

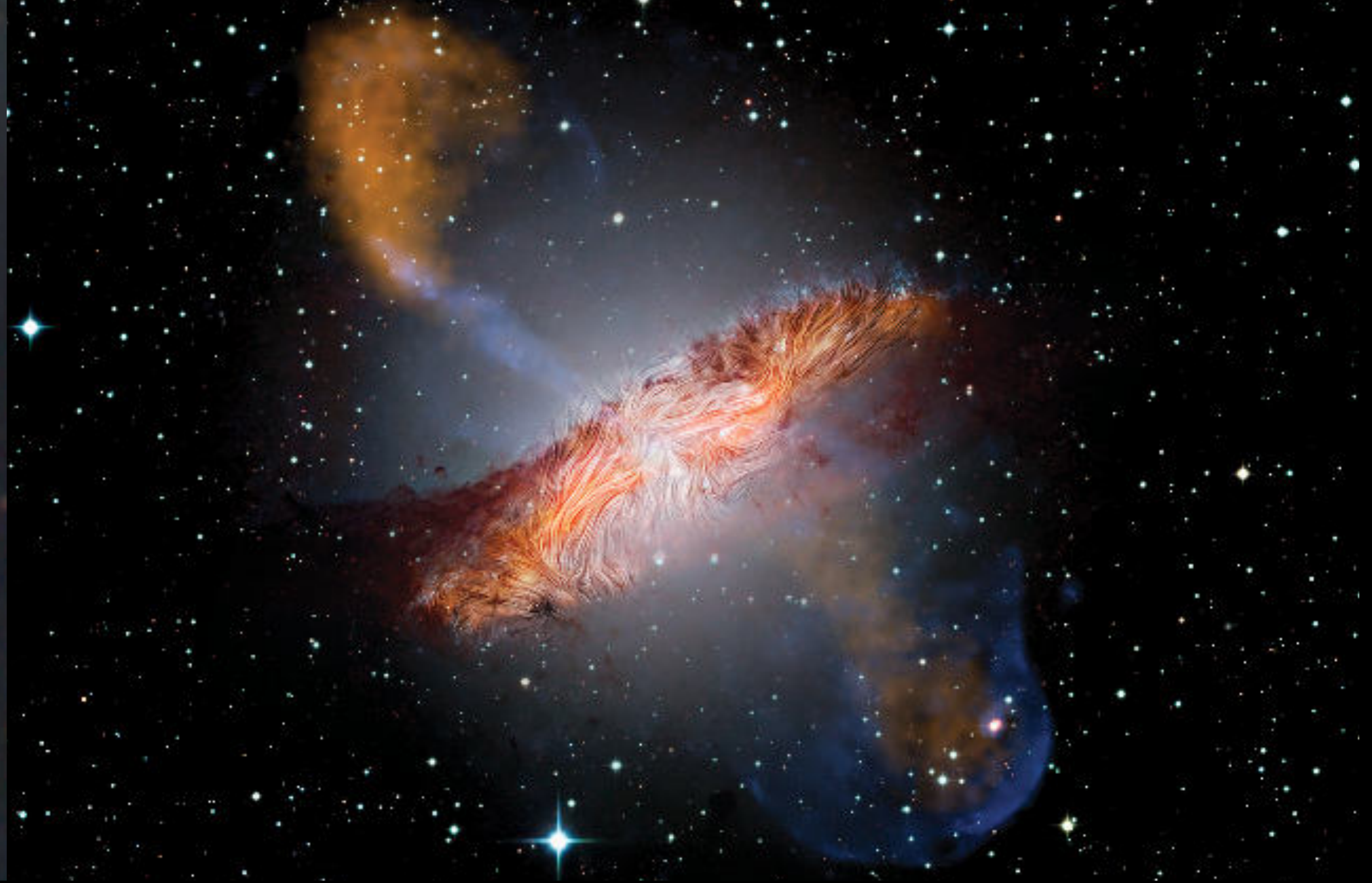

# First-year results of SALSA: Survey of extragALactic magnetiSm with SOFIA

Enrique Lopez-Rodriguez
Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)
Stanford University



# LEGACY TEAM

| Team Member | Affiliation |
|---|---|
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| **Sui Ann Mao (co-PI)** | **Max Planck For Radio Astronomy at Bonn, Germany** |
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| Susan Clark | Stanford University, USA |
| Daniel Dale | University of Wyoming, USA |
| Ignacio del Moral Castro | Instituto de Astrofisica de canarias, Spain |
| Tanio Diaz-Santos | University of Crete, Greece |
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| Doyal A. Harper | University of Chicago, USA |
| Annie Hughes | IRAP, Toulouse, France |
| Pamela Marcum | NASA Ames Research Center, USA |

| Team Member | Affiliation |
|---|---|
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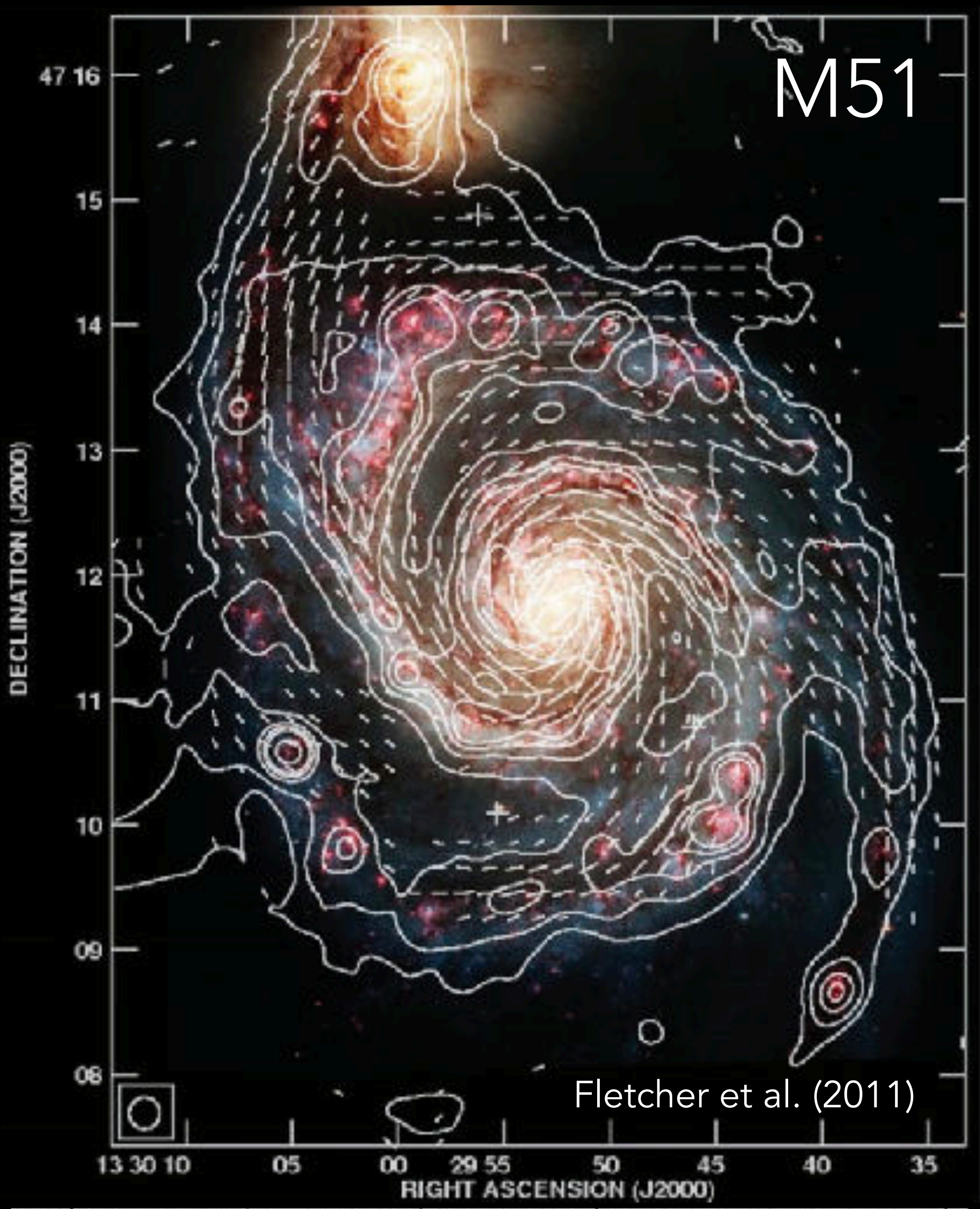
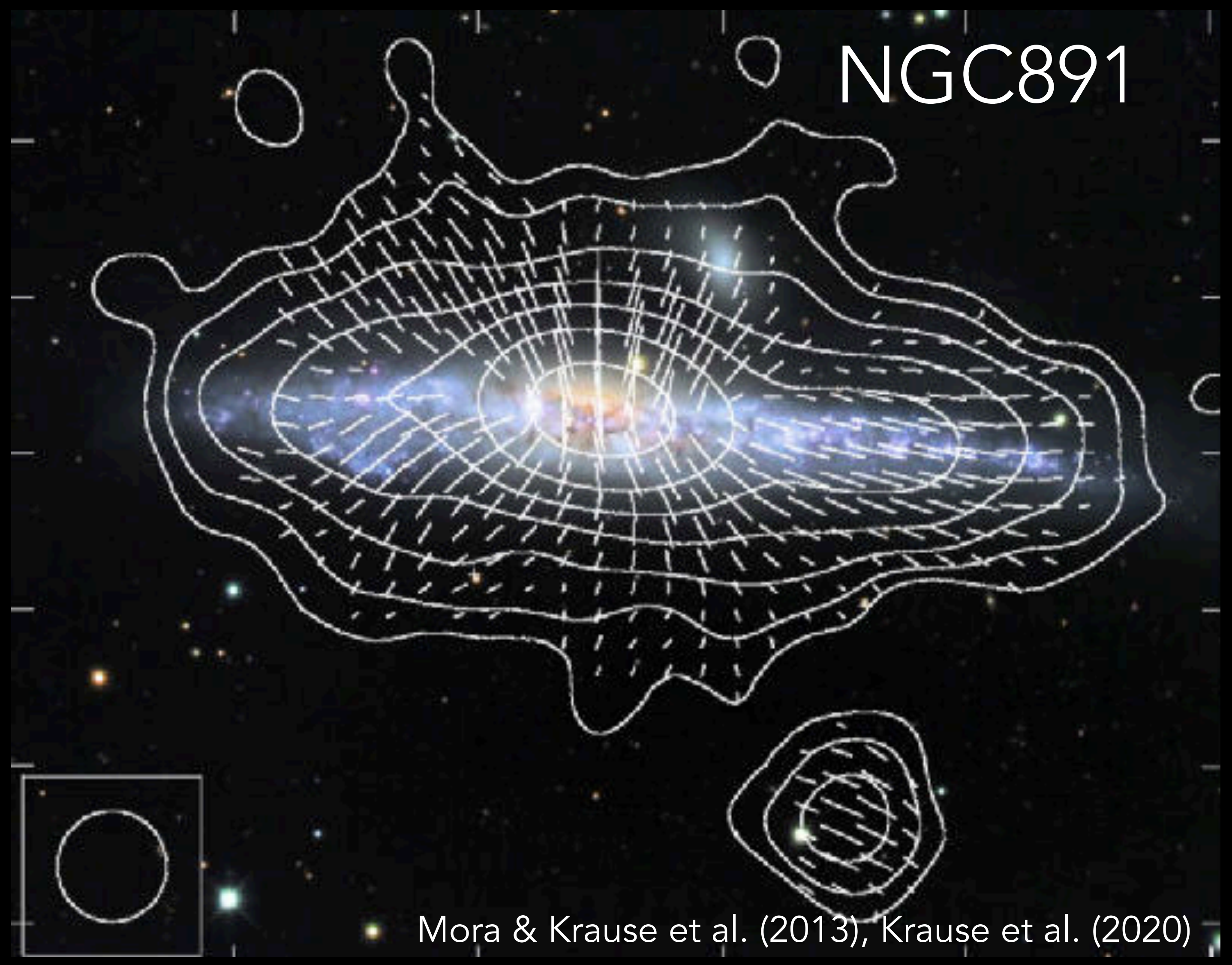
| Evangelia Ntormousi | University of Crete, Greece |
| Gina Panopoulou | CalTech, USA |
| William T. Reach | SOFIA Science Center, NASA Ames, USA |
| Julia Roman-Duval | Space Telescope Science Institute, USA |
| Alejandro Serrano Borlaff | NASA Ames, USA |
| Kandaswamy Subramanian | Inter-University Centre for Astronomy and Astrophysics, India |
| Mehronoosh Tahani | KIPAC/Stanford |
| Konstantinos Tassis | University of Crete, Greece |
| Ngoc Tram Le | SOFIA Science Center, NASA Ames, USA |
| Ellen Zweibel | University of Winsconsin, USA |

# OUR CURRENT KNOWLEDGE BASED ON RADIO POLARIMETRIC OBSERVATIONS

<u>Spiral galaxies</u>

- Highly polarized in the interarm regions of the galaxy.
- Contribution of ordered and turbulent fields along the spiral arms.
- Late-type galaxies had enough time for the galactic dynamo to take place and order the large-scale B-fields.



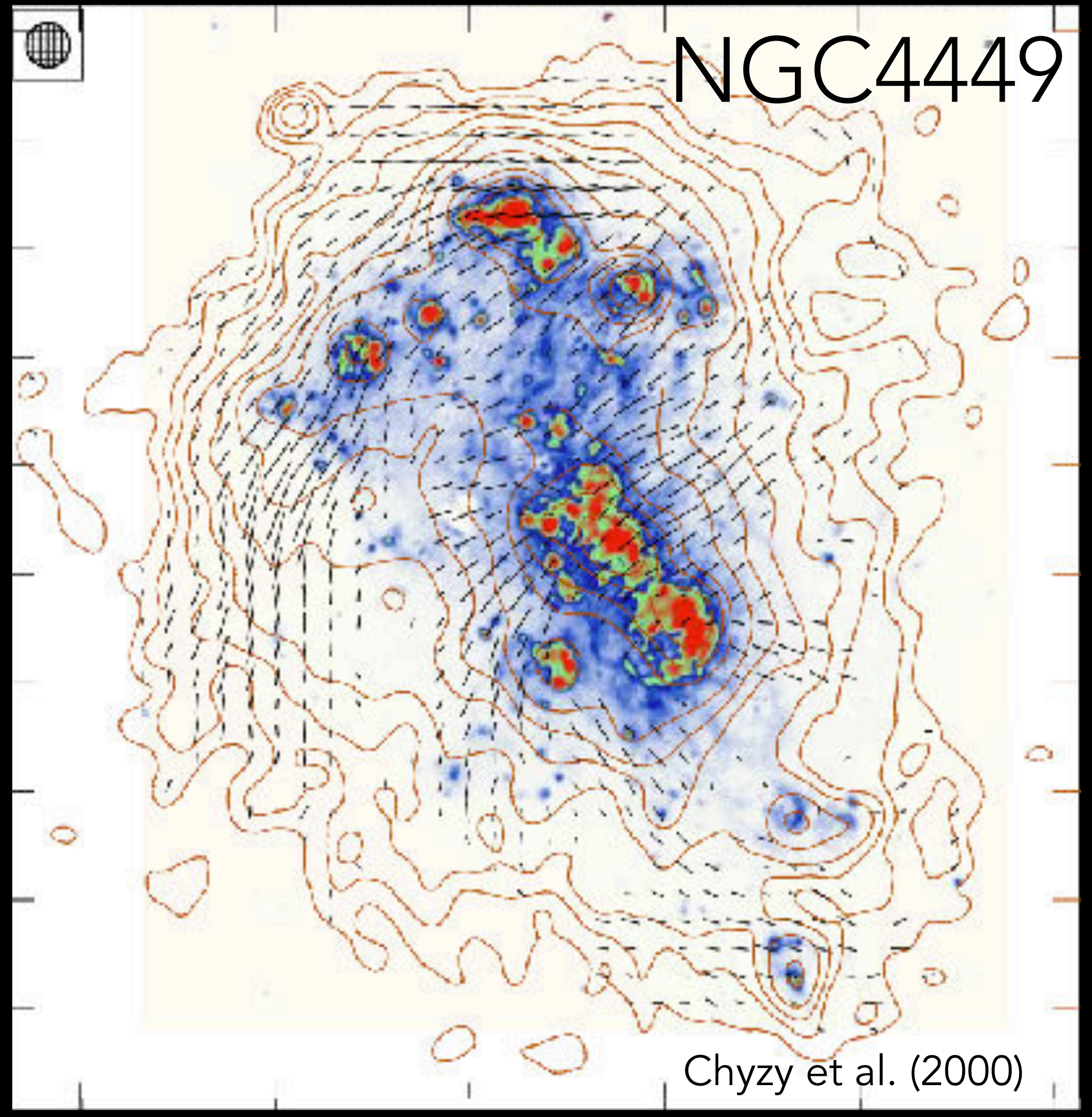



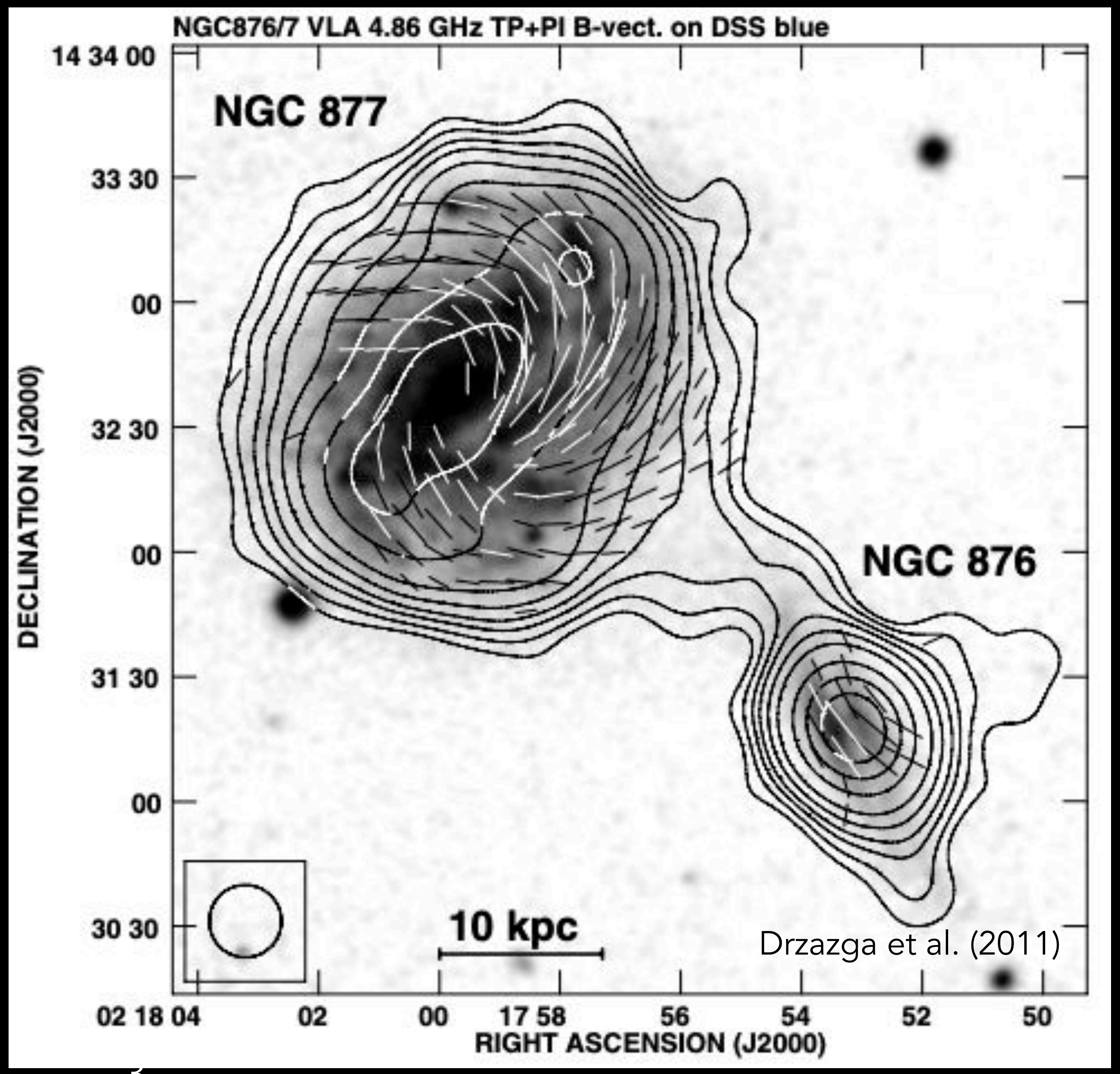

<u>Edge-on galaxies</u>

- X-shape structure is an underlined feature of spiral galaxies and extends several kpc into the halo.

<u>Irregular galaxies</u>

- Slowly rotating galaxies may reveal strong total magnetic fields.
- Partially ordered/regular field, spiral pattern, and radial pattern.
- $\alpha - \Omega$ may be operating.




<u>Interacting galaxies</u>

- B-fields become aligned along the compression front or perpendicular to the velocity gradients.
- Gas flows, due to merger, make turbulent fields highly anisotropic.
- Average B-field strength is stronger than normal galaxies, but the mean P is low, implying tangled B-fields.

Beck et al. (2015, 2019)

## Stellar and gas distribution as a function of cosmic time

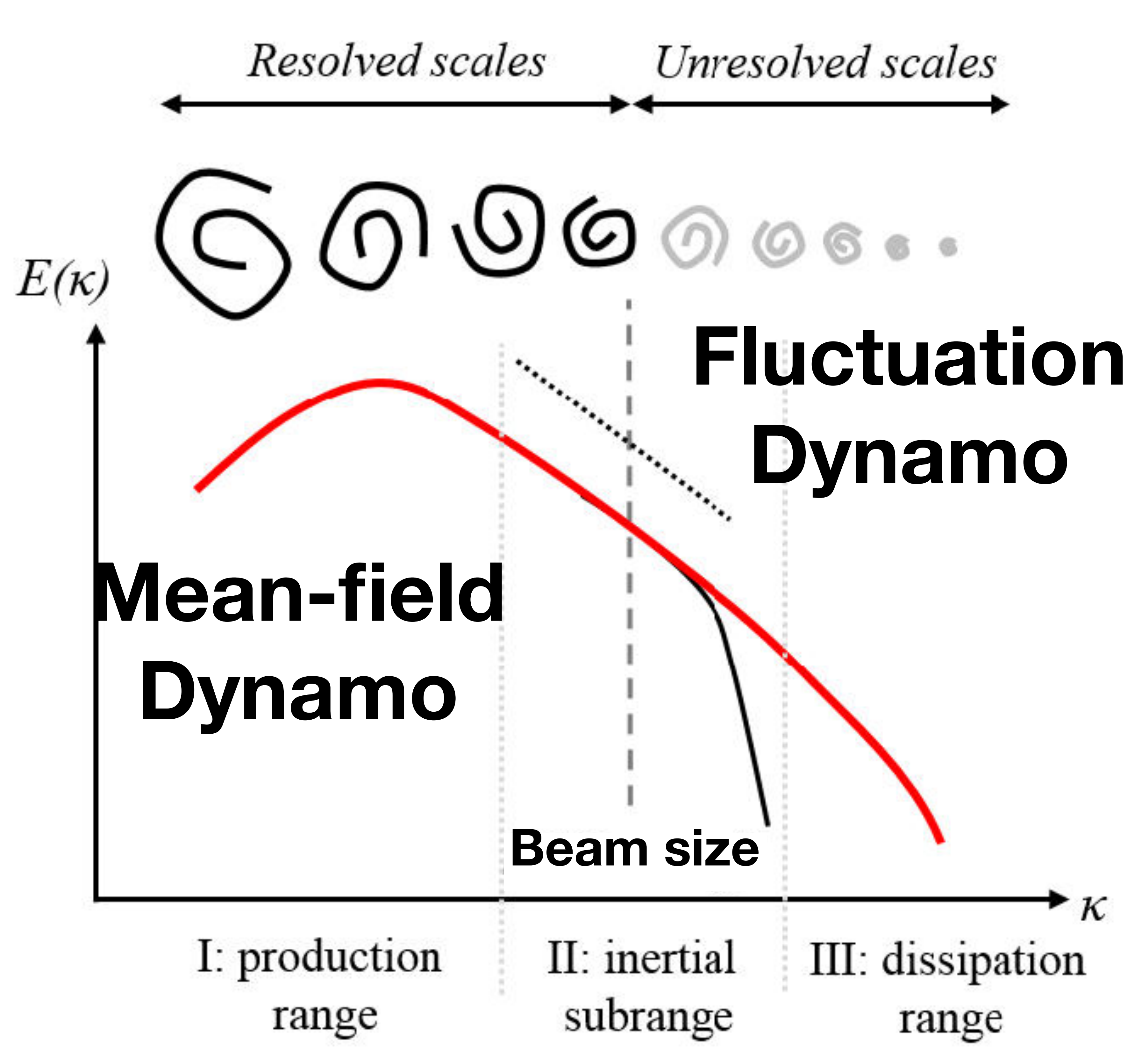

Martin-Alvarez et al. (2022: Pandora Proje

# Stellar and Magnetic Field distribution as a function of cosmic time

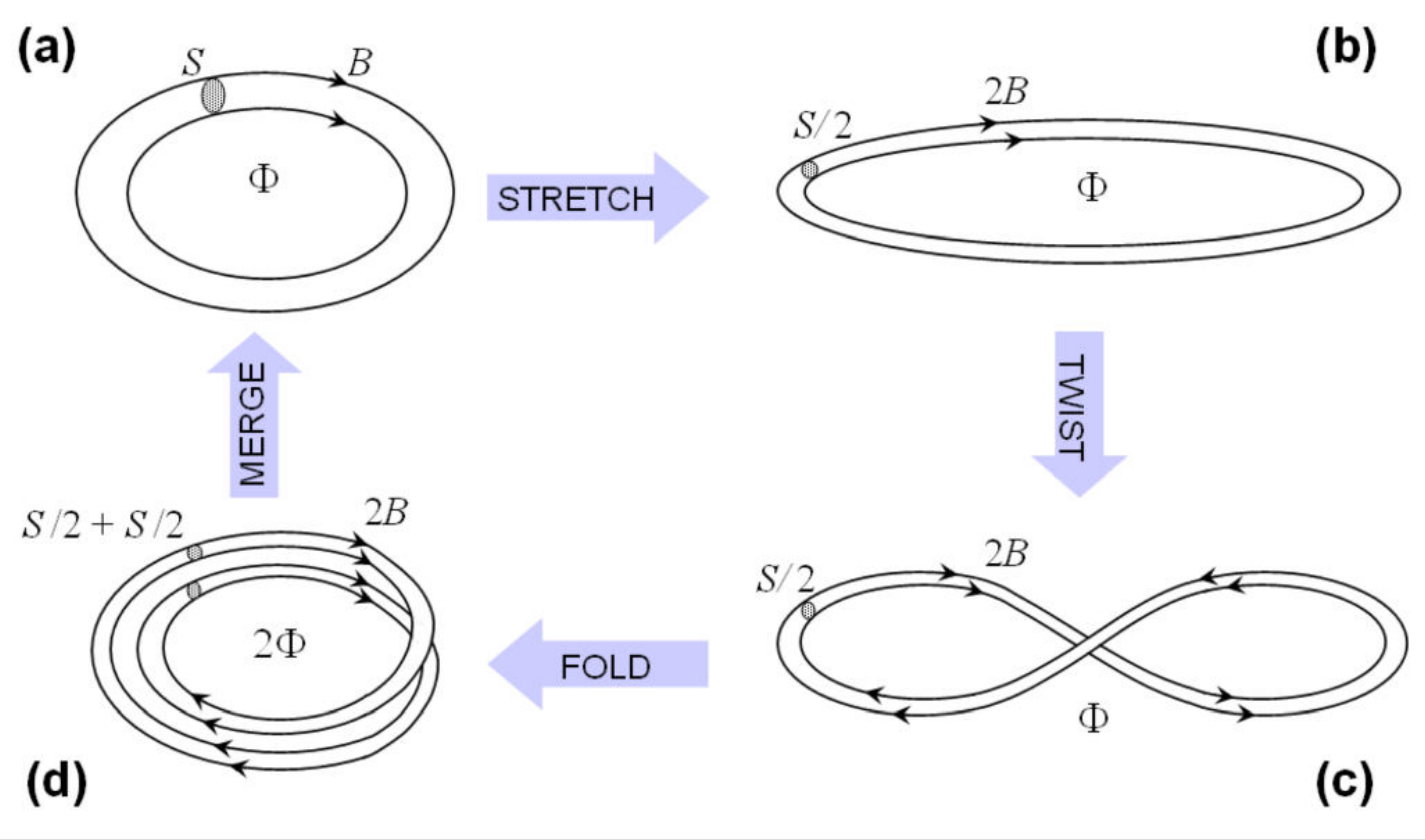
Martin-Alvarez et al. (2022: Pandora Project I)

# GALACTIC FLUCTUATION DYNAMOS

Turbulent cascade
(Dissipation)




B-field amplification
(electromagnetic induction)




Turbulent coherent length of ~50-100 pc driven by SN explosions in spiral galaxies
(e.g. Haverkorn 2008, Brandenburg & Subramanian 2005)

# OPEN QUESTIONS

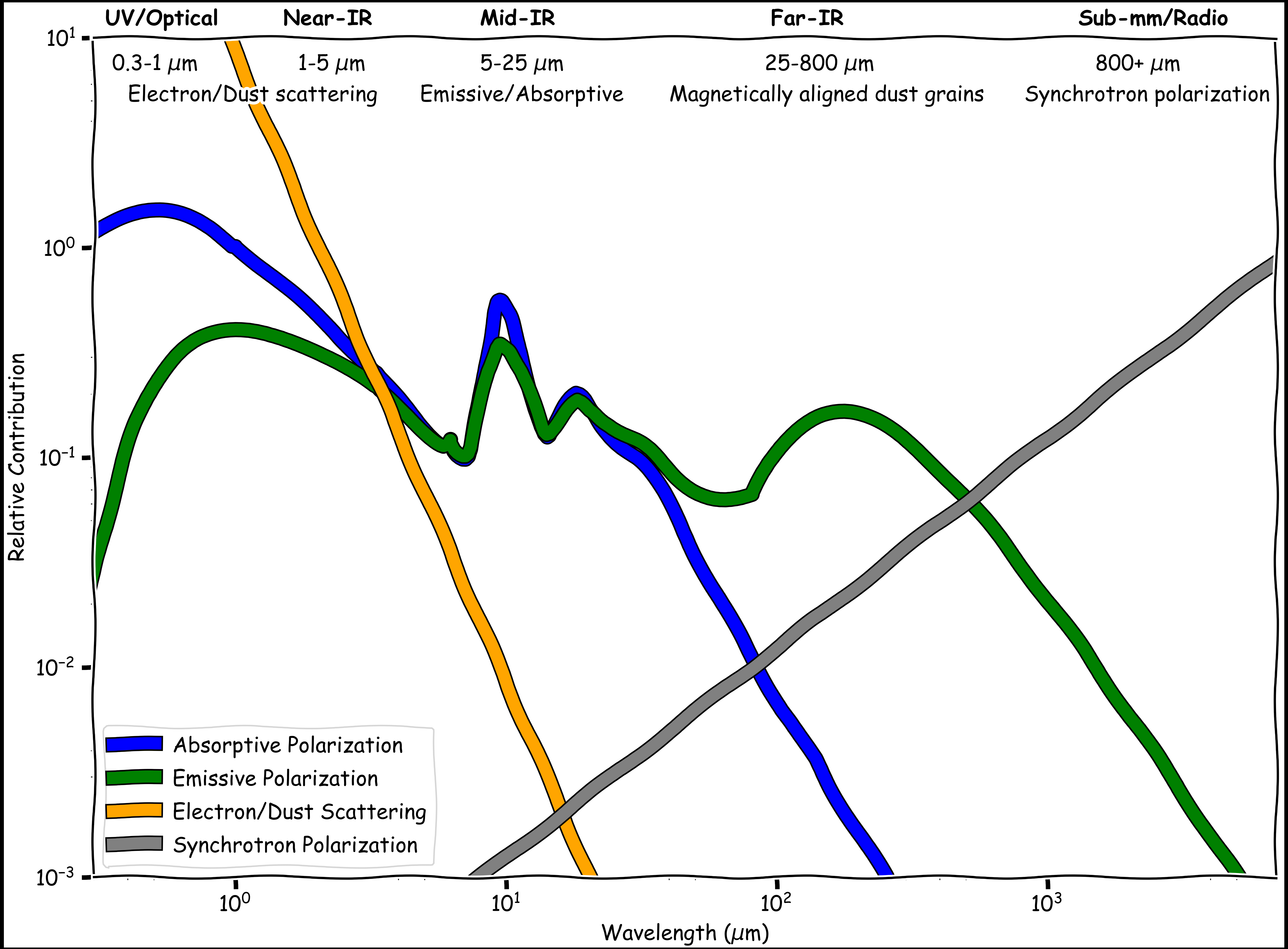
- How did the evolution of galaxies in mergers affect magnetic fields?

