Future Observations of Cosmic Magnetic Fields with the **Square Kilometre Array** and its Precursors

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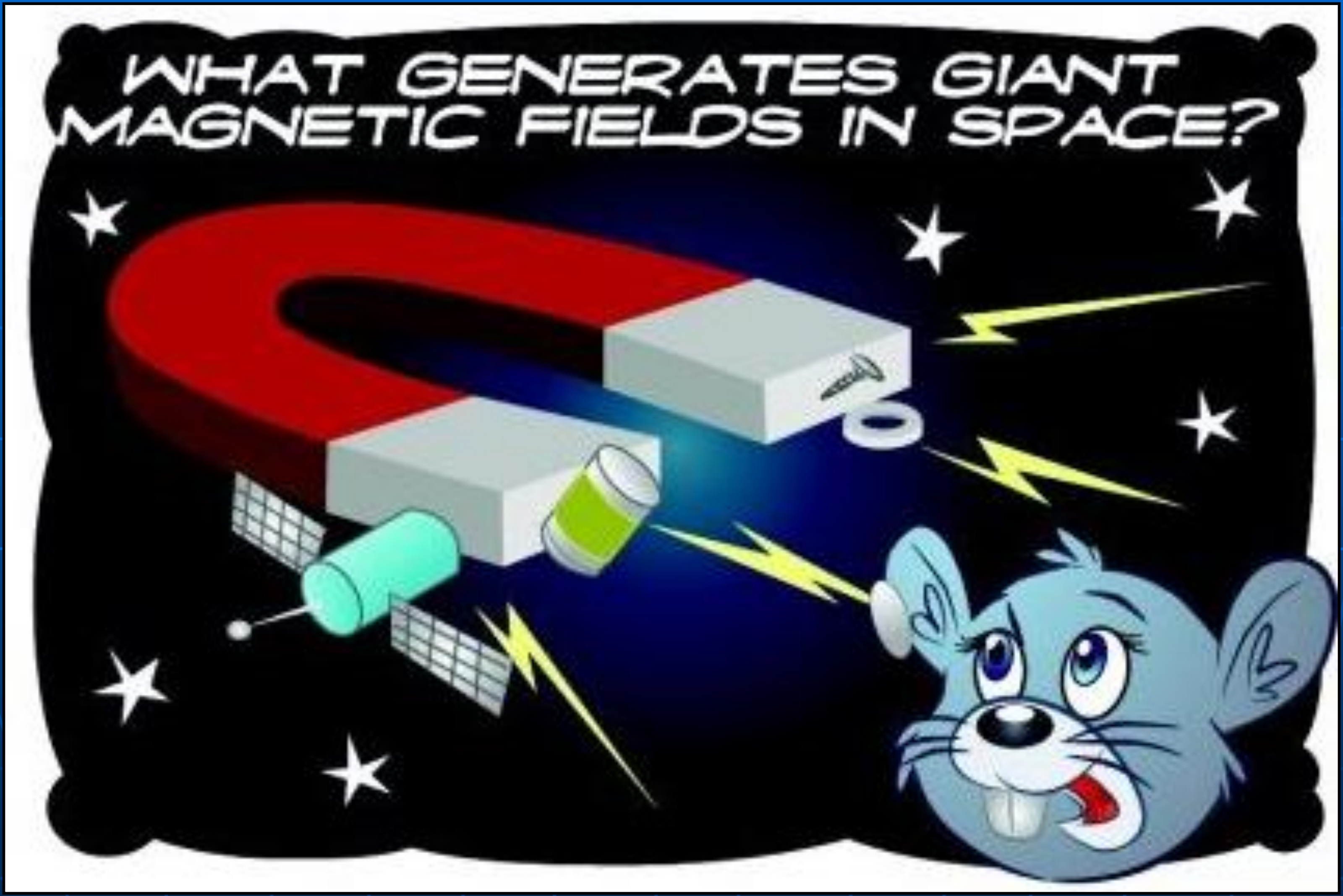
Fundamental questions on cosmic magnetic fields

- 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 clusters?
- Is intergalactic space magnetic ?

The adventures of the SKANIMALS no.1



Future magnetic fields observations with radio telescopes

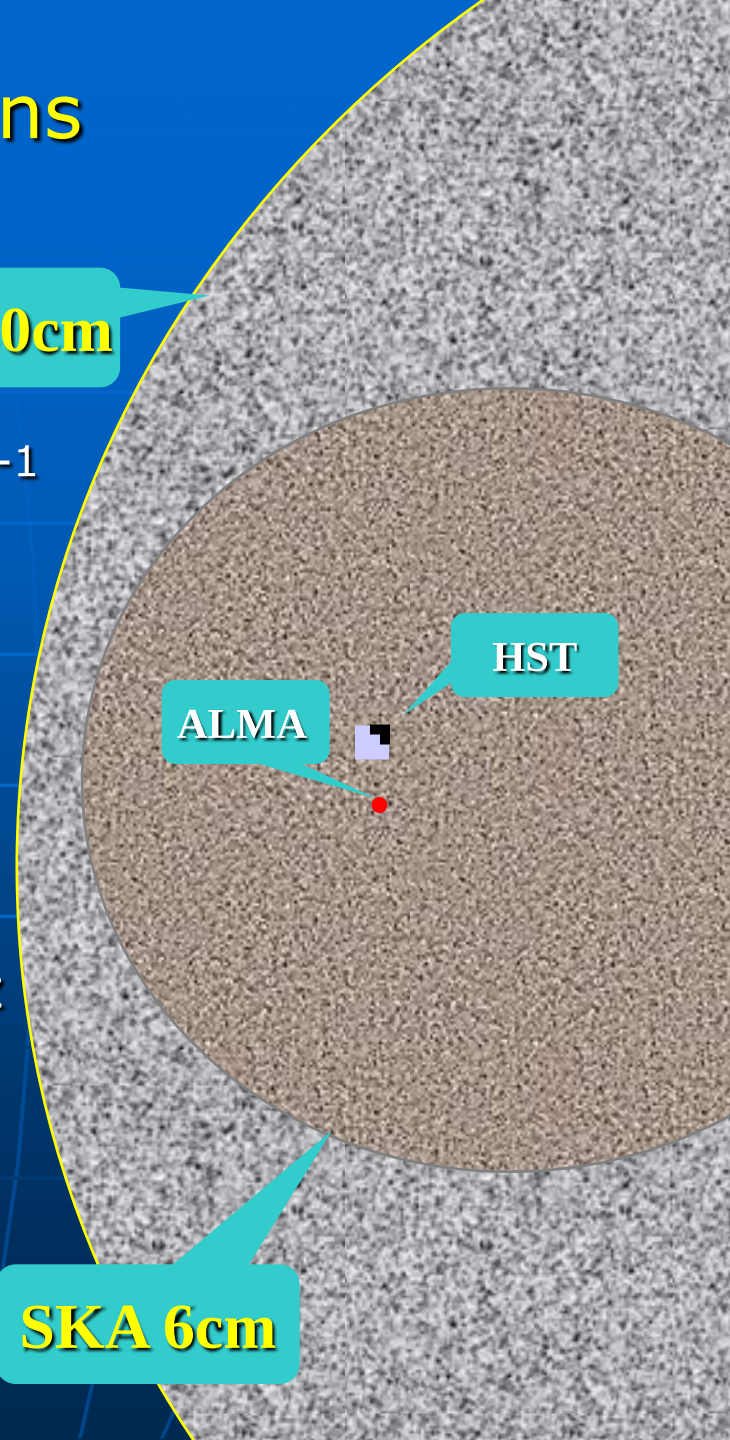
- Low frequencies:
  Higher accuracy to detect small rotation measures
  (LOFAR, LWA, MWA, **SKA**)

- High frequencies:
  Higher resolution and/or higher survey speed
  (EVLA, ASKAP, APERTIF, MeerKAT, **SKA**)

- New analysis method:
  Faraday spectrum allows Faraday tomography
  (Radio continuum spectro-polarimetry, "RM Synthesis")

SKA Specifications

- Sensitivity (A/T_{sys}): 4000 – 12000 $m^2\ K^{-1}$
- Field of view (FoV): 1 – 200 deg^2
- $\geq$8 independent beams
- Resolution: $\leq$1"
- Frequency range: 70 MHz – 10 (35) GHz
- Dynamic range: $\leq 10^6$
- Polarization purity: –30 dB over FoV

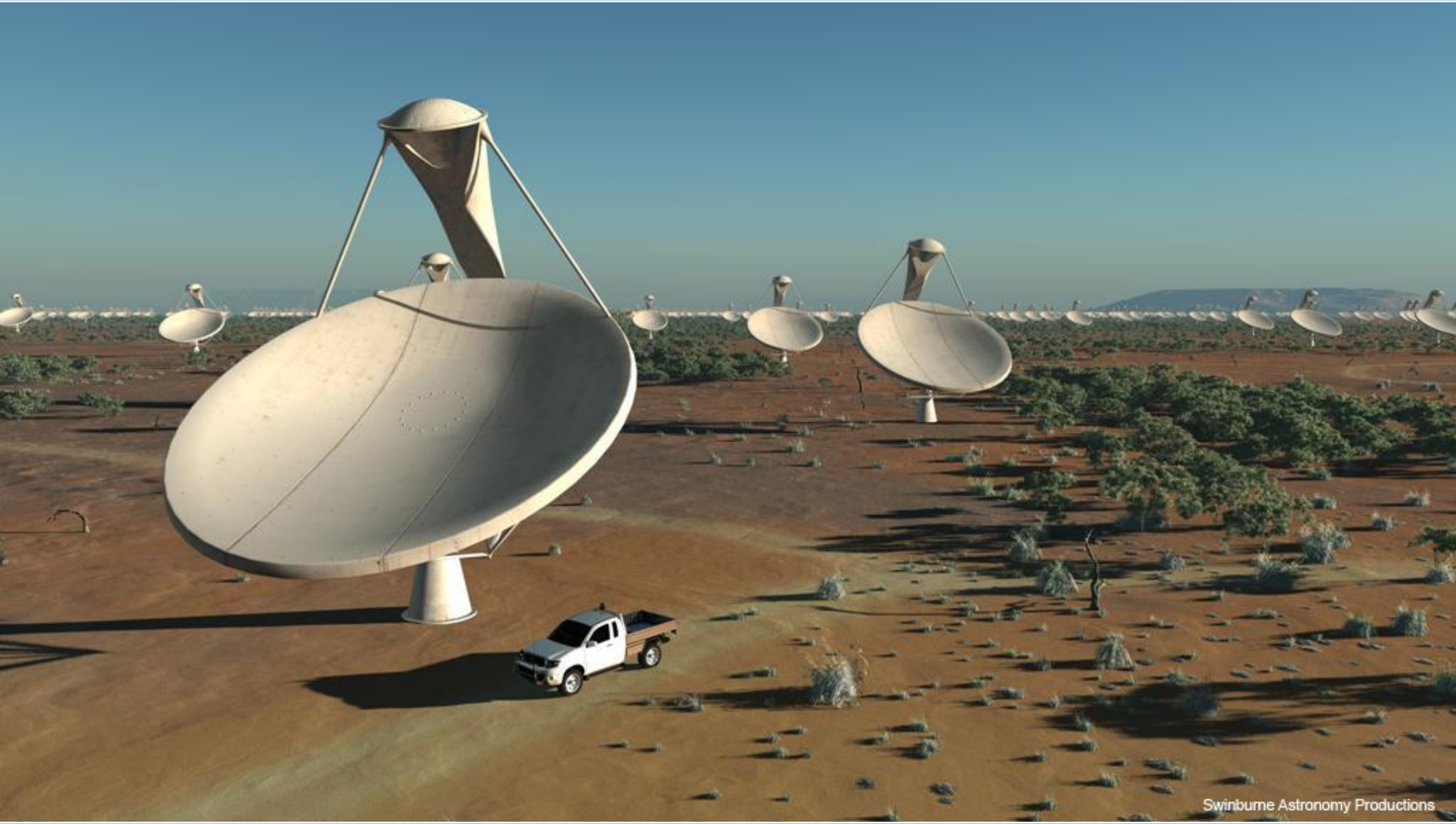


SKA Reference Design

SQUARE KILOMETRE ARRAY
www.skatelescope.org

1. Array of ≈15m parabolic dishes (Phase 1)
   - ≈0.45-3 GHz:
   - Wide-band single-pixel feeds, FoV ≤10 deg^2 , or:
   - Focal-plane phased arrays, FoV 10-50 deg^2 ("radio camera")
2. Sparse low-frequency aperture array (Phase 1)
   - ≈0.07-0.45 GHz: Dipoles, FoV ≈200 deg^2
3. Dense medium-frequency aperture array (Phase 2)
   - ≈0.5-1 GHz: Tiles, independent multiple fields
4. High frequencies (Phase 2)
   - Upgrade of systems for dishes to 10 GHz
5. High frequencies (Phase 3)
   - Upgrade of dishes to ≈35 GHz

Phase 1: SKA dishes (450 MHz–3 (10) GHz)



SKA Project Office
+ Swinburne Astr. Prod.

