Characterizing the Structure of Magnetic Fields in Spiral Galaxies with Radio and Far-Infrared Polarimetric Observations

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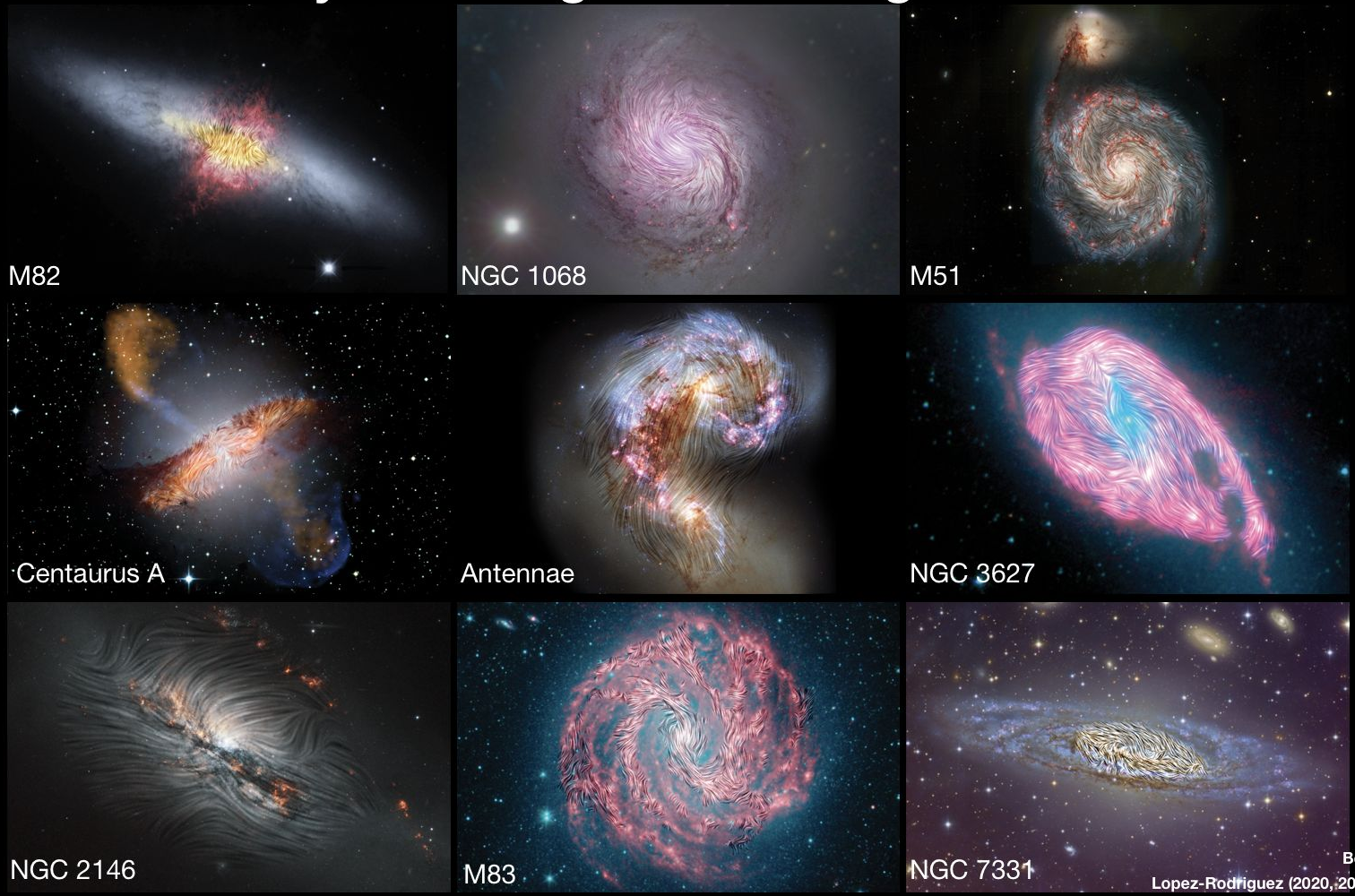
arXiv: 2302.07278

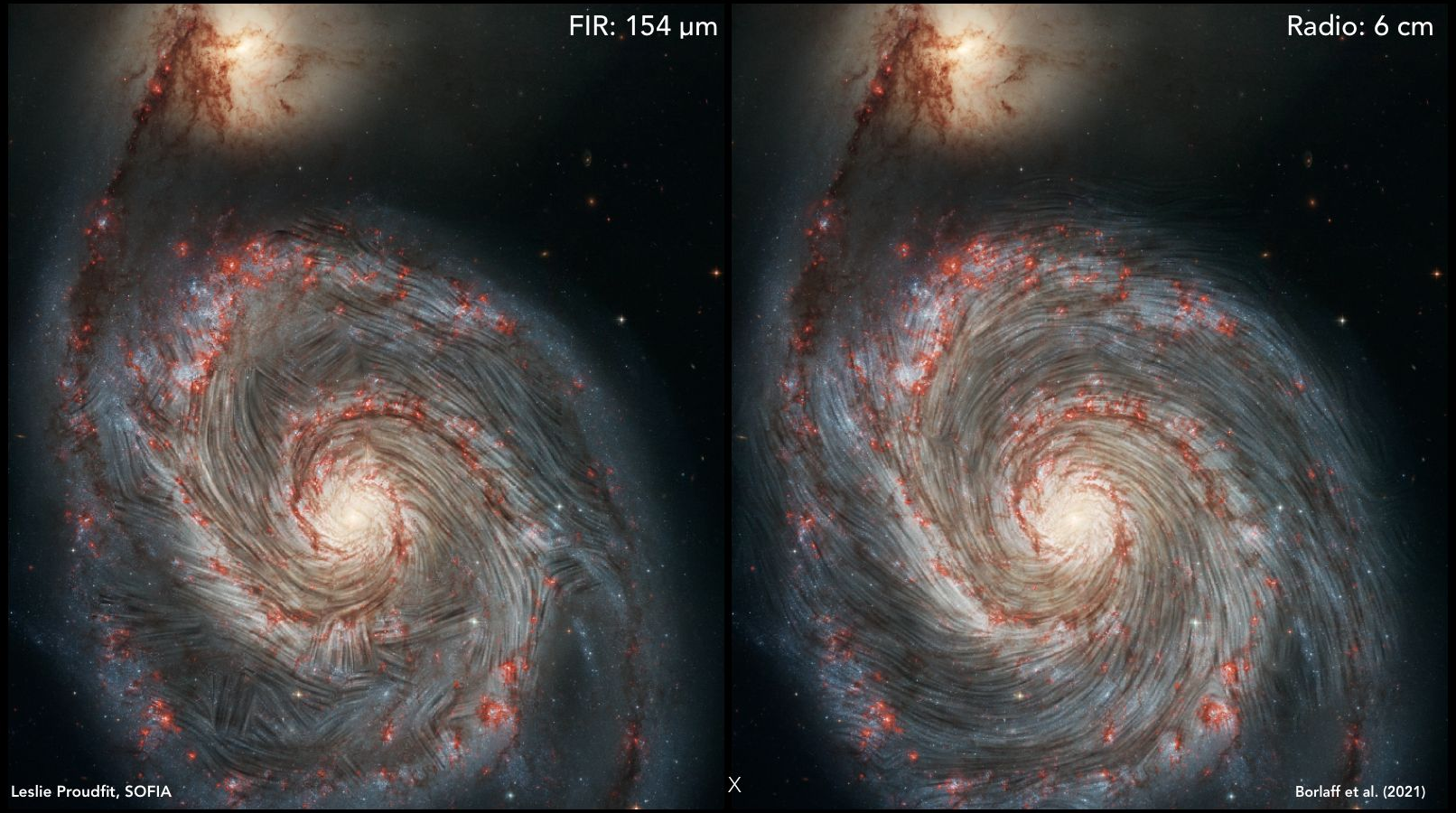
SALSA: Survey of extragALactic magnetiSm with SOFIA