- Is the circumgalactic medium magnetized?

- How has the magnetic field been amplified by interaction/SF in galaxies?

- How can the fluctuation dynamo be traced?

# POLARIZATION MECHANISMS



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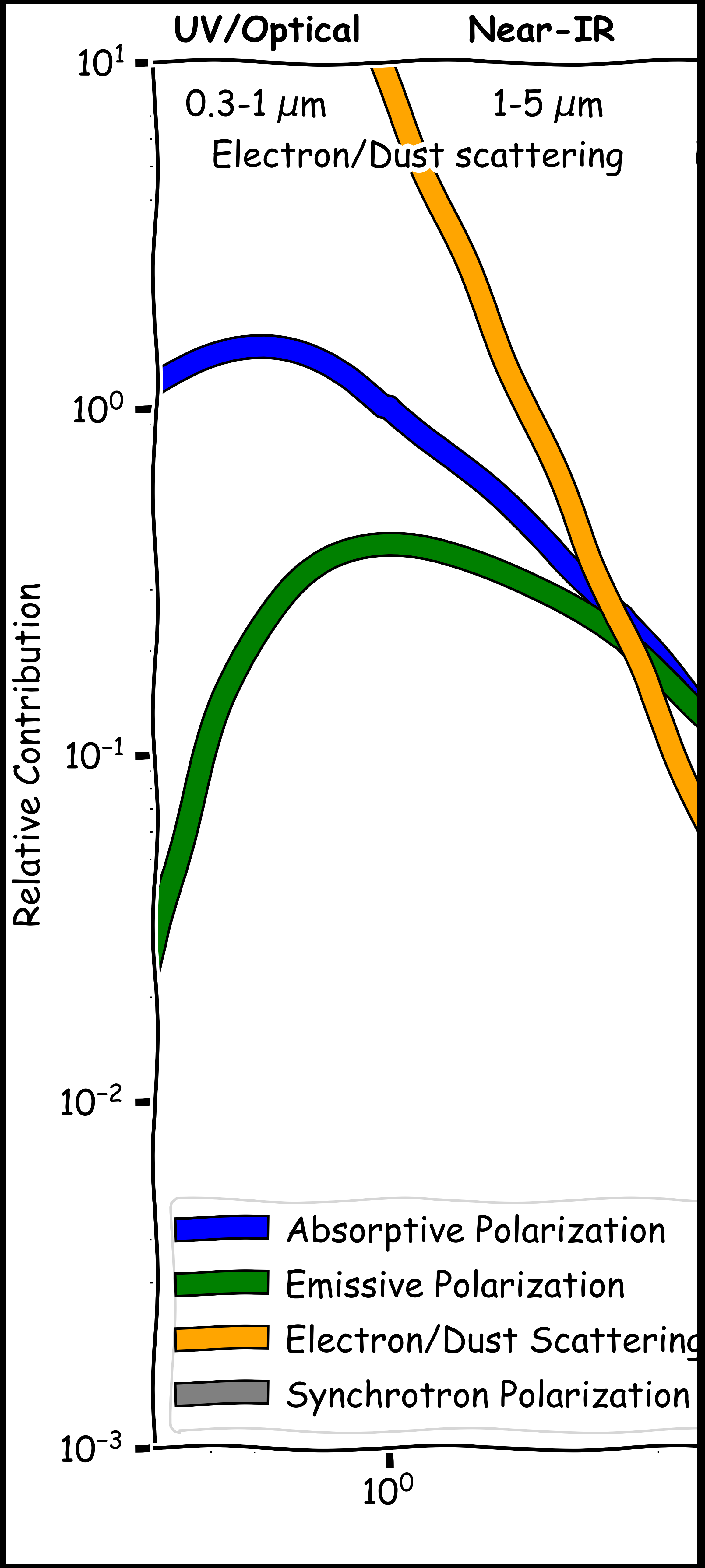
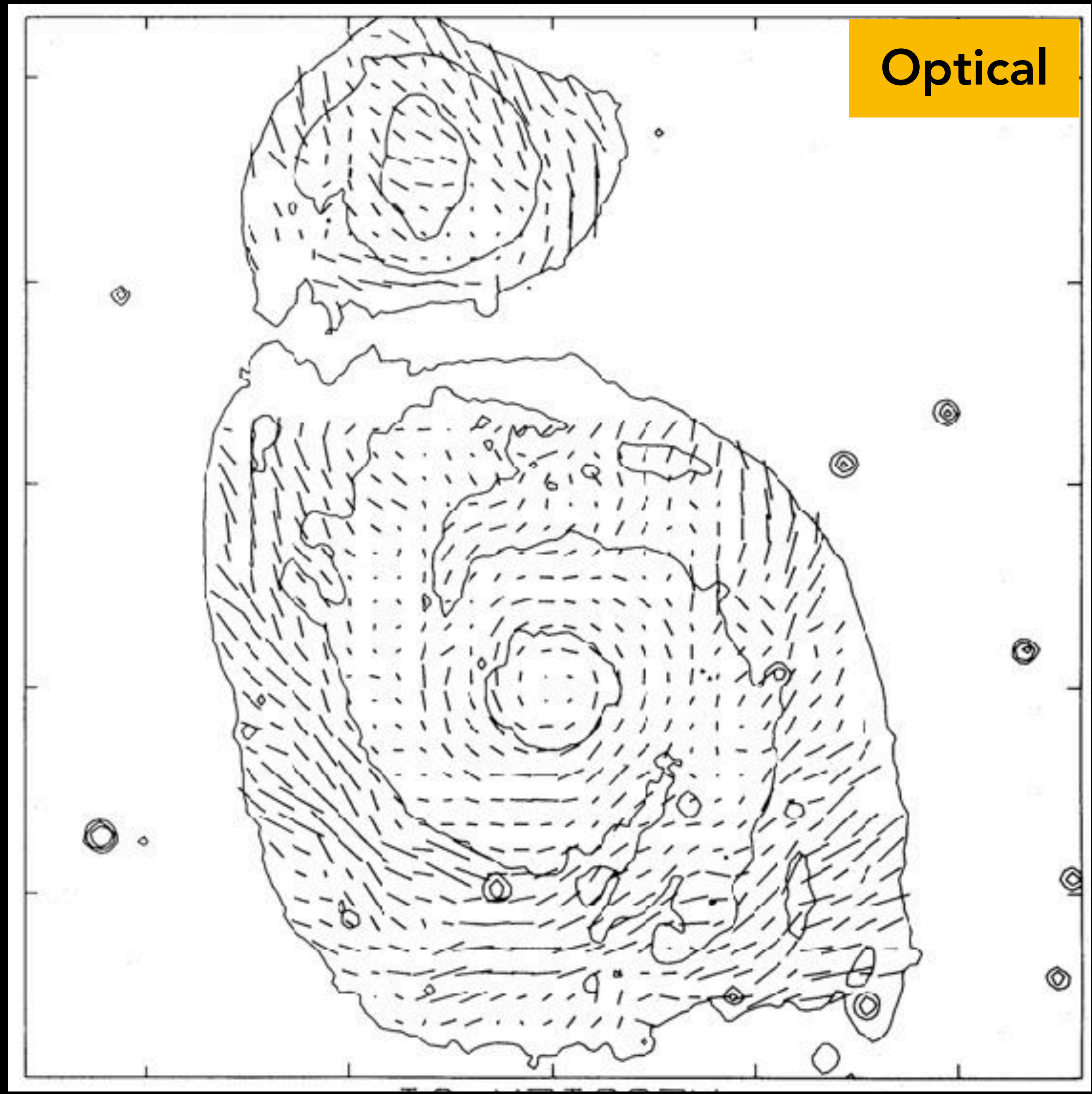
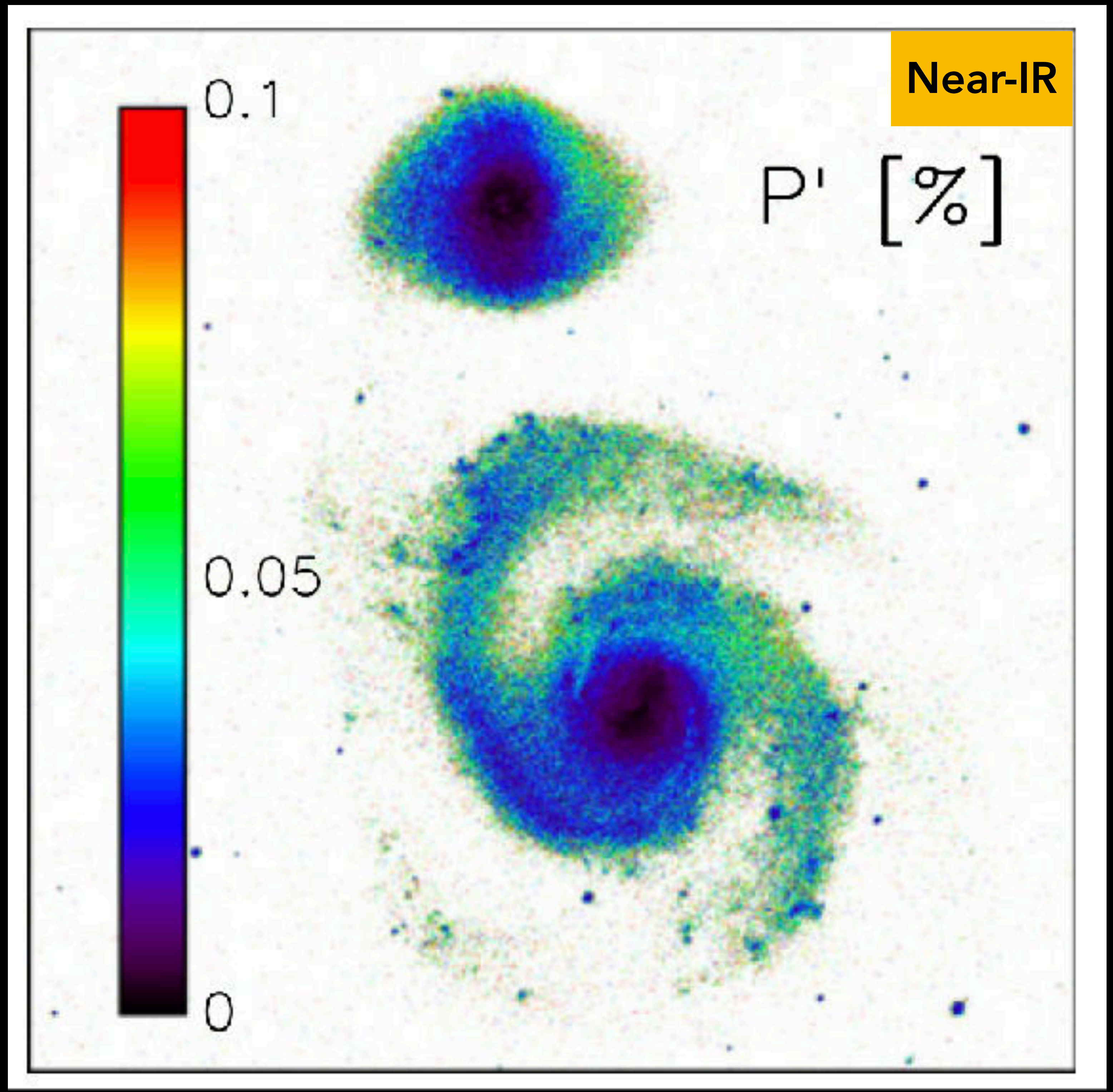


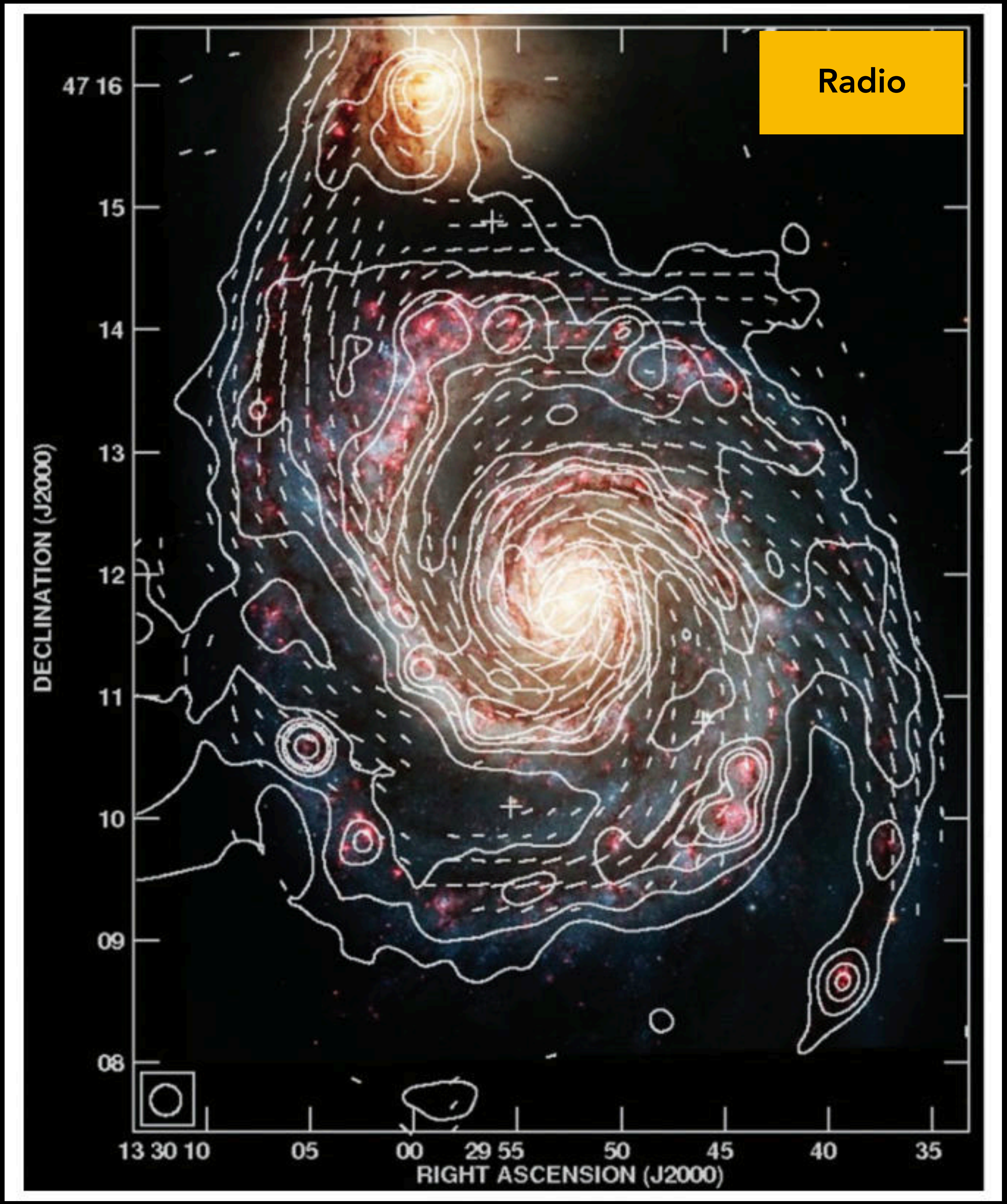




Scarrot, Ward-Thompson & Warren-Smith (1987)

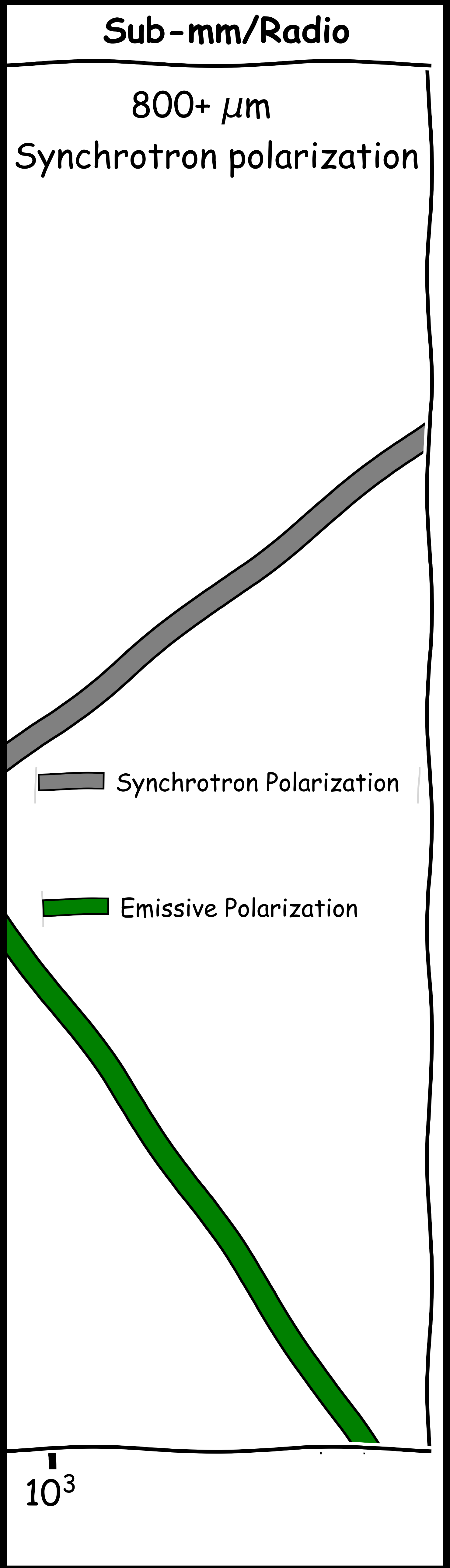



Pavel & Clemens (2012)

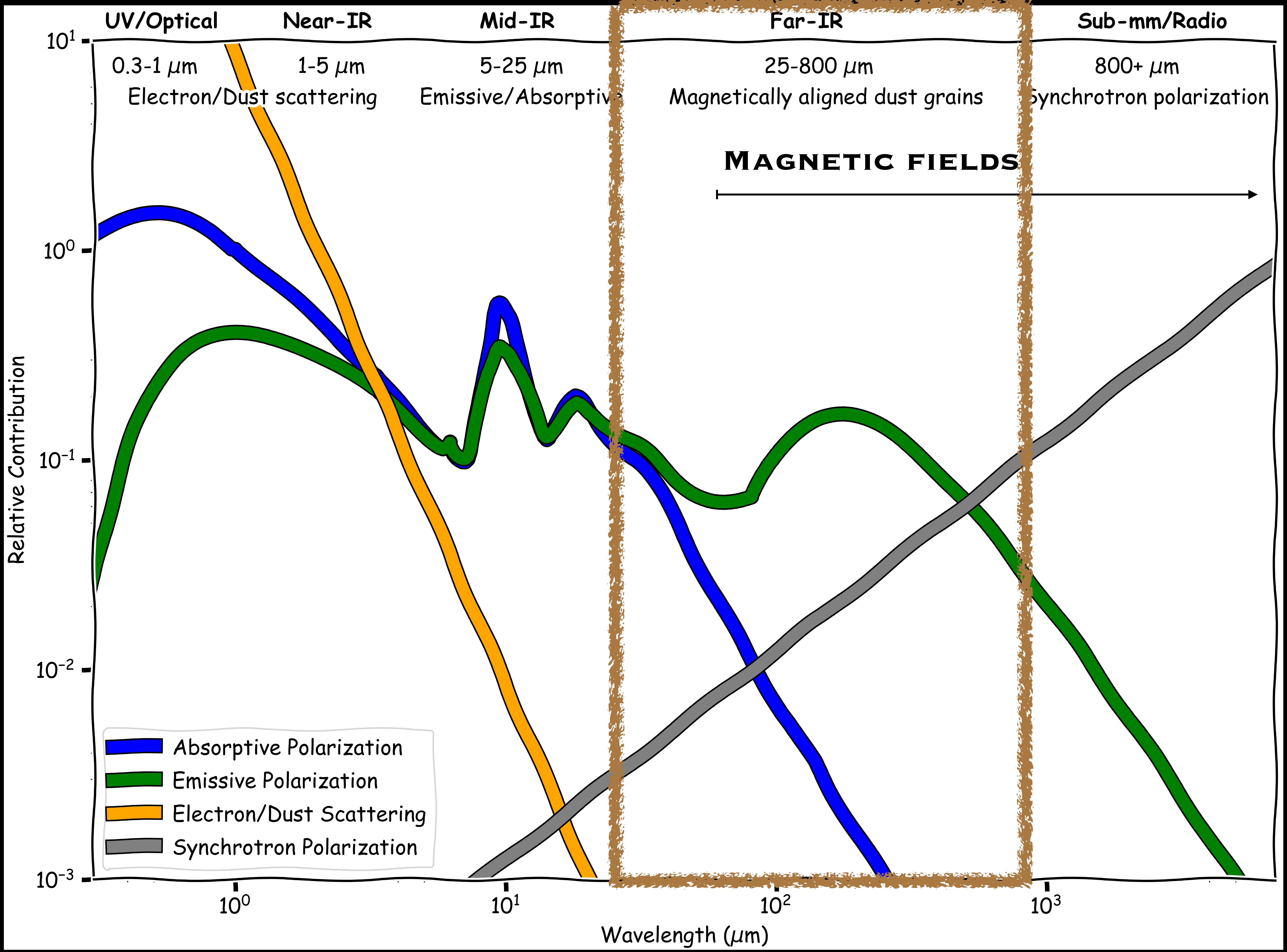
# POLARIZATION MECHANISMS




Fletcher et al. (2011)



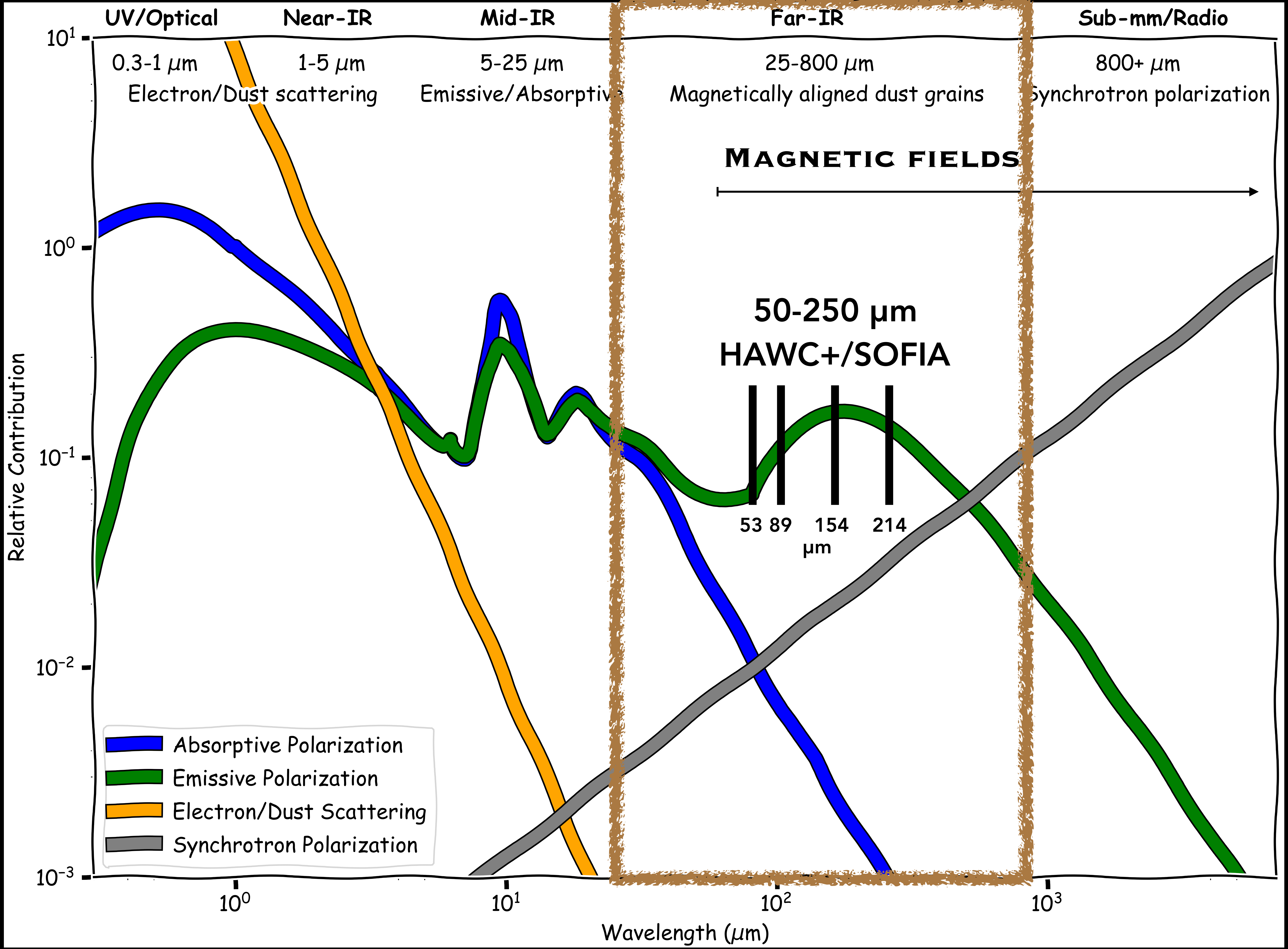
# OUR APPROACH: MAGNETICALLY ALIGNED DUST GRAINS



# MAGNETICALLY ALIGNED DUST GRAINS


Andersson et al. (2015). Image: David Chuss

# OUR APPROACH: MAGNETICALLY ALIGNED DUST GRAINS



# SURVEY OF EXTRAGALACTIC MAGNETISM WITH SOFIA (SALSA)

GOAL:

First comprehensive study of the B-fields in the multi-phase ISM of nearby galaxies as a function of gas dynamics and galaxy types from hundred- to kpc-scale galactic environments.

