RADIO POLARIZATION MEASUREMENTS WITH LOFAR

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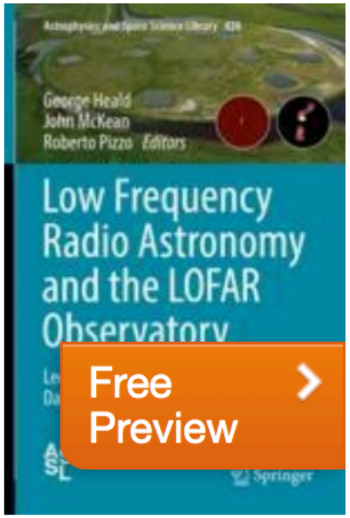
Astrophysics and Space Science Library



Low Frequency Radio Astronomy and the LOFAR Observatory

Lectures from the Third LOFAR Data Processing School

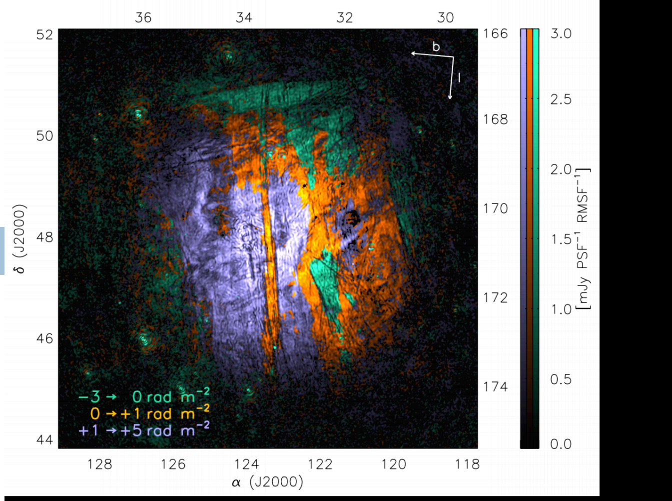
Editors: **Heald**, George, **McKean**, John, **Pizzo**, Roberto (Eds.)

- https://www.springer.com/gp/book/9783319234335

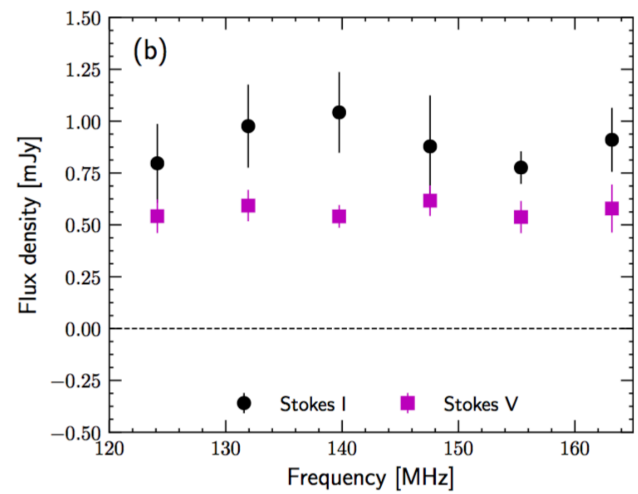
Part III Advanced Topics in LOFAR Data Processing

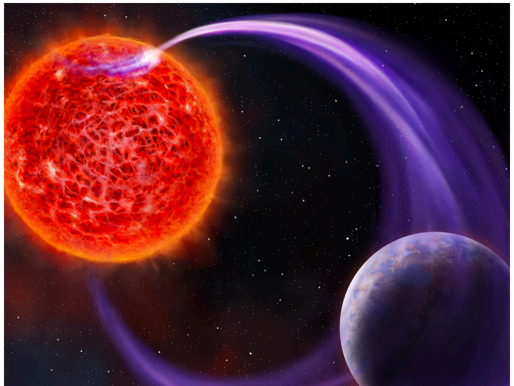
Polarization with LOFAR

- What I <u>won't</u> talk about:
  - diffuse linear polarization (Galactic emission)
    - eg. Jelic+15, Van Eck+19, …
  - circulation polarization
    - AGN jets: synchrotron, Faraday conversion
      - eg. O'Sullivan+13
    - stellar systems: coherent emission, highly (circularly) polarized
      - eg. Vedantham+20
  - pulsar polarization: linear & circular
    - eg. Gould & Lyne '98
- What I <u>will</u> talk about:
  - Linear polarization from radio galaxies (synchrotron emission) and Faraday rotation
    - Just HBA, not LBA (yet…)



Jelic et al., 2015, A&A

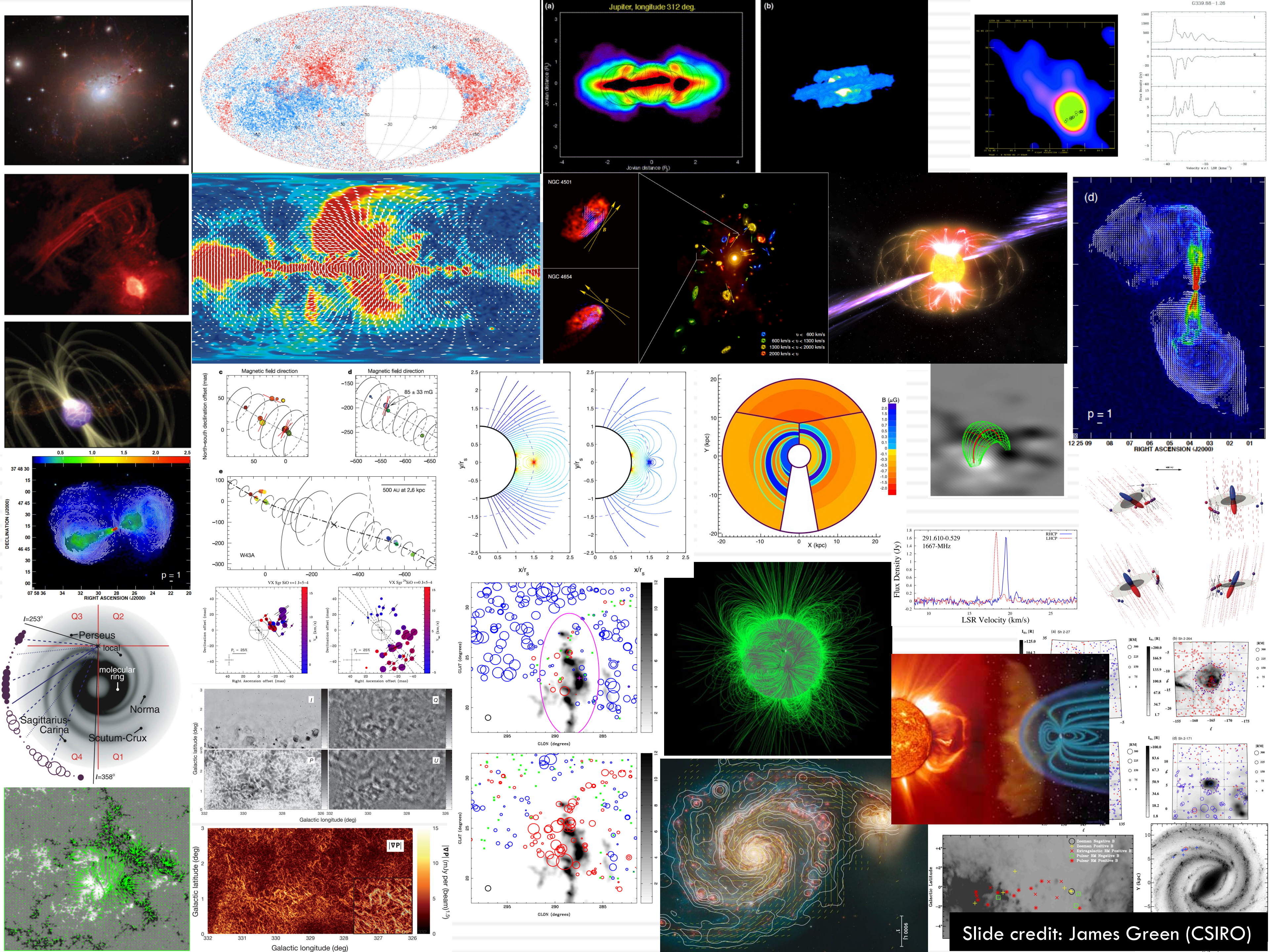




Why do we care about polarization?

