Observing Cosmic Magnetism with the **Square Kilometre Array**

Rainer Beck

MPIfR Bonn & SKA Magnetism Working Group

www.skatelescope.org

www.scholarpedia.org/article/Square_kilometre_array

Radio telescopes: big beasts, but still…

SKA
SQUARE KILOMETRE ARRAY

LOFAR 44x 80-m

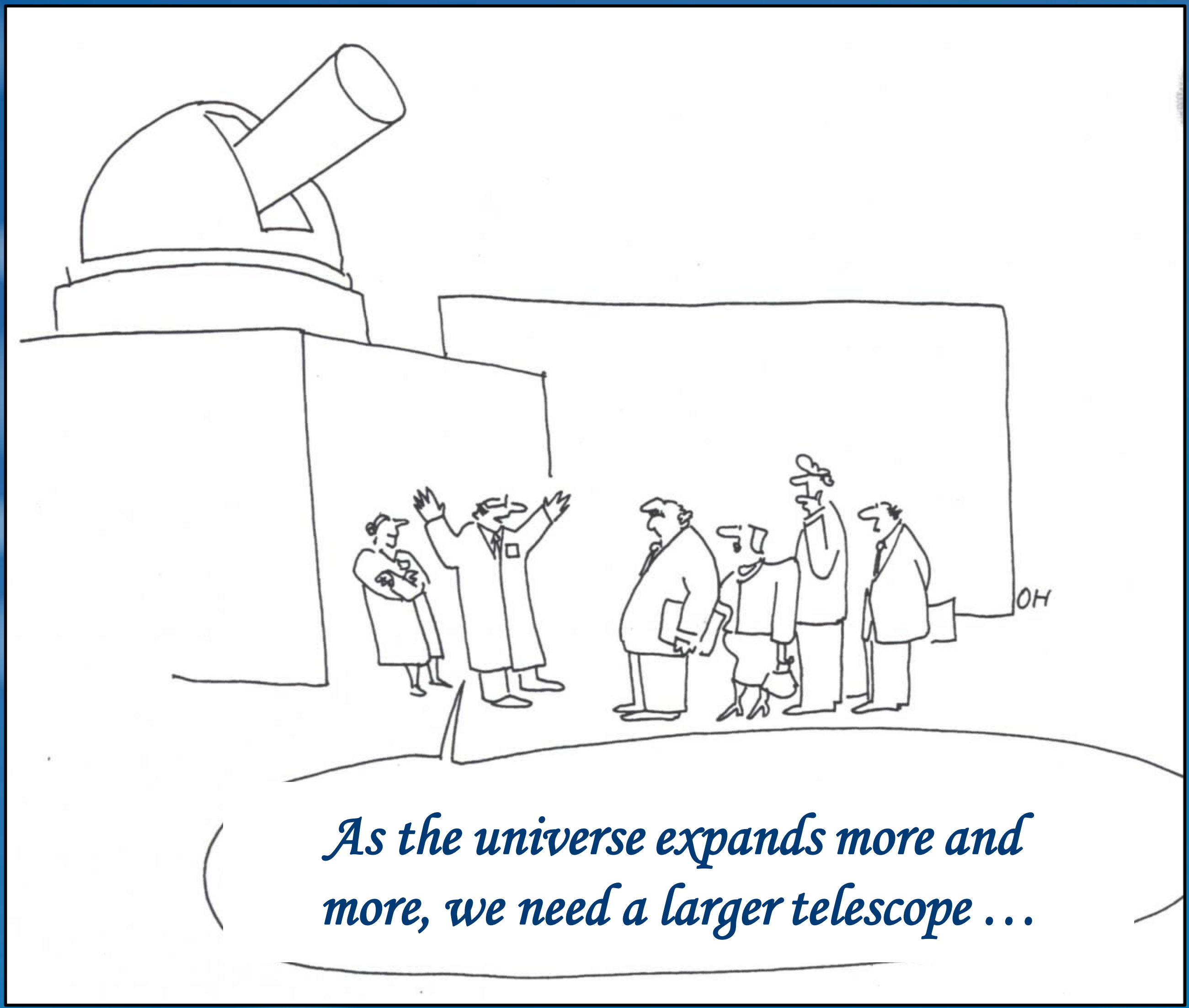
GBT 100-m

Arecibo 300-m

Effelsberg 100-m

VLA 27x25-m

Parkes 64-m


OH
As the universe expands more and more, we need a larger telescope …

The ultimate radio telescope for the 21th century

- A global observatory:
  to be built on two continents, worldwide funding, worldwide research infrastructure
- Challenging technology project
- Potential for "transformational" science, answering (some of) the fundamental questions

SKA specification goals:

High spatial resolution (<1")

+

High sensitivity (4000 – 8000 m^2 K^{-1})

+

Large frequency coverage (50 MHz – 14 GHz)

+

Large field of view (1 – 100 deg^2)

+

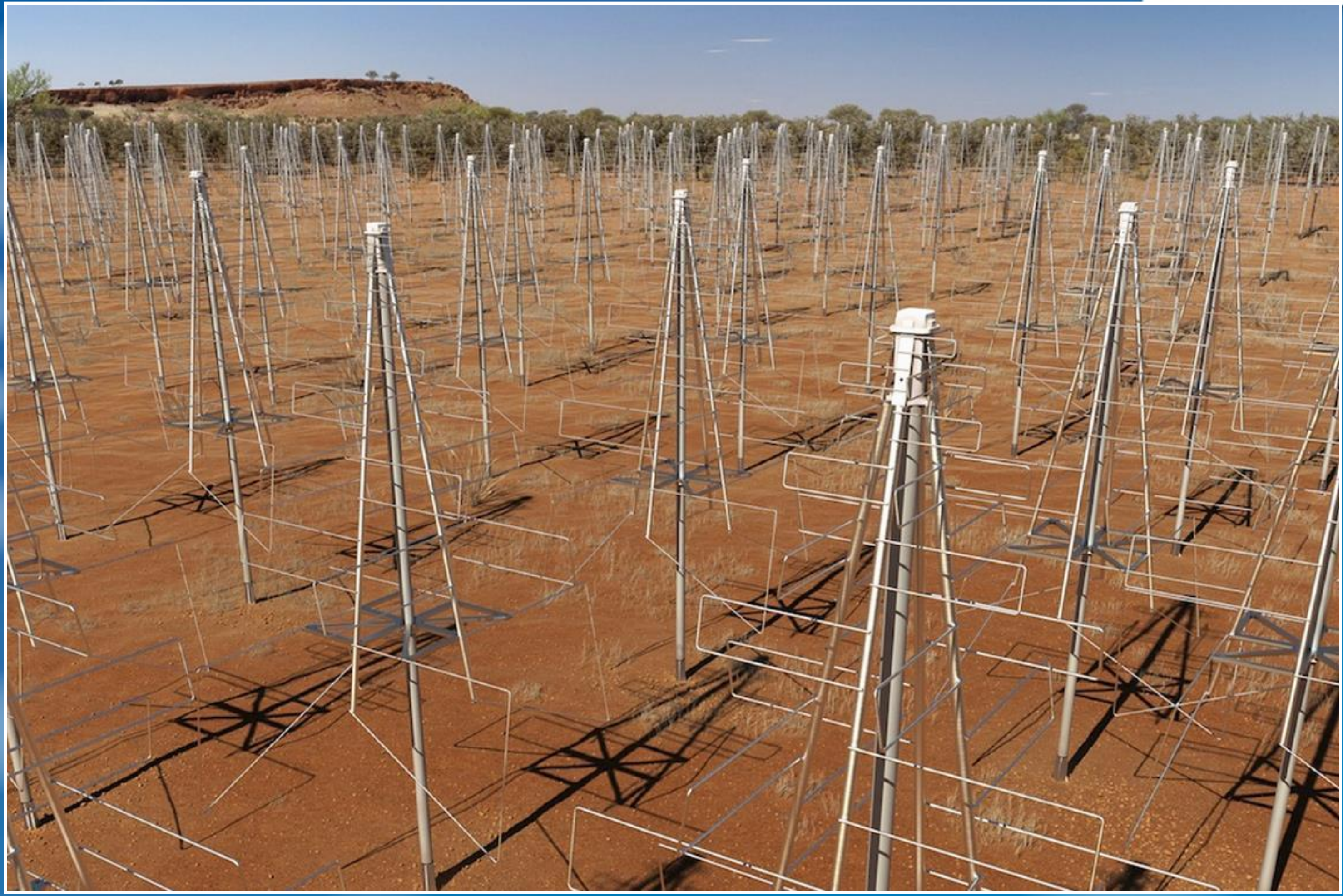
Excellent polarization performance (-30 dB)

SKA
SQUARE KILOMETRE ARRAY

SKA1-low: sparse aperture array
(50 - 350 MHz)

SKA Project Office
+ Swinburne Astr. Prod.

SKA1-low: sparse aperture array
(50 - 350 MHz)

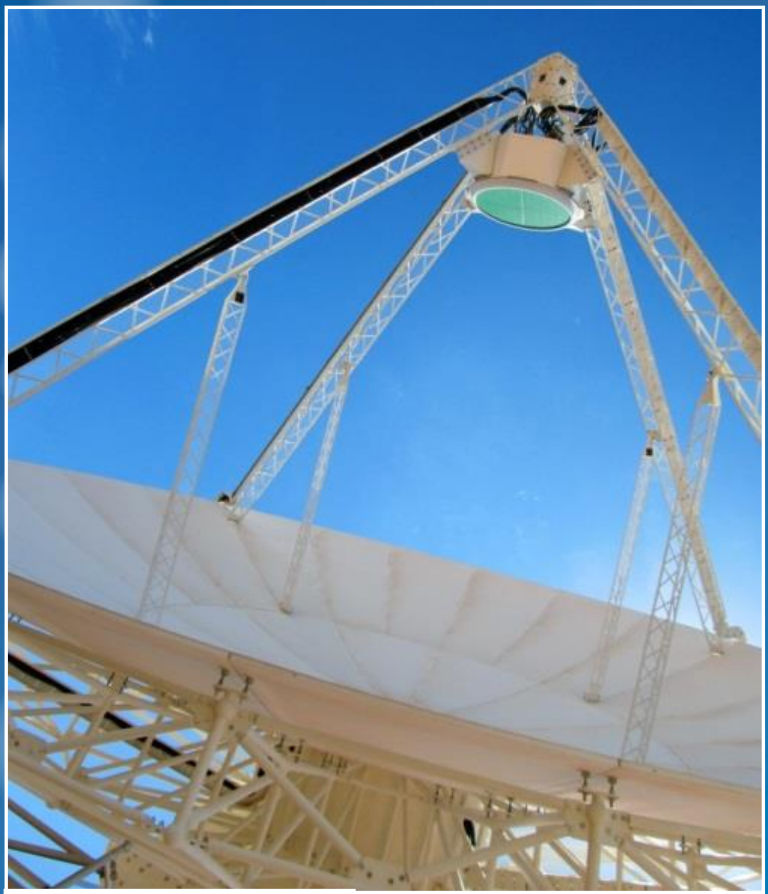


SKA Project Office
+ Swinburne Astr. Prod.

SKA1-mid: offset parabolic dishes
(350 MHz – 14 GHz)

SKA Project Office
+ Swinburne Astr. Prod.

