Magnetic Fields in Evolving Spiral Galaxies and their Observation with the SKA

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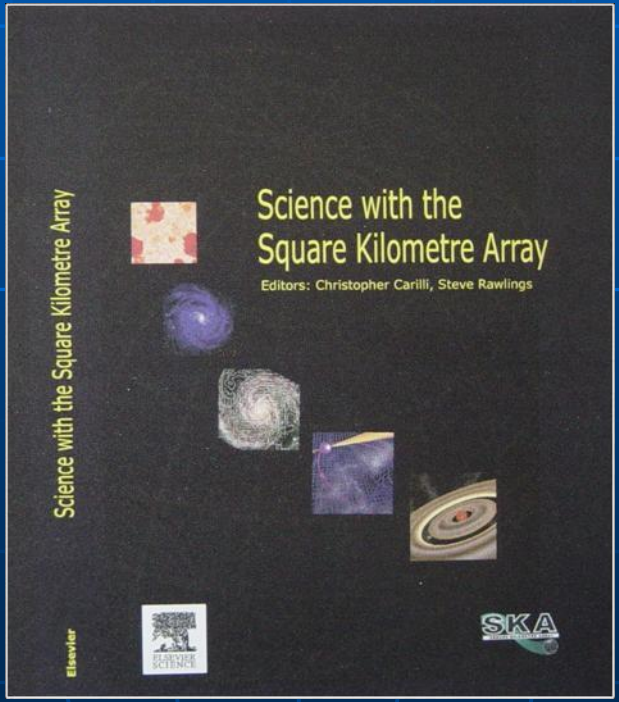
MPIfR Bonn & SKA Science Working Group

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 ?

Observing Cosmic Magnetism with the SKA

(selected as a Key Science Project in 2003)



SKA Magnetism Science Team

Name	Institution
Melanie Johnston-Hollitt – Co-Chair	Victoria Univ. Wellington
Federica Govoni – Co-Chair	INAF-OA Cagliari
Tobia Carrozzi	
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Bryan Gaensler	Univ. Sydney
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- Annalisa Bonafede, Univ. Hamburg
- Dominic Schnitzeler, MPIfR
- Rainer Beck, MPIfR
- *Ann Mao, Madison/MPIfR*

SKA Magnetism Science Team: Research Interests

1. Magnetic fields in the Milky Way and nearby galaxies:

- Role of gas flows, shocks turbulence, dynamo action for field amplification and ordering
- Dynamical effects of magnetic fields in galaxy formation, disk stability, triggering of star formation, cosmic-ray acceleration and propagation, inflows / outflows
- *Magnetic fields in gas clouds (Zeeman splitting)*

2. Magnetic fields in distant galaxies:

- Amplification by starbursts and interactions
- First appearance of ordered fields

SKA Magnetism Science Team: Research Interests

3. Magnetic fields in galaxy clusters:

- Turbulent fields in cluster halos
- Field compression in cluster relics
- Field compression in interacting galaxies

4. Magnetic fields in intergalactic filaments:

- Tracing intergalactic shocks
- Role in structure formation

5. *Magnetic fields in AGNs and jets*

SKA Magnetism Science Team: Priorities for SKA1 (draft)

- All-sky survey of polarized sources and their Faraday rotation measures (RM)
  - SKA1-Survey
  - 650-1670 MHz (PAF Band 2)

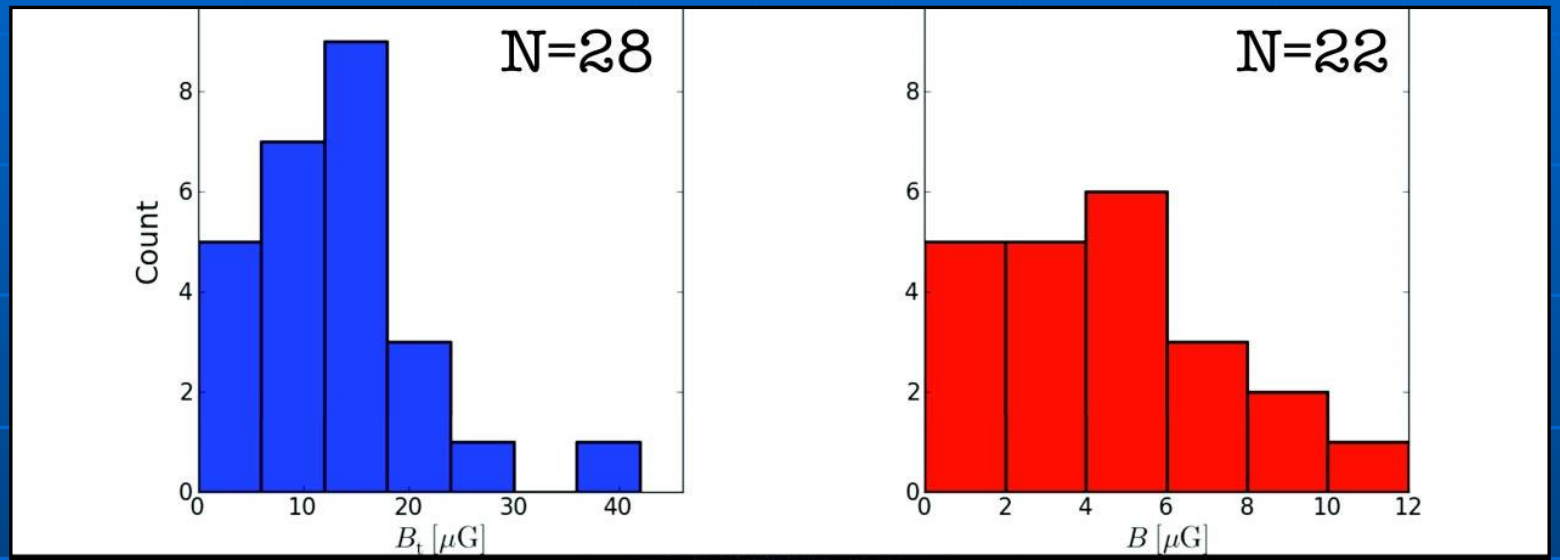
- Deep survey of polarized sources and RMs in selected fields
  - SKA1-Mid
  - 950-1760 MHz (Band 2)

- Deep search for polarized emission of intergalactic filaments, galaxy groups and interacting galaxies
  - SKA-Mid
  - 350-1050 MHz (Band 2)

- High-resolution imaging of galaxies, galaxy clusters and AGNs
  - SKA-Mid
  - 4.6-13.8 GHz (Band 5)

Present-epoch galaxies: Strengths of total and ordered fields

(compilation by Fletcher 2010)



