Illuminating the magnetized cosmic web
with LOFAR

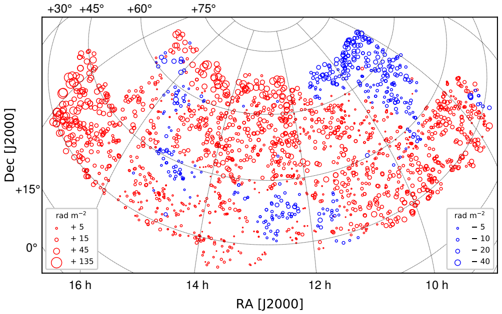
Shane O'Sullivan

Dublin City University
shane.osullivan@dcu.ie
www.cfar.ie

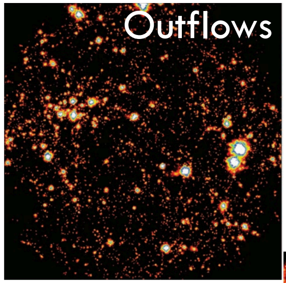
LOFAR Surveys & Magnetism Key Science Projects

Magnetism with radio telescopes

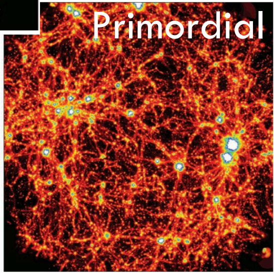
- The construction of a wide-area "RM Grid" is a key SKA goal for the study of the origin and evolution of cosmic magnetism
  - ie. a catalogue of discrete radio sources with Faraday rotation measures (RMs)
  - Synchrotron emission from radio galaxies → Faraday rotation and depolarization due to cosmic 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
  - Allows us to constrain the expected RM signatures for different magnetogenesis scenarios, eg. primordial versus astrophysical



Different expected distribution of magnetic fields on the largest scales

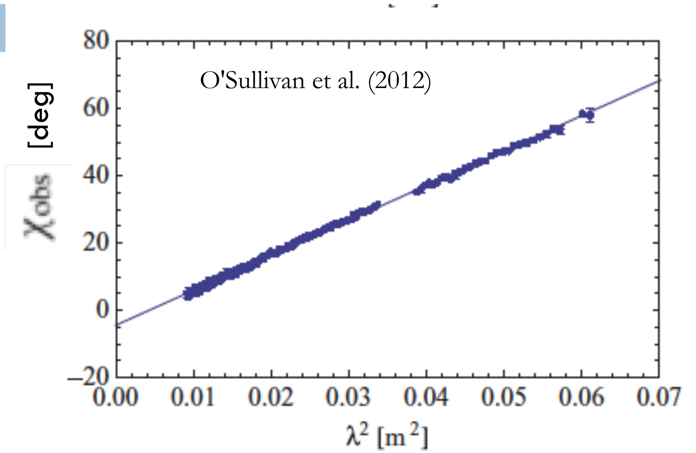


e.g. Donnert+09

Linear polarization & Faraday rotation

- Linear polarisation vector

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

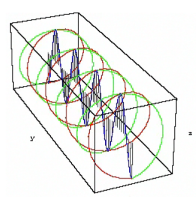


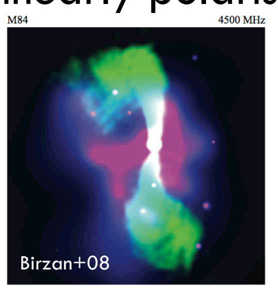
$$\mathrm{RM}_{[\mathrm{rad\ m^{-2}}]} = 0.812 \int_{\mathrm{source}}^{\mathrm{telescope}} n_{e\,[\mathrm{cm^{-3}}]}\, B_{||\,[\mu\mathrm{G}]}\, dl_{\,[\mathrm{pc}]}$$

+RM: $B_{||}$ pointing towards us

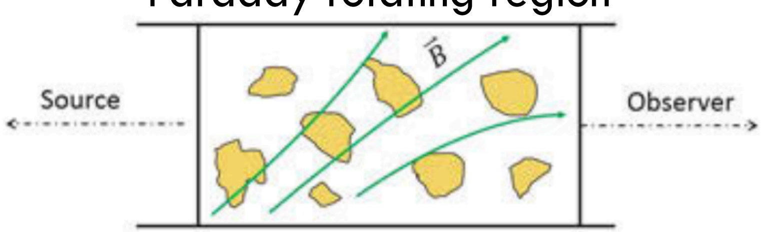
– RM: $B_{||}$ pointing away from us

Synchrotron emission from a radio galaxy (linearly polarised)