SKA1-survey: dishes with wide-field focal plane arrays
(650 MHz–1.67 GHz)



ASKAP Australia

ASKAP checkerboard

Westerbork Apertif

SKA Precursors
(under construction)

Australia:

Australian SKA Pathfinder (ASKAP) (0.7-1.8 GHz)

South Africa:

Karoo Array Telescope (MeerKAT) (0.6-14.5 GHz)

Technical challenges

- Power consumption: ≈100 MW
- Data rates: PetaBytes/s
- Data volume: ExaBytes per year
- Processing requirements: ExaFlops
- Software for high-resolution, wide-field calibration

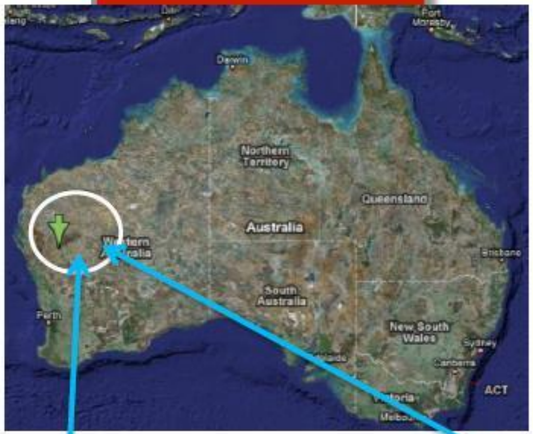
(David Mulcahy and Michiel Brentjens will tell you more …)

SKA Phase 1 (SKA1)
Cost €650M, construction start 2017

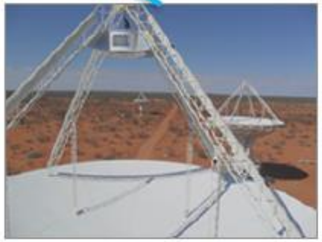
Southern Africa

SKA1_MID
254 Dishes including:
64 x MeerKAT dishes
190 x SKA dishes

Australia



SKA1_LOW
Low Frequency Aperture
Array Stations



SKA1_SURVEY
96 Dishes including:
36 x ASKAP
60 x SKA dishes

SKA Baseline Design Phase 1
(status of 2013)

1. SKA1-low:
   Array of 260 000 elements in 911 35-m stations (289 per station)
   Maximum radius: 45 km
   One frequency band: ≈50-350 MHz
   Receivers: dipoles, FoV 2-39 deg^2

2. SKA1-mid:
   Array of 64 13.5-m + 190 15-m parabolic dishes
   Maximum radius: 100 km
   Five (?) frequency bands: ≈0.35-14 (?) GHz
   Receivers: Wide-band single-pixel feeds, FoV ≤1.4 deg^2

3. SKA1-survey:
   Array of 36 12-m + 60 15-m parabolic dishes
   Maximum radius: 25 km
   Three (?) frequency bands: ≈0.35-4 (?) GHz
   Receivers: focal-plane phased arrays, FoV 3-63 deg^2, 36 beams

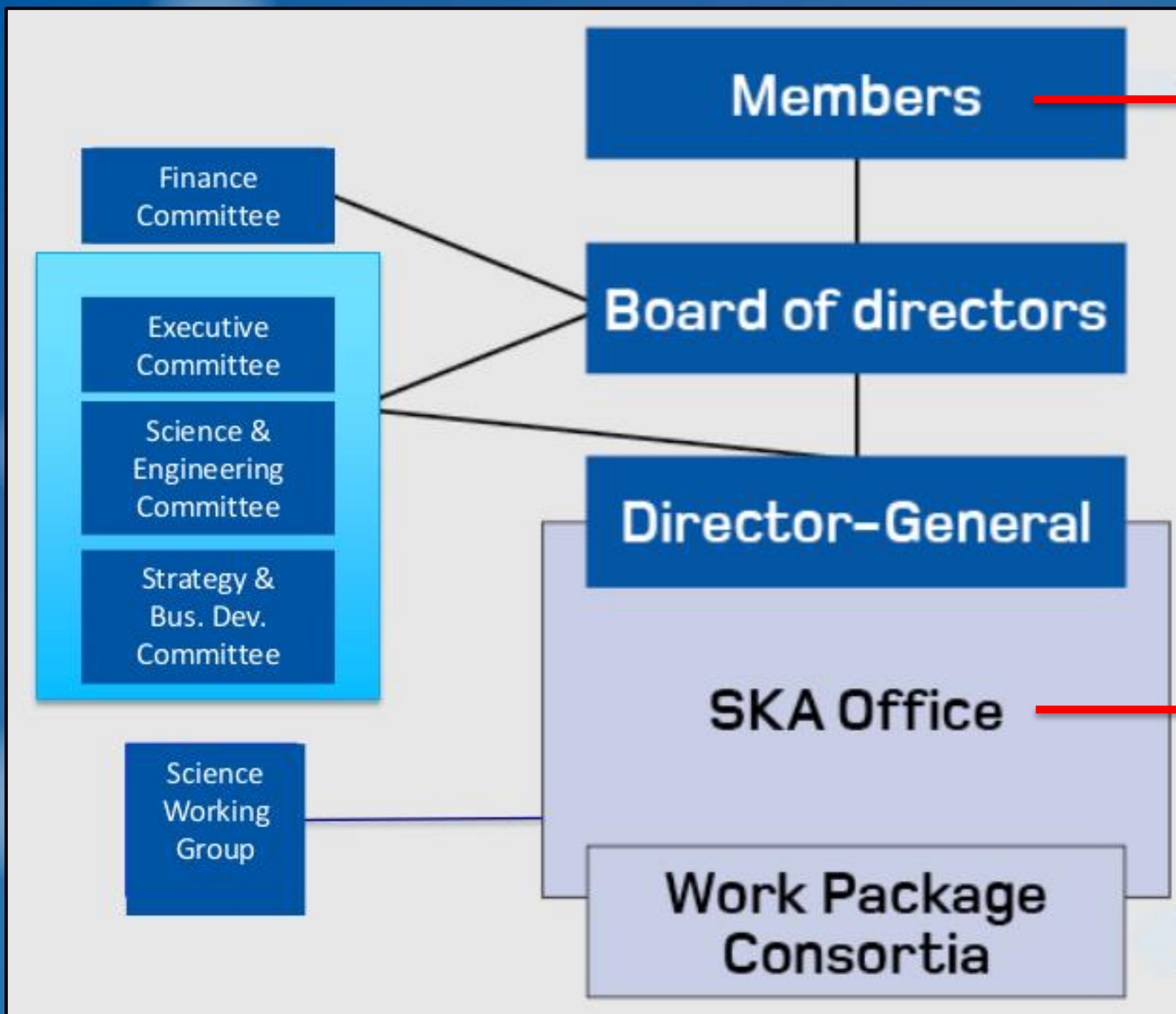
SKA Baseline Design Phase 2

1. SKA2-low:
   Larger collecting area (more dipoles),
   higher resolution (larger array radius)

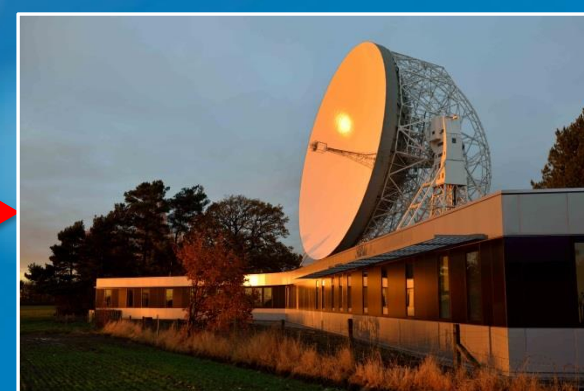
2. SKA2-mid:
   Larger collecting area ($\leq 1\ km^2$),
   larger frequency range (≤ 14 GHz),
   higher resolution (array radius of several 1000km)

3. SKA2-survey:
   More focal plane arrays to extend the frequency range,
   higher resolution (array radius ≈ 50km)

SKA organisation



Australia, China, Canada, India,Italy, Netherlands, New Zealand, South Africa, Sweden, UK, *Germany*



Jodrell Bank / UK

SKA timeline

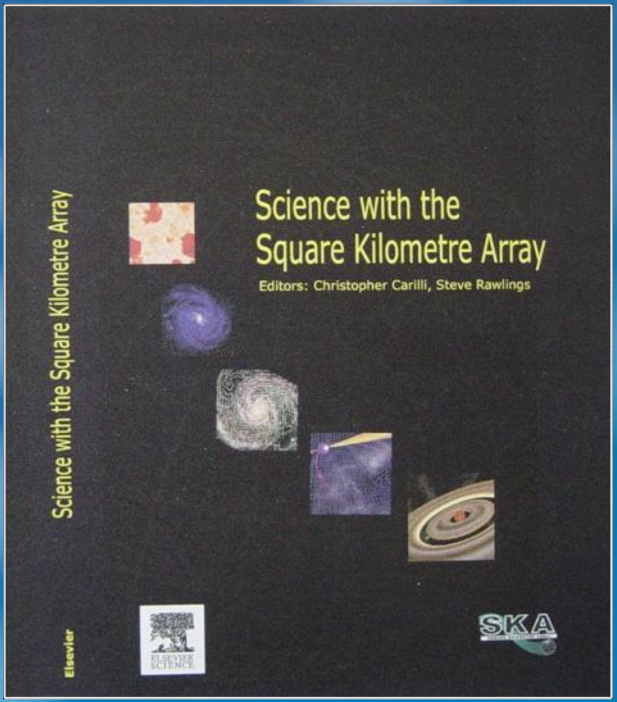
- 2013 – 2016: pre-construction, detailed design
  - March 2013: Request for Proposals
  - June 2013: Responses
  - July 2013: Evaluation
  - July – Nov 2013: Consortia begin work
  - June – Sept 2014: SRR/PDR
  - June 2016: CDR
- 2014 – 2015/16: partners seek SKA1 funding
- 2017: tender for and procure construction
- 2017 – 2021: construction of SKA1
- 2019/20: early science begins
- 2022 – 2025: construction of SKA2
- SKA operational for 50 years.

Political challenges

- Funding for Phase 1 not yet secured
- Design of 2013 does not meet "Cost Cap" of €650M
- German government announced to resign from SKA membership in 2015
- US does not (yet?) participate

SKA Science Book 2004

Magnetism selected as a Key Science Project in 2003



SKA Key Science Projects

Phase 1:

- History and role of neutral hydrogen - from dark ages (EoR) to the present day
- Testing theories of gravitation & discover gravitational waves with pulsar timing

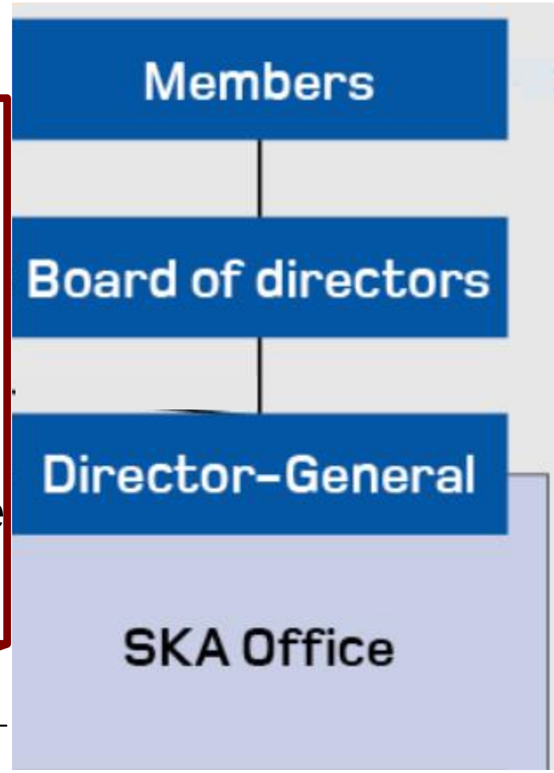
Phase 2:

- Measuring Dark Energy (HI line)
- Cosmic magnetism (polarization)
- The Cradle of Life (protoplanetary systems, biomolecules)

SKA Organisation

1) Epoch of Reionisation & the Dark Ages
2) Fundamental Physics with Pulsars
3) HI and Galaxy Evolution
4) Cosmology
5) Cosmic Magnetism
6) Astrobiology/Cradle of Life
7) Continuum Surveys
8) Radio Transients

Science Working Groups

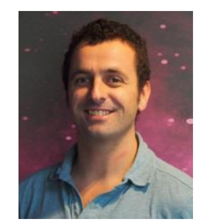


DIRECTOR
Phil Diamond

SCIENCE DIRECTOR
Robert Braun

PROJECT SCIENTISTS





James Green Tyler Bourke Jeff Wagg

Cosmic Magnetism Working Group :

