Observations of Magnetic Fields in Galaxy Clusters

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23- 27 October 2017 - Leiden
Diffuse Synchrotron Emission in Clusters of Galaxies – What's Next?

Observations of Magnetic Fields in Galaxy Clusters

Magnetic fields in galaxy clusters can be studied using different sources:

- Radio Relics (at the cluster periphery)

- Radio Halos (at the cluster center)

- Faraday Rotation of Radio Galaxies → Incidence, strength, and morphology of magnetic fields in galaxy clusters, regardless of the presence of a diffuse radio source (relic, halo)

FARADAY ROTATION

I-part of the talk:

Faraday Rotation studies

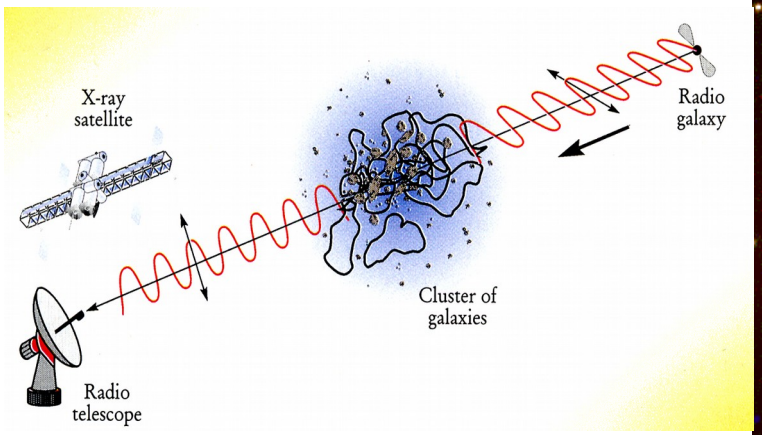
II-part of the talk:

SMOG-project: polarimetric properties of cluster radio sources to constrain the non-thermal component in galaxy clusters

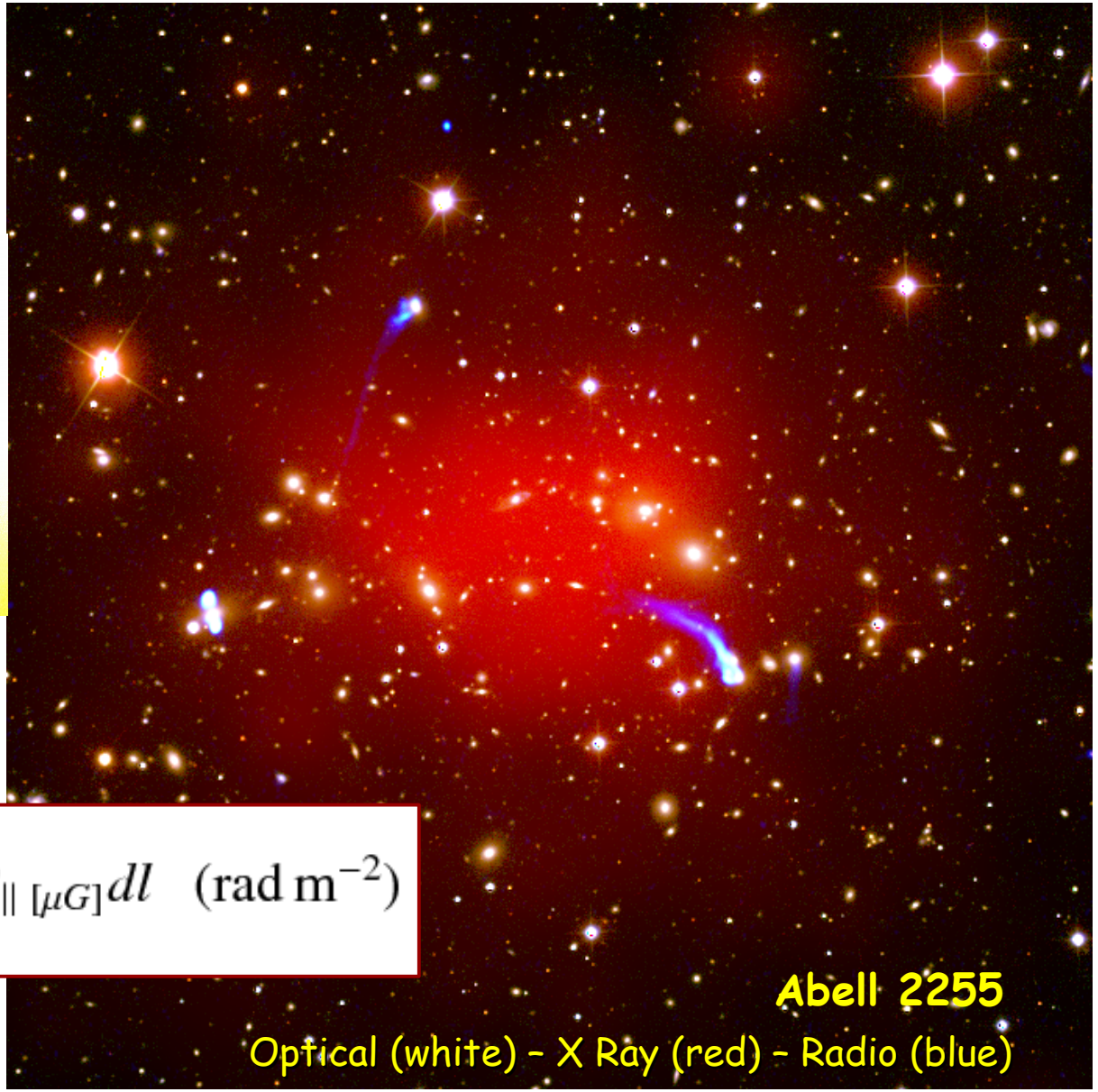
Faraday Rotation

Rotation Measure of radio galaxies located within or in the background of a galaxy cluster

$$\Delta\chi = \chi_0 + RM \times \left(\frac{c}{\nu}\right)^2$$



$$RM = 812 \int_0^{L_{[kpc]}} n_{e\ [cm^{-3}]} B_{\parallel\ [\mu G]} dl \quad (\mathrm{rad\,m^{-2}})$$



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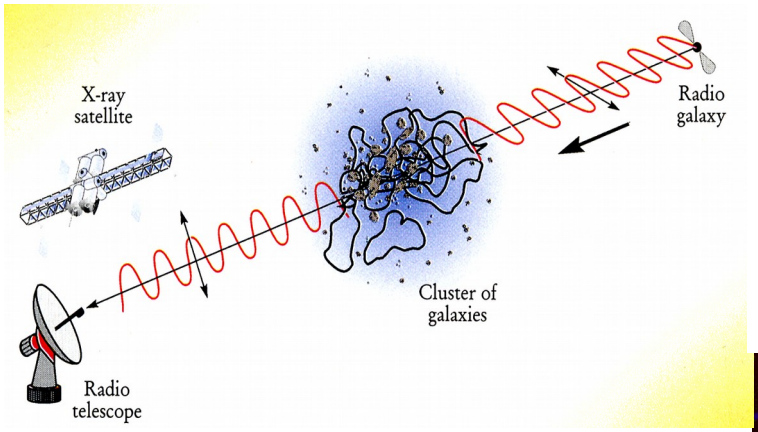
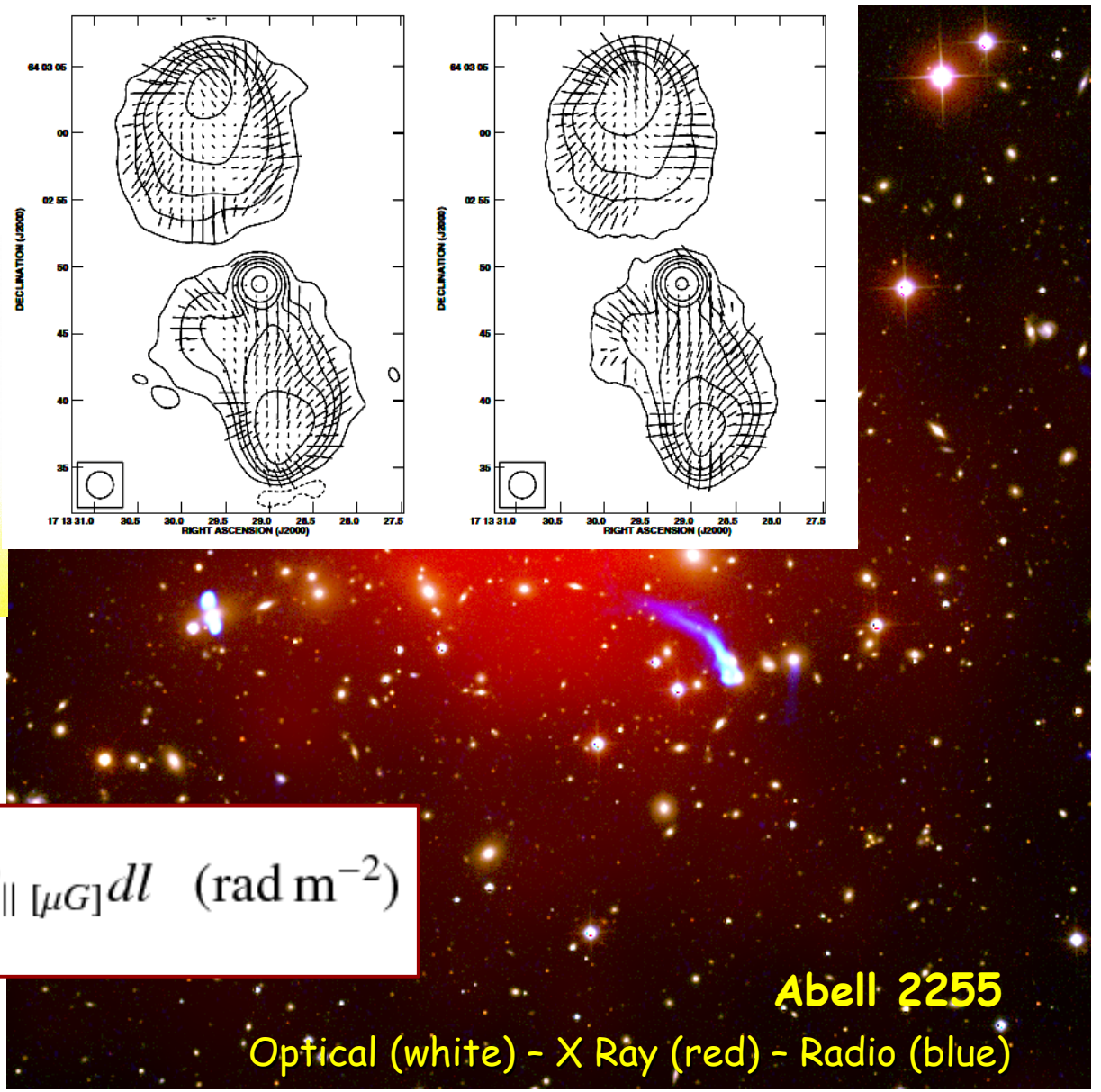


3 CM

6 CM



Abell 2255

Optical (white) – X Ray (red) – Radio (blue)

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Faraday Rotation

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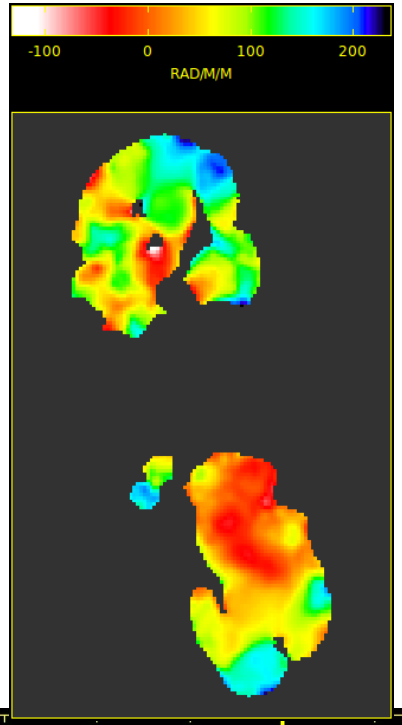

