A LOFAR Faraday rotation measure grid for studying cosmic magnetic fields

Shane O'Sullivan (Hamburg Observatory)
+ MKSP: RM Grid Taskforce
+ SKSP: LoTSS Tier 1

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21/05/19

LOFAR Science 2019

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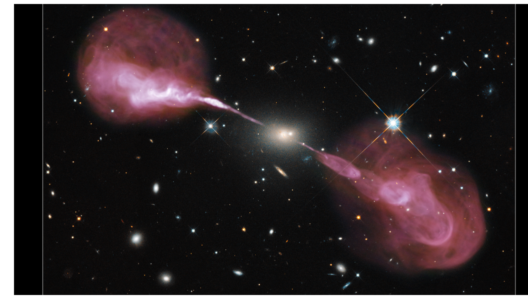
Cosmic B-fields with LOFAR

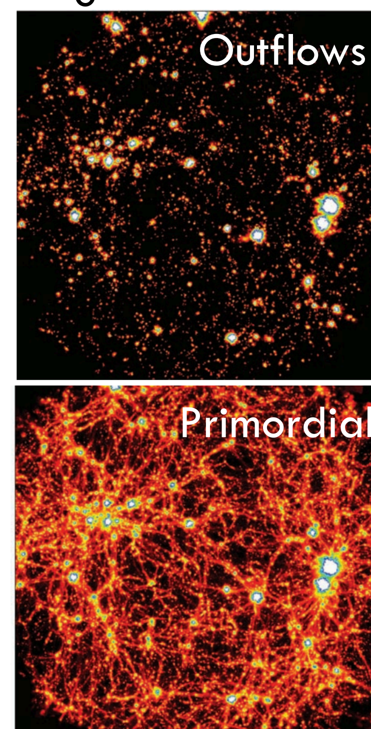


- Using the linearly polarized synchrotron emission from radio galaxies to measure the Faraday rotation and depolarization due to cosmic magnetic fields

- m-spectropolarimetry with LOFAR
  - LOFAR Two-Metre Sky Survey (120 – 168 MHz @ 100 kHz)
  - High RM accuracy ($\Delta\lambda^2_{LoTSS}/\Delta\lambda^2_{VLA} \sim 40$)
    - LoTSS (120 – 168 MHz): $\delta\phi \sim 1$ rad/m^2 (20”)
    - VLASS (2 – 4 GHz): $\delta\phi \sim 200$ rad/m^2 (3”)
    - NVSS (~1.4 GHz): $\delta\phi \sim 700$ rad/m^2 (60”)

- A key science goal: the intergalactic magnetic field (IGMF)
    - e.g. O’Sullivan et al. (2019)
  - Discriminate between competing models for origin of cosmic magnetism
    - Primordial seed field, injected/outflows?
  - Complement to imaging of synchrotron cosmic web

e.g. Donnert+09

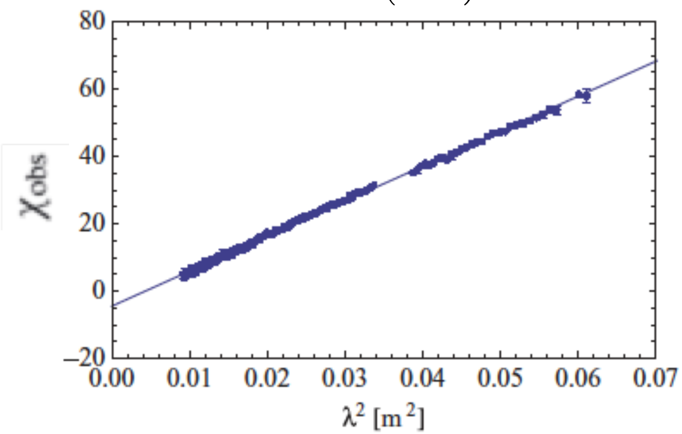


Linear polarisation & Faraday rotation

- Linear polarisation vector

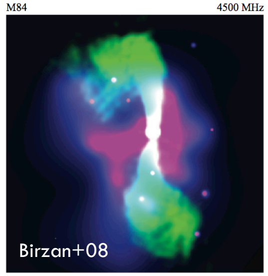
$$\mathbf{P} = Q + iU = pIe^{2i\chi} = p\,I\,e^{2i(\chi_0 + \mathrm{RM}\lambda^2)}$$

O'Sullivan et al. (2012)

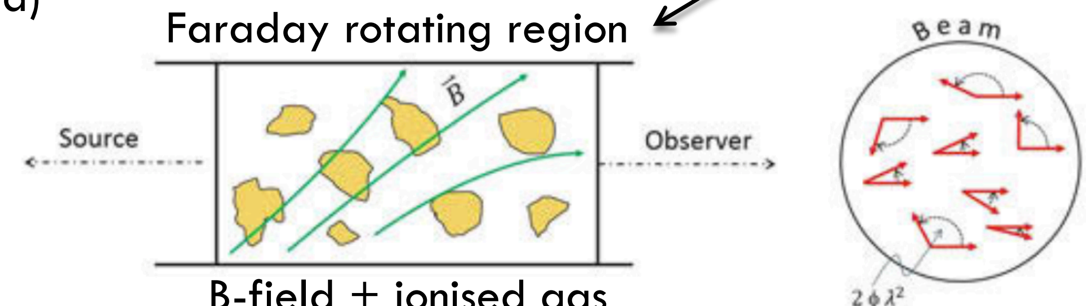


$$\mathrm{RM}_{[\mathrm{rad\ m^{-2}}]} = 0.812 \int_{\mathrm{source}}^{\mathrm{telescope}} n_{e\ [\mathrm{cm^{-3}}]}\, B_{||\ [\mu\mathrm{G}]}\, dl_{\ [\mathrm{pc}]}$$

Synchrotron emission (linearly polarised)



Faraday rotating region



B-field + ionised gas

Telescope

Faraday rotation and depolarisation

- Linear polarisation vector

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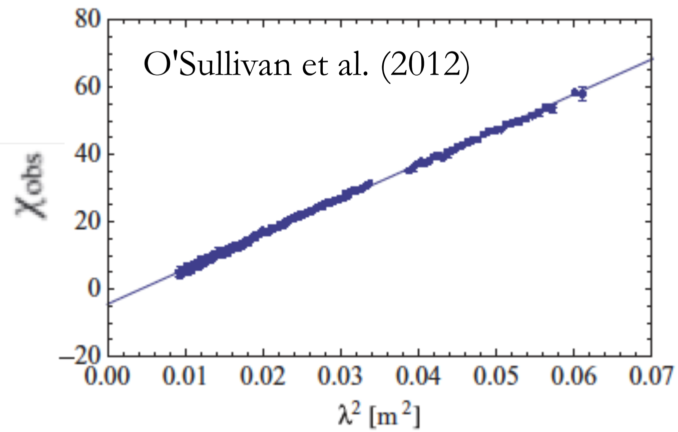
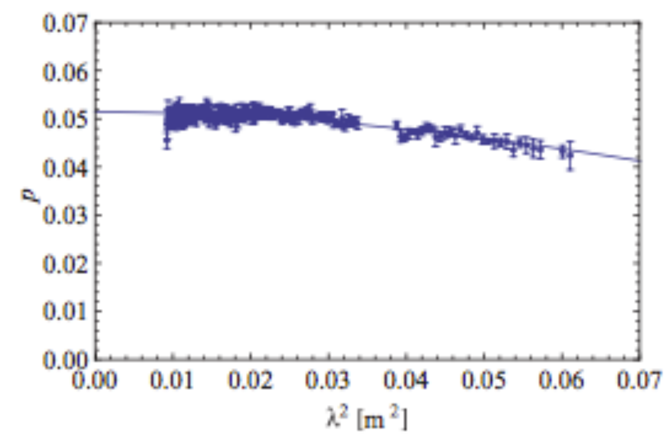


$$\mathbf{P} = p_0 e^{2i(\chi_0 + \mathrm{RM}\,\lambda^2)} e^{-2\sigma^2_{\mathrm{RM}}\lambda^4}$$



Synchrotron emission (linearly polarised)

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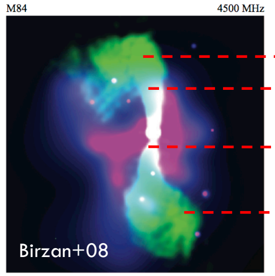
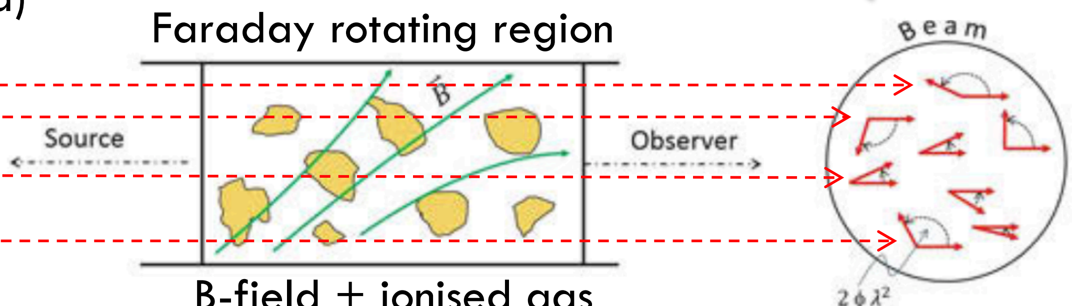