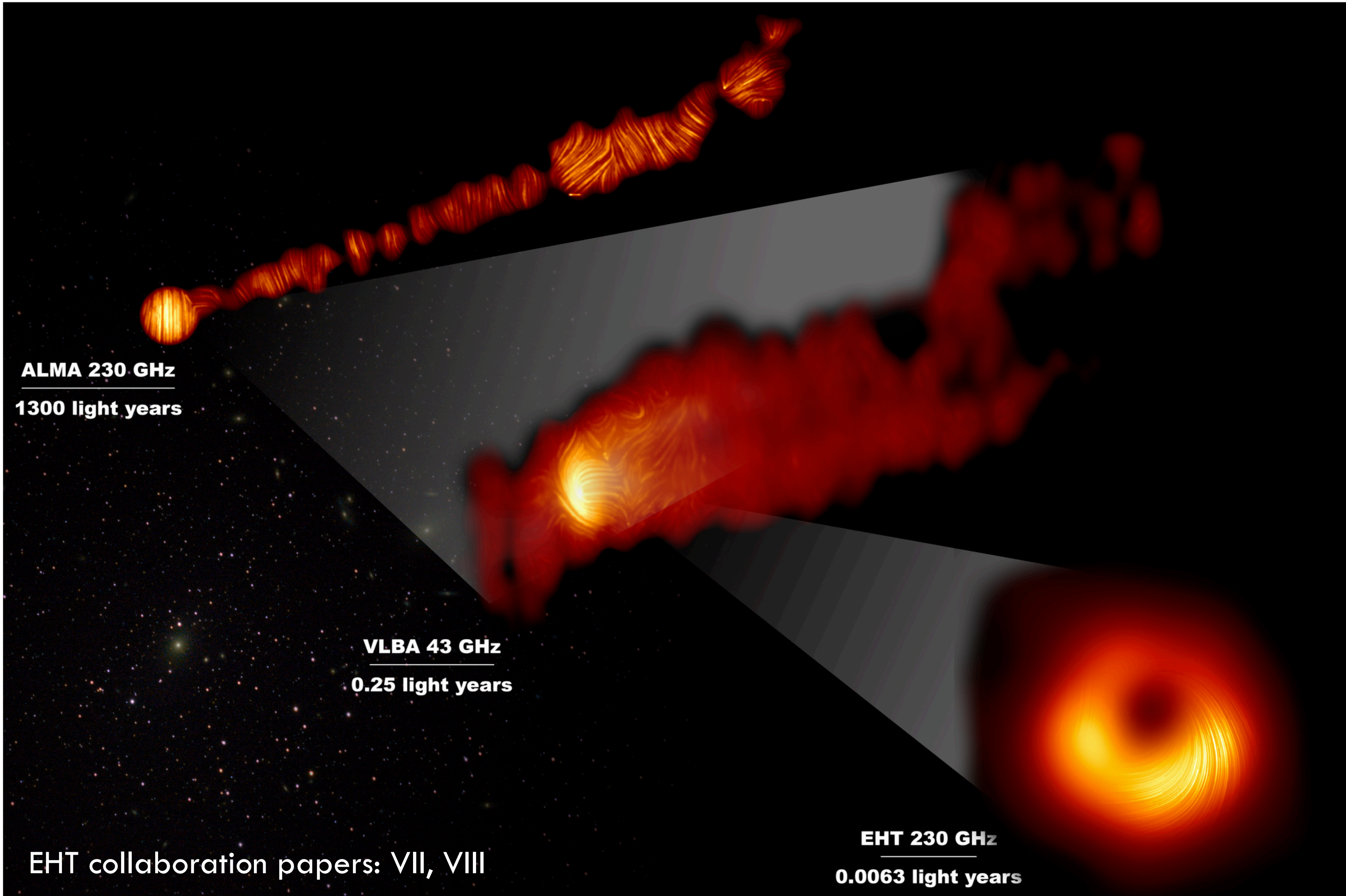
- Because the Universe is magnetized
- Polarization observations provide insight to magnetic fields
  - eg. degree of order of the field in the emission region, can infer strength of magnetic fields in otherwise "invisible" thermal plasma through propagation effects (eg. Faraday rotation)
  - The origin and evolution of magnetic fields in the cosmic web are key open questions in astrophysics

- Within the Milky Way:
  - Interstellar medium, stars & planets, pulsars, star formation regions, …
- Extragalactic:
  - AGN jets and lobes, fast radio bursts, the intergalactic medium, …
- Cosmological:
  - Primordial magnetic fields, the cosmic web: voids, walls & filaments



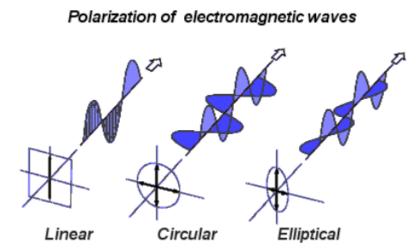
Jupiter, longitude 312 deg.
Jovian distance (R_J)
NGC 4501
NGC 4654
Magnetic field direction
85 ± 33 mG
500 AU at 2.6 kpc
W43A
p = 1
RIGHT ASCENSION (J2000)
DECLINATION (J2000)
Q3
Q2
Q4
Q1
Perseus
local
molecular ring
Norma
Sagittarius-Carina
Scutum-Crux
l=253°
l=358°
291.610-0.529
1667-MHz
RHCP
LHCP
Flux Density (Jy)
LSR Velocity (km/s)
B (μG)
X (kpc)
Y (kpc)
Galactic latitude (deg)
Galactic longitude (deg)
|∇P|
GLON (degrees)
GLAT (degrees)
Slide credit: James Green (CSIRO)

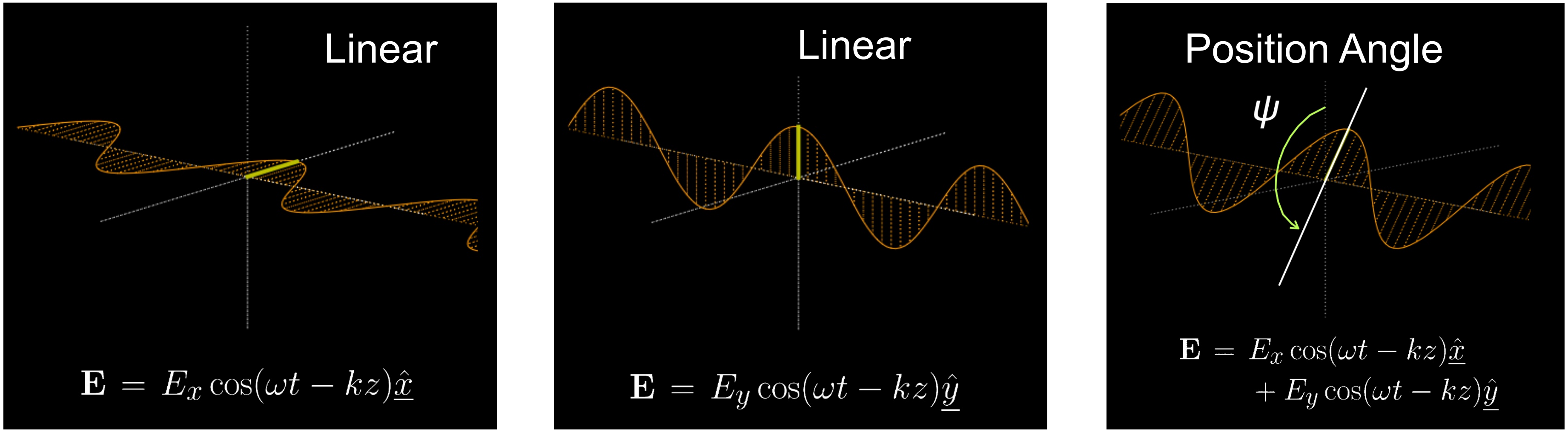
Polarized SMBH "shadow" @ ~20 μas



EHT collaboration papers: VII, VIII

Linear polarization





[image credit D. McConnell]

Linear polarization flux density: $LP = \sqrt{Q^2 + U^2}$

Linear polarization angle: $\chi = \frac{1}{2}\tan^{-1}(U/Q)$

Circular polarization: $CP = V$

$$I = \langle E_x E_x^* \rangle + \langle E_y E_y^* \rangle \tag{10.24}$$

$$Q = \langle E_x E_x^* \rangle - \langle E_y E_y^* \rangle \tag{10.25}$$

$$U = \langle E_x E_y^* \rangle + \langle E_y E_x^* \rangle \tag{10.26}$$

$$V = -\mathrm{i}\left(\langle E_x E_y^* \rangle - \langle E_y E_x^* \rangle\right). \tag{10.27}$$

Linear polarization vector:

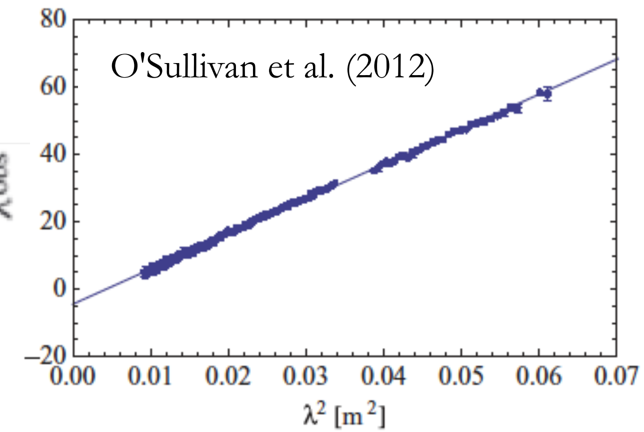
$$\boxed{\begin{aligned} P &= Q + iU \\ P &= pe^{2i\chi} \end{aligned}}$$

cf. Chapter 10 of LOFAR book (slide 2)

Linear polarization & Faraday rotation

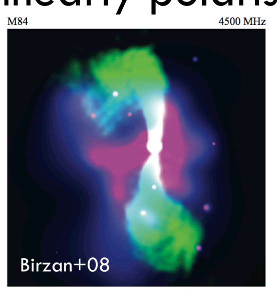
- Linear polarisation vector

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

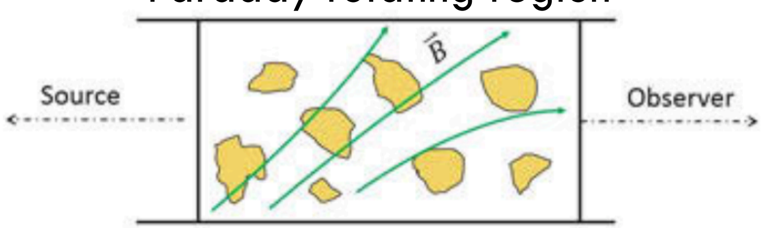


$$\mathrm{RM}_{[\mathrm{rad\ m^{-2}}]} = 0.812 \int_{\mathrm{source}}^{\mathrm{telescope}} n_{e\ [\mathrm{cm^{-3}}]}\, B_{||\ [\mu\mathrm{G}]}\, dl_{\ [\mathrm{pc}]}$$

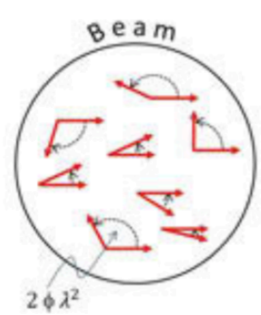
Synchrotron emission from a radio galaxy (linearly polarised)



