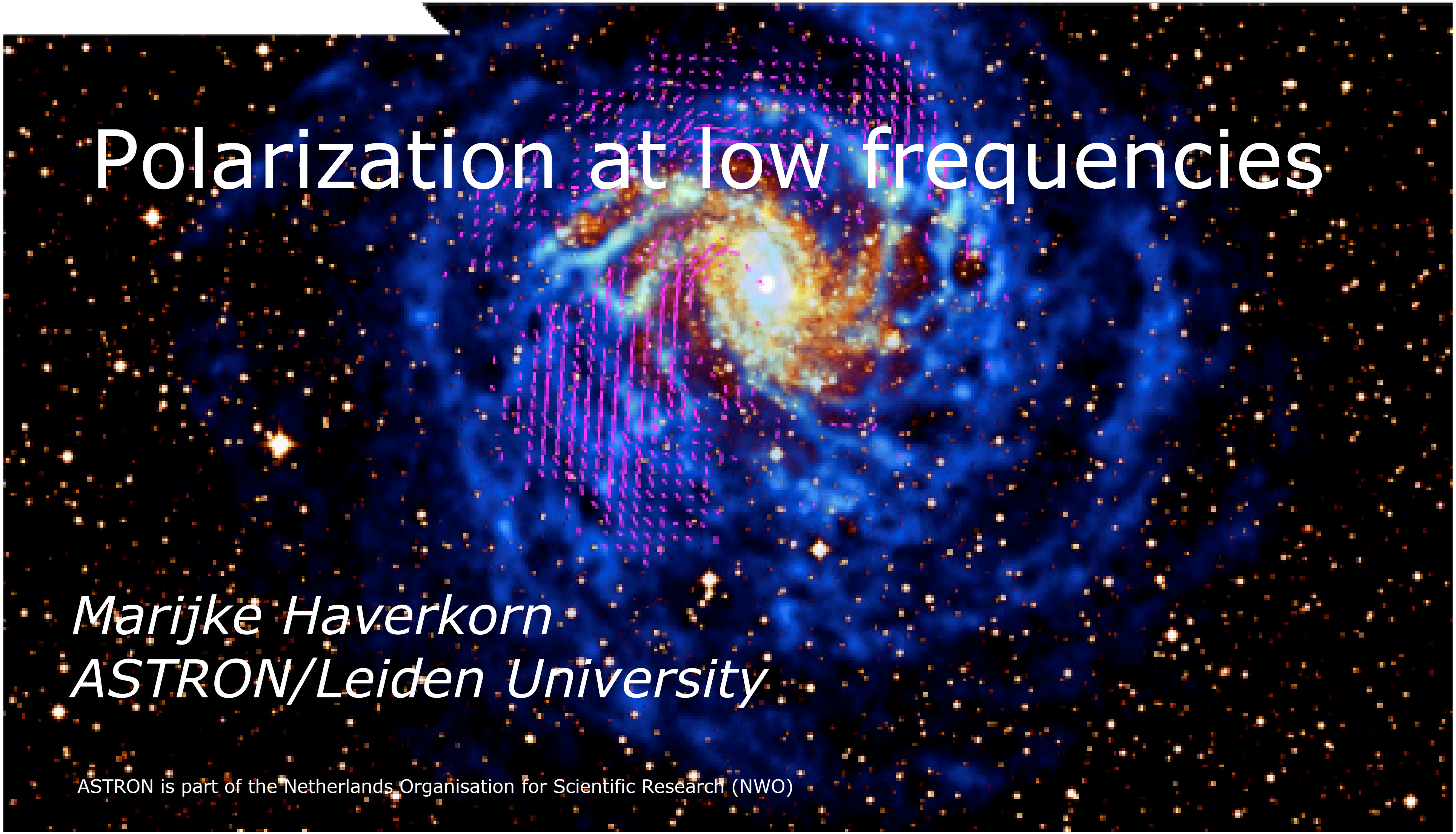


Polarization at low frequencies

Marijke Haverkorn
ASTRON/Leiden University

Outline

Methods of radio spectro-polarimetry:

1. Synchrotron emission
2. Faraday rotation of point sources: The Rotation Measure (RM) Grid
3. Faraday rotation of diffuse polarization: RM Synthesis

Goals of radio spectro-polarimetry

- characterize magnetic fields in (the halo of) the Milky Way and external galaxies
- explore the role of magnetism in perturbed galaxies
- detect and characterize intergalactic magnetic fields
- explore the origin and evolution of cosmic magnetism: test dynamo theories
- find the magnetic structure of stellar and AGN jets

Stokes parameters I, Q, U, V measure polarization

I = total intensity

Q = linear polarization

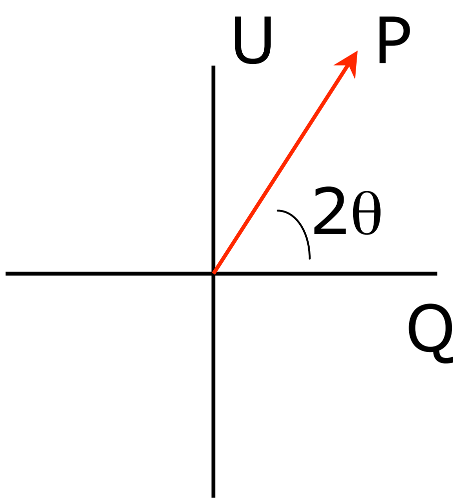
U = orthogonal linear polarization

V = circular polarization

$$V_{pq} = J_p B J_q^{\ddagger} = J_p \begin{pmatrix} I+Q & U+iV \\ U-iV & I-Q \end{pmatrix} J_q^{\ddagger}$$

linear pol. intensity $P = \sqrt{(Q^2+U^2)}$

Pol. angle $\theta = 0.5\ \mathrm{atan}(U/Q)$



1. Synchrotron emission

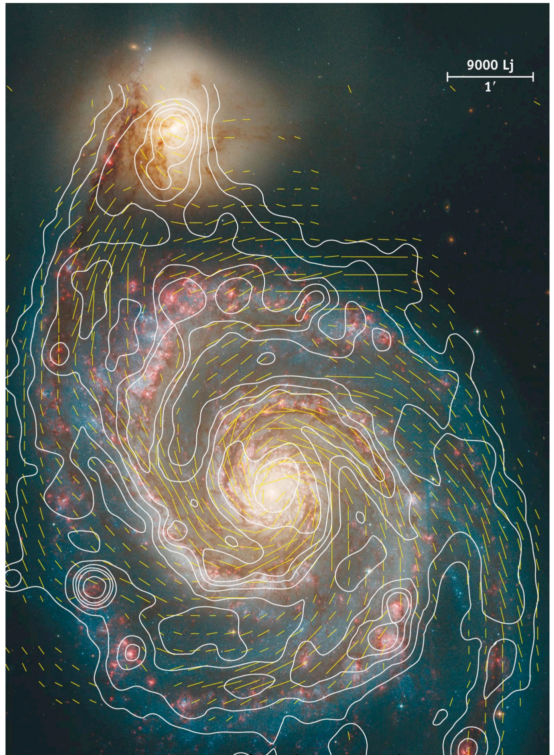
Observed degree of polarization $p \propto \frac{B^2_{\perp,reg}}{B^2_{\perp,tot}}$

Assuming equipartition between magnetic and cosmic ray energy:

$$I_\nu \propto \nu^{-\alpha} B_{eq}^{\alpha+3}$$

$$T_B \propto \nu^{-(\alpha+2)} B_{eq}^{\alpha+3}$$

α is synchrotron spectral index $S \propto \nu^{-\alpha}$



Fletcher, Beck, SuW & Hubble heritage team

So for a fixed minimum T_B the minimum detectable magnetic field strength is $B_{min} \propto \nu^{(\alpha+2)/(\alpha+3)}$

Assuming $\alpha = 0.8$:
10x lower frequency means 5x weaker magnetic field (at lower resolution)
[means 2x weaker field at constant sensitivity and resolution]

1. Synchrotron emission

The extent of synchrotron sources depends on the **lifetime** and **propagation speed** of the relativistic electrons.

Lifetime is limited by synchrotron and inverse Compton losses

$$t_{1/2} = 1.59 \times 10^9 \frac{B^{1/2}}{B^2 + B_{CMB}^2}\left[\left(\frac{\nu}{GHz}\right)(1+z)\right]^{-1/2}$$

where B_{CMB} = 3.25(1+z)^2 μG is the equivalent magnetic field strength of the CMB at redshift *z.*

E.g. for dominating synchrotron losses: $t_{syn} \approx 2\text{x}10^8$ yr for a 5 μG field at 200 MHz, while $t_{syn} \approx 8\text{x}10^7$ yr at 1400 MHz

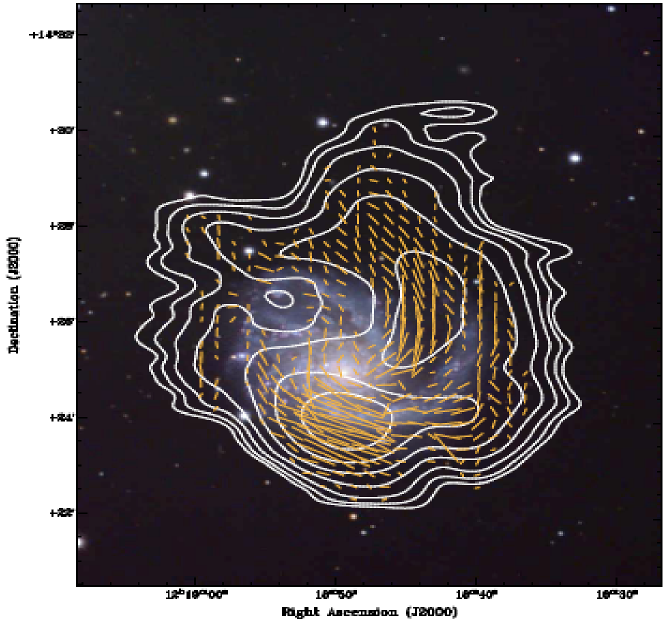
Propagation speed = diffusion speed in a turbulent magnetic field = Alfven speed $v_a = B/\sqrt{(4\pi n_i m_i)} \approx 70$ km s^{-1} (B/μG)

Then propagation length $\Delta L \approx 80$ kpc $(B/\mu\text{G})^{-0.5}$ $(\nu/\text{GHz})^{-0.5}$

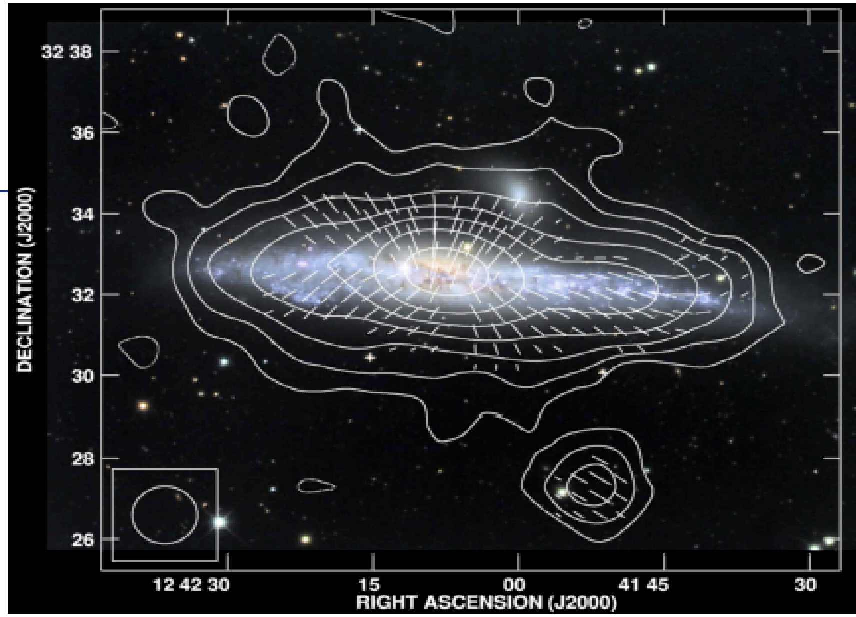
So: $\Delta L \approx 180$ kpc $(B/\mu\text{G})^{-0.5}$ at 200 MHz