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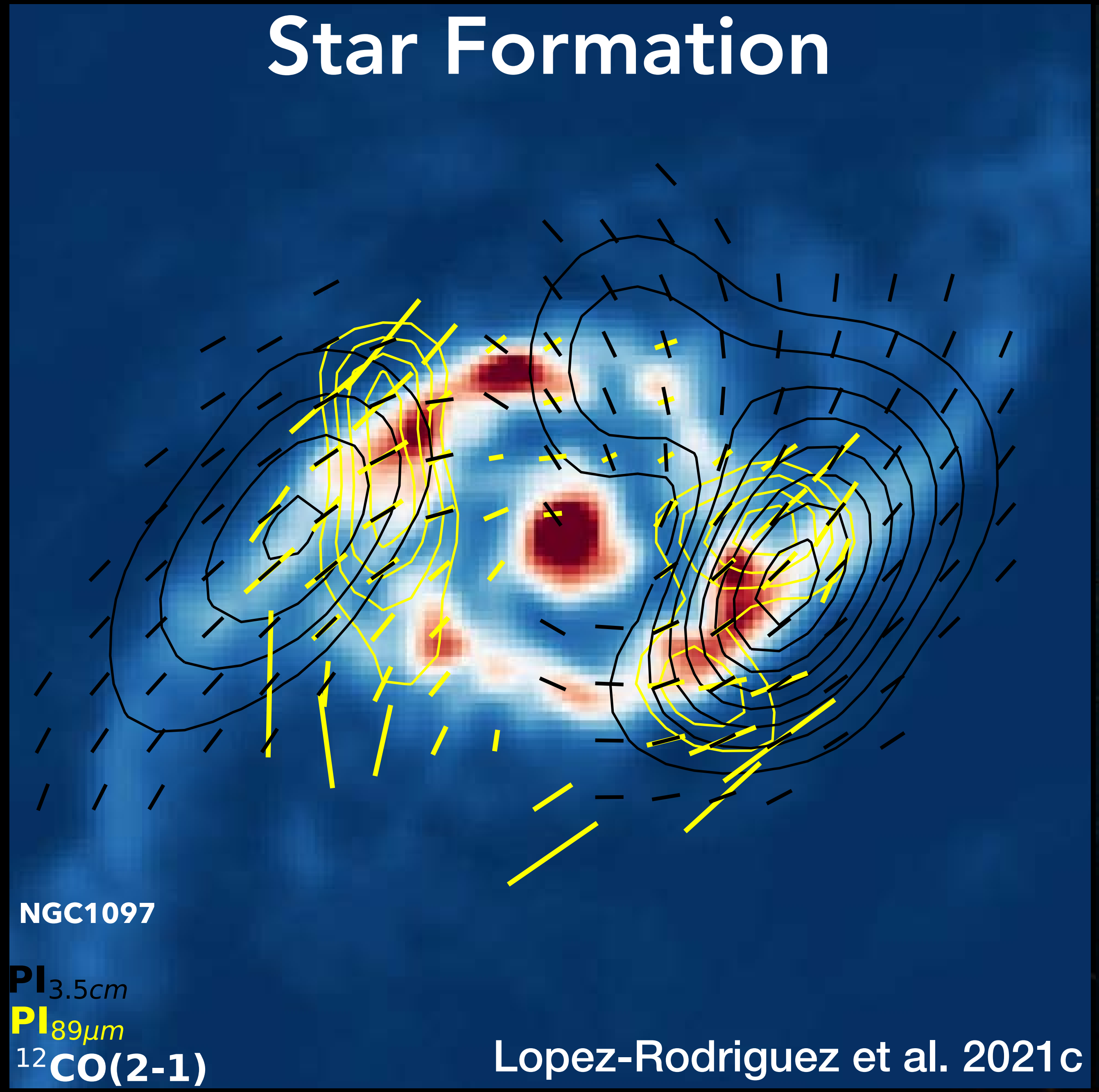
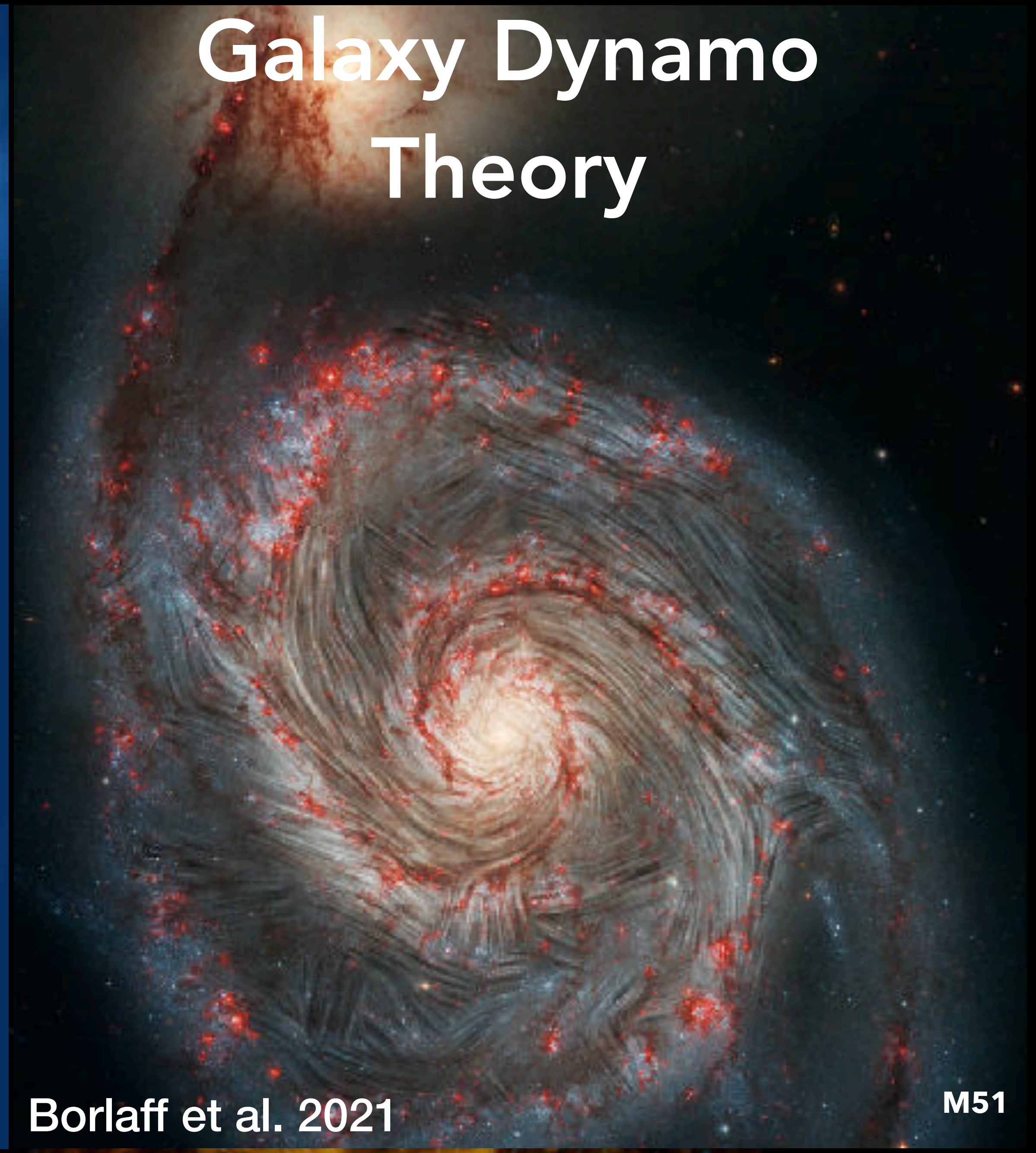
First comprehensive study of the B-fields in the multi-phase ISM of nearby galaxies as a function of gas dynamics and galaxy types from hundred- to kpc-scale galactic environments.

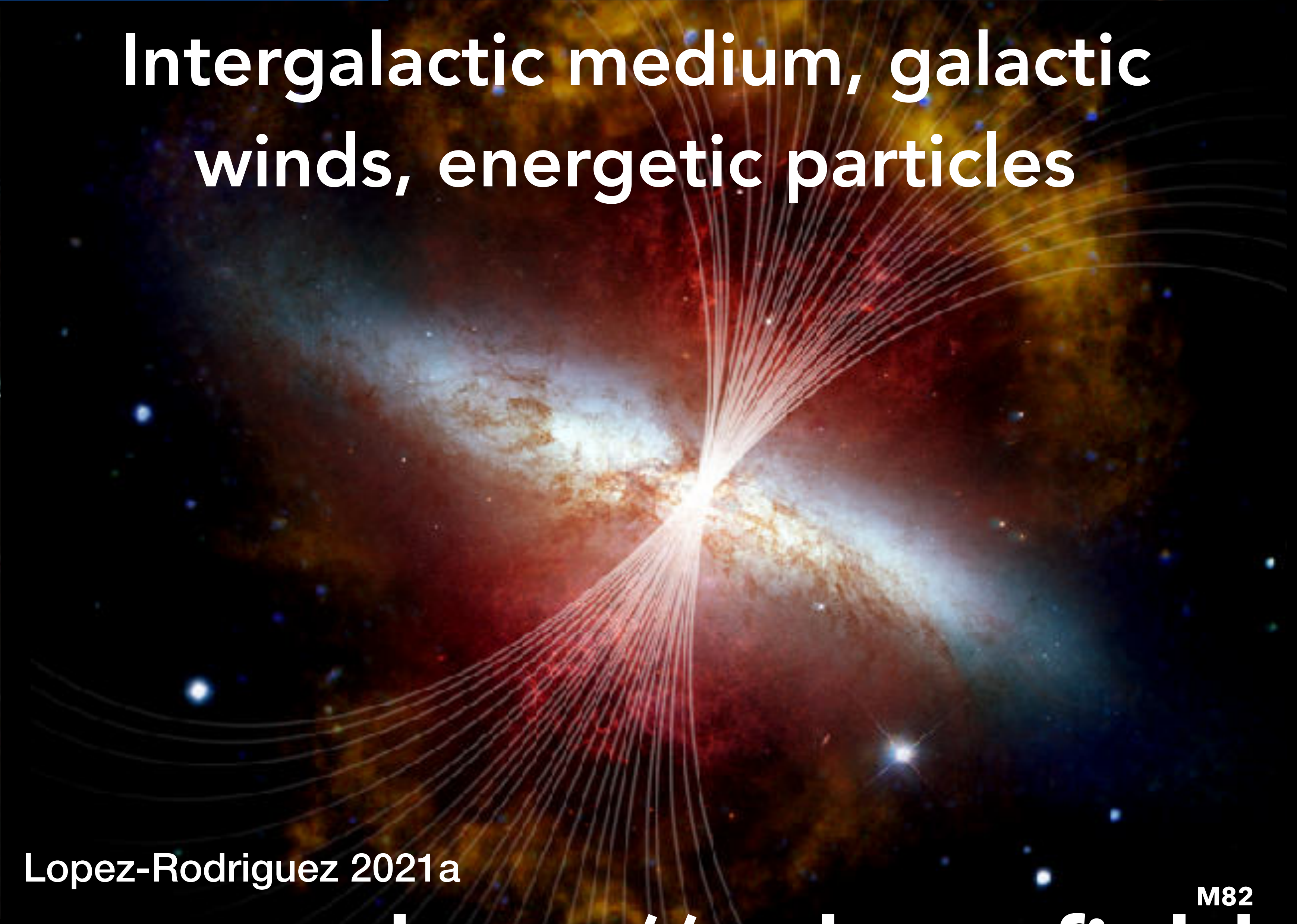
| ISM Phase | Instrument | Tracers |
|---|---|---|
| **Dense and cold** | FIR/HAWC+/ SOFIA and ALMA | Continuum dust total/polarized emission of aligned dust<br>B-field orientation |
| **Warm and diffuse** | Radio/VLA/ Effersberg | Synchrotron emission<br>B-field orientation/direction/strength |
| **Molecular gas (CO)** | Sub-mm/ALMA | Line emission morphology<br>Velocity field<br>Velocity dispersion (turbulent kinetic energy) |
| **Neutral gas (HI)** | 21cm (varios telescopes) | Line emission morphology<br>Velocity field<br>Velocity dispersion (turbulent kinetic energy) |

# KEY SCIENCE TOPICS OF THE LEGACY PROGRAM

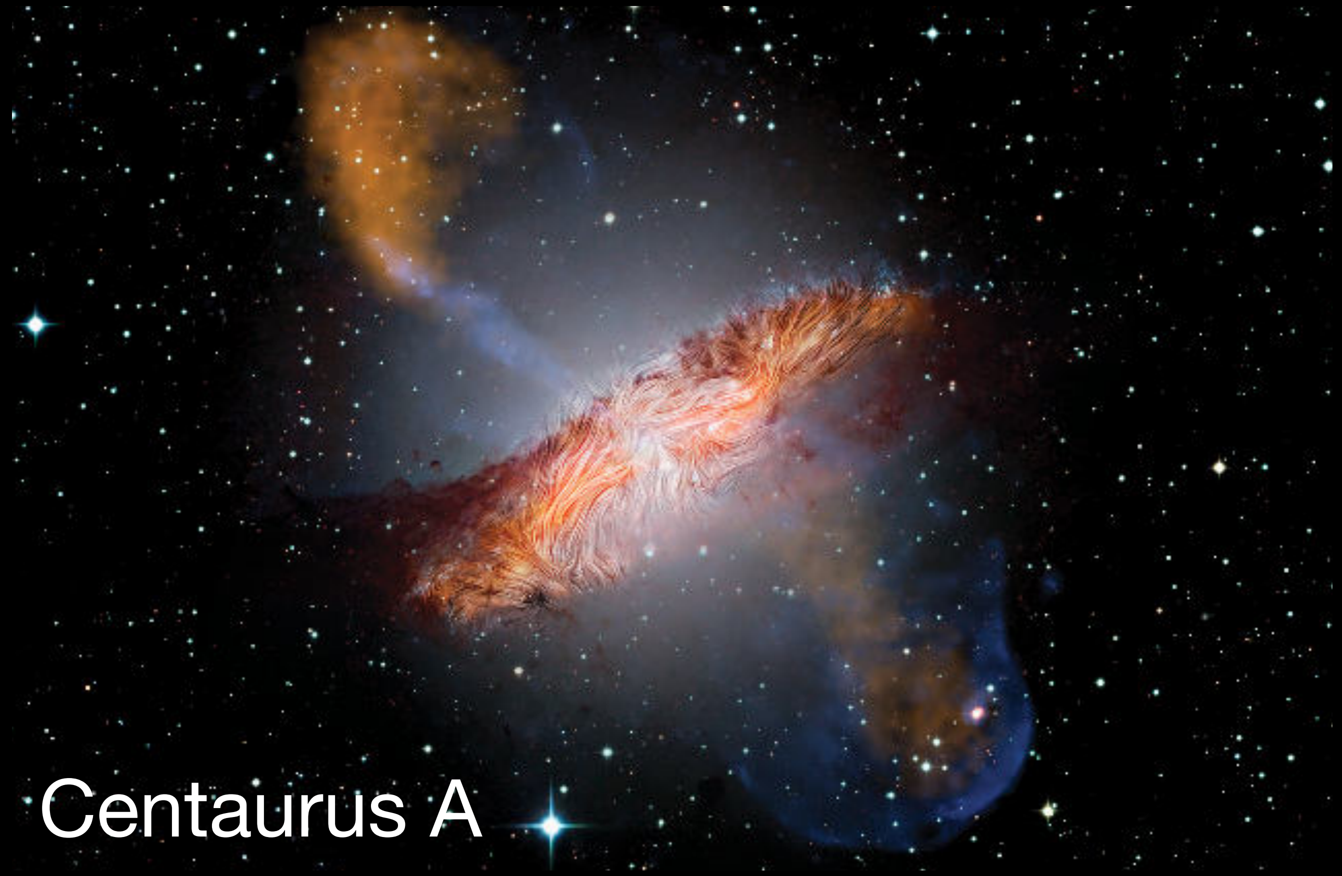




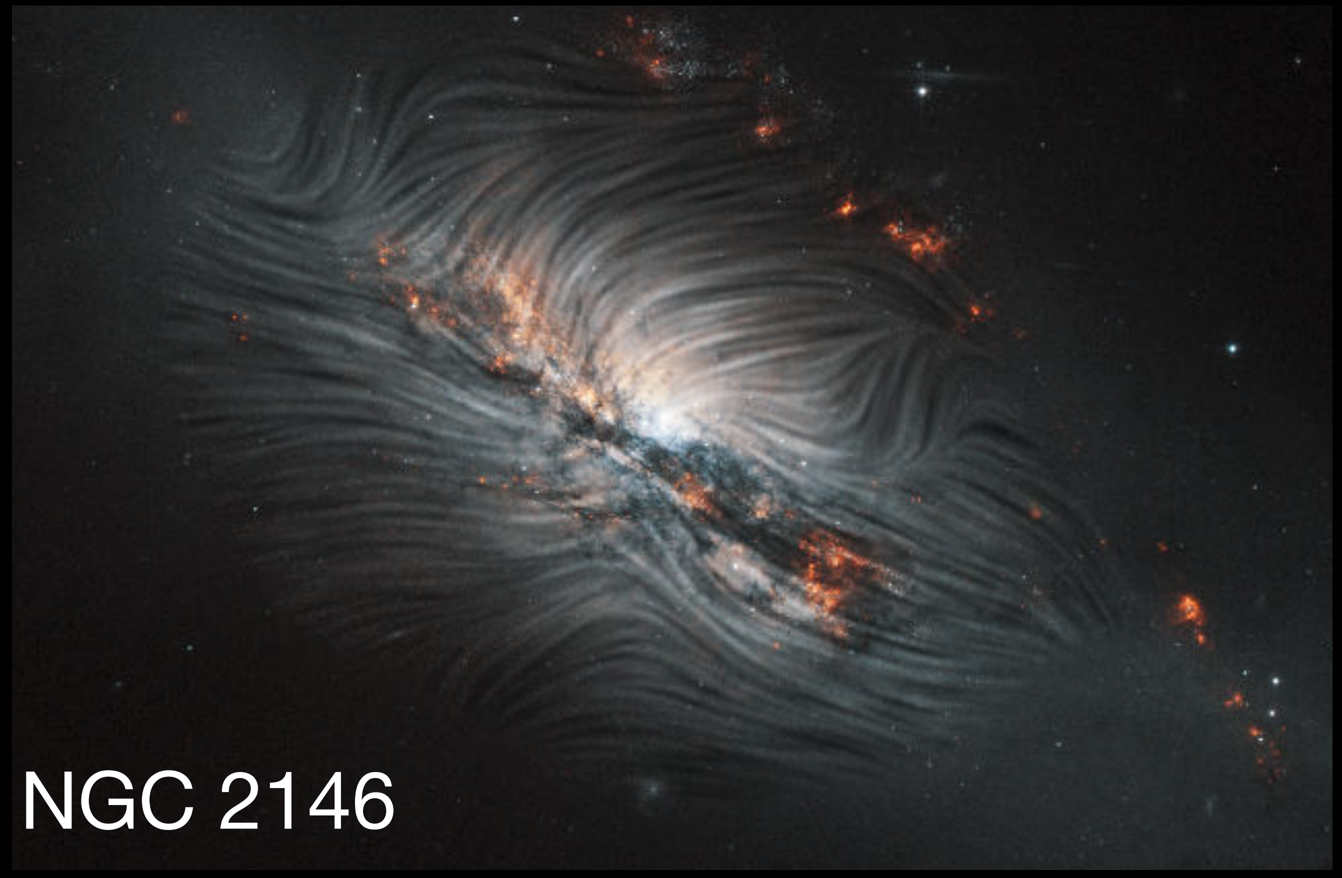

http://galmagfields.com/

# Magnetic fields permeate the interstellar and intergalactic medium





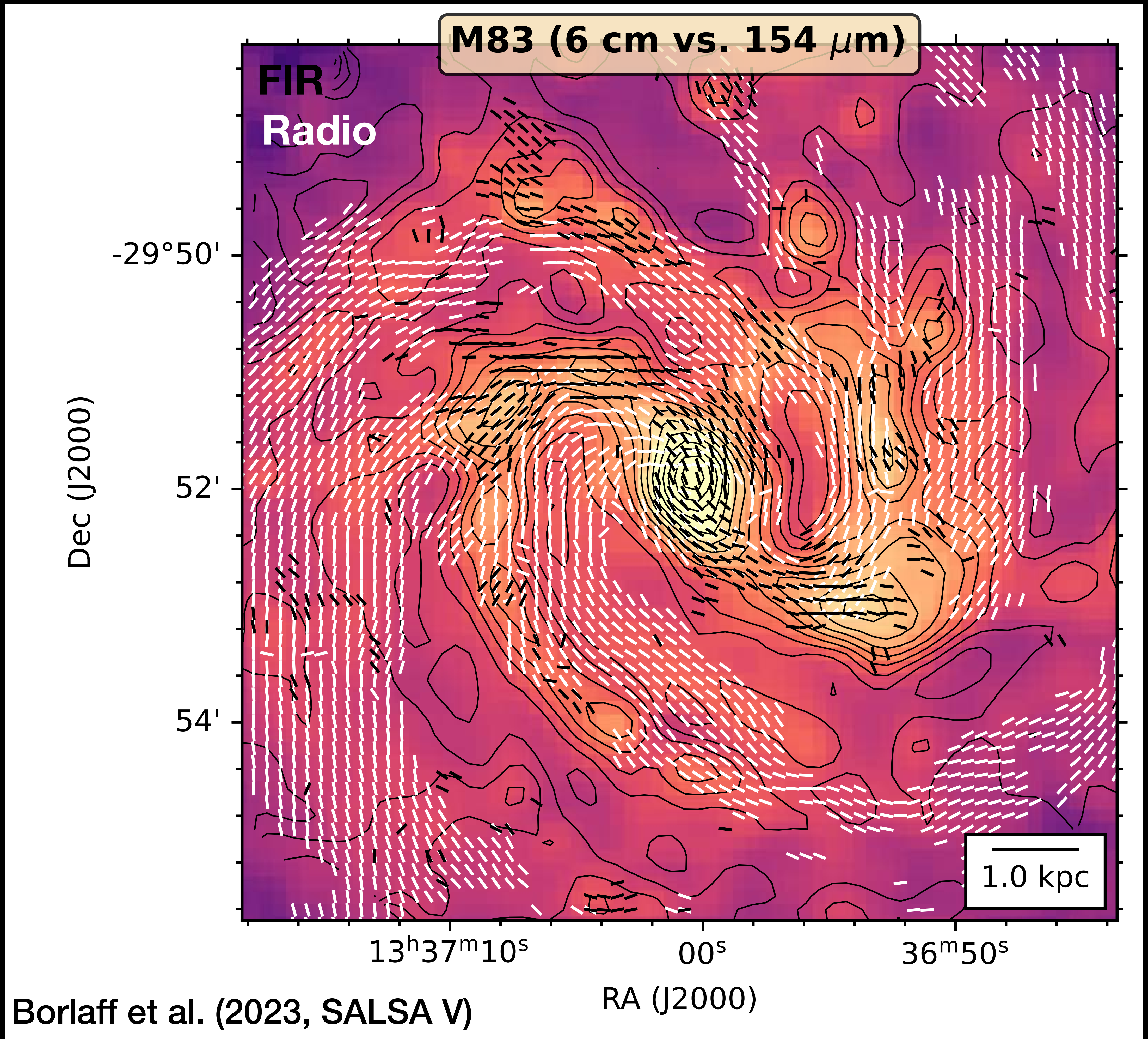



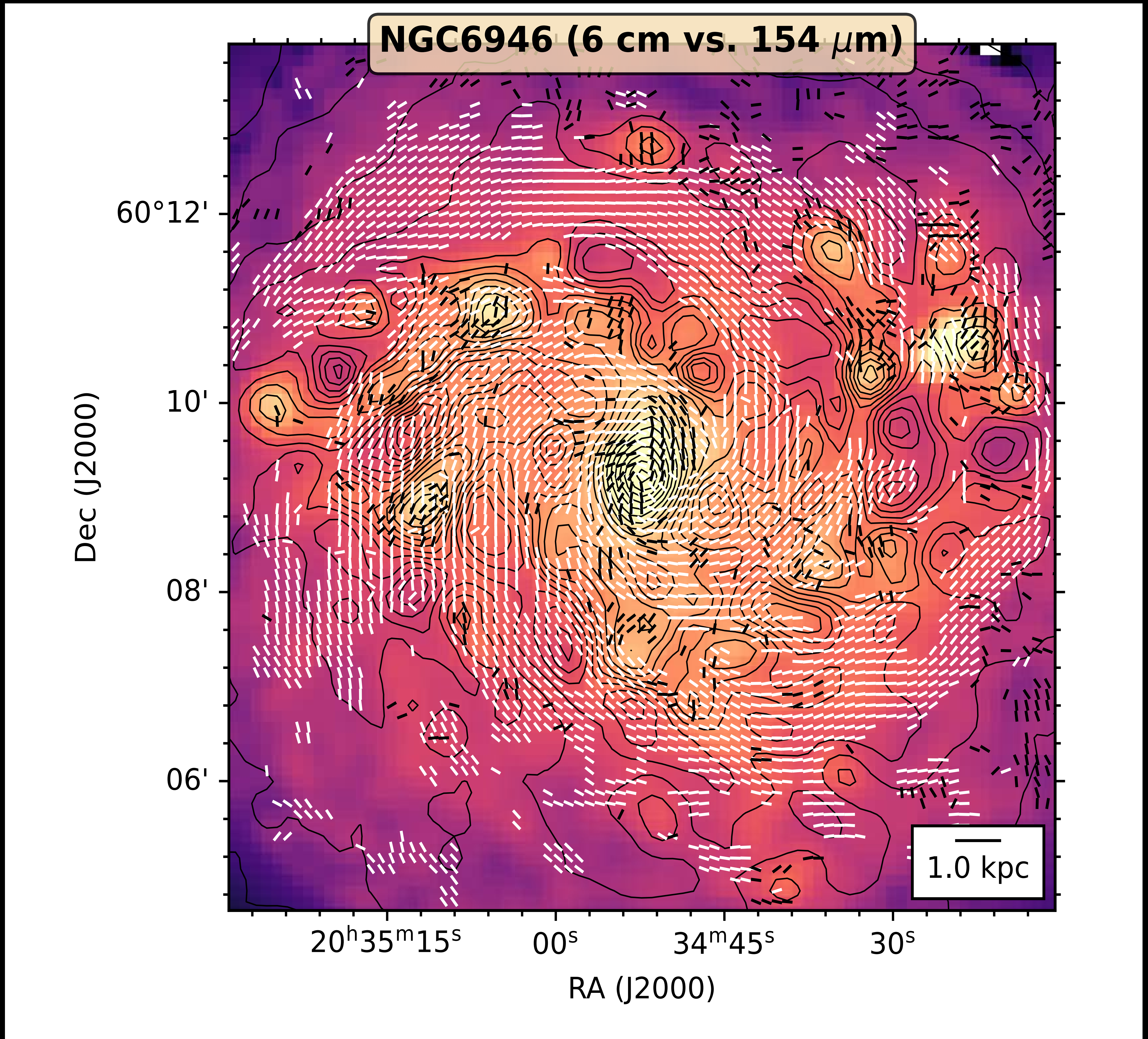



Borlaff et al. (2021)
Lopez-Rodriguez (2020, 2021a,b, 2022b,c)

# FIR vs. Radio B-field morphology

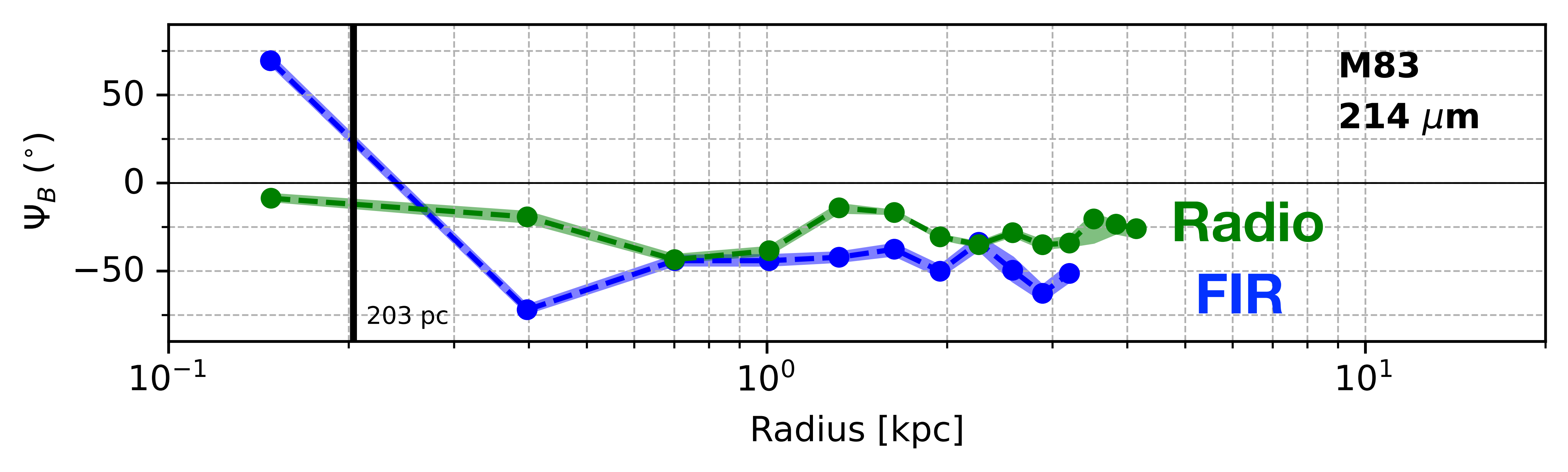
Large-scale spiral ordered B-fields dominate at both FIR and Radio wavelengths

