Revealing Cosmic Magnetism with the Square Kilometre Array (SKA)

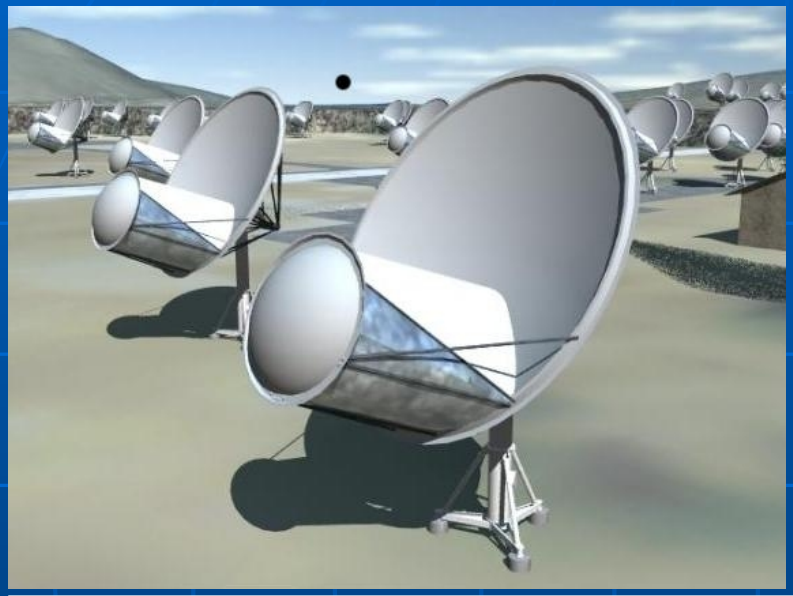
Rainer Beck

MPIfR Bonn

SKA specifications

Parameter	Design Goal
A_{eff}/T_{sys}	2×10^4 m^{2}K^{-1}
Total Frequency Range	f = 0.15 - 20 GHz
Independent Beams	> 4
Number of Instantaneous Pencil Beams	100
Maximum Primary Beam Separation low frequency high frequency	 100 degrees 1 degree at 1.4 GHz
Angular Resolution	0.1 arcsec at 1.4 GHz
Surface Brightness Sensitivity	1 K at 0.1 arcsec (continuum)
Instantaneous Bandwidth	0.5 + f/5 GHz
Number of Spectral Channels	10^4
Number of Simultaneous Frequency Bands	2
Imaging Dynamic Range	10^6 at 1.4 GHz
Polarization Purity	-40 dB

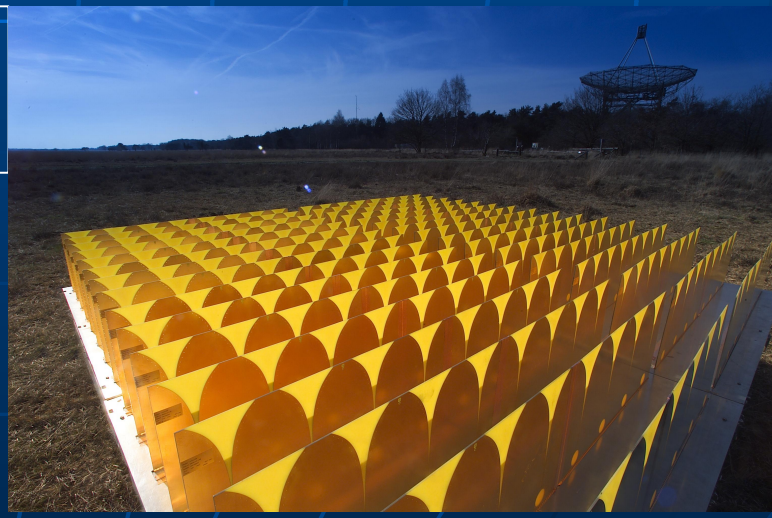
SKA Concepts

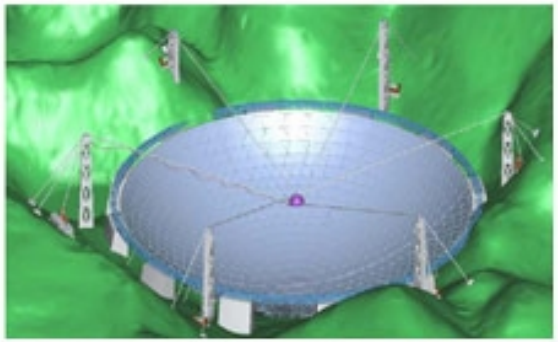


USA: Small parabolic reflectors

Australia: Focal plane arrays

Europe:
Phased Array



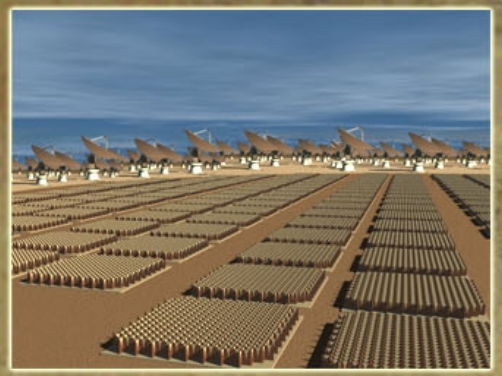


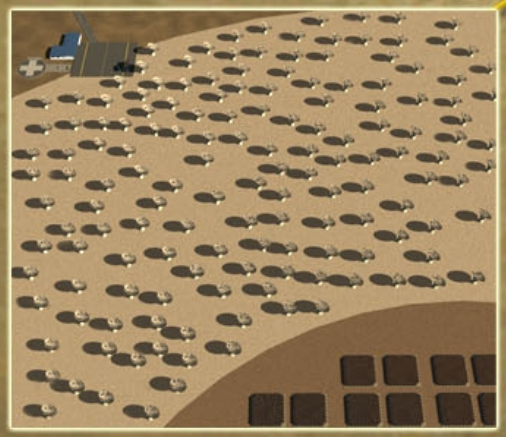
FAST - 3D image (Courtesy of Dr. Cao Yang)

China: Large spherical mirrors

SKA Reference Design

Xilostudios and SKA Project Office

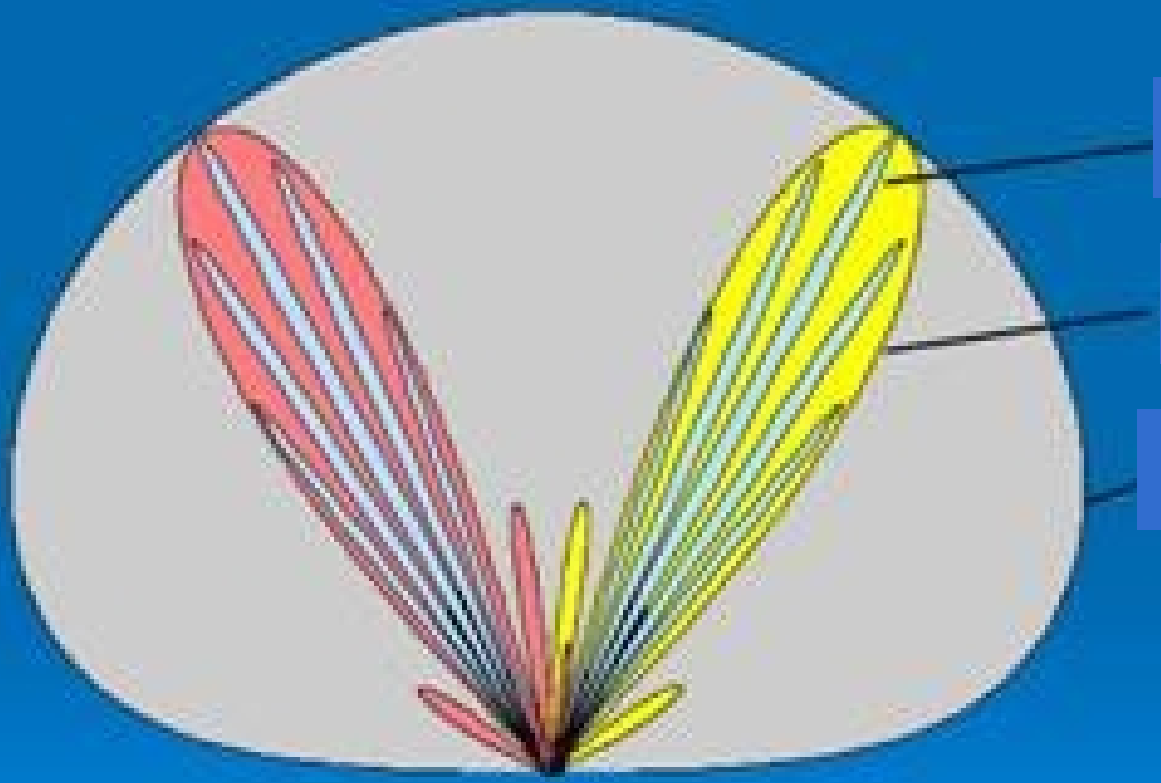




Inner core

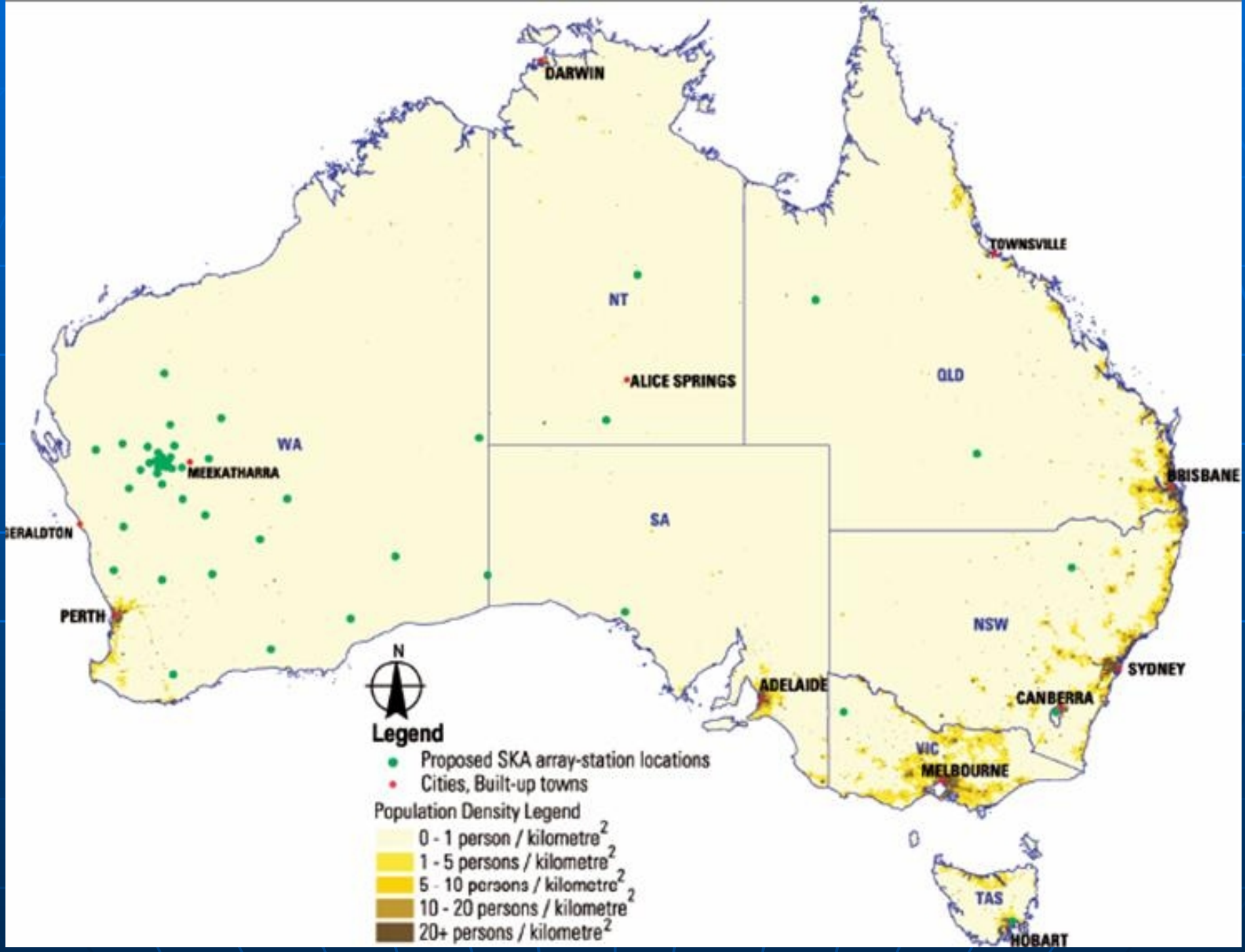
Station

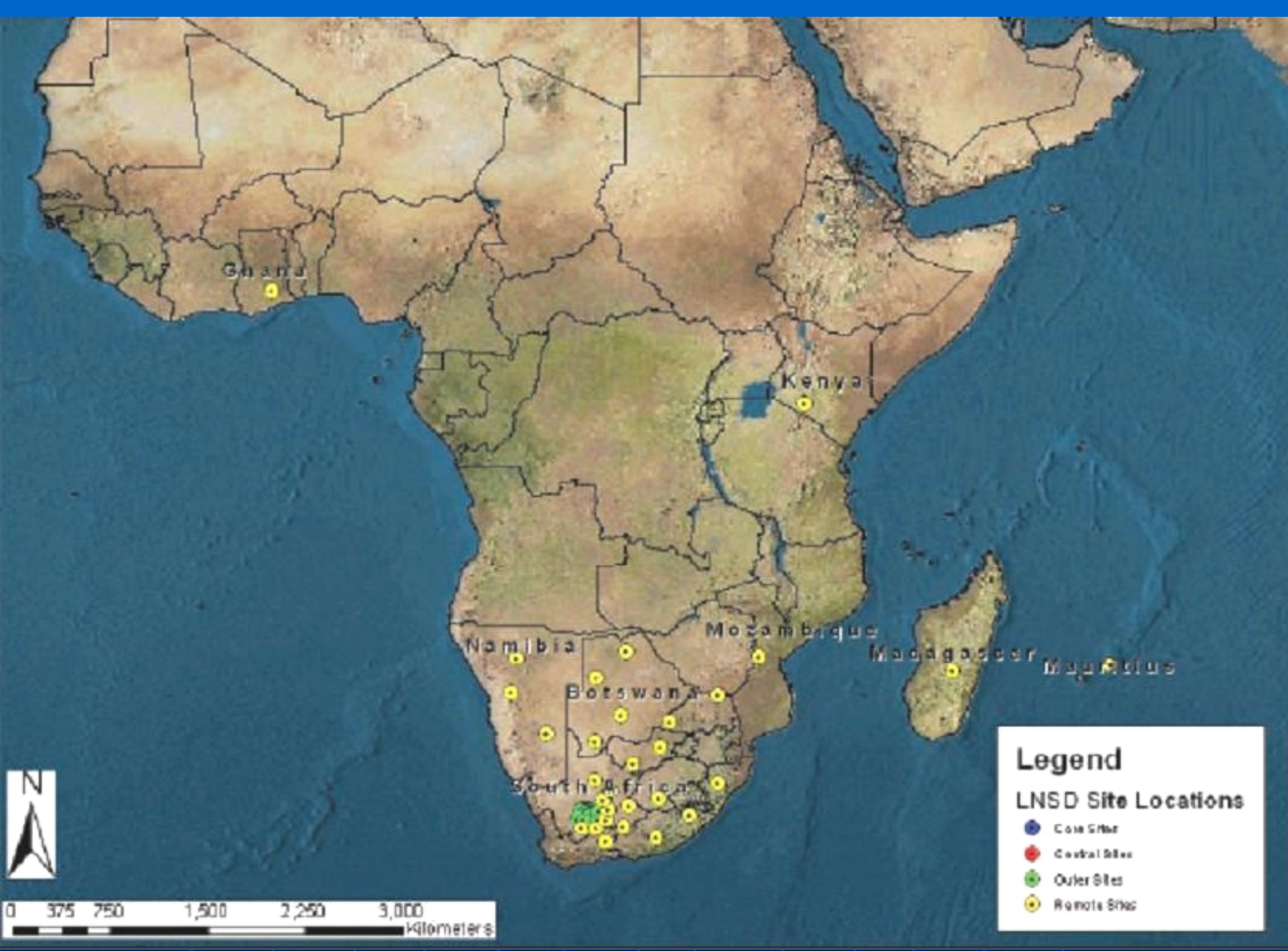
Multi-beaming



Proposed SKA Sites

- *Western Australia*
- *South Africa (+ Mozambique + …)*
- *China (Karst region)*
- *Argentina (+ Brazil)*
- *…*


DARWIN
TOWNSVILLE
NT
ALICE SPRINGS
QLD
WA
MEEKATHARRA
BRISBANE
SA
PERTH
NSW
SYDNEY
ADELAIDE
CANBERRA
VIC
MELBOURNE
TAS
HOBART
N
Legend
Proposed SKA array-station locations
Cities, Built-up towns
Population Density Legend
0 - 1 person / kilometre2
1 - 5 persons / kilometre2
5 - 10 persons / kilometre2
10 - 20 persons / kilometre2
20+ persons / kilometre2


Ghana
Kenya
Namibia
Botswana
Mozambique
Madagascar
Mauritius
South Africa
N
0 375 750 1,500 2,250 3,000
Kilometers
Legend
LNSD Site Locations
Core Sites
Central Sites
Outer Sites
Remote Sites

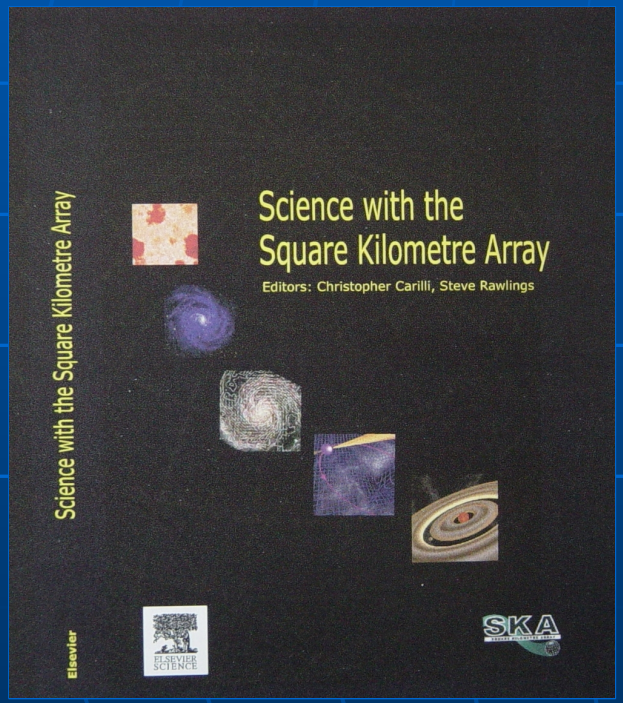
SKA Schedule

- 2008-9: Selection of site
- 2009: Selection of design
- 2012-15: Construction of Phase 1
  (10% of full array)
- 2015-20: Construction of full array

SKA Key Science

- Testing theories of gravitation
- Galaxy evolution & large-scale structures
- The Dark Ages
- The Cradle of Life
- Cosmic magnetism

SKA science book



Science with the Square Kilometre Array

Eds: C.Carilli & S.Rawlings,
New Astronomy Reviews,
Vol.48, Elsevier, Dec. 2004

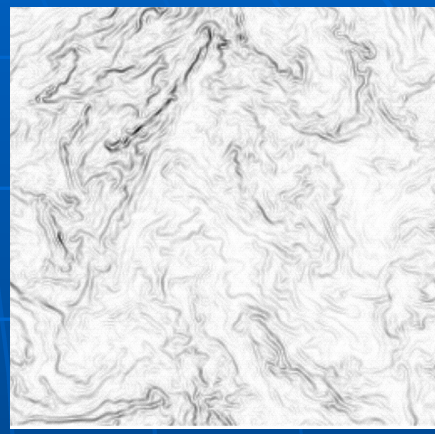
www.skatelescope.org

Cosmic Magnetism

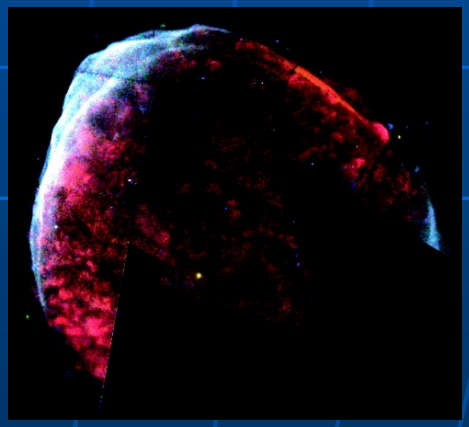
Magnetism is crucial in :

- cloud collapse / star formation
- stellar activity / stellar outflows
- ISM turbulence / gas motions
- supernova remnants
- stability of galactic disks
- acceleration / propagation / confinement of cosmic rays
- heating in galaxy clusters
- AGNs / Jets

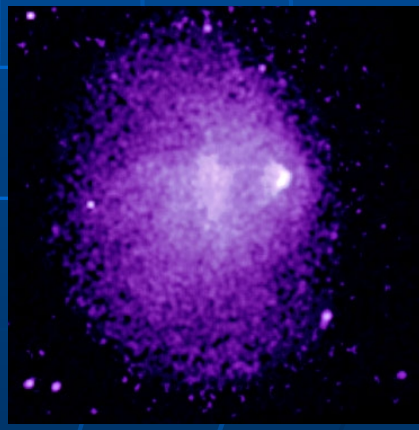
Proplyd in Orion



MHD turbulence



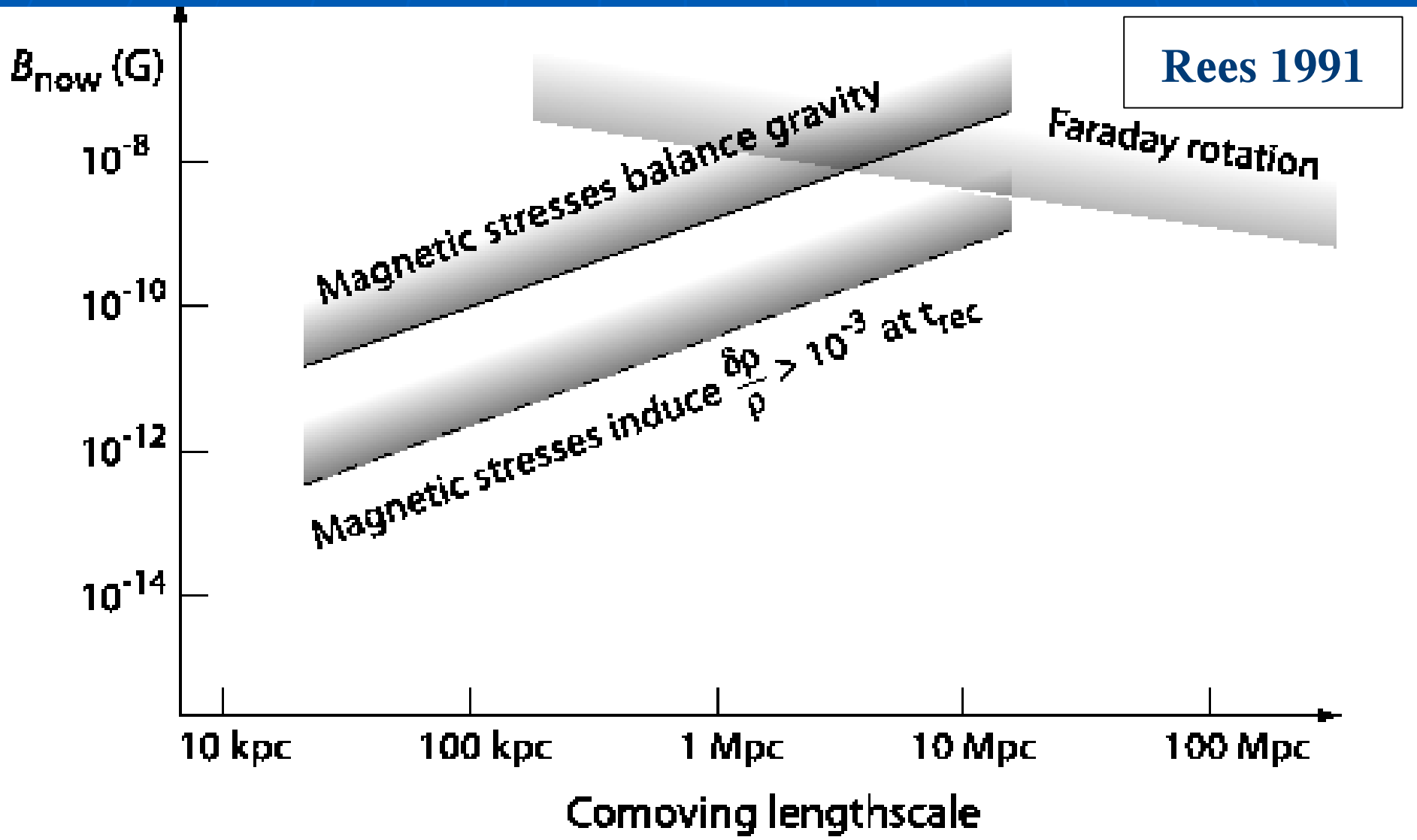
SN 1006



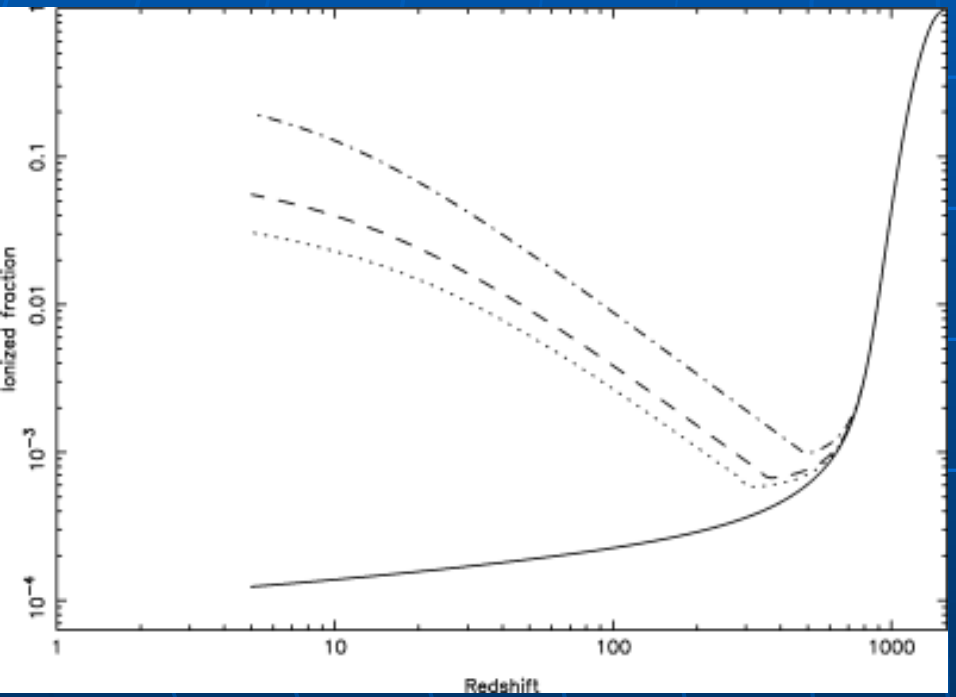
Merger in gal. cluster

Magnetism is one of the fundamental forces in Nature, but its role and origin is largely unknown !

