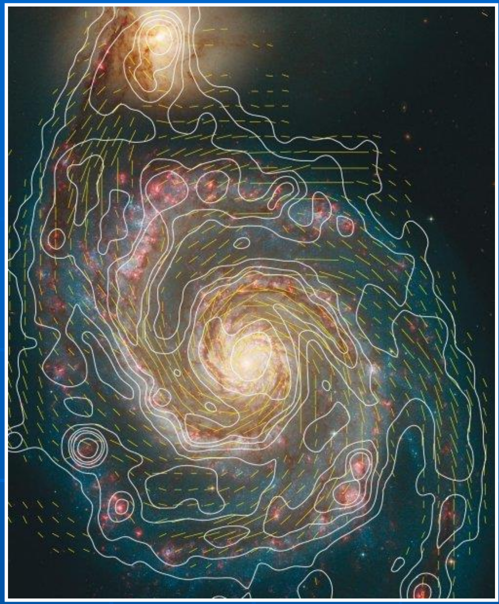


Lecture 6:

Magnetic Fields in External Galaxies

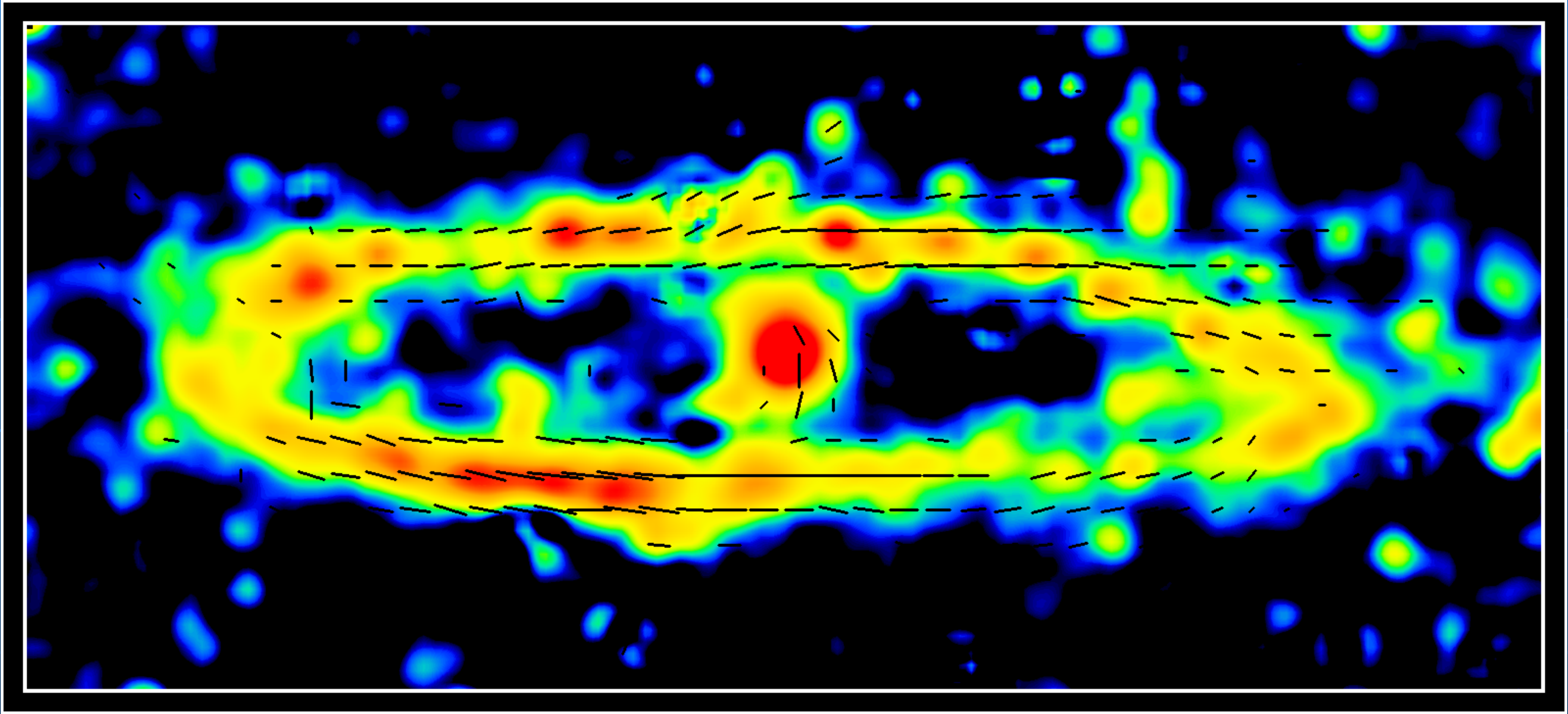
Rainer Beck, MPIfR Bonn

Interstellar medium in galaxies:

Magnetic forces are important

Synchrotron emission of the Andromeda galaxy

Berkhuijsen et al. 2003



Average total magnetic field strength ≈ 6 μG

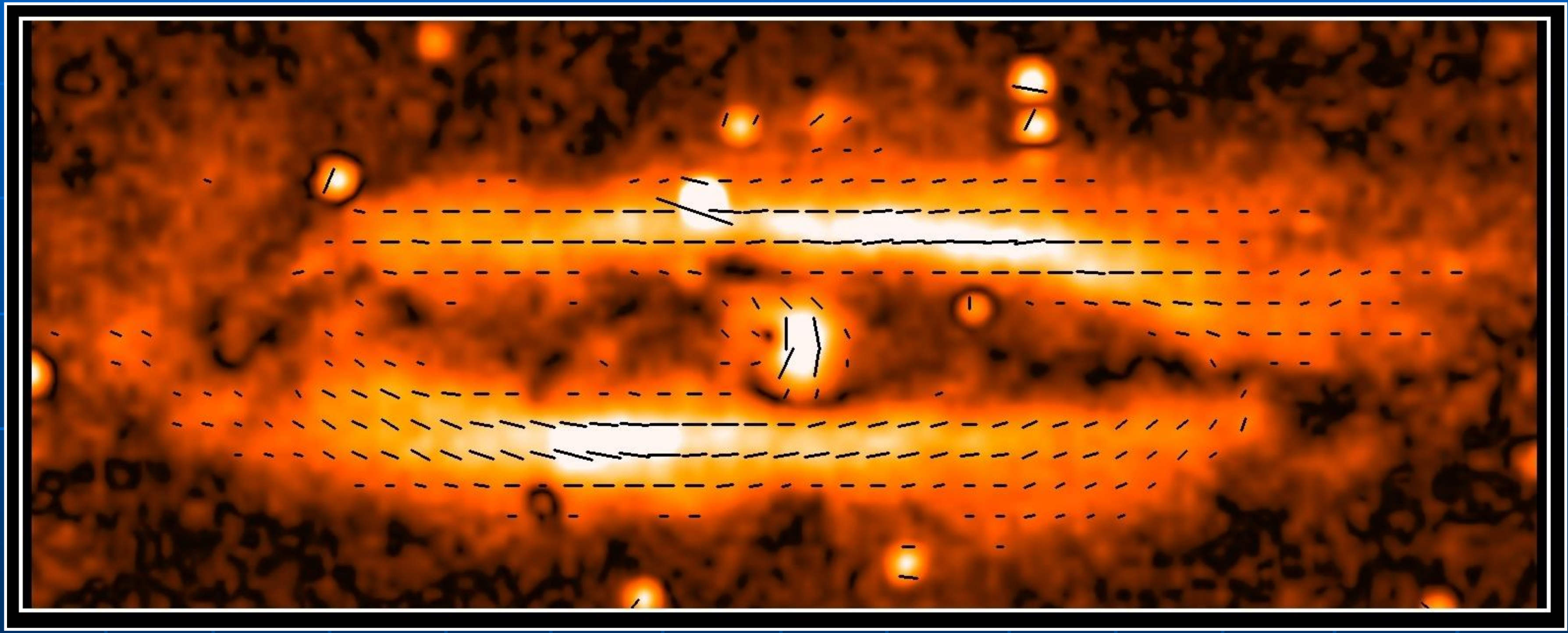
Polarization observations:

Ordered magnetic fields

New deep polarization survey of M31

(Effelsberg 6cm)

Gießübel et al., in prep.



Ordered fields extend out to > 25 kpc

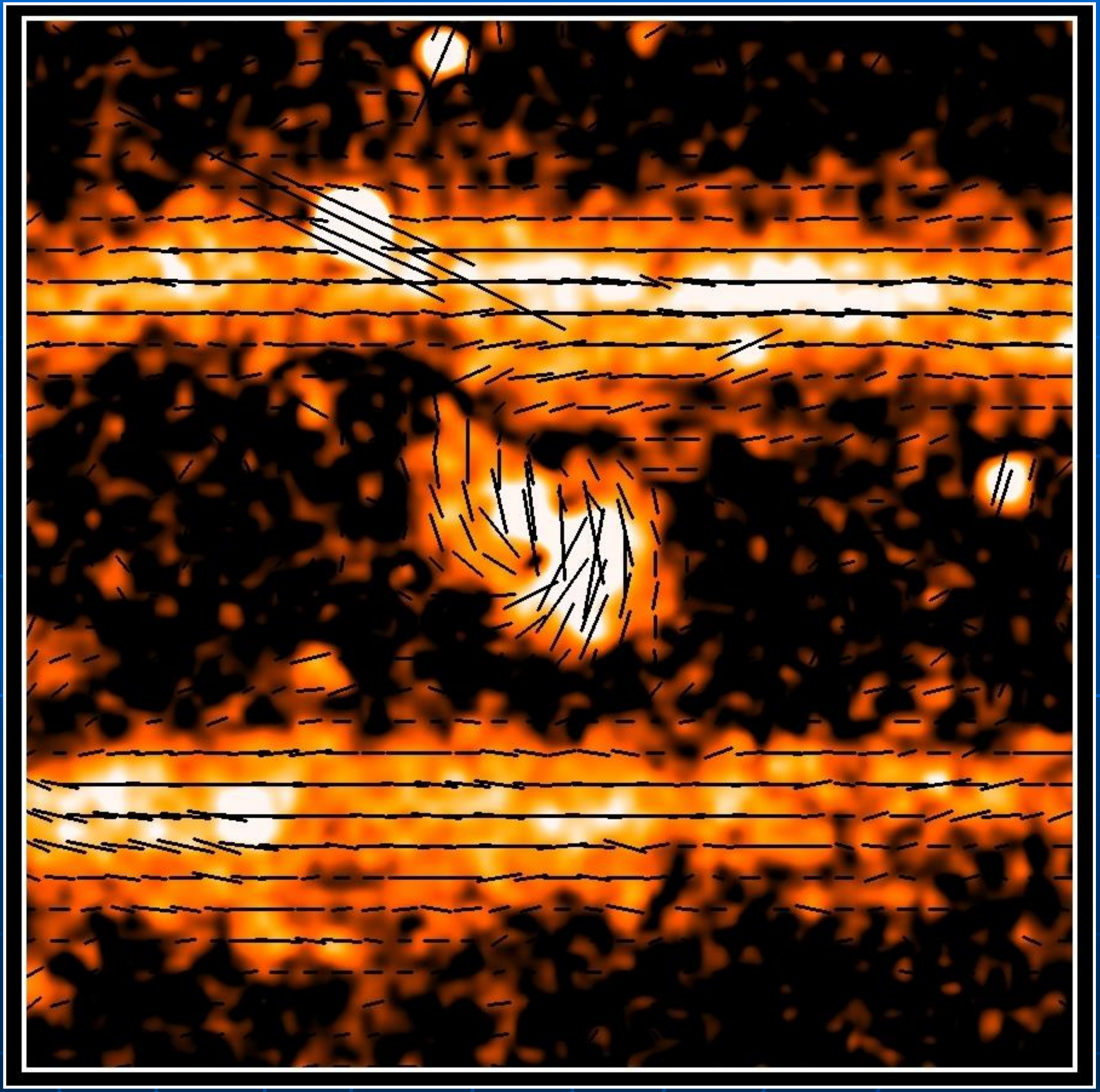
M 31

3cm Effelsberg
Polarized intensity
+ B-vectors

High resolution
(300pc):

Highly ordered
field in the "ring",
spiral field in
the central region

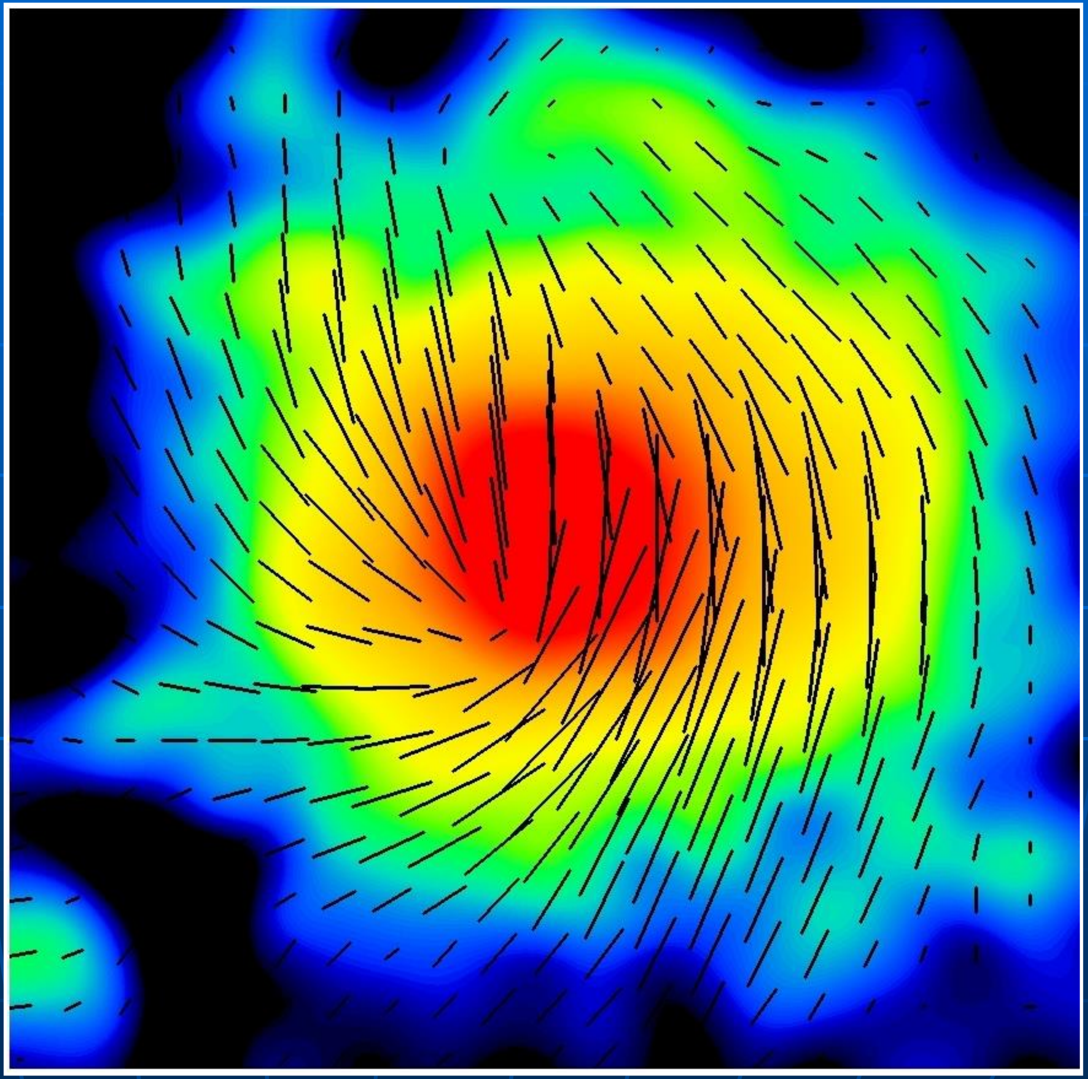
Gießübel et al., in prep.



M 31

Central region

3cm Effelsberg
Total intensity
+ B-vectors



Independent dynamo in the central region?

Gießübel et al., in prep.

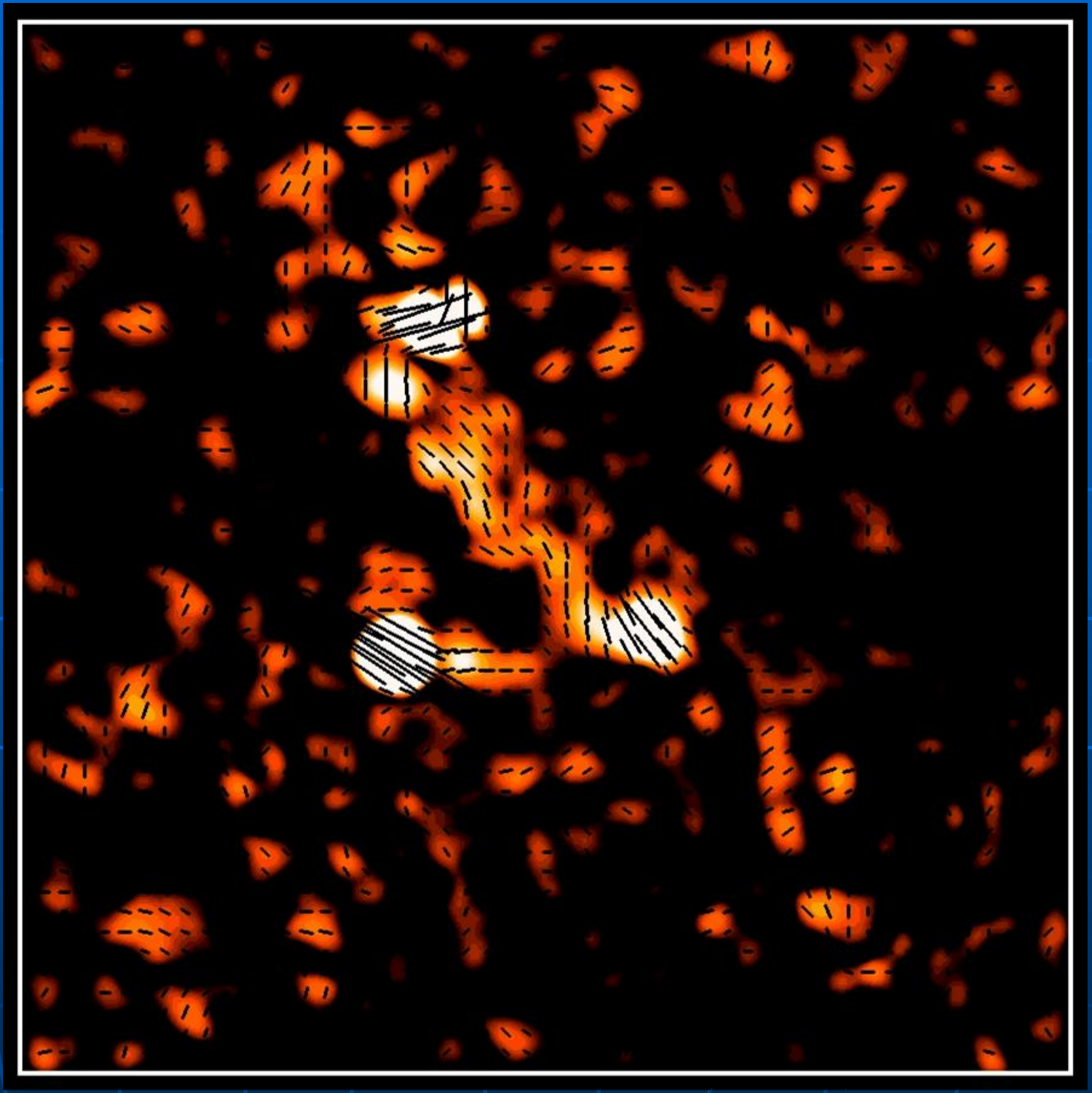
M 31

Northern arm

6cm VLA
Polarized intensity
+ B-vectors

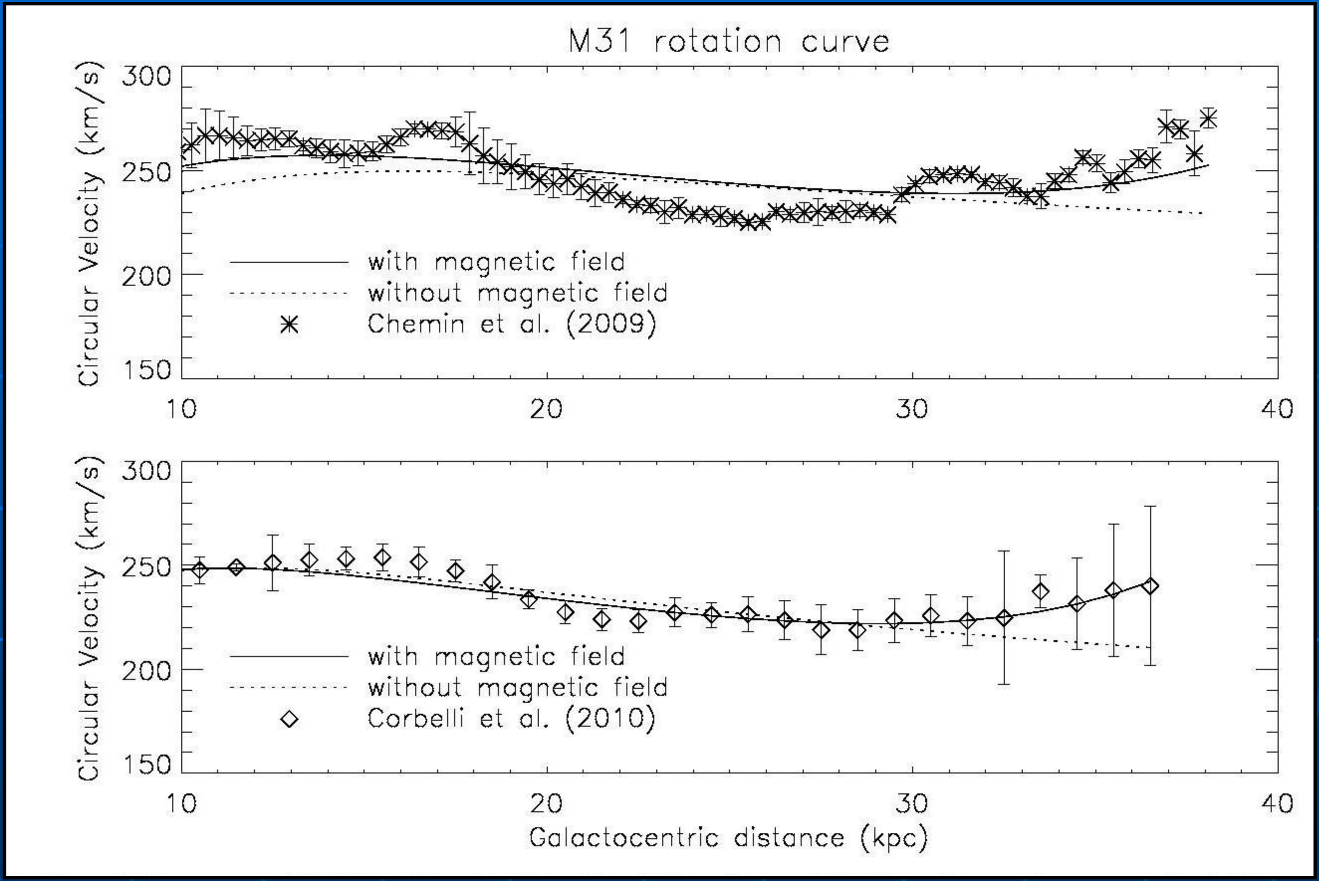
High resolution (100pc):

Helical field ?



Beck 2008

Can magnetic fields affect galactic rotation ?

