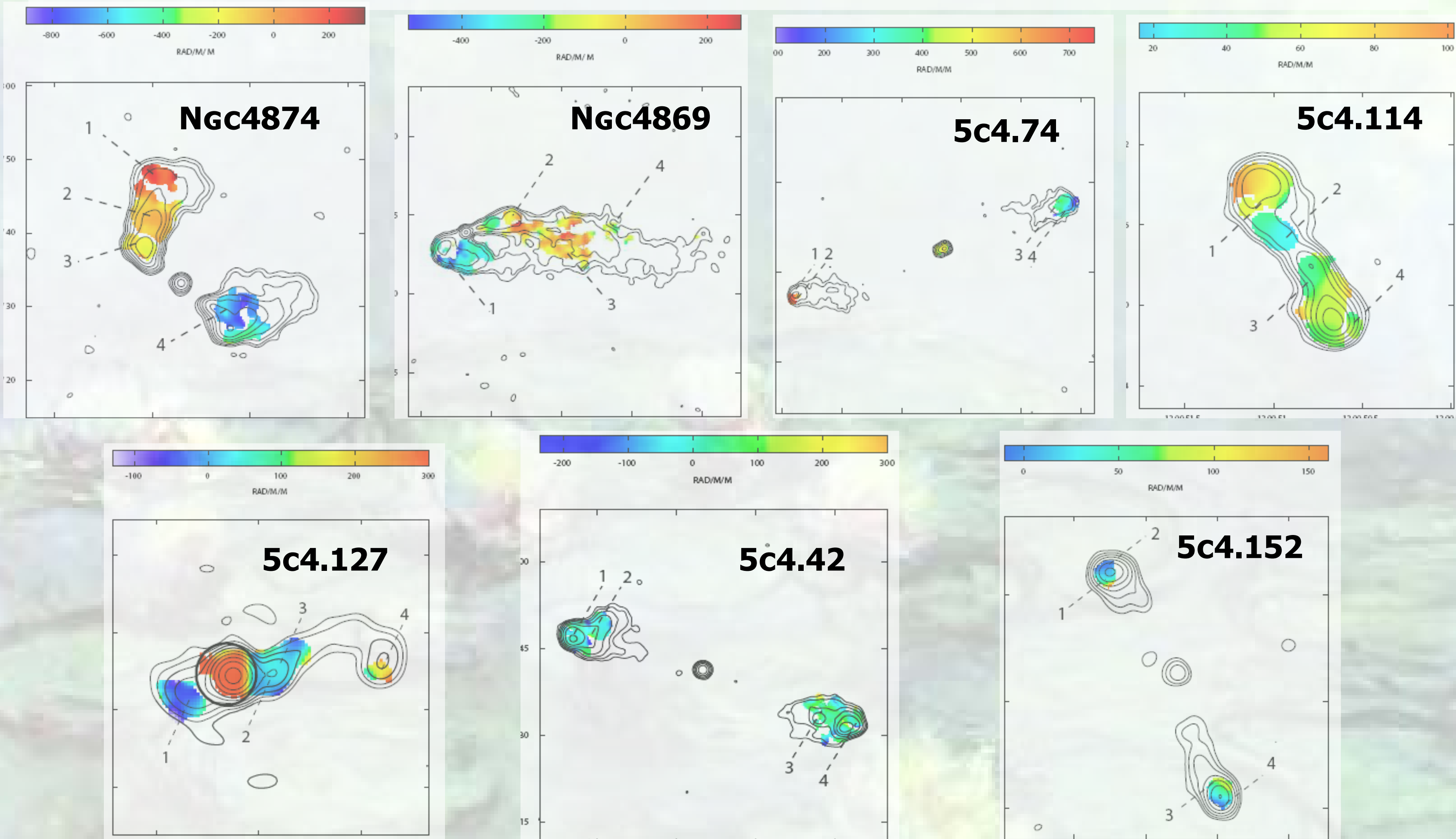

**Colors: X ray 0.1-2.4 keV band from RASS**

**Contours: radio at 1.4 GHz from NVSS**

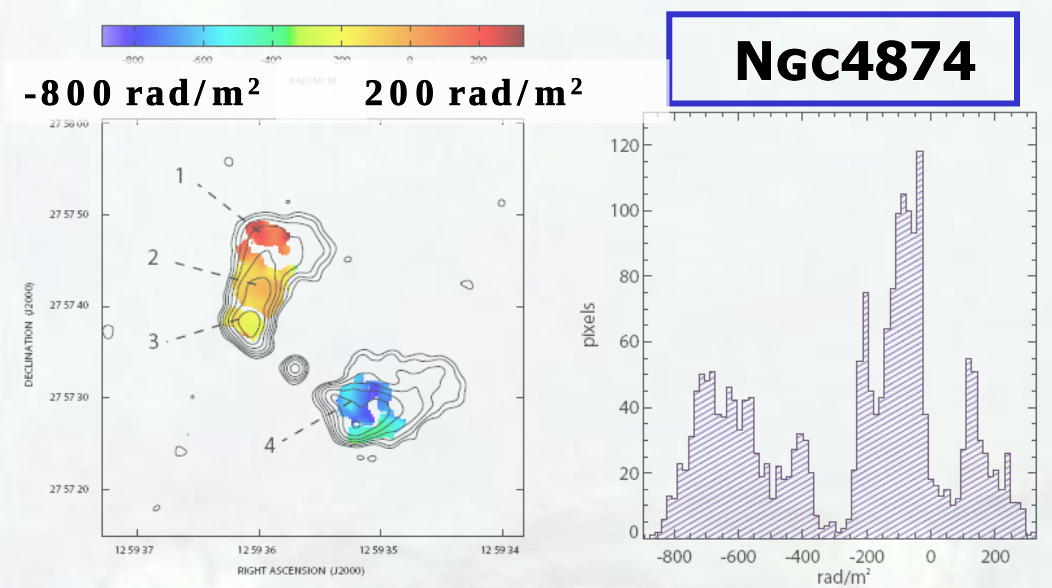
# Rotation Measure fits

RM fits obtained with the **PACERMAN** algorithm *Dolag et al. (2005)*

*RM in low signal-to-noise regions obtained exploiting the information on