The LOFAR Faraday Rotation Measure Grid

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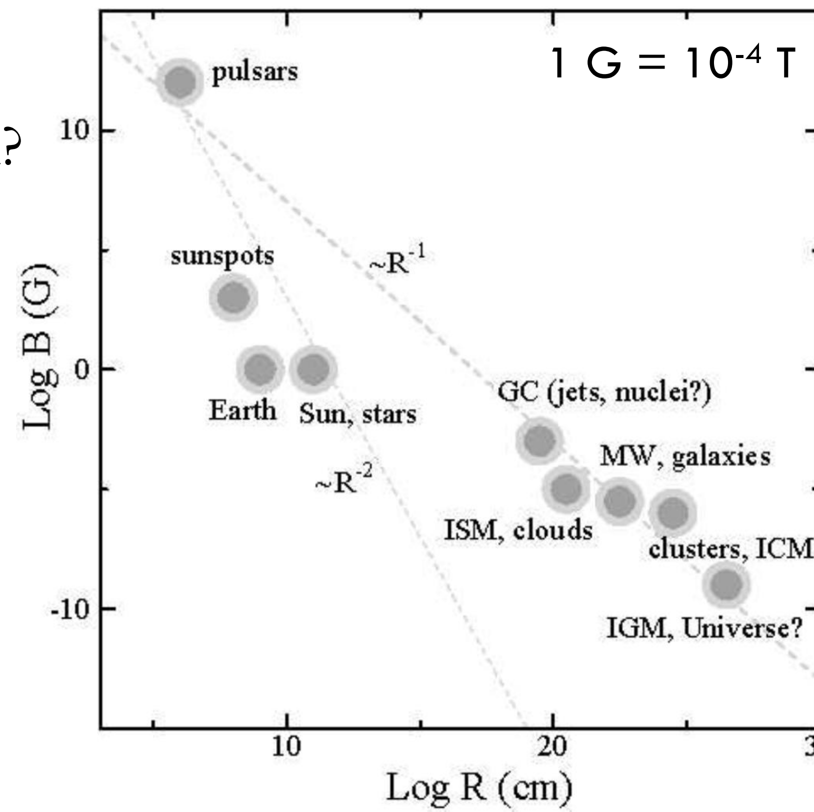
LOFAR Surveys & Magnetism Key Science Projects
https://lofar-surveys.org/, https://lofar-mksp.org/

O'Sullivan+23

Cosmic magnetic fields

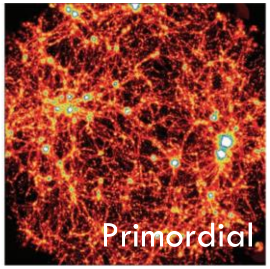
- Planets, stars, galaxies, galaxy clusters
  - Magnetic field properties known
- What is the origin of cosmic magnetism?
  - Key science goal for the SKA
- Did 'seed fields' originate in the very early Universe (i.e. primordial)?
  - Then amplified during structure formation
- Astrophysical mechanisms at later times
  - Pollute intergalactic space through outflows (galactic & AGN)

Akahori+17

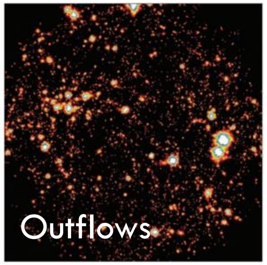


Donnert+09

Magnetic field strength @ z = 0



Magnetic field strength @ z = 0



GUAIX

Magnetism with radio telescopes

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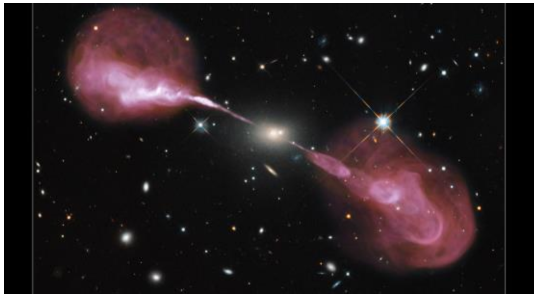
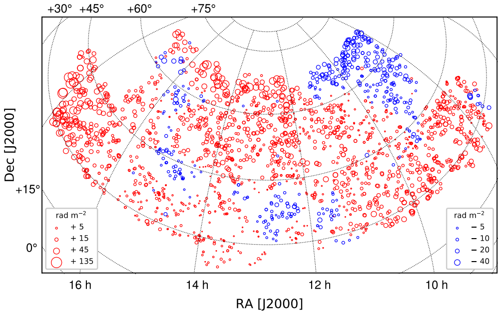
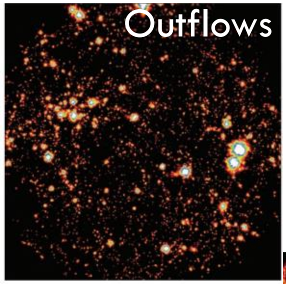
- The construction of a wide-area "RM Grid" is a key science goal for the study of cosmic magnetism with the SKA
  - ie. a catalog of discrete radio sources with Faraday rotation measures (RMs)
  - Synchrotron emission from radio galaxies → Faraday rotation and depolarization due to cosmic magnetic fields



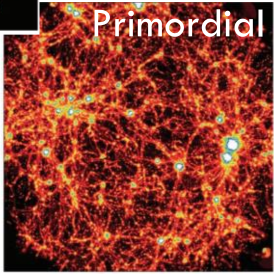


- The importance of RM studies at metre-wavelengths
  - LOFAR Two-Metre Sky Survey: 6" @ 144 MHz
    - $RM_{err} \leq 0.1$ rad/m^2
  - High precision RM values ($\Delta\lambda^2_{LoTSS}/\Delta\lambda^2_{cm} \sim 100$)
  - Unique probe of weakly magnetised, low density environments
  - Radio galaxy & blazar physics, group/cluster environments, intergalactic magnetic fields, Milky Way magnetism, pulsars



Different expected distribution of magnetic fields on the largest scales

e.g. Donnert+09



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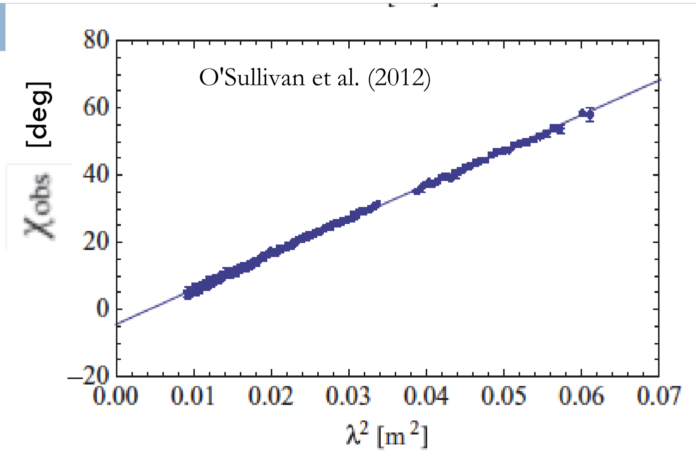
Linear polarization & Faraday rotation

- Linear polarisation vector

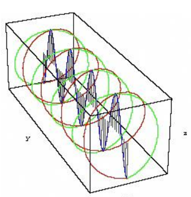
$$\mathbf{P} = Q + iU = pIe^{2i\chi} = p\,I\,e^{2i(\chi_0 + \mathrm{RM}\lambda^2)}$$

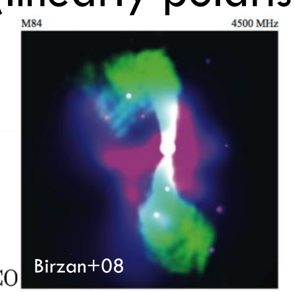


$$\mathrm{RM}_{[\mathrm{rad\ m^{-2}}]} = 0.812 \int_{\mathrm{source}}^{\mathrm{telescope}} n_{e\ [\mathrm{cm^{-3}}]}\, B_{||\ [\mu\mathrm{G}]}\, dl_{\ [\mathrm{pc}]}$$

+RM: $B_{||}$ pointing towards us
– RM: $B_{||}$ pointing away from us

Synchrotron emission from a radio galaxy (linearly polarised)





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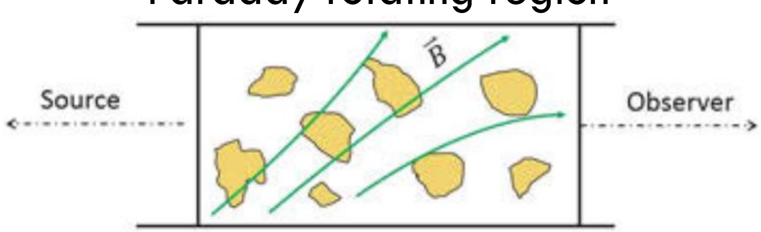
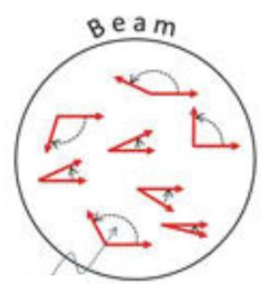
Faraday rotating region



B-field + ionised gas



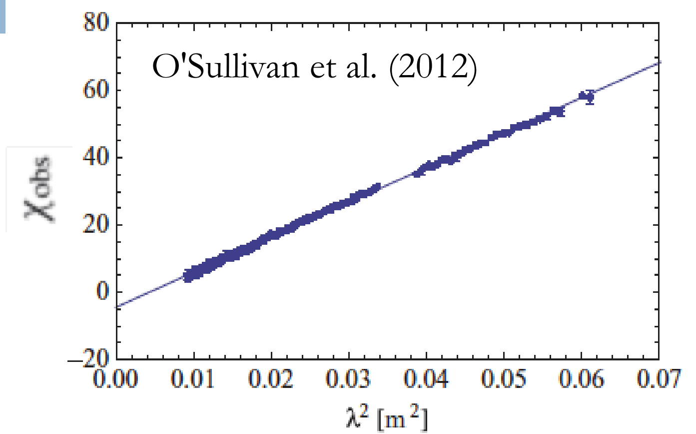
2 RM λ^2

Telescope

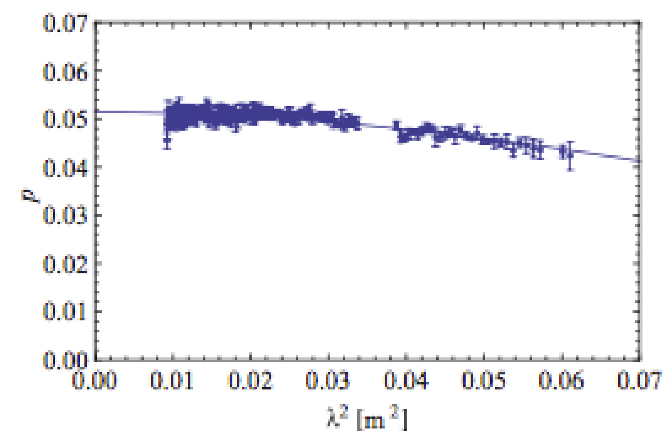
Faraday rotation and depolarisation

- Linear polarisation vector

$$\mathbf{P} = Q + iU = pIe^{2i\chi} = p\,I\,e^{2i(\chi_0 + \mathrm{RM}\lambda^2)}$$



