DIAGNOSING THE INVISIBLE: COSMIC MAGNETISM AND THE RADIO SKY

Magnetic fields are ubiquitous.
Yet very little is known about their origin(s) and evolution.

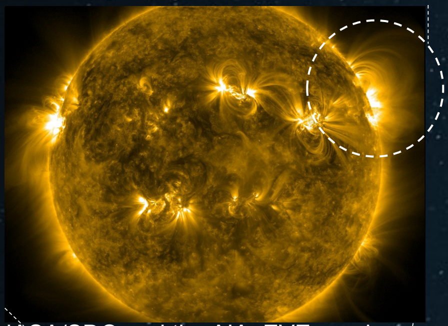
The Northern lights – also known as the aurora borealis – dancing across the night sky in Alaska.

Background credit: The National Geographic's Short Film Showcase by Alexis Coram

SEEING THE INVISIBLE

Charged particles emit *light* as they spiral along the magnetic fields of the Sun and the Earth. Seeing the light allows us to trace the otherwise invisible magnetic fields!

Magnetic arches towering over the active solar surface



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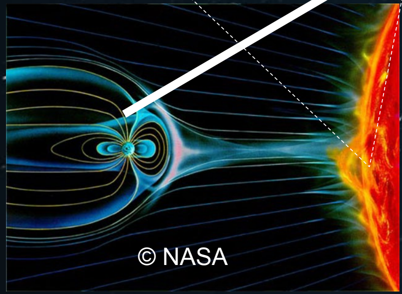

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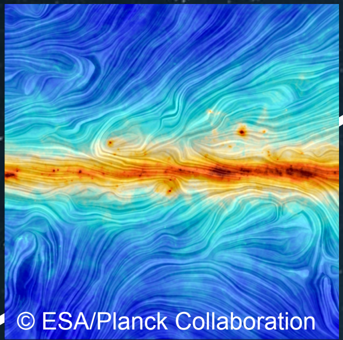
The solar wind carries with it the Sun's magnetic field that interacts with the Earth's magnetosphere (in blue).

The direction of the polarised light emitted by *dust* tells us the magnetic field orientation.



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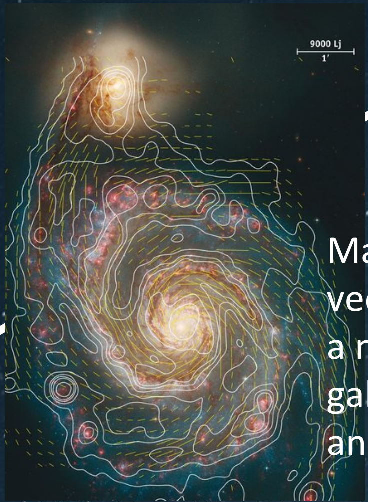
Magnetic fingerprint of our Galaxy – the Milky Way

On *larger* scales, we use *radio* observations to trace the magnetic fields.

larger structure

weaker field



Magnetic field vectors of a nearby galaxy – M51, and a galaxy group – Stephan's Quintet

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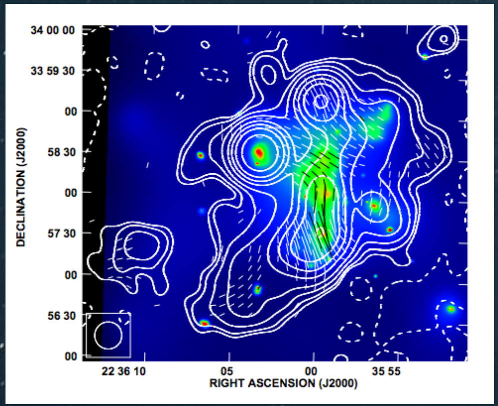
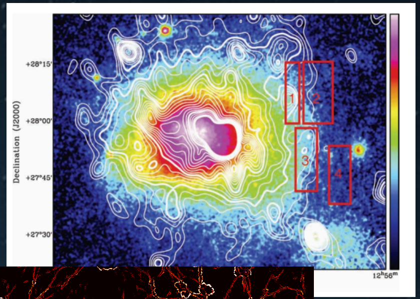
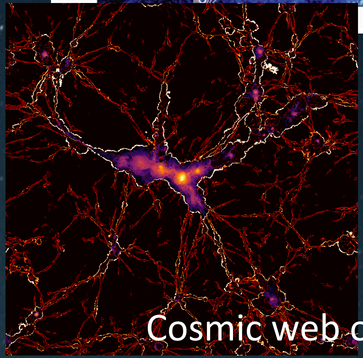


© Nikiel-Wroczyński+ (2013)

Coma cluster © Brown+ (2011)