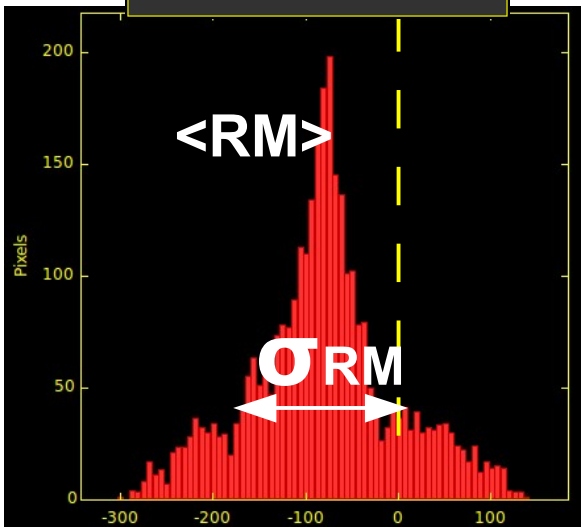

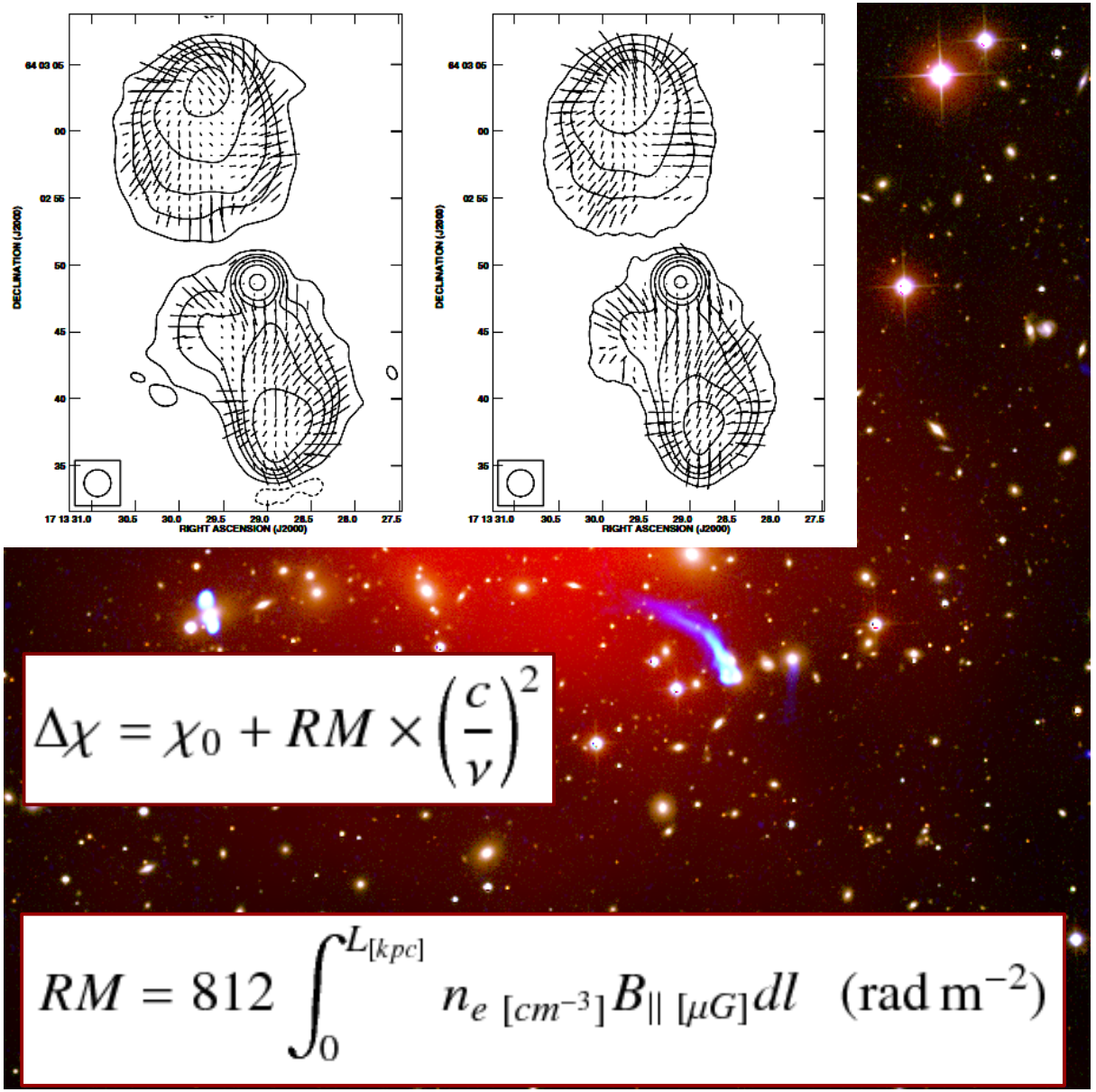

$$\Delta\chi = \chi_0 + RM \times \left(\frac{c}{\nu}\right)^2$$

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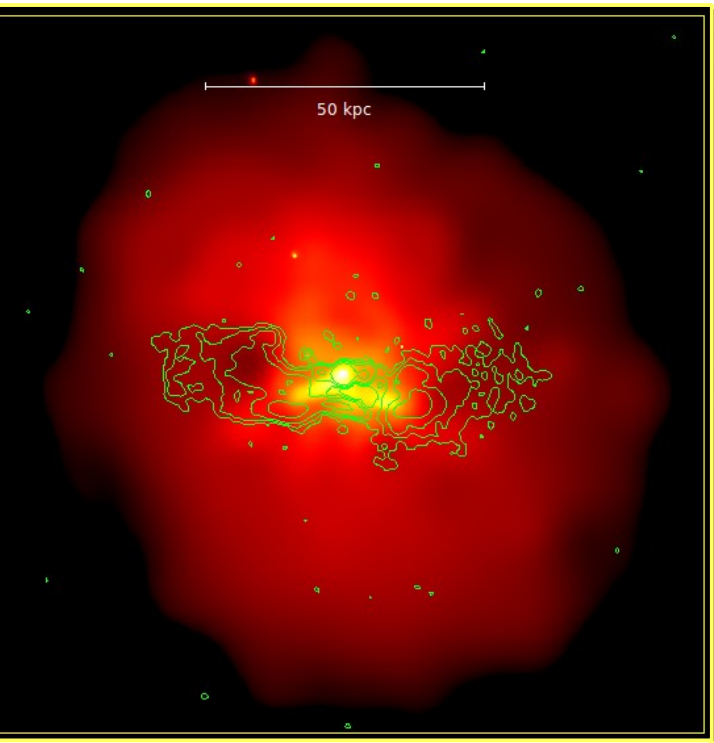
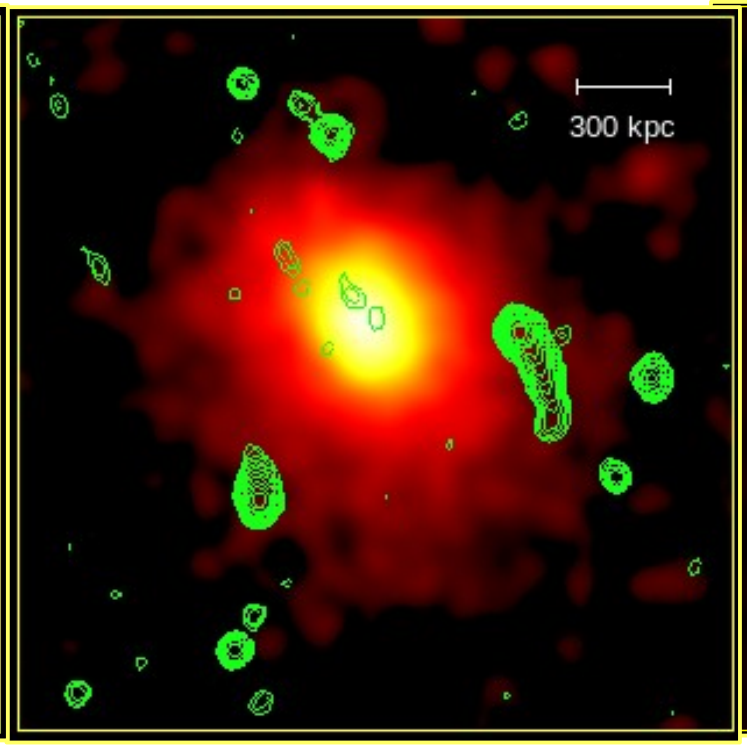
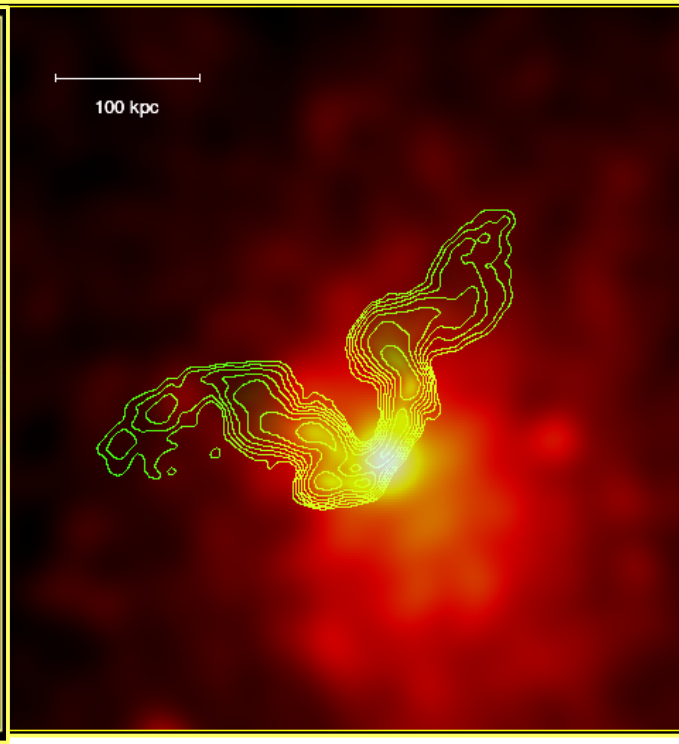
Faraday Rotation: Observations







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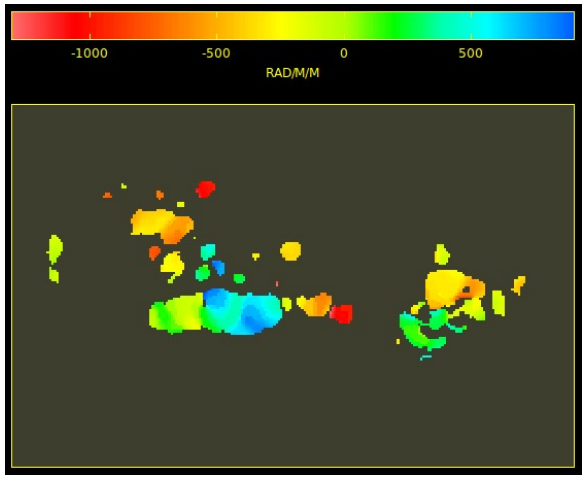
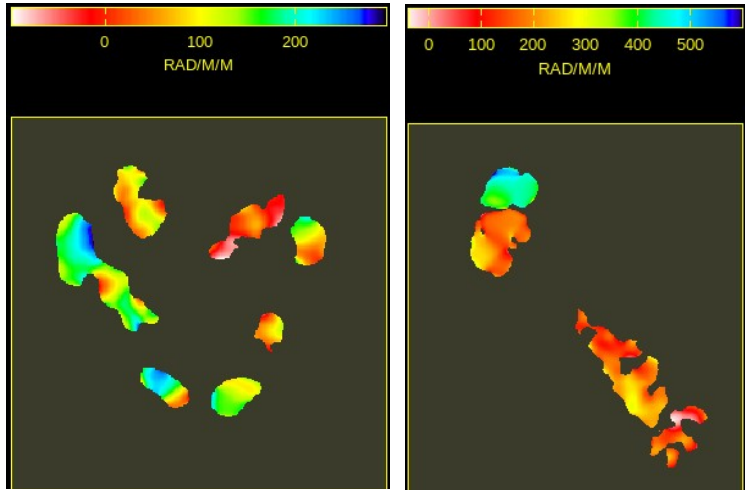


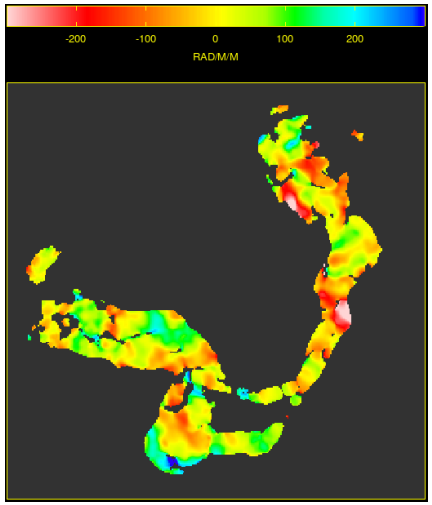
Vacca et al. (2012)

A401



Govoni et al. (2010)

A400

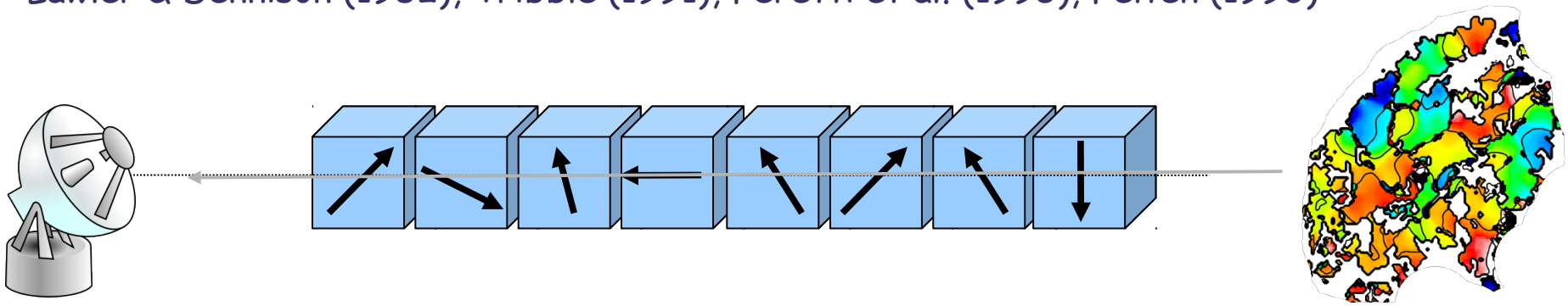


Eilek & Owen (2002)

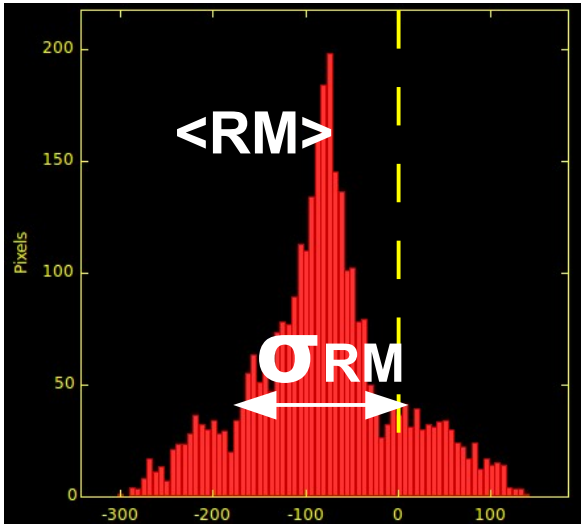
Faraday Rotation: Analitycal Formulation