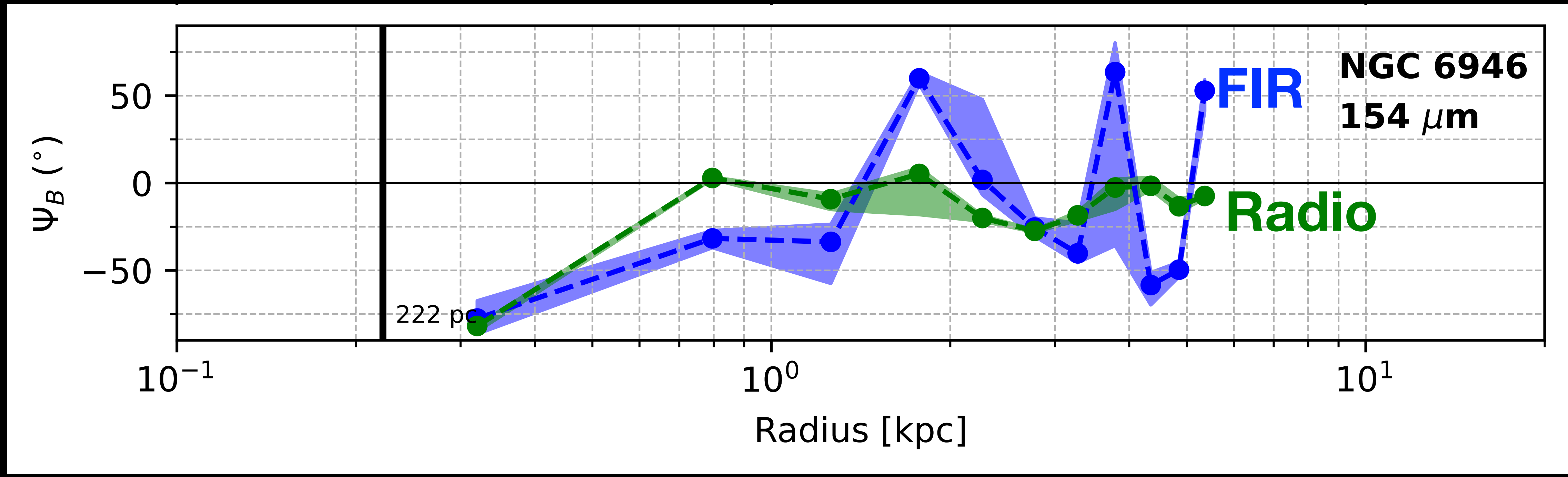


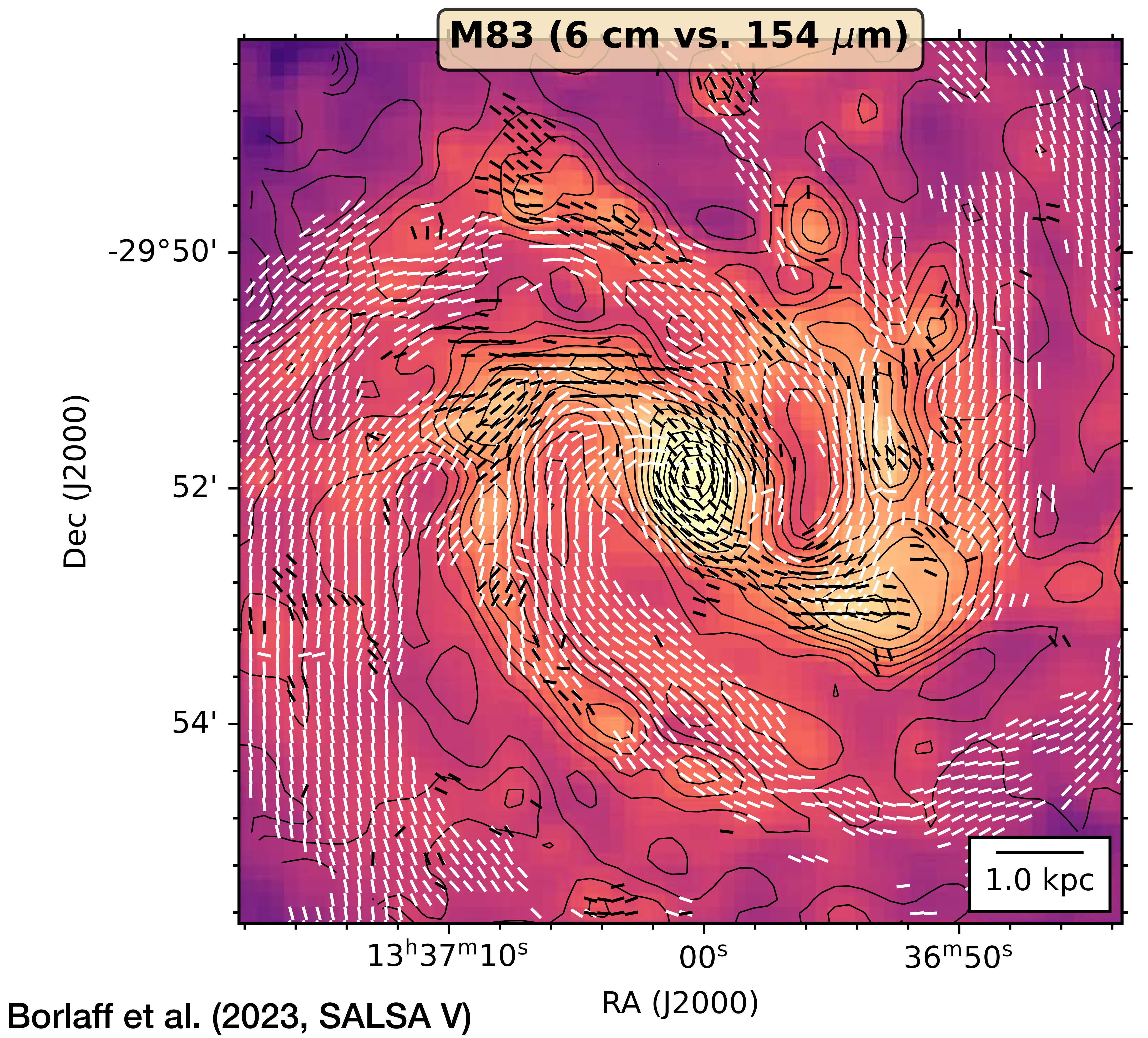



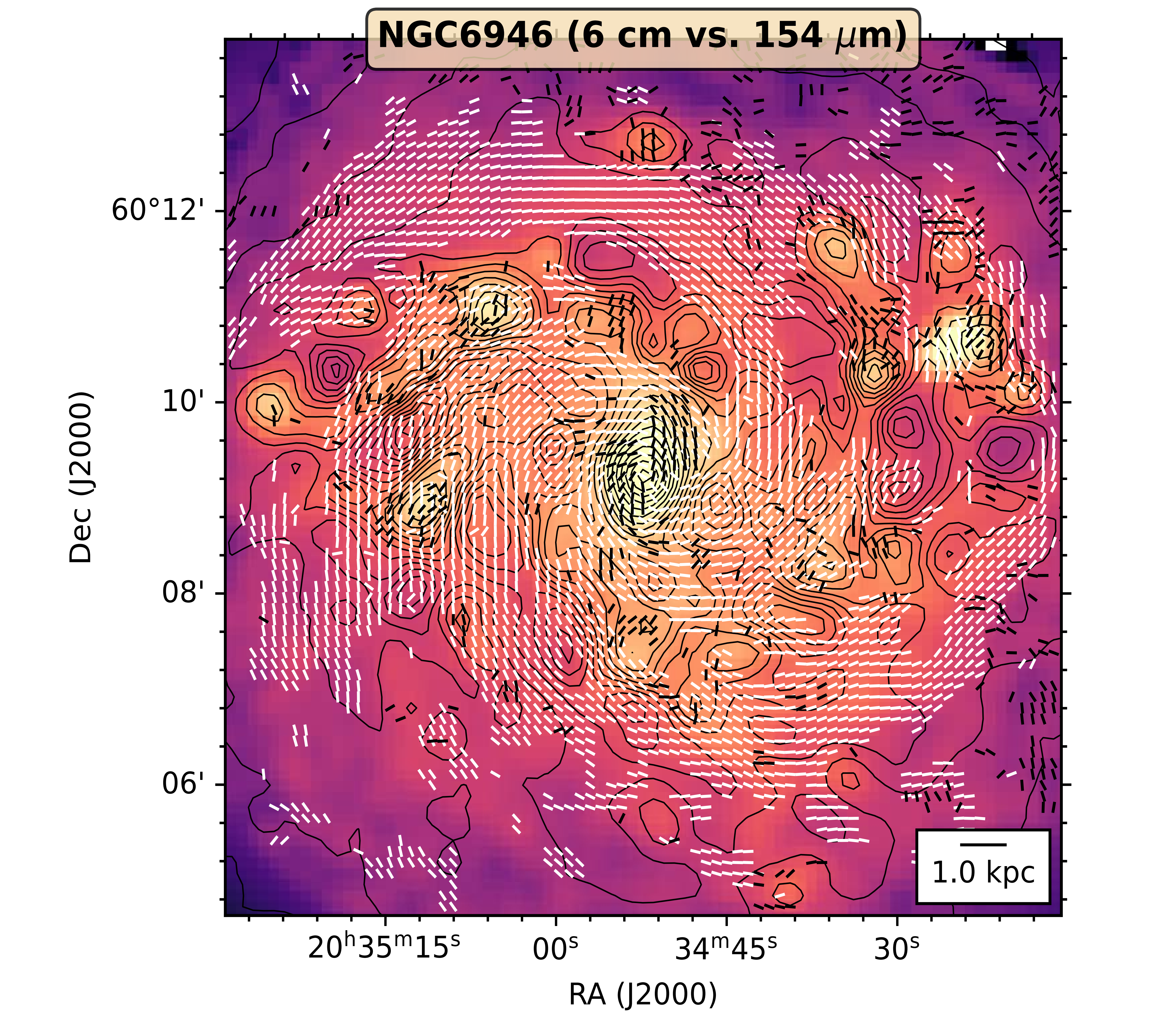

Borlaff et al. (2023, SALSA V)

# FIR B-field is more turbulent than the Radio B-field



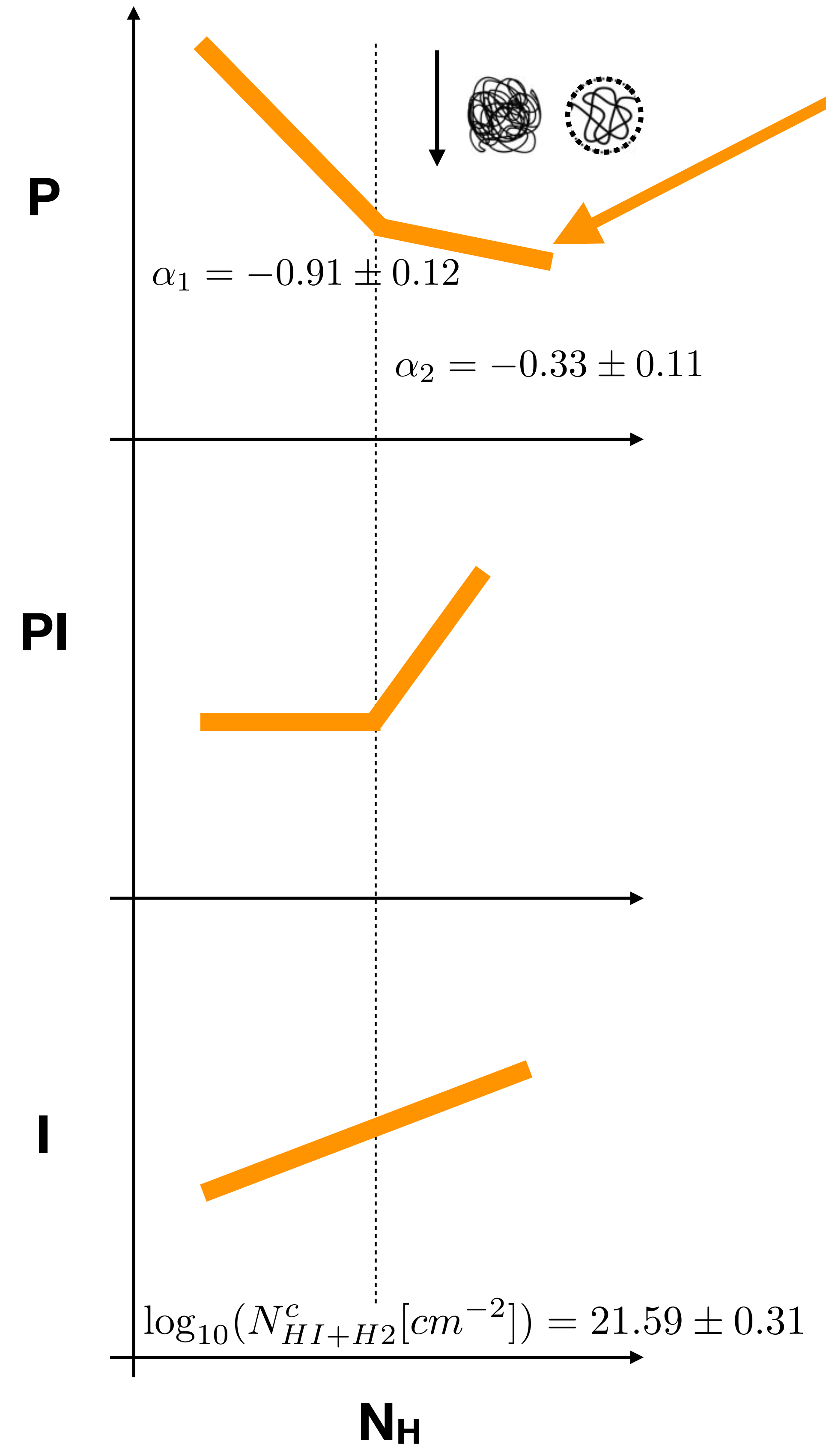

Borlaff et al. (2023, SALSA V)

# Where does the FIR turbulence B-field come from?

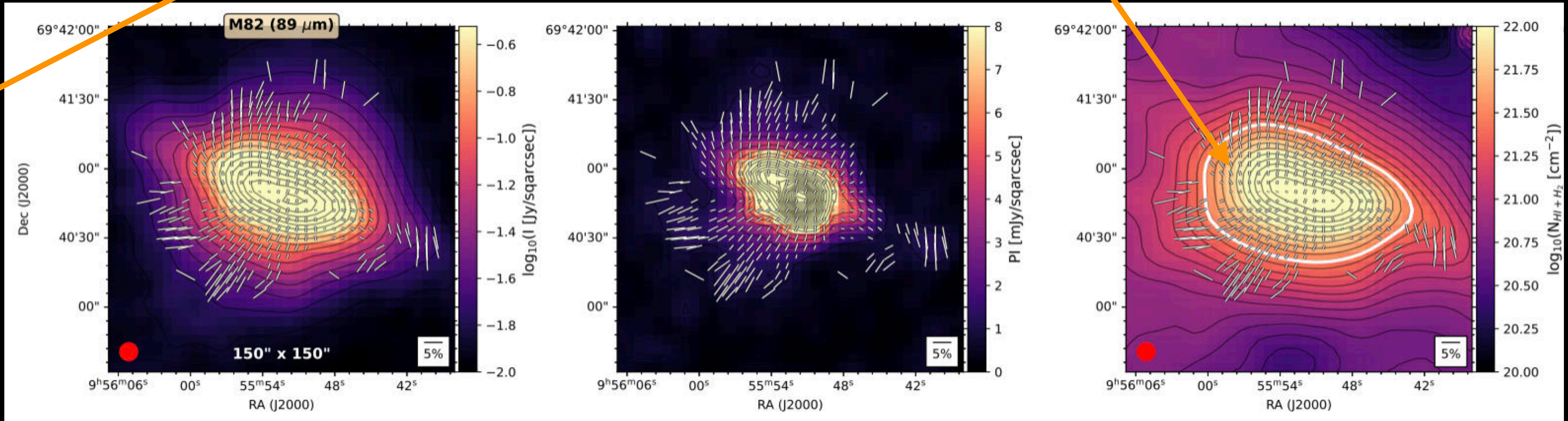
## Group 1

**Compressed and sheared B-fields**

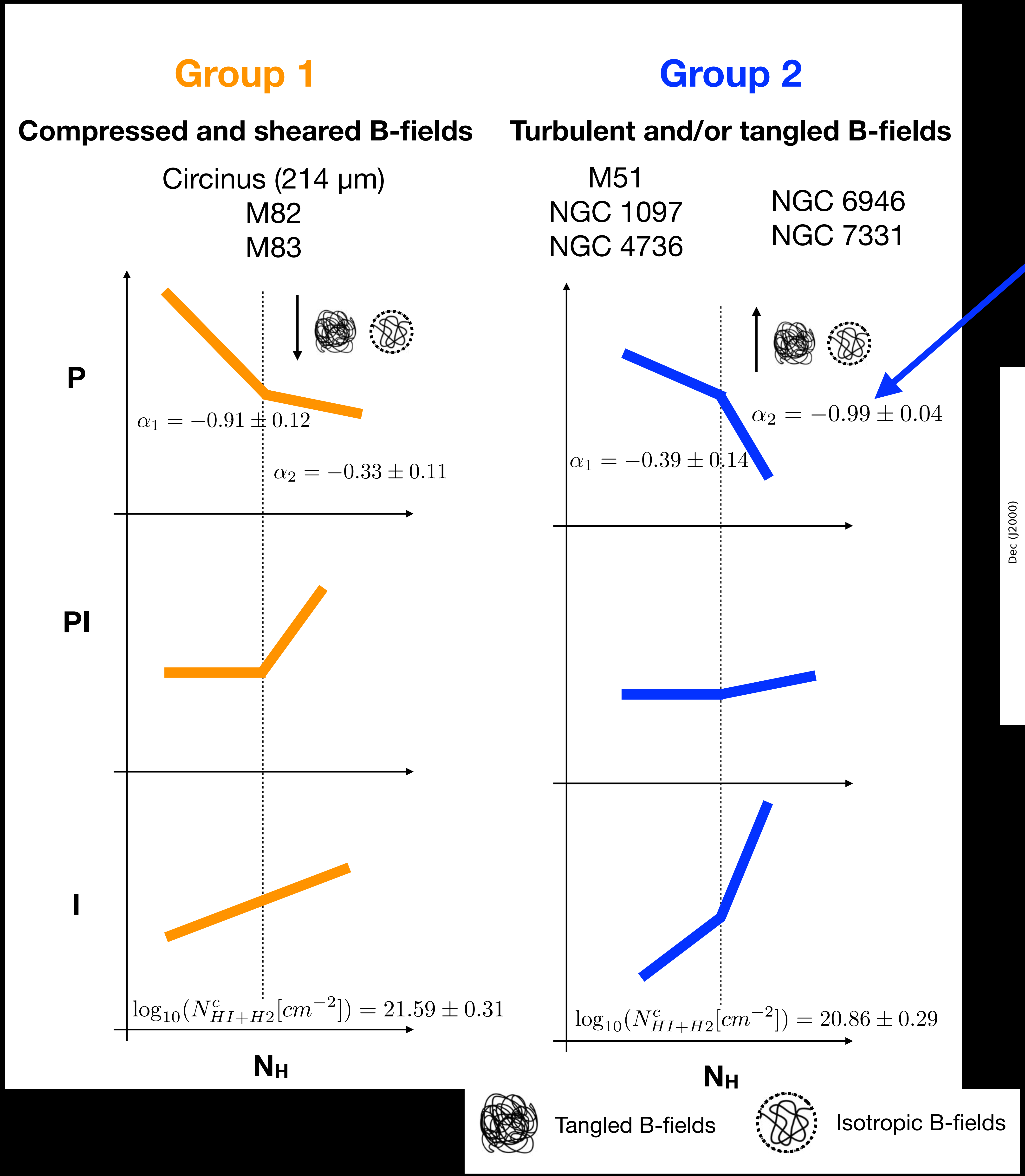
Circinus (214 μm)
M82
M83



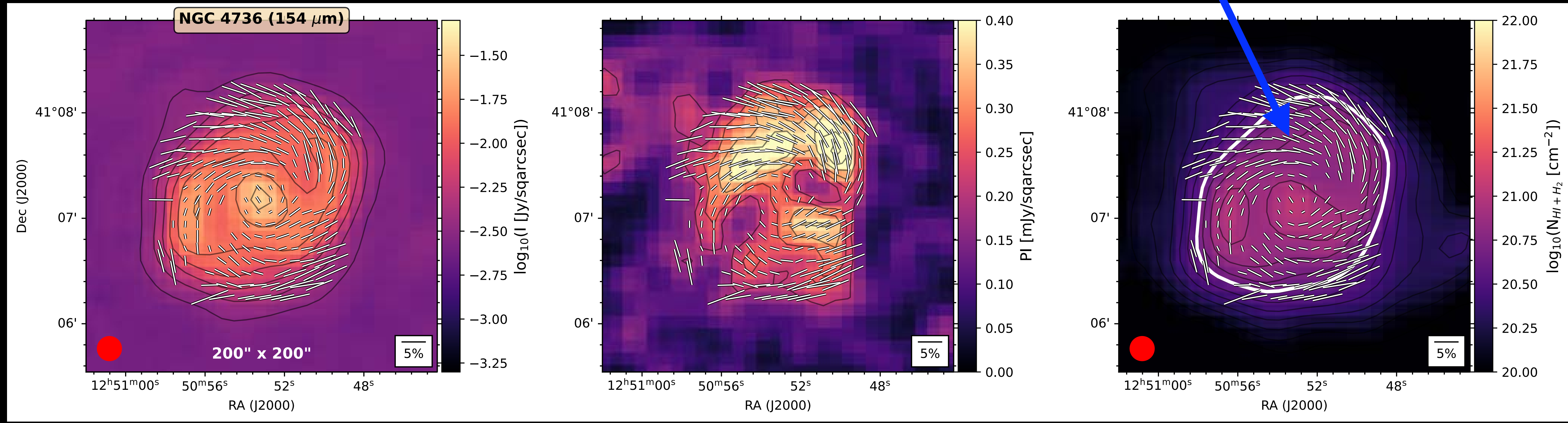

**Starburst compresses and shears the galactic B-field along the galactic outflow**




# Where does the FIR turbulence come from?

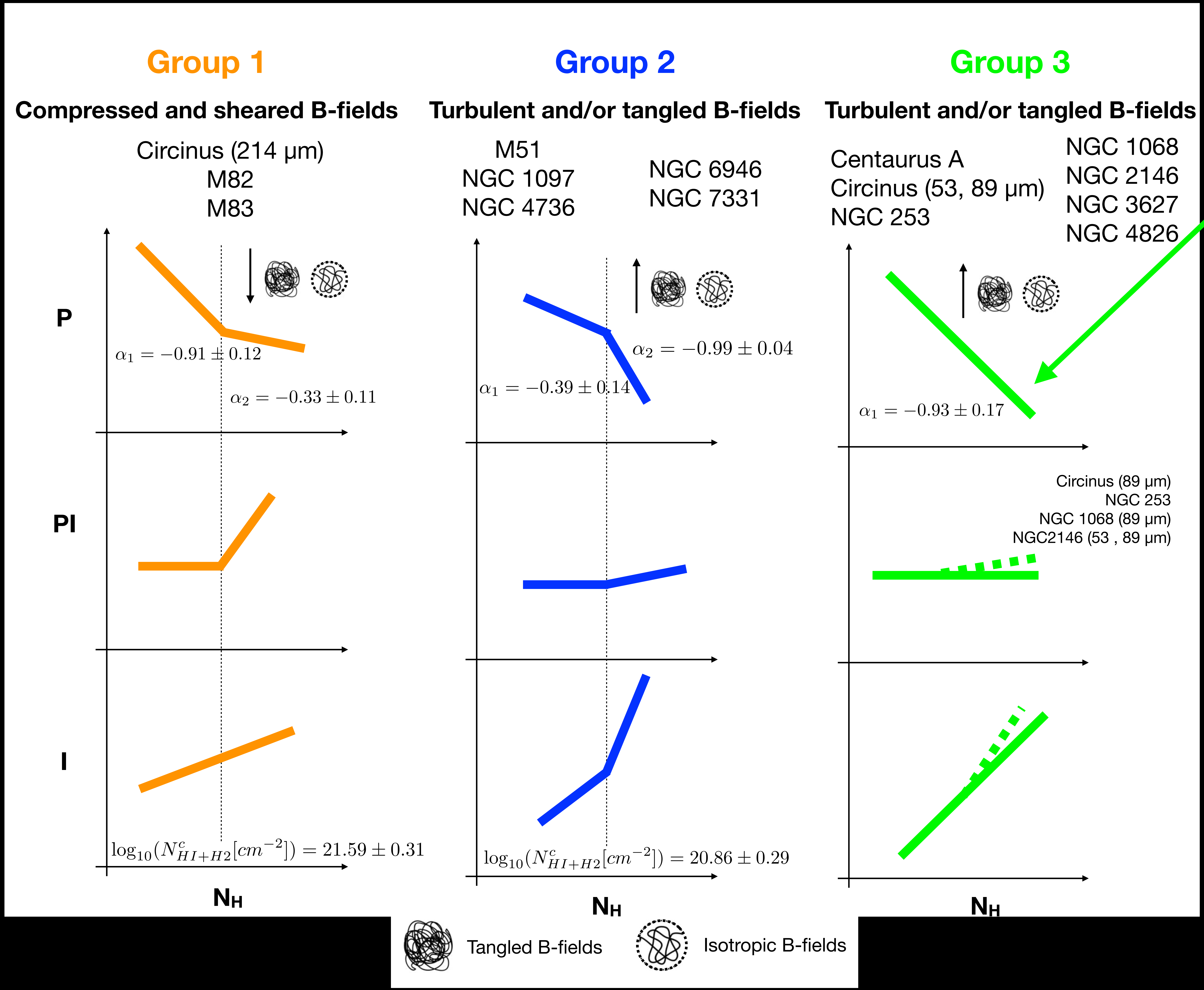


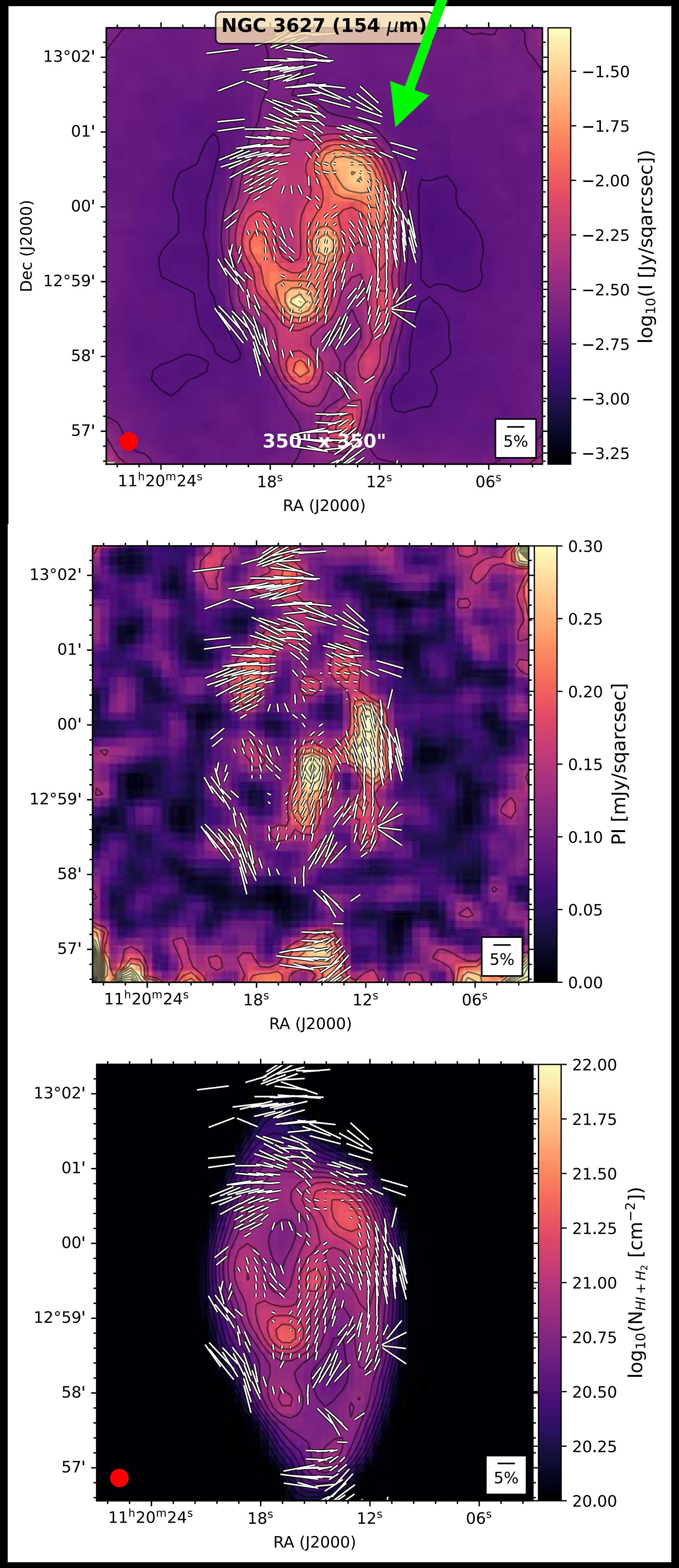

**Star-forming regions inject turbulent and/or tangle the B-fields**



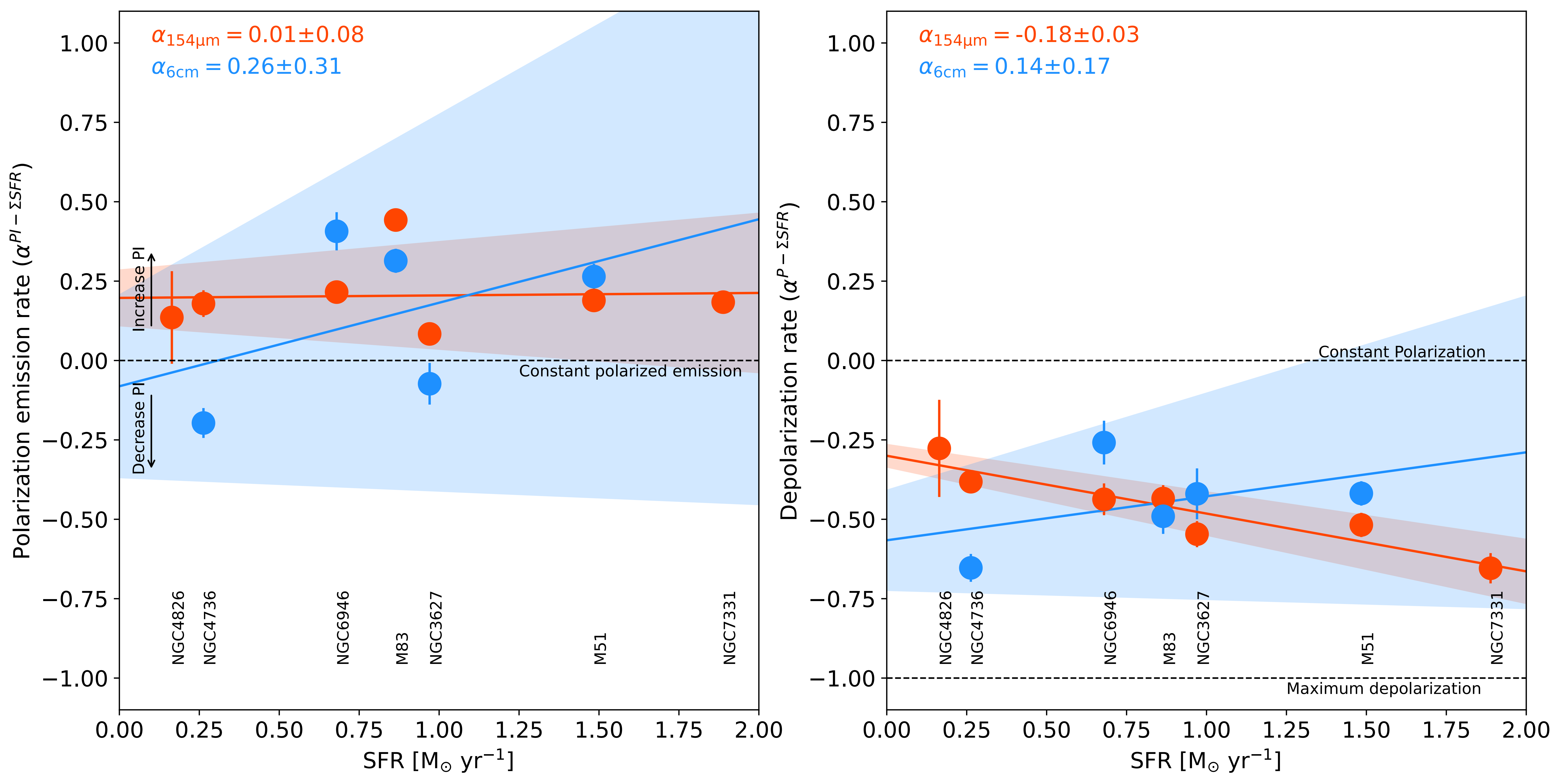
# Where does the FIR turbulence come from?