Average: 16 ±15 μG

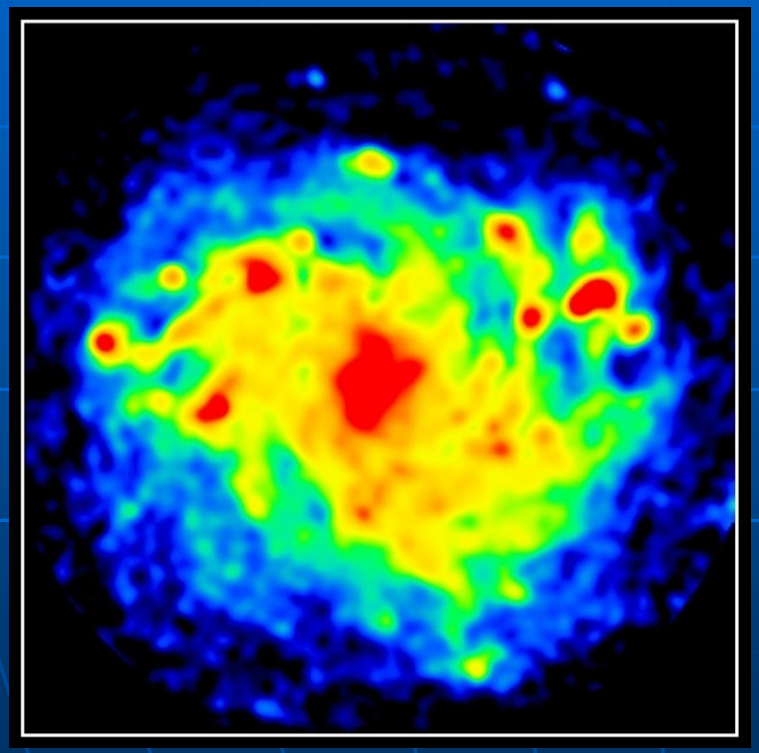
Excl. starburst: 12 ±6 μG

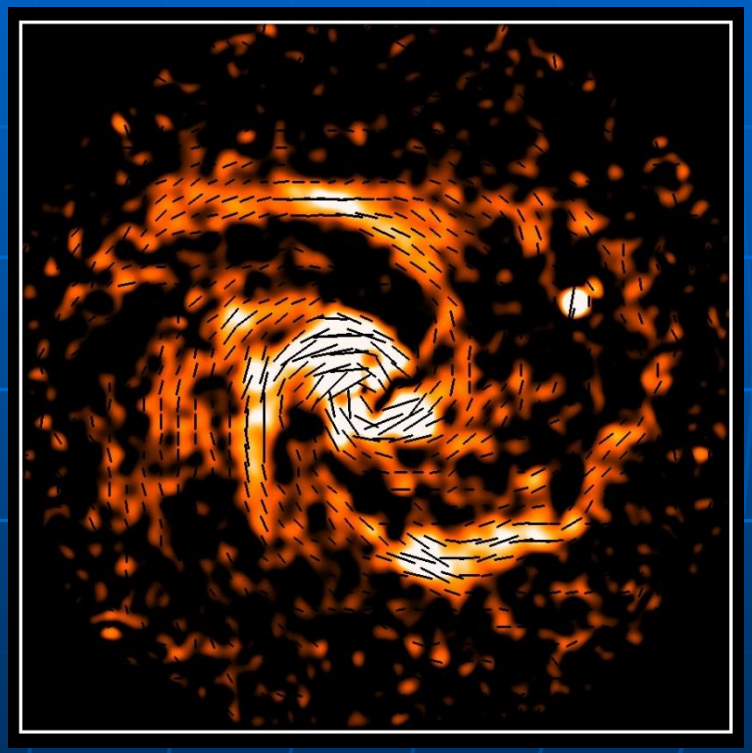
Average: 4 ±3 μG

Magnetic fields in nearby galaxies are strong and dynamically important

Nearby galaxy NGC 6946:
Total and polarized synchrotron emission
(VLA+Effelsberg 5 GHz)

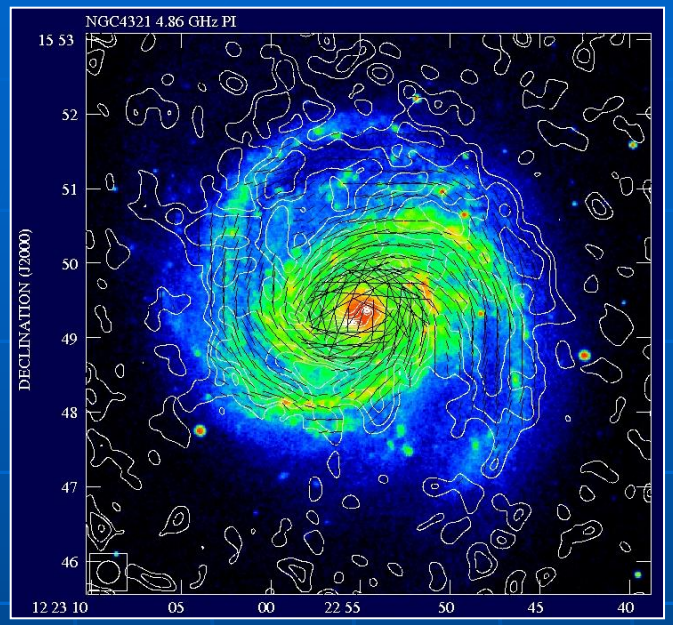
Beck & Hoernes 1996

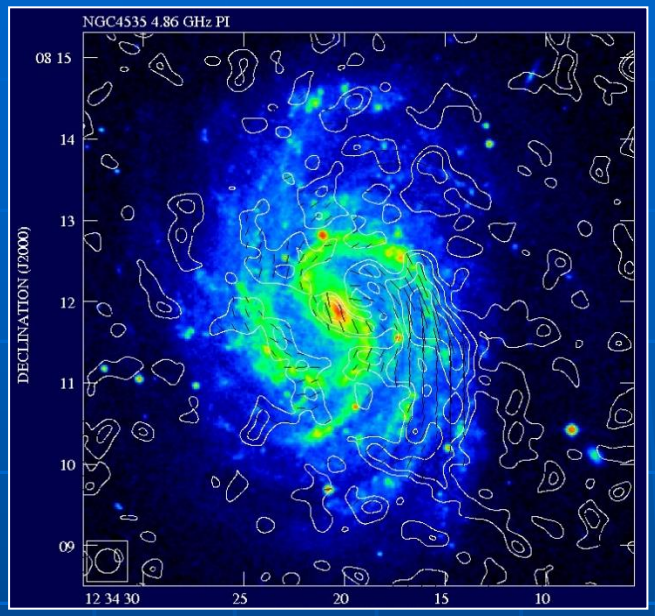




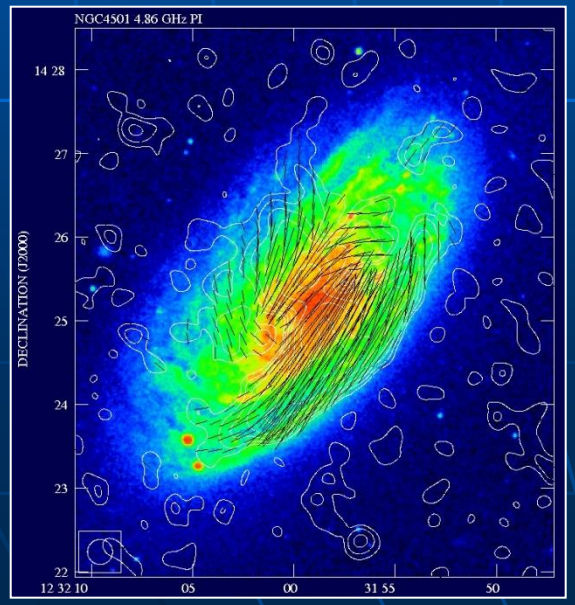
- The turbulent field is related to star formation
- The ordered field is related to spiral arms

