MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Radioastronomie

Magnetic fields in spiral galaxies

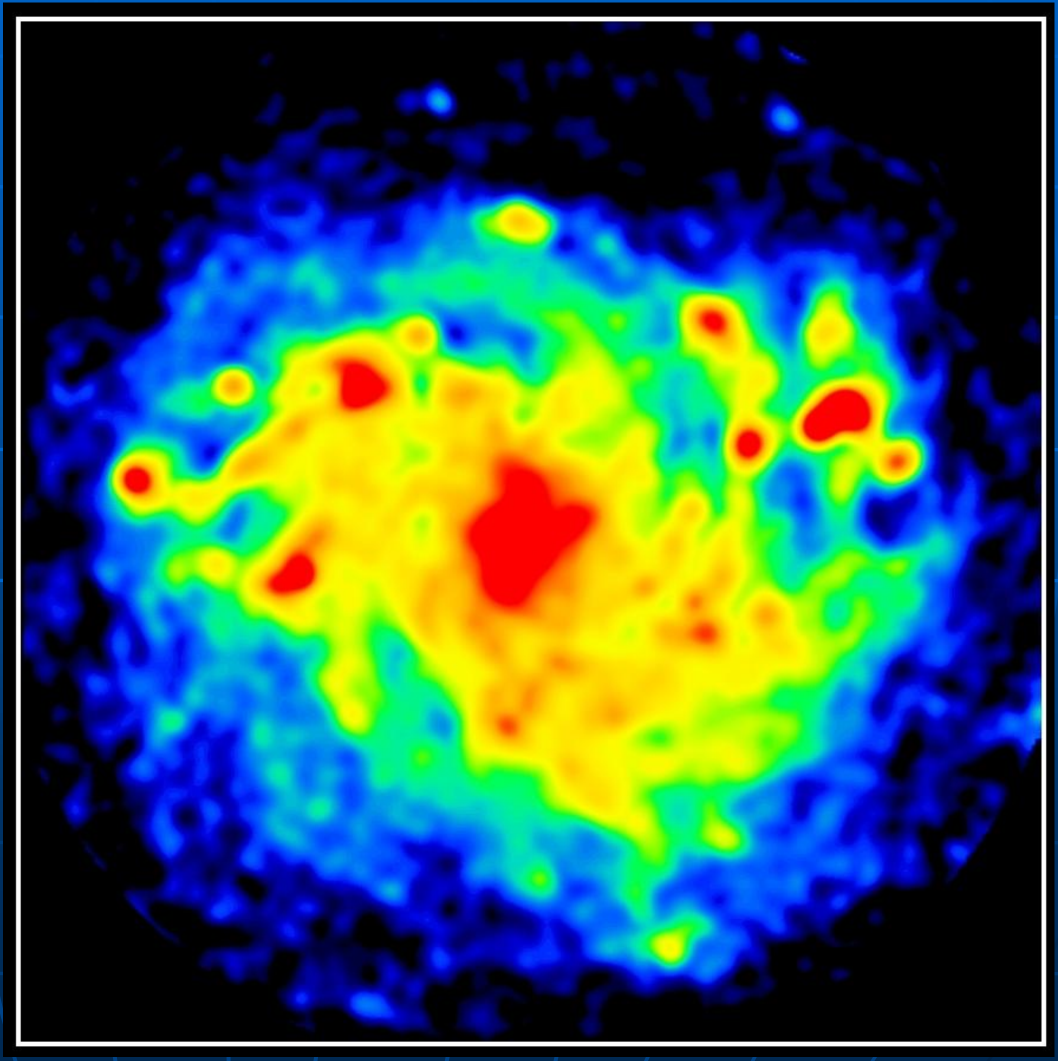
Rainer Beck

Total radio emission of NGC 6946
6.3cm Effelsberg+VLA

Beck 2007

Exponential disk of total magnetic fields –

extent limited by energy losses of cosmic-ray electrons



Radial scale lengths of radio disks
(compilation by A. Fletcher)

	Scale length [kpc]			
	l_{syn}	B	R_{25} [kpc]	Source
NGC 6946	4	16	9	Beck 2007
NGC 253	3 & 7	7 & 13	17	Heesen et al. 2009
NGC 1569	0.4		1.8	Kepley 2010
M33	5.8	24	6.5	Tabatabaei 2007
M81	3.5	13	7	Beck et al. 1985
IC 342	4.7		7	Krause et al. 1989
Milky Way	3–4	10		Strong 2000 Beuermann 1985

Typical scale lengths of radio disks

- Synchrotron intensity: ≈ 4 kpc
  (smaller in dwarf galaxies)

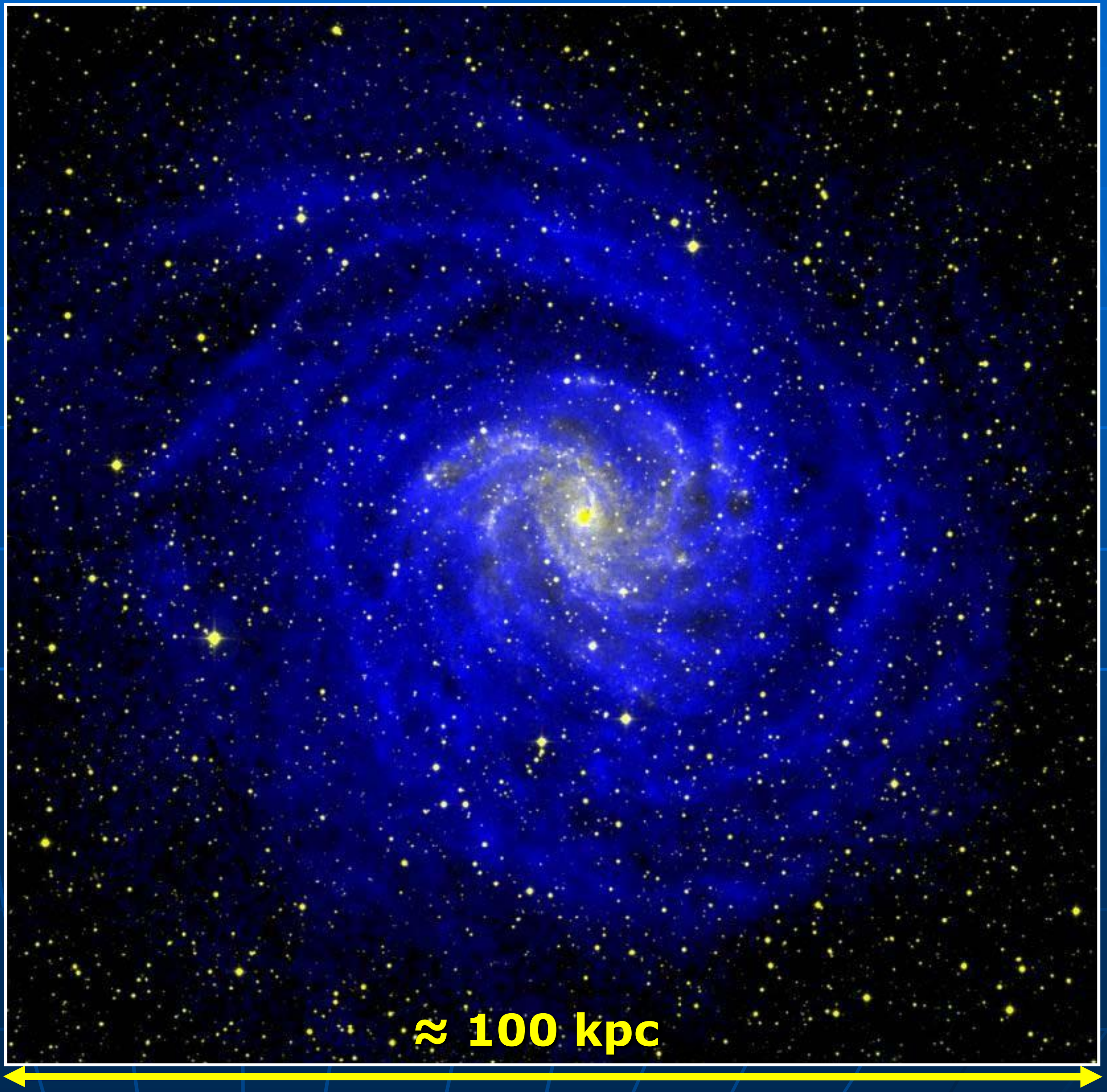
- Cosmic-ray electrons: ≤ 8 kpc
  $(3+\alpha)/2$ times larger than synchrotron ($\alpha \approx 0.8$), assuming **equipartition**,
  this gives an upper limit in case of energy losses

- Total magnetic field: ≥ 16 kpc
  $(3+\alpha)$ times larger, lower limit

NGC 6946

WSRT HI line
+ optical
(Boomsma et al. 2006)

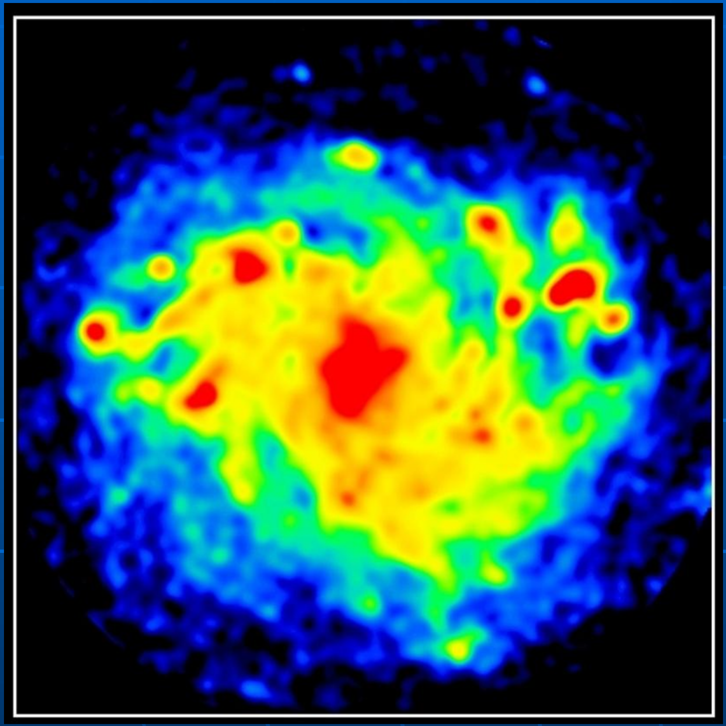
Gas in the outer disk:
all magnetic?

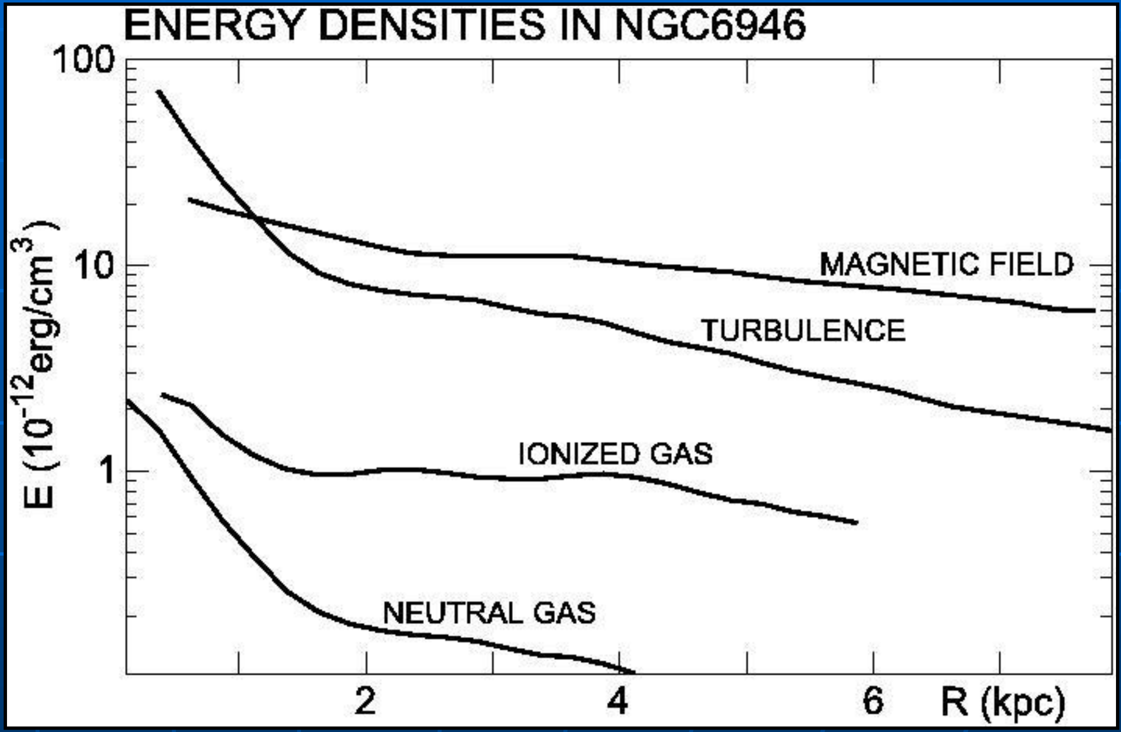


Energy densities

(assuming equipartition between energies of magnetic fields and cosmic rays)

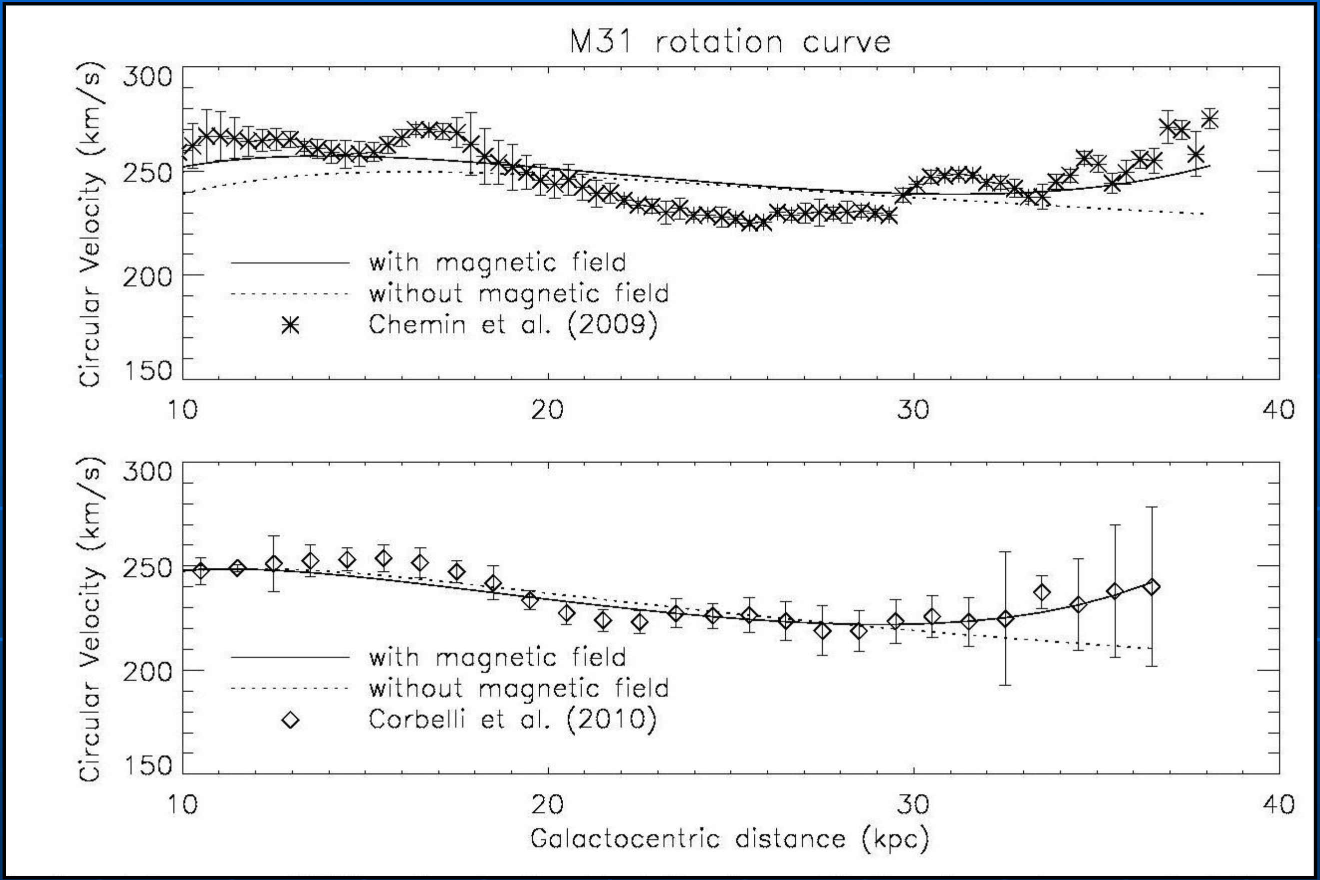
Beck 2007





The average magnetic energy density is similar or larger than that of turbulent gas motions

Can magnetic fields affect galactic rotation ?