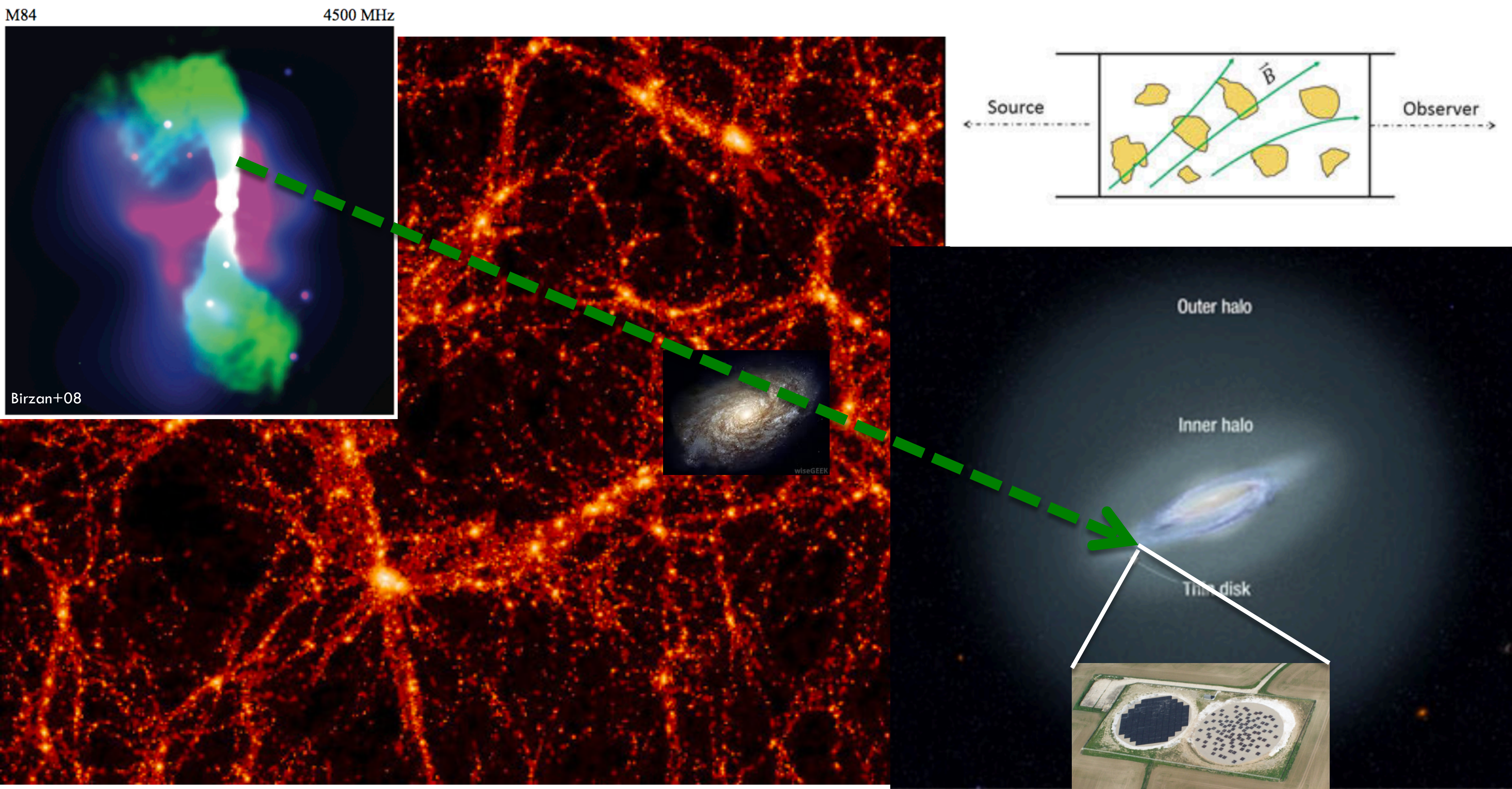
Faraday rotating region



B-field + ionised gas

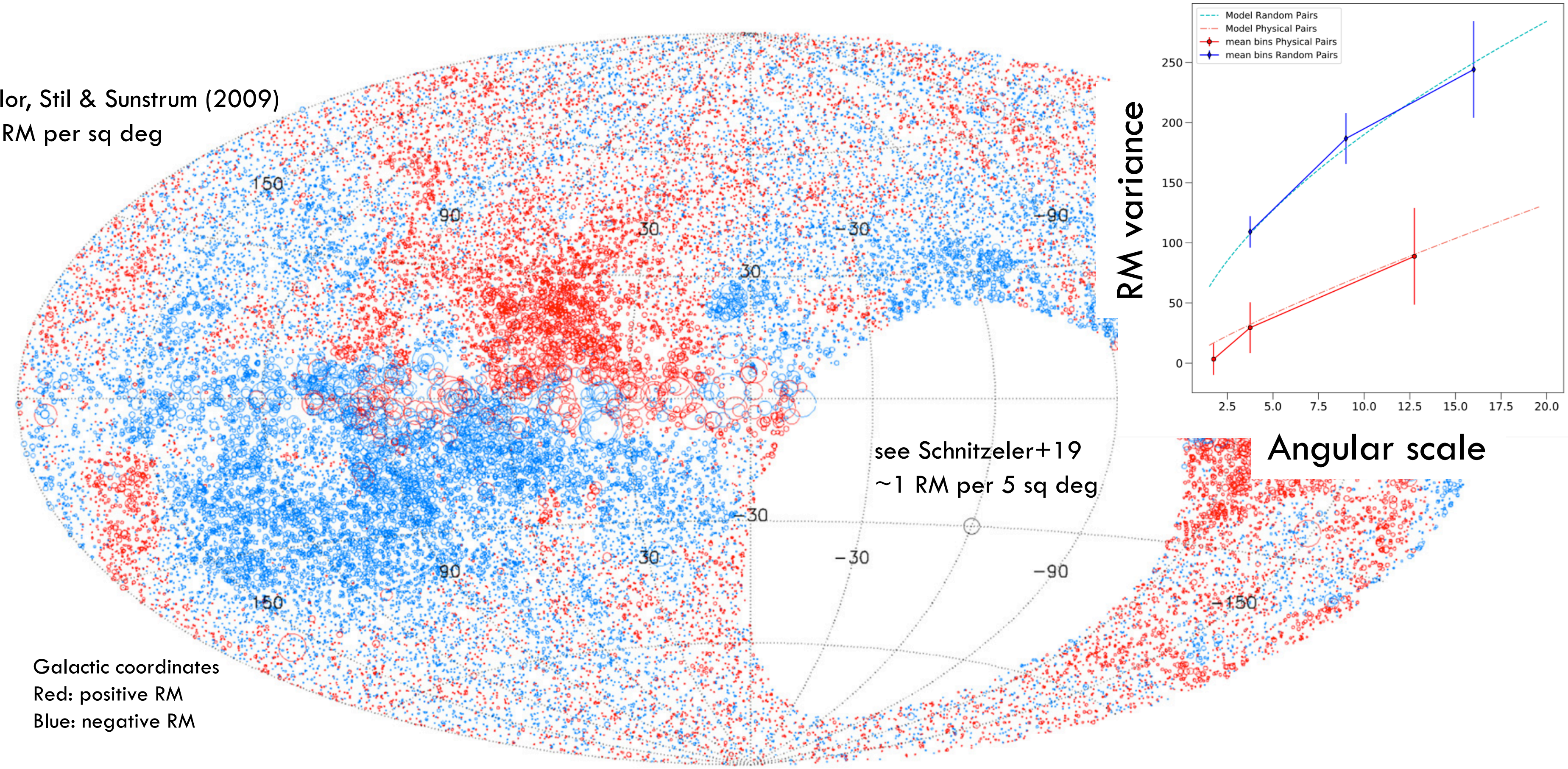
$$\mathrm{RM}_{total} = \underbrace{\mathrm{RM}_{int}}_{O(1\ \mathrm{rad/m^2})} + \underbrace{\mathrm{RM}_{local}}_{O(10\text{-}1000\ \mathrm{rad/m^2})} + \underbrace{\mathrm{RM}_{IGMF}}_{O(<1\ \mathrm{rad/m^2})} + \underbrace{\mathrm{RM}_{gal}}_{O(10\ \mathrm{rad/m^2})} + \underbrace{\mathrm{RM}_{MW}}_{O(10\text{-}100\ \mathrm{rad/m^2})} + \underbrace{\mathrm{RM}_{ion}}_{O(1\ \mathrm{rad/m^2})}$$

- Use Faraday rotation to probe the magnetised universe
- Many contributions along line of sight, and on different scales

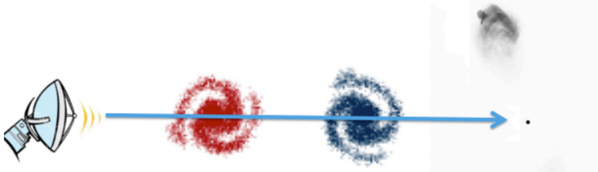


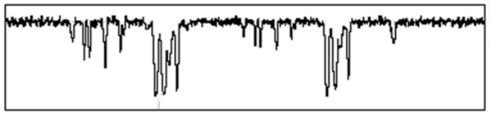
An RM Grid

- How to discriminate between all these RM contributions?
- Statistical approach to isolate different magnetised regions along the line of sight
  - e.g. different RM variance for different source selections: Vernstrom+19

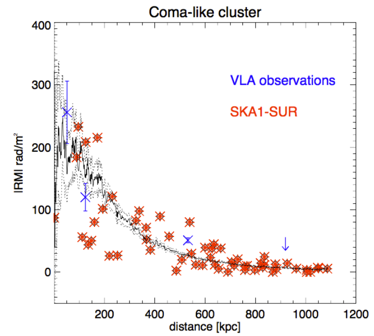


RM grid science

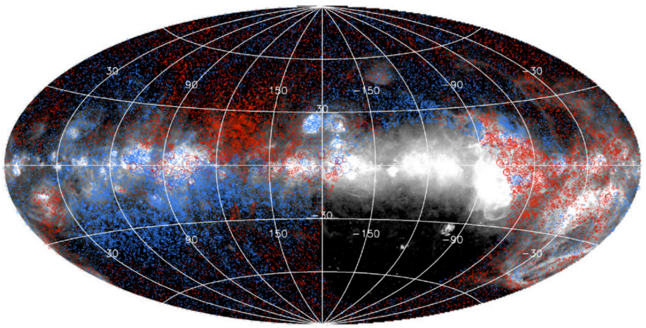




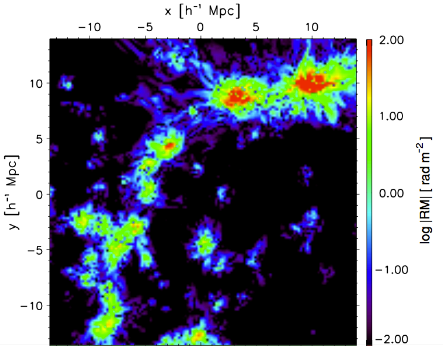
- How magnetic fields emerge and grow in galaxies (Farnes+14, +16, Kim+16)