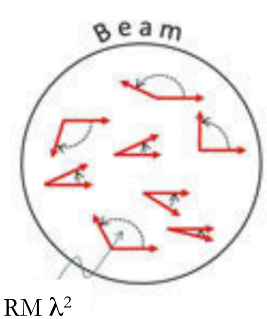




Faraday rotating region



B-field + ionised gas



Telescope

Intergalactic magnetic fields

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

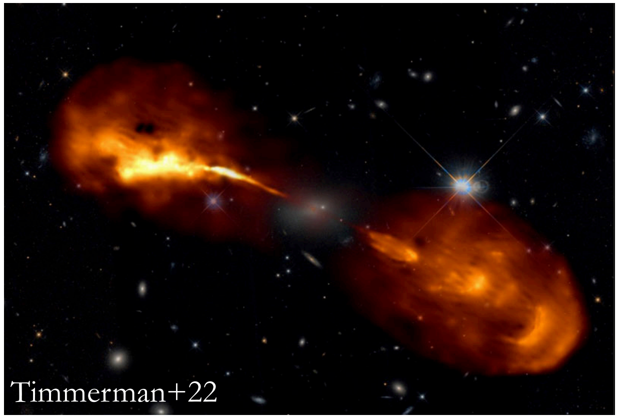
$$\mathrm{RM}_{[\mathrm{rad\ m}^{-2}]} = 0.812 \int_0^L n_{e\ [\mathrm{cm}^{-3}]}\ B_{||\ [\mu\mathrm{G}]}\ dl_{\ [\mathrm{pc}]}$$

- e.g. Cosmic web filament overdensity of ~50: ~10^{-5} cm^{-3}
  using a path length of 1 Mpc and
  a uniform magnetic field 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

- Low Frequency Array
  - 10 – 240 MHz (30 – 1.25 m)
    - LBA: 10 – 80 MHz
    - HBA: 120 – 240 MHz
  - Dutch stations: D ~ 100 km (~5” angular resolution)
  - 0.3” possible with international baselines

