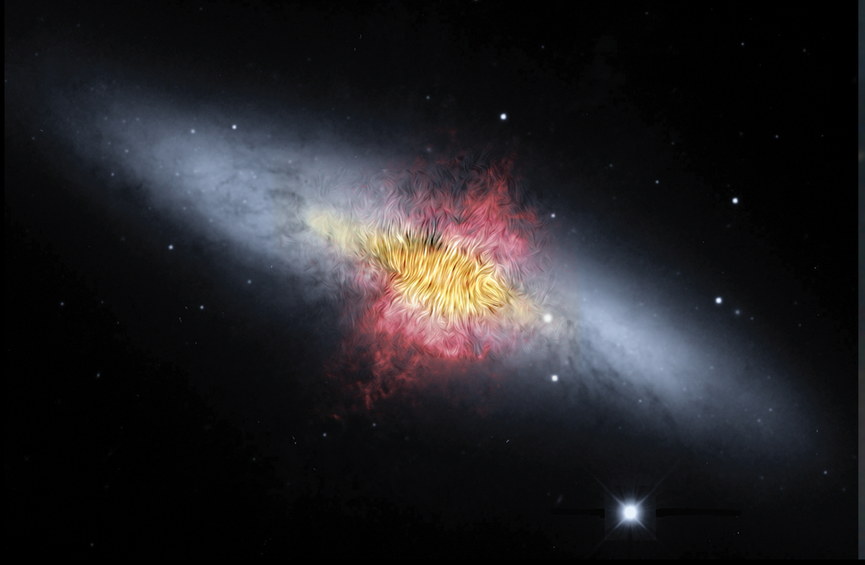


SALSA: Survey of extragalactic magnetism with SOFIA

Enrique Lopez-Rodriguez

Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)

Stanford University

Fall 2024 —> Associate Professor at the University of South Carolina

(Soon: hiring 3+ faculty to join the astronomy group)



SURVEY OF EXTRAGALACTIC MAGNETISM WITH SOFIA (SALSA)

LEGACY TEAM

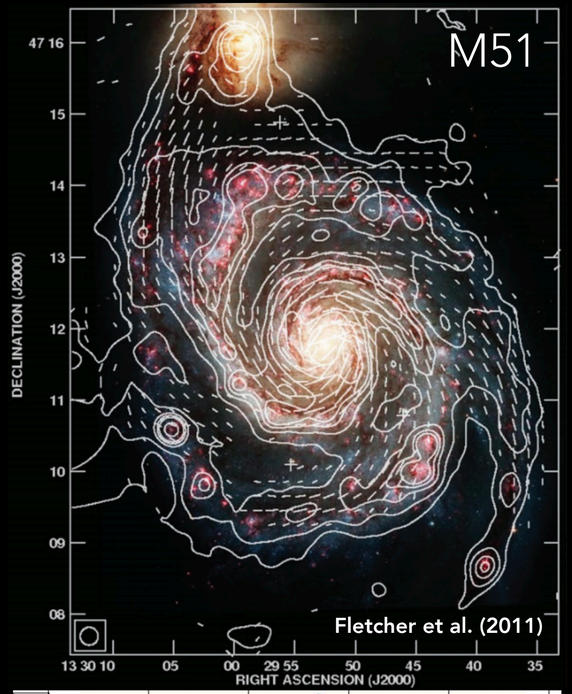
Team Member	Affiliation
Enrique Lopez-Rodriguez (PI)	**KIPAC, Stanford University, USA**
Sui Ann Mao (co-PI)	**Max Planck For Radio Astronomy at Bonn, Germany**
Rainer Beck	Max Planck For Radio Astronomy at Bonn, Germany
John Beckman	Instituto de Astrofisica de Canarias, Spain
Susan Clark	Stanford University, USA
Daniel Dale	University of Wyoming, USA
Ignacio del Moral Castro	Universidad Católica de Chile, Chile
Tanio Diaz-Santos	University of Crete, Greece
Darrell C. Dowell	Jet Propulsion Laboratory, USA
Doyal A. Harper	University of Chicago, USA
Annie Hughes	IRAP, Toulouse, France
Pamela Marcum	NASA Ames Research Center, USA

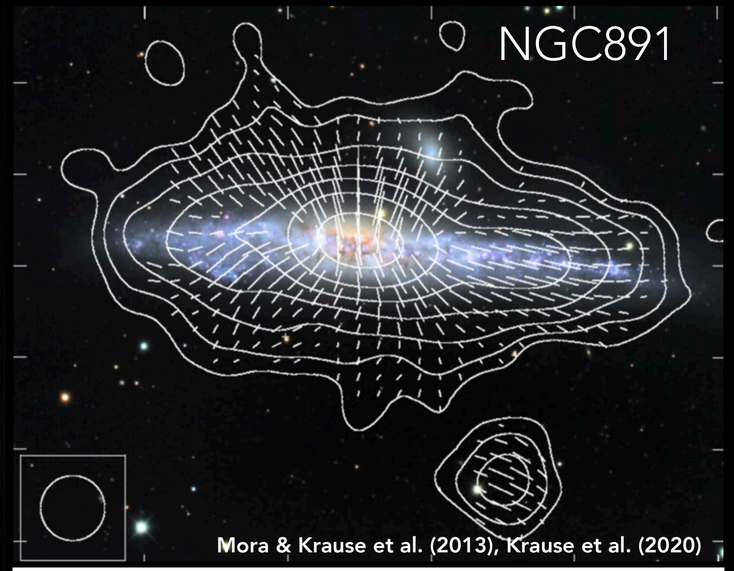
Team Member	Affiliation
Sergio Martinez Alvarez	KIPAC/Stanford, USA
Evangelia Ntormousi	University of Crete, Greece
Gina Panopoulou	Chalmers University
William T. Reach	SOFIA Science Center, NASA Ames, USA
Julia Roman-Duval	Space Telescope Science Institute, USA
Alejandro Serrano Borlaff	NASA Ames, USA
Kandaswamy Subramanian	Inter-University Centre for Astronomy and Astrophysics, India
Mehrnoosh Tahani	KIPAC/Stanford
Konstantinos Tassis	University of Crete, Greece
Le Ngoc Tram	Max Planck For Radio Astronomy at Bonn, Germany
Ellen Zweibel	University of Winsconsin, USA

OUR CURRENT KNOWLEDGE USING RADIO POLARIMETRIC OBSERVATIONS

Spiral galaxies

- 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.





Edge-on galaxies

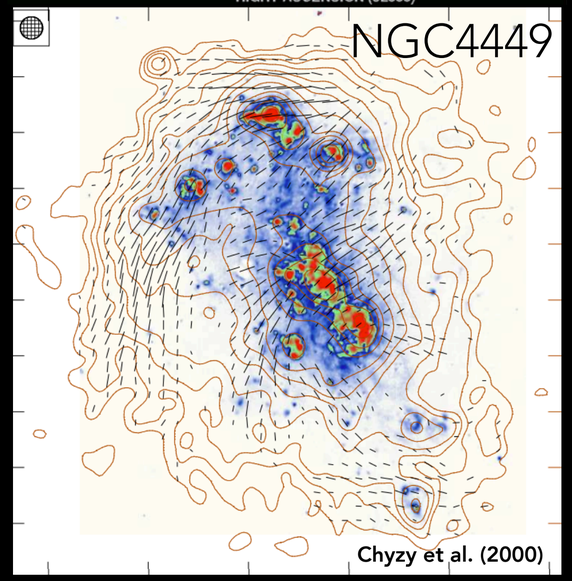
- X-shape structure is an underlined feature of spiral galaxies and extends several kpc into the halo.

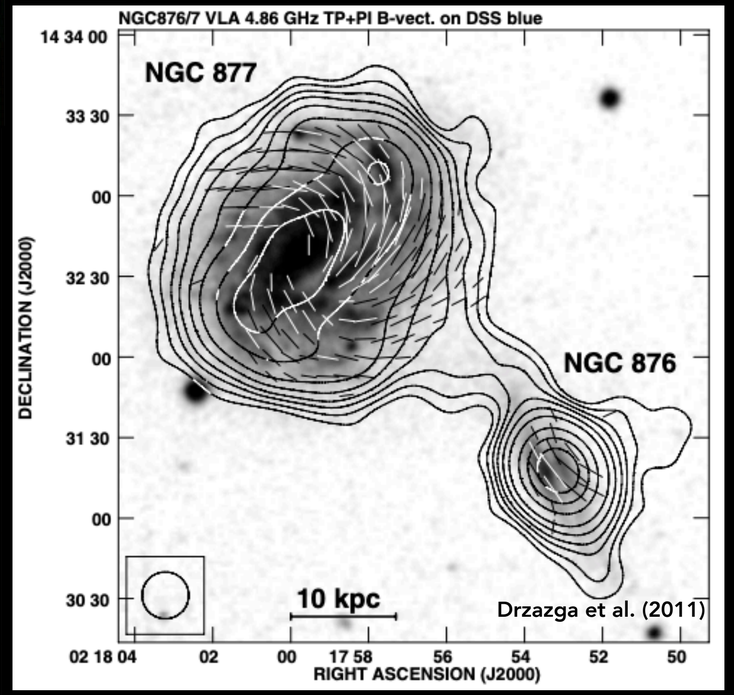
Irregular galaxies

-Slowly rotating galaxies may reveal strong total magnetic fields.

-Partially ordered/regular field, spiral pattern, and radial pattern.

- α –Ω may be operating.