$\Delta L \approx 70$ kpc $(B/\mu\text{G})^{-0.5}$ at 1400 MHz

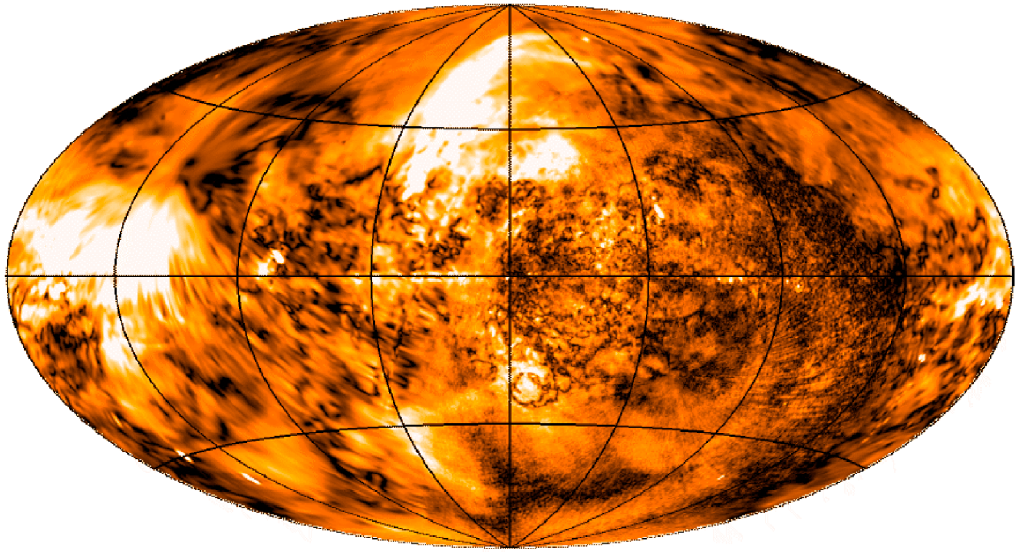
1. Synchrotron emission



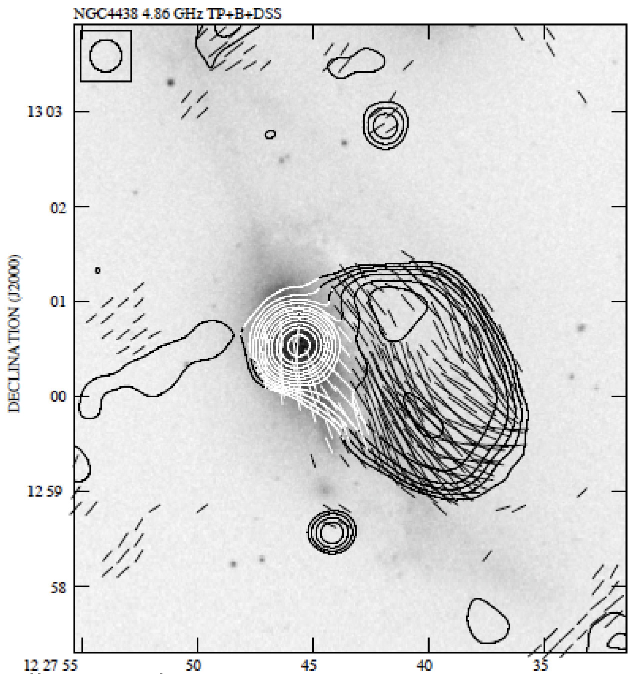
NGC4254, Heald et al 2009, optical courtesy Robert Gendler



NGC4631, Krause 2008

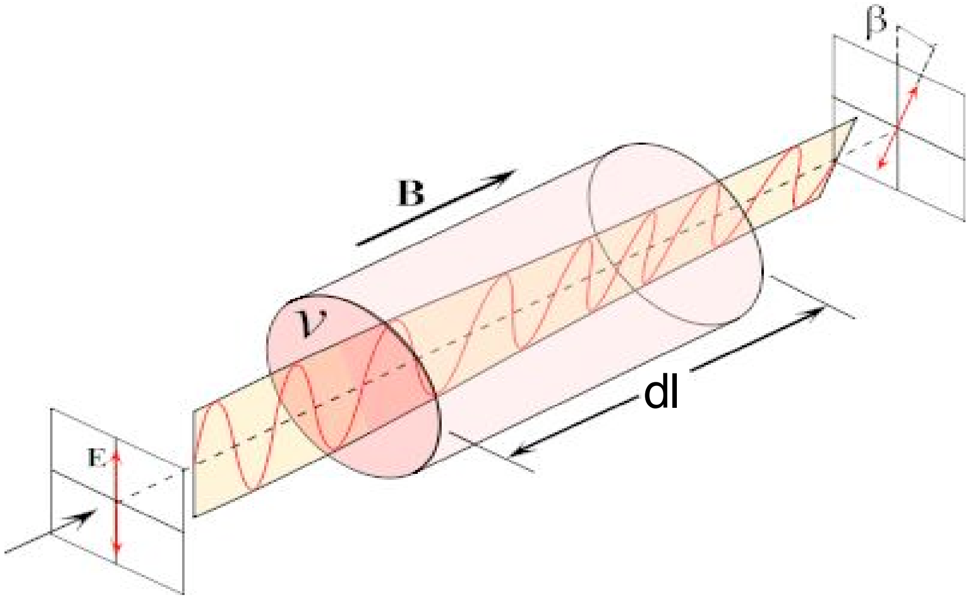


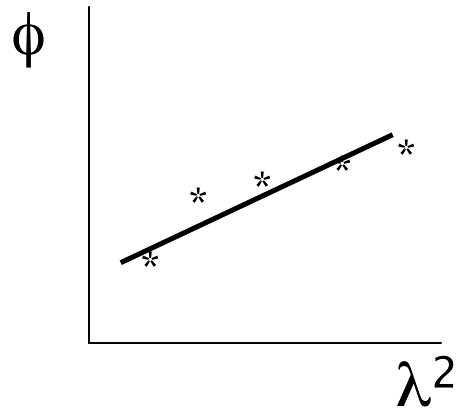
1.4 GHz Polarized intensity, Reich et al 2009



Vollmer et al 2007

2. + 3. Faraday rotation





Polarization angle $\phi = \phi_0 + RM\,\lambda^2$
Rotation measure $RM = 0.81 \int n_e\, B \cdot dl$
(for n_e in cm^{-3}; B in μG; dl in pc and RM in rad m^{-2})

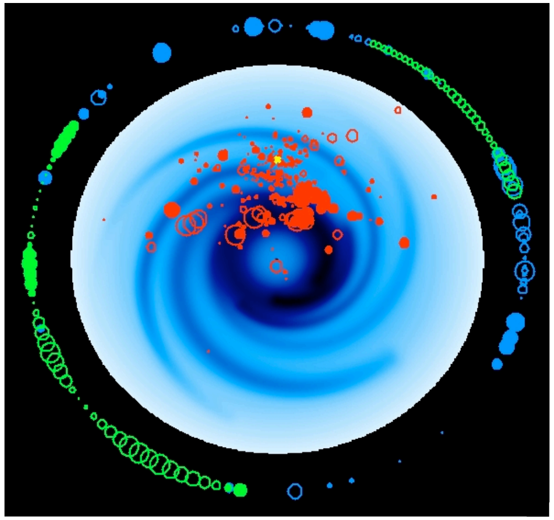
Source can be - pulsars
- polarized extragalactic point sources
- diffuse synchrotron emission --> RM Synthesis

2. Faraday rotation of point sources

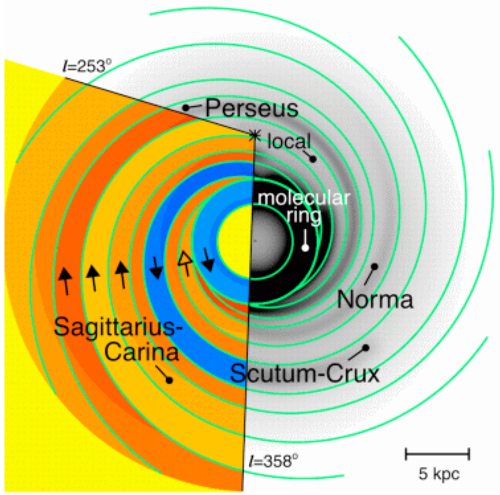
Pulsars:
- ☺ at known distances: 3D sampling of the Galaxy
- ☺ additional info about n_e in dispersion measure: DM = $\int n_e\, ds$
- ☺ no intrinsic Faraday rotation
- ☹ large distance uncertainties
- ☹ mostly in or near Galactic plane

Extragalactic sources:
- ☺ evenly distributed over the sky
- ☺ many many sources (abt 1500 now) --> “RM grid”
- ☹ intrinsic Faraday rotation

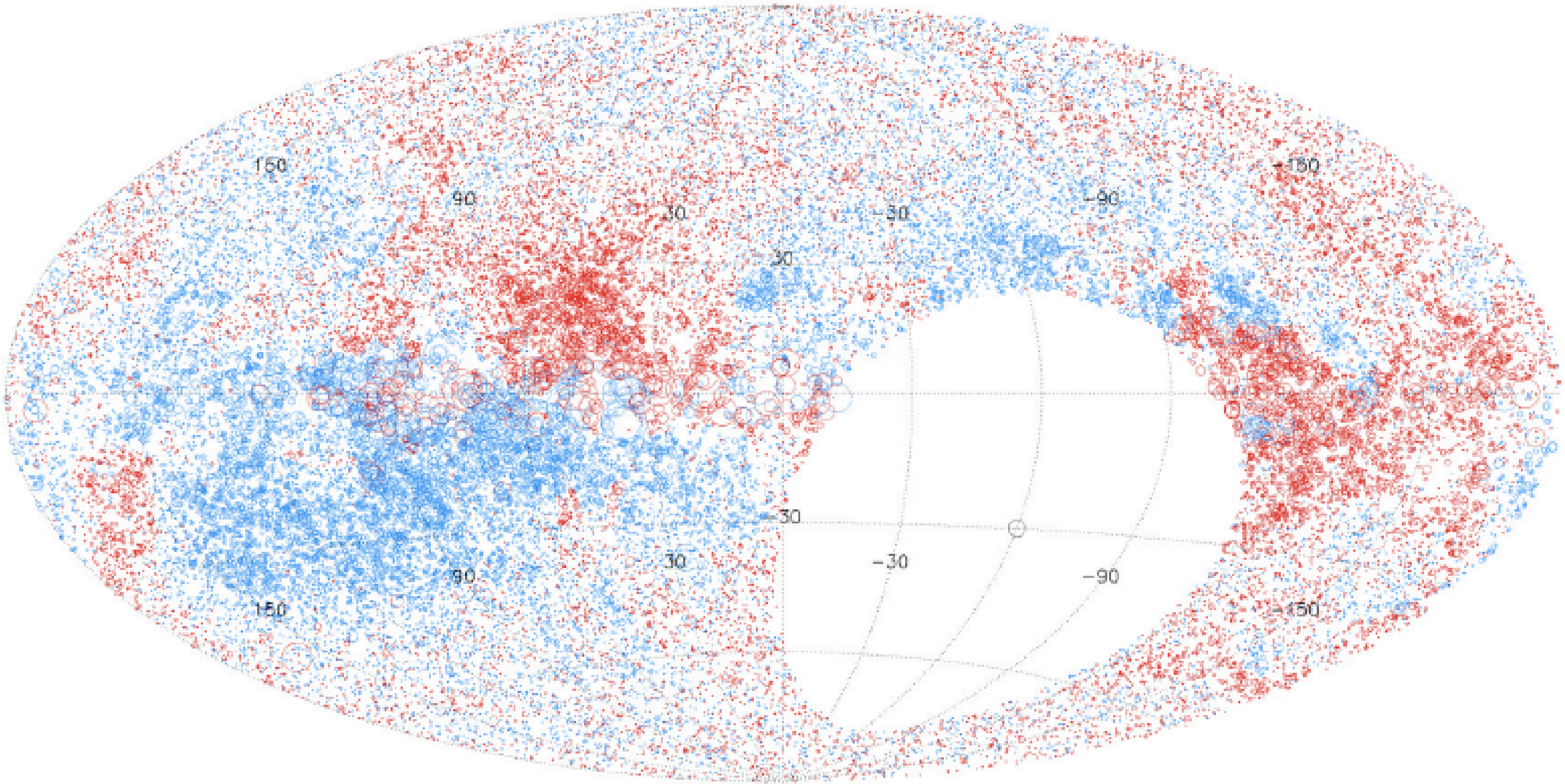
$$\boxed{RM = 0.81\int n_e B \cdot ds}$$



Brown et al 2007



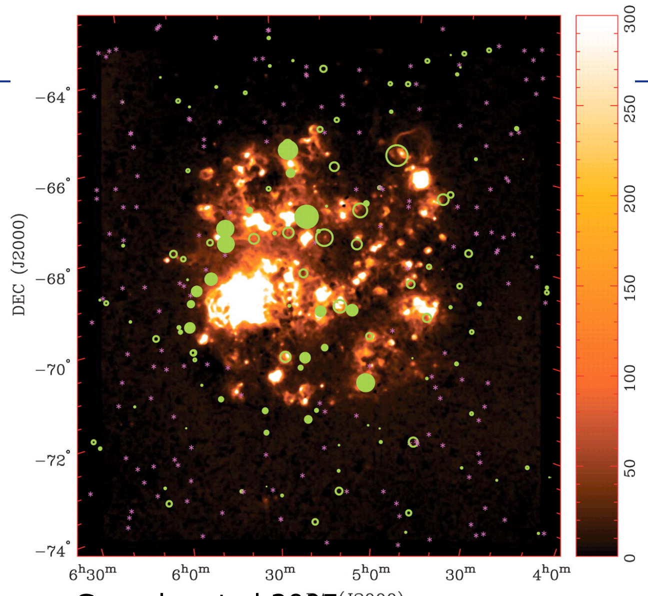
2. A RM grid of background (point) sources