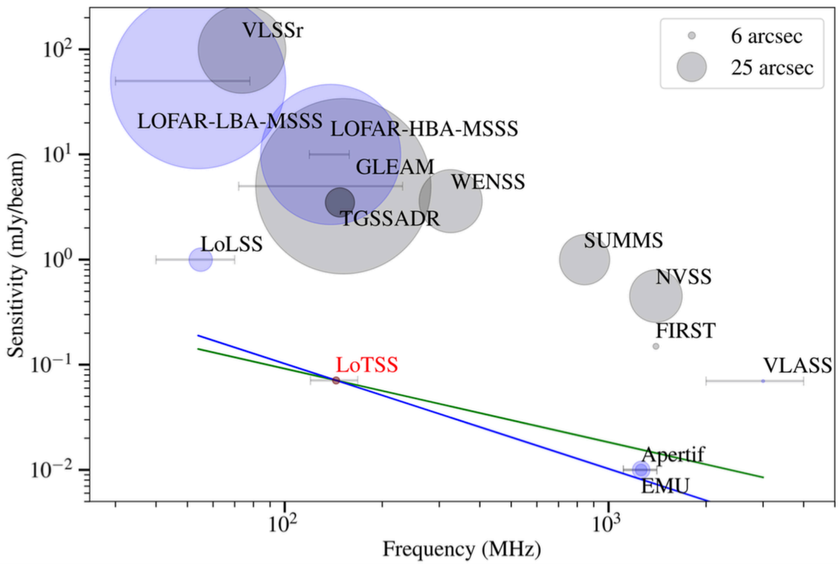

Timmerman+22

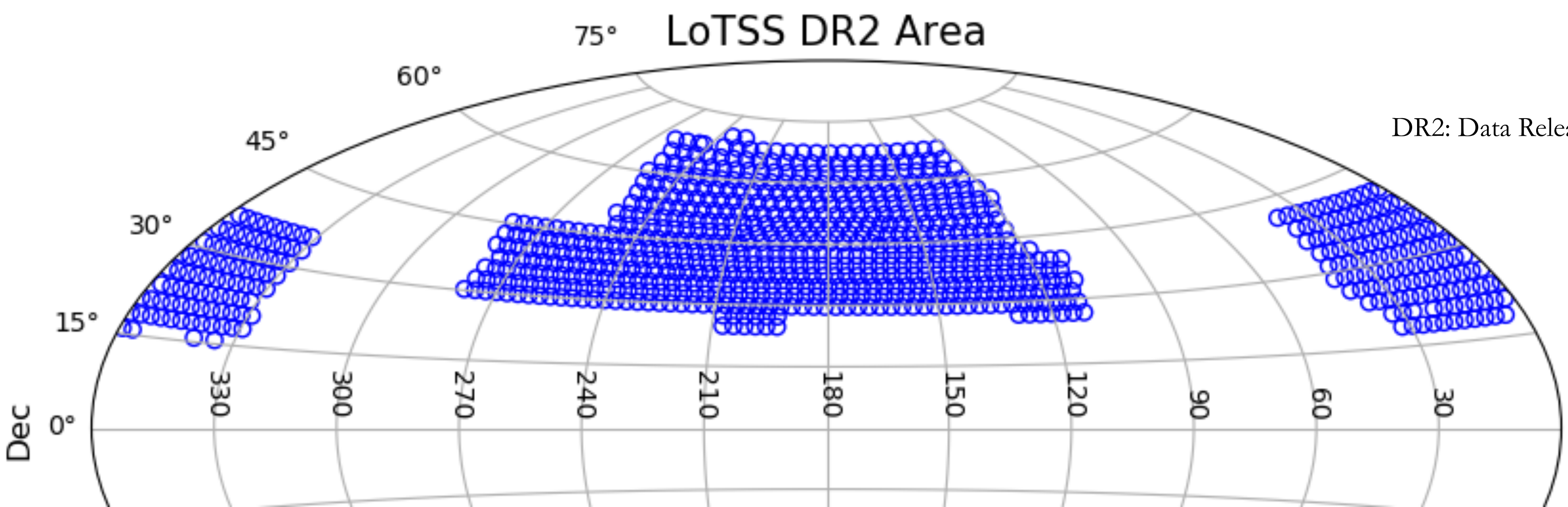
Superterp: The Netherlands

LOFAR station: eg. I-LOFAR

The LOFAR Two-metre Sky Survey

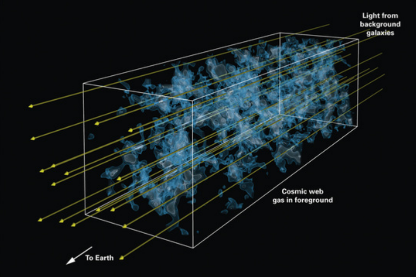
- LoTSS RM Grid: LOFAR Surveys & Magnetism KSP collaboration
- 120 – 168 MHz, 20" cubes, σ_{QU} ~ 0.1 mJy/beam
  - ~27% of northern sky, $RMSF_{FWHM}$ ~ 1.16 rad/m^2
- DR2: 0h and 13h fields, 5720 square degrees
  - ~4.4 million radio sources (Shimwell et al. 2022)
  - ~1.2 x 10^6 sources with peak flux > 1 mJy/beam,
  - Only ~2,500 polarized above 8σ_{QU} (~0.2% of sources)
  - Excellent RM precision: O(0.1 rad/m^2)

