



An SKA-Low RM Grid for constraining the origin of cosmic magnetism

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Understanding the origin and evolution of cosmic magnetic fields is a key science goal for the SKAO. Recent advances in metre-wavelength (m - λ) Faraday rotation measure (RM) grids are enabling precision probes of cosmic magnetism, with implications extending to early-Universe physics, AGN feedback, and the magnetized circumgalactic medium. Here we model the m - λ polarized source counts to predict an RM Grid density with SKA-Low of $N(> P) \sim 5(P/100\mu\text{Jy})^{-0.75} \text{ deg}^{-2}$, where P is the polarized intensity detection threshold. This represents at least an order of magnitude improvement over the current state-of-the-art. For a representative wide-area SKA-Low AA4 survey covering $10,000 \text{ deg}^2$ in $\sim 3,200$ hours, we predict more than 50,000 RMs. Coupled with an expected RM precision of $\sim 0.05 \text{ rad/m}^2$, SKA-Low promises to produce the leading RM Grid survey for constraining the origin of cosmic magnetism in the SKA era.

These predictions can be partially tested during the Science Verification phase using the AA* Sky Model data. For example, at a nominal detection threshold of $240 \mu\text{Jy/beam}$ (8 times the noise in Stokes Q and U), we expect $\sim 2.6 \text{ RMs/deg}^2$ (5x the current best m - λ RM Grid density). Combining both wide-area and all-sky data, SKA-Low could detect up to 100,000 m - λ RMs across its observable sky.

Finally, we demonstrate new constraints on the origin of cosmic magnetism by comparing cosmological MHD simulations with the LOFAR m - λ RMs, and highlight the transformative advances an SKA-Low RM Grid will enable for precision studies of cosmic magnetism.

1 Introduction

Understanding the origin and evolution of cosmic magnetic fields is one of the key science goals for the SKAO (Heald et al., 2020; Johnston-Hollitt et al., 2015). Radio synchrotron radiation, its linear polarization, and the ensuing Faraday rotation provide some of the best ways of studying extragalactic magnetic fields (e.g. Beck and Gaensler, 2004; Vazza et al., 2015; van Weeren et al., 2019; Vernstrom et al., 2021, 2023; Carretti et al., 2023). In addition, there are many multi-wavelength tracers of the properties of cosmic magnetic fields, providing complementary constraints, such as γ -ray cascades (Neronov and Vovk, 2010), ultra-high energy cosmic rays (Hackstein et al., 2018), the CMB (Planck Collaboration et al., 2016), mm-polarized dust emission from galaxies (Geach et al., 2023), and the Lyman- α forest (Pavičević et al., 2025).

Recent studies using Faraday rotation measure (RM) Grids at metre-wavelengths (Van Eck et al., 2018; Riseley et al., 2020; O’Sullivan et al., 2023) have highlighted their important contribution to our understanding of the origin of cosmic magnetism (Carretti et al., 2025; Neronov et al., 2024), the physics of the early Universe (Neronov et al., 2021; Mtchedlidze et al., 2024), the maximum extent of feedback from AGN and galaxy outflows (Blunier and Neronov, 2024; Bondarenko et al., 2024; Vazza et al., 2025), and the properties of the circumgalactic medium (Heesen et al., 2023; Ramesh et al., 2023). While the focus of this chapter is on using an SKA-Low RM Grid to advance our understanding of the origin of cosmic magnetism, we note that the science applications are much broader than this. For example, RM Grids can be used to probe the inventory of matter within and beyond virialised halos out to cosmic noon (Anderson et al., 2024; Böckmann et al., 2023), which has strong synergies with other current and planned facilities, such as the Simons Observatory (Ade et al., 2019), ELT-MOSAIC (Pelló et al., 2024) and At-LAST (Booth et al., 2024).

The current weight of evidence indicates the presence of relatively strong primordial magnetic fields, with $B_{0,\text{Mpc}} \sim 0.4$ nG (Carretti and Vazza, 2025, and references therein). Such primordial fields can have a considerable impact on early galaxy evolution (Sanati et al., 2024), in addition to potentially alleviating the Hubble tension (Jedamzik and Pogosian, 2020). Being able to robustly constrain the properties of primordial fields leads us into an era where we have a new observational probe of early-Universe physics (Brandenburg et al., 2024), with exciting links to the production of stochastic gravitational waves signatures (Neronov et al., 2021; Agazie et al., 2023).

To predict the properties of an SKA-Low RM Grid, in Section 2 we use models of extragalactic radio source counts and constrain them with our current best knowledge of the m-wavelength polarized sky. In Section 3, we use these constrained models to extrapolate the polarized-source counts to SKA-Low AA4 sensitivities in order to outline nominal SKA-Low RM Grid survey possibilities. We then highlight two complementary approaches to constraining the properties of primordial magnetic fields, using the redshift evolution of the RM (Section 4). Finally, we list some of the exciting opportunities for new discoveries provided by a wide-area SKA-Low RM Grid (Section 5).

2 Polarized-source counts at SKA-Low frequencies

The Tiered Radio Extragalactic Continuum Simulation (T-RECS; Bonaldi et al., 2019, 2023), provides model catalogues of the radio-continuum sky from 150 MHz to 20 GHz. It simulates

two primary populations: Active Galactic Nuclei (AGN) and Star-Forming Galaxies (SFG), along with their respective sub-populations. The outputs have been validated against up-to-date data compilations, showing excellent agreement in luminosity functions, number counts in total intensity, and clustering properties. The T-RECS code is publicly available and can be used to produce radio source catalogs with user-defined frequencies, areas, and depths. This makes it a valuable tool for extrapolating to what can be observed from surveys with the SKA-Mid and SKA-Low telescopes.

An updated 150 MHz model was developed by Lin et al. (2024) based on the LOFAR Deep Field Data Release 1 (Best et al., 2023). This work recast radio source classifications into High Excitation Radio Galaxies (HERG), Low Excitation Radio Galaxies (LERG), Radio-Quiet AGN (RQ-AGN), and SFG. They found that the simulated source counts more closely match the observed data at $z > 4$ than the original T-RECS, while also reproducing the observed differential source counts in total intensity at the faint end (0.1–1 mJy). They also provide updates to the public T-RECS code¹.

T-RECS incorporates polarized emission across all frequency bands, characterized statistically for each population. However, while it produces robust results compared to 1.4 GHz polarized source counts, recent polarization observations near 150 MHz (Van Eck et al., 2018; Riseley et al., 2020; O’Sullivan et al., 2023; Piras et al., 2024) show that it significantly over-predicts the polarized source counts at m-wavelengths. This is due to the effects of Faraday depolarization at m-wavelengths, which suppresses the polarized emission for Faraday dispersions within the telescope beam of $\gtrsim 0.3 \text{ rad/m}^2$ (Stuardi et al., 2020; Mahatma et al., 2021). Here we modify the updated T-RECS model output at 150 MHz to more accurately represent the polarized source counts at 150 MHz and their known statistical properties, with the aim of using it to extrapolate to SKA-Low sensitivities.

