# Using Magnetism to Reveal the Mysteries of the Universe

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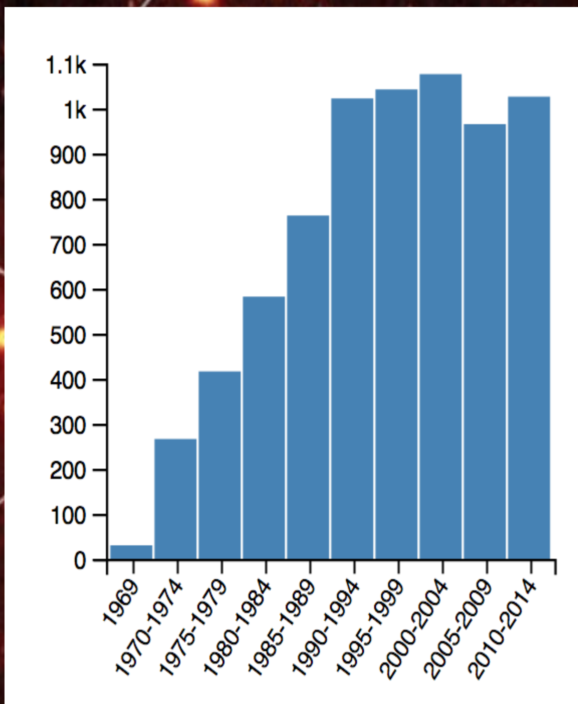
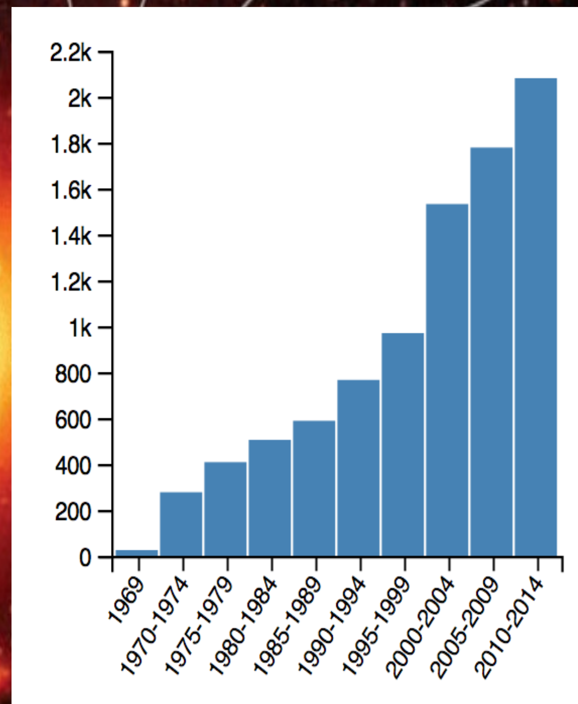
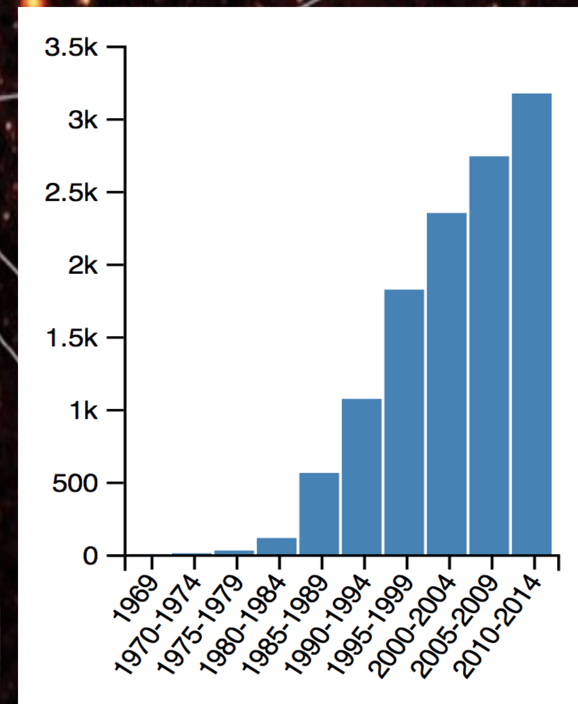
# Magnetic Fields

- Magnetic fields manifest on all scales in the Universe and are important in a number of astrophysics areas including:
  - Large Scales: Cosmic fields, clusters of galaxies, halos & relics, filaments of the cosmic web
  - Intermediate scales: Galactic fields including the Milky Way, AGN jets
  - Small scales: Pulsass, masers, SNRs, HVCs, bubbles & shells in the Milky Way and other galaxies. Science
- Additionally understanding magnetic foregrounds is crucial for the EoR, inflation theory using B-mode polarisation of the CBM or to unveil the magnetic structure of the cosmic web.

# Magnetic Field + X



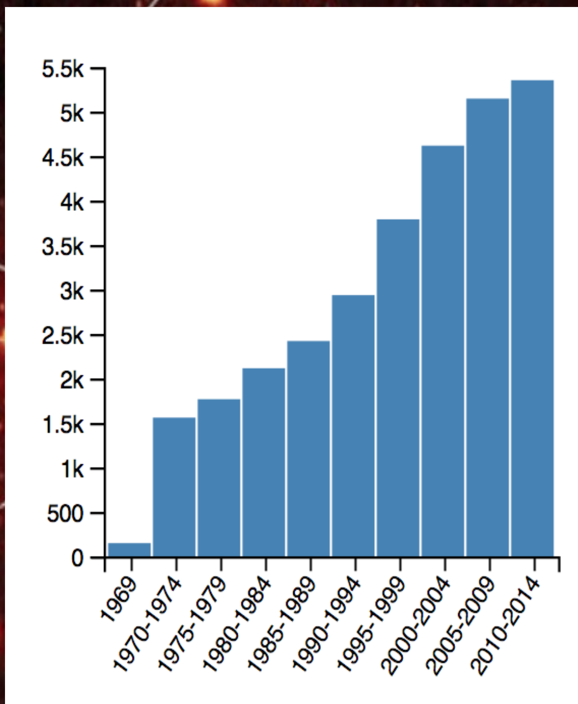



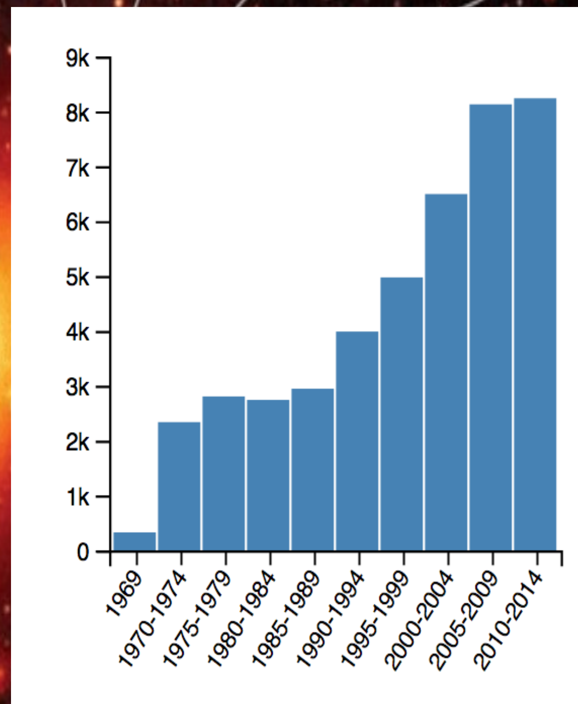

Magnetic Field + Spiral Galaxy
Total 7628
Over 250 papers per year now

Magnetic Field + Galaxy Cluster
Total 9657
Over 500 papers per year now

Magnetic Field + AGN
Total 17,919
Over 900 papers per year now

# Magnetic Field + X




Magnetic Field + Pulsar
Total 31,495
Over 1300 papers per year now

Magnetic Field + Cosmic Rays
Total 49, 325
Over 2000 papers per year now

I challenge you to try this for your own favourite type of source!

Magnetism is important for over 5000 papers annually!!