Borlaff etal. (2021,2022)
Lopez-Rodriguez (2020, 2021a,b, 2022a,b,2023a)

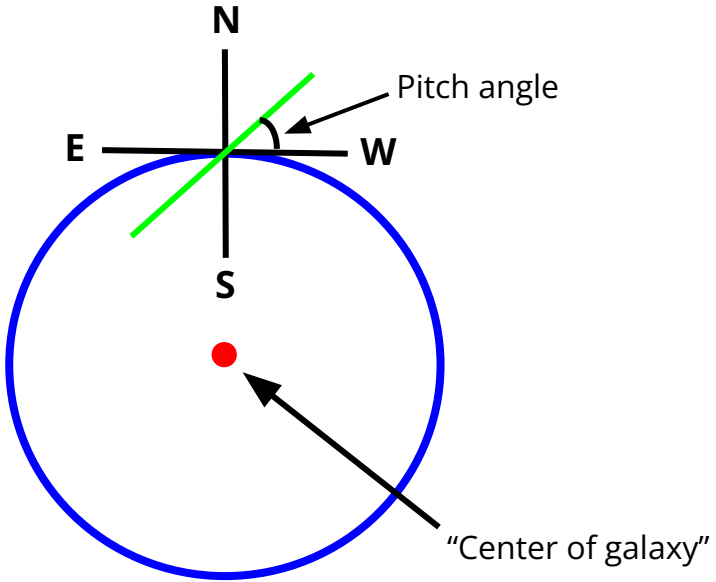
M51: SPIRAL GALAXY WITH COMPANION

THE SPIRAL MAGNETIC FIELD IN THE MULTI-PHASE ISM



Some Background

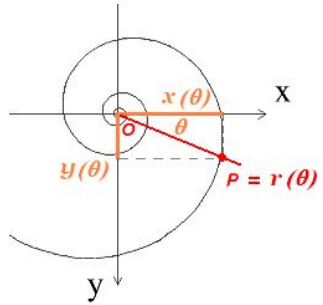
- Large-scale B-fields are frequently observed in spiral galaxies
- The full 3D structure of galactic B-fields is not directly measurable
- Often the disk magnetic field is summarized via the pitch angle

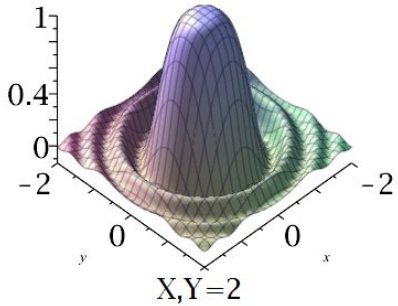


Motivation

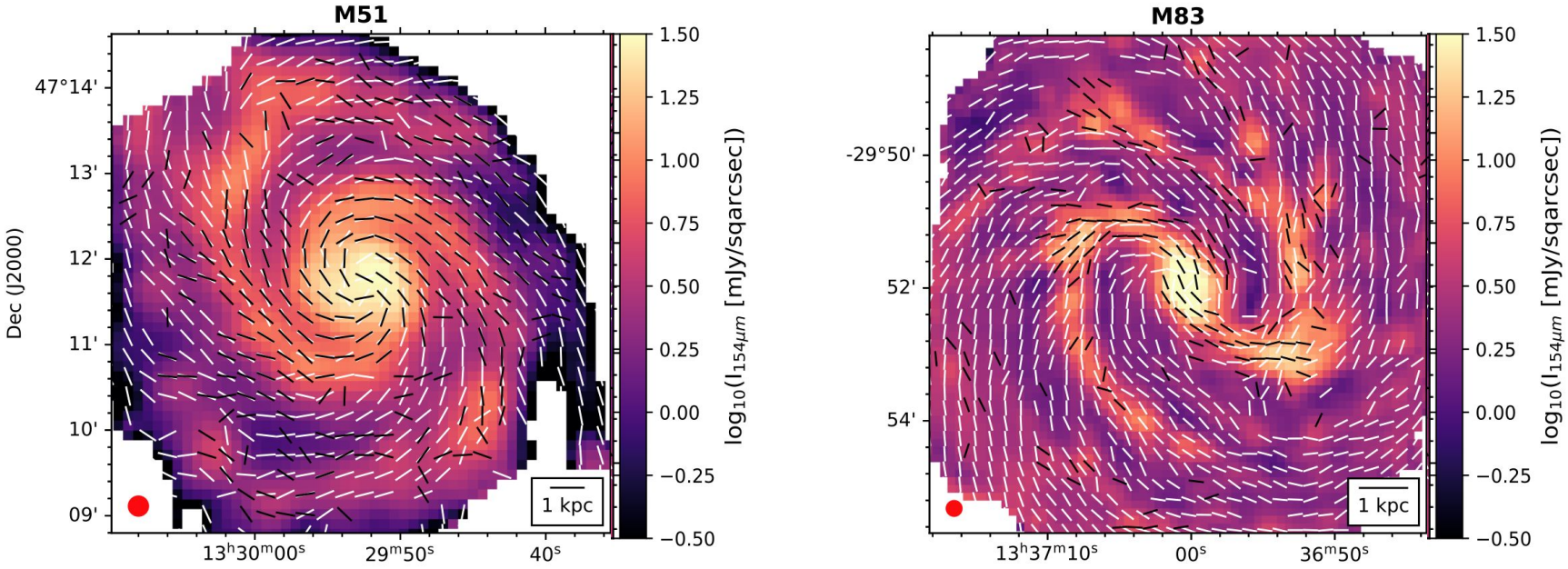
- Previous methods of estimating the pitch angles of spiral galaxies were model-dependent
- Some methods assumed a logarithmic function as a priori function of a spiral arm (i.e. logarithmic spirals) (Fletcher et al. 2011; Van Eck et al. 2015)
- Wavelet-based approaches depend on user-defined parameters to define the shape and width of the kernel (Frick et al. 2016; Borlaff et al. 2021)

$$\begin{cases} x(\theta) = r(\theta)\cos\theta \\ y(\theta) = r(\theta)\sin\theta \end{cases}$$



