Cosmic Magnetism with LOFAR

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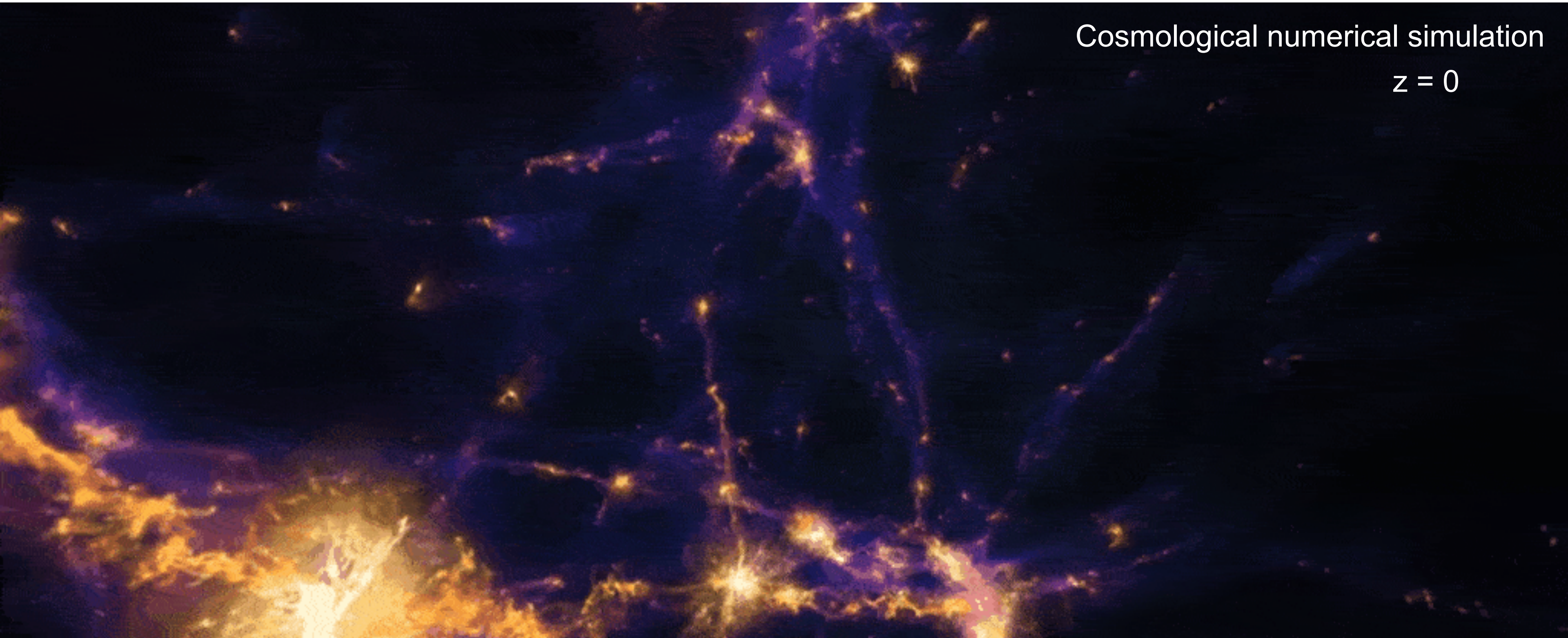
The cosmic web

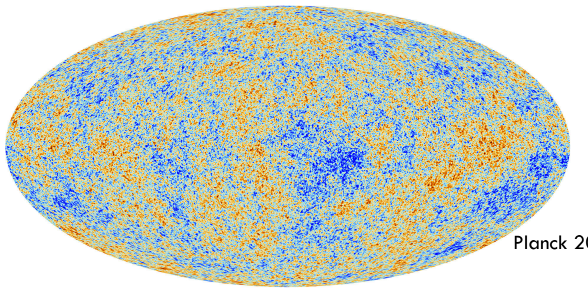
- Normal matter: ~20% in stars/galaxies/galaxy clusters
  - ~80% in the intergalactic medium (we expect…)
- Does the intergalactic medium have a magnetic field?
  - If so, what is its origin?

Credit: Illustris TNG

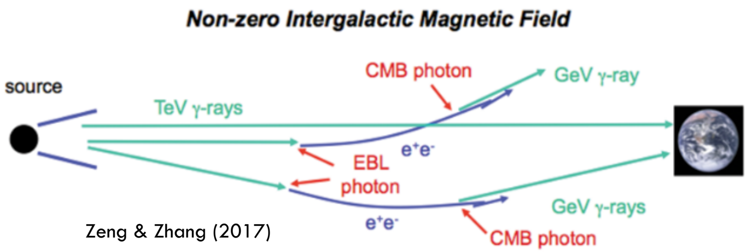


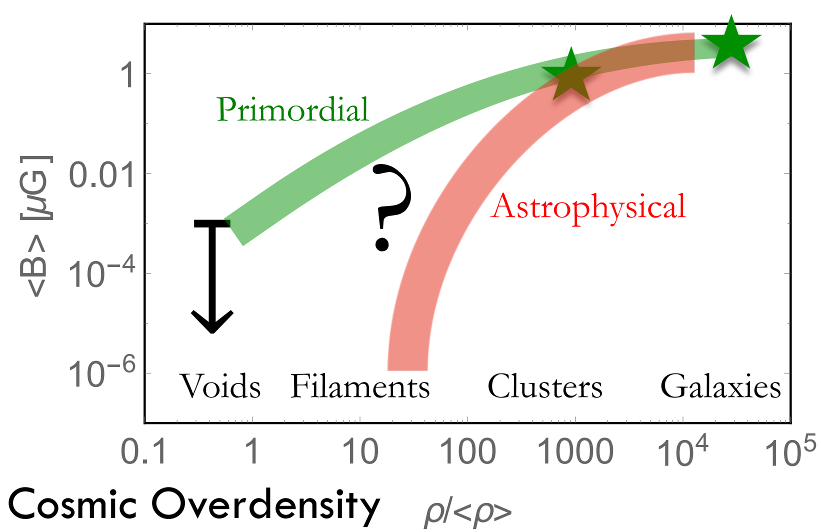
Cosmic magnetic field limits

- Upper limits from CMB temperature anisotropies: **B < few nG** on Mpc scales
  - Planck XIX (2015): Magnetically induced anisotropies are predicted to be strongly non-Gaussian
- Lower limits from TeV γ-ray observations: **B > 10^{-7} nG** on Mpc scales
  - GeV halo around TeV γ-ray sources and time-delayed GeV photons not detected because $e^{\pm}$ deflected by B-field
- Magnetic field in >99% of the Universe unconstrained across at least ~7 orders of magnitude
  - Different expectation for primordial versus astrophysical magnetogenesis