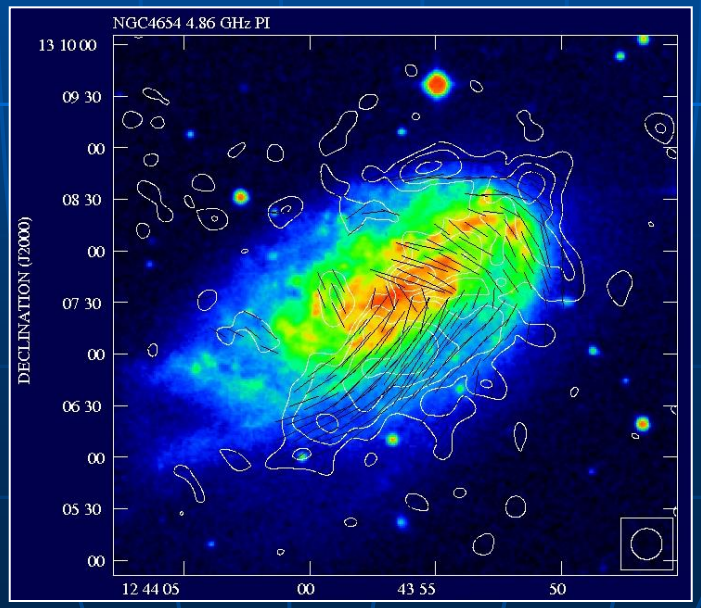
Virgo polarization survey (VLA 5 GHz)





Vollmer et al. 2007, 2013





Field compression by interaction

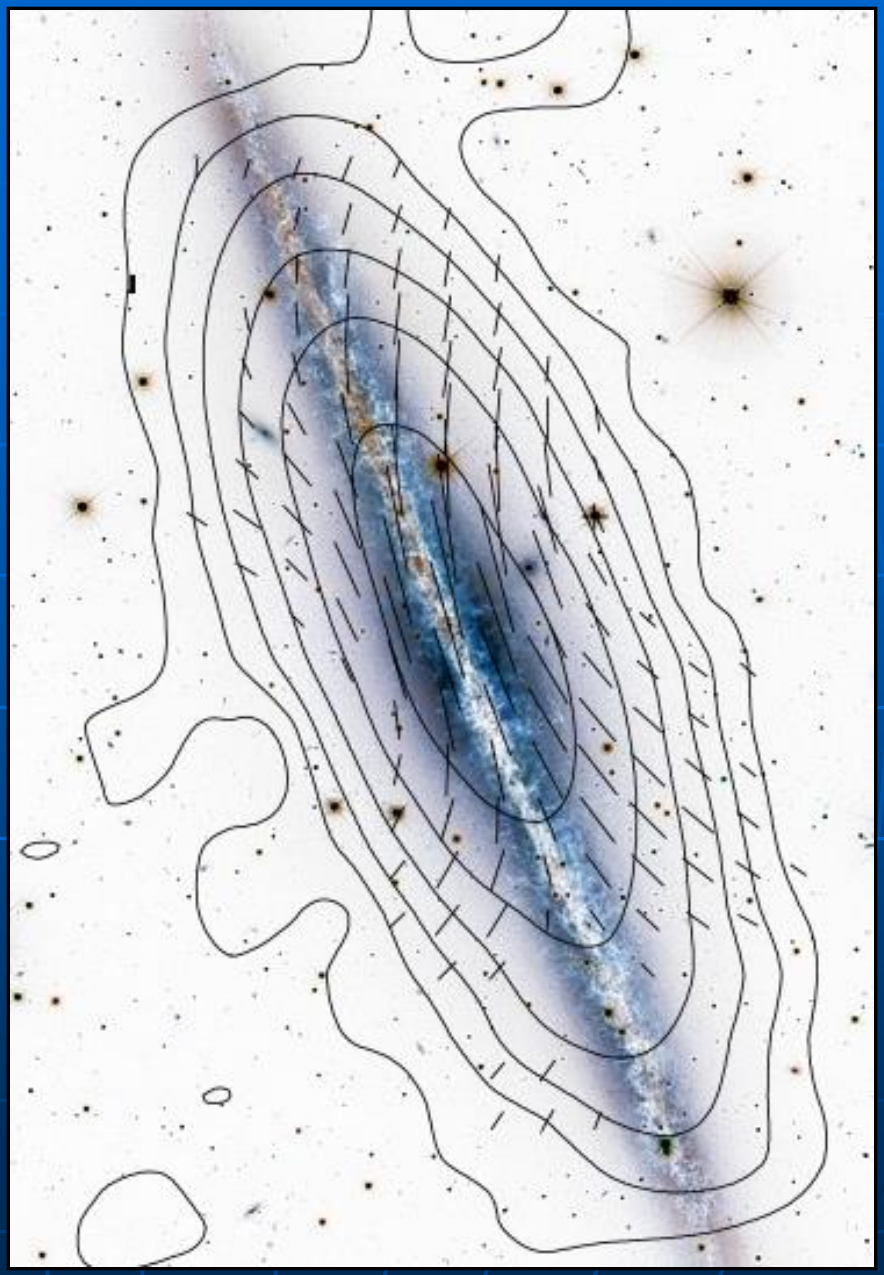
Milky Way-type galaxy NGC 891

(Effelsberg 8 GHz)

Krause 2007

X-shaped magnetic field in the halo:

Signature of outflows



Magnetic field model for the Milky Way

The Milky Way is similar to external galaxies – except for two field reversals

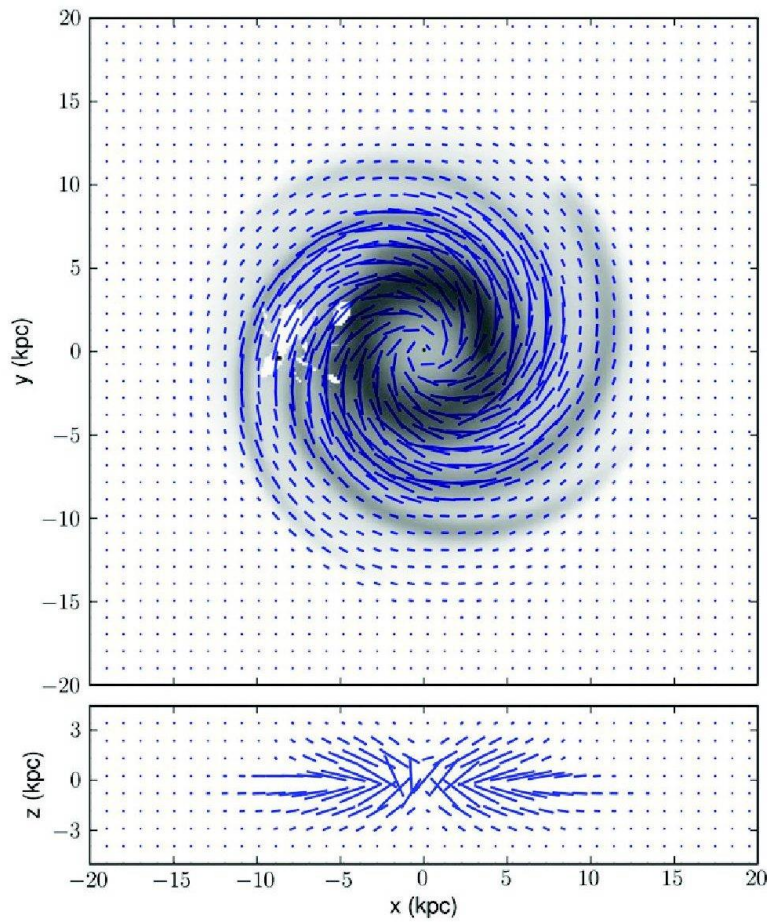


Figure 9. Milky Way as seen (in polarization) by an extragalactic observer, face-on (above) and edge-on (below). Plotted "bars" (sometimes referred to as "vectors") are the would-be-observed polarization angles, rotated 90° to line up with the magnetic field orientation. Lengths of bars are proportional to polarization intensity. Faraday depolarization and beam depolarization are neglected. The face-on plot is overlaid on the NE2001 thermal electron distribution.

Jansson & Farrar 2012

Generation and amplification of cosmic magnetic fields

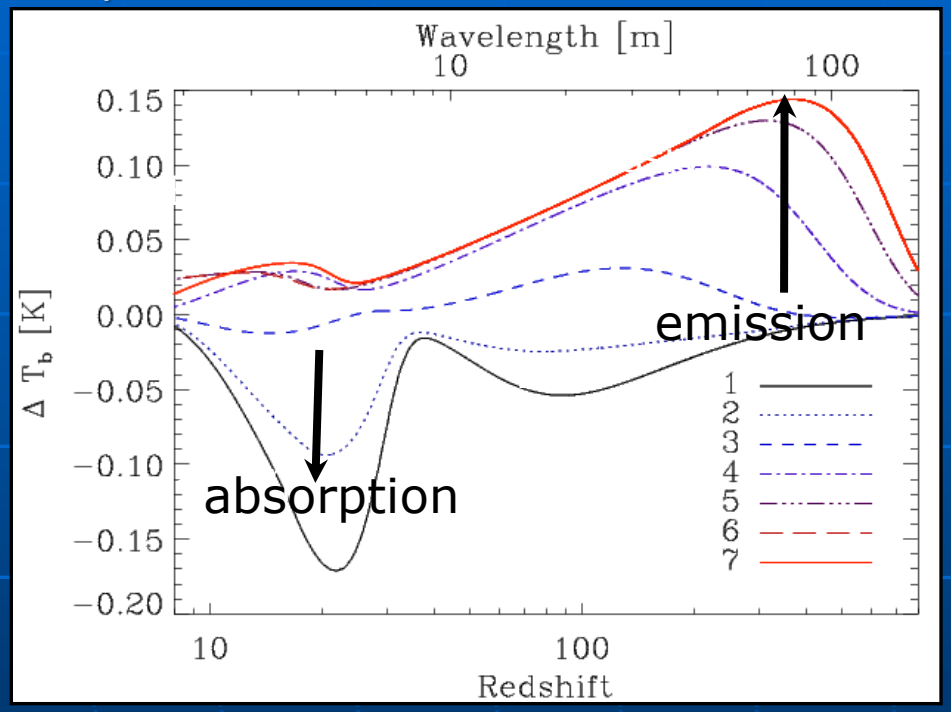
Stage 1: Field seeding

Stage 2: Field amplification

Stage 3: Field ordering

Primordial seed 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%

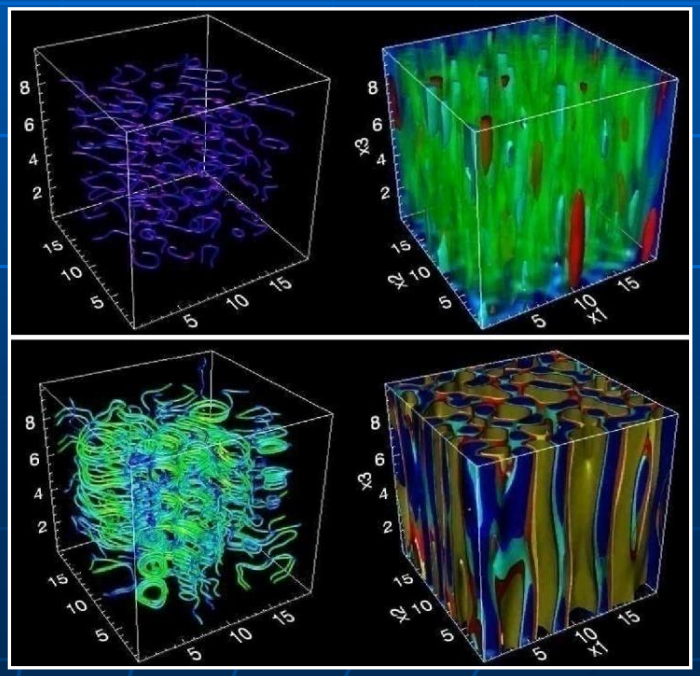
Strong impact on predicted HI spectra

Evolution of magnetic fields (1)

Phase 1 ($z \approx 40$-20): Formation of halos

- Generation of seed magnetic fields
  by the Biermann battery
  or the Weibel instability
  or plasma fluctuations

- Amplitude: $\approx 10^{-18}$ G - 10^{-6} G (locally)