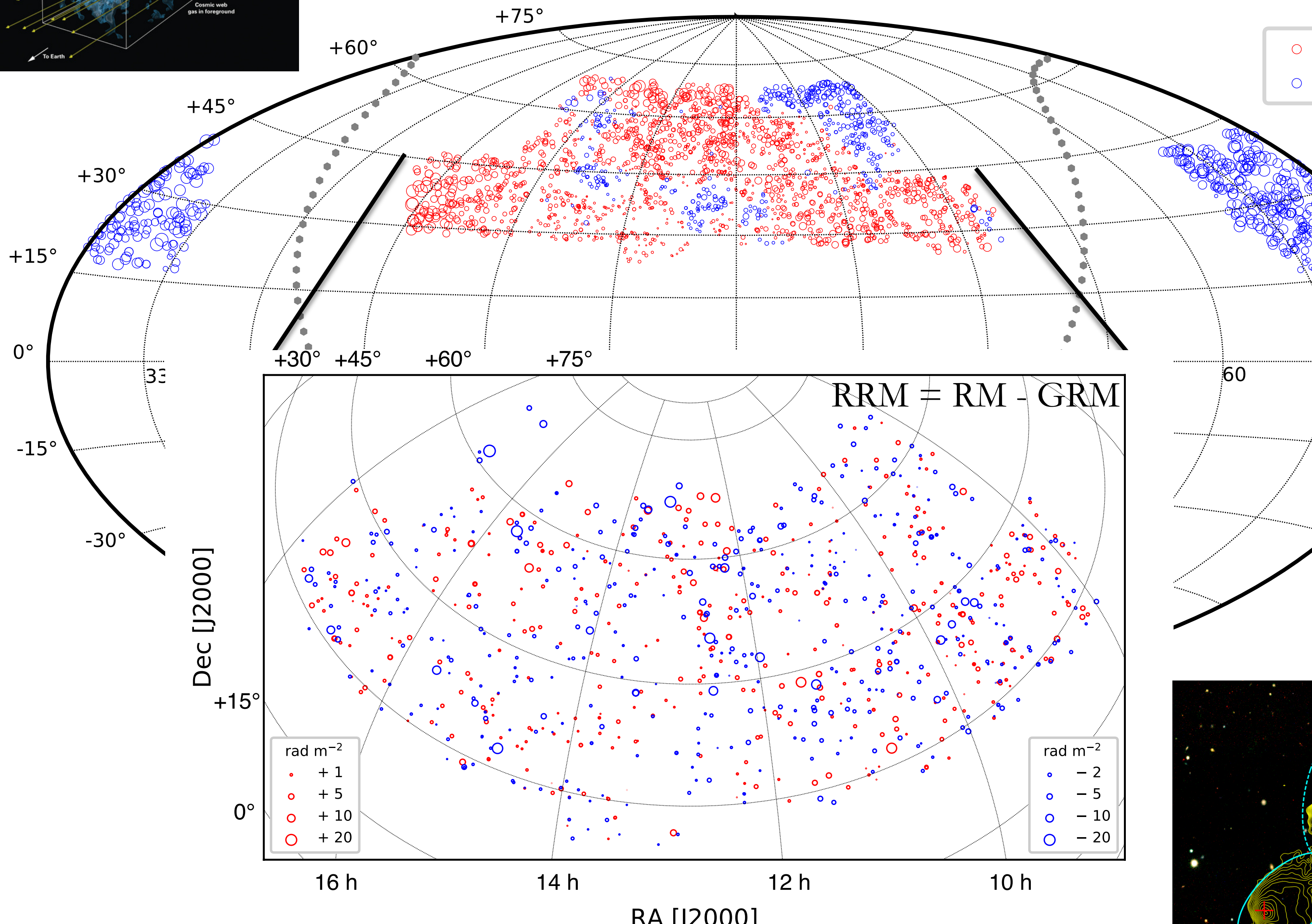


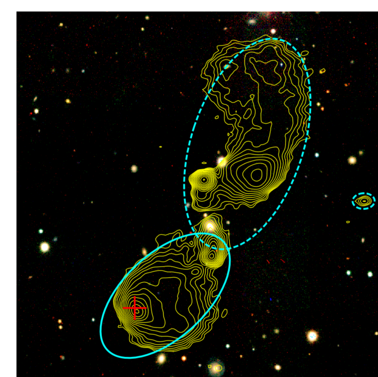


DR2: Data Release 2

LOFAR Two-Metre Sky Survey (LoTSS) RM Grid

