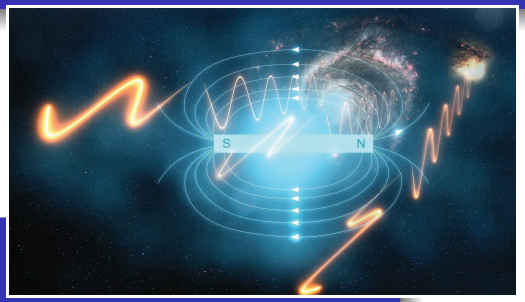

Cosmic magnetism

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Journées radio SKA-LOFAR

Paris – 11 - 13 February, 2014

Outline

Outline

Introduction

- Cosmic magnetic fields play an important role in the structure, dynamics, energetics & evolution of most astrophysical objects.
- The best probes of cosmic magnetic fields are radio waves.
- Cosmic magnetism is key science for the new and upcoming large radio telescopes.

☞ LOFAR Magnetism KSP

☞ SKA SQUARE KILOMETRE ARRAY Cosmic Magnetism SWG

LOFAR Key Science Project

Cosmic magnetism in the nearby universe

- Management team

  Rainer Beck (PI), George Heald, Anna Scaife

- 32 full members

  Germany [14], Netherlands [11], United Kingdom [3], Poland [2], Italy [1], Sweden [1]

- 60 associated members

  Germany [25], United Kingdom [10], Netherlands [5], Poland [5], Sweden [4], Australia [2], France [2], Japan [2], Canada [1], India [1], Italy [1], Korea [1], USA [1]

SKA Science Working Group

The origin and evolution of cosmic magnetism

- 2 co-chairs

  Federica Govoni, Melanie Johnston-Hollitt

- 23 members

  Italy [4], Australia [3], Germany [3], Netherlands [3], Canada [2], USA [2], France [1], Japan [1], South Africa [1], United Kingdom [1], SKA [2]

Outline

Outline

Present radio observations

- **Zeeman splitting**

  In neutral (molecular & atomic) regions

  $\rightarrow$ $B_{\parallel}$ (strength & sign)

- **Faraday rotation**

  In ionized regions

  $\rightarrow$ $B_{\parallel}$ (strength & sign)

- **Synchrotron emission**

  In general ISM

  $\rightarrow$ $\vec{B}_{\perp}$ (strength & orientation)

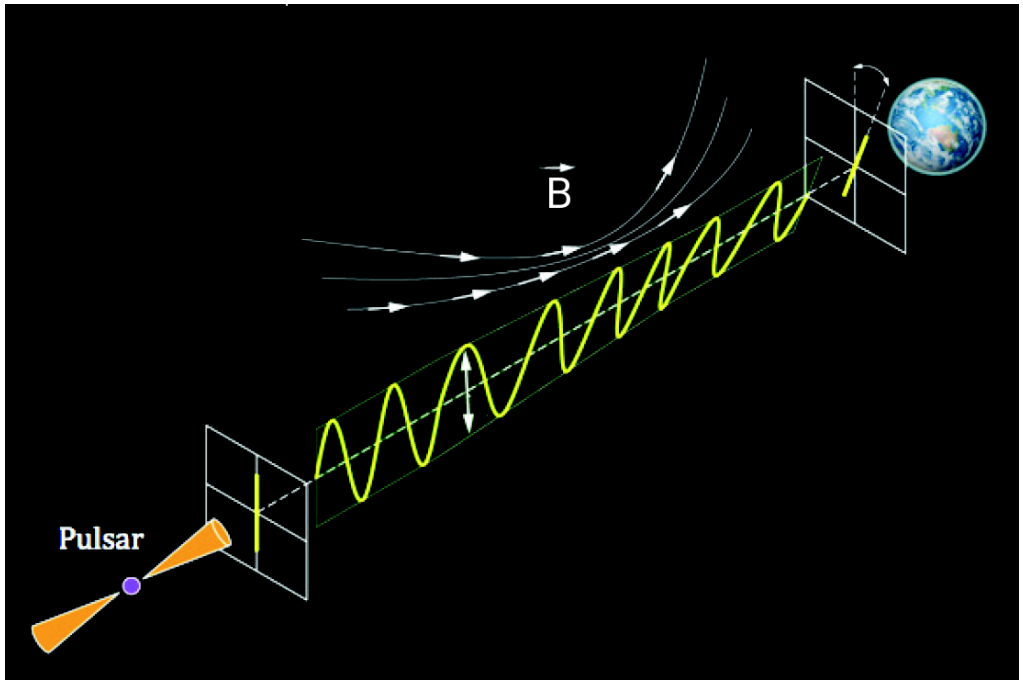
- **Faraday tomography**

  Combines synchrotron emission & Faraday rotation

Faraday rotation of point sources

$\Delta\theta = \mathrm{RM}\ \lambda^2$ where $\mathrm{RM} = C \int n_\mathrm{e}\ B_{||}\ dl$

$\Rightarrow$ RM probes $B_{||}$ in ionized regions

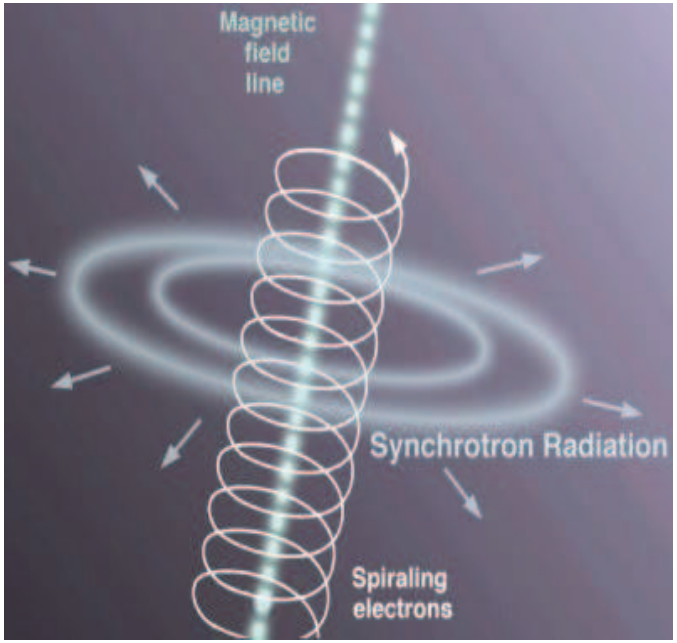


Diffuse synchrotron emission

$\mathcal{E} = f(\alpha)\, n_{\rm rel}\, B_\perp{}^{\alpha+1}\, \nu^{-\alpha}$ & $\vec{\mathcal{E}} \perp \vec{B}_\perp$

