

The 4th National Workshop on the SKA Project - Sharpening the Italian science case for the SKAO
Catania - 29/11/2023

The magnetized Universe



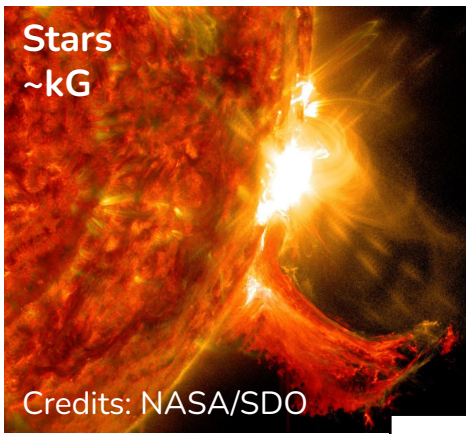
Francesca Loi

INAF-OAC

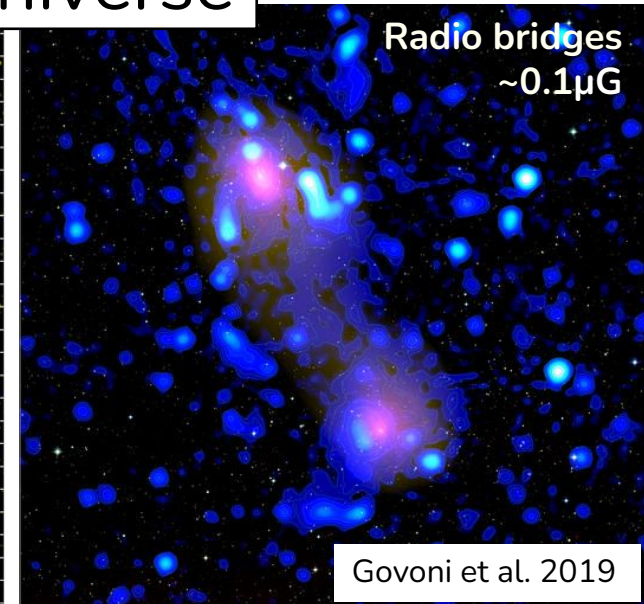
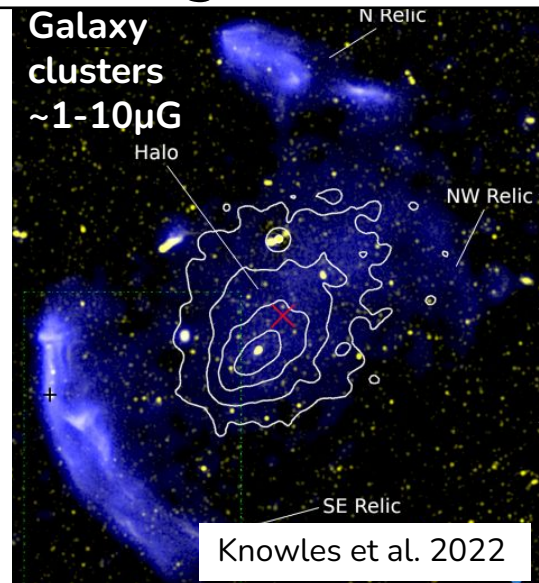
E-mail: francesca.loi@inaf.it

Outline

- Scientific introduction
- Open questions
- Ongoing surveys and projects
- Future SKA survey



We all live in a magnetized Universe



The impact of magnetic fields at different scales

1. Cosmology:

- Structure formation [see e.g. Subramanian et al. 2016]
- duration of the EoR

2. Cluster physics:

- heat conduction, propagation of relativistic particles, gas mixing, star formation of cluster galaxies

talk by A.
Bonafede
on Wed.

3. Galaxy physics and evolution:

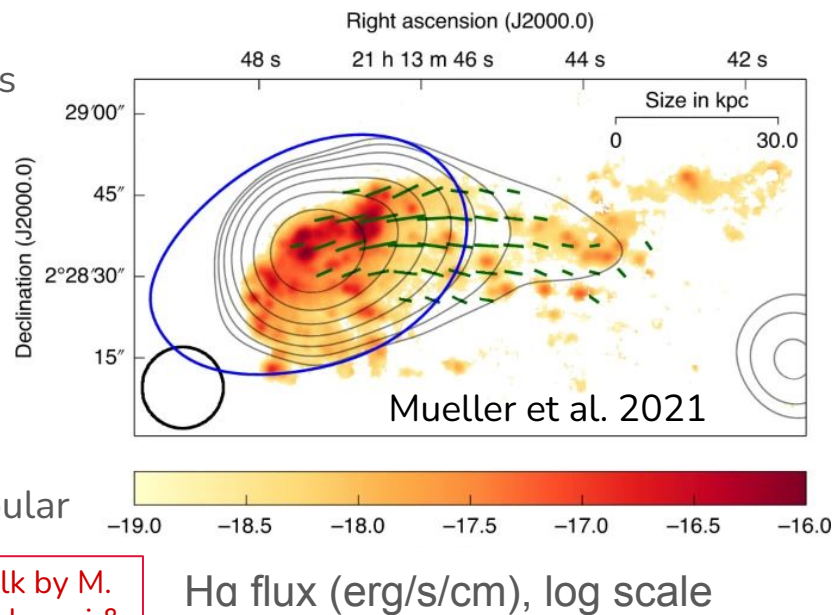
- SFR, feedback, outflows
- accretion around AGN
- formation of relativistic jets in AGN

4. Milky Way:

- morphology of SNR, planetary nebulae, HII region, globular clusters, life in exoplanets
- formation and collapse of dense molecular clouds

talk by C.
Trigilio on
Thu.

talk by M.
Padovani &
A. Traficante
on Wed.

