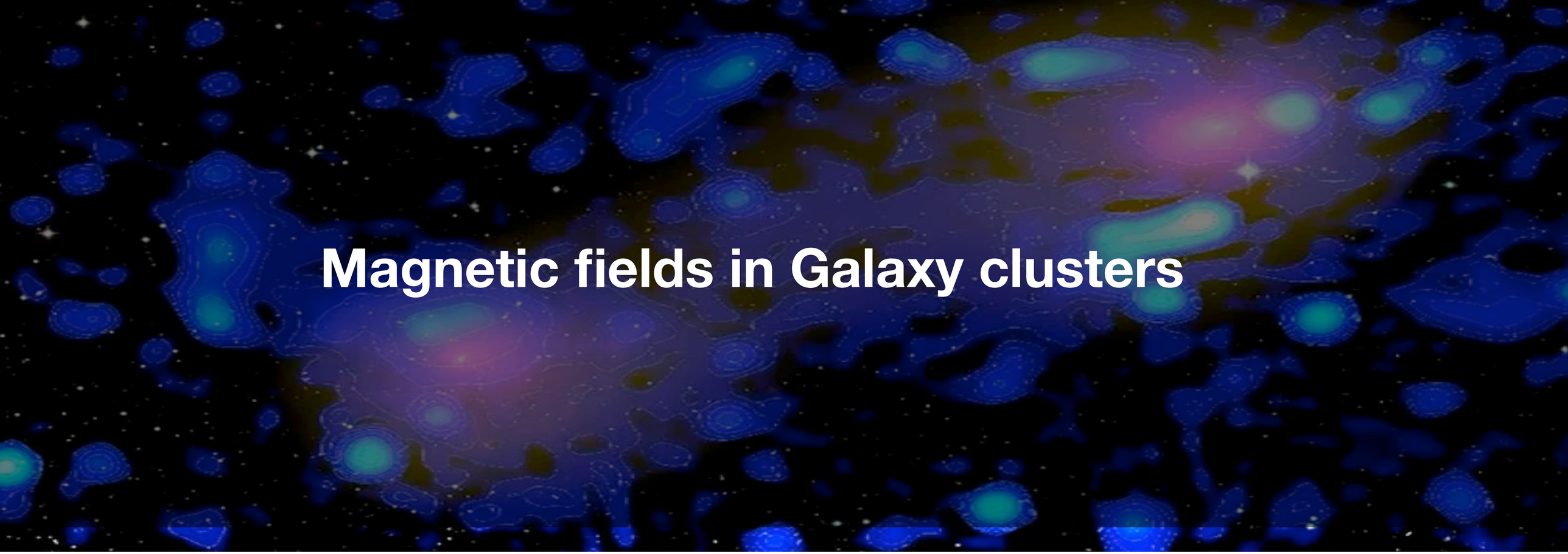


Magnetic fields in Galaxy clusters

Annalisa Bonafede

Università di Bologna

&

IRA INAF

THIS TALK

Part I:
techniques to constrain magnetic fields using radio polarisation observations

Quiz 1

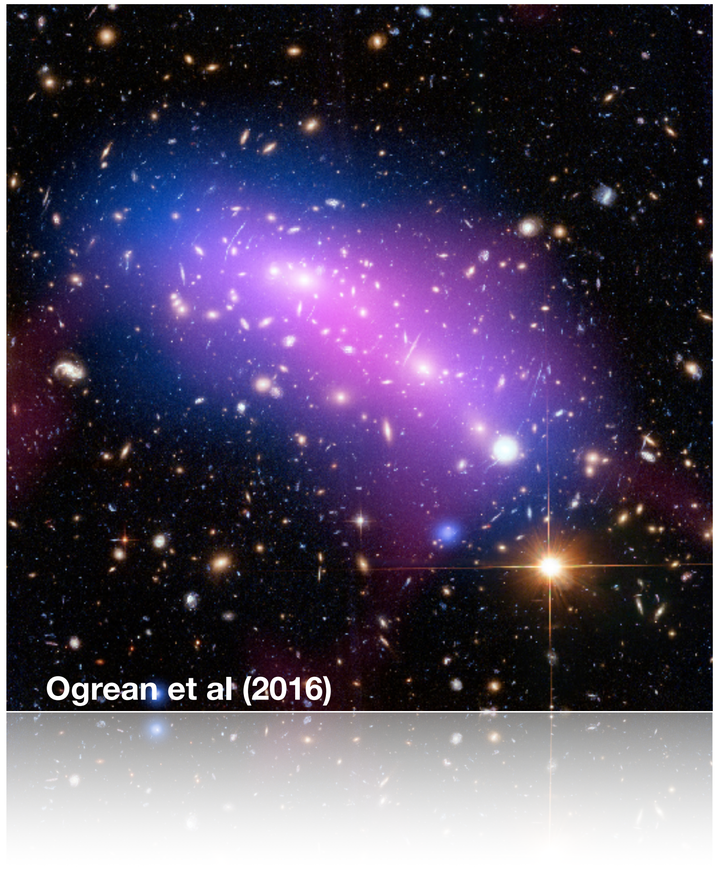
Part II:
Magnetic field estimates in galaxy clusters
results, limitations and perspectives

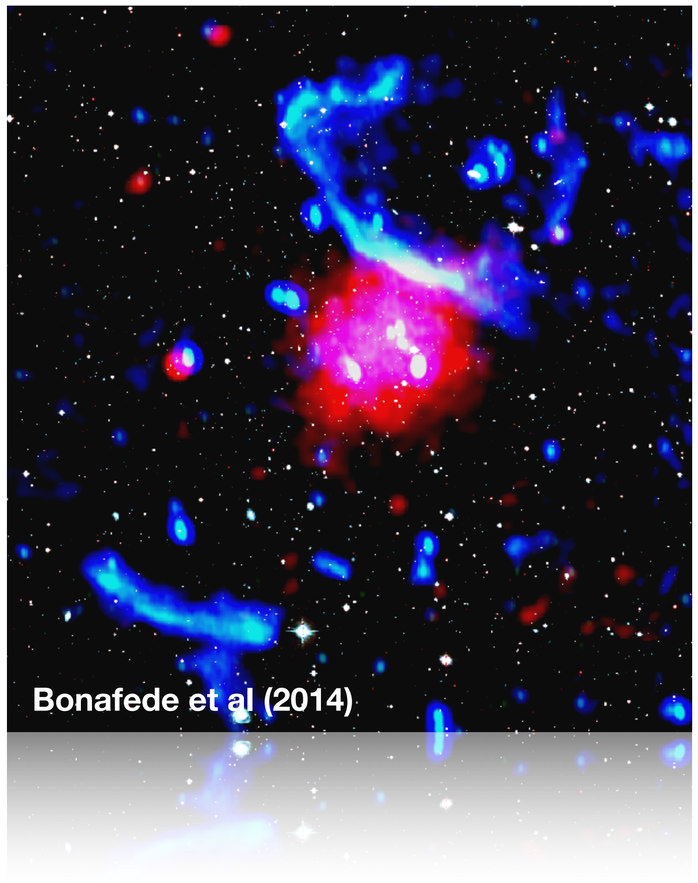
Quiz 2

Part III:
Origin and amplification of the magnetic field in galaxy clusters

RADIO DIFFUSE EMISSION IN CLUSTERS

van Weeren et al (2019)


Ogrean et al (2016)


Bonafede et al (2014)

Radio halos, mini halos, and relics
probe the existence of magnetic fields but do not
offer a way to constrain them

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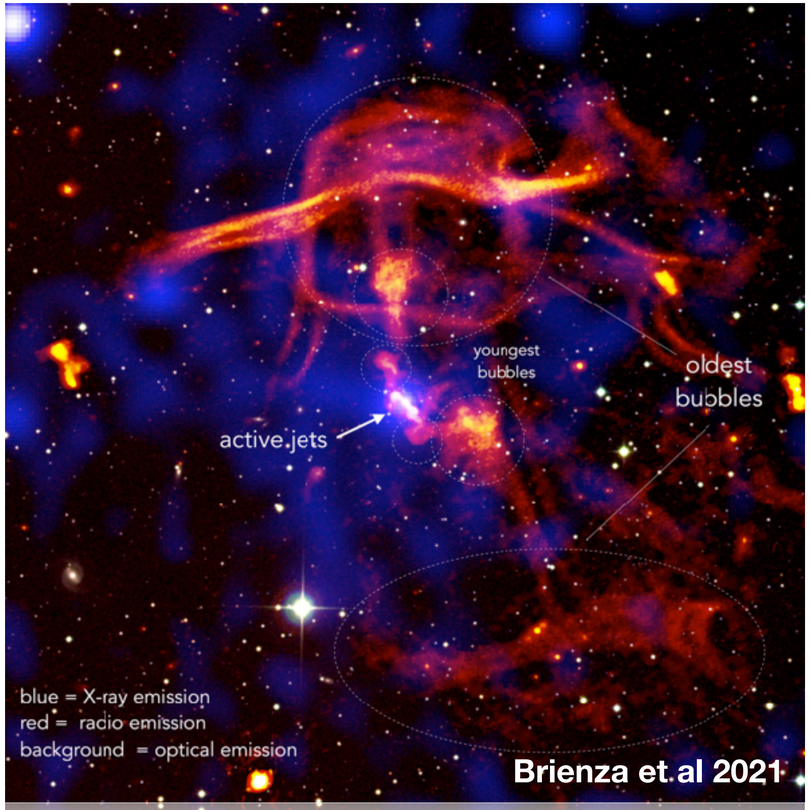
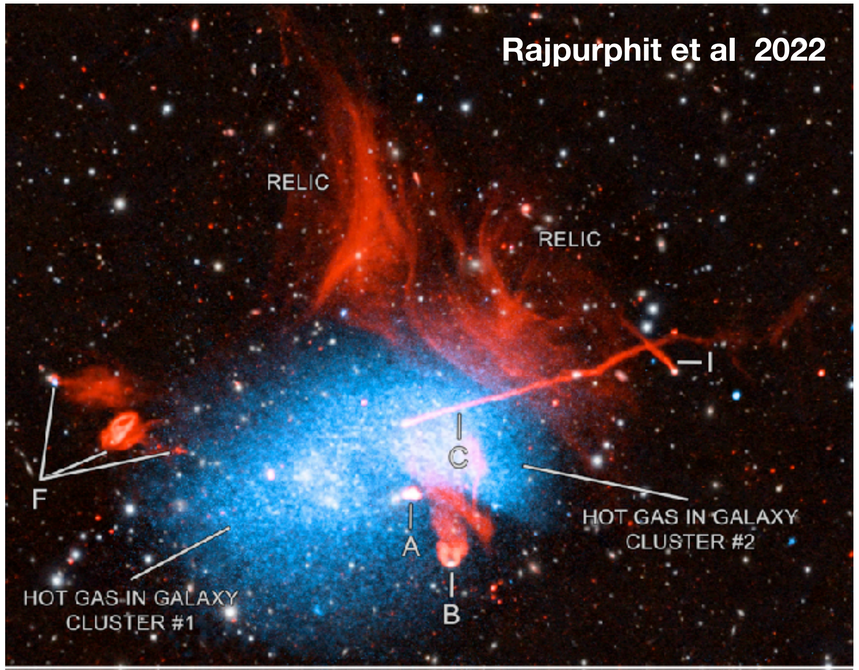
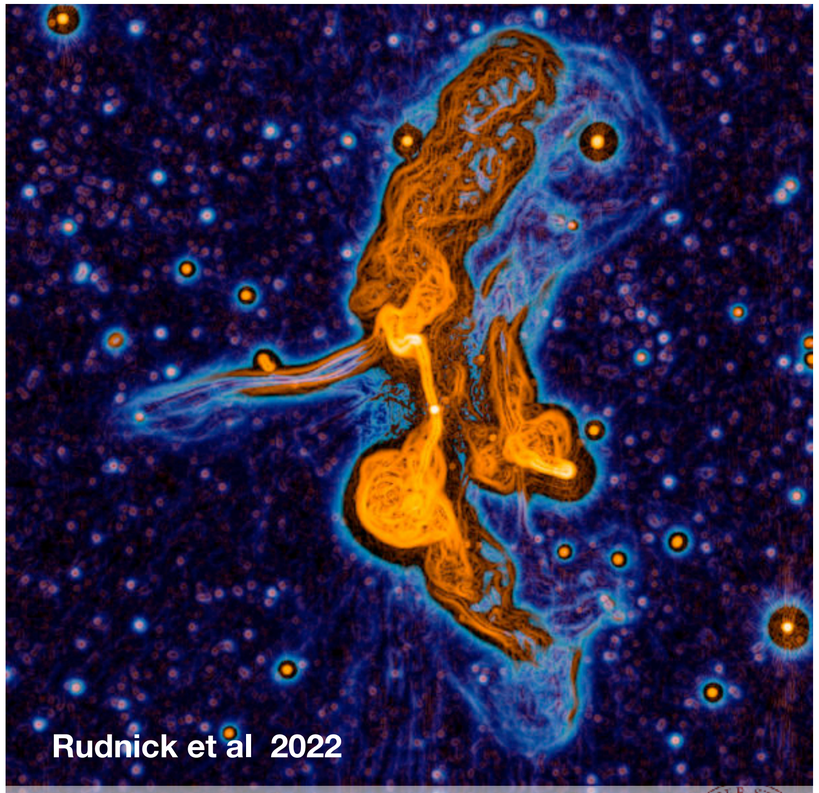
EVIDENCE FOR B IN CLUSTERS: FILAMENTS AND SUBSTRUCTURES



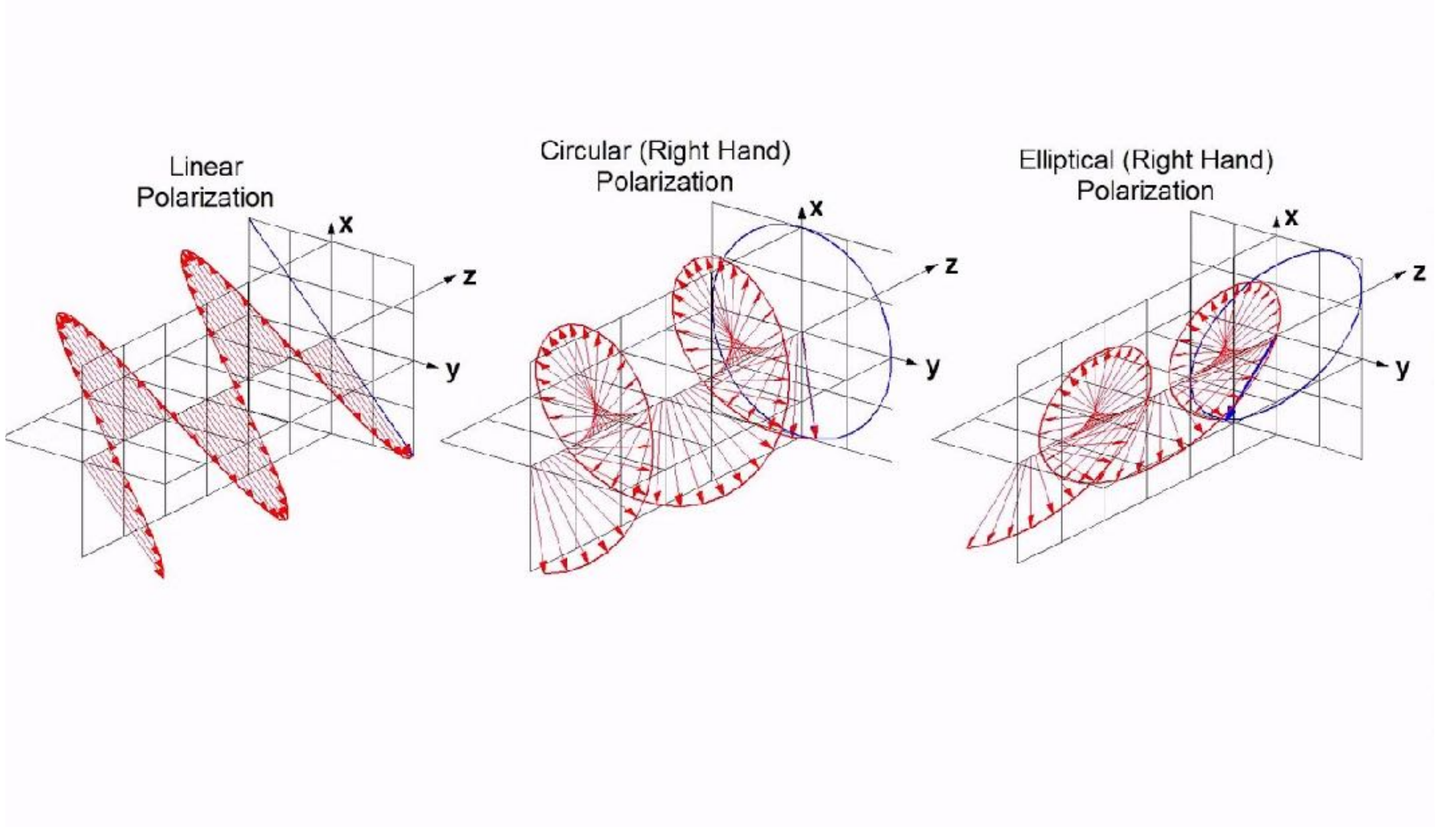




HOW CAN WE CONSTRAIN MAGNETIC FIELDS IN CLUSTERS?

