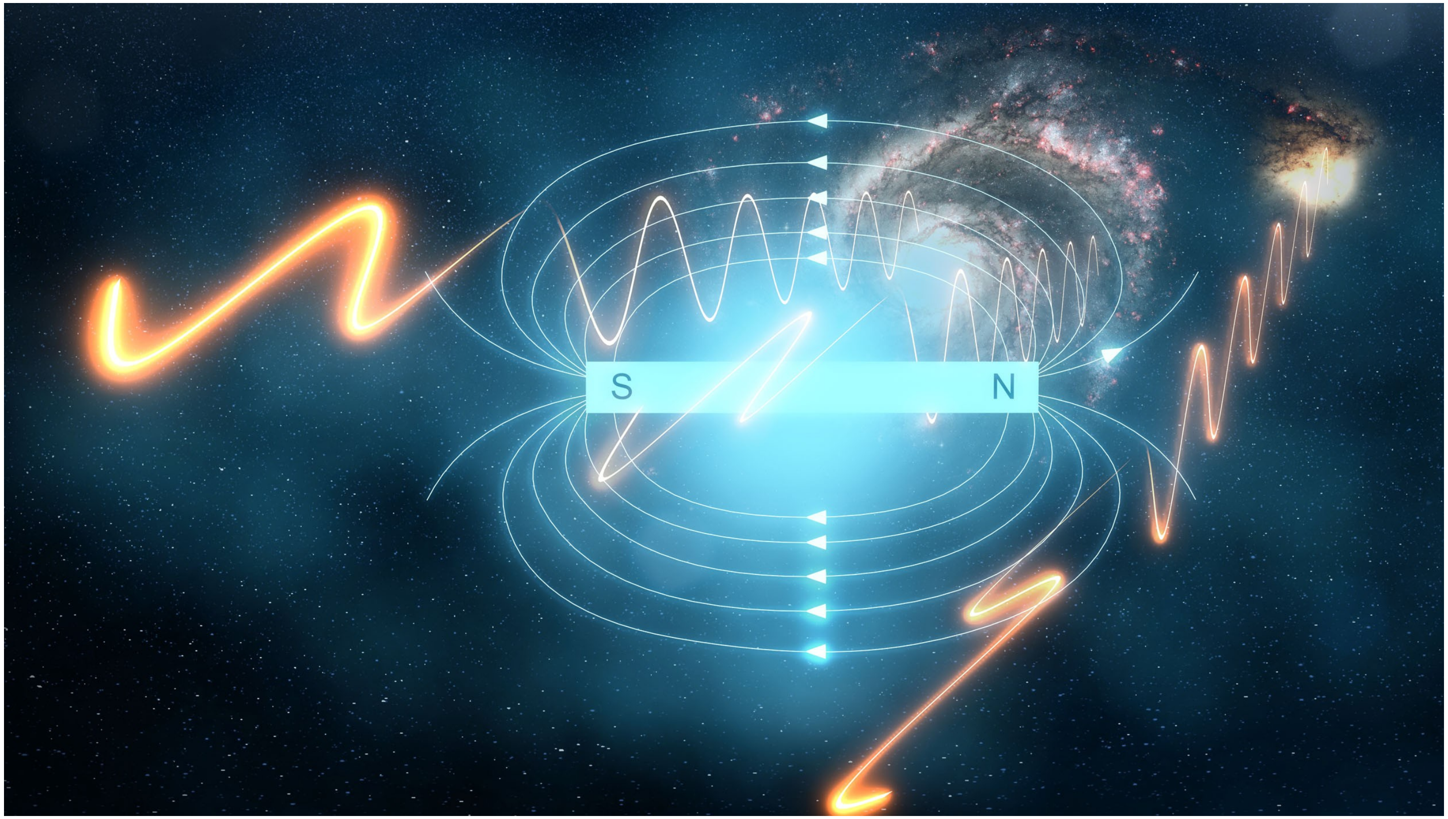
Work in progress of the SKA Cosmic Magnetism SWG

Federica Govoni
INAF – Osservatorio Astronomico di Cagliari (Italy)



Cosmic Magnetism SKA1 Assessment Workshop
SKA HQ (Jodrell Bank) 22-24 January 2014

Work in progress of the SKA Cosmic Magnetism SWG

Cosmic Magnetic Science in the SKA1 Era

Authors
I. Agudo, T. Akahori[1], R. Beck, A. Bonafede, T.D. Carozzi, L. Feretti, K. Ferrière, B.M. Gaensler, F. Govoni (co-chair), L. Harvey-Smith, M. Haverkorn, G.H. Heald, M. Johnston-Hollitt (co-chair), S.A. Mao, L. Rudnick, D. Schnitzeler, A. Scaife, J.M. Stil, K. Takahashi, A.R. Taylor, O. Wucknitz.

Executive Summary
The capability of the Square Kilometre Array (SKA) will already permit in its Phase-1 (SKA1) to explore Cosmic Magnetism in a variety of astrophysical sources. Wide-band spectro-polarimetry surveys at $\simeq$1 GHz, complemented by deep polarization observations at lower and higher frequencies, will be crucial to build the foundation for SKA Phase-2 (SKA2) experiments and will allow initial studies of magnetic fields in the Milky Way, in many external galaxies and clusters, and the overall magnetized intergalactic medium.

With the intent to maximize the scientific return of the science drivers discussed in this document, we underline some inputs to the SKA1 System Baseline Design, important in the Cosmic Magnetism context. Some of the following inputs have already been discussed in the SKA1 Continuum Assessment workshop (9-11 September 2013, Manchester), and in the SKA Engineering Meeting (7-11 October 2013, Manchester). In the following we summarize our main requirements and we give specific recommendations in Sect. 2:

- Proper information on polarization performances are missed in the Baseline Design.
- We support the possibility of having SKA1-low with a collecting area better distributed over longer baselines. This will permit not only reduction in the confusion limit, but also of the beam depolarization.
- We support the possibility of VLBI capabilities and, if feasible, high frequency coverage (up to 15−22 GHz) at least for part of the array. This is probably more easily implemented on SKA1-mid by employing Wide Band Single Pixel Feeds.
- There is an apparent similarity between SKA1-mid and SKA1-survey capabilities. We suggest to optimize some aspects of one of the two instruments for deep observations and some aspects of the other instrument for wide-field observations. A higher survey speed is recommended for the instrument dedicated to wide-field observations.
- To not limit the possibility to detect large angular scale structures, we recommend to reduce as much as possible the distance between dishes (SKA1-mid and SKA1-survey) and between the stations (SKA1-low). We also recommend SKA1-low stations no larger than $\simeq$35 m in diameter.
- It is desirable not to have gaps in frequency range between SKA1-low and SKA1-survey/SKA1-mid, even in the initial phases of the project.

1 Introduction

Much of what is known about Cosmic Magnetism comes from sensitive total intensity (Stokes I) and polarization (Stokes Q and U) radio observations. This is because the radio emission of astrophysical sources is mainly due to synchrotron radiation which is a direct probe of relativistic electrons gyrating around magnetic field lines. The observed total intensity of the synchrotron emission is related to the field strength, while the fraction of polarized emission is related to the field's degree of ordering.

In addition, the observed polarization angle Ψ of a source is modified from its intrinsic value (Ψ_0) by the effect of Faraday rotation, caused by a magneto-ionic medium (e.g. interstellar, intracluster,

[1] On behalf of the Japan SKA consortium cosmic magnetism (SKAJP-Magn).