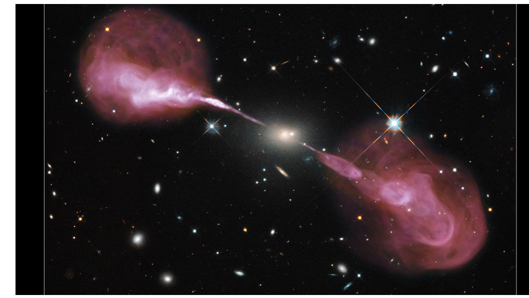


Planck 2015

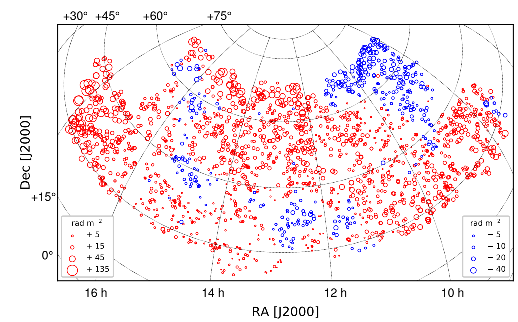




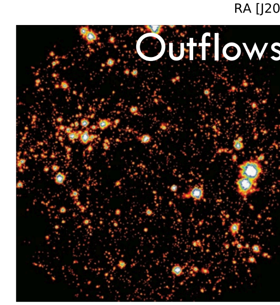
Magnetism with radio telescopes



- The construction of a wide-area "RM Grid" is a key science goal for the study of cosmic magnetism with the SKA and precursor/pathfinder telescopes
  - 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

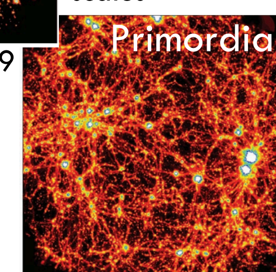


- The importance of RM studies at metre-wavelengths
  - LOFAR Two-Metre Sky Survey: 6" @ 144 MHz
    - $\mathrm{RM_{err}} \leq 0.1$ rad/m^2
  - High precision RM values ($\Delta\lambda^2_{\mathrm{LoTSS}}/\Delta\lambda^2_{\mathrm{cm}} \sim 100$)
  - Unique probe of weakly magnetised, low density environments
  - 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



Intergalactic magnetic fields

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

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

- 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° at cm-wavelengths, but **200° at metre-wavelengths**
  - Easier to measure this effect at long (metre) wavelengths
  - Higher RM precision (~100x): $\leq$ 0.1 rad/m^2
  - Use the Low Frequency Array (LOFAR)

LOFAR

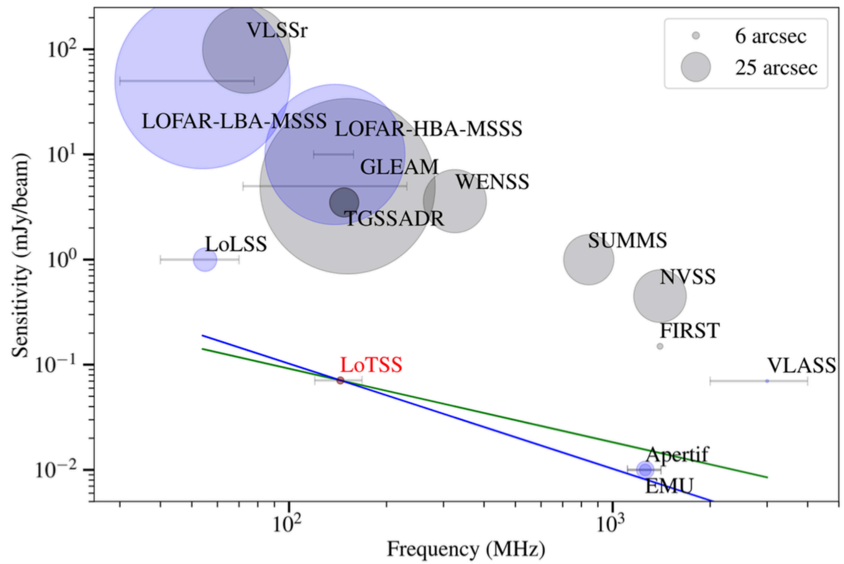
- Low Frequency Array
  - 10 – 240 MHz (30 – 1.25 m)
    - LBA: 10 – 80 MHz
    - HBA: 120 – 240 MHz
  - Dutch stations: D ~ 100 km (~5” angular resolution)
  - 0.3” possible with international baselines