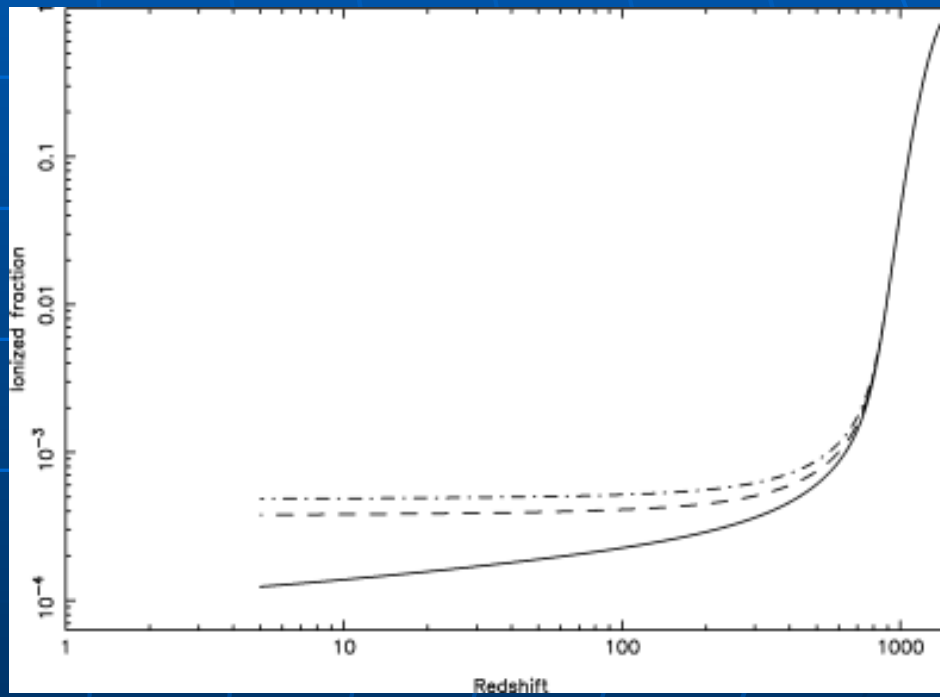
Dynamical importance of primordial intergalactic fields



Magnetic fields and structure formation in the early Universe



Dissipation of magnetic energy by ambipolar diffusion



Dissipation of magnetic energy by decaying turbulence

Sethi & Subramanian 2005

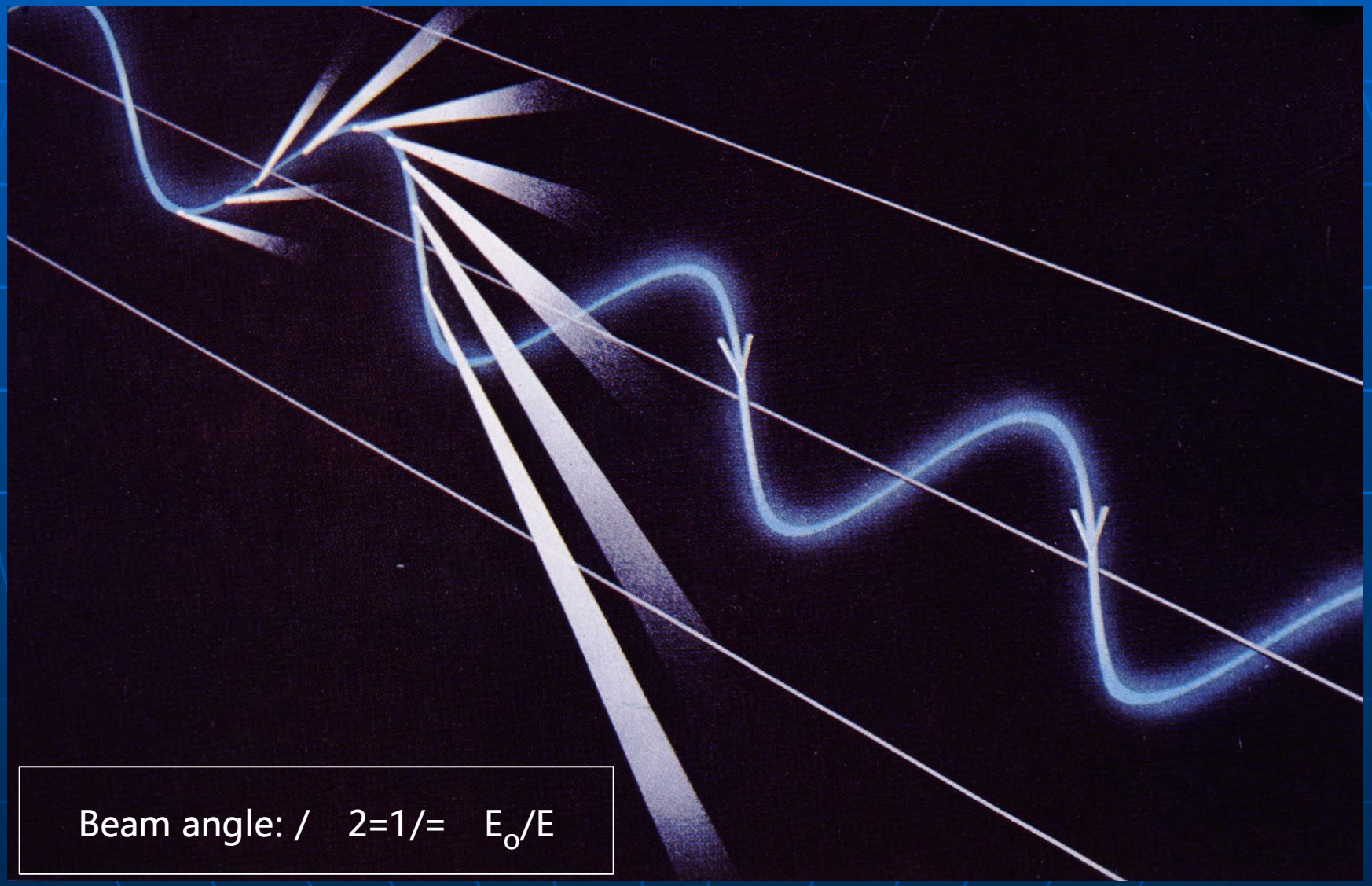
Fundamental questions

- ***STRUCTURE***
  - *What are the **strength and structure** of cosmic magnetic fields ?*
  - *Do magnetic fields fill the whole intergalactic space ?*
- ***EVOLUTION***
  - *How were magnetic fields **amplified** and maintained ?*
  - *What is the **interplay** between magnetic fields and gas ?*
- ***ORIGIN***
  - *When and how were the **first magnetic fields** generated ?*

Observing magnetic fields

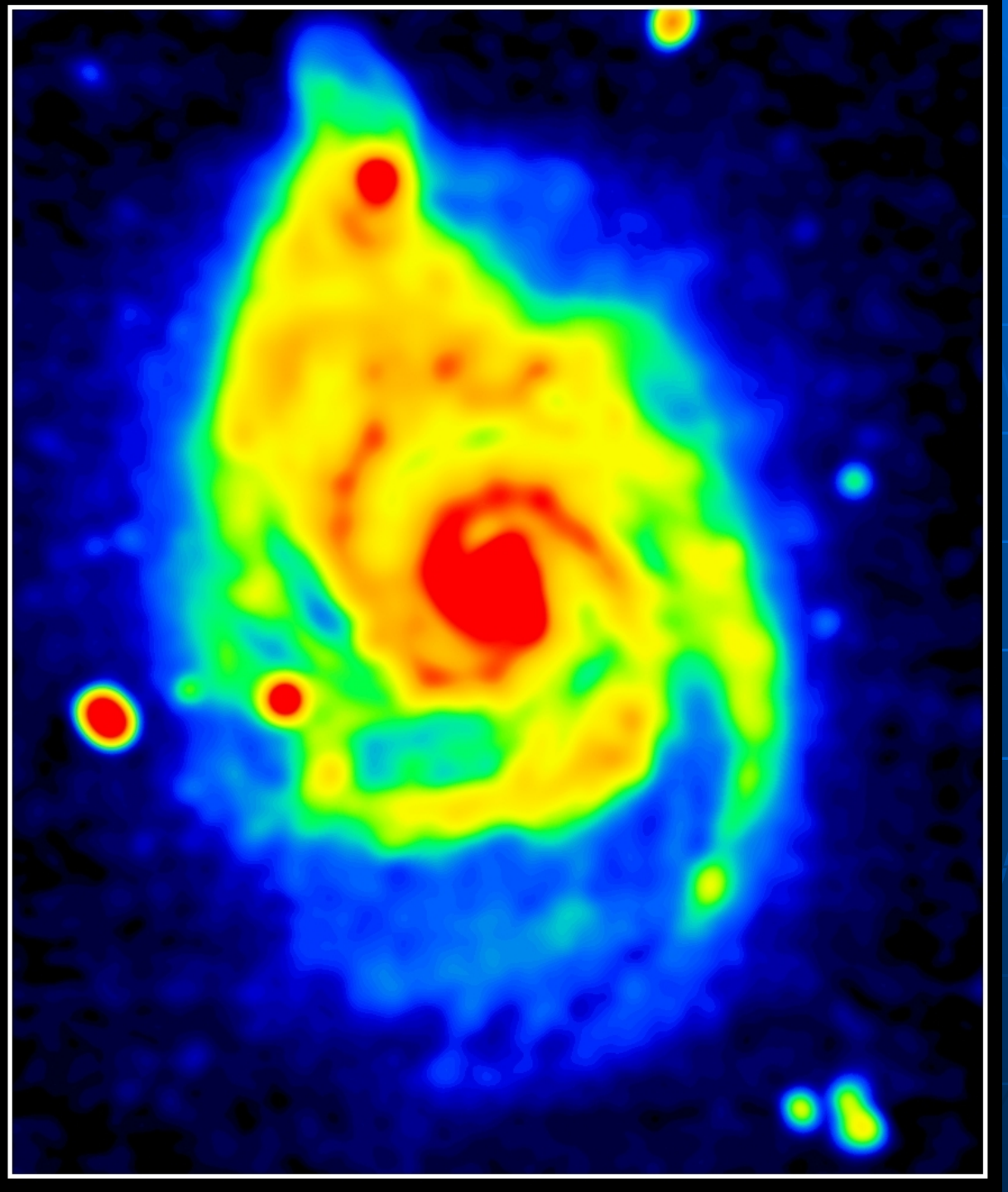
- Optical polarization (absorption by aligned, rotating, paramagnetic dust grains)
- Infrared polarization (emission from aligned dust grains)
- Zeeman effect (radio spectral lines)
- Radio synchrotron emission & Faraday rotation

Synchrotron emission



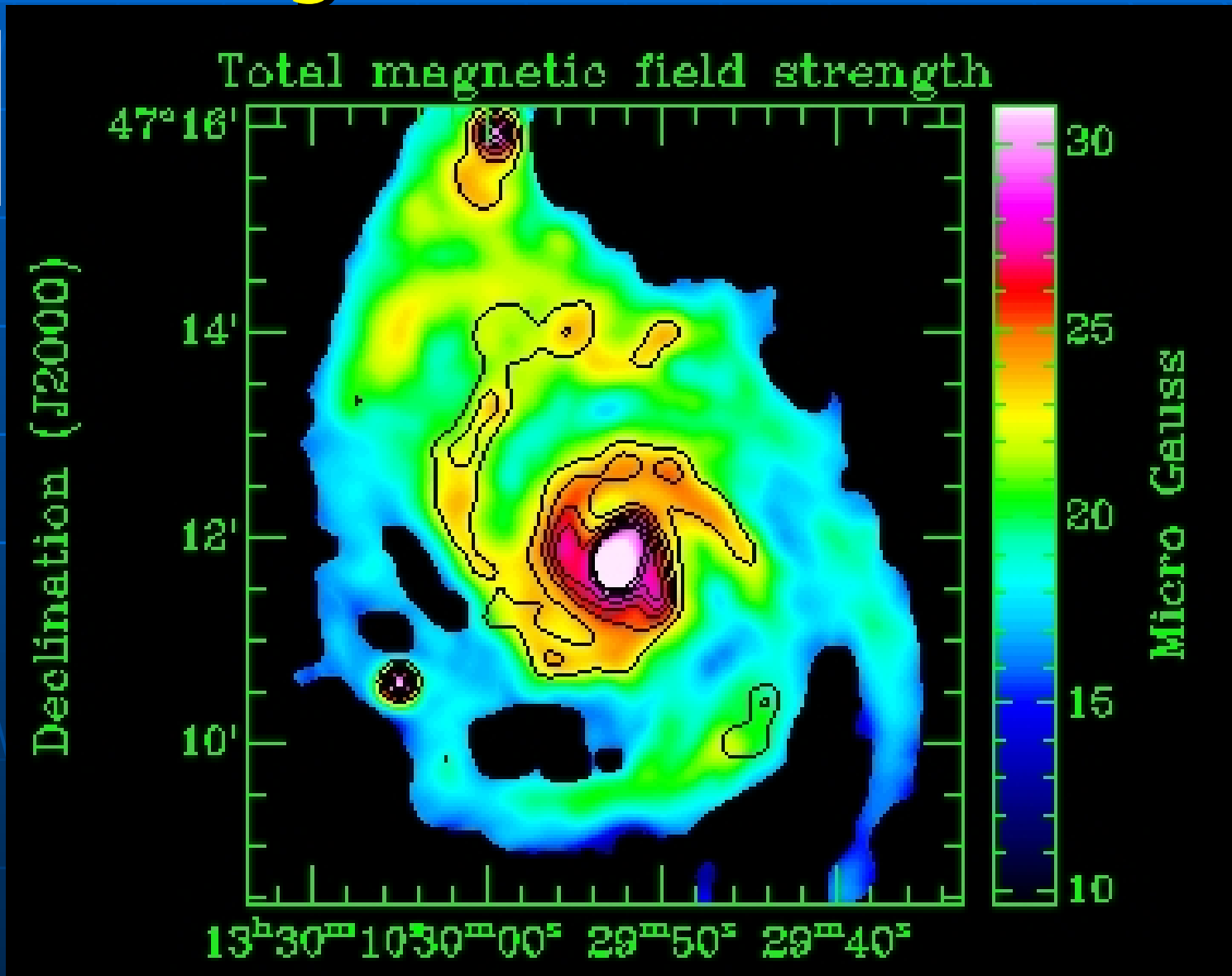
M51

(Fletcher, Beck et al. 2006)



Equipartition magnetic field strengths in M51

Fletcher, Beck et al. (2005)

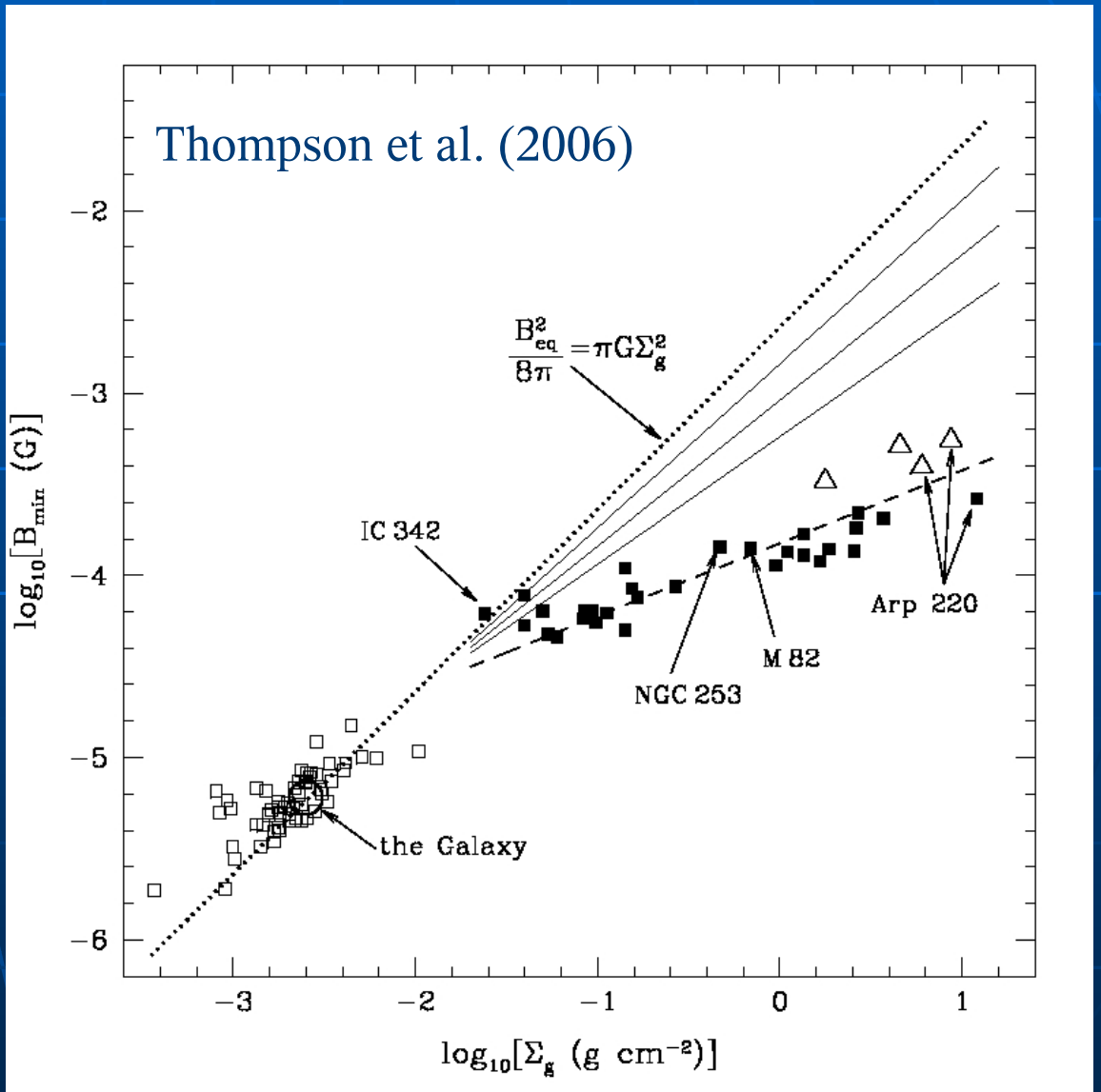


Equipartition field strengths in galaxies

- Weakly star-forming galaxies (Sb, Irr):
  5-10 μG
- Strongly star-forming galaxies (Sc):
  10-20 μG
- Starburst galaxies (Sm):
  50-100 μG

Magnetic fields and gas surface density

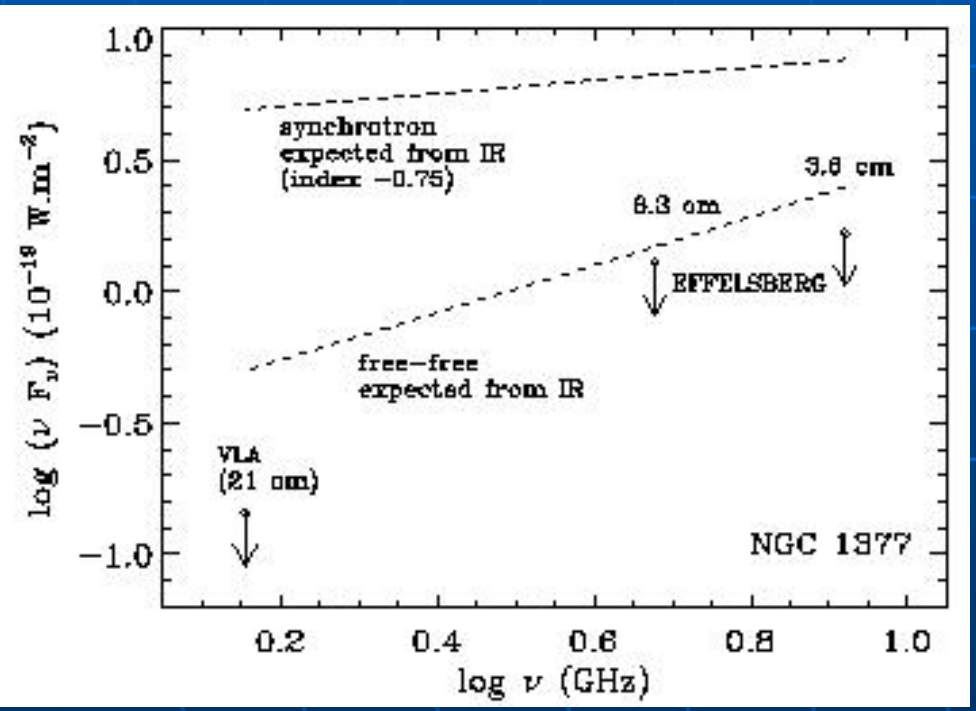
Equipartition magnetic field strengths in starburst galaxies possibly are underestimates



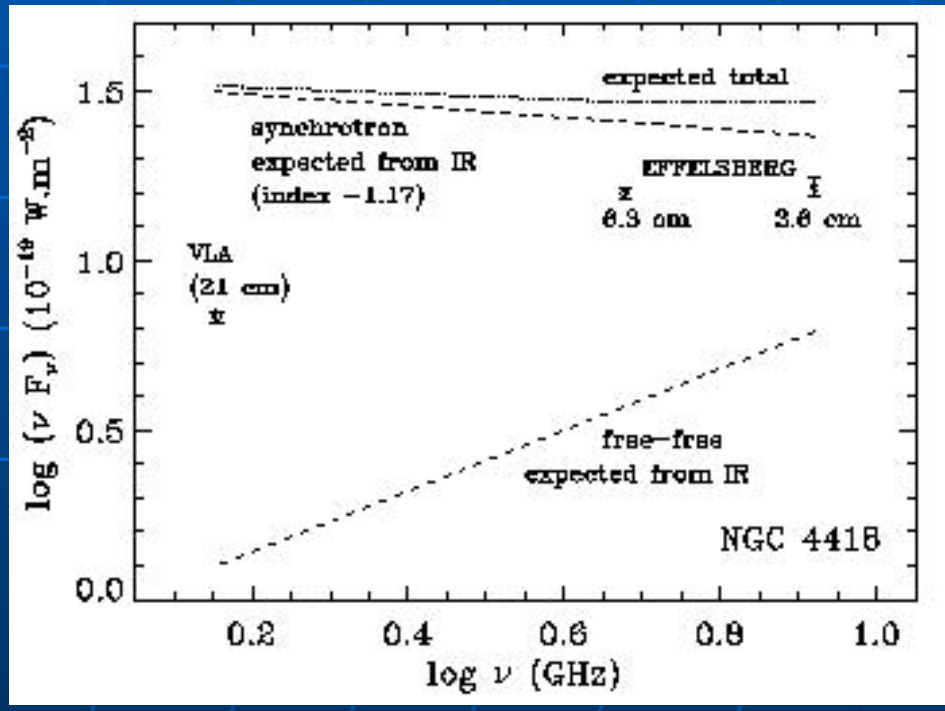
Very young starburst galaxies

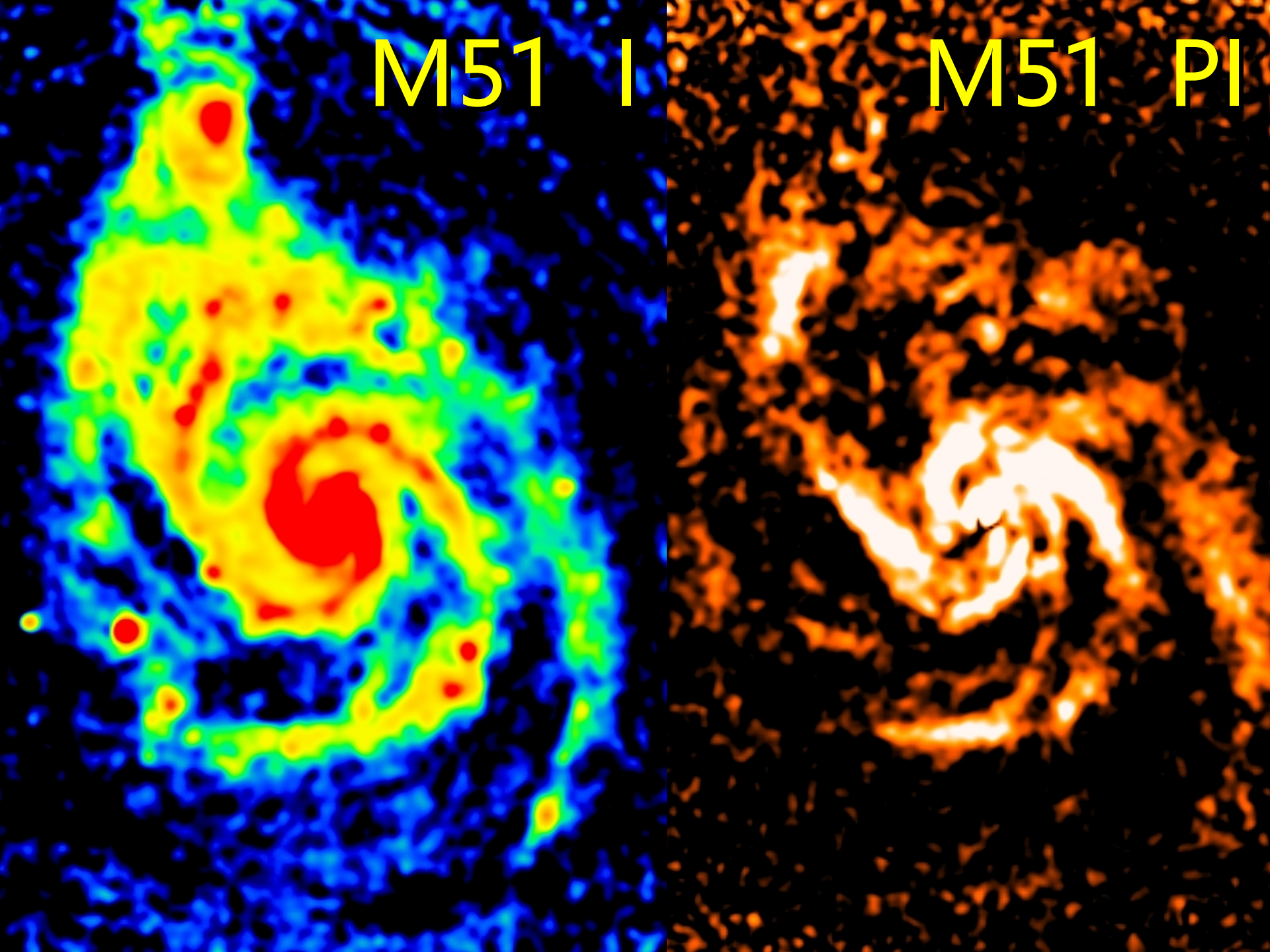
Roussel et al. (2003)

