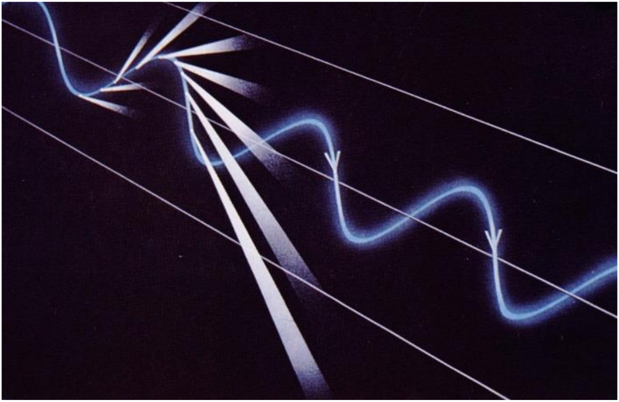


Lecture 3:

Measuring Cosmic Magnetic Fields

Rainer Beck, MPIfR Bonn

History

- Magnetit (Fe_3O_4): known since > 2000 years
- Magnetism: probably named after *Magnesia* in Thessalia/Greece
- Compass: invented in China about 200 BC,
  first used by Chinese sailors about 1000 AD

James Clerk Maxwell (1864)

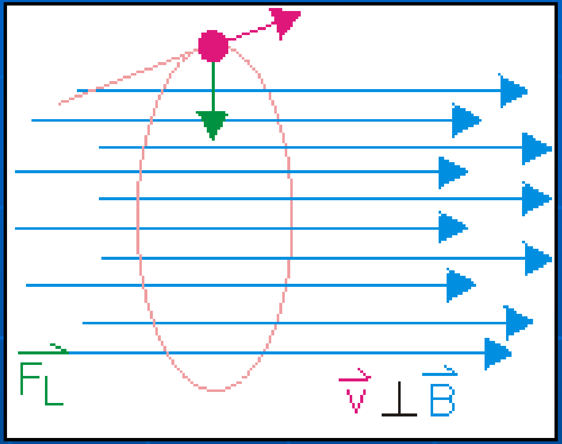
$$\nabla \times \overrightarrow{E} = -\frac{\partial \overrightarrow{B}}{\partial t} - \overrightarrow{M}$$

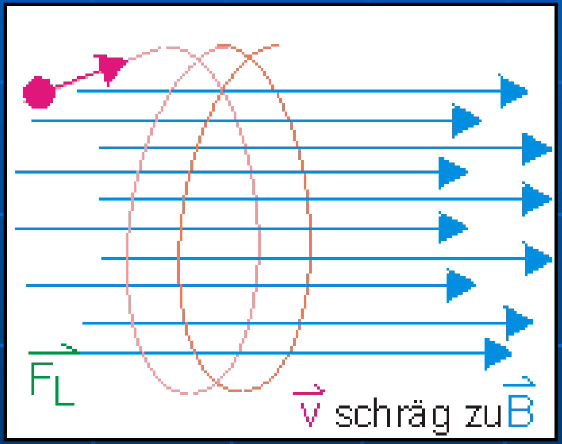
$$\nabla \times \overrightarrow{H} = -\frac{\partial \overrightarrow{D}}{\partial t} + \overrightarrow{J}$$

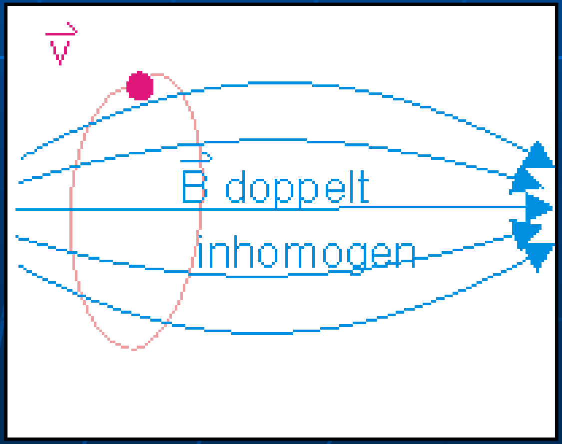
$$\nabla \cdot \overrightarrow{D} = \rho$$

$$\nabla \cdot \overrightarrow{B} = 0$$

Charged particles moving in magnetic fields: Lorentz force $F = q\,(v \times B)$





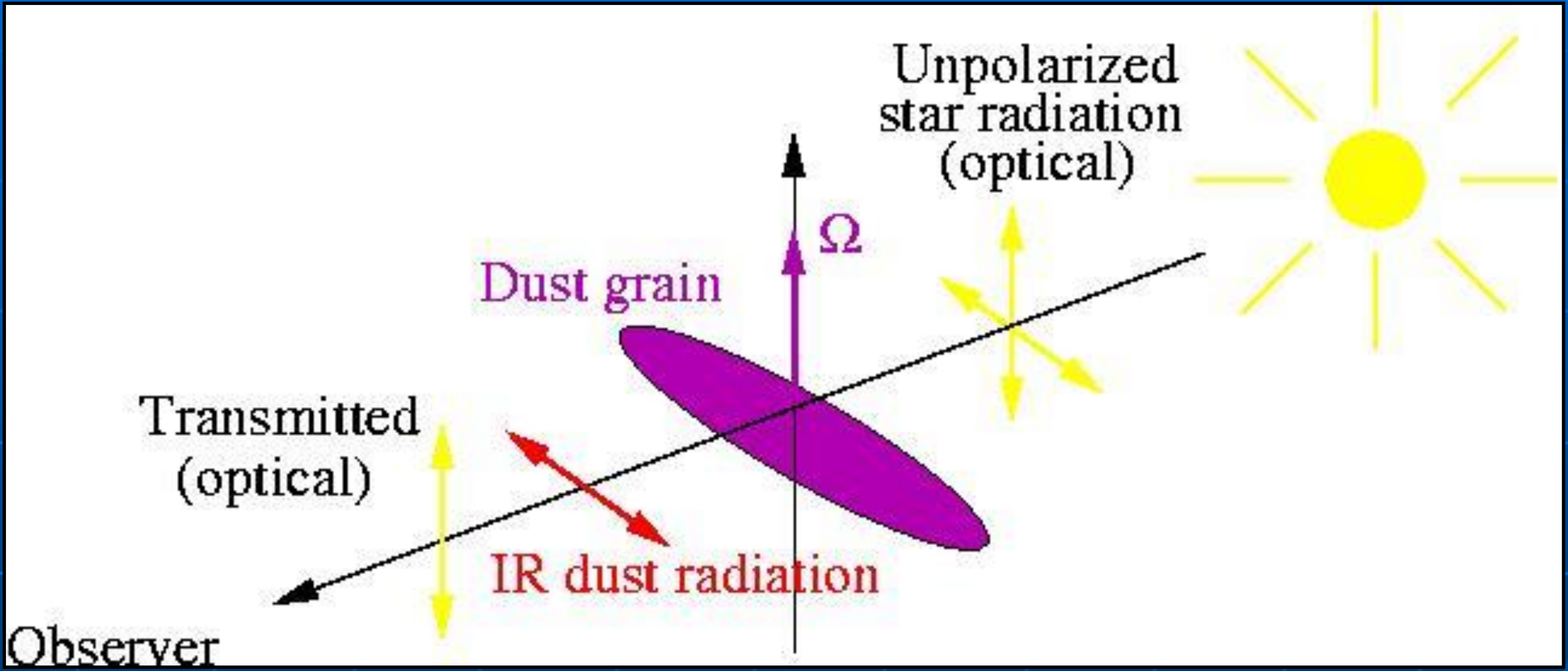


"magnetic bottle"

Tools to study cosmic magnetic fields

- Polarization by dust grains (optical or infrared or submm continuum emission)
- Zeeman effect (line emission)
- Goldreich-Kylafis effect (line emission)
- Total synchrotron intensity (radio or optical continuum)
- Polarized synchrotron intensity (radio or optical)
- Faraday rotation of polarization plane (radio)
- Faraday depolarization (radio)

Dust grain alignment in magnetic fields



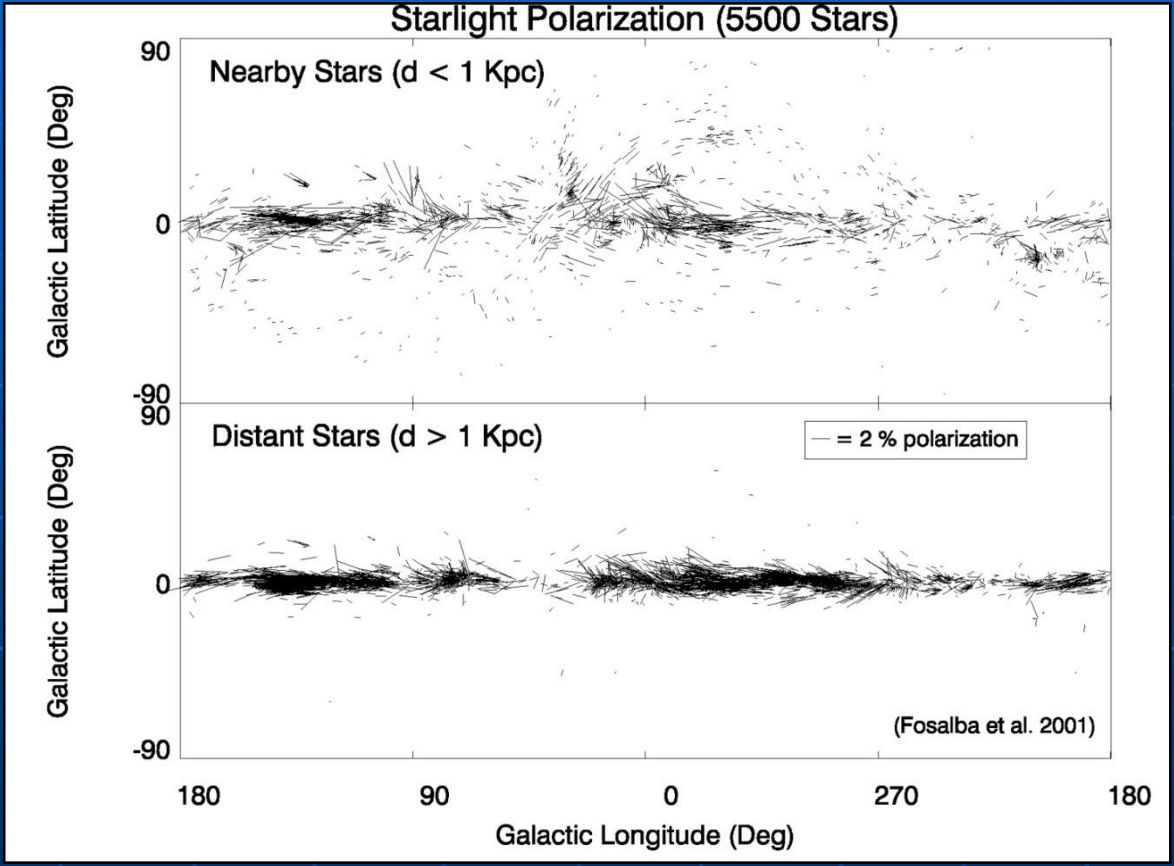
- Optical polarization: ∥ magnetic field line
- IR polarization: ⊥ magnetic field line

Dust grain alignment in magnetic fields

Physics of alignment:

- Paramagnetic dissipation of energy (very slow)
  (Davis & Greestein 1951)
- Radiative torque alignment
  (Hoang & Lazarian 2008)

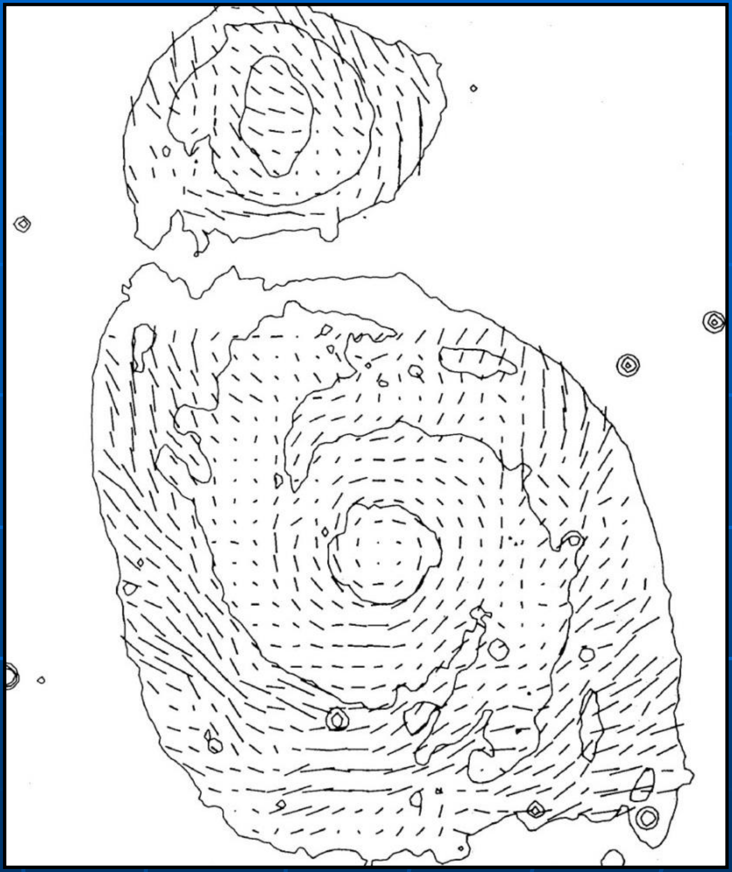
Starlight polarization: Ordered fields ($B_\perp$)



Large-scale ordered field along the Galactic plane

Fosalba et al. 2002

Starlight polarization in the galaxy M 51



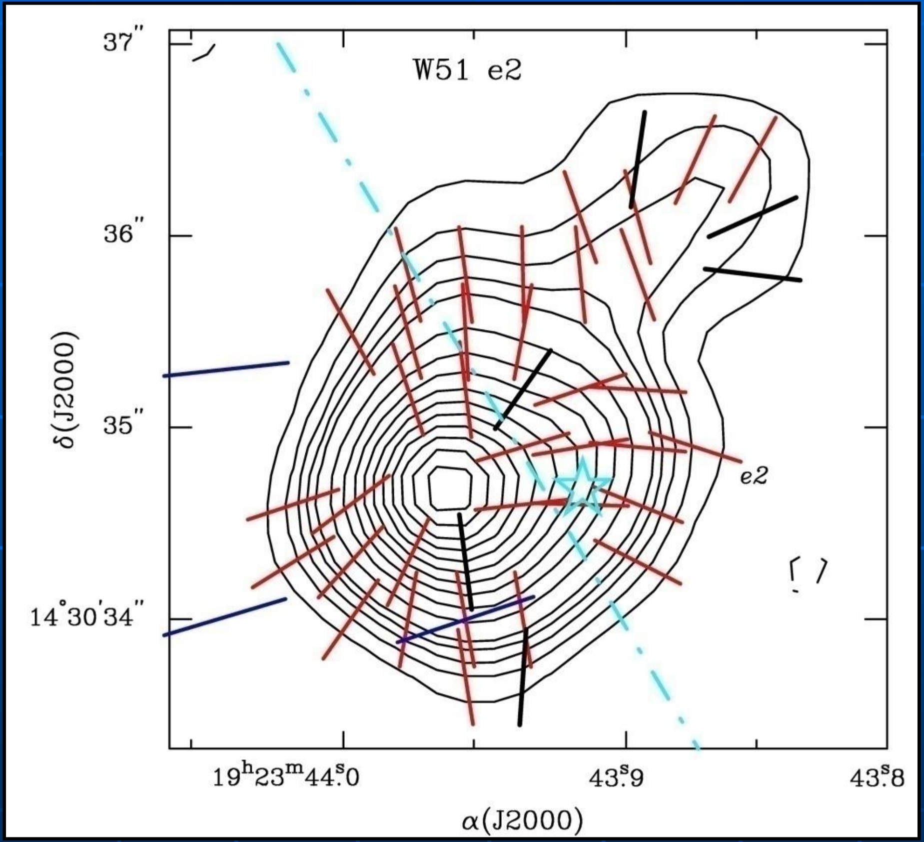
Large-scale spiral field - or scattered light ?

Scarrott et al. 1977

Practical problems with measuring magnetic fields from optical polarization

- Contamination by polarization from scattered light
- Degrees of polarization are very small:
  bright sources are needed
- Physics of grain alignment not understood:
  field strengths can hardly be measured

Submm polarization:
Ordered magnetic fields in a molecular gas disk
(SMA 870 μm, 0.02 pc resolution)



X-shaped field:
Ambipolar diffusion?

Tang et al. 2009

Practical problems with measuring magnetic fields from infrared/submm polarization

- Degrees of polarization are low: bright sources are needed
- Molecular clouds are small: high angular resolution needed
- Physics of grain alignment not understood: field strengths can hardly be measured

Chandrasekhar-Fermi method (1953)

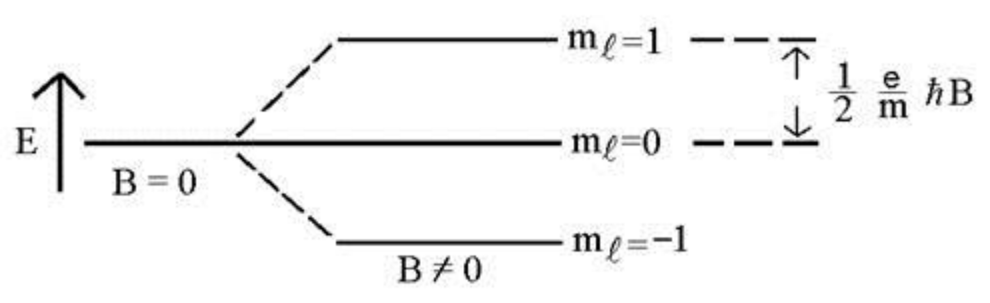
- Competition between magnetic force and turbulent gas motions in the interstellar medium (v) with density ρ
- Strong field: straight field lines, small dispersion of polarization vectors (α)
- The dispersion α allows to estimate the field strength B:

$$\mathbf{B \approx (4/3\, \pi\, \rho)^{1/2}\ v\ /\ \alpha}$$

- Improved method: correct for errors in polarization angle, signal integration (Hildebrand et al. 2009, Houde et al. 2009, 2011)
- Applied also to radio polarization vectors (Houde et al. 2013)

Zeeman effect

- Splitting of spectral lines by a magnetic field into three components (-σ, π,+σ):

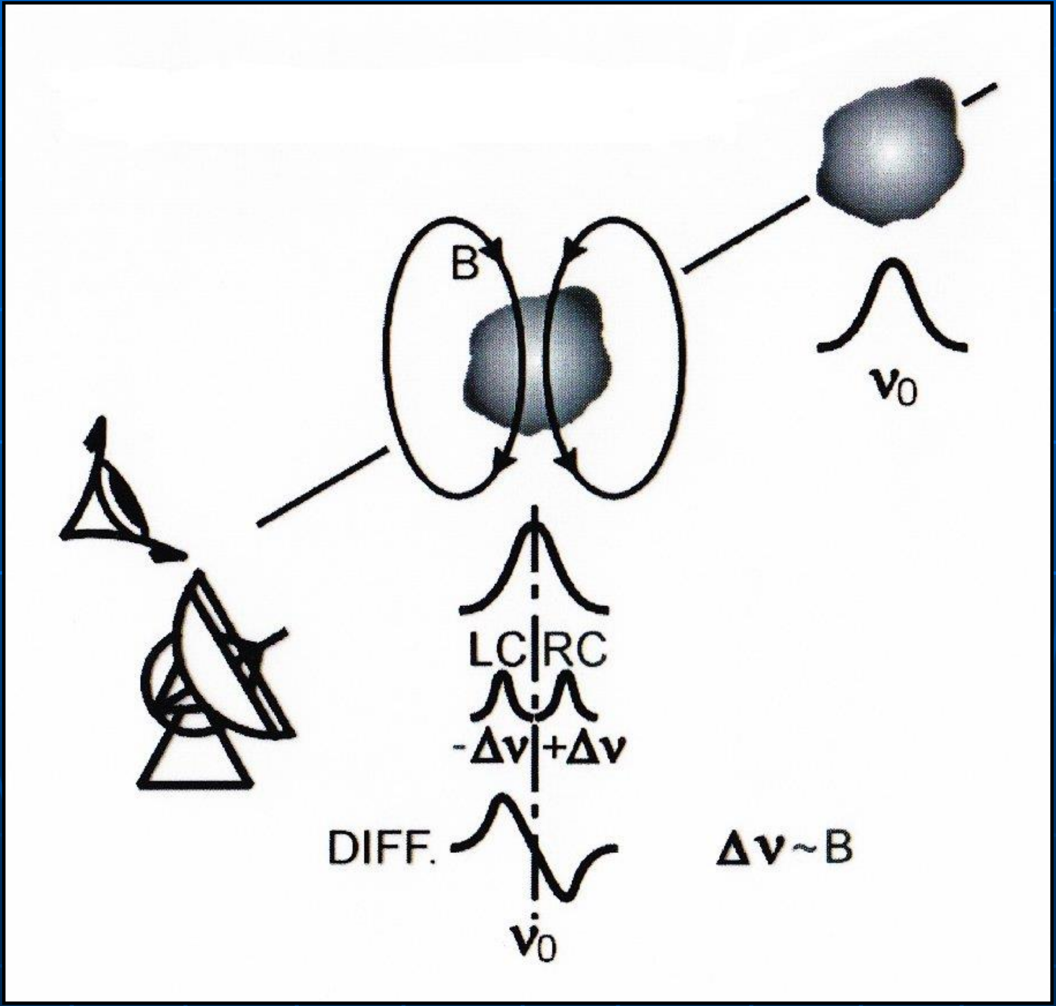


- Line of sight parallel to B (longitudinal Zeeman effect):