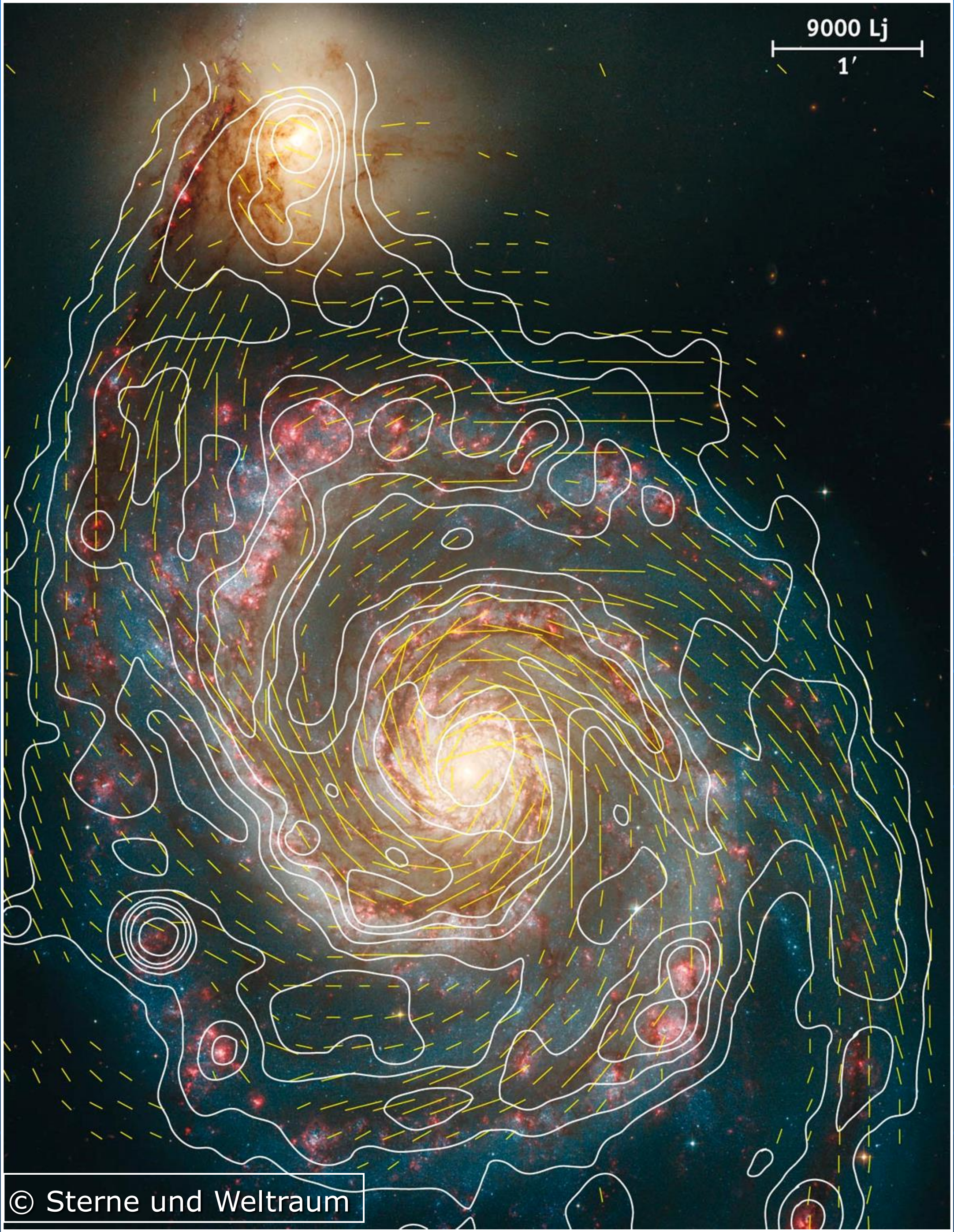


Magnetic forces may explain the rising rotation curve

Ruiz-Granados et al. 2010

M 51

6 cm
VLA+Effelsberg
Total intensity
+ B-vectors
+ optical (HST)



High degrees of pol (≤50%)

Ordered fields are mostly parallel to the optical spiral arms

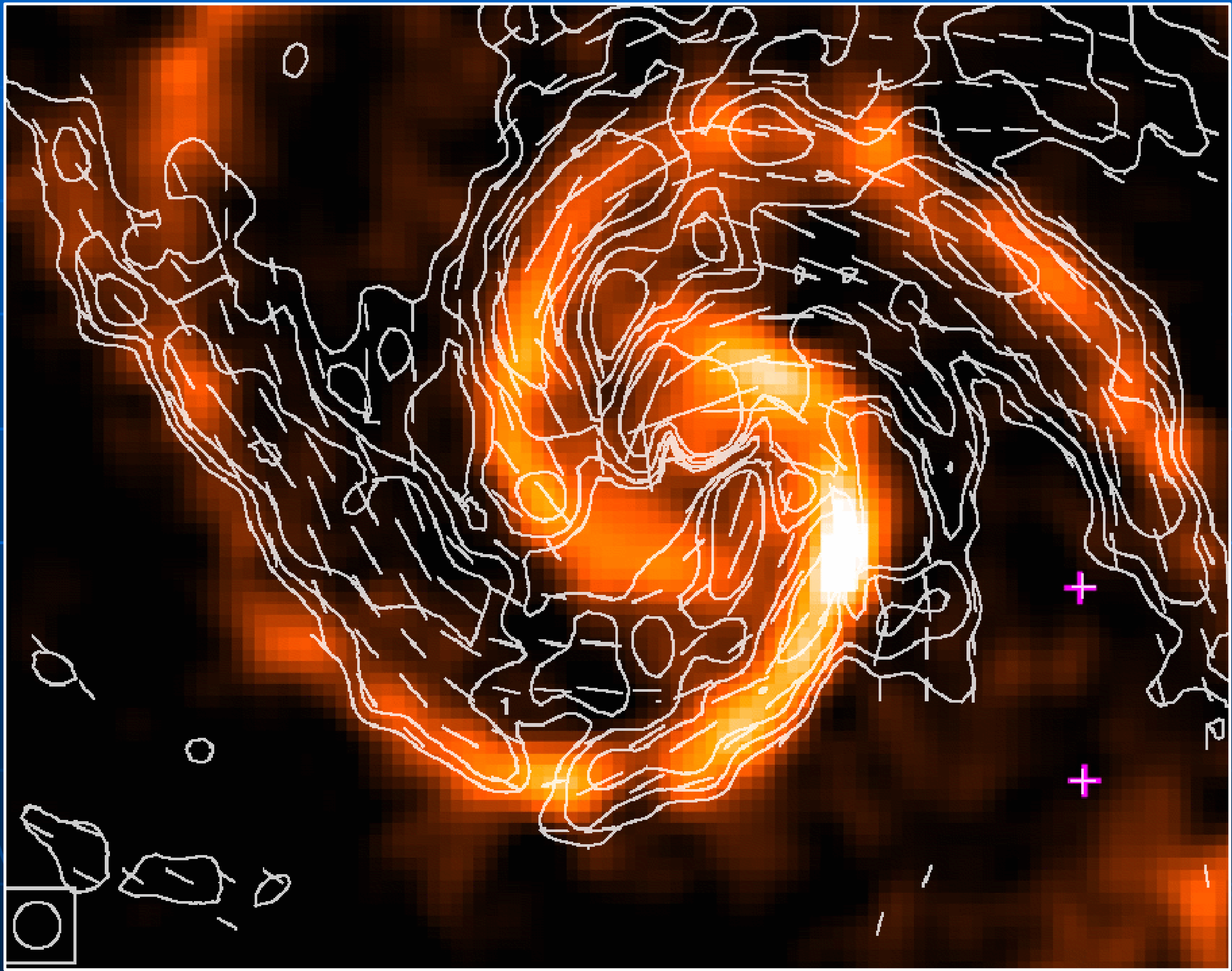
Fletcher et al. 2011

Magnetic fields and molecular gas

Polarized intensity (Effelsberg+VLA) and BIMA CO data (Regan et al. 2001)

Smooth transition between interarm and arm regions:

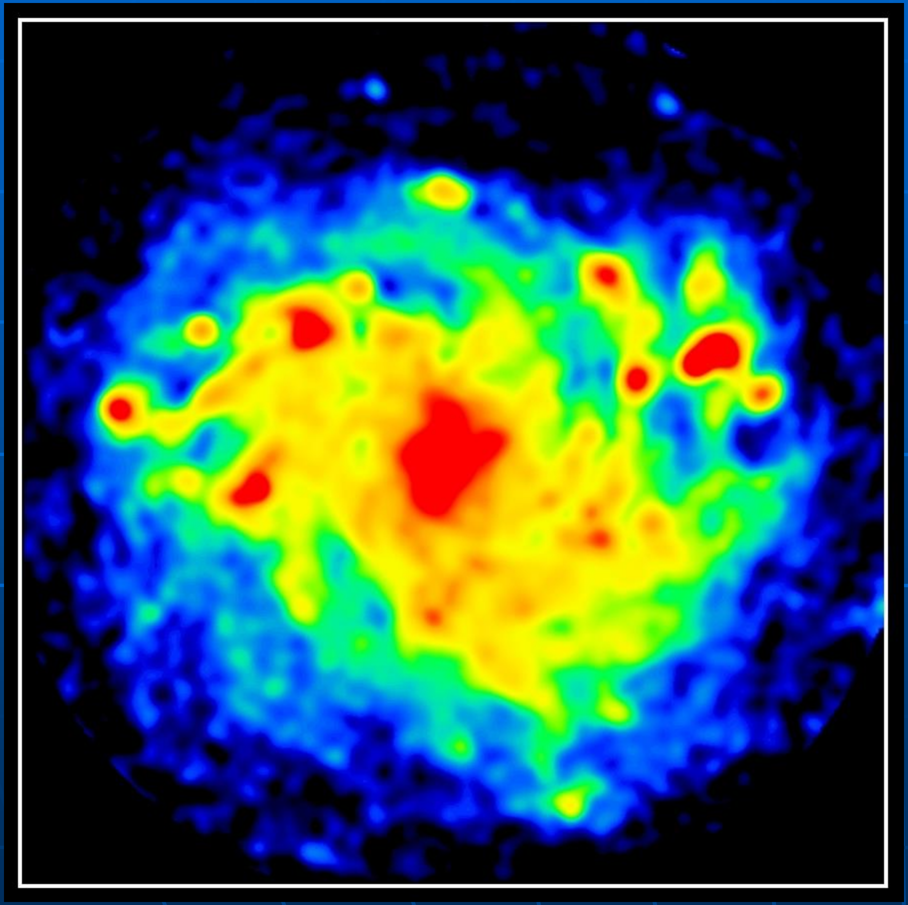
no shock

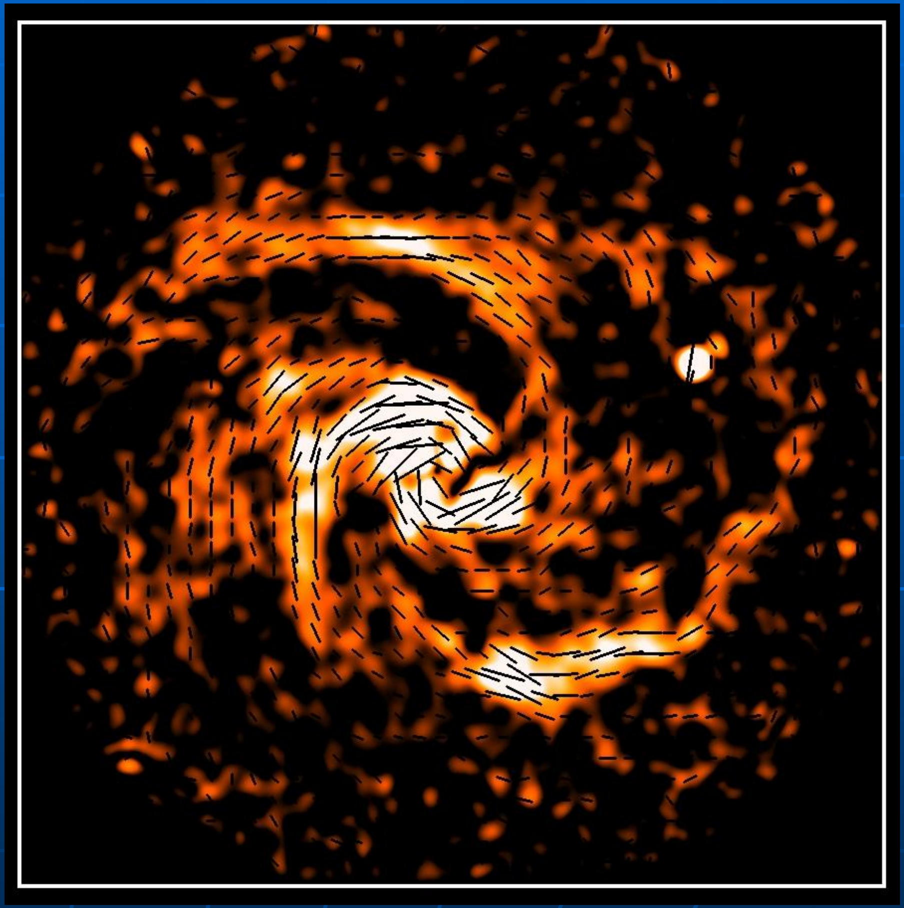


Patrikeev et al. 2006

Total and polarized emission of NGC 6946 at 6cm

(Effelsberg+VLA)

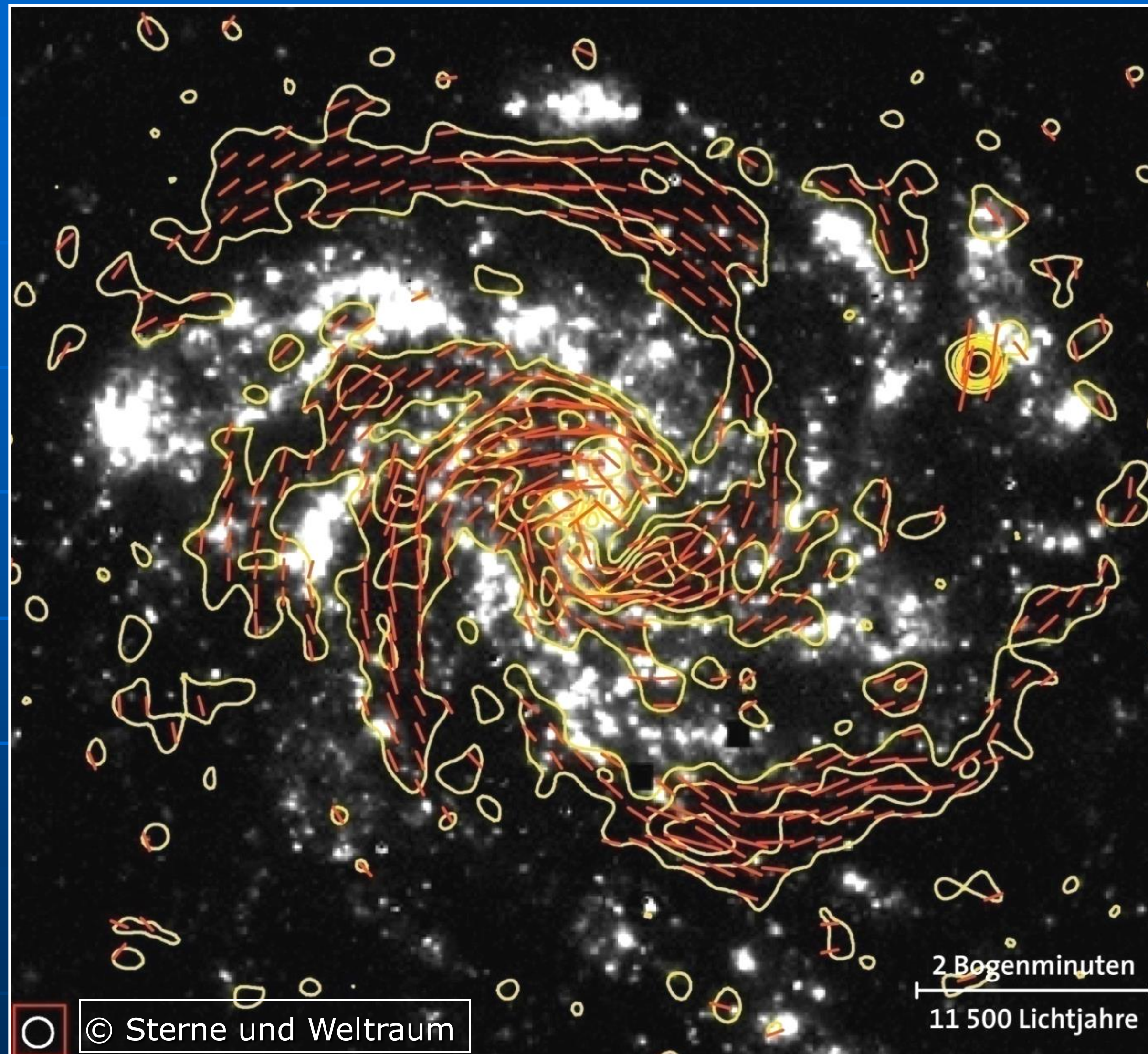




Beck & Hoernes 1996

NGC 6946

VLA+Effelsberg
6 cm
Polarized intensity
+ B-vectors



"Magnetic arms":

Ordered fields concentrated in interarm regions

Beck & Hoernes 1996

Interarm fields in large spiral galaxies

- Magnetic arms (contrast in polarized intensity ≥2, not filling all the interam space):
  NGC6946, 2997, 3627, IC342, M51?

- Ordered fields in interarm regions:
  M33, M81, M83, M101, NGC1566, 4254, 4535

- Ordered fields along spiral arms:
  M51, NGC2997, 3627

- Unclear:
  M31 (high inclination),
  NGC1097, 1365, 2442 (barred galaxies)

Proposed origins of the "magnetic arms"

- Slow MHD waves (?)
  (Lou & Fan 1998, Lou & Bai 2006)
- m=2 mode of the mean-field dynamo
  (Rohde et al. 1999)
- Coupling between density wave and dynamo wave
  (Chamandy et al. 2012, 2013)
- Injection of turbulent fields in spiral arms
  (Moss et al. 2013)

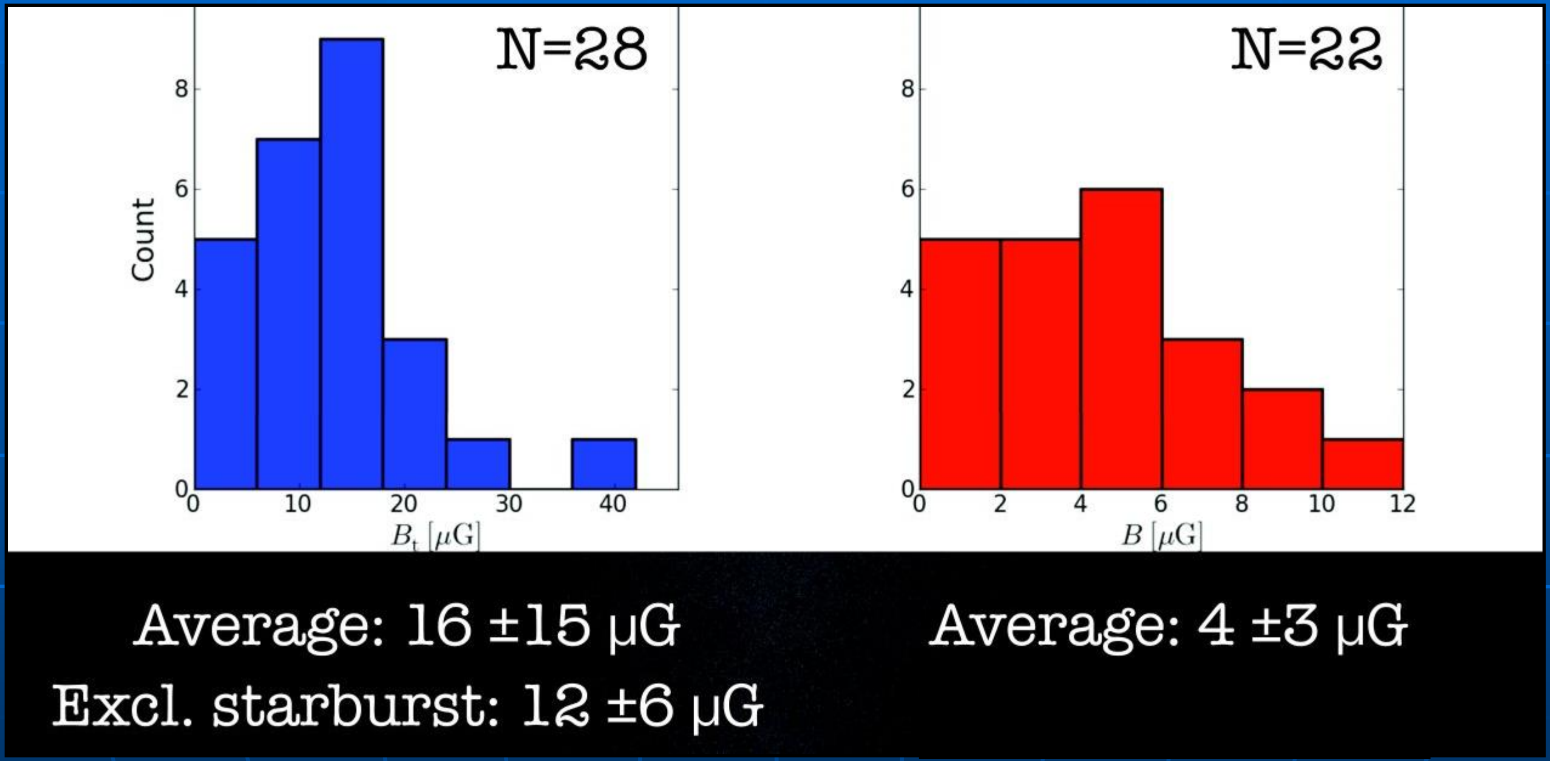
Magnetic field strengths in spiral galaxies

(from total synchrotron intensity, assuming equipartition between the energy densities of magnetic fields and cosmic rays)

Total (mostly turbulent) field in spiral arms:	**20 - 30 μG**
Ordered field in interarm regions:	**5 - 15 μG**
Total field in circum-nuclear rings:	**40 – 100 μG**
Total field in Galactic center filaments:	**≈ 1 mG**

10 μG = 1 nT

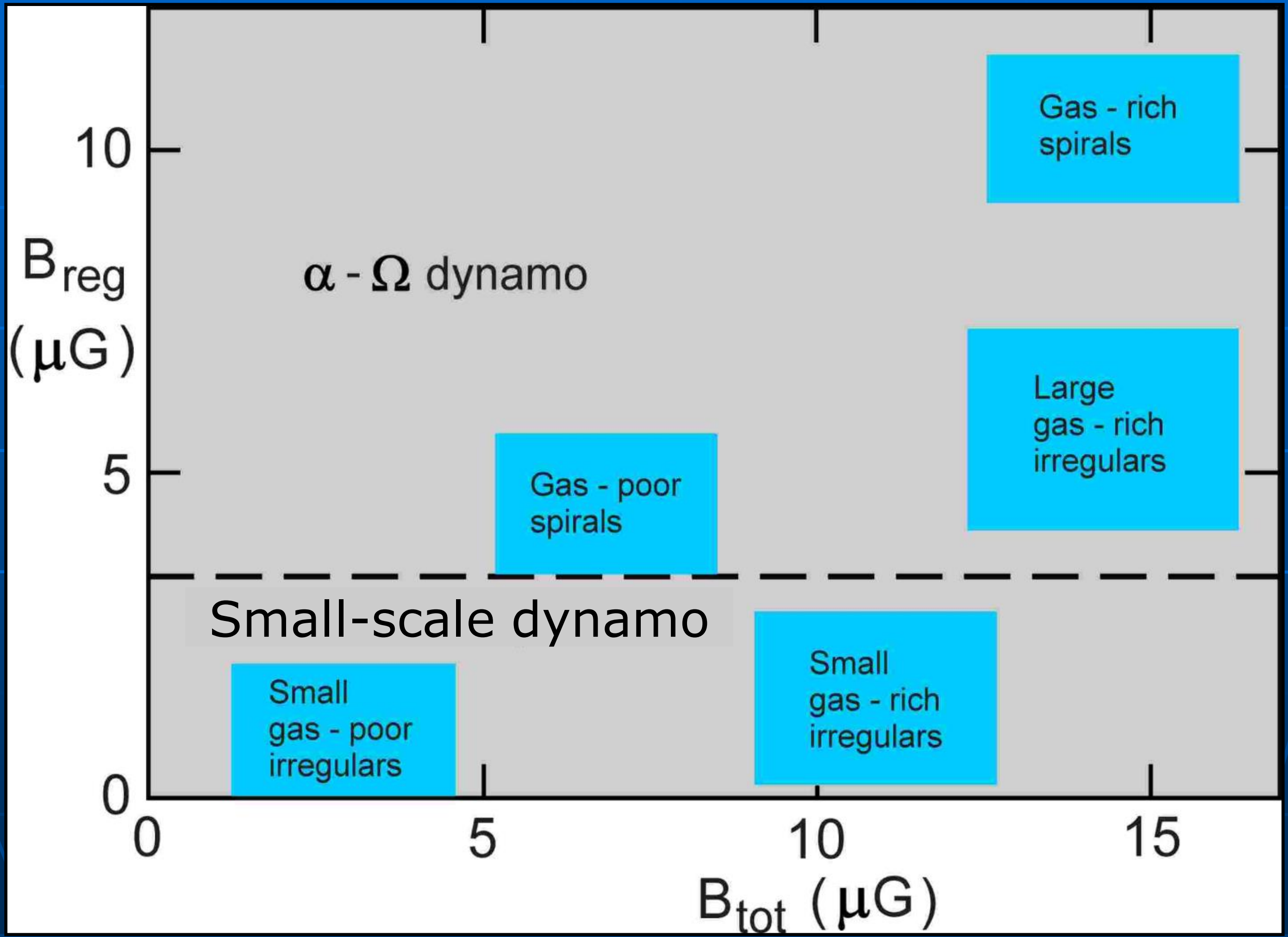
Total and ordered field strengths
(compilation by A. Fletcher)



