COSMIC MAGNETIC FIELDS

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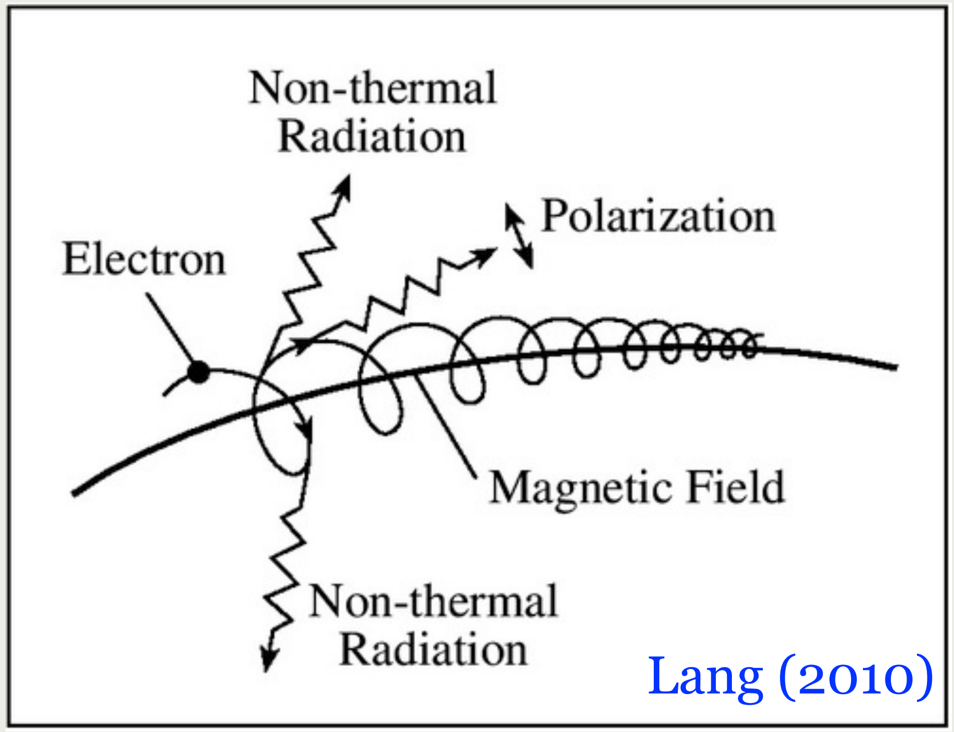
Galaxies

POLARIZATION SIGNATURES OF MAGNETIC FIELDS

synchrotron radiation

strong linear polarization

$\overrightarrow{B}_{\mathrm{rad}} \parallel \overrightarrow{B}_{\mathrm{src},\perp}$



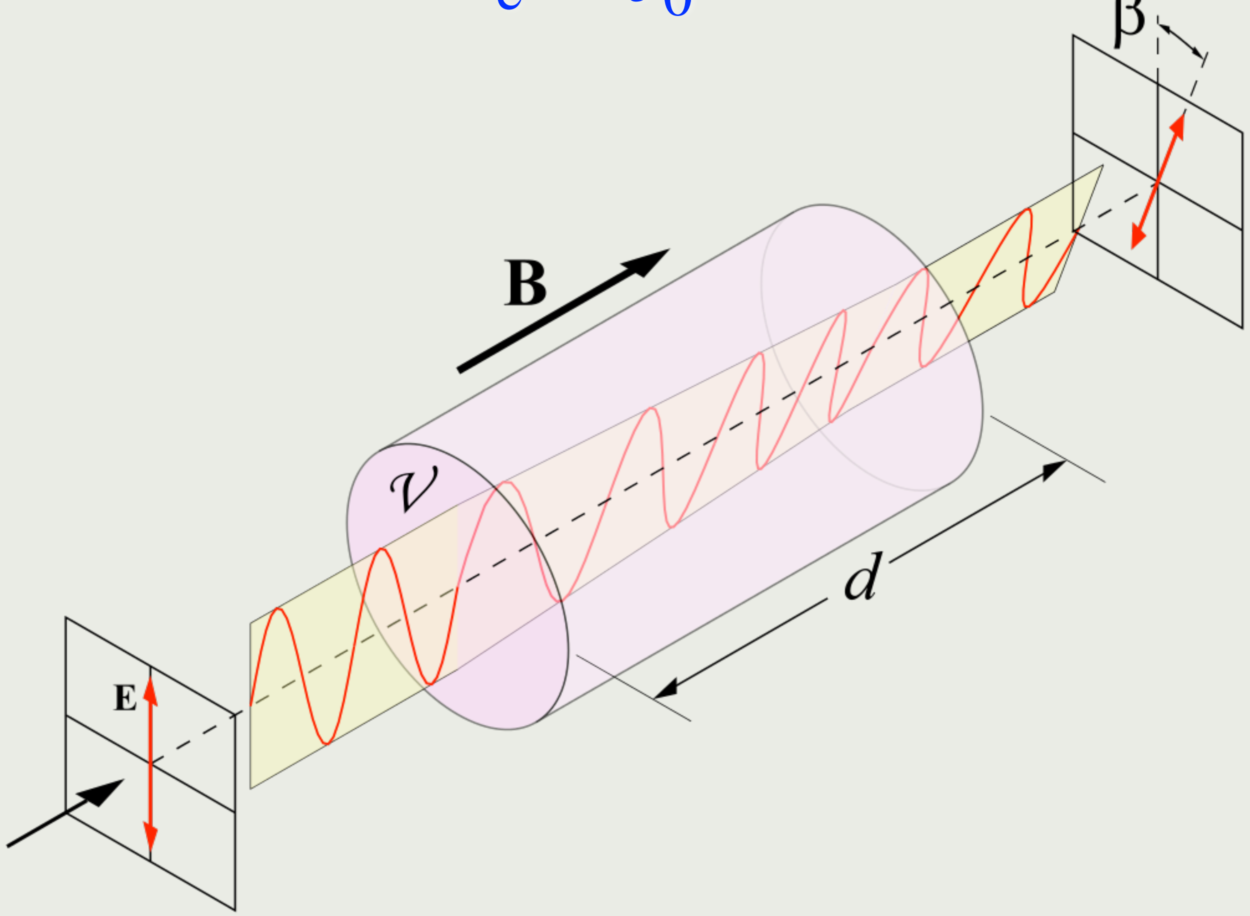
Lang (2010)

Faraday rotation

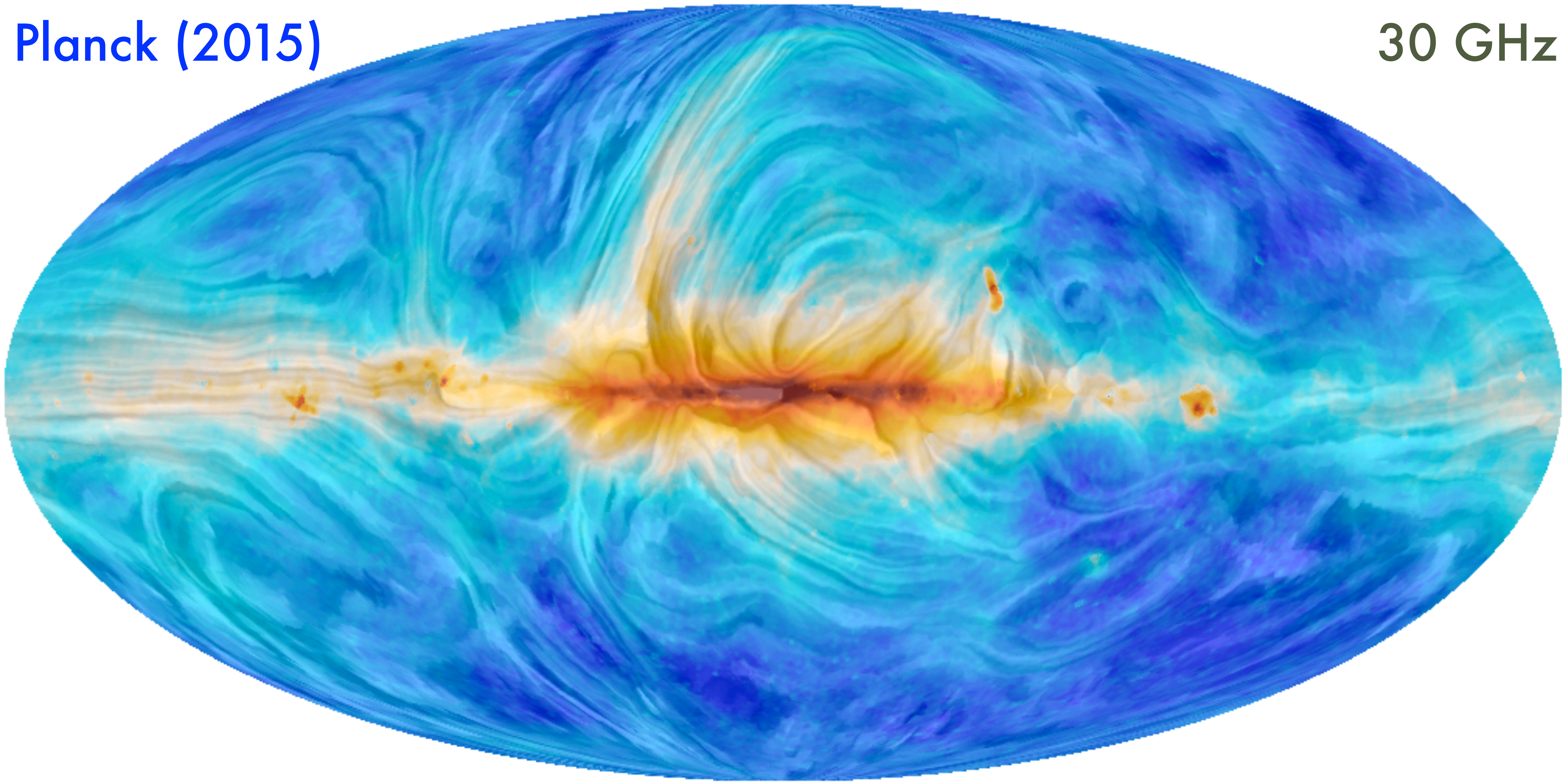
$\beta \simeq \mathrm{RM}\,\lambda^2$

rotation measure:

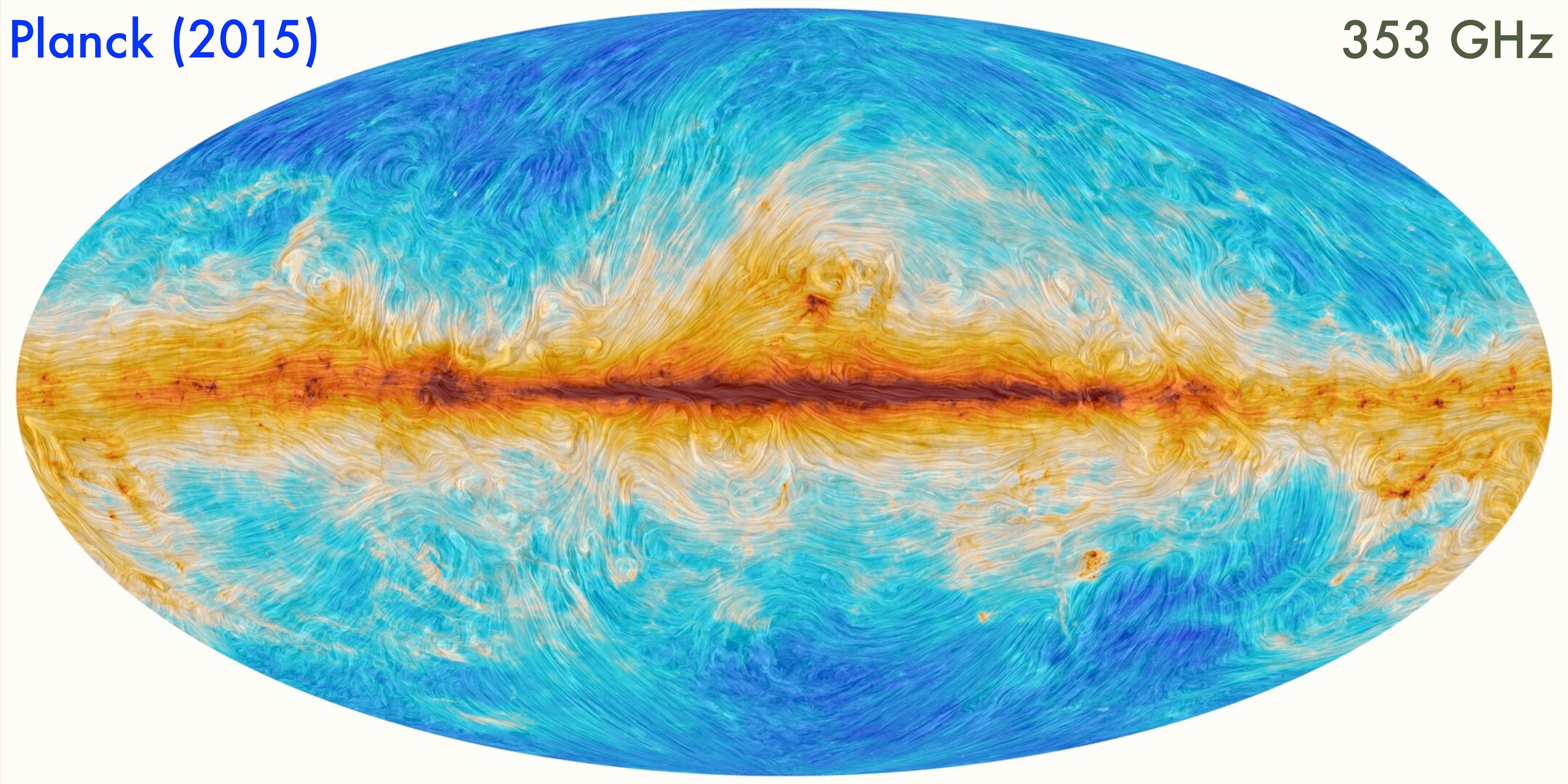
$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int_0^d n_e(s) B_{\parallel}(s)\,\mathrm{d}s$$