Radio-quiet



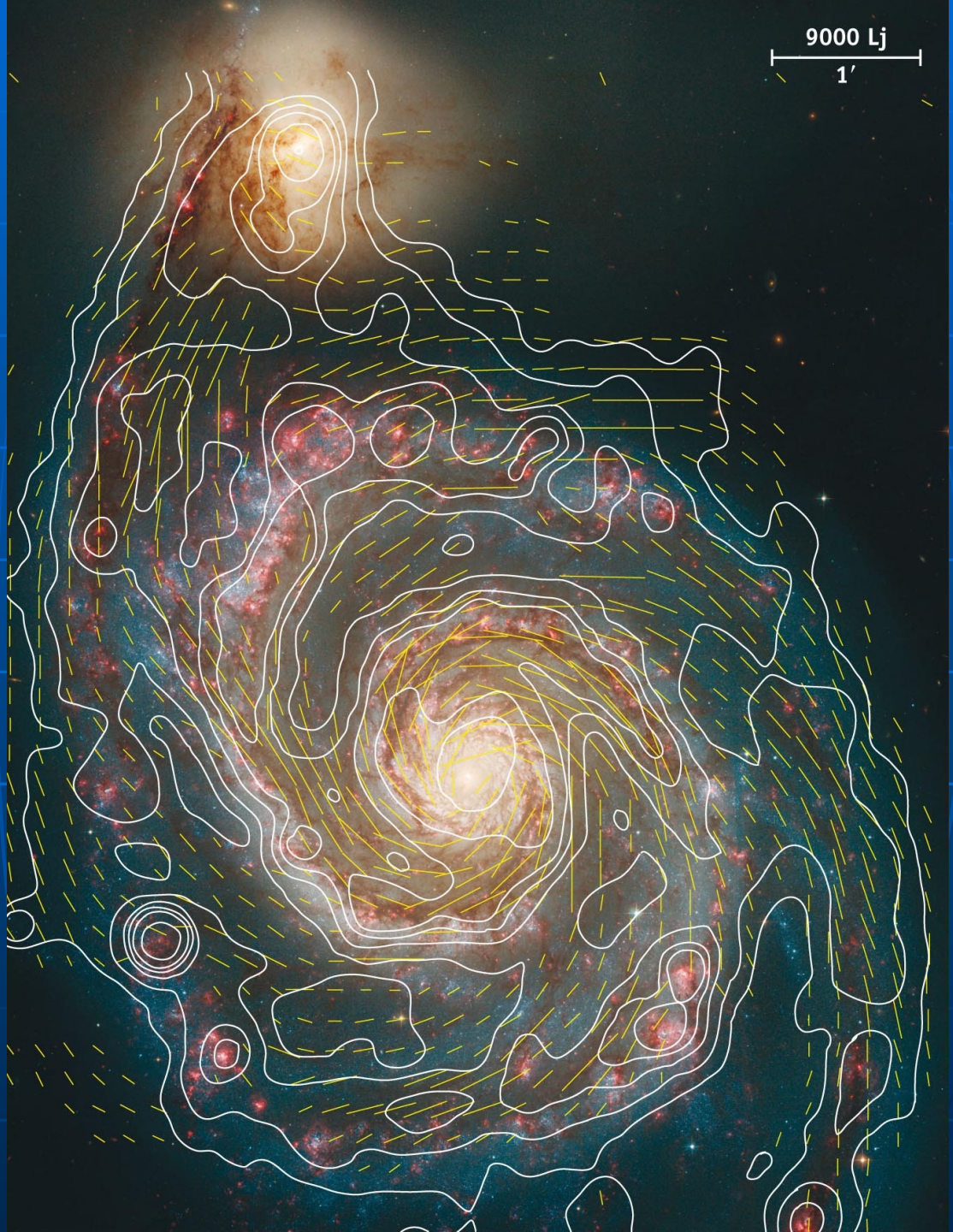
Radio-deficient



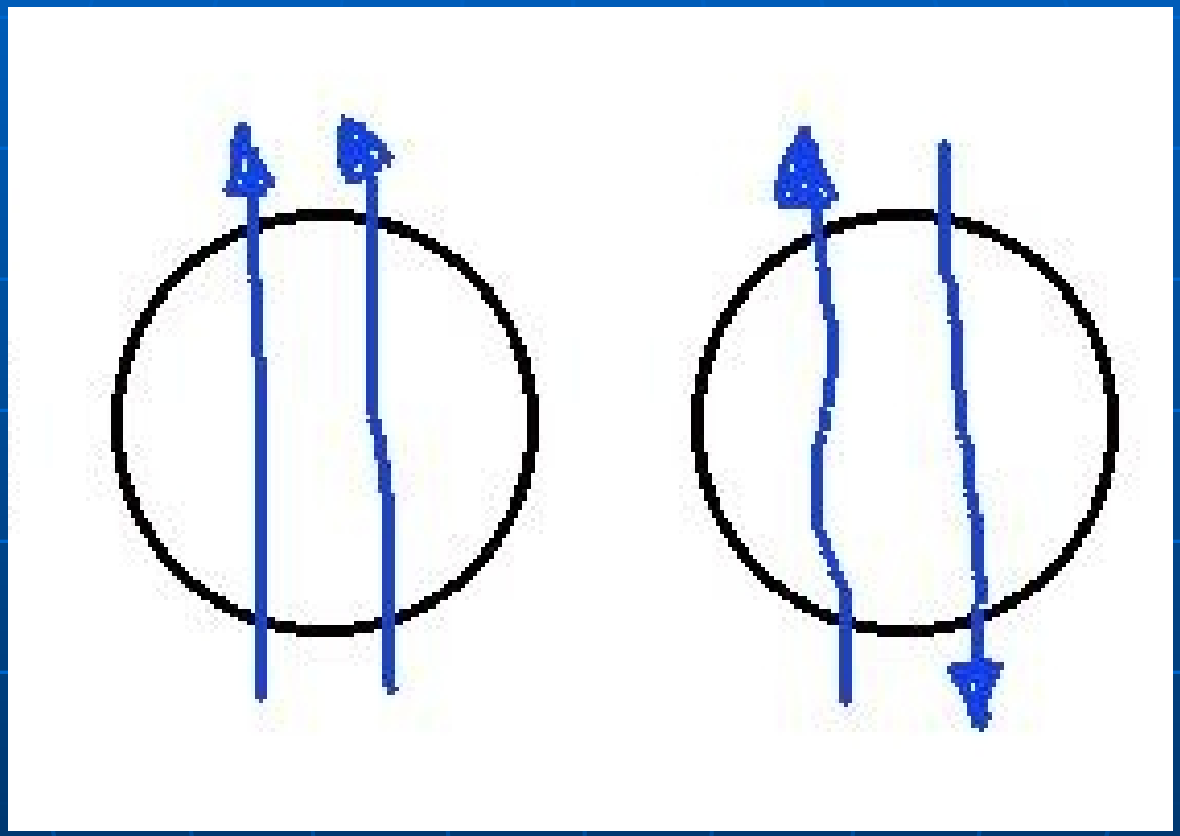

M51 I
M51 PI

M51

(Fletcher, Beck et al. 2006)



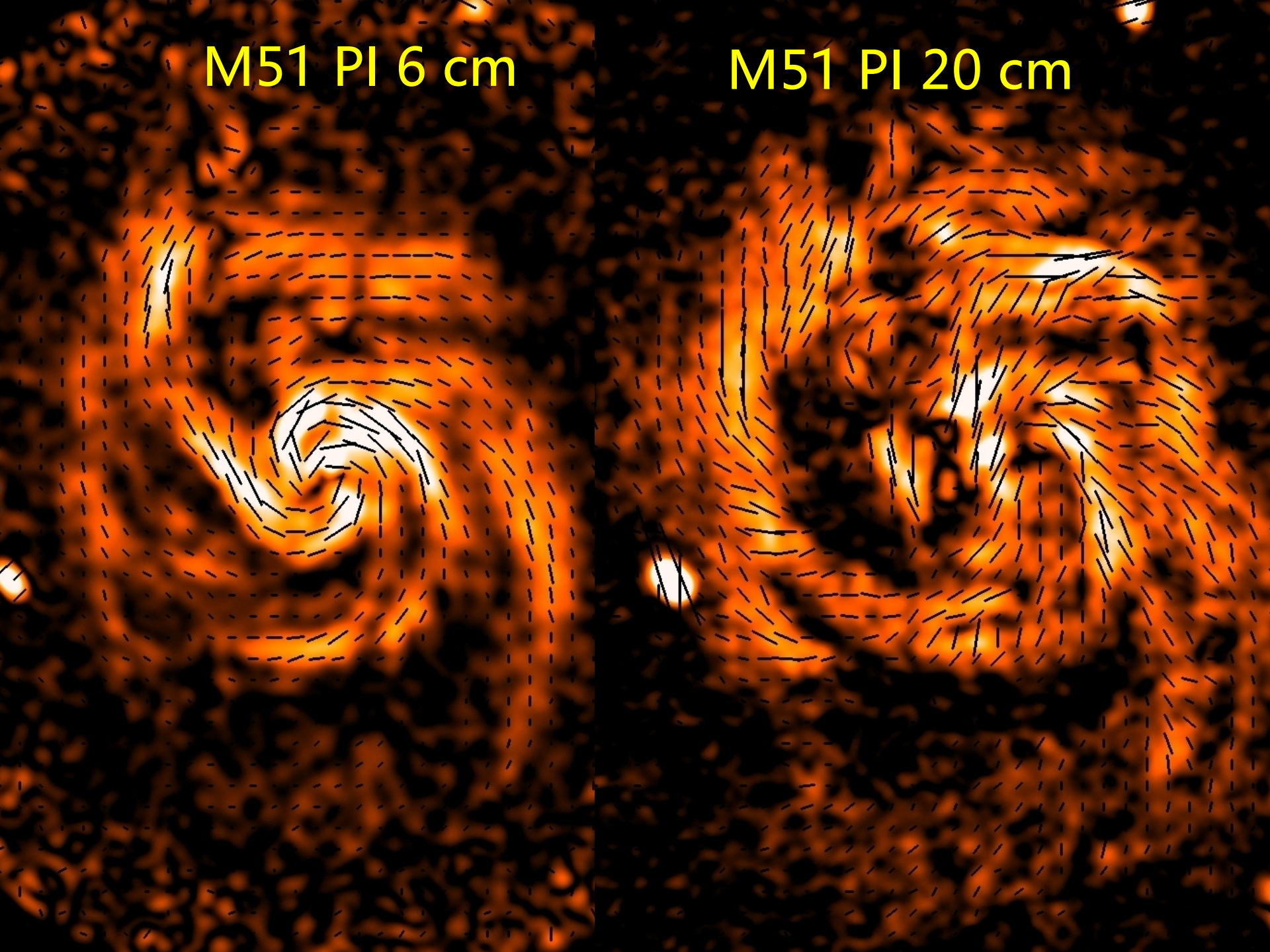
Magnetic field components



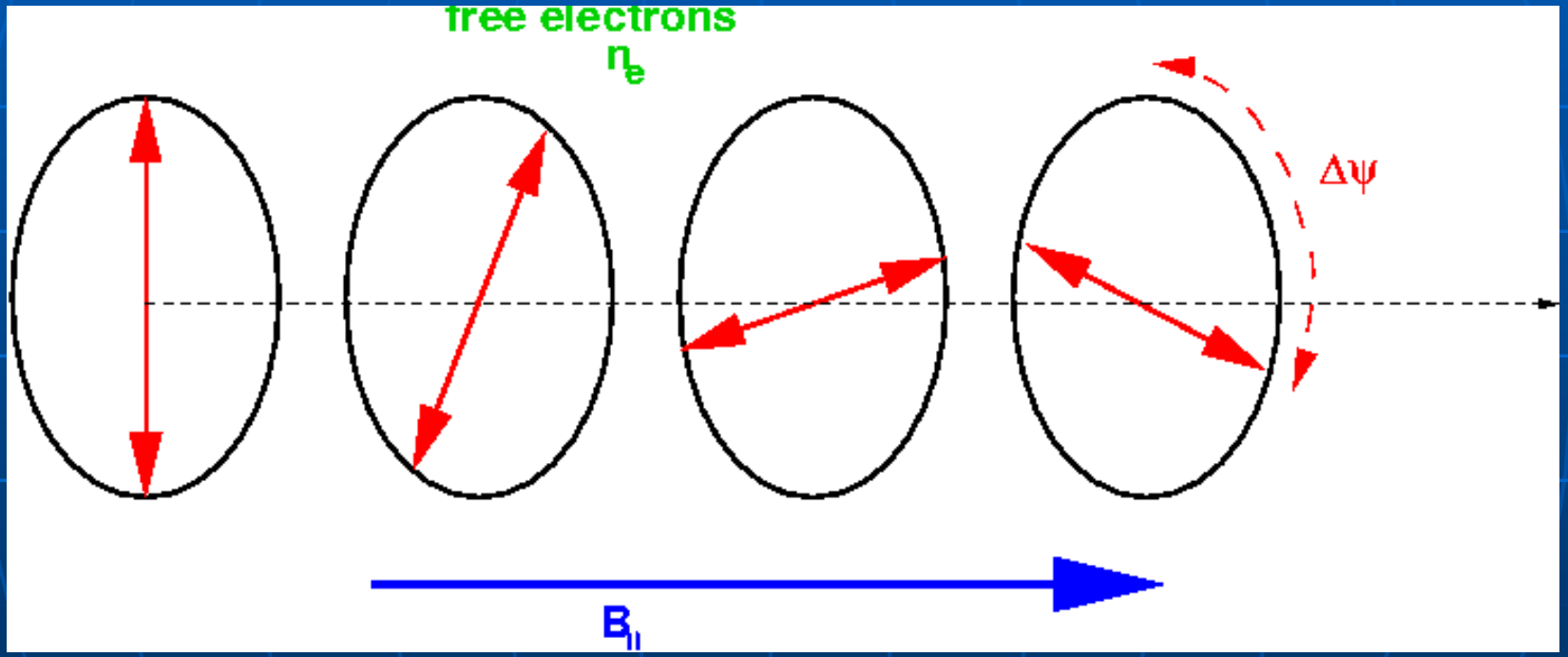
Highly polarized

Coherent field

Incoherent field


M51 PI 6 cm
M51 PI 20 cm

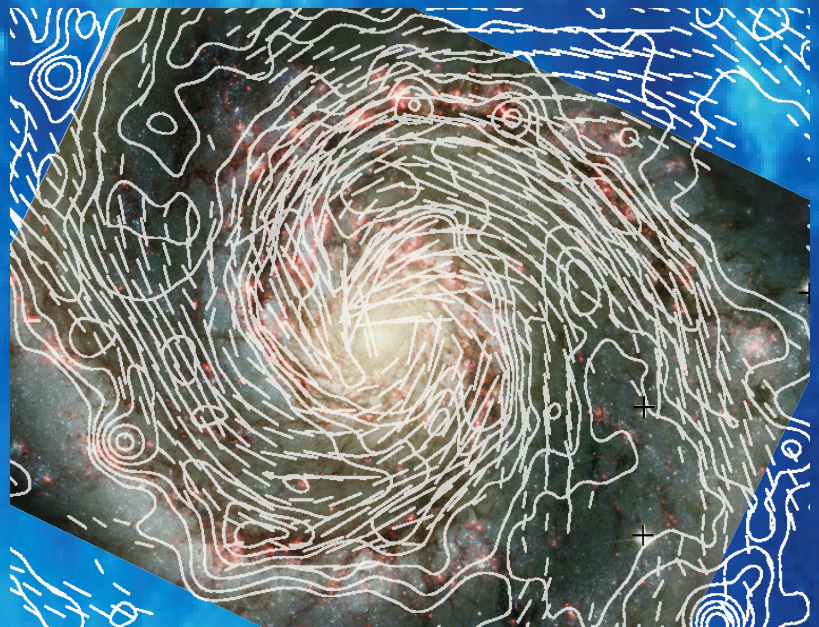
Faraday rotation is a signature of *coherent* regular fields



$$\propto \quad ^{2} \bullet n_e B_{reg} \quad dl$$

The Origin and Evolution of Cosmic Magnetism

- The SKA will probe of cosmic magnetic fields everywhere in the Universe
- The SKA will provide detailed 3D pictures of cosmic magnetic fields



The origin and evolution of cosmic magnetism

29 August - 2 September 2005
CNR Area della Ricerca, Bologna, Italy

CONSIGLIO NAZIONALE DELLE RICERCHE

Scientific Organizing Committee

Rainer Beck *MPIfR, Germany, Co-Chair*
Klaus Dolag *MPA, Germany*
Luigina Feretti *IRA, Italy, Co-Chair*
Bryan Gaensler *CfA, USA, Co-Chair*
Massimo Giovannini *CERN, Switzerland*
Phil Kronberg *LANL, USA*
Angela Olinto *University of Chicago, USA*
Martin Rees *University of Cambridge, UK*
Dongsu Ryu *Chungnam National University, Korea*
Kandu Subramanian *IUCAA, India*
Lawrence Widrow *Queen's University, Canada*
Ellen Zweibel *University of Wisconsin, USA*

Invited Speakers

Axel Brandenburg, Stirling Colgate, Klaus Dolag, Torsten Ensslin, Yutaka Fujita, Bryan Gaensler, Maurizio Gasperini, Federica Govoni, Dario Grasso, Jongsoo Kim, Arthur Kosowsky, Hui Li, Martin Rees, Dongsu Ryu, Etienne Parizot, Kandu Subramanian, Ellen Zweibel

Local Organizing Committee

Marco Bondi, Gianfranco Brunetti, Luigina Feretti *Chair*, Marcello Giroletti, Federica Govoni, Karl-Heinz Mack, Barbara Neri, Isabella Prandoni

Organizing Institute

INAF - Istituto di Radioastronomia, Bologna, Italy

www.ira.cnr.it/~magnetic/

Proceedings:
Astr. Nachr.
Vol. 327 (2006)

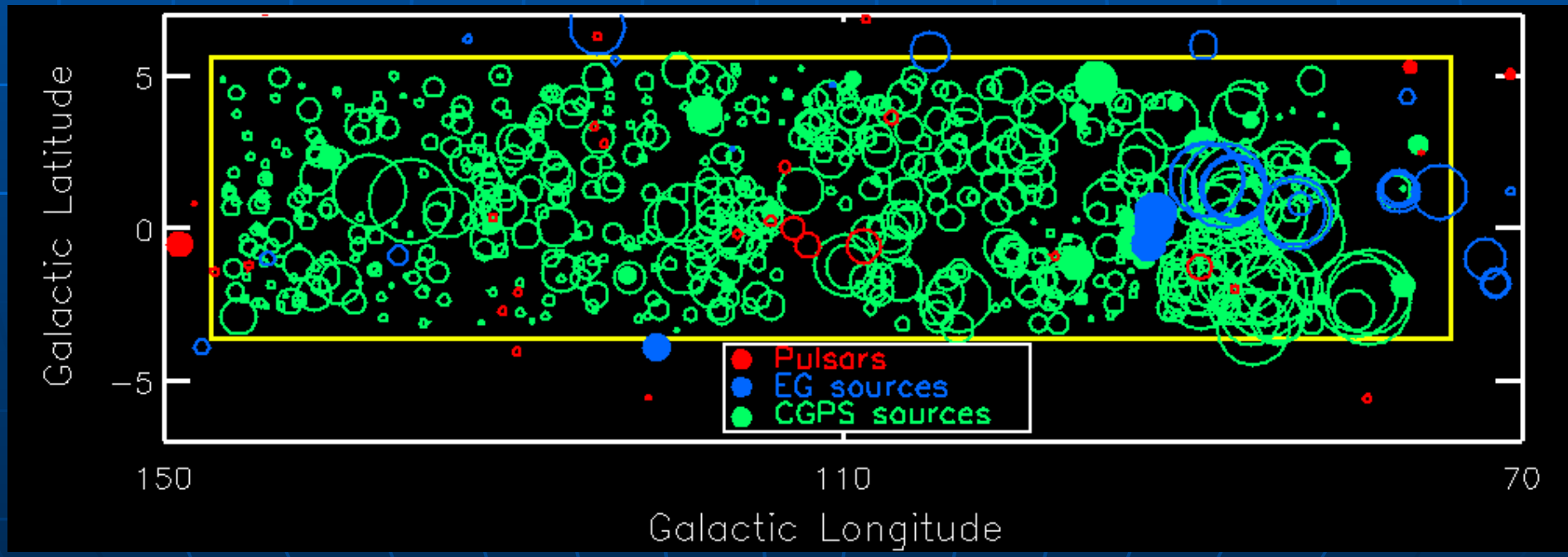
The Origin and Evolution of Cosmic Magnetism

Projects :

- **All-sky survey of Faraday rotation measures**
- Faraday tomography of the Milky Way and nearby galaxies
- High-resolution polarization mapping of nearby galaxies and clusters

RMs of Background Sources

- Until 2000: RMs of ~1200 polarized extragalactic sources, plus ~300 pulsars
- Galactic plane surveys with ATCA & DRAO: several 100 new RMs
- New Effelsberg survey: ~1500 new RMs



DRAO Canadian Galactic Plane Survey (Brown et al. 2003, 2004)

SKA RM Survey

- Image the whole sky to S ≈ 0.1 Jy at 1.4 GHz,
  FoV • 1 deg^2 , 1h / pointing (~1 year total) :

- RMs for **~(1–5) x 10^7**
  polarized extragalactic sources expected,
  spaced by only ~ 60"–90" on the sky

- RM mapping of the Milky Way, nearby galaxies, clusters and distant intervening galaxies

- Search for magnetic fields in the first galaxies, clusters and in the intergalactic medium

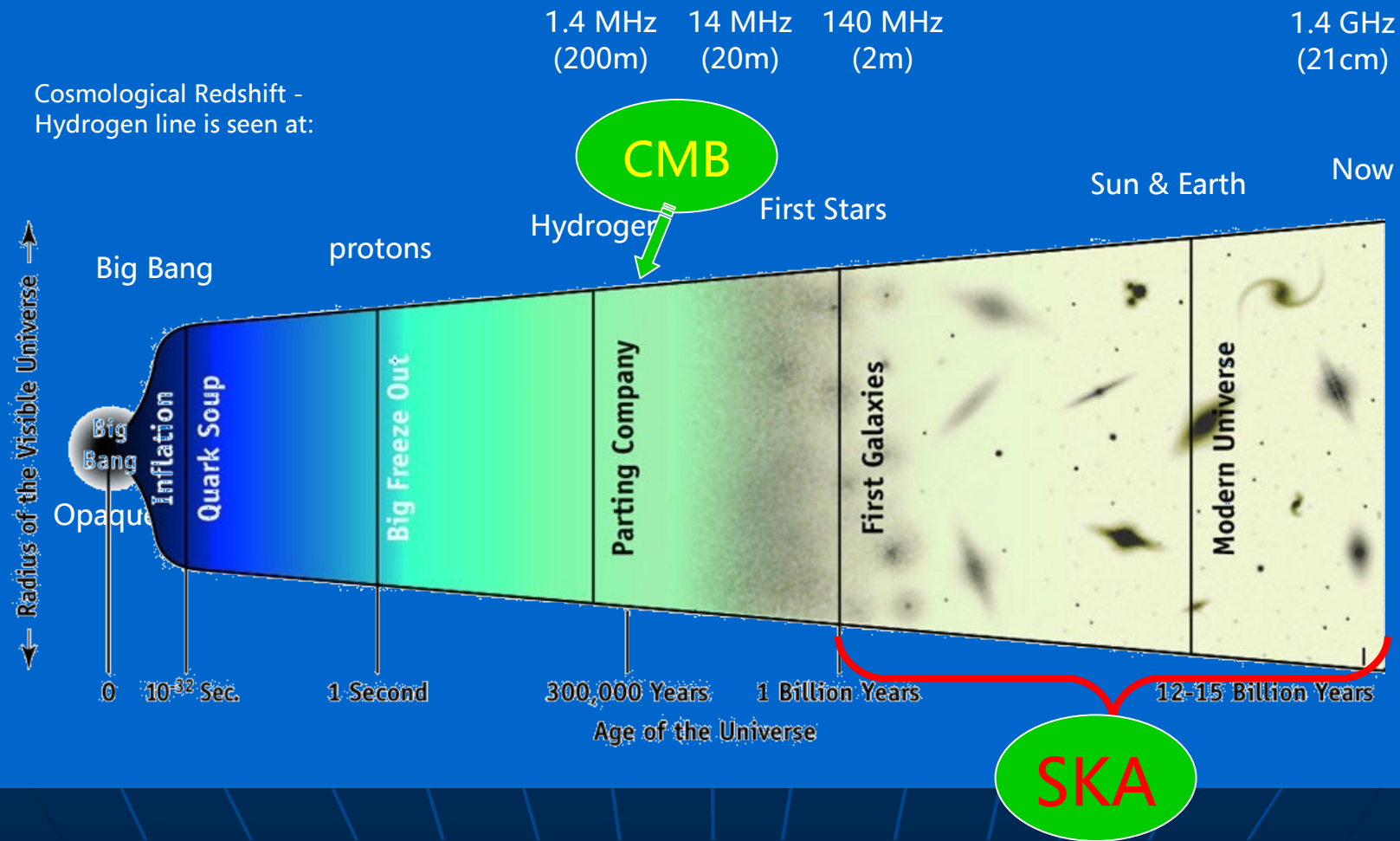
SKA Design Study - Simulations

(SKADS *DS2-T1-WP3*, MPIfR & Cavendish Lab. Cambridge/UK)

Preparing for future projects on magnetism by simulating the polarized sky:

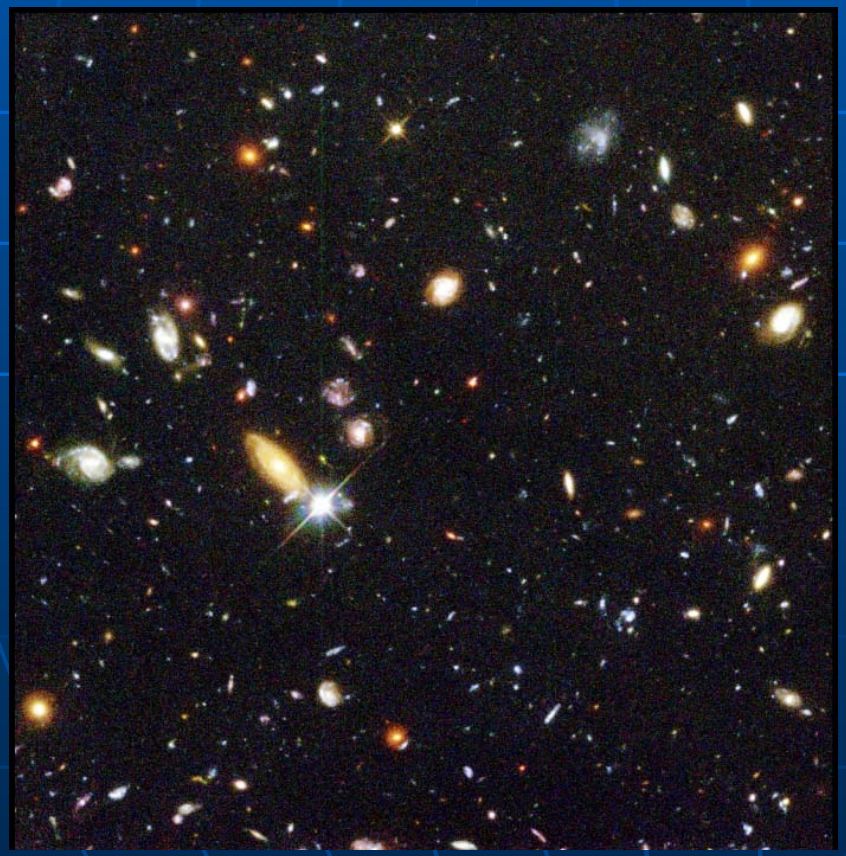
- diffuse Galactic emission
- polarized background sources
- density of RM grid

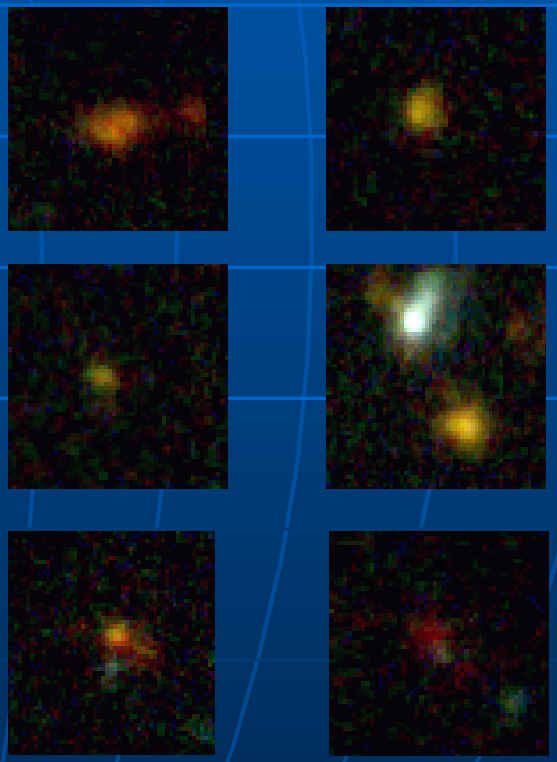
Evolution of the Universe



Young galaxies

Normal spiral galaxies at z ~ 3 detectable with the SKA (1.4 GHz : size = 1 - 3″ (?) , flux • 0.2 Jy)



