Cosmic Magnetism

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on behalf of the SKA Cosmic Magnetism SWG

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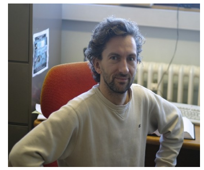

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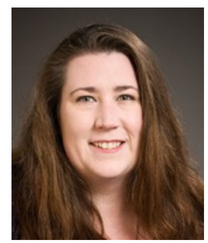

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Jeroen Stil

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SKA Engineering Meeting - Manchester (7-11 October 2013)

Outline of the Talk

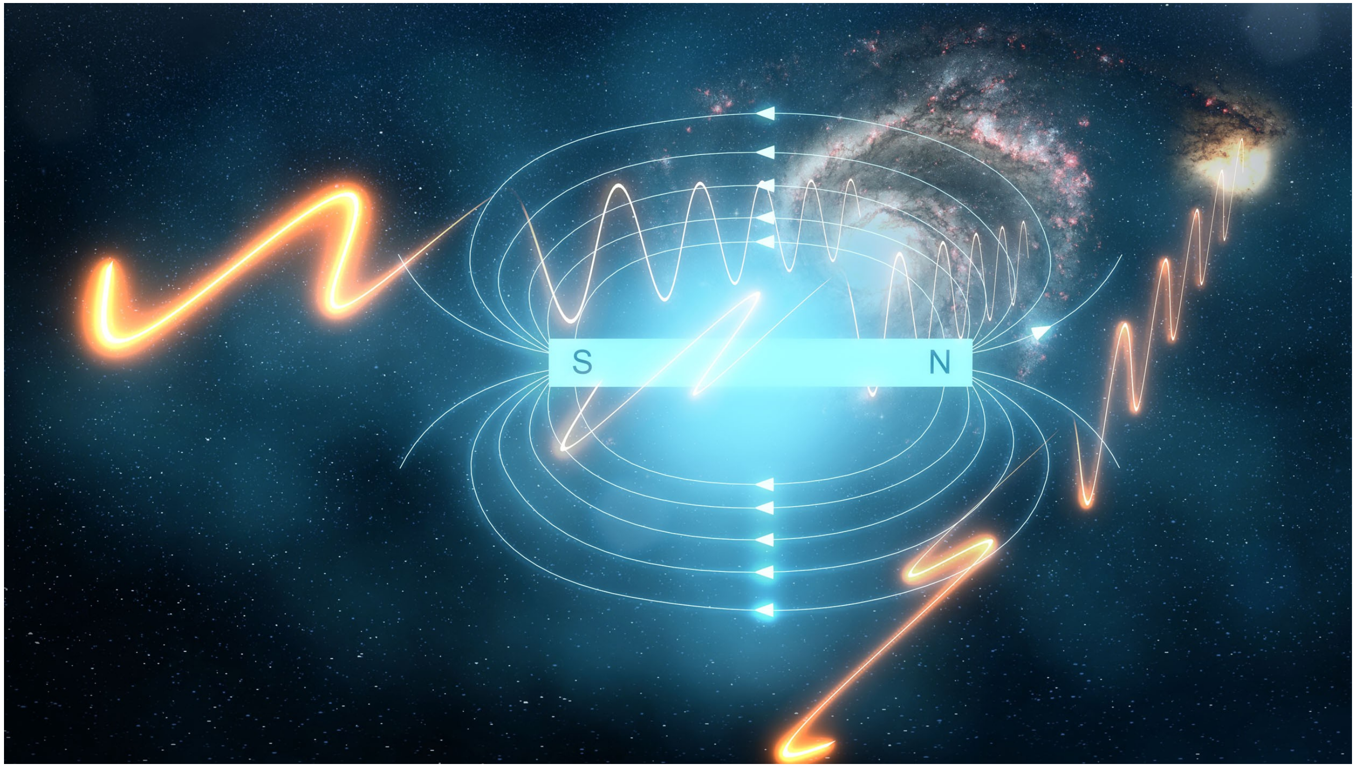
- Cosmic magnetism science drivers in the SKA1 era
- Observational techniques
- Key SKA1 observations for cosmic magnetism
- Scientific improvements with SKA1
  (Milky Way, external galaxies, cluster of galaxies, cosmic web)
- Inputs to the baseline design

Cosmic Magnetism Science Drivers

Magnetic fields play an important role in the formation and evolution of many astrophysical objects.

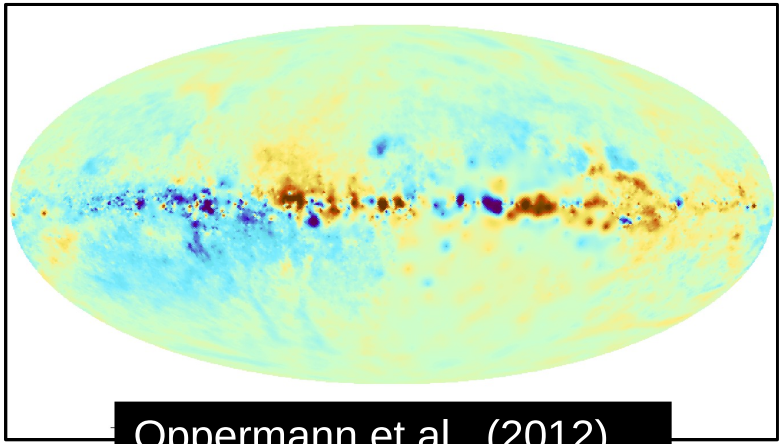
Despite their importance, the evolution, structure, and origin of magnetic fields are still open questions.

SKA1 will open a new era in the observation of astrophysical magnetic fields.



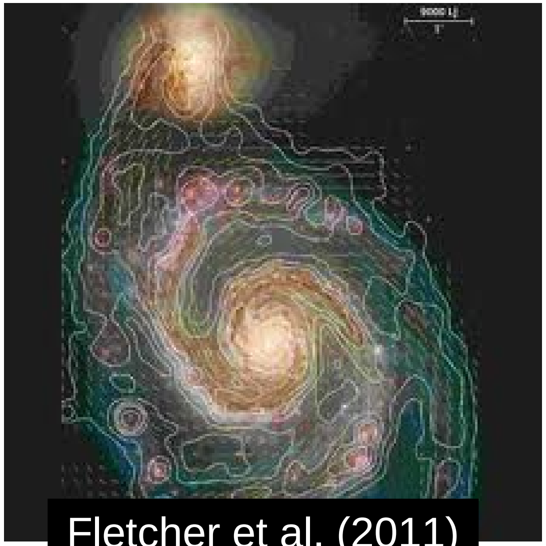
Cosmic Magnetism Science Drivers

1) The Galactic magnetic field



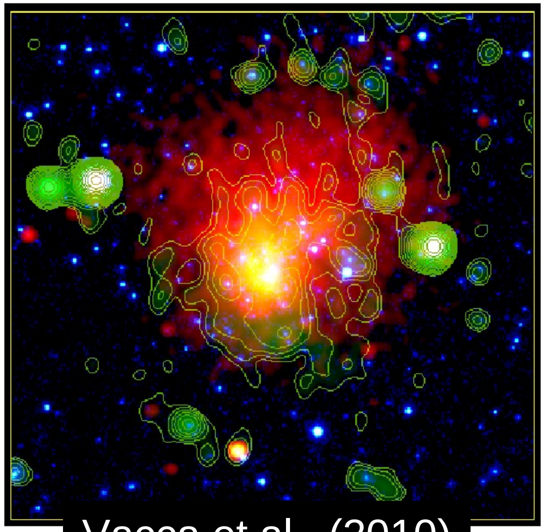
Oppermann et al. (2012)

2) Magnetism and galaxy evolution



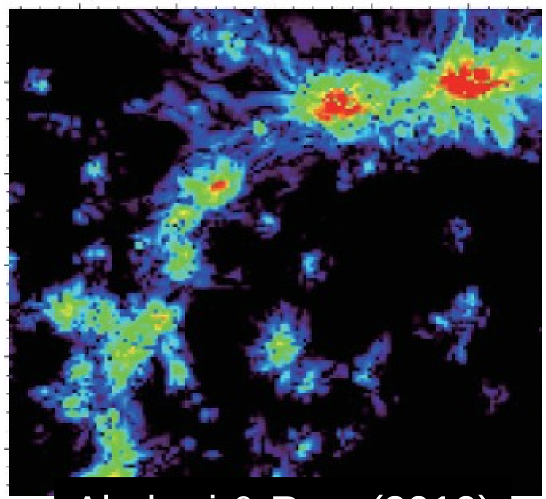
Fletcher et al. (2011)

3) Magnetic fields in galaxy clusters



Vacca et al. (2010)

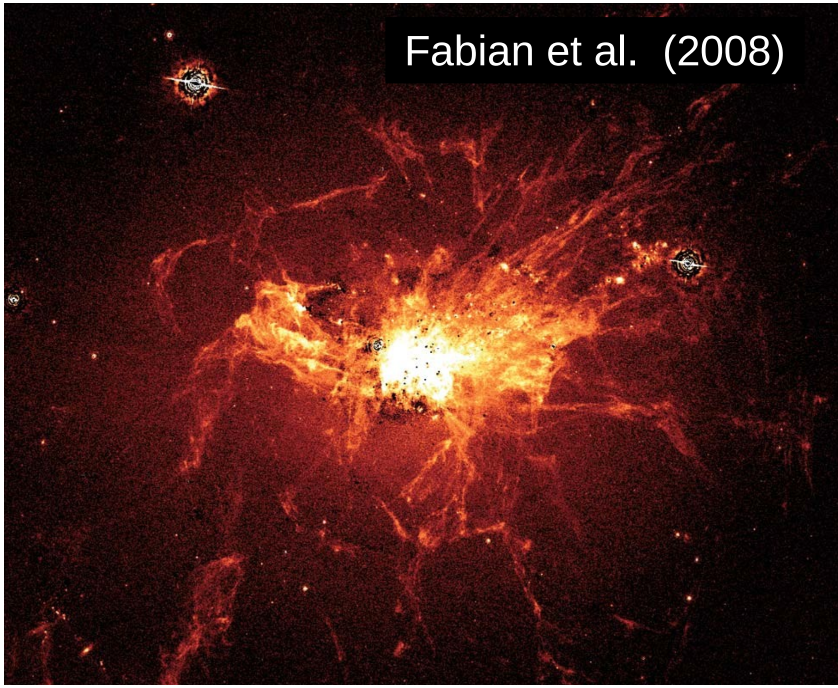
4) Detection and characterization of magnetic fields in the cosmic web



Akahori & Ryu (2010)

Cosmic Magnetism Science Drivers

Magnetic field studies to address important questions:



- What is the relation between super-massive black holes and their environment?

Broadband depolarization → thermal environment of radio galaxies and AGN.

e.g. O'Sullivan et al. (2013)

- How do galaxies and structures evolve over cosmic time?

Broadband polarization → overall evolution of magnetic fields with redshift

e.g. Hammond et al. (2012)

- What are the physical properties of absorbing systems?

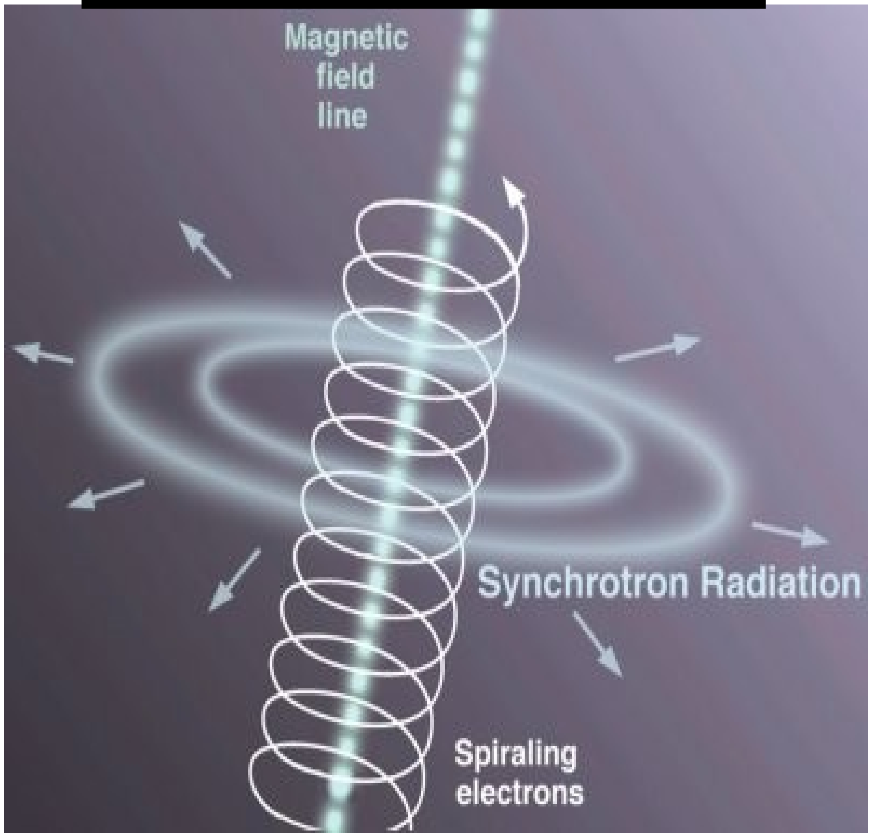
Broadband Faraday Rotation → covering fraction and turbulence