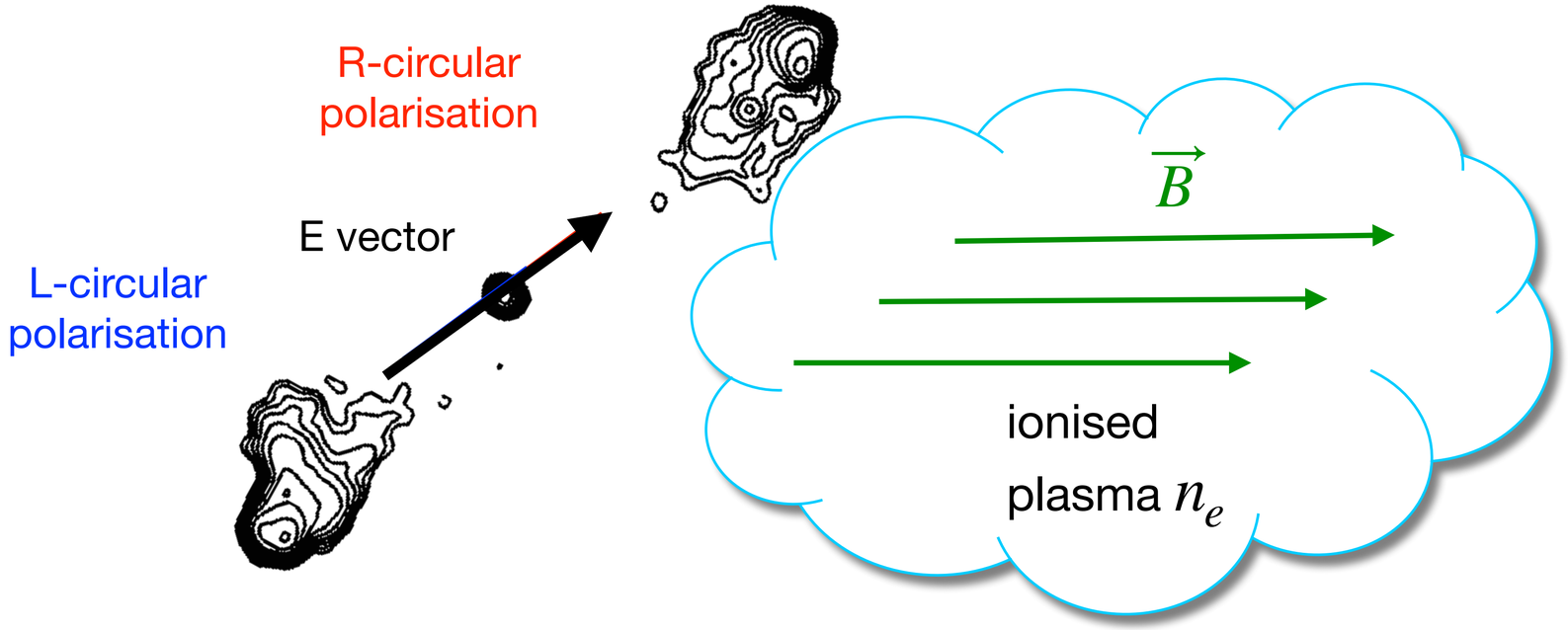
Back to the basics:

Polarisation of electromagnetic waves indicates the direction of oscillation of the electric field of the wave



Synchrotron emission is linearly polarised, with $\vec{E}$ perpendicular to $\vec{B}$ of the source

THE FARADAY EFFECT



$$n_{R,L} = \left(1 - \frac{\omega_p^2}{\omega^2 \pm \omega\Omega_e}\right)$$

ω_p = plasma frequency

ω = freq of emitted radiation

Ω_e = Lorentz freq of electrons

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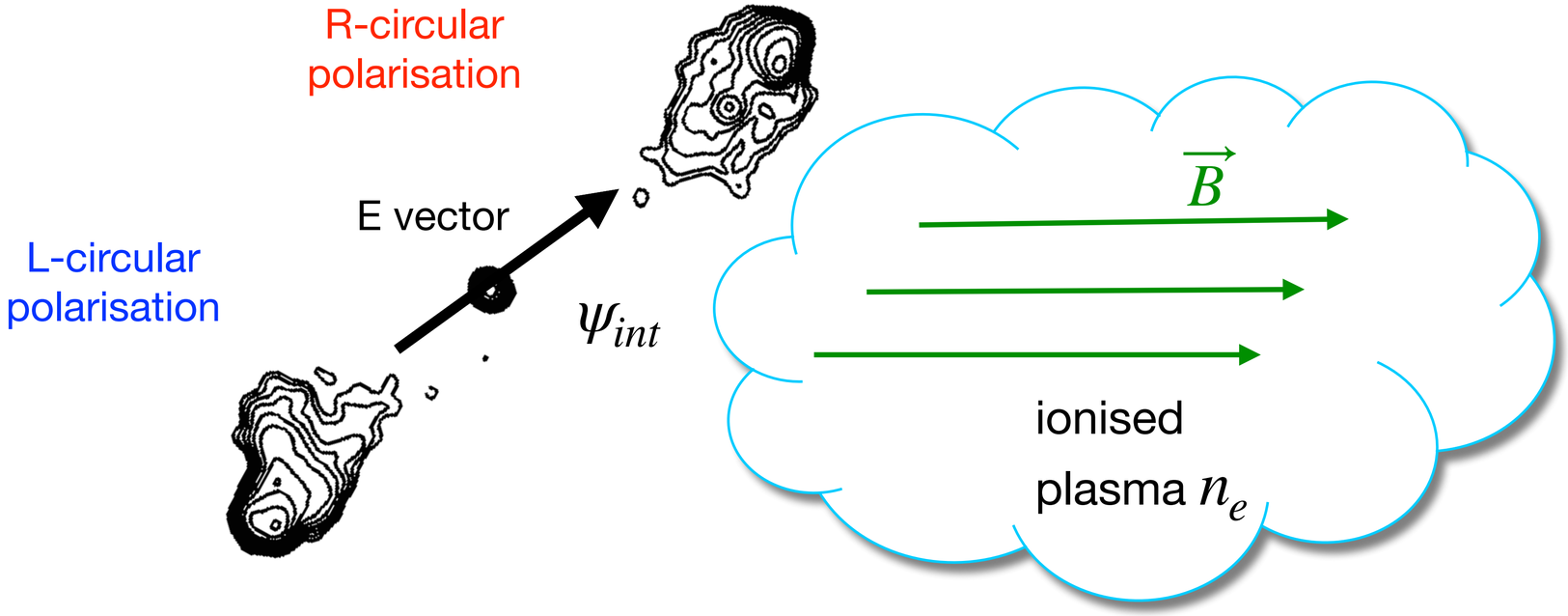
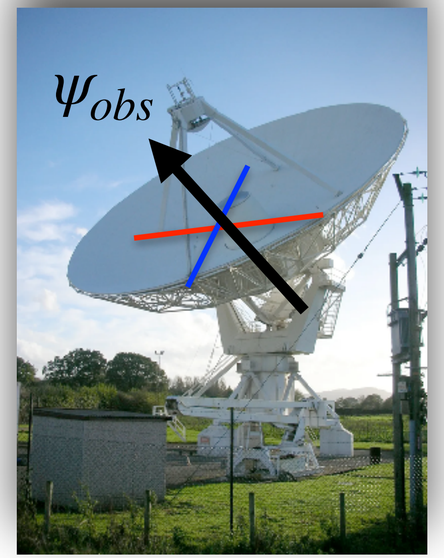
THE FARADAY EFFECT





$$\psi_{obs} = \psi_{int} + \mathrm{RM}\lambda^2_{\mathrm{obs}} \qquad \mathrm{RM} = \mathrm{K}\int_{\mathrm{los}} \mathrm{B}_{//}\mathrm{n_e dl}$$

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THE FARADAY EFFECT

$$\psi_{obs} = \psi_{int} + \mathrm{RM}\lambda^2_{\mathrm{obs}}$$

$$\mathrm{RM} = 812 \int_{\mathrm{los}} \frac{\mathrm{B}_{//}}{\mu\mathrm{G}} \frac{\mathrm{n_e}}{\mathrm{cm}^{-3}} \frac{\mathrm{dl}}{\mathrm{kpc}}$$

If we observe a synchrotron source in the background of a cluster at multiple wavelengths, we can derive the RM which gives us information about the magnetic field

- It's a rotation of the polarisation vector → the intensity of the polarisation is not changed
- The same RM will produce a different $\Delta\psi = \psi_{obs} - \psi_{int}$ → large rotation at long λ

THE FARADAY EFFECT: EXAMPLE

$$\psi_{obs} = \psi_{int} + \mathrm{RM}\lambda^2_{\mathrm{obs}} \qquad \mathrm{RM} = 812 \int_{\mathrm{los}} \frac{\mathrm{B}_{//}}{\mu\mathrm{G}} \frac{\mathrm{n_e}}{\mathrm{cm}^{-3}} \frac{\mathrm{dl}}{\mathrm{kpc}}$$

- A magnetic field of 1 μG, in a density medium of 1 cm^{-3}, crossing los=100 kpc will produce
  RM = 81.2 $\mathrm{rad/m}^2$

- We measure angles $\Delta\psi = \mathrm{RM}\lambda^2$ with errors! :
  - if we observe at 10 GHz $\rightarrow 0.073$ radians $\sim 4°$
  - if we observe at 2 GHz $\rightarrow 1.82$ radians$s \sim 104°$

- If you expect low $\Delta\psi$, you need to observed at low frequencies

POLARIZATION: COMPLEX NOTATION

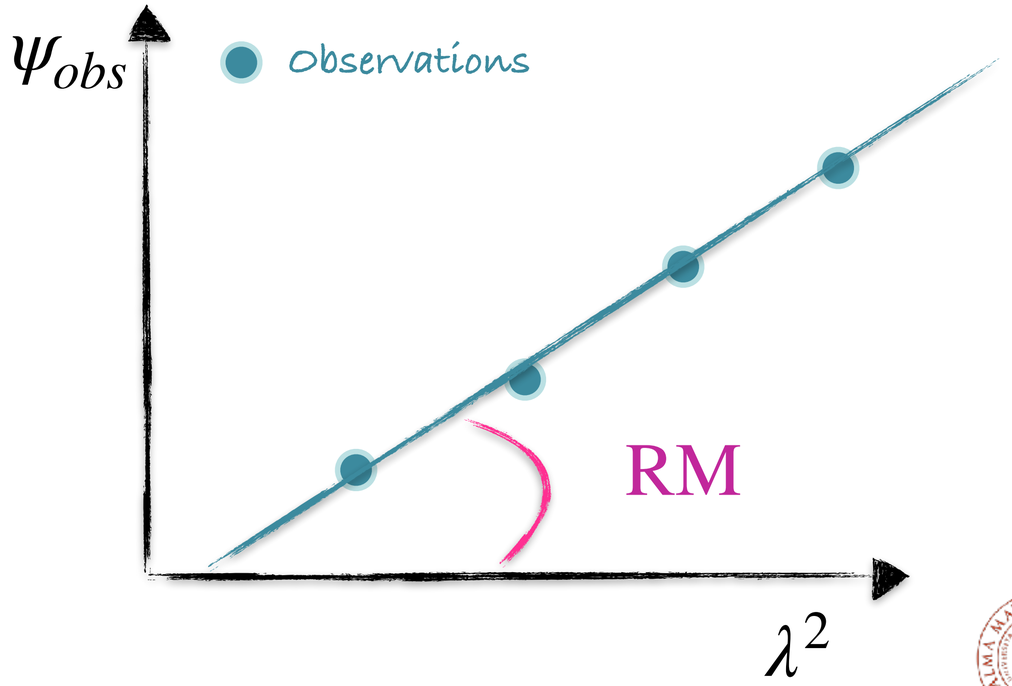
$$\overrightarrow{P} = p \cdot e^{i2(\psi_0 + RM\lambda^2)} = p \cdot e^{i2\psi_0} e^{2iRM\lambda^2}$$

Intrinsic polarisation

Faraday rotation
just adding a phase term

Obtaining the RM in practice:

- Observe at several λ a source in the background of a medium with B and free electrons
- Derive ψ_{obs} at different λ
- Fit ψ_{obs} versus λ^2 , the slope is the RM
- RM >0 if the magnetic field is directed towards the observer along the line of sight



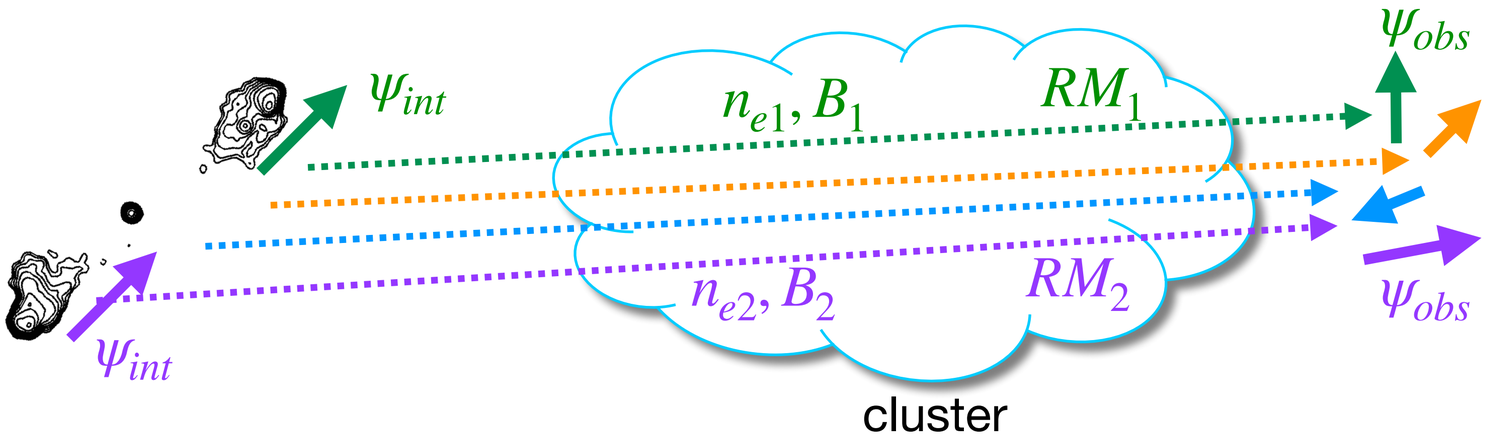
FROM FARADAY ROTATION TO B

- Every medium between you and the source will contribute to the RM if it contains B and free electrons (including our Galaxy, the Earth ionosphere, …) → the resulting RM will be the sum of the different media

$$RM \propto \int_{Galaxy} B_{//} n_e dl + \int_{cluster} B_{//} n_e dl$$

FROM FARADAY ROTATION TO B

- The magnetic field and the gas density are not uniform: different regions of the background source will produce different RM



$$\langle RM \rangle \approx 0 \text{ but } \sigma_{RM} \neq 0,$$

→ σ_{RM} is a better proxy for the magnetic field in the cluster

→ The polarization intensity will decrease (depolarisation)

