ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

SKAO

Magnetic Fields in Proto-clusters towards the SKAO Era

Annalisa Pagliotta

PhD student

University of Bologna (DiFA), INAF – IRA

annalisa.pagliotta@unibo.it

Supervisor:
Annalisa Bonafede (University of Bologna)
Co-supervisors:
Chiara Stuardi (INAF – IRA),
Christopher J. Riseley (University of Bochum)

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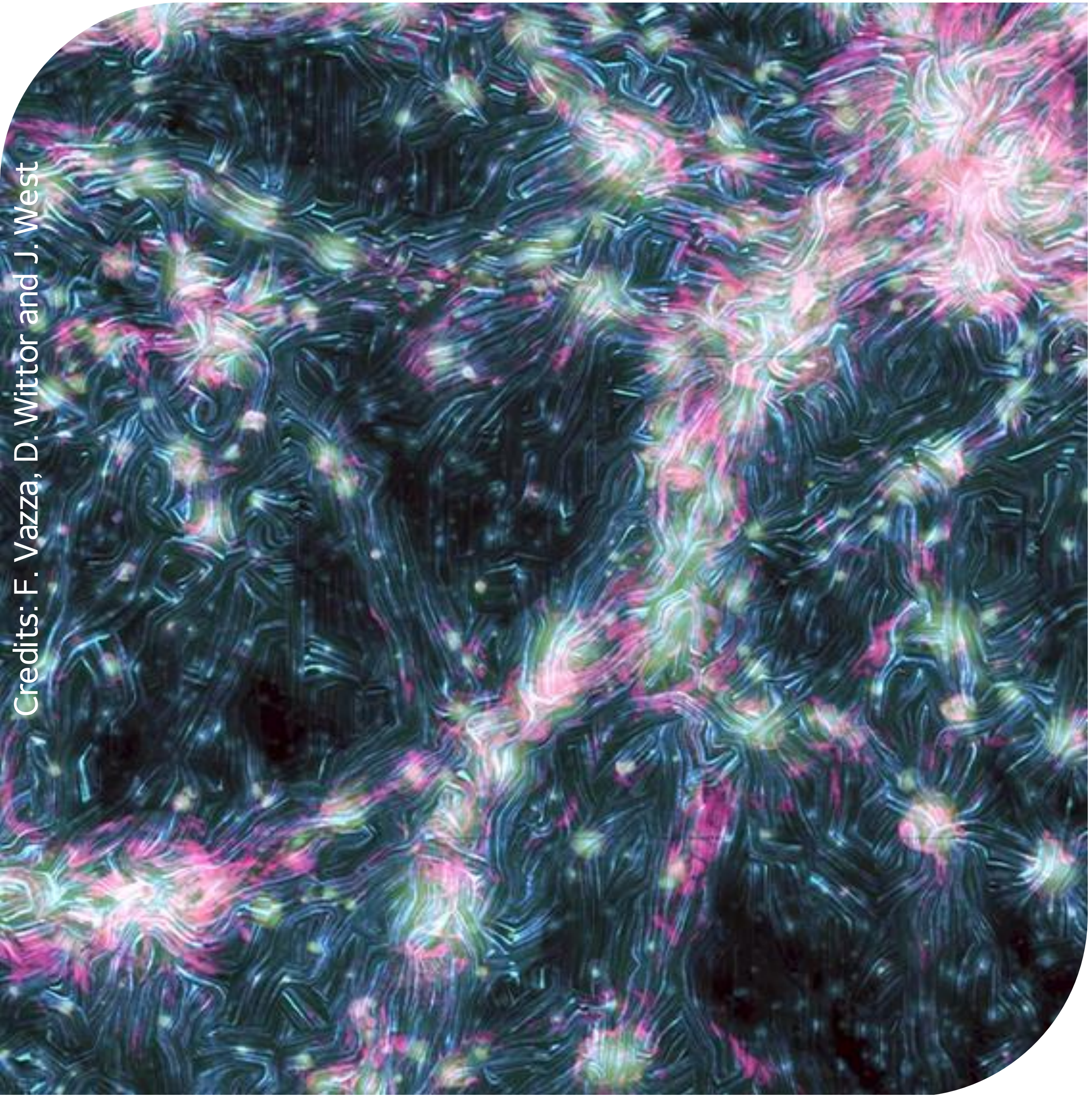
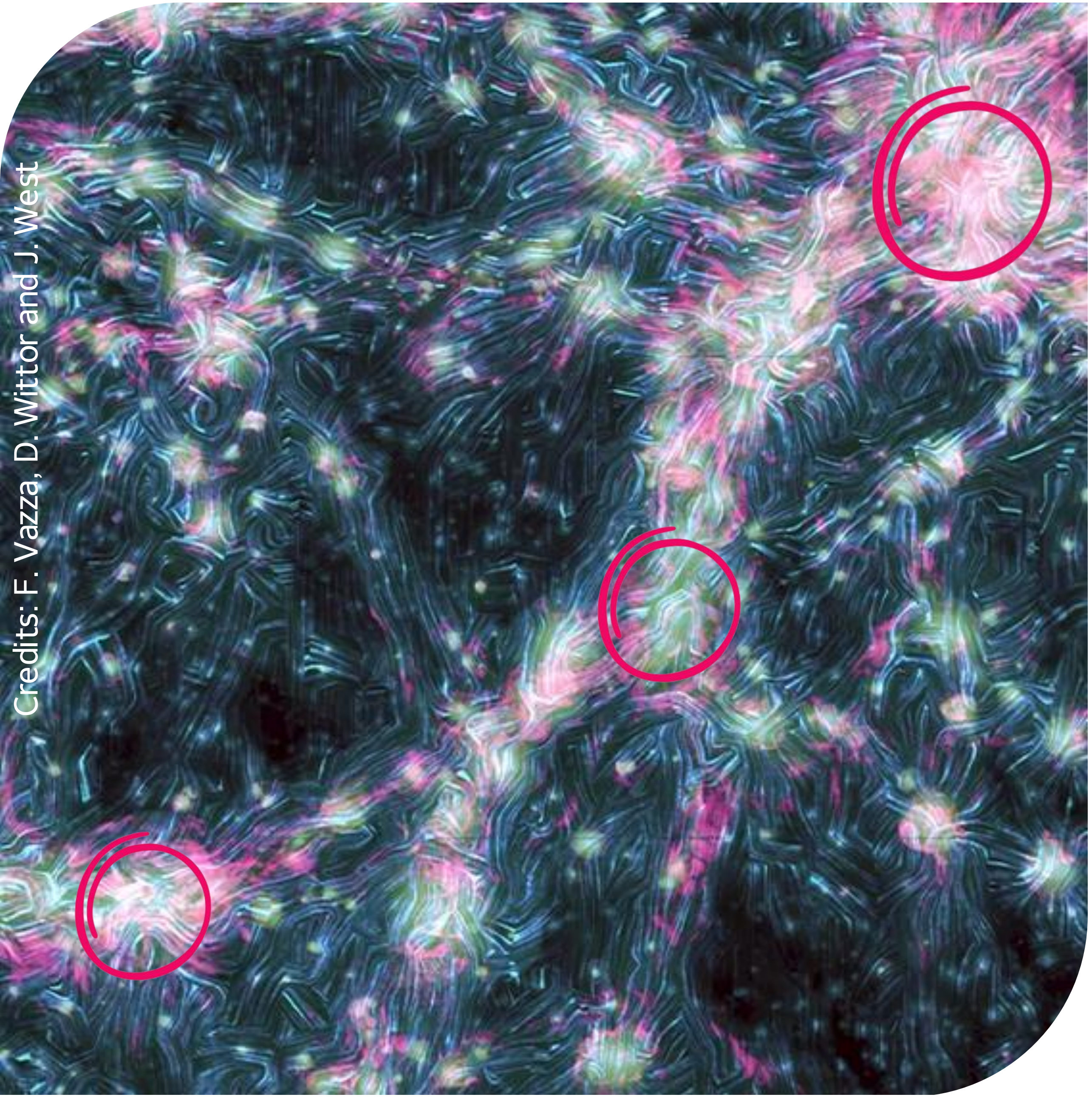
Large scale Magnetic Fields



Introduction

Magnetic fields are *everywhere* in the Universe...



Introduction

Magnetic fields are *everywhere* in the Universe...

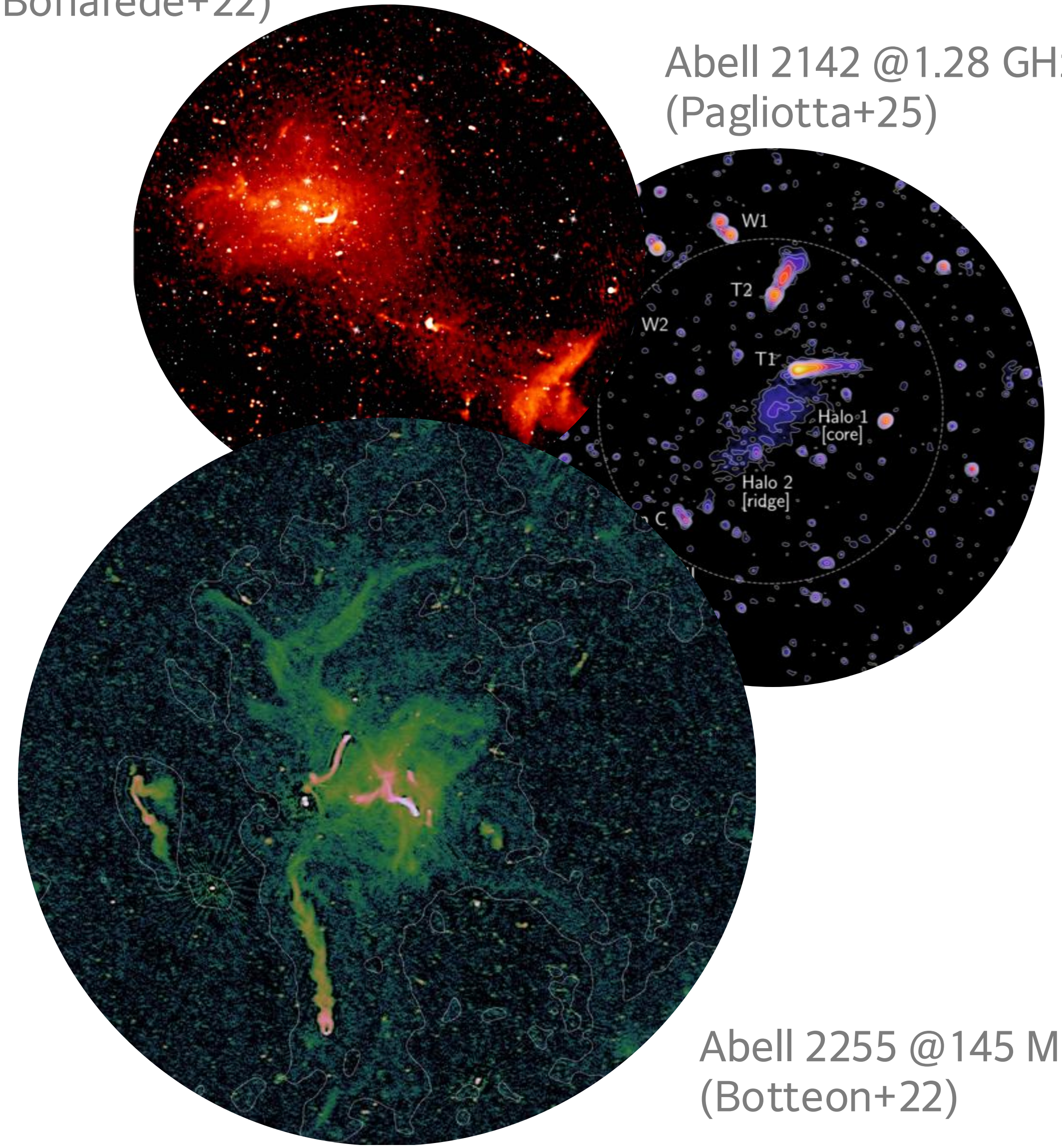
... at the *nodes* of the Cosmic Web:

Galaxy clusters

Introduction

Coma @144 MHz
(Bonafede+22)

Abell 2142 @1.28 GHz
(Pagliotta+25)



Abell 2255 @145 MHz
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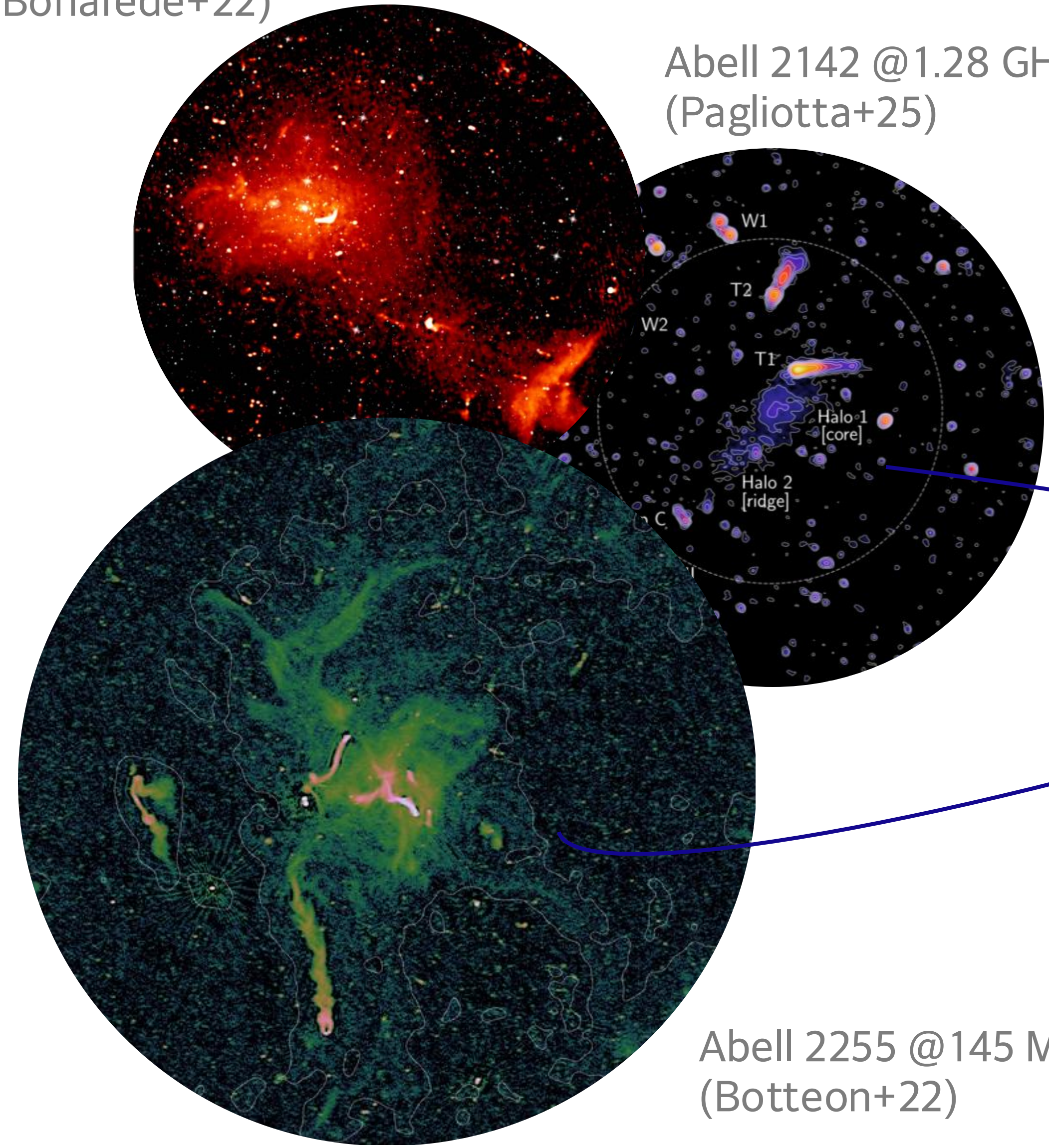

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Magnetic fields are *everywhere* in the Universe...

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Galaxy clusters

diffuse radio synchrotron emission as a probe of the **Intra-cluster Medium (ICM)** to be **magnetised**

Large scale Magnetic Fields

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Abell 2142 @1.28 GHz
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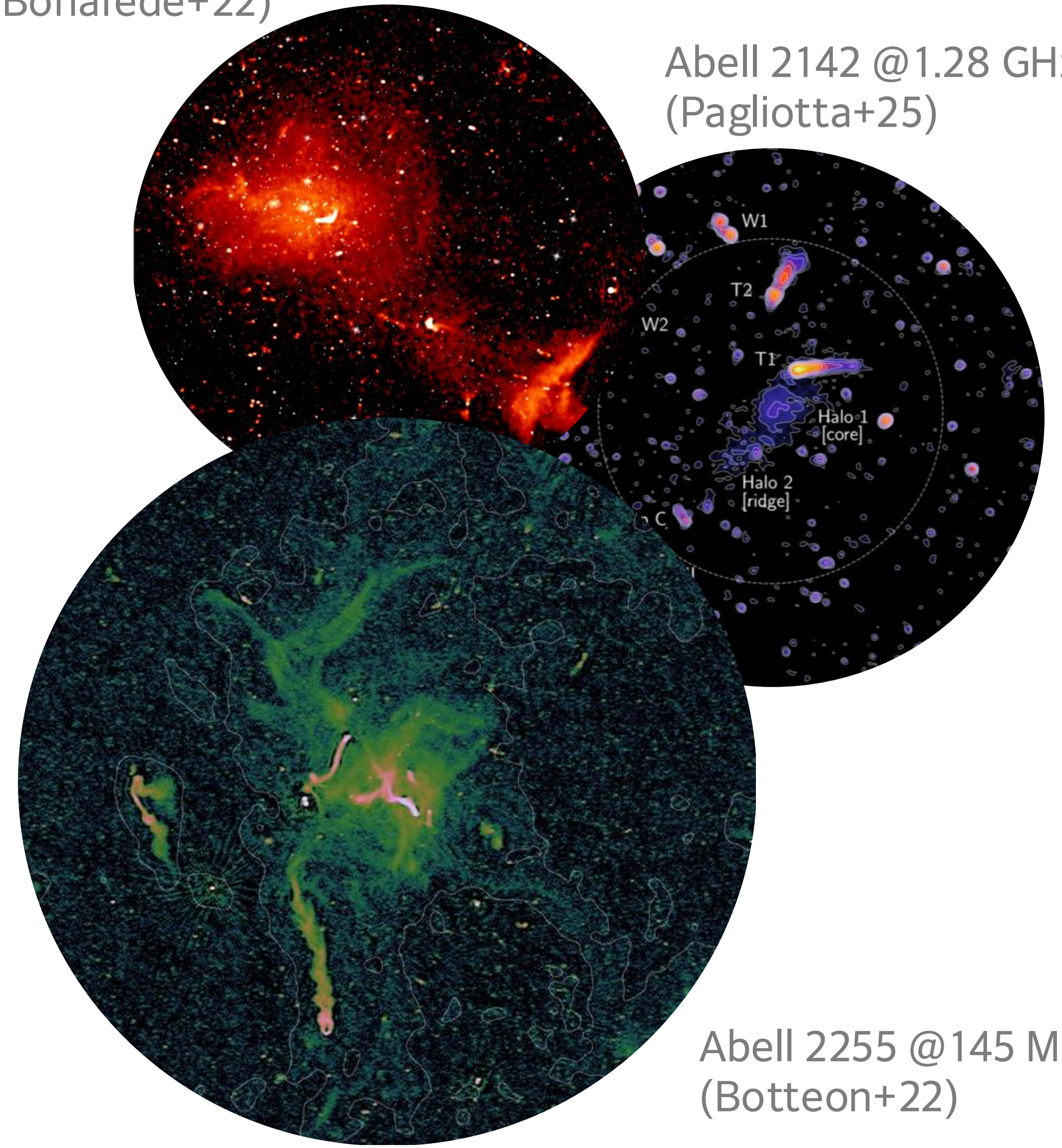

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Introduction

Magnetic fields are *everywhere* in the Universe…

… at the *nodes* of the Cosmic Web:

Galaxy clusters

Low redshift

- Limited number of studies (**~ 10**)
- *Intensity:* **1-12** μG (at the centre)
- *Turbulent* configuration

Open Questions

1

Origin

Primordial, astrophysical seeds

2

Amplification

Intensity, structure, mechanisms, timescale

3

Evolution

Open Questions

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Origin

Primordial, astrophysical seeds

Recent studies *favour a primordial origin* (e.g. Carretti+25)

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Large scale Magnetic Fields

Open Questions

1 **Origin**

Primordial, astrophysical seeds

Recent studies *favour a primordial origin* (e.g. Carretti+25)

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Intensity, structure, mechanisms, timescale

Amplification of weak seeds by structure formation, accretion and mergers (e.g. Steinwandel+22)

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Open Questions

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Intensity, structure, mechanisms, timescale

Amplification of weak seeds by structure formation, accretion and mergers (e.g. Steinwandel+22)

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Evolution

High redshift

Galaxy clusters: μG intensity by z ~ 0.6 - 0.9; fast amplification (Di Gennaro+20)

Dawn of Structure Formation

To study the *origin* and the *evolution* of **magnetic fields**, *earlier phases of galaxy clusters* need to be probed, namely

Proto-clusters

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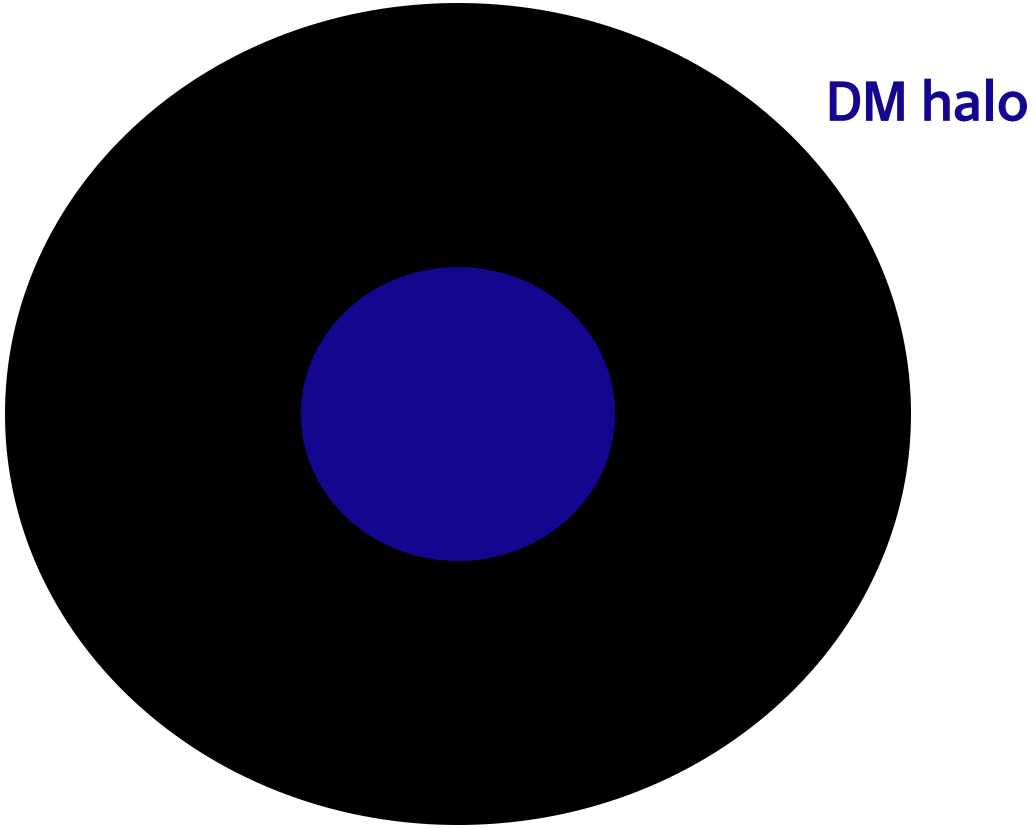
"A proto-cluster is a structure that will, at some stage, collapse into a galaxy cluster." (Overzier+16)



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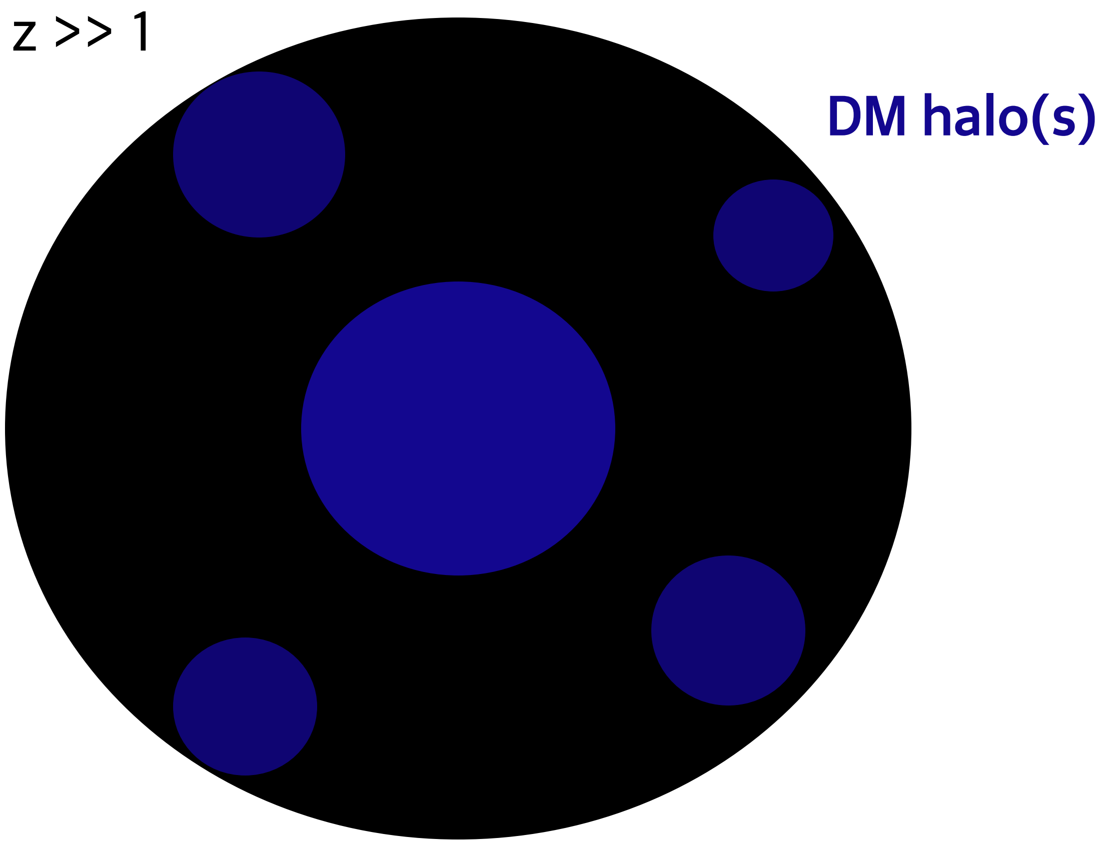