**The whole galaxy has a highly turbulent and/or tangled B-field**



# FIR turbulent B-field is located in the dense and cold ISM associated with SF regions




| | | | |
|---|---|---|---|
| **Radio** | – PI rate ~ increases with SFR. | – P rate ~ constant with SFR. | Increase of anisotropic random B-fields (tentative) |
| **FIR** | - PI rate is constant with SFR. | – P rate decreases with SFR. | Increase of isotropic random B-fields |

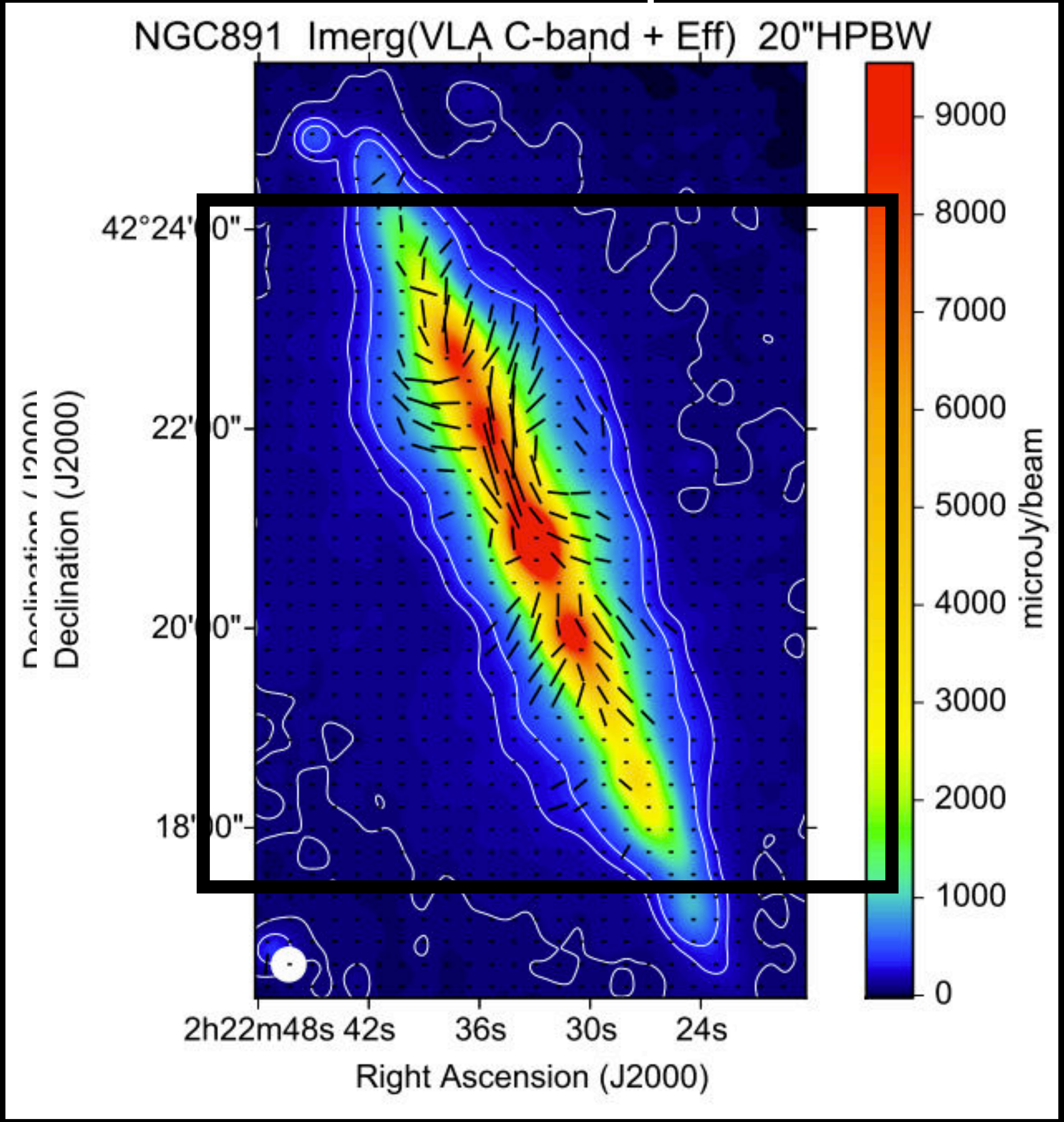
**FIR turbulent B-field arises from the injection of turbulent energy driven by SF in the dense ISM.**

FIR has a tighter depolarization rate with SFR than at radio wavelengths.

# Structure of the B-field using radio and FIR polarimetric observations

**Radio: warm and diffuse ISM**

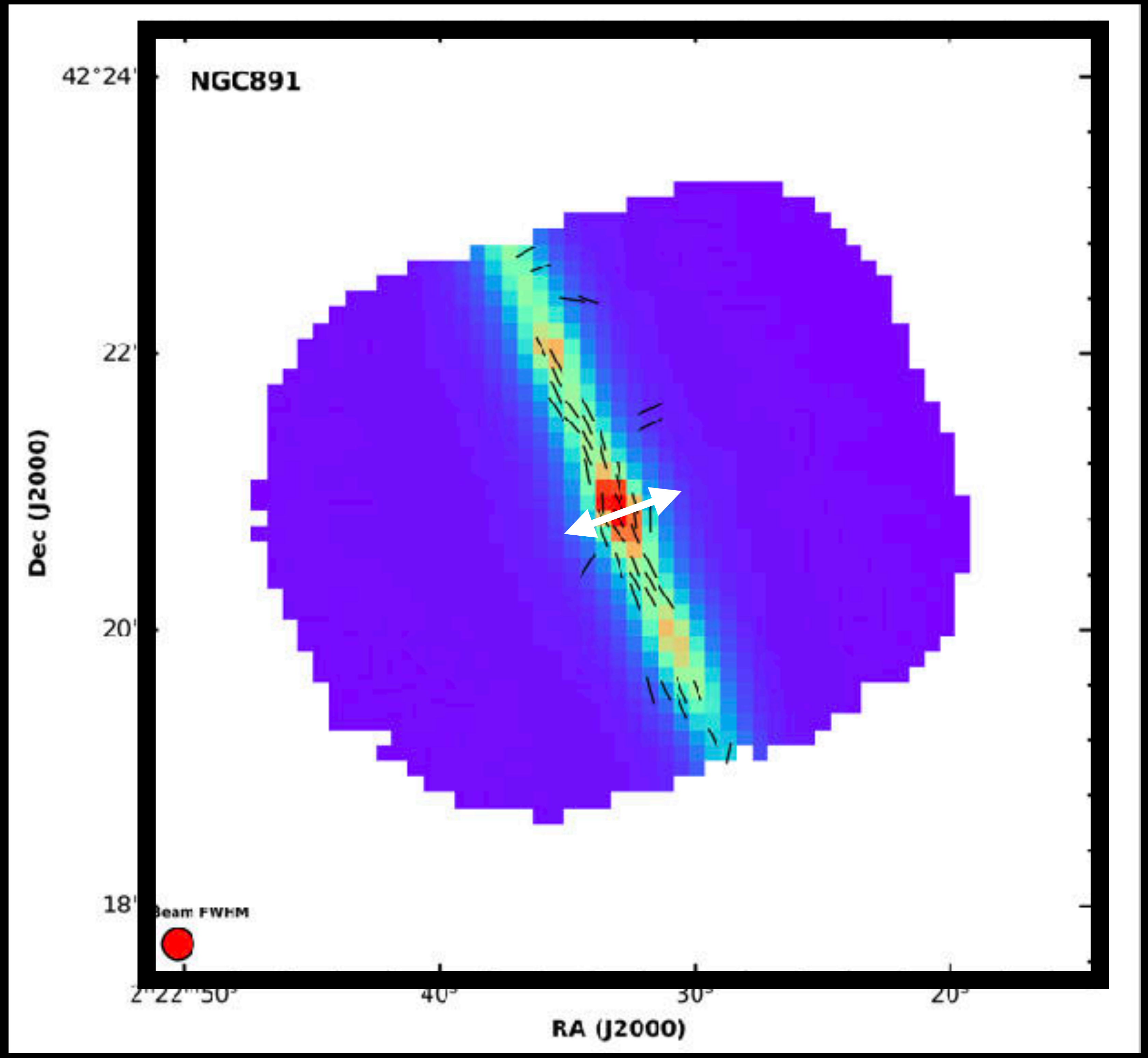
**h ~ 1-2 kpc**




*Krause et al. (2018,2020)*

**FIR: cold and dense ISM**

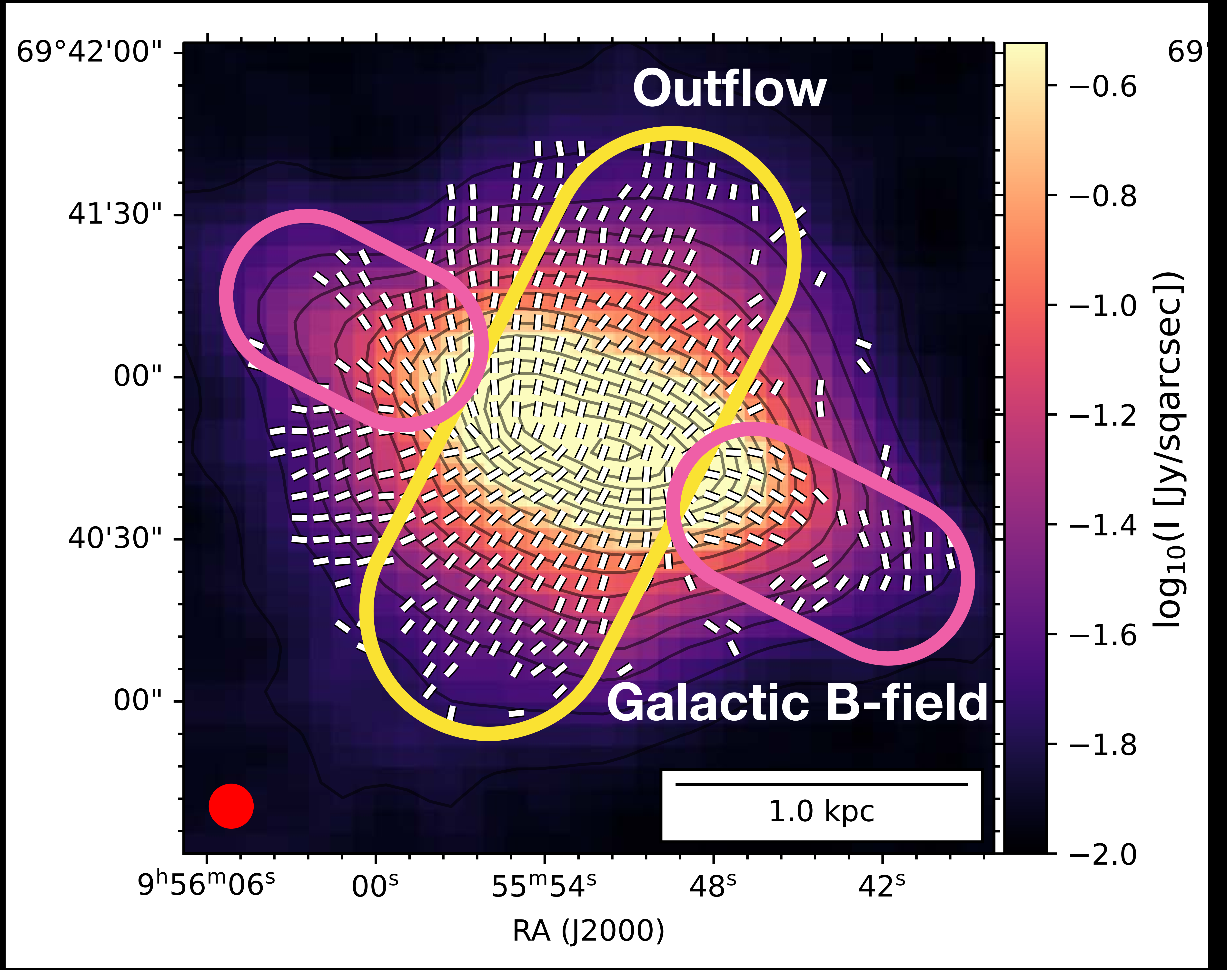
**h < 0.5 kpc**




*Jones et al. (2020)* FWHM (HAWC+): 13.6”

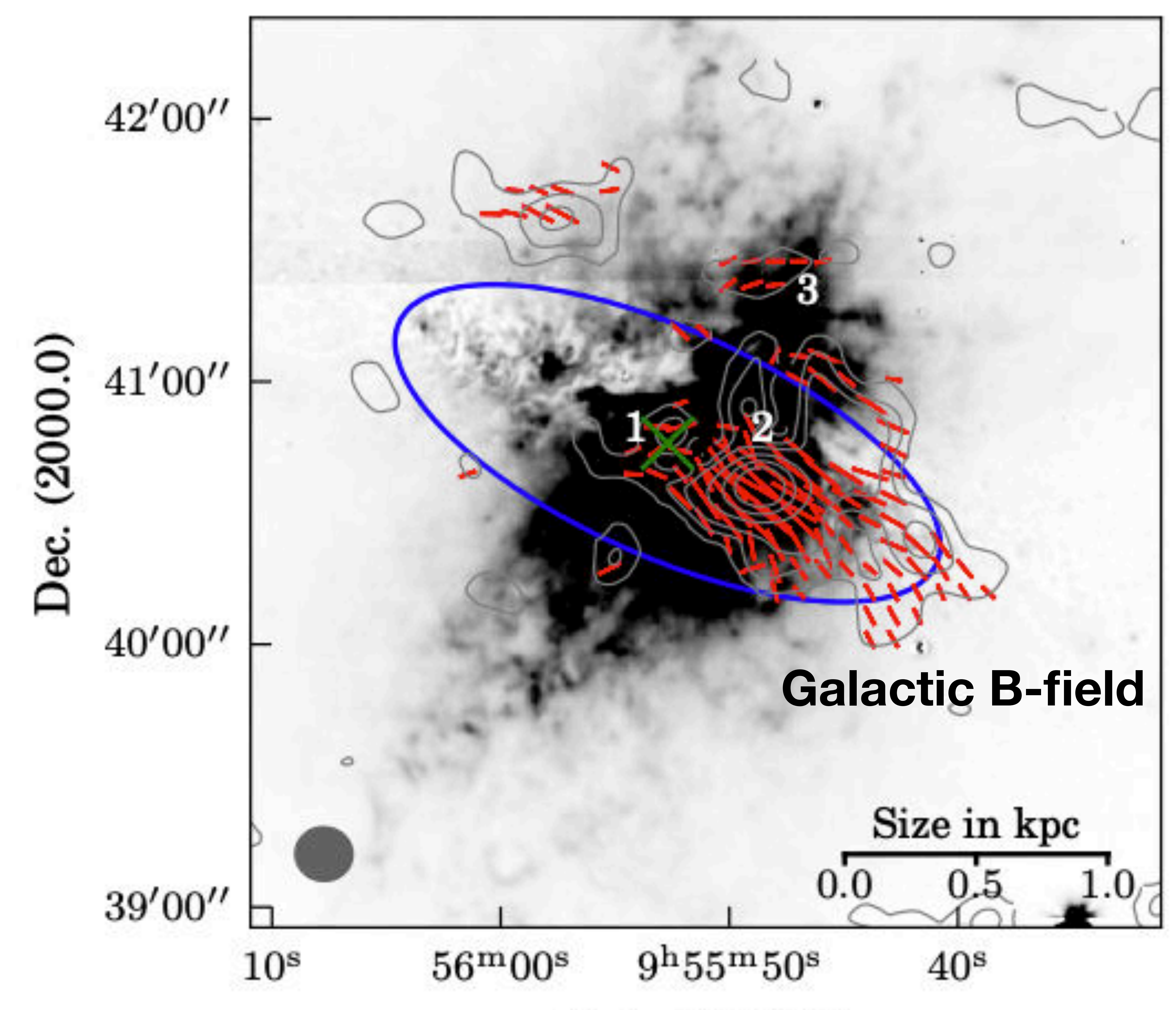
# FIR polarization traces the B-field along galactic outflows

**FIR (89 um)**



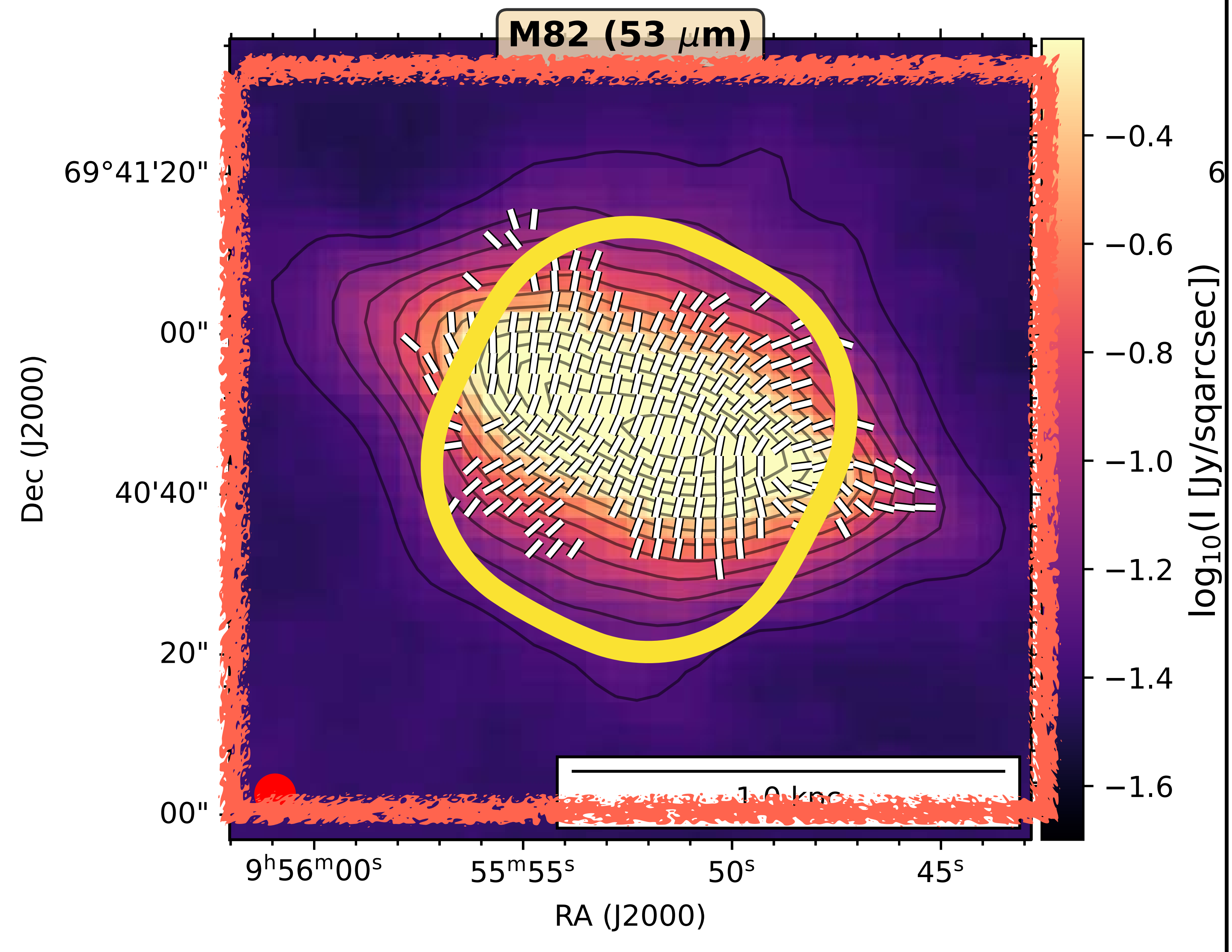

Lopez-Rodriguez et al. (2021, 2022b: SALSA IV)

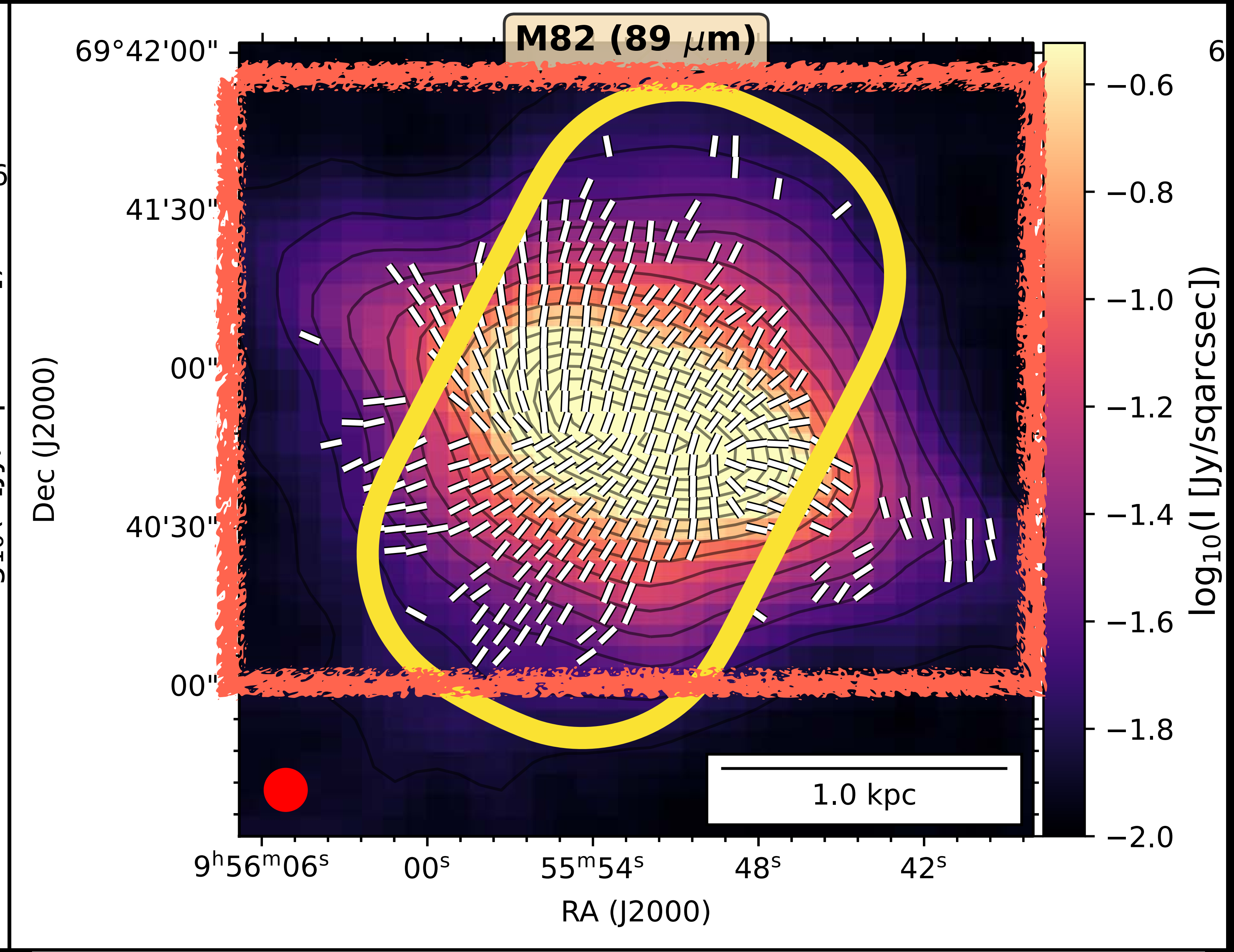
**Radio (18 and 22 cm)**

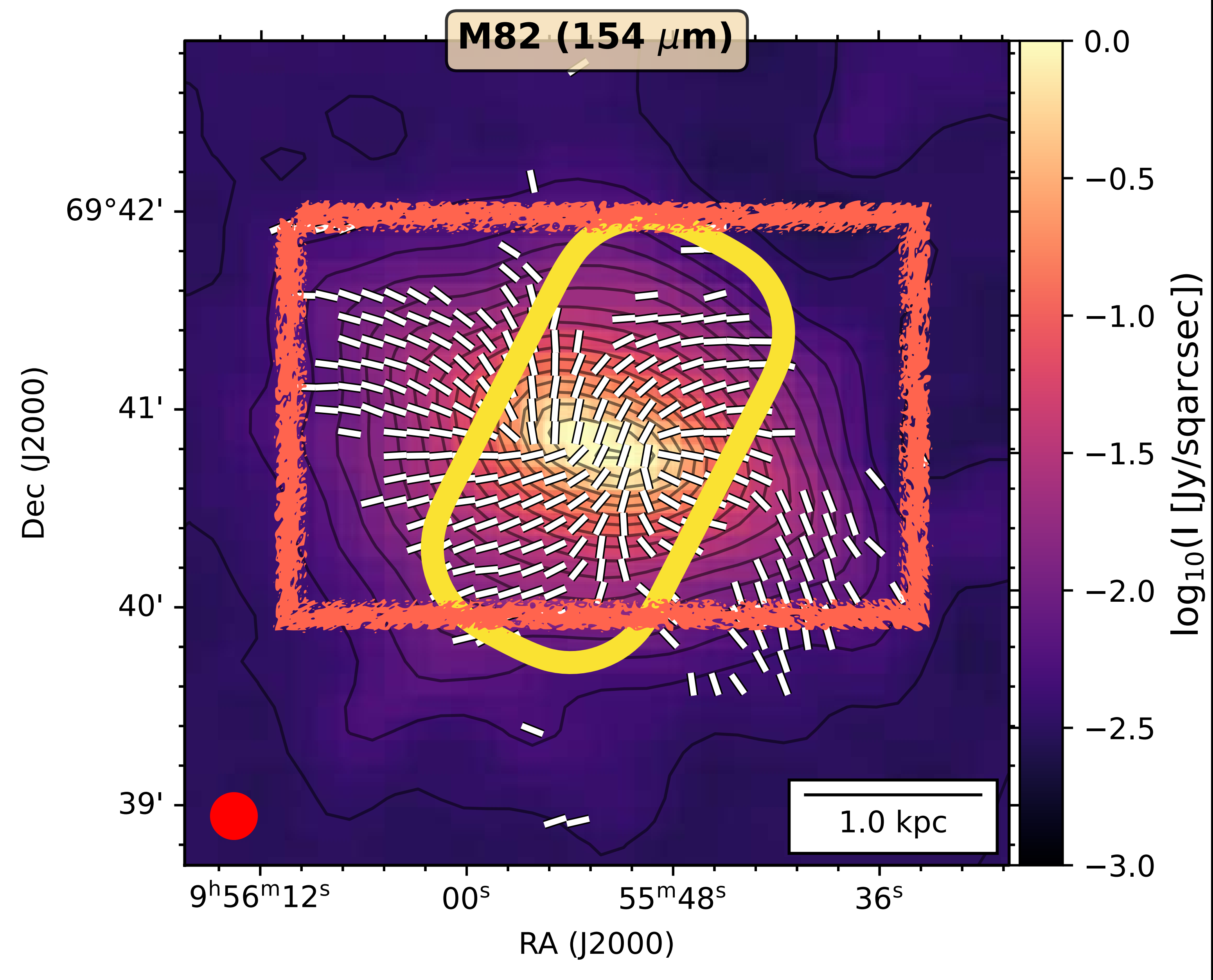


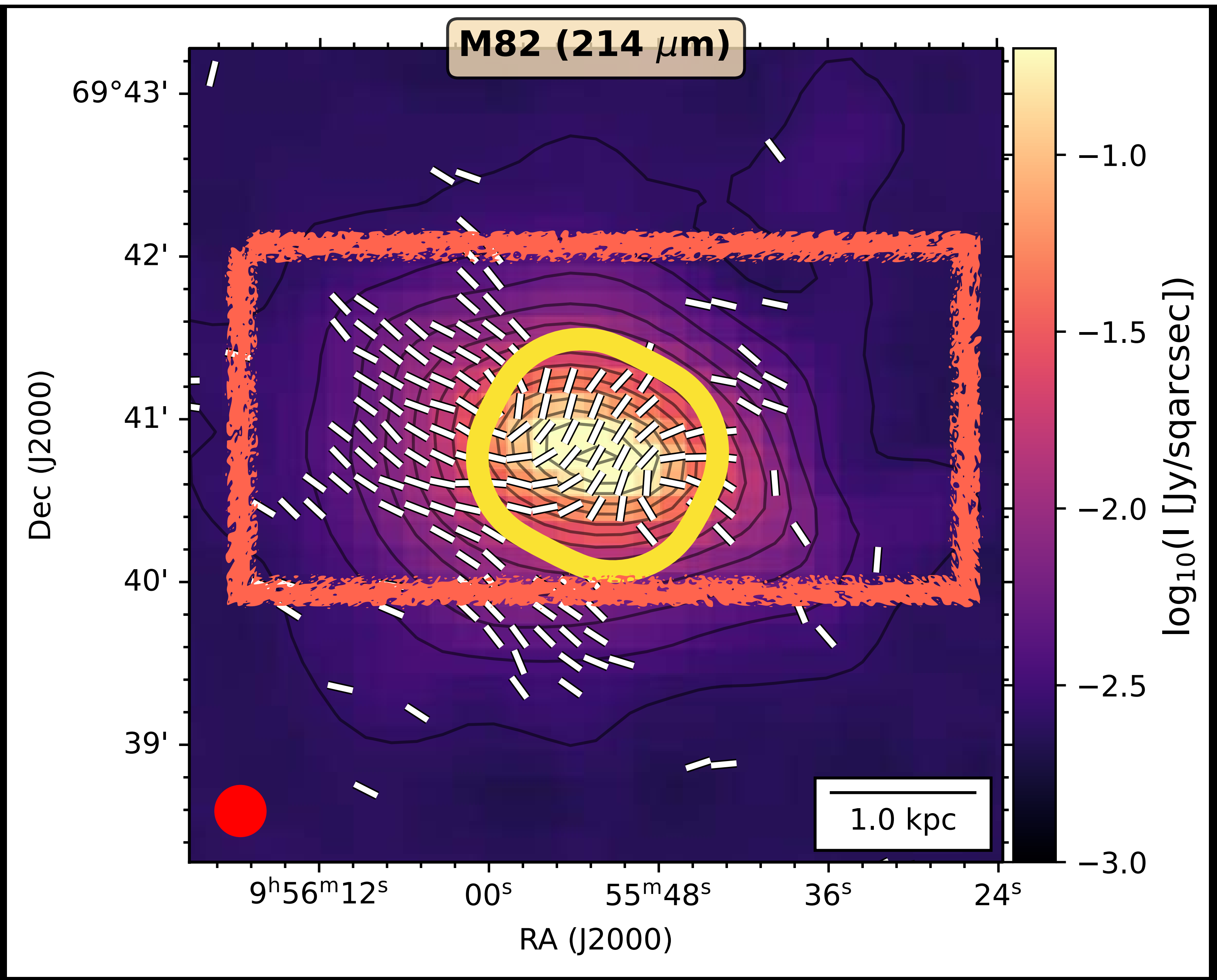

Adebahr et al. (2017)

