Magnetic fields in spiral galaxies

Marita Krause

Max-Planck-Institut für Radioastronomie Bonn

Magnetic field structure: CHANG-ES EVLA survey on 35 galaxies

M51 (Sui Ann Mao et al. 2015)

Radio scale heights in edge-on galaxies

Continuum
HAlos in
Nearby
Galaxies – an
EVLA
Survey
→ **CHANG-ES**

35 galaxies

1.5 GHz, 6 GHz
in B,C,D-array

405 hours observing time

Probing CRs and magnetic fields at the interface between galaxies and the IGM

The consortium (31 members at present, 8 PhDs)

Judith Irwin, Queen's University (**PI**), Kingston, Canada
Rainer Beck, Max-Planck-Institut für Radioastronomie, Bonn
Robert Benjamin, University of Wisconsin
Ancor Damas, Max-Planck-Institut für Radioastronomie
Ralf-Jürgen Dettmar, Ruhr-Universität Bochum,
Jayanne English, University of Manitoba, Canada
George Heald, Netherlands Institute for Radio Astronomy
Richard Henriksen, Queen's University, Kingston, Canada
Megan Johnson, CSIRO, Epping, Australia
Amanda Kepley, National Radio Astronomy Observatory
Marita Krause, Max-Planck-Institut für Radioastronomie
Jiang-Tao Li, University of Massachusetts
Zhiyuan Li, Nanjing University (NJU), China
Arpad Miskolczy, Ruhr-Universität Bochum
Silvia Carolina Mora, Max-Planck-Institut für Radioastronomie, Bonn
Eric Murphy, Spitzer Science Center, Calteh, Pasadena
Tom Oosterloo, Netherlands Institute for Radio Astronomy
Elena Orlando, Stanford University
Troy Porter, Stanford University, Palo Alto
Richard Rand, University of New Mexico
D. J. Saikia, National Centre for Radio Astrophysics, Pune, India
Philip Schmidt, Max-Planck-Institut für Radioastronomie, Bonn
Carlos Sotomayor, Ruhr-Universität Bochum
Yelena Stein, Ruhr-Universität Bochum
Andrew Strong, Max-Planck-Institut für extraterrestrische Physik, Garchng
Carlos Vargas**, New Mexico State University, Las Cruces PhD**
Rene Walterbos, New Mexico State University, Las Cruces
Daniel Wang, University of Massachusetts, Amherst
Marek Wezgowiec, Ruhr-Universität Bochum
Theresa Wiegert, Queen's University, Kingston, Canada
Yang Yang**, Nanjing University (NJU), China**

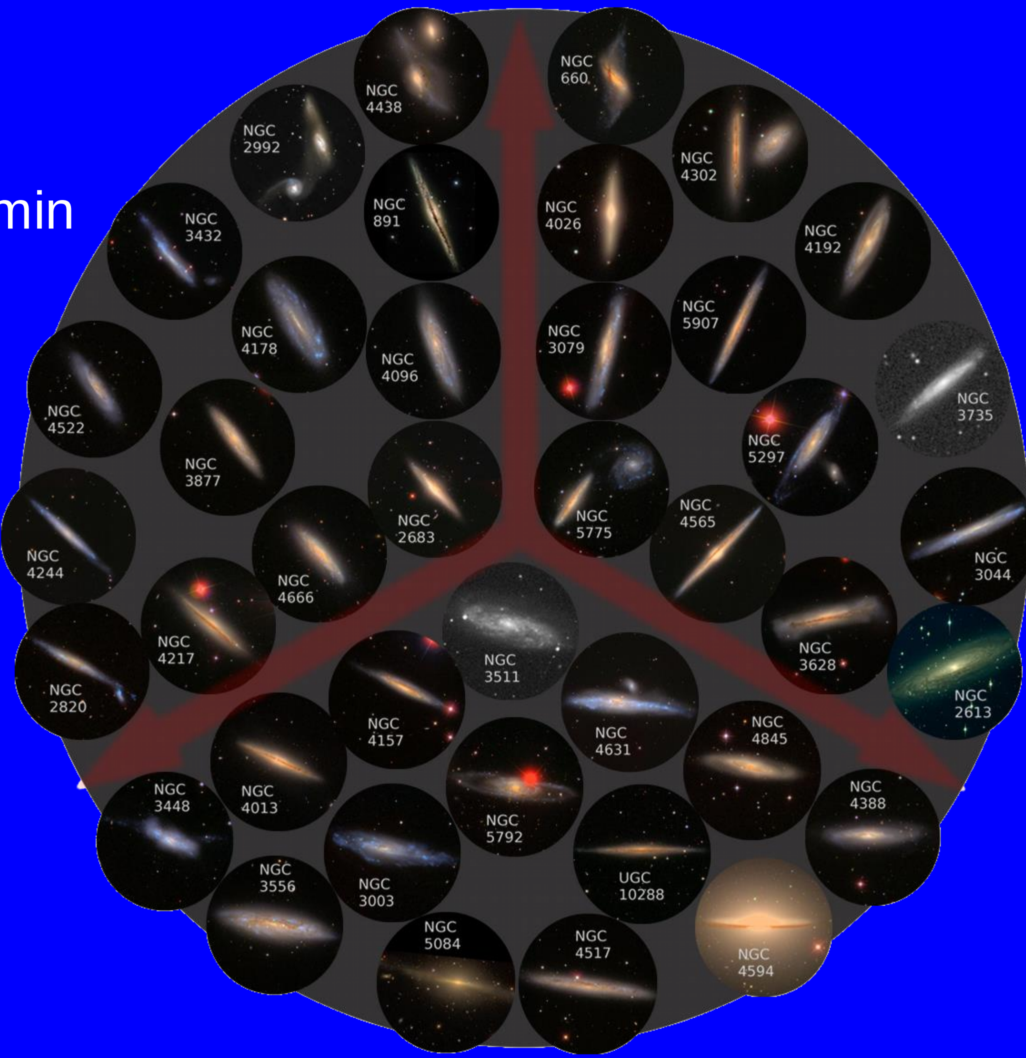
Galaxies & selection criteria

from Nearby Galaxies Catalog:

- inclination > 75 °
- 4 ≤ d_blue isophotal ≤ 15 arcmin
- δ > -25 °
- 1.4 GHz fluxes > 20 mJy
- plus N4244, N4565, N5775

→ **35 galaxies in total**, mixture of AGN, LINERs, SFR, interacting

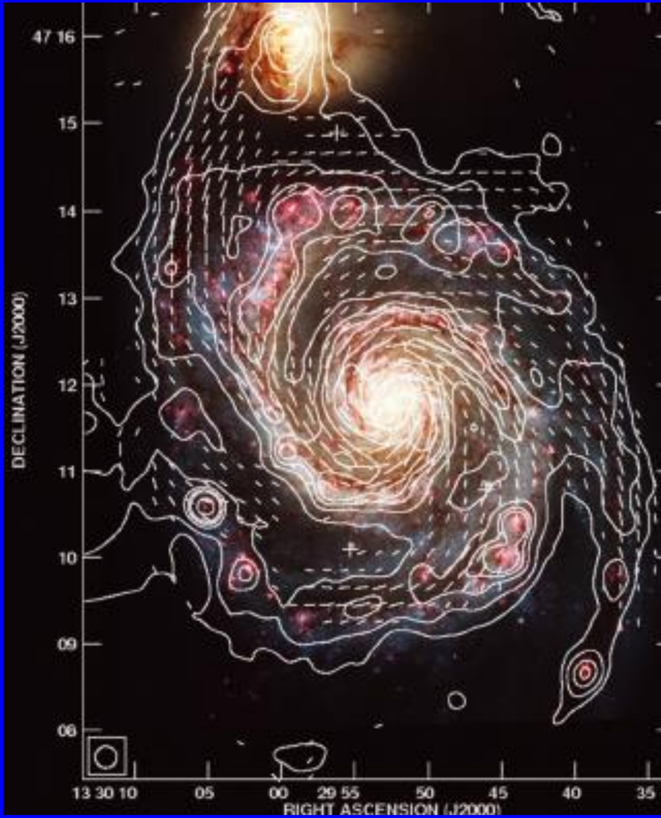
5 papers published:
Irwin et al. 2012, 2013, 2015
Wiegert et al. 2015