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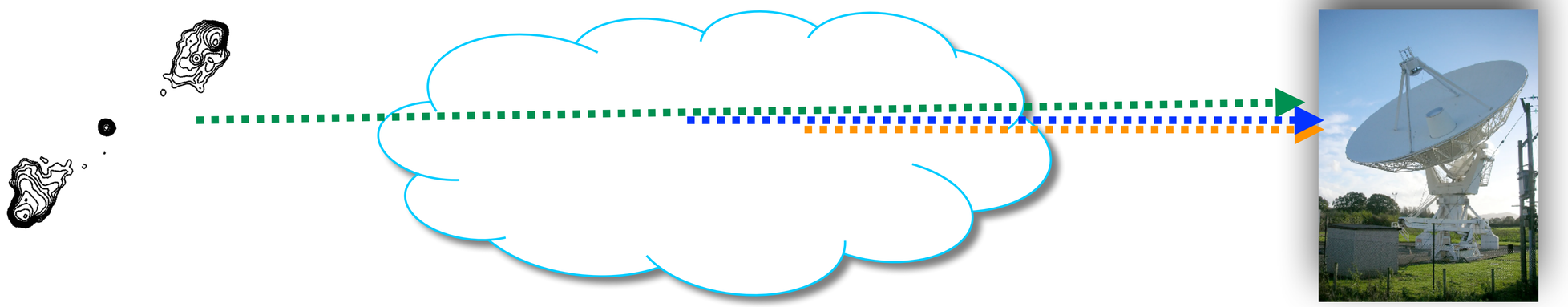
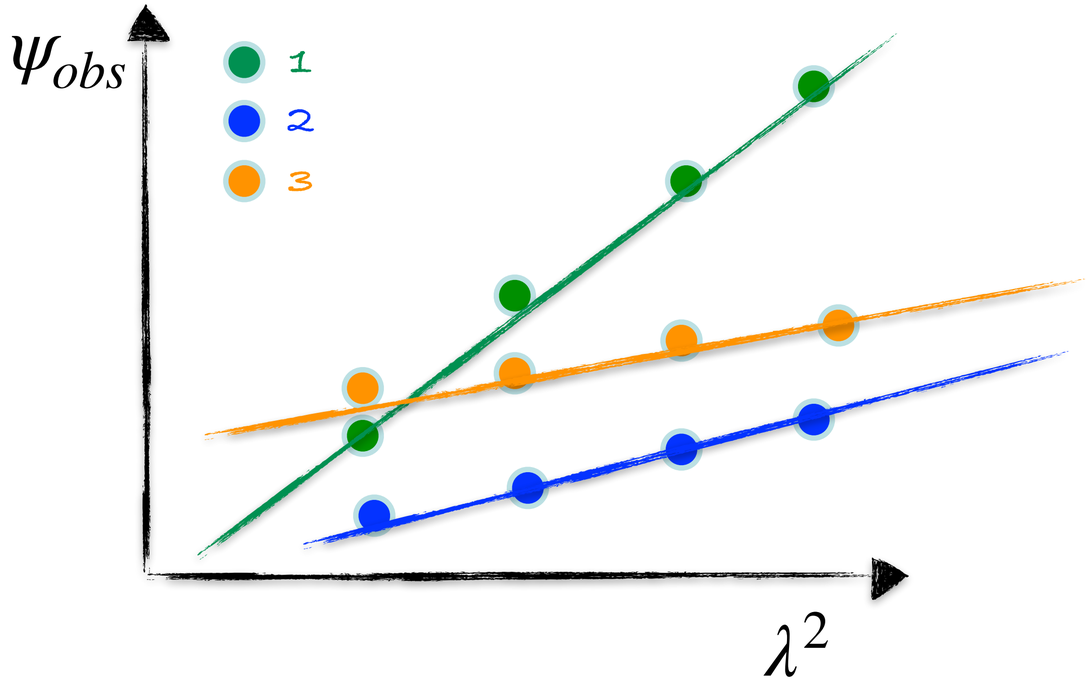
FROM FARADAY ROTATION TO B

In more complex situations, the rotation medium (cluster) may emit synchrotron radiation itself →different layer of the medium will produce different RM along the same line of sight





In these more complex, but realistic, cases, the polarisation angle is not going linear with λ^2

more sophisticated techniques have been developed

THE RM SYNTHESIS TECHNIQUE - ADVANCED -

Faraday depth $\Phi = \frac{d\psi_{obs}}{d\lambda^2}$

$$P(\lambda^2) = \int_{-\infty}^{+\infty} F(\Phi) \cdot e^{i2\Phi\lambda^2} d\Phi$$

Observable

Contains the different RM along the line of sight

$P(\lambda^2) \Longleftrightarrow F(\Phi)$

Fourier conjugates!

With the RM synthesis technique one can recover the Faraday rotation of the different emitting sources along the line of sight

<u>This is the technique used nowadays</u>

Brentjens and de Bruyn 2005

FARADAY RM: TAKE HOME MESSAGES

From multifrequency radio observations in polarisation

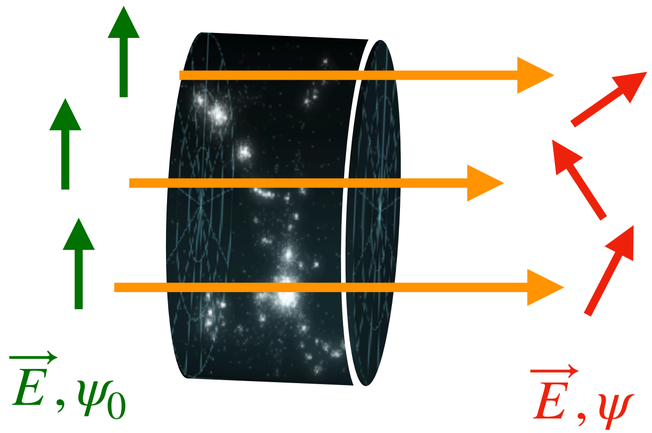
$$\mathrm{RM} \propto \int B_{//} n_e dl$$

Magnetic field along the los

Gas density from X-ray observations

RM is the observable! Not B

If n_e and $\overrightarrow{B}$ are not uniform



$$\langle RM \rangle = 0$$

$$\sigma_{RM} \neq 0$$

σ_{RM} is a better proxy for $\overrightarrow{B}$ than the RM

Regions with $\sigma_{RM} \neq 0$ will also decrease the intensity of the polarised radiation

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Time for the first quiz

THIS TALK

Part I:
techniques to constrain magnetic fields using radio polarisation observations

Part II:
Magnetic field estimates in galaxy clusters results, limitations and perspectives

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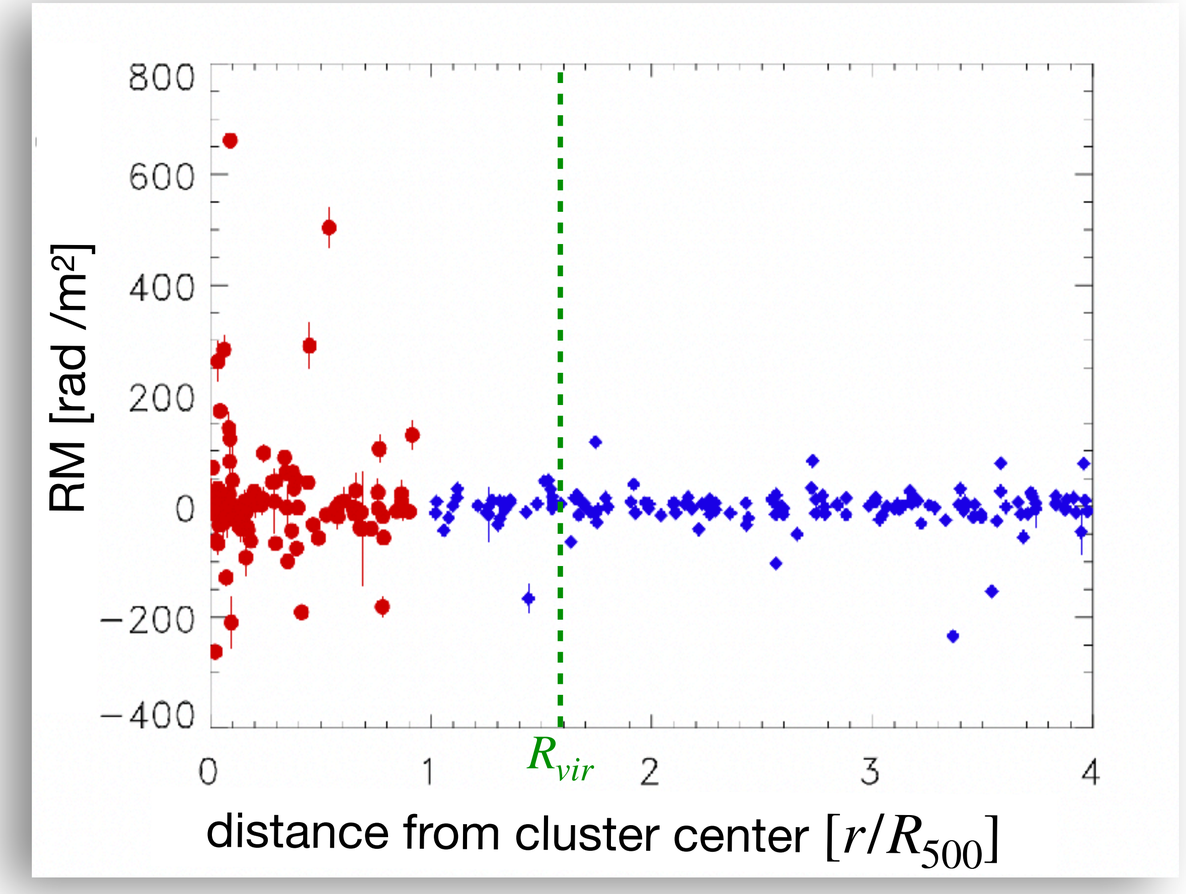
RM in CLUSTERS: OBSERVATIONS

- Increase in RM value at low projected distances from the cluster center
- RM are positive and negative
- RM approaches 0 at $r \approx R_{vir}$



Bohringer et al (2016)

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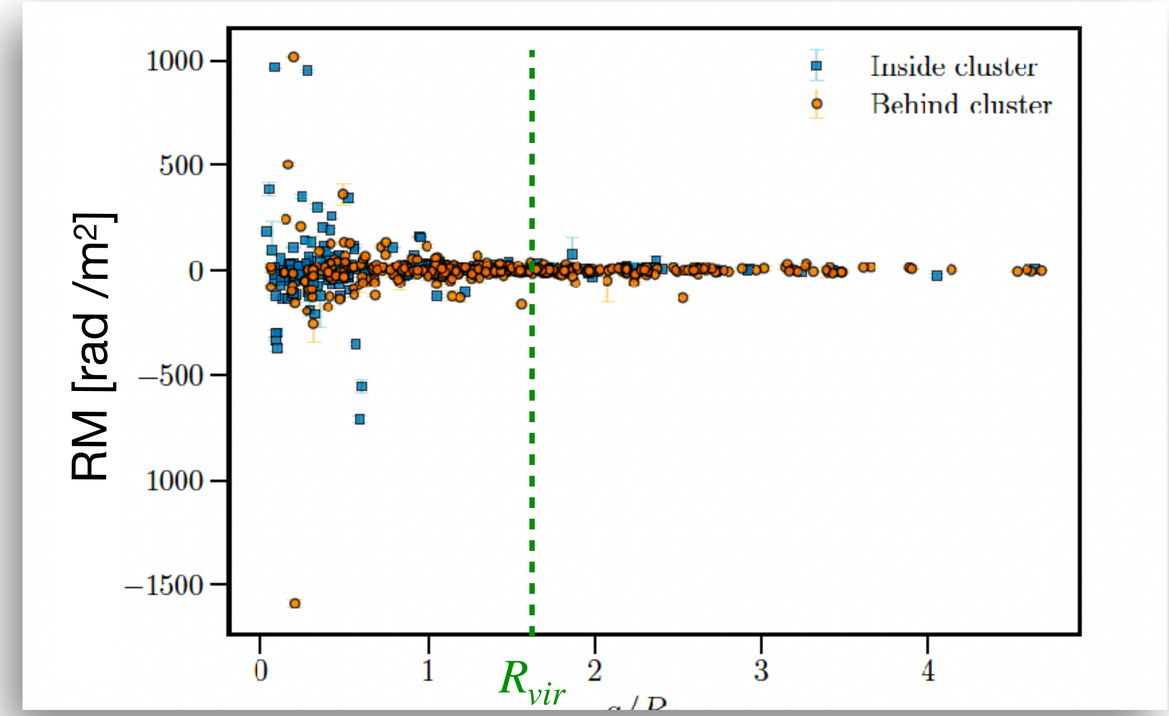
RM in CLUSTERS:OBSERVATIONS

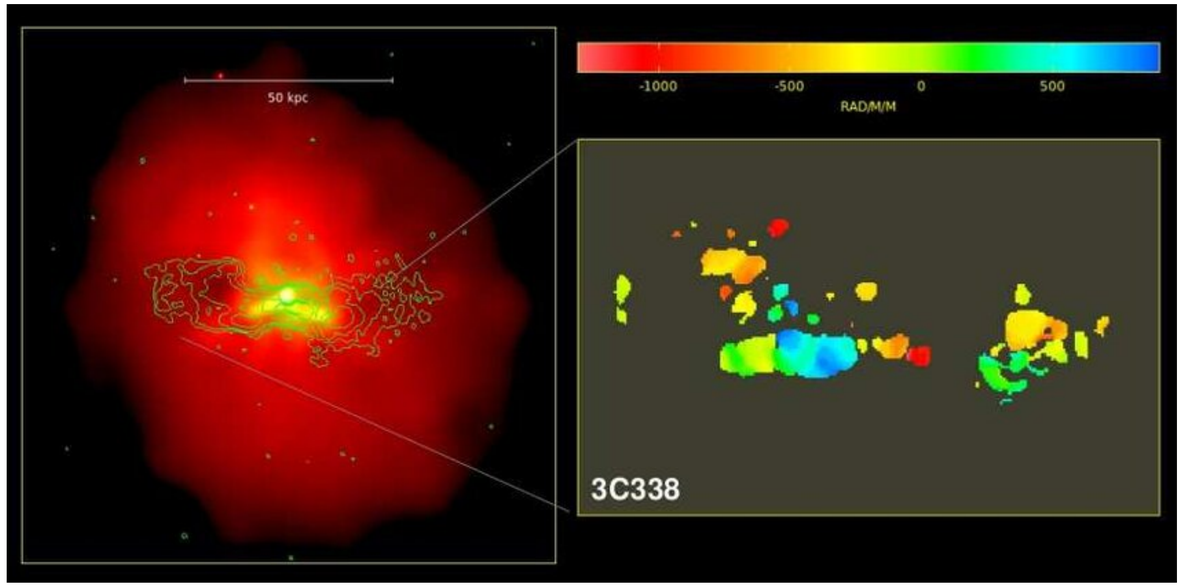
- 124 clusters, for a total of 819 sources
- RM are positive and negative
- Note the higher values with respect to the plot before, due to the higher resolution and sensitivity