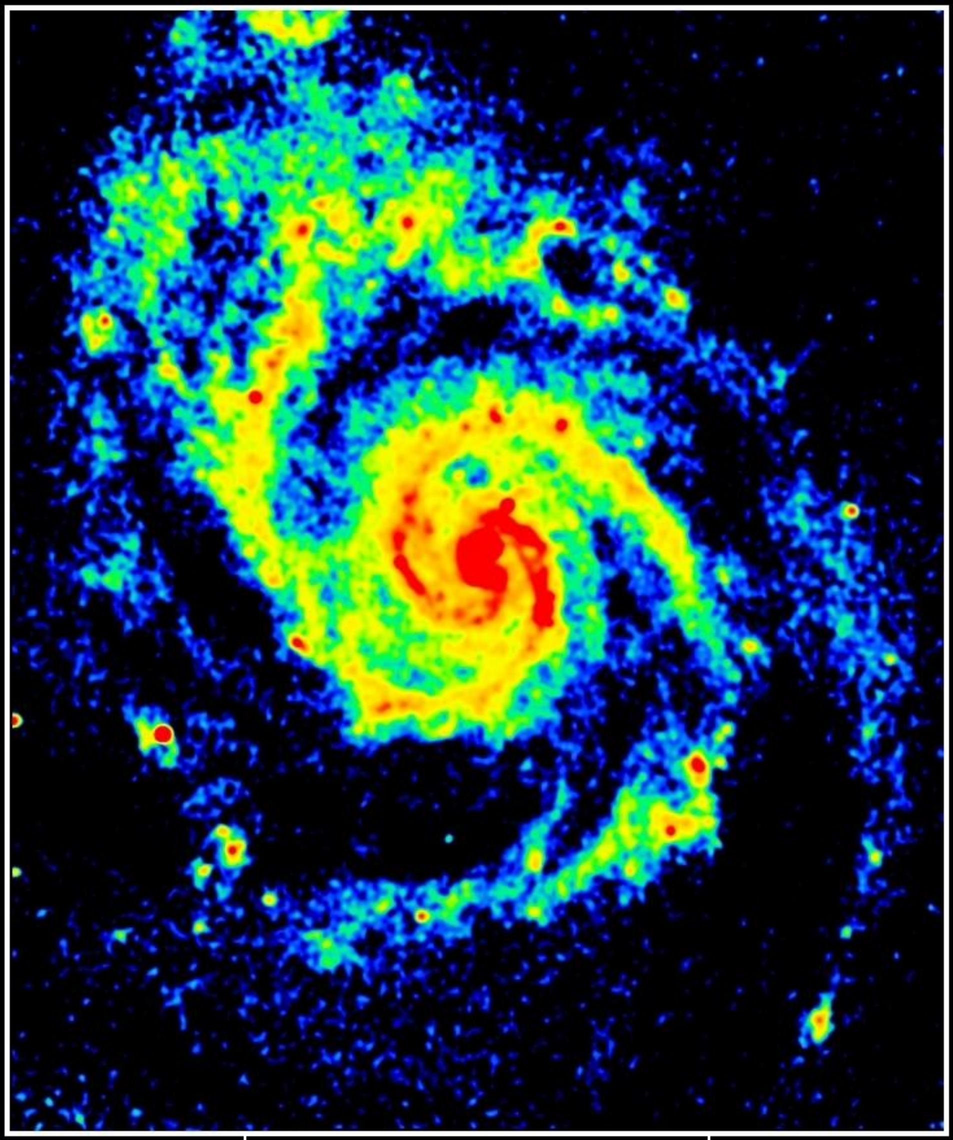


Ruiz-Granados et al. 2010

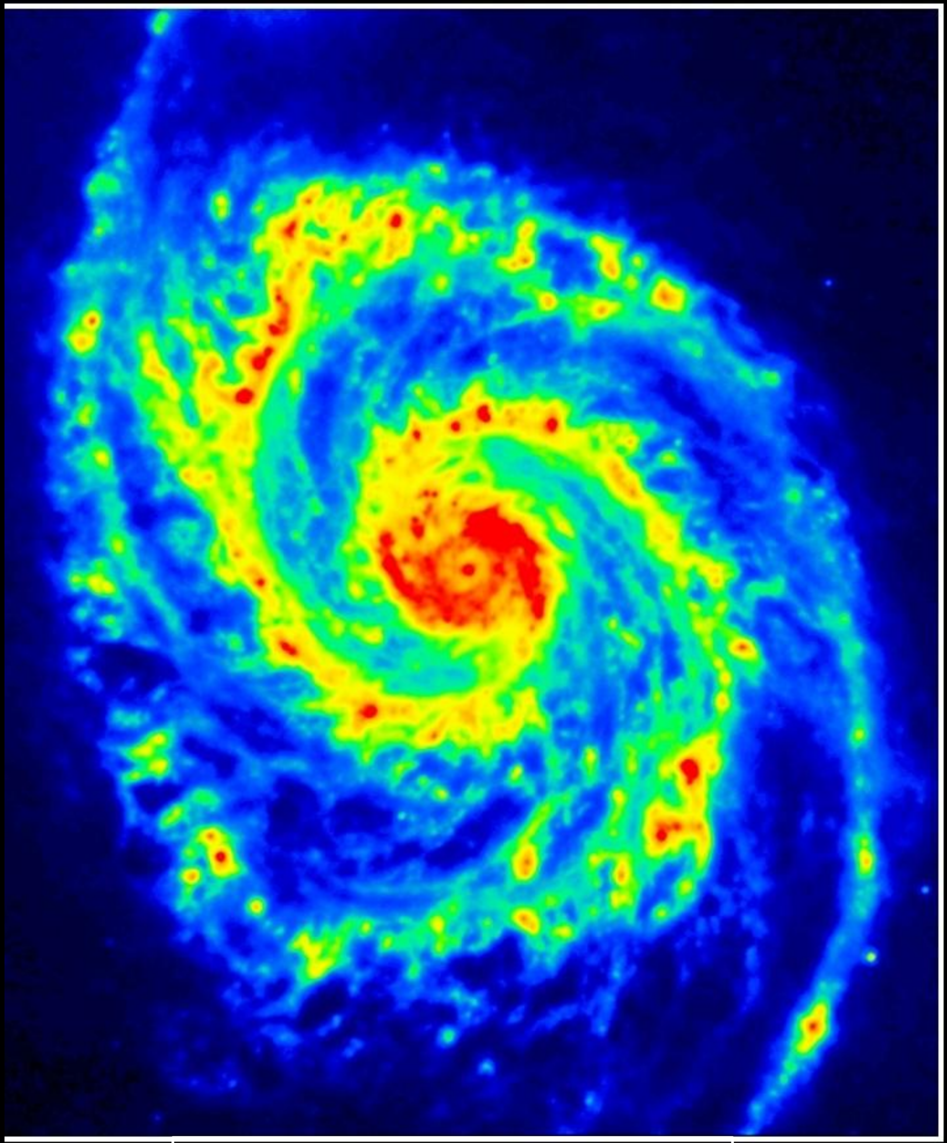
Exponential field profiles can exert forces on the gas

Radio continuum intensity
(VLA + Effelsberg 6cm)

Infrared intensity
(Spitzer 8μm)

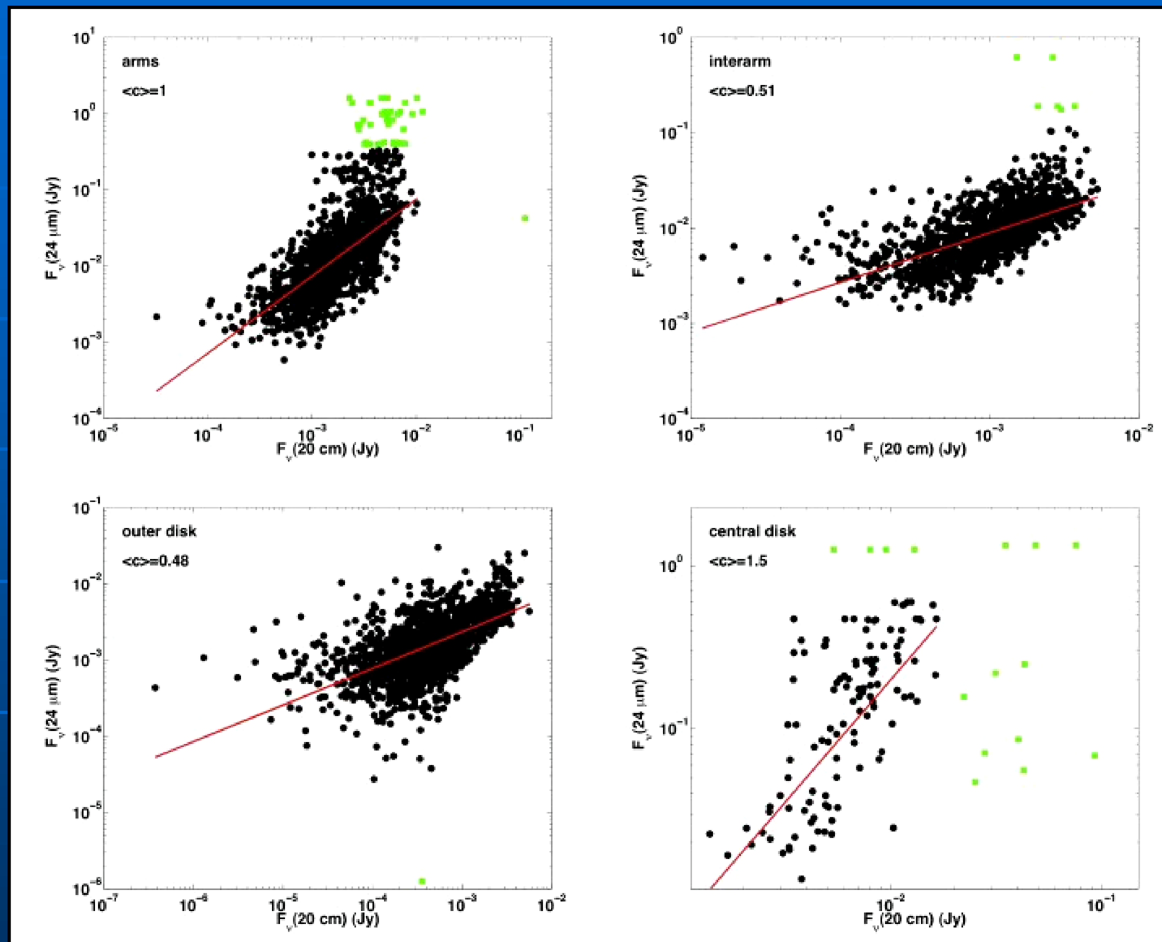


Fletcher et al. 2011



Schinnerer et al. 2006

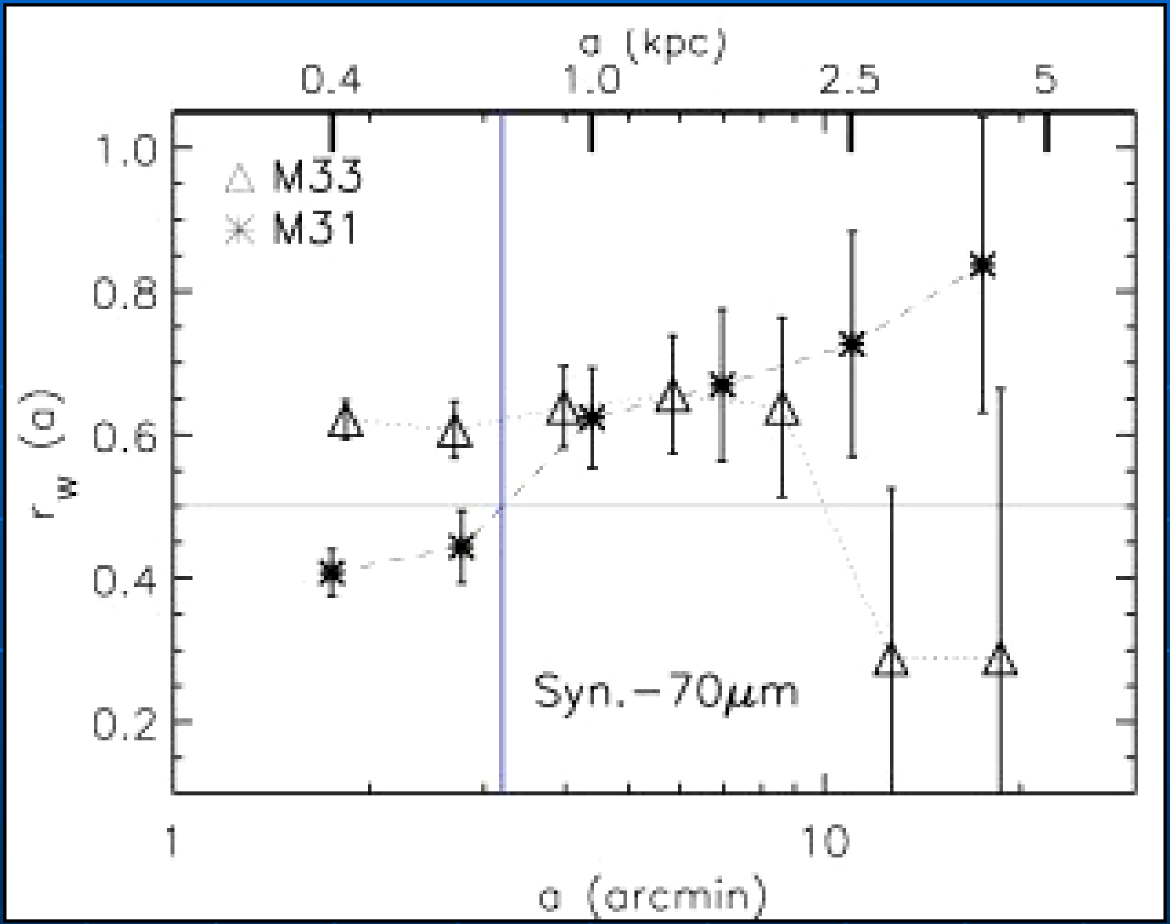
Radio – IR correlation in M51



Dumas et al. 2011

Slope of the correlation is different in spiral arms, interarm regions, outer disk and the central region → effect of magnetic field structure?