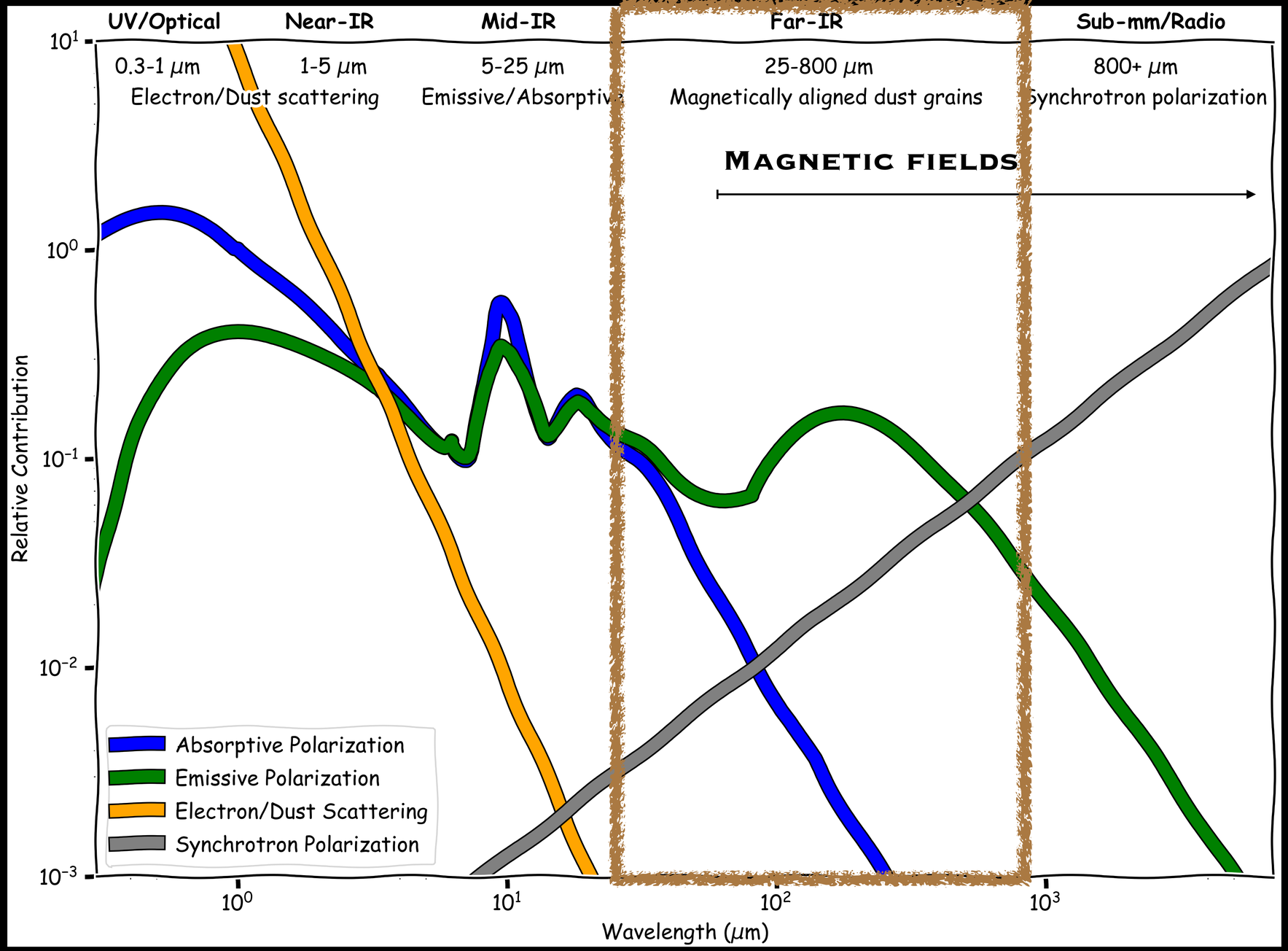


Interacting galaxies

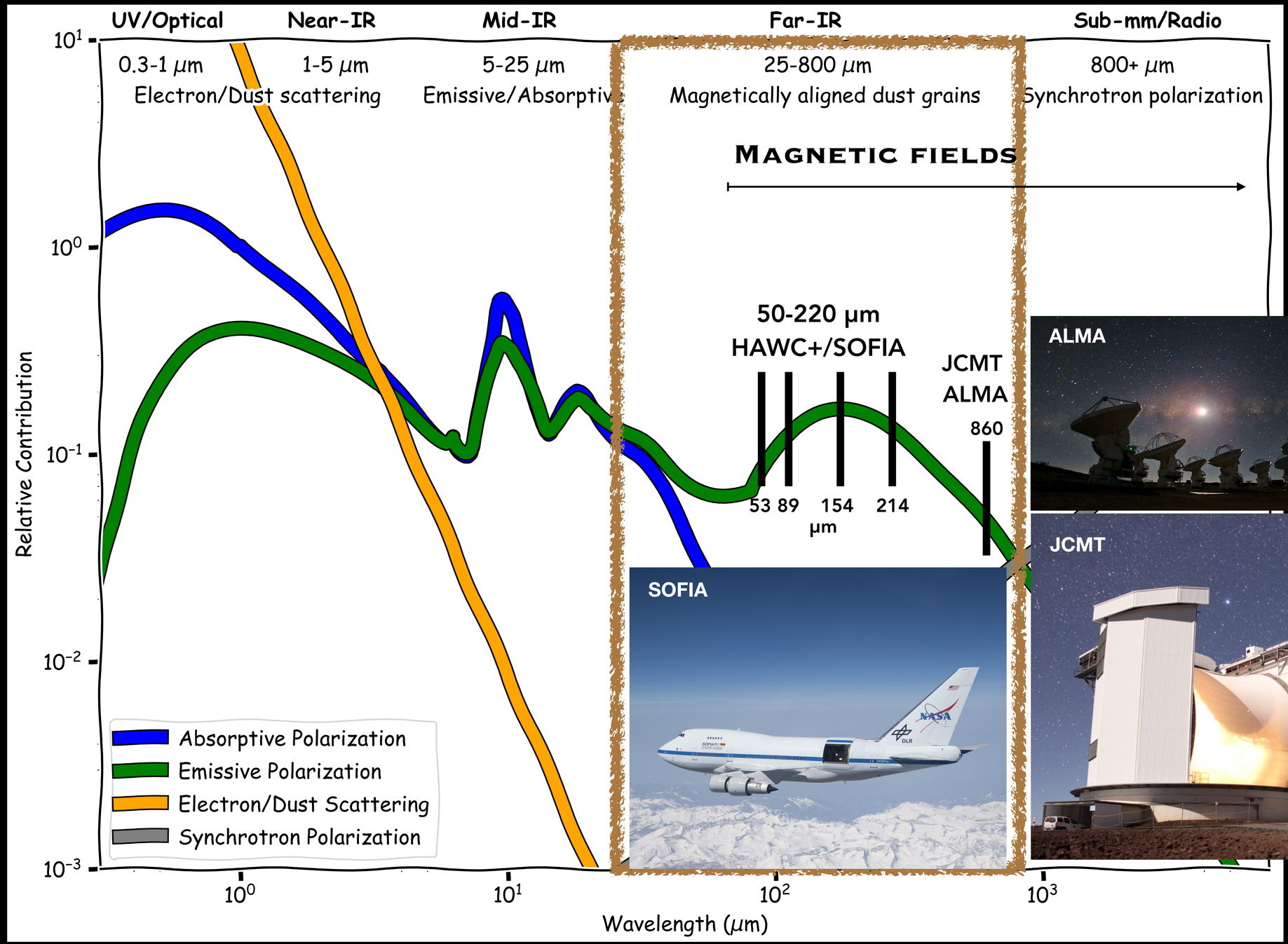
- B-fields become aligned along the compression front or perpendicular to the velocity gradients.
- Gas flows, due to merger, make turbulent fields highly anisotropic.
- Average B-field strength is stronger than in normal galaxies, but the mean P is low, which implies tangled B-fields.

Beck et al. (2015, 2019)

OUR APPROACH: MAGNETICALLY ALIGNED DUST GRAINS



FIR-SUB-MM OBSERVATIONS: MAGNETICALLY ALIGNED DUST GRAINS



SURVEY OF EXTRAGALACTIC MAGNETISM WITH SOFIA (SALSA)

GOAL

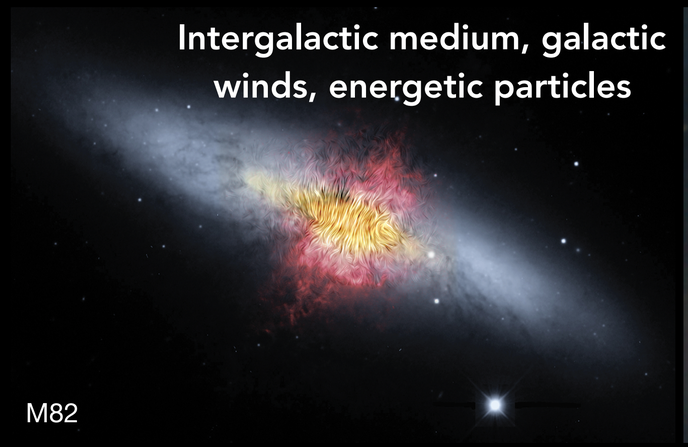
First comprehensive study of the B-fields in the multi-phase ISM of nearby galaxies as a function of gas dynamics and galaxy types from hundred- to kpc-scale galactic environments.

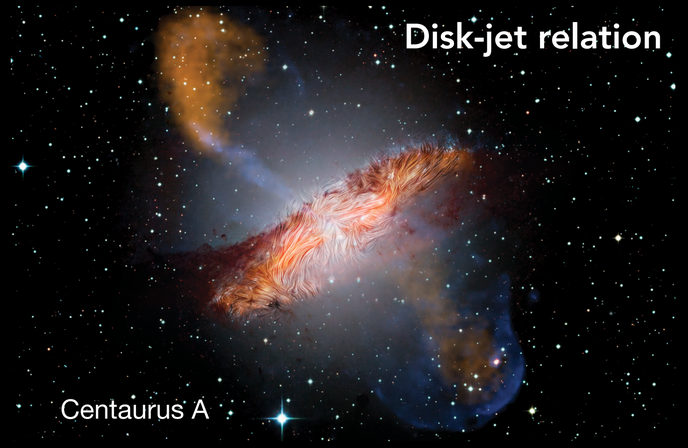
Data ready for science at **http://galmagfields.com/**

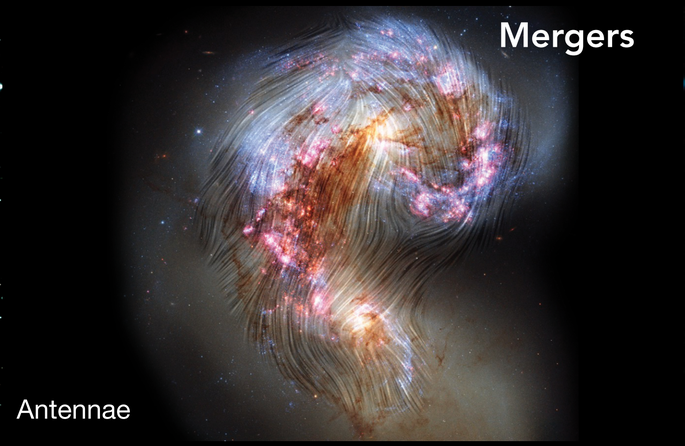
Data products:

- FIR polarimetric observations (Stokes IQU)
- Radio polarimetric observations (Stokes IQU)
- CO and HI gas (moments 0, 1, 2)
- Dust temperature and column density
- MOHAWC python code to perform analysis of magnetic pitch angles

SALSA RESULTS: B-FIELDS PERMEATE THE DENSE AND COLD ISM AND CGM

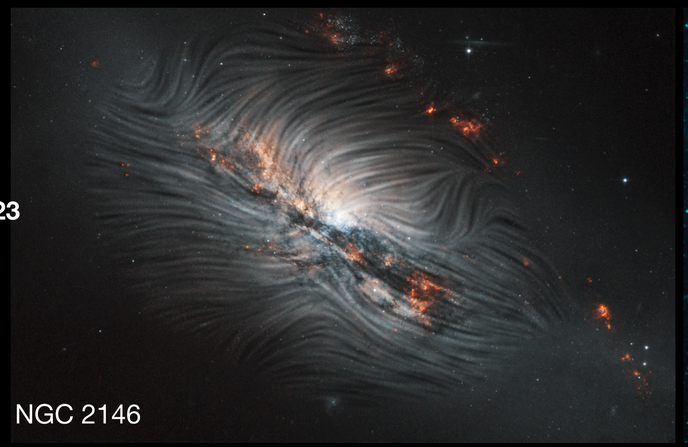


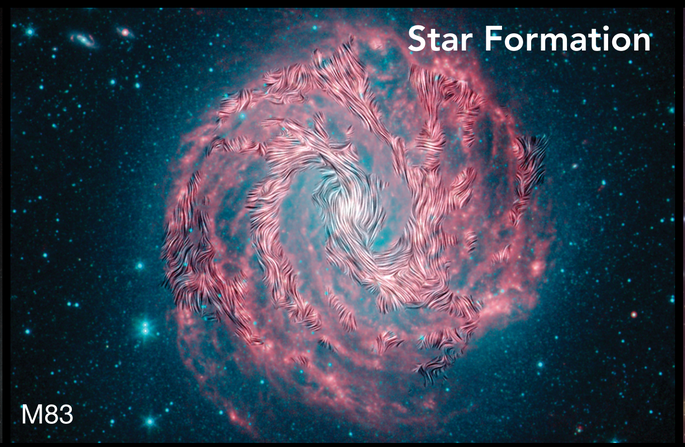




Undergrad
Surgent et al. 2023

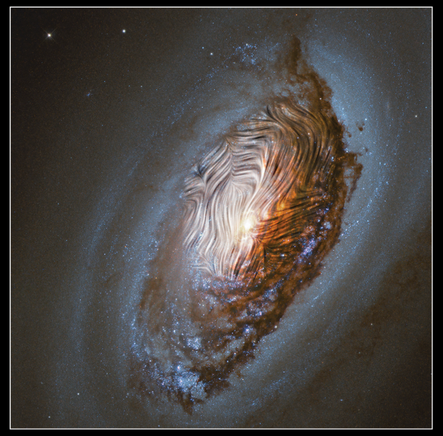
Postdoc
Borlaff et al. 2021, 2023





Borlaff et al. (2021, 2023)
López-Rodríguez (2020, 2021a,b, 2022b,c, 2023a,c)
Martin-Alvarez et al. (2024)