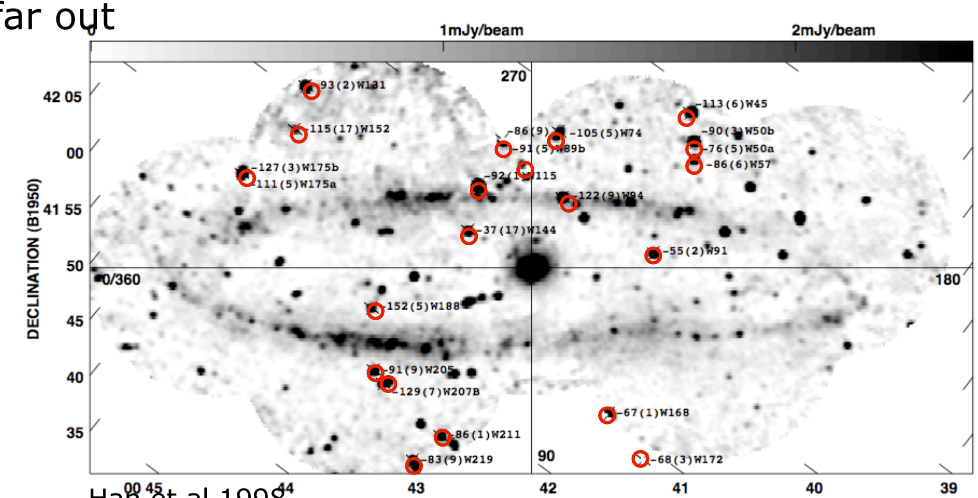
2. A RM grid of background (point) sources

Large Magellanic Cloud: ~100 background sources reveal a large-scale azimuthal magnetic field

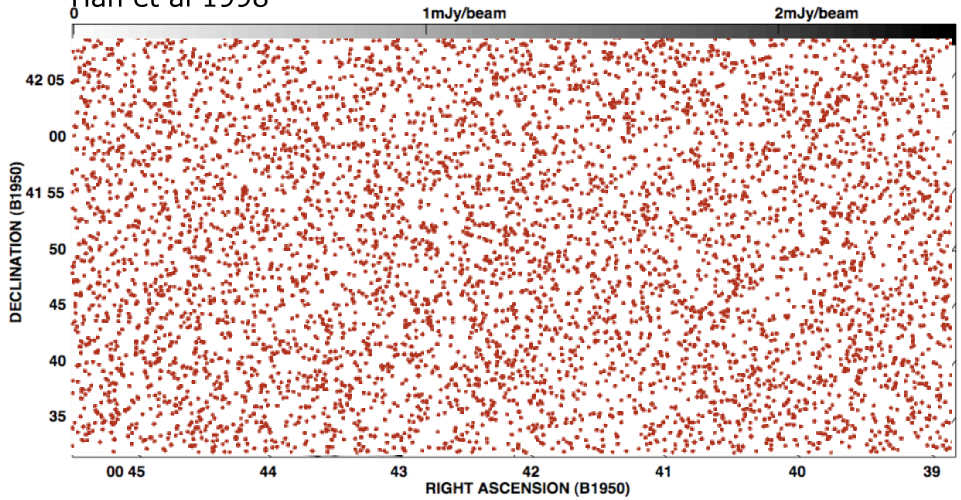
M31: (only) 21 sources hint at axisymmetric field structure, detect field far out

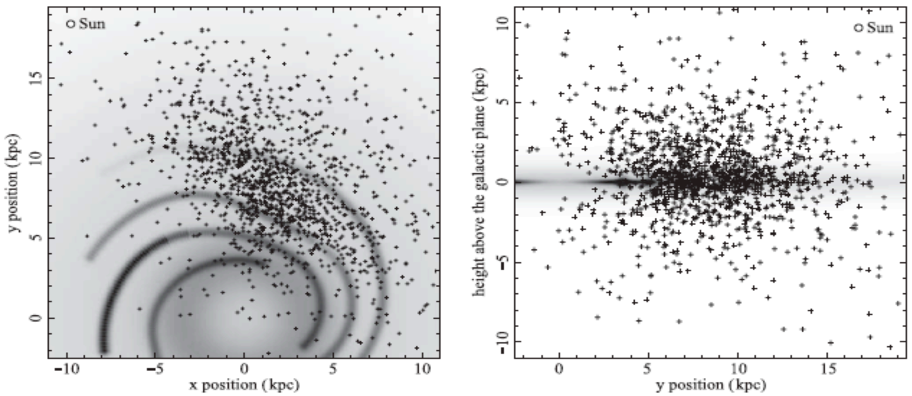


Gaensler et al 2005



Han et al 1998





van Leeuwen and Stappers 2010

1000+ new pulsars

Low frequencies = sensitive RM detection

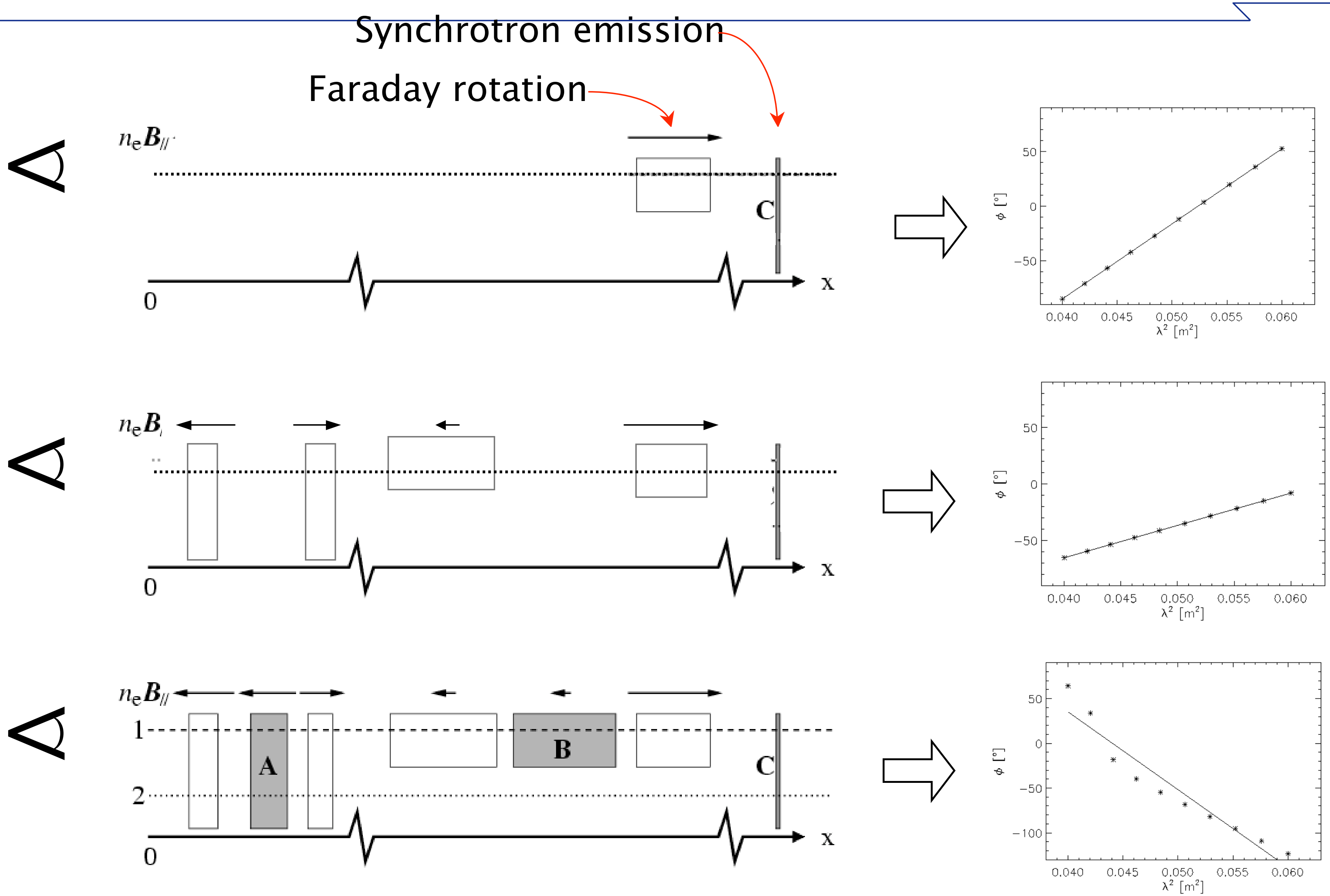
For a S/N = 10, a frequency range [210, 240] MHz allows detecting a δ***RM*** **≈ 0.1 rad m^{-2}** across the band.

Compare: frequency range [1410,1440]: $\delta RM \approx 27$ rad m^{-2}

RM can potentially see out to even larger distances from galaxies: for comparable scale heights *L* of magnetic, cosmic ray and thermal gas energy densities (e.g. away from star forming regions), the scale length L:

$$\left.\begin{aligned} L_{synchrotron} &= 2L/(\alpha+3) \\ L_{RM} &= 2L/3 \end{aligned}\right\} \quad \boldsymbol{L_{RM} > L_{synchrotron}}$$

3. Faraday rotation of diffuse polarization: RM Synthesis



3. RM Synthesis

(Burn 1966, de Bruyn 1996, Killeen et al 2000, Brentjens & de Bruyn 2005)

$$\phi(s) = 0.81 \int_{far}^{near} n_e \vec{B} \bullet \vec{ds}$$

Faraday depth ≈ RM component

$$P(\lambda^2) = \int_{-\infty}^{\infty} F(\phi) e^{2i\phi\lambda^2} d\phi$$

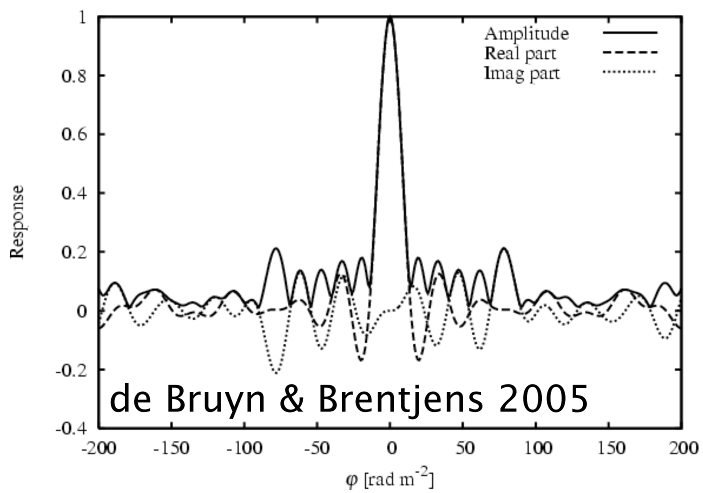
$P(\lambda^2)$: complex polarized surface brightness
$F(\phi)$: Faraday dispersion function/spectrum

$$\begin{cases} \tilde{P}(\lambda^2) = W(\lambda^2) P(\lambda^2) \\ \tilde{F}(\phi) = F(\phi) * R(\phi) \end{cases}$$