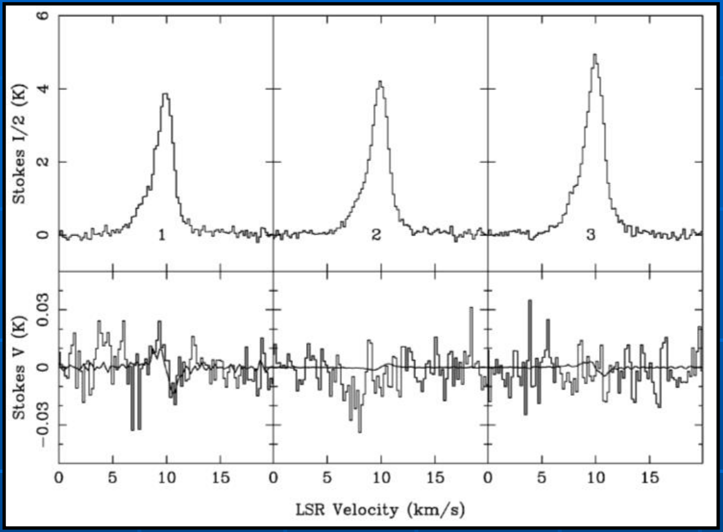
  two σ lines (circularly polarized)

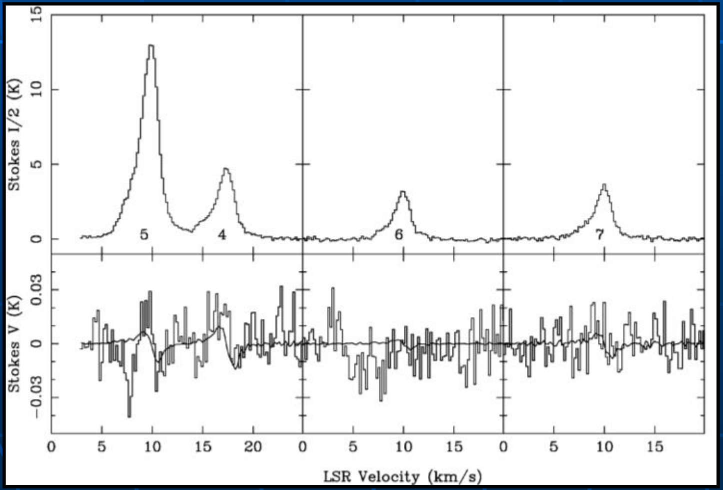
- Line of sight perpendicular to B (transversal Zeeman effect): two σ lines + one π line (all linearly polarized)

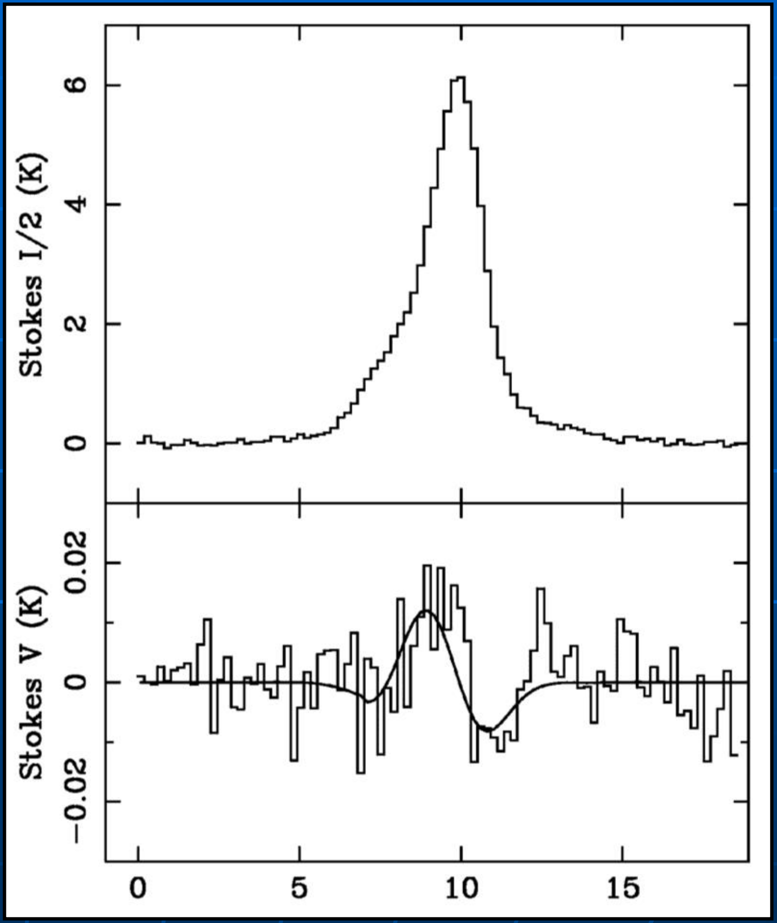
Zeeman effect (longitudinal): Ordered fields ($B_\parallel$) in gas clouds



Orion MC1:
CN(1-0) Zeeman (113 GHz, 7 hyperfine lines)



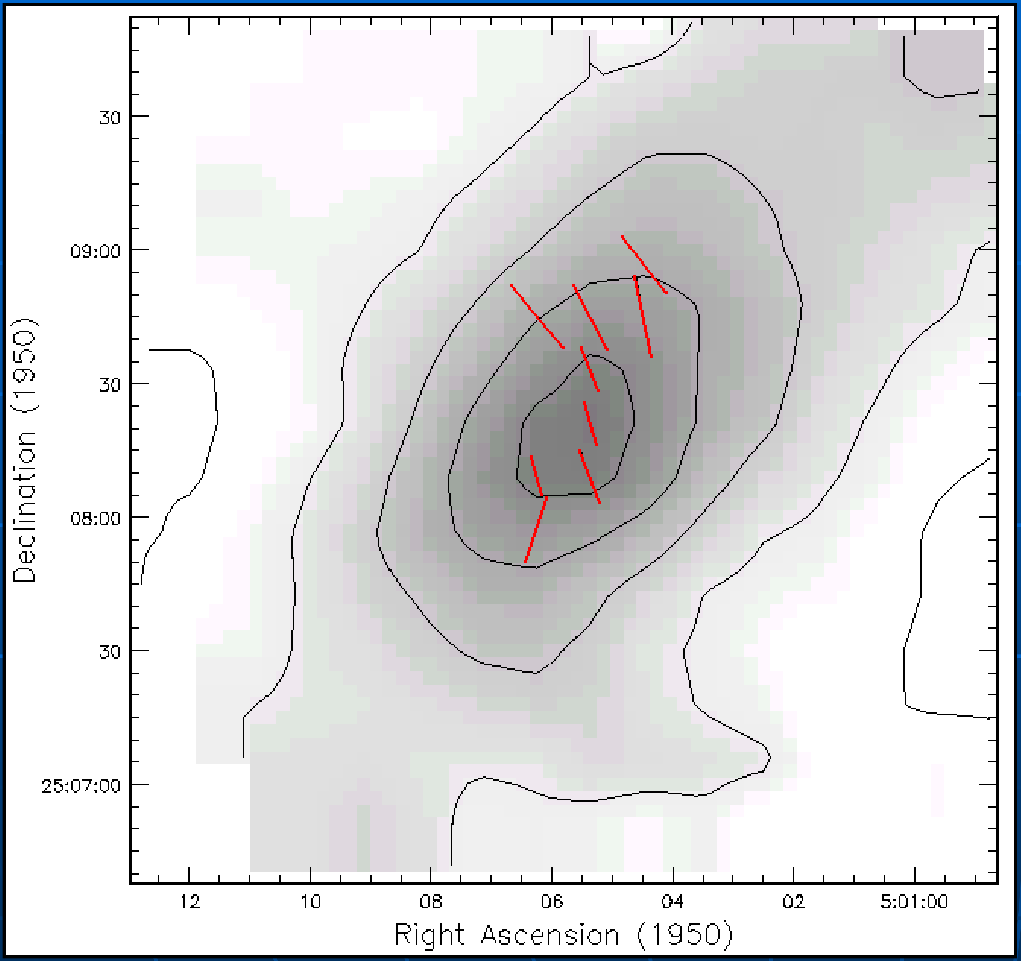


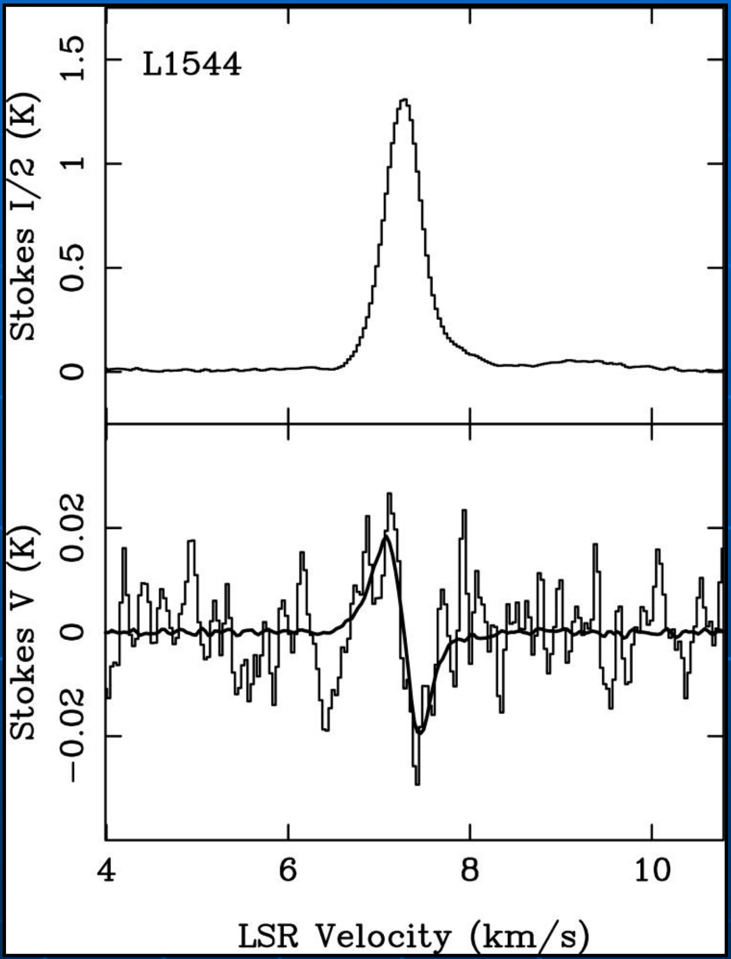


$B_{\parallel}$ = –0.36 ± 0.08 mG

(Crutcher et al. 1999)

L1544 Starless Core:
Dust pol (850 μm) and OH Zeeman (1.67 GHz)





n(H_2) ≈ 5 × 10^5 cm^{-3}, **$B_\perp$ ≈ 140 μG**
(Crutcher et al. 2004)

n(H_2) ≈ 1 × 10^4 cm^{-3}, **$B_\parallel$ = +11 μG**
(Crutcher & Troland 2000)

Goldreich-Kylafis effect (1981)

- Line of sight perpendicular to B (transversal Zeeman effect): two σ lines + one π line (linearly polarized)

- Symmetric conditions: no polarization detectable

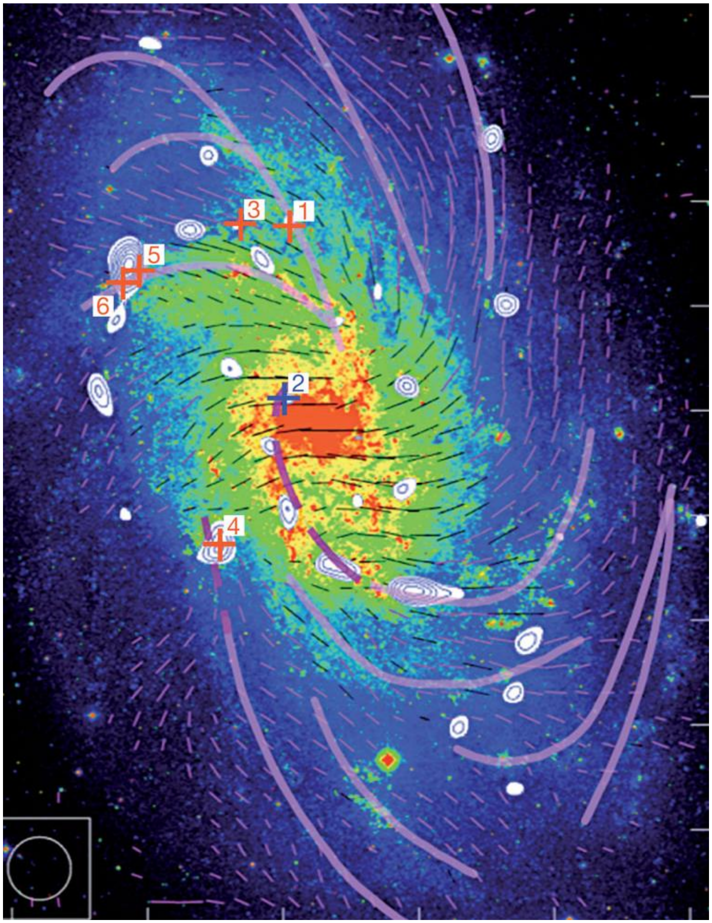
- Detection of linearly polarized lines becomes possible for:
  - *Unequal populations of the different sublevels*
  - *Gradient in optical depth or velocity*
  - *Anisotropic velocity field*

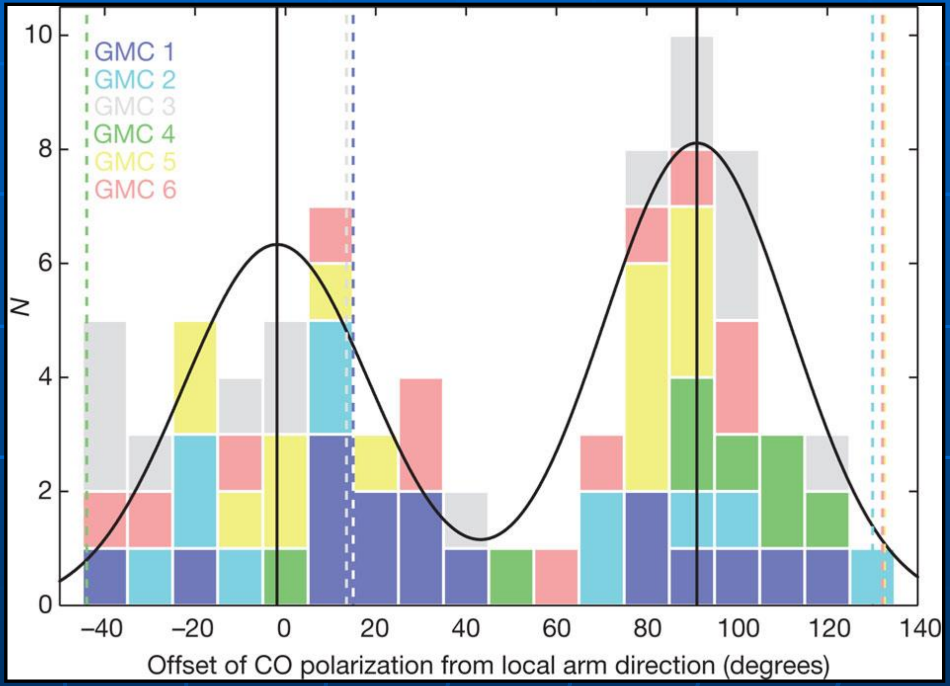
- Linear polarization can be parallel or perpendicular to the magnetic field orientation

- Detections: molecular clouds, star-forming regions, outflows of young stellar systems, supernova remnants

Goldreich-Kylafis effect: CO lines + synchrotron polarization in M 33

(Li & Henning 2011)





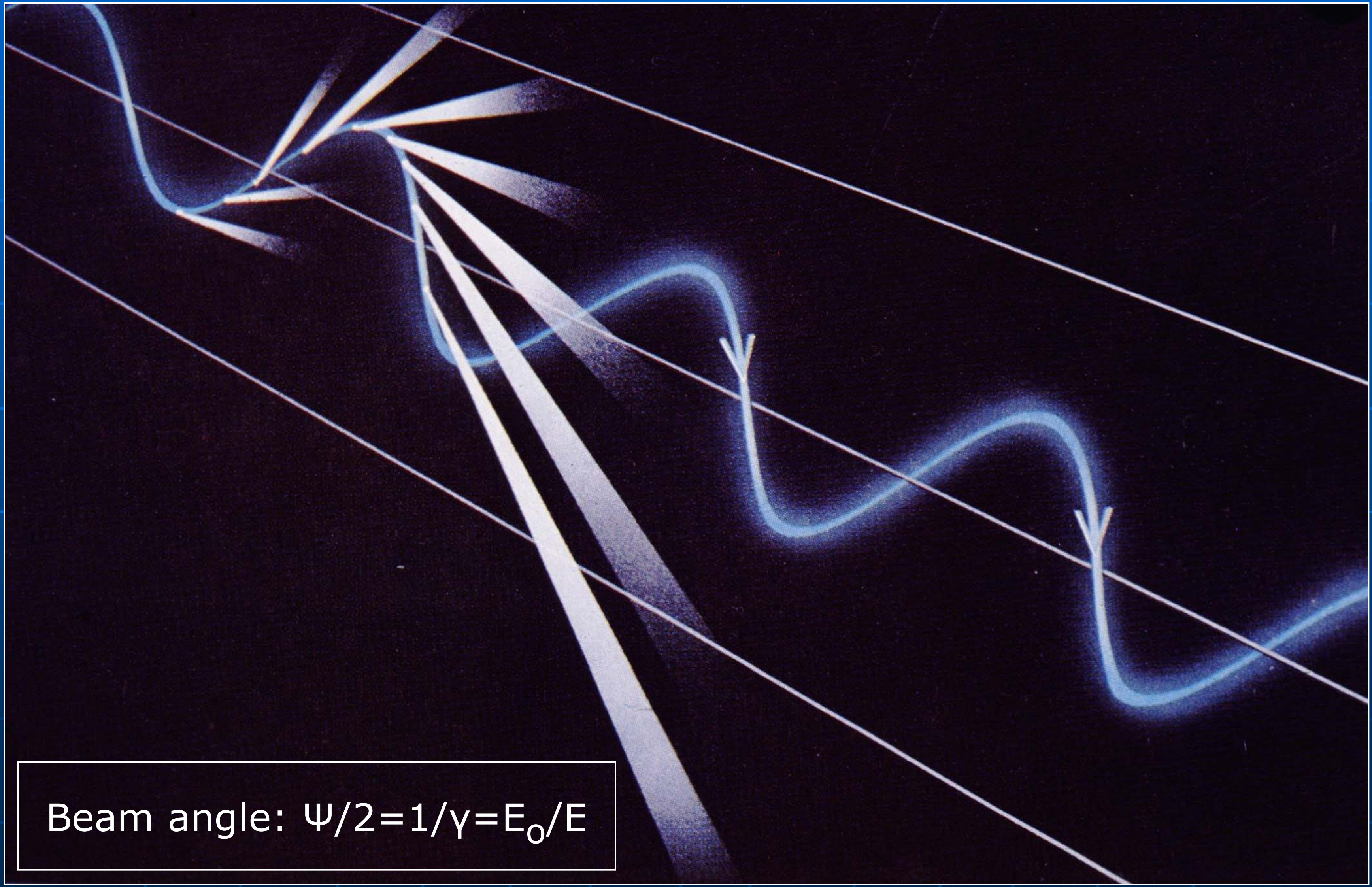
Magnetic fields in the molecular clouds
are aligned with the spiral arms

Practical problems with measuring Zeeman splitting

- Weak effect: low instrumental polarization required
- HI line traces only diffuse (warm) gas
- Other suitable lines (e.g. OH, CN) are much weaker
- Goldreich-Kylafis effect: magnetic field orientation is ambiguous by ±90°

Synchrotron emission:

Magnetic fields illuminated by cosmic-ray electrons



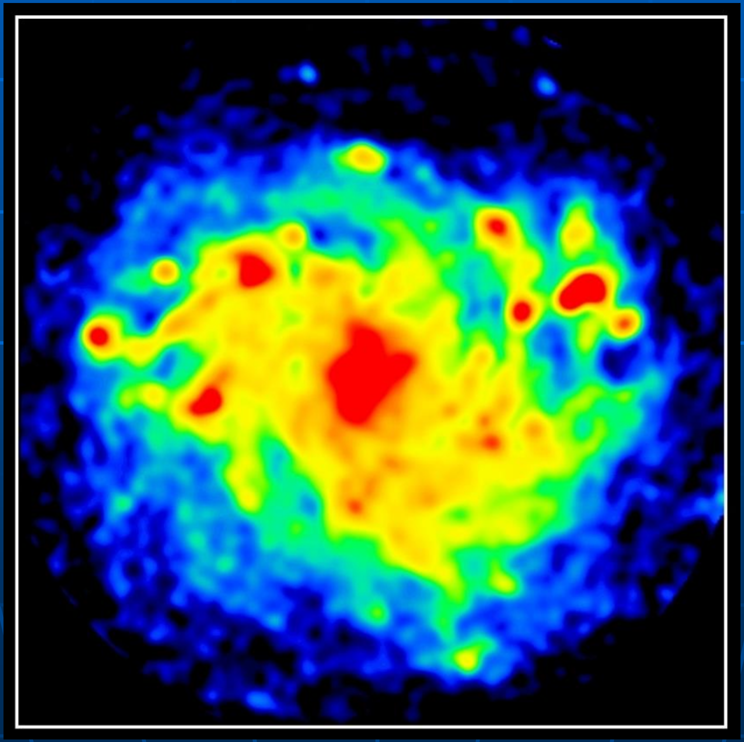
Beam angle: $\Psi/2=1/\gamma=E_o/E$

Practical problems with measuring synchrotron emission

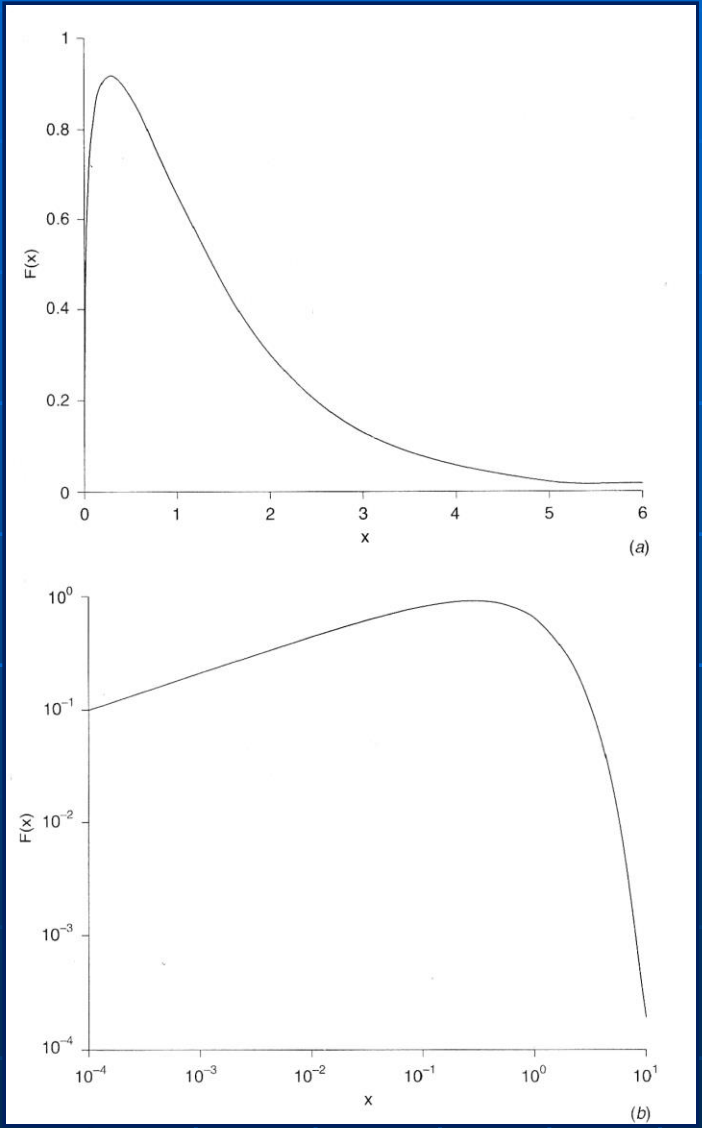
- High-energy cosmic-ray electrons needed
- Thermal emission needs to be subtracted

Total synchrotron emission (NGC 6946):

Tracer of total magnetic fields



Synchrotron emission



Intensity spectrum of
a single cosmic-ray electron
(linear and logarithmic scale)

Maximum emission:

$$\nu_{max} \approx 5 \text{ MHz } E\,[\text{GeV}]^{2}\, B_{\perp}\,[\mu\text{G}]$$

Longair, High Energy Astrophysics

Synchrotron emission

- Cosmic-ray electrons:

Power-law energy spectrum with spectral index ε_e

$$N(E)\, dE = N_0\, E^{-\varepsilon_e}\, dE$$

- Intensity of synchrotron spectrum:

$$I_\nu = c_5(\varepsilon_e) \int N_0\, B_\perp^{(\varepsilon_e+1)/2}\, (\nu/2c_1)^{-(\varepsilon_e-1)/2}\, dL$$

- Synchrotron spectral index:

$$\alpha = (\varepsilon_e-1)/2$$

Energy spectra of cosmic rays

Diffusive shock acceleration:

$\varepsilon \geq 2$

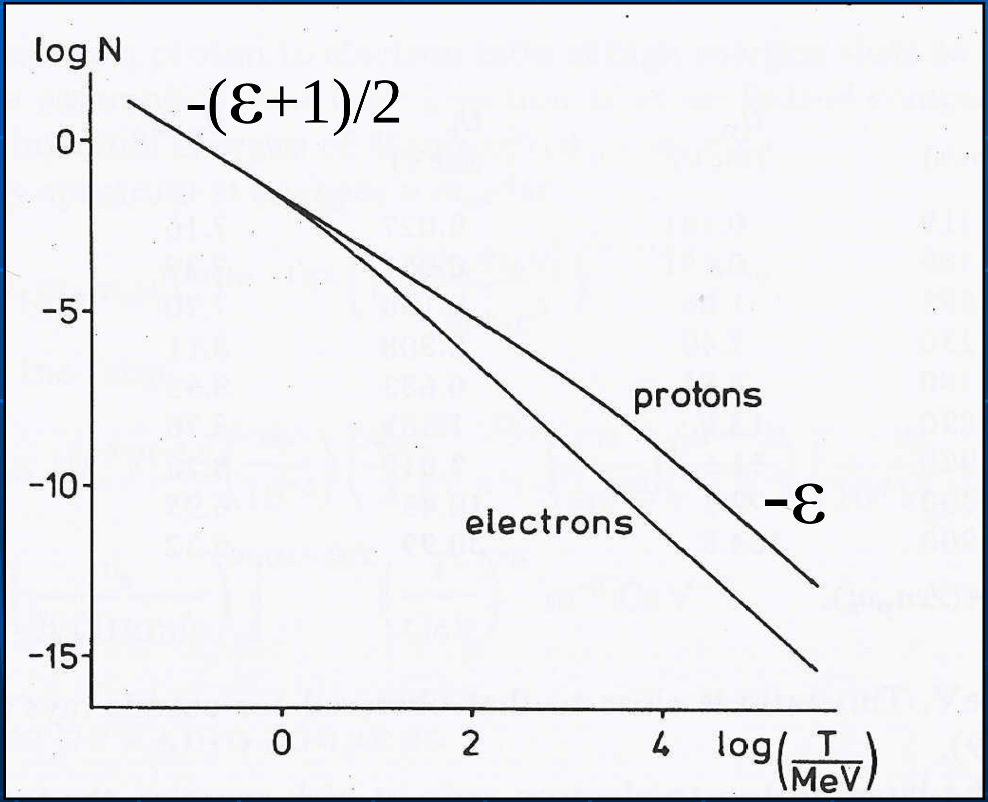
$\alpha \geq 0.5$

E > 1 GeV:

$K=(m_p/m_e)^{(\varepsilon-1)/2}$

$\varepsilon \approx 2.2$: **$K \approx 90$**

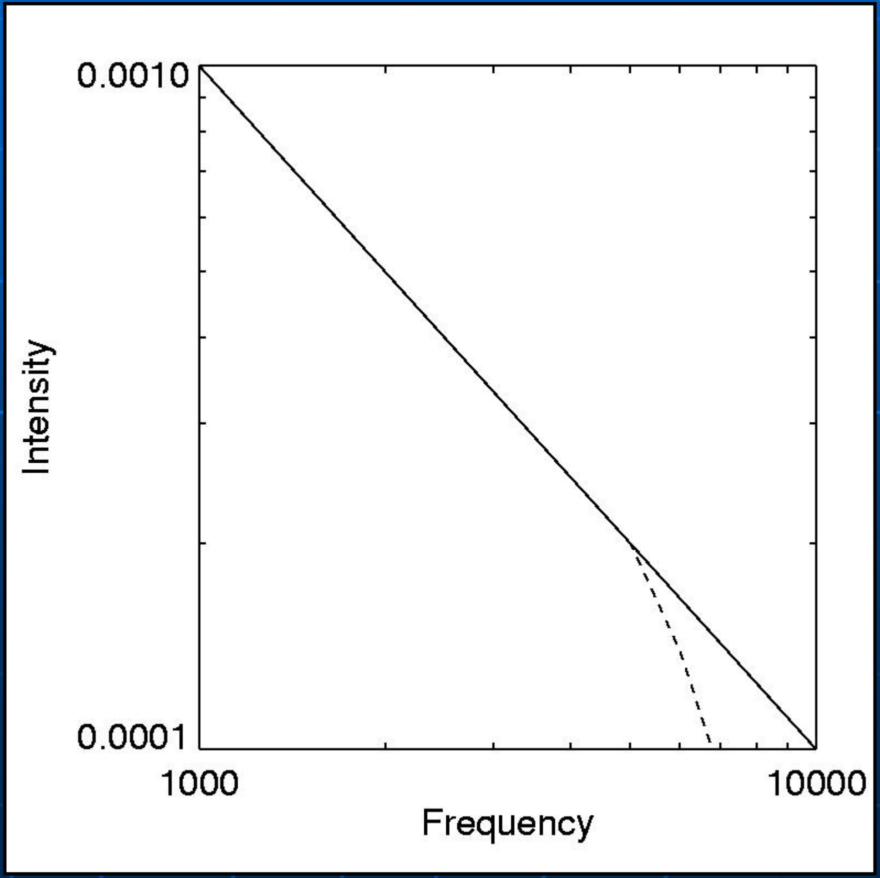
Bell 1978



Lifetime of synchrotron-emitting electrons

$$t_{syn} \approx 1\ \mathrm{Gyr}\ \ B_{\perp\,[\mu G]}^{-1.5}\ \ \nu_{syn\,[GHz]}^{-0.5}$$

Synchrotron spectrum steepens above a critical frequency

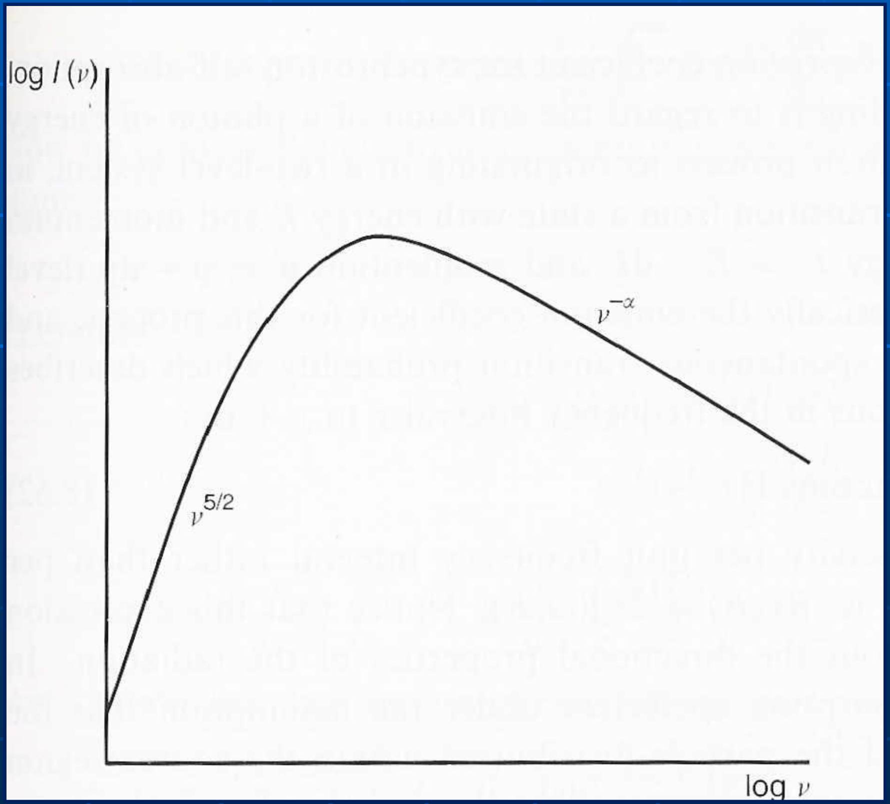


Synchrotron self-absorption

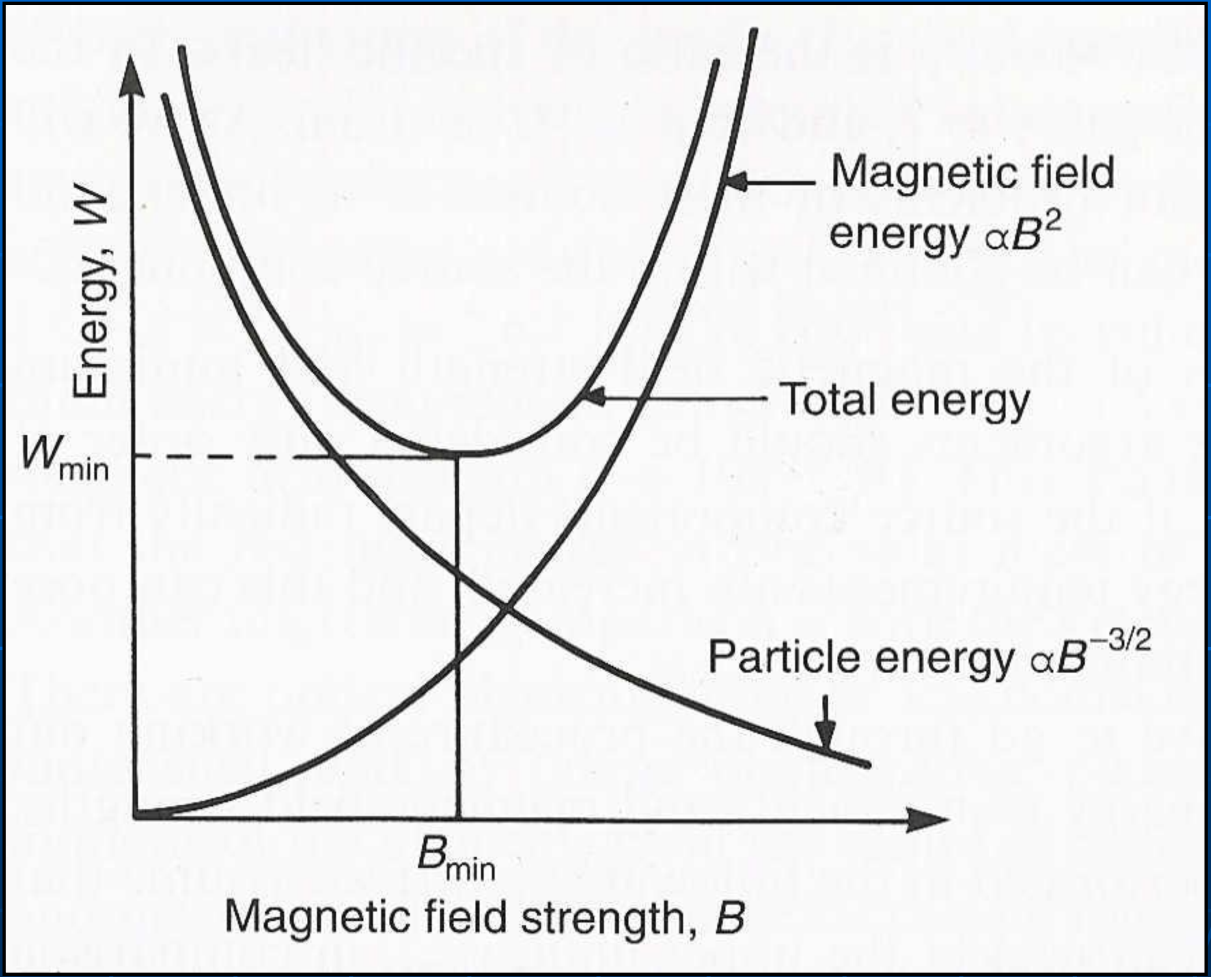
$$\nu_{sa} \approx 34\ \mathrm{MHz}\ \left(S_{[\mathrm{Jy}]} / \theta_{[\mathrm{arcsec}]}^{2}\right)^{2/5}\ B_{\perp\,[\mathrm{G}]}^{\ 1/5}$$

Measurement of field strength

Observable in bright,
compact sources



Minimum-energy field strength



Longair, High Energy Astrophysics

Energy equipartition formula

$$B_{eq,\perp} \propto \left(I_{sync} \, (K+1) \, / \, L \right)^{1/(3+\alpha)}$$

$B_{eq,\perp}$: Strength of the equipartition field in the sky plane

I_{sync}: Synchroton intensity

K: Proton/electron ratio

L: Pathlength through source

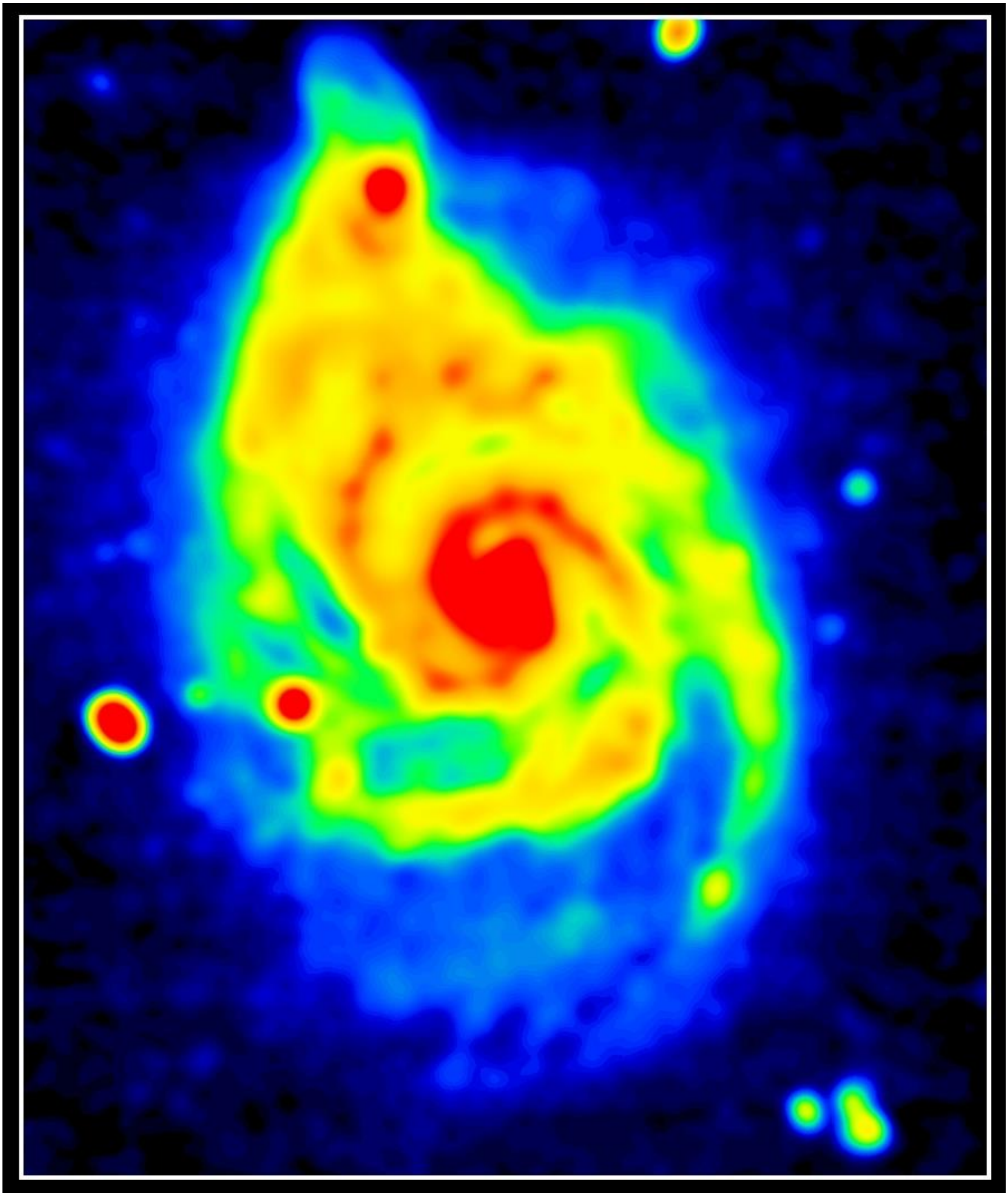
α: Slope of the synchrotron spectrum (spectral index)