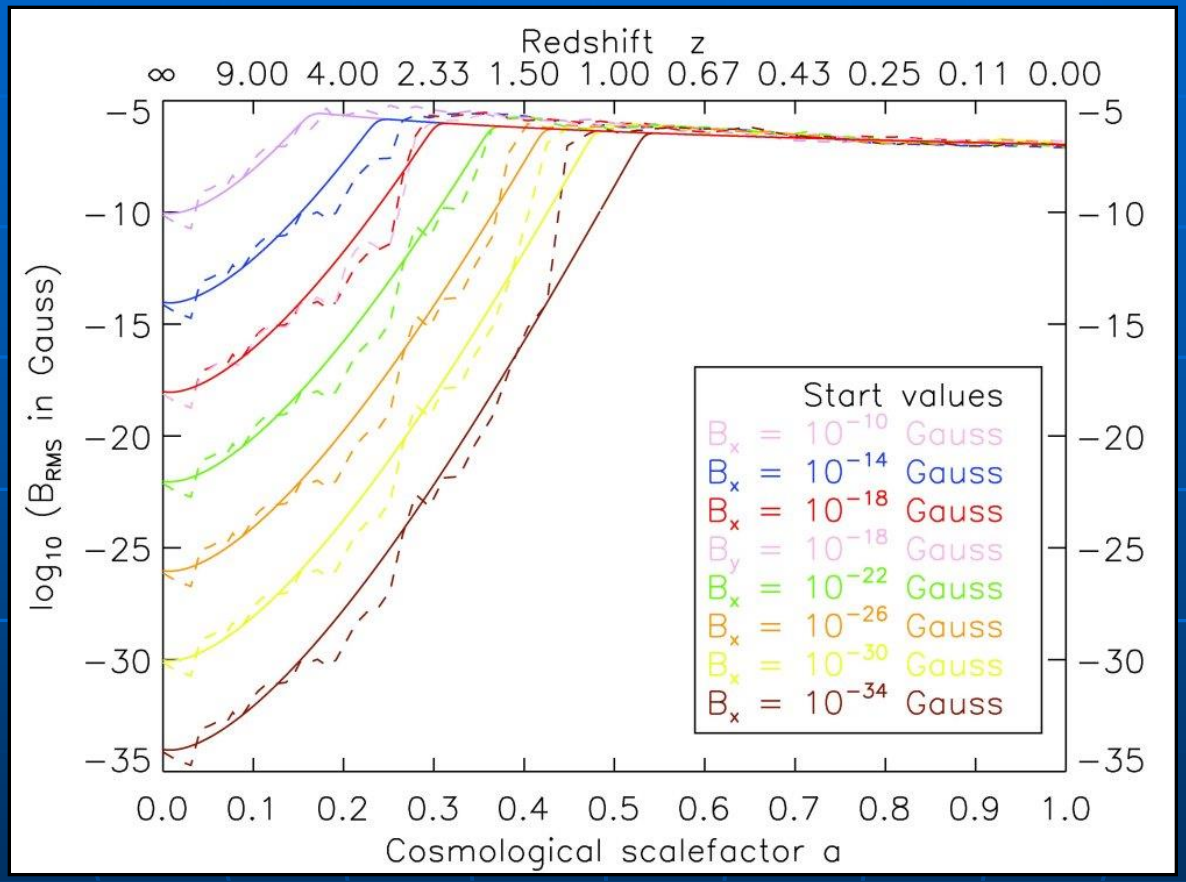
Medvedev et al. 2004

Evolution of magnetic fields (2)

Phase 2 ($z \approx 20$-10): Merging of halos and virialization:

- Amplification of seed fields by turbulent gas flows (small-scale dynamo)
- Turbulence is driven by accretion shocks and SN explosions
- Timescale of amplification: $\approx 3\ 10^8$ Gyr
- Amplitude: $\approx 10^{-5}$ G

Simulation of a small-scale dynamo in young galaxies



A. Beck et al. 2012

Equipartition with turbulent energy is reached within $\approx 10^8$ yr, almost independent of the seed field

Evolution of magnetic fields (3)

Phase 3 ($z \approx 10$-2): Formation of disks

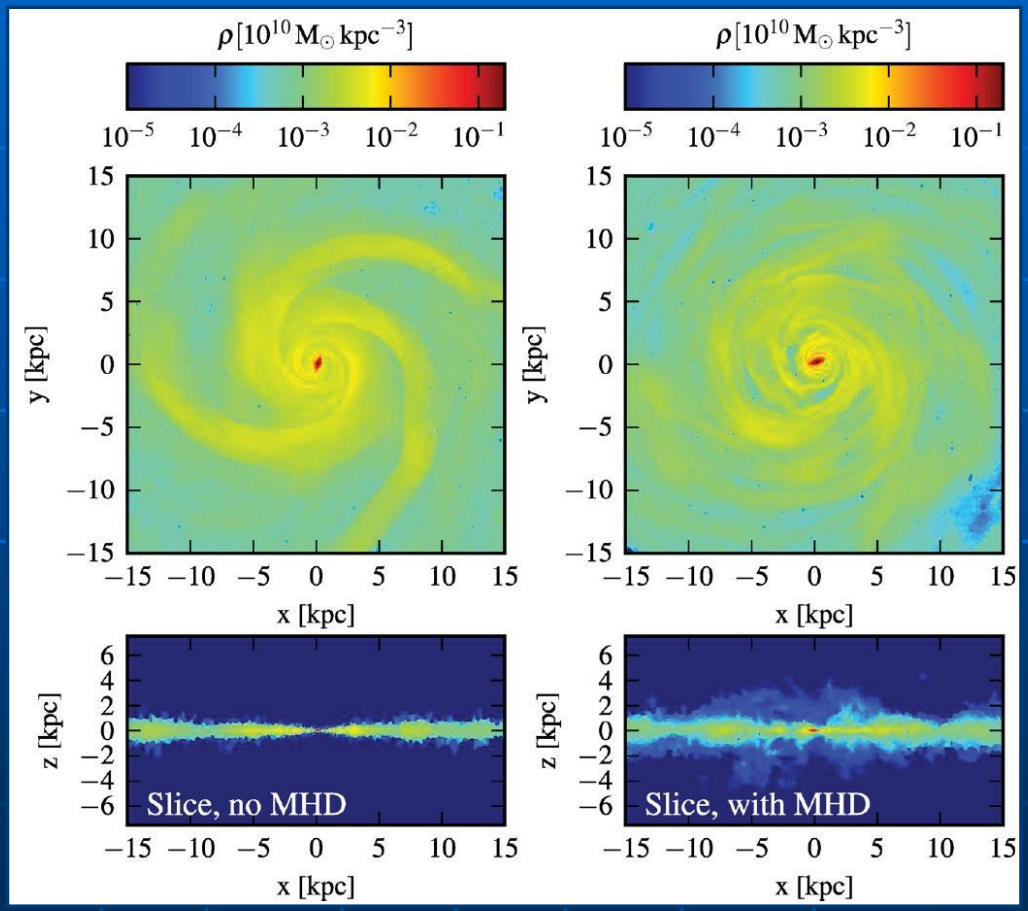
- Turbulence is driven by SN explosions and MRI in the disk
- Field ordering (stretching) by shear
- Field ordering (regular fields) by the mean-field (large-scale) dynamo
- No further amplification needed
- Timescale of ordering: ≈ 1-$2\ 10^9$ Gyr

MHD-MRI model of spiral galaxies
(without large-scale dynamo action)

