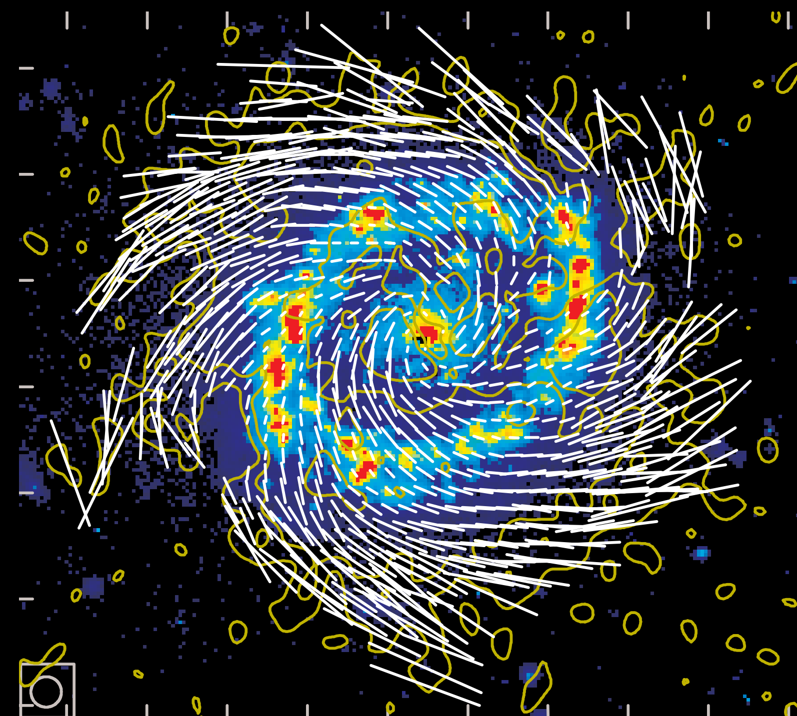
Galactic magnetic fields: what do we really know?

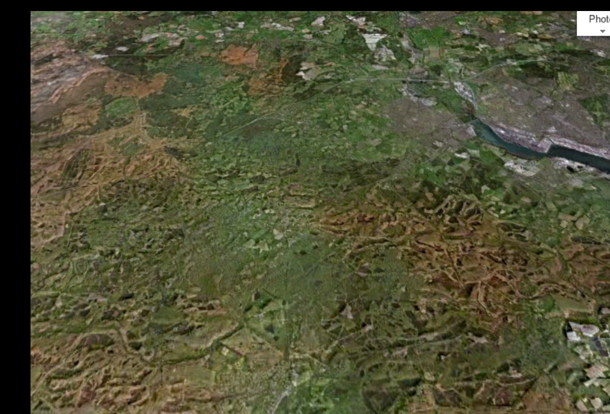
Andrew Fletcher, Newcastle University, UK
andrew.fletcher@ncl.ac.uk

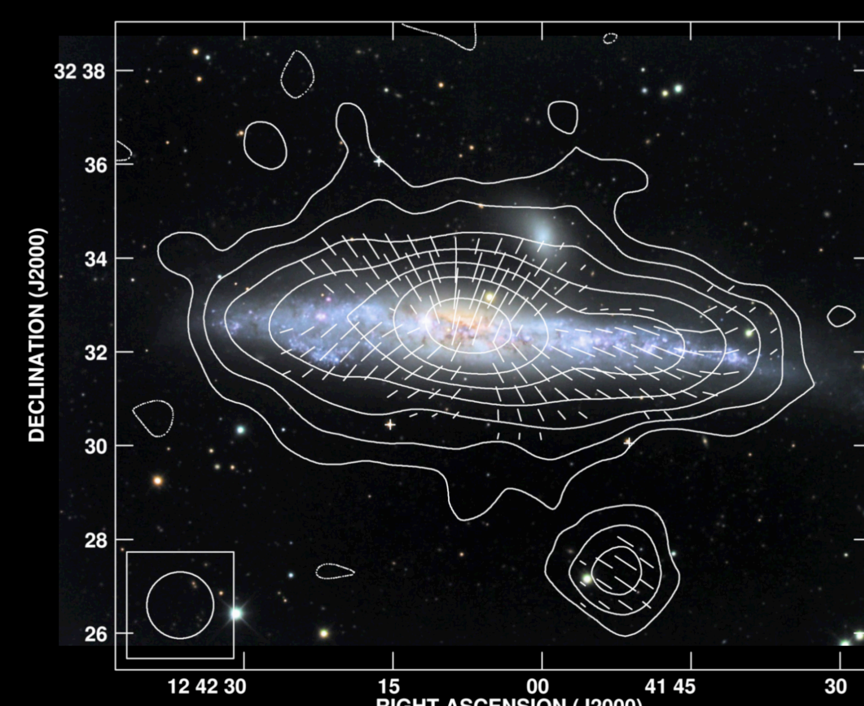
Lots of observations:

Fletcher et al. 2011

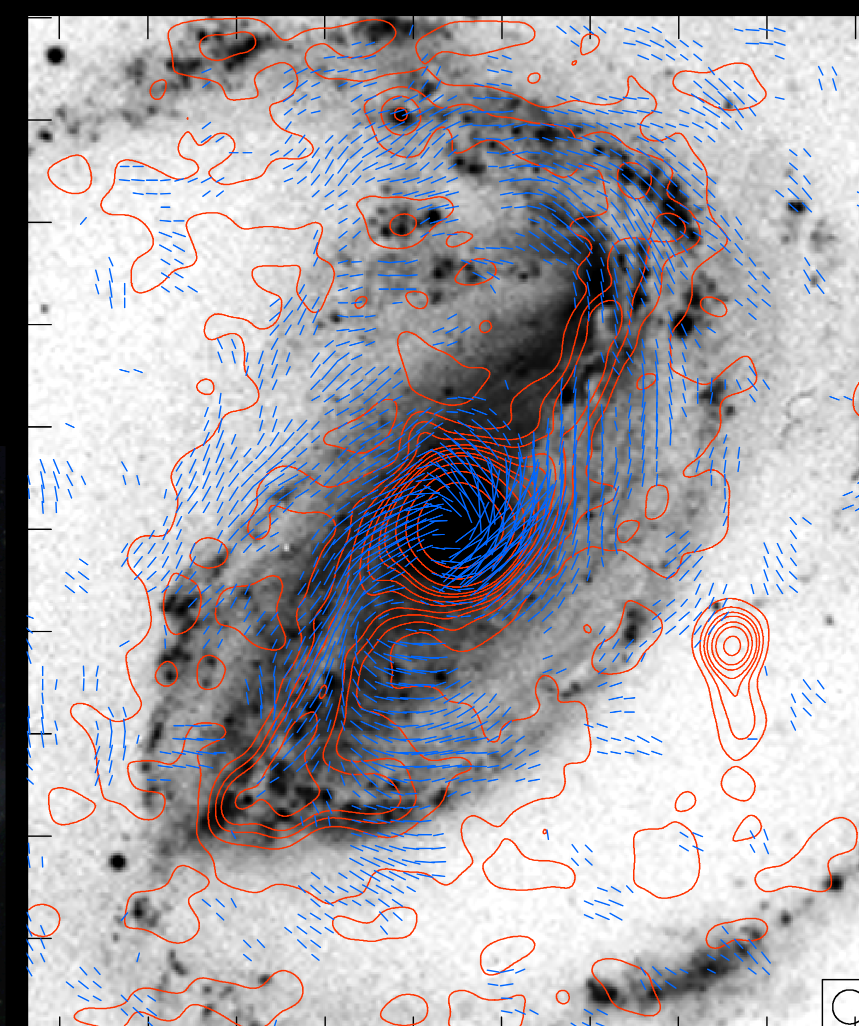


Chyzy & Buta 2007



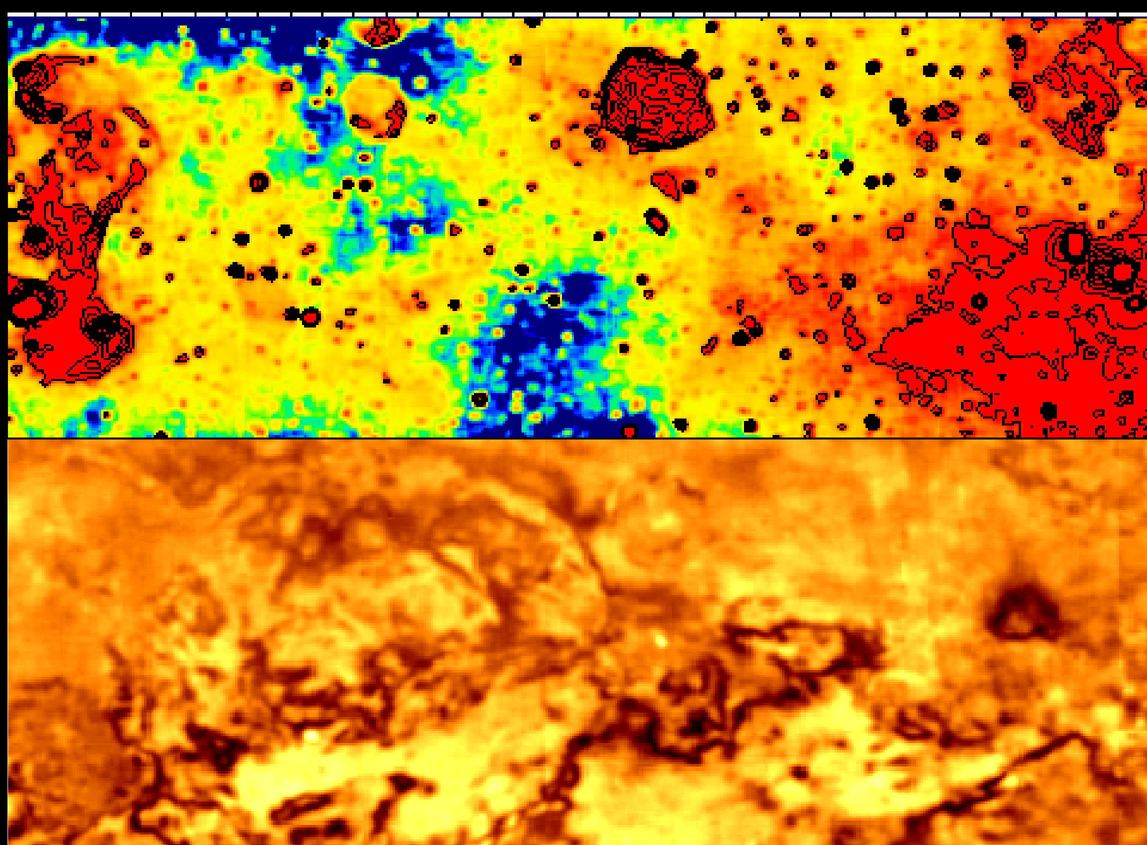


Krause 2009



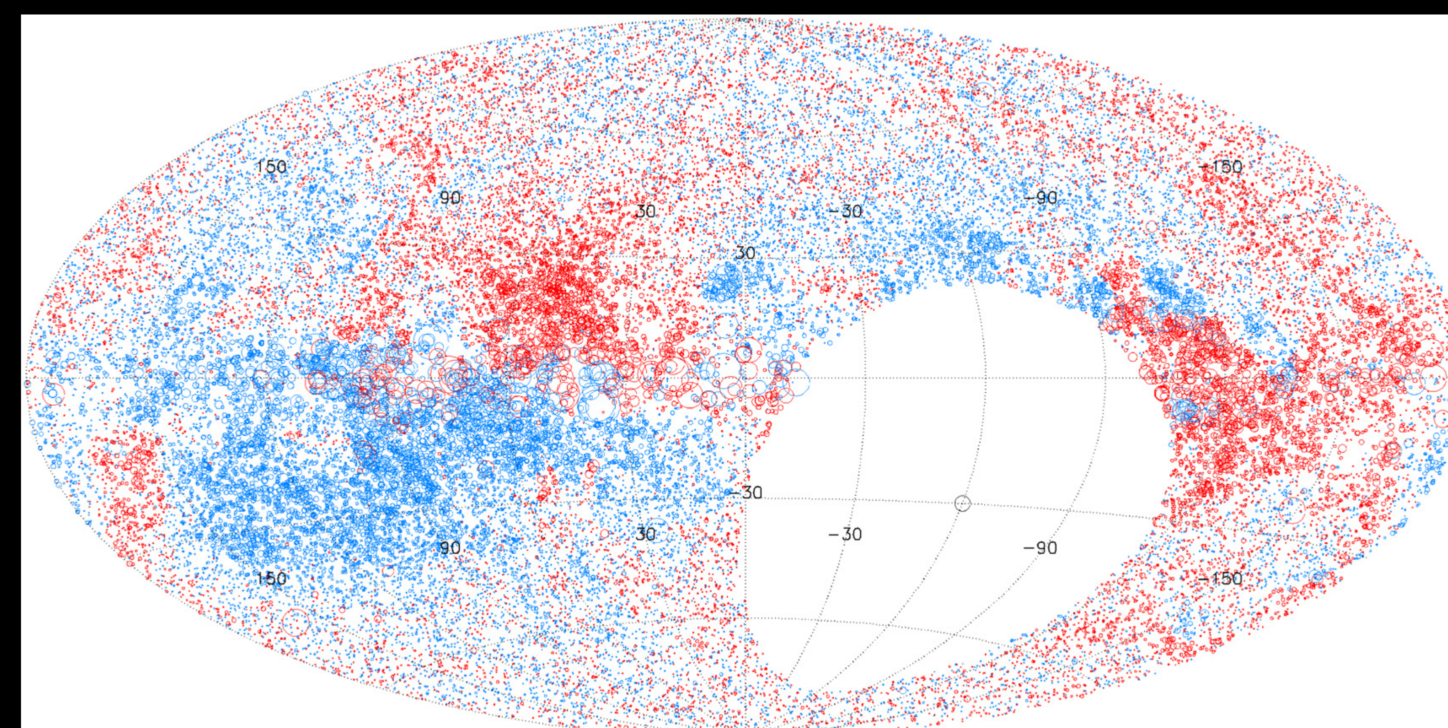
Beck et al. 2005

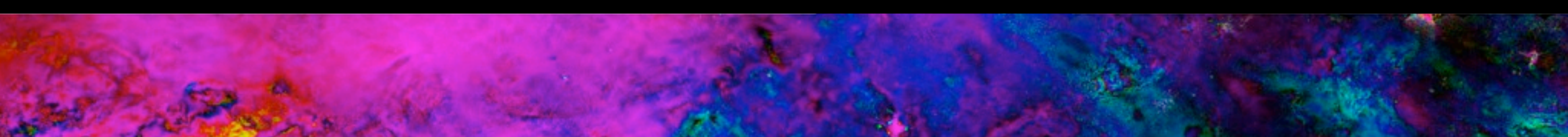
Lots of observations:



Reich et al. 2004

Taylor et al. 2009





Landecker et al. 2010

What are common properties?