Faraday rotating region



B-field + ionised gas

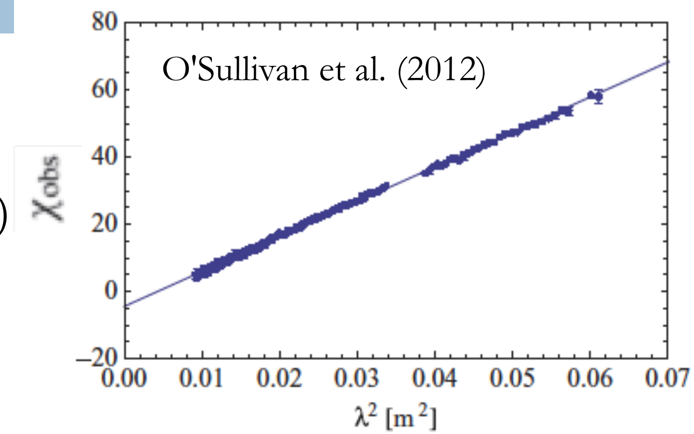


Telescope

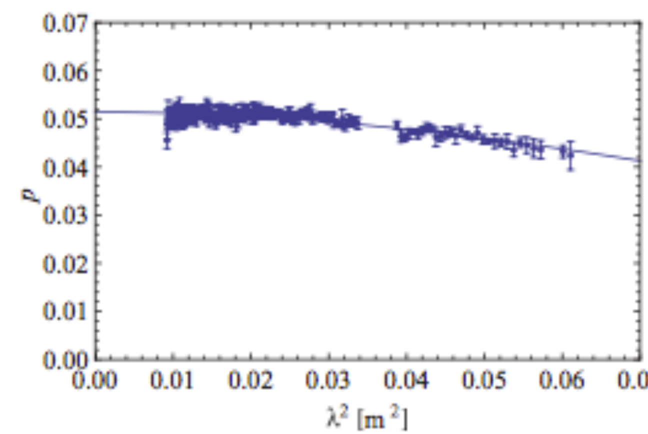
Faraday rotation and depolarisation

- Linear polarisation vector

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

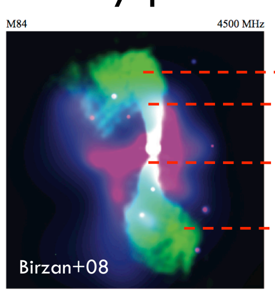


$$\mathbf{P} = p_0 e^{2i(\chi_0 + \mathrm{RM}\,\lambda^2)} e^{-2\sigma^2_{\mathrm{RM}}\lambda^4}$$



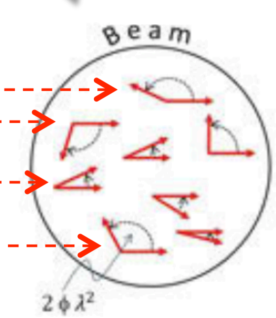
Synchrotron emission (linearly polarised)

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



Faraday rotating region

B-field + ionised gas

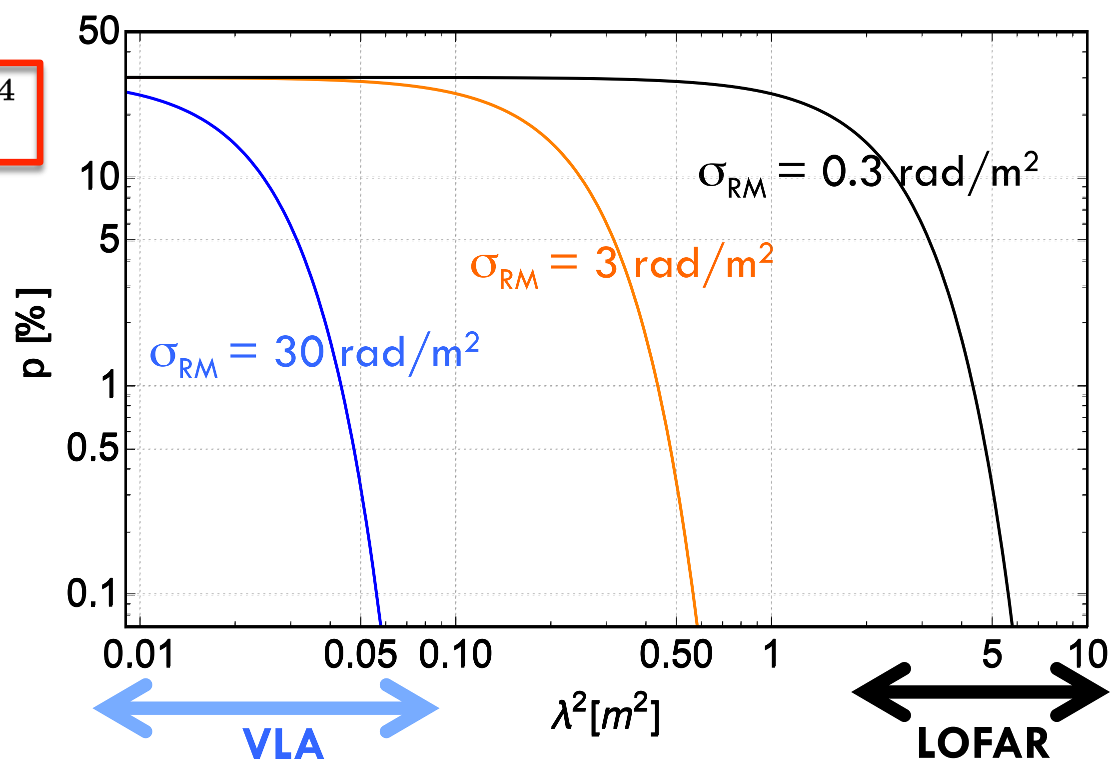


LOFAR polarized sources

- 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)

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

- 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



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

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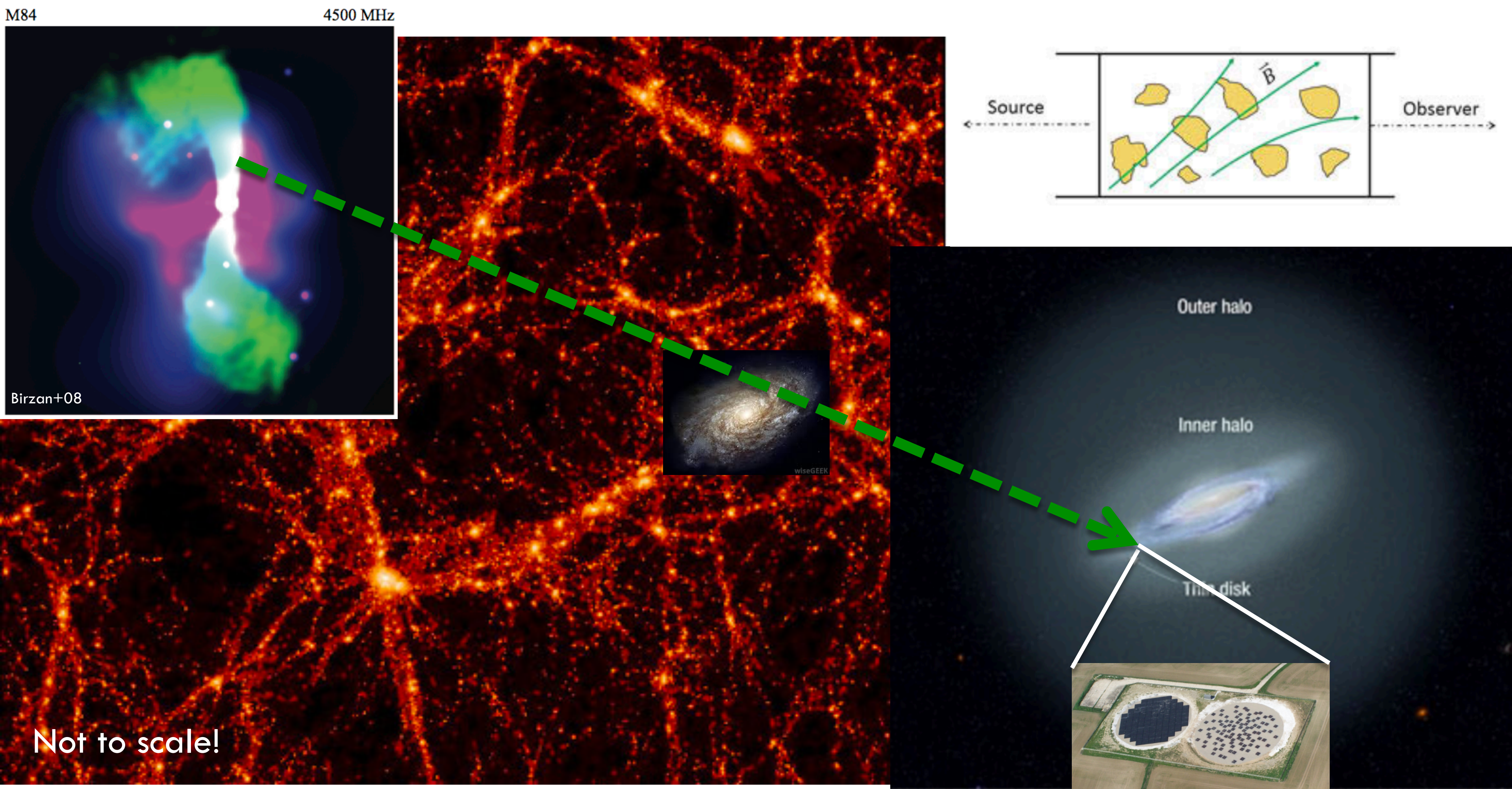
- Using Faraday rotation to probe the magnetised universe
- Many contributions along line of sight, and on different scales



LOFAR's competitive advantage

- Why is measuring polarization important (at long wavelengths)?