Scale-dependent radio-infrared correlation



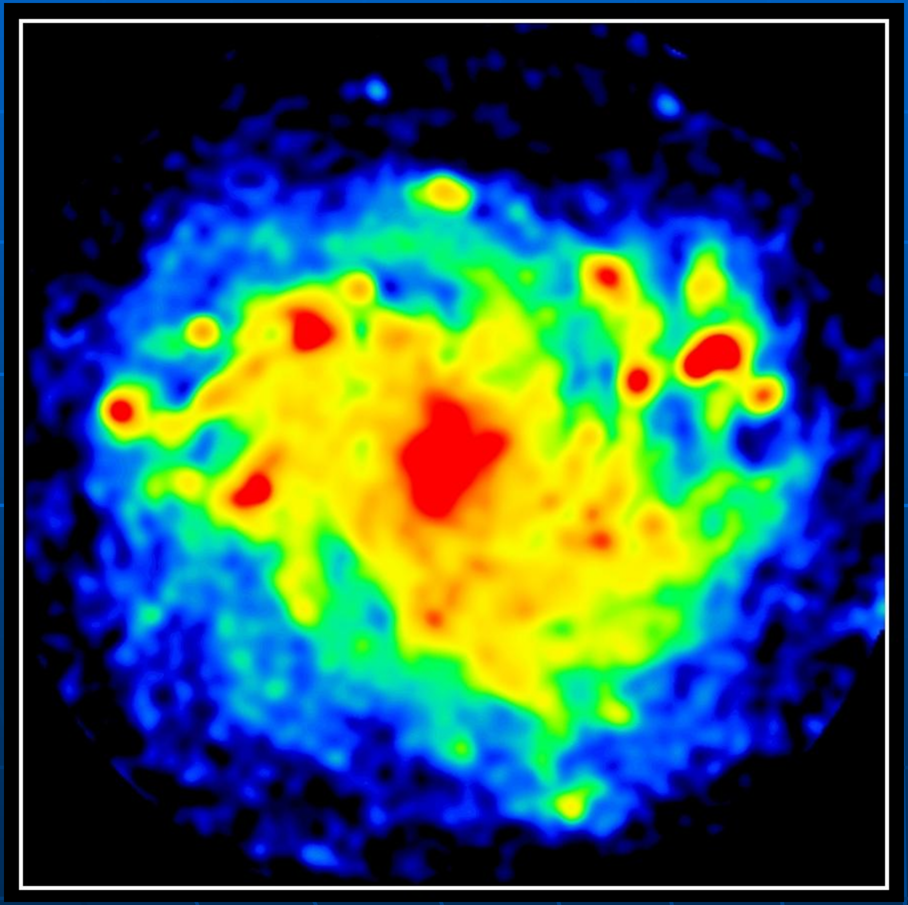
Tabatabaei et al., in prep.

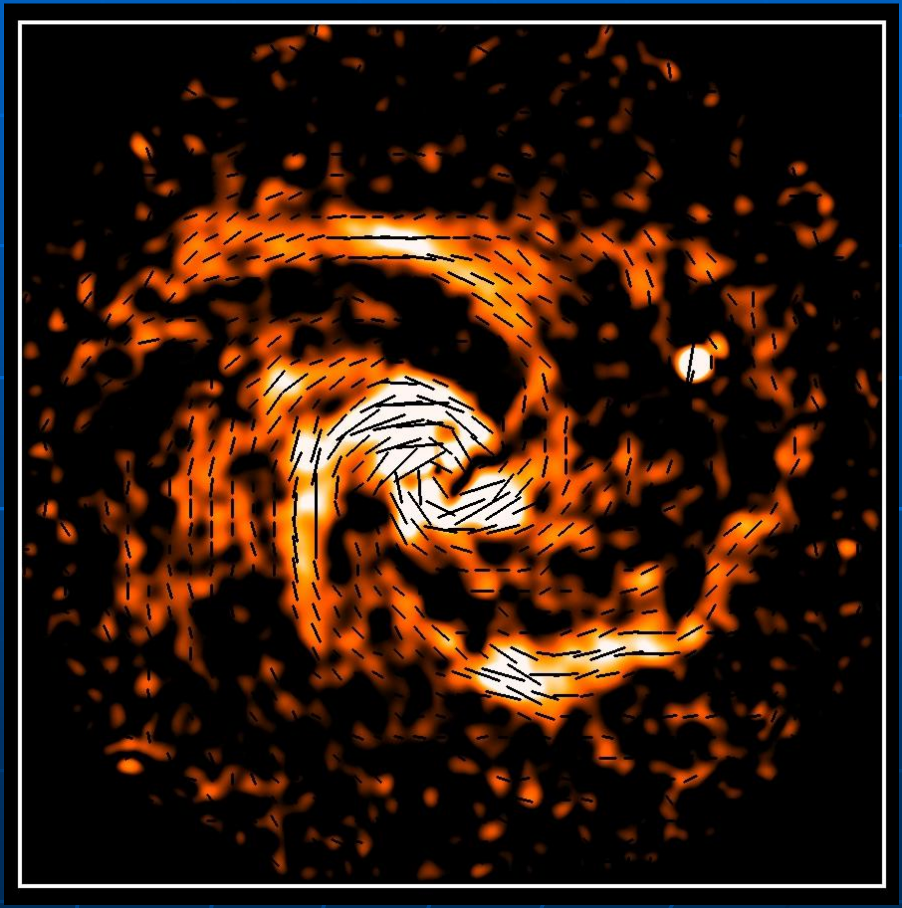
Correlation in M31 breaks down below a certain scale: measures the propagation length of cosmic-ray electrons (CRE)

Total and polarized emission of NGC6946: Total and ordered magnetic fields

6.3cm Effelsberg+VLA

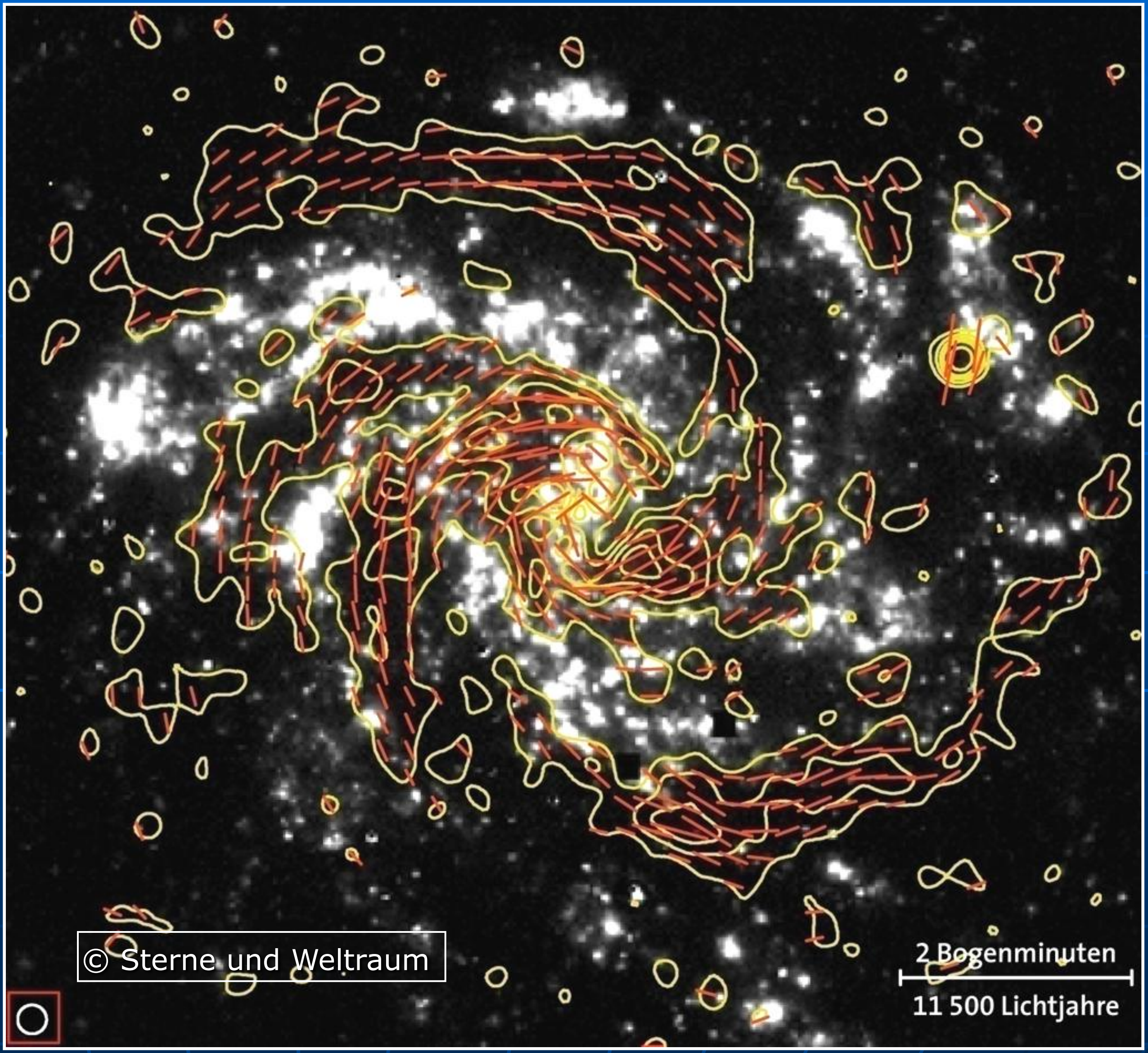
Beck & Hoernes 1996





NGC 6946

6cm VLA+Effelsberg
Polarized intensity
+ B-vectors
(Beck & Hoernes 1996)



"Magnetic arms":

Ordered fields concentrated in **interarm** regions

Proposed origins of the "magnetic arms"

- High mode of the mean-field dynamo ? (Rohde et al. 1999)
- Slow MHD waves ? (Lou & Fan 1998, Lou & Bai 2006)
- Coupling between density wave and dynamo wave ? (Chamandy et al. 2012)

Magnetic fields possibly support the formation of spiral arms

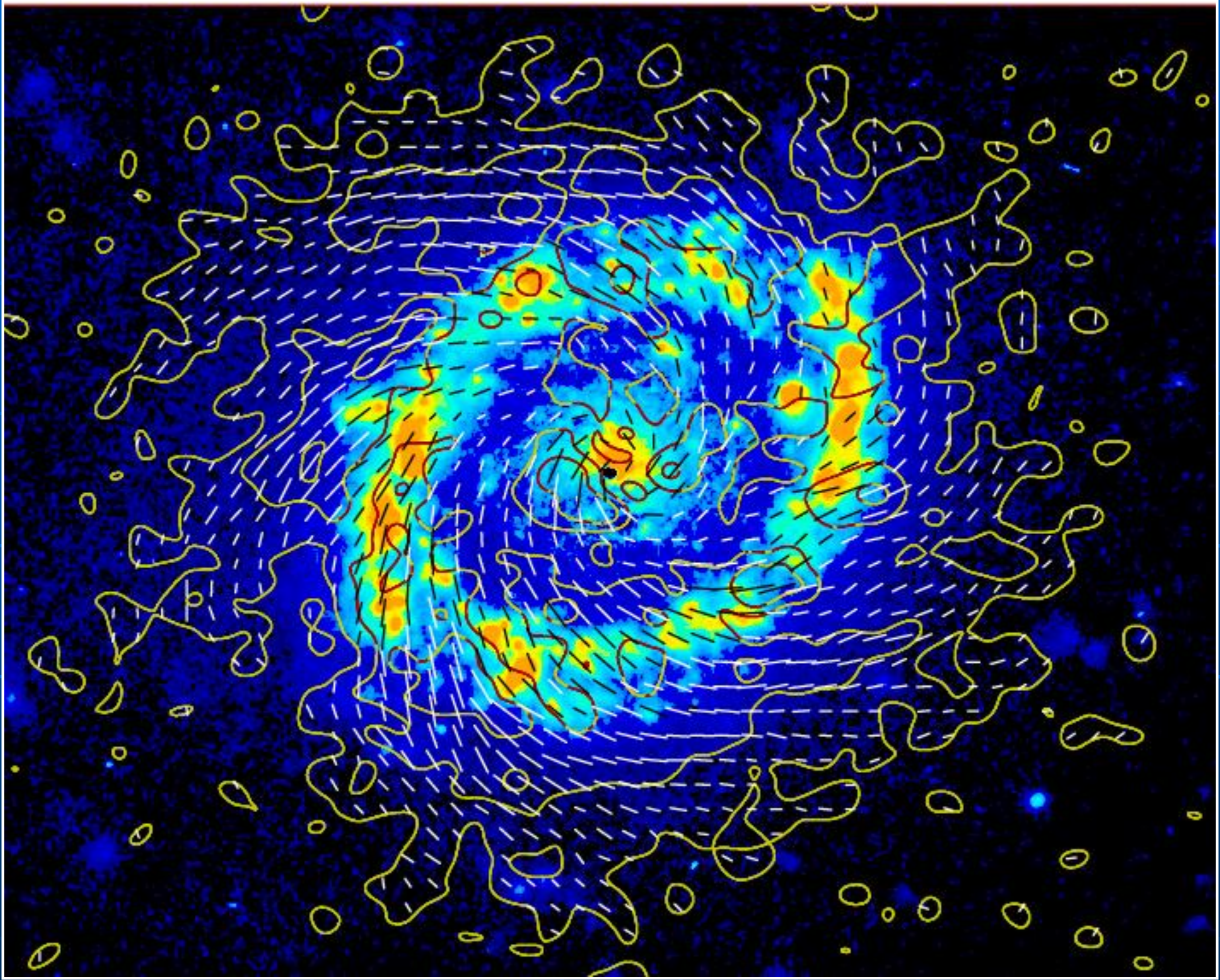
NGC 4736

3cm VLA

Polarized intensity

+ B-vectors

(Chyzy & Buta 2007)