$\Rightarrow$ - *Total intensity* probes $B_\perp$ (strength only)

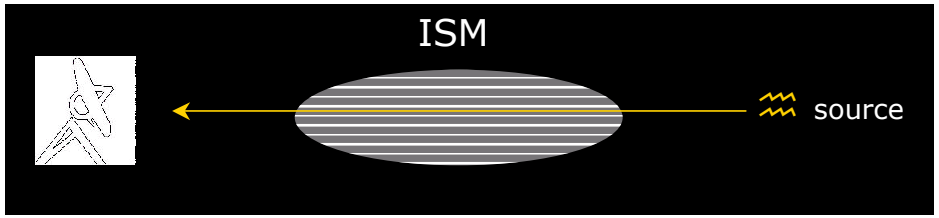
- *Polarized intensity* probes $(\vec{B}_{\rm ord})_\perp$ (strength & orientation)



Faraday tomography

- **Faraday rotation of background source**

  $\Delta\theta = \mathrm{RM}\ \lambda^2$ with $\mathrm{RM} = C \int n_\mathrm{e}\ B_{||}\ dl$ (rotation measure)

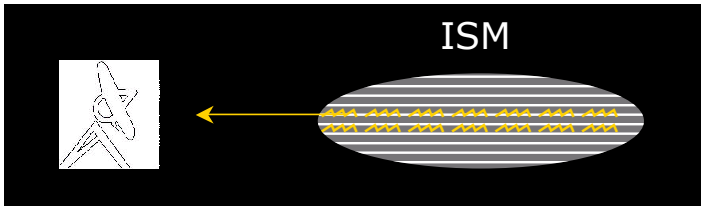


- **Faraday rotation of diffuse synchrotron emission**

  Synchrotron emission & Faraday rotation are *spatially mixed*

  $\vec{P}(\lambda^2) = \int \vec{P}(\Phi)\ e^{2i\Phi\lambda^2}\ d\Phi$ with $\Phi = C \int n_\mathrm{e}\ B_{||}\ dl$ (Faraday depth)

  ☞ *Fourier transform* of polarized intensity : $\vec{P}(\lambda^2) \rightarrow \vec{P}(\Phi)$



Credit: *Marijke Haverkorn*

Faraday tomography

Also known as rotation measure synthesis

(Burn 1966; Brentjens & de Bruyn 2005)

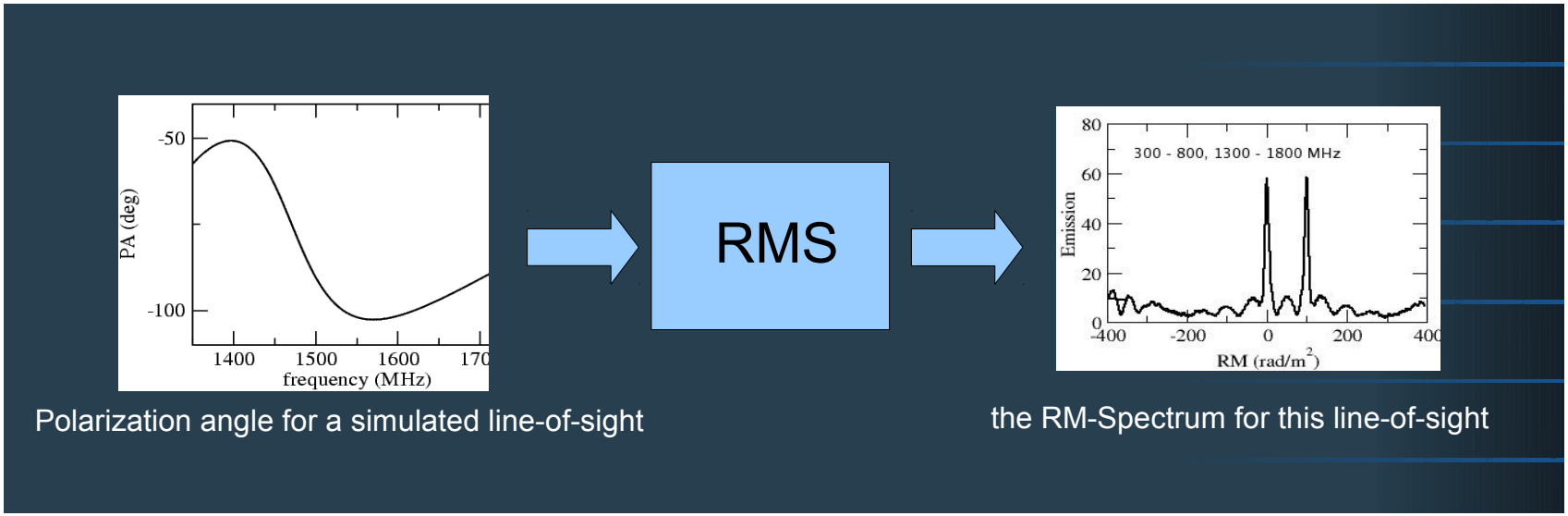


Figure Credit: *Maik Wolleben*

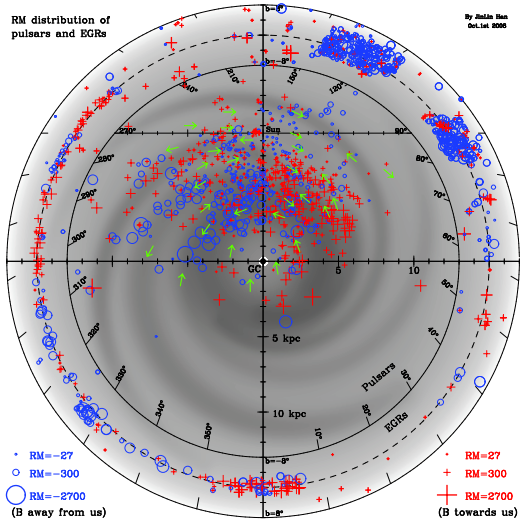
Outline

Faraday rotation of point sources

$$\Delta\theta = \mathrm{RM}\ \lambda^2 \quad \text{where} \quad \mathrm{RM} = C \int n_\mathrm{e}\ B_{||}\ dl$$