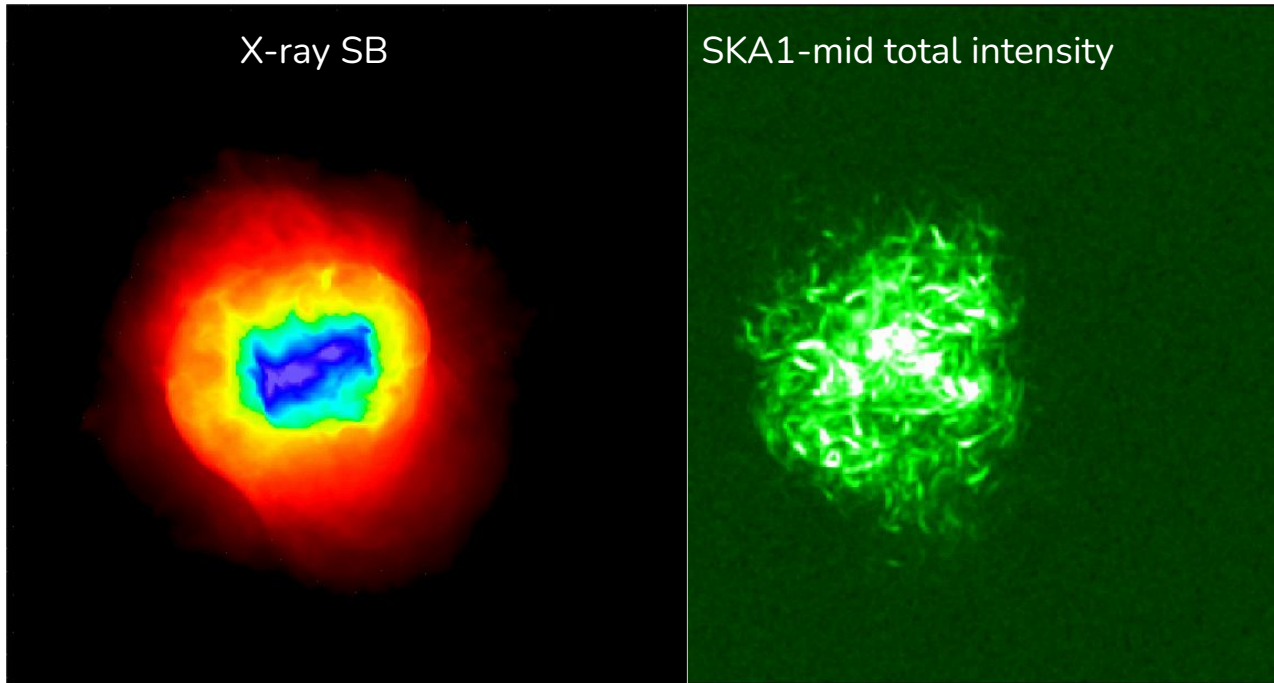


Open questions

1. What is the origin of large-scale magnetic fields?

Open questions

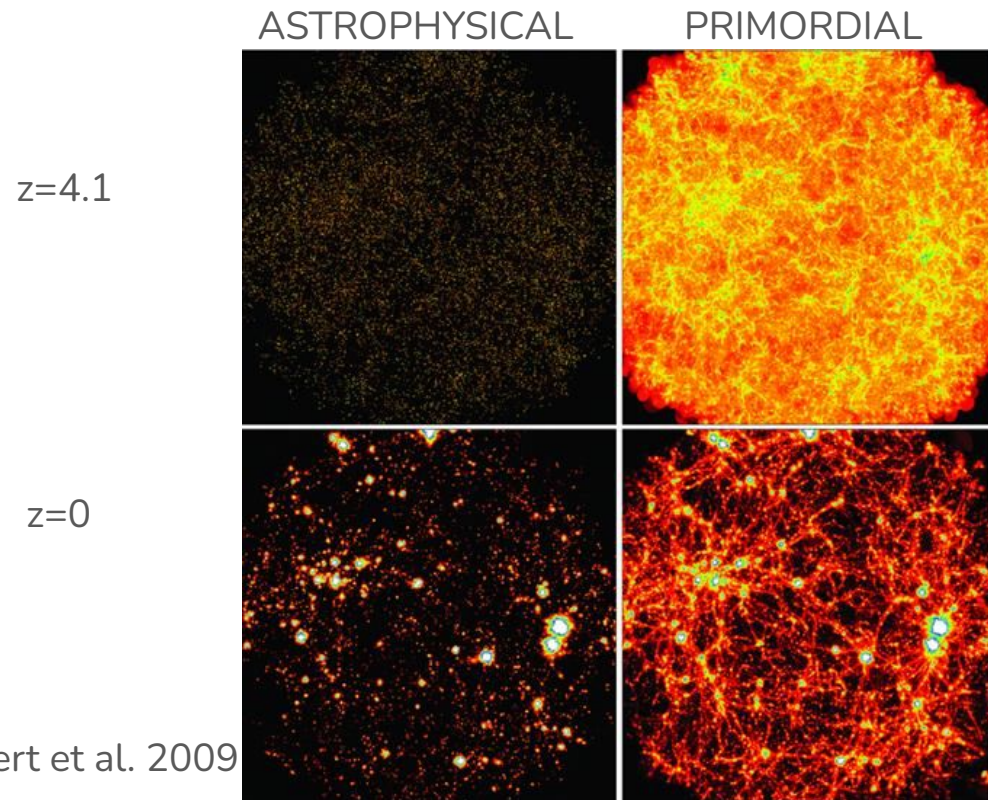
1. What is the origin of large-scale magnetic fields?



Loi et al. 2019a,b

Open questions

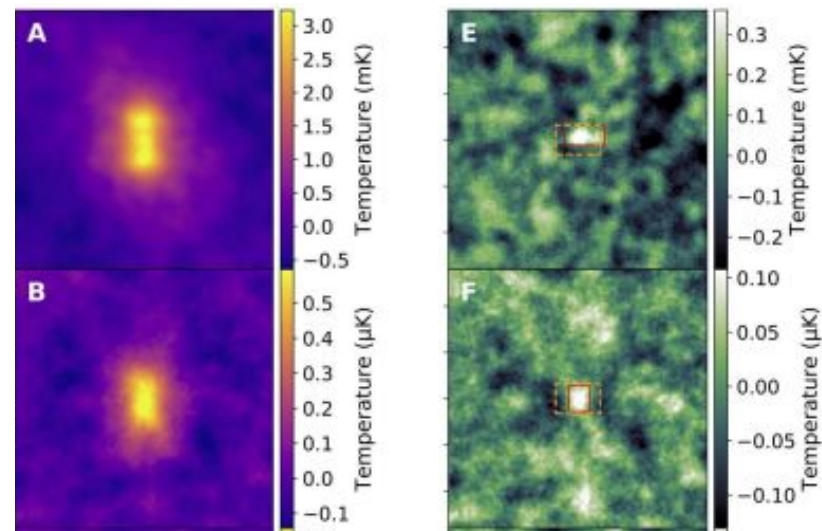
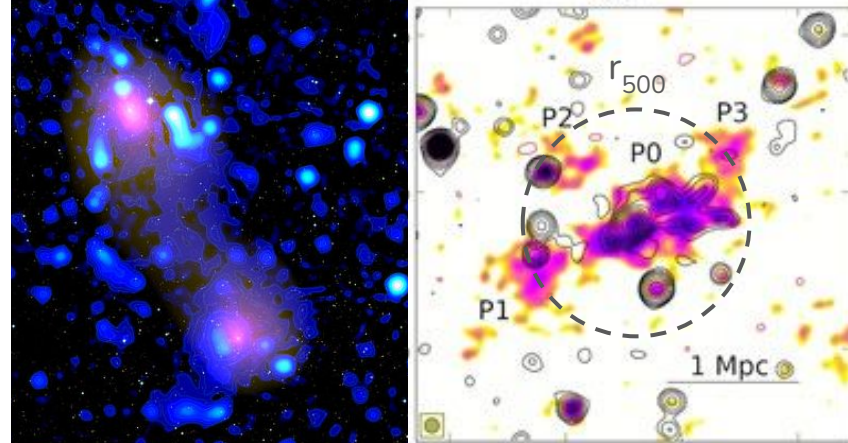
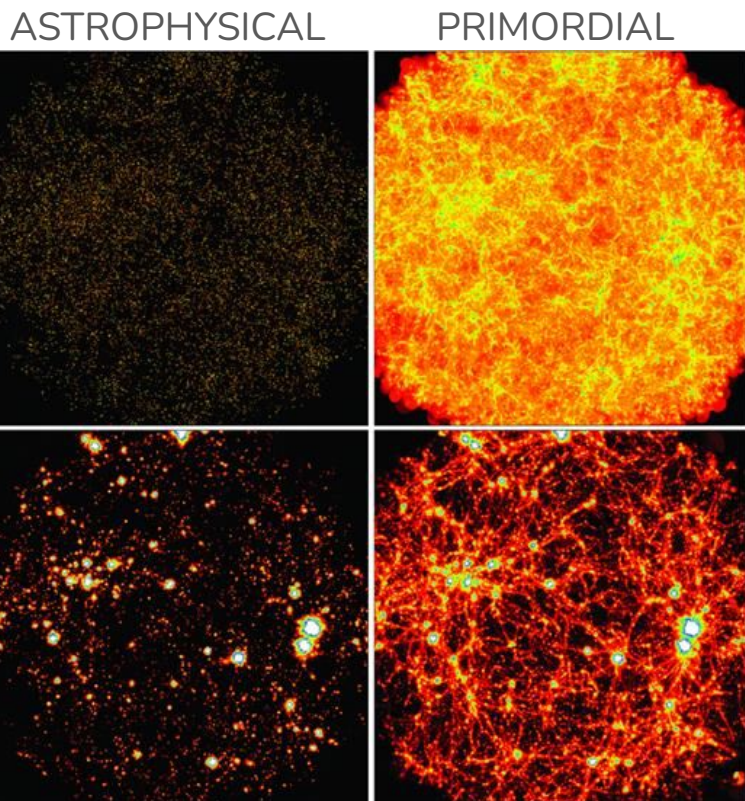
1. What is the origin of large-scale magnetic fields?



Donnert et al. 2009

Open questions

1. What is the origin of large-scale magnetic fields?



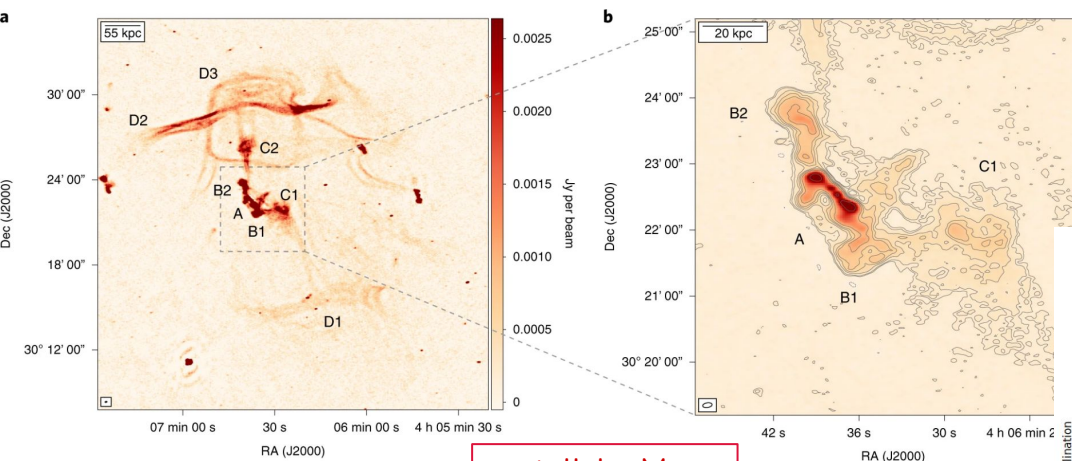
[Vernstrom et al. 2023]

Open questions

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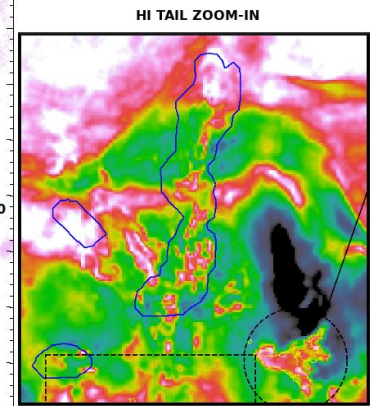
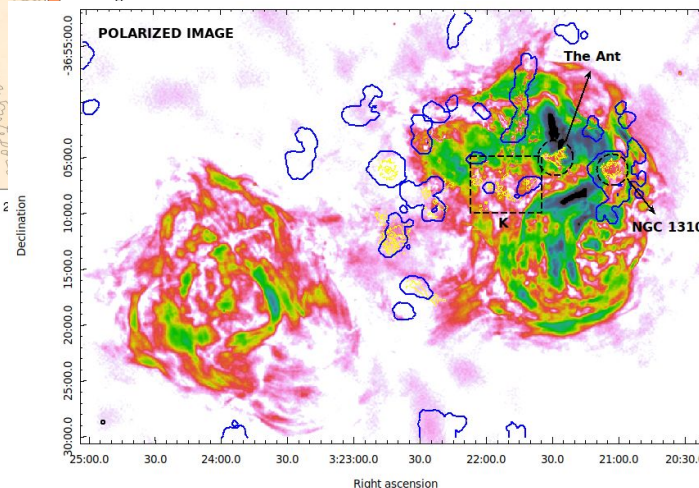
ASTROPHYSICAL

PRIMORDIAL



Brienza et al. 2022

talk by M.
Brienza on Wed.