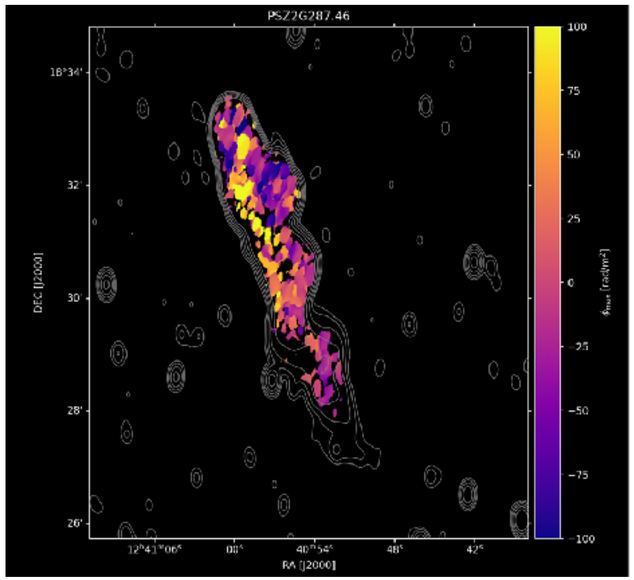


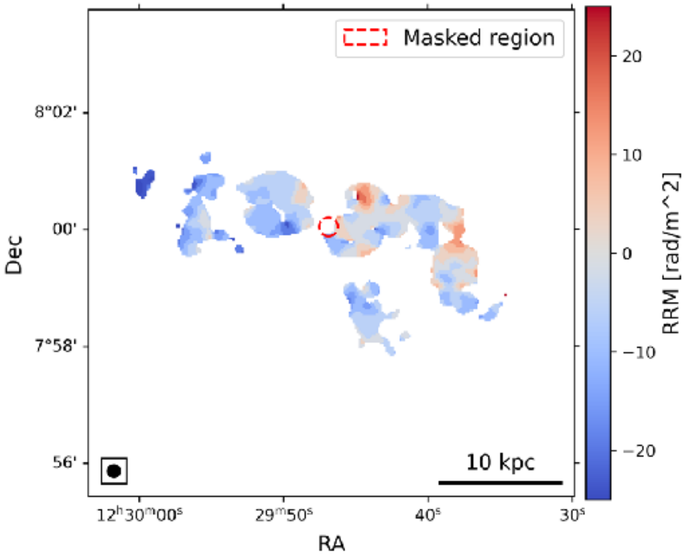
Osinga et al (2025)

RM MAPS of sources in CLUSTERS

- RM positive and negative
- $\sigma_{RM} \neq 0$ indicating a turbulent magnetic field







Credits: Bonafede, Vacca, Spasic

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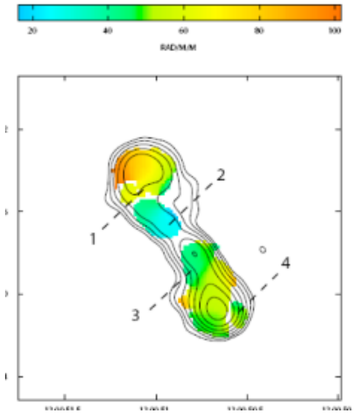
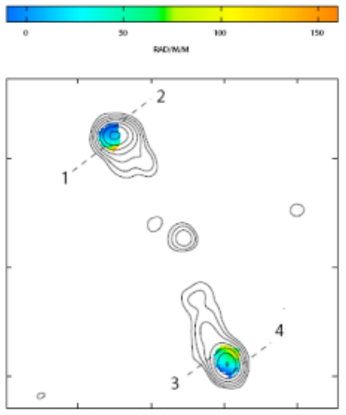
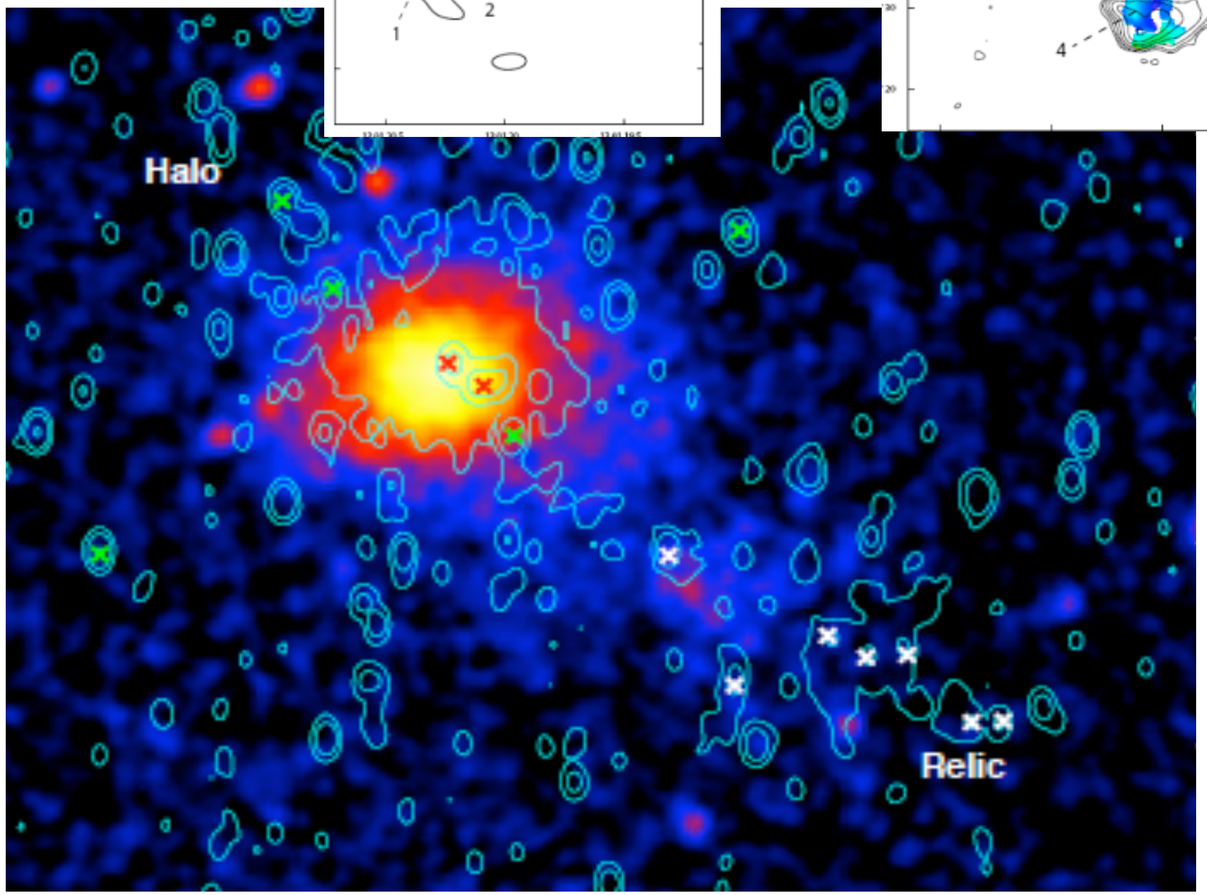
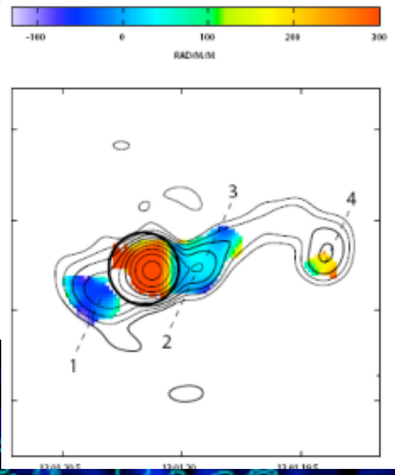
FROM RM IMAGES to MAGNETIC FIELDS ESTIMATE

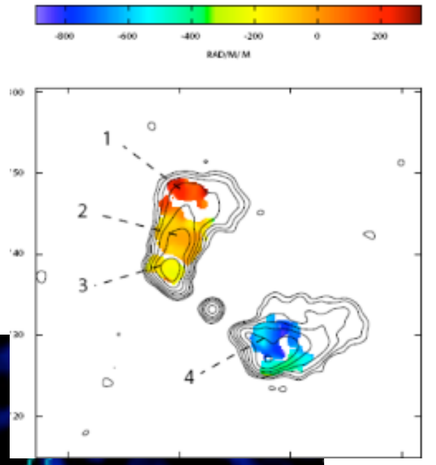
Example:
The Coma cluster

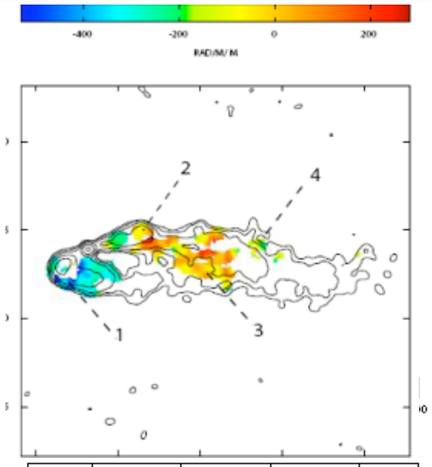


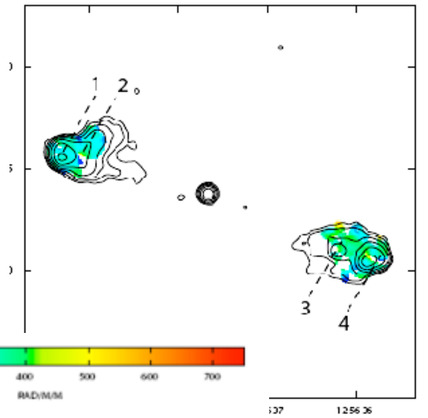


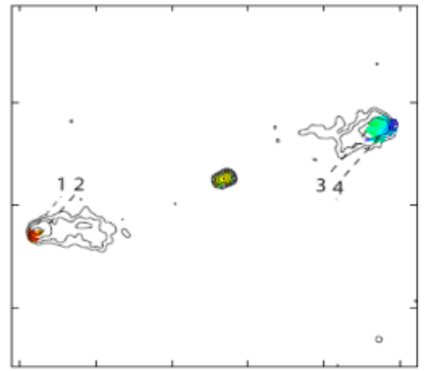












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FROM RM IMAGES to MAGNETIC FIELDS ESTIMATE

- Decreasing trend of $|\langle RM \rangle|$ versus distance from cluster centre

- Zero-order estimate:

$n_e = 10^{-4} cm^{-3}$

$L = 1.5$ Mpc

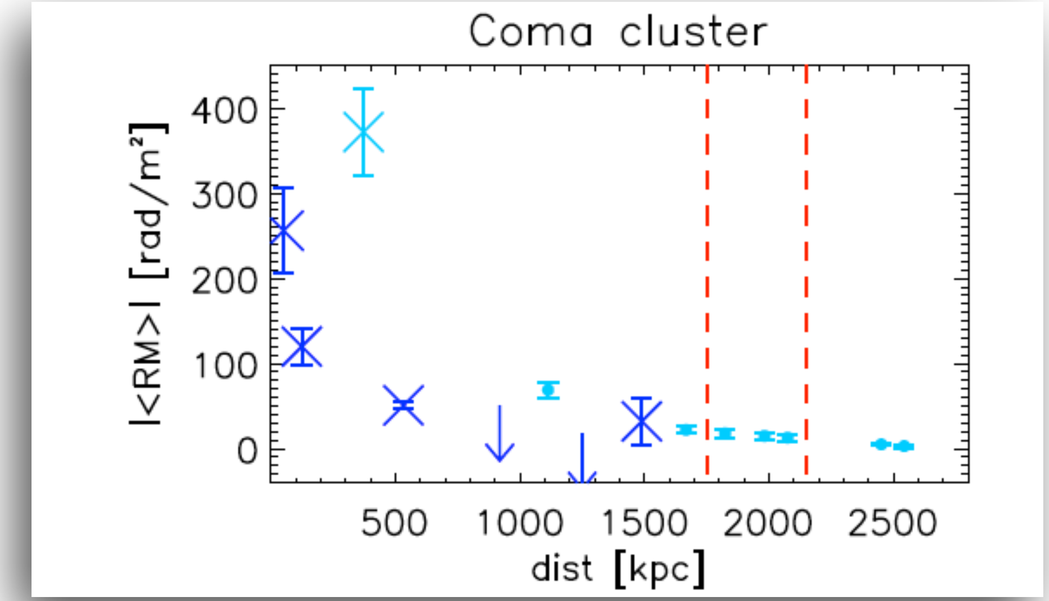
RM of the central source: RM = 250 rad/m²

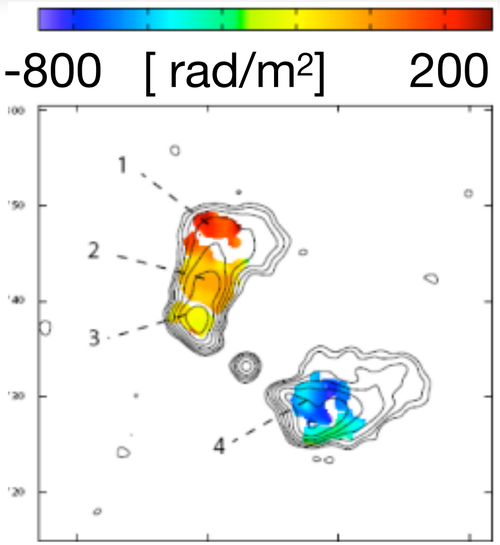
$$\mathrm{RM} = 812 \int_{\mathrm{los}} \frac{\mathrm{n_e}}{\mathrm{cm^{-3}}} \frac{\mathrm{B_{//}}}{\mu\mathrm{G}} \frac{\mathrm{dl}}{\mathrm{kpc}}$$

$$B \approx \frac{RM}{812 n_e L} \approx 2\mu G$$

- We are assuming:
  - constant B
  - constant n_e

we know they're not! (RM varies)





RM image of the central source

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FROM RM IMAGES to MAGNETIC FIELDS ESTIMATE

- Numerical approach (Murgia et al 2004, others followed - Bonafede- Osinga - …)

$$RM = K \int_{los} n_e B_{//} dl$$

$$n_e(r) = n_e(0)\left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3/2\beta}$$

β model, parameters known from X-ray observations

Let's model the magnetic field profile:

Assume that the magnetic field has Gaussian random components that follow a power spectrum

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

and a global profile

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

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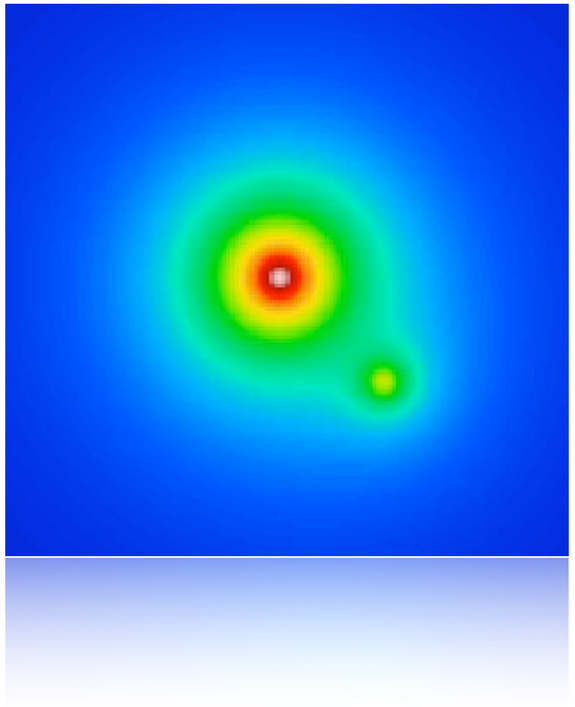
FROM RM IMAGES to MAGNETIC FIELDS ESTIMATE