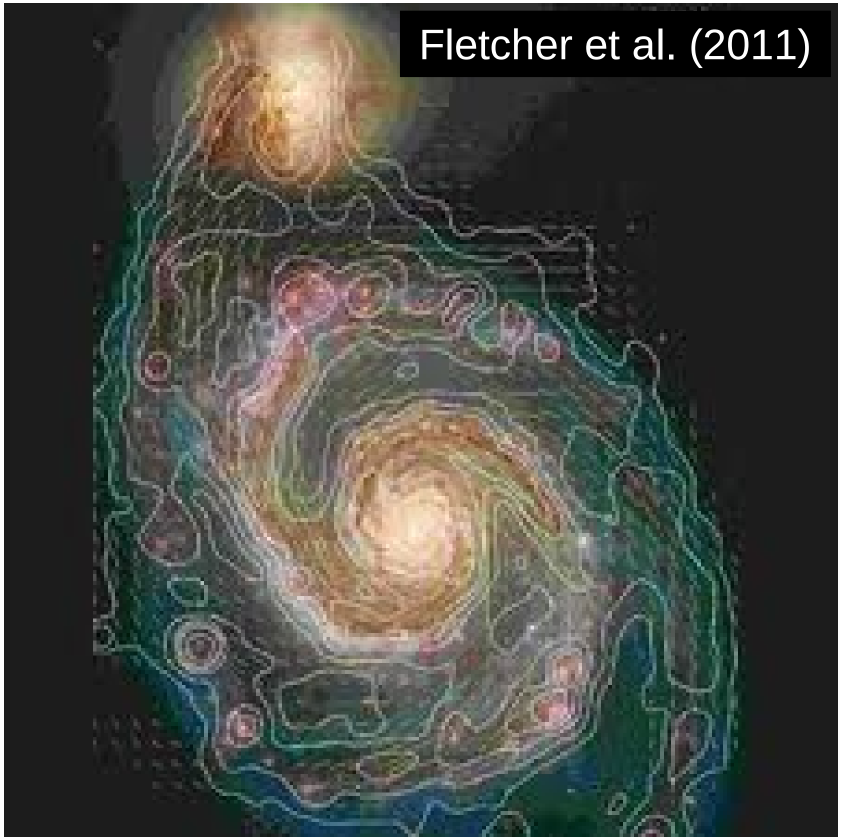
e.g. Bernet et al. (2012)

Observational Techniques

Much of what we know about cosmic magnetism comes from sensitive total intensity (Stokes I) and polarization (Stokes Q and U) radio observations.

Synchrotron Radiation

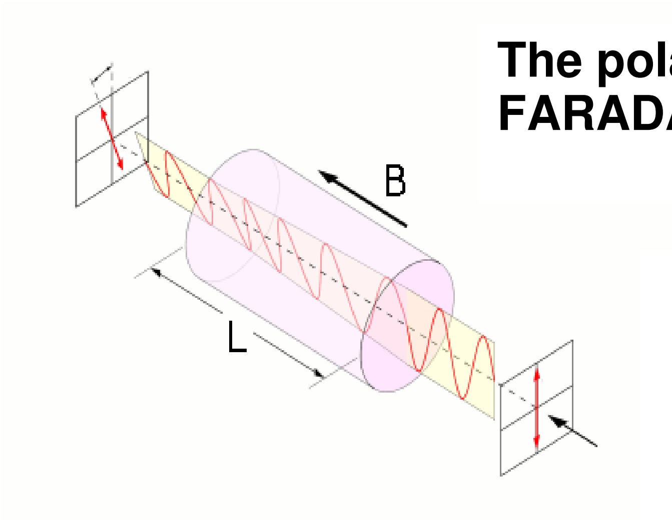




- **Presence of field**
- **Orientation of field**
- **Strength of field**
- **Spatial scales of field**

Observational Techniques

Faraday Rotation



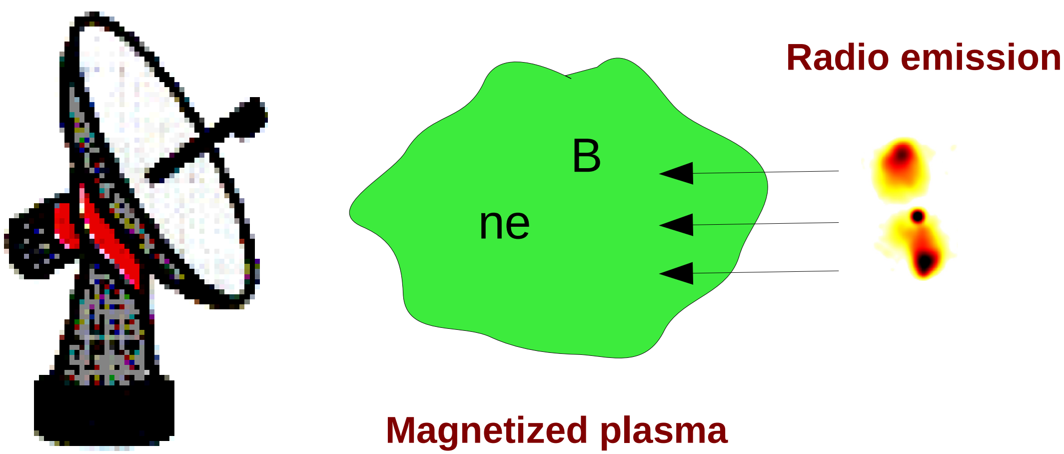
The polarized angle of the radio signal is subject to the FARADAY ROTATION as it traverses a magnetized plasma.

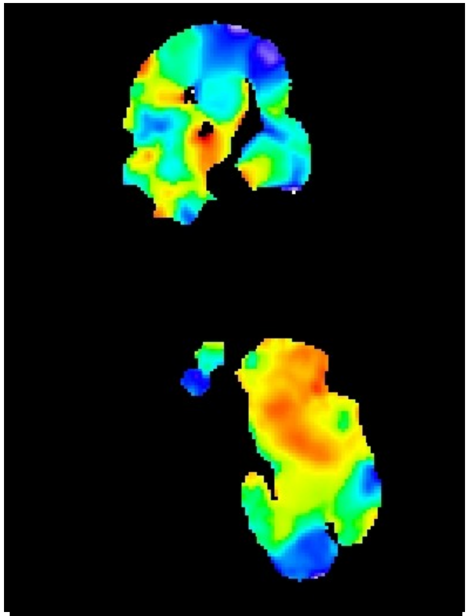
FARADAY DEPTH:

$$\phi_{[\mathrm{rad/m^2}]} = 812 \int_{\mathrm{L[kpc]}}^{0} \mathrm{n_{e[cm^{-3}]}} \mathrm{B}_{||_{[\mu G]}} \mathrm{dl}$$

Radio emission in the background of an external Faraday screen:
Faraday depth = Rotation Measure (RM)

$$\Psi_{\mathrm{Obs}} = \Psi_{\mathrm{Int}} + \mathrm{RM}\lambda^2$$

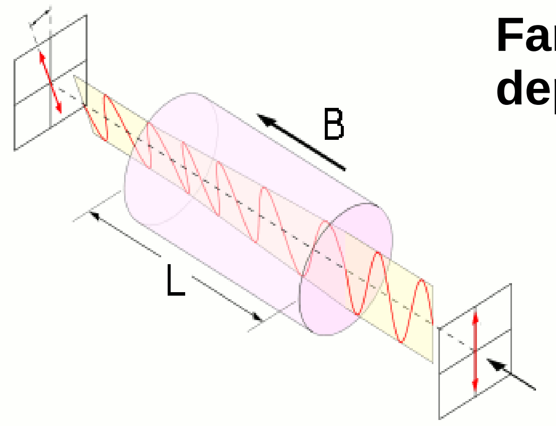




Govoni et al. (2006)

Observational Techniques

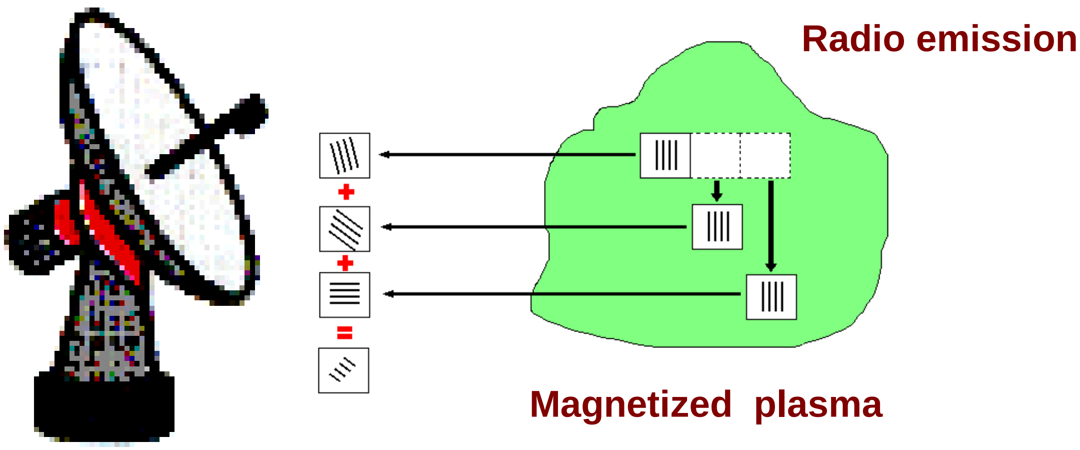
Faraday Rotation



Radio emission emitted by a magnetized plasma: Faraday Rotation effect leads to a frequency-dependent depolarization of the signal.

FARADAY DEPTH:

$$\phi_{[\mathrm{rad/m^2}]} = 812 \int_{\mathrm{L[kpc]}}^{0} n_{e[\mathrm{cm^{-3}}]} B_{||[\mu G]} \, dl$$



Rotation Measure Synthesis to recover the polarized signal

Burn (1966),
Brentjens & de Bruyn (2005),
Heald (2009),
Pizzo et al.(2011)

- **To avoid significant internal depolarization the polarized emission is better studied at high frequencies (~1GHz or higher).**

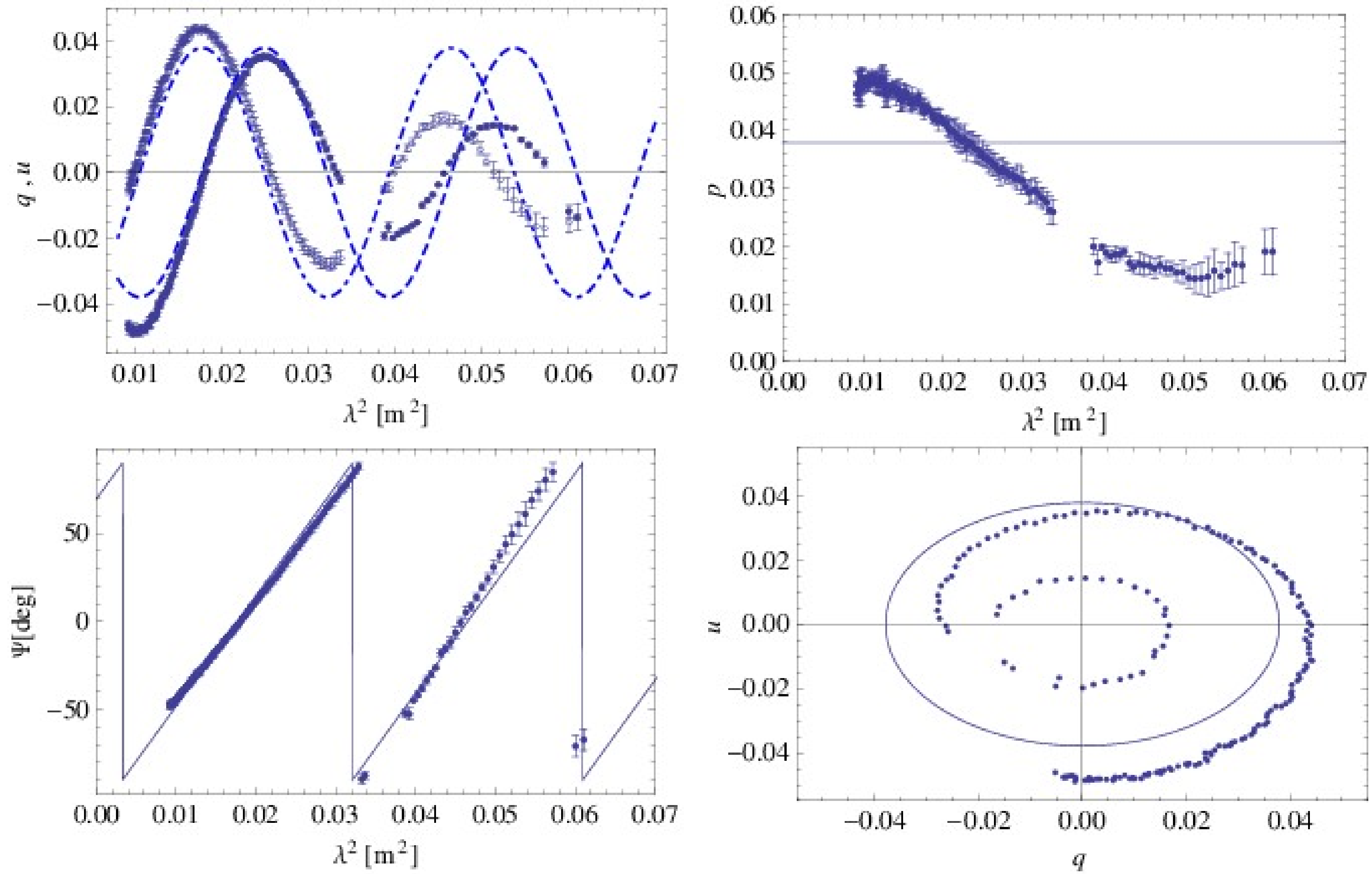
- **A high Faraday resolution can be achieved much more easily at low frequencies.**

Therefore we need both, high and low frequencies.