- The role of magnetic fields in galaxy cluster formation and evolution (eg. Bonafede+15)
- The structure of the Galactic magnetic field from sub-parsec to kpc-scales (eg. Stil+11)



- The magnetised component of the large-scale structure of the Universe (Akahori & Ryu '10, Vazza+15, Vernstrom+19)



- In addition to studying the detailed physics of radio sources themselves (e.g. O'Sullivan+18a)

The LoTSS RM Grid

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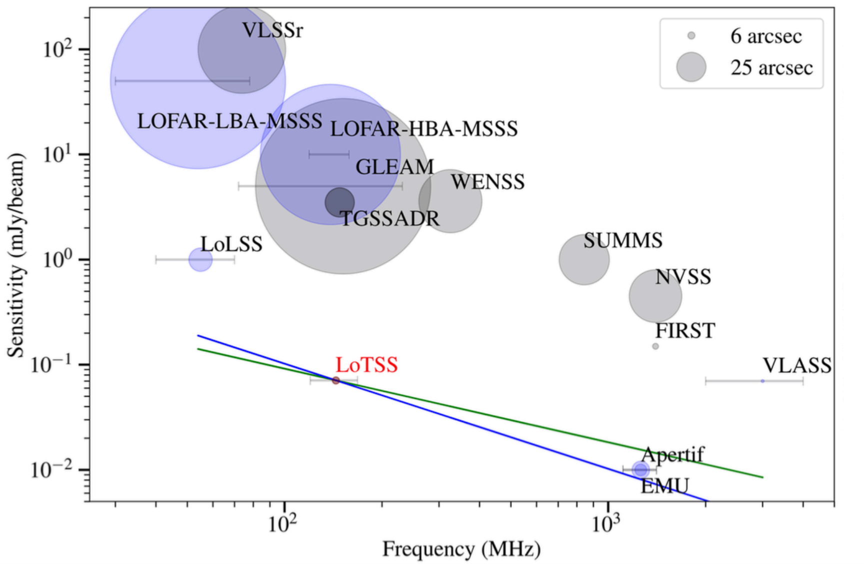
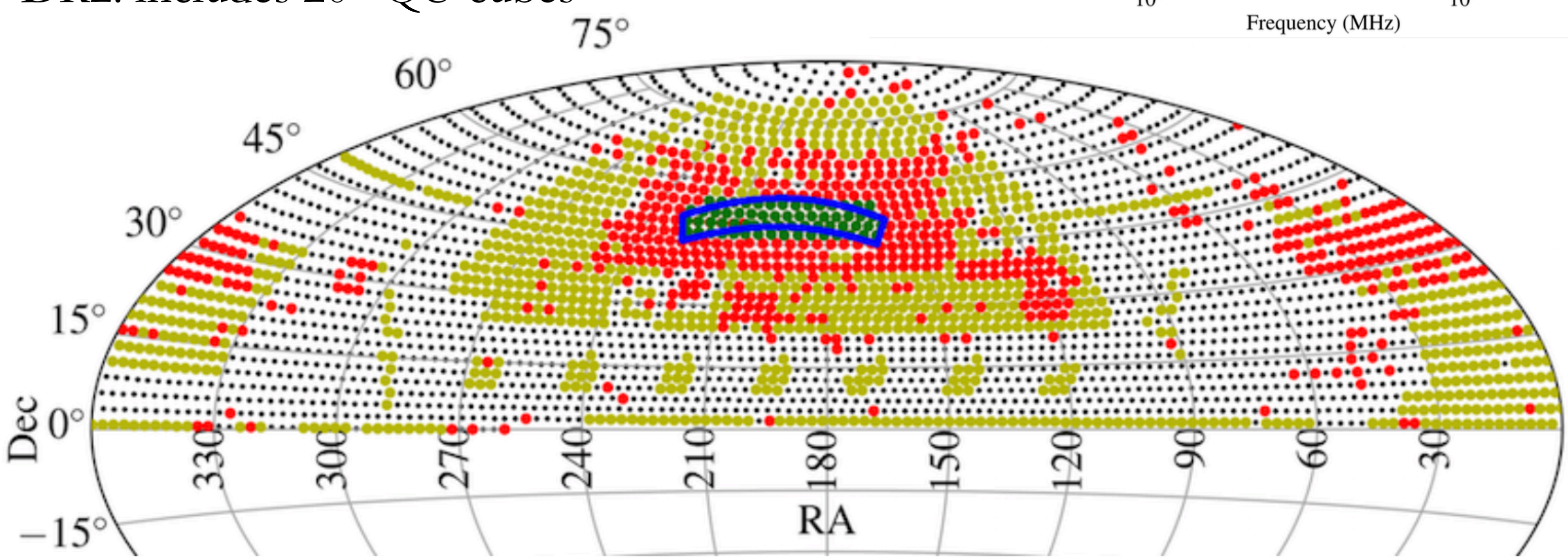
LOFAR Two-metre Sky Survey

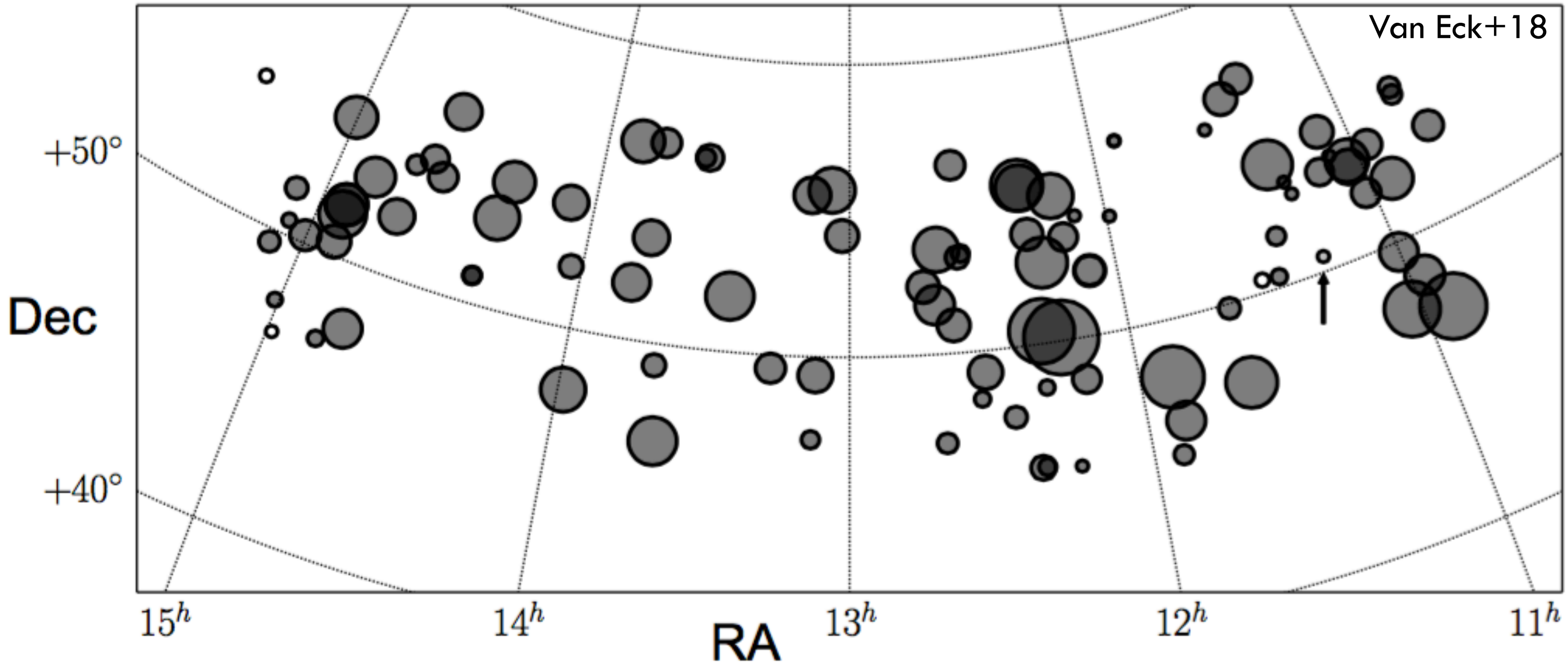
- LoTSS: 120 – 168 MHz, ~6”
  - Shimwell et al. (2017, 2019)
- 3168 x 8 hour pointings to cover the northern sky
- High RM accuracy (ΔRM ~ 0.1 rad/m^2)
- DR1: HETDEX Spring Field
  - ~400 sq deg, ~70 uJy/beam, 325,000 sources
- DR2: includes 20” QU cubes





LoTSS DR1: polarized sources

- HETDEX field: 4.3' resolution, 92 sources, ~1/6 deg^2
  - Van Eck, Haverkorn, et al. (2018)
- Mulcahy+14, Neld+18: ~20'' resolution, 1 source per ~3 deg^2



- Why is the polarised source density low in LoTSS?