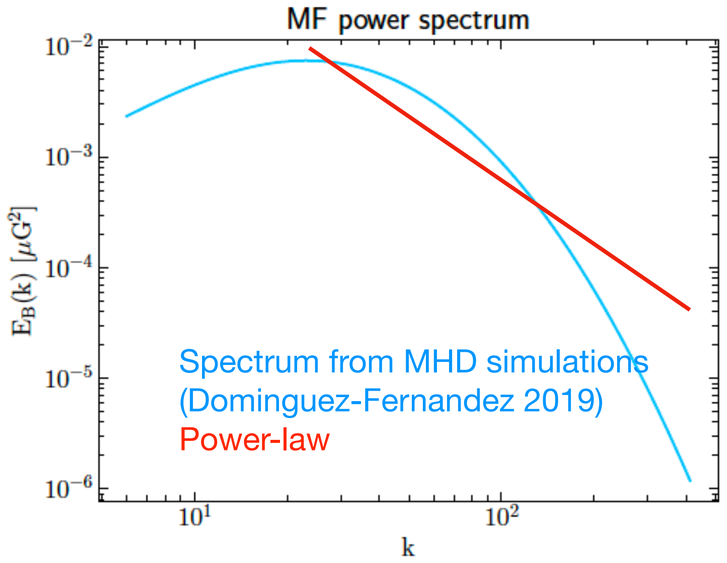
$$RM \propto \int n_e \, B_{||} \, dl$$

3D model
from X-ray observations

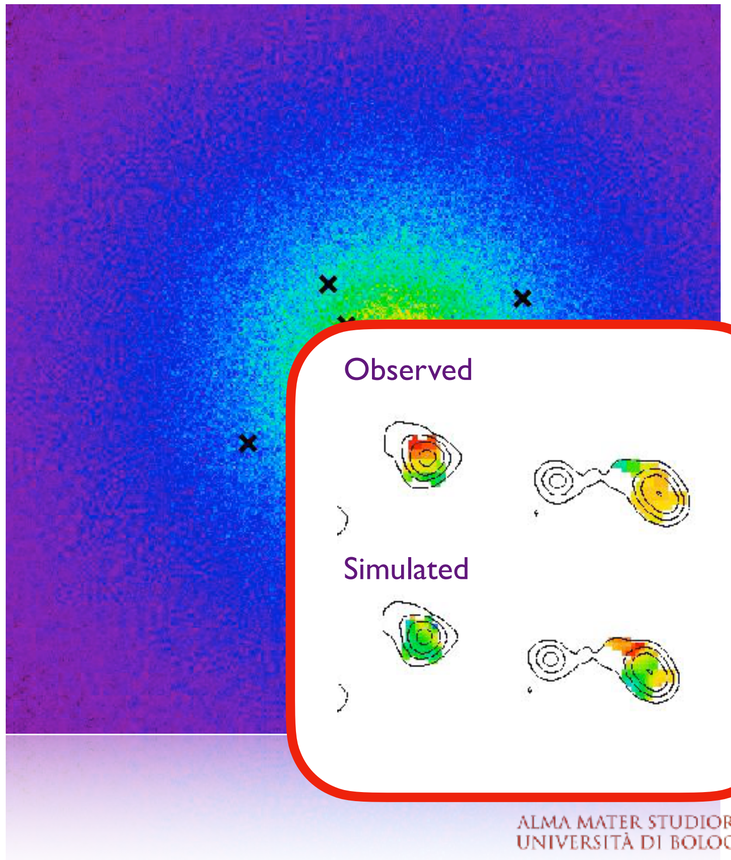


3D Numerical model for B, including a
power spectrum and a scaling with gas density

$$B(r) = B_0 \left(\frac{n_e(r)}{n_e(0)} \right)^{\eta}$$



Simulated RM image



FROM RM IMAGES to MAGNETIC FIELDS ESTIMATE

Example:
The Coma cluster

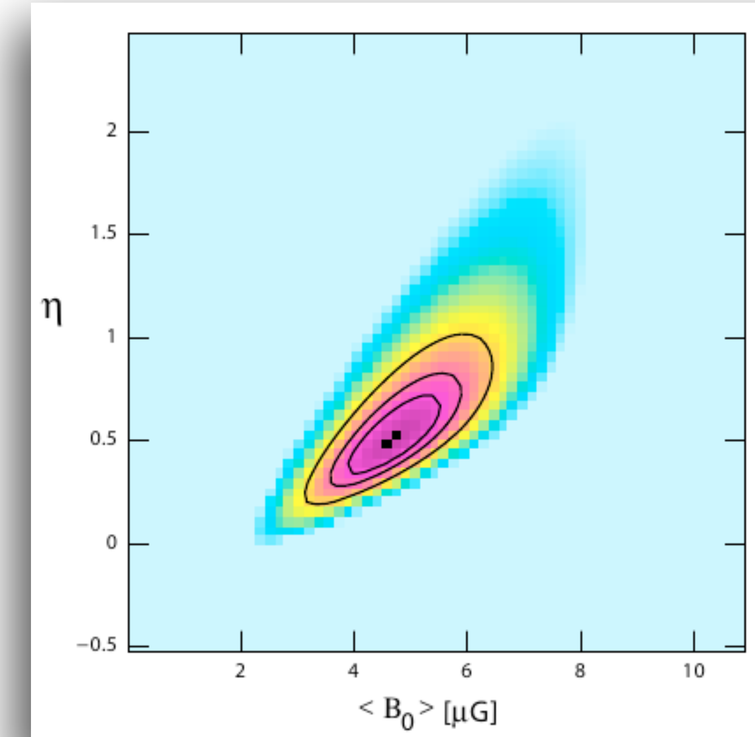
$$B(r) = B_0 \left(\frac{n_e}{n_0} \right)^{\eta}$$

$$B \propto k^n; k_{min} < k < k_{max}$$

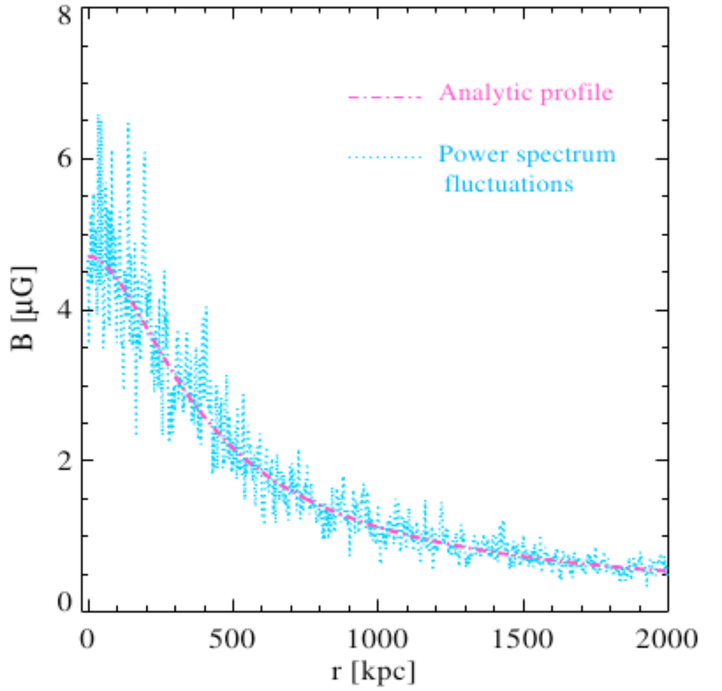
Free parameters:

$$B_0, \eta, k_{min}, k_{max}, n$$

χ^2 plot



best fit profile



$B_0 = 4.7 \mu G, \eta = 0.5$

assuming a kolmogorov power spectrum

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MAGNETIC FIELD in the COMA CLUSTER

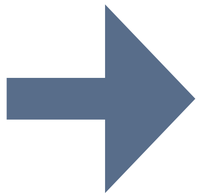
$$B_0 = 4.7\mu G, \eta = 0.5 \qquad B(r) = B_0 \left(\frac{n_e}{n_0} \right)^{\eta}$$

- $B \propto n^{0.5} \rightarrow$ magnetic energy density scaling like the thermal energy density

  Note: flux-freezing would predict $B \propto n_e^{2/3}$

- Is magnetic field energetically important?

  remember: β plasma parameter $\beta = \dfrac{n_e k_B T}{B^2/8\pi}$



Given $n_e = 10^{-3} cm^{-3}$, $T \sim 10^8 K$ $\beta \sim 300$

magnetic pressure subdominant with respect to thermal pressure

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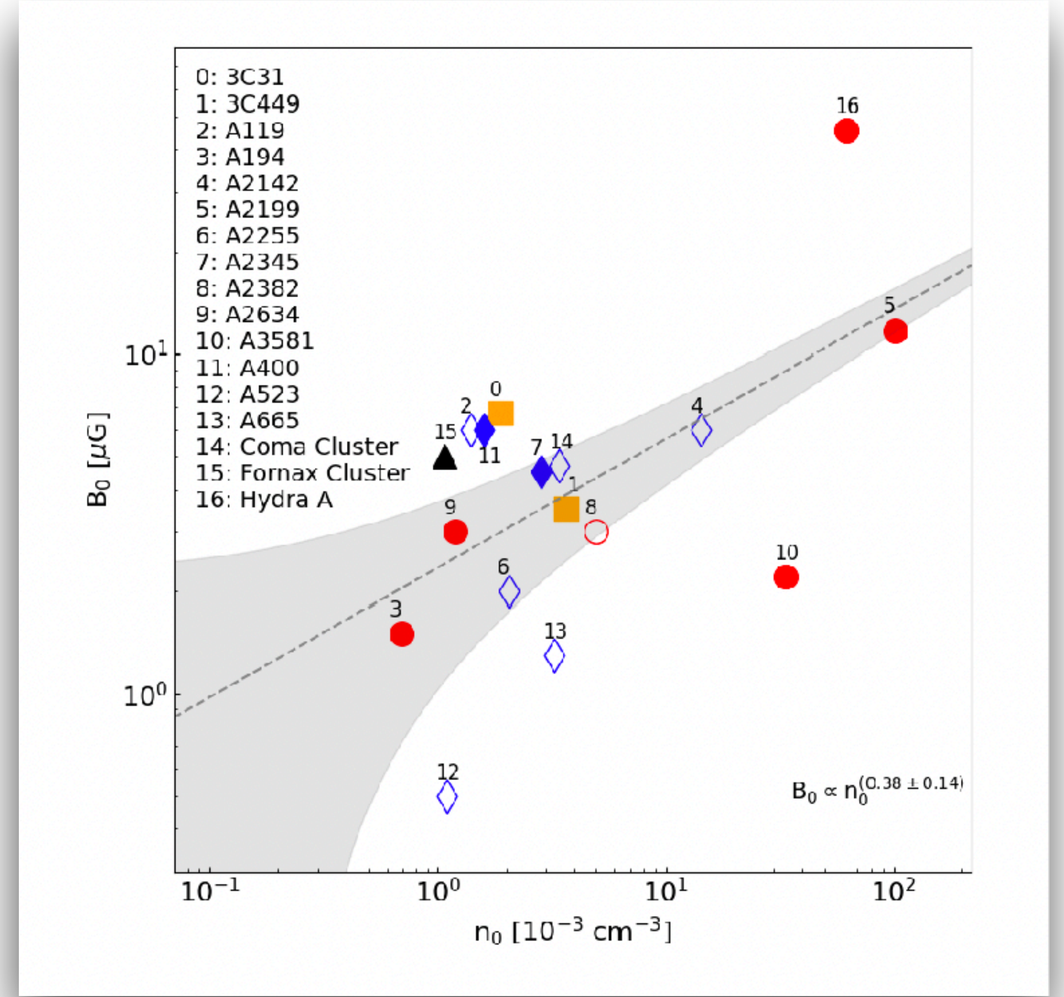
MAGNETIC FIELD in OTHER CLUSTERS

In total, we have B estimates through RM in 17 clusters

B of few -10 μG in the centres scaling as $B \propto n_e^{\eta}$ with $\eta = 0.5 - 1$



Credits: Loi et al 2025

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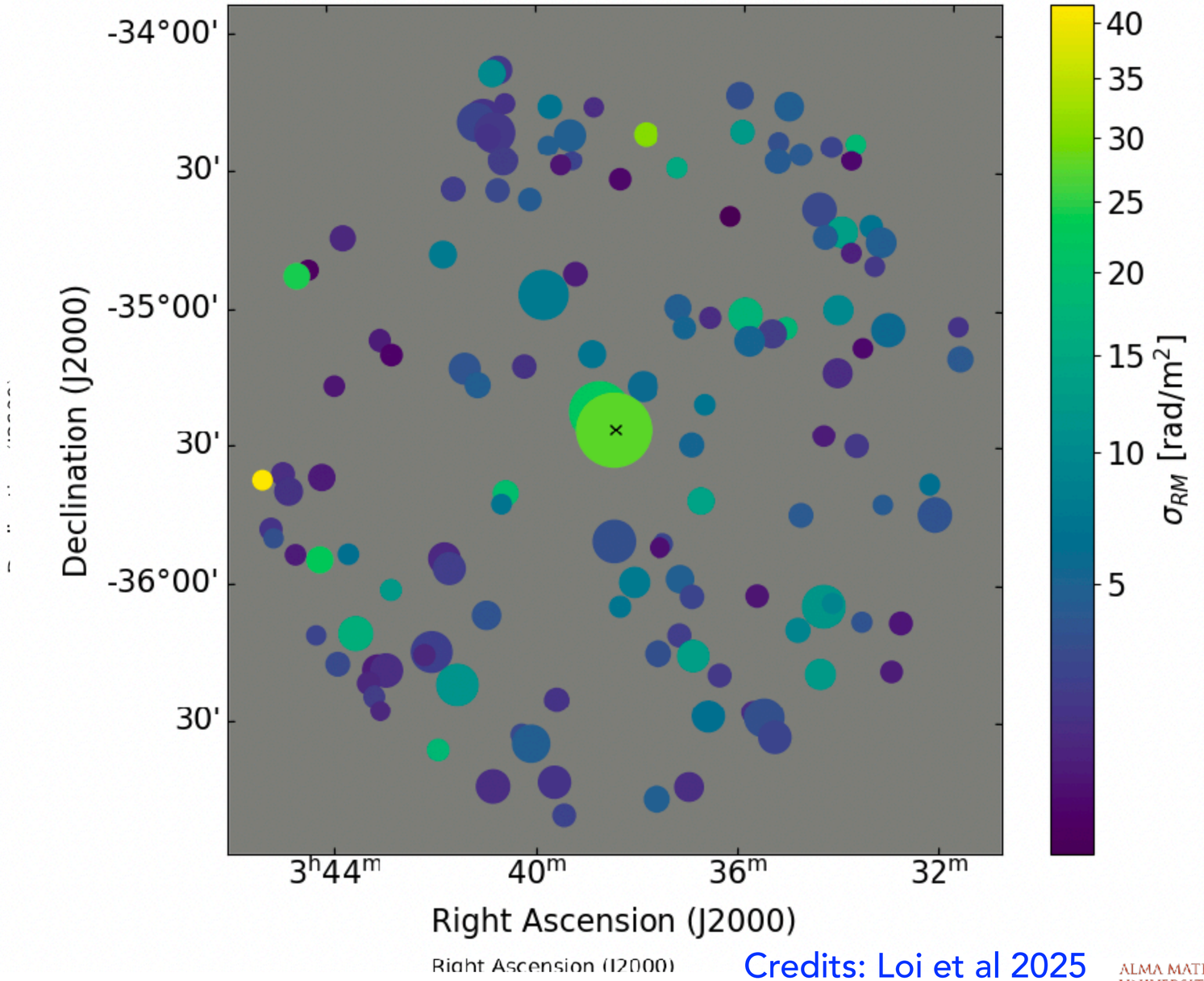
WHY SO FEW CLUSTERS WITH A CONSTRAINED B?