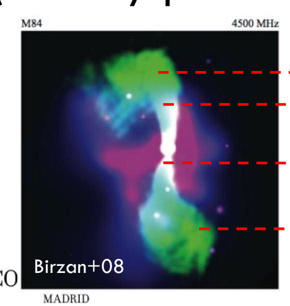
$$\mathbf{P} = p_0 e^{2i(\chi_0 + \mathrm{RM}\,\lambda^2)} e^{-2\sigma^2_{\mathrm{RM}}\lambda^4}$$

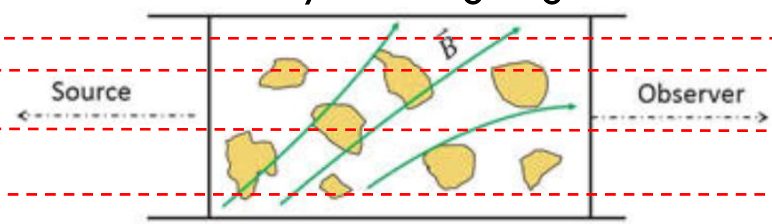


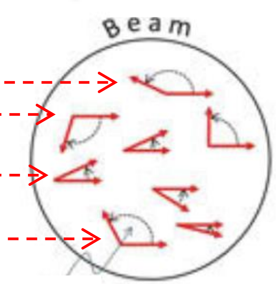
Synchrotron emission (linearly polarised)

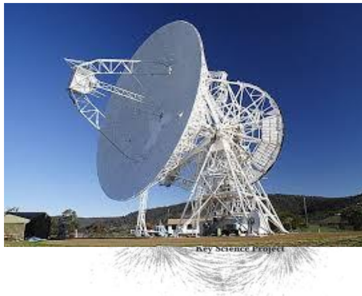
$$\mathrm{RM}_{[\mathrm{rad\ m^{-2}}]} = 0.812 \int_{\mathrm{source}}^{\mathrm{telescope}} n_{e\ [\mathrm{cm^{-3}}]}\, B_{||\ [\mu\mathrm{G}]}\, dl_{\ [\mathrm{pc}]}$$

Faraday rotating region









B-field + ionised gas

2 RM λ^2

Intergalactic magnetic fields

- What is the expected value of the Faraday Rotation Measure (RM)?

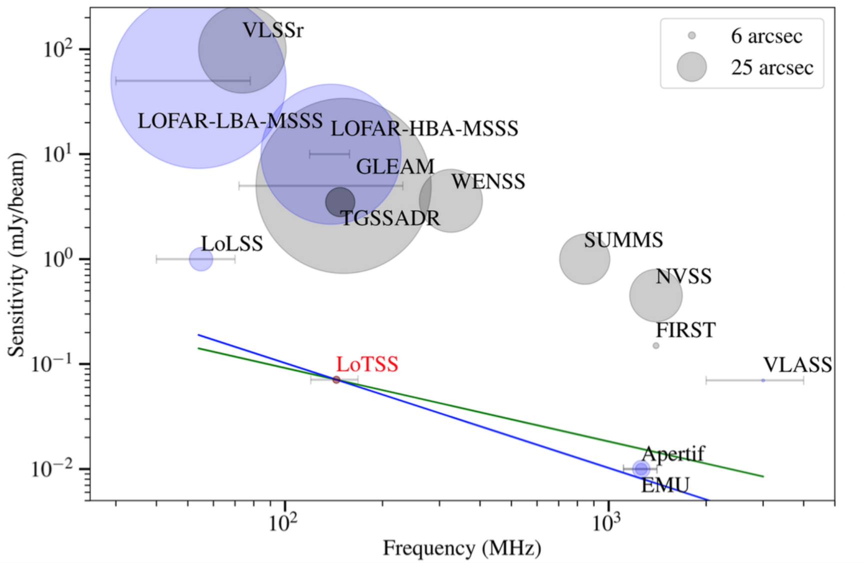
$$\mathrm{RM}_{[\mathrm{rad\ m^{-2}}]} = 0.812 \int_0^L n_{e\ [\mathrm{cm^{-3}}]}\ B_{||\ [\mu\mathrm{G}]}\ dl_{\ [\mathrm{pc}]}$$

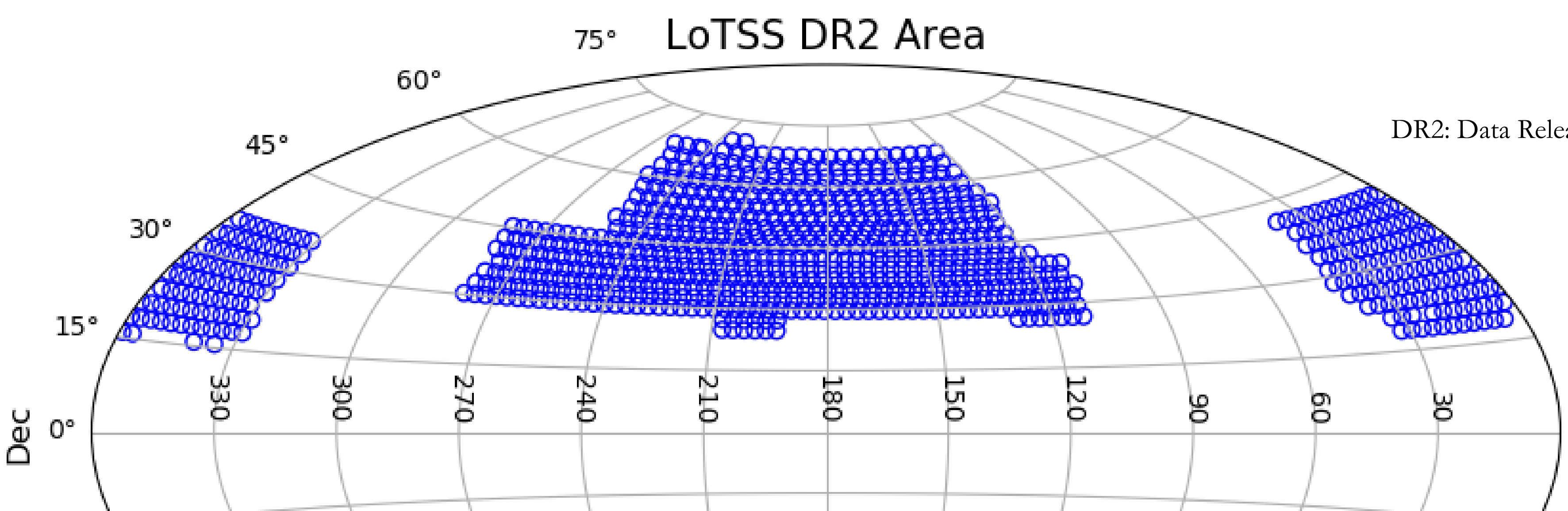
- e.g. Cosmic web filament overdensity of ~50: ~10^{-5} cm^{-3}
  using a path length of 1 Mpc and
  a magnetic field strength of 100 nG = ~1 rad/m^2

- 1 rad/m^2 rotates the linear polarization angle by ~2^o at cm-wavelengths, but **200^o at metre-wavelengths**
  - Easier to measure this effect at long (metre) wavelengths
  - Higher RM precision (~100x): ≤ 0.1 rad/m^2
  - Use the Low Frequency Array (LOFAR)

LOFAR Two-metre Sky Survey (LoTSS)

- 120 – 168 MHz, 20” QU cubes
  - DR2: 0h and 13h fields, 5720 deg^2
  - ~4.4 million sources (Shimwell et al. 2022)
  - ~1.2 x 10^6 with peak flux > 1 mJy/beam
  - 2,461 polarized (> $8\sigma_{QU}$)
    - ~0.2% of detectable sources
  - Excellent RM precision: $O(0.1\ rad/m^2)$





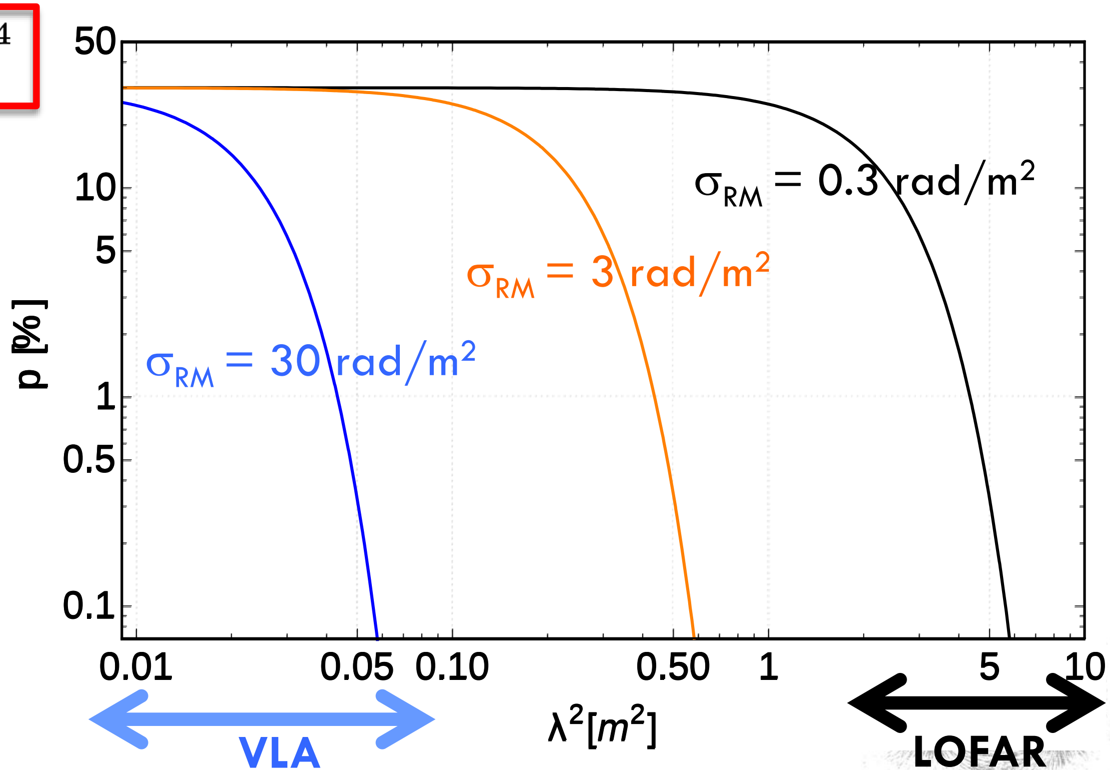
DR2: Data Release 2

LOFAR polarized sources

- Linearly polarised sources rare at low frequencies due to depolarization
  - wavelength-independent depolarization (vector-average over source)
    - Excellent angular resolution of LOFAR helps mitigate this (6”, 0.3”)
- Faraday dispersion (wavelength-dependent depolarization)

$$\mathbf{P} = p_0 e^{2i(\chi_0 + \mathrm{RM}\,\lambda^2)} e^{-2\sigma^2_{\mathrm{RM}}\lambda^4}$$