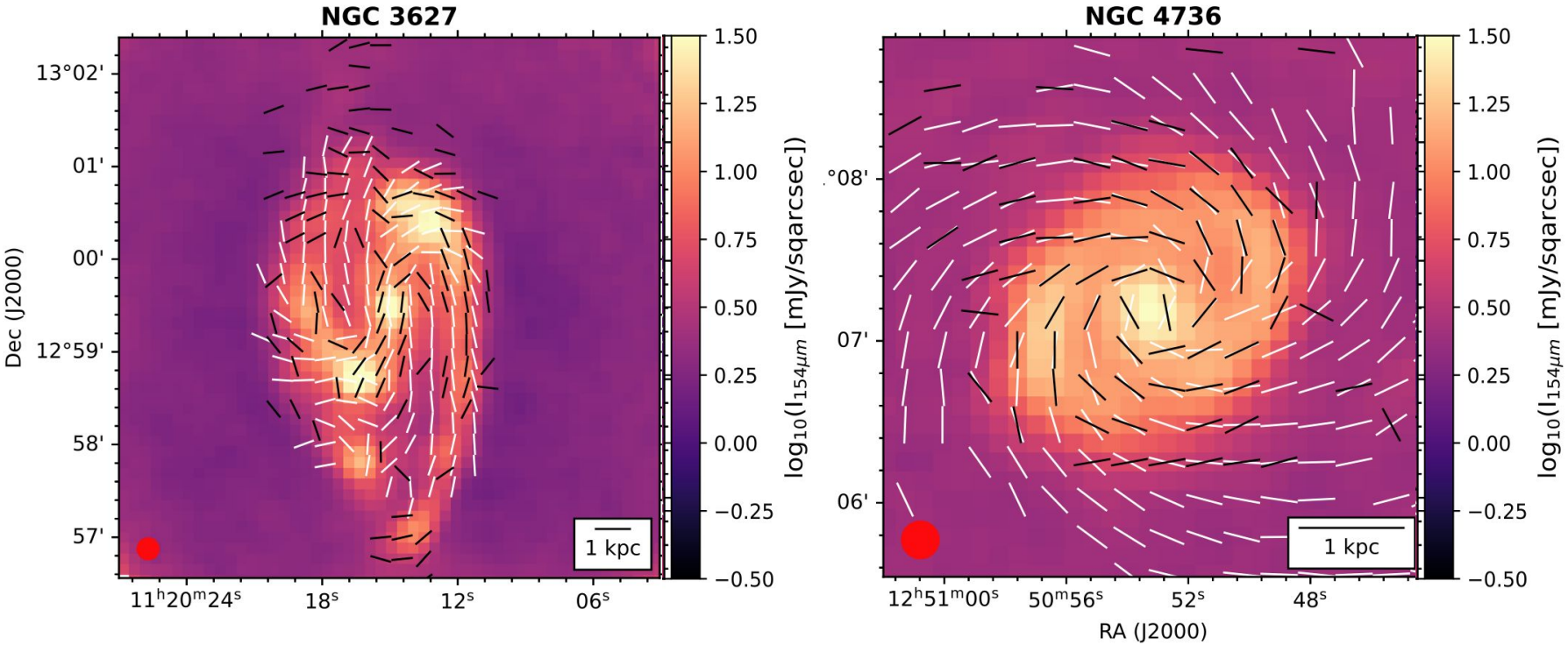


M51 and M83 B-field orientation

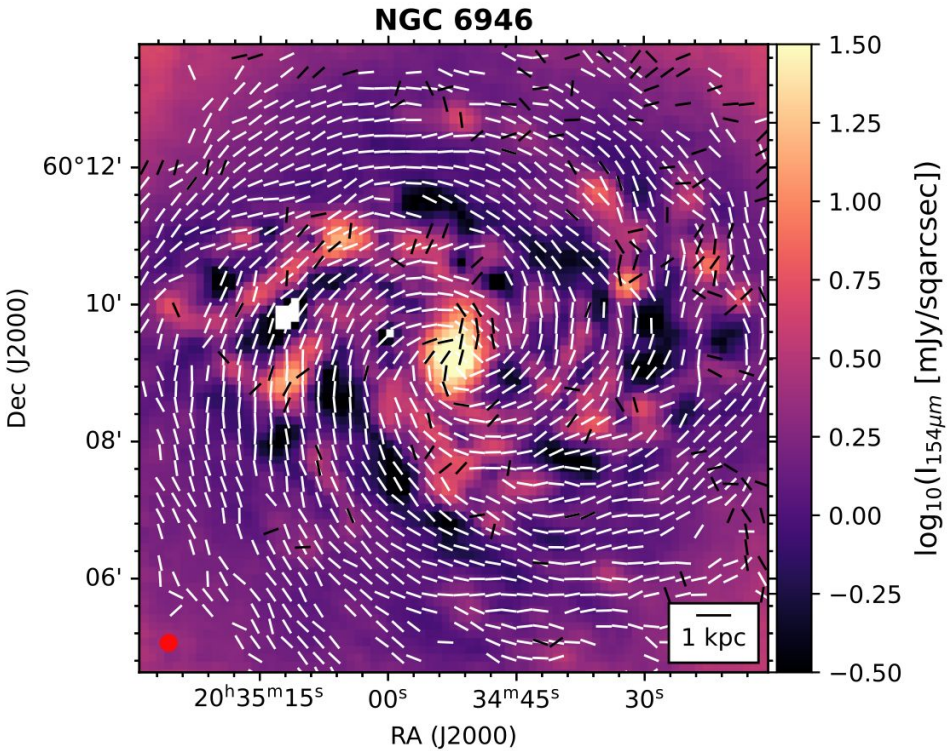


Black lines: 154 μm B-field orientation. White lines: 6 cm B-field orientation. Both are overlaid on the 154 μm total intensity (color scale).