- $B_{turb} / B_{ord} \le 3$ (low resolution)

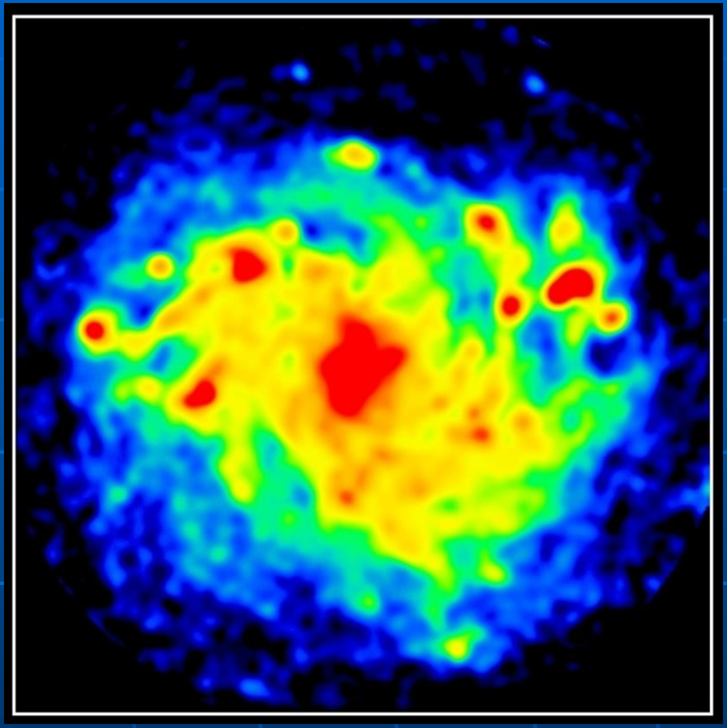
- Prediction by dynamo models: 2-10
(Arshakian et al. 2009, Gressel et al. 2012)

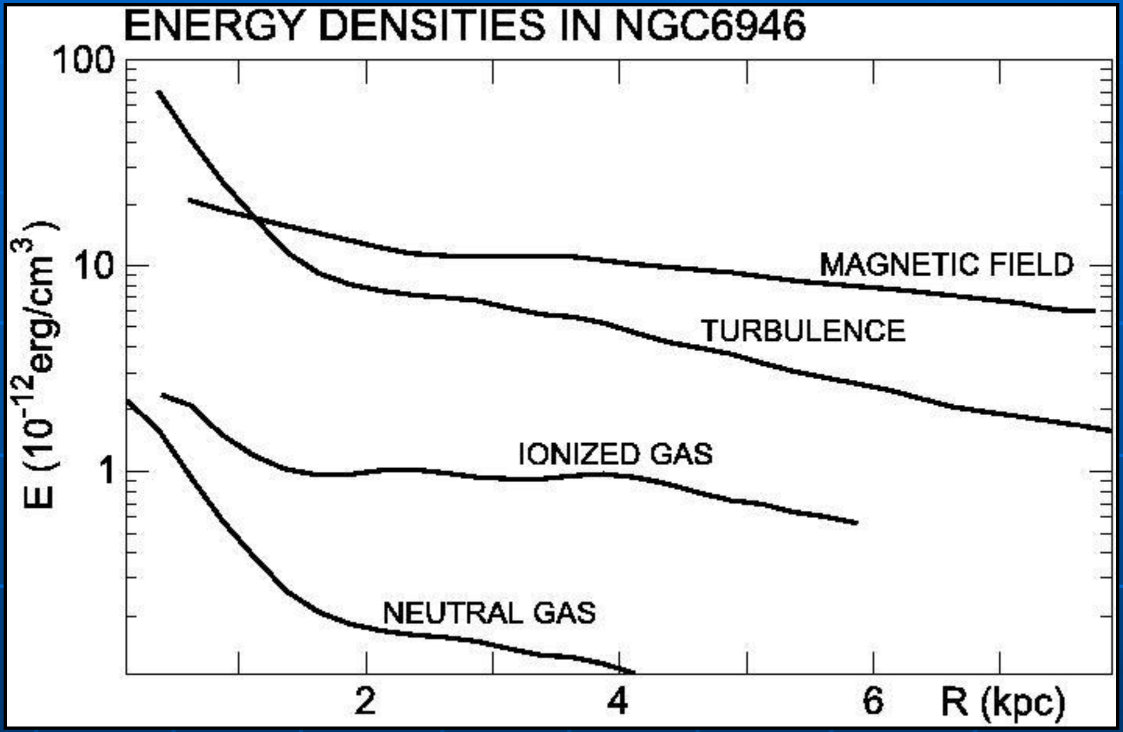
Equipartition field strengths in galaxies



Magnetic energy density in NGC 6946

(assuming equipartition with cosmic rays)





Magnetic energy density is similar to that of turbulent gas motions, but **larger** in the outer disk

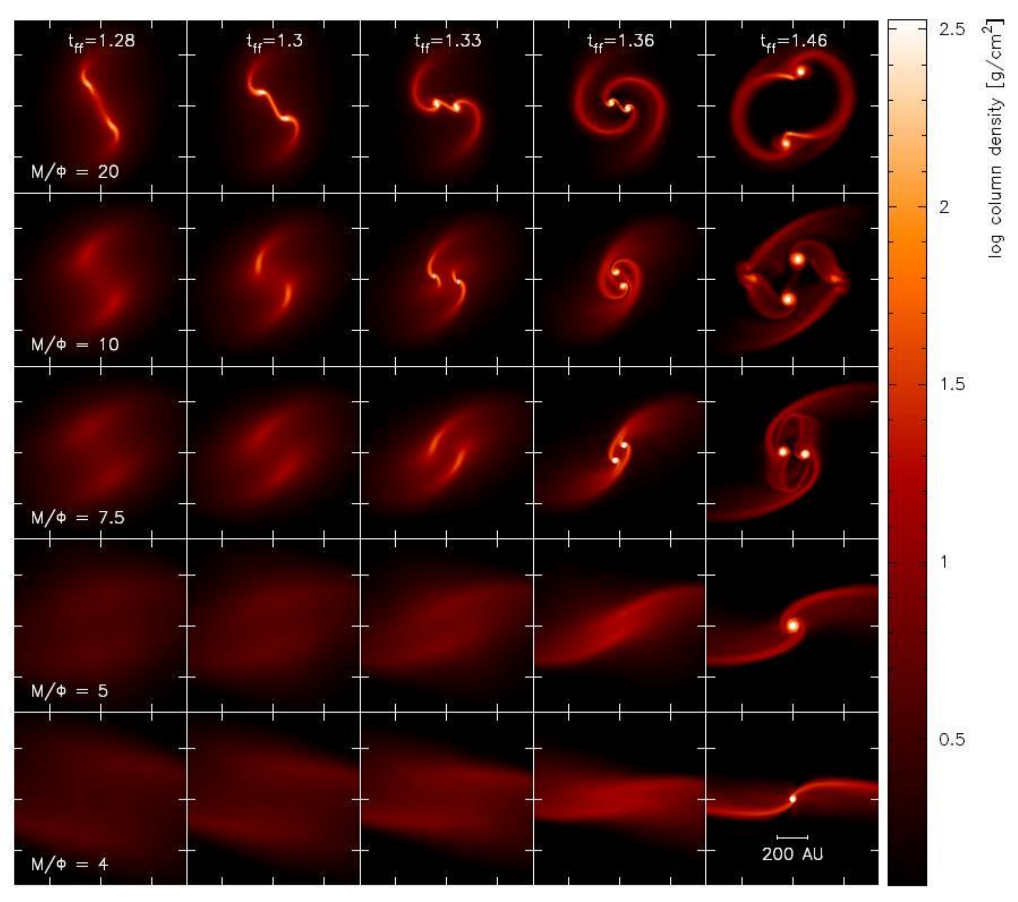
Beck 2007

Dynamical effects of magnetic fields in galaxies

Star formation: 3D MHD simulations

(Price & Bate 2007, 2008, 2009)

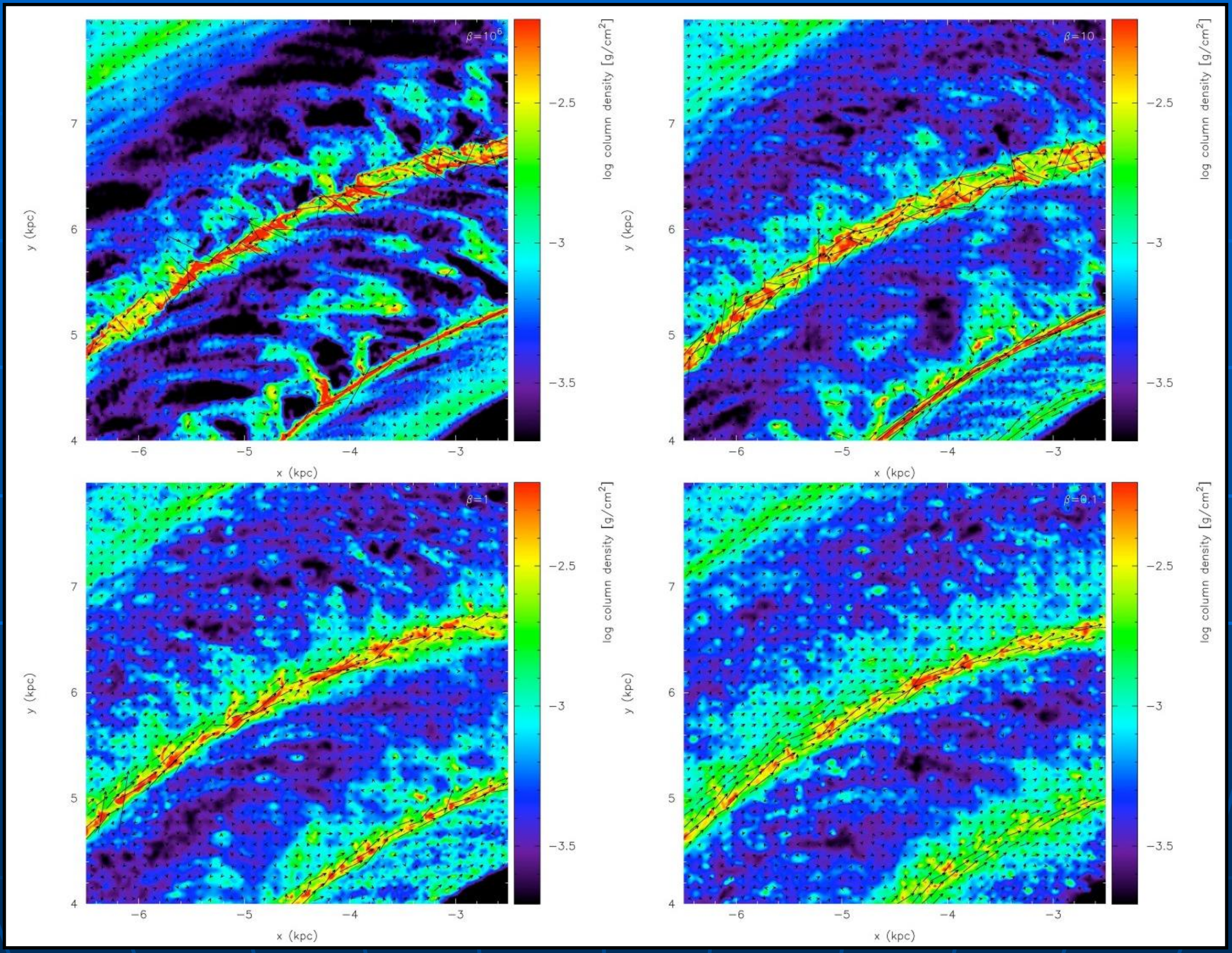
- Less cloud fragmentation for strong magnetic fields
- Less efficient star formation for strong magnetic fields
- Less low-mass stars for strong magnetic fields
- Less binary stars for strong magnetic fields



Spiral arms
(3D MHD simulations)

$\beta = 10^6$

$\beta = 10$



$\beta = 1$

$\beta = 0.1$

Dobbs & Price 2008

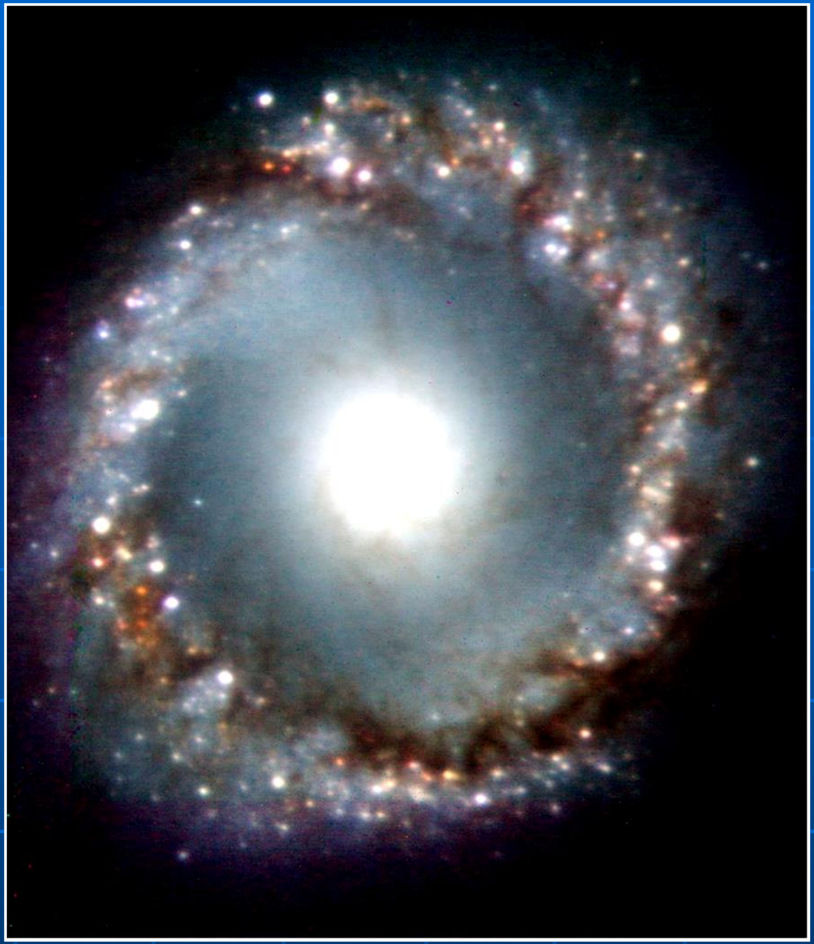
Spiral arms are smoother for strong magnetic fields

Barred galaxies

NGC 1097

ESO/Gendler

NGC 1097
Circumnuclear ring
Optical (VLT)

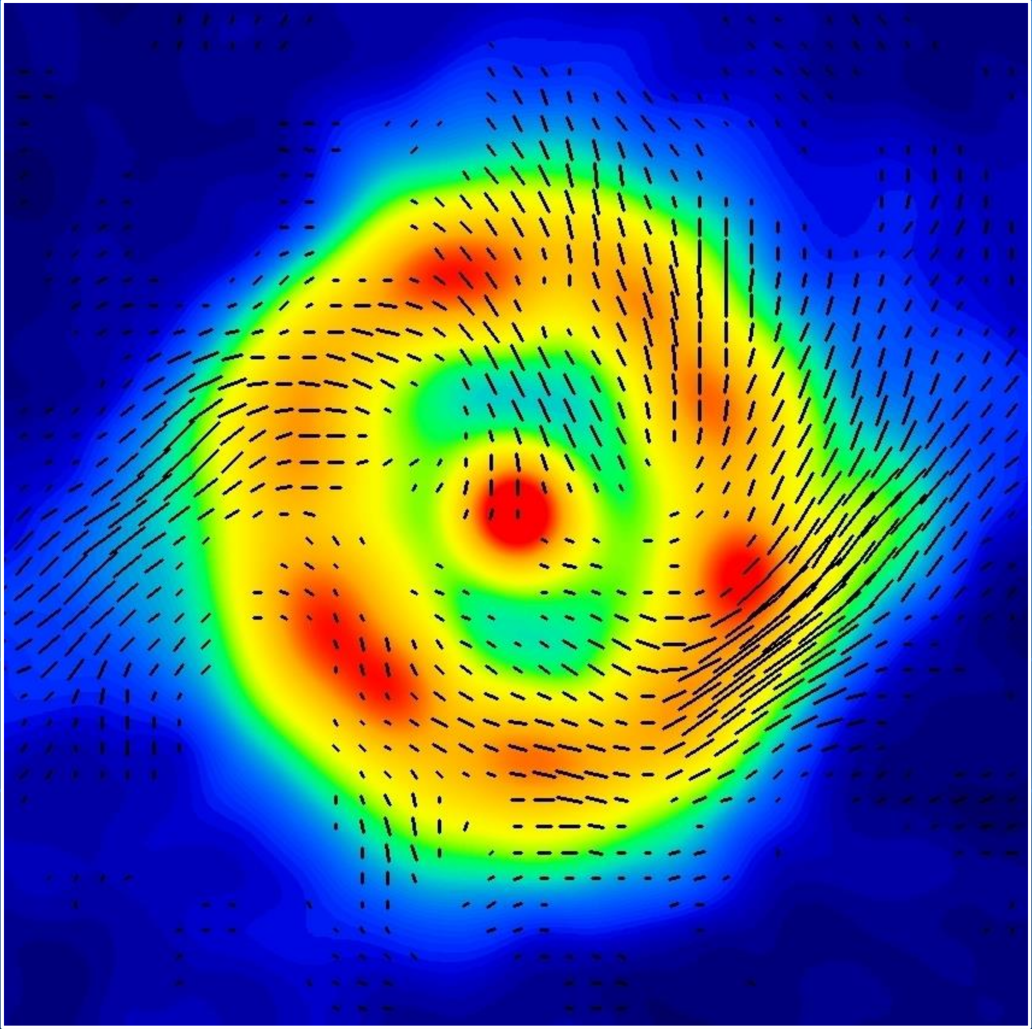


Prieto et al. 2005

How to feed an active galactic nucleus ?

NGC 1097 Circumnuclear ring

VLA 3 cm
Total intensity
+ B-vectors



Strong field in the circumnuclear ring ($\approx$60 μG)

Beck et al. 2005

Accretion by magnetic stress

(Beck et al. 1999, 2005)

$$dM/dt = -h/\Omega\ (< B_{tot,r}\ B_{tot,\Phi} > + < B_{reg,r}\ B_{reg,\Phi} >)$$

NGC 1097:

h=100 pc, v=450 km/s,

$B_{tot,r} \approx B_{tot,\Phi} \approx 50\mu G$, $B_{reg,r} \approx B_{reg,\Phi} \approx 10\mu G$:

$dM/dt \approx 1\ M_o/yr$

Magnetic fields are able to drive accretion!

2D MHD model of barred galaxies

(Kim & Stone 2012)

β = 1

β =3

β = 10

β = ∞

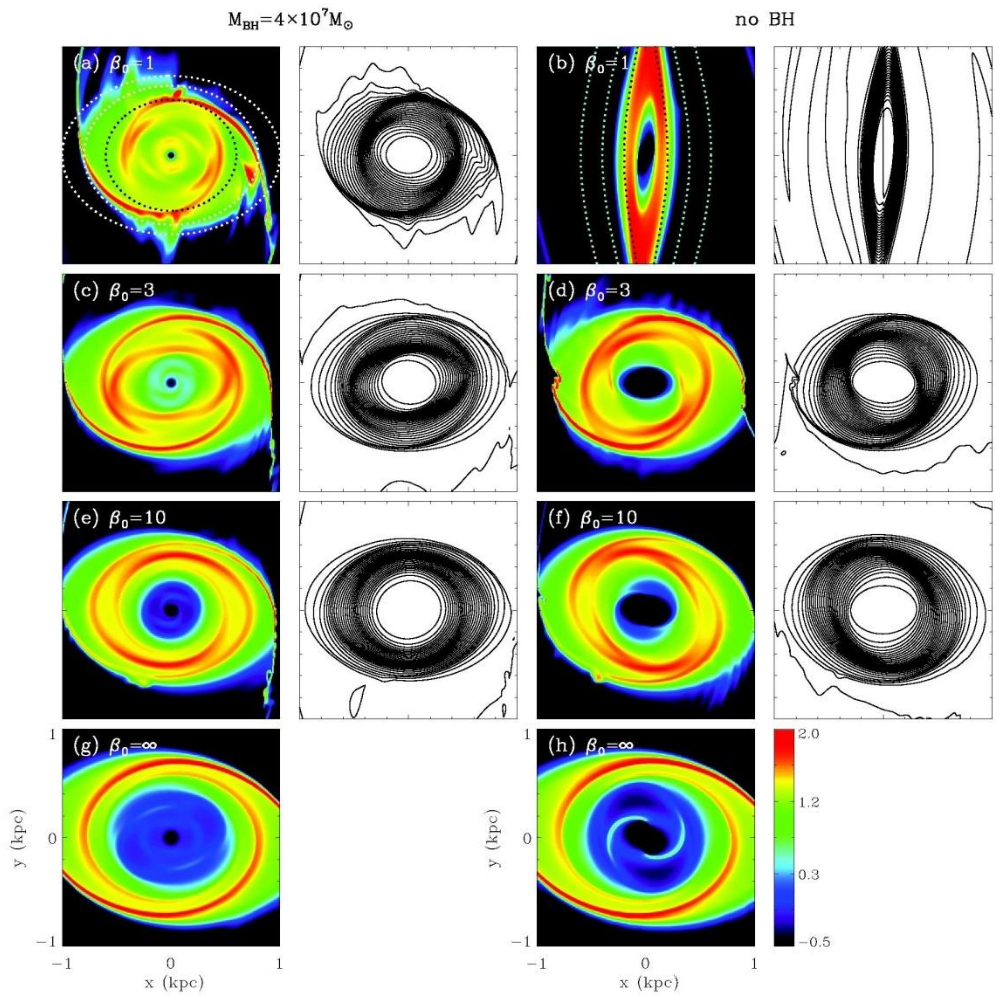


Fig. 9.— Logarithm of the density distribution (color scale) and magnetic field configuration (contours) in the inner 1 kpc regions of all models at $t = 800$ Myr. Dotted curves in (a) draw the x_2-orbits that cut the x-axis at $x_c = 0.6, 0.8, 1.0$ kpc, while those in (b) are for the x_1-orbits with $x_c = 0.2, 0.4, 0.6$ kpc.