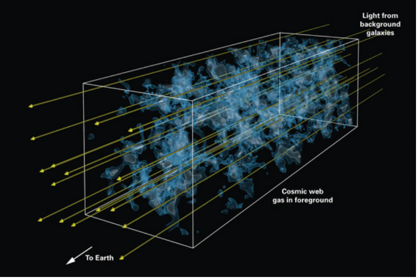


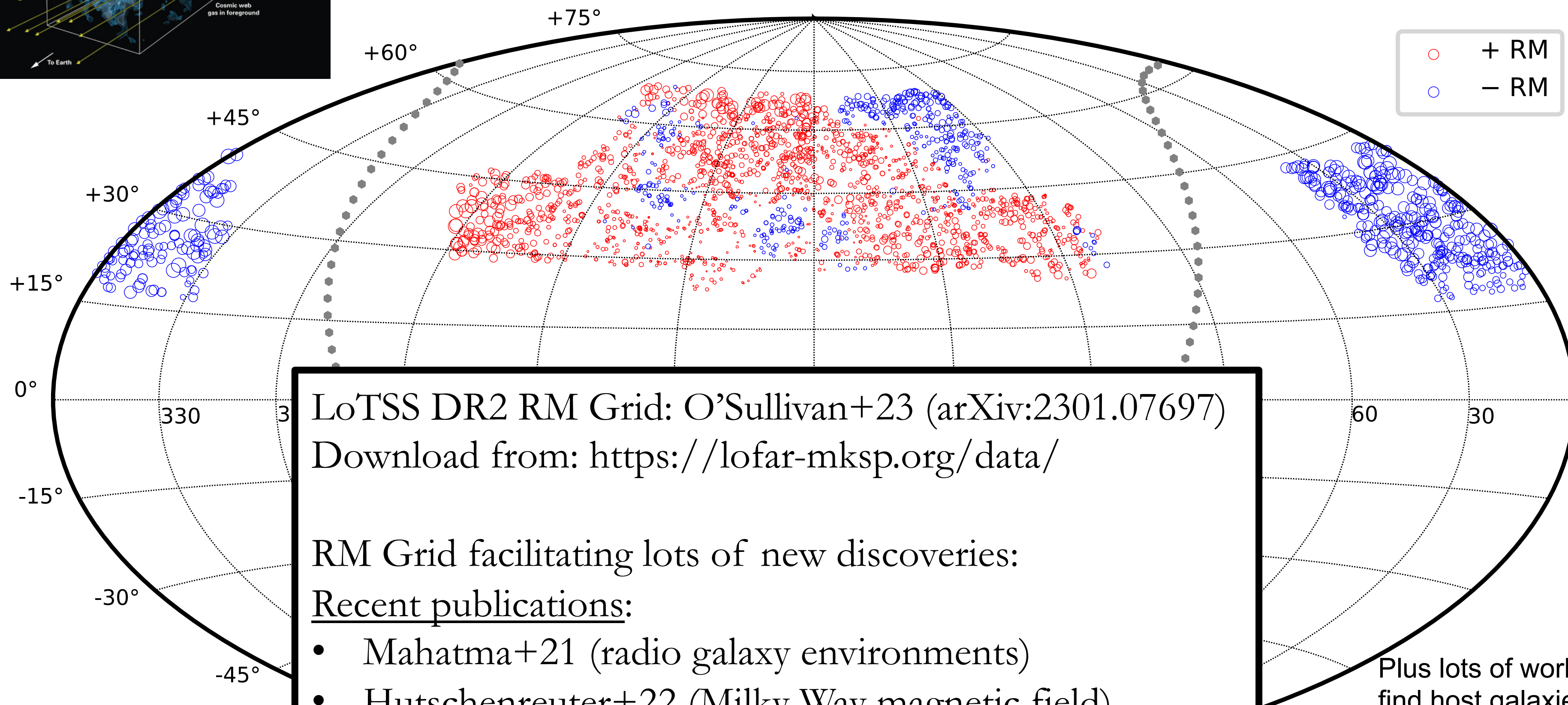




O'Sullivan et al. (2023)

