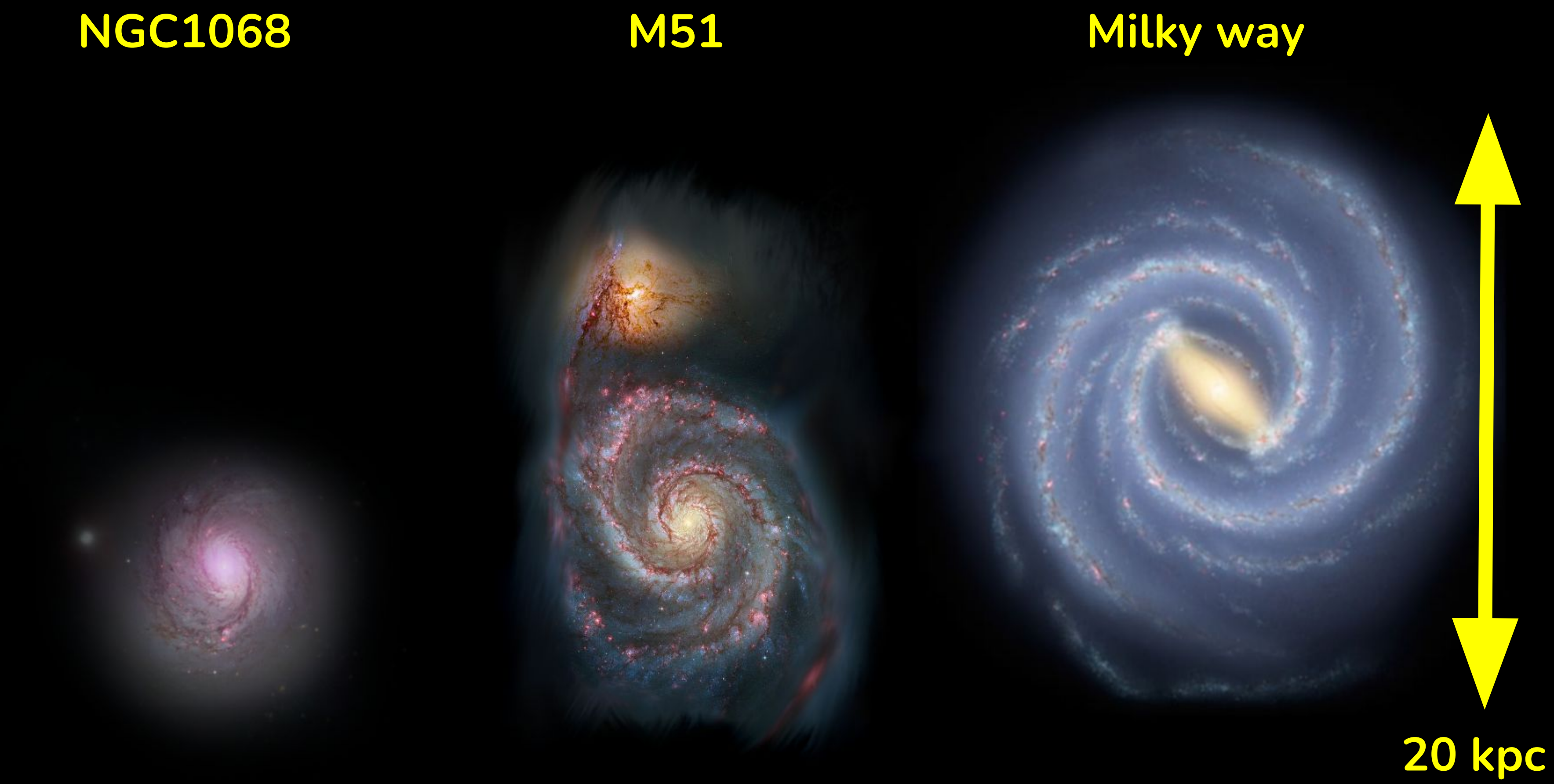
The Multiphase Magnetic field of M51

Alejandro S. Borlaff, E. López-Rodriguez, P. Marcum, R. Beck, E. Ntormousi, J. E. Beckman, R. Stepanov, K. Tassis, L. Proudfit, L. Grosset et al.

March 2nd 2022 SOFIA UCLA

a.s.borlaff@nasa.gov @asborlaff

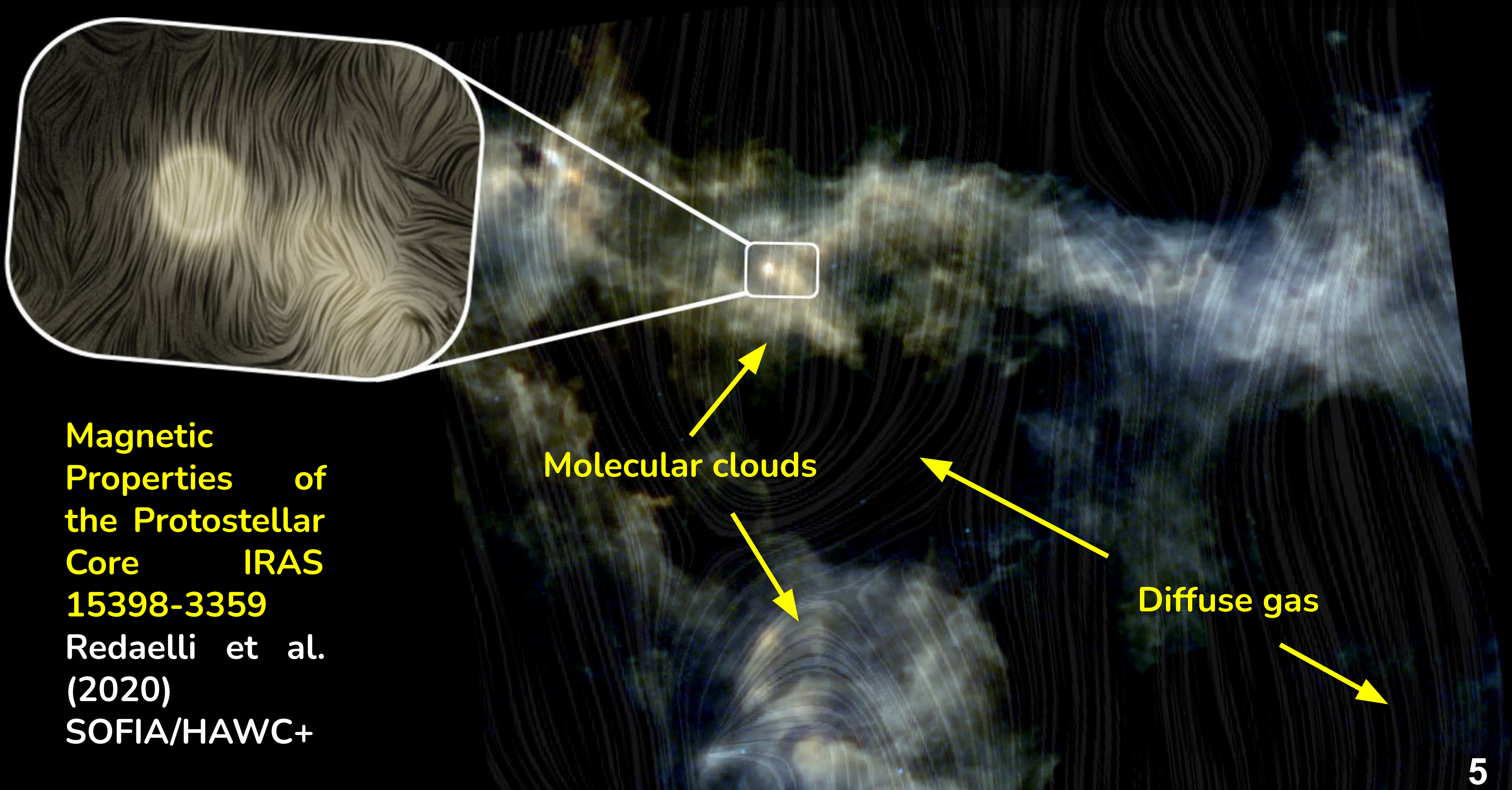
NASA Postdoctoral Program


NGC1068
M51
Milky way
20 kpc

Illustris TNG50 simulation scaled to the real size of Malin 1

Illustris TNG50 simulation scaled to the real size of Malin 1

Magnetic fields are vital for galaxy & star formation

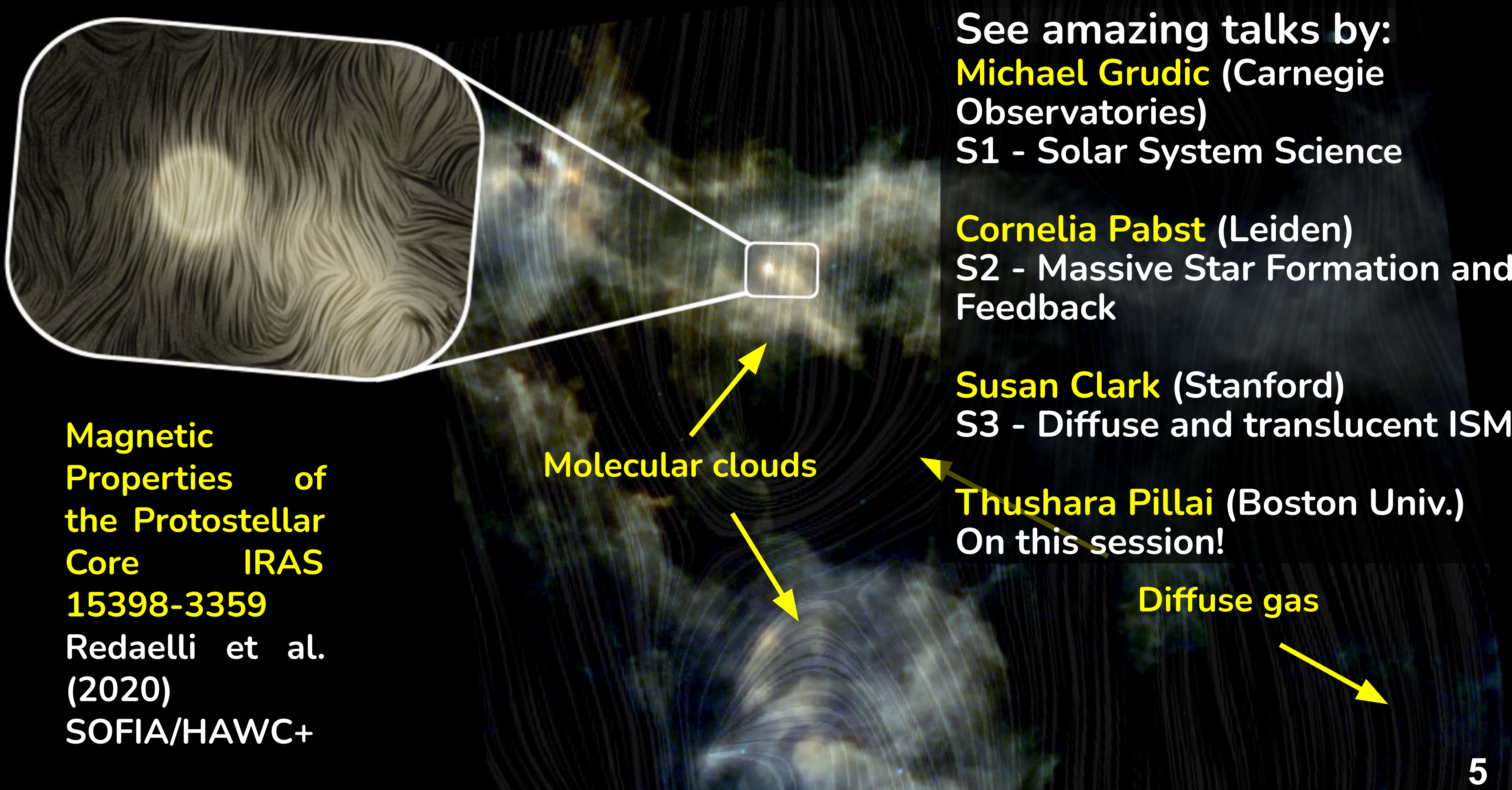


Magnetic Properties of the Protostellar Core IRAS 15398-3359

Redaelli et al. (2020)

SOFIA/HAWC+

Magnetic fields are vital for galaxy & star formation



See amazing talks by:

Michael Grudic (Carnegie Observatories)
S1 - Solar System Science

Cornelia Pabst (Leiden)
S2 - Massive Star Formation and Feedback

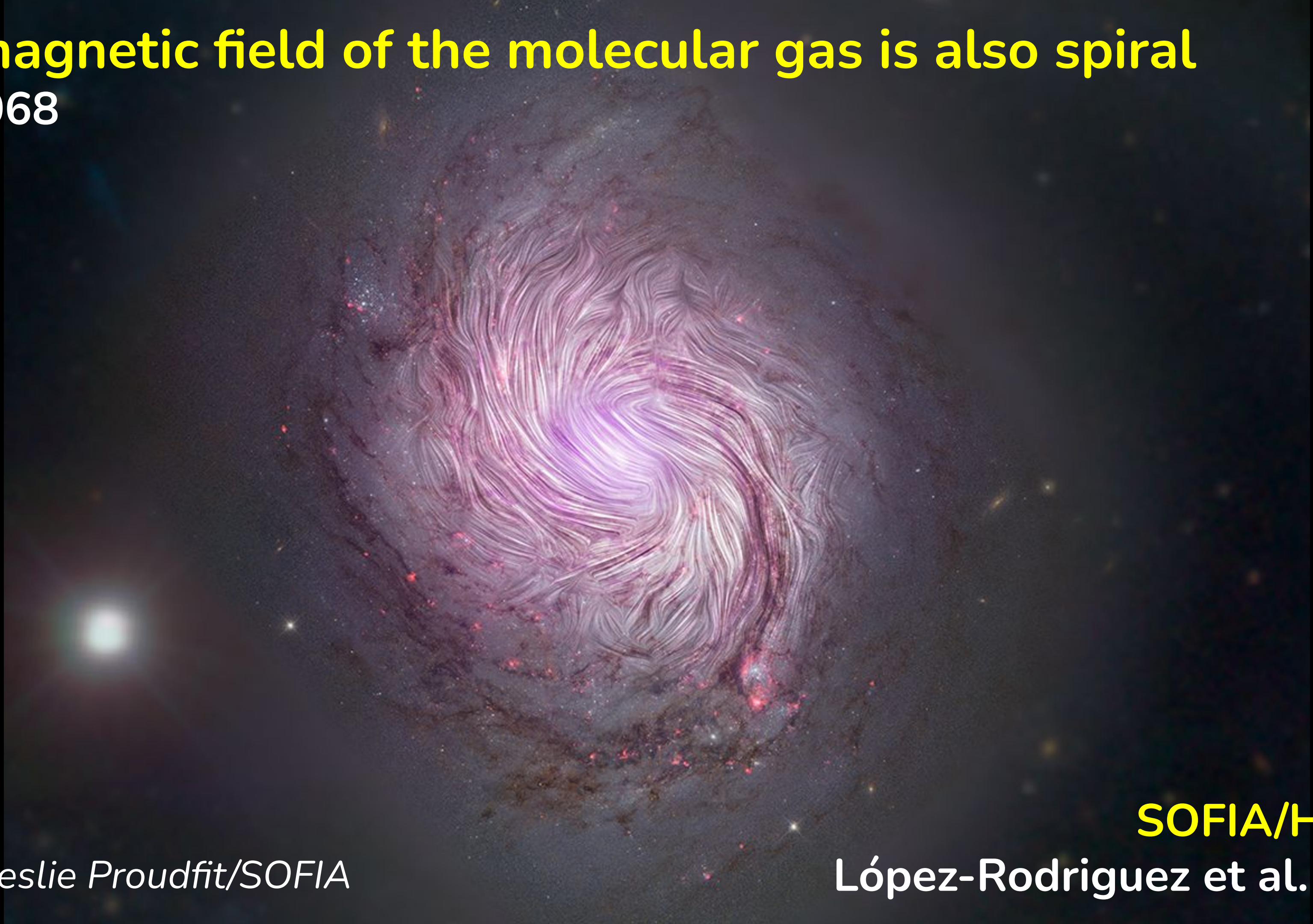
Susan Clark (Stanford)
S3 - Diffuse and translucent ISM

Thushara Pillai (Boston Univ.)
On this session!

Magnetic Properties of the Protostellar Core IRAS 15398-3359
Redaelli et al. (2020)
SOFIA/HAWC+

The magnetic field of the molecular gas is also spiral

NGC1068

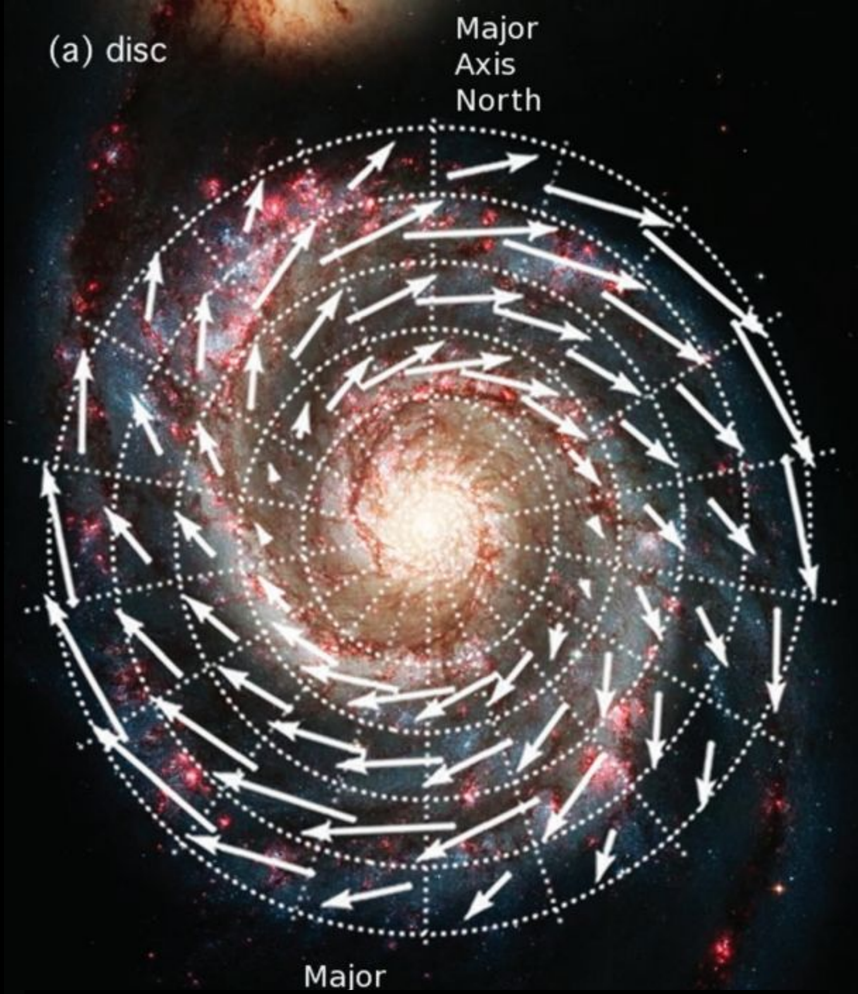


Credit: Leslie Proudfit/SOFIA

SOFIA/HAWC+

López-Rodriguez et al. (2020)


SOFIA/HAWC+ (Far-infrared)
López-Rodriguez et al. (2020)


(a) disc
Major
Axis
North
Major
Fletcher et al. 2011
VLA/Effelsberg 100m
(Radio)

Magnetic fields as Dark Matter alternatives

Nelson (1988), Battaner et al. (1992, 1995): Can magnetic fields support the flat rotation velocity curve observed in spiral galaxies?