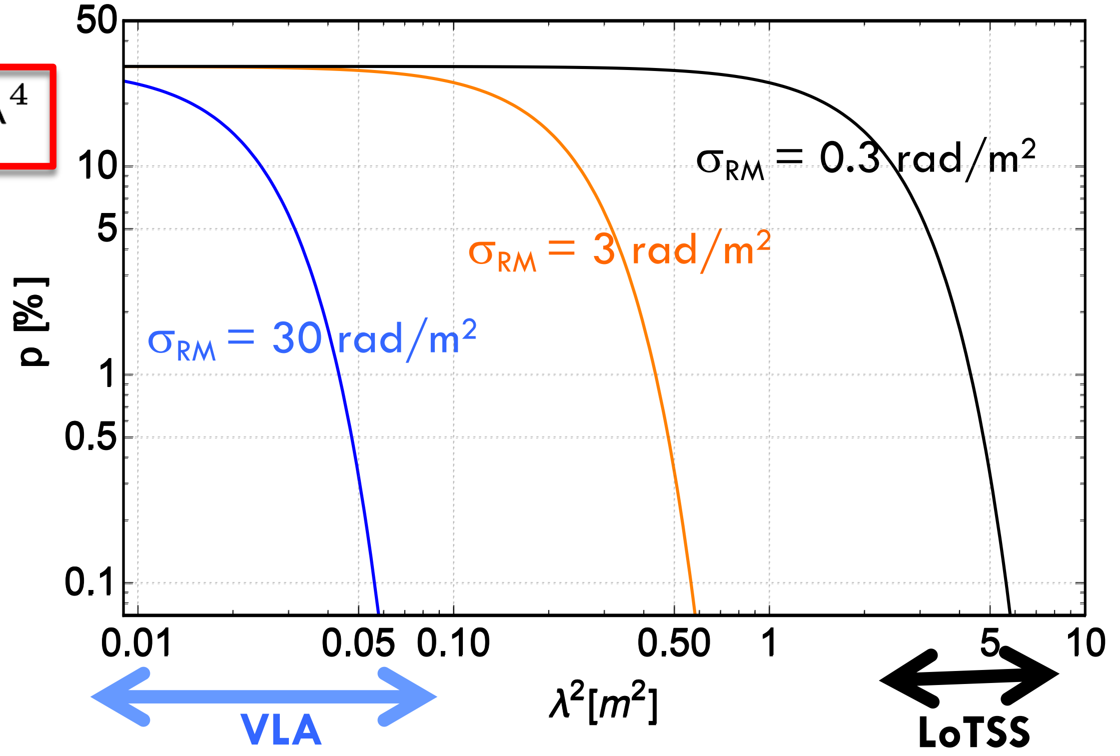
LoTSS DR1: polarized sources

- Polarised sources rare at low frequencies due to depolarisation
- Van Eck+18: 4' angular resolution
  - wavelength-independent depolarisation (vector-average over source)

Faraday dispersion
(wavelength-dependent)

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

- Need very small amounts of Faraday depolarisation
  - Low gas density environments
  - Compact emission region
- High angular resolution helps resolve large fluctuations in Faraday screen
  - Expect more sources at 20"

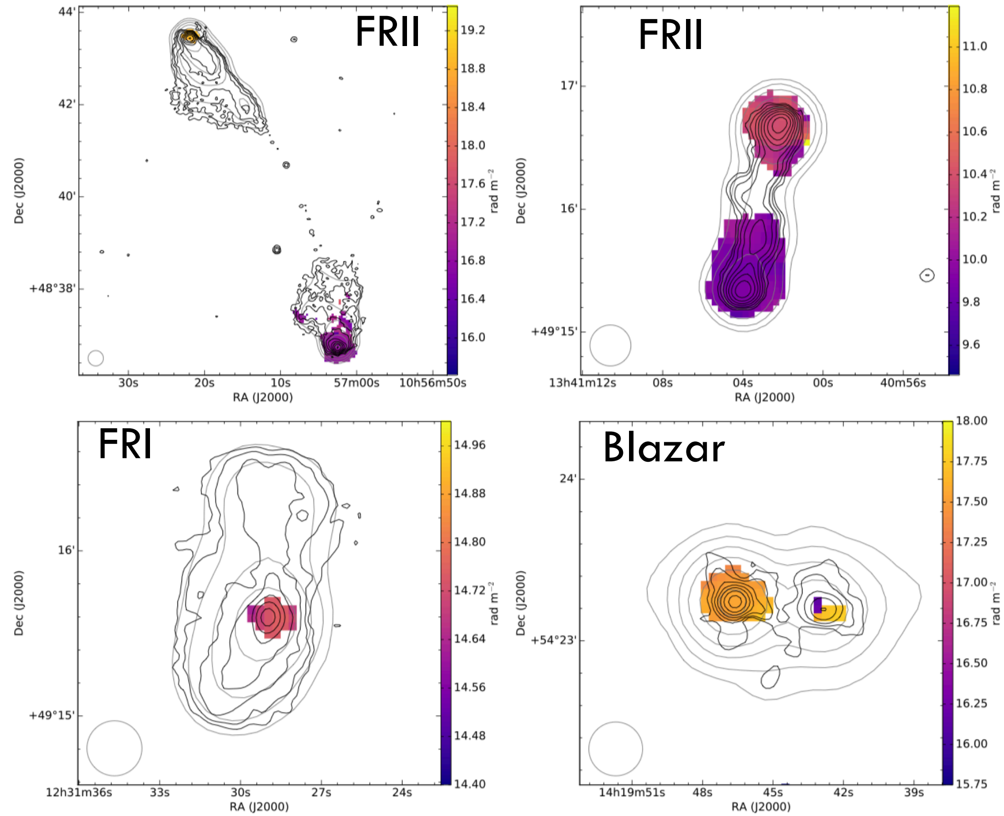


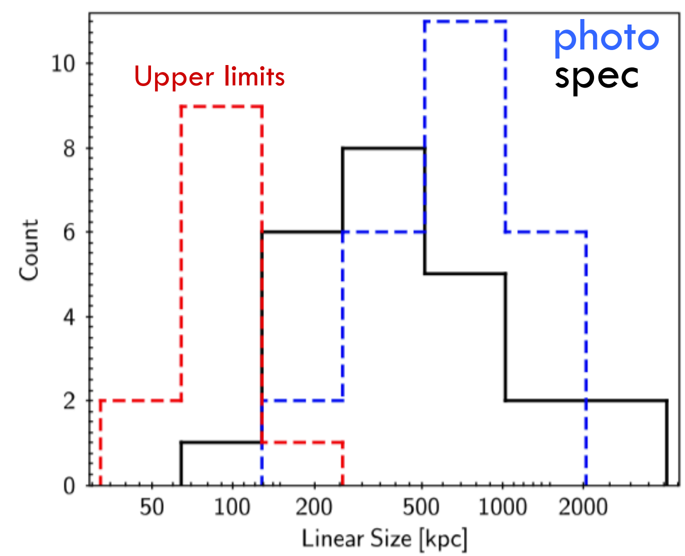
LoTSS DR1

- Majority of polarised sources (~64%) are large FRII radio galaxies
  - Median linear size of 710 kpc
  - Median radio luminosity at 144 MHz of 4×10^{26} W/Hz
- 13% of all polarised sources have linear size > 1 Mpc
- ~10% blazars

- Redshifts from LoTSS value-added catalogs (Duncan+19, Williams+19)
  - $0.1 < z < 1.5$
  - ~80% with z
  - Median z of 0.5

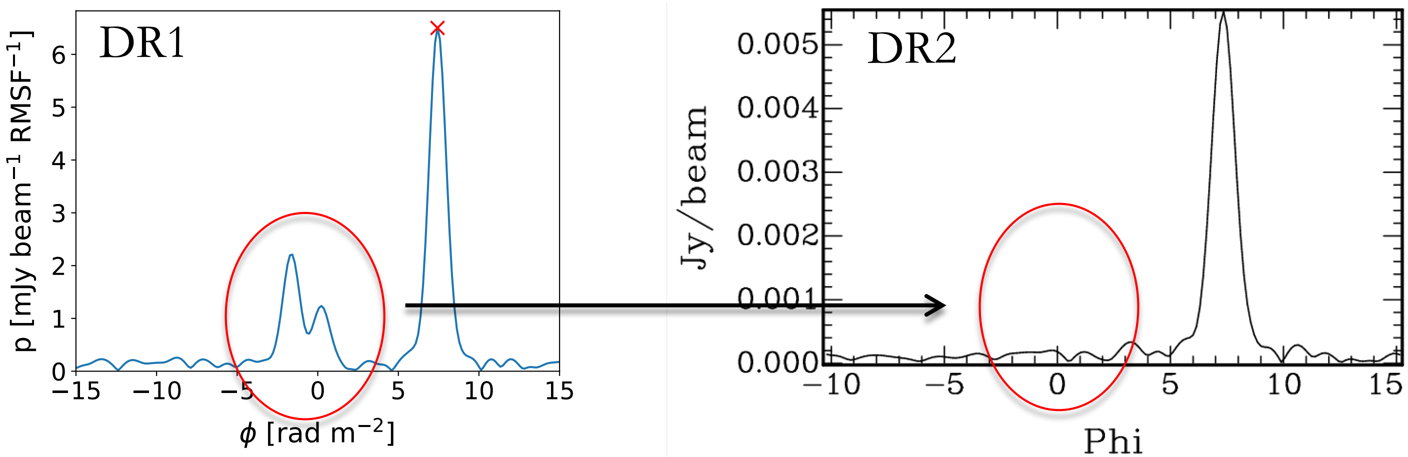
- See O’Sullivan+18b for details





LoTSS DR2: linear polarisation

- 20” QU cubes (dirty) after direction-dependent calibration
  - Provided as output from the LoTSS DR2 pipeline
  - 97.6 kHz channels, |RM| up to ~ 450 rad/m^2
  - RM synthesis applied to regions with Stokes I > 1 mJy/beam
  - Significant leakage improvement in DR2



- Initial test field: 13 sources > $8\sigma_{QU}$ (~1 per sq deg)
- Higher number density of polarised sources
  - Due to improved calibration and higher angular resolution