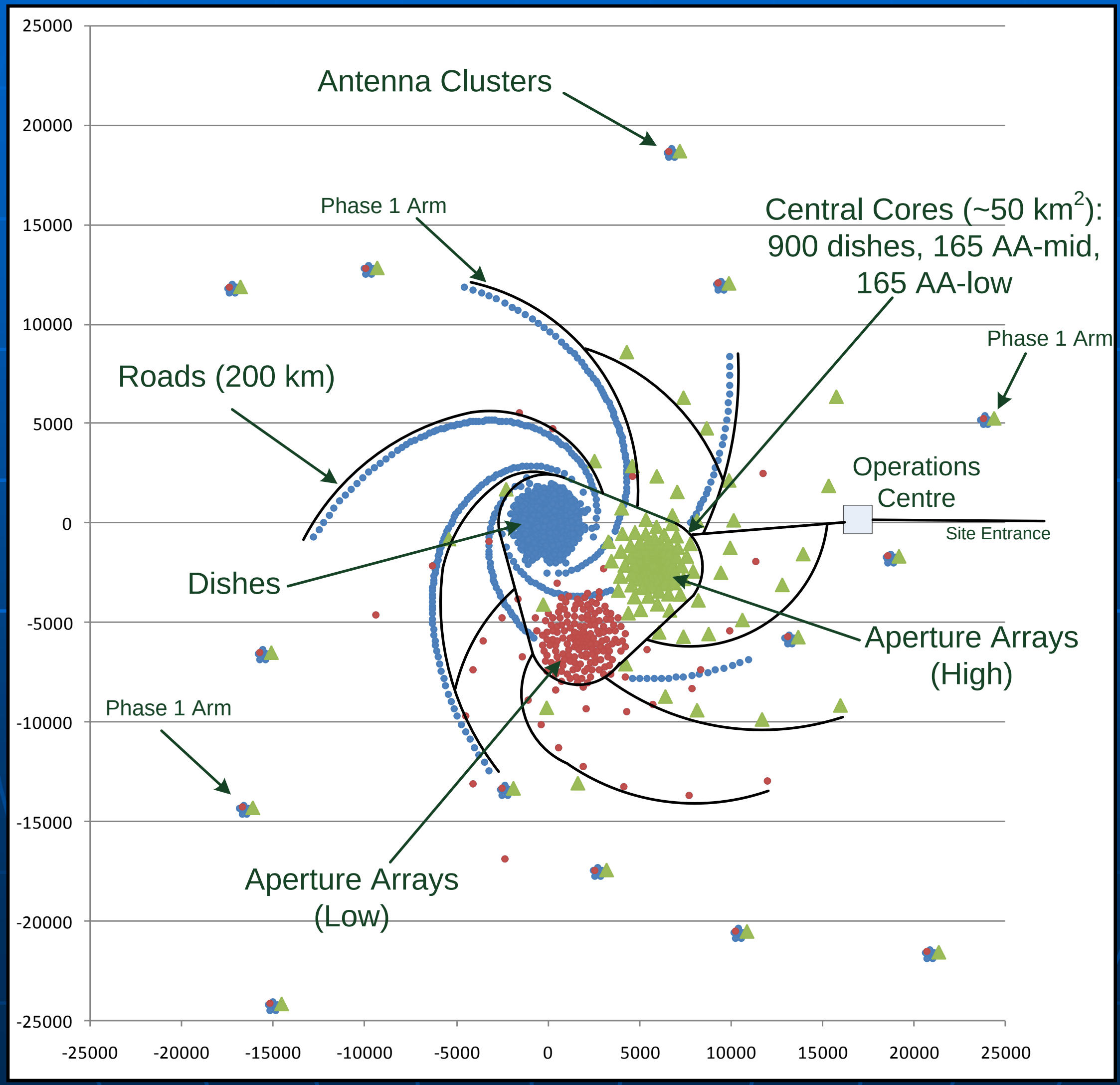
Phase 1: SKA sparse aperture array (70-450 MHz)

SKA Project Office
+ Swinburne Astr. Prod.

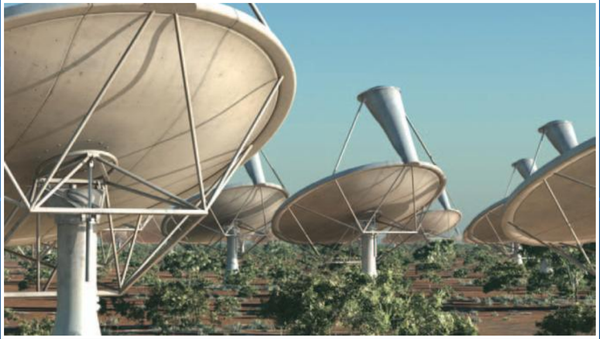
Phase 2: SKA dense aperture array (500-1000 MHz)

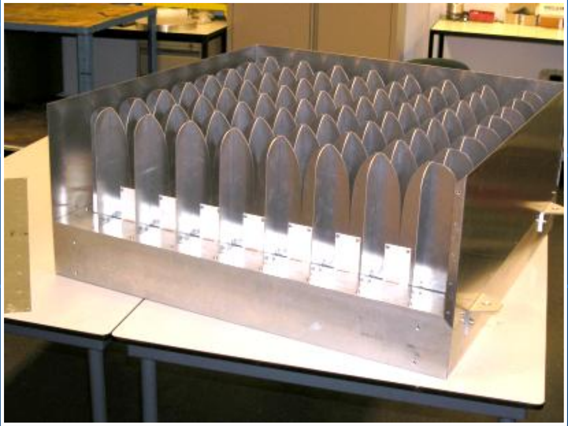
SKA Project Office
+ Swinburne Astr. Prod.

SKA Phase 2 central site



SKA technology developments





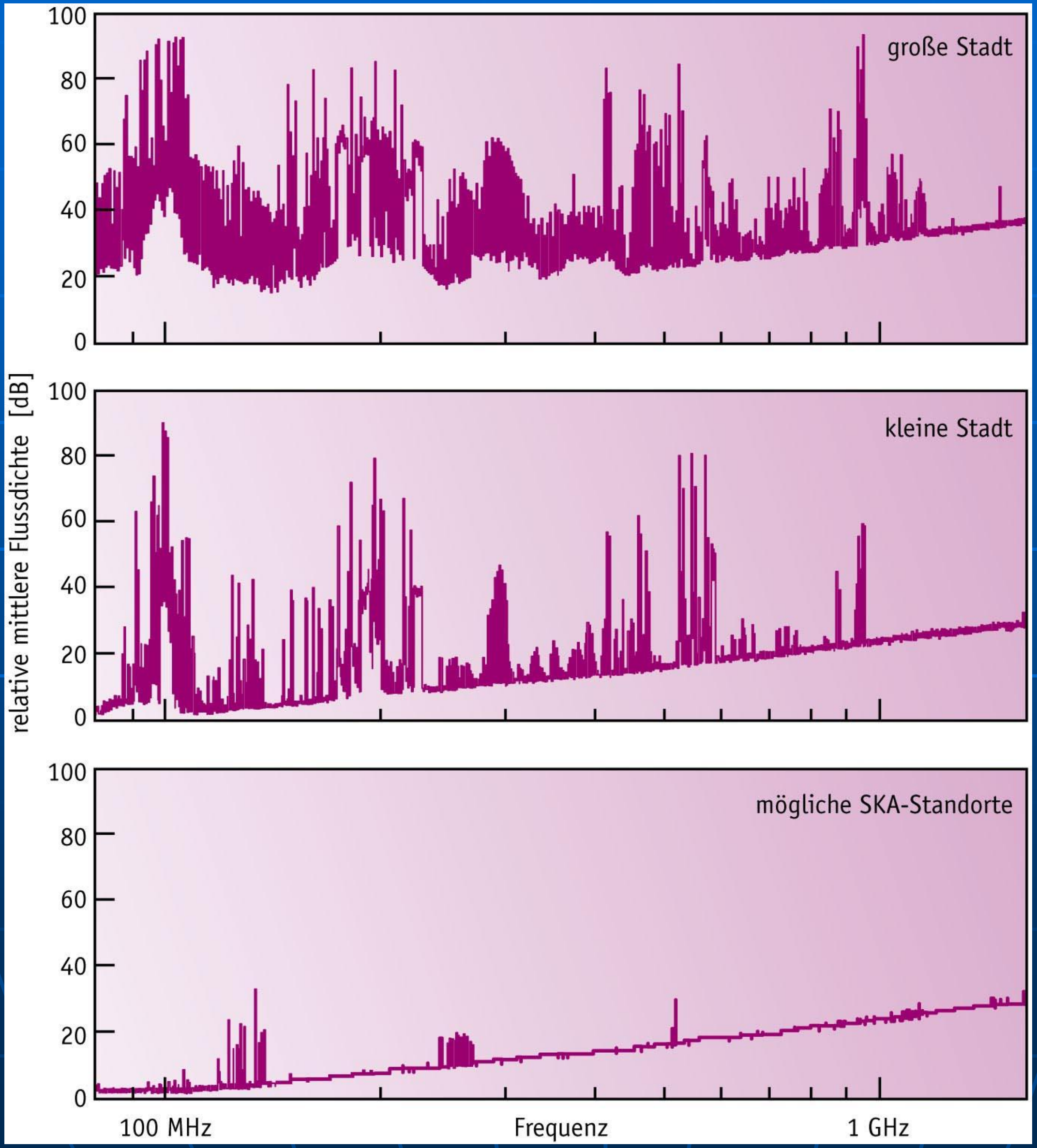
SKA technology development

- Novel dish antenna construction
- Aperture arrays
- Large field of view
- Wide-band feeds
- Cheap (uncooled) receiving systems
- Focal plane arrays
- Fast signal transmission
- Processing and data management
- "Green" energy supply

Challenges

- Data rates: PetaBytes/s
- Data volume: ExaBytes
- Processing requirements: ExaFlops/s
- Power: 100 MW