Pakmor & Springel 2013

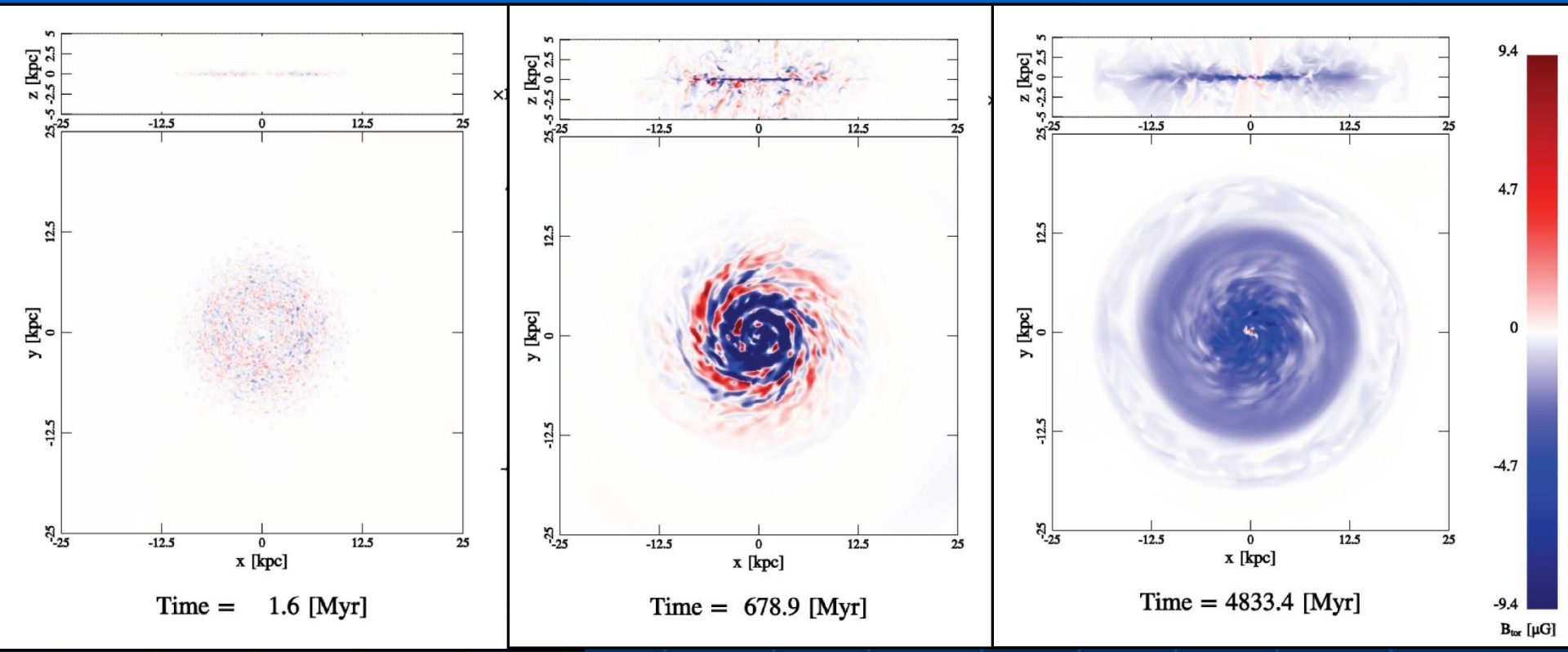
The magnetic field affects the galaxy evolution:

- Spiral arms are more patchy
- Star-formation rate is lower
- Vertical outflows occur



Global cosmic-ray driven large-scale dynamo model

Hanasz et al. 2009



Predictions of the dynamo model

Arshakian et al. 2009

- Strong turbulent magnetic fields at $z < 10$
  → Total synchrotron emission from young galaxies can be observed at **$z < 10$**

- Strong but "spotty" regular fields at $z < 3$
  → Polarized radio emission and *some* Faraday rotation can be observed at **$z < 3$**

- Large-scale coherent regular magnetic fields in dwarf or Milky Way-type galaxies at $z < 0.5$
  → Large-scale patterns of Faraday rotation can be observed at **$z < 0.5$**

- Large galaxies (>15 kpc) may not yet have generated fully coherent fields

- Major mergers may disrupt regular fields, but increase the turbulent field strength (Moss et al., submitted)

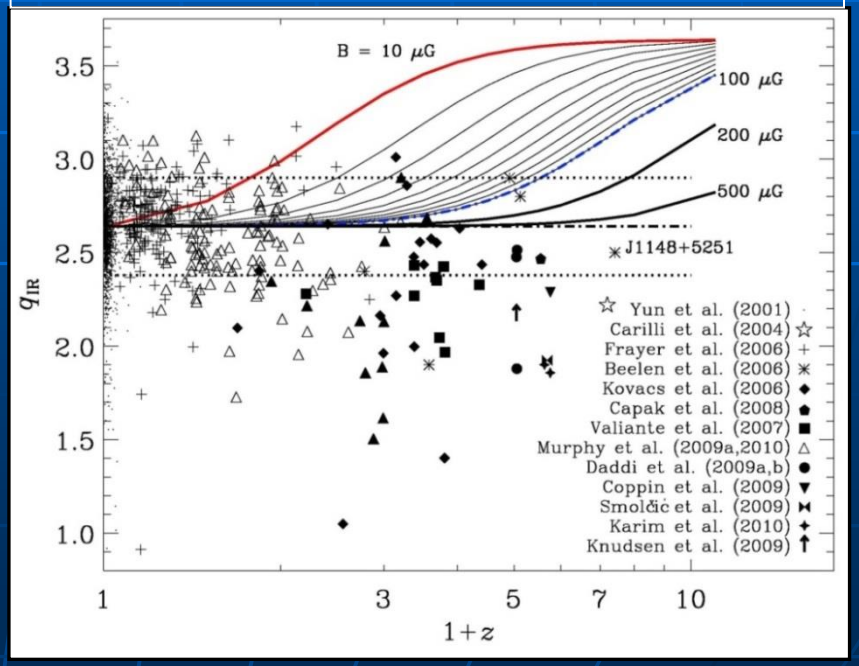
The radio-FIR correlation: Magnetic fields in distant galaxies

- Total radio synchrotron emission should break down at some redshift z due to Inverse Compton loss with the CMB background
- FIR/radio ratio should increase with z
- This is ***not*** observed:
  Magnetic fields must still be strong in distant galaxies:

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

- Synchrotron emission seems to even increase relative to FIR
- *But this cannot hold at very high redshifts*