the n-pi ambiguity obtained in high signal-to-noise regions*

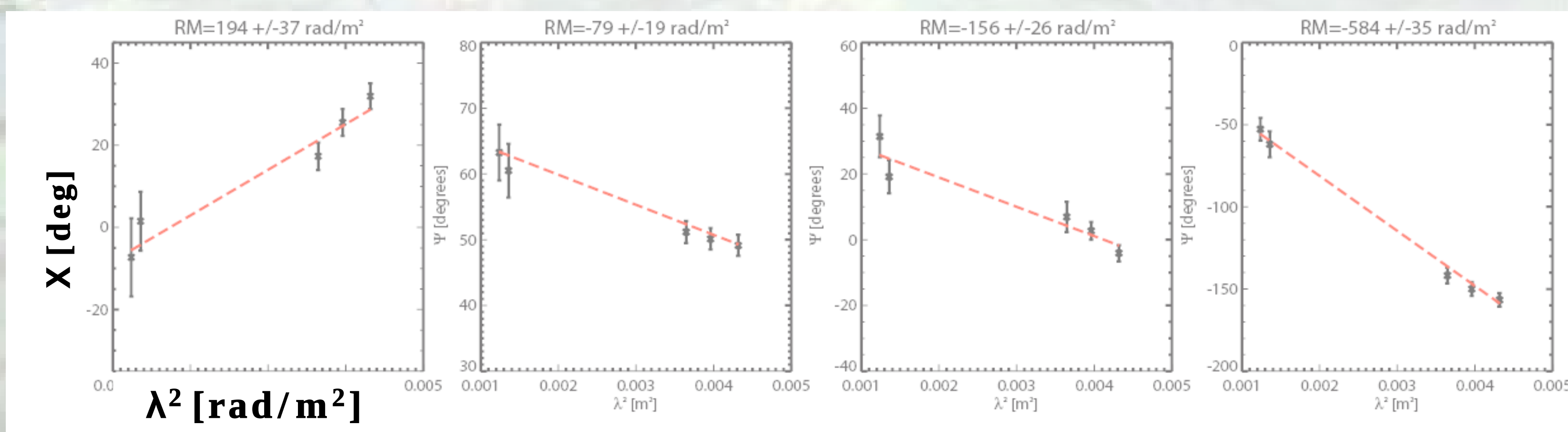


## An example: the central source

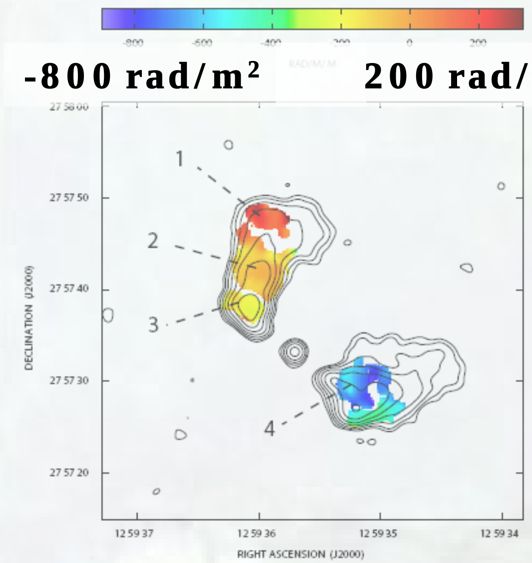



**Foreground Faraday screen or internal rotation?**

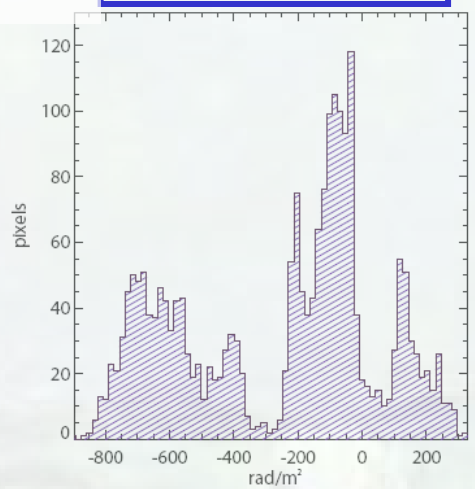
**$\lambda^2$ trend of $\chi$ consistent with external screen**