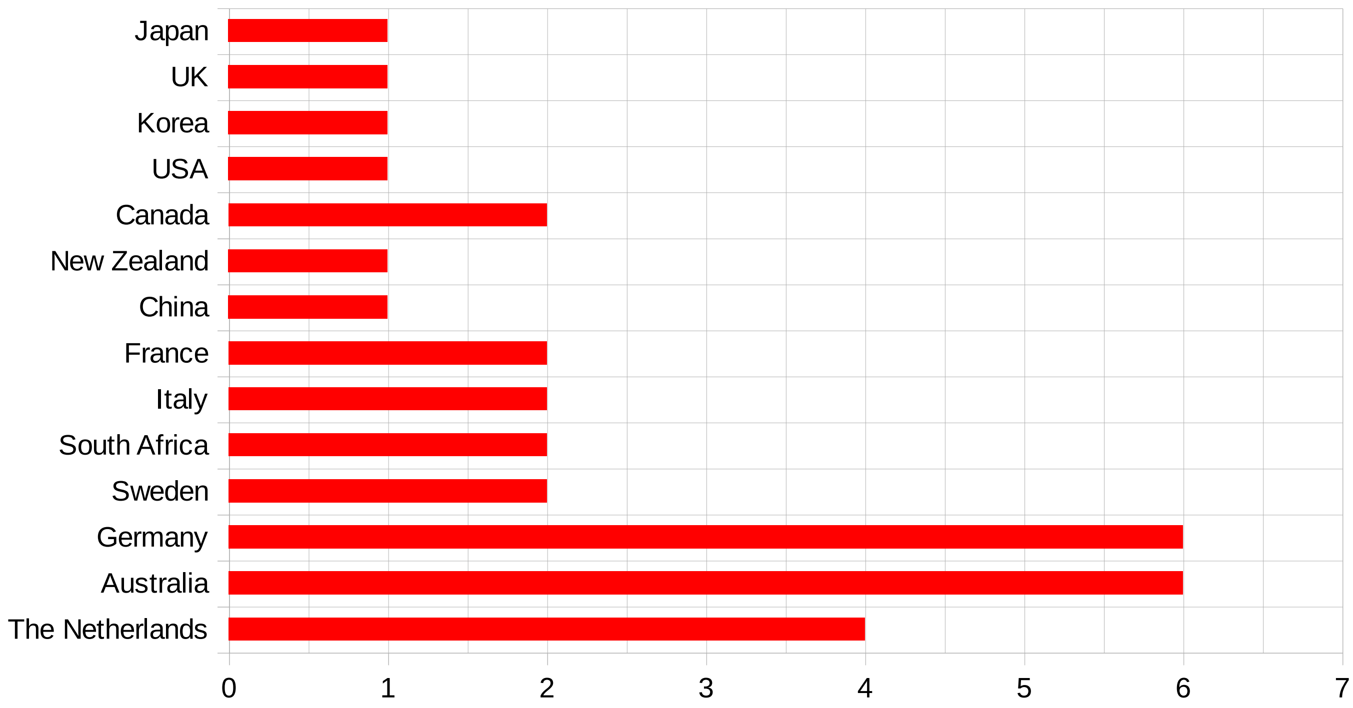
Co-chairs: Federica Govoni, Melanie Johnston-Hollitt

Core-Team members + associated members

http://astronomers.skatelescope.org/documents

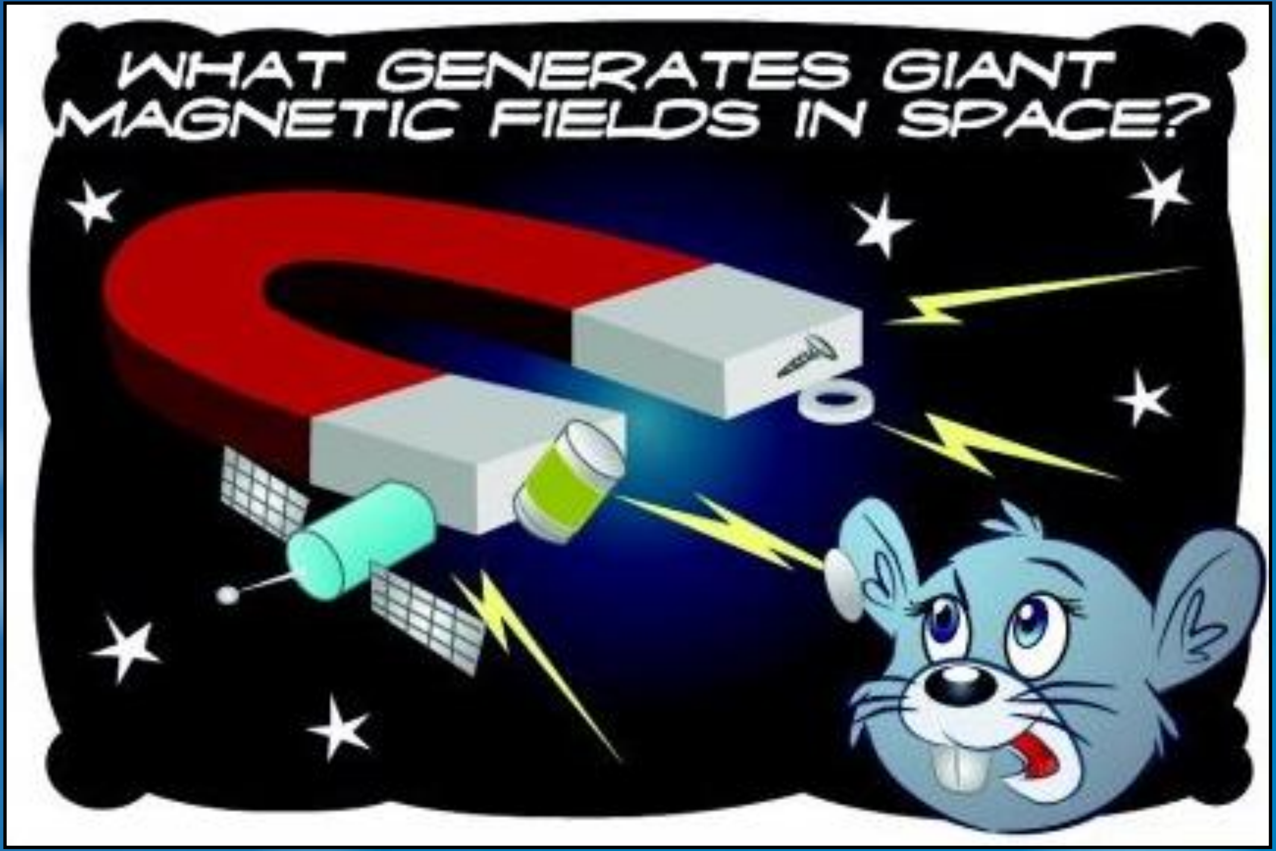
SKA Cosmic Magnetism Science Working Group

Geographical distribution:



33 members from 14 countries,
among them 16 Core Team members

Origin of cosmic magnetism



Fundamental magnetic questions

- When and how were the first fields generated ?
- Did significant fields exist before galaxies formed ?
- How and how fast were fields amplified in galaxies and galaxy clusters?
- How did fields affect the evolution of galaxies and galaxy clusters?
- Is intergalactic space magnetic ?

Generation and amplification of cosmic magnetic fields

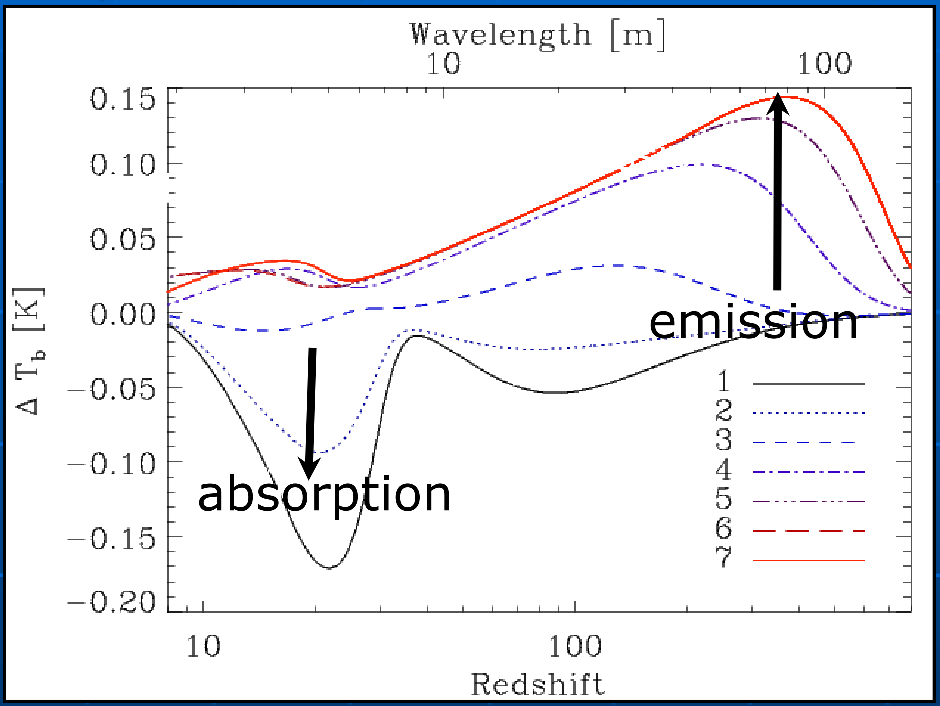
Stage 1: Field seeding

Stage 2: Field amplification

Stage 3: Field ordering

Primordial fields in the Epoch of Reionization

Brightness temperature

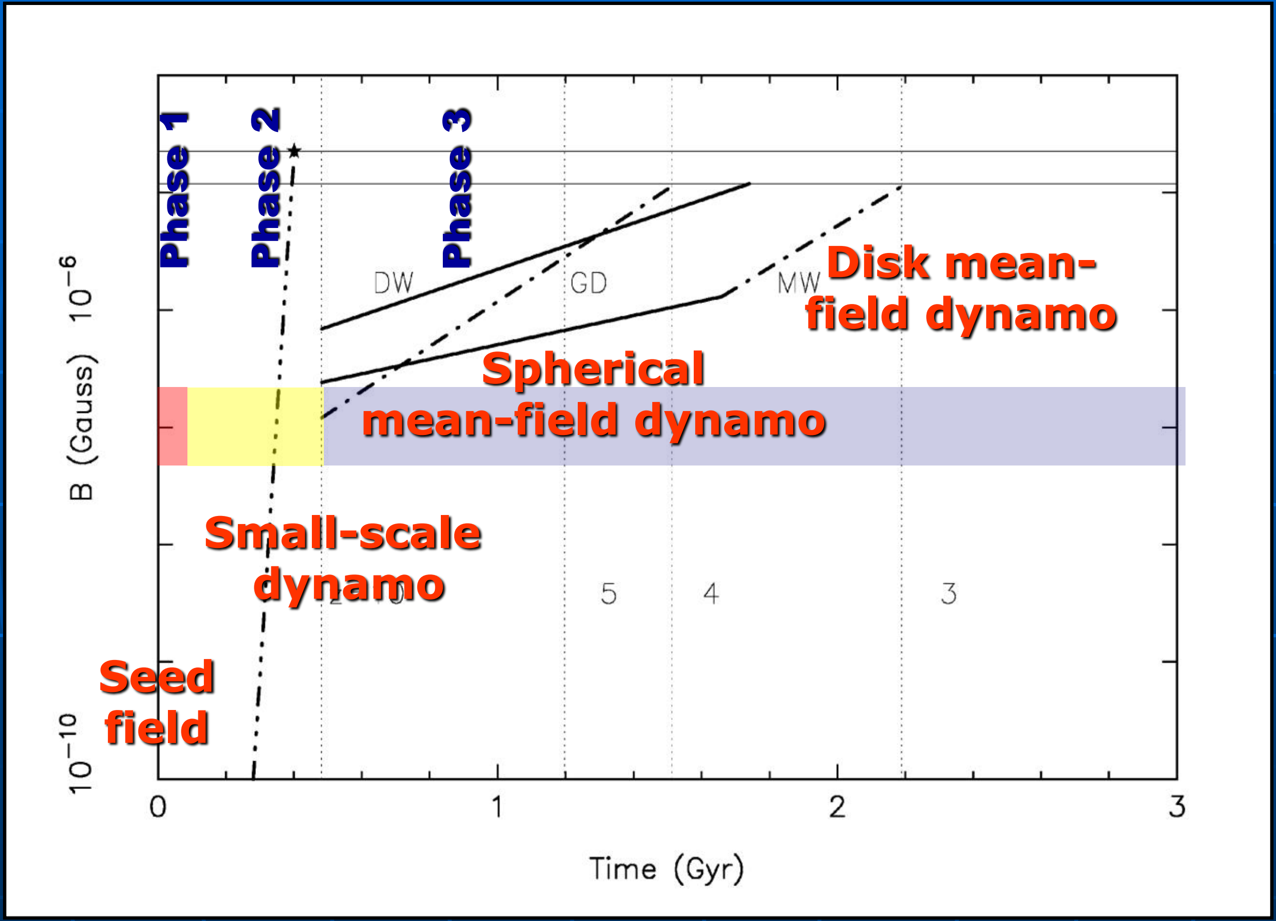


Schleicher et al. 2009

Model	B_0 [nG]	f_*
1	0	0.1%
2	0.02	0.1%
3	0.05	0.1%
4	0.2	0.1%
5	0.5	0.1%
6	0.8	0.1%
7	0.8	1%