**SKA is a unique tool to probe magnetic fields -> big science impacts across**

# Measuring Magnetism

- There are a number of ways in which magnetic fields can be investigated:
  - Faraday Rotations Measures
  - Polarisation of Synchrotron emission (vector maps and depolarisation)
  - Zeeman Effect

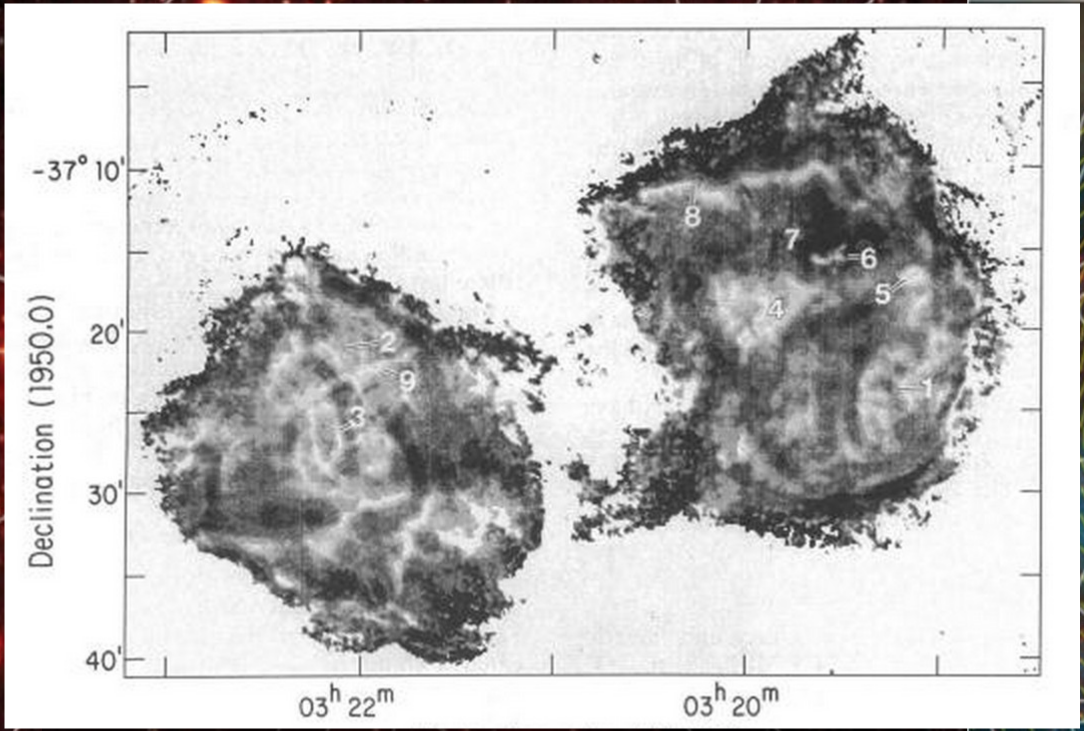
# SKA & Magnetism

- Historically it has been difficult to do detailed studies of the magnetic field of large numbers of objects due to limited sensitivity, resolution and polarisation calibration of the previous generation of radio telescopes.
- Additionally understanding the complex nature of polarised signals was difficult until the advent of techniques to allow us to probe the Faraday Spectra and to statistically disentangle effects of foregrounds along the line of sight.
- With the current generation of new or upgraded instruments along with better analysis techniques and computer modelling we are starting to see an increase in the science we can do with polarisation.
- In the age of the SKA this will only continue as we move to the Era of Precision Magnetism

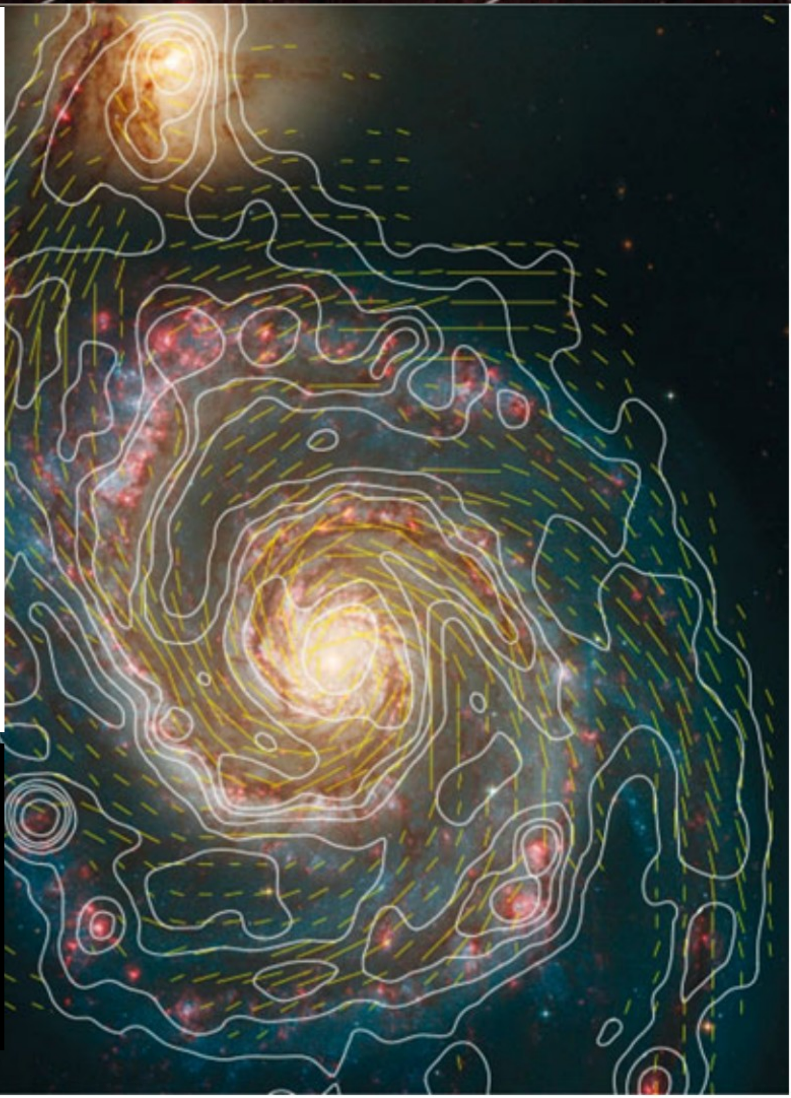
# Era of Precision Magnetism

- The SKA will give us
  - Higher sensitivity
  - Broader bandwidths
  - Wide fields of view
- Each of which provides a unique capability for probing cosmic magnetism.

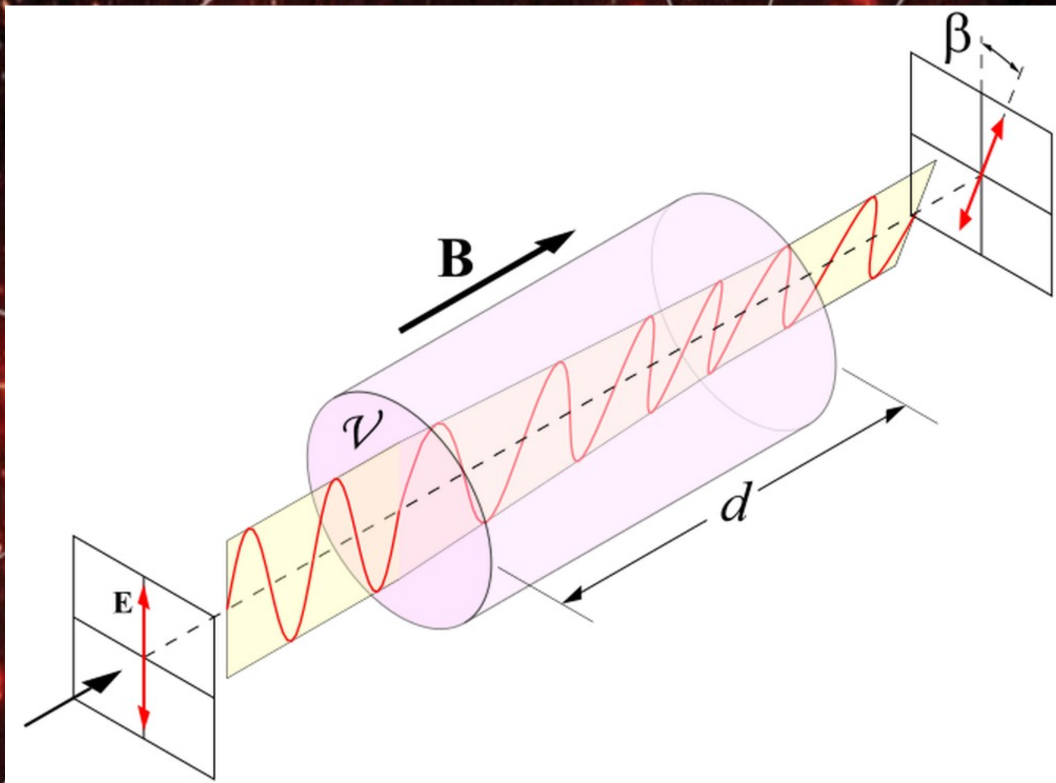
# Synchrotron Radiation




Depolarisation in Fornax A; white is depolarised several features have been shown to be the result of intervening gas (see Fomalont et al. 1989 & Bland-Hawthorn et al. 1995)