Beck & Krause 2005

M 51

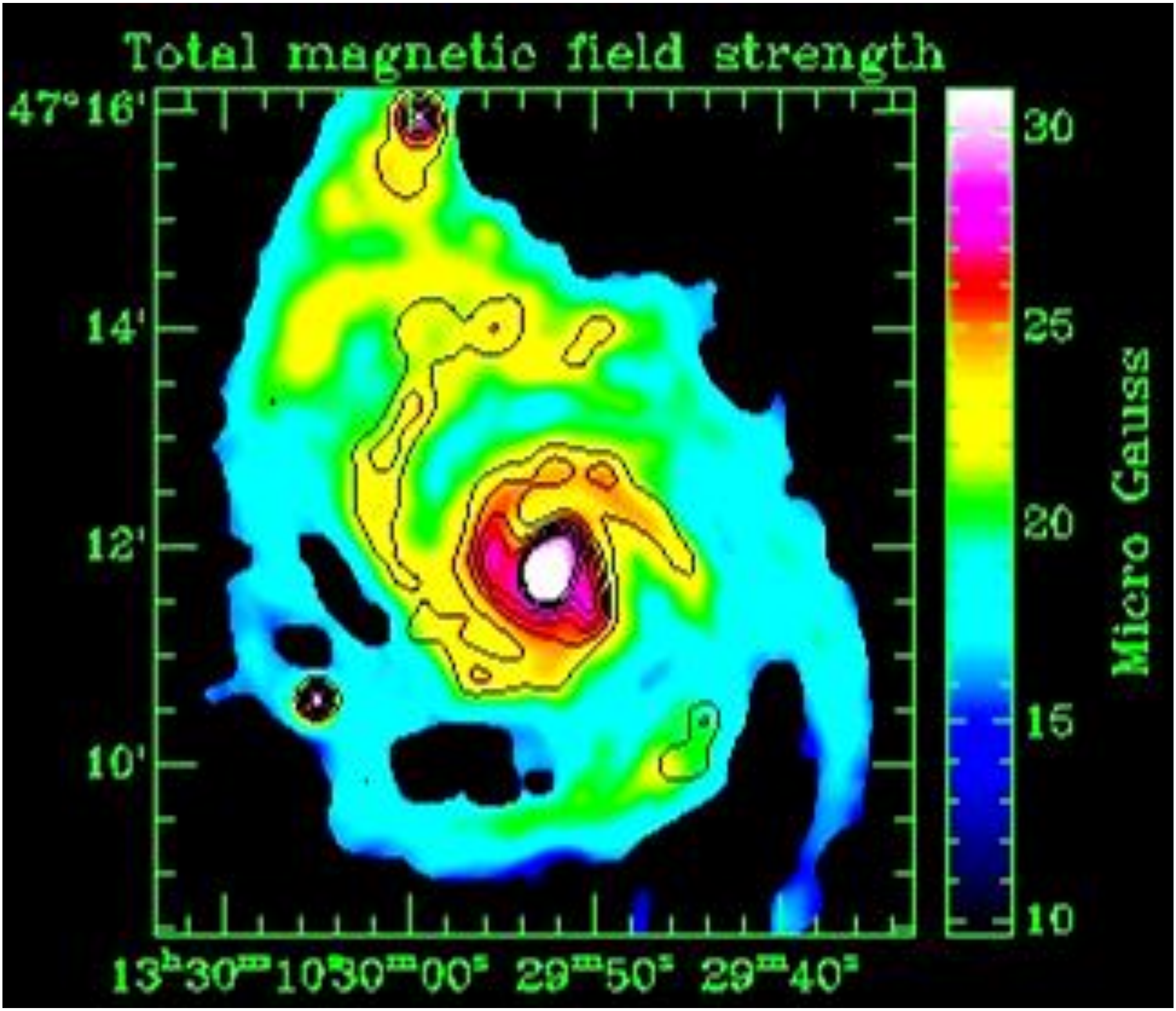
VLA 20 cm

Total intensity



Fletcher et al. 2011

Equipartition field strengths in M 51



Fletcher et al. 2011

Equipartition field strengths in galaxies

Average total field in spiral galaxies: **5 – 15 μG**

Total field in spiral arms: **20 - 30 μG**

Total field in starburst galaxies: **40 – 100 μG**

Note: Field strengths may be underestimated due to energy losses of cosmic-ray electrons

Energy densities

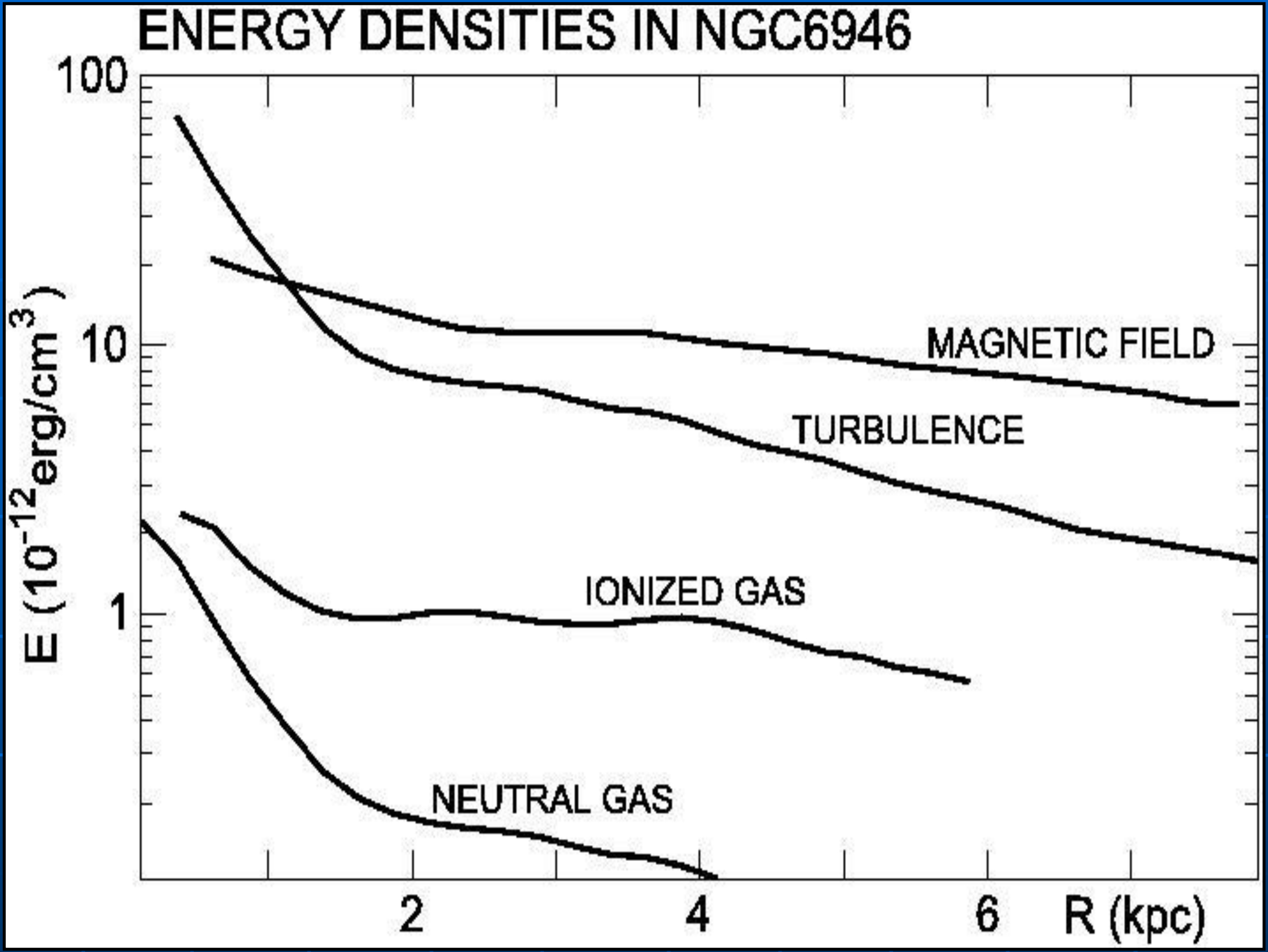
- $E_{magn} = B^2 / 8 \pi$
- $E_{turb} = 1/2\ n\ v_{turb}^2$
- $E_{therm} = 3/2\ n\ k\ T$

$V_{turb} \approx 7$ km/s

$T_e \approx 10^4$ K

$T_n \approx 50$ K

Beck 2007



The energy density of the total magnetic field is roughly in equipartition with that of the turbulent cloud motions

Practical problems with measuring magnetic field strengths with the equipartition assumption

- Equipartition may be violated on small time scales and/or spatial scales
- Cosmic ray energy dominated by protons, but only electrons are observable in the radio range
- Energy spectra of protons and electrons can be different
- Needed: independent data on cosmic-ray proton spectrum (e.g. from γ rays)

Linear polarization of synchrotron emission

- Tracer of ordered magnetic fields in the sky plane ($B_\perp$)
- B-vector: oriented along the magnetic field line
  (if no Faraday rotation occurs)
- Intrinsic degree of linear polarization
  (if no depolarization occurs):

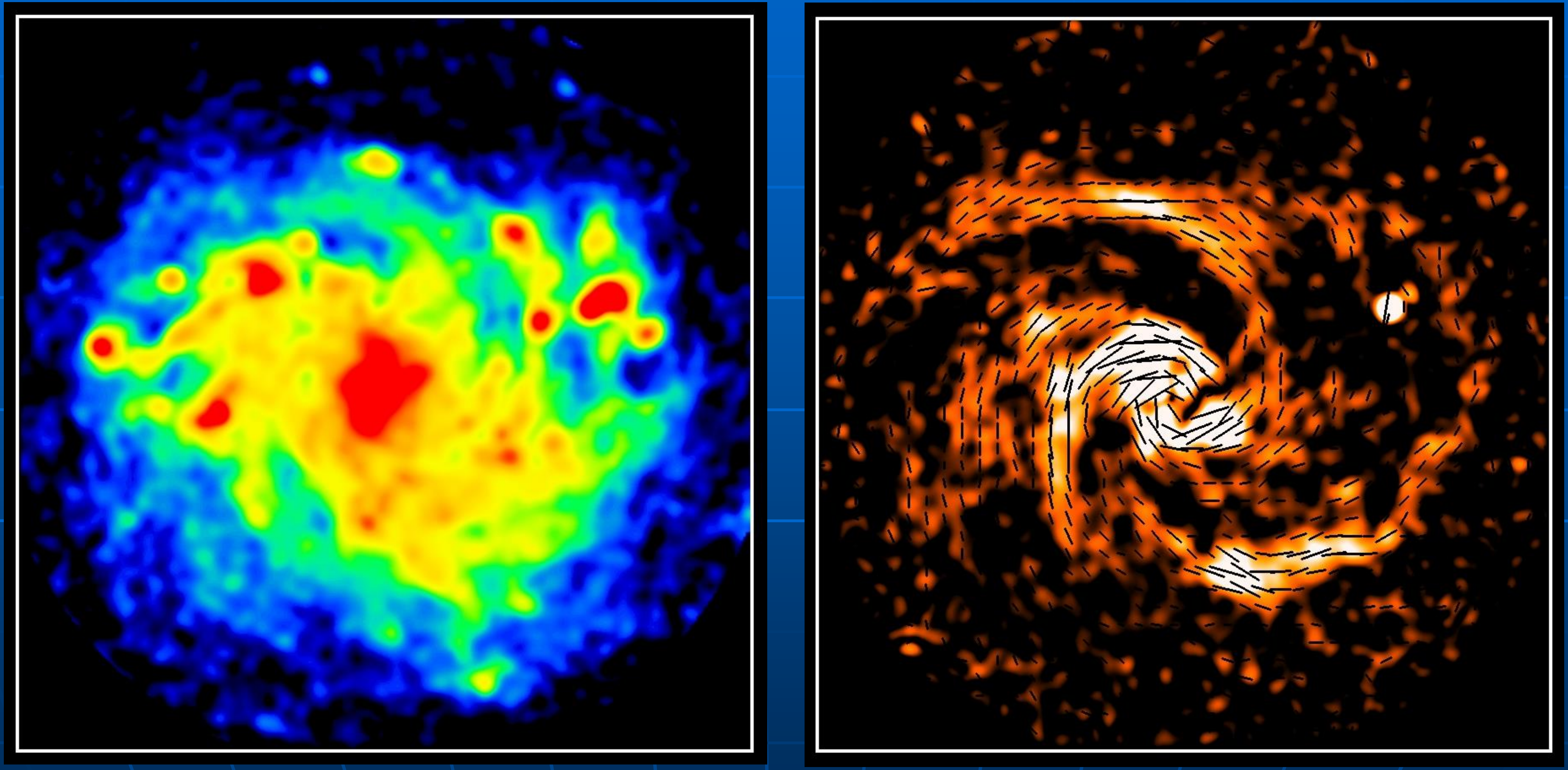
$$p_o = (\varepsilon+1) / (\varepsilon+7/3)$$
$$= (\alpha+1) / (\alpha+5/3)$$

Typical value: $\alpha=0.9$, $p_o=74\%$

- Circular polarization: generally negligible

Synchrotron polarization

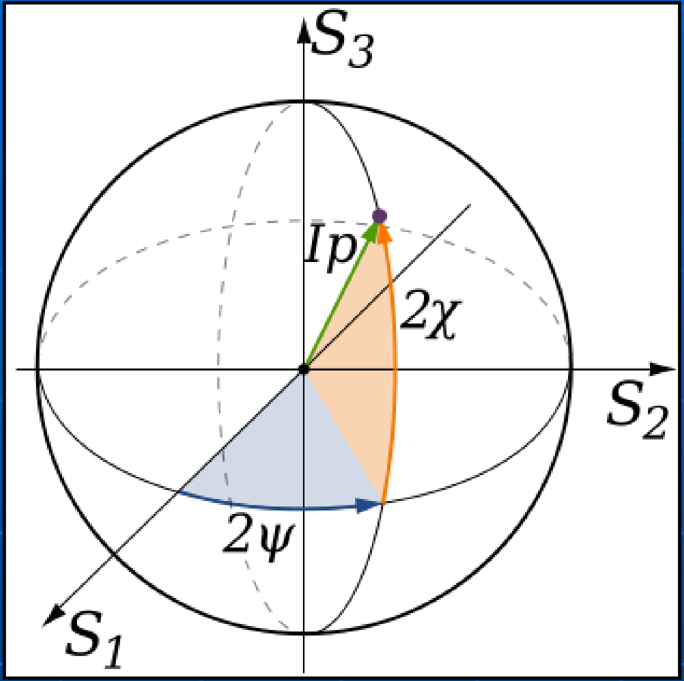
Beck & Hoernes 1996



NGC 6946: Total and polarized intensity at 6cm

Stokes parameters

Poincaré sphere



I

$Q = I\ p\ \cos 2\psi \cos 2\chi$

$U = I\ p\ \sin 2\psi \cos 2\chi$

$V = I\ p\ \sin 2\chi$

p: degree of polarization

ψ: Angle of linear polarization

$\psi = 0.5 \arctan (U/Q)$

χ: "Angle" of circular polarization

Linear polarization in complex notation

$$\boxed{\mathbf{P} = \mathbf{p}\ \mathbf{exp}\ (\ 2\ \mathbf{i}\ \psi\ )}$$

The projected polarization plane is NOT a vector !

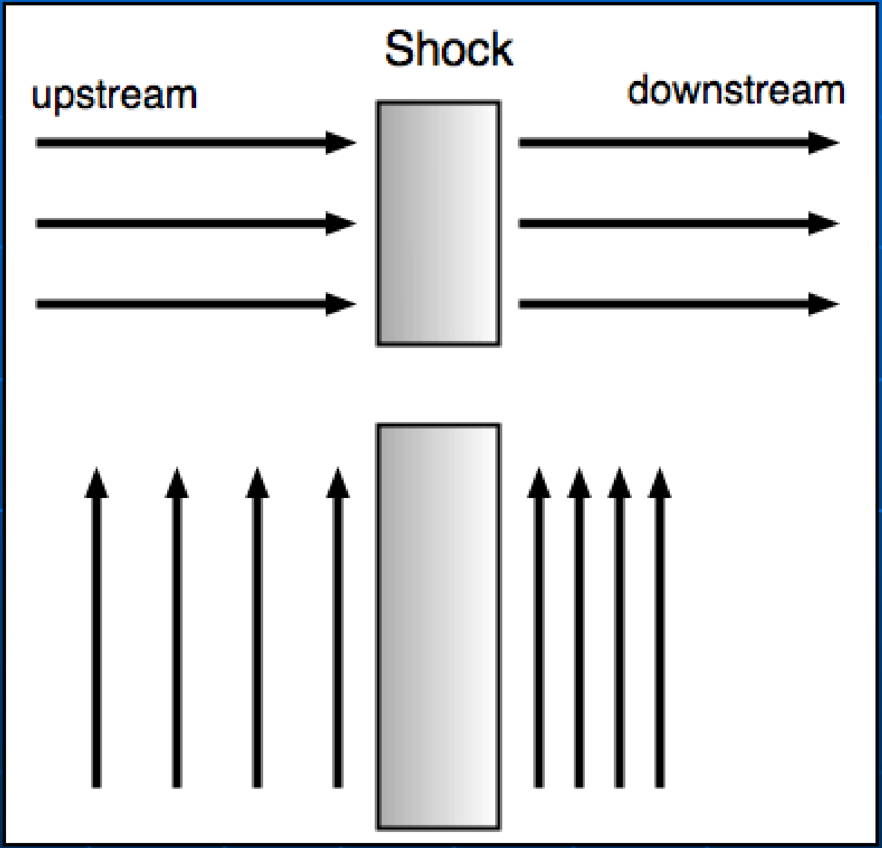
(no direction, only orientation)

The effect of shocks on the magnetic field (1)

- A shock perpendicular to field has no effect
- A parallel shock increases the magnetic field strength

$$B \propto \rho$$

$$PI \propto \rho^{2\rightarrow 4}$$

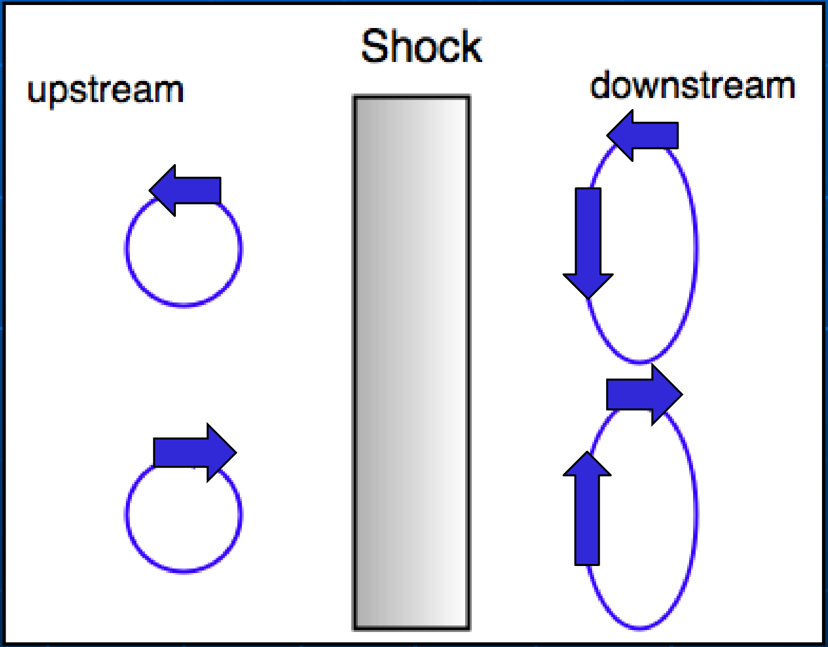


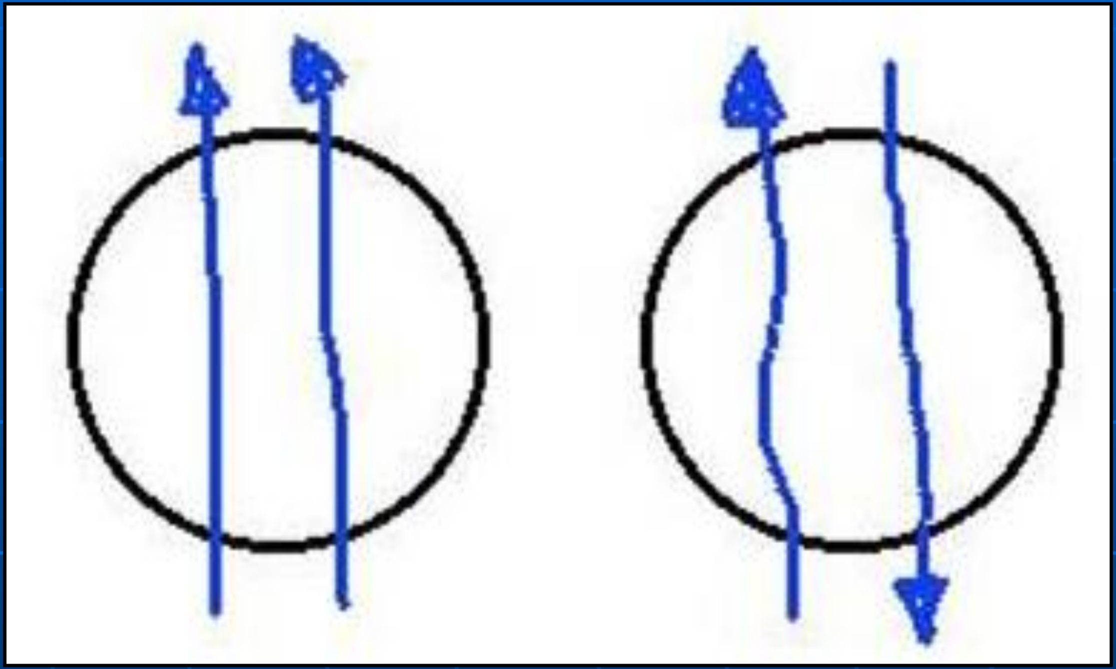
The effect of shocks on the magnetic field (2)

- An isotropic turbulent magnetic field is made anisotropic

- **Isotropic turbulent field**:
  produces I but no PI

- **Anisotropic turbulent field**:
  produces PI and I





	Regular (coherent) field	Anisotropic turbulent (incoherent) field
Polarization :	strong	strong
Faraday rotation :	**high**	low

Fletcher 2004

Magnetic field components

- Total field **B_{tot}**
  (measured by total synchrotron intensity)

- Isotropic turbulent field **B_r**
  (measured by unpolarized synchrotron intensity)

- Anisotropic turbulent field **B_{an}**
  (measured by polarized synchrotron intensity)