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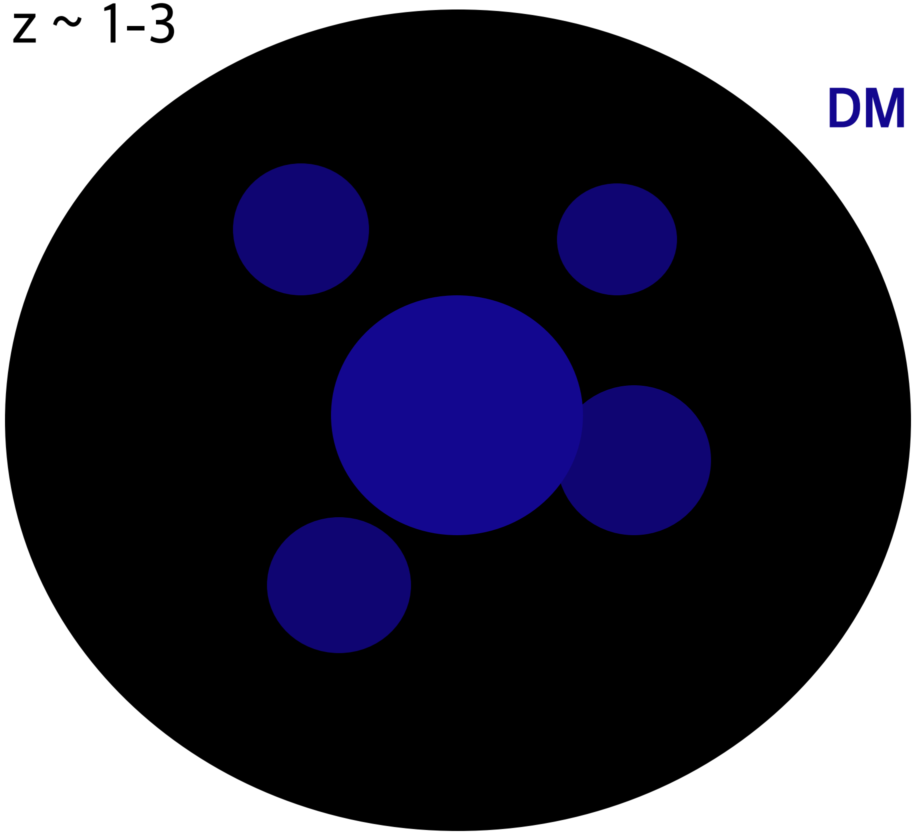
Proto-clusters

z ~ 1-3



DM halo(s)

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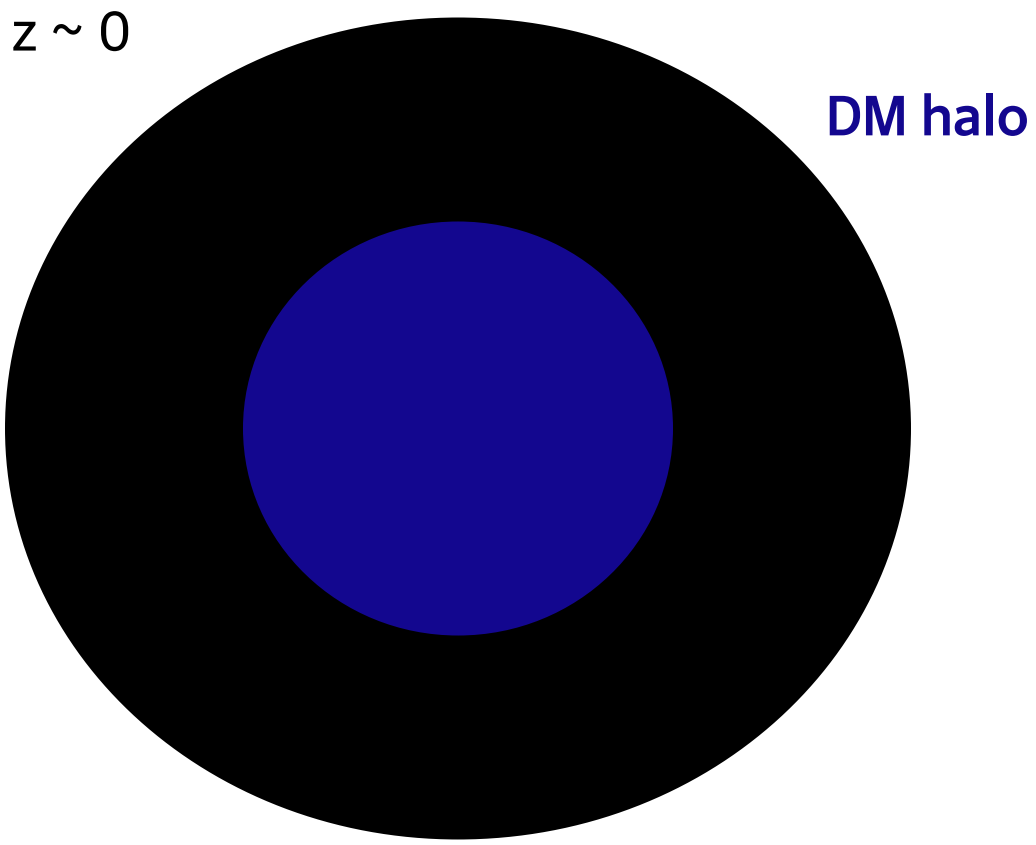

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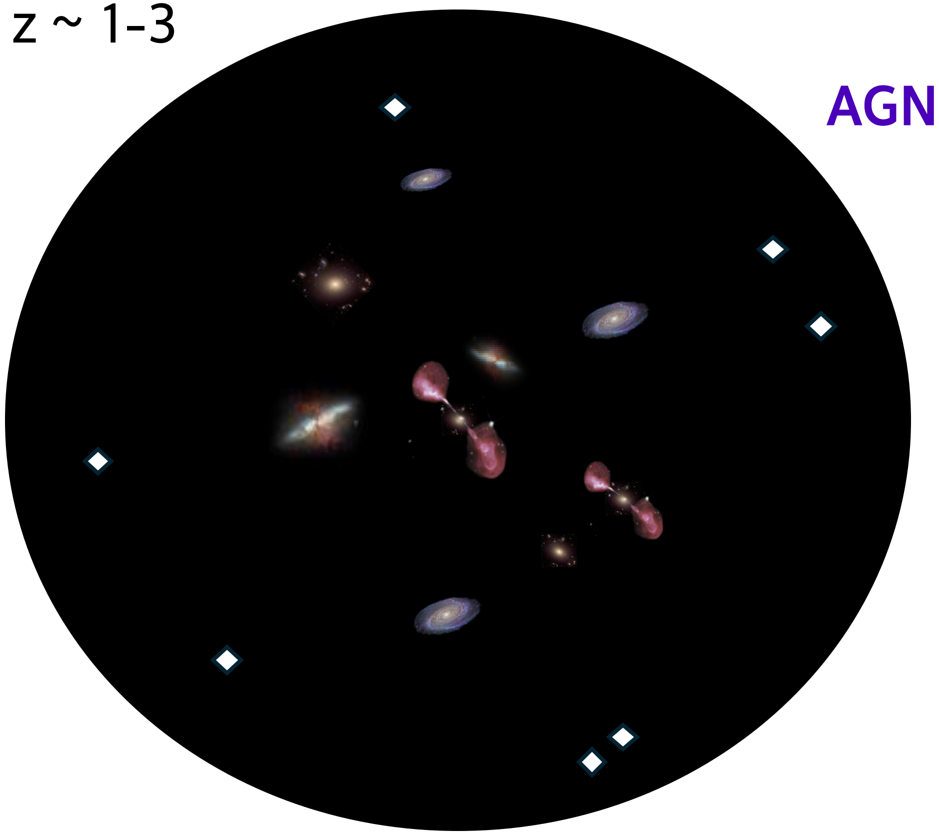

AGN and galaxies

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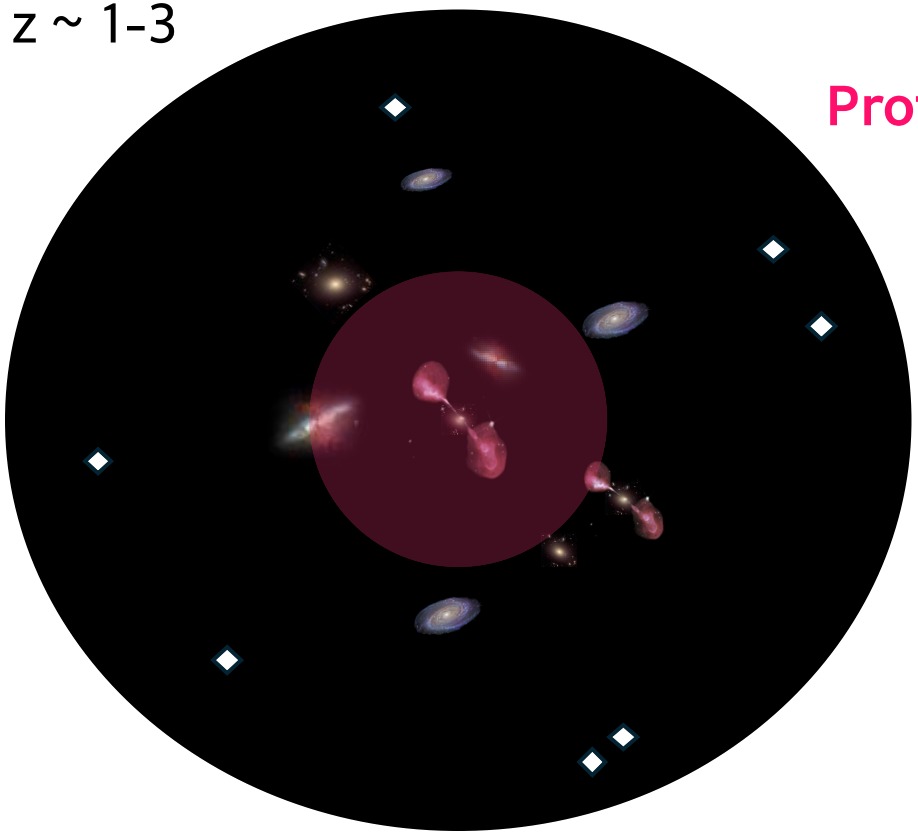

Proto-ICM

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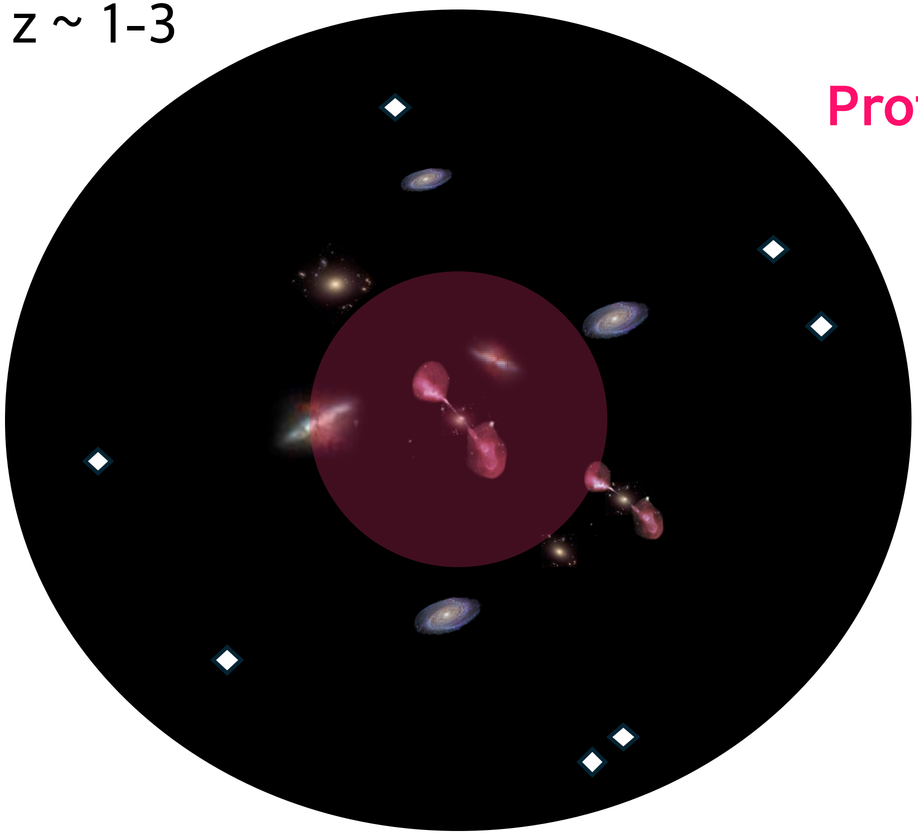
Dawn of Structure Formation

- predicted by *simulations* (e.g. Remus+23)

z ~ 1-3

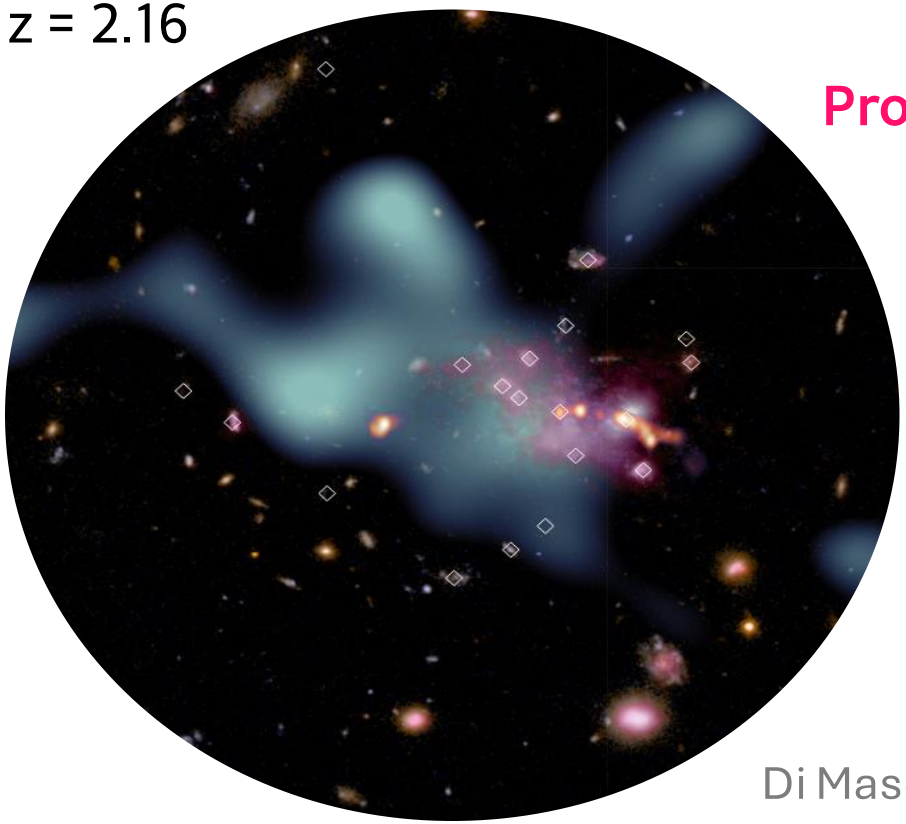


Proto-ICM

Dawn of Structure Formation

Spiderweb proto-cluster

z = 2.16



Di Mascolo+23

Proto-ICM

- predicted by *simulations* (e.g. Remus+23)
- *observations:* **X-ray** (Tozzi+22, Lepore+24) and **Sunyaev-Zeldovich** (Di Mascolo+23) thermal gas in the **Spiderweb proto-cluster**

Dawn of Structure Formation

Spiderweb proto-cluster

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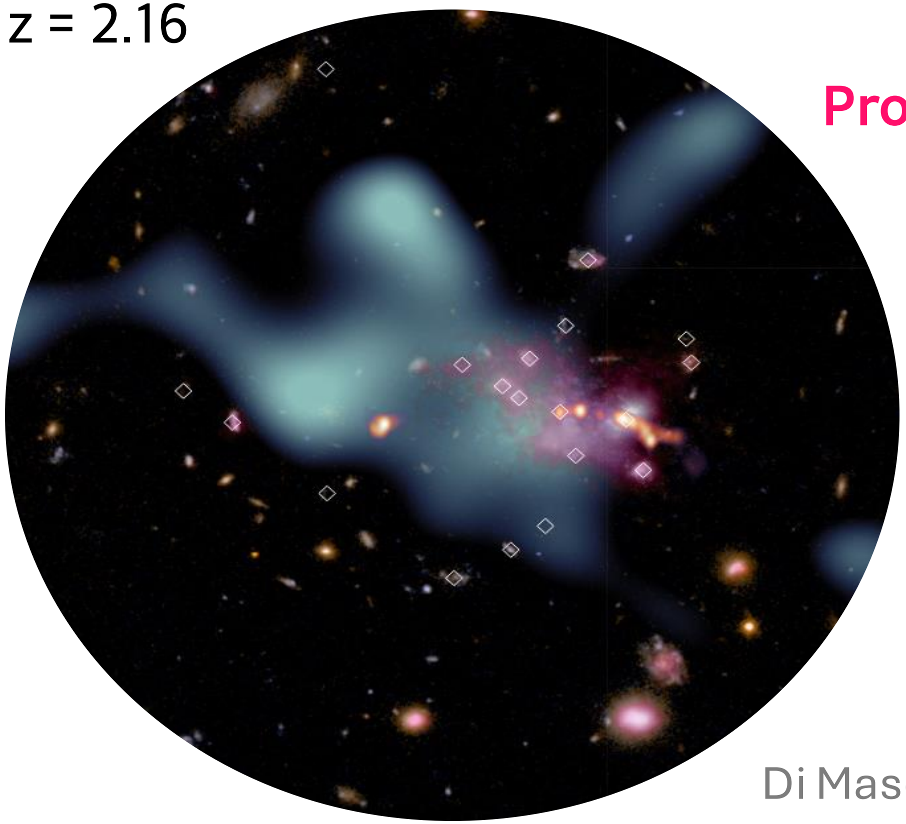

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To date, **only magnetic field estimate** in the proto-ICM

B < 1 μG

Anderson+22

Key **questions** to answer

1

Level of *amplification* and *structure* of magnetic fields in the proto-ICM

2

Contribution of *astrophysical sources* (e.g., AGN) to the magnetisation

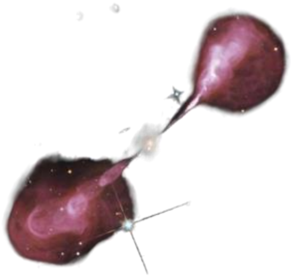
CARLA sample

First systematic study in **9** *proto-clusters* (1.37< z < 2.80) of the

ClusterAroundRadioLoudAGN survey (Wylezalek+13,+14)

(CARLA)

1. strongly polarised radio-loud AGN at the centre

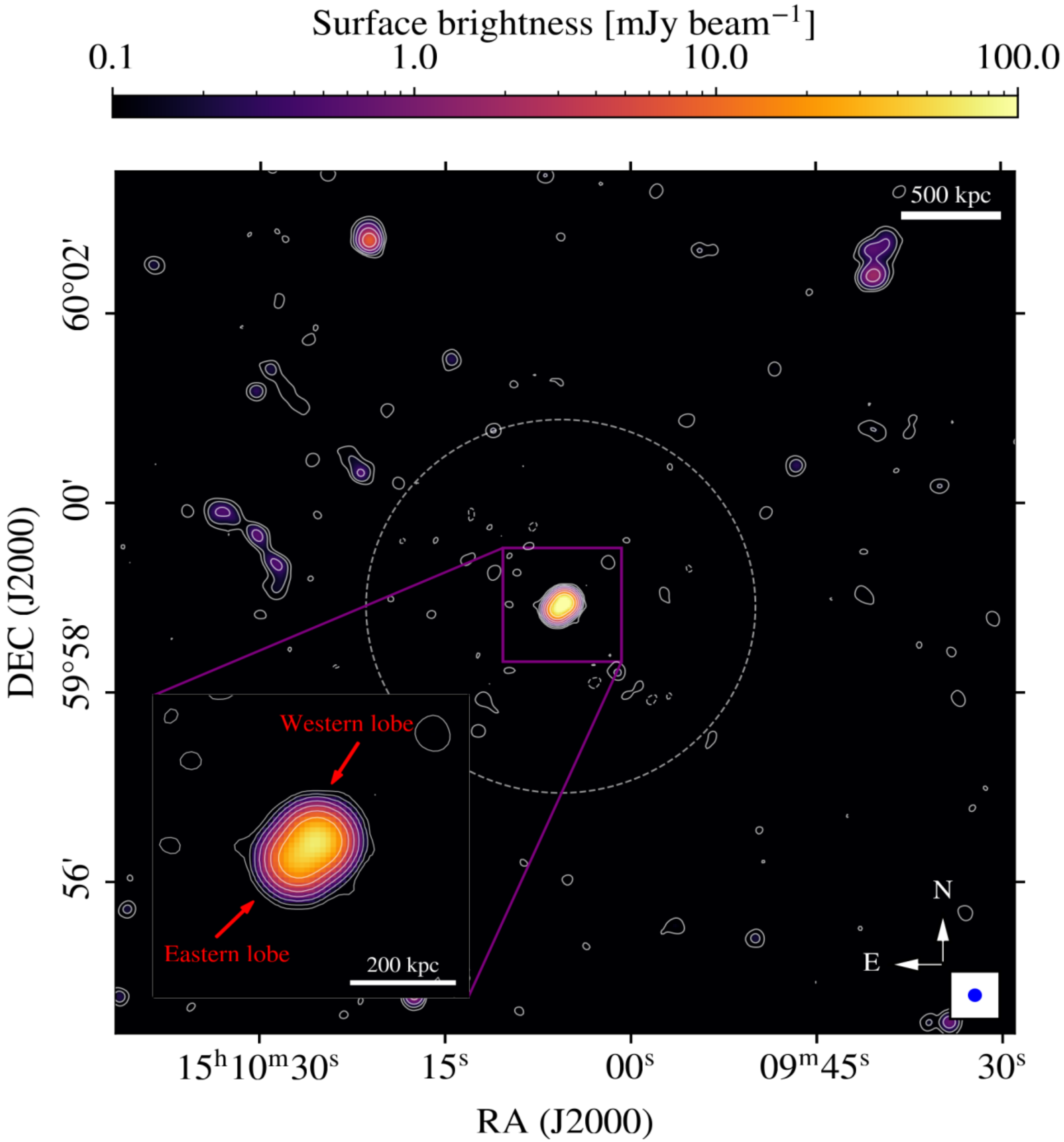


2. spectroscopically confirmed (Noirot+18)

3. Very Large Array (VLA) L-band (1-2 GHz)

Magnetic Fields in Proto-clusters

CARLA J1510+5958 & J1358+5752



CARLA J1510+5958 (Pagliotta et al., in prep.)

- $z = 1.72$
- $Log_{10}M_{halo} = 14.2$ (Mei+23)
- *Spec. Conf. Members* = 6 (Noirot+18)

Stokes I MFS image at 1.5 GHz

Restoring beam of 7'' × 7'' (~ 59 kpc)

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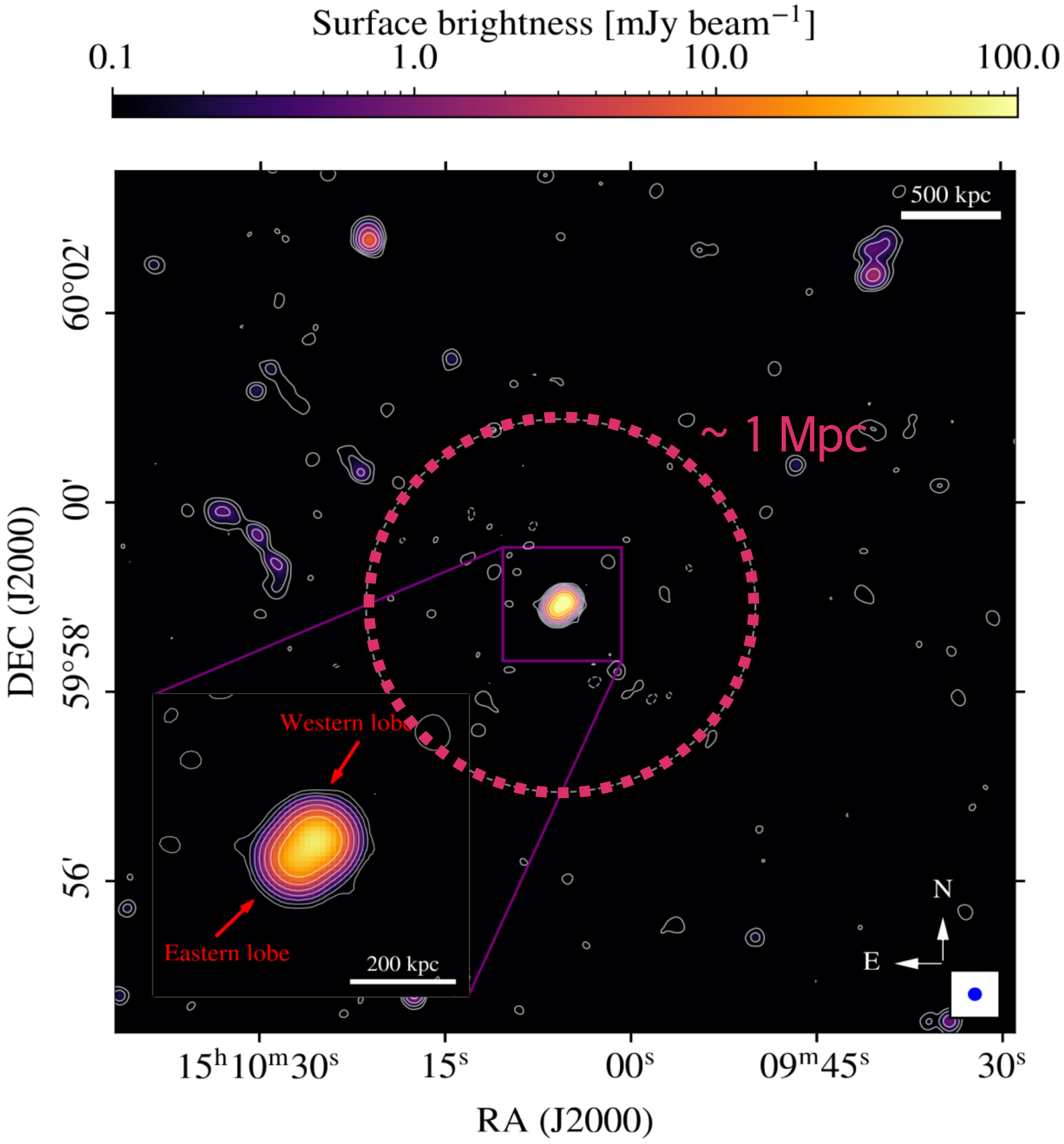