## An example: the central source




**Ngc4874**

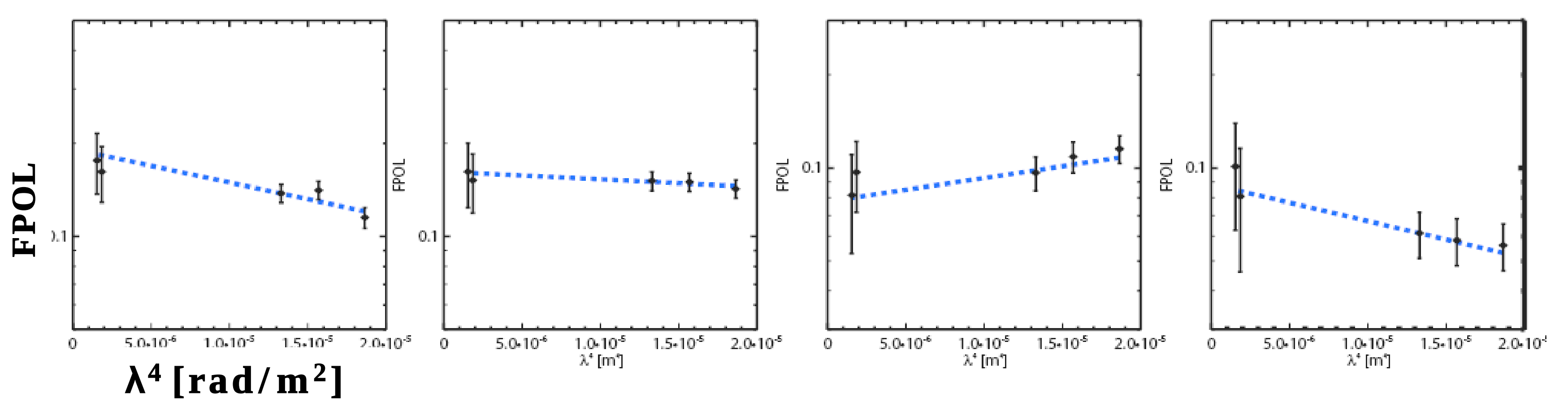


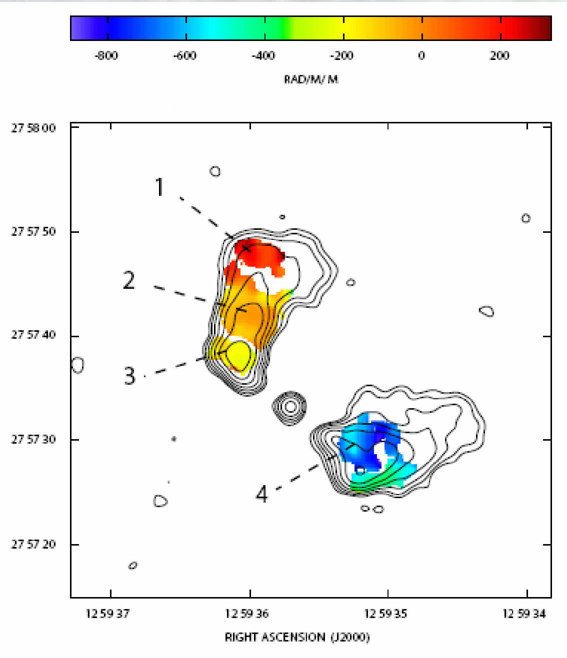

**FOREGROUND FARADAY SCREEN OR INTERNAL ROTATION?**

$$p(\lambda) = p(0)\exp(-k\lambda^4)$$

**Depolarization:**

**$\lambda^4$ trend of $p(\lambda)$ and slight depolarization**



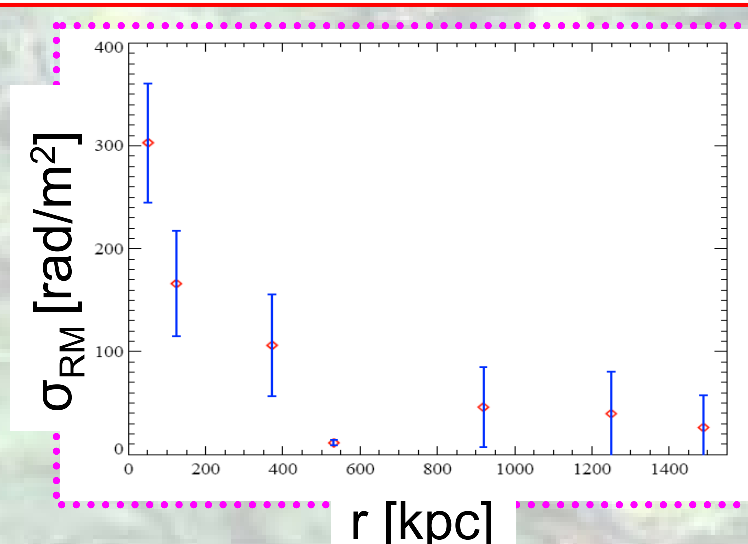



**<RM> ≠0**
B on scales larger than the source size

**MULTI-SCALE MAGNETIC FIELD**

**RM gradients on small scales**
B on scales smaller than the source size

**MAGNETIC FIELD RADIAL PROFILE**




**Larger $\sigma_{RM}$**
in the central sources

# The Coma cluster magnetic field from Faraday Rotation Measures

## Assumptions

- Faraday Rotation originates entirely in an external screen
- The magnetic field has Gaussian components

