MEASURING MAGNETIC FIELDS IN GALAXY CLUSTERS THROUGH RADIO OBSERVATIONS

Annalisa Bonafede
Hamburg University

OUTLINE

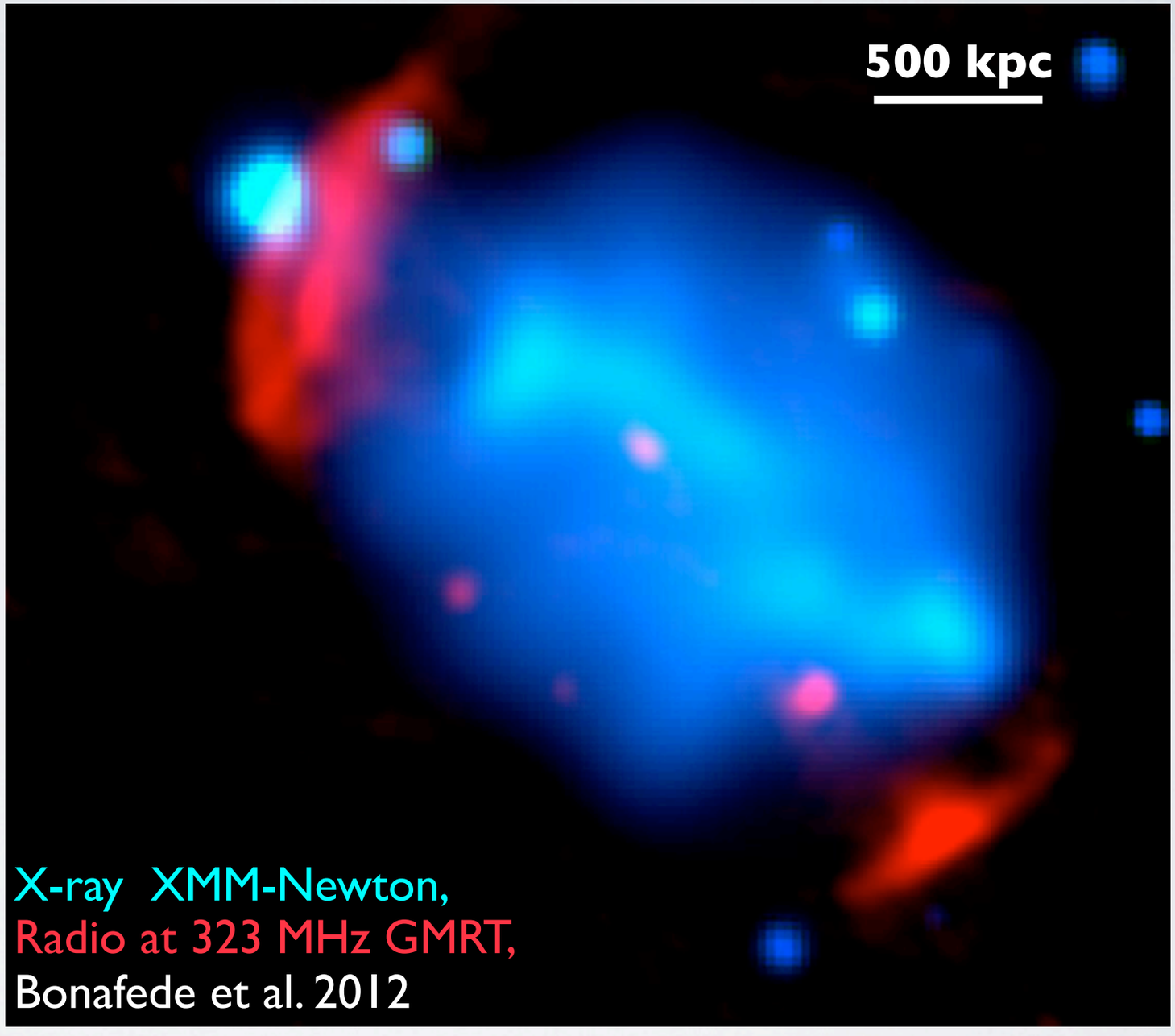
- Clusters & magnetic fields
- Methods: I The Faraday Rotation
- Results on the Coma clusters & ALP
- Methods: II Depolarisation analysis
- Limits of Faraday rotation approach
- SKA perspectives

GALAXY CLUSTERS

Dark Matter

Revealed by gravitational lensing

~80% of the Mass



X-ray XMM-Newton,
Radio at 323 MHz GMRT,
Bonafede et al. 2012

GALAXY CLUSTERS

Dark Matter

Revealed by gravitational lensing

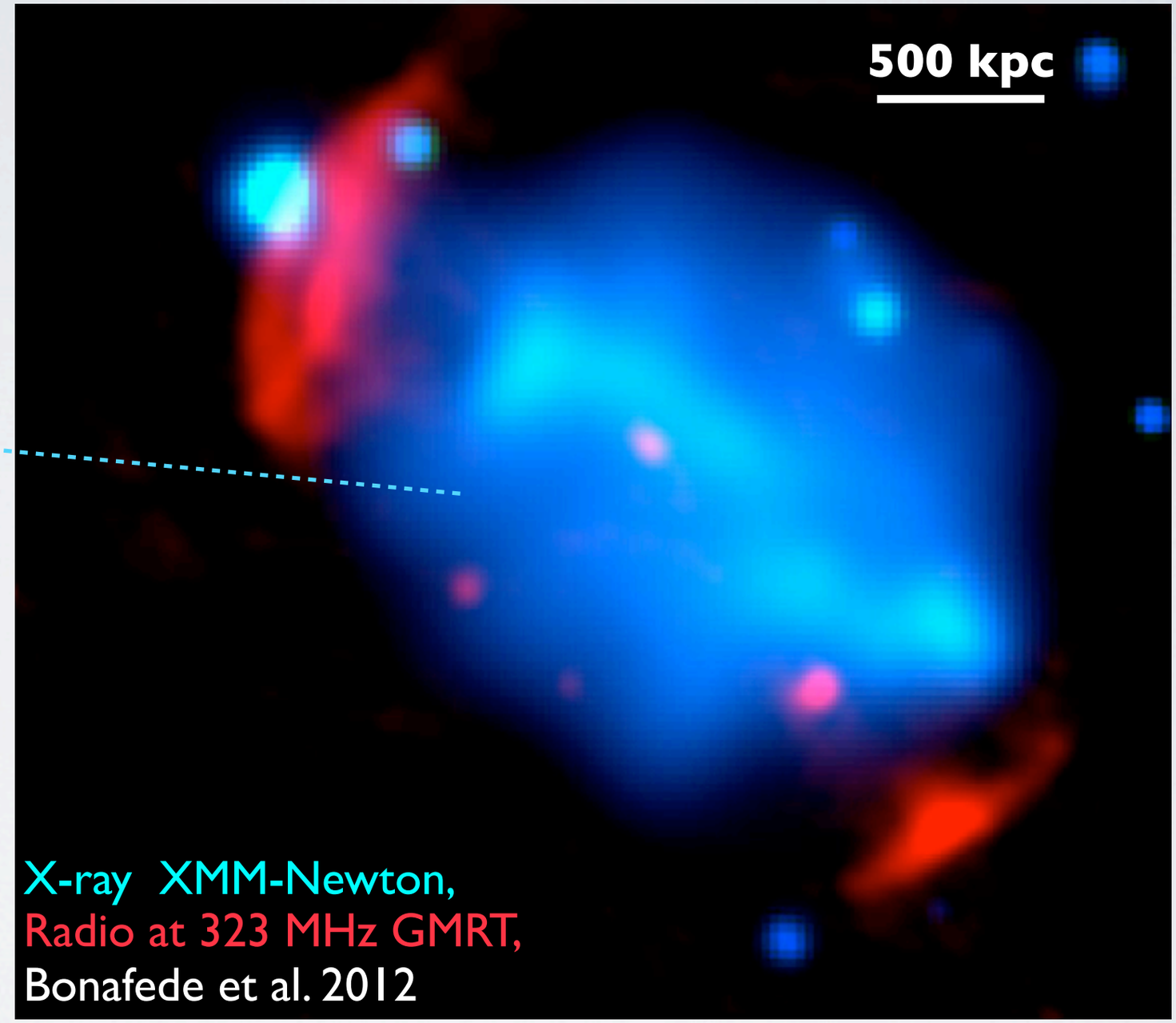
~80% of the Mass

Hot Gas (10^7 - 10^8 °K)

Bremsstrahlung emission

Soft X

~15% of the Mass



GALAXY CLUSTERS

Dark Matter

Revealed by gravitational lensing

~80% of the Mass

Hot Gas (10^7 - 10^8 °K)

Bremsstrahlung emission

Soft X

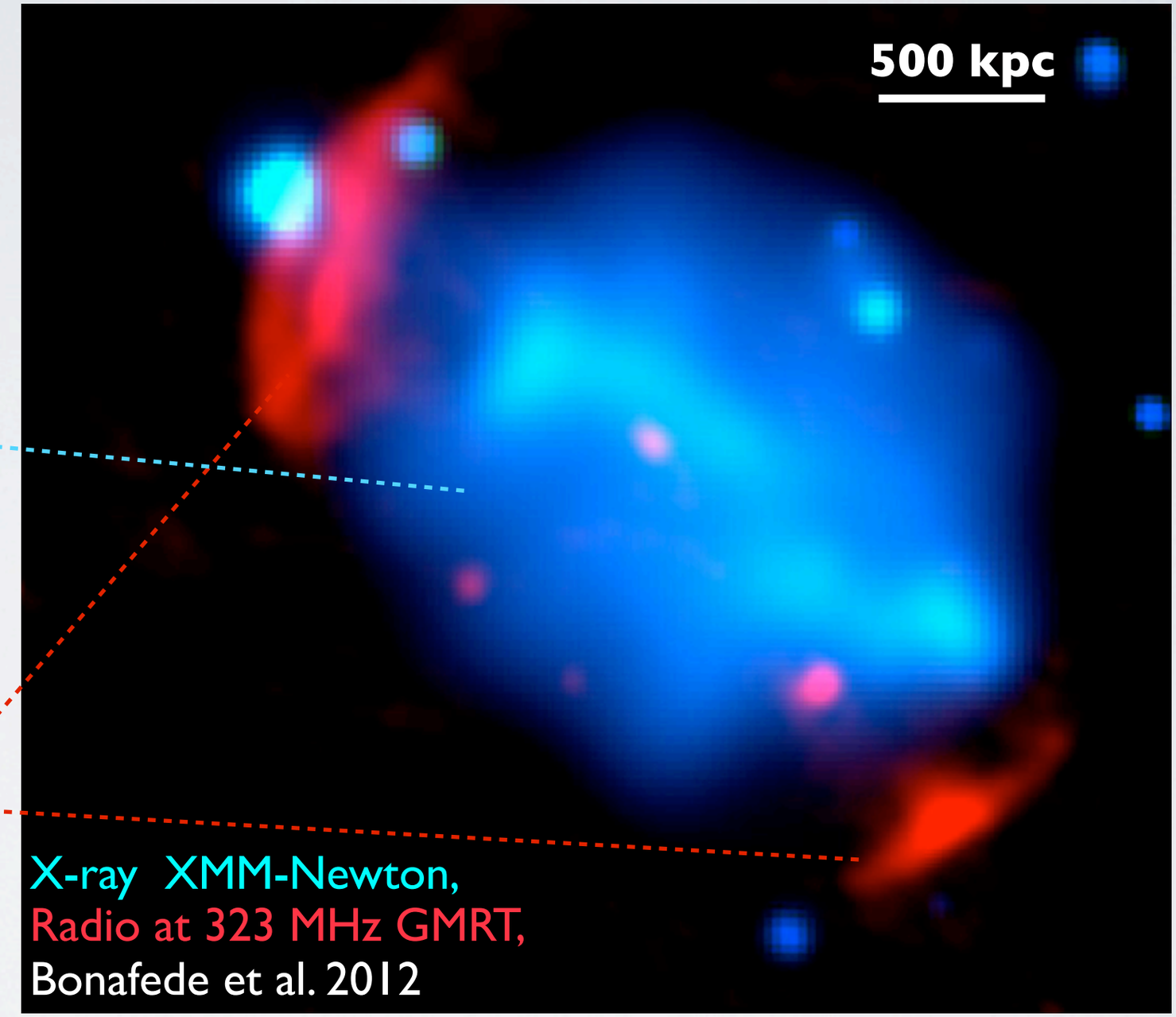
~15% of the Mass

Magnetic fields

and relativistic e

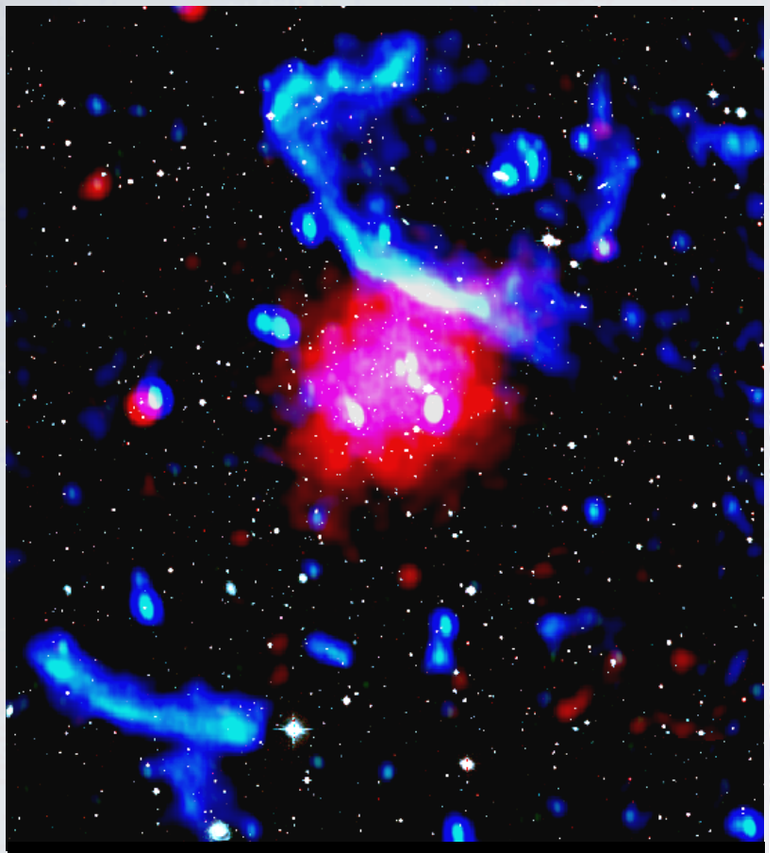
Radio synchrotron emission Mpc scale

Radio relics and radio halos



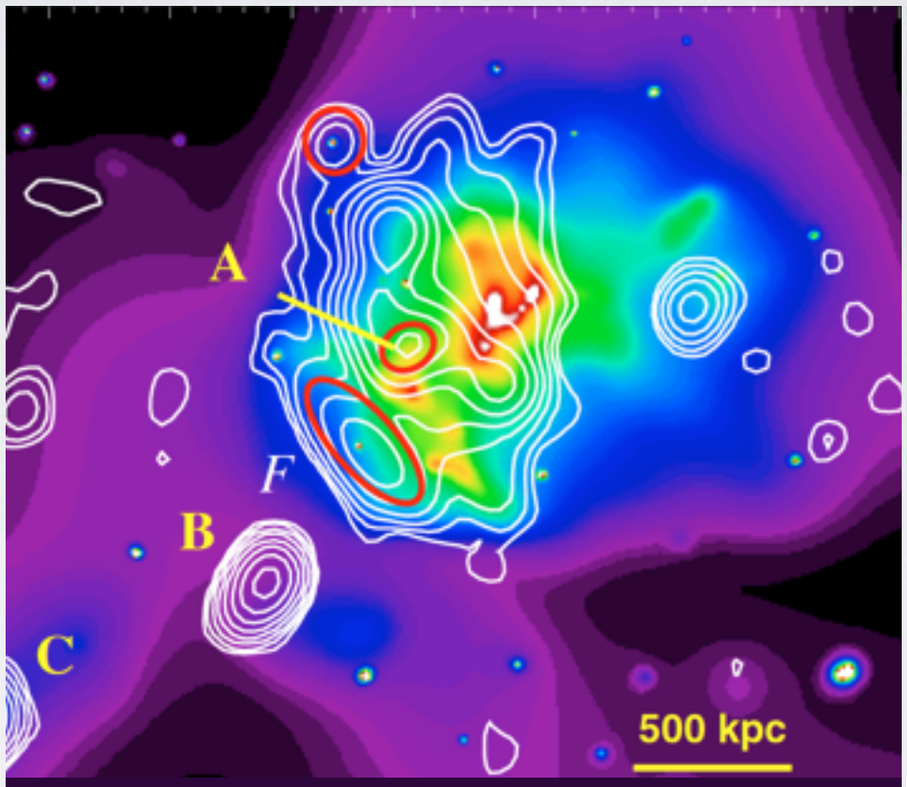
RADIO HALOS AND RELICS

Radio relics



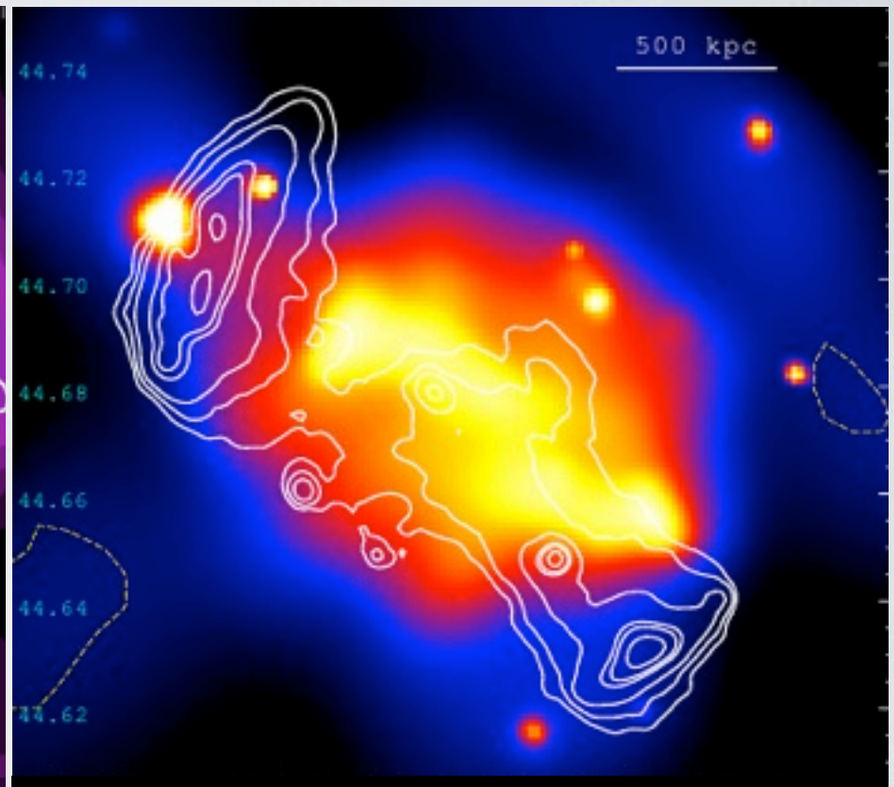
Radio 300 MHz
X-ray
,Bonafede et al. 2014)

Radio halo



X ray in colors
Radio in contours
(Bonafede et al 2009)

Radio halo and 2 relics



X ray in colors
Radio in contours
(Bonafede et al 2009)

Magnetic fields on Mpc-scale in the Intra-cluster medium

RADIO HALOS AND RELICS: ORIGIN?

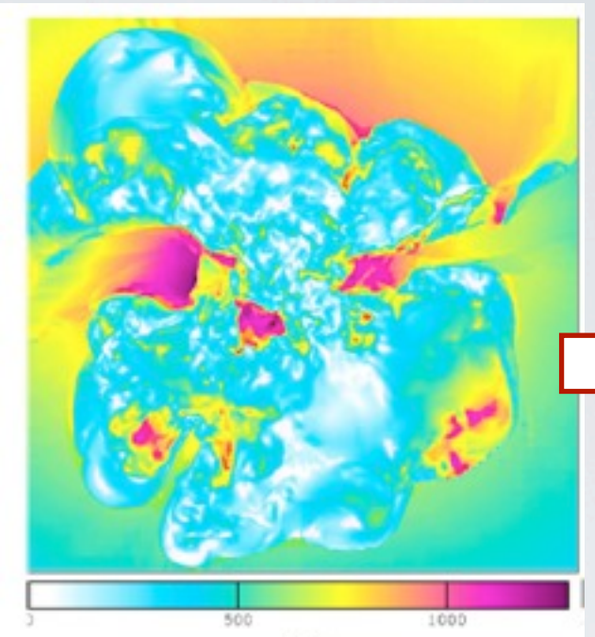
cluster-cluster merger

$E \sim 10^{64}$ erg

Turbulence

B amplified?

Shocks

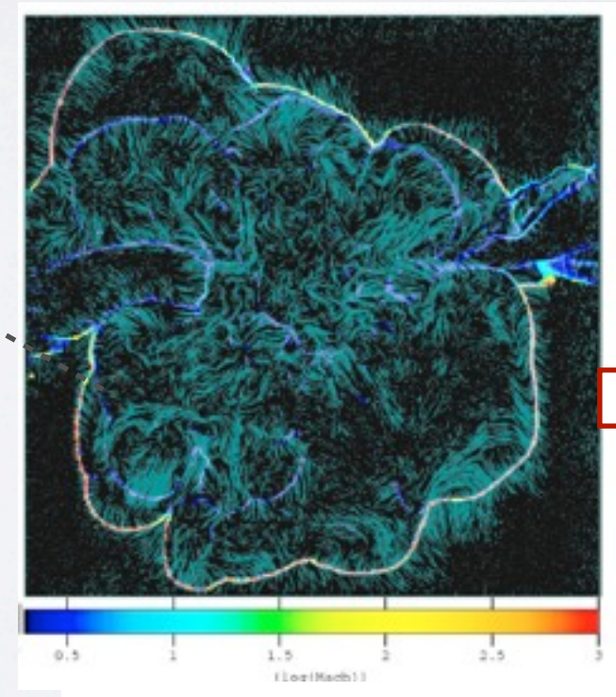


total gas velocity

Vazza et al. 2009

?