Signatures of nano-Gauss fields visible in HI spectra at long wavelengths (SKA-low)

Magnetic field amplification by galactic dynamos
(remember the talks by M. Hanasz, E. Vishniac, L. Chamandy & A. Beck)



Arshakian et al. 2009

GD	– giant disk galaxy	(>15 kpc)
MW	– Milky Way type galaxy	(≈ 10 kpc)
DW	– dwarf galaxy	(≈ 3 kpc)

Predictions of dynamo models

Arshakian et al. 2009

SKADS

- **Young galaxies are magnetized !**
  → Total synchrotron emission from young galaxies at **z < 10**
- Strong but "spotty" regular fields at z < 3
  → Polarized radio emission and *some* Faraday rotation at **z < 3**
- Large-scale coherent regular magnetic fields at z < 0.5
  → Large-scale patterns of Faraday rotation at **z < 0.5**
- Large galaxies (>15 kpc) may not yet have generated fully coherent fields
- Major mergers can disrupt regular fields, but increase the turbulent field strength (Moss et al. 2014)

The radio-FIR correlation: Magnetic fields in distant galaxies

- Total radio synchrotron emission should break down beyond some redshift *z* due to Inverse Compton loss with the CMB background

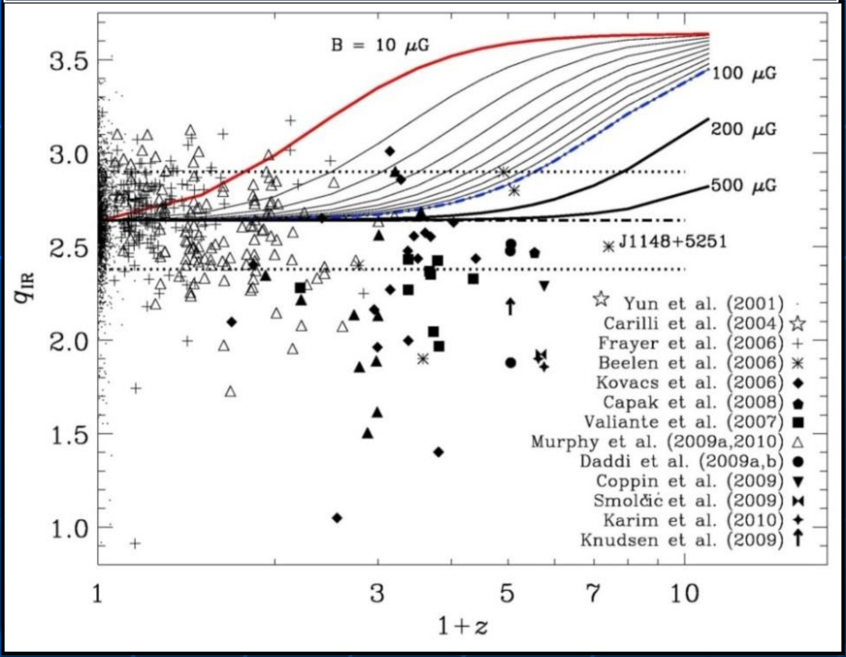
- FIR/radio ratio should increase with *z*

- This is ***not*** yet observed:
  Magnetic fields must still be
  strong in distant galaxies:

  $B > B_{CMB} = 3.25\ \mu G\ (1+z)^2$

- *But this cannot continue to very high redshifts*

q: ratio of FIR/radio luminosities



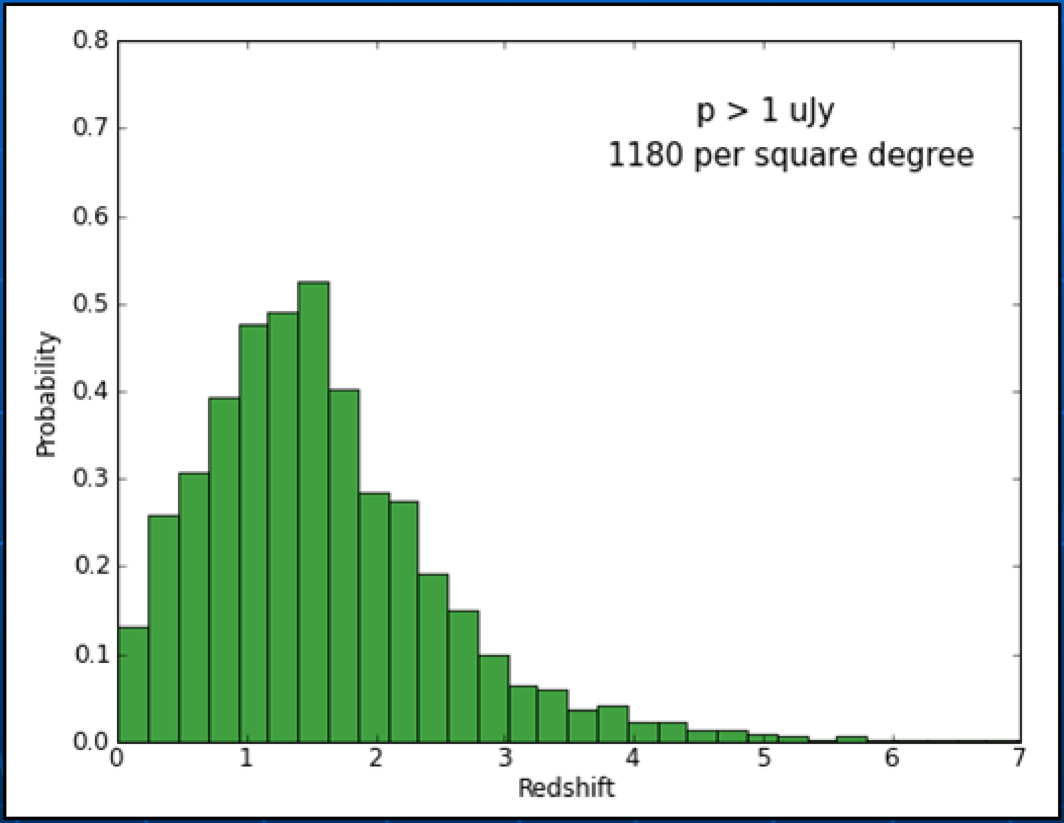
Murphy 2009

The critical redshift of the breakdown of the radio-FIR correlation will give us information on the evolution of magnetic fields in young galaxies

(Schleicher & Beck 2013)

Needed: high sensitivity (SKA-mid)

Detecting polarized emission from distant galaxies with SKA1-mid (deep survey)



Stil & Taylor, in prep.

Origin of small-scale fields

- There are two types of small-scale fields: turbulent and tangled
- Small-scale dynamo action can supply turbulent fields
- However: There is **no** conclusive evidence for turbulent field amplification on the solar surface (Stenflo 2012)
- Small-scale solar fields are probably generated from large-scale fields by tangling

How to distinguish the two types of small-scale fields by observations ?

Turbulent fields:

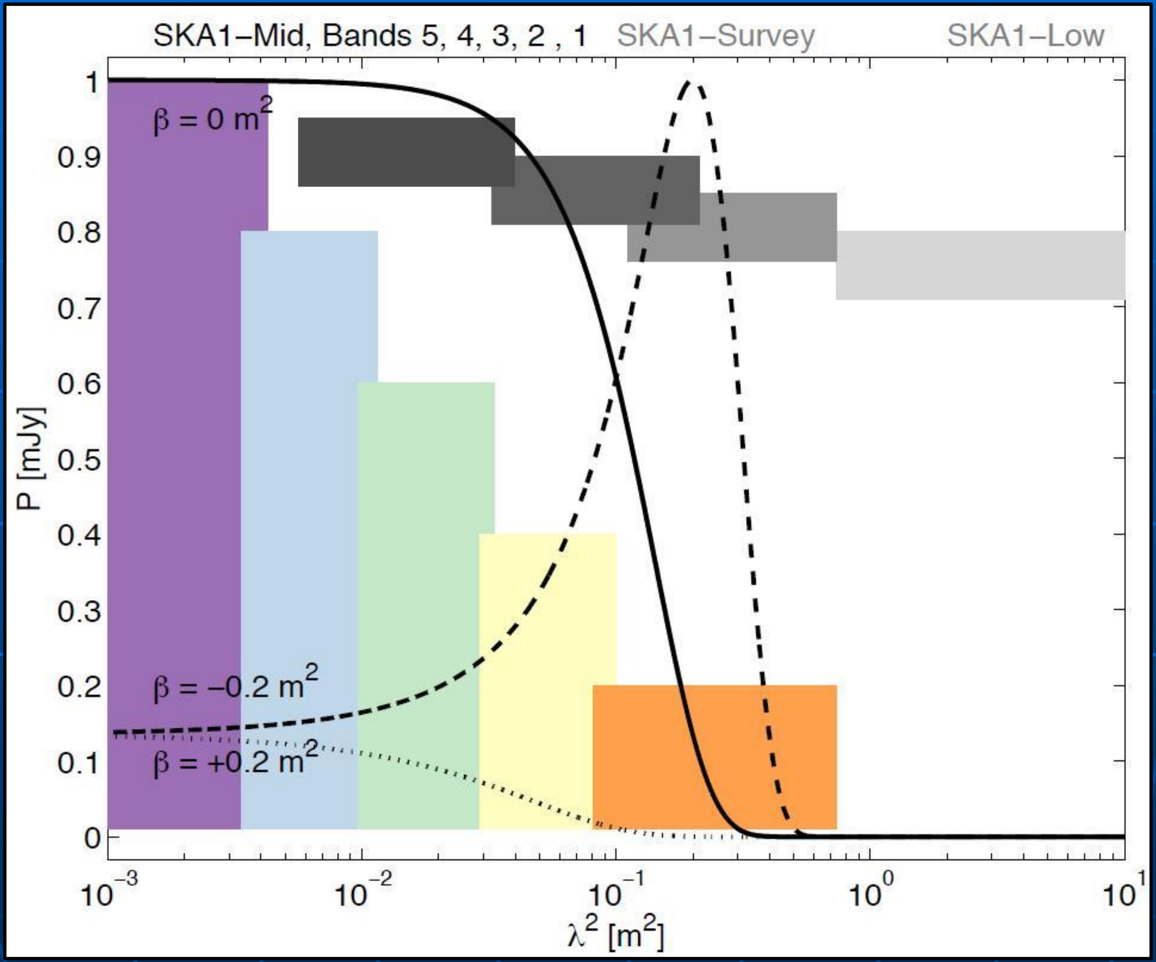
- Power-law turbulence spectrum (Kolmogorov)
- Related to star-forming activity
- Low volume filling factor
- Large fluctuations in synchrotron emission

Tangled fields:

- Shape of power spectrum not known
- Related to regular fields
- High volume filling factor
- Moderate fluctuations in synchrotron emission

Needed: high resolution & sensitivity (SKA-mid)

Helical fields
(remember the talks by A. Brandenburg, R. Stepanov & A. Fletcher)



Horellou & Fletcher 2014

β: Ratio of helical twist to Faraday twist

Needed: wide frequency coverage (SKA-mid)