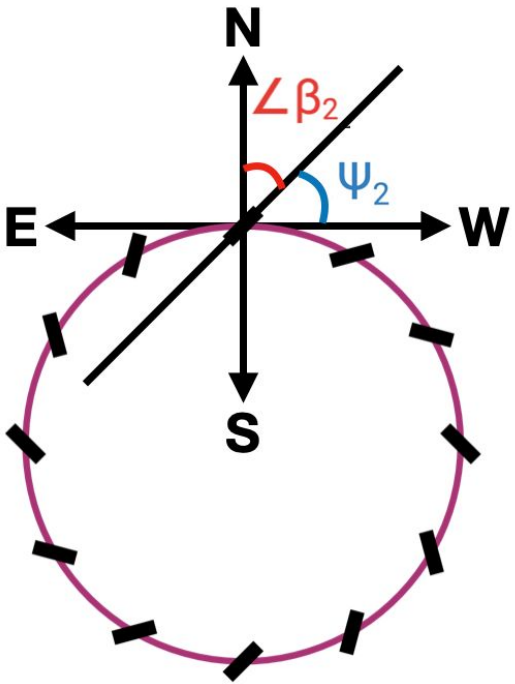
NGC 3627 and NGC 4736 B-field orientation



NGC 6946


NGC 6946
60°12'
10'
08'
06'
Dec (J2000)
20h35m15s
00s
34m45s
30s
RA (J2000)
1 kpc
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
log10(I154μm [mJy/sqarcsec])

Method of Decomposition



Polarization Field:

$$P(\rho,\phi) \equiv Q(\rho,\phi) + iU(\rho,\phi)$$

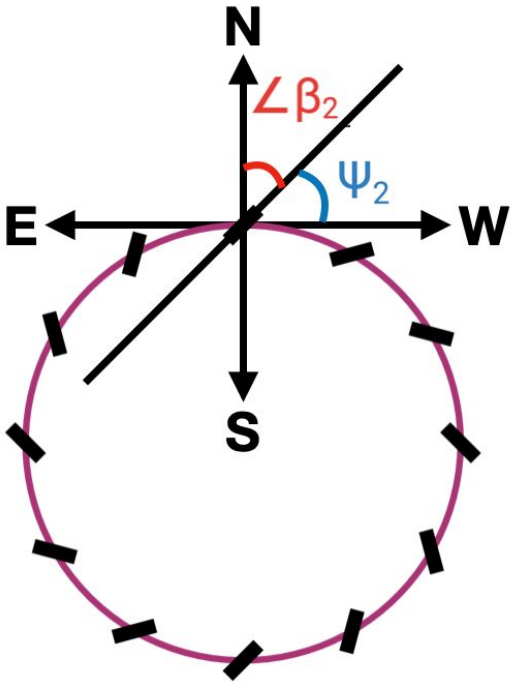
$$P_{\rm B}(\rho,\phi) \equiv -Q(\rho,\phi) - iU(\rho,\phi)$$

Decomposition Definition:

$$\beta_m = \frac{1}{I_{\rm ann}} \int_{\rho_{\rm min}}^{\rho_{\rm max}} \int_0^{2\pi} P_B(\rho,\phi) e^{im\phi} \rho d\phi d\rho$$

(Palumbo et al. 2020)

Method of Decomposition



$$\beta_2 = -i$$

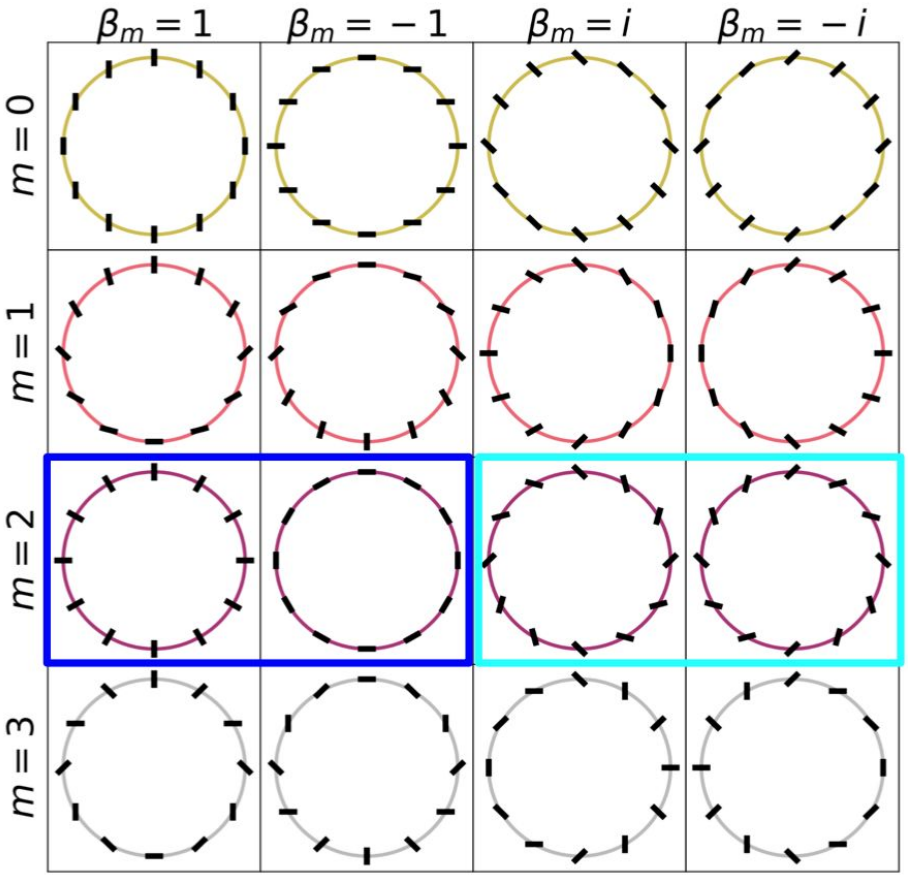
Angle of Offset:

$$\beta_m = (\Re(\beta_m) + \Im(\beta_m))$$

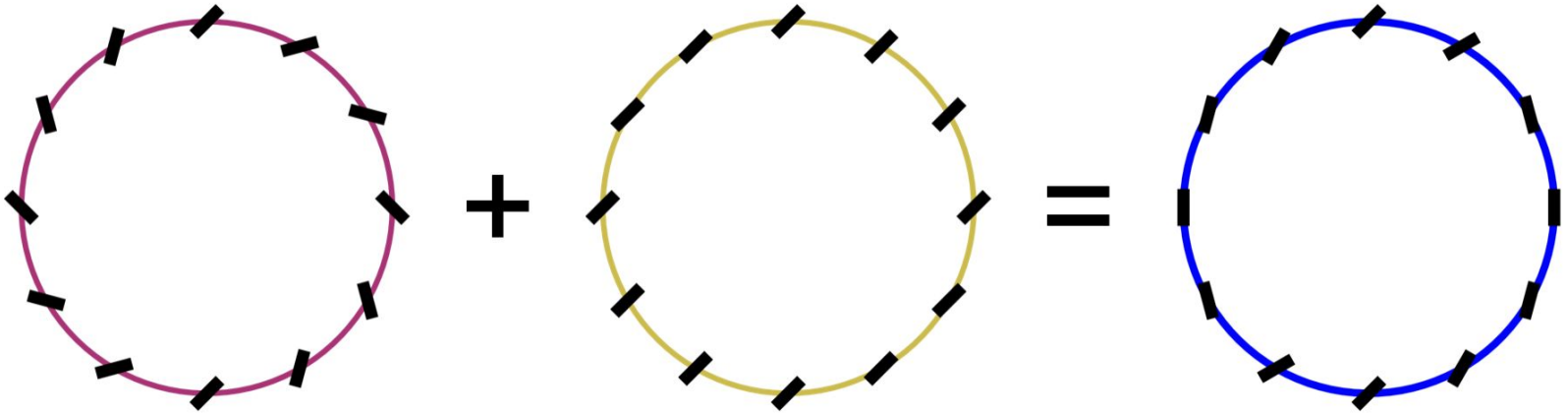
$$\angle\beta_m = \frac{1}{2}\arctan\left(\frac{\Im(\beta_m)}{\Re(\beta_m)}\right)$$