Logo by J. English

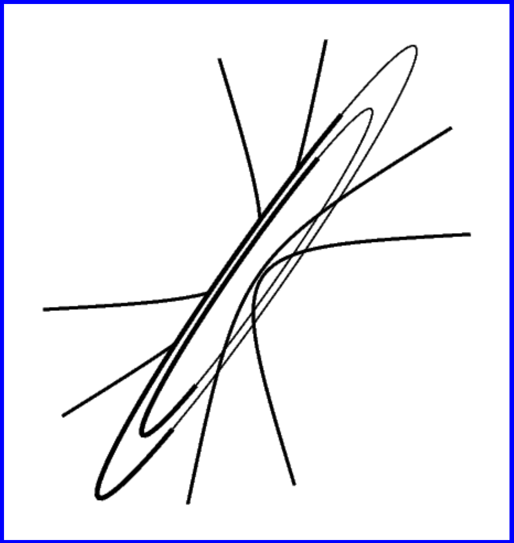
Magnetic fields in spiral galaxies

M51

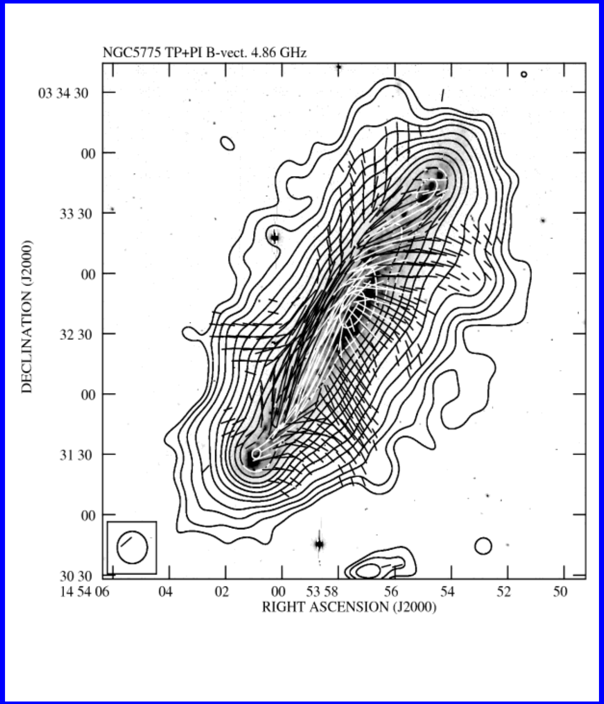


Fletcher et al. 2011

Scetch of toroidal disk field and halo field



NGC5775 i = 86°

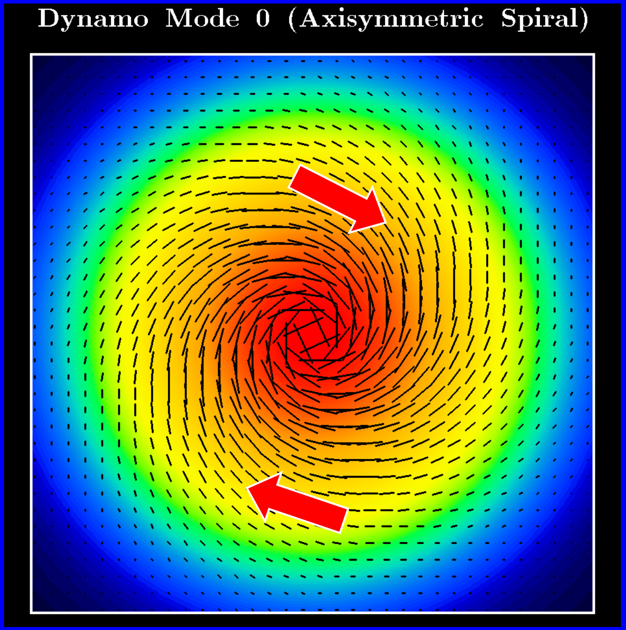


Soida, Krause, Dettmar, Urbanik 2011

Face-on galaxies show a spiral magnetic field along the disk → disk-parallel field in edge-on galaxies

Large-scale field strength in the halo comparable to disk field strength

A dynamo generated large-scale magnetic field in the disk



courtesy to R. Beck

→ASS disk-field

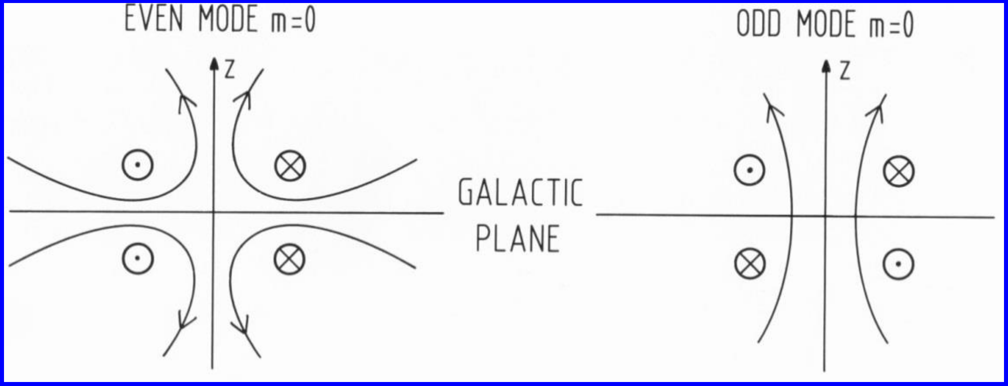
Large-scale RM-pattern indicates an ASS disk-field. Its poloidal component alone cannot explain the observed halo fields.