If the magneto-ionic medium is approximated by uniform cells of size Λ_c with random orientation in space

Lawler & Dennison (1982), Tribble (1991), Feretti et al. (1995), Felten (1996)



Faraday rotation from a physical depth L (>>Λ_c) is expected to be a Gaussian with zero mean and dispersion given by:



$$\sigma^2_{RM} = \langle RM^2 \rangle = 812^2 \Lambda_c \int_L (n_e B_{||})^2 dl \quad (\mathrm{rad^2 m^{-4}})$$

$$\sigma_{RM} = 812 \sqrt{\Lambda_c} \sqrt{L} n_e \sigma_{B_{||}}$$

Faraday Rotation: Statistical Analysis

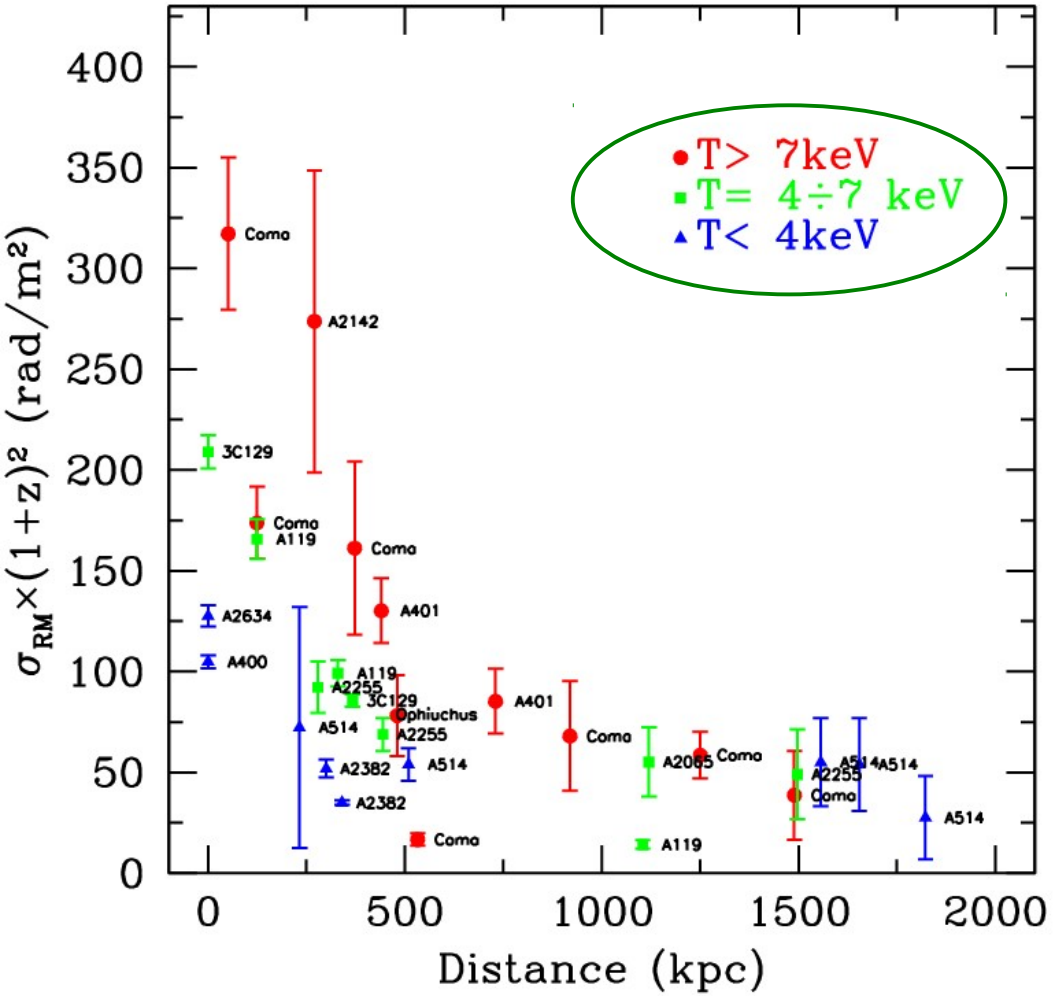
Cluster	T [keV]	Source	Distance [kpc]	σ_{RM} [rad/m^2]	Reference
A514	3.8	A514B2	232	63	Govoni et al. 2001
		A514D	509	47	"
		A514A	1556	48	"
		A514E	1654	47	"
		A514C	1822	24	"
Coma	8.4	5C4.85	51	303	Bonafede et al. 2010
		5C4.81,NGC4869	124	166	"
		5C4.74	372	154	"
		5C4.114	532	16	"
		5C4.127	919	65	"
		5C4.42	1250	56	"
		5C4.152	1489	37	"
A2255	6.9	1712.4+6401	279	79	Govoni et al. 2006
		J1713.5+6402	444	59	"
		J1713.3+6347	1497	42	"
A400	2.3	3C75	0	100	Eilek & Owen 2002
A2634	3.7	3C465	0	120	"
A119	5.8	0053-015	124	152	Feretti et al. 1999
		0053-016	330	91	"
		3C29	1104	13	"
3C129	5.6	3C129.1	0	200	Taylor et al. 2001
		3C129	367	82	"
A2382	2.9	PKS2149-158C	300	46	Guidetti et al. 2008
		PKS2149-158	340	31	"
A401	8.3	A401A	440	113	This work
		A401B	730	74	This work
A2142	8.8	A2142A	270	230	This work
A2065	5.4	A2065A	1120	48	This work
Ophiuchus	10.3	OPHIB	480	74	This work

Mean β-model parameters:
<β>=0.7
<rc>=285 kpc
<n0>=4.4e-03 cm-3

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

Statistical Analysis: Analitycal Formulation

Trend of σRM as a function of the distance from the cluster center



Govoni et al. (2010)

Different colors represent different cluster temperature

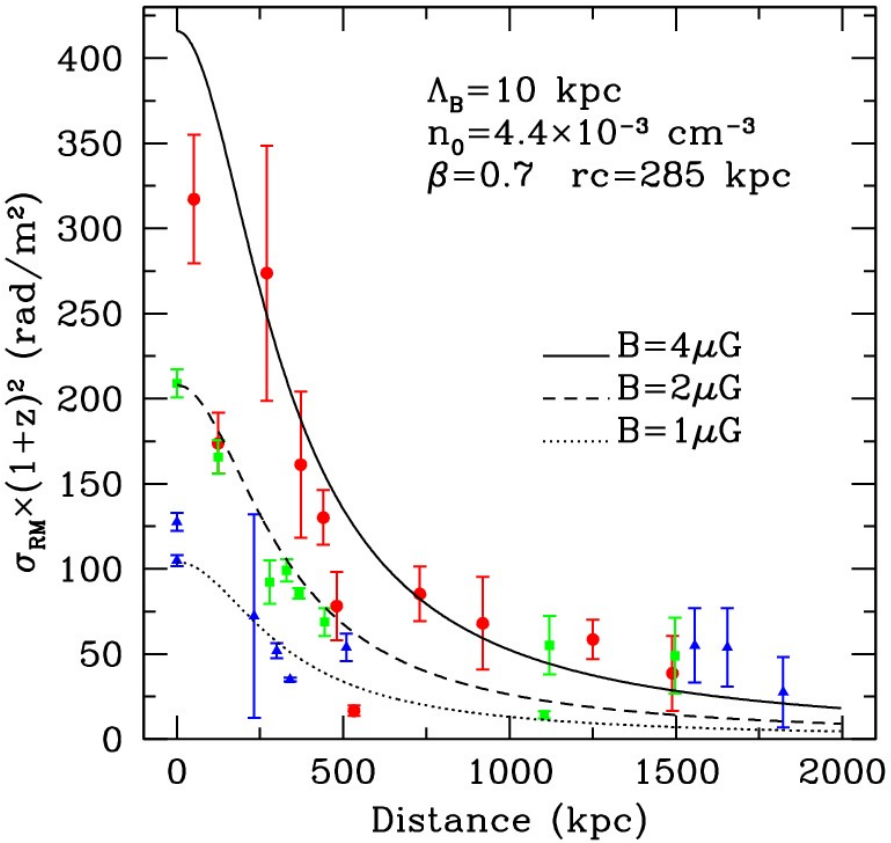
Positive trend between the cluster temperature and σRM. For a fixed projected distance from the cluster centre, clusters with higher temperature show a higher σRM.

These trends indicate that magnetic fields are common in galaxy clusters, in agreement with the results by Clarke et al. (2004) and Johnston-Hollitt & Ekers (2004) who analyzed the <RM> of sources located behind and within clusters

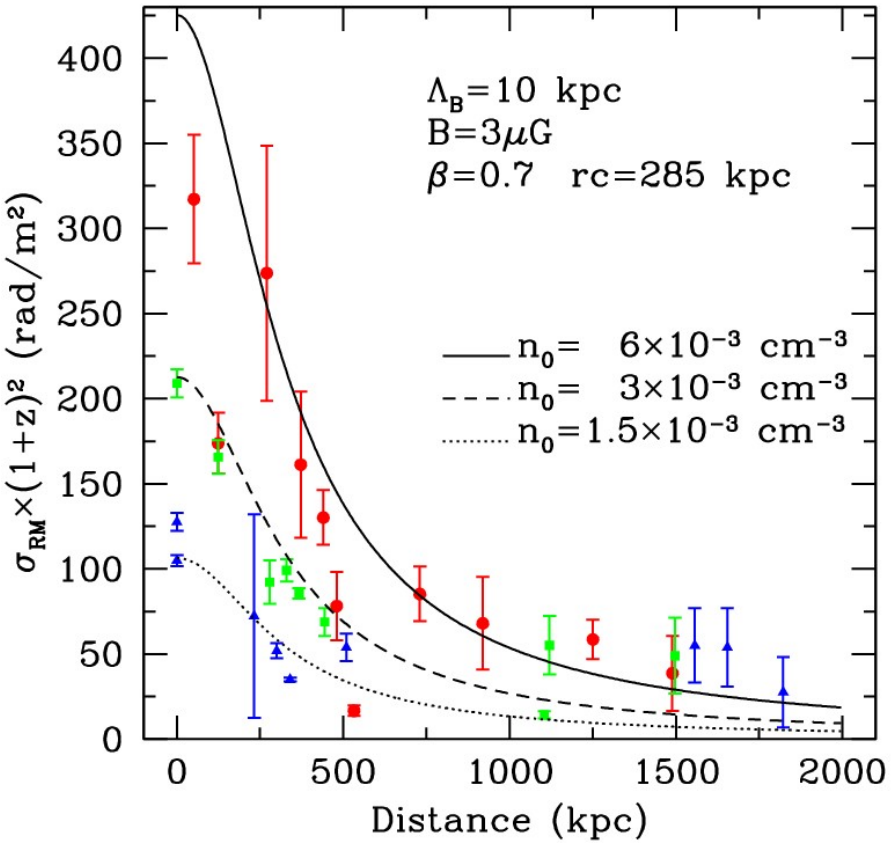
Statistical Analysis: Analitycal Formulation

Predictions of the analytical formulation obtained by assuming a magnetic field scale ΛB=10 kpc, and by keeping fixed the X-ray parameters to the mean values of the cluster sample (β=0.7, rc=285 kpc)

Govoni et al. (2010)



We fixed the central gas density and we present the expectations for different Central magnetic fields.



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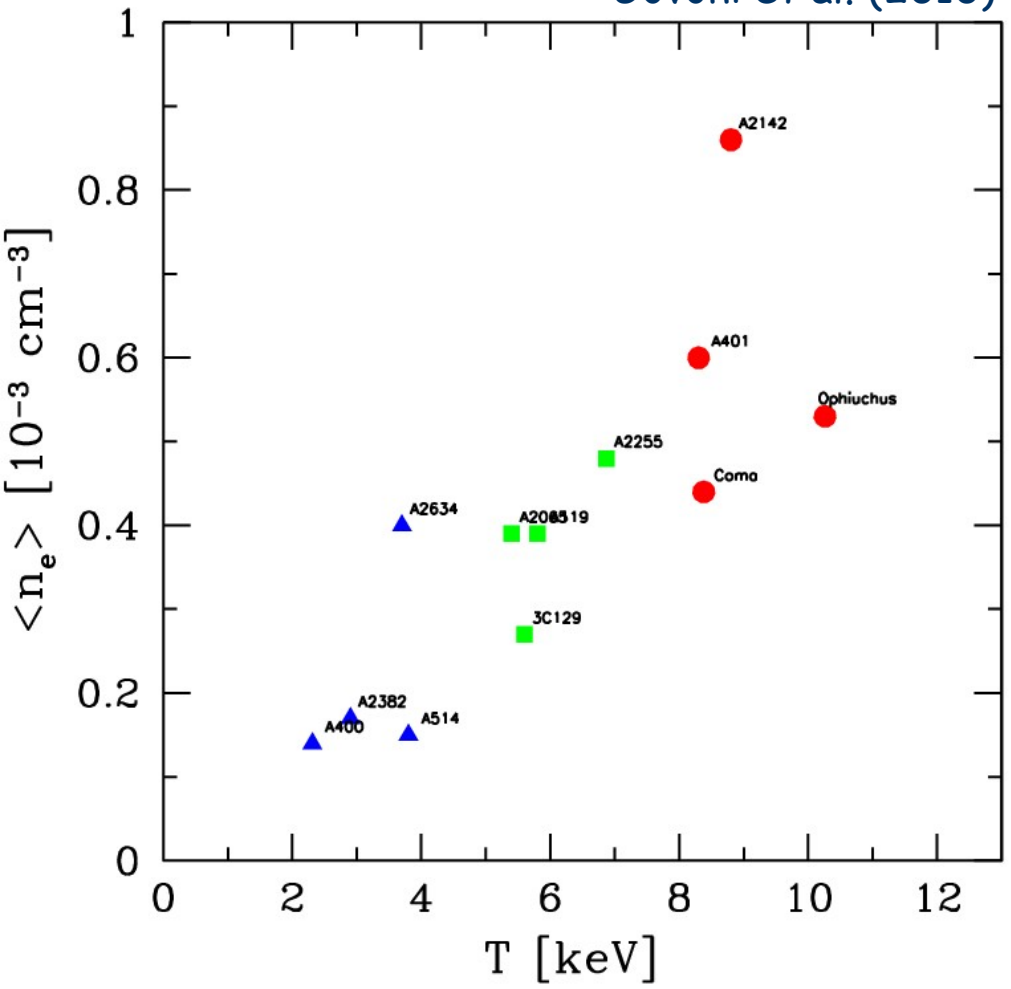
Statistical Analysis: Analitycal Formulation

Mean cluster density plotted versus the temperature of the clusters

Govoni et al. (2010)



Different colors represent different cluster temperature

The higher σRM in hotter clusters may be explained if they have a higher Magnetic field strength and/or if they have a higher gas density.