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

- The magnetic field is isotropic

**$k_{min}$, $k_{max}$, $n$**

- The magnetic field strength varies with the thermal gas density in the cluster

$$<B>(r) = B_0 \left( \frac{n_e}{n_0} \right)^{\eta}$$

**$B_0$, $\eta$**

The **magnetic field power spectrum** is **proportional** to the **RM power spectrum**

**5 free parameters,**
**2 degeneracies**

# The Coma cluster magnetic field from Faraday Rotation Measures

## Strategy to obtain information on the magnetic field

$$RM \propto \int_{LoS} n_e B_{//} dl$$

From Radio observations

From X-ray observations

Target

**Numerical Simulations of different magnetic field models**

***(FARADAY*** **code by Murgia et al. 2004)**

**Synthetic RM images**

**Comparison with observed ones**

## Modeling the magnetic field power spectrum

- **The vector potential A(k)** with a given **power spectrum**

$$|A_k|^2 \propto k^{-\zeta}$$

Fourier components A(k)
Rayleigh distribution
phases random

- **The magnetic field** $\tilde{B}_k = ik \times \tilde{A}_k$

FFT → $B_z$ in the real space

$$\nabla \cdot \vec{B} = 0$$

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

**Power spectrum degeneracy** (higher n, lower $k_{min}$)

**Schuecker et al 04**
from pseudo-pressure map
**KOLMOGOROV POWER SPECTRUM** n=11/3

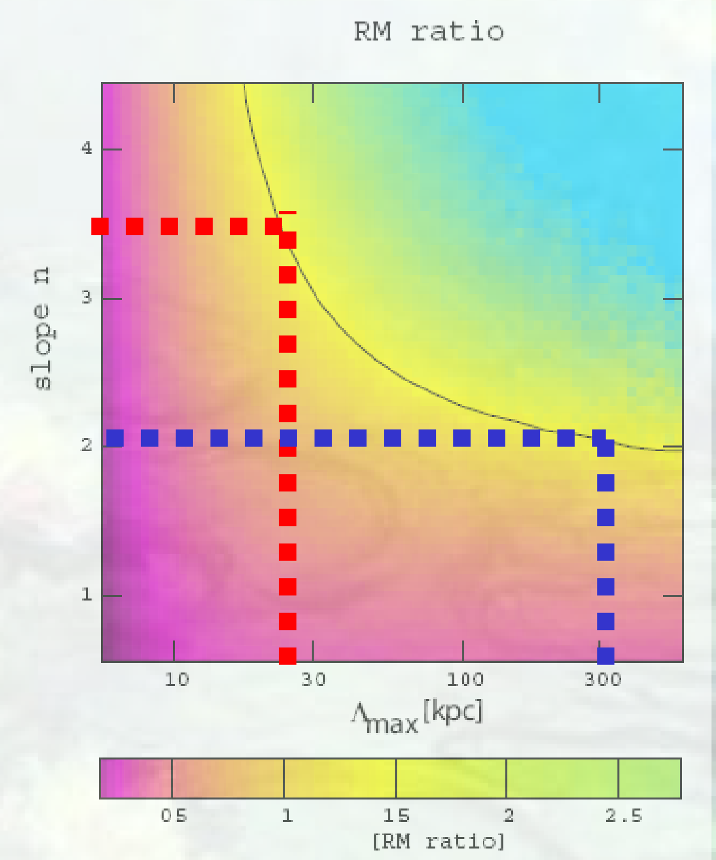
## The RM ratio

$$RM\ \ Ratio \equiv \frac{\sigma_{RM}}{|\langle RM \rangle|}$$

The ratio is sensitive to the power spectrum slope **n**

*(see Murgia et al. 2004)*

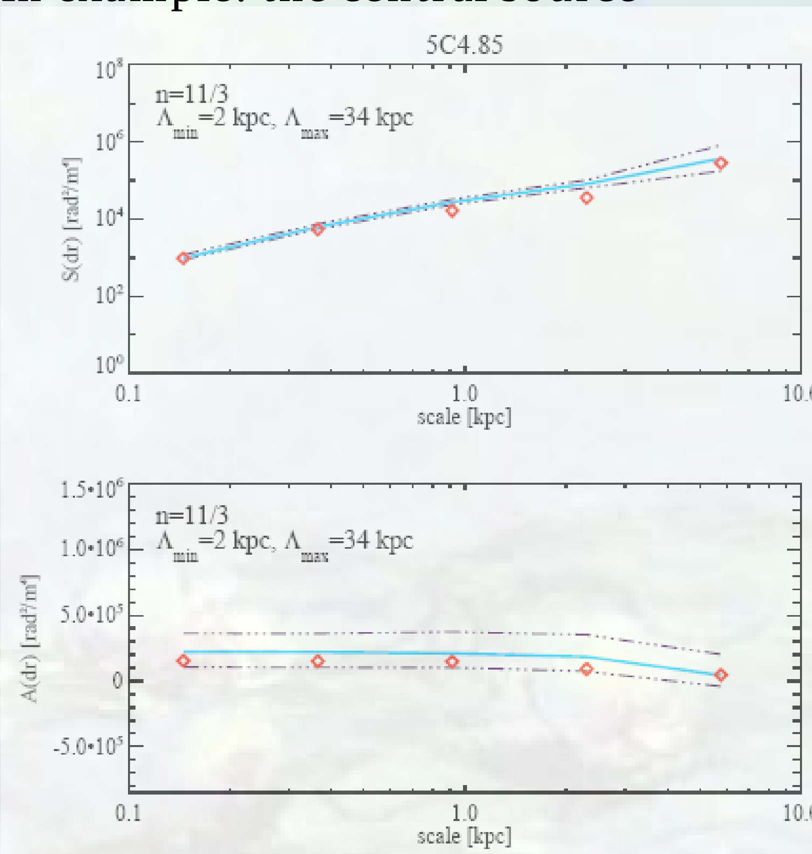
$$|B_\Lambda|^2 \propto \Lambda^n$$




- **Kolmogorov slope** → we expect Λmax ~ 30 kpc
- **n=2** → we expect Λmax ~ 100s kpc