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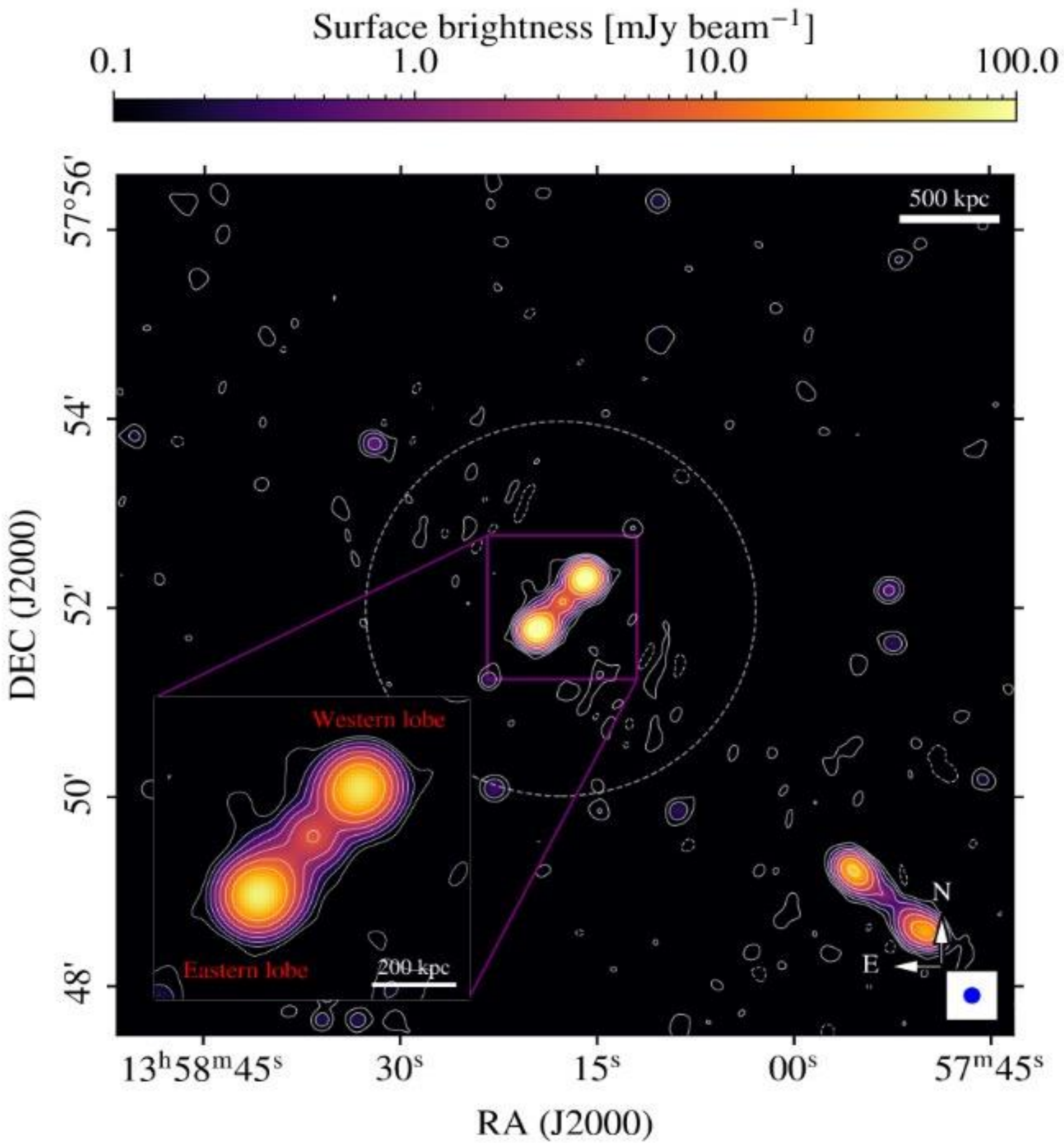

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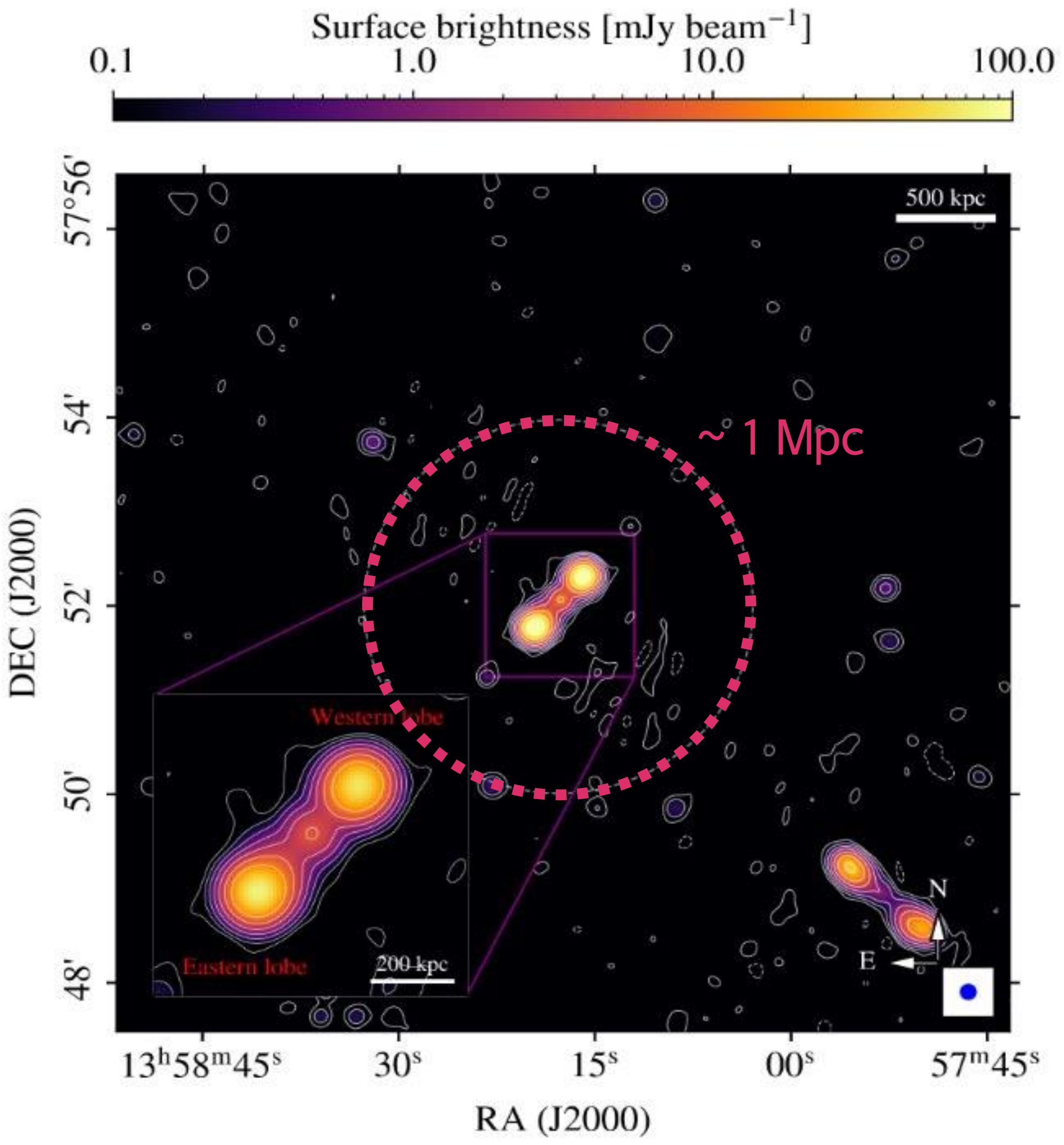

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- *Spec. Conf. Members* = 14 (Noirot+18)

Stokes I MFS image at 1.5 GHz

Restoring beam of 9″ × 9″ (~ 76 kpc)

General approach

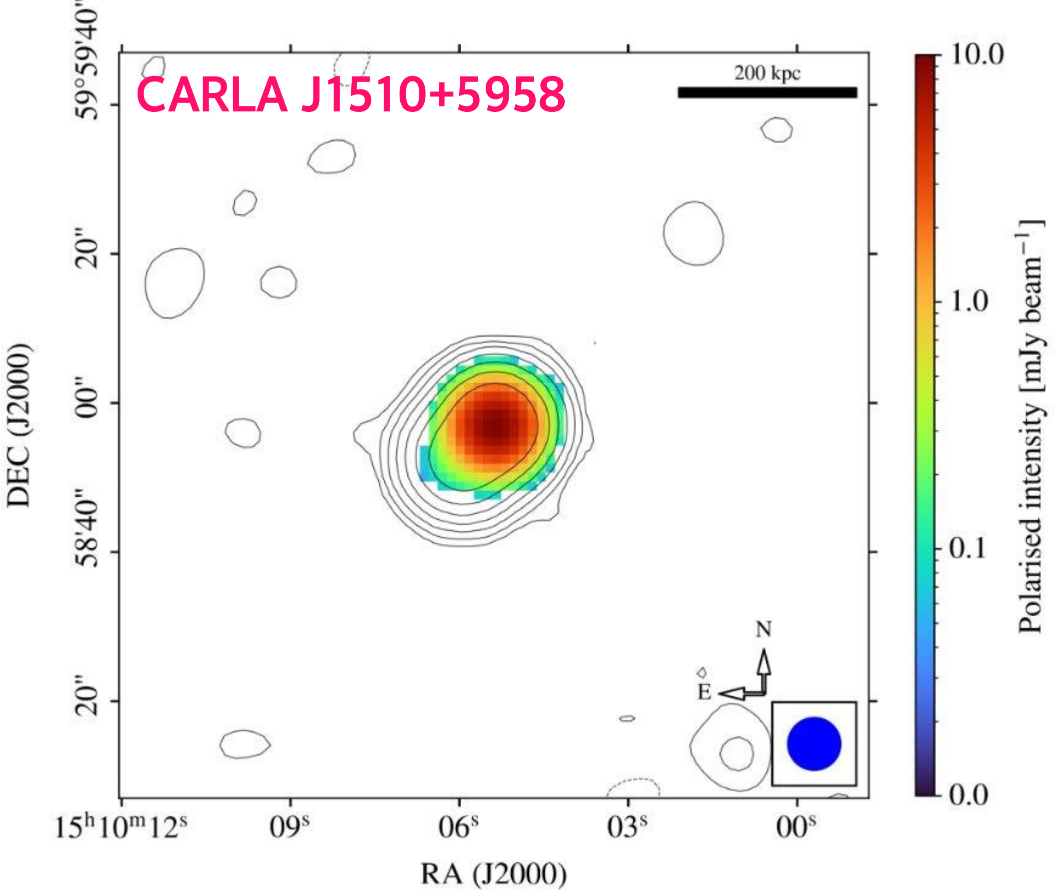
1 Study the *polarisation* and *RM properties* through the **RM synthesis technique**

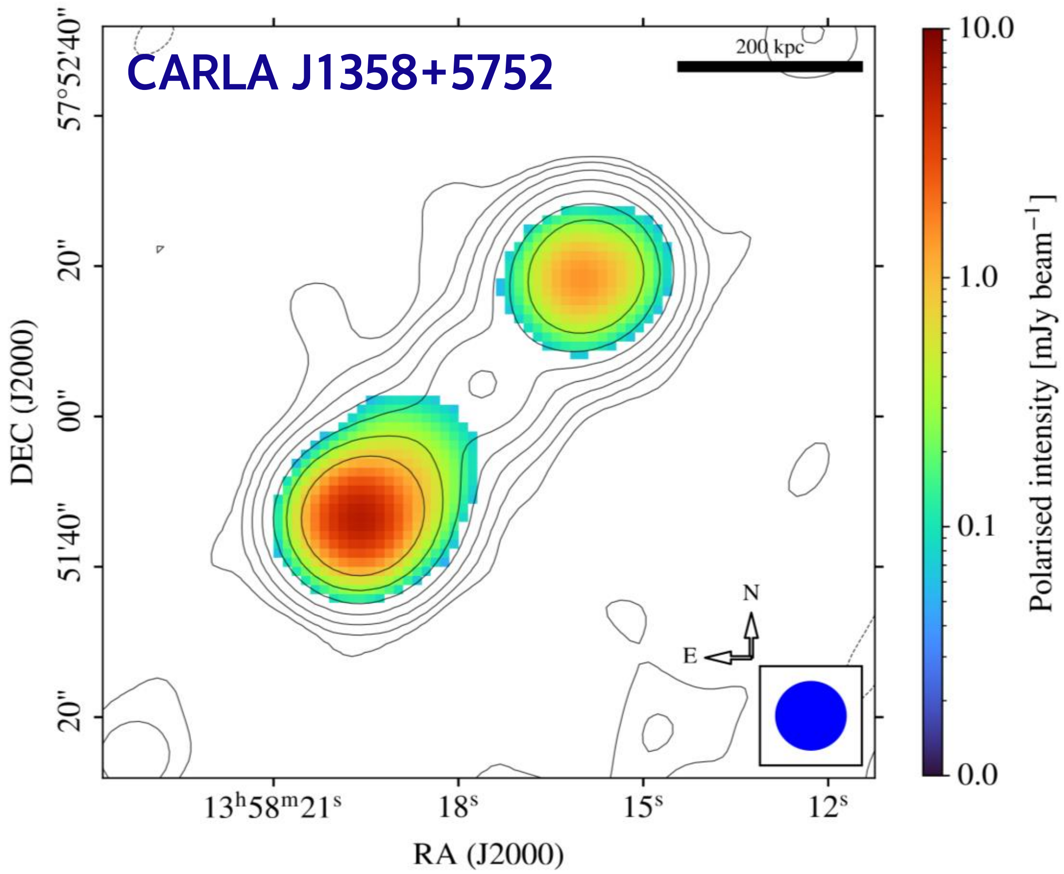
2 Constrain the *magnetic field intensity* and *structure* through the comparison with **simulations**

$$\mathrm{RM} = 812 \int_{z_s}^{0} \frac{n_e(z)_{[cm^{-3}]} B_{\parallel}(z)_{[\mu G]}}{(1+z)^2} \frac{dl_{[kpc]}}{dz} dz \ \ \mathrm{rad\ m}^{-2}$$

CARLA J1510+5958 & J1358+5752

Maximum polarised intensity + *total intensity contours* at 1.5 GHz





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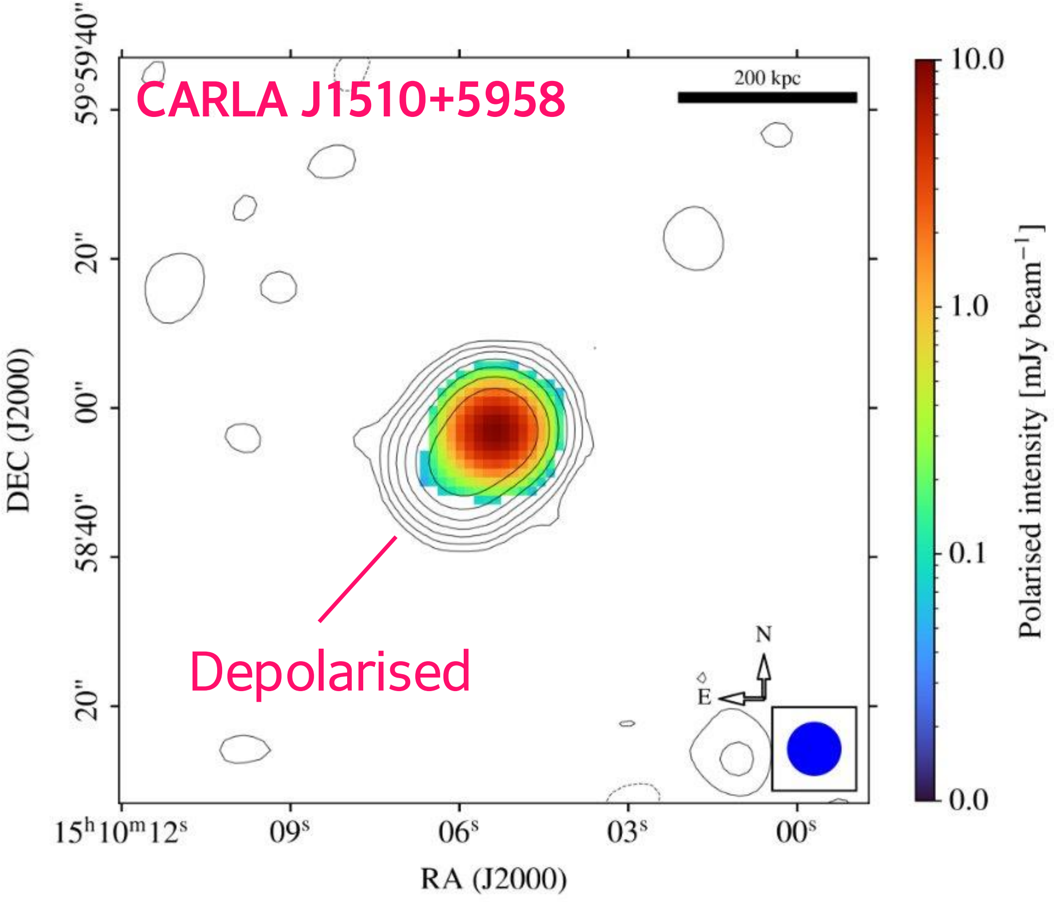

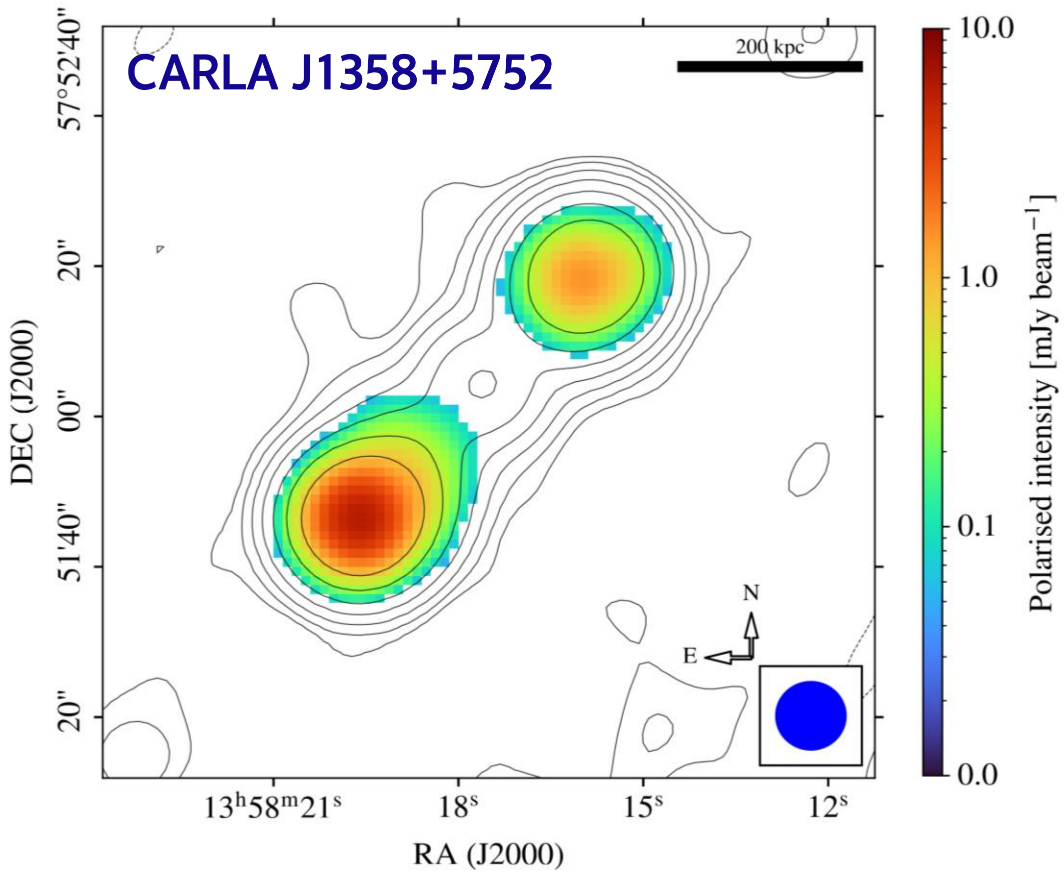

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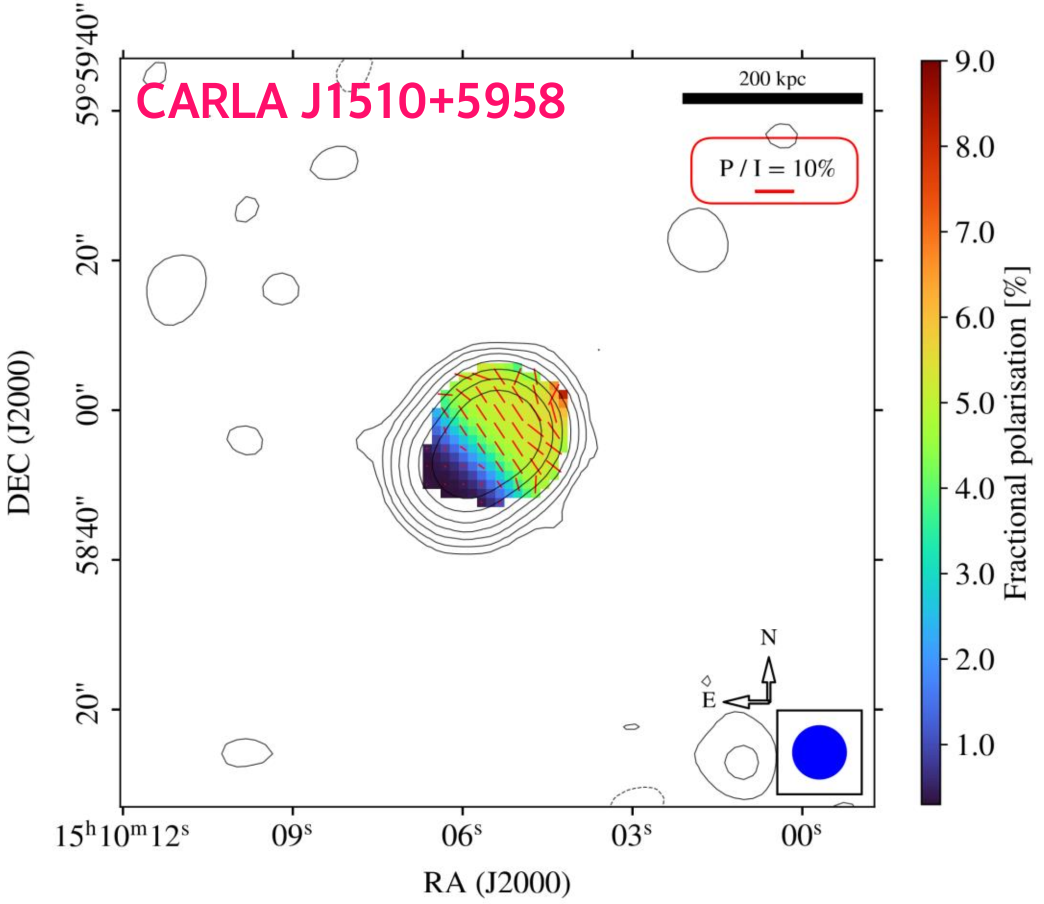
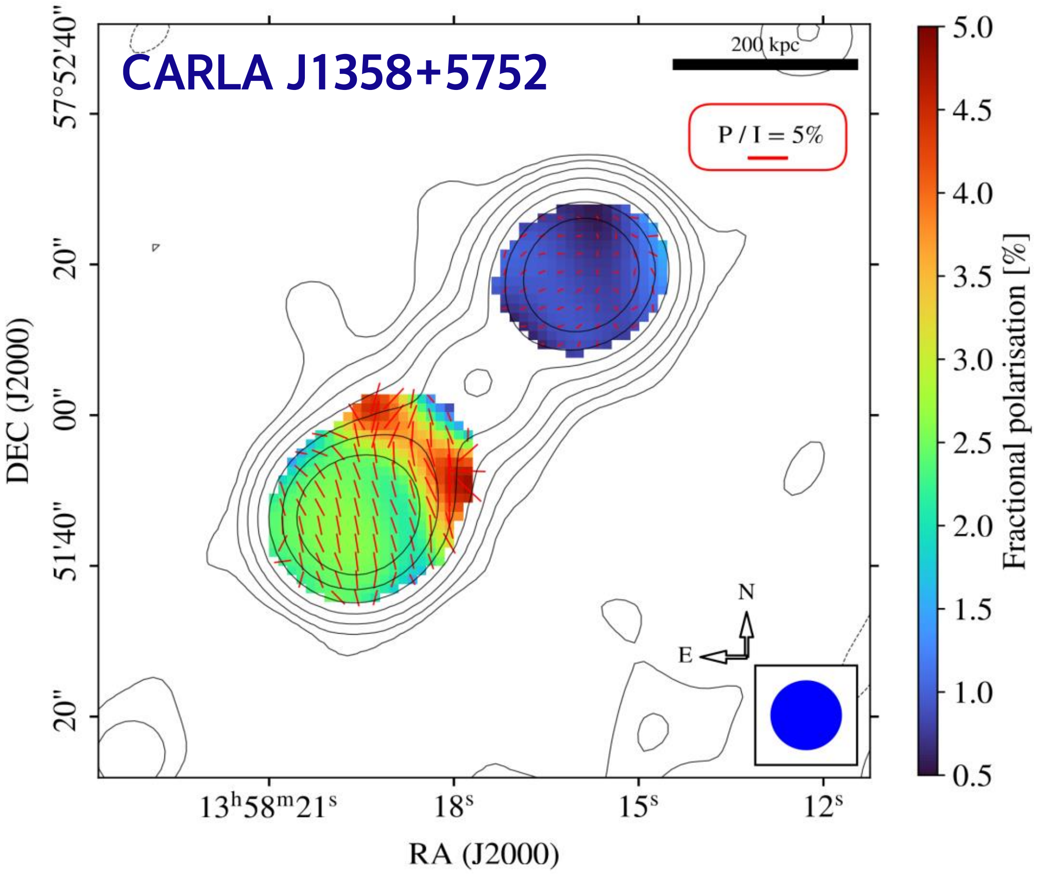
Magnetic Fields in Proto-clusters

CARLA J1510+5958 & J1358+5752

Polarisation Fraction + *total intensity contours* at 1.5 GHz





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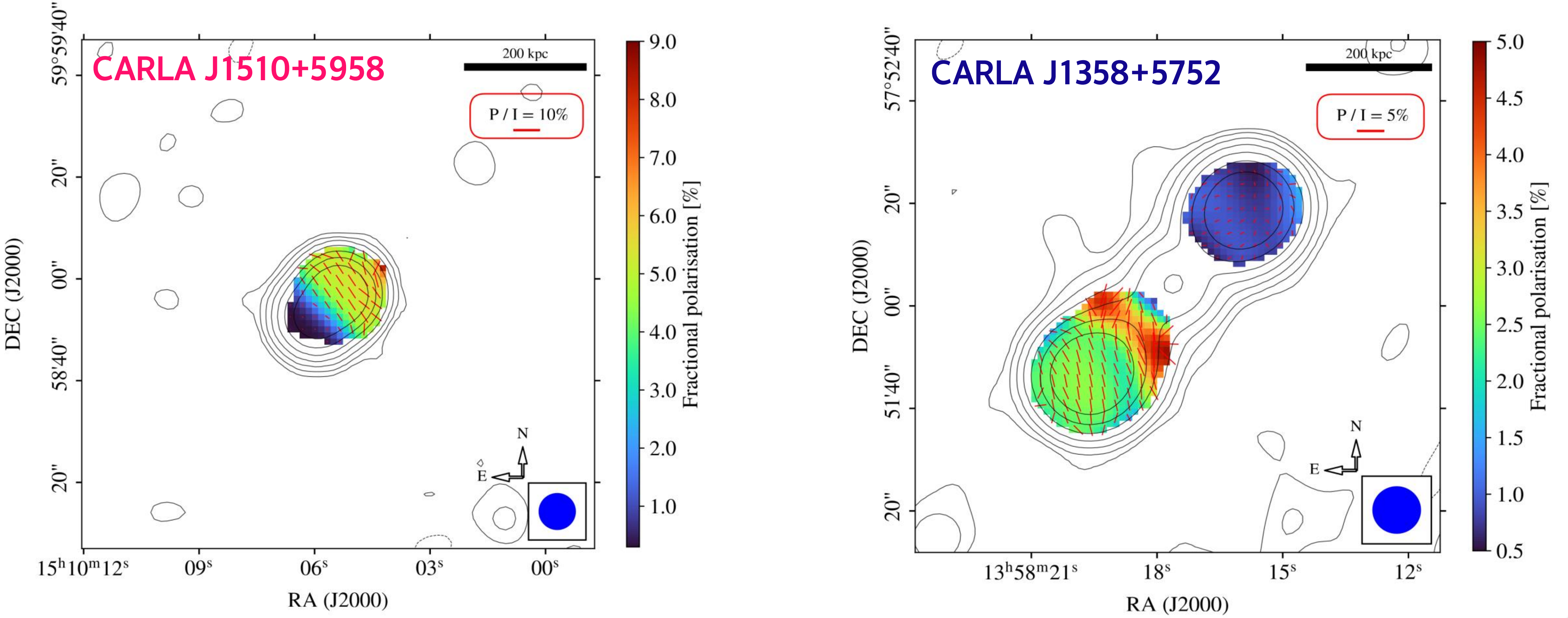
Polarisation Fraction