An overview with:

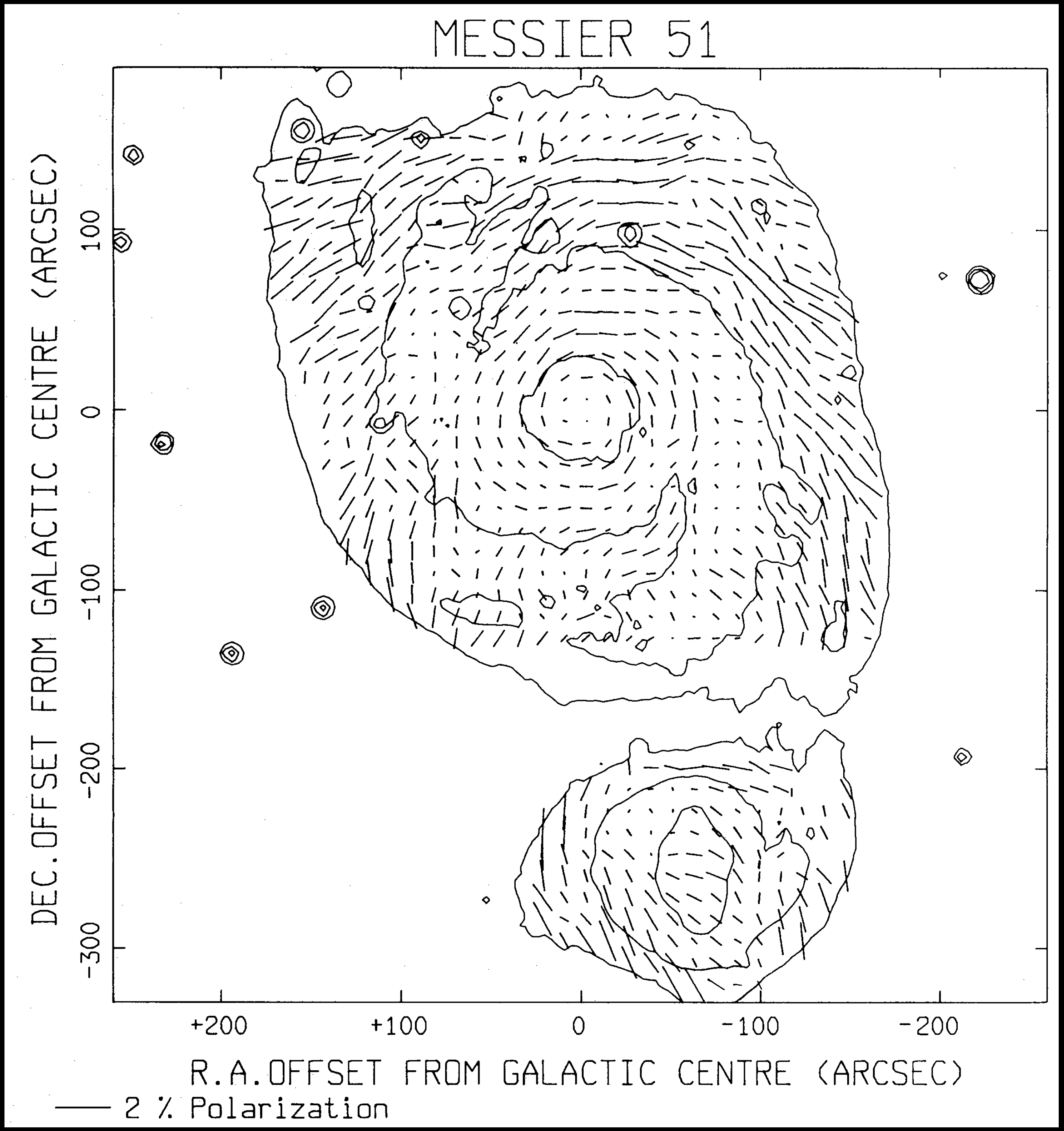
Summary statistics (few and far between)
Properties in common (not unusual features)

Magnetism of diffuse ISM i.e. not molecular clouds

What we don’t know

Optical polarization?

Optical



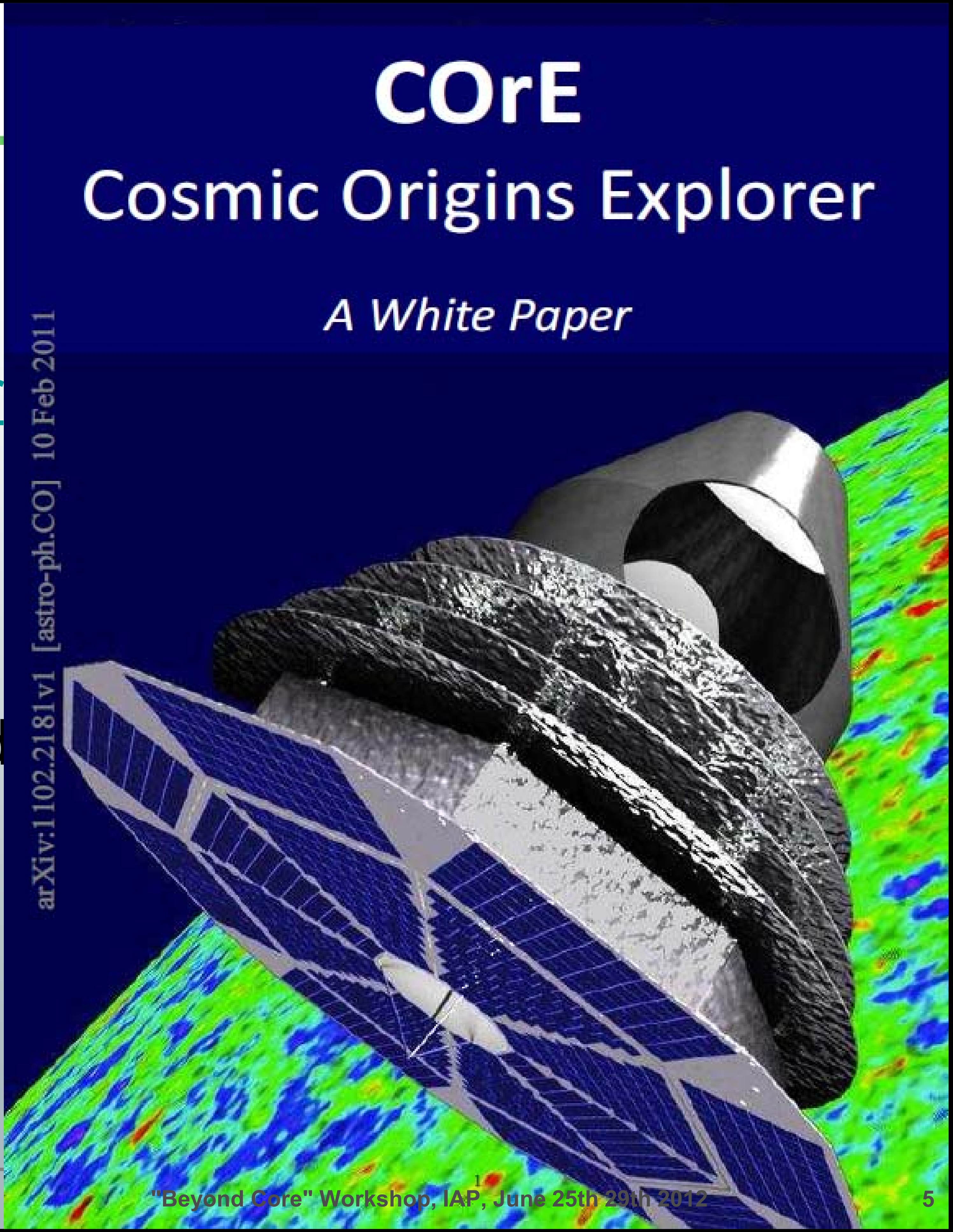
Scarrott et al. 1987

Synchrotron

Fletcher et al. 2011

- http://www.core-mission.org/
- Details in white paper arXiv:1102.2181

- Last minute update: After being shortlisted Did not make it a few days ago for the M3 Study
- I'll be back!