Halos



Mach number

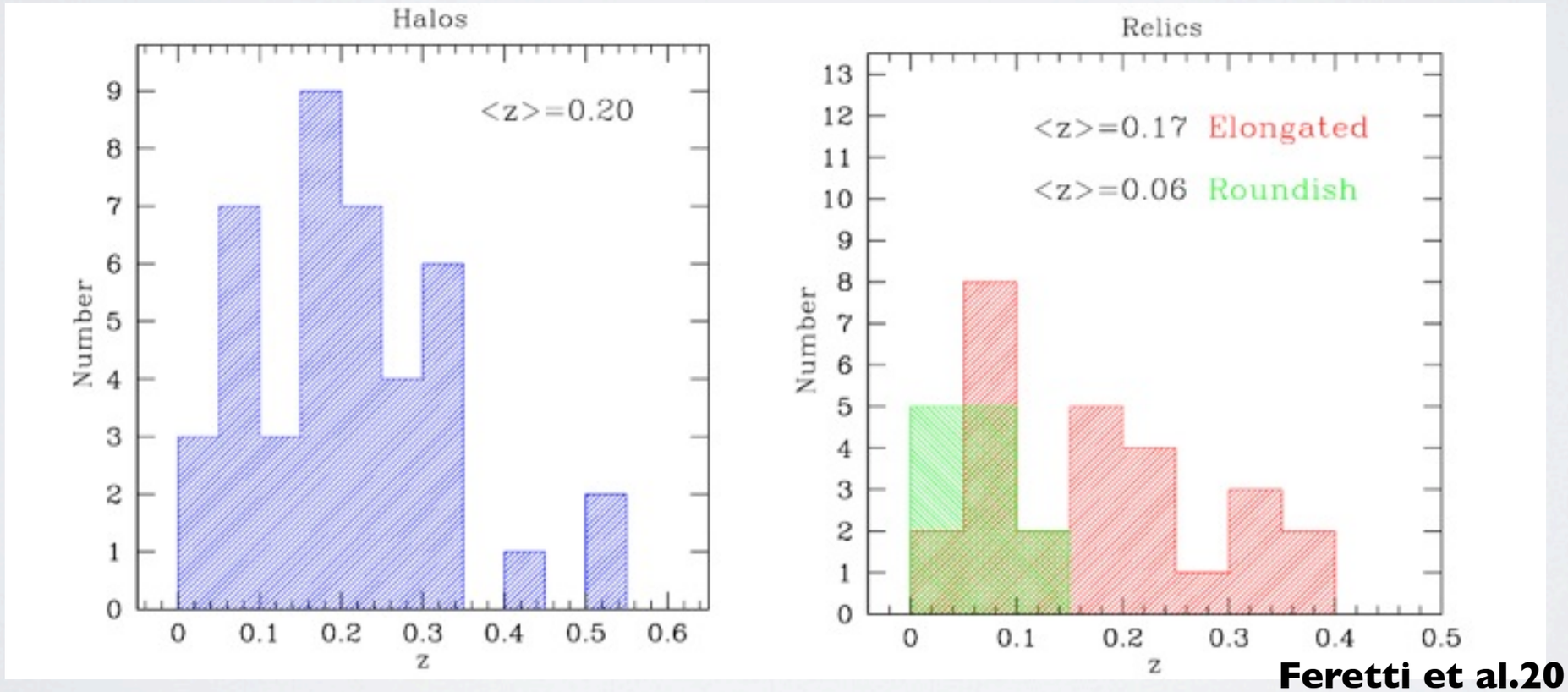
?

Relics

RADIO HALOS AND RELICS: HOW MANY?

Steep spectrum and low surface brightness at ν~GHz

⇨ Detection limited

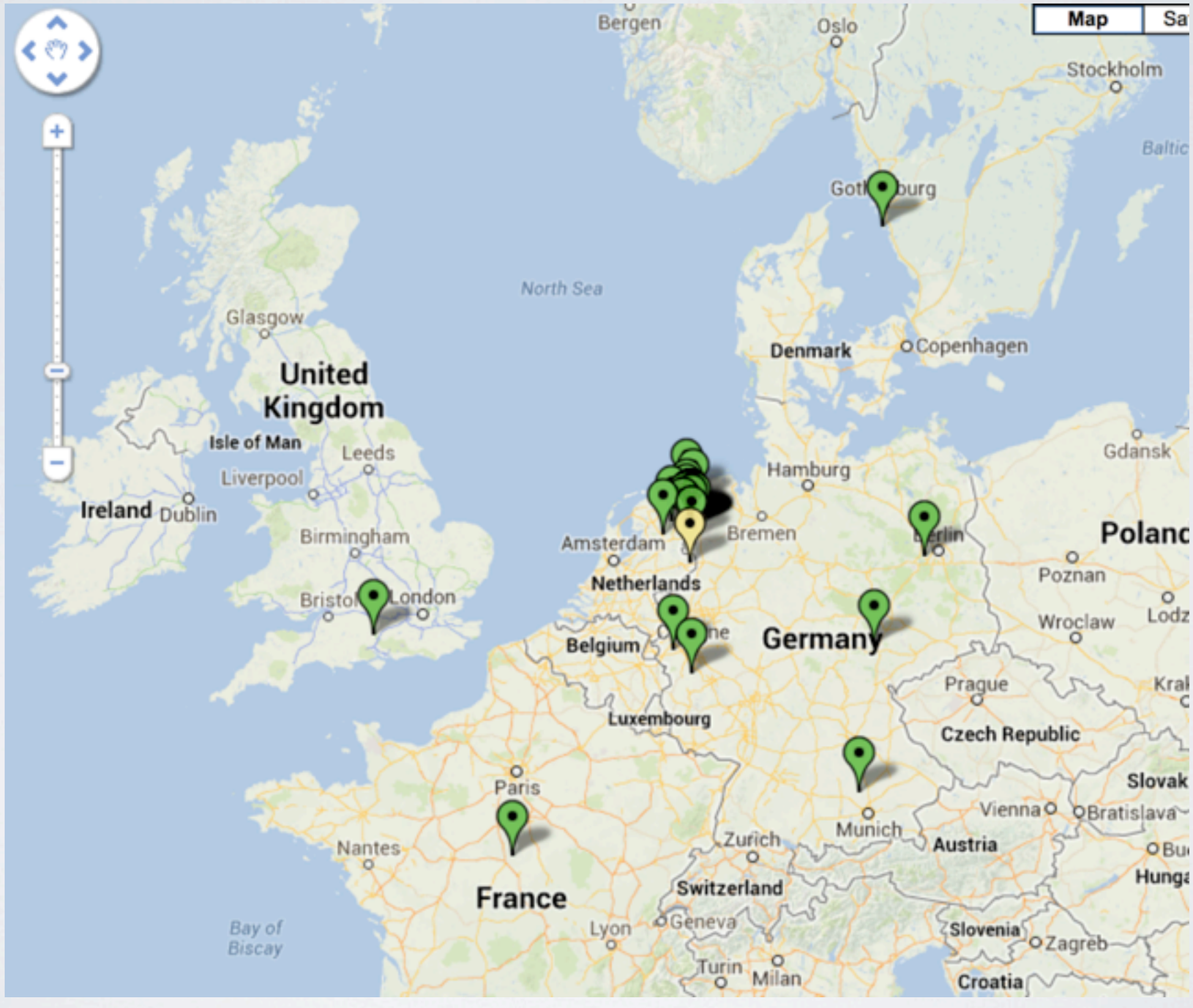


Feretti et al.2012

About 60 halos/relics

THE LOW FREQUENCY ARRAY - LOFAR

- New observational window 15-250 MHz
- Expected discovery of 100s halos/relic



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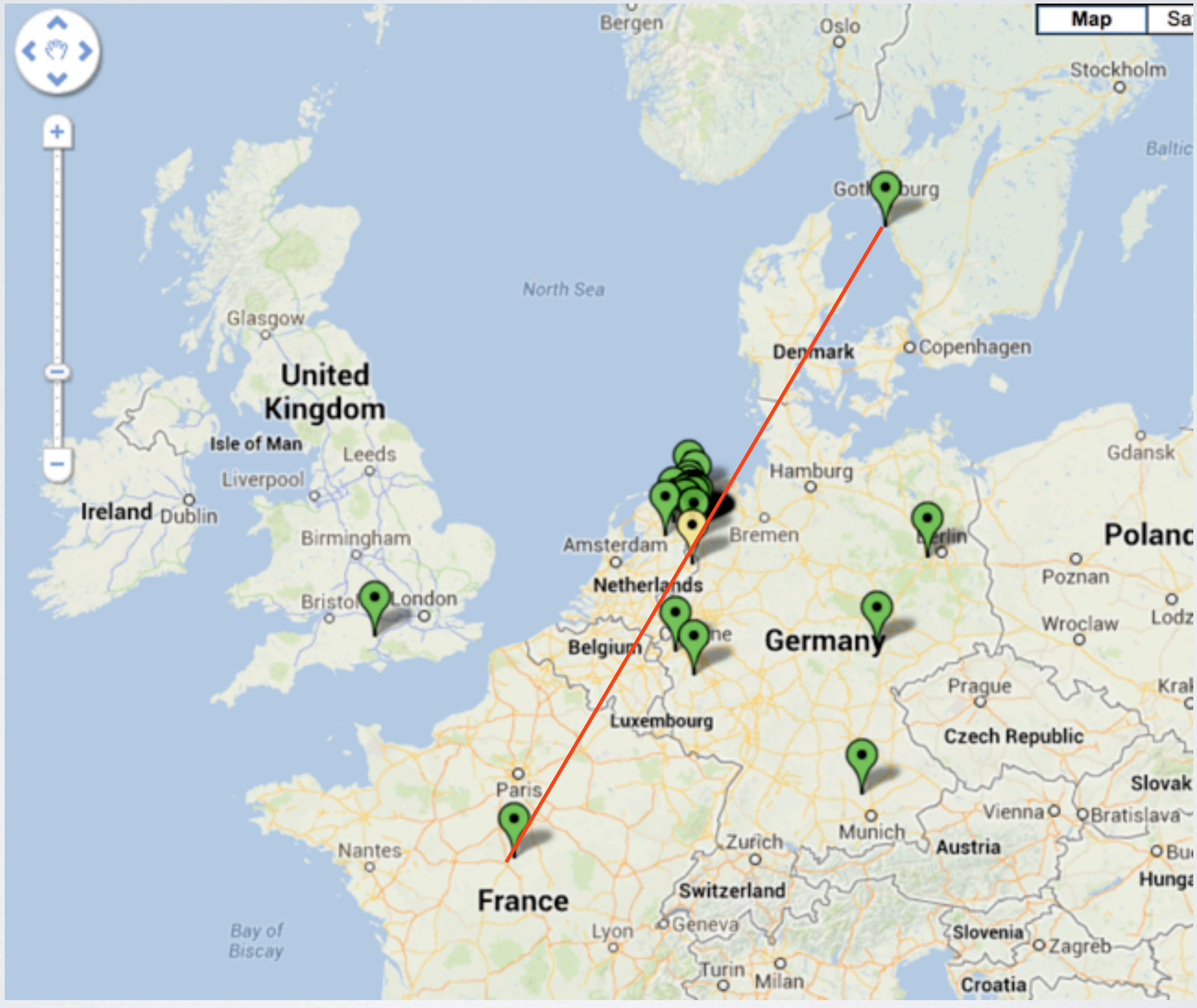

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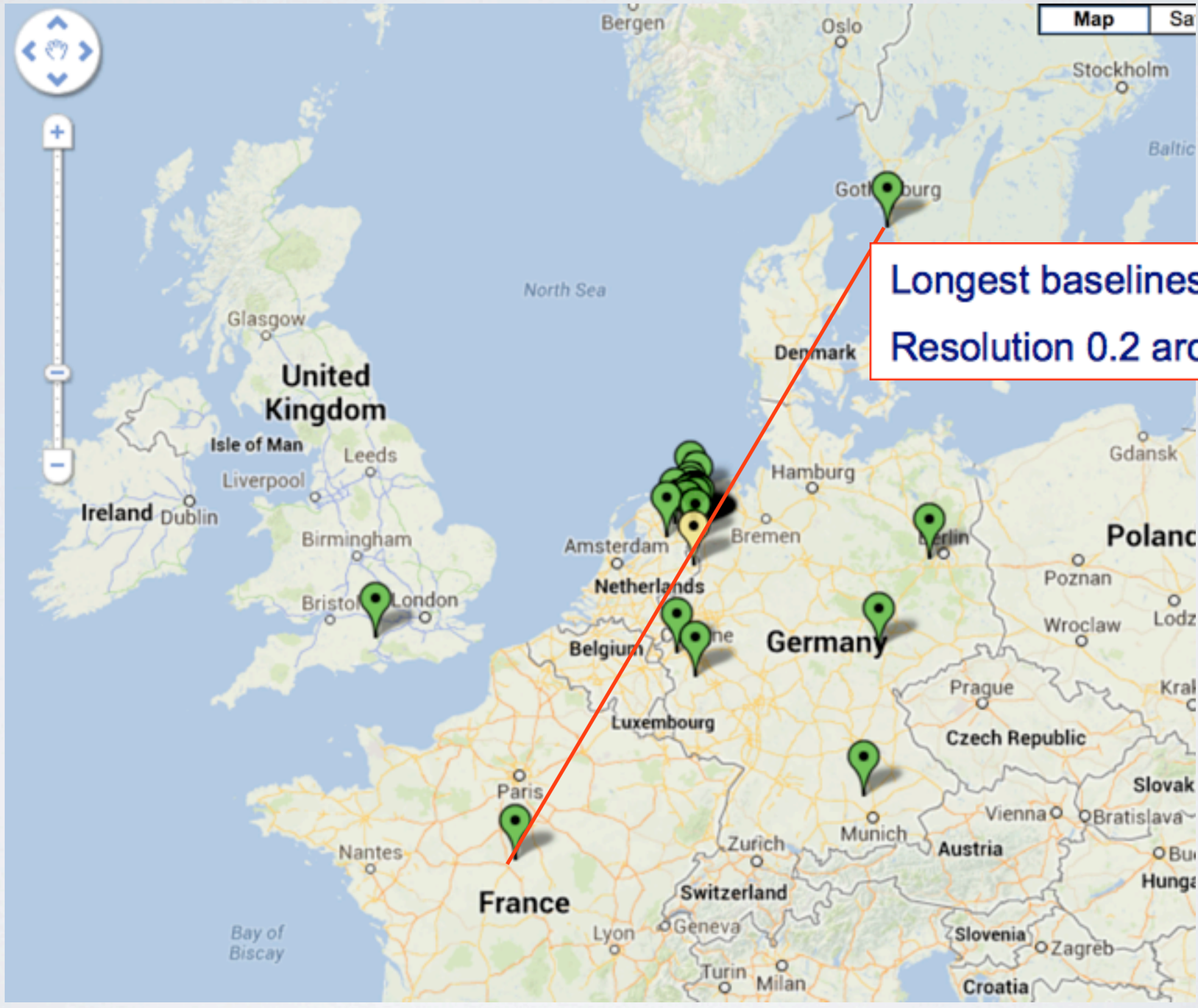

THE LOW FREQUENCY ARRAY - LOFAR

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The LOFAR super terp

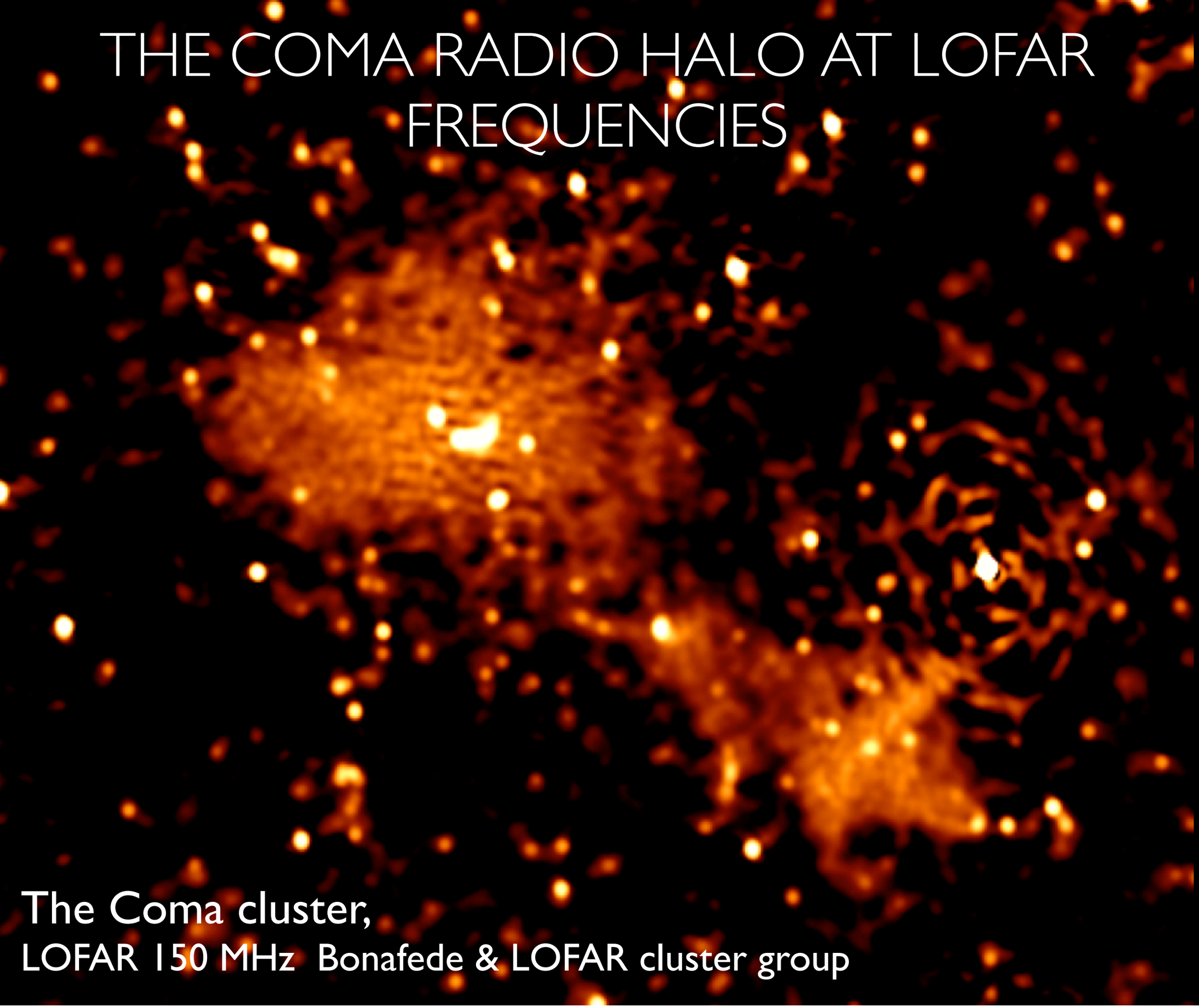
6 stations, 320 m

Sensitivity to Large angular scale

Longest baselines ~1000 km

Resolution 0.2 arcsec

THE COMA RADIO HALO AT LOFAR FREQUENCIES



The Coma cluster,
LOFAR 150 MHz Bonafede & LOFAR cluster group

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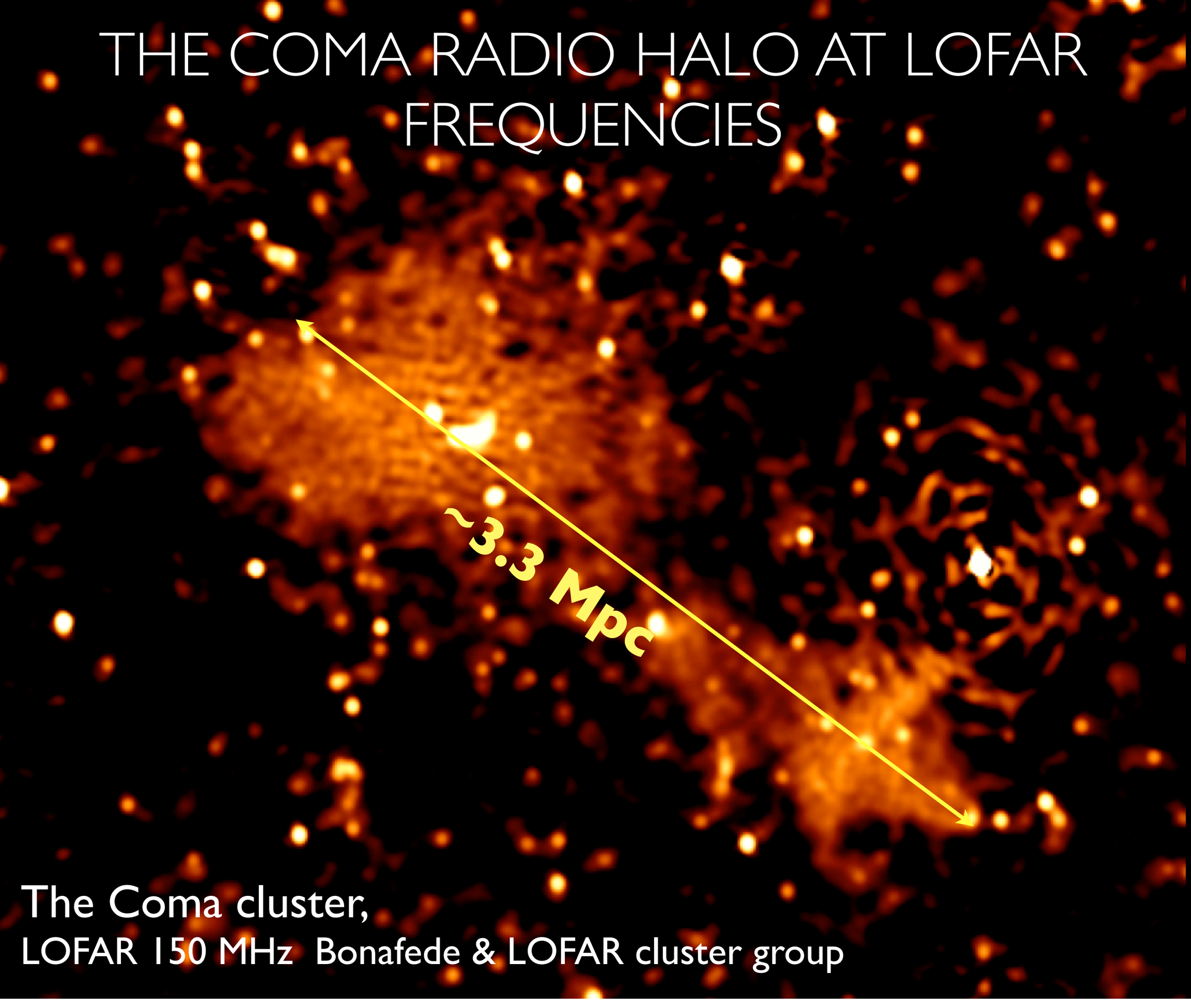