2.1 Observed properties of polarized sources at 150 MHz

The largest catalogue of polarized sources at m-wavelengths to date is provided by the LOFAR Two-Metre Sky Survey (LoTSS) Data Release 2 (DR2) RM Grid (O’Sullivan et al., 2023, OS23), with 2,461 polarized sources (with corresponding RMs) over a sky area of 5,720 deg². They used a polarized source detection threshold of 8 times the local noise in Stokes Q and U , which translates to $\sim 0.5 \text{ mJy/beam}$ (99.5% of sources are detected above this threshold). The polarized sources were extracted from data at an angular resolution of 20'', across a frequency range of 120 to 168 MHz with a spectral resolution of 97.6 kHz. The median degree of polarization of these sources is 1.8%, with $\sim 25\%$ of sources classified as compact/unresolved and $\sim 75\%$ as resolved (with a median Largest-Angular-Size of $\sim 1'$ and a median linear size of $\sim 400 \text{ kpc}$). Host galaxy identifications were obtained for 88% of sources, resulting in a redshift estimate for 79% of the sources (37% photometric, 42% spectroscopic). The median spectral luminosity at 150 MHz is $5 \times 10^{26} \text{ W/Hz}$.

Deeper polarization results at 150 MHz (~ 4 times deeper than OS23) were provided by Piras et al. (2024), across 25 deg² of the ELAIS-N1 field, at a resolution of 6''. They found 31 polarized sources, with similar statistical properties to the LoTSS DR2 RM Grid. They also provide the first robust polarized source counts at 150 MHz, for flux densities $> 0.2 \text{ mJy}$ (which we reproduce in Fig. 1). For comparison purposes, we crudely estimate the polarized source counts for the LoTSS DR2 RM Grid, shown also in Fig. 1. For this we assume a uniform polarized noise distribution

¹https://github.com/nxdtxdyka/f150_ps_simulation

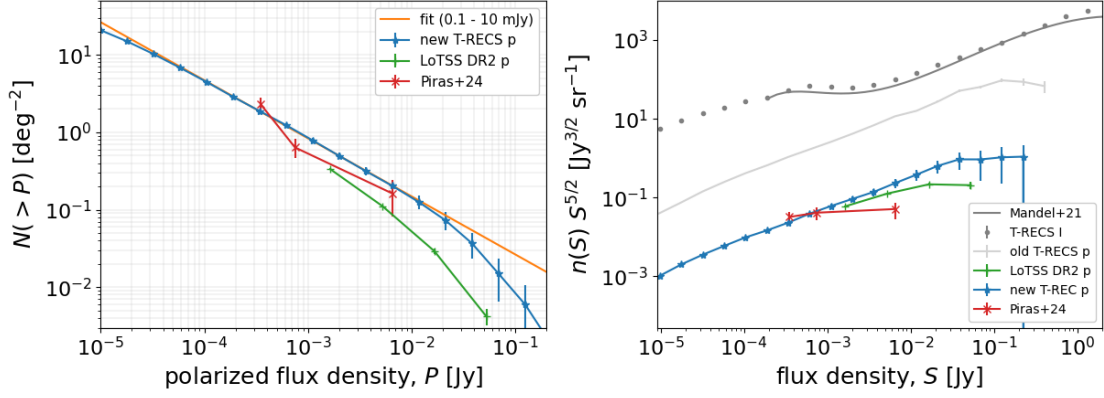


Figure 1: Left: Cumulative polarized-source number counts: updated T-RECS polarization (blue), LOFAR deep field polarized source counts from Piras et al. (2024) (red), LoTSS DR2 RM Grid counts (green), power-law fit to model between 0.1 and 10 mJy (orange). Right: Euclidean-normalised source counts: T-RECS total intensity (grey points), LOFAR total intensity deep field counts from Mandal et al. (2021) (grey line), previous T-RECS polarization (light grey), new polarized source counts (same as left plot).

across the entire DR2 area, which is inaccurate due to the presence of bright sources, field-to-field quality variations (such as poor ionosphere conditions), and the absence of mosaicking in Q and U . However, we find these estimates to be a useful lower bound for consistency checks at higher polarized flux densities and compared to the Piras et al. results. It’s also worth noting the decreased effect of beam depolarization due to the ~ 3 times higher angular resolution of the Piras et al. observations, which could also help explain the differences.

No polarized emission from any SFG has been found at 150 MHz (all identified extragalactic sources thus far are either radio galaxies or blazars). Therefore, in our modelling we only consider the radio AGN population from T-RECS. We consider this the conservative approach, since even with much deeper observations with SKA-Low, it may remain challenging to detect a statistical sample of SFGs at m-wavelengths due to the known significant depolarization effects (Stil et al., 2009).

2.2 Modelling the polarized source counts at 150 MHz

To model the polarized source counts we start from the T-RECS total intensity model for AGN (labelled as HERGs and LERGs in the updated 150 MHz version, with `RADIOCLASS==1` and `2`, respectively). We simulate a 200 deg^2 area to have a sufficiently large sample of bright radio galaxies ($\sim 50,000 > 1 \text{ mJy}$) to compare statistically with the LoTSS DR2 AGN sample ($\sim 500,000 > 1 \text{ mJy}$, in Hardcastle et al. (2025) with $\sim 20\%$ having reliable size estimates). The median luminosities of the bright AGN are comparable (10^{25} W/Hz), but the median angular size in T-RECS is ~ 2.5 times smaller than in LoTSS. Thus, we increased all T-RECS sizes by a factor of 2.5.

To model the polarized sources, we assign a degree of polarization (p) to each Stokes I source randomly from a log-normal distribution with parameters $\mu = 0.49$ and $\sigma = 1.06$. These values were obtained by fitting to the observed p distribution of the LoTSS DR2 RM Grid. We retain the drawn p value if it is in the range 0.05 to 30%, (as in the LoTSS DR2 RM Grid) and redraw

otherwise. We split the sample into resolved (size $> 20''$) and compact (sizes between $10''$ and $20''$, and linear size > 20 kpc, to avoid selecting low-luminosity AGN), and randomly retain only 25% of the compact sample. This is done to match the statistics of the resolved and compact sources found in the LoTSS DR2 RM Grid. To reproduce the observed polarized source counts at the faint end (Fig. 1), we randomly retained 35% of all the sources assigned polarization.

This produced an output median p of 1.9%, for the sources assigned polarization (close to the observed median in the LoTSS DR2 RM Grid of 1.8%). The median luminosity of the polarized sources remains comparable to the observations, while the boosted sizes closely match the size distribution of the observed polarized sources (all sources < 5 Mpc and median of ~ 300 kpc). Furthermore, the model matches the Piras et al. (2024) source counts at the faint end, while over-predicting the LoTSS DR2 counts at the bright end. We retain this over-prediction given that the LoTSS DR2 counts are approximate and likely significantly underestimated (Section 2.1).