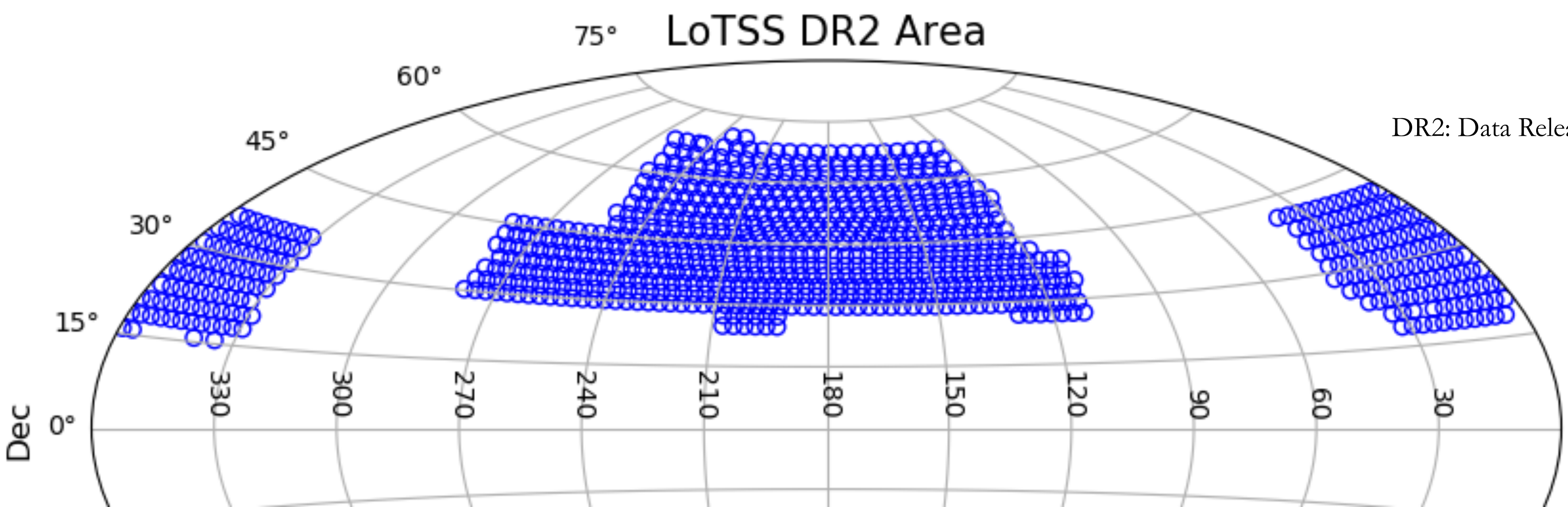
Superterp: The Netherlands

LOFAR station: eg. I-LOFAR

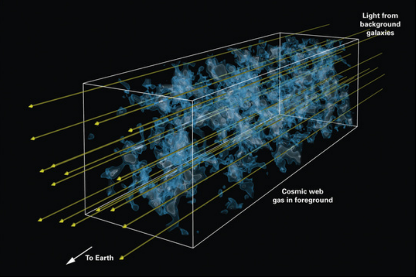
The LOFAR Two-metre Sky Survey

- RM Grid: Collaboration between LOFAR Surveys & Magnetism KSPs
- LoTSS DR2: 120 – 168 MHz, 20'' QU cubes
  - ~27% of northern sky covered
- DR2: two main fields (841 pointings)
  - The 0h and 13h fields, 5720 square degrees in total
  - ~4.4 million radio sources (Shimwell et al. 2022)