→ **dynamo action in the halo**

or

galactic wind needed

↔ observations & simulations

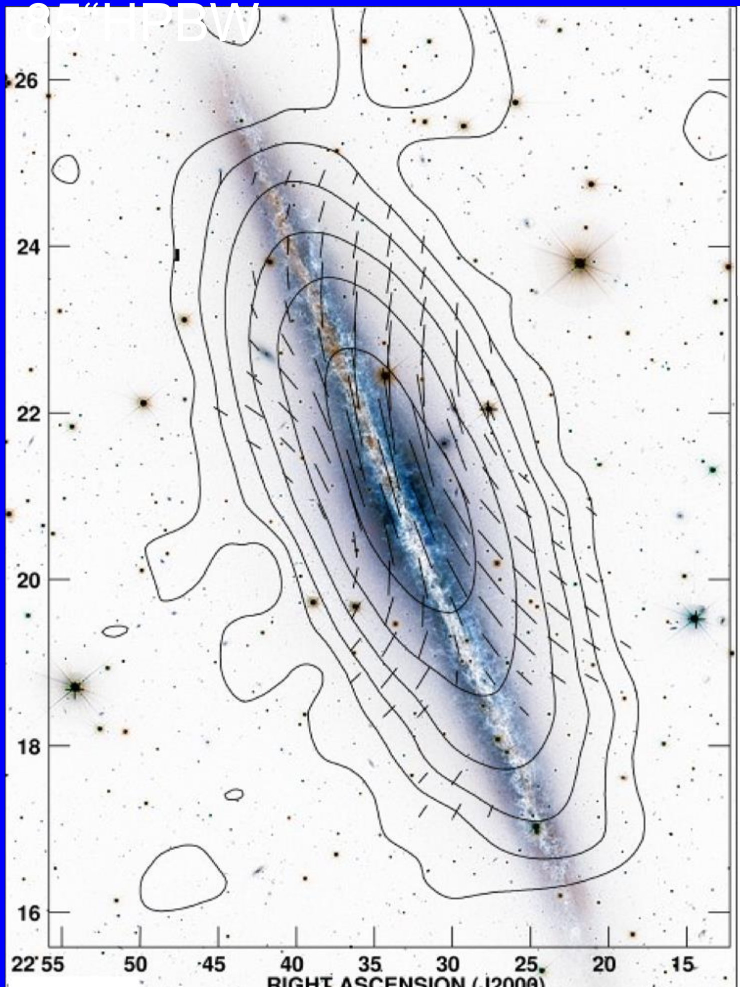


NGC 891

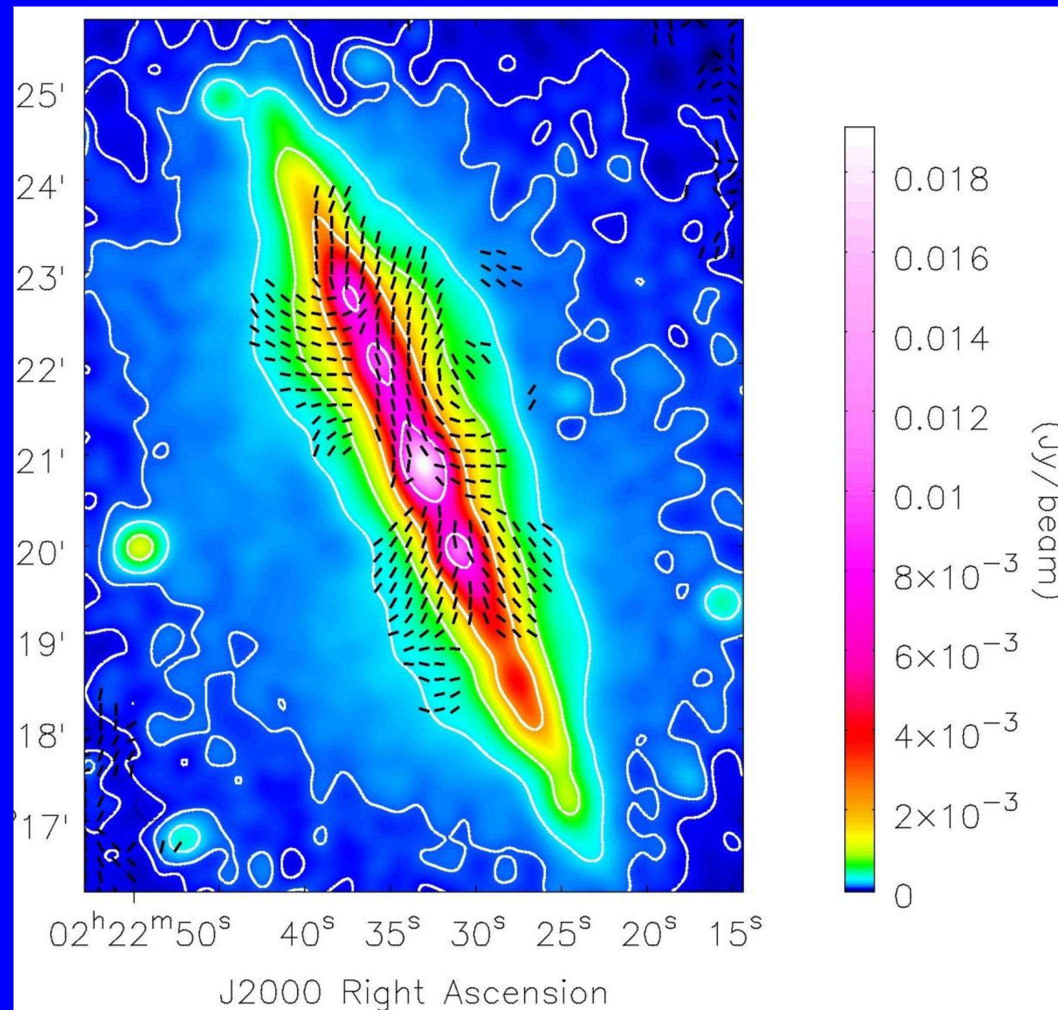
CHANG-ES

EVLA C-band D-array 20“ HPBW
TP: 6cm Effelsberg + EVLA

Effelsberg 3.6cm
85“HPBW



M. Krause 2009

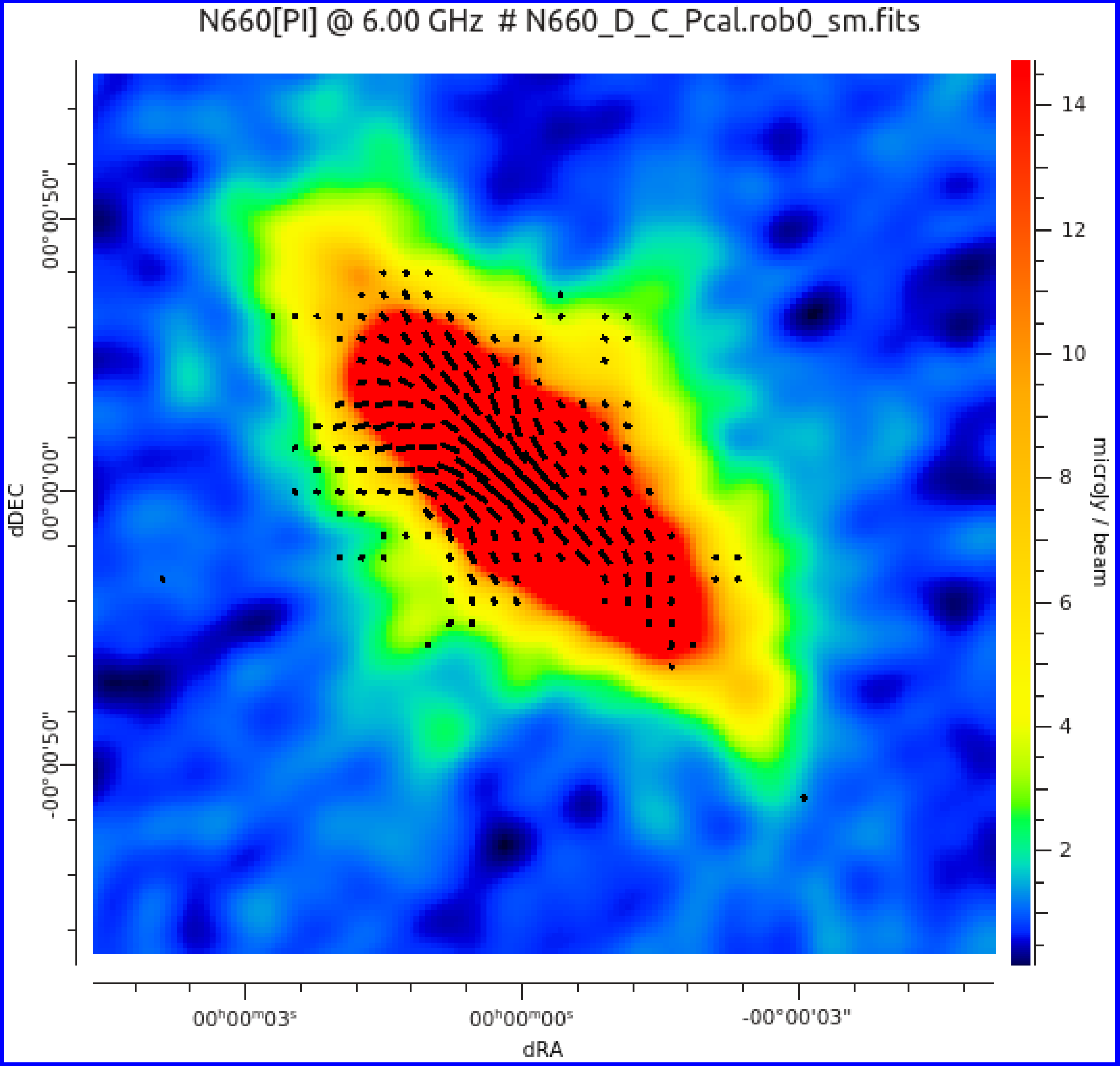


PhD Philip Schmidt, Bonn

NGC 660 SBa i=77° 12.3Mpc SFR=2.7$M_{\odot}$/yr

polar ring galaxy, LINER

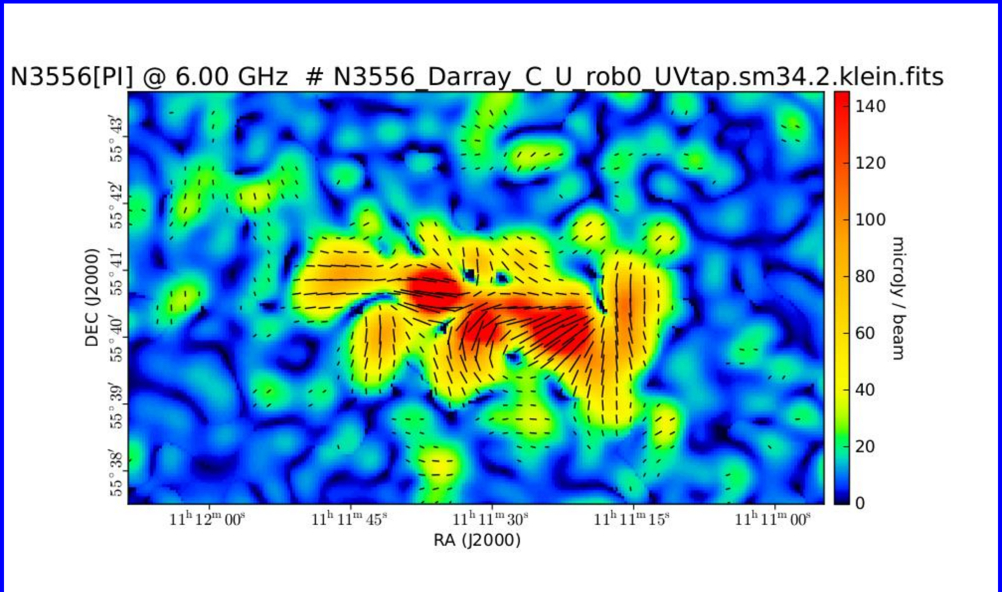
C-band D-array,



Disk-field:
plane-parallel