Loi et al. 2021

Open questions

1. What is the origin of large-scale magnetic fields?
 - level of dynamo amplification in filaments, memory of B “seed”
 - duration of EoR (if B seeding by EoR)
2. What are the properties of intracluster magnetic fields?
 - ICM turbulence scale
 - evolution of the magnetic field?
3. How AGN/SFG interact with the environment?
4. Why large-scale magnetic fields are present in SFG?
 - large-scale dynamo models
5. What are the properties of the turbulent interstellar magnetic field?
6. What is the structure and the strength of the Milky Way magnetic field? (implications on measurements)

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SKA: The telescope to understand cosmic magnetism

SKA magnetism working group

Chairs:

V. Vacca (INAF) and T. Vernstrom (Western Australia Univ.)

65 members, 14 working in Italy:

A. Bonafede*, E. Carretti*, L. Feretti*, F. Govoni*, C. Riseley*, G. Brunetti, G. Giovannini, F. Loi, F. Marchegiani, M. Murgia, M. Padovani, M. Regis, R. Paladino, F. Vazza.

*core members

Francesca Loi – INAF-OAC

Cosmic Magnetism Science Working Group

The Cosmic Magnetism Science Working Group is focused on defining the role of magnetic fields in the physical processes that determine the structure and evolution of the Universe. SKA observations will establish the origin and evolution of magnetic fields throughout the cosmos.

Magnetic fields are a major agent of energetic processes in various cosmic objects, from star forming regions and stellar remnants, through galaxies, including our own Milky Way, to the large-scale structure of the Universe. Magnetism has long been recognized as a crucial element in these processes, but new technology is required to make the observational progress needed for a full understanding of how they unfold in practice.

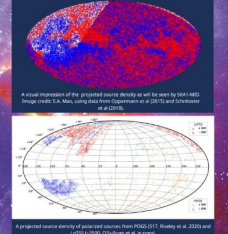
Radio astronomy provides the most effective probes of cosmic magnetism. The SKA's revolutionary capability promises to take our study of magnetic fields to a new level of precision, and expand our horizon to distant objects that are inaccessible in sufficient detail today. Specifically, its unparalleled sensitivity and resolving power, combined with wide frequency coverage, makes the SKA ideal for probing magnetism across the Universe through the study of polarized synchrotron emission and its Faraday rotation, and Zeeman splitting (for more details see Heald et al. 2020).

A dense Faraday Rotation Measure (RM) Grid

The SKA will produce a Faraday RM Grid, comprising polarimetric detections of 2-3 million radio galaxies, a factor two better than POSSUM. In addition to understanding the nature of the polarized sources themselves, the SKA RM Grid will be used to probe a wide range of extended, intervening foreground sources, including:

- Milky Way and sources within (HI regions, SNRs, HVCs, masers, ...)
- Magellanic Clouds
- Nearby galaxies
- Galaxy Clusters
- Radio Galaxies
- Cosmic Web

The extremely high density of background RMs will enable the study of individual objects as well as statistical investigations of source classes. SKA-LOW will complement the SKA-MID RM Grid. Despite the low density of polarized sources detected to date at low with respect to mid frequencies, the 100x better precision in RM will permit very high-accuracy magnetic field measurements in some sources



Right: EB045 HI 21 cm brightness temperature (blue) with LOFAR HBA Faraday tomographic data (orange) and Planck magnetic field orientation at 855 GHz (diagonal pattern) of a 64 deg² field at mid-Galactic latitude. This figure highlights the mutual correspondence of morphological structures that also correlate with the planck-disk-like orientation of the magnetic field (Bacco et al. 2020).

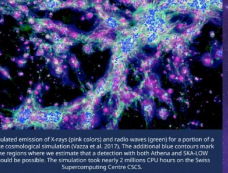
What is the role of magnetic fields in the evolution of cosmic objects?

The unmatched surface brightness sensitivity and angular resolution of the SKA will permit the imaging and detailed study of the diffuse magnetized media in the Milky Way and in nearby galaxies. This will allow us to uncover the role of magnetic fields in the star formation process. Combined with the detailed view of the magnetized medium in galaxy clusters and in the cosmic web, the SKA will probe magnetic fields from the smallest to the largest scales and determine the mechanisms that shaped and amplified magnetic fields.

Left: Radio/Optical composite image of the region near galaxy NGC 4237. Magnetic field lines (green), revealed by MRA, reveal the dense and turbulent structure of the galaxy. Credit: S. van der Laan (OAC), M. Regis (OAC), M. Murgia (OAC), D. Bell (OAC), H. Marshall (OAC), G. Bernardi (OAC), A. Maccagni (OAC), U.S. K. Reich (OAC), and J. van Driel (OAC).

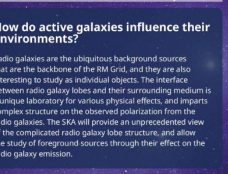
What is the structure of the Universe on the largest scales?

Our standard cosmology predicts that the majority of baryonic matter in the Universe exists as a cosmic web of diffuse, magnetized plasma. However, the distribution and properties of this extremely diffuse material are not yet well understood. Recent low frequency observations of SKA precursors and pathfinders, as LOFAR and MWA, proved to be very useful in detecting and constraining magnetic fields in the large-scale structure of the Universe, both through diffuse synchrotron emission and Faraday rotation of background radio sources. Understanding the cosmic web will allow us to address longstanding questions of modern astrophysics such as the thermal and dynamical evolution of galaxy clusters, the origin of the ultra-high energy cosmic rays, magnetogenesis and evolution of magnetic fields, and the inflationary theory of cosmology.



How do active galaxies influence their environments?

Radio galaxies are the ubiquitous background sources that are the backbone of the RM Grid, and they are also interesting to study as individual objects. The interface between radio galaxy lobes and their surrounding medium is a unique laboratory for various physical effects, and imparts complex structure on the observed polarisation from the radio galaxies. The SKA will provide an unprecedented view of the complicated radio galaxy lobe structure, and allow the study of foreground sources through their effect on the radio galaxy emission.



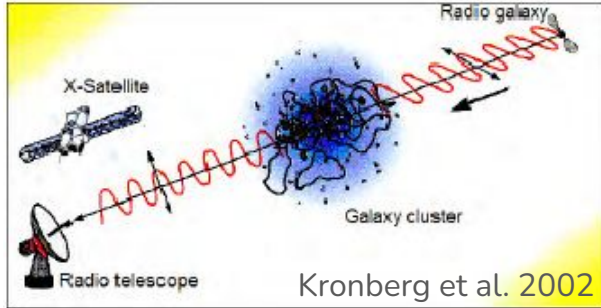
Techniques & strategies

Diffuse emission in total
and polarized intensity

Faraday effect

Zeeman effect
(clouds)