Broadband Polarimetry: a unique physical probe

A broadband frequency coverage is necessary to properly interpret the data

Polarimetry of PKS B1610-771



O'Sullivan et al. (2012)

Broadband Polarimetry: a unique physical probe

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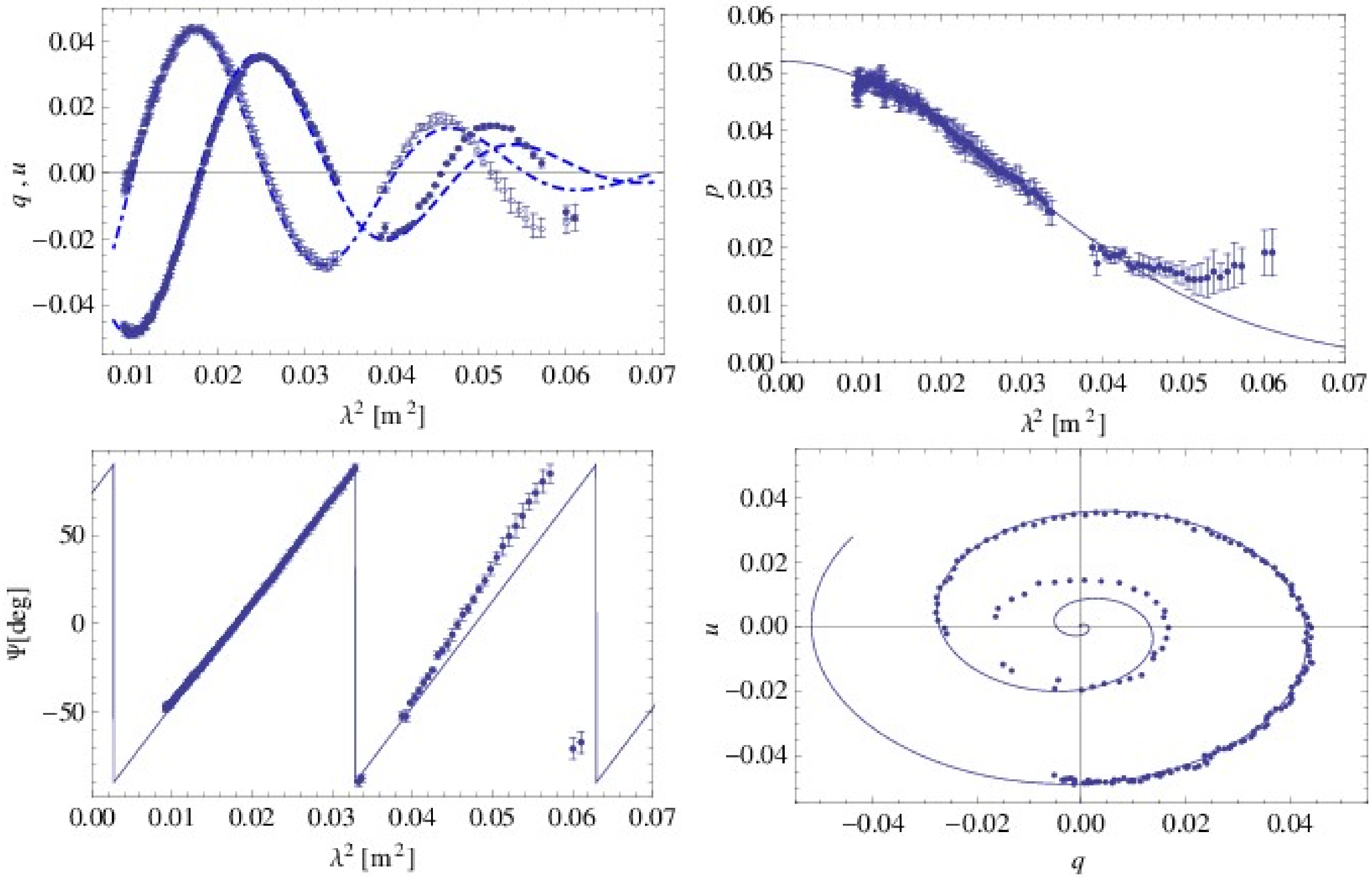

O'Sullivan et al. (2012)

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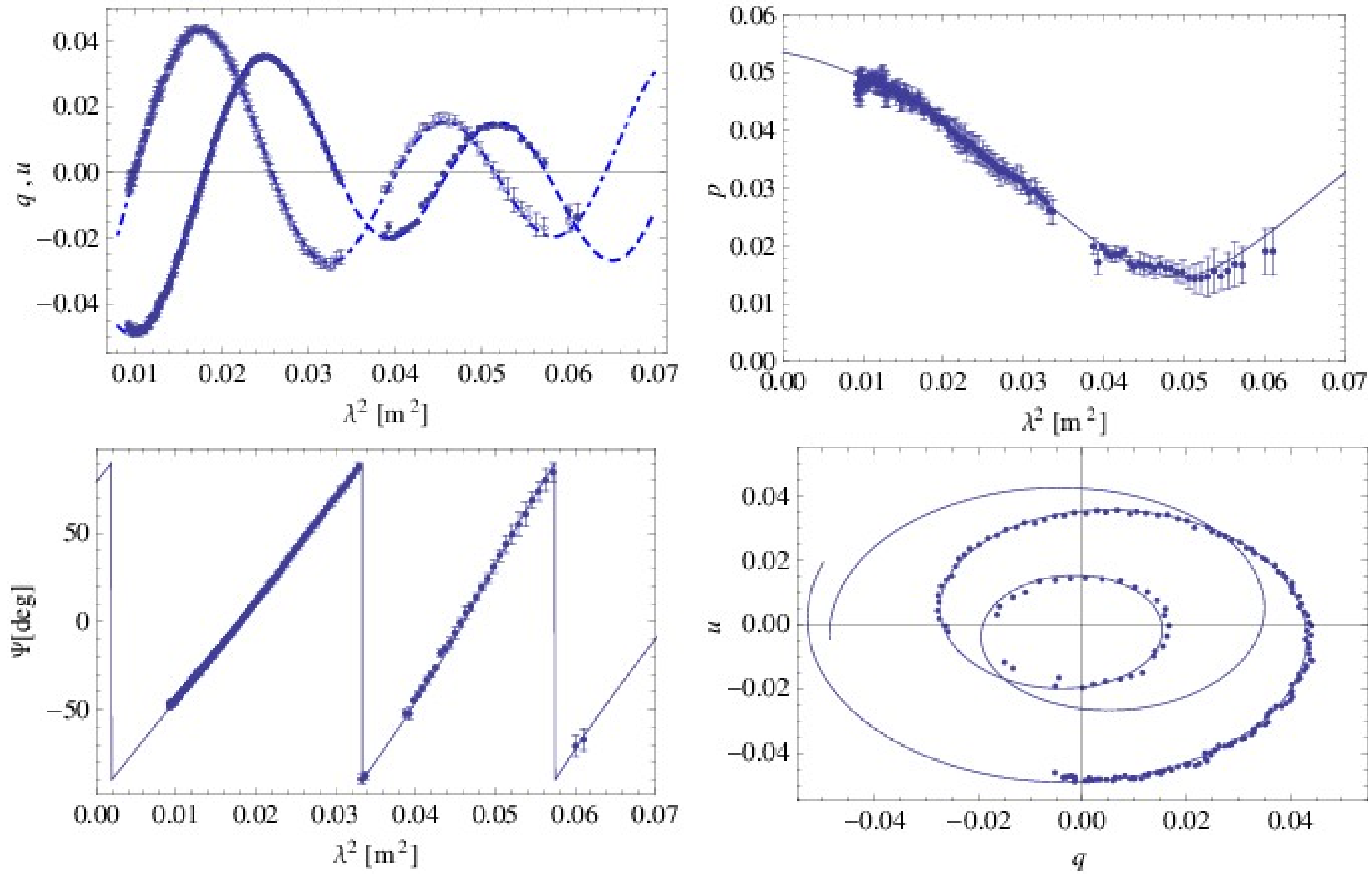


O'Sullivan et al. (2012)

Key SKA1 Observations for Cosmic Magnetism

To pave the way for broadband spectropolarimetric surveys to be performed with SKA1 and SKA2 Gaensler et al. (2004), Beck & Gaensler (2004)

there are several polarization surveys under way or planned e.g.

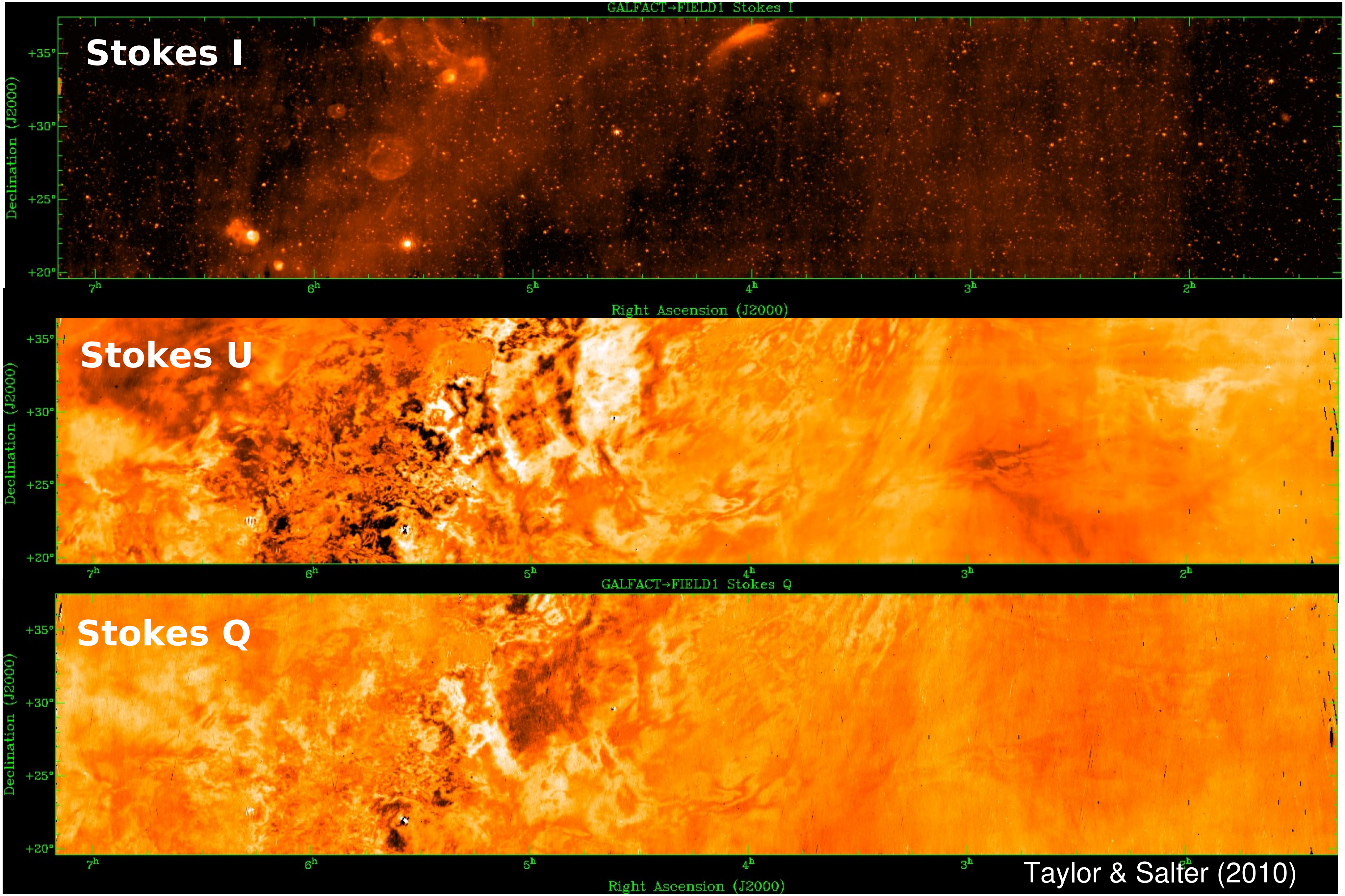
LOFAR Heald et al. (2012), Beck et al. (2013)

POSSUM with ASKAP Gaensler et al. (2010)

GMIMS with single-dish telescopes Wolleben et al. (2009)

GALFACTS with Arecibo Taylor & Salter (2010)

Key SKA1 Observations for Cosmic Magnetism



GALFACTS: Arecibo Sky Polarization Survey

Key SKA1 Observations for Cosmic Magnetism

Wide-band spectropolarimetric surveys at ~1 GHz will be crucial to build the foundation for SKA2 experiments and will guide initial studies of magnetic fields in the Milky Way, in many external galaxies and clusters, and in the overall magnetized intergalactic medium.