+ *total intensity contours* at 1.5 GHz



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0.3 % < Fp < 8.2 %

Magnetic Fields in Proto-clusters

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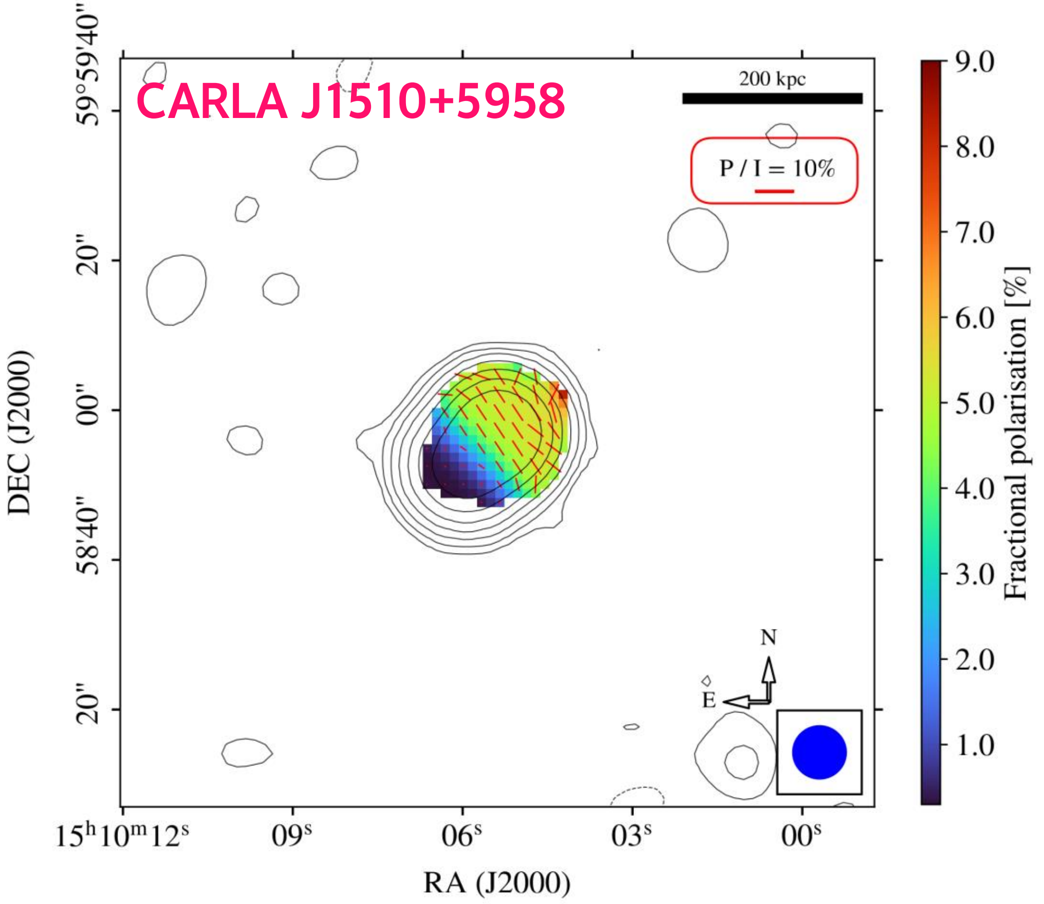
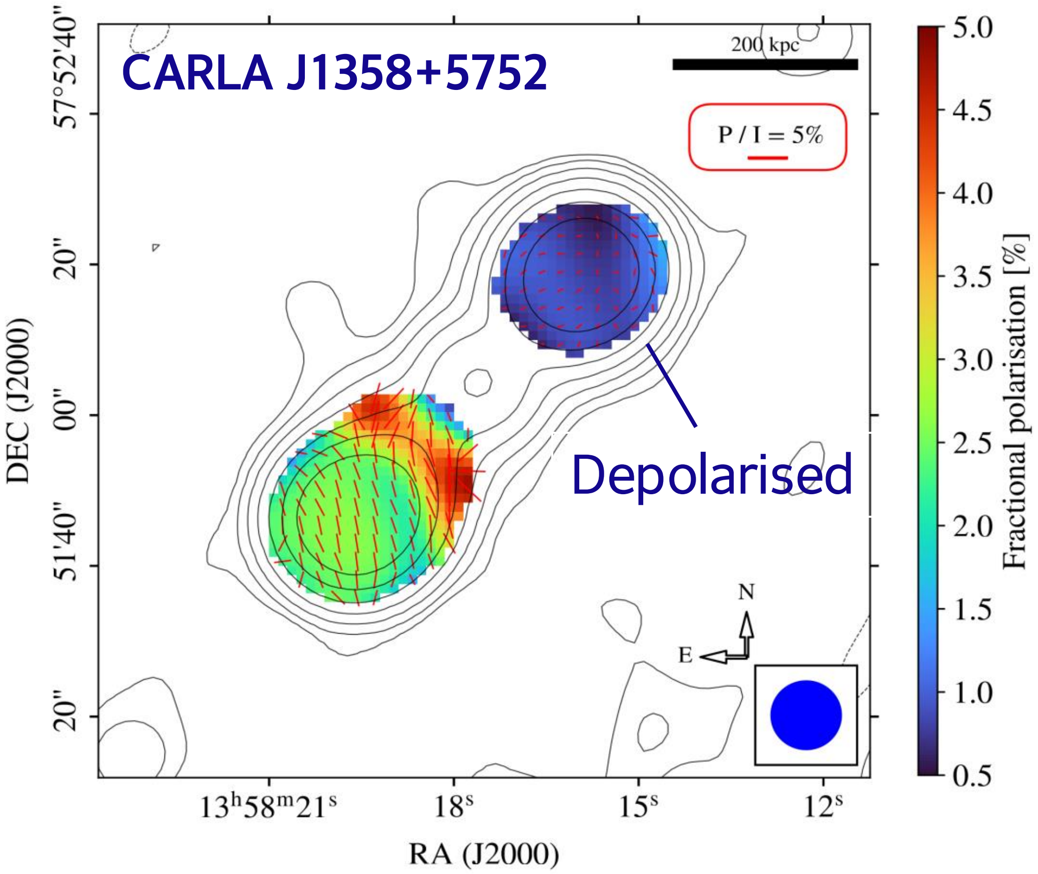
Polarisation Fraction + *total intensity contours* at 1.5 GHz





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0.3 % < Fp < 8.2 %

0.6 % < Fp < 4.8 %

Magnetic Fields in Proto-clusters

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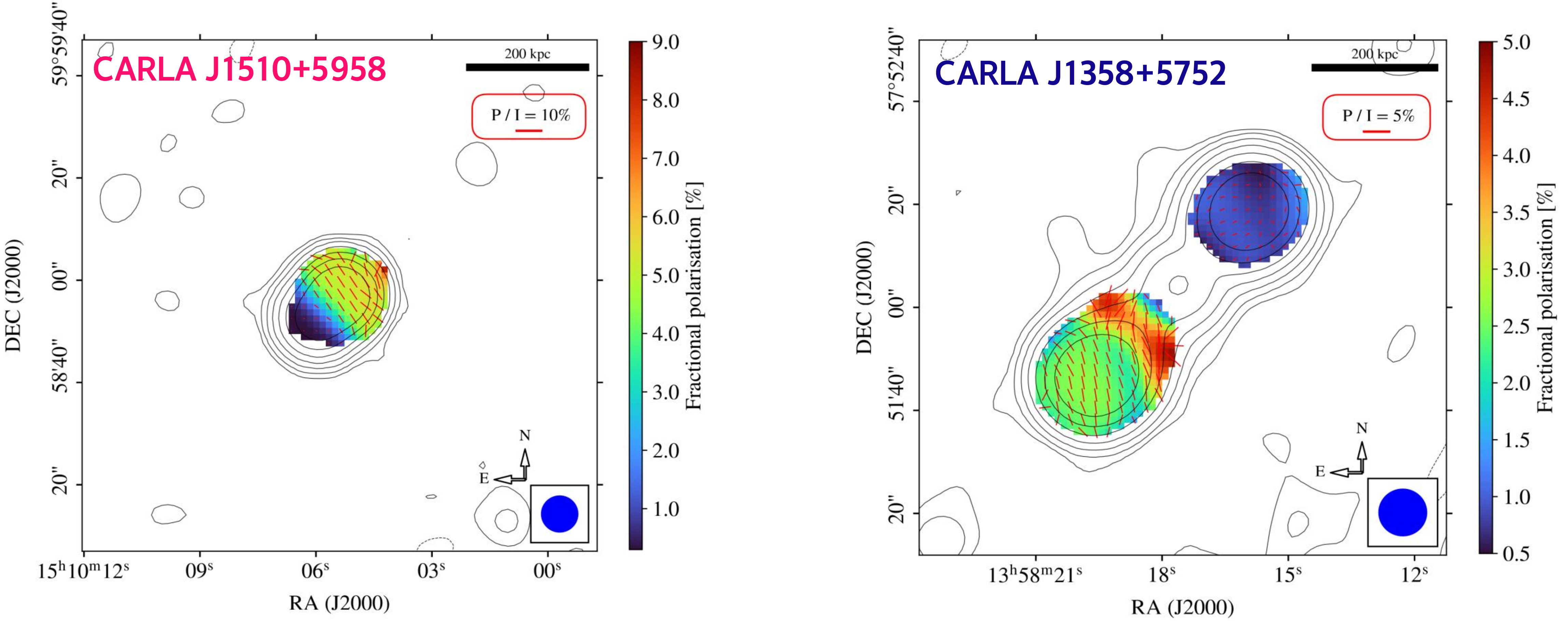
Polarisation Fraction + *total intensity contours* at 1.5 GHz



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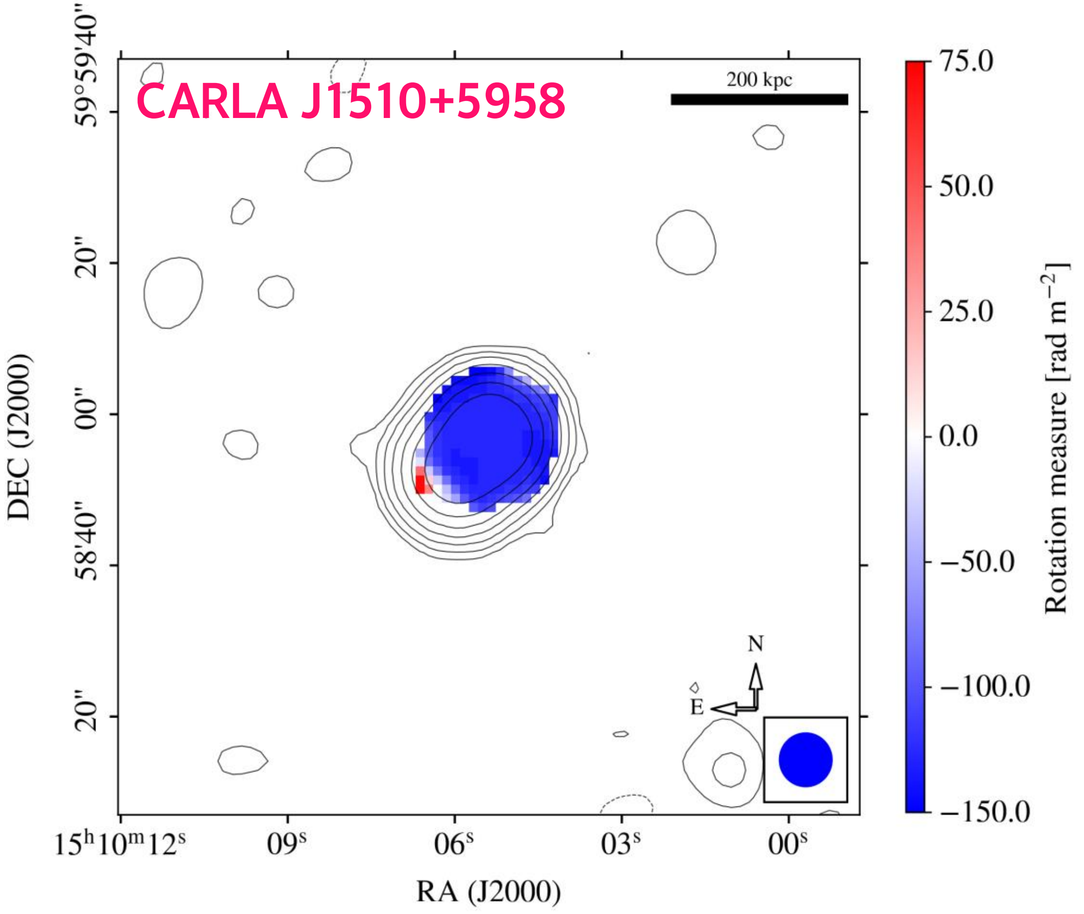
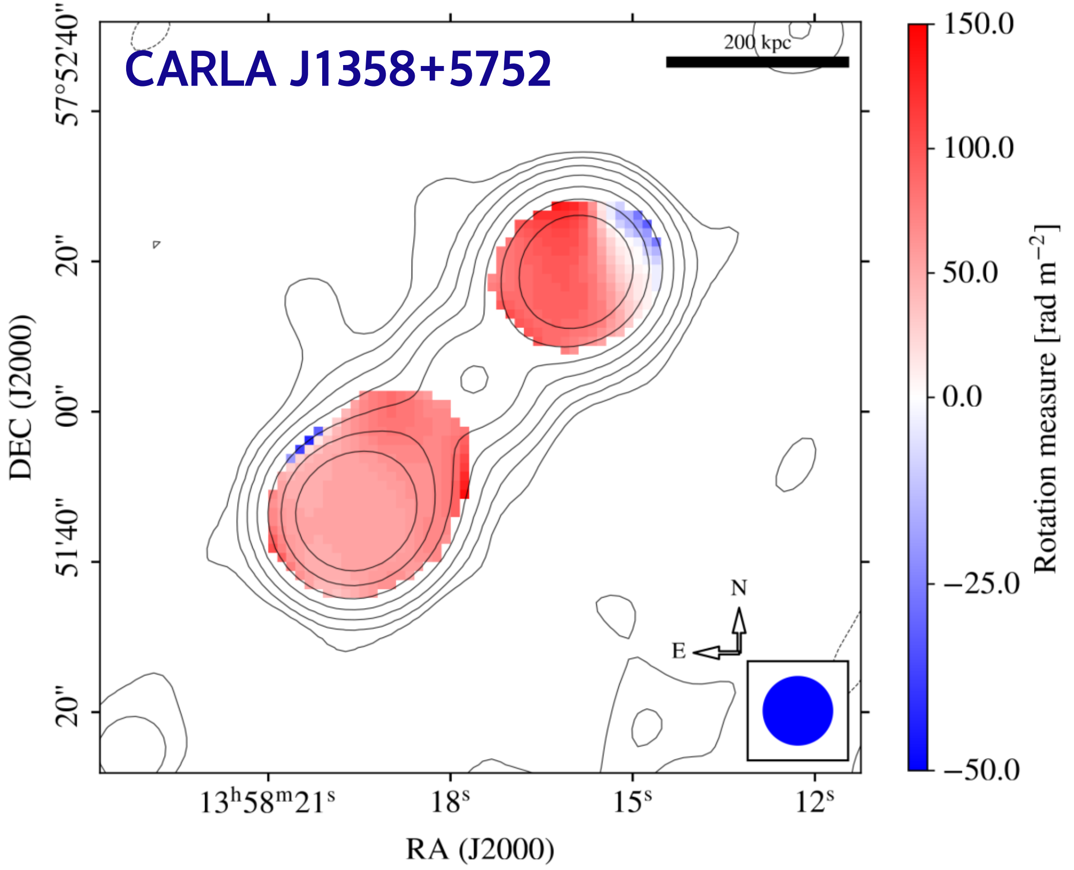
Projected magnetic field vectors

Magnetic Fields in Proto-clusters

CARLA J1510+5958 & J1358+5752

Rotation Measure + *total intensity contours* at 1.5 GHz





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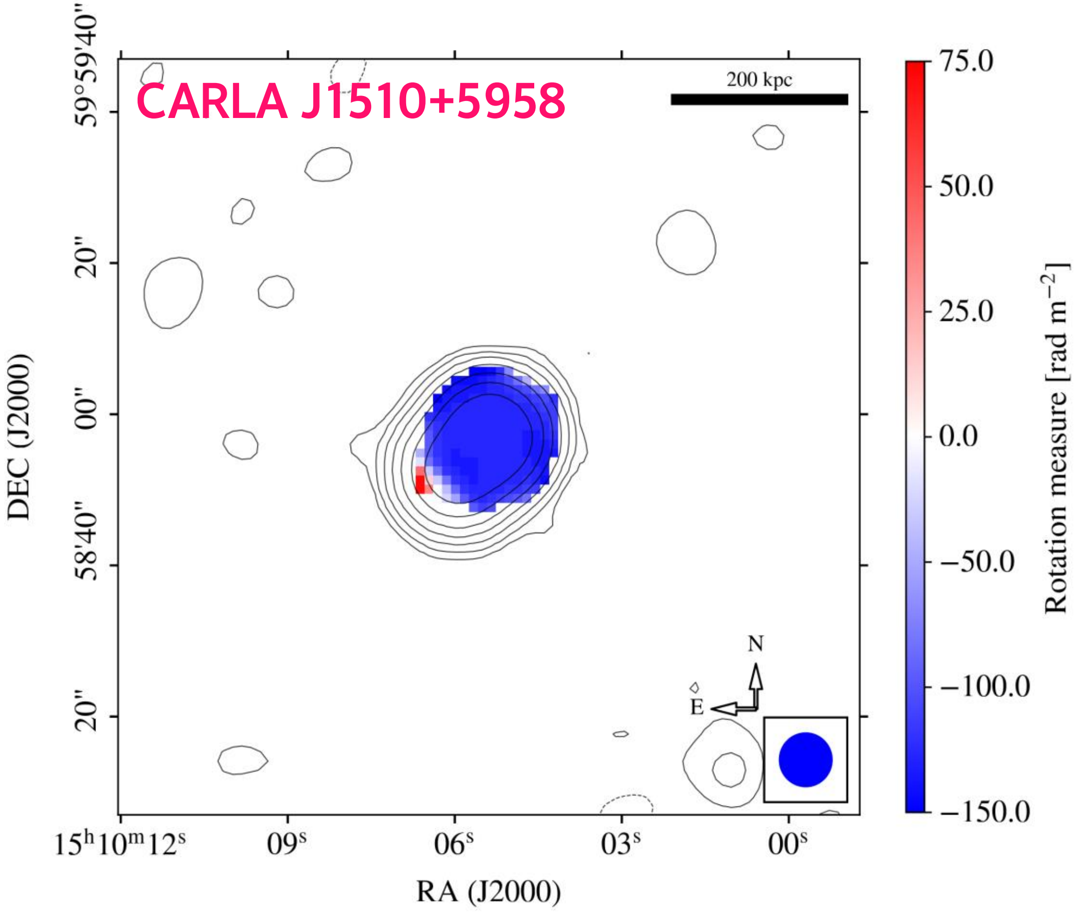
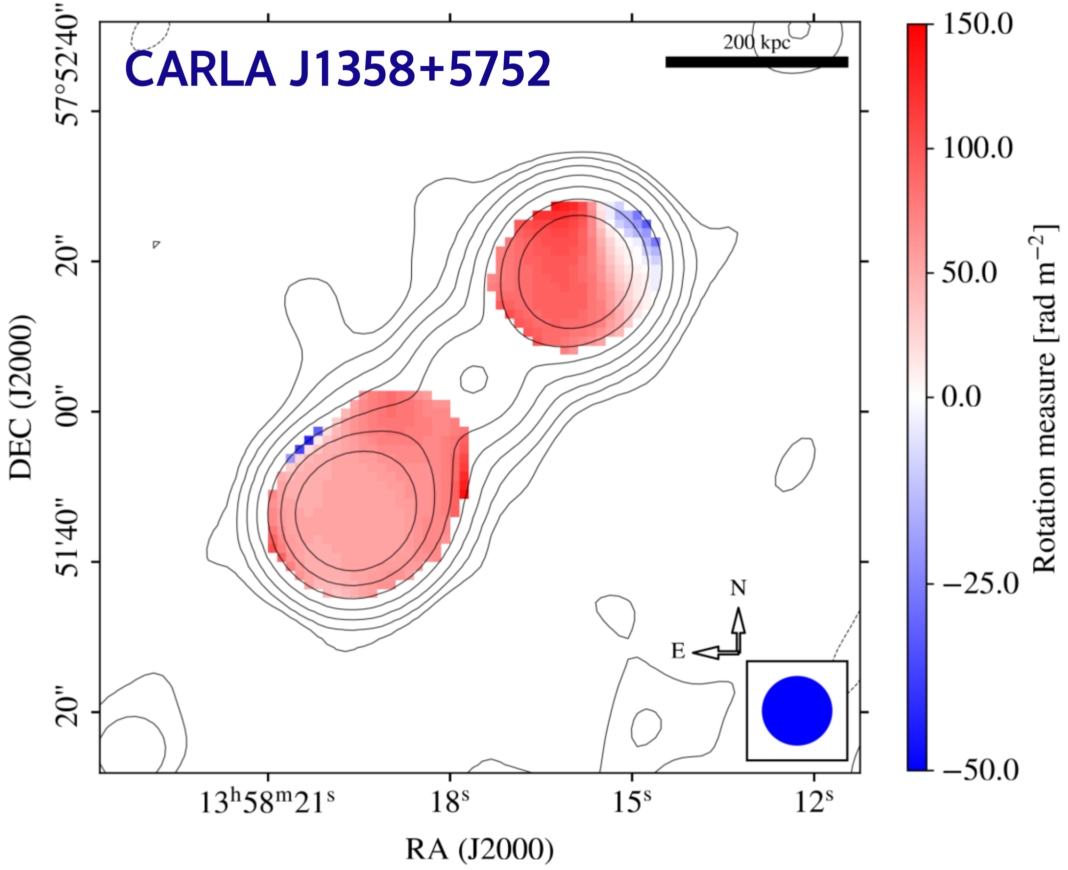




(only pixels above $6\sigma_P$ are shown)

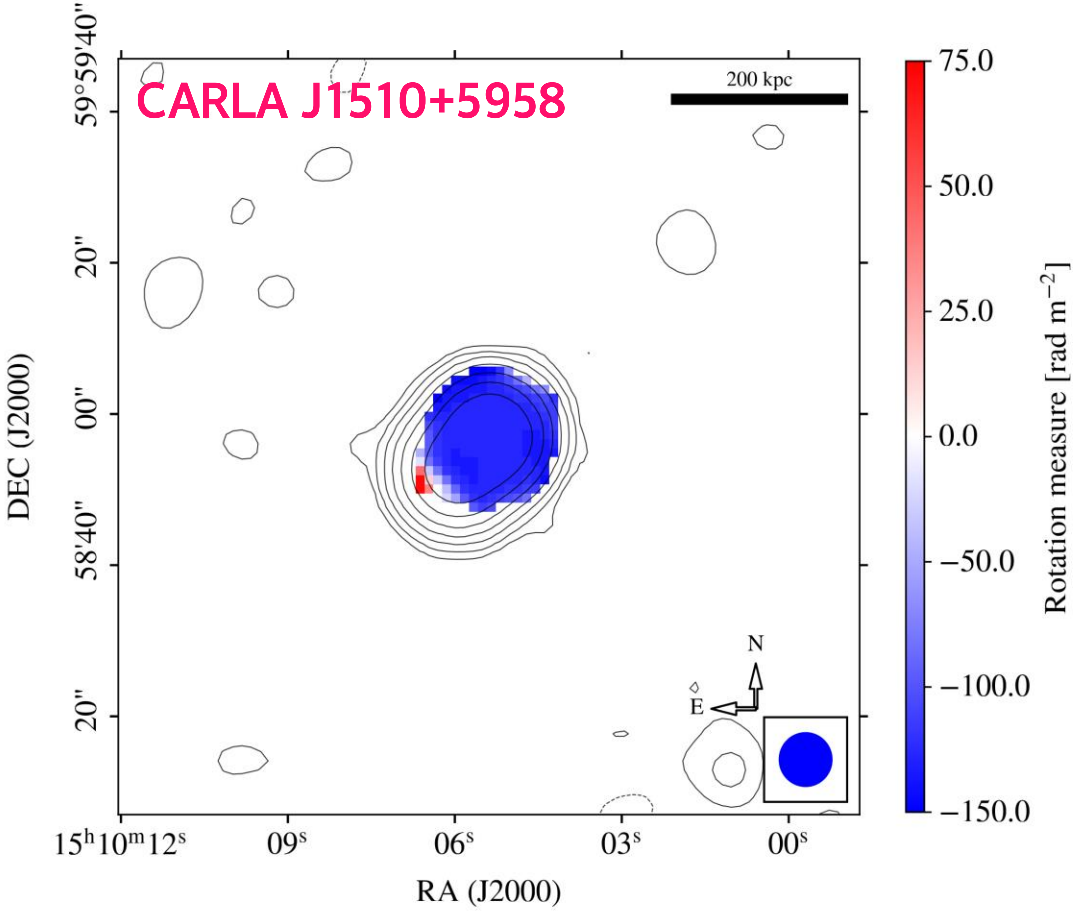
-150 rad m^{-2} < RM < +72 rad m^{-2}

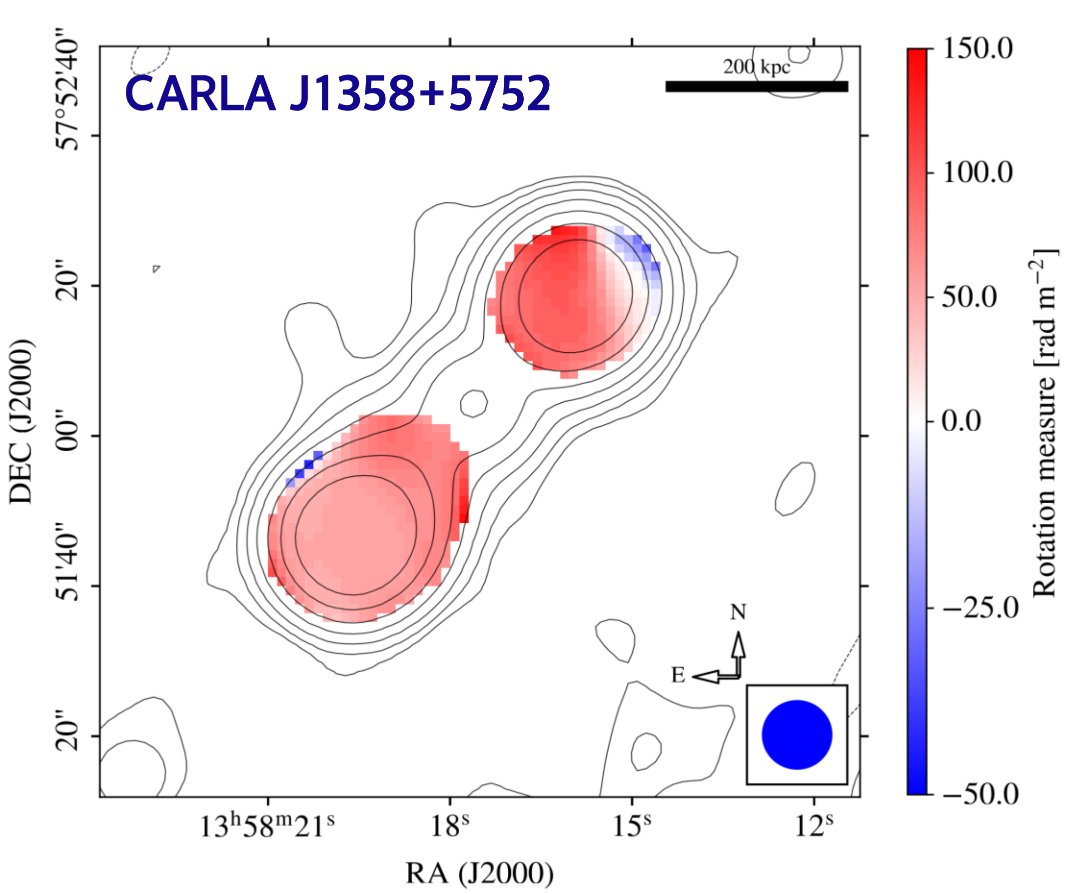
Magnetic Fields in Proto-clusters

CARLA J1510+5958 & J1358+5752

Rotation Measure

\+ *total intensity contours* at 1.5 GHz





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-150 rad m^{-2} < RM < +72 rad m^{-2}