## Structure function and auto-correlation function

An example: the central source




$$S(dx,dy)=\left\langle \left[RM(x,y)-RM(x+dx,y+dy)\right]^2 \right\rangle_{(x,y)}$$

$$A(dx,dy)=\left\langle \left[RM(x,y)\times RM(x+dx,y+dy)\right] \right\rangle_{(x,y)}$$

**Simulations**

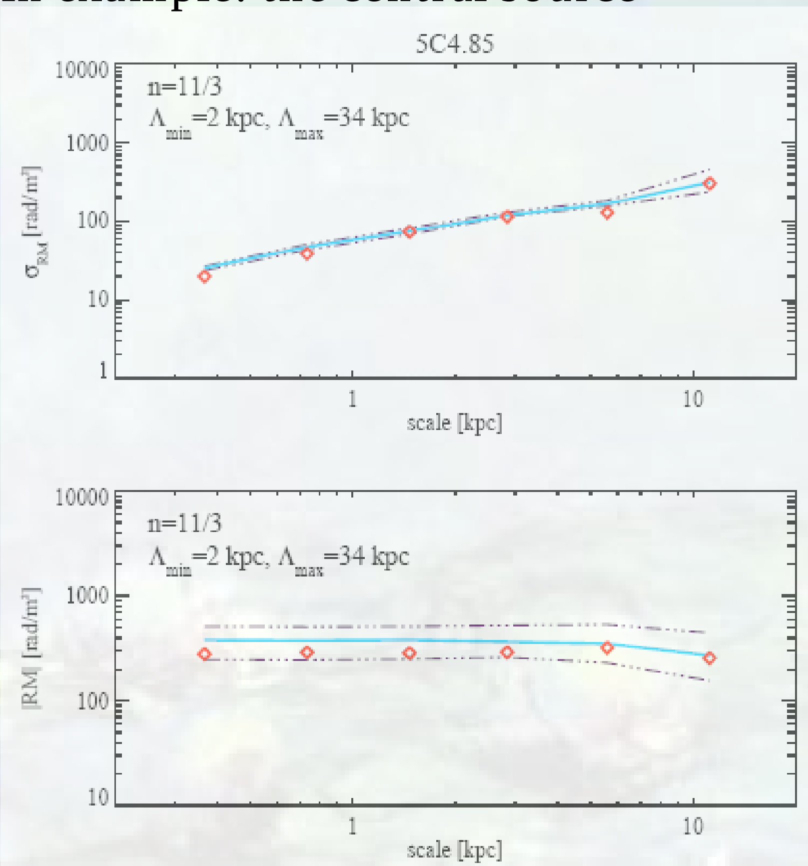
◇ **Data**

Random nature of the field
→ 30 sim for each model

# Constraining the magnetic field power spectrum

## Multi Scale Statistics

An example: the central source




Simulations

Data

$RM\ dispersion:\ \sigma_{RM}$

$RM\ mean:|RM|$

BEST MODEL:
n=11/3
Λmin = 2 kpc
Λmax = 34 kpc

- Magnetic field radial profile

$$< B > (r) = B_0 \left( \frac{n_e}{n_0} \right)^{\eta}$$

**B profile degeneracy**
(higher η, higher $B_0$)

- Gas density radial profile

Gas density: "β −model"
*(Cavaliere & Fusco-Femiano, '76)*

$$n(r) = n_0 \left( 1 + \frac{r^2}{r_c^2} \right)^{-\frac{3}{2}\beta}$$

$n_0$= 3.44 ± 0.04 $10^{-3}$ $cm^{-3}$
$\beta$ =0.75 ±0.03
rc=290 ±15 kpc
(Briel et al. 1992)