Classification

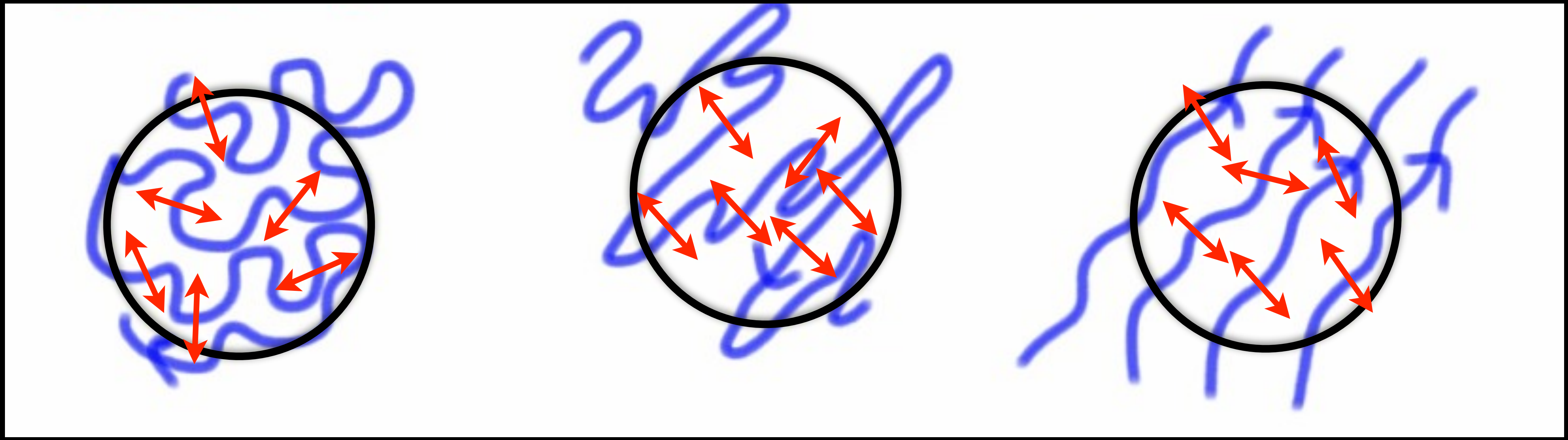
random ordered

isotropic anisotropic mean

Classification

random ordered

isotropic anisotropic mean



$p = 0$	$p > 0$	$p > 0$

Classification

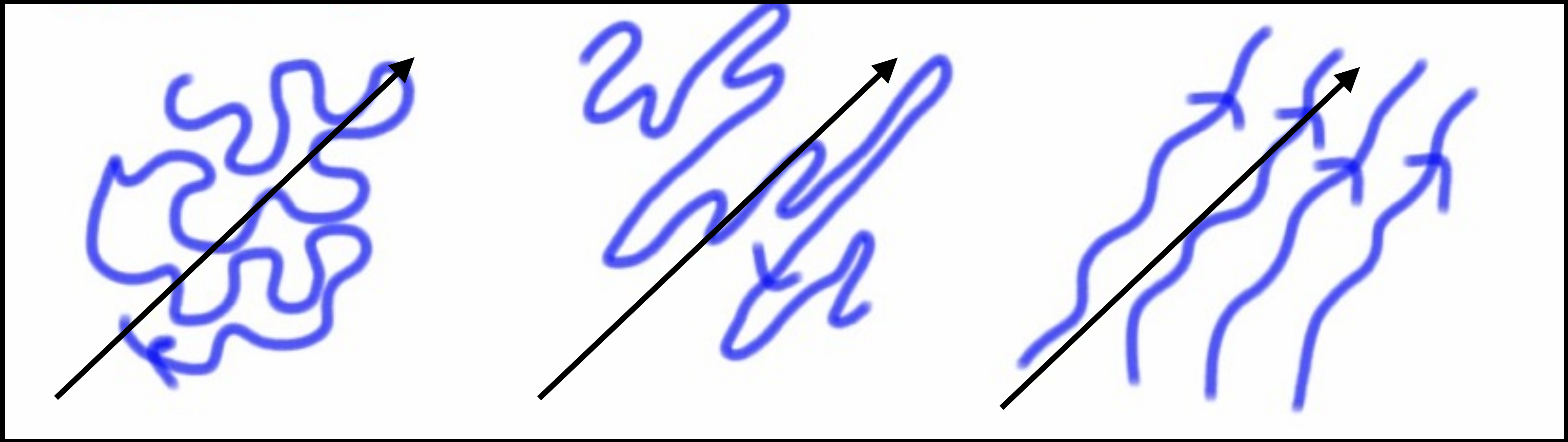
random ordered

isotropic anisotropic mean

Classification

random ordered

isotropic anisotropic mean



RM = 0	RM ≈ 0	|RM| > 0

Classification

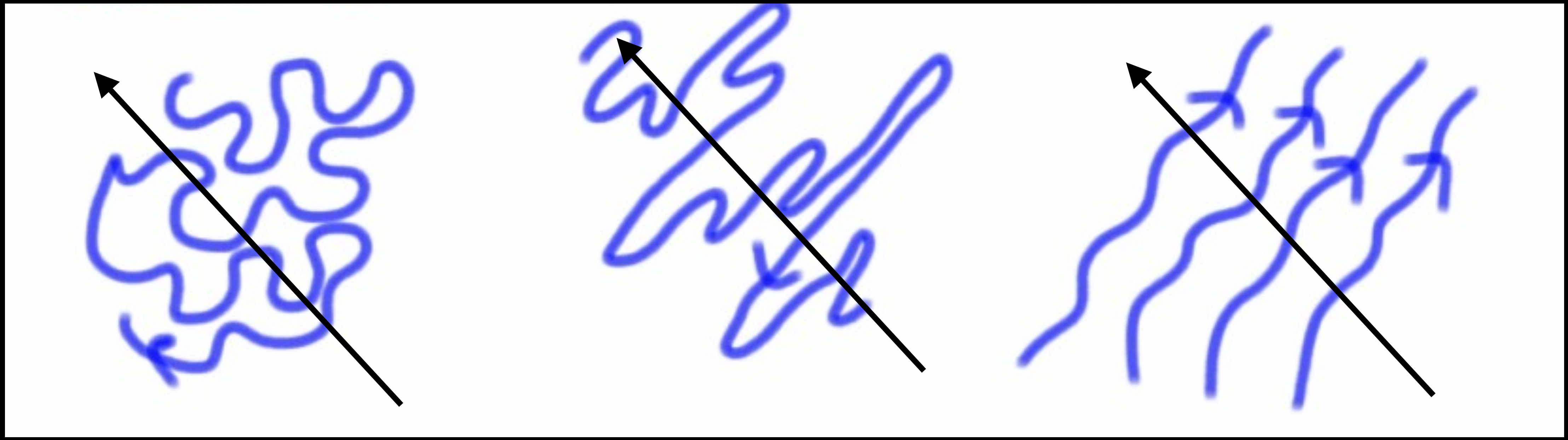
random ordered

isotropic anisotropic mean

Classification

random ordered

isotropic anisotropic mean



RM = 0	RM ≈ 0	RM ≈ 0

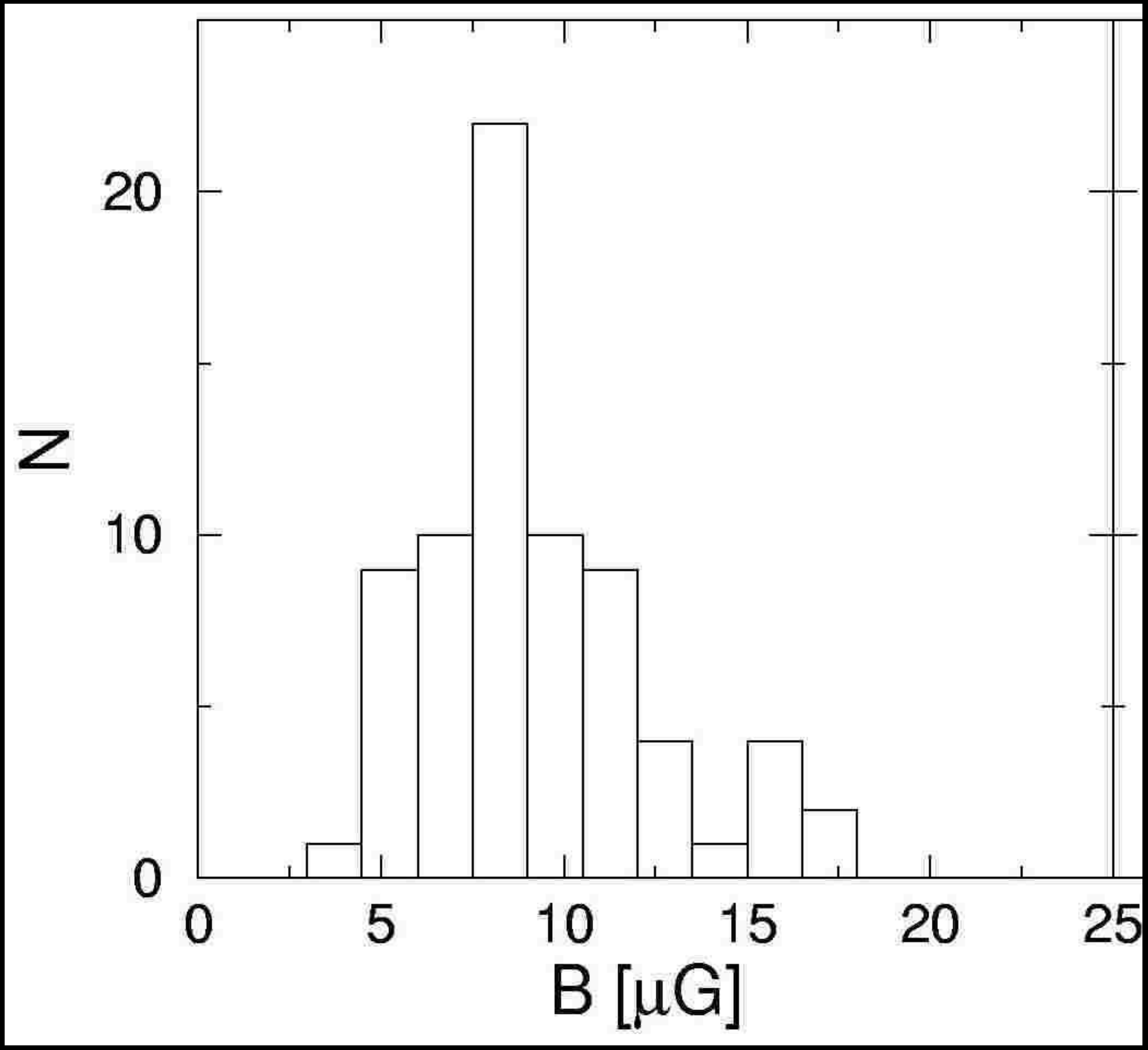
Classification

random ordered

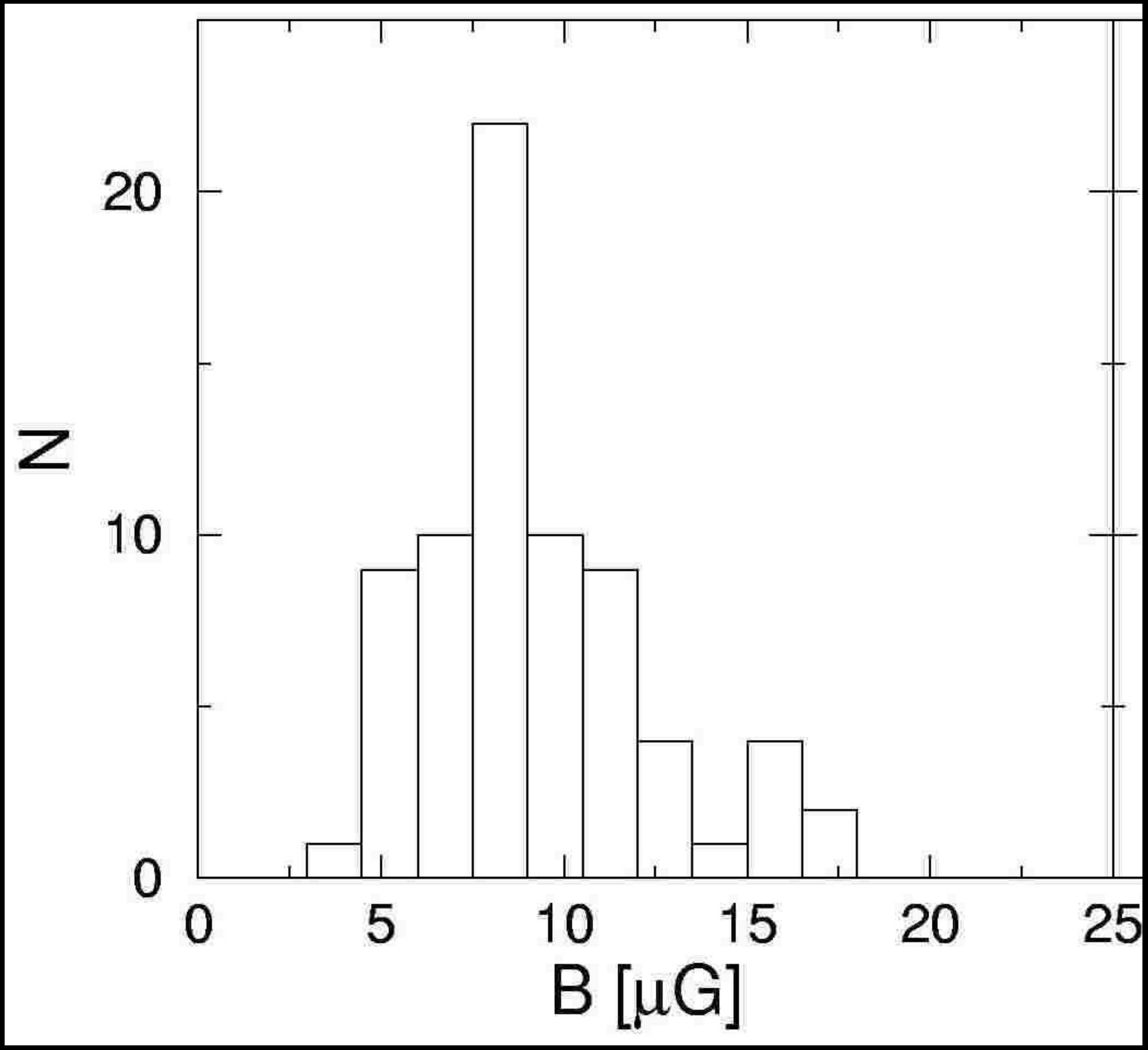
isotropic anisotropic mean

Magnetic field strength

Niklas PhD thesis, Bonn 1995



Magnetic field strength



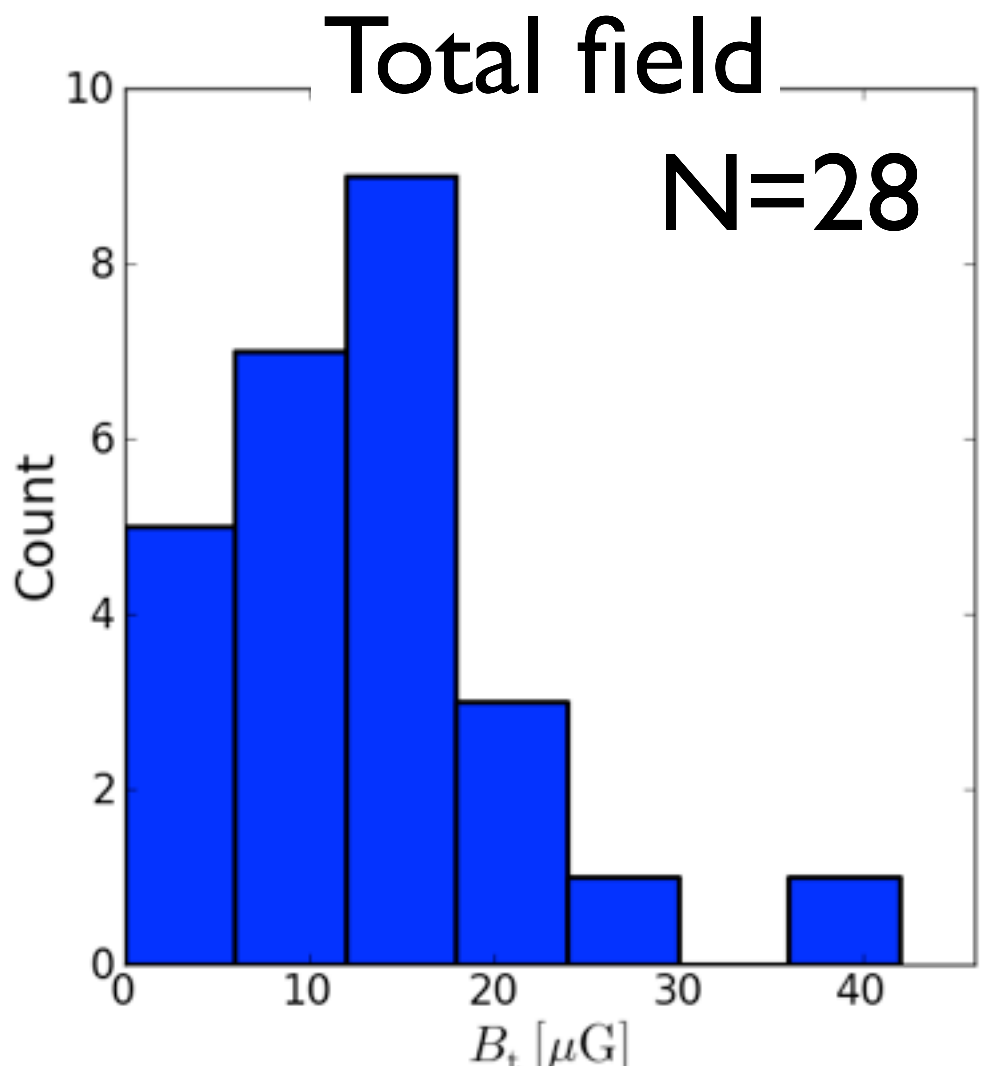
Niklas PhD thesis, Bonn 1995

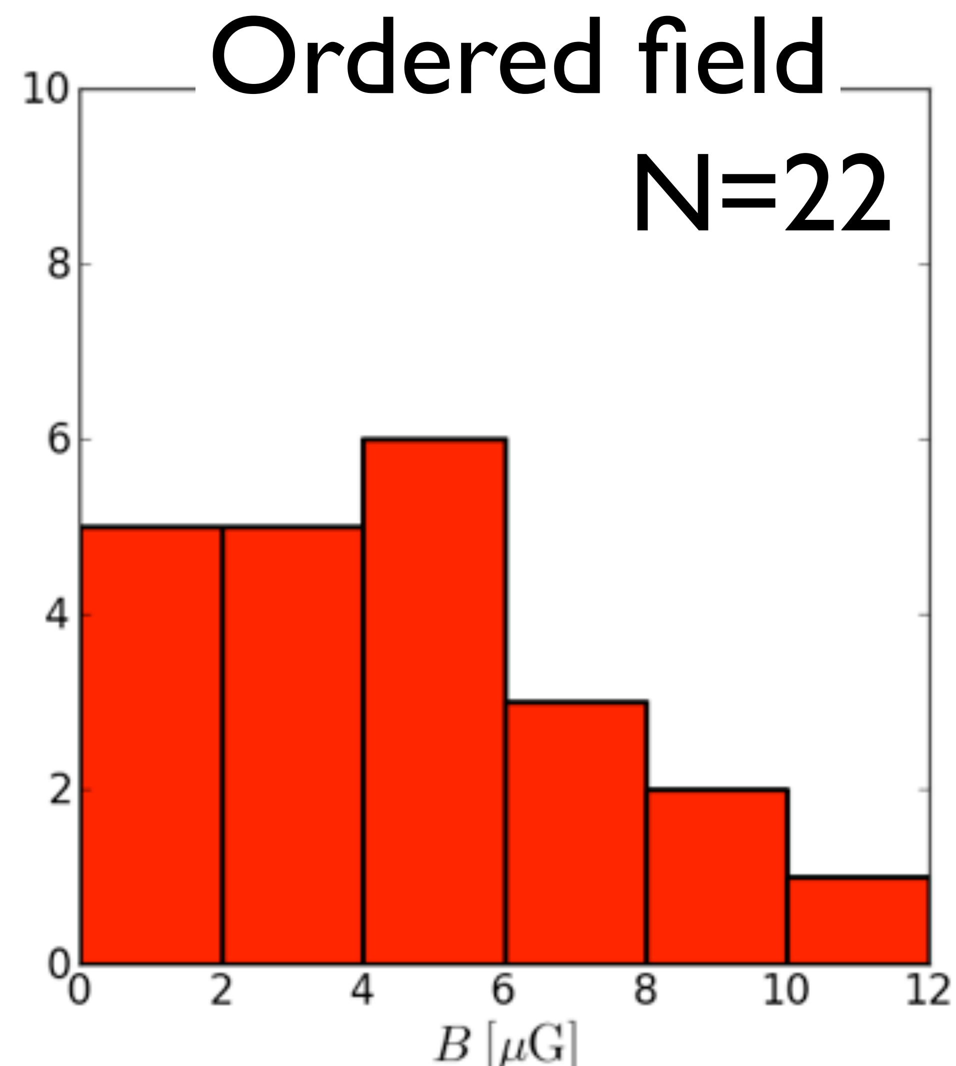
Hummel's (1986) sample of 88 Sbc galaxies has a mean minimum-energy field of ≃ 8 μG, using K = 100. Using the same value of K for the sample of 146 late-type galaxies by Fitt & Alexander (1993), one obtains a mean total minimum-energy field strength of 10 ± 4 μG.