- m-spectropolarimetry with LOFAR
  - eg. LOFAR Two-Metre Sky Survey (120 – 168 MHz @ 100 kHz)
  - High RM precision ($\Delta\lambda^2_{LoTSS}/\Delta\lambda^2_{VLA}$ >~ 40)
    - LoTSS (120 – 168 MHz): $\delta\phi \sim 1$ rad/m^2 (20", 6", 0.3")
    - 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: probing the magnetisation of the cosmic web
  - LOFAR enables precision probes of the tenuous, weakly magnetised regions of the intergalactic medium ($n_e < 10^{-4}$ cm^{-3}, $B < 100$ nG)
    - e.g. O'Sullivan et al. (2020)
  - Help discriminate between competing models for origin of cosmic magnetism
    - ie. a primordial seed field scenario vs. outflows from galaxies/AGN

Faraday depth & RM synthesis

- Here I've replaced RM with ϕ to denote the "Faraday depth" of different emission regions along the line of sight

$$\mathbf{P} = Q + iU = pIe^{2i\chi} = pIe^{2i(\chi_0 + \phi\lambda^2)}$$

  - Divide by Stokes I to remove frequency dependence of synchrotron radiation.

- In reality, the net observable polarization is obtained by summing the polarized emission from all possible Faraday depths within the synthesized beam of the telescope:

$$\boldsymbol{P}(\lambda^2) = \int_{-\infty}^{\infty} \boldsymbol{F}(\phi) e^{2i\phi\lambda^2} d\phi$$

$$\phi = 0.812 \int_L^{\text{telescope}} n_e \boldsymbol{B}.\mathrm{d}\boldsymbol{s}$$

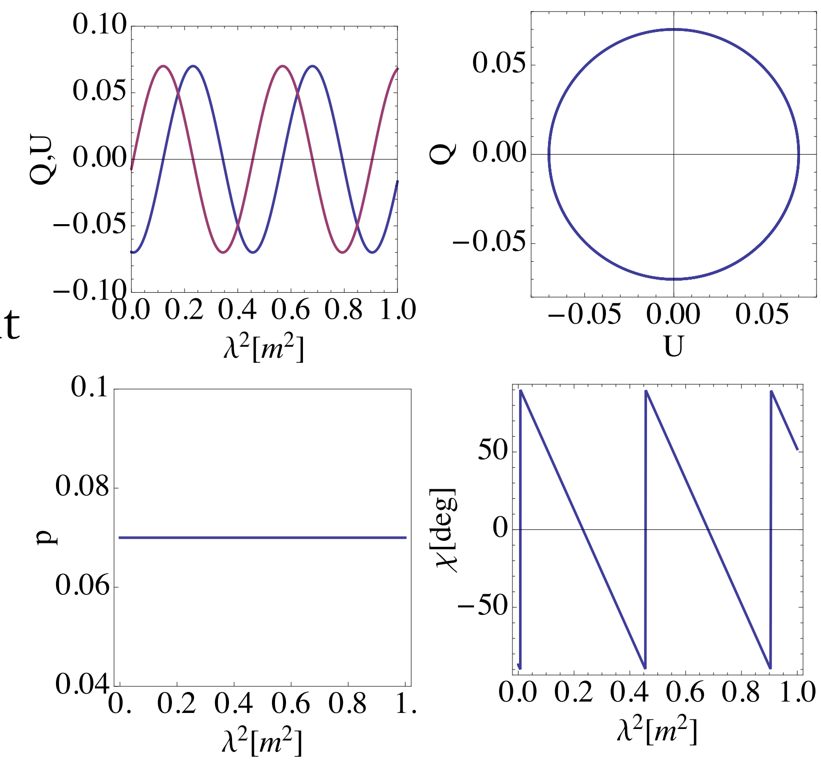
- Where $\mathbf{F}(\phi)$, the Faraday dispersion function, specifies the distribution of polarized emission as a function of Faraday depth along the line of sight.

- We can then attempt to Fourier invert $\mathbf{P}(\lambda^2)$ to get $\mathbf{F}(\phi)$

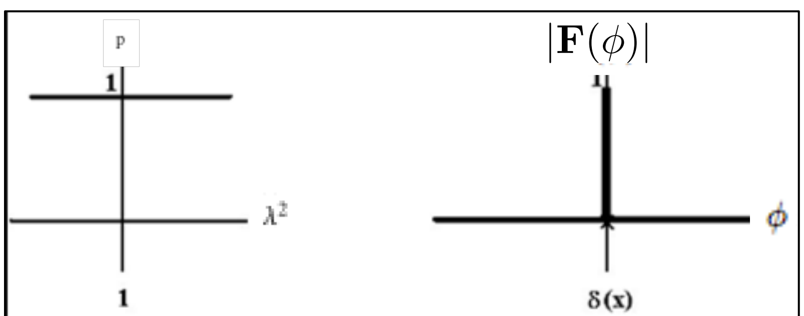
Faraday depth & RM synthesis

$$P(\lambda^2) = \int_{-\infty}^{\infty} F(\phi) e^{2i\phi\lambda^2} d\phi$$

- Example 1: A single polarized emission region (ϕ = RM)
  - $|F(\phi)|$ is a delta-function
  - p(λ^2) is constant
  - Linear $\chi(\lambda^2)$



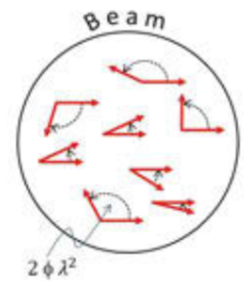
- Faraday "thin" or single RM component

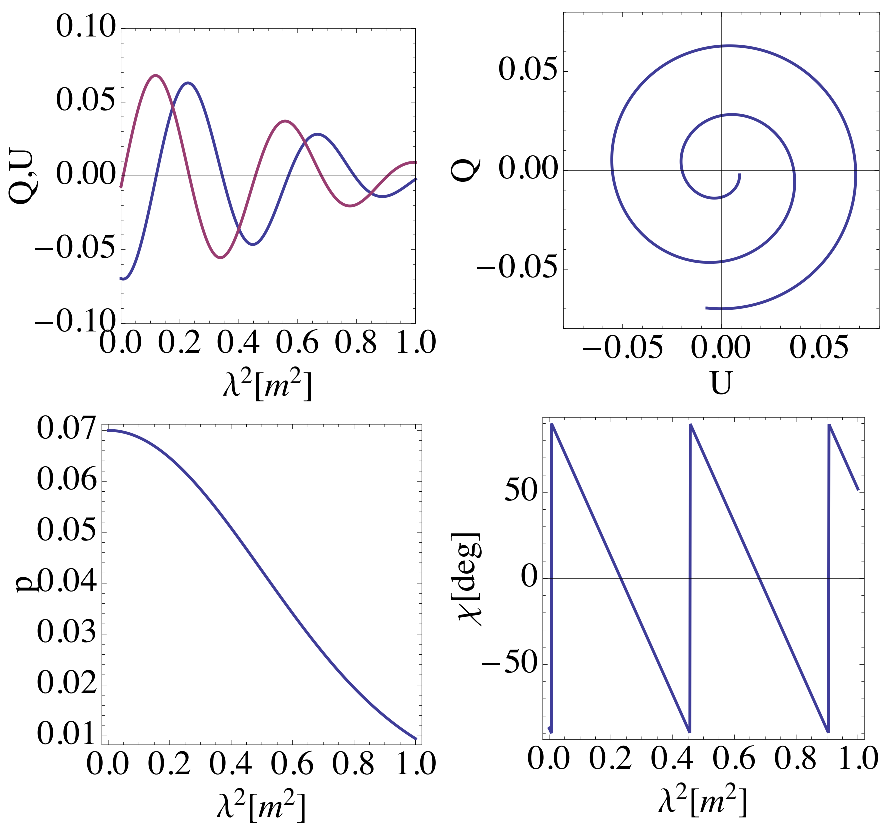


Faraday depth & RM synthesis

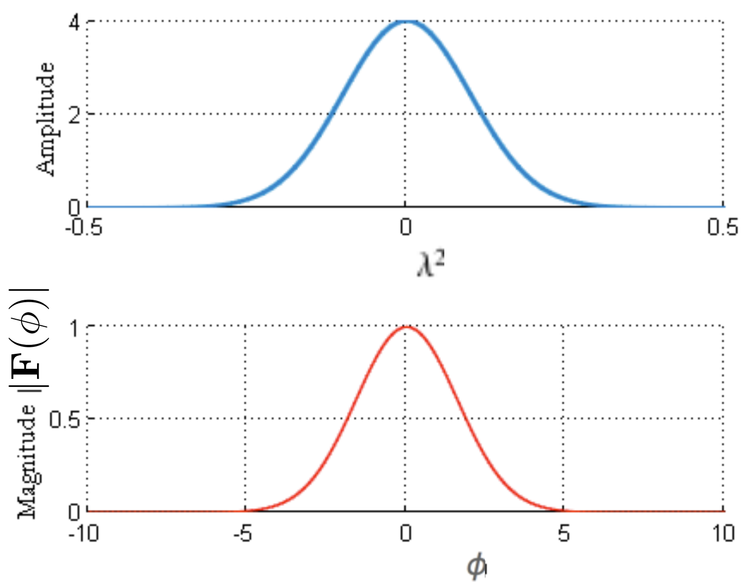
- Example 2: External Faraday Dispersion

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





$$\boldsymbol{P}(\lambda^2) = \int_{-\infty}^{\infty} \boldsymbol{F}(\phi) e^{2i\phi\lambda^2} d\phi$$



How to reconstruct $F(\phi)$?