Radio interference

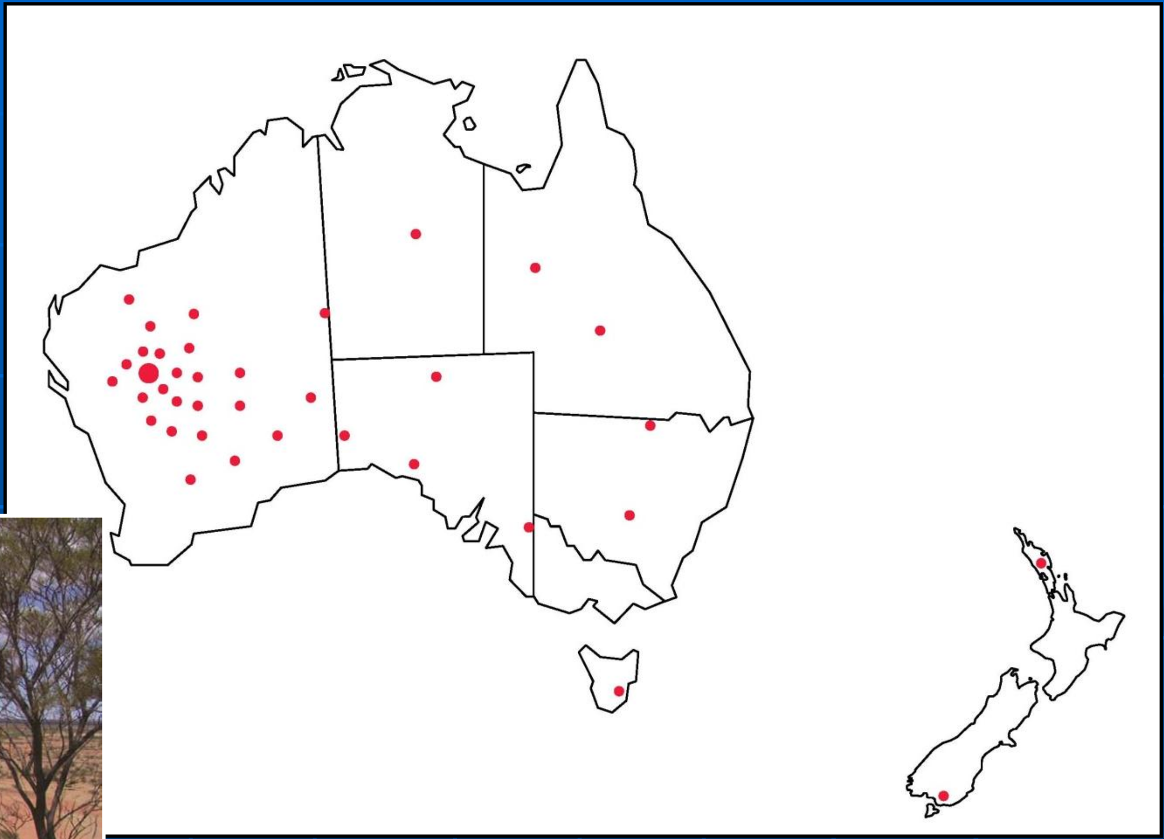


large city

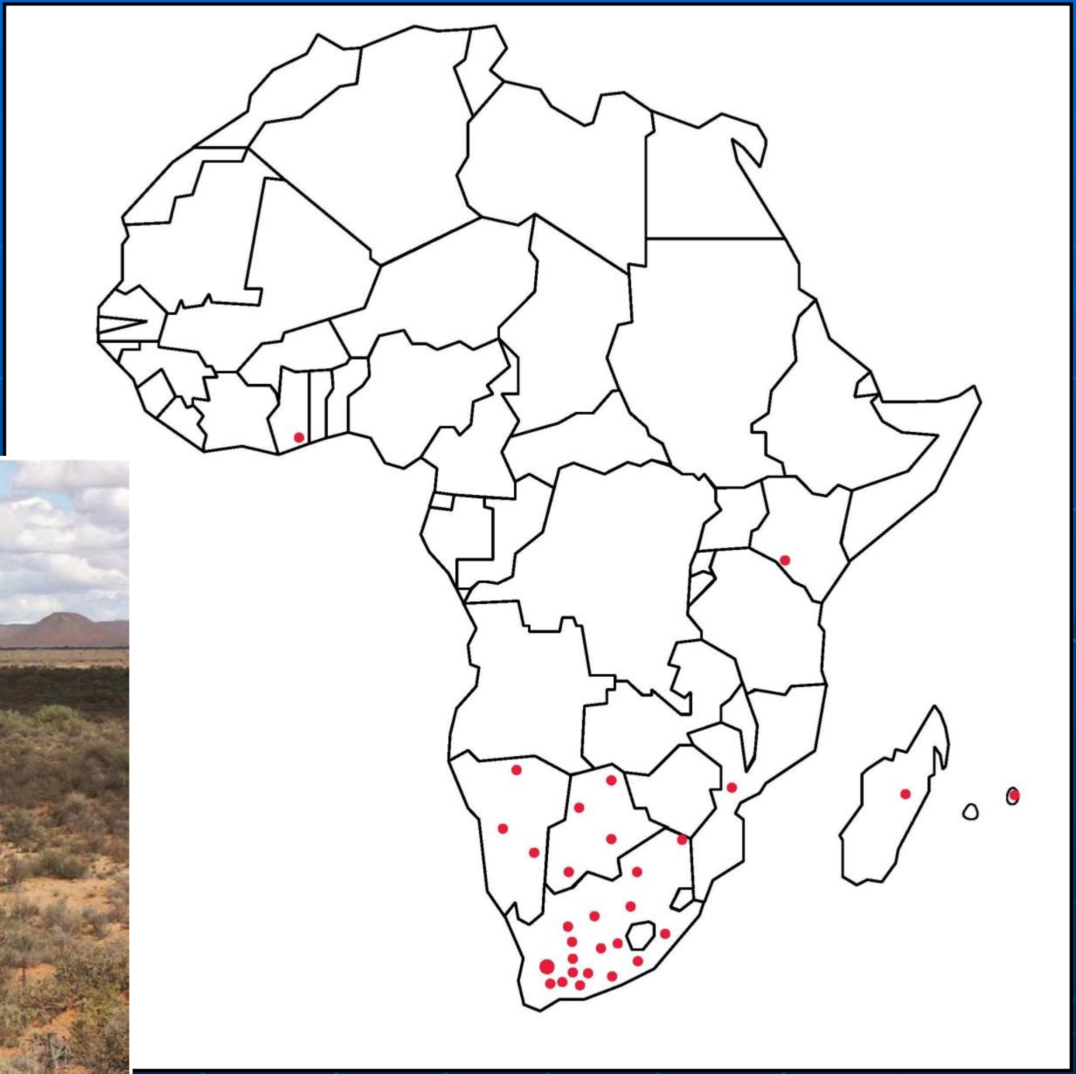
small city

SKA cite

Candidate site: Australia & New Zealand



Candidate site: South Africa



Pre-construction phase governance

- Interim Founding Board created on 2 April 2011

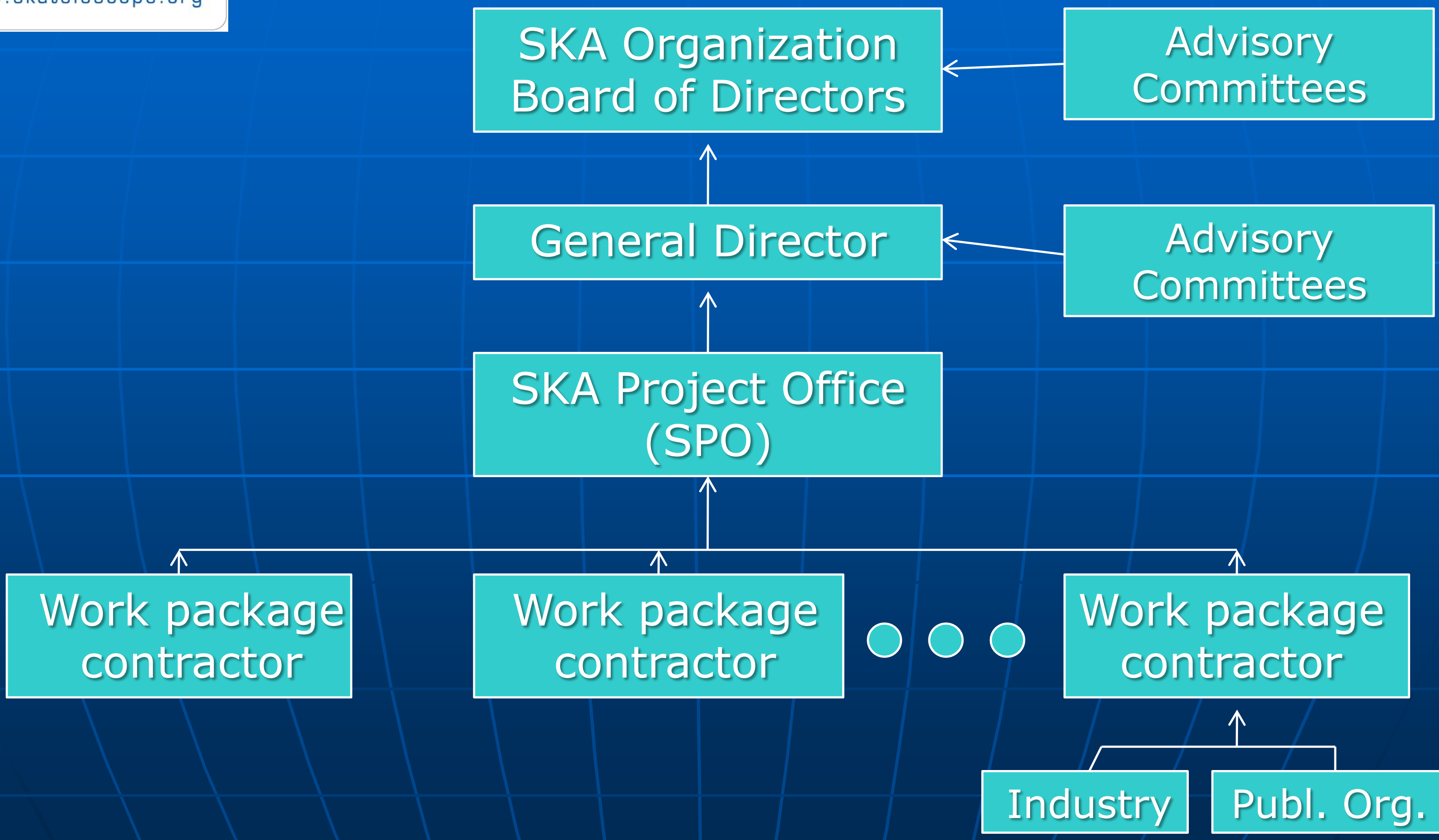
Tasks :

1. Establish a legal entity for the SKA organisation
2. Decide location of the SKA Project Office
   (done: Jodrell Bank Observatory in the UK)
3. Agree on a resourced Project Execution Plan

- Nine signatories at government or funding agency level:

Australia, China, France, Germany, Italy, Netherlands, New Zealand, South Africa, UK (+ observers: Canada, India, Japan, Korea)

Governance
(>January 2012)



SKA timeline

SKA Preparatory Phase	Phase 1 Pre-Construction Phase	Phase 1 Construction, Verification, Commissioning, Acceptance, Integration & First Science	Phase 2 Construction , Commissioning, Acceptance, Integration & First Science	SKA Operations
2008 - 2012	2013 - 2015	2016 - 2019	2018 - 2023	2020 onwards

Site decision: 29 Feb. 2012
(by Board of Directors)

SKA Key Science Projects

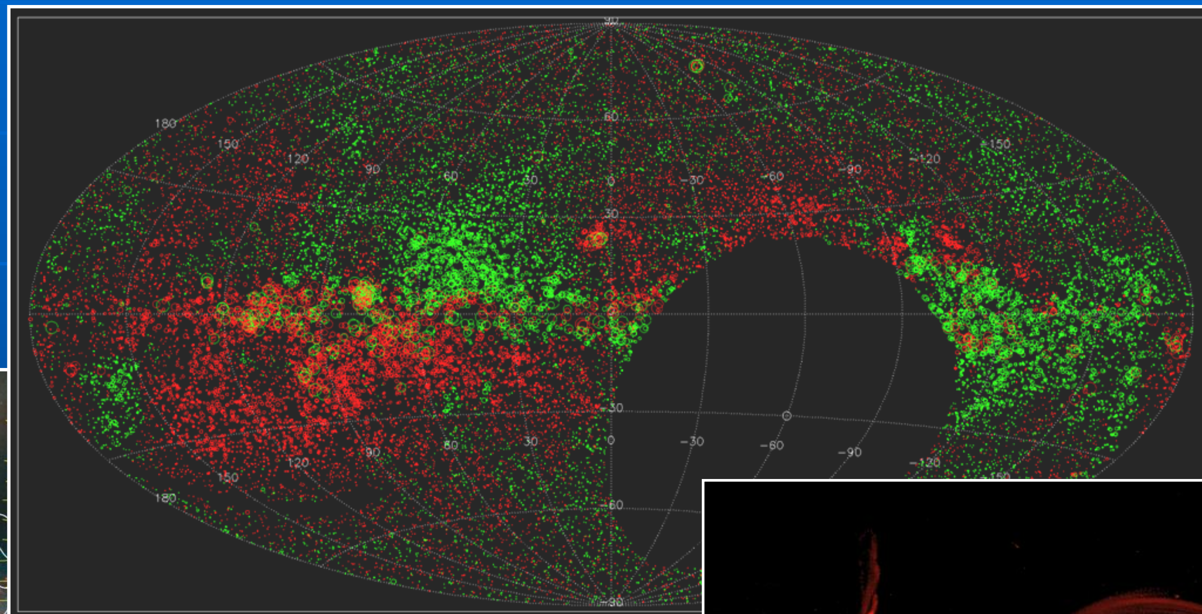
Phase 1:

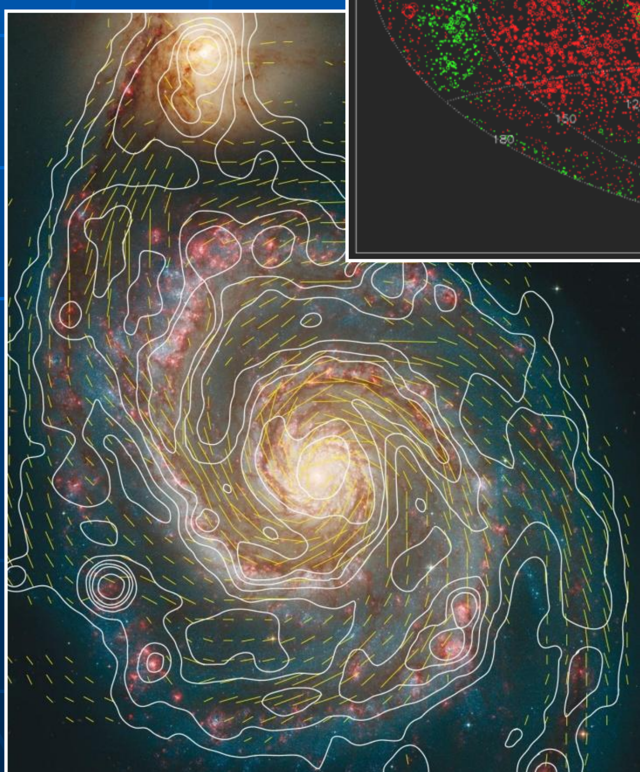
- History and role of neutral hydrogen - from dark ages (EoR) to the present day
- Testing theories of gravitation & discover gravitational waves with pulsar timing

Phase 2:

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

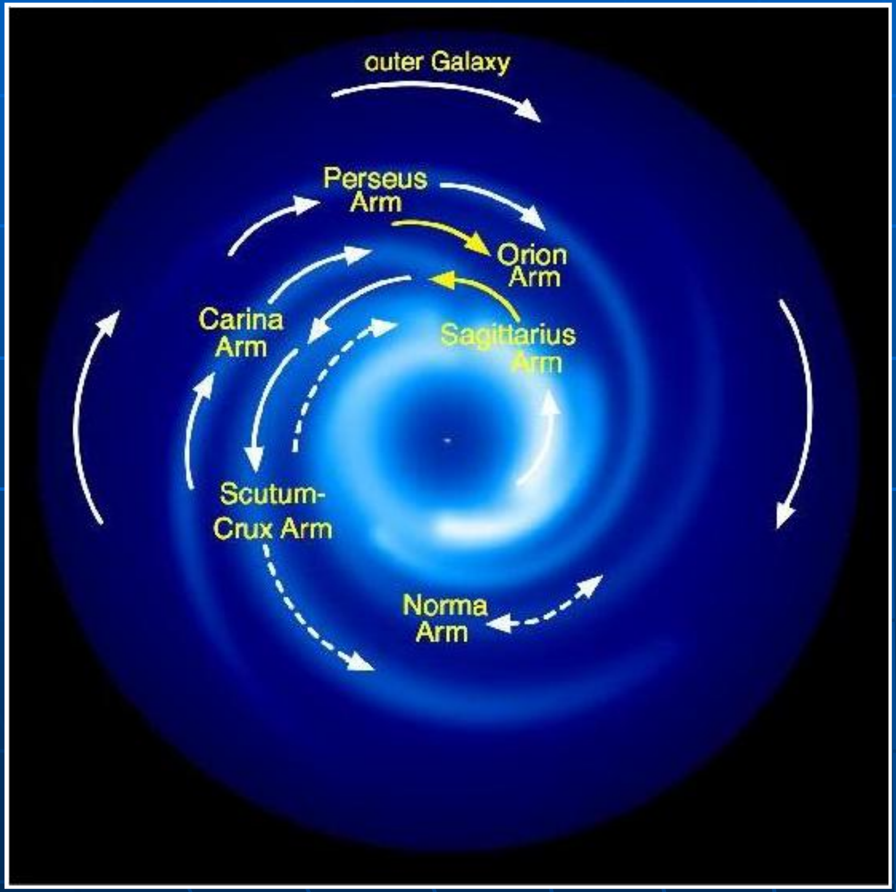
SKA Key Science Project:
Origin and evolution of magnetic fields





The large-scale Galactic magnetic field from pulsar RM data

(Han et al. 2006, Brown et al. 2007, 2010, Noutsos et al. 2008)

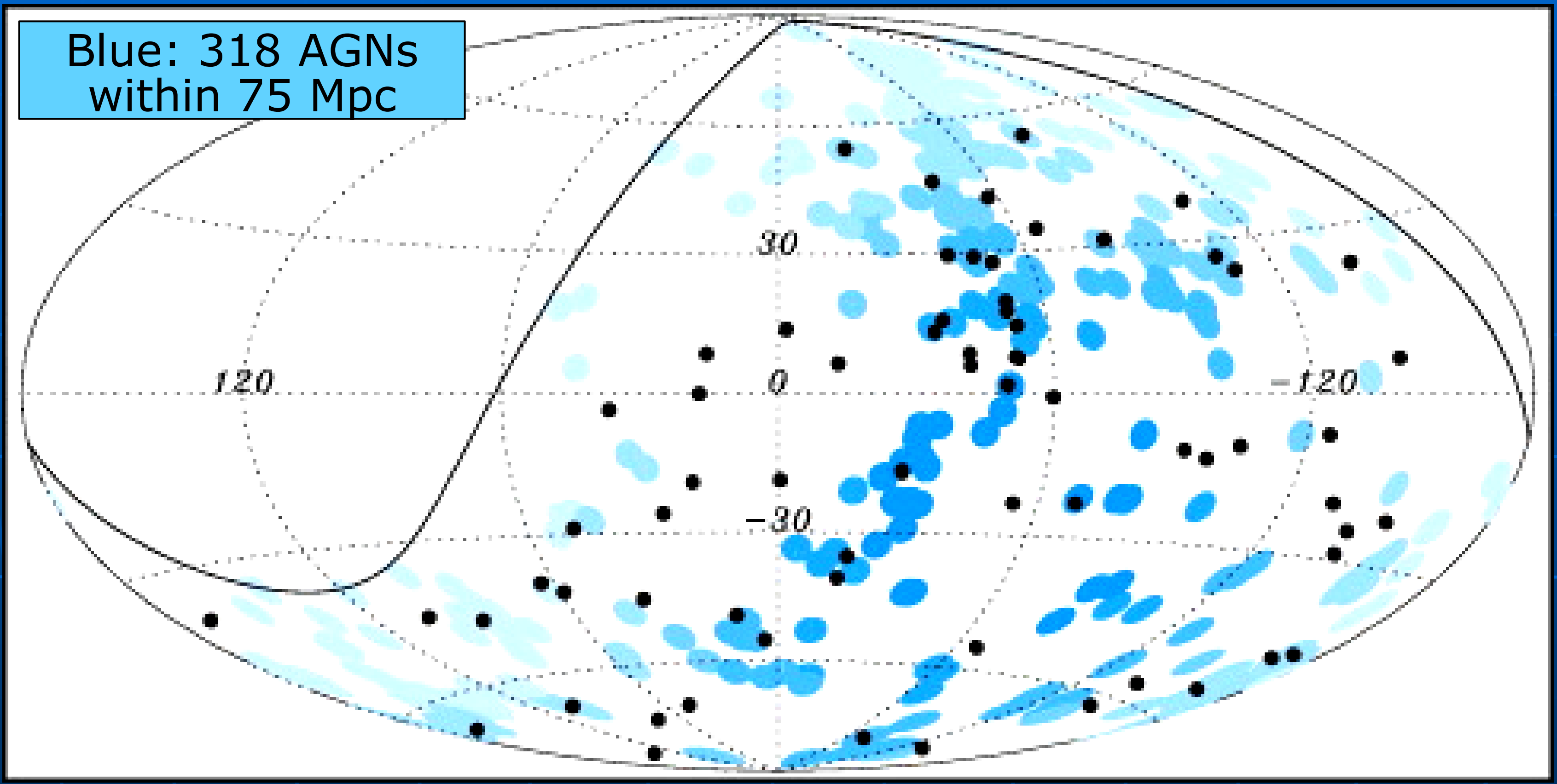


- Local field is clockwise
- Field in Sagittarius arm is counter-clockwise

→ ***Reversal*** between arms
(nothing similar is observed in external galaxies so far)

69 AUGER UHECR events (> 5.5 10^{19} eV)

Abreu et al. 2010



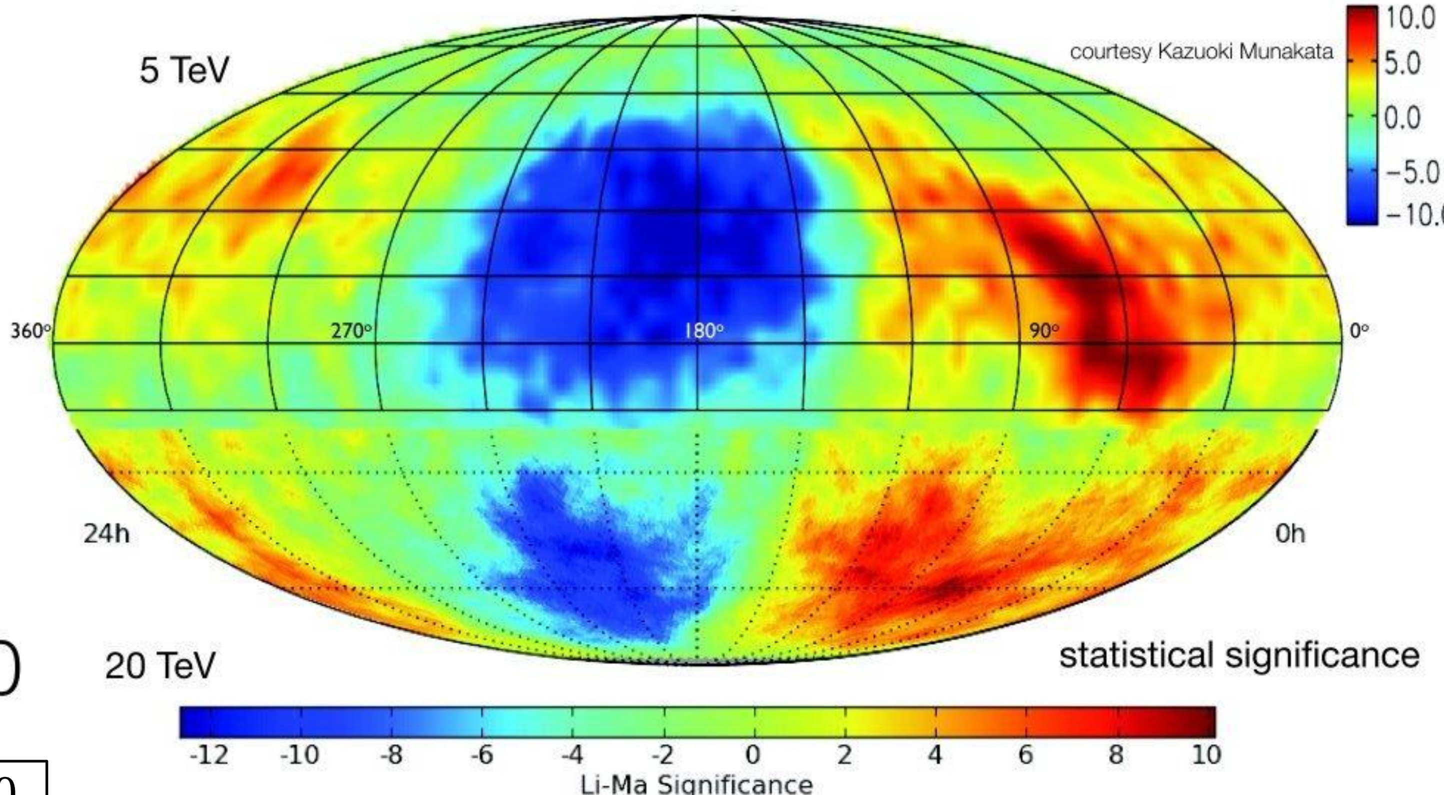
Localizing the UHECR sources requires detailed knowledge about the Milky Way's magnetic field *- but the existing field models are insufficient*

cosmic ray anisotropy in arrival direction

PRELIMINARY

Tibet-III

(5° smoothing)