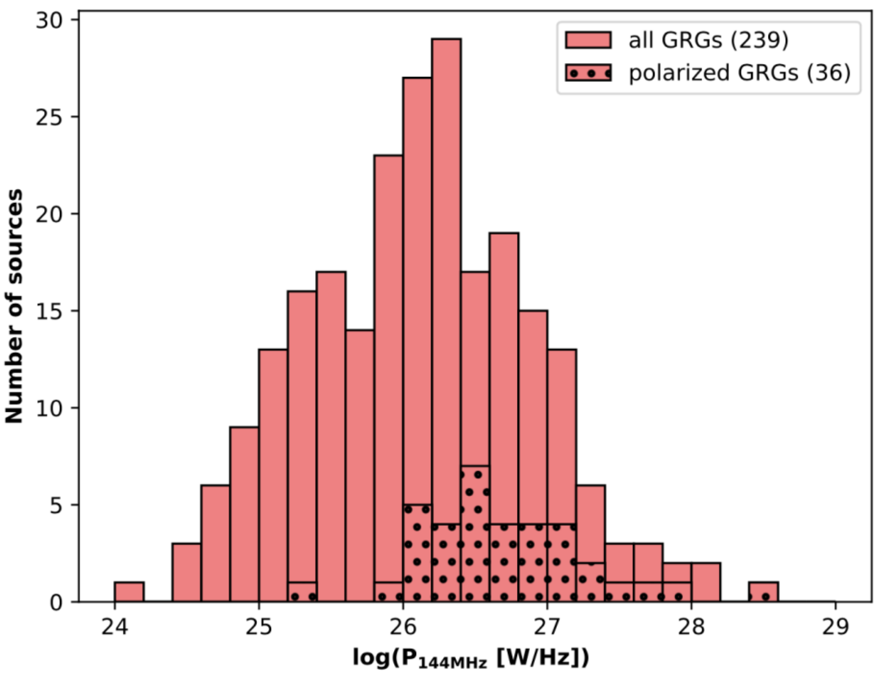
- Require very small variations in RM across the extent of emission region within the synthesized beam
  - Low gas density environments
  - Compact emission region
- High angular resolution helps resolve large fluctuations in Faraday screen

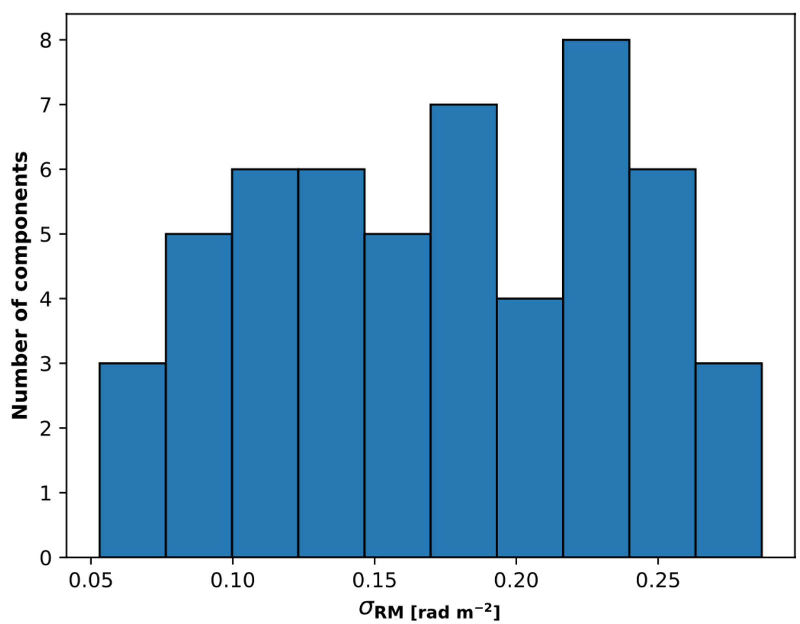


LOFAR depolarization

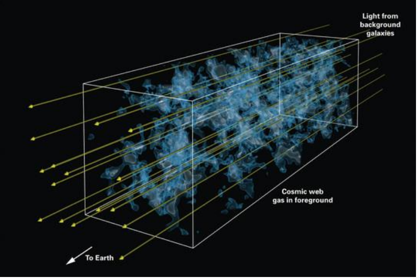
Stuardi, et al. (2020), A&A, 638, 48. arXiv:2004.05169

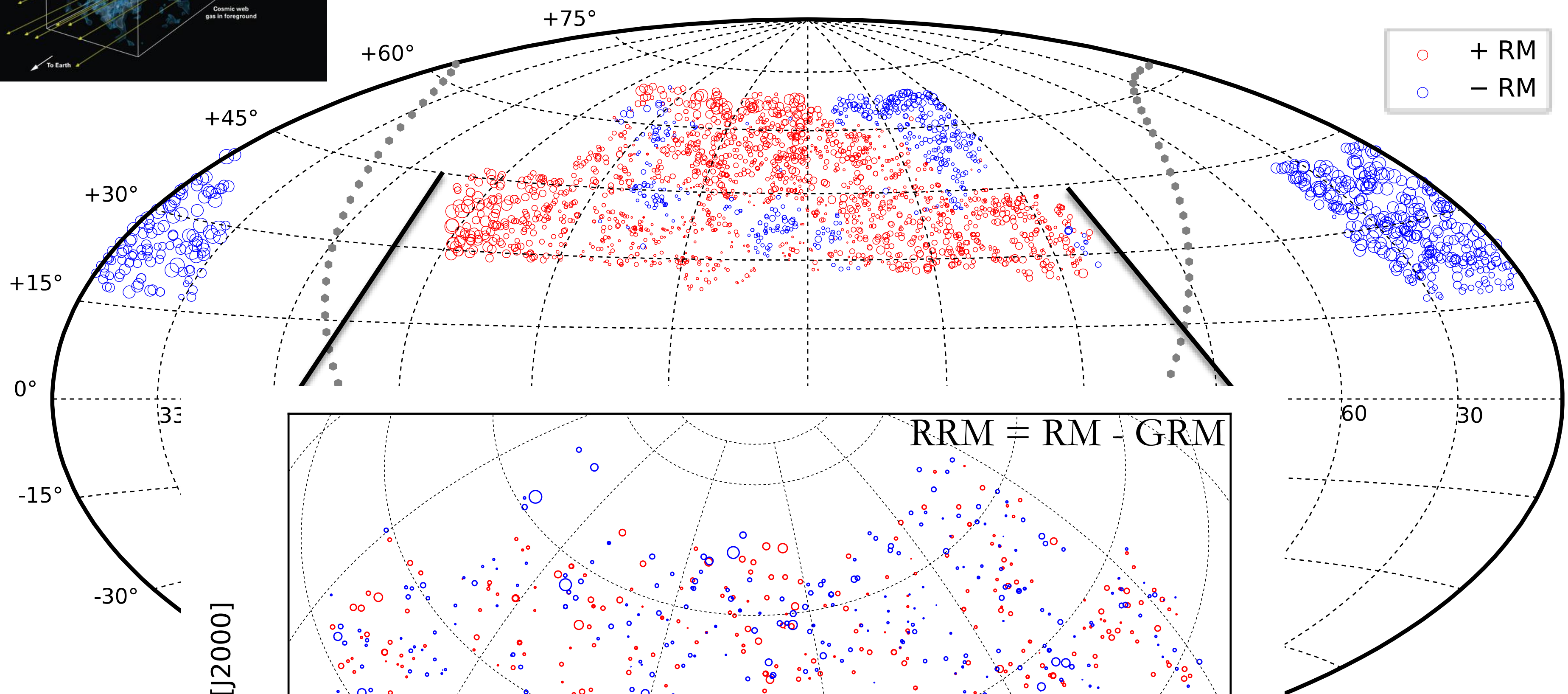
- Sample of 240 GRGs (Dabhade+20): 37 sources polarized
- Comparison of degree of polarization at 1.4 GHz (NVSS) and 144 MHz is consistent with a small amount of Faraday depolarization ($\sigma_{RM} < 0.3$ rad/m^2)
- Consistent with low-density ($<10^{-5}$ cm^{-3}) local environment, with weak magnetic fields (< 0.1 μG) with fluctuations on scales of 3 to 25 kpc