2D MHD model of barred galaxies

(Kim & Stone 2012)

Much stronger inflow in the magnetic case

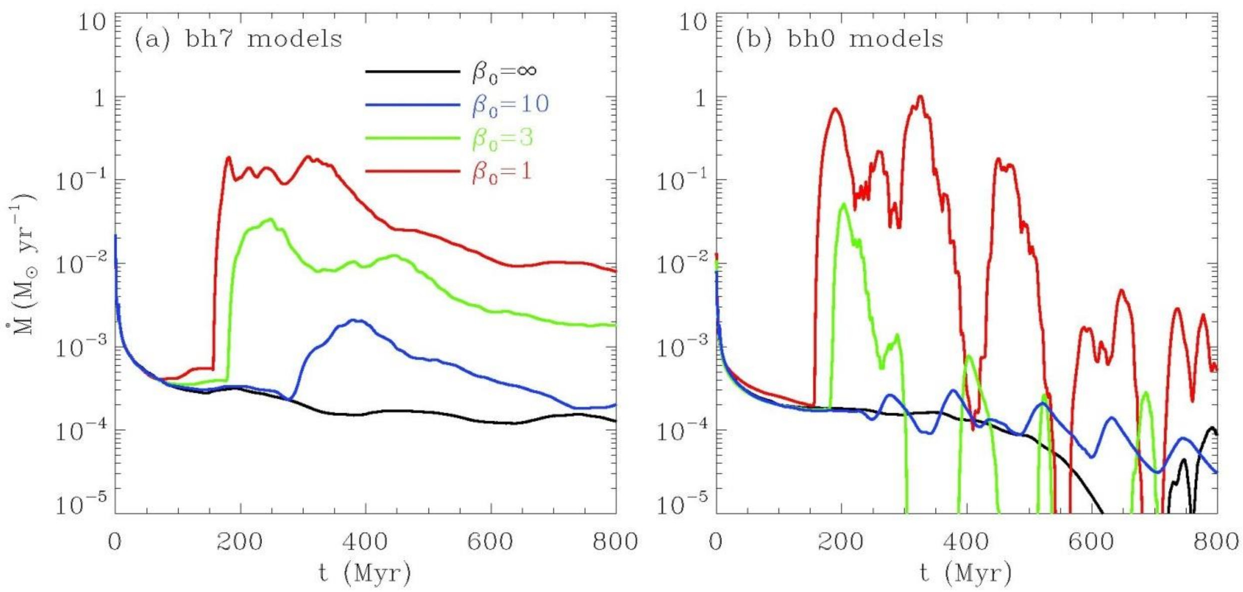
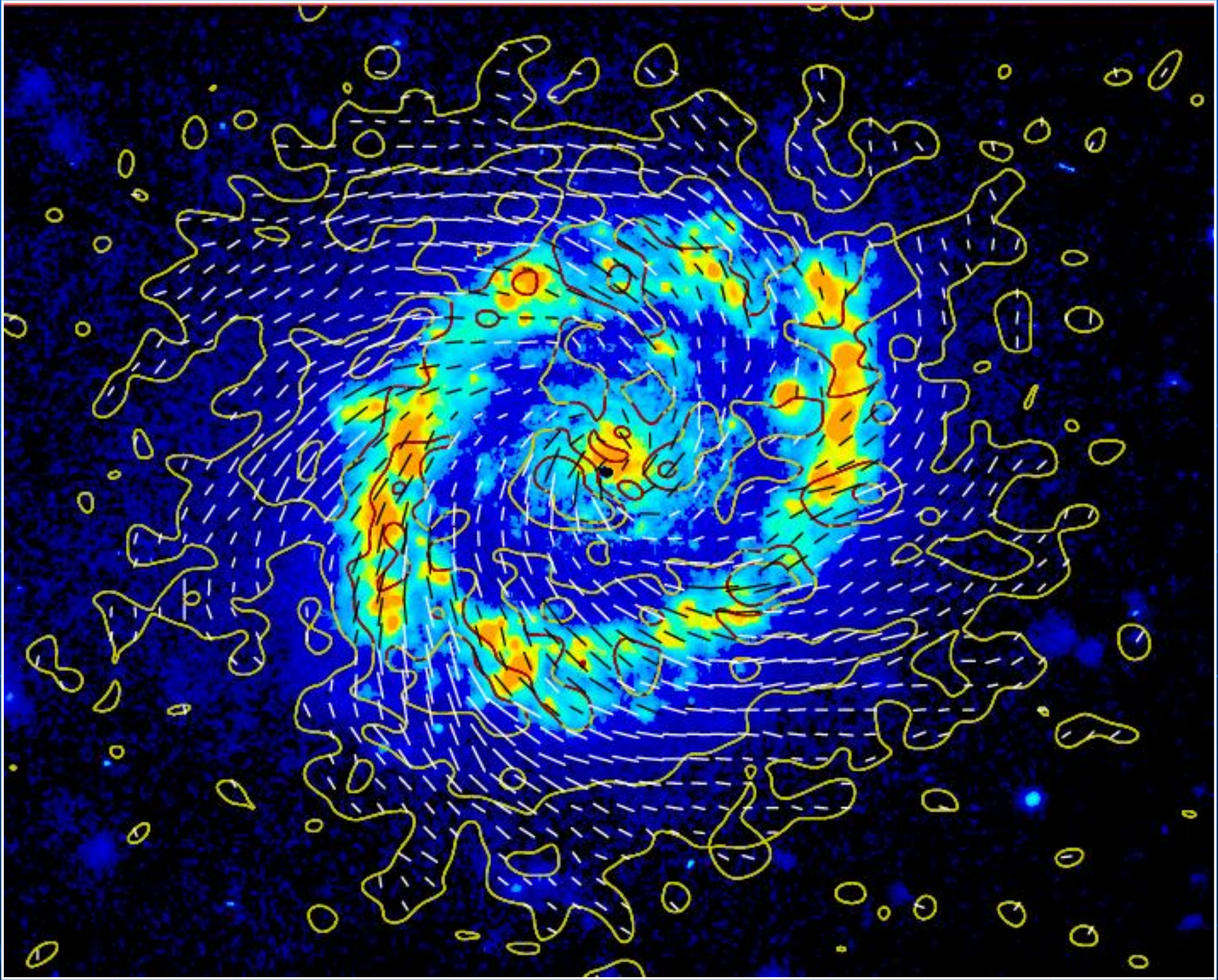


Fig. 13.— Temporal variations of the mass inflow rates $\dot{M}$ for (a) models with $M_{\rm BH} = 4 \times 10^7$ $M_\odot$ and (b) models with no BH. Magnetized models with $\beta = 1$ have $\dot{M}$ larger by more than two orders of magnitude than unmagnetized models. In bh7 models, $\dot{M}$ is sustained, while it becomes relatively intermittent in bh0 models.

No dynamo action possible - 3D models needed

NGC 4736

VLA 3 cm
Polarized intensity
+ B-vectors



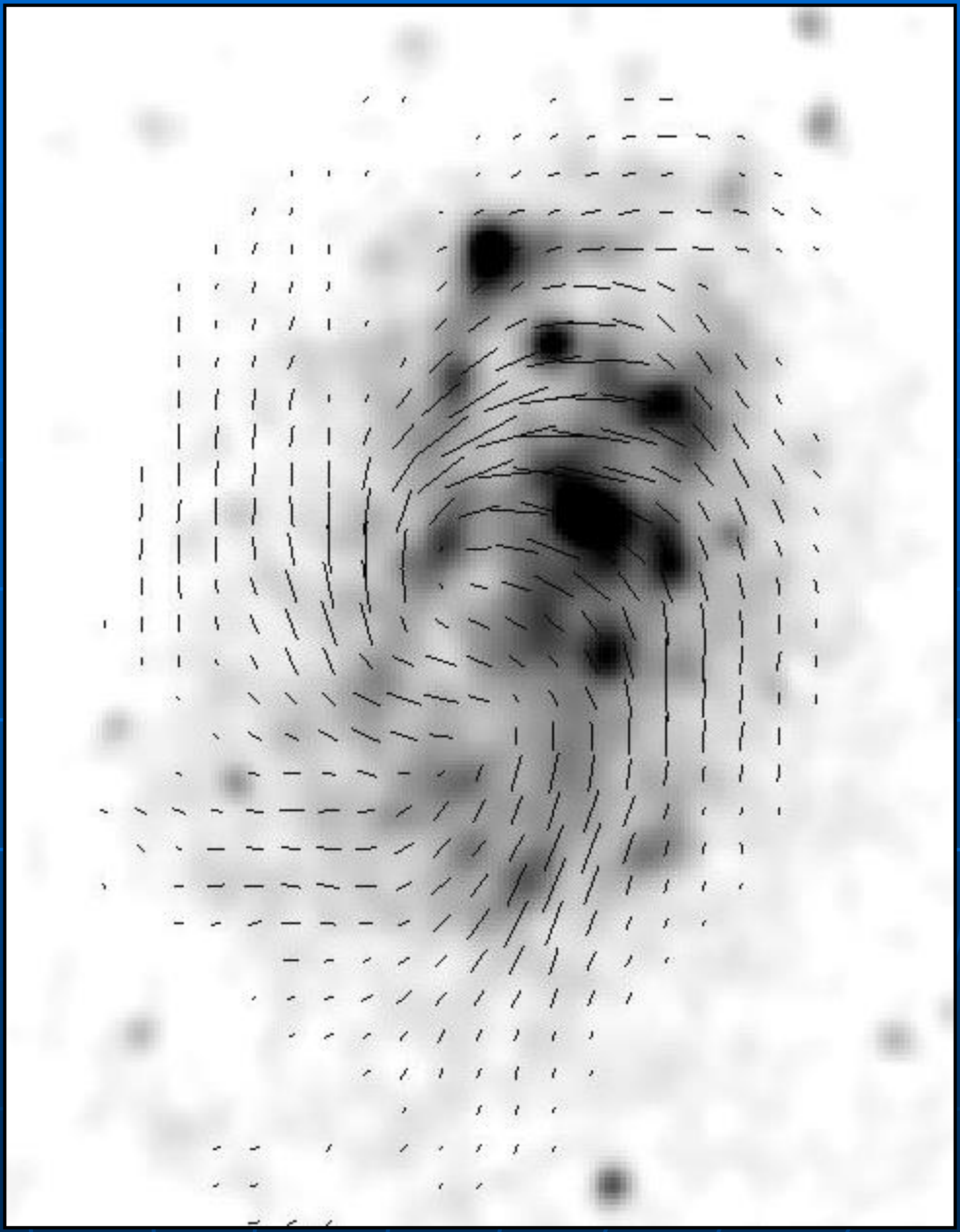
Spiral fields in a ring-like galaxy

Chyzy & Buta 2007

NGC 4414

VLA 3 cm
Ionized gas
+ B-vectors

Flocculent galaxies:
spiral field exists
even without
optical spiral arms

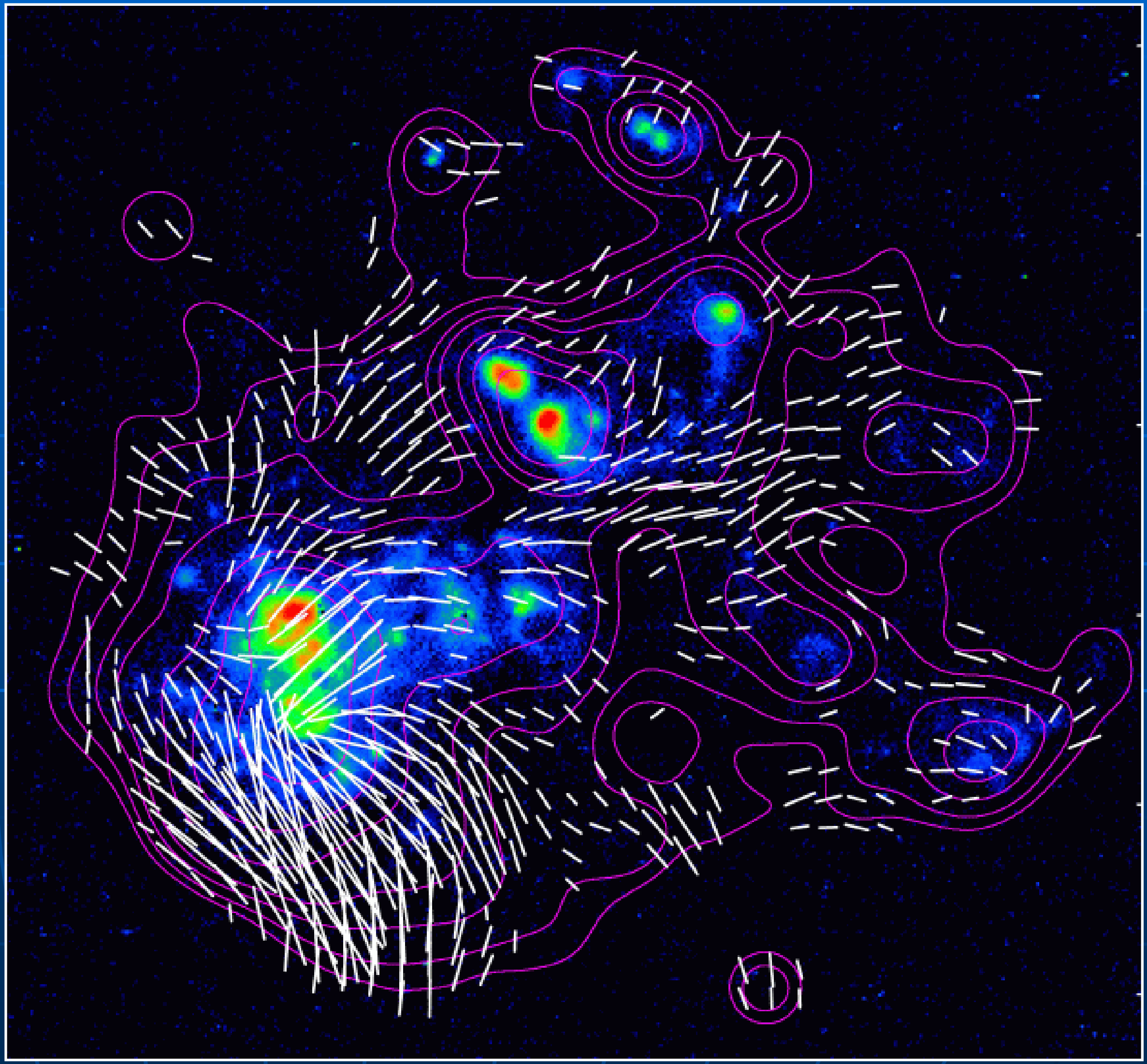


Soida et al. 2002

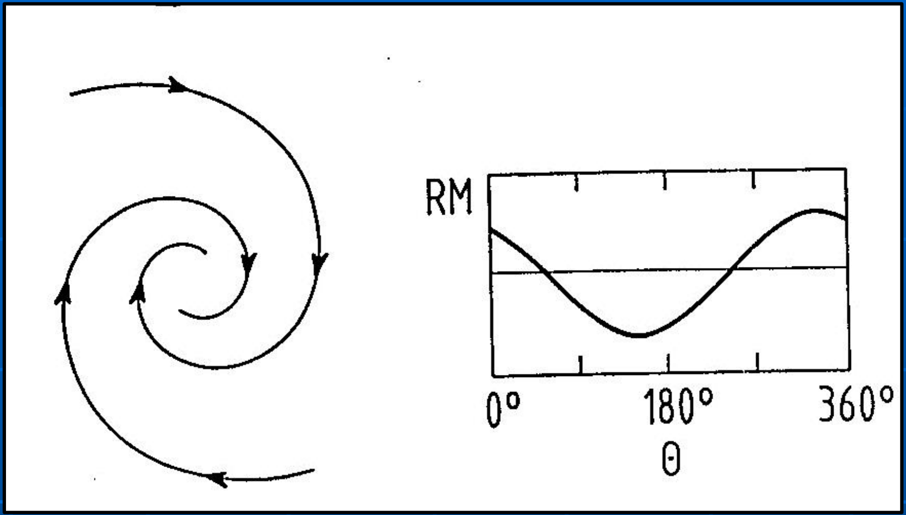
IC 10

VLA 6 cm
Total intensity
+ B-vectors
(Chyzy et al., in prep)

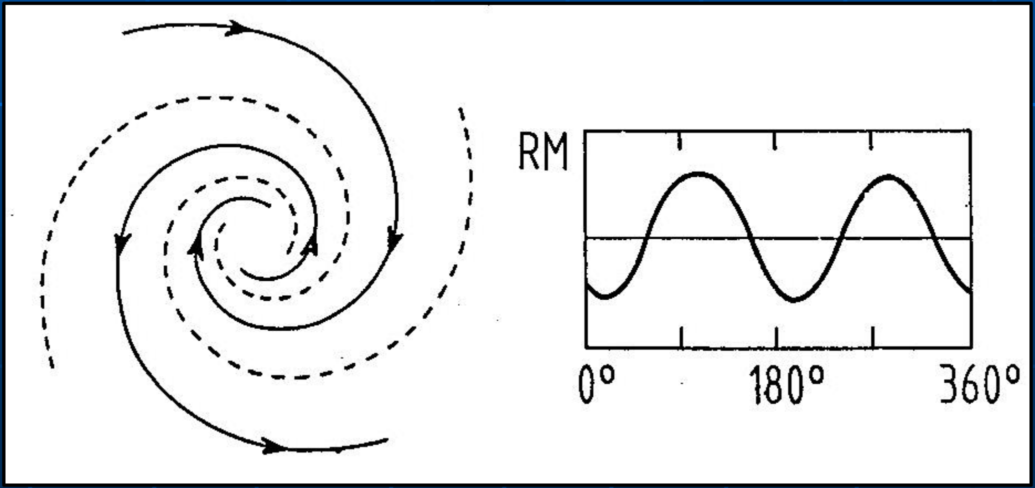
No large-scale
ordered fields
in irregular galaxies



Finding dynamo modes:
Azimuthal variation of Faraday rotation



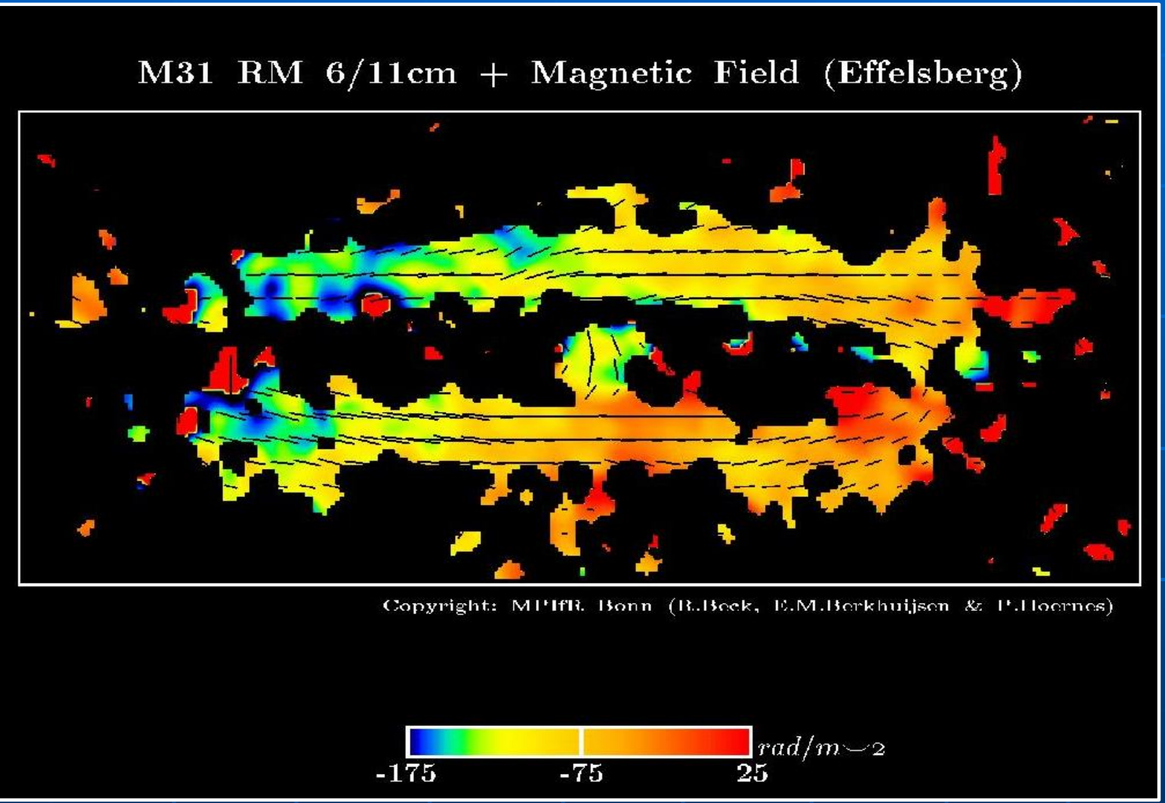
Axisymmetric spiral
(mode m=0)



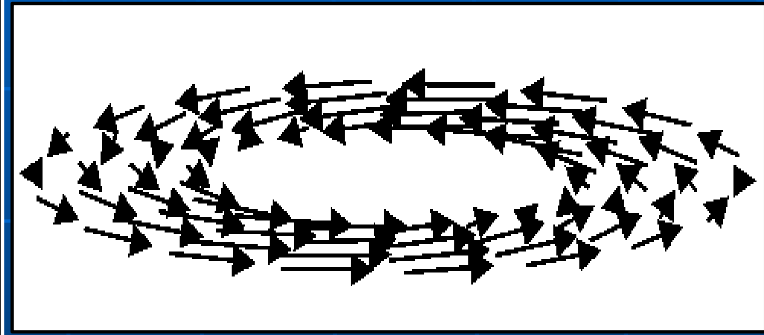
Bisymmetric spiral
(mode m=1)

Krause 1990

M31: The dynamo is working !