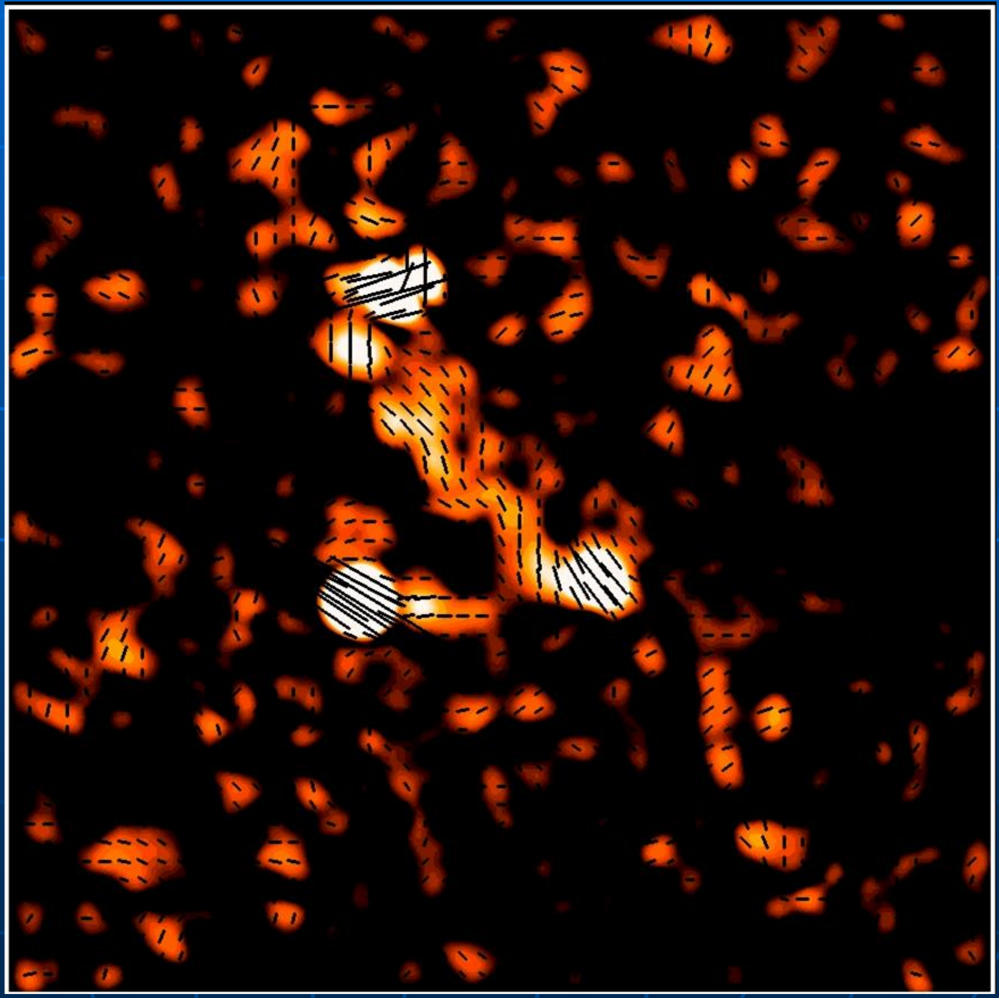
M 31: The nearest external spiral galaxy

Brighest segment of the northern spiral arm
Polarized intensity VLA 6 cm

Beck 2008

Resolution 25"
(≈100 pc):

- Parker loops ?
- Helical field ?

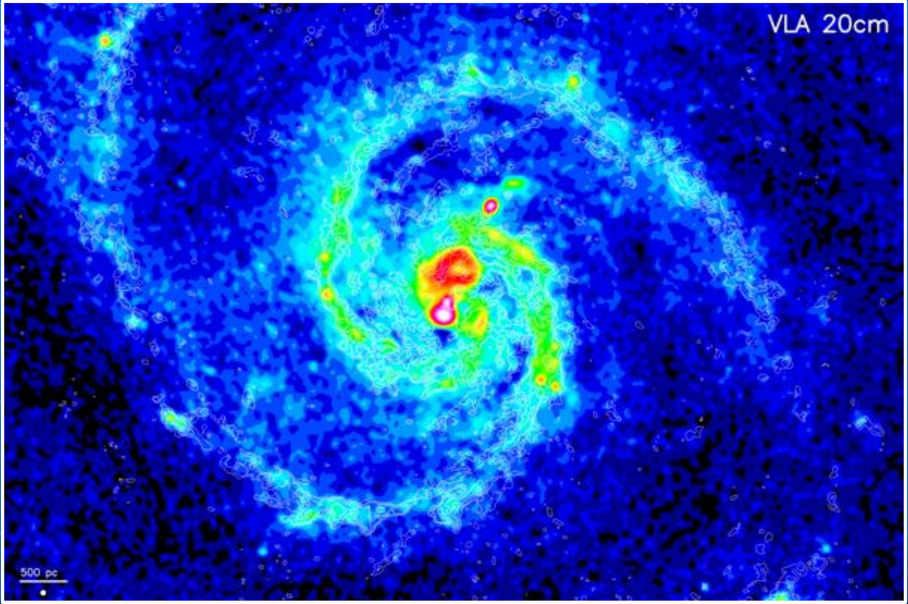


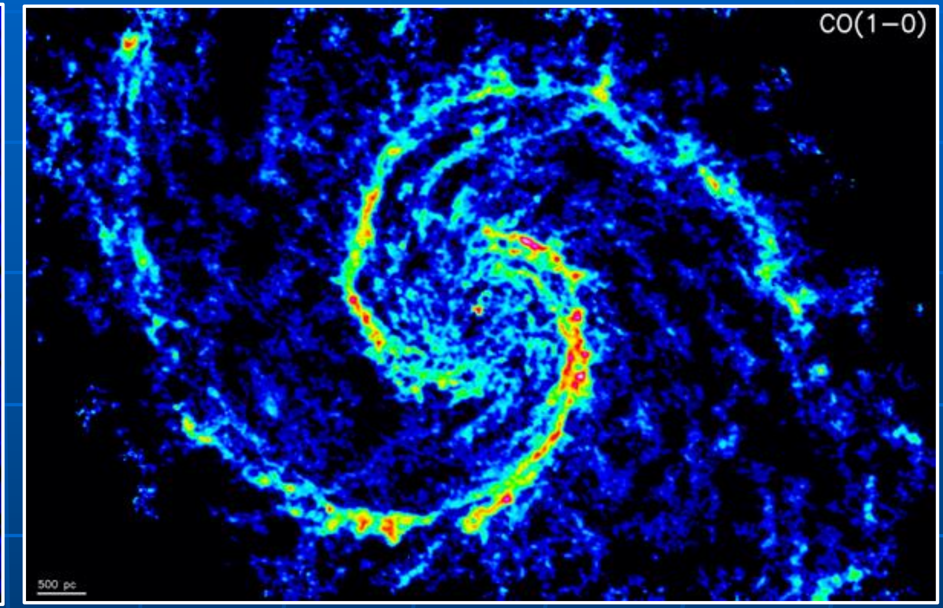
Are small-scale magnetic fields primarily related to star-forming regions or to gas clouds ?

M51: Radio continuum (VLA 20 cm, 1.4" resolution)

Molecular gas (CO(1-0)) (IRAM PdBI+30m, 1" resolution)

Schinnerer et al. 2013





Excellent radio-CO correlation on small scales (≈60 pc)

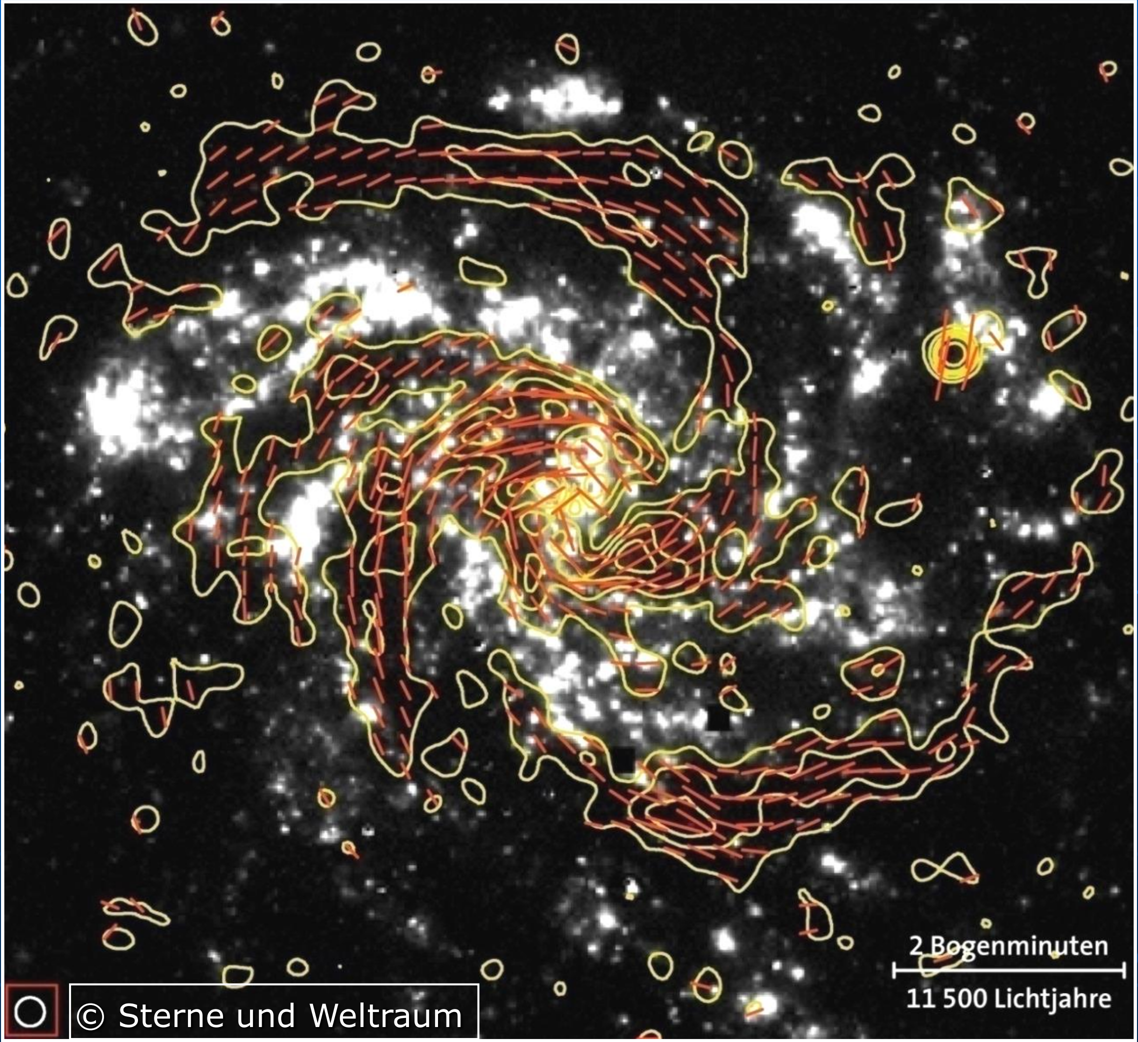
→ Coupling between magnetic fields and gas clouds ?

Or: secondary CREs from molecular clouds ?

Needed: high resolution (SKA-mid + ALMA)

Magnetic arms in NGC 6946:
Ordered fields concentrated in interarm regions

Beck 2007



Proposed origins of "magnetic arms"

Anisotropic random fields:

1) Magnetic reconnection (Zimmer, Lesch & Birk 1997)
2) Slow MHD wave (Lou & Fan 1998)
3) Spiral arm forcing (Kotarba et al. 2009, Kulpa-Dybel et al. 2011)

Regular fields:

4) Coupling between density wave and dynamo wave (Chamandy et al. 2012, 2013)
5) Injection of small-scale fields in spiral arms (Moss et al. 2013)
6) Suppression of dynamo action in arms by outflows (Chamandy et al. 2014)

Needed: Observation of diffuse polarization + Faraday rotation of a large sample of galaxies observed with high resolution (SKA-mid)

Saturation of large-scale dynamo action and galaxy properties

Van Eck et al., in prep.

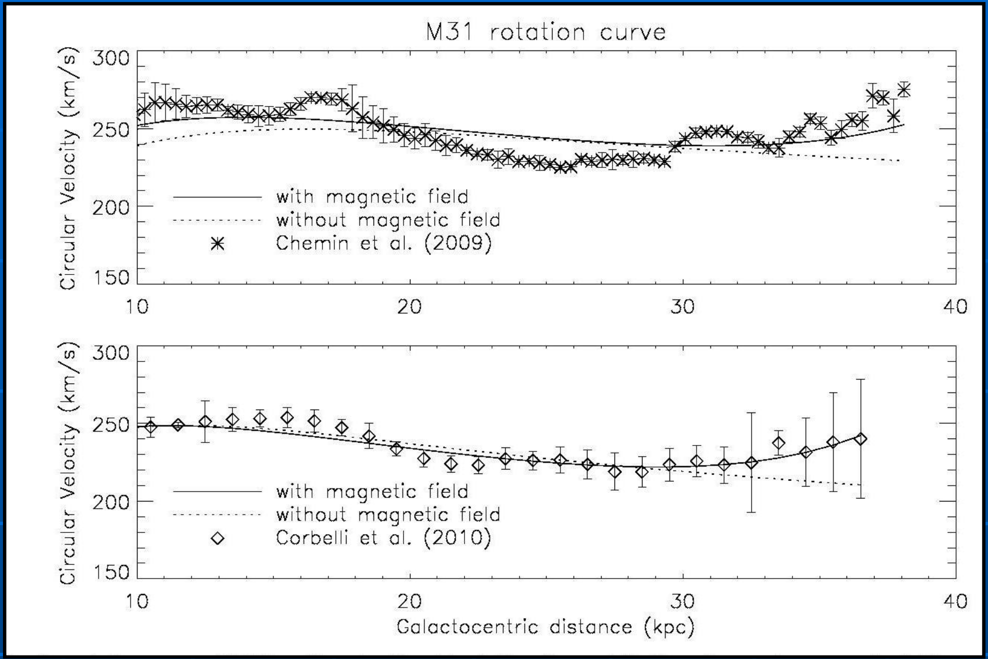
(1) Energy equipartition: $B_{reg} \sim \Sigma_{gas}^{0.5}$

(2) Coriolis force = Lorentz force: $B_{reg} \sim (\Sigma_{gas}\,\Omega)^{0.5}$

(3) Helicity balance in outflow: $B_{reg} \sim \Sigma_{*}^{0.5}$

- Observables in galaxies (gas density, SFR, rotation) should be related to the regular magnetic field strength
- Required: a sample of galaxies observed with similar physical resolution (<100 pc) (SKA-mid)

Can magnetic fields affect galactic rotation ?