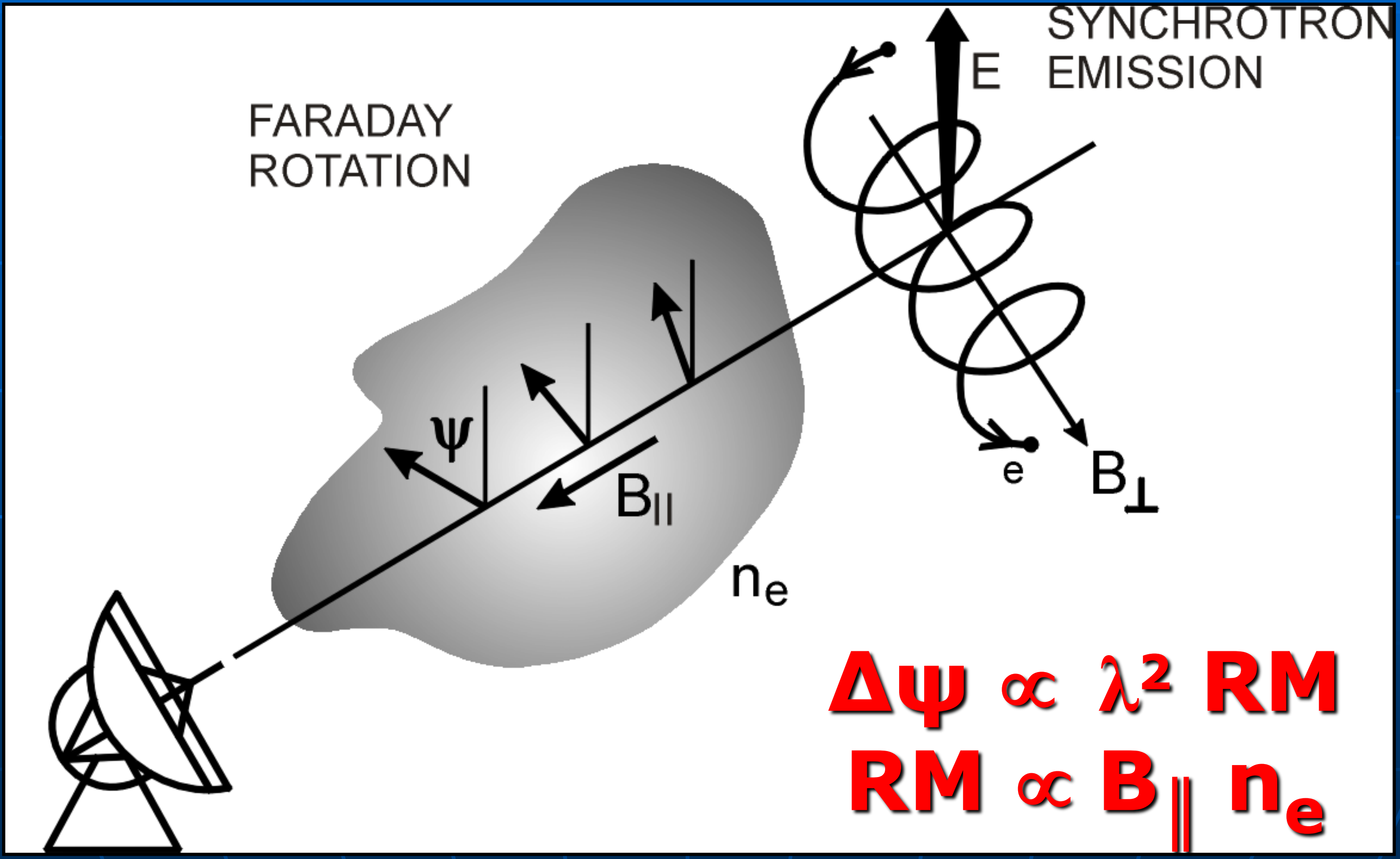
- Coherent (regular) field **B_{reg}**
  (measured by polarized synchrotron intensity **and** Faraday rotation)

$$B_{tot}^2 = B_r^2 + B_{an}^2 + B_{reg}^2$$

Observational test:

Regular fields should give rise to Faraday rotation

Faraday rotation of polarized emission: Ordered magnetic fields

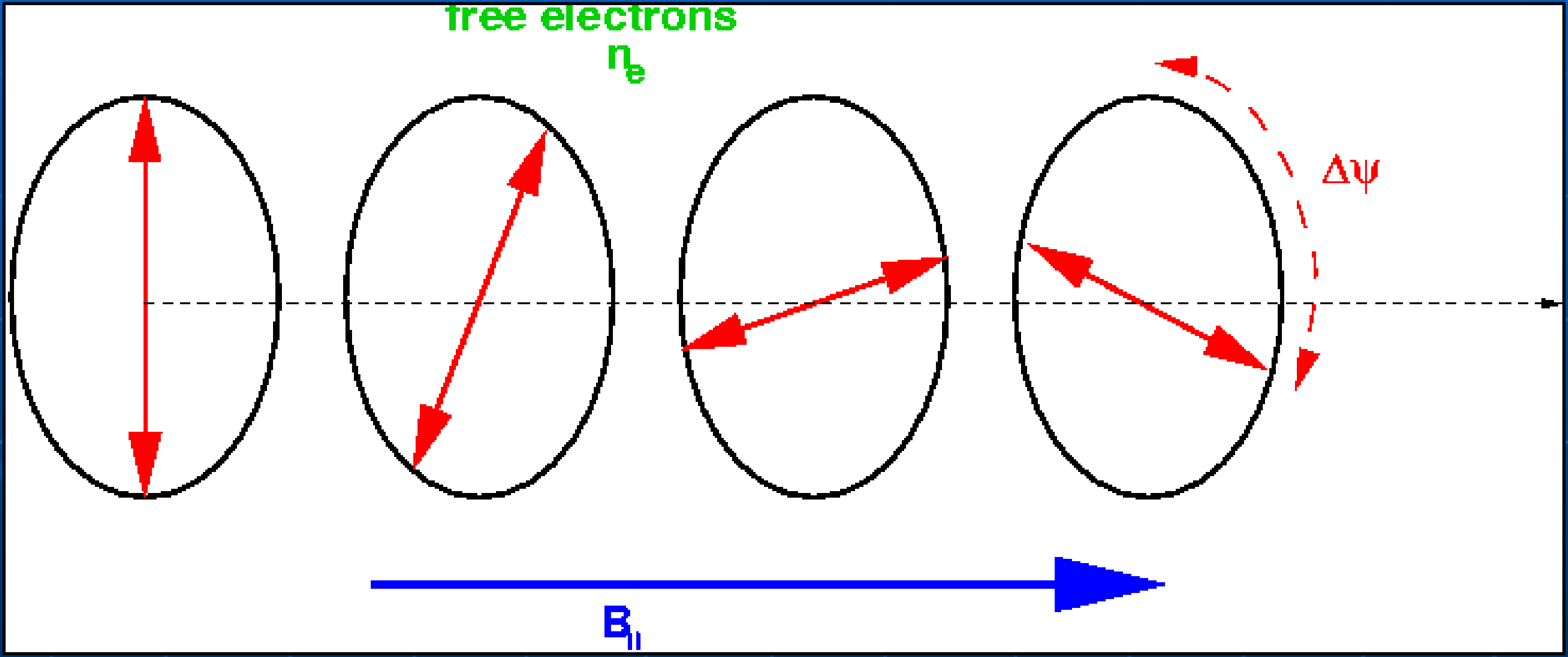


$$\Delta\psi \propto \lambda^2 \, RM$$

$$RM \propto B_\parallel \, n_e$$

RM: Faraday rotation measure

Faraday rotation



Faraday rotation

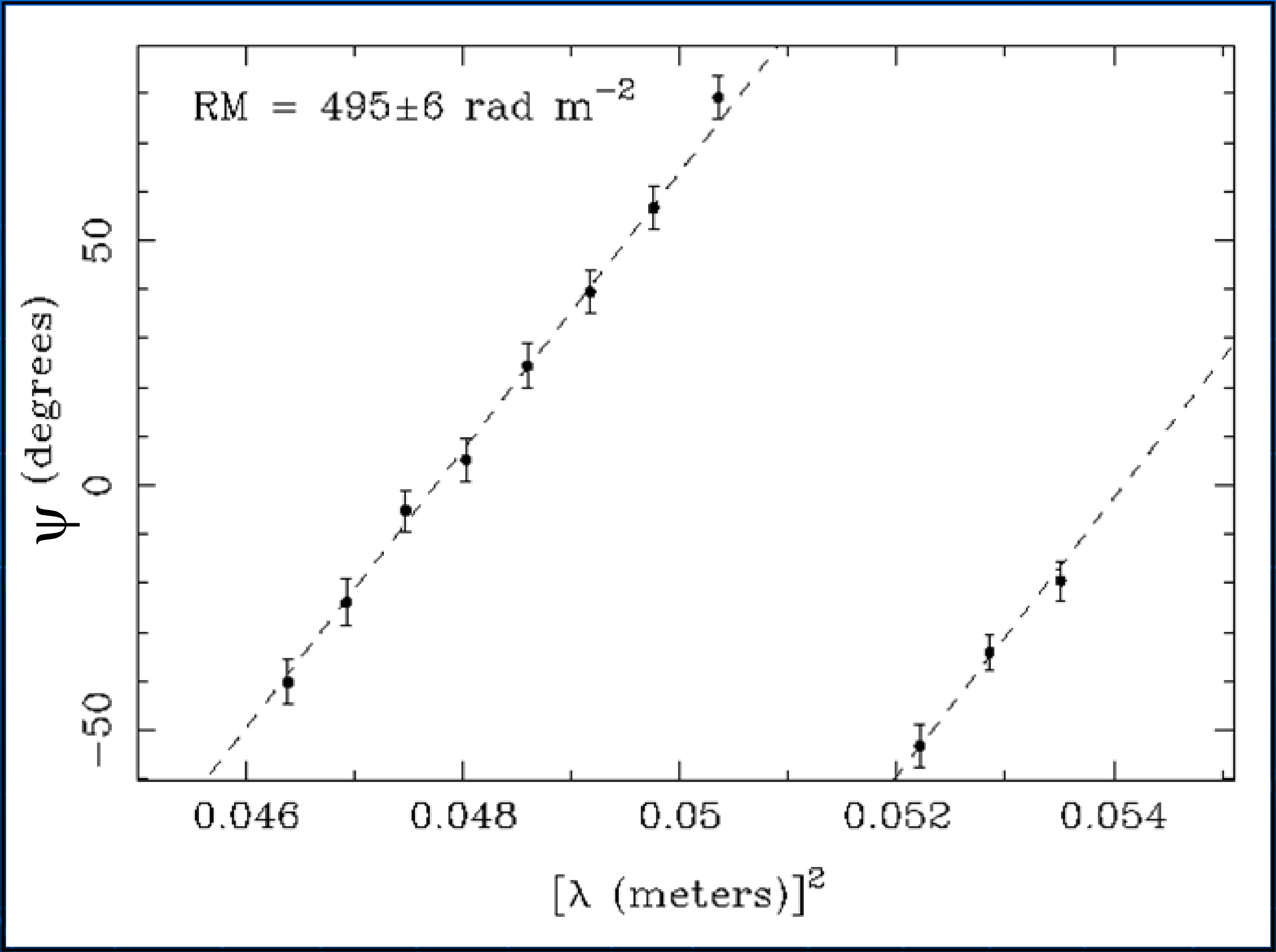
$$\Delta\psi = 0.81\ \text{(rad)}\ \lambda\ \text{(m)}^2 \int n_e\ (\text{cm}^{-3})\ B_{\text{reg}\parallel}\ (\mu\text{G})\ dl\ \text{(pc)}$$

$$= \mathbf{RM}\ \lambda\ \text{(m)}^2$$

Classical measurement of RM:

Fitting $\Delta\chi$ as a function of λ^2

Faraday rotation of a pulsar



Typical Faraday rotation measures

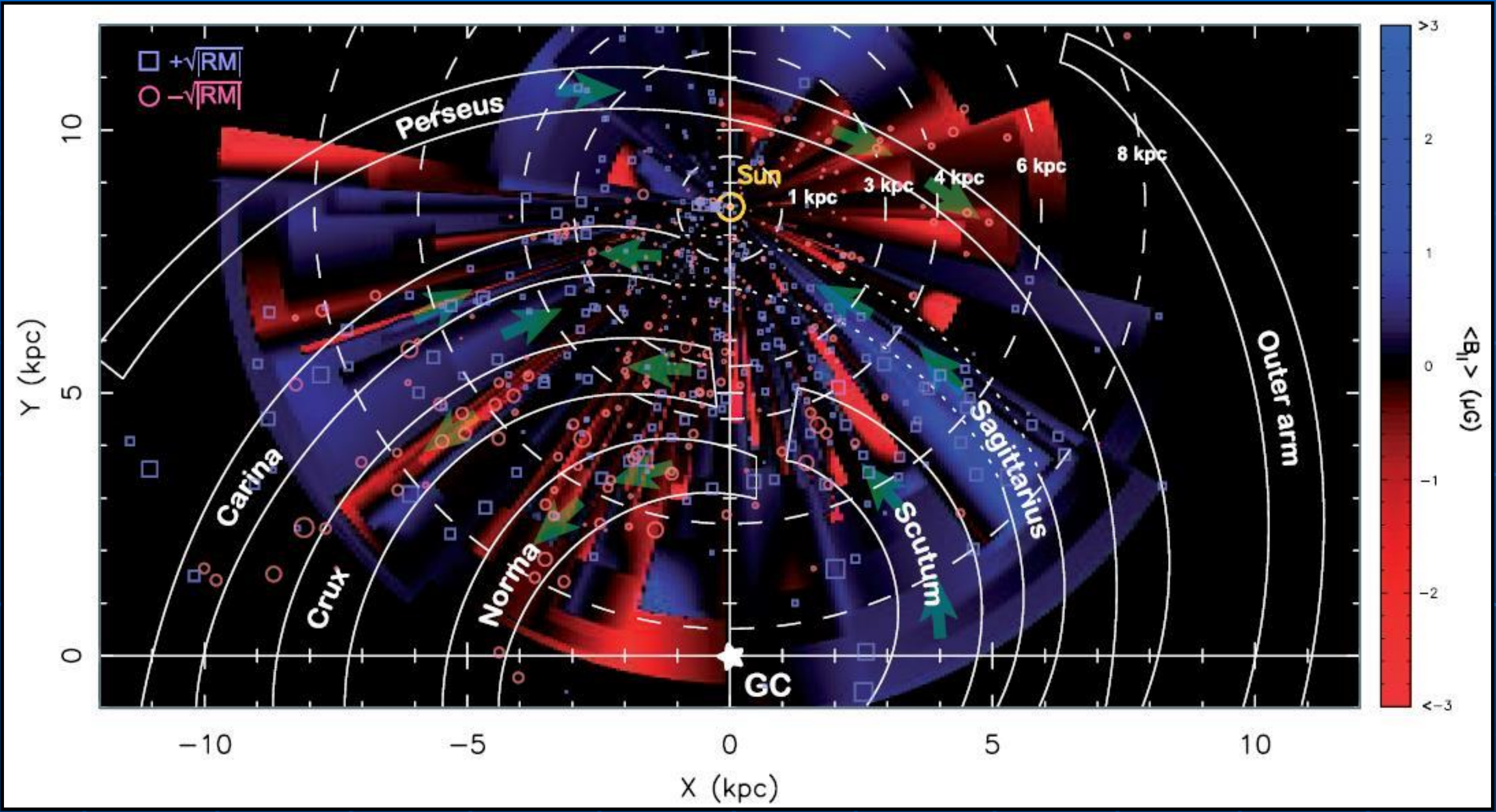
- Intergalactic medium: ≈ 0.01-0.1 rad m^{-2}
- Galactic halos: ≈ 0.1-1 rad m^{-2}
- Galactic disks: ≈ 10-100 rad m^{-2}
- Galaxy clusters: ≈ 100-1000 rad m^{-2}
- Cooling cores of clusters: ≈ 1000-10000 rad m^{-2}

Faraday rotation angles

$\vert \mathrm{RM} \vert$	=	100	10	1	0.1	rad m^{-2}
1400 MHz	$\Delta\chi$ =	263°	26°	3°	0.3°	
200 MHz	$\Delta\chi$ =	12900°	1290°	129°	13°	
120 MHz	$\Delta\chi$ =	35800°	3580°	358°	36°	

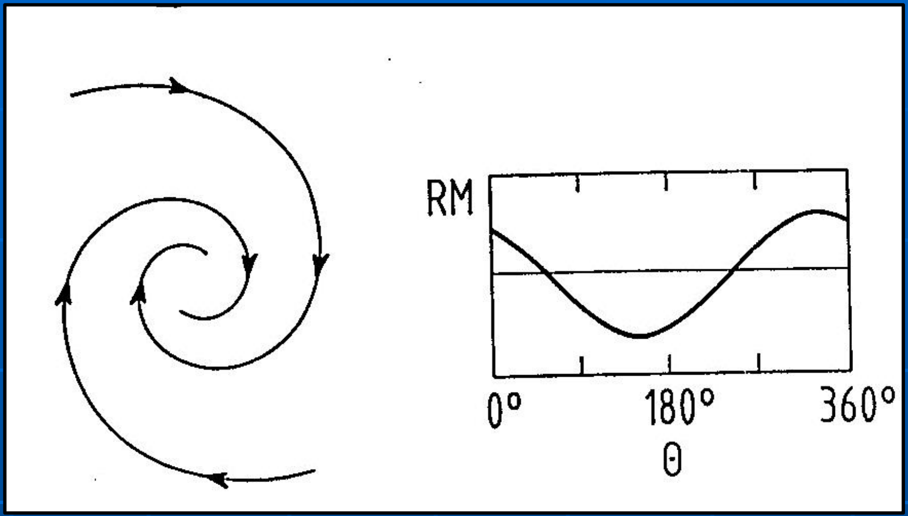
Faraday rotation of pulsars in the Milky Way

Noutsos 2010

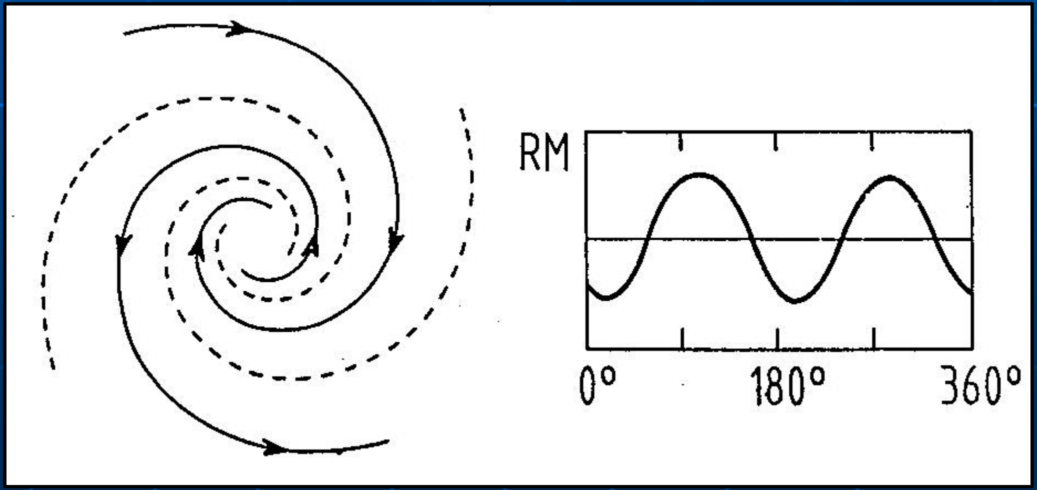


- Pulsars are highly polarized
- RM is well defined
- But distances are not well known

Azimuthal variation of Faraday rotation in galaxies



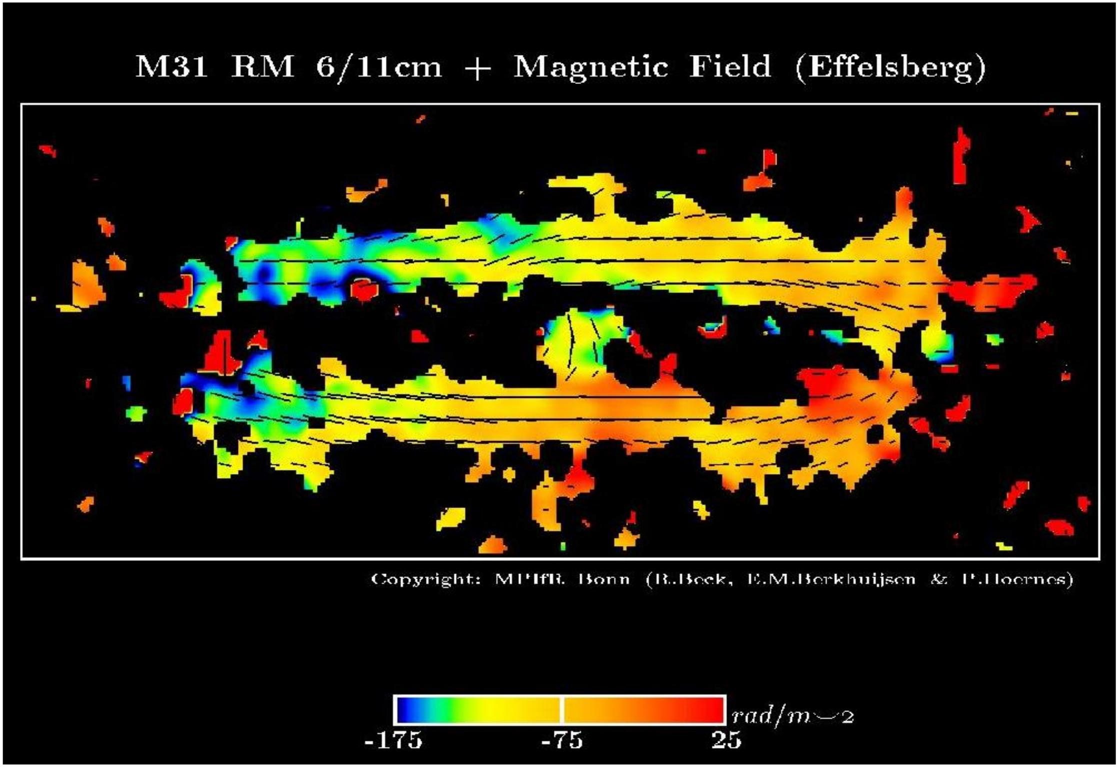
Axisymmetric spiral
(mode m=0)