# Constraining the magnetic field radial profile

• **3-Dim simulations**

with the power spectrum obtained in the previous analysis

2048^3 cube, pixel-size 0.5 kpc

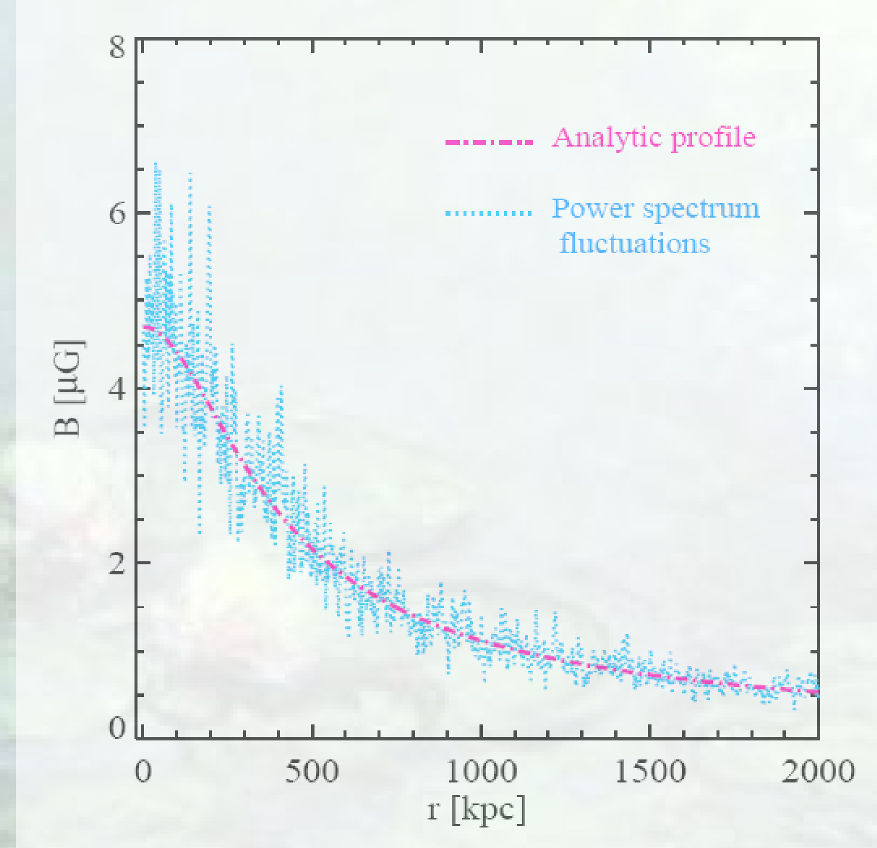
**Magnetic field models with different $B_0$ and η**

$$< B > (r) = B_0 \left( \frac{n_e}{n_0} \right)^{\eta}$$

Synthetic RM images

+ Convolution with observed beam

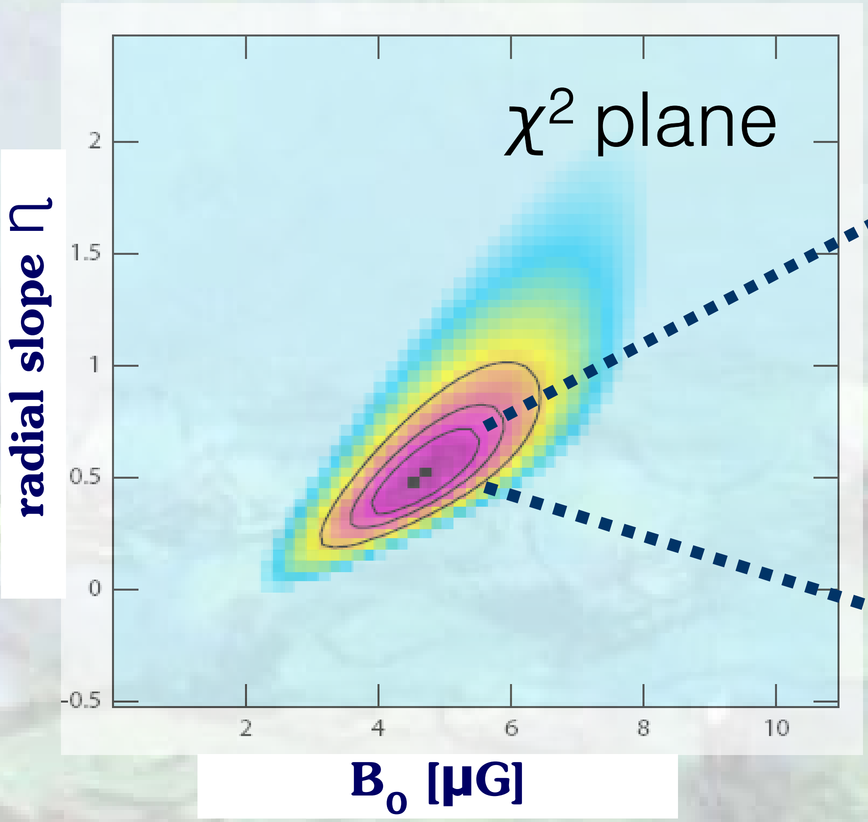
**Comparison with observed RM ($\chi^2$ test)**




Best model:
B0=4.7 *μG*, η=0.5

# Constraining the magnetic field radial profile

$$< B > (r) = B_0 \left( \frac{n_e}{n_0} \right)^{\eta}$$




Inside **68% confidence** level
**η=0.67**
Magnetic field frozen into the gas

**$B_0$>7 μG or <3μG**
**η>1 or < 0.2**
excluded at **99%** confidence level

# Comparison with other estimates

- **Inverse Compton estimate** from Hard-X *(Fusco Femiano et al. 2007)*

  ·Bepposax: PDS field of view: 1.3° → $\langle B \rangle \sim 0.2\ \mu G$

Our best model averaged over the same volume → $\langle B \rangle \sim 0.8\ \mu G$

The model with $B_0$=6.4, $\eta$=0.95 → $\langle B \rangle \sim 0.2\ \mu G$

Wik et al 2009, using XMM & Suzaku

Lutovinov et al. 2008, using ROSAT RXTE and INTEGRAL

Ajello et al.2009, using XMM, Swift/XRT & BAT data

→**No evidence for non-thermal excess**

***(Still consistent with Fusco Femiano et al if the emission comes from regions larger than the radio halo)***

**FOR A ROBUST COMPARISON, THE ENERGETIC AND SPATIAL DISTRIBUTION OF THE EMITTING ELECTRONS SHOULD BE KNOWN!**

# Comparison with other estimates

- **Radio Equipartition** from the Coma radio halo *(Thierback 2003)*

  $\langle B \rangle \sim 0.7 - 1.9\ \mu G$ over the halo Volume

**Our best model** averaged over the same volume

→ $\langle B \rangle \sim 2\ \mu G$

# Discussion: Magnetic field and heat transport in the ICM

- **Kunz et al. (2010)** have investigated the large scale transport process in the ICM.