Berkhuijsen et al. 2003

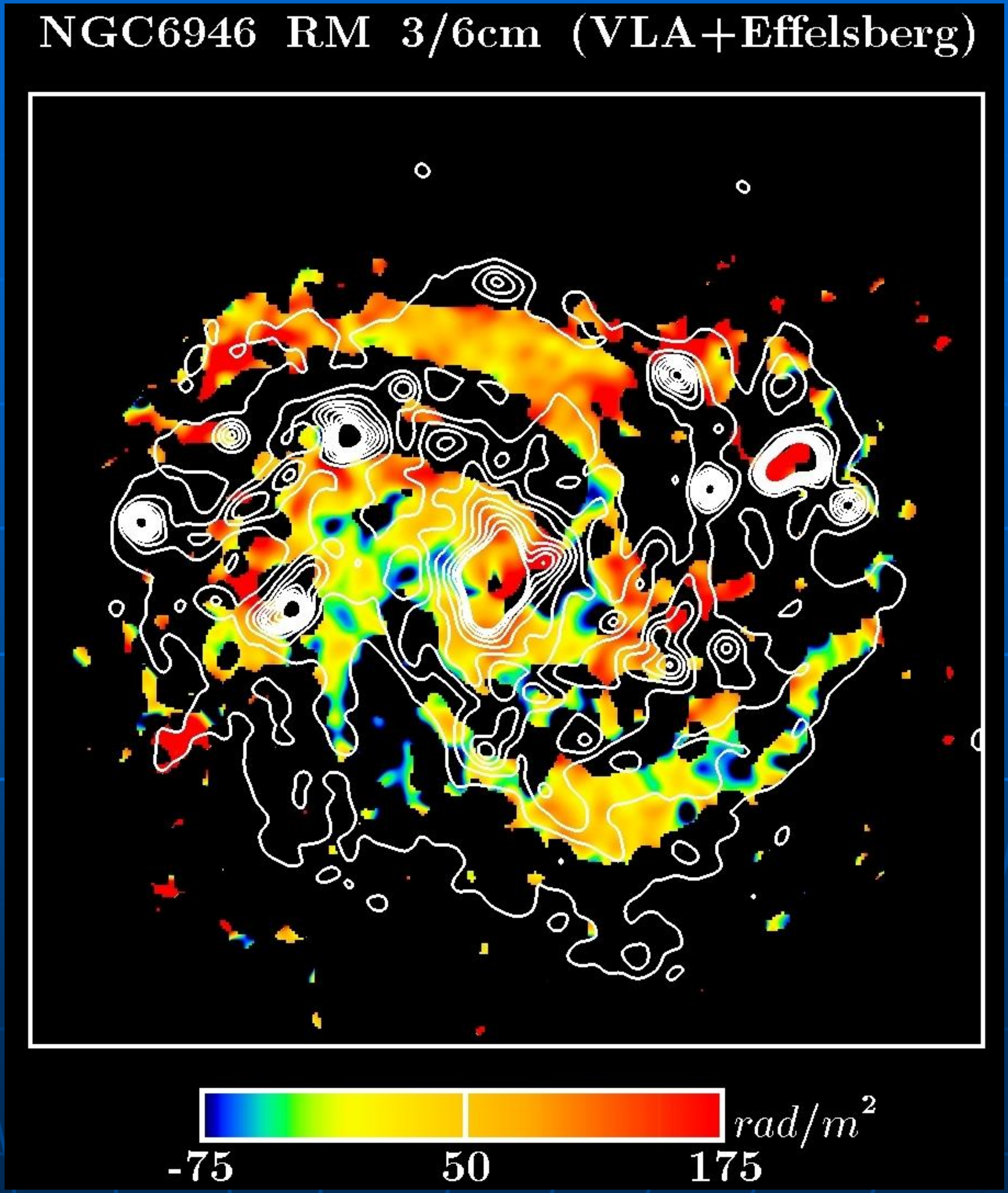


Fletcher et al. 2004

The spiral field of M31 is coherent and axisymmetric

NGC 6946

RM 3/6 cm
VLA+Effelsberg
(Beck 2007)



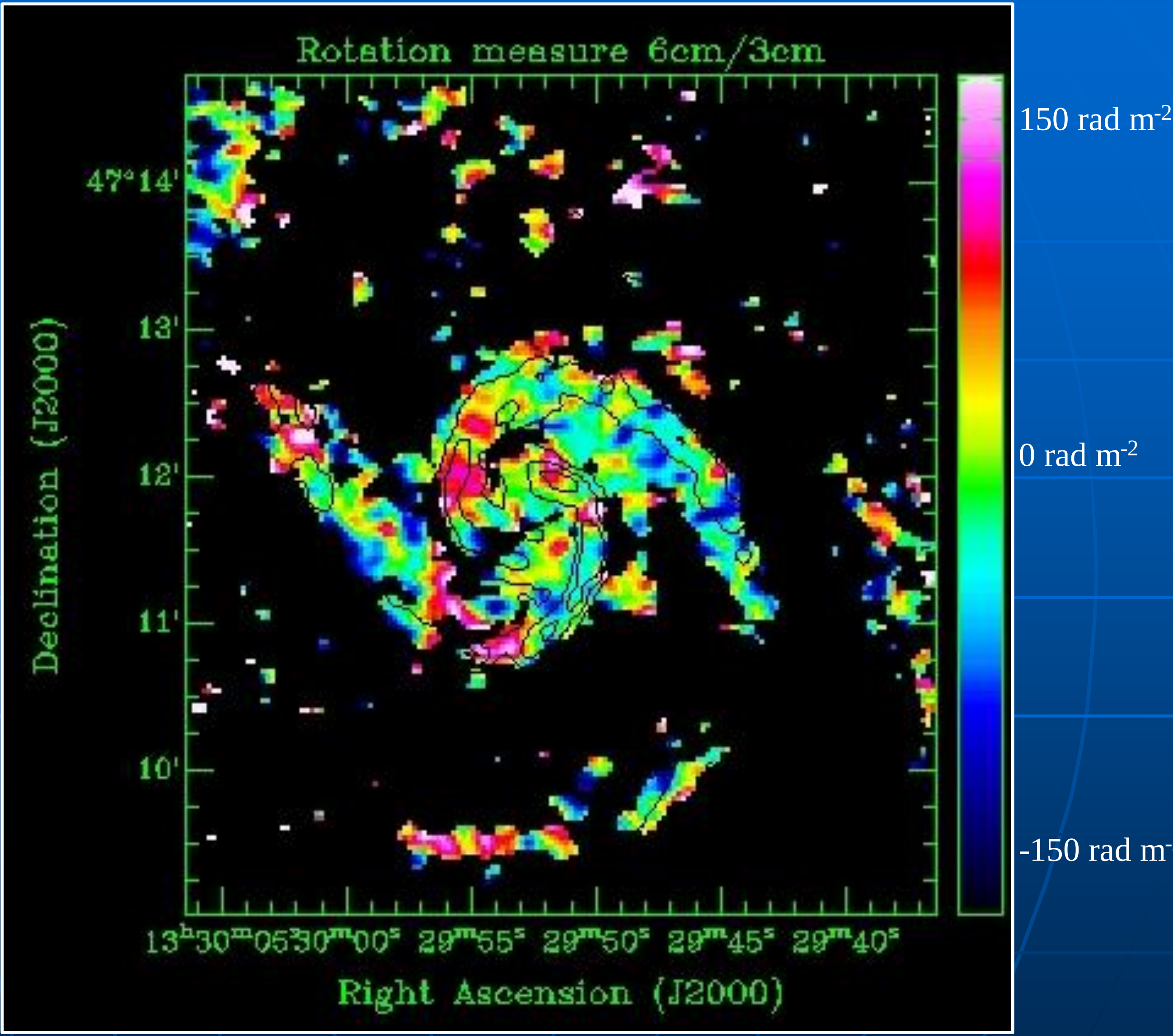
Inward-directed field along magnetic arms:

Superposition of two dynamo modes (m=0 + m=2) ?

M 51

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

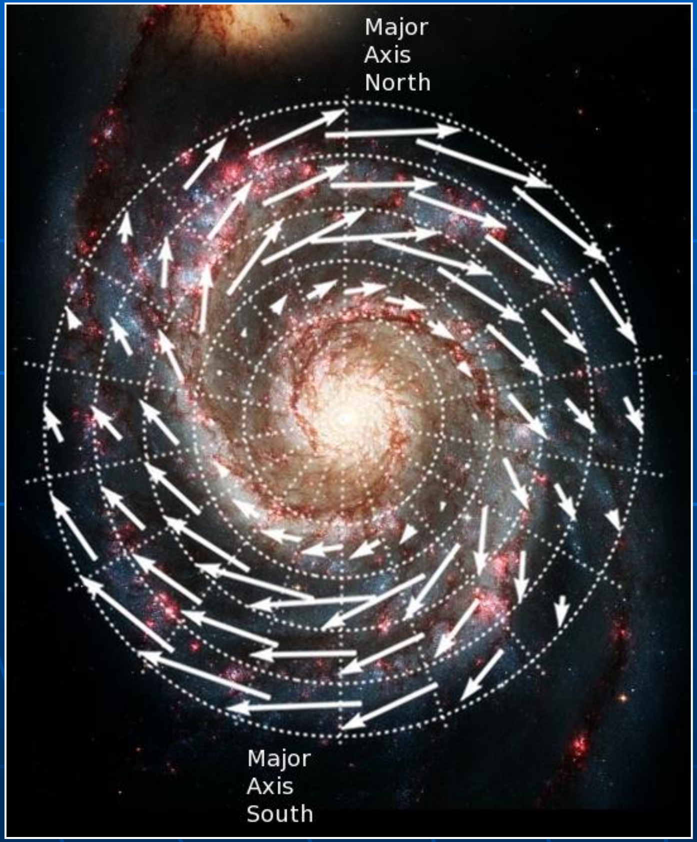
Complicated RM pattern:
Two *weak* dynamo modes (m=0+2),
plus strong anisotropic fields



Large-scale magnetic fields in M51

Fletcher et al. 2011

Disk: ASS (m=0) + m=2 modes



Upper layer: BSS (m=1) mode

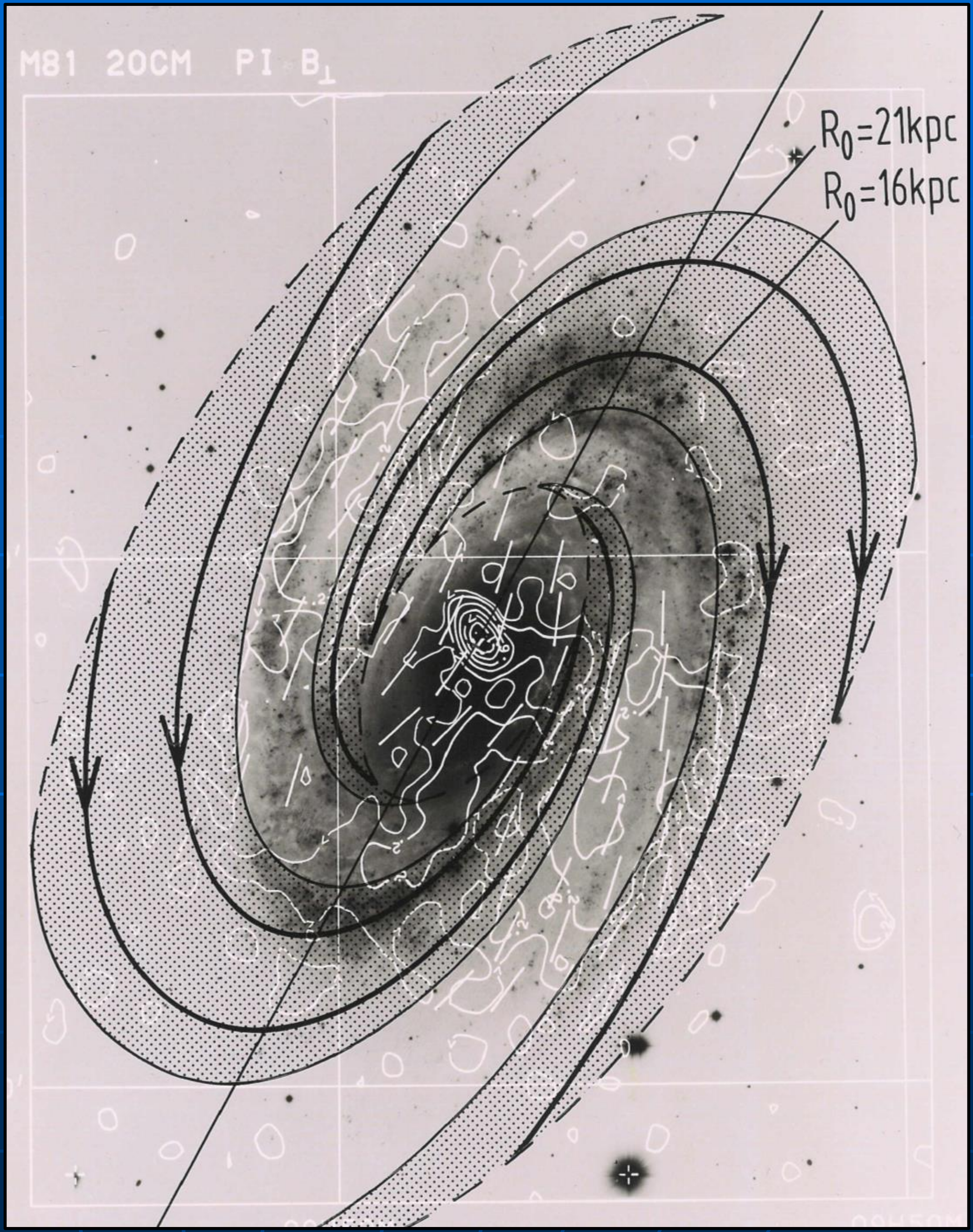
Field reversal between northern disk and inner halo – similar to that found for the Milky Way (Sun et al. 2008)

M 81

(M.Krause et al. 1989)

Two large-scale field reversals:

Bisymmetric dynamo field (m=1) ?



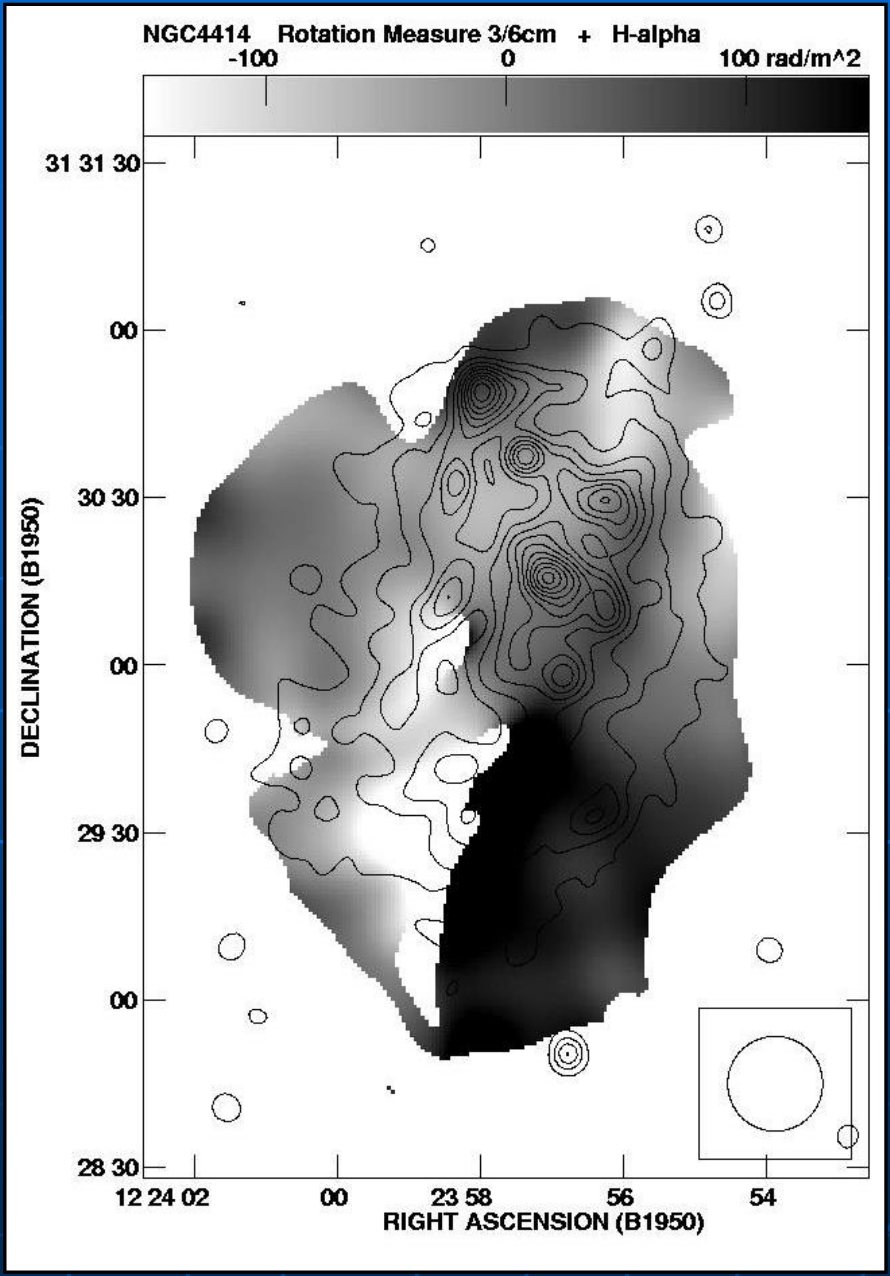
NGC 4414

VLA

RM 3/6cm

(Soida et al. 2002)

One large-scale field reversal (??)



Observations of large-scale dynamo modes

- Dominant axisymmetric (m=0) mode are frequent
  (M31, NGC253, NGC4254, NGC4736, NGC5775, IC342, LMC?)
- Dominating bisymmetric (m=1) modes are rare
  (M81?, M51 halo?)
- Magnetic arms can be described by a superposition of m=0 and m=2 modes
  (M83, NGC2997, NGC6946)
- In most cases the field is a superposition of more than two modes (still unresolved), or the field is mostly anisotropic, or the field is not yet fully developed

Summary: magnetic modes

Fletcher 2011

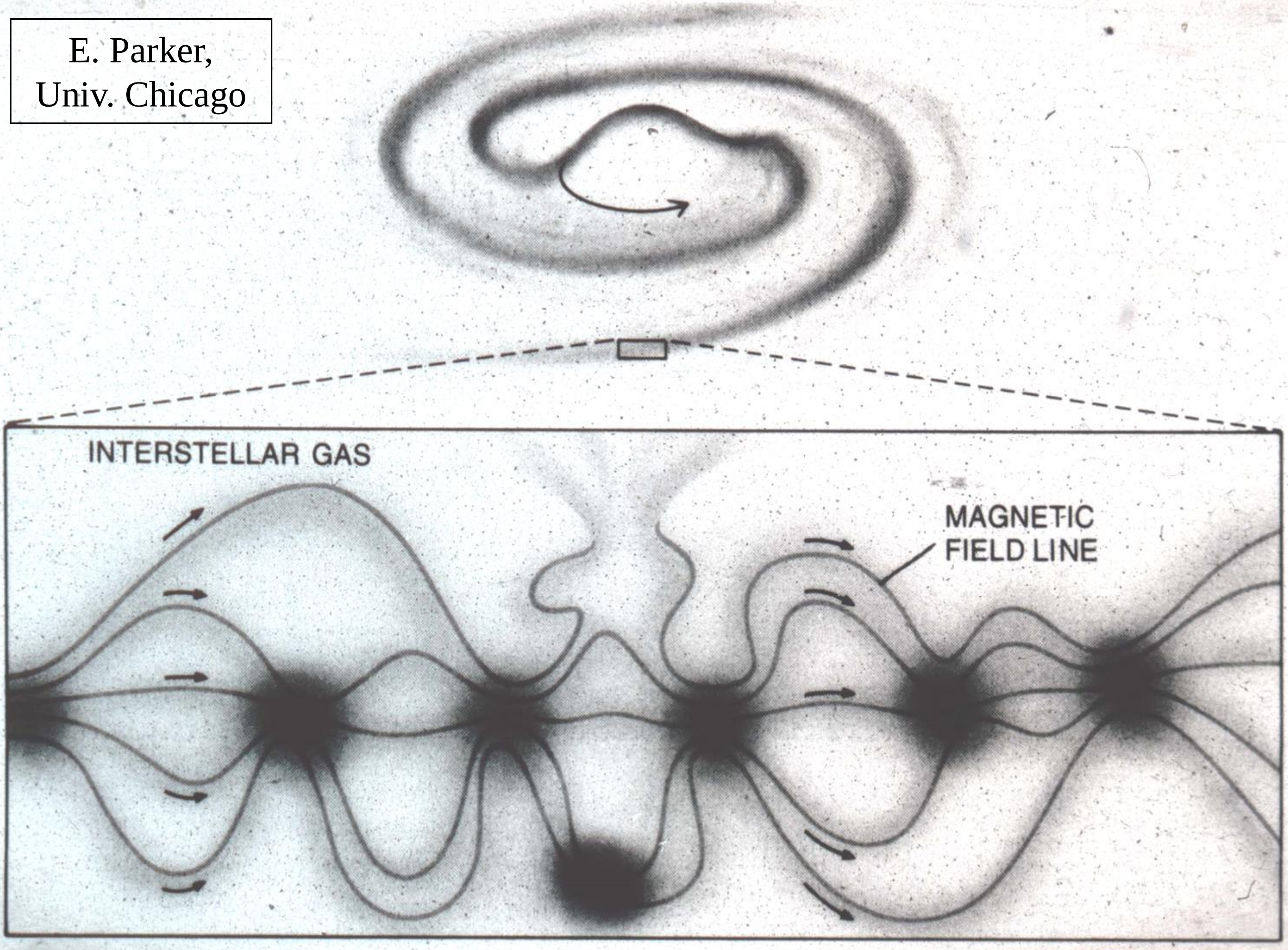


Galaxy	m=0	m=1	m=2	Ref.
IC 342	1	-	-	Krause et al. 1989
LMC	1	-	-	Gaensler et al. 2005
M31	1	0	0	Fletcher et al. 2004
M33	1	1	0.5	Tabatabaei et al. 2008
M51	1	0	0.5	Fletcher et al. 2011
M81	-	1	-	Krause et al. 1989
NGC 253	1	-	-	Heesen et al. 2009
NGC 1097	1	1	1	Beck et al. 2005
NGC 1365	1	1	1	Beck et 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

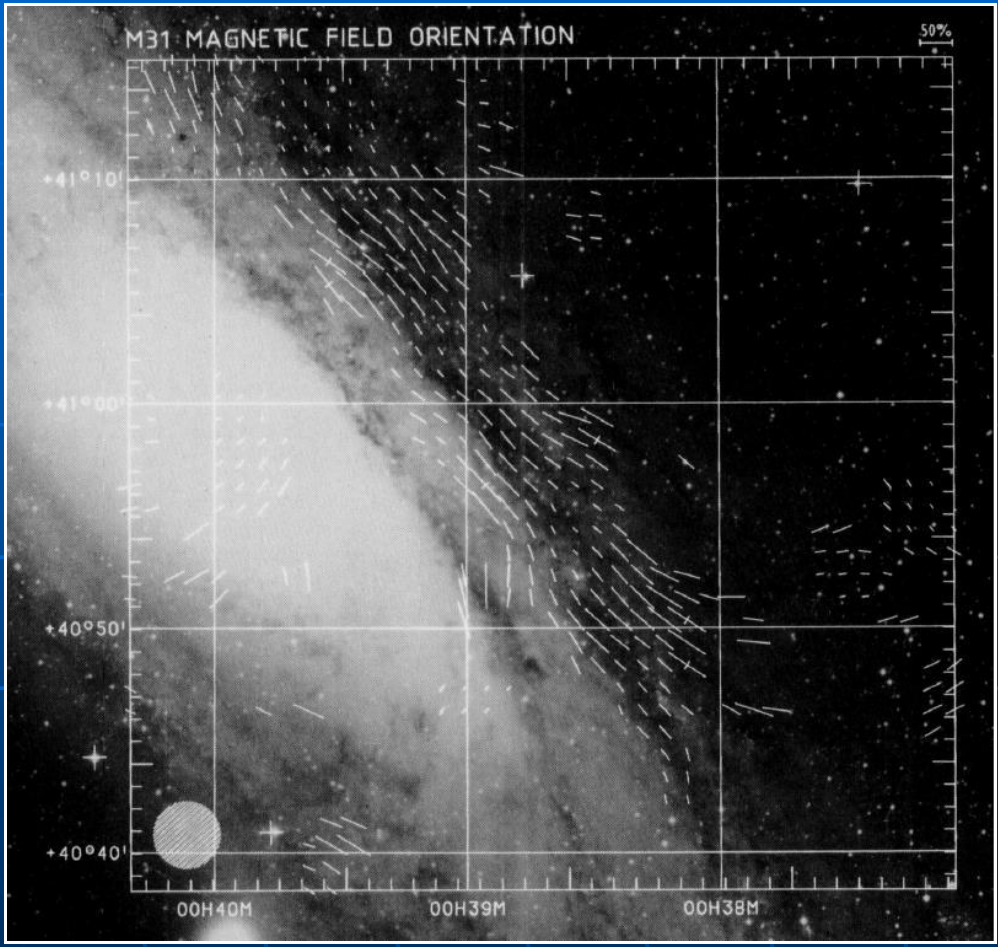
Evidences for the action of large-scale dynamos in galaxies

- Magnetic and turbulent energy densities are similar
- Spiral patterns exist in almost all galaxies
- Large-scale regular fields exist in many galaxies
- Axisymmetric spiral fields dominate
- No preference of one direction of the radial field component

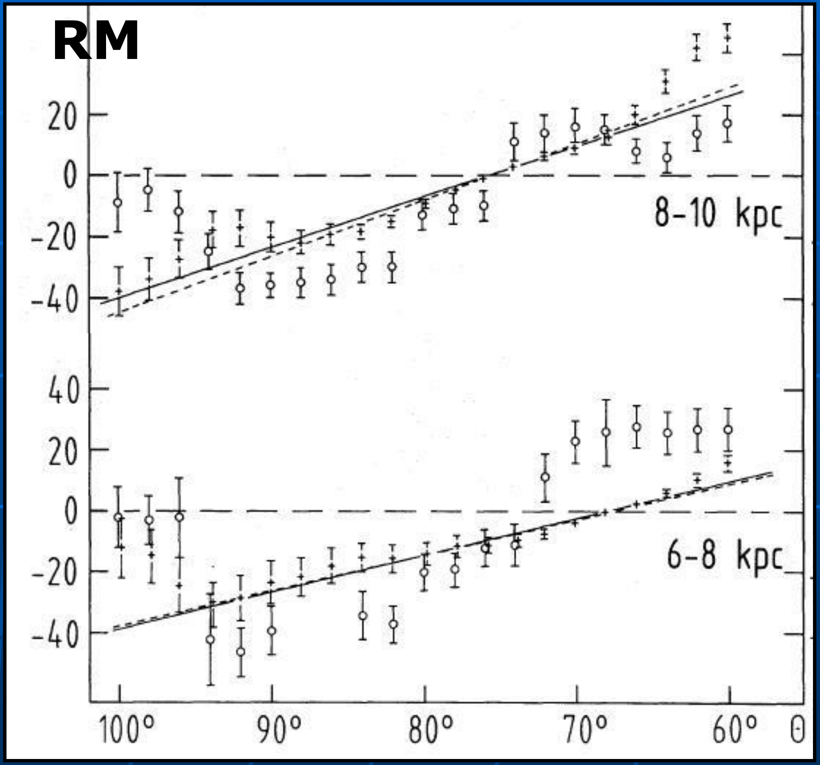
E. Parker,
Univ. Chicago



Parker loops in M 31 ?