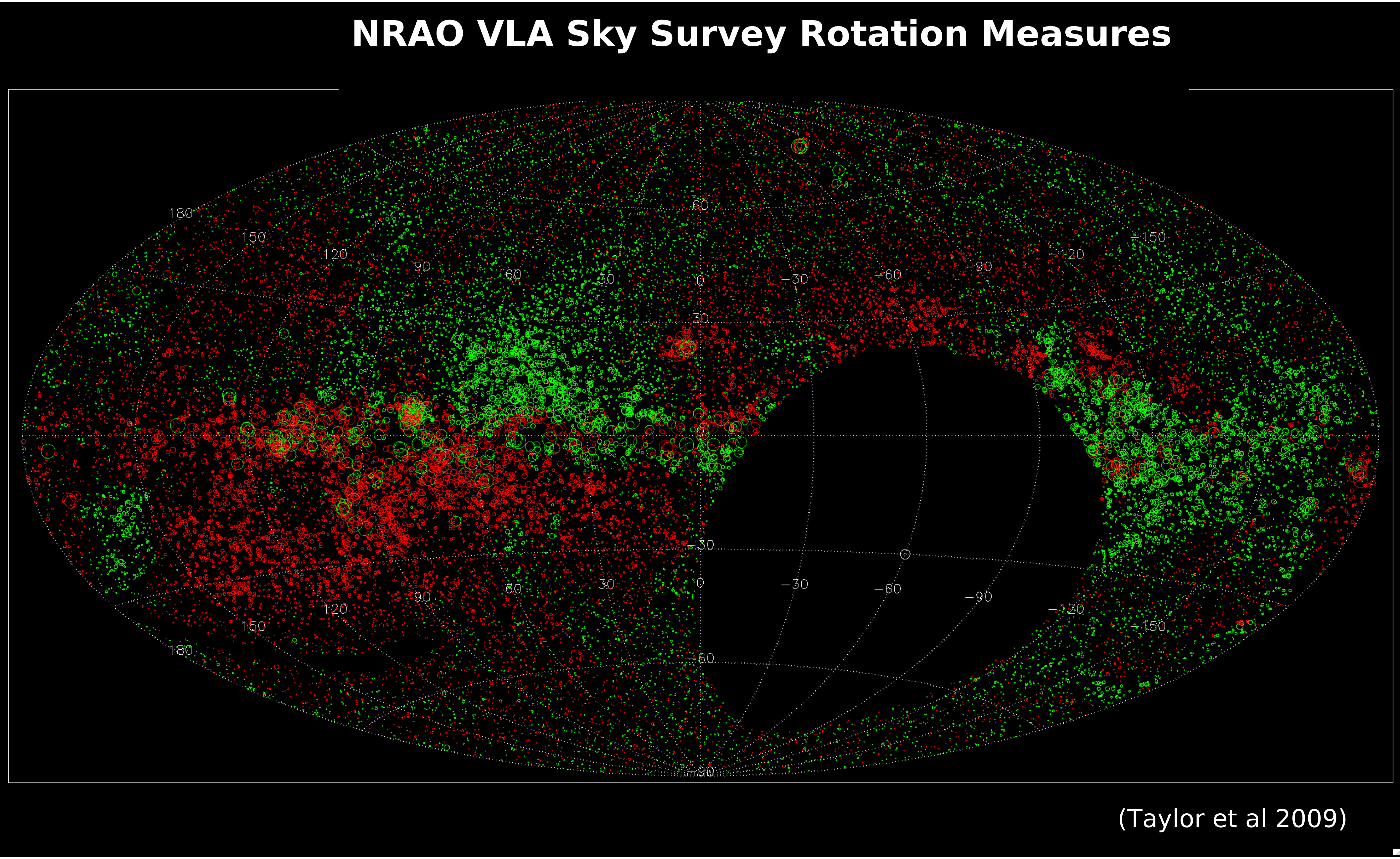
Possible SKA1 surveys suitable for cosmic magnetism studies

Instrument	Frequency	Field of View	Resolution	Sensitivity
SKA1-mid SKA1-survey	~1 GHz	30 deg^2	1''	0.01μJy/beam
SKA1-mid SKA1-survey	~1 GHz	30.000 deg^2	2''	1μJy/beam

1) Dense spaced RM grid of background sources
2) Faraday Rotation synthesis approach

An all-sky grid of Faraday rotation measures ~300-1000x denser than the most accurate all-sky map actually available

(Taylor et al 2009)



≈40000 sources (≈1 source per deg2)

The Galactic Magnetic Field

Magnetic fields play a crucial role in our Galaxy:

1) Govern the structure and the dynamics of the interstellar medium

2) Regulate the process of star formation

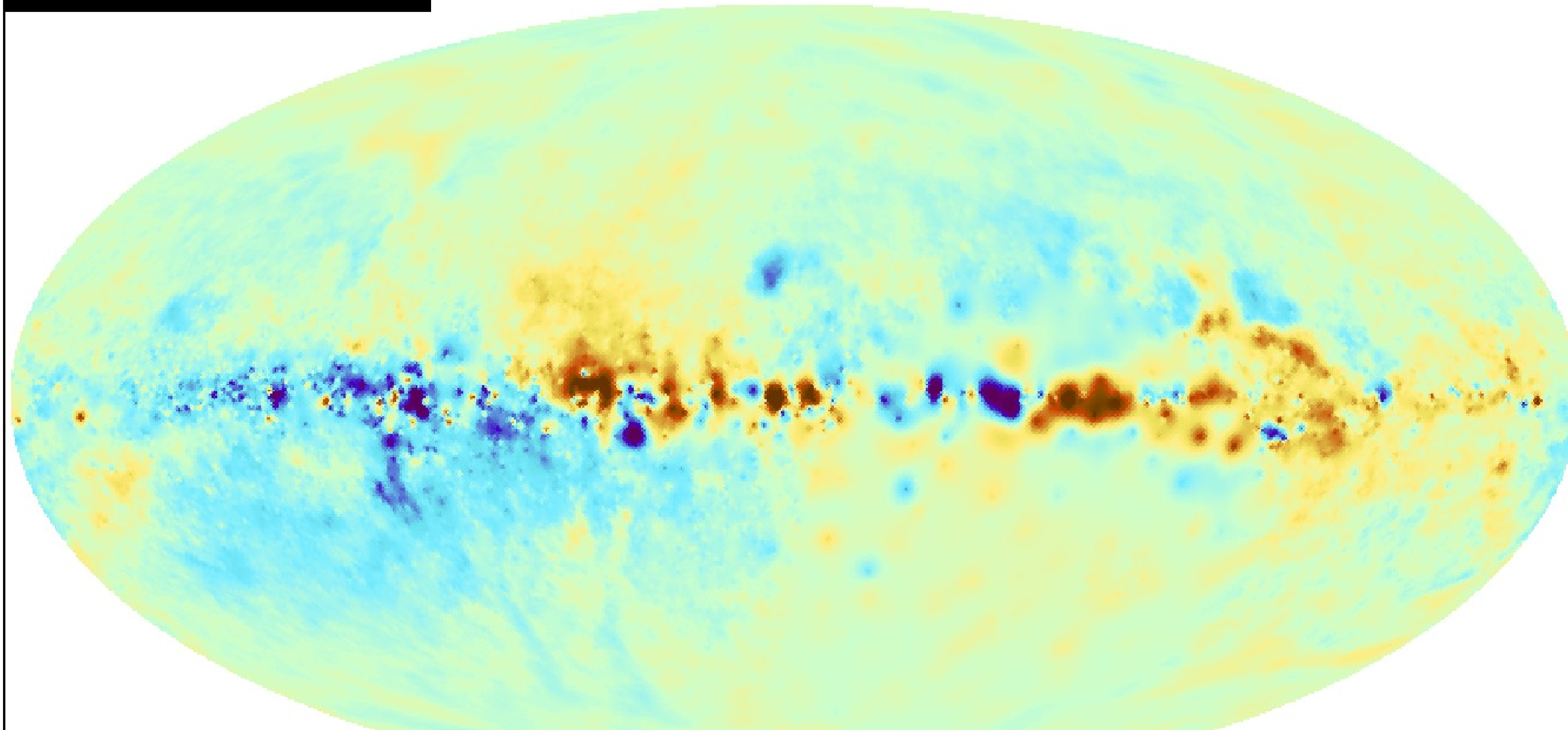
3) Accelerate cosmic rays

Being able to model the Galactic magnetic field is very important for accurate foreground subtraction to address magnetic fields in the Cosmic web, CMB polarization, Epoch of Reionization and propagation of Ultra-High Energy Cosmic Rays.

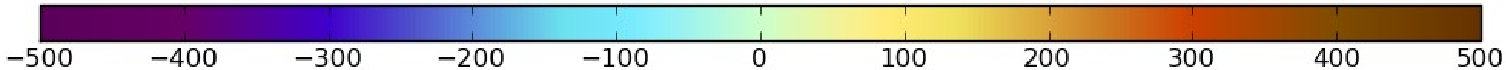
The Galactic Magnetic Field

RM probes of the Galactic Magnetic Field

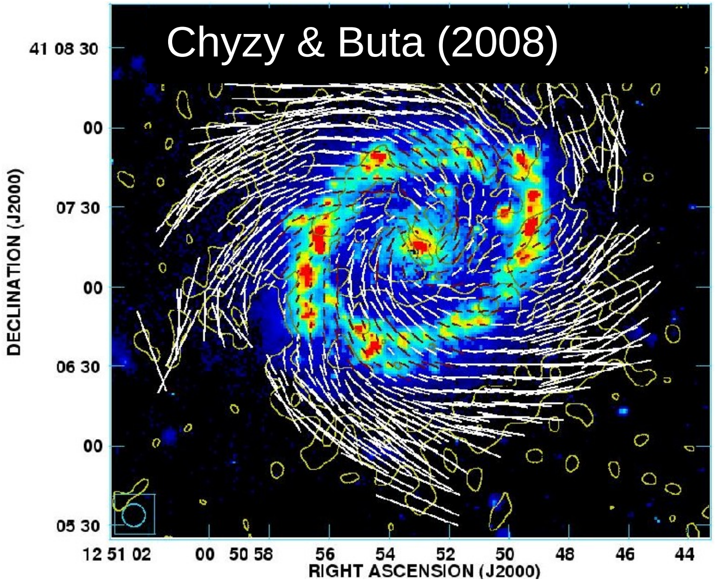
Oppermann et al. (2012)



Reconstruction of the Galactic Faraday depth, mostly based on the Taylor et al. (2009) data.



Magnetism and Galaxy Evolution



SKA1 will permit detailed investigation of the structure of the magnetic fields in the interstellar medium of galaxies and in galaxy halos, and to measure the magnetic field power spectrum.