The hottest clusters of our sample have a higher mean gas density. Therefore, the σRM distribution does not confirm a strict link between the magnetic field strength and the gas temperature of the intracluster medium.

Faraday Rotation: Simulations

Dedicated software tools and Bayesian approaches have been proposed to interpret the Faraday Rotation effect and constraint the magnetic field parameters (Esslin & Vogt 2003, Murgia et al. 2004, Laing et al. 2008, Kuchart & Ensslin 2011, Bonafede et al. 2013)

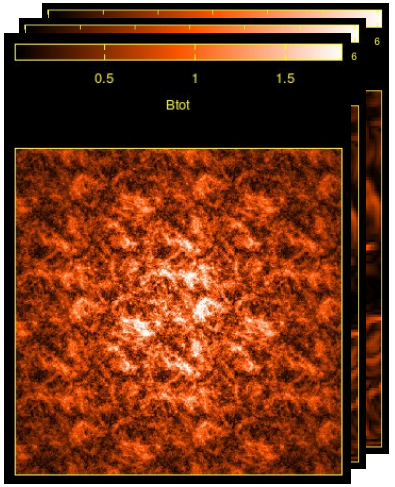
MAGNETIC FIELD

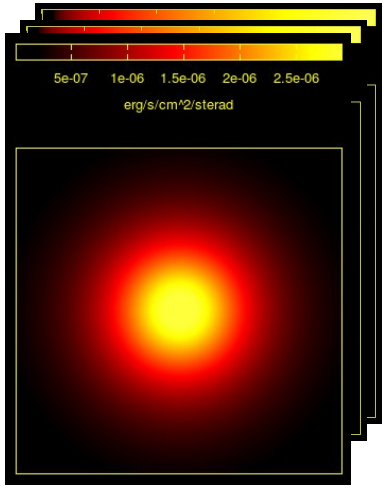
$$|\mathbf{B_k}|^2 \propto \mathbf{k}^{-\mathbf{n}}$$

$$\mathrm{B(r)} = \mathrm{B_0}\left[\frac{n_e(r)}{n_0}\right]^{\eta}$$

THERMAL GAS

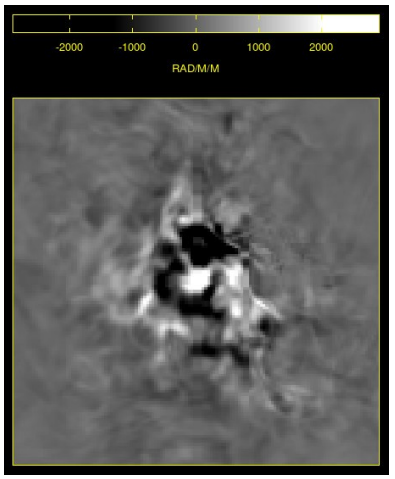
$$\mathrm{n_e(r)} = \mathrm{n_0}\left[1+\frac{r^2}{r_c^2}\right]^{-\frac{3}{2}\beta}$$





Faraday Software
Murgia et al. (2004)

Rotation Measure



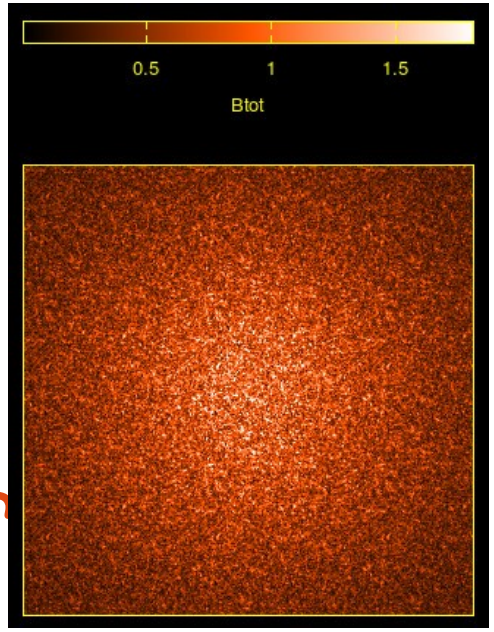
$$RM = 812 \int_0^{L_{[kpc]}} n_{e\ [cm^{-3}]} B_{\parallel\ [\mu G]} dl \quad (\mathrm{rad\ m^{-2}})$$

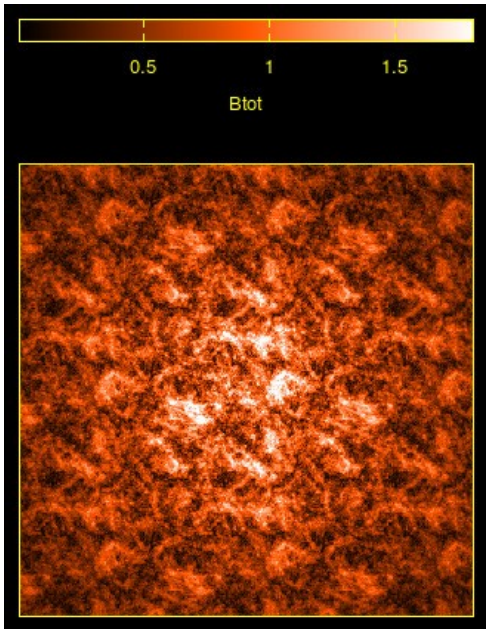
COMPARISON WITH DATA

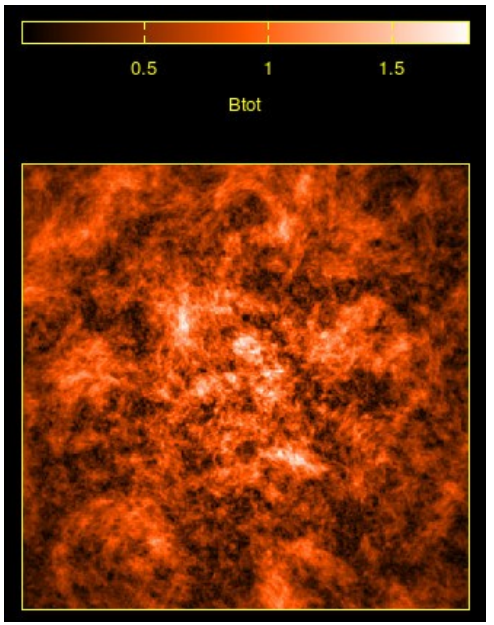
Frequency

Faraday Rotation: Simulations

Magnetic Field







Faraday Software Murgia et al. (2004)