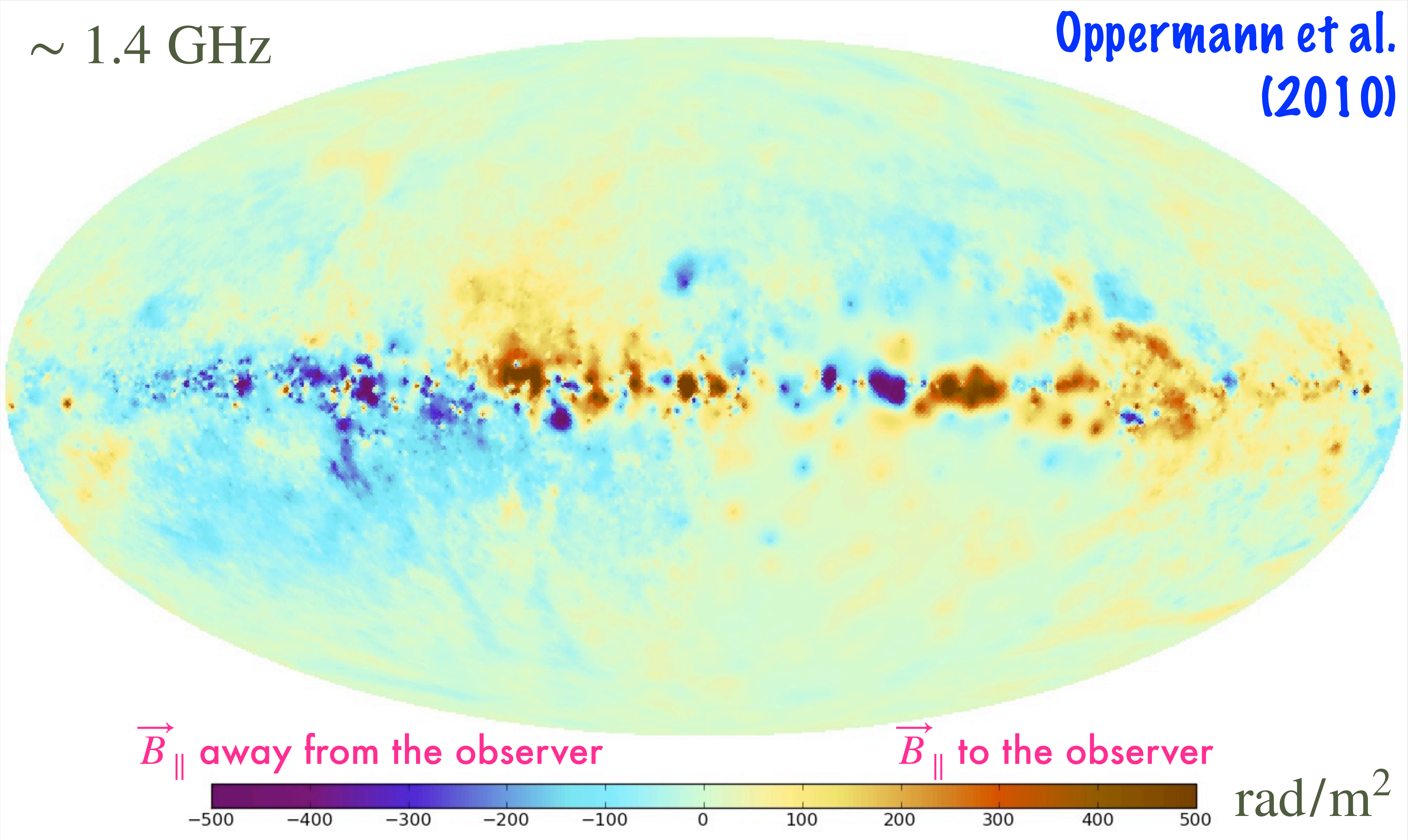
POLARIZED SYNCHROTRON EMISSION



POLARIZED DUST EMISSION

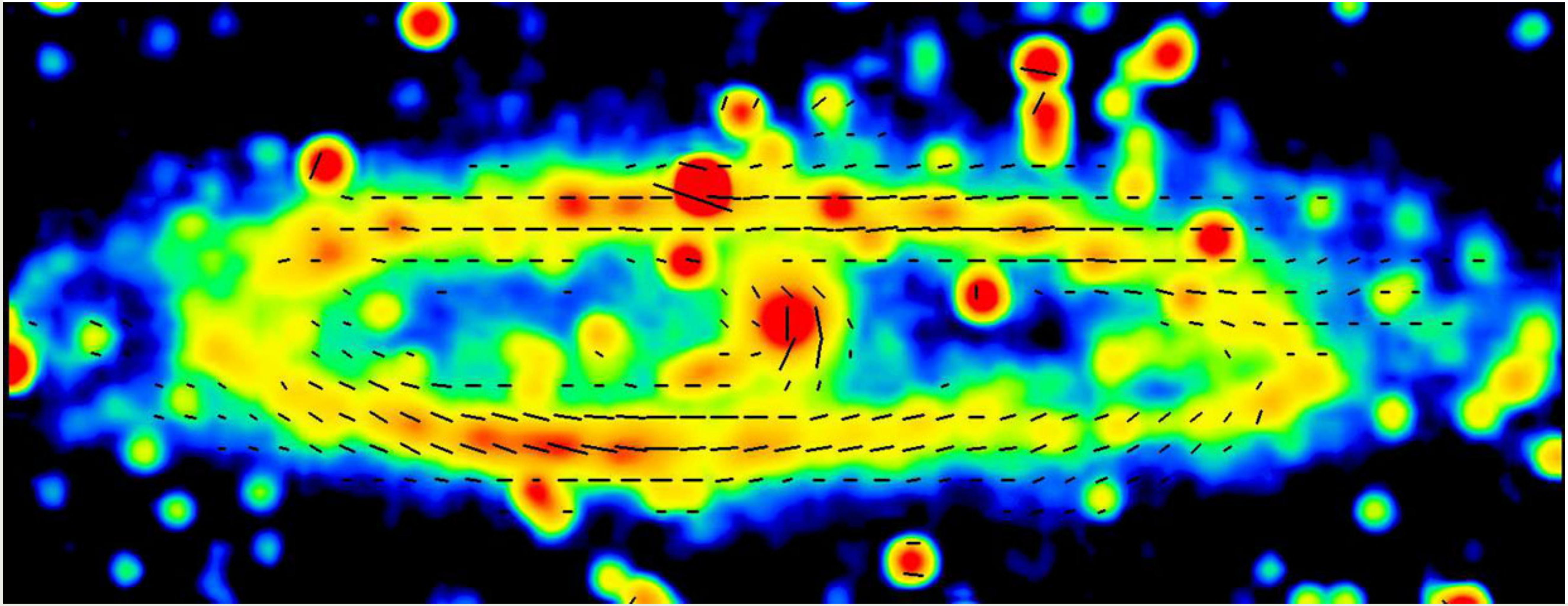


GALACTIC ROTATION MEASURE



- The interstellar medium (ISM) is a low-β plasma: $\beta = P/P_{\mathrm{B}} = 8\pi P/B^2 < 1$; magnetic fields are dynamically important.

ANDROMEDA GALAXY (M31)



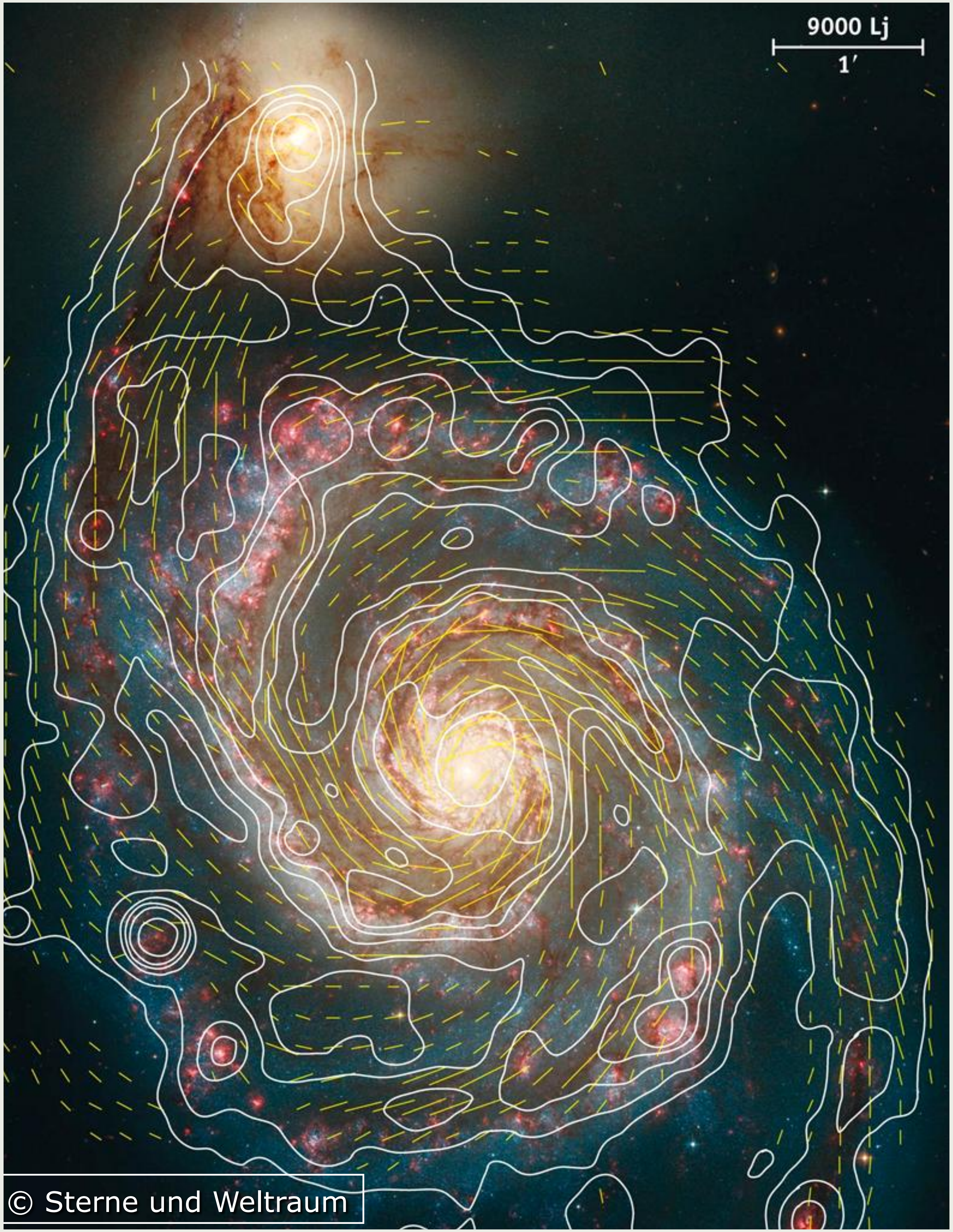
Effelsberg, 6cm
Beck (2015)

- toroidal B-field
- axisymmetric (m=0) ring

M51 (WHIRLPOOL)

- Spiral magnetic fields with pitch angles ~ 20°: parallel to the gas spiral arms, rather than to circular stellar orbits.

presentation by R. Beck (2010)
based on Fig. 1b
in Fletcher et al. (2011)
6cm data from VLA+Effelsberg
with HST background



M51

Fletcher et al. (2011)