Beck et al. 1996

Magnetic field strength

Compilation: Fletcher 2010

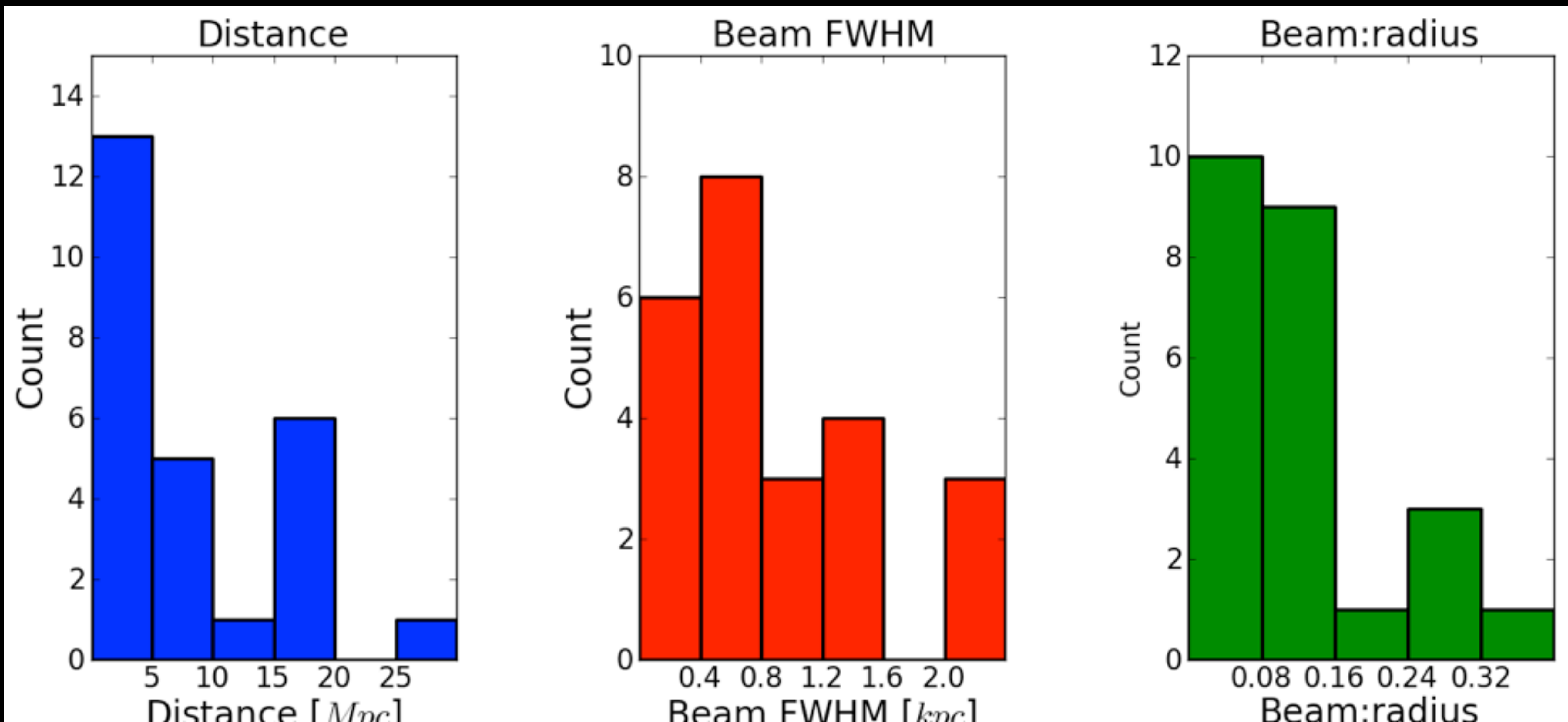




Average: 16 ±15 μG
Excl. starburst: 12 ±6 μG

Average: 4 ±3 μG
B_{ord}/B_{ran} 0.4 ±0.2

Galaxy sample



4 Mpc, 1 arcmin ~ 1kpc

median FWHM ~ 0.5 arcmin

FWHM / R_{25}

Field strength summary

Source	Total B [μG]	N	Notes
Hummel 1986	8	88	Sbc galaxies
Fitt & Alexander 1993	10 ± 4	146	Late type galaxies
Niklas 1995	9	74	
Fletcher 2010	16 ± 15	28	Resolved, 1990+

Total field ≈ 10 μG
Ordered field ≈ 4 μG
Random field ≈ 10 μG

Global structure: radial

	Exp. scale length [kpc]			
	I_{syn}	B_{eq}	R_{25} [kpc]	Source
NGC 6946	4	16	8.0	Beck 2007
NGC 253	3 & 7	7 & 13	11.7	Heesen et al. 2009
NGC 4214	0.6	2.4	5.7	Kepley
M33	5.8	24	4.1	Tabatabaei et al. 2007
M81	3.5	13	10.5	Beck et al. 1985
IC 342	4.7	19	9.9	Krause et al. 1989
Milky Way	3-4	10		Strong 2000 Beuermann 1985

$$I(r) = I_0 \exp\left(-r/l\right)$$

	Exp. scale length [kpc]			
	$I_{\rm syn}$	$B_{\rm eq}$, $B_{\rm n0}$	R_{25} [kpc]	Source
NGC 1313	1.34	4.9, 2.3	6.0	Harnett 1987
NGC 1566	1.73	6.6, 3.1	10.2	Harnett 1987
NGC 1672	3.74	13.9, 6.5	13.3	Harnett 1987
NGC 3059	5.33		8.6	Harnett 1987
M83	2.52	10.4, 5.3	8.8	Harnett 1987
NGC 6753	6.79		19.8	Harnett 1987
M101	7.1	28.4	32.1	Hummel 1990

Global structure: radial

Average scale length of synchrotron $\approx 0.4\ R_{25}$

Average scale length of magnetic field $\approx 1.6\ R_{25}$

(assuming equipartition with cosmic ray energy)

Global structure: radial

Average scale length of synchrotron $\approx 0.4\ R_{25}$

Average scale length of magnetic field $\approx 1.6\ R_{25}$

(assuming equipartition with cosmic ray energy)

$$B^2(r) = B_0^2 \exp\left(-2r/l\right)$$

Global structure: radial

Average scale length of synchrotron $\approx 0.4\, R_{25}$

Average scale length of magnetic field $\approx 1.6\, R_{25}$
(assuming equipartition with cosmic ray energy)

$$B^2(r) = B_0^2 \exp\left(-2r/l\right)$$

Magnetic energy drops by 1/2 in
0.35 x scale-length ~ 0.5 optical disc radius

Energy densities

Energy: $B^2 \sim nkT \sim mv^2$

GALACTIC HYDROSTATIC EQUILIBRIUM WITH MAGNETIC TENSION AND COSMIC-RAY DIFFUSION

AHMED BOULARES
Max-Planck-Institut für Extraterrestrische Physik

AND

DONALD P. COX
Space Physics Laboratory, University of Wisconsin—Madison
Received 1989 December 11; accepted 1990 June 15

The structure of the *z*-distribution of mass and pressure in the solar neighborhood are explored. Three gravitational potentials were tried, differing in their content of dark matter in the Galactic plane. The weight integrals, combined with the observed contributions to the total midplane pressure yield a quite restrictive range $P(0) \approx (3.9 \pm 0.6) \times 10^{-12}$ dyn cm^{-2}, with roughly equal contributions from magnetic field, cosmic-ray, and kinetic terms (of which the actual thermal pressure is quite small). This boundary condition restricts both

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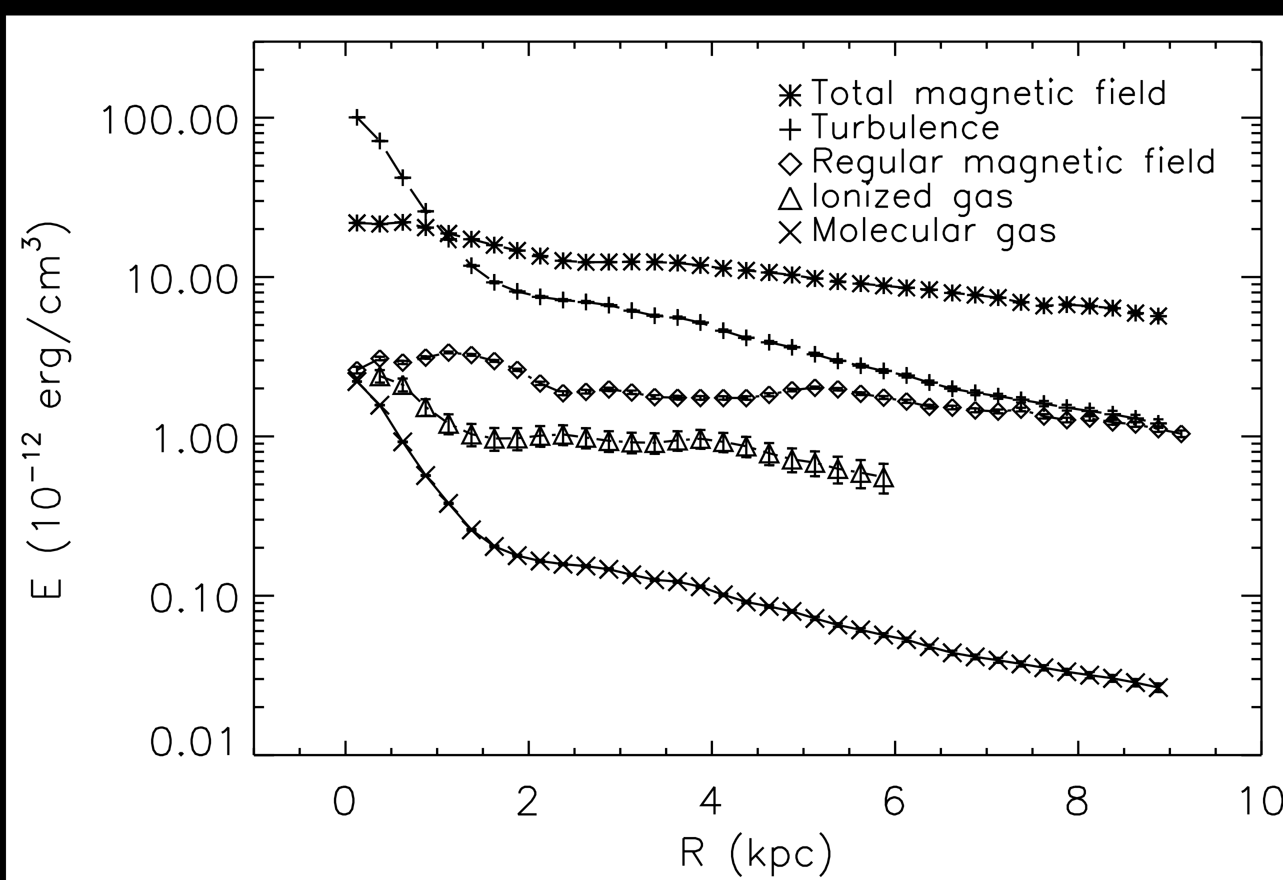
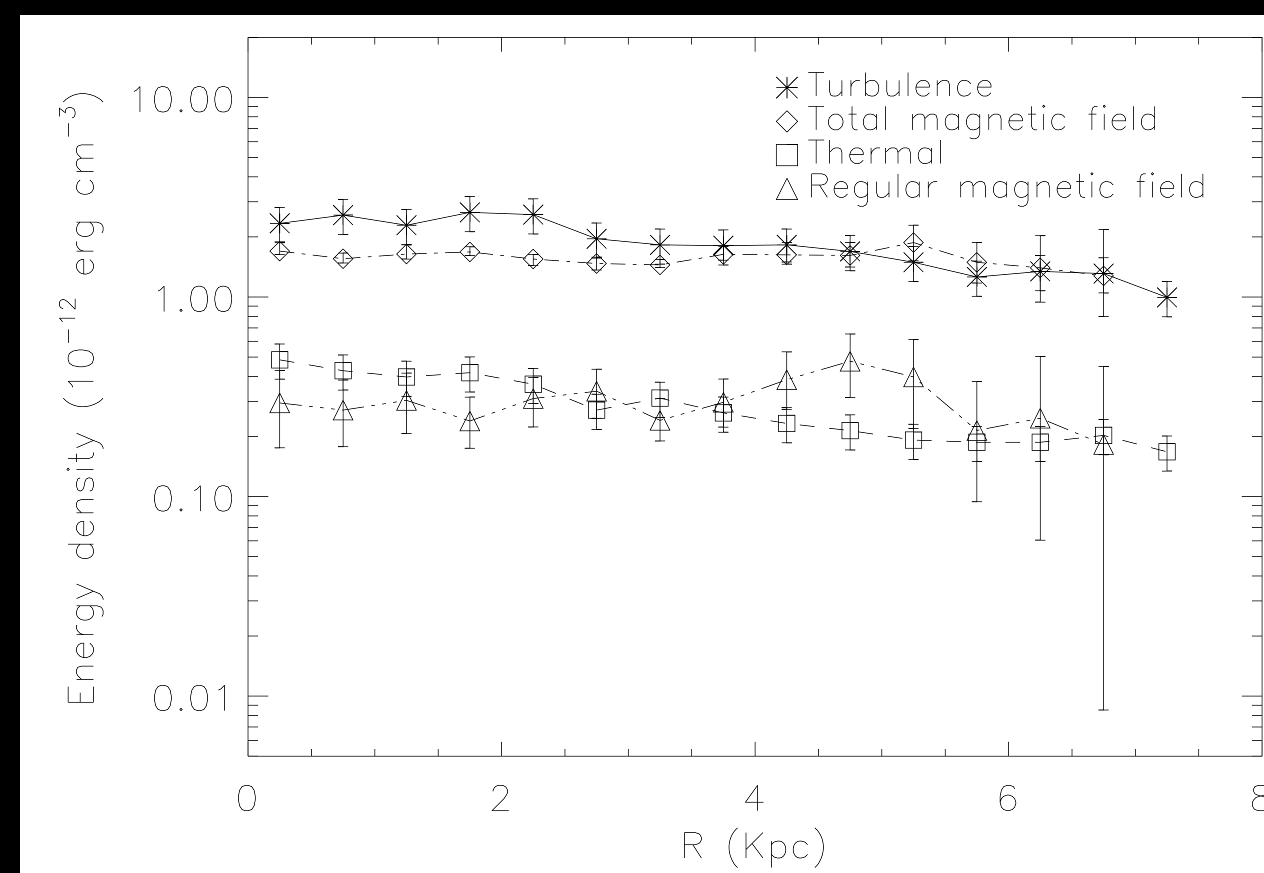
NGC 6946



Beck 2007

M33



Tabatabaei et al. 2008

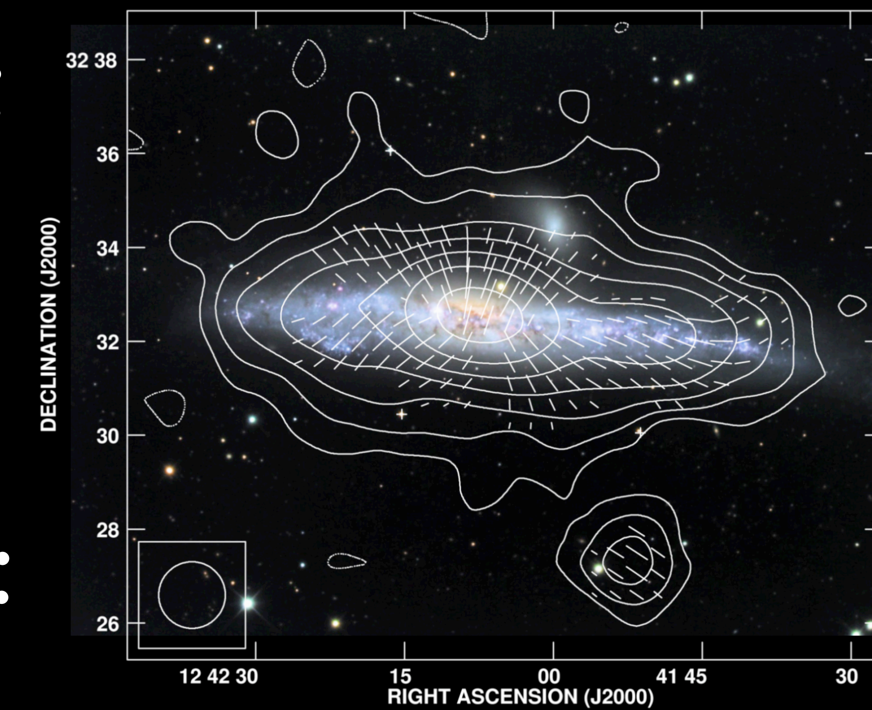
Global structure: height

Krause 2009

Exponential scale height of 4 galaxies:

$I_{\rm syn} \approx$ 0.3 & 1.8 kpc

$B \approx$ 1.2 & 7.2 kpc

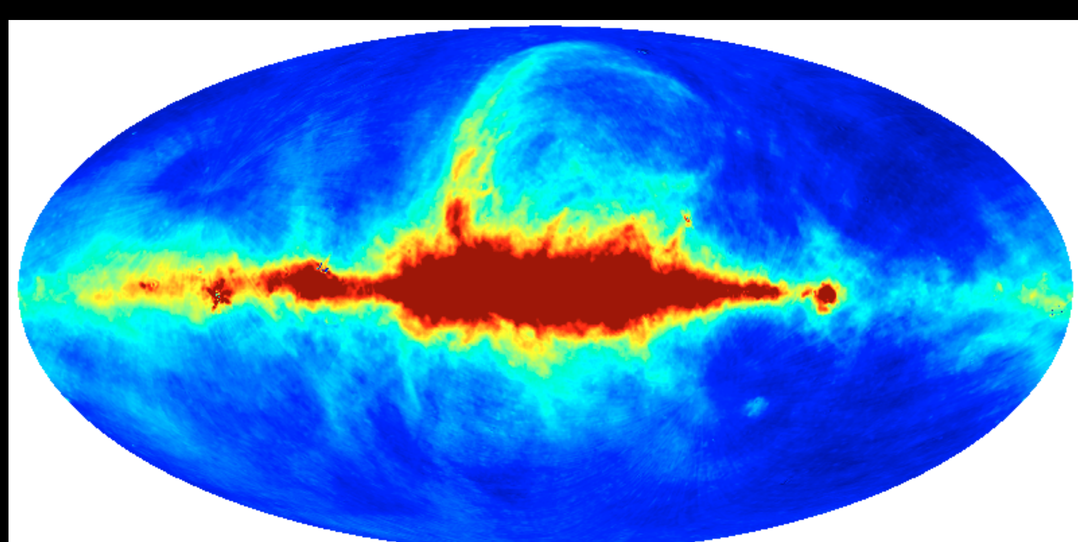


Hummel 1990

Gaussian scale height of 13 galaxies:

$I_{\rm syn} \approx$ 0.6 kpc

$B \approx$ 2.4 kpc



Milky Way scale height:

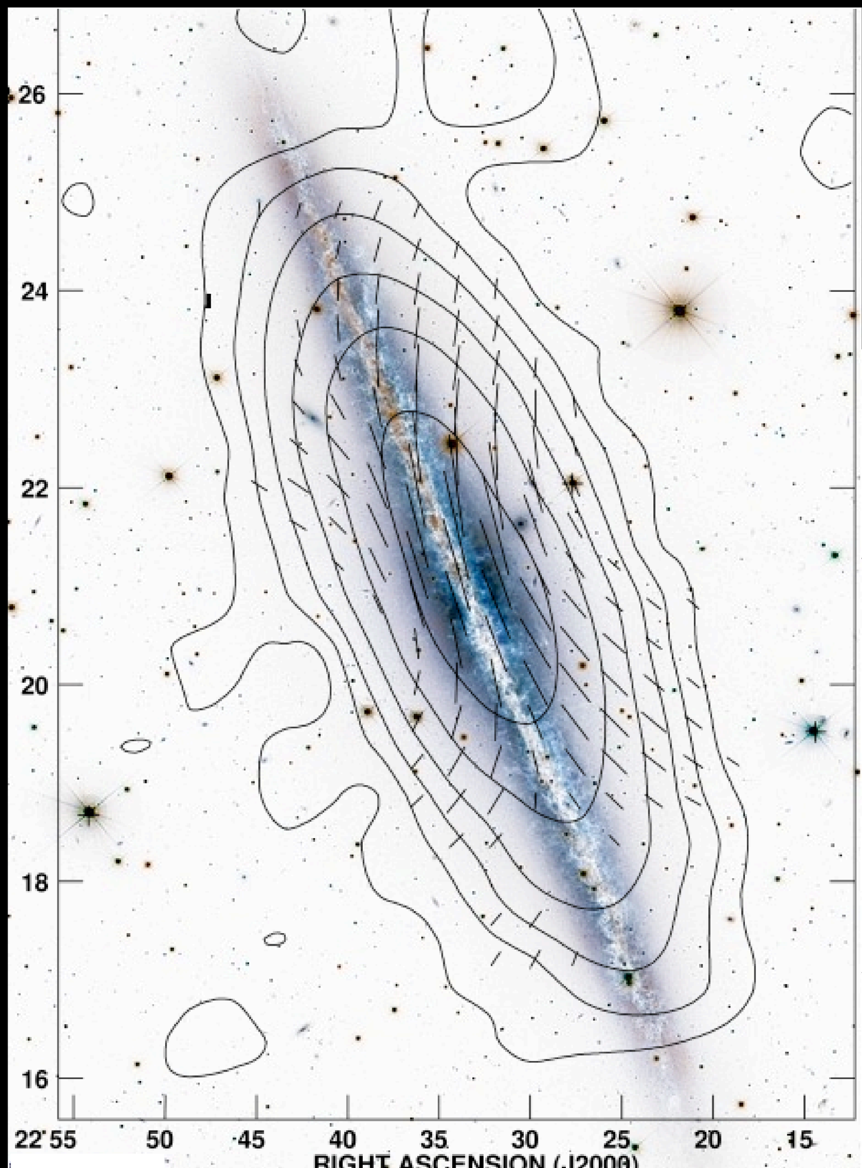
$I_{\rm syn} \approx$ 0.1-0.3 & 1-3 kpc

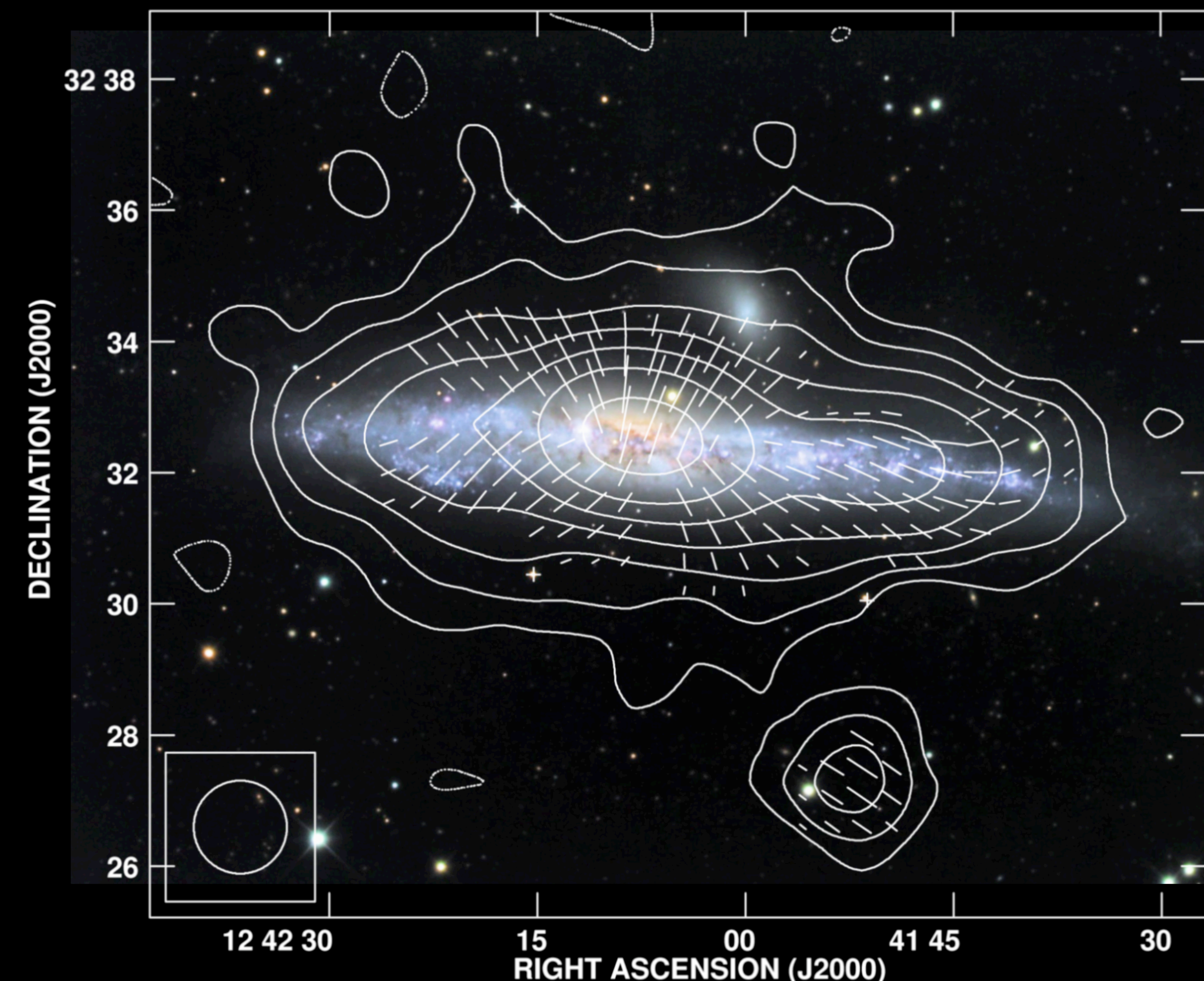
$B \approx$ 1-6 kpc

Beuermann et al. 1985

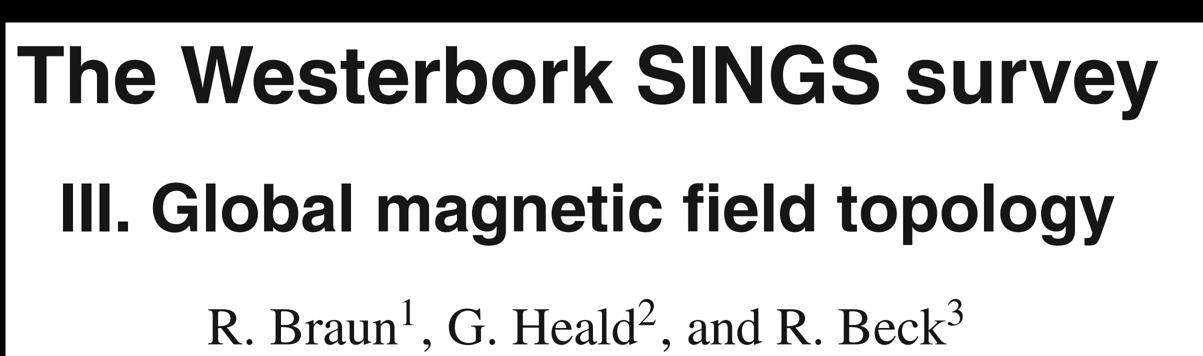
Global structure: halo

Krause 2009





Krause 2009



The Westerbork SINGS survey

III. Global magnetic field topology

R. Braun[1], G. Heald[2], and R. Beck[3]

"The field topology in the upper halo of galaxies is a mixture of two distinct types: a simple extension of the axisymmetric spiral quadrupole field of the thick disk and a radially directed dipole field."

Global structure: azimuth

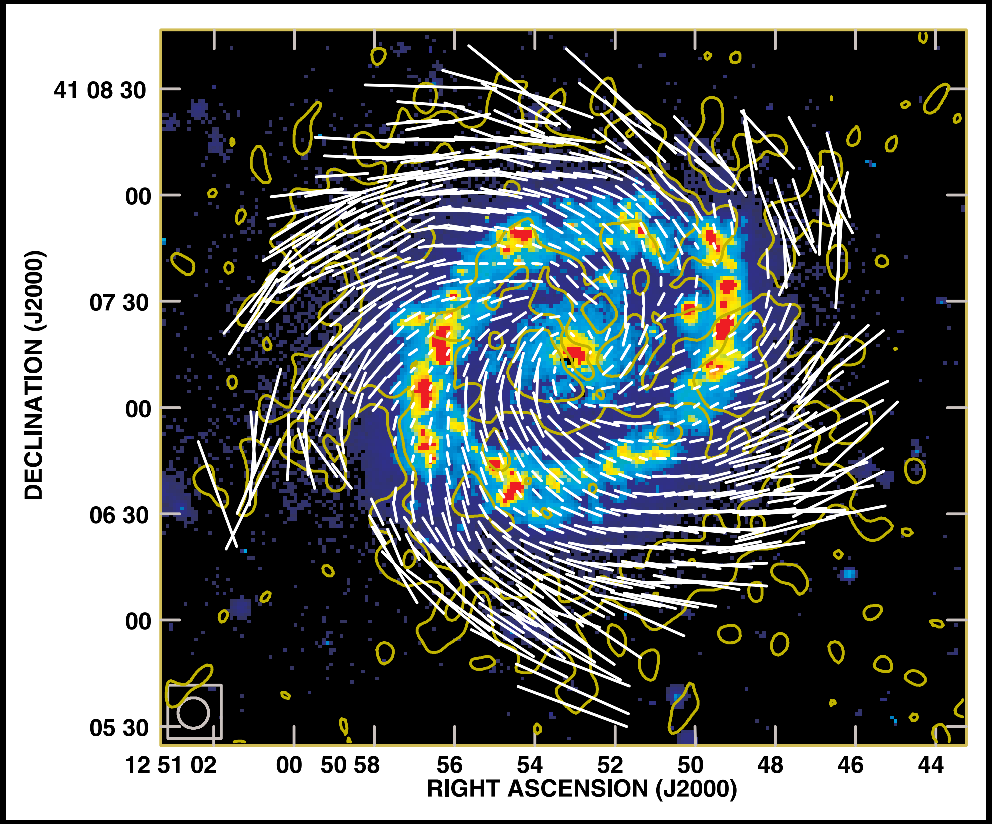
Should be known, but nothing systematic:

arm-interarm contrast in I, PI, B, b, etc. ?
(known for M51, NGC1097, NGC1365, NGC6946)