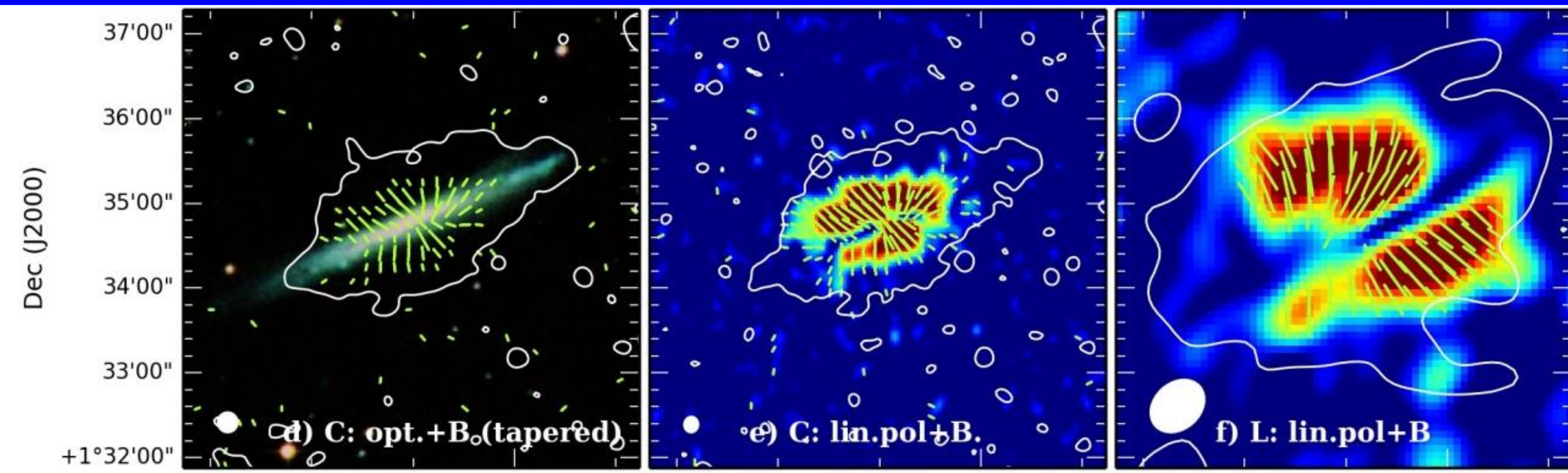
Halo-field:
X-shaped

NGC 3556 SBc i=82° 14 Mpc SFR=2.2 $M_\odot$/yr

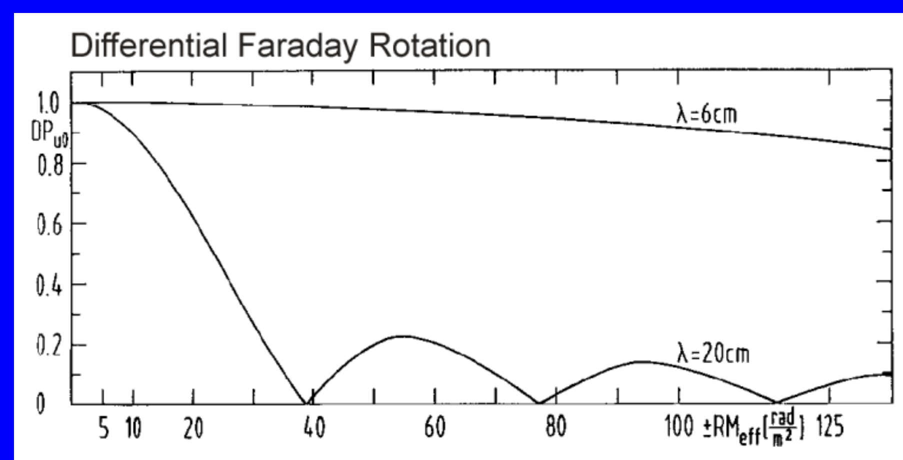


C-band D-array
17.3″ HPBW

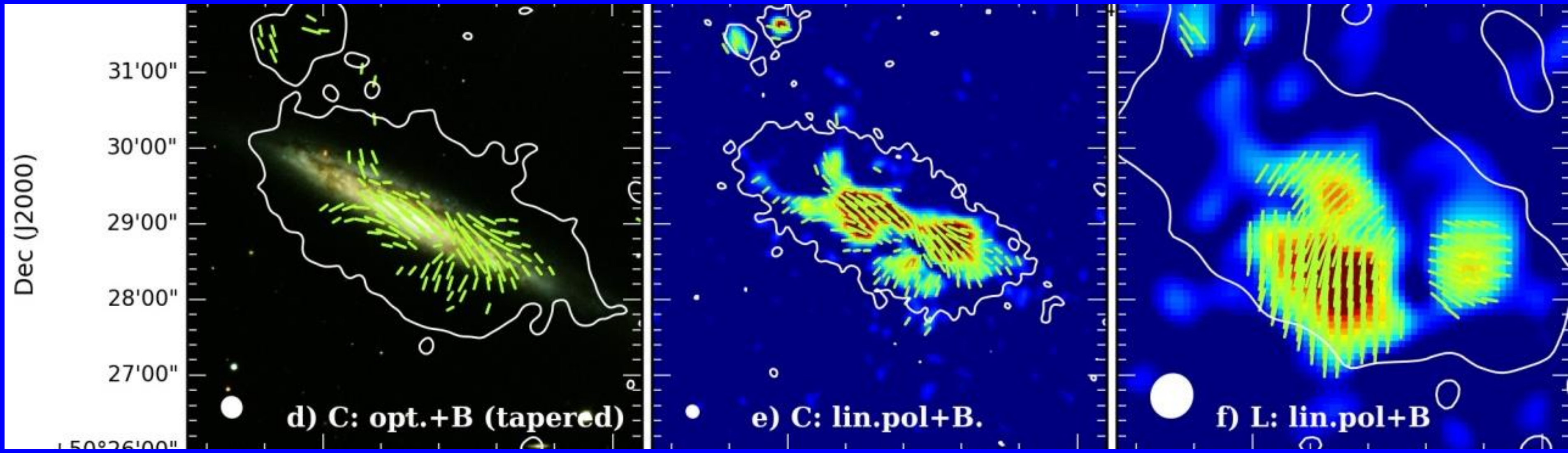
NGC 3044 SBc i=85° 20 Mpc SFR=1.0 $M_\odot$/yr



In **L-band not Faraday thin** →
only layer in front side visible

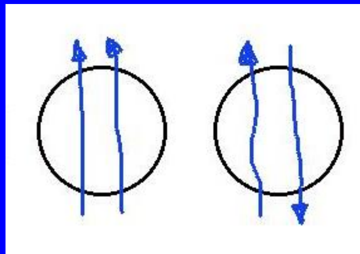


NGC 4157 SABb i=83° 16 Mpc SFR= 1.3 $M_\odot$/yr



Asymmetric depolarization along disk

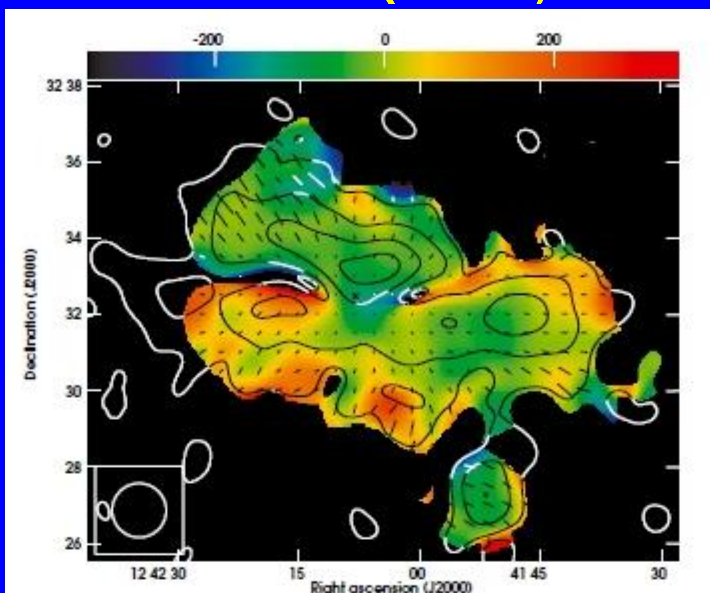
Are halo magnetic fields regular or coherent?