- RM synthesis: Burn (1966); Brentjens & de Bruyn (2005)
- Take the Fourier transform of the complex polarization vector

$$\boldsymbol{P}(\lambda^2) = \int_{-\infty}^{\infty} \boldsymbol{F}(\phi) e^{2i\phi\lambda^2} d\phi \quad \longrightarrow \quad \mathbf{F}(\phi) = \frac{1}{\pi} \int_{-\infty}^{\infty} \mathbf{P}(\lambda^2) e^{-2i\phi\lambda^2} d\lambda^2$$

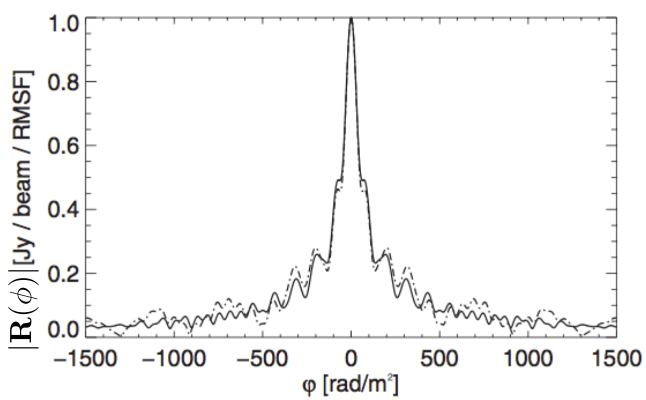
- But incomplete coverage in λ^2-space leads to an approximate reconstruction.

$$\tilde{F}(\phi) = F(\phi) * R(\phi) = K \int_{-\infty}^{+\infty} \tilde{P}(\lambda^2) \mathrm{e}^{-2i\phi\lambda^2}\, \mathrm{d}\lambda^2$$

$$R(\phi) = K \int_{-\infty}^{+\infty} W(\lambda^2) \mathrm{e}^{-2i\phi\lambda^2}\, \mathrm{d}\lambda^2$$

$$K = \left(\int_{-\infty}^{+\infty} W(\lambda^2)\, \mathrm{d}\lambda^2 \right)^{-1}.$$

- $F(\phi)$ is convolved with $R(\phi)$ after Fourier filtering by the weight function $W(\lambda^2)$
- $R(\phi)$ is the rotation measure spread function (analogous to PSF)



RM Synthesis software links

- pyrmsynth
  - https://github.com/mrbell/pyrmsynth
- pyrmsynth_lite (optimised for LoTSS)
  - https://github.com/sabourke/pyrmsynth_lite
- RM-synthesis
  - https://github.com/brentjens/rm-synthesis
- RM-tools
  - https://github.com/CIRADA-Tools/RM-Tools

Polarization with LOFAR

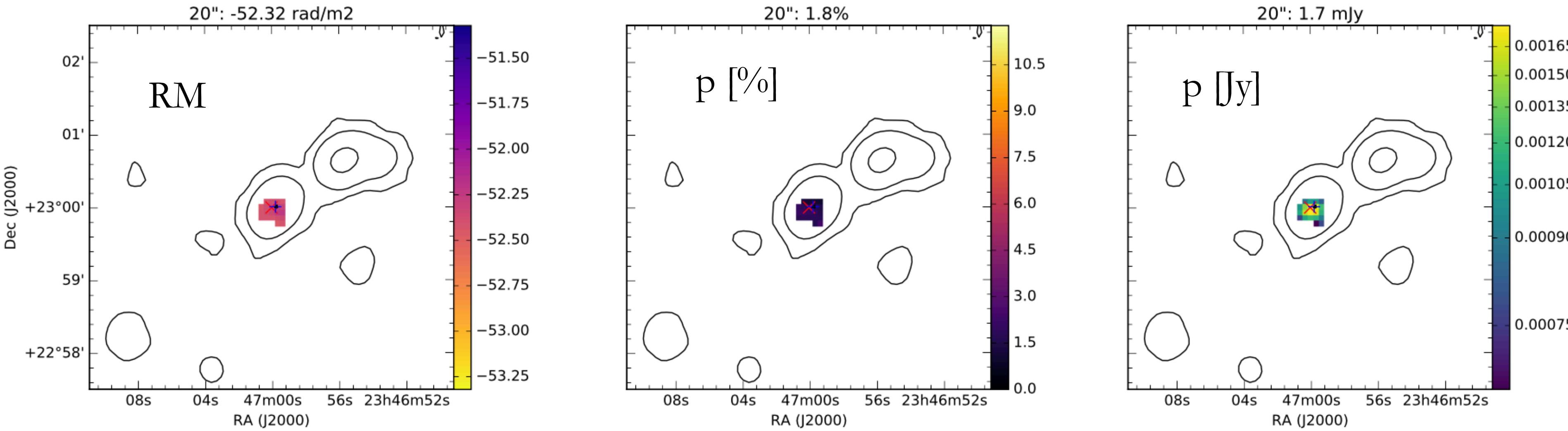
- Prefactor data
  - Can already inspect the polarization properties (at low resolution), as long as RMextract step is done
  - Need direction-dependent calibration for high resolution imaging

- Need to image Q, U channels (eg. at 97.6 kHz intervals from 120 to 168 MHz for LoTSS data) and use RM synthesis to recover band-averaged polarized intensity and RM

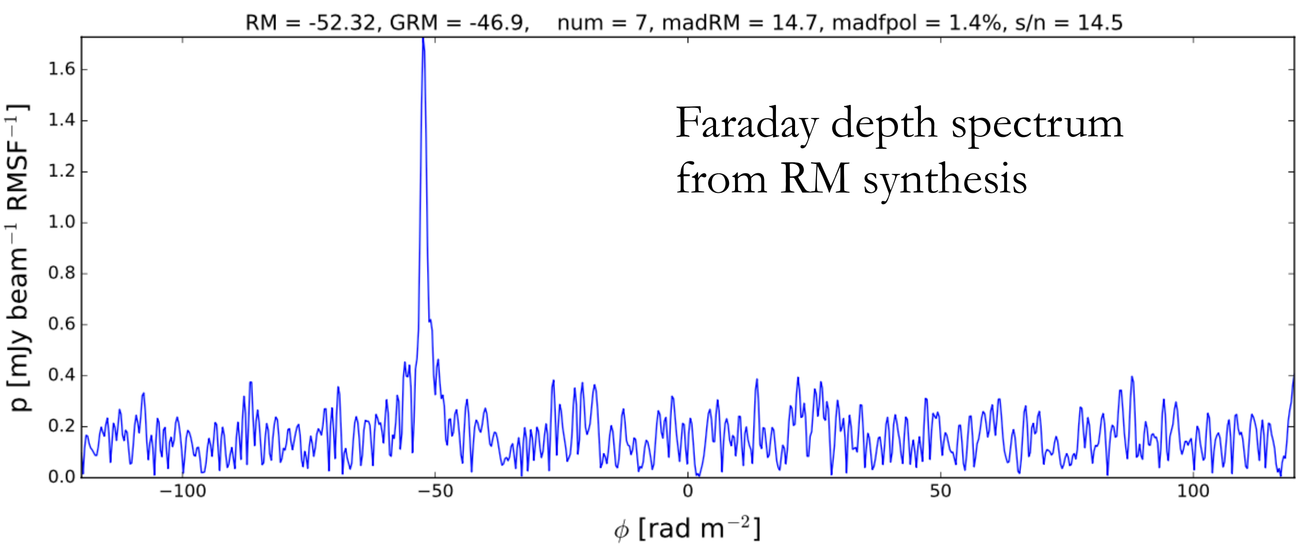
- Widefield instrumental polarization a significant problem for LOFAR (and other telescopes)
  - leakage of a fraction of the Stokes I signal into Q, U (and V)
    - Calibration improvements needed
    - eg. updated beam models

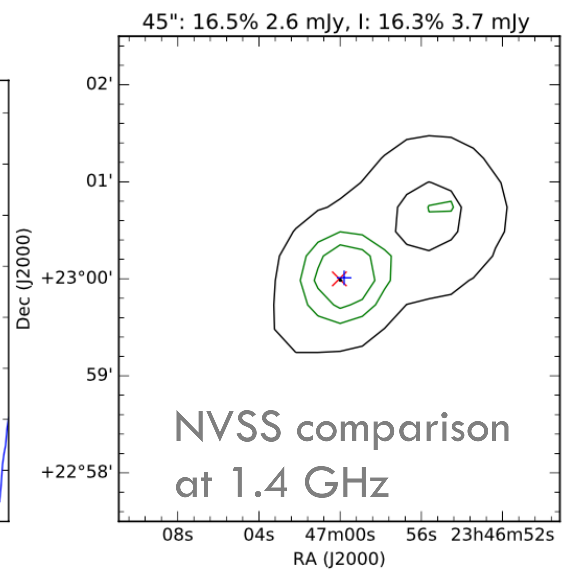
- The wide (wavelength)^2 coverage capabilities of LOFAR helps in isolating this "leakage" signal from the real astrophysical signal
  - narrow RMSF helps for sources with $|RM|$ > a few rad/m^2

Example LOFAR data:



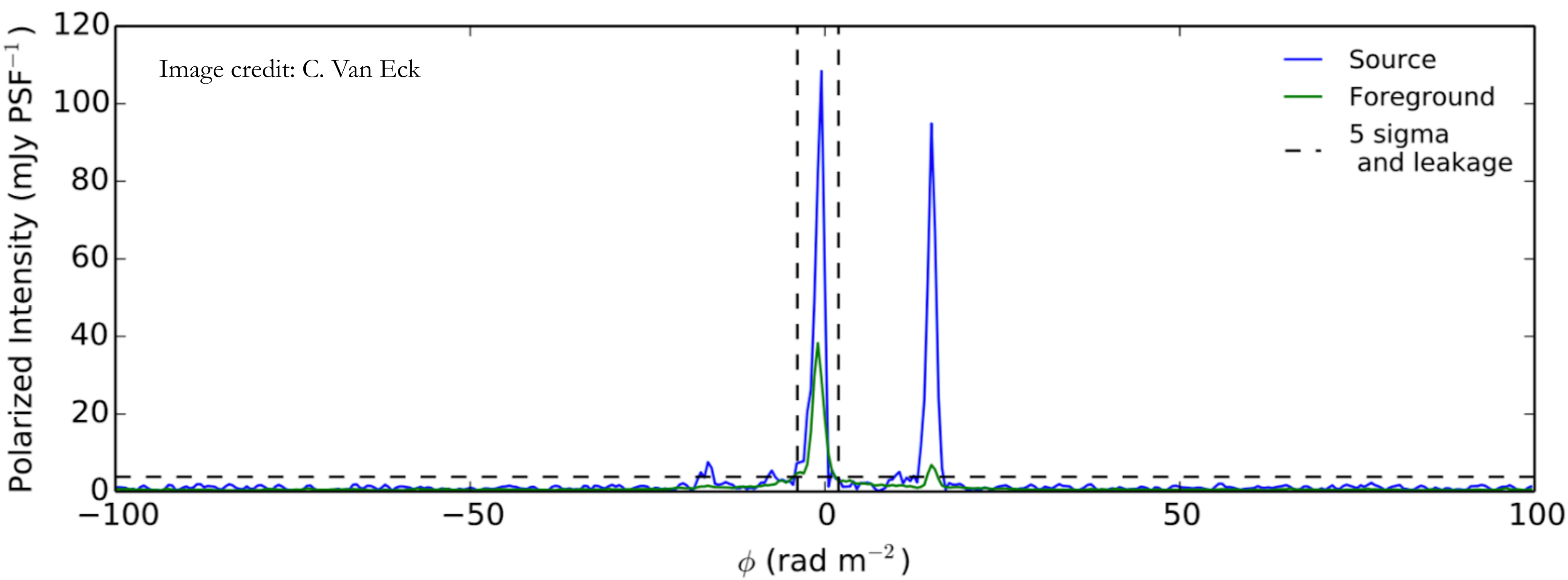
LoTSS: 120 – 168 MHz @ 97.6 kHz

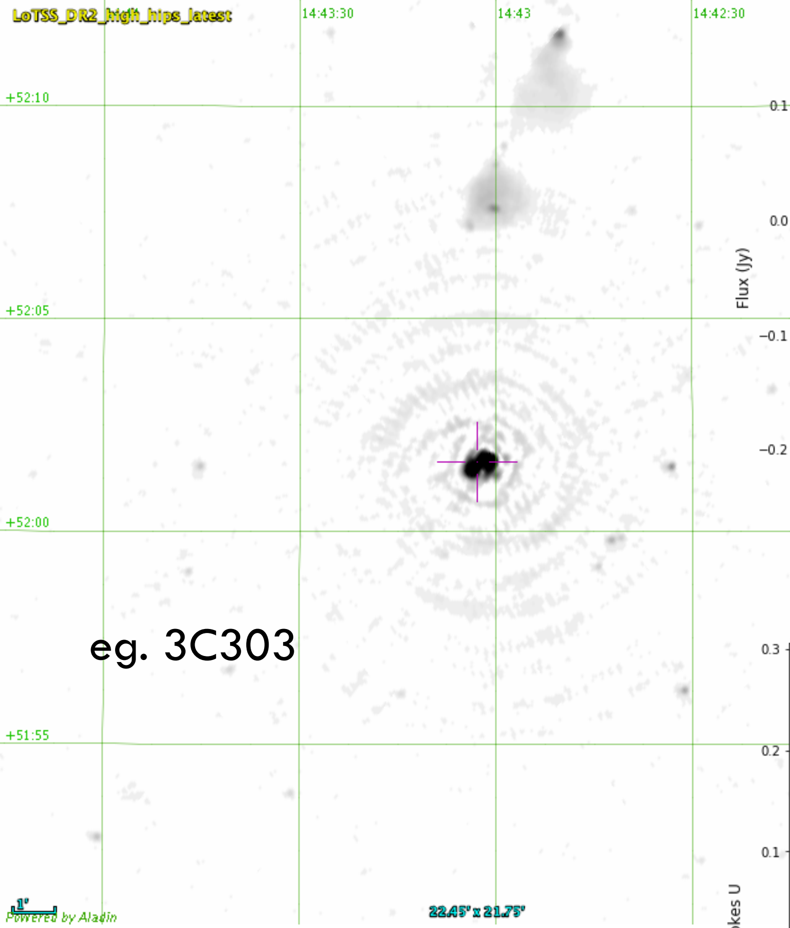




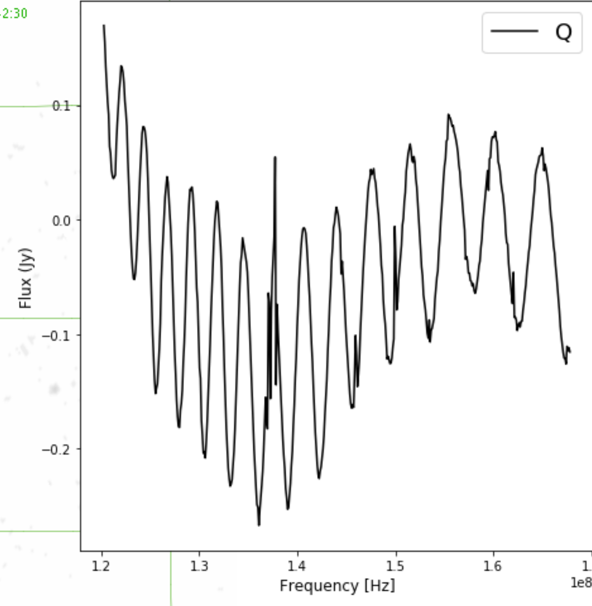
Instrumental polarization

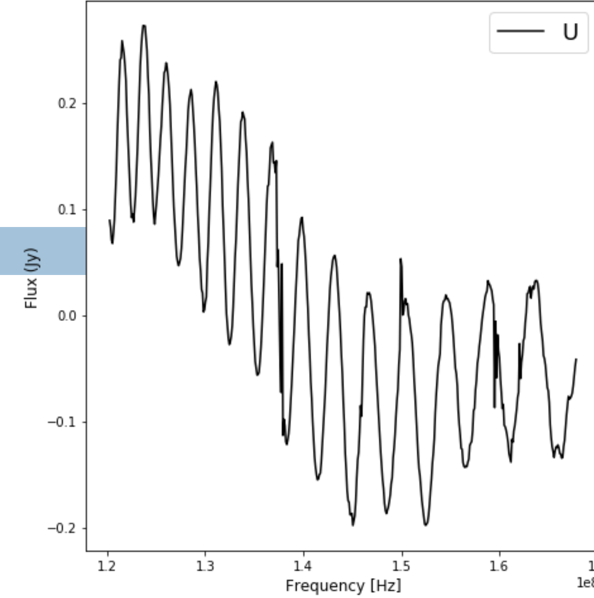
- Example of imperfect polarization calibration, leading to leakage of a fraction of Stokes I (eg. 1%) into Stokes Q and U.
- Appears in Faraday depth spectrum around 0 rad/m^2, shifted a little due to ionosphere RM correction (RMextract)