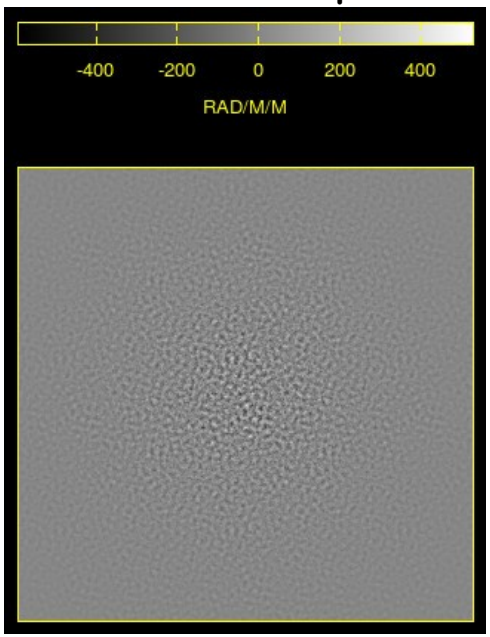
Λmax=30 kpc

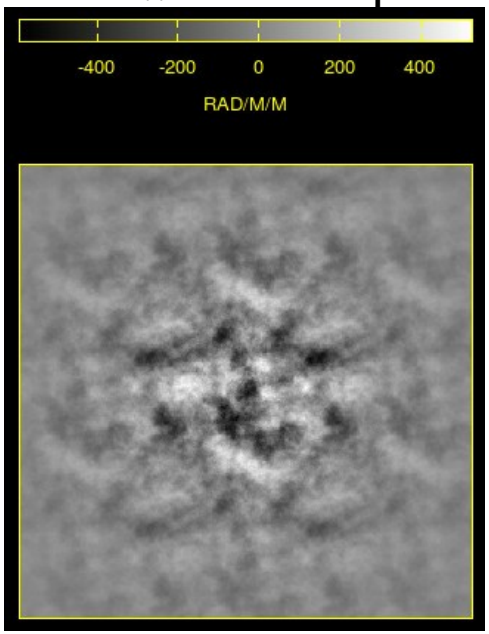
Λmax=300 kpc

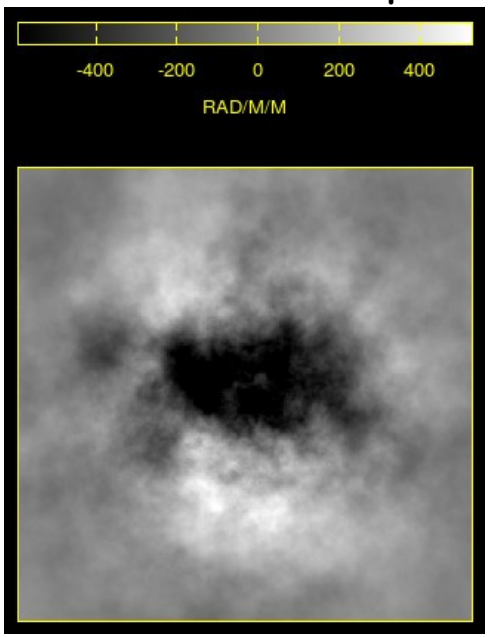
Λmax=1000 kpc

Kolmogorov (n=11/3)
B0=1 μG
Λmin=2 kpc

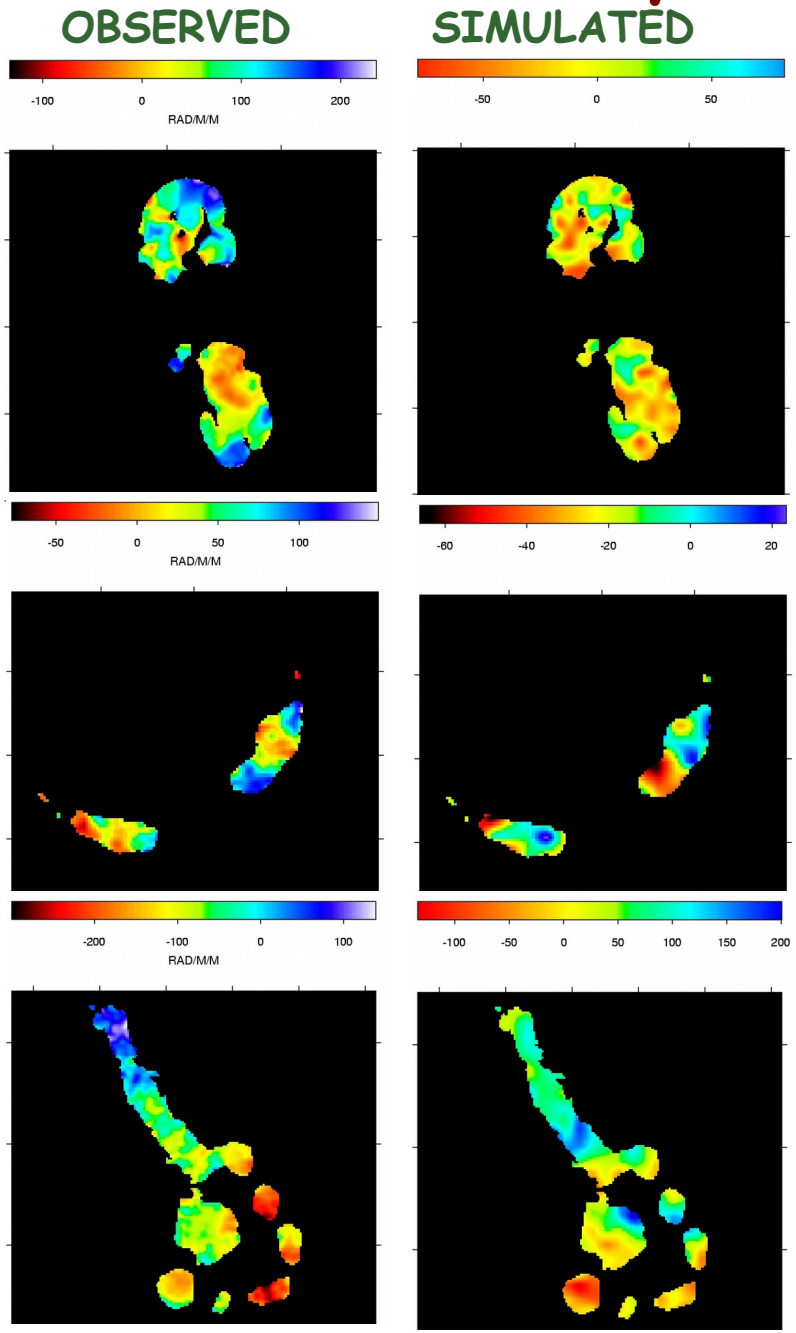
Rotation Measure







Faraday Rotation: Simulations

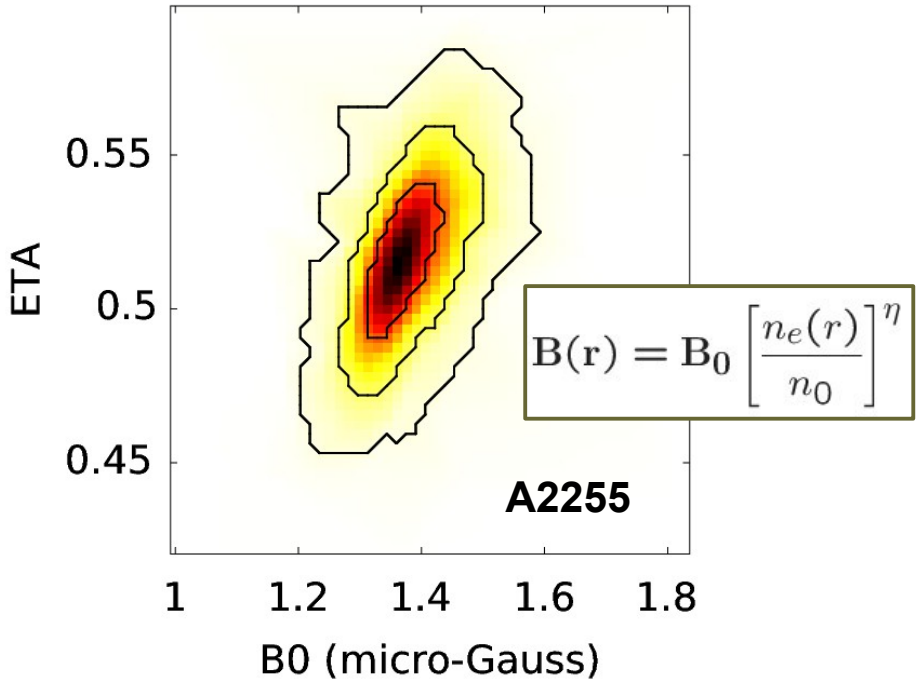


Govoni et al. (2006)

B0 ~1-3 μG in merging galaxy clusters
B0 ~10 μG in cooling core galaxy clusters

Magnetic fields fluctuate over a wide range of spatial scales

Magnetic fields decreases following the thermal gas density

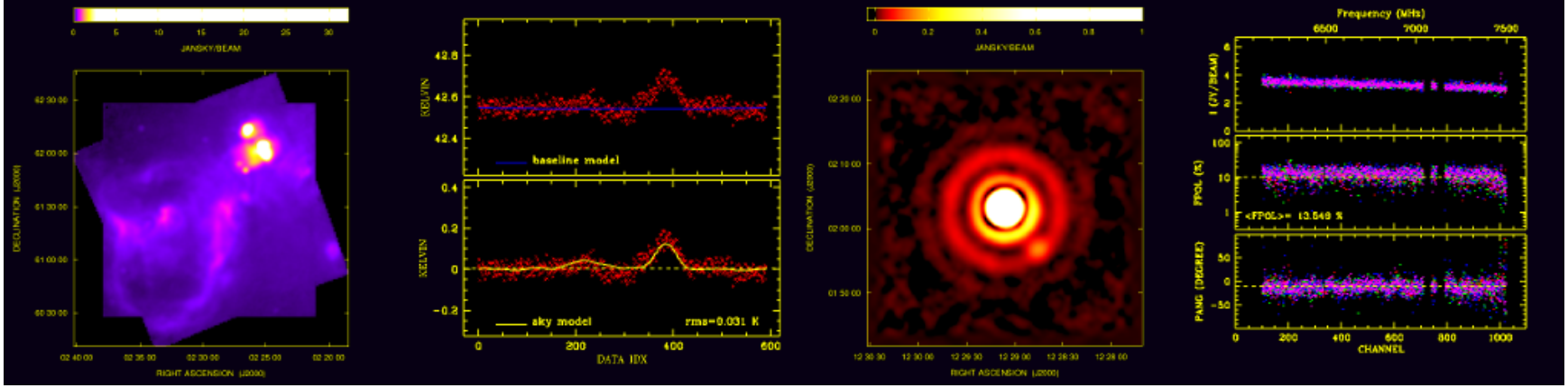


RM studies are demanding and a few radio galaxies per cluster and a few galaxy clusters have been studied in detail.

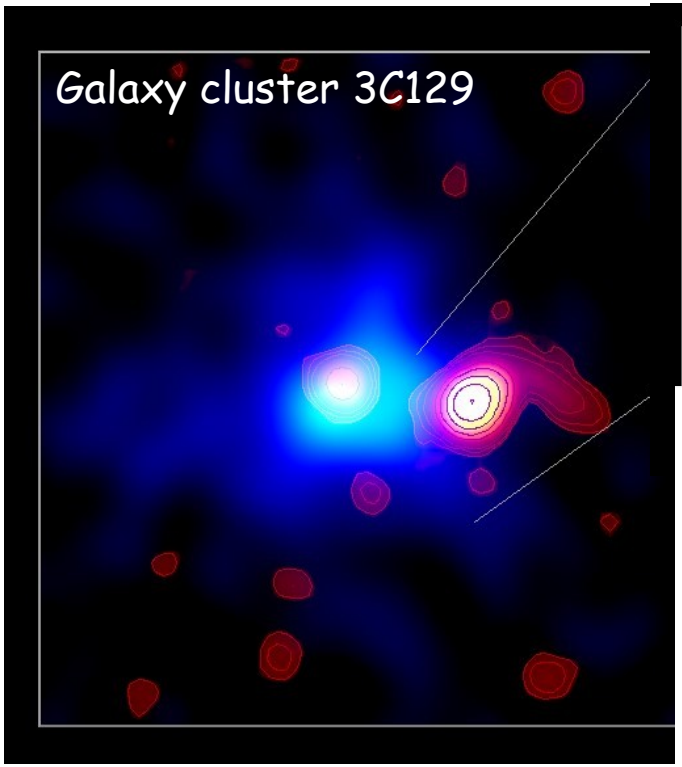
Single-dish Spectral-polarimetry Software

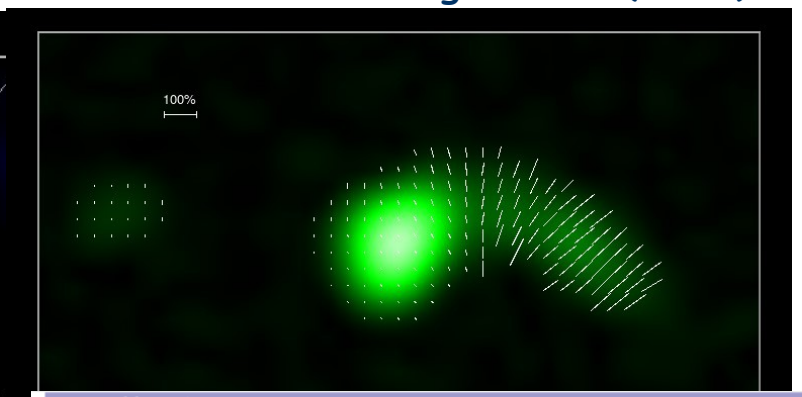
Developed and mantained by M. Murgia and F. Govoni

S C U B E



Murgia et al. (2016)





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Sardinia Radio Telescope wide-band spectral-polarimetric observations of the galaxy cluster 3C 129

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SRT Multi-frequency Observations of Galaxy clusters

SRT Early Science Program (PI M. Murgia)

Wide-band and wide-field SRT spectral-polarimetric observations (320 hours) of a sample of galaxy clusters at L, C, and K band

MAIN GOAL: study the spectral and polarization properties of cluster radio sources with the SRT to determine the age of the synchrotron plasma and the magnetic field strength and structure in the intra-cluster medium.

TARGETS: sample of nearby galaxy clusters hosting either diffuse radio halos, relics, or extended radio galaxies with an angular size larger than LAS > 15 '

Name	Institution
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Federica Govoni	INAF-OA Cagliari
Valentina Vacca	INAF-OA Cagliari
Francesca Loi	INAF-OA Cagliari
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Andrea Melis	INAF-OA Cagliari
Raimondo Concu	INAF-OA Cagliari
Sergio Poppi	INAF-OA Cagliari
Giuseppe Valente	ASI
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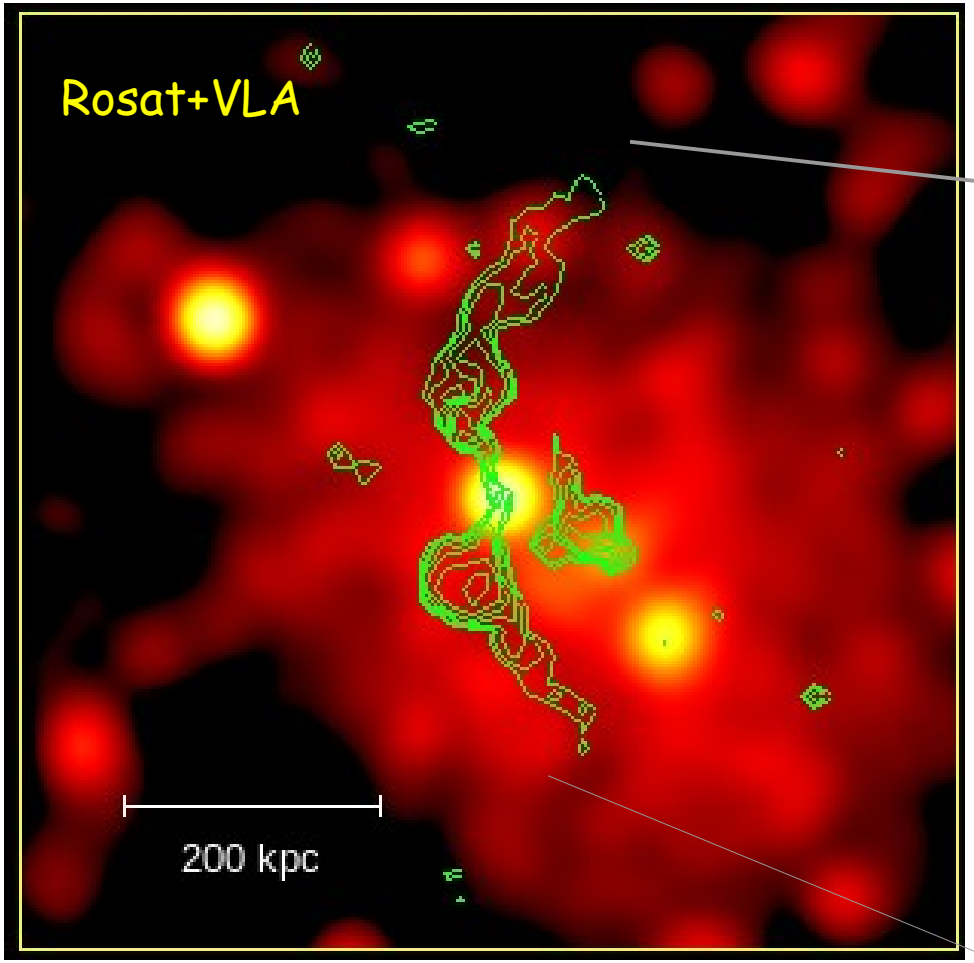
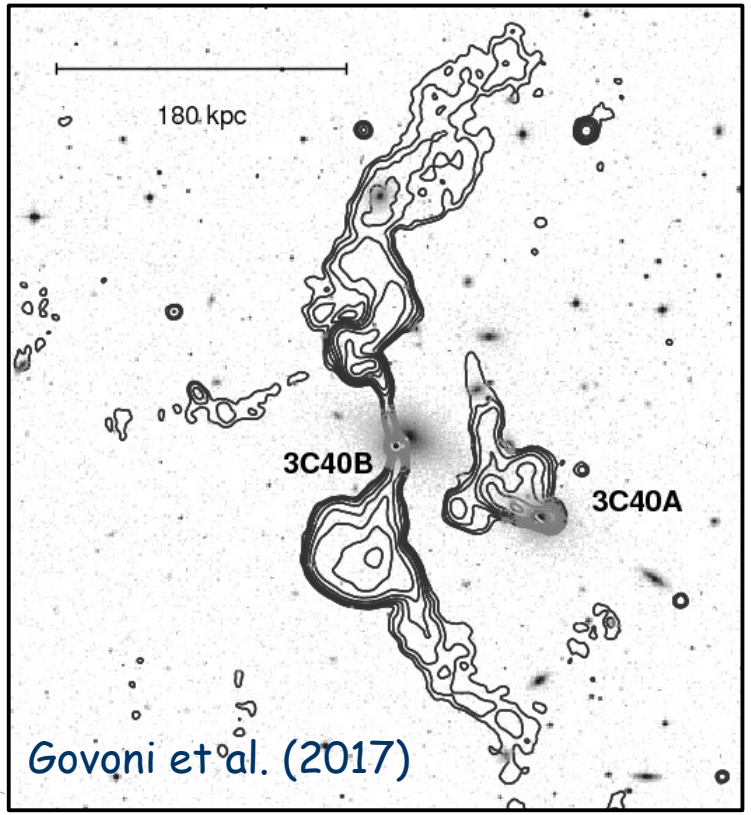
Luigina Feretti	INAF-IRA Bologna
Gabriele Giovannini	INAF-IRA Bologna
Paola Parma	INAF-IRA Bologna
Loretta Gregorini	INAF-IRA Bologna
Annalisa Bonafede	INAF-IRA Bologna
Franco Vazza	Univ. Bologna
Fabio Gastaldello	INAF-IASF Milano
Marisa Girardi	Univ. Triste
Walter Boschin	INAF - TNG
Emanuela Orrù	ASTRON
Marisa Brienza	ASTRON
Francesco de Gasperin	Univ. Leiden
Gianni Bernardi	SKA Africa/Rhodes Univ.
Chiara Ferrari	Obs. De la Cote d'Azur
Torsten Ensslin	MPA-Garching
Henrik Junklewitz	AifA-Bonn
Tracy Clarke	NAVY Naval Research Lab.
Greg Taylor	Univ. New Mexico
Rick Perley	NRAO Socorro
Melanie Jhonston-Hollitt	Univ. Wellington, New Zealand
Sergio Colafrancesco	Univ. Johannesburg, South Africa