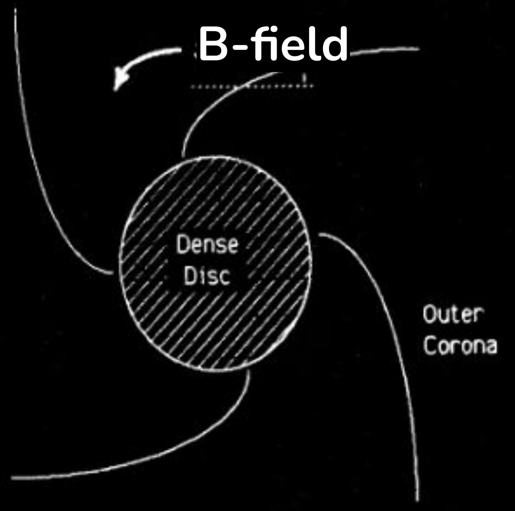
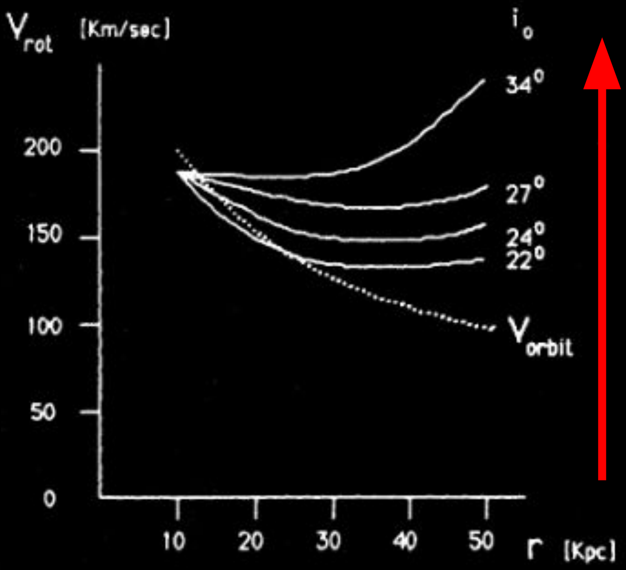


Figure 1. Geometry of the spiral field lines in the outer disc corona.



Higher pitch angle

Higher *magnetic* rotational support

Magnetic fields as Dark Matter alternatives

Nelson (1988), Battaner et al. (1992, 1995): Can magnetic fields support the flat rotation velocity curve observed in spiral galaxies?

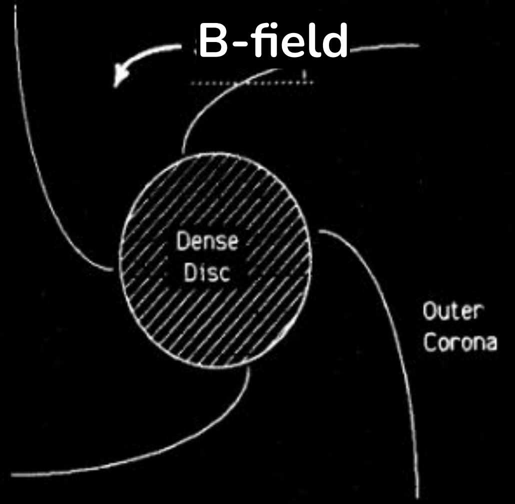
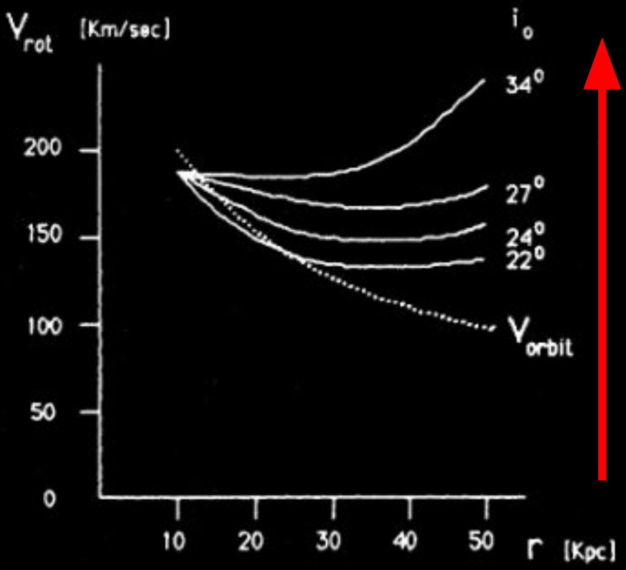


Figure 1. Geometry of the spiral field lines in the outer disc corona.



Higher pitch angle

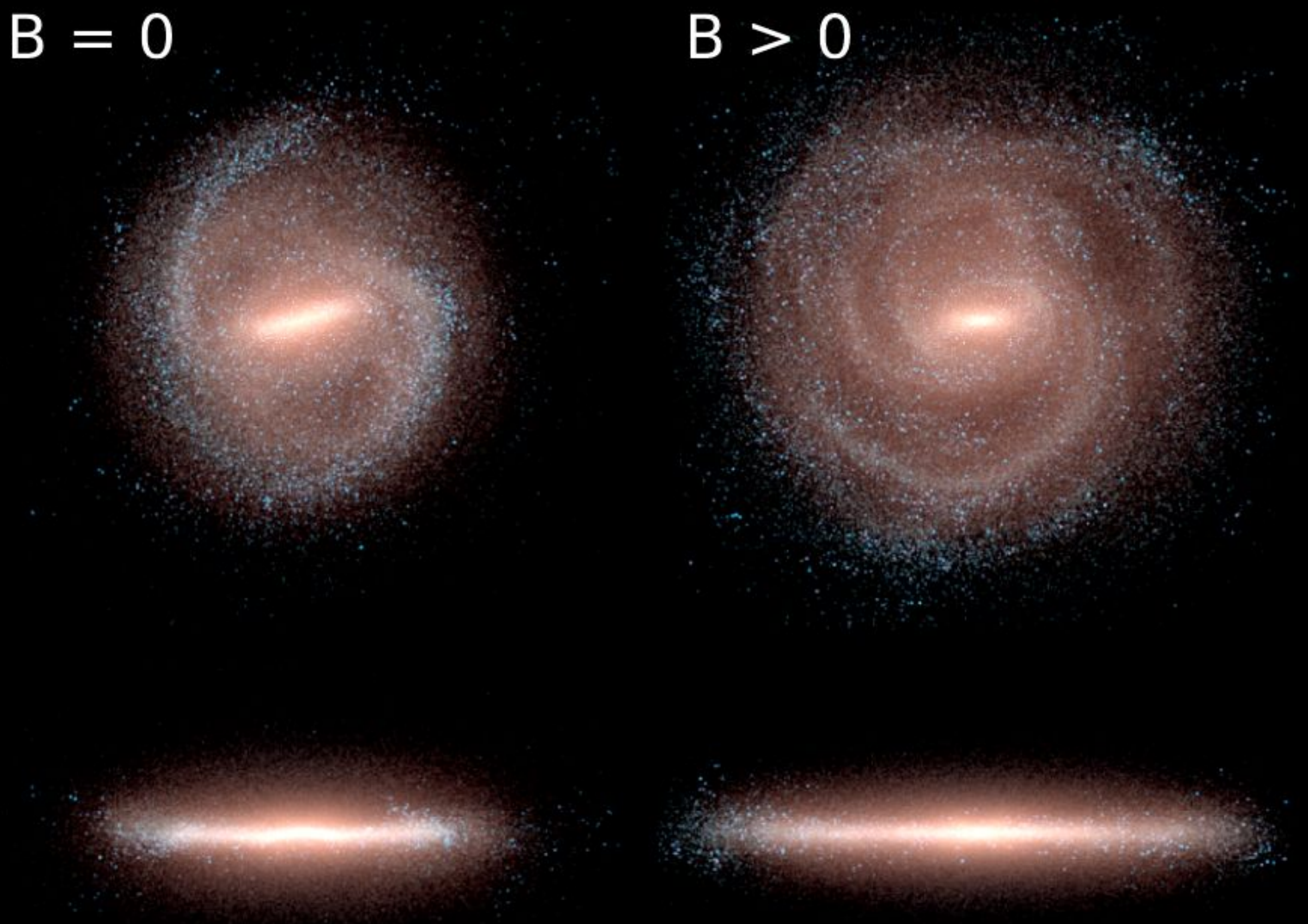
Higher *magnetic* rotational support

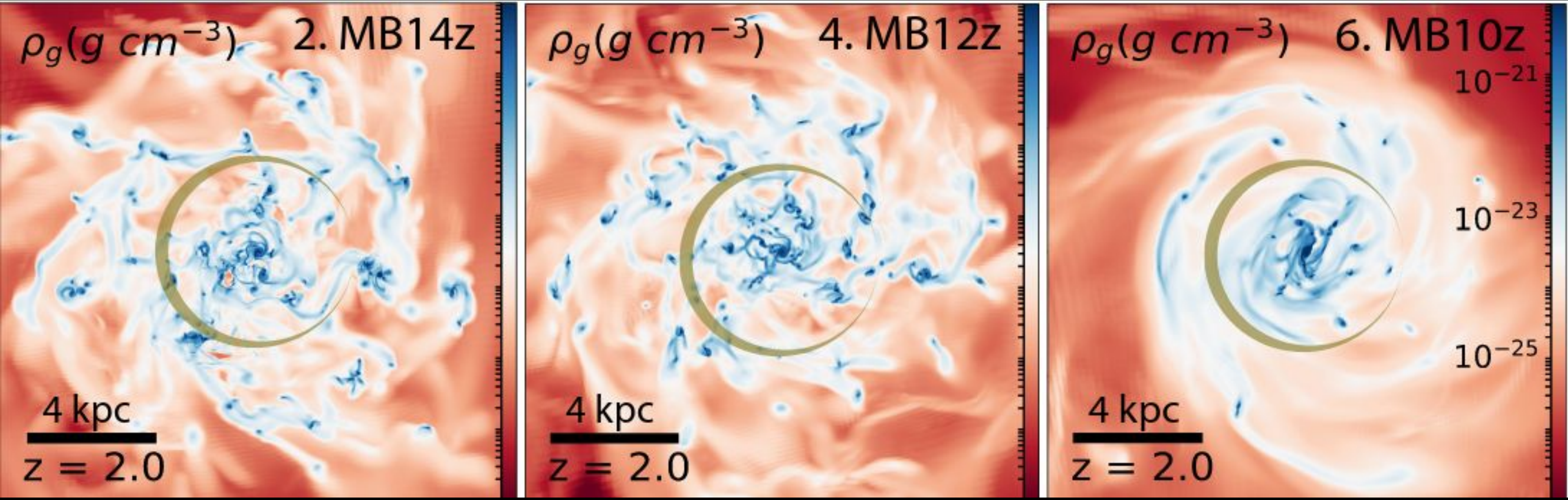
Sanchez-Salcedo et al. (2013), Elstner et al. (2014): B-field in the detectable regions of galaxies not strong enough. *B* would impede rotation, not enhance it.

Auriga simulations - Van de Voort et al. (2021)

If B > 0

- Galaxies are more **disk-dominated**
- **Central BH is** more massive
- **HI extended disks** around the galaxy are more massive





How primordial magnetic fields shrink galaxies - Martin-Alvarez et al. (2020)

Strong primordial B-fields delay star formation + remove rotational support
-> Reduction radial size of the galactic disk
-> Gas towards centre.
-> Higher light concentration.

Magnetic braking?

Diffuse warmer gas:
Too diffuse to condense
Detectable in radio
Since 70's

Molecular clouds:
Ready to form stars!
Detectable in far-infrared
Since 2020

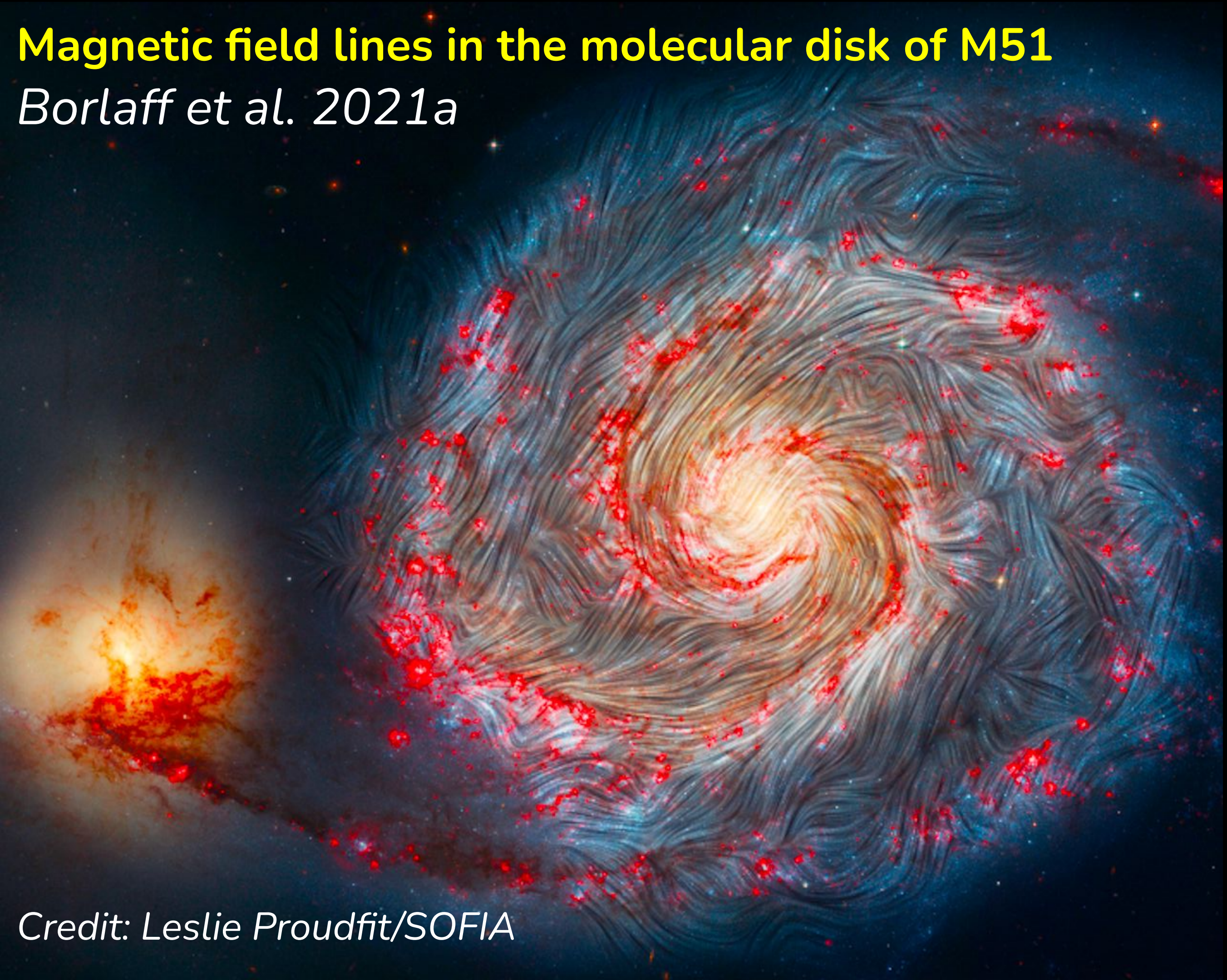
In order to answer: **Do magnetic fields shape galaxies?**

First we need to address:

Magnetic field diffuse gas = Magnetic field molecular gas ?

Magnetic field lines in the molecular disk of M51

Borlaff et al. 2021a



Credit: Leslie Proudfit/SOFIA

The diffuse gas and the molecular clouds *feel* the same magnetic field?

What do we compare?
Synchrotron polarized radio emission (diffuse gas) vs. magnetically aligned dust grain thermal FIR emission (molecular clouds)

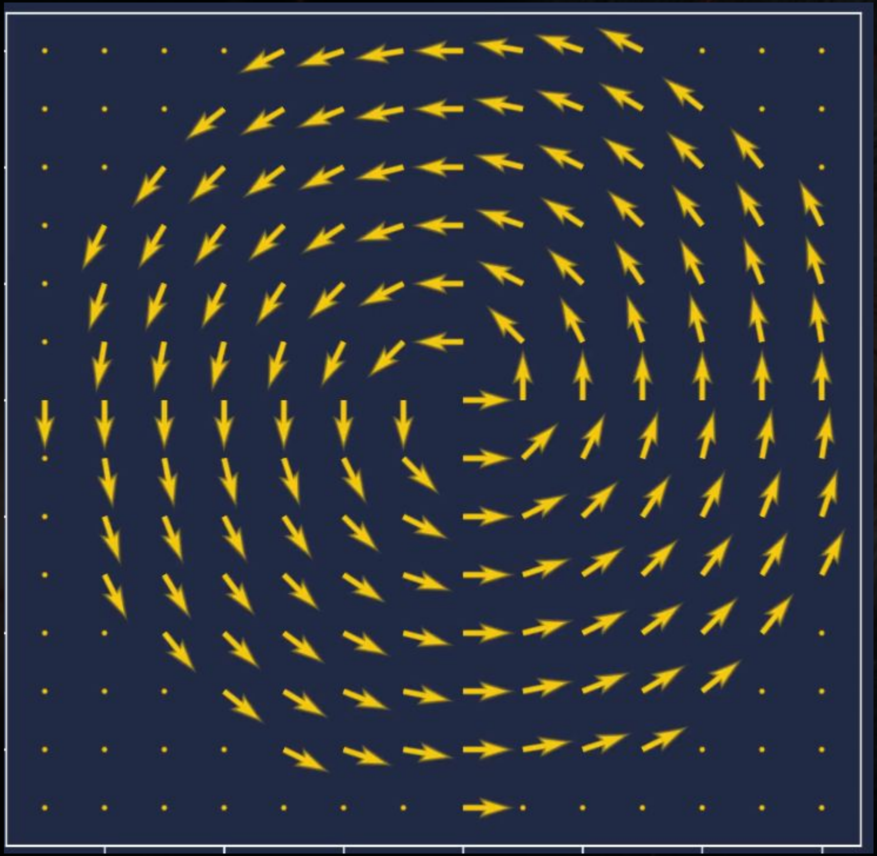
How?
Magnetic *pitch angle*

Magnetic field lines in the molecular disk of M51

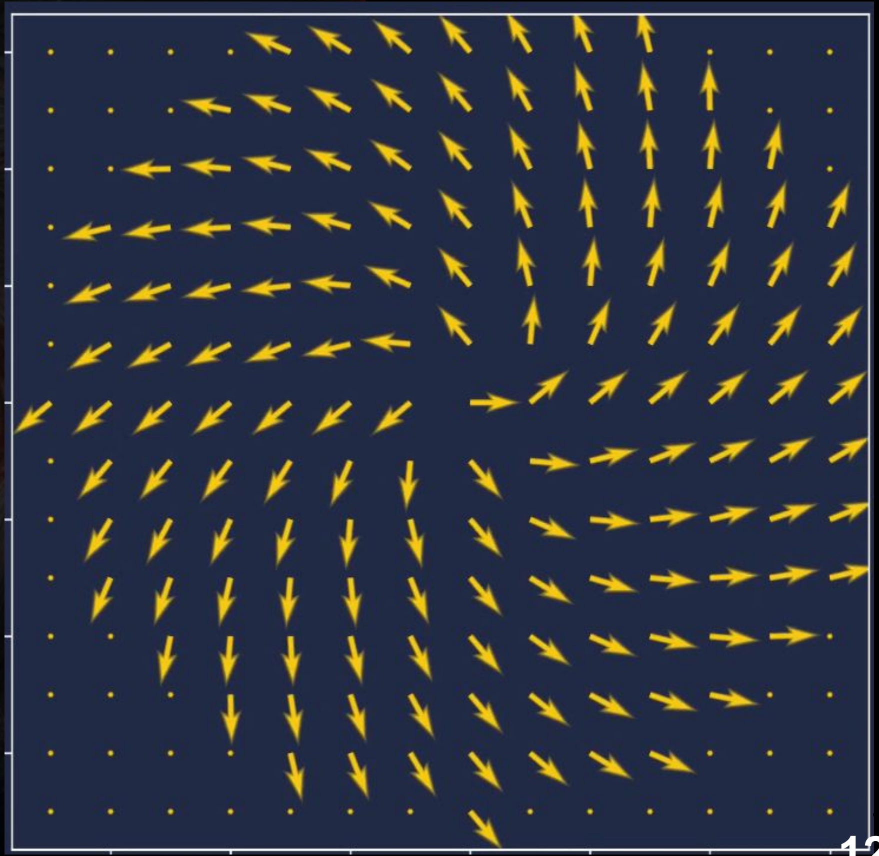
Borlaff et al. (in prep)

The diffuse gas and the molecular clouds feel the same

Low pitch angle (more circular)