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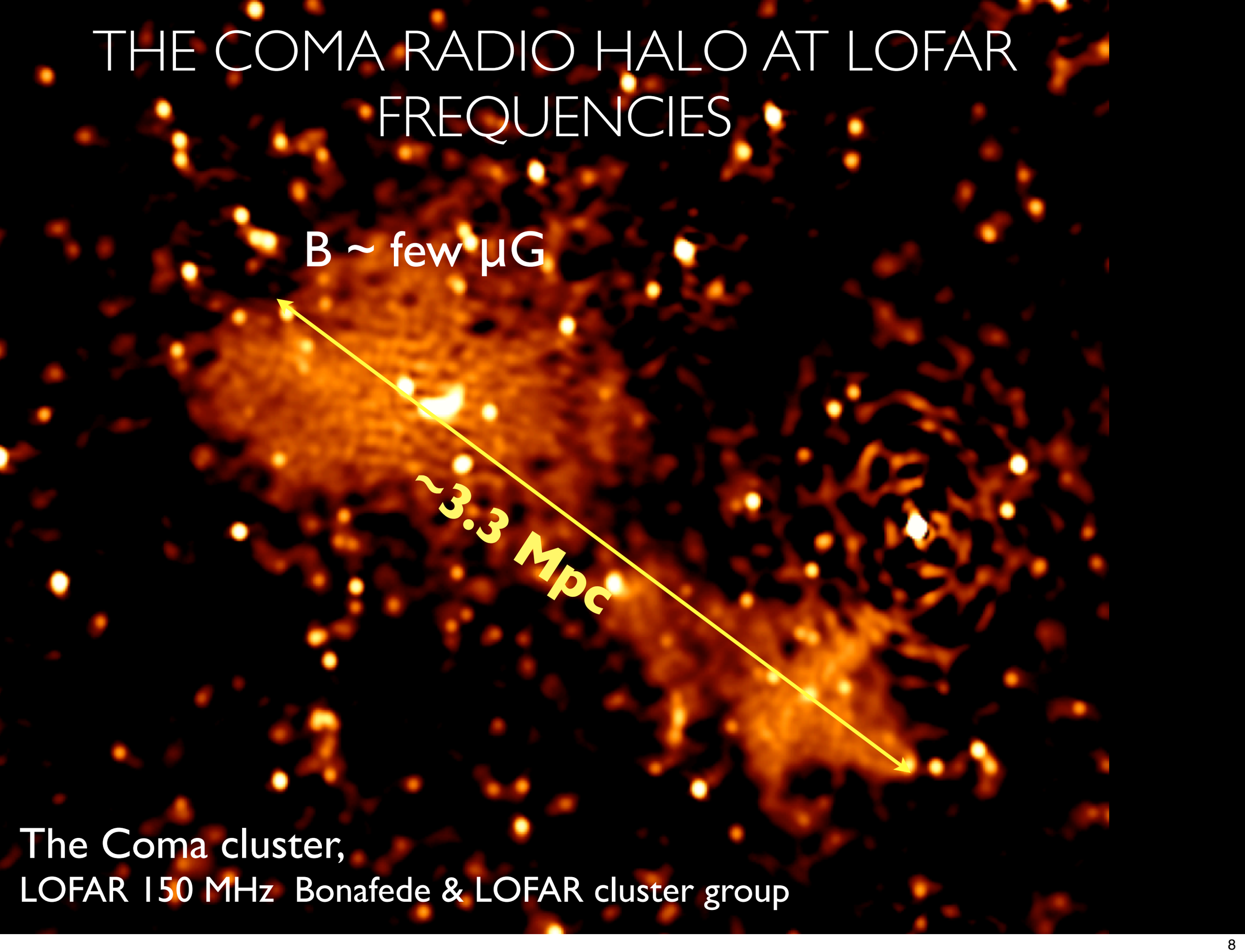

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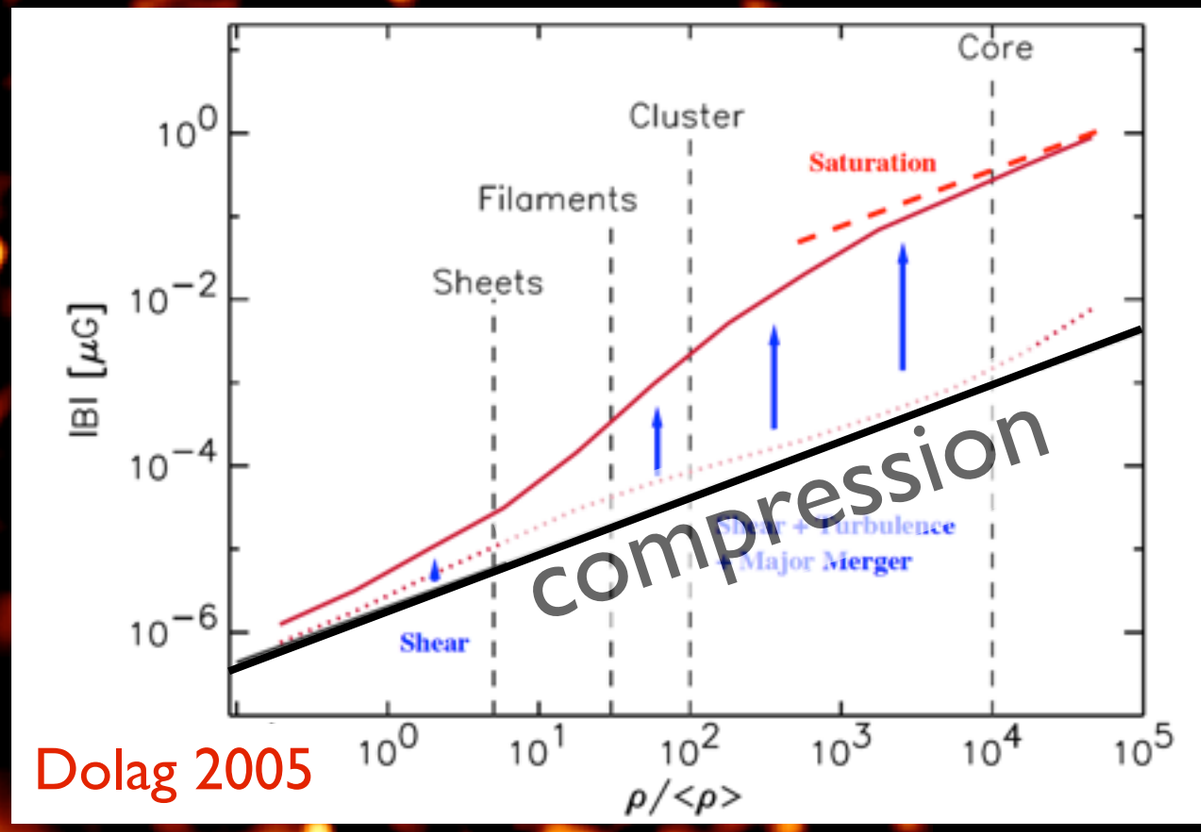
THE COMA RADIO HALO AT LOFAR FREQUENCIES

B ~ few μG

~3.3 Mpc



Dolag 2005

The Coma cluster,
LOFAR 150 MHz Bonafede & LOFAR cluster group

B IN CLUSTERS AND ALPS (WHY I AM SPEAKING HERE TODAY)

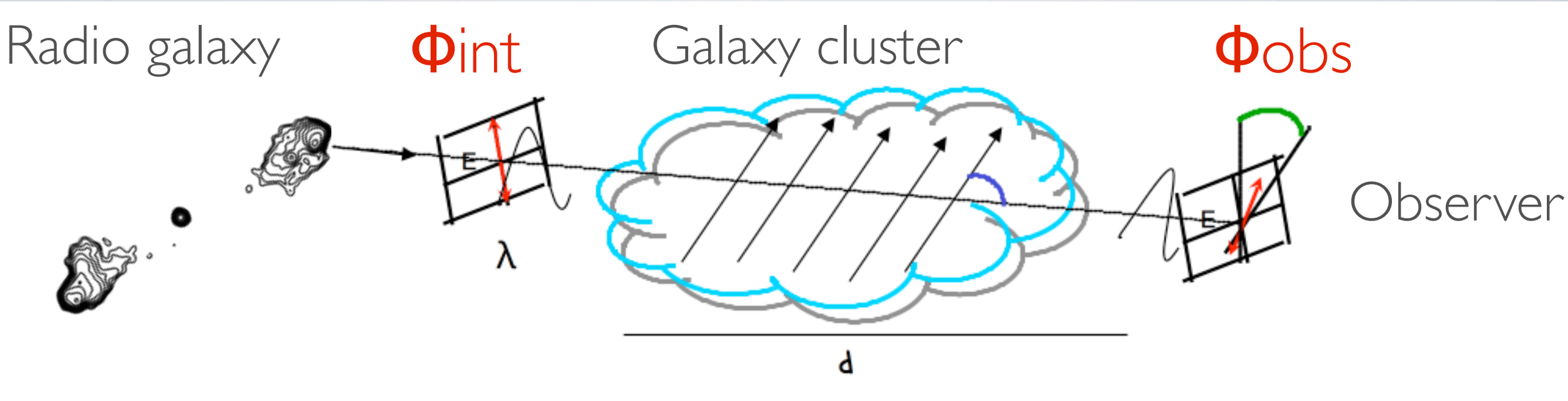
- B ~μG but on Mpc scale; coherence length 1-100 kpc

$$P_{a\to\gamma} = \frac{1}{4}\left(\frac{B_\perp L}{M}\right)^2$$

- X-ray UV excess in clusters (e.g. Lieu et al 1996, Bonamente et al. 2002) ⇒ conversion of Cosmic Axion Background to photons in the cluster B (Conlon et al. 2013)

- Other possible origins (e.g. IC from relativistic CRe, WHIM, thermal)

THE FARADAY ROTATION



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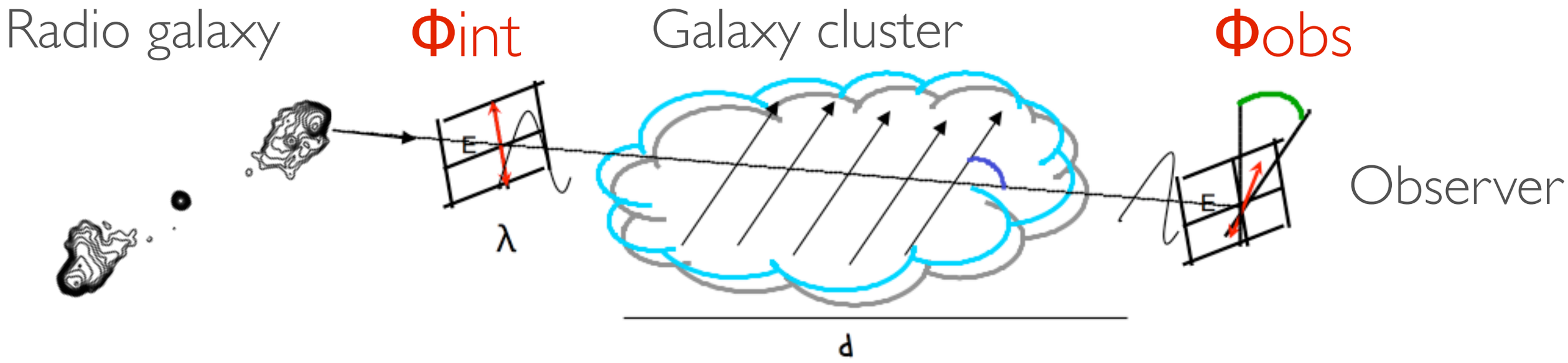


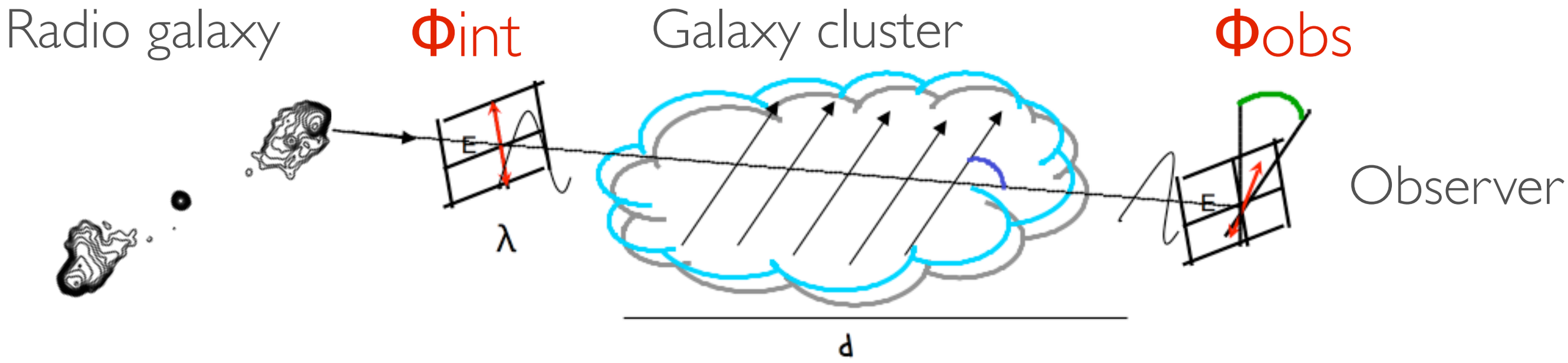
Rotation Measure

RM

$$\Phi_{obs} = \Phi_{int} + RM\lambda^2$$

$$RM = \int_0^d B_{los} n dl$$

THE FARADAY ROTATION



Rotation Measure RM

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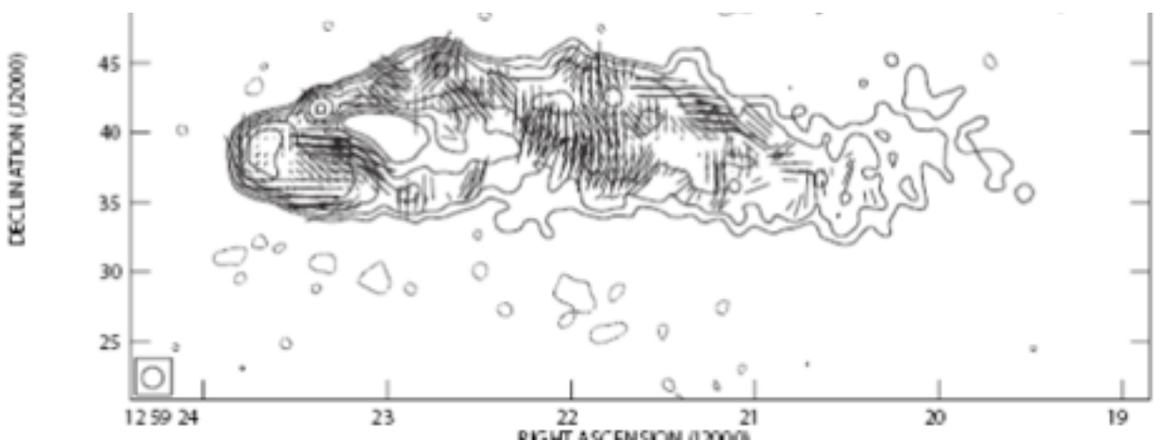
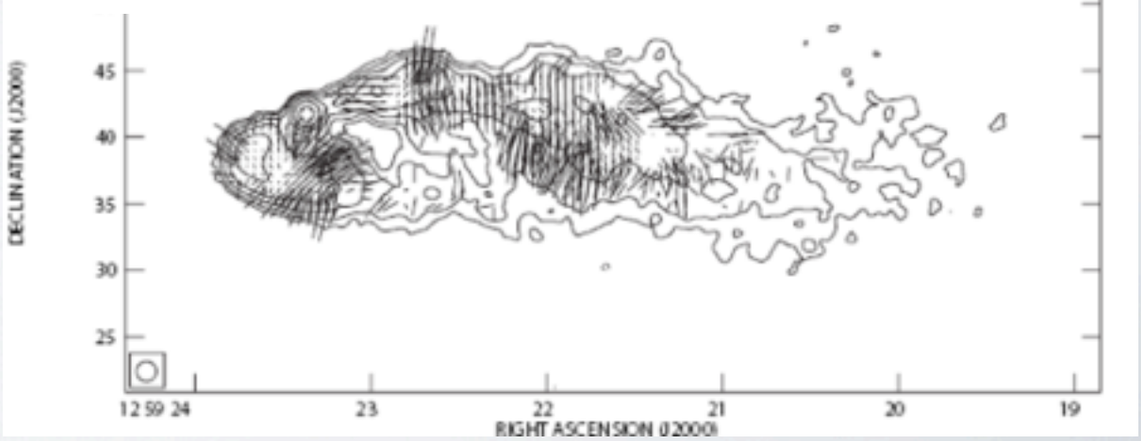
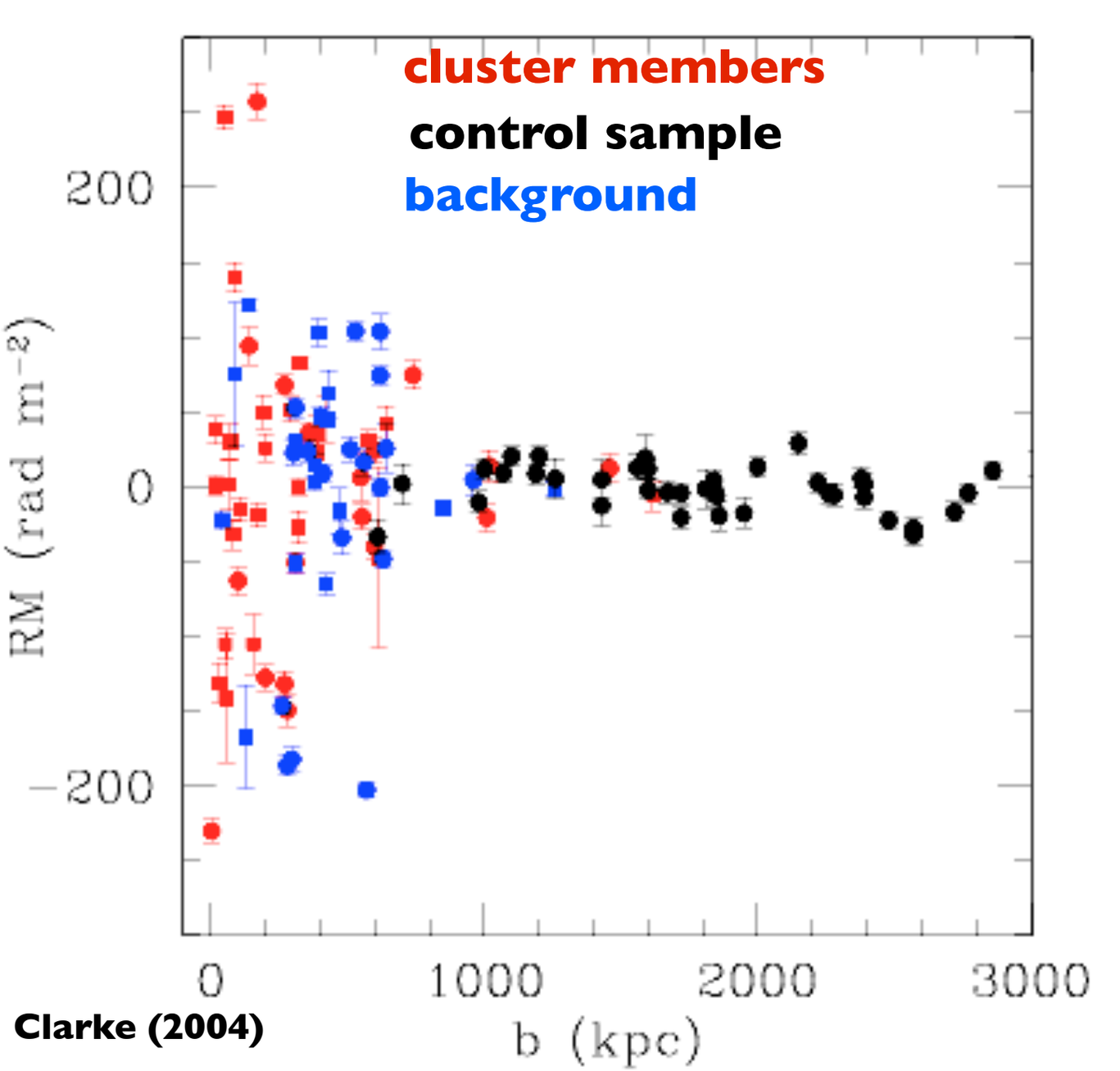
E vectors at λ= 6cm



E vectors at λ= 3cm



THE FARADAY ROTATION MEASURE (RM)

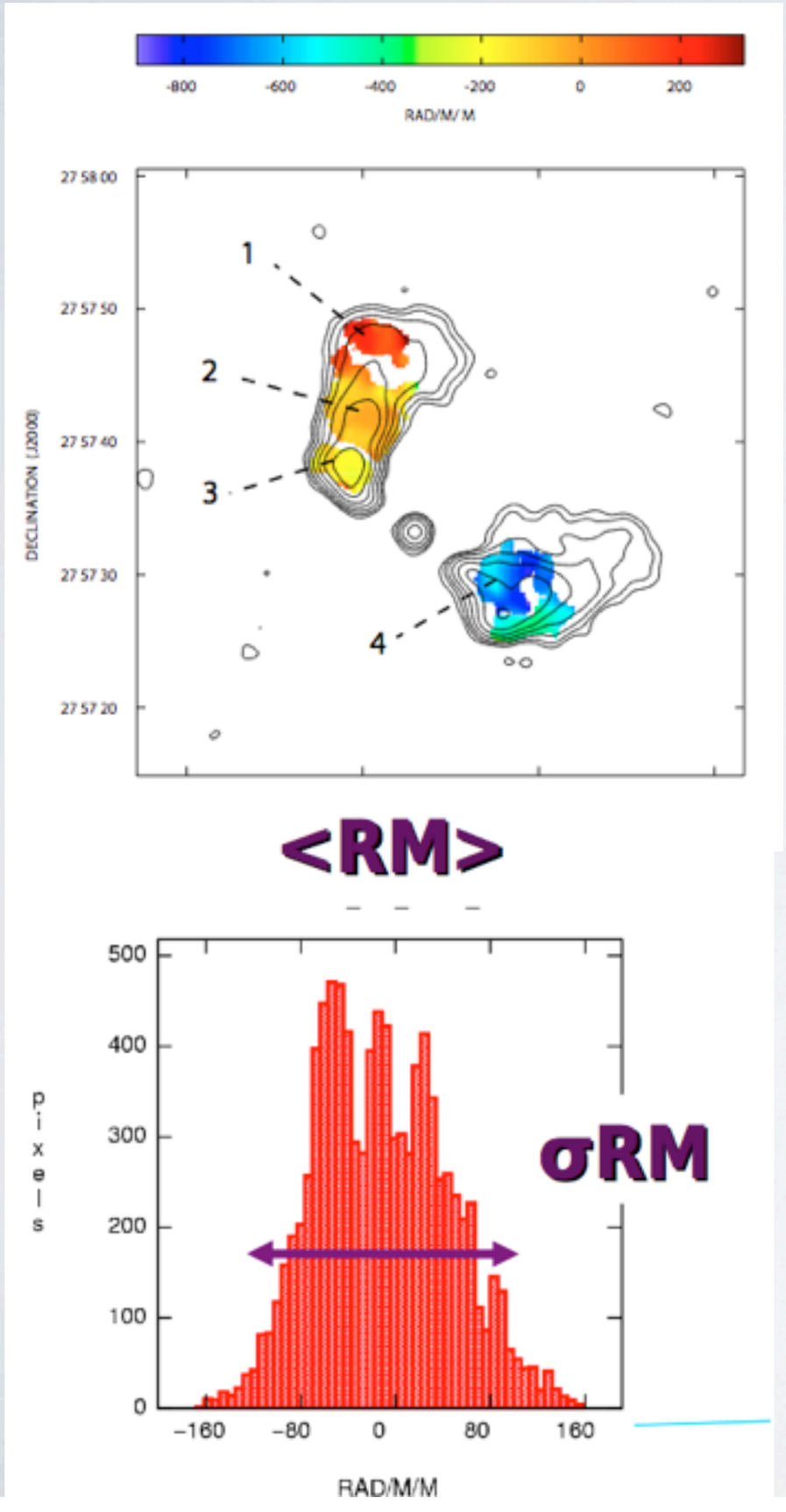


Clarke (2004)

$$\Phi_{obs} = \Phi_{int} + RM\lambda^2$$

$$RM = \int_0^d B_{los} n dl$$

THE FARADAY ROTATION MEASURE (RM)