Azimuthal Modes

- The m = 2 mode is analogous to the E and B mode decomposition commonly used in studies of CMB polarization
- The real part of β_2 is the E-mode (dark blue box) and the imaginary part is the B-mode (cyan box)

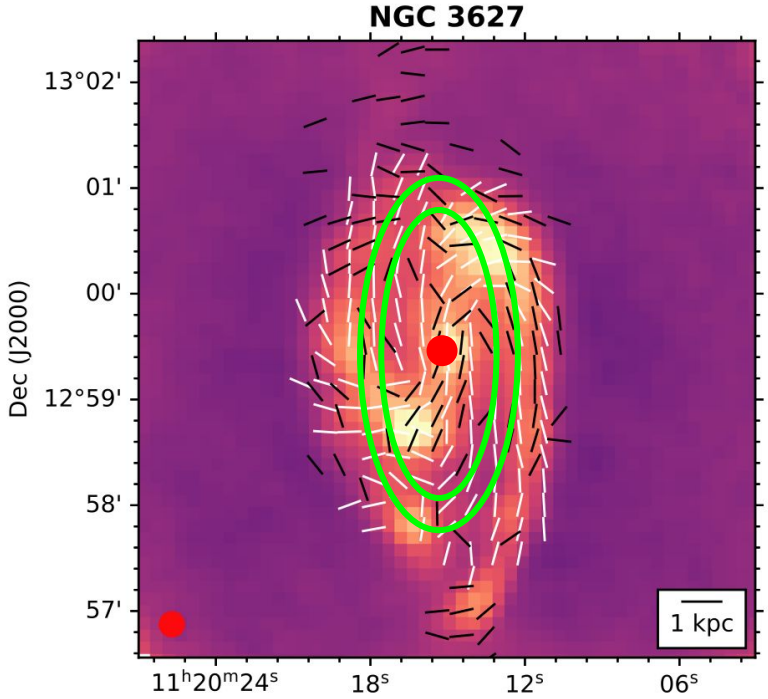


Simple Example



$\beta_2 = -i$ $\beta_0 = -i$

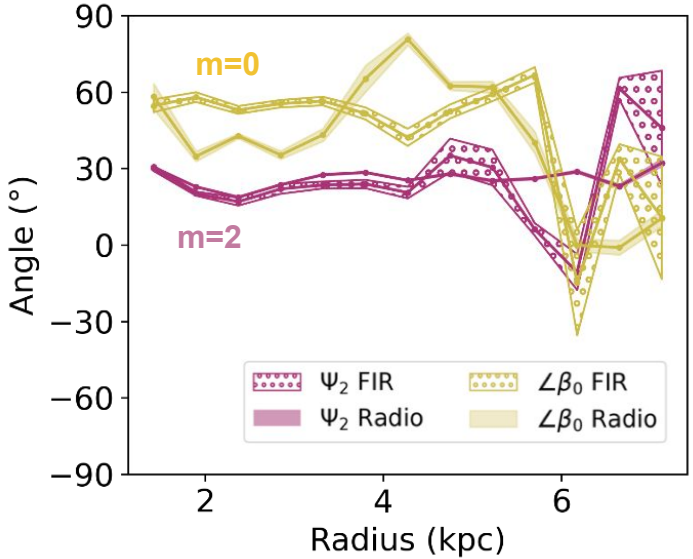
The Process of Decomposition

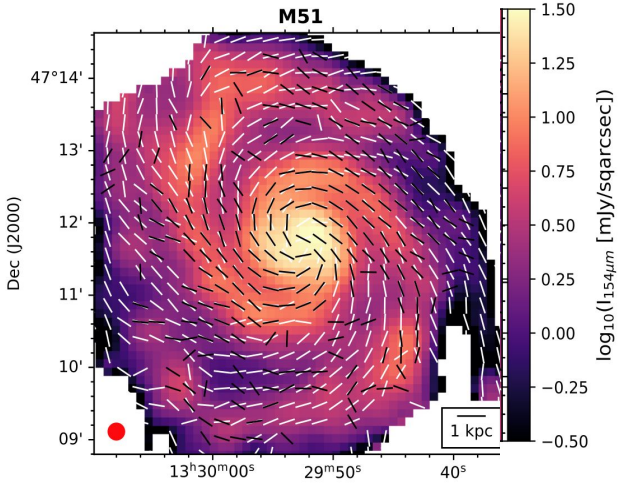


Center of galaxy given by red dot at center of plot. Green rings to show an arbitrary annulus of selected data.

- Projected annulus of data as a function of distance from the center of the galaxy
- Compute decomposition coefficient over each annuli
- Calculate |B_m| and ∠B_m for each mode

Results (M51)