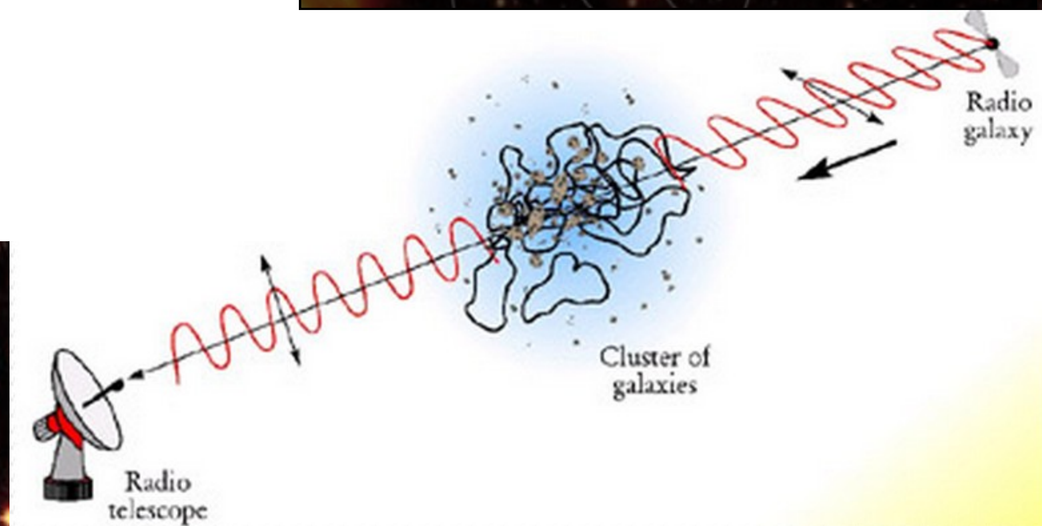


# Faraday Rotation



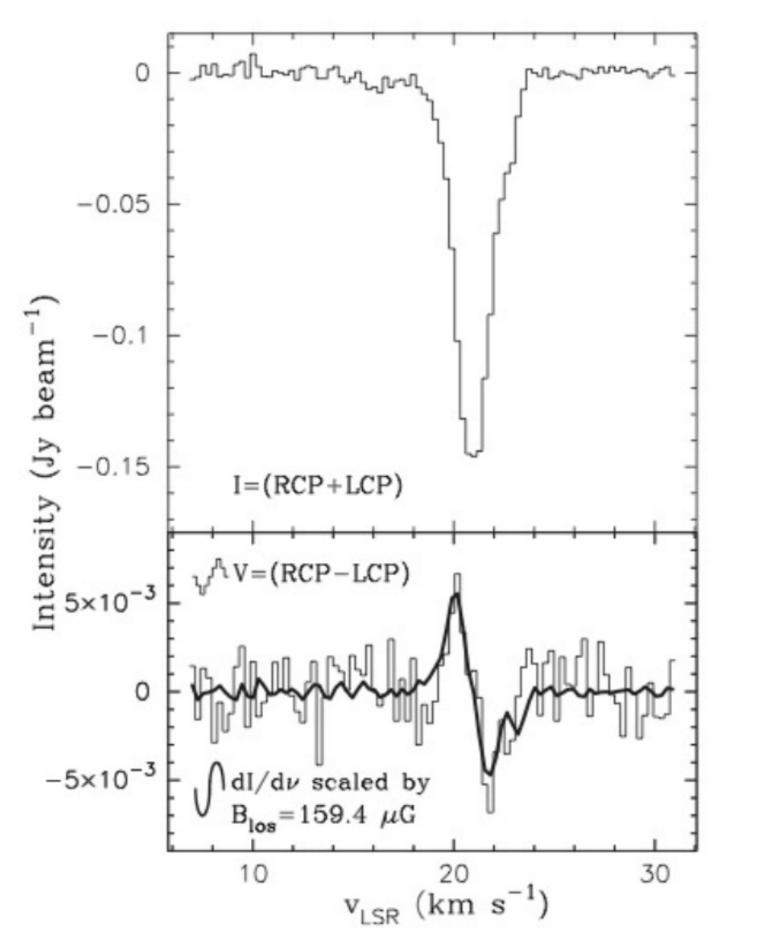

- Rotation Measures are a frequency dependent rotation of the polarisation position angle due to the intervening magnetic field.
- Gives integral of the line of site B-field time Ne

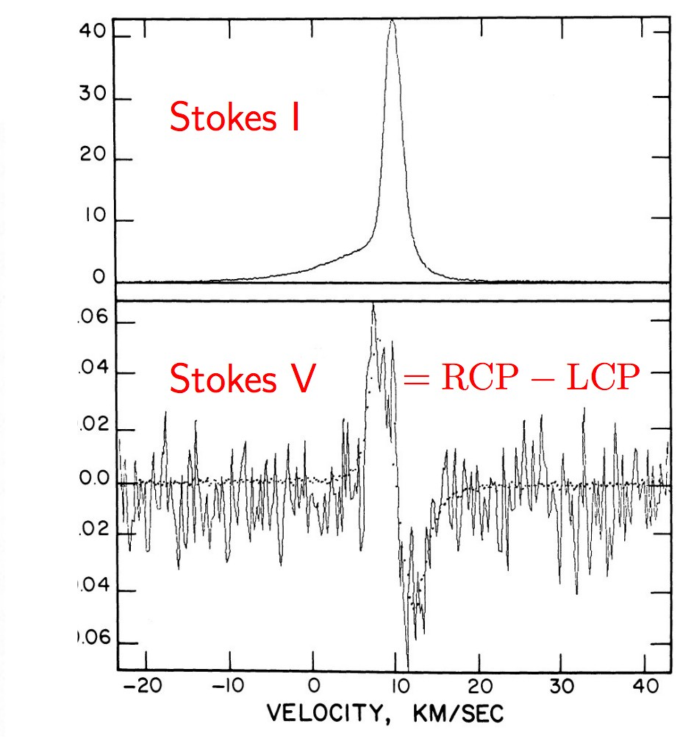
$$\mathrm{RM} = 812 \int_0^L n_e B_{\|} \mathrm{d}l \quad \mathrm{rad\ m^{-2}}$$



# Zeeman Splitting

- Splitting of a spectral line into different polarised componen ts. Gives a direct estimate of the ling of site B-field but is very weak.




Troland & Heiles 1982, ApJ Lett., 260, L19

Zeeman splitting of OH maser emission: Sarma et al. 2013

# Polarisation Survey

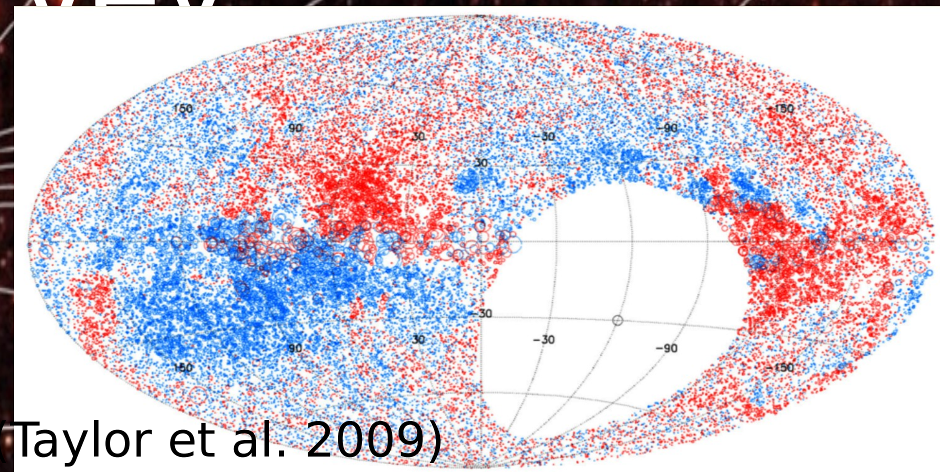
- All-sky with Band 2 (650 – 1760 MHz) down to 4 uJy commensal with continuum survey. Requires 2 years of observing + overheads (Prandoni et al private communication)

- Deeper Survey on Band 2 over a limited area of sky down to 75 nJy. (10 sq. deg = 1 year)