Spiral fields in a ring-like galaxy

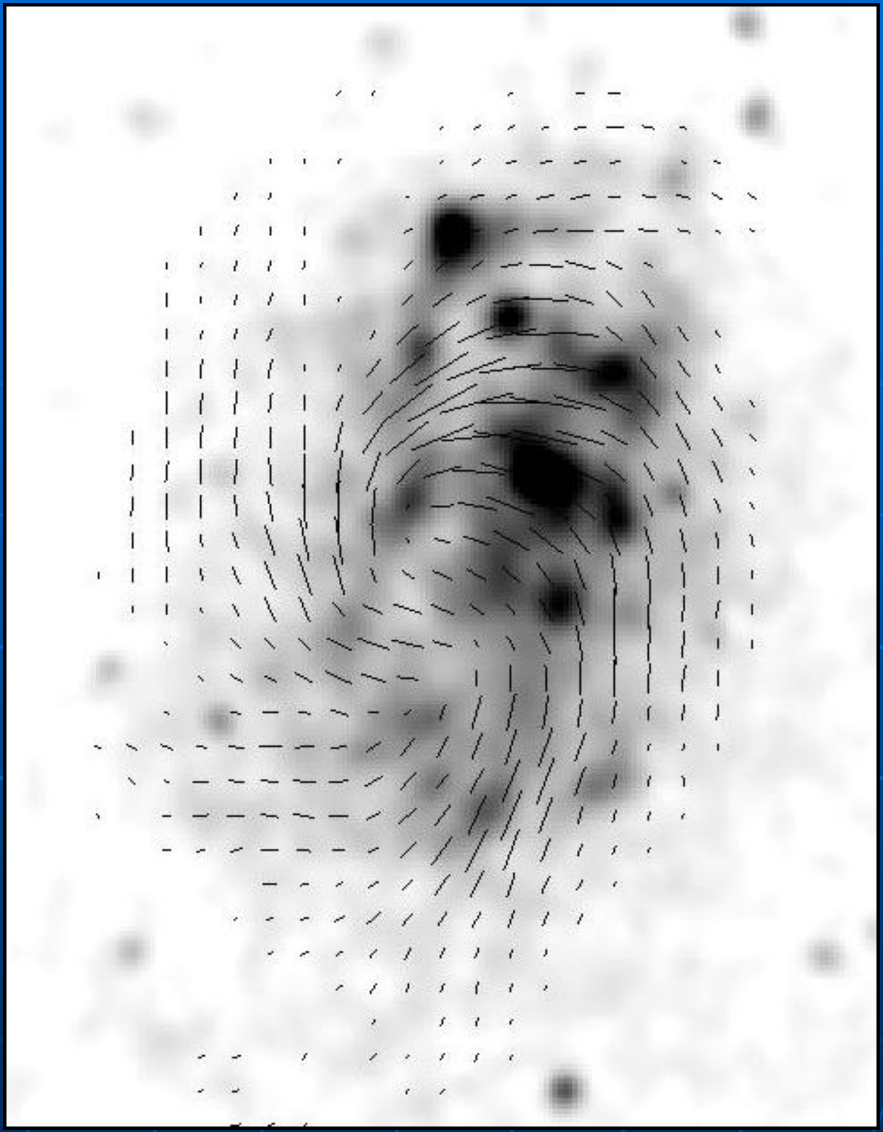
NGC 4414

3cm VLA

H-alpha

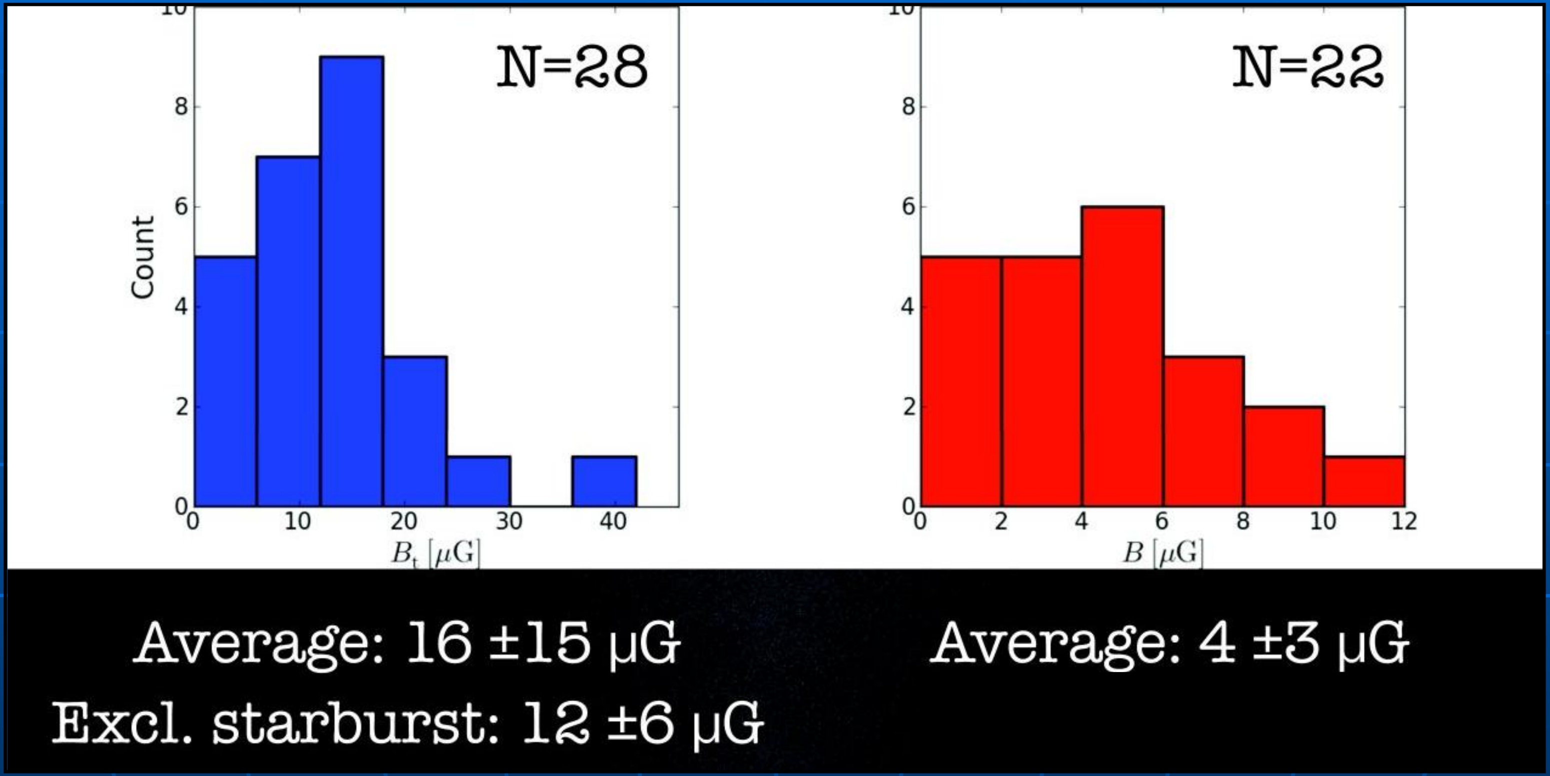
+ B-vectors

(Soida et al. 2002)



Flocculent galaxies: spiral field without optical spiral arms

Total and ordered field strengths
(compilation by A. Fletcher)



- B_{turb} / B_{ord} ≤ 3 (low resolution)
- Prediction by dynamo models: 2-10

(Arshakian et al. 2009, Gressel et al. 2012)

Magnetic field generation and amplification

Stage 1: Field seeding

Primordial, Biermann battery, Weibel instability;
ejection by supernovae, stellar winds or jets

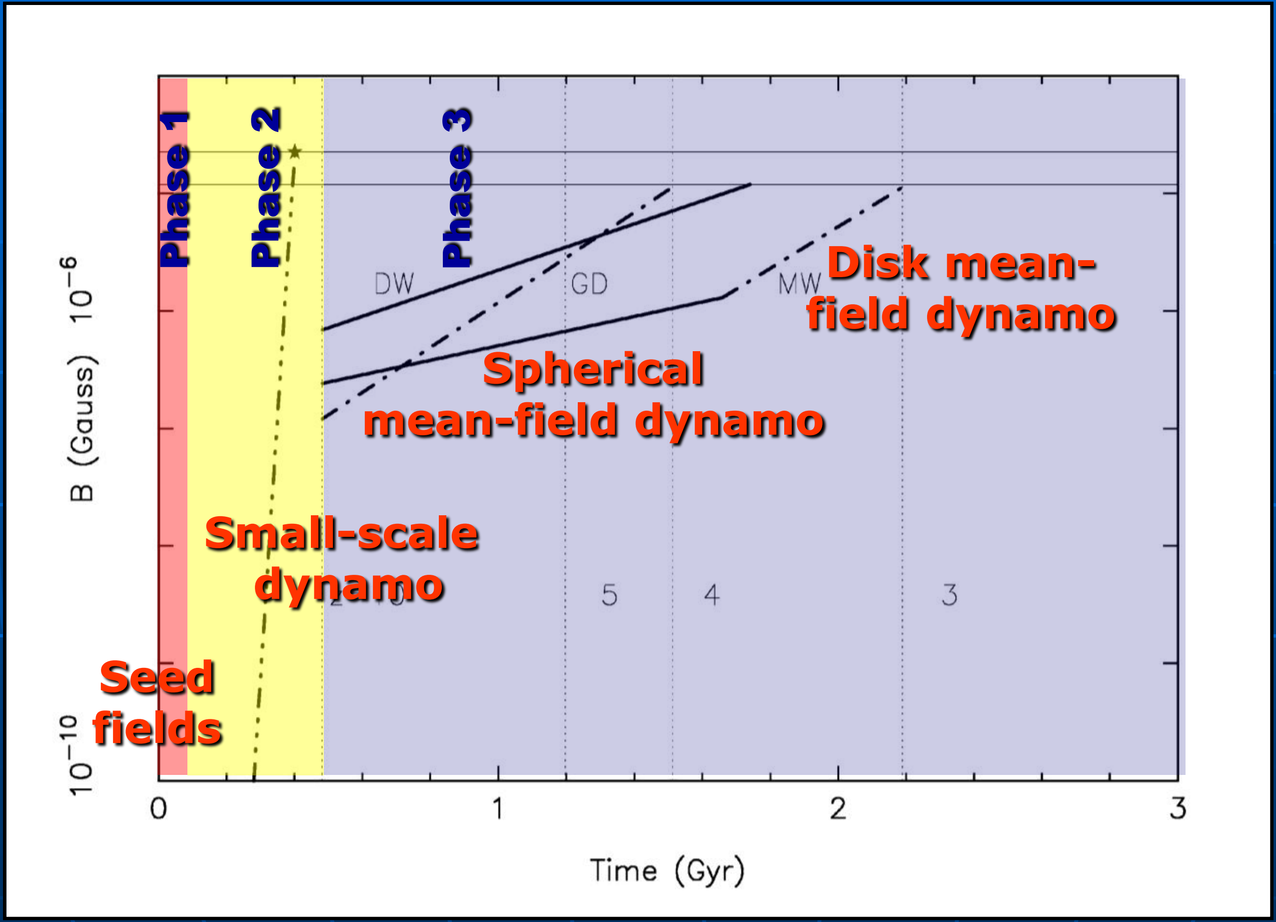
Stage 2: Field amplification

MRI, compressing flows, shearing flows,
turbulent flows, small-scale (turbulent) dynamo

Stage 3: Coherent field ordering

Large-scale (mean-field) dynamo

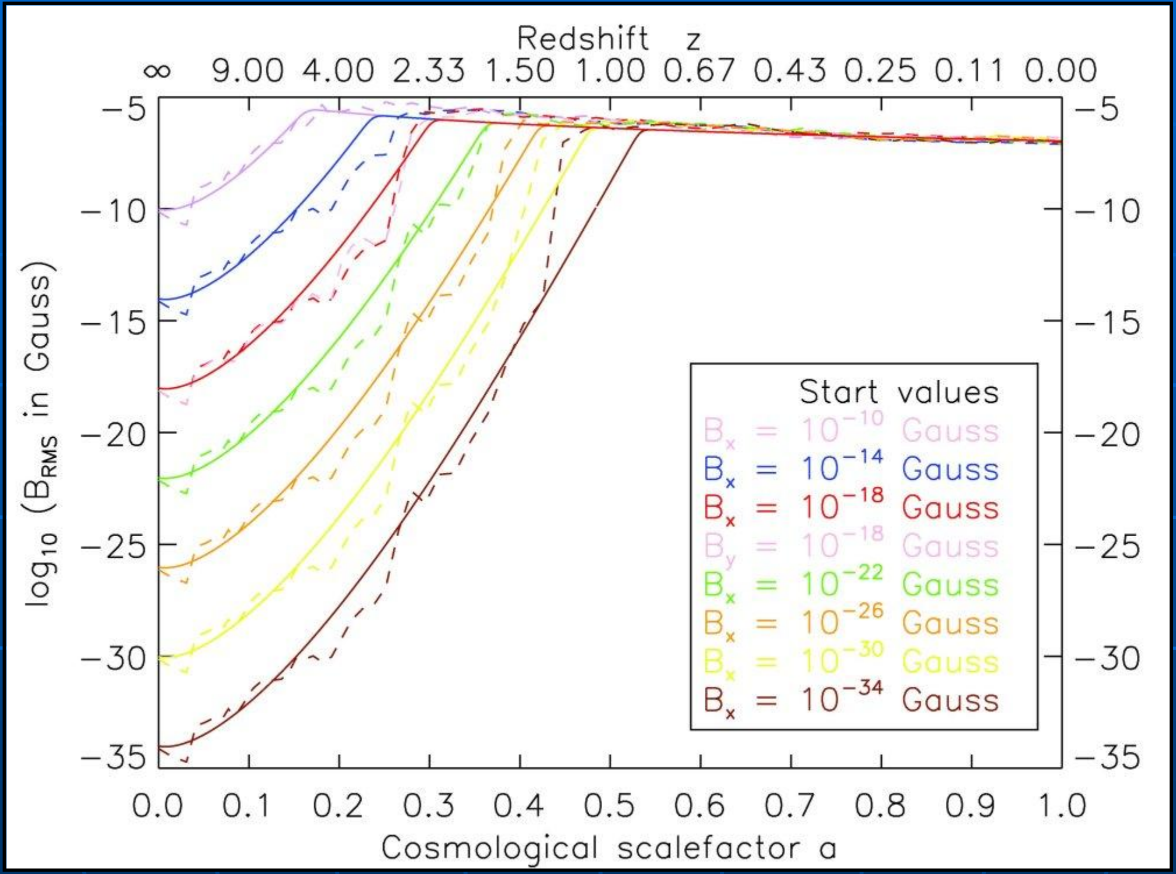
Magnetic field amplification by galactic dynamos