Fourier transform

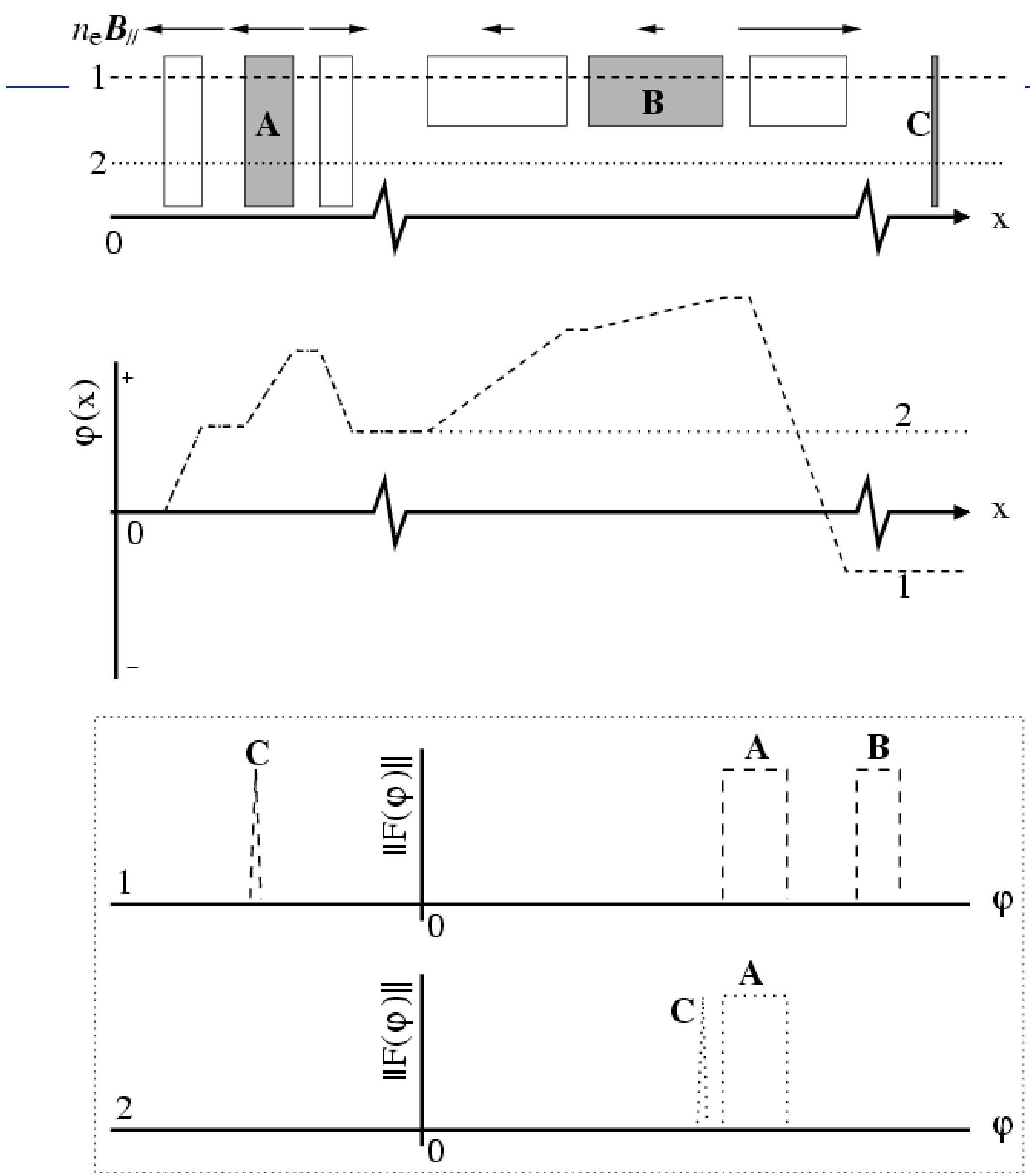
$$R(\phi) = \frac{\int_{-\infty}^{\infty} W(\lambda^2) e^{-2i\phi(\lambda^2 - \lambda_0^2)} d\lambda^2}{\int_{-\infty}^{\infty} W(\lambda^2) d\lambda^2}$$

Rotation Measure Spread Function (RMSF)

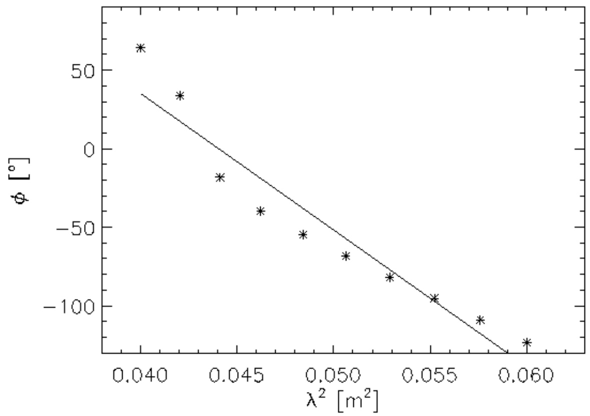


de Bruyn & Brentjens 2005

3. RM Synthesis



VS



3. RM synthesis parameters

Width wavelength distribution $\Delta\lambda^2 \rightarrow \phi$ resolution: $\delta\phi \approx \frac{2\sqrt{3}}{\Delta\lambda^2} = \frac{2\sqrt{3}}{\lambda_1^2 - \lambda_2^2}$

Minimum wavelength $\lambda_{min} \rightarrow$ maximum ϕ scale: $L_{\max} \approx \frac{\pi}{\lambda_{\min}^2}$

Channel thickness $d\lambda^2 \rightarrow$ maximum ϕ: $|\phi_{\max}| \approx \frac{\sqrt{3}}{\delta\lambda^2}$

But take care!

- For maximum scale > resolution: $\lambda_{min}{}^2 < \Delta\lambda^2$
- NO distance information in the various Faraday depth components
- Sidelobes of the RMSF can mimic real sources
- "Beating" of two Faraday depth components can mimic a third component

3. RM synthesis: analogy to interferometry

RM synthesis

$$\tilde{P}(\lambda^2) = \int_{-\infty}^{\infty} F(\phi) * R(\phi) e^{2i\phi\lambda^2} d\phi$$

RMSF $R(\phi)$

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

$$L_{\max} \approx \frac{\pi}{\lambda_{\min}^2}$$

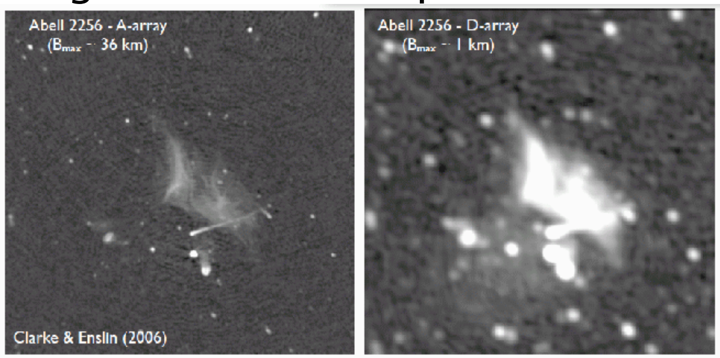
interferometry

$$V(\vec{B}) = \int\int A'(\vec{\sigma}) I(\vec{\sigma}) e^{i2\pi(\frac{\vec{B}}{\lambda}.\sigma)} d\Omega$$

beam pattern $A'(\sigma)$

$$\theta \approx \frac{\lambda}{B}$$

short baselines: large-scale structure
long baselines: compact structure



3. RM synthesis parameters for various instruments

	Parkes Galileo	ATCA 20cm	WSRT MFFEs	LOFAR HBA
$\Delta\nu$ [GHz]	2.18-2.42	1.25-1.78	0.31-0.39	0.24-0.12
$\delta\nu$ [MHz]	2	1	0.4	0.1
$\delta\phi$ [rad m^{-2}]	970	119	10	0.74
L_{max} [rad m^{-2}]	204	111	5	2
ϕ_{max} [rad m^{-2}]	58539	33460	1031	166

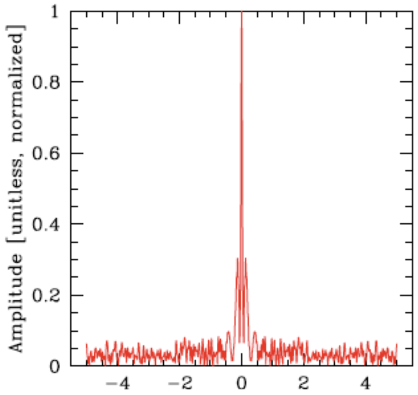
REMINDER

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

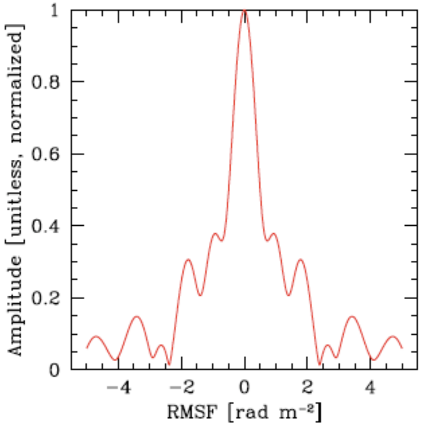
$$L_{\mathrm{max}} \approx \frac{\pi}{\lambda^2_{\mathrm{min}}}$$

$$|\phi_{\mathrm{max}}| \approx \frac{\sqrt{3}}{\delta\lambda^2}$$

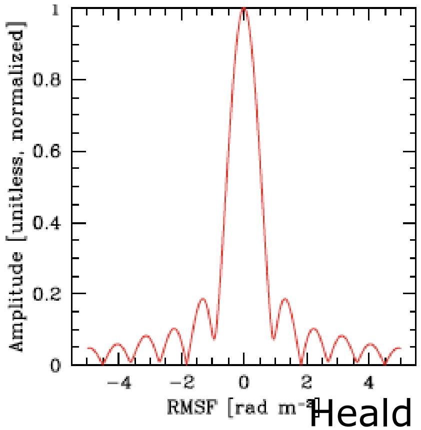
3. RM synthesis parameters for LOFAR



ν = 30-50 + 60-80 MHz
$\Delta\nu$ = 16 MHz
$\delta\phi$ = 0.05 rad m^{-2}
ϕ_{max} = 19 rad m^{-2}
L_{max} = 0.2 rad m^{-2}



ν = 120-150 + 180-210 MHz
$\Delta\nu$ = 16 MHz
$\delta\phi$ = 1.0 rad m^{-2}
ϕ_{max} = 1200 rad m^{-2}
L_{max} = 1.5 rad m^{-2}



ν = 120-180 MHz
$\Delta\nu$ = 40 MHz
$\delta\phi$ = 1.1 rad m^{-2}
ϕ_{max} = 1200 rad m^{-2}
L_{max} = 1.1 rad m^{-2}

Heald 2009

REMINDER

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

$$L_{\max} \approx \frac{\pi}{\lambda^2_{\min}}$$

$$|\phi_{\max}| \approx \frac{\sqrt{3}}{\delta\lambda^2}$$

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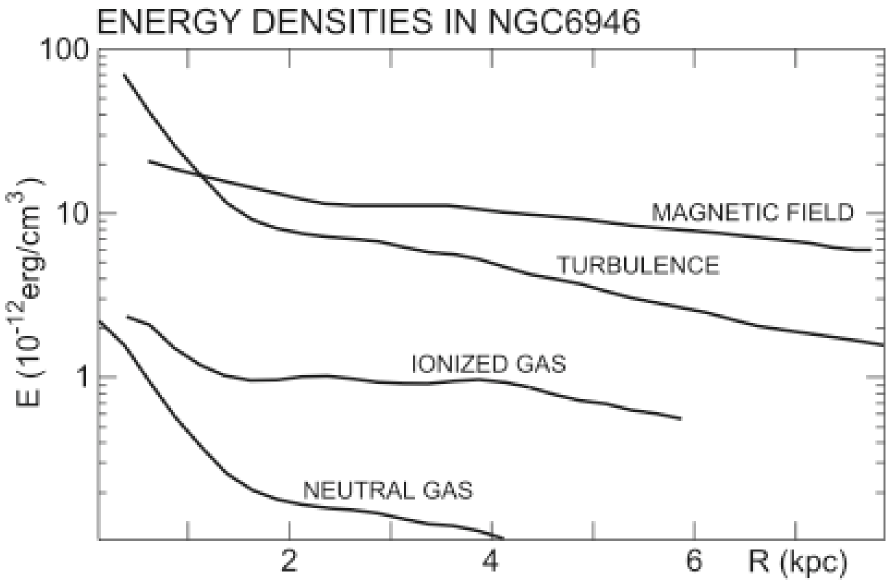
- explore the origin and evolution of cosmic magnetism: test dynamo theories
- find the magnetic structure of stellar and AGN jets

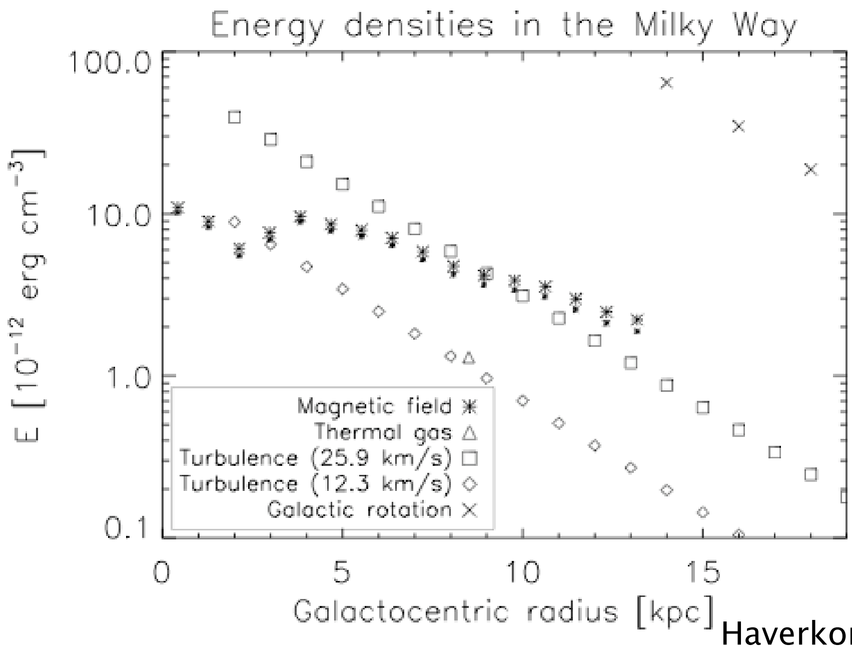
Understanding of the interstellar matter is only possible when understanding magnetic fields