- Other commensal RM observations and pointed targets for individual objects

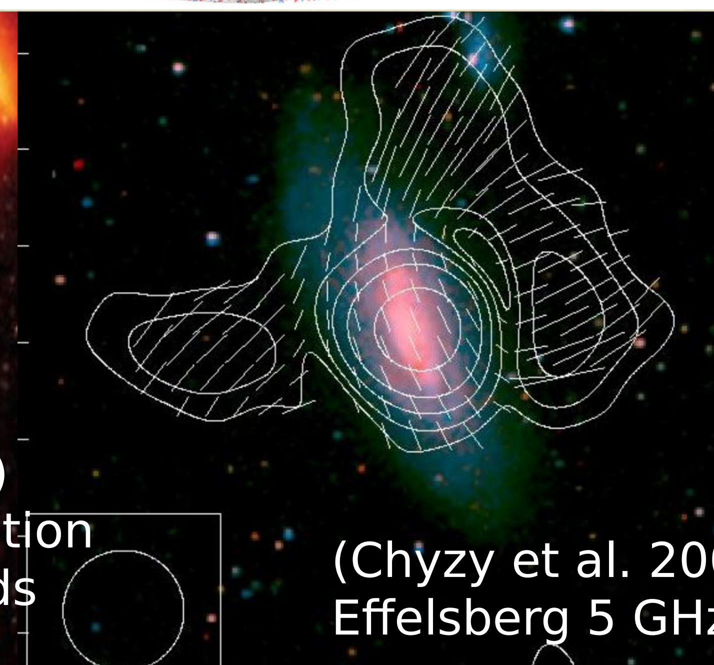
# Science Highlights of the Survey

- B-Field of the Milky Way
- B-Fields in nearby Galaxies
- B-Fields in Galaxy Clusters
-



(Taylor et al. 2009)

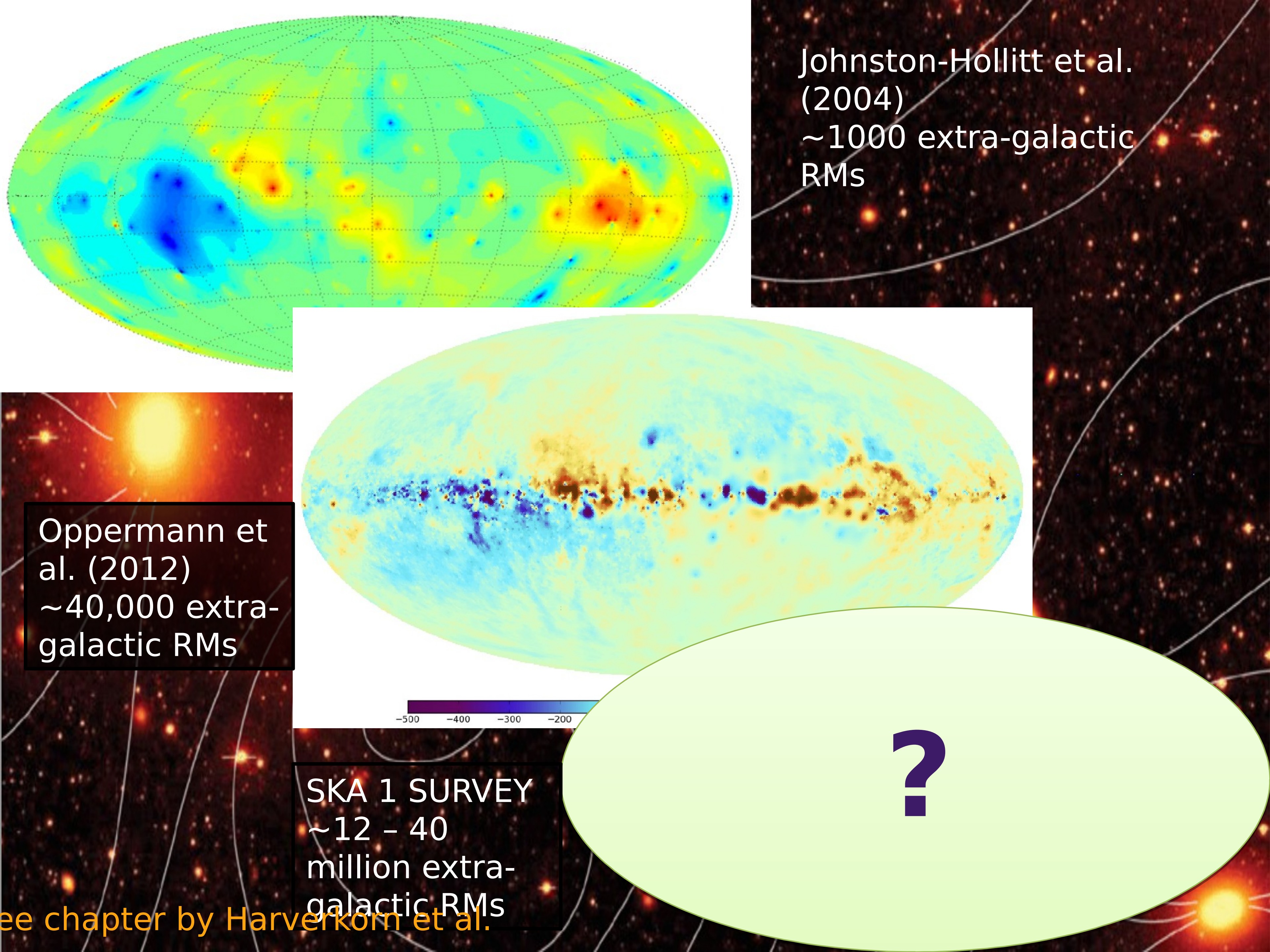

(Govoni et al. 2012)
Cluster Halo Simulation
from realistic B-fields



(Chyzy et al. 2006
Effelsberg 5 GHz

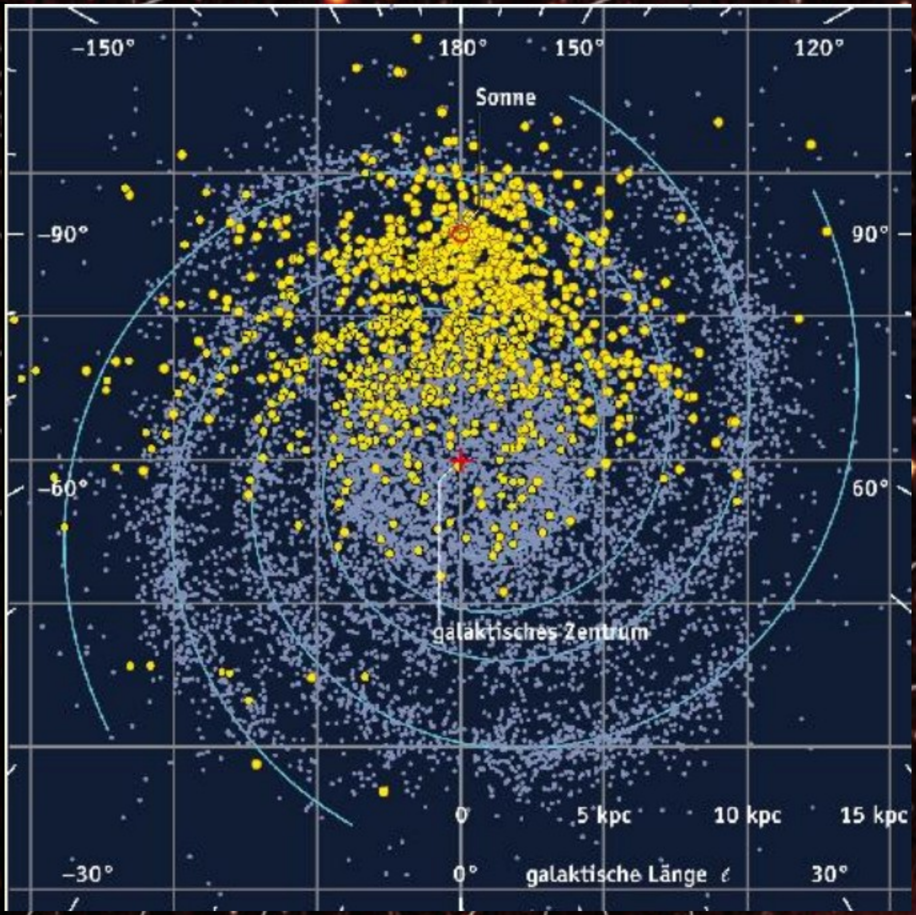
# Magnetic Field of the Milky Way

- RMs obtained from extragalactic sources & pulsars combined with sophisticated statistical analysis will provide an unprecedented tomographic view of the magnetic field of our Galaxy.
- While the large-scale field is less likely to improve, the details of the turbulent component of the Galactic field will be much more constrained.
- Additionally the magnetic fields of Galactic objects on scales less than 100 pc will be probed in detail.