SPIRAL GALAXIES

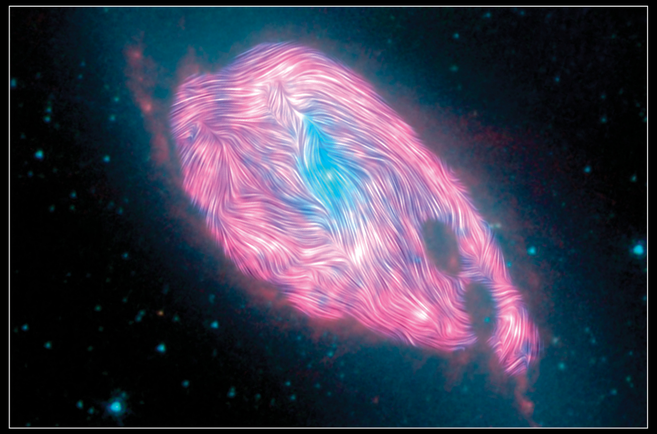


NGC 4826

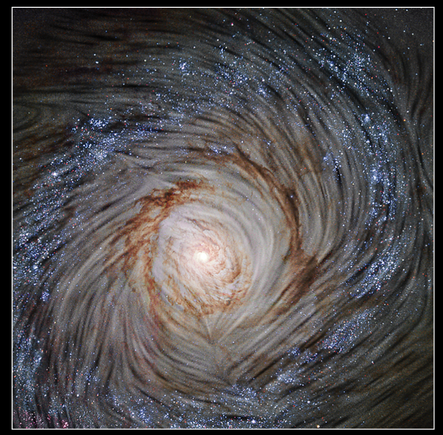
NGC 1068

M51

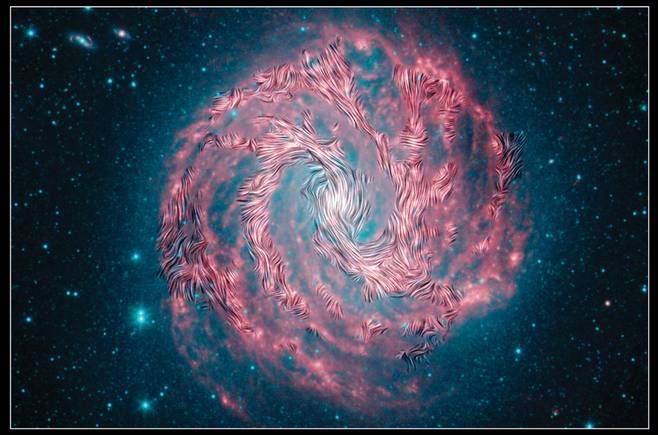
NGC 6946



NGC 3627



NGC 4736



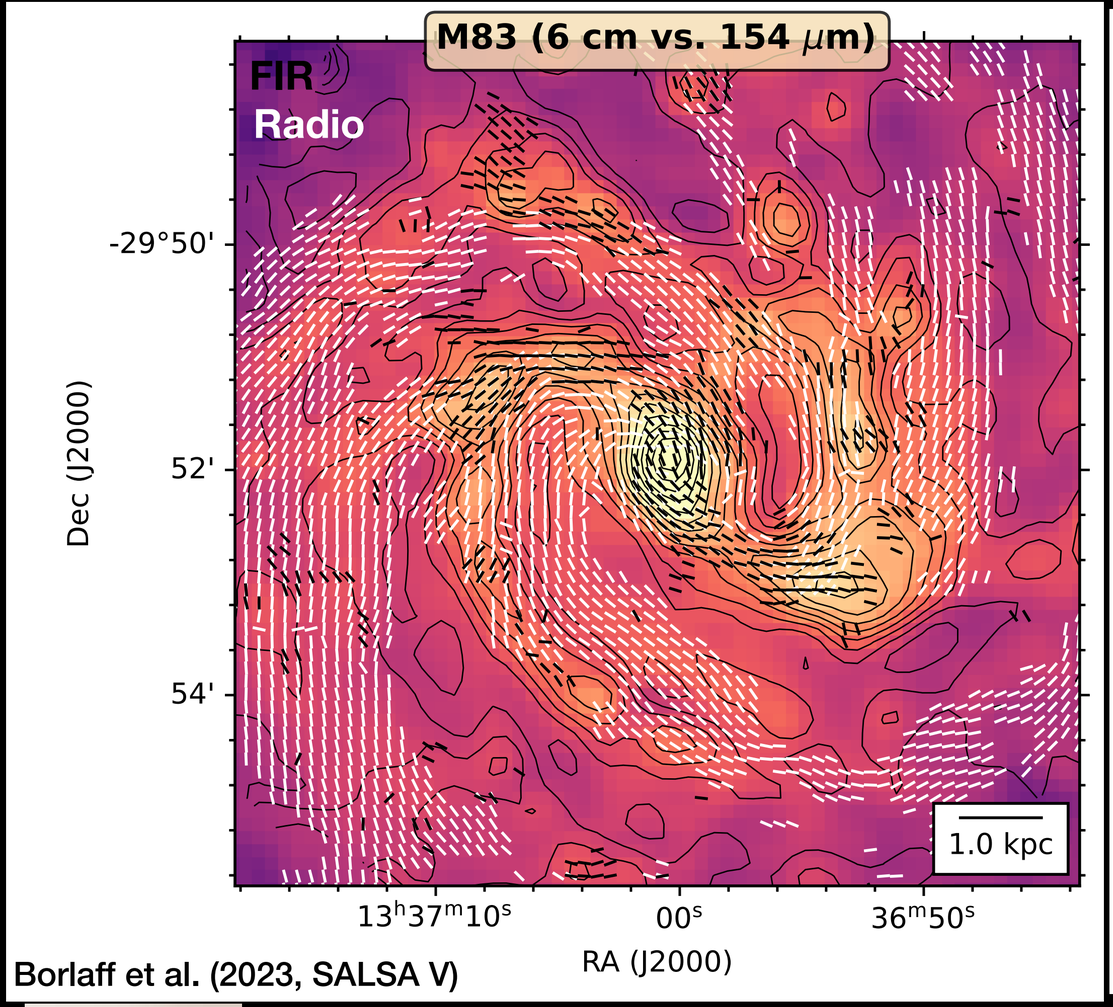
M83

NGC 7331

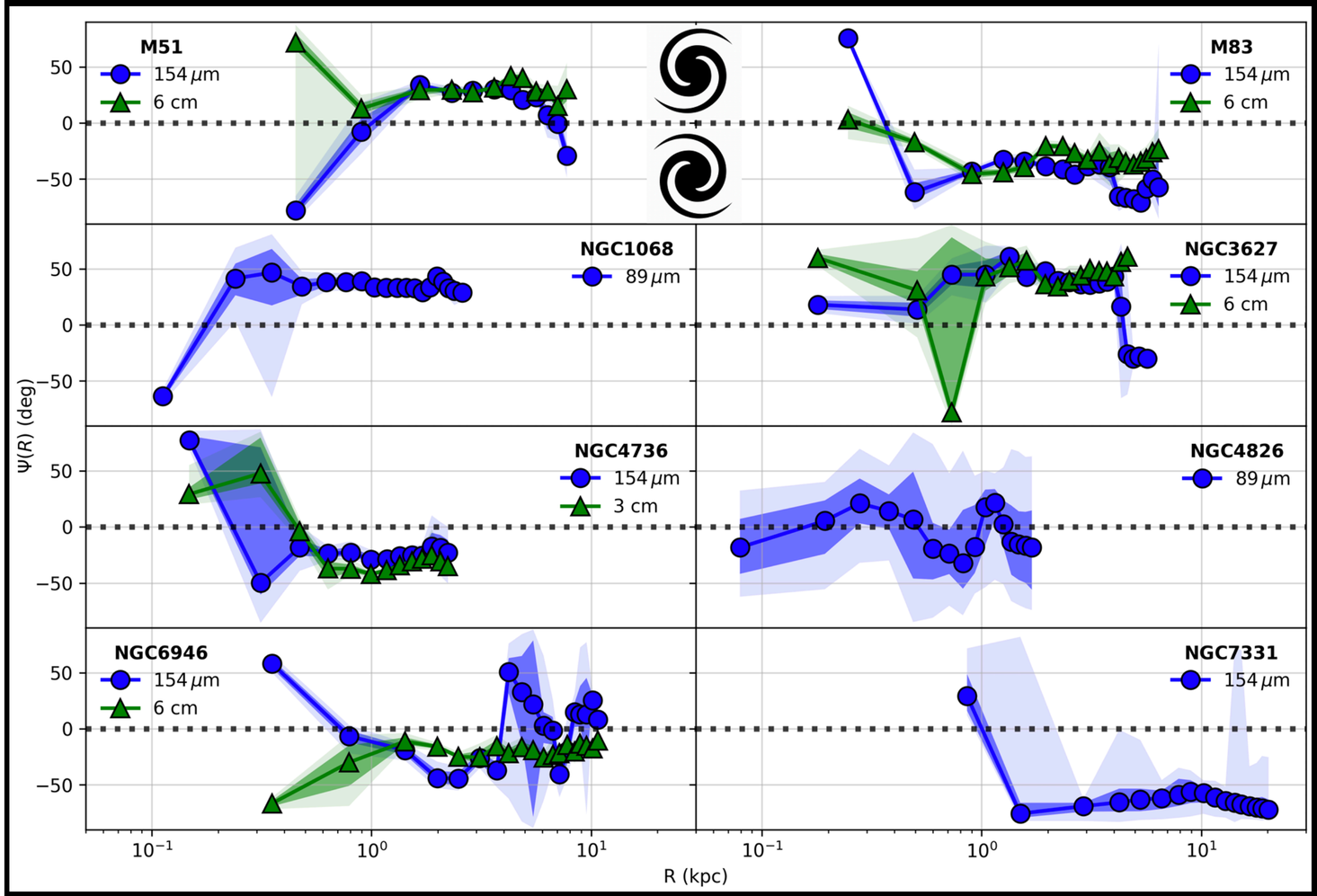
Borlaff et al. (2021, 2023)
Lopez-Rodriguez et al. (2022b,c)

FIR vs. Radio B-field morphology

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

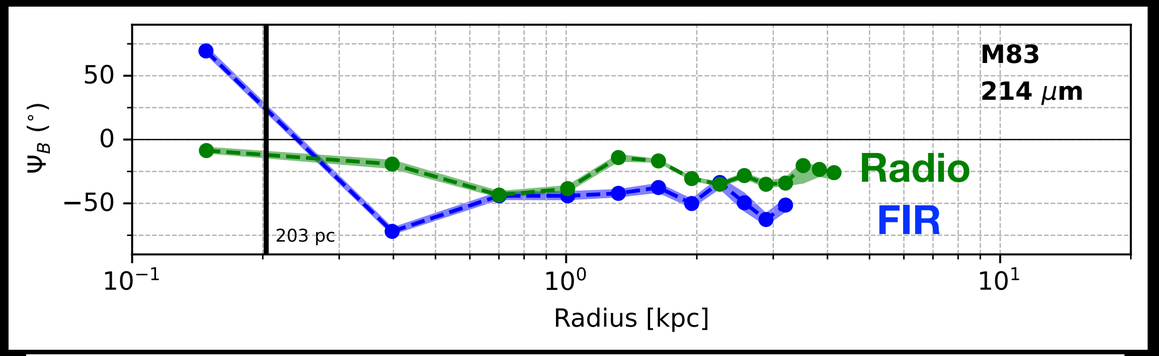


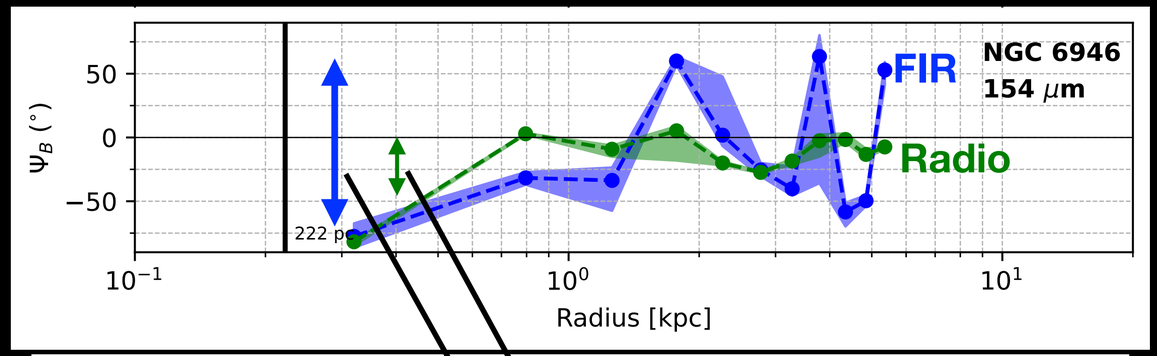
Borlaff et al. (2023, SALSA V)

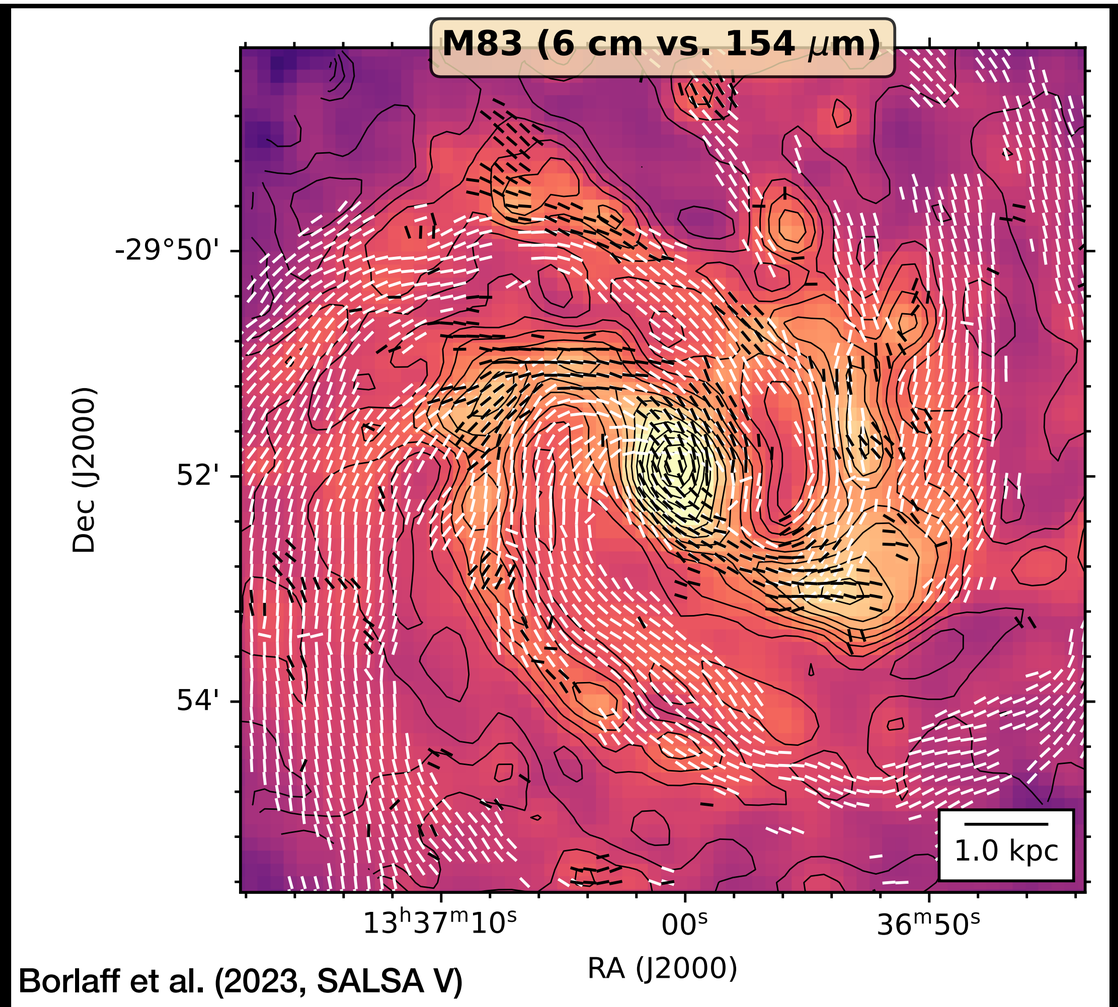


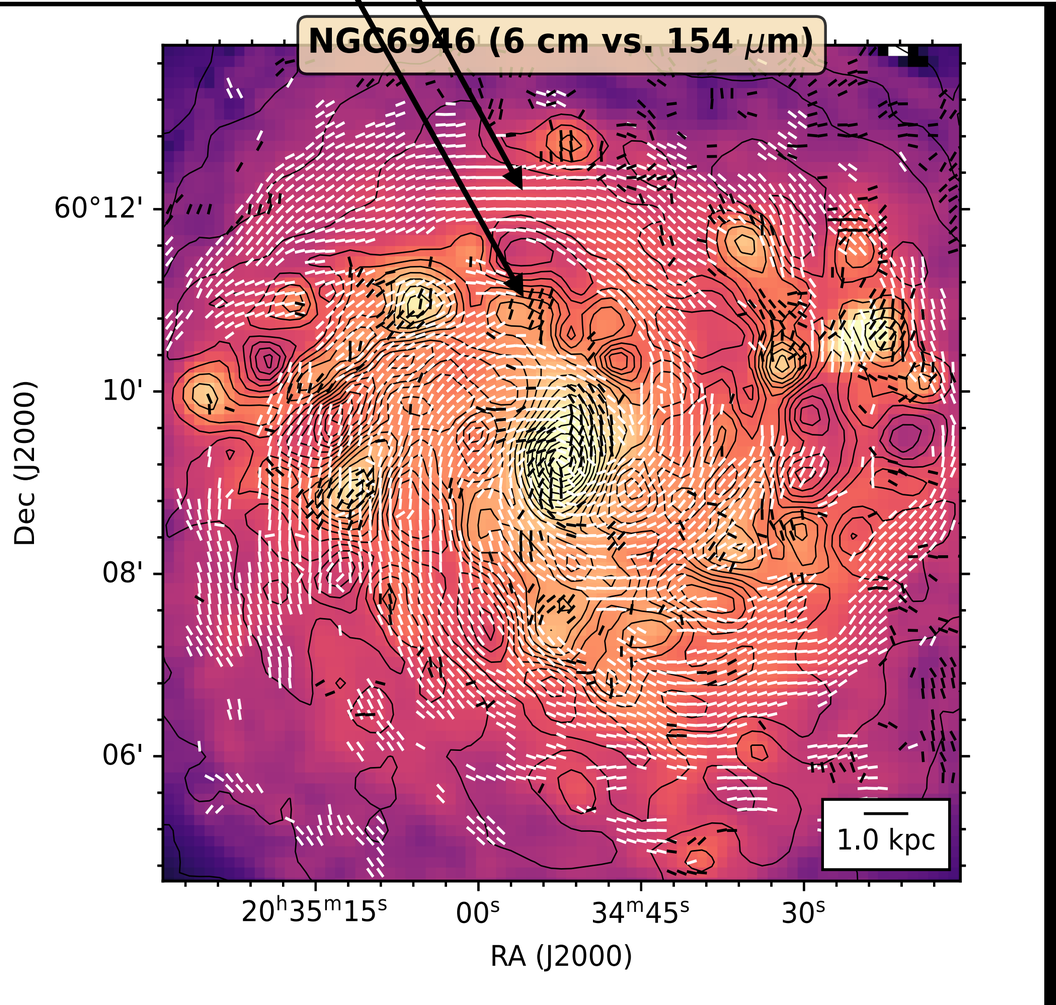
Postdoctoral project published in ApJ: Borlaff et al. 2021, 2023