Cosmic web of filaments and voids

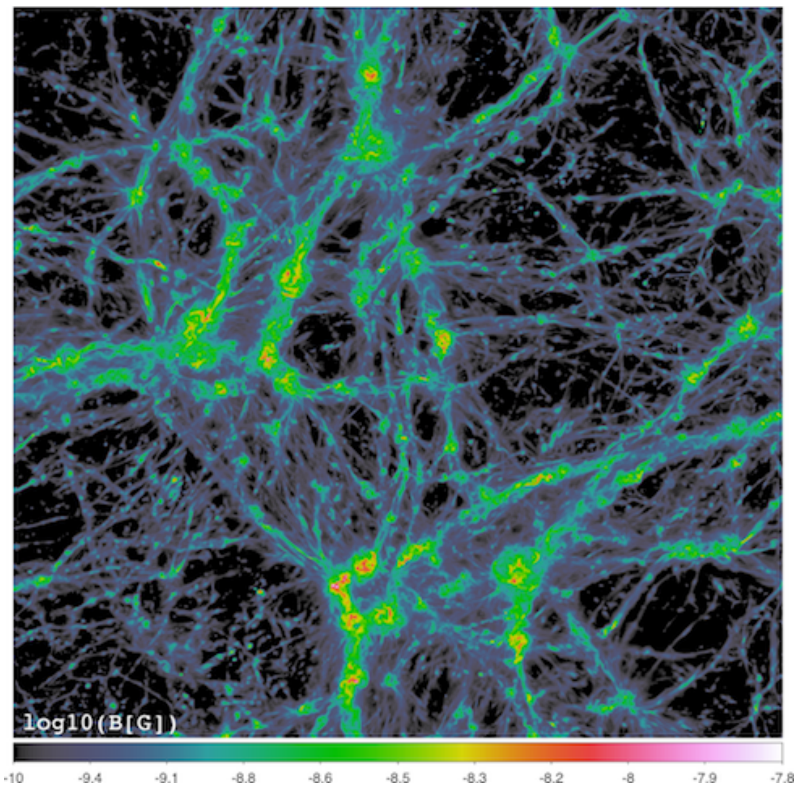
© TNG Collaboration

How do we correctly infer the magnetic field properties in galaxy clusters and beyond?

Background credit: Just the night sky by Stefan Cosma

THE COSMIC WEB

The first magnetic fields: primordial in origin, or astrophysical?



Projected magnetic field strength at z = 0 across a (50 Mpc)^3 cosmological simulation (Vazza+ 2014)

Numerical simulations
(e.g. Ryu+ 1998, Ryu+ 2008, Akahori & Ryu 2010, Vazza+ 2014)

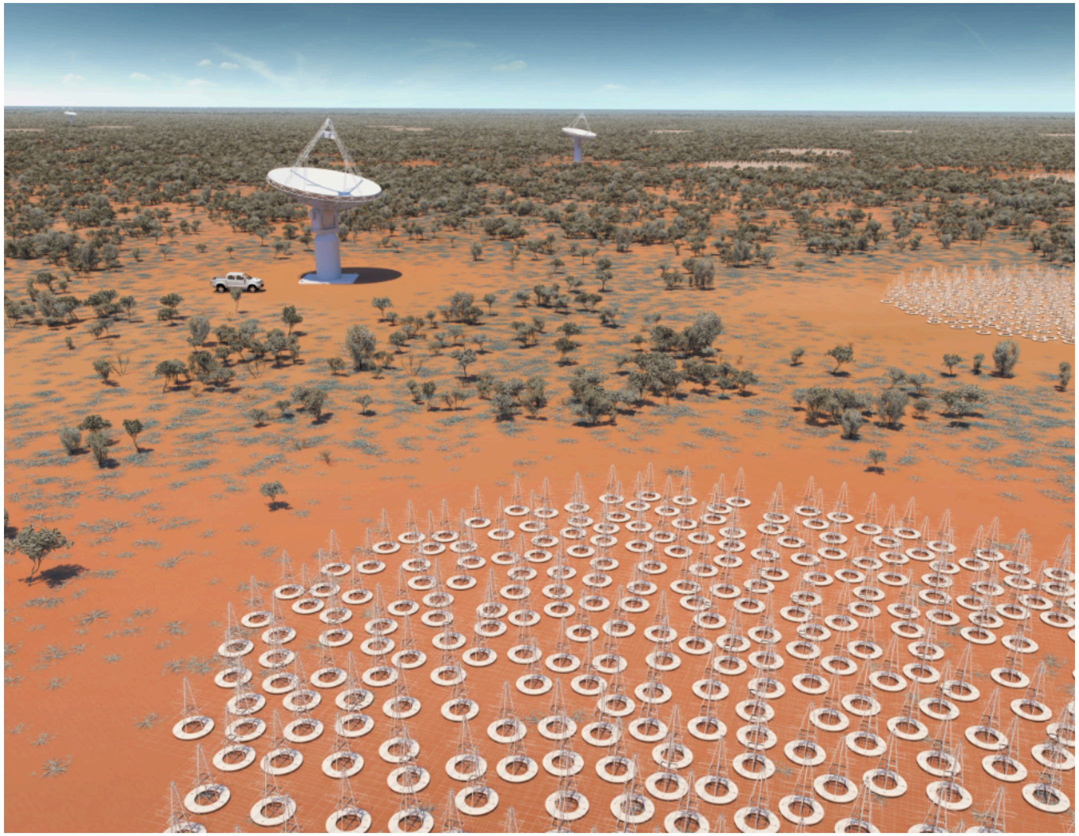
Radio observations
(e.g. Xu+ 2006, Giovannini+ 2015, Govoni+ 2019)