Magnetic field power spectrum in ABELL 194

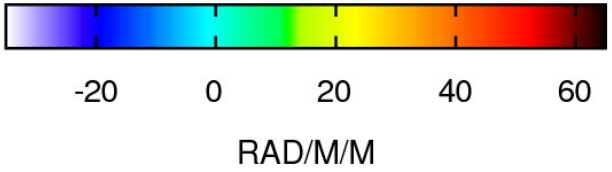


VLA 1443 MHz
FWHM=19''
σI=0.34 mJy/Beam

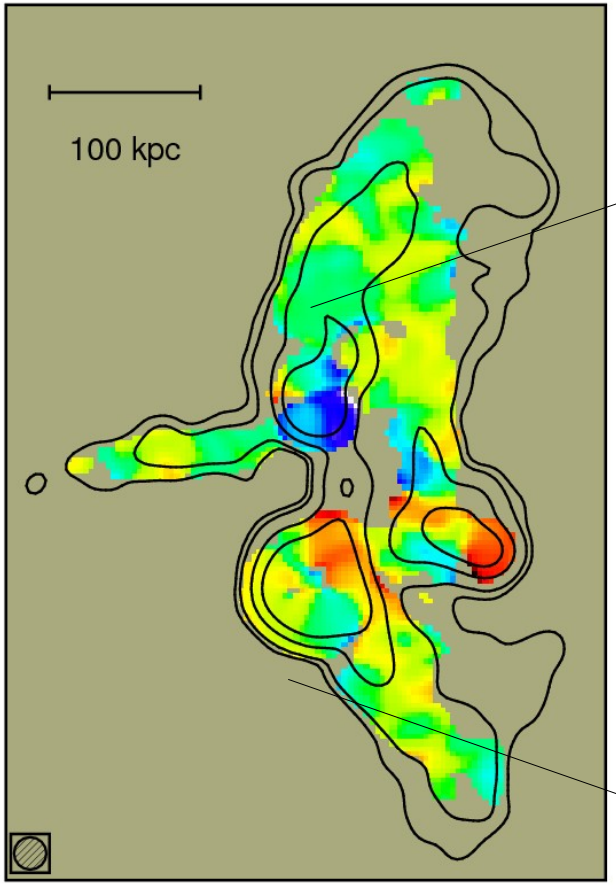


We studied the intra-cluster magnetic field in the nearby (z=0.018) and poor galaxy cluster Abell 194 by complementing radio data, at different frequencies, with data in the optical and X-ray bands

Magnetic field power spectrum in ABELL 194

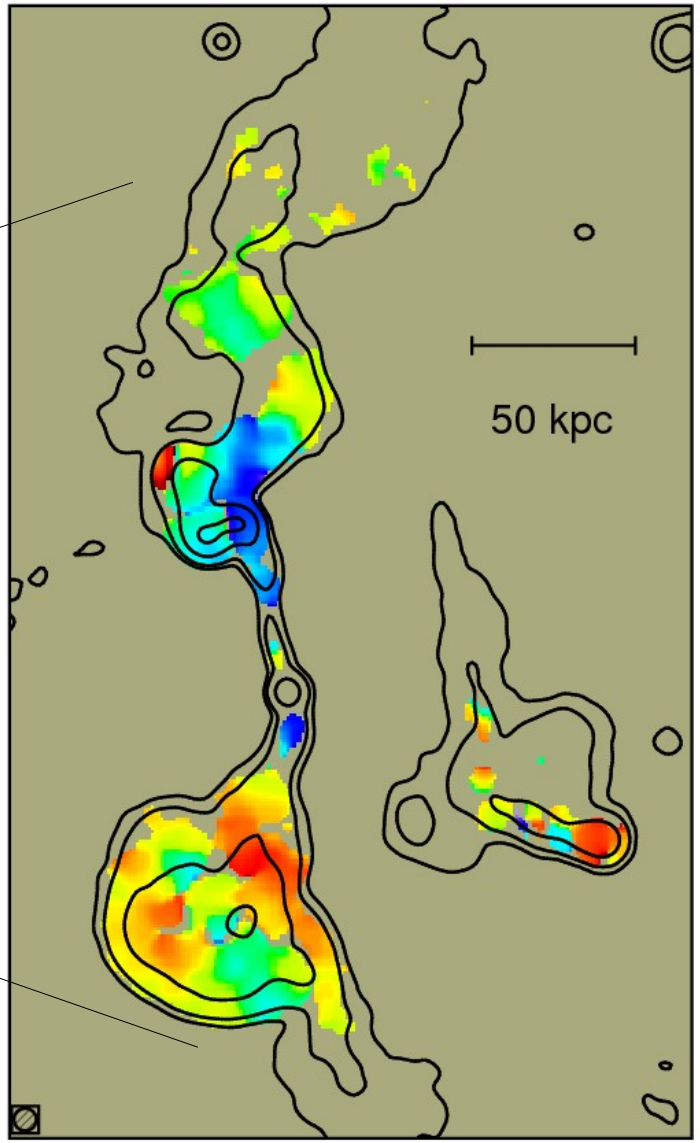


Govoni et al. (2017)

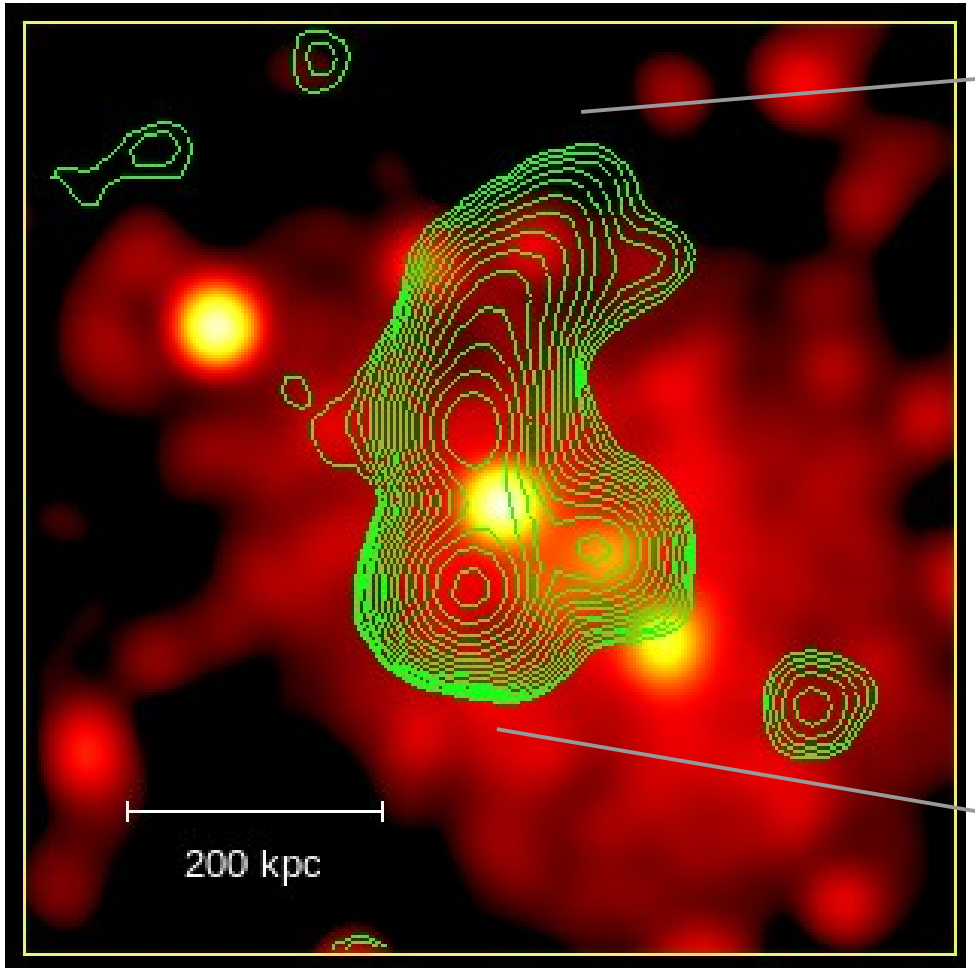


VLA 1443, 1465, 1515, 1630 MHz
FWHM=60''

VLA 1443, 1630, 4535, 4885 MHz
FWHM=19''

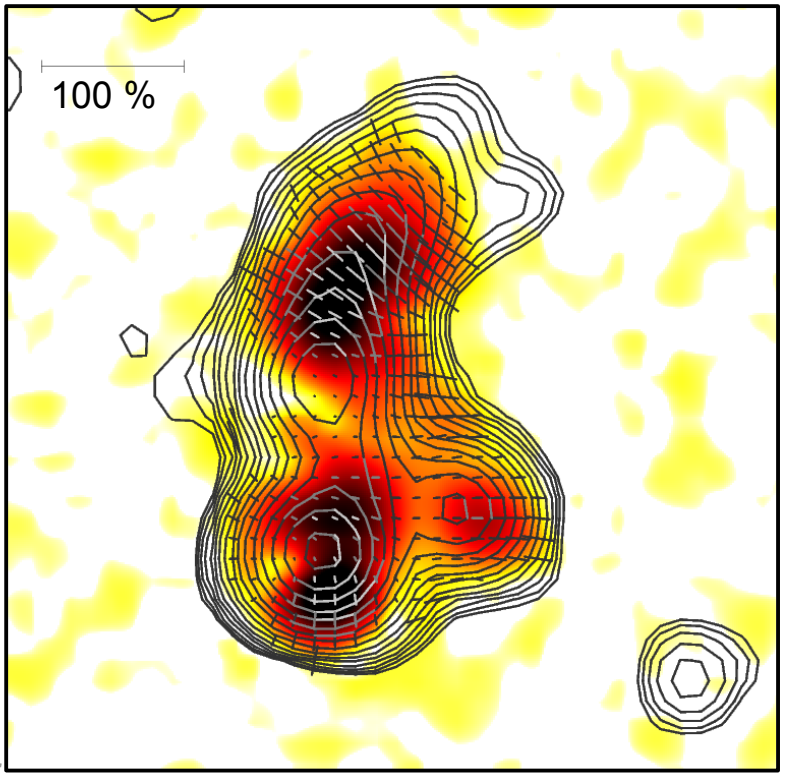


Magnetic field power spectrum in ABELL 194



SRT, 6.6 GHz
FWHM=2.9'
σI=1 mJy/Beam

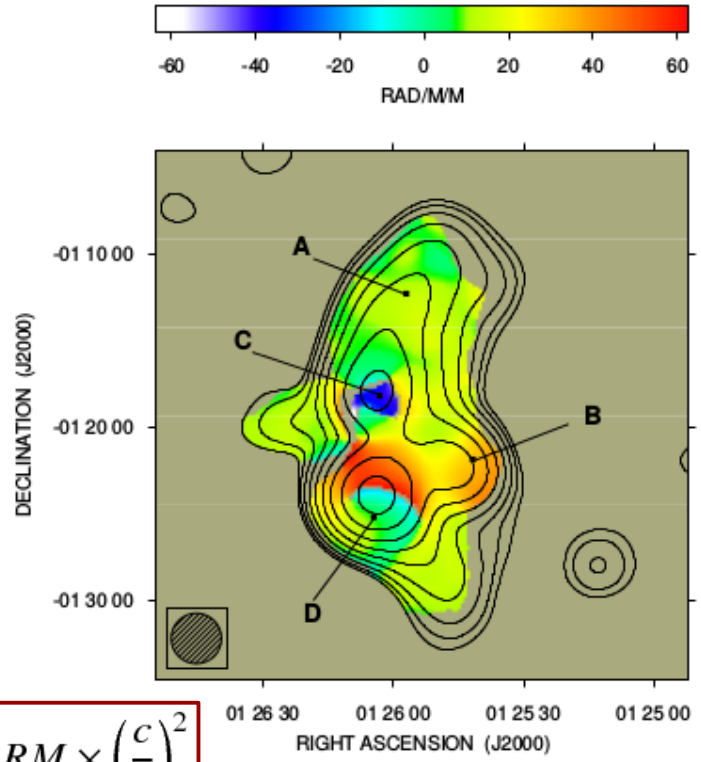
Govoni et al. (2017)

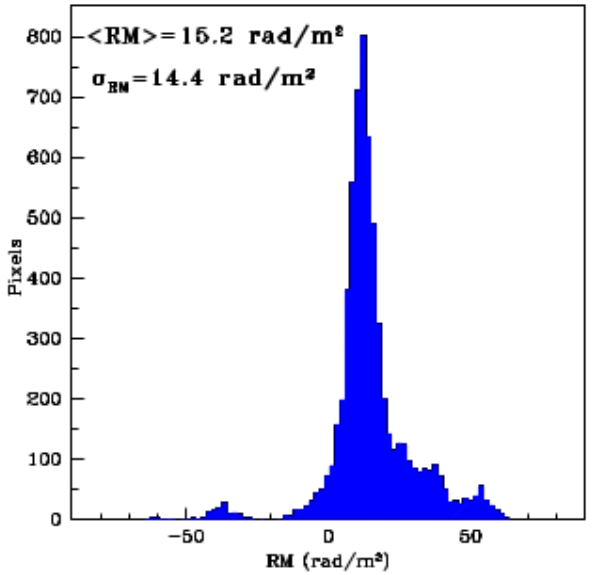


We detected polarization for both sources with a global fractional polarization of ~9%