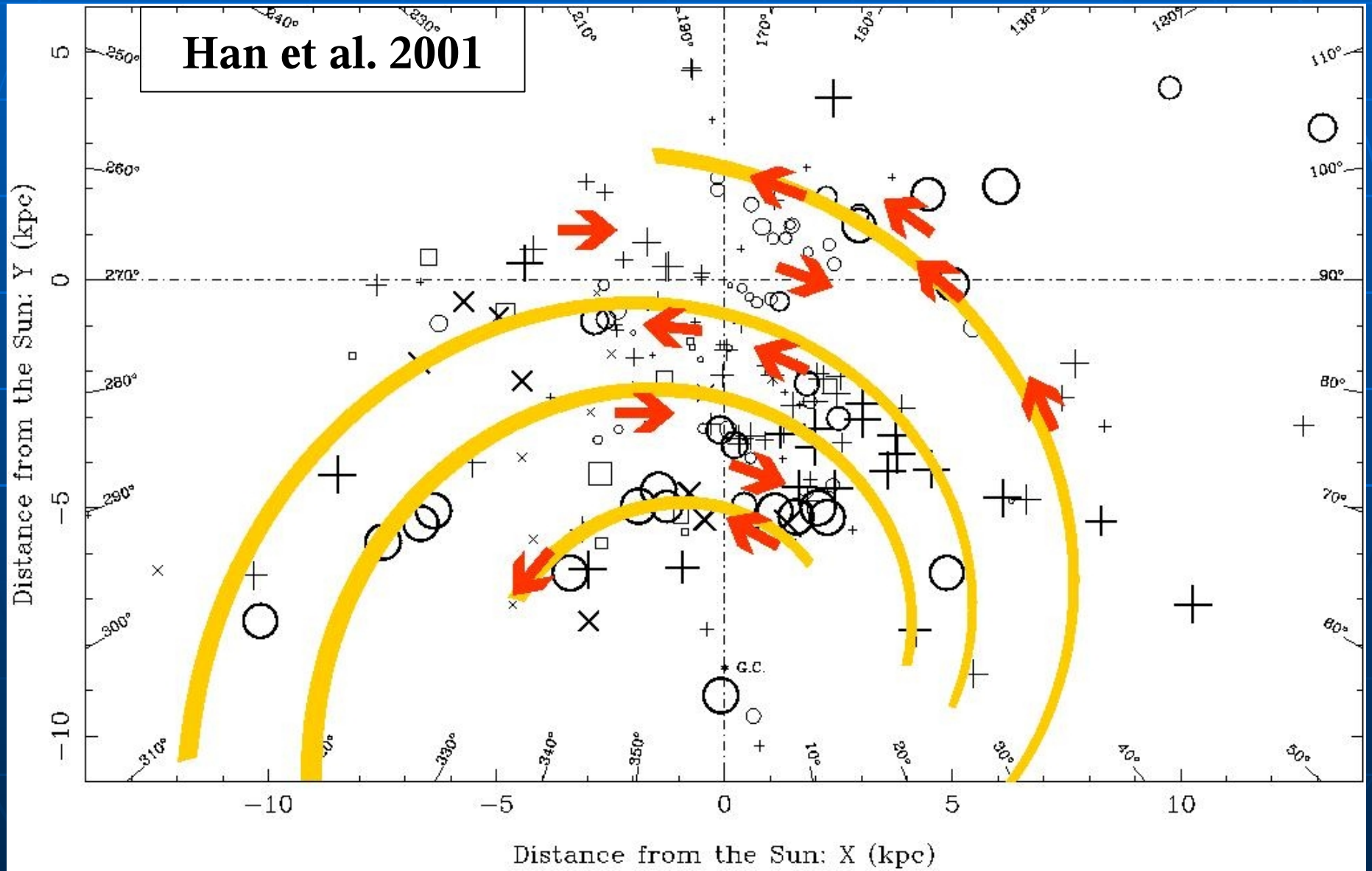


HDF galaxies with z > 4
(Driver et al. 1998)

The mystery of Galactic field reversals:

Is our Galaxy special?

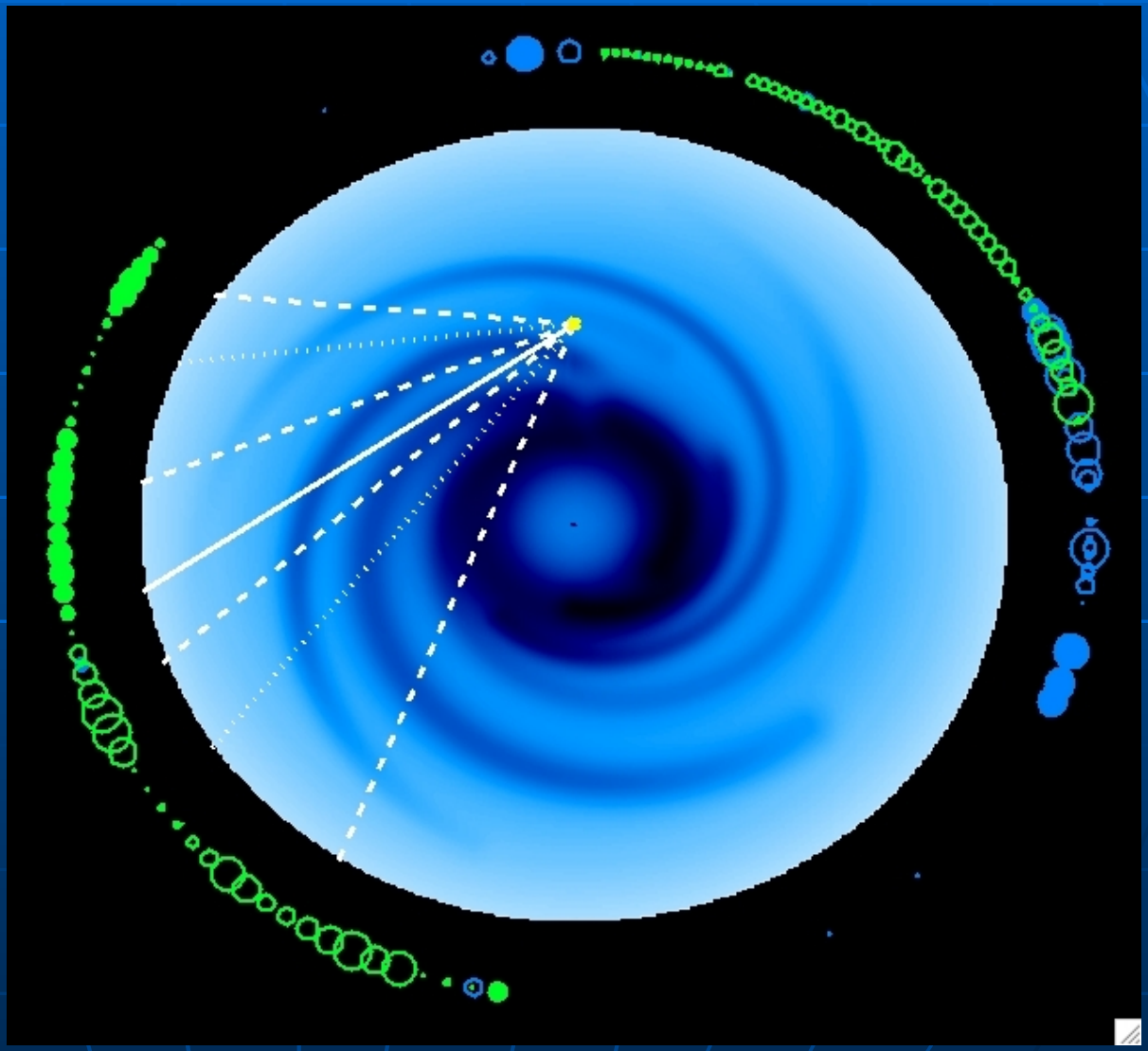
Rotation measures of Galactic pulsars



RMs of extragalactic sources

Brown et al. (2006)

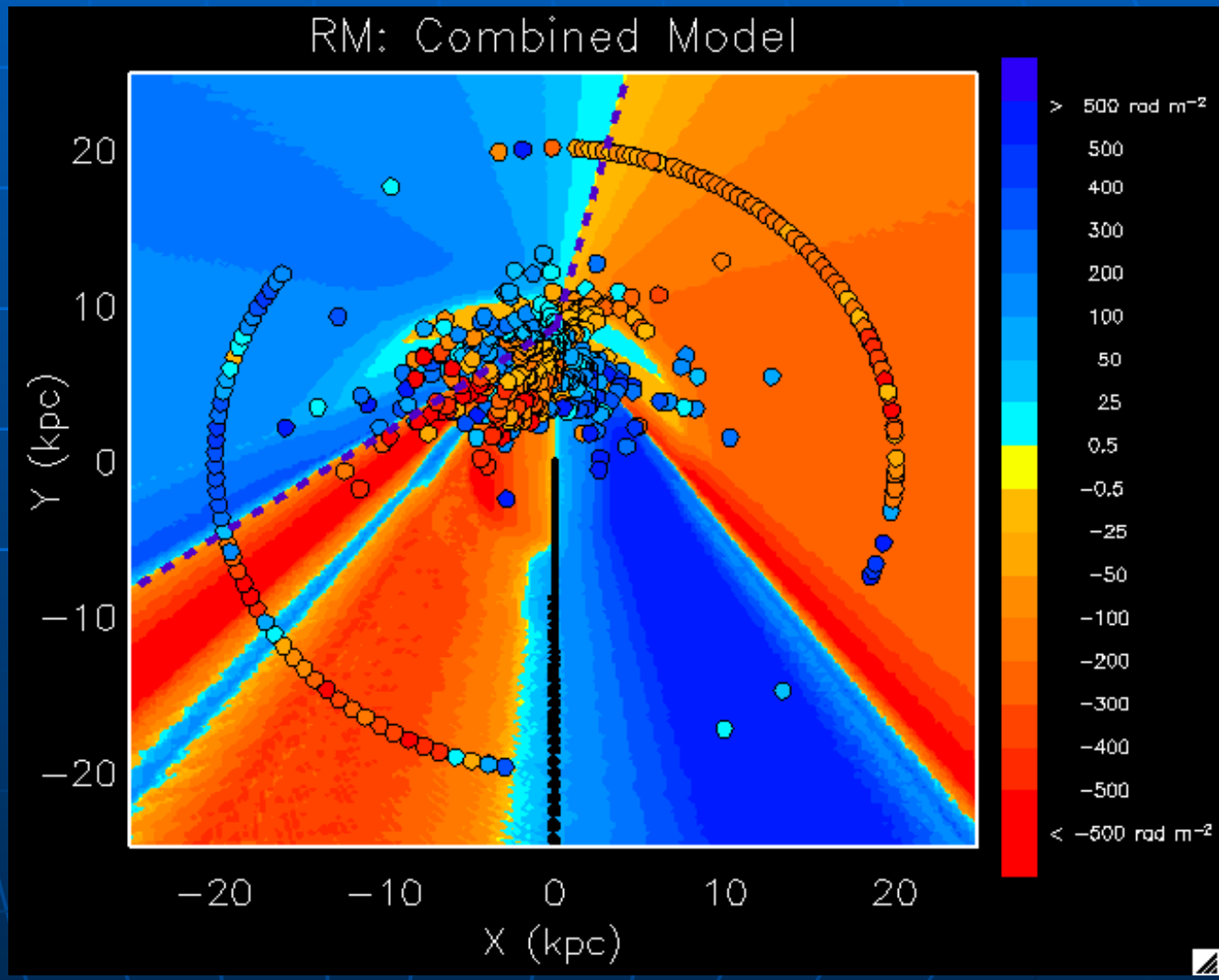
Only one reversal is required



RMs of extragalactic sources + pulsars

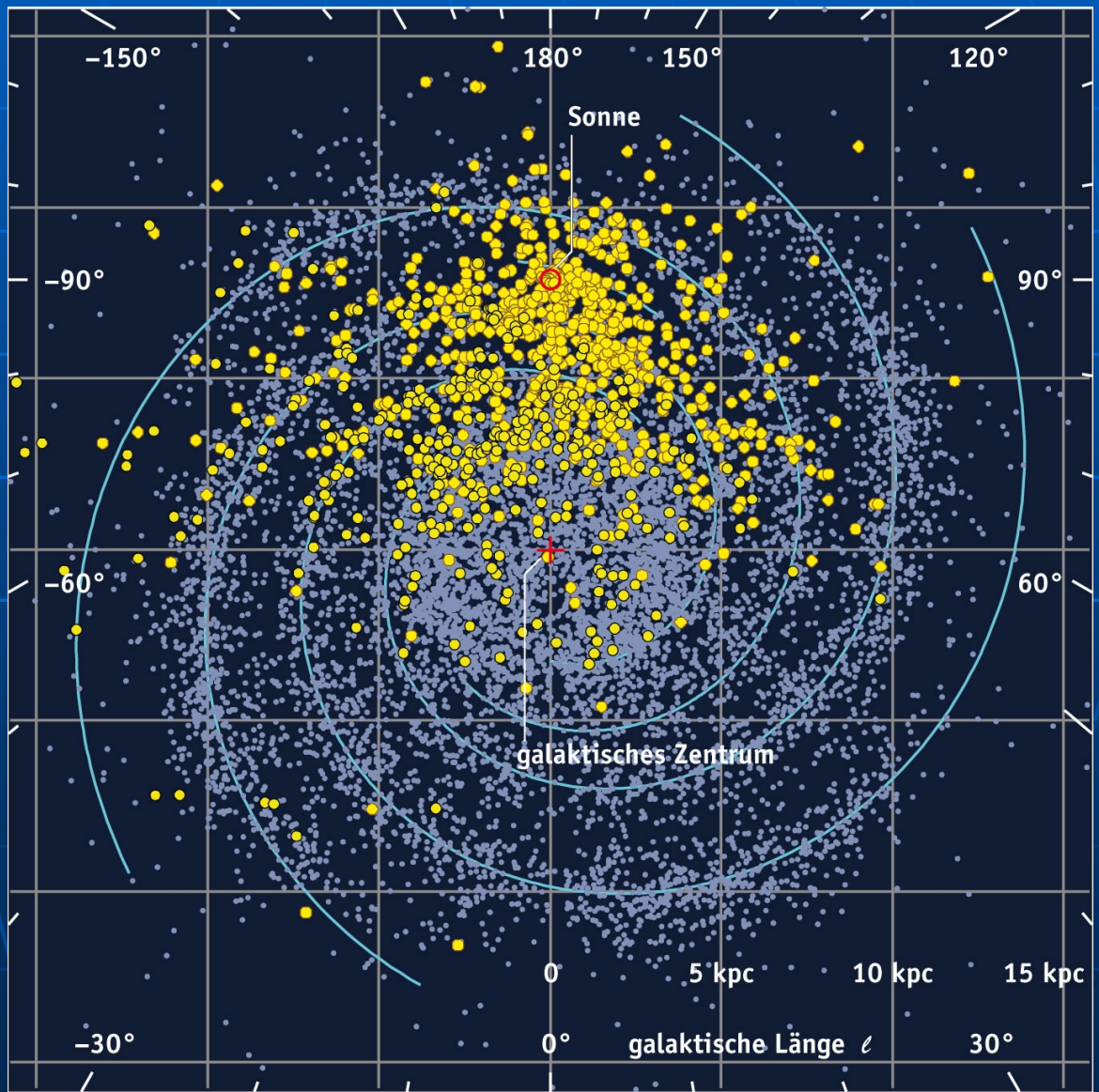
Brown et al. (2006)

Only one reversal is required



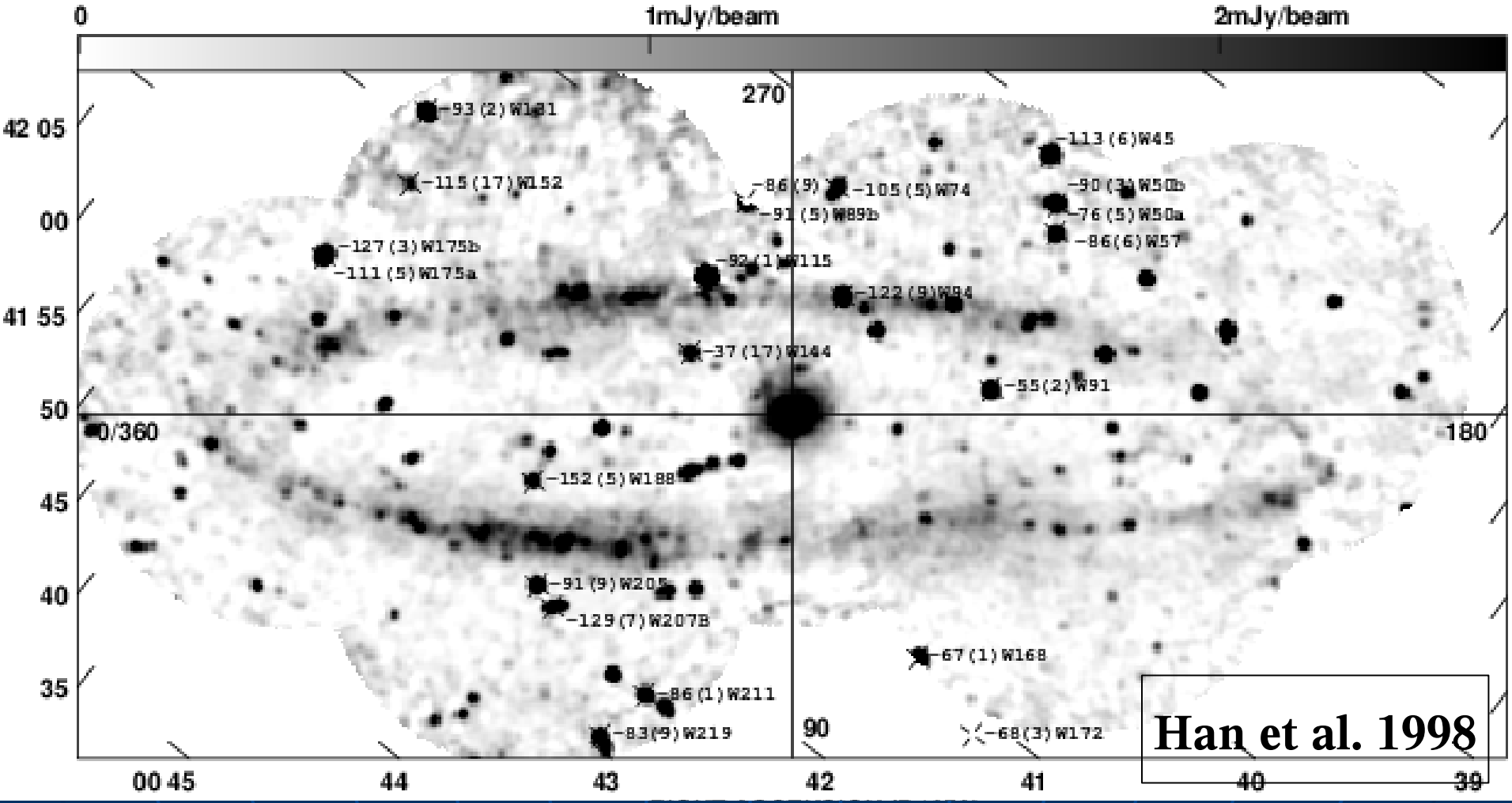
Future rotation measures of pulsars in the Milky Way

Known pulsars and pulsars to be detected with the SKA



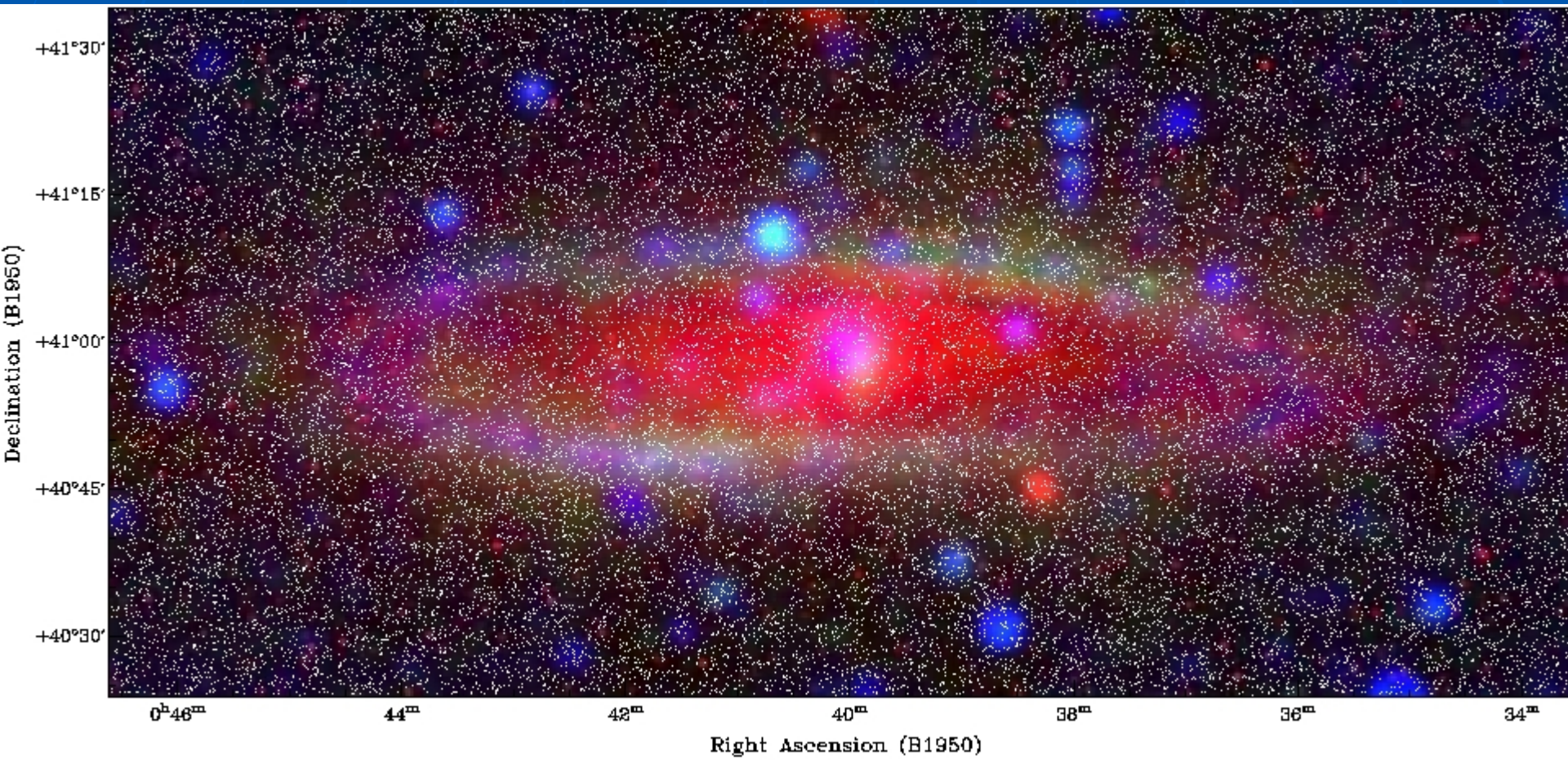
Cordes 2001

RMs through galaxies



RMs of 21 polarized sources shining through M31

RMs through M31 with the SKA (simulation by B. Gaensler)



~10000 polarized sources shining through M31

SKA low-frequency RM survey

- Galaxy halos, cluster halos, relics:

  $n_e=10^{-3}$ cm^{-3}, $B_{||}=1$ G, L=1 kpc: RM~1 rad m^{-2}

  1.4 GHz: 3° rotation

- Magnetic fields in intergalactic filaments:

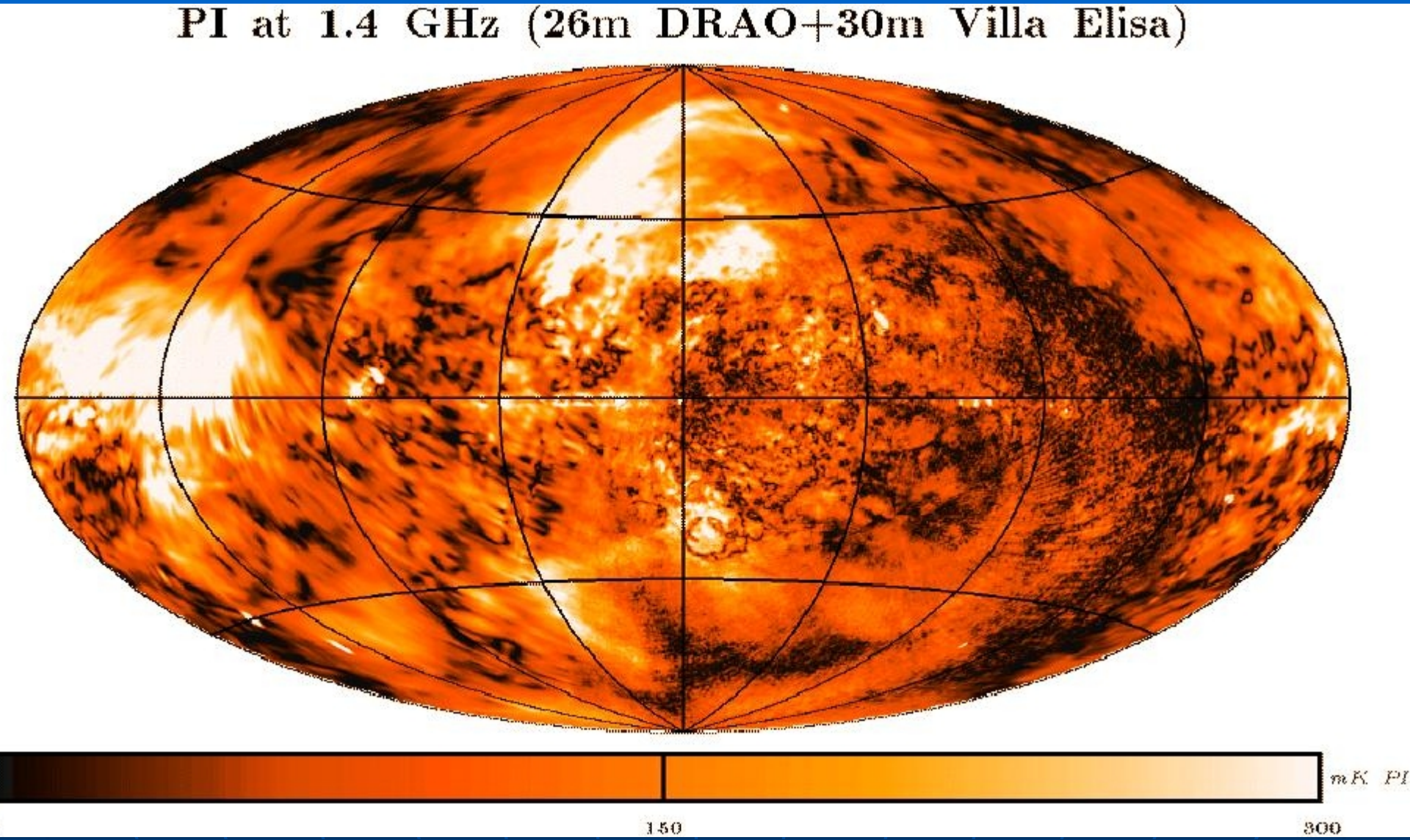
  $n_e=10^{-3}$ cm^{-3}, $B_{||}=0.1$ G, L=1 kpc: RM~0.1 rad m^{-2}