B-field strength order:

$$\sim \mathrm{nG} \;\; \text{to} \;\; < 1\,\mu\mathrm{G}$$

DECODING AN UNPRECEDENTED RADIO SKY

Square Kilometre Array (SKA) – the world's largest radio telescope



Artist impression: SKA Organisation/Swinburne Astronomy Productions

DECODING AN UNPRECEDENTED RADIO SKY

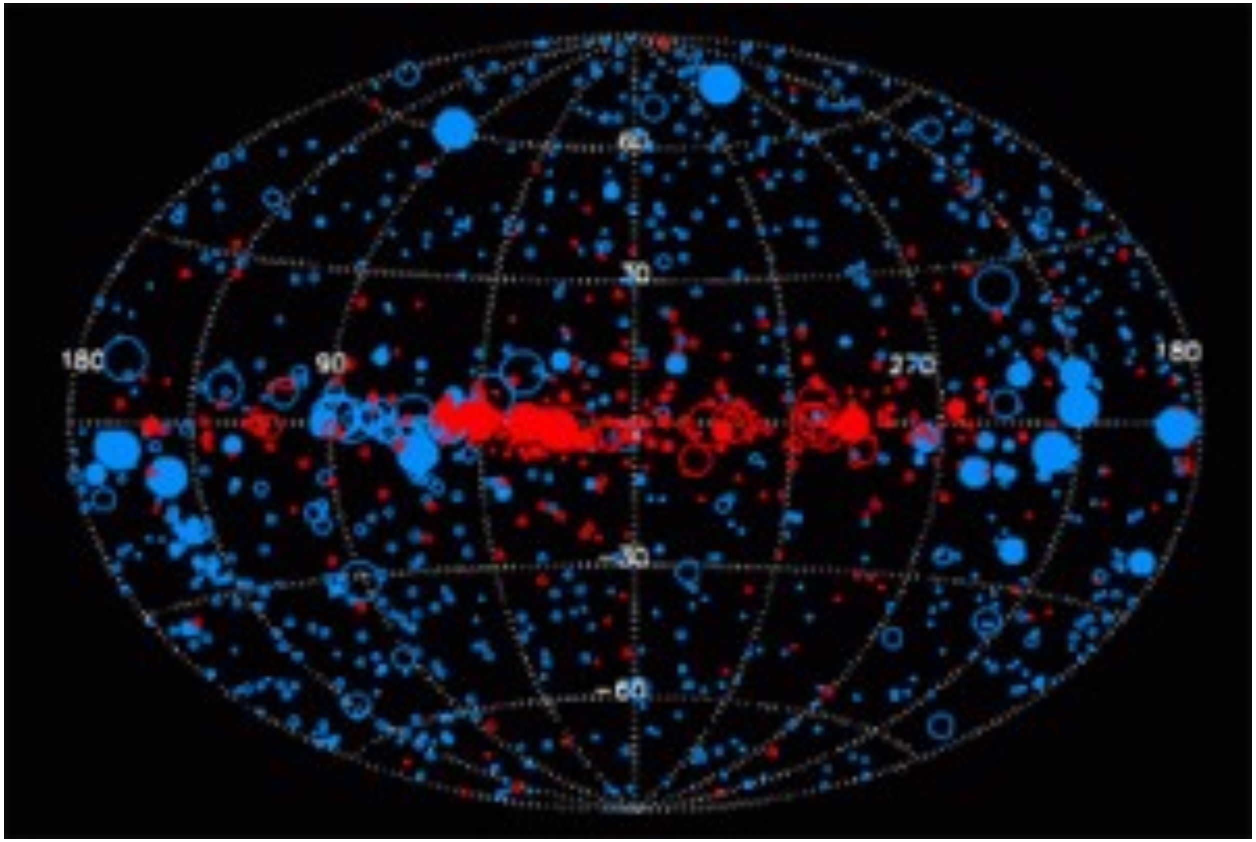
Square Kilometre Array (SKA) – the world's largest radio telescope
Machine Learning and Big Data: all-sky survey of over ten million RMs!