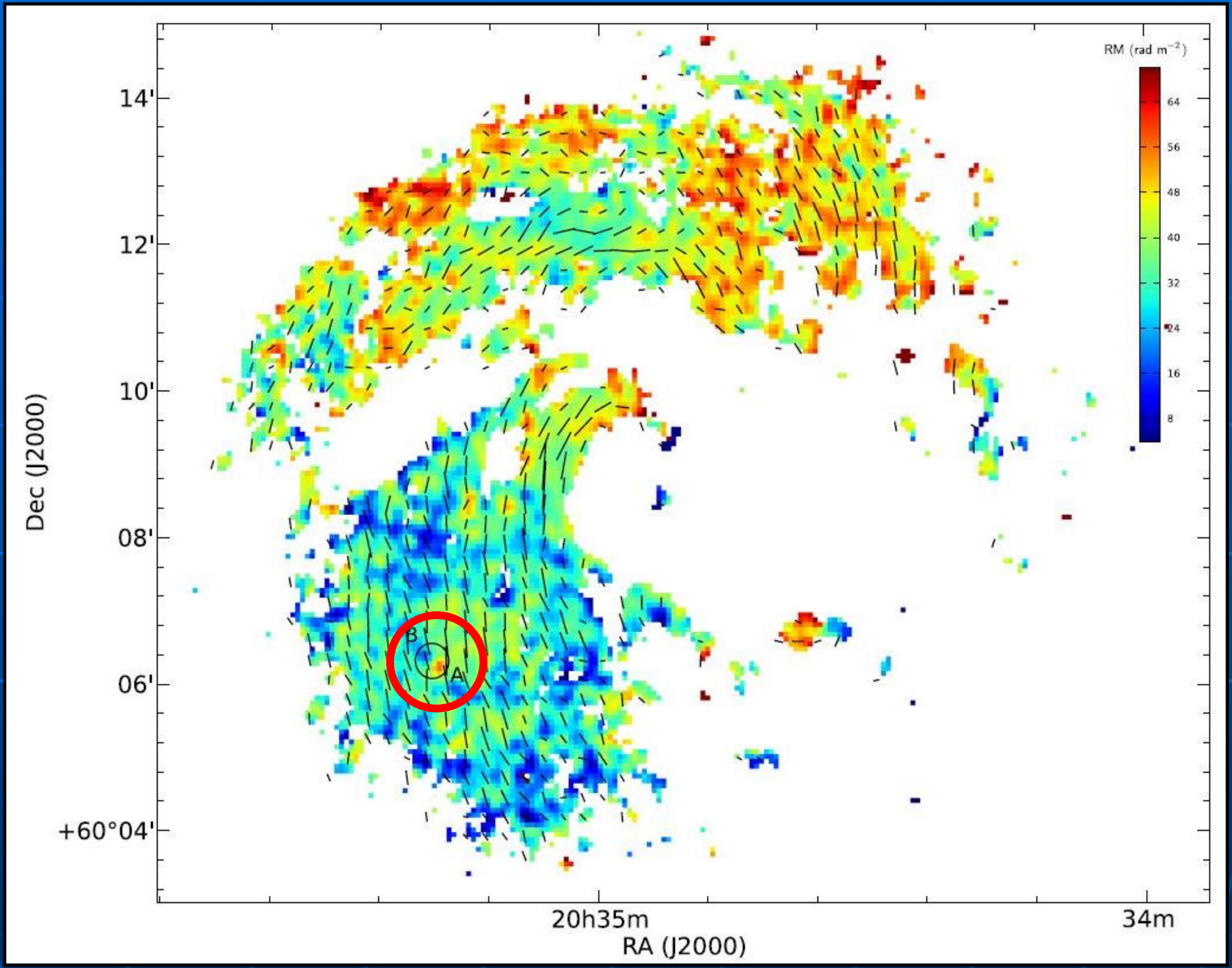


Beck et al. 1989



Periodic variations in field orientation and RM
with a wavelength of about 4 kpc

Parker loop in NGC 6946 ?



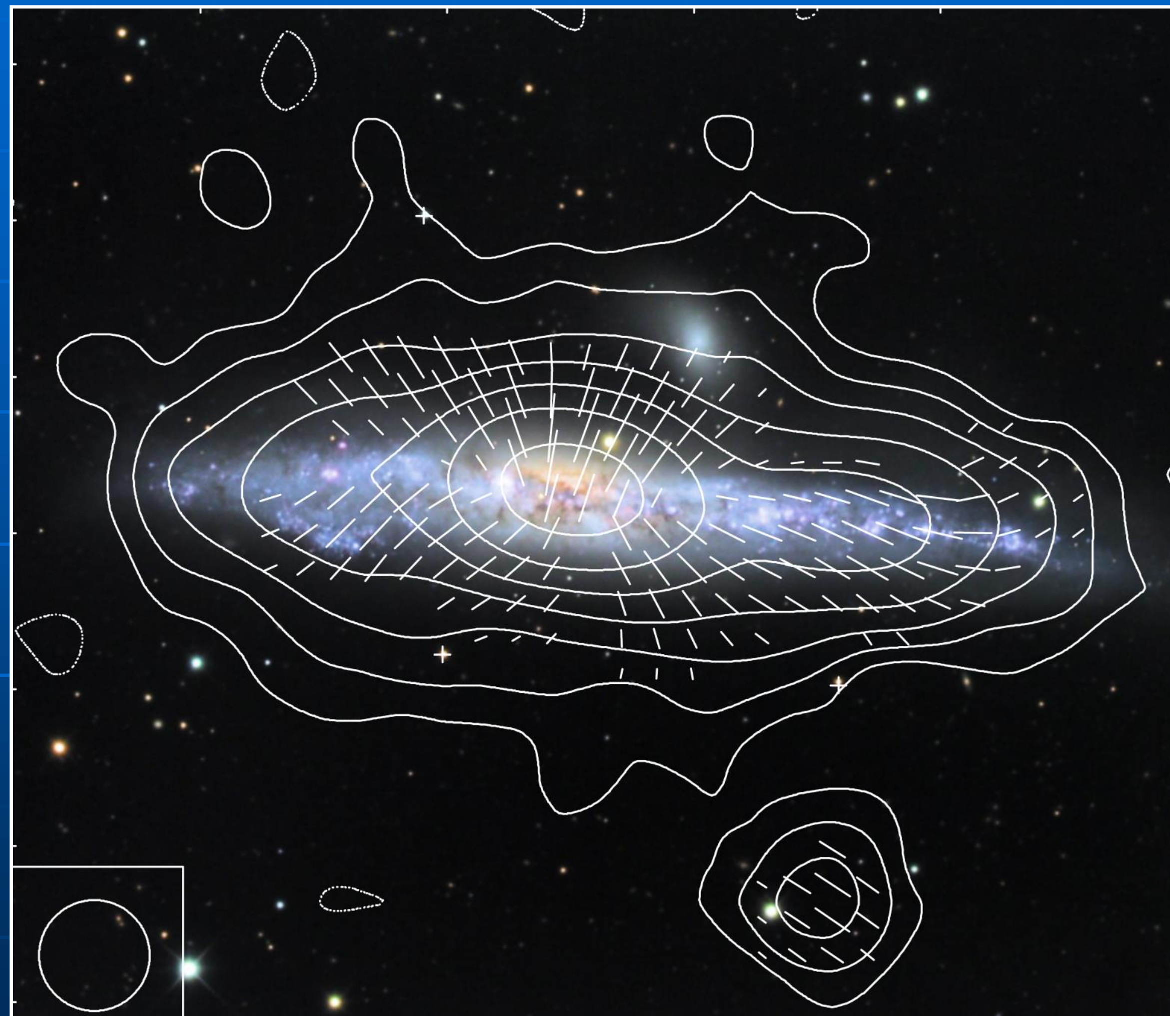
Heald 2012

RM reversal on 600 pc scale across an HI hole

Magnetic fields of edge-on galaxies

NGC 4631

Effelsberg 3 cm
Total intensity
+ B-vectors

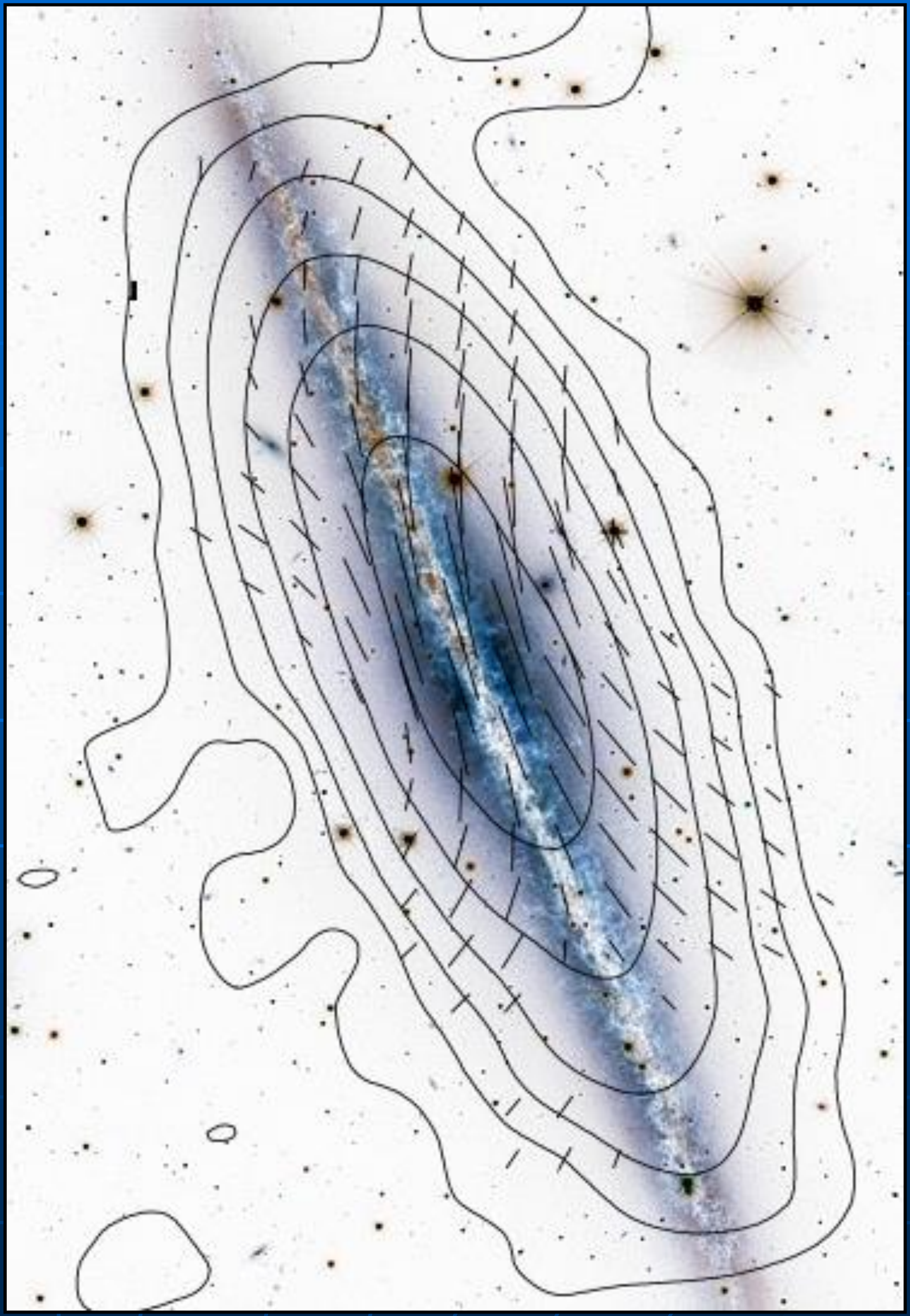


X-shaped
halo field,
driven by a
galactic wind

Krause 2009

NGC 891

Effelsberg 3 cm
Total intensity
+ B-vectors

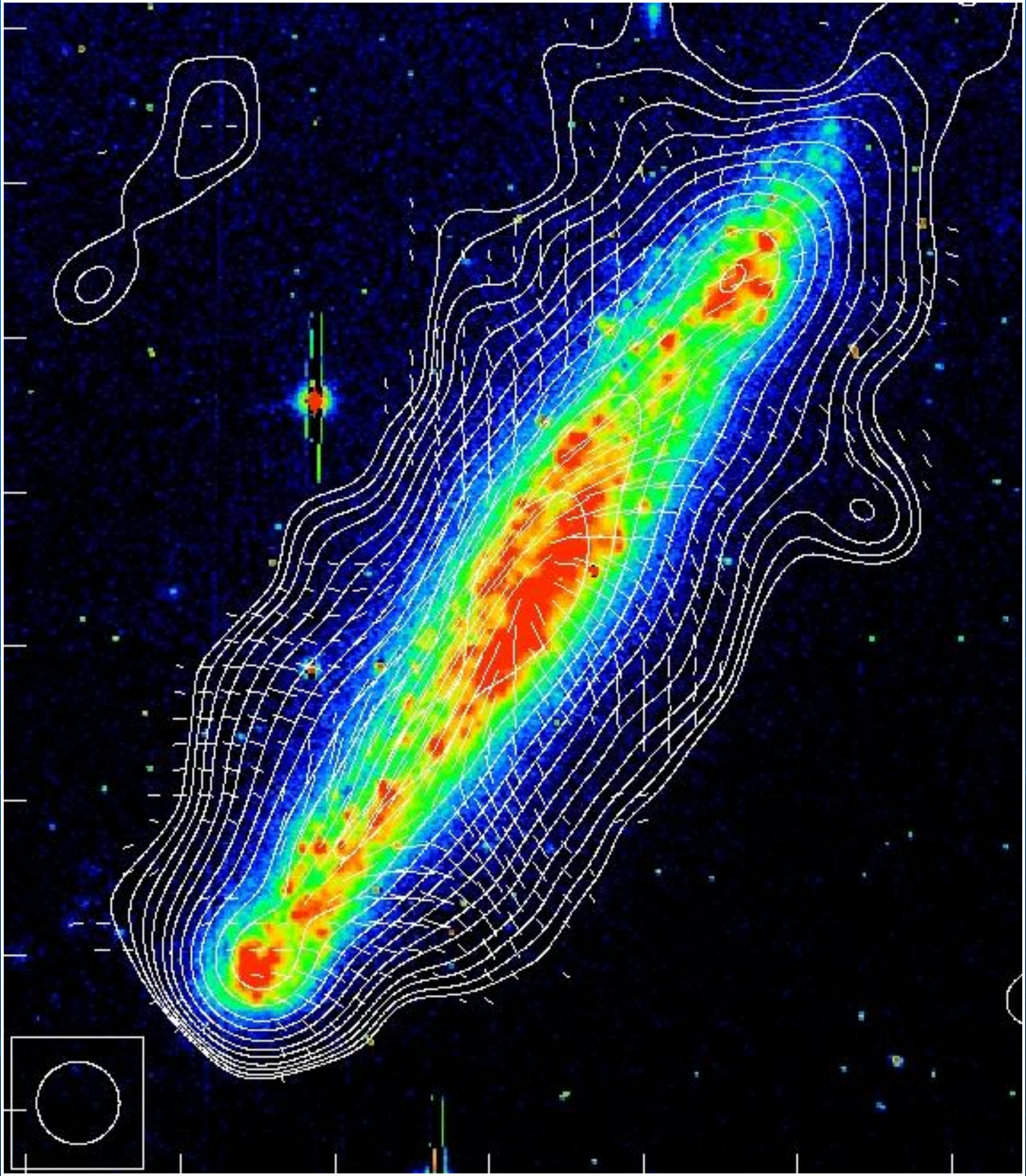


Bright radio halo with
X-shaped field pattern

Krause 2007

NGC 5775

VLA+Effelsberg 3 cm
Total intensity
+ B-vectors

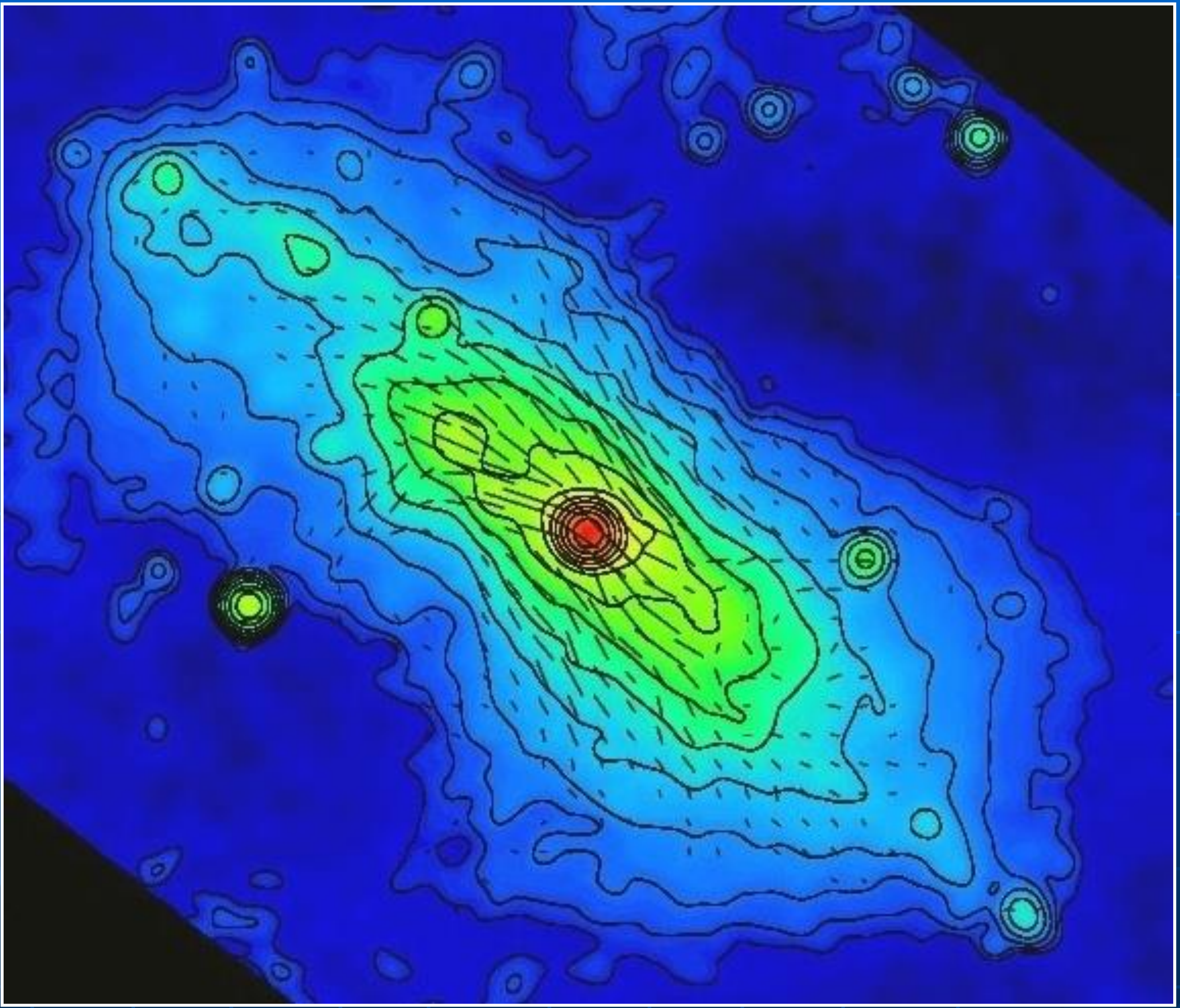


X-shaped
halo field

Soida et al., in prep.

NGC 253

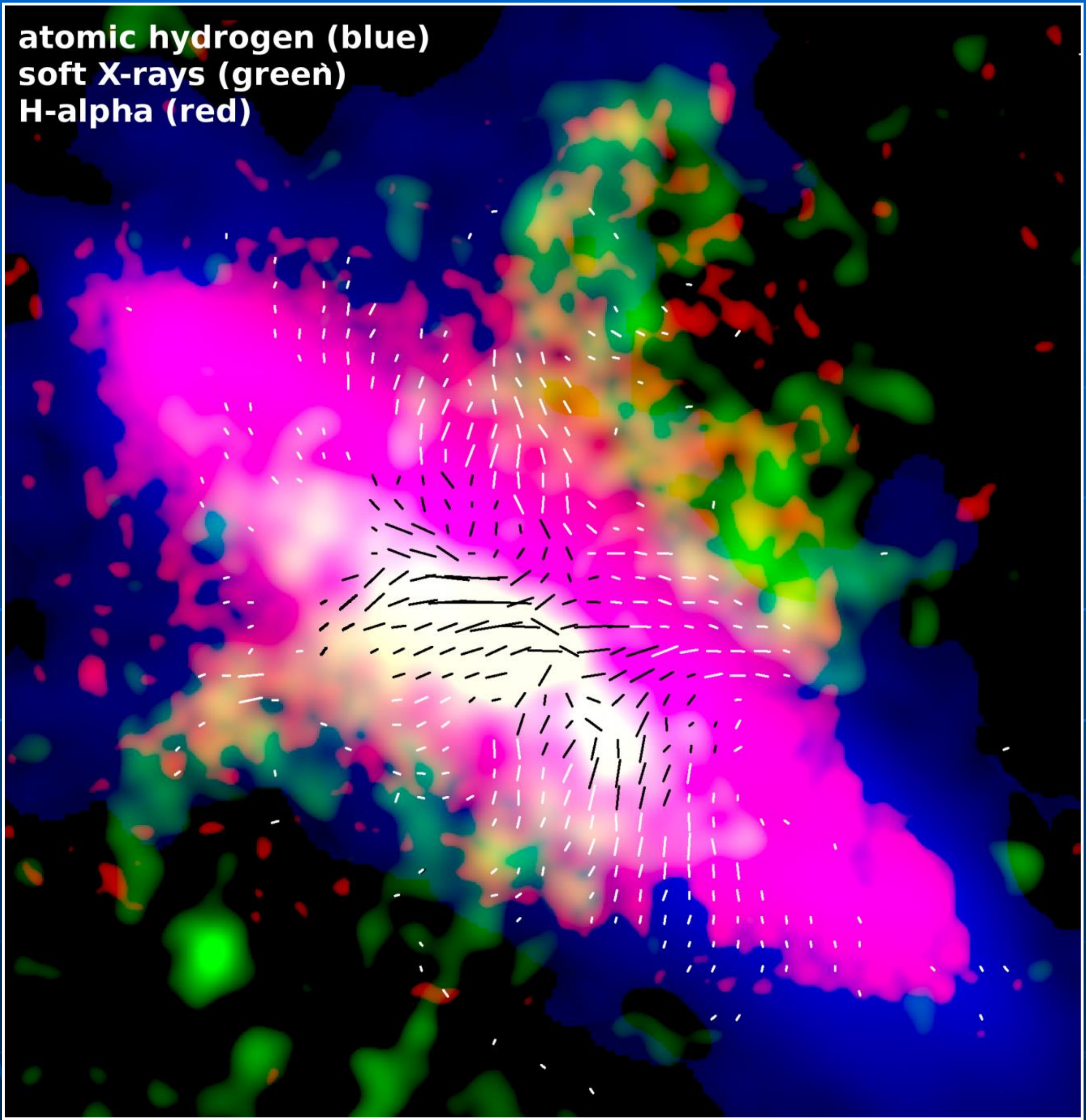
VLA+Effelsberg
6 cm
Total intensity
+ B-vectors