Starting point for the discussion to be held during the SKA Cosmic Magnetism Assessment Workshop

Science Drivers for SKA1 (see also Gaensler et al. 2004 and Beck & Gaensler 2004)

SKA1 Observations for Cosmic Magnetism

Inputs to the SKA1 Baseline Design on the basis of the scientific requirements of the Cosmic Magnetism

SKA-TEL-SKO-DD-001
Revision : 1

SQUARE KILOMETRE ARRAY

SKA1 SYSTEM BASELINE DESIGN

...mber.......... SKA-TEL-SKO-DD-001
.... 1
.... P.E. Dewdney
.... 2013-03-12
.... Released

	Designation	Affiliation	Date	Signature
Owned by:				
...dney	SKA Architect	SKA Office	Peter E. Dewdney	Digitally signed by Peter E. Dewdney DN: cn=Peter E. Dewdney, o=SKA Organisation, ou, email=dewdney@skatelescope.org, c=GB Date: 2013.03.12 07:50:17 Z
Additional Authors				
W. Turner, R. Millenaar, R. McCool, J. Lazio, T. J. Cornwell				
Approved by:				
Joseph Lazio	Science Director (Acting)	SKA Office		[signature]
Released by:				
P. Diamond	Director-General	SKA Office		[signature]

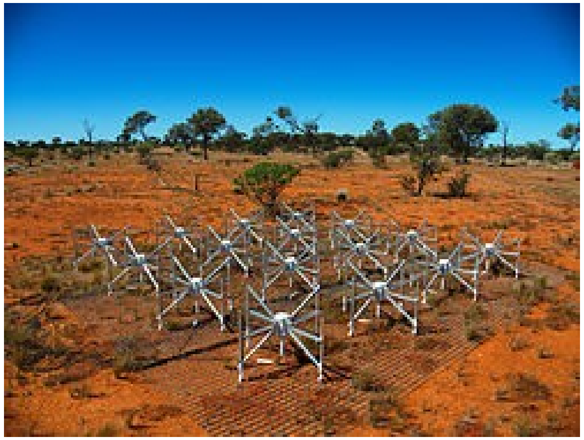
Dewdney et al. (2013)

2013-03-12 Page 1 of 98

Key SKA1 Observations for Cosmic Magnetism

To pave the way for broadband spectropolarimetric surveys to be performed with SKA1 and SKA2 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)



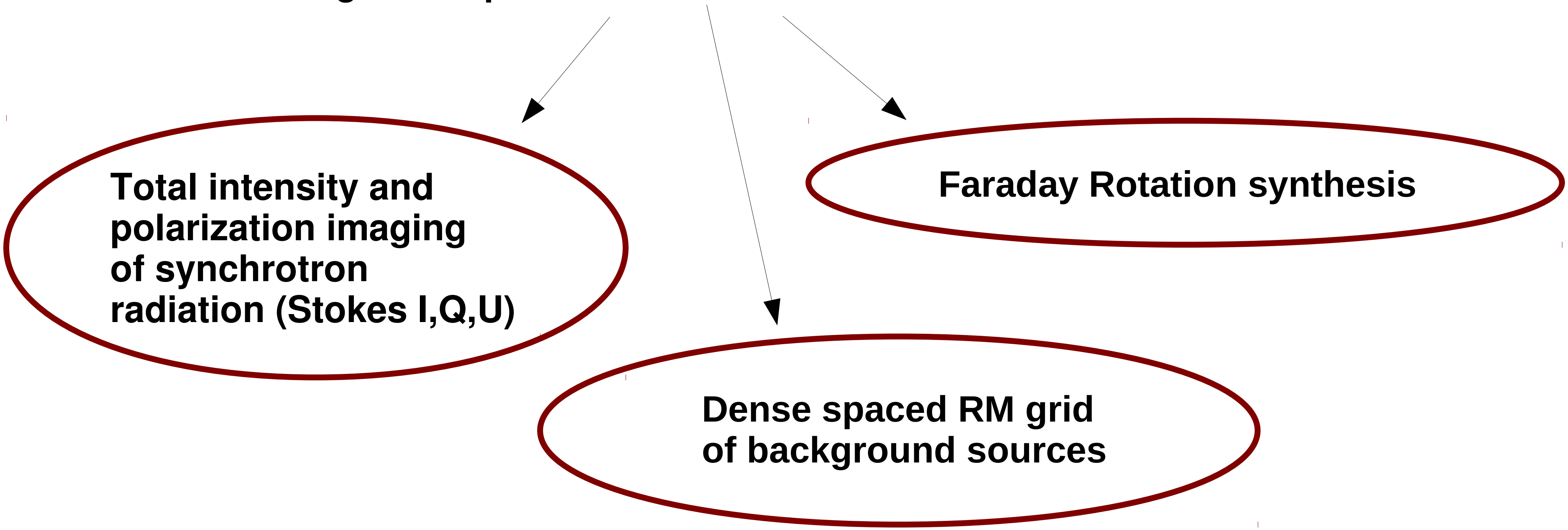
Presentation by Rainer Beck "Observing cosmic magnetism with LOFAR and lessons for the SKA"

Presentation by Emil Lenc "Observing cosmic magnetism with MWA"

Presentation by Anna Scaife "Cosmic magnetism science with KAT7"

Key SKA1 Observations for Cosmic Magnetism

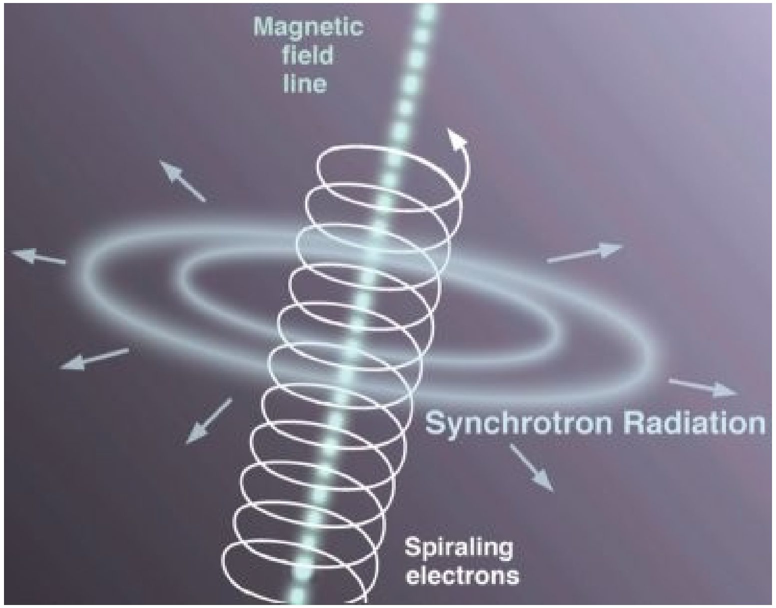
1) Polarization all Sky Survey at ~1GHz
2) Polarization deep field at ~1GHz
Complemented by deep targeted polarization observations of specific objects, at lower and higher frequencies



Key SKA1 Observations for Cosmic Magnetism

1) Polarization all Sky Survey at ~1GHz
2) Polarization deep field at ~1GHz
Complemented by deep targeted polarization observations of specific objects, at lower and higher frequencies

Total intensity and polarization imaging of synchrotron radiation (Stokes I,Q,U)



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

Key SKA1 Observations for Cosmic Magnetism

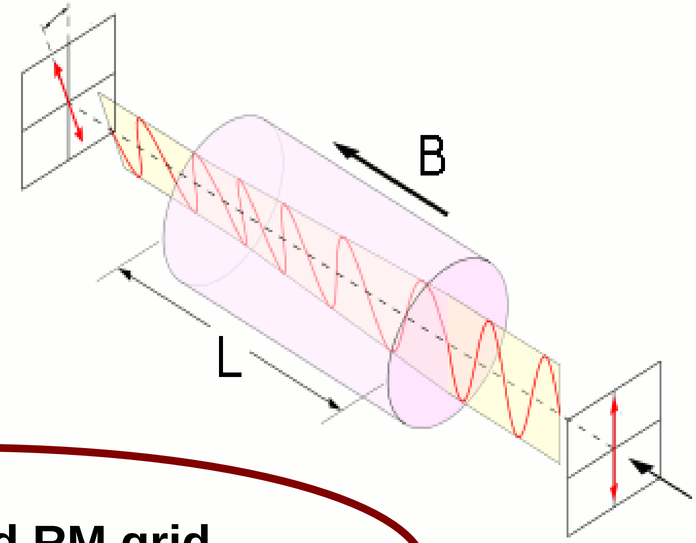
1) **Polarization all Sky Survey at ~1GHz**
2) **Polarization deep field at ~1GHz**

Complemented by deep targeted polarization observations of specific objects, at lower and higher frequencies

FARADAY DEPTH:

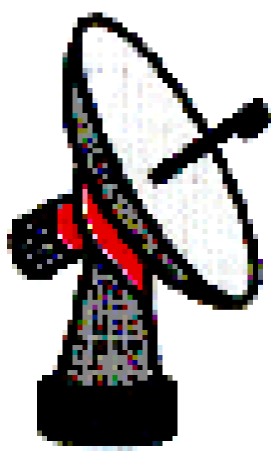
$$\phi_{[\mathrm{rad/m^2}]} = 812 \int_{\mathrm{L[kpc]}} n_{e[\mathrm{cm^{-3}}]} B_{||[\mu G]} dl$$