~ 1200 RMs

closed: +ve
open: -ve

~ 900 extragalactic sources (blue)

~ 300 radio pulsars (red)



More FRBs?

More quasars?

Figure courtesy of Jo-Anne Brown (2012), SKA official webpage

MEASURING THE INVISIBLE

Faraday rotation measure (RM) at radio wavelengths is commonly used to diagnose large-scale magnetic fields.

RM

observed wavelength

$$\mathcal{R} = (\Delta\varphi)\,\lambda^{-2} = (\varphi - \varphi_0)\,\lambda^{-2}$$

observed polarisation angle

intrinsic polarisation angle

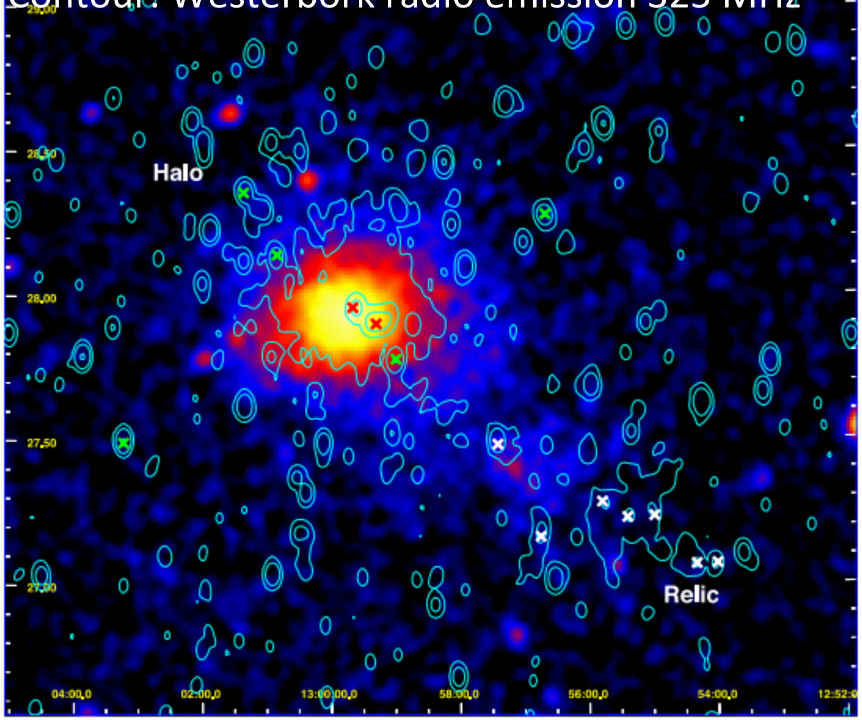
BEYOND GALACTIC SCALES

Magnetic fields are relatively weaker and more difficult to be observed

radio emission and Faraday rotation measure as probes

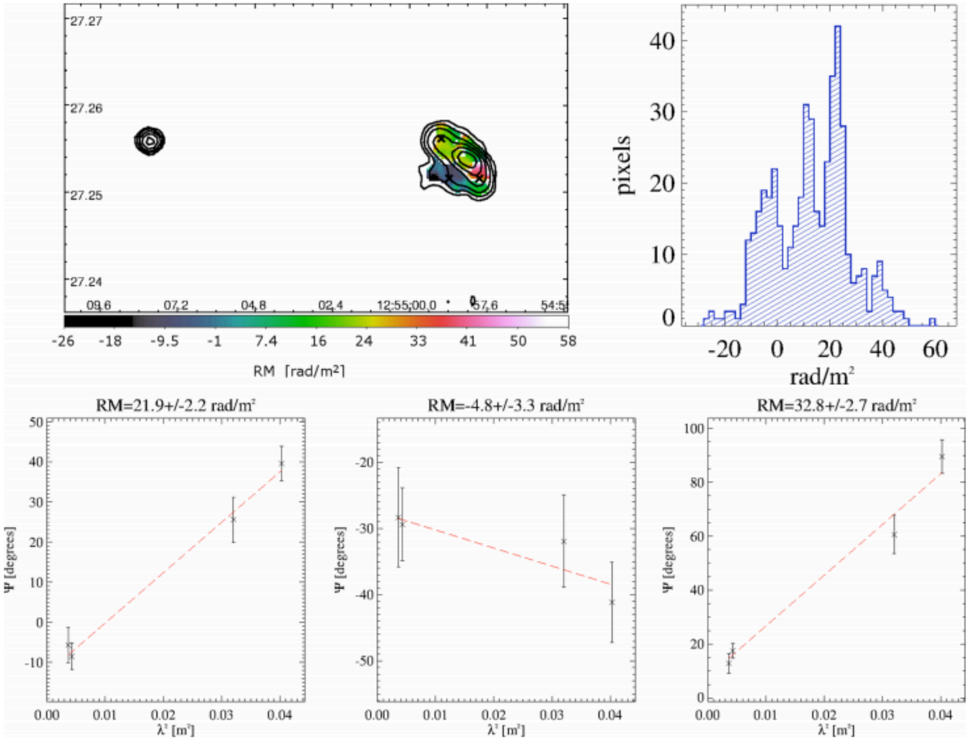
Colour: ROSAT X-ray

Contour: Westerbork radio emission 325 MHz



Coma cluster and NGC 4839 group

Colour: RM   Contour: Total radio intensity 1.4 GHz



a radio background source 5C4.24

(Bonafede+ 2013)

ROTATION MEASURE

In the context of polarised radiative transfer

distance between the source and observer

$$\mathcal{R}(s) = 0.812 \int_{s_0}^{s} \frac{\mathrm{d}s'}{\mathrm{pc}} \left(\frac{n_{\mathrm{e,th}}(s')}{\mathrm{cm}^{-3}}\right) \left(\frac{B_{\parallel}(s')}{\mu\mathrm{G}}\right) \,\mathrm{rad\,m}^{-2}$$

thermal electron number density

B-field strength along line-of-sight

assuming:

no absorption, no emission, no Faraday conversion

only thermal electrons

The correlations in the observed RM fluctuations (RMF) are used to probe the length scales on which magnetic fields vary.