LOFAR Two-Metre Sky Survey (LoTSS) RM Grid





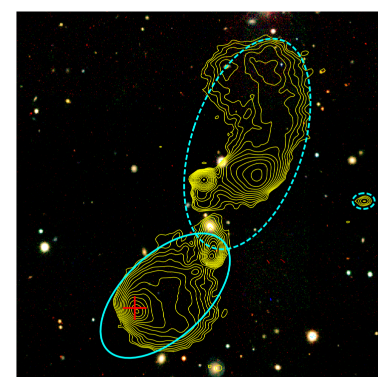
LoTSS DR2 RM Grid: O'Sullivan+23 (arXiv:2301.07697)
Download from: https://lofar-mksp.org/data/

RM Grid facilitating lots of new discoveries:

Recent publications:

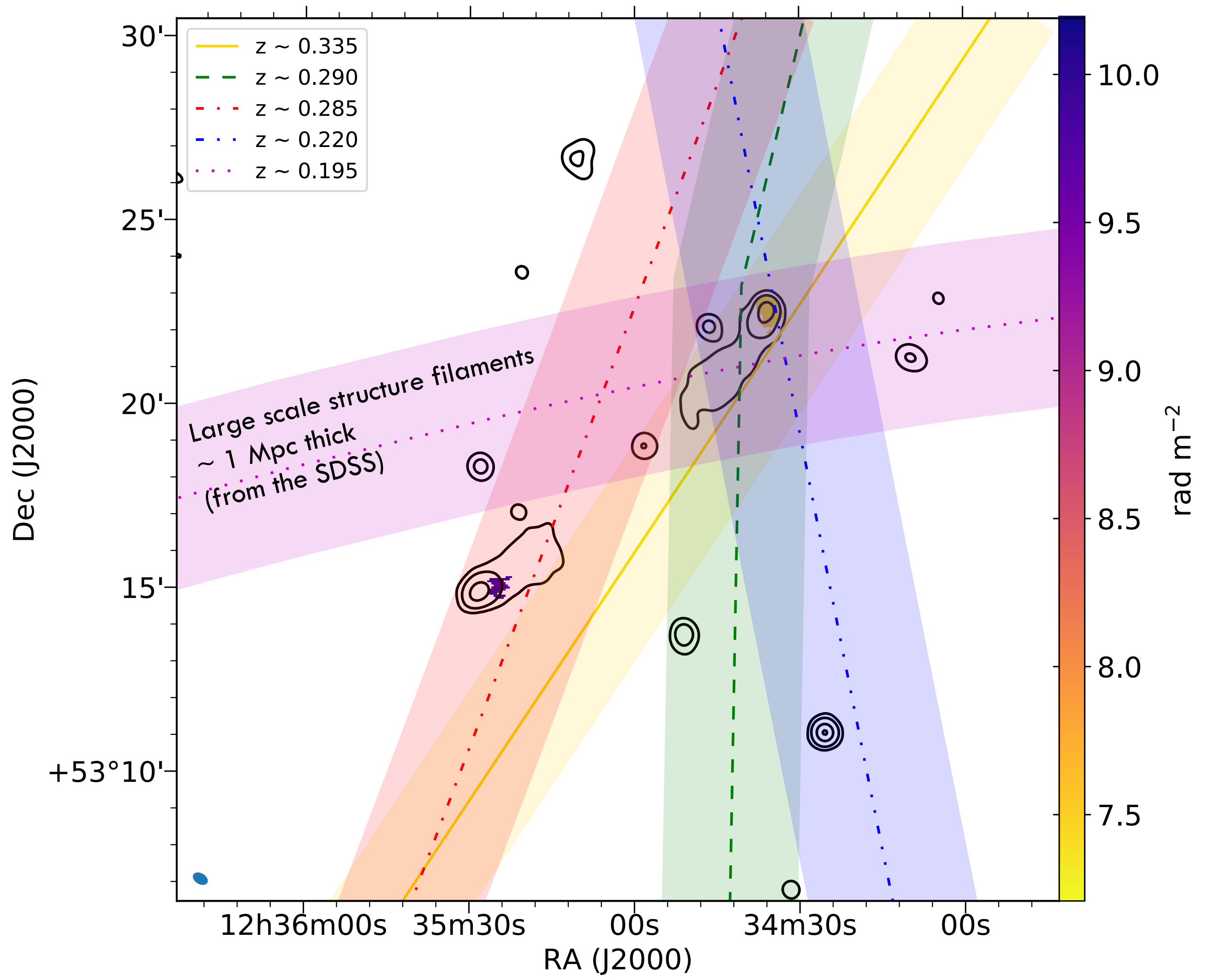
- Mahatma+21 (radio galaxy environments)
- Hutschenreuter+22 (Milky Way magnetic field)
- Stuardi+20 (giant radio galaxies)
- Sobey+22 (new pulsars)
- O'Sullivan+19, 20 (cosmic magnetism)
- Carretti+22a,b (magnetisation of cosmic filaments)
- Pomakov+22 (evolution of cosmic magnetism)