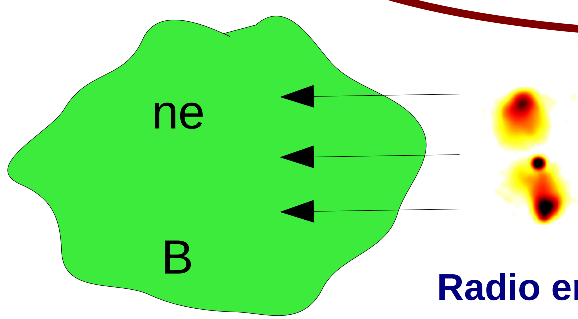
$$\Psi_{\mathrm{Obs}} = \Psi_{\mathrm{Int}} + \mathrm{RM}\lambda^2$$



Radio emission in the background
Faraday depth = RM

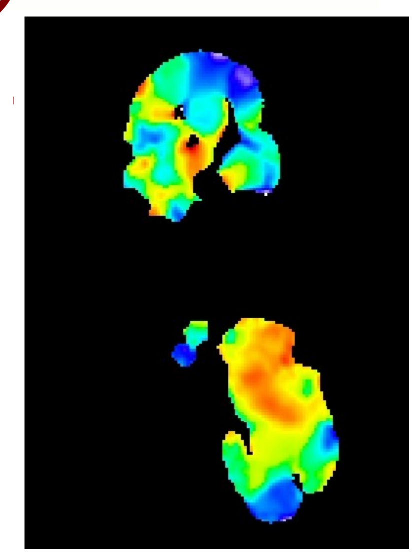
Dense spaced RM grid of background sources





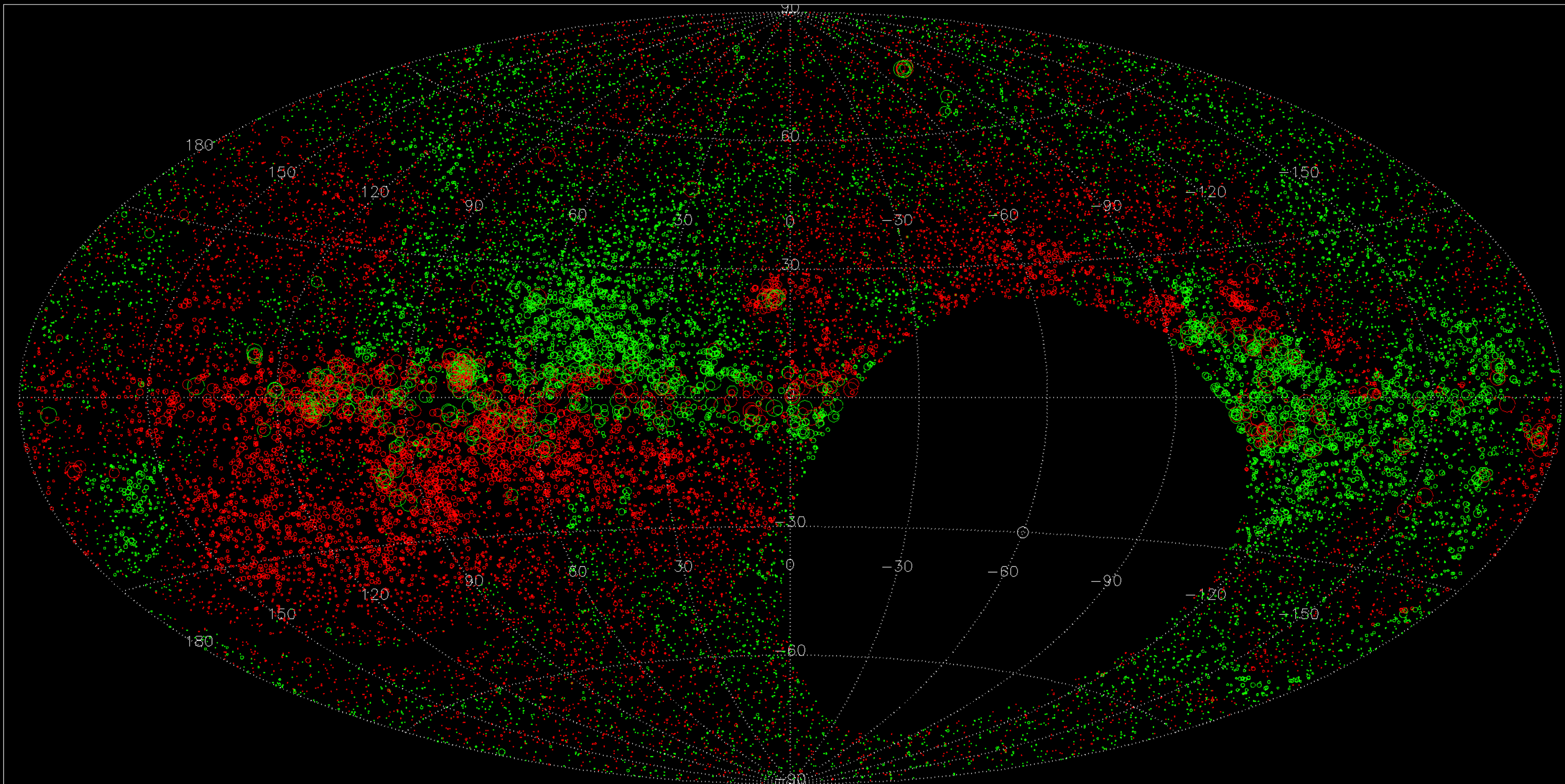
Radio emission

Magnetized plasma



Presentation by Larry Rudnick: "What polarized sources will we see at microJy levels?"

NRAO VLA Sky Survey Rotation Measures



≈40000 sources (≈1 source per deg2)

Taylor et al. (2009)

SKA1 may provide an all-sky grid of Faraday rotation measures ~300-1000x denser than the most accurate all-sky map actually available

Key SKA1 Observations for Cosmic Magnetism

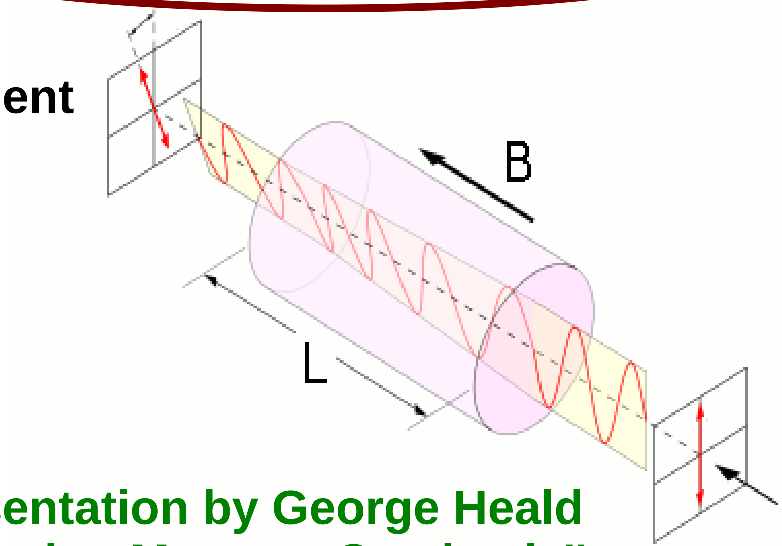
1) Polarization all Sky Survey at ~1GHz
2) Polarization deep field at ~1GHz
Complemented by deep targeted polarization observations of specific objects, at lower and higher frequencies

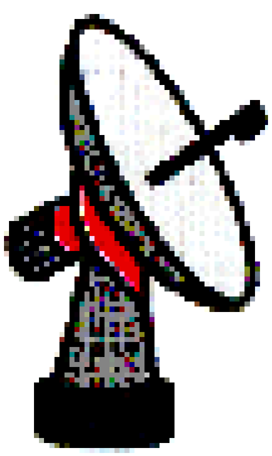
FARADAY DEPTH:

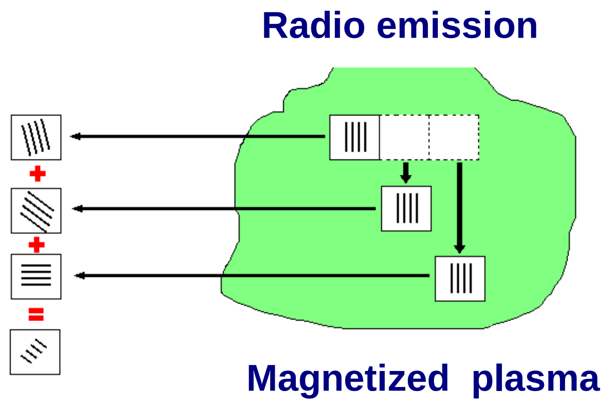
$$\phi_{[\mathrm{rad/m^2}]} = 812 \int_{\mathrm{L[kpc]}} \mathrm{n}_{\mathrm{e[cm^{-3}]}} \mathrm{B}_{||[\mu\mathrm{G}]} \mathrm{dl}$$