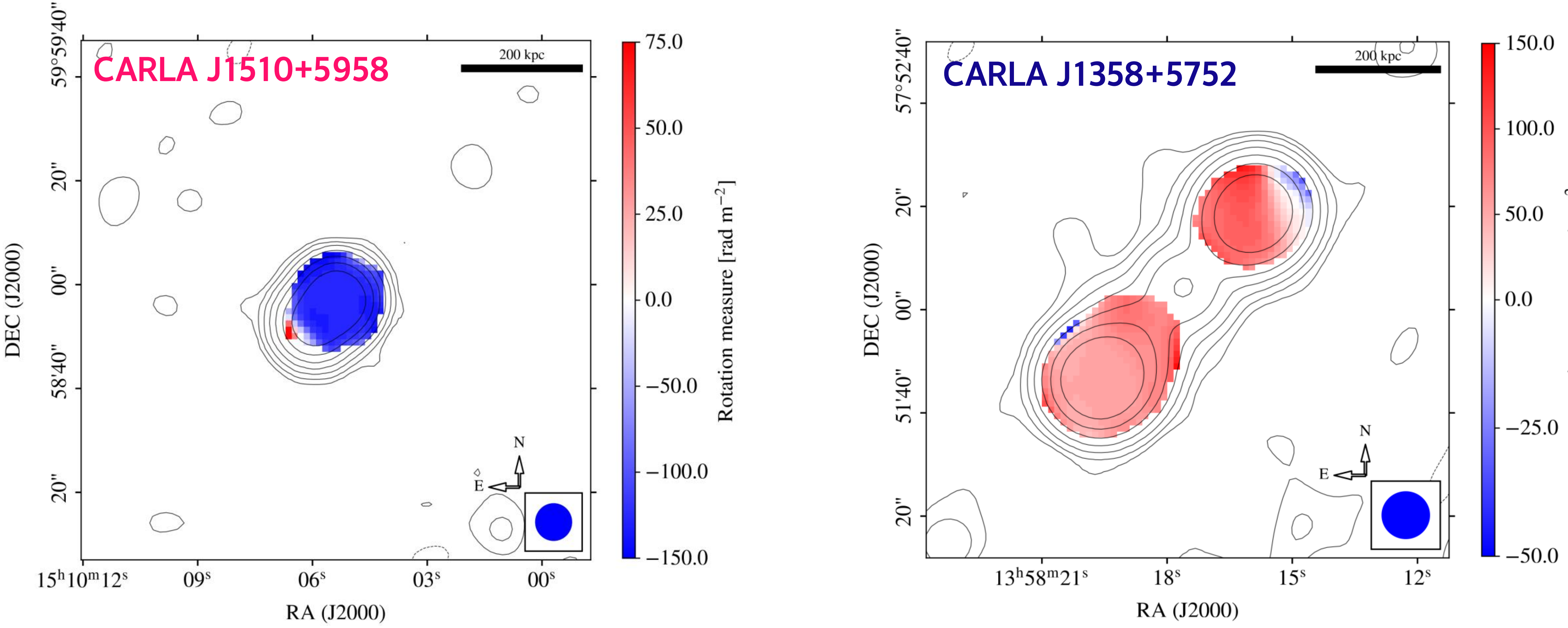
-43 rad m^{-2} < RM < +143 rad m^{-2}

Magnetic Fields in Proto-clusters

CARLA J1510+5958 & J1358+5752

Rotation Measure

+ *total intensity contours* at 1.5 GHz



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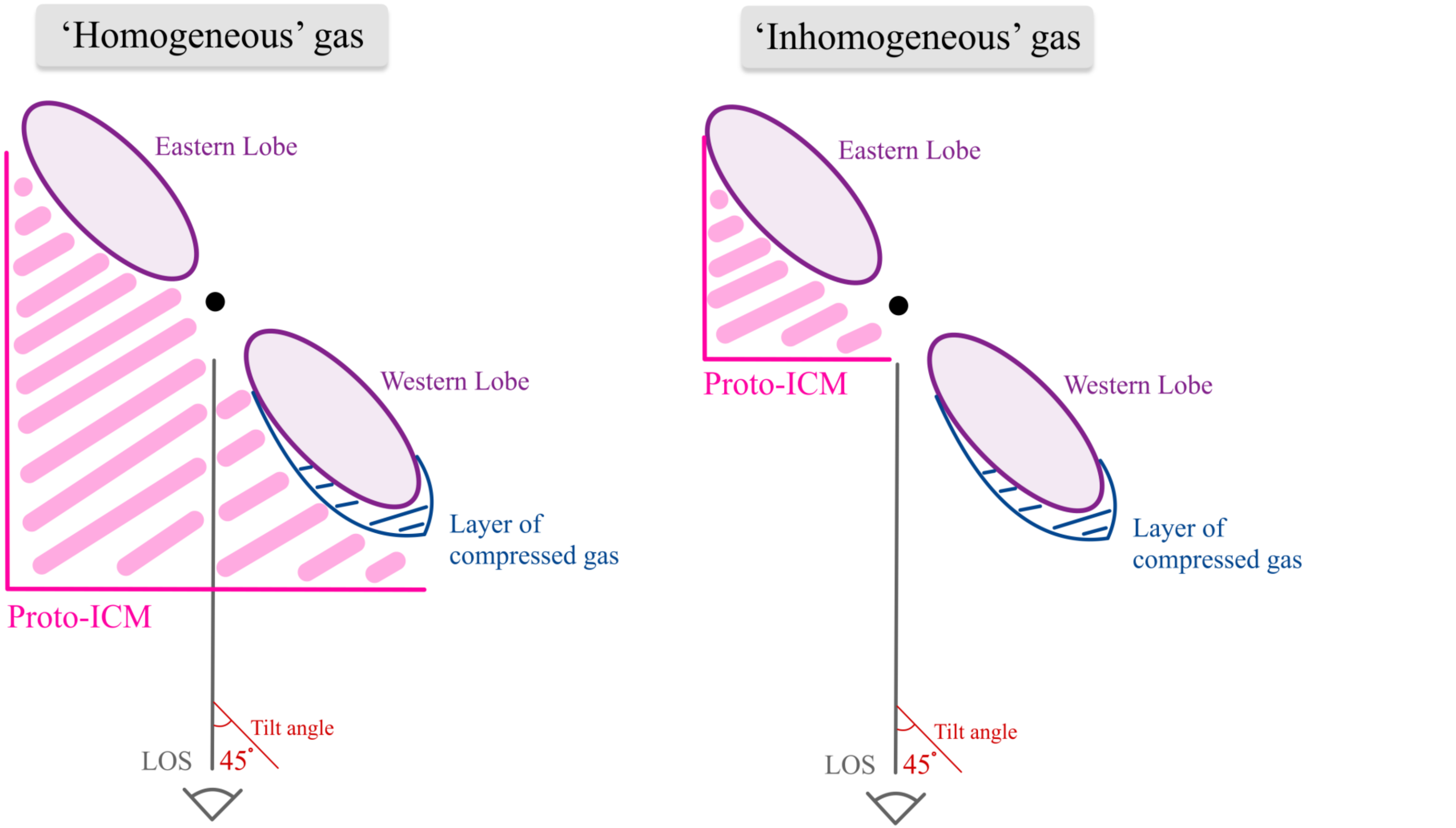
σ_{RM} ~ 36 rad m^{-2}

$\sigma_{RM,W}$ ~ 39 rad m^{-2}; $\sigma_{RM,E}$ ~ 17 rad m^{-2}

CARLA J1510+5958 & J1358+5752

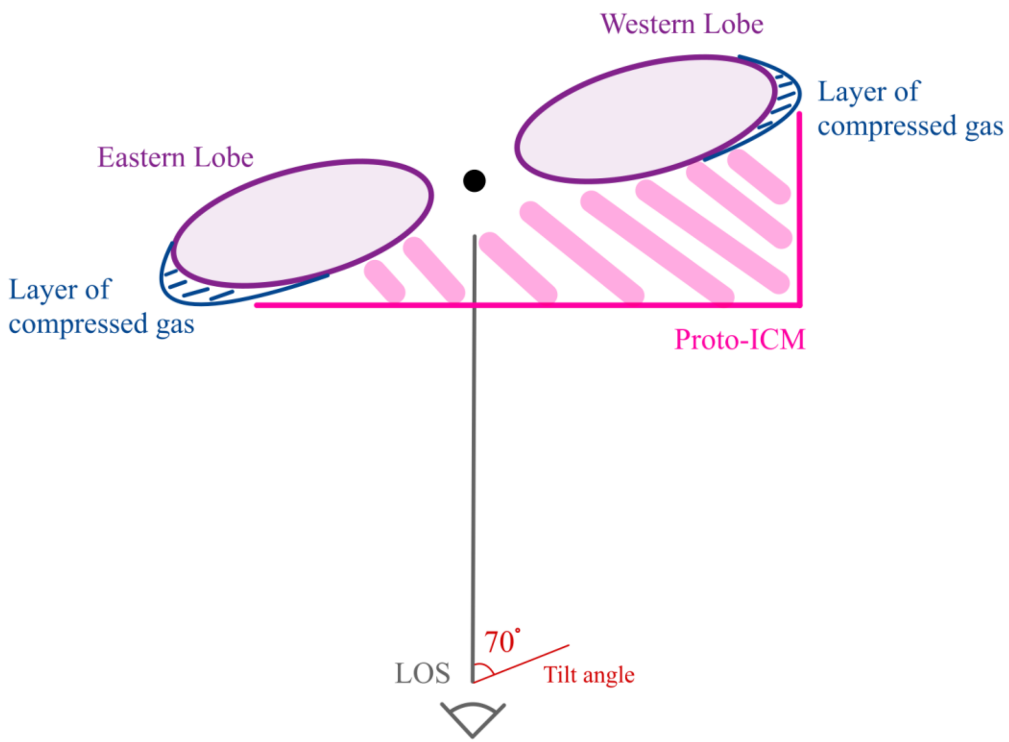
CARLA J1510+5958



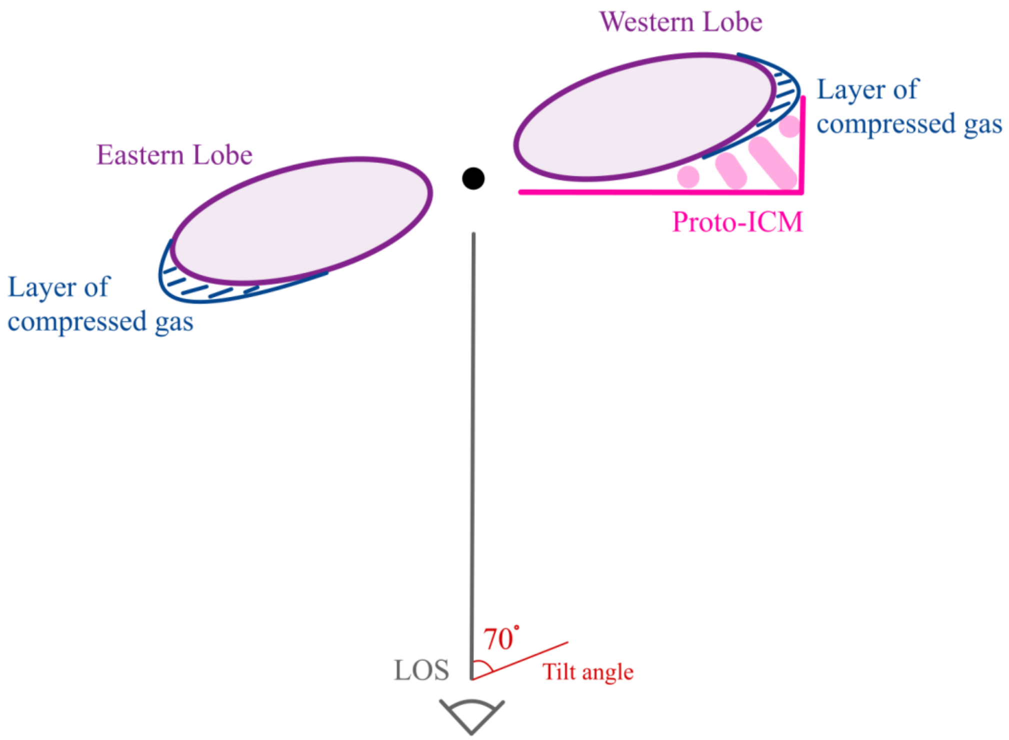
CARLA J1510+5958 & J1358+5752

CARLA J1358+5752

‘Homogeneous’ gas



‘Inhomogeneous’ gas



Magnetic Field Estimate

CARLA J1510+5958

Lower limits

of the magnetic field intensity from the *non-detection* of the Eastern lobe (via comparison with simulations)

CARLA J1358+5752

Constrain

of the magnetic field intensity from the *depolarisation* of the Western lobe (via comparison with simulations)

Semi-analytical simulations with MIRO' (Bonafede+13)

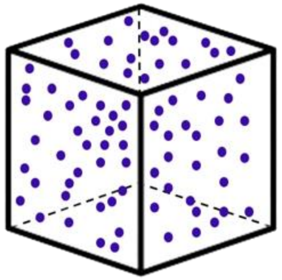
Semi-analytical simulations with MIRO' (Bonafede+13)

1

3D gas density model

Cube with a mean gas density and fluctuations of 5%

n_e



Semi-analytical simulations with MIRO' (Bonafede+13)

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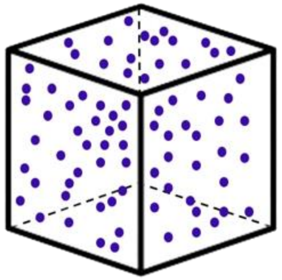
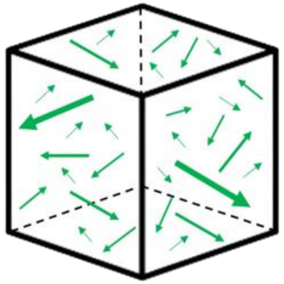


2

3D magnetic field model (random distribution)

Kolmogorov power spectrum

B



Semi-analytical simulations with MIRO' (Bonafede+13)

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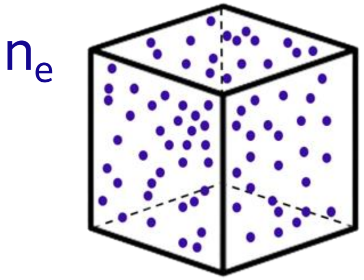

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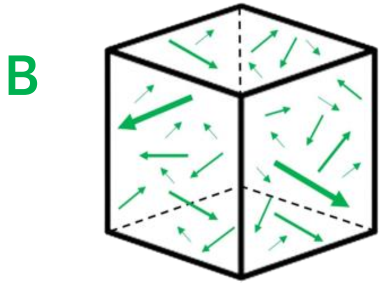
3D magnetic field model (random distribution)

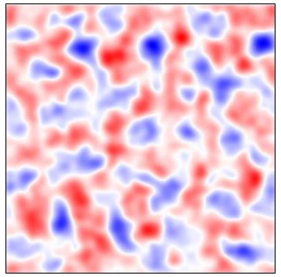
Kolmogorov power spectrum



3

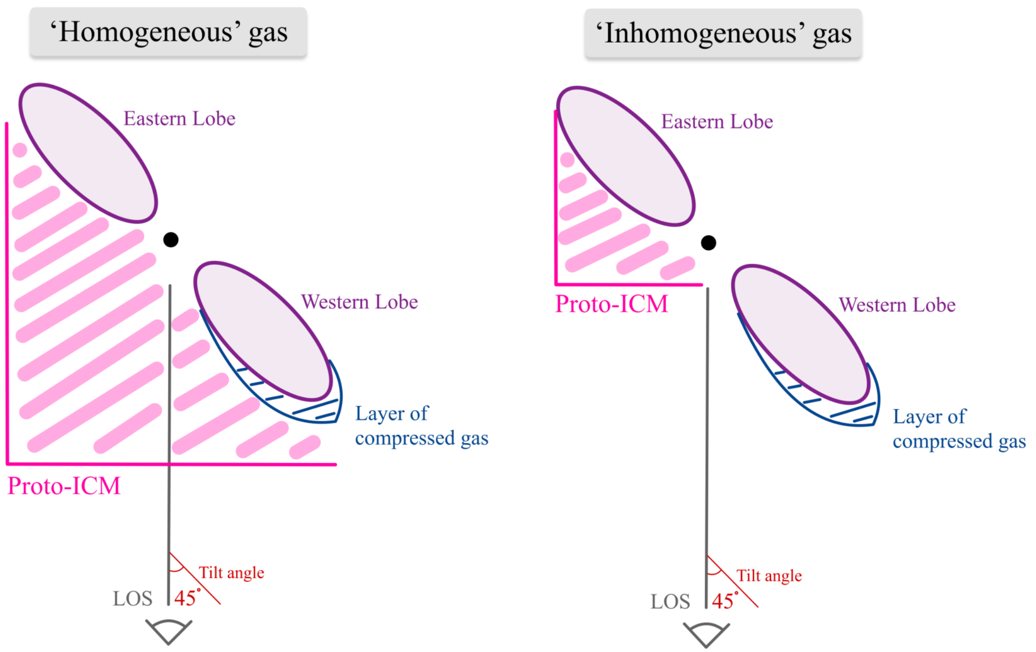
2D RM map

$$\mathrm{RM} \propto \langle n_e \rangle \cdot \langle B \rangle \cdot L$$



CARLA J1510+5958 & J1358+5752

CARLA J1510+5958



Upper limit in the **polarisation fraction** of the Eastern lobe:

~ 2%

Lower limit for the **RM dispersion:**

$$\Pi(\lambda) = \Pi_0 \, e^{-2\sigma_{\rm RM}^2 \lambda^4}$$

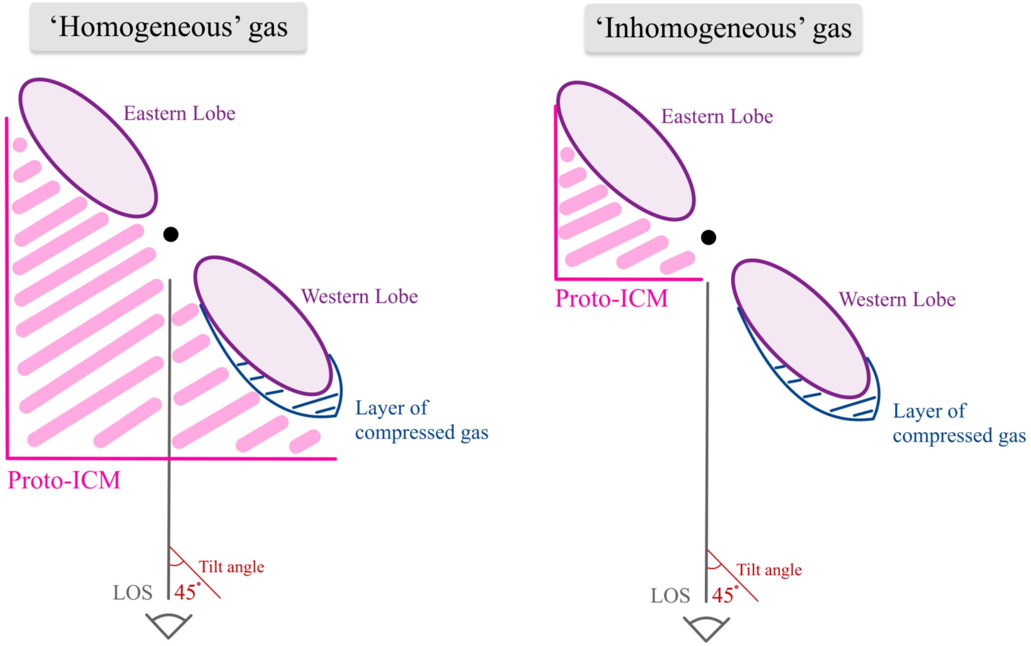
155 rad m^{-2}

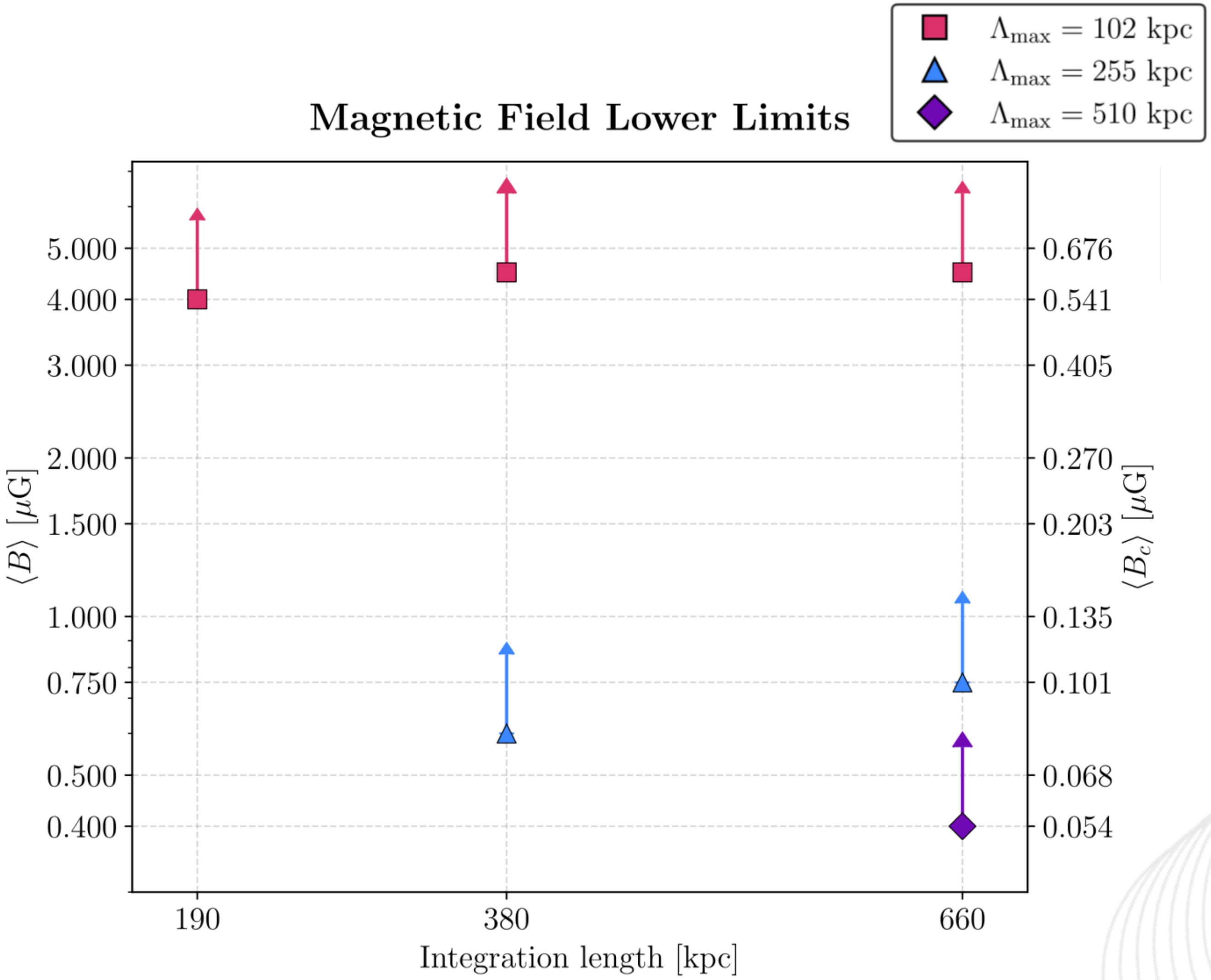
vs simulations

Lower limit of the **magnetic field intensity**

CARLA J1510+5958 & J1358+5752

CARLA J1510+5958

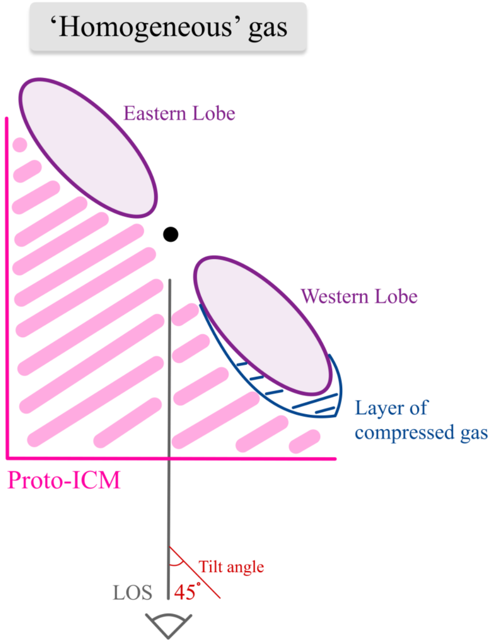


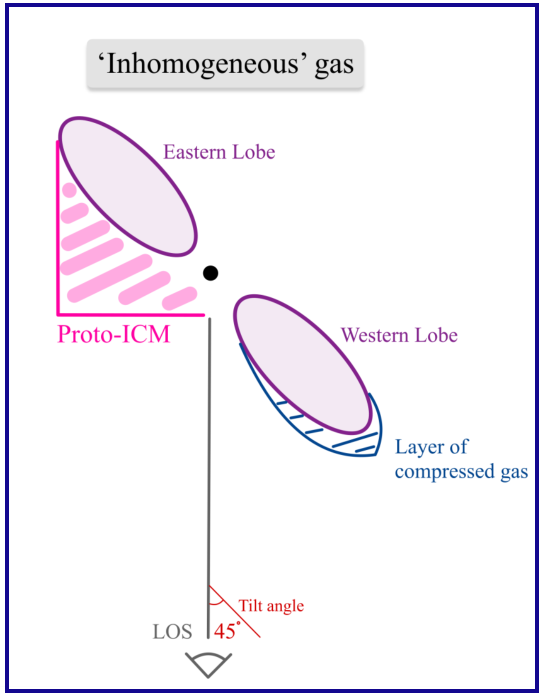


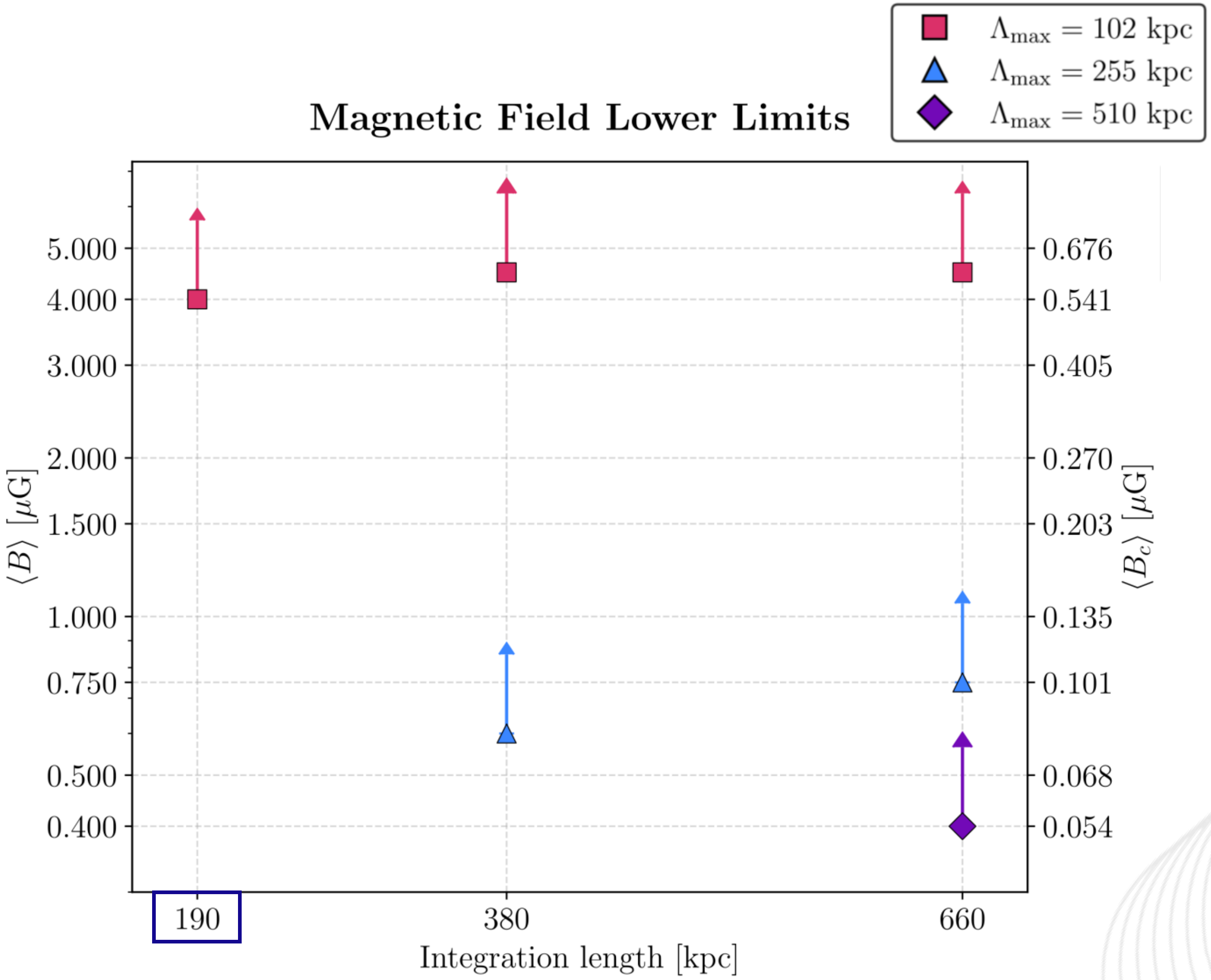
Magnetic Fields in Proto-clusters

CARLA J1510+5958 & J1358+5752

CARLA J1510+5958



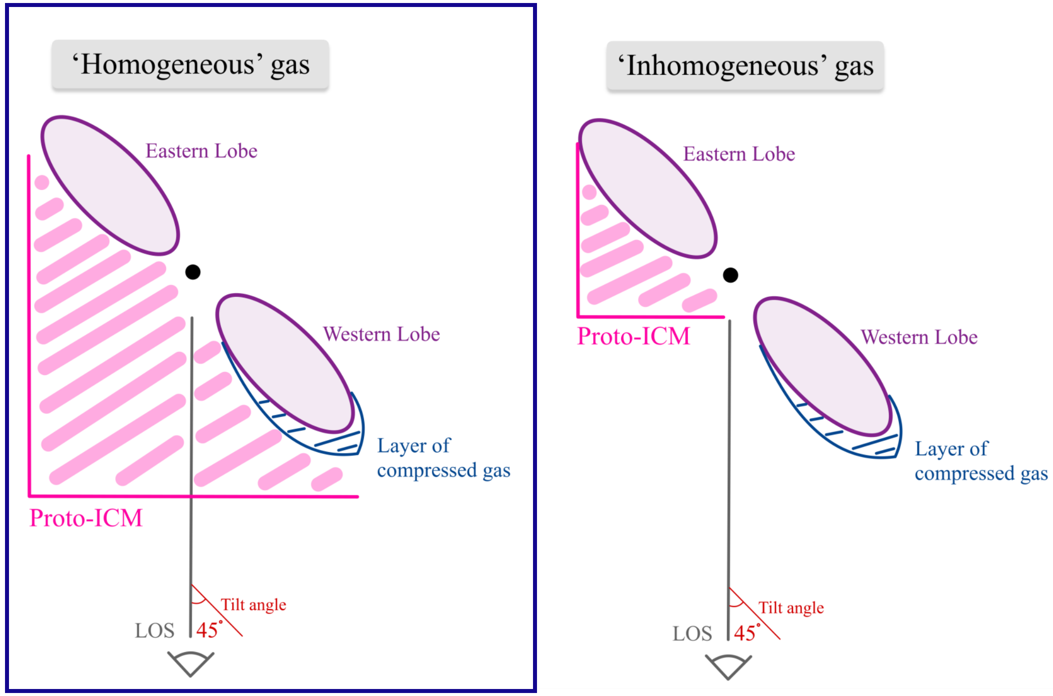


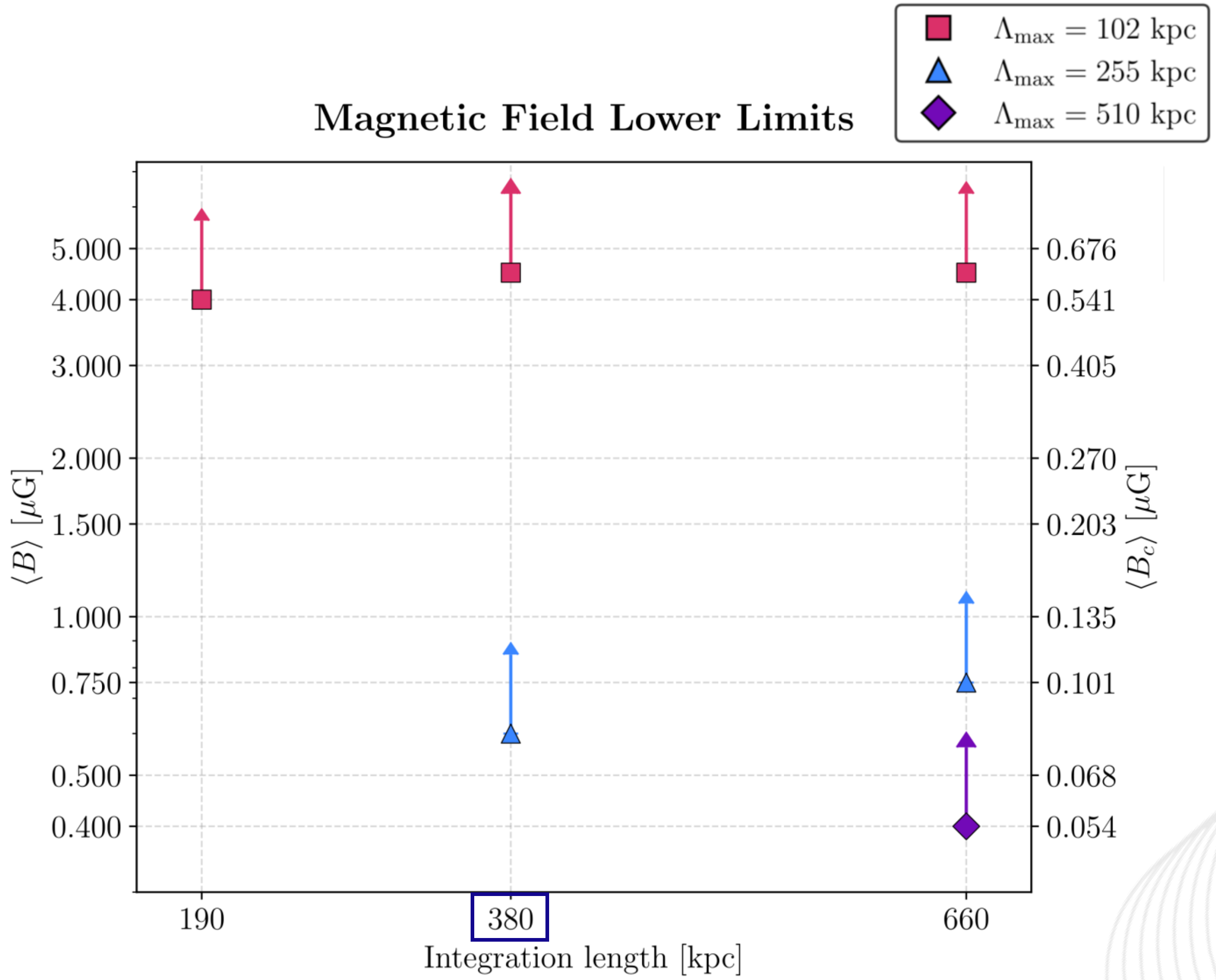


Magnetic Fields in Proto-clusters

CARLA J1510+5958 & J1358+5752

CARLA J1510+5958

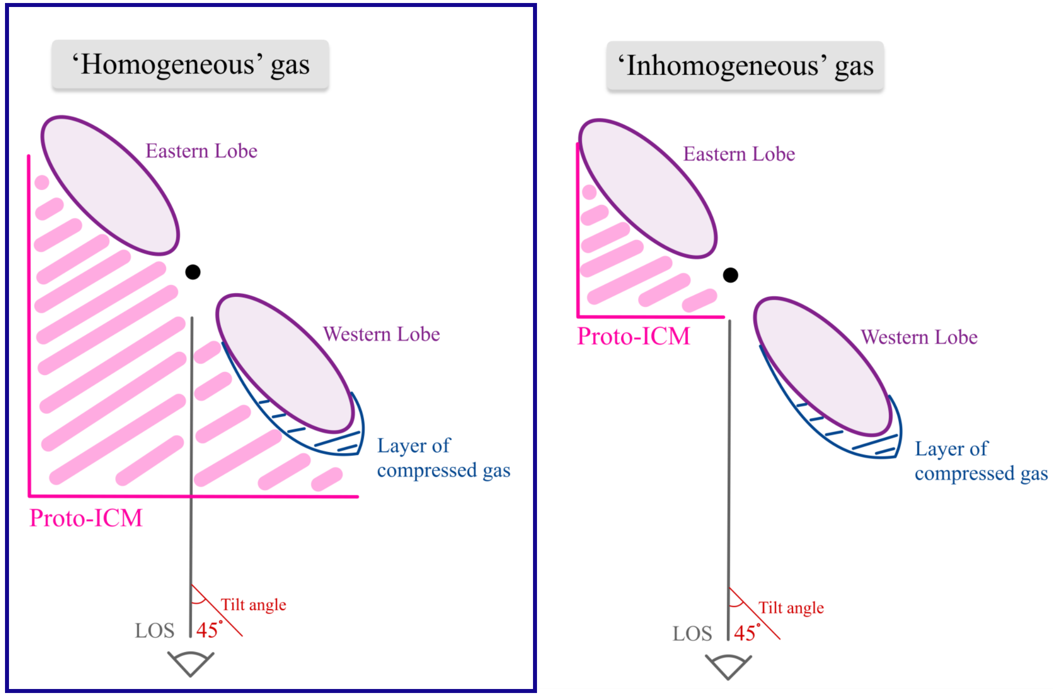




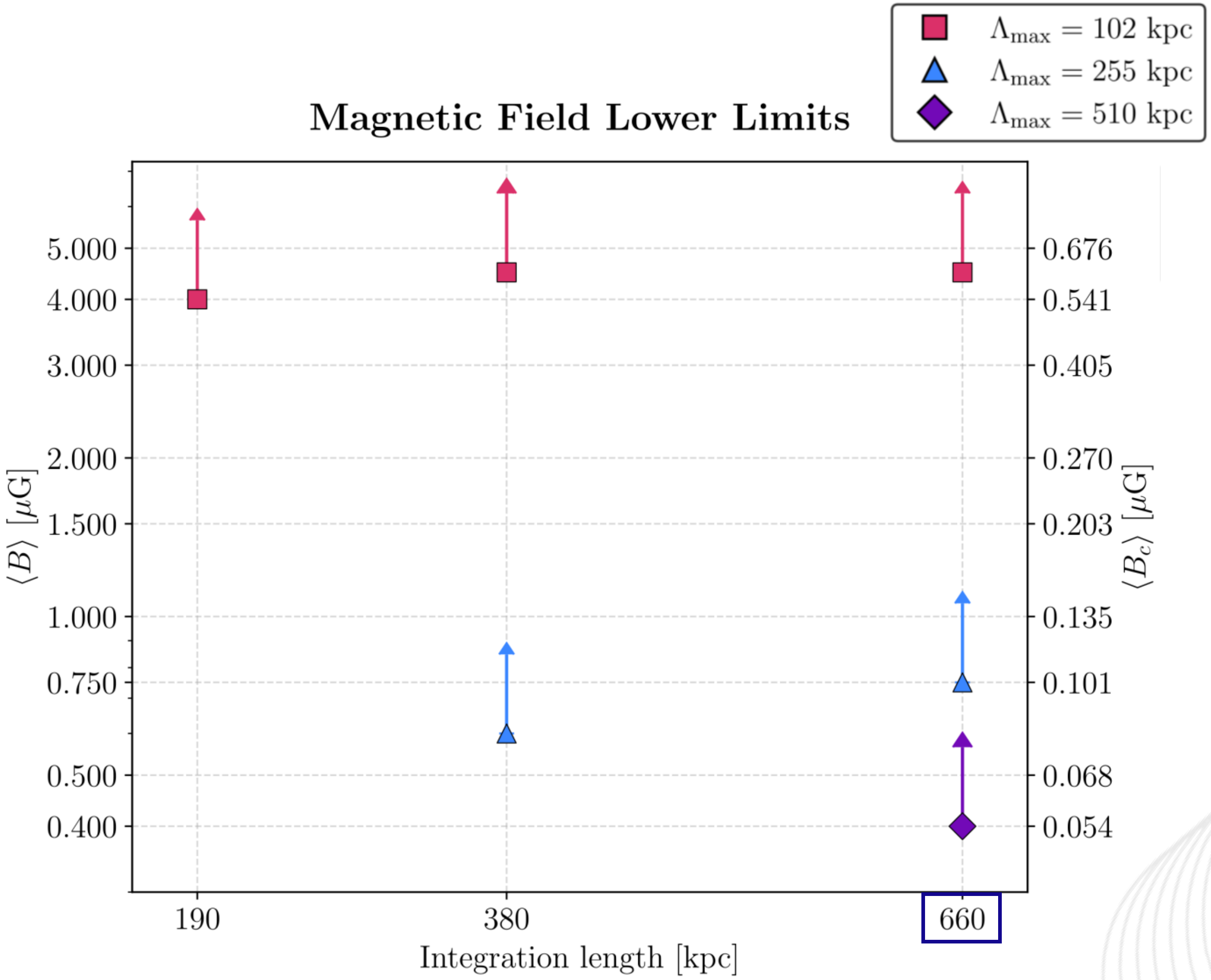
Magnetic Fields in Proto-clusters

CARLA J1510+5958 & J1358+5752

CARLA J1510+5958

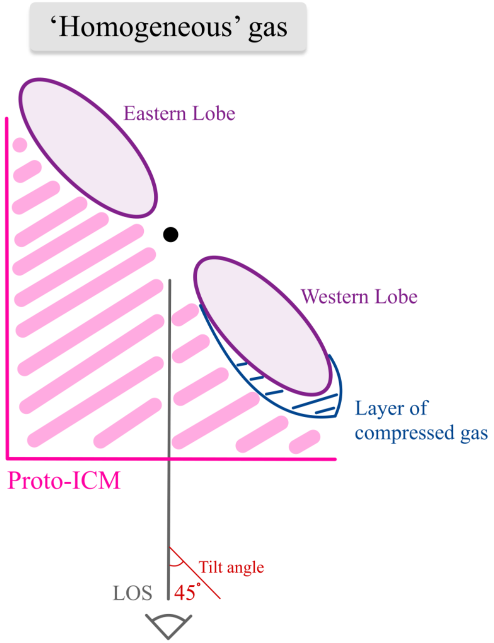


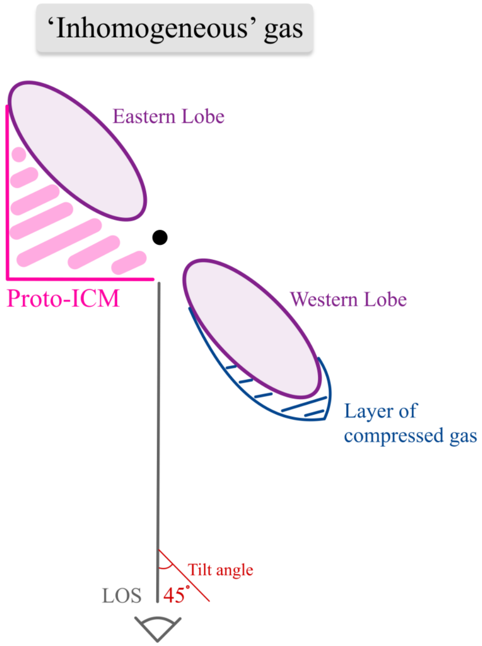
30°

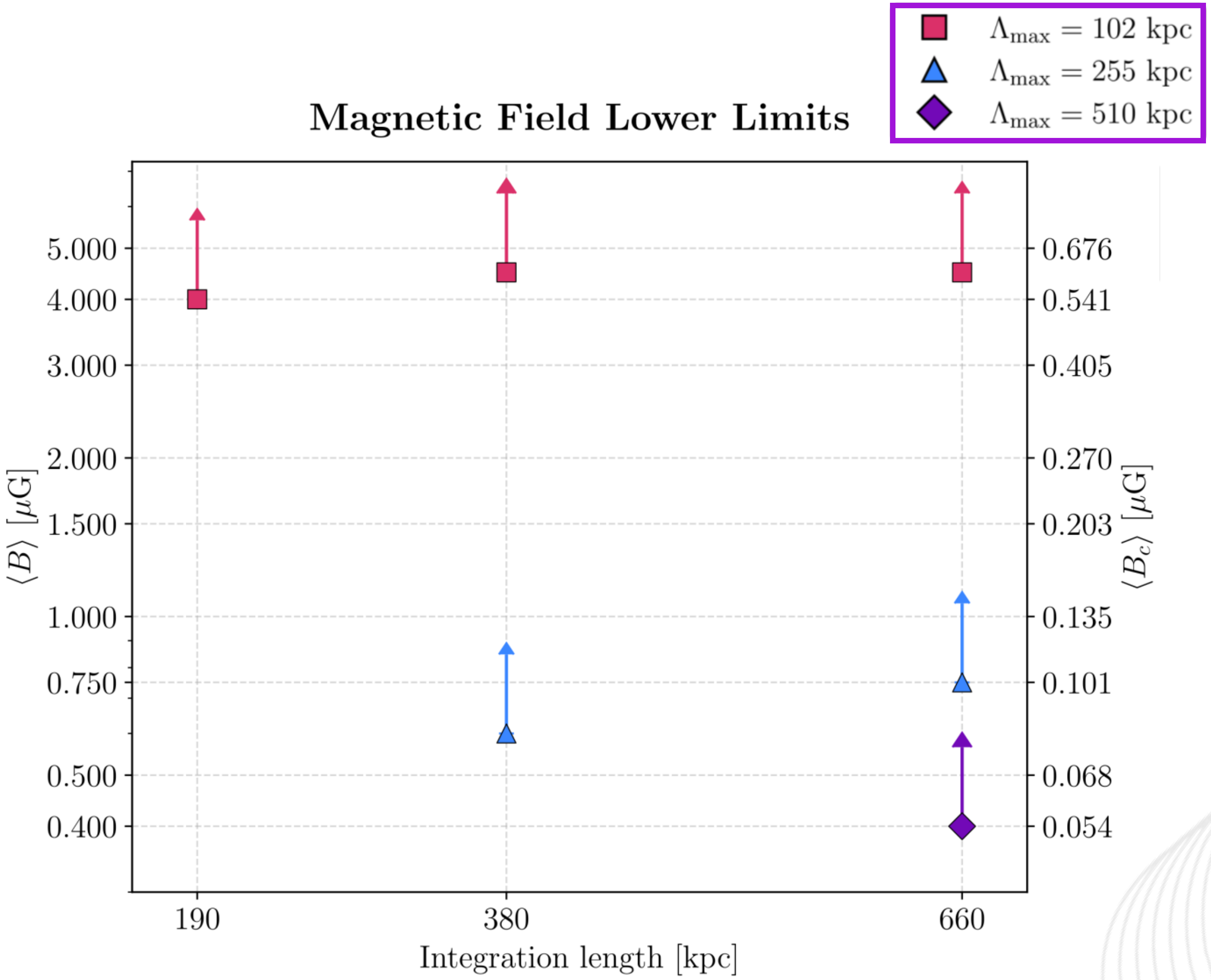


CARLA J1510+5958 & J1358+5752

CARLA J1510+5958



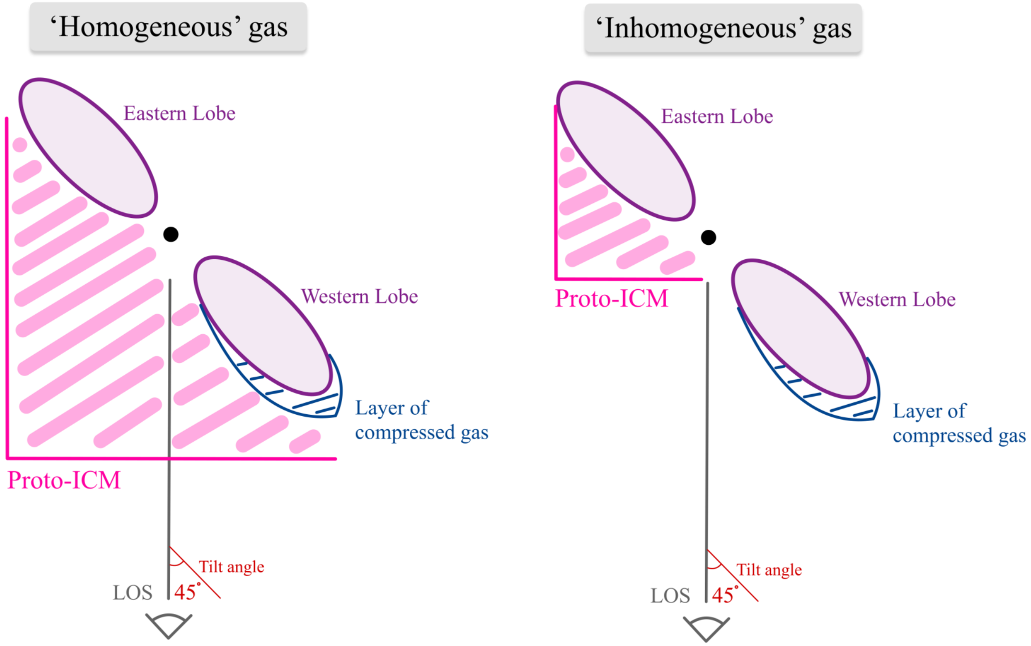


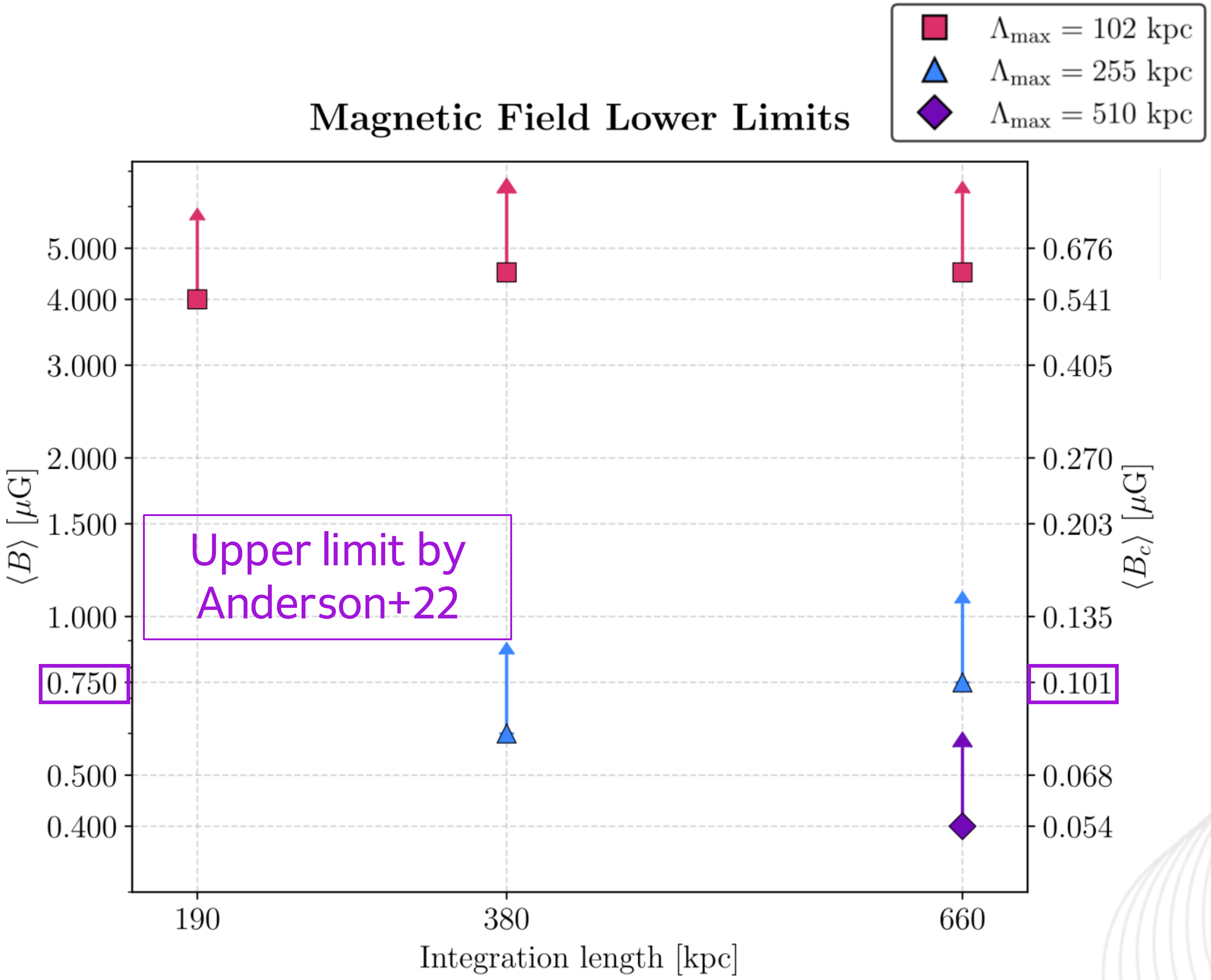


Magnetic Fields in Proto-clusters

CARLA J1510+5958 & J1358+5752

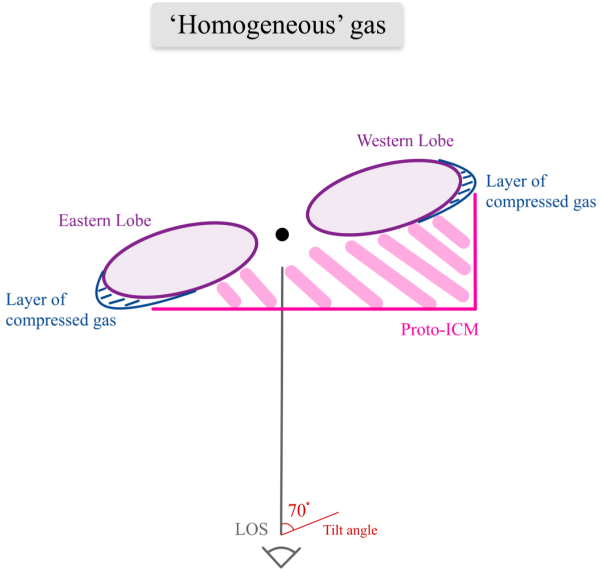
CARLA J1510+5958

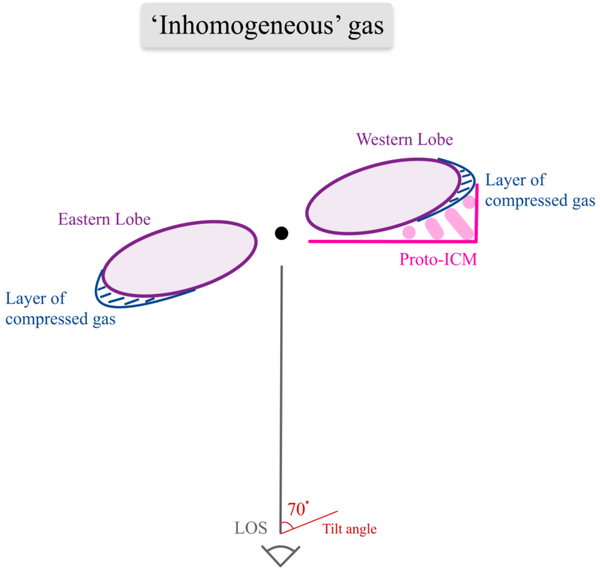




CARLA J1510+5958 & J1358+5752

CARLA J1358+5752





Average polarisation fraction of the lobes:

(2.8 ± 2.0)% (E. Lobe); (0.9 ± 0.6)% (W. Lobe)

Value for the **RM dispersion:**

$$\Pi(\lambda) = \Pi_0 \, e^{-2\sigma^2_{\mathrm{RM}}\lambda^4}$$

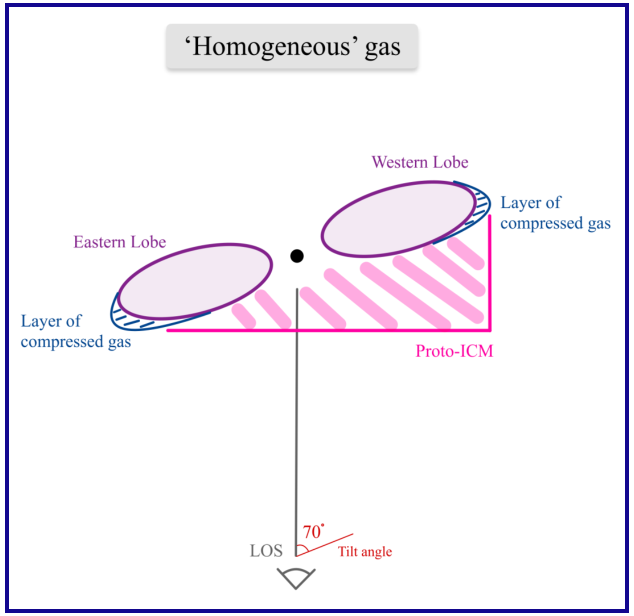
(106 ± 44) rad m^{-2}

vs simulations

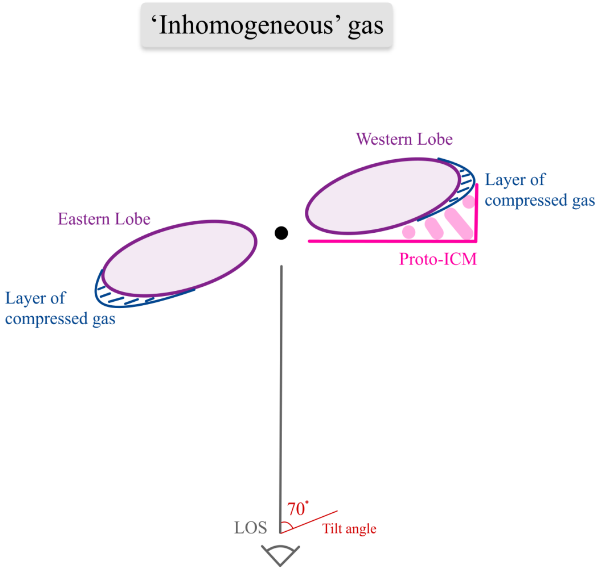
Constrain of the **magnetic field intensity**

CARLA J1510+5958 & J1358+5752

CARLA J1358+5752



60°



- Integration = 284 kpc
- n_e = 2.709 x 10^{-3} cm^{-3}
- Λ = [10.15, 252.5] kpc

1

σ_{RM} = (77.8 ± 14.9) rad m^{-2}

<B> = 1.5 μG

ChiSq = 0.37

2

σ_{RM} = (142.8 ± 40.4) rad m^{-2}

<B> = 1.75 μG

ChiSq = 0.38

SKAO

1 *Large bandwidth* to cover both the lower and higher frequencies

High resolution in *Faraday space*
Low values of the RM

High *spatial* resolution
High values of the RM

Telescope	Band	Frequency Range (MHz)	Available Bandwidth (MHz)	Notes (MHz)
SKA1-Low	N/A	50 - 350	300	(1)
SKA1-Mid	1	350 - 1050	700	(1)
	2	950 - 1760	810	(1)
	3	1650 - 3050	1400	(2)
	4	2800 - 5180	2380	(2)
	5a	4600 - 8500	3900	(1)
	5b	8300 - 15400	2 x 2500	(1)

www.skao.int

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	4	2800 - 5180	2380	(2)
	5a	4600 - 8500	3900	(1)
	5b	8300 - 15400	2 x 2500	(1)

With the AA* (15-m only dishes) the bandwidth is **fully covered**

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Band 1 (350 – 1050 MHz)

- Resolution in Faraday space: **5 rad m^{-2}**

↓

Discriminate between the contribution of *multiple components* along the LOS

SKAO

Band 1 (350 – 1050 MHz)

- Resolution in Faraday space: **5 rad m^{-2}**

↓

Discriminate between the contribution of *multiple components* along the LOS

Band 2 (950 – 1760 MHz)

- Spatial resolution: **4" x 4"**

↓

Minimise the *beam depolarisation*

Resolve the source

Derive a *dispersion of the RM*

+ **Band 3** (1650 – 3050 MHz) for higher spatial resolution

SKAO

Minimum Frequency [GHz]	Channel [MHz]	Φ_{max} [rad m^{-2}]	$\Phi_{max, source frame}$ [rad m^{-2}]
0.350	1	414	3,063
	4	105	777
	8	53	392
0.950	1	8,263	61,133
	4	2,076	15,359
	8	1,044	7,724
1.650	1	43,265	320,092
	4	10,845	80,236
	8	5,442	40,262

SKAO

Minimum Frequency [GHz]	Channel [MHz]	Φ_{max} [rad m^{-2}]	$\Phi_{max, source\ fram}$… [rad m…
0.350	1	414	[illegible]
	4	[illegible]	…77
	8	[illegible]	392
0.950	[illegible]	…,263	61,133
[illegible]	[illegible]	2,076	15,359
	8	1,044	7,724
[illegible]	1	43,265	320,092
	4	10,845	80,236
	8	5,442	40,262

Complete view of what it is happening in the proto-cluster

SKAO

2 High *flux sensitivity*

Continuum flux sensitivity (1 h) : 5.50 μJy beam^{-1} (Band 1)
2.50 μJy beam^{-1} (Band 2)

~ flux sensitivity in polarisation

SKAO

2 High *flux sensitivity*

Continuum flux sensitivity (1 h) :	5.50 μJy $beam^{-1}$ (Band 1)
	2.50 μJy $beam^{-1}$ (Band 2)

~ flux sensitivity in polarisation

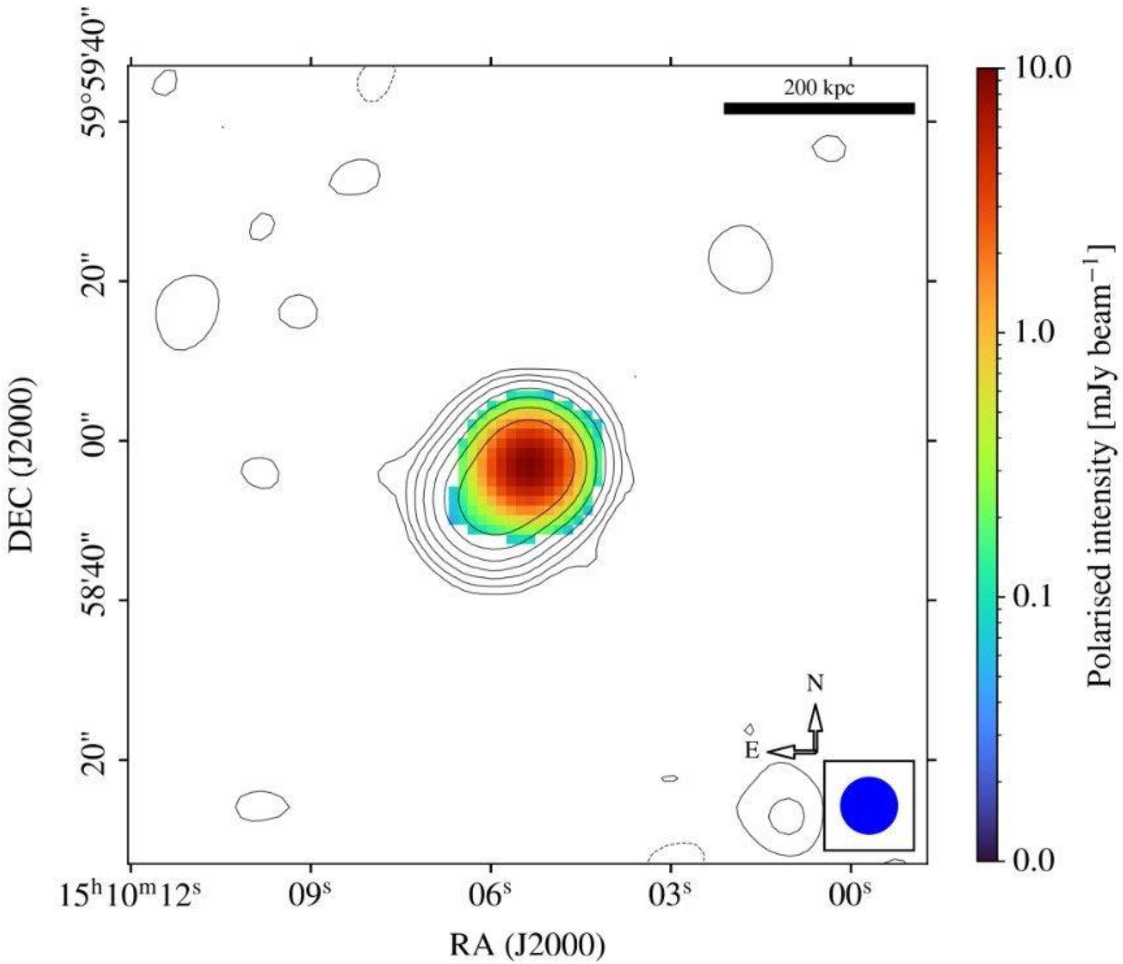
... to recover the very *faint polarised radiation* coming from:

- the central source

CARLA J1510+5958: Eastern Lobe

Total surface brightness peak:

22.80 mJy beam^{-1}



SKAO

CARLA J1510+5958: Eastern Lobe

Total surface brightness peak:

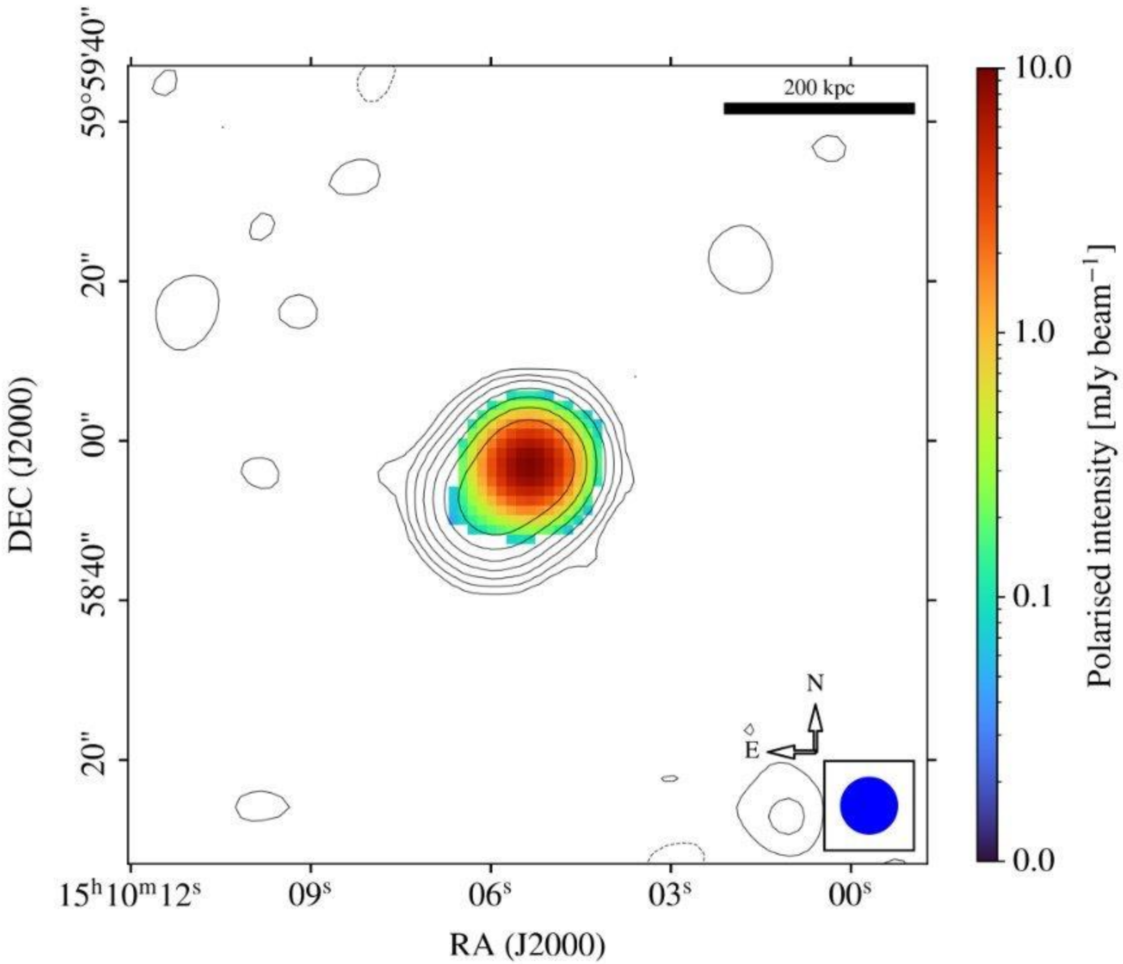
22.80 mJy $beam^{-1}$

Pol. surface brightness peak:

$0.02 \times S_{I,peak}$

$= 0.46$ mJy $beam^{-1} > 3\sigma_I$

Detected with SKAO Band 2



2 High *flux sensitivity*

Continuum flux sensitivity (1 h) :	5.50 μJy $beam^{-1}$ (Band 1)
	2.50 μJy $beam^{-1}$ (Band 2)

~ flux sensitivity in polarisation

... to recover the very *faint polarised radiation* coming from:

- the central source
- proto-cluster member or background sources...

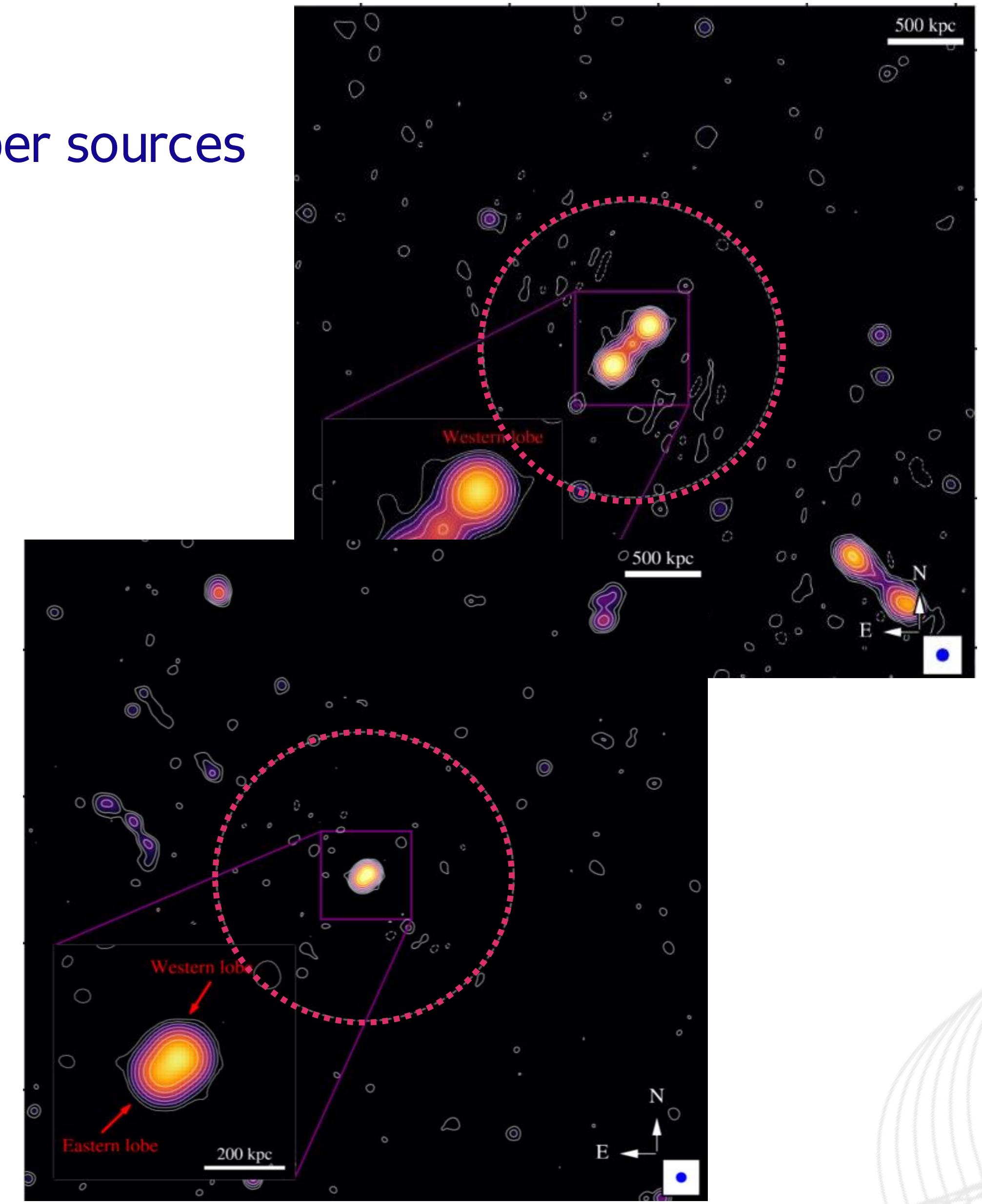
SKAO

CARLA J1510+5958 & J1358+5752: Background and member sources

Few sources could be detected if polarised to 5-10% with 1 hr observation

With 2 hr observation the flux sensitivity improves by a factor of $(2)^{1/2}$

Detection of a larger number of polarised sources



Conclusions

- probe early phases of galaxy clusters to shed light on **origin** and **evolution** of magnetic fields

- exploit VLA data (1-2 GHz) of 2 proto-clusters: **CARLA J1510+5958 & J1358+5752**

  - from observations:
    1) uniform distribution of the **RM** or gradients related to local variations
    2) depolarisation of **one lobe** (total or partial)

  - from simulations:
    1) CARLA J1510+5958: **B > 0.5 μG** from non-detection
    2) CARLA J1358+5752: **B ~ 1.6 μG**

AGN immersed into an early-magnetised proto-ICM

- Future: SKAO Band 1 and Band 2 (+ Band 3) combination will provide high spatial resolution, Faraday resolution, flux sensitivity and large Faraday coverage

Recover the polarised emission from fainter sources

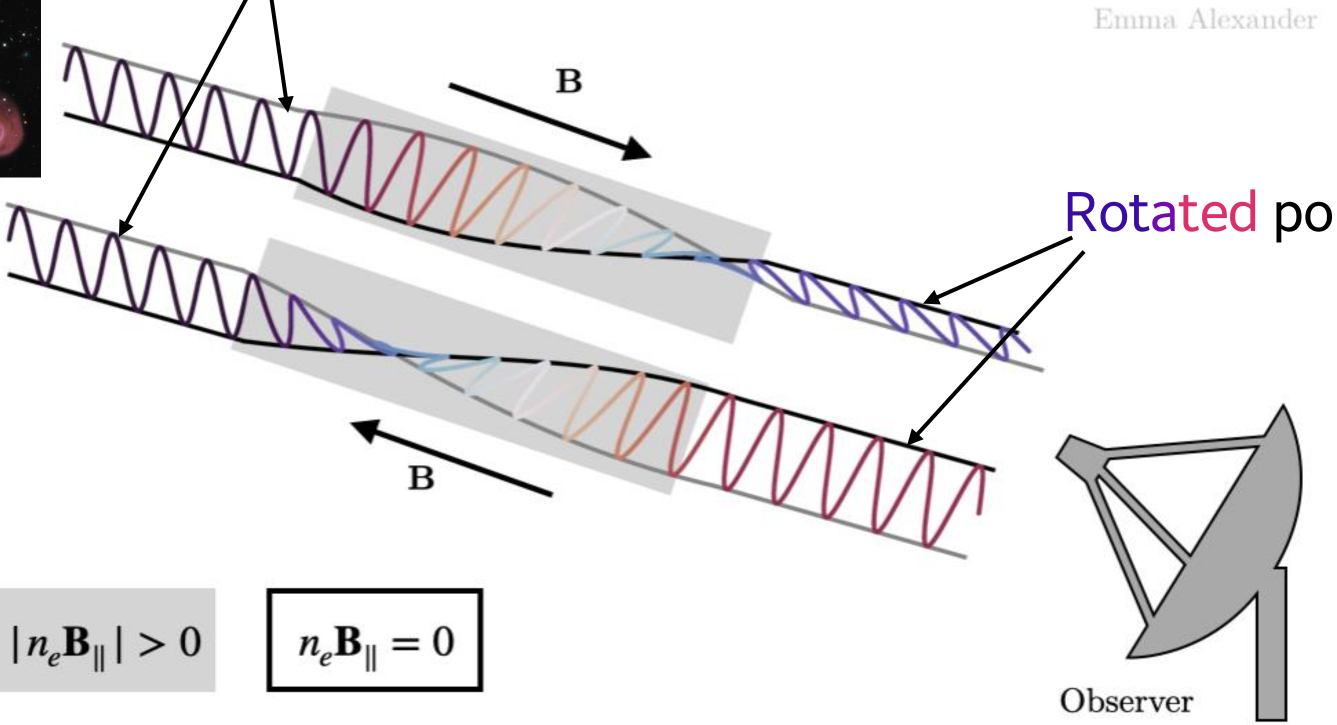
Thank you!