The Rotation Measure grid



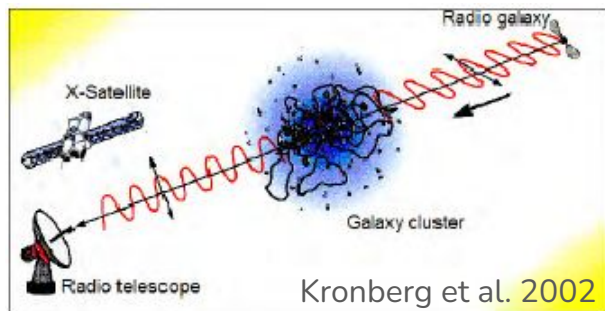
Faraday effect

$$\Delta\Psi = \text{RM} \cdot \lambda^2$$

$$\text{RM} = \int B_{\parallel} \cdot n_e \cdot dl$$

- Bandwidth
- Sensitivity
- Space and frequency resolution

The Rotation Measure grid

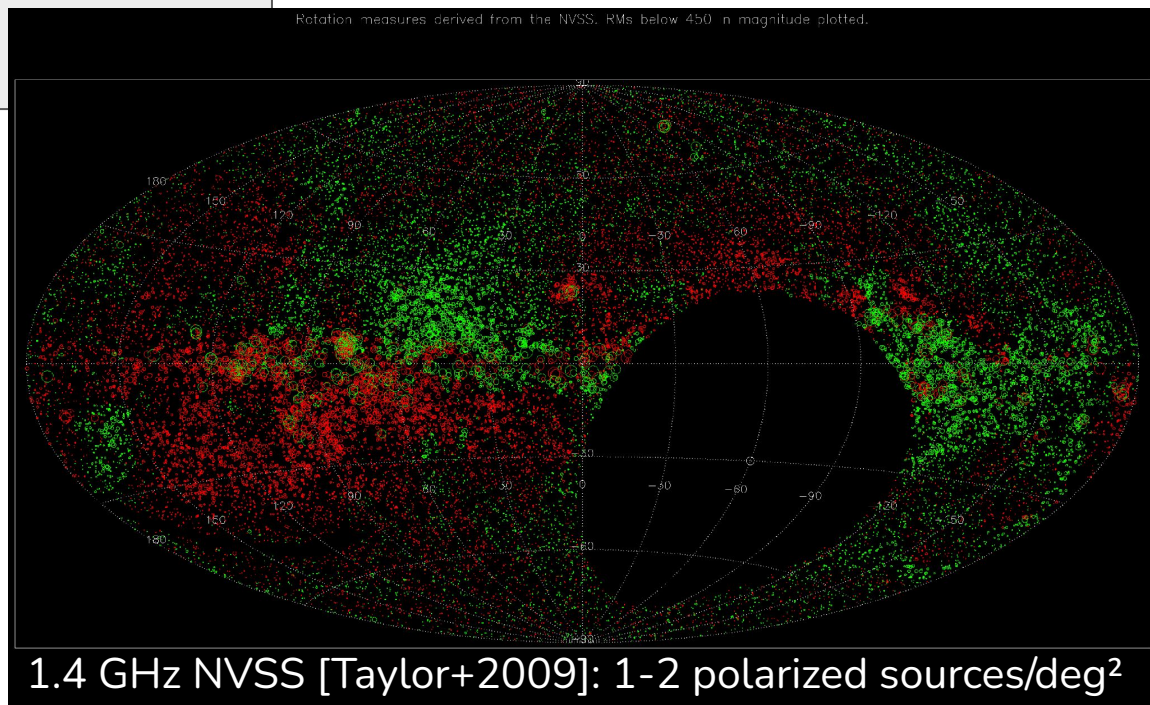


Faraday effect

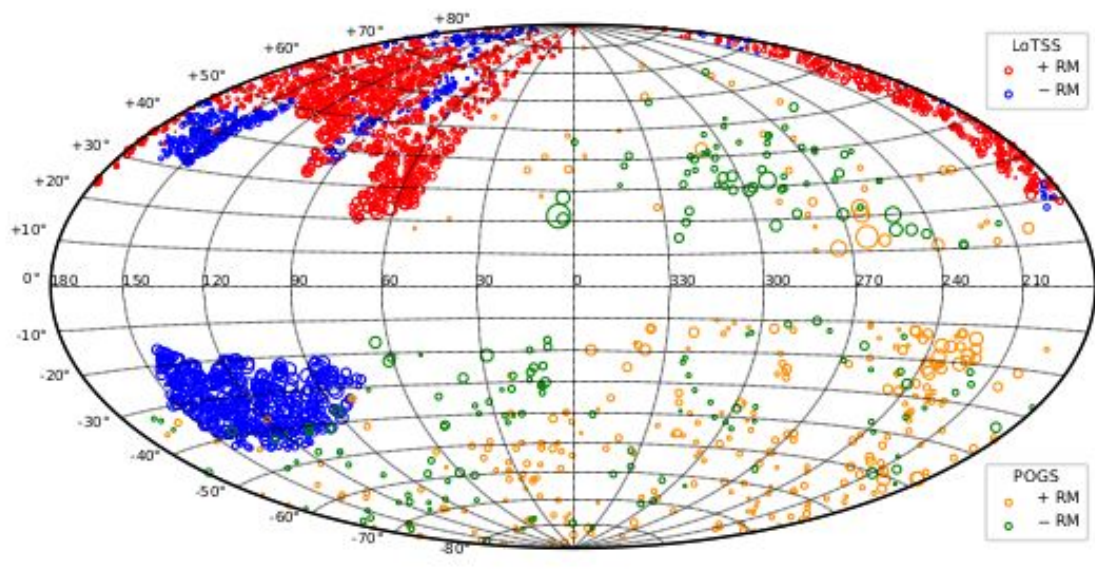
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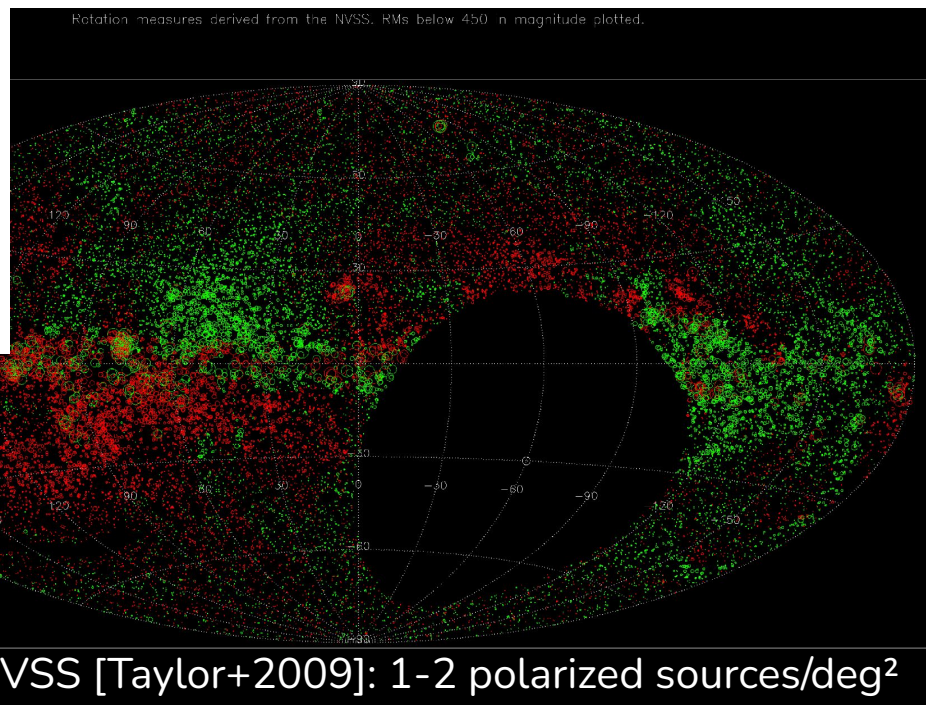


144 MHz LoTSS [O'Sullivan et al. 2023]:

0.29-0.48 p.s./deg²

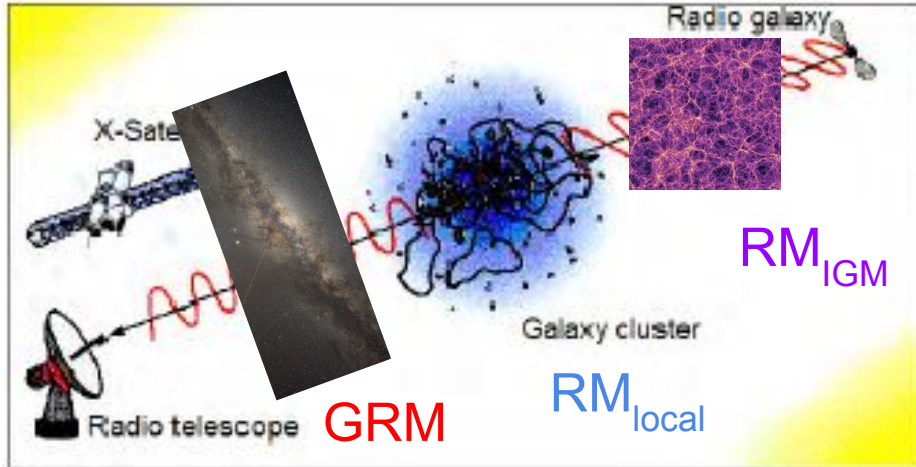
200 MHz POGS [Riseley et al. 2020]:

0.019 p.s./deg²



Magnetic fields in cosmic filaments with LoTSS-DR2

(Carretti et al. 2022-2023)

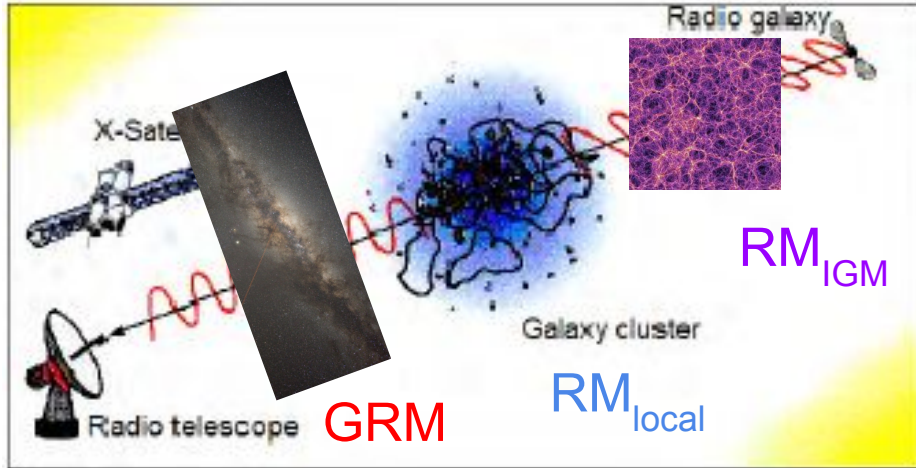


$\Delta\Psi = RM \cdot \lambda^2$; large $\Delta\Psi$ within a frequency channel destroys the polarization