Faraday Rotation synthesis

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







Rotation Measure Synthesis to recover the polarized signal

Presentation by George Heald "Rotation Measure Synthesis"

Presentation by Dominic Schnitzeler "Technical issues with broadband Polarimetry"

Cosmic Magnetism Science Drivers

Magnetic field studies to address important questions:

- **How do magnetic fields in galaxies and structures evolve over cosmic time?**

  Presentation by Jeroen Stil "Evolution of galaxies - a magnetic twist"

- **What are the physical properties of absorbing systems?**

- **What are the properties of magnetic fields in Active Galactic Nuclei and what is the relation between super-massive black holes and their environment?**

  Presentation by Ivan Agudo "Polarization Studies of Extragalactic Relativistic Jets from Supermassive Black Holes"

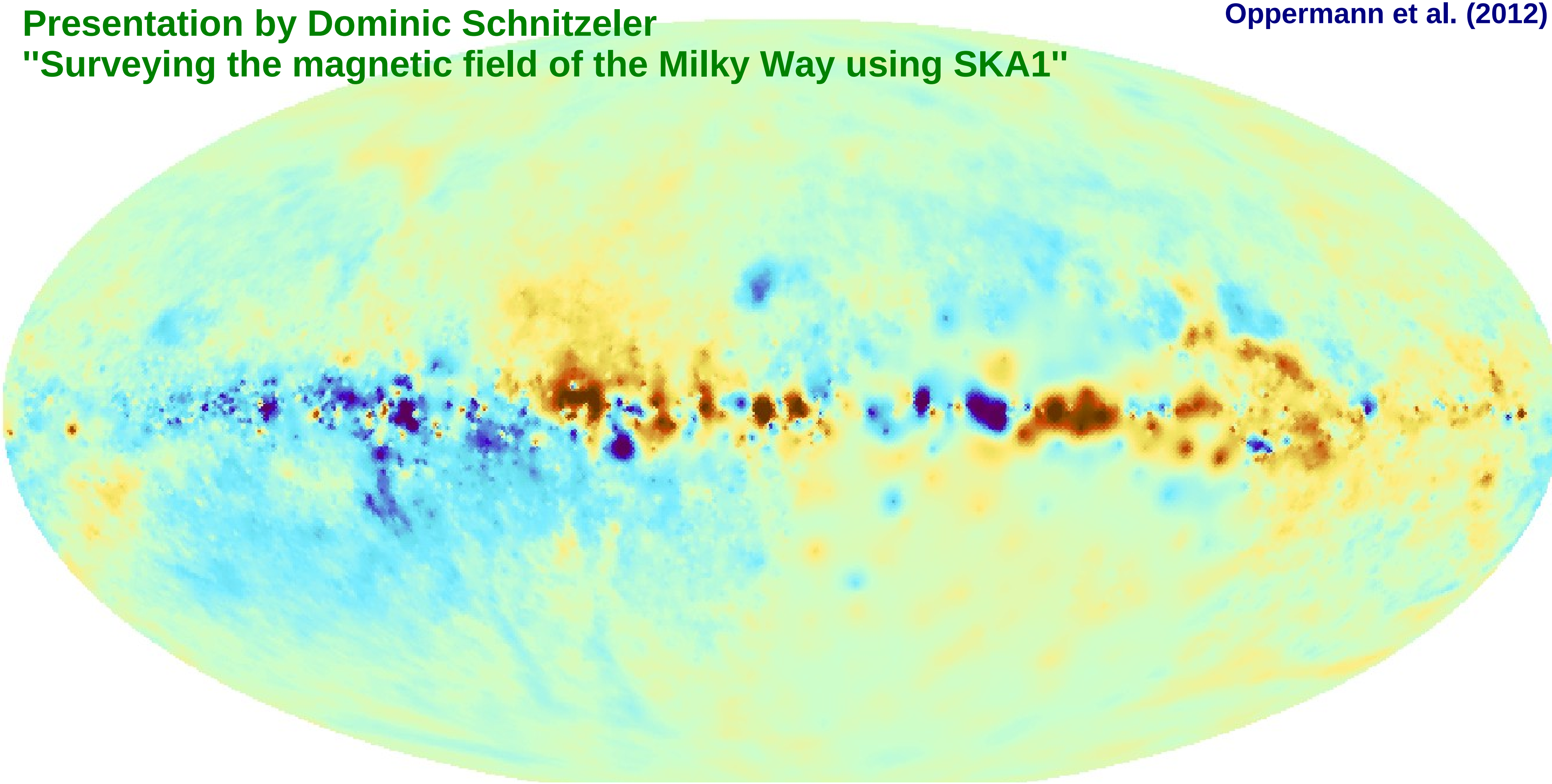
Cosmic Magnetism Science Drivers

Magnetic fields play a crucial role in our Galaxy:

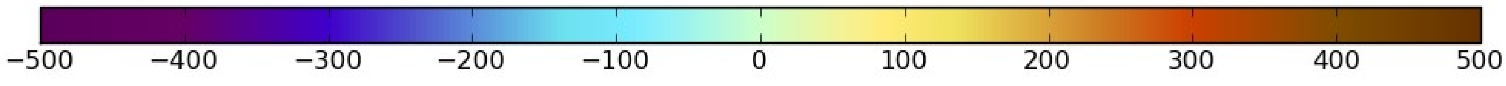
- **Govern the structure and the dynamics of the interstellar medium**
- **Regulate the process of star formation**
- **Accelerate cosmic rays**

Presentation by Dominic Schnitzeler
"Surveying the magnetic field of the Milky Way using SKA1"

Oppermann et al. (2012)

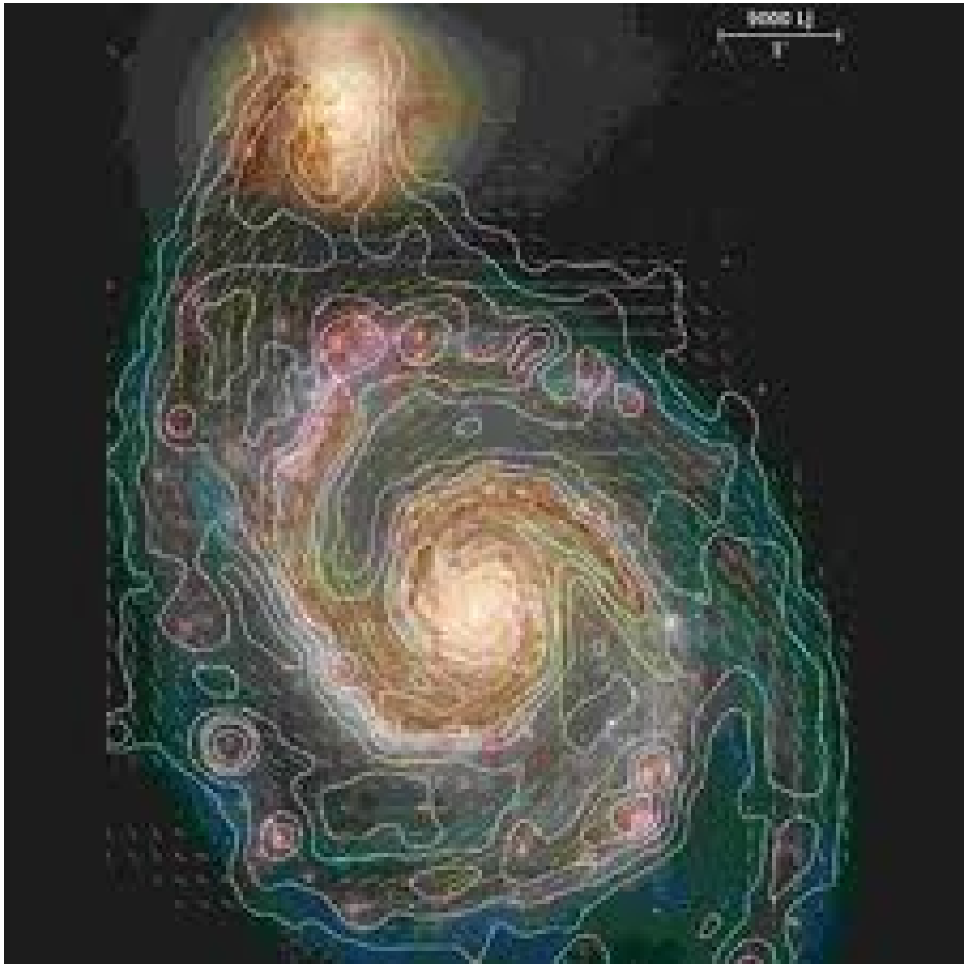


Reconstruction of the Galactic Faraday depth, mostly based on the Taylor et al. (2009) data.