Arshakian et al. 2009

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

Simulation of a small-scale dynamo in young galaxies

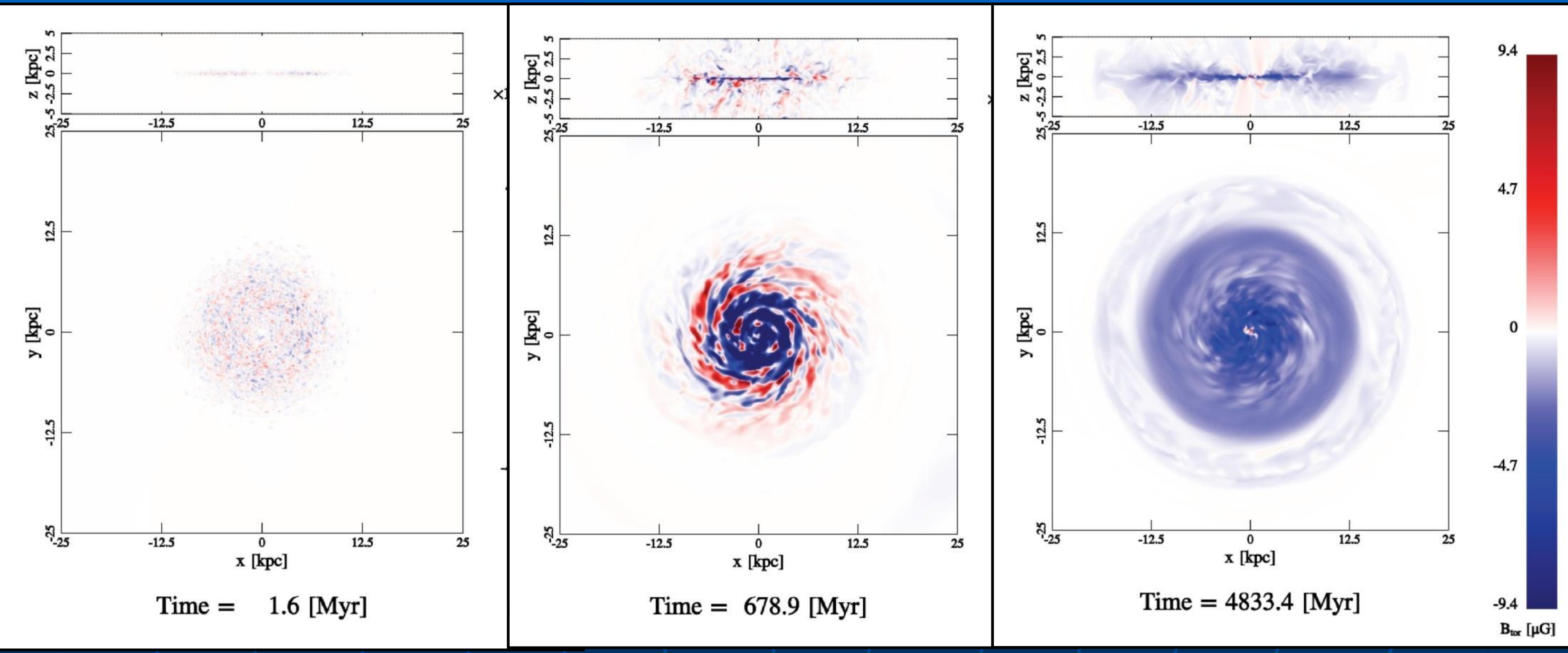


A. Beck et al. 2012

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

Global cosmic-ray driven MHD model of a mean-field dynamo

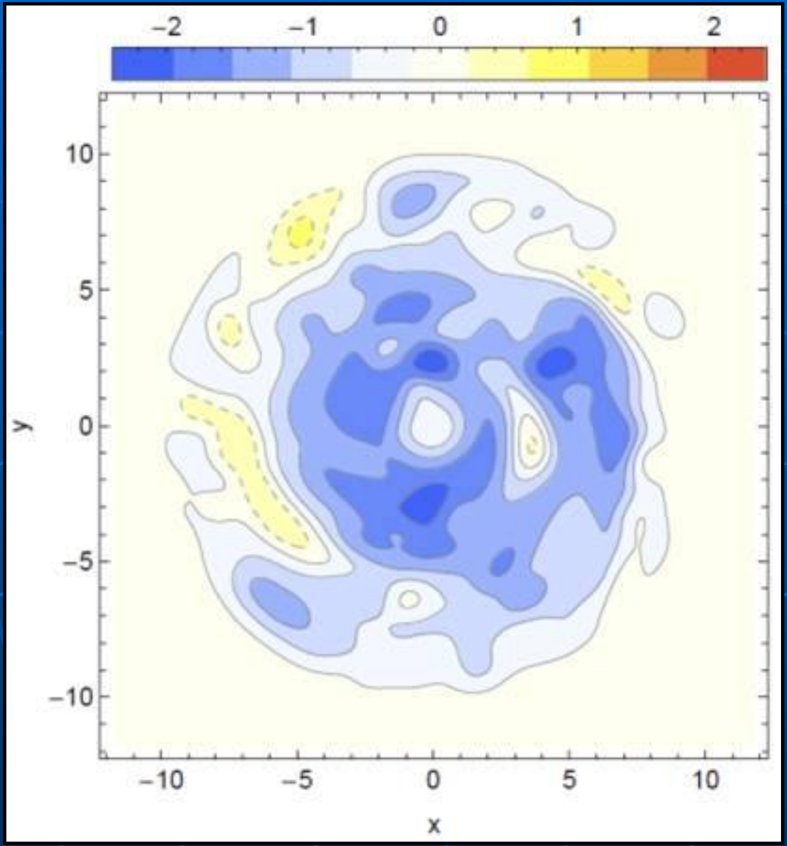
Hanasz et al. 2009

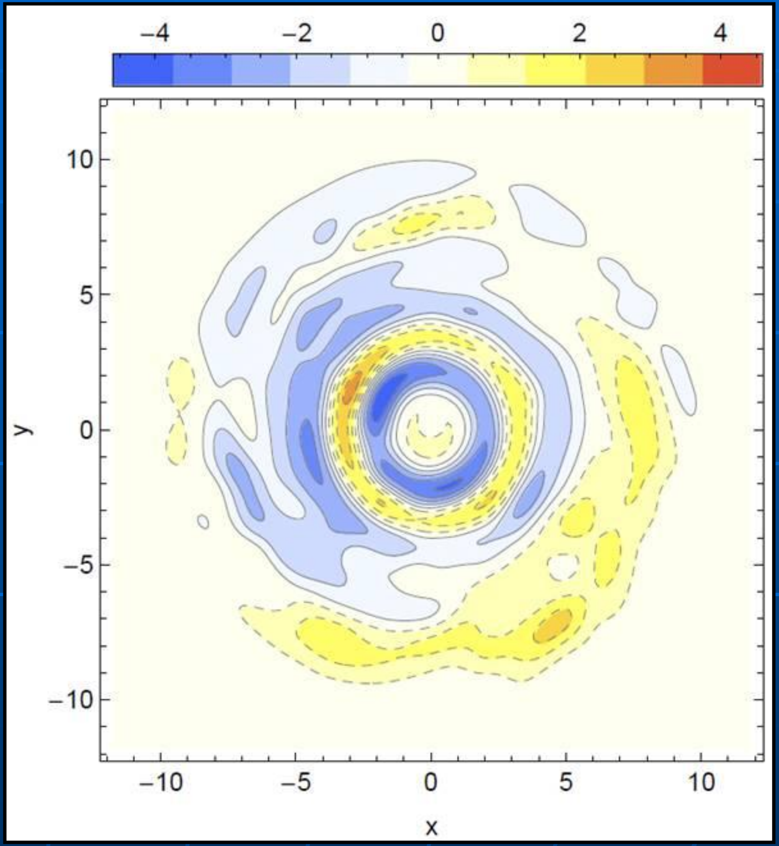


Final axisymmetric field is too smooth

Dynamo model with continuous injection of turbulent fields

Moss et al. 2012





Moderate dynamo number:
Axisymmetric spiral field

High dynamo number R:
Spiral field with large-scale reversal

High-resolution dynamo simulation
(box of 1x1x2 kpc^3)

Gent et al. 2012

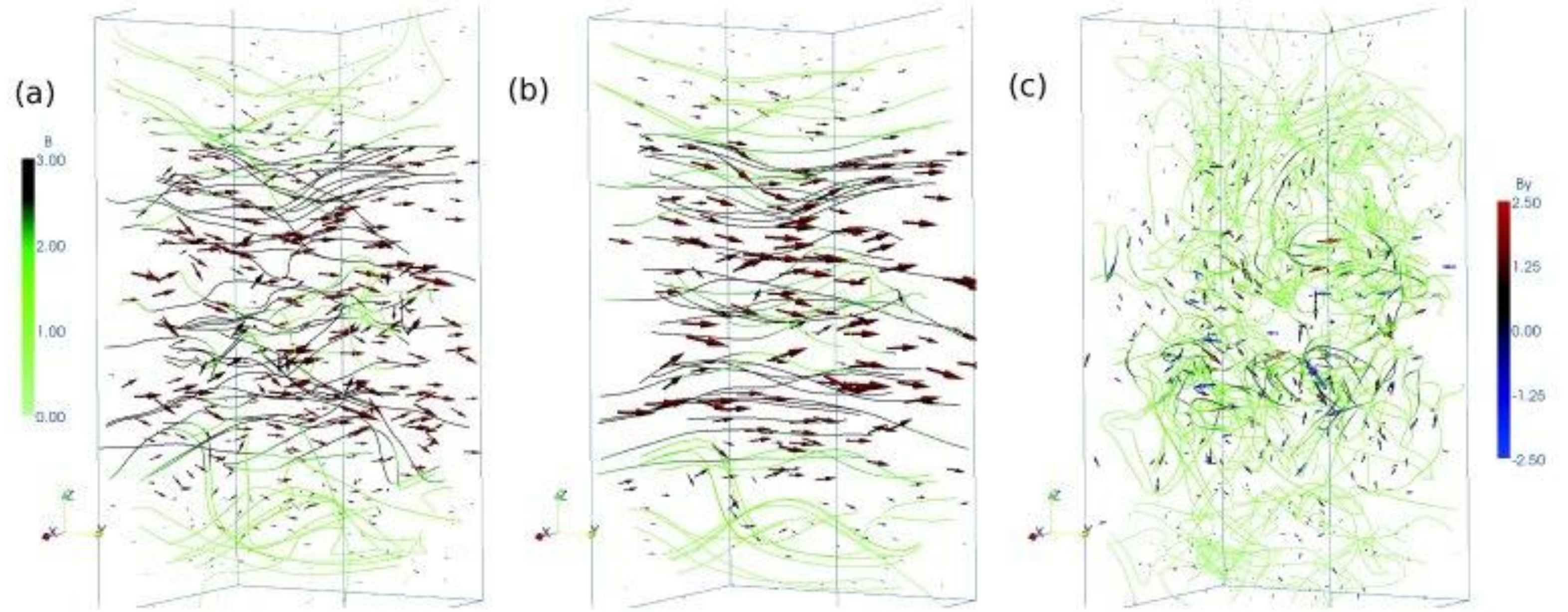


Figure 3. Field lines of (a) the total magnetic field $\boldsymbol{B}$, (b) its averaged part $\boldsymbol{B}_\ell$, (c) the fluctuations $\boldsymbol{b}$, obtained by averaging with $\ell = 50$ pc, for $t = 1.625$ Gyr. Field directions are indicated by arrows. The colour of the field lines indicates the field strength (colour bar on the left), whereas the vectors are coloured according to the strength of the azimuthal (y) component (colour bar on the right).

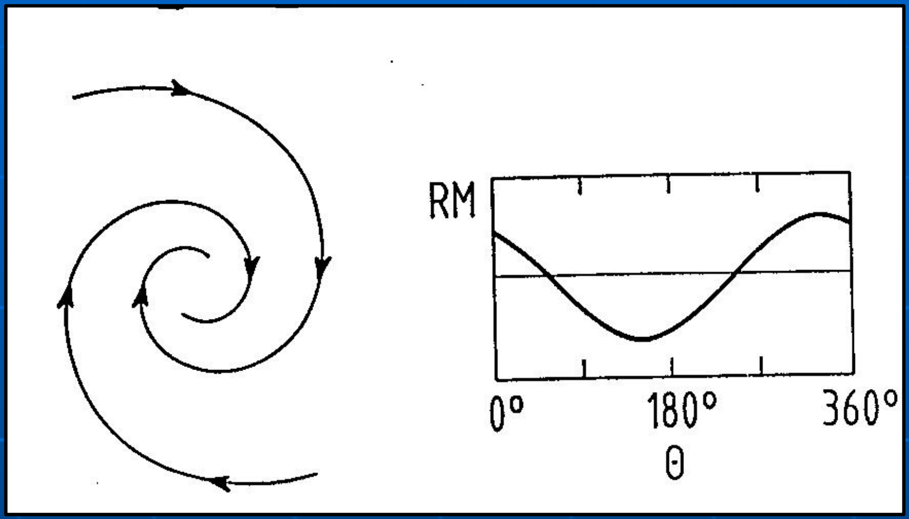
Total field Regular field Turbulent field

Observational test:

Regular fields generated by dynamos should give rise to Faraday rotation

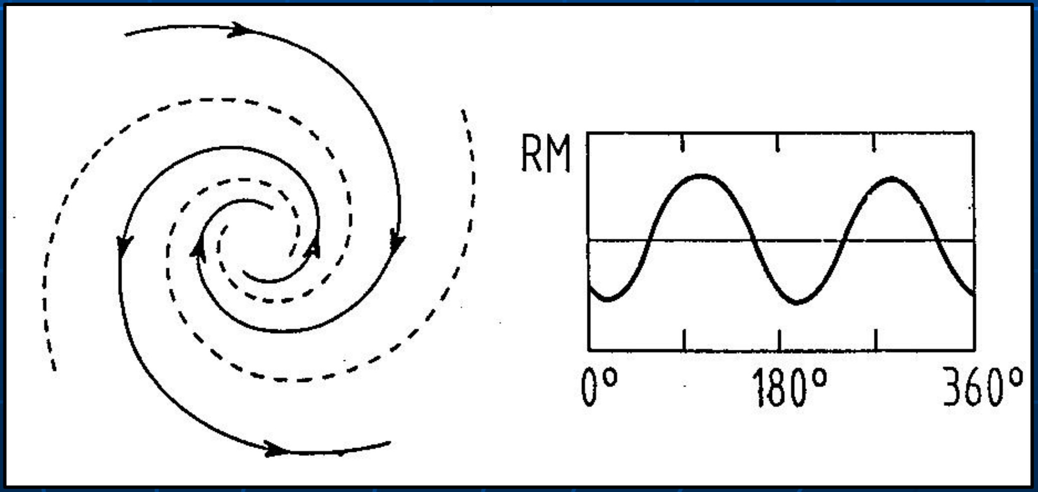
Finding dynamo modes: Azimuthal variation of Faraday rotation

Krause 1990

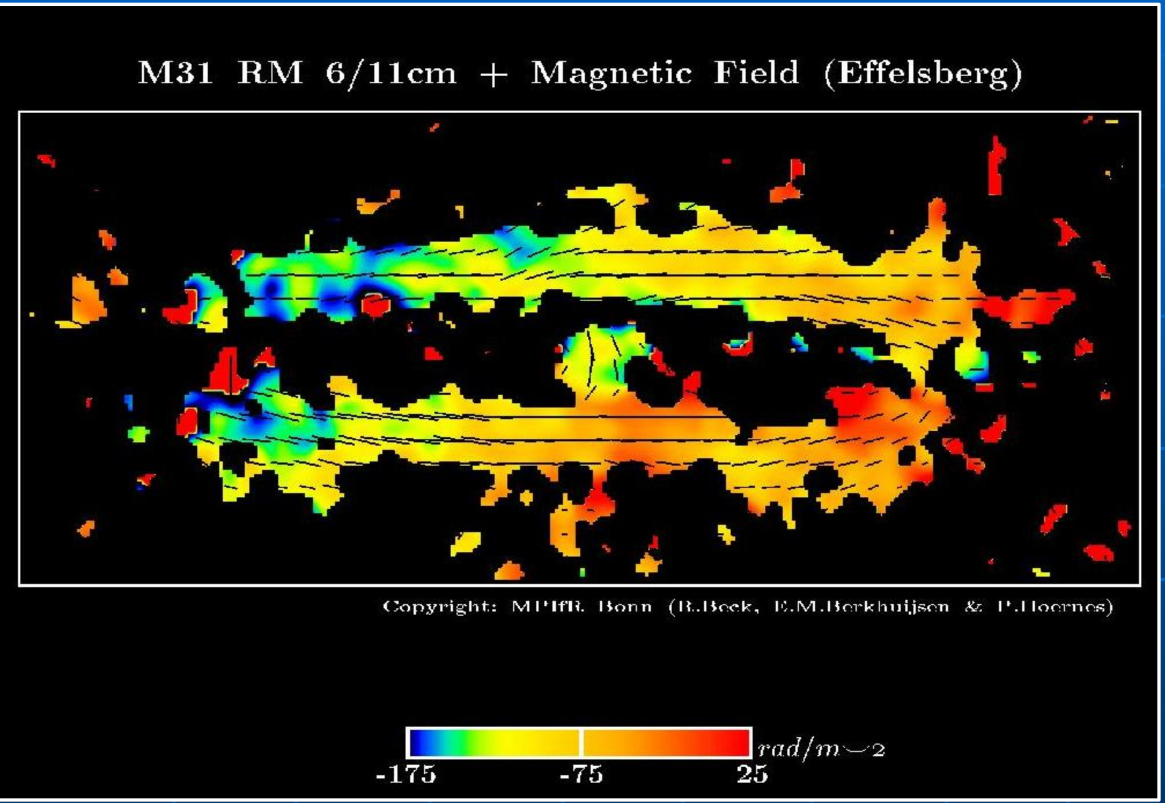


Axisymmetric spiral
(m=0)

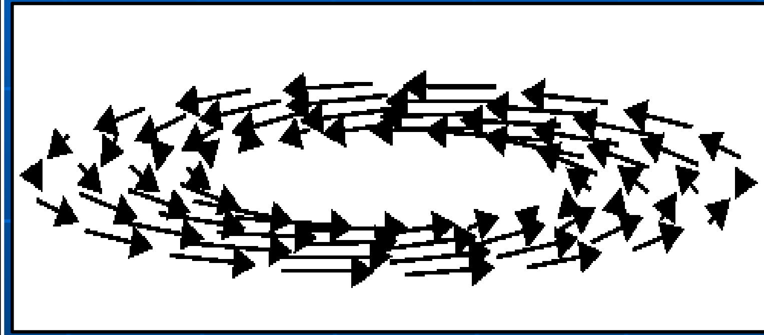
Bisymmetric spiral
(m=1)



M31: The dynamo is working !