# MULTI-WAVELENGTH ANALYSIS OF THE GALACTIC OUTFLOW'S B-FIELD



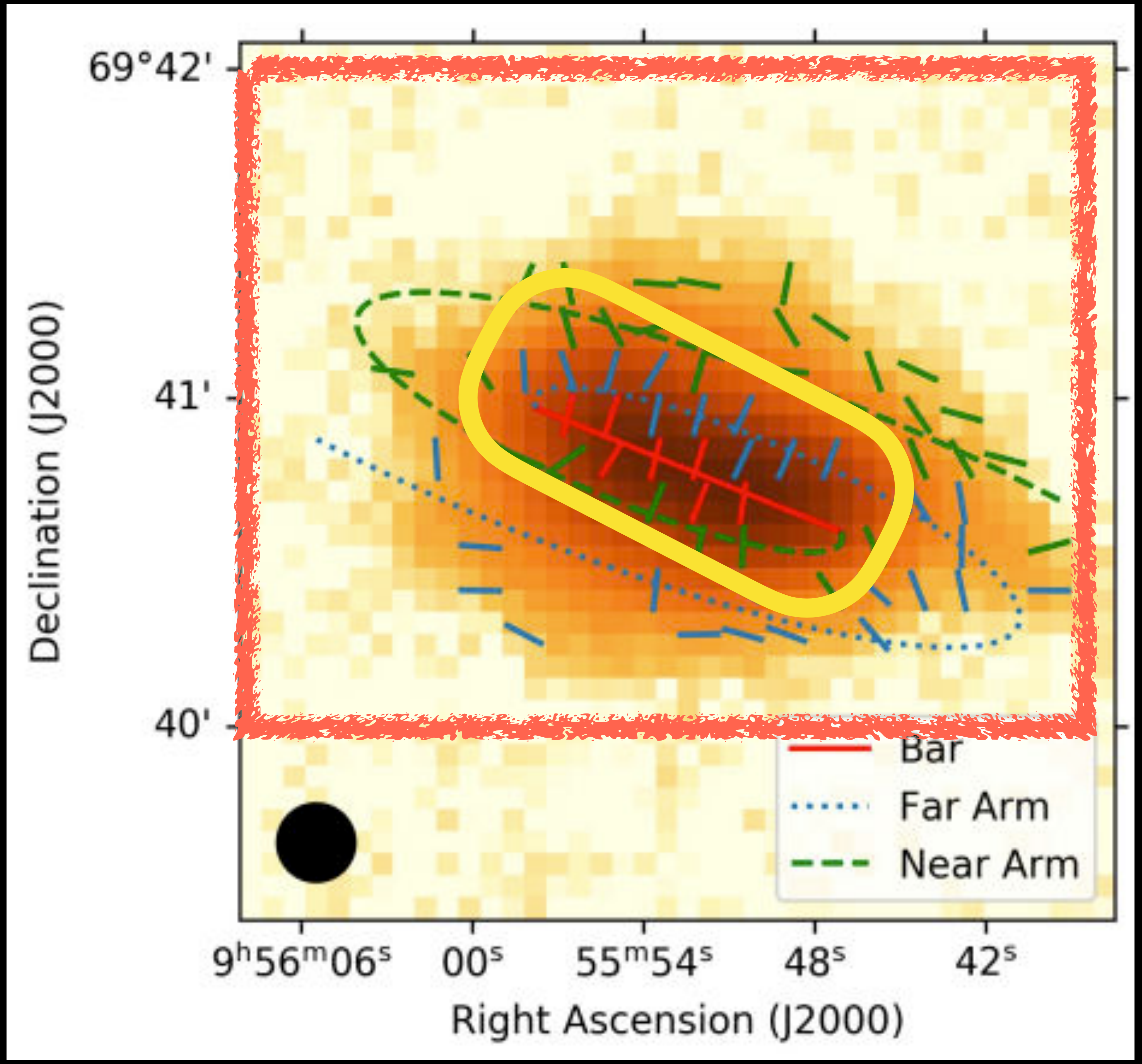



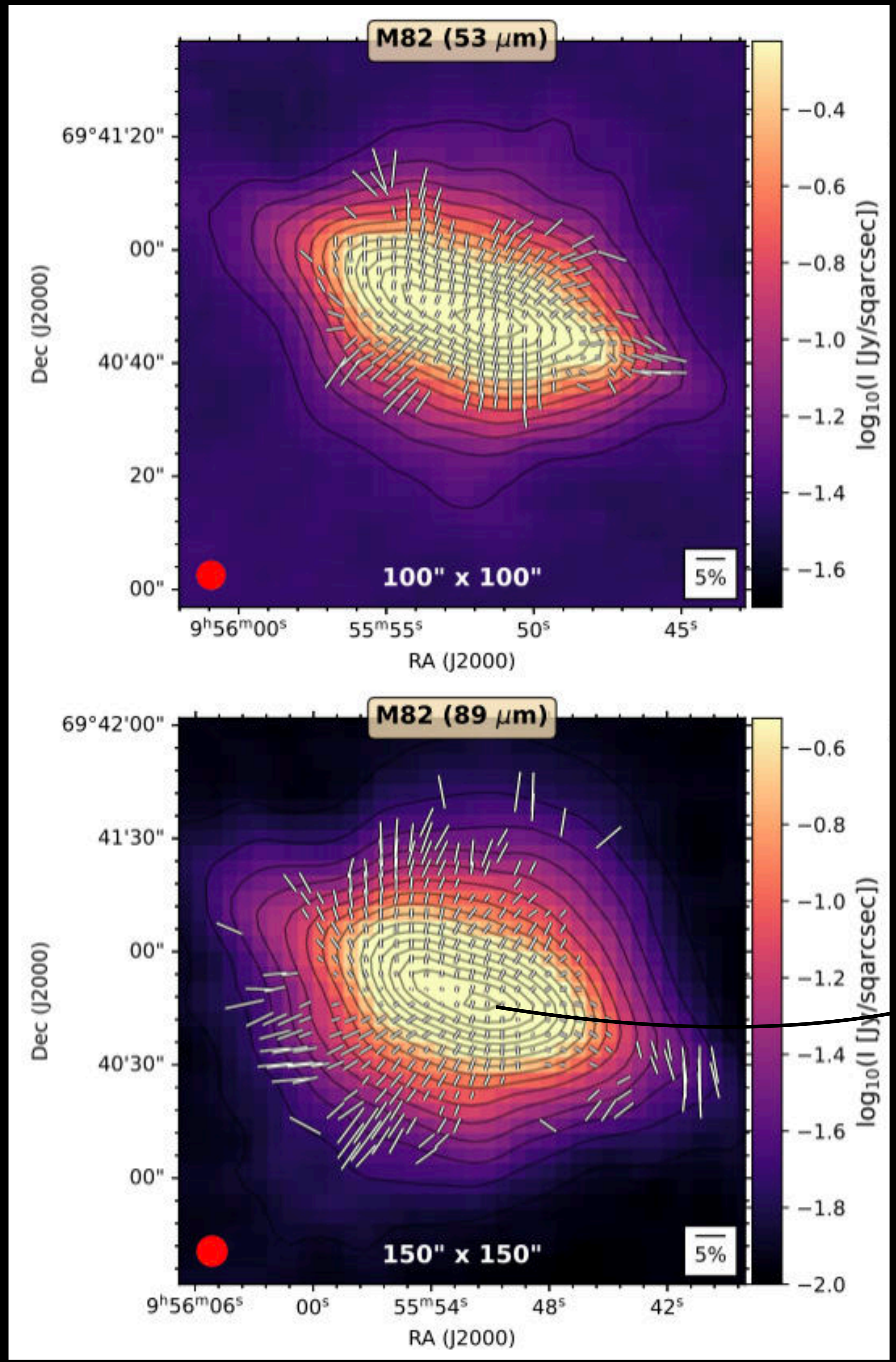

Lopez-Rodriguez et al. (2022b)

## FIR (850 um)

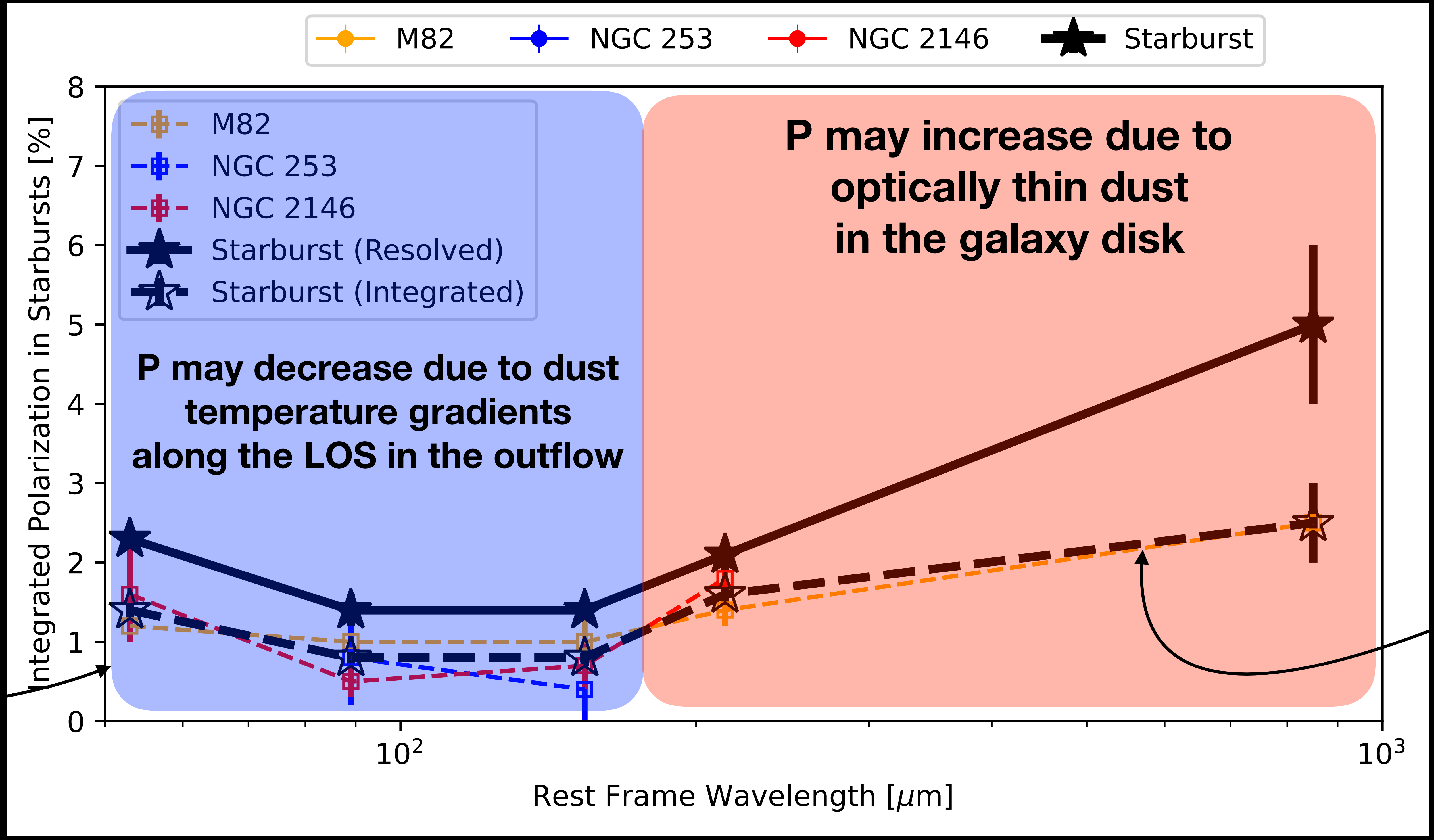


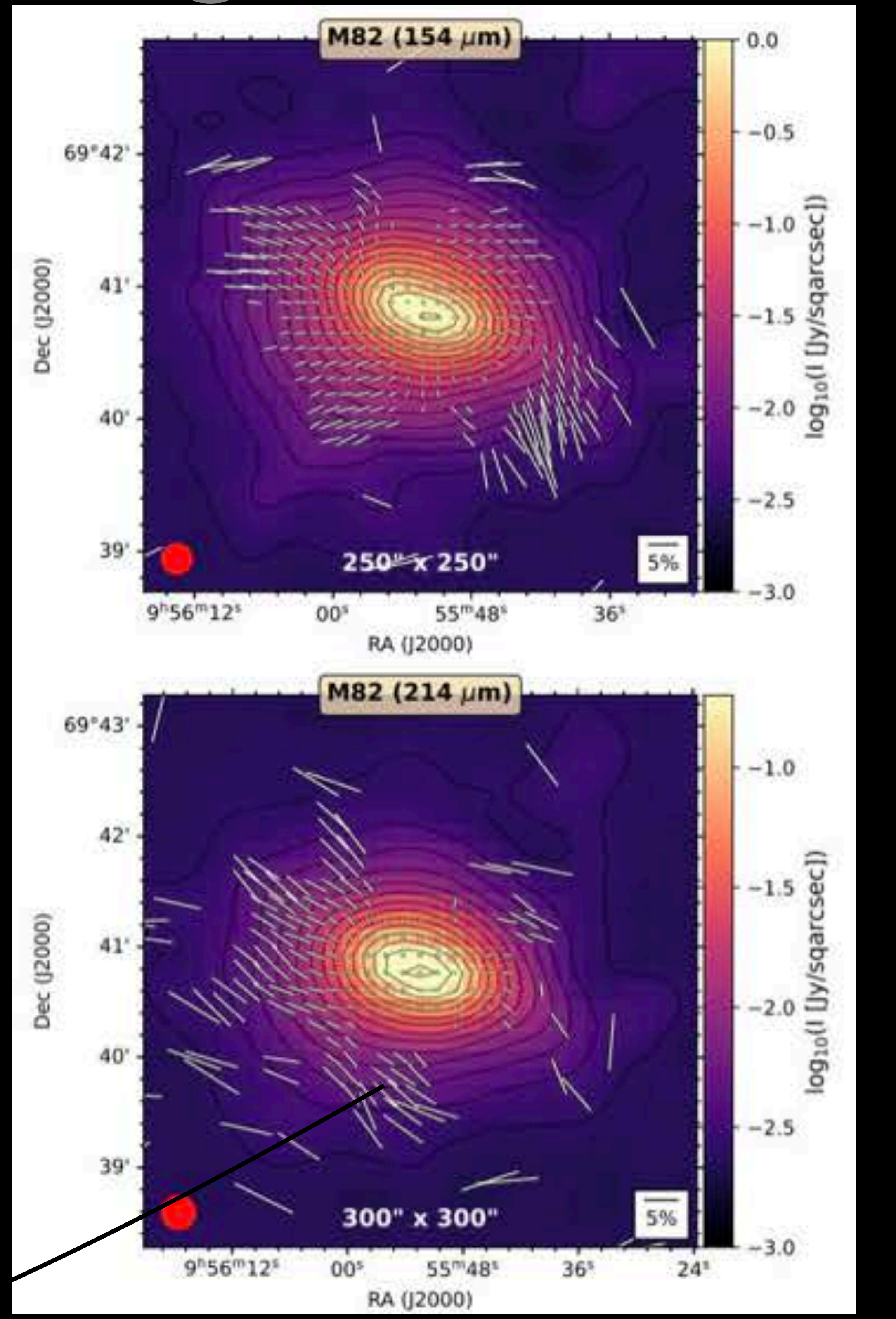

Pattle et al. (2021)

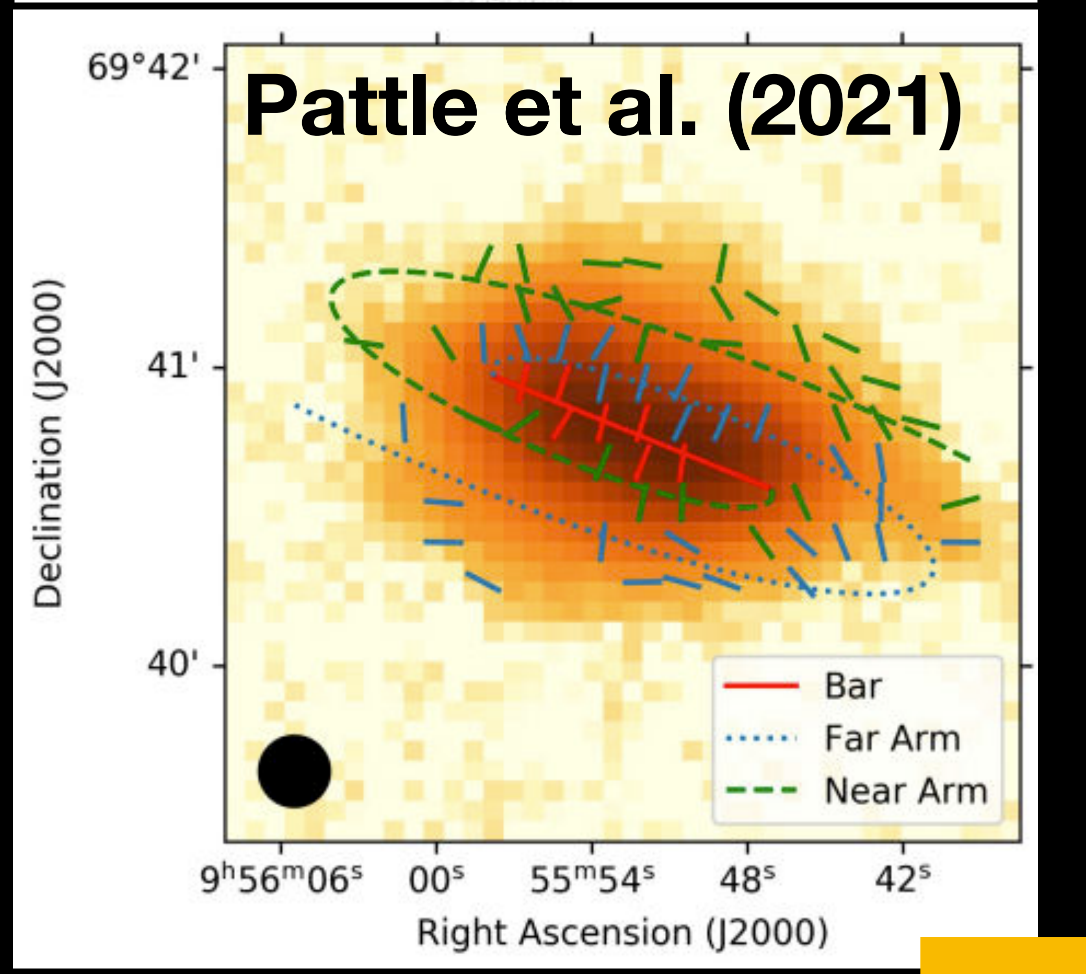
# Dust properties: FIR polarized spectrum of Starburst galaxies




At least two dust components are required to explain the polarized SED of starbursts.




At short wavelengths, the hot dust from the galactic outflow dominates up to scales of ~4 kpc above and below the disk.

At longer wavelengths, the cold dust from the galactic disk dominates.

**Lopez-Rodriguez et al. (2022b, SALSA IV)**

# The turbulent kinetic and magnetic energy are in equipartition in the outflow

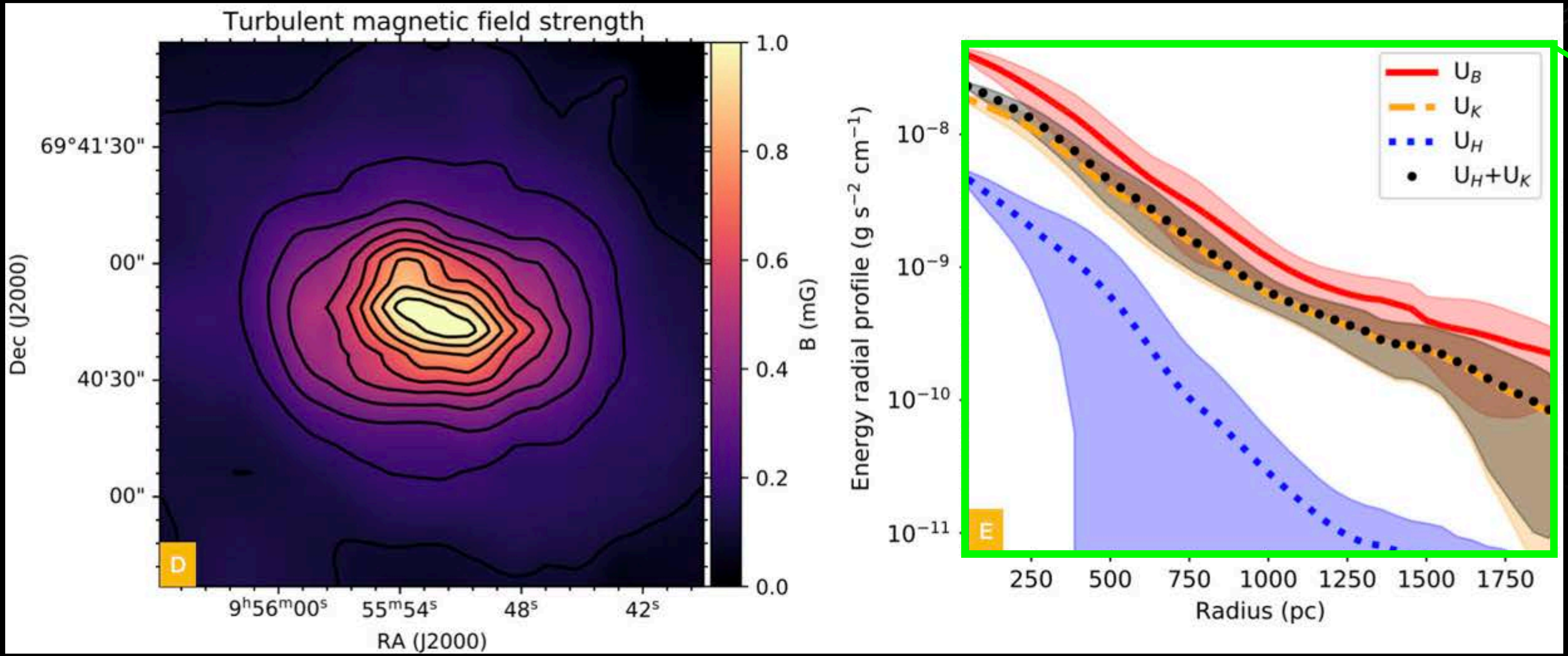
Energy budget:

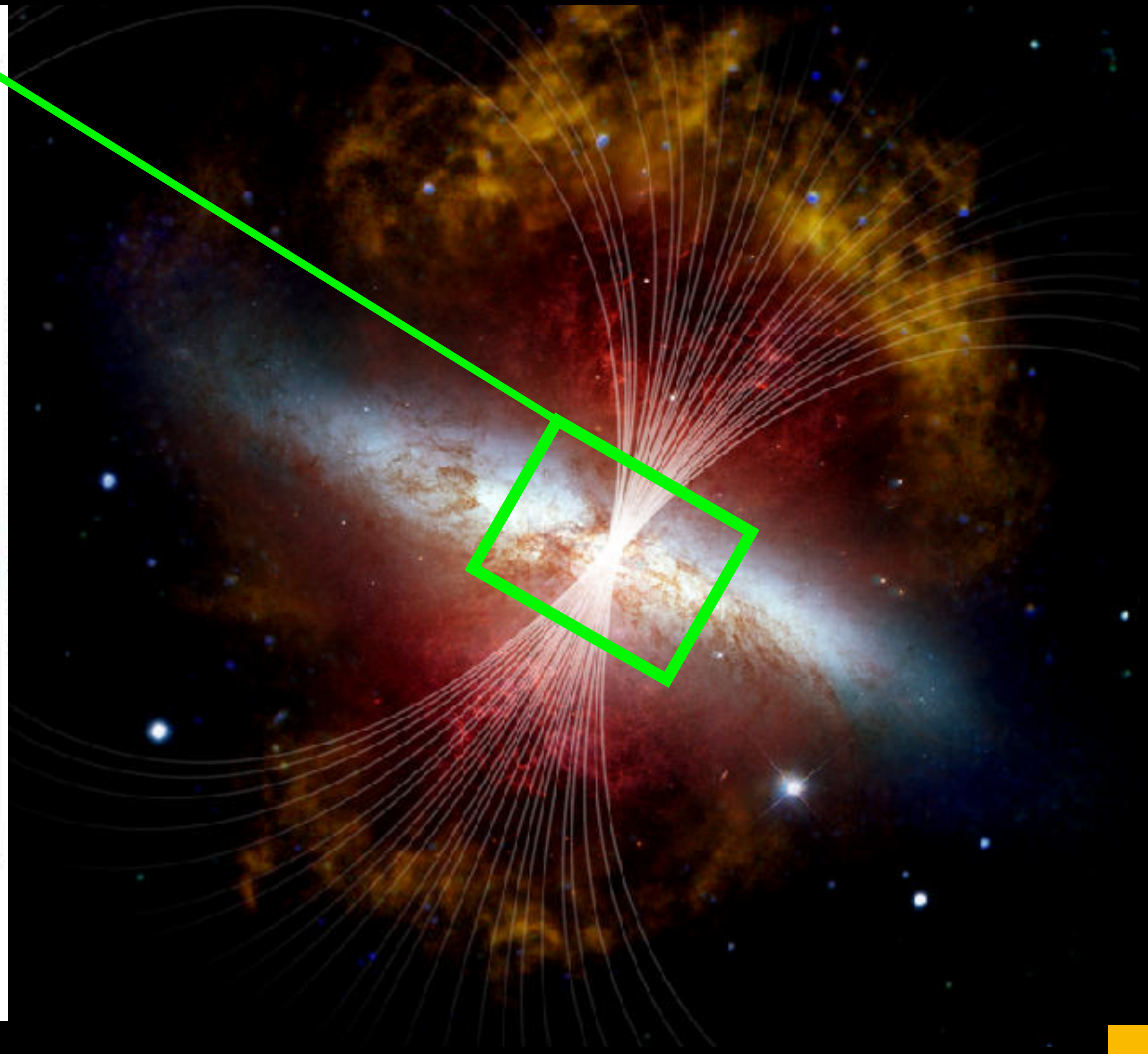
- The beta parameter defines the entrainment between kinetic, thermal, and magnetic energies: $$\beta' = \frac{U_K + U_H}{U_B}$$

Our method:

- The corrected DCF (i.e., large-scale flow) method provides the mean B-field strength within the starburst mask.
- The energy balance shows that turbulent magnetic and kinetic energies are in close equipartition. $\beta' = 0.56 \pm 0.23$

**Galactic outflows permeate the CGM and IGM with astrophysical B-fields**



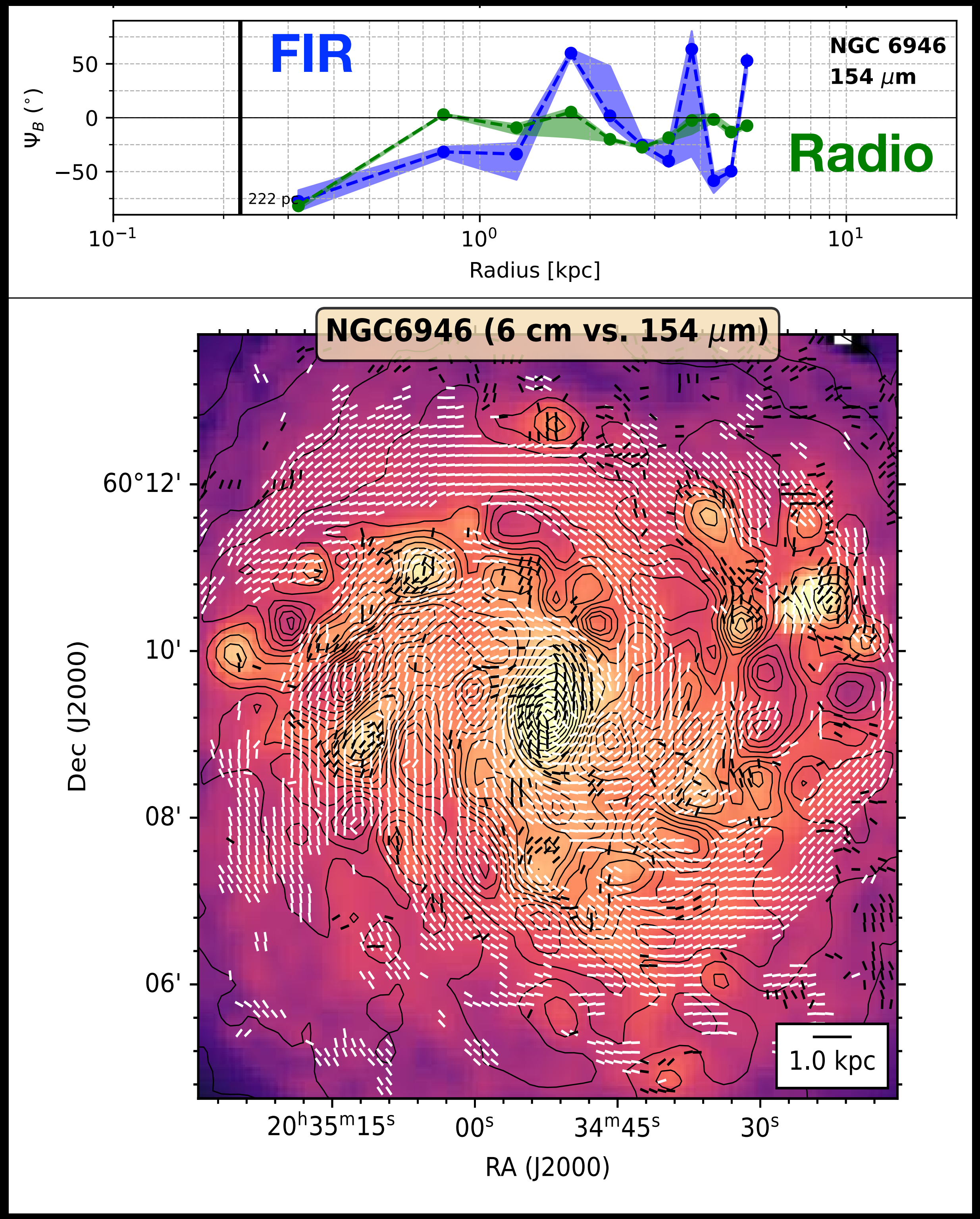
**Lopez-Rodriguez et al. (2021)**

# OUR CURRENT KNOWLEDGE BASED ON RADIO AND FIR OBSERVATIONS

- FIR and Radio B-fields are dominated by a large-scale ordered spiral B-field.