Cosmic Magnetism Science Drivers

Fletcher et al. (2011)



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.

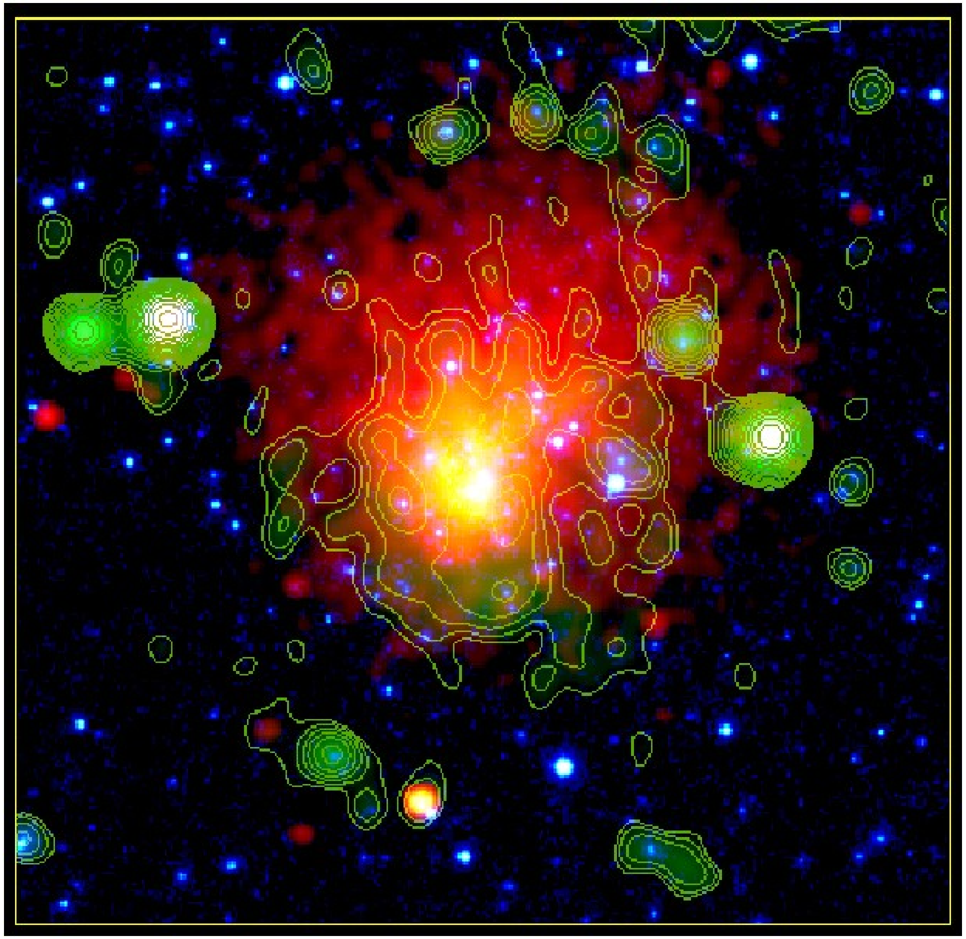
- Global galaxy energetics?
- How cosmic magnetism in galaxies evolve with time?
- Interaction with intergalactic environment?

Presentation by Rainer Beck "Magnetic fields in evolving spiral galaxies and their Observation with the SKA"

Presentation by Keitaro Takahashi "Faraday dispersion function of galaxies predicted from galaxy simulations"

Cosmic Magnetism Science Drivers

Vacca et al. (2011)



Detailed description of the strength, structure, and radial decrease of cluster magnetic fields.

Investigation of the polarized emission of diffuse synchrotron sources in galaxy clusters.

Investigation of the Rotation Measure toward a large number of sources located the background or embedded within the intra-cluster medium.

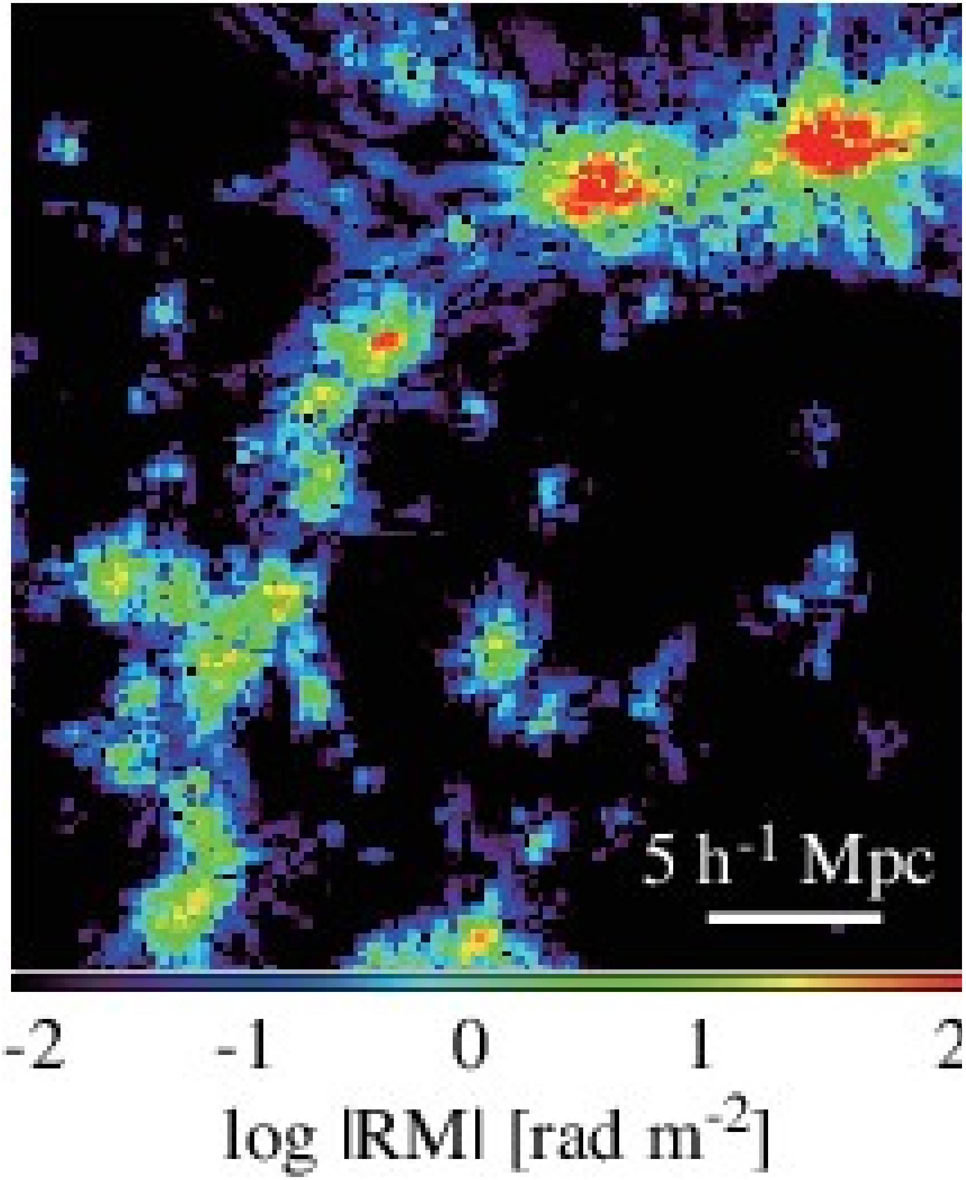
Presentation by Melanie Johnston-Hollitt "Using extended sources to probing cluster magnetic fields"

Presentation by Annalisa Bonafede "Magnetic field in galaxy clusters and intergalactic filaments: results from the VLA, LOFAR and SKA perspectives"