courtesy R. Beck

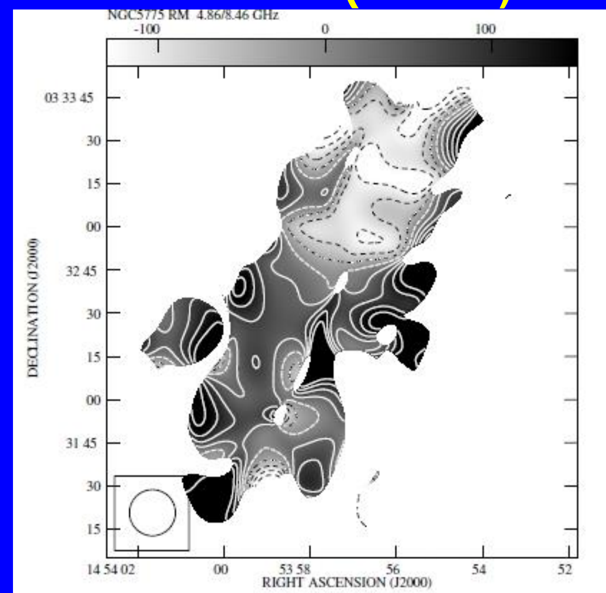
Both give **PI**, only regular field yield **RM**

NGC4631 RM(6-3cm) 85″



Mora & Krause 2013

NGC5775 RM(6-3cm) 16″



Soida, Krause et al. 2011

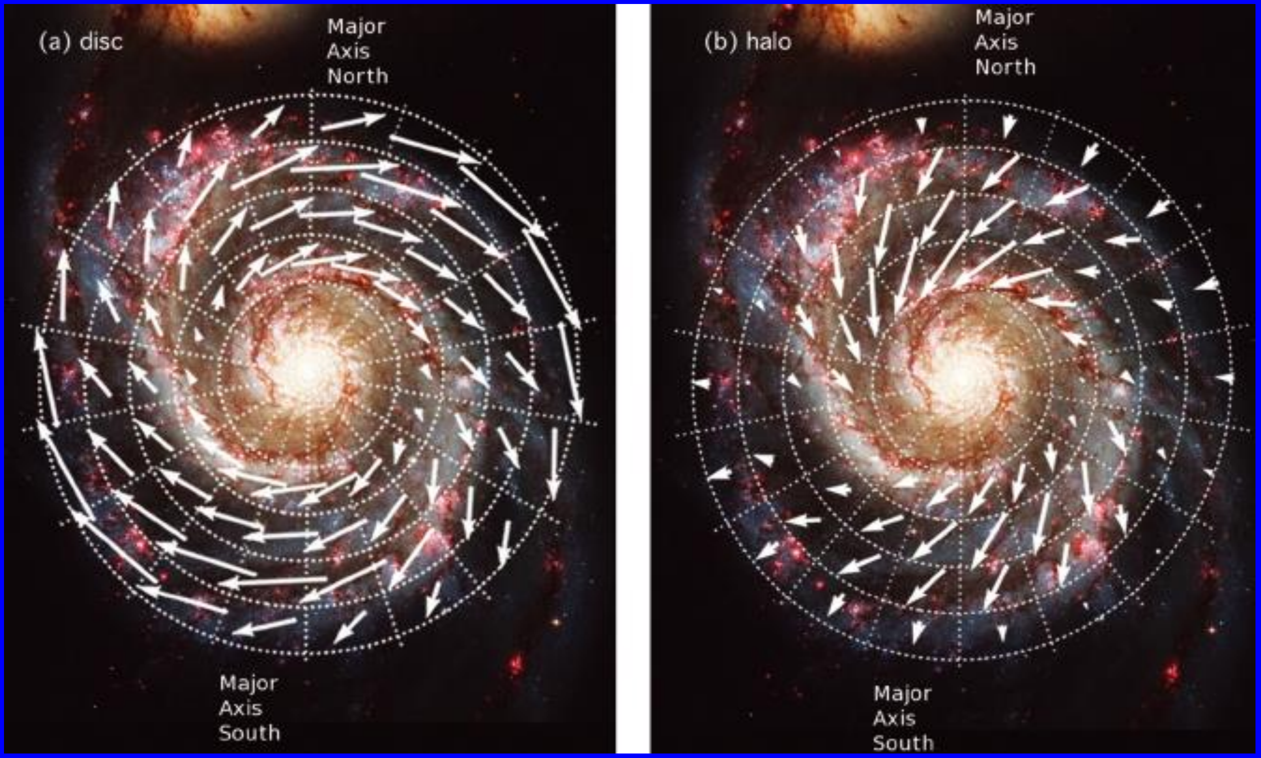
No clear large-scale RM-pattern deteted up to now, however: **│RM│ does not generally decrease with z**

→ **indication of regular field**

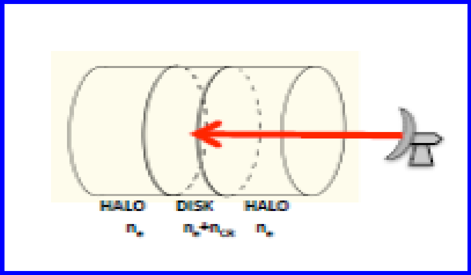
What can we learn from face-on galaxies about the halo magnetic field?

M51

- Different azimuthal large-scale field structures in disk and halo (Berkhuijsen, Horellou, Krause et al. 1997)
- ASS field in disk, BSS field in halo (Fletcher at al. 2011)



Disk is not transparent at L-band (20cm) in polarization



- L-band EVLA observations analyzed with RM synthesis:
  Wide-band polarimetry can trace the magneticed medium in the halo of M51 (Ann Mao et al. 2015)

EVLA L-band observations of M51 (Ann Mao et al. 2015)

- 1-2 GHz ;11”x9”resolution
- ~ 400 MHz usable bandwidth
- $Q(\lambda^2)$ and $U(\lambda^2)$ image cubes

  → RM Synthesis → $Q(\Phi)$ and $U(\Phi)$

  → Extract peak Φ and PI
- |RM| ~ few 10s rad m^{-2}
  - behavior different from a strong large-scale disk field
  - << $|RM_{3+6cm}|$
  - mid-plane likely depolarized at L band
  - Emission at L band from top of synchrotron disk