For a power-law fit to the polarized source counts model for polarized flux densities (P) between 0.1 and 10 mJy, one obtains a polarized source number density (N) at 150 MHz of

$$N(> P) \sim 5 \left(\frac{P}{100 \mu\text{Jy}} \right)^{-0.75} \text{ deg}^{-2}, \quad (1)$$

providing a useful parameterisation for predictions within this range. It should be kept in mind that this model is mainly constrained at the faint end by the results from a single LoTSS Deep Field covering 25 deg^2 of sky at $6''$. Thus, our predictions are subject to significant uncertainties, such as cosmic variance, in addition to the polarization performance of the LOFAR telescope. Variations up to a factor of 2 in the predicted number of polarized sources at a given detection threshold between 0.1 and 10 mJy should not be unexpected.

3 SKA-Low RM Grid

To assess the potential scientific gains of nominal SKA-Low RM Grid surveys, we can use the 150 MHz polarized source counts model (Section 2) to extrapolate (with significant uncertainty) to SKA-Low-relevant flux-density detection thresholds. We consider two broad categories of survey below: a wide-area survey of $\sim 10,000 \text{ deg}^2$ of extragalactic sky to maximise the total number of RMs with redshifts, and an ultra-deep survey of ~ 25 to 100 deg^2 to explore the discovery potential of future SKA-Low polarization surveys.

Adopting “Zoom Mode 4” from the SKA-Low Sensitivity Calculator User Guide², we consider a frequency resolution of ~ 100 kHz and a bandwidth of ~ 200 MHz (for context, the LoTSS RM Grid used 97.6 kHz channels and 48 MHz of bandwidth). The optimal frequency range is from 100 to 300 MHz to balance detectability of polarized emission with RM precision.³ A central frequency of 200 MHz should lead to a slightly higher number density of polarized sources compared to 150 MHz (due to the reduced impact of wavelength-dependent depolarization); although the sensitivity-weighted central frequency may be closer to 150 MHz, depending on radio-frequency interference

²<https://sensitivity-calculator.skao.int/low>

³Although the RM precision increases with λ^2 coverage, only one polarized radio galaxy has been detected below 100 MHz (O’Sullivan et al., 2018), mostly likely due to depolarization effects.

(RFI) and the final performance of the array. The presence of RFI would also impact the quality of the Rotation Measure Spread Function (RMSF). However, as long as the lower half of the band remains largely unaffected, then the FWHM of the RMSF should be ~ 0.5 rad/m² for this setup.

3.1 An SKA-Low wide-area RM Grid survey

Using the SKA-Low sensitivity calculator for AA4, an integration time of 8 hrs with a Briggs robust imaging weighting of -1 gives an rms sensitivity of ~ 5 μ Jy/beam at an angular resolution of $\sim 5''$ (2 to 3 times above the confusion noise at this resolution). For the same input parameters, but with AA*, the sensitivity calculator gives an rms of ~ 7 μ Jy/beam and a similar resolution. Considering the likely impact of RFI across the observing bandwidth and variable ionospheric conditions, in addition to the final array performance, we adopt an rms sensitivity of 10 μ Jy/beam for a single 8 hr observation as a conservative estimate for a typical extragalactic field. For a Field of View (FoV) of 5 deg, a 10,000 deg² survey could be completed in $\sim 3,200$ hours of observing time.

For a polarized source detection threshold of 80 μ Jy (i.e. $8\sigma_{QU}$), Eqn. 1 predicts ~ 5.9 RMs/deg², implying a total count of $\sim 59,000$ RMs for a 10,000 deg² survey. This would be $\gtrsim 20$ times the number of known RMs at m-wavelengths (OS23), providing a dramatic improvement in the discovery potential for cosmic magnetism science (assuming the majority will have host galaxy identifications and redshift estimates). The RM error at the detection threshold would be ~ 0.03 rad/m². However, the current best ionospheric RM modelling (Mevius, 2018) leaves residual errors of ~ 0.05 rad/m² (OS23). Therefore, the expected level of the residual ionosphere RM errors means the RM precision would not improve for higher S/N sources (as it dominates even at the detection threshold).

Context within RM Grid landscape: For comparison with other RM Grid survey configurations (i.e. area vs. depth vs. frequency band), one can define a figure-of-merit (FoM) related to the statistical precision of a sample of RMs, such as $\text{FoM} = 10^{-3} \sqrt{N_{\text{total}}} / \delta\text{RM}$, which combines the RM number density and survey area (where N_{total} is the total number of RMs), as well as the frequency coverage and survey depth (where δRM is the RM error at the detection threshold). We divide by 10^3 to normalise to numbers of order unity. The higher the FoM the better. The nominal FoM for the wide-area SKA-Low RM Grid ranges from $\text{FoM}_{\text{SKA-Low,wide}} = 5$ to 8, limited on the low end by the assumed residual ionosphere RM error, with the high end corresponding to the true RM precision at the detection threshold.

Table 1: Comparison of the Figure of Merit ($\text{FoM} = 10^{-3} \sqrt{N_{\text{total}}} / \delta\text{RM}$) for various RM Grid surveys, combining RM number density, survey area, and λ^2 -coverage (higher values of FoM are better). The resolution for SKA-Low and Mid telescopes are nominally for 150 MHz and 1 GHz, respectively.

Survey	Resolution [arcsec]	Sky area [deg ²]	δRM [rad m ⁻²]	Freq. [MHz]	RMs/deg ² [deg ⁻²]	FoM
SKA-Low wide-area	5	10,000	0.05	100–300	5.9	5
LoTSS DR2	20	5720	0.05	120–168	0.43	1
SKA-Mid wide-area	0.5	10,000	1.5	950–1760	100	0.7
ASKAP-POSSUM	20	20,000	1.5	800–1100	40	0.6
NVSS	45	34,000	10	~ 1400	1	0.02

Even assuming the limiting scenario of no improvements in the current ionosphere RM correction methods, the $\text{FoM}_{\text{SKA-Low,wide}}$ exceeds all other ongoing and planned RM surveys (Table 1). For example, the LoTSS RM Grid has $\text{FoM}_{\text{LoTSS,DR2}} \sim 1$, while $\text{FoM}_{\text{POSSUM}} \sim 0.6$ for ASKAP-POSSUM and $\text{FoM}_{\text{SKA-Mid,wide}} \sim 0.7$ for SKA-Mid. For POSSUM we use a median $\delta\text{RM}_{\text{med}} = 1.5 \text{ rad/m}^2$ for 800 to 1088 MHz, with 40 RMs/deg² and the full 20,000 deg² area (Vanderwoude et al., 2024; Gaensler et al., 2025), while for SKA-Mid we use $\delta\text{RM}_{\text{med}} = 1.5 \text{ rad/m}^2$ for Band 2 (950 to 1760 MHz), with 100 RMs/deg² and a nominal 10,000 deg² survey area (Heald et al., 2020). This FoM highlights the key scientific discovery advantage of an SKA-Low RM Grid, in particular for statistical studies of the low-density, weakly magnetised Universe.