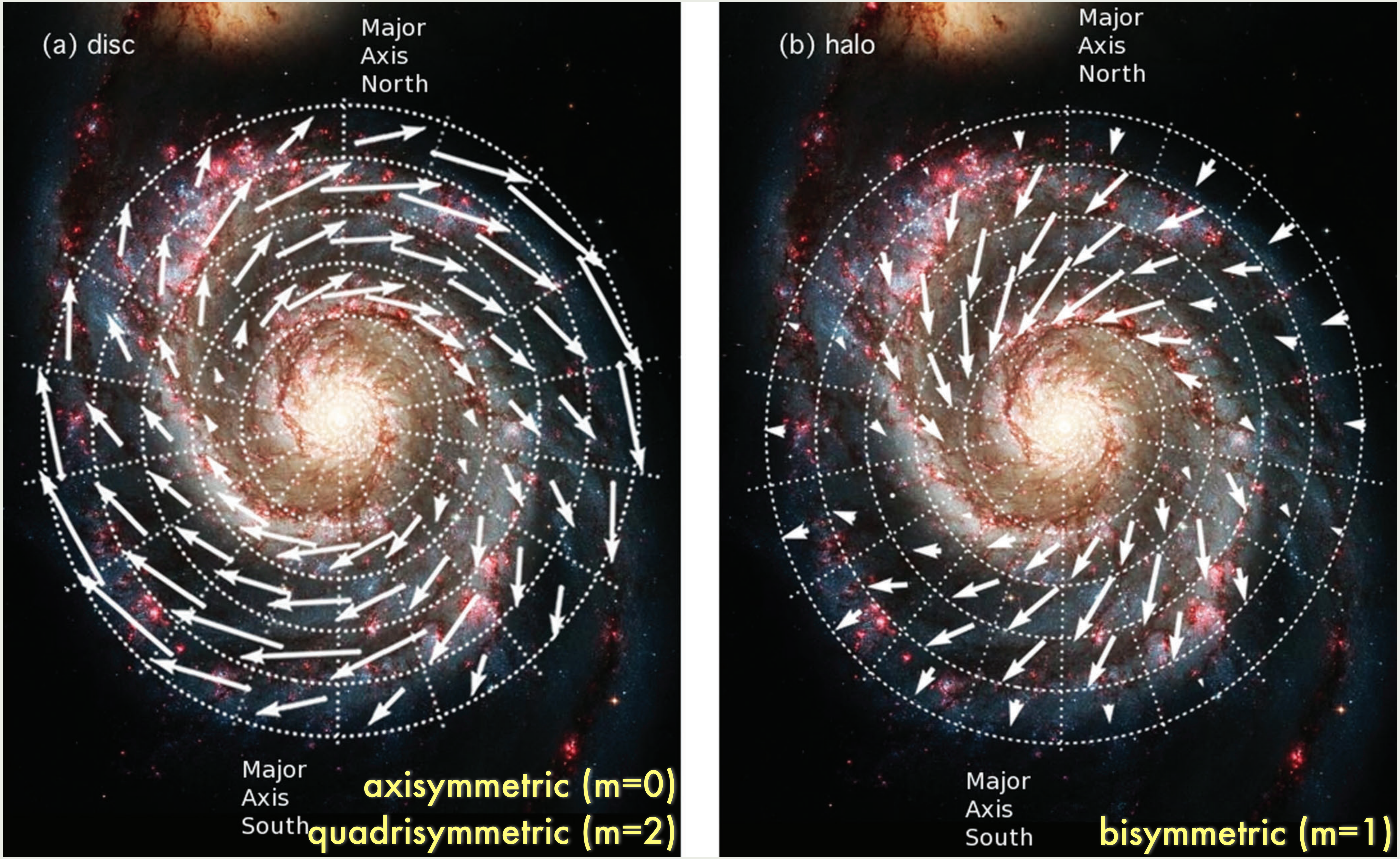
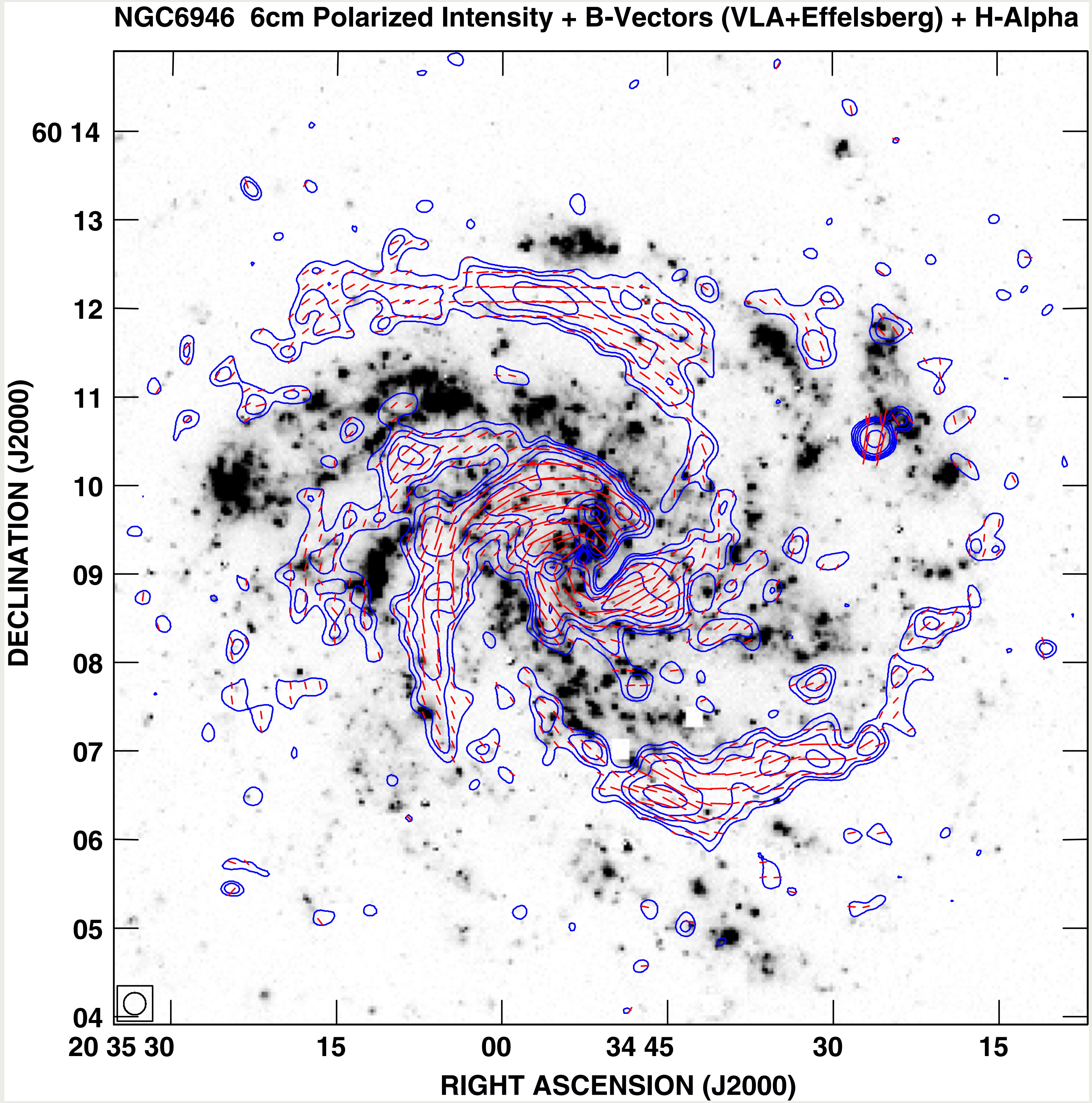


Figure 14. The regular magnetic field derived from fitting a model to the observed polarization angles at $\lambda\lambda\lambda\lambda 3$, 6, 18, 20 cm, with the length of the magnetic field vectors proportional to the field strength, overlaid on the same optical image as in Fig. 1. (a) The regular magnetic field in the galactic disc. (b) The regular magnetic field in the galactic halo. Ring boundaries are at 2.4, 3.6, 4.8, 6.0 and 7.2 kpc and all sectors have an opening angle of 20°. The major axis is indicated: the mid-points of these two sectors correspond to $\phi = 0°$ and 180°, respectively.

NGC 6946

- Magnetic field is often strongest between the optically bright spiral arms.



Beck (2015), Fig. 13
VLA+Effelsberg (6cm)
Hα background

PARKER INSTABILITY

- Parker (1966) considered the question what is confining the Galactic magnetic field.
  - Were it confined by the Galactic bulge, it would have to increase towards the center at least like R^{-2}, becoming much too strong dynamically.
  - He concluded that the field must be confined to the Galactic disk.

- Parker instability means that magnetic fields are buoyantly unstable, they try to escape confinement, do not mix well with the gas.

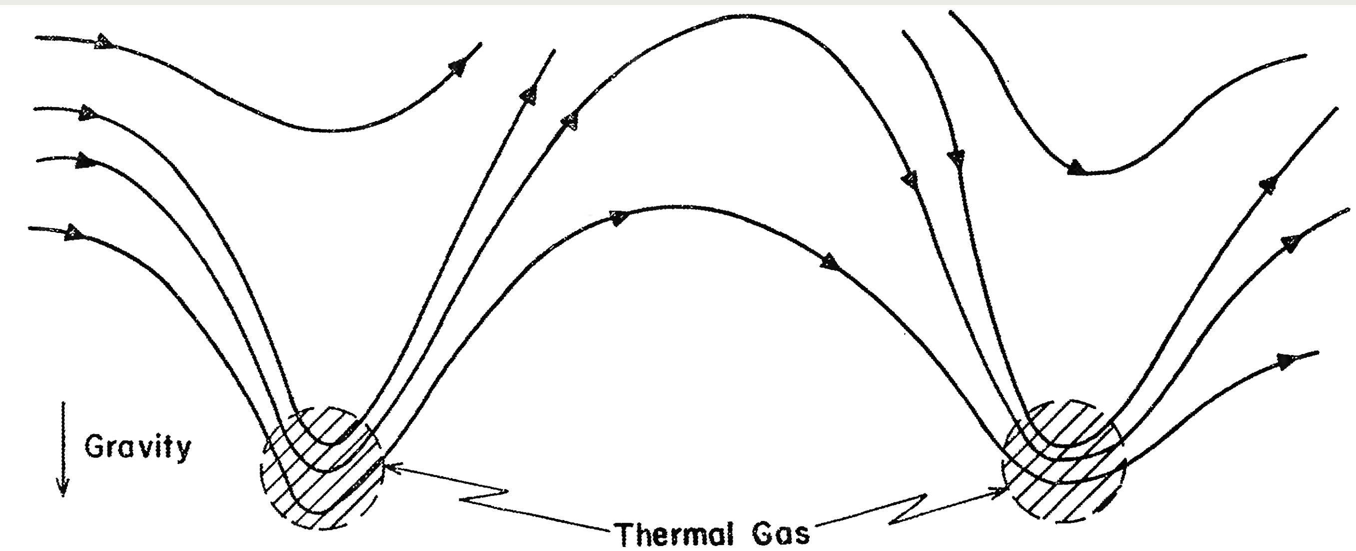


FIG 2.—Sketch of the local state of the lines of force of the interstellar magnetic field and interstellar gas-cloud configuration resulting from the intrinsic instability of a large-scale field along the galactic disk or arm when confined by the weight of the gas.