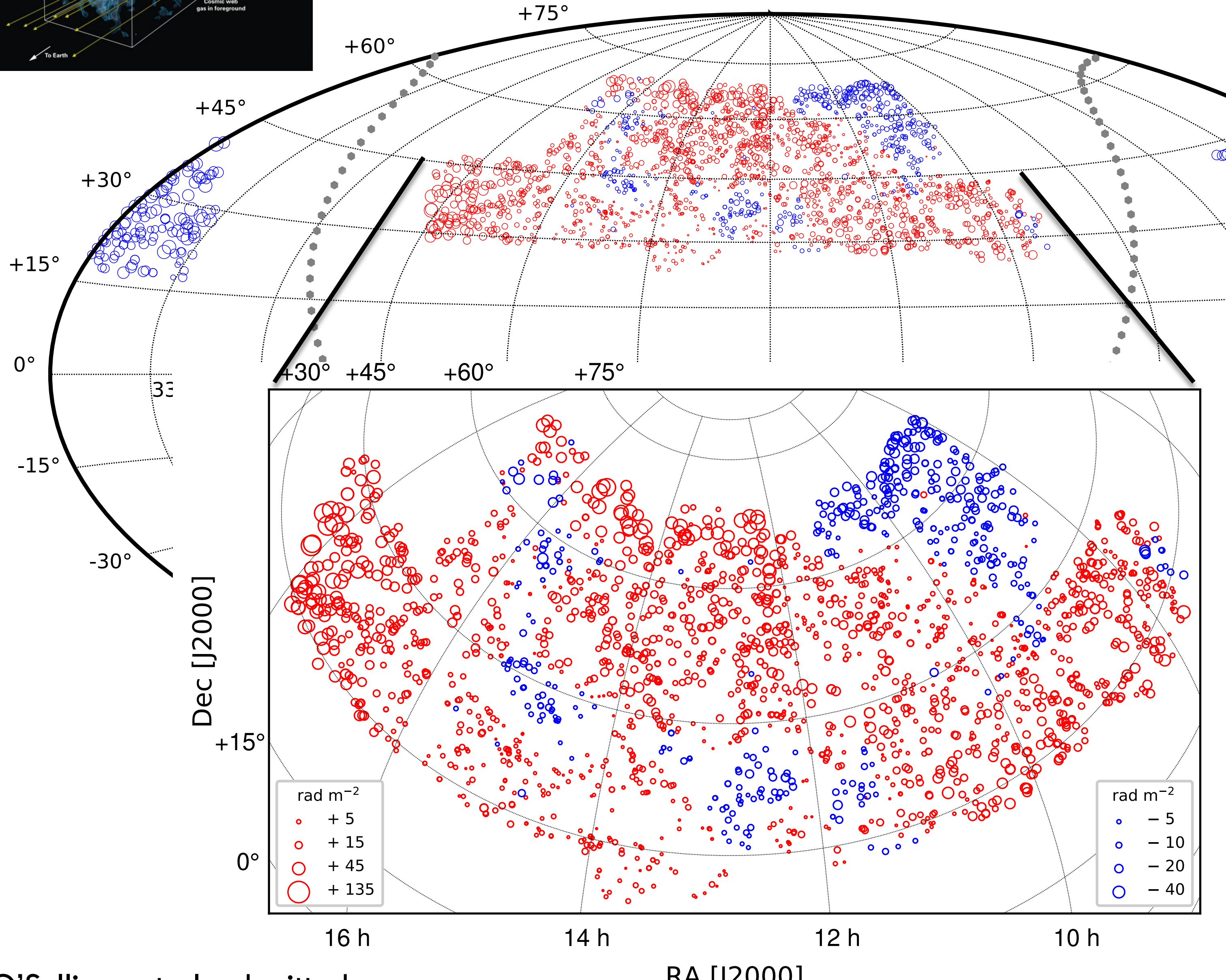


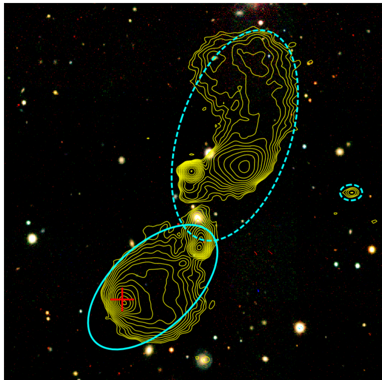


DR2: Data Release 2



LOFAR Two-Metre Sky Survey (LoTSS) RM Grid





O'Sullivan et al. submitted

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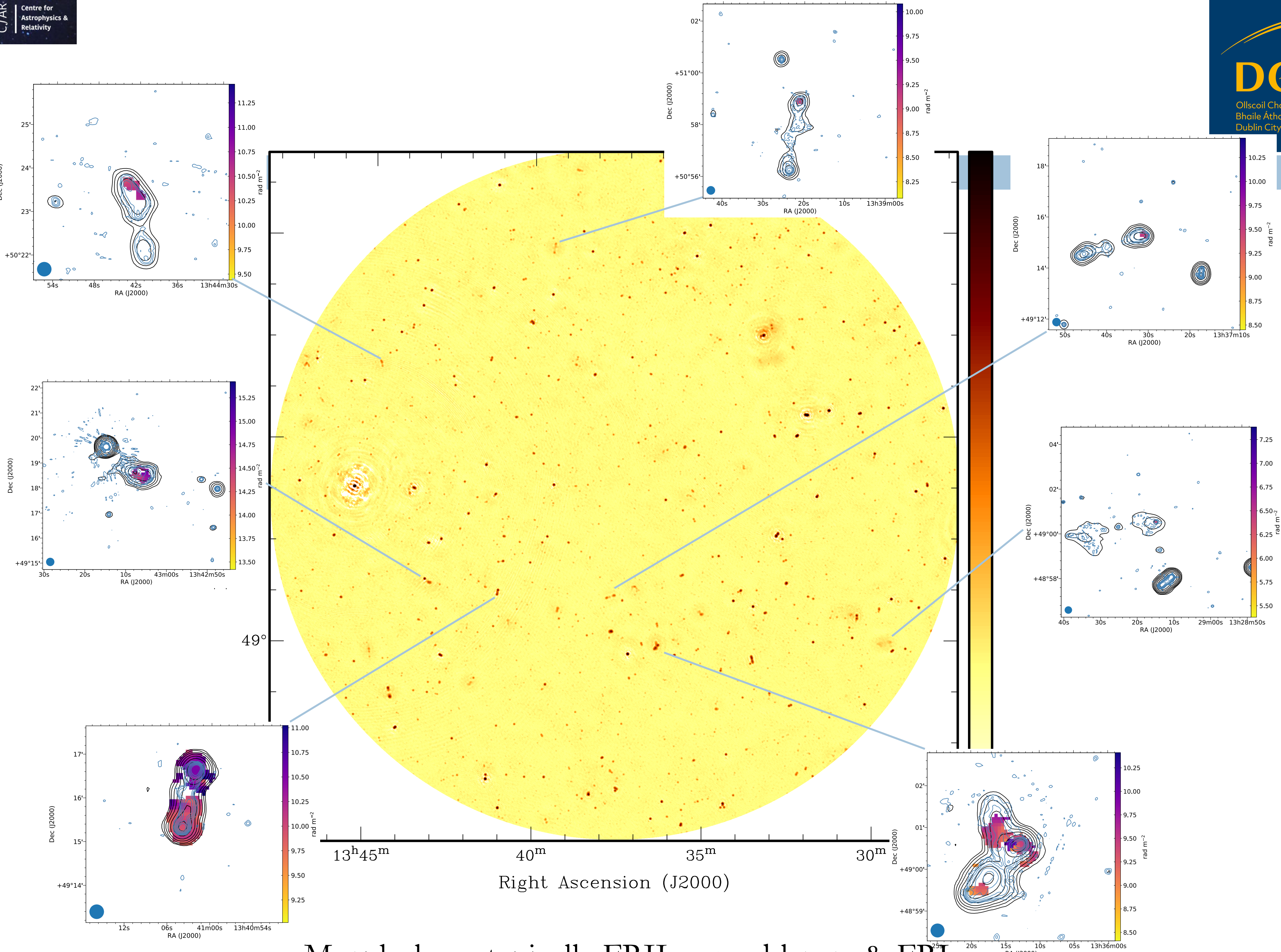


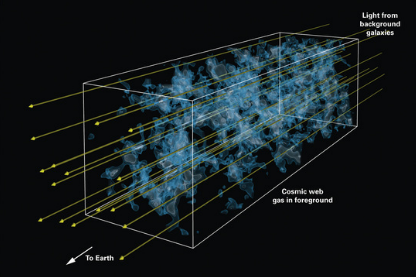
Morphology: typically FRII, some blazars & FRI

Median of 4 sources per field, max 13, min 0.