(**On**+ 2019)

ROTATION MEASURE FLUCTUATIONS (RMF)

Conventional approach – pseudo random-walk process

equal step size $\overline{\Delta s}$
density and magnetic field uncorrelated
only thermal electrons present

standard deviation of RM

$$\sigma_{\mathcal{R}} = \frac{e^3}{2\pi m_e^2 c^4} \sqrt{\frac{L}{\overline{\Delta s}}}\, \overline{\Delta s}\, \overline{n}_{\mathrm{e,th}}\, B_{\parallel \mathrm{rms}}$$

$$= 0.812 \sqrt{\frac{L}{\overline{\Delta s}}} \left(\frac{\overline{\Delta s}}{\mathrm{pc}}\right) \left(\frac{\overline{n}_{\mathrm{e,th}}}{\mathrm{cm}^{-3}}\right) \left(\frac{B_{\parallel \mathrm{rms}}}{\mu \mathrm{G}}\right) \mathrm{rad\ m}^{-2} \qquad (1)$$

Most studies on large-scale magnetic fields use this expression.

(e.g. Sokoloff+ 1998, Blasi+ 1999, Dolag+ 2001, Govoni+ 2004, Subramanian+ 2006, Cho+ 2009, Sur 2019).

(**On**+ 2019)

ASSESSING THE RMF APPROACH

When is it justified? When does it deserve caution?

- carried out Monte Carlo simulations to compute the RMF
- built models of various magnetic field configurations and thermal electron number density distributions
- applied divergence-free filter
- normalised to galaxy cluster scale

$$\mathcal{R}_{\perp} = 0.812 \sum_{\parallel} \frac{\overline{\Delta s}}{\mathrm{pc}} \left[\left(\frac{n_{\mathrm{e,th}}(i,j,k)}{\mathrm{cm}^{-3}} \right) \left(\frac{B(i,j,k)}{\mu\mathrm{G}} \right) \right]_{\parallel} \mathrm{rad\ m}^{-2} \qquad (2)$$