X-SHAPED FIELDS IN EDGE-ON GALAXIES

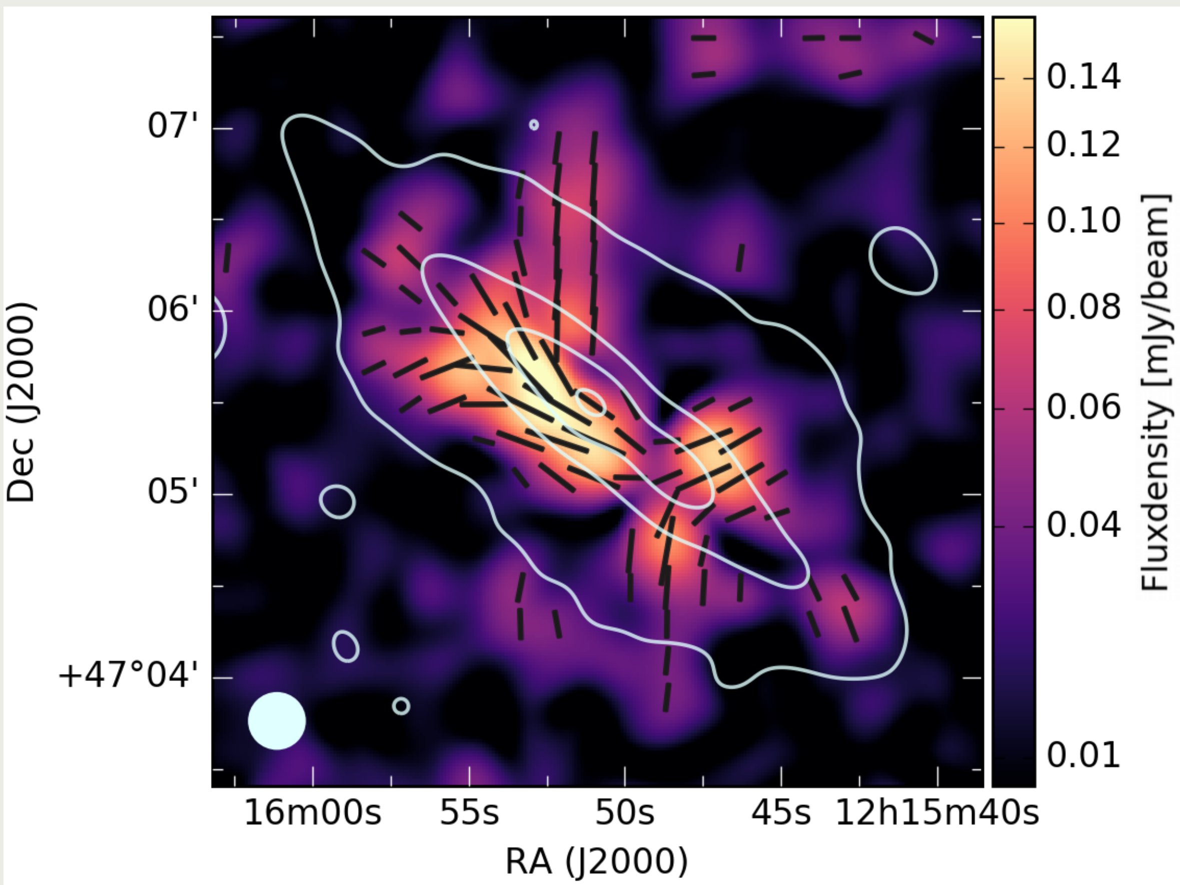


Fig. 14. Polarized intensity image of NGC 4217 from Stokes Q and U at C-band with a σ of 13.5 μJy beam^{-1}. The robust parameter of clean was set to two, smoothed to a resulting beam size of $18'' \times 18''$, shown in the bottom left. Total intensity (Fig. 1 smoothed to $18''$) contours at 3, 120, 360, 690σ levels with a σ of 7.0 μJy beam^{-1}. The apparent magnetic field orientations, not corrected for Faraday rotation, are shown in black and clipped below 3σ.