$$RM = GRM + RM_{\text{local}} + RM_{\text{IGM}} + RM_{\text{noise}}$$

Magnetic fields in cosmic filaments with LoTSS-DR2

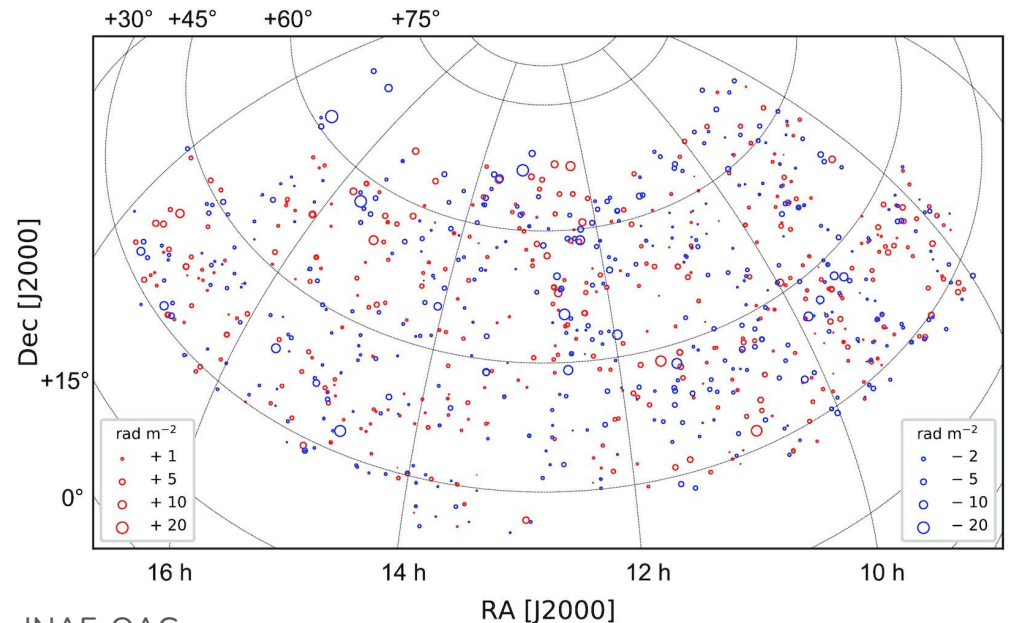
(Carretti et al. 2022-2023)



Residual RM: $RRM = RM - GRM$
more than 90% is due to filaments!

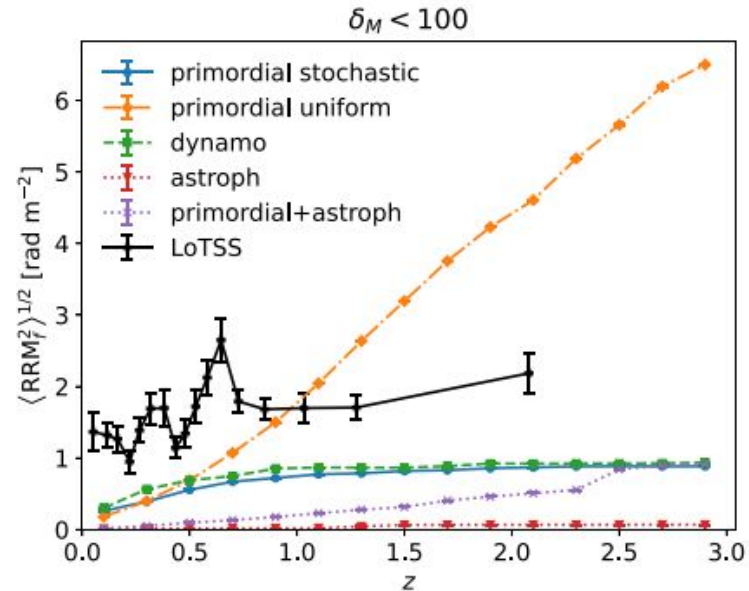
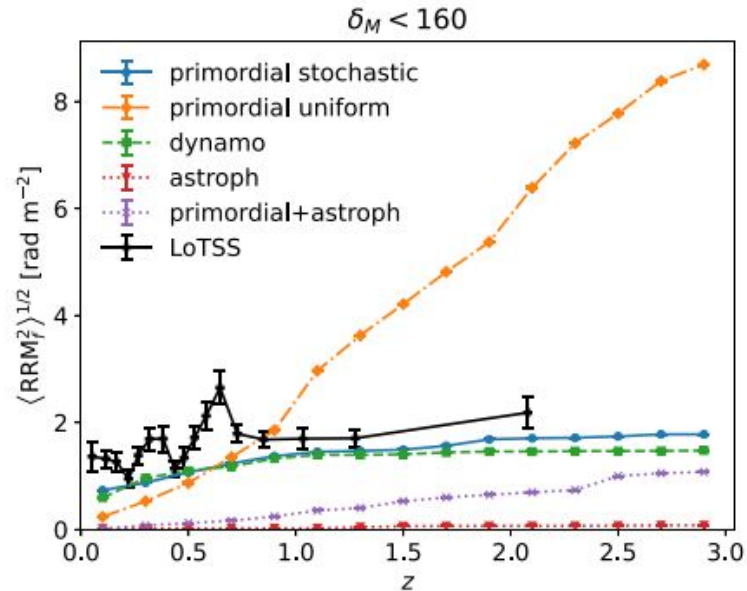
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Magnetic fields in cosmic filaments with LoTSS-DR2

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Primordial uniform model excluded.

Primordial stochastic magnetic field model with comoving $B=0.04\text{-}0.11$ nG

Consistent with CMB u.l. of $0.12\text{-}0.13$ nG (Paoletti & Finelli 2019; Paoletti et al. 2022).

The MeerKAT Fornax Survey (P.I. Paolo Serra)

Goals:

Studying the evolution of galaxies

talks by P. Serra
and A. Loni on
Wed.

Mapping the Fornax cluster magnetic field

talk by me
on Wed.

Methods:

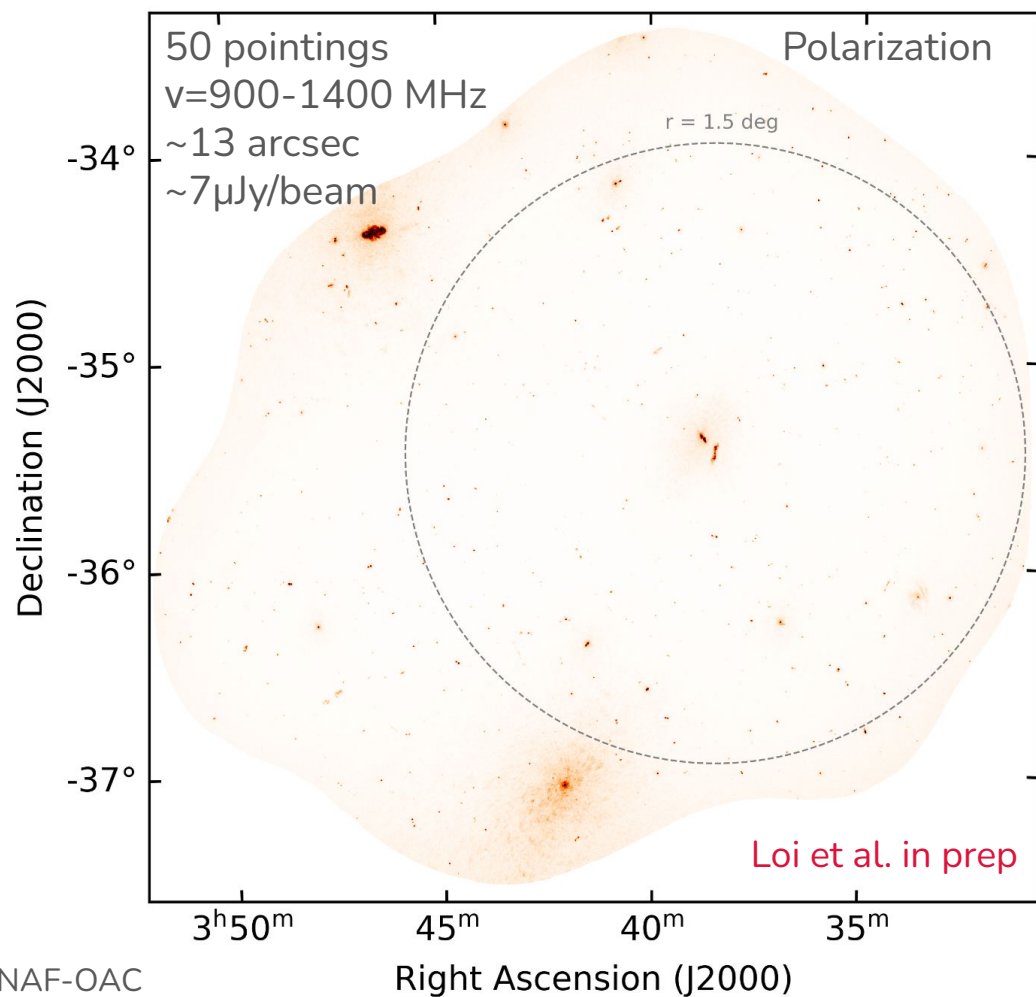
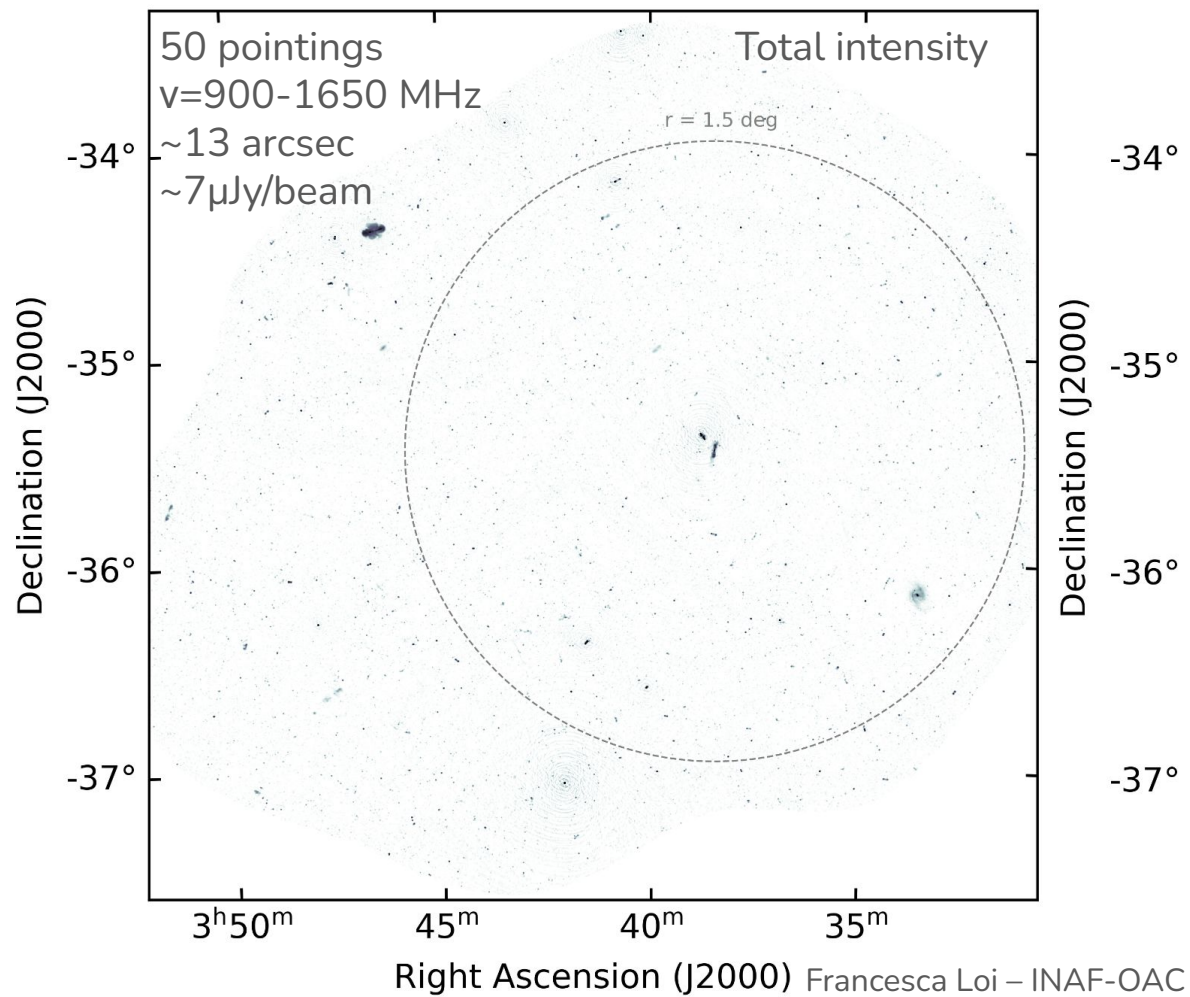
HI detection