Parallel viscous heating is regulated by the saturation of micro-scale plasma instabilities and can balance radiative cooling in cool core clusters.

Given observed density and temperatures, this balance implies specific values for B strength and profile.

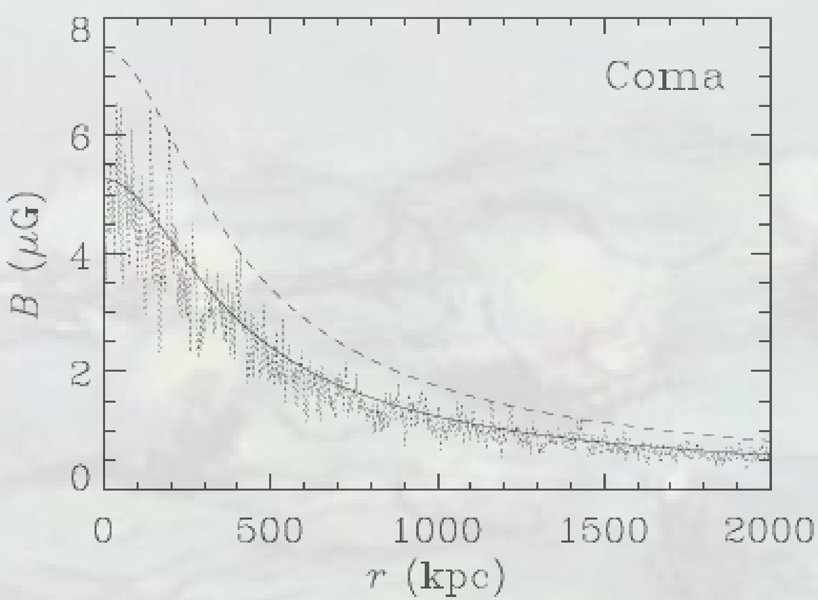
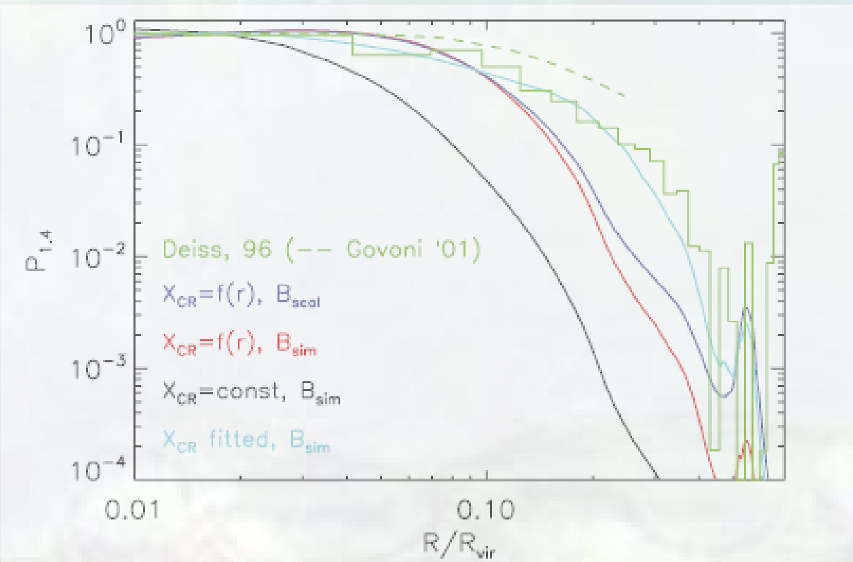


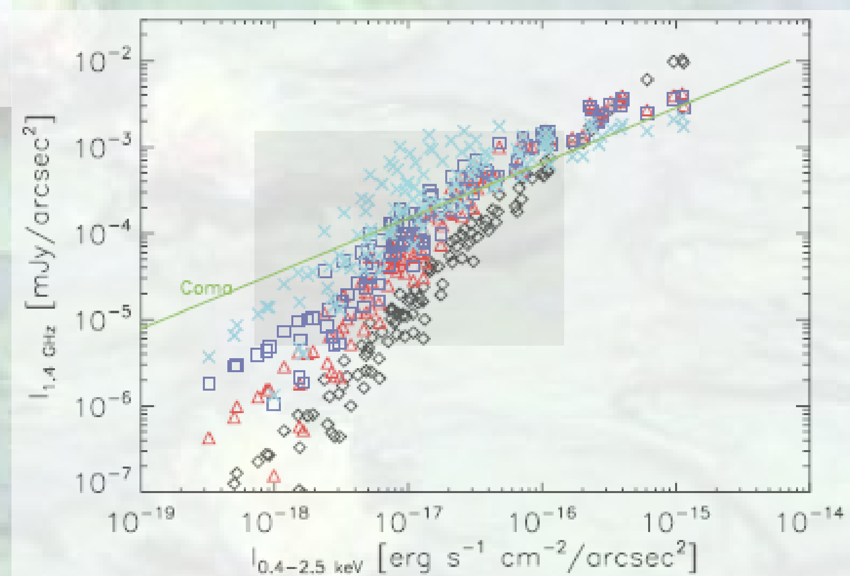

**Figure 3.** Profile of the predicted magnetic field strength $B$ in the non-cool-core cluster Coma for $|\xi| = 1$ (firehose instability threshold; solid line) and $|\xi| = 0.5$ (mirror instability threshold; dashed line). The dotted line represents the observed magnetic field power spectrum fluctuations, as determined by Bonafede et al. (2010).