- Main limit: number of sources detectable in polarization
- Deep MeerKAT observations of the Fornax cluster:
  80 sources / sq degree
  (noise 3 μJy/beam, beam 13”)
- obtained with 50 different pointings of 5h each



Credits: Loi et al 2025

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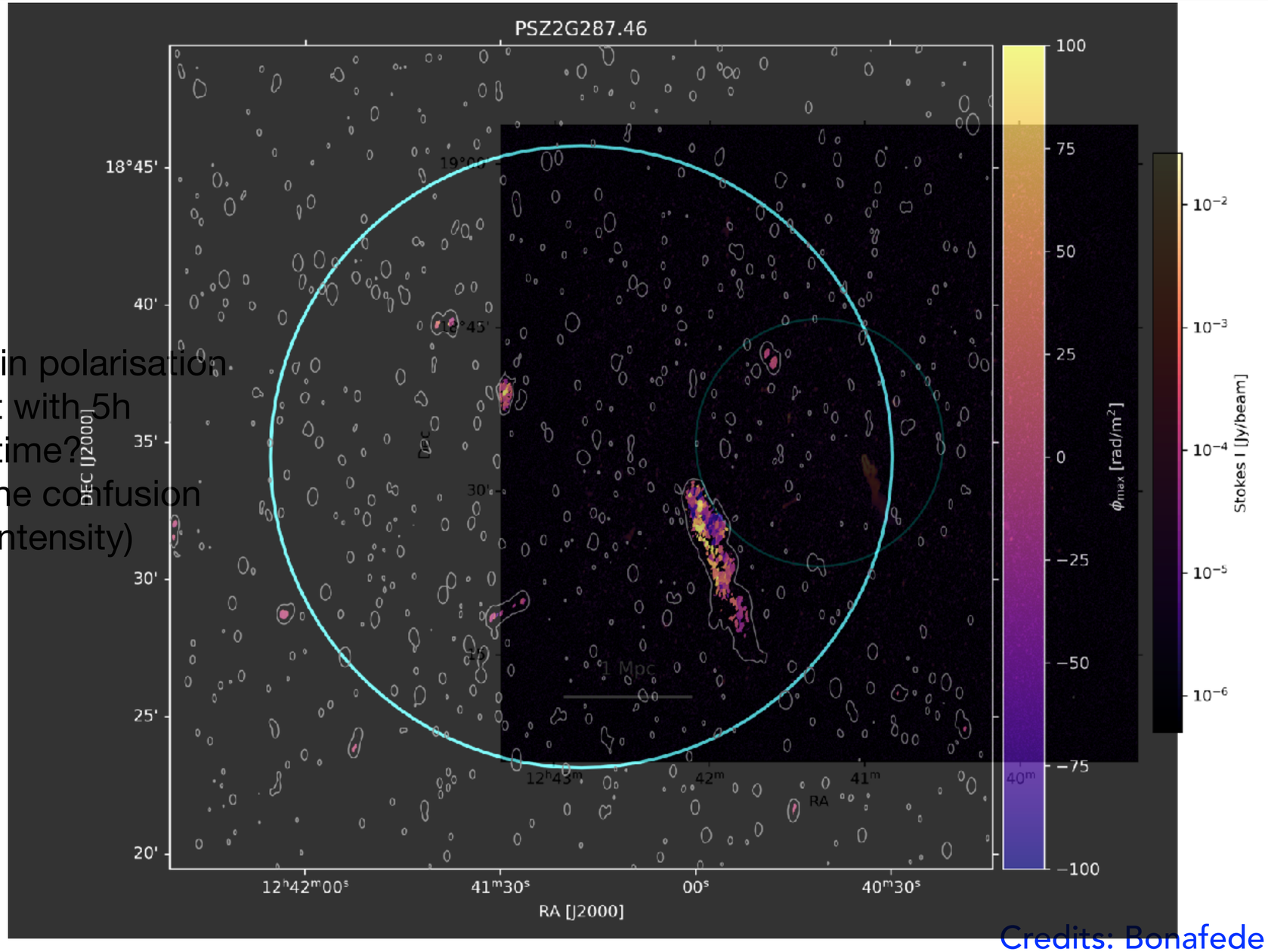
WHY SO FEW CLUSTERS WITH A CONSTRAINED B?

How many sources in polarisation can we detect with 5h observing time?
(we are reaching the confusion noise in total intensity)



Credits: Bonafede

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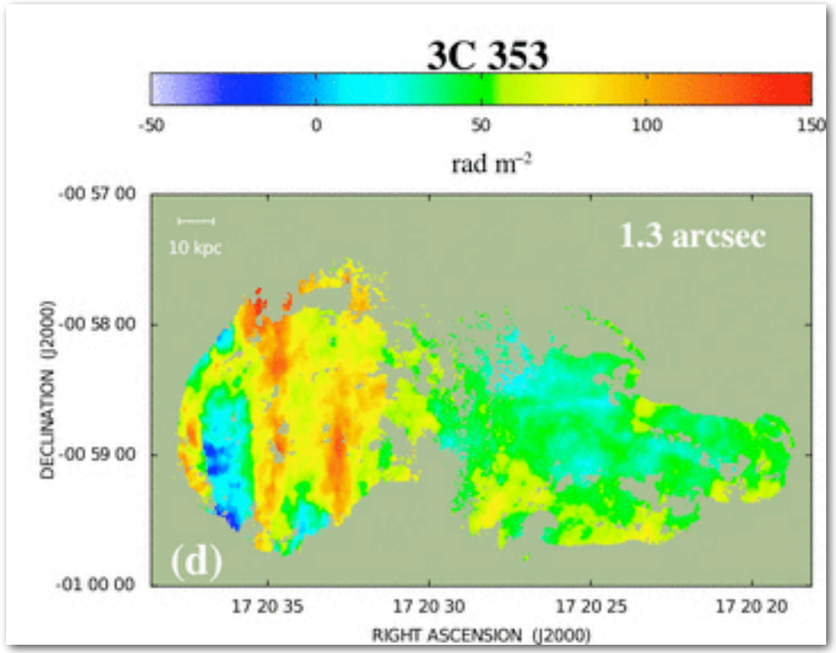
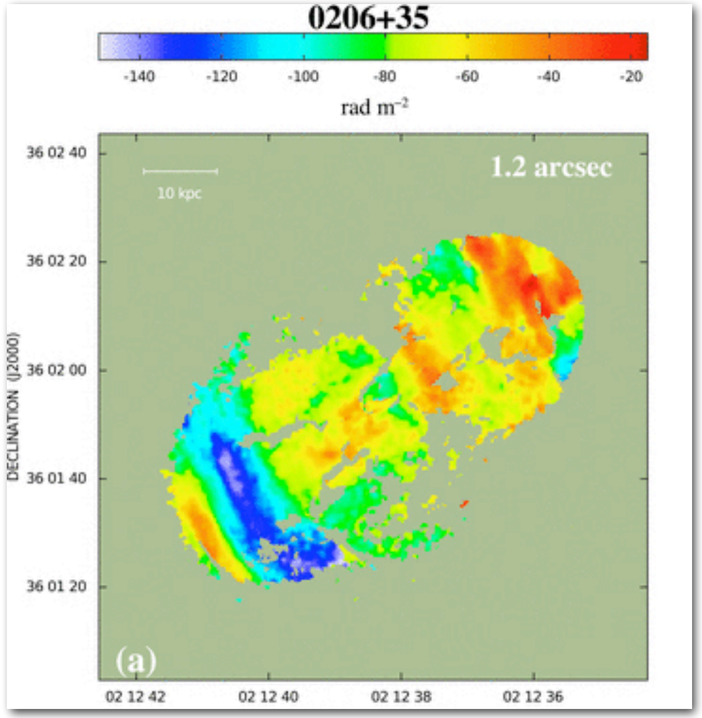
MAGNETIC FIELDS FROM RM: CHALLENGES AND LIMITS

- Low number of polarised sources per cluster
- Position of the source along the line of sight unknown
- There could be a local contribution of RM for cluster members if for example due to local compression of the gas





Credits: Laing et al (2008)

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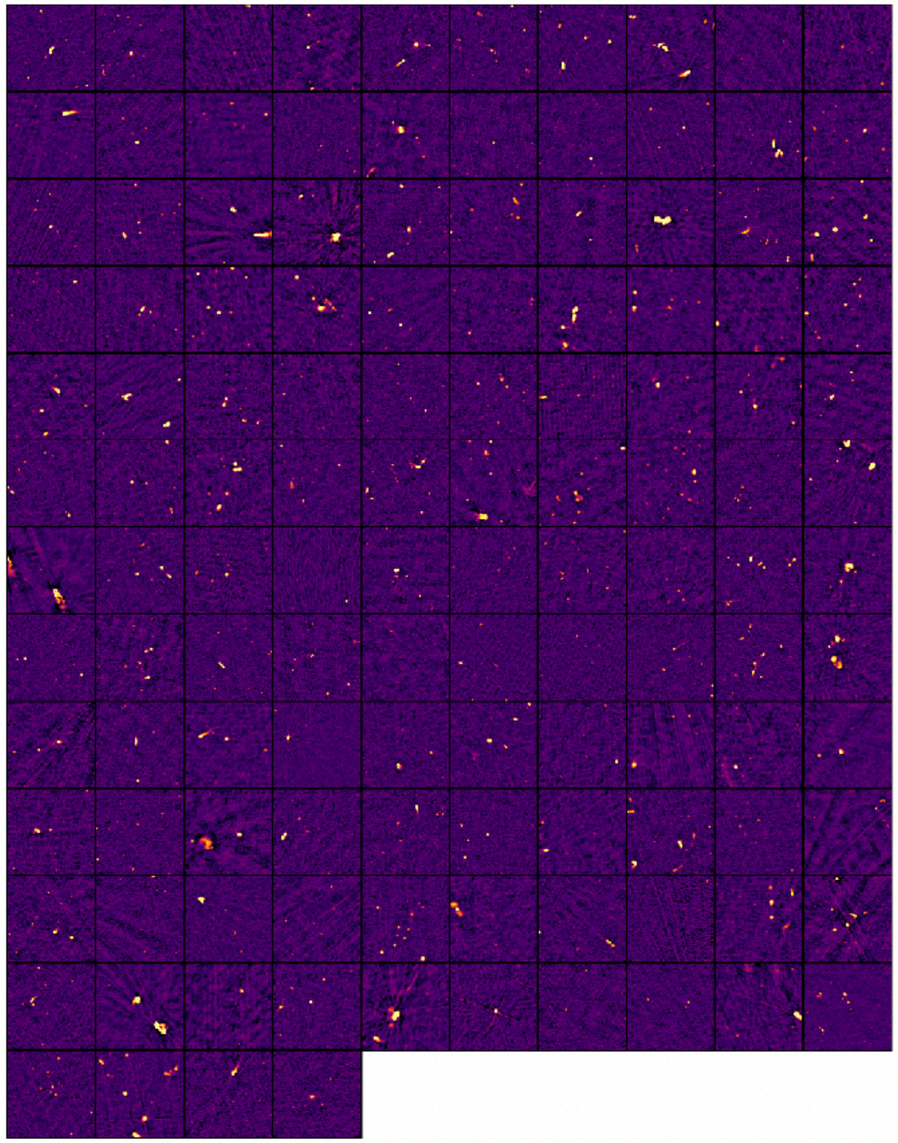
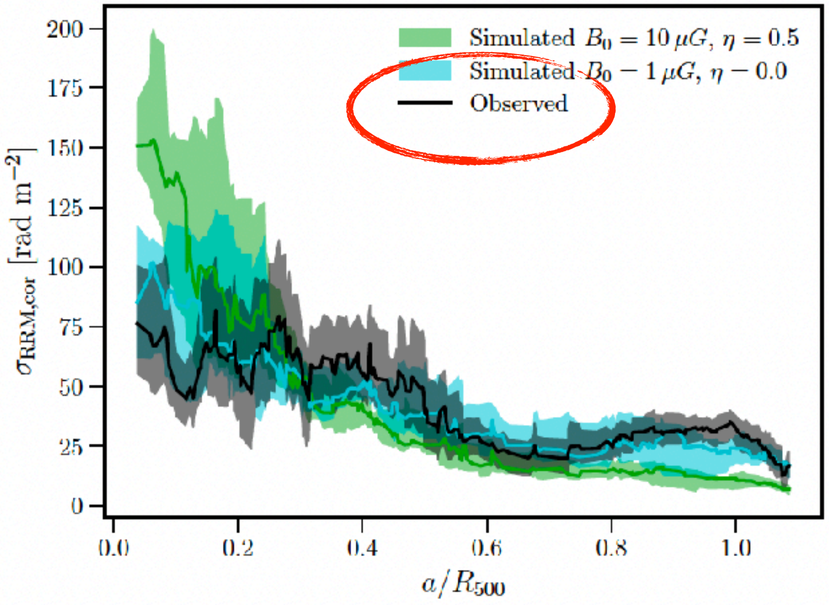
MAGNETIC FIELDS FROM RM: PERSPECTIVES

Statistical study of sample of clusters with similar properties

Attempt by Osinga et al (2024)
124 clusters with known X-ray properties

Clusters span a range of z and mass too large be considered together





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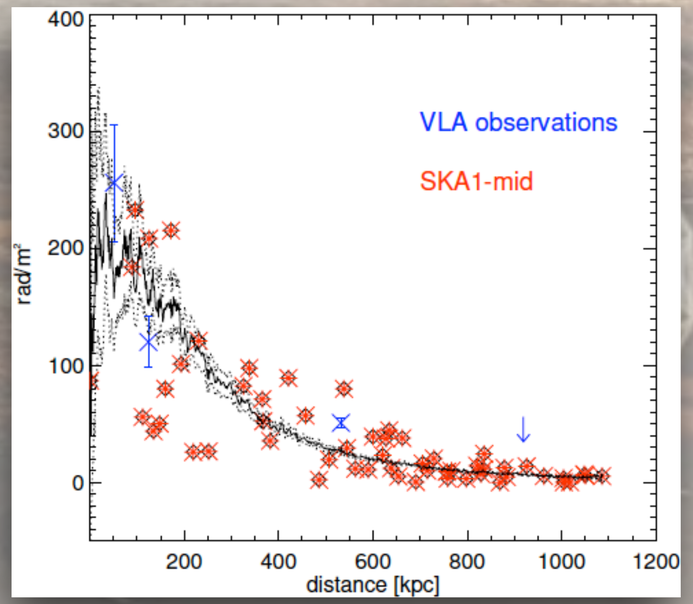
MAGNETIC FIELDS FROM RM: PERSPECTIVES with SKA

SKA mid
Band 2: 0.96 - 1.7 GHz

N density of sources in polarisation:
- 15 min (mosaic) **110 sources/sq degree**
- 10h (deep targeted field) **414 sources/sq degree**

A Coma like cluster



B in CLUSTERS: TAKE HOME MESSAGES

- Few clusters with reliable estimates of B through RM studies

- B modelled as $$B(r) = B_0 \left(\frac{n_e(r)}{n_e(0)} \right)^{\eta}$$

$$B_0 \sim 1 - 10\,\mu\mathrm{G}$$
$$\eta \sim 0.5 - 1$$

- These values indicate a magnetic field which is dynamically subdominant, but relevant for small-scale processes (particle acceleration, thermal conduction, …)

Time for the second quiz

THIS TALK

Part I:
techniques to constrain magnetic fields using radio polarisation observations

Part II:
Magnetic field estimates in galaxy clusters
results, limitations and perspectives

Part III:
Origin and amplification of the magnetic field in galaxy clusters

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ORIGIN OF MAGNETIC FIELDS IN CLUSTERS

- We need to explain magnetic fields of 1-10 μG on Mpc scale
- No coherent circular motions (like spiral galaxies) → mechanisms like $\alpha - \Omega$ dynamo do not work
- Is it enough assume the same seed field needed to explain the magnetic field in galaxies?