FIR B-fields are more disordered than the Radio B-fields









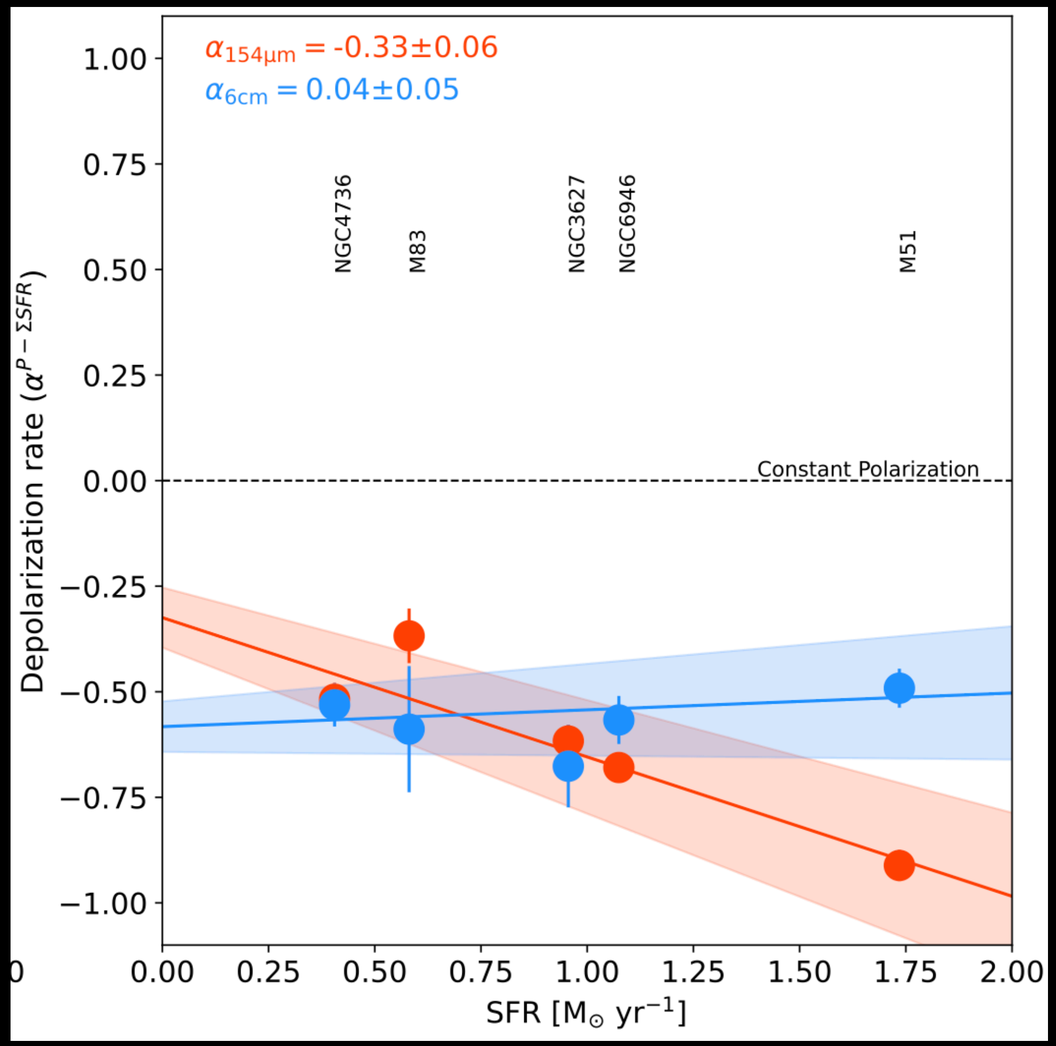
Borlaff et al. (2023, SALSA V)

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

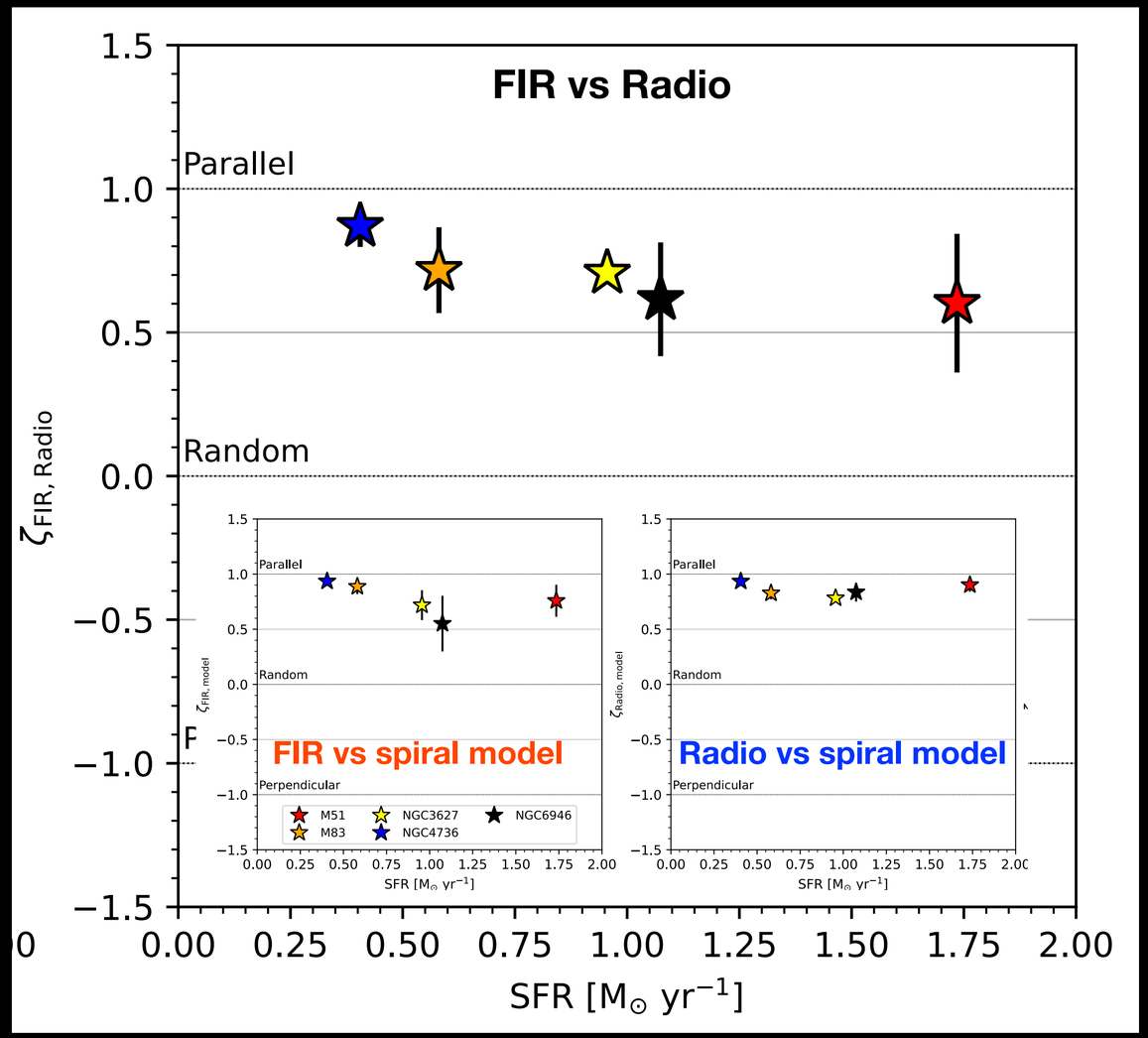
- FIR polarimetry is more sensitive to the turbulent B-field driven by SF regions than Radio polarimetric obs.

<u>Need:</u> large statistical sample of nearby galaxies —> Future FIR imaging polarimeter

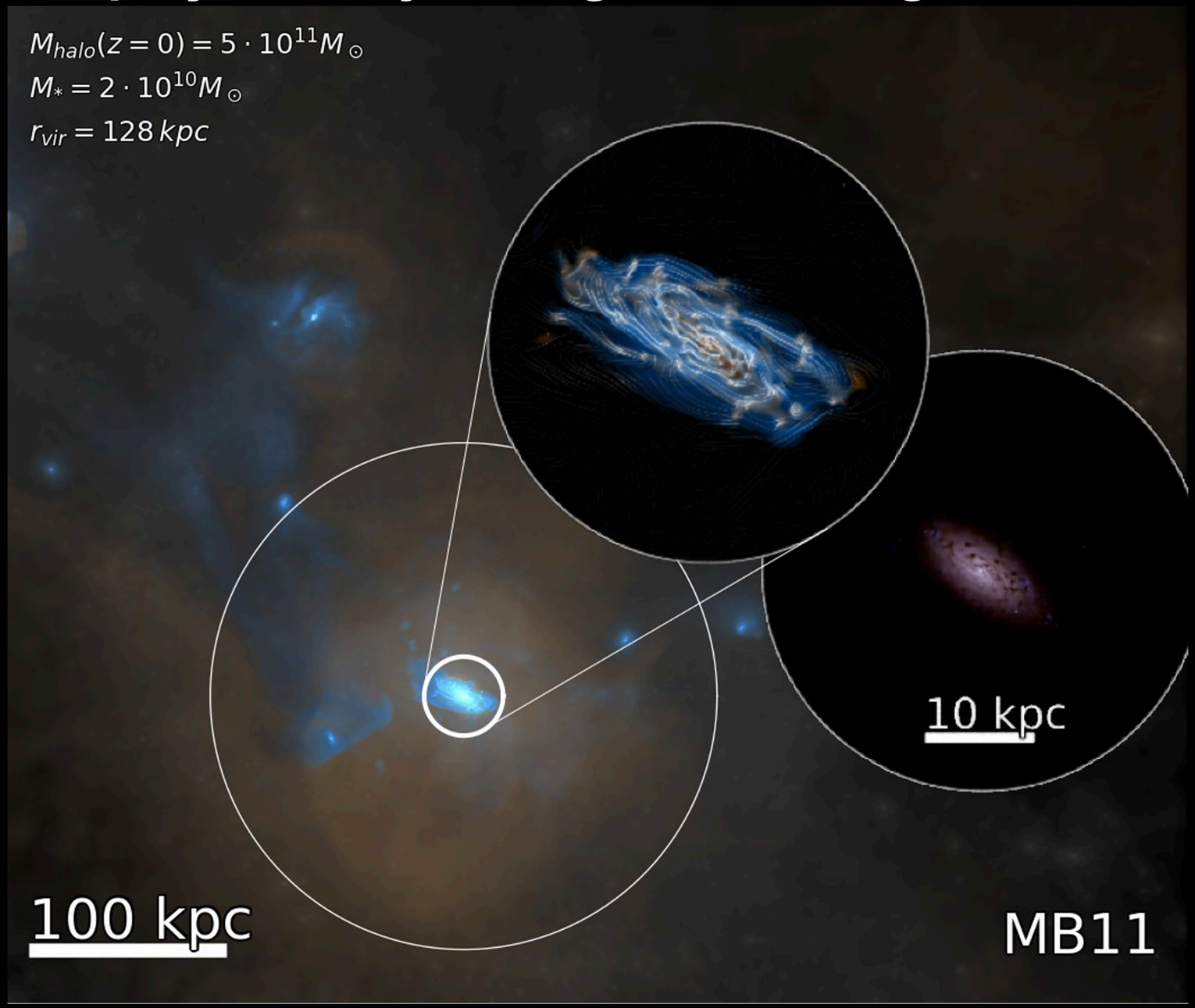
Depolarization rate vs SFR of the galaxy