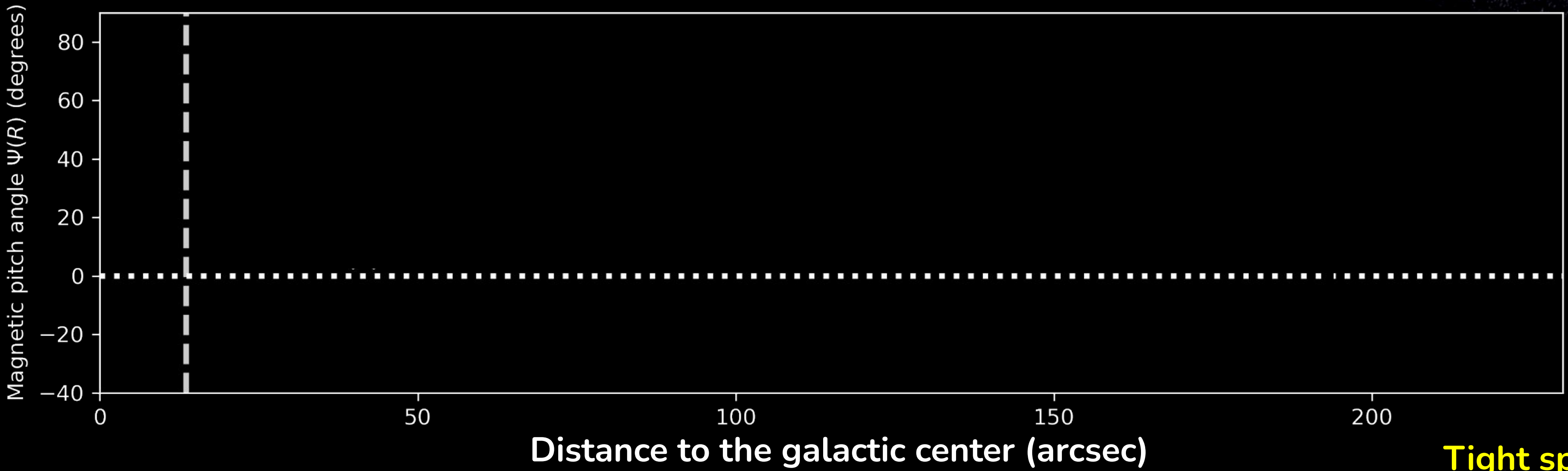


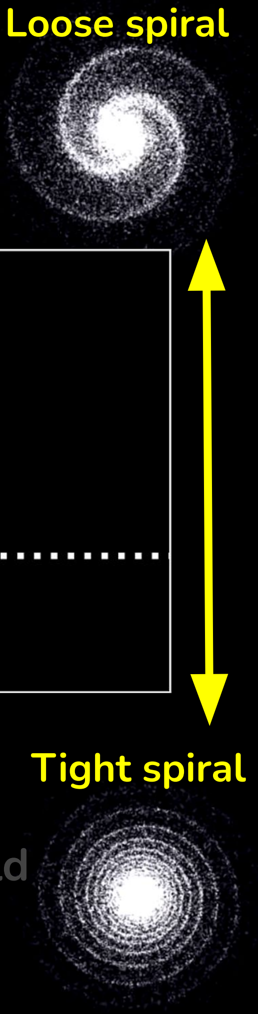
High pitch angle (more radial)



Radio vs. FIR magnetic pitch angle profiles

Borlaff et al. 2021a





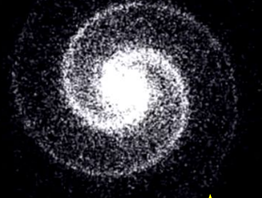
1 - The diffuse gas has a regular uniform spiral magnetic field

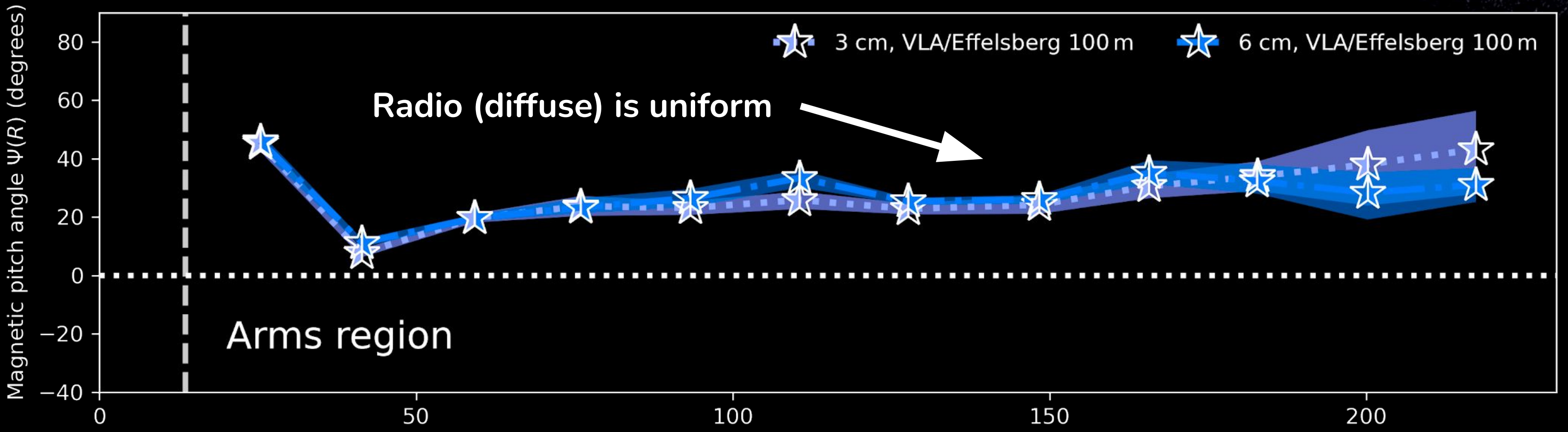
2 - The magnetic field of the outer molecular disk is highly distorted

Radio vs. FIR magnetic pitch angle profiles

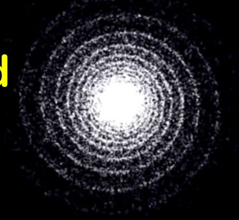
Borlaff et al. 2021a

Loose spiral





Tight spiral

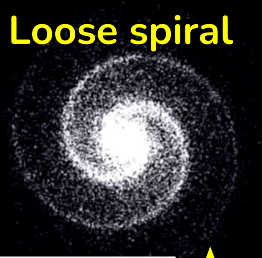


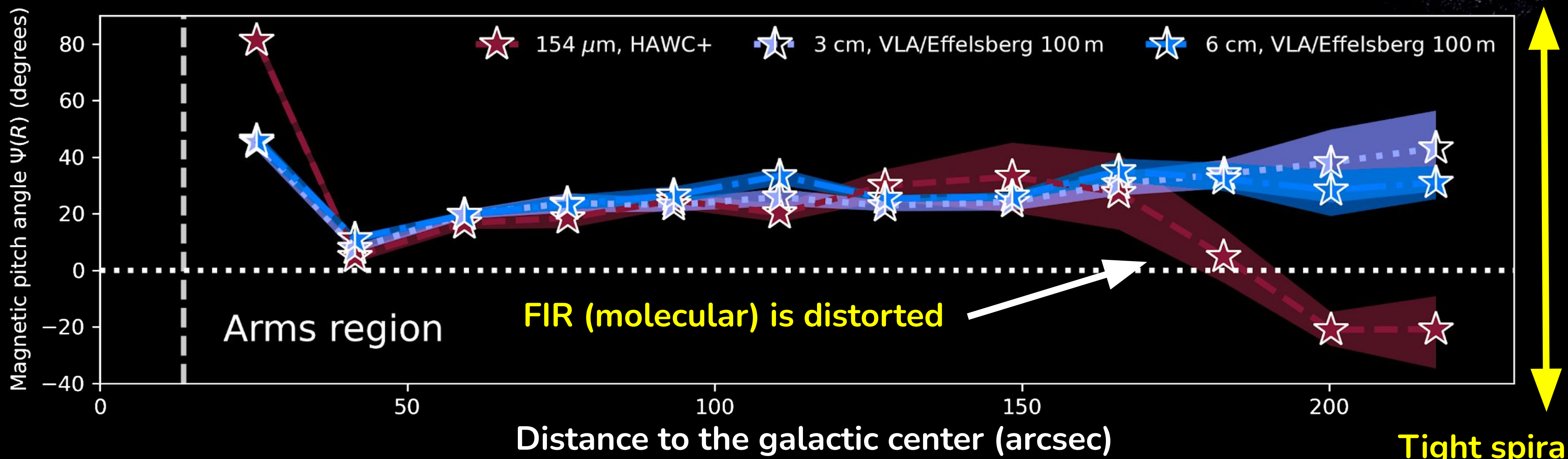
1 - The diffuse gas has a regular uniform spiral magnetic field

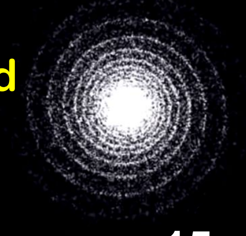
2 - The magnetic field of the outer molecular disk is highly distorted

Radio vs. FIR magnetic pitch angle profiles

Borlaff et al. 2021a







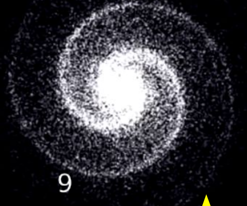
1 - The diffuse gas has a regular uniform spiral magnetic field

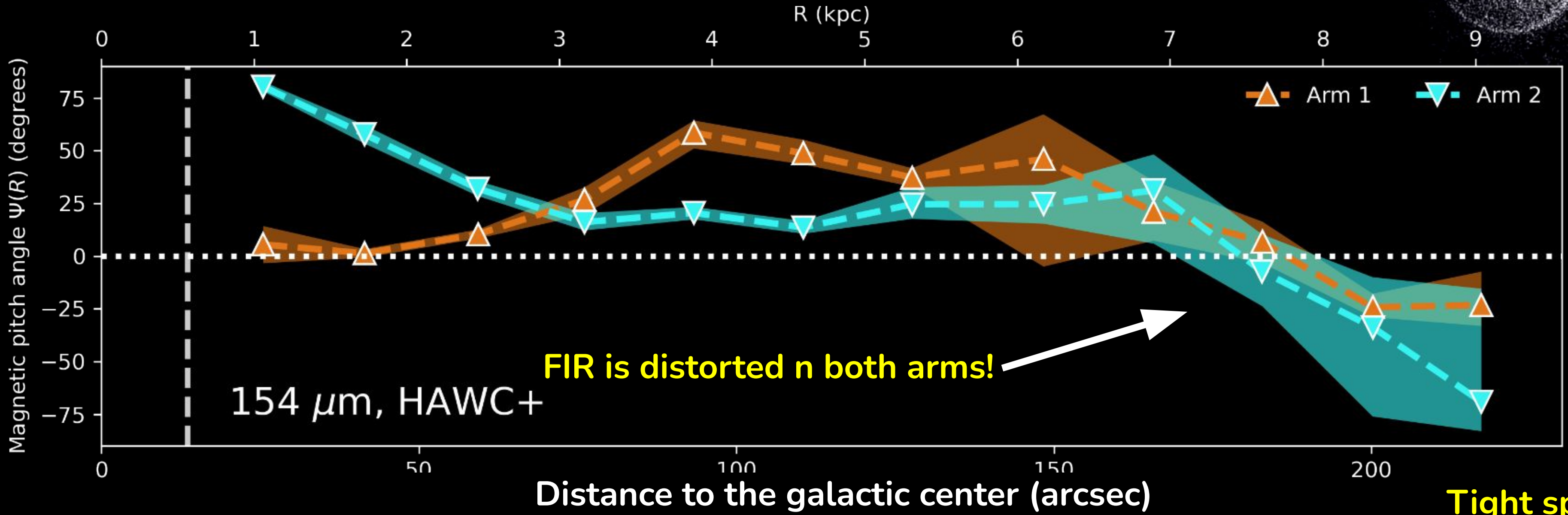
2 - The magnetic field of the outer molecular disk is highly distorted

Radio vs. FIR magnetic pitch angle profiles

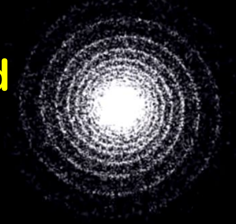
Borlaff et al. 2021a

Loose spiral





Tight spiral



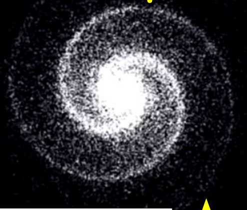
1 - The diffuse gas has a regular uniform spiral magnetic field

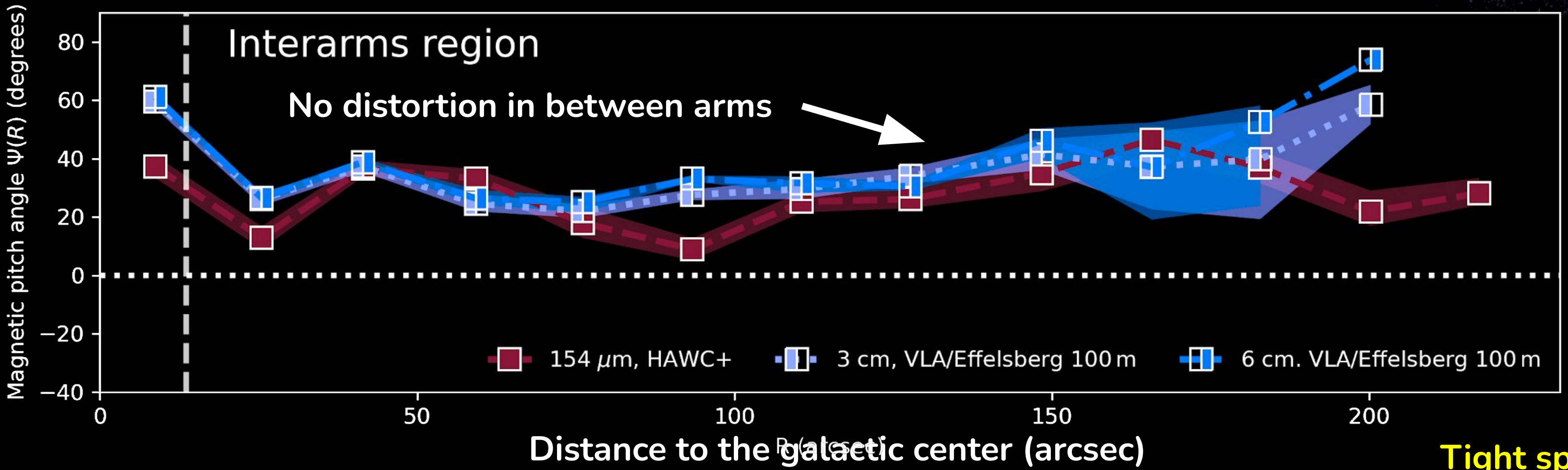
2 - The magnetic field of the outer molecular disk is highly distorted

Radio vs. FIR magnetic pitch angle profiles

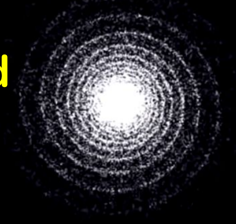
Borlaff et al. 2021a

Loose spiral



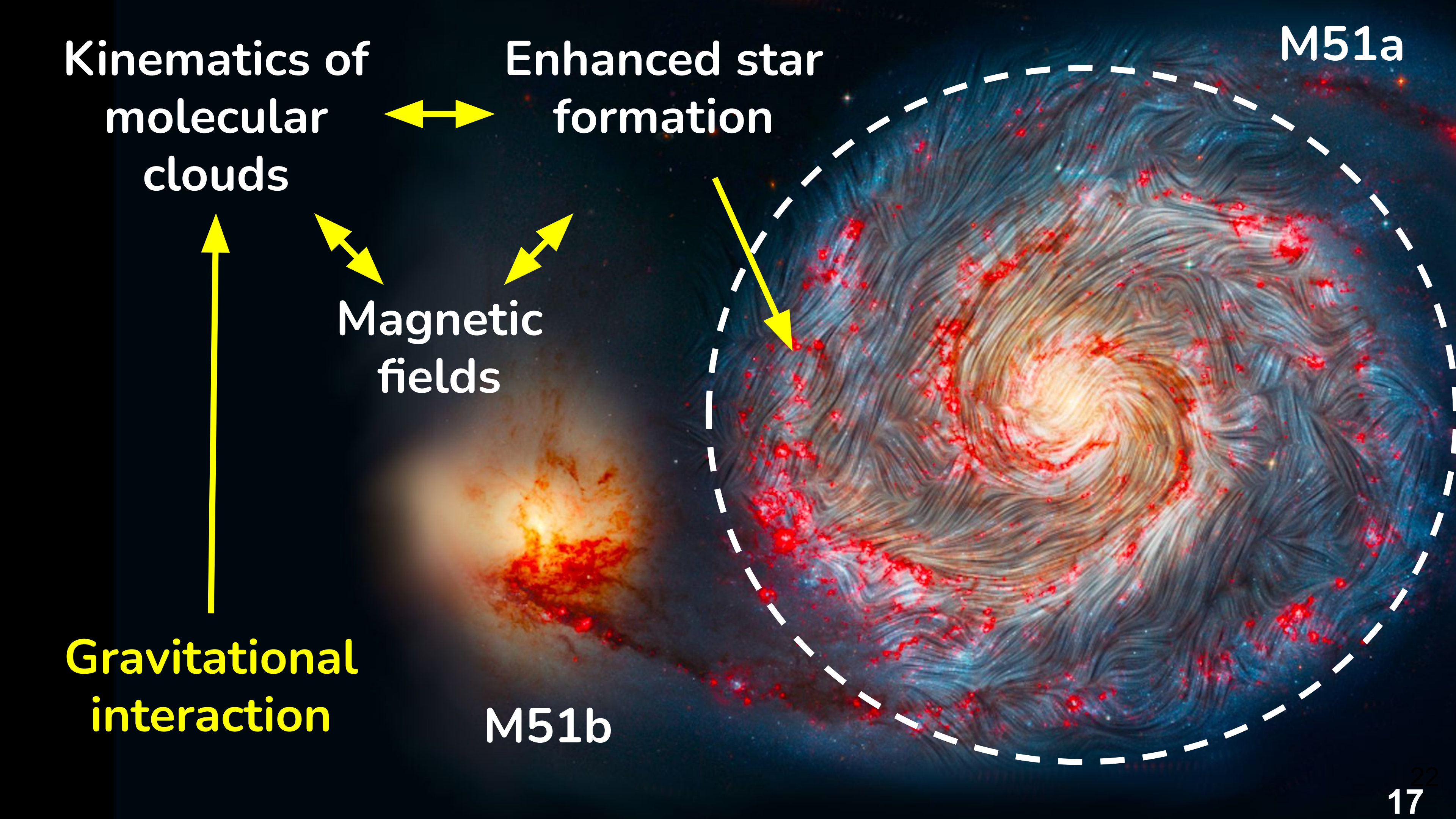


Tight spiral

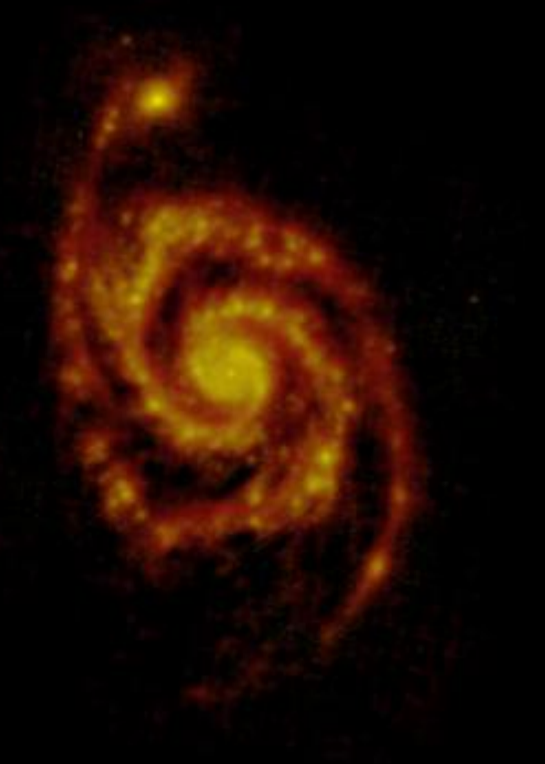


1 - The diffuse gas has a regular uniform spiral magnetic field

2 - The magnetic field of the outer molecular disk is highly distorted

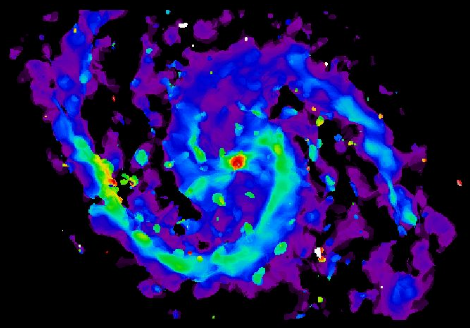

Kinematics of molecular clouds
Enhanced star formation
M51a
Magnetic fields
Gravitational interaction
M51b