Broad band spectro-polarimetric observations ($\nu=900-1650$ MHz)

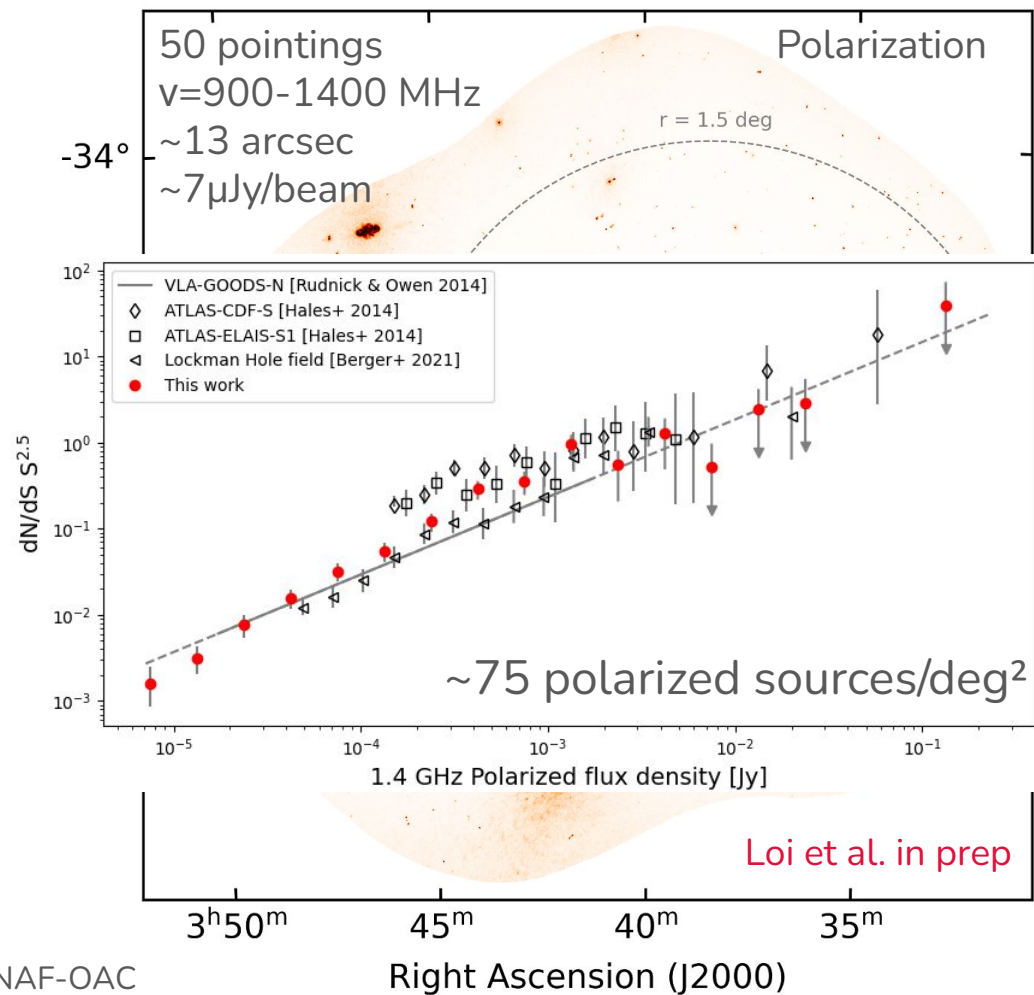
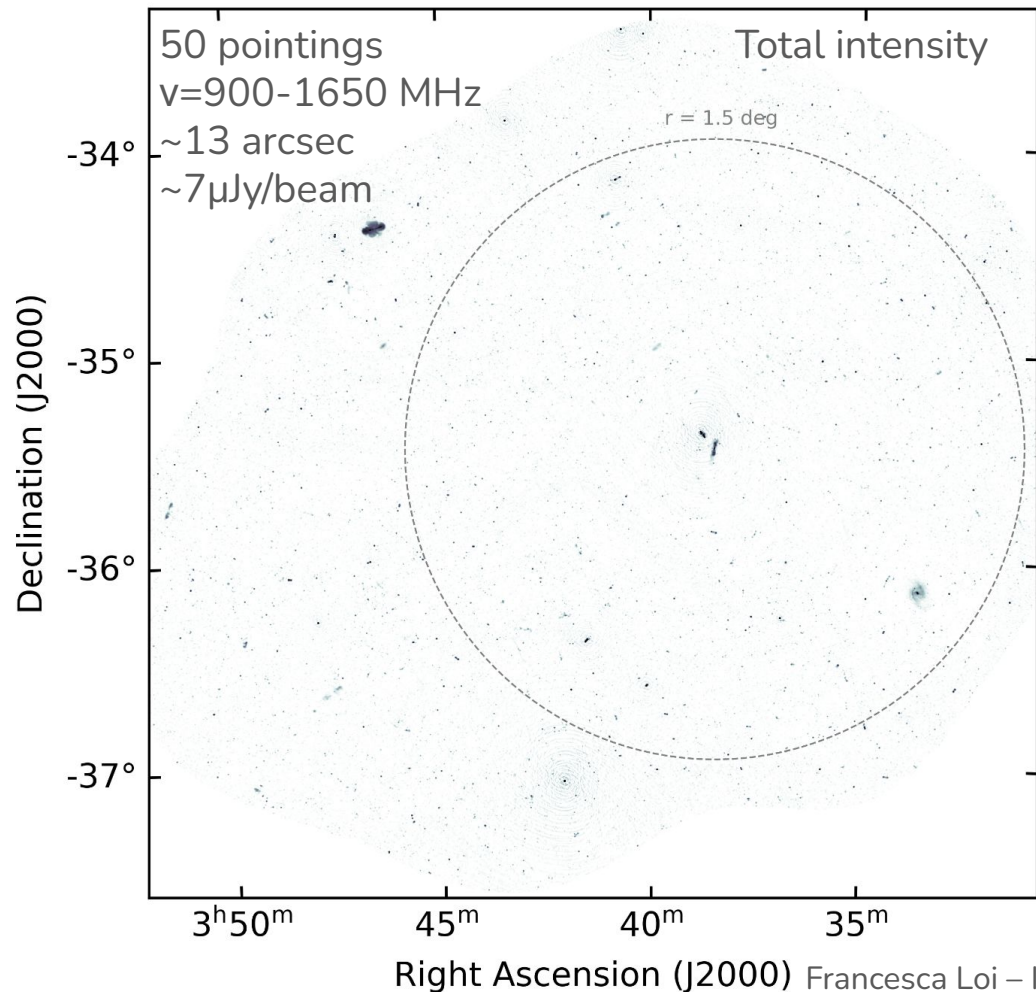
Why Fornax?