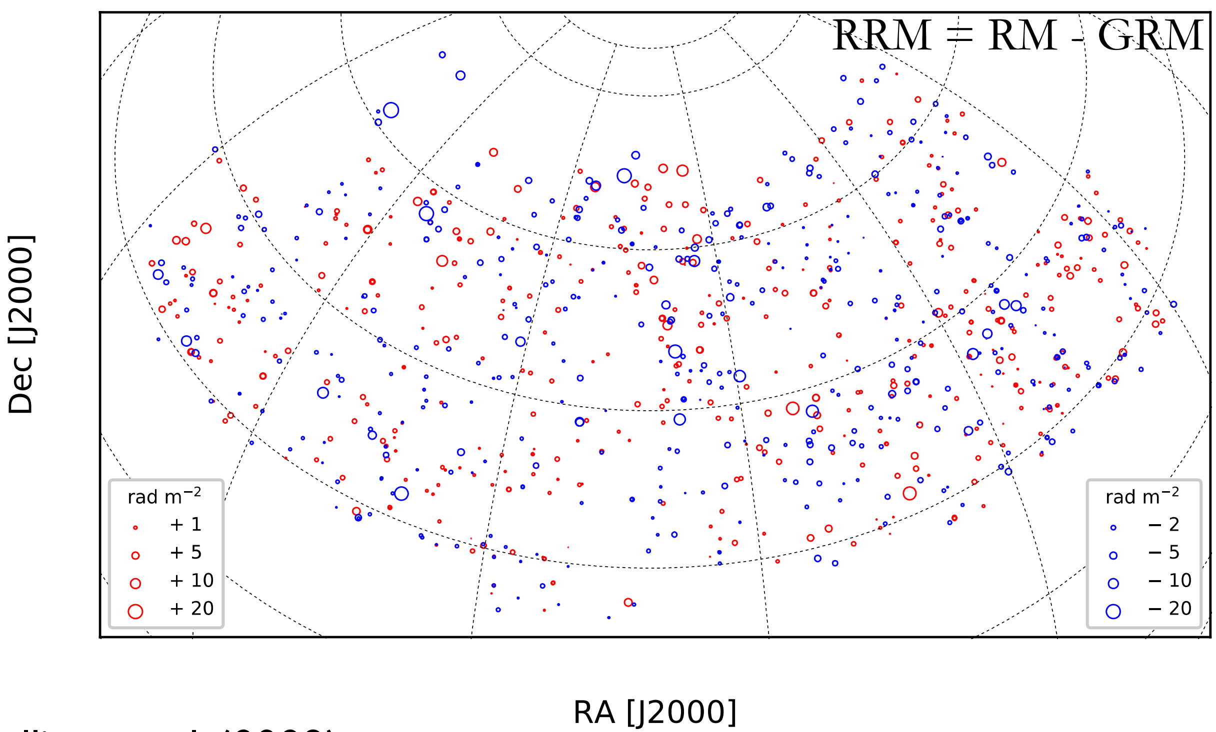


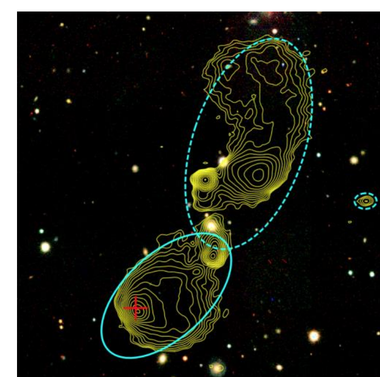


LOFAR Two-Metre Sky Survey (LoTSS) RM Grid









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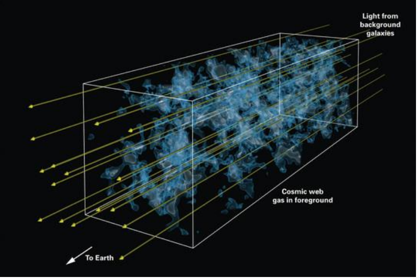
O'Sullivan et al. (2023)



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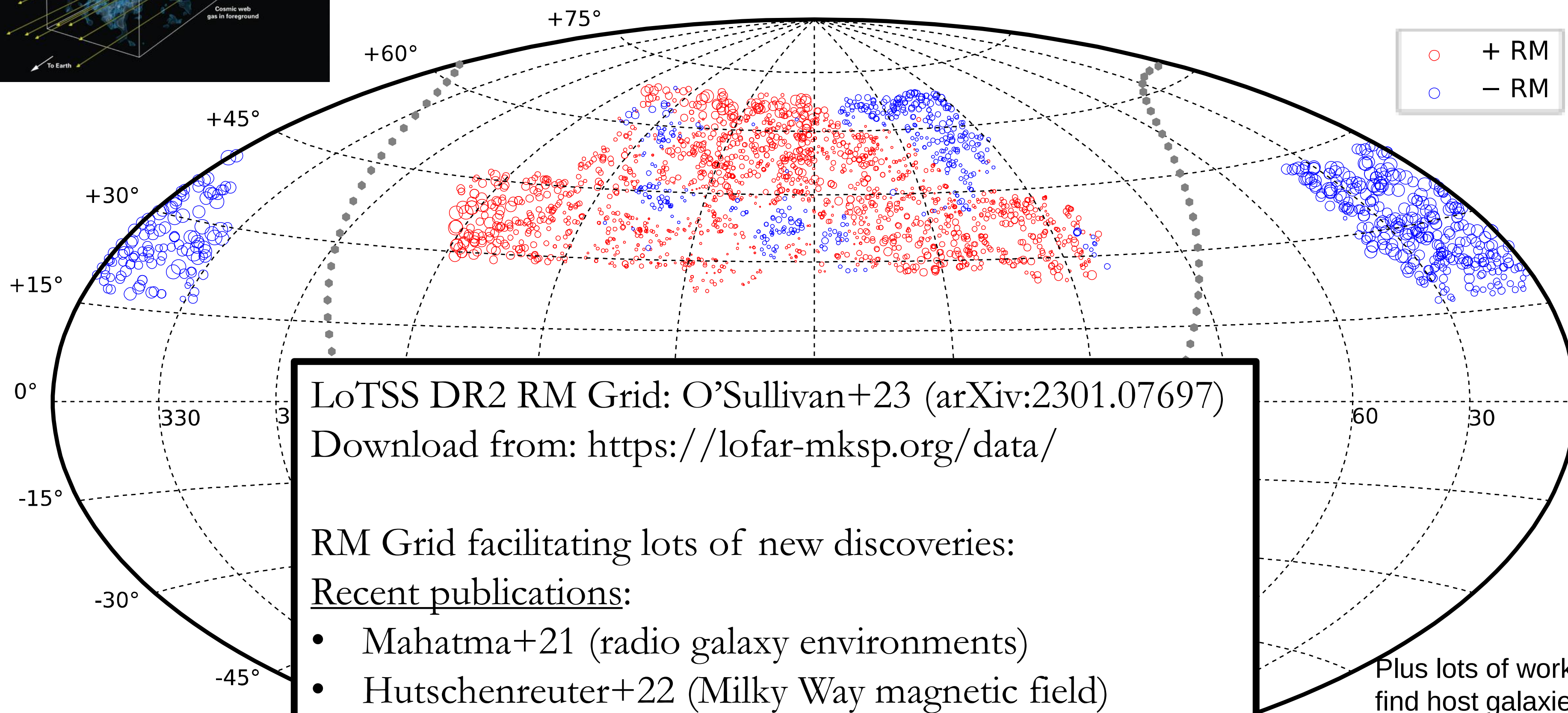


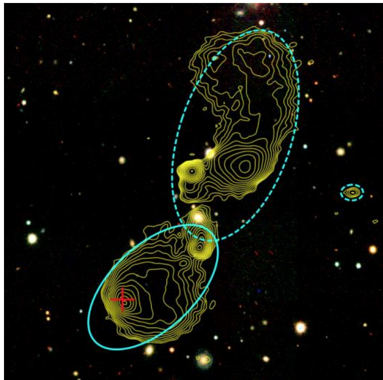
LoTSS DR2 RM Grid: O'Sullivan+23 (arXiv:2301.07697)
Download from: https://lofar-mksp.org/data/

RM Grid facilitating lots of new discoveries:

<u>Recent publications</u>:

- Mahatma+21 (radio galaxy environments)
- Hutschenreuter+22 (Milky Way magnetic field)
- Stuardi+20 (giant radio galaxies)
- Sobey+22 (new pulsars)
- O'Sullivan+19, 20 (cosmic magnetism)
- Carretti+22a,b (magnetisation of cosmic filaments)
- Pomakov+22 (evolution of cosmic magnetism)
- Heesen+23 (magnetised CGM of nearby galaxies)