Berkhuijsen et al. 2003

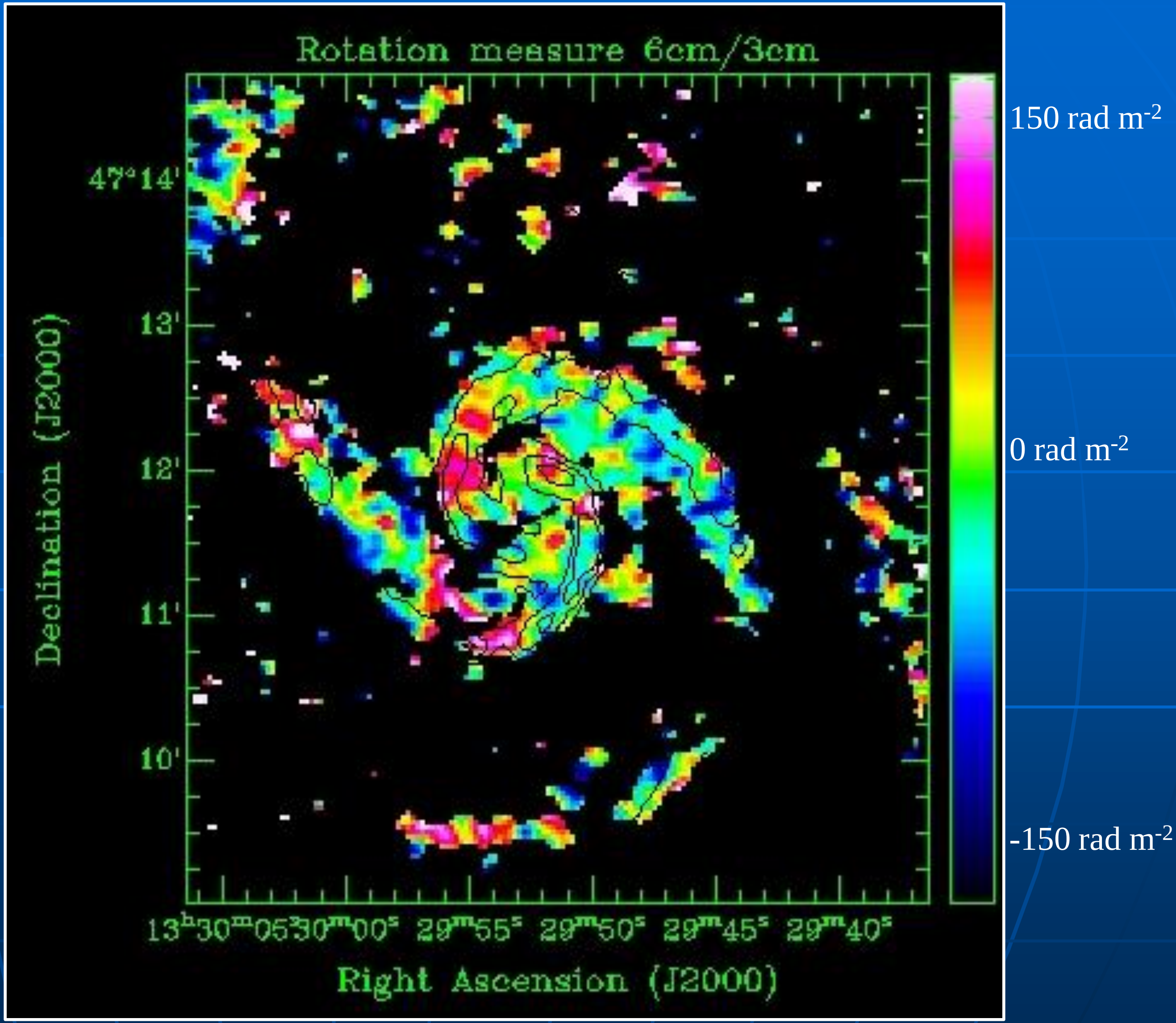


Fletcher et al. 2004

The spiral field of M31 is coherent and axisymmetric
(small spiral pitch angle)

M 51

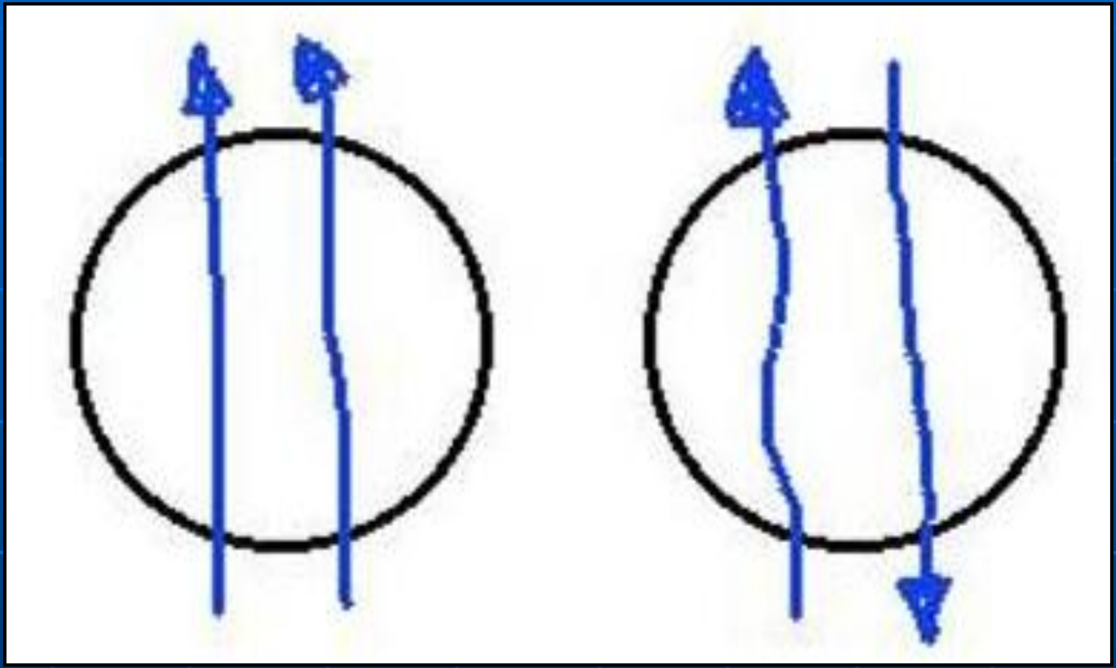
VLA+Effelsberg
RM 3/6cm
(Fletcher et al. 2011)



Dominating anisotropic field plus two *weak* dynamo modes (m=0+2)

Fletcher 2004

Regular field | Anisotropic field



	Regular field	Anisotropic field
Polarization :	strong	strong
Faraday rotation :	**high**	low

Magnetic modes

Fletcher 2011



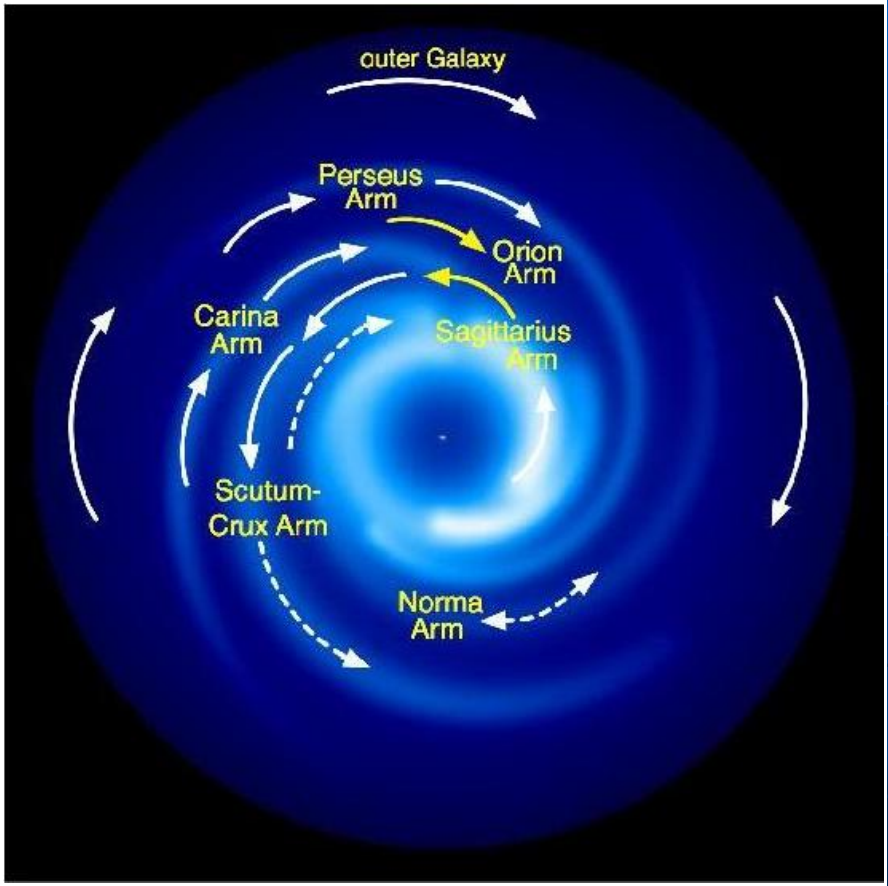
Galaxy	m=0	m=1	m=2	Ref.
IC 342	1	-	-	Krause et al. 1989
LMC	1	-	-	Gaensler et al. 2005
M31	1	0	0	Fletcher et al. 2004
M33	1	1	0.5	Tabatabaei et al. 2008
M51	1	0	0.5	Fletcher et al. 2011
M81	-	1	-	Krause et al. 1989
NGC 253	1	-	-	Heesen et al. 2009
NGC 1097	1	1	1	Beck et al. 2005
NGC 1365	1	1	1	Beck et al. 2005
NGC 4254	1	0.5	-	Chyży 2005
NGC 4414	1	0.5	0.5	Soida et al. 2002
NGC 6946	1	-	-	Ehle & Beck 1993

Large-scale dynamo modes

- Single dominant axisymmetric (m=0) mode are frequent
- Superpositions of m=0, m=1 and m=2 modes are frequent
- Dominating higher modes are rare
- In many cases the field is more complicated

Do regular fields exist in irregular and dwarf galaxies ?

The large-scale magnetic field in the Milky Way
(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
$\rightarrow$ ***reversal*** between arms

Magnetic field model for the Milky Way

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

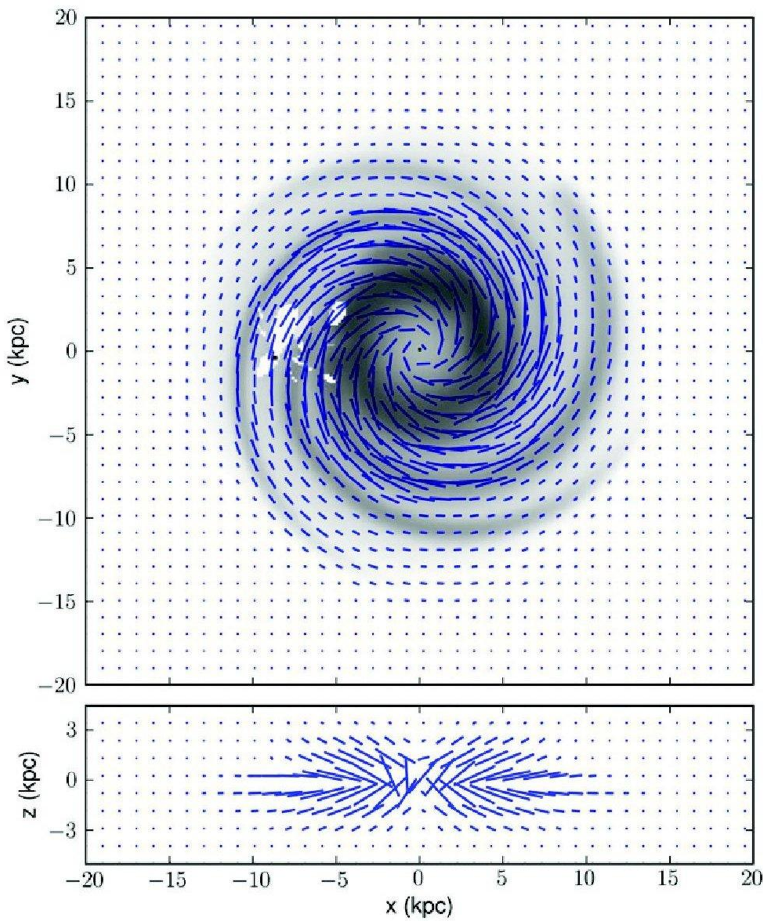
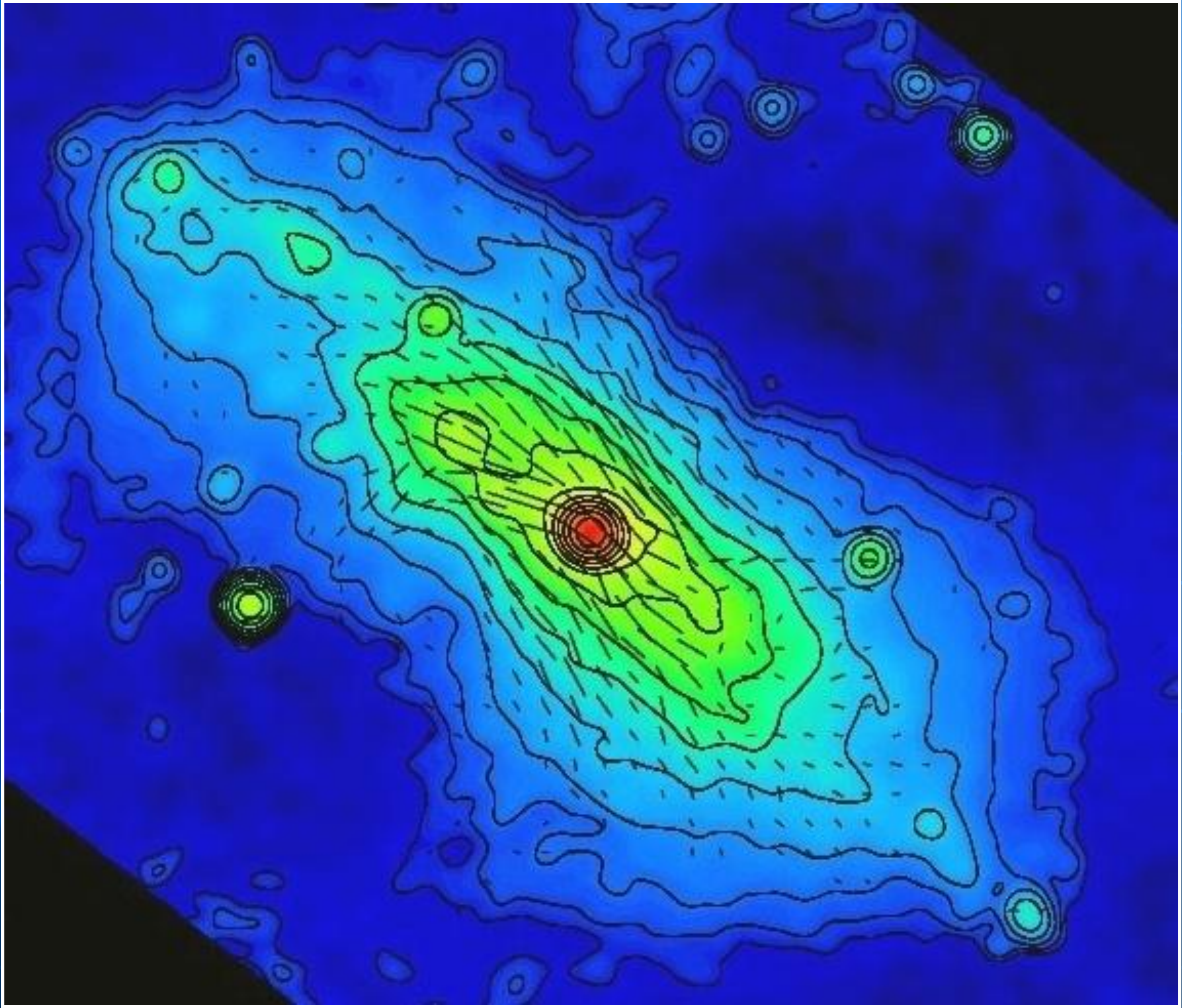