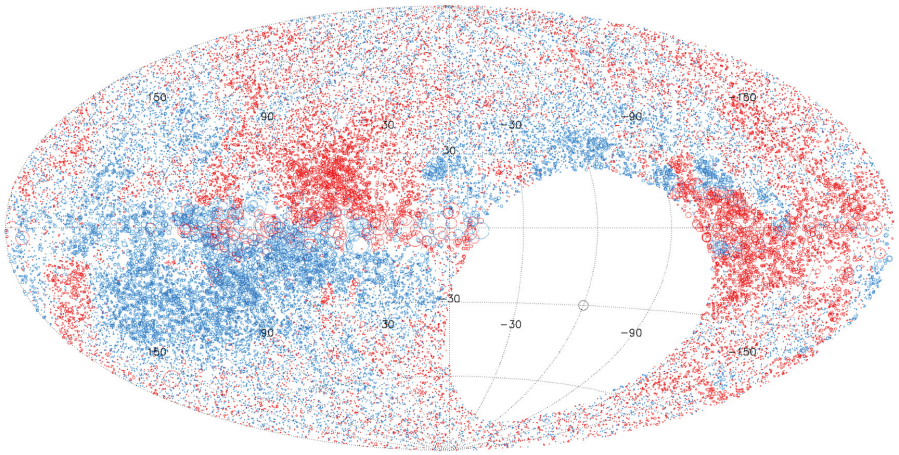
$\Rightarrow$ RM probes $B_{||}$ in ionized regions

RMs of pulsars & EGRSs with $|b| < 8°$



Han (2009)

RMs of EGRSs with $\delta > -40°$



Taylor et al. (2009)

Faraday rotation of point sources

In ionized regions

☞ - $\vec{B}$ has *regular* & *fluctuating* components

Near the Sun : $B_{\rm reg} \simeq 1.5\ \mu$G & $B_{\rm fluct} \sim 5\ \mu$G

- In Galactic disk : $\vec{B}_{\rm reg}$ is horizontal & mostly azimuthal

Near the Sun : $\vec{B}_{\rm reg}$ is CW $(p \simeq -8°)$

$\vec{B}_{\rm reg}$ reverses direction with decreasing radius

$\vec{B}_{\rm reg}$ is neither pure ASS nor pure BSS

- In Galactic halo : $\vec{B}_{\rm reg}$ is CCW at $z > 0$ & CW at $z < 0$

$\vec{B}_{\rm reg}$ has vertical component

Diffuse synchrotron emission

$\mathcal{E} = f(\alpha)\, n_{\rm rel}\, B_\perp{}^{\alpha+1}\, \nu^{-\alpha}$ & $\vec{\mathcal{E}} \perp \vec{B}_\perp$

$\Rightarrow$ - *Total intensity* probes $B_\perp$ (strength only)

- *Polarized intensity* probes $(\vec{B}_{\rm ord})_\perp$ (strength & orientation)

TI at 1.4 GHz (25m Stockert + 30m Villa Elisa)

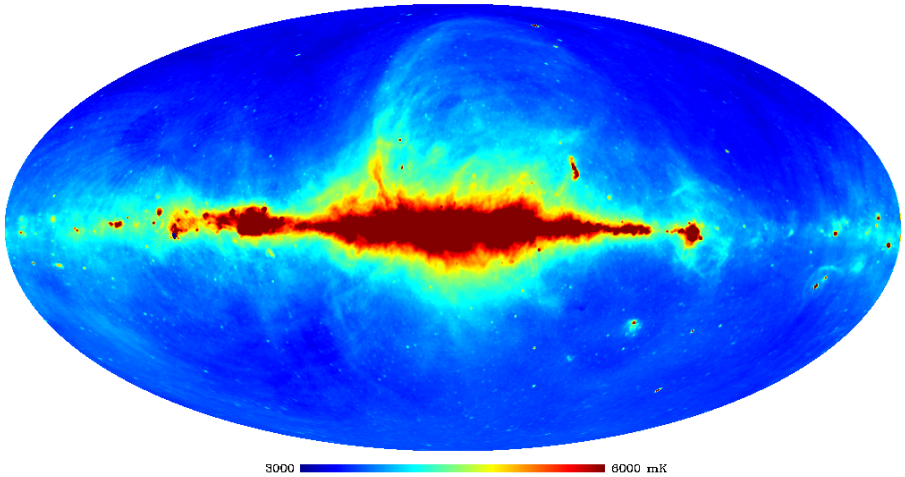


Figure Credit: *Tess Jaffe*

PI at 1.4 GHz (26m DRAO + 30m Villa Elisa)