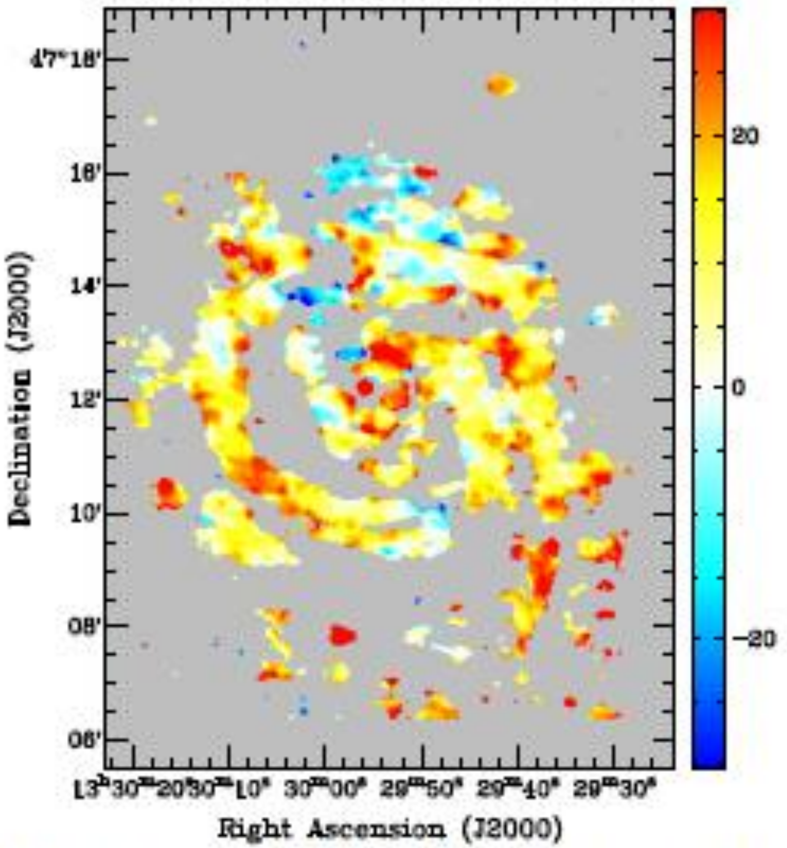


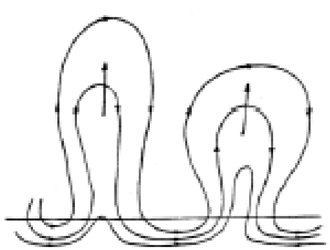
Figure 7. Faraday depth distribution of M51 at *L* band derived from RM synthesis. The color scale is in units of rad m^{-2}.

Predicted BSS halo field of Fletcher et al. 2011 can be reconciled with the new observations by adding an **additional vertical coherent halo field ($RM = -9$ rad/m^2)**

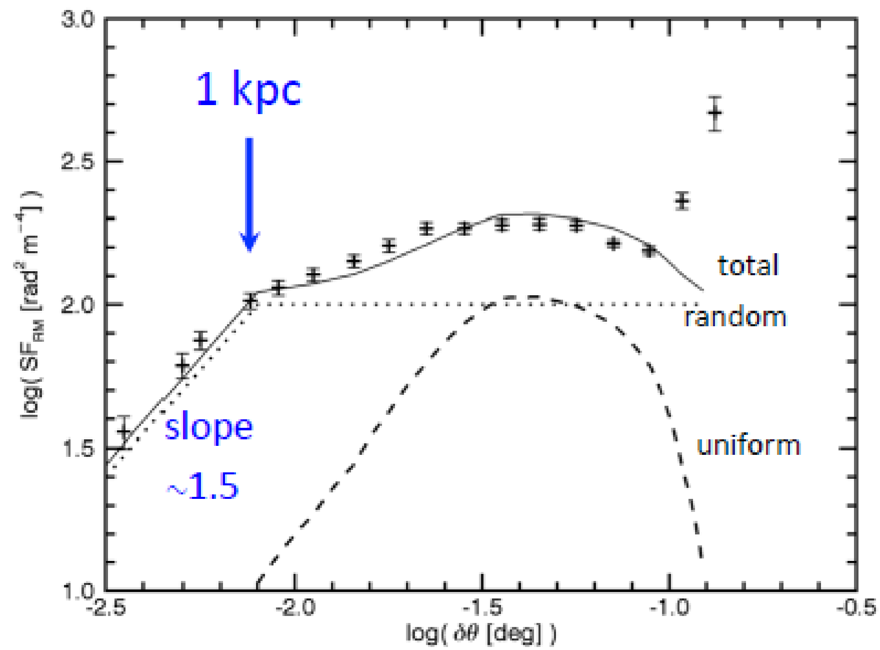
What can we learn about the magnetic field scales?

Rotation Measure SF using New L band Data

- Amplitude: $SF_{RM} \rightarrow \sigma_{RM} \sim 13$ rad m^{-2}
  - $<< \sigma_{RM,3+6cm} \sim 50$ rad m^{-2}
  - L band data do not probe through the turbulent disk
- Shape: reproduced by the sum of
  - uniform halo B field component from Fletcher et al. 2011
  - Kolmogorov slab with $r_{out} \sim 1$ kpc
- $r_{out,halo} \sim 1$ kpc, comparable to
  - size of superbubbles
  - typical size of Parker Loops



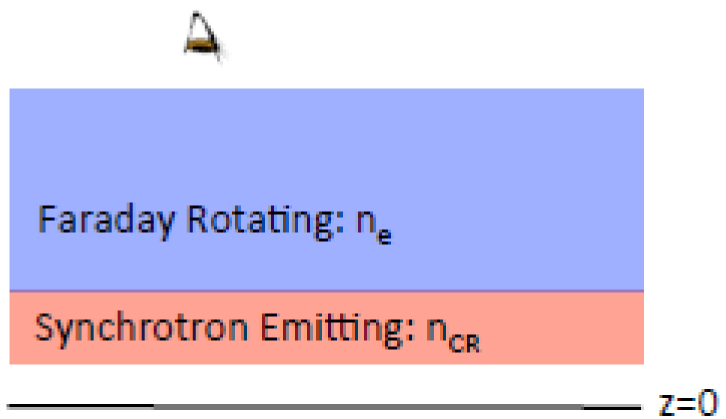
Parker 1992

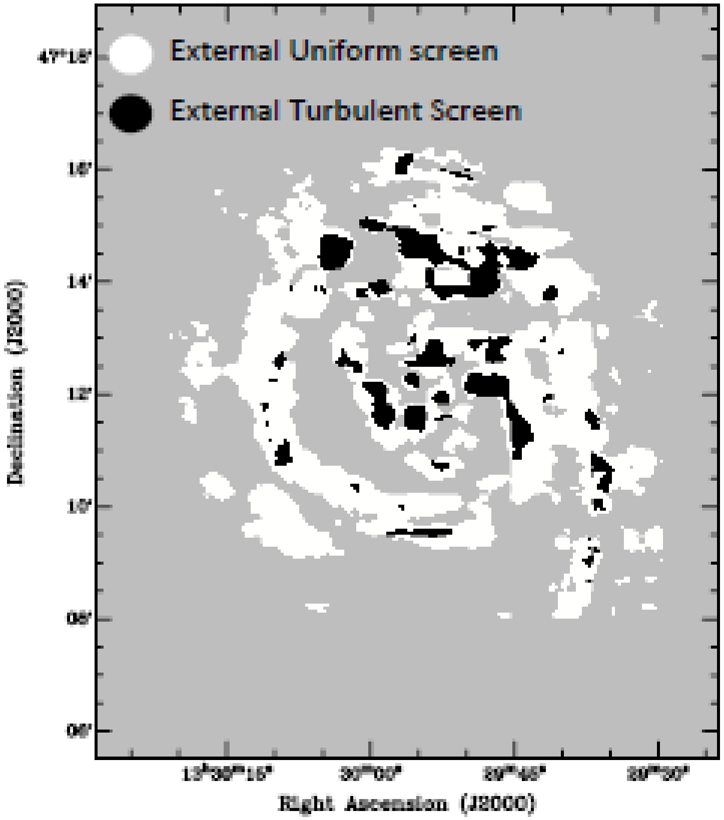


Pixel-by-pixel maximum likelyhood fitting of Q(λ²) and U(λ²) to various depolarization models:

The Nature of the Faraday Rotating Medium

- All sightlines well fitted by FR in an external screen
  - 84% uniform screen (no depol)
  - 16% turbulent screen
- Pol. emission from top of the sync. disk, then FR in the near-side halo