- But, FIR and Radio polarimetric observations do not necessarily trace the same B-field in the ISM of galaxies.

- FIR B-field is statistically more turbulent than Radio B-field.



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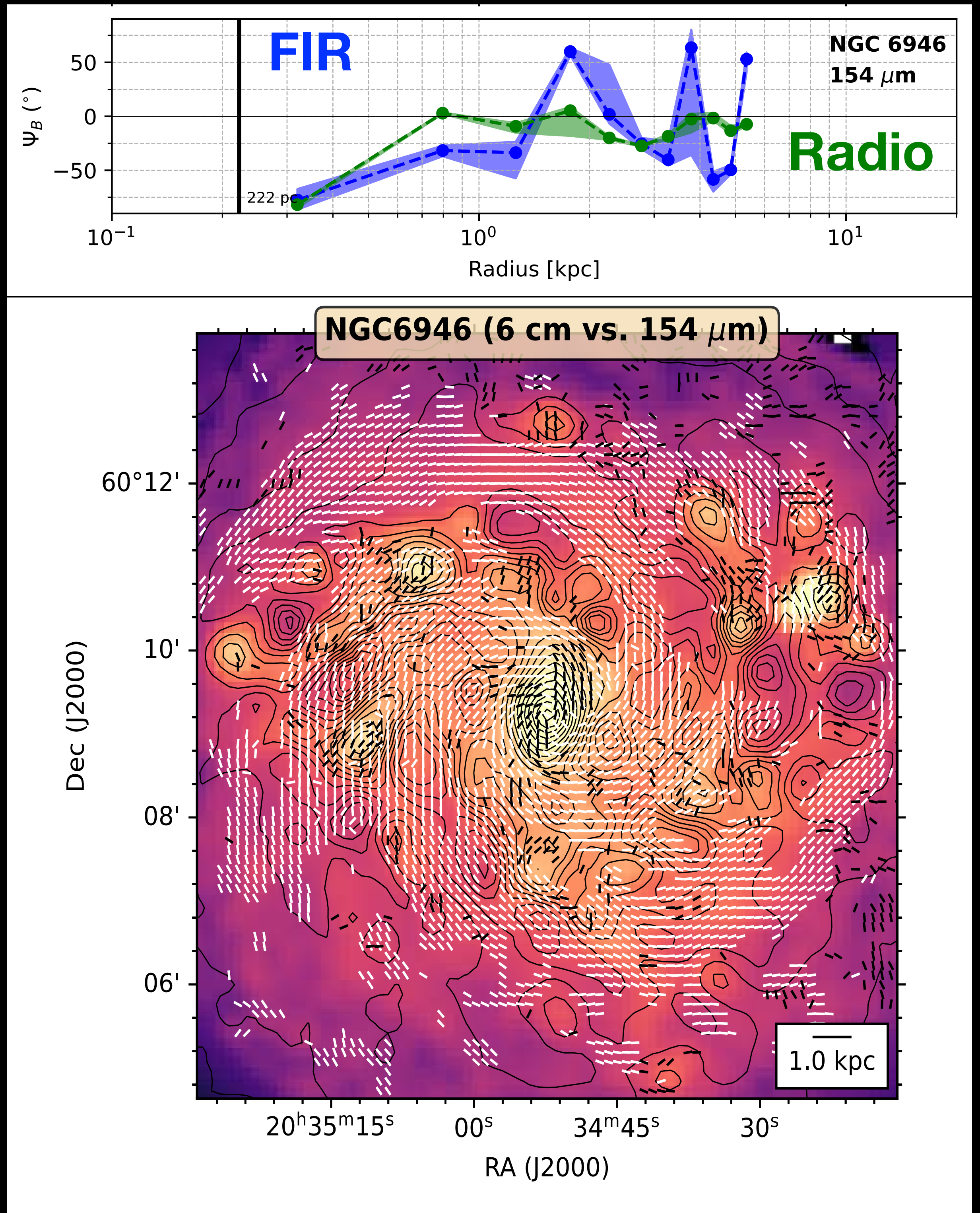


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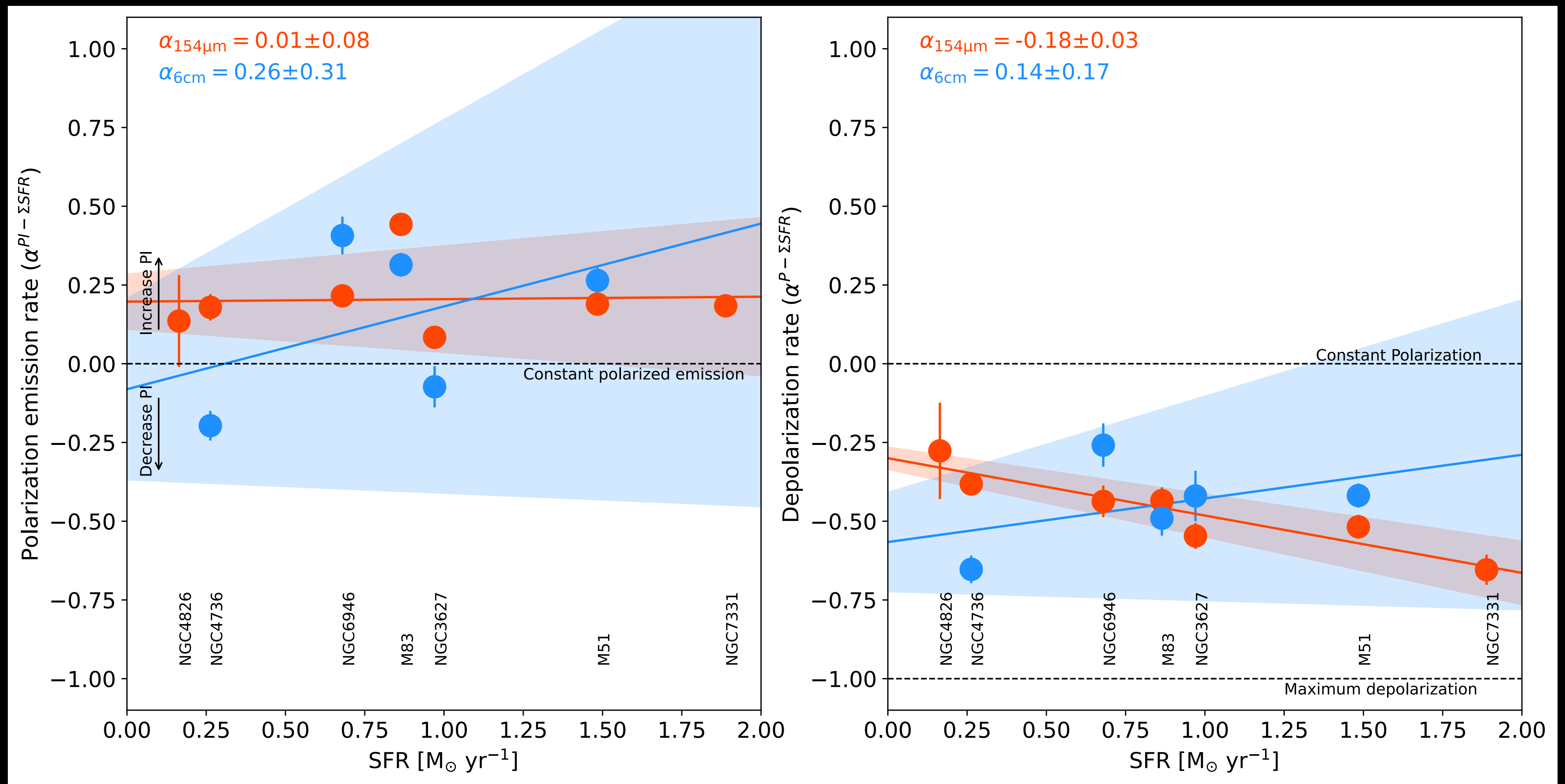
- FIR turbulent B-field arises from the injection of turbulent energy driven by SF in the dense ISM.



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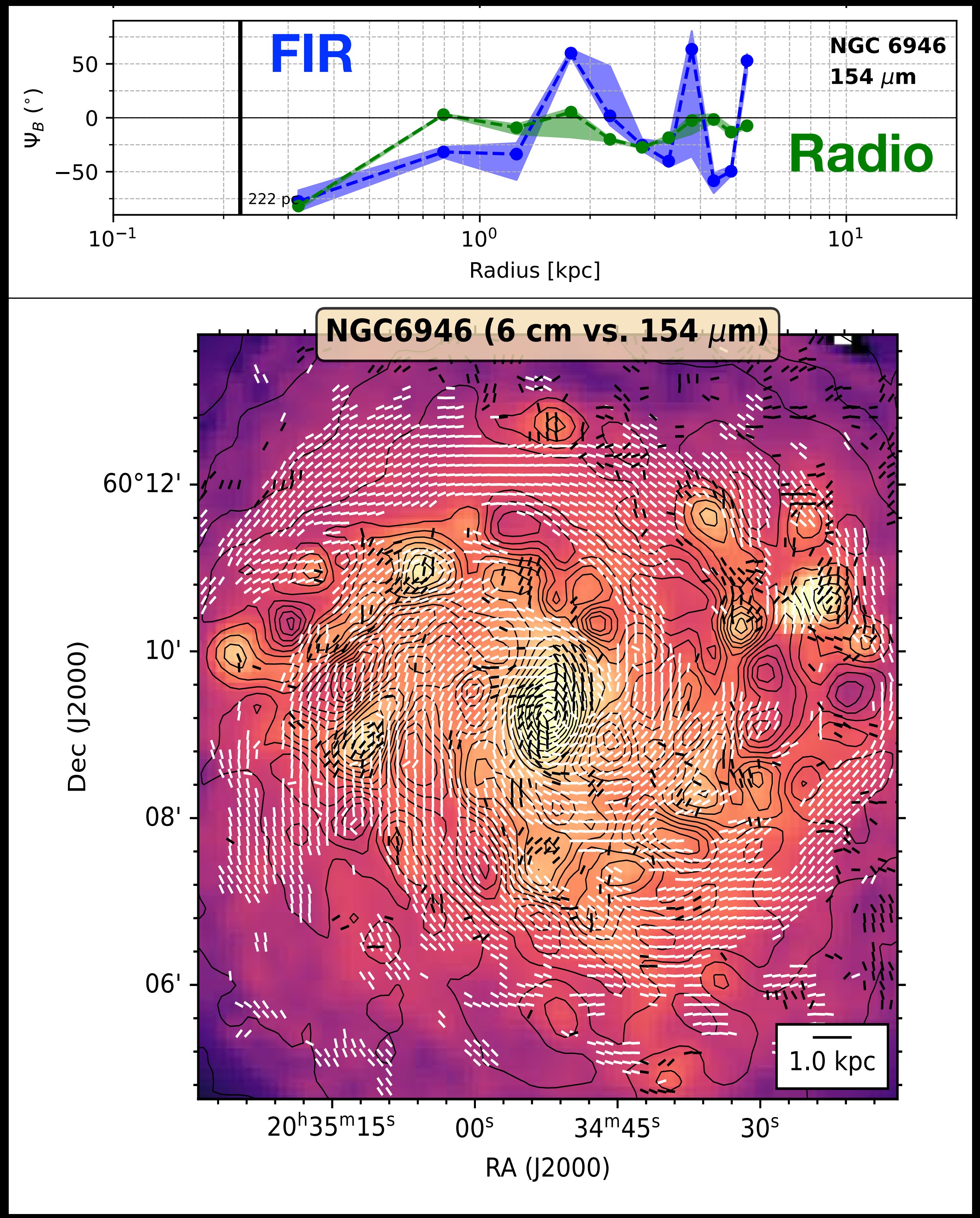
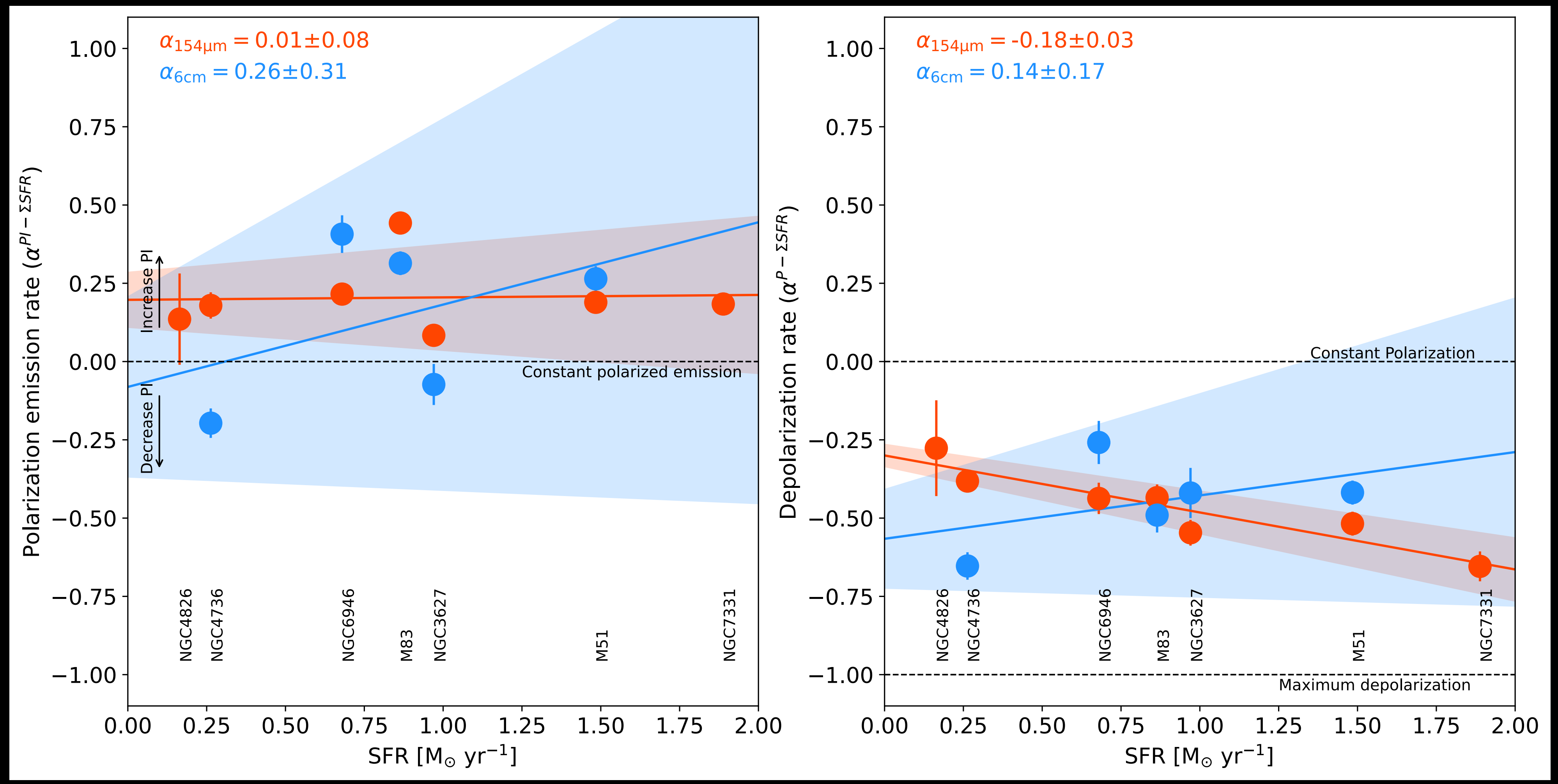


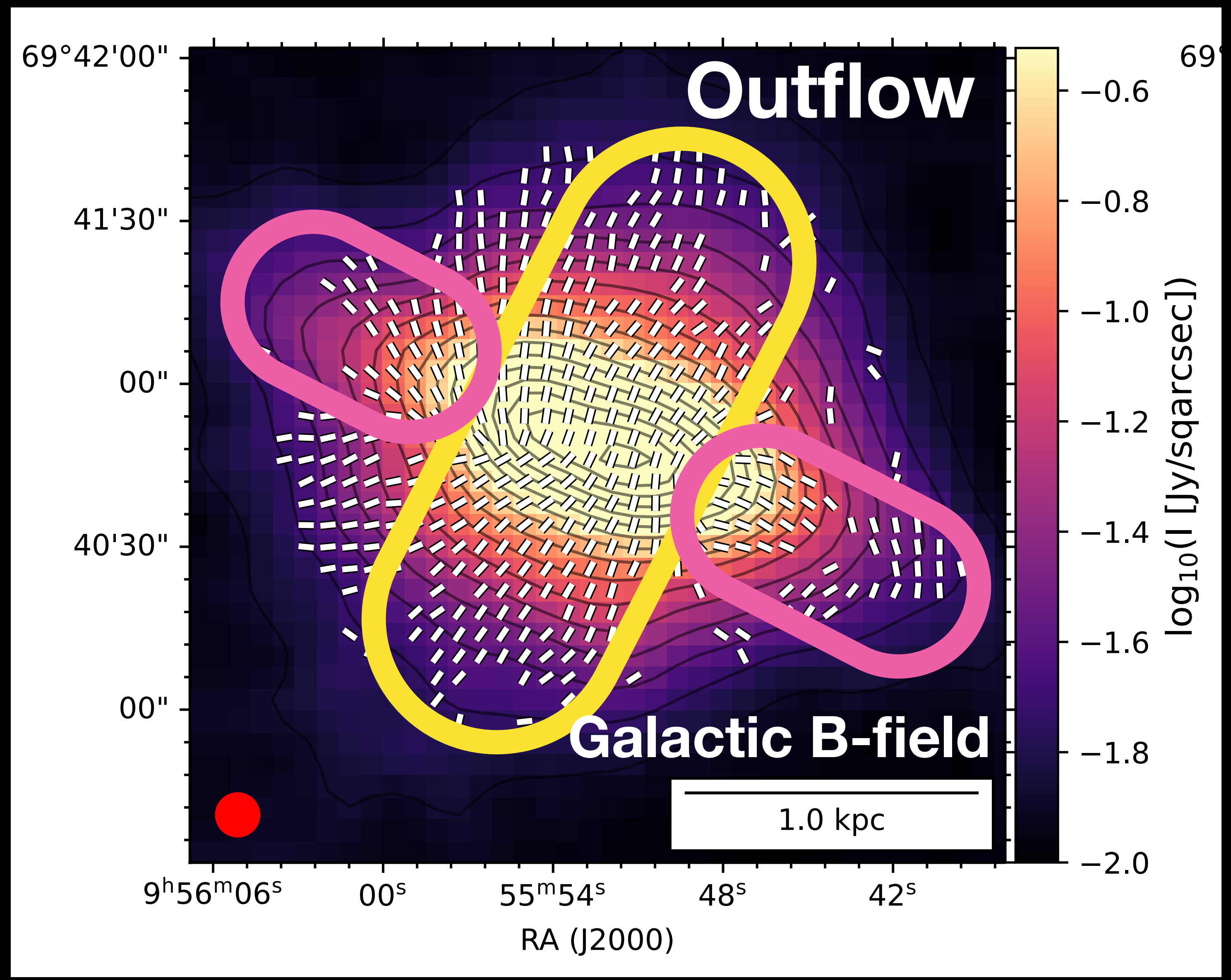

- FIR B-field seems more tightly related to the SF regions than the radio B-fields.
- FIR turbulent B-field arises from the injection of turbulent energy driven by SF in the dense ISM.

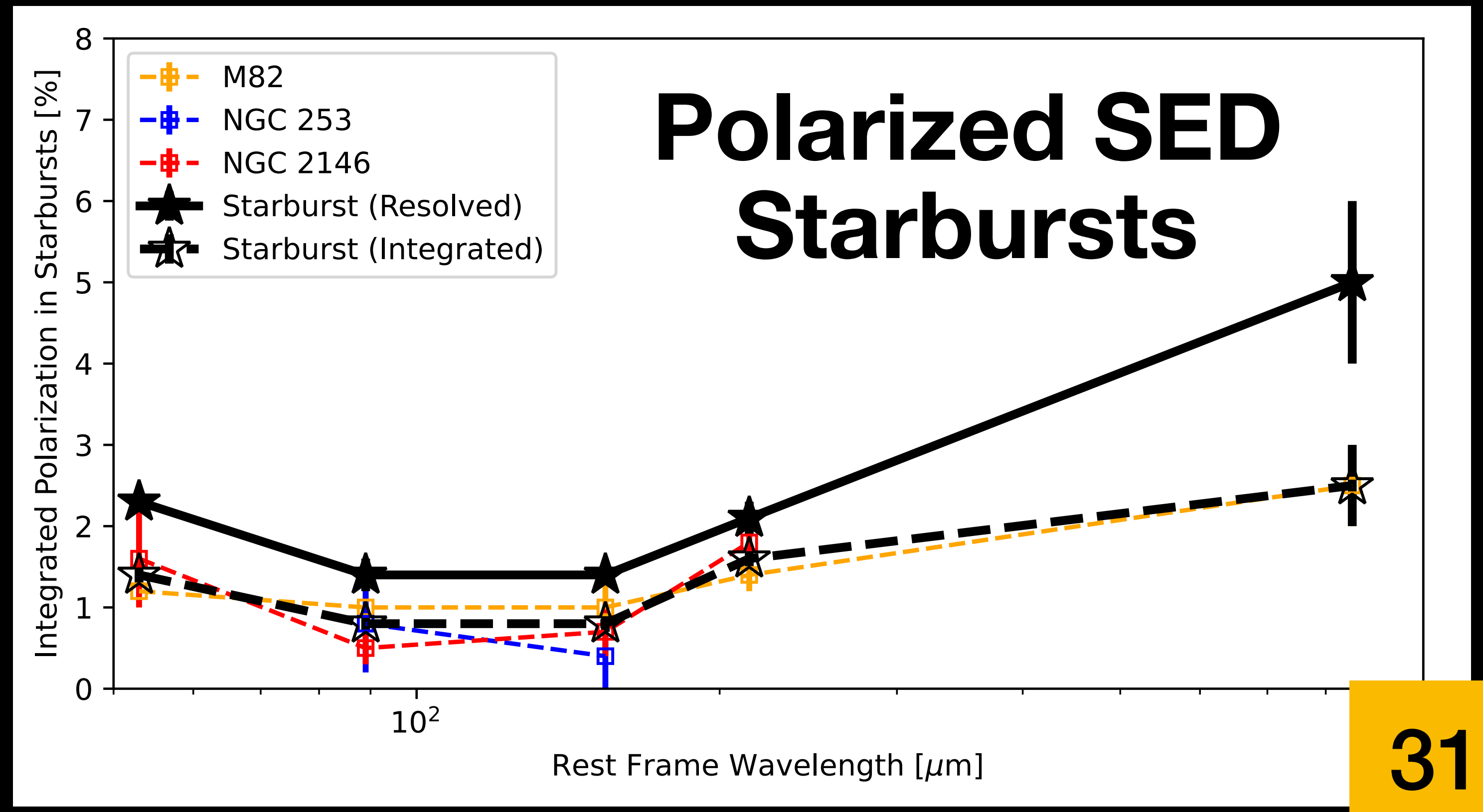



More at

**http://galmagfields.com/**

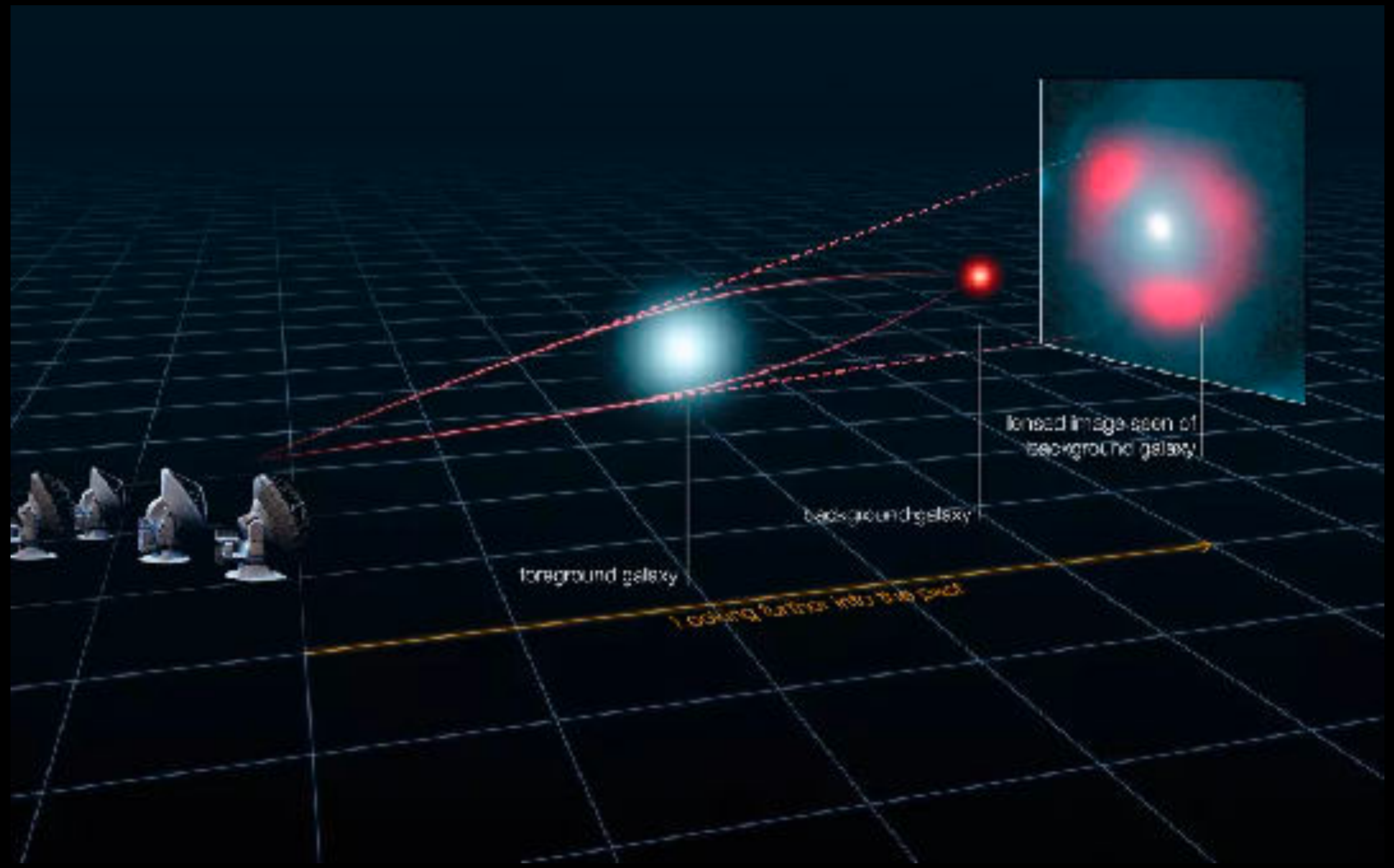
- FIR polarimetric observations can trace the galactic B-fields in starburst galaxies.
- Polarized SED of starburst shows the need for several dust components in galactic outflows.