Ruiz-Granados et al. 2010

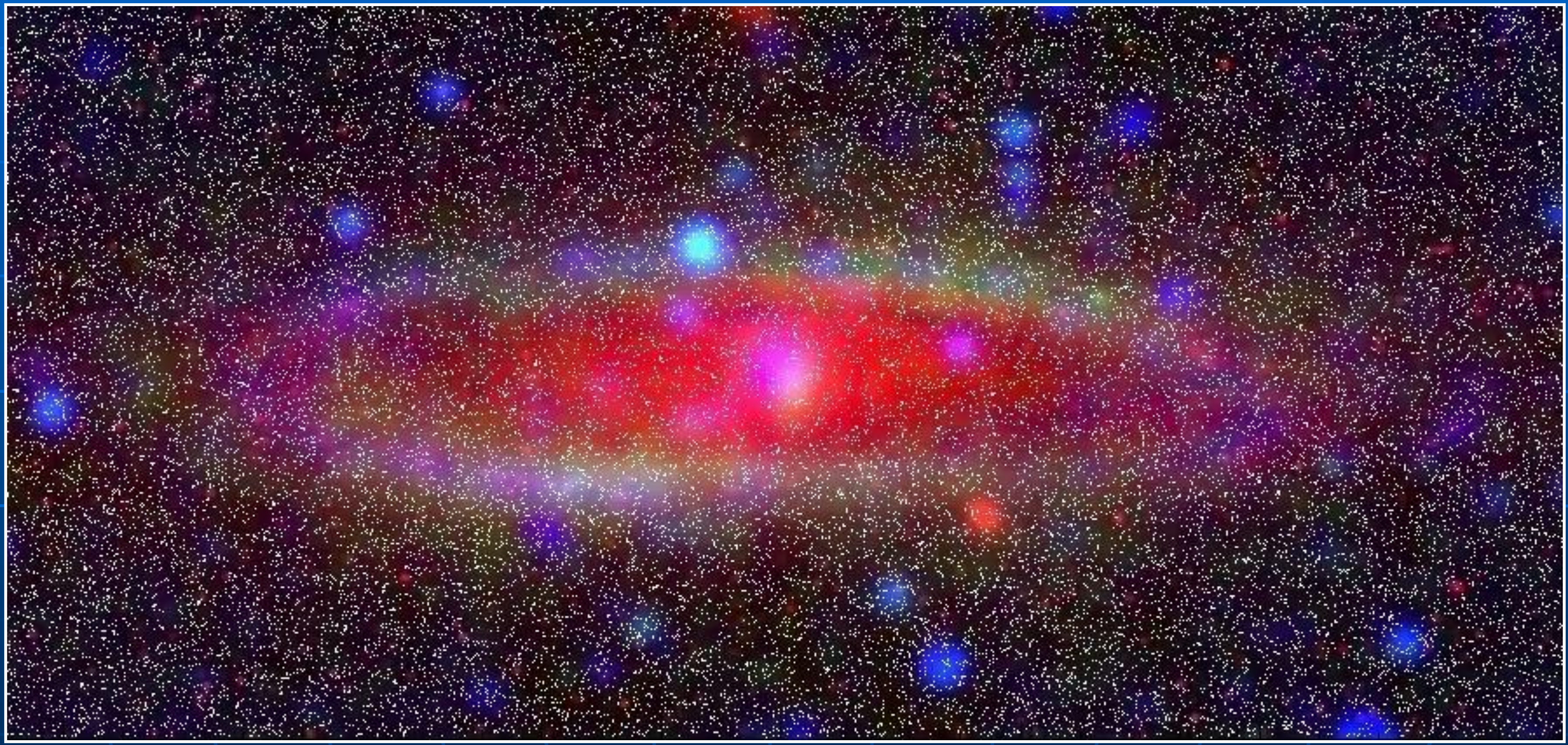
- Magnetic forces may explain wiggles of the rotation curve
- Crucial: measure radial profiles of the regular+turbulent magnetic fields

(Elstner, Beck & Gressel 2014)

Needed: Dense RM grid (SKA-mid)

SKA: RM grid around M31

(simulation by Bryan Gaensler)



Deep field: ≈10000 polarized sources shining through M31

Proposed SKA1 project for galaxies

High spatial resolution with high S/N:

- Restrict to a sample of ≈30 nearby galaxies
- Resolve ≈1 pc in the LMC/SMC, ≈20 pc in M33 and ≈100 pc in M83 and NGC253
- Detect field strengths of ≥10-15 μG

⟶ **Angular resolution of ≈5" (≈1" for SKA2)**

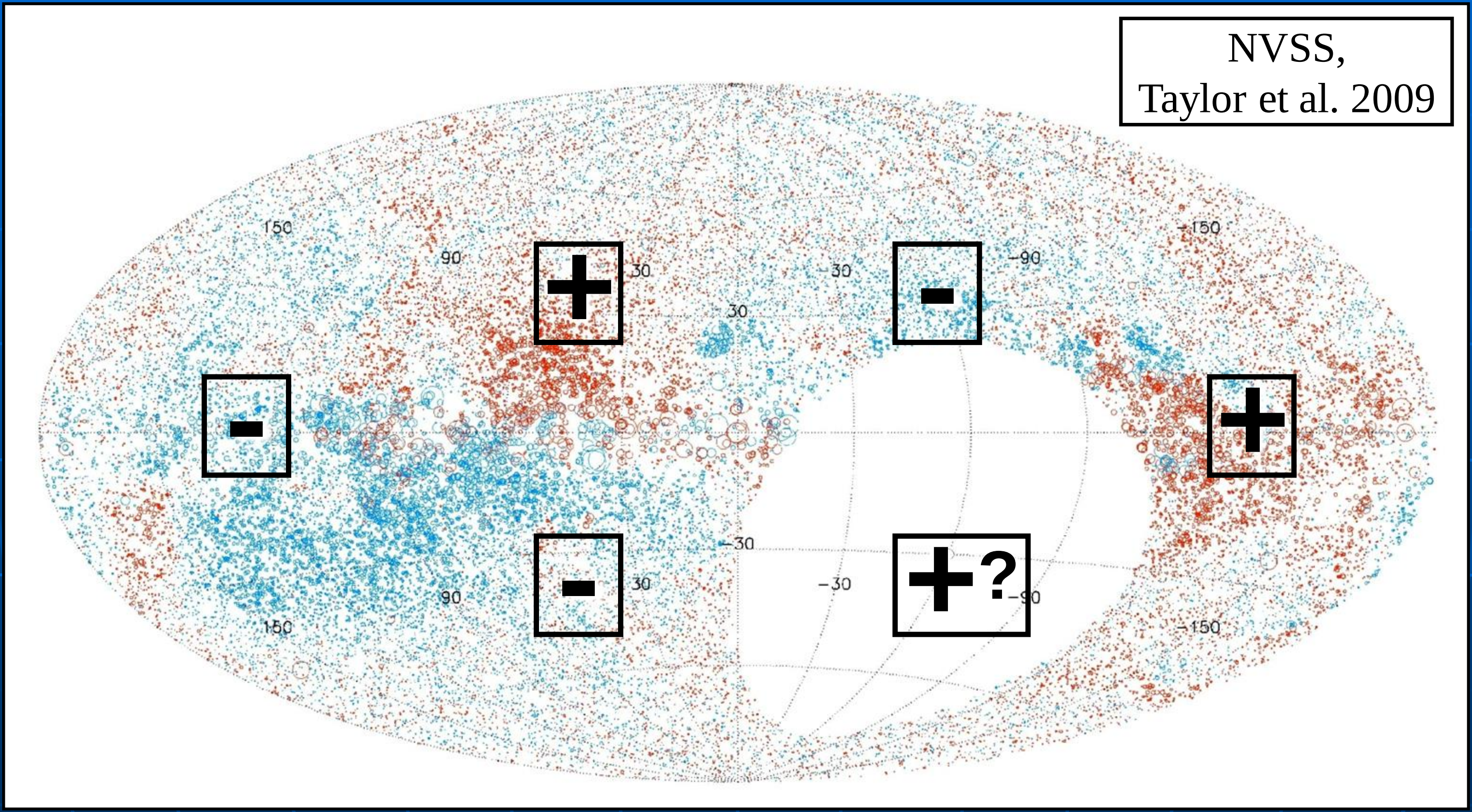
Measure intrinsic structure and angles of strong ISM magnetic fields with high precision:

- Small Faraday depolarization

⟶ **SKA-MID Band 4 (2.8–5.18 GHz)**

Magnetic fields in the Milky Way

(remember the talks by M. Haverkorn, R. Kothes, N. Oppermann & V. Jelic)



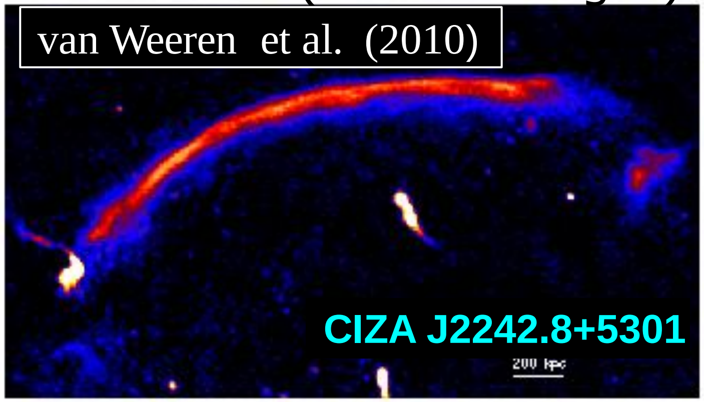
Field reversal in inner Galaxy: foreground ?