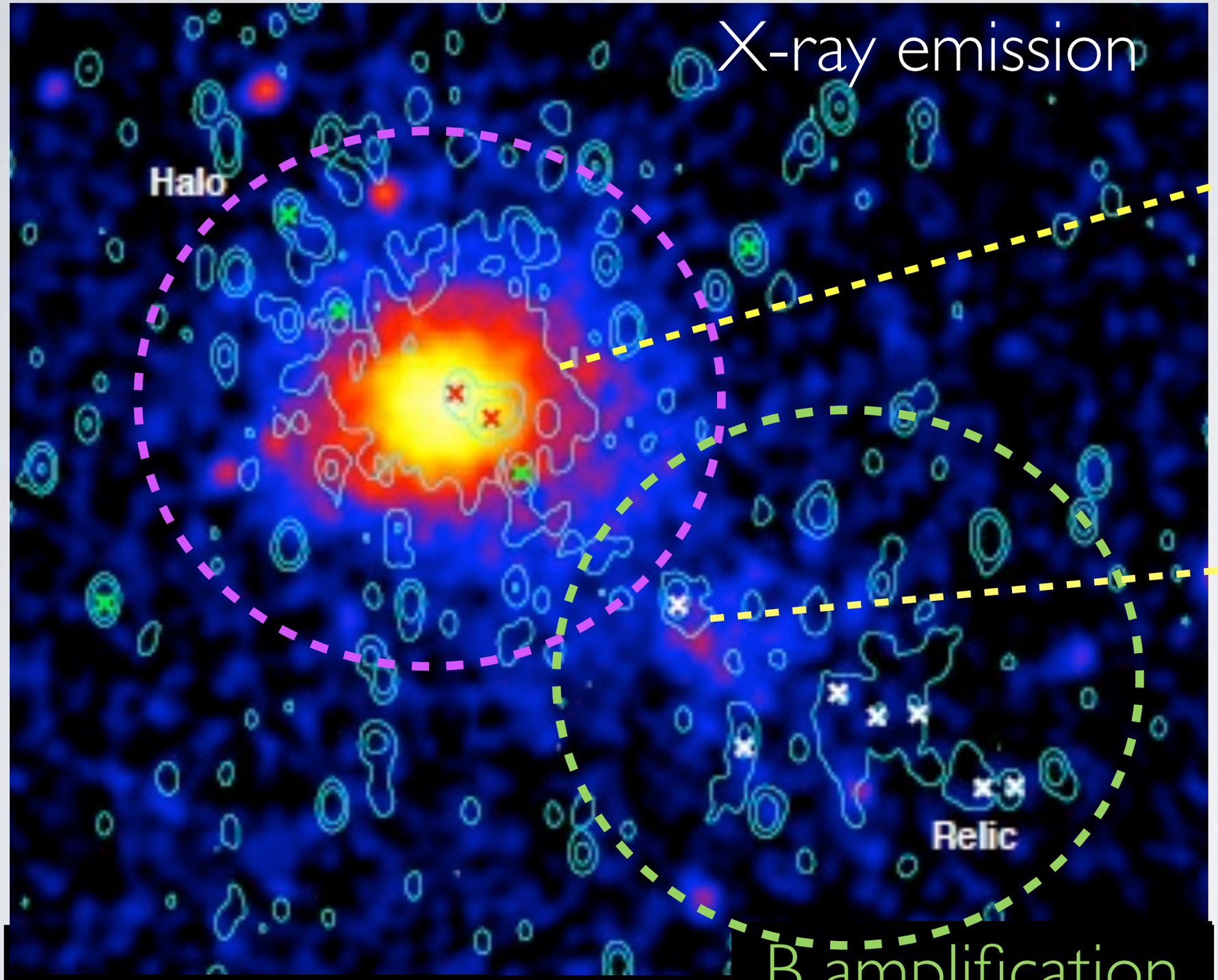
$$RM = \int_0^d B_{los} n dl$$

Extract B properties
from RM images:

- RM distribution
- autocorrelation function
- structure function

RM power spectrum proportional
to B power spectrum

COMA CLUSTER



Coma cluster

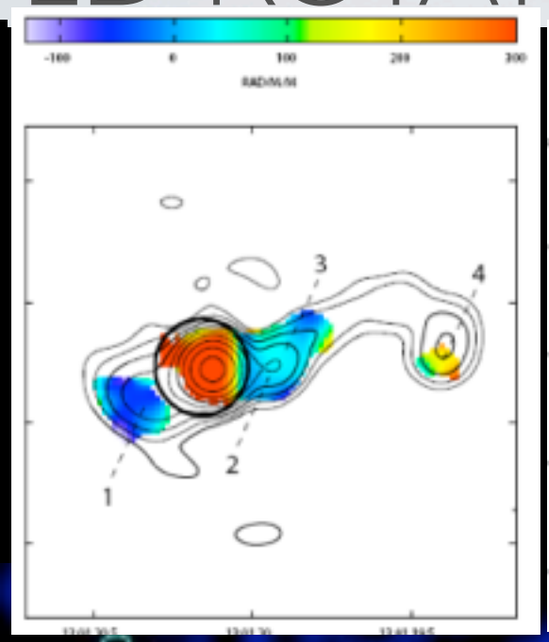
Sub-group accreting

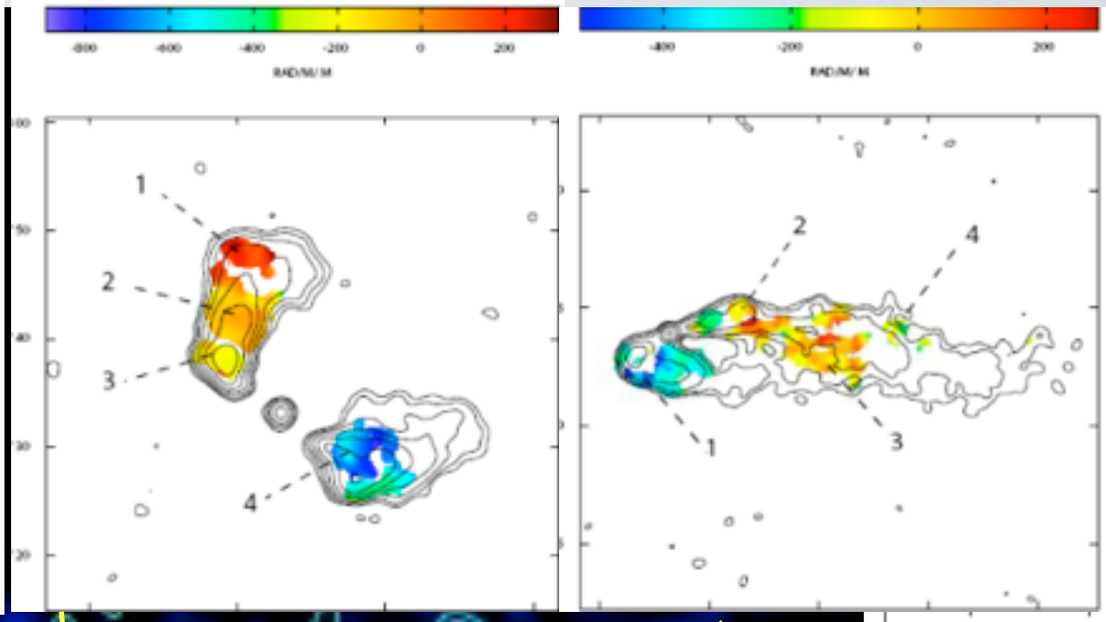
B in the cluster

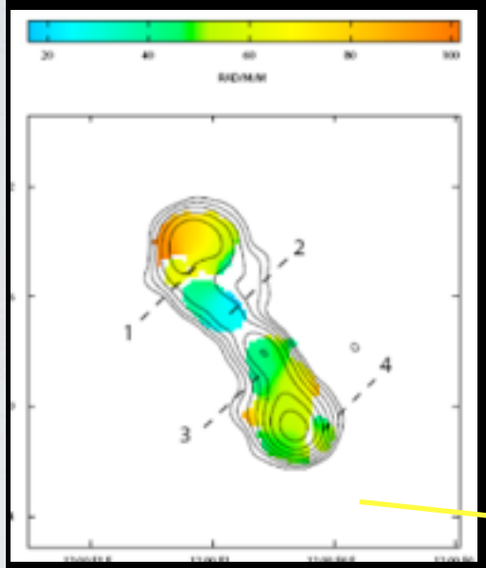
B amplification in the relic?

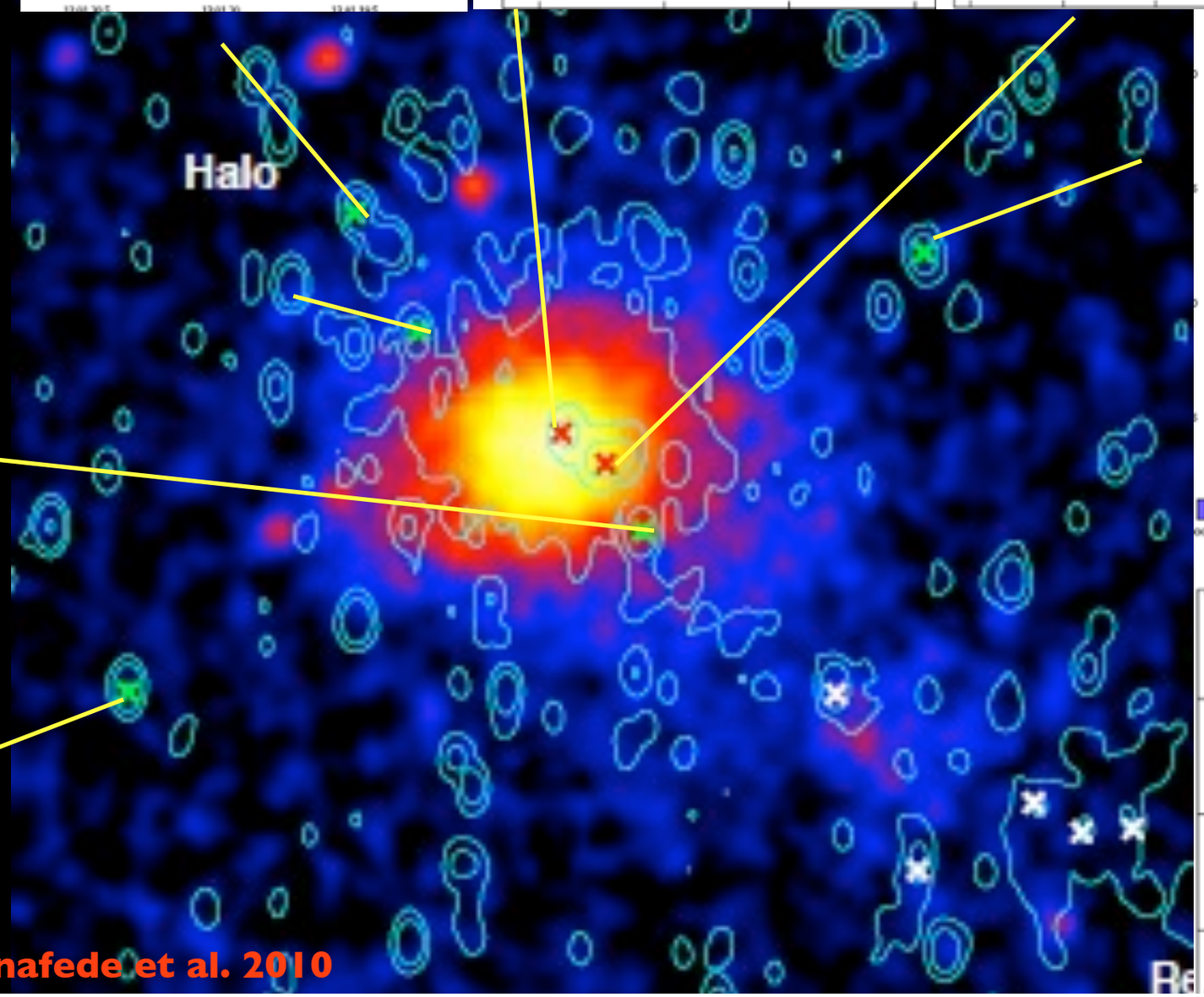
OBSERVED ROTATION MEASURE IMAGES

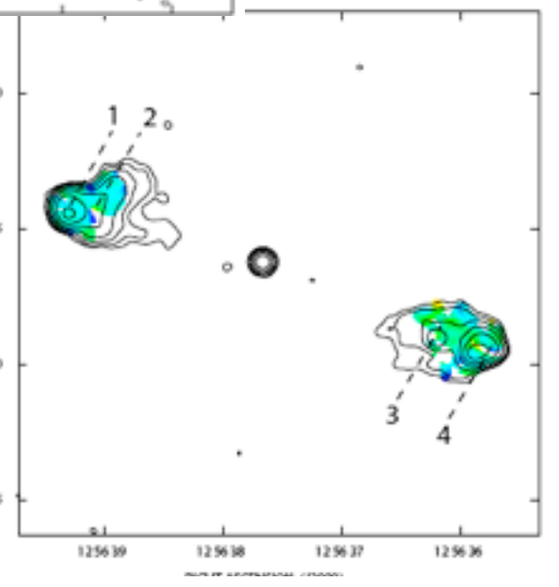
RM images
4.3,4.8, 8.0,8.5 GHz
Very Large Array
Resolution ~1 kpc

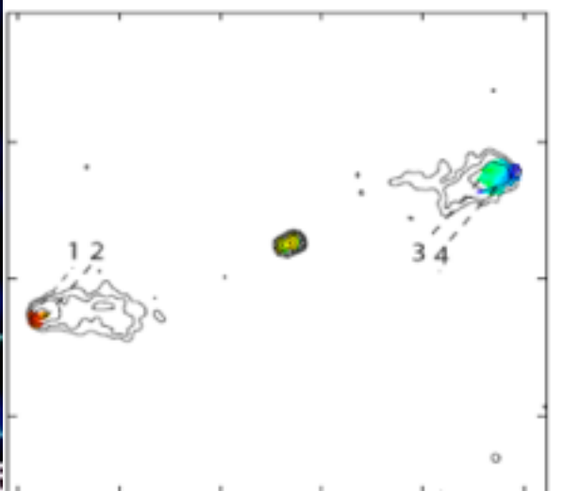








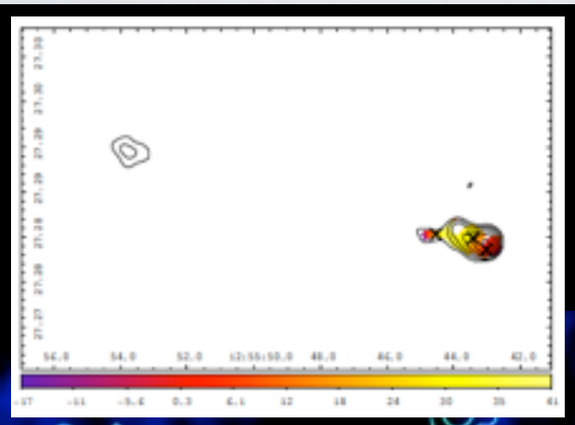


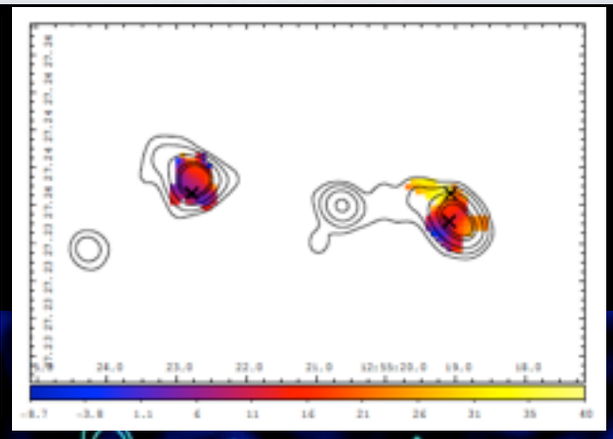


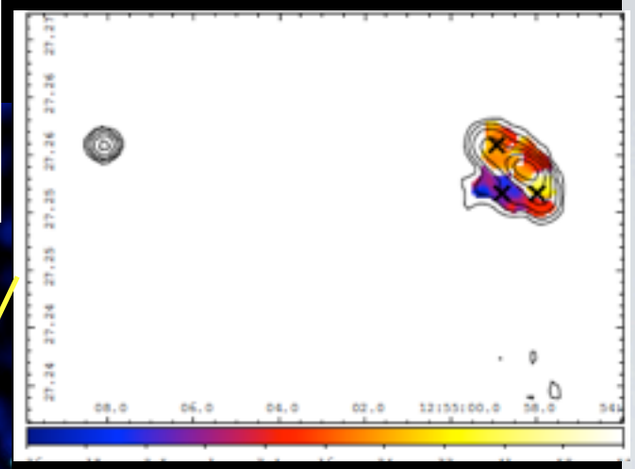
Bonafede et al. 2010

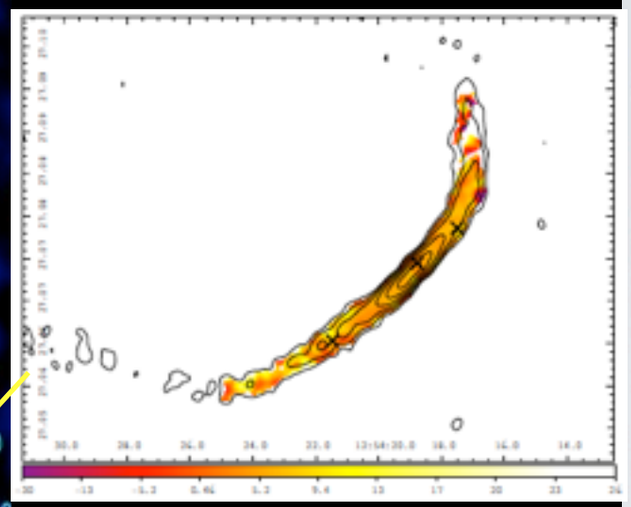
OBSERVED ROTATION MEASURE IMAGES

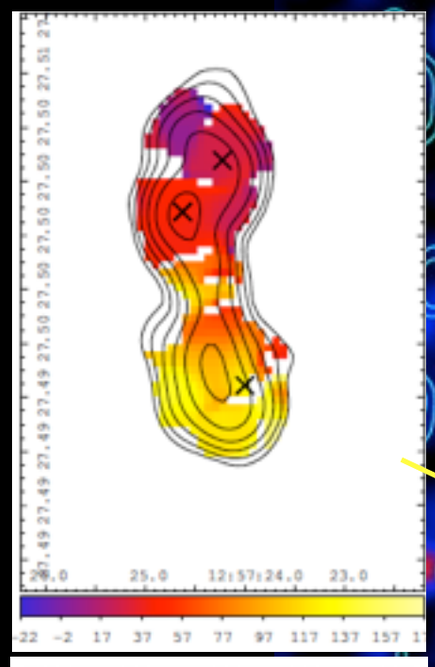
RM images
1.4, 1.8, 4.3,4.8 GHz
Very Large Array
Resolution ~1 kpc