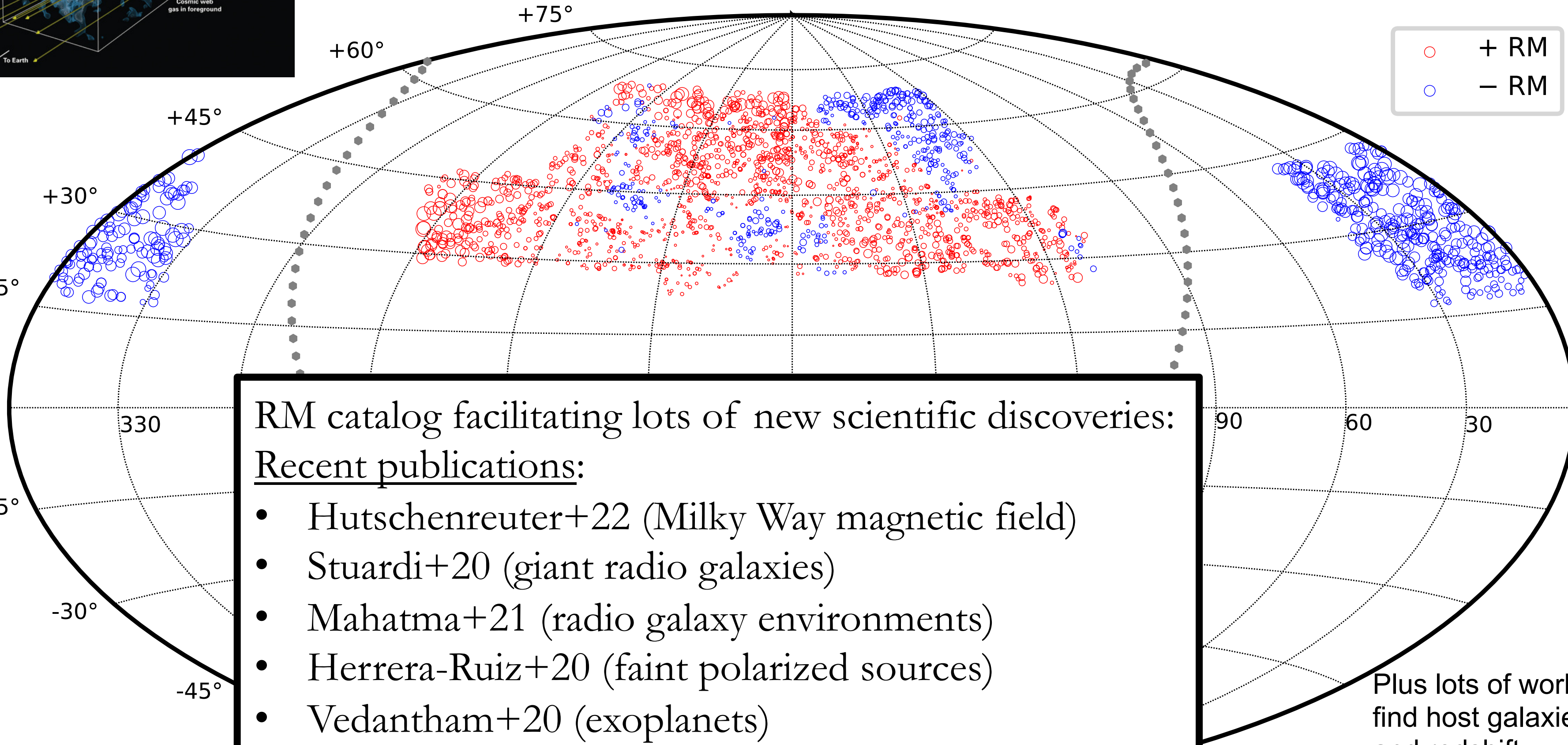
LoTSS DR2 RM Grid results

O'Sullivan, et al. (2022), submitted

- 5720 deg^2 sky area, 120 – 168 MHz @ 20", σ_{QU} ~0.1 mJy/beam
  - Search for polarization in ~1.2 x 10^6 sources, peak flux > 1 mJy/beam
- 2,461 linearly polarized > $8\sigma_{QU}$ (~0.2% of all sources)
  - 1 pol source per 2.3 deg^2
  - Median RM error 0.05 rad/m^2
  - Median p = 1.8%, Min p: 0.05%, Max p: 31%
- Associated redshift for 79% of polarized sources
  - Median linear size of 300 kpc, median luminosity of 5 x 10^{26} W/Hz
  - FRII dominant class: at least 40% of sources
  - 85% of polarized sources are well resolved at 20"
- 172 known blazars (~7%)
- 25 pulsars, excluded from RM Grid



LOFAR Two-Metre Sky Survey (LoTSS) RM Grid



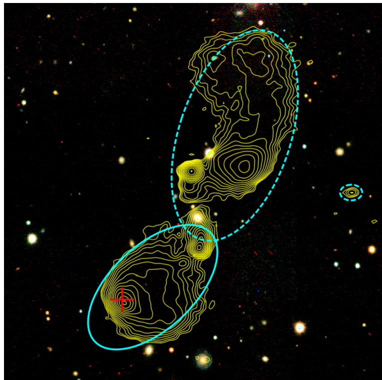
RM catalog facilitating lots of new scientific discoveries:

Recent publications:

- Hutschenreuter+22 (Milky Way magnetic field)
- Stuardi+20 (giant radio galaxies)
- Mahatma+21 (radio galaxy environments)
- Herrera-Ruiz+20 (faint polarized sources)
- Vedantham+20 (exoplanets)
- Sobey+22 (new pulsars)

- O'Sullivan+19, 20 (cosmic magnetism)
- Carretti+22 (magnetisation of cosmic filaments)
- Pomakov+22 (evolution of cosmic magnetism)

Plus lots of work to find host galaxies and redshift



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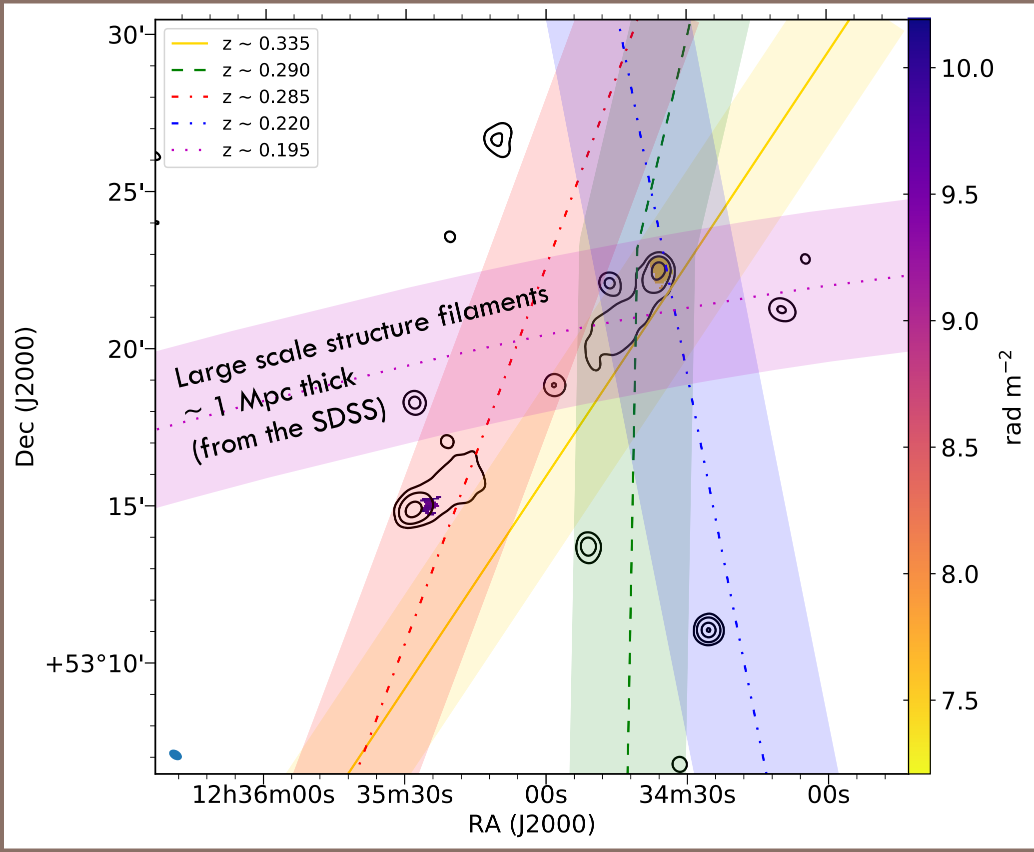