Calculated the standard deviation across the sky plane

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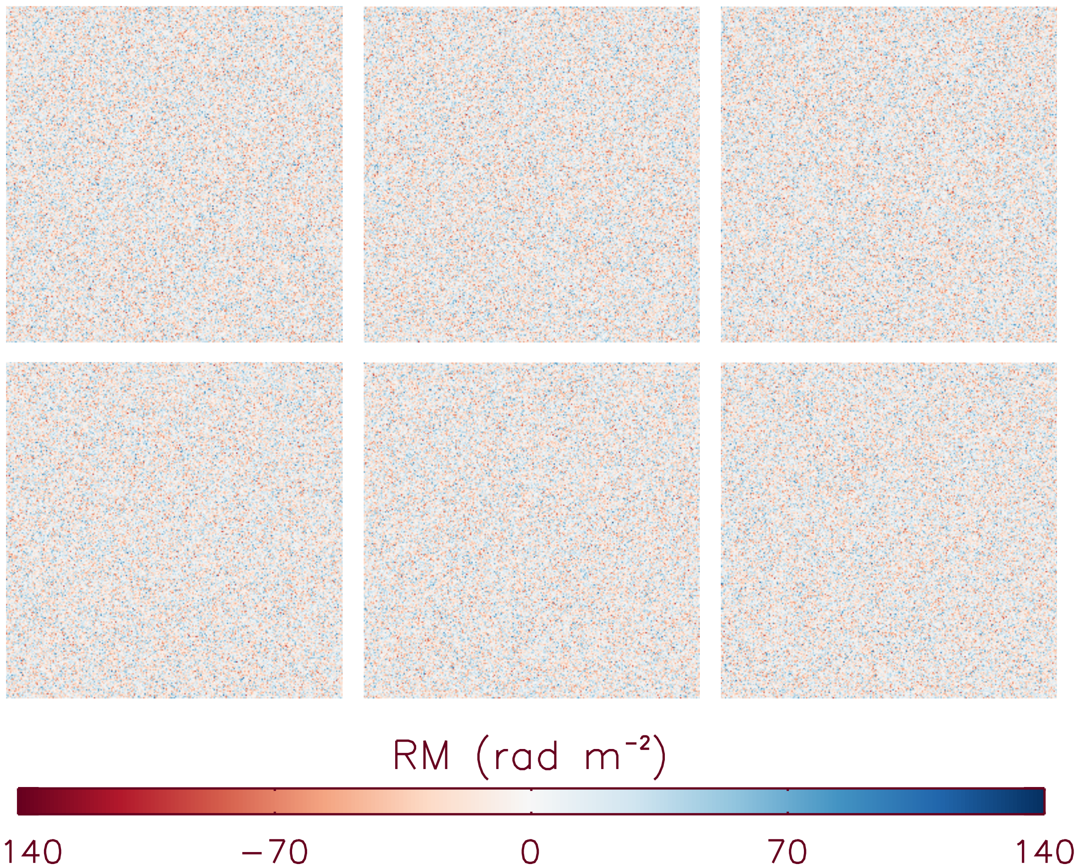
AN EYE TEST

Can you spot any difference between each panel?



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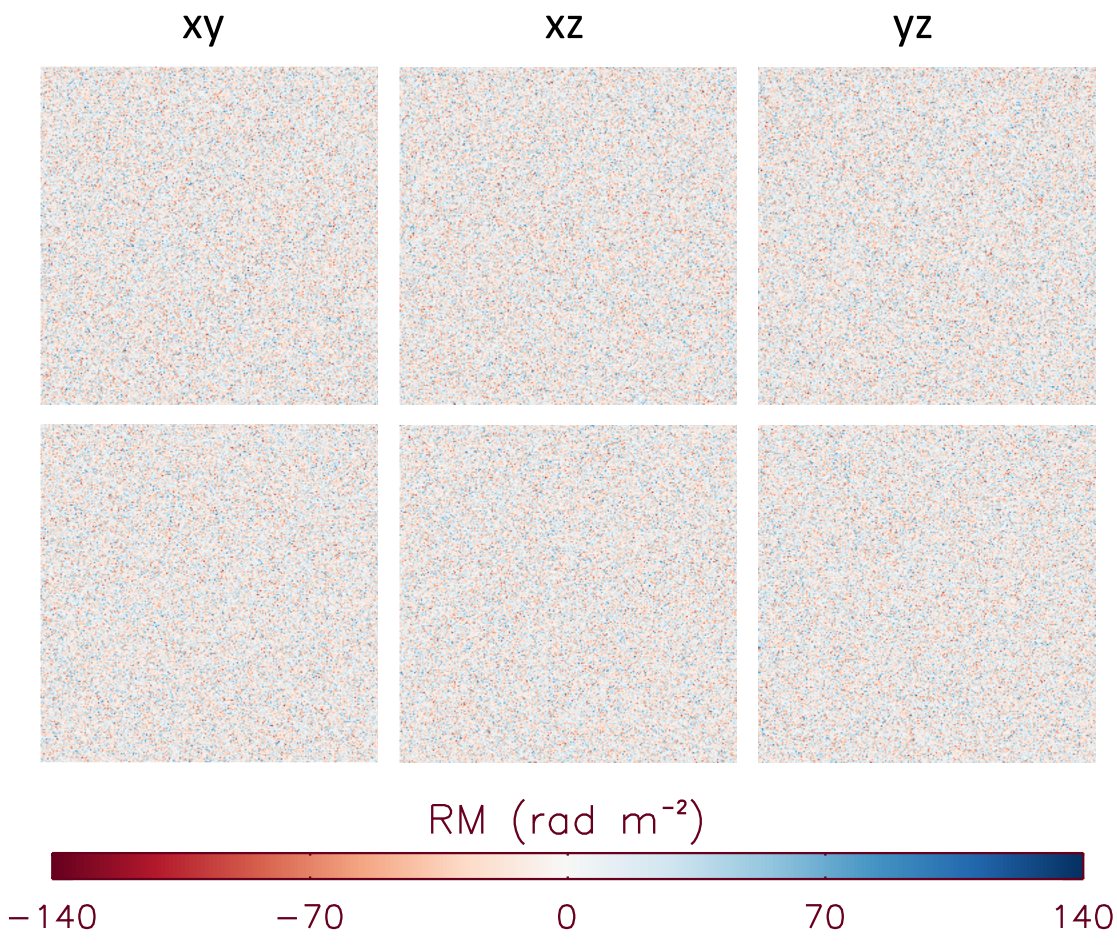
SYNTHETIC RM MAPS