IceCube-40

(3° smoothing)

Abbasi et al. 2010

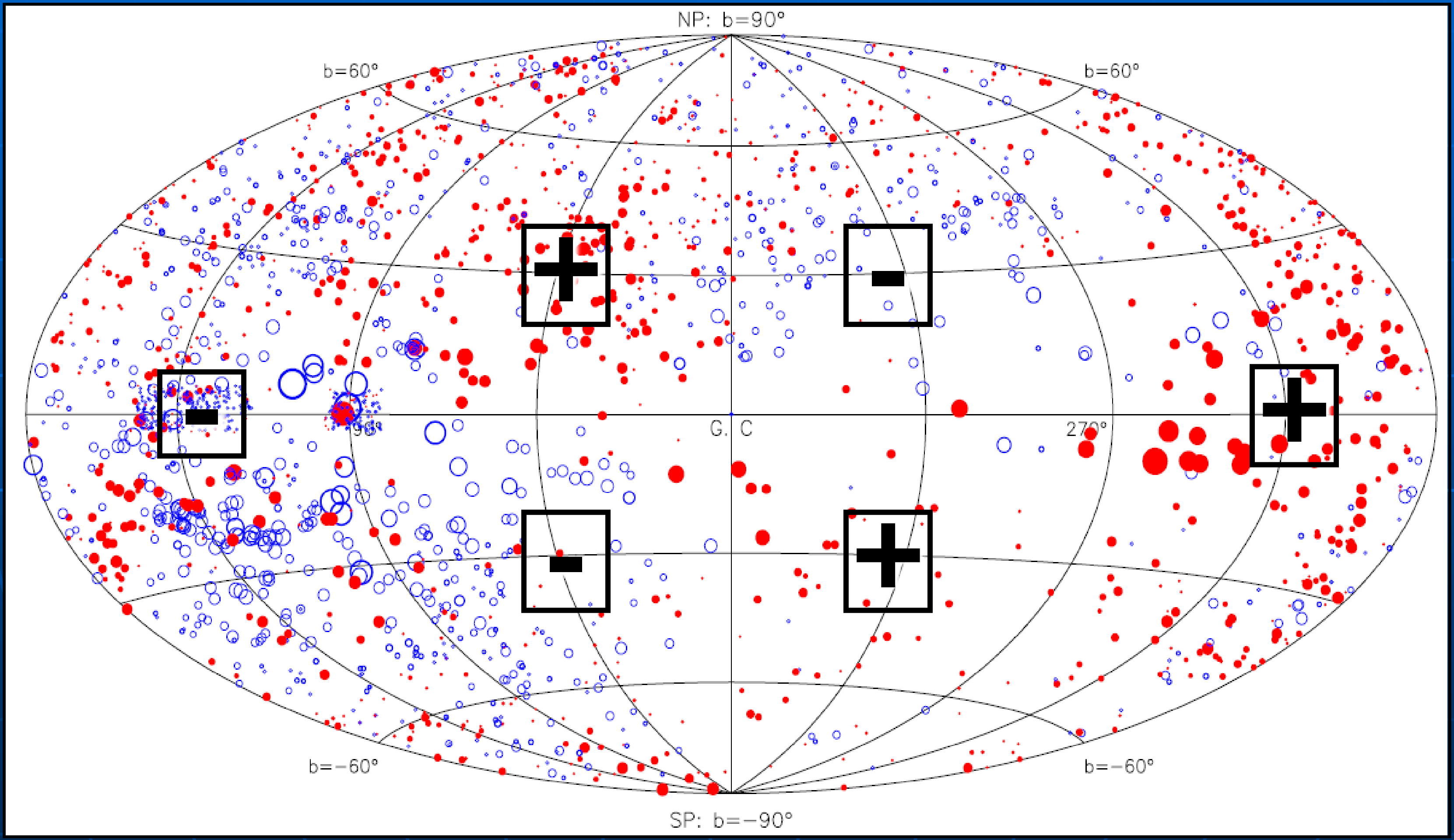
equatorial coordinates

- data from March 2008 to May 2009
- 324 days livetime
- $15 \cdot 10^9$ events
- median angular resolution ~ 3°
- median CR energy ~ 20 TeV

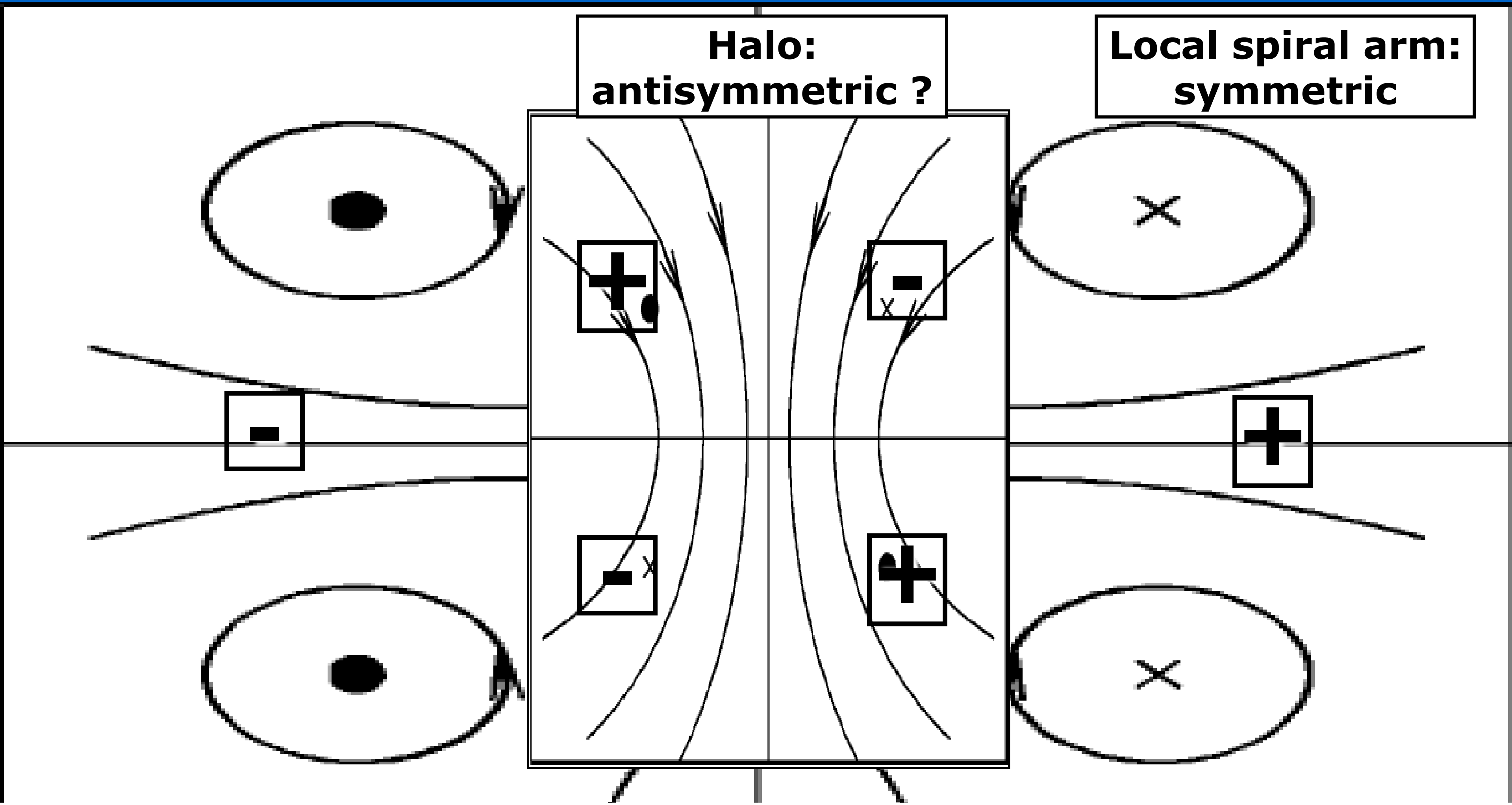
RMs of background sources ($B_\parallel$)

≈2000 sources (≈0.05 sources per deg^2)

Han et al. 2007



RMs of background sources ($B_{\parallel}$)



Evidence for an antisymmetric (dipolar) halo field ?

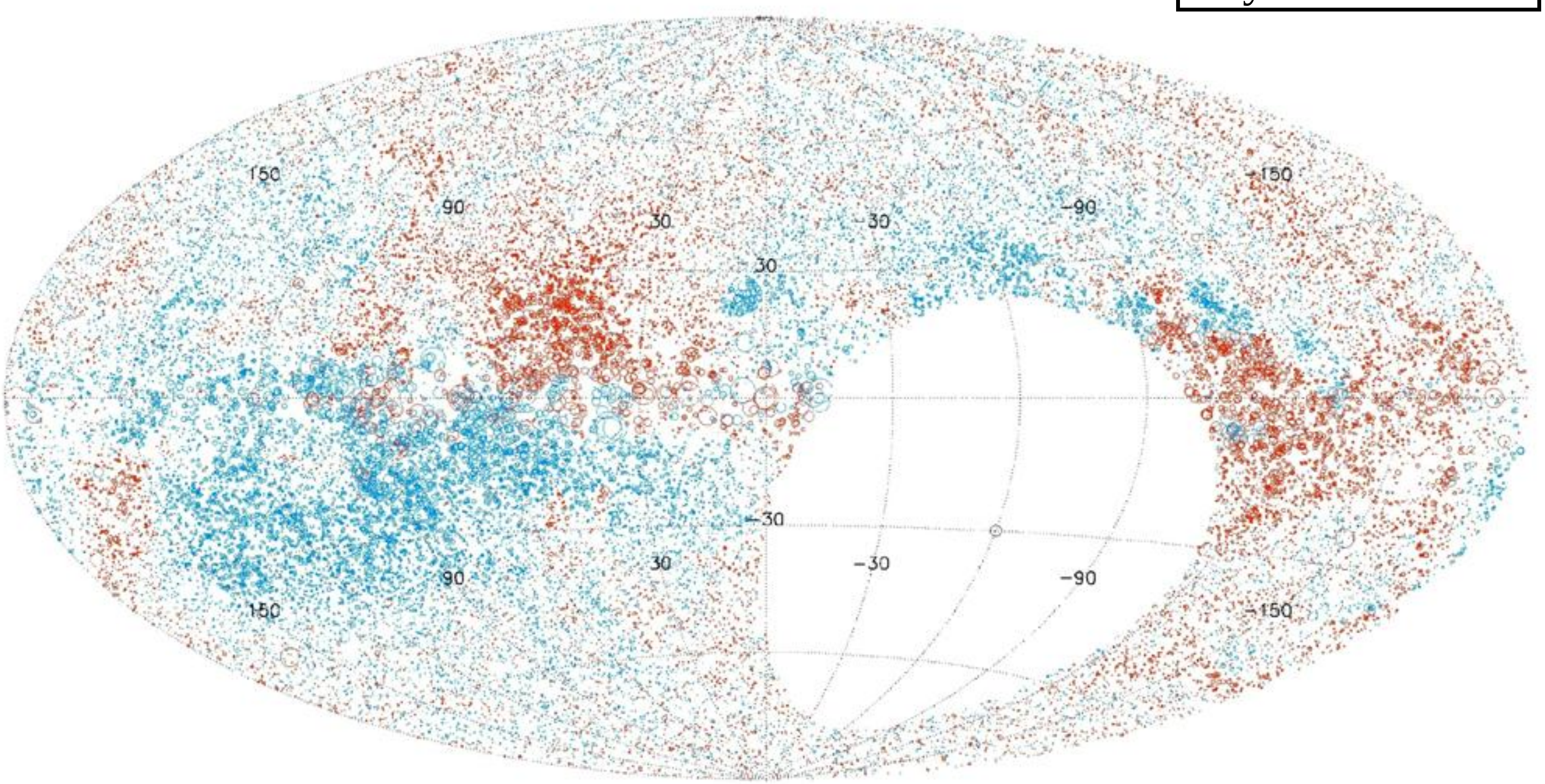
→ *denser RM grid needed*

RMs of background sources ($B_{\parallel}$)