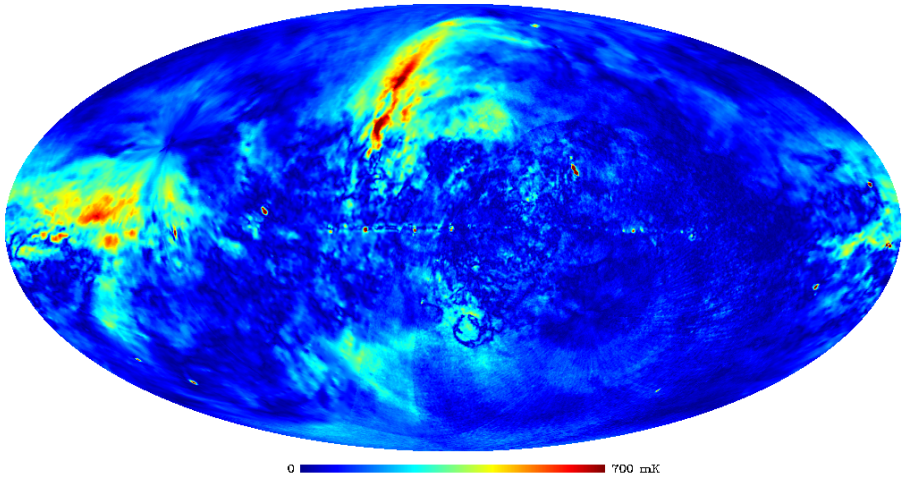


Figure Credit: *Tess Jaffe*

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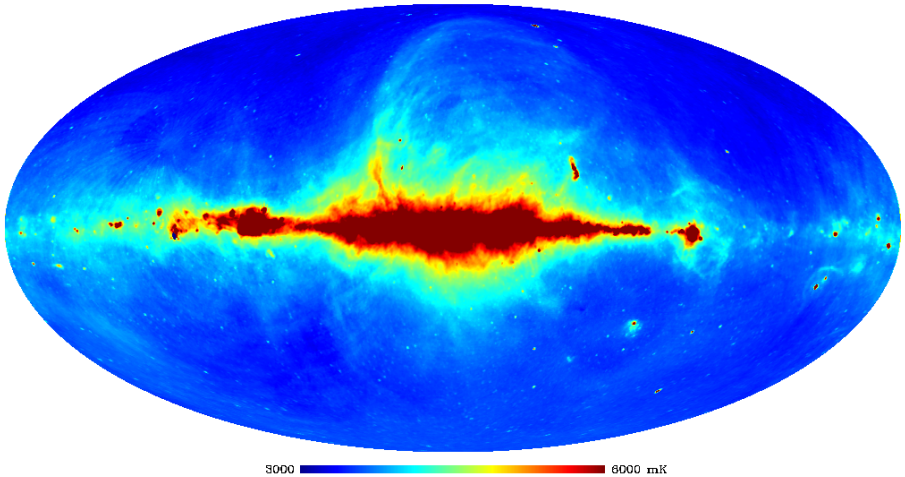


Figure Credit: *Tess Jaffe*

PI at 23 GHz (WMAP)

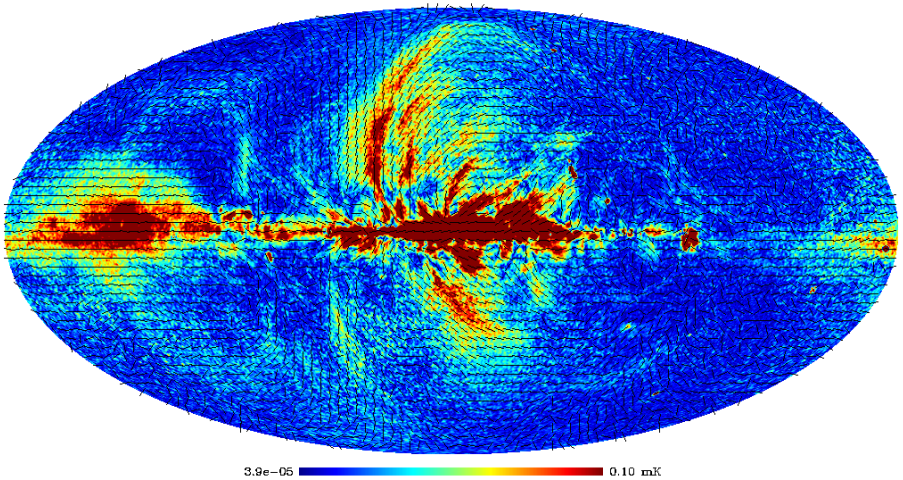


Figure Credit: *Tess Jaffe*

Diffuse synchrotron emission

In general ISM

☞ - Near the Sun : $B_{\rm ord} \sim 3\ \mu$G & $B_{\rm tot} \sim 5\ \mu$G

- In Molecular Ring : $B_{\rm tot} \sim 7\ \mu$G

- In Galactic disk : $\vec{B}_{\rm ord}$ is horizontal

- In Galactic halo : $\vec{B}_{\rm ord}$ has vertical component

- Global spatial distribution : $L_{\rm B} \sim 12$ kpc & $H_{\rm B} \sim 4.5$ kpc

Outline

Magnetic fields in external galaxies

- Spiral galaxies

  - All spirals have large-scale, regular / ordered $\vec{B}$

  - In disk : $B_{\rm ord} \sim (1-5)\ \mu$G & $B_{\rm tot} \sim (5-20)\ \mu$G
    In halo : $B_{\rm tot} \lesssim 10\ \mu$G

  - Edge-on spirals $\rightarrow$ In disk : $\vec{B}_{\rm ord}$ is horizontal
    In halo : $\vec{B}_{\rm ord}$ is X-shaped

    Face-on spirals $\rightarrow$ $\vec{B}_{\rm ord}$ follows spiral arms

- Elliptical galaxies

  - No large-scale, regular / ordered $\vec{B}$
    Only small-scale, fluctuating $\vec{B}$