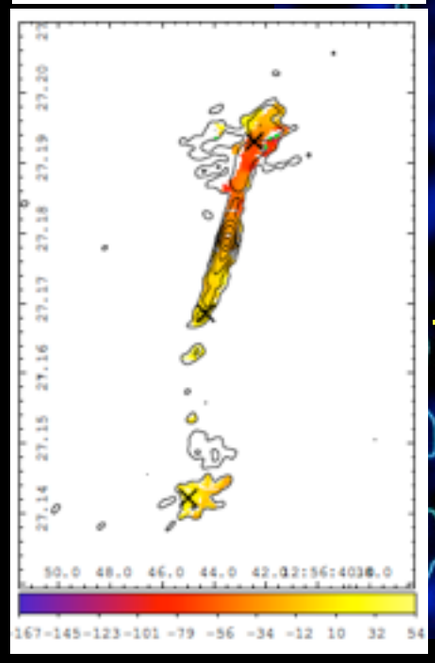


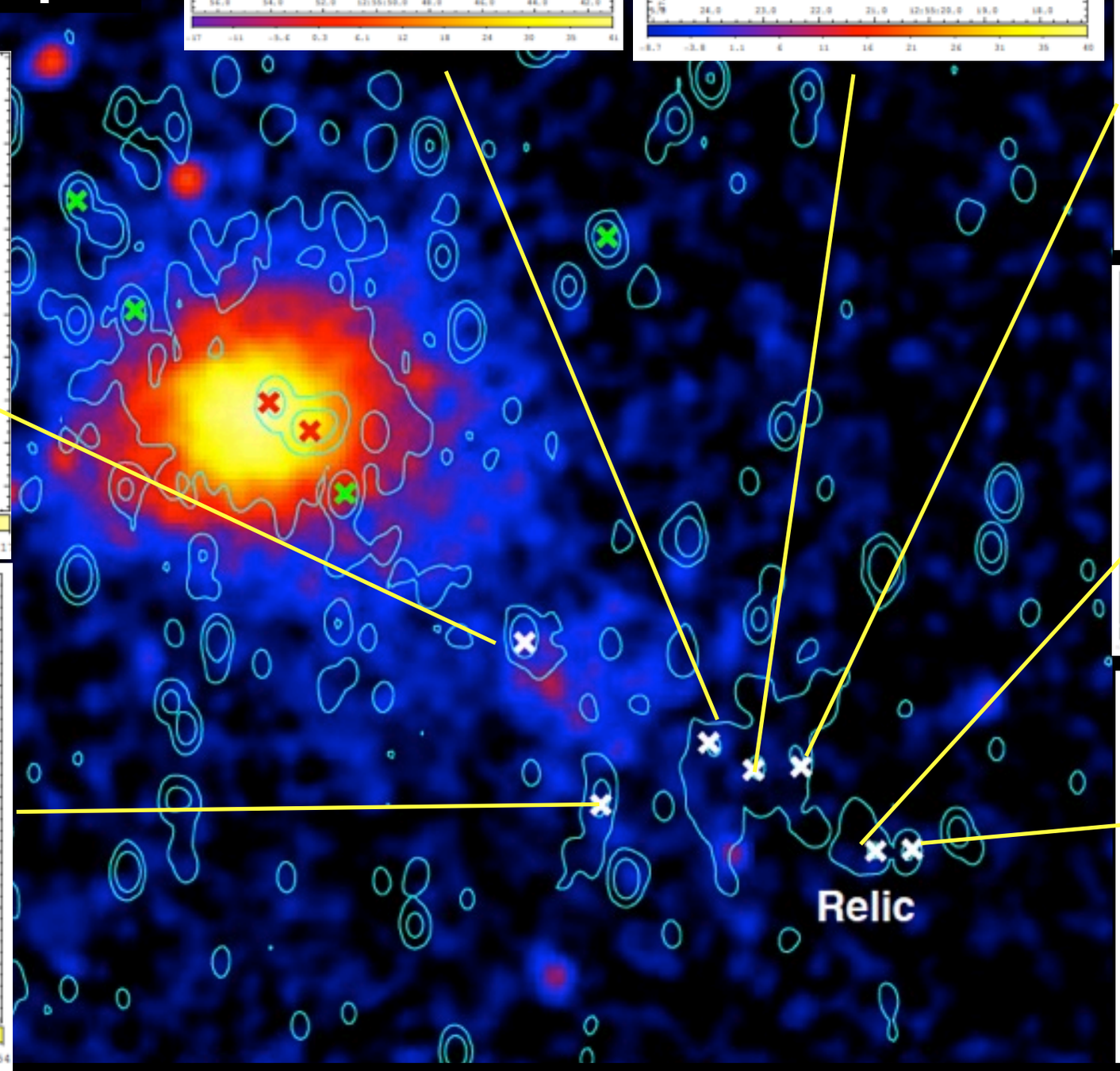


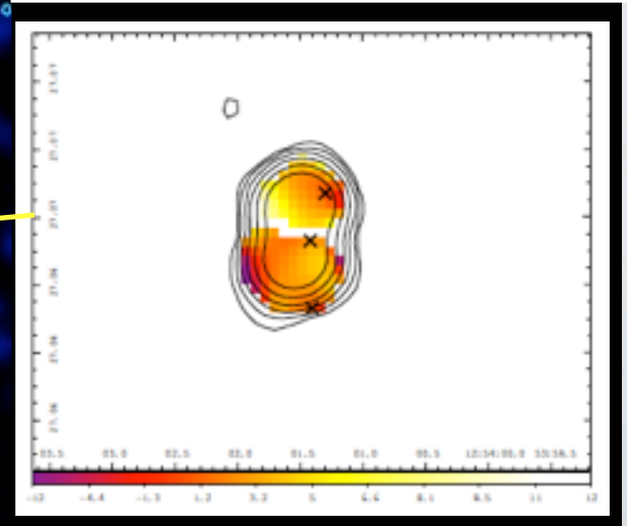






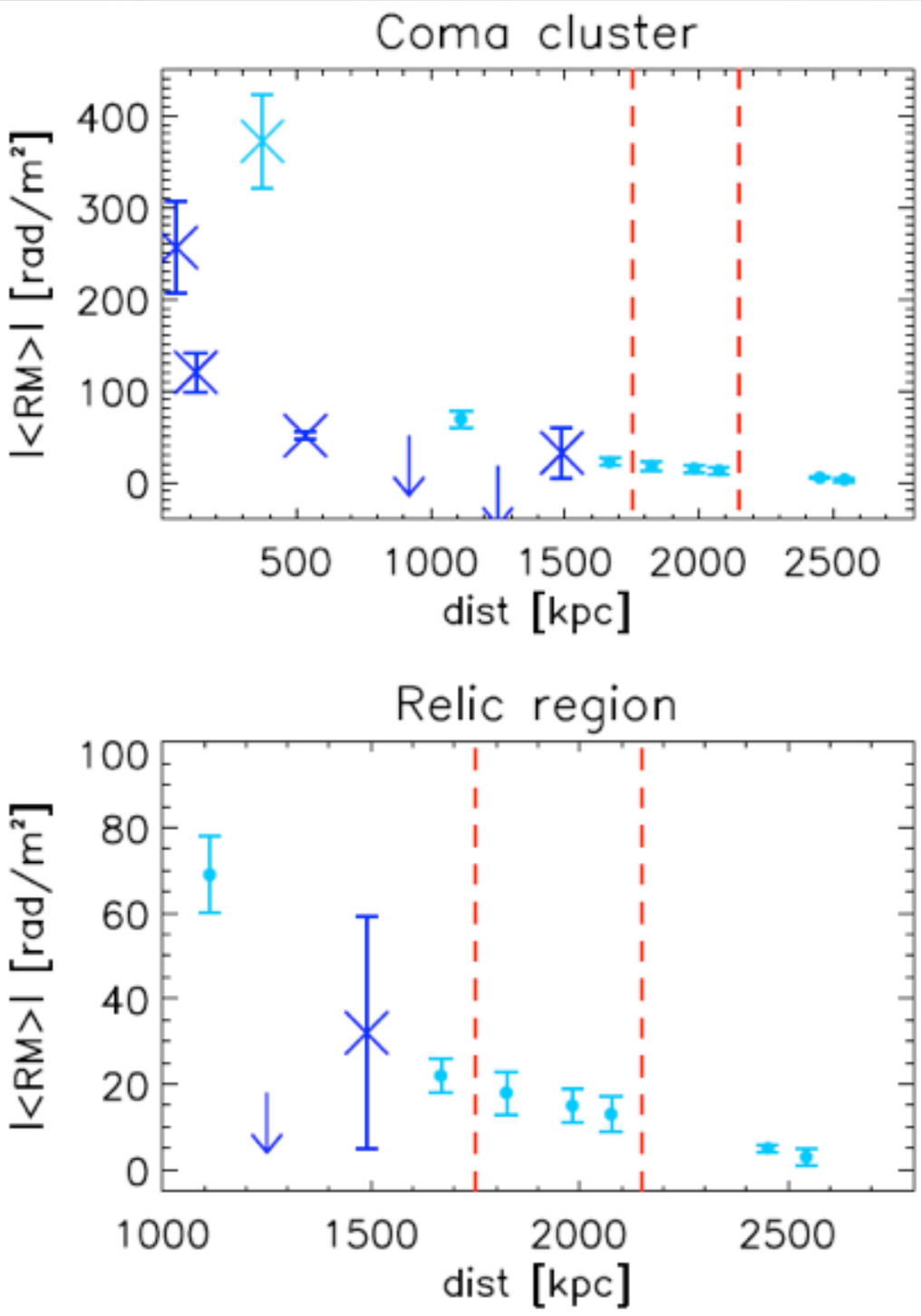


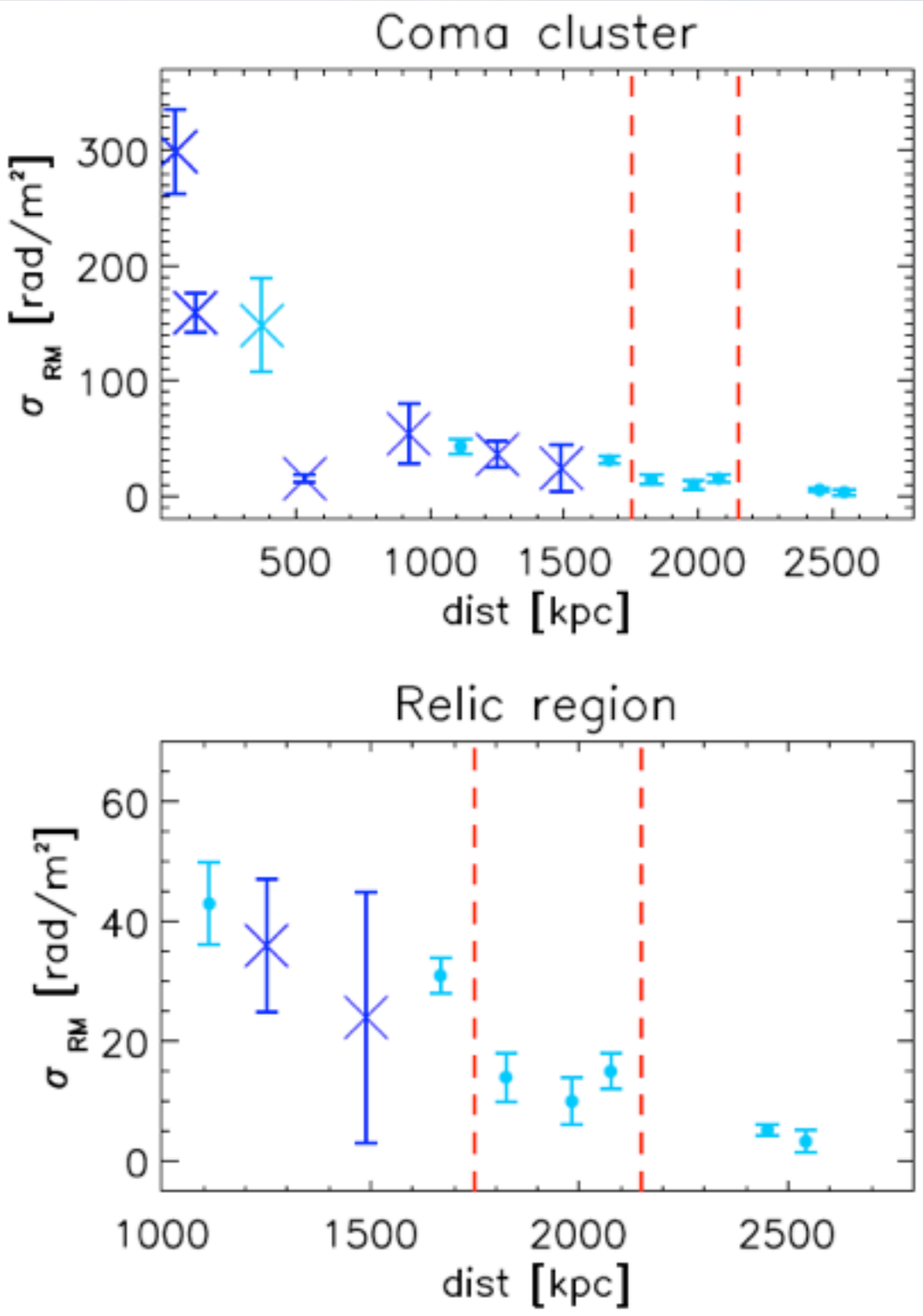




Bonafede et al. 2013

OBSERVED ROTATION MEASURE TREND





Bonafede et al. 2013

OBTAINING MOCK ROTATION MEASURE IMAGES

observed $RM = \int_0^d B_{los} n dl$

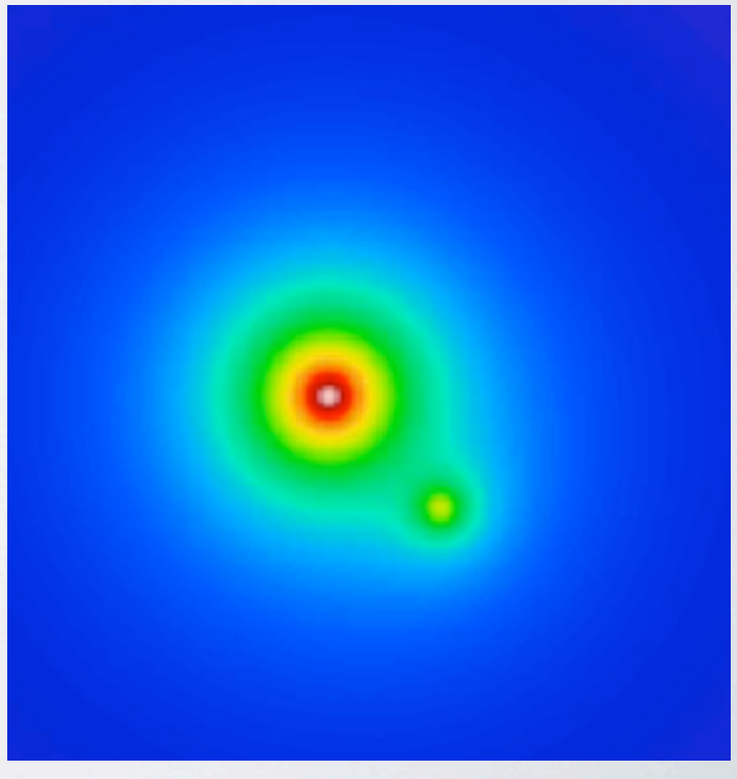
Bonafede et al. 2013

OBTAINING MOCK ROTATION MEASURE IMAGES

observed $RM = \int_0^d B_{los} n dl$

model for gas distribution

2 isothermal gas spheres in equilibrium matching X-ray observations



Bonafede et al. 2013

OBTAINING MOCK ROTATION MEASURE IMAGES

observed $RM = \int_0^d B_{los} n dl$

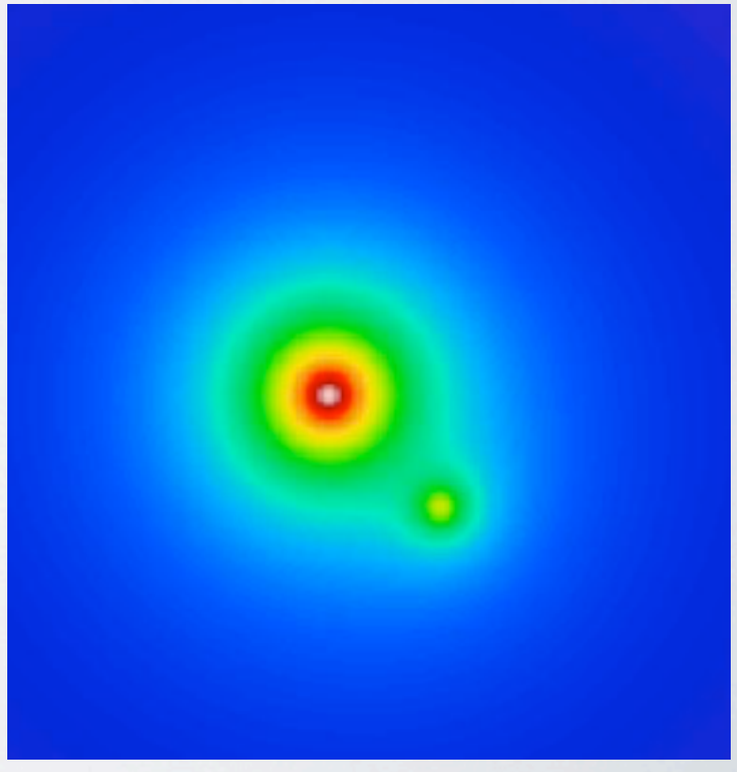
3D model for the magnetic field

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

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

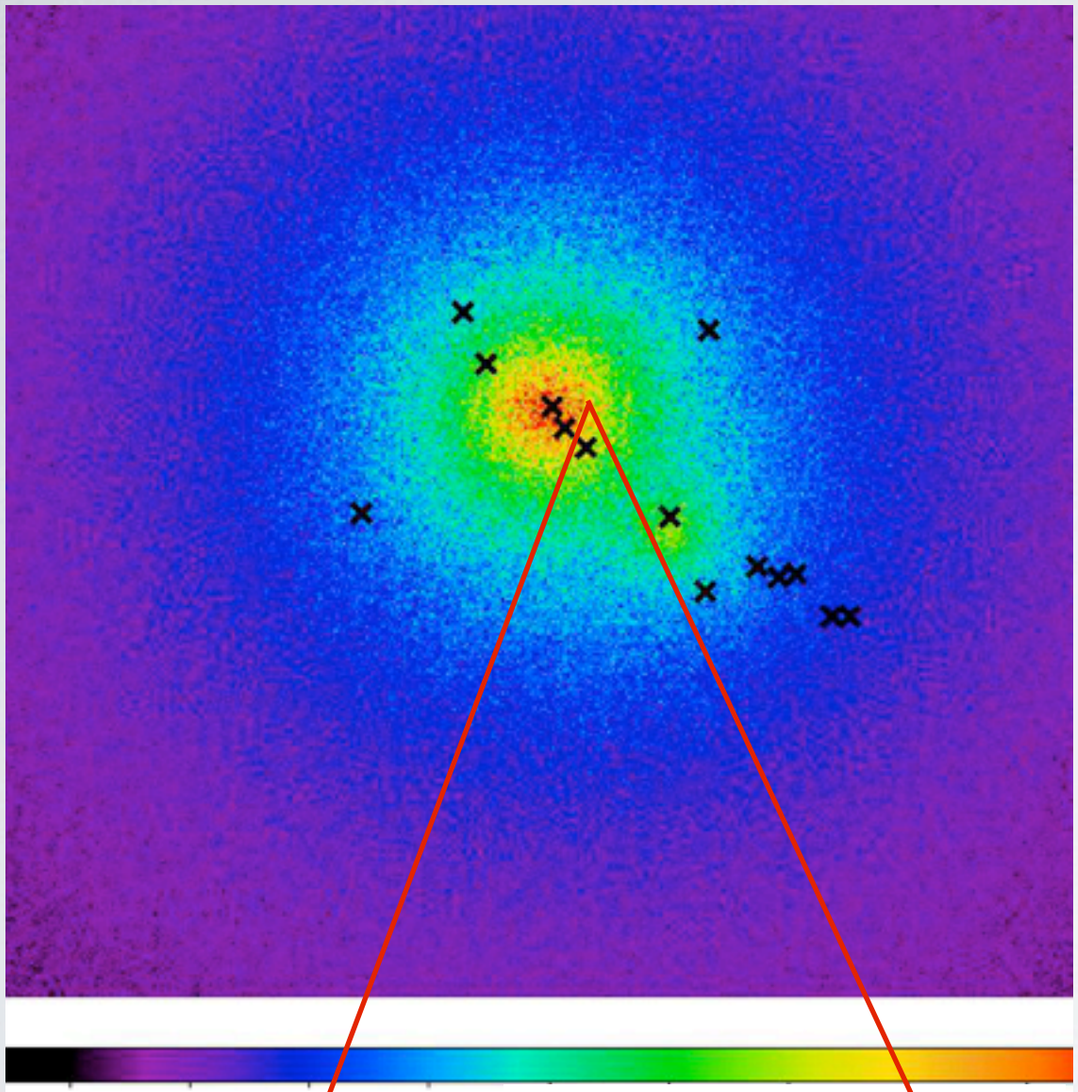
model for gas distribution

2 isothermal gas spheres in equilibrium matching X-ray observations

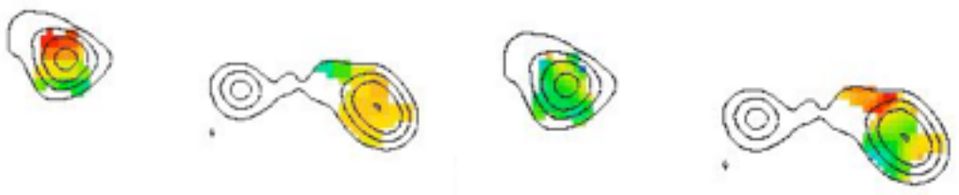


Bonafede et al. 2013

MOCK ROTATION MEASURE OBSERVATIONS



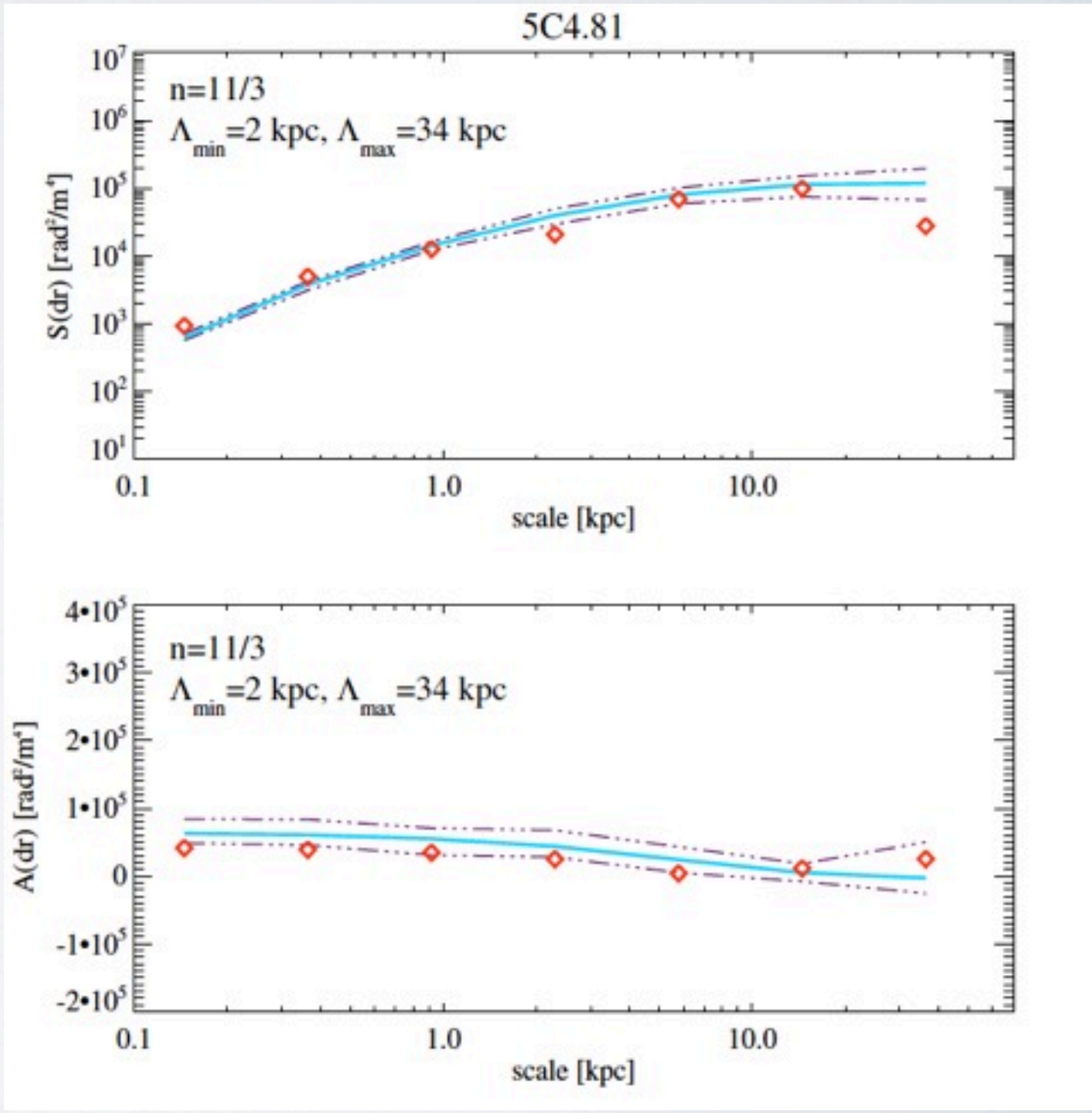
observed mock



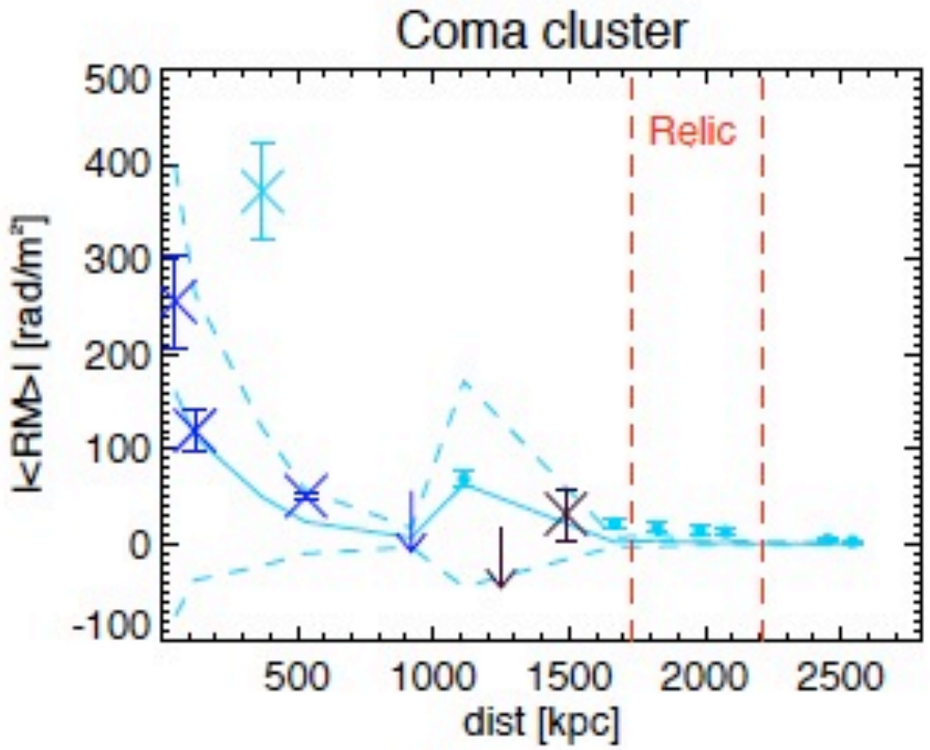
$$B(r)=B_0\left(\frac{n_e}{n_0}\right)^{\eta}$$