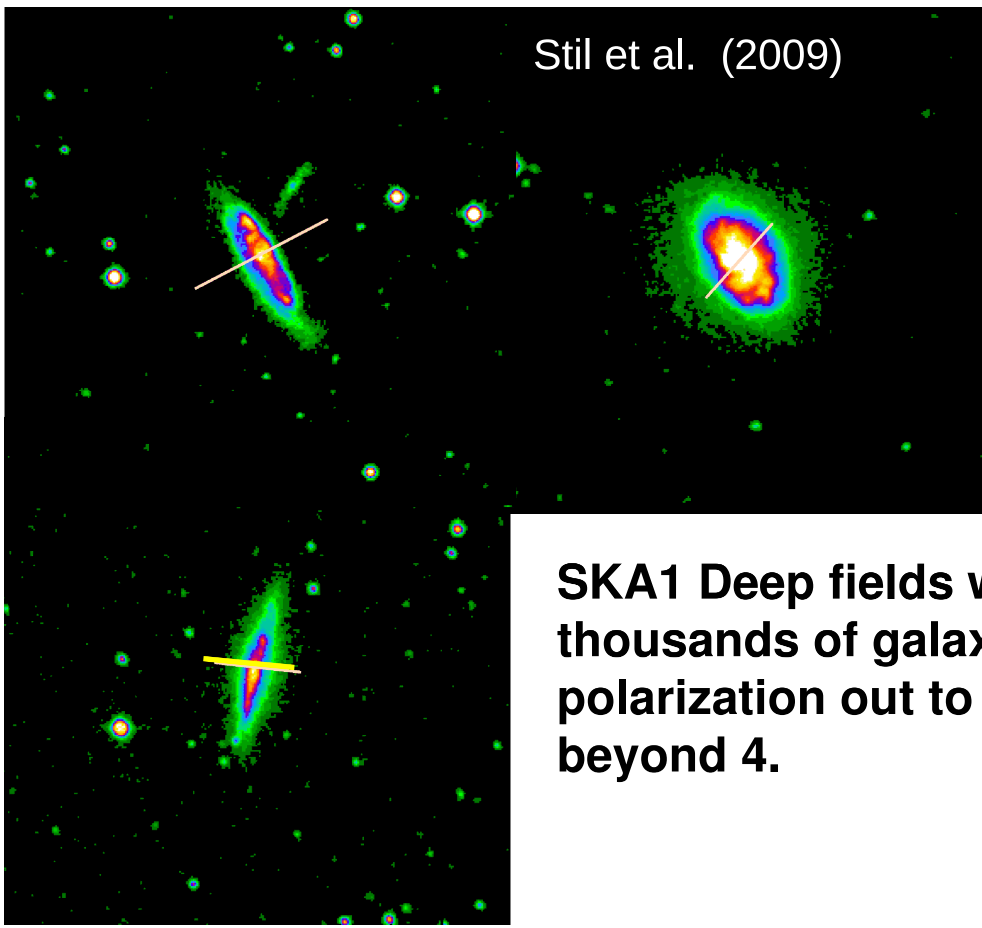
- Global galaxy energetics?
- How cosmic magnetism in galaxies evolve with time?
- Interaction with intergalactic environment?

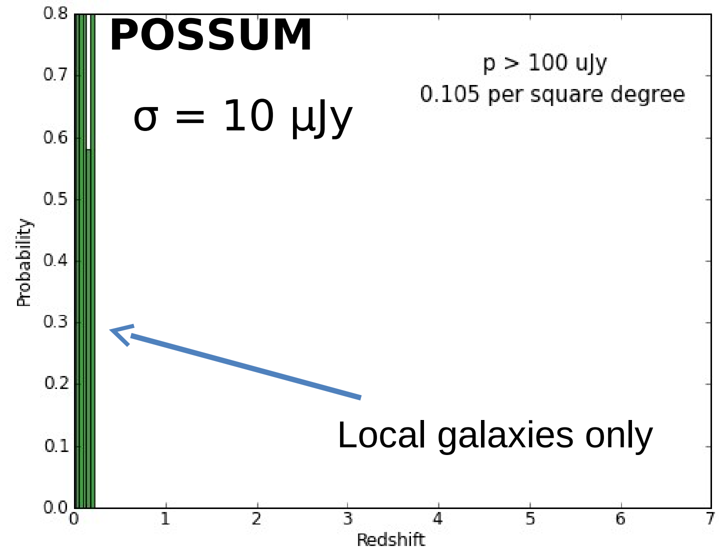
Polarimetry of galaxies at high redshift

- ***Integrated polarimetry to quantify measure disk fields to high redshift.*** Stil et al. (2009), Arshakian et al. (2009)
- ***RM Synthesis of emission from background QSOs may reveal the field structure in the disk or halo of intervening galaxies.*** Beck et al. (2012), Bernet et al. (2013)

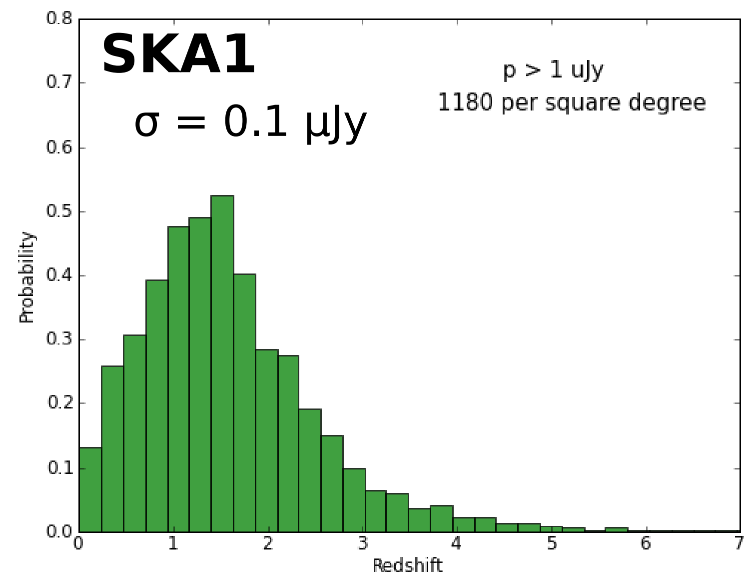
Magnetism and Galaxy Evolution

Effelsberg imaging of integrated polarization reveals presence of global fields in disk galaxies.

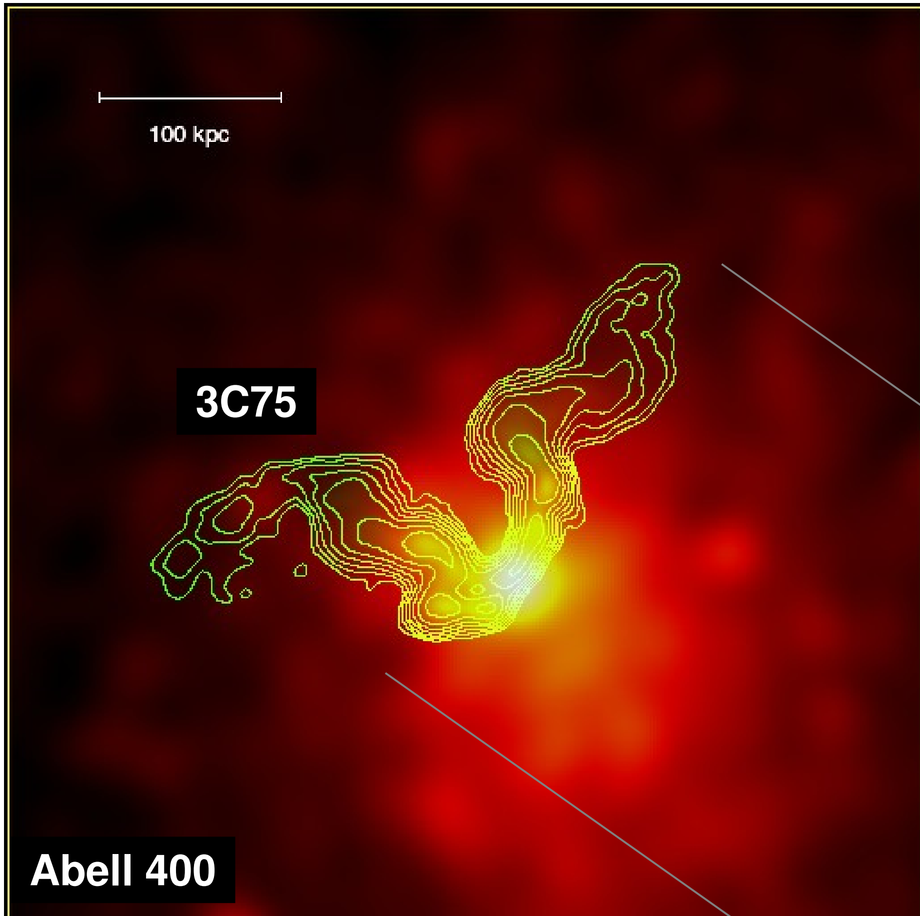




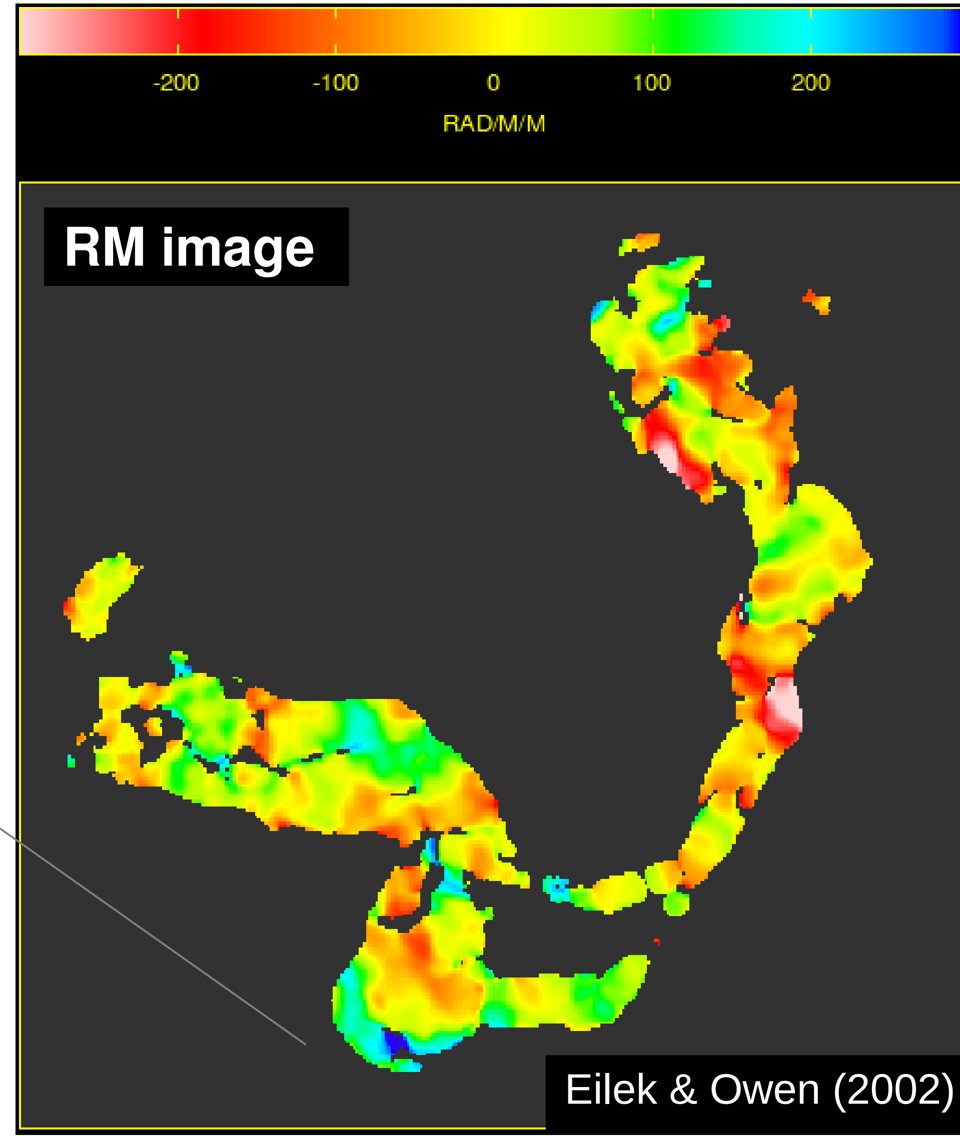
SKA1 Deep fields will detect thousands of galaxies in polarization out to redshifts beyond 4.



Magnetic Fields in Galaxy Clusters



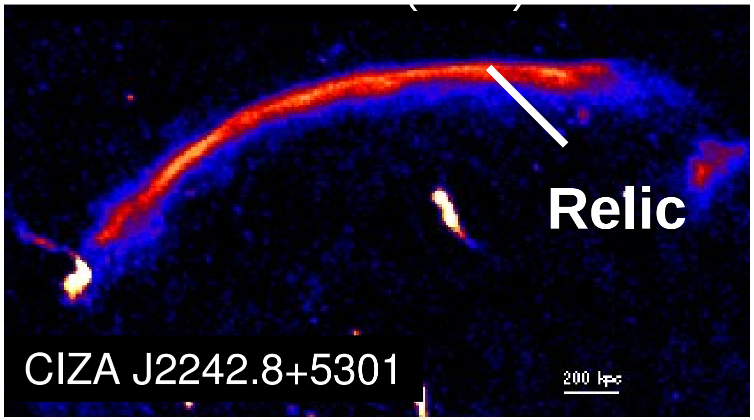
The sensitivity of current radio facilities limit the RM studies to a few radio galaxies per cluster.