Plus lots of work to find host galaxies and redshift



O'Sullivan et al. (2023)

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

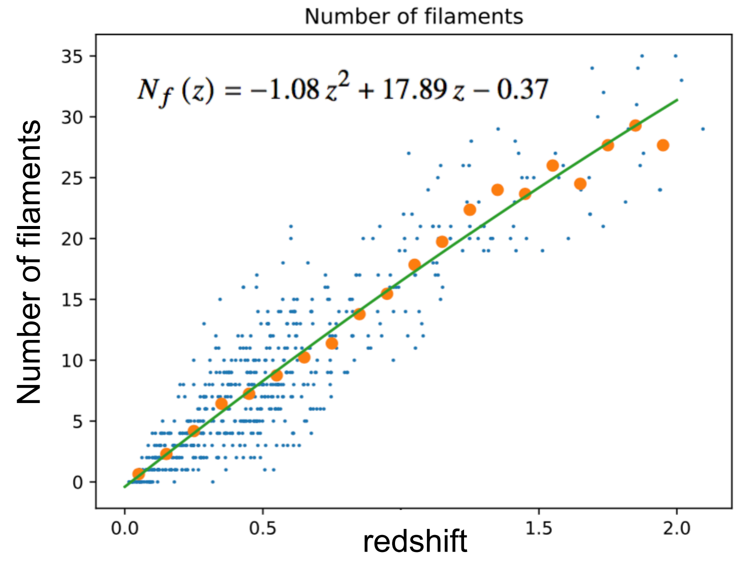
- RM vs z analysis for 1003 RMs at z < 2
- Comparison with the number of cosmic filaments identified from optical galaxy surveys along each line of sight
  - Chen+15, Carrón-Duque+21
- $RRM_{0,rms}$ expected to increase with redshift as $N_f^{1/2}$ (Akahori & Ryu 2011)

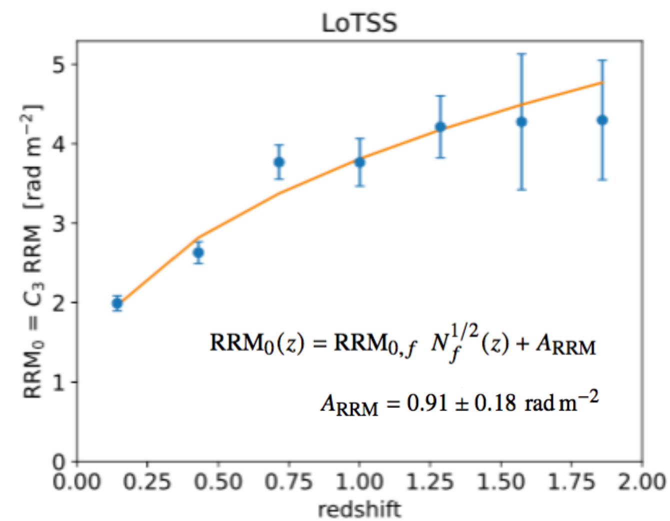
$$\mathrm{RRM}_0(z) = \mathrm{RRM}_{0,f}\ N_f^{1/2}(z) + A_{\mathrm{RRM}}$$

- 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 $n_{e,f} \sim 10^{-5}$ cm^{-3} and mean path length through a filament $L_f \sim 3$ Mpc (Cautun+14)

  => average B_f **~ 30 nG**

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





LoTSS DR2: magnetogenesis scenarios

Carretti, O'Sullivan, et al. (2023), MNRAS, 518, 2273. arXiv:2210.06220 (Paper II)