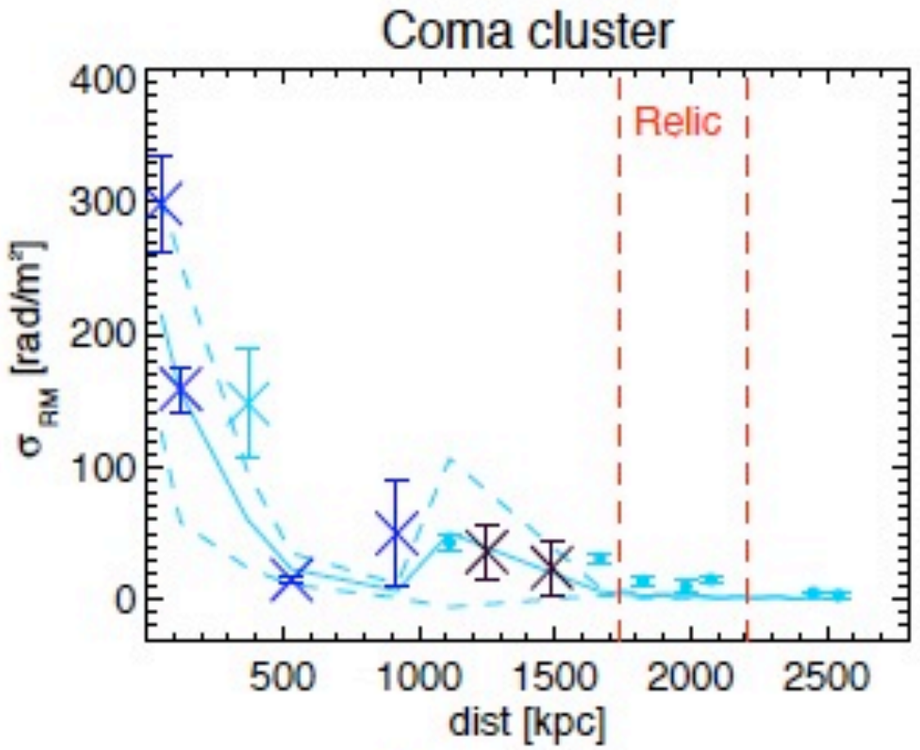
$$|B_k|^2 \propto k^{-n}$$

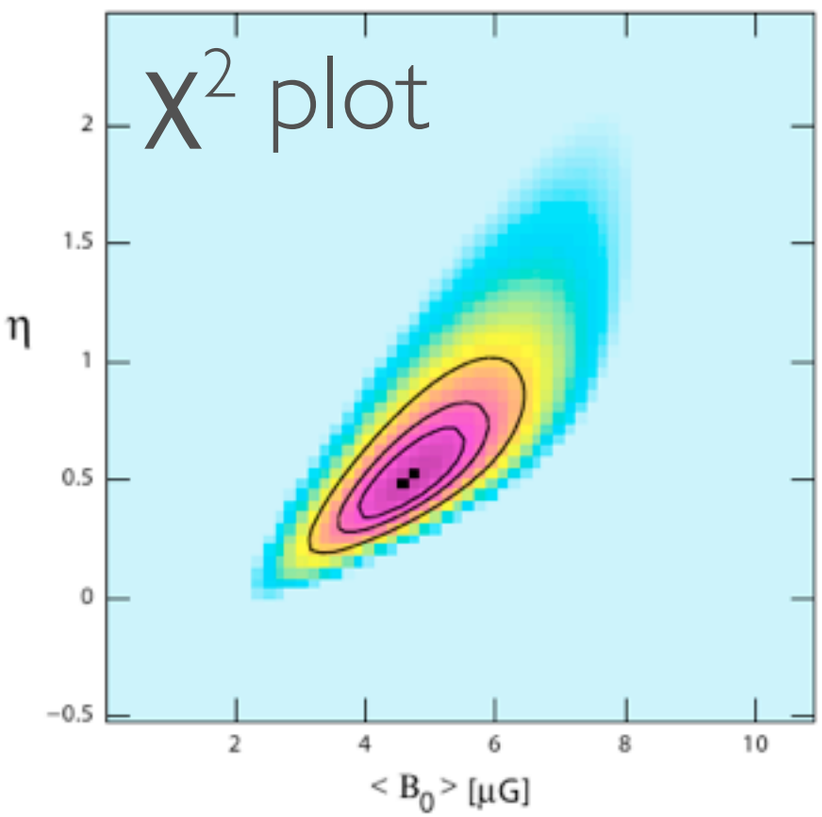
Fit of Structure function and autocorrelation function

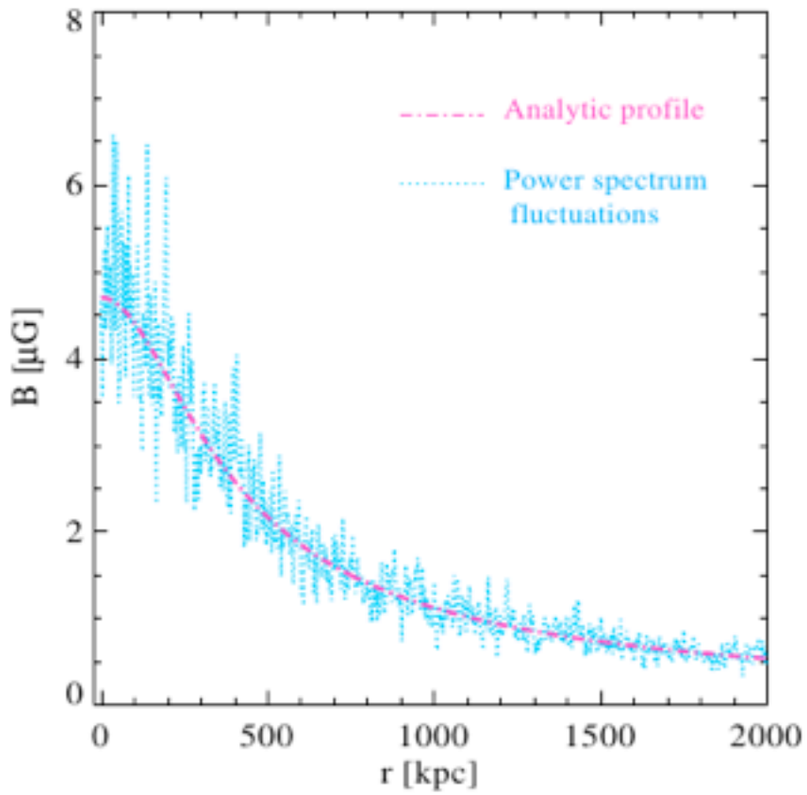


MAGNETIC FIELD IN THE COMA CLUSTER







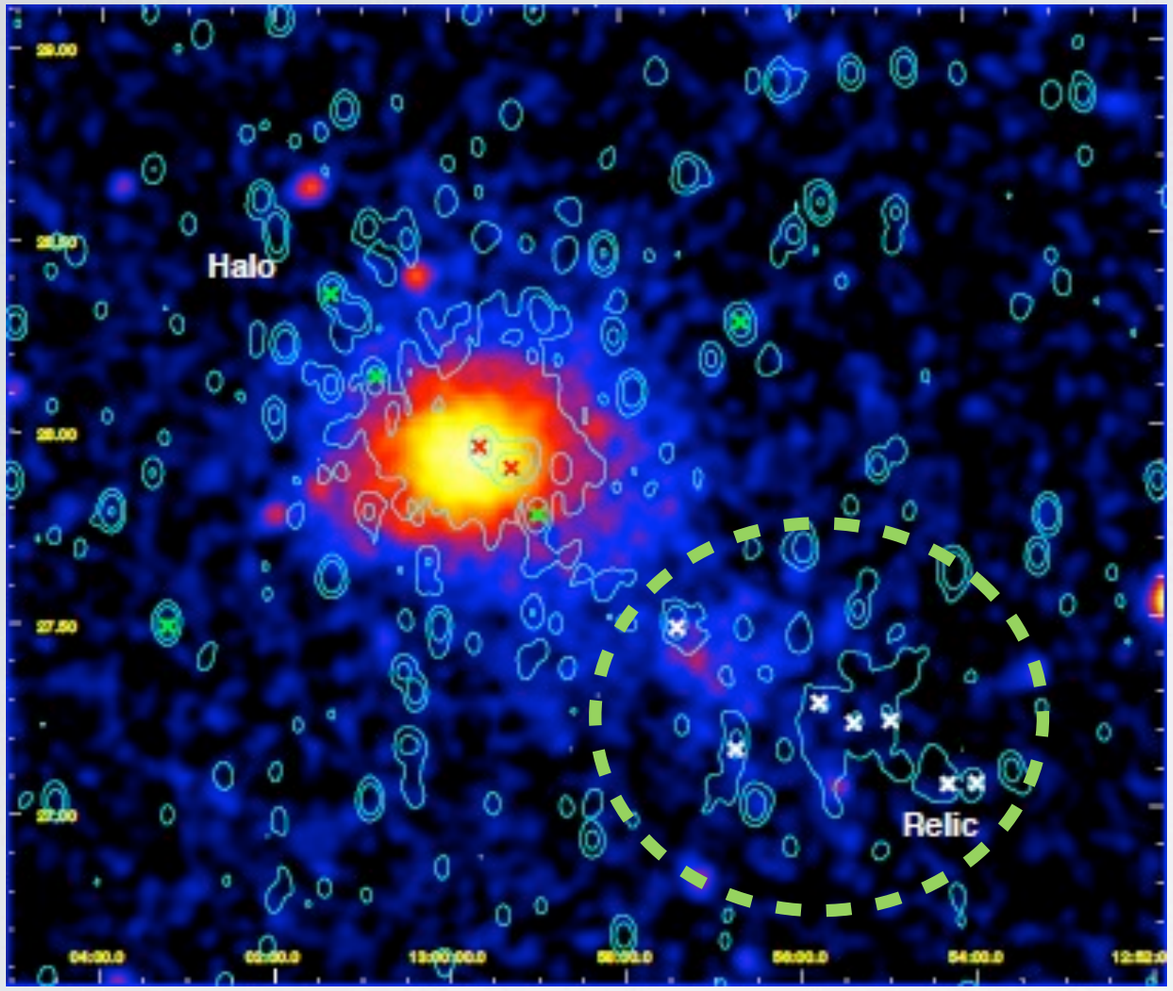


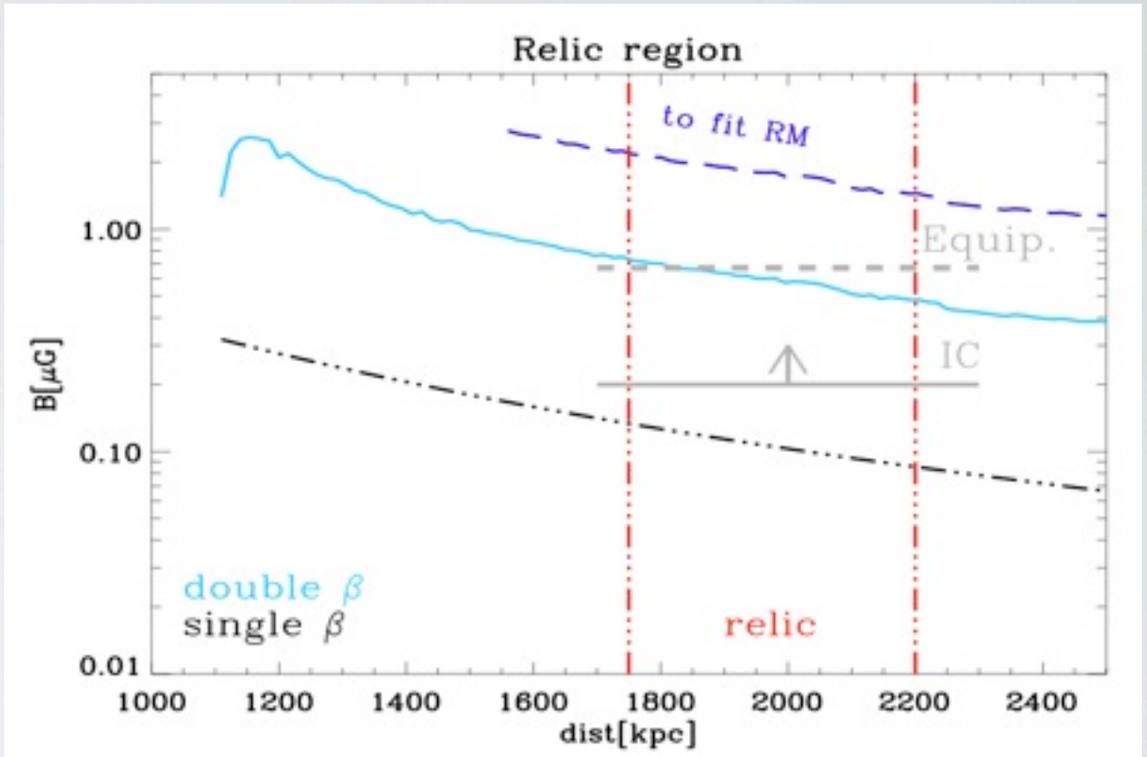
$$B \propto B_0 n_{gas}^{\eta}$$

Bo=4.7 μG,
η=0.5

Bonafede et al. 2010, 2013

B AMPLIFICATION IN THE RELIC?





- Magnetic field amplified by a factor 3 in the relic region
- no Jump at the relic (shock)
- filament?

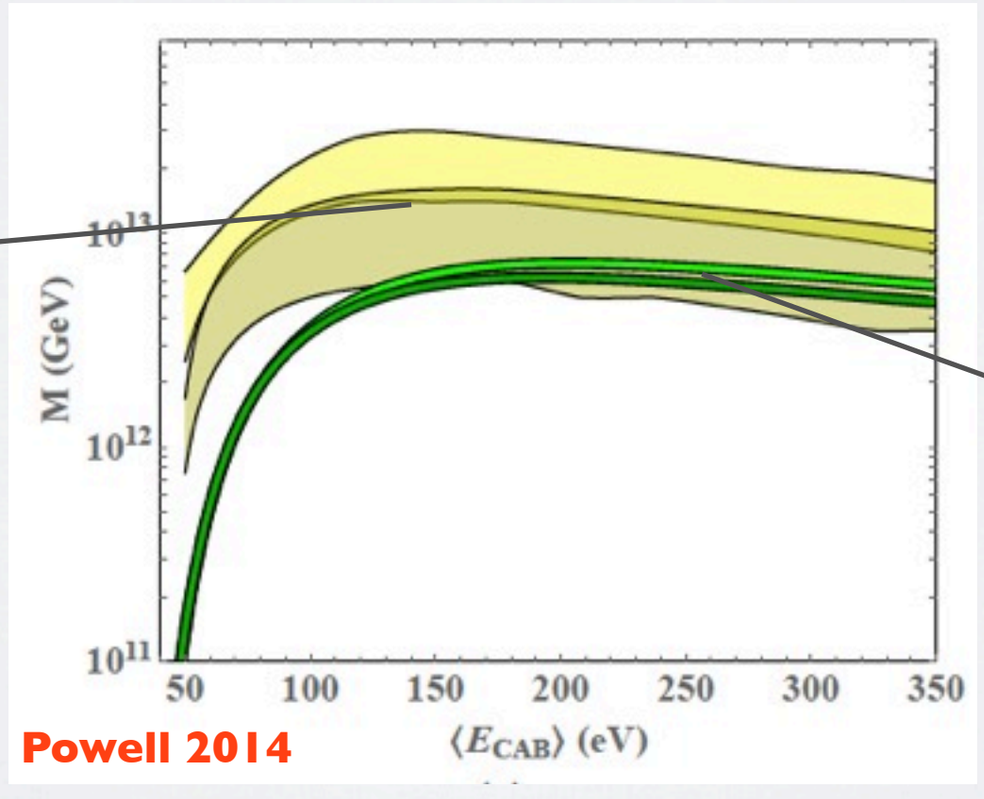
Bonafede et al. 2013

MAGNETIC FIELD IN COMA AND ALP

- Numerical simulations of ALP-photon conversion (central 0.5deg) 0.1 -1 kev + Coma magnetic field (Bonafede et al 2010)⇒ match the observed X-ray excess (Conlon et al. 2013)

- X-ray excess in the outskirts of Coma consistent ALP-photon conversion simulations + B field in the outskirts (Kraljic et al, 2014, Powell 2014)

Best fit regions for Coma outskirts



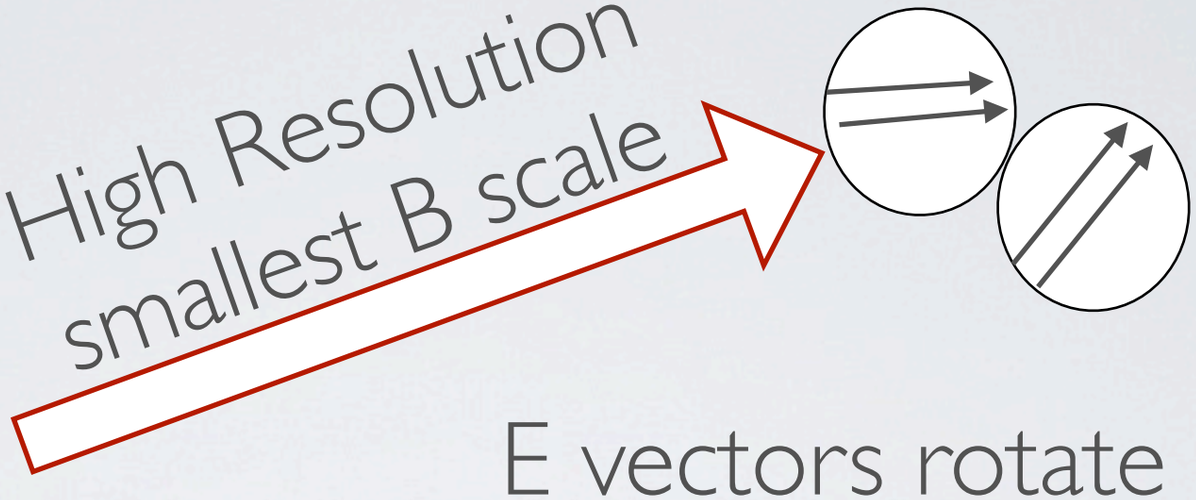
Powell 2014

Best fit regions for Coma centre

MAGNETIC FIELD THROUGH DEPOLARISATION

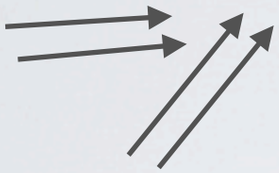
$$\Phi_{obs} = \Phi_{int} + RM\lambda^2$$

$$RM = \int_0^d B_{los} n dl$$

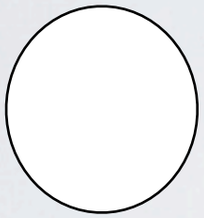


no change in polarisation

E vectors rotate by RM$\boldsymbol{\lambda}^2$



E vectors



resolution

MAGNETIC FIELD THROUGH DEPOLARISATION

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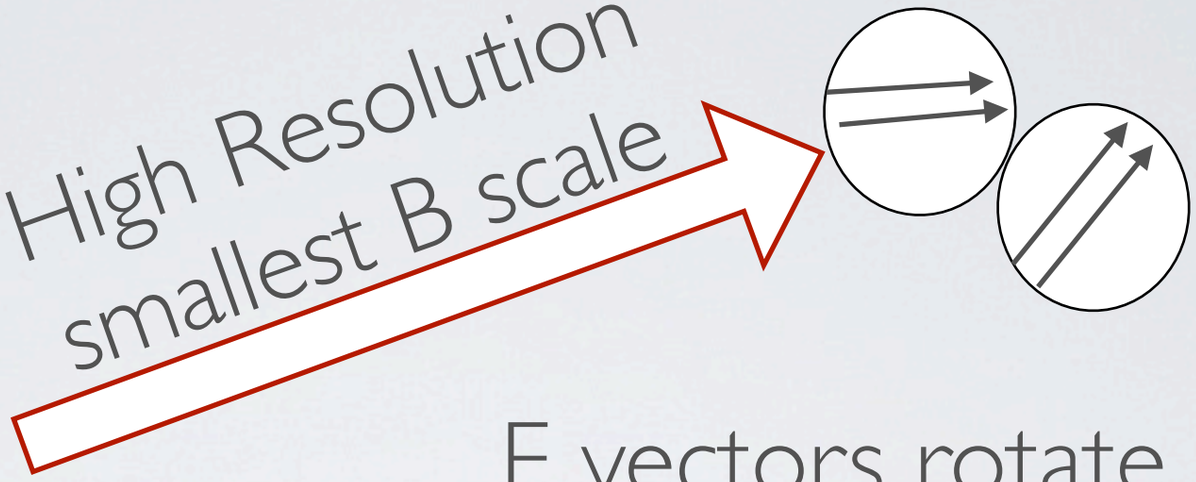
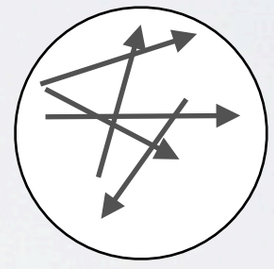