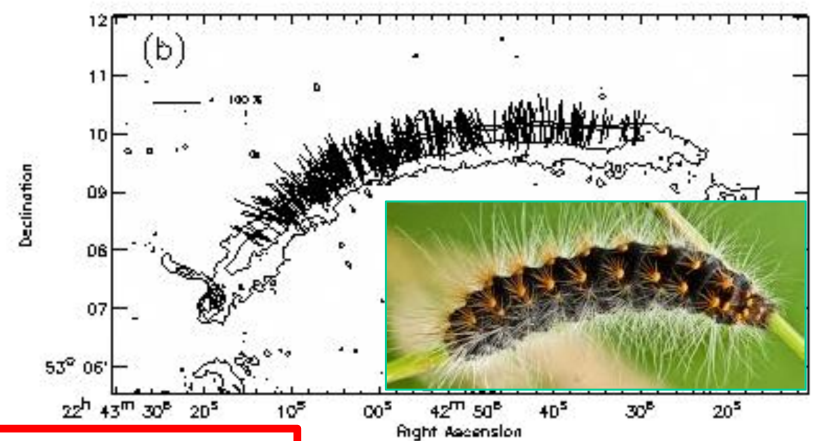
Needed: Dense all-sky RM grid (SKA-survey)

(>100x denser than NVSS)

Diffuse radio emission from galaxy clusters

Radio Relic ("the Sausage")





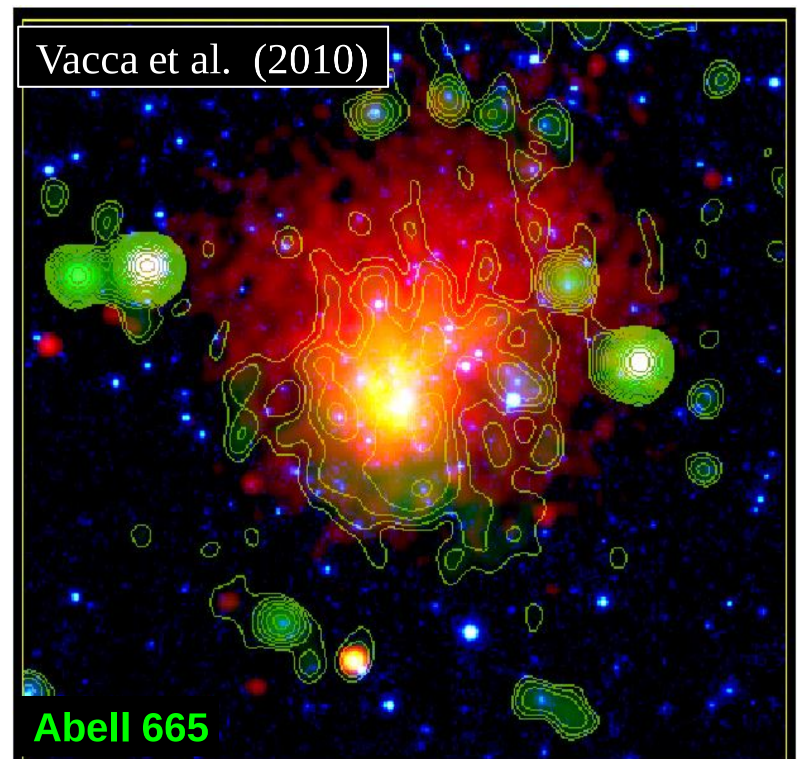
VLA 6cm
E vectors

Radio relics are typically strongly polarized, with fractional polarizations up to 30-50%. Polarization from radio halos has not yet been detected.

Relics are the largest magnetic structures in the Universe observed so far !

SKA1 will permit to investigate the polarized emission from radio halos and relics. These studies are the key to investigate the magnetic field power spectrum in galaxy clusters and to find merger shocks in the intracluster medium not visible in X-ray images.

Radio Halo



Simulations of galaxy clusters

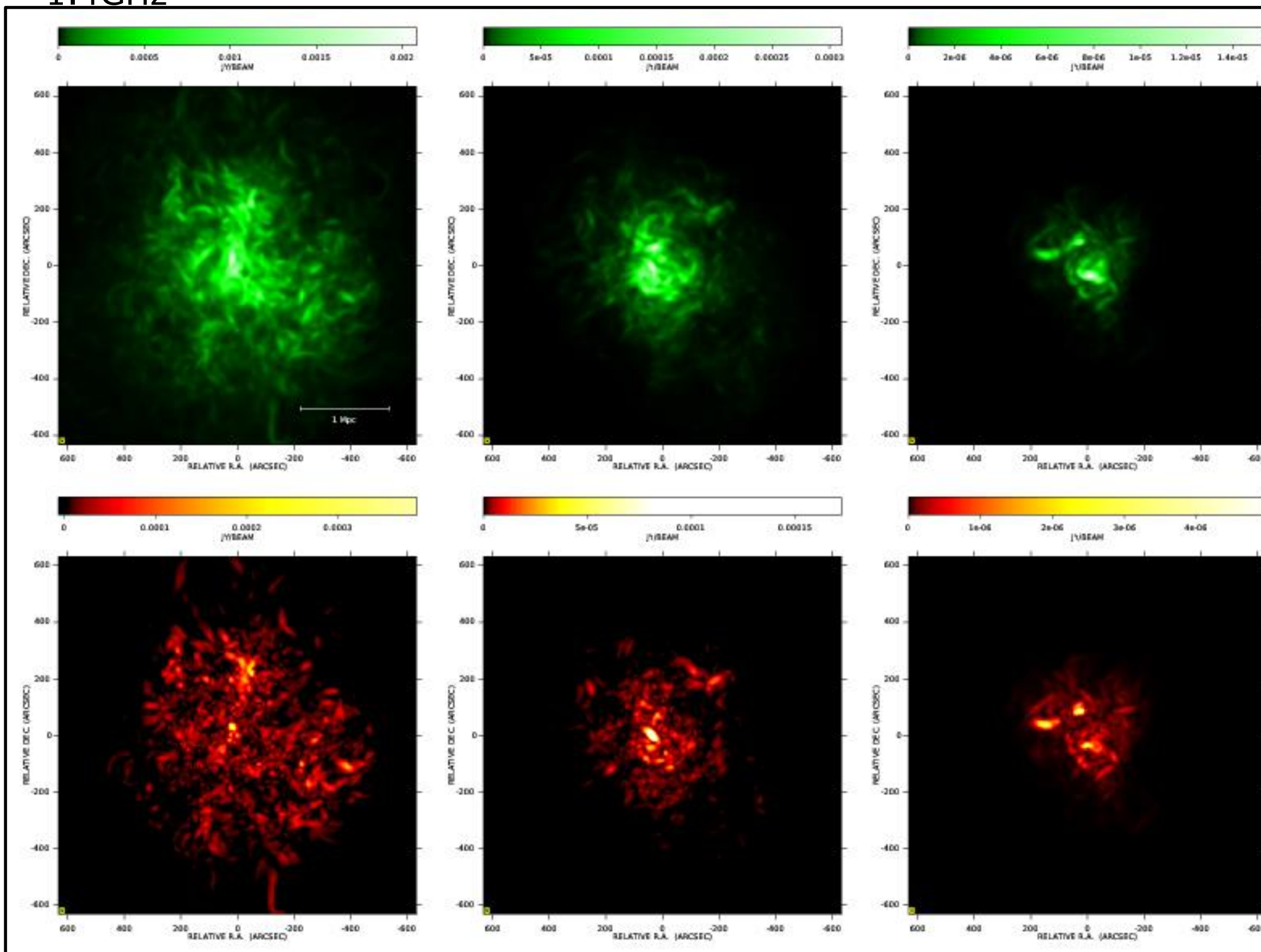
Xu et al. 2012, Govoni et al. 2013

Frequency 1.4 GHz - Bandwidth 300 MHz - Resolution 15''

$L_{1.4GHz}$ = 2 10^{25} W/Hz   2 10^{24} W/Hz   3 10^{22} W/Hz

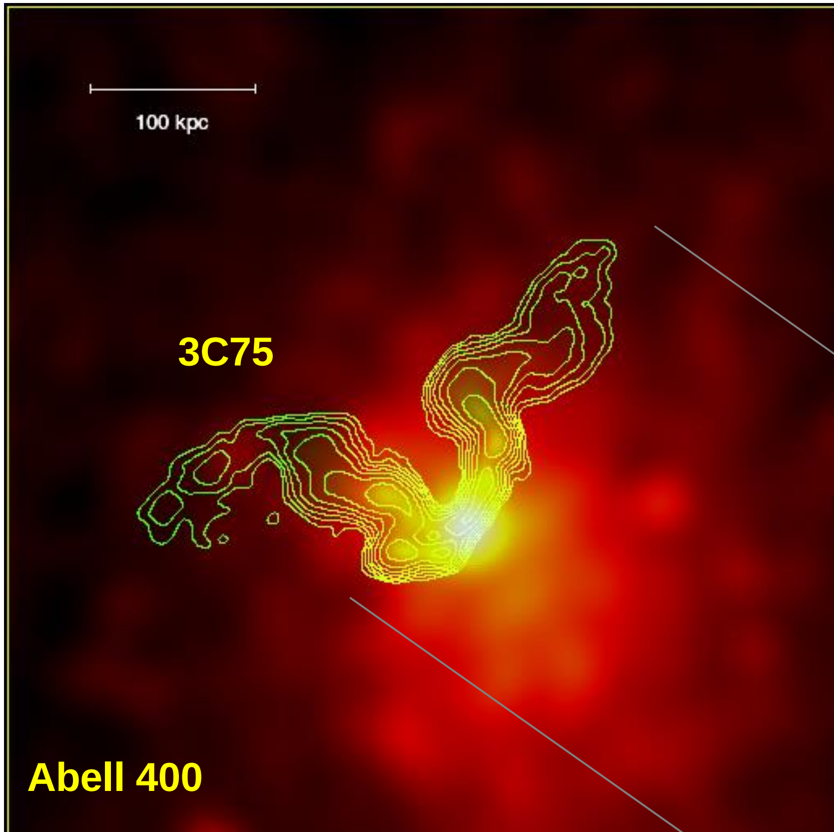
Total Intensity

Polarized Intensity (p=20-70%)

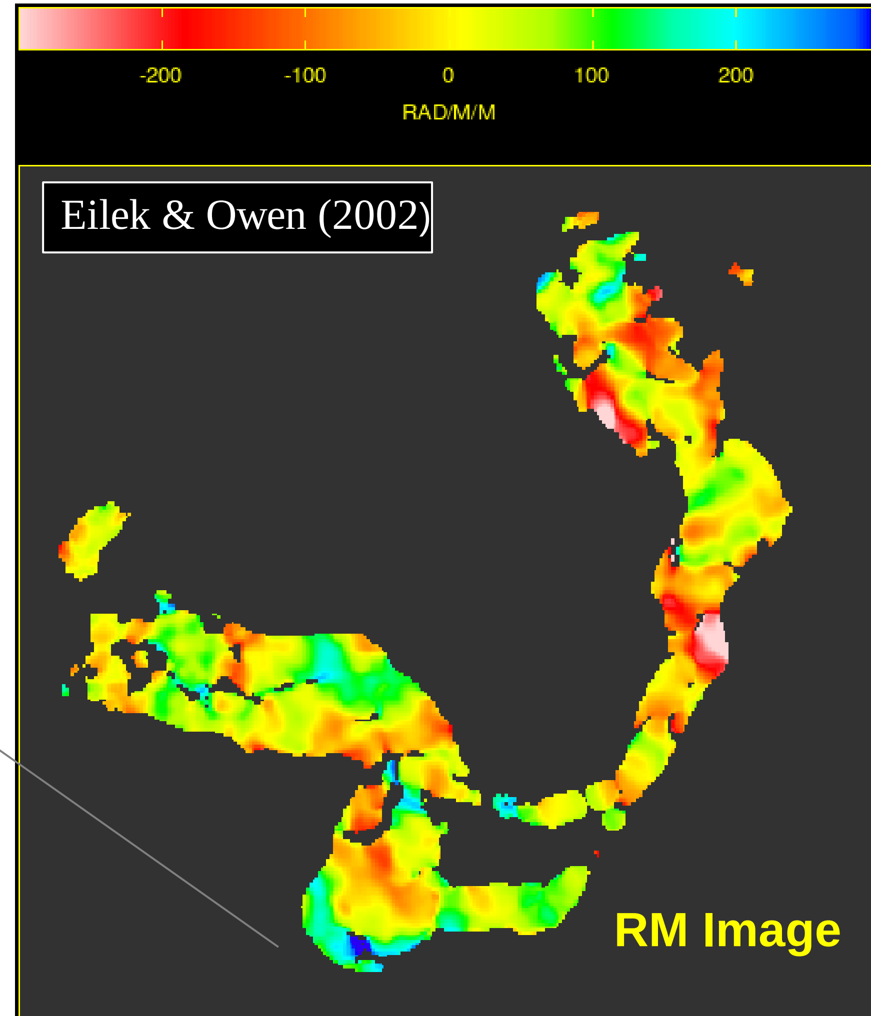


RM Synthesis was applied to recover the polarized signal

Rotation Measures in galaxy clusters



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



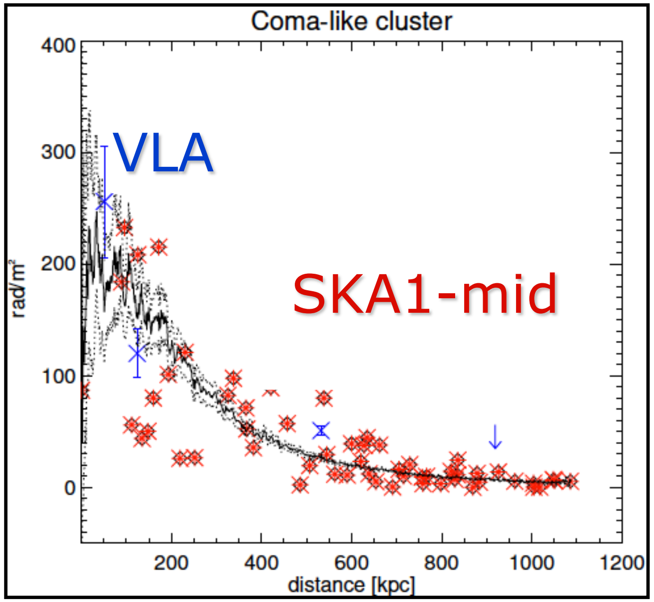
SKA1 has the potential of measuring the RMs toward a large number of sources and deriving a detailed description of the strength, structure and radial decrease of cluster magnetic fields.