Nearby (~ 20 Mpc) low-mass cluster ($M \sim 6 \cdot 10^{13} M_{\text{sun}}$) with substructures.

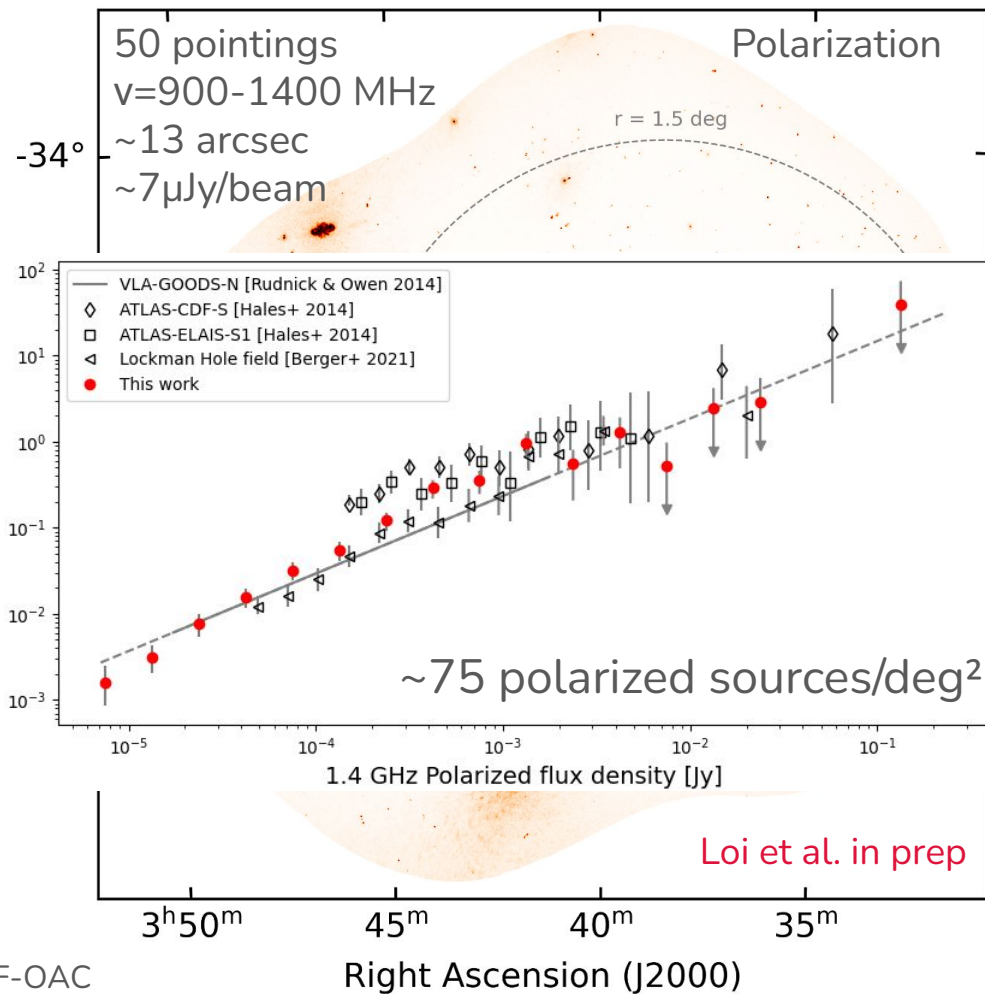
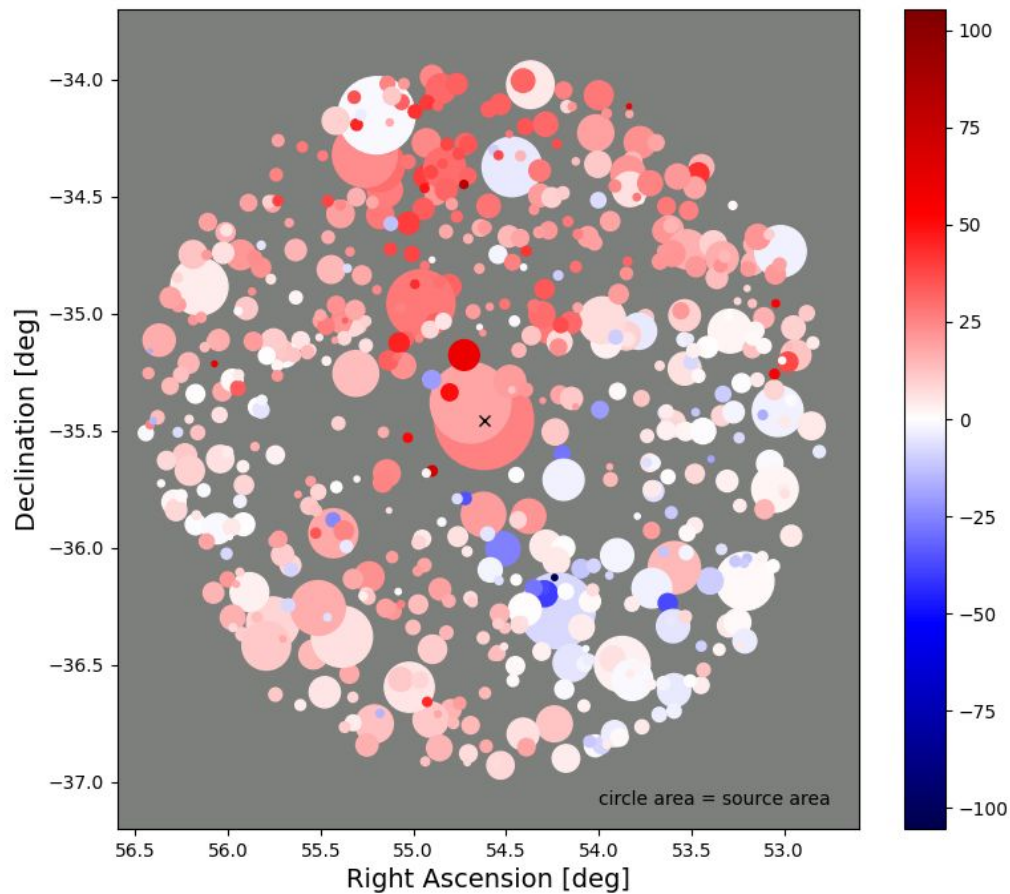
MeerKAT Fornax Survey