Indistinguishable – non-trivial to characterise the thermal electron number densities and the magnetic field strengths from the observed RM fluctuations alone



Gaussian-distributed densities

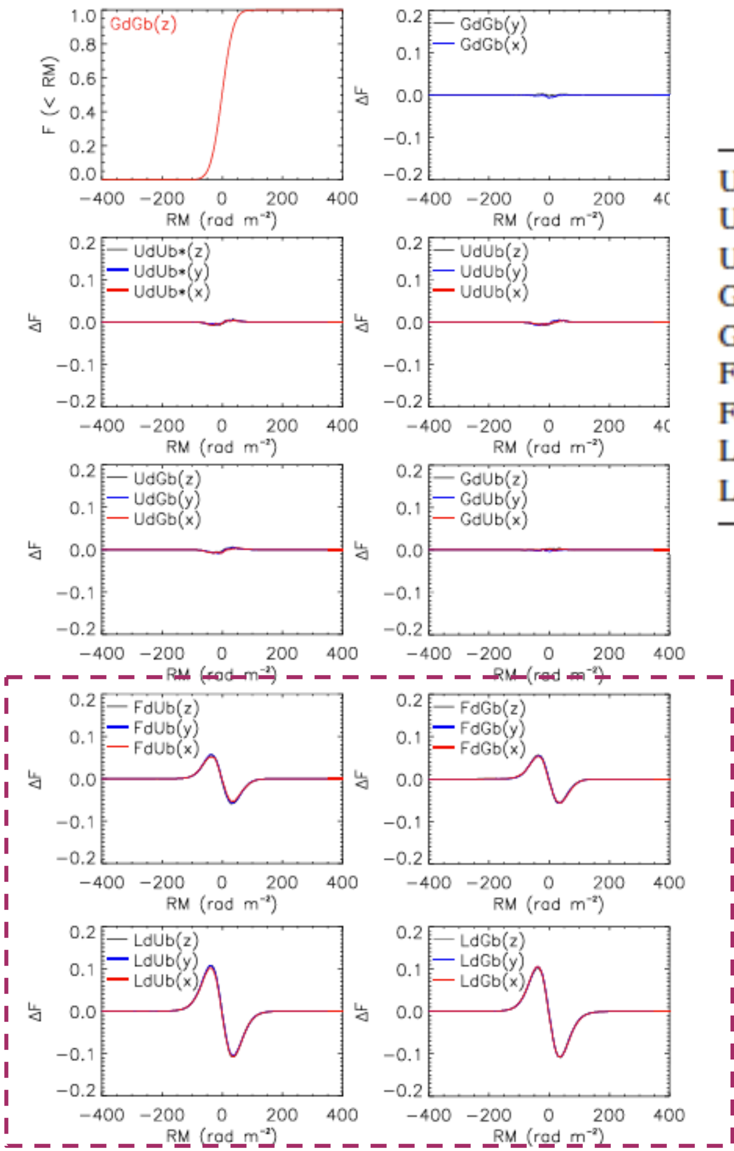
Gaussian-distributed magnetic field strengths
random magnetic field orientations

uniformly-distributed densities

uniformly-distributed magnetic field strengths
random magnetic field orientations
non-divergence free – unphysical!

(**On**+ 2019)

ASSESSING THE CONVENTIONAL RMF ANALYSES



distribution		conventional (eq. 1)			standard deviation (eq. 2)		
		$\sigma_{\mathcal{R}}^{xy}$	$\sigma_{\mathcal{R}}^{xz}$	$\sigma_{\mathcal{R}}^{yz}$	$\varsigma_{\mathcal{R}}^{xy}$	$\varsigma_{\mathcal{R}}^{xz}$	$\varsigma_{\mathcal{R}}^{yz}$
Ud	Ub*	29.2971	29.2975	29.2962	29.2861	29.3151	29.3042
Ud	Ub	29.2962	29.2977	29.2970	29.3101	29.3198	29.3278
Ud	Gb	29.2965	29.2965	29.2979	29.3231	29.2934	29.3299
Gd	Ub	29.2982	29.2961	29.2966	29.9263	29.8972	29.8994
Gd	Gb	29.2970	29.2973	29.2966	29.9113	29.8854	29.8902
Fd	Ub	29.2987	29.2965	29.2956	39.1187	39.1392	39.1134
Fd	Gb	29.2975	29.2966	29.2968	39.1185	39.1357	39.1186
Ld	Ub	29.2969	29.2968	29.2972	48.3524	48.3218	48.3327
Ld	Gb	29.2975	29.2964	29.2970	48.3058	48.3017	48.3146

The conventional RMF analyses *cannot distinguish* between various distinct distributions of densities and magnetic field strengths.