HI + H2 column density



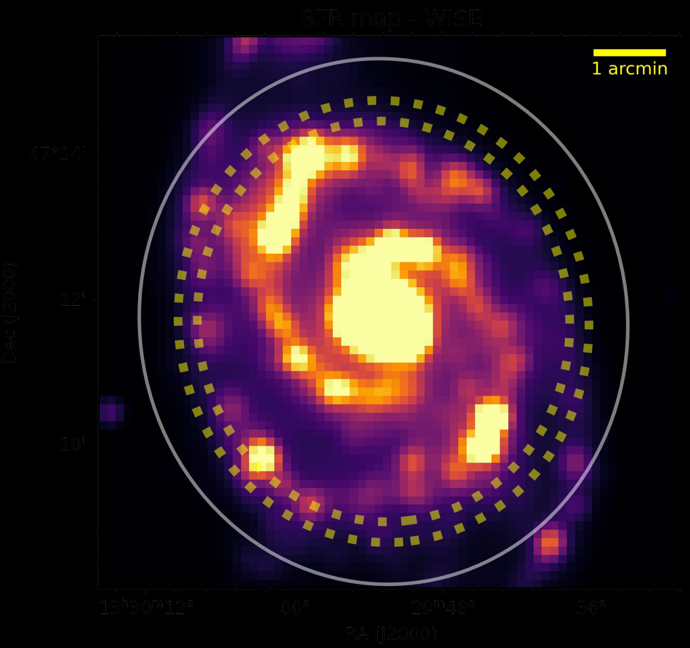
Herschel PACS/SPIRE
PID/Wilson 2007

^{12}CO velocity dispersion



PAWS PdBI/IRAM-30 m
Pety et al. 2013
Colombo et al. 2014

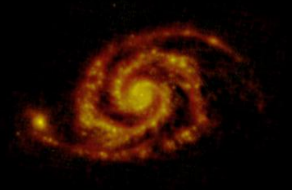
Star Formation Rate



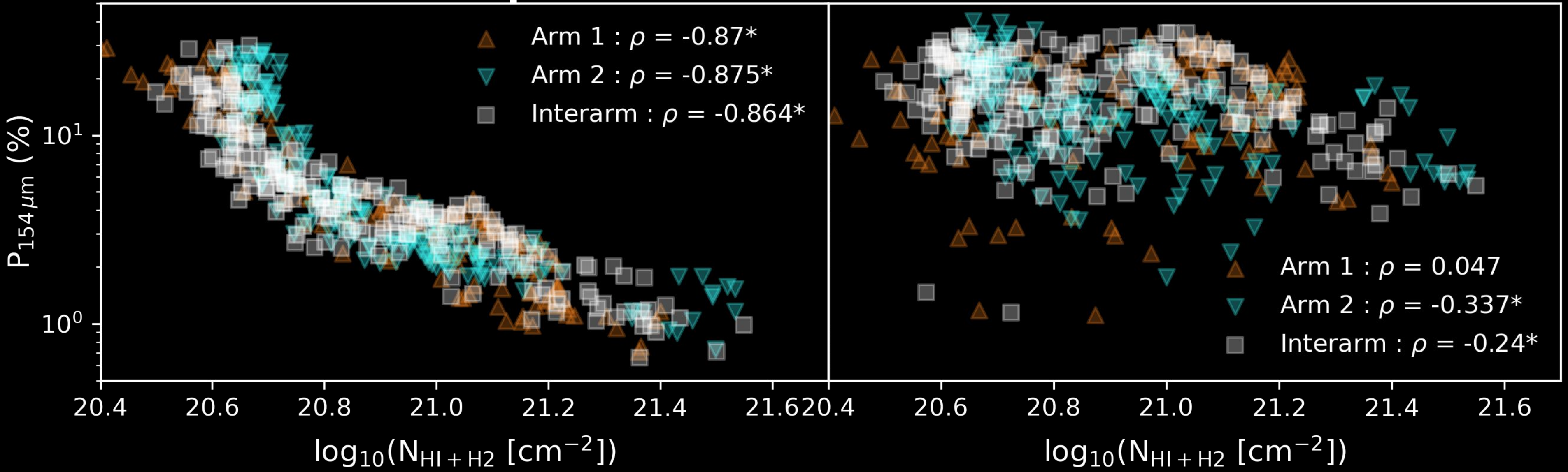
WISE
Leroy et al. 2019

Polarization fraction vs. Column density

Borlaff et al. 2021a



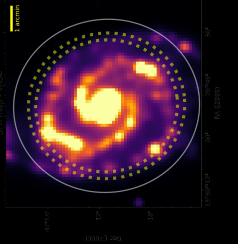
FIR 154 µm | **Radio 3 cm**

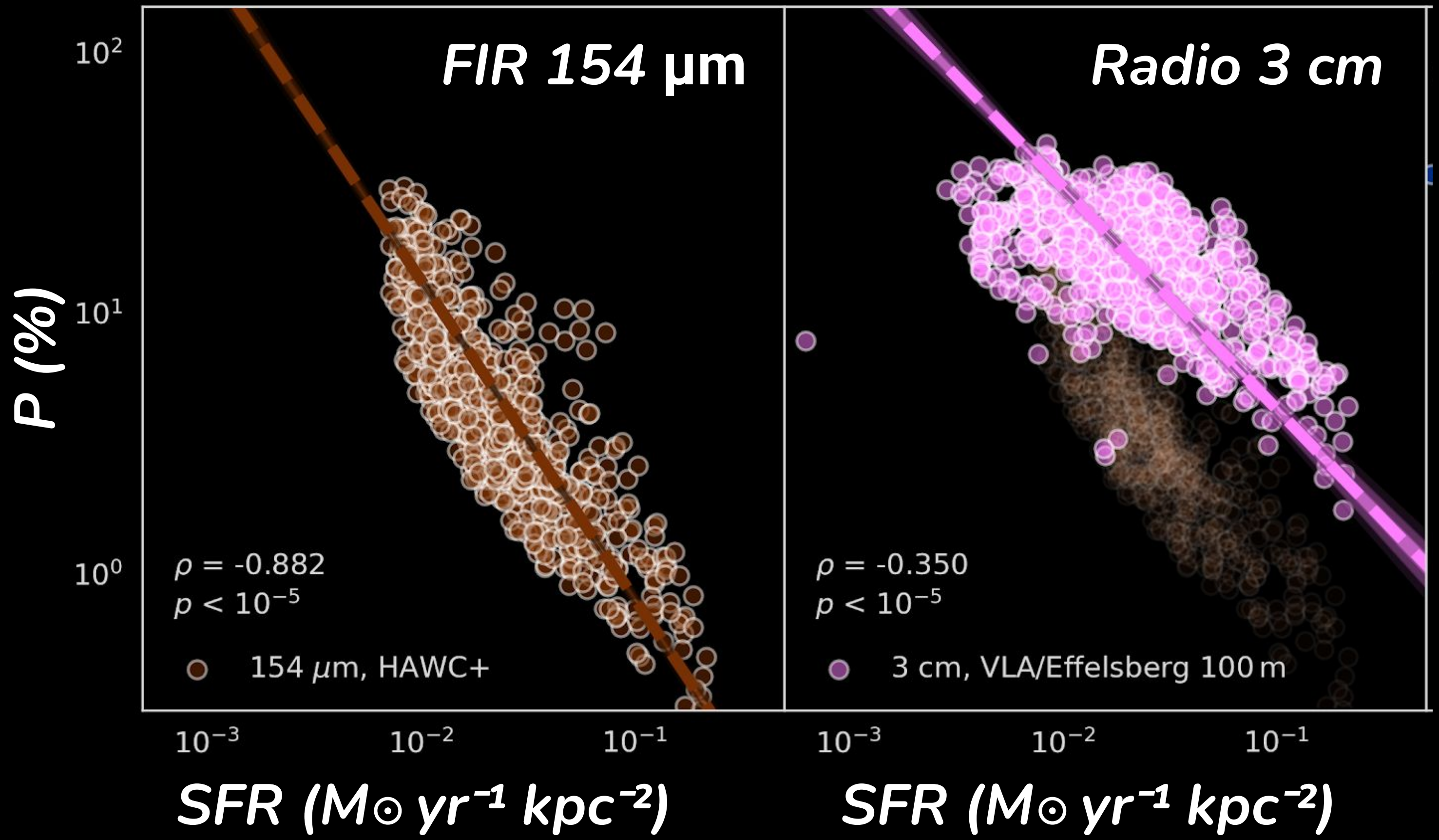


Higher density → **Lower FIR P(%)**
→ **Same radio P(%)**

Polarization fraction vs. Star Formation Rate

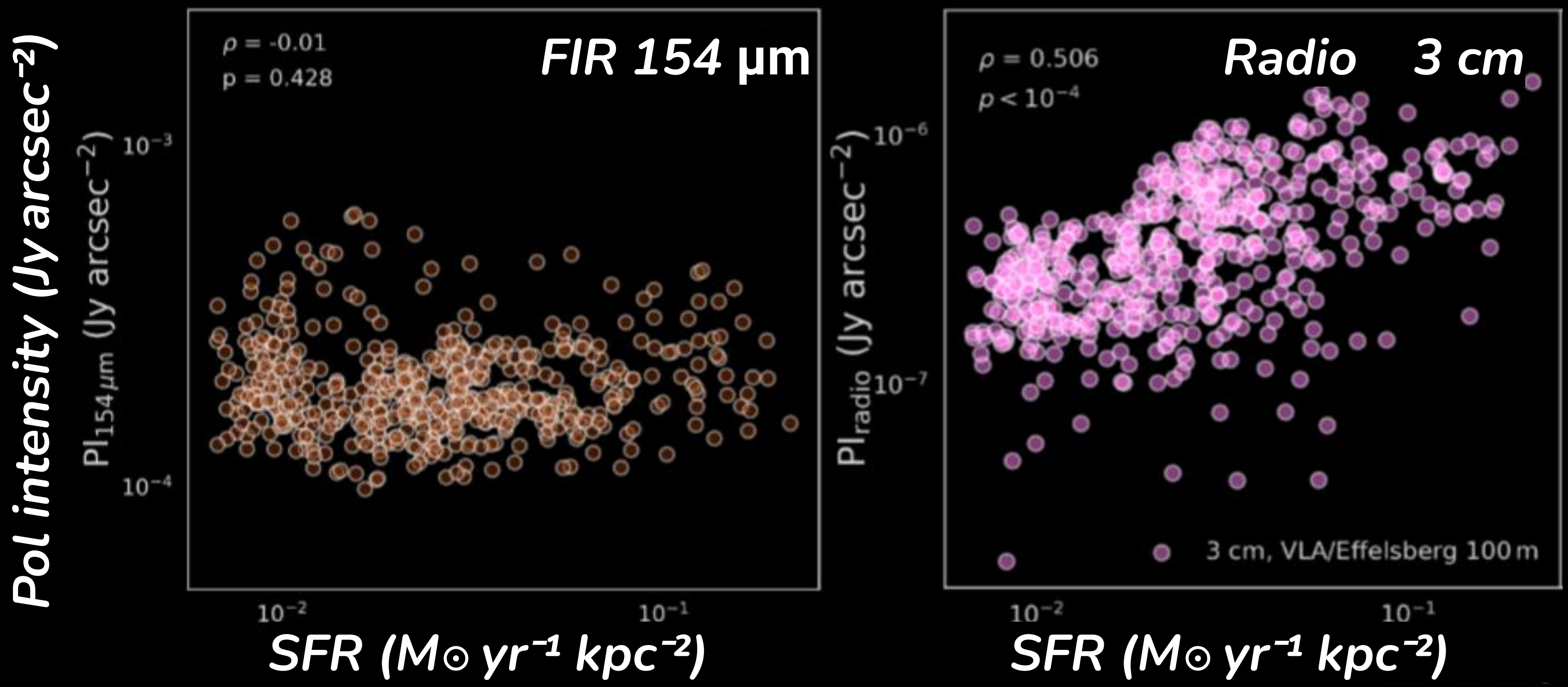
Borlaff et al. 2021a





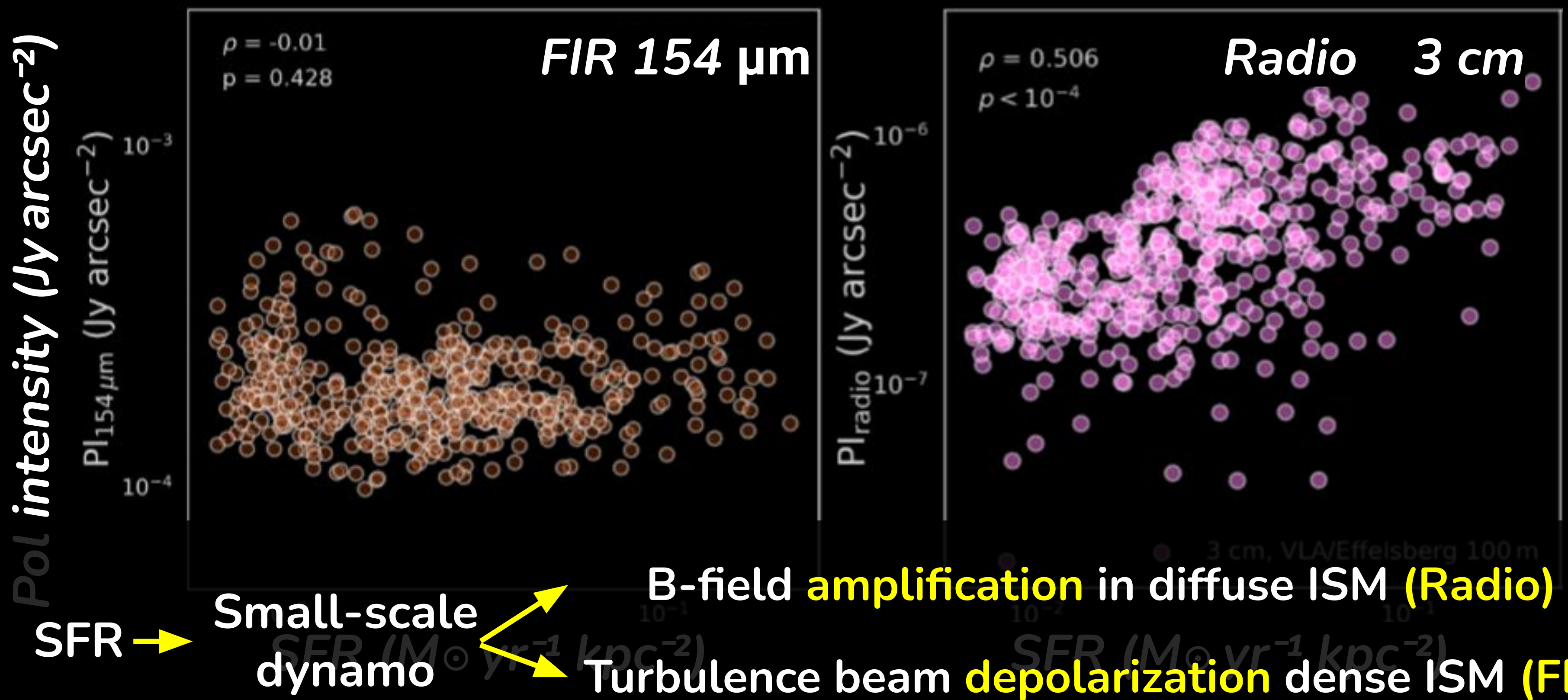
Polarized intensity vs. Star Formation Rate

Borlaff et al. 2021a



Polarized intensity vs. Star Formation Rate

Borlaff et al. 2021a



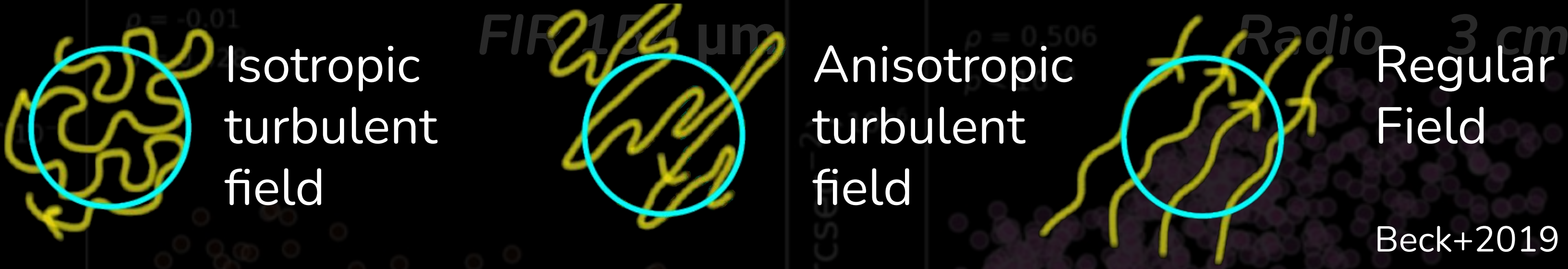
SFR → Small-scale dynamo

→ B-field **amplification** in diffuse ISM **(Radio)**

→ Turbulence beam **depolarization** dense ISM **(FIR)**

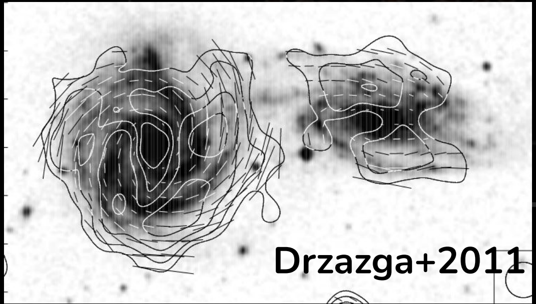
Polarized intensity vs. Star Formation Rate

1 - P(%) vs. SFR: Complex molecular clouds structure inside each beam - FIR **depolarization** dense ISM? (Fissel et al. 2016)



Beck+2019

2 - Variation of the **dust grain alignment efficiency** as a function of the total intensity towards regions of high column density (Hoang et al. 2021)

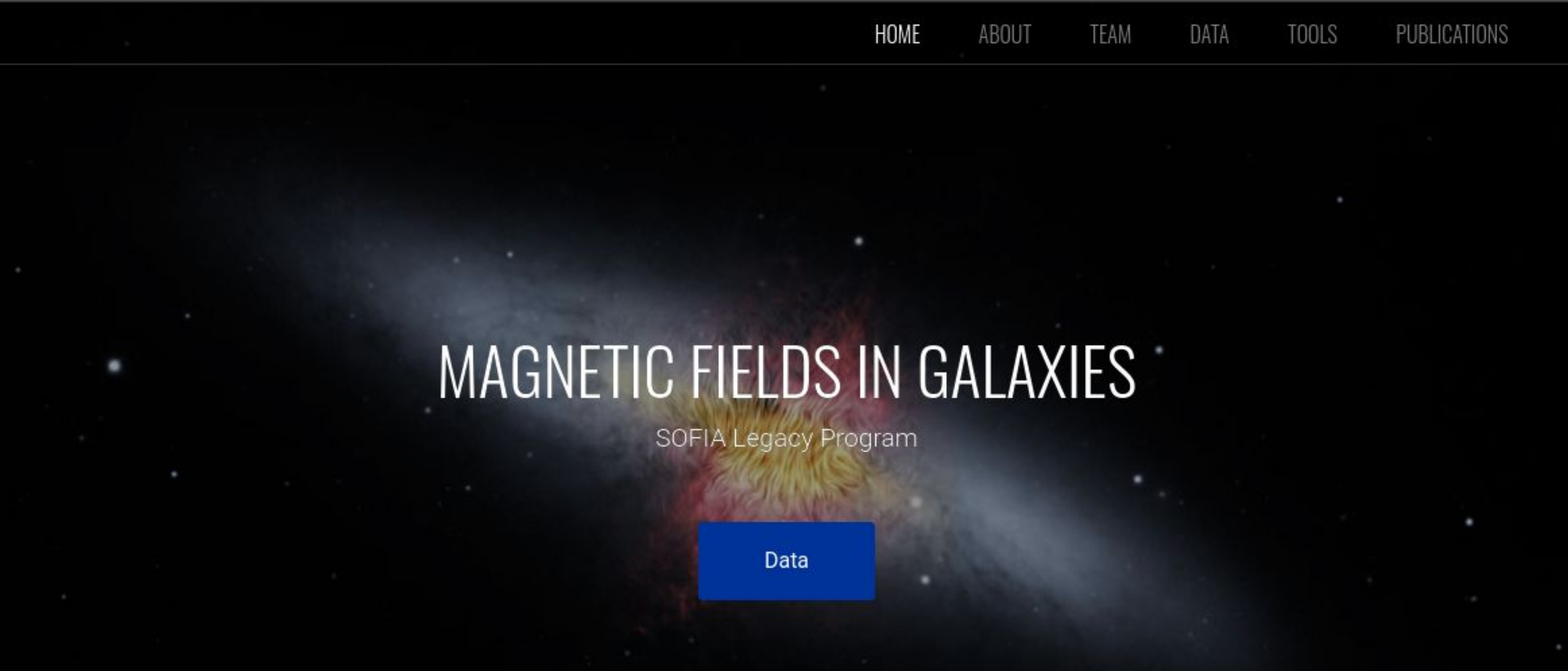


Drzazga+2011

2 - PI **increases** with Column density / velocity dispersion / SFR - Radio pol. traces B-strength

→ Turbulence generates isotropic B-fields

Shear? Merger? Shocks?