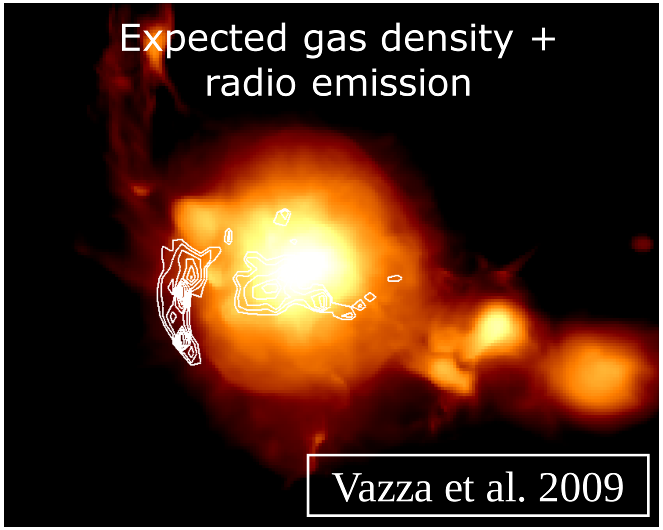
Detection of magnetic fields in galaxy clusters

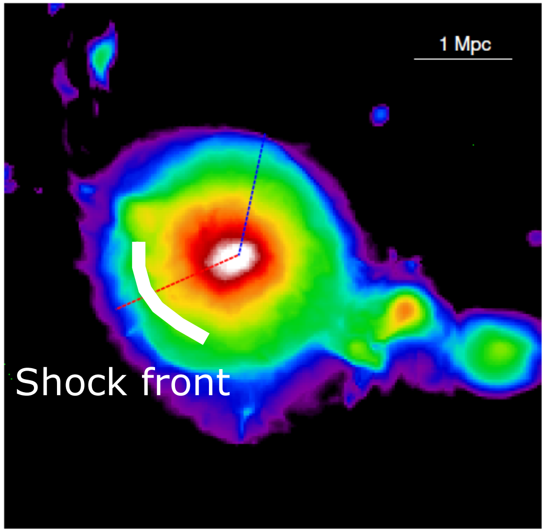
- Massive galaxy clusters (~10^{15} M_{sun}):
  SKA1 will detect 100s RM in a Coma-like cluster

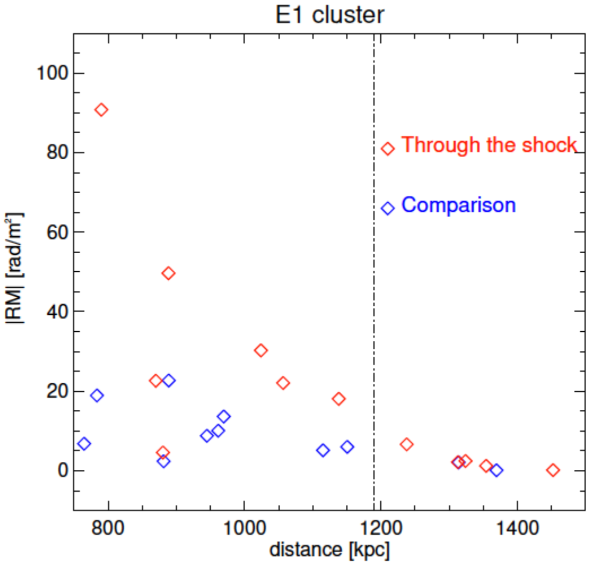
- Smaller clusters and groups (down to ~10^{13} M_{sun}):
  unfeasible with present radio telescopes

Needed: high resolution & high sensitivity (SKA-mid, Band 1, 350-1050 MHz)



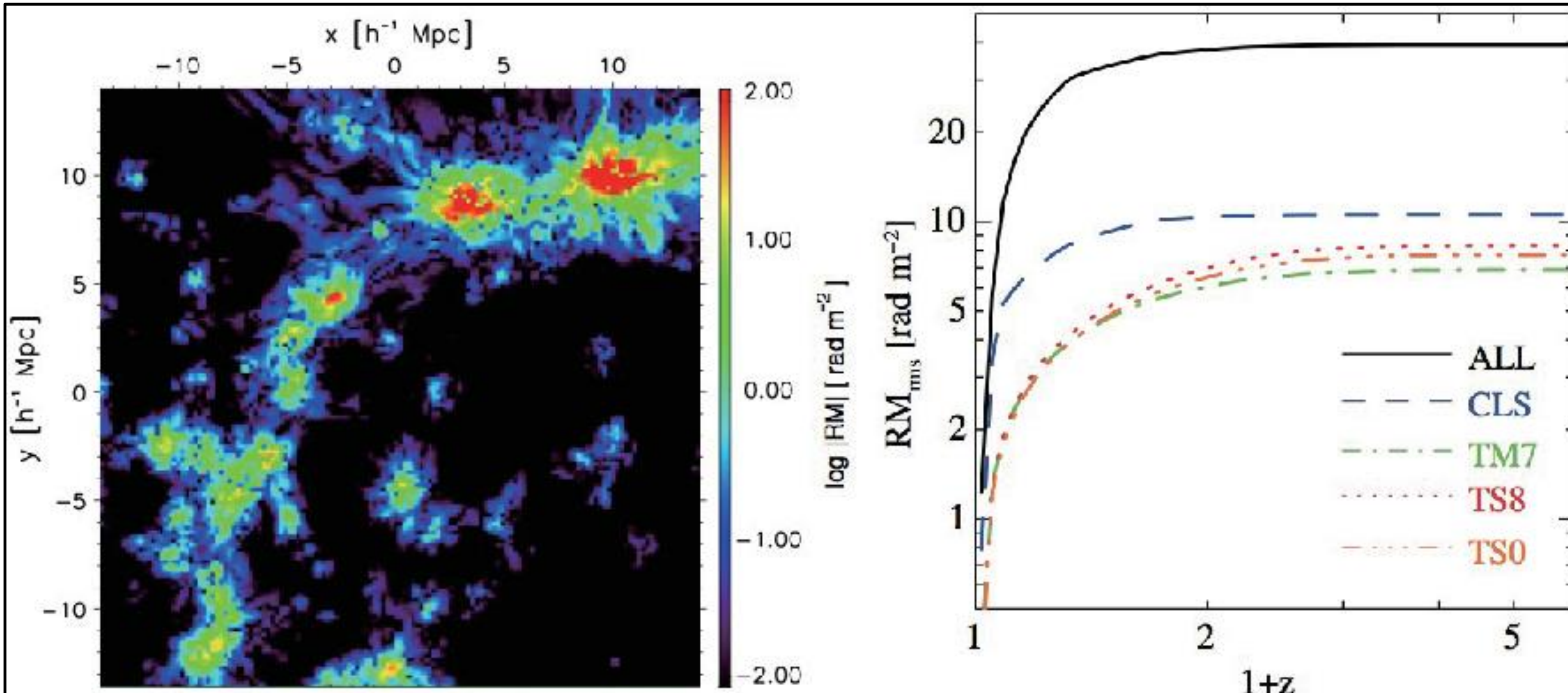






Detection of magnetic fields in the Cosmic Web
(see D. Ryu's talk for details)

- What are their properties and relation to large scale structure of matter?
- How did they arise?



Akahori & Ryu (2010)

Needed:
- Rotation Measure Grid
- Total and polarized diffuse synchrotron emission
- **SKA1-mid, Band 1 (350-1050 MHz)**

SKA Magnetism Science Team: Priorities for SKA1

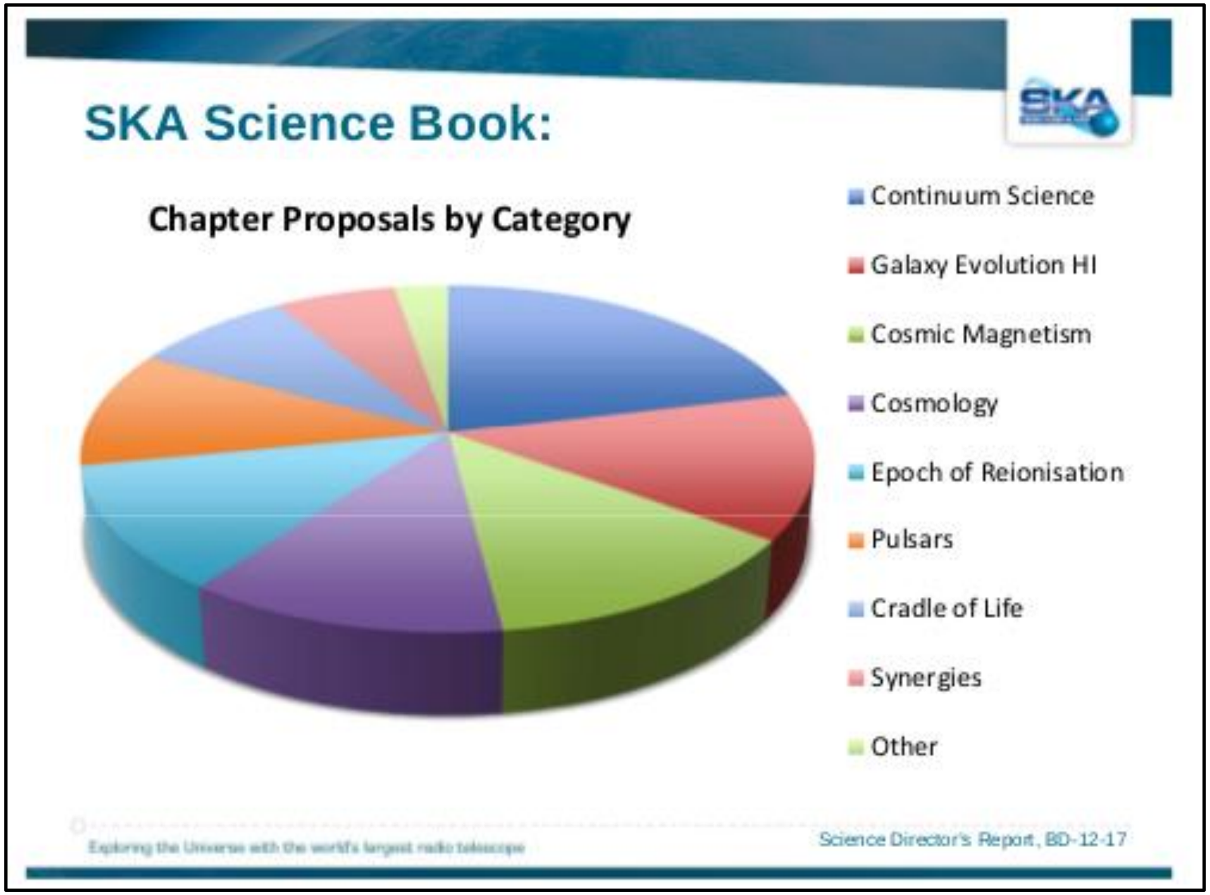
- **All-sky survey of polarized sources and their Faraday rotation measures (RM)**
  - SKA1-survey (≈2" resolution, 2μJy/beam sensitivity)
  - 650-1670 MHz (PAF Band 2)

- **Deep survey of polarized sources and their RMs in selected fields**
  - SKA1-mid (≈1" resolution, 0.1μJy/beam sensitivity)
  - 950-3050 MHz (Bands 2+3)

- **Deep search for polarized emission of intergalactic filaments, galaxy clusters and interacting galaxies**
  - SKA1-mid (3-30" resolution, 0.2μJy/beam sensitivity)
  - 350-1050 MHz (Band 1)

- **High-resolution imaging of galaxies and AGNs**
  - SKA1-mid (≈5" resolution, 0.2μJy/beam sensitivity)
  - 4.6-13.8 GHz (Band 5)

SKA Science Book 2015: Cosmic Magnetism Science



19 chapters related to magnetic fields

We are entering a Golden Age

of cosmic magnetism observations

(but much needs to be done)

Join the SKA-SWG !