Plus lots of work to find host galaxies and redshift



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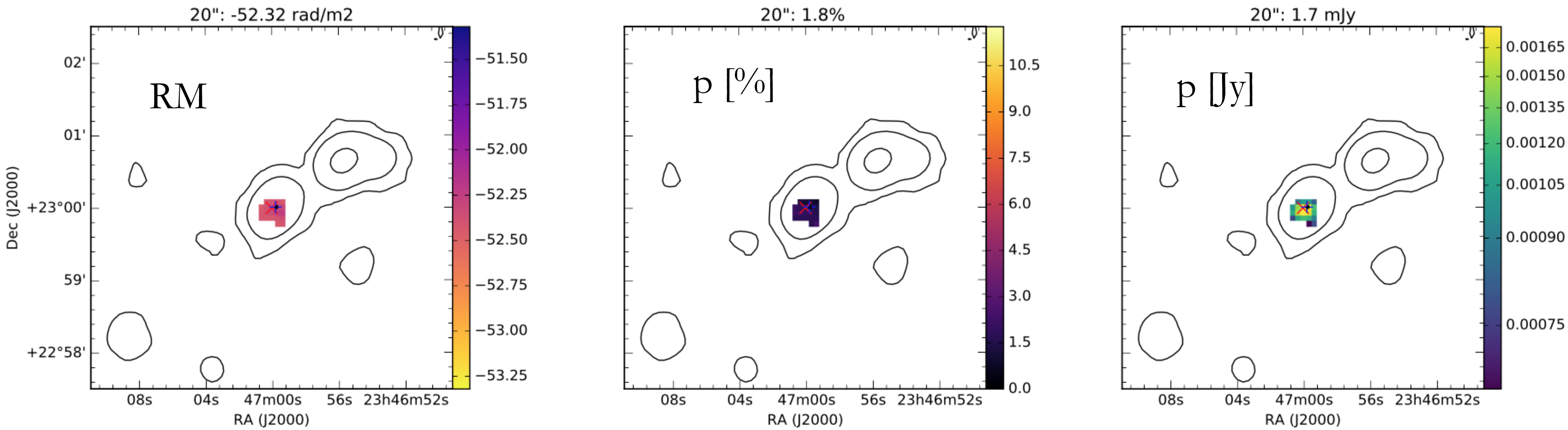
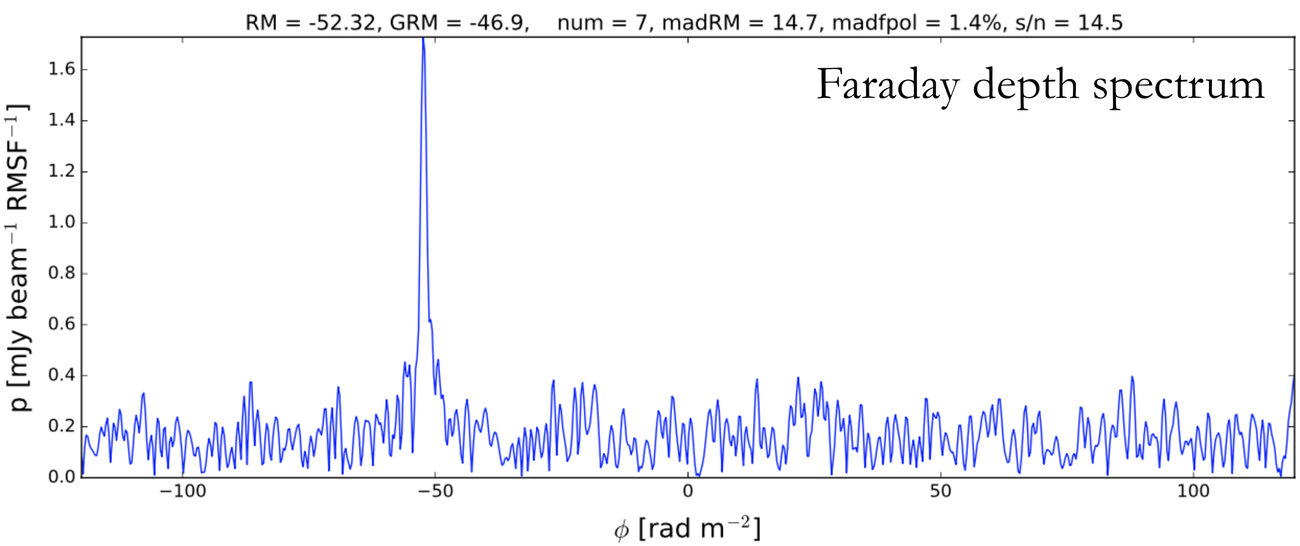
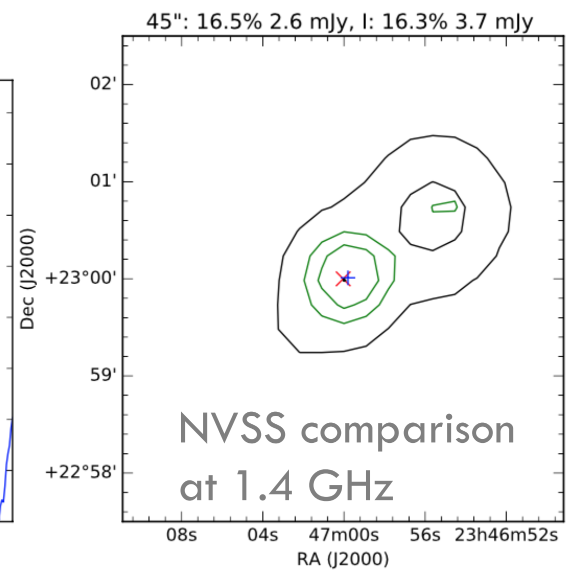
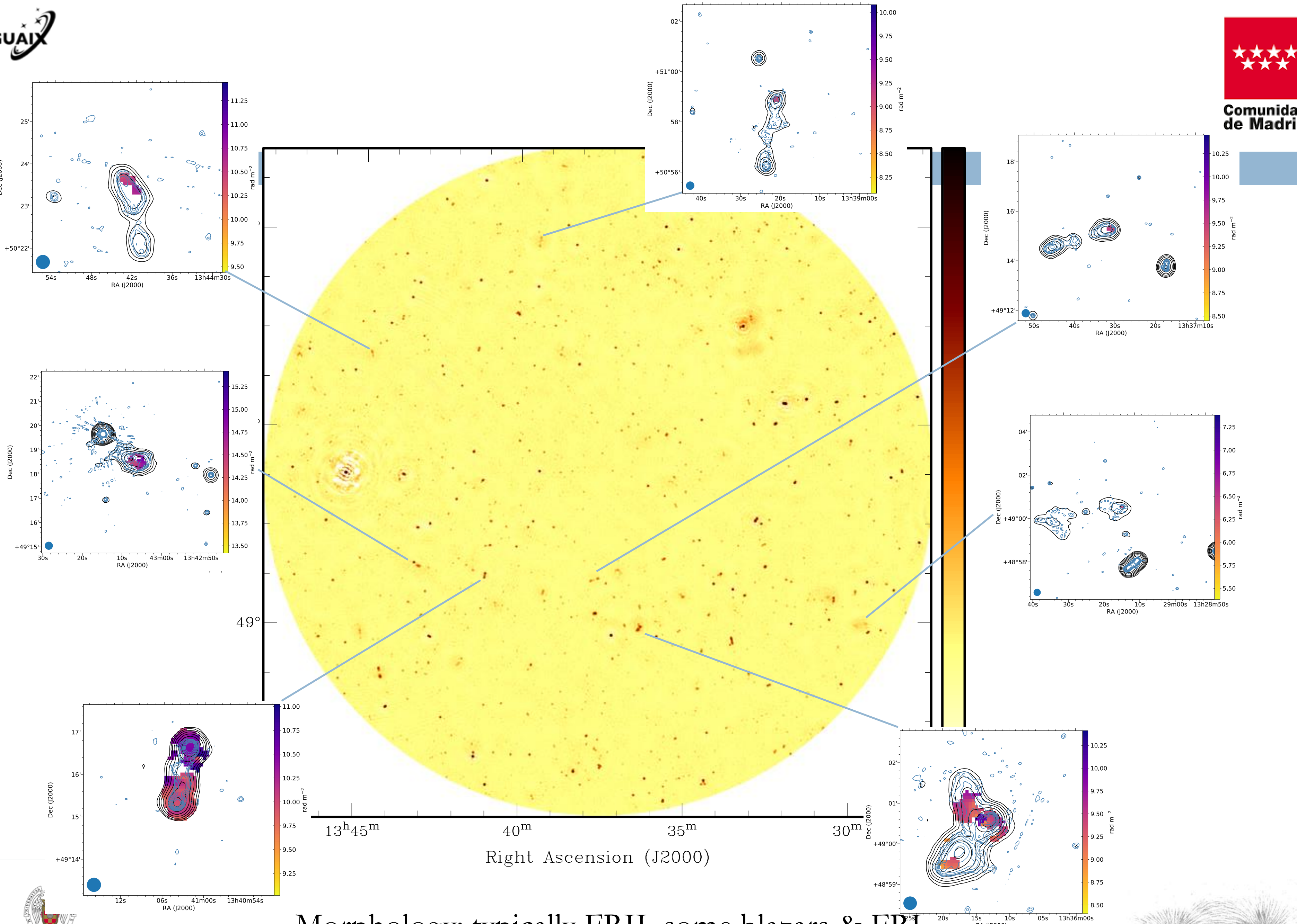
RM Grid example source









Morphology: typically FRII, some blazars & FRI

~75% well resolved, ~25% compact

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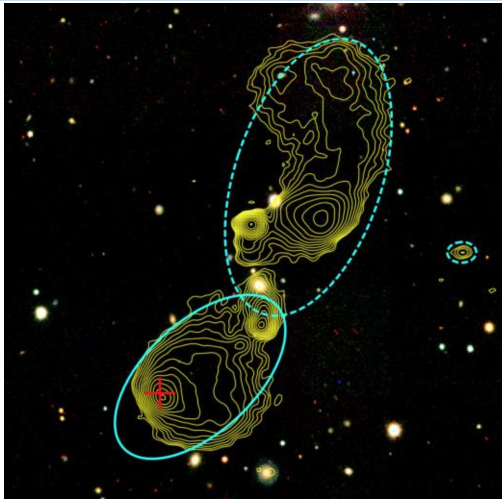
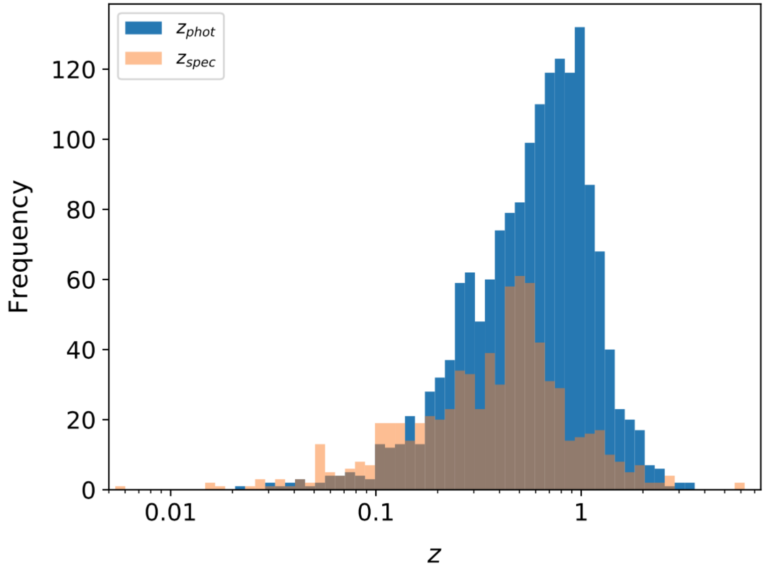
LoTSS DR2 RM Grid results