Paper I - M51 - Borlaff et al. 2021a

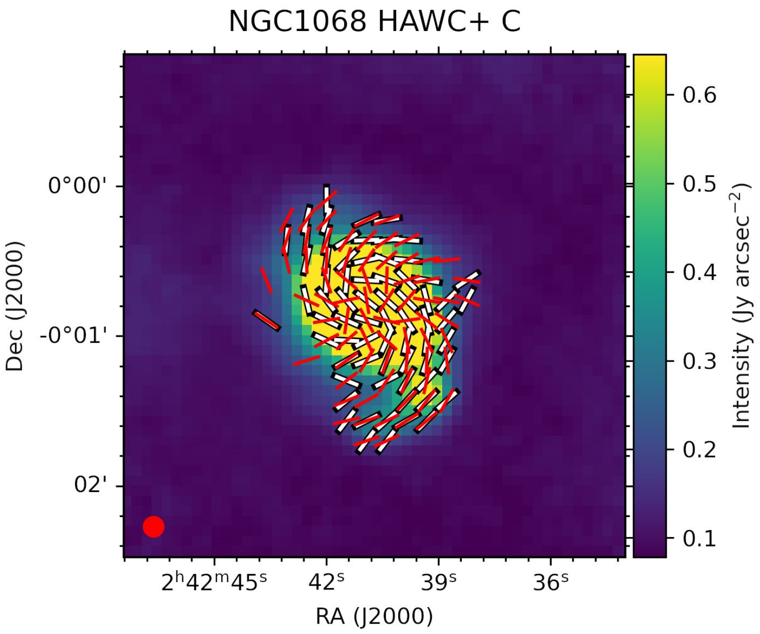
Paper II - NGC1097 - López-Rodriguez et al. 2021

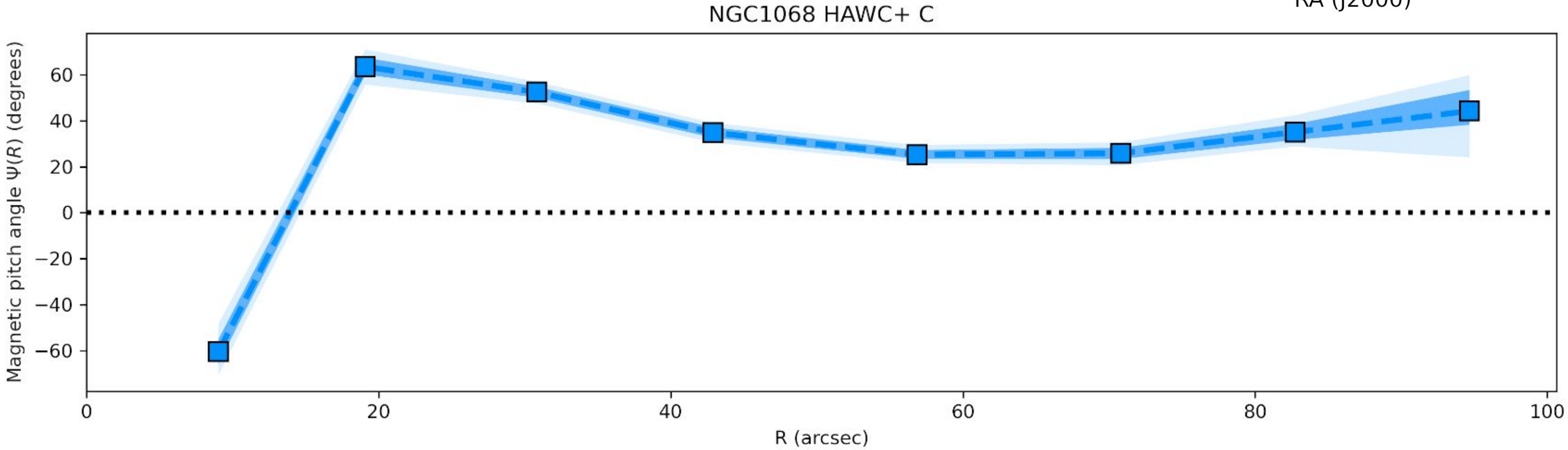
Paper III - Data Release I - López-Rodriguez et al. 2022 (in prep.)

NGC1068

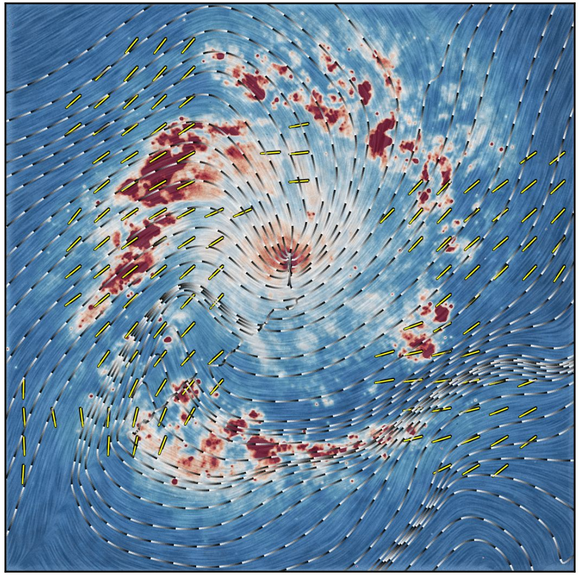
B-field →

Pitch angle profile ↓





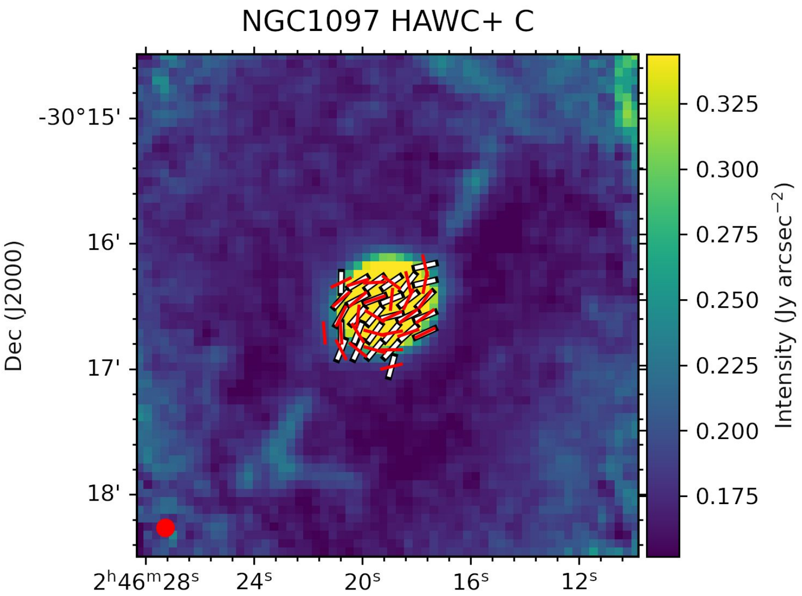
Starburst ring of NGC 1097: B-field orientation and direction within 1 Kpc