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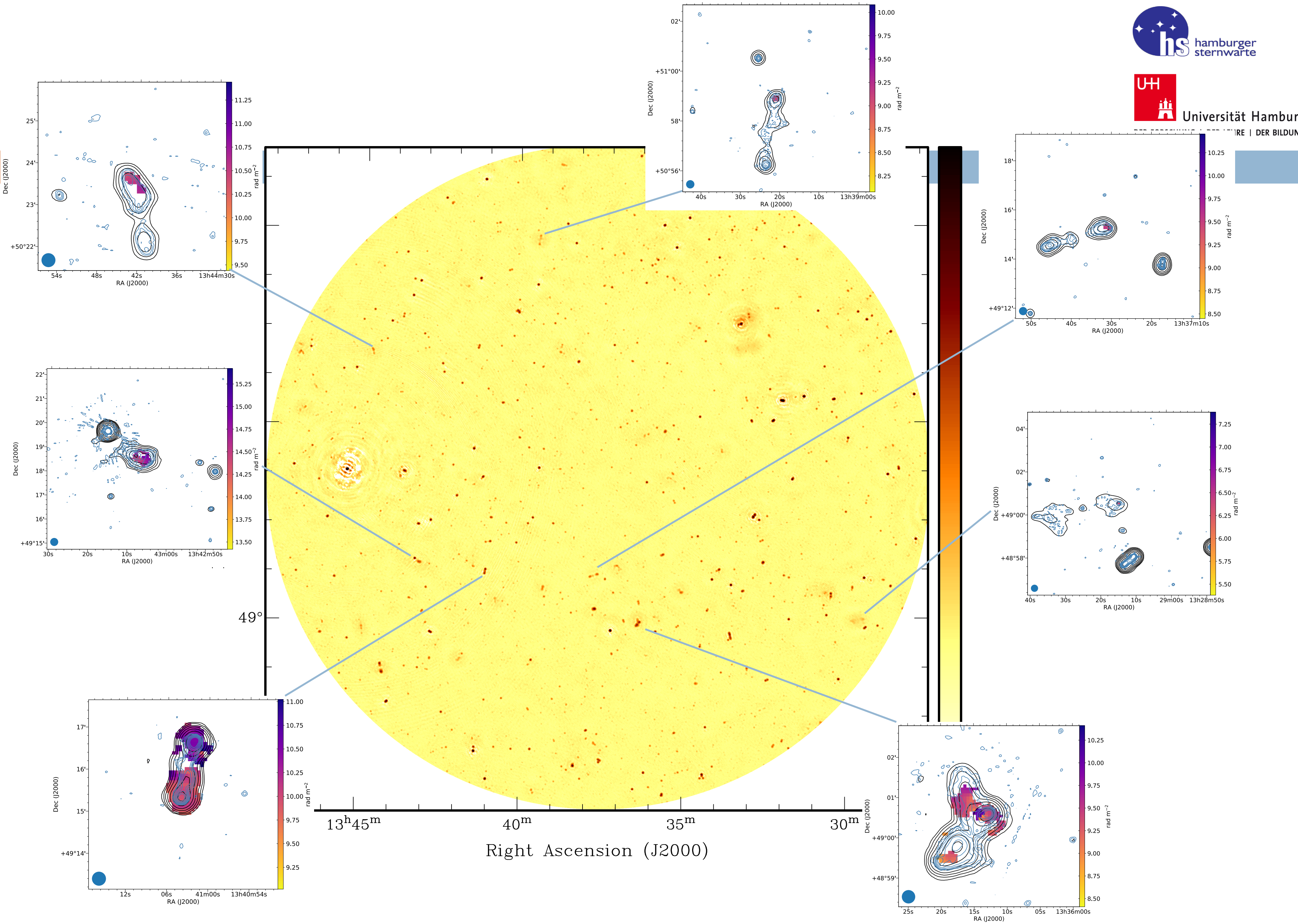
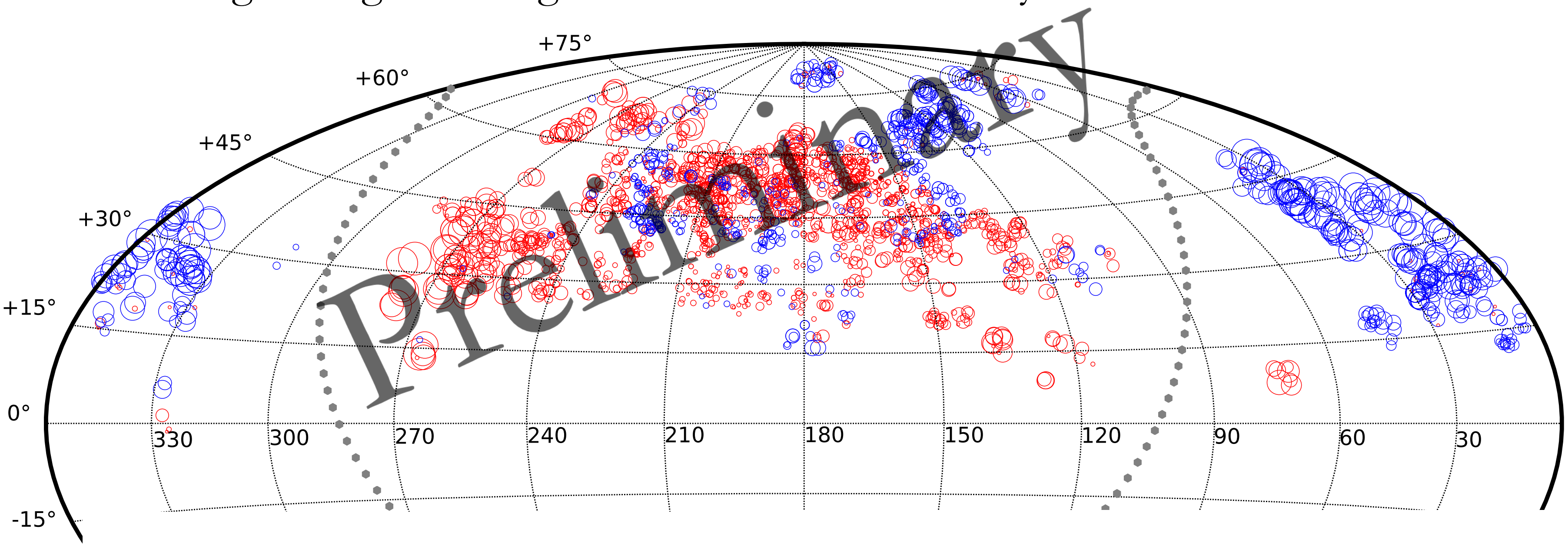


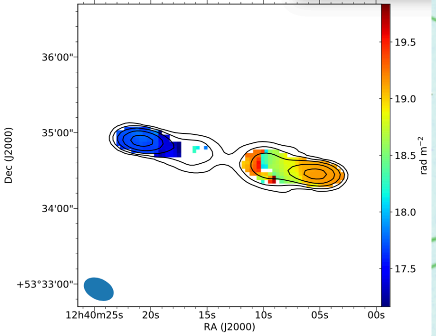
LoTSS DR2 RM Grid: in progress

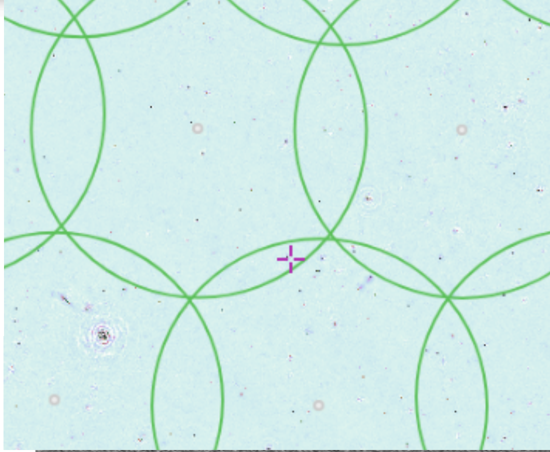
- Large fraction of DR2 pointings (500+) processed with RM synthesis
- Initial goal: RM catalogue later this year (O'Sullivan+19b, in prep.)
  - Data validation in progress (MKSP RM Grid Taskforce)
- Long term goal: RM grid for whole northern sky

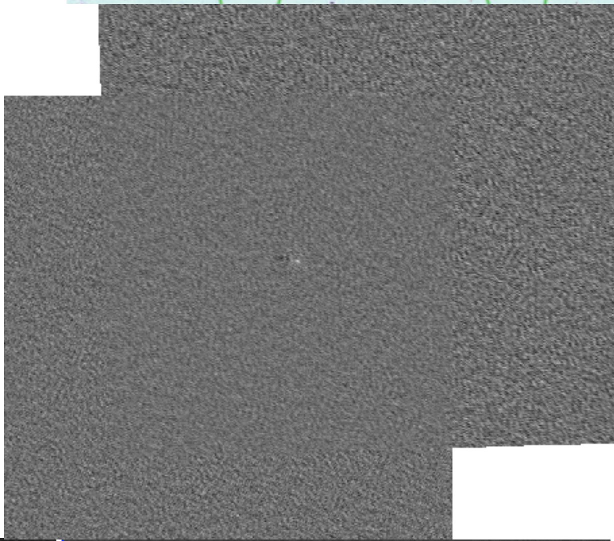


- Key science goals
  - Intergalactic magnetic fields
  - Galactic magnetic field model
  - Blazar physics, radio galaxy hotspots
  - Pulsar RMs + new pulsars