O'Sullivan et al. (2019)

The magnetised cosmic web as seen by LOFAR

LoTSS DR2: *B* in cosmic filaments

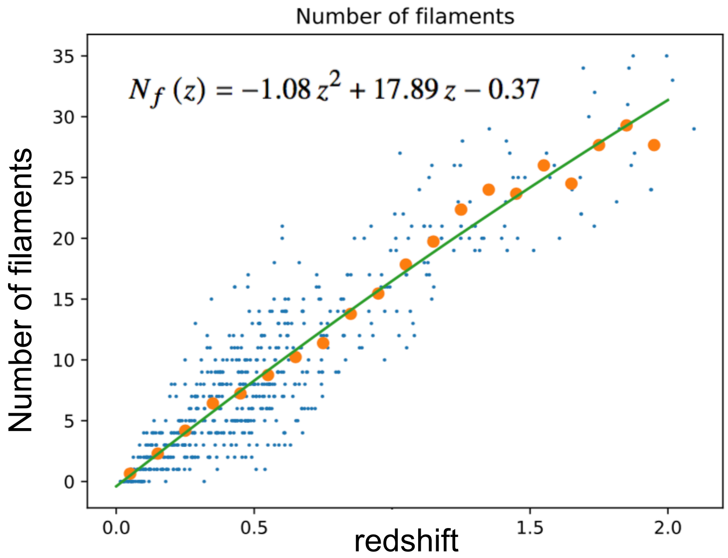
Carretti, Vacca, O'Sullivan, et al. (2022), MNRAS, 512, 945. arXiv:2202.04607

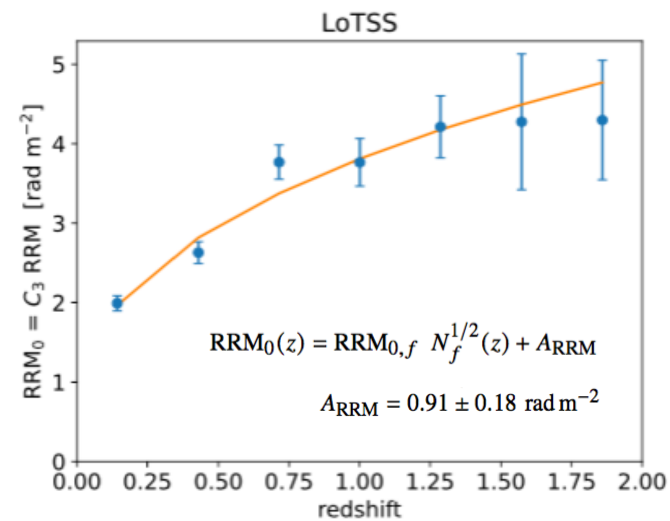
- RM vs z analysis for 1003 RMs at $z < 2$
- Comparison with the number of cosmic filaments identified from optical galaxy surveys along each line of sight
  - Chen+15, Carrón-Duque+21
- $\mathrm{RRM}_{0,\mathrm{rms}}$ expected to increase with redshift as $N_f^{1/2}$ (Akahori & Ryu 2011)

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

- Best-fit result gives: $\mathrm{RRM}_{0,f} = 0.71 \pm 0.07\ \mathrm{rad\,m^{-2}}$
  - Average |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 $\boxed{B_f \sim \mathbf{32 \pm 3\ nG}}$





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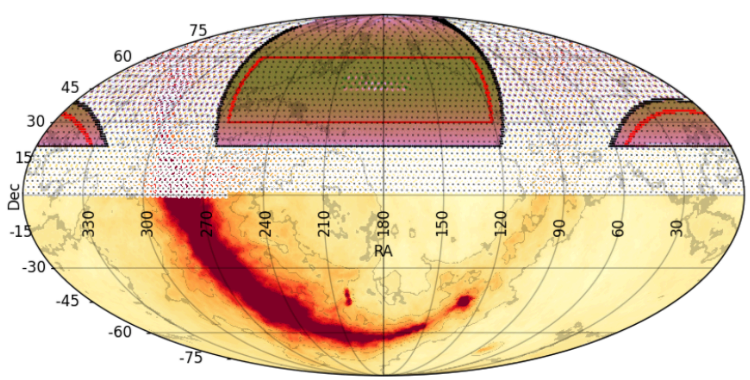
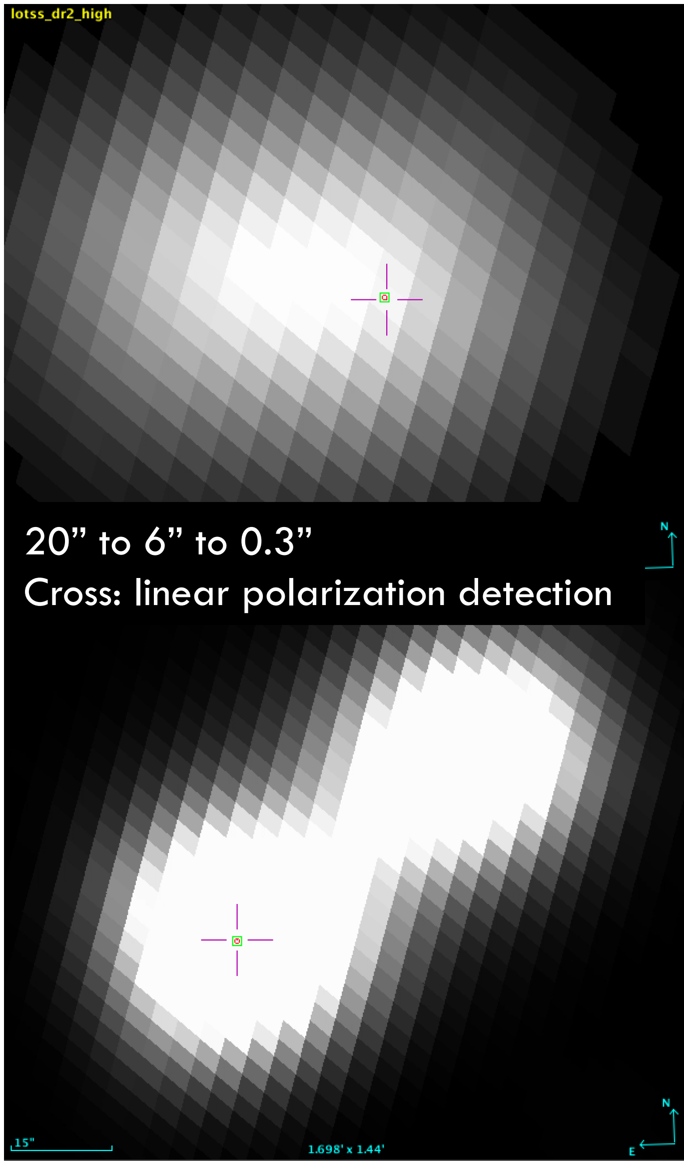
Next frontier: LOFAR2.0