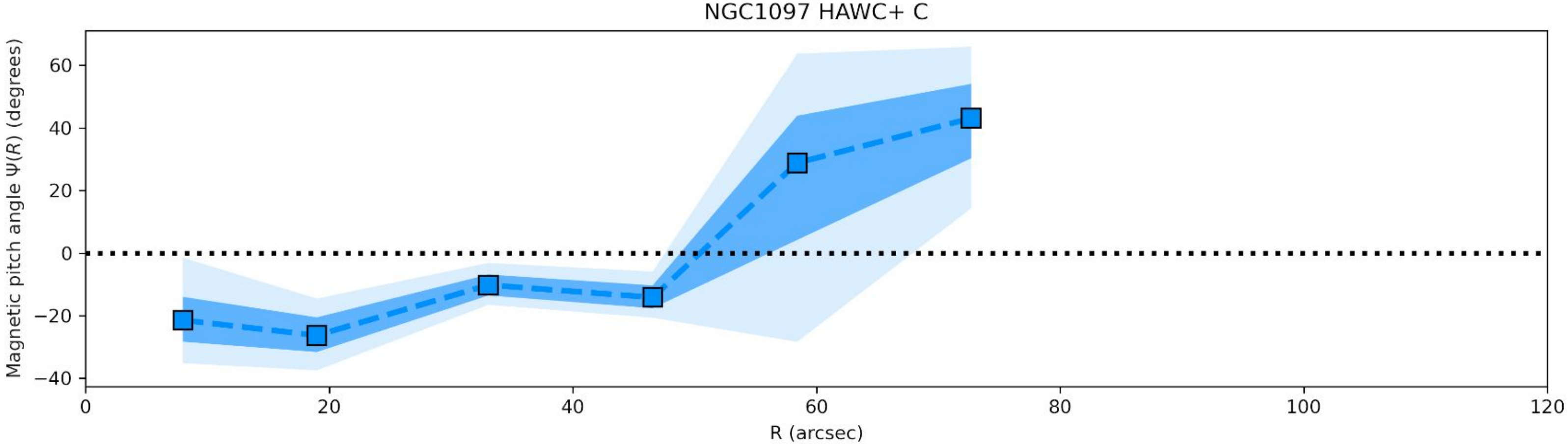


NGC1097

B-field →

Pitch angle profile ↓

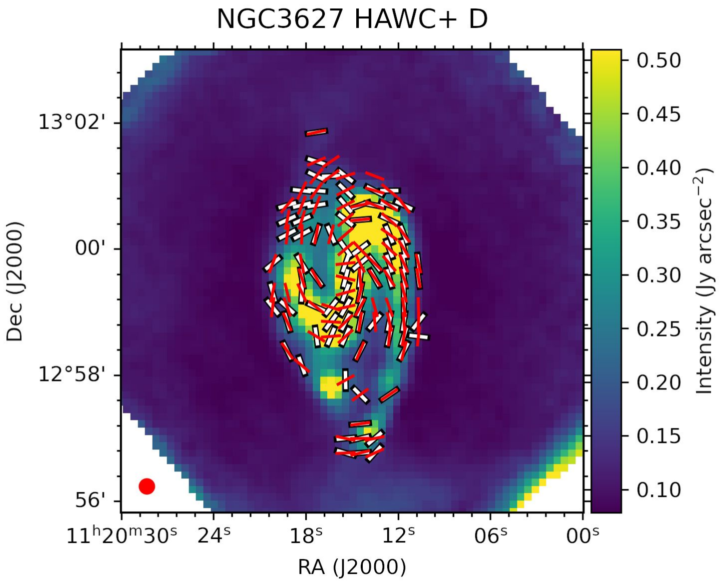


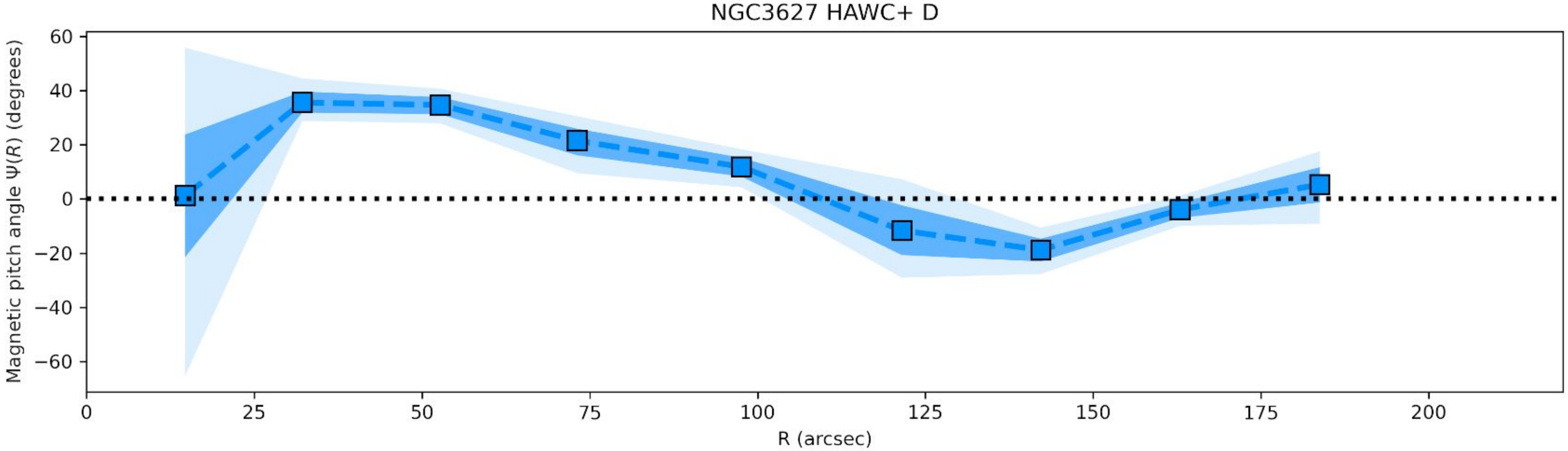


NGC3627

B-field

Pitch angle profile

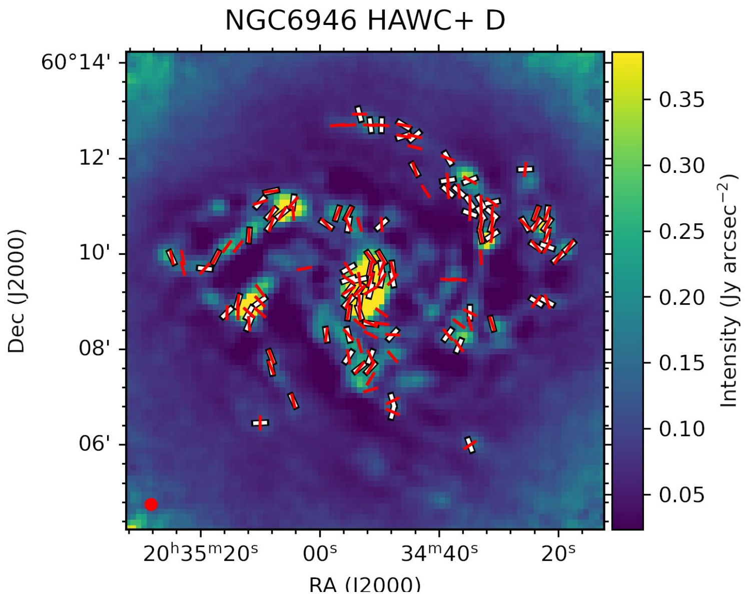


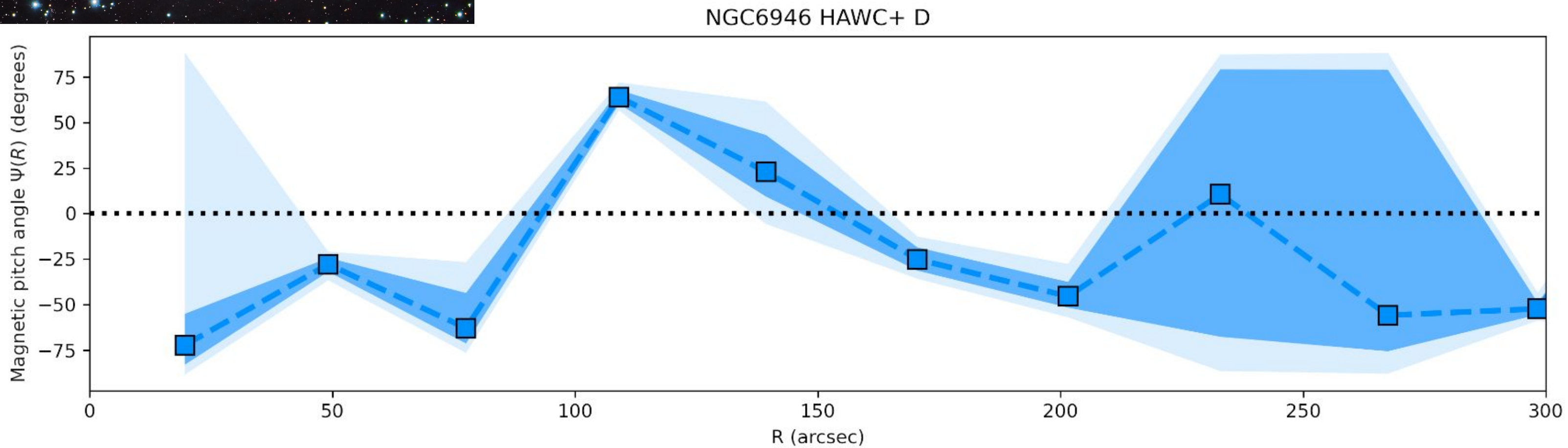


NGC6946

B-field →

Pitch angle profile ↓

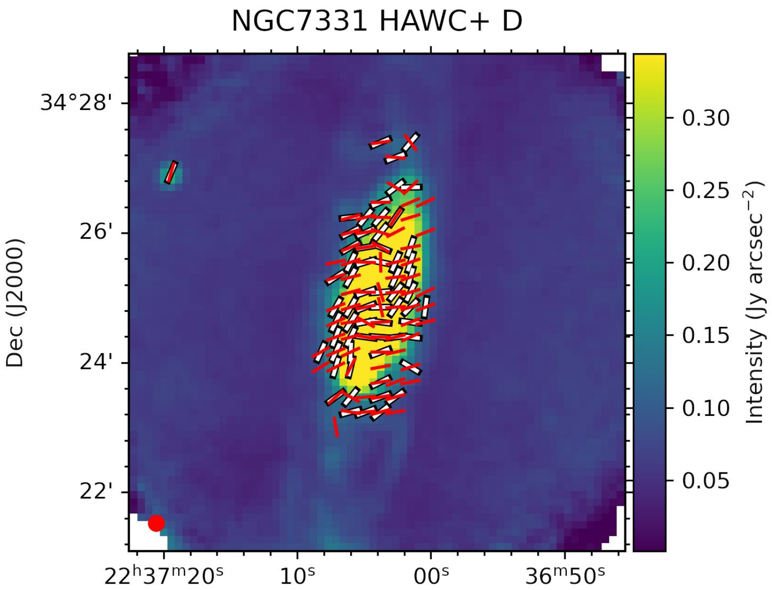


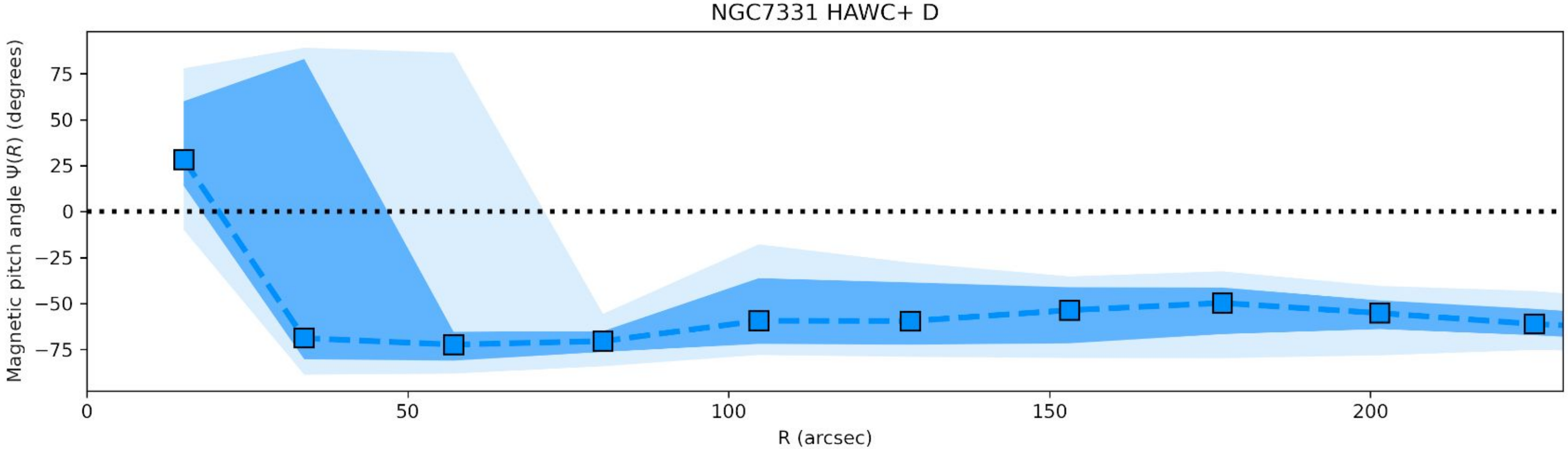


NGC7331

B-field

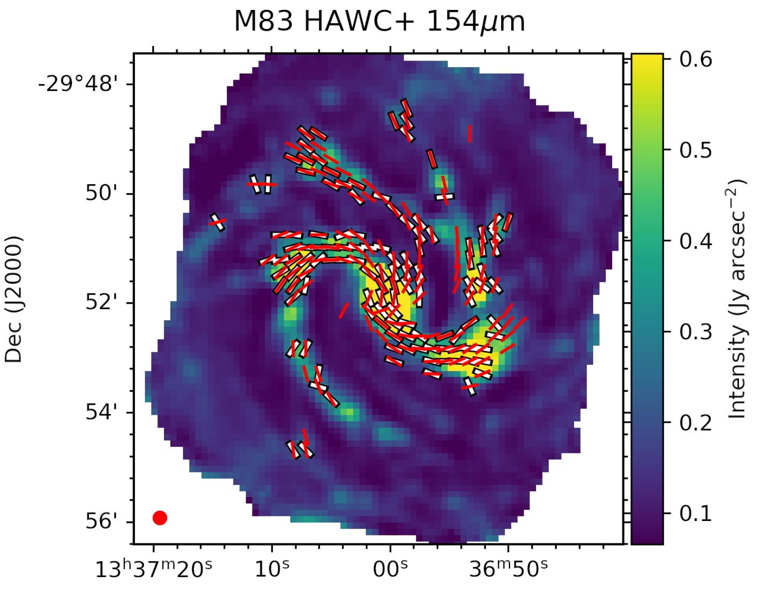
Pitch angle profile



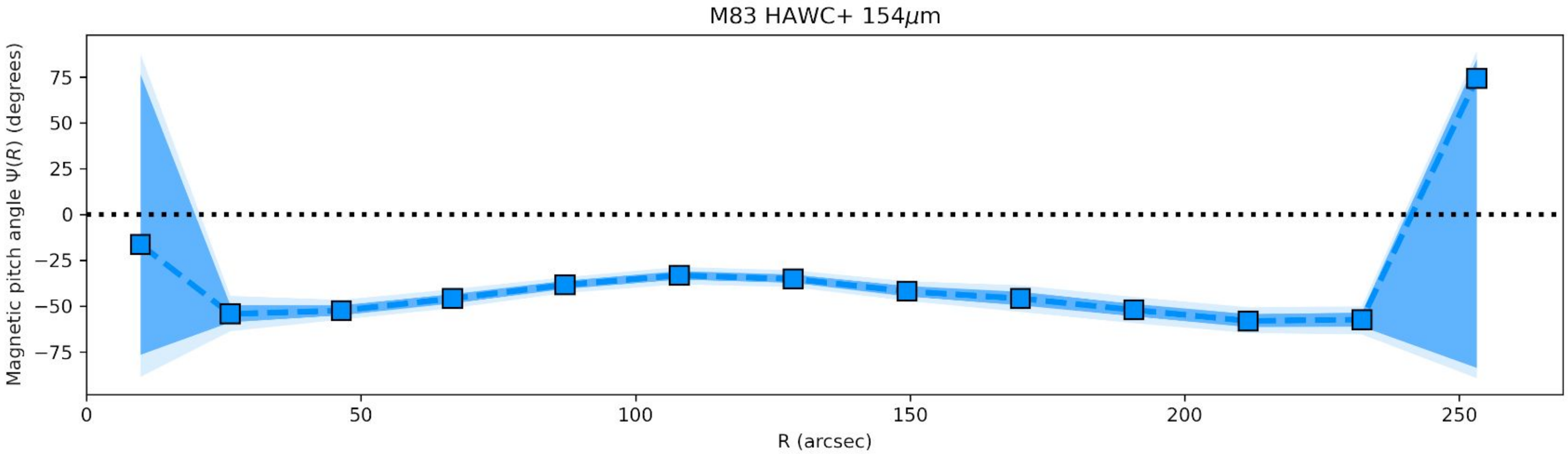


M83

B-field →



Pitch angle profile ↓



Conclusions

Magnetic field **diffuse gas** ≠ Magnetic field **molecular gas**

Star formation, gas kinematics, magnetic fields are interlinked factors that potentially shape spiral galaxies

Radiative alignment torques vs. ρ ISM

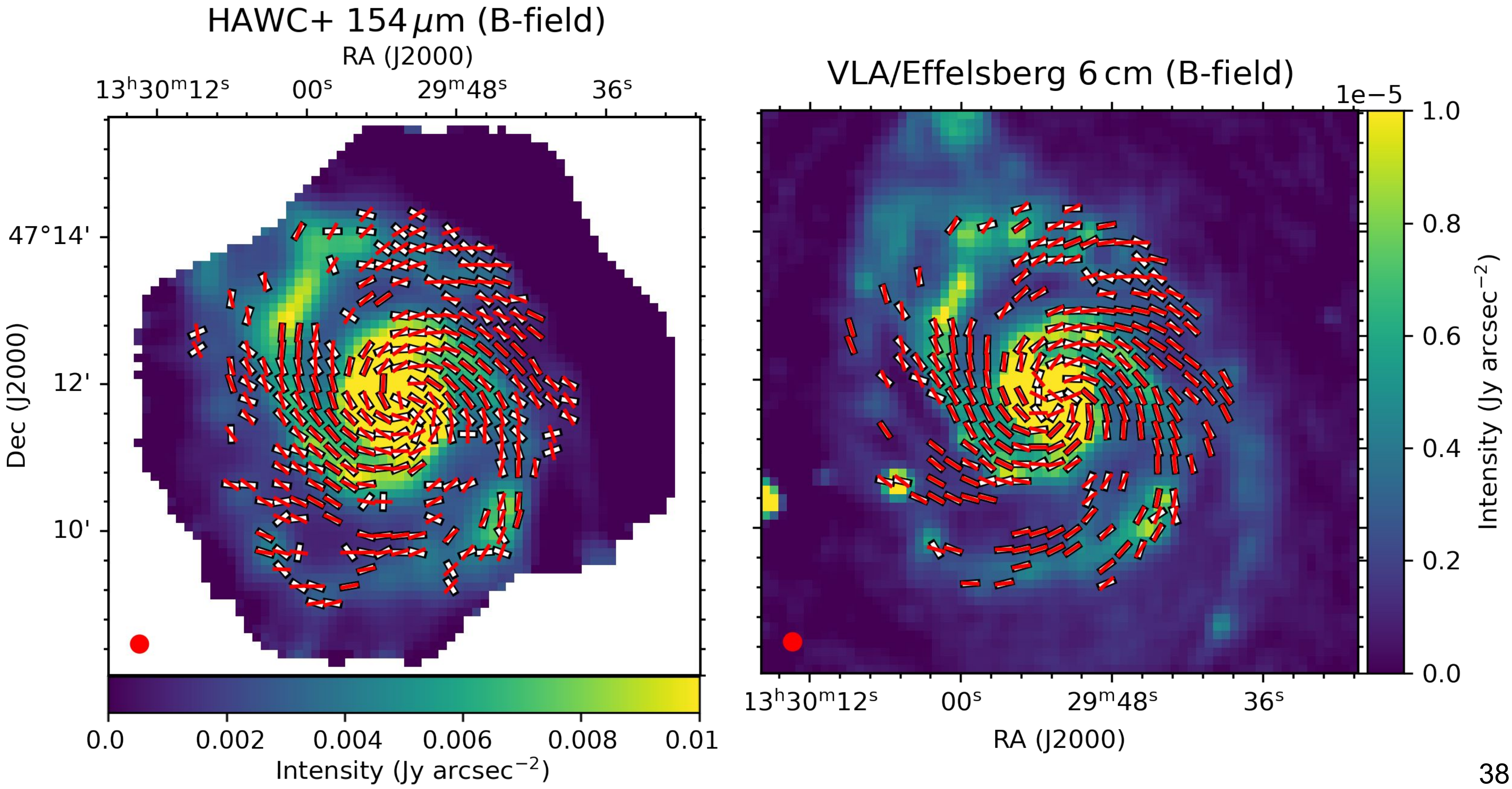
Beam depolarization? Higher resolution needed

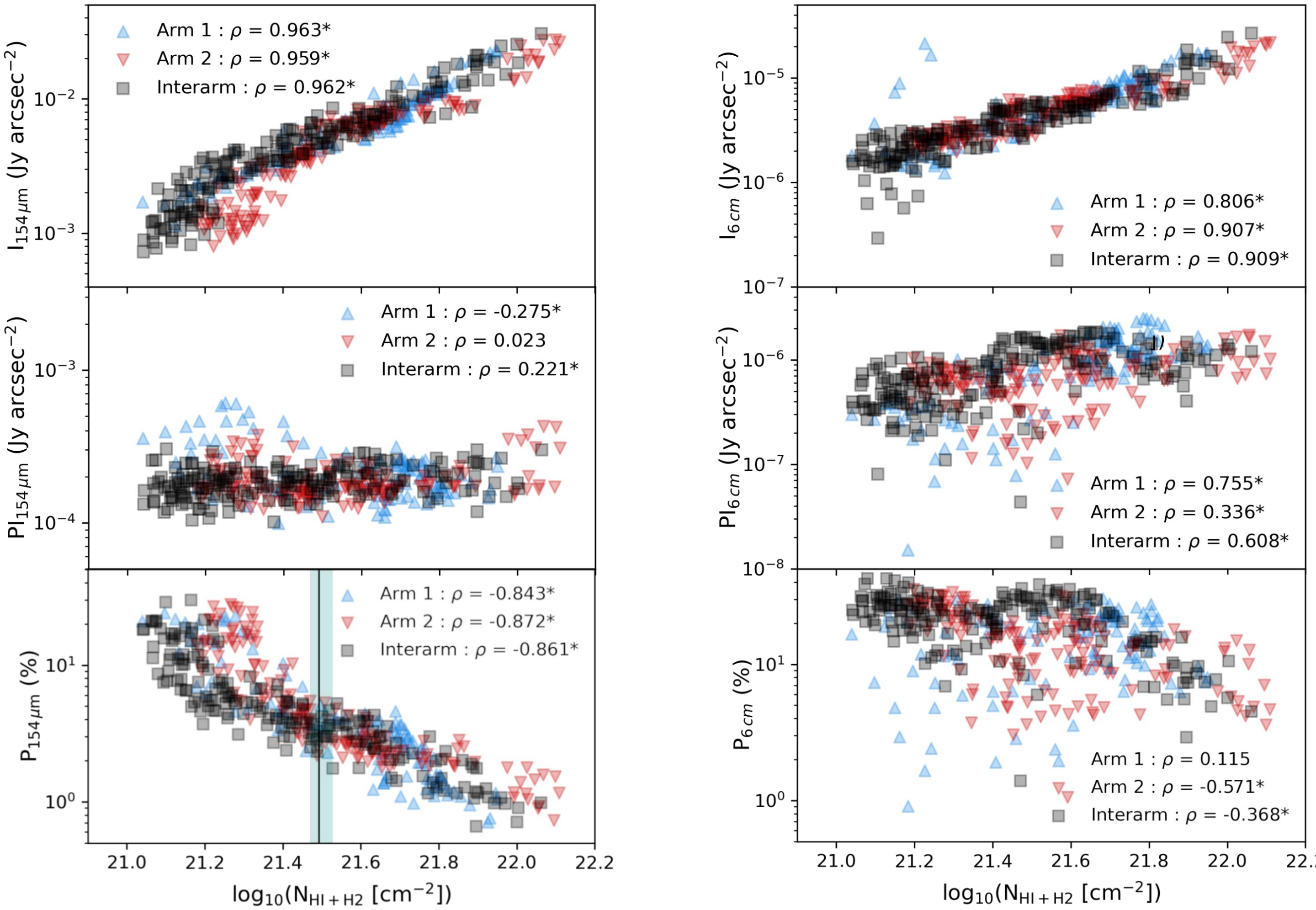
Stand by for next talk on SOFIA/HAWC+ López-Rodríguez **Legacy Program DR1**

Contact: a.s.borlaff@nasa.gov

http://galmagfields.com/

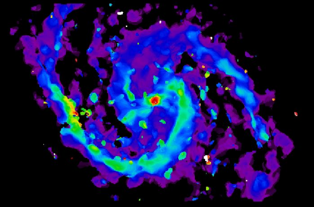

SOFIA
STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY
NASA
DLR
N747NA
NASA
843

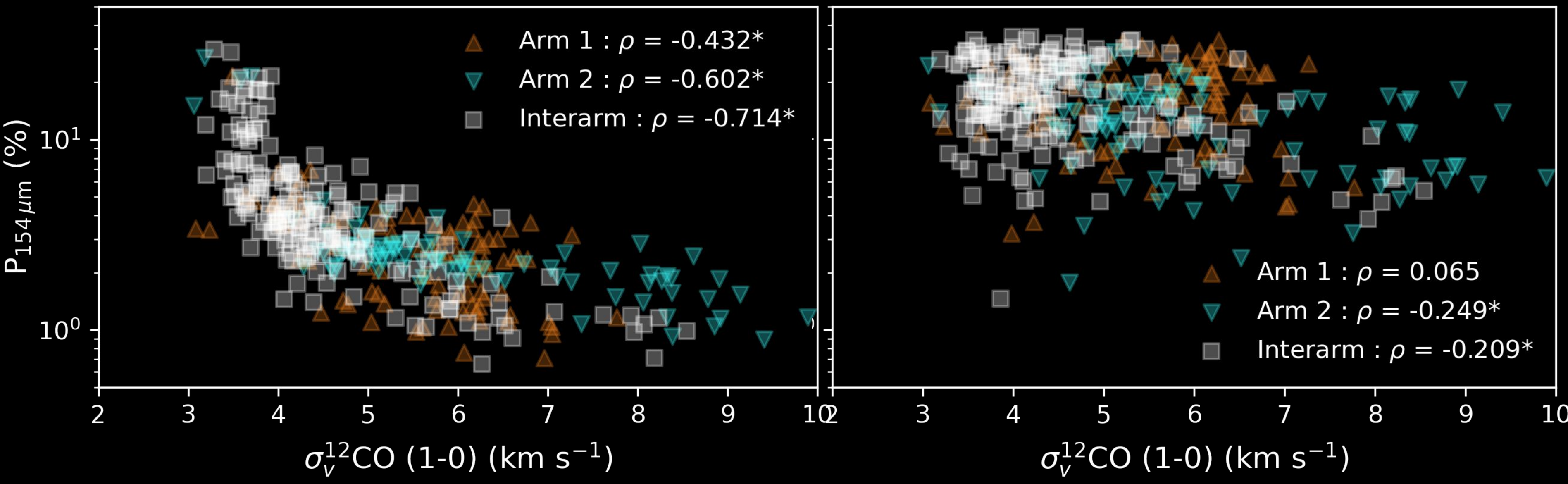

HAWC+ 154 μm (B-field)
RA (J2000)
13h30m12s
00s
29m48s
36s
47°14'
12'
10'
Dec (J2000)
0.0
0.002
0.004
0.006
0.008
0.01
Intensity (Jy arcsec−2)
VLA/Effelsberg 6 cm (B-field)
1e−5
1.0
0.8
0.6
0.4
0.2
0.0
Intensity (Jy arcsec−2)
13h30m12s
00s
29m48s
36s
RA (J2000)


Arm 1 : ρ = 0.963*
Arm 2 : ρ = 0.959*
Interarm : ρ = 0.962*
I154μm (Jy arcsec−2)
Arm 1 : ρ = 0.806*
Arm 2 : ρ = 0.907*
Interarm : ρ = 0.909*
I6cm (Jy arcsec−2)
Arm 1 : ρ = -0.275*
Arm 2 : ρ = 0.023
Interarm : ρ = 0.221*
PI154μm (Jy arcsec−2)
Arm 1 : ρ = 0.755*
Arm 2 : ρ = 0.336*
Interarm : ρ = 0.608*
PI6cm (Jy arcsec−2)
Arm 1 : ρ = -0.843*
Arm 2 : ρ = -0.872*
Interarm : ρ = -0.861*
P154μm (%)
Arm 1 : ρ = 0.115
Arm 2 : ρ = -0.571*
Interarm : ρ = -0.368*
P6cm (%)
log10(NHI+H2 [cm−2])
log10(NHI+H2 [cm−2])

Polarization fraction vs. ^{12}CO velocity dispersion

Borlaff et al. 2021a

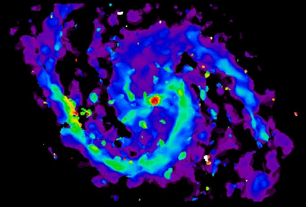




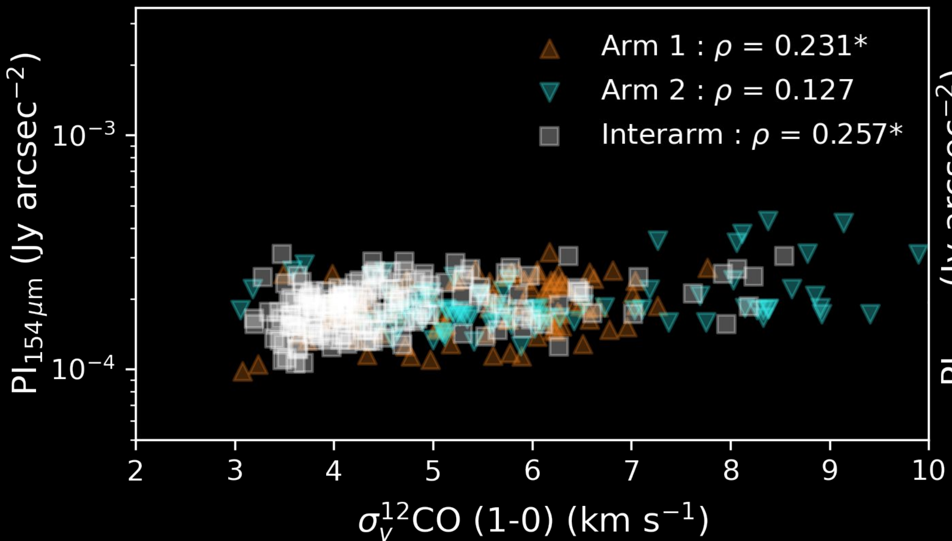
Higher density → Higher molecular gas turbulence → Lower FIR P(%) / Same radio P(%)