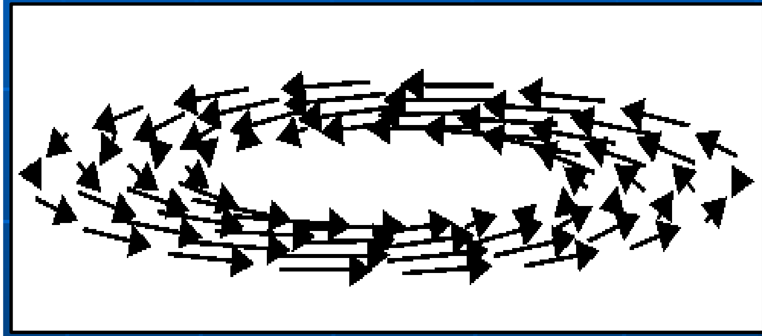
Bisymmetric spiral
(mode m=1)

Krause 1990

The dynamo of M31



Berkhuijsen et al. 2003



Fletcher et al. 2004

The spiral field of M31 is coherent and axisymmetric

Practical problems with measuring field strengths with Faraday rotation

- Faraday rotation measures the average product of thermal electron density n_e and field strength:

  Independent data about n_e needed, e.g. from thermal emission or from radio recombination lines

- $< n_e B_\| > \neq < n_e > < B_\| >$:

  A correlation or anticorrelation between n_e and $B_\|$ affects the field strength estimate

- Several emitting & rotating regions along the line of sight:

  polarization angle does **not** vary with λ^2

- Faraday depolarization occurs:

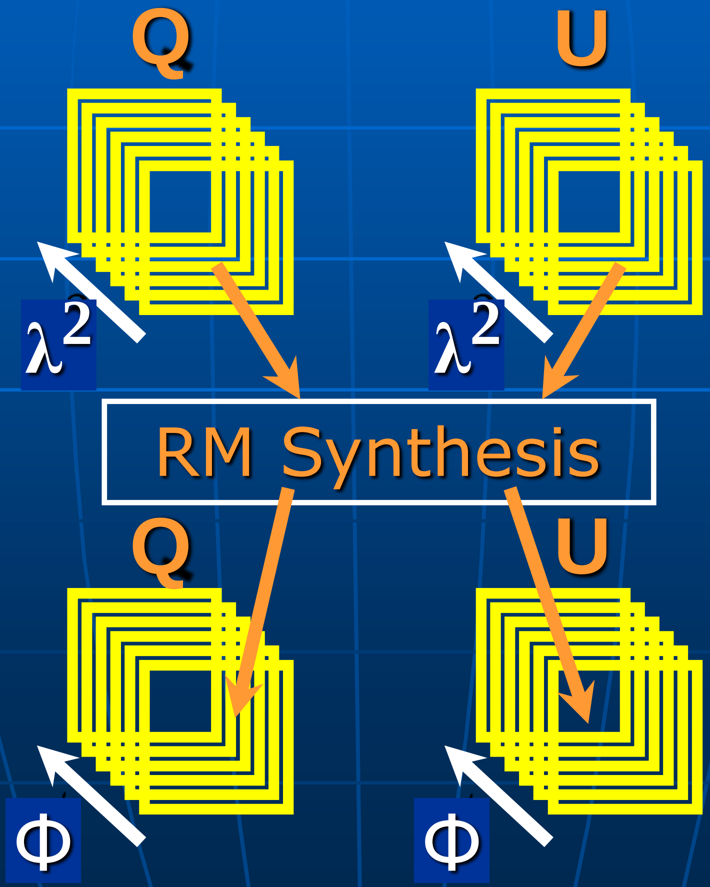
  polarization angle does **not** vary with λ^2

RM Synthesis
opens a new dimension
in the phase space
of observations:

the Faraday Space

The future: Spectro-polarimetry (RM Synthesis)

- RM synthesis works on observed Q,U cubes in wavelength to produce **RM-cubes** in Faraday depth:

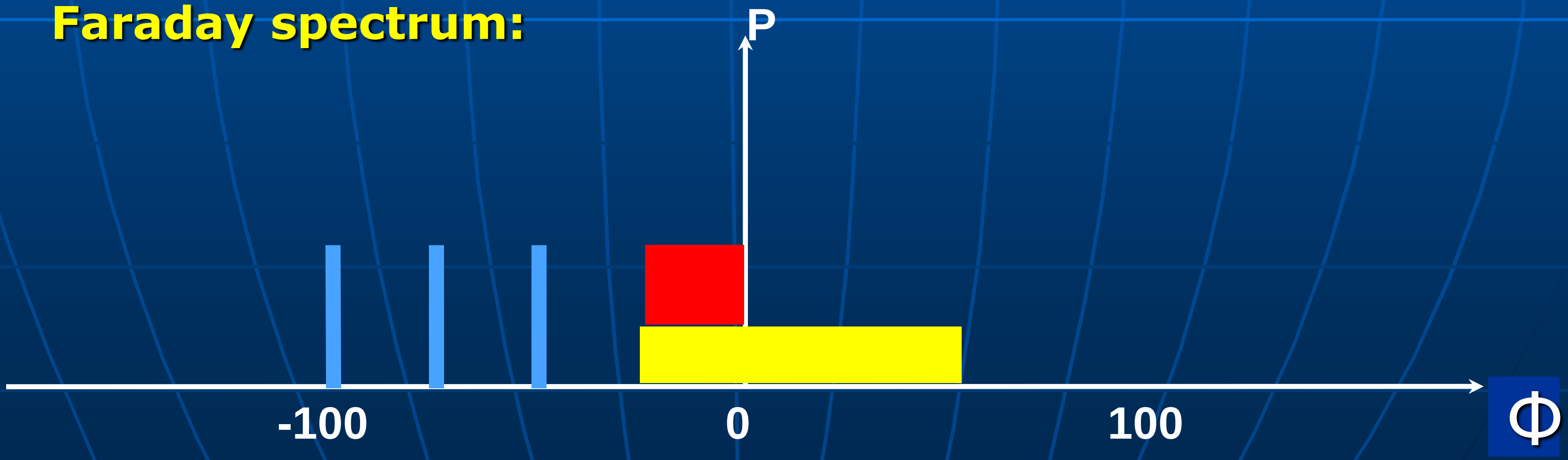


RM Synthesis: basic facts

- The *Faraday spectrum* F(φ) is the Fourier transform of the observed complex polarized intensity P(λ^2)
- *Faraday depth* ($\varphi \propto \int B_\parallel\, n_e\, dl$) is generally different from classical rotation measure *RM*
- Foreground *Faraday screen*: φ = RM
- Homogeneous mixed emitting & rotating layer, no depolarization: φ = 2 RM
- The λ^2 coverage of observations determines the resolution in Faraday space (*RM Spread Function, RMSF*)

Example

Faraday spectrum:



Resolution in Faraday space:

$$\Delta\varphi \approx 2\,\sqrt{3} / \Delta\lambda^2 = \sqrt{3}\,(\nu_0/\Delta\nu) / \lambda_0^2$$

Needed: long wavelength ***and*** large bandwidth

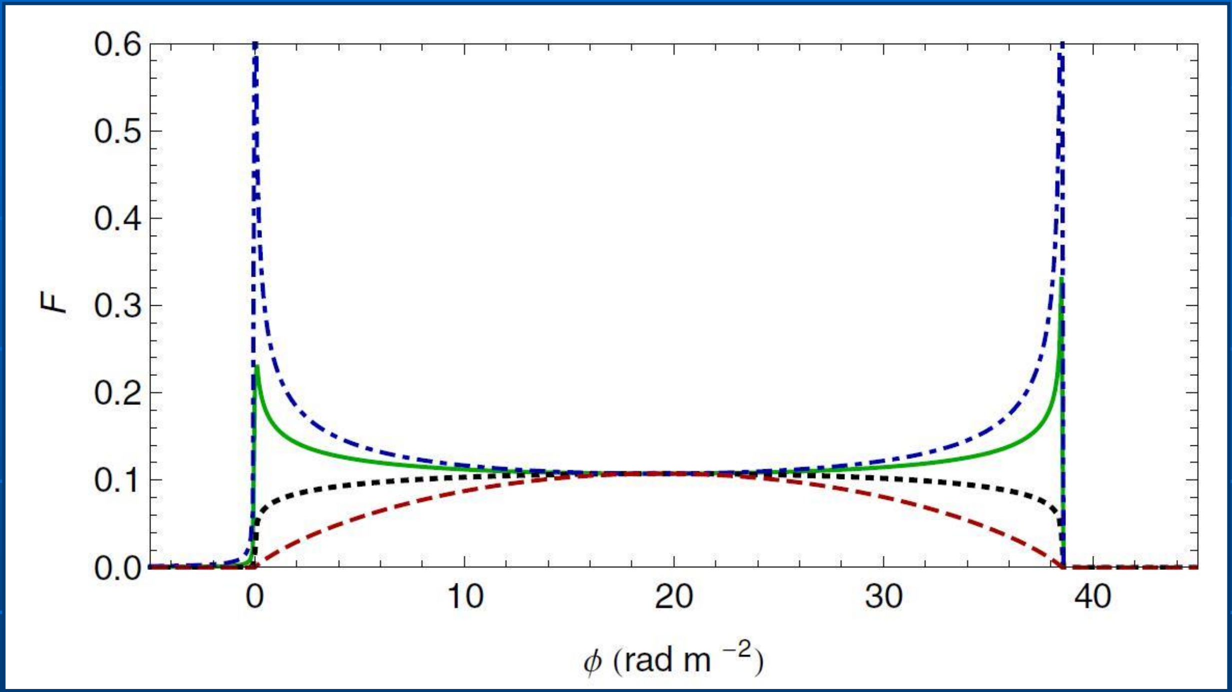
Measurement precision of a narrow FD component:

$$\varphi_i = \Delta\varphi / (2\,(S/N))$$

(S/N): Signal-to-noise of the polarized intensity

$\Delta\lambda^2$ is as important as signal-to-noise

Faraday spectrum of an extended source with a regular field: "Faraday horns"

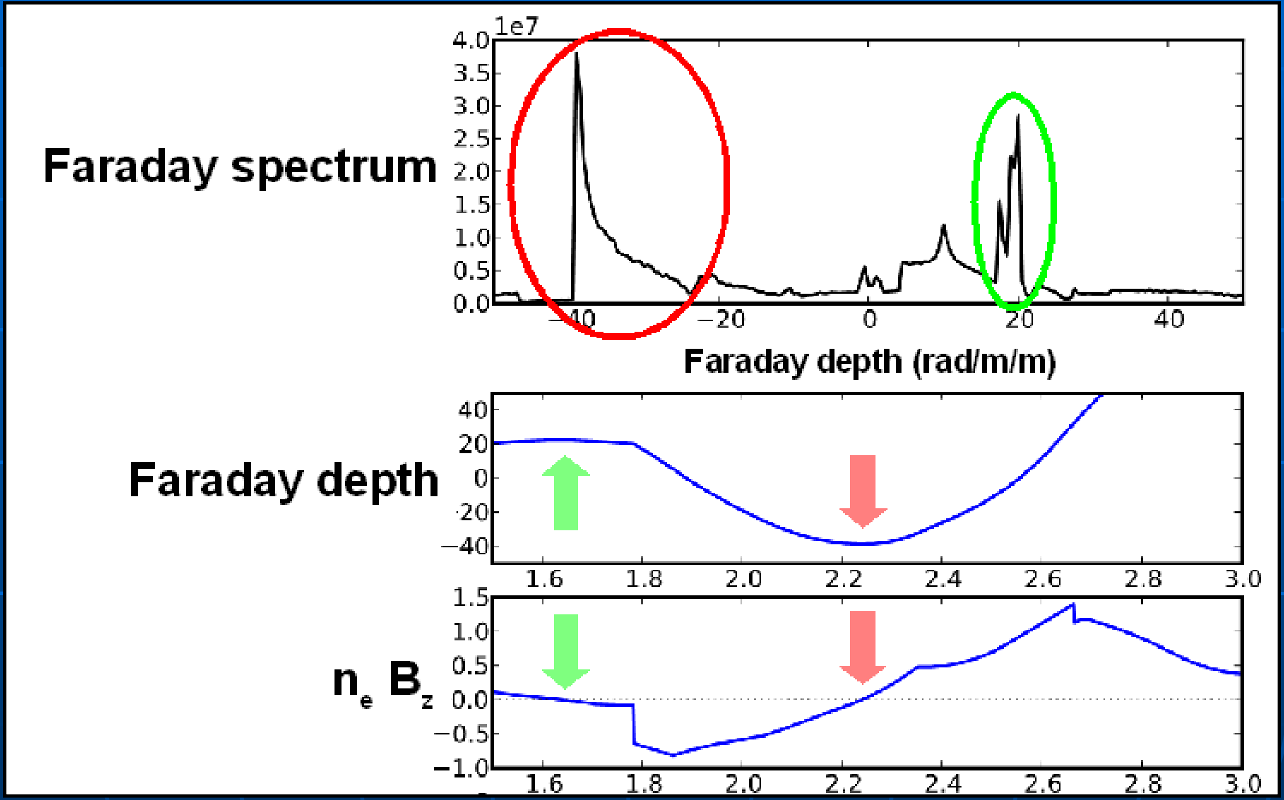


Beck et al. 2012

- Two symmetric Faraday horns indicate an extended source
- Height of the horns shows relative distribution of cosmic-ray and thermal electrons

Field reversals generate "Faraday caustics"

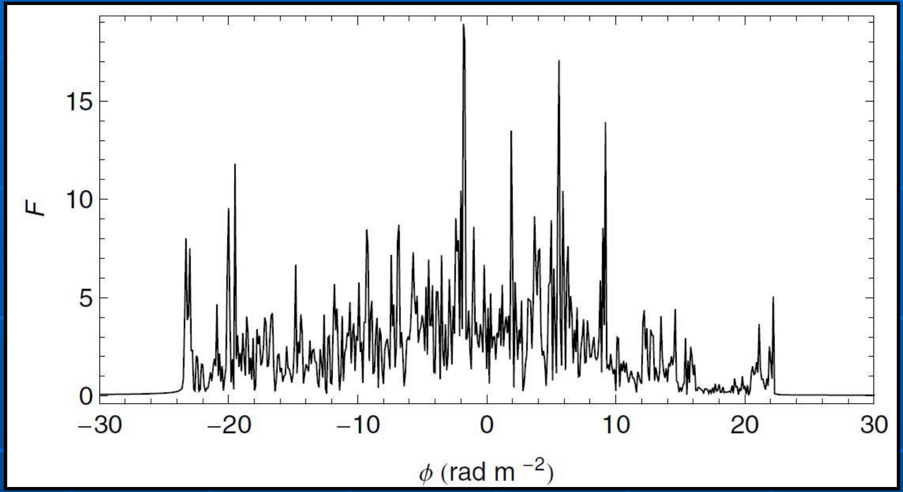
Bell et al. 2011

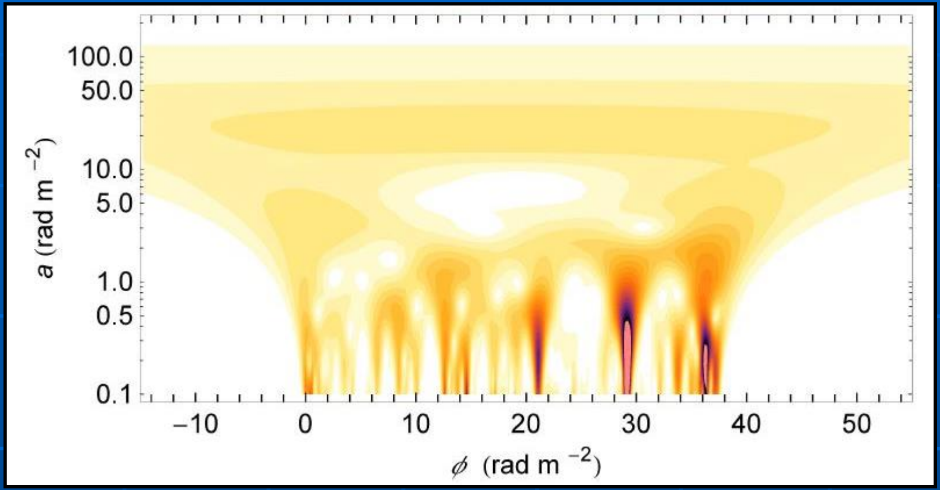


Asymmetric FD components: high FD resolution & large wavelength ratio required

Turbulent fields generate a "Faraday forest"

Beck et al. 2012





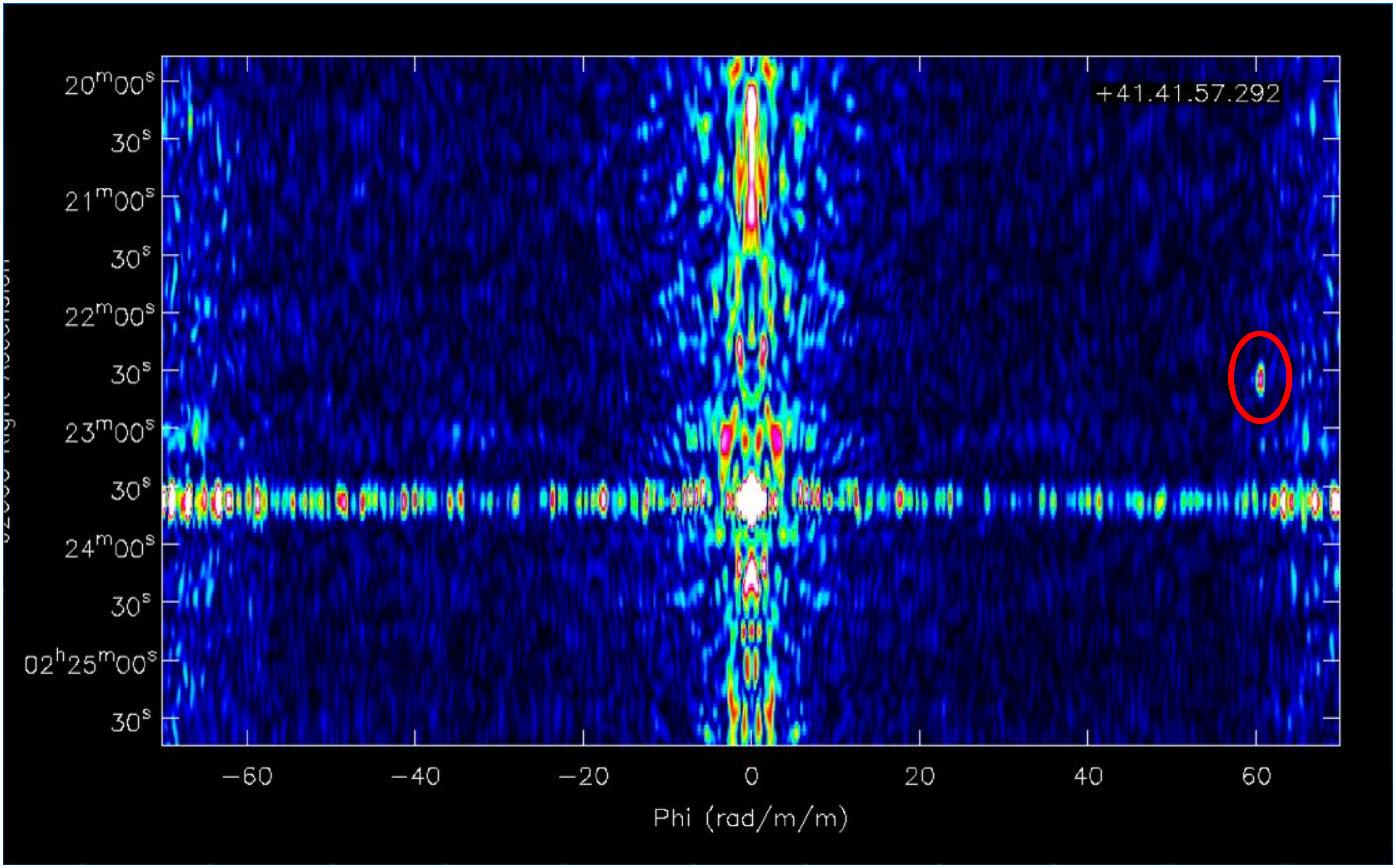
Many FD components:
high FD resolution required (i.e. large coverage in λ^2)