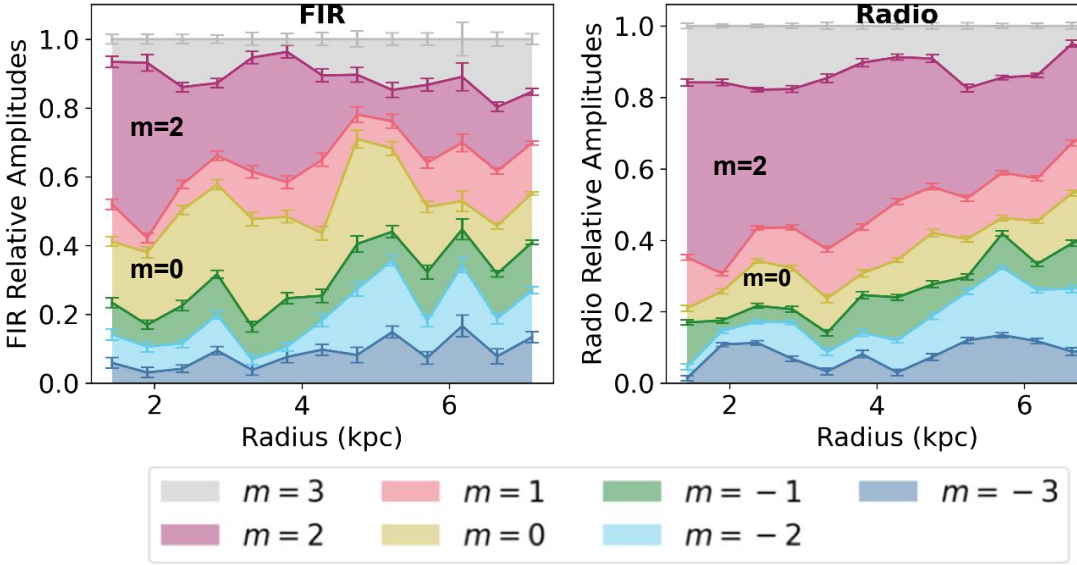


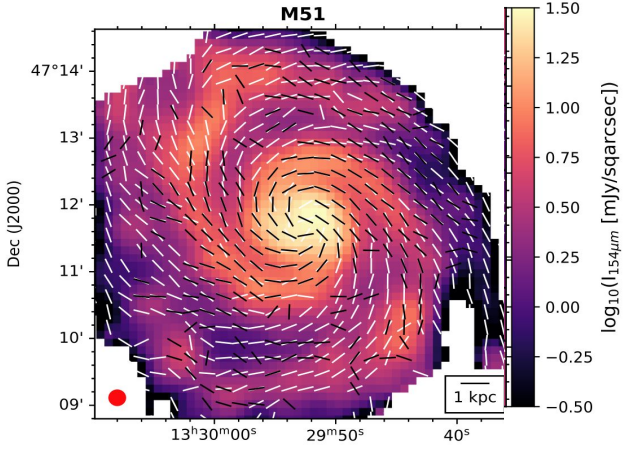


On the left: Plot of FIR and radio pitch angles and averaged pointwise rotation of B-field for m = 0 mode as a function of radial distance from the center of M51

On the right: Black lines: 154 μm B-field orientation. White lines: 6 cm B-field orientation. Both are overlaid on the 154 μm total intensity (color scale).

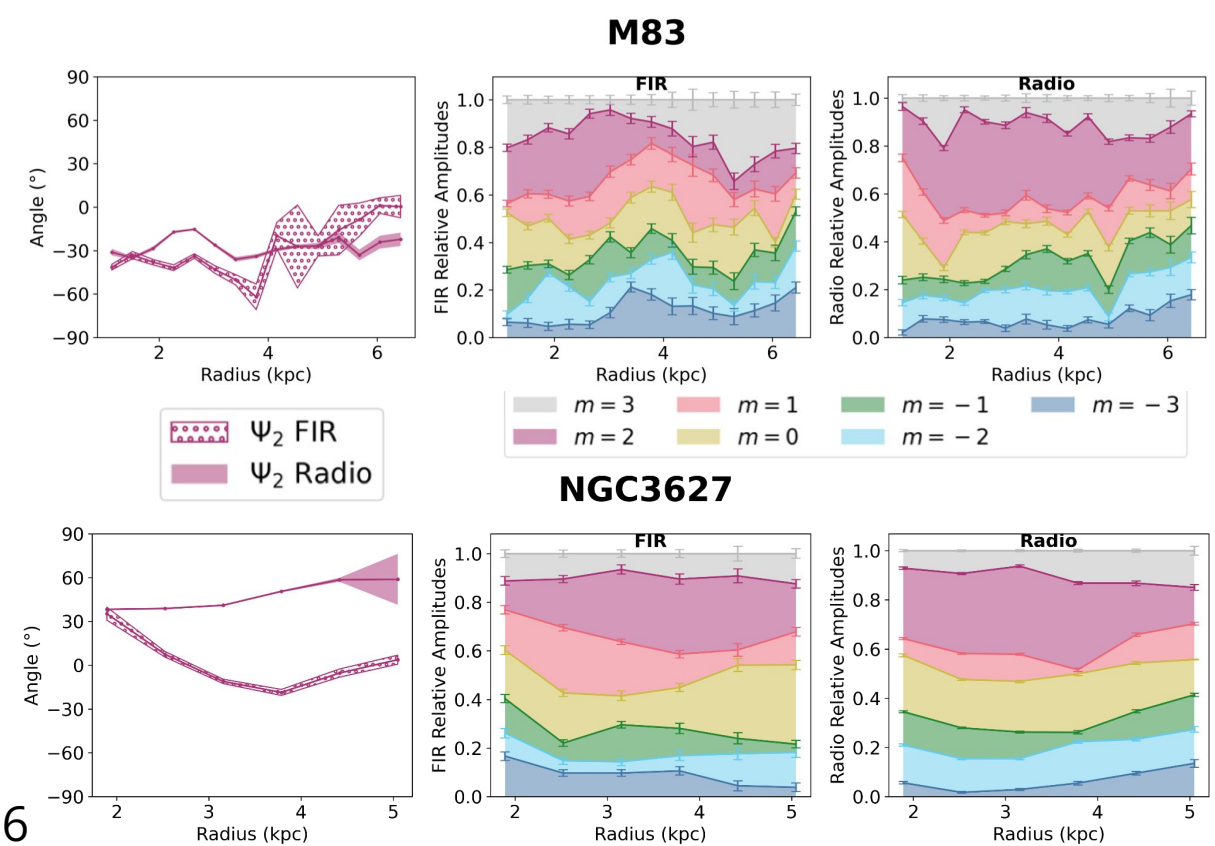
Results (M51)