  - $B_{\rm tot} \sim$ a few μG

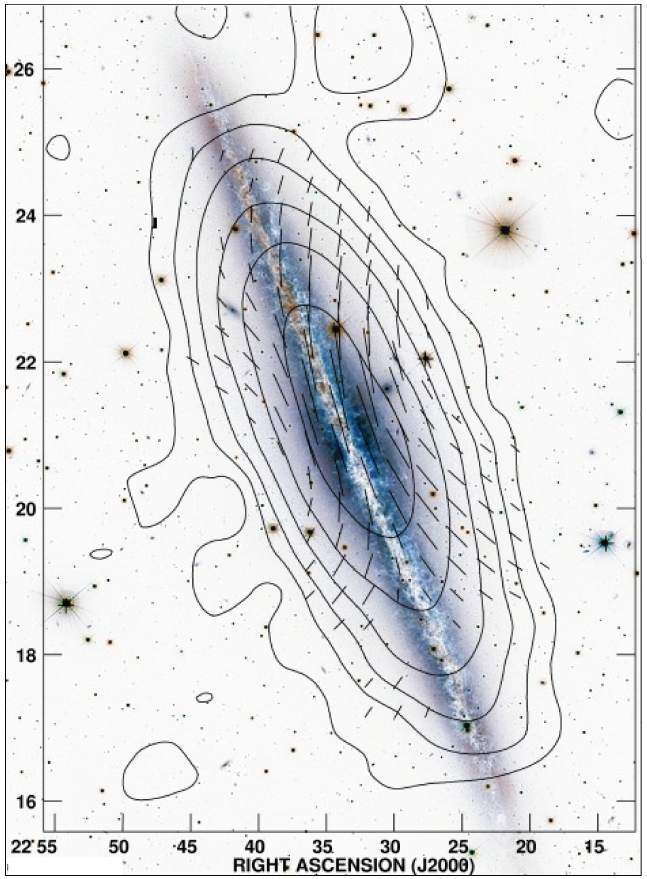
Edge-on spiral galaxy: NGC 891

Total intensity contours
+ $\vec{B}$ vectors
at λ 3.6 cm

(100m Effelsberg)

Optical image

(CFHT)



© MPIfR Bonn *(Krause 2009)*

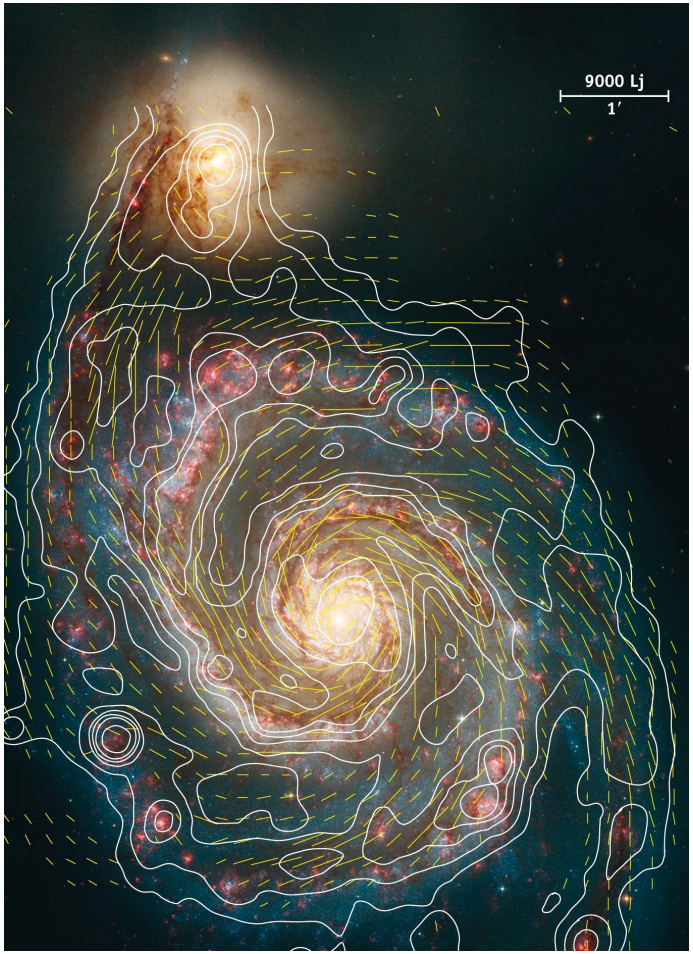
Face-on spiral galaxy: M 51

Total intensity contours
+ $\vec{B}$ vectors
at λ 6 cm

(100m Effelsberg + VLA)

Optical image

(HST)



Fletcher et al. (2009)

Outline

Magnetic fields in clusters of galaxies

- Clusters have an intergalactic magnetic field

- No large-scale, regular / ordered $\vec{B}$
  Only small-scale, fluctuating $\vec{B}$

- *Faraday rotation* ☞ $B \sim$ a few μG & $\ell_{\rm cor} \sim$ a few 10 kpc

- *Synchrotron emission* ☞ $B_{\rm tot} \sim (0.1 - 1)\ \mu$G

Outline

Outline

Low-frequency radio observations

- Faraday rotation

  - $\Delta\theta = \mathrm{RM}\ \lambda^2$ with $\mathrm{RM} \propto \int n_\mathrm{e}\ B_{||}\ dl$

  $\Rightarrow$ Can probe small RMs $\rightarrow$ regions with *low* n_e and *weak* B

- Diffuse synchrotron emission

  - Emission is *almost purely synchrotron* (no contamination by thermal emission)

  - $\mathcal{E} \propto n_\mathrm{rel}\ B_\perp^{\alpha+1}\ \nu^{-\alpha}$

  $\Rightarrow$ Can probe regions with *low* n_rel and *weak* B

  - $\nu \propto E^2\ B_\perp$ & $t_\mathrm{syn} \propto E^{-1}\ B_\perp^{-2}$

  $\Rightarrow$ Can probe *low-energy* CR electrons
  which live *longer* and propagate *farther* from their sources

- Faraday tomography

  - *High-resolution* Faraday-depth spectra

  - Strong *Faraday depolarization* (differential Faraday rotation & internal Faraday dispersion)

Low-frequency radio observations

☞ Low frequencies are ideal to study magnetic fields in

- galactic outer disks & halos
- tails of interacting or stripped galaxies
- intergalactic medium

Rotation measure grid

- Galactic pulsars
  - Strong polarized fluxes $\rightarrow$ good polarization calibrators
  - $B_{\parallel} \propto \mathrm{RM}/\mathrm{DM}$ $\rightarrow$ excellent accuracy on $B_{\parallel}$
  - Expect $\gtrsim 1\,000$ new pulsars
- Extragalactic point sources
  - Expect $\approx 7 \times 10^6$ new sources at 200 MHz
  - Most sources will be strongly Faraday depolarized
  - Altogether, expect few new *polarized* sources

All-sky images in the 4 Stokes parameters

- Single core station (Effelsberg – 3 August, 2012)
- Single channel at 32 MHz, 200 kHz bandwidth
- 1.3 sec integration time, 11° resolution