  For a detection, frequencies of <200 MHz are needed (giving >12° rotation)

The Origin and Evolution of Cosmic Magnetism

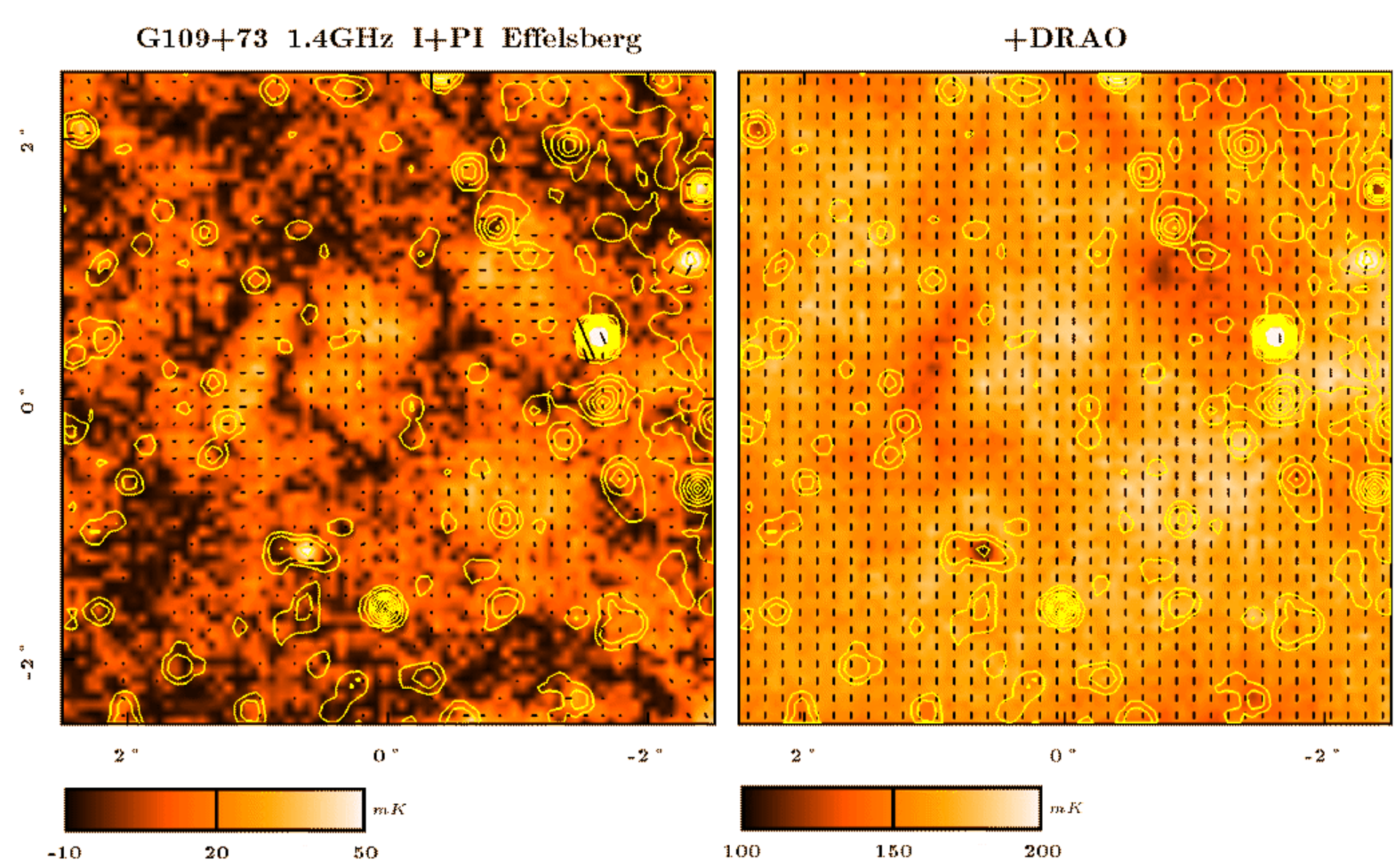
Projects :

- All-sky survey of Faraday rotation measures
- **Faraday tomography of the Milky Way and nearby galaxies**
- High-resolution polarization mapping of nearby galaxies and clusters

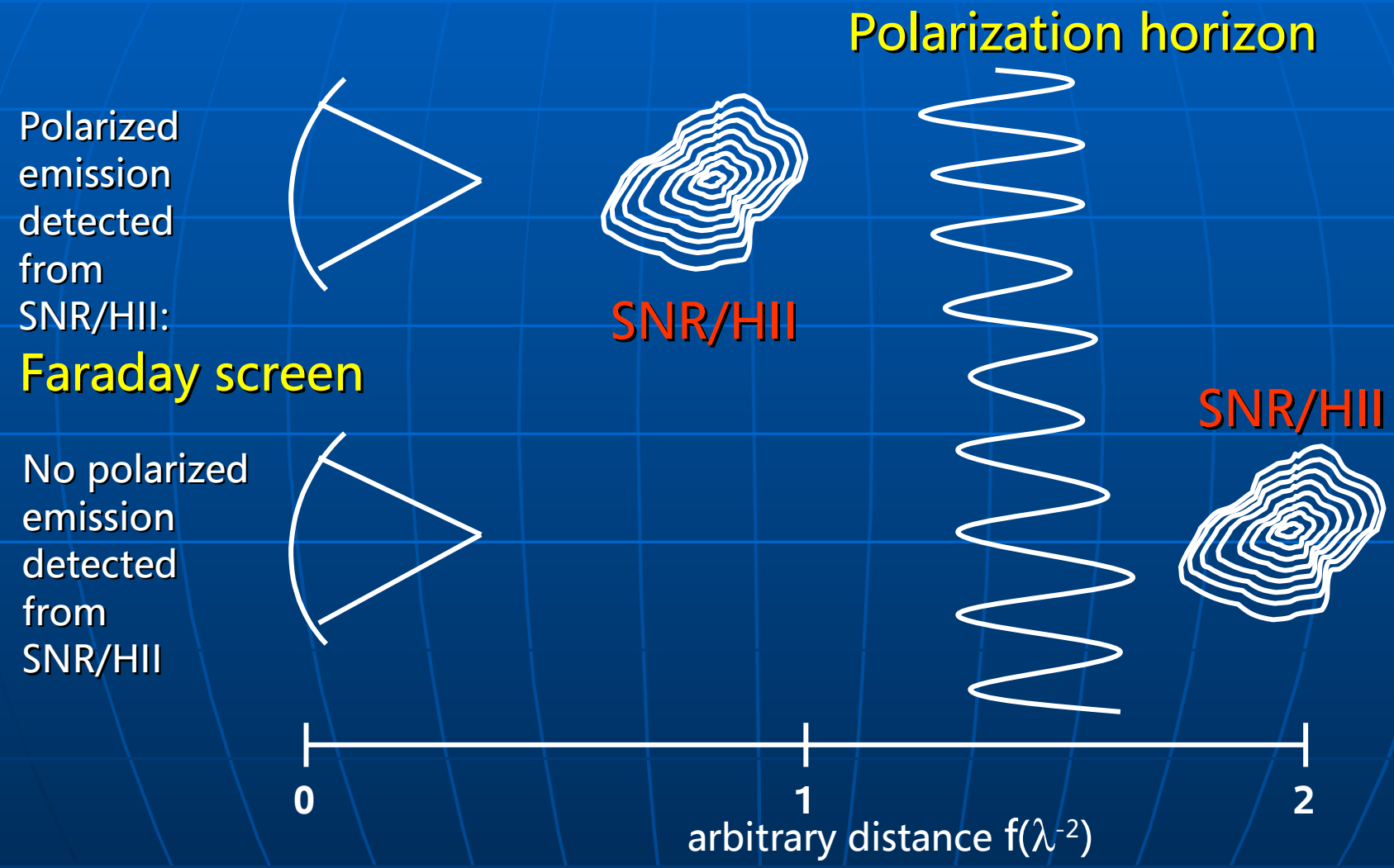


21cm DRAO+Villa Elisa all-sky polarization survey

(Reich et al., combined from Wolleben et al. 2005 & Testori et al. in prep.)



High latitude field with dominating large-scale emission:
Canals disappear !


Polarization horizon
Polarized emission detected from SNR/HII:
Faraday screen
SNR/HII
SNR/HII
No polarized emission detected from SNR/HII
0
1
2
arbitrary distance f(λ-2)

Faraday Screen

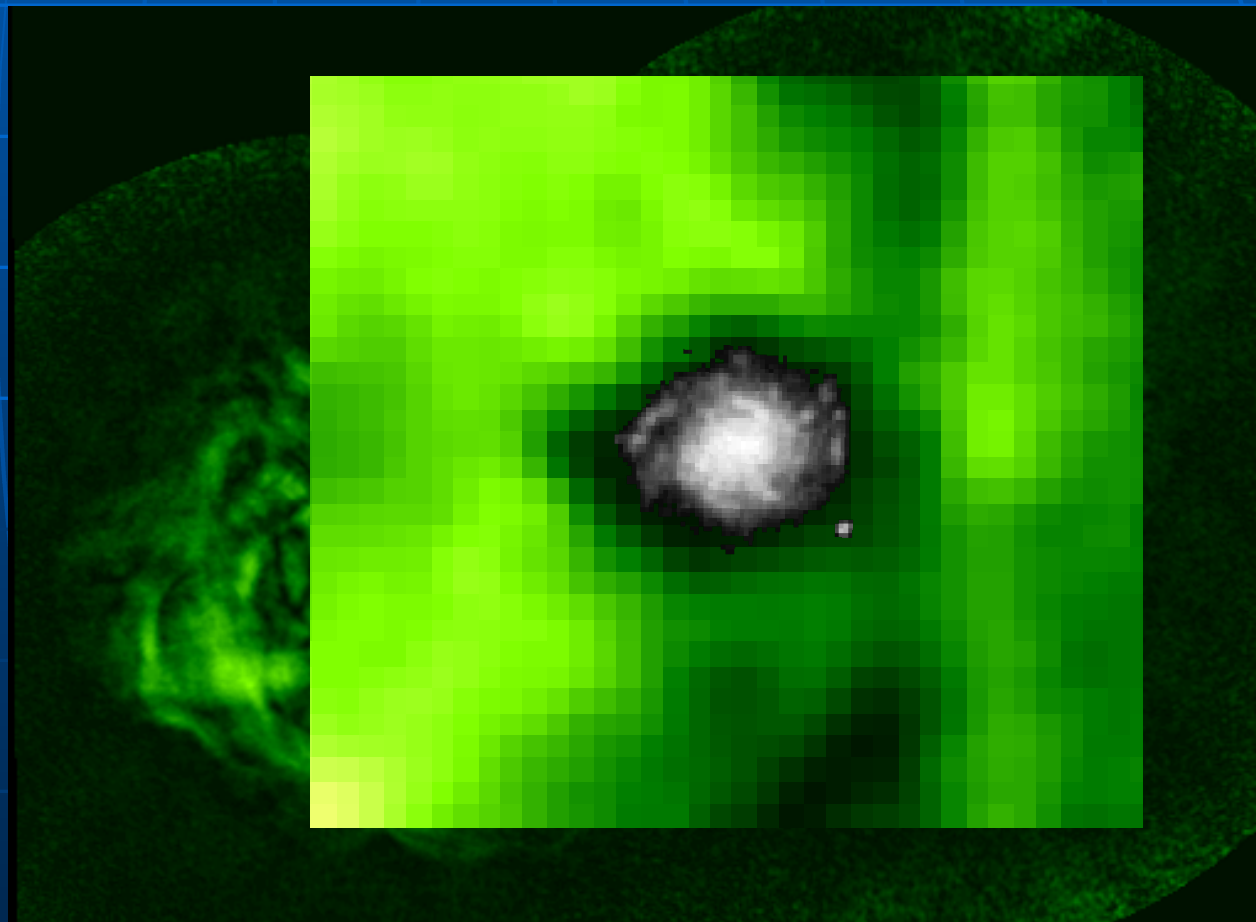
from Tom Landecker

Polarization silhouettes

Modification of extended foreground (Galactic) or background emission by Faraday rotation

NGC 1310 against Fornax A:

Faraday depolarization of polarized background emission
(Fomalont et al. 1989)

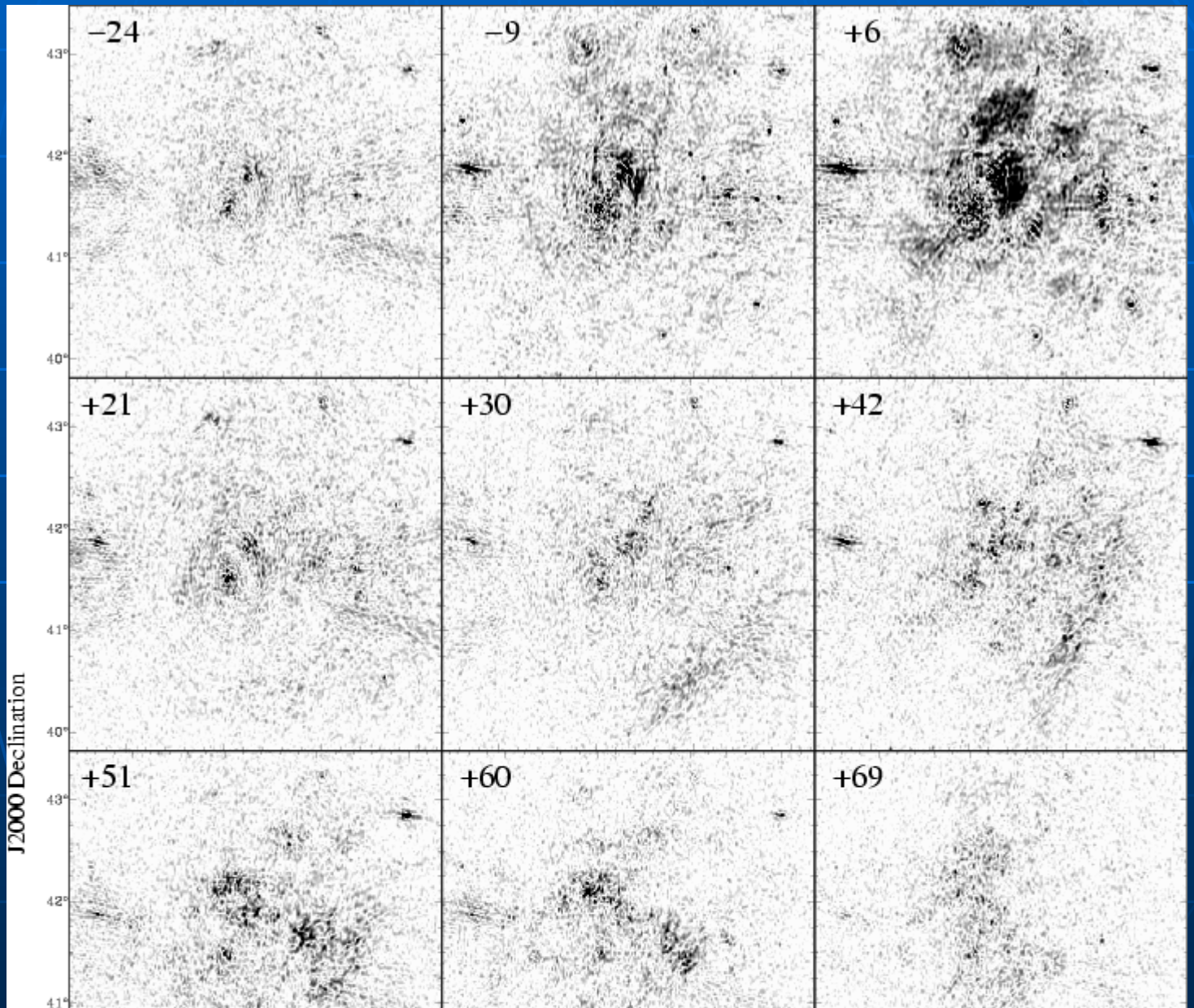


Spectro-polarimetry
(*RM synthesis or tomography*) :

Different RMs trace different layers along the line of sight

RM Synthesis in the Perseus cluster

de Bruyn & Brentjens (2005)



The Origin and Evolution of Cosmic Magnetism

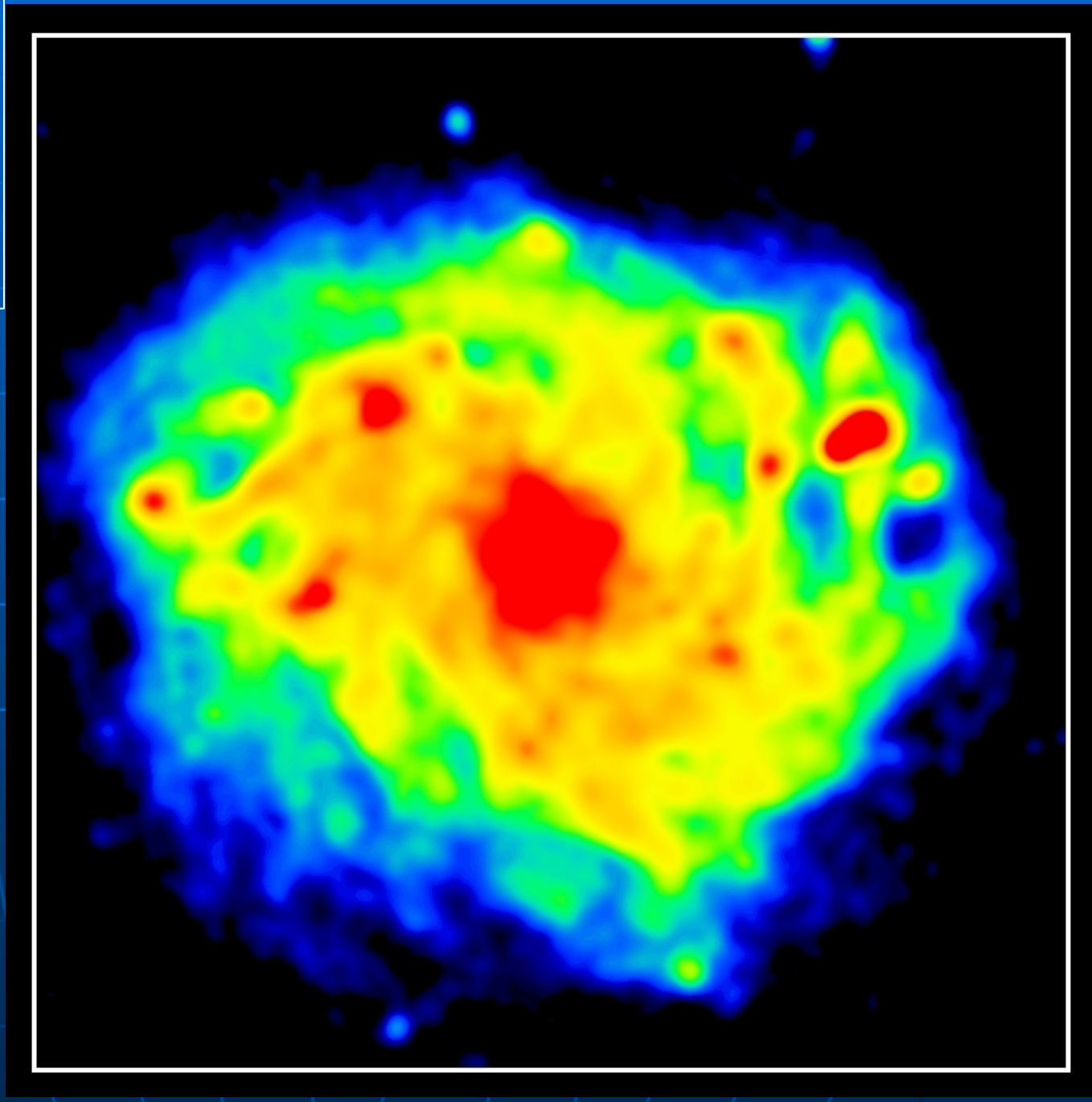
Projects :

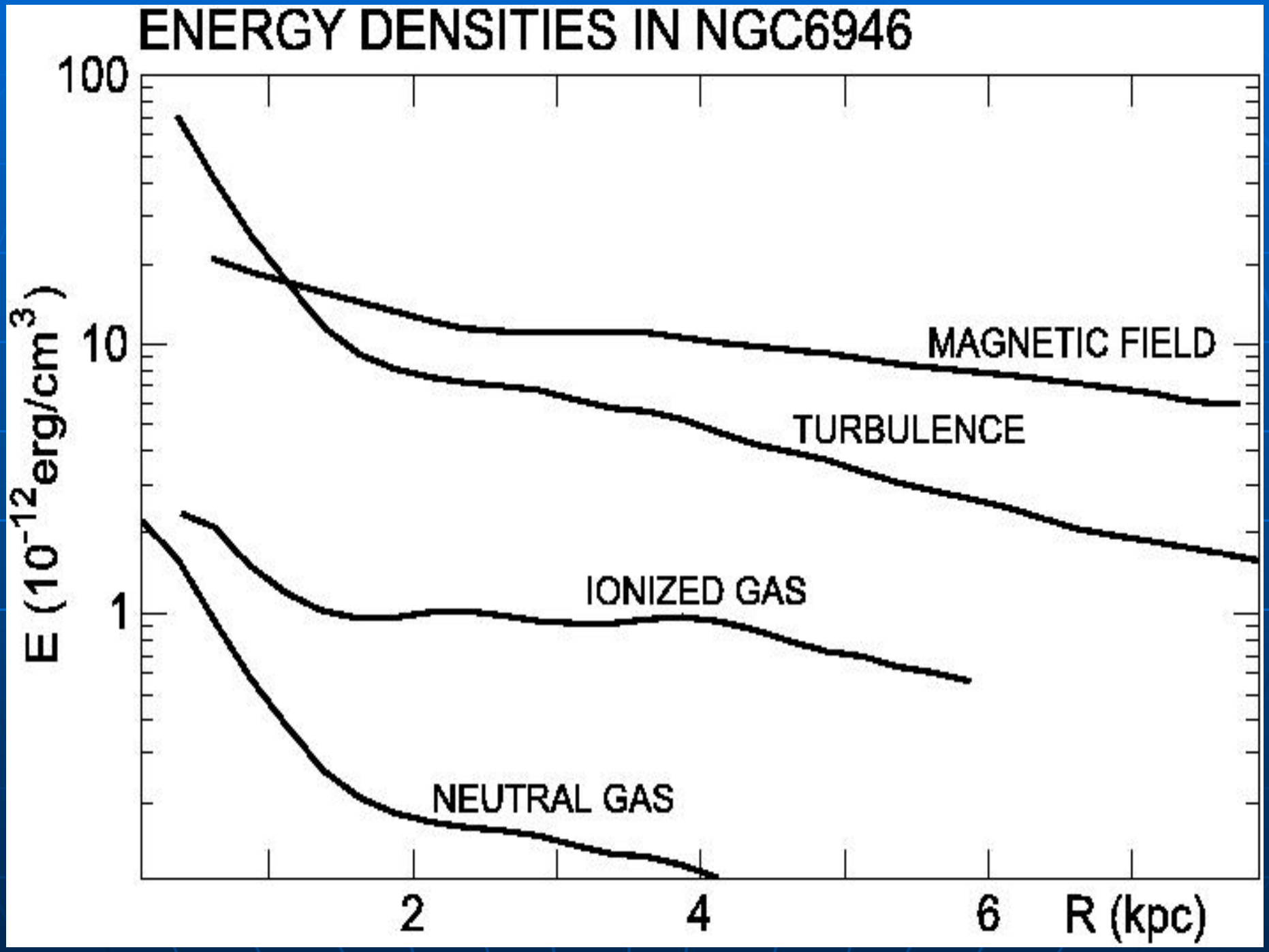
- All-sky survey of Faraday rotation measures
- Faraday tomography of the Milky Way and nearby galaxies
- **High-resolution polarization mapping of nearby galaxies and clusters**

NGC6946

20cm Total synchrotron

(Beck 2006)

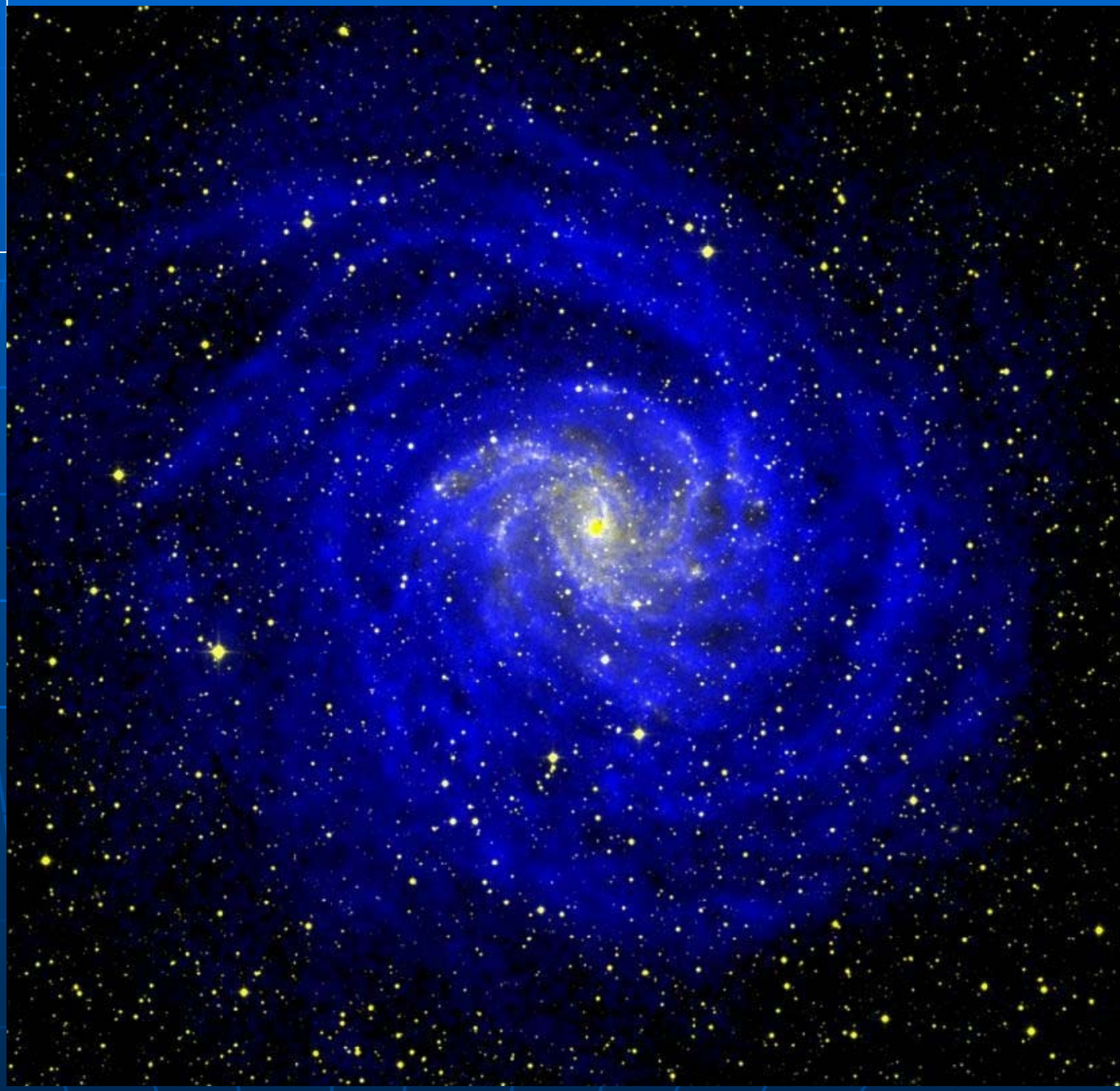



ENERGY DENSITIES IN NGC6946
100
10
1
E (10^-12 erg/cm^3)
MAGNETIC FIELD
TURBULENCE
IONIZED GAS
NEUTRAL GAS
2
4
6
R (kpc)