(VLA NVSS 21cm)

≈37000 sources (≈1 source per deg^2)

Taylor et al. 2009



Faraday rotation grids with the SKA

All-sky survey (1h per field):

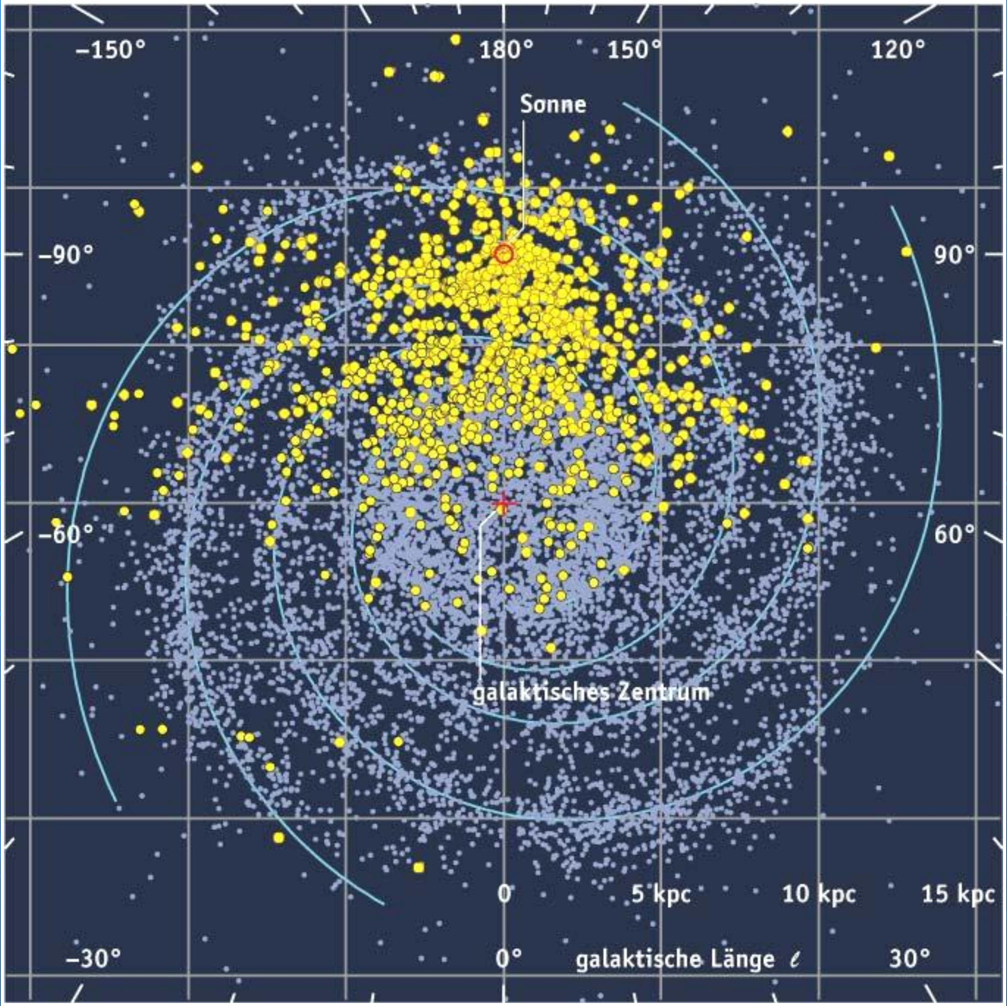
- ≈ 2000 polarized sources per deg^2
  (≈ 0.5 RMs per $arcmin^2$)
- **Total number of RMs: ≈ $8\ 10^7$!**

Deep fields (12h integration):

- ≈ 8000 polarized sources per deg^2
  (≈ 2 RMs per $arcmin^2$)

SKA: RM grid of pulsars in the Milky Way

Known pulsars and pulsars to be detected with the SKA (≈30000)



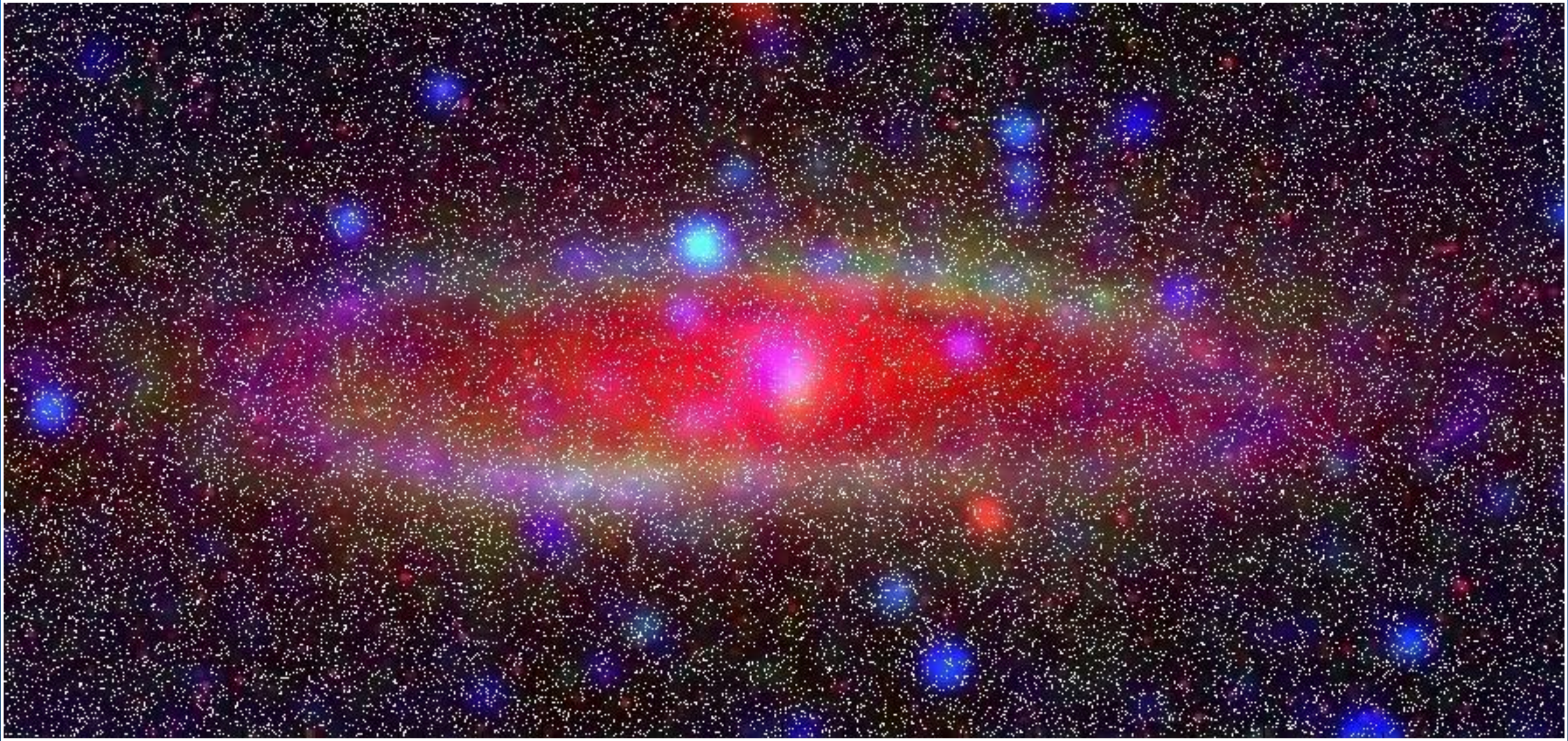
Cordes 2001

Origin of magnetic fields in galaxies

(see also talks in Session 5)

- Large-scale patterns of RM are observed: regular fields, probably generated by the galactic dynamo
- Superpositions of dynamo modes are needed to explain the data
- Large-scale field reversals (like in the Milky Way) are rare
- *But: statistics are still poor*
- *Little is known about the evolution of magnetic fields*

SKA: RM grid of galaxies
(simulation by Bryan Gaensler)



≈10000 polarized sources shining through M31

RM grids: Measuring field structures via polarized background sources

Stepanov et al. 2008

Recognition of patterns of regular fields in galaxies:

- At least 10 RM values per galaxy needed
- Can be applied to galaxies out to ≈100 Mpc distance

3-D reconstruction of field patterns in galaxies:

- A few 1000 RM values per galaxy needed
- Can be applied to galaxies out to ≈10 Mpc distance

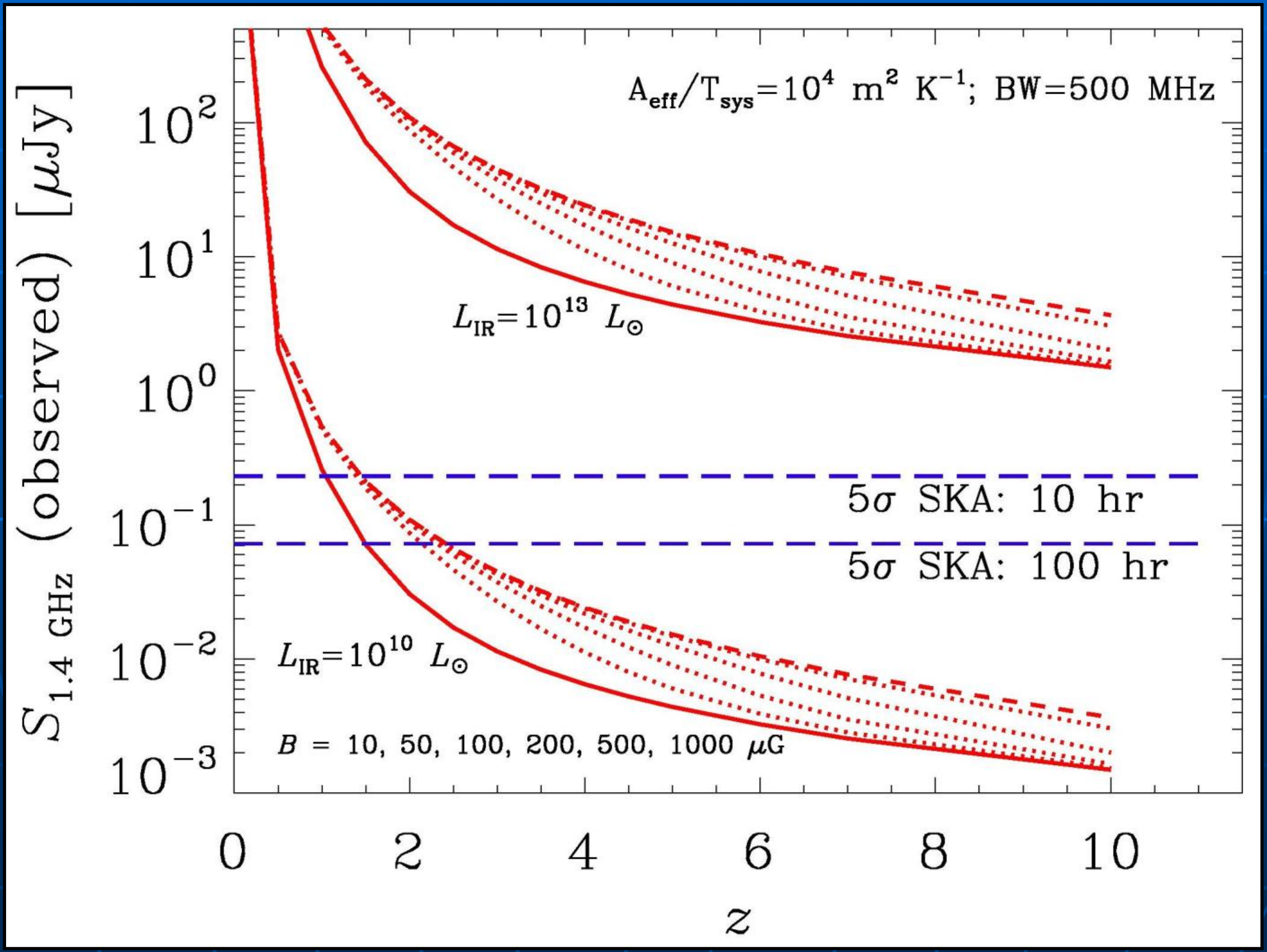
Recognition of turbulent field patterns in galaxy clusters:

- Turbulence spectrum of ICM magnetic fields

Krause et al. 2009

Observation of distant galaxies with the SKA

Murphy 2009



Evolving galaxies:
Simulated radio emission and RM at 5 GHz
(rest frame)

Arshakian et al. 2011

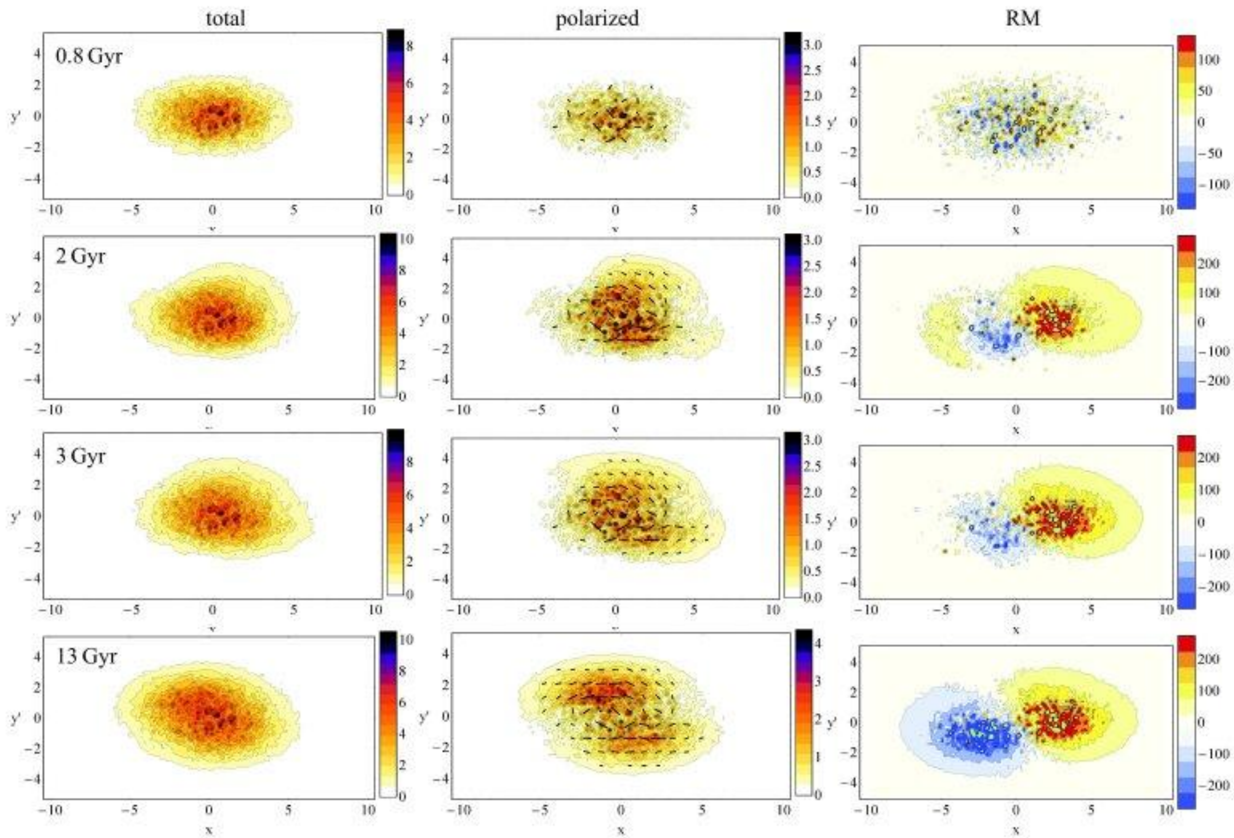
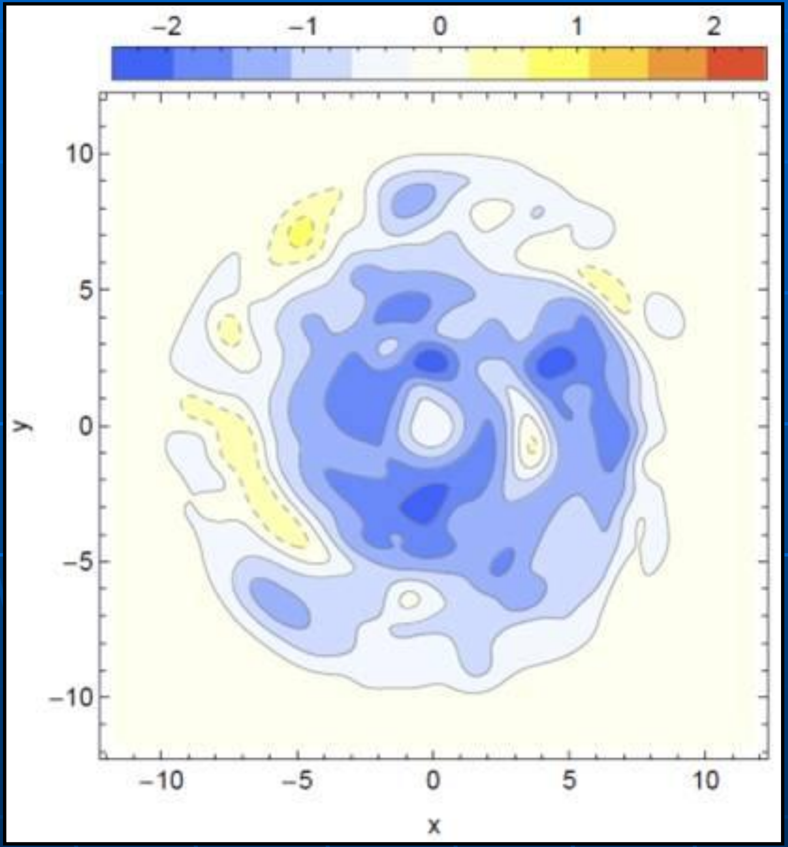


Fig. 4 The *rest frame* simulations of the total intensity (*left panel*), polarization (*middle panel*), and Faraday rotation (*right panel*) at **5 GHz** for a galaxy with an inclination angle of 60°, turbulent (6.2 μG) and regular (from 1.3 μG to 3.1 μG, see Table 2) magnetic fields, and star-formation rate of 10 $M_\odot$ yr^{-1} are shown for 0.8 Gyr, 2 Gyr, 3 Gyr, and 13 Gyr after disk formation. The frame units are given in kpc. The color bars in the first and second columns (total and polarized intensity) are given given in arbitrary units. The color bar of the third column (Faraday rotation measure) is given in units of rad m^{-2}.

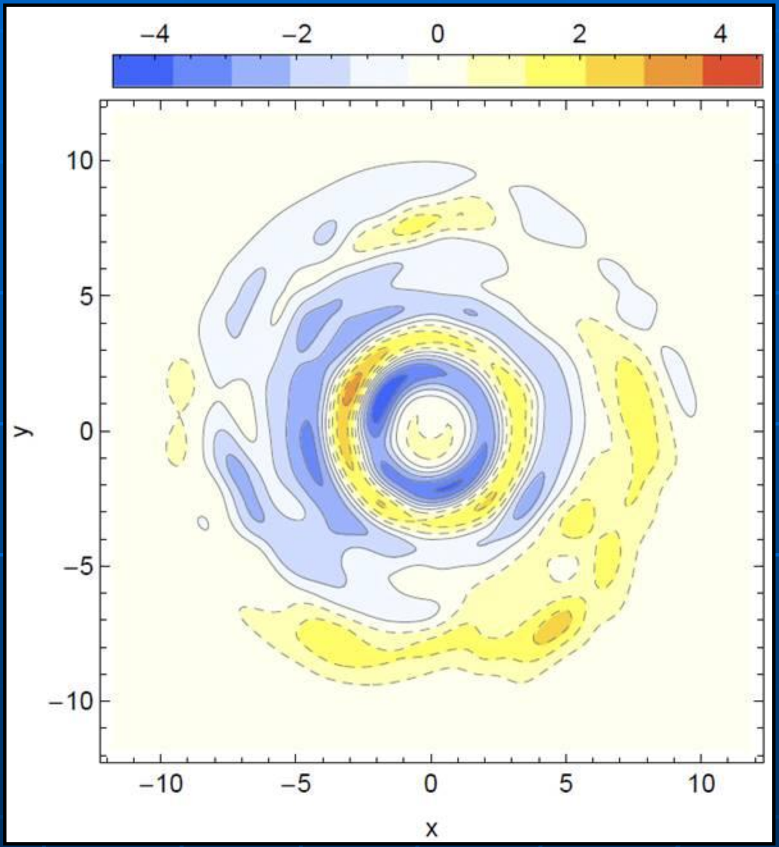
Dynamo model:
Moderate and high dynamo numbers R

(present epoch)

Moss et al. 2011



Axisymmetric spiral field



Spiral field with large-scale reversal

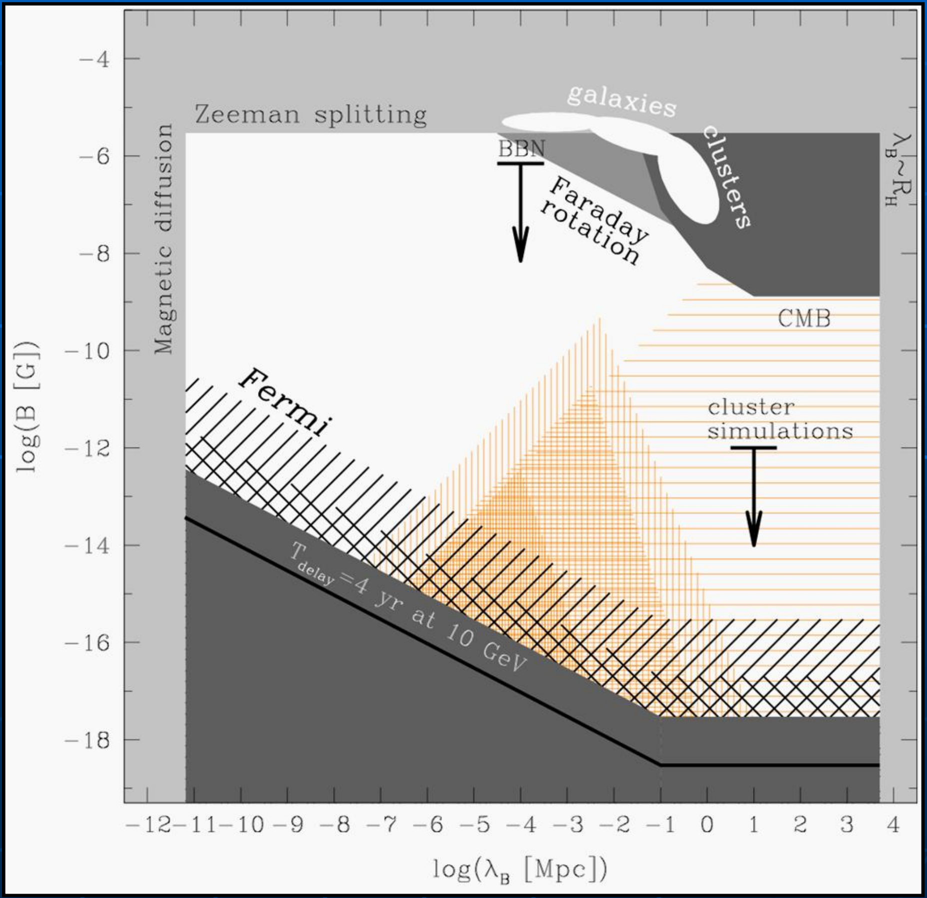
Galaxy clusters

see talks in Session 6

Particle scattering by IGM magnetic fields

(see also review talk by Michael Kachelriess)

Neronov & Vovk 2010



Blazars:
Detected at TeV γ-rays by HESS, but not in the GeV range by FERMI:

$B_{IGM} \geq 10^{-17...-16}$ G

SKA may detect an IGM field of $\geq 10^{-9}$ **G** from statistical analysis of a large number of RMs of distant quasars

Observation of magnetic fields with the SKA

Deep SKA observations :

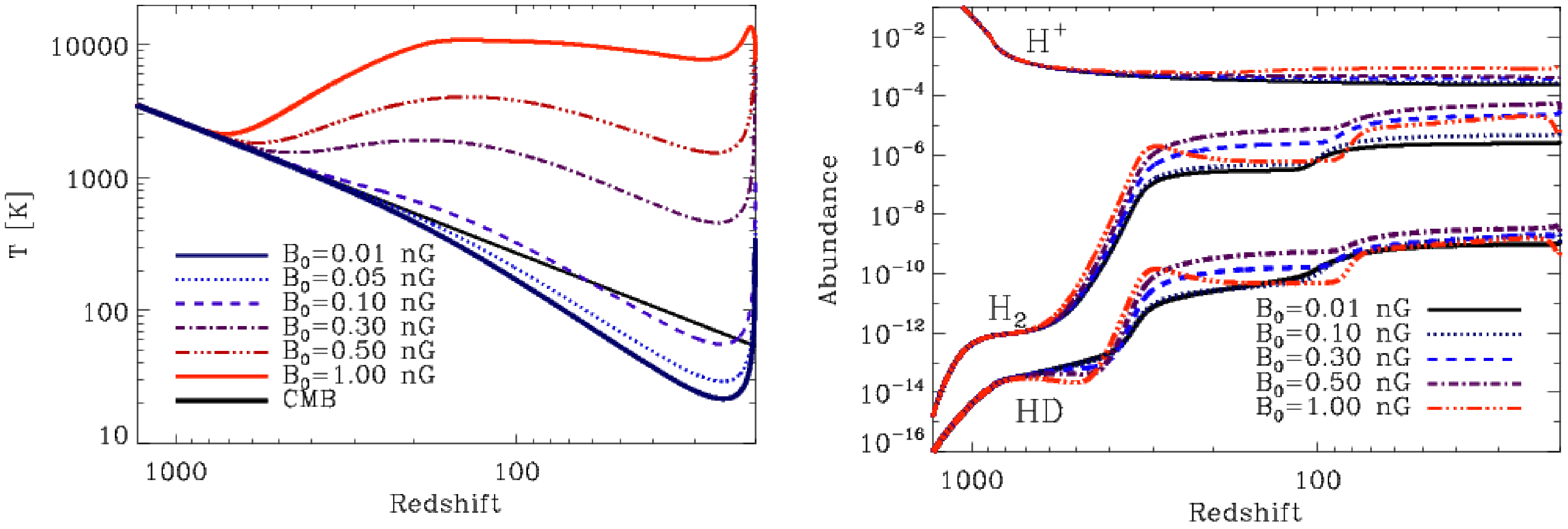
- Total synchrotron emission of galaxies (z < 3-5)
- Polarized synchrotron emission of galaxies (z < 3)
- Large-scale RM patterns of galaxies (z < 1)
- Faraday rotation of background quasars in galaxies, galaxy clusters and IGM fields (z < 5)

SKA:

The evolution of magnetic fields in galaxies and galaxy clusters can be measured

Influence of primordial magnetic fields on the IGM temperature during the EoR

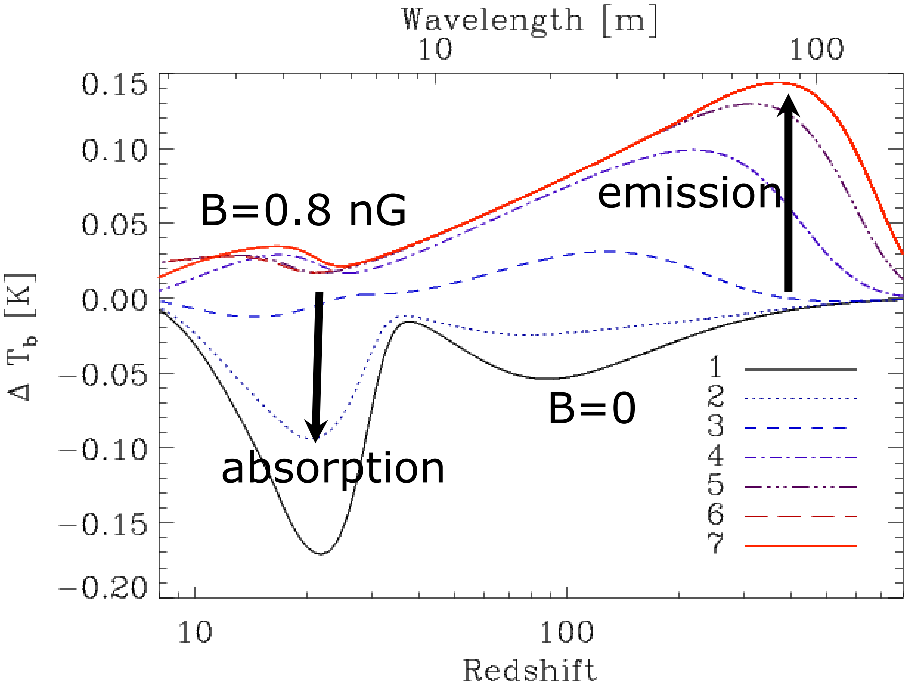
Schleicher et al. 2009 – see his talk in Session 5



Strong impact of primordial magnetic fields on gas temperature and chemistry

HI brightness temperature in the EoR

Schleicher et al. 2009 – see his talk in Session 5



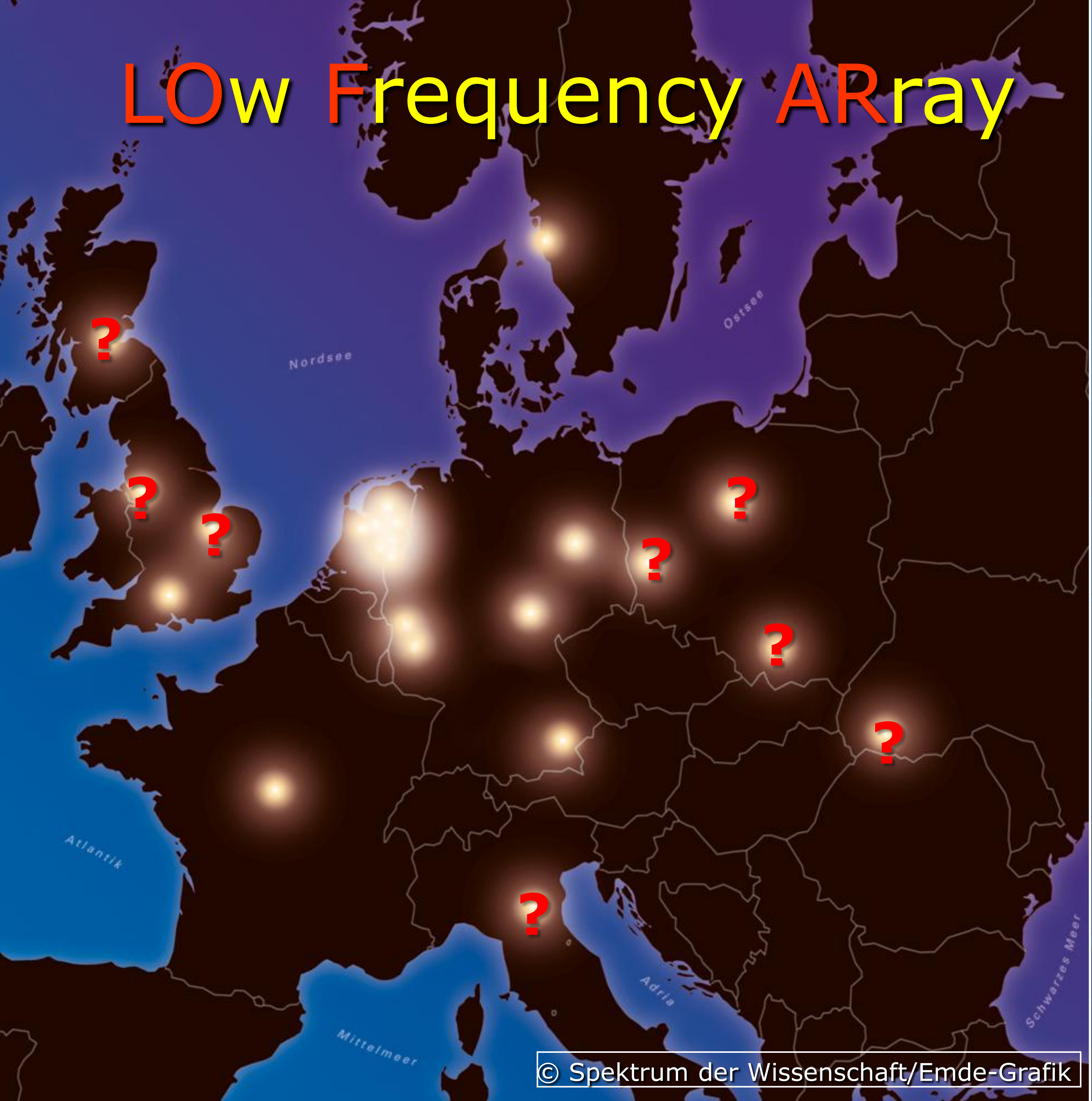
Strong field:
→ no absorption at small z, but emission at higher z

Ideal probe: Observations at z ≥ 50 (≤ 30 MHz): Extend the frequency range of the SKA?

SKA Pathfinders

- Europe: *Low Frequency Array* (LOFAR) (30-240 MHz)
  Aperture Tile In Focus (APERTIF) (1.0-1.75 GHz)
- China: *Five hundred meter Aperture Spherical Telescope* (FAST) (0.3-2 GHz)
- USA: *Extended Very Long Array* (EVLA) (1-50 GHz),
  Long Wavelength Array (LWA) (10-88 MHz),
  Allen Telescope Array (ATA) (1-10 GHz)
- Australia: *Murchison Widefield Array* (MWA) (80-300 MHz)

LOw Frequency ARray



LOFAR

see talks by
James Anderson
& David Mulcahy

APERTIF
(Aperture Array In Focus, Netherlands)

12 Westerbork antennas of 25m diameter, max. baseline 1.6 km, focal-plane arrays (8 deg^2), $\nu \approx 1000$ - 1750 MHz, start in 2013

Proposed projects:

FRIGG: *Faraday Rotation Investigation of Galaxies and Groups*

- Mapping and RM grids of
  4 galaxies and 5 galaxy groups

BEOWULF: *B-field Estimation and Observational Wide-field Understanding of Large-scale Faraday-structure*

- Mapping and RM grid of the Perseus-Pisces supercluster

SKA Precursors

ASKAP
(Australian SKA Pathfinder)

36 antennas of 12m diameter, max. baseline 6km, frequency range 0.7 - 1.8 GHz, 30 deg^2 field of view

POSSUM: *POlarization Survey of the Universe´s Magnetism*

- All-sky polarized continuum survey at 1.4 GHz
- Rotation measures for ≈ 1.5 million sources (≈ 80 RMs/deg^2 in 12h)

MeerKAT
(South African SKA pathfinder)

80 antennas of 12m diameter, max. baseline 60km, frequency range 0.6 - 14.5 GHz, 1 deg^2 field of view

Deep imaging of synchrotron polarization & RM grids of galaxies and galaxy clusters ($\approx$400 RMs/deg^2 in 12h)

7-KAT

Summary: Future observations

Diffuse polarization:

- Polarization survey of distant galaxies and clusters:
  ASKAP, APERTIF, MeerKAT, **SKA**
- Detailed magnetic field structure in nearby galaxies and clusters:
  EVLA, LOFAR, **SKA**
- Detailed magnetic field structure in molecular clouds: ALMA, **SKA**

RM grids of background sources:

- Field patterns in Milky Way, galaxies and clusters:
  EVLA, ASKAP, APERTIF, MeerKAT, **SKA**
- Evolution of galactic and intergalactic magnetic fields: **SKA**

Pulsar RMs:

- Structure of the Milky Way's field: LOFAR, ASKAP, APERTIF, **SKA**

We are entering a Golden Age of cosmic magnetism observations