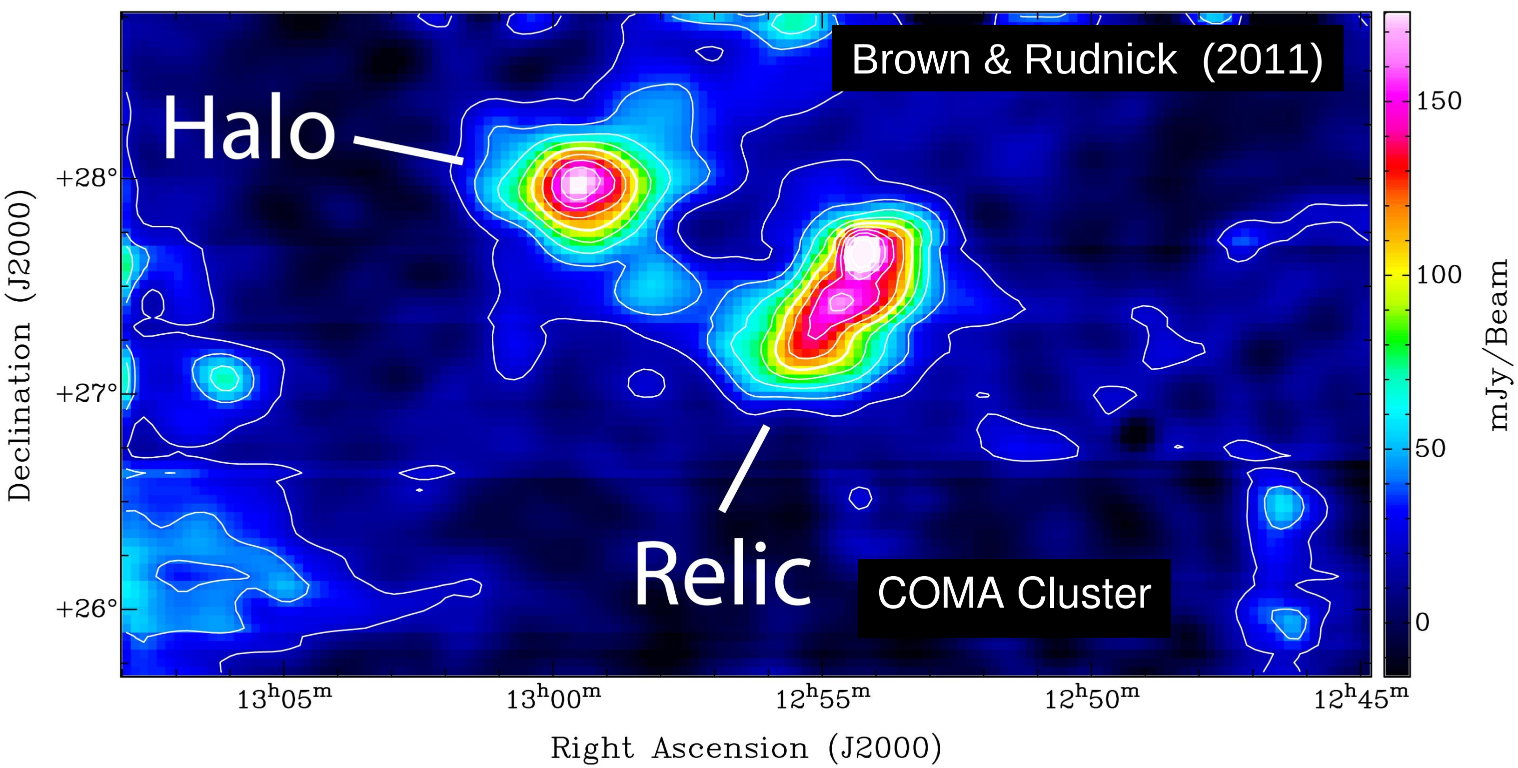
SKA1 will have the potential of measuring the RM toward a large number of sources by deriving a detailed description of the strength, structure, and radial decrease of cluster magnetic fields.

Magnetic Fields in Galaxy Clusters

SKA1 will permit to investigate the polarized emission from radio halos and relics. Relics are bright and highly polarized and hence are observable until high redshifts, even if not resolved.

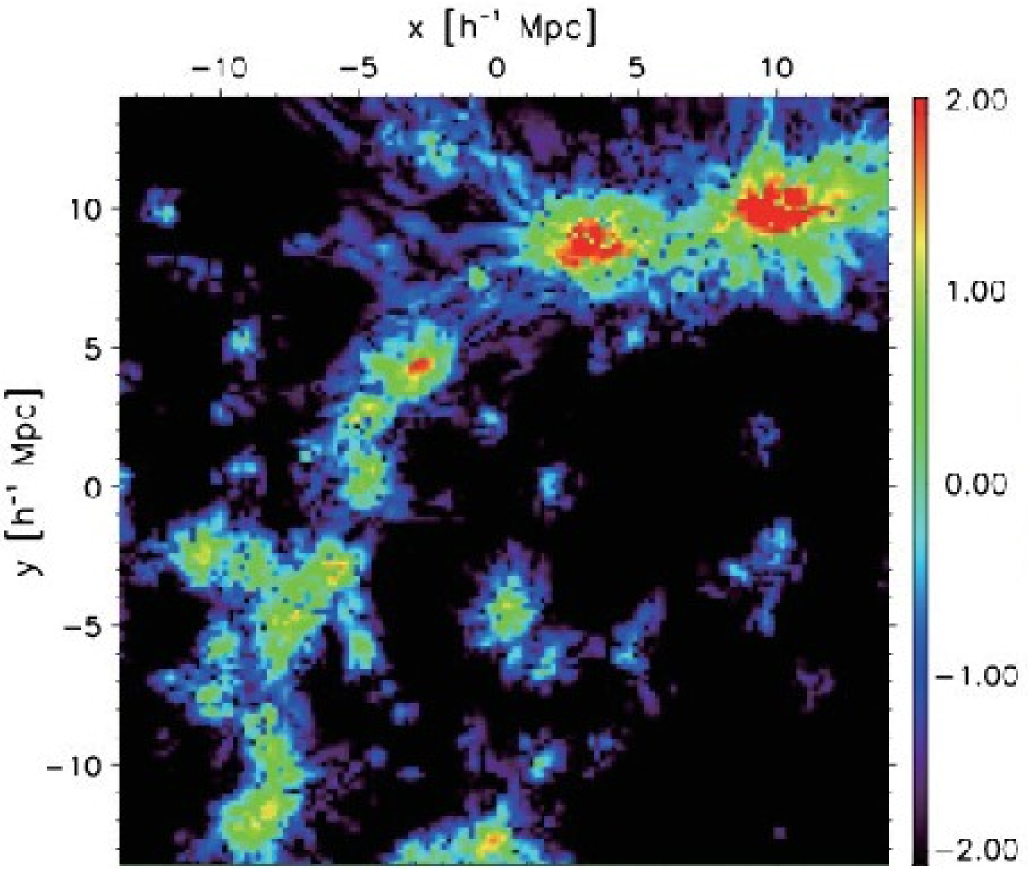


- **Constrain the cluster magnetic field power spectrum.** Murgia et al. (2004)
- **Detect merger shocks in the intracluster medium not visible in X-ray images.**

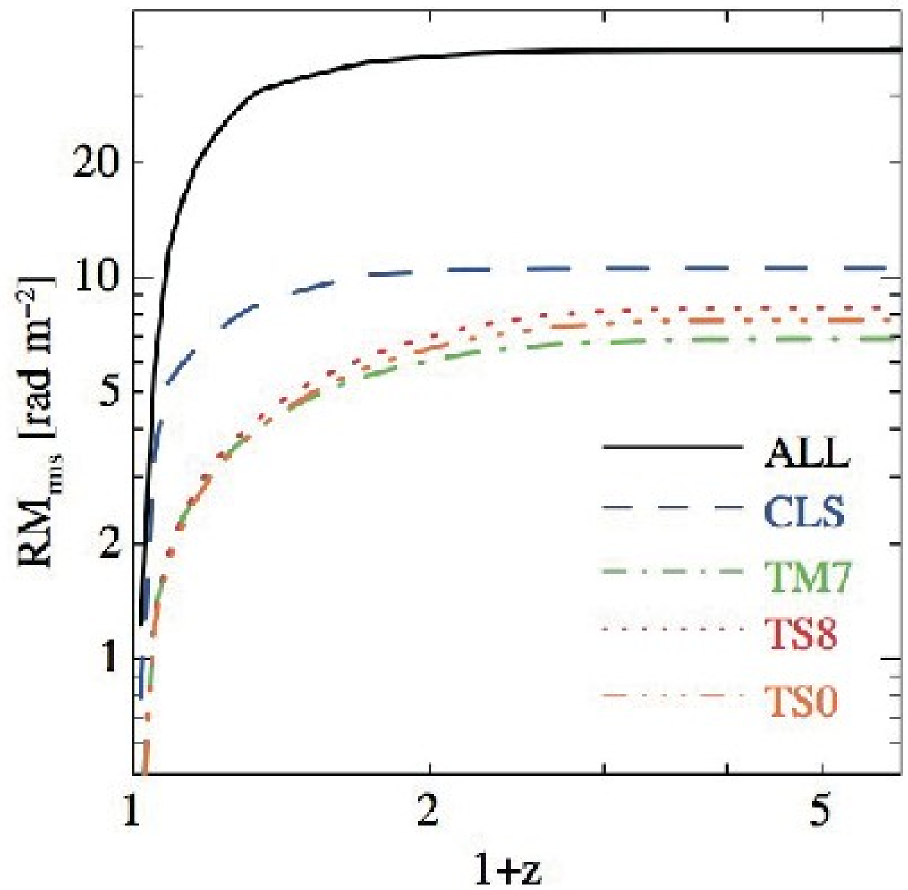


Magnetic fields in the Cosmic Web

- Can it be detected?
- How did it arise?
- What are its properties and relation to large scale structure of matter?



Akahori & Ryu (2010, 2011)



Frequency Range of SKA1

$$\phi_{[\mathrm{rad/m^2}]} = 812 \int_{L[\mathrm{kpc}]}^{0} n_{e[\mathrm{cm^{-3}}]} B_{||[\mu G]} dl$$

Instrument	Frequency Range MHz	$\Delta\lambda^2$	λ^2_{min}	$\delta\Phi$ rad/m²	$L\Phi_{max}$ rad/m²
SKA1-low	50-350	35.2	0.73	0.1	4.3
SKA1-mid	350-1050 (Band 1)	0.65	0.08	5.3	38.5
	950-1760 (Band2)	0.07	0.03	49.0	108.3
SKA1-survey	650-1670 (PAFBand2)	0.18	0.03	19.2	97.5
SKA1	50-1760 (full coverage)	35.9	0.03	0.1	108.3

Maximum observable Faraday depth width

$$L_{\phi,max} \simeq \frac{\pi}{\lambda^2_{min}}$$

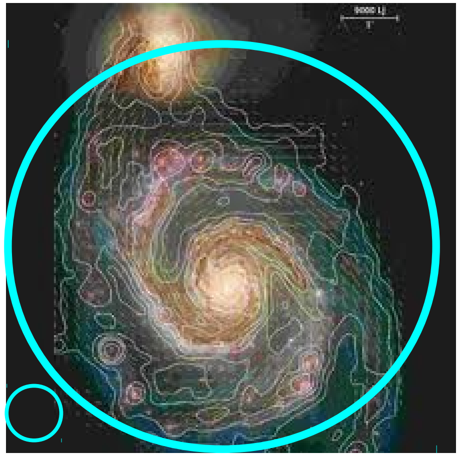
Resolution in Faraday depth space

$$\delta\phi \simeq \frac{2\sqrt{3}}{\Delta\lambda^2}$$

Cosmic magnetism needs a frequency range as large as possible. It is important not to have gaps in frequency range between the instruments, already in the initial phases of the project.

For SKA1-survey, if PAF Band1 will not be initially available, going to slightly lower frequencies would be better for RM synthesis. In this case, starting from 500 MHz would be better than starting from 650 MHz.