FIR vs Radio B-field alignment

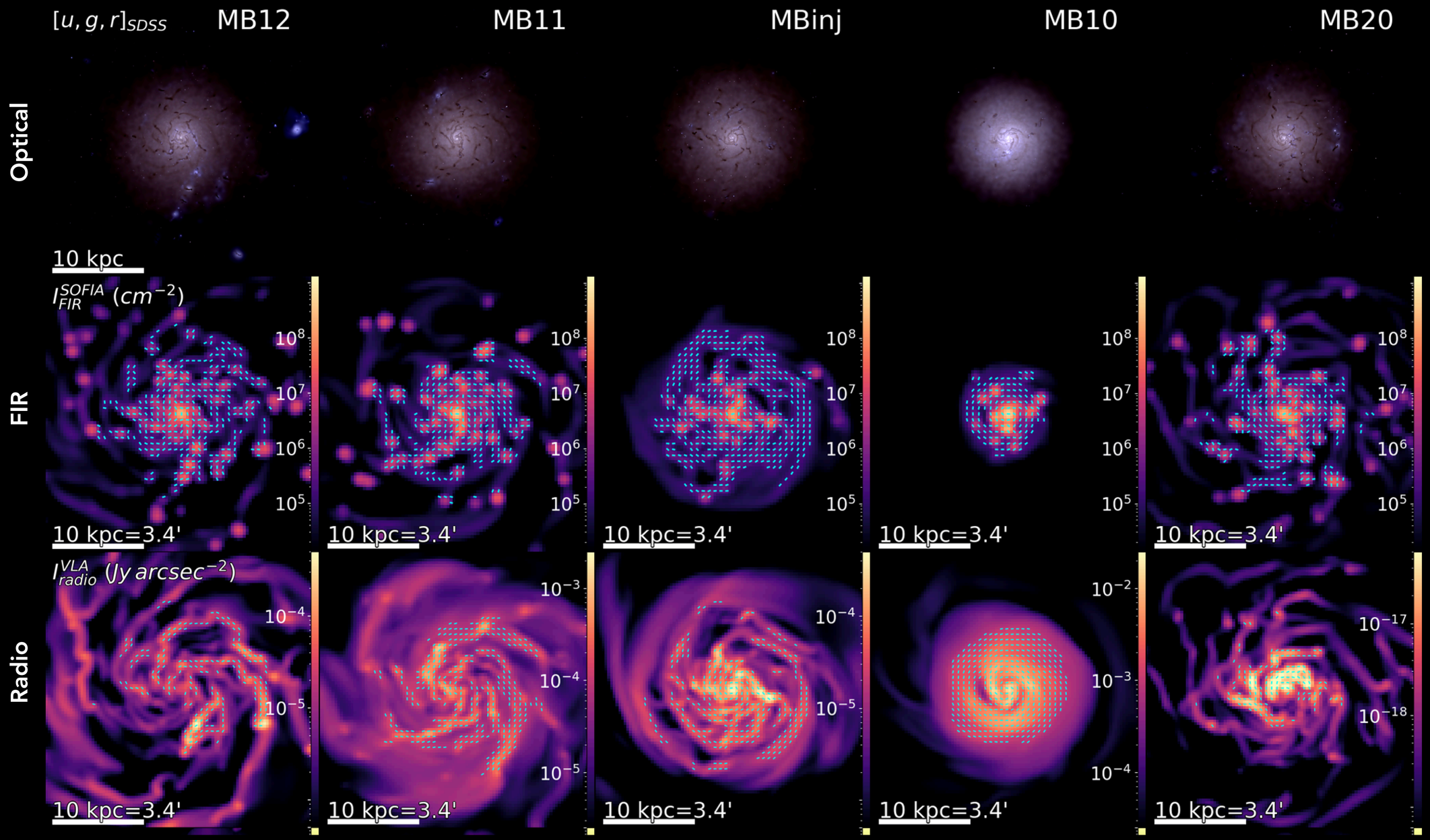


Obtaining the physics by using cosmological MHD simulations



Postdoctoral project published in ApJ: Martin-Alvarez et al. 2024 (SALSA VII)

Testing different magnetization levels in the same galactic environment



Martin-Alvarez et al. 2024 (SALSA VII)

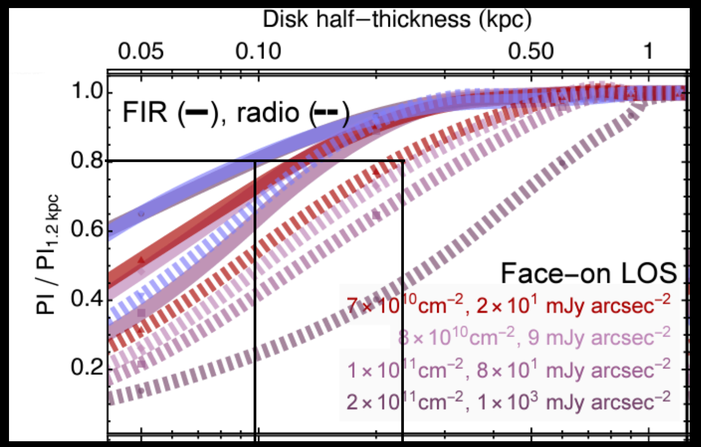
Spatial correspondence of the FIR and radio polarized emission

FIR and Radio polarization trace different phases of the ISM

— FIR polarized emission traces the B-field in the CNM
— Radio polarized emission traces the B-field in the WNM (and some CNM).

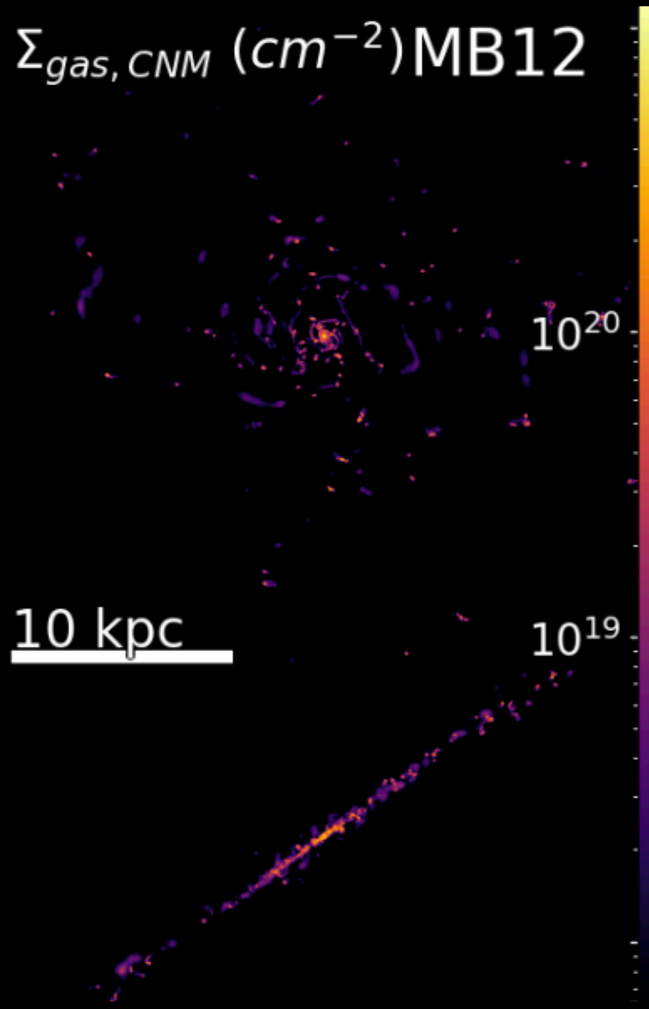
Radio emission has double the vertical scale height of FIR emission

— FIR polarized emission is cospatial with the disk
  - vertical scales <100 pc
— Radio polarized emission is cospatial with gas above and below the disk (extended and pervasive).
  - vertical scales > 200 pc



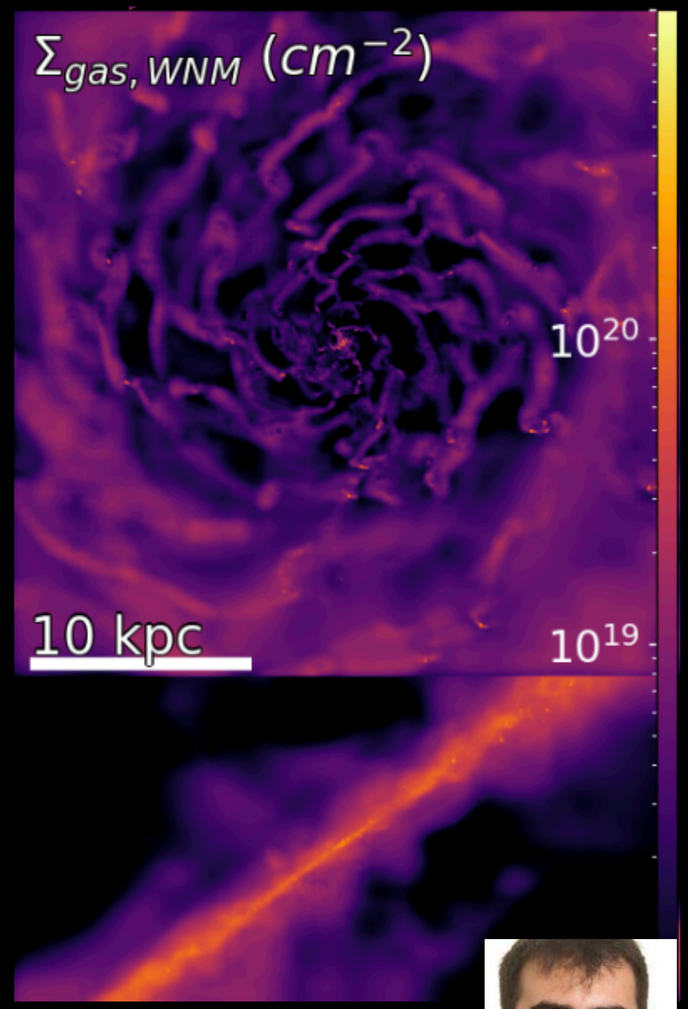
CNM

Cold neutral medium



WNM

Warm neutral medium

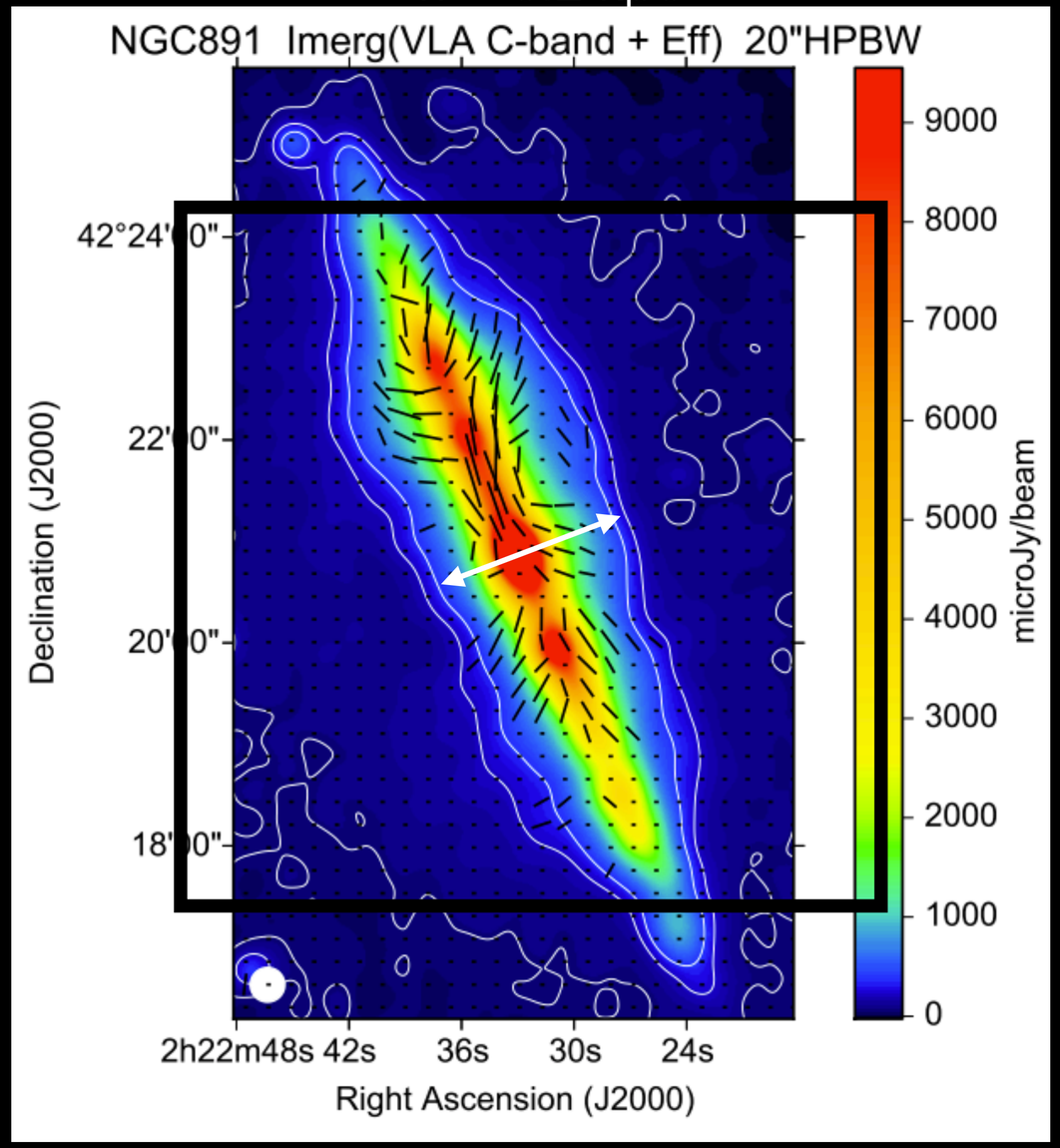


Postdoctoral project published in ApJ: Martin-Alvarez et al. 2024 (SALSA VII)