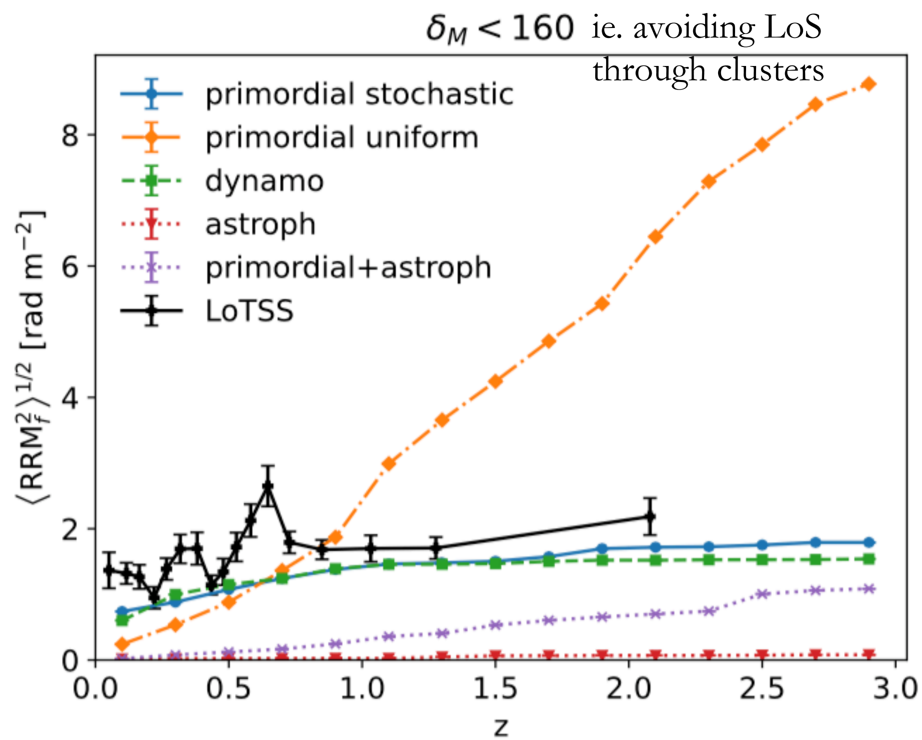
- LoTSS RM Grid sources avoid cluster environments
  - < 10% of sources have LoS within $\sim R_{100}$ (or $\delta_M \sim 160$)
  - NB. RM signal not dominated by magnetised gas in clusters

- Comparison with RMs derived from cosmological MHD sims (Vazza+21)
  - Excluding LoS through clusters

- $RM_{rms,voids(\delta < 1)} \sim 10^{-4}\, RM_{rms,IGM\,(\delta < 160)}$
  - ie. voids have negligible contribution; dominant signal from filaments

- Primordial uniform $B_0 \sim 0.1$ nG ruled out (orange)
- Primordial stochastic B consistent (blue) $B_{0,Mpc} \sim 0.04$ nG
  - Plus many other scenarios!

ie. avoiding LoS through clusters



Centre for Astrophysics & Relativity

Summary

- LoTSS DR2 RM Grid: O'Sullivan et al. (2023), arXiv:2301.07697
- 2461 RMs from extragalactic radio sources (i.e. radio-loud AGN)
  - Unrivalled RM precision (~0.05 rad/m^2) & redshifts for ~79% of sources

- LoTSS DR2 RM Grid results
  - RM associated with filaments: consistent with magnetised WHIM
  - Average magnetic field strength in cosmic web filaments: ~10 - 50 nG (z ~ 0)
  - Evolution of RM in filaments allows us to rule uniform primordial models for the origin of cosmic magnetic fields
    - Carretti et al. (2022a,b), arXiv:2202.04607, arXiv:2210.06220
    - O'Sullivan et al. (2020), arXiv:2002.06924, Pomakov et al. (2022), arXiv:2208.01336

(see talk on Thurs at 3pm)

- Larger datasets in the near future
  - Metre-wavelengths: Full LoTSS RM Grid at 6" (4x area, ~3x resolution)
  - Can further constrain magnetogenisis scenarios with better statistics for measuring the evolution of the magnetic field in filaments
  - Comparisons with cm-wavelengths: VLASS, APERTIF (overlap with LoTSS), ASKAP-POSSUM & MeerKAT (southern sky)