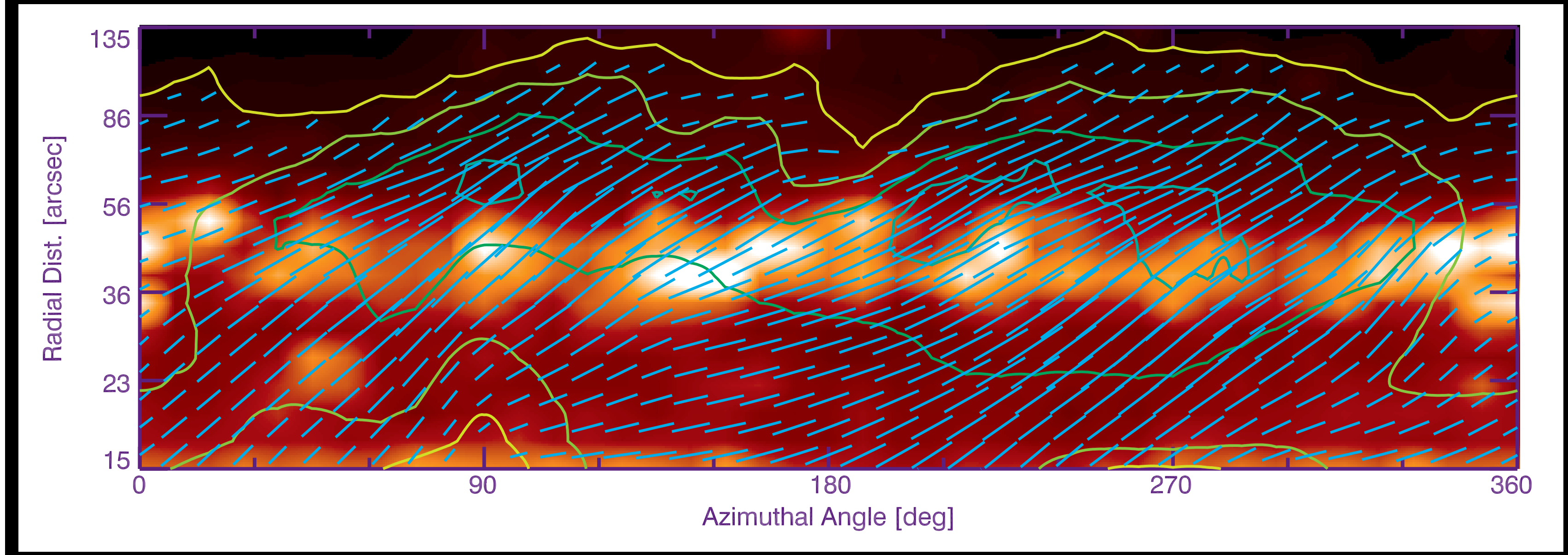
magnetic arms and spiral arms; streaming, corotation, alignment, ... ?
("magnetic arms" in NGCs6946, 4254, 2997, M51)

Ordered B lines spirals

NGC 4736 / M94

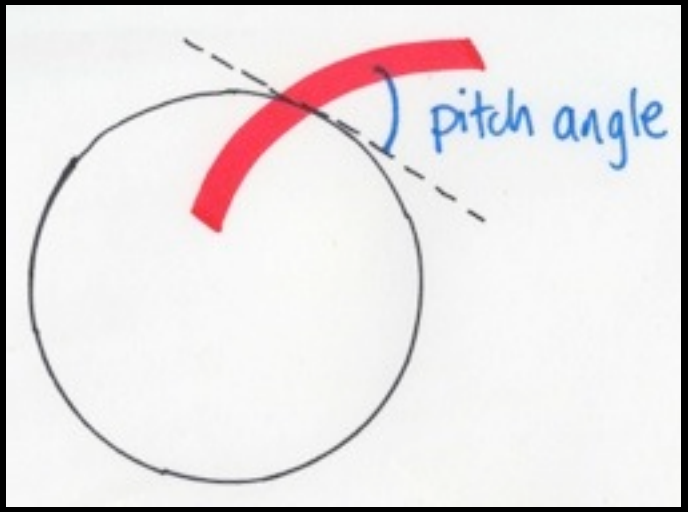


NGC 4736 / M94

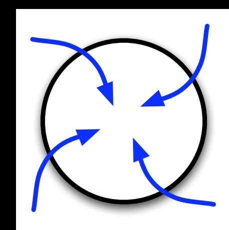
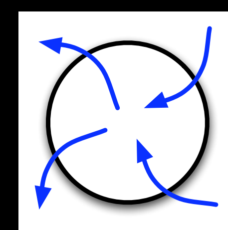
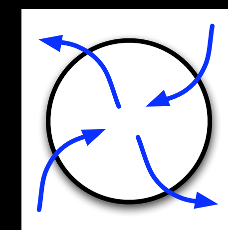


Chyzy & Buta 2007

$$\tan p = \frac{B_r}{B_\theta} \neq 0$$



Mean B-field structure

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

all spiral $p \geq 10°$

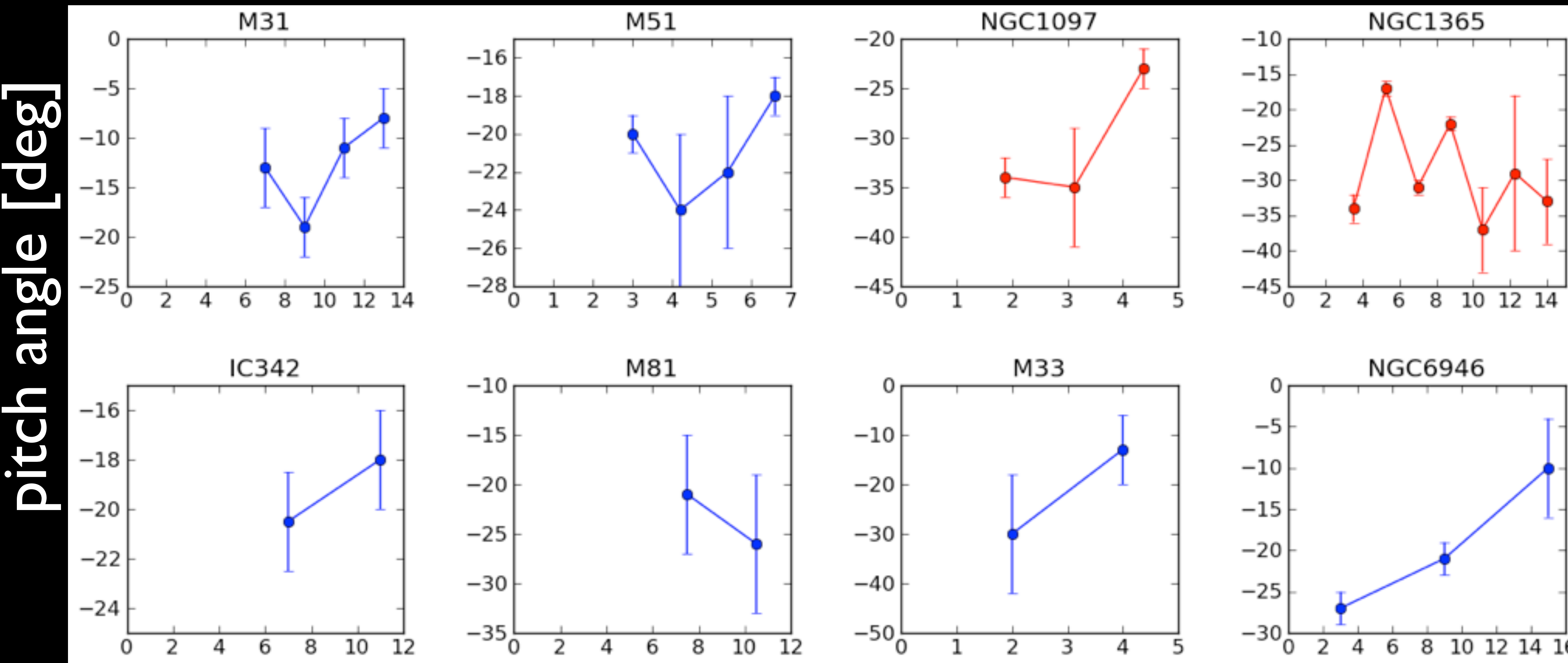
Pitch angles: spiral arms

	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

Pitch angles: azimuth

Galaxy	amplitude of pitch angle variation	Ref.
IC 342	30°	Graeve & Beck 1988
M31	0°	Fletcher et al. 2004
M33	30°	Tabatabaei et al. 2008
M51	30°	Patrikeev, Fletcher et al. 2006
M81	50°	Beck et al. 1985
NGC 1566	0°	Ehle et al. 1996
NGC 6946	5°-9°	Ehle & Beck 1993

Pitch angles: radius



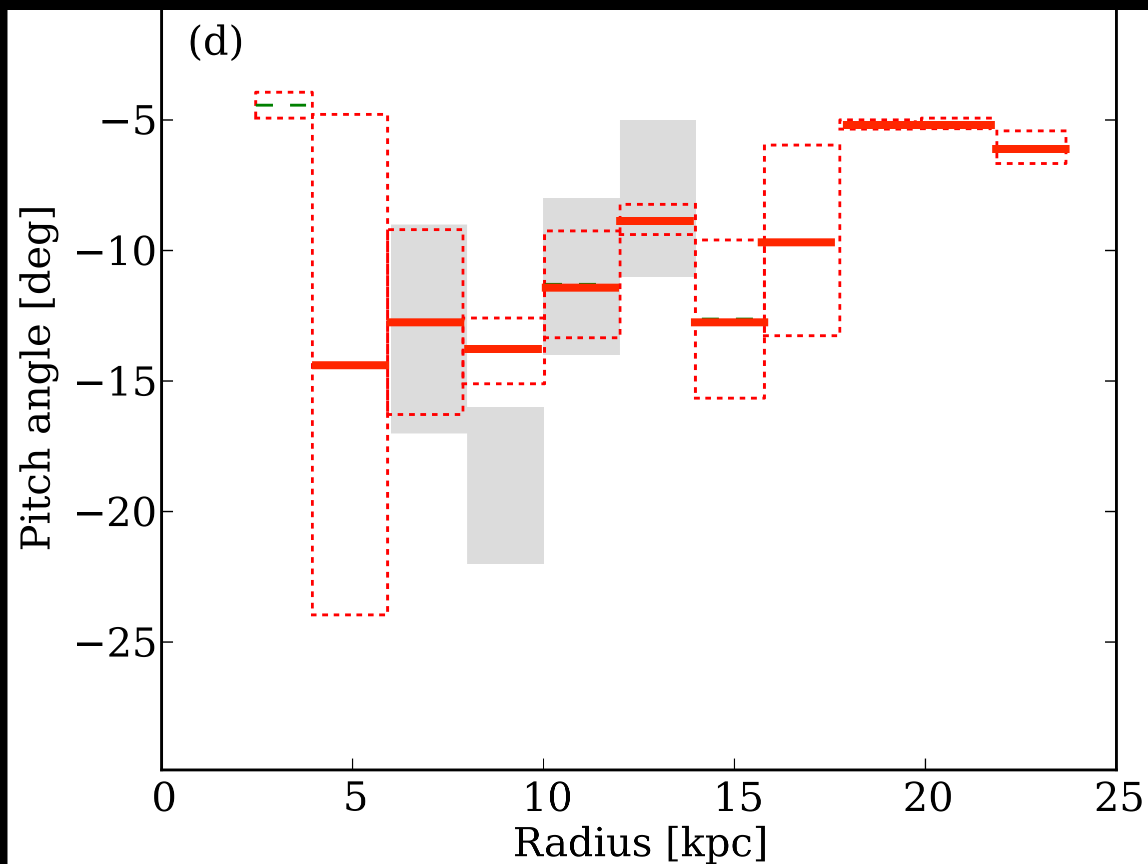
radius [kpc]

$$\tan p = \frac{B_r}{B_\theta} \propto \sqrt{\frac{\pi l^2}{h(r)^2}}$$

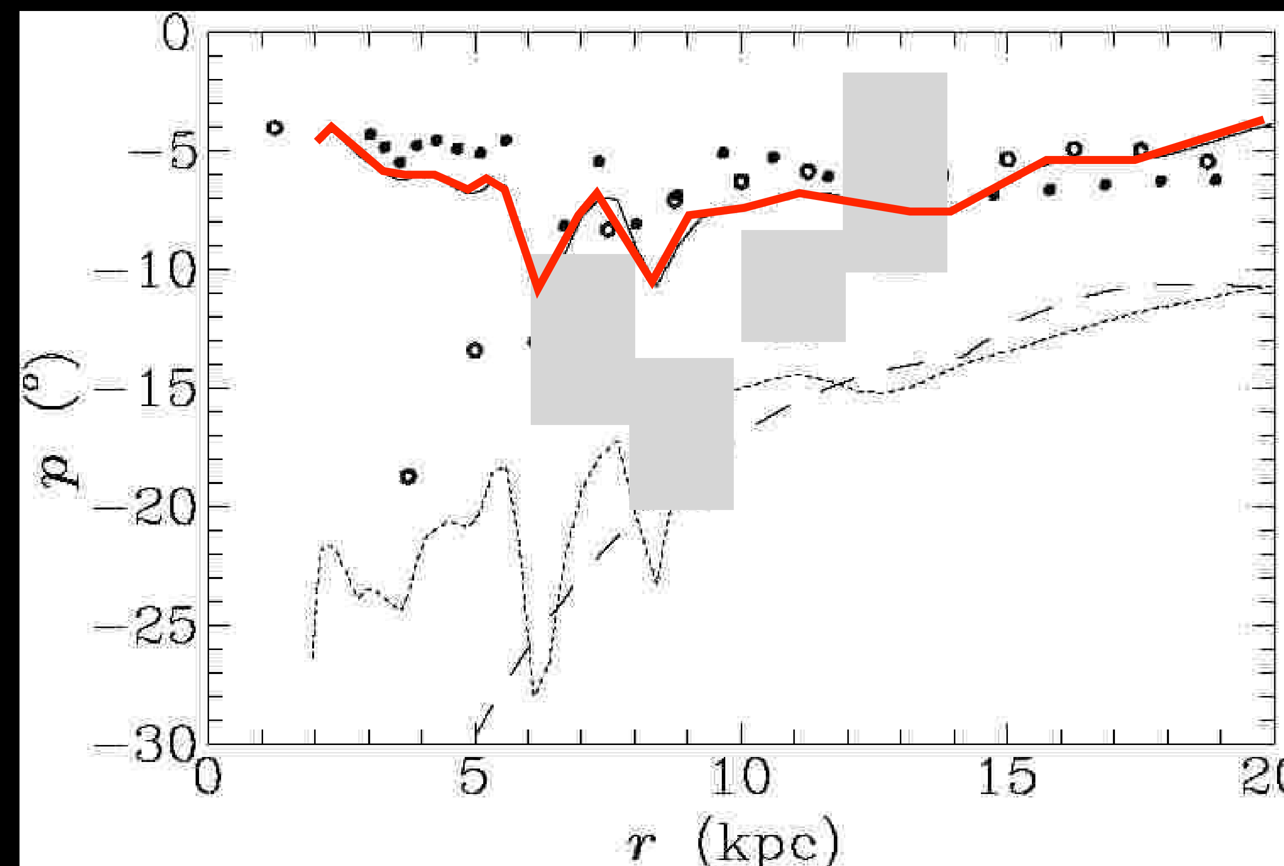
Pitch angles: M31

Smith PhD Thesis 2011

Dynamo with outflow

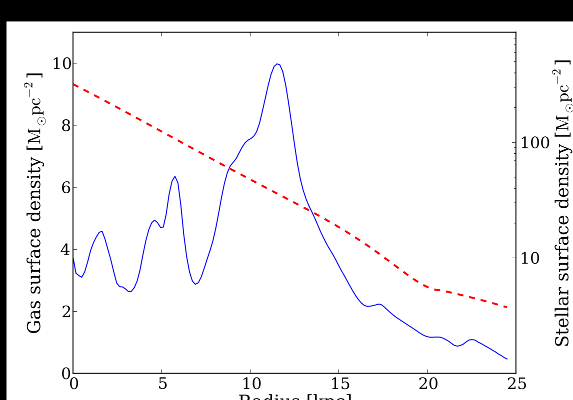


Dynamo no outflow

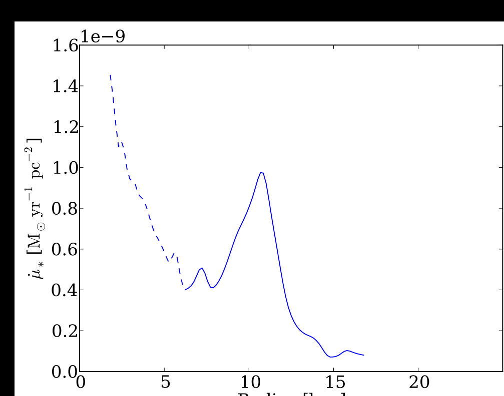


Beck et al. 1998 in Shukurov 2004

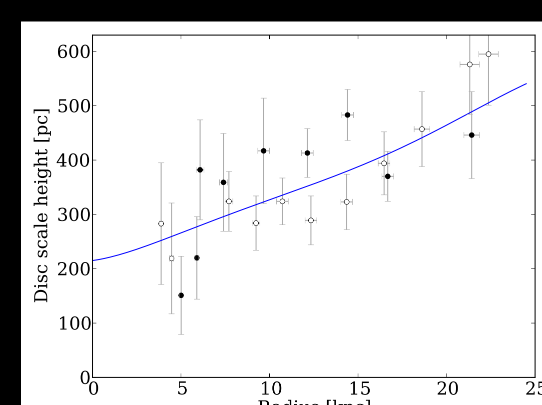
Σ(r)