no change in polarisation

E vectors rotate by RM$\boldsymbol{\lambda}^2$

E vectors

resolution

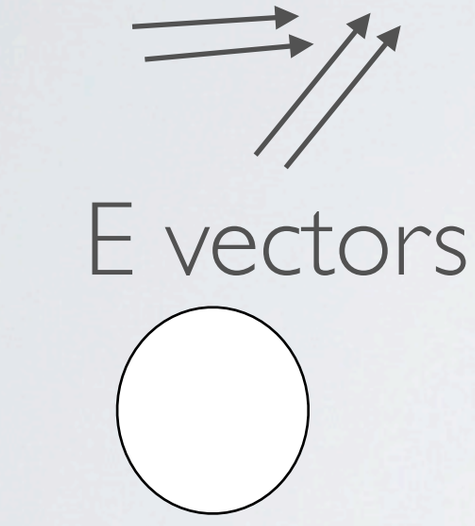


net polarisation becomes smaller

MAGNETIC FIELD THROUGH DEPOLARISATION

$$\Phi_{obs} = \Phi_{int} + RM\lambda^2$$

$$RM = \int_0^d B_{los} n dl$$



E vectors rotate by RM$\boldsymbol{\lambda}^2$

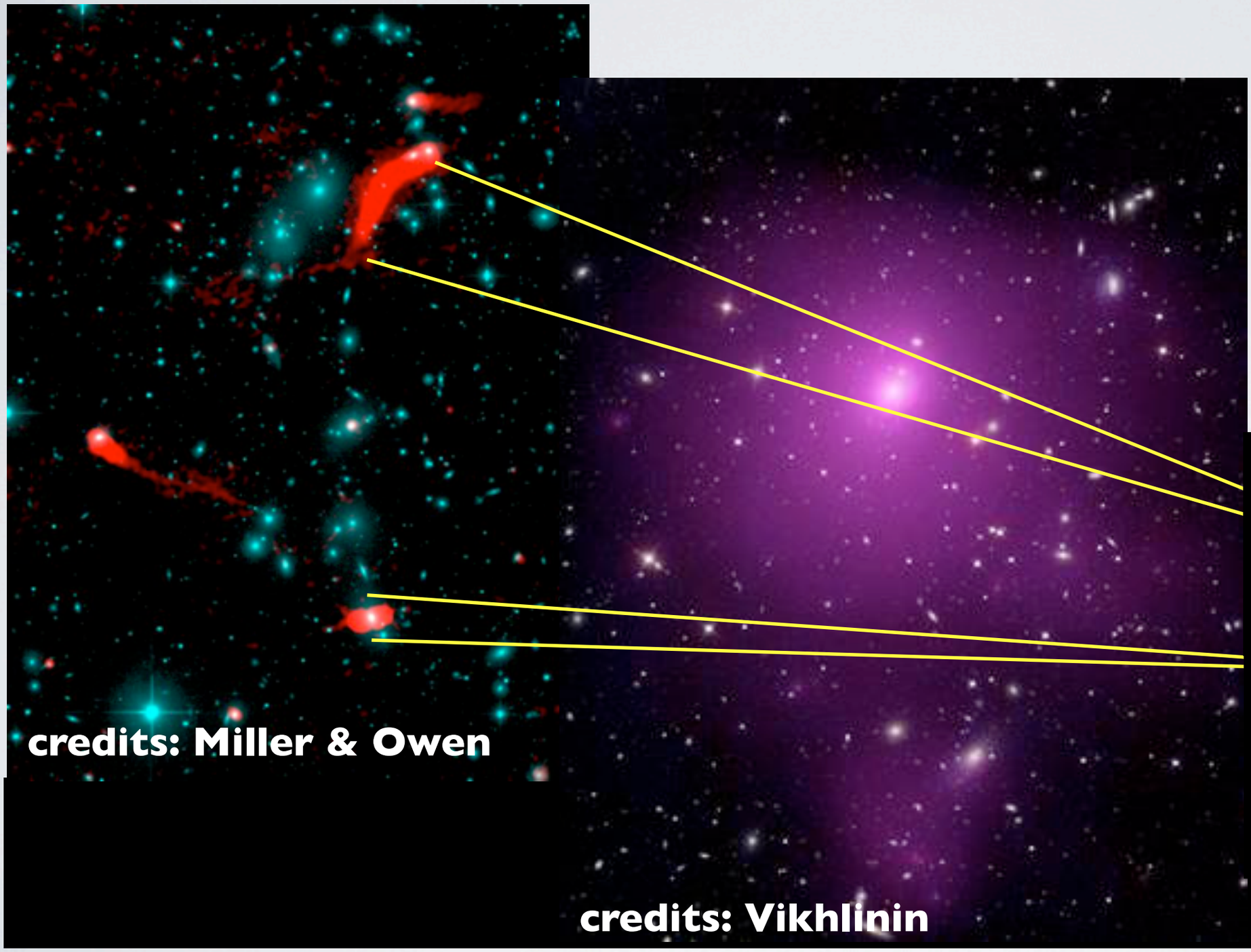
no change in polarisation

net polarisation becomes smaller

Low resolution ⇒ lower polarisation

Lower level of polarisation tracks regions with higher RM

MAGNETIC FIELD THROUGH DEPOLARISATION



credits: Miller & Owen

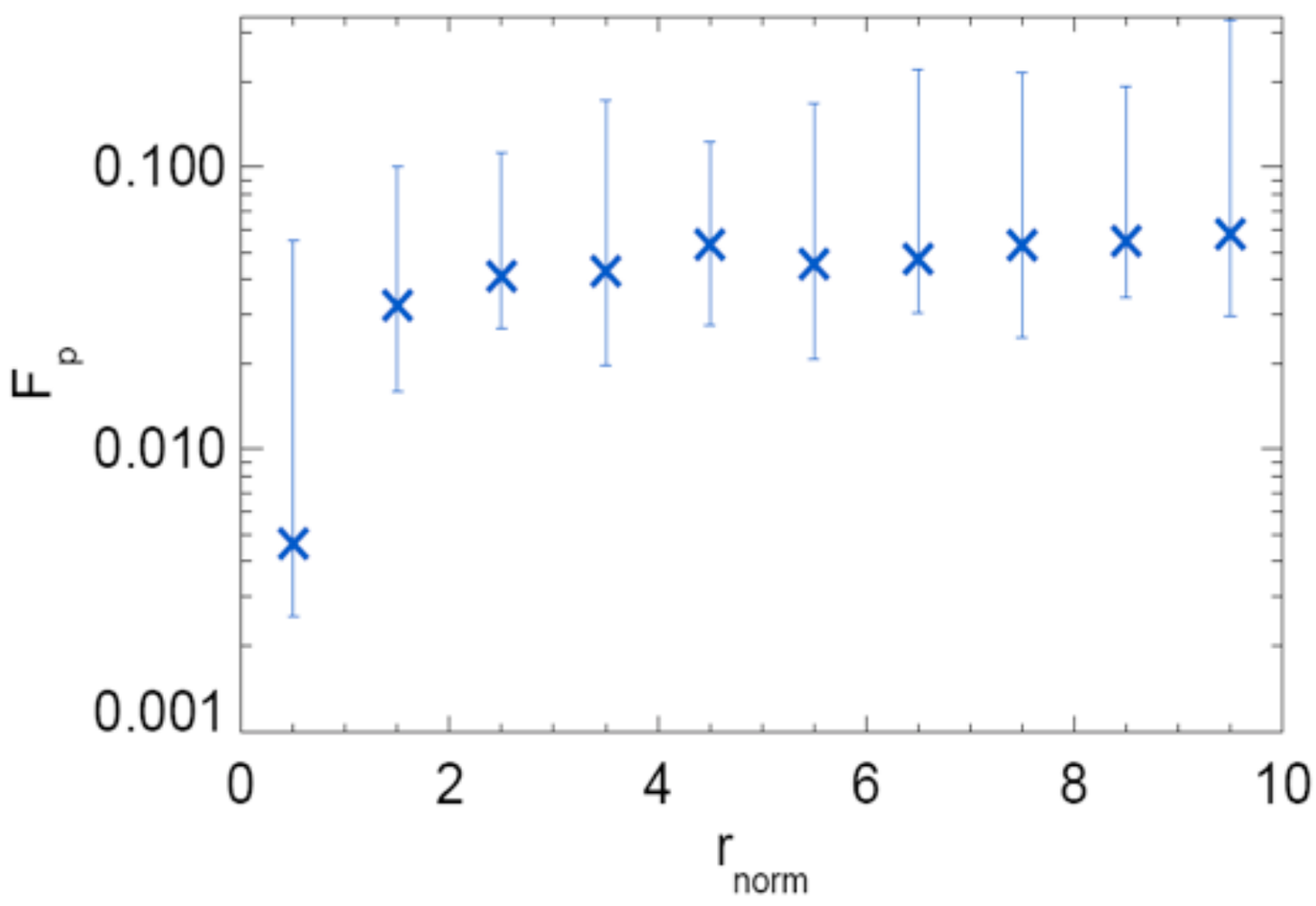
credits: Vikhlinin

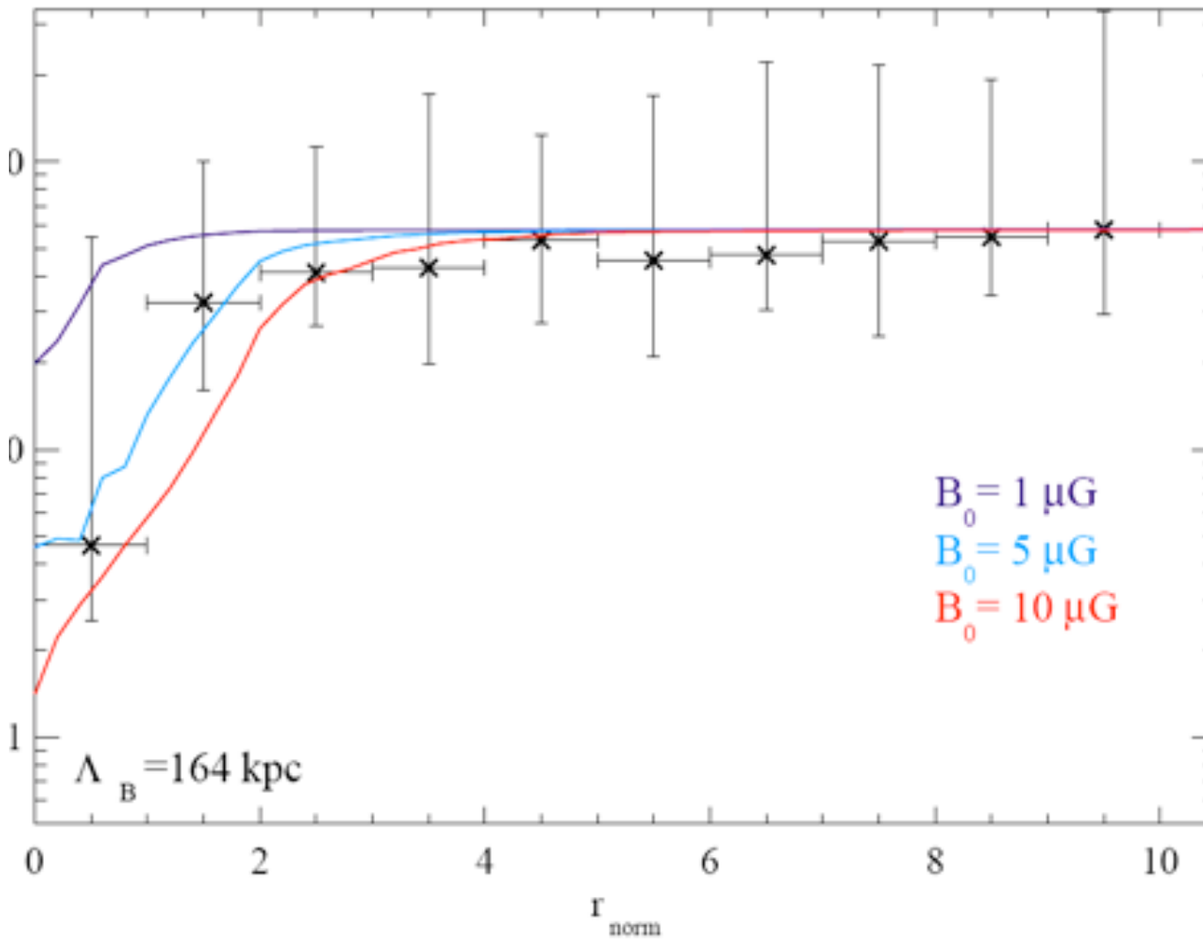
Higher RM
lower fractional polarisation

lower RM
higher fractional polarisation

MAGNETIC FIELD THROUGH DEPOLARISATION

Sample of 32 massive galaxy clusters from HIFLUGCS (Reiprich & Boehringer 2002)
Northern VLA Sky Survey 1.4 GHz, 45" resolution

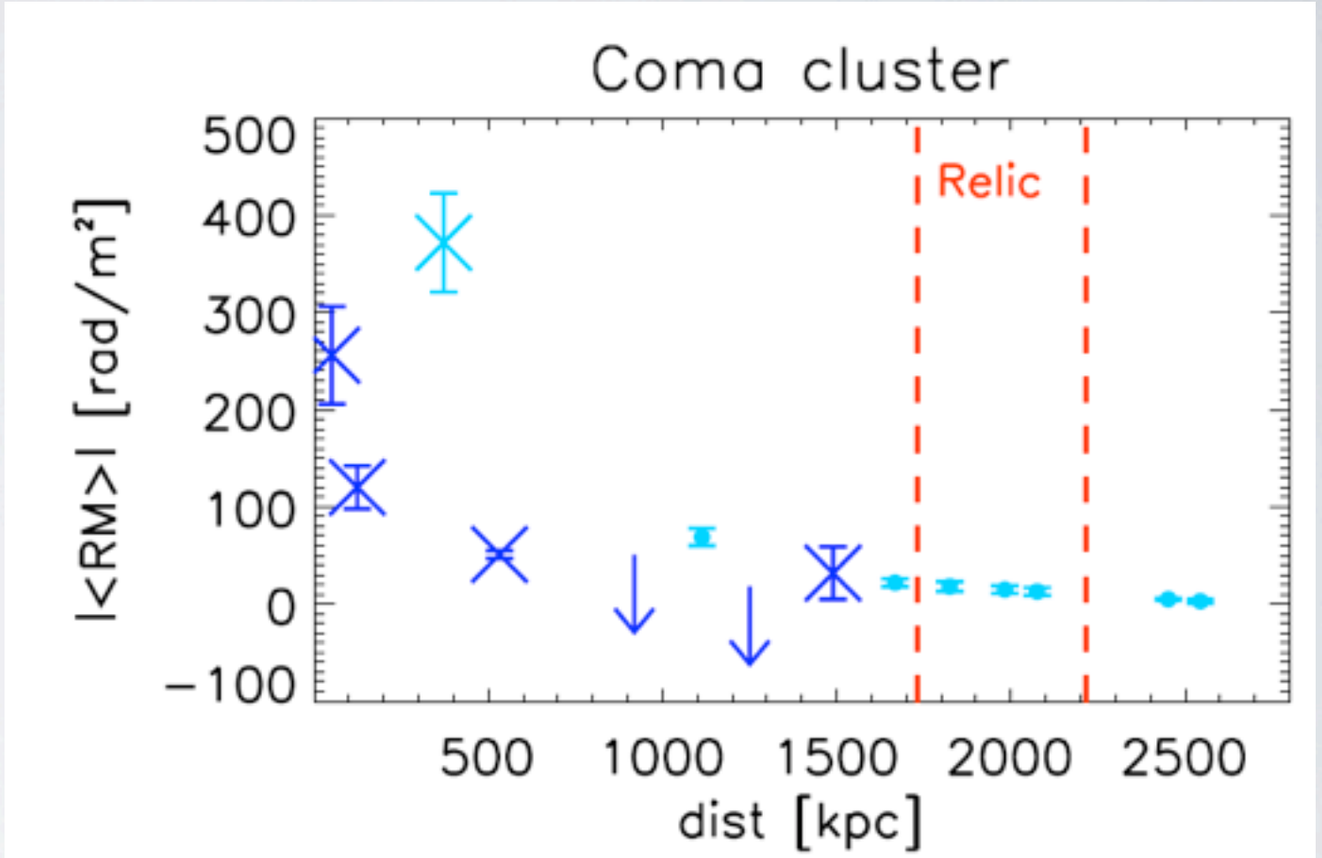




Magnetic field common constituent of clusters
best fit with B_0=5μG

LIMITS

1) Main limit to B studies in clusters today: Number of sources detectable through the cluster

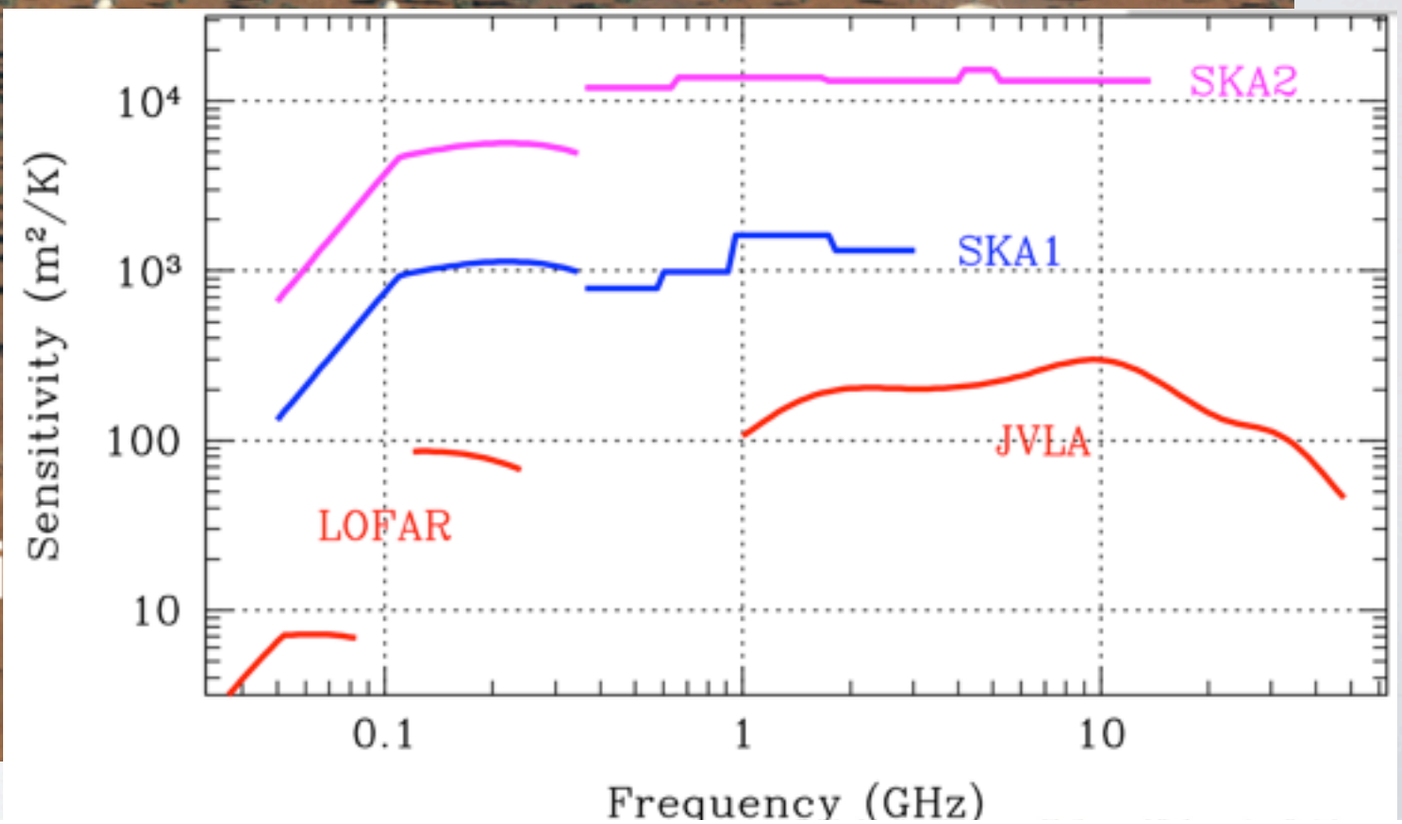


14 sources
~150h observing time

2) Cluster members: local effect?

FUTURE PROSPECTS
THE SQUARE KILOMETER ARRAY

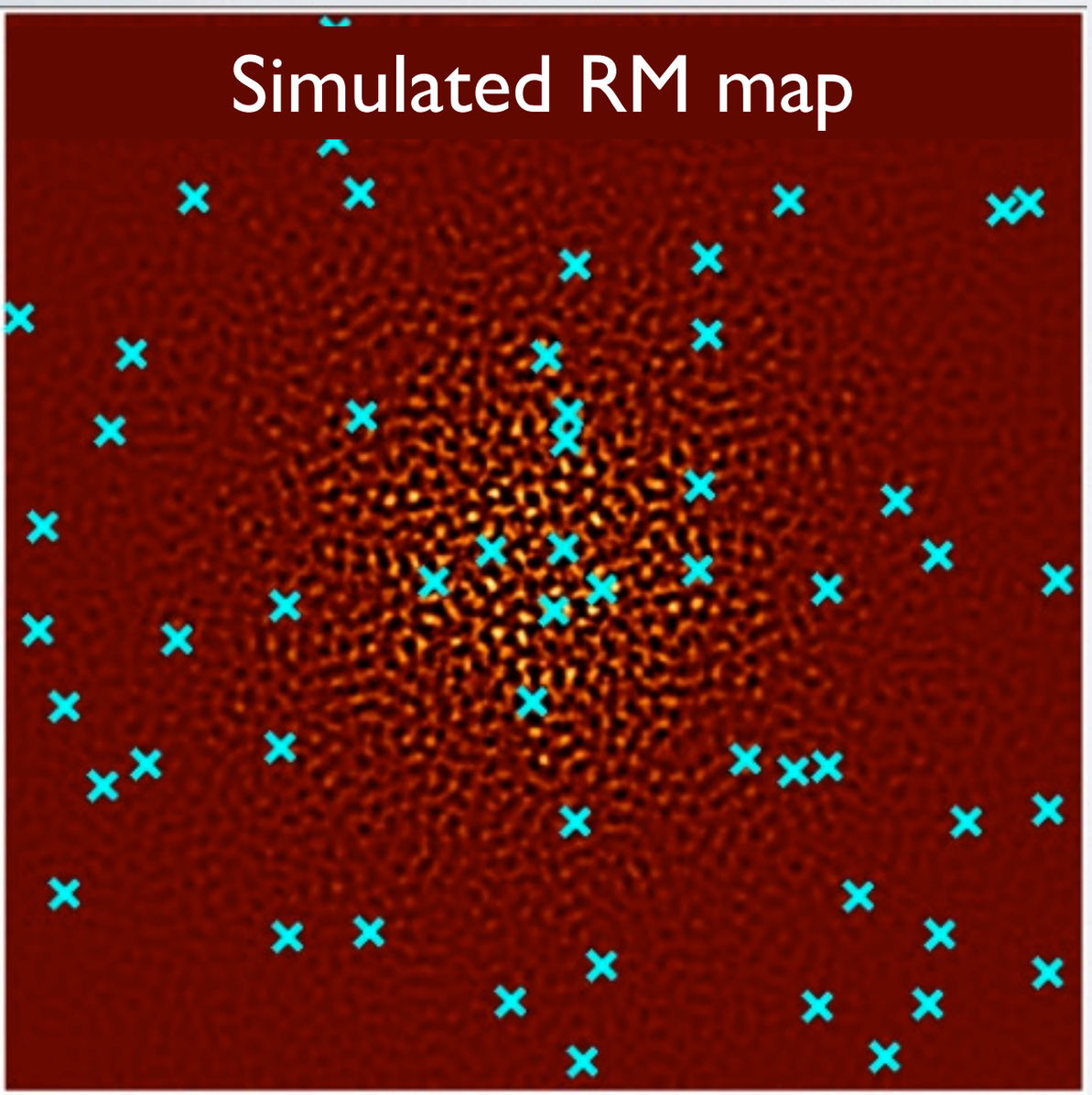
FUTURE PROSPECTS
THE SQUARE KILOMETER ARRAY