Magnetic pressure	$P_B = \frac{B^2}{8\pi}$	$\approx (0.4-1.4)\ 10^{-12}$	dyn cm^{-2}
Cosmic ray pressure	P_{CR}	$\approx (0.8-1.6)\ 10^{-12}$	dyn cm^{-2}
Turbulent gas pressure	$P_{turb} \propto \rho\sigma^2$	$\approx (1.0-1.5)\ 10^{-12}$	dyn cm^{-2}
(Thermal gas pressure	P_{therm}	$\approx 0.3\ 10^{-12}$	dyn cm^{-2})

Boulares & Cox 1990

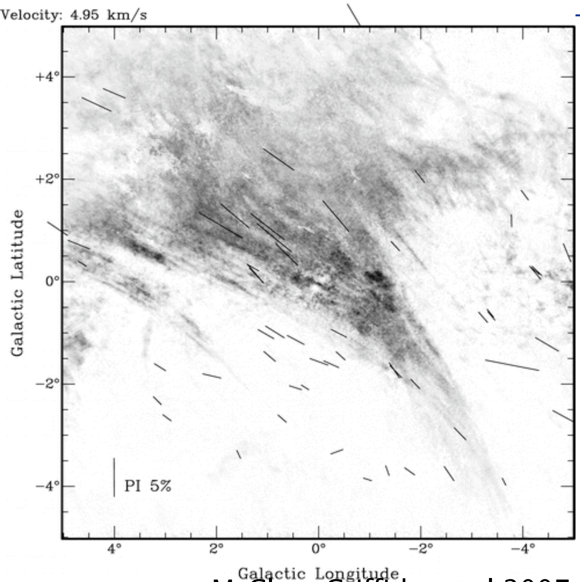


Beck 2004



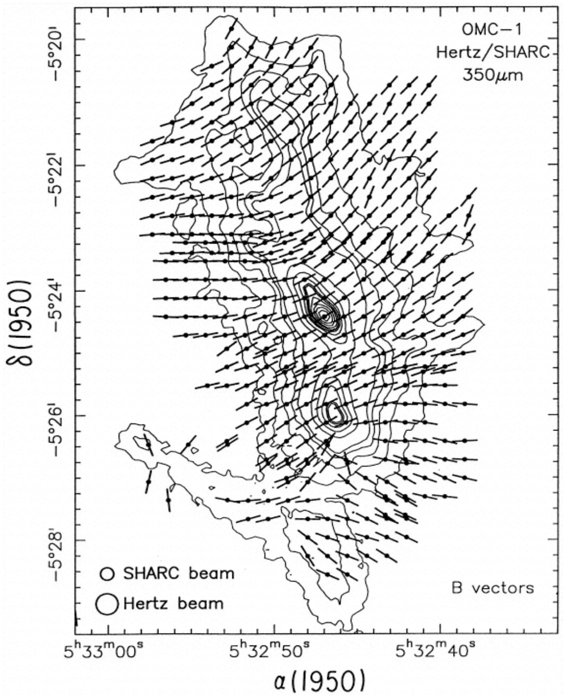
Haverkorn 2010

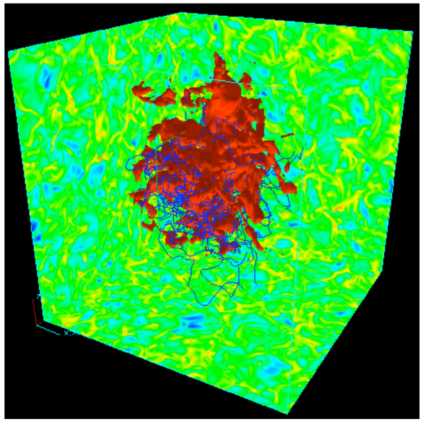
Magnetic fields in galaxies: interaction with gas dynamics

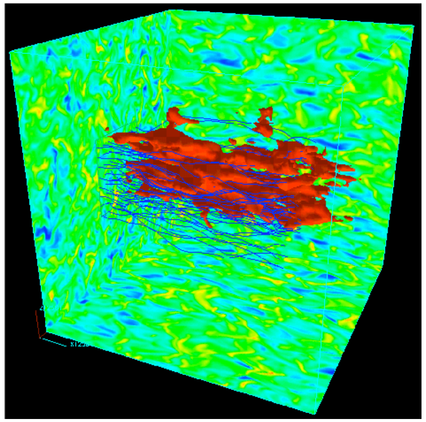


McClure-Griffiths et al 2007

Hildebrand et al 2000

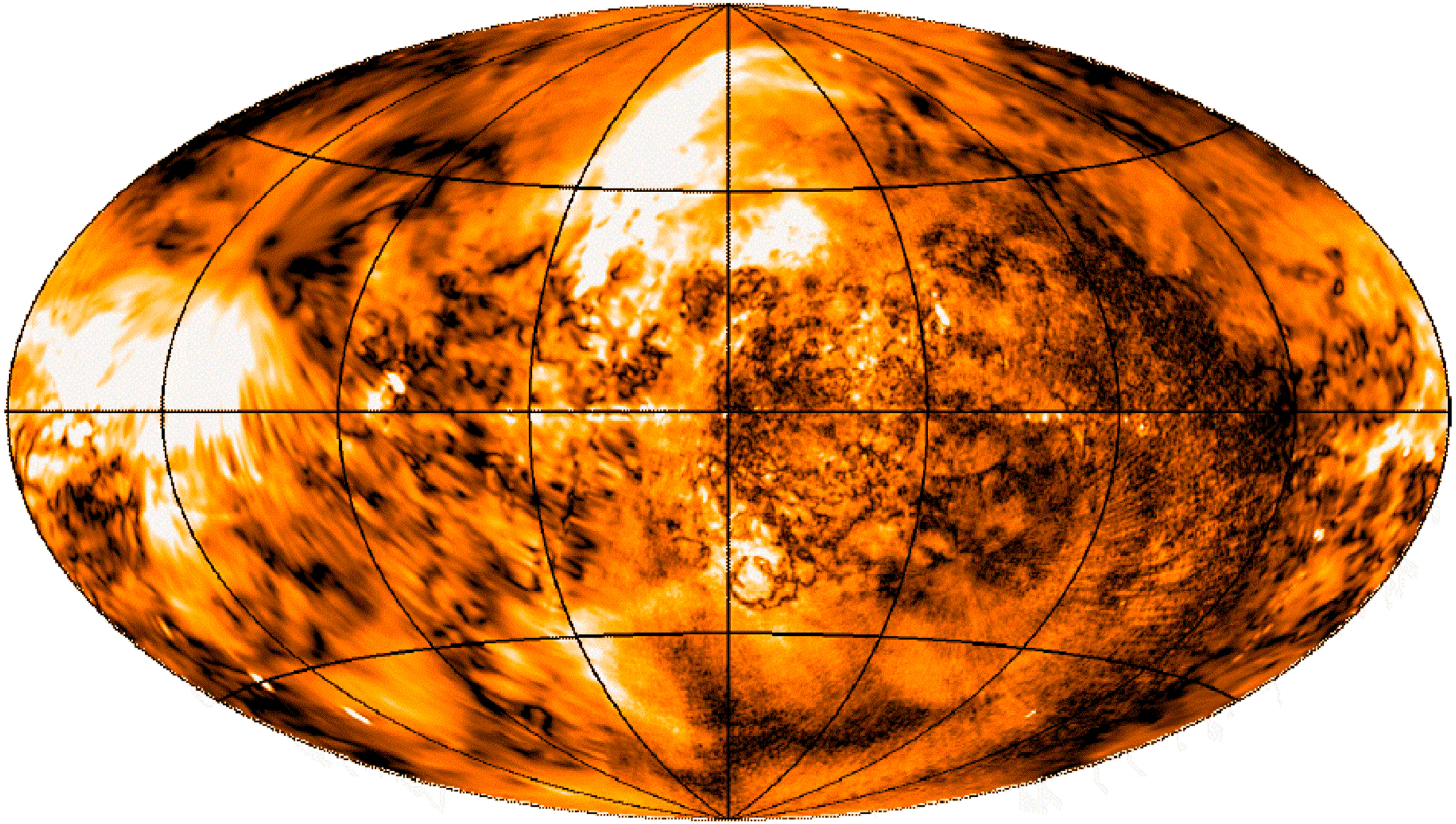






images courtesy Jim Stone

Magnetic fields in galaxies: interaction with gas dynamics



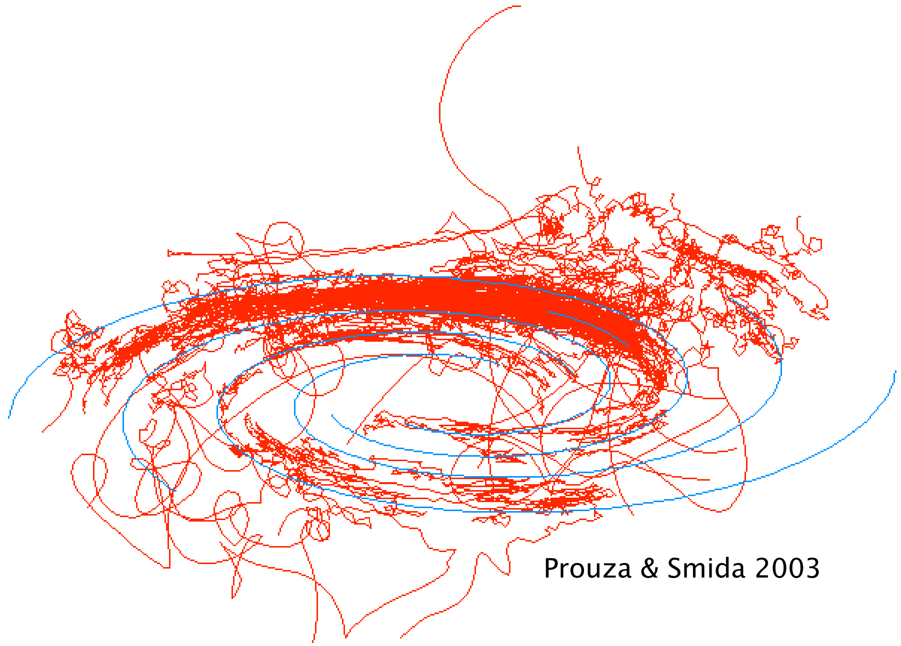
Reich et al 2008; Wolleben et al 2006; Testori et al 2003

Magnetic fields in the Milky Way: deflecting (ultra-) high energy cosmic rays

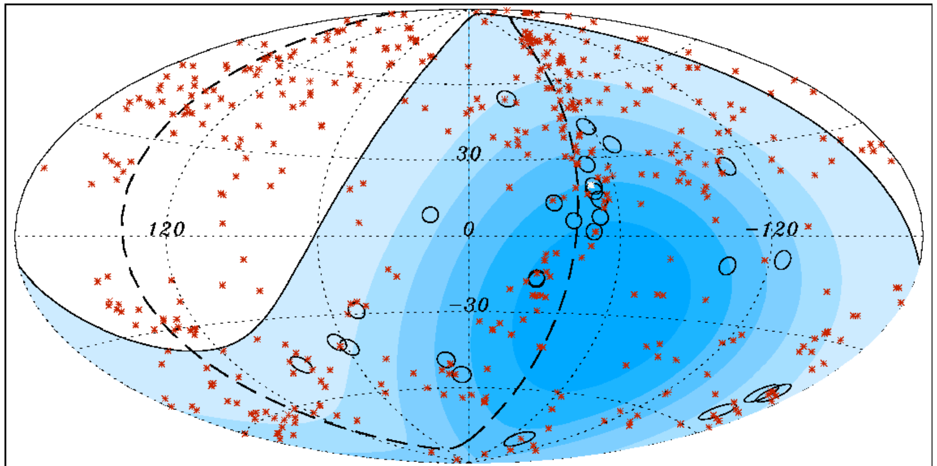
Cosmic rays are deflected by the Galactic magnetic field, randomizing their directions and containing them inside the Galaxy.

Cosmic rays are accelerated in supernova shocks that interact with the magnetised ISM.