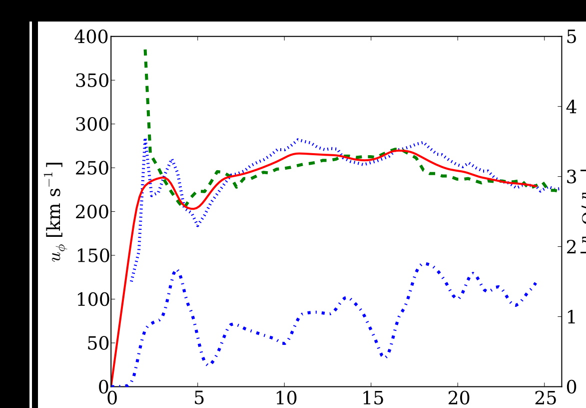
SFR(r)



h(r)



V(r)



Magnetic field pitch angles

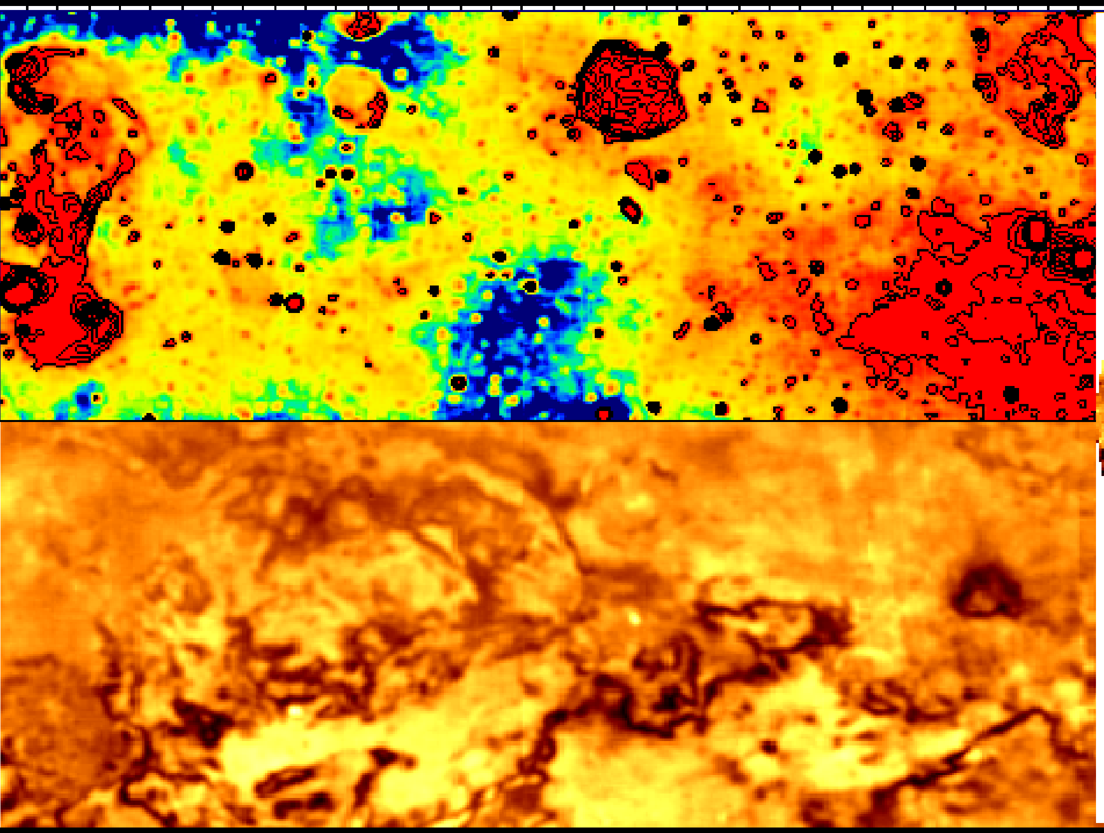
+ easy to observe (Stokes Q & U),
+ easy to quantify,
+ related (simply) to astrophysics,

- Faraday rotation at low frequency,
- line-of-sight effects, | + — = nothing.

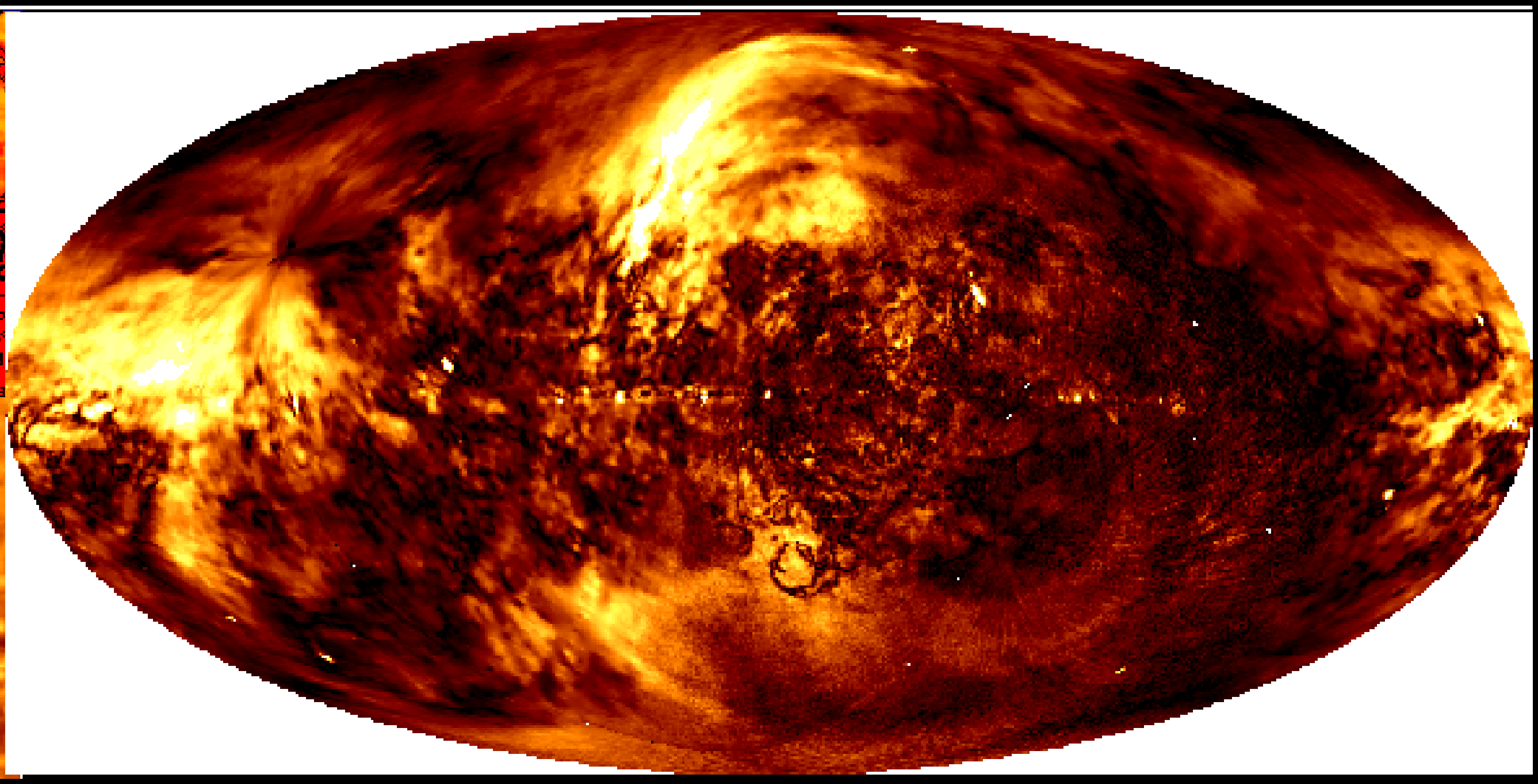
Best diagnostic to test mean field dynamo theory.

The small-scale, random magnetic field

Ordered field ≈ 4 μG
Random field ≈ 10 μG



Reich et al. 2004



Wolleben et al. 2006, Testori et al. 2008, Sun et al. 2008

Correlation scale of b

Galaxy	Analysis	scale [pc]	Ref.
Milky Way	autocorrelation I_{syn}	90	Lazaryan & Shutenkov 1990
LMC	RM structure function	90	Gaensler et al. 2005
Milky Way	RM structure function	arm < 10 interarm 100	Haverkorn et al. 2006
M51	depolarization by σ_{RM}	50	Fletcher et al. 2011
M51	dispersion of pol. angles	65	Houde, Fletcher et al. in prep.

Anisotropy: qualitative

Anisotropy: quantitative

$$\mathbf{B} = \mathbf{B_0} + \mathbf{b}$$
$$\mathbf{b} = (b_x, b_y, b_z)$$

Standard deviation

$$\sigma_x^2 = \langle b_x^2 \rangle$$

$$\sigma_x = \sigma_y = \sigma_z$$ **isotropic**

$$\sigma_x \neq \sigma_y \neq \sigma_z$$ **anisotropic**

$$p = p_0 \frac{\sigma_x^2 - \sigma_y^2}{\sigma_x^2 + \sigma_y^2}$$

Sokoloff et al. 1998

Anisotropy: quantitative

$$\mathbf{B} = \mathbf{B_0} + \mathbf{b}$$
$$\mathbf{b} = (b_x, b_y, b_z)$$

Standard deviation

$$\sigma_x^2 = \langle b_x^2 \rangle$$

$$\sigma_x = \sigma_y = \sigma_z \quad \textbf{isotropic}$$

$$\sigma_x \neq \sigma_y \neq \sigma_z \quad \textbf{anisotropic}$$

$$p = p_0 \frac{\sigma_x^2 - \sigma_y^2}{\sigma_x^2 + \sigma_y^2}$$

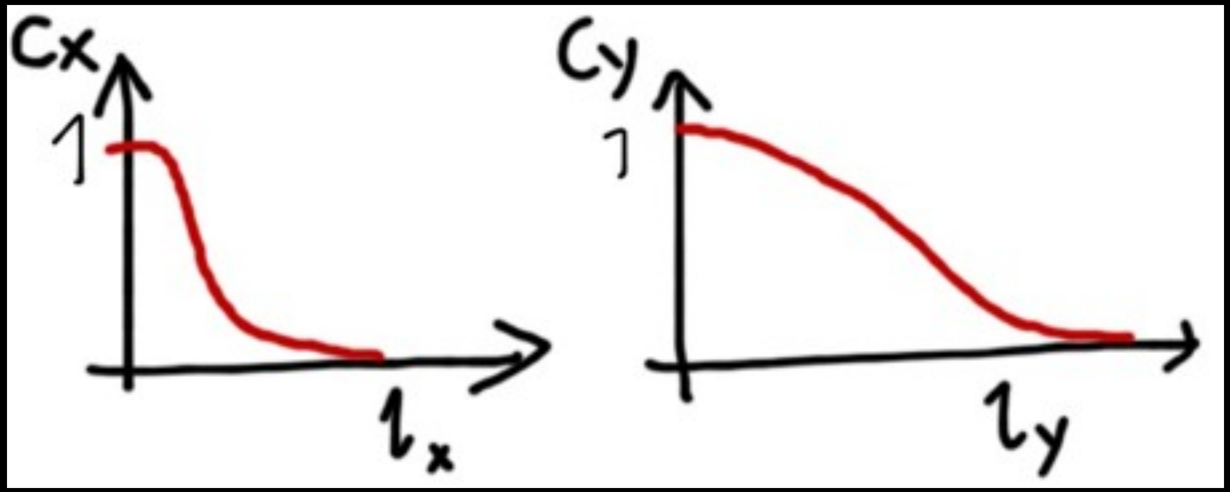
Sokoloff et al. 1998

Correlation

$$C_x(l_x) = \langle f(\mathbf{r} + l_x) f(\mathbf{r}) \rangle / \sigma_f^2$$

$$C_x = C_y = C_z$$

$$C_x \neq C_y \neq C_z$$



"Observed" anisotropy of small-scale magnetic field

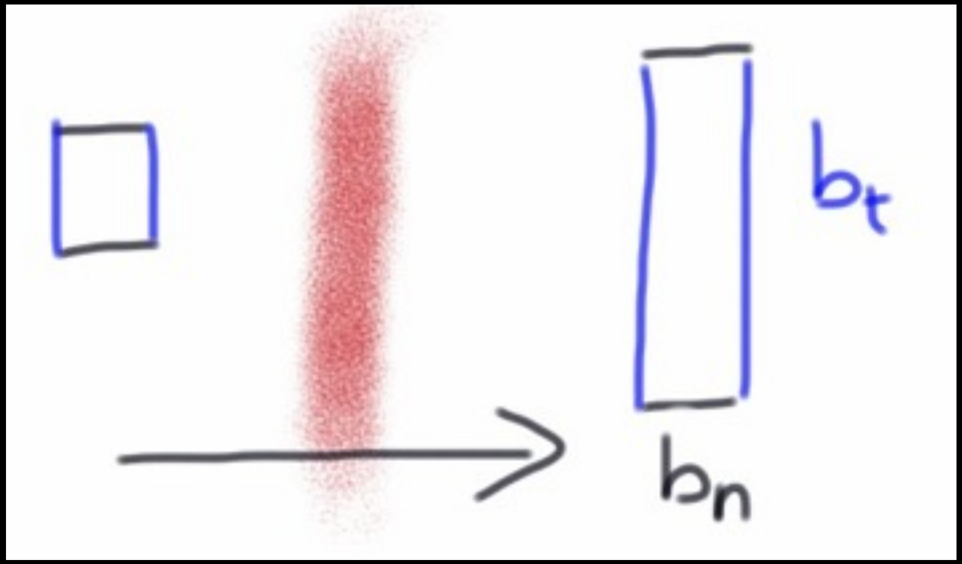
Galaxy	Source	Ref.
Milky Way	$\sigma_{\rm RM} \propto \overline{\rm RM}$	Brown & Taylor 2001
NGCs 1097 & 1365	I and PI pre- & post-shock	Beck, Fletcher et al. 2005
Milky Way	I, PI & RM in Galactic plane	Jaffe et al. 2008
M51	$B_{\rm ord}$ [PI] >> $\overline{B}$ [RM]	Fletcher et al. 2011
Milky Way	I, PI & RM whole sky	Jansson & Farrar 2012
M51	Dispersion of pol. angles	Houde, Fletcher et al. in prep.