The conventional RMF analyses *do not work* for fractal and lognormal density distributions.

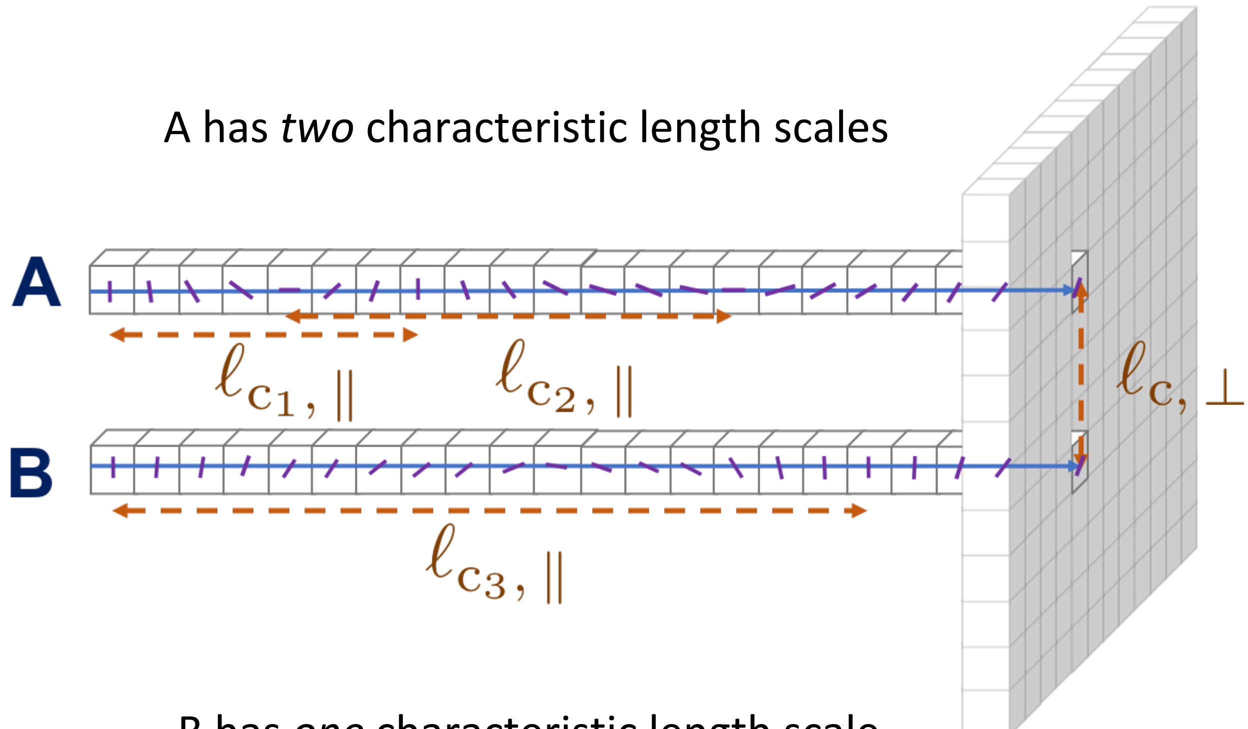
(**On**+ 2019)

SUBTLETIES IN QUANTIFYING THE RMF

Fluctuations of density and magnetic fields along the line-of-sight and across the sky plane can be different

A has *two* characteristic length scales

Polarisation angle changes along each line-of-sight



(1) Resulting polarisation angles we see on the sky are the same

B has *one* characteristic length scale

(2) $l_{c,\,perp} \neq l_{c1,\,\parallel} \neq l_{c2,\,\parallel} \neq l_{c3,\,\parallel}$

(Chan, Wu, **On**+ 2018; **On**+ 2019)

TAKE-HOME MESSAGES

- Density fluctuations can mask the effect of magnetic field fluctuations, affecting the correlation length of magnetic fields inferred from the conventional RMF analyses.
- We caution against interpretations of RMF analyses in lognormal-distributed and fractal-like density structures.
- The spatial correlations are generally not the same along the line-of-sight and across the sky plane.
- In complex situations, a covariant polarised radiative transfer calculation is essential to properly track all radiative and transport processes, otherwise the interpretations of magnetism in galaxy clusters and larger scale cosmological structures would be ambiguous.

ABOUT THE AUTHOR

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On+ (2019)

Chan+ (2018)