Applications of RM Synthesis

Polarized emission from PSR J0218+4232

LOFAR - Cut along RA at constant DEC

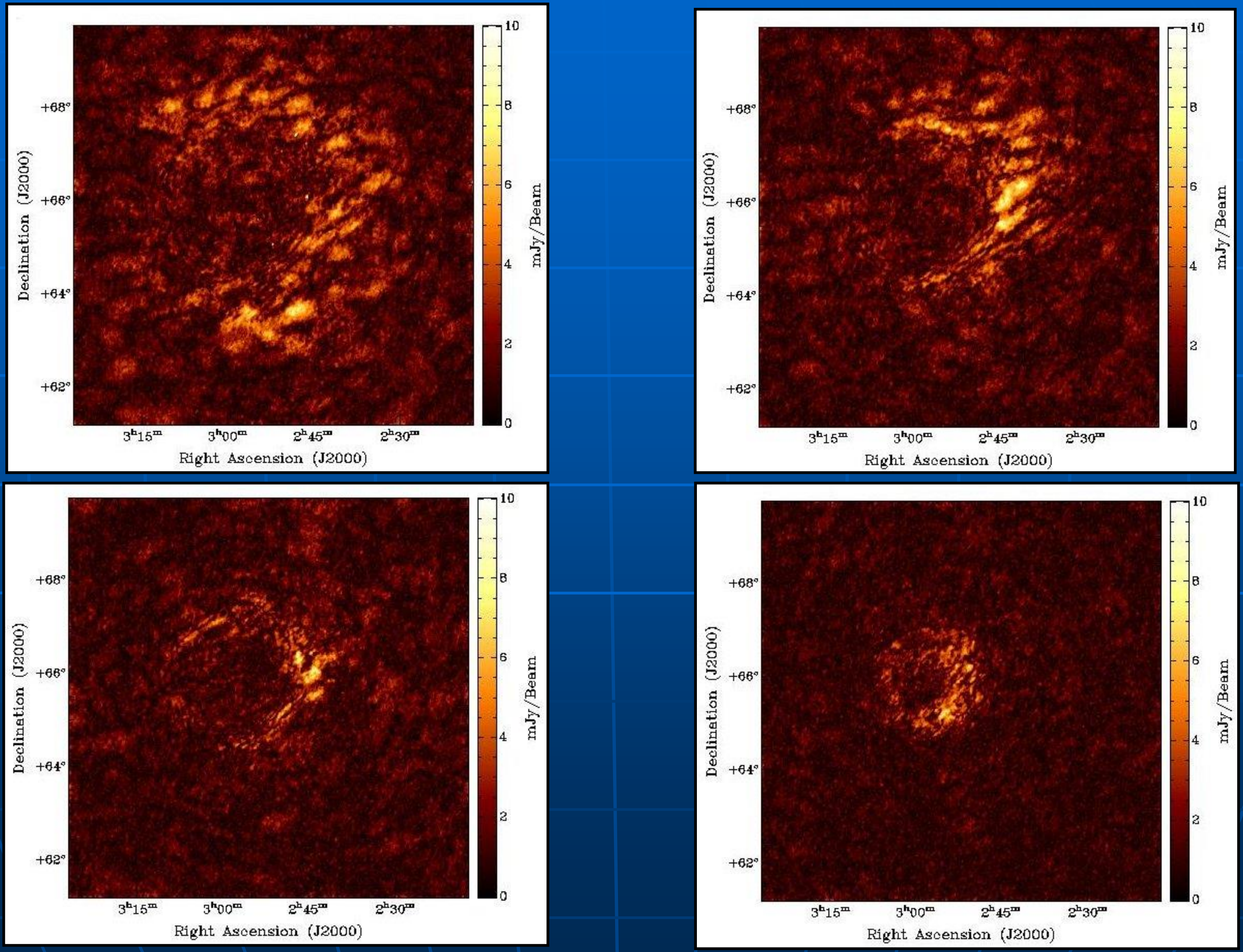
(A. Noutsos, C .Sobey, M. Bell, A. Horneffer)



- Strong instrumental polarization visible around 0 rad/m^2
- Polarized pulsar detected at 61 rad/m^2

Polarization from the FAN region of the Milky Way

LOFAR HBA 120-180 MHz, Faraday depths φ=-1 … -5 rad/m^2

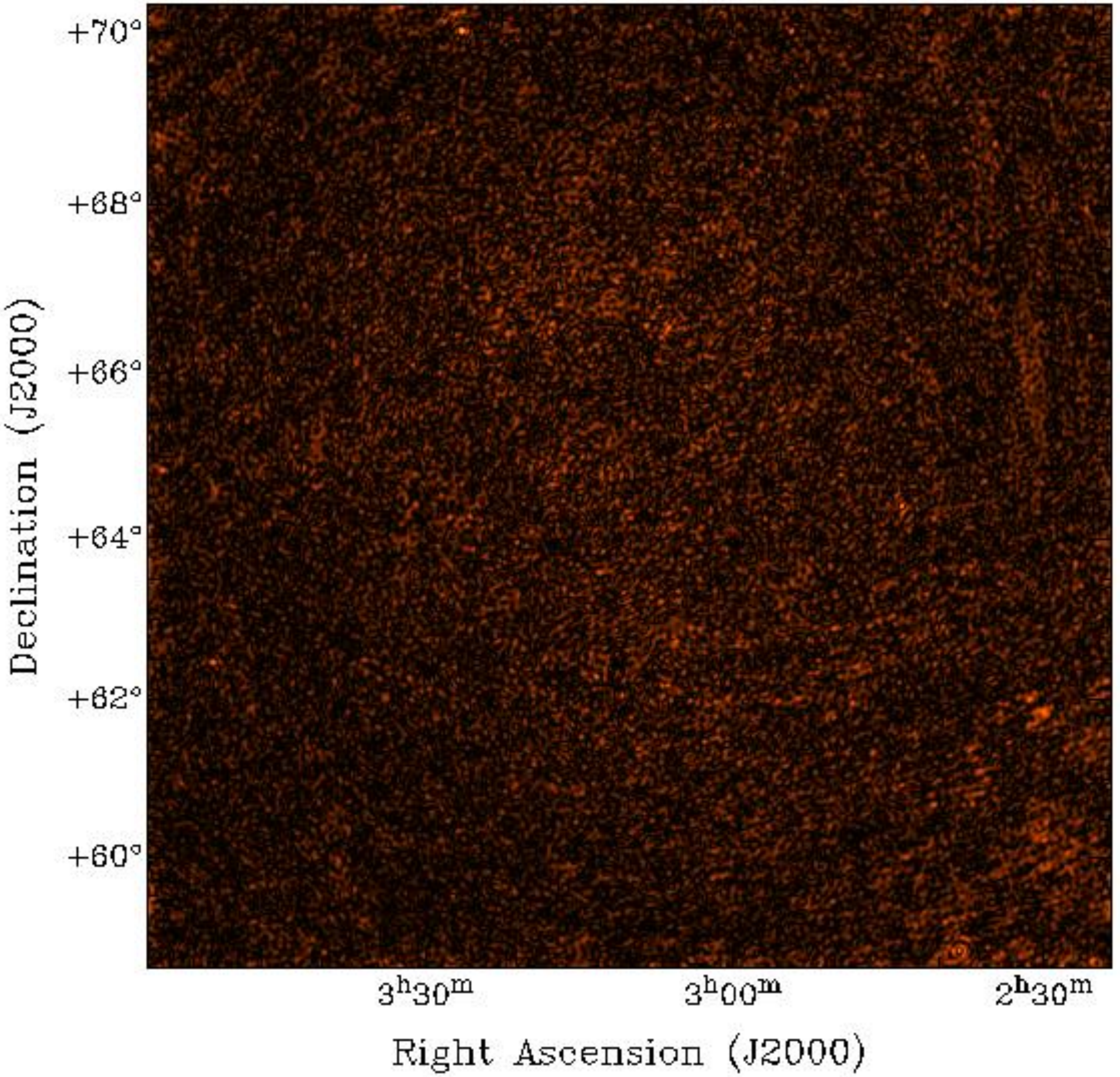


Iacobelli et al. 2013

FAN region of the Milky Way

Westerbork 310-376 MHz

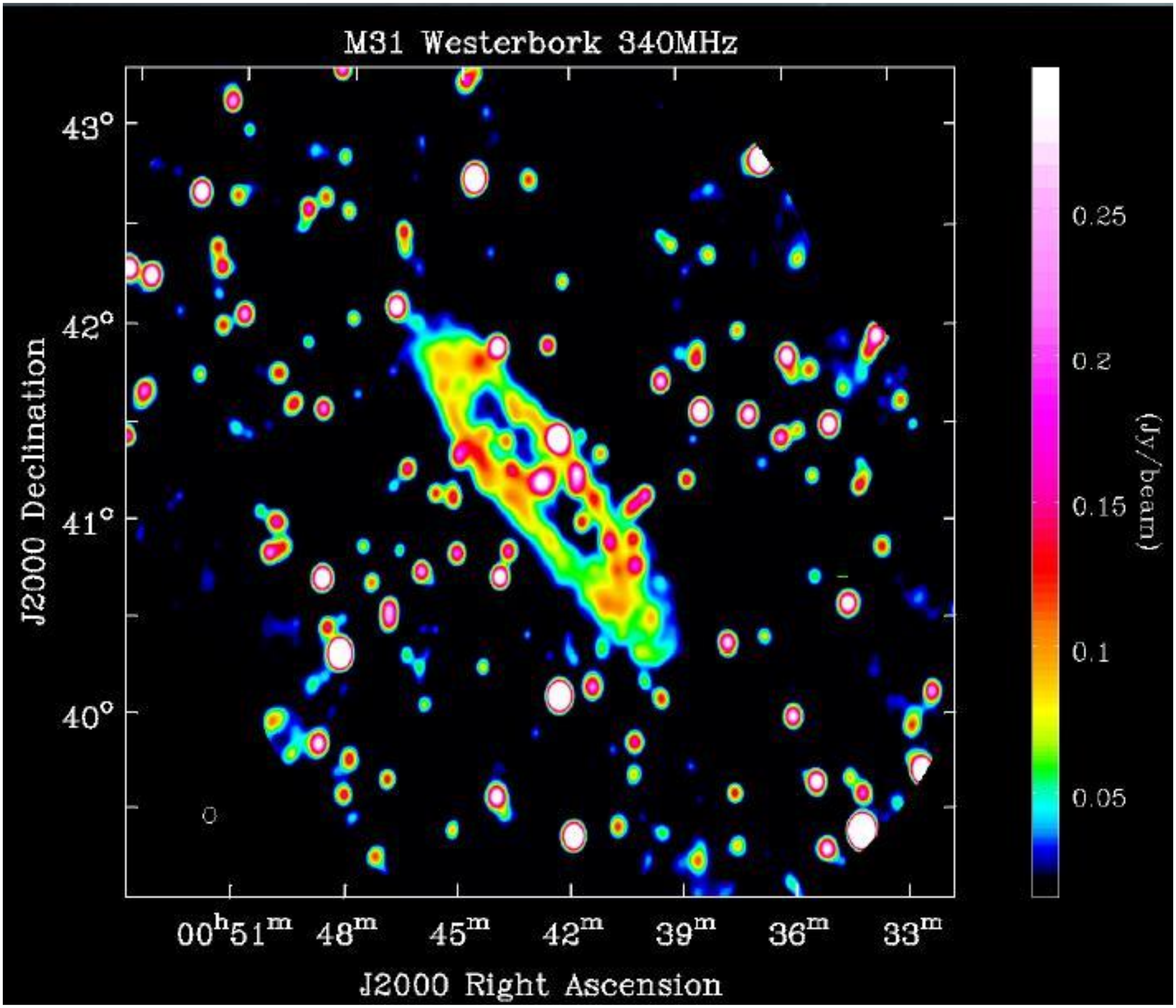
FD = 9.000000e+00



Bernardi et al. (2009)

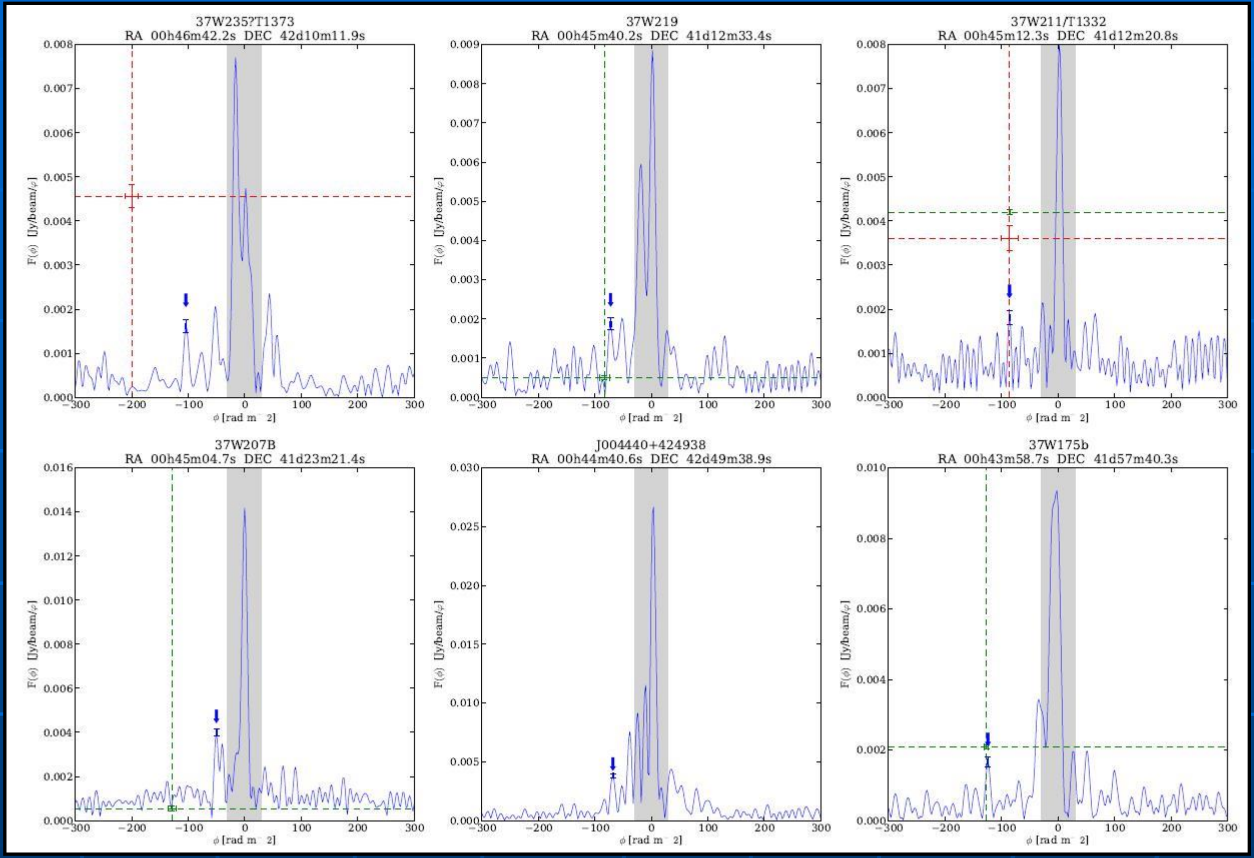
M31 WSRT 310-376 MHz: Total intensity

Gießübel et al. 2013



M31 WSRT 310-376 MHz Faraday spectra

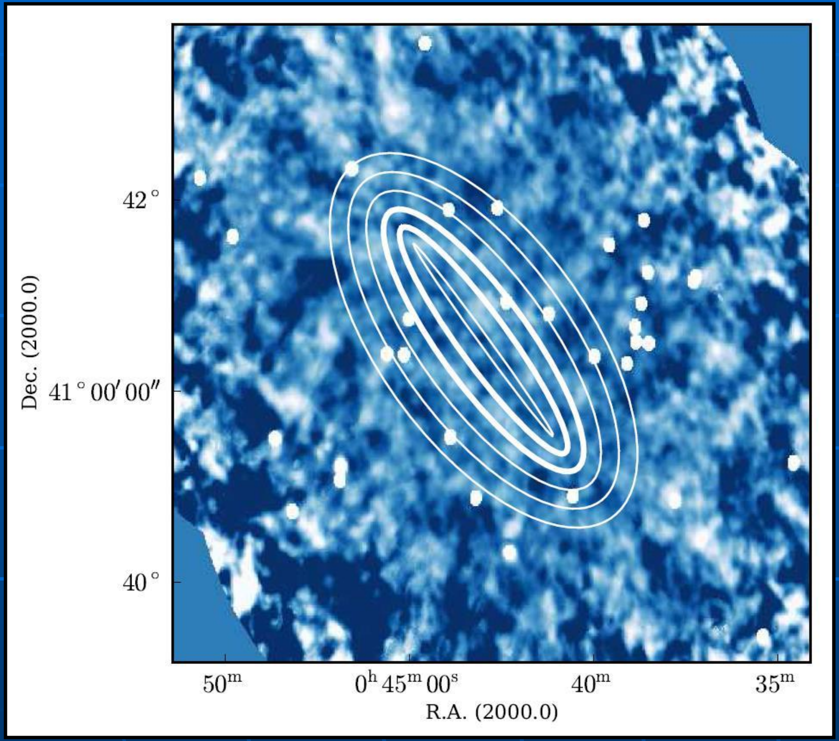
Gießübel et al. 2013

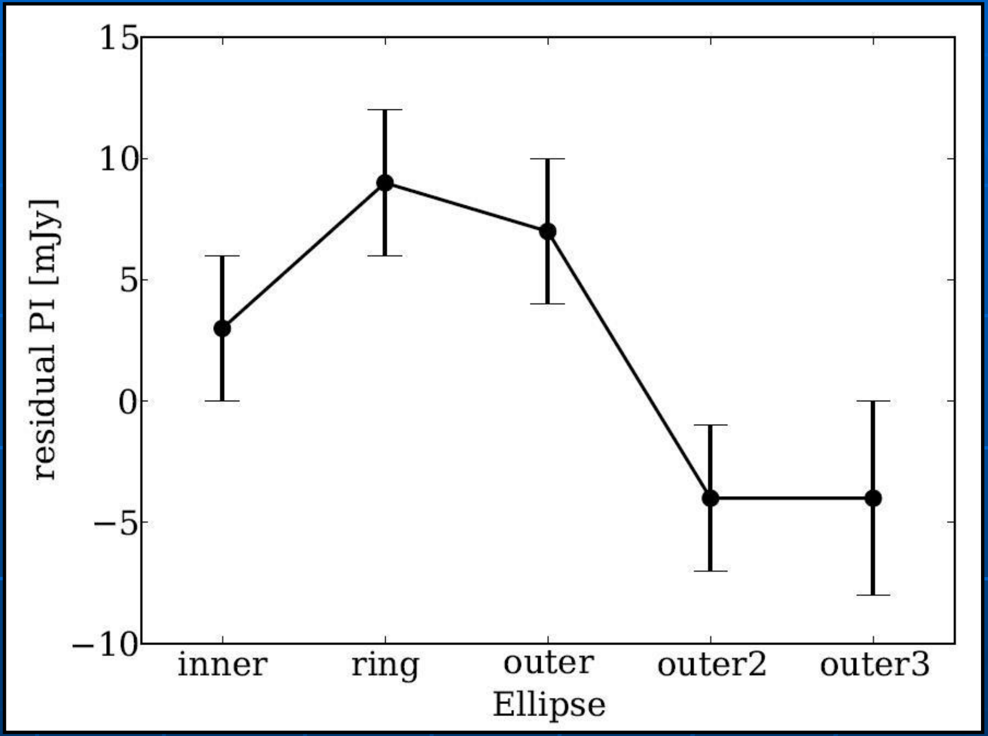


- 18 of 33 sources have complex spectra
- All 8 sources with deviating FDs have complex spectra
- Both sources with less DP have simple spectra

M31 WSRT 310-376 MHz: Polarized intensity

Gießübel et al. 2013





- Detection of very low polarization (**0.21 ± 0.05% !**) by integration of Faraday spectra

- Strong depolarization: DP (90cm/6cm) = 0.005 ± 0.002

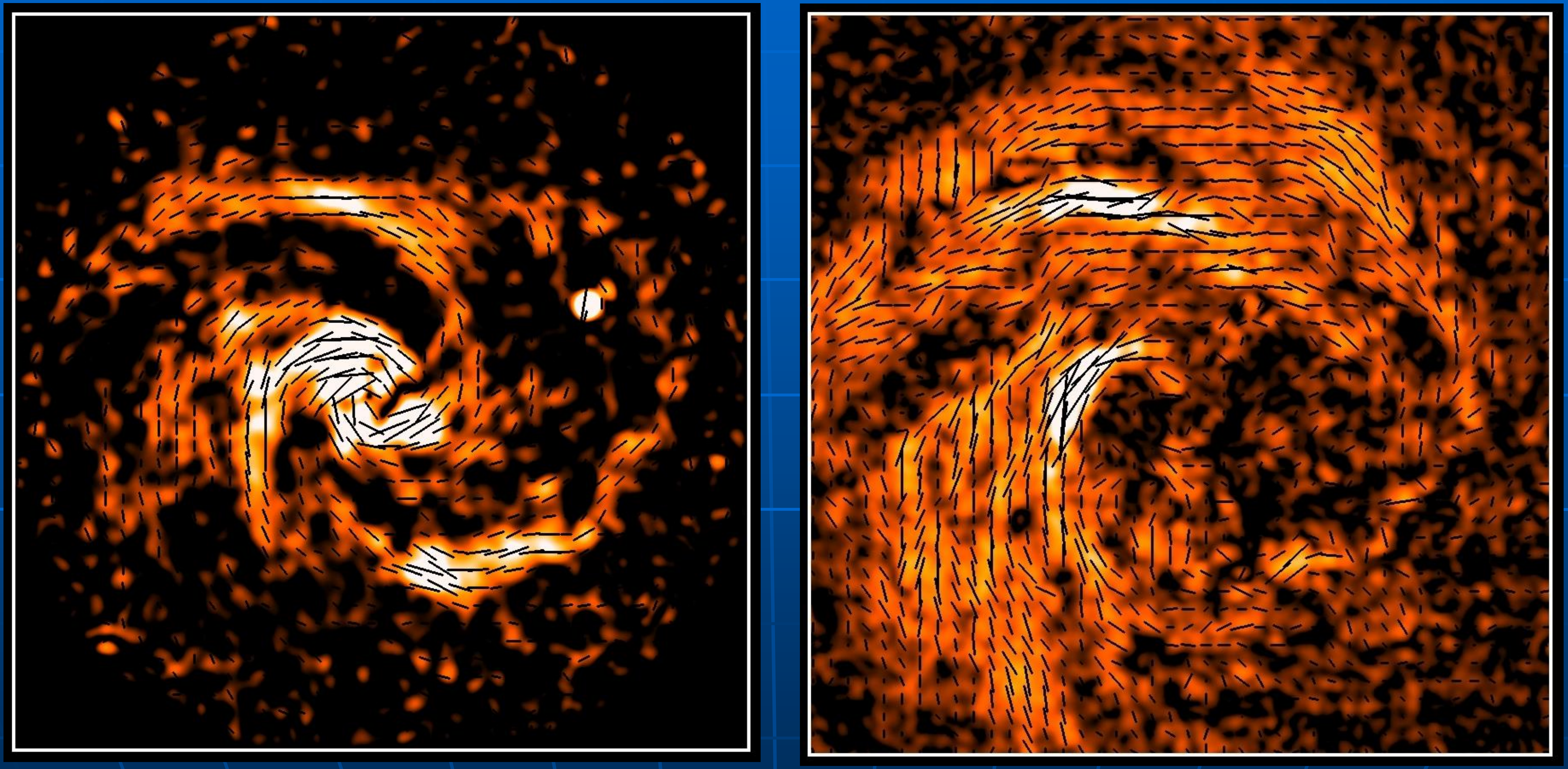
Strengths of RM Synthesis

- Multi-component sources can be resolved in Faraday space even if not angularly resolved
- Multi-component medium can be resolved in Faraday space even if not angularly resolved
- The 3-D Faraday cube yields a 3-D picture of the magneto-ionic ISM or IGM (*Faraday tomography*) – but …