Mosaicing

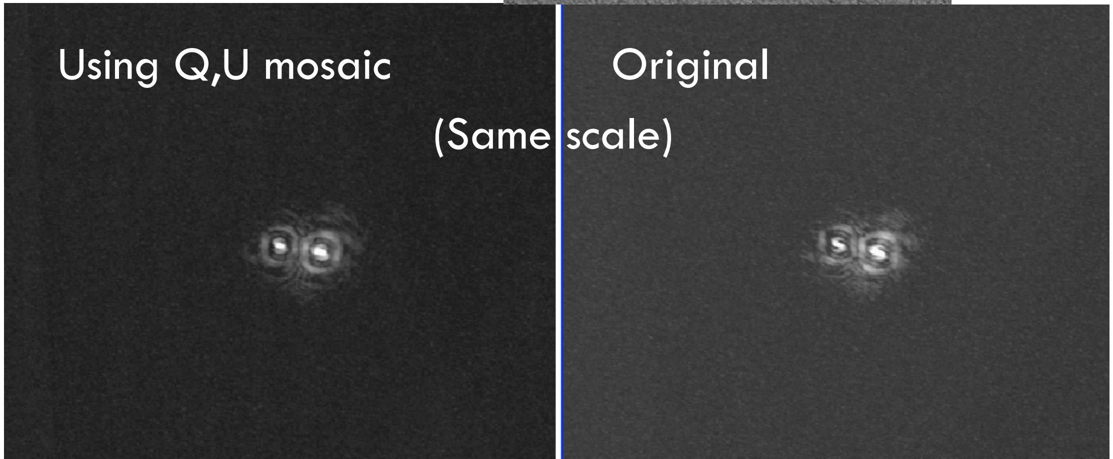






- Led by Noelia Herrera-Ruiz (Bochum)
- Focus on bright pol source (p ~ 20 mJy/beam) in an overlapping region
- Mosaicing Q and U channel images, weighted by the square of the primary beam
- Initial results
  - Noise improvement: ~1.7 (sqrt(3) as expected)
  - But depolarisation: peak p 1.3x smaller
  - S/N improvement in this case

- Alignment of polarisation angles to minimise depolarisation
- Important for deep field data
  - Combine many pointings



PyRMSynth optimised, parallelised, distributed for DR2

pyrmsynth_lite

- Load DR2 cubes directly
- Significantly faster
- Auto-flagging (Heald)
- Noise maps
- On-the-fly masking
- CLEAN thresholding based on the noise
- and more, see:

github: sabourke/pyrmsynth_lite

pipeline

- Mulit-node, multi-core
- MPI for data distribution
- cfitsio fitscopy for split
- pyrmsynth_lite
- Singularity for deployment
- Slurm (imposed by cluster)
- 18 mins / DR2 low pointing
  - Full field + RMClean

Using LOFAR to constrain intergalactic magnetic fields

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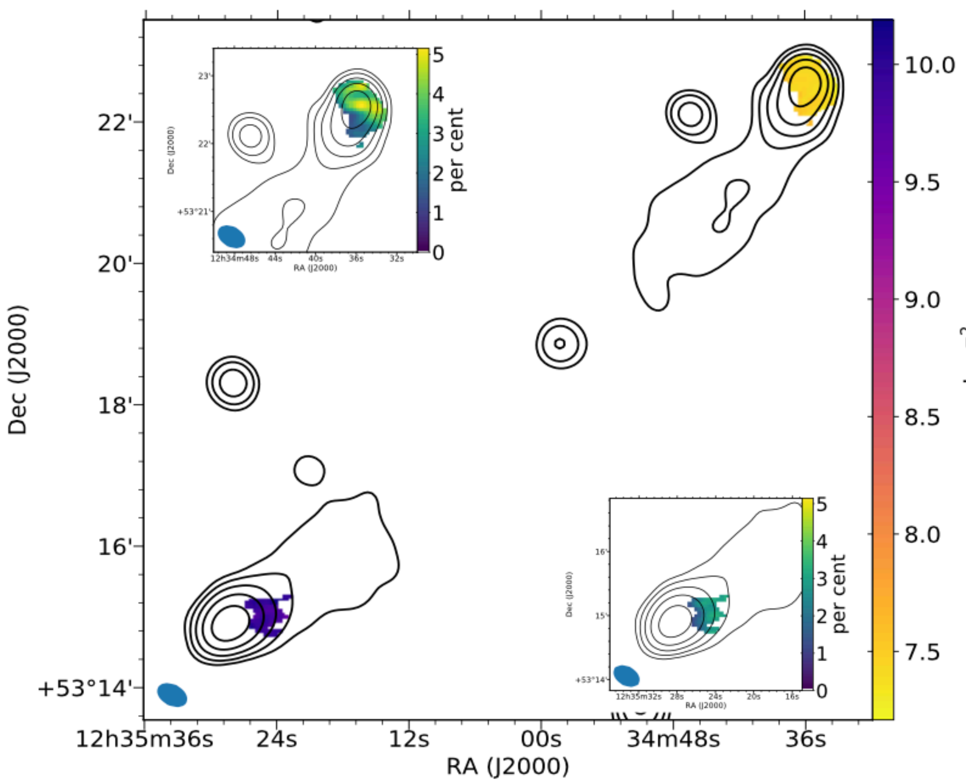
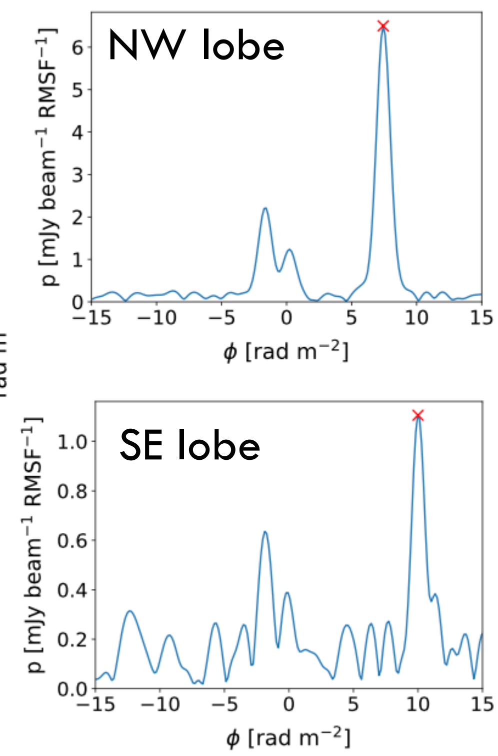
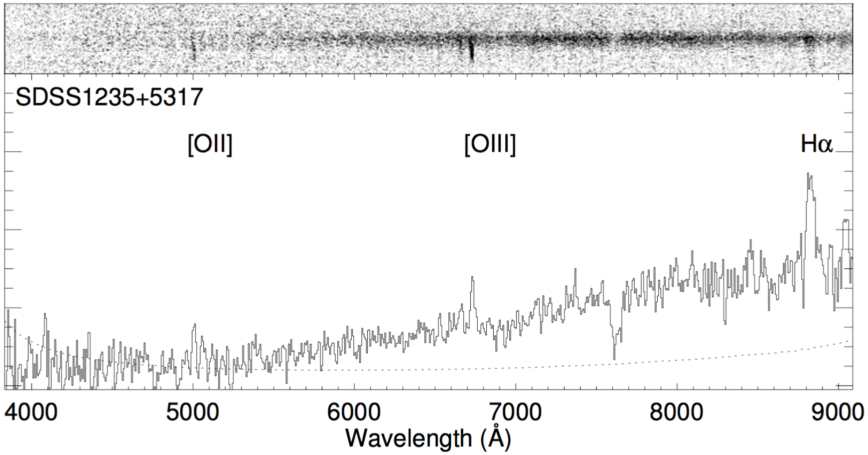
Intergalactic magnetic fields

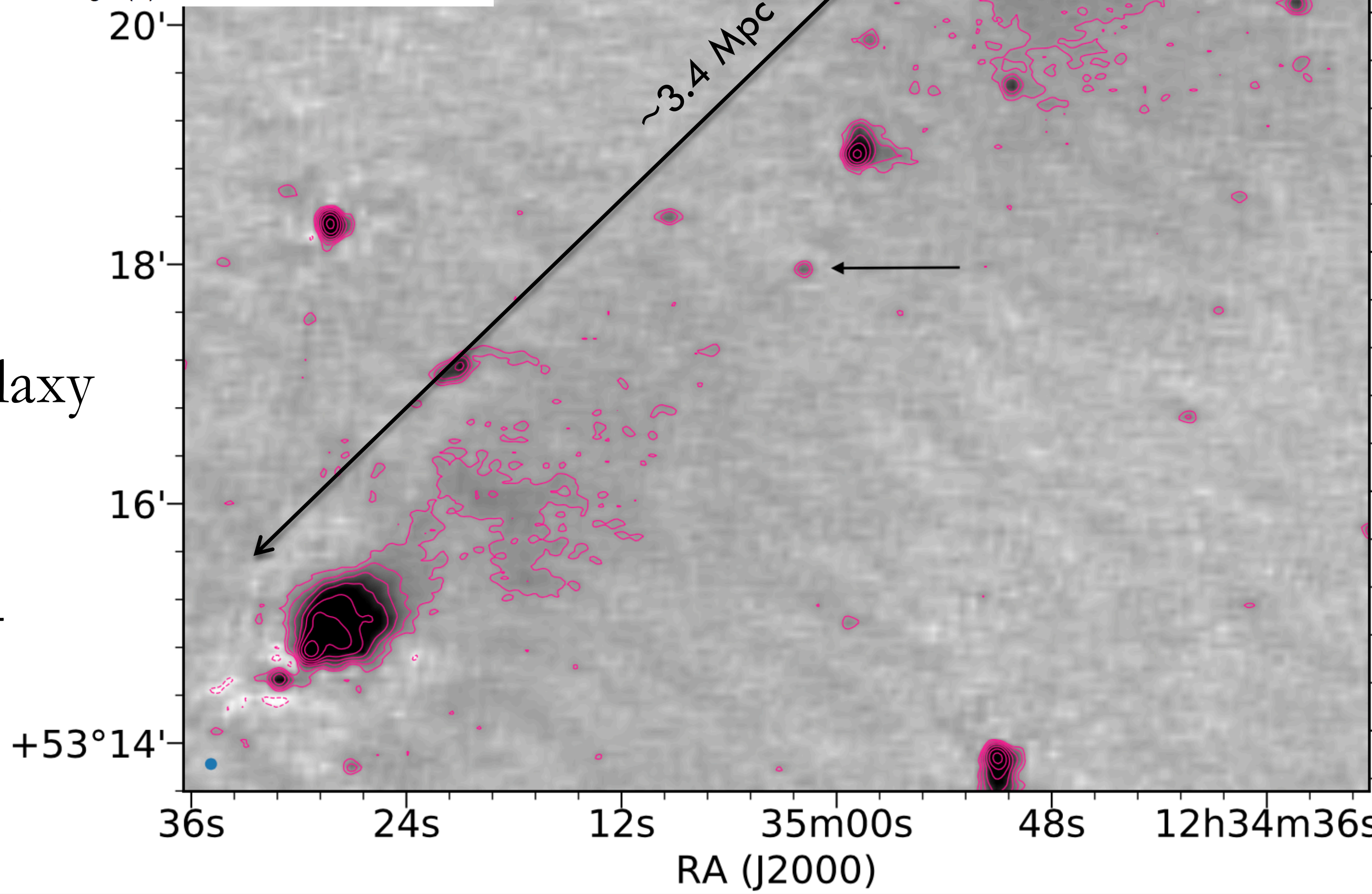
- Demonstrating the capability of LOFAR
  - O'Sullivan et al. (2019), A&A LOFAR Special Issue (DR1 data release)
- Constraining magnetic fields associated with large-scale-structure filaments (cosmic web)