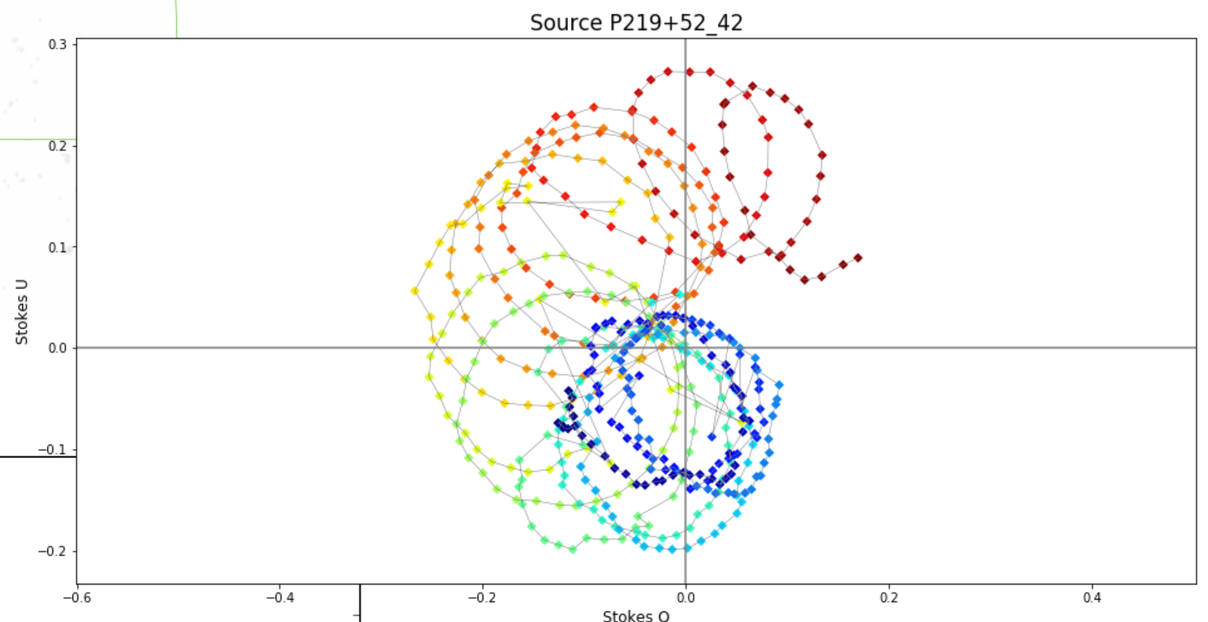




eg. 3C303







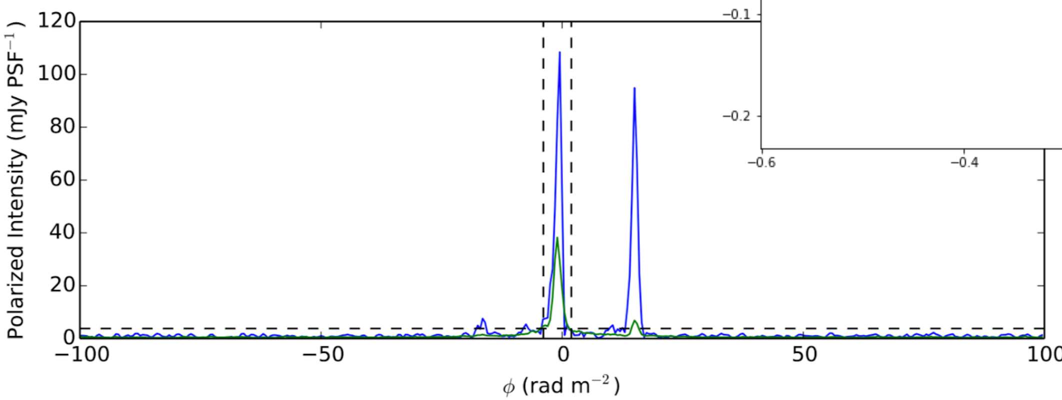
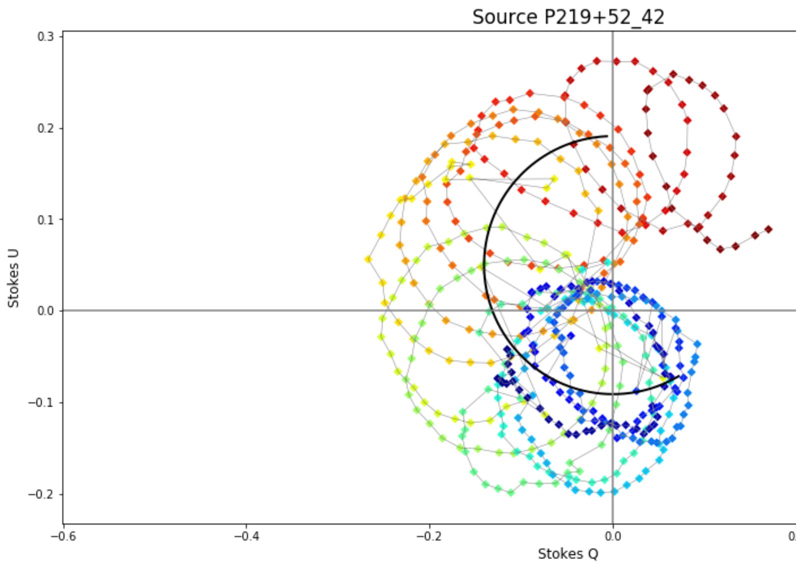
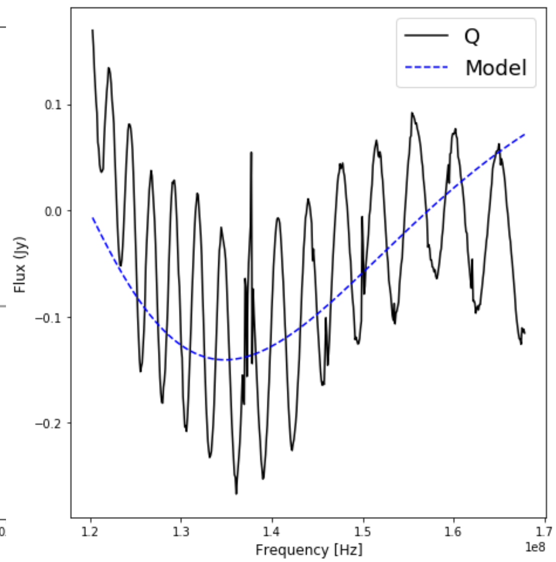
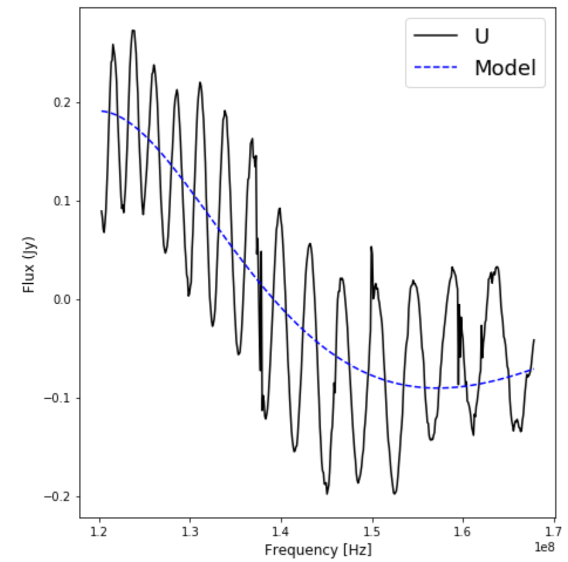
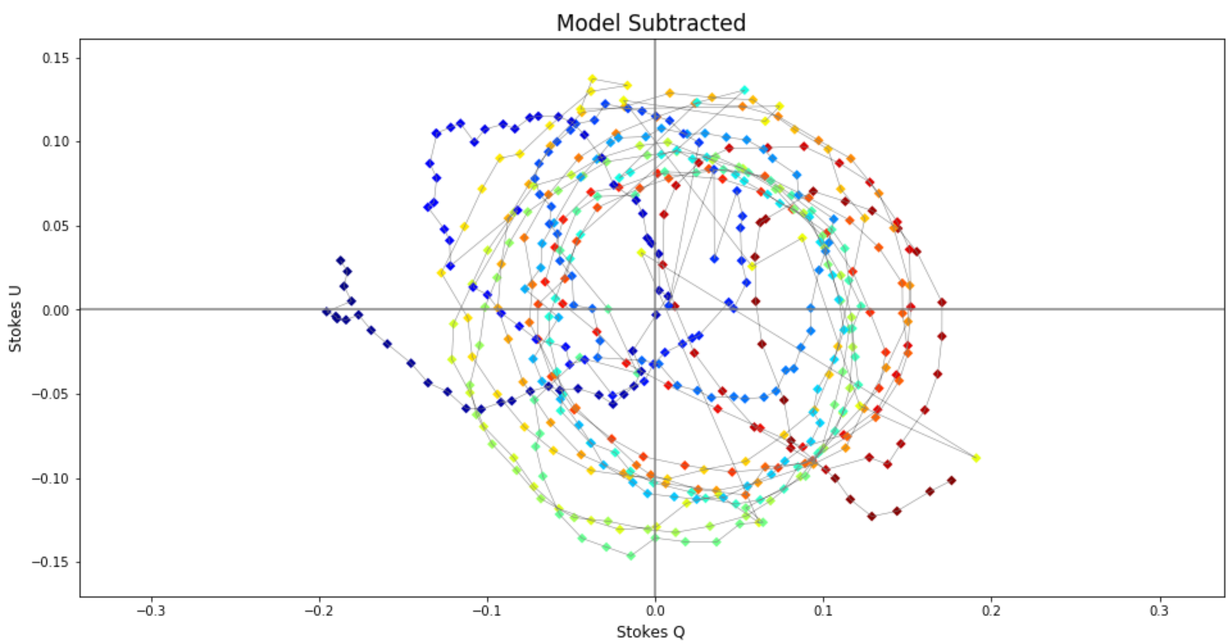


Image credit: C. Van Eck









- Single emission region with ϕ = RM and ~no depolarization

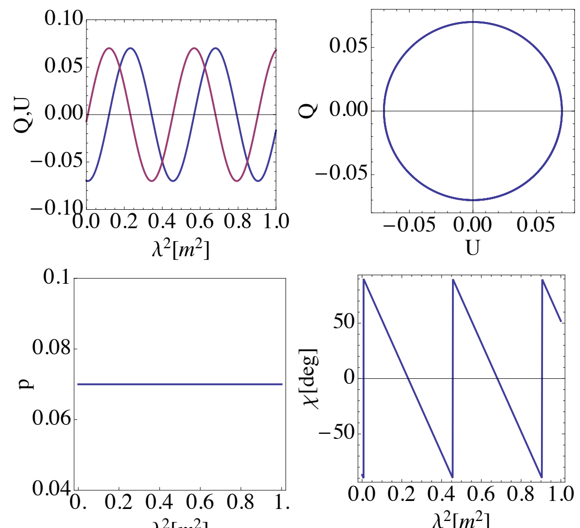
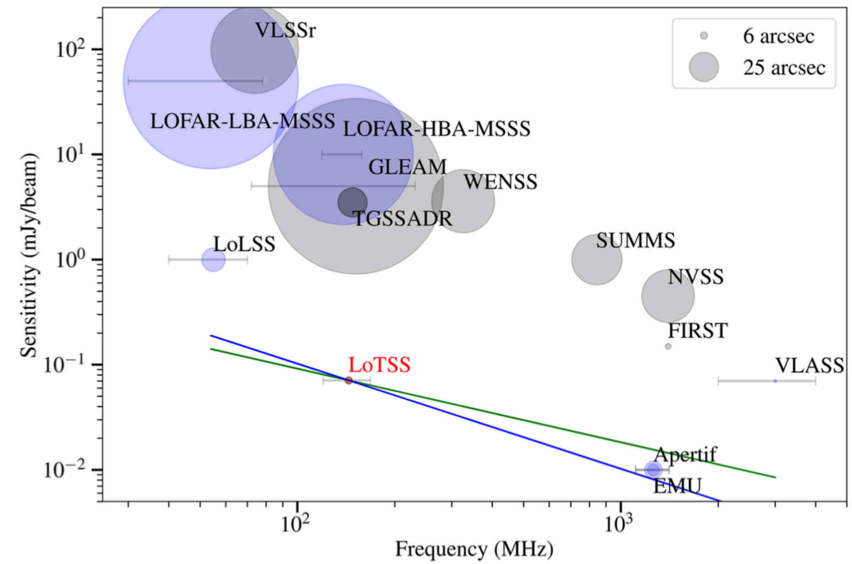
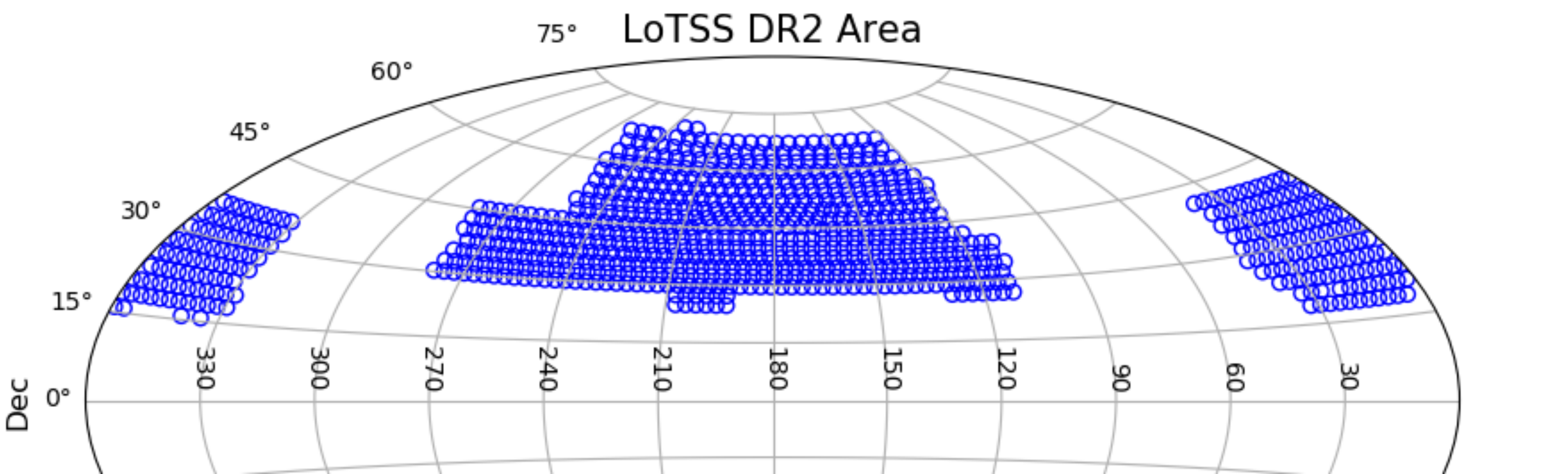