Polarized intensity vs. ^{12}CO velocity dispersion

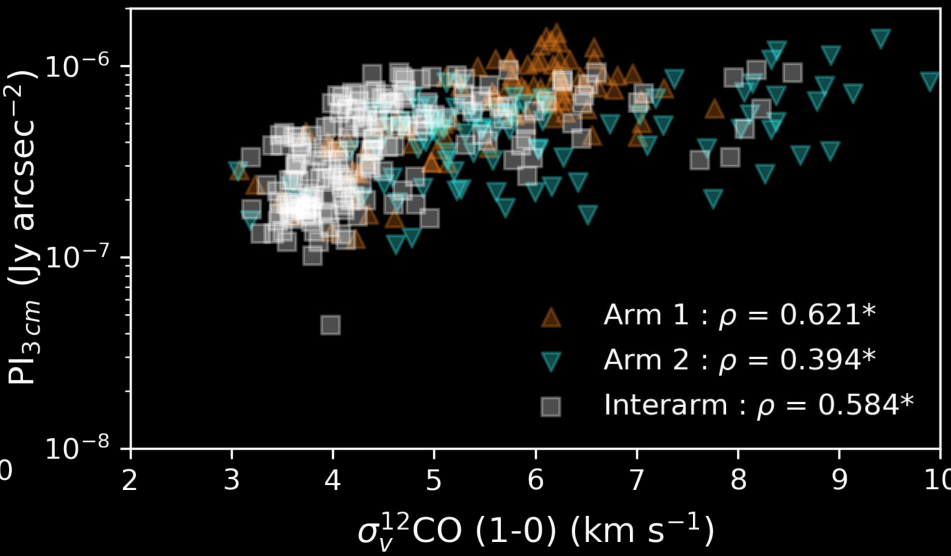
Borlaff et al. 2021a



FIR 154 µm



Radio 3 cm



Anisotropic turbulent field

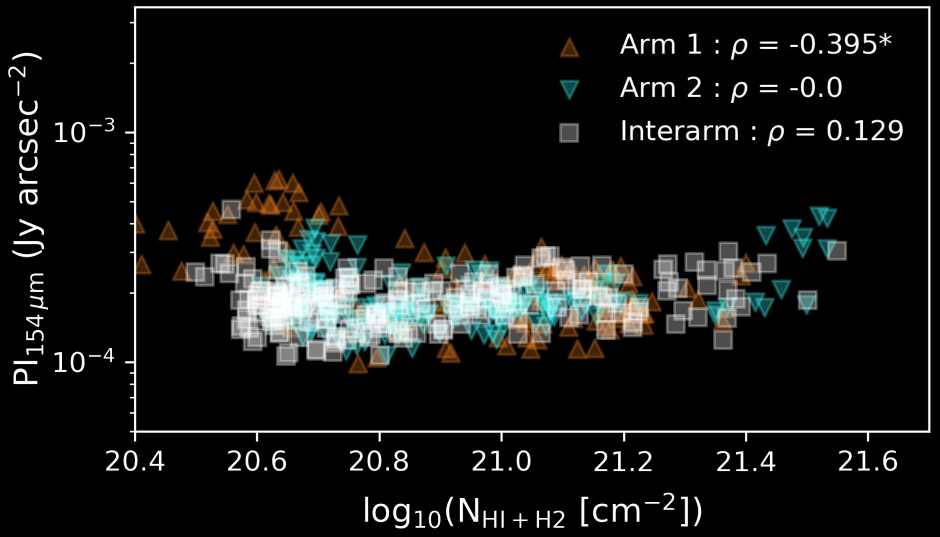
→ B-field **amplification** in diffuse ISM **(Radio)**

→ Turbulence beam **depolarization** dense ISM **(FIR)**

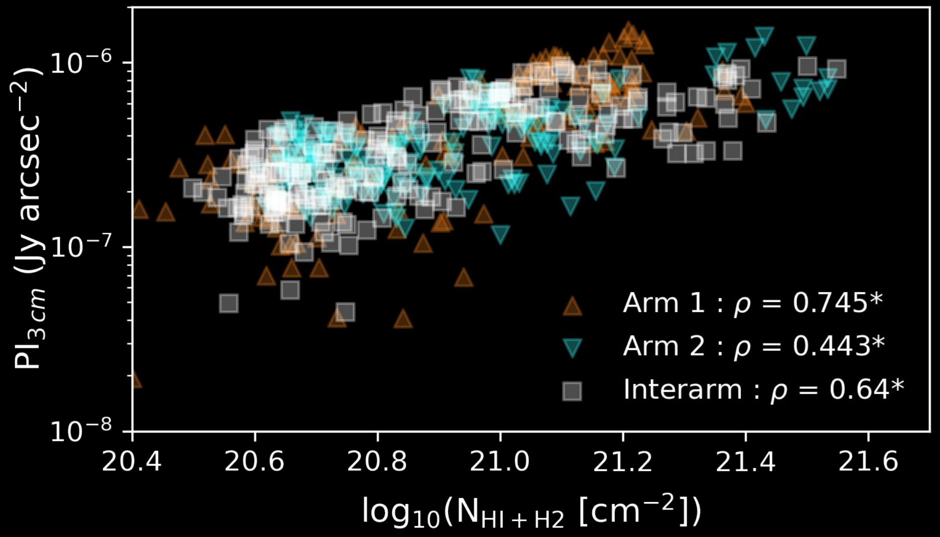
Polarized intensity vs. Column density

Borlaff et al. 2021a

FIR 154 μm



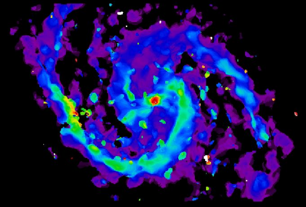
Radio 3 cm



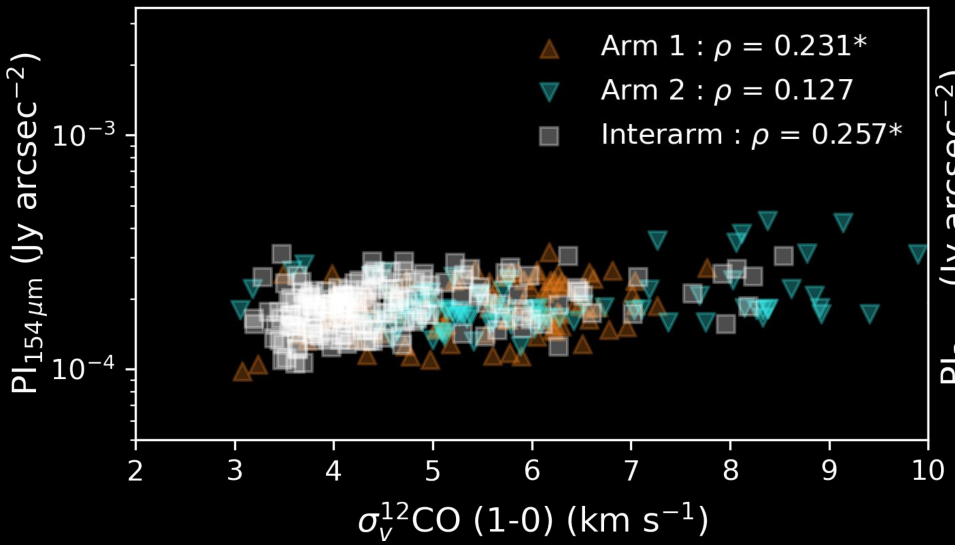
PI in radio traces B-field strength **Regular or Anisotropic fields?**

Polarized intensity vs. ^{12}CO velocity dispersion

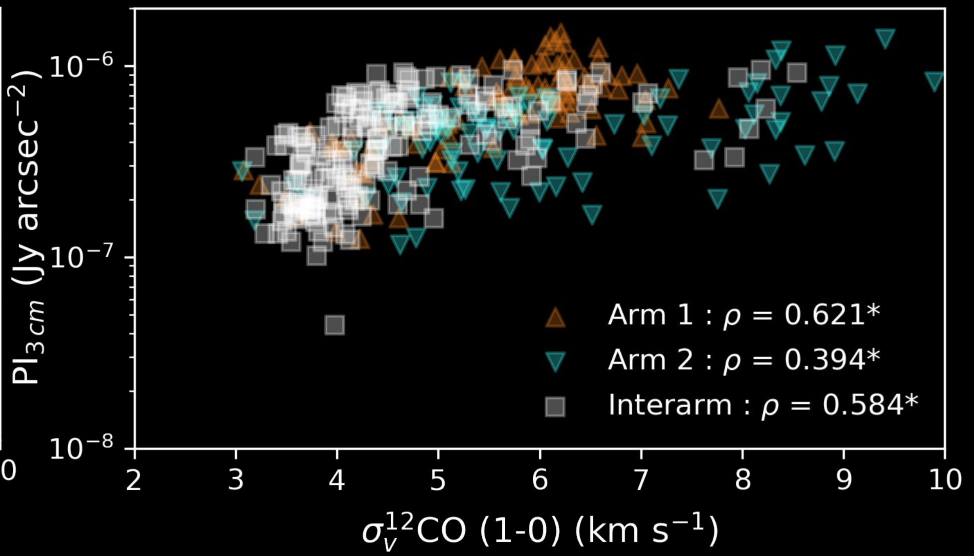
Borlaff et al. 2021a



FIR 154 μm



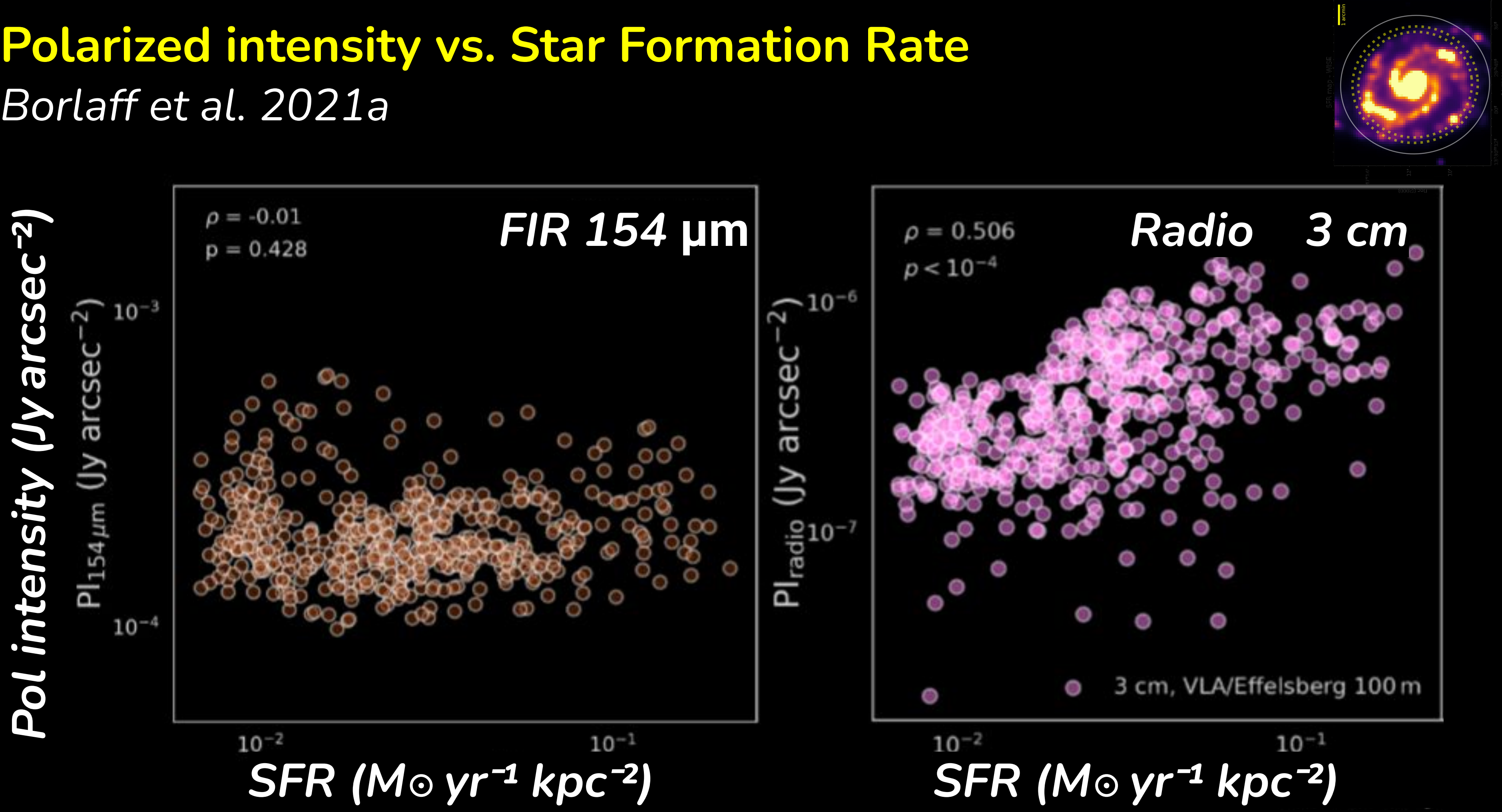
Radio 3 cm



PI in radio traces B-field strength **Regular or Anisotropic fields?**

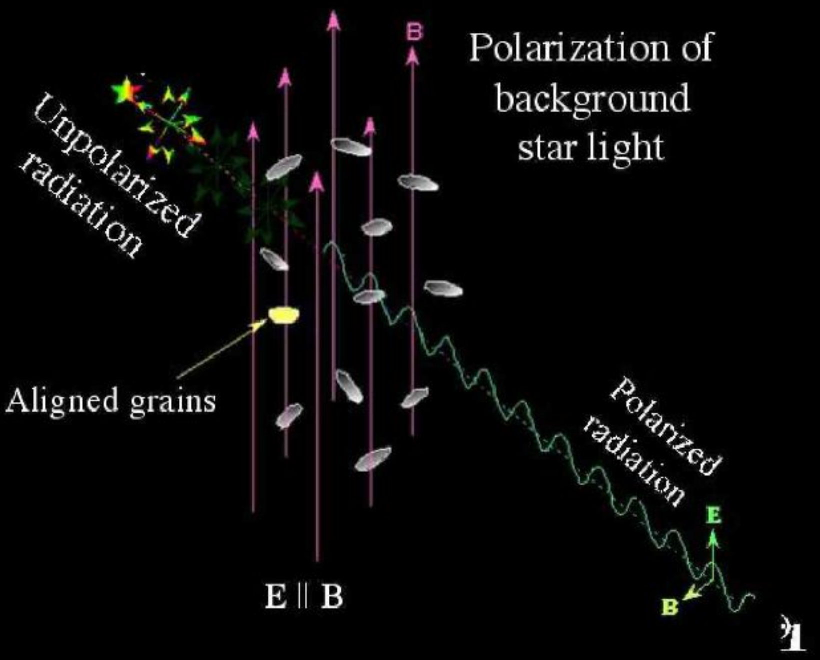
Polarized intensity vs. Star Formation Rate

Borlaff et al. 2021a



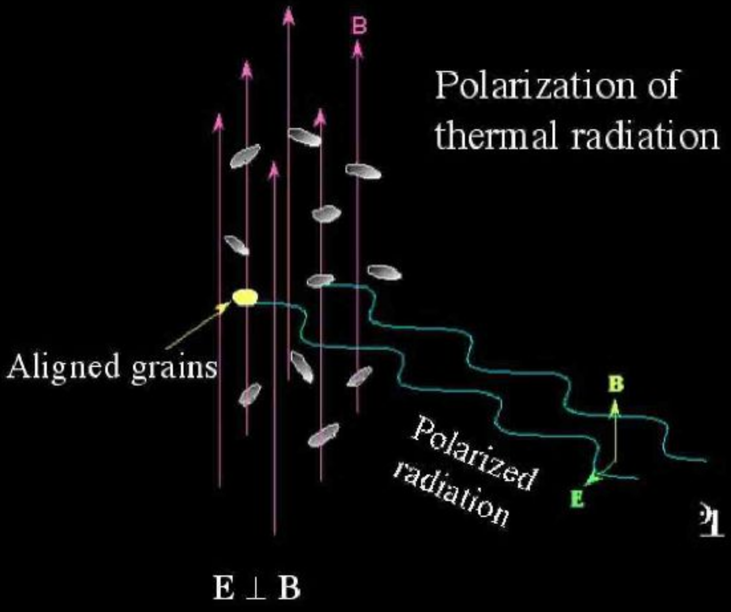
Optical starlight polarization

The direction of polarization (E) is parallel to the plane of the sky direction of magnetic field



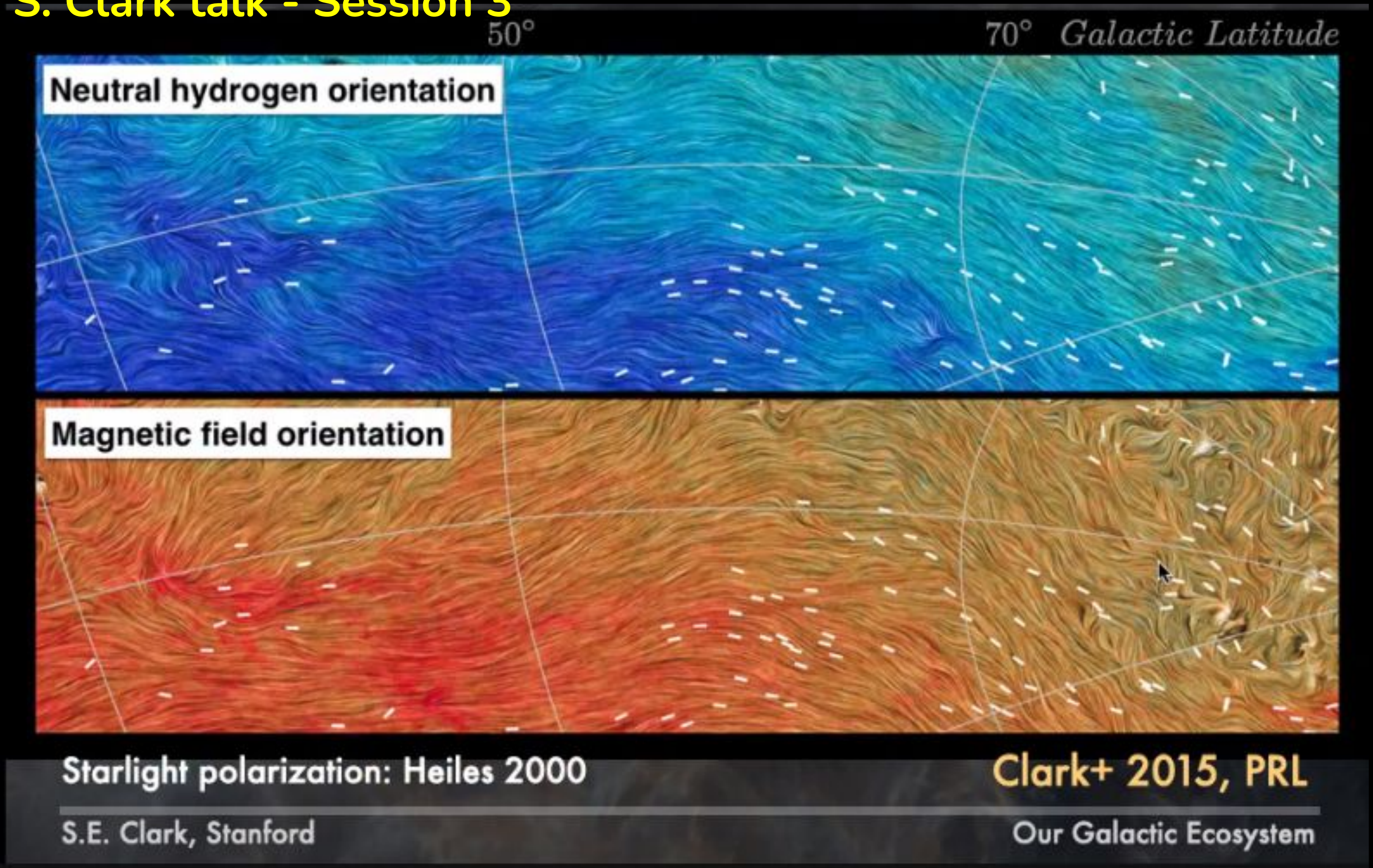
FIR dust grain polarization

The direction of polarization (E) is perpendicular to the plane of the sky direction of magnetic field



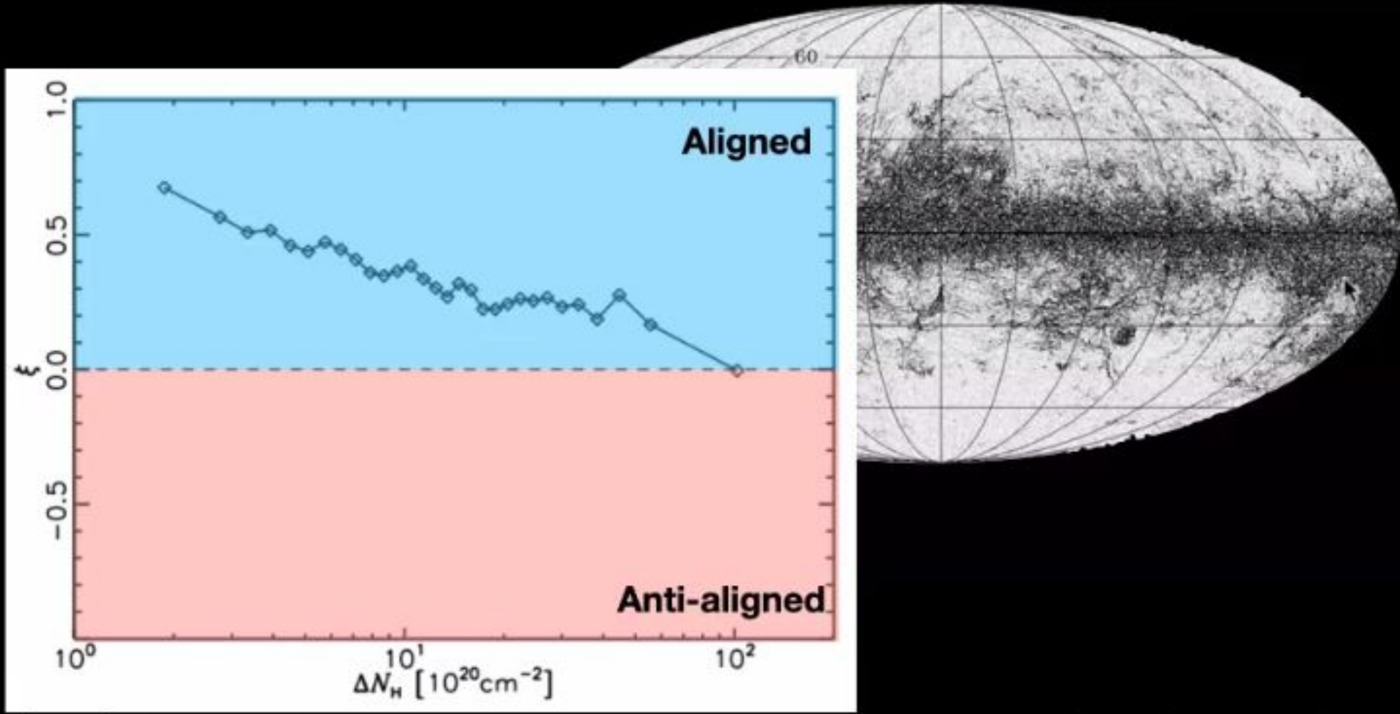
Credit: Lazarian (2007)

From S. Clark talk - Session 3



From S. Clark talk - Session 3

Planck enabled statistical studies of the magnetic field and ISM filaments.