q: ratio of FIR/radio luminosities



Murphy 2009

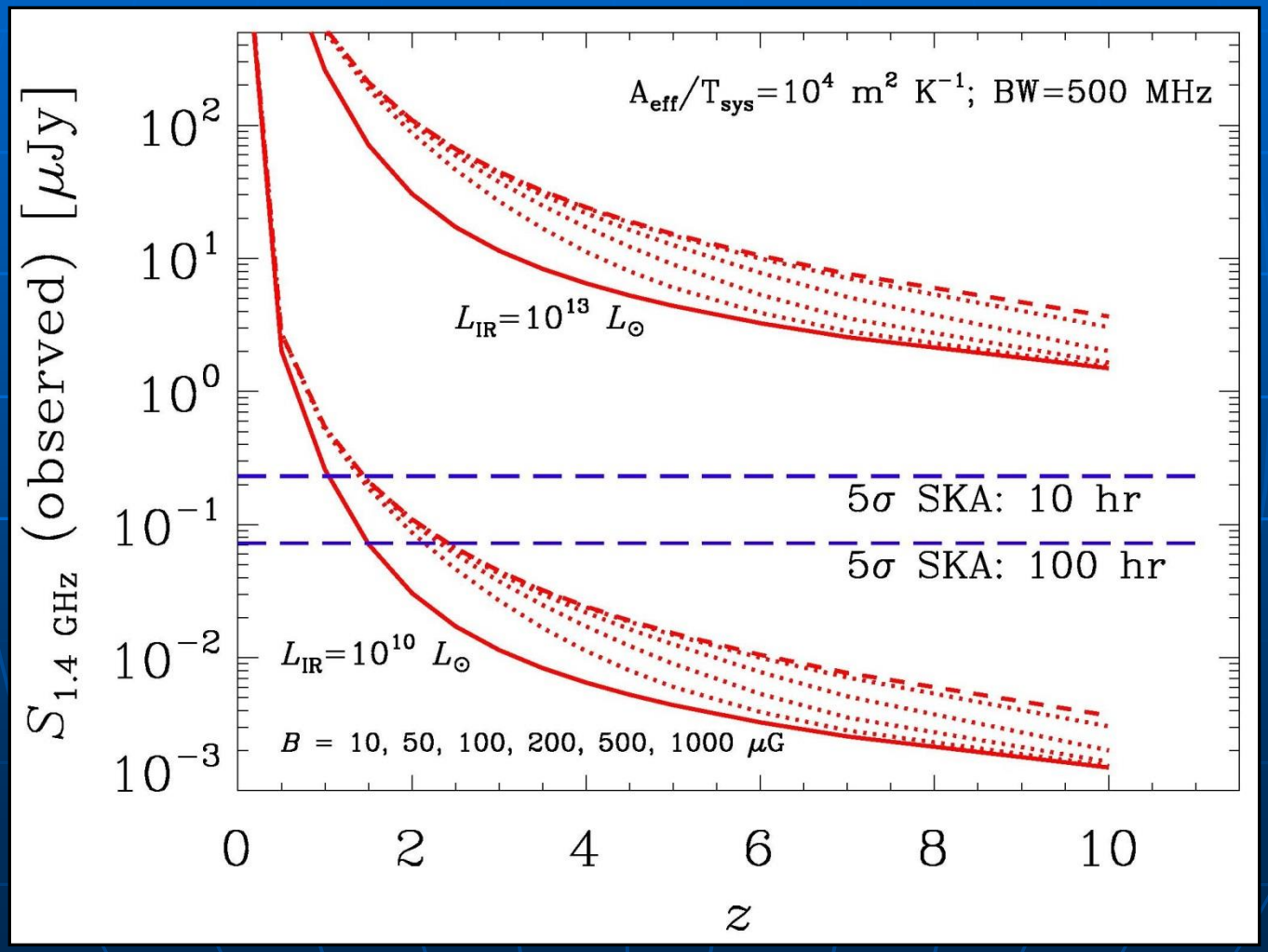
The radio-FIR correlation: Magnetic fields in distant starburst galaxies

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

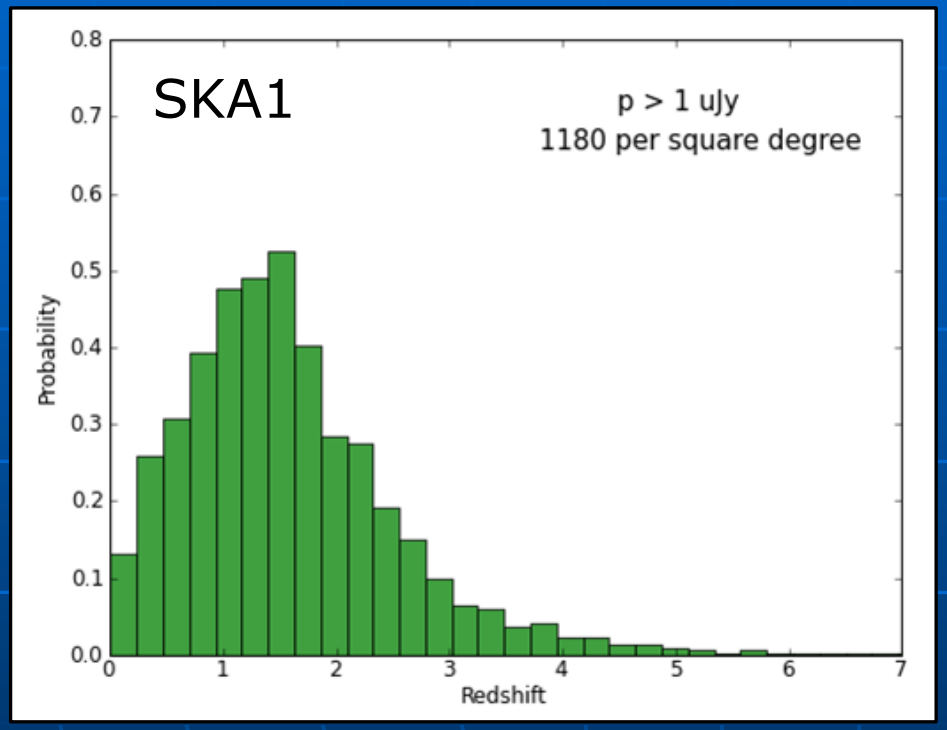
(Schleicher & Beck 2013 – see Dominik's talk)