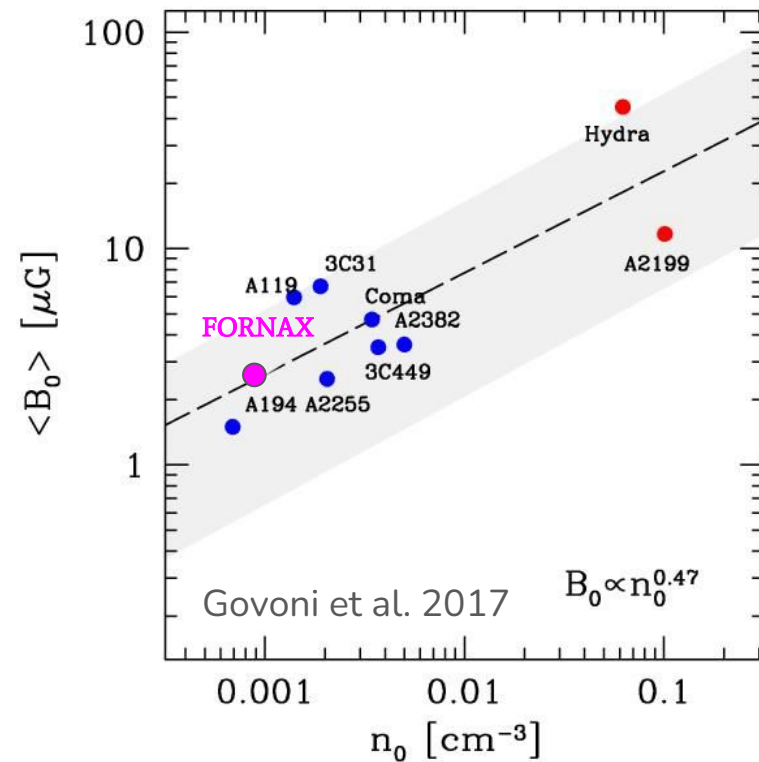
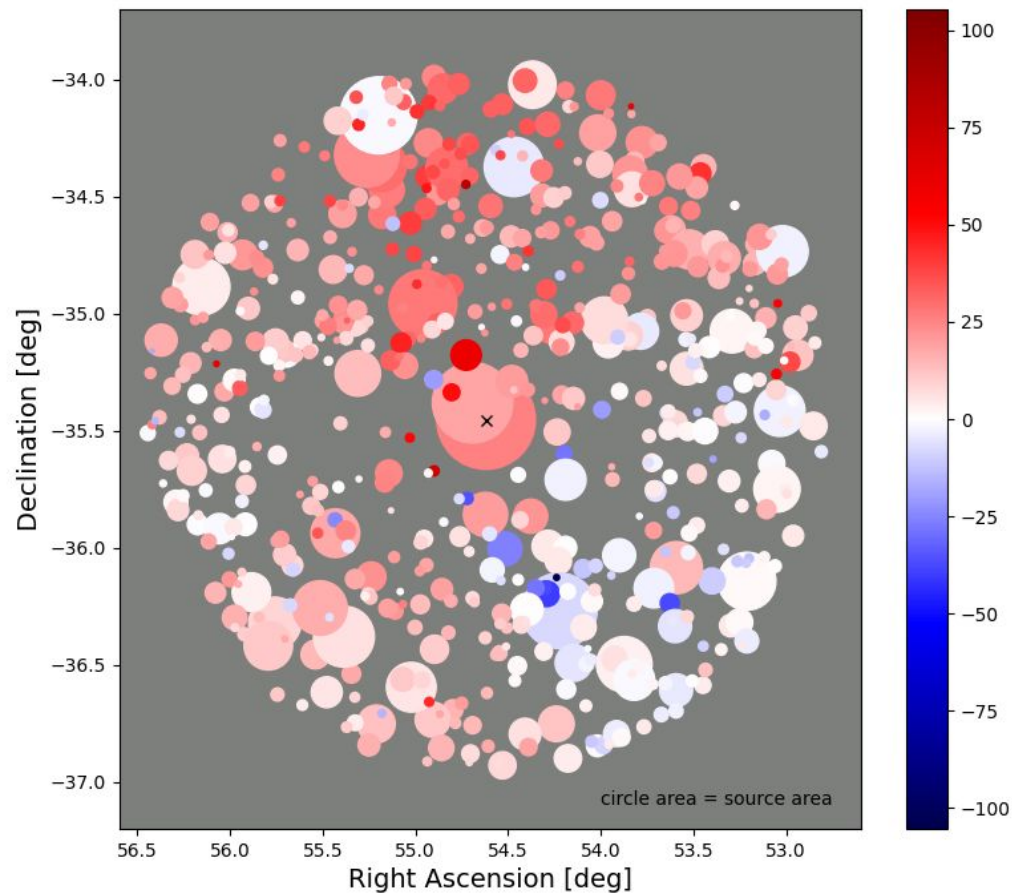
MeerKAT Fornax Survey



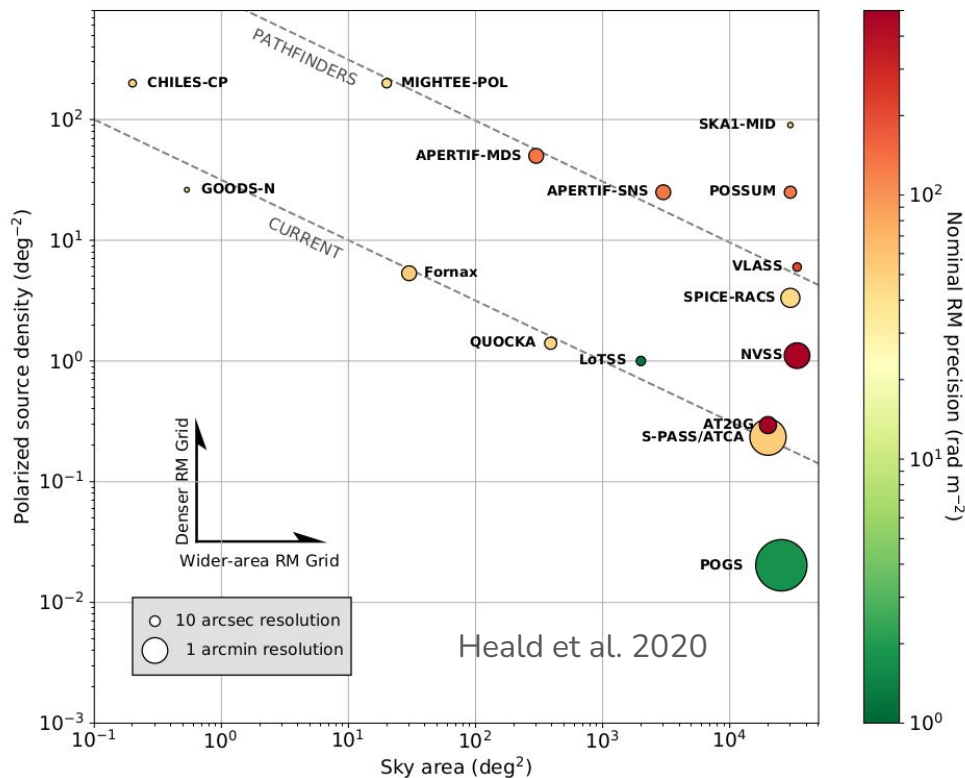
MeerKAT Fornax Survey



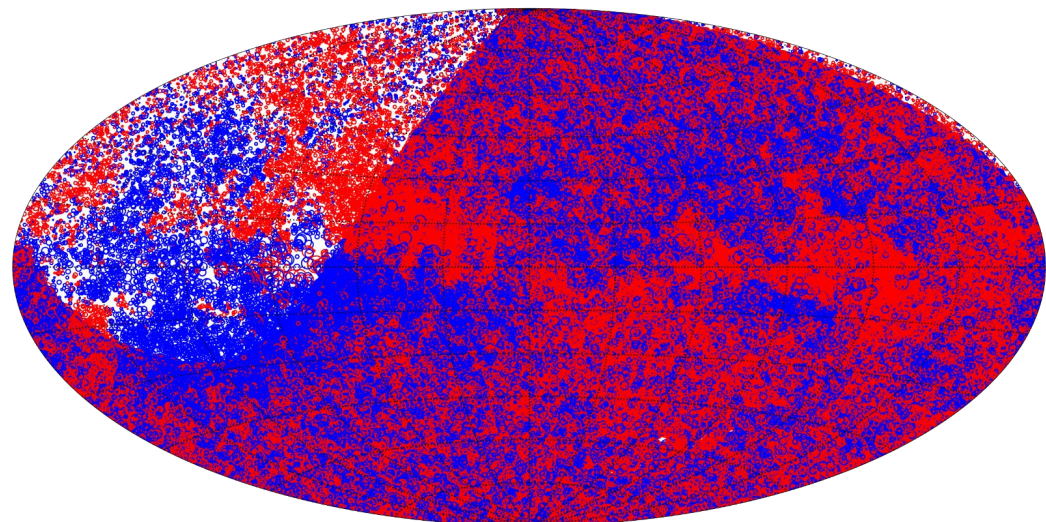
MeerKAT Fornax Survey



The Future: SKA1-mid Survey



950-1760 MHz
 4 μJy/beam of sensitivity
 2 arcsec of resolution
 60-90 pol.sources/deg²
 LAS ~ 0.5-1 degree
 30'000 pointings, 15 min on each
 The survey will last 2.5 years.



credits: S.A. Mao, using data from Oppermann et al (2015) and Schnitzeler et al (2018)

Conclusion

SKA1-mid is going to explore the Universe in polarization

Its unprecedented capabilities will help us to better understand cosmic magnetism

A lot of commensality projects will be carried out with the same data

Thank you

Magnetism projects with SKA pathfinders at low frequency

LOFAR	Magnetism Key Science Project	P.I.: O' Sullivan and V. Heesen
	Milky way	Chairs: M. Iacobelli (ASTRON) and V. Jelić (Ruđer Bošković Institute)
	Nearby galaxies	Chairs: R. Paladino (INAF) and K. Chyzy (Jagiellonian University)
	Radio galaxies	Chairs: E. Orrú (ASTRON) and M. Jamrozy (Jagiellonian University)
	IGM & LLS	Chairs: A. Bonafede (INAF) and E. Carretti (INAF)
	Deep fields	Chairs: V. Vacca (INAF) and I. Prandoni (INAF)
	RM grid task force	P.I.: S. O' Sullivan (Madrid University)
	GOODS-N deep field	P.I. V. Vacca (INAF)

Magnetism projects with SKA precursors at mid frequency*

ASKAP projects	POSSUM collaboration	P.I. C. Anderson (NRAO), G. Heald (CSIRO), N. McClure-Griffiths (ACT)
	P009: Magnetic fields in the LSS with a Bayesian approach	P.I. E. Carretti (INAF)
	P004: A detailed RM study of the poorly known Abell 3718 galaxy cluster	P.I. F. Loi (INAF)
	M010: Rise of a phoenix in Hickson Compact Group (HCG) 15: shocked fossil plasma revealed by ASKAP, LOFAR, and the GMRT	P.I. C. Riseley (INAF)
MeerKAT key science projects	The MeerKAT Fornax Survey - polarization	P.I. P. Serra (INAF)
	MIGHTEE - polarization working group	Chairs: A. Scaife (Manchester Univ.) & R. Taylor (UCT)

*project related to polarization/RM with an italian PI-ship

Open questions

1. What is the origin of large-scale magnetic fields?

Polarized accretion shocks from the cosmic web
[Vernstrom+2023]

Organization of local magnetic fields by strong shock waves