Figure 9. Milky Way as seen (in polarization) by an extragalactic observer, face-on (above) and edge-on (below). Plotted "bars" (sometimes referred to as "vectors") are the would-be-observed polarization angles, rotated 90° to line up with the magnetic field orientation. Lengths of bars are proportional 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

NGC 253

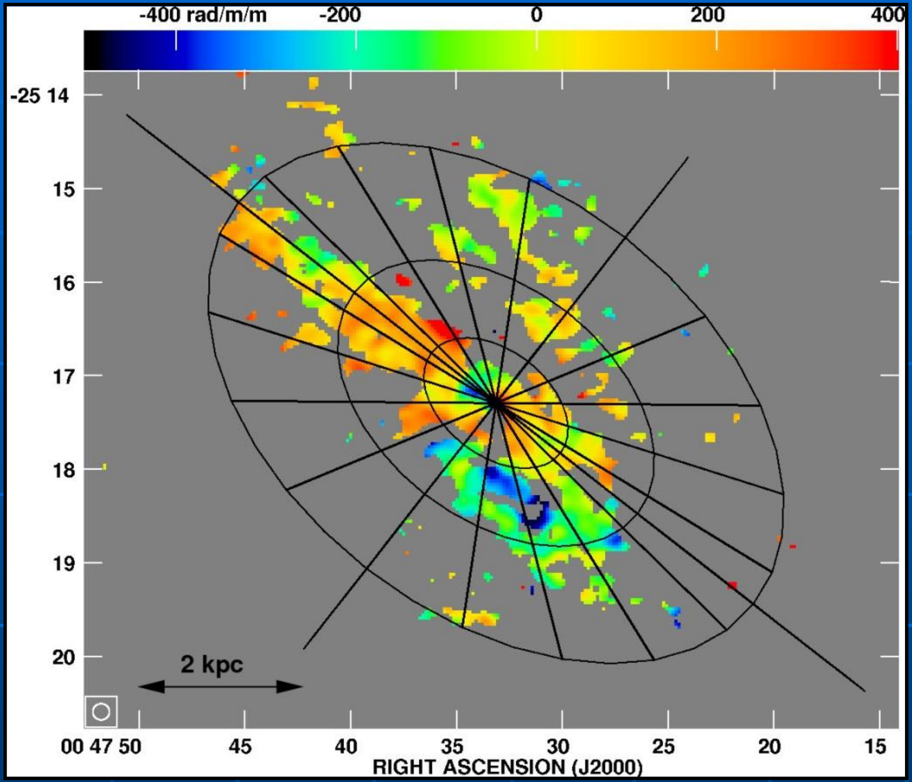
6cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Heesen et al. 2009)



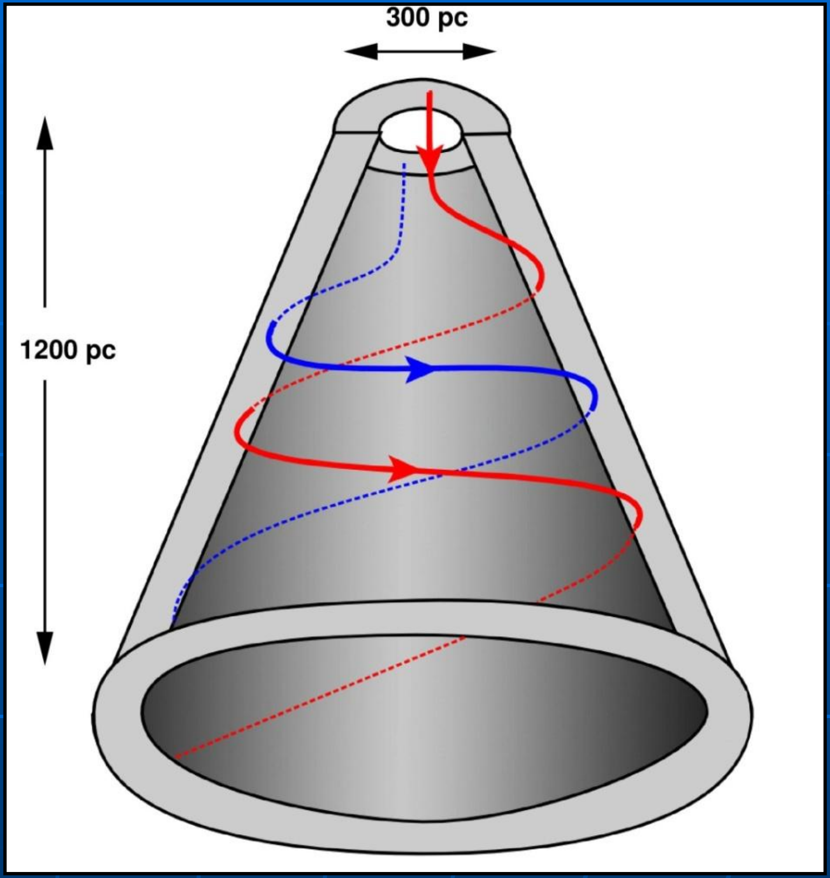
Halo fields:
X-shaped –
neither quadrupolar
or dipolar –

can be reproduced
by dynamo models
(Hanasz, Gressel)

NGC 253
Central region
(Heesen et al. 2011)



Faraday rotation 3/6cm:
Field reversal across the outflow cone in front of the disk



Helical field in the outflow cone

First detection of a regular magnetic field in a nuclear outflow

Evidences for the action of large-scale dynamos in galaxies

- Magnetic and turbulent energy densities are similar
- Spiral patterns exist in all massive galaxies
- Large-scale regular fields exist in many galaxies
- Axisymmetric disk fields dominate
- Symmetric (quadrupolar-type) halo fields dominate

  (Braun et al. 2010)

There is no alternative model to explain regular fields

Magnetic field pitch angles

Fletcher 2011

	pitch angle			
Galaxy	inner	outer	optical	Ref.
IC 342	-20°±2	-16°±2	-19°±5	Krause et al. 1989
M31	-17°±4	-8°±3	-7°	Fletcher et al. 2004
M33	-48°±12	-42°±5	-65°±5	Tabatabaei et al. 2009
M51	-20°±1	-18°±1	-20°	Fletcher et al. 2011
M81	-14°±7	-22°±5	-11° → -14°	Krause et al. 1989
NGC 6946	-27°±2	-21°±2	-43° → -22°	Ehle & Beck 1993
Milky Way	-11.5°	0°	-11.5° (n_e)	Van Eck et al. 2011

Dynamos in outer disks

- Dynamo number (efficiency):

  $D = (h / r)^2 \; (v_{rot} / v_{turb})^2$

  Outer disk: weaker dynamo (not observed)

- Magnetic pitch angle:

  $\tan p \sim (r / h)^{0.5} \; (\alpha / v_{rot})^{0.5} \sim L_{turb} / h$

  Outer disk: constant pitch angle (not observed)

- Disk flaring ?

The future of radio astronomy

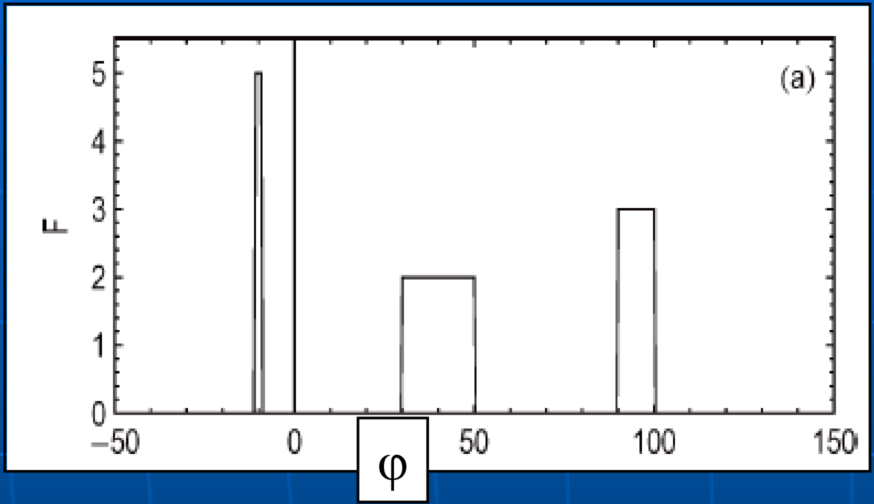
- New telescopes at low frequencies:
  High sensitivity for weak magnetic fields and small RMs
  (LOFAR, LWA, MWA, SKA)

- Upgraded and new telescopes at high frequencies:
  Higher resolution, larger sensitivity
  (EVLA, ALMA, SKA and precursors)

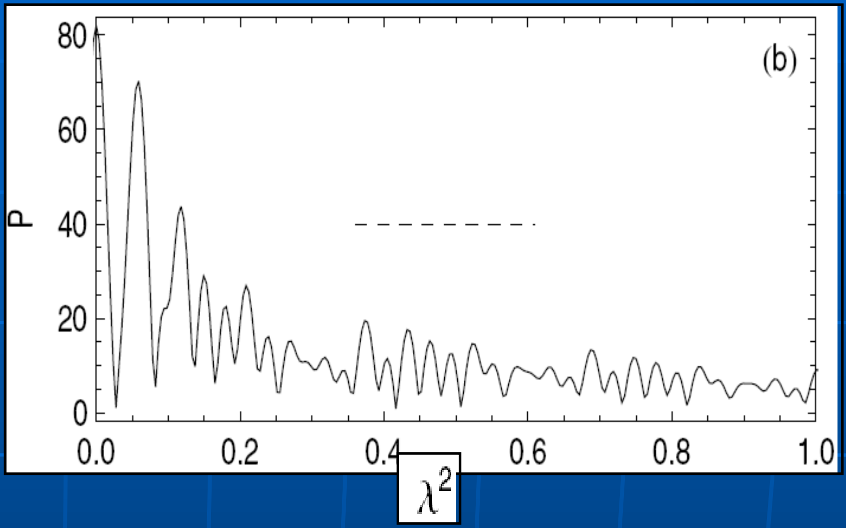
- New method:
  Radio continuum spectro-polarimetry ("RM Synthesis")
  → **PPF** (position-position-Faraday depth) data cubes

RM Synthesis

Source distribution in Faraday space



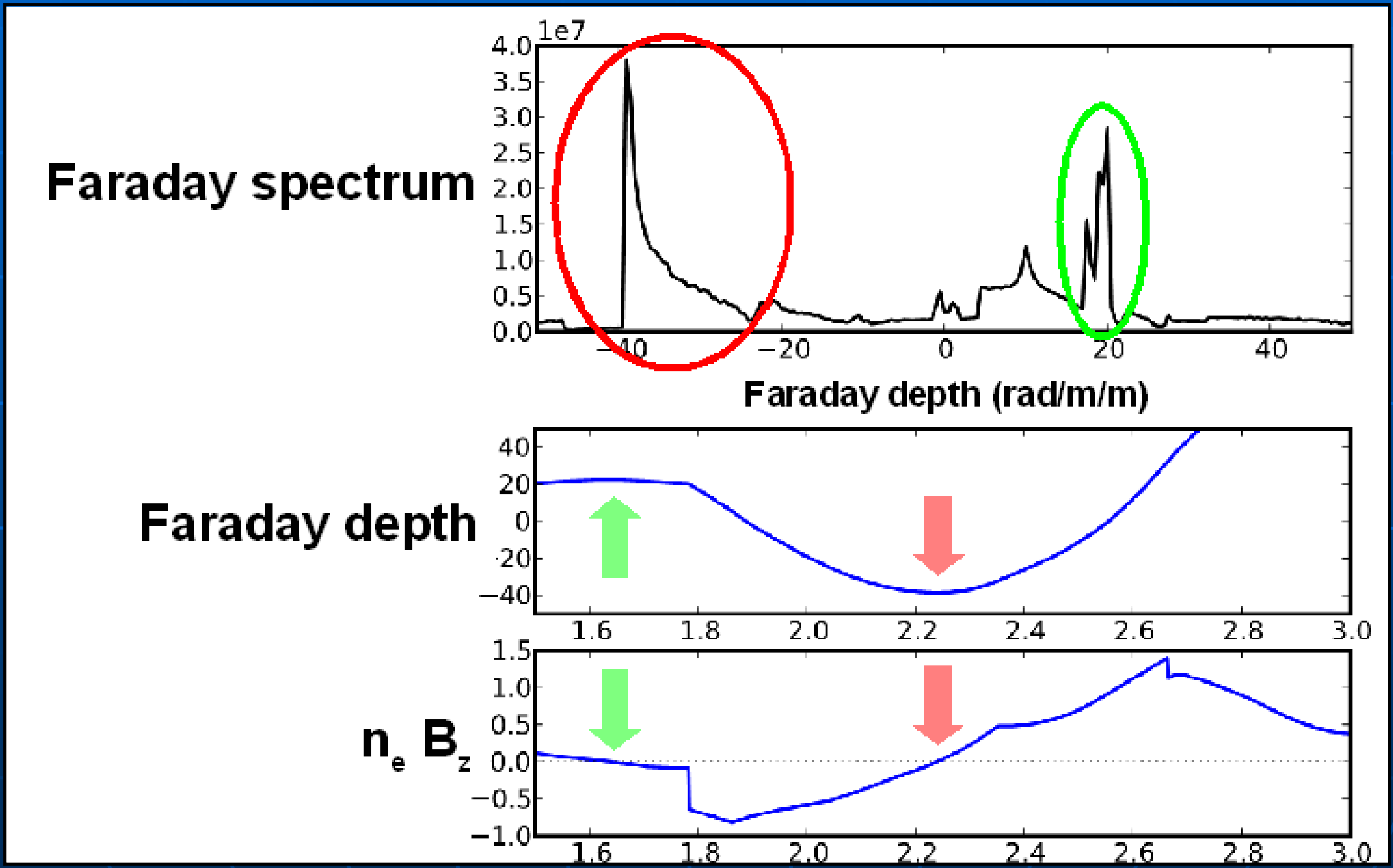
Observed spectrum of polarized intensity



- The observed complex polarized intensity *P* is the Fourier transform of the complex Faraday spectrum $F(\varphi)$
- The Faraday spectrum can be calculated from *P* by RM Synthesis
- Faraday depth ($\varphi \propto \int B_{\parallel}\, n_e\, dl$) is different from classical rotation measure

Field reversals generate Faraday caustics

Bell et al. 2011



Faraday spectra

from wavelet transformation of modeled magnetic fields

Beck et al. 2012

Regular fields ($h_{CR} > h_{th}$)