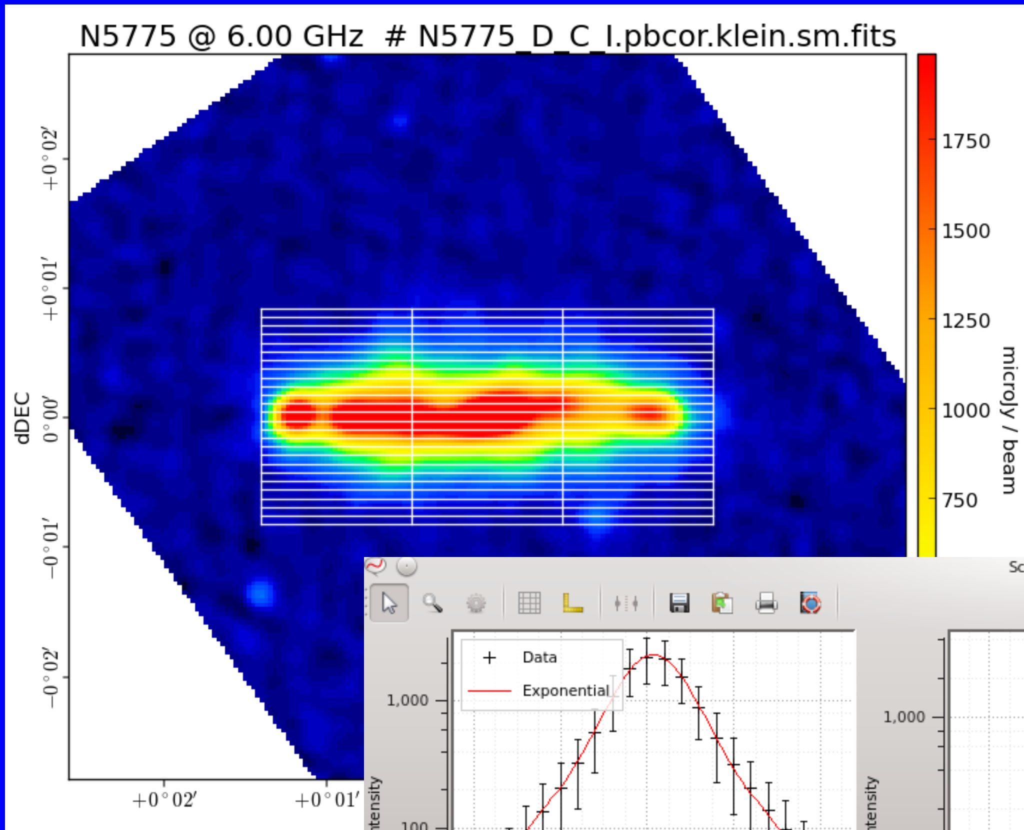
- $h_{\text{thermal ne}} > h_{\text{synchrotron 20cm}} \sim 1.2$ kpc

Vertical radio scale heights of CHANG-ES sample

- **35** galaxies in total in C-band, D-array
- **26** galaxies **≤ 5'** (**23** galaxies **≤ 4'**, without N2613, N3432, N3079)
- **8** galaxies refused because **i ≤ 80°** (after tests for all galaxies with nod3) (N2992, N3448, N4388, N4096, N4438, N4666, N5297, N5792
- 4 galaxies omitted because of nuclear actvitiy, strong interaction, etc. (N660, N2992 (part of Arp 245), N4845, N5084)

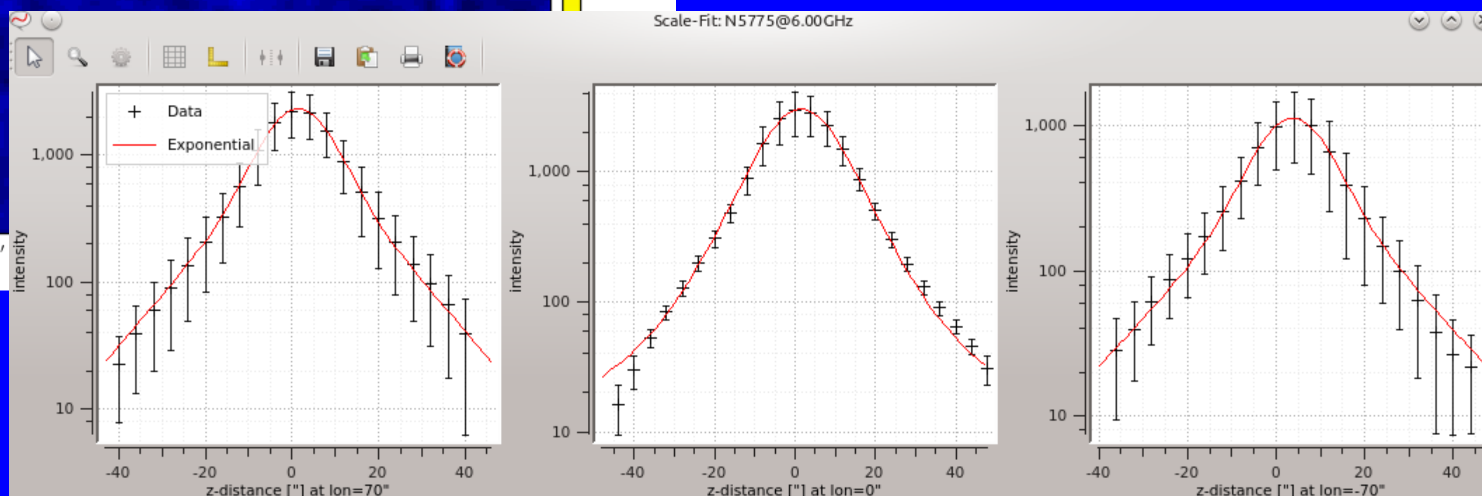
→ radio scale heights of 15 galaxies determined

Boxintegration for the scale height determination



i = 86°
p.a. = -35°
2-comp. exponential fit

h_1 = 400 ± 170 pc
h_2 = 1.7 ± 0.4 kpc



Galaxy scale height fit results

```
# effective Beam = 13.013"    Beam(map) = 10.700"

l = 70     w0(Exponential) = 4155    +/- 202      z0(Exponential) = 2.918   +/- 0.5705    chi2 = 0.1777
l = 70     w1(Exponential) = 1206    +/- 361.3    z1(Exponential) = 10.99   +/- 1.441     chi2 = 0.1777

l = 0      w0(Exponential) = 5244    +/- 303.6    z0(Exponential) = 6.391   +/- 0.7612    chi2 = 1.361
l = 0      w1(Exponential) = 125.8   +/- 424.7    z1(Exponential) = 29.2    +/- 71.21     chi2 = 1.361

l = -70    w0(Exponential) = 1736    +/- 124      z0(Exponential) = 3.753   +/- 0.796     chi2 = 0.09386
l = -70    w1(Exponential) = 528.7   +/- 212.5    z1(Exponential) = 13.42   +/- 2.467     chi2 = 0.09386
```

Averaged CHANG-ES values of 15 galaxies:

Mean 250 ± 140 pc 1.2 ± 0.4 kpc

Previous observations:

	Vertical scale heights at 6.2cm		SFR(IR)	SFE	B_t	i	type
	thin disk	**thick disk/halo**	$M_☉$/yr]	[$L_☉$/ $M_☉$]	[μG]	[°]	
NGC253	380 ± 60 pc	1.7 ± 0.1 kpc	6.3	14	12	78	Sc
NGC891	270	1.8	3.3	5.0	6	88	Sb
NGC3628	300	1.8	1.1	4.9	6	89	Sb pec
NGC4565	280	1.7	1.3	3.2	7	86	Sb
NGC5775	240 ± 30 pc	2.0 ± 0.2 kpc	7.3	6.1	8	86	Sbc

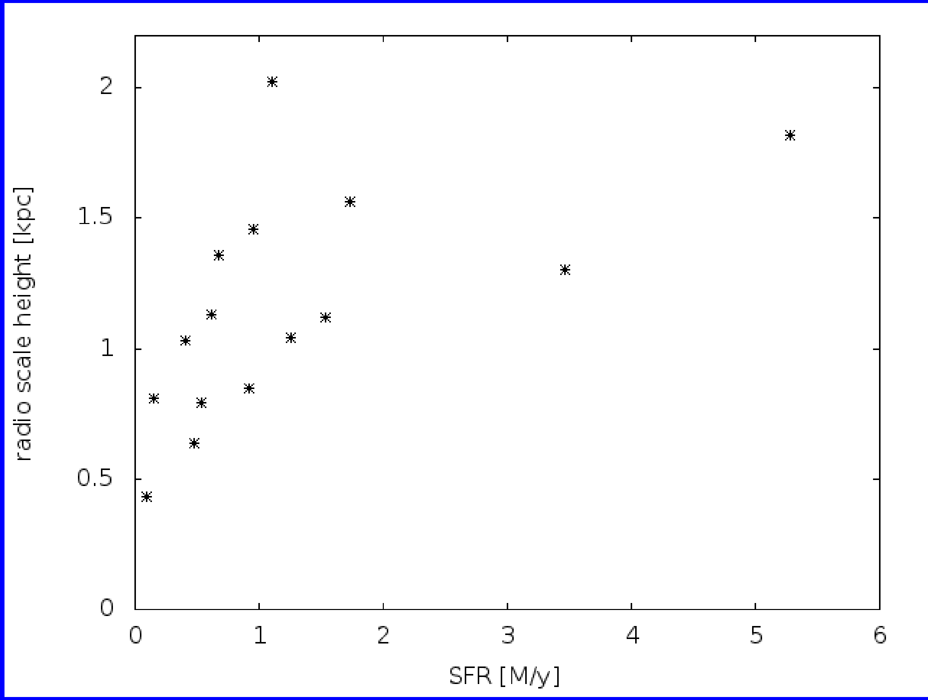
Mean 300 ± 50 pc 1.8 ± 0.2 kpc

→ bias towards nearby and large objects with larger scale heights?