NGC6946

HI + optical

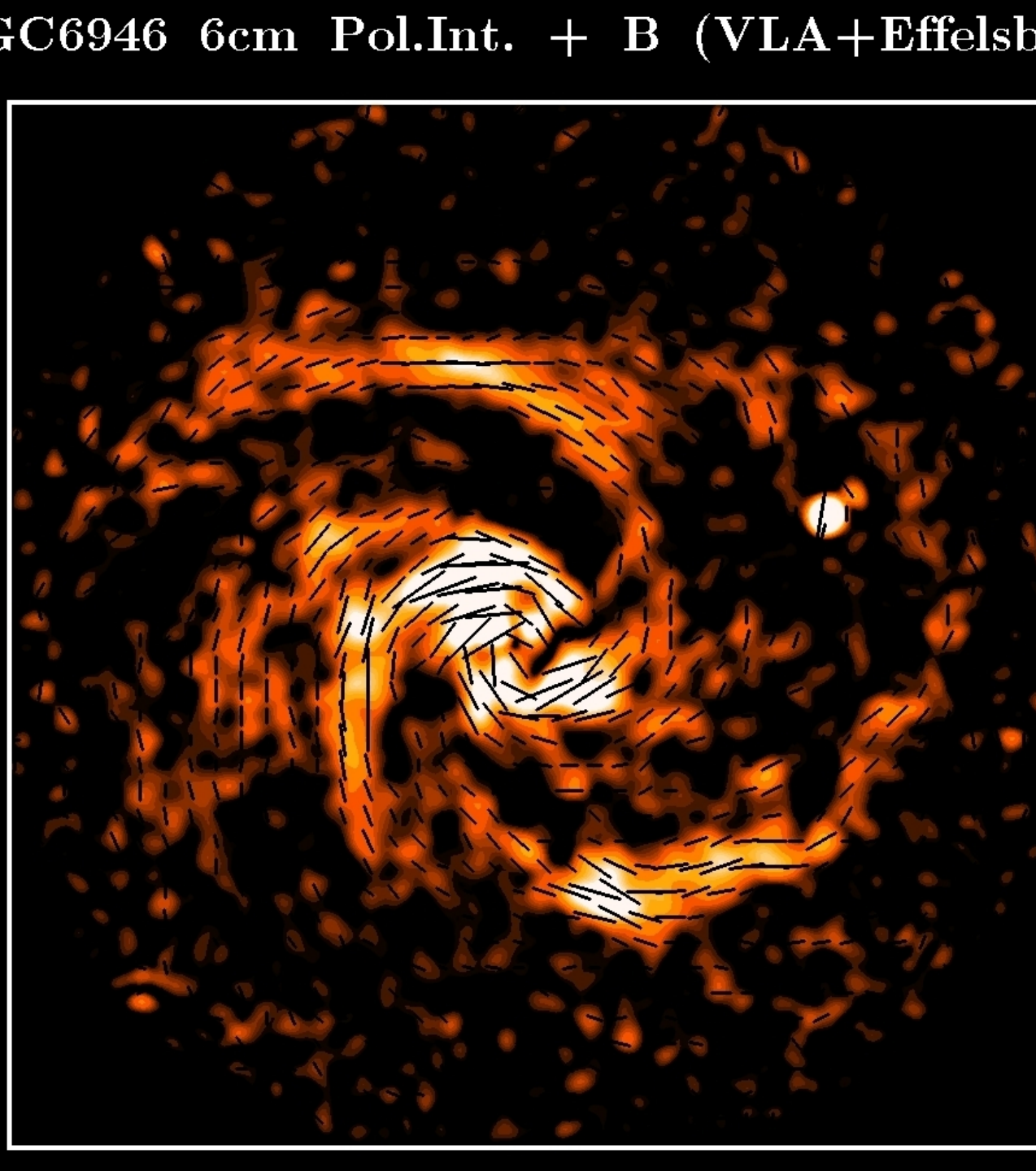
(Braun 2006)



NGC6946

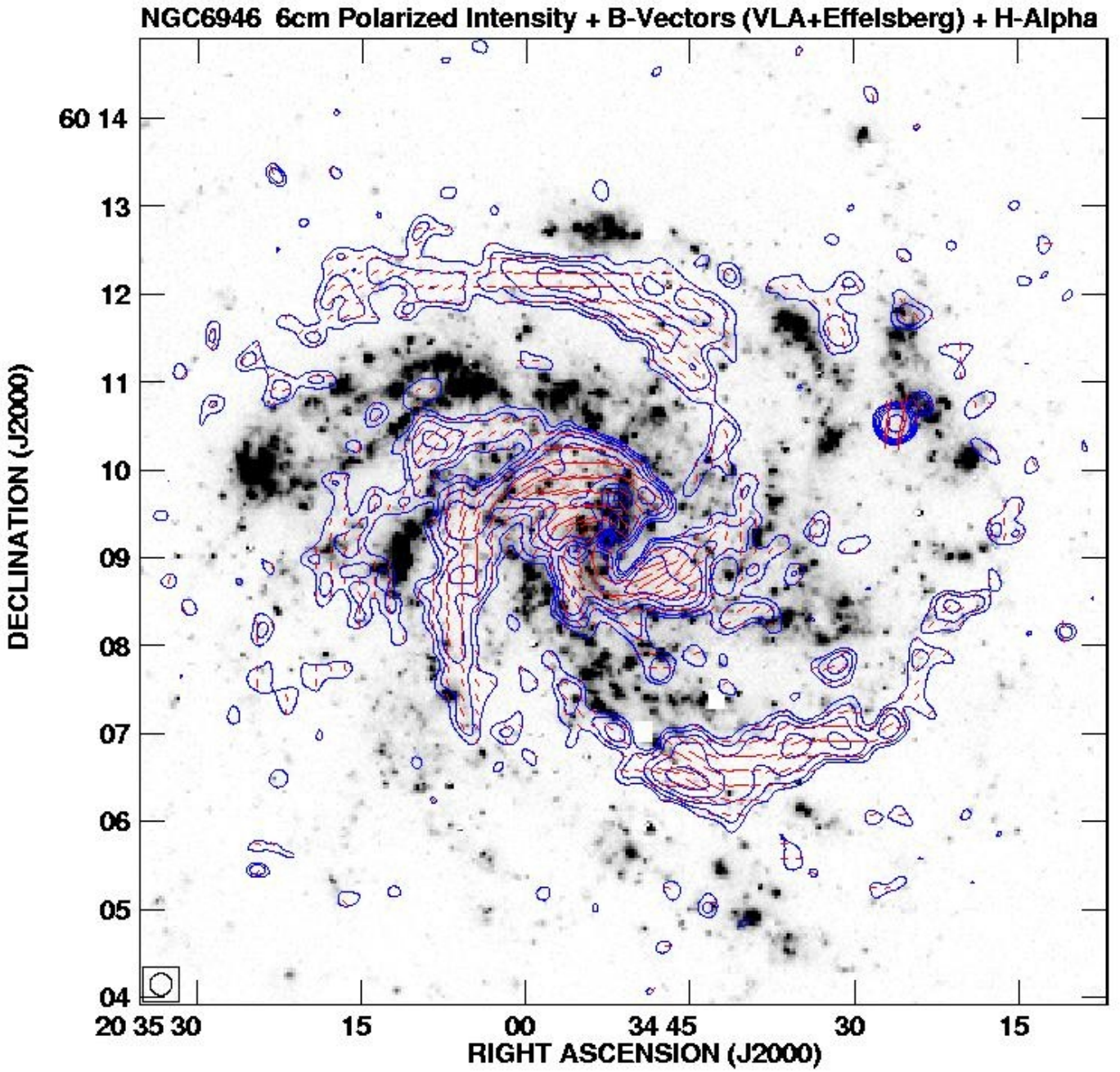
(Beck & Hoernes 1996)

Magnetic arms



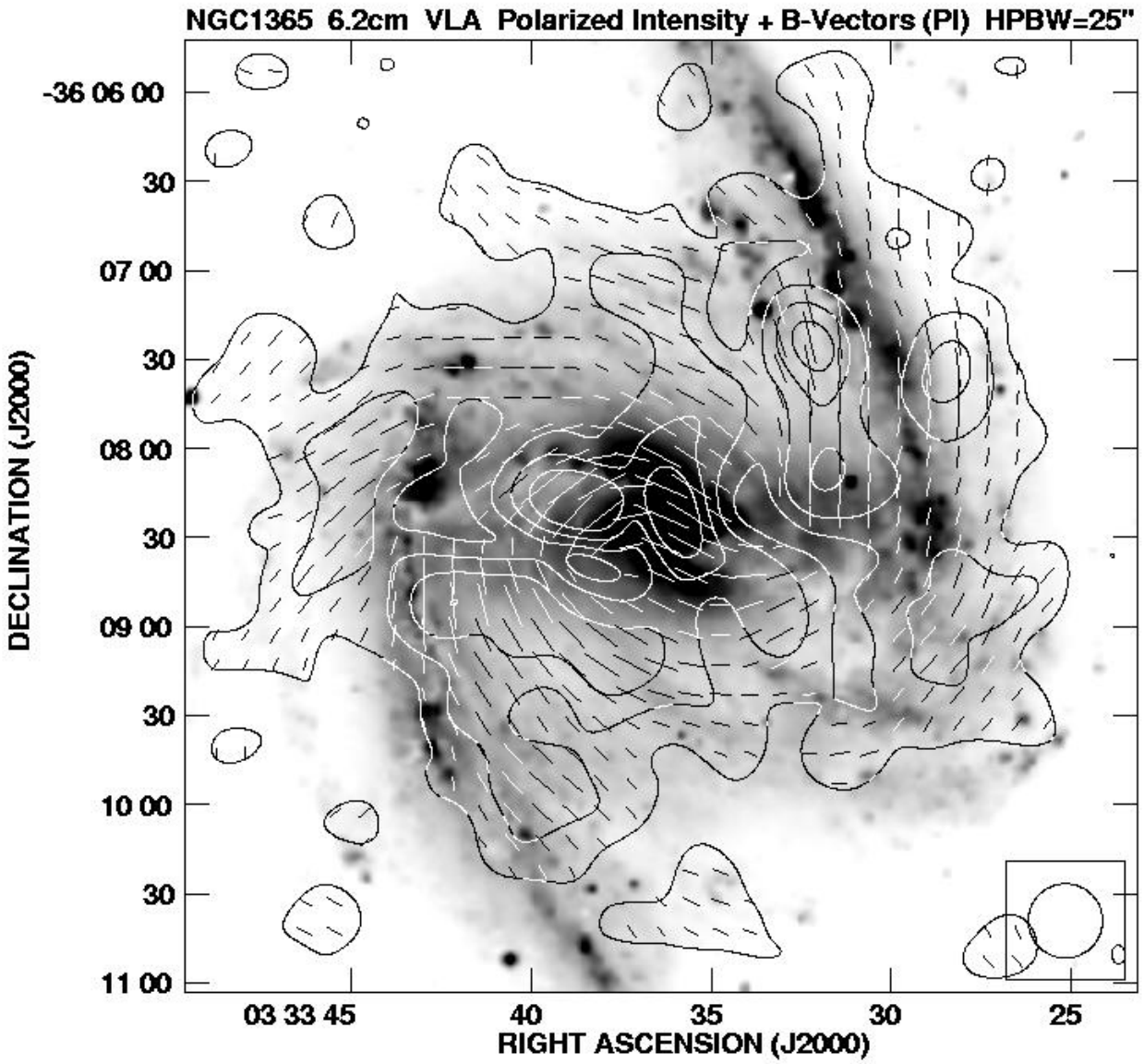
NGC6946

(Beck & Hoernes 1996)



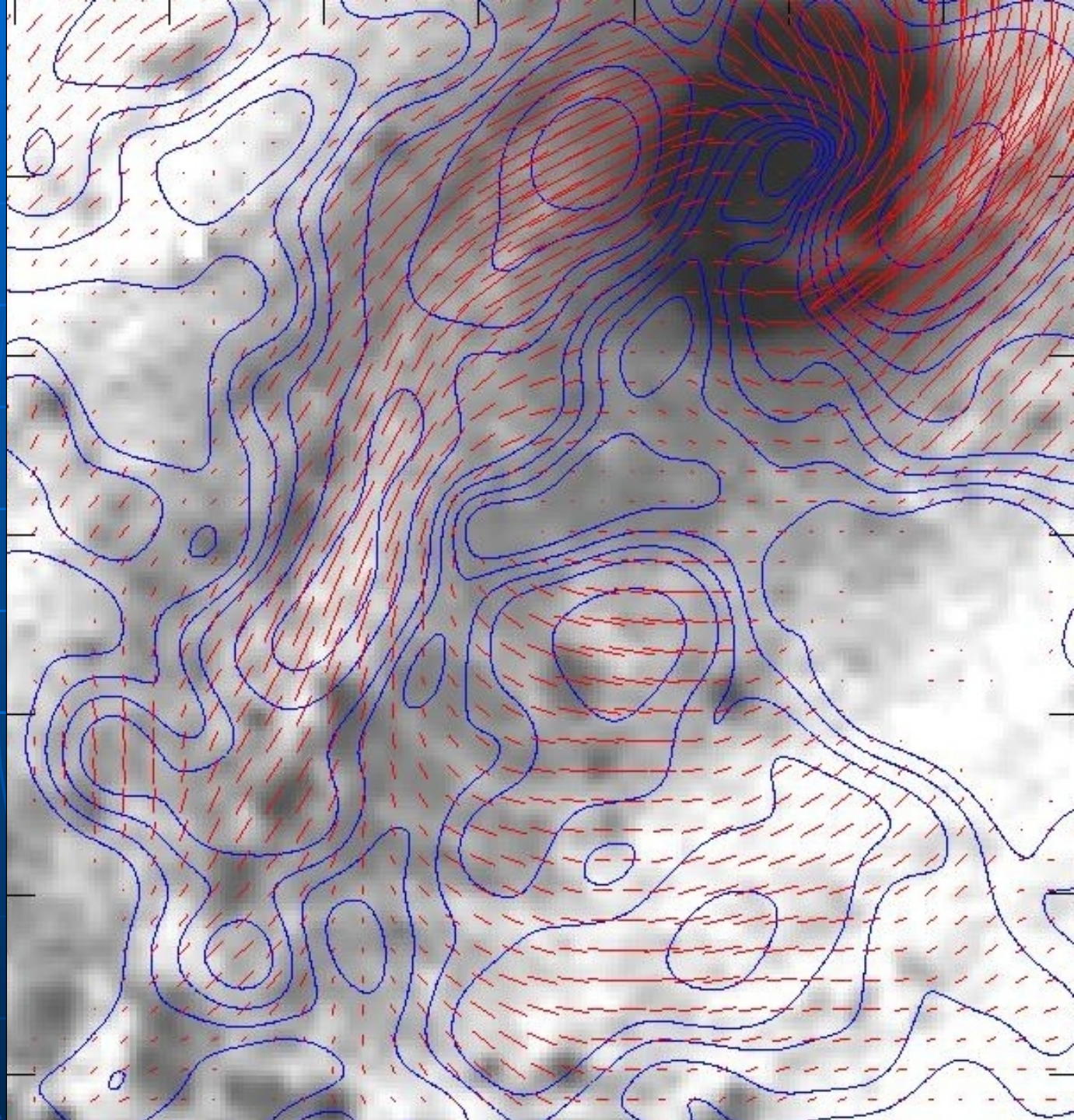
NGC1365
(Beck et al. 2005)

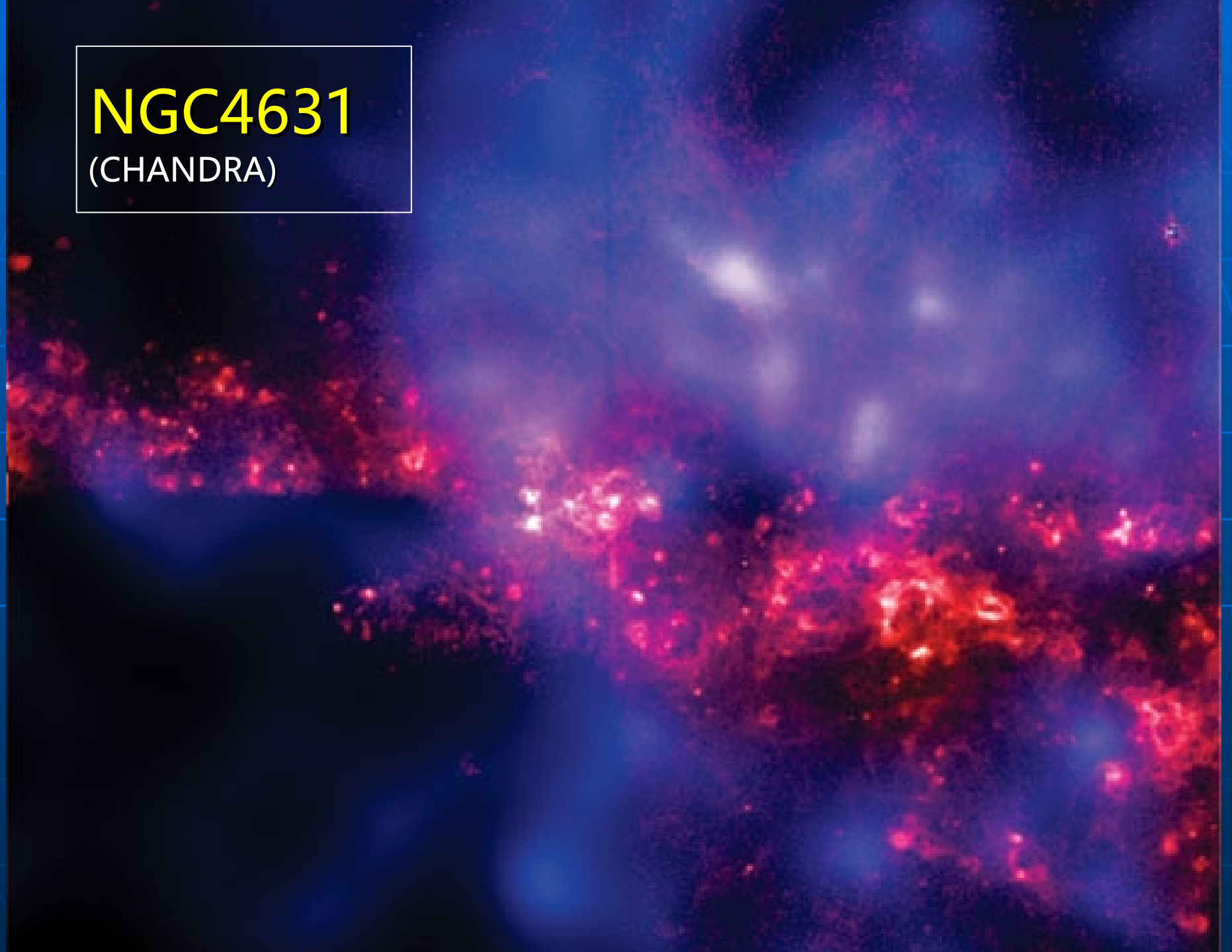
Barred galaxies:
strong spiral fields
outside the bar



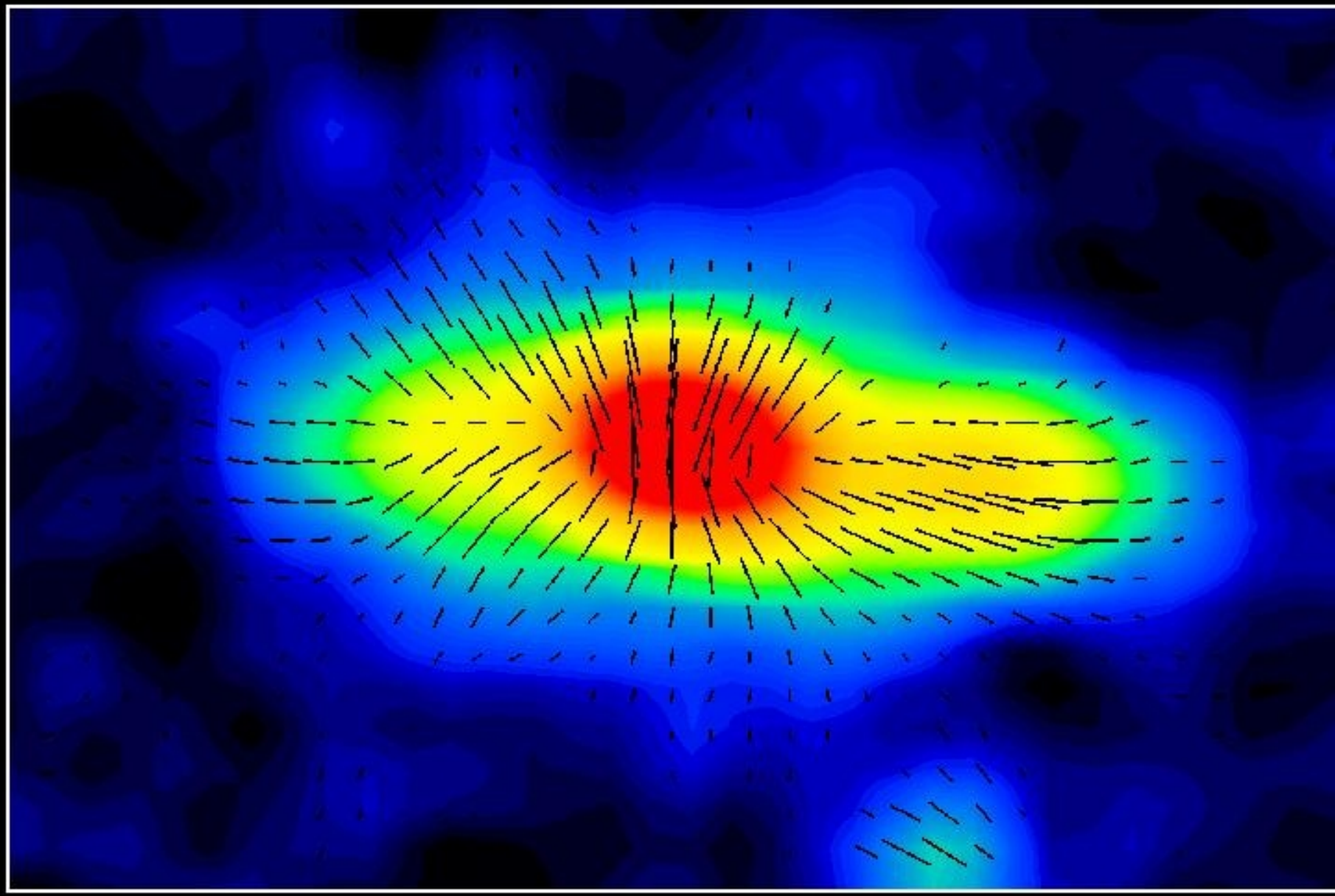
NGC1097
(Beck et al. 2005)

The magnetic field of NGC1097 decouples from the cold gas




NGC4631
(CHANDRA)

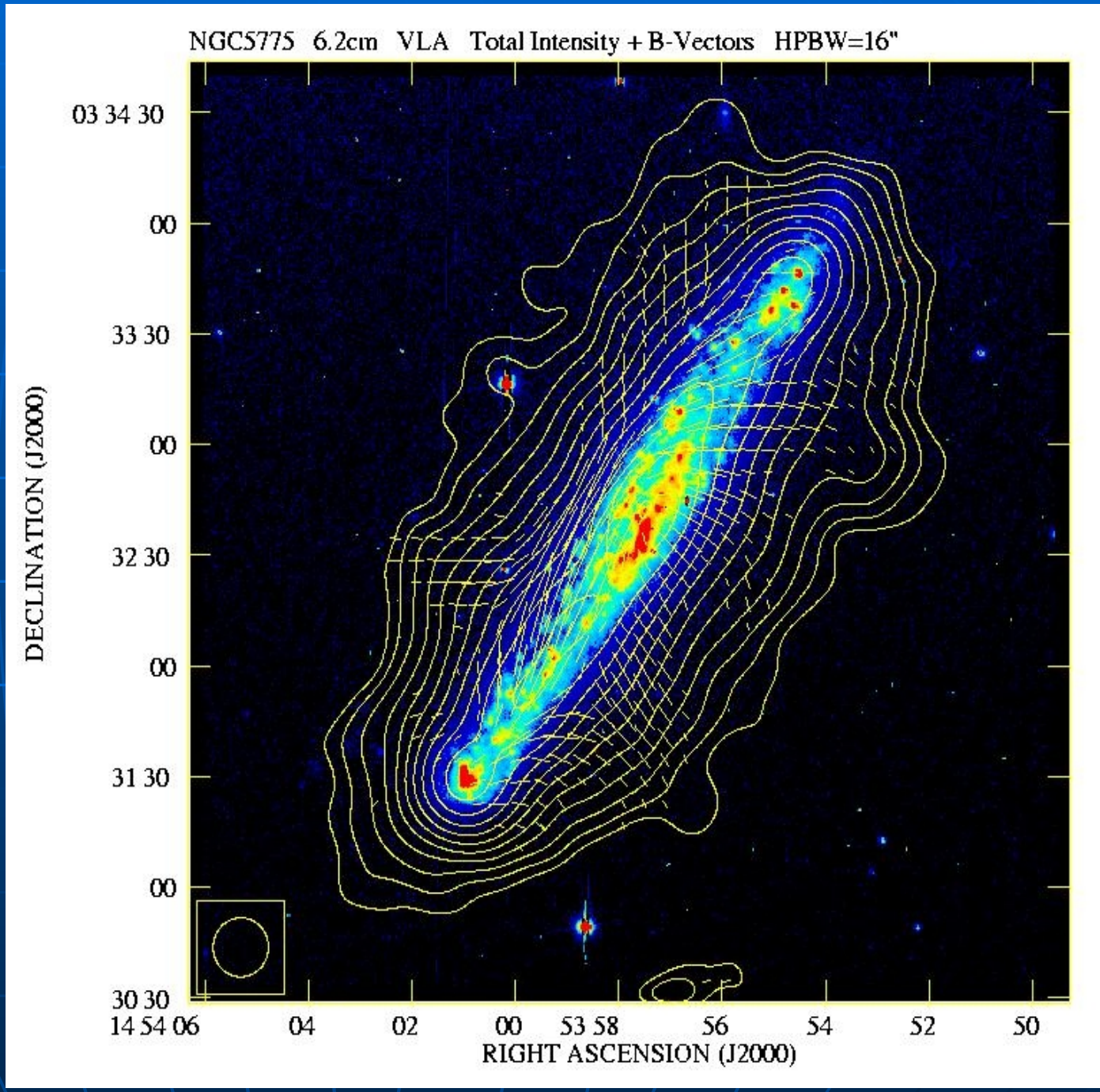
NGC4631 3.6cm Total Intensity + B-Vectors (Effelsberg)



NGC5775

(Tüllmann et al. 2001)