- 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 (ESA optical to NIR space telescope, launch 2023/2024)
  - Much greater fraction of polarized sources? Overcoming Faraday and beam depolarization





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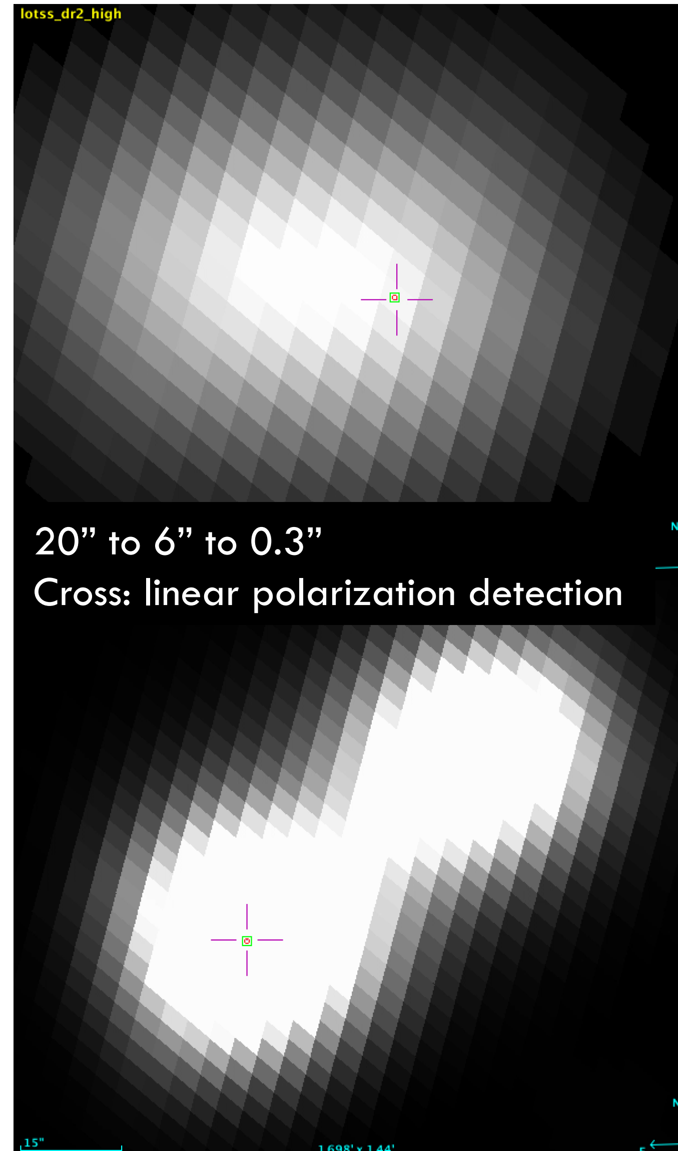


Summary

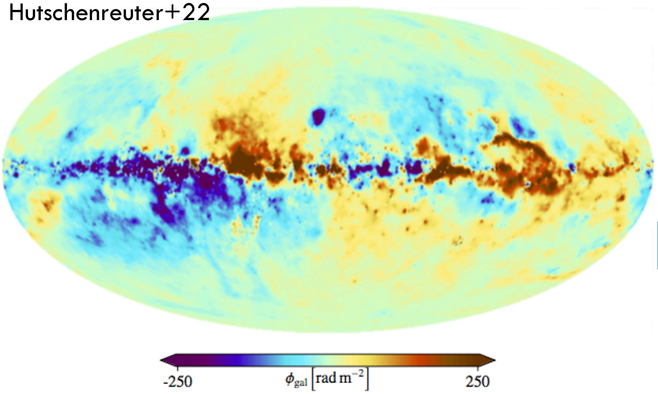
- O'Sullivan et al. (2022), in review: LoTSS DR2 RM Grid
- 2,461 RMs from extragalactic radio sources (i.e. radio-loud AGN)
  - Only ~0.2% of sources are detected in polarization at 20"
  - Unrivalled RM precision (~0.05 rad/m^2) & redshifts for ~79% of sources