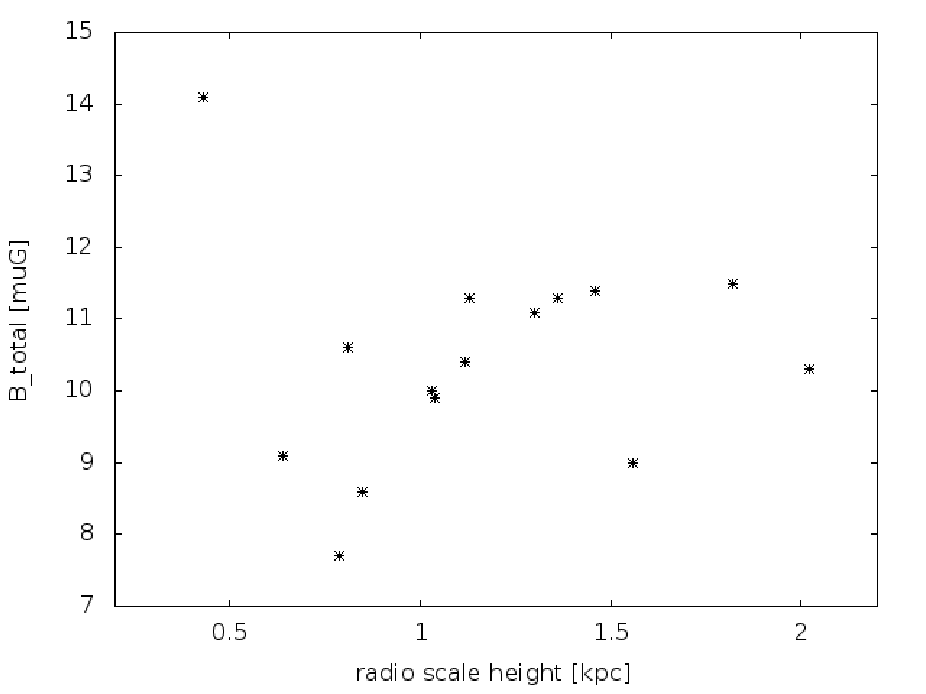
First analysis of 15 galaxies < 5'

No obvious effects of missing spacings visible

radio scale height - SFR



B_total – radio scale height

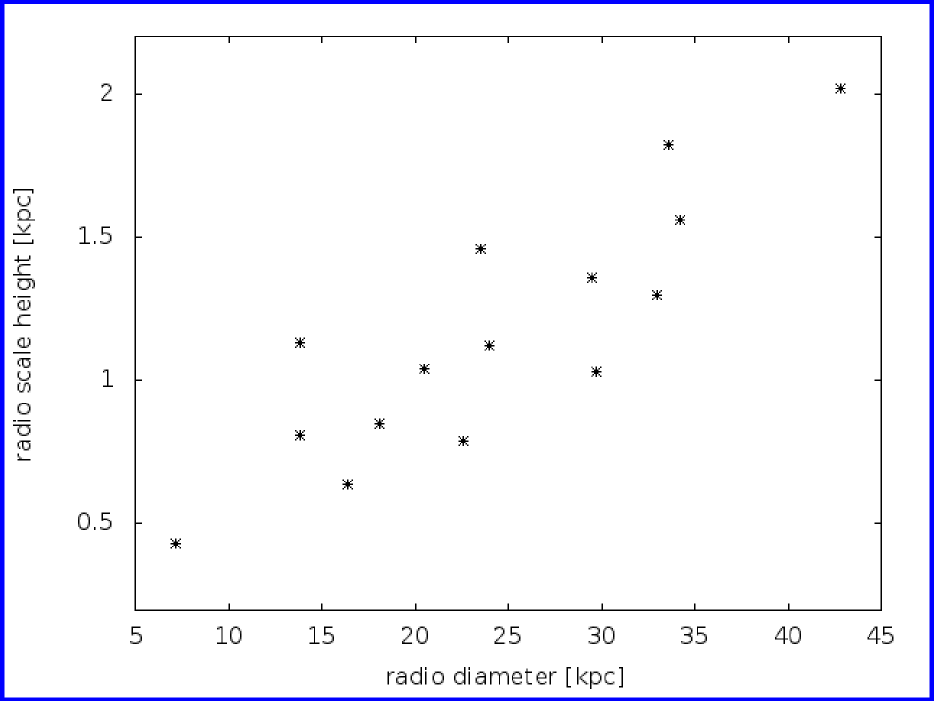


Equipartition model of Radio-FIR correlation (Niklas & Beck 1997):

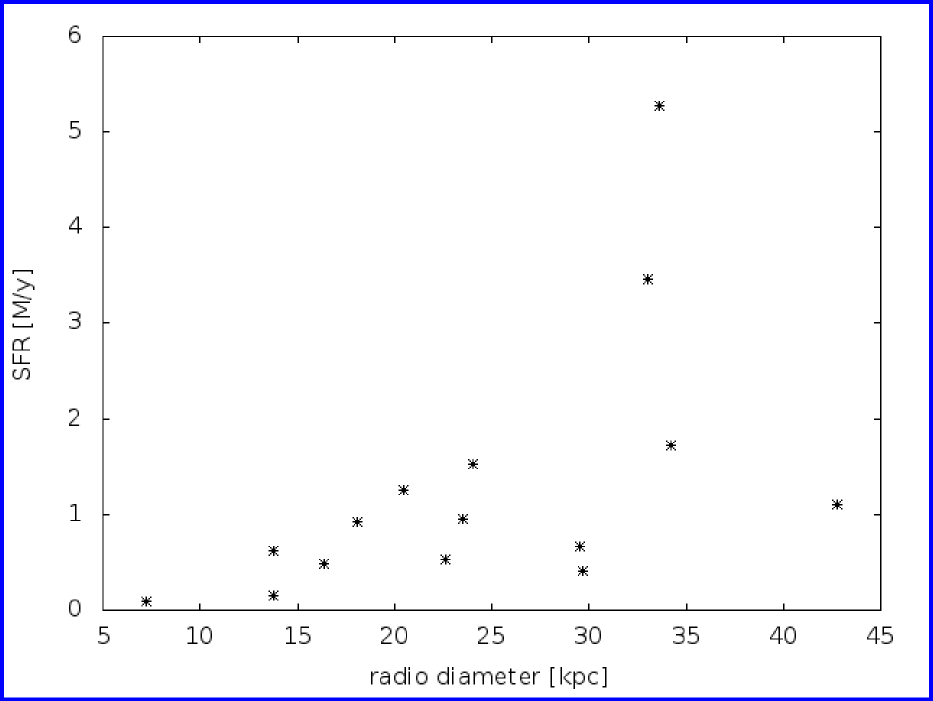
total magnetic field strength $B_t \sim SFR^{\approx 0.34}$

First analysis of 15 galaxies

radio scale height - diameter



SFR – diameter



Next step: determination of radial scalelengths instead of ‚diameter‘

Conclusions

EVLA results of CHANG-ES galaxies and M51 lead to a consistant picture of B in spiral galaxies:

- Sample for edge-on galaxies now significantly extended
- **Parallel disk field, X-shaped halo, also vertical field in M51**
- **Asymmetric depolarization** in one half of the galaxy (also observed in face-ons (Braun, Heald, Beck 2010))
- Mean value of scale heights is lower than before, with larger range of values: **1.2 ± 0.4 kpc instead of 1.8 ± 0.2 kpc** (bias towards larger objects)
- For the first time seen a trend, that **radio scale heights increase with SFR, B_total, and their diameters.**

Cyan: C-band C-array total intensity
Darker cyan: combined all-array, all frequency total intensity
Orange: WISE 12 μm
Yellow: Spitzer 3.6 μm
Rose: Hα
Blue: SDSS r-band
Purple: SDSS g-band
Spatial resolutions vary and have been chosen for visual effects

Thank you for your attention