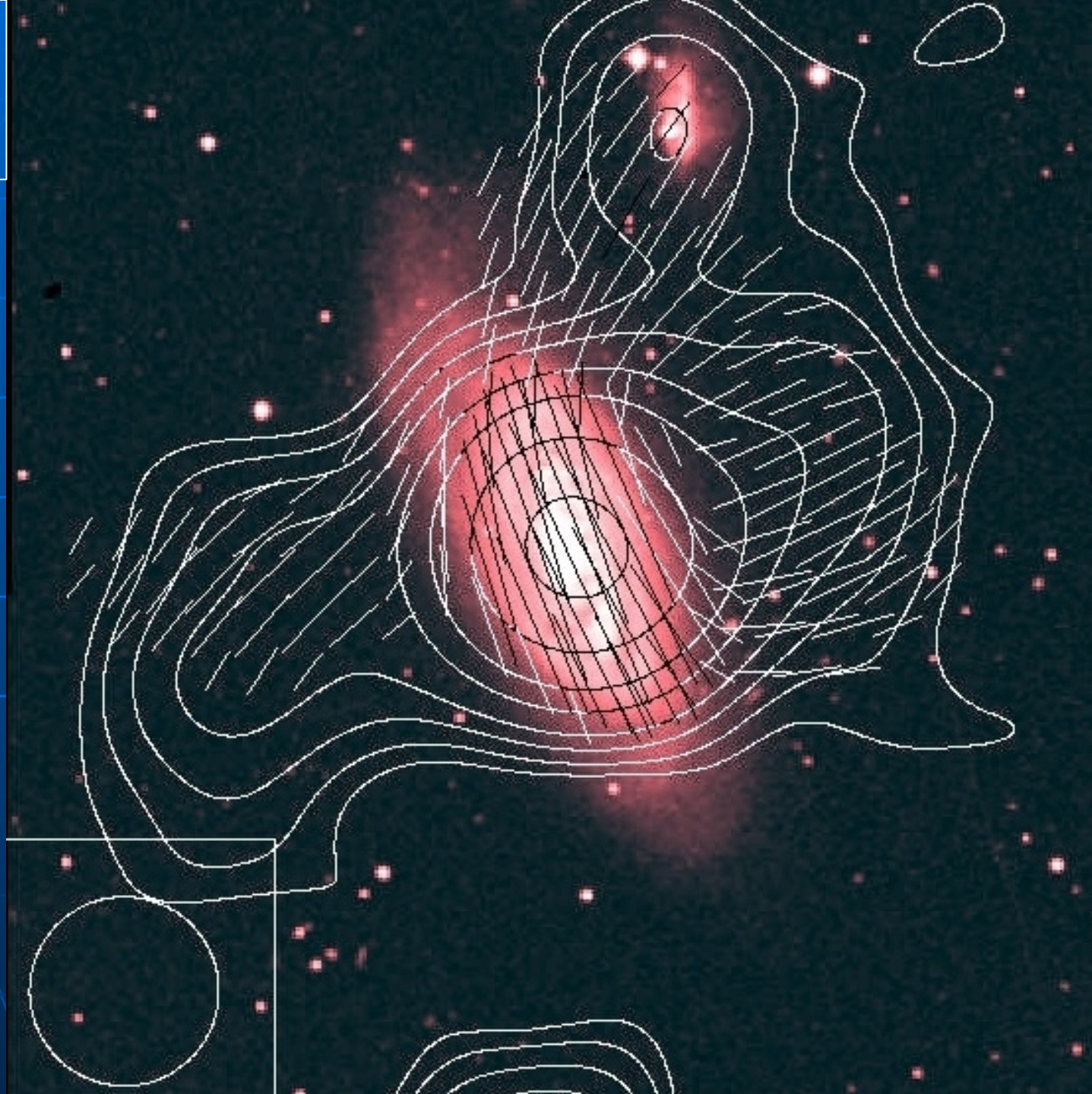
Field pushed out by a galactic wind



NGC4569

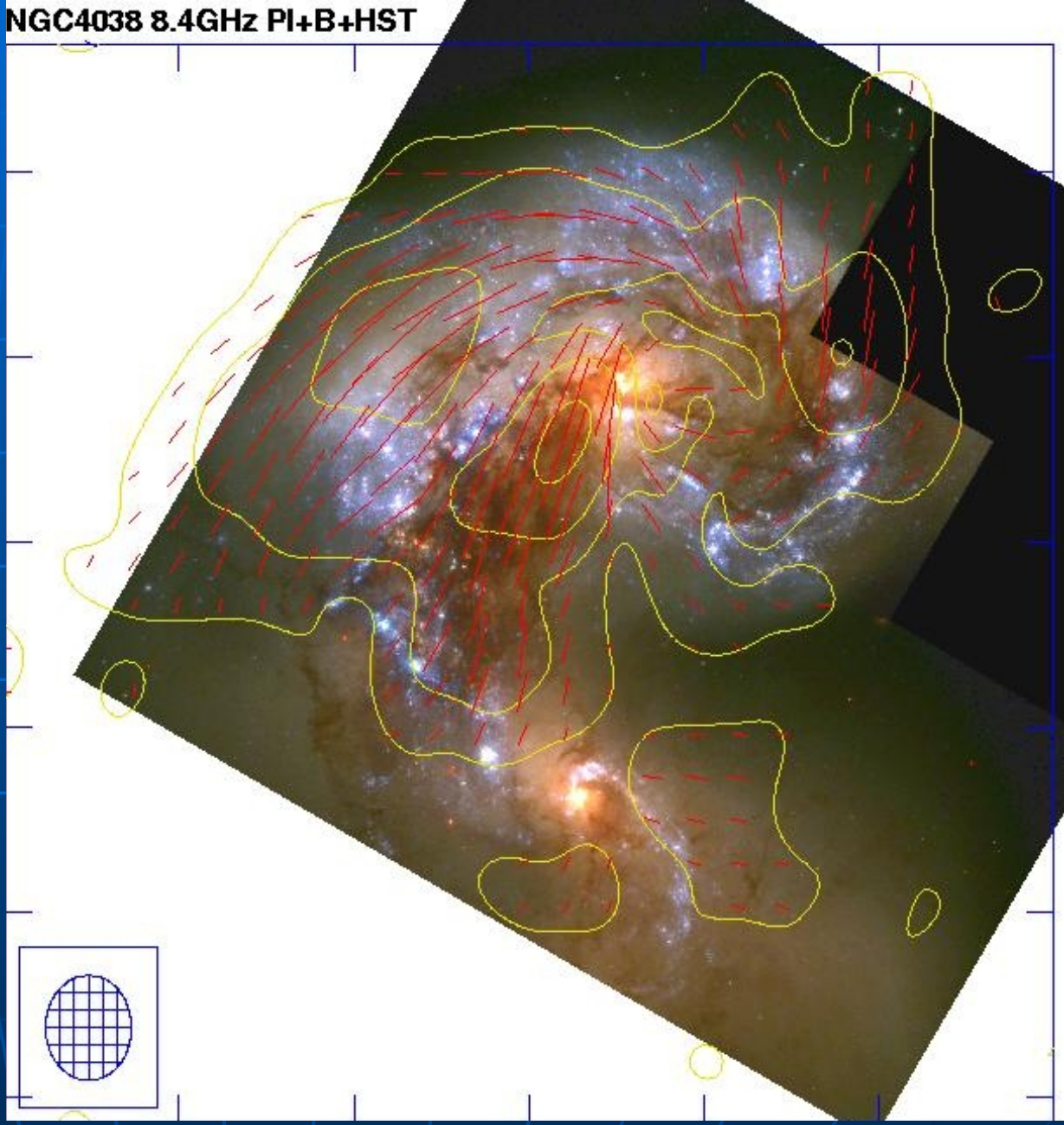
(Chyzy et al.)

Field pushed out by interaction



The Antennae

(Chyzy & Beck 2004)

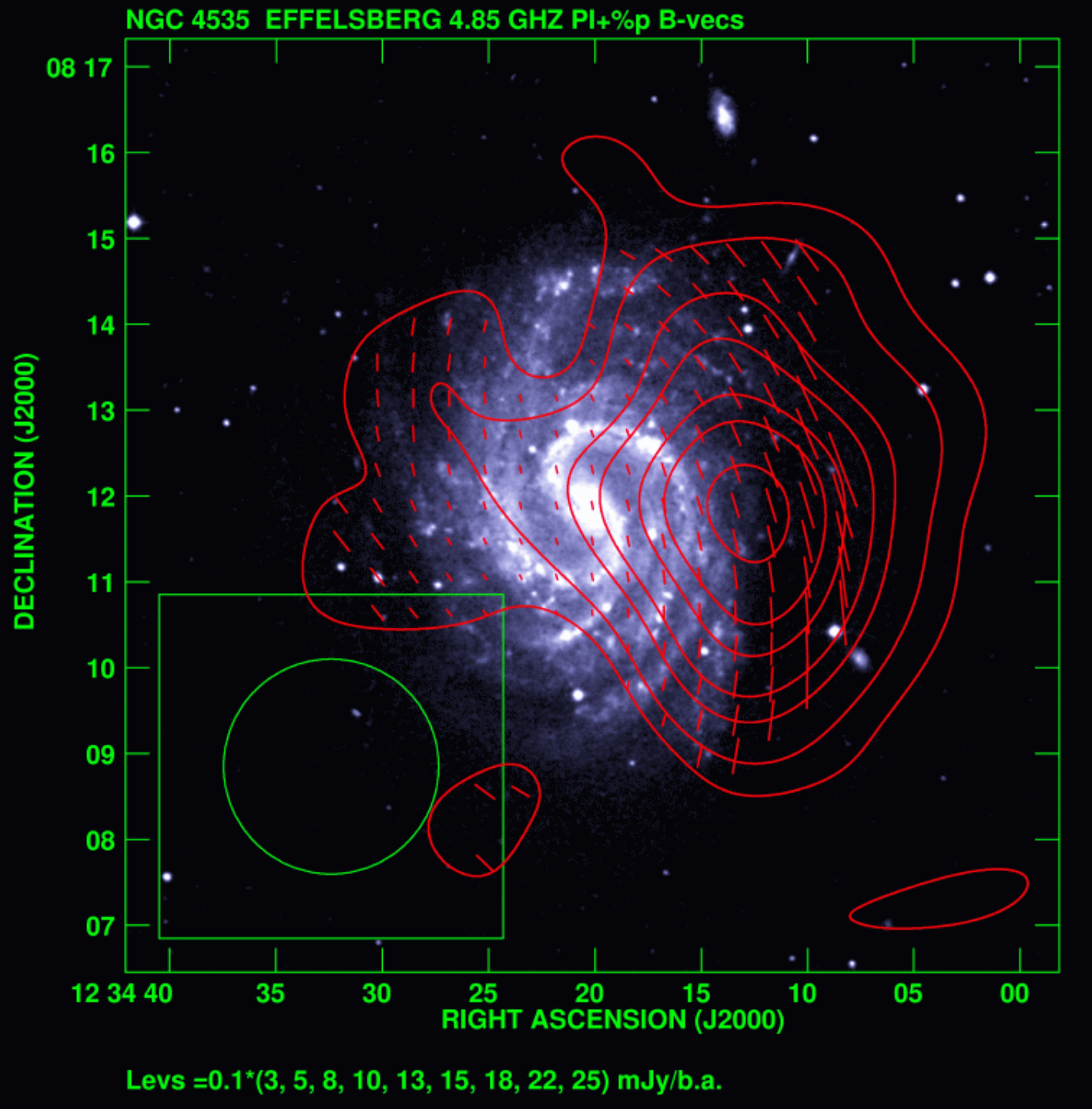


Field amplified by compression

NGC4535

(Chyzy et al.)

Field compressed by ram pressure



The origin of galactic magnetic fields

- *Stage 1*: Field seeding

(primordial, Weibel instability, ejection of seed fields by jets, radio lobes, SNRs, stellar wind etc.)

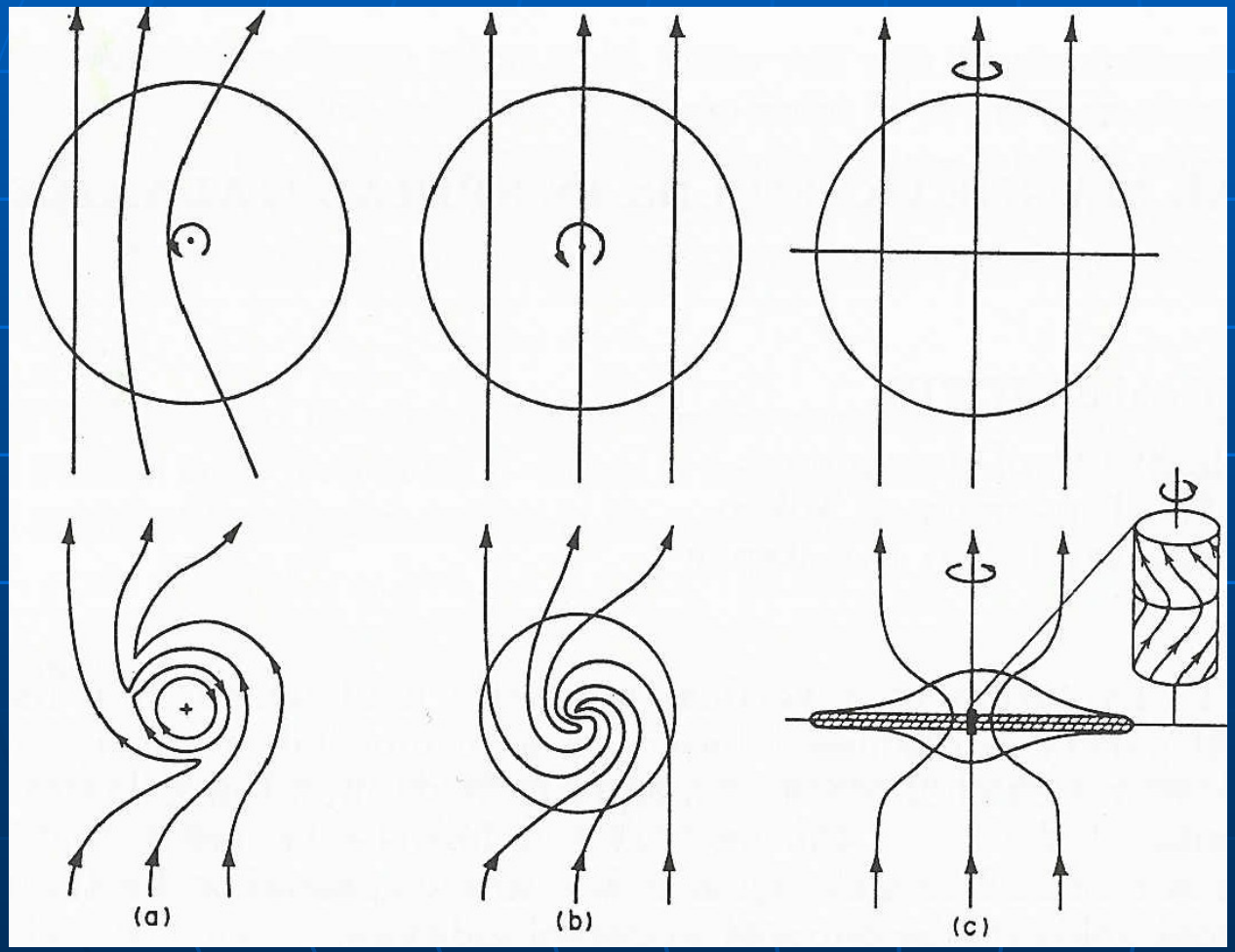
- *Stage 2*: Field amplification

(magneto-rotational instability, compression flows, shear flows, turbulent flows, dynamo)

- *Stage 3*: Field ordering

(large-scale flows, large-scale dynamo)

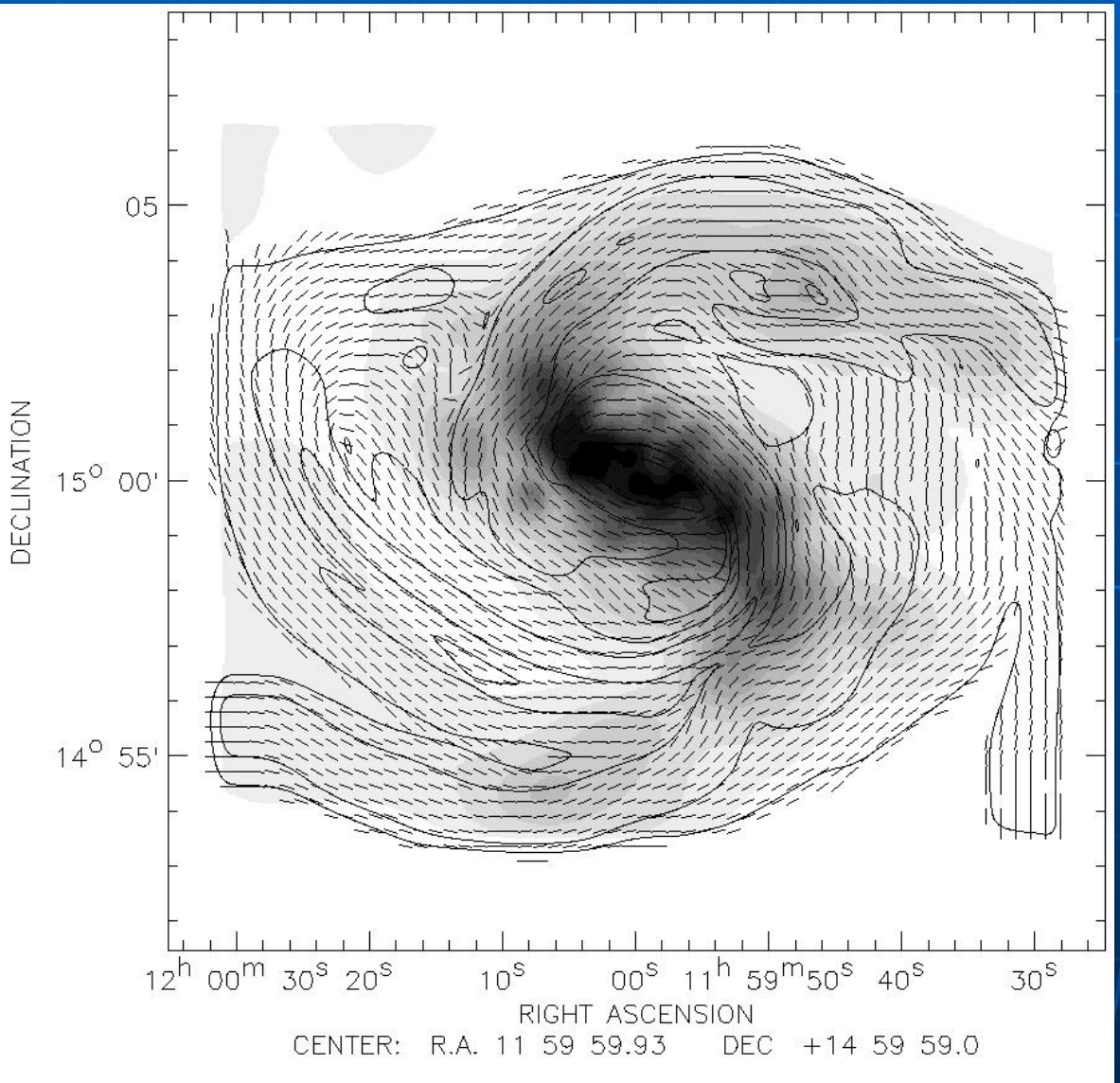
"Primordial" model



Generation of large-scale bisymmetric or dipolar fields

Sofue 1990

MHD flow model of a barred galaxy



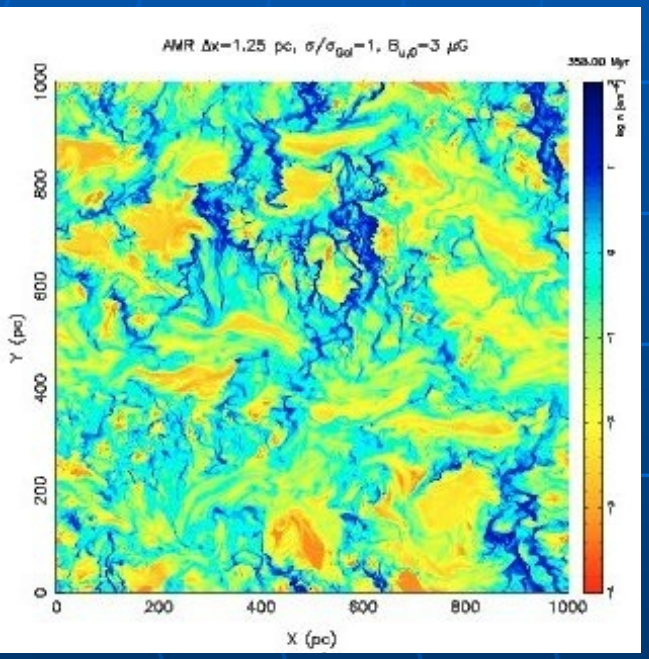
Generation of coherent fields

Coherence length:

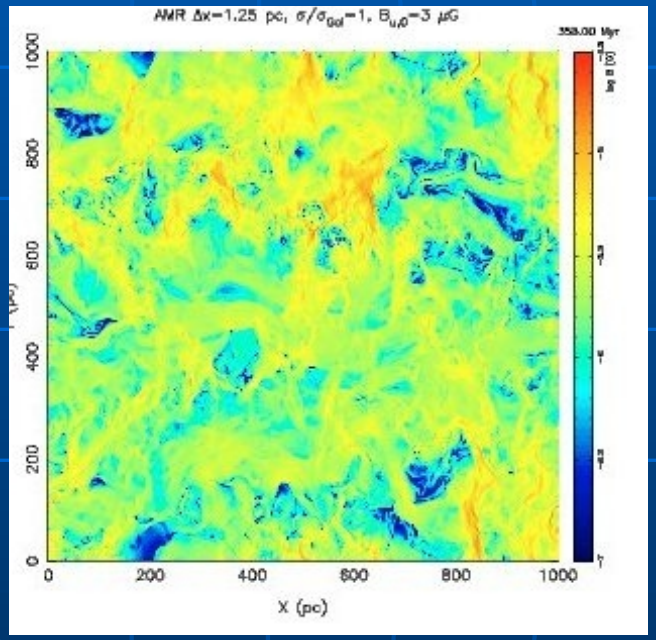
•1 kpc

Otmianowska-Mazur, Elstner, Soida & Urbanik 2002

3D MHD model of turbulence in the interstellar medium



Gas density



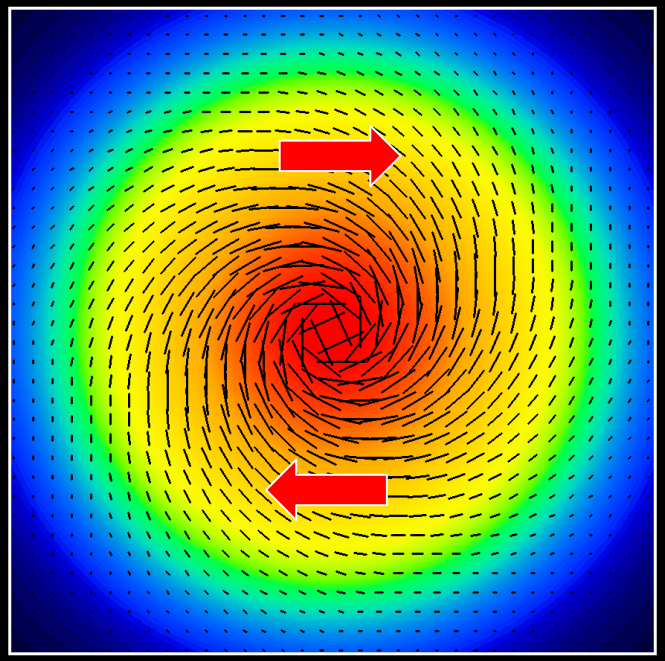
Magnetic field strength

Generation of anisotropic fields

de Avillez & Breitschwerdt 2005

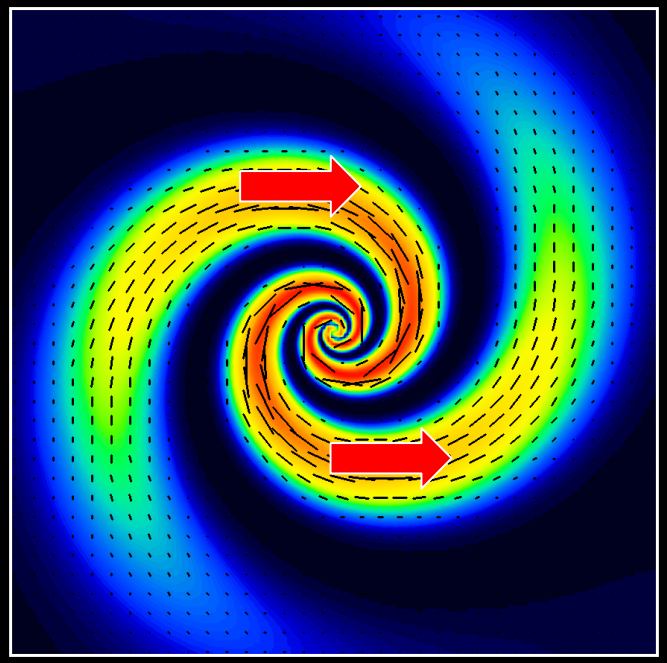

Scharlach
3 Watt
d'Allemagne

Dynamo Mode 0 (Axisymmetric Spiral)

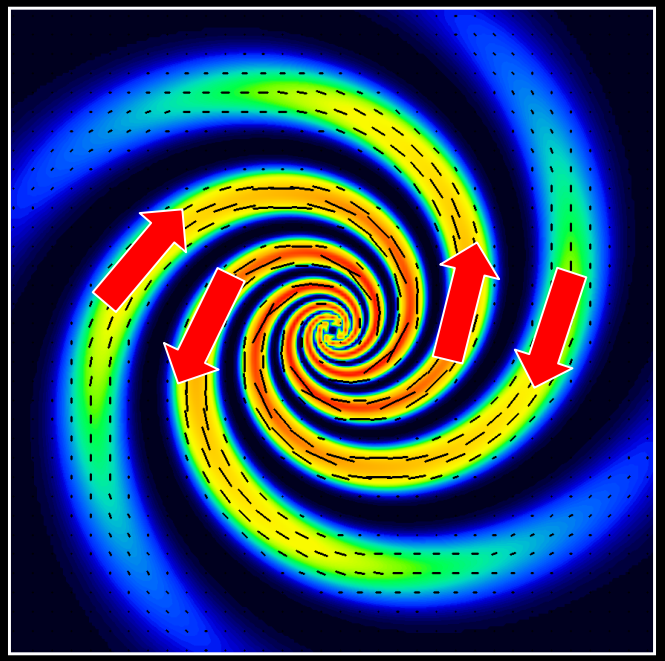


dyna

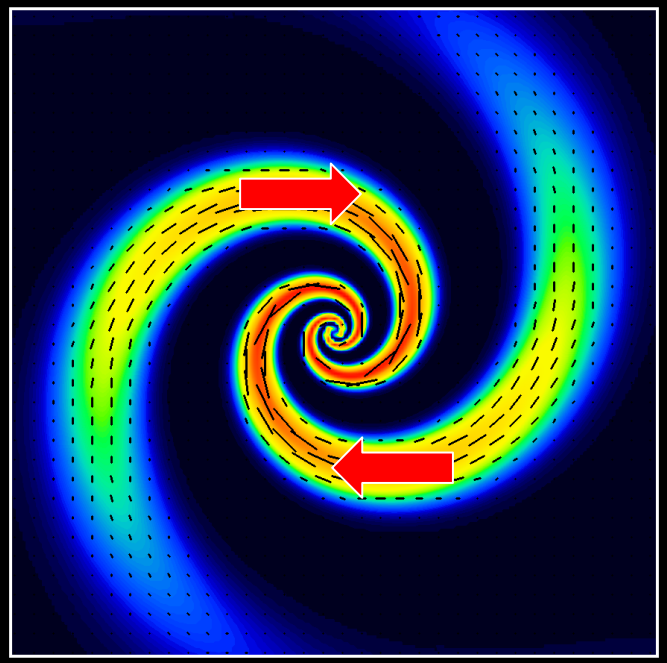
Dynamo Mode 1 (Bisymmetric Spiral)