Presentation by Federica Govoni "Polarization of cluster radio halos with upcoming radio interferometers"

Cosmic Magnetism Science Drivers

Akahori & Ryu (2010)

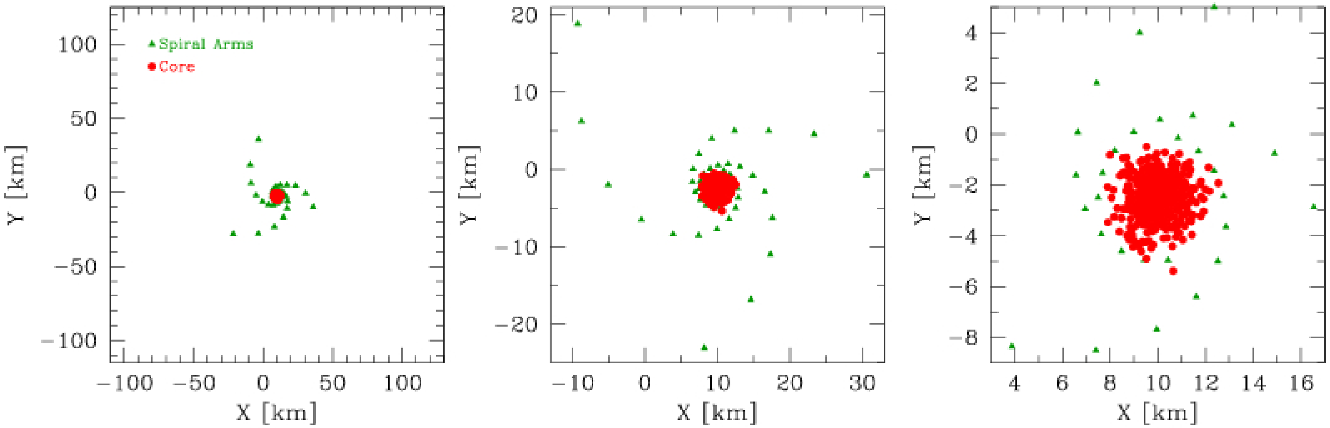


Magnetic Fields in the Cosmic Web

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

Presentation by Takuya Akahori "Probing RMs due to magnetic fields in the cosmic web"

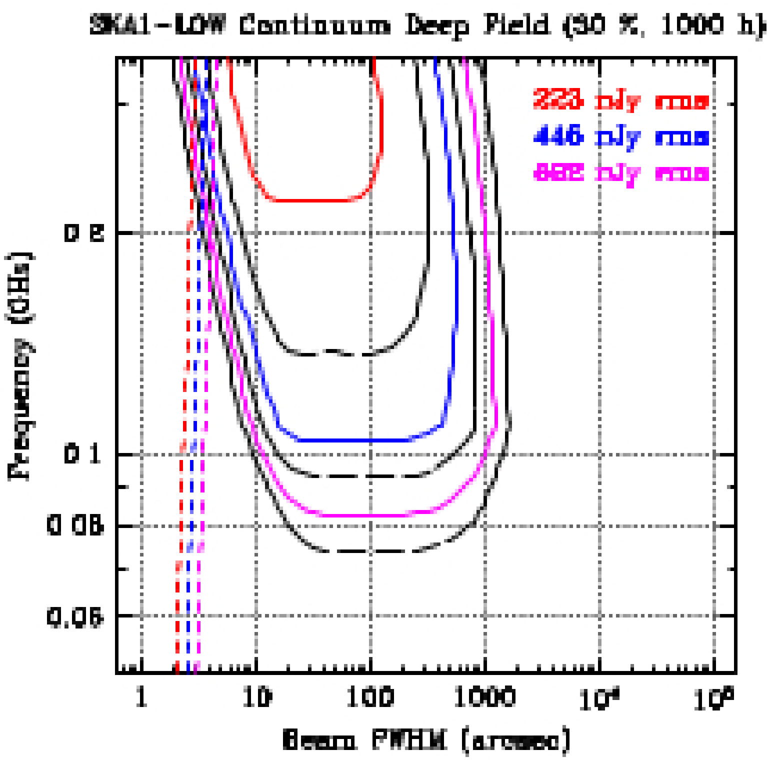
SKA1 Baseline Design



SKA1-low Australia

911 Stations of 35 m diameter
(866 core+ 45 arms)
289 antennas per station
(~250000 antennas)

Braun (in preparation)

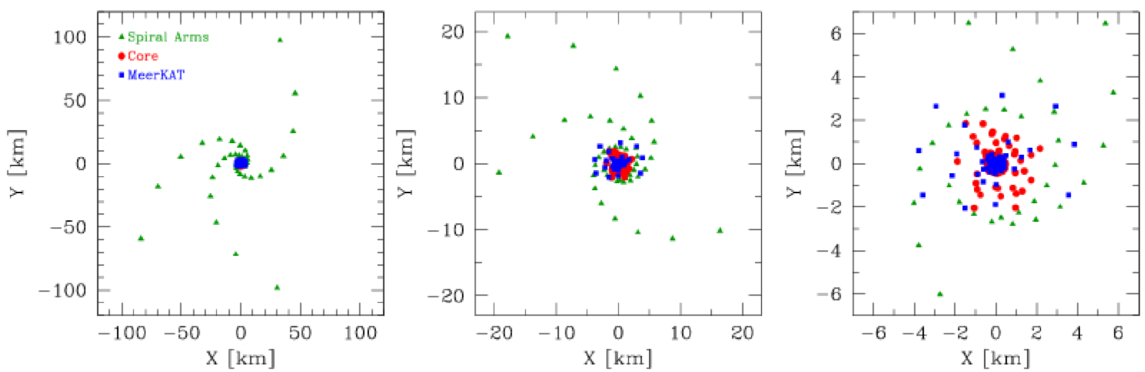


Frequency Range [MHz]	Field of view [deg²]
50 – 350	27

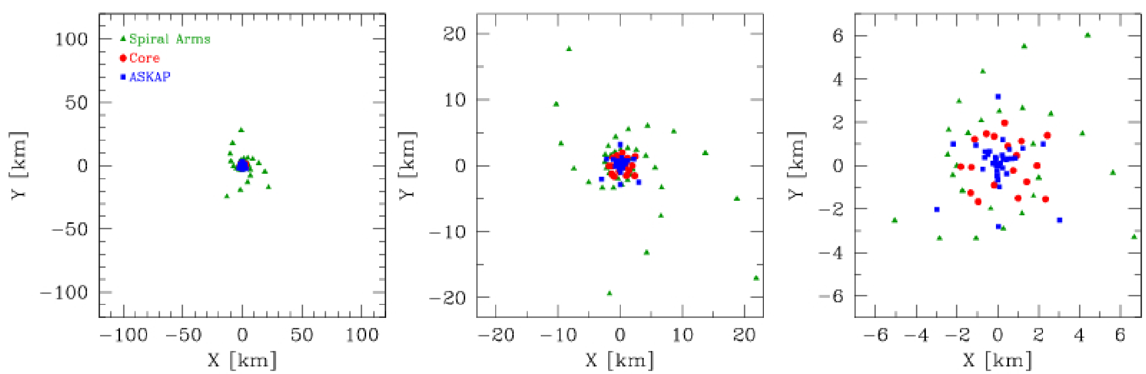
SKA1 Baseline Design

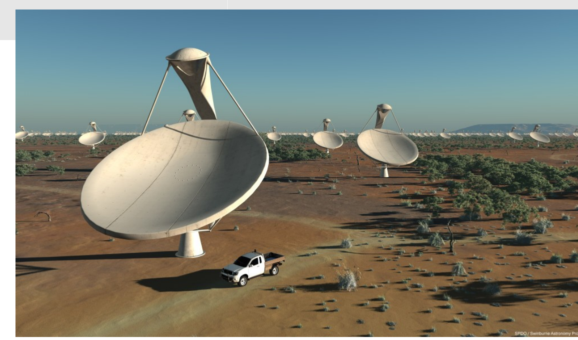
SKA1-mid South Africa

254 Dishes (64 MeerKAT + 190 SKA)
Resolution sub-arcsecond
Field of View ~0.5 deg²



	Frequency Range [MHz]	Frequency Range Initially Available [MHz]
Band1	350 – 1050	580 – 1015
Band2	950 – 1760	950 – 1670
Band3	1650 – 3050	
Band4	2800 – 5180	
Band5	4600 – 13800	
PAF Band1	350 – 900	
PAF Band2	650 – 1670	650 – 1670
PAF Band3	1500 – 4000	