3D structure of the B-field using radio and FIR wavelengths

Radio: warm and diffuse ISM

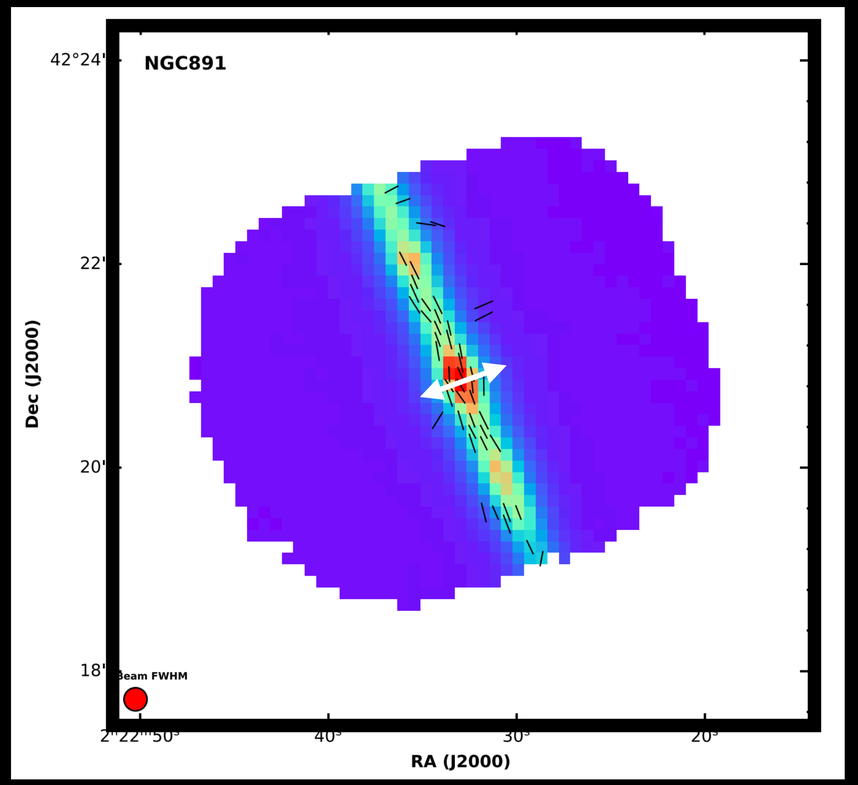
h > 0.2 kpc



Krause et al. (2018,2020)

FIR: cold and dense ISM

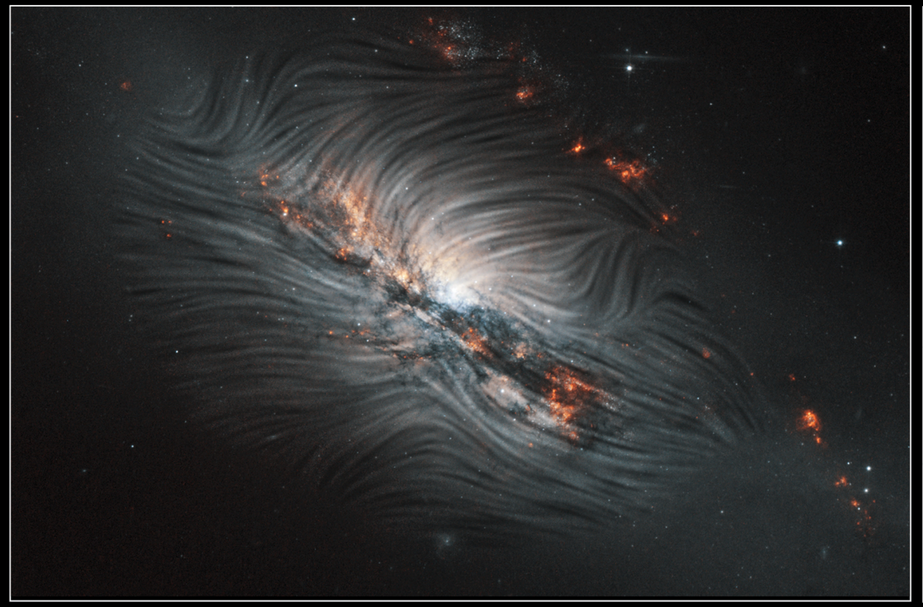
h < 0.1 kpc



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

STARBURST GALAXIES

M82



NGC 2146

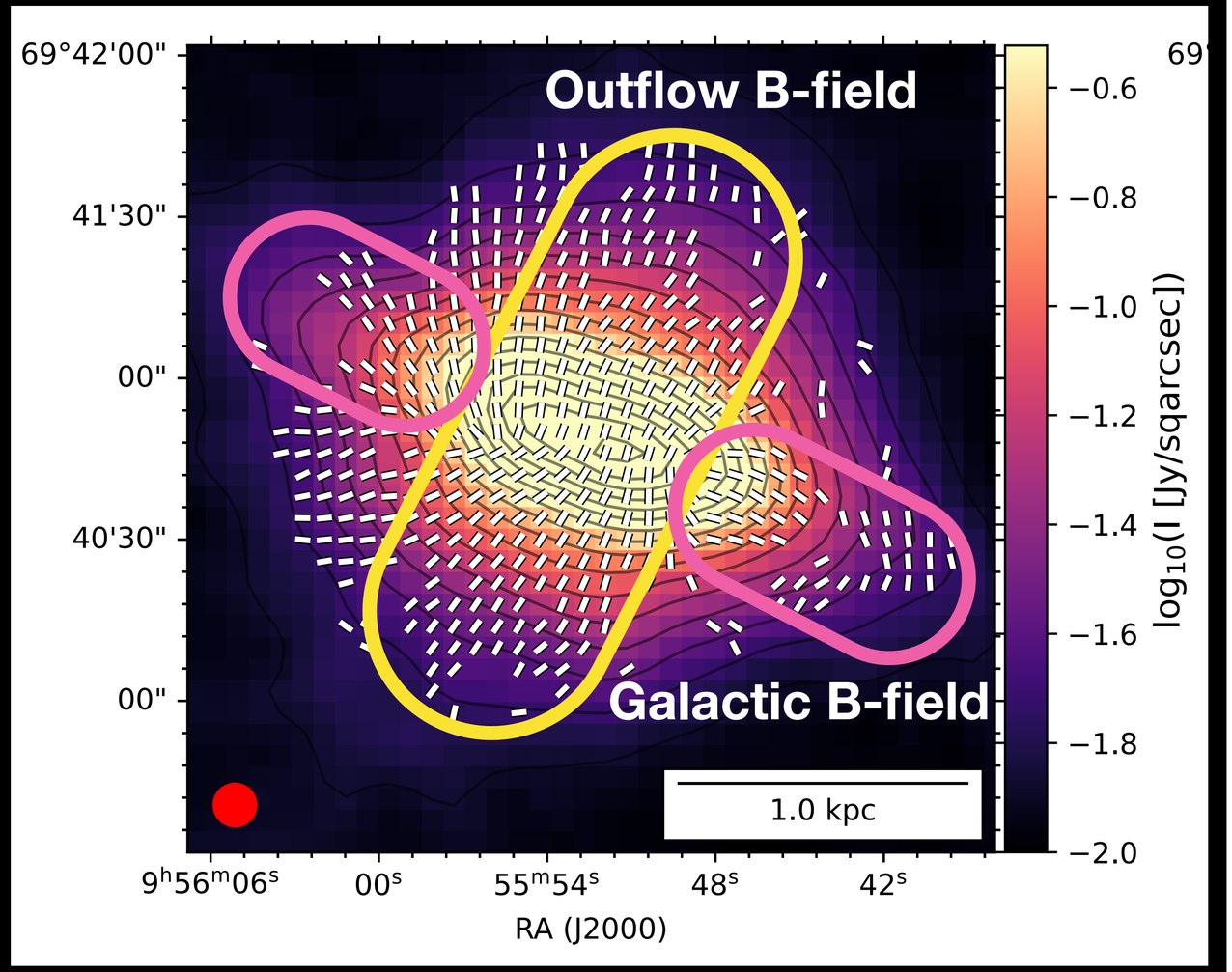
NGC 253

Borlaff et al. (2023)

Lopez-rodriguez et al. 2021, 2022b, 2023c

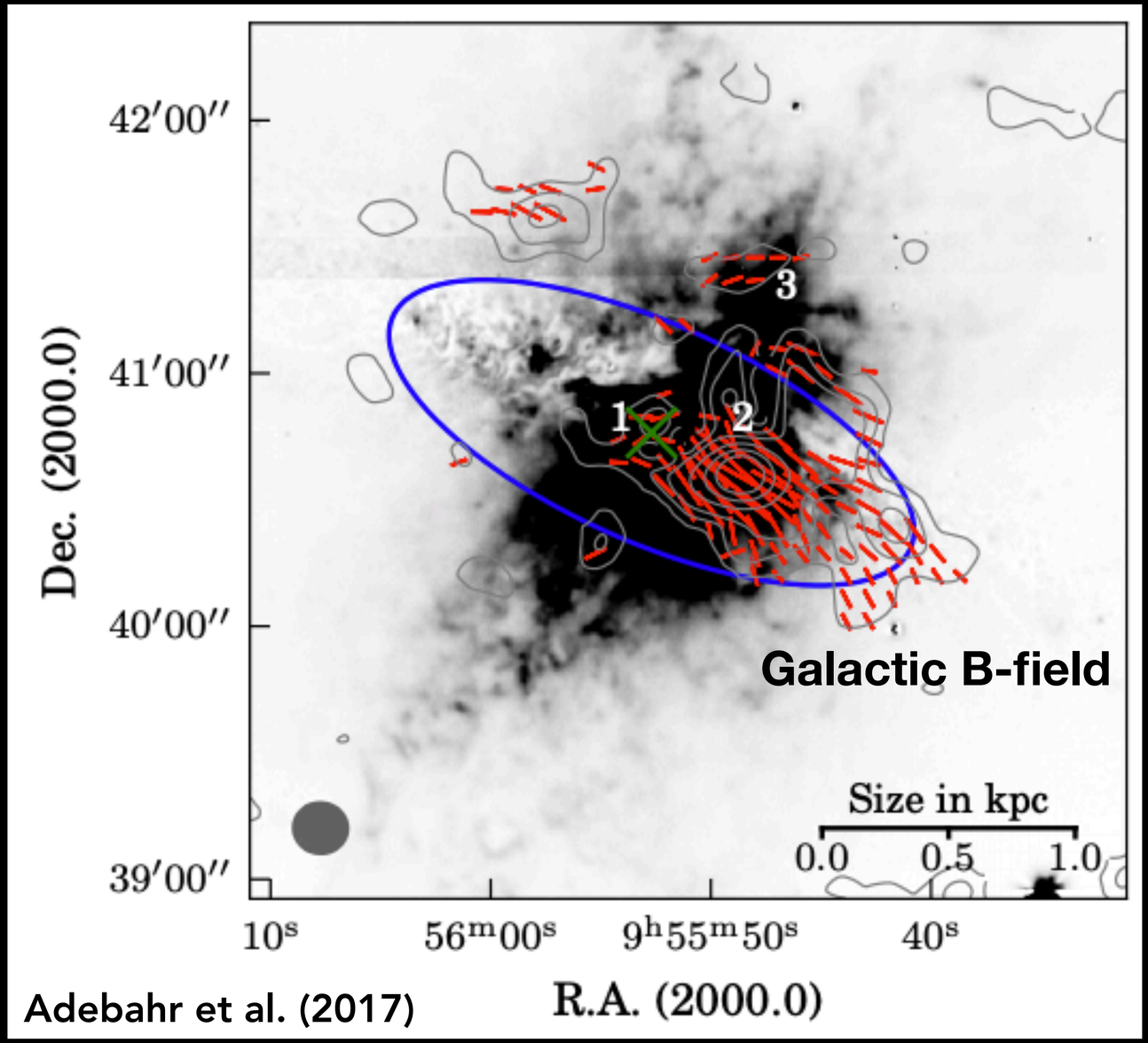
FIR polarization traces the B-field in the cold galactic outflows

FIR (89 um)



Lopez-Rodriguez et al. (2021, 2022b, 2023c)

Radio (18 and 22 cm)



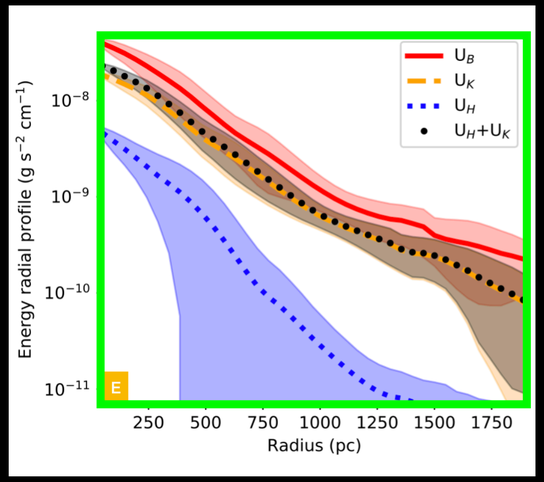
Adebahr et al. (2017)

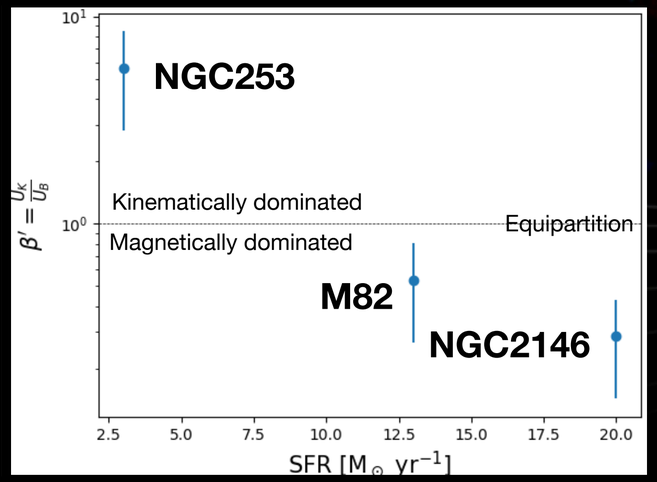
MAGNETIC FIELD ALONG THE GALACTIC OUTFLOW

Magnetic fields are 'open' (at least within ~10 kpc)

Material scapes to the circumnuclear galactic medium driven away by the kinetic energy of the galactic outflow.