# Near-Future: B-fields at high redshift using sub-mm polarimetry

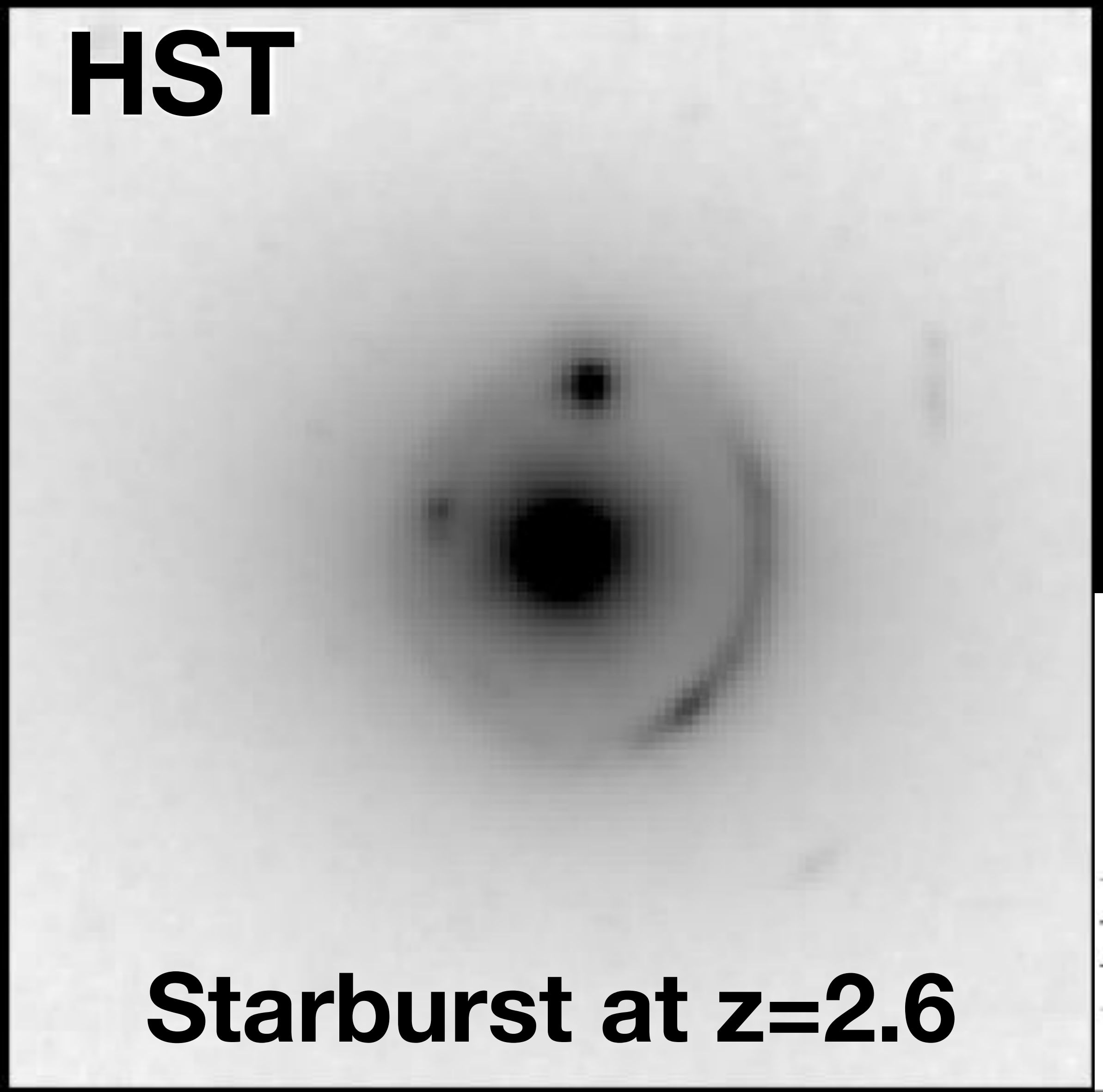
Gravitationally lensed galaxies at high-redshift

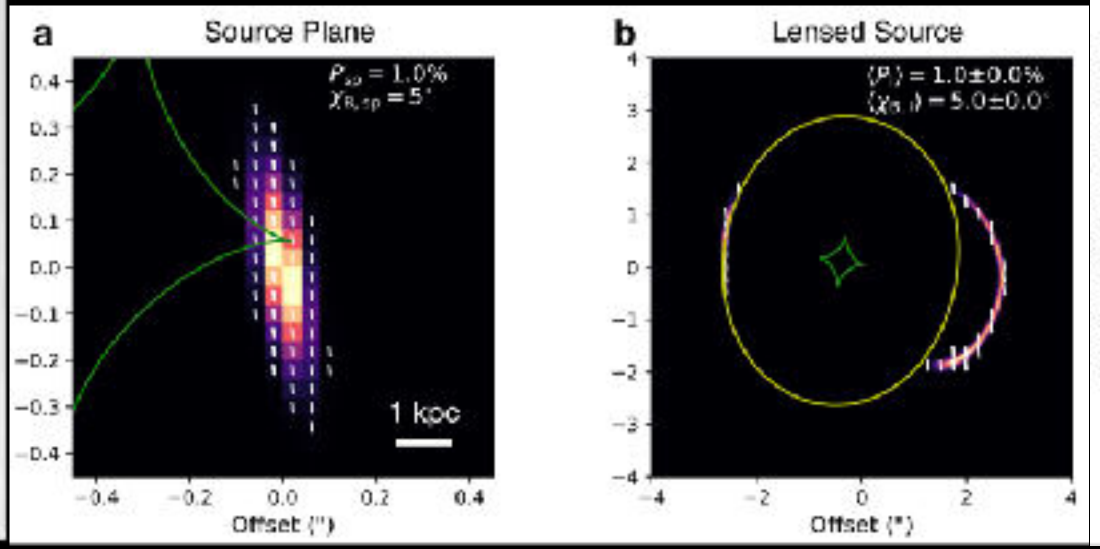


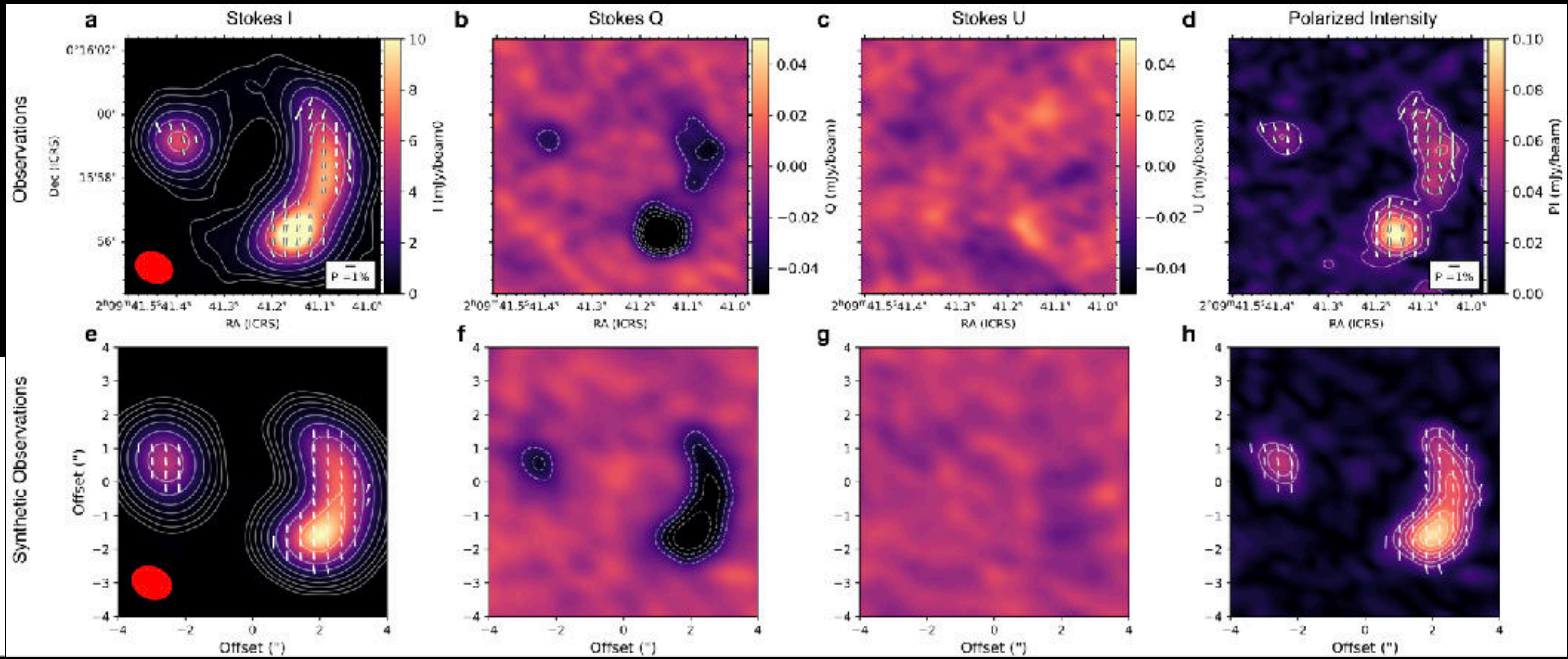
2 kpc-scale ordered B-field parallel to a fast rotating disk in a starburst at 3Gyr after Big Bang.

ALMA polarimetric observations

860 um (dust continuum polarization) at 0.5” resolution



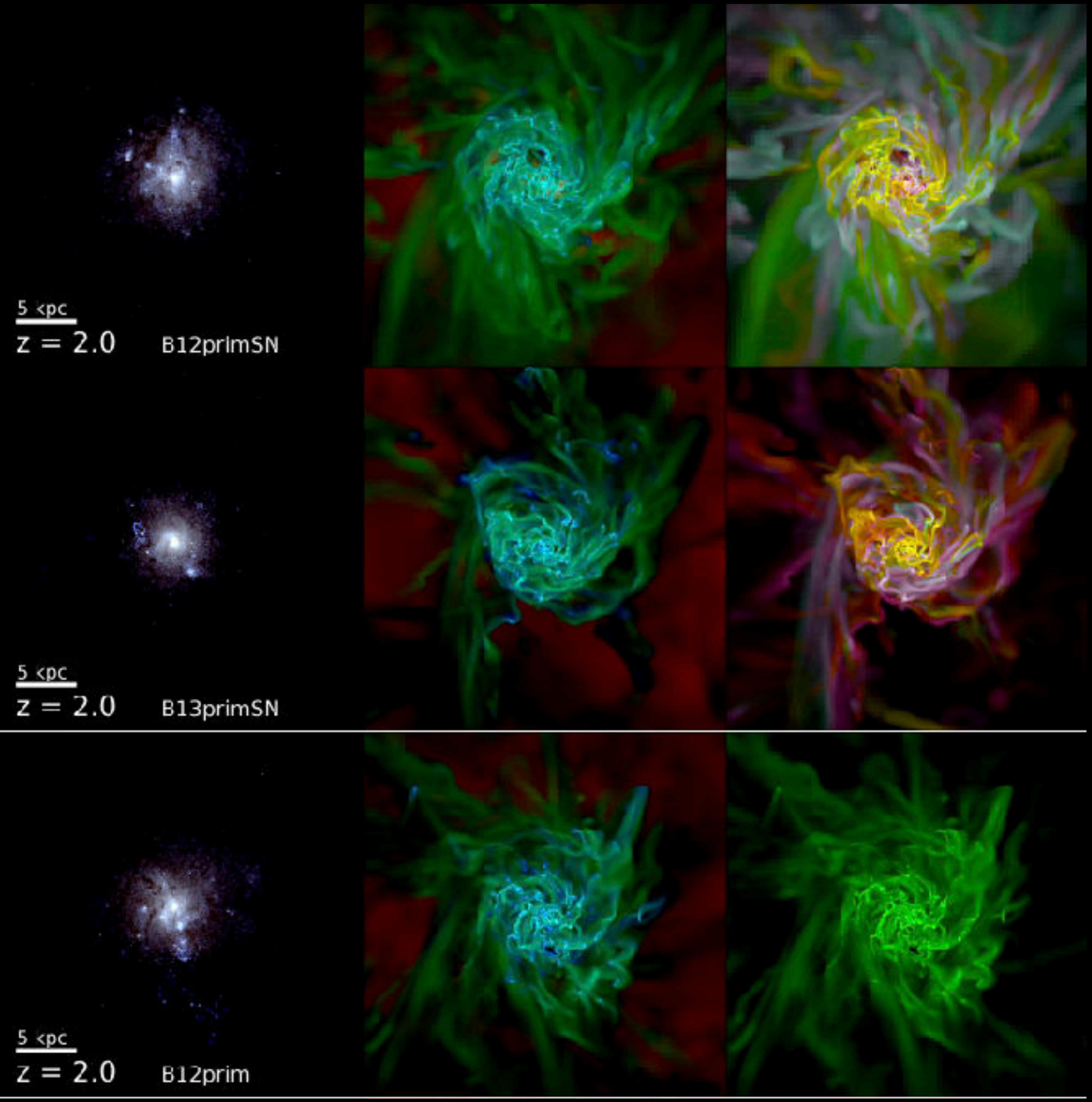

Geach, Lopez-Rodriguez et al. (in prep.)

Gravitational lensing polarimetric model

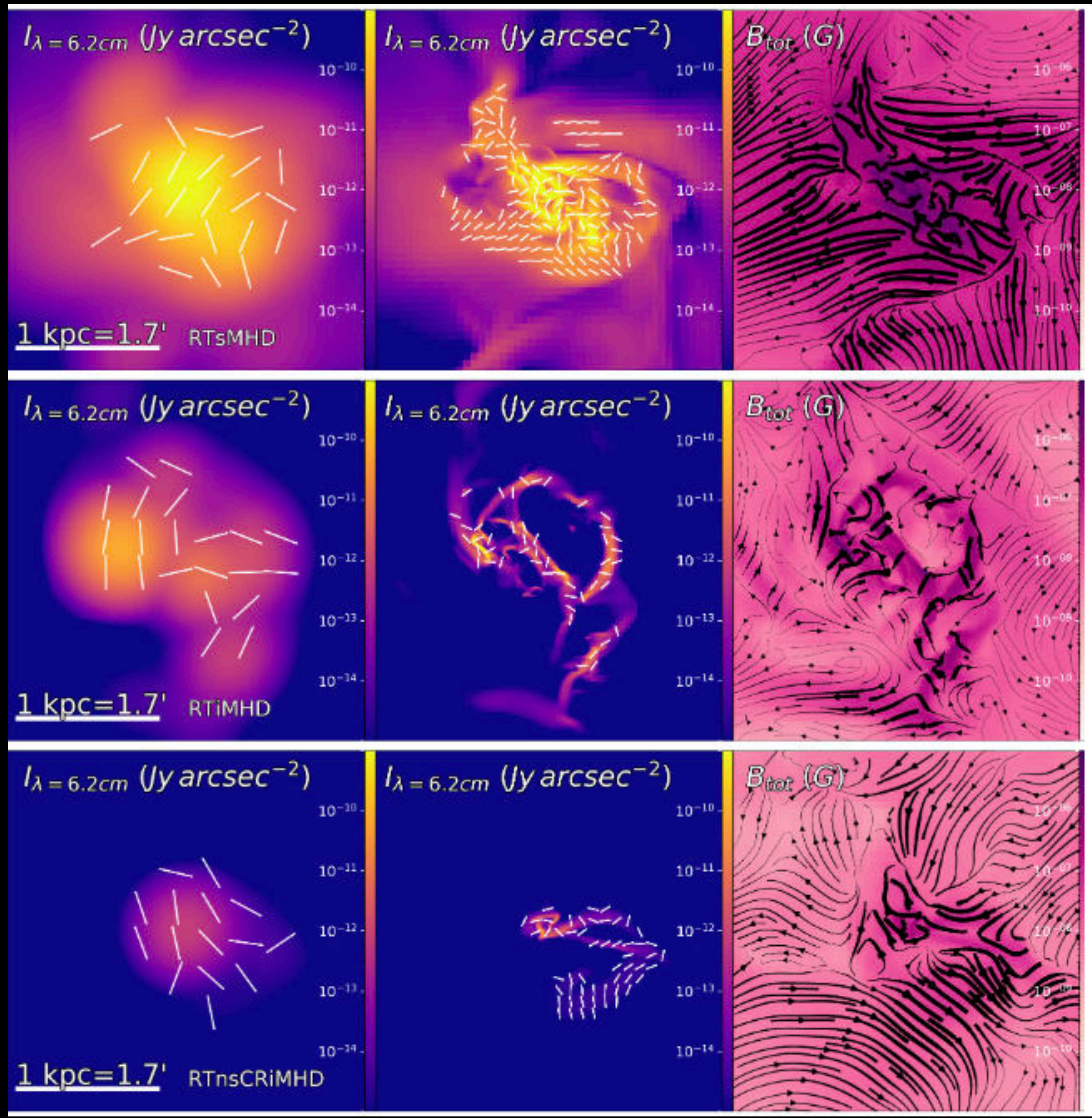
# Near-Future: MHD simulations of galaxies

RTCRMHD simulations

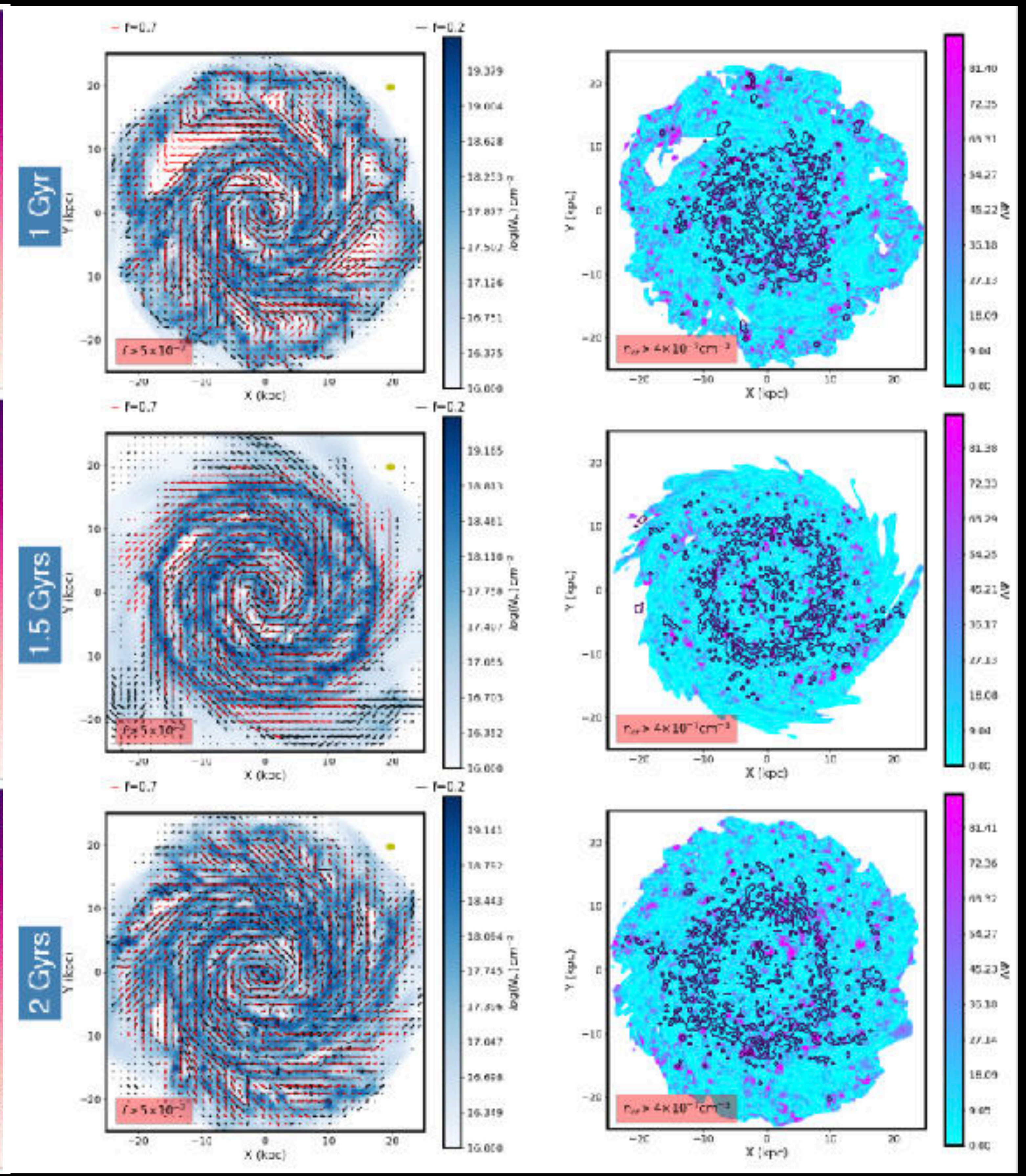
Synthetic observations at radio and FIR wavelengths




Martin-Alvarez, S. et al. (2020)




Martin-Alvarez, S. et al. (2022)




Ntormousi, E. et al. (2023, in prep.)

# Study how molecular clouds inherit their B-fields within the galactic environment

**MHD model** **Simulated observations** **Zoom-in** **Quantification of magnetization in molecular clouds**


- MHD simulations with 10 pc spatial resolution (Martin-Alvarez et al. 2022).
- Simulated observations at 50 pc spatial resolution as observed with PRIMA within 1h on-source time.
- B-field orientation vs. density gradients for a strong and a weak B-field.

# THE COSMIC HISTORY OF THE B-FIELDS IN GALAXY EVOLUTION USING FIR/SUB-MM POLARIMETRY

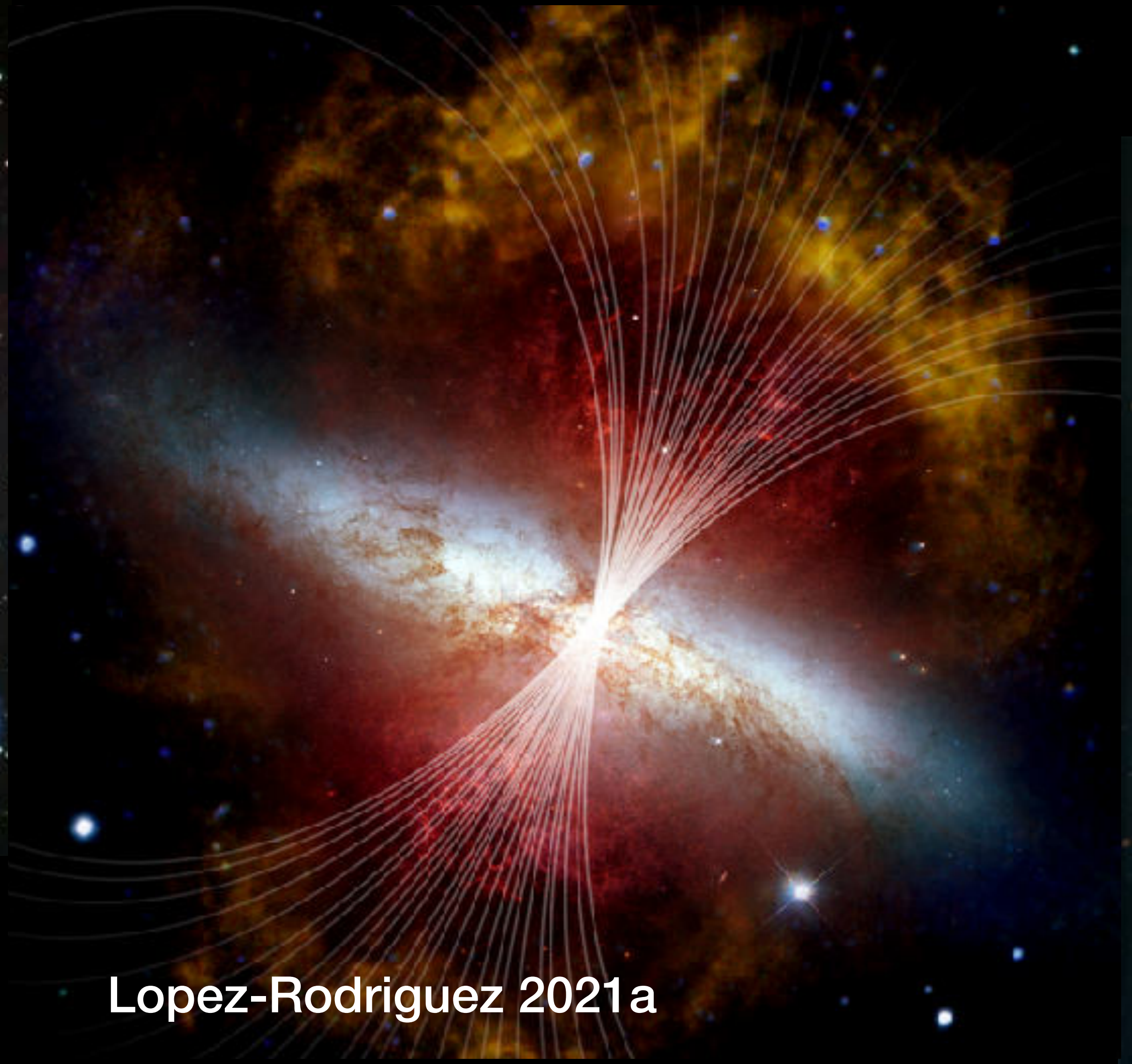
**Mergers**

Lopez-Rodriguez 2022c

**Active galaxies, mergers**

Lopez-Rodriguez 2021b

**Galactic Outflows**

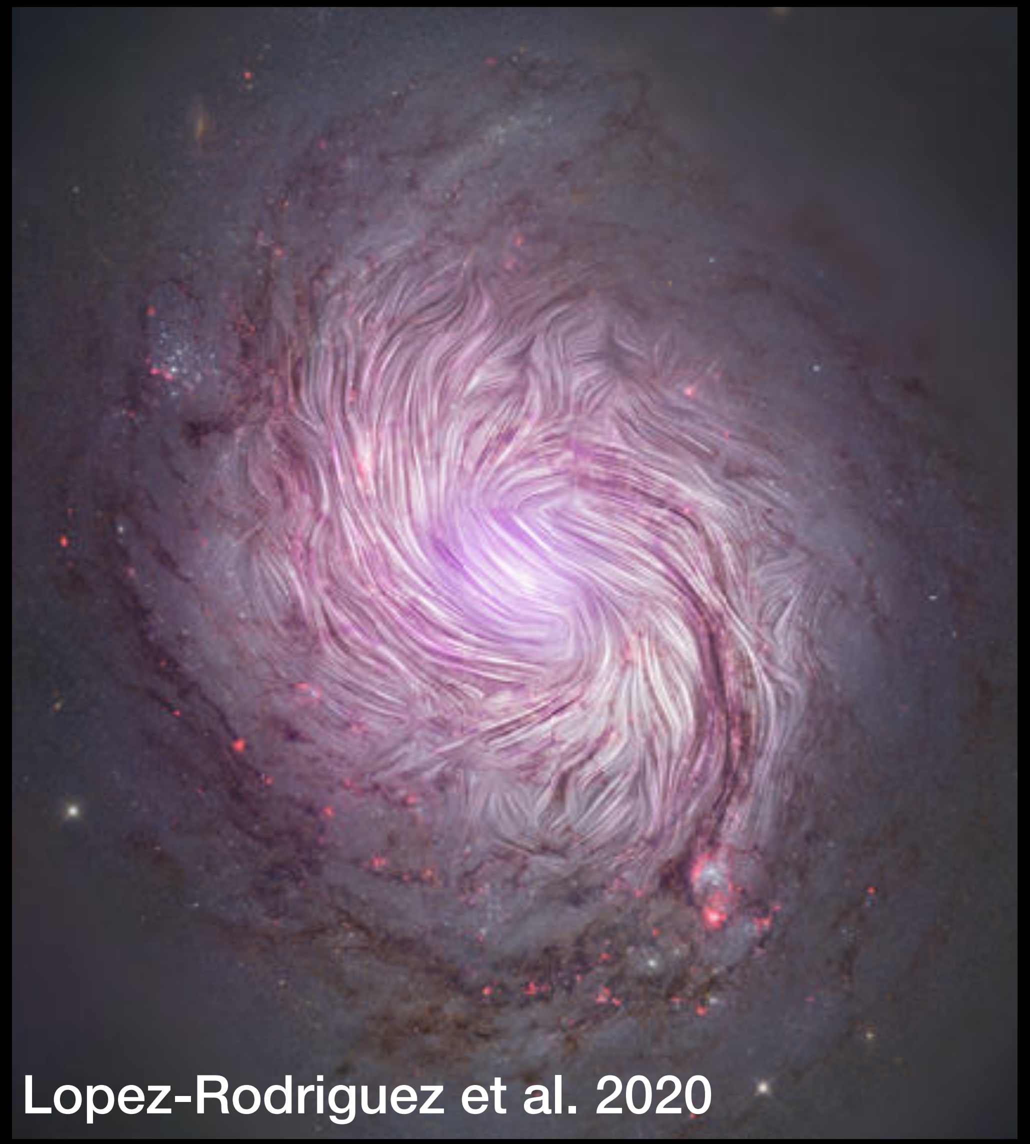


Lopez-Rodriguez 2021a

**Interaction, Star formation, galactic dynamo**

Borlaff et al. 2021

**AGN, Star formation, galactic dynamo**



Lopez-Rodriguez et al. 2020

- How did the evolution of galaxies in mergers affect magnetic fields?
- Is the circumgalactic medium magnetized?
- How has the magnetic field been amplified by interaction/SF in galaxies?
- What is the structure of the magnetic field around an active nucleus?