However, for studies of extragalactic magnetic fields, it is not sufficient to consider only the nominal measurement uncertainty; an accurate subtraction of the Milky Way RM is also essential (e.g. Carretti and Vazza, 2025). At present, the best Galactic rotation measure (GRM) models (Hutschenreuter et al., 2022) propagate an uncertainty of order 1 rad/m² into the extragalactic RMs, even though they are primarily constrained by the NVSS RM catalogue (Taylor et al., 2009; Van Eck et al., 2023), which has a low sky density ($\sim 1 \text{ RM/deg}^2$) and typical individual RM uncertainties of $\sim 10 \text{ rad/m}^2$. Considering that the SKA-Low RM Grid area would overlap with the POSSUM survey, one can expect at least an order of magnitude improvement in the accuracy of the GRM estimation, especially on angular scales of less than 1 degree. This is because POSSUM has an RM number density 40 times that of the NVSS, in addition to almost 10 times smaller RM errors. The inclusion of the high-precision SKA-Low RMs, and SKA-Mid RMs where available, can further enhance the GRM models. A goal of having the residual GRM errors at least comparable to the SKA-Low RM measurement errors, in high Galactic latitude regions, may not be unrealistic. Improvements in algorithms for the statistical separation of the GRM and noise from the extragalactic RM will further improve the scientific inferences in this area (Vacca et al., 2026).

Survey strategy: To maximise the RM Grid capability for extragalactic science, the host galaxies and redshifts are needed. Areas of sky with deep optical photometry and spectroscopy are therefore preferred for wide-area RM Grids. Considering the modest sensitivity difference at 5'' between AA* and AA4, the wide-area survey could begin with AA* and continue with AA4, potentially without repeating sky areas (assuming the data quality is good). The ideal extragalactic sky area would start with the DES area (Abbott et al., 2018, $\sim 5,000 \text{ deg}^2$) and continue to expand outwards into the Euclid planned area (Euclid Collaboration et al., 2022). Overlap with the Simons Observatory Large Area Telescope survey (Abitbol et al., 2025, $\sim 16,000 \text{ deg}^2$) will also provide exciting synergies for characterising the magnetic fields properties of the ionized gas detected through the Sunyaev-Zeldovich effect (e.g. high- z galaxy clusters, dense phases of the Warm-Hot-Ionized Medium (WHIM), etc.). The deep photometry of Euclid and the Rubin Telescope (Ivezić et al., 2019) will further assist in identifying high redshift host galaxies. This has a significant scientific impact, as the strongest constraints on the models for the origin of cosmic magnetism and the strength of primordial magnetic fields come at the highest redshifts (Carretti and Vazza, 2025).

There is an opportunity to produce a high-impact early RM Grid using AA* Global Sky Model data⁴ (e.g. to a nominal depth of $\sim 30 \mu\text{Jy/beam}$). We predict 2.6 RMs/deg² (~ 5 times LoTSS) for an

⁴<https://www.skao.int/en/science-users/642/science-user-qa>

$8\sigma_{QU}$ detection threshold, in regions outside the Galactic plane ($|b| > 10^\circ$). The feasibility of this could be investigated during the Science Verification phase (2027–2029). Such an RM Grid would better inform the strategy for a deeper survey (both technically and scientifically), in relation to the optimal wide-area survey region and integration time that would provide the best scientific return. Given that SKA-Low can in principle observe $\sim 75\%$ of the sky, an “all-sky” survey combined with a deeper wide-area survey could eventually reach 100,000 RMs.

3.2 An SKA-Low ultra-deep RM Grid survey

An SKA-Low AA4 deep survey would be close to confusion limited in Stokes I after ~ 30 hours (based on the calculator). However, given the low sky-density of polarized sources at m-wavelengths, it would not be confusion-limited in polarization (Heald et al., 2020). Integrating on a single field for ~ 1000 hours could in theory reach a noise level of $\sim 1 \mu\text{Jy}/\text{beam}$ in Stokes Q and U . We do not predict the exact number of RMs based on Eqn. 1 because this would extrapolate too far outside the known regime. However, it is clear that for a given survey time, a wide-area survey will provide a greater total number of RMs than an ultra-deep one. For example, even with a sky density of order $10 \text{ RMs}/\text{deg}^2$ and 4000 hours of integration time (on four fields, for 100 deg^2 coverage) the total number of RMs would remain an order of magnitude less than the wide-area survey.

The scientific goals of an ultra-deep RM Grid are likely more related to the discovery potential for the types of polarized sources that would be detected, although targeted observations of individual structures (e.g. a local cosmic web filament or galaxy cluster) could be rewarding (Vacca et al., 2024). It would also be the most reliable means to plan for future RM surveys by advancing our knowledge of the properties of the faintest polarized sources and their RMs (e.g. Piras et al., 2024). It may be challenging to reliably identify the host radio galaxy of the RM due to Stokes I confusion, which would be required to identify the optical host galaxy and redshift. Follow-up SKA-Low VLBI⁵ observations could be necessary, and/or complementary SKA-Mid deep field observations (Loi et al., 2019).

Similar to an SKA-Low wide-area RM Grid, the full benefit of the signal-to-noise would not be accrued if the residual ionospheric RM errors remain at $\sim 0.05 \text{ rad}/\text{m}^2$. Any improvements in the ionospheric RM modelling provided by, for example, TEC monitoring at the SKA-Low station locations would have a significant scientific impact. Minimising ionospheric contributions to the RM error budget improves RM accuracy and reduces depolarization from temporal ionospheric RM variability, thereby increasing both the recovered polarized flux and the number of detected polarized sources in RM grid surveys. We note that a study of close pairs of RMs (Section 4.3) would not be subject to the ionospheric RM error when taking the difference of the RM pairs for the same observation.