Heesen et al. 2009

NGC 253

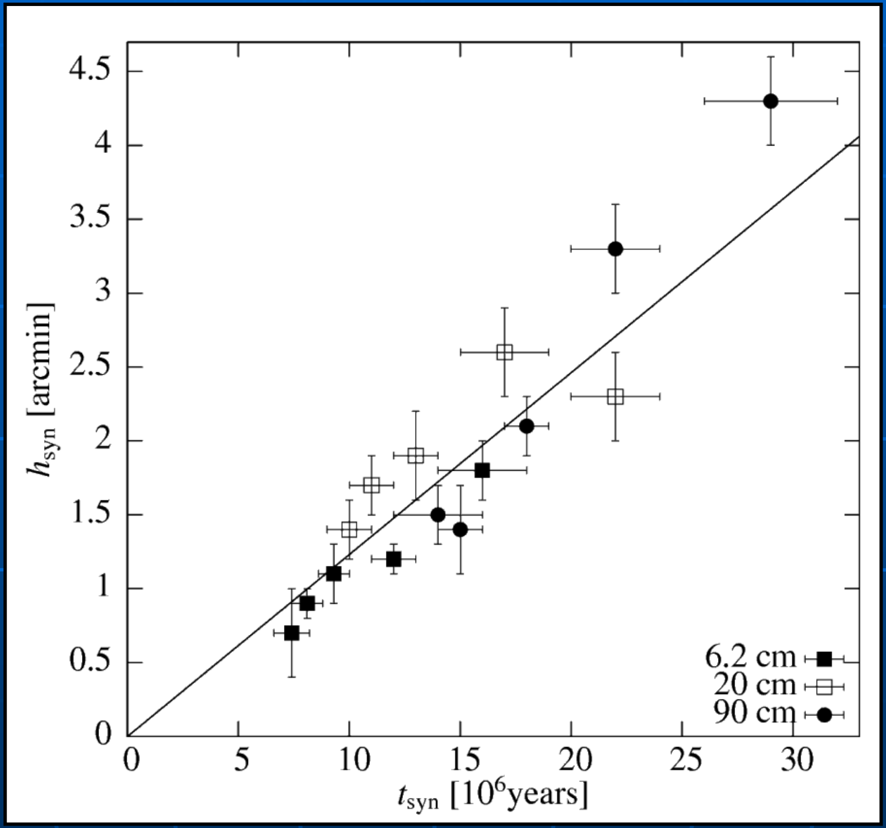
6 cm B-vectors
+ Hα + X-rays + HI



Interaction between warm & hot gas and ordered magnetic fields

Heesen et al. 2009

Scale heights of cosmic-ray electrons in NGC 253

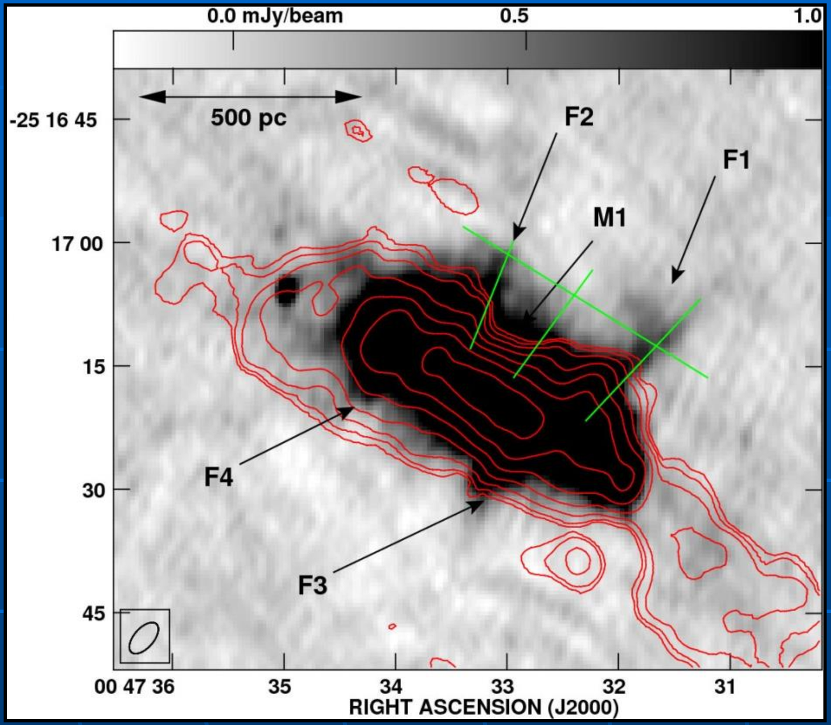


Heesen et al. 2009

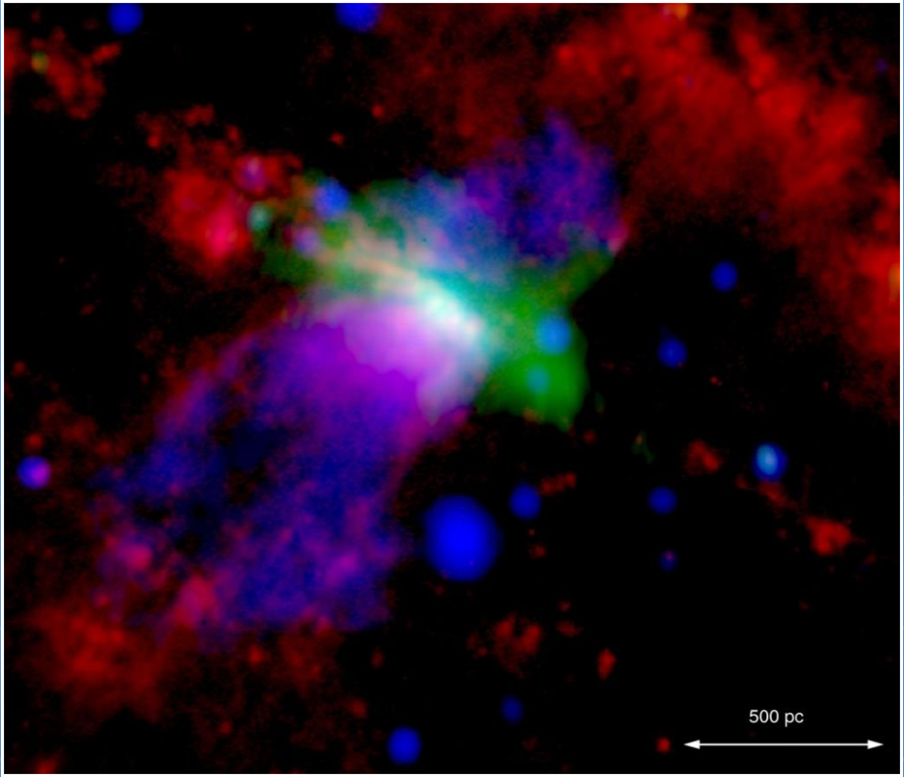
Wind-driven outflow, CRE bulk speed $v_z = 300 \pm 30$ km/s

NGC 253
Central region

Heesen et al. 2011



VLA 20cm + CO(2-1)

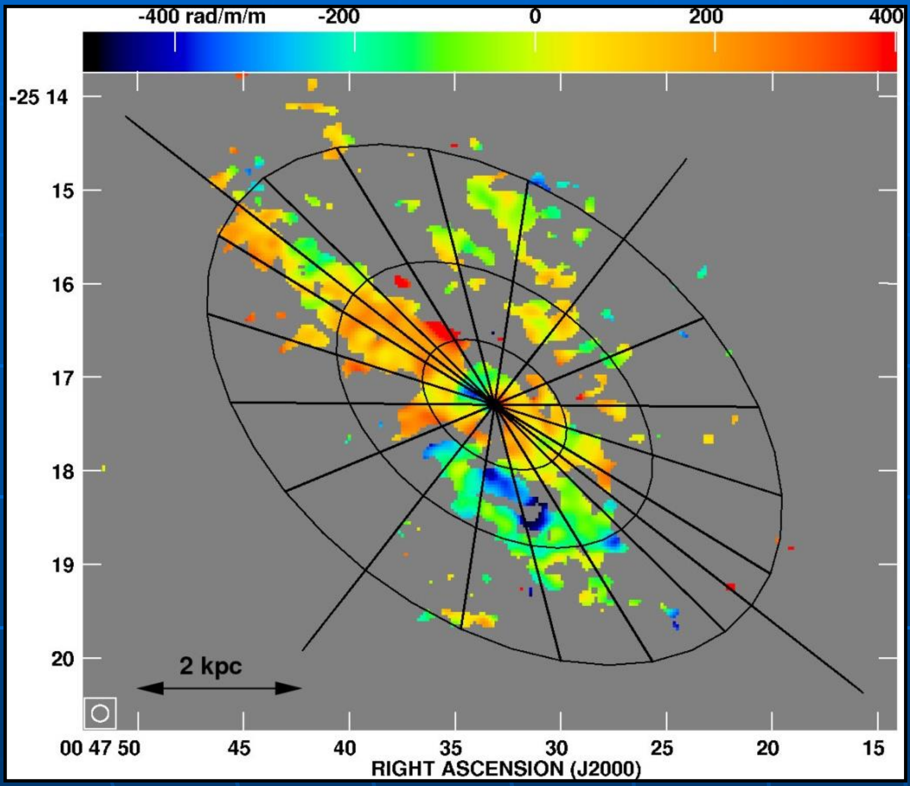


VLA 20cm (green)
X-ray CHANDRA (blue)
Hα (red)

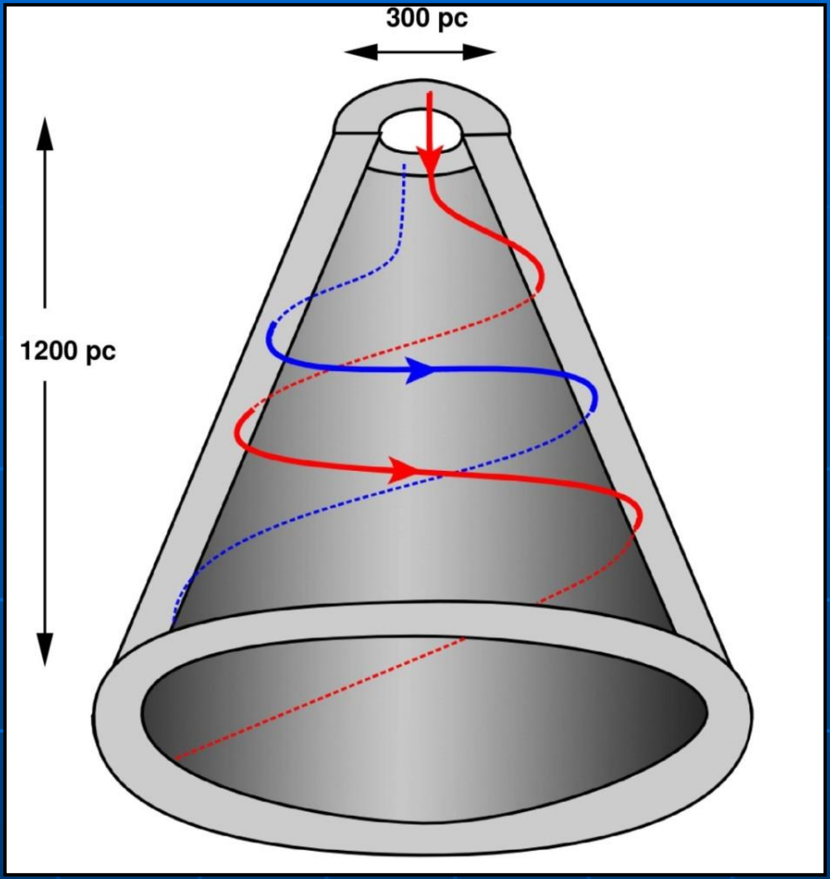
- Total field strengths: ≥160μG (central region), ≥40μG (filaments)
- Radio filaments mark the boundaries of the outflow cone
- Outflow bulk velocity of the cosmic-ray electrons: ≥300 km/s

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 (garden sprinkler model)

First detection of a regular magnetic field in a nuclear outflow

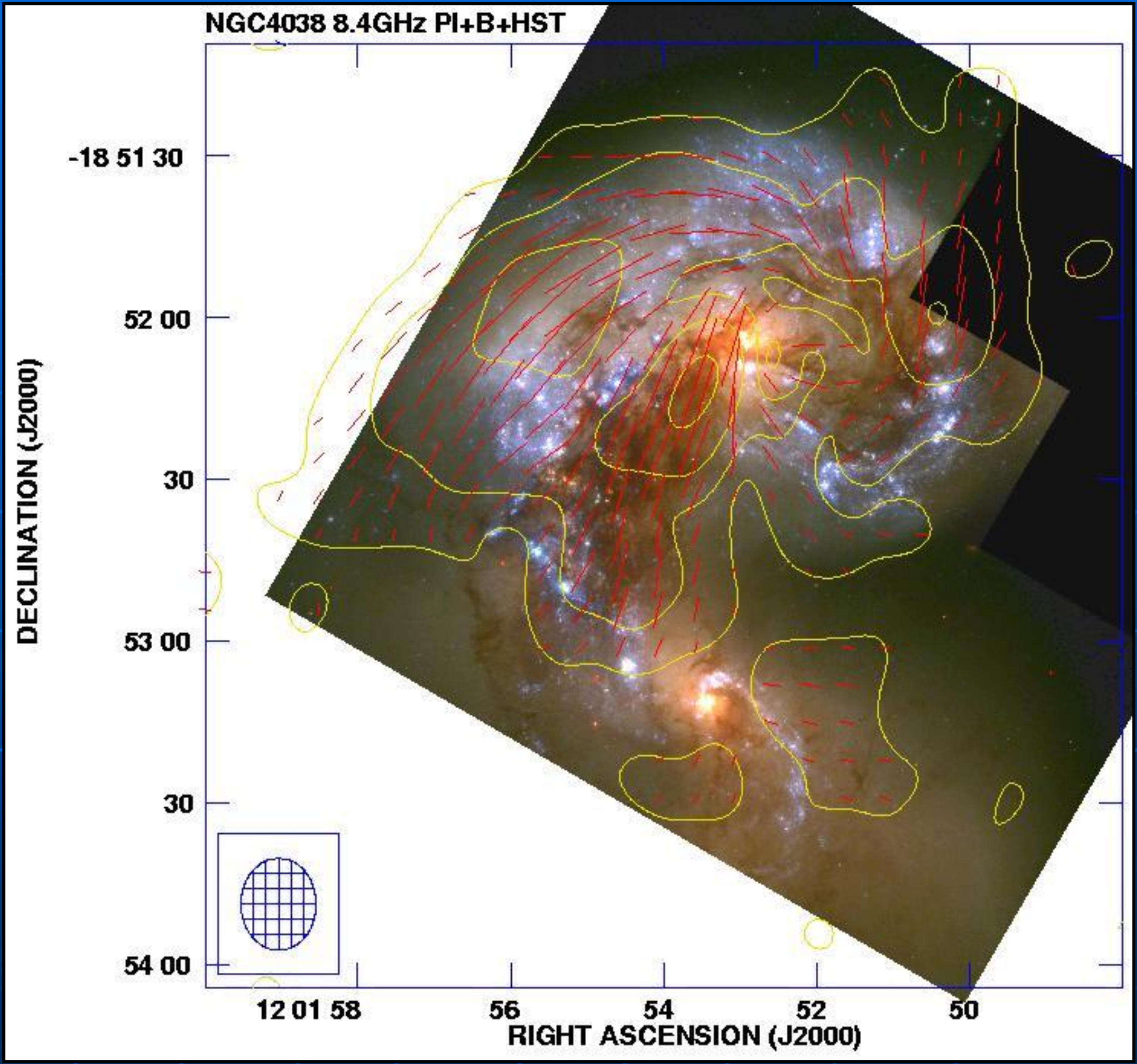
Summary:
Magnetic fields in nearby galaxies

- Ordered fields in large, gas-rich galaxies are spiral
- Ordered fields are compressed by strong density waves
- Ordered fields are often concentrated in interarm regions
- Faraday rotation reveals large-scale regular fields
- No large-scale reversals between spiral arms were found so far
- Irregular galaxies may host strong turbulent fields, but only weak ordered fields
- No magnetic fields detected so far in quiet elliptical galaxies

Magnetic fields
in interacting galaxies

NGC 4038/39

VLA 3 cm
Total intensity
+ B-vectors



Chyzy & Beck 2004

Stephan's Quintet

VLA 6 cm
Total intensity
+ B-vectors

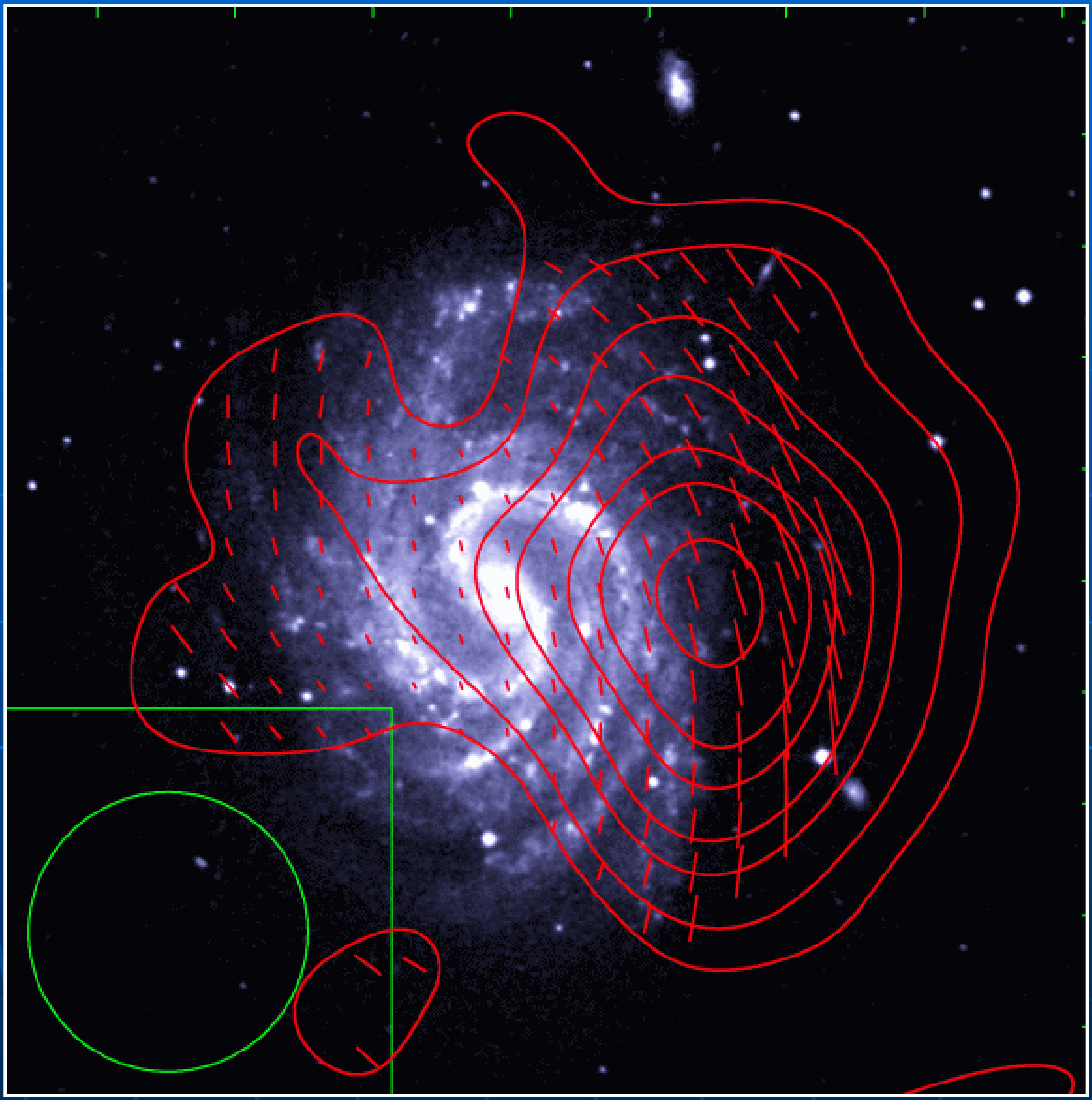
Ordered intergalactic fields by shocks and mergers

Nikiel-Wroczyński et al. 2013

NGC 4535

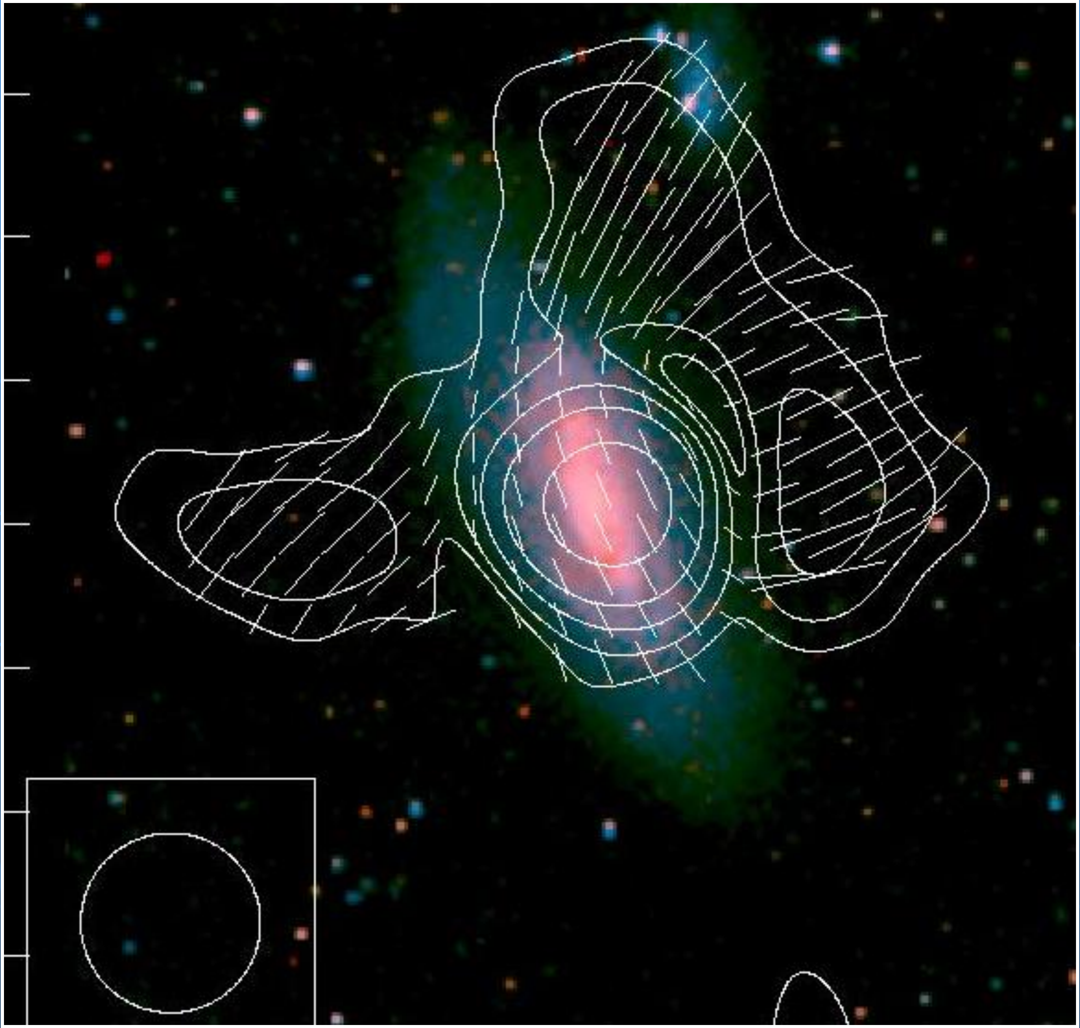
Effelsberg 6 cm
Polarized intensity
+ B-vectors
(Wezgowiecz et al. 2007)