Angular Resolution of SKA1

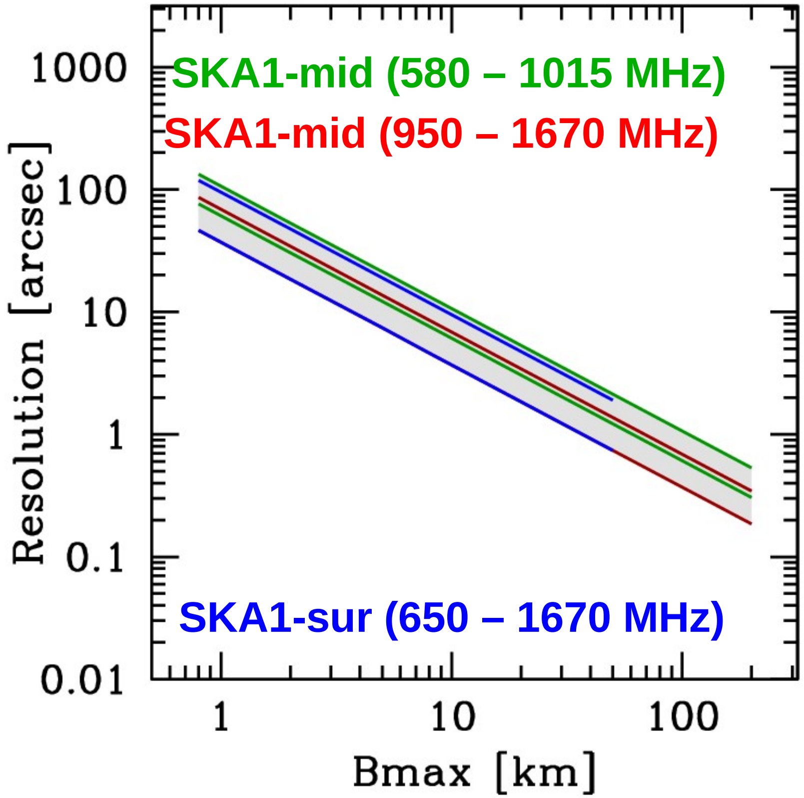


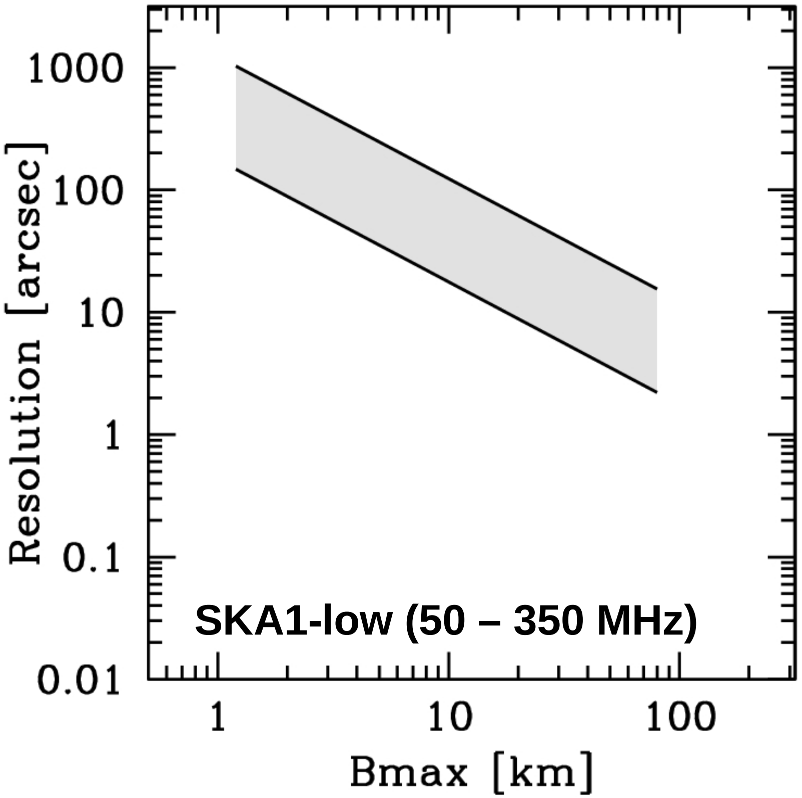
Beam depolarization

High angular resolution is necessary to:
- Obtain detailed RM images (external Faraday screen)
- Avoid Beam depolarization

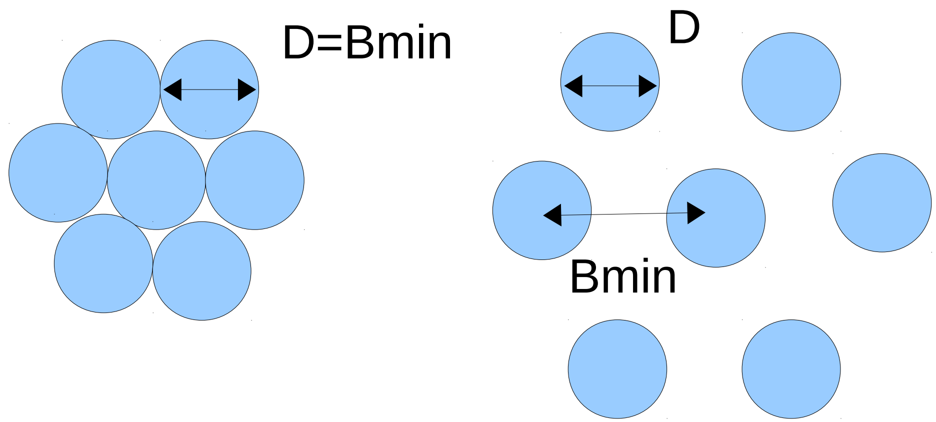
SKA1-low may not provide a sufficient resolution to overcome the beam depolarization.

We support the possibility to have SKA1-low with longer baselines to reduce the beam depolarization.





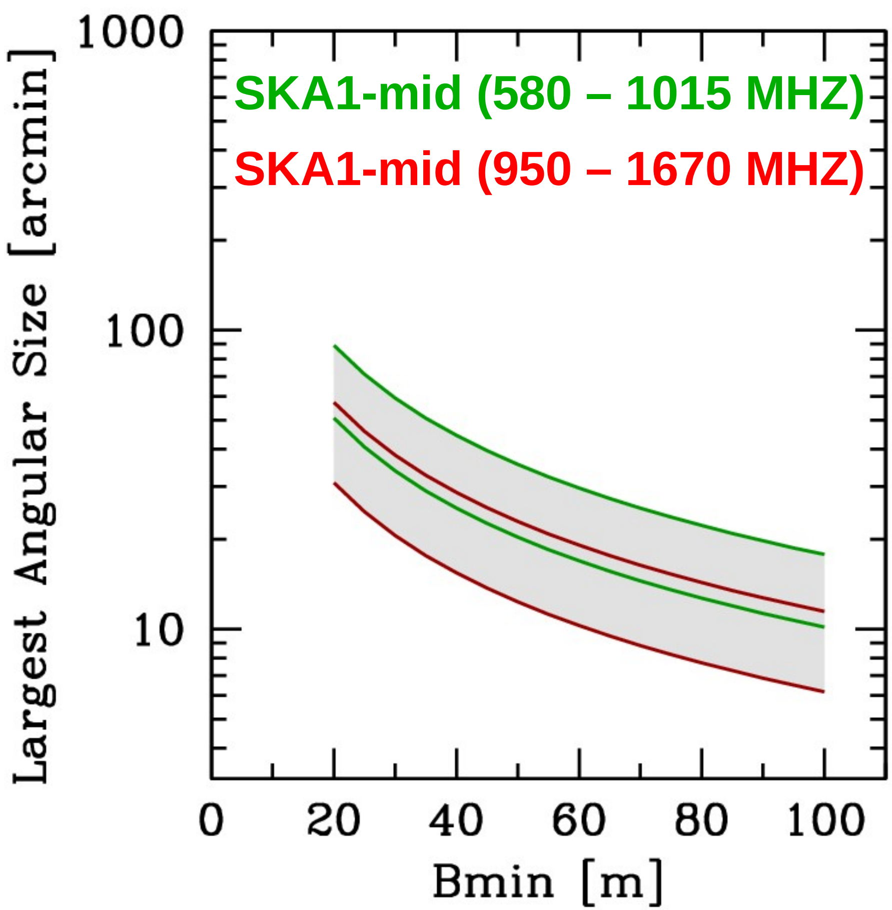
Detection of Large Scale Structure with SKA1

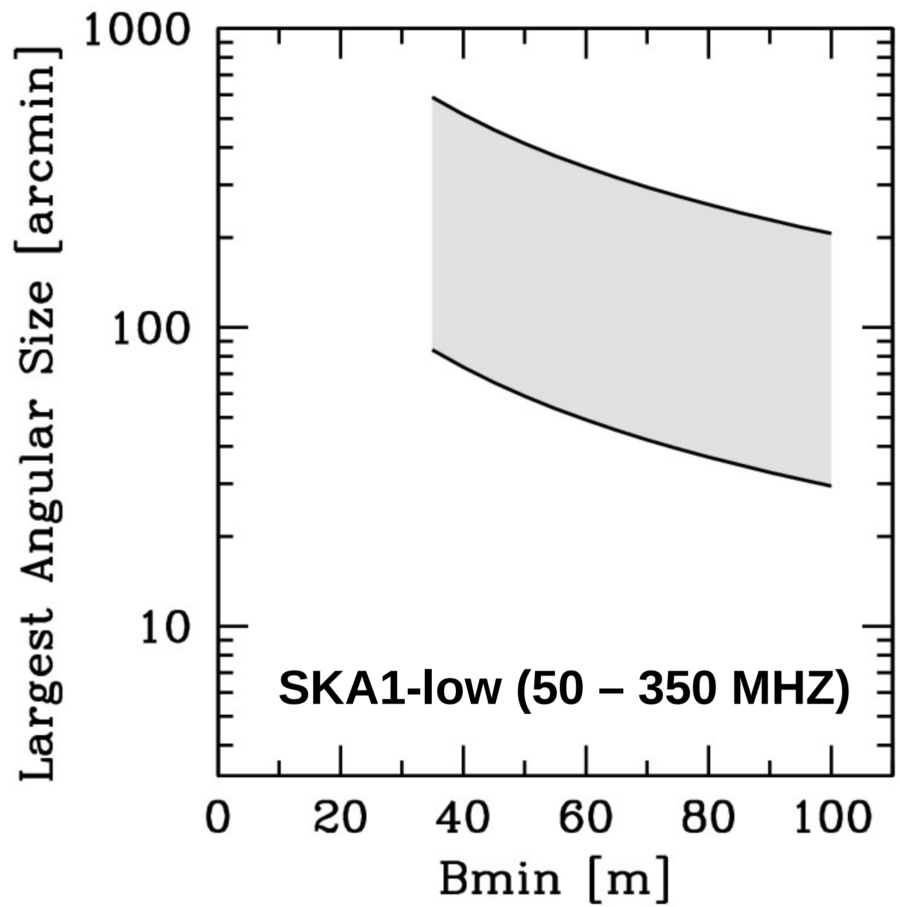


Field of View ~ λ/D

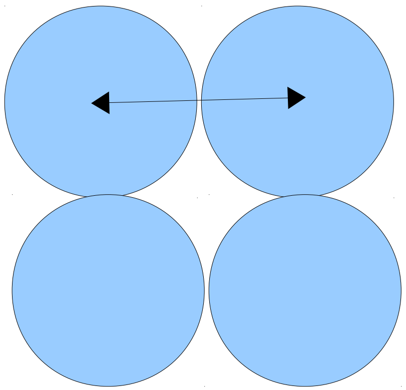
Large Angular Scale ~ λ/Bmin

Detection of Large Scale Structures with SKA1





Detection of Large Scale Structure with SKA1



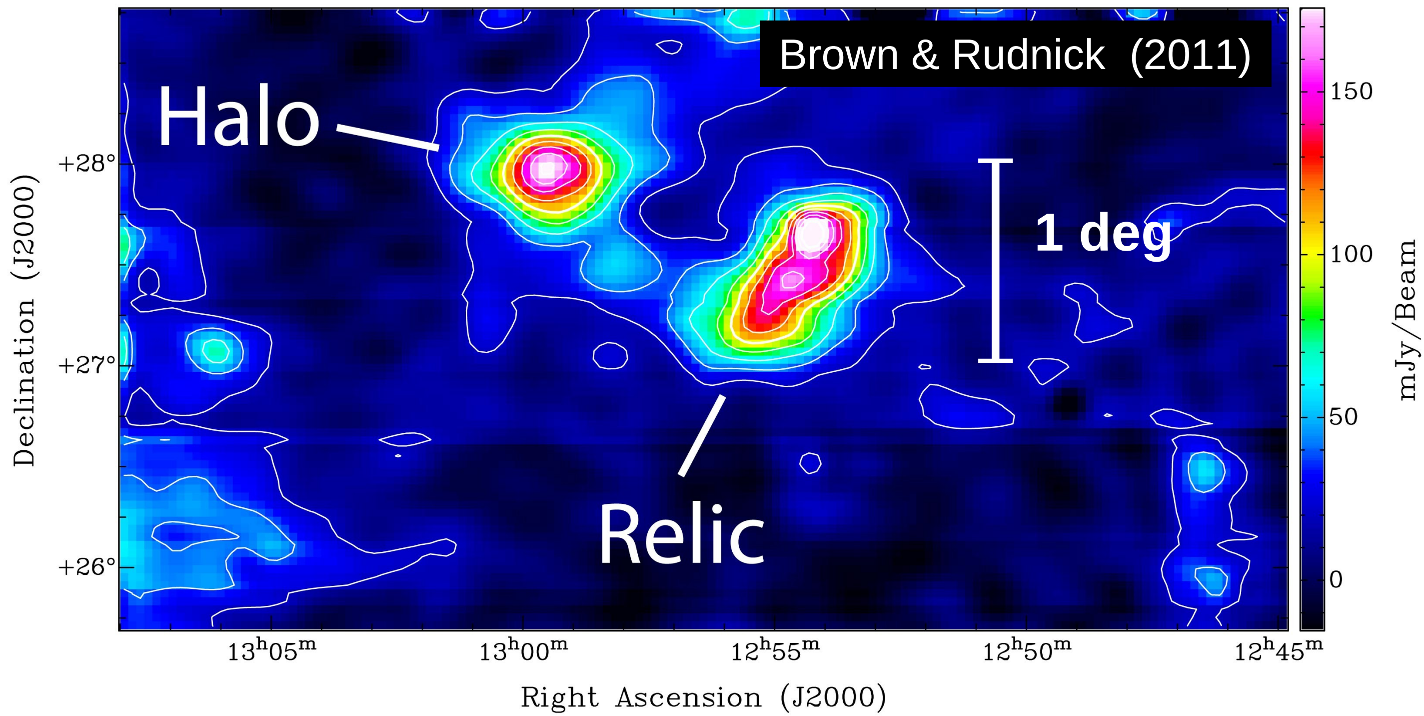
D=Bmin

Field of View ~ λ/D

Large Angular Scale ~ λ/Bmin

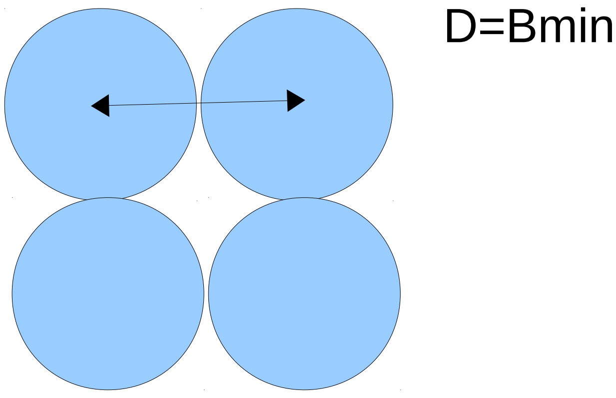
Increasing the size stations of SKA1-low will reduce the FoV and increase the minimum baseline. The latter effect may limit the possibility to detect large angular scale structures even with mosaicing observations.

