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An Iterative Reconstruction Algorithm for Faraday Tomography

arXiv:2011.10840

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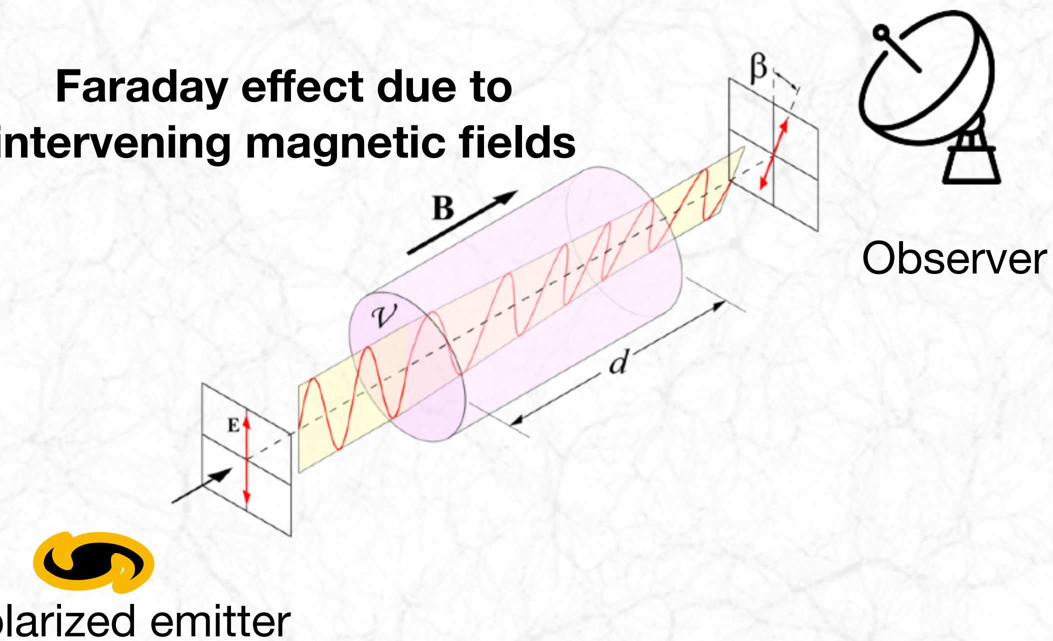
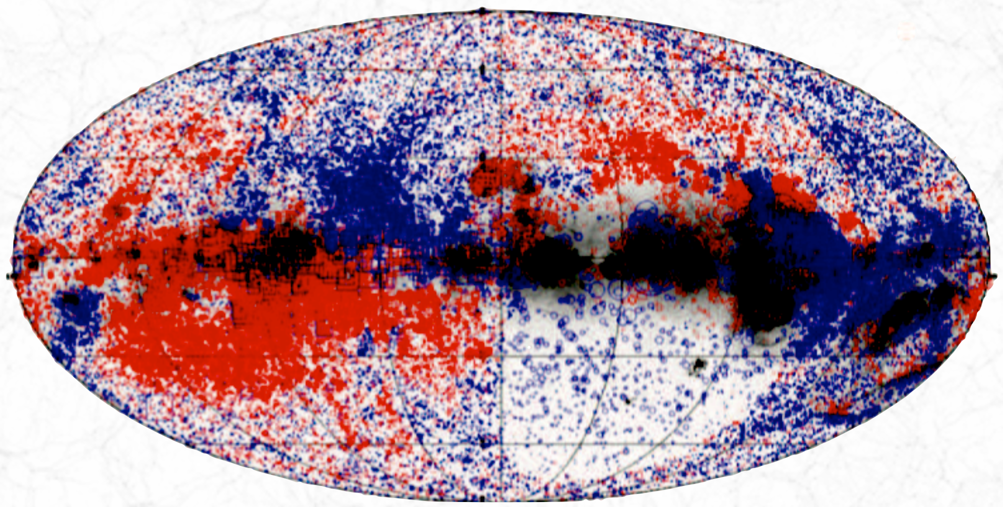
Observing Magnetism in the Universe

- Magnetic fields in the Universe can be explored only by indirect observations
- When an electromagnetic wave passes through a magnetic field, it under goes frequency-dependent rotation (**Faraday effect**)
- Traditionally, two linear polarization measurements of a radio source (e.g., AGNs) at different frequencies was used to obtain a **rotation measure** (RM)
- **RM** corresponds to the **integrated** contribution by magnetic fields along the line of sight

Faraday effect due to intervening magnetic fields



credit: wikipedia

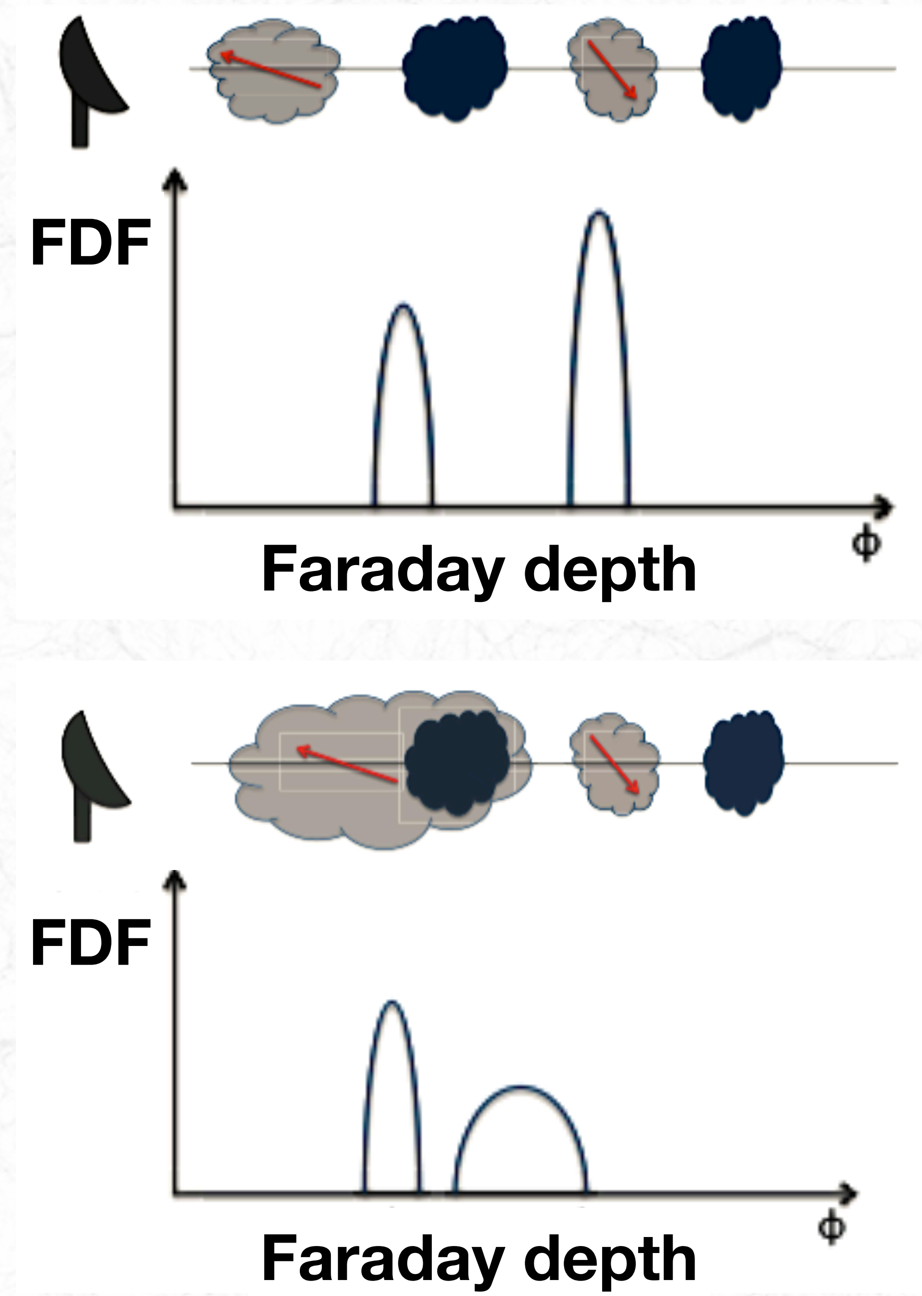


Rotation Measure map in Galactic coordinates. **Blue**/**red** corresponds to magnetic fields pointing **toward**/**away** from the observer

Dominic Schnitzeler, Ferrière (2016)

What is Faraday Tomography?

- Modern and next generation radio telescopes like the Square Kilometre Array (SKA) can record polarizations for many spectral channels (**spectropolarimetry**)
- With a complete linear polarization spectrum, we can dissect the line of sight components as a **Faraday dispersion function** (FDF)
- Converting the observed linear polarization spectrum to obtain 3D information of magnetic fields is called **Faraday Tomography**



Faraday tomography of **synchrotron emitting** (dark blue) and **Faraday rotating** (light gray with red arrows showing magnetic strength) bodies. The configurations are shown by FDF.

Ferrière (2016)

Basics of Faraday Tomography

Faraday dispersion function $F(\phi)$ and the **linear polarization spectrum $P(\lambda^2)$** is related by Fourier transforms (FT),

$$\boxed{P\left(\lambda^2\right)} = \int_{-\infty}^{\infty} \boxed{F(\phi)} e^{2i\phi\lambda^2} d\phi \qquad \boxed{F(\phi)} = \frac{1}{\pi}\int_{-\infty}^{\infty} \boxed{P\left(\lambda^2\right)} e^{-2i\phi\lambda^2} d\lambda^2$$

Fourier transform **Inverse Fourier transform**

λ: wavelength, ϕ: Faraday depth

However, the **observable wavelength range is only positive and limited by the telescope**

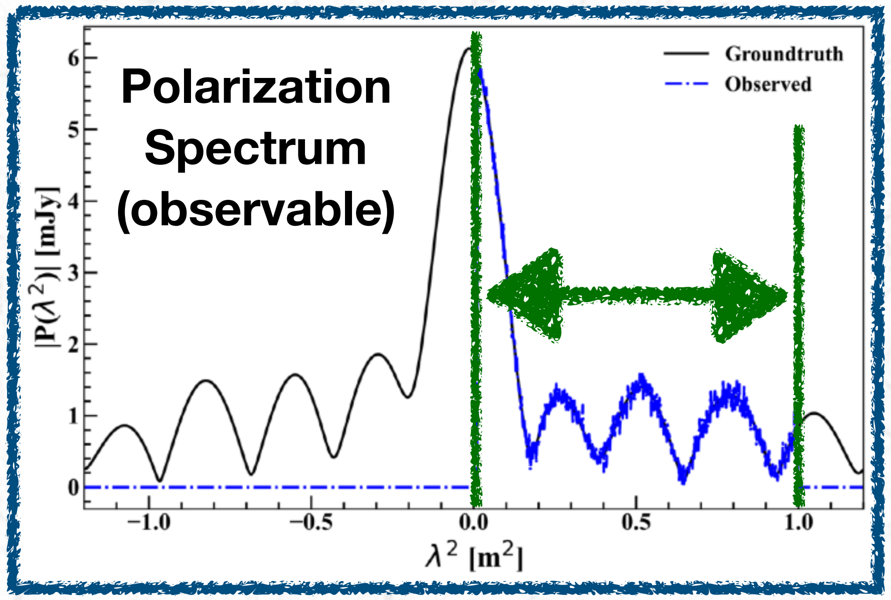
Wavelength coverage window

$$\tilde{F}(\phi) = \frac{1}{\pi}\int_{-\infty}^{\infty} \boxed{W\left(\lambda^2\right)} P\left(\lambda^2\right) e^{-2i\phi\lambda^2} d\lambda^2$$

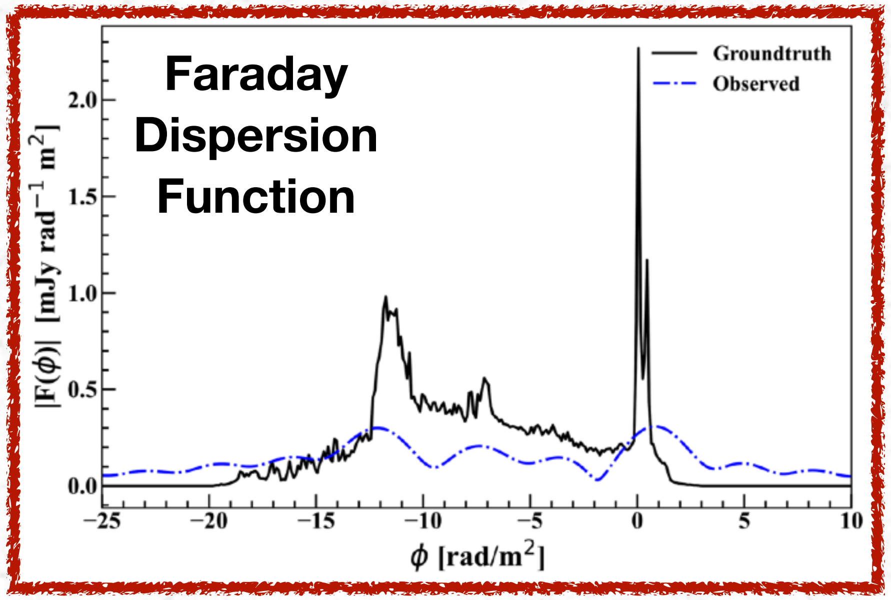
Observed FDF

No satisfactory algorithms to solve this problem yet (Sun et al. 2015)

▹ **Requires solving an inverse problem!**



FT
Inverse FT



A example FDF (Ideguchi et al. 2014) of a realistic galaxy simulation (Akahori et al. 2013) and its polarization spectrum

Inverse Problem of Faraday Tomography

- We solve the following inverse problem

$$P\left(\lambda^2\right) = W^{-1}\left(\lambda^2\right)\tilde{P}\left(\lambda^2\right)$$

Reconstructed Spectrum **Inverse Window** **Observed Spectrum**

- The Faraday tomography problem is equivalent to **interferometric imaging** and thus existing methods for Faraday tomography are mostly borrowed (e.g., CLEAN, Sparse Modeling)
- In this work, we suggest a new iterative technique called **Constraining and Restoring iterative Algorithm for Faraday Tomography** (CRAFT)
- Iterative methods have been around since the 70s (Papoulis 1974, Gerchberg 1974) and are at the core of the present data science methods
- They are **computationally inexpensive** and **flexible** to incorporate any prior information

Assumption for reconstruction

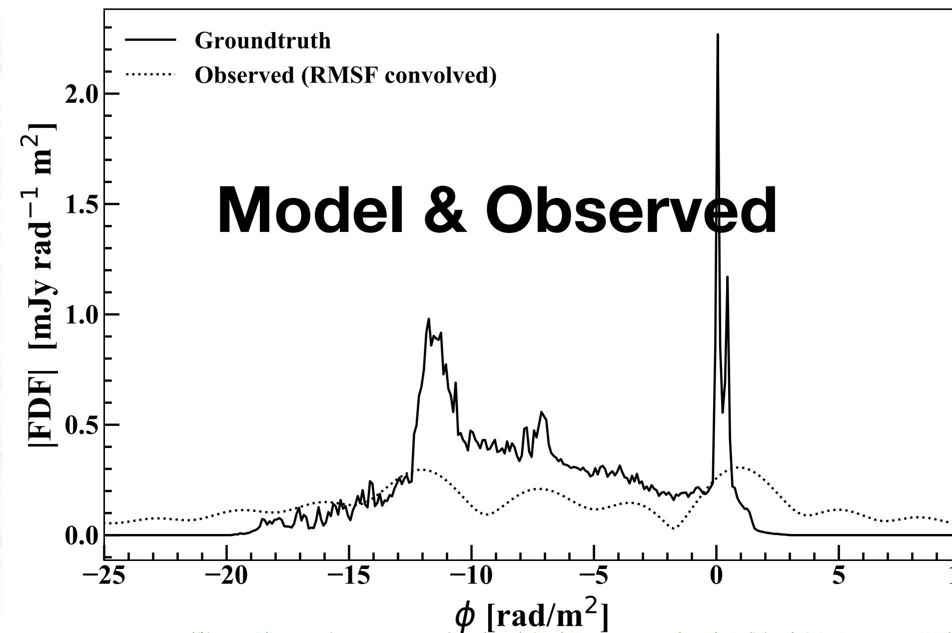
Simulations show that the bodies are restricted to a small region in Faraday depth. Therefore, parts of the FDF is assumed to be zero. We also assume some smoothness

Reconstruction Performance

The methods were tested on a realistic simulation of a galaxy

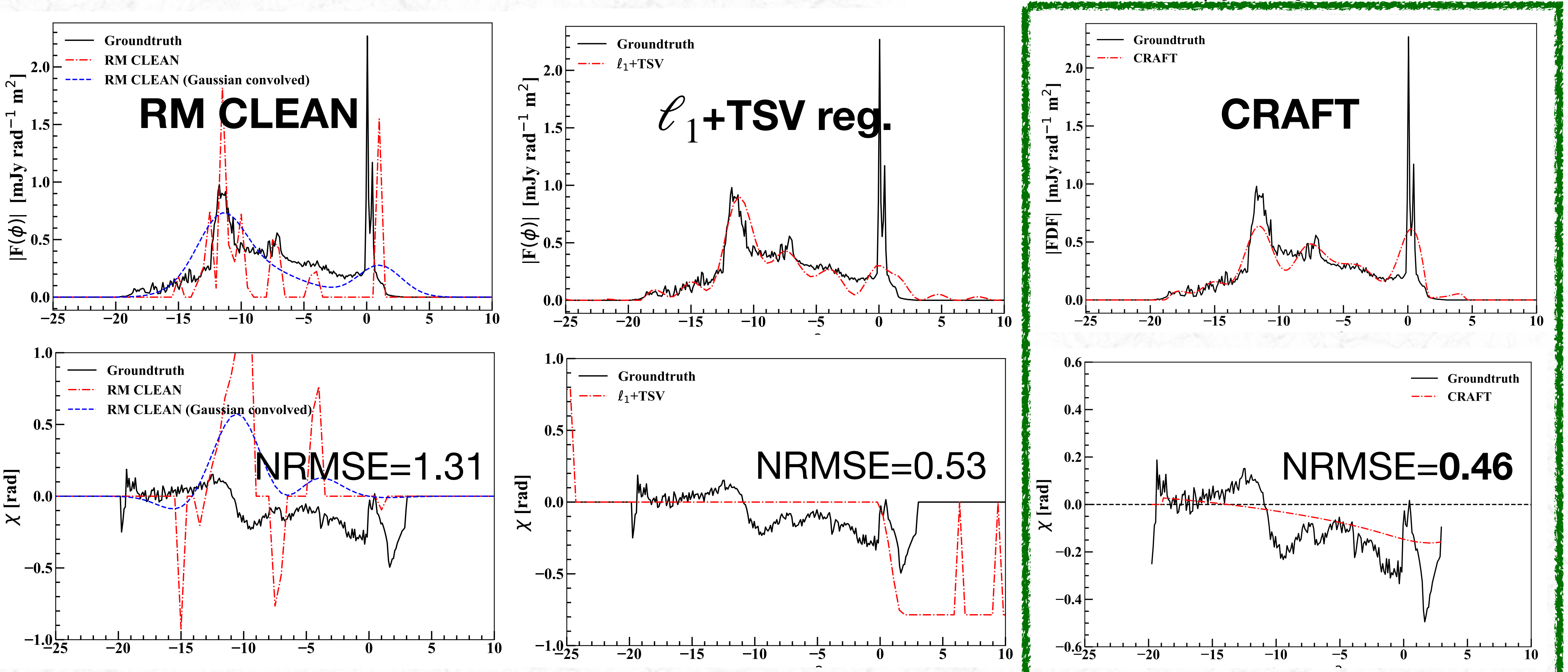
Volume integrated FDF simulation for a Milky Way-like galaxy with a sophisticated galactic model, incorporating Magneto-hydrodynamic turbulence (Ideguchi et al. 2014, Akahori et al. 2013)

We consider a frequency range of **300 MHz to 3000MHz** (Akahori et al.2018b)



Amplitude

Phase (Polarization angle)



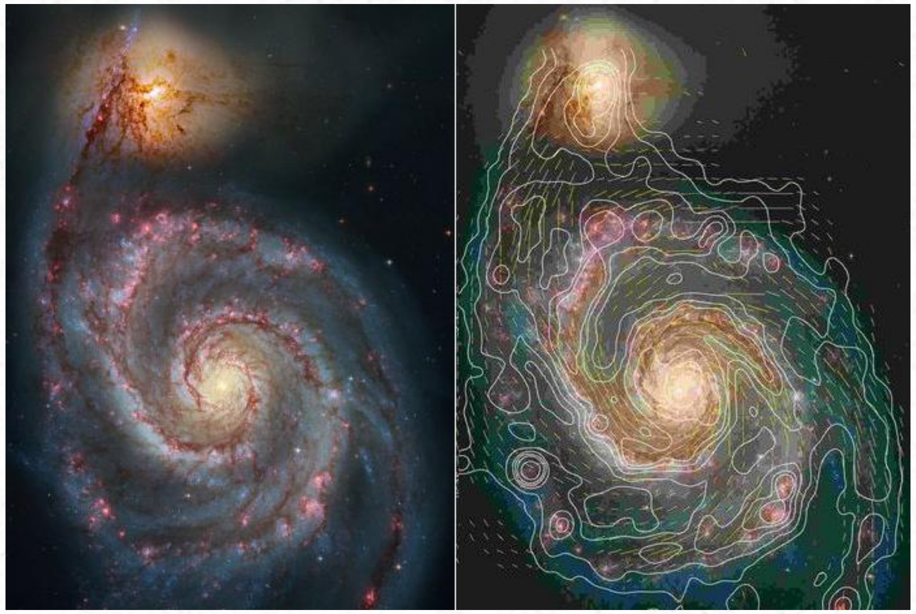
Advantages over current techniques

- CRAFT captures **multi-scale features** of the FDF better than any other techniques while producing good agreements on the polarization angle reconstructions
- Comparatively computationally inexpensive
  - CRAFT takes **few seconds** for what sparse modeling takes **1.5 hours**
  - **Efficiency is important for the large amounts upcoming of data**
- The general reconstruction technique is described in Cooray et al. (2020 PASJ, 72, id.61; arXiv:2004.06979)

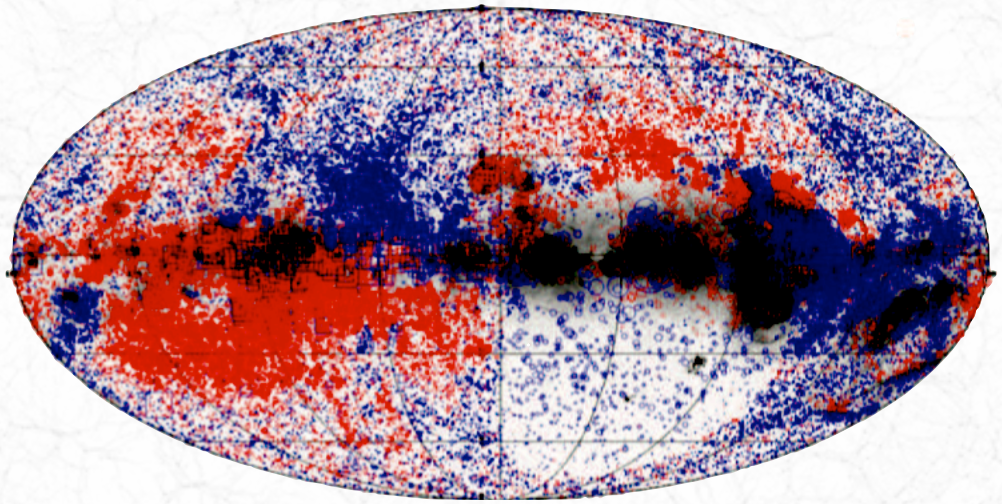
CRAFT provides a way to accurately map the cosmic magnetic fields!

A Way for New Cosmic Magnetism Studies...

- Magnetism influences astrophysical phenomena of all scales from the interstellar medium to the cosmic web and beyond.
- For example, galaxy properties such as morphology, star formation rates, supernova/stellar wind feedback, and AGNs are all tightly related to the galactic magnetic field.
- **Faraday tomography with CRAFT and next generation observations (SKA) will be a powerful tool to study the less understood nature of magnetism and its influence on baryonic matter**



Visible matter and their connection to the magnetic field. Whirlpool galaxy M51. Credit: MPIfR Bonn



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Dominic Schnitzeler, Ferrière (2016)

Thank you!