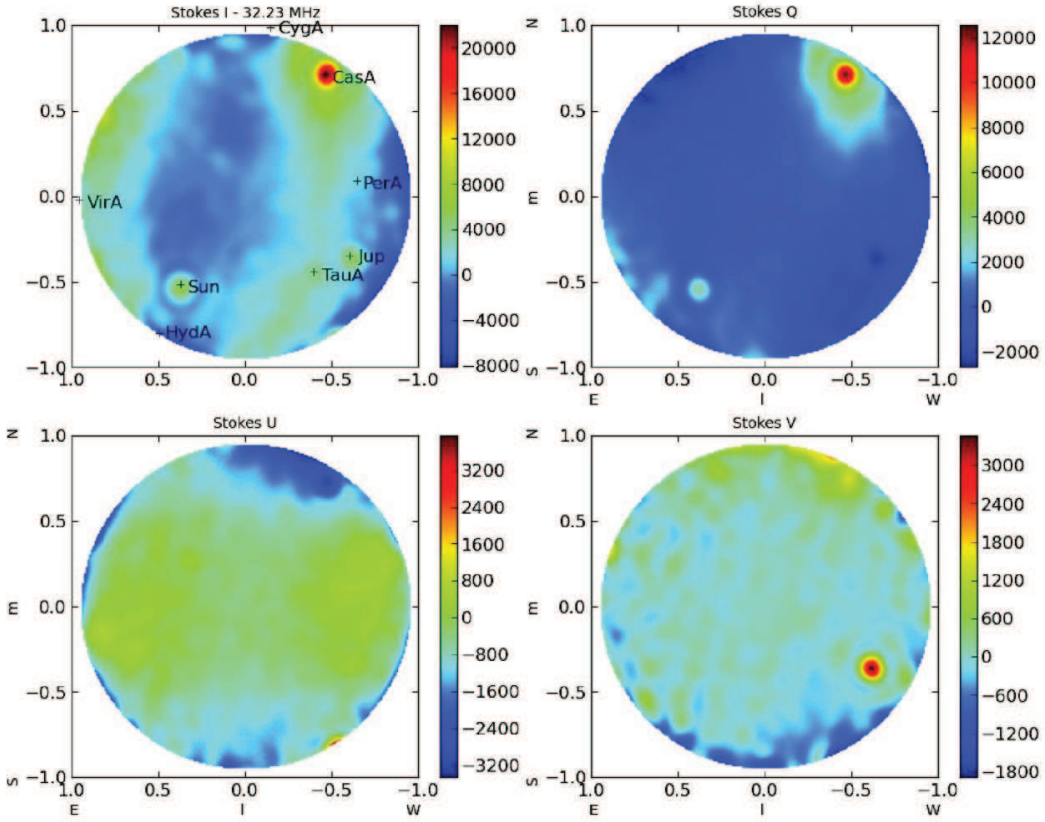
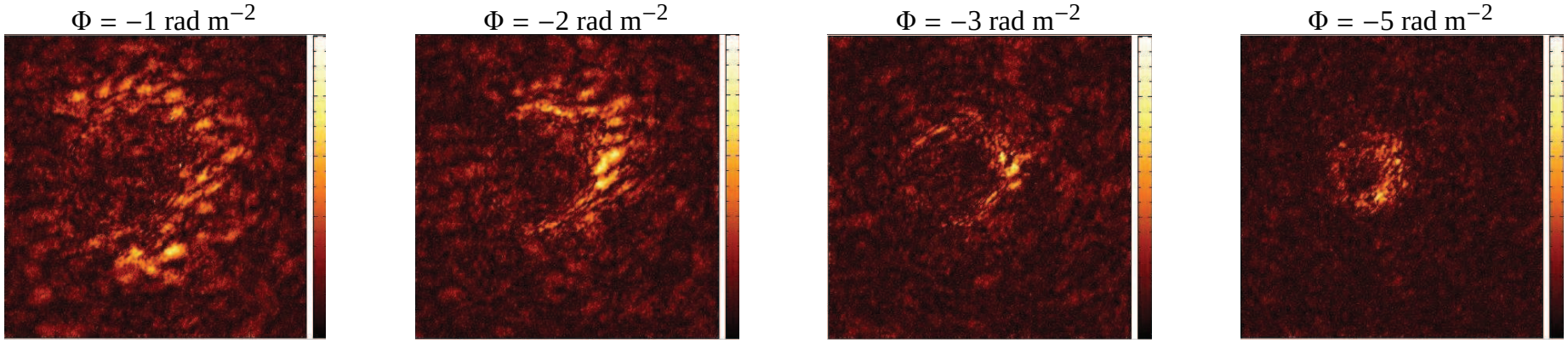


Figure Credit: *Rainer Beck* (from *Jana Köhler & James Anderson*)

Faraday tomography of the Fan region

- LOFAR HBA
- Stokes U at 4 different Faraday depths



Iacobelli et al. (2013)

Nearby galaxies

16 nearby galaxies have already been observed

- M 33 (HBA & LBA, Cycle 0 DDT)
- M 51 (HBA, commissioning & Cycle 0)
- M 81, M 82 (HBA & LBA, Cycle 0)
- M 101 (HBA, Cycle 0)
- NGC 628 (HBA, Cycle 1)
- NGC 891 (HBA, commissioning)
- NGC 3079 (HBA, Cycle 0)
- NGC 3432 (HBA, Cycle 1)
- NGC 3627, NGC 3628 (HBA, Cycle 0)
- NGC 4631 (HBA, commissioning & Cycle 0)
- NGC 6946 (HBA, Cycle 0)
- IC 10 (HBA & LBA, Cycle 0)
- IC 342 (HBA & LBA, Cycle 0)
- Stefan's Quintet (HBA, Cycle 0)

Credit: *Rainer Beck (Cosmic Magnetism SKA 1 Assessment Workshop, January 2014)*

Nearby galaxy M 51

- Total intensity image

  - LOFAR HBA
  - 170 subbands in [120,180] MHz, 36 MHz total bandwidth
  - 6 h observation time, $20''$ resolution