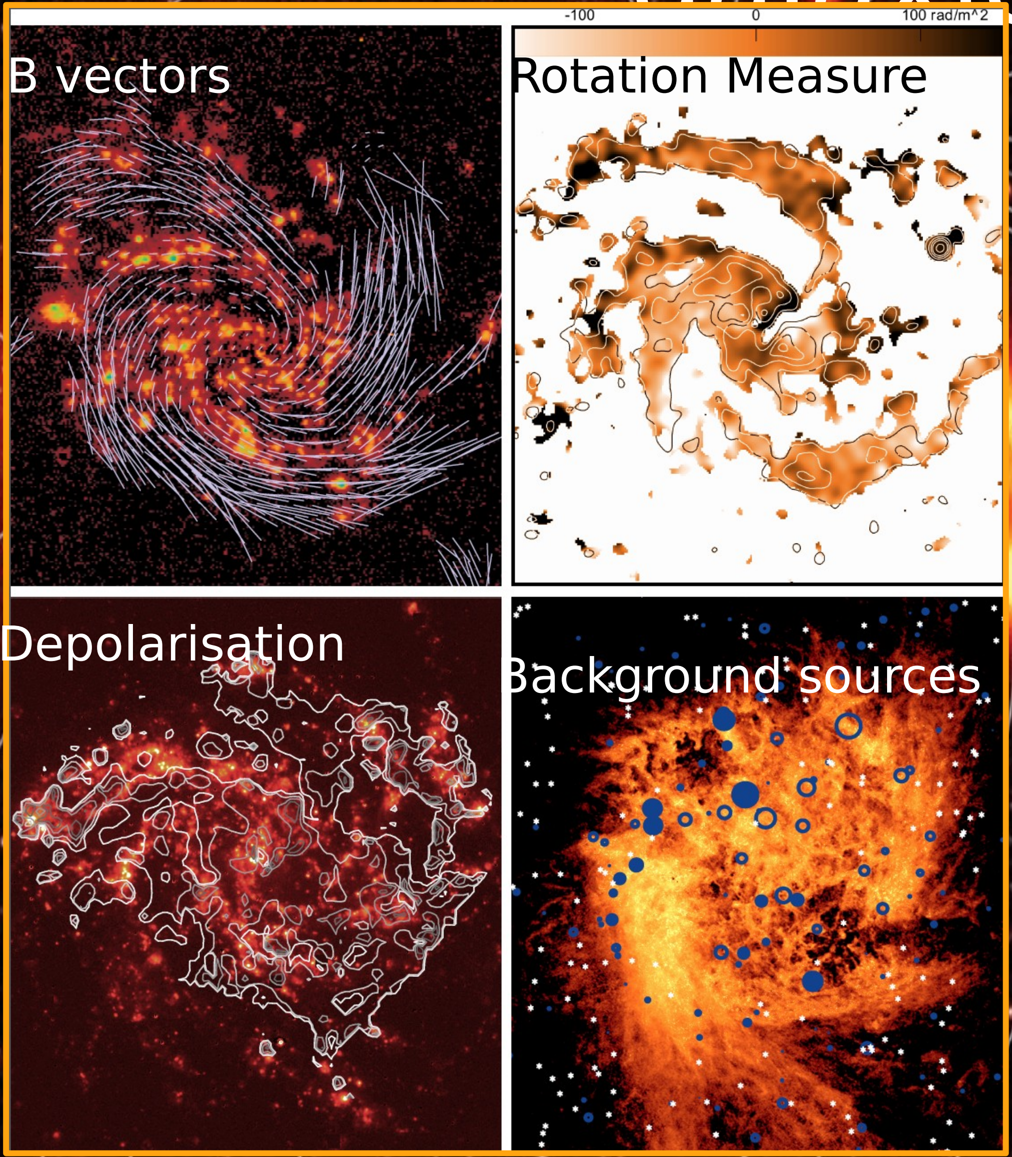

Johnston-Hollitt et al. (2004)
~1000 extra-galactic RMs
Oppermann et al. (2012)
~40,000 extra-galactic RMs
−500 −400 −300 −200
SKA 1 SURVEY
~12 – 40 million extra-galactic RMs
?
See chapter by Harverkorn et al.

# Magnetic Field of the Milky Way

- Complementary information will be provided by pulsars, masers & Zeeman splitting (chapter by Robishaw et al.).
- 2300 pulsars currently known, SKA1 to increase that 10 fold. Pulsar timing gives accurate distances for many of these -> 3D tomography (see chpater by JinLin Han).



# Magnetic Fields of other galaxies

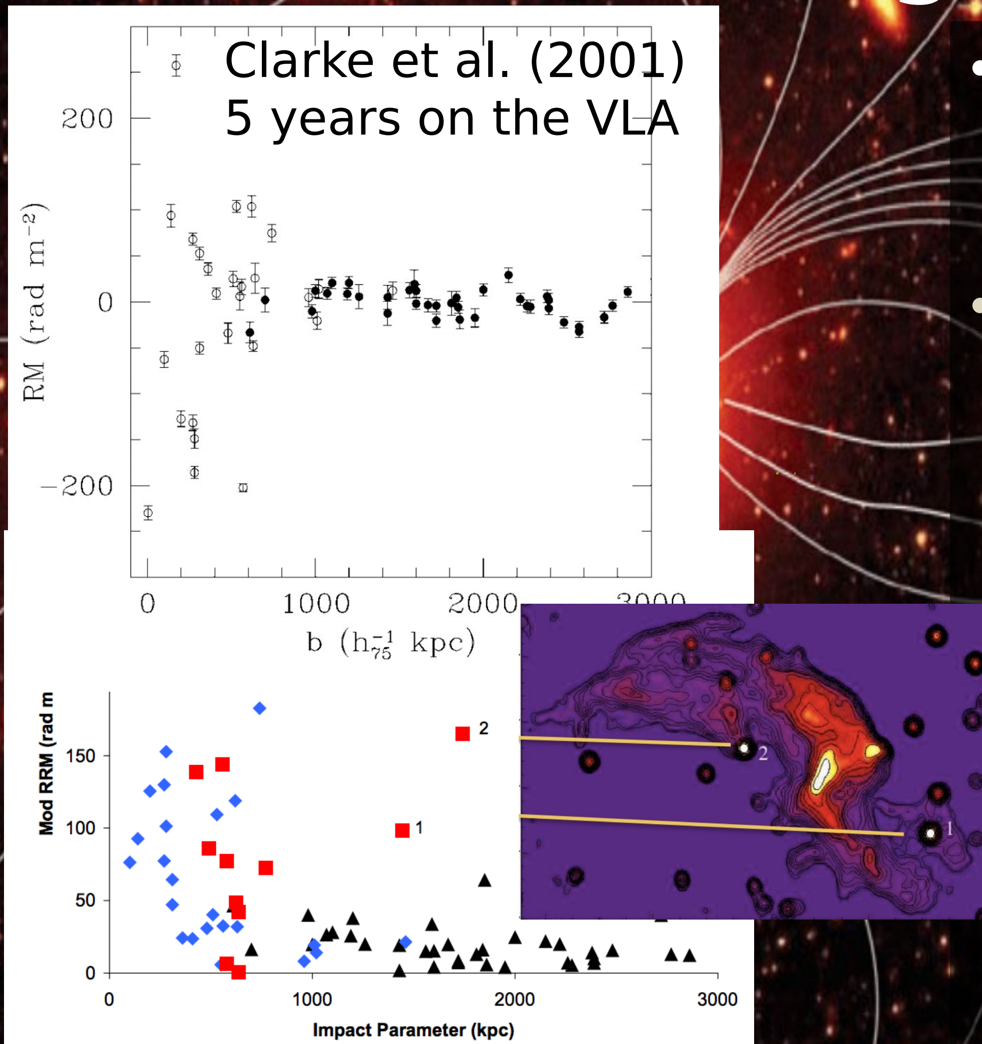



- A polarisation survey will allow not only direct imaging of the magnetic field of other galaxies, but also statistical RMs to be examined over the disk of theses galaxies
- With at least 10 RMs per galaxy it is possible to determine the overall field type, with 1000 RMs we can do 3D tomography