EXAMPLE OF A LARGE ANGULAR SCALE STRUCTURE
Total intensity



The minimum baseline of SKA1-mid, SKA1-survey, and SKA1-low should be clearly discussed in the Baseline Design.
We recommend reducing the minimum baseline as much as possible. We also recommend considering SKA1-low stations not larger than 35 m.

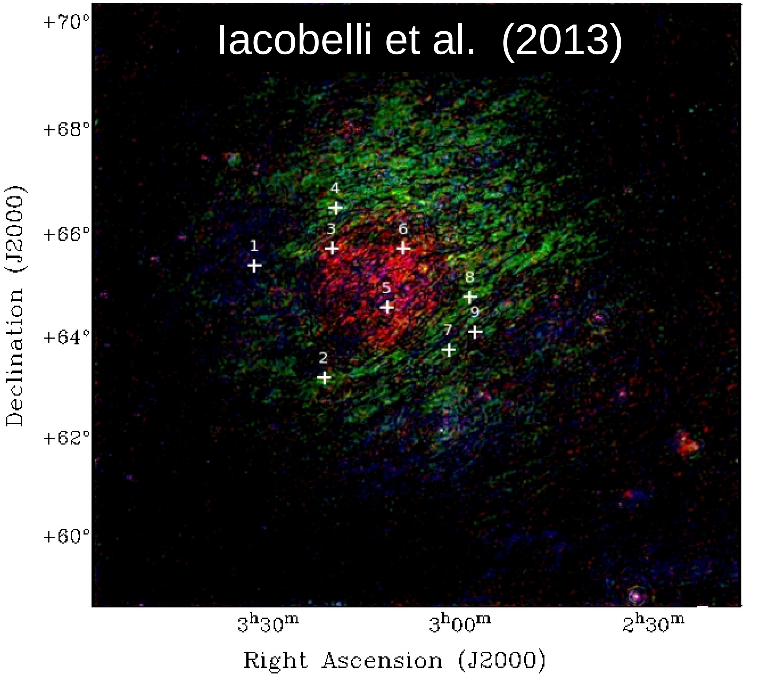
Detection of Large Scale Structure with SKA1



Field of View ~ λ/D

Large Angular Scale ~ λ/Bmin

EXAMPLE OF A LARGE ANGULAR SCALE STRUCTURE
Polarization Intensity



Increasing the size stations of SKA1-low will reduce the FoV and increase the minimum baseline. The latter effect may limit the possibility to detect large angular scale structures even with mosaicing observations.

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Polarization Purity of SKA1

A high polarization purity is fundamental to detect polarized signal from astrophysical sources seen down to sub-mJy levels.

Tab. 5 Baseline Design

Table 5 Subset of Dish Performance Requirements

Equivalent physical aperture diameter	15 m	
Low Frequency	350 MHz	
High Frequency	20 GHz	
Optics	Clear aperture	
Efficiency	>77 %	
Total spillover noise	3 K	L-band
Other losses	<2 K	L-band
1st sidelobe	-21 dB	
Far-out sidelobe level	<-50 dB	
Polarization purity	-30 dB	Within HPBW
Beam symmetry	TBD	
Receivers	5	Cryo-cooled, spanning frequency range
Elevation limit	<15 deg	
Azimuth range	±270 deg	
Pointing repeatability	10, 17,180 arcsec	P, S, D respectively arcsec, rms
Receiver noise temperature & Feed Losses	<15 K	Assumed for performance estimates
Classes of Environmental Operating Conditions	Precision	Wind <7 m/s; night
	Standard	Wind <7 m/s; day
	Degraded	Wind <20 m/s
Operation	continuous	Except for extreme weather.

-30 dB

SKA1-survey
SKA1-mid

This should be sufficient on axis, but the proper specification for PAF systems need more details: covering issues of the PAF beams, polarization stability

Note that we intend post-calibration polarization purity!!

Information on polarization performances of SKA1-low is missing in the Baseline Design.
Proper specification on polarization are required for SKA1-mid and SKA1-survey.

Survey Speed of SKA1

Tab. 1 Baseline Design

Table xxx: Parameters for Comparable Telescopes															
		eMERLIN	JVLA	GBT	GMRT	Parkes MB	LOFAR	FAST	MeerKAT	WSRT	Arecibo	ASKAP	SKA1-survey	SKA1-low	SKA-mid
A_{eff}/T_{sys}	m^2/K	60	265	276	250	100	61	1250	321	124	1150	65	391	1000	1630
FoV	deg^2	0.25	0.25	0.015	0.13	0.65	14	0.0017	0.86	0.25	0.003	30	18	27	0.49
Receptor Size	m	25	25	101	45	64	39	300	13.5	25	225	12	15	35	15
Fiducial frequency	GHz	1.4	1.4	1.4	1.4	1.4	0.12	1.4	1.4	1.4	1.4	1.4	1.67	0.11	1.67
Survey Speed FoM	$deg^2\ m^4 K^{-2}$	9.00×10^2	1.76×10^4	1.14×10^3	8.13×10^3	6.50×10^3	5.21×10^4	2.66×10^3	8.86×10^4	3.84×10^3	3.97×10^3	1.27×10^6	2.75×10^6	2.70×10^7	1.30×10^6
Resolution	arcsec	$10\text{-}150 \times 10^{-3}$	1.4 - 44	420	2	660	5	88	11	16	192	7	0.9	11	0.22
Baseline or Size	km	217	1 - 35	0.1	27	0.064	100	0.5	4	2.7	225	6	50	50	200
Frequency Range	GHz	1.3-1.8, 4-8, 22-24	1 - 50	0.2 - 50+	0.15, 0.23, 0.33, 0.61, 1.4	0.44 to 24	0.03 – 0.22	0.1 – 3	0.7 - 2.5, 0.7 - 10	0.3 – 8.6	0.3 - 10	0.7-1.8	0.65-1.67	0.050 – 0.350	0.35-14
Bandwidth	MHz	400	1000	400	450	400	4	800	1000	160	1000	300	500	250	770
Cont. Sensitivity	$\mu Jy\text{-}hr^{-1/2}$	27.11	3.88	5.89	6.13	16.26	266.61	0.92	3.20	20.74	0.89	28.89	3.72	2.06	0.72
Sensitivity, 100 kHz	$\mu Jy\text{-}hr^{-1/2}$	1714	388	373	411	1029	1686	82	320	830	89	1582	263	103	63
SEFD	Jy	46.0	10.4	10.0	11.0	27.6	45.2	2.2	8.6	22.3	2.4	42.5	7.1	2.8	1.7

$2.75X10^6$ deg^2 m^4/K^2

SKA1-survey

$1.30X10^6$ deg^2 m^4/K^2

SKA1-mid

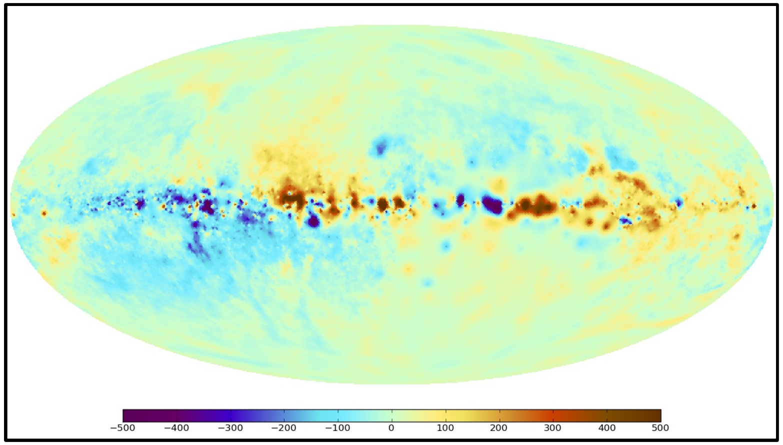
SKA1-mid has better resolution than SKA1-survey, a slightly better frequency coverage than SKA1-survey and it is only a factor of 2 down in survey speed. SKA1-mid can do surveys almost as well as SKA1-survey.

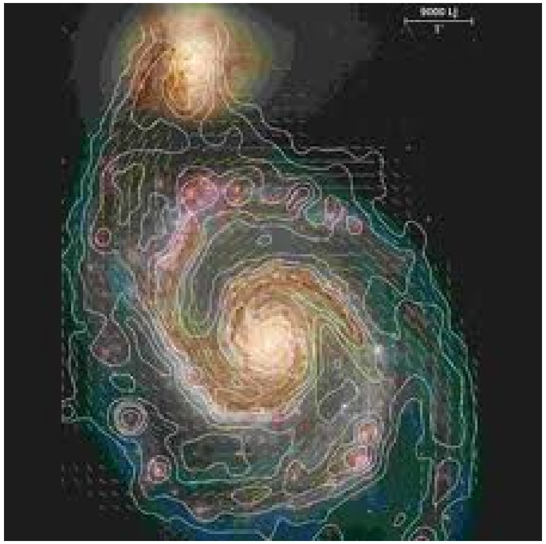
Given the apparent similarity in capabilities, we suggest optimizing some aspect of one of the two instruments for deep cm observations and some aspect of the other instrument for wide-field cm observations.

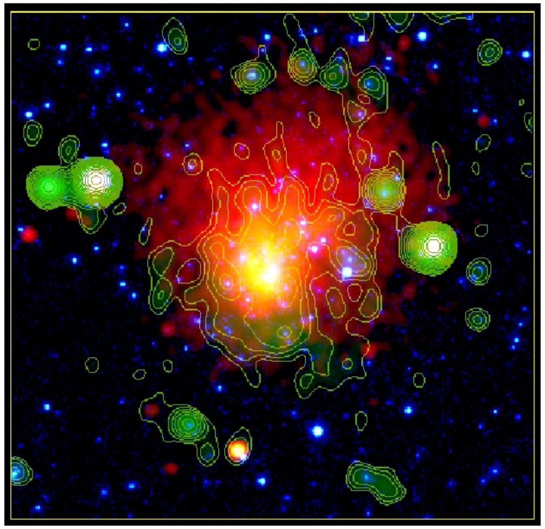
An even higher survey speed is recommended for the instrument dedicated to wide field observations.

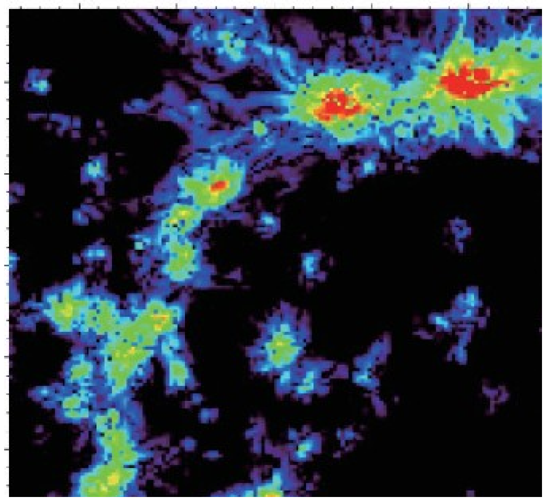
Conclusions

SKA1 will open a new era in the observation of astrophysical magnetic fields.









Conclusions

Inputs to the SKA1 System Baseline Design (Dewdney et al. 2013) in order to maximize scientific return in the context of Cosmic Magnetism.

1) Frequency

Cosmic magnetism needs a frequency range as large as possible. It is important not to have gaps in frequency range between the instruments, already in the initial phases of the project. For SKA1-survey, if PAF Band1 will not be initially available, going to slightly lower frequencies would be better for RM synthesis.

2) Angular Resolution

High angular resolution reduce beam depolarization.
(SKA1-low: longer baselines)

3) Largest Angular Scale

Minimum baseline to be reduced as much as possible.
(SKA1-low stations not larger than 35 m).

4) Polarization Purity

Proper information on polarization performances are missed in the Baseline Design.

5) Survey Speed

Apparent similarity in capabilities between SKA1-mid and SKA1-survey.
An even higher survey speed is recommended for the instrument dedicated to wide field observations.