Ultra-high energy cosmic rays are deflected a few (tens) of degrees in the Milky Way magnetic field: good magnetic field models allow back-tracing to their sources



Prouza & Smida 2003



The Auger collaboration

Magnetic fields in the Milky Way: polarization in discrete objects

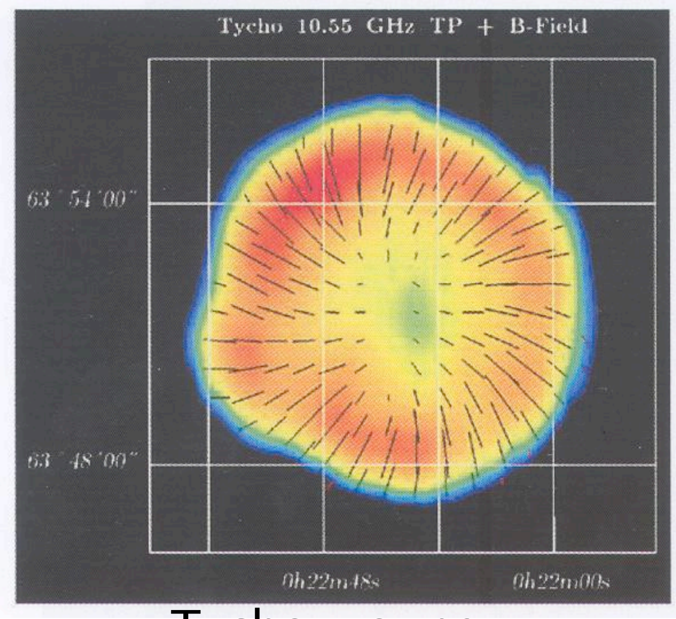
Supernova remnants:

Young shells (Tycho, SN1006, Kepler):

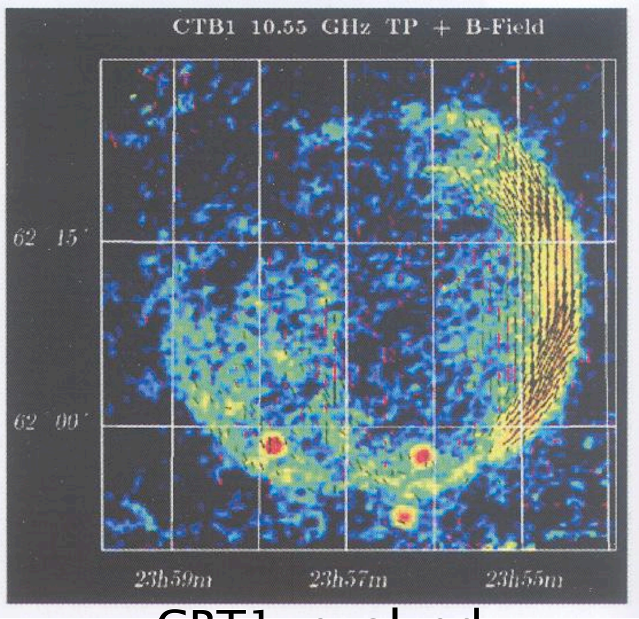
radial magnetic field, due to Rayleigh-Taylor instabilities between shock and ejecta.

p = 4% - 15%: large fraction of field is random

Evolved shells: magnetic field along shock front



Tycho: young



CBT1: evolved

Fürst & Reich 2001

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, Kepler):

Rayleigh-Taylor

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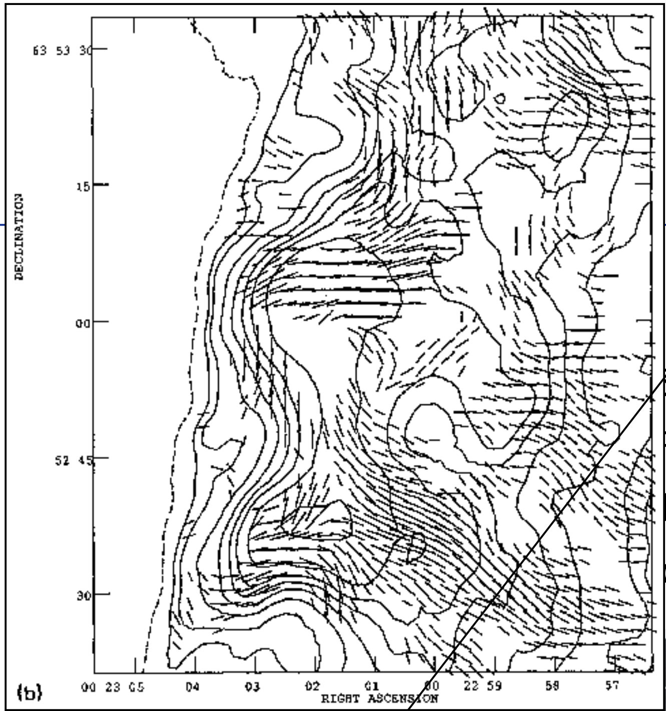
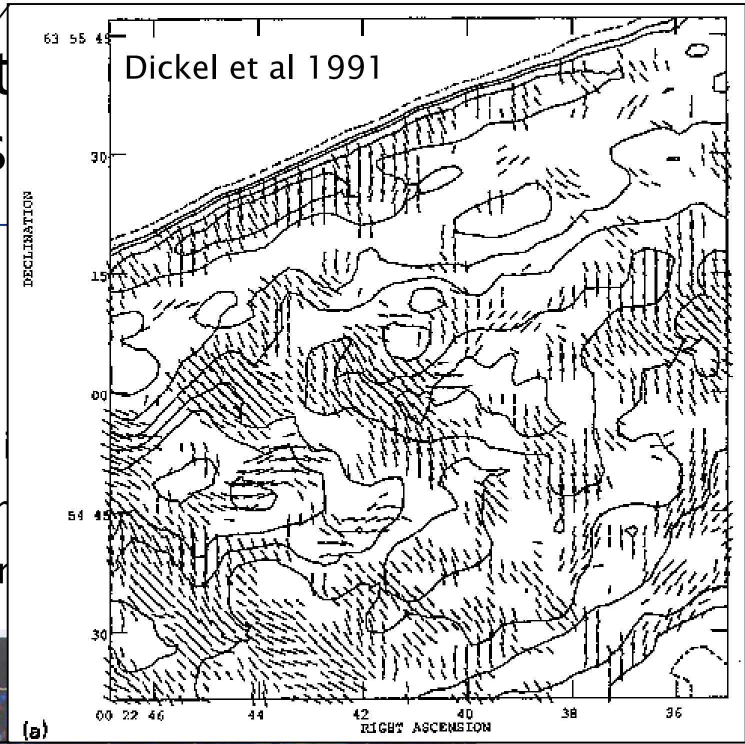
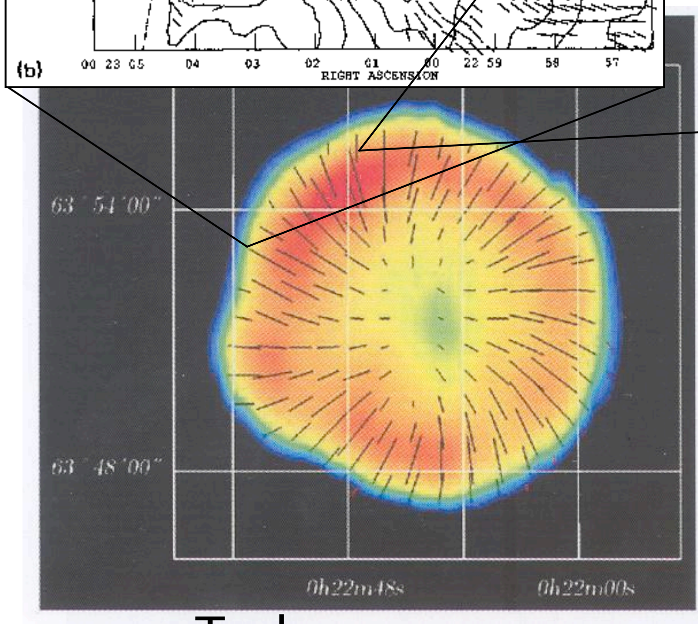
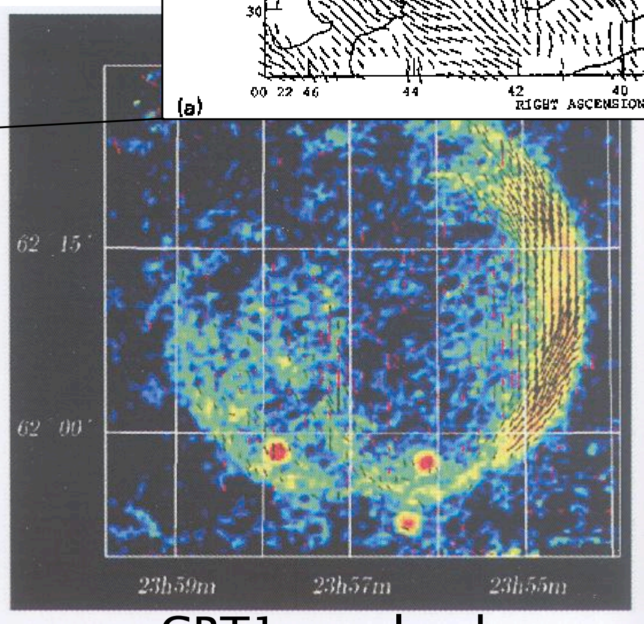






Tycho: young



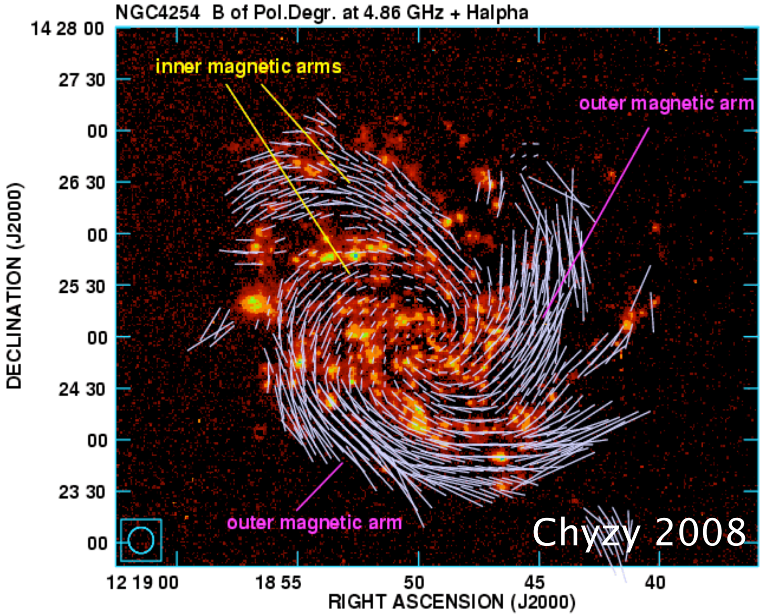
CBT1: evolved

Fürst & Reich 2001

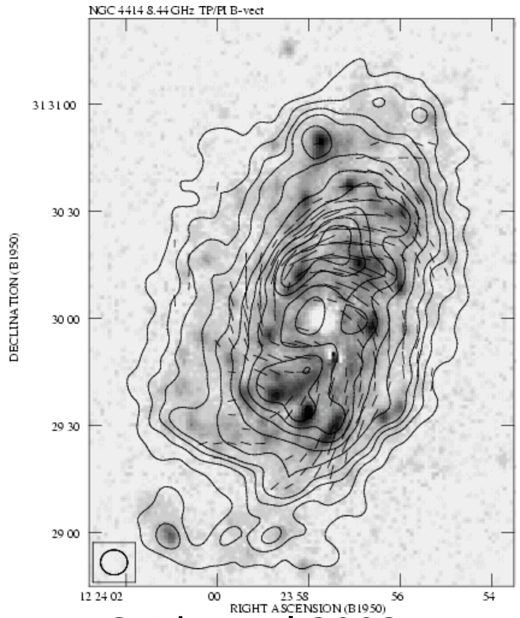
Magnetic fields in nearby external galaxies

Spirals: $B \approx 10\ \mu G$ in typical spirals (M31, M33);
$B \approx 15\ \mu G$ for high-star forming galaxies (M51)
$B \approx 30\ \mu G$ for starburst galaxies (M82, Antennae)

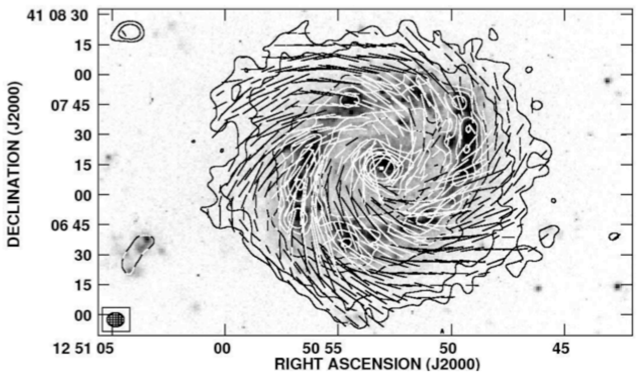
$B_{uniform}$ is the strongest in the interarm regions



Chyzy 2008



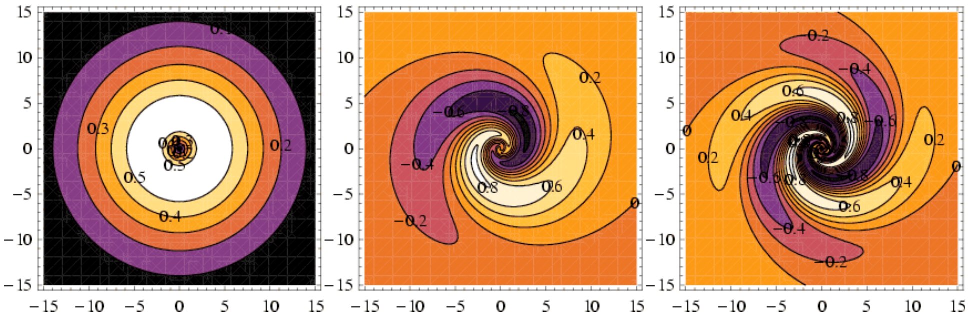
Soida et al 2002



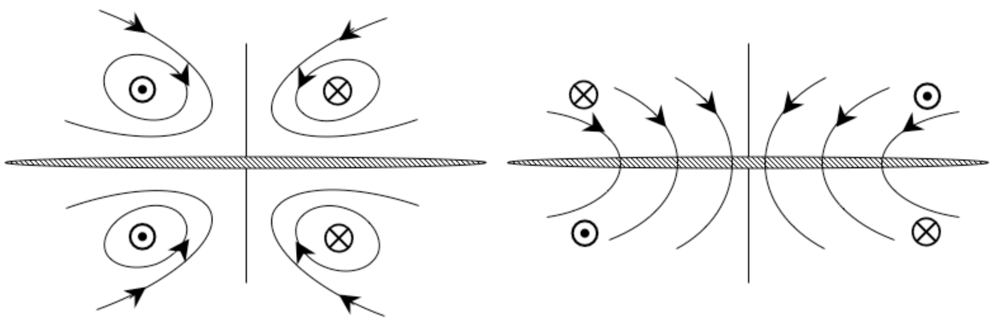
Chyzy & Buta 2009

Spiral magnetic field exists in almost all galaxies, even the ringed and flocculent ones

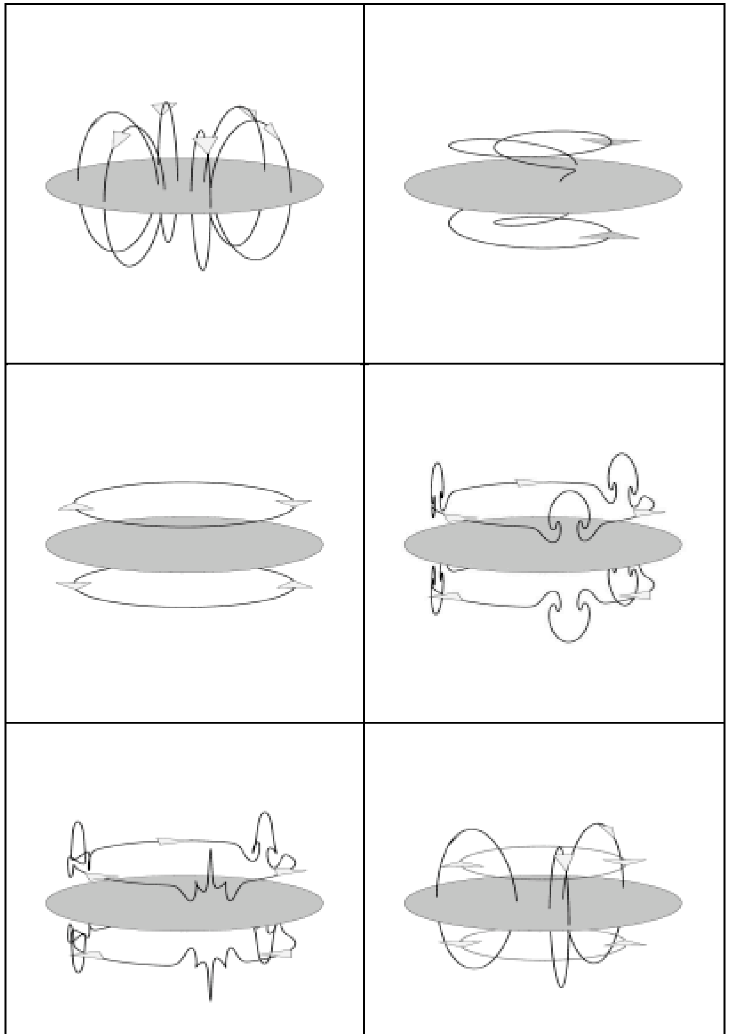
The origin and evolution of cosmic magnetism



Stepanov et al 2007



quadrupolar vs dipolar



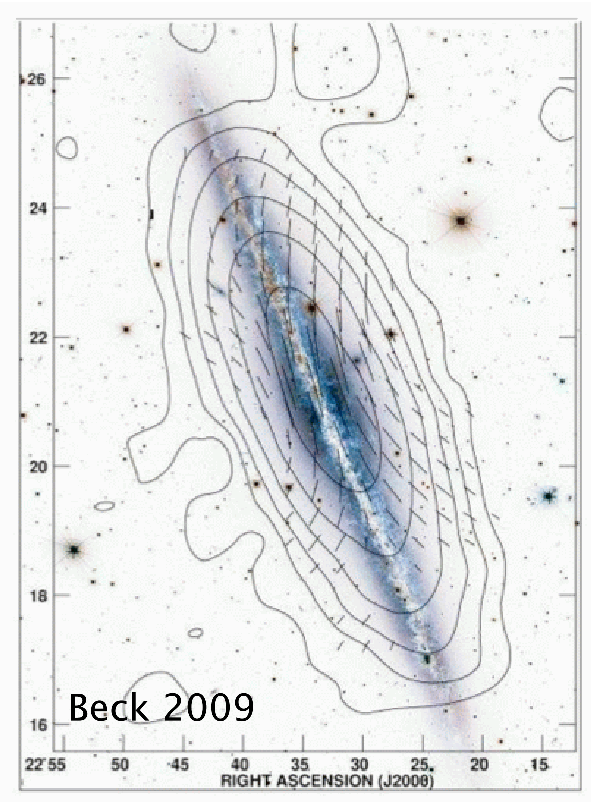
Widrow 2002

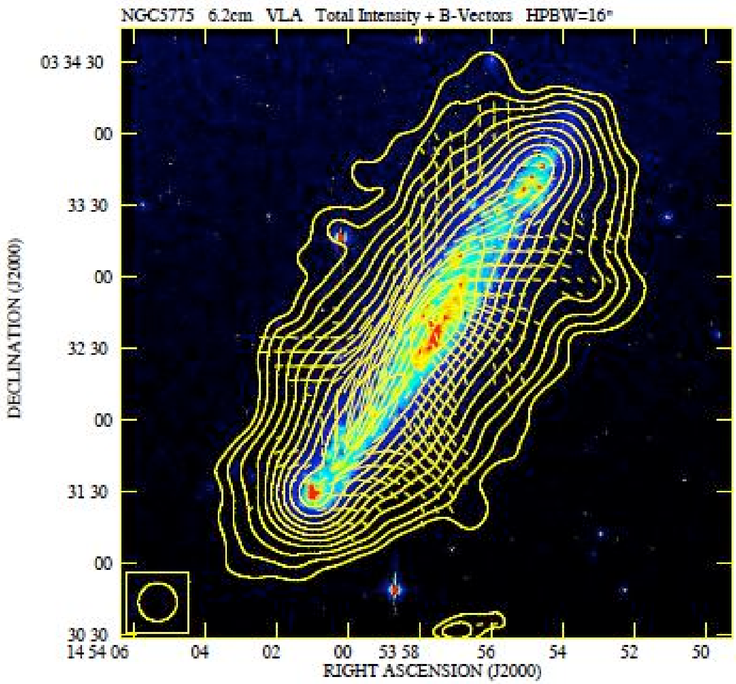
Magnetic fields in nearby external galaxies

Halos are seen around disks of many edge-on spirals.

Radio intensity and halo extent vary greatly

There is a rough correlation with Hα and X-rays : star formation in the disk is an energy source for halo formation

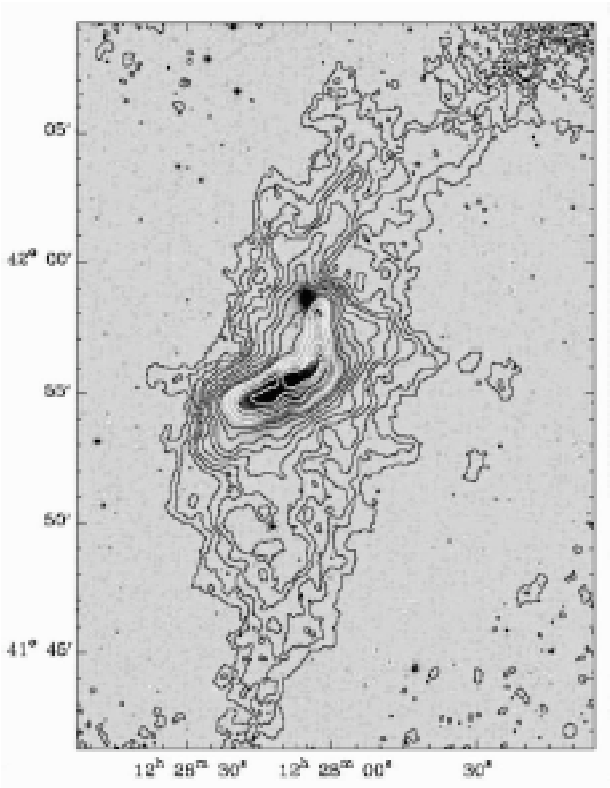


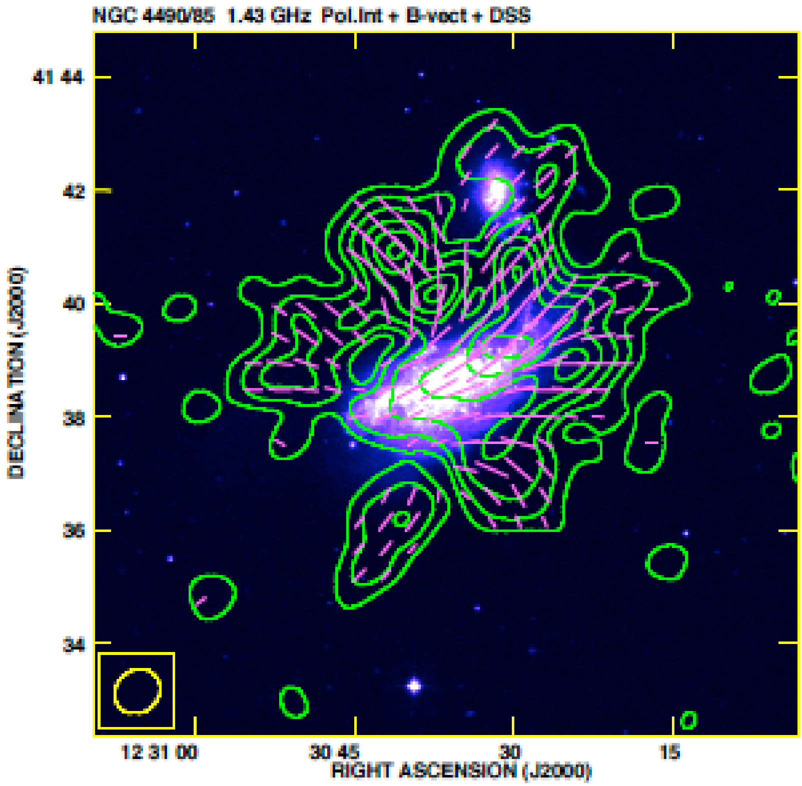


Tüllmann et al 2000

Magnetic fields in nearby external galaxies

Probe magnetic fields in and between interacting galaxies





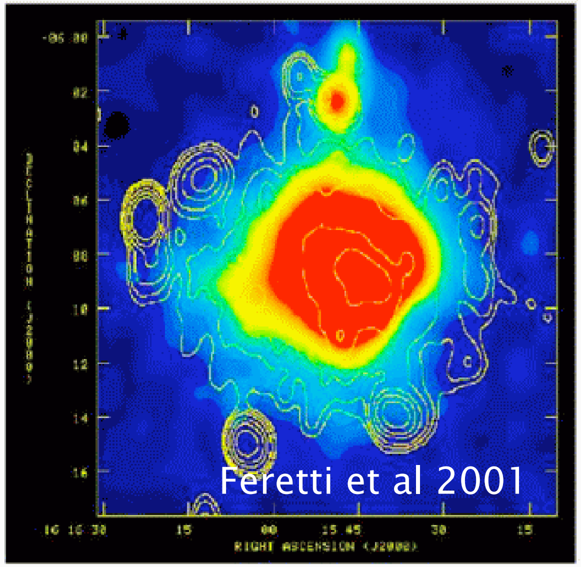
NGC4490/85 interacting galaxies:

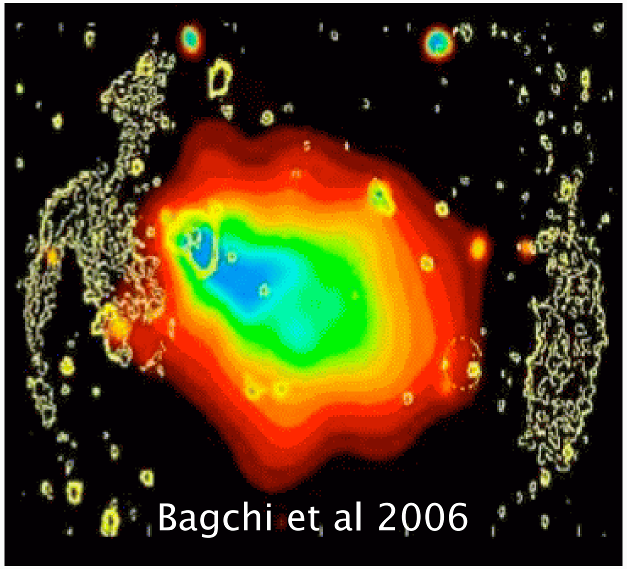
Left: HI overlaid on optical (Clemens et al 1998).

Right: VLA 1.4 GHz polarized continuum (Knapik et al in prep)

Magnetic fields in galaxy clusters

Some fraction of galaxy clusters - mostly the X-ray bright ones - have diffuse radio emission.
Origin of cluster magnetic fields can be outflows from Active Galactic Nuclei, turbulent wakes, cluster mergers etc.



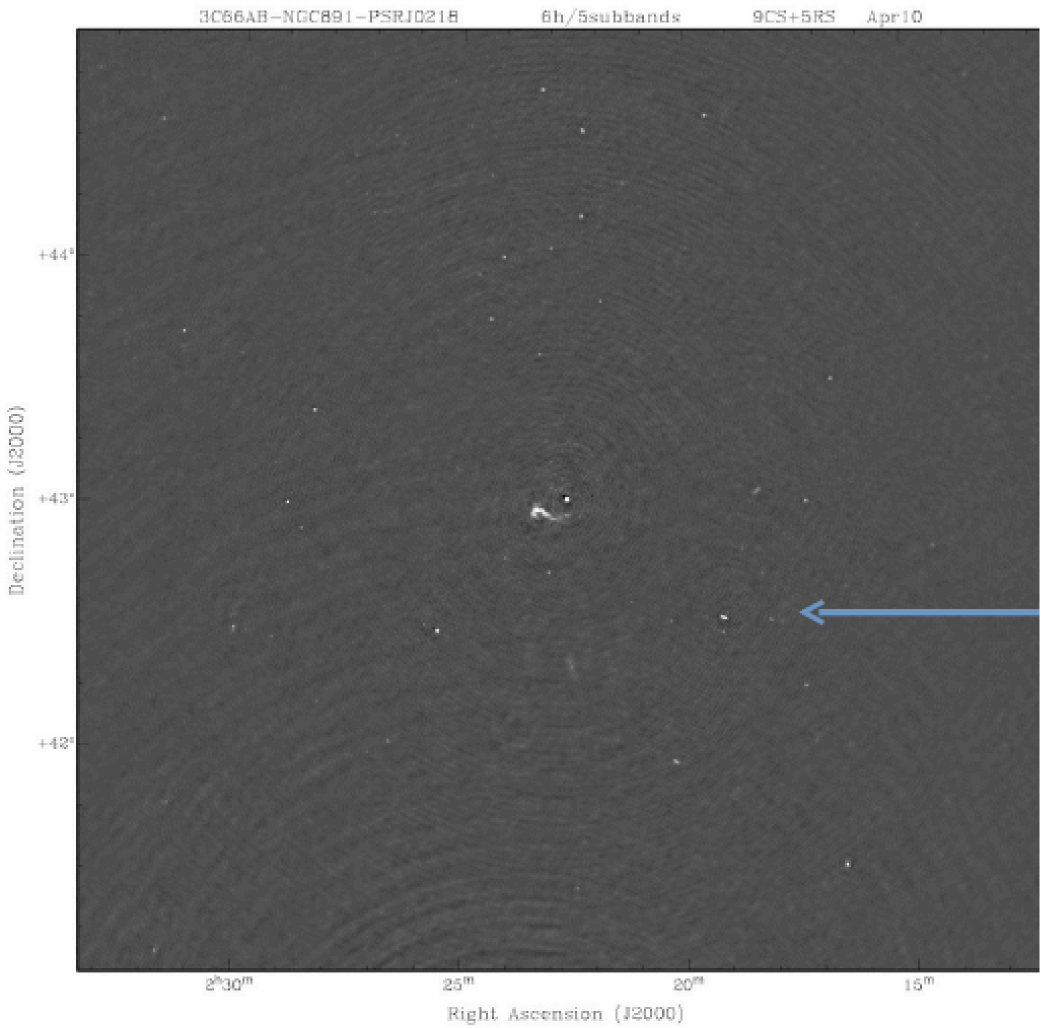


Radio halos:
in cluster center;
unpolarised synchrotron;
from turbulent intracluster magnetic fields

Radio relics:
in cluster periphery;
highly polarised synchrotron;
due to merger shocks

The first LOFAR sky polarization detection!

3C66, NGC891 and PSR J0218+4232 (Scaife, Heald, de Bruyn)

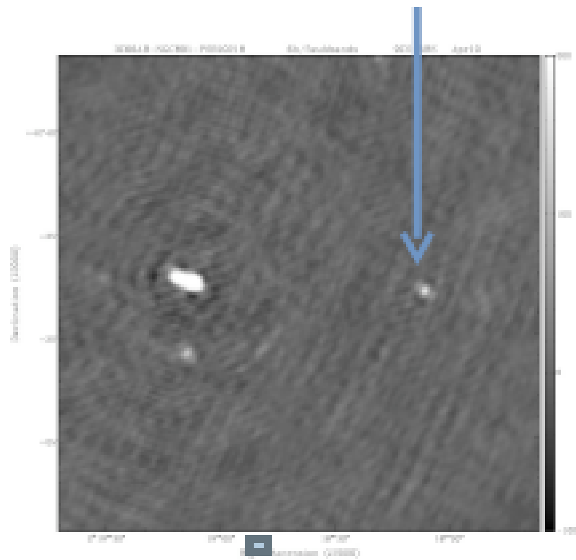


PSR J0218+4232

6 hours HBA

S_{150MHz} = 150 mJy

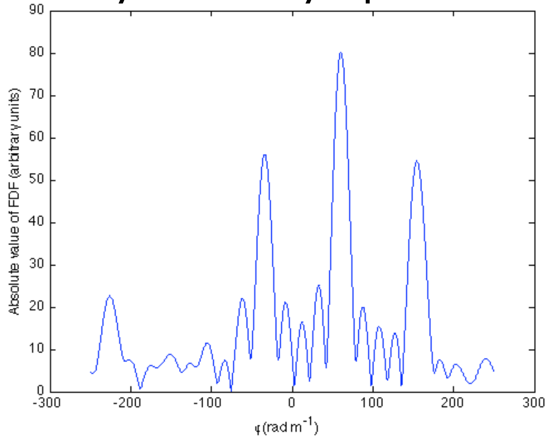
~50% polarized



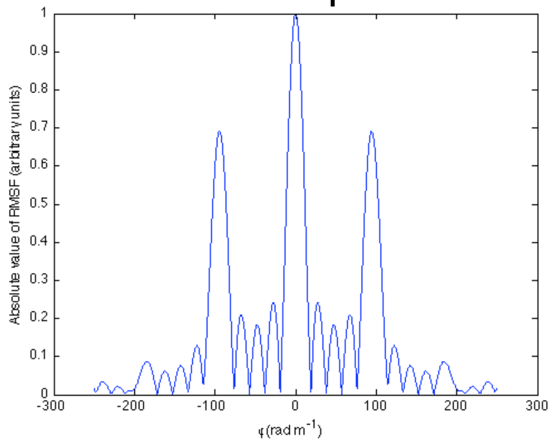
slide courtesy Ger de Bruyn

The first LOFAR sky polarization detection!

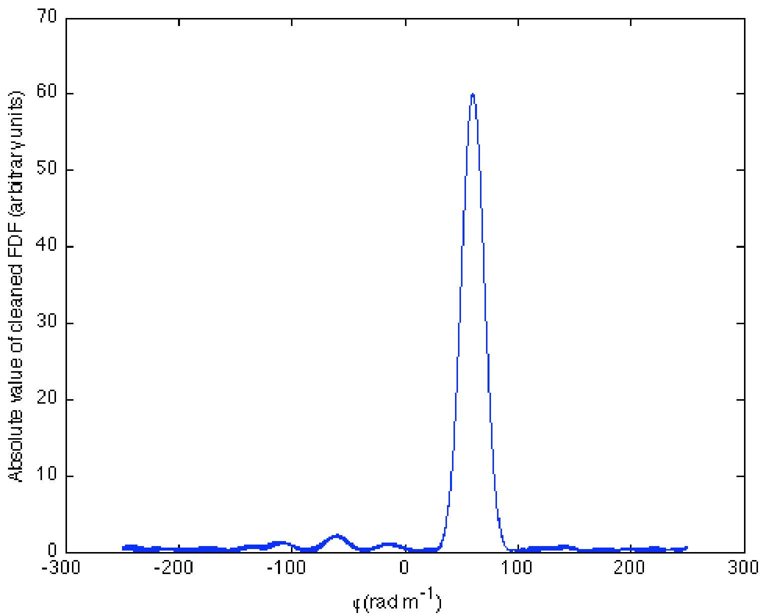
Dirty Faraday spectrum



Rotation Measure Spread Function



RM-CLEANed Faraday spectrum



ν = 129 MHz

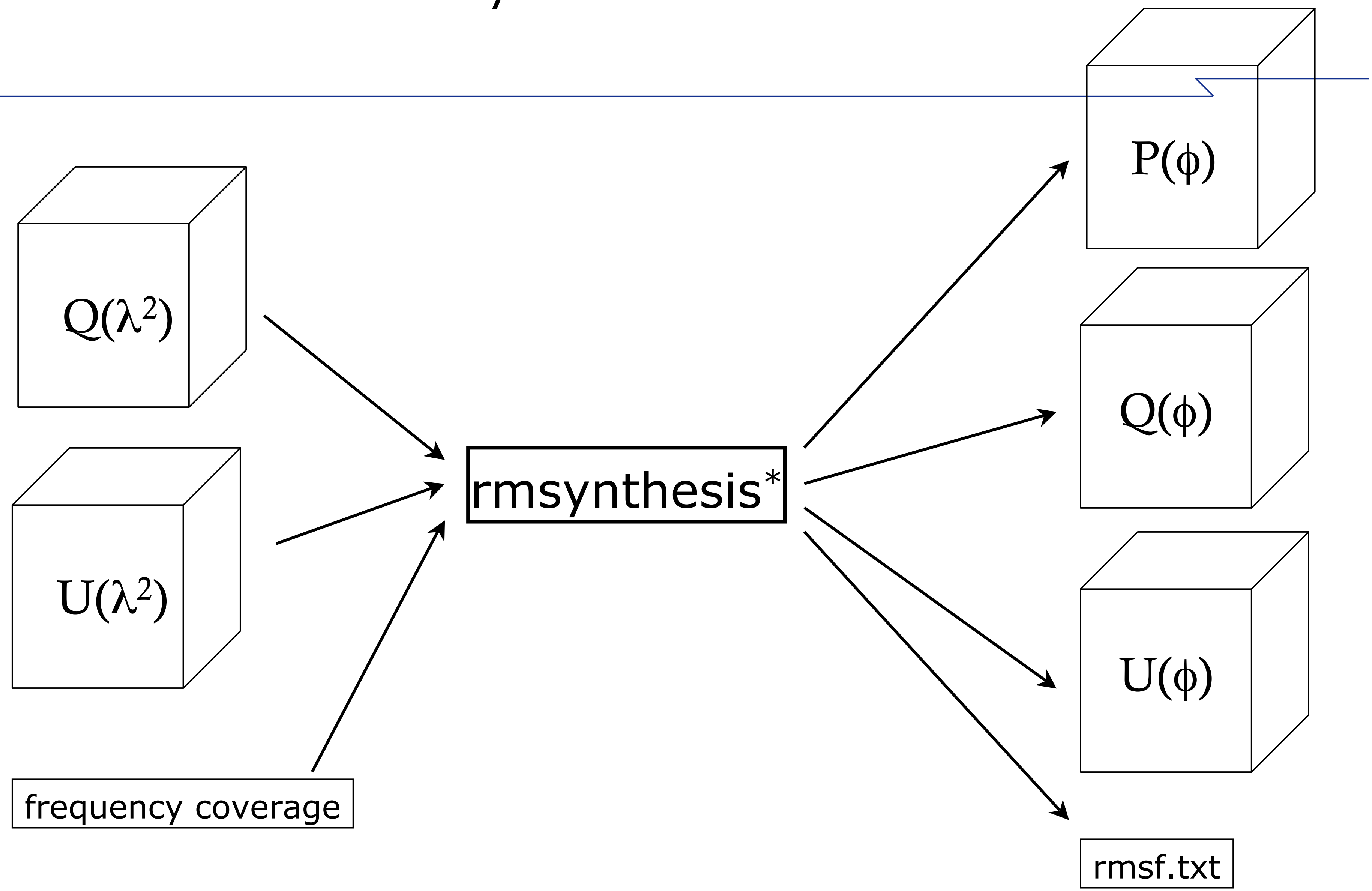
$\Delta\nu$ = 1 MHz

RM_{LOFAR} = 60 rad/m^2

RM_{true} = -61 rad/m2

slide courtesy Ger de Bruyn

RM Synthesis Exercises



*Thank you Michiel Brentjens!