Field compressed
by ram pressure



NGC 4569

Effelsberg 6 cm
Polarized intensity
+ B-vectors



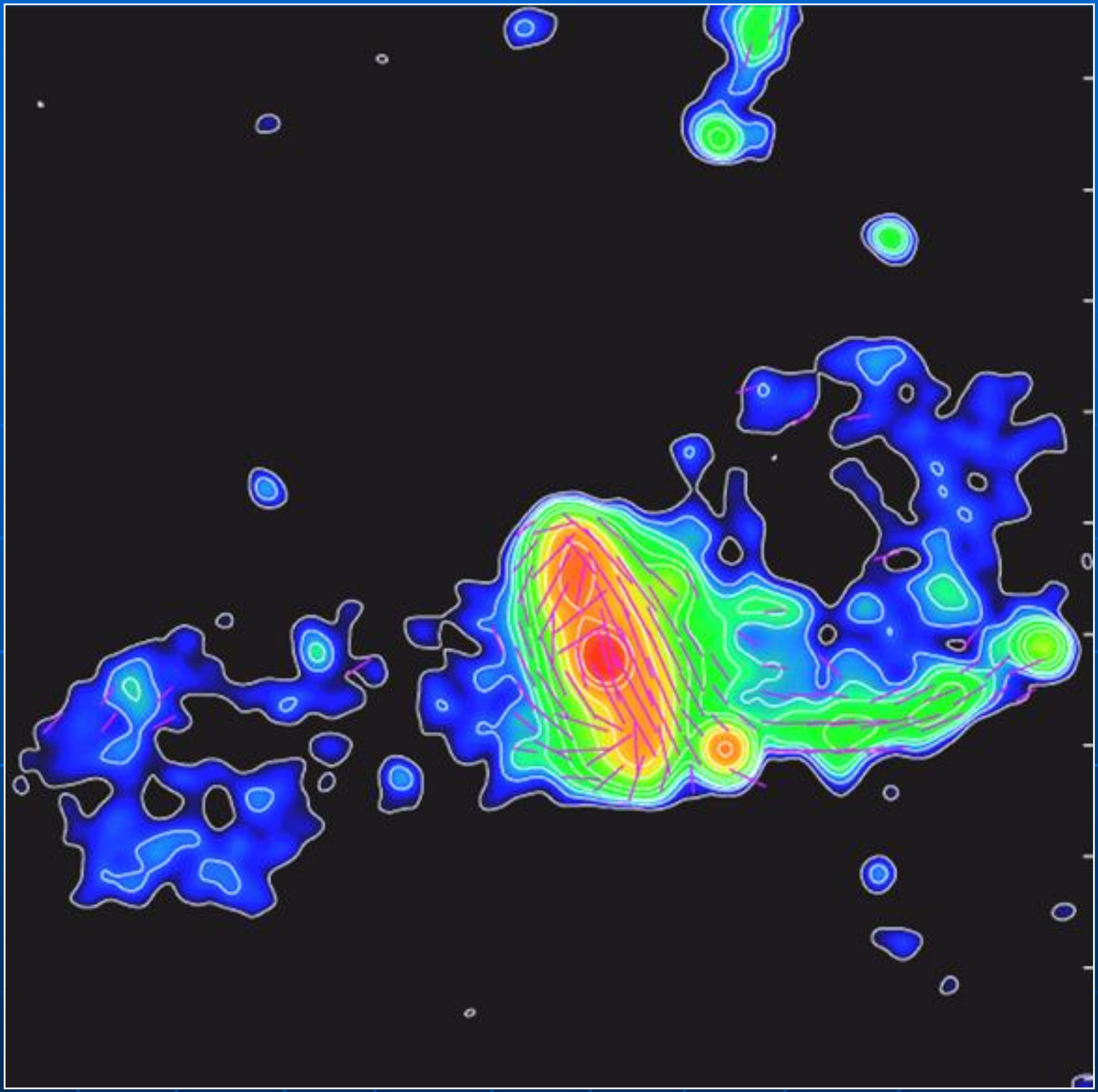
Pulled-out field:

Tracer of
past interactions ?

Chyzy et al. 2006

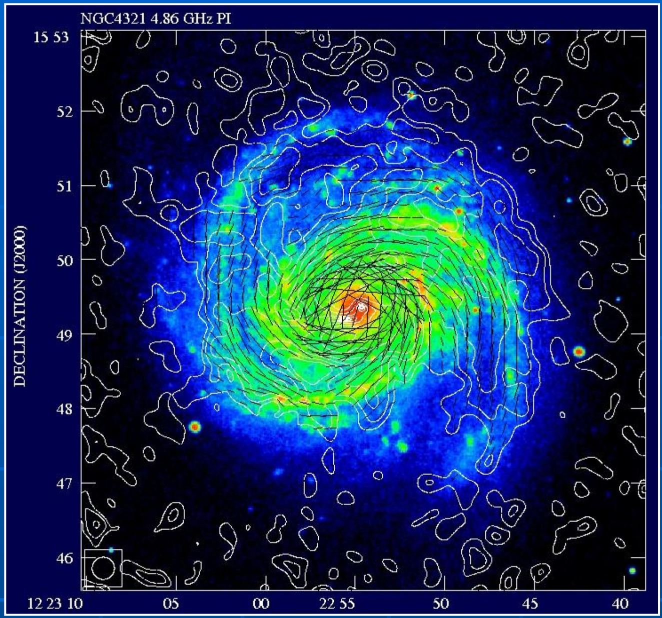
NGC 4569

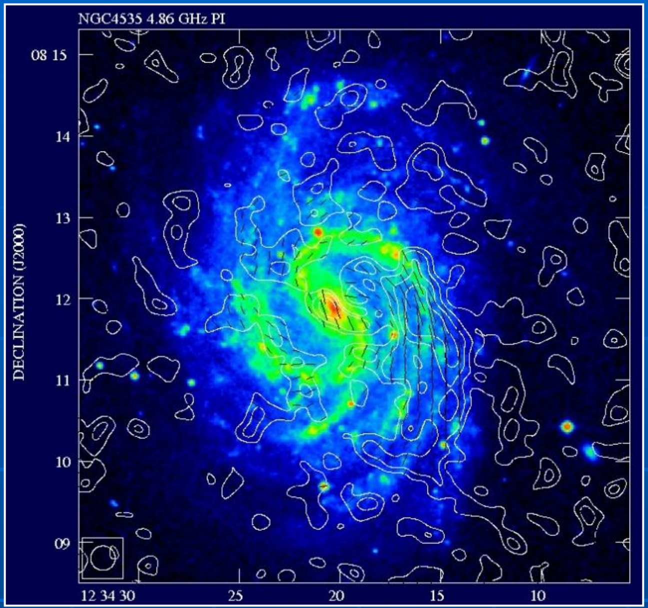
VLA 6 cm
Total intensity
+ B-vectors
(Chyzy et al., in prep.)



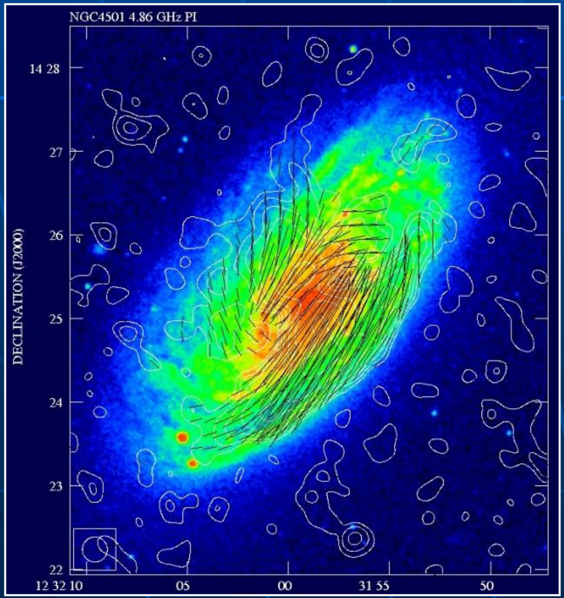
Field pulled out
and ordered
by past interaction

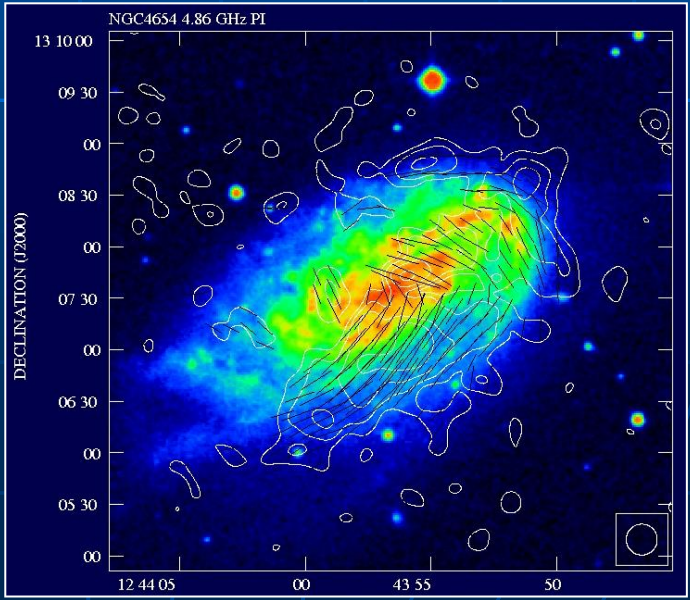
Virgo polarization survey (6cm VLA)





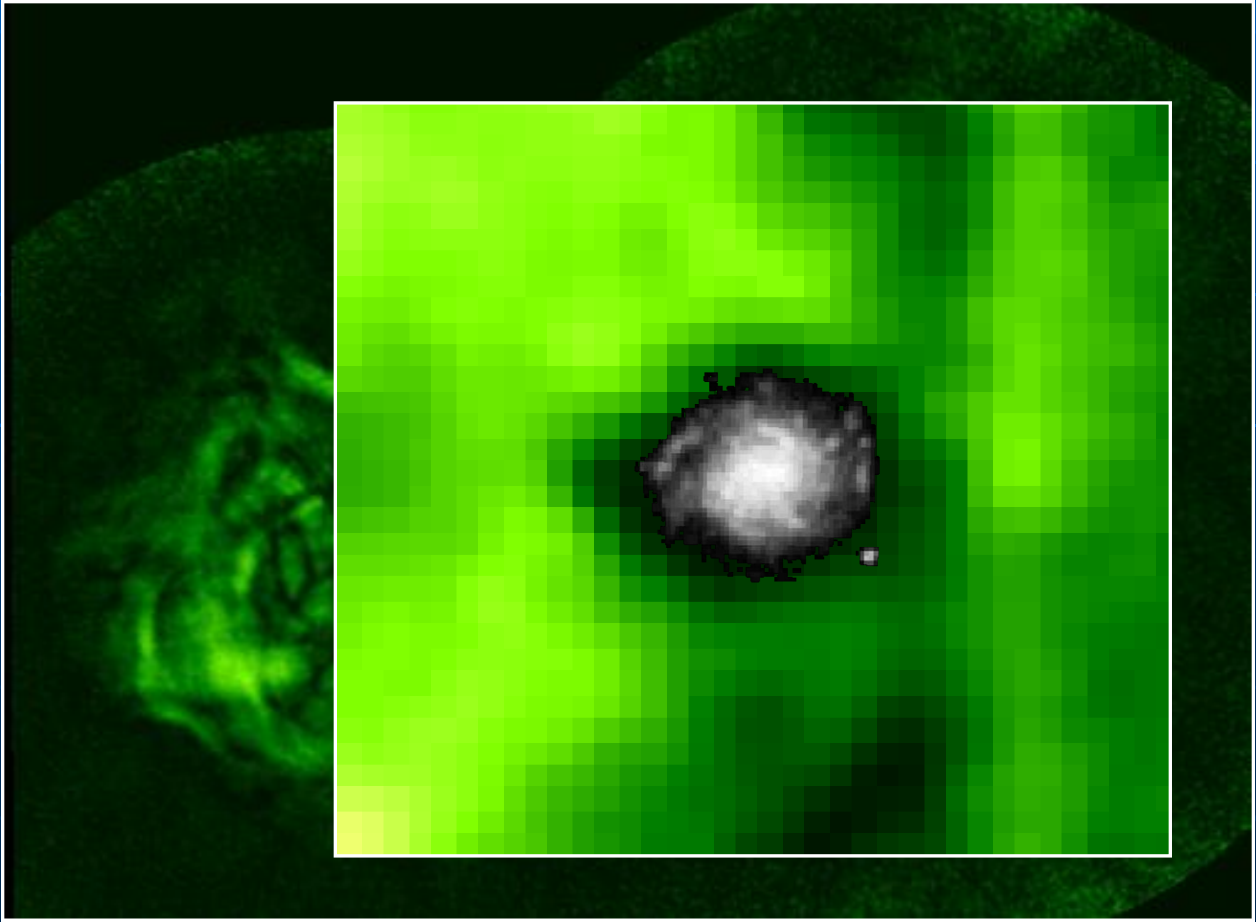
Vollmer et al. 2007





Faraday screens:
Probing galactic magnetism in distant galaxies

Faraday depolarization
of Fornax A
by NGC 1310
(VLA)

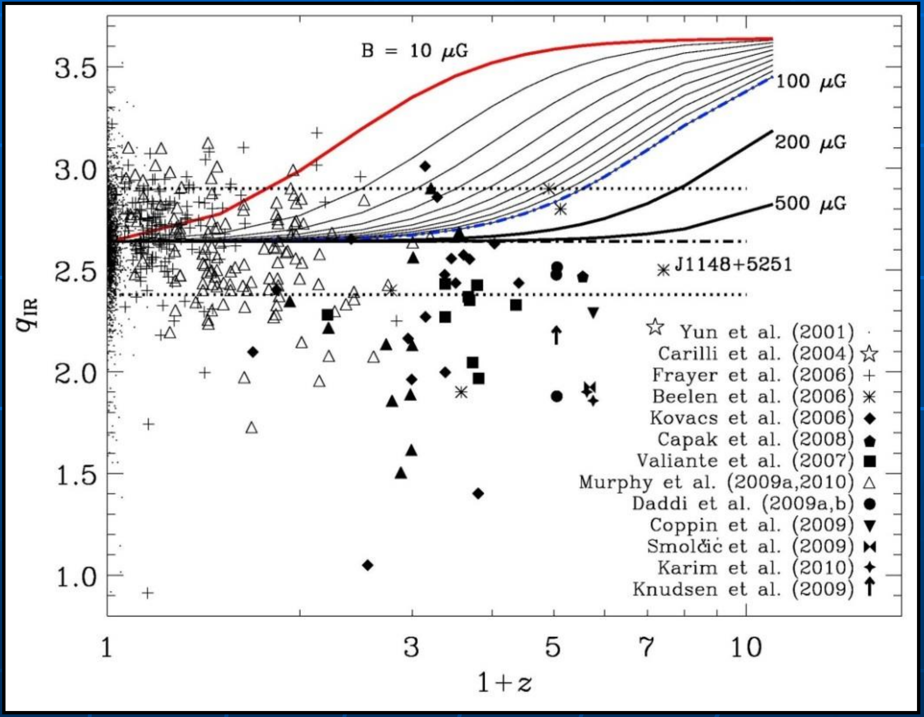


Fomalont et al. 1989

Magnetic fields at high redshift z

- Radio synchrotron emission should break down at large redshift z due to IC loss
- IR/radio ratio q should increase
- This is *not* observed:
  Magnetic fields are strong
  in distant **starburst** galaxies:
  $B > B_{CMB} = 3.25\ \mu G\ (1+z)^2$

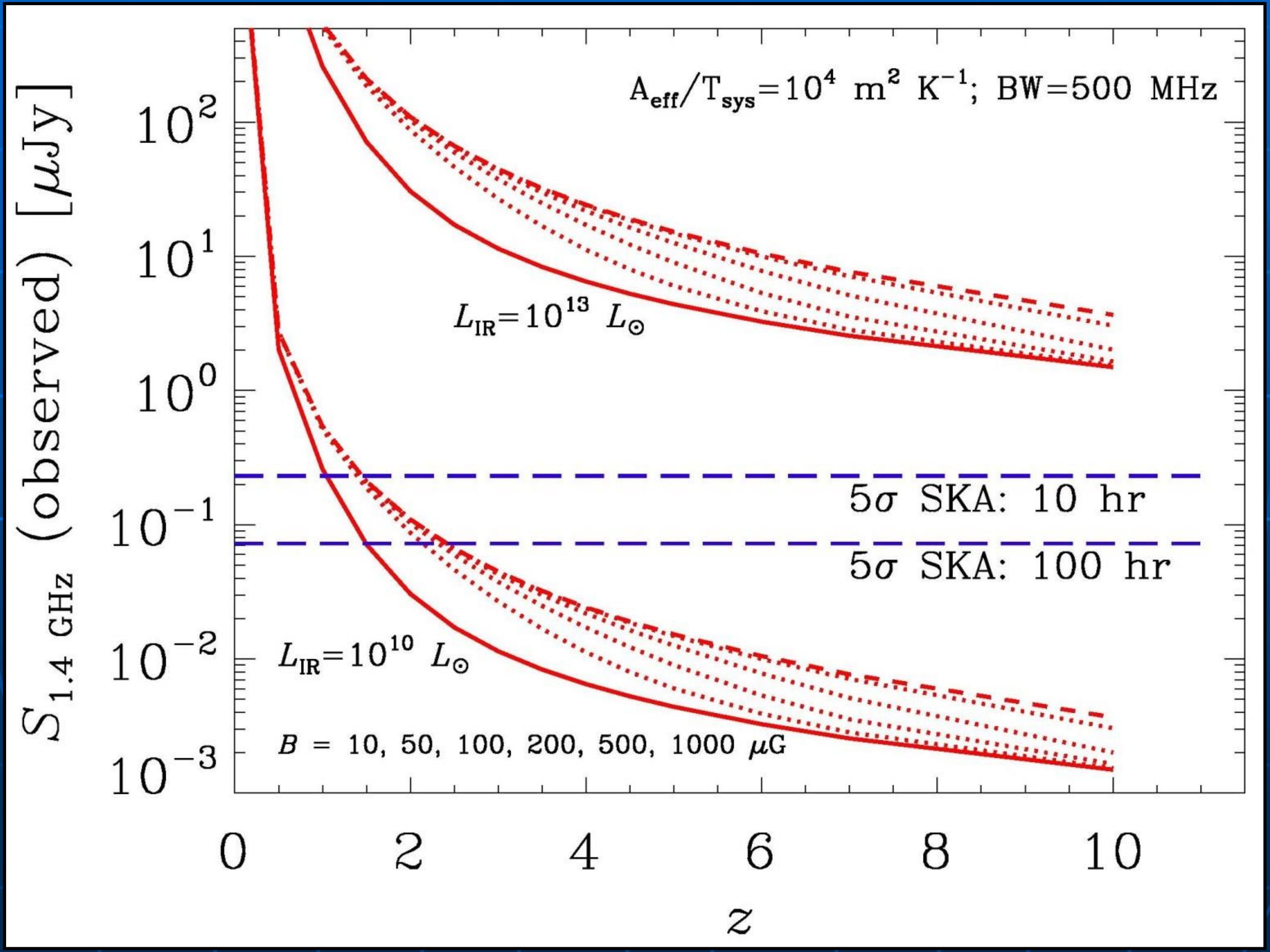
Murphy 2009

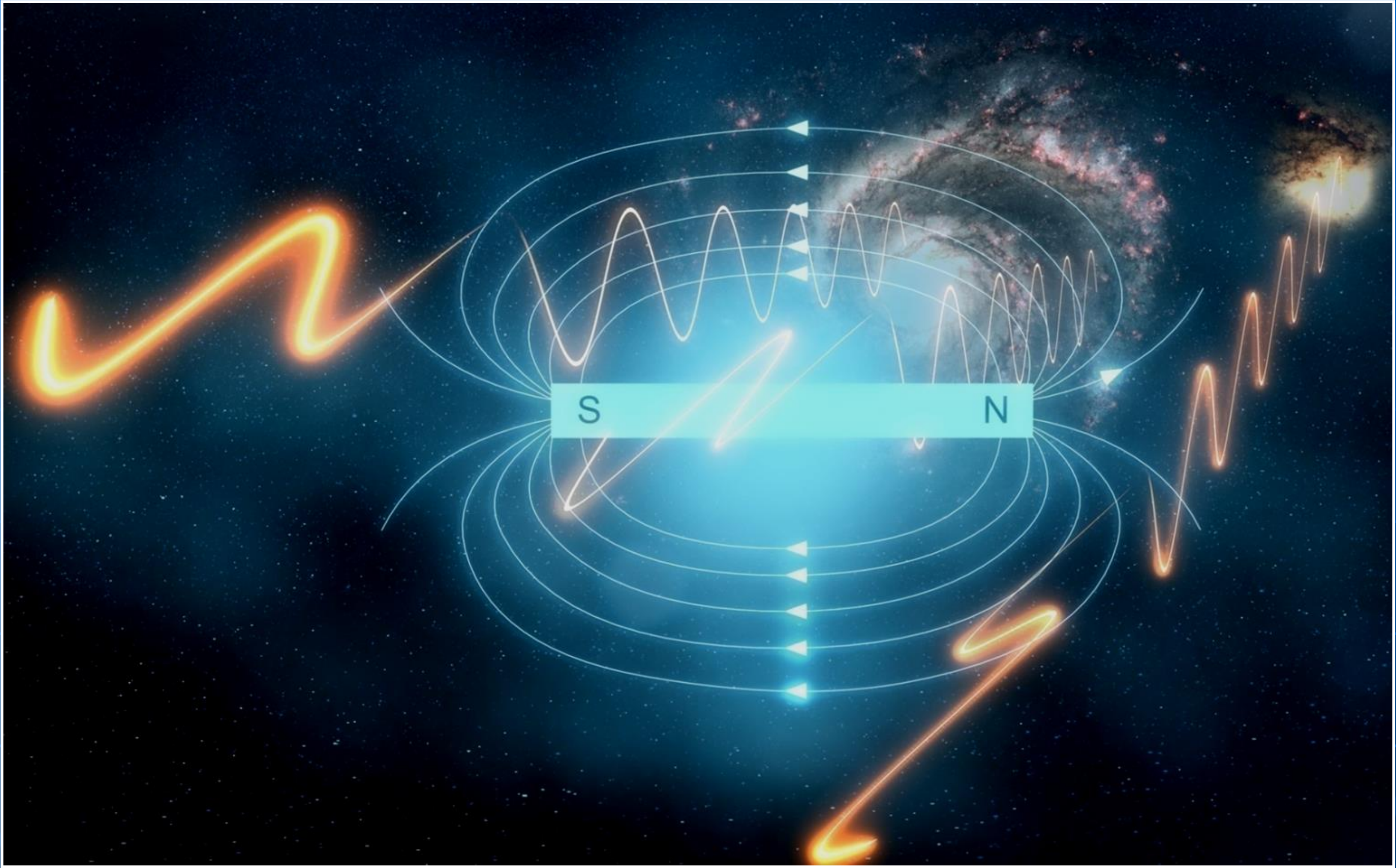


IR/radio luminosity ratio

Observation of distant galaxies with the SKA

Murphy 2009





We are entering a Golden Age

of cosmic magnetism observations

Planets, Stars and Stellar Systems
2013, pp 641-723

Magnetic Fields in Galaxies

Dr. Rainer Beck, Prof. Richard Wielebinski

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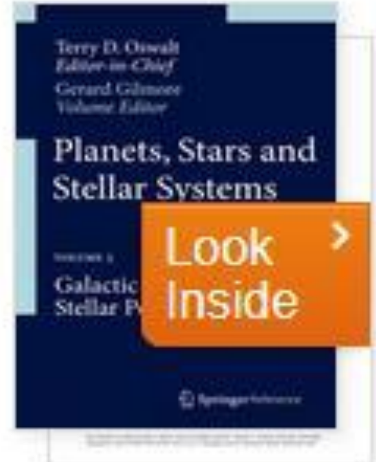

Abstract

Most of the visible matter in the Universe is ionized so that cosmic magnetic fields are quite easy to generate and, due to the lack of magnetic monopoles, hard to destroy. Magnetic fields have been measured in or around practically all celestial objects, either by in situ measurements of spacecrafts or by the electromagnetic radiation of embedded cosmic rays, gas, or dust. The Earth, the Sun, solar planets, stars, pulsars, the Milky Way, nearby galaxies, more distant (radio) galaxies, quasars, and even intergalactic space in clusters of galaxies have significant magnetic fields, and

Within this Entry