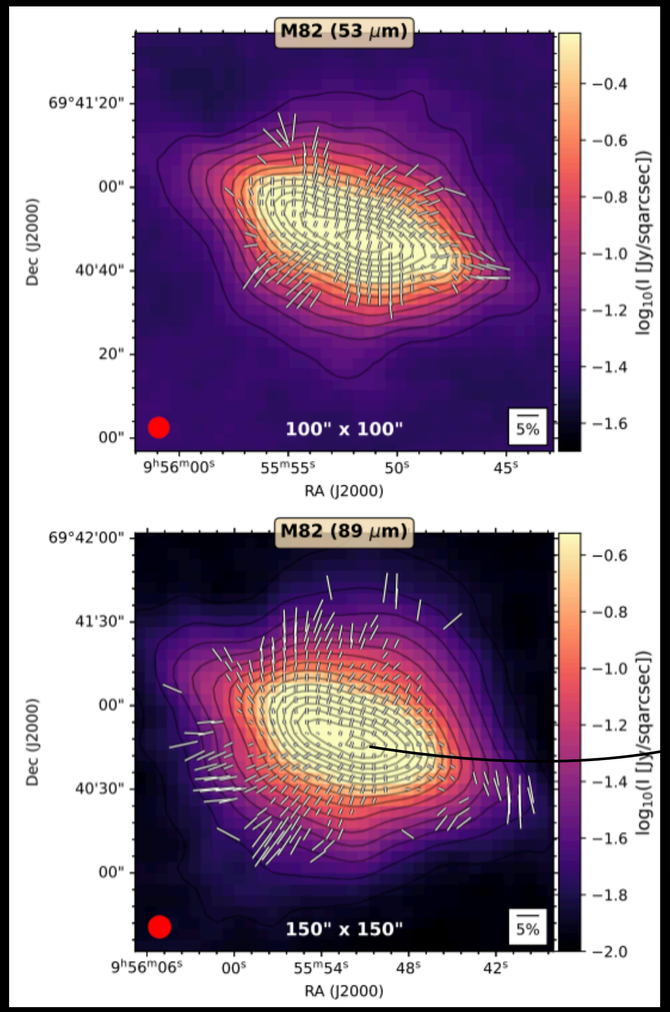
Turbulent kinetic and magnetic energy and in close equipartition in the outflow



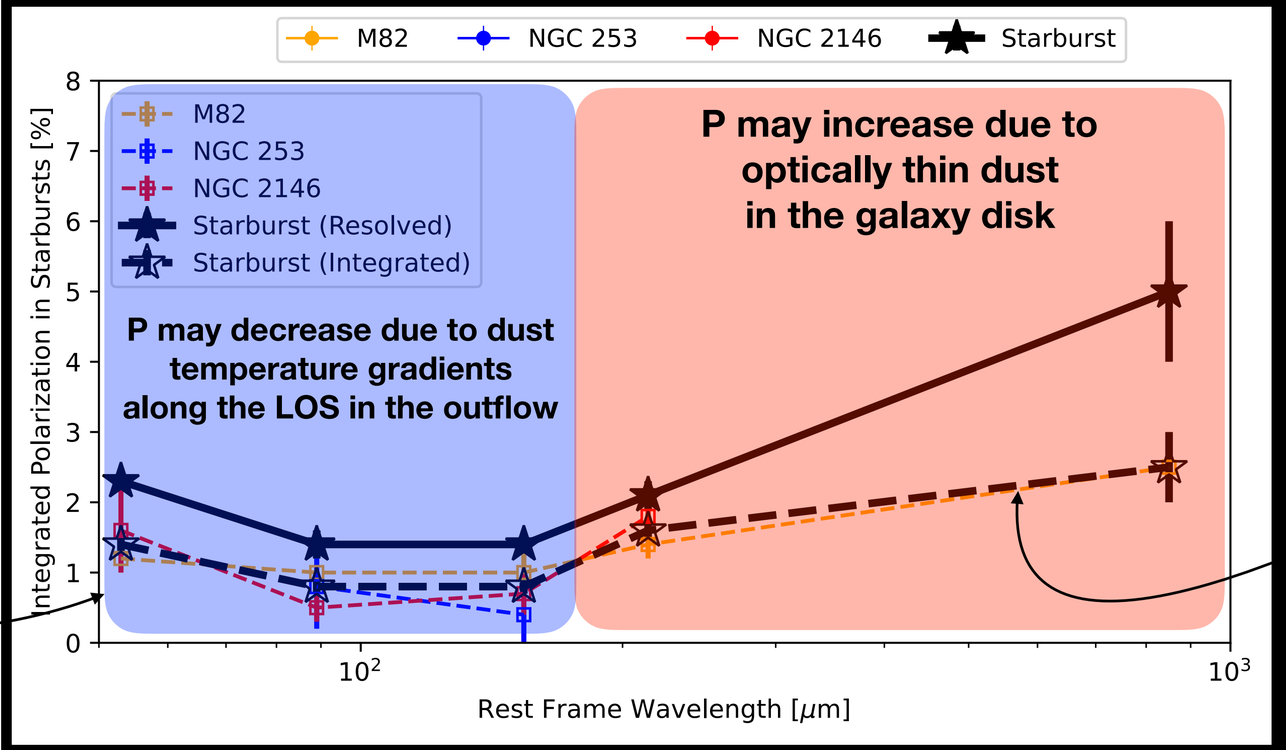


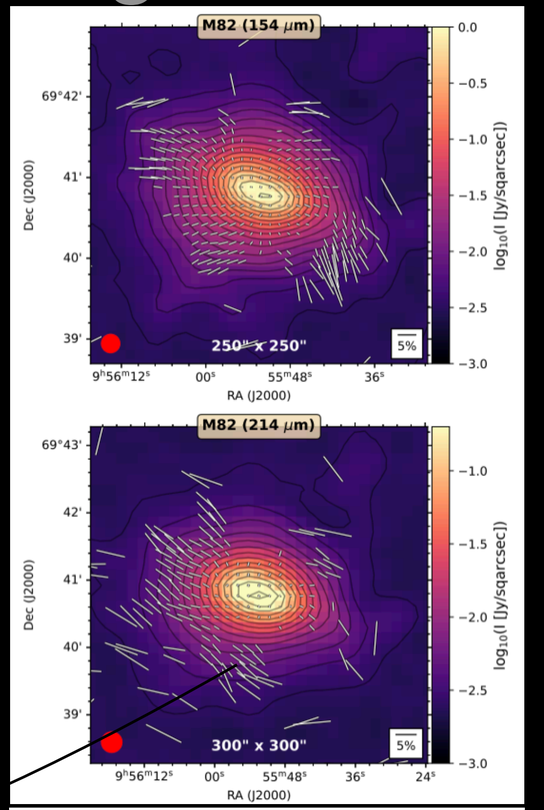
Lopez-Rodriguez et al. (2021)
Lopez-Rodriguez (2023c)

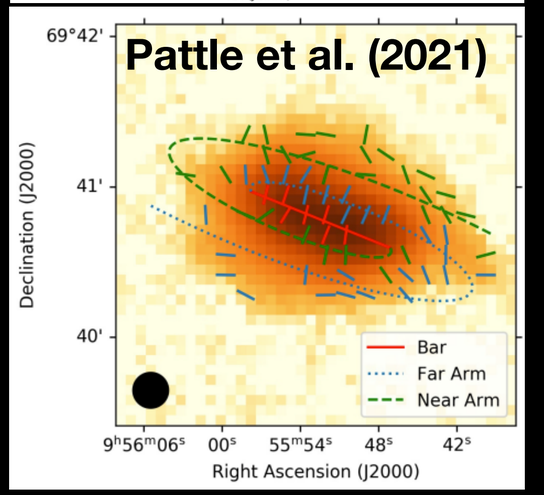
Dust properties: FIR polarized spectrum of Starburst galaxies



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





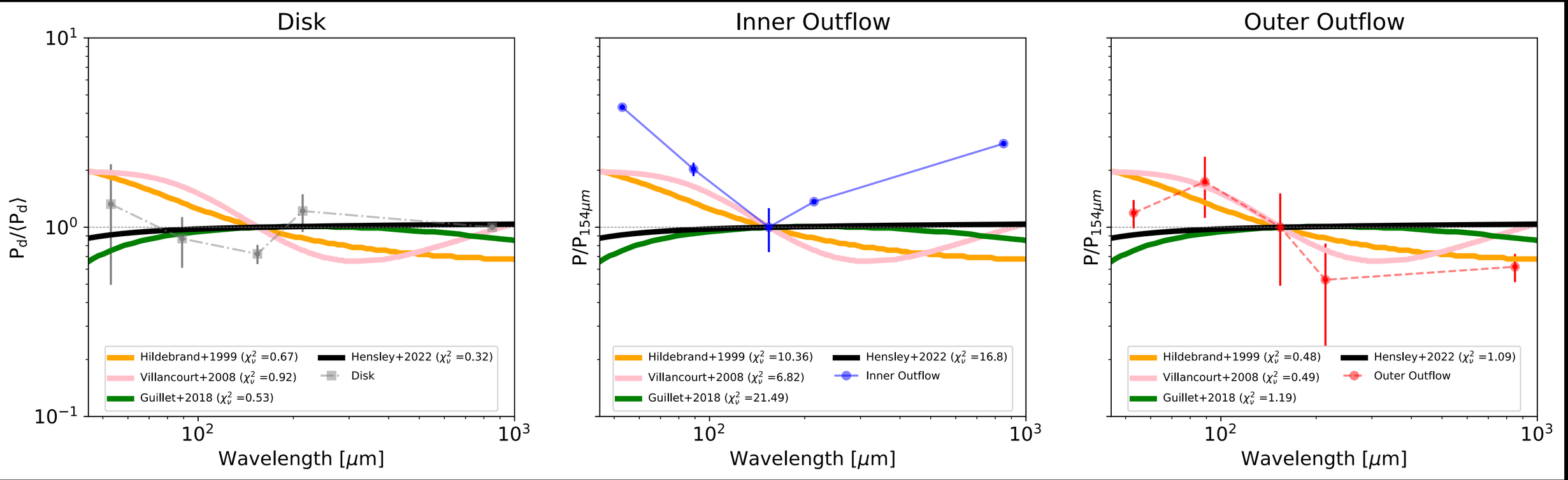


At short wavelengths, the hot dust from the galactic outflow dominates up to scales of ~4 kpc above and below the disk.

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

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

Dust properties: FIR polarized spectrum of Starburst galaxies



Disk:

— polarized spectrum consistent with a flat distribution.

— Astrodust (Hensley+2022) with U=10^3 (strong radiation field) and single component best reproduce the polarized spectrum

Outer Outflow:

— polarized spectrum shows a ’S’ shape.

— two-phase component (Hildebrand+1999, Villancourt+2008) best reproduce the observations.

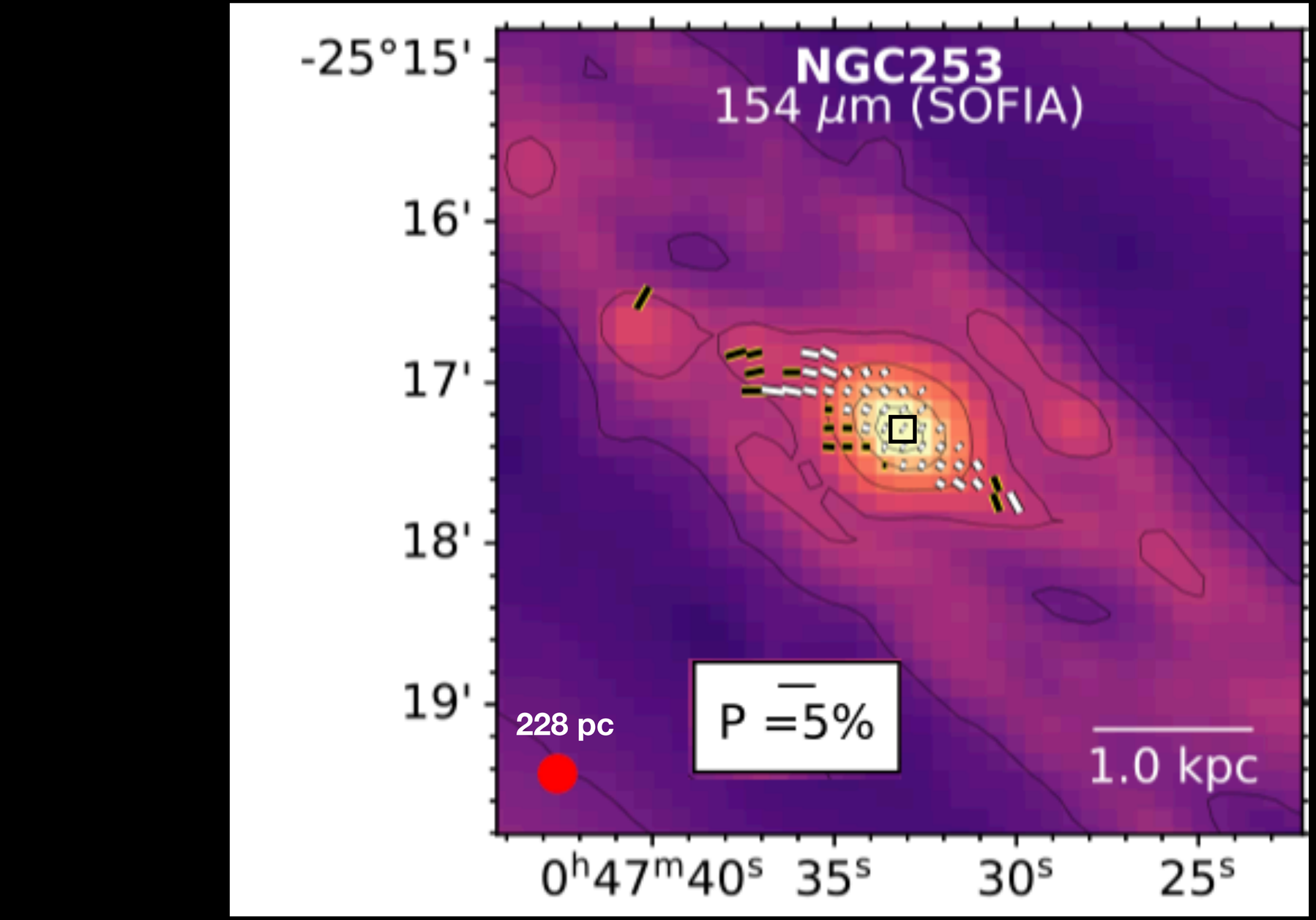
Inner Outflow:

— polarized spectrum shows a ’V’ shape.