# Cluster Magnetic Fields

- We know there are magnetic fields in galaxy clusters. We don't know their extent, filling factors, or relationship to or influence on the dynamical state of the cluster.
- Statistical studies of RMs through clusters have been undertaken since the late 80s (Hennesey et al. 1989, Kim et al. 1999, Clarke et al. 2001, Johnston-Hollitt et al 2004,… Bonafede et al. 2013)
- Results have been hampered by:
  - Contributions from foregrounds (intrinsic and extrinsic)
  - Poor sampling (low no. of sources across a cluster)
  - Poor polarisation data (nπ-ambiguity, bad fits)
- A decade ago it was proposed that the SKA would address many of these issues (Feretti & Johnston-Hollitt 2004)

# Cluster Magnetic Fields




ohnston-Hollitt & Ekers (2004)
3 years on the ATCA

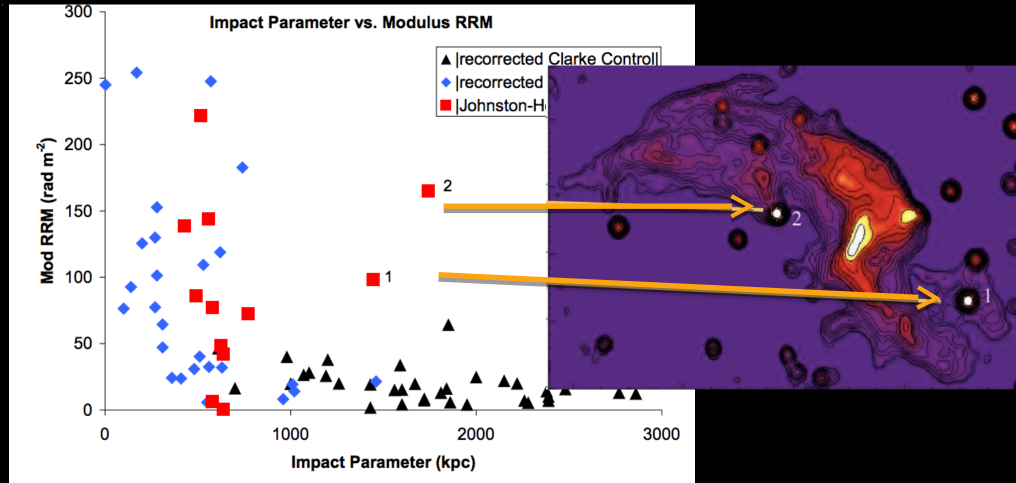
- Previously cluster B-fields detected statistically with 1-2 RMs per cluster
- Now can do 10s of RMs through a cluster eg Bonafede et al. 2010, 2013 obs of Coma on JVLA

With SKA will do thousands of RMs per cluster eg A3667 3 RMs in 3 years a decade ago vs 1000 – 3000 possible with SKA.

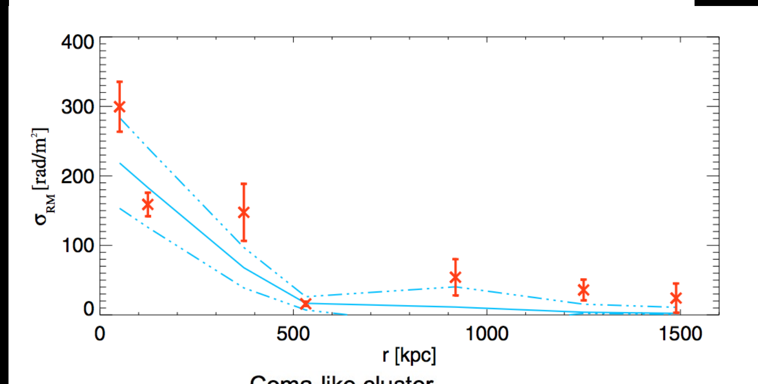
Decade ago: Statistical observations of 30+ clusters

5 years ago: JVLA observations of 1 cluster

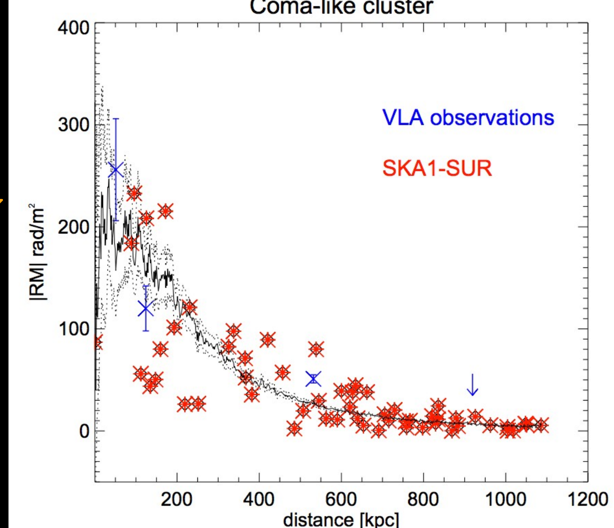
SKA1: Simulated observations of a cluster




Johnston-Hollitt & Ekers (2004) Including data from Clarke et al (2001)



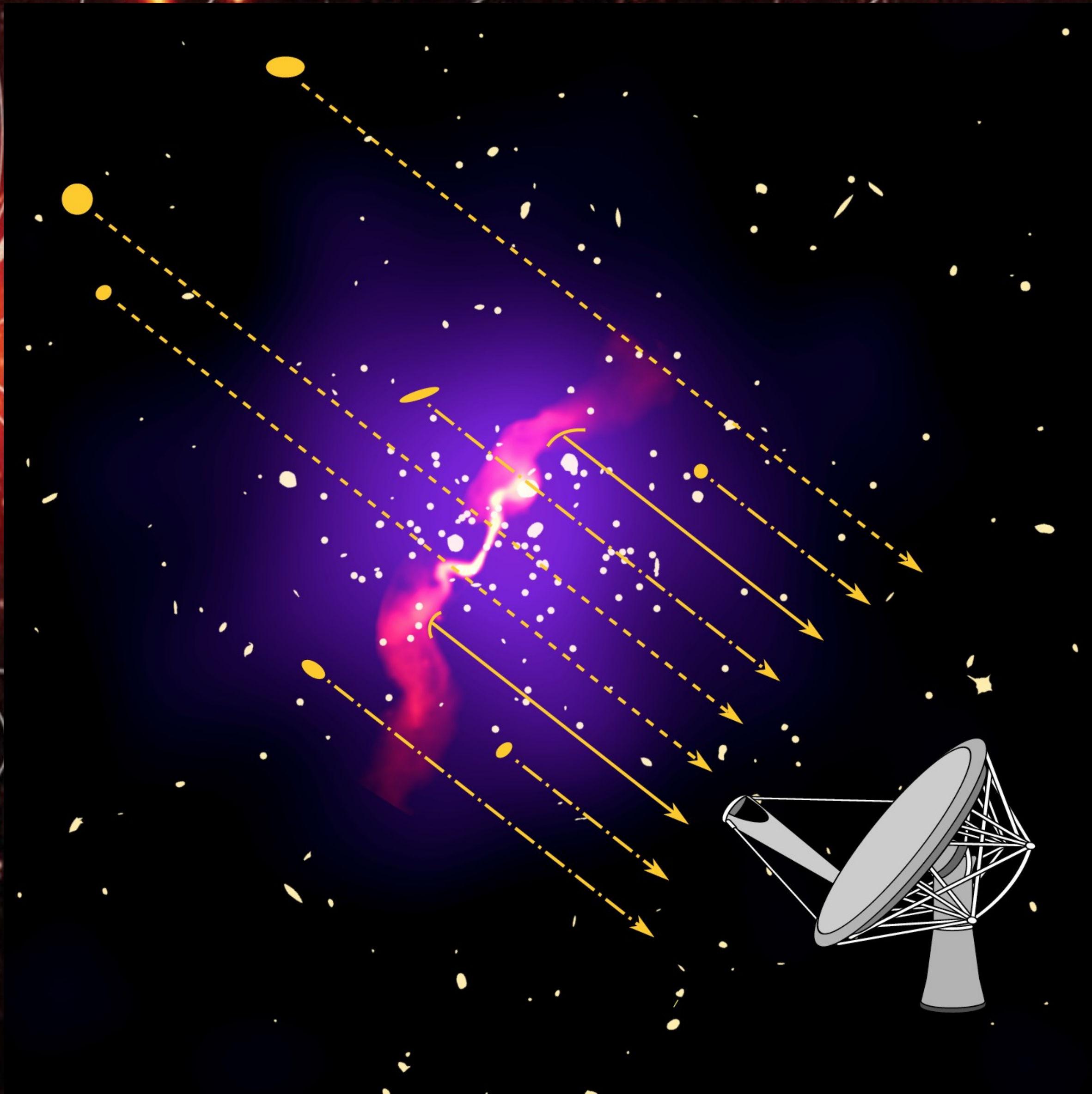

Bonafede et al. (2010)