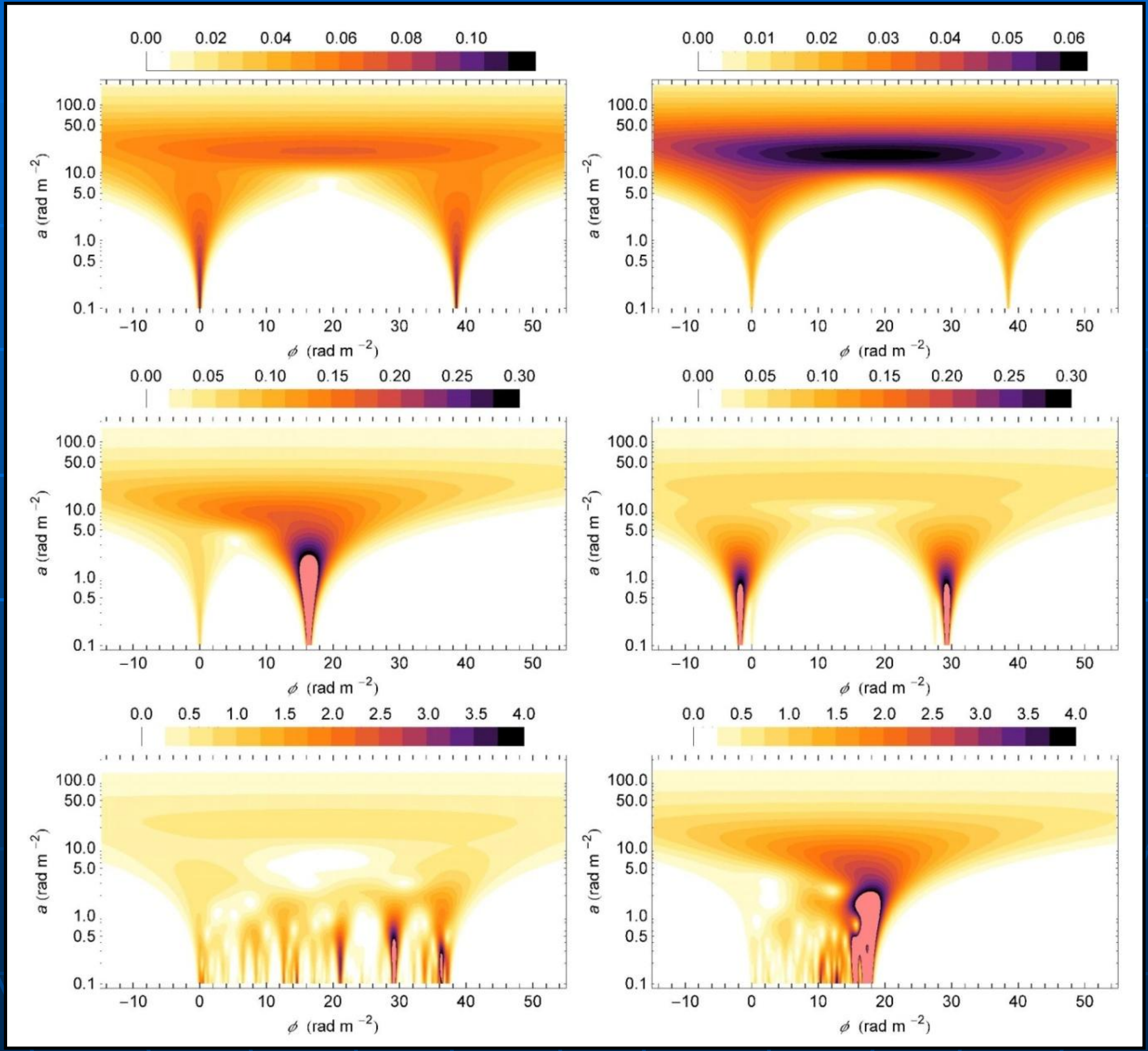
Regular fields ($h_{CR} = h_{th}$)

Regular fields (1 reversal)

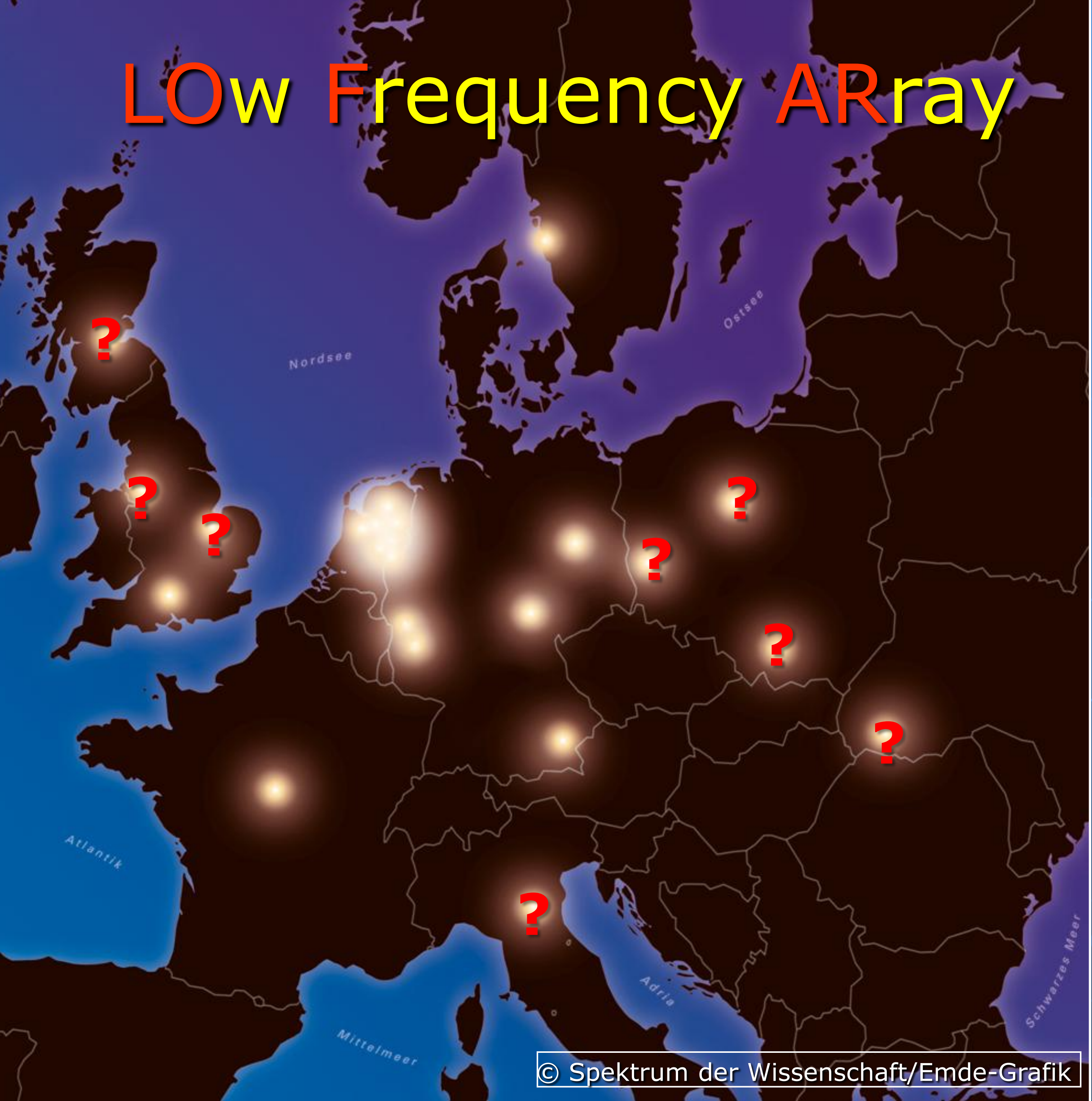
Regular fields (2 reversals)

Regular + turbulent fields

Regular field (1 reversal) + turbulent field



LOw Frequency ARray



LOFAR

10-80 MHz
110-240 MHz

33+8 stations

www.lofar.org

www.lofar.de

“Magnetic goals” for LOFAR

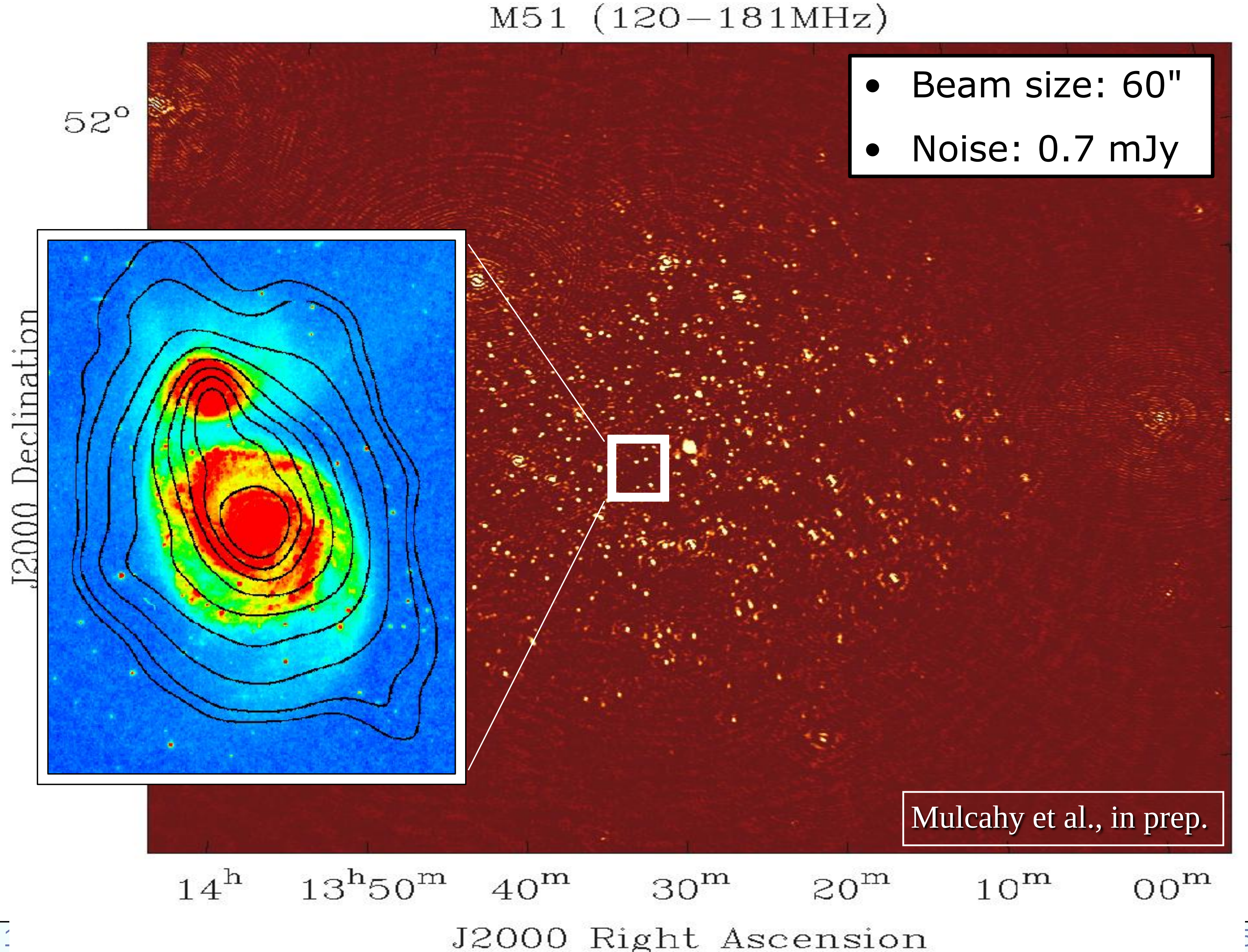
- Survey of pulsars in the Milky Way:
  detailed structure of the local magnetic field
- Extent of galactic magnetic fields
- Search for primordial magnetic fields in the Epoch of Reionization

RMs of pulsars: Magnetic fields in the Milky Way

(C. Sobey & A. Noutsos)

PSR	RM (rad m^{-2})	DM (pc cm^{-3})	$B_{\parallel}$ (μG)
B0834+06	25.26 ± 0.05	12.889 ± 0.006	1.960 ± 0.004
B1642-03	16.04 ± 0.18	35.727 ± 0.003	4.49 ± 0.05
B1919+21	-16.92 ± 0.07	12.455 ± 0.006	-1.358 ± 0.006
B2217+47	-35.60 ± 0.11	43.519 ± 0.012	-0.818 ± 0.003

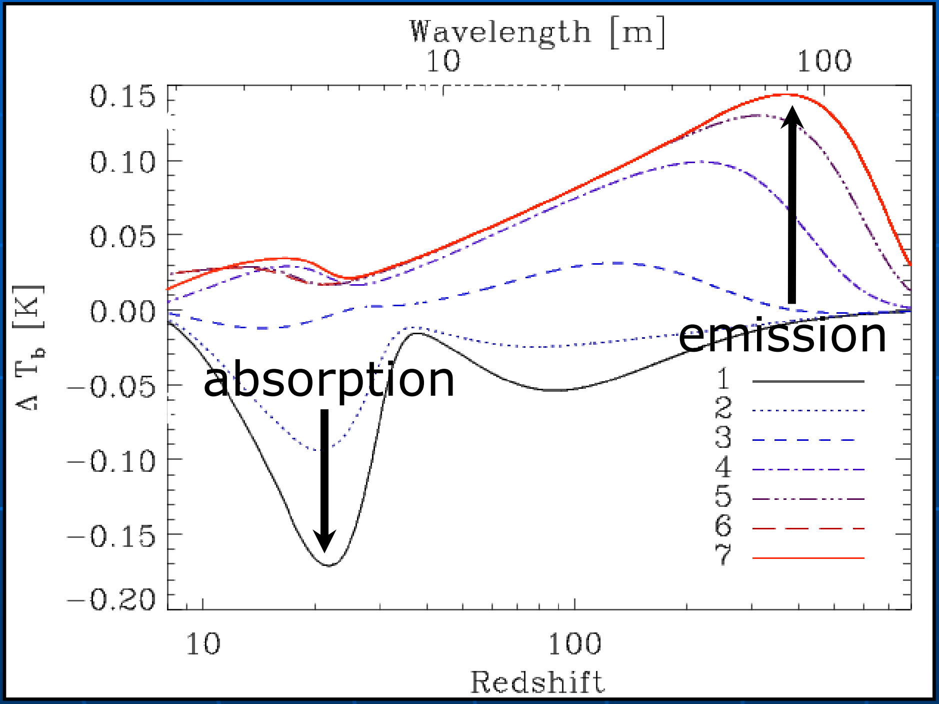
- **$B_{\parallel}$ ~ RM / DM**
- Excellent precision of magnetic field strength measurements


M51 (120−181MHz)
Beam size: 60"
Noise: 0.7 mJy
52°
J2000 Declination
Mulcahy et al., in prep.
14h
13h50m
40m
30m
20m
10m
00m
J2000 Right Ascension

Primordial fields in the Epoch of Reionization

Schleicher et al. 2009

Brightness temperature



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

Square Kilometre Array (SKA)

Three array concepts:

- Low (70 - 450 MHz)
- Mid (500 - 1000 MHz)
- High (450 - 3000 MHz)

“Magnetic goals” for the SKA

- Survey of pulsars in the Milky Way:
  detailed structure of the overall magnetic field
- Evolution of magnetic fields in distant galaxies
- Search for intergalactic magnetic fields

SKA Key Science Project:
All-Sky Faraday rotation grid

All-sky survey (1h integration per field):
≈ 2000 polarized sources per deg^2
(≈ 0.5 RMs per $arcmin^2$)

Total number of RMs: ≈ 8 10^7

Observation of magnetic fields in distant galaxies with the SKA

Deep SKA observations:

- Total synchrotron emission ($z < 3$-5)
- Polarized synchrotron emission ($z < 3$)
- Faraday rotation against background quasars ($z < 5$)

- The evolution of galactic magnetic fields can be measured
- Large-scale intergalactic fields can be detected

We are entering a Golden Age of cosmic magnetism observations