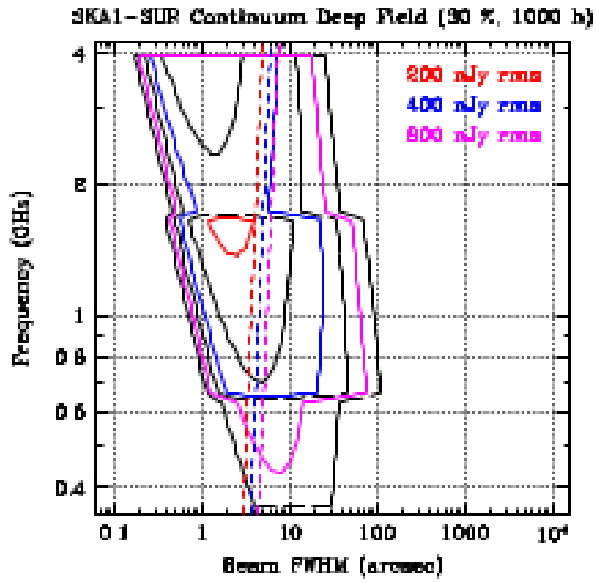


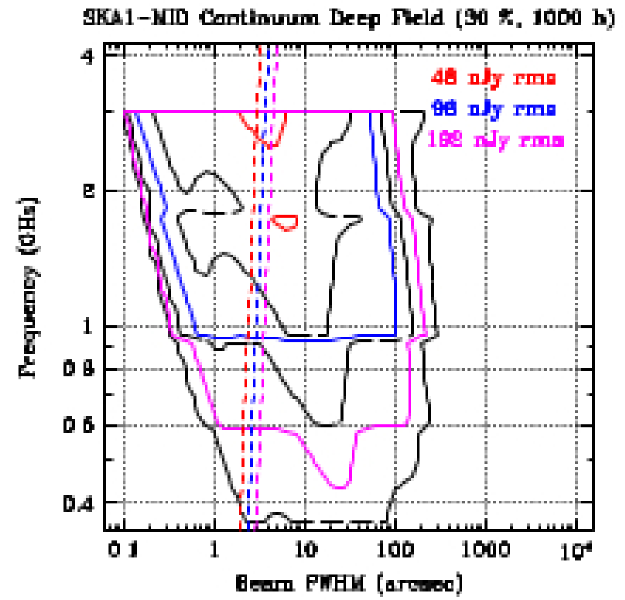
SKA1-survey Australia

96 Dishes (36 ASKAP + 60 SKA)
Resolution arcsecond
Field of View ~18 deg²

SKA1 Baseline Design

Braun (in preparation)





SKA1-mid / SKA1-survey
- Similar resolution
- Similar frequency coverage

SKA1-mid / SKA1-survey
- SKA1-survey larger field of view
- SKA1-mid better sensitivity

→ **SKA1-mid is only a factor of 2 down in survey speed**

Table 1

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	1.27×10^5	2.75×10^6	2.70×10^7	1.30×10^6
Resolution	arcsec	$10\text{-}150\times10^{-3}$	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

SKA1-survey
2.75e6 $deg^2\ m^4/K^2$

SKA1-mid
1.30e6 $deg^2\ m^4/K^2$

SKA1 Baseline Design

Cosmic magnetism needs a frequency range as large as possible.

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

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

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

Resolution in Faraday depth space

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

Maximum observable Faraday depth width

SKA1 Baseline Design

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

Table 5

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

Information on polarization performances of SKA1-low is missing in the Baseline Design.

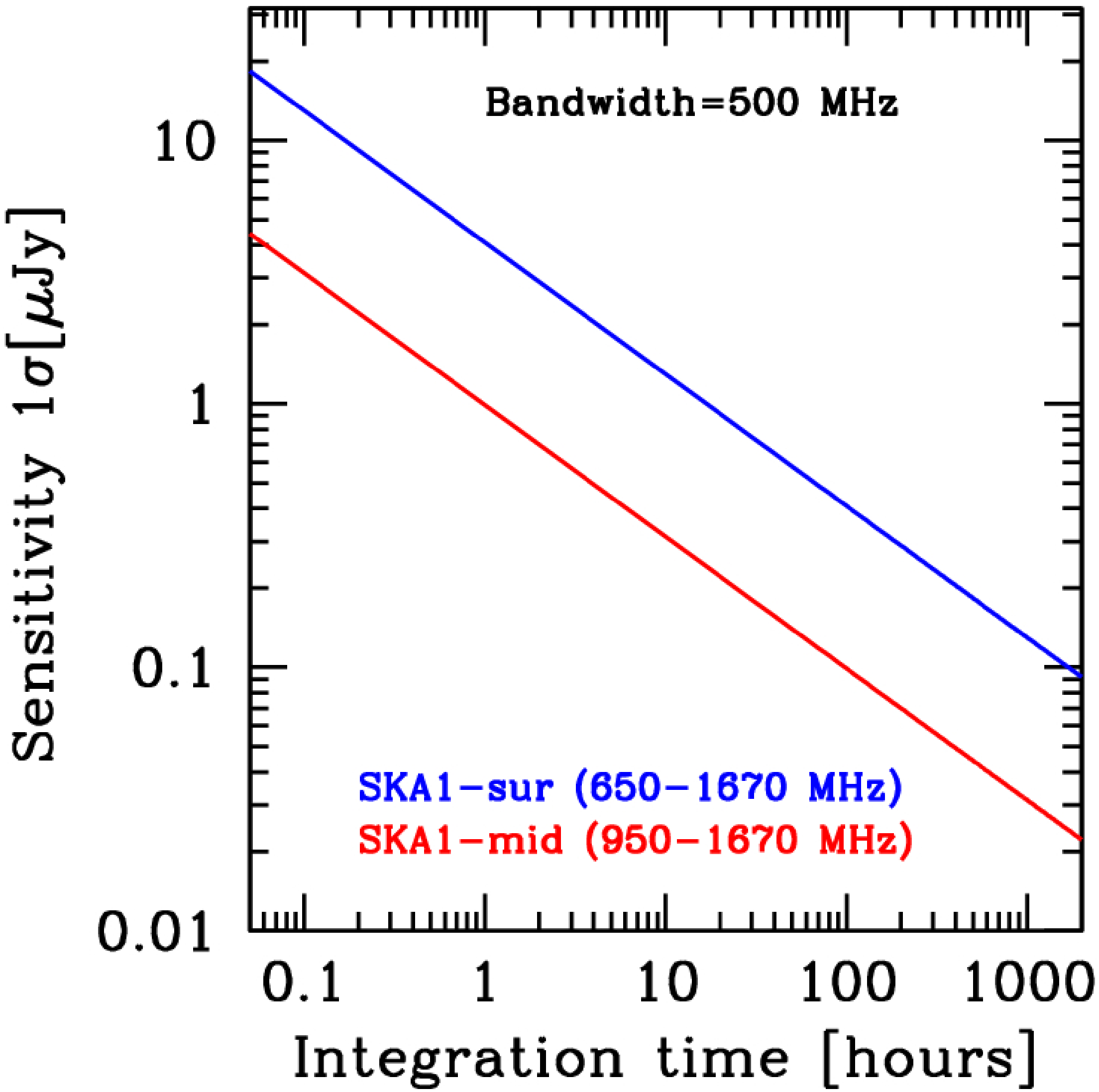
Proper specification on polarization are required:
- **Temporal stability of instrumental polarization**
- **Model how polarization purity deteriorates toward the periphery of the beam and the levels reached at the edge of the field of view**

Presentation by Tobia Carozzi "Assessing SKA Polarimetry Requirements"

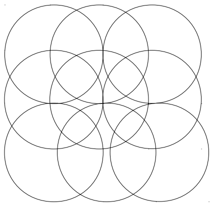
Key SKA1 Observations for Cosmic Magnetism

All Sky Survey in Polarization

Instrument	Frequency	Field of View	Resolution	Sensitivity
SKA1-mid SKA1-survey	~1 GHz	30.000 deg²	2''	1μJy/beam



SKA1-survey
FOV~18 deg²
1μJy/beam → 16hours
30000 deg²
~6.1 years on sky integration



SKA1-mid
FOV~0.5 deg²
1μJy/beam → 1hours
30000 deg²
~13.7 years on sky integration

Key SKA1 Observations for Cosmic Magnetism

All Sky Survey in Polarization

Instrument	Frequency	Field of View	Resolution	Sensitivity
SKA1-mid SKA1-survey	~1 GHz	30.000 deg²	2''	~~1μJy/beam~~ **2μJy/beam**

R. Braun (in preparation)

SKA1 Top Level Science Requirements

SKA1 will provide researchers with a general-purpose astrophysics facility to permit state-of-the-art observations of astronomical sources over a wide range of angular resolutions between radio frequencies of 50 MHz and at least 3 GHz (within the context of an upgrade path to at least 20 GHz). The facility will be optimised for both large area surveys as well as deep pointed observations and will provide point-source sensitivity at least five times greater than currently existing facilities in this frequency range and a survey speed at least 25 times as great.