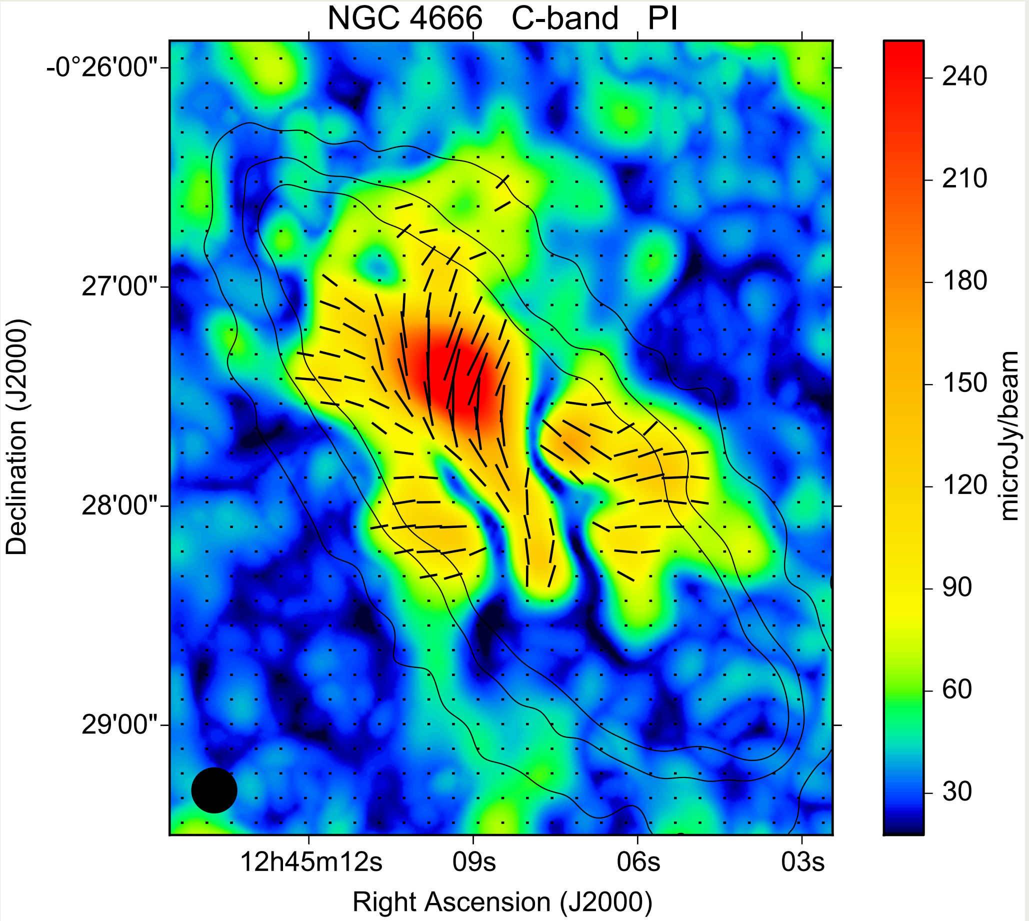
CHANG-ES survey on JVLA

C-band: 6 GHz

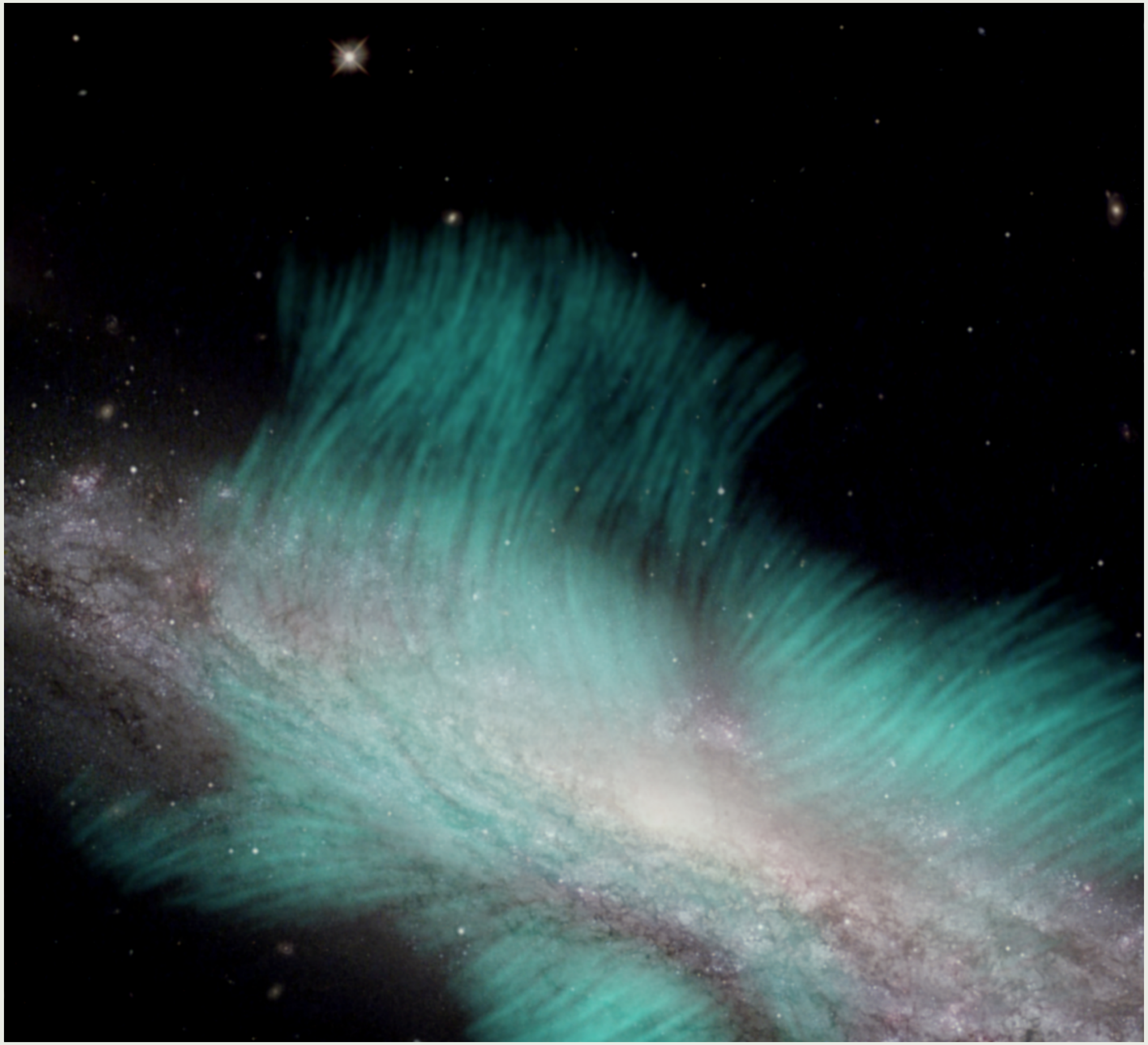
Stein et al. (2020)

Fig. 13. NGC 4217 magnetic field orientations represented by flow lines in green on optical SDSS image as well as the Hα image of Rand (1996). The magnetic field flow lines are produced from the same data as shown in Fig. 14.

NGC 4666

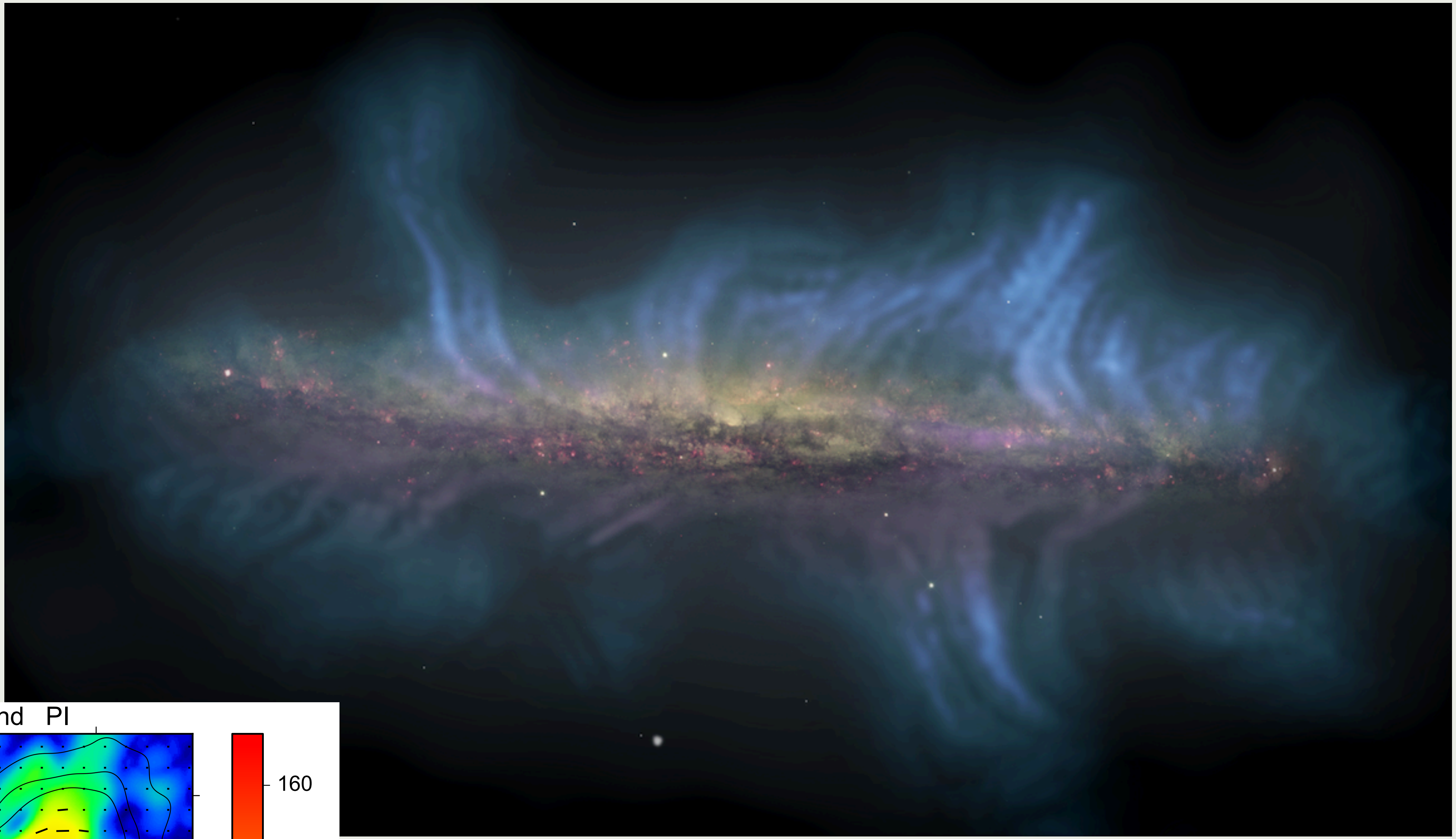


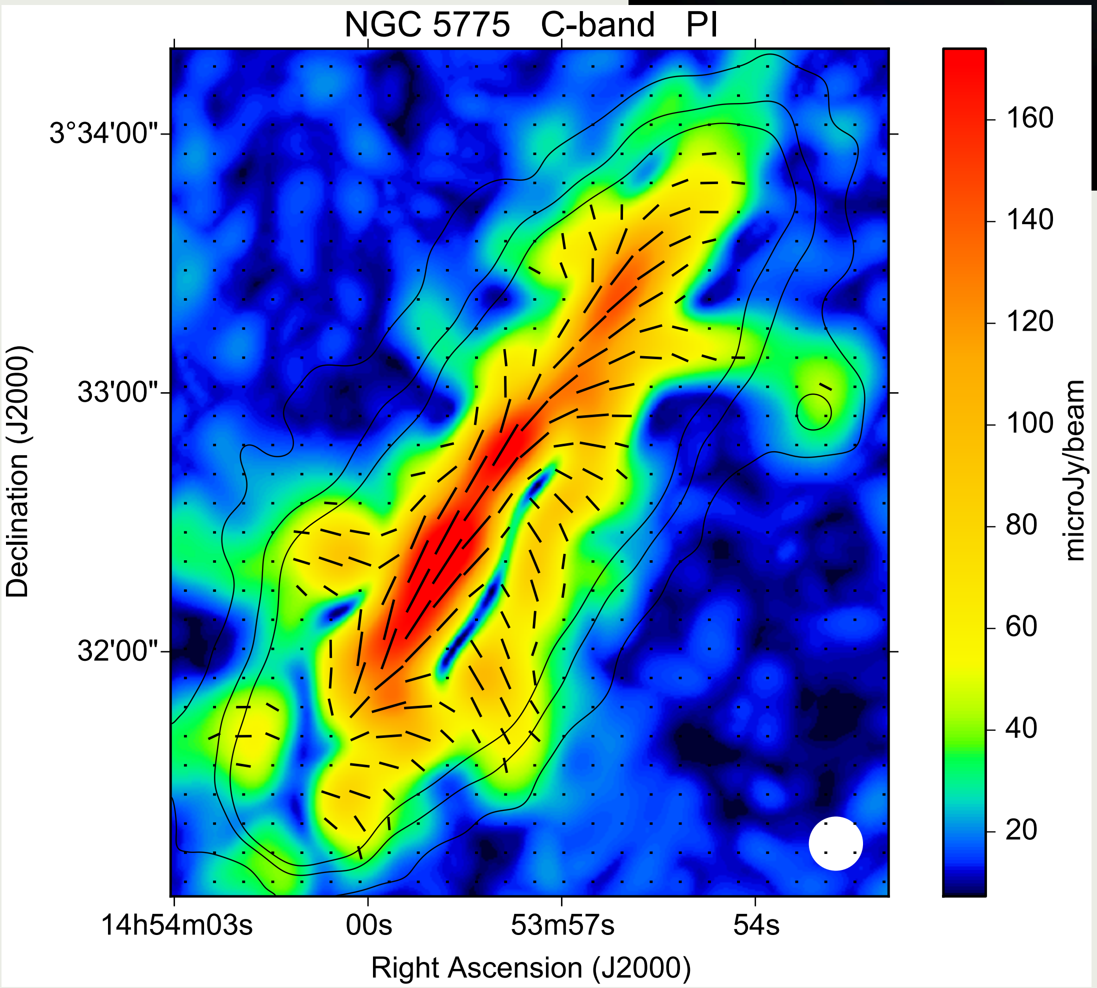
Krause et al. (2020)
Fig. A.19
CHANG-ES survey on JVLA