**B profile derived from RM data**

- **Donnert et al. (2010)** computed the radio emission expected from the Coma radio halo, by using cosmological MHD simulations and re-scaling the magnetic field profile to match the observed one




**Purely hadronic models for the origin of the emitting particles are disfavored**



# Discussion: magnetic field dissipation in cosmological mhd simulations

- **Bonafede & Dolag (in prep):** re-simulations at high resolution of a sample of 25 massive clusters - the **Dianoga** sample

- Ideal MHD implementation in Gadget code (Dolag & Stasyzyn 08)

Un-realistic magnetic field strength

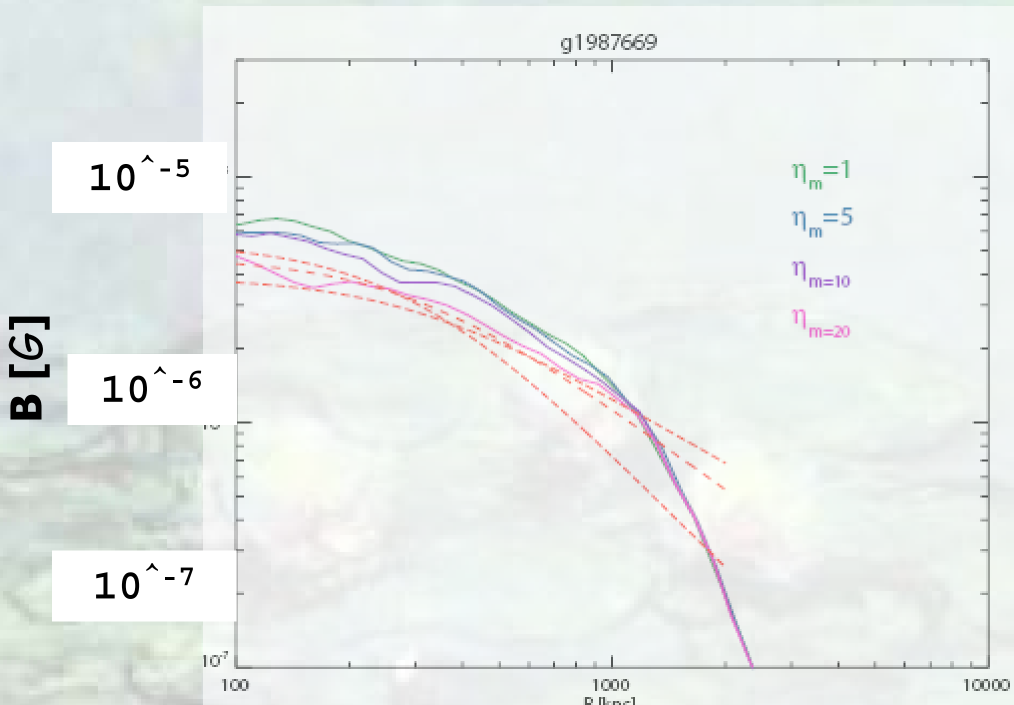
- Implementation of resistive MHD including a spatially constant magnetic diffusivity in the induction equation

$$\frac{d\vec{B}}{dt} = (\vec{B}\cdot\nabla)\vec{v} - \vec{B}(\nabla\cdot\vec{v}) + \eta\nabla^2\vec{B}$$

# Discussion: magnetic field dissipation in cosmological mhd simulations

$$\frac{d\vec{B}}{dt} = (\vec{B}\cdot\nabla)\vec{v} - \vec{B}(\nabla\cdot\vec{v}) + \eta\nabla^2\vec{B}$$

**------**
**COMA PROFILE COMPATIBLE WITH RM DATA**




hydro
$\eta = 1$
$\eta = 5$
$\eta = 10$
$\eta = 20$

# Conclusions

Magnetic in the Coma cluster has been studied through RM observations and comparision wih 3D simulations

- The magnetic field power spectrum: Kolmogorov, scales from 2 to 40 kpc
- The magnetic field radial profile: $B_0$=5 μG, η=0.5
- Values of $B_0$ outside the range 3–7 μG rejected at 99% CL by these data
- Values of η outside the range 0.2 – 1 rejected at 99& CL by these data
- Agreement (despite the many assumptions) with equipartition estimate and marginal agreement with the dibated IC estimate
- *Magnetic field profile in agreement with that required to balance viscous heating and radiative cooling (Kuntz et al 2010)*
- *Magnetic field profile + cosmlogical simulations disfavour hadronic models for the origin of the radio halo (Donnert et al.2010)*
- *Magnetic field allows to constrain dissipation (Bonafede & Dolag in prep)*