Bonafede et al. (2015)

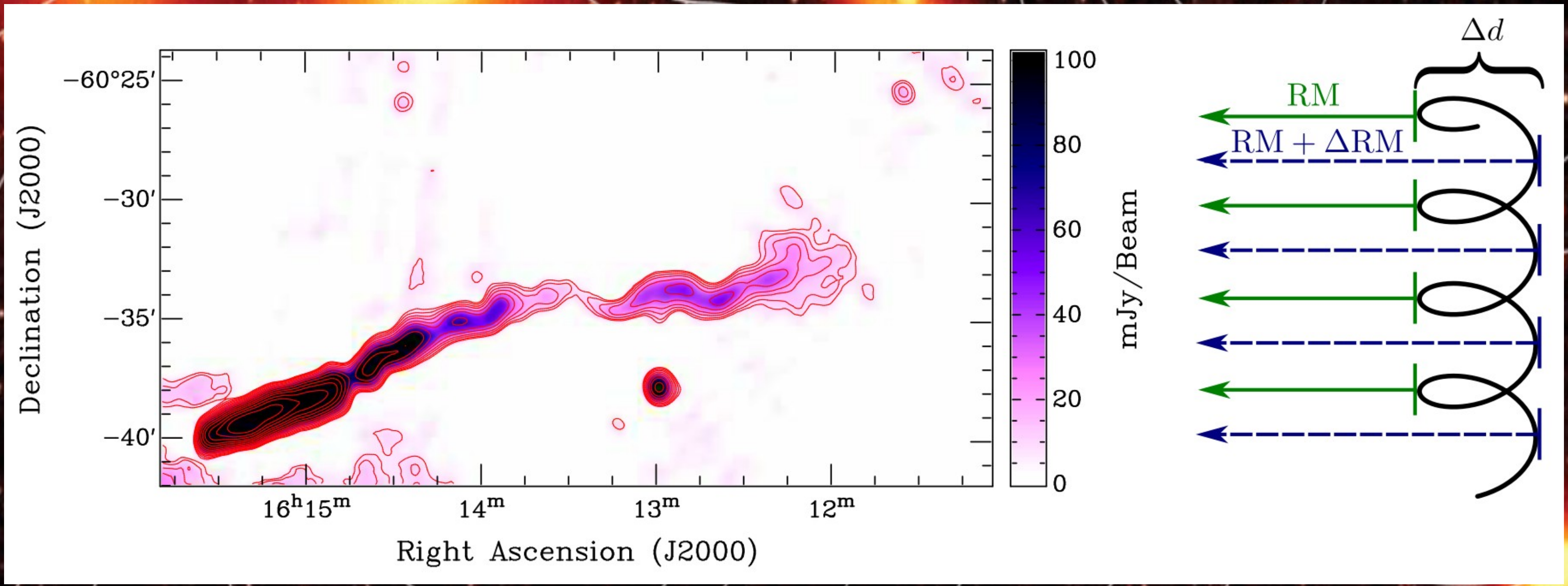
# Cluster Magnetic Fields

- Increase in cluster RMs gives possibilities such as probing the magnetic field through cluster relics and using extended sources in the cluster as RM screens to probe the internal structure of the magnetic field.



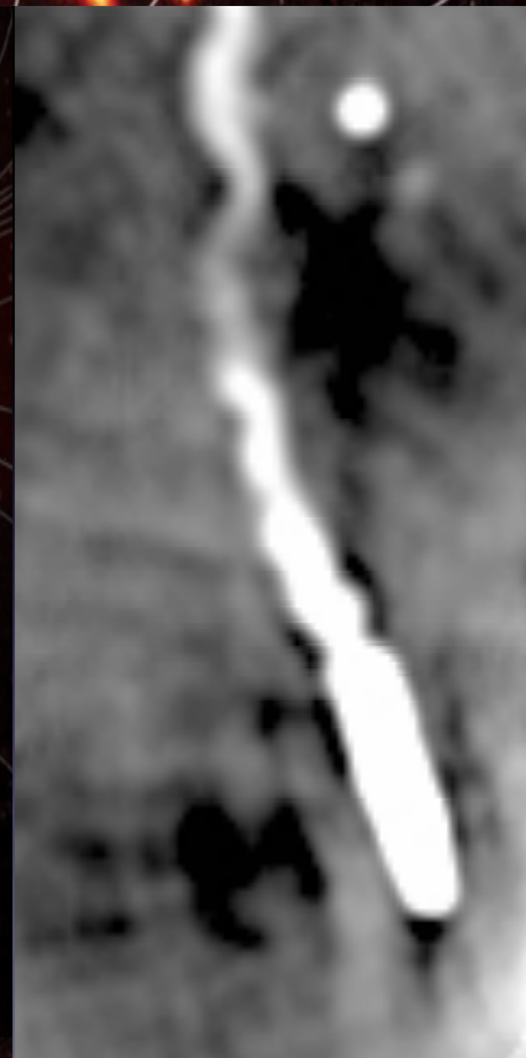
# Cluster Magnetic Fields

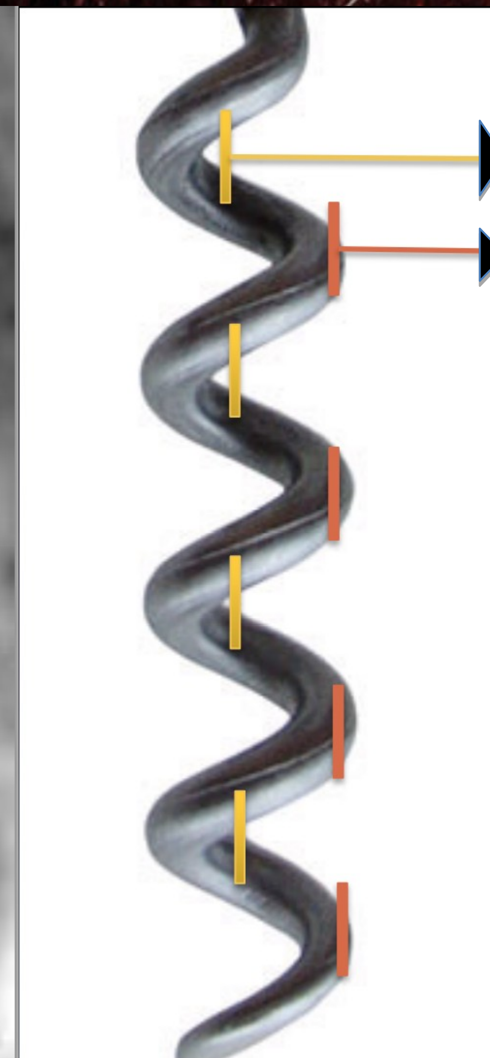
- Looking to SKA2 the increase in sensitivity will be coupled with an increase in resolution which provides interesting possibilities to probe the small scale turbulent field in cluster by use of ‘corkscrew’ radio galaxies.



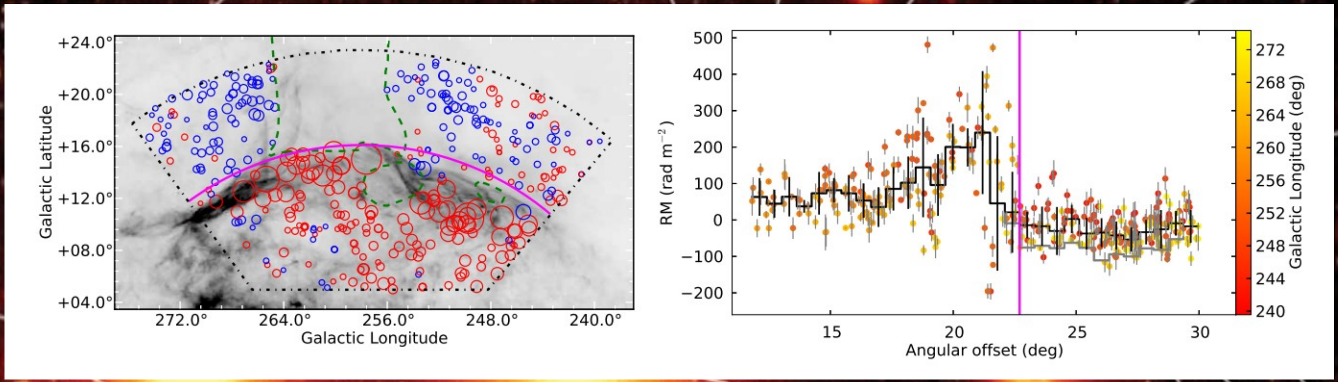
# Cluster Magnetic Fields

- Path length through the cluster is the same for the red and yellow patches. Therefore can look for statistical differences which will probe the B-field on very small scales.
- For sources with long tails, transverse to the cluster we can measure a change as a function of radius.
- SKA2 should find 5000 – 20,000 of these sources (Johnston-Hollitt et al. 2015).