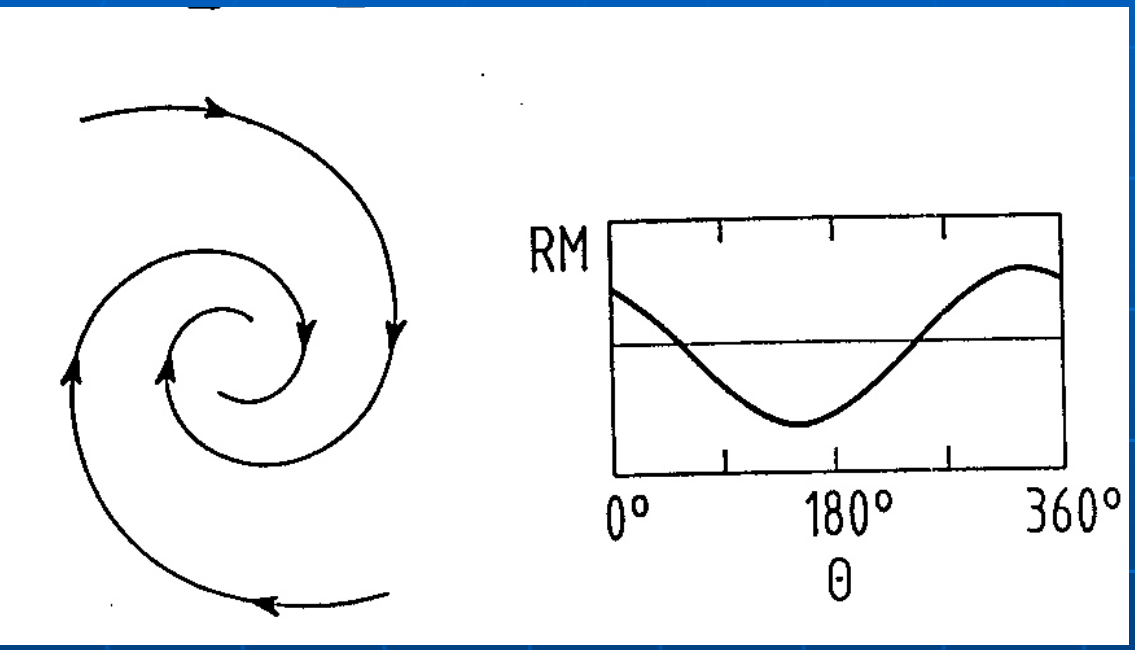
Dynamo Mode 2 (Quadrisymmetric Spiral)



Dynamo Modes 0 + 2



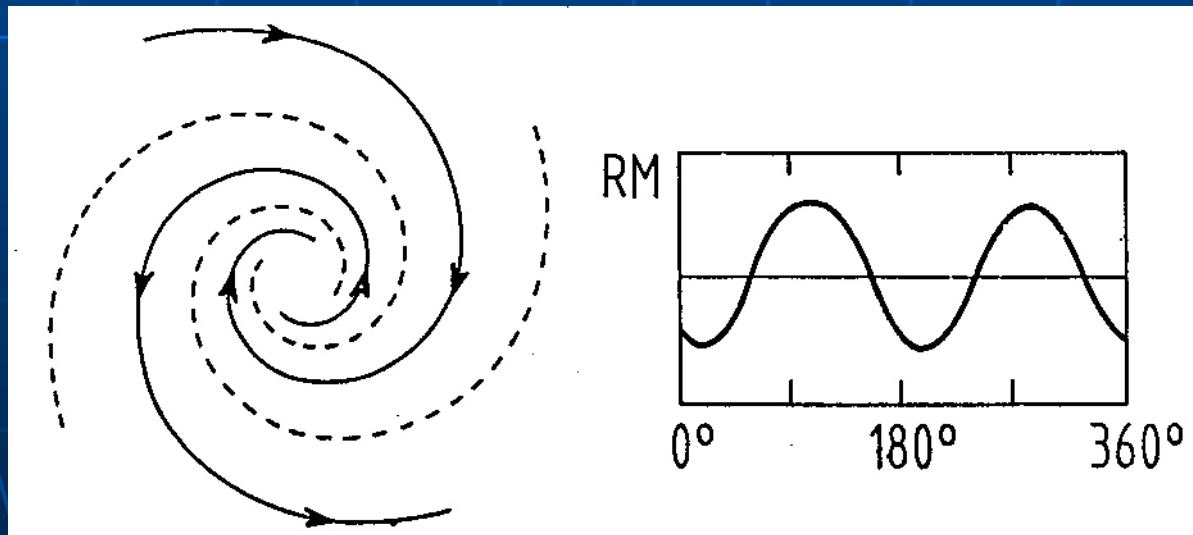
Dynamo modes & Faraday rotation



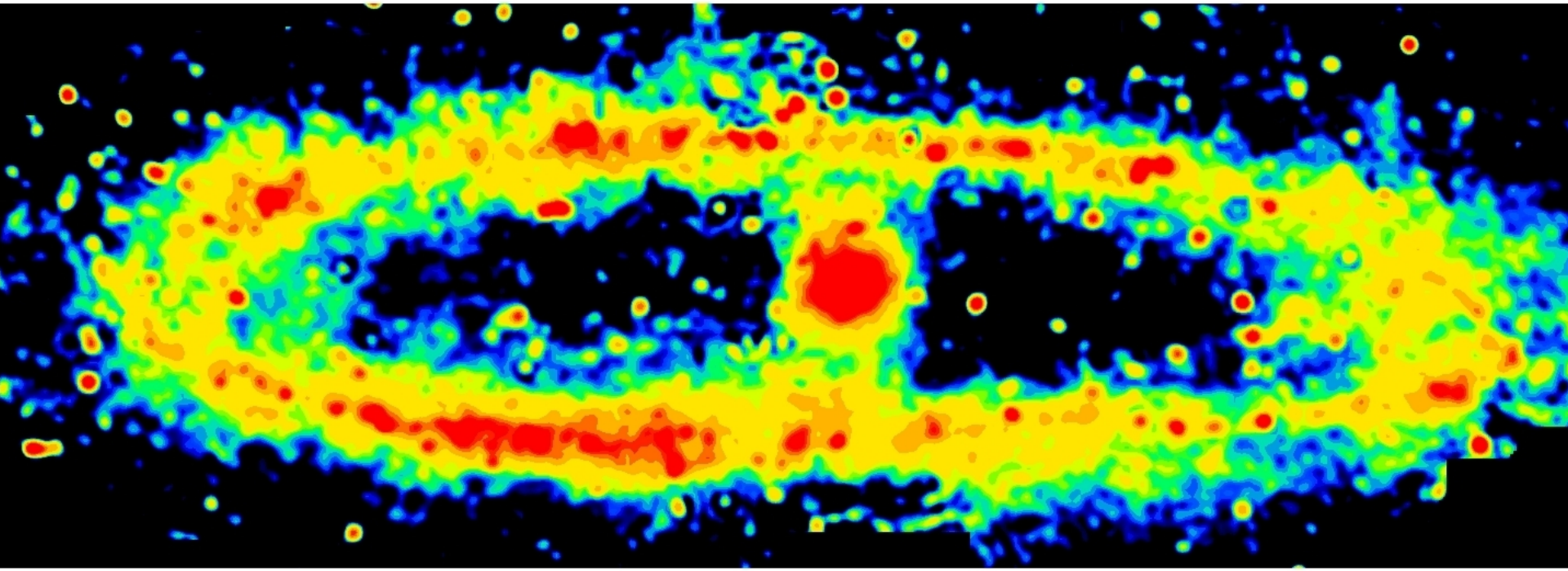
M.Krause 1990

Axisymmetric spiral
(m_a=0)

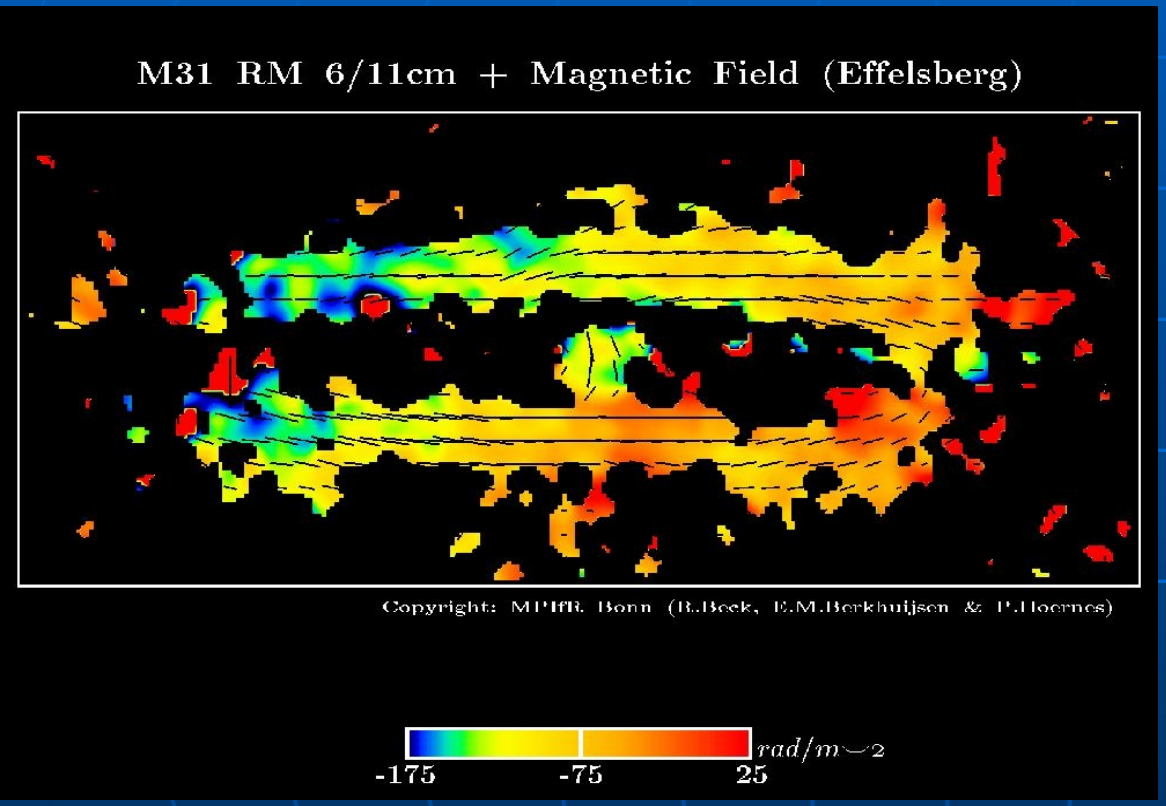
Bisymmetric spiral
(m_a=1)



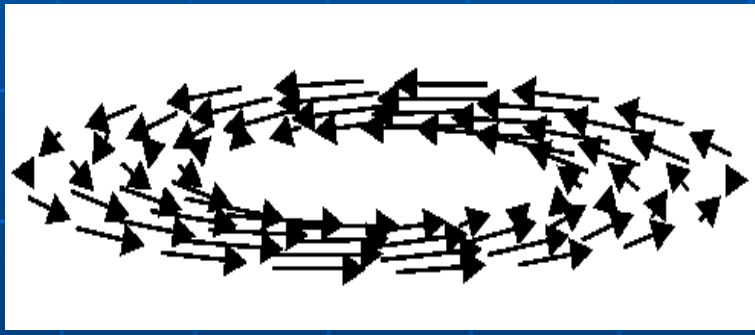
M31 20cm Total Intensity (VLA + Effelsberg)



M31: The classical dynamo case



Berkhuijsen et al. 2003



Fletcher et al. 2004

The spiral field of M31 is coherent and of axisymmetric spiral type

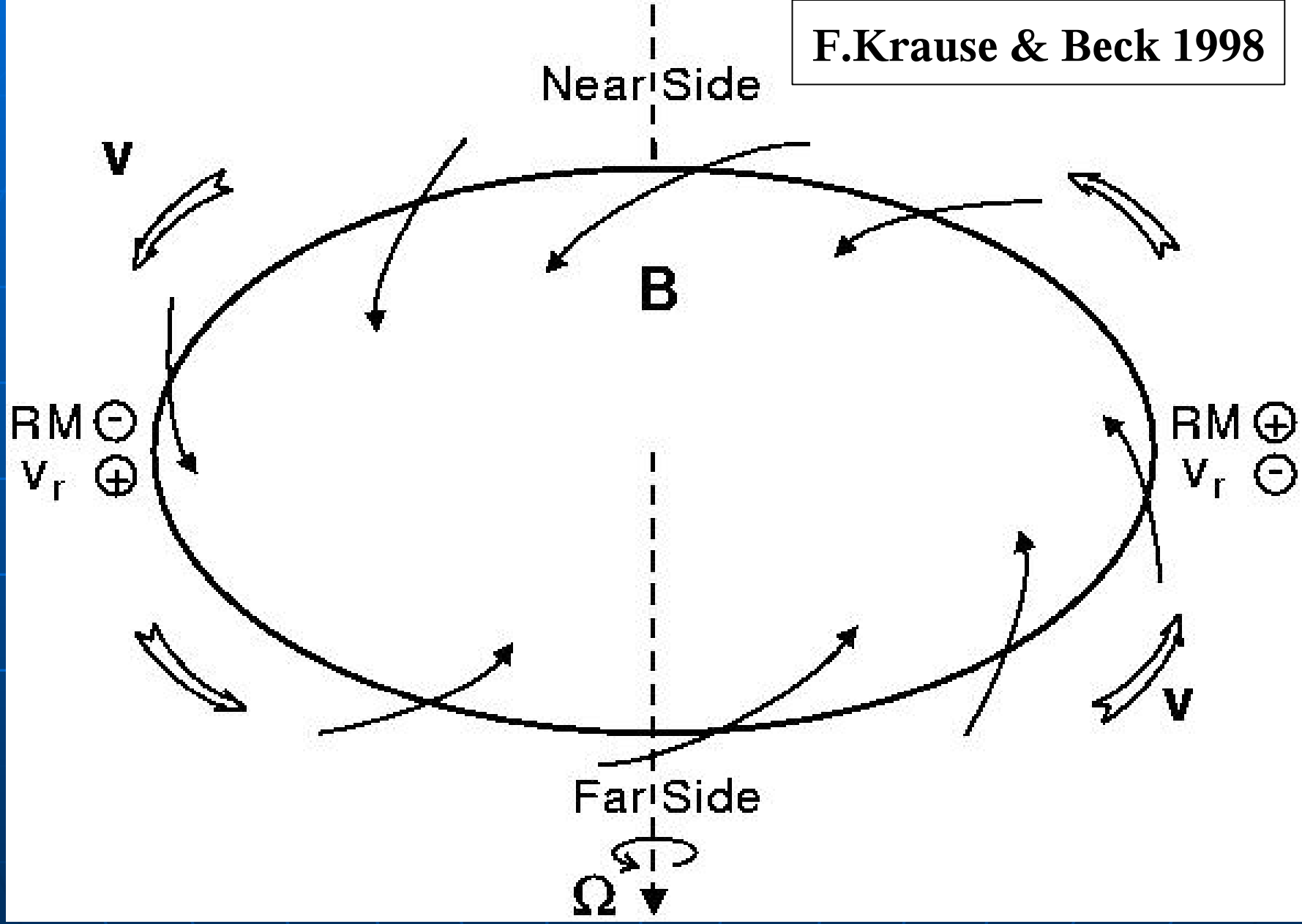
Faraday rotation

is the key to detect
coherent fields
and hence to test
large-scale dynamo action

Resolving dynamo modes with the SKA

To resolve a spectrum of *m*•4 modes in a typical spiral galaxy at D=100 Mpc, a resolution of •1 is needed

The dynamo preserves the direction of its large-scale seed field



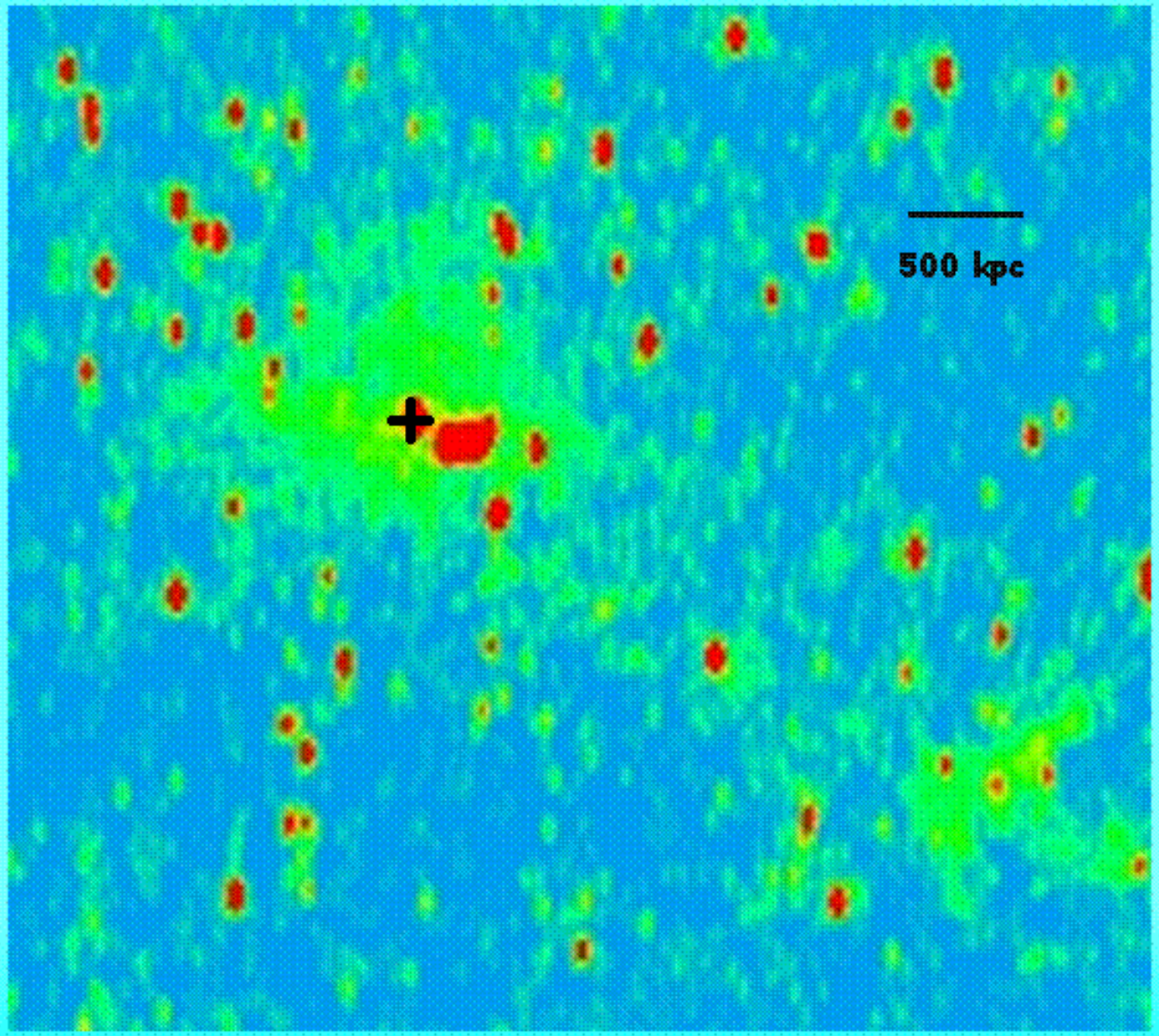
Preferred direction of the seed field ?

Direction of the radial component of axisymmetric spiral fields

- Inwards:
  M31, IC342, NGC253, NGC1097, NGC6946

- Outwards:
  M51 (??)

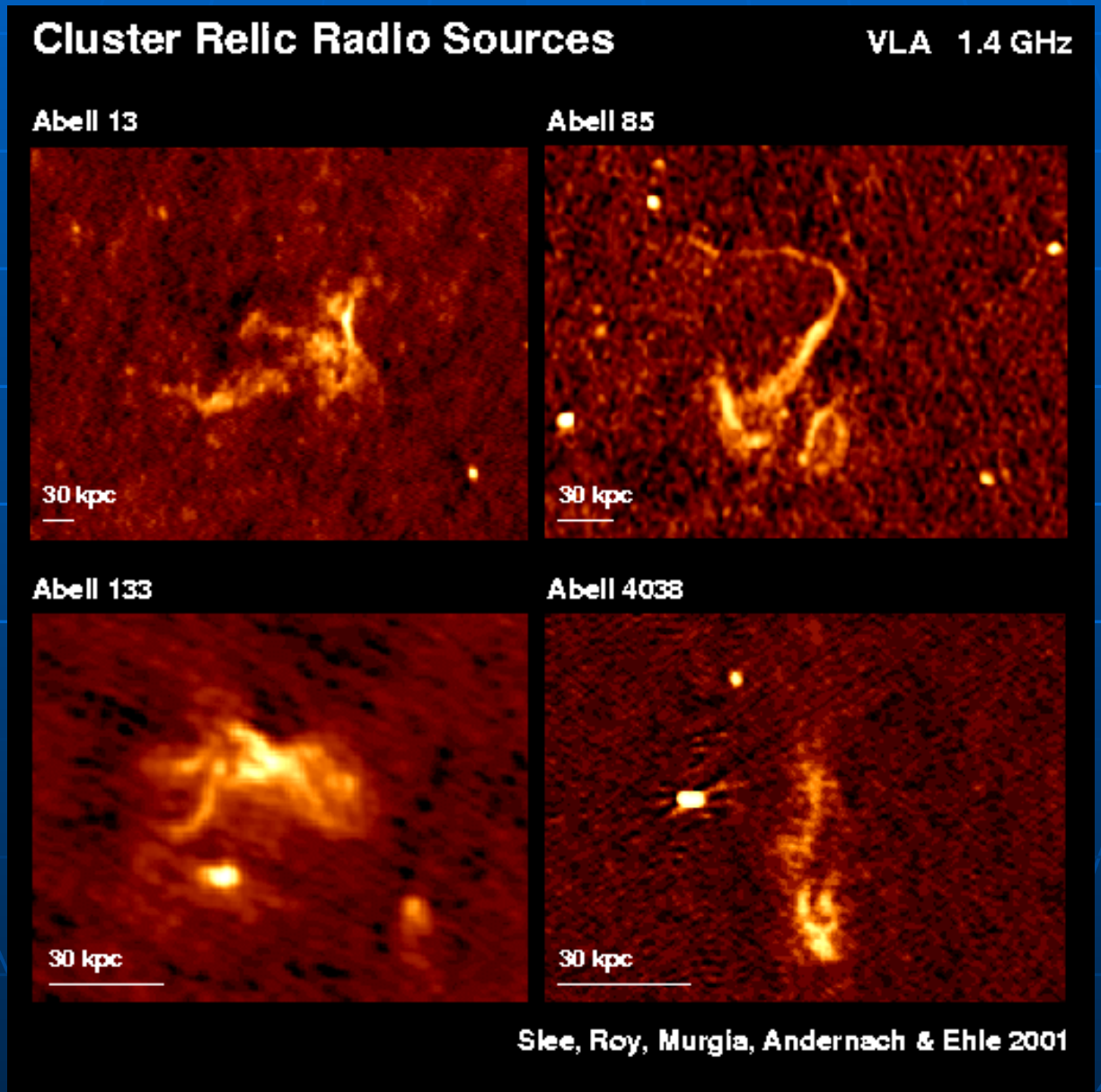
COMA Cluster

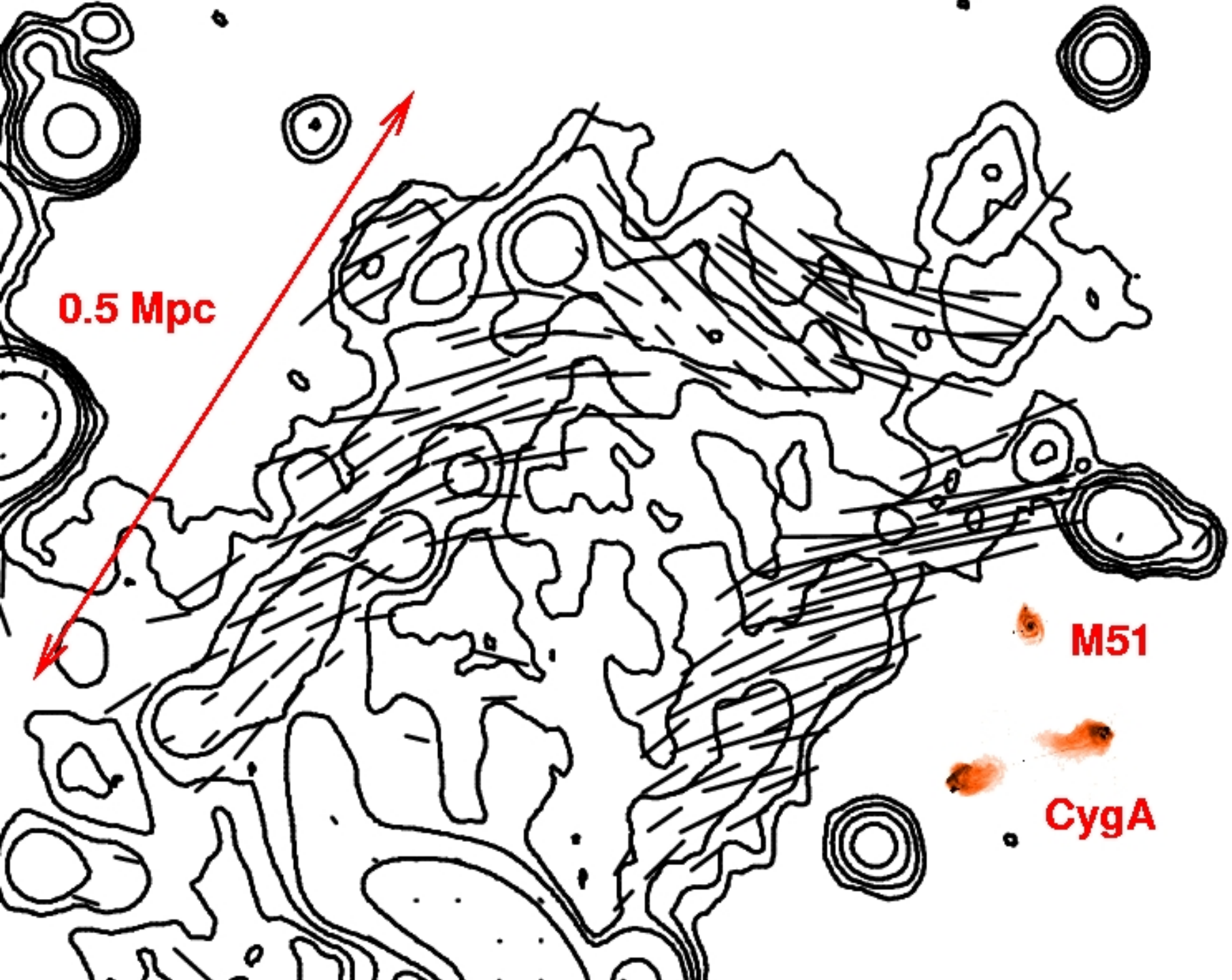


Center

RADIO: WSRT, 90 cm (Feretti et al.1998)

Radio Relics




0.5 Mpc
M51
CygA

Faraday rotation of the CMB ?

Kosowsky et al. 2005:

A primordial field of 10^{-9} G may cause Faraday rotation of the CMB of a few degrees at ~30 GHz

The SKA offers excellent prospects for understanding cosmic magnetism

As the universe expands more and more, we need a larger telescope …