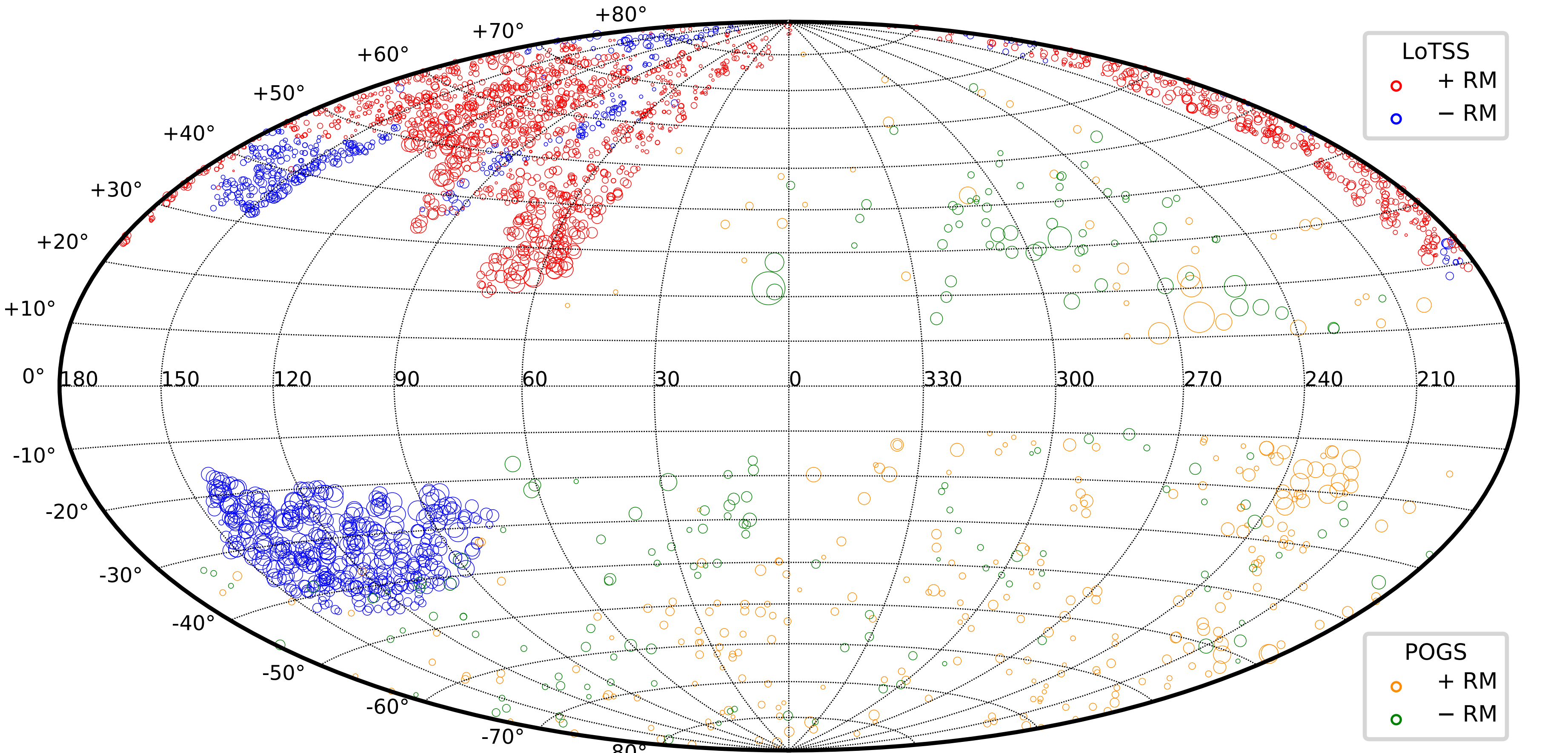
- Carretti et al. (2022), MNRAS, 512, 945. arXiv:2202.04607
  - Average magnetic field strength in cosmic web filaments: ~30 nG ($z < 2$)
  - RM associated with filaments also highlights presence of diffuse ionised gas (i.e. WHIM)

- Larger datasets in the near future
  - Metre-wavelengths: Full LoTSS RM Grid (4x area, 3x resolution)
    - LOFAR2.0 RM Grid (60x resolution => many more sources…)
  - Can constrain magnetogenisis scenarios by measuring the evolution of the magnetic field strength in cosmic web filaments

Galactic projection

Hutschenreuter+22





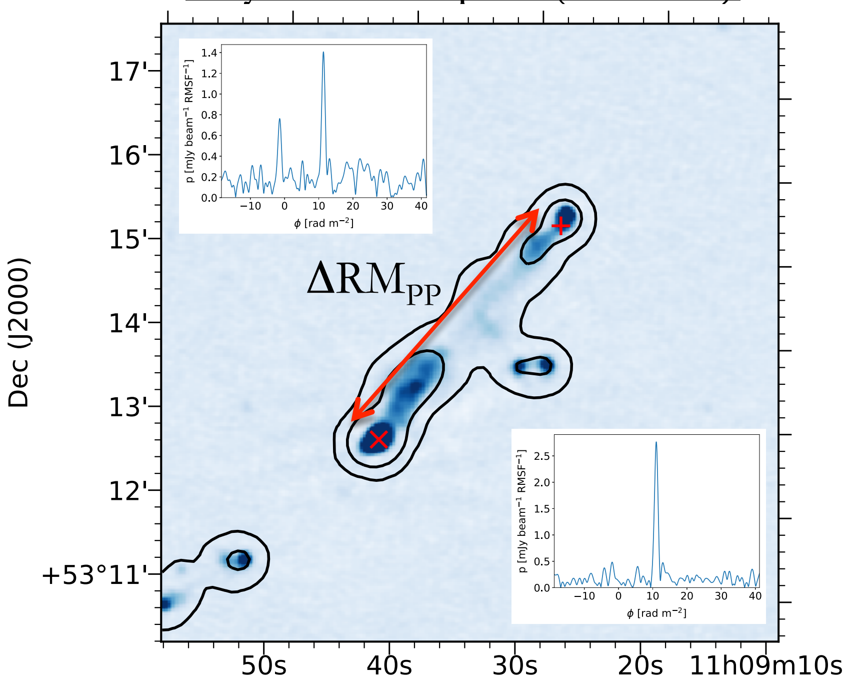
POGS: MWA (Riseley+20)
~500 sources

LoTSS DR2: *B*(z) evolution

Pomakov, O'Sullivan, Brüggen, Vazza, et al. (2022), MNRAS, accepted

- RM pair analysis with z: $\Delta \mathrm{RM}_{\mathrm{Random\ Pair}}(z) \Rightarrow \mathrm{RM}_{\mathrm{IGM}}(z)$
  - Physical pairs as a control sample

<u>Physical RM pair (Δθ ~ 3')</u>



<u>Random RM pair (Δθ ~ 4')</u>