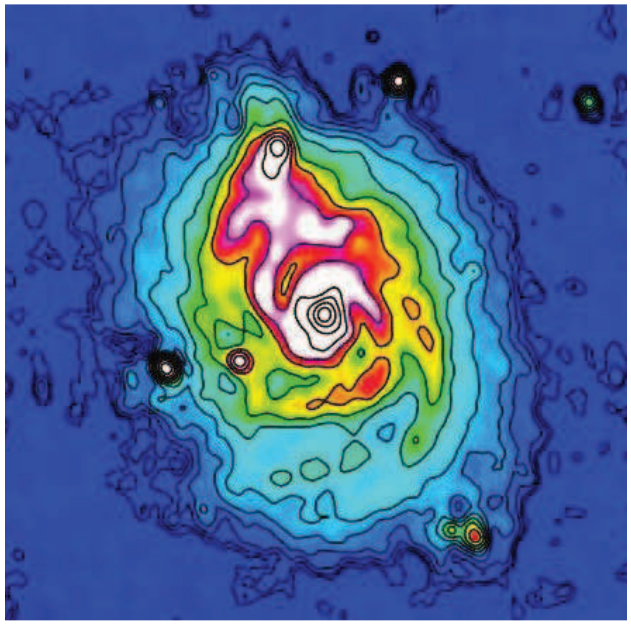


Figure Credit: *David Mulcahy*

Nearby galaxy M 51

- Polarization image
  - Diffuse polarized emission from Galactic foreground, not from M 51
  - Diffuse emission from M 51 is strongly *Faraday depolarized*
  - Only 4 resolved background polarized sources (not enough for RM grid)
- Faraday tomography
  - Strongest component in Faraday spectra due to instrumental polarization
  - One component due to Galactic foreground (Faraday screen)
  - One component internal to M 51
  - Several unresolved background polarized sources

Credit: *Rainer Beck (Cosmic Magnetism SKA 1 Assessment Workshop, January 2014)*

Nearby galaxies in the LOFAR HBA MSSS

MSSS = Multifrequency Snapshot Sky Survey *(George Heald et al.)*

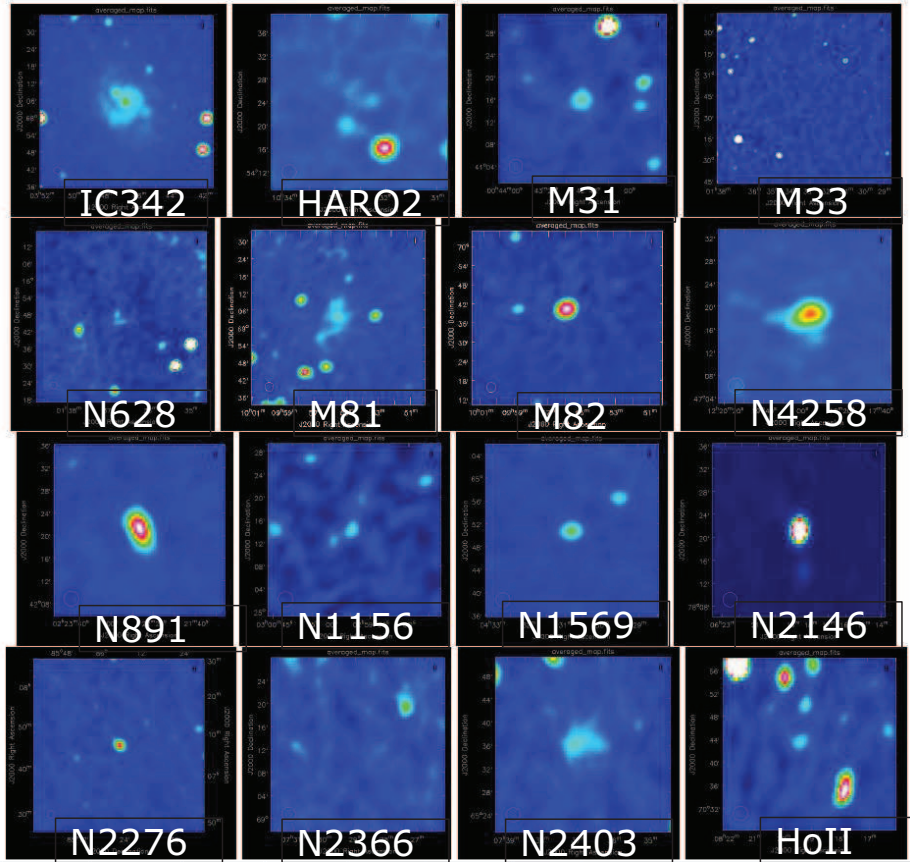


Figure Credit: *Rainer Beck* (from *Chris Chyży & MSSS Team*)