4 Updated constraints on the origin of cosmic magnetic fields

4.1 Overview of the cosmological MHD simulations used

To produce updated model predictions for comparison with the observed LOFAR extragalactic RM behaviour as a function of redshift (Sections 4.2, 4.3), we use a recent set of cosmological magneto-

⁵<https://www.atnf.csiro.au/projects/instrumentation/lambda/>

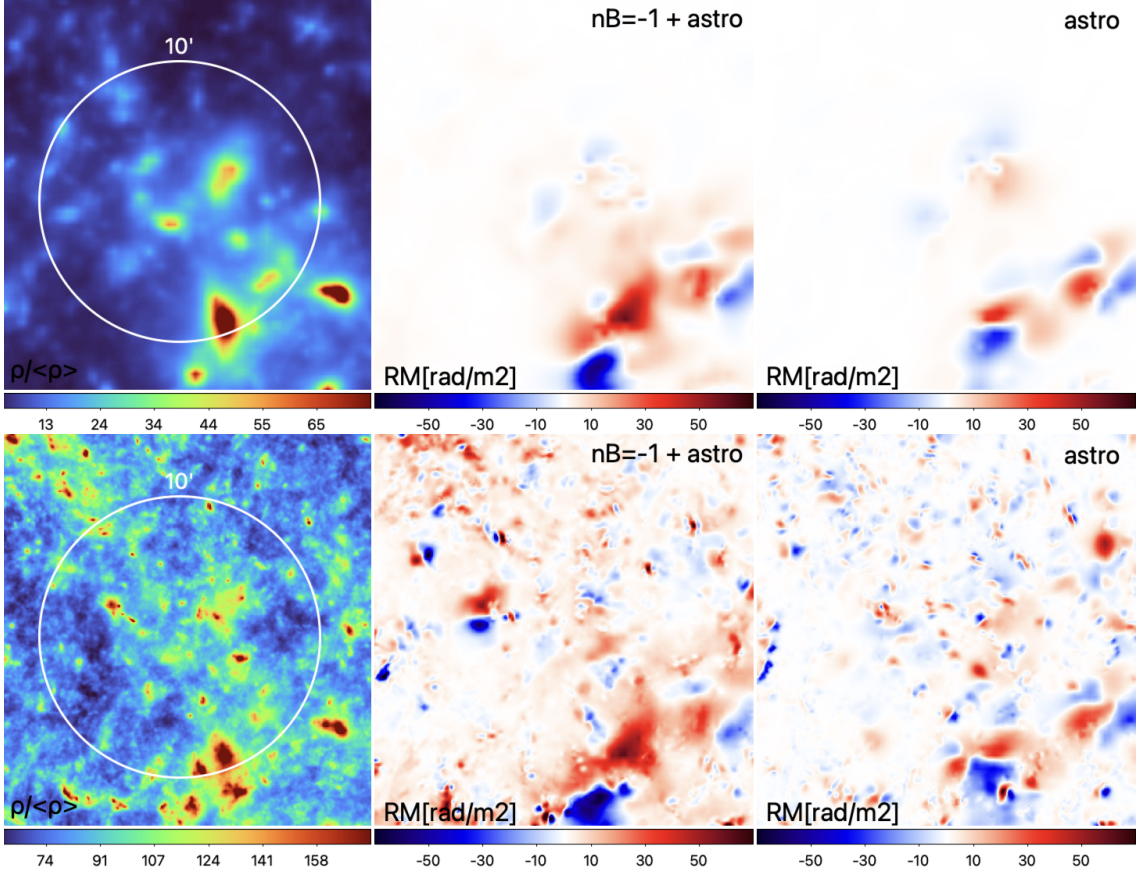


Figure 2: Left panels: projected average dark matter overdensity along the line of sight, for a simulated integration up to $z = 0.1$ (top) or up to $z = 2$ (lower panel). Central and right panels: integrated RM up to $z = 0.1$ or $z = 2$, for our fiducial model comprising a primordial magnetic field model ($n_B = -1$ spectrum with 0.37 nG normalisation, Section 4.1) with an astrophysical seeding by galaxy processes (central panels), and for a comparison model only including astrophysical seeding of magnetic fields (right panels).

hydrodynamical (MHD) simulations, obtained with the cosmological Eulerian code ENZO⁶, and introduced in Vazza et al. (2025). These simulations explore a broad suite of cosmological magnetization scenarios, including variations in both primordial and astrophysical seeding processes. The covered volume is 42^3 Mpc³ comoving, with a uniform spatial resolution of 41.5 kpc/cell. The simulations were calibrated to reproduce several key observables of the galaxy distribution, which can be used to predict the maximal magnetization by feedback processes (from AGN and star formation) in a realistic way. The same simulations have been compared with LOFAR RM observations in Carretti et al. (2025), hereafter C25, showing that no astrophysical magnetization mechanism, alone, can account for the observed RM behaviour at $z \geq 1$.

Here we use a single simulated magnetization scenario that best matches the current observational data (Carretti and Vazza, 2025), which we refer to as the baseline model. This scenario is predominantly primordial, but includes a realistic astrophysical contribution as a result of galaxy

⁶<https://enzo-project.org>

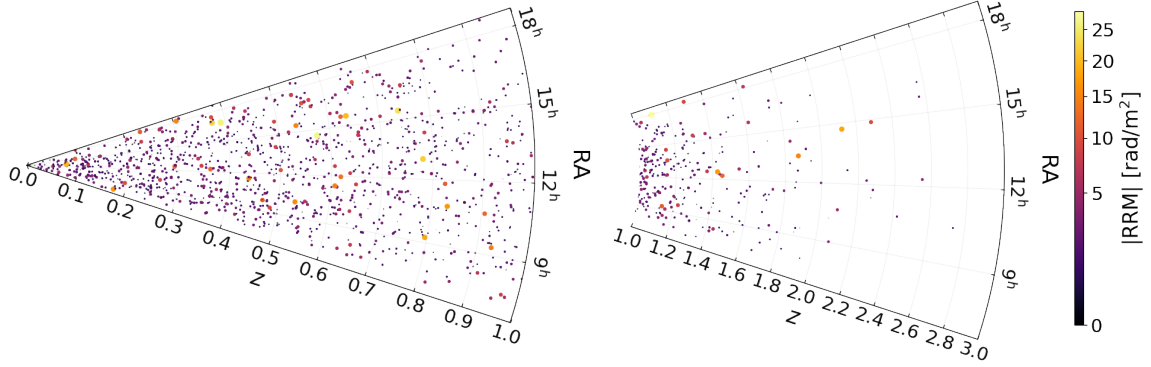


Figure 3: The RRM(z) distribution from the LoTSS DR2 RM Grid, for $0 < z < 1$ (left) and $z > 1$ (right). One can clearly see the sharp fall-off in the number of data points beyond $z = 1$, which are crucial for constraining the origin of cosmic magnetism and the strength of primordial magnetic fields (Section 4).

formation-related processes (Figure 2). The stochastic primordial initialization of magnetic fields is obtained by drawing magnetic field vectors from a power-law spectrum: $P_B(k)dk \propto k^{n_B}dk$, with $n_B = -1$ and with a normalization set to $\sqrt{\langle B^2 \rangle} \approx 0.37$ nG after smoothing the field to a physical scale of 1 Mpc (comoving), as usually done in CMB analysis (e.g. Paoletti and Finelli, 2019). This particular normalization, set mainly by the comparison with the LOFAR RMs, yields a normalization ~ 5 times below existing CMB constraints. While the primordial magnetic field obtained in such a scenario dominates the magnetization in most of the cosmic volume, the addition of the injection of magnetic fields from star formation and AGN feedback, as explained in detail in Vazza et al. (2025), improves the comparison to the observed RM data at low redshift.