Backup Slides

Faraday Rotation Effect

Radio loud AGN

Linearly polarised radiation



Rotated polarised radiation

Magneto-ionic medium
(e.g. ICM, proto-ICM, ⋯)

Credits: Emma Alexander

RM

from X-ray observations

Electron gas number density

Extension along the LOS

$$\mathrm{RM} = 812 \int_{z_s}^{0} \frac{n_e(z)_{[cm^{-3}]} B_{\parallel}(z)_{[\mu G]}}{(1+z)^2} \frac{dl_{[kpc]}}{dz} dz \;\; \mathrm{rad\ m}^{-2}$$

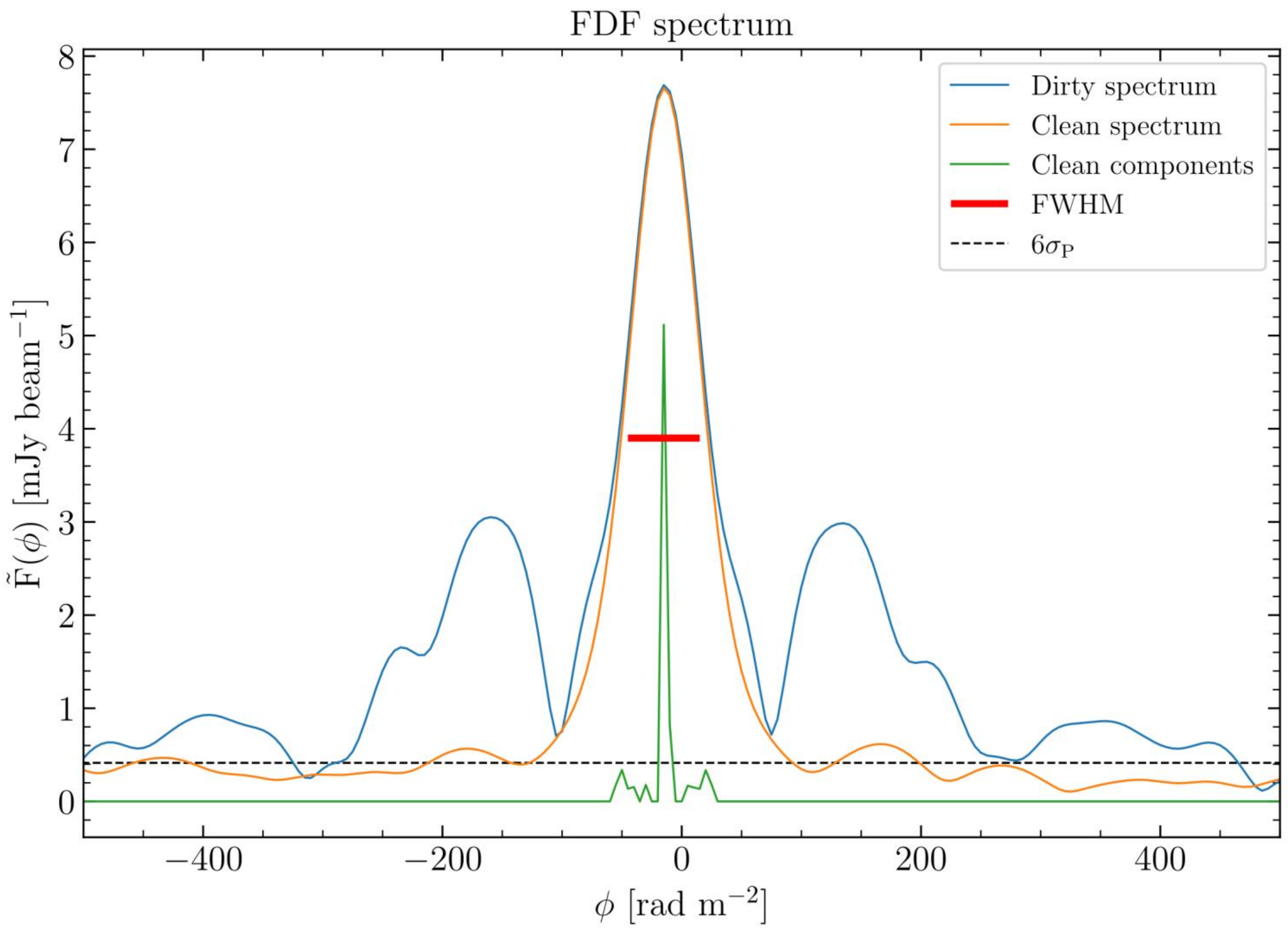
Rotation Measure

from radio observations

Magnetic field component along the LOS

LOS = line-of-sight

FDF



CARLA J1510+5958

FWHM = 60.23 rad m^{-2}

peak at −14 rad m^{-2}(*)

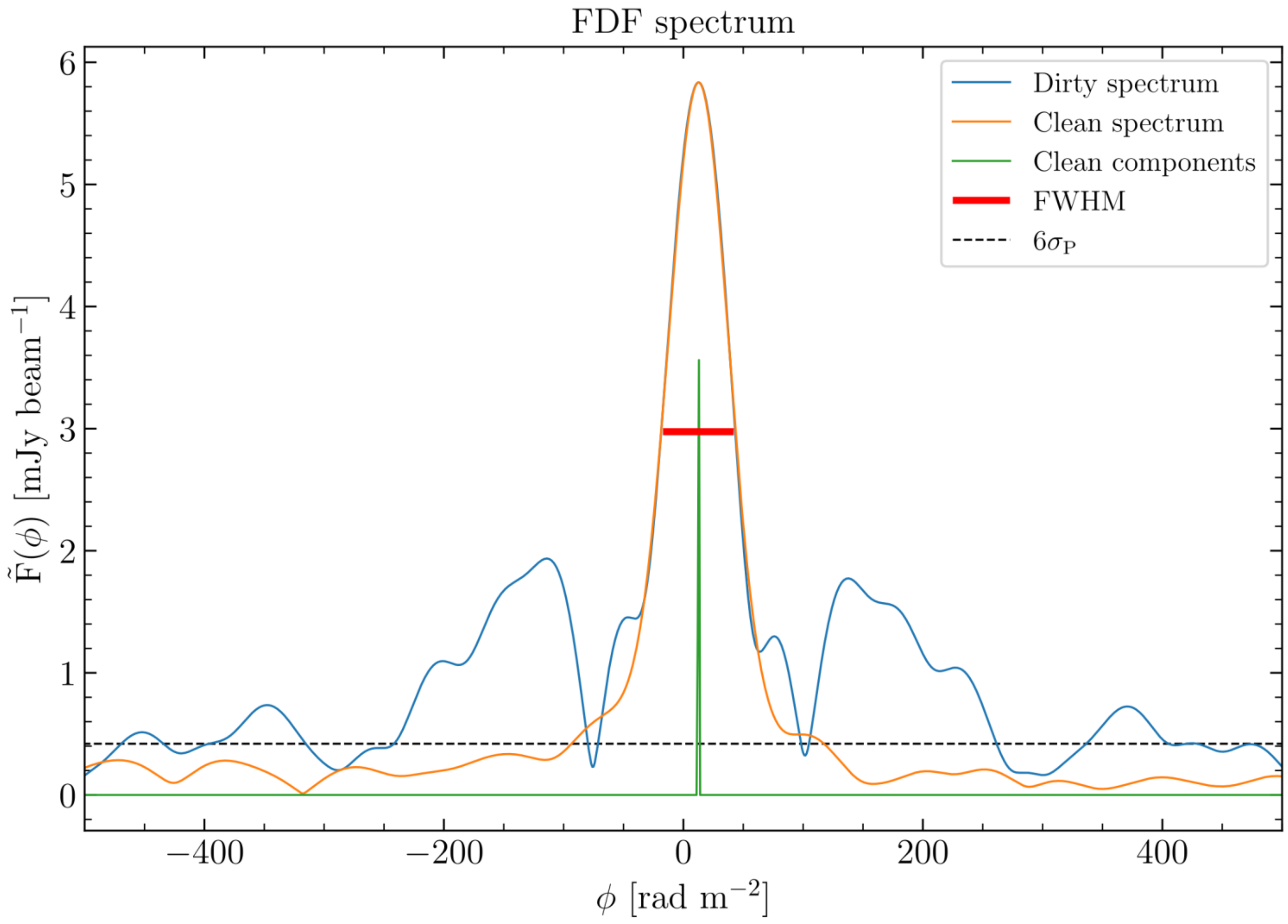
Maximum Faraday depth

1322 rad m^{-2}

~ 9780 rad m^{-2}
(source rest-frame)

(*) values not in the source rest-frame

FDF



CARLA J1358+5752

FWHM = 58.98 rad m^{-2}

peak at +13 rad m^{-2}(*)

Maximum Faraday depth

1291 rad m^{-2}

~ 7251 rad m^{-2}
(source rest-frame)

(*) values not in the source rest-frame

MF Estimate

CARLA J1510+5958

Lobe	$<RM>_s$	n_e	L	$B_{//}$ (physical)	$B_{//}$ (comoving)
W	-115 rad m^{-2}	10^{-3} – 10^{-1} [cm^{-3}]	100 kpc	1.416 - 0.014 μG	0.191 - 0.002 μG

CARLA J1358+5752

Lobe	$<RM>_s$	n_e	L	$B_{//}$ (physical)	$B_{//}$ (comoving)
W	66 rad m^{-2}	10^{-3} – 10^{-1} [cm^{-3}]	200 kpc	0.406 - 0.004 μG	0.072-0.001 μG
E	60 rad m^{-2}	10^{-3} – 10^{-1} [cm^{-3}]	100 kpc	0.739 - 0.007 μG	0.132-0.001 μG

Lobe	σ_s	n_e	L	c	$B_{//}$ (physical)	$B_{//}$ (comoving)
W	39 rad m^{-2}	"	200 kpc	10 kpc	1.074 - 0.011 μG	0.191-0.002 μG
E	18 rad m^{-2}	"	100 kpc	10 kpc	0.701 - 0.007 μG	0.125-0.001 μG

Simulation specifics

CARLA J1510+5958

Fixed parameters

Size	*Resolution*	Λ_{min}	η	n
400 pxl	5.10 kpc	10.25 kpc	0.5	5/3

Free parameters

Λ_{max}	B_{norm}	*Integration*	n_e
[51, 102, 255, 510] kpc	[0.3,...,5.0] μG	[190, 380, 660] kpc	[9.880, 6.491, 4.385] x 10^{-3} cm^{-3}

Simulation specifics

CARLA J1358+5752

Fixed parameters

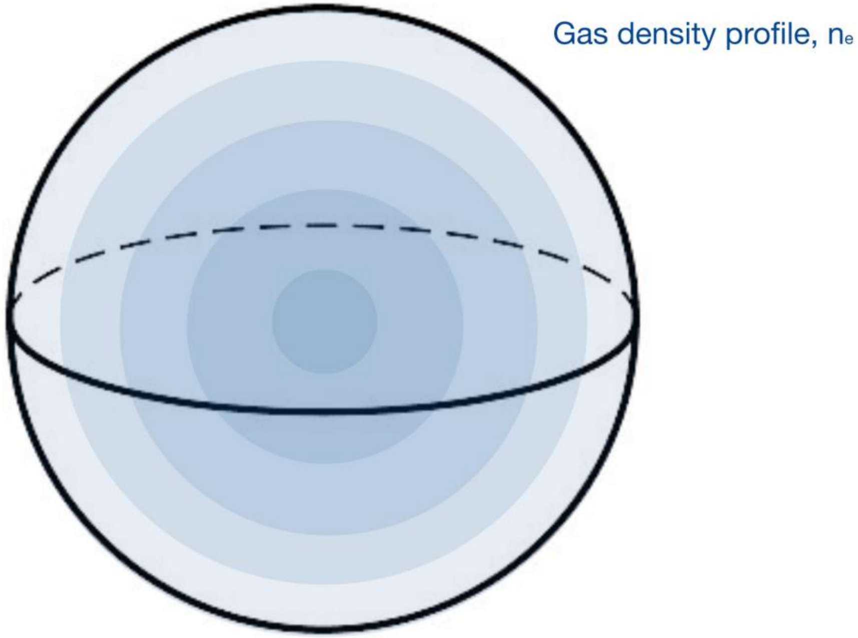
Size	*Resolution*	Λ_{min}	η	*n*
400 pxl	5.05 kpc	10.15 kpc	0.5	5/3

Free parameters

Λ_{max}	B_{norm}	*Integration*	n_e
[25.25, 50.50, 101, 252.5] kpc	[1.0,…,8.0] μG	[43, 86, 90, 180, 142, 284] kpc	[3.750, 3.696, 3.674, 3.157, 3.368, 2.709] x 10^{-3} cm^{-3}

Density Estimate

'uniform density that would produce, if projected on a box of depth *integration length*, the same column density of the average cluster profile at that z (integrated over *integration length* and averaged over a circular aperture of diameter *projected size of the central AGN*)'



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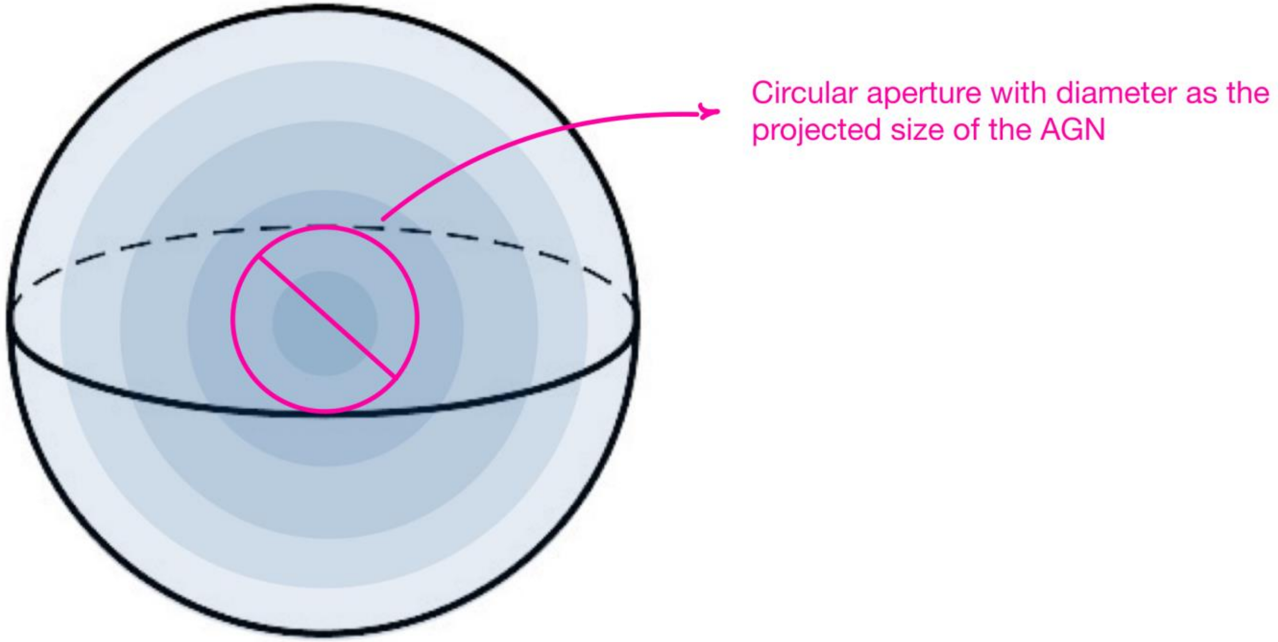

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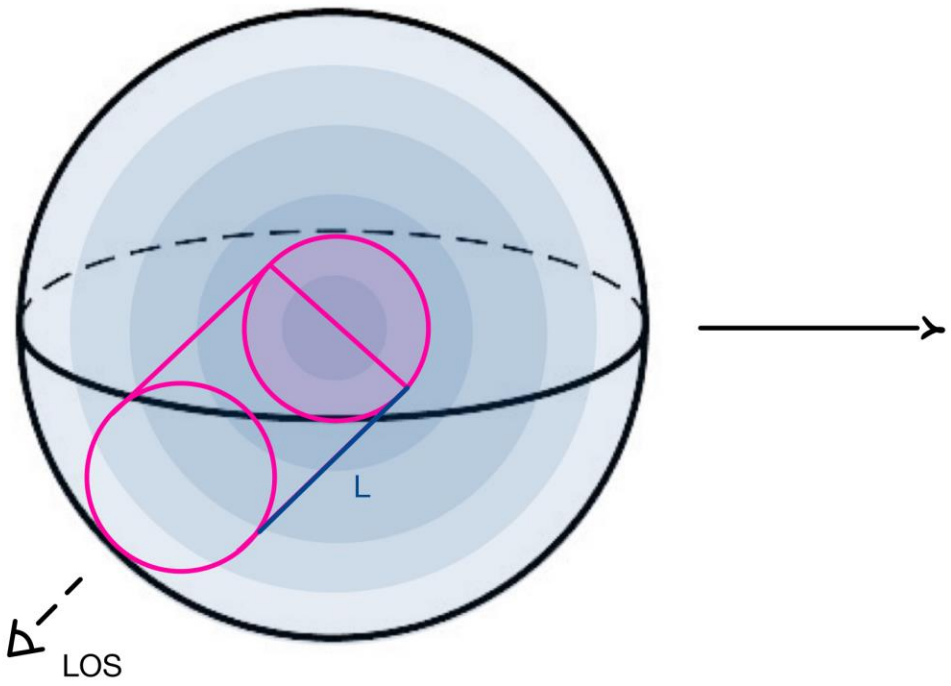
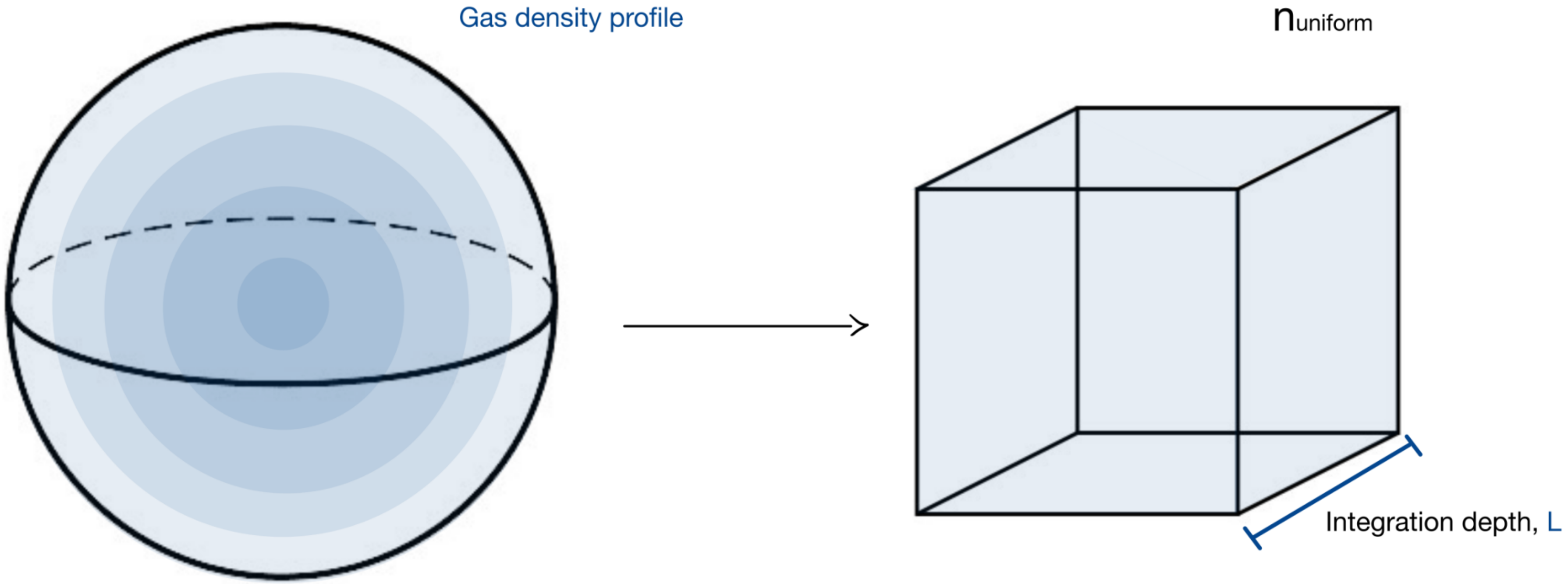


1. $\Sigma_{n_e} = \int_L n_e(r)\, dl$

2. $\langle \Sigma_{n_e} \rangle_{aperture}$

Density Estimate

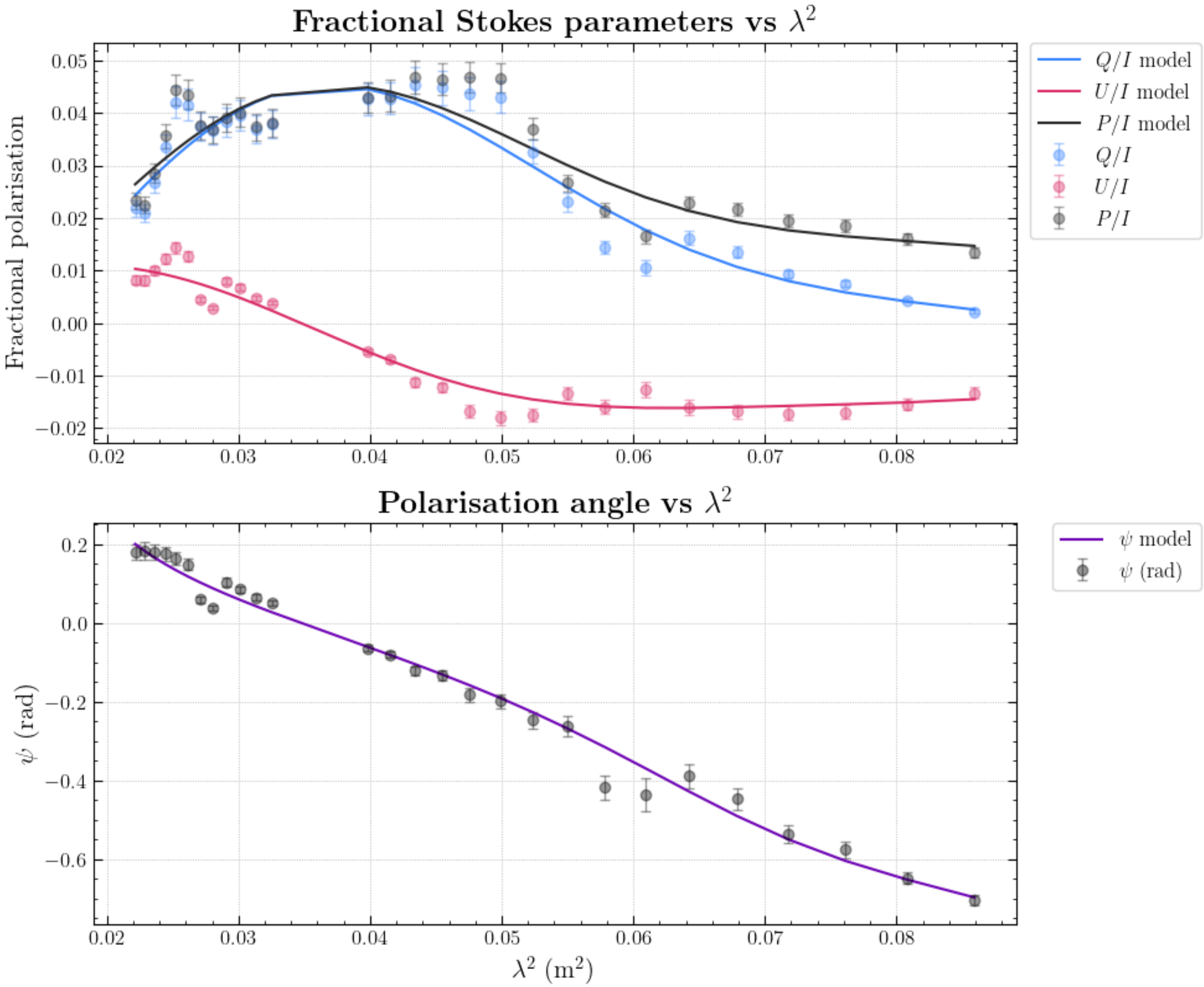
'uniform density that would produce, if projected on a box of depth *integration length*, the same column density of the average cluster profile at that z (integrated over *integration length* and averaged over a circular aperture of diameter *projected size of the central AGN*)'



$$n_{uniform} = \frac{\langle \Sigma_{n_e} \rangle}{L}$$

QU Fitting

CARLA J1510+5958



Single Faraday simple component and one component with **differential** Faraday rotation + common **external** dispersion term

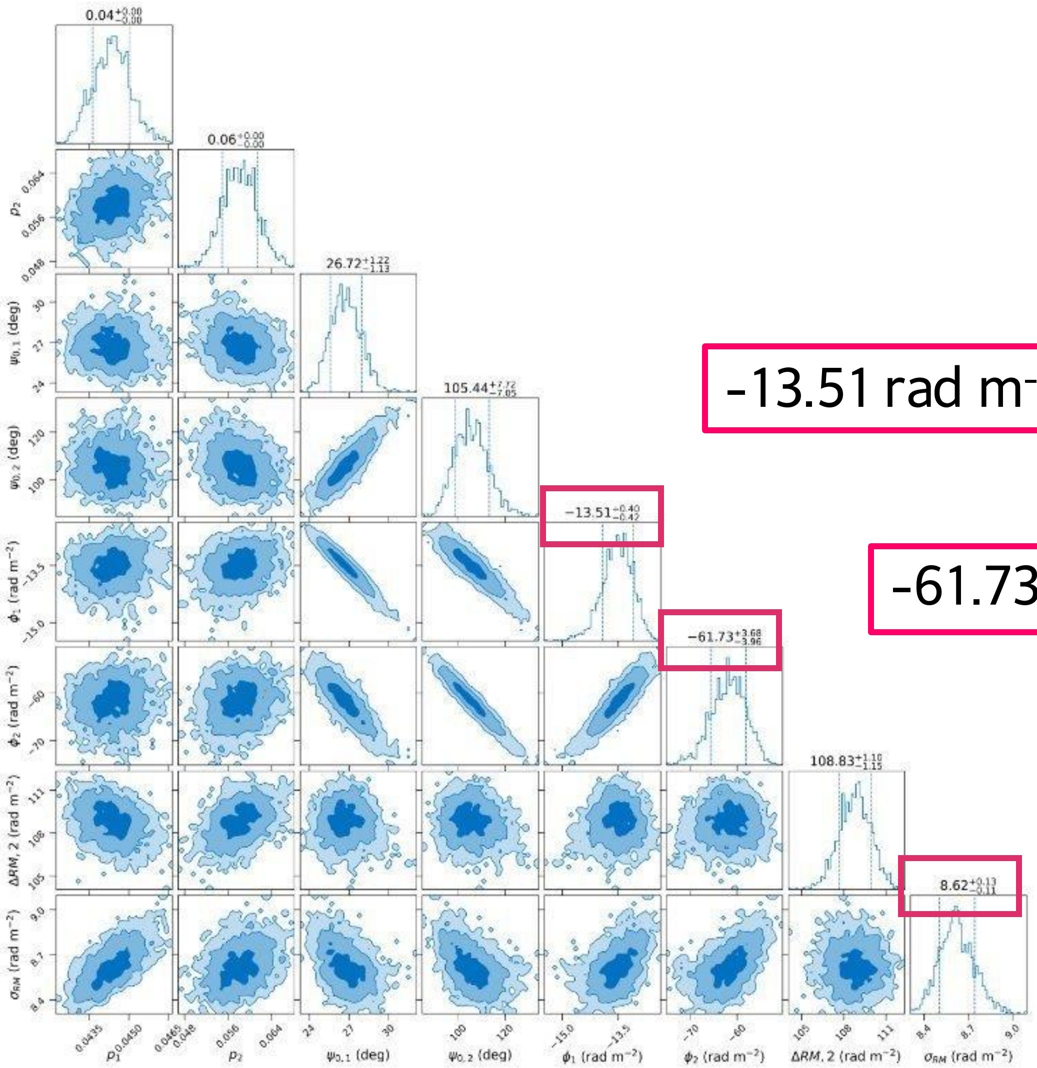
$$p = \{p_{i,1} \cdot \exp\left[2i\left(\psi_{0,1} + RM_1 \cdot \lambda^2\right)\right] +$$

$$+ p_{i,2} \cdot \exp\left[2i\left(\psi_{0,2} + \left(RM_2 + \tfrac{1}{2}\Delta RM_2\right)\lambda^2\right)\right] \cdot \frac{\sin(\Delta RM_2 \cdot \lambda^2)}{\Delta RM_2 \cdot \lambda^2}\}$$

$$\cdot \exp\left(-2\sigma_{RM}^2 \cdot \lambda^4\right)$$

QU Fitting

CARLA J1510+5958



-13.51 rad m^{-2}

-61.73 rad m^{-2}

8.62 rad m^{-2}

Single Faraday simple component and one component with **differential** Faraday rotation + common **external** dispersion term

$$p = \left\{ p_{i,1} \cdot \exp\left[2i\left(\psi_{0,1} + RM_1 \cdot \lambda^2\right)\right] + \right.$$

$$\left. + p_{i,2} \cdot \exp\left[2i\left(\psi_{0,2} + \left(RM_2 + \tfrac{1}{2}\Delta RM_2\right)\lambda^2\right)\right] \cdot \frac{\sin(\Delta RM_2 \cdot \lambda^2)}{\Delta RM_2 \cdot \lambda^2} \right\}$$

$$\cdot \exp\left(-2\sigma_{RM}^2 \cdot \lambda^4\right)$$