Magnetic chaos hidden in the Whirlpool Galaxy

Alejandro S. Borlaff, E. López-Rodriguez, P. Marcum, R. Beck, L. Grosset et al.

8th Sept 2021 SOFIA Teletalks

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NASA POSTDOCTORAL PROGRAM

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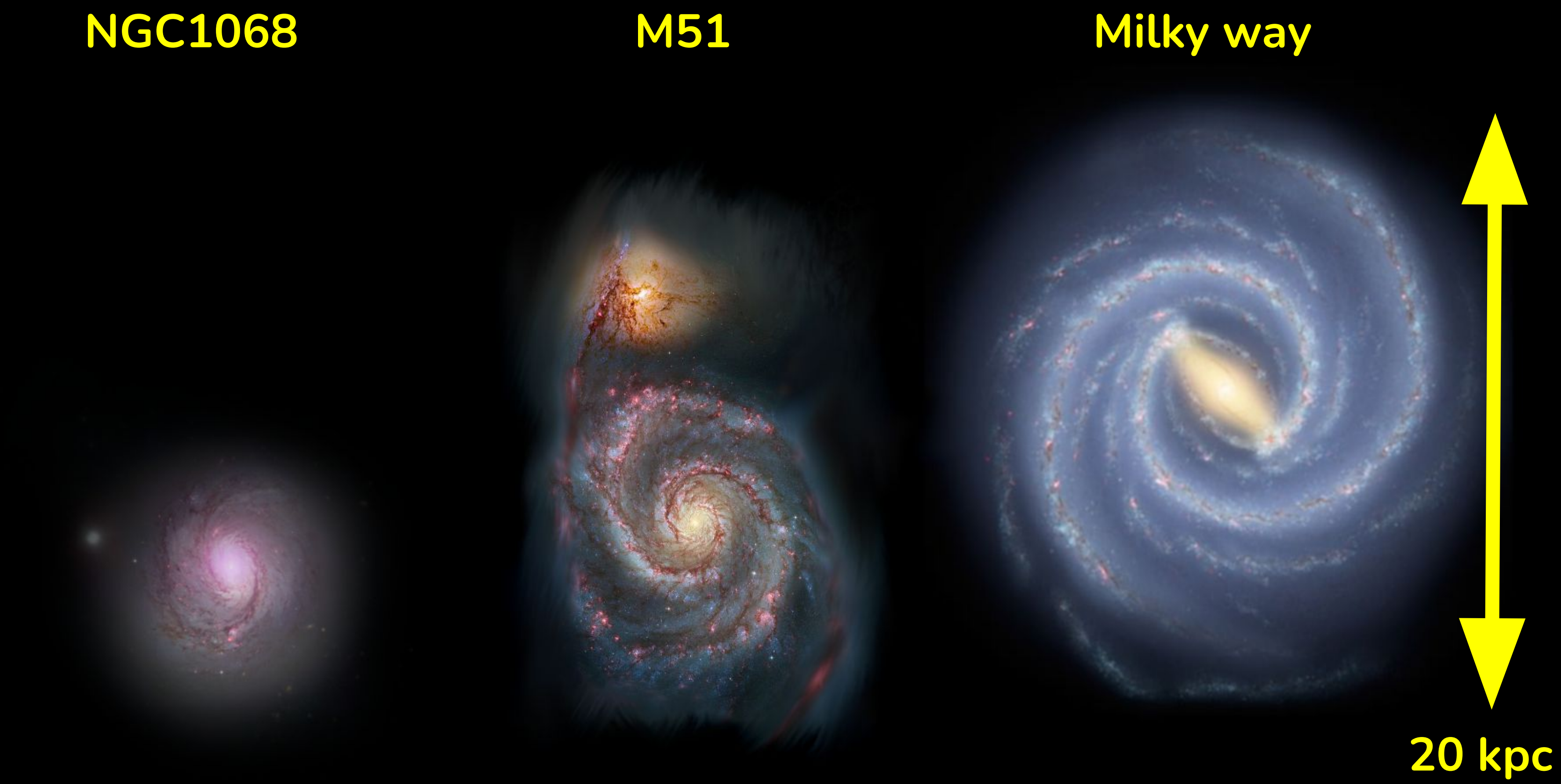
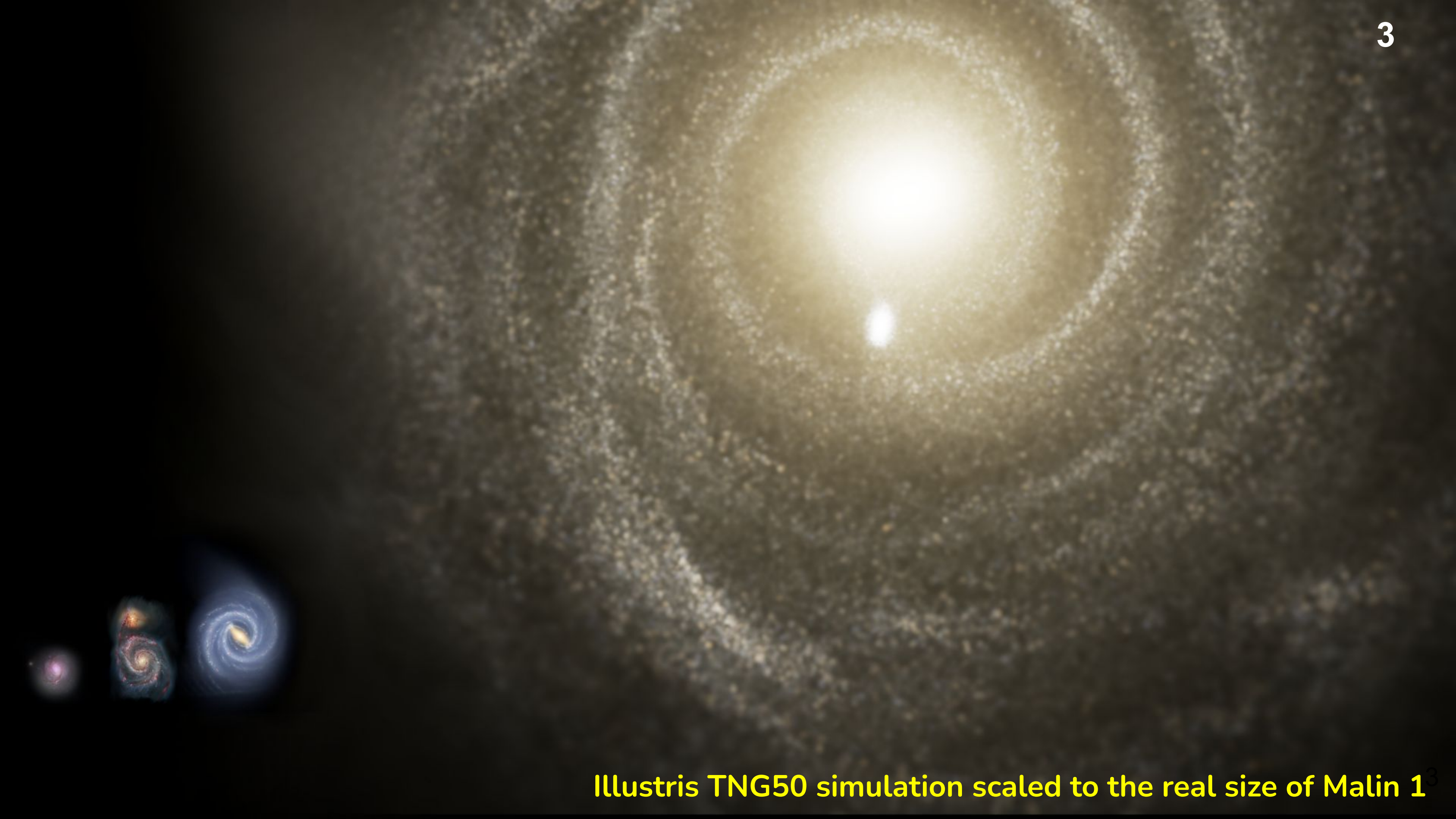
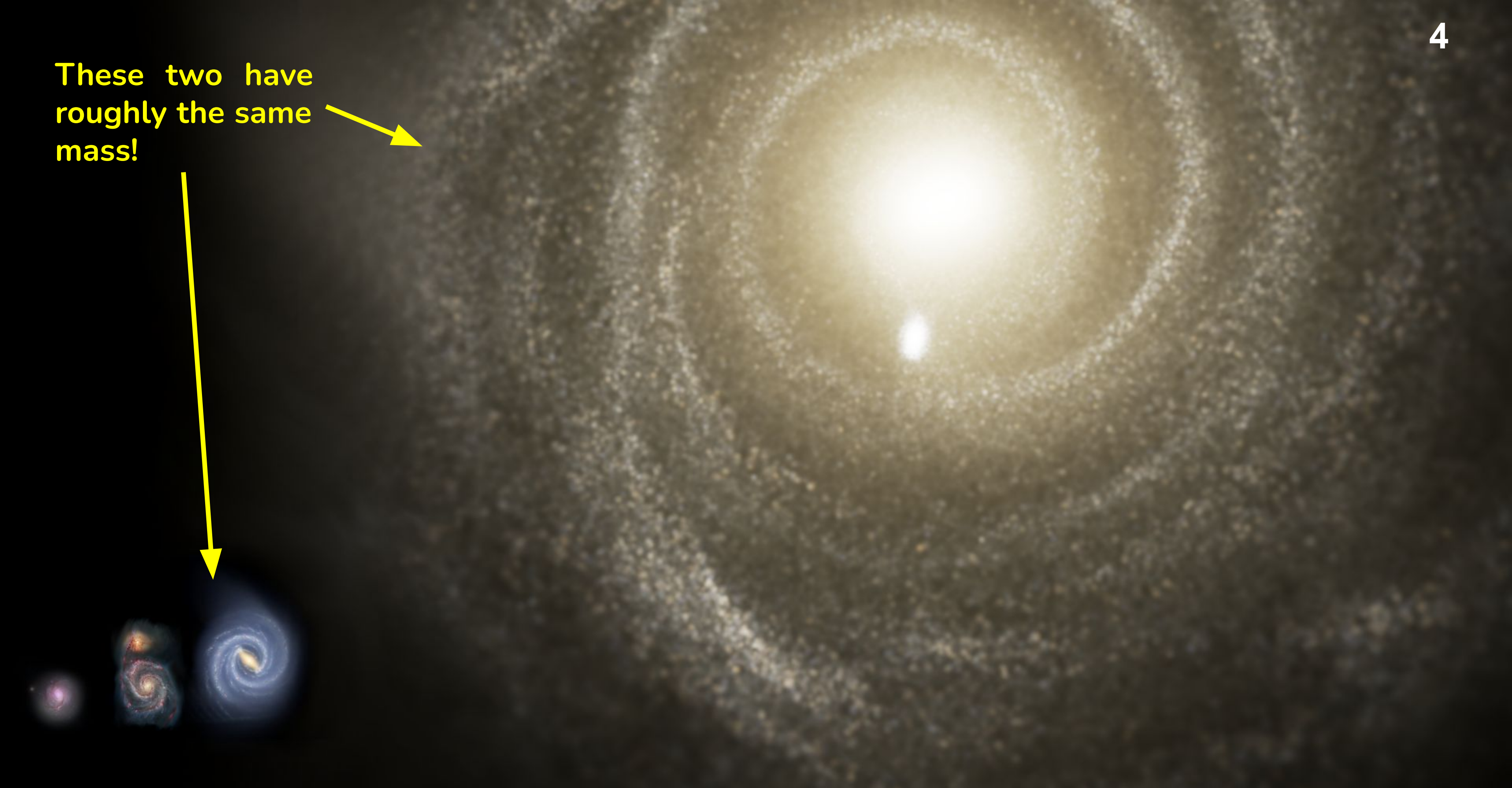

NGC1068
M51
Milky way
20 kpc