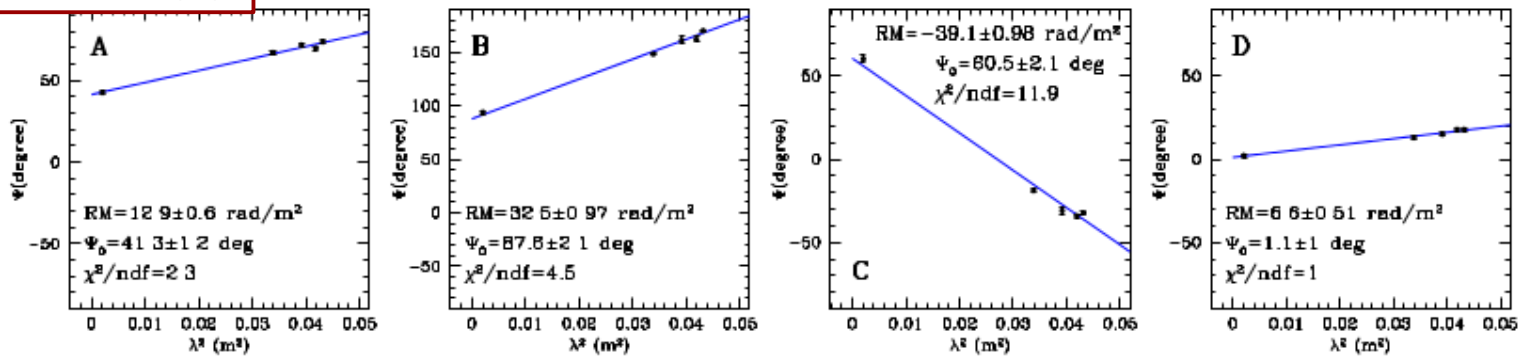
Magnetic field power spectrum in ABELL 194

Govoni et al. (2017)





$$\Delta\chi = \chi_0 + RM \times \left(\frac{c}{\nu}\right)^2$$



4 frequencies at Lband (VLA 1443, 1465, 1515, 1630 MHz) + SRT 6600MHz
FWHM=2.9'

Magnetic field power spectrum in ABELL 194

OBSERVABLES

RM structure function $S(dx,dy)=\langle[RM(x,y) - RM(x+dx,\ y+dy)]^2\rangle(x,y)$

Depolarization at the different frequencies $FPOL=FPOL_0 exp(-a\lambda^4)$

Trends of **σRM** and **<RM>** against the distance from the cluster center

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

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

Mean β-model parameters:
<β>=0.67
<rc>=248 kpc
<n0>=0.69 e-03 cm-3

PARAMETERS OF INTEREST

magnetic field power spectrum index n → Fixed n=11/3 Kolmogorov
minimum scale of fluctuation Λmin → Fixed Λmin=1 kpc

maximum scale of fluctuation Λmax

2-D Analysis in the RM image at a resolution of 19"

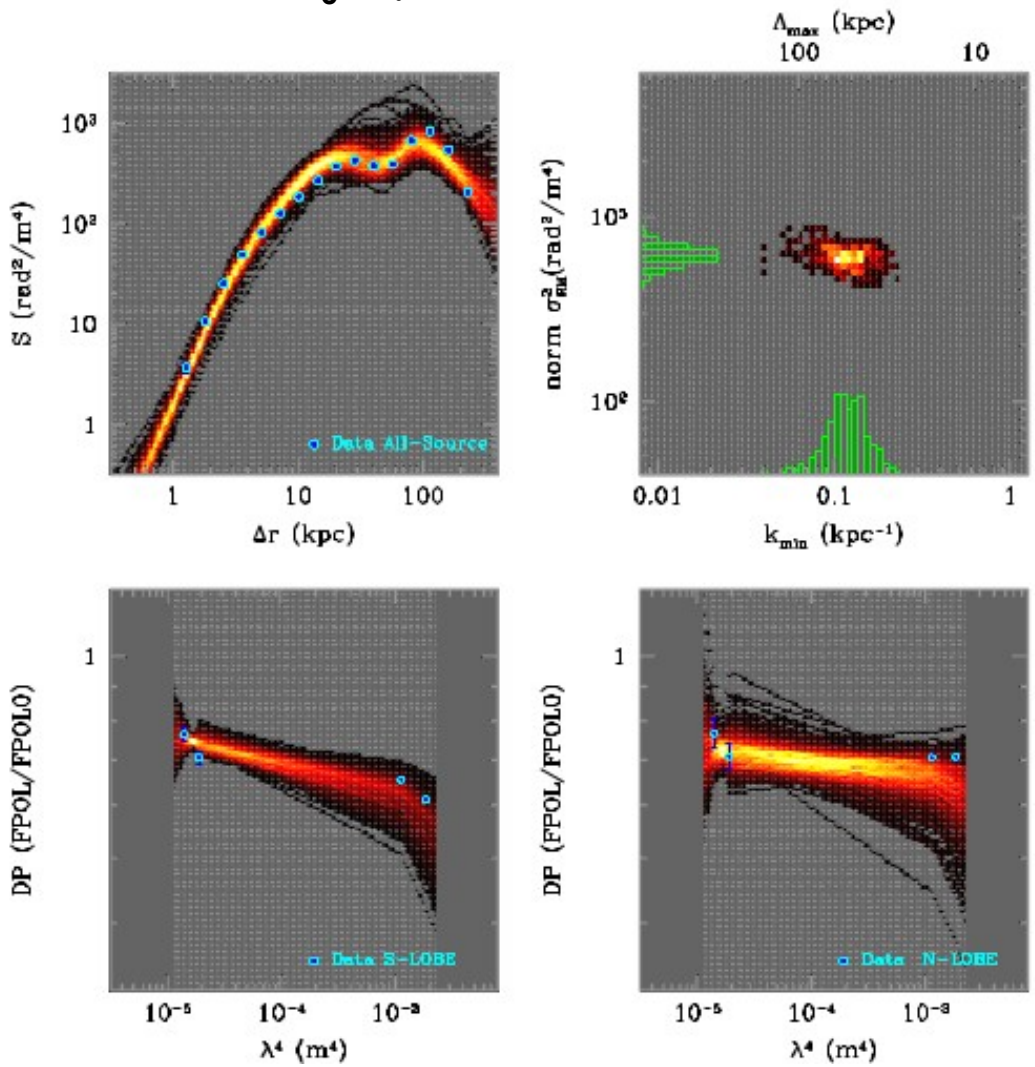
magnetic field intensity at cluster center <B0>
magnetic field radial decrease η

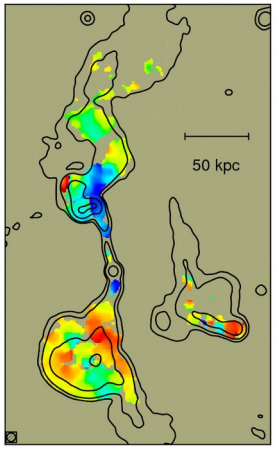
3-D Analysis in the RM image at a resolution of 2.9'

Magnetic field power spectrum in ABELL 194

$S(dx,dy)=\langle[RM(x,y) - RM(x+dx,\ y+dy)]^2\rangle(x,y)$

$FPOL=FPOL_0 exp(-a\lambda^4)$





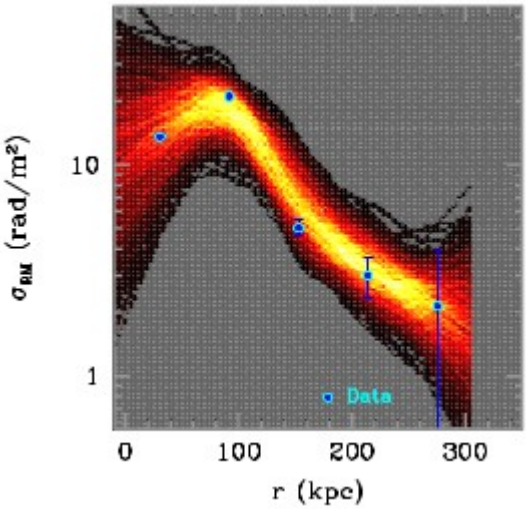
$$|B_k|^2 \propto k^{-n}$$

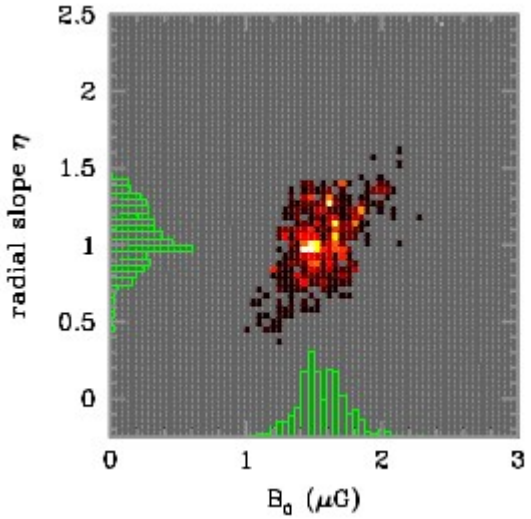
2-D Analysis in the RM image at a resolution of 19"

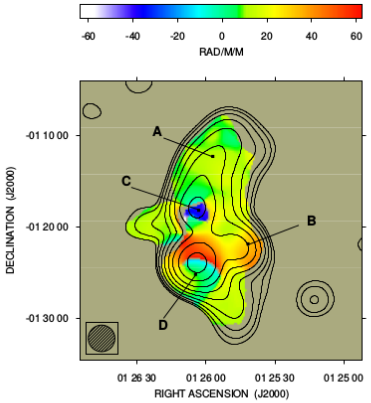
$\Lambda_{max}=(64\pm24)$ kpc

Magnetic field power spectrum in ABELL 194

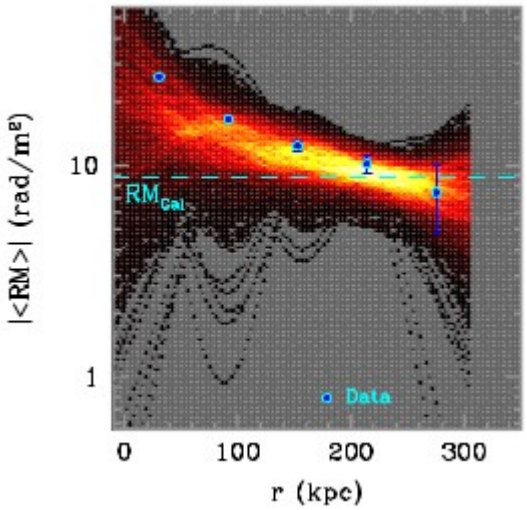
Trends of **σRM** and **<RM>** against the distance from the cluster center

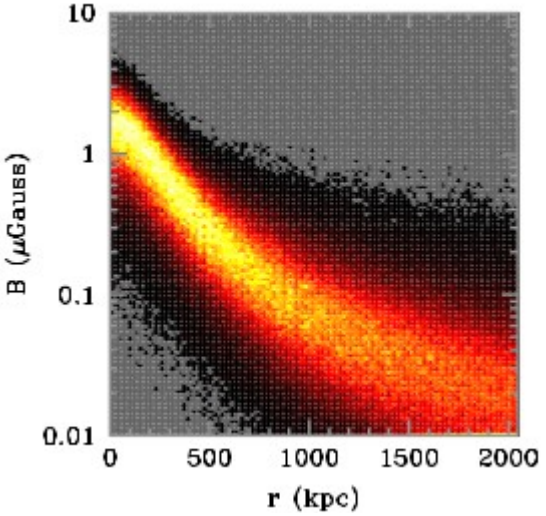






3-D Analysis in the RM image at a resolution of 2.9′





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

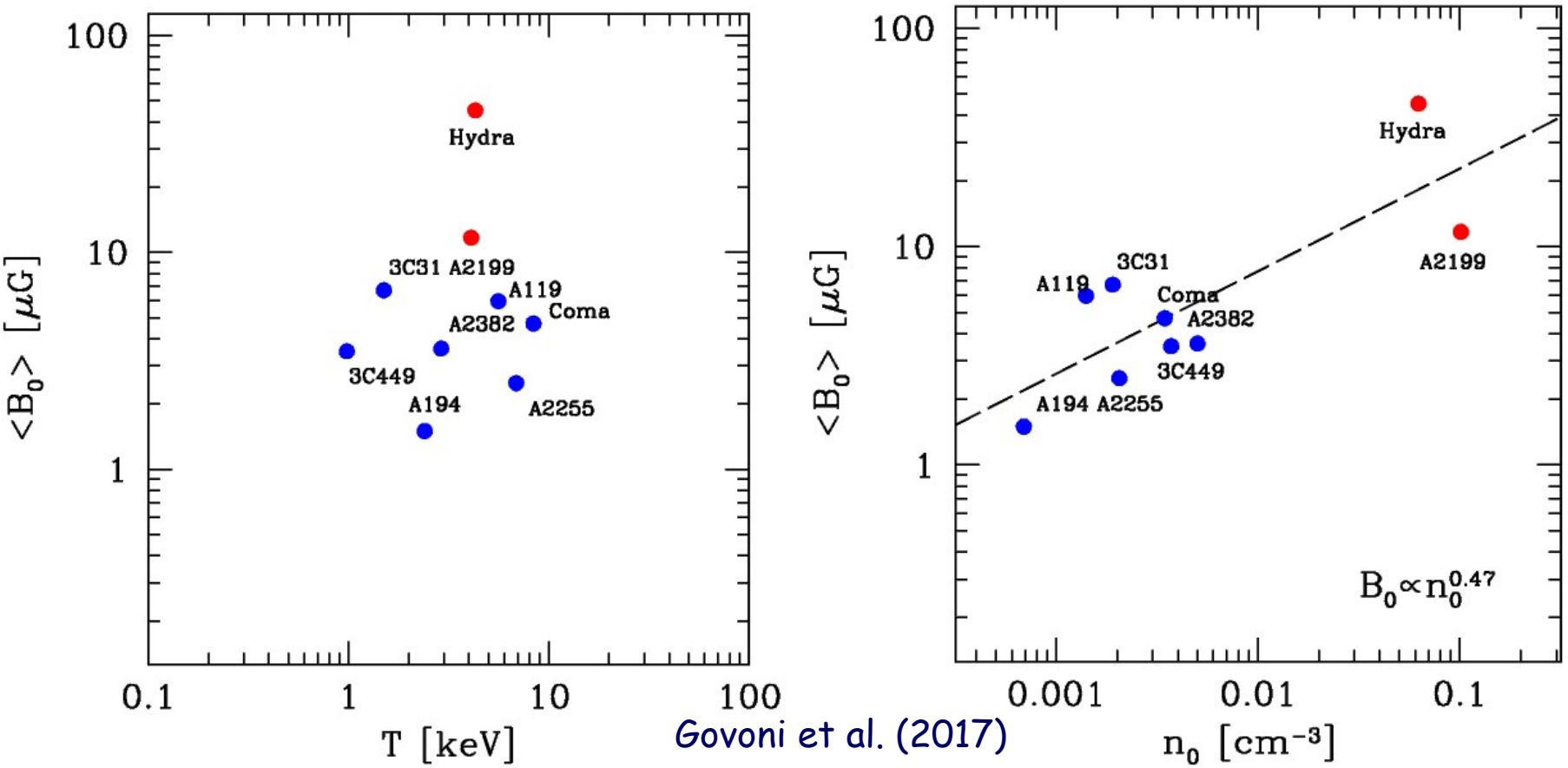
<B$_0$>= (1.5±0.2) μG

The field decrease with the radius following the gas density to the power **η=1.1 ± 0.2**