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ORIGIN OF MAGNETIC FIELDS IN CLUSTERS

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$$Br^2 = const \qquad \text{from flux freezing}$$

$$B_{gal} r_{gal}^2 = B_{cluster} r_{cluster}^2$$

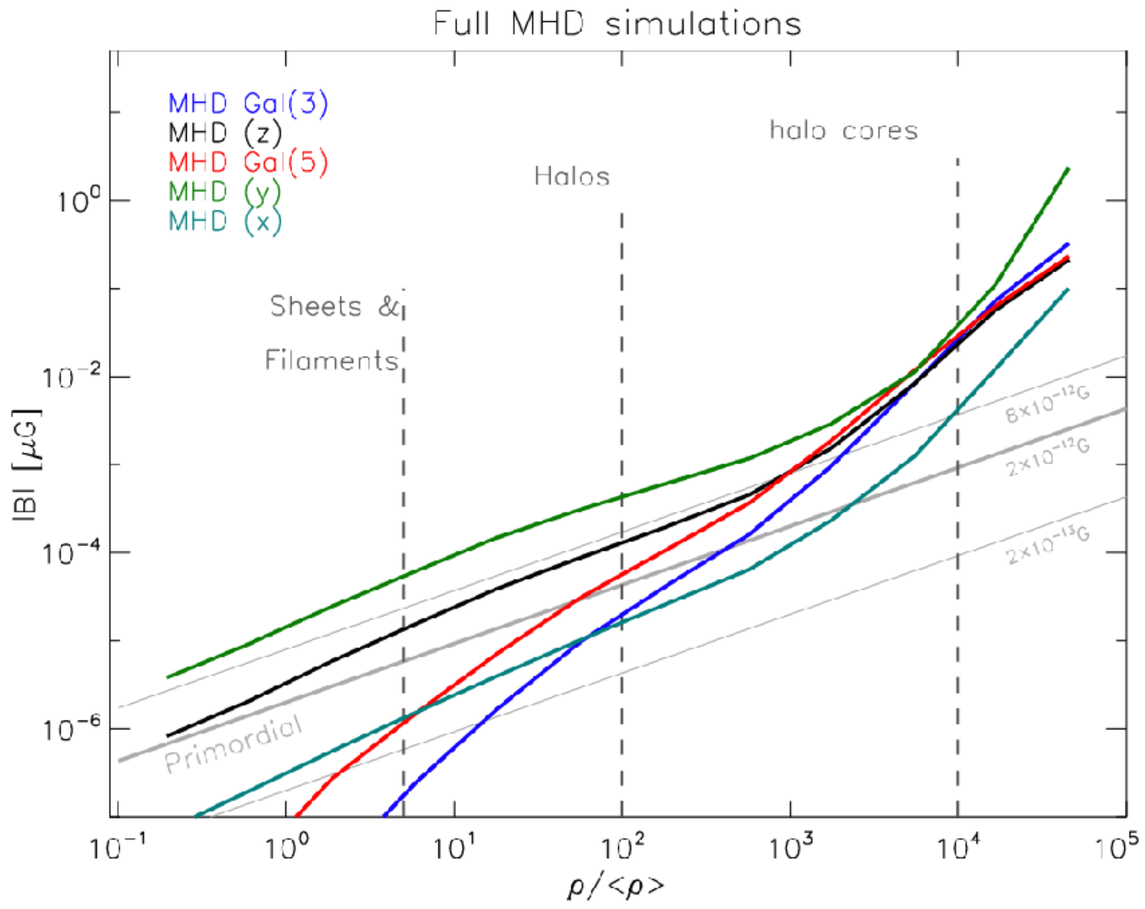
$$B_{gal} \approx 5\mu G \qquad r_{gal} \approx 10 \text{ kpc} \qquad r_{cluster} \approx 500 \text{ kpc}$$

$$B_{clusters} \approx 0.002\mu G$$

- The magnetic field must have been amplified

ORIGIN OF MAGNETIC FIELDS IN CLUSTERS

Fig. 1 Magnetic field strength as a function of over density in cosmological SPH simulations. Starting from 3 different cosmological seed field strengths: 2×10^{-13} G (dark green), 2×10^{-12} G (black), 8×10^{-12} G (green) (Dolag et al. 2008, 2005a). Adiabatic evolution solely by compression in grey. Runs with galactic seeds are in red and blue



Donnert et al (2019)

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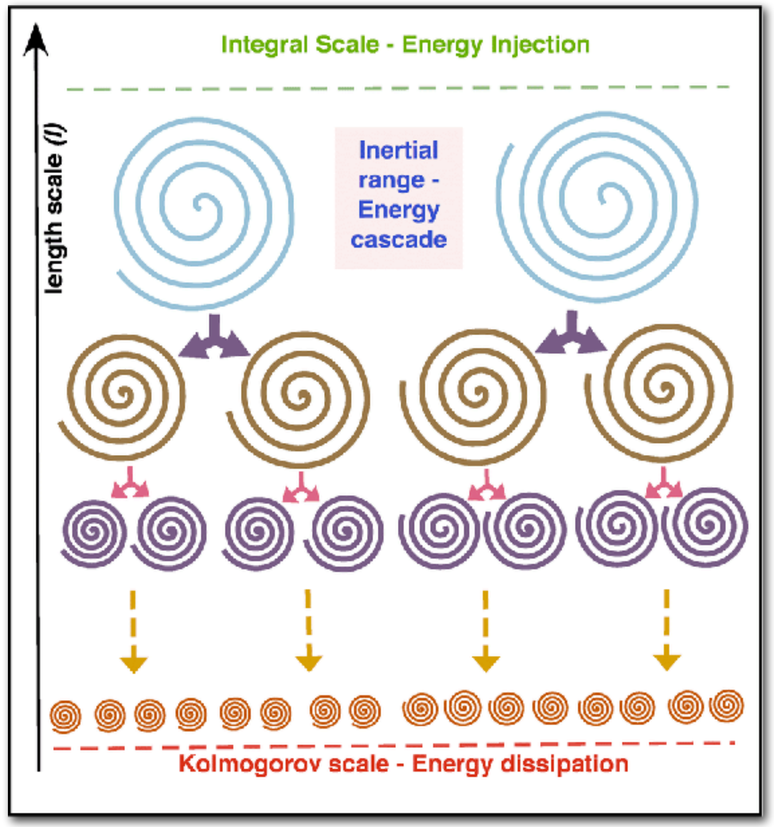
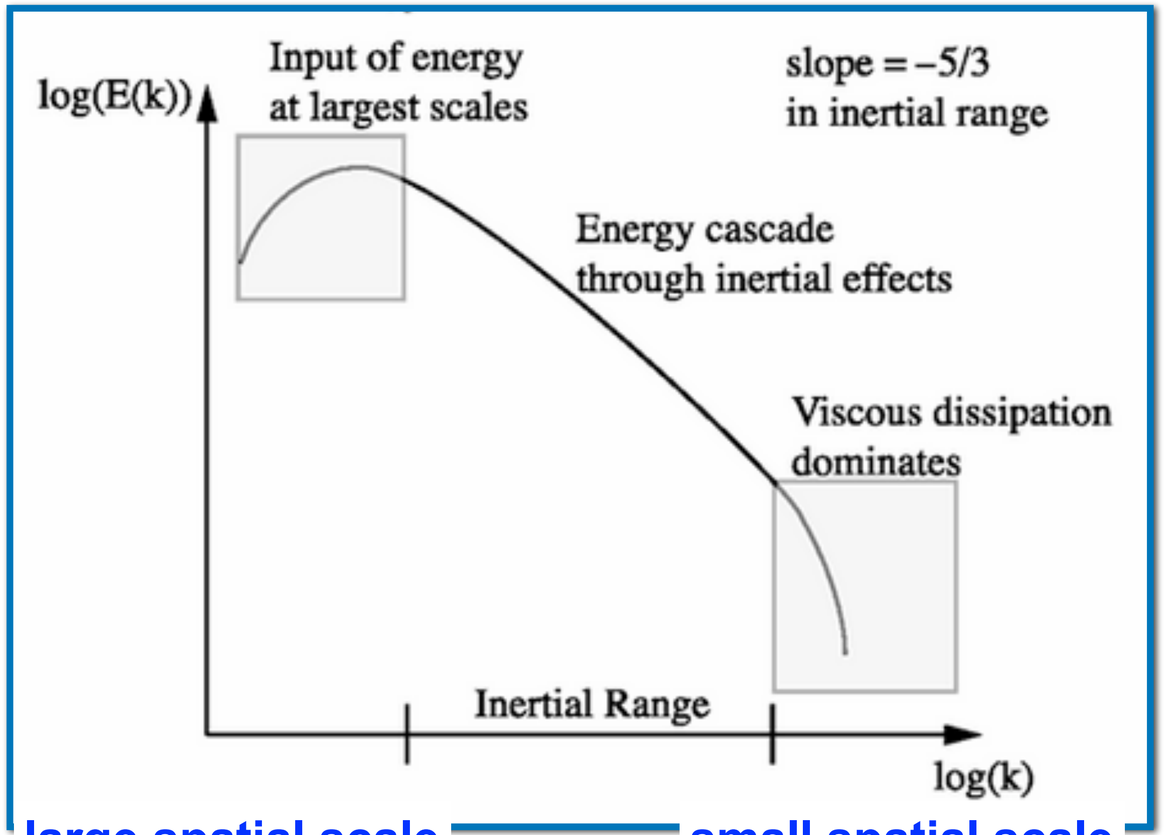
B AMPLIFICATION THROUGH SMALL-SCALE DYNAMO

- Fluid perturbation will induce turbulence in the intra-cluster medium, Turbulence decays to smaller and smaller scales
- In brief, Kolmogorov theory of turbulence: random fluid motion with velocity dispersion v on scale l (eddies) breaks up into two smaller eddies of size $l/2$ due to the convective term $\vec{v} \cdot \nabla \vec{v}$ in the fluid equation

→ Energy cascade





large spatial scale — **small spatial scale**

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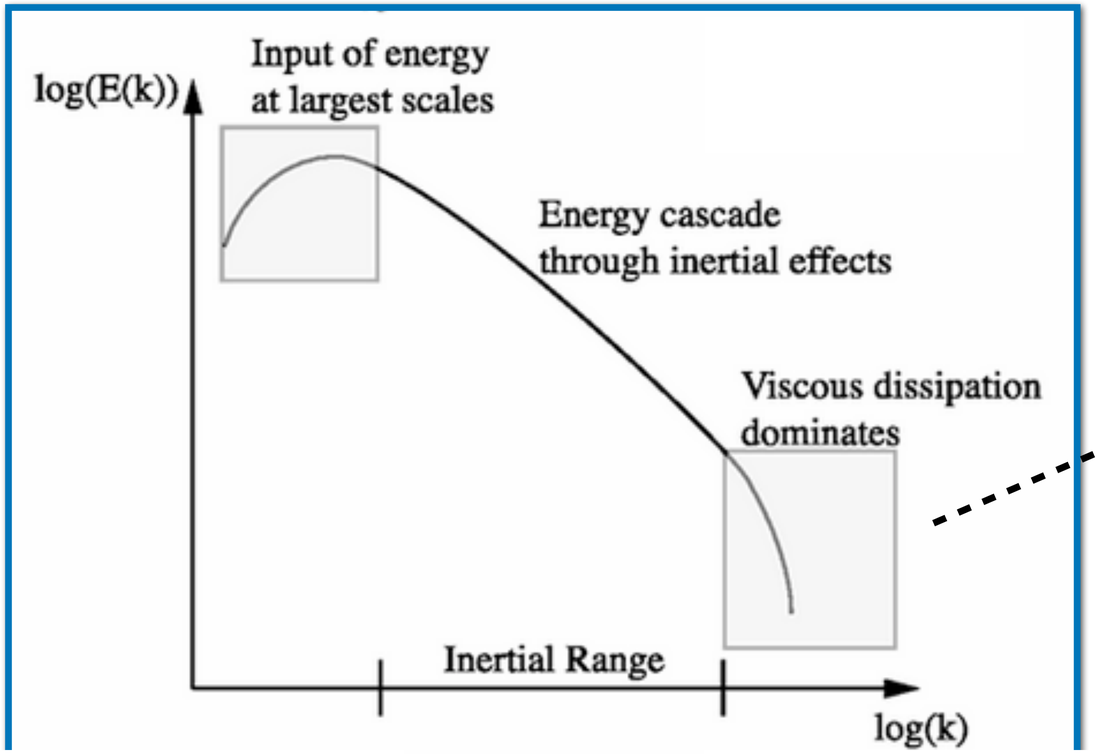
MAGNETIC FIELDS AMPLIFICATION IN CLUSTERS

- Energy cascade from large spatial scales (small k) to small partial scales (large k)



large spatial scale — **small spatial scale**

At some point, the scale reached by the eddies has a kinetic energy comparable to viscous forces or to the Lorentz force

At this scale, the kinetic energy of the flow is dissipated into thermal energy

The magnetic field is stretched and folded by the random velocity field

STRETCHING AND FOLDING OF MAGNETIC FIELD LINES: AMPLIFICATION

Credits:
Steinwandel et al
(2024)

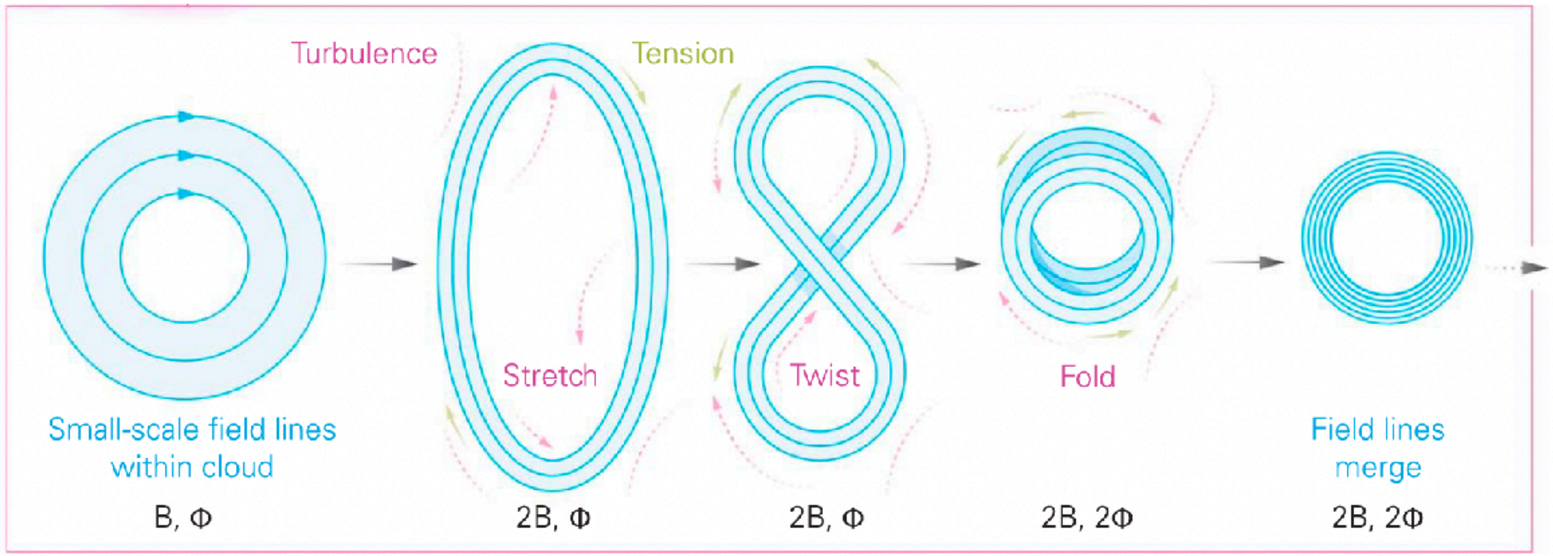


Figure 1. Schematic sketch of the small-scale turbulent dynamo that illustrates the stretching, twisting, and folding of field lines driven by ICM turbulence. As magnetic tension becomes stronger due to subsequent stretching, twisting, and folding, the process slows down and finally saturates when the turbulent kinetic energy in the smallest eddies that drive the process are in equipartition with the magnetic energy density.