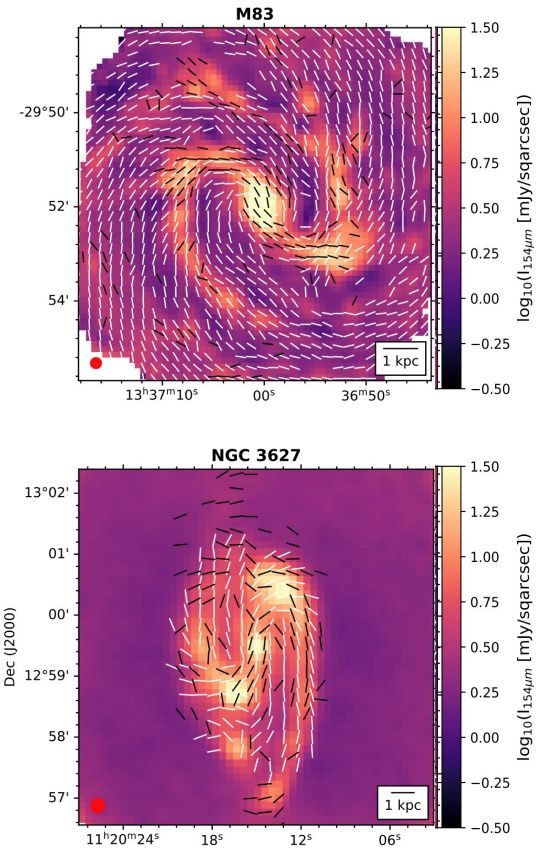




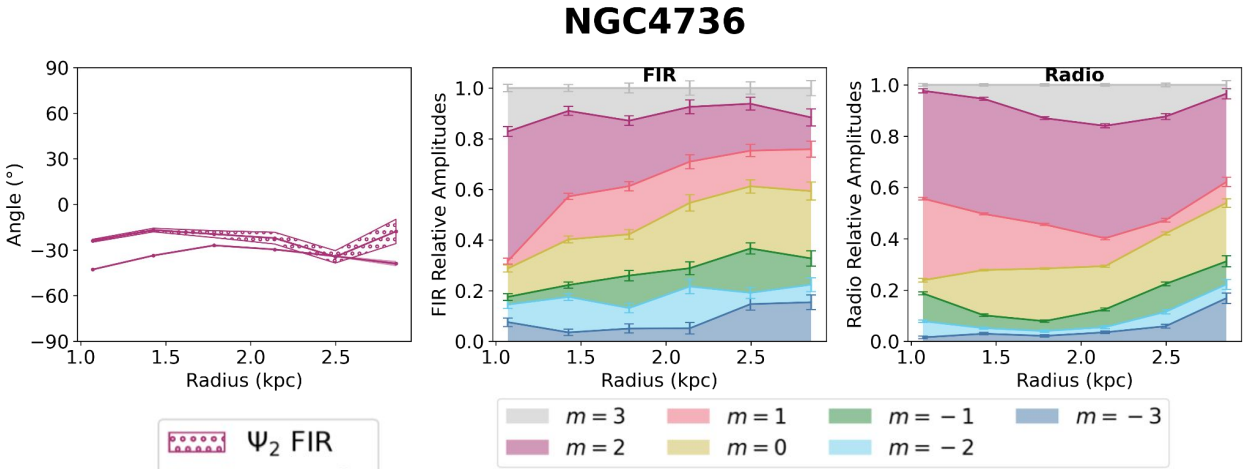
Left two plots: stacked area plot of mode amplitudes as a function of radial distance from the center of M51

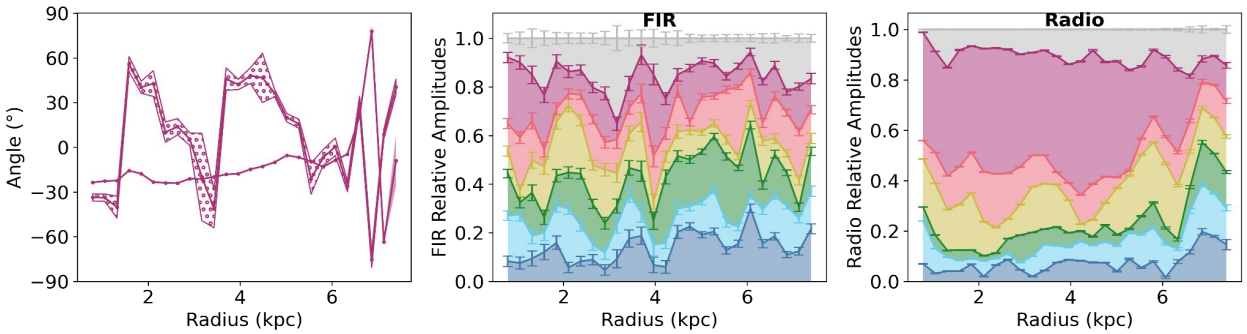
Results (M83 and NGC 3627)

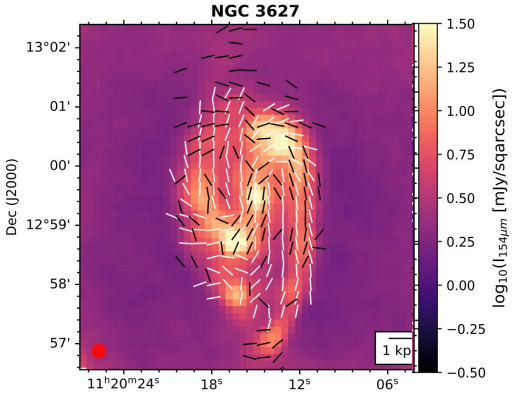


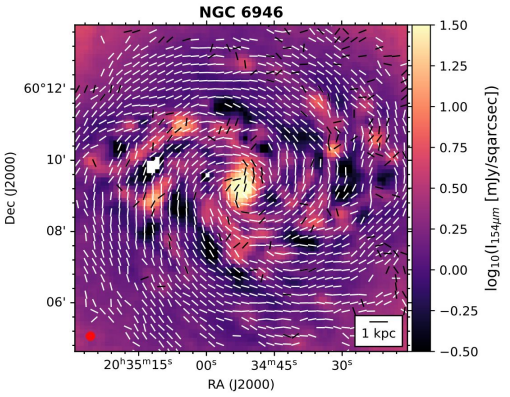


Results (NGC 4736 and NGC 6946)