The lowest magnetic field measured so far in galaxy clusters, based on Faraday Rotation analysis

Magnetic fields- thermal gas density - temperature

Comparison of Abell 194 with a small sample of galaxy clusters with detailed magnetic field investigation (Murgia et al. 2004; Govoni et al. 2006; Vacca et al. 2012; Guidetti et al. 2008,2010; Laing et al. 2008, Bonafede et al. 2010)



Govoni et al. (2017)

- No correlation seems to be present between the mean central magnetic field and the cluster temperature in agreement with Govoni et al. (2010)
- There is a hint of a trend between central electron density and magnetic field strengths among different clusters

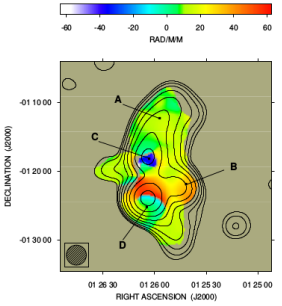
Conclusion:

The power spectrum of the intra-cluster magnetic field can be constrained if detailed RM images of cluster radio sources are available

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

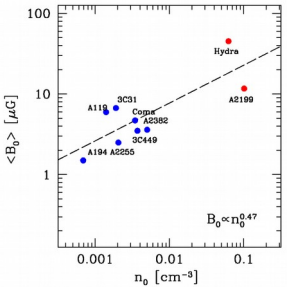
Typical magnetic field strength are of a few μG, but can be larger than 10 μG at the center of cool-core clusters. There are evidences that the magnetic field decreases following the gas density

Results of the SMOG project (Abell 194)



On the basis of the current data, seems not possible to establish a strict link between the magnetic field strength and the gas temperature of the intracluster medium (Govoni et al. 2010, Govoni et al. 2017)

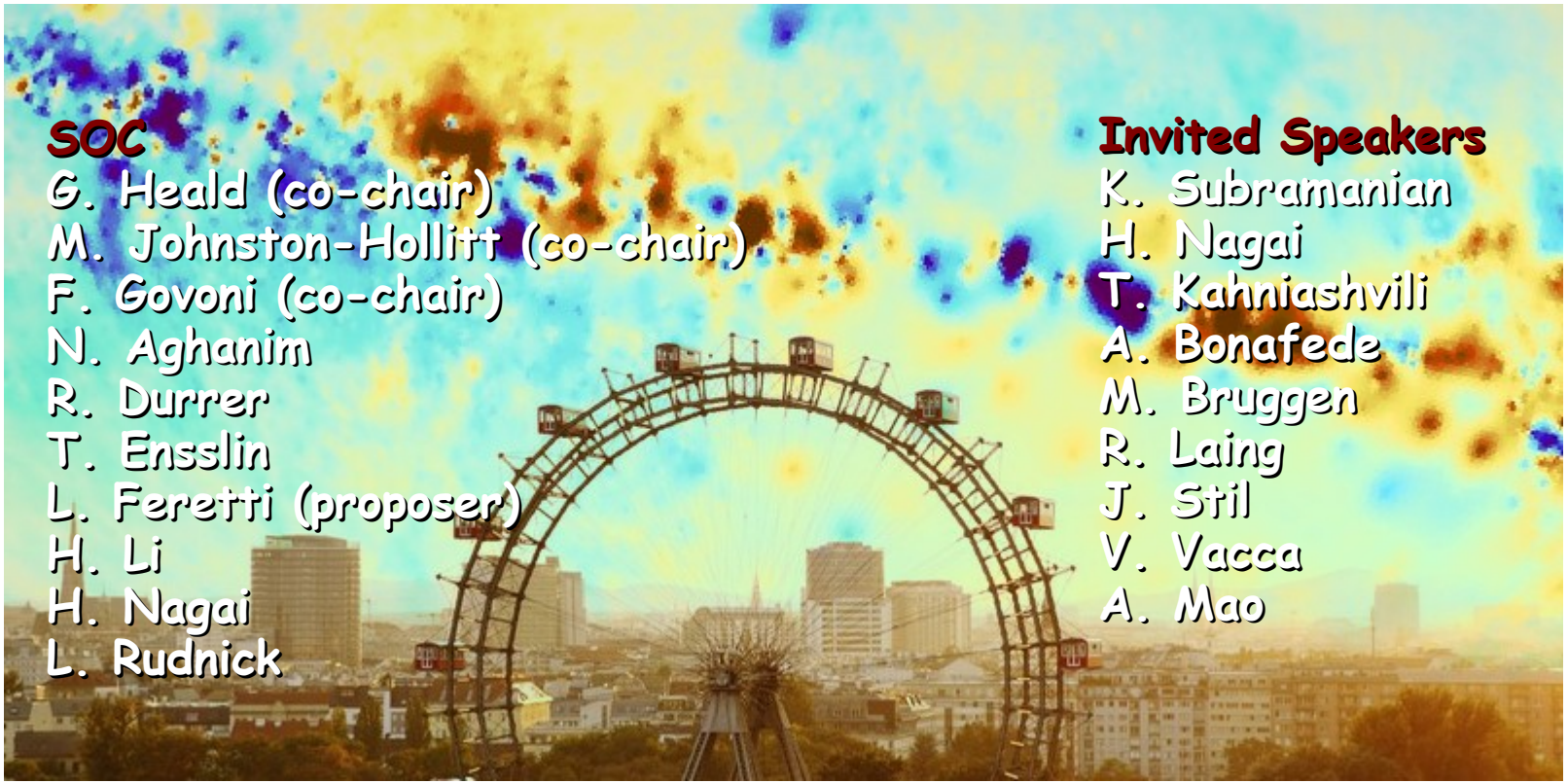
There is a hint of a trend between central electron density and magnetic field strengths



https://iau2018fm8magnetism.wordpress.com/

New Insights in Extragalactic Magnetic Fields

Focus Meeting 8 at the XXX IAU General Assembly,
Vienna (Austria 2018)



SOC

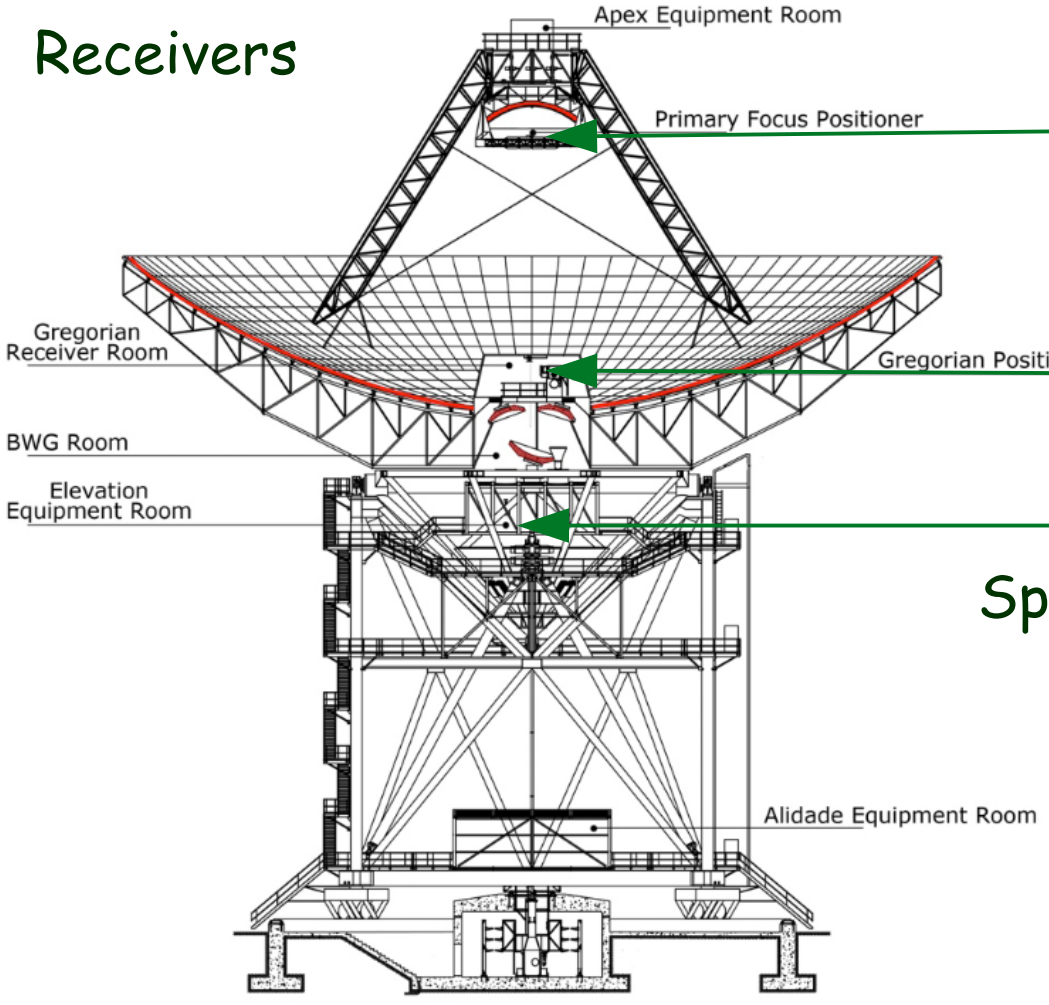
G. Heald (co-chair)
M. Johnston-Hollitt (co-chair)
F. Govoni (co-chair)
N. Aghanim
R. Durrer
T. Ensslin
L. Feretti (proposer)
H. Li
H. Nagai
L. Rudnick

Invited Speakers

K. Subramanian
H. Nagai
T. Kahniashvili
A. Bonafede
M. Bruggen
R. Laing
J. Stil
V. Vacca
A. Mao

Sardinia Radio Telescope

Receivers

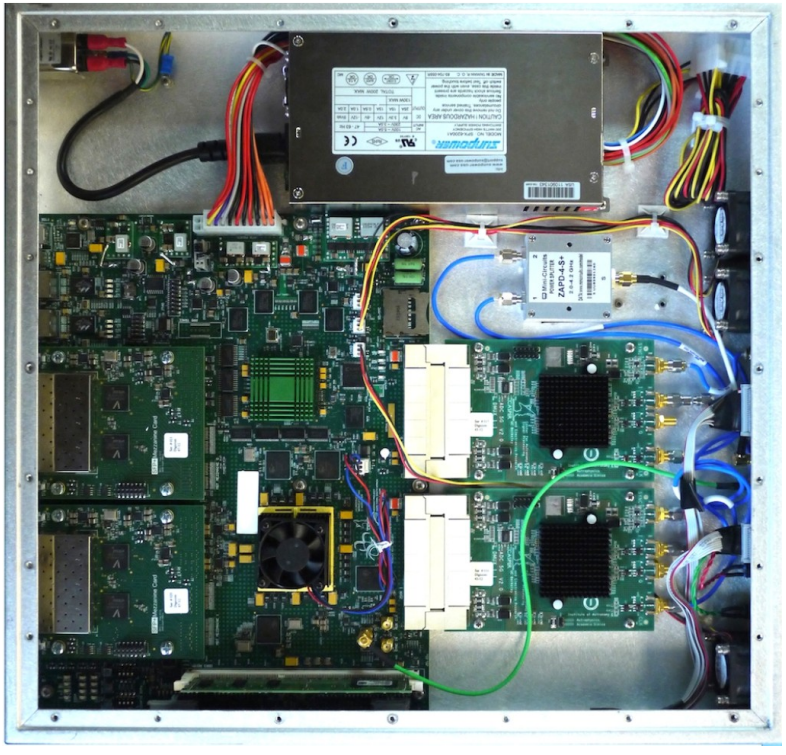


Dual **L-band** (1.3-1.8 GHz)
and **P-band** (305-425 MHz)
coaxial

K-band multibeam (18-26 GHz)

C-band (5.7-7.7 GHz)

Spectro-polarimetric Back-end



SARDARA
SArdinia **R**oach2-based **D**igital **A**rchitecture
for **R**adio **A**stronomy
up to 2500 MHz and 16k-channels, seven beams