Planck Int. XXXII

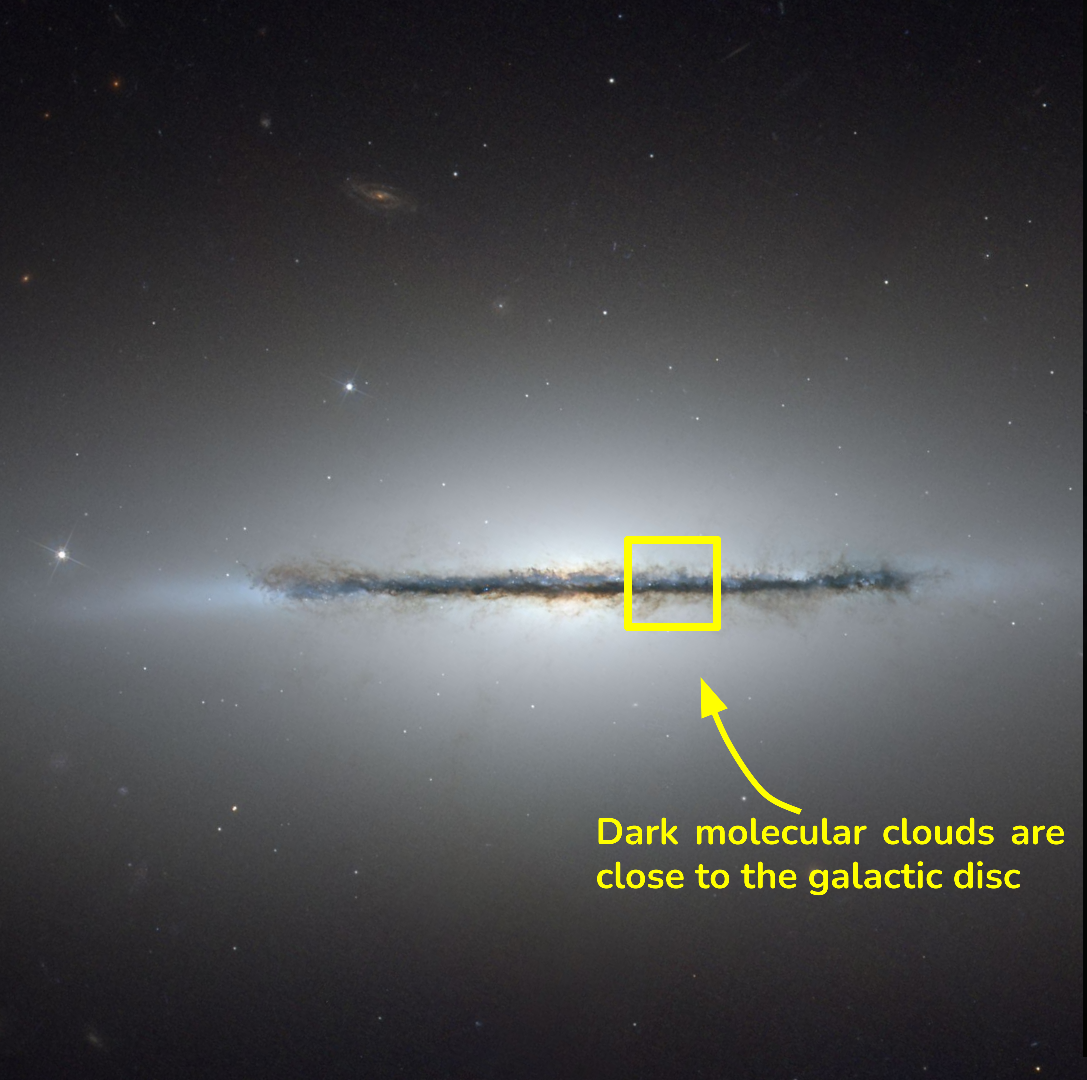
See also Alina+ 2019

Molecular clouds are morphologically complex and unresolved!

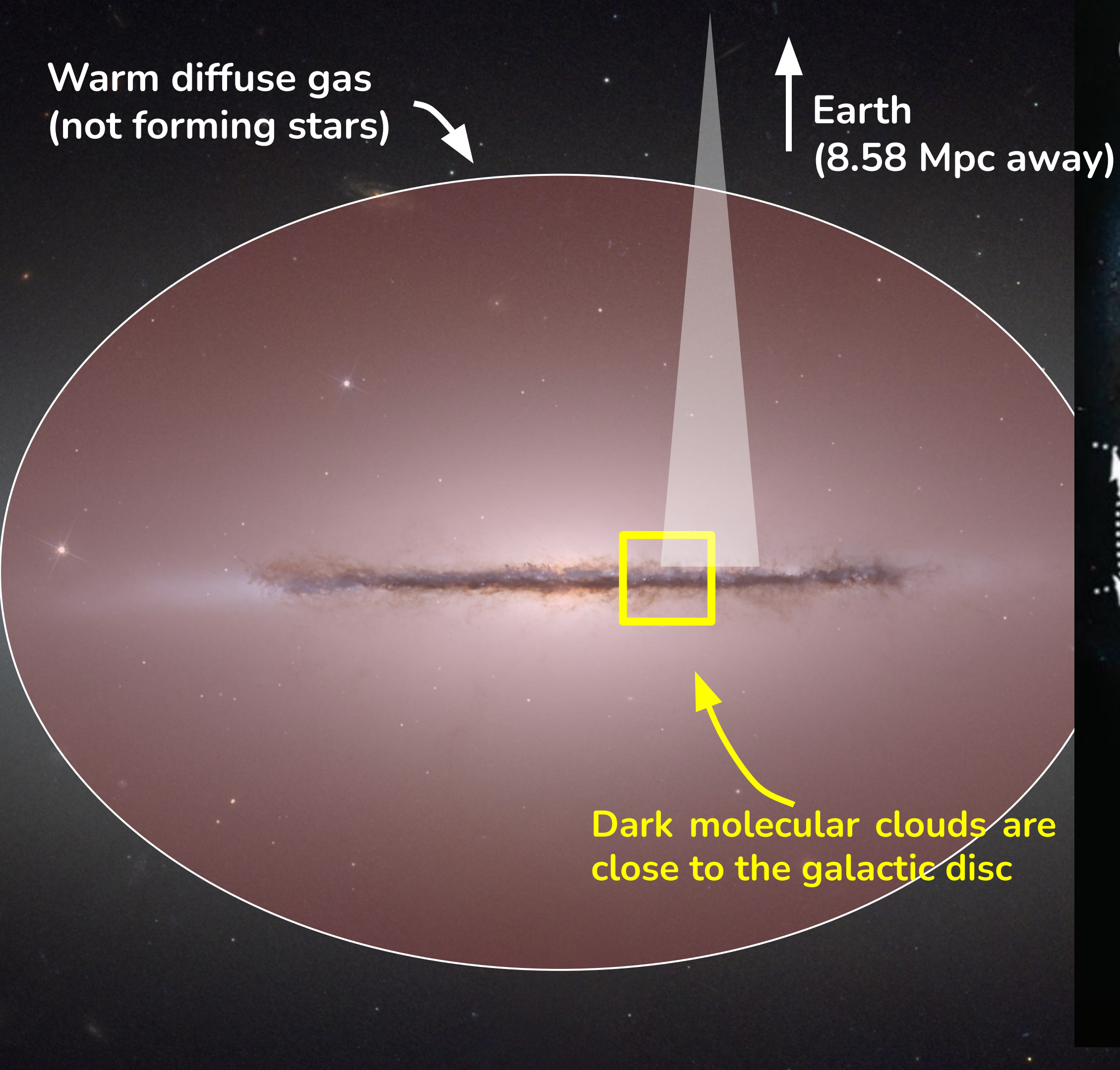
Serpens South cluster star forming region
Pillai et al. (2020)

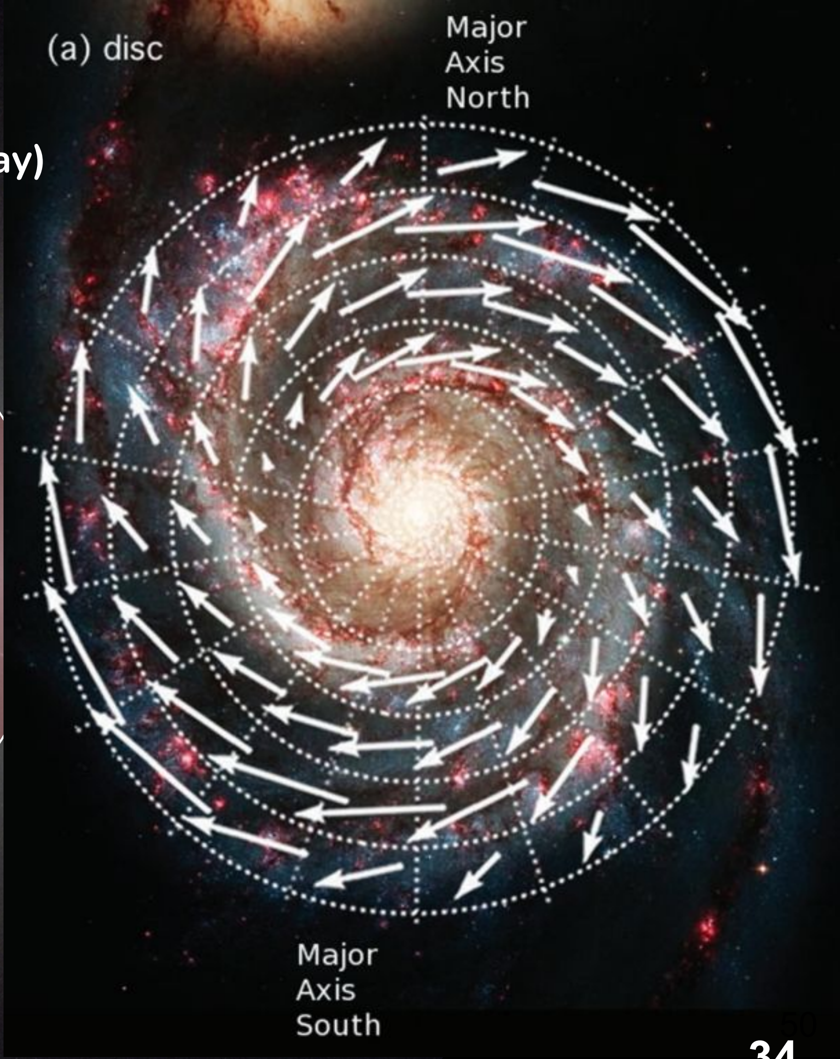
Credit: L. Proudfit

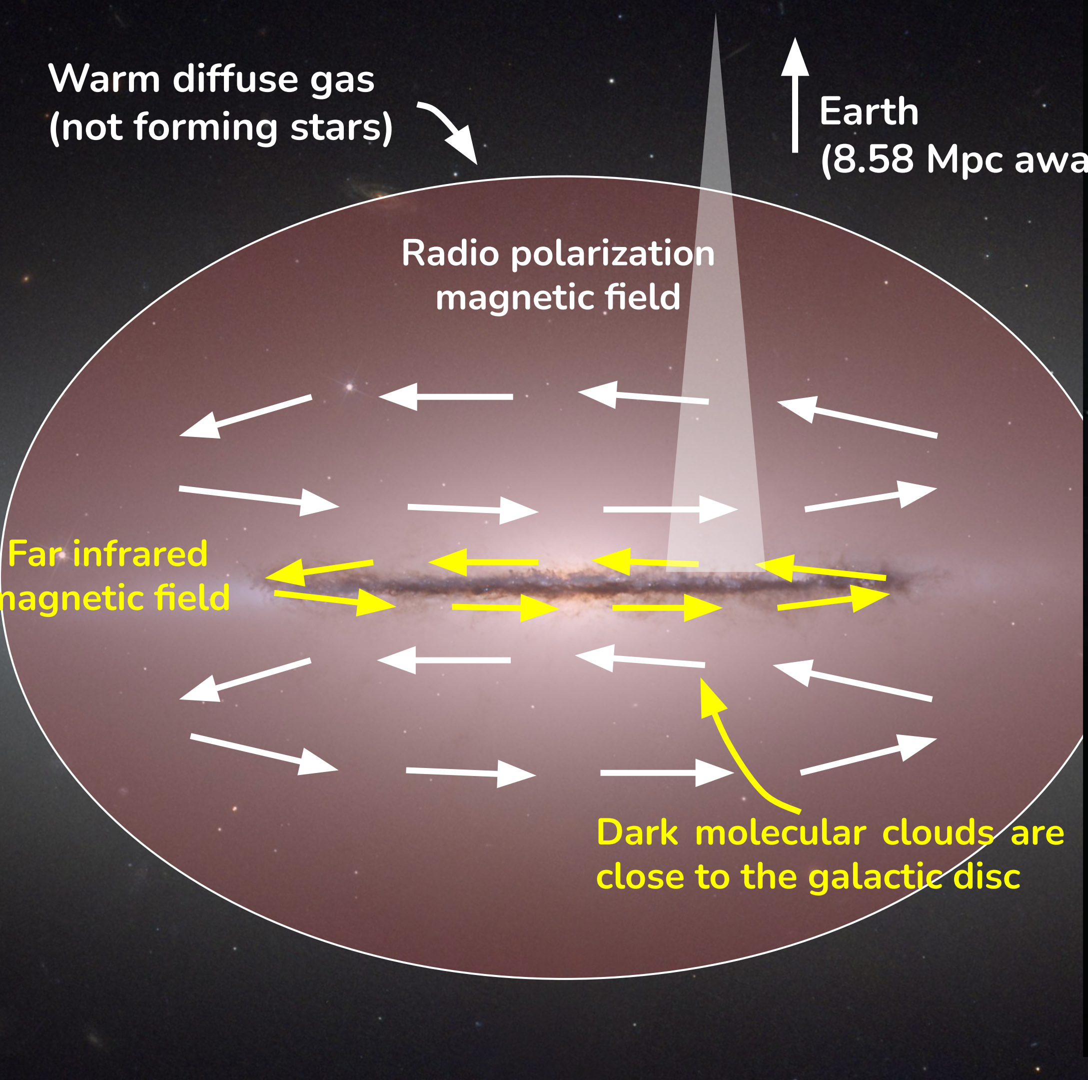
Our equivalent beam size in M51 is ~ 570 pc!



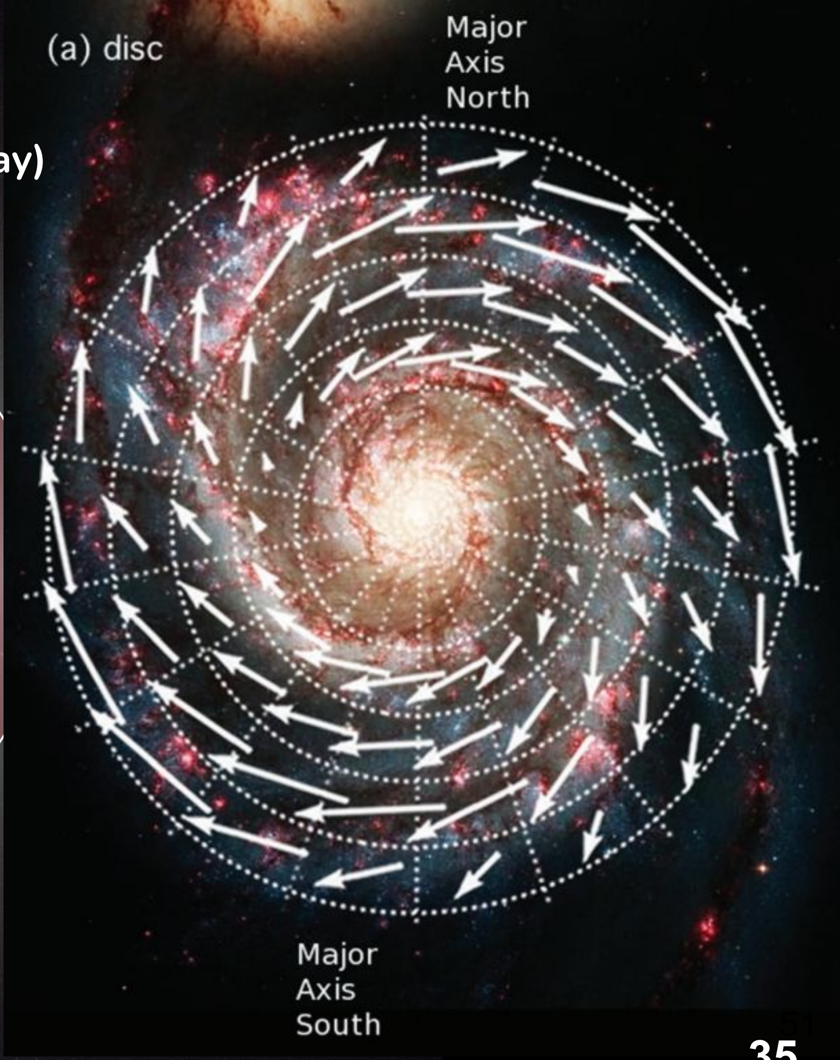
Dark molecular clouds are close to the galactic disc


Warm diffuse gas
(not forming stars)
Earth
(8.58 Mpc away)
Dark molecular clouds are
close to the galactic disc


(a) disc
Major
Axis
North
Major
Axis
South



Warm diffuse gas
(not forming stars)
Earth
(8.58 Mpc away)
Radio polarization
magnetic field
Far infrared
magnetic field
Dark molecular clouds are
close to the galactic disc



(a) disc
Major
Axis
North
Major
Axis
South