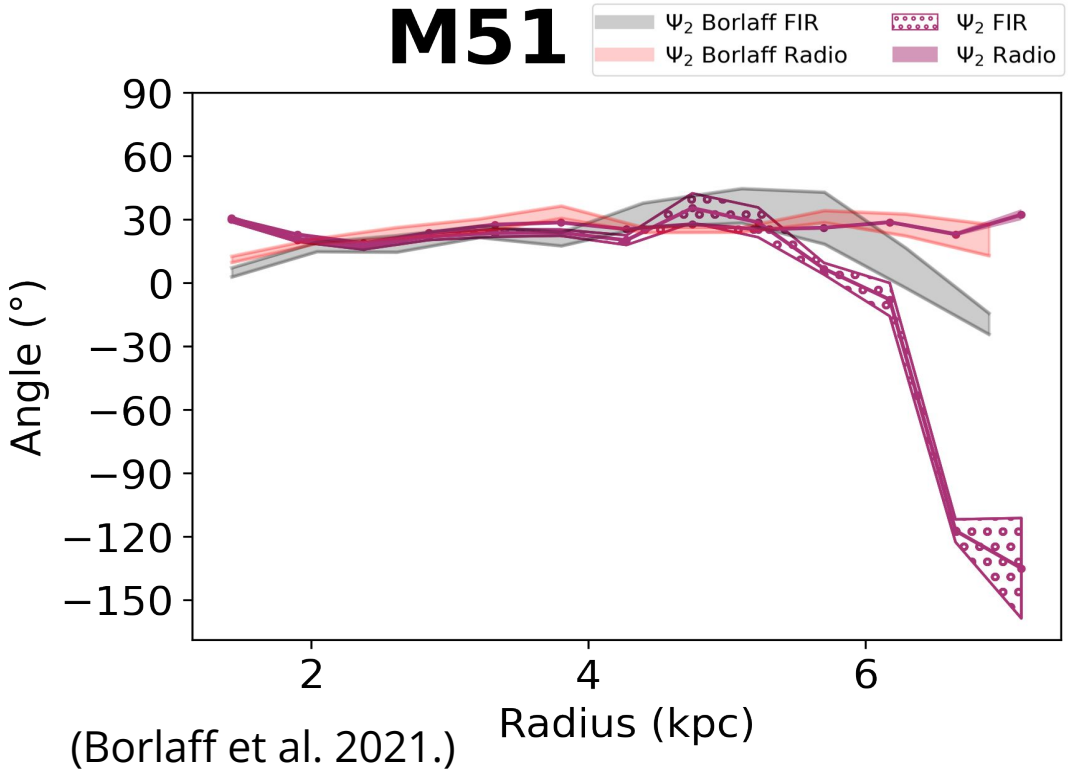








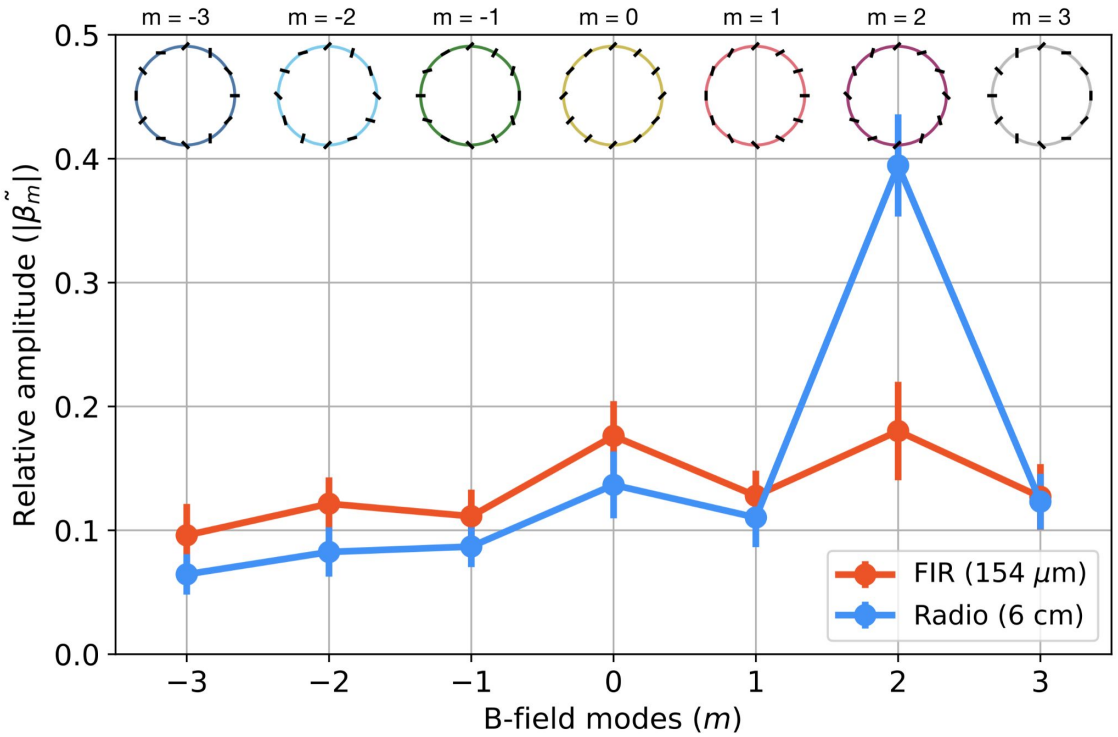
Comparison Plot with Borlaff



(Borlaff et al. 2021.)

Image of M51 merging with M51b

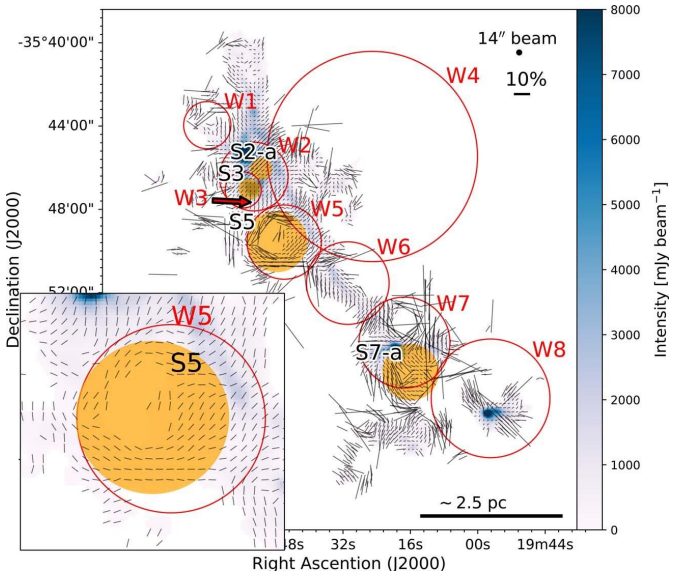
Spiral Galaxies B-field Summary



Mean relative amplitudes of the B-field modes of a composited spiral galaxy. FIR (red) and radio (blue) relative amplitudes for modes −3 ≤ m ≤ 3 are shown. The B-field pattern associated with each mode is shown at the top.

Future Applications

- This method can be applied to any vector field where a circle or ellipse is a geometry of particular interest
- ISM morphologies (i.e. supernova remnants or wind-blown bubbles in star-forming regions, or radio synchrotron loops
- Quantify the morphology of galaxy structure observed via the total intensity distribution at different wavelengths



Magnetic fields of the HII regions associated with NGC 6334 (Tahani et al. 2023).

Conclusions

- We have applied a new model-independent magnetic field decomposition approach which measures the large-scale ordered magnetic field
- These spiral galaxies were mainly composed of the m = 2 at radio wavelengths, followed by m = 0, m = 3, and m = 1
- At FIR wavelengths the galaxies were composed of the m = 2 and m = 0 modes with smaller contributions from m = 1 and m = 3
- Mean pitch angle is smaller in the FIR data than in radio, indicating that radio spiral magnetic fields are more open than FIR spiral magnetic fields
- FIR wavelengths had greater angular dispersion, meaning FIR spiral magnetic fields are less ordered than radio spiral magnetic fields

Image References

Image on slide 1:
https://www.nasa.gov/feature/magnetic-chaos-hidden-within-the-whirlpool-galaxy

Images on slides 3:
https://www.maa.org/sites/default/files/images/upload_library/23/picado/seashells/espiraleng.html

https://en.wikipedia.org/wiki/Sombrero_function

Image on slide 18:

https://www.nasa.gov/mission_pages/chandra/multimedia/spiral-galaxy-m51.html