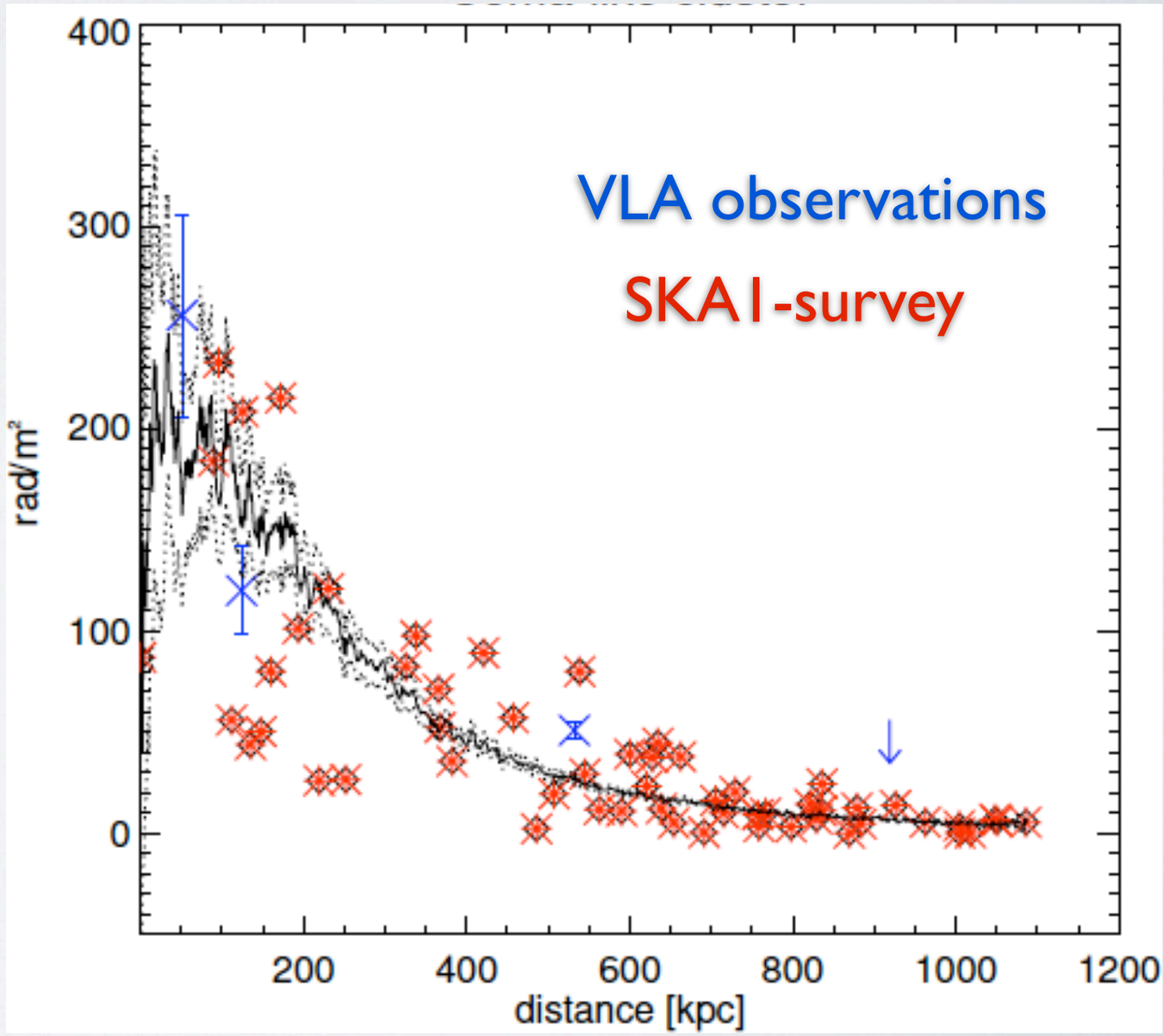


SKA1 A COMA-LIKE CLUSTER

300 polarised
sources/sq deegree

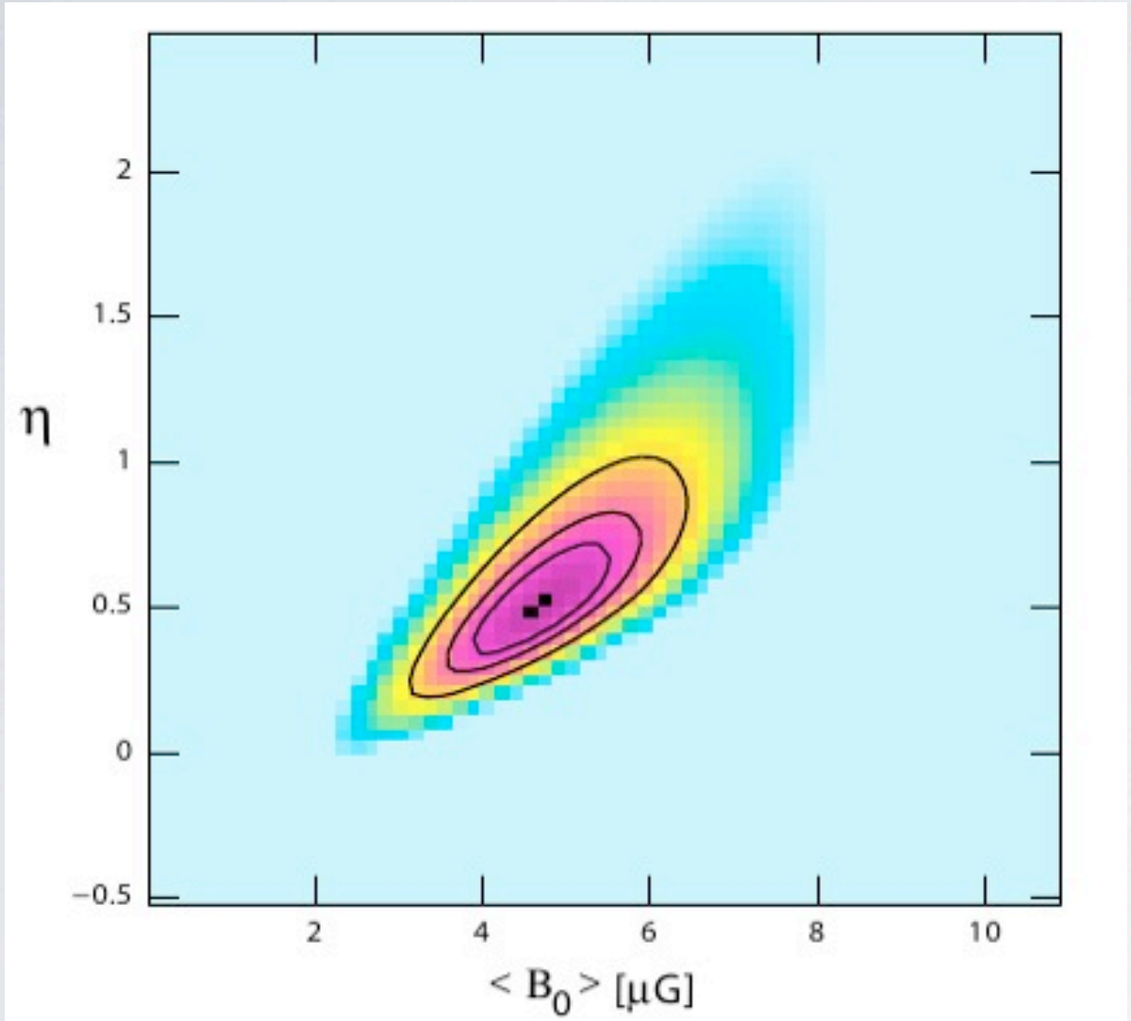
$$B \propto B_0 n_{gas}^{\eta}$$





SKA1 A COMA-LIKE CLUSTER

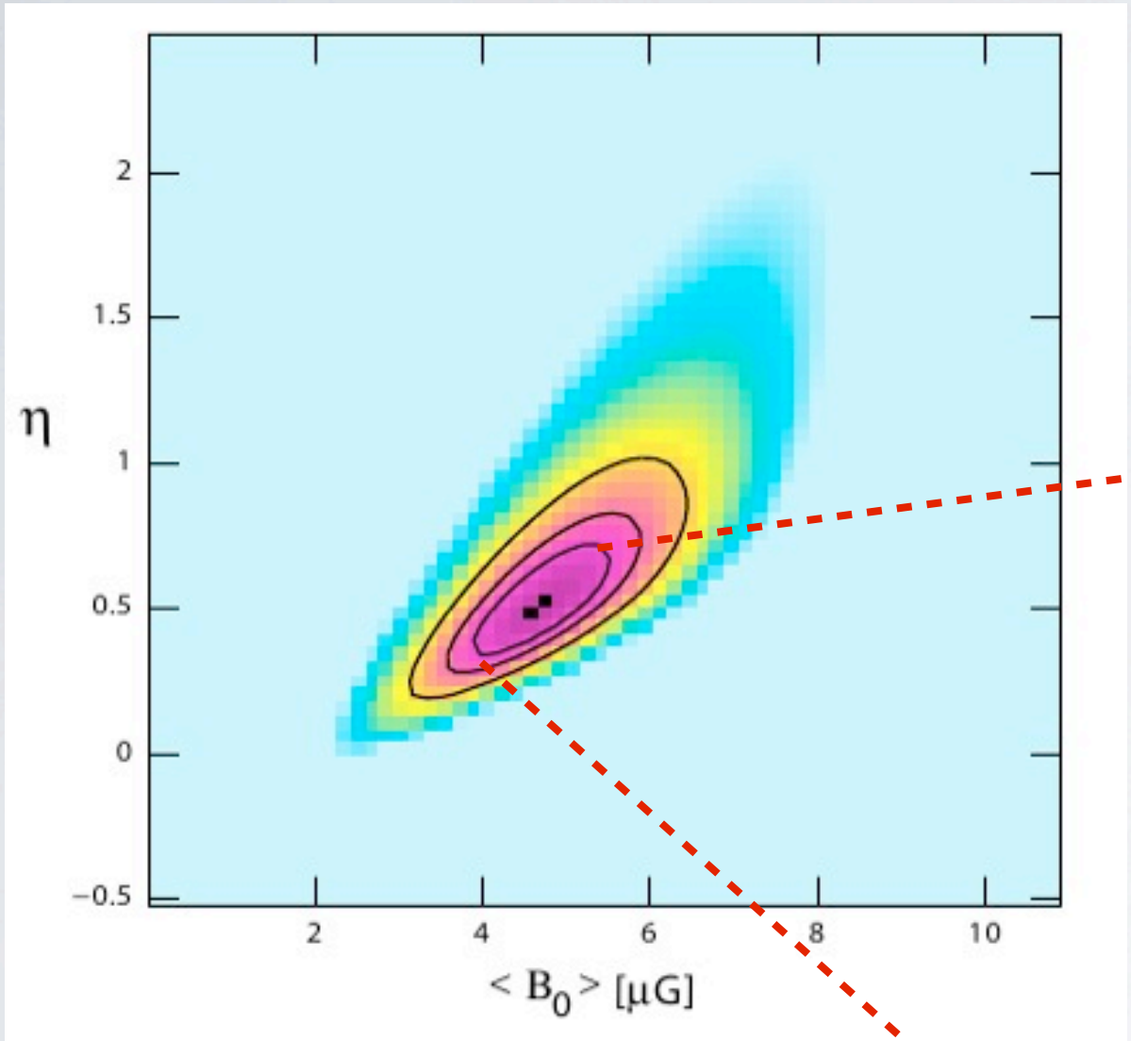
VLA data -> χ^2 plane



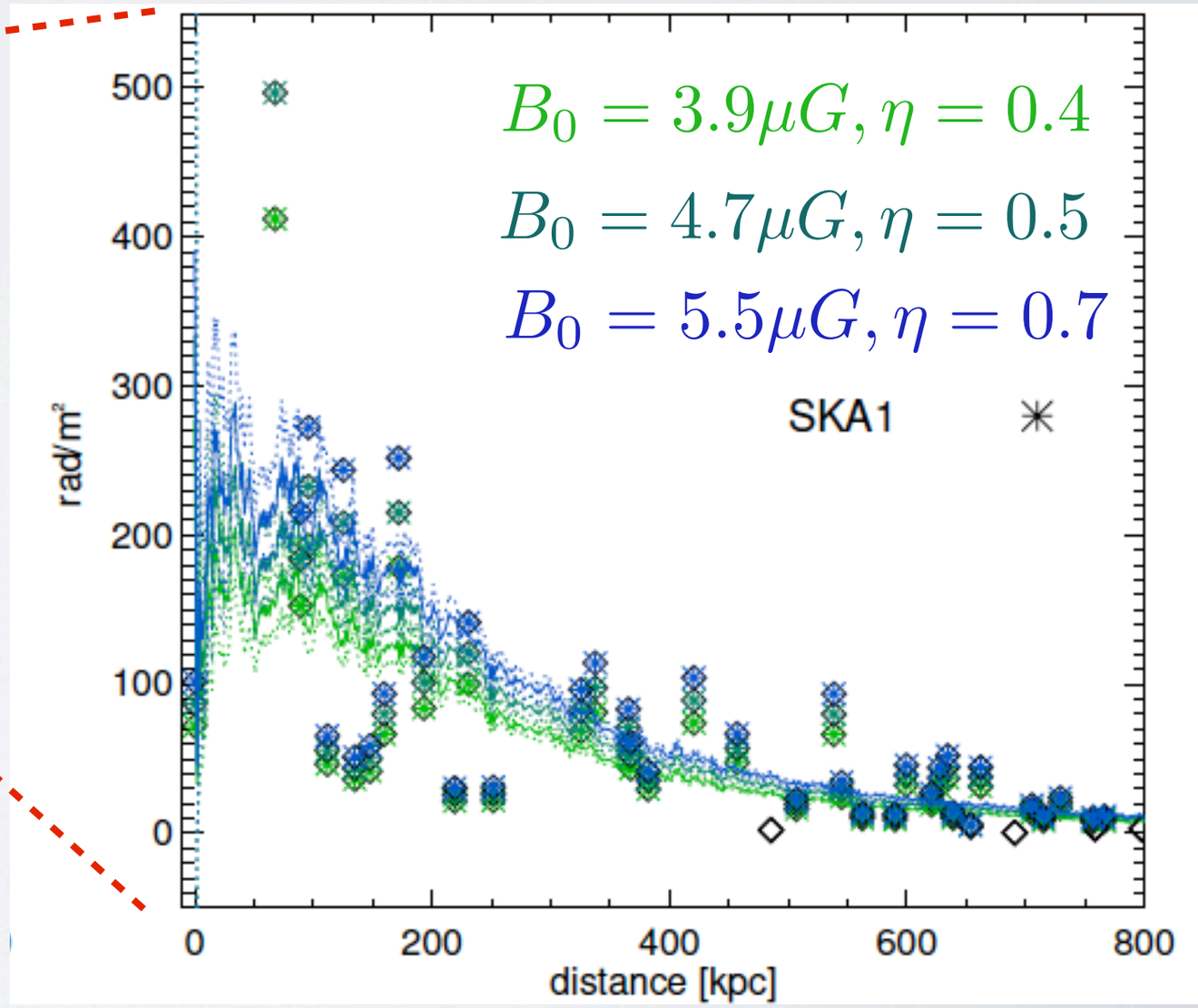
$$B \propto B_0 n_{gas}^{\eta}$$

SKA1 A COMA-LIKE CLUSTER

VLA data -> χ^2 plane



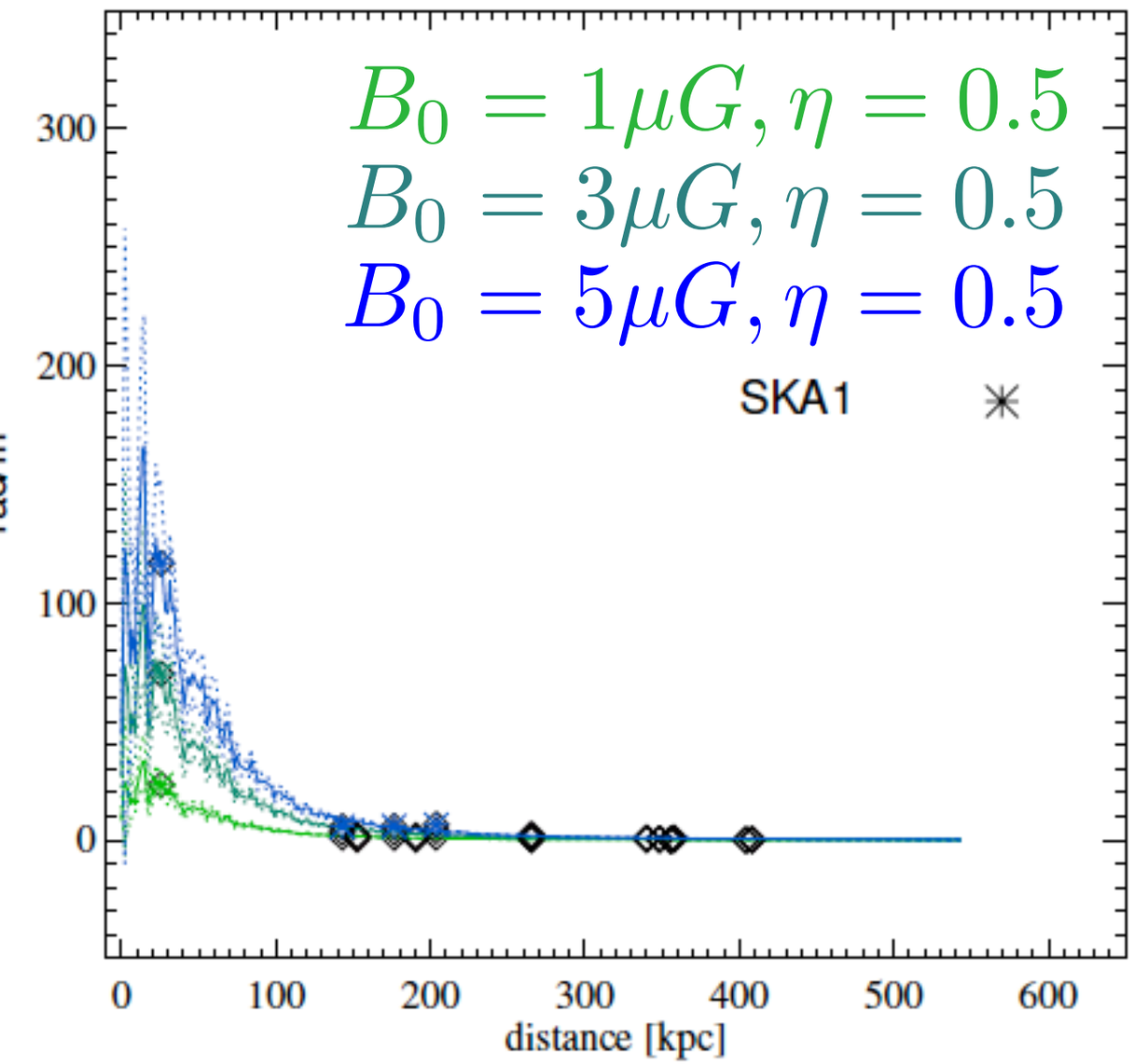
$$B \propto B_0 n_{gas}^{\eta}$$



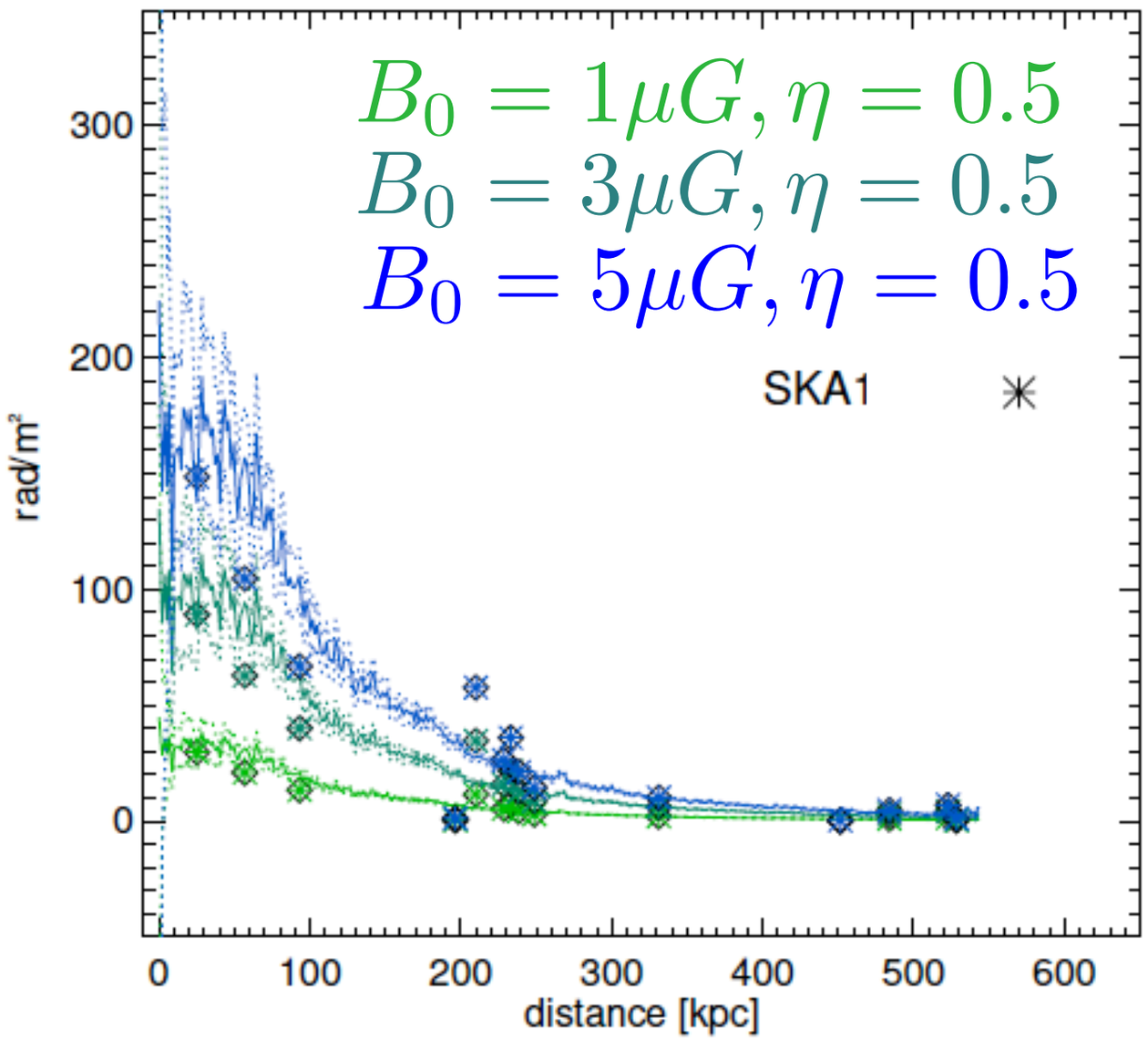
SKA1 LOWER MASS CLUSTERS AND GROUPS

$$B \propto B_0 n_{gas}^{\eta}$$

$M \approx 10^{13} M_{\odot}$



$M \approx 10^{15} M_{\odot}$



CONCLUSIONS

- Galaxy clusters: B on Mpc scale - best place to search for ALP
- Faraday Rotation most powerful technique
- Future is bright: SKA B in samples of clusters and groups