Practical problems with RM Synthesis

- Negative λ^2 cannot be observed: Fourier transform is limited
- Present-day radio telescopes cover only a small range in λ^2
- Faraday depth (FD) is ***not*** geometrical depth
- Only emitting & rotating regions generate separate components
- *The interpretation of Faraday spectra is not straight forward: modelling needed*

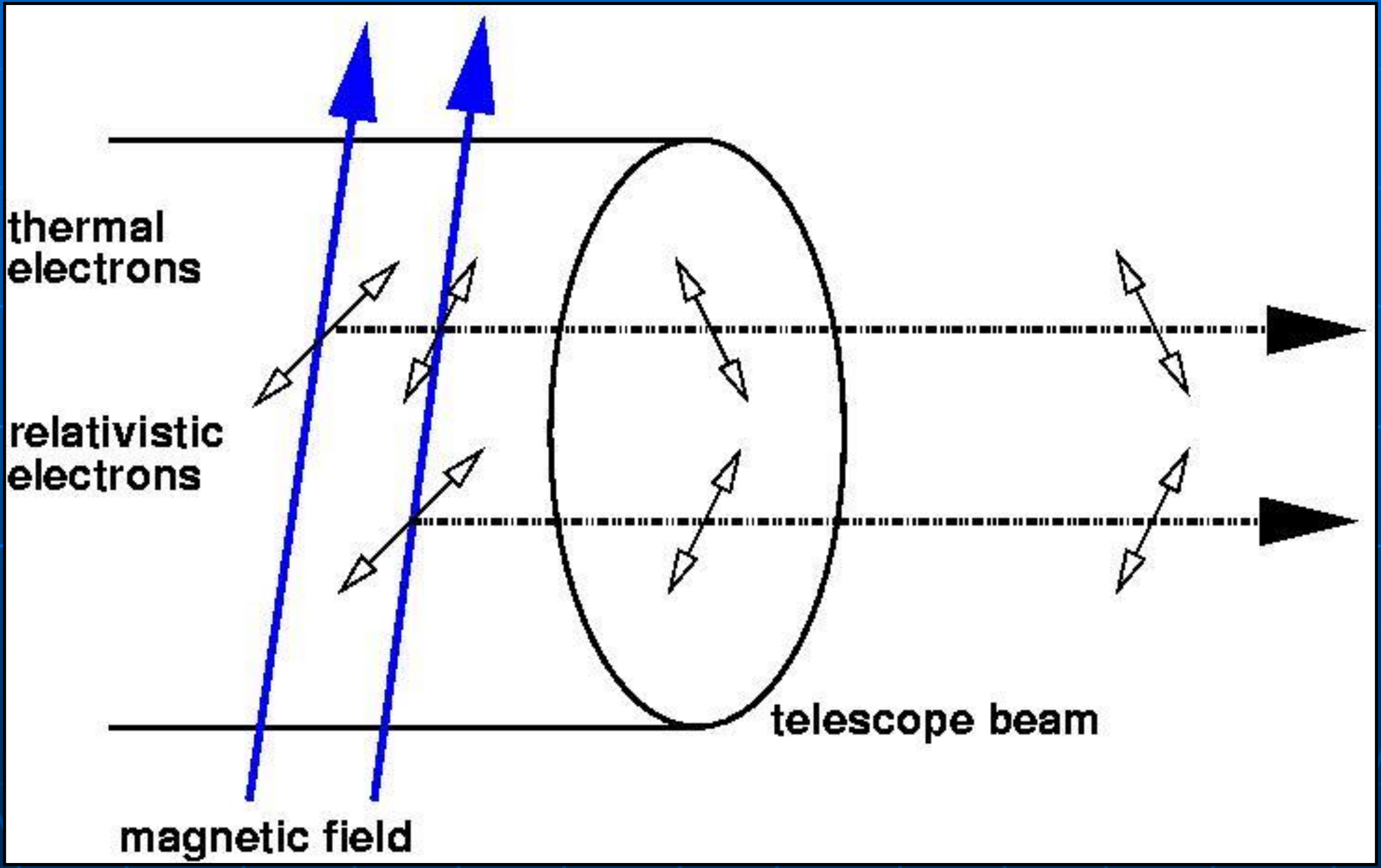
Faraday depolarization



Beck 2007

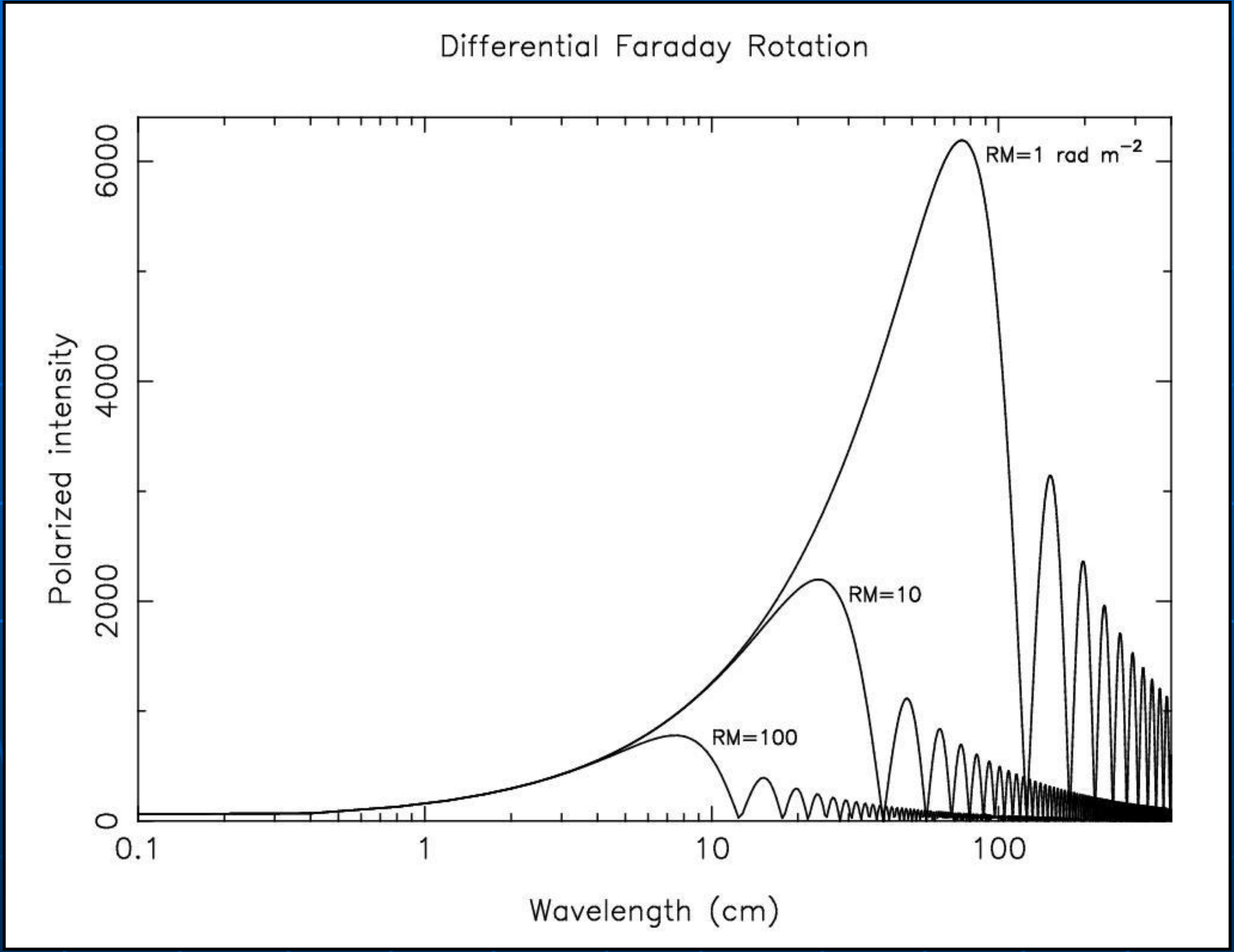
NGC 6946: Polarized intensity at 6 cm and 20.5 cm

Depolarization by differential Faraday rotation (regular field)



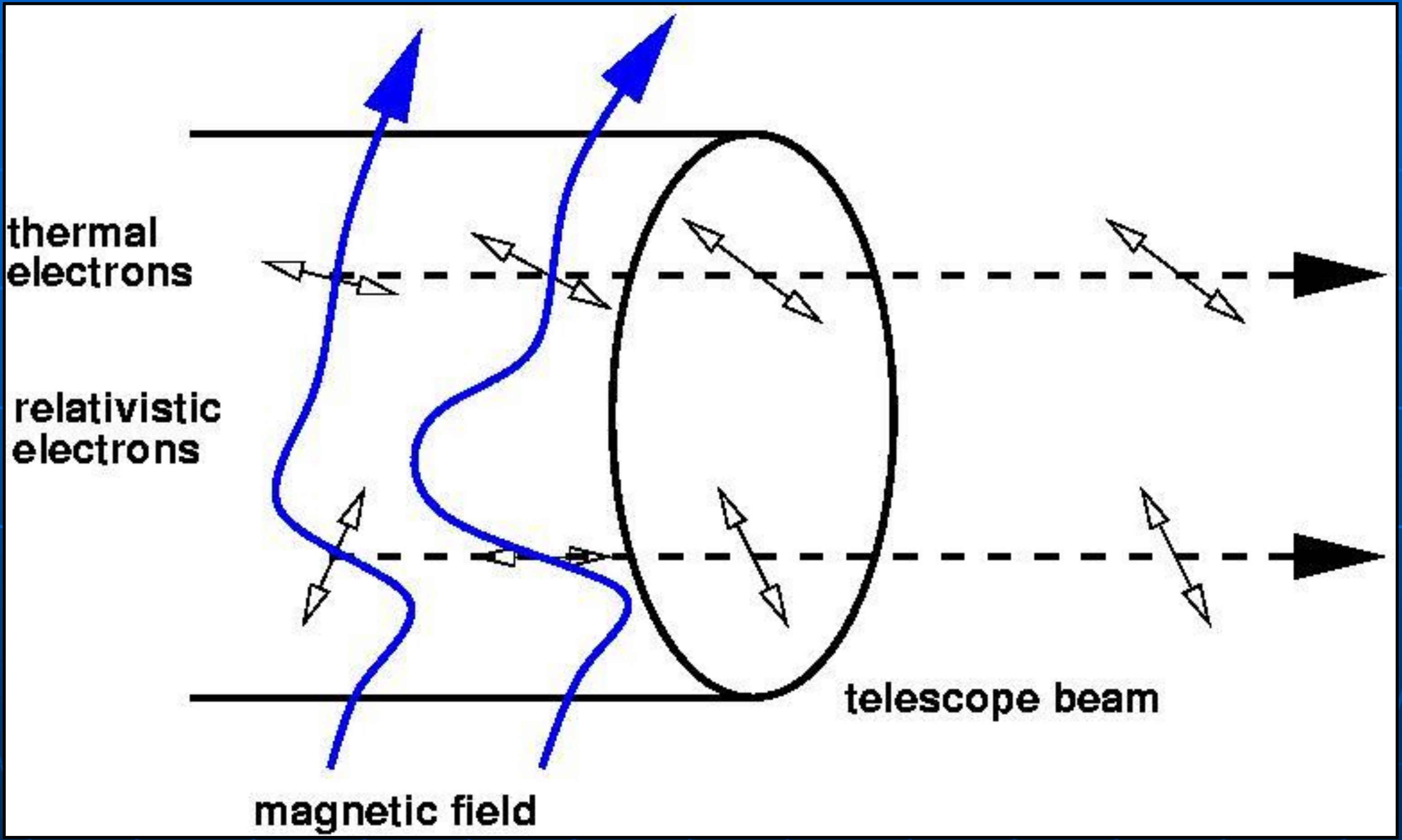
Fletcher et al. 2004

Maximum polarized intensity (regular field)



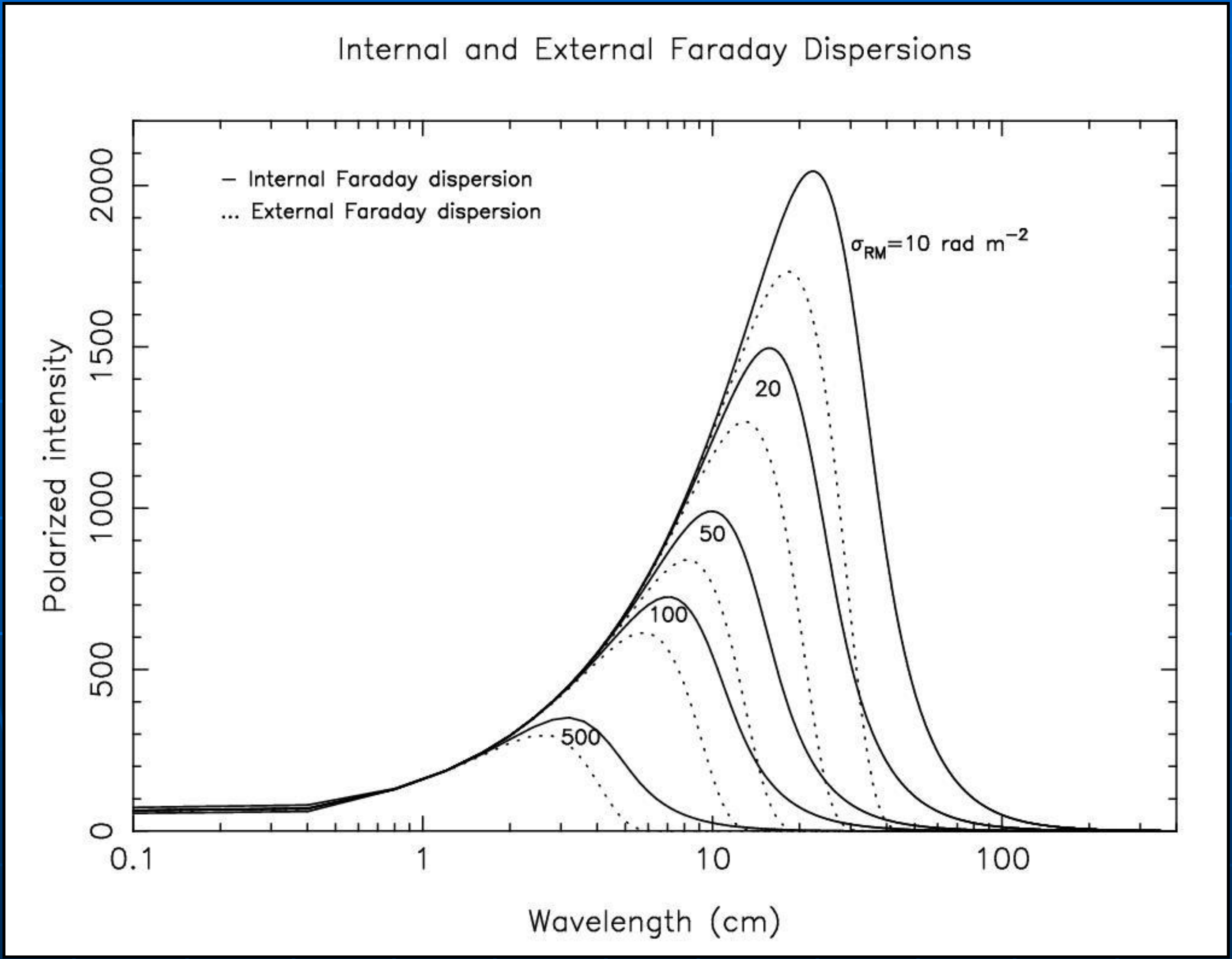
Arshakian & Beck 2011

Depolarization by internal Faraday dispersion (turbulent field)



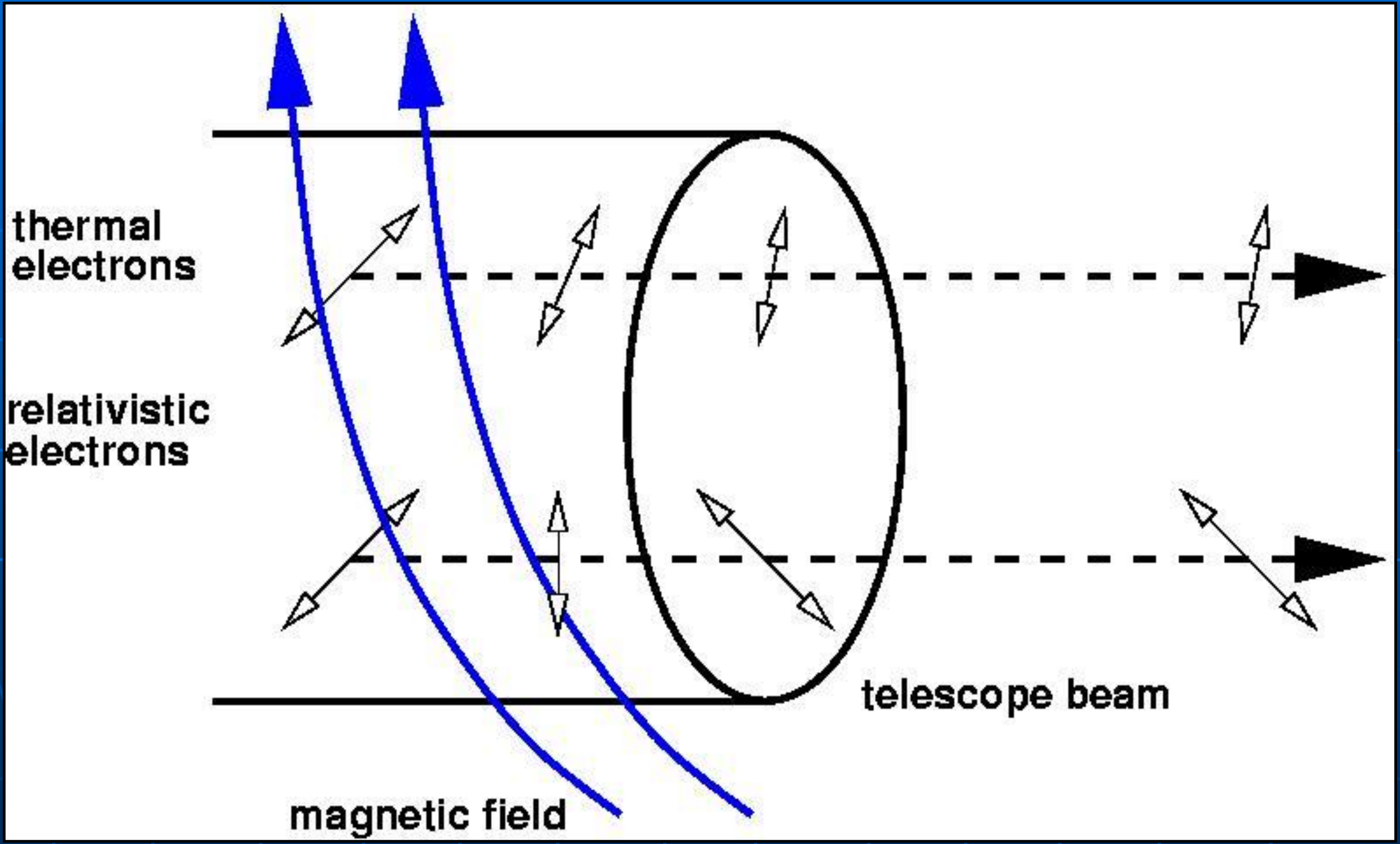
Fletcher et al. 2004

Maximum polarized intensity (turbulent field)



Arshakian & Beck 2011

Depolarization by rotation measure gradient



Fletcher et al. 2004

Summary: Depolarization effects

- Beam DP by turbulent fields (wavelength-independent):

$$p = p_o / N^{1/2}$$

(where *N* is the number of turbulent field cells)

- Differential Faraday rotation (wavelength-dependent):

$$p = p_o \, |\sin (2\, RM\, \lambda^2)| \, / \, (2\, RM\, \lambda^2)$$

- Internal Faraday dispersion (wavelength-dep.):

$$p = p_o \, (1 - \exp(-2\, \sigma_{RM}{}^2\, \lambda^4)) \, / \, (2\, \sigma_{RM}{}^2\, \lambda^4)$$

- External Faraday dispersion (wavelength-dependent):

$$p = p_o \exp(-2\, \sigma_{RM}{}^2\, \lambda^4)$$

- RM dispersion:

$$\sigma_{RM}{}^2 = (0.81\, n_e\, B_r)^2\, L\, d\, f_v$$

(B_r is the turbulent field strength, *d* the size of the turbulent cells, f_v the volume filling factor)

Martin Harwit, Cosmic Discovery (1981) :

Polarization is an

independent dimension

in the phase space

of observations

Summary

- Polarization is essential to observe cosmic magnetic fields
- The Universe looks different through “polarization goggles”
- However, some new telescopes are designed without taking care of polarization purity
- Join program committees and telescope design commissions !