Composite image by Yelena Stein of the Centre de Données astronomiques de Strasbourg (CDS), support by J. English (University of Manitoba). VLA radio data from Yelena Stein and Ralf-Juergen Dettmar (Ruhr-University Bochum). The observations are part of the project Continuum HAlos in Nearby Galaxies — an EVLA Survey (CHANG-ES) led by Judith Irwin (Queen's University, Canada). The optical data are from the Hubble Space Telescope (HST) Wide Field Camera 3 (WFC3)/UVIS camera. The ionized hydrogen data (magenta) are from the 1.5m telescope of the Cerro Tololo Inter-American Observatory, collected by Matthew D. Lehnert. The software code for tracing the magnetic field lines was adapted by Y. Stein and Arpad Miskolczi (Ruhr-University Bochum) from the scipy Linear Integral Convolution code (https://scipy-cookbook.readthedocs.io/items/LineIntegralConvolution.html). The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

NGC 5775



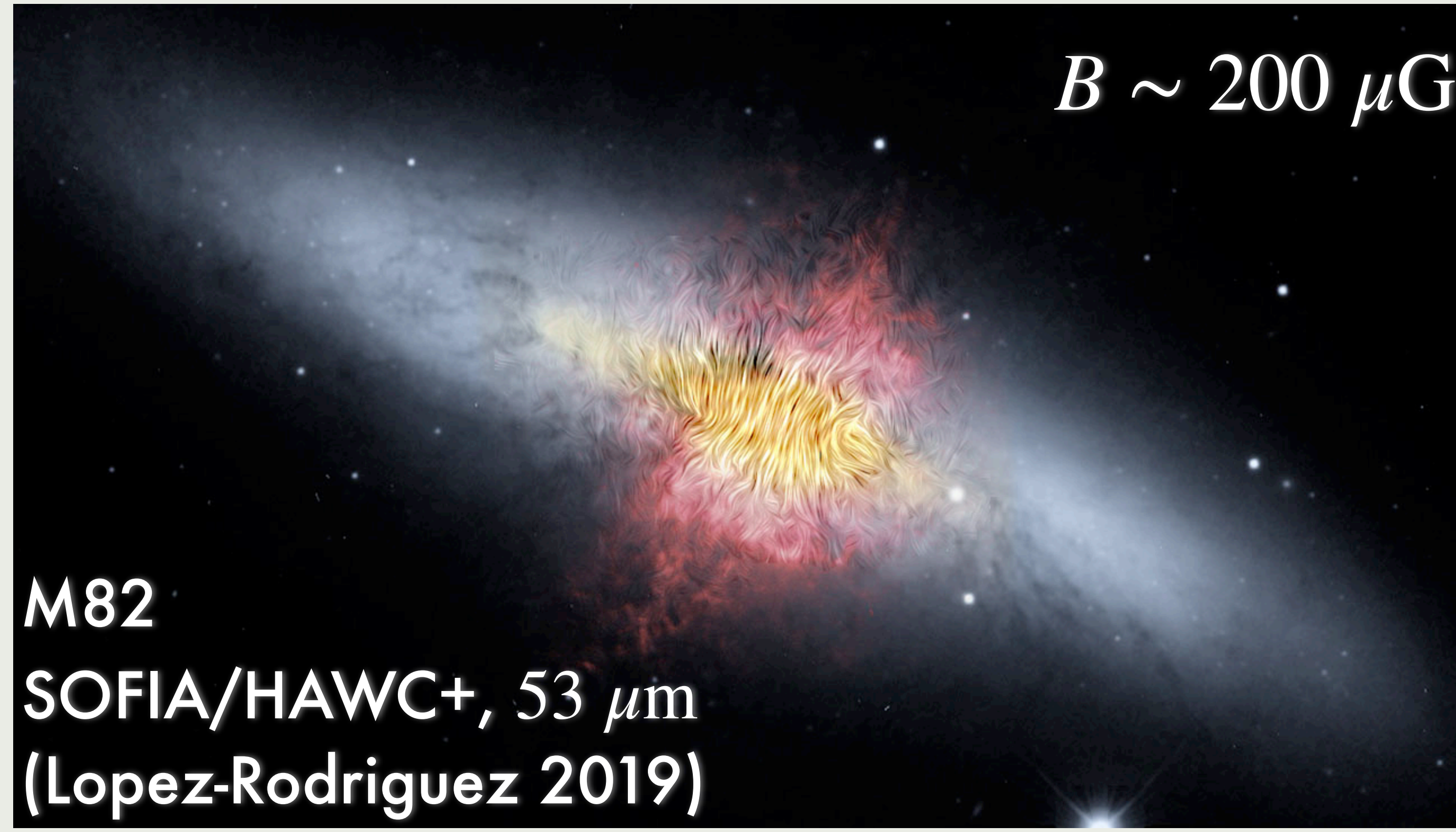


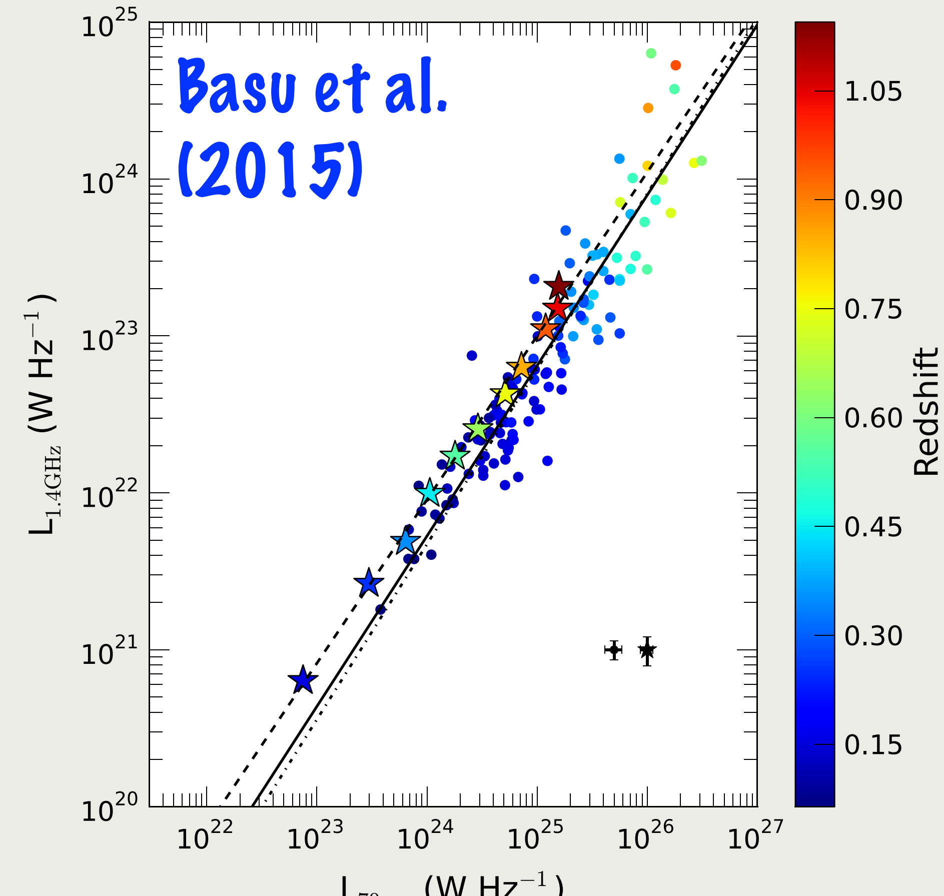
Composite image by Jayanne English (University of Manitoba). NRAO VLA data processed by Yelena Stein (CDS) for the Continuum HAlos in Nearby Galaxies — an EVLA Survey (CHANG-ES) led by Judith Irwin (Queen's University, Canada). The optical data are from the Hubble Space Telescope (HST) Wide Field Camera 3 (WFC3). The software code for tracing the magnetic field lines was adapted by Y. Stein, J. English and Arpad Miskolczi (Ruhr-University Bochum) from the scipy Line Integral Convolution code (https://scipy- cookbook.readthedocs.io/items/LineIntegralConvolution.html).