— No model reproduces the observations. Potentially due to strong dust temperature variations and/or tangled B-fields along the LOS

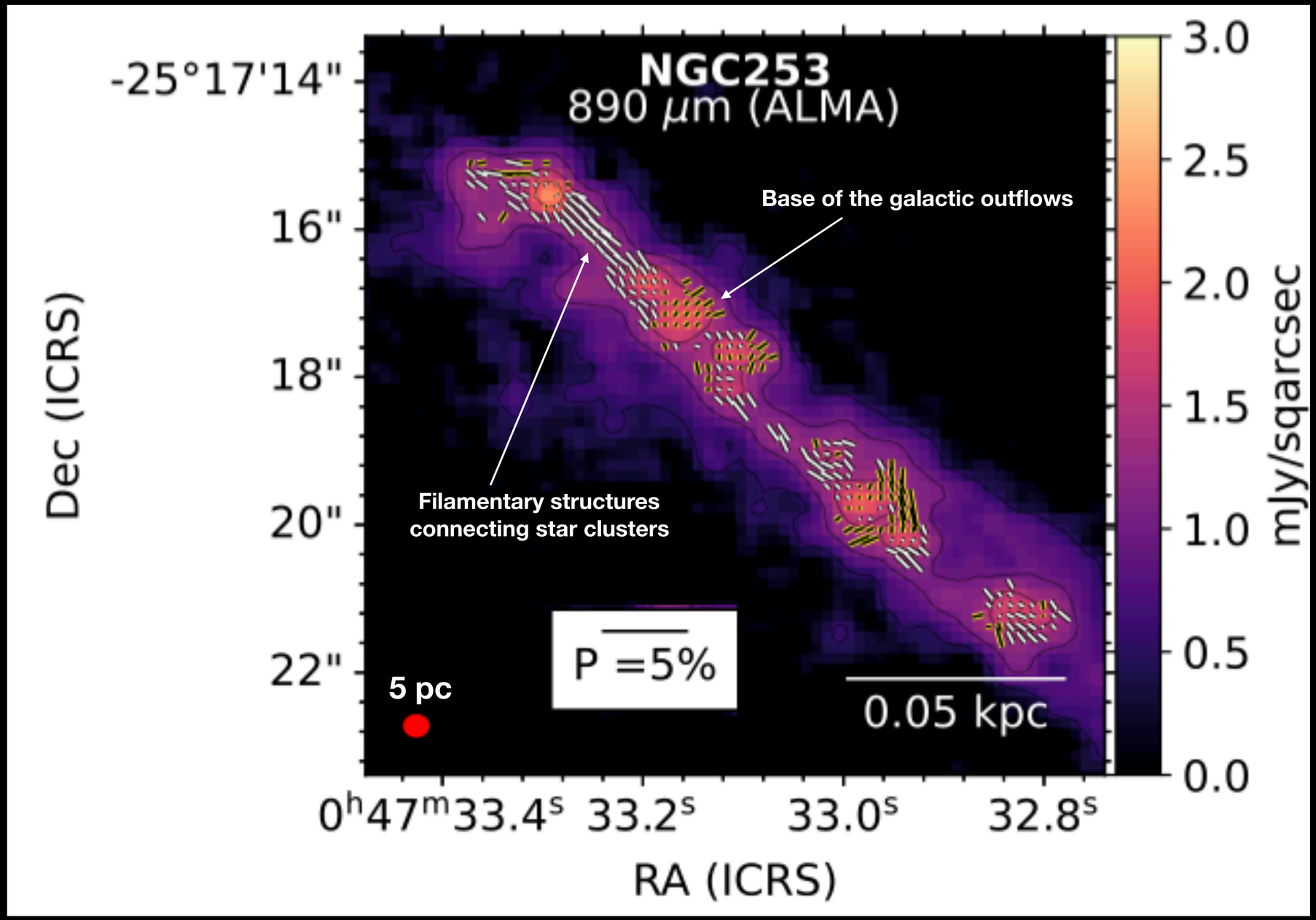
Lopez-Rodriguez (2023c)

Zoom-in NGC253: 45x resolution from SOFIA to ALMA



Lopez-Rodriguez (2023c)

Zoom-in NGC253 using ALMA polarimetric observations



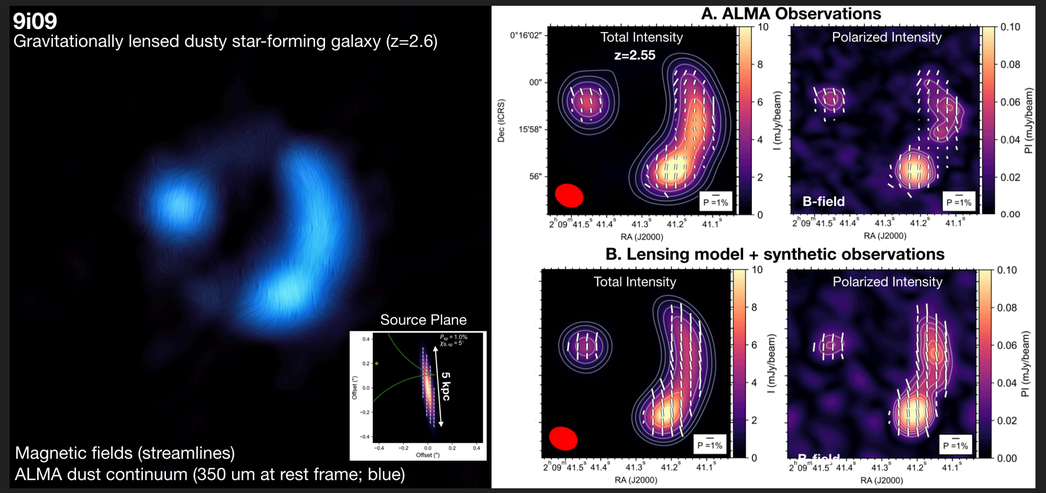
Lopez-Rodriguez (2023c)

B-fields at high redshift using sub-mm polarimetry

Gravitationally lensed dusty star-forming galaxies at high-redshift

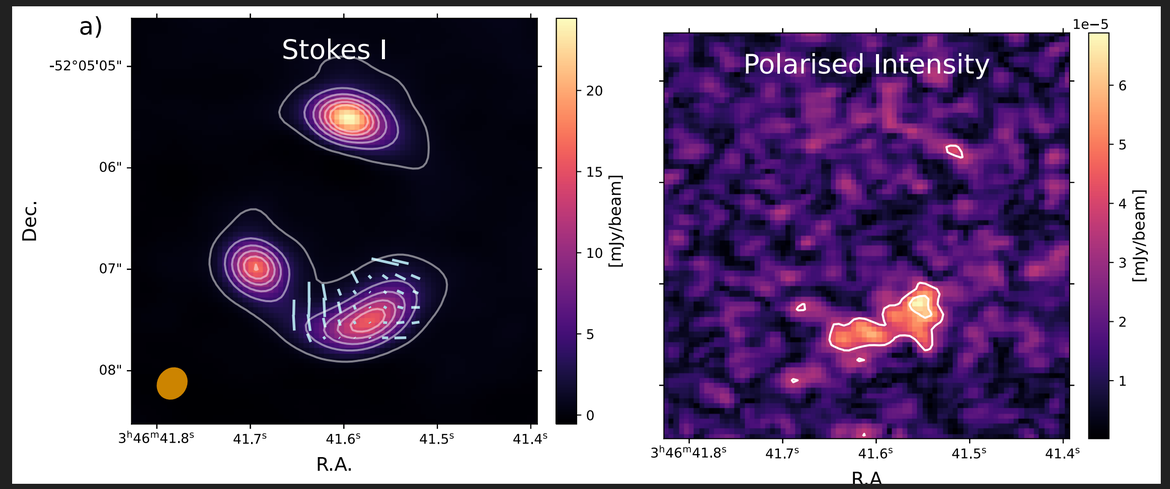
z=2.6

~5 kpc-scale ordered B-field parallel to a fast rotating disk in a starburst at 3Gyr after Big Bang.

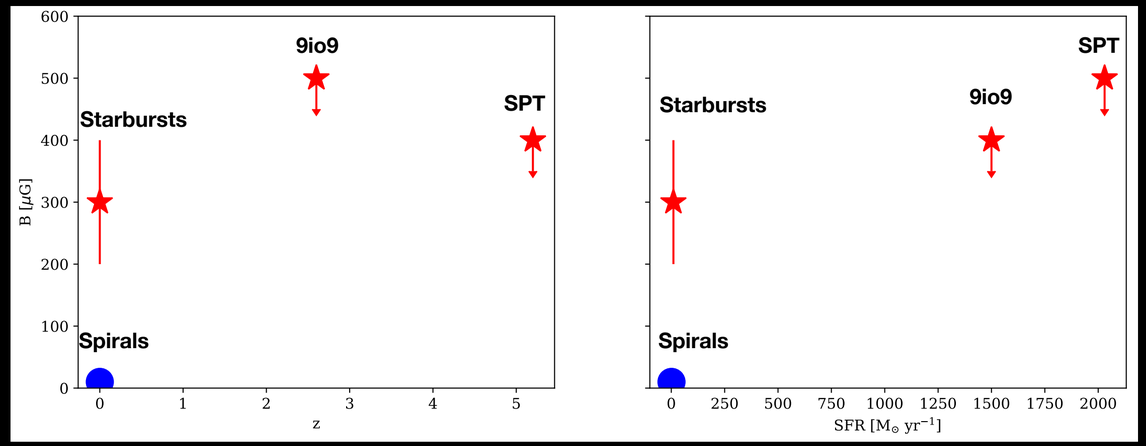


z=5.3

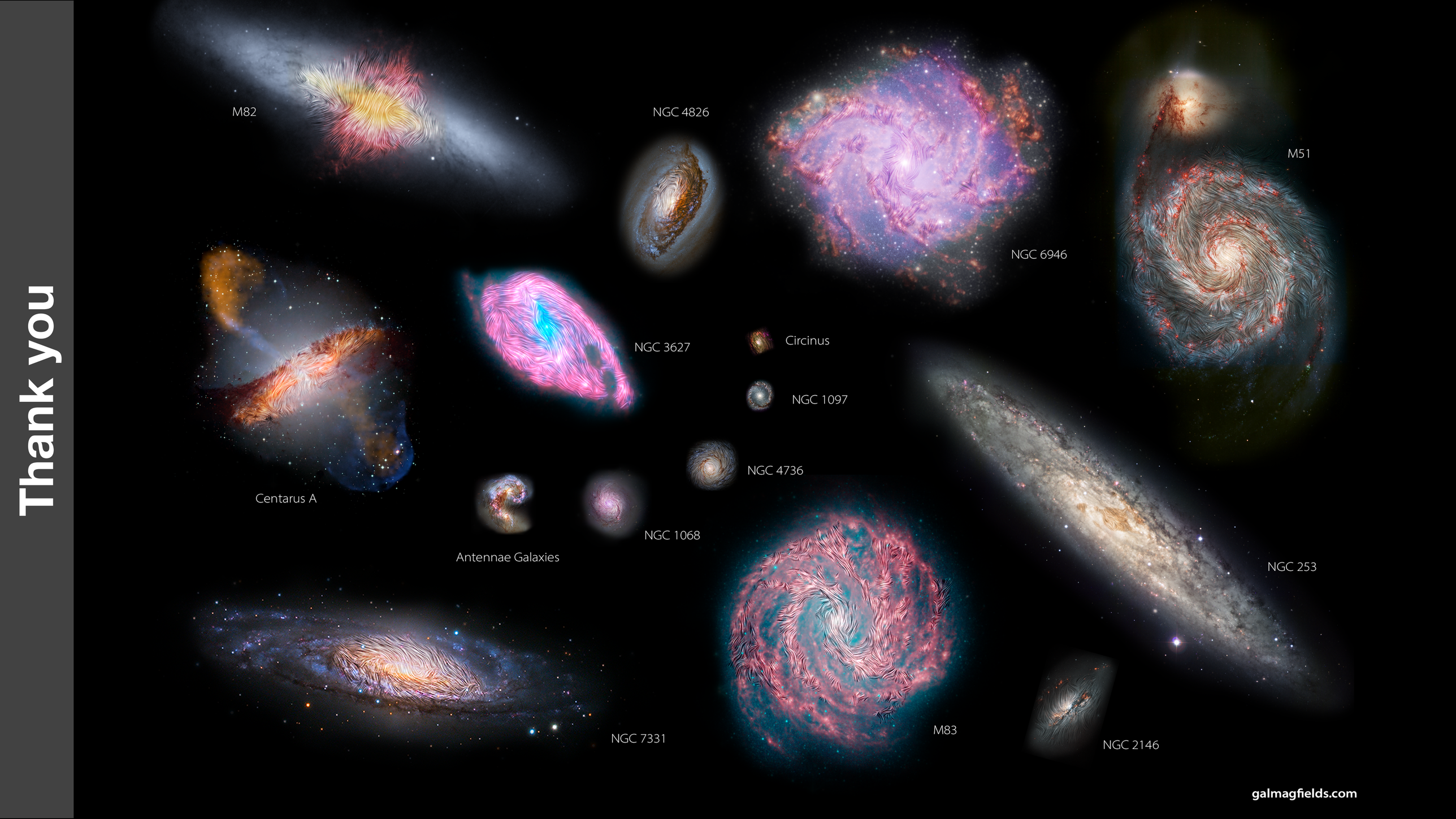
~3 kpc-scale ordered B-field parallel to the overlap between a merger galaxy (or outflow, or disk)



Variation of B-fields as a function of cosmic time and SFR



Thank you



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