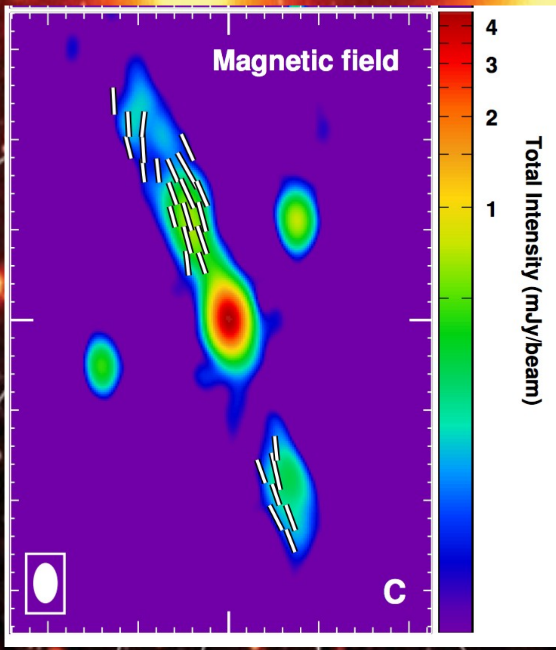


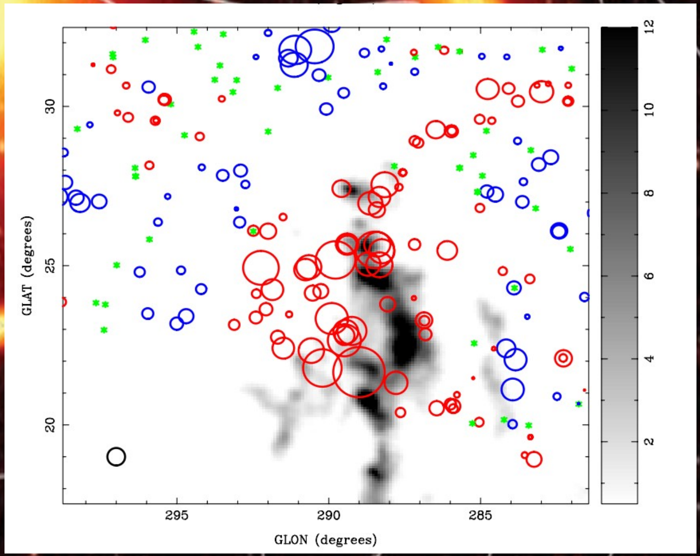


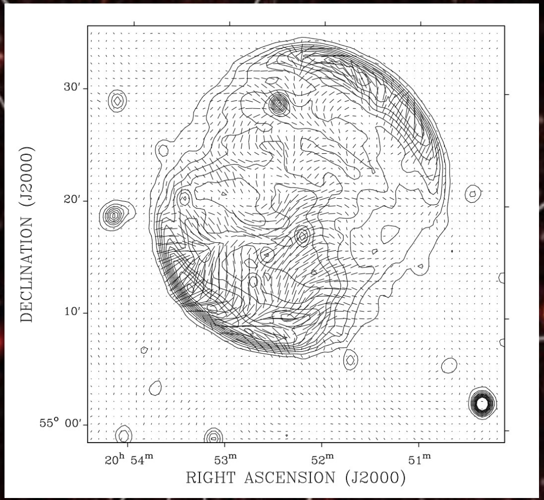
# Galactic Objects




Gum Nebula: Purcell et al. (2015)




HVC: McClure-Griffiths et al. (2010)

SNR: Reynoso et al. 1997
in Reynolds, Gaensler &

ets from YSOs: Carrasco-Gonzalez et al. 2010

# Not just about number of RMs

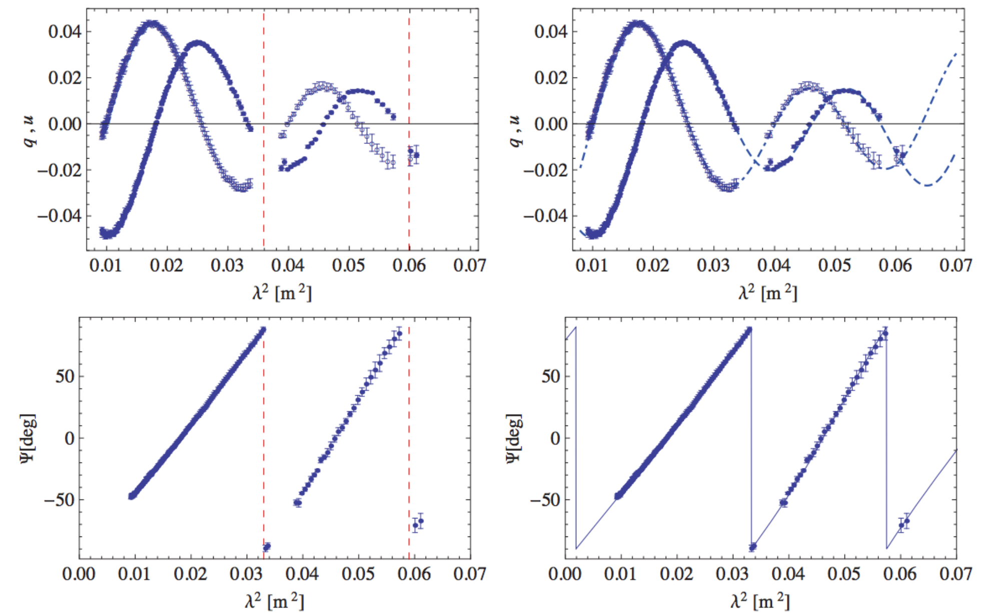



**Figure 1:** Polarisation data for PKS B1610–771 over the frequency range 1.1 to 3.1 GHz (adapted from Figure 12 of O'Sullivan et al. 2012). Top panel: $q$ (open circles) and $u$ (filled circles) vs $\lambda^2$. On the left-hand side, the vertical red lines show the range in $\lambda^2$ corresponding to an observation of bandwidth 350 MHz centred on 1.4 GHz; on the right-hand side, the data are fit over the full bandwidth to a model containing two RM components. Bottom row: as for the top row, but showing polarisation angle vs $\lambda^2$.

- Previously RMs were done on linear fits to only a few data points.
- This leads to poor results in complex cases and doesn't account for screens along the line of sight.
- Broadbands on modern telescopes have revolutionized RMs allowing for complex Faraday spectra to be recovered.
- This allows the possibility to not only use the polarised light from background galaxies to understand large-scale foregrounds, but to study the intrinsic properties of the sources themselves. See chapter by Bryan Gaensler

Gaensler et al (2015)

# SKA 1

- Ultimately SKA1 surveys will give us the ability to:
  - Obtain an unprecedented view of the magnetic field of the Milky Way which combined with Pulsars will allow a 3D model accurate to scales of hundreds of pcs to be constructed.
  - Probe the magnetic field of galaxy clusters not just statistically but individually allowing understanding of the extent of the fields & constraints on the filling factors and turbulence scales.
  - Examine in detail the magnetic fields of nearby galaxies both directly and through RMs projected through such sources.
  - Provide fundamentally better understanding of complex Faraday spectra leading to new astrophysics.

# Summary


" What about magnetic fields? "

Answer: Well, from the SKA we know…

- The SKA is a unique instrument for probing magnetic fields across cosmic time.
- It will provide "transformational" science in the field of magnetism.
- This science will be broadly applicable across much of astrophysics.

# How do you get involved?

- Look at your polarisation data!
- Join existing magnetism projects such as the forthcoming POSSUM survey on ASKAP
- Join SKA Cosmic Magnetism WG
- Consider how your science not matter what it is will benefit from the increased information about magnetic fields on all scales that the SKA will generate.