Detecting total emission from distant galaxies with SKA2

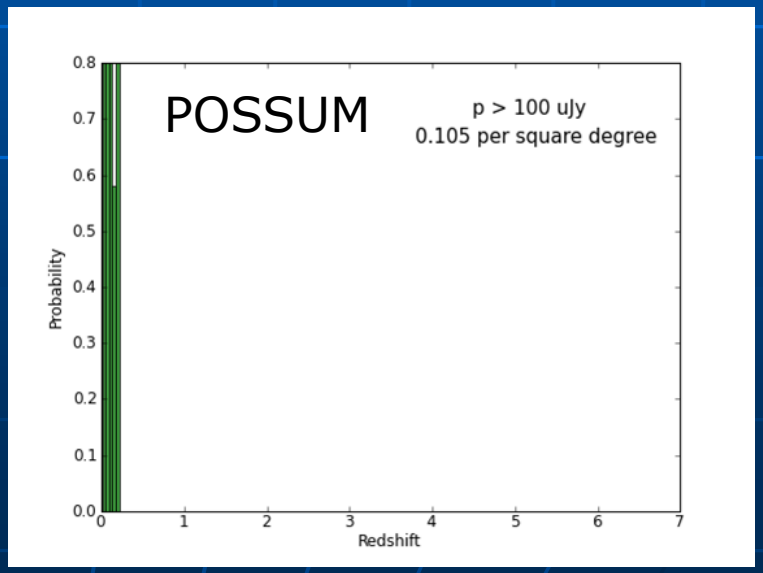
Murphy 2009



Detecting polarized emission from distant galaxies with SKA1



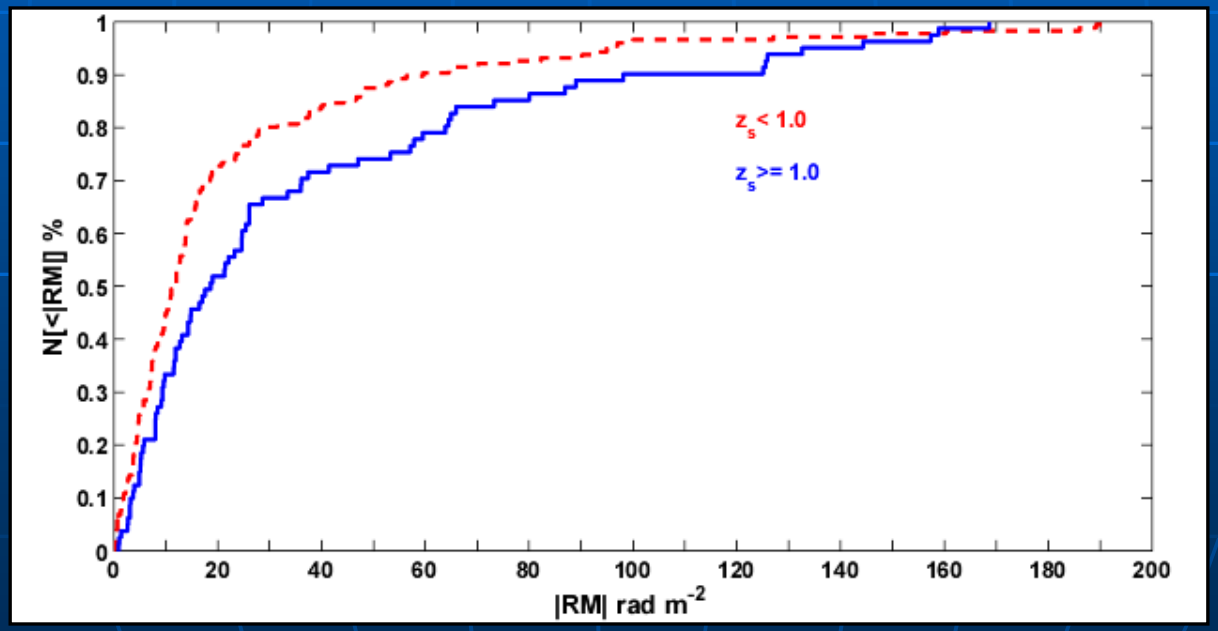
Stil & Taylor, unpubl.



Magnetic fields in distant intervening galaxies

- Population of intervening galaxies towards polarized quasars: Faraday rotation at high frequencies (≈5-10 GHz) is stronger for more distant quasars (z>1)

⟶ kpc-scale, μG-strong **regular** fields exist in distant galaxies



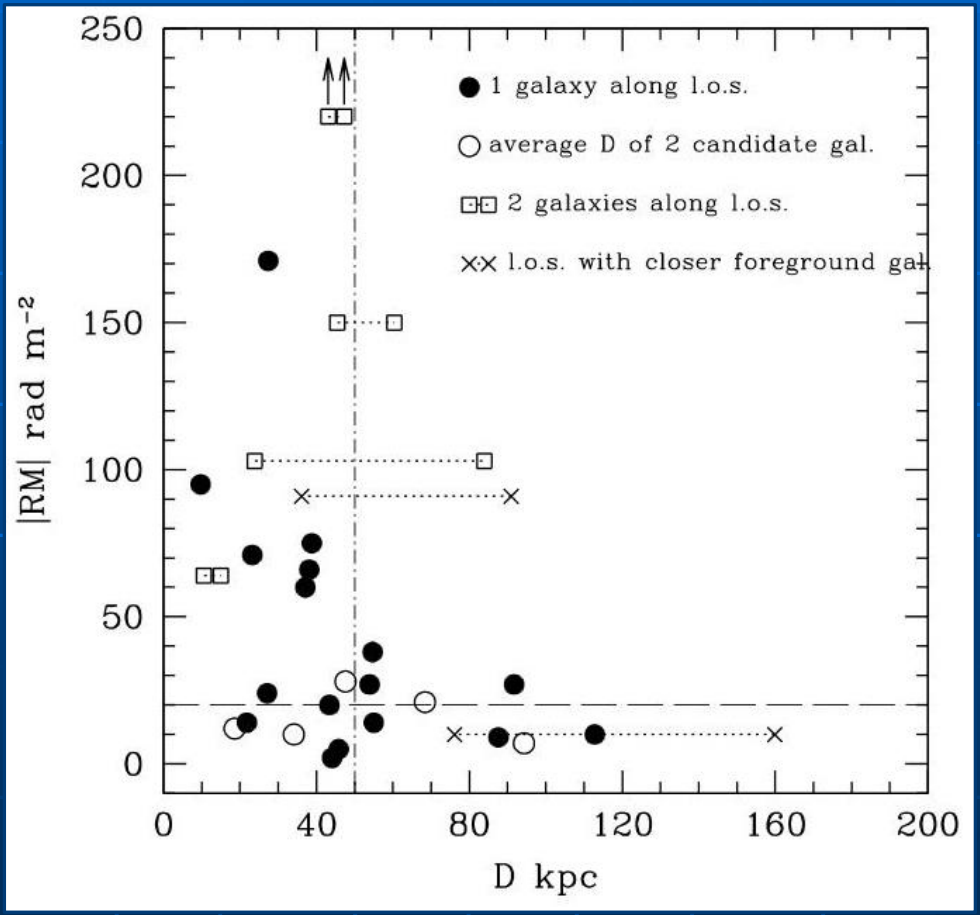
Kronberg et al. 2008, Bernet et al. 2008

Magnetic fields in distant intervening galaxies

Bernet et al. 2013

Magnetized outflows of galaxies are huge:

- Intervenors may be very frequent
- Dispersion of transient signals may be strong



Observation of magnetic fields in distant galaxies with SKA1 deep fields

- Total synchrotron emission ($z < 3$-4)
- Polarized synchrotron emission ($z < 2$-3)
- Faraday rotation in intervening galaxies against background sources ($z < 5$)

The evolution of galactic magnetic fields can be traced for the first time

Summary: Observing cosmic magnetism with SKA1

Diffuse polarization:

- Polarization survey of distant galaxies and cluster relics:
  SKA1-MID (deep)
- Detailed magnetic field structure in nearby galaxies:
  SKA1-MID high band (deep)
- Weak magnetic fields in cluster halos and intergalactic filaments:
- SKA1-MID low band or SKA1-LOW high end (deep)

RMs of polarized background sources:

- Field pattern of the Milky Way:
  SKA1-SUR (survey)
- 3-D structure of the Milky Way's magnetic field (pulsar RMs):
  SKA1-MID (survey)
- Evolution of galactic magnetic fields:
  SKA1-MID (deep)
- Evolution of galactic and intergalactic magnetic fields (intervenors):
  SKA1-SUR (survey)