Faraday spectrum





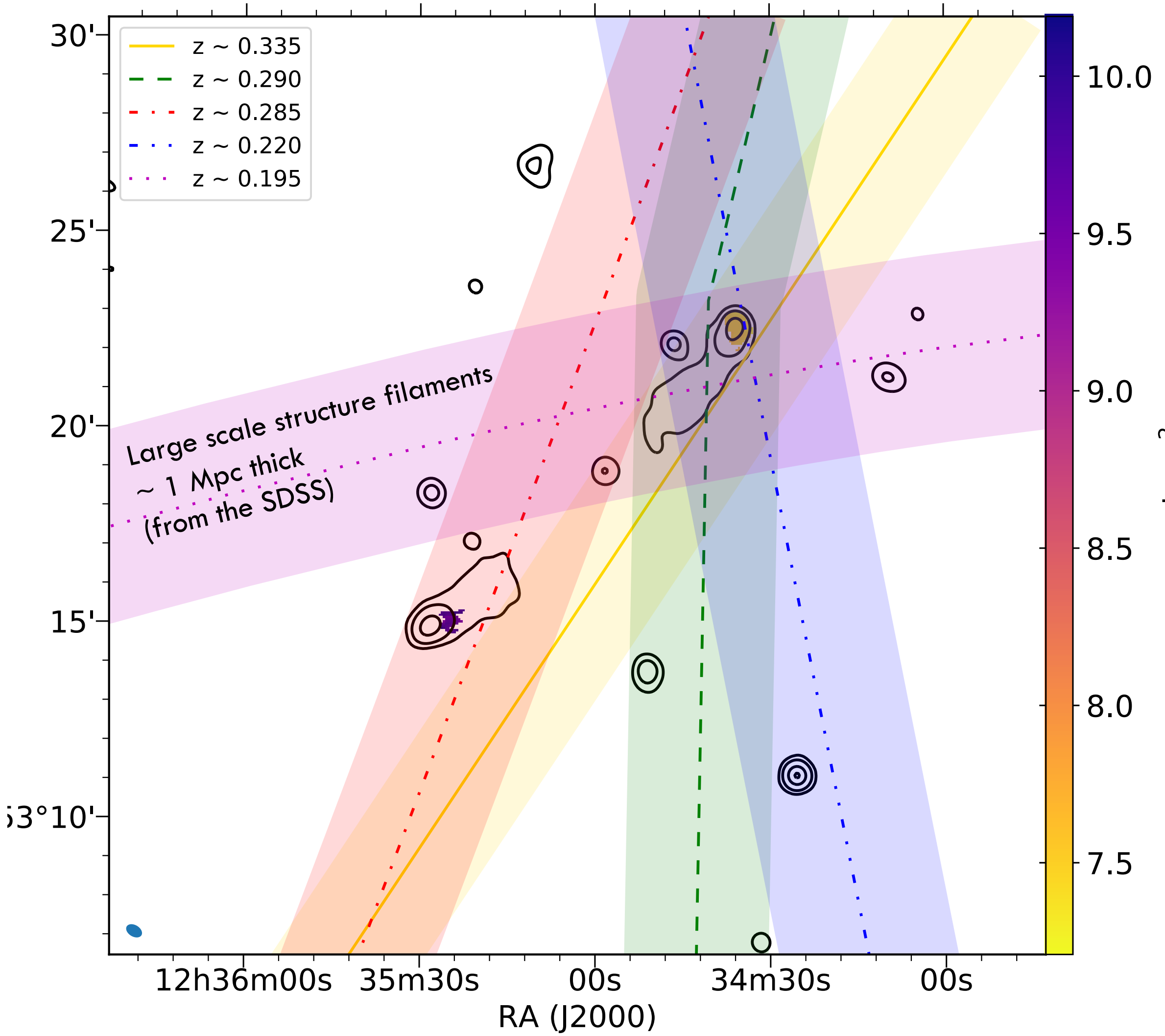


- Host galaxy ID and redshift
- z ~ 0.34

Intergalactic magnetic fields

S. P. O'Sullivan, et al. (2019), A&A, LOFAR Surveys Key Science Project and Magnetism Key Science Project Collaborations

- ILT J123459.82+531851.0
  - z = 0.3448 ± 0.0003
  - Linear size: 3.4 Mpc
  - RM difference between lobes of 2.5±0.1 rad/m^2
- More large-scale-structure (LSS) filaments along line of sight to NW lobe
  - B_{LSS} ~ 0.3 μG, if *all* RM difference due to filaments
- MHD simulations: small probability (<5%) of all 2.5 rad/m^2 due to IGMF
- Galactic RM variation on 11' scales likely the dominant factor
  - Need better RM grid!



O'Sullivan et al. (2019)

Summary

- Faraday rotation measures (RMs) can be used to probe magnetic fields throughout the Universe
  - Key SKA goal: construction of high density RM grid to study the origin and evolution of cosmic magnetic fields

- m-wavelength potential for this still relatively unexplored
  - ~Two orders of magnitude higher RM accuracy than at cm-wavelengths
  - LOFAR RM Grid: expect $\mathcal{O}(10^4)$ for full LoTSS
  - ~1 polarised source per square degree

- Demonstration of the capability of LOFAR to probe IGMF (O'Sullivan+19)
  - RM distribution of Giant Radio Galaxy found in LoTSS data
  - Found difference of ~2.5 rad/m^2 on ~3.4 Mpc scales
  - Excess of potential LSS filaments covering N-W hotspot
  - MHD sims: low probability of being entirely due to IGMF
  - Galactic RM variations may explain majority of excess
  - Need statistical sample to better probe IGMF --> LoTSS RM Grid

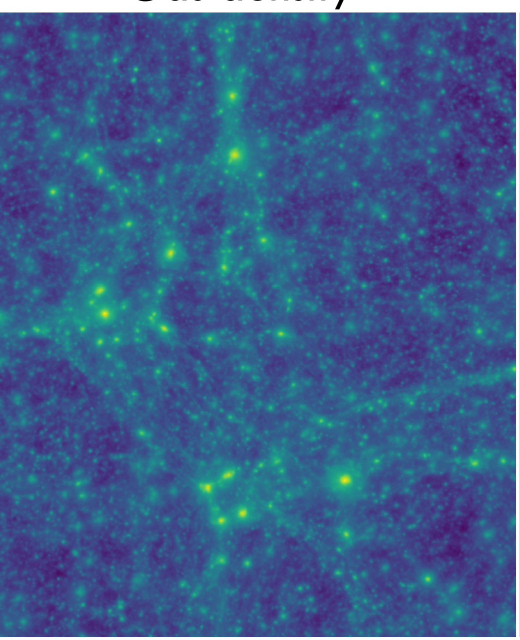
- The end

RM contribution from IGMF

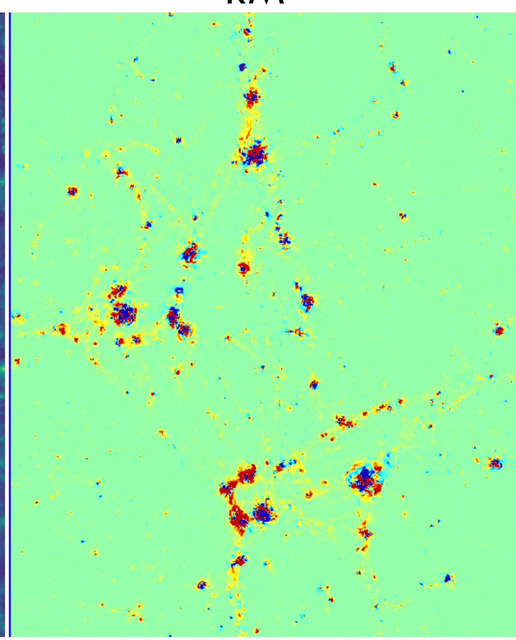
O'Sullivan, Machalski, Van Eck, Heald, Brüggen, Vazza, Hardcastle, Shimwell, et al. (2018), in preperation

- Recent cosmological simulations of IGMF in filaments (Vazza et al. 2014)
  - 50^3 Mpc^3 volumes, with spatial resolution of 20 kpc, stacked up to z ~ 0.34
  - ~5% probability of 2.5 rad/m^2 excess due to IGMF, if the magnetic fields have been seeded at cosmological epochs, at the level ~1 nG (Planck CMB limit)
    - ~0% for 0.1 nG seed field

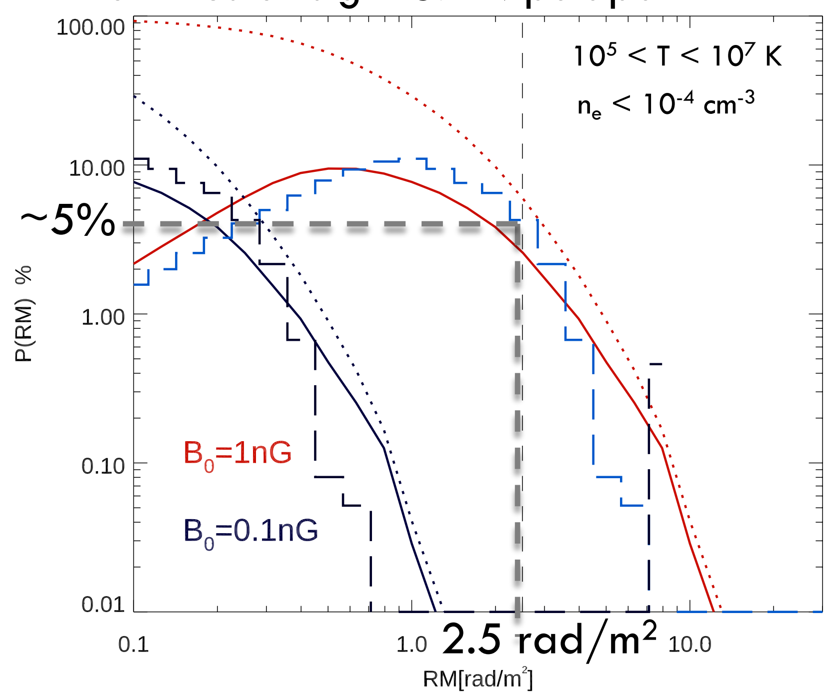
Gas density



RM

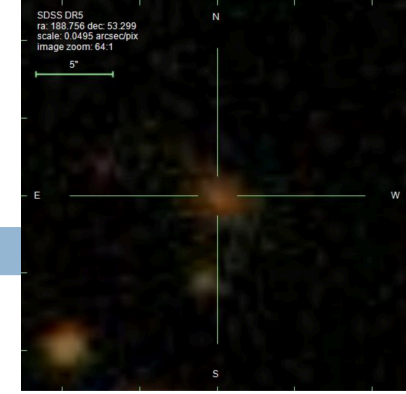


Distribution functions of RM in "filaments" for lines of sight 3.4 Mpc apart



Local RM contribution

O'Sullivan, Machalski, Van Eck, Heald, Brüggen, Vazza, Hardcastle, Shimwell, et al. (2018), in preperation

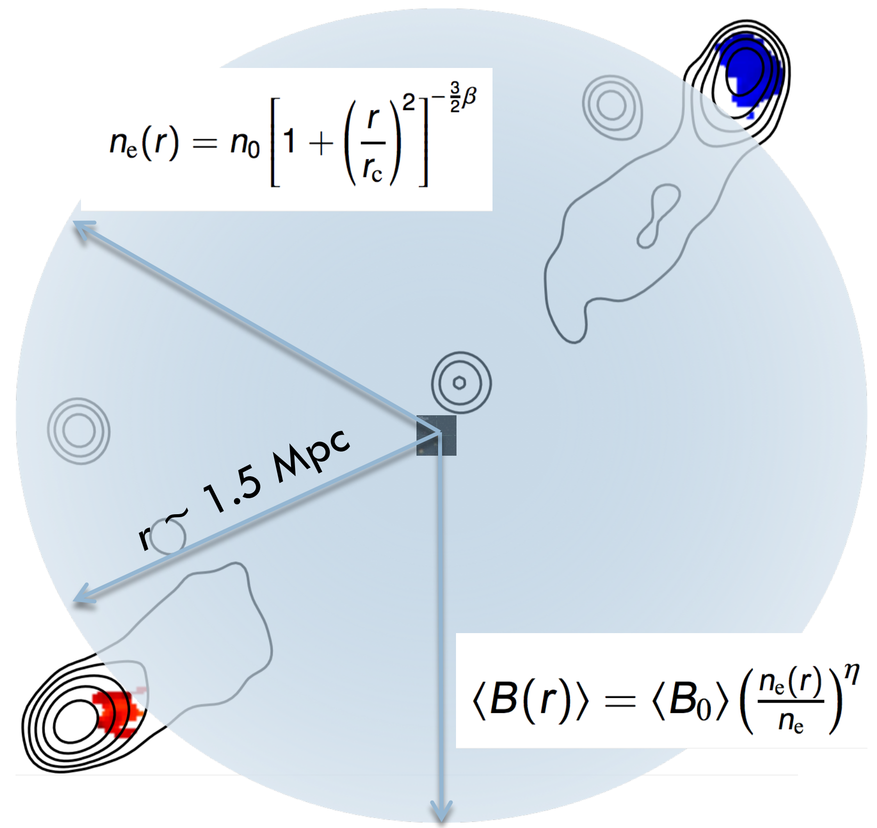


- SDSS J123501.52+531755.0
  - Central galaxy of group at z ~ 0.34 (Hao+10)
  - Lobes ~plane of sky (no bright jet)
  - Crude RM estimate from group gas & B-field scaling, with field fluctations on range of scales

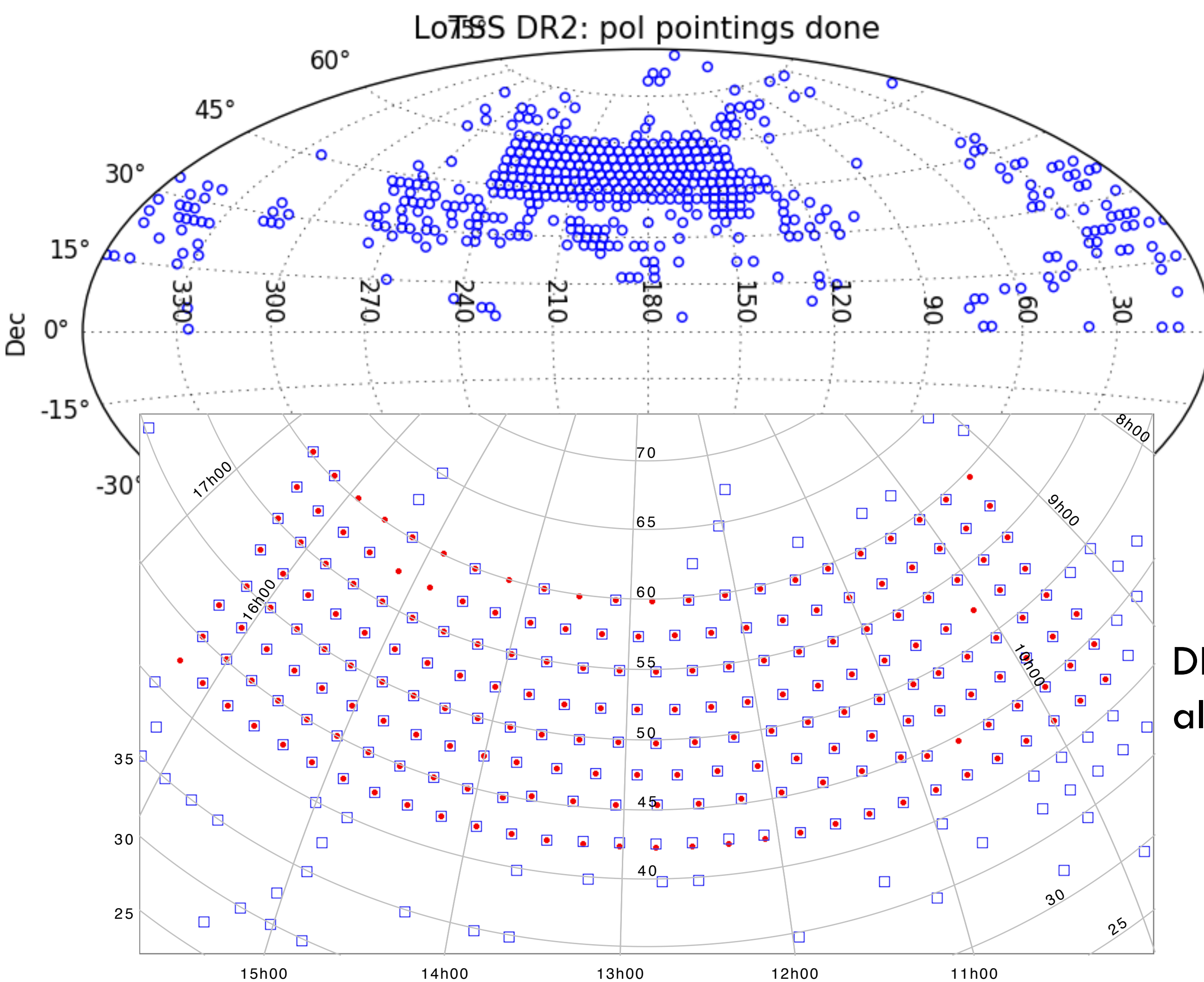
    $\beta \sim 0.5$, $\eta \sim 0.9$, $n_0 \sim 10^{-3}$ cm^{-3}, $B_0 \sim 5\ \mu$G, $\Lambda_C \sim 10$ kpc

    $B(1.5\,\mathrm{Mpc}) \sim 0.1\ \mu\mathrm{G}$
    $n_e(1.5\,\mathrm{Mpc}) \sim 2 \times 10^{-5}\ \mathrm{cm}^{-3}$
    gives $\sigma_{\mathrm{RM}} \sim 0.1\ \mathrm{rad/m}^2$
- Even if we assume and outer-scale for field fluctuations of ~500 kpc, can only produce <RM> ~ 0.4 rad/m^2

e.g. Dolag+01, Enßlin & Vogt 03, Murgia+04, Laing+08, Guidetti+07,+10, Bonafede+10,13, Vacca+10,+12, Govoni+18



Progress: 500+ RM cubes



DR2 “main” area almost complete

Software development

- pyrmsynth_lite
  - https://github.com/sabourke/pyrmsynth_lite
  - Stephen Bourke (Onsala)

- More user-friendly version for DR2 data
  - Additional features over standard pyrmsynth:
    - Use LoTSS-DR2 cubes directly
    - Significantly faster when using a mask
    - Save only wanted output cubes
    - Auto flag data after loading
    - Exclude a specified Phi range from the integrated maps
    - Generate a noise map from a specified Phi range
    - Save output in single or double precision format
    - Use an input mask to specify areas to do RMCLEAN
    - RMCLEAN down to a factor of the Phi noise
    - Create a mask on the fly from a Stokes I image and cutoff value.