Exponential increase of the magnetic energy that generates an "inverse cascade" from small to large scales

REMEMBER: flux freezing - incompressible fluid

any motion that increases l will also increase B: $B \propto l$

implies that: Field B_1 on scale l_1 stretched to scale l_2 : $B_2 = B_1 \frac{l_2}{l_1}$

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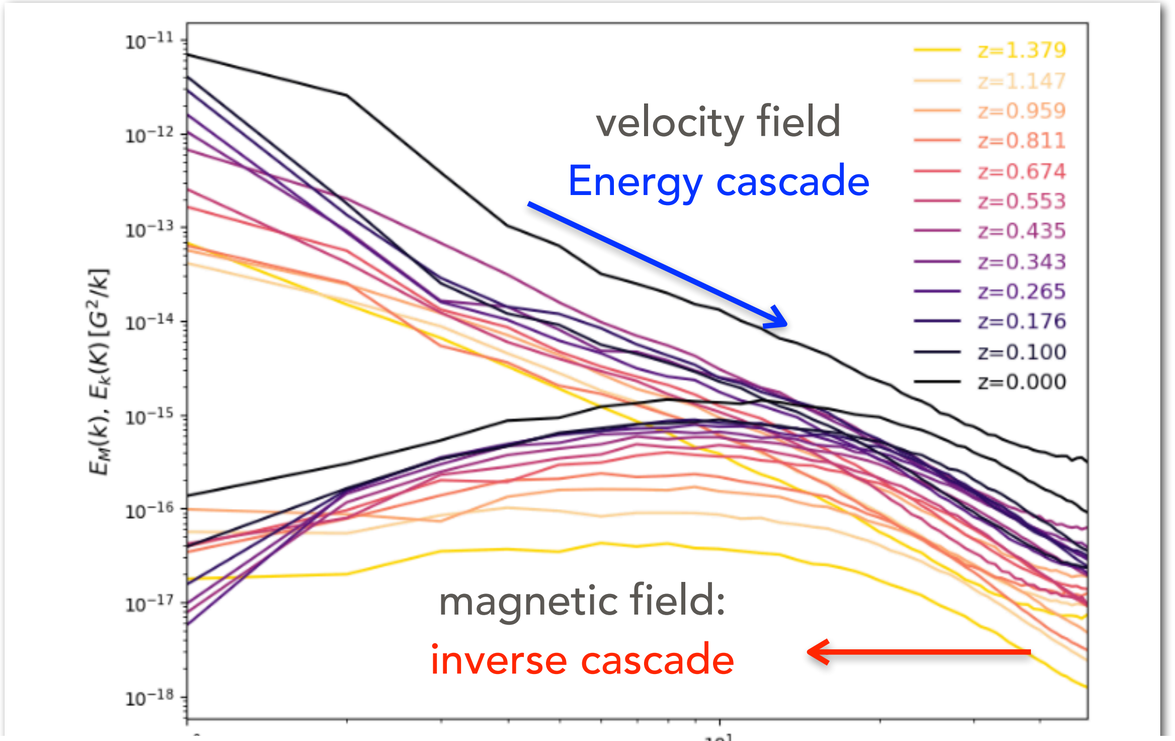
B AMPLIFICATION THROUGH SMALL-SCALE DYNAMO



Large spatial scales ——— **small spatial scales**

Exponential growth of the small scale dynamo does not proceed to infinity, as magnetic field starts to back react to the flow

"inverse cascade" up to a maximum scale l_B where B energy ~turbulent kinetic energy

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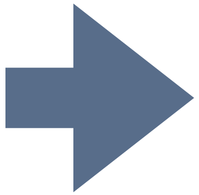
B AMPLIFICATION THROUGH SMALL-SCALE DYNAMO

- The exponential growth of magnetic field is clusters is very fast→ the dynamo saturates at the very beginning of cluster formation

- Every weak seed will be amplified by the dynamo



Dynamo will erase all imprints of the initial seed field

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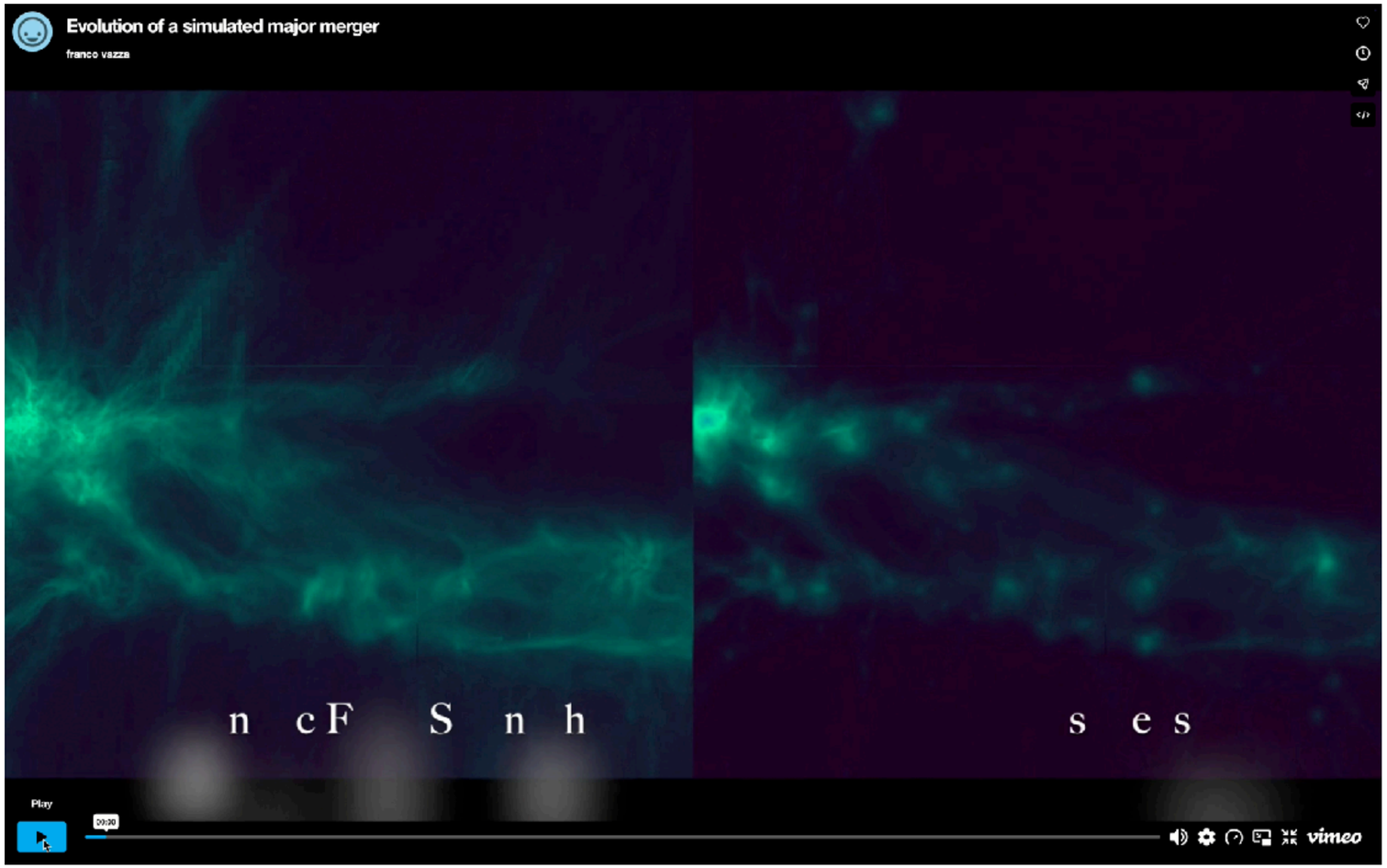
B AMPLIFICATION in CLUSTERS

- Dynamo is not the only process that shapes B in clusters:
  - clusters undergo multiple mergers and turbulent cascades start at different scales at once
  - Also compression from shocks and shear motion impact the shape and strength of the magnetic field



The resulting amplification of the magnetic field strength is a complex interplay between compression and the small-scale dynamo

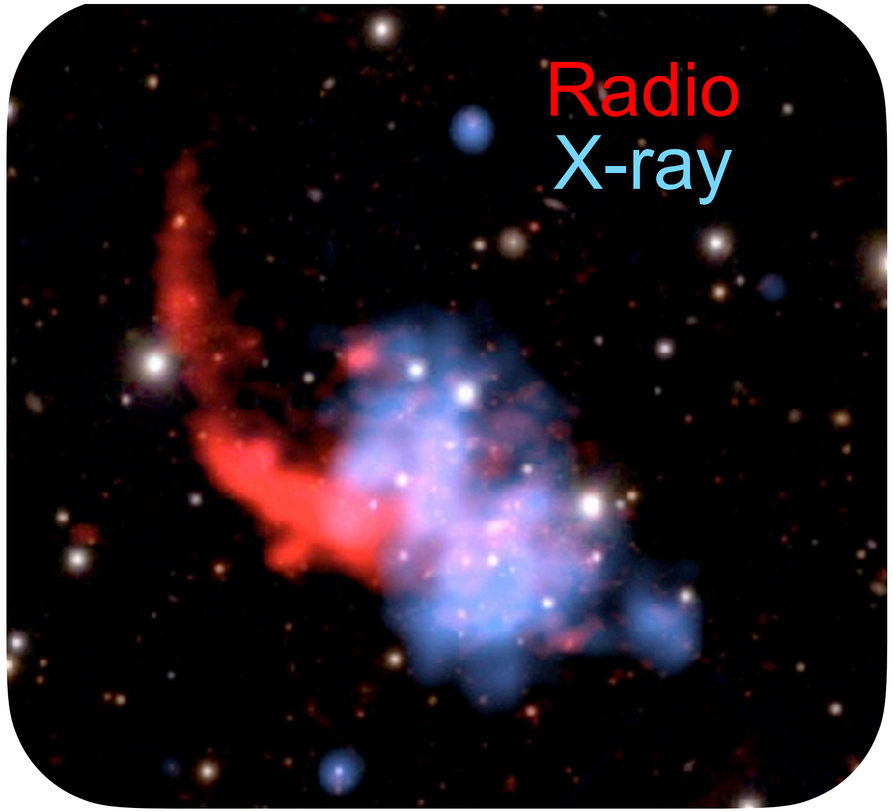
RECENT UNEXPECTED RESULTS

- Radio halos found in high-z clusters
  $0.7 < z < 0.9$
  Inverse Compton losses should be strong
  $(\frac{dE}{dt} \propto (1+z)^4)$

- To be visible in radio, B must be already amplified at z ~0.7 as in local clusters

- We need a fast amplifications (only few Gyrs from cluster formation)

Challenging dynamo models



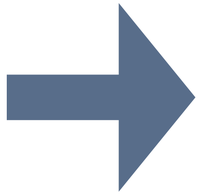
Di Gennaro et al Nature astronomy, 2020

ORIGIN AND AMPLIFICATION of B in CLUSTERS: TAKE HOME MESSAGES

- Magnetic field must be amplified to reach the μG level that we observe in clusters.

- The amplification depends on complex small-scale physics, likely involving small-scale dynamos

- The amplification must be fast! How much? It depends on the saturation value which is not constrained yet



we need robust constrain on magnetic fields on large samples of clusters to understand the amplification process

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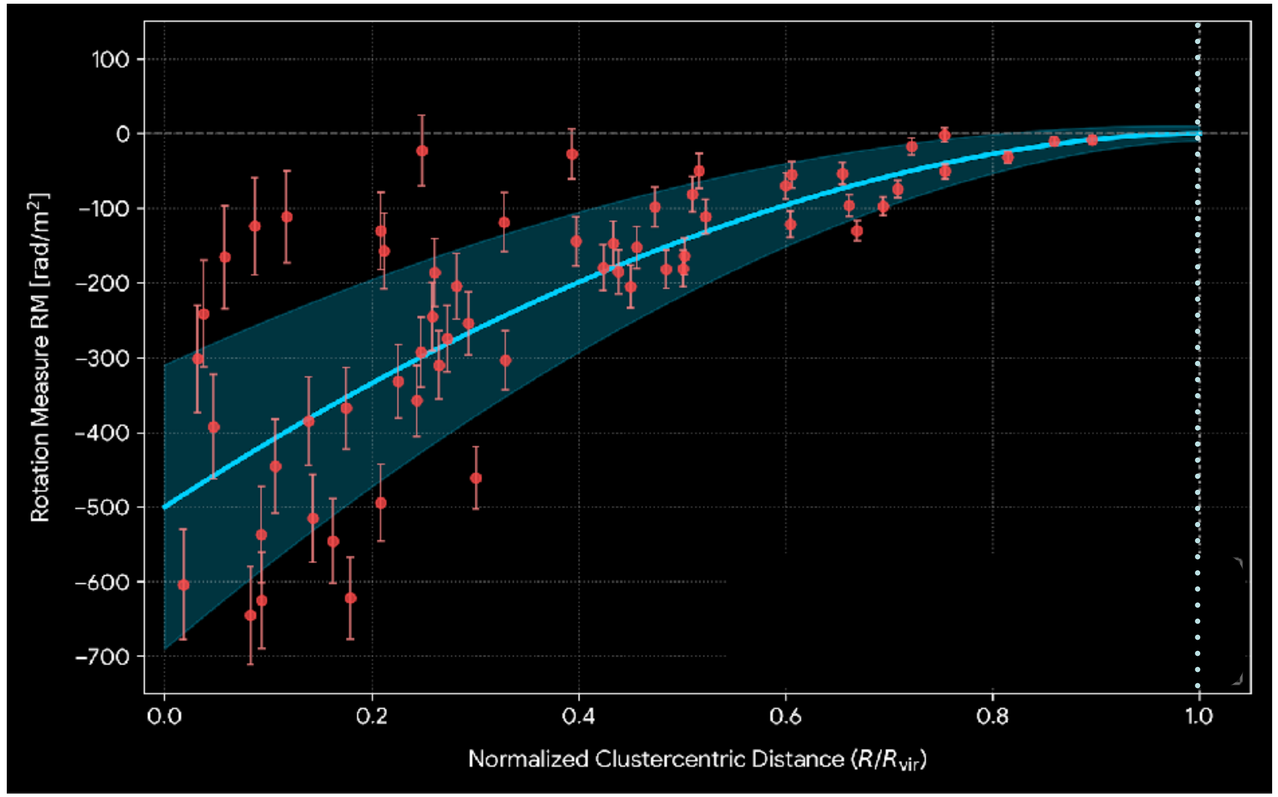
100
0
−100
−200
−300
−400
−500
−600
−700
Rotation Measure RM [rad/m²]
0.0
0.2
0.4
0.6
0.8
1.0
Normalized Clustercentric Distance (R/R_{vir})