Krause et al. (2020)
Fig. A.20
CHANG-ES survey on JVLA

OTHER GALAXIES

- **Starburst galaxies**: high star formation rate and stronger magnetic fields
- **Young/distant galaxies**: radio luminosity well correlated with the far-IR luminosity tracing the star formation rate up to $z \simeq 1.2$
- **Inactive ellipticals**: radio quiet

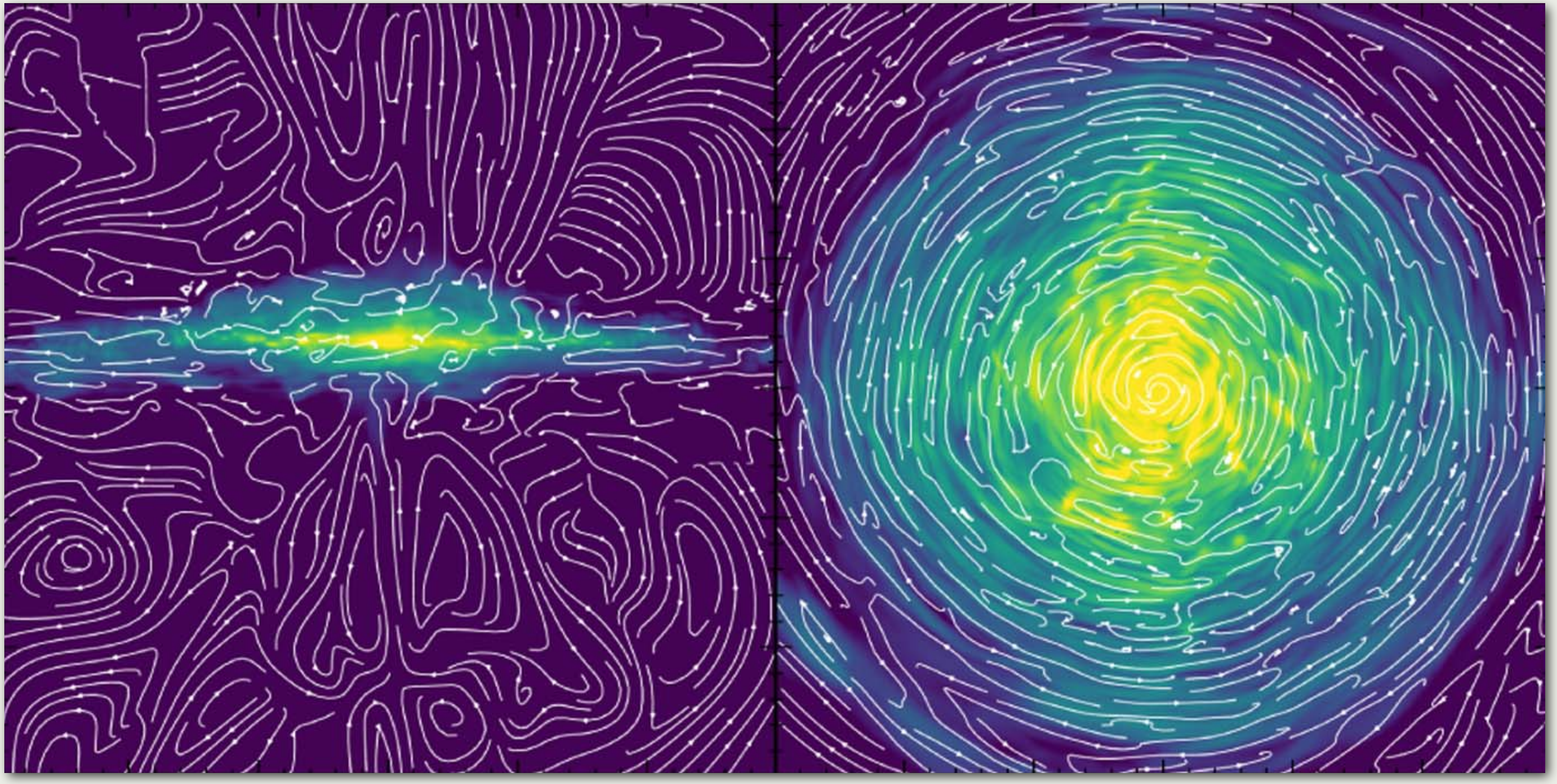




GALACTIC MAGNETIC FIELDS: SEEDED BY SUPERNOVAE?

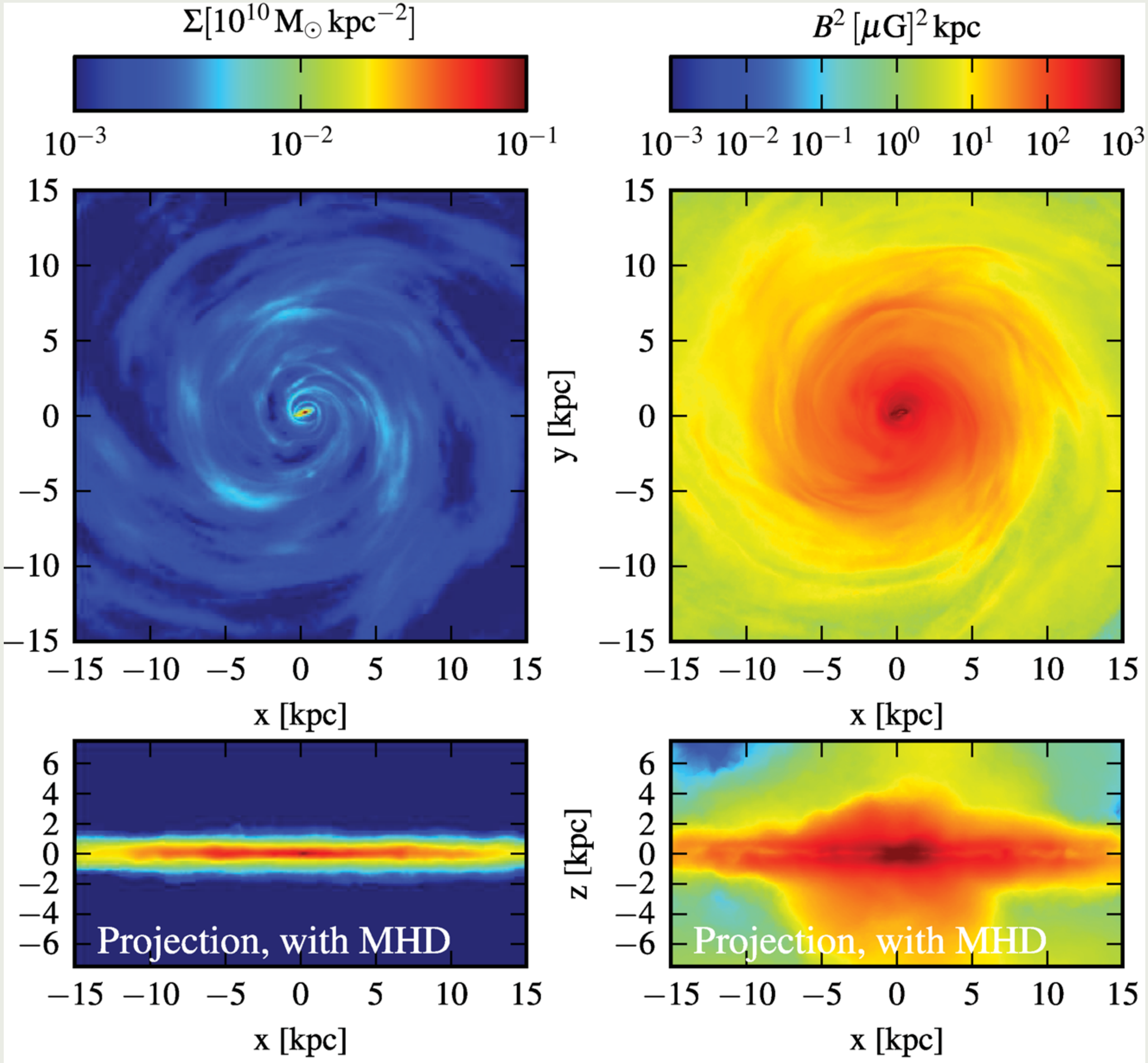
- The turbulent kinetic energy in the interstellar medium (ISM) of our Galaxy corresponds to $\sim$ 5000 supernovae.

- Supernova remnants (SNR) produce strong shocks that dominate the production of PeV cosmic rays, they also amplify magnetic fields.



Butsky et al. (2017)

MAGNETOROTATIONAL INSTABILITY



- Quadrupolar (plane-symmetric) magnetic fields for in-plane galaxies may be signatures of MRI (Kitchatinov & Rüdiger 2004).

Pakmor & Springel (2013)

SUMMARY

- Spiral galaxies (like the Milky Way, but even young galaxies) have regular magnetic fields of typical strength $B \sim 10\,\mu$G.
- The fields often form magnetic spiral arms between (and parallel to) the gas spiral arms.
- In edge-on galaxies, the magnetic field shows plane-symmetric quadrupolar structure.
- Galactic magnetic fields require an efficient dynamo with turbulent motions seeded by supernovae and MRI.