Galaxies in the Virgo Cluster

LOFAR HBA

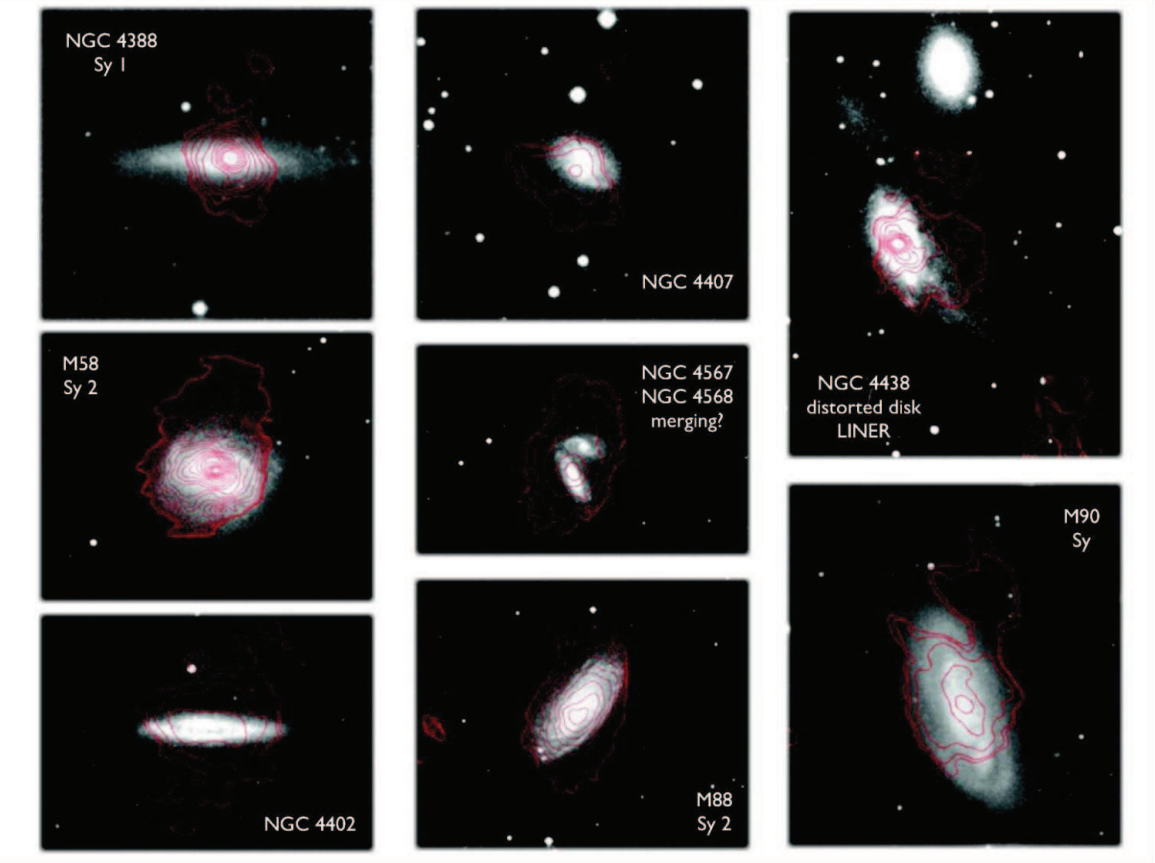


Figure Credit: *Rainer Beck* (from *de Gasperin et al., in prep.*)

Outline

Observations with SKA 1

- Key SKA 1 observations
  - Polarization all-sky survey at ~ 1 GHz
  - Polarization deep field at ~ 1 GHz
  - Deep targeted polarization observations of specific objects at lower and higher frequencies

- Key science drivers
  - Cosmic evolution of magnetic fields in galaxies and clusters
  - Detailed structure of magnetic fields in galaxies and clusters
  - Properties of magnetic fields in AGNs
    Relation between supermassive black holes and their environment
  - Detection of magnetic fields in the Cosmic Web
    Properties and relation to the large-scale structure

Credit: *Federica Govoni (Cosmic Magnetism SKA 1 Assessment Workshop, January 2014)*

Rotation measure grid

- High sensitivity, high resolution, whole sky coverage
  $\rightarrow$ All-sky, closely-spaced grid of RMs
- Observations at $\gtrsim 1$ GHz to reduce Faraday depolarization
- Expect $\approx 20\,000$ RMs of Galactic pulsars [$\approx 6\ \mathrm{deg}^{-2}$ in GD],
  i.e., all Galactic pulsars beaming towards us *(Smits et al. 2009)*
- Expect $\approx (1-4)\times 10^7$ RMs of background polarized sources
  [$\approx (300-1\,000)\ \mathrm{deg}^{-2}$] with SKA 1 *(Larry Rudnick, SKA1 Assessment Workshop)*

☞ Powerful tool to study cosmic magnetic fields at all redshifts

The Milky Way

- Pulsar RMs + distance estimates (from parallax or DMs)
  → 3D structure of large-scale ($\gtrsim 100$ pc) magnetic field in GD
  - number & location of field reversals
  - magnetic spiral *vs* optical spiral

- RM grid of extragalactic point sources
  → - structure of large-scale magnetic field in GH & outer GD
  - magnetic fields in SNRs & H II regions
  - power spectrum of magneto-ionic turbulence (down to $\lesssim 1'$)

- Faraday tomography
  → high-resolution 3D map of local ($\lesssim 5$ kpc) magnetic field
  → - small-scale ($\gtrsim 0.1$ pc) magnetic features
  - properties of magneto-ionic turbulence

External galaxies

- Low-z galaxies

  - Deep RM grid of background compact sources
  - Mapping of diffuse (total + polarized) synchrotron emission
    + Faraday tomography (in the nearest galaxies)

- Nearest galaxies (LMC, SMC, M 31)
  $\sim 10^5$ RMs (deep obs.) + Faraday tomography
  $\rightarrow$ very detailed 3D map of magnetic field structure

- Galaxies out to ~ 10 Mpc (~ 100 galaxies)
  $\gtrsim 100$ RMs + synchrotron mapping
  $\rightarrow$ 3D reconstruction of large-scale magnetic field structure

- Galaxies out to ~ 100 Mpc ($\sim 60\,000$ galaxies)
  $\gtrsim 10$ RMs
  $\rightarrow$ recognition of simple magnetic patterns (ASS, BSS...)

External galaxies

- Galaxies at $z \gtrsim 0.1$
  - Detailed study of individual galaxies
    - Too small $(\lesssim 1')$ for RM grid of background *compact* sources
    - RMs of background *extended* sources
    $\rightarrow$ maps of magnetic field structure
    $\rightarrow$ temporal evolution of galactic magnetic fields
  - RM statistics of (unresolved) Lyα absorbers
    $\rightarrow$ trends of $\mathrm{RM}_{\mathrm{source}}$ *vs* z & $\mathrm{RM}_{\mathrm{Ly}\alpha}$ *vs* z separately
    $\rightarrow$ evolution of magnetic fields in galaxies & protogalaxies

Clusters of galaxies

- RM grid of background compact sources
  ($\sim 1\,000$ RMs behind a typical nearby cluster)
  + RMs toward embedded sources
  $\rightarrow$ $\pm$ detailed map of magnetic field structure

- Detection/mapping of diffuse synchrotron emission (deep obs.)
  $\rightarrow$ - estimates of magnetic field strength
  - map of magnetic field structure
  - global radial dependence of B