4.2 RRM(z) analysis of the magnetised cosmic web

4.2.1 Summary of previous results

As shown in Carretti and Vazza (2025), and references therein, m-wavelength RM Grids are a powerful tool for the study of the origin of cosmic magnetism. They used the LoTSS DR2 RM Grid (OS23) to analyse the behaviour of the residual RM (RRM) as a function of redshift (Fig. 3) in comparison with expectations from cosmological MHD simulations of different magnetogenesis scenarios (Section 4.1). Through this approach, they find a strong preference for the existence of sub-nG primordial seed magnetic fields. Key to this analysis is the separation of the GRM from the extragalactic RM. They used the ‘Faraday Sky’ map of Hutschenreuter et al. (2022) to estimate the GRM (as the average map value within a 1 degree region surrounding each source) in order to subtract it from total RM ($RRM = RM - GRM$).

They focused on a sub-sample of the LoTSS RMs, which had spectroscopic redshifts and $|GRM| < 14$ rad/m². This was done in an attempt to minimise the propagated error from the GRM model into the RRM data. Future dense RM Grids from SKA Precursors, and the expected SKA-Mid RM Grid with up to 100 RMs/deg² (Loi et al., 2026), will be essential to robustly assess and isolate the GRM contribution on scales less than 1 degree. The final sub-sample contained 653 RRM (with a

median redshift of 0.47 and a maximum of 3.22), and displayed a correlation with redshift (linear fit slope of 0.25 ± 0.08), but with non-monotonic behaviour at $z < 1$ (referred to as “wiggles”). No obvious physical origin for these wiggles could be identified, and it remains to be determined if they persist in samples with higher statistical significance or not. These wiggles are not seen in the cosmological simulations but one physical possibility could be a signature of supercluster structures (e.g. Pignataro et al., 2025; Alonso-López et al., 2026), which can only be sampled in cosmological volumes much larger than provided by most MHD simulations.

The total rms RRM of this sub-sample is $1.54 \pm 0.05 \text{ rad/m}^2$, which is substantially lower than the typical extragalactic rms RRM of 6 to 8 rad/m^2 found from cm-wavelength RM Grids (Schnitzeler, 2010; Oppermann et al., 2015; Anderson et al., 2024). This is generally interpreted as a selection effect on the m-wavelength RMs caused by Faraday depolarization, which strongly suppresses any polarised emission with RM variations $> 0.3 \text{ rad/m}^2$ within the telescope angular resolution (Stuardi et al., 2020; Mahatma et al., 2021). While this makes the detection of large samples of polarized sources at m-wavelengths very challenging, the upside is that those that are detected typically probe more underdense lines-of-sight (LoS) through the Universe than at cm-wavelengths, which is ideal for studies of cosmic web filaments. This interpretation is supported by the identification of a sub-sample of LoTSS RMs whose LoS pass within the virial radius of known galaxy clusters and have an rms RRM of $\sim 7 \text{ rad/m}^2$ (consistent with the extragalactic background from cm-wavelength RM Grids). These sources contribute only $\sim 10\%$ to the total rms RRM. Further detailed comparisons with known intervening structures leads Carretti et al. (2025) to estimate contributions up to 20% from clusters, groups and intervening (bright) galaxies to the total rms RRM. Independent RM pairs studies (Section 4.3) indicate that only $\sim 15\%$ of the total rms is produced in the local environment of the radio galaxies (Pomakov et al., 2022). These studies thus imply that the majority of the rms RRM is most likely due to the magnetised WHIM of cosmic web filaments.

4.2.2 Updated results

To quantify the RM contribution of cosmic web filaments, C25 use a model of the filament RM contribution (RRM_f) in addition to the A_{rrm} parameter designed to account for other astrophysical components constant with redshift, either local or by intervening objects. While C25 combined these terms linearly, we employ a slight modification here by combining them in quadrature as

$$\text{RRM}_{\text{rms}} = \langle \text{RRM}^2 \rangle^{1/2} = \sqrt{\left(\frac{A_{rrm}}{(1+z)^2} \right)^2 + \text{RRM}_f^2} \quad (2)$$

with

$$\text{RRM}_f = \int_z^0 \frac{n_e(z') B_{||,f}(z')}{(1+z')^2} dl, \quad (3)$$

where $n_e(z)$ is taken directly from the density distribution of the cosmological simulations and the physical magnetic field strength of each filament is defined as $B_f(z) = B_{0,f}(1+z)^\alpha$. The simulation LoS are restricted to matter overdensities that best match our estimate of the overdensities probed by the LoTSS RM observations (see C25 for details). Therefore, the model only contains three free parameters: the magnetic field strength in filaments at redshift $z = 0$, the power-law index α and the

A_{rrm} term. Repeating the analysis for 100 $n_e(z)$ realisations from the same simulation⁷, we find $B_{0,f} = 40 \pm 8$ nG and $\alpha = 1.0 \pm 0.6$. This implies, for example, a comoving filament field strength of $B_{c,f} \sim 27$ nG at the median redshift $z_{\text{med}} = 0.47$. The best-fit A_{rrm} is 1.24 ± 0.11 rad/m², which indicates $\sim 15\%$ of non-filament contributions to the total RRM rms, again for $z_{\text{med}} = 0.47$.

4.3 $\Delta\text{RRM}(\Delta z)$ analysis of the magnetised cosmic web

One of the most challenging aspects of the $\text{RRM}(z)$ analysis (Section 4.2) is the robust isolation of the GRM from the true extragalactic RM. An alternative approach that minimises the impact of the GRM, is to take the RM difference between close pairs of sources (or source components) on the sky. In regions away from the Galactic plane ($|b| > 20^\circ$), the contribution of the GRM to the difference between RMs on small angular scales ($\theta < 10'$) is expected to be small or sub-dominant compared to the extragalactic RM (e.g. Leahy, 1987; Stil et al., 2011).

4.3.1 Summary of previous results

This approach was used in Vernstrom et al. (2019), using RM observations at 1.4 GHz, to analyse extragalactic magnetic fields by splitting their RM sample into physical pairs (i.e. double-lobed radio galaxies) and non-physical or “random” pairs (i.e. sources at different redshifts but close in projection on the sky). They found a large and significant difference between the RM distributions of the physical pairs (PP) and the non-physical pairs (NPP). In particular, for overlapping angular scales (3 to 11 arcmin), the NPP rms RM was larger by ~ 5 rad/m², which can be most straightforwardly interpreted as the RM contribution from the intergalactic medium (IGM) along the additional path lengths probed by the NPP compared to the PP. Inferring the IGM magnetic field properties from this measurement is challenging without accounting for realistic distributions of cosmic structures along the different lines of sight probed by these observations.

Similar RM pair studies were conducted by O’Sullivan et al. (2020) and Pomakov et al. (2022) but at 150 MHz using the LoTSS DR2 RM Grid. They found a smaller RM difference between the PP and NPP samples of ~ 1.6 rad/m². The difference between the m-wavelength and cm-wavelength results can be attributed to the systematically different lines of sight (LoS) probed by the respective RMs. For example, sources that are embedded in rich environments (with large local variations in magnetic field and gas density) or whose LoS pass through such environments, can experience small-scale RM variations of 10s of rad/m², which will produce significant Faraday depolarization. While this reduces the observed degree of polarization at cm-wavelengths, it can suppress the polarized emission at m-wavelengths enough to make these sources effectively undetectable. Therefore, the m-wavelength RMs are missing the contributions from overdense structures such as groups and clusters of galaxies, making them more precise probes of the unbound gas in cosmic web filaments.

4.3.2 Updated observational results

Based on the same LOFAR data, we show in Figure 4 (left) the median $|\Delta\text{RRM}|$ for the NPP as a function of redshift difference (Δz) with an equal number of sources per bin (57). We show the bootstrap errors on the medians (to compare with the median values from the simulations), as well as the interquartile range (IQR) of the $|\Delta\text{RRM}|$ data per bin (to compare with the intrinsic scatter

⁷The differences in $n_e(z)$ between simulations are minimal, as shown in Carretti et al. (2023).

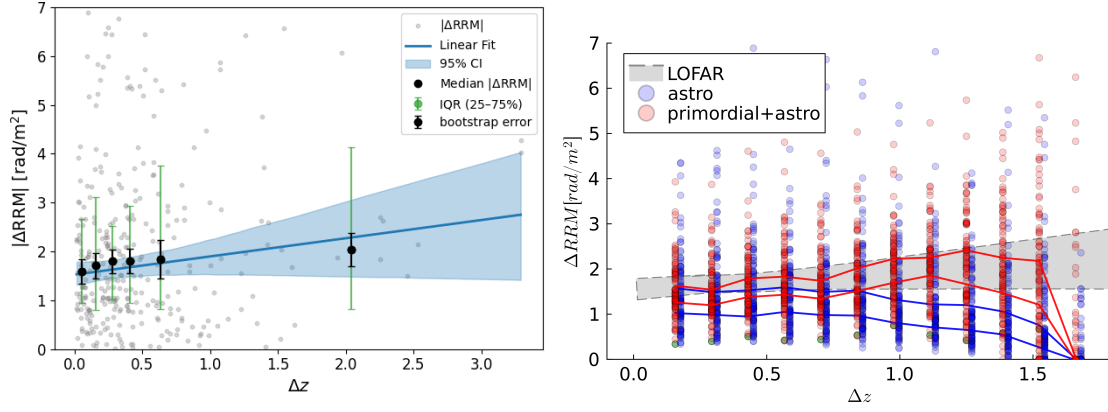


Figure 4: Left: Observational data from the LoTSS DR2 RM Grid of $|\Delta\text{RRM}(\Delta z)|$ of non-physical pairs. A linear fit to the data gives a slope of ~ 0.3 , however the data remain consistent with a flat behaviour. The median $|\Delta\text{RRM}(\Delta z)|$ are shown for six bins with equal numbers of sources per bin (57), with their bootstrap errors and the interquartile range (IQR). Right: Simulated $|\Delta\text{RRM}(\Delta z)|$ for the baseline (primordial+astrophysical) magnetogenesis model (red), and for a model using only astrophysically seeded magnetic fields (blue). The solid lines for each model give the range of the bootstrap errors obtained as in the left image, while the colored points give the distribution of generated random pairs. The grey area show the existing constraints from LOFAR (as in the left plot).

of the simulation data). There is a hint of a correlation in the $|\Delta\text{RRM}(\Delta z)|$ data, with a linear fit yielding a slope of ~ 0.3 . However, the slope is consistent with 0 within the 95% confidence interval.

4.3.3 New simulation of $\Delta\text{RRM}(\Delta z)$ for SKA-like Observations

To investigate constraints that could be provided by the SKA telescope capabilities, we simulated the observable properties of the $\Delta\text{RRM}(\Delta z)$ statistics, using the simulations described in Section 4.1. This was done by generating a series of light cones with the integrated RM along the line of sight (LoS), and by placing two sources at randomly different redshift differences along the LoS, in order to mimic the effect of the Faraday Rotation by intergalactic magnetic fields, similar to previous work (O’Sullivan et al., 2020; Vazza et al., 2021). Each generated light cone has an aperture of $20'$, a angular resolution of $\approx 2''$, and it integrates the simulated comoving volume up to $z = 2$, by opportunely rescaling the comoving simulated volume at increasing redshift based on the angular scale distance for the assumed cosmology, and after applying the redshift-dependent correction factors. We removed from every LoS the contribution from cells in the simulation with a gas matter over-density larger than 50 times the cosmic average gas density, to minimise the RM contamination by cluster halos and approximately match the estimated density range of LoTSS RM observations (Carretti et al., 2023). Finally, at every crossing of the comoving volume, the field of view is randomly shifted in the image plane to avoid the production of artifacts connected to the repetition of the same cosmic structures along the LoS (see e.g. Mtchedlidze et al., 2024).

Figure 2 shows the RM along the line of sight in our simulation, integrating the volume out to $z = 0.1$ (top row) or out to $z = 2$ (bottom row). For comparison, we also show the integrated dark matter density in the same volume, and the RM is calculated for our aforementioned baseline model (including both a primordial and an astrophysical seeding of magnetic fields, Section 4.1) and a

comparison run in which only the astrophysical seeding is included.

4.3.4 Comparison of simulated $\Delta\text{RRM}(\Delta z)$ with observational data

Figure 4 (right) shows the simulated relation of the median $|\Delta\text{RRM}|$ between non-physical pairs as a function of their redshift difference (Δz), for the baseline magnetogenesis model, and for a model only using astrophysical seeding. Both are contrasted with existing constraints from LOFAR (Pomakov et al., 2022) and Figure 4 (left; grey shaded region). The angular separation of the two sources is randomly chosen in the $4'' \leq \theta \leq 10'$ range, and their two redshifts are also independently drawn in the $0.02 \leq z \leq 2$ range. The median of both scenarios is not far from LOFAR observations, consistent with our previous work (O’Sullivan et al., 2020), but the data show a statistical preference for the baseline primordial model, which within the errors is consistent with the LOFAR data.

We also report a significantly larger scatter in the astrophysical scenario, reflecting the smaller filling factor of magnetic fields in the cosmic volume in this latter case, where magnetic “bubbles” fill less than $\sim 20\%$ of the volume (Vazza et al., 2025). We also report a significant drop of the relation at large Δz , which is explained by the fact that the peak of magnetisation from stars and AGN is in the $z \sim 2$ range: so the absolute value of $|\Delta\text{RRM}|$ tends to be smaller for large Δz , as one of the two sources is far from the maximum of magnetisation by purely astrophysical sources in our model (considering that our simulated volume only reaches $z = 2$). This trend, as well as the larger scatter, represent additional tools to further disentangle primordial from astrophysical models with the order-of-magnitude more RM data provided by SKA-Low. Figure 4 shows the significant scatter in both observed and simulated data, and we estimate that ~ 4 to 9 times more sources are needed (if errors scale as \sqrt{N}) to robustly discriminate between the two simulation scenarios.

5 Advances provided by an SKA-Low wide-area RM Grid

The expected RM number density of ~ 5.9 RMs/deg² from an SKA-Low wide-area RM Grid (Section 2.2) provides an exciting opportunity to significantly advance our knowledge beyond the current best m-wavelength RM Grids (~ 0.4 RMs/deg²). In terms of the study of extragalactic magnetic fields, one essential aspect is to identify the host radio sources of the RM as well as obtaining the ancillary host galaxy properties of the radio sources.

As the polarized sources are part of the relatively bright radio galaxy population, the expected excellent image fidelity and good angular resolution of SKA-Low should make the identification (ID) of the host galaxy more reliable. Several automated and semi-automated procedures for obtaining host IDs have been developed (e.g. Hardcastle et al., 2023; Gupta et al., 2024; Gordon et al., 2023) and continue to be developed further. Additionally, given the current and planned deep and wide-area optical imaging and spectroscopic surveys of the southern sky (e.g. DES, DESI, 4MOST: Verdier et al. (2025), Euclid, Rubin Telescope), we can expect to match or better the host galaxy ID and redshift statistics of the LoTSS RM Grid (89% with host IDs, 80% with redshift estimates). This would mean at least 45,000 RMs with redshift estimates; more than 20 times greater than in the LoTSS DR2 RM Grid. The deep optical surveys should also enhance the $z > 1$ statistics, meaning a potentially larger relative gain is expected at high redshifts, where the strongest constraints on magnetogenesis scenarios can be obtained.

These greater statistics open up an array of additional options to analyse the $RM(z)$ data, and will allow us to control for many possible systematic effects (e.g. source type/morphology, sky position, GRM quality, etc.). In turn, this enables more robust inferences of the properties of magnetic fields in cosmic web filaments and thus the nature of primordial magnetic fields, in addition to better constraining the RM properties of intervening objects (e.g. galaxy halos, intercluster and intergroup media). For example, with many more RMs one could conduct a full Bayesian fit for all free parameters in Eqn. 2 to constrain both the astrophysical RM evolution as well as that from cosmic web filaments (Section 4.2). We could determine the $RRM(z)$ trend with much more precision, with lower statistical errors in each bin. This would allow us to confirm the existence of the “wiggles” and to determine their nature, to search for new features, and to test for any curvature (i.e. currently we can only constrain a linear fit). Furthermore, the complementary $\Delta RRM(\Delta z)$ analyses can provide independent tests of the magnetogenesis scenarios (Section 4.3).

Cross-correlation with filament catalogues: Statistical detections of cosmic web filaments have been found using X-ray, the thermal Sunyaev-Zeldovich effect (Tanimura et al., 2020b,a) and radio synchrotron emission (Vernstrom et al., 2021) by cross-correlation with optical galaxies as filament tracers. RM cross-correlations have only been able to provide upper-limits thus far (Amaral et al., 2021), due to the limited quality and quantity of the RM data. Considering the exceptional advances in the identification and study of cosmic web filaments with, for example Euclid, significant detections should be expected by cross-correlating with an SKA-Low RM Grid in the overlapping sky area. Cross-correlations with local Universe structures will also be essential to identify the contributions of, for example, nearby superclusters of galaxies (Pignataro et al., 2025; Alonso-López et al., 2026).

Magnetic field of individual filaments: There are several recent X-ray detections of individual filaments between galaxy clusters (Dietl et al., 2024; Veronica et al., 2024; Migkas et al., 2025), with properties closer to those expected from the WHIM, as opposed to denser regions such as intercluster bridges (Govoni et al., 2019; Botteon et al., 2020; Venturi et al., 2022; Pignataro et al., 2025). Some of these nearby filaments have a large enough angular size (several deg^2) such that their expected RM dispersion of 0.5 to 1 rad/m^2 (Carretti et al., 2022), could be detectable as long as a sufficient number of RMs can cover the filament (e.g. 30 RMs would give a statistical precision of $\sim 0.3 \text{ rad/m}^2$ on the $m\text{-}\lambda$ extragalactic background RM of $\sim 1.5 \text{ rad/m}^2$). However, this would likely require a negligible GRM error contribution, which may prove challenging.

Broader applications: Of course $m\text{-}\lambda$ RM Grids can be, and have been, used for many other science goals, not just determining the origin of cosmic magnetism as we focus on here. For example, high-precision RMs contribute to the study of the Milky Way magnetic field structure (e.g. Hutschenreuter et al., 2022; Unger and Farrar, 2024), while they can also be used to determine the maximum spatial extent of AGN feedback (Blunier and Neronov, 2024), the properties of the magnetised circumgalactic medium in nearby galaxies (Heesen et al., 2023), and the physics of radio AGN and their environments (Mahatma et al., 2021; Stuardi et al., 2020). They also provide a means to discover new pulsars and transients (Sobey et al., 2022), and may provide useful constraints on the possible existence and nature of dynamical dark energy (Naokawa, 2025).

6 Conclusion

An SKA-Low RM Grid can enable a dramatic step-change in our understanding of the magnetised Universe by providing possibly up to 100,000 high-precision RMs over the SKA-Low-observable sky (~ 20 times more than the current best metre-wavelength surveys). Combined with the upcoming deep optical photometric surveys and new spectroscopic data across the southern sky, this RM Grid will enable a wide range of investigations, from pulsars to early-Universe physics. In this chapter we have focused on the robust determination of the magnetic field evolution in cosmic web filaments. We find that an SKA-Low RM Grid will help solve some long-standing open problems in extragalactic astrophysics, such as the extent of magnetic pollution of the cosmic web by galaxies, and the origin of cosmic magnetism.

Acknowledgements

SPO acknowledges support from the Comunidad de Madrid Atracción de Talento program via grant 2022-T1/TIC-23797, and grant PID2023-146372OB-I00 funded by MICIU/AEI/10.13039/501100011033 and by ERDF, EU. FV acknowledges the CINECA award "IscrB_CREW" under the ISCRA initiative, for the availability of high-performance computing resources and support. VV acknowledges support from the Prize for Young Researchers “Gianni Tofani” second edition, promoted by INAF-Osservatorio Astrofisico di Arcetri (DD n. 84/2023).

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