- SKA1 shall achieve a Stokes-Q and -U sensitivity of 2 μJy RMS at 1 – 2 GHz ($\Delta\nu/\nu$=0.3) with 2.0 arcsec resolution over 30,000 deg^2 within two years on-sky integration;

This will enable an all-sky grid of Faraday rotation measures with a density of several hundreds of sources per square degree, allowing us to measure the magnetic fields in a huge number of intervening galaxies out to high redshifts, to search for a pervasive intergalactic magnetic field, and to investigate the detailed structure of the magnetic field in the Milky Way.

- SKA1 shall achieve thermal noise-limited imaging performance with a Stokes-Q and -U sensitivity of 75 nJy RMS at 0.9 – 1.8 GHz ($\Delta\nu/\nu$=0.3) at 0.5 arcsec resolution over 1 deg^2 within 1000 hours of integration;

This will enable us to measure the magnetic field structure and its relation to gas flows in a large number of galaxies, AGNs, galaxy clusters, and intergalactic filaments with unprecedented precision.

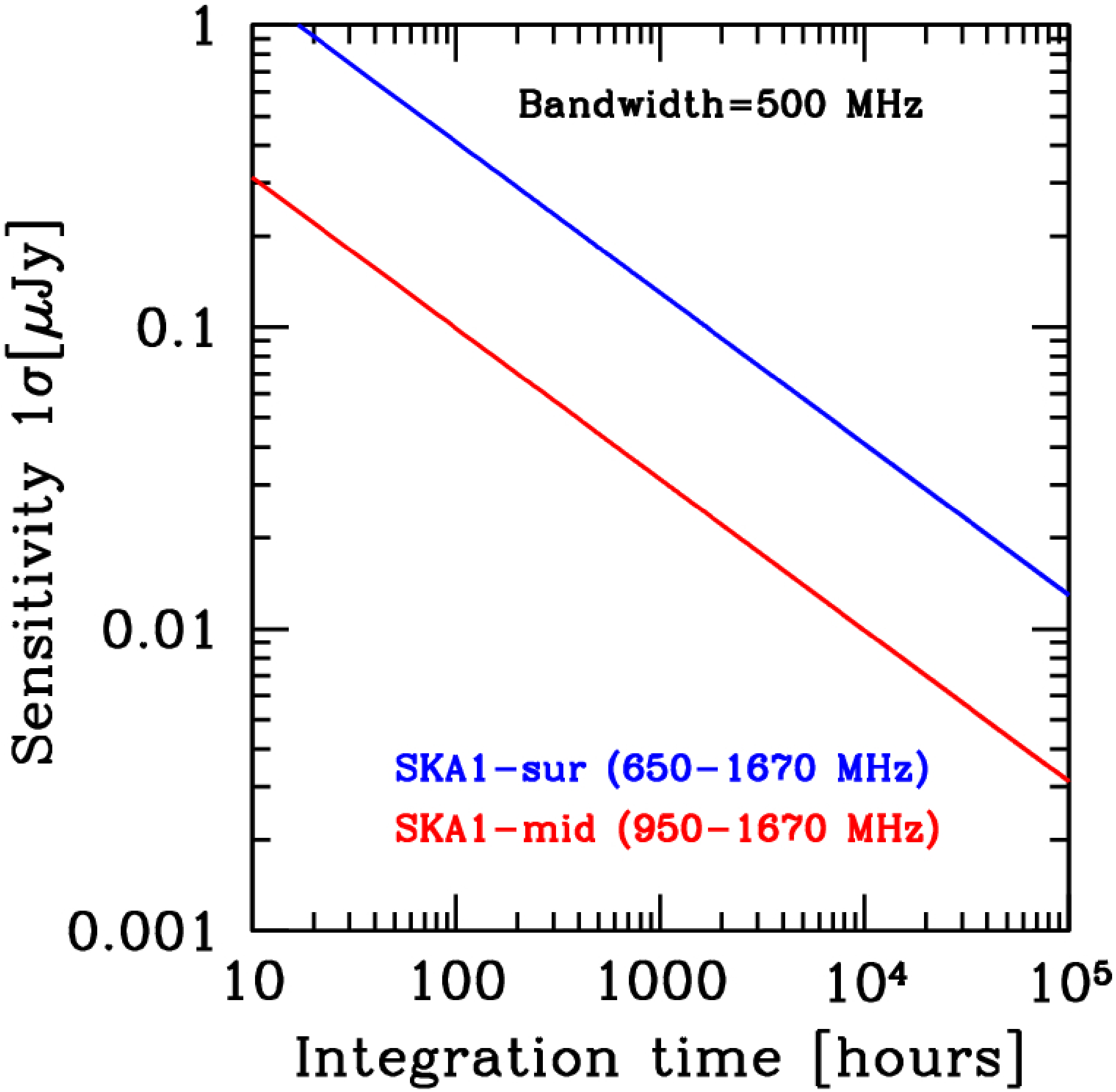
SKA1-survey
2μJy/beam → 4hours per pointing (500 MHz bandwidth)

30000 deg²
~1.5 years on sky integration

Key SKA1 Observations for Cosmic Magnetism

Polarization deep field

Instrument	Frequency	Field of View	Resolution	Sensitivity
SKA1-mid SKA1-survey	~1 GHz	30 deg²	1"	0.01μJy/beam



SKA1-survey
0.01μJy/beam → >10^5 hours per pointing

SKA1-mid
0.01μJy/beam → 10^4 hours per pointing

Key SKA1 Observations for Cosmic Magnetism

Polarization deep field

Instrument	Frequency	Field of View	Resolution	Sensitivity
SKA1-mid SKA1-survey	~1 GHz	30 deg^2 **????**	~~1''~~ **0.5''**	~~0.01µJy/beam~~ **0.075µJy/beam**

SKA1-mid
0.075µJy/beam → 170hours per pointing (500 MHz bandwidth)

R. Braun (in preparation)

SKA1 Top Level Science Requirements

SKA1 will provide researchers with a general-purpose astrophysics facility to permit state-of-the-art observations of astronomical sources over a wide range of angular resolutions between radio frequencies of 50 MHz and at least 3 GHz (within the context of an upgrade path to at least 20 GHz). The facility will be optimised for both large area surveys as well as deep pointed observations and will provide point-source sensitivity at least five times greater than currently existing facilities in this frequency range and a survey speed at least 25 times as great.

- SKA1 shall achieve a Stokes-Q and -U sensitivity of 2 µJy RMS at 1 – 2 GHz ($\Delta\nu/\nu$=0.3) with 2.0 arcsec resolution over 30,000 deg^2 within two years on-sky integration;

This will enable an all-sky grid of Faraday rotation measures with a density of several hundreds of sources per square degree, allowing us to measure the magnetic fields in a huge number of intervening galaxies out to high redshifts, to search for a pervasive intergalactic magnetic field, and to investigate the detailed structure of the magnetic field in the Milky Way.

- SKA1 shall achieve thermal noise-limited imaging performance with a Stokes-Q and -U sensitivity of 75 nJy RMS at 0.9 – 1.8 GHz ($\Delta\nu/\nu$=0.3) at 0.5 arcsec resolution over 1 deg^2 within 1000 hours of integration;

This will enable us to measure the magnetic field structure and its relation to gas flows in a large number of galaxies, AGNs, galaxy clusters, and intergalactic filaments with unprecedented precision.

1 deg^2?
we probably need
a larger field of view

Work in progress of the SKA Cosmic Magnetism SWG

Science Drivers

SKA1 Observations

Observational Techniques

1) Polarization Performances

2) Frequency Coverage and Broadband Capabilities

3) Angular Resolution

4) Sensitivity

5) Field of View

6) Survey Speed

7) Possibility to detect large angular scale structures

8) VLBI capabilities