I : total intensity
PI : polarized intensity

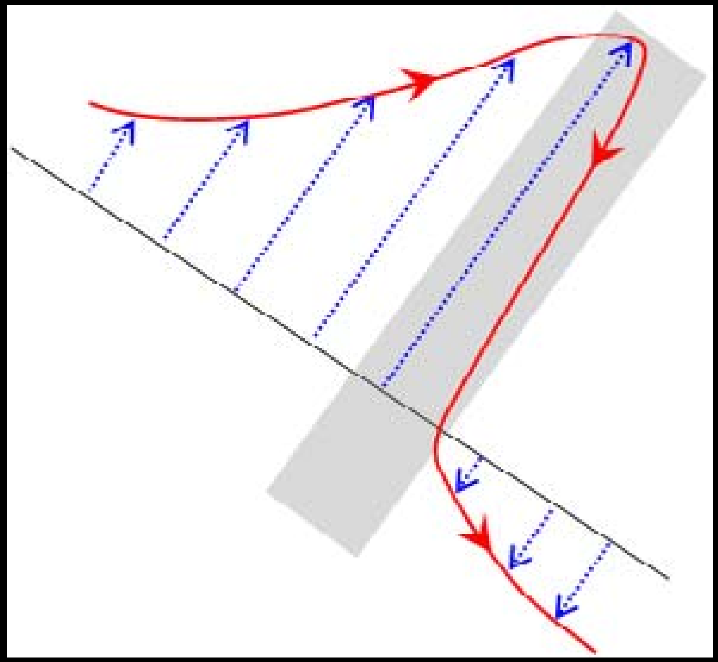
$\sigma_{\rm RM}$: RM standard dviation
$\overline{\rm RM}$: mean rotation measure

Origin of anisotropy

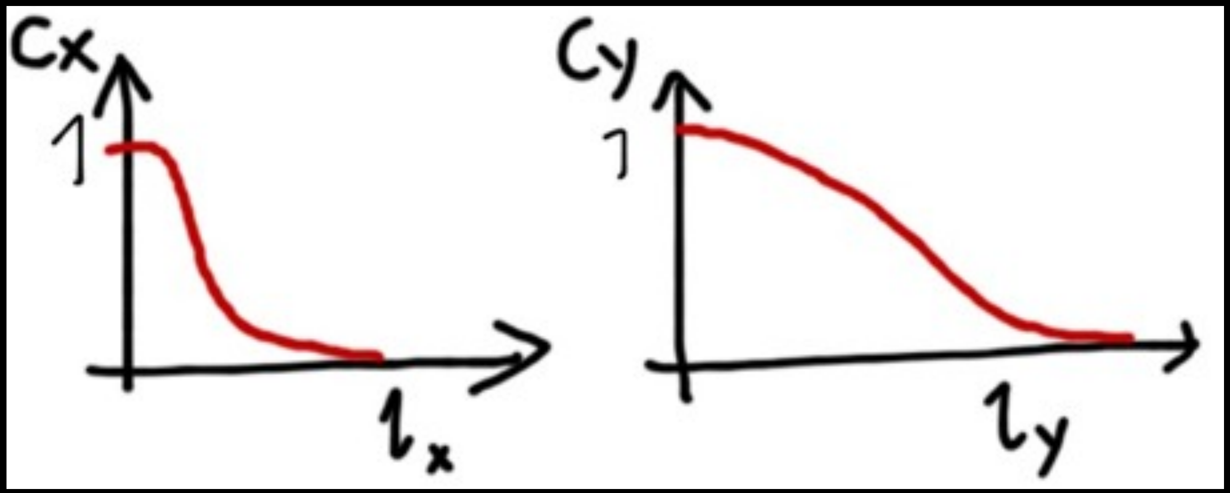
Compression (shocks, large & small)



Shear (differential rotation, streaming)



MHD turbulence ($k_\perp > k_{||}$)



Unknown

Galaxies evolve [rotation(t), SFR(t), spiral pattern(t), scale-height(t), ...]:
how does B evolve?

What happens at large radius and height?
LOFAR should answer

What is the relation (if any) between
magnetic fields and star formation?

Unknown

Most properties of small-scale magnetic field:

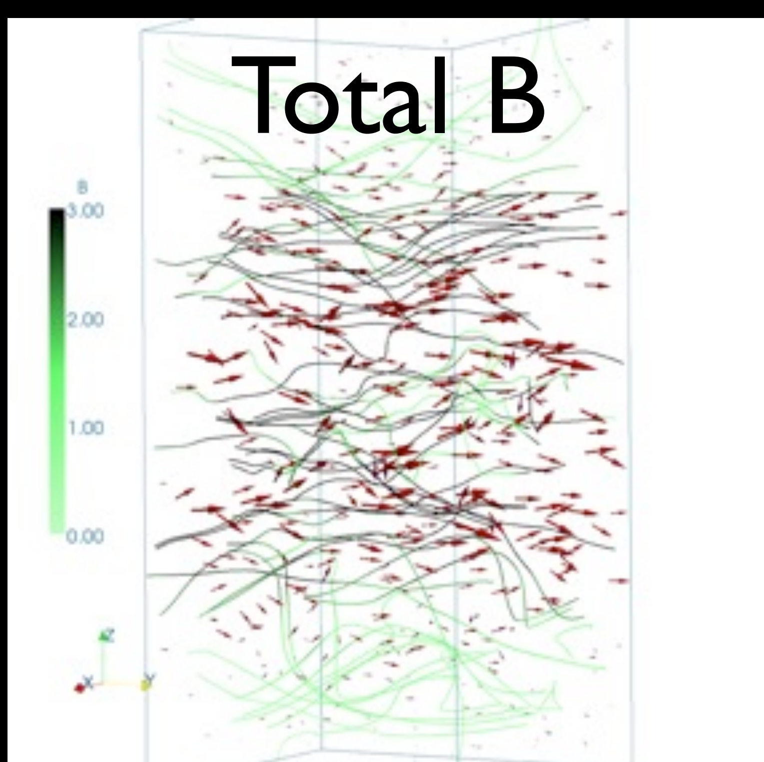
- power spectrum?
- turbulence and/or ‘structure’ (SNR, winds, ...)?
- volume filling or intermittent?
- origin: tangling or fluctuation dynamo?
- helicity?

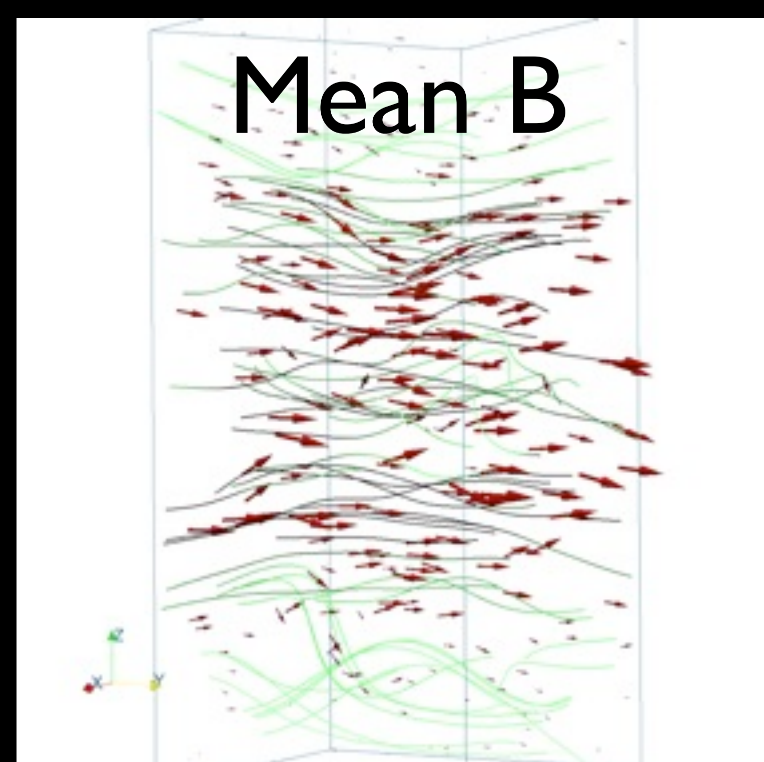
What is the relation (if any) between magnetic fields and star formation?

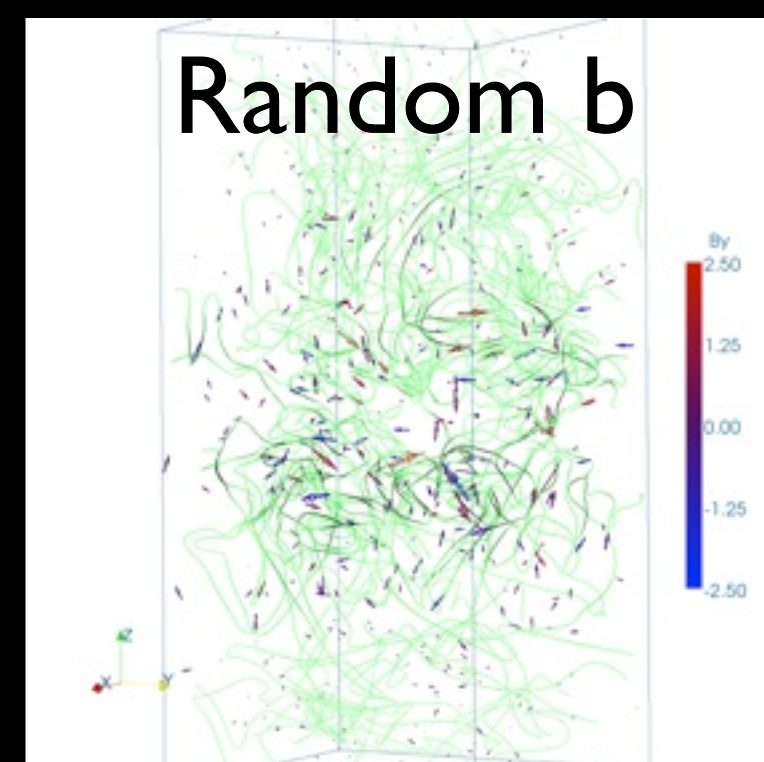
Unknown

Connection of magnetic field to ISM:

- which phase (cold, warm, hot)?
- spiral arms and spiral field lines?
- relative distributions of B, gas, cosmic rays?
- connection to velocity field?

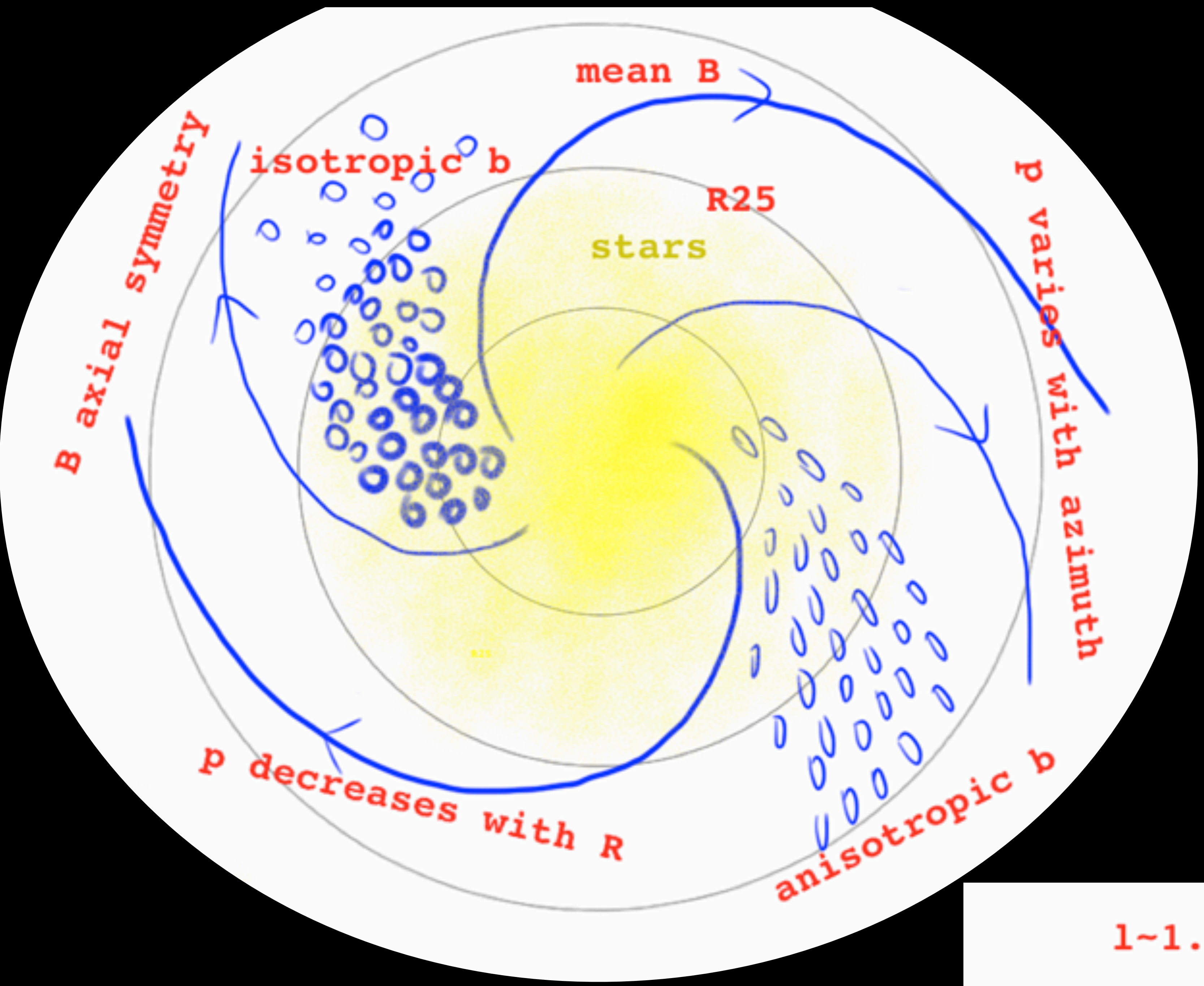






Simulations: Fred Gent

Summary



Face-on

Edge-on