Image credit: C. Van Eck

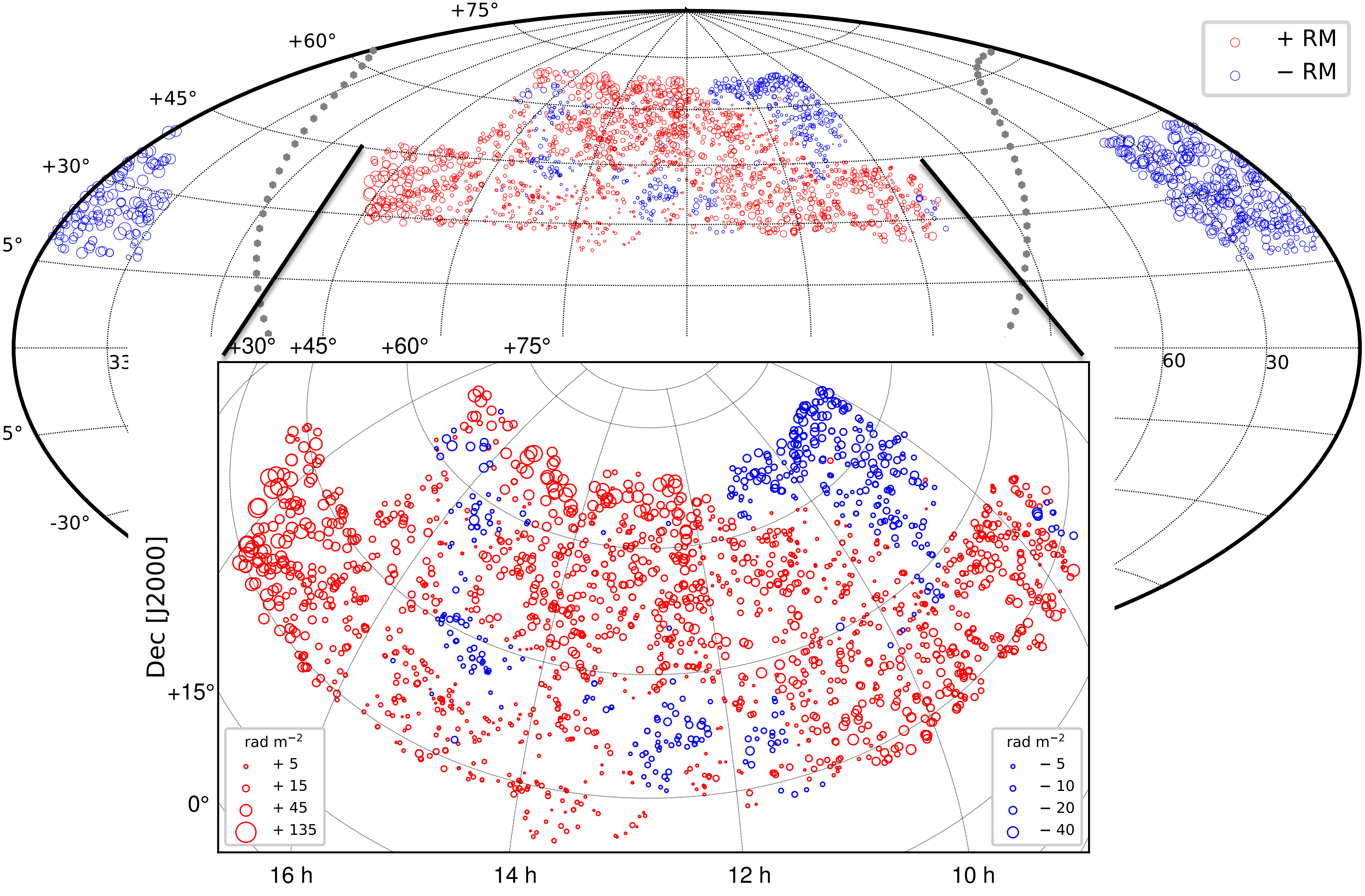
The LoTSS DR2 RM Grid

- Collaboration between SKSP and MKSP
- LoTSS DR2: 120 – 168 MHz, 20” QU cubes
  - ~25% of northern sky covered
- DR2: two main fields (841 pointings)
  - The 0h and 13h fields, 5720 square degrees in total
  - ~4.5 million radio sources
  - Only ~2,500 polarized above $8\sigma_{QU}$
  - Excellent RM precision: $O(0.1\ \mathrm{rad/m^2})$

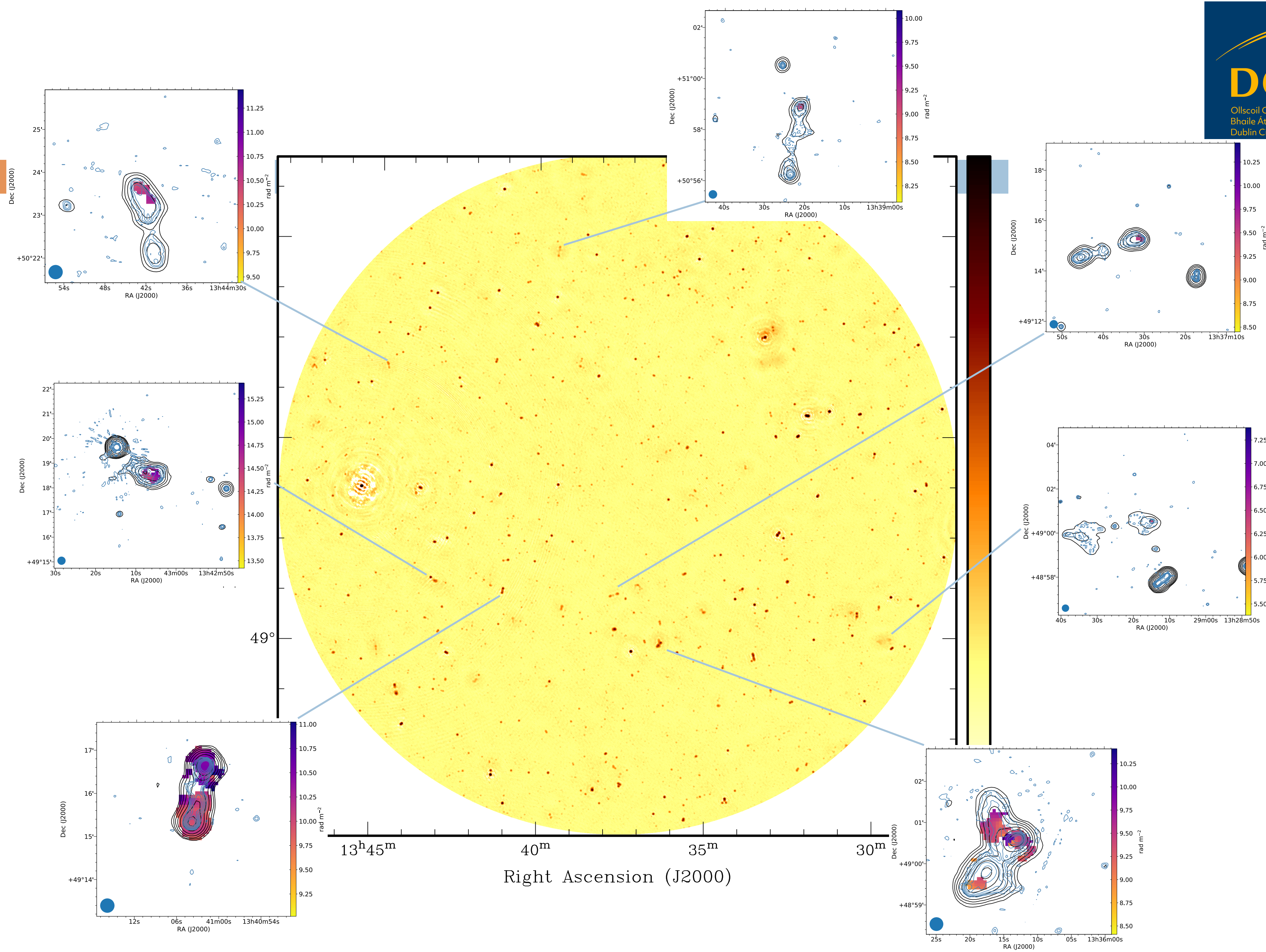




LoTSS DR2 RM Grid



O'Sullivan et al. in prep.



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End

- QUestions?