O'Sullivan, et al. (2023), MNRAS, 519 5723, arXiv:2301.07697



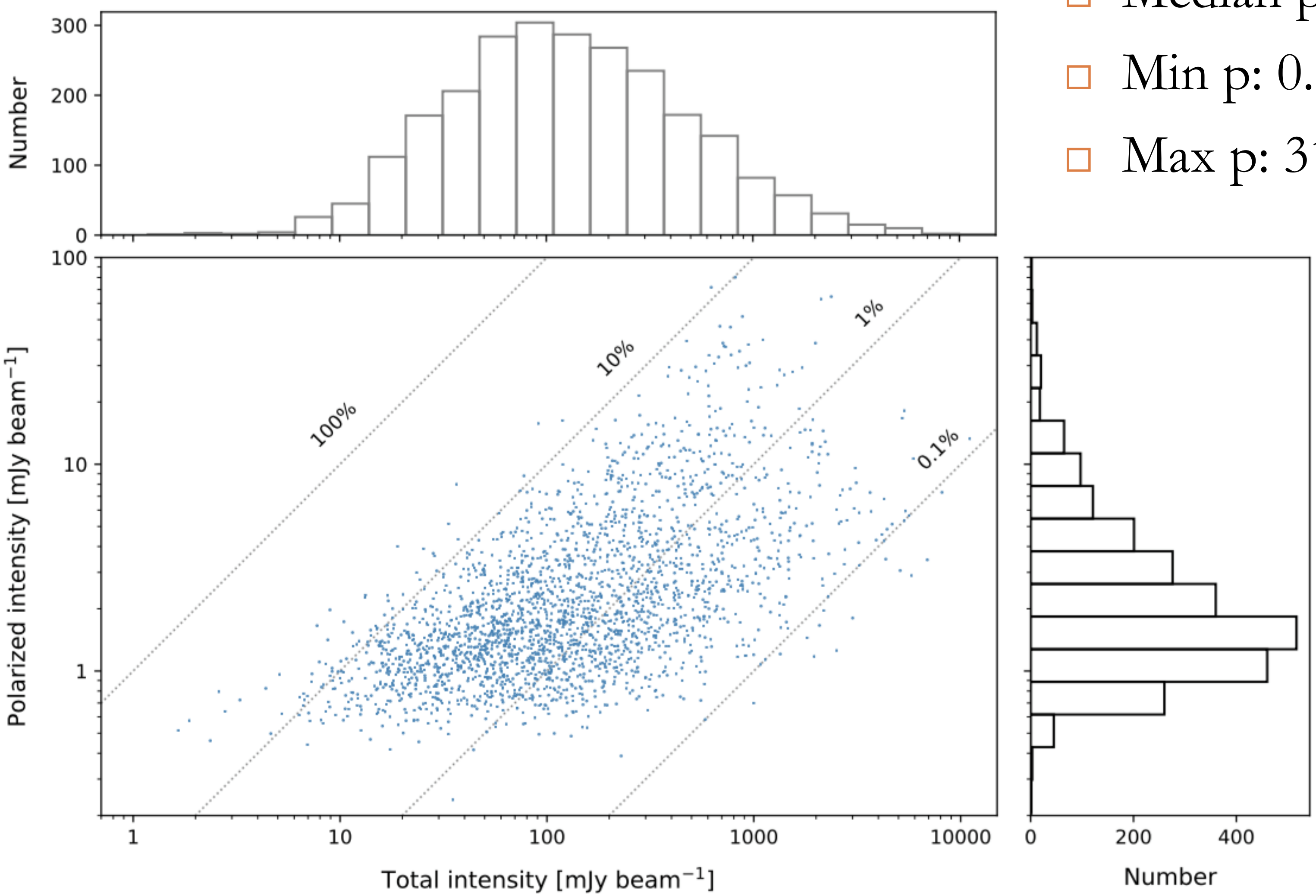
- 2,461 polarized sources in 5720 deg^{-2} sky area
  - 1 pol source per 2.3 deg^{-2}
    - Van Eck+19: 1 per 6.2 deg^{-2} (4.3', 570 sq deg)
    - Mulcahy+14, Neld+18: 1 per 3.3 deg^{-2} (20", single field)
    - Herrera Ruiz+20: 1 per 1.6 deg^{-2} (20", 6 single fields)
- Optical IDs and redshifts
  - Internal LOFAR Galaxy Zoo effort: Host galaxy ID for ~88% of sources!
    - Phot-z for 75% of ID'd sources
    - Spec-z for ~40% from literature
  - Redshift estimate for 75% of the sample: median z of 0.6
  - Median linear size of ~400 kpc
  - Median luminosity of ~5 x 10^{26} W/Hz
  - 172 known blazars (~7%)



- 25 pulsars, with new discoveries (Sobey+22)

LoTSS DR2 RM Grid results

O'Sullivan, et al. (2023), MNRAS, 519 5723, arXiv:2301.07697

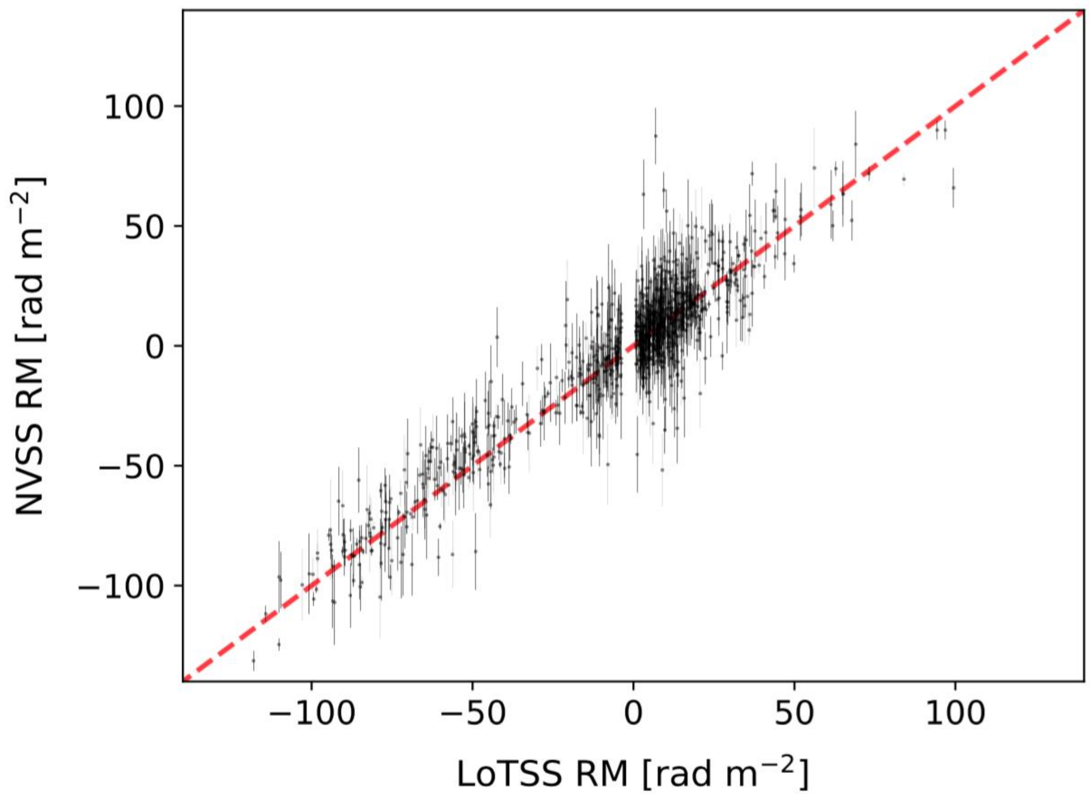


- Median p = 1.8%
- Min p: 0.05%
- Max p: 31%

LoTSS DR2 RM Grid results

O'Sullivan, et al. (2023), MNRAS, 519 5723, arXiv:2301.07697

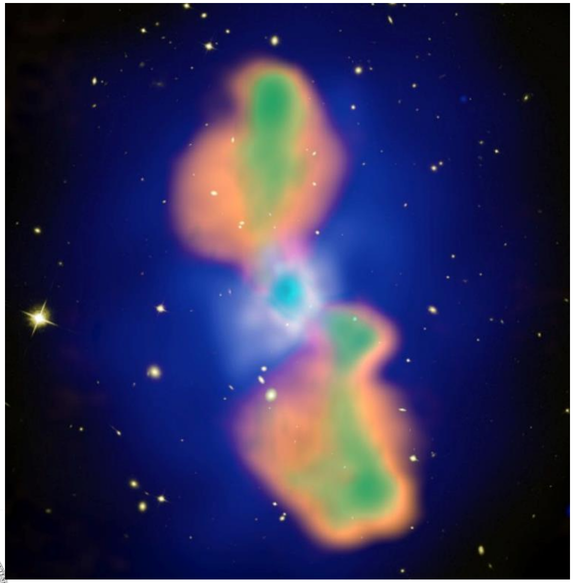
- NVSS RM comparison
  - 37% overlap → 1,551 unique RMs
  - 90% agree within 3σ
  - Absence of Faraday complex sources: ideal RM Grid
- 14 sources in common with Adebahr+22
  - Apertif SVC, 56 deg^2
  - Only 3 discrepant RMs
    - Two from the opposite lobe of the same source, while the other is a BL Lac
- MWA-POGS RMs consistent
  - but 5 extra polarized sources in overlap region not found by LoTSS



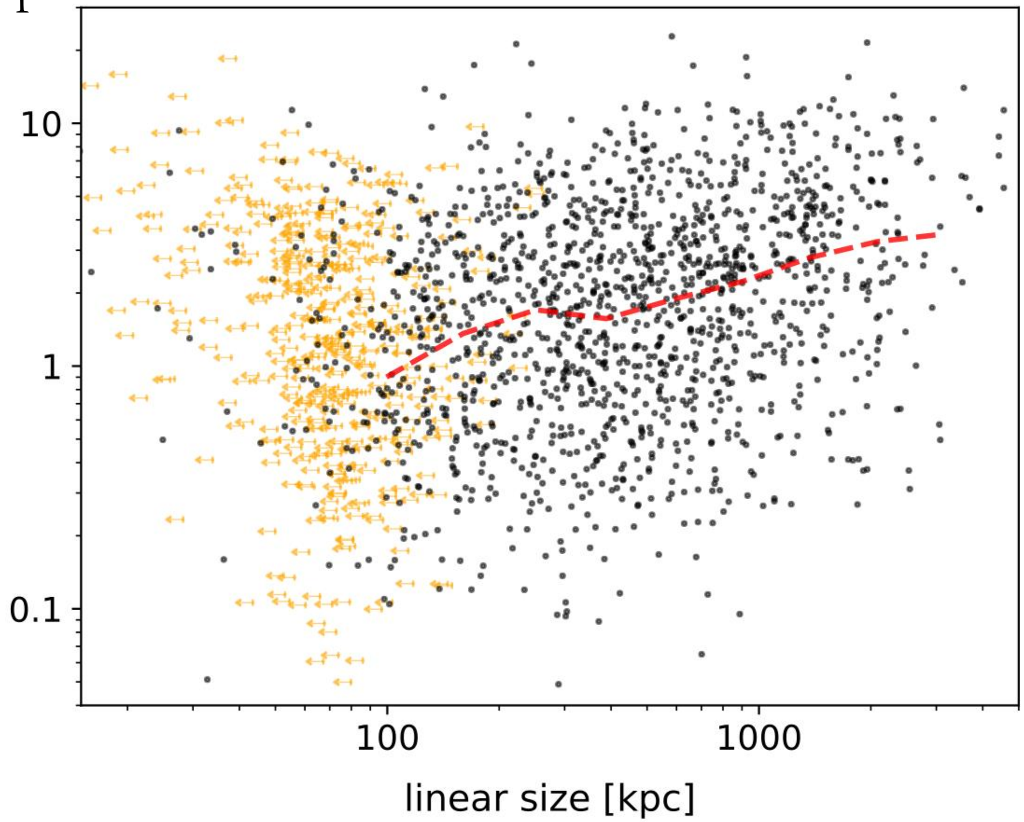
LoTSS DR2 RM Grid results

O'Sullivan, et al. (2023), MNRAS, 519 5723, arXiv:2301.07697

- Higher %p for larger size, indicative of lower depolarization further from host galaxy halo/local environment
- Median p:
  - 0.9% at 100 kpc, 2.4% at 1 Mpc

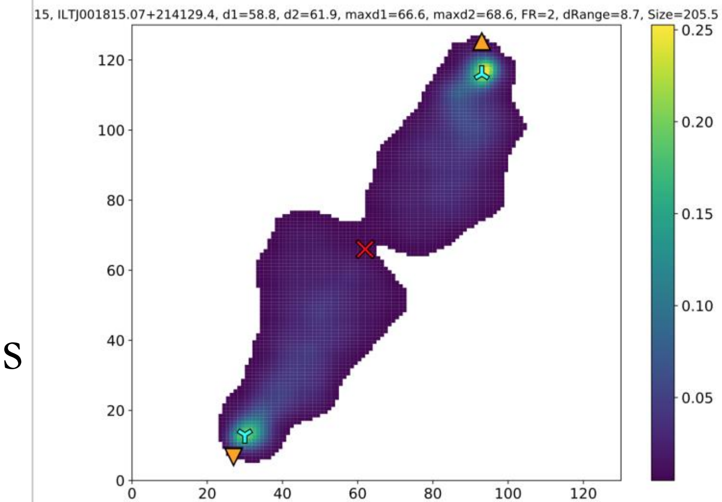


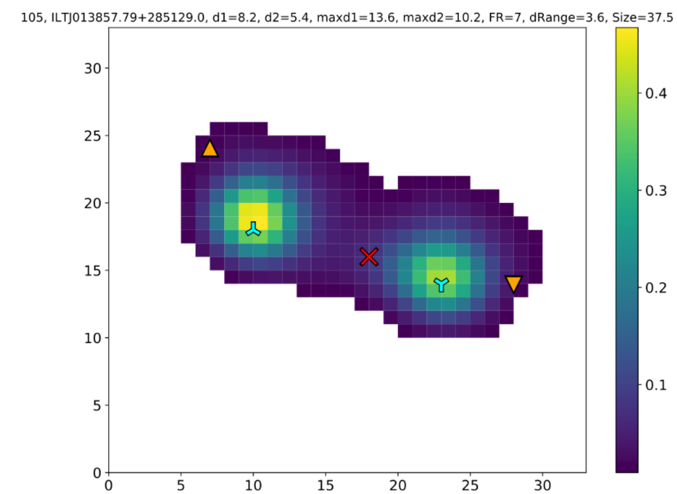
Biava+21: MS0735.6+7421



Morphology of LoTSS RM Grid sources

- LoMorph (Mingo+19)
  - Automated morphological classification
    - https://github.com/bmingo/LoMorph
- Preliminary analysis for RM Grid sources
  - FRII (~40%), FRI (~20%), hybrid (~15%)
    - ~2x more FRII than FRI, in contrast to general population of bright sources where ~2 to 3x more FRI than FRII
  - Small & unresolved sources (~25%)
  - Wealth of additional information
    - Integrated flux, deconvolved linear size, core-hotspot distances & angles, further classifications of "small" into FRI/II/hybrid

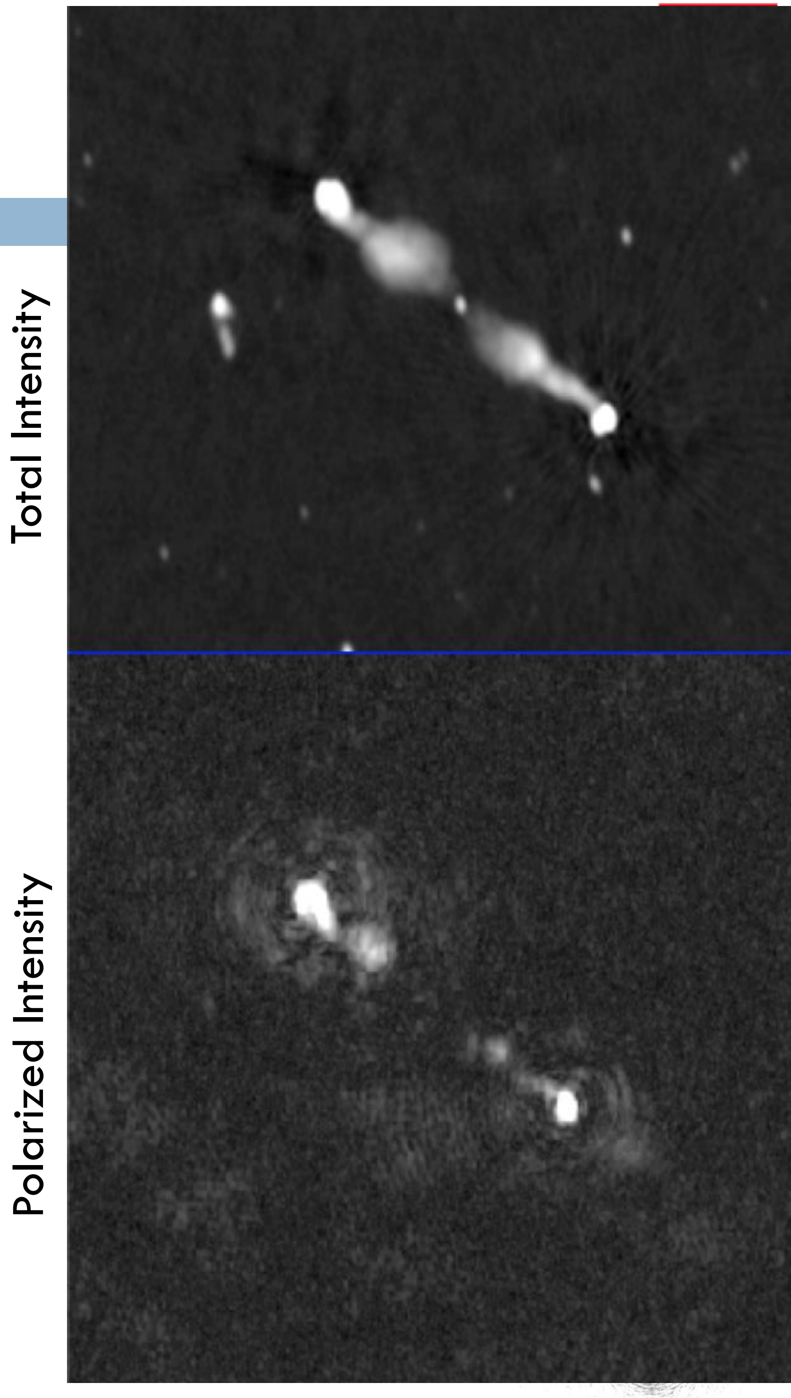




Polarization at 6”

- Several radio galaxies show extended diffuse polarization structure
  - FRII, FRI and double-doubles
  - Special conditions (intrinsic?, environment?)

- Raw QU LoTSS images not deconvolved
- Need LoTSS uv-data to re-image and clean in Stokes Q and U at 6”
  - Polarization also now detected at 0.3” (cf. Reinout’s talk)



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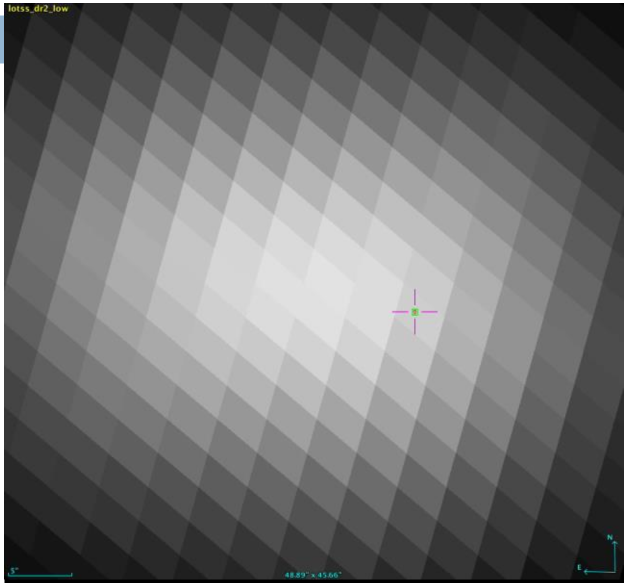
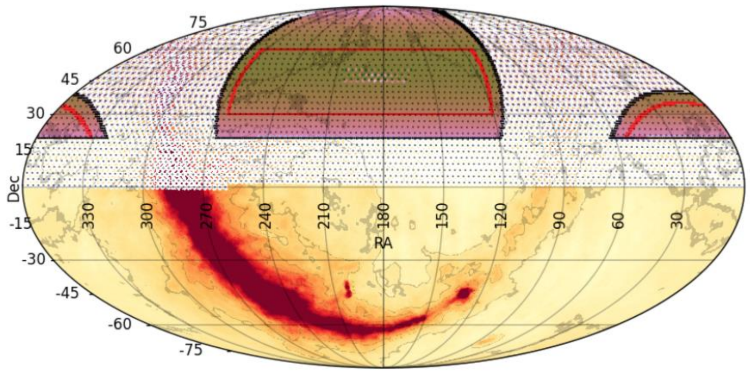
Next frontier: LOFAR2.0

- LOFAR2.0: a series of upgrades to enhance LOFAR capabilities (2025+)
  - eg. co-observing with HBA+LBA, full sensitivity of LBA array, routine 0.3” imaging, etc.
  - ILoTSS: Proposing to cover 7,000 sq deg at 0.3” to 30 uJy/beam at 150 MHz
  - Matched resolution imaging with EUCLID (optical to NIR, launch 2023)
  - Much greater fraction of polarized sources? Overcoming Faraday and beam depolarization



20” to 6” to 0.3” to optical

Cross: linear polarization detection



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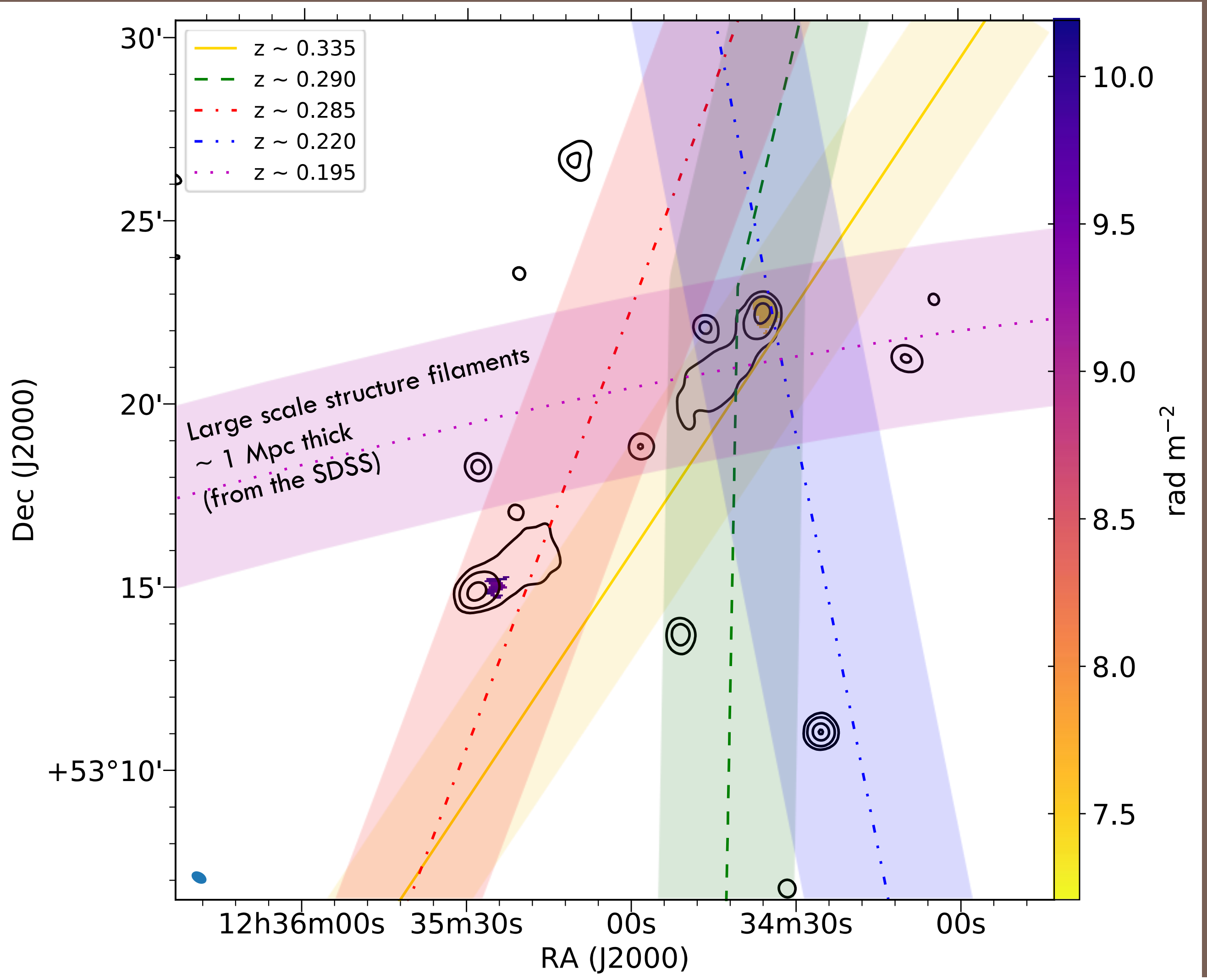
The magnetised cosmic web with LOFAR



O'Sullivan et al. (2019)

LoTSS DR2: *B* in cosmic filaments

Carretti, Vacca, O'Sullivan, et al. (2022), MNRAS, 512, 945. arXiv:2202.04607 (Paper I)

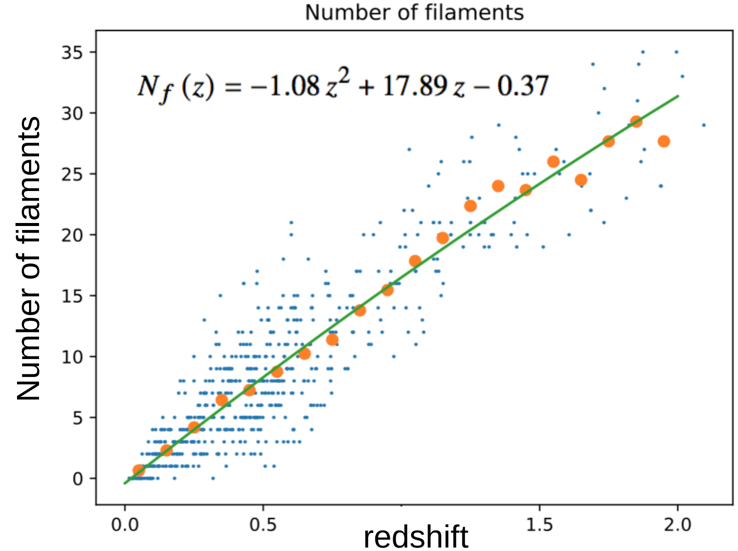
- (R)RM vs z analysis for 1003 RMs at z < 2
- Comparison with the number of cosmic filaments identified from optical galaxy surveys along each line of sight
  - Chen+15, Carrón-Duque+21
- $\mathrm{RRM}_{0,\mathrm{rms}}$ expected to increase with redshift as $N_f^{1/2}$ (Akahori & Ryu 2011)

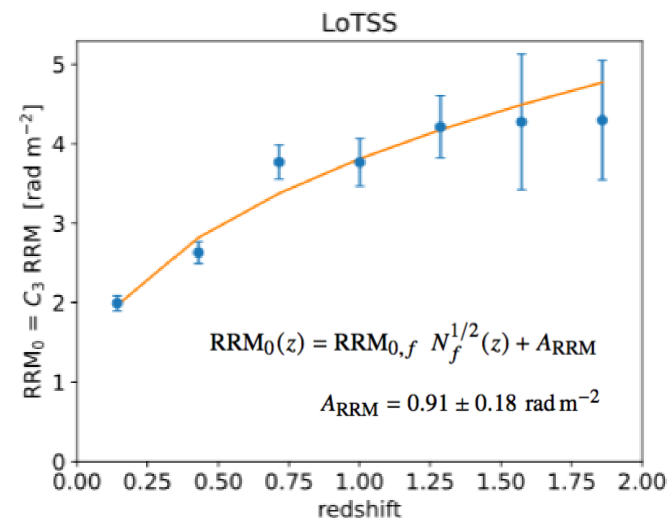
$$\mathrm{RRM}_0(z) = \mathrm{RRM}_{0,f}\ N_f^{1/2}(z) + A_{\mathrm{RRM}}$$

- Best-fit result gives: $\mathrm{RRM}_{0,f} = 0.71 \pm 0.07\ \mathrm{rad\,m^{-2}}$
  - Characteristic |RM| of an individual filament
- Assuming typical $n_{e,f} \sim 10^{-5}\ \mathrm{cm^{-3}}$ and mean path length through a filament $L_f \sim 3$ Mpc (Cautun+14)

  => average $\boldsymbol{B_f \sim 30}$ **nG**

  Or ~10 to 50 nG at z = 0 depending on density model





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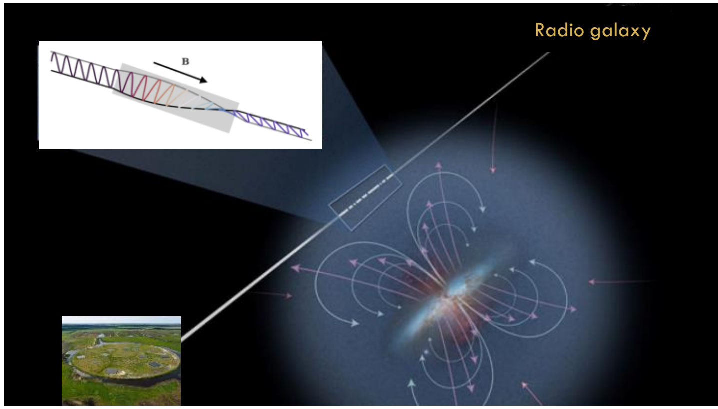
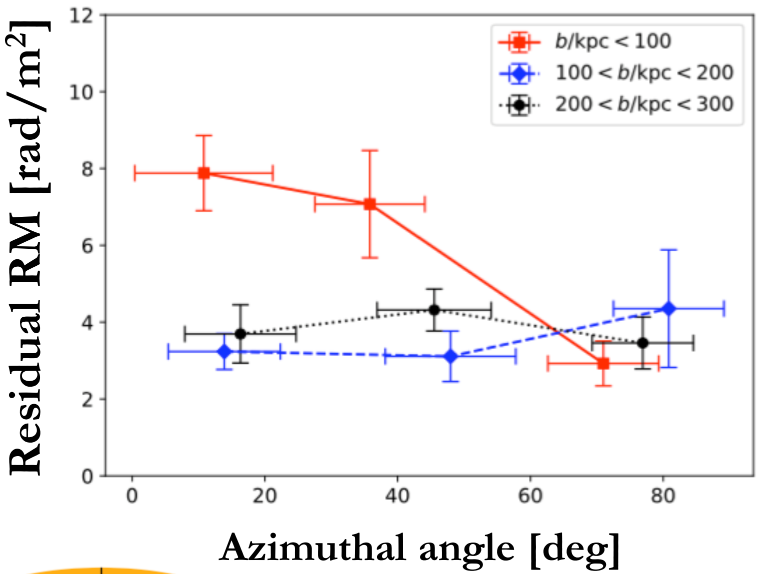
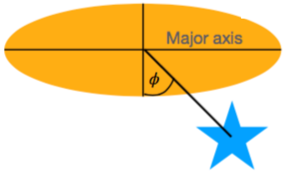
LoTSS DR2: Magnetised CGM of nearby galaxies

Heesen, O'Sullivan, Brüggen, et al. (2023), A&A, 670, 23. arXiv:2302.06617

- Residual RM vs impact parameter for 183 nearby galaxies (D_{median} ~ 18 Mpc)
- Excess RM signal at < 100 kpc, only for galaxies with high inclination angle, and sightlines close to minor axis
  - RM excess of ~3.7 ± 0.9 rad/m^2 (~4σ)
  - Leads to ~0.5 μG for n_e ~ 10^{-4} cm^{-3} at ~50 kpc, β ~ 1 (for hot CGM)
  - Dependence on the azimuthal angle also seen in MgII absorption eg. Bouche+12
  - Median M_* ~ 10^9 M_{sol}
  - Consistent with bipolar winds in simulations of massive galaxies
- Slow decrease in $B(r)$, expected if CGM magnetised by winds and outflows
  - As seen in simulations eg. Pakmor+20







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Summary

Scan the QR code to download the RM Grid data and the description paper

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- LoTSS DR2 RM Grid: O'Sullivan et al. (2023), arXiv:2301.07697
  - 2,461 RMs from extragalactic radio sources (i.e. radio-loud AGN)
  - Only ~0.2% of bright sources are detected in polarization at 20"
  - Unrivalled RM precision (~0.05 rad/m^2) & redshifts for ~79% of sources

- LoTSS residual RM associated with cosmic web filaments
  - Consistent with magnetised WHIM, with B ~ 10 – 50 nG (z ~ 0)
    - Carretti et al. (2022a,b), arXiv:2202.04607, arXiv:2210.06220

- RM signal associated with magnetised CGM in nearby galaxies
    - consistent with magnetised outflows up to 100 kpc along minor axis

- Larger datasets in the near future
  - Metre-wavelengths: Full LoTSS RM Grid at 6" (4x area, ~3x resolution)
  - LOFAR2.0: ILoTSS RM Grid at 0.3"
  - Complemented by cm-wavelengths: VLASS, APERTIF (LoTSS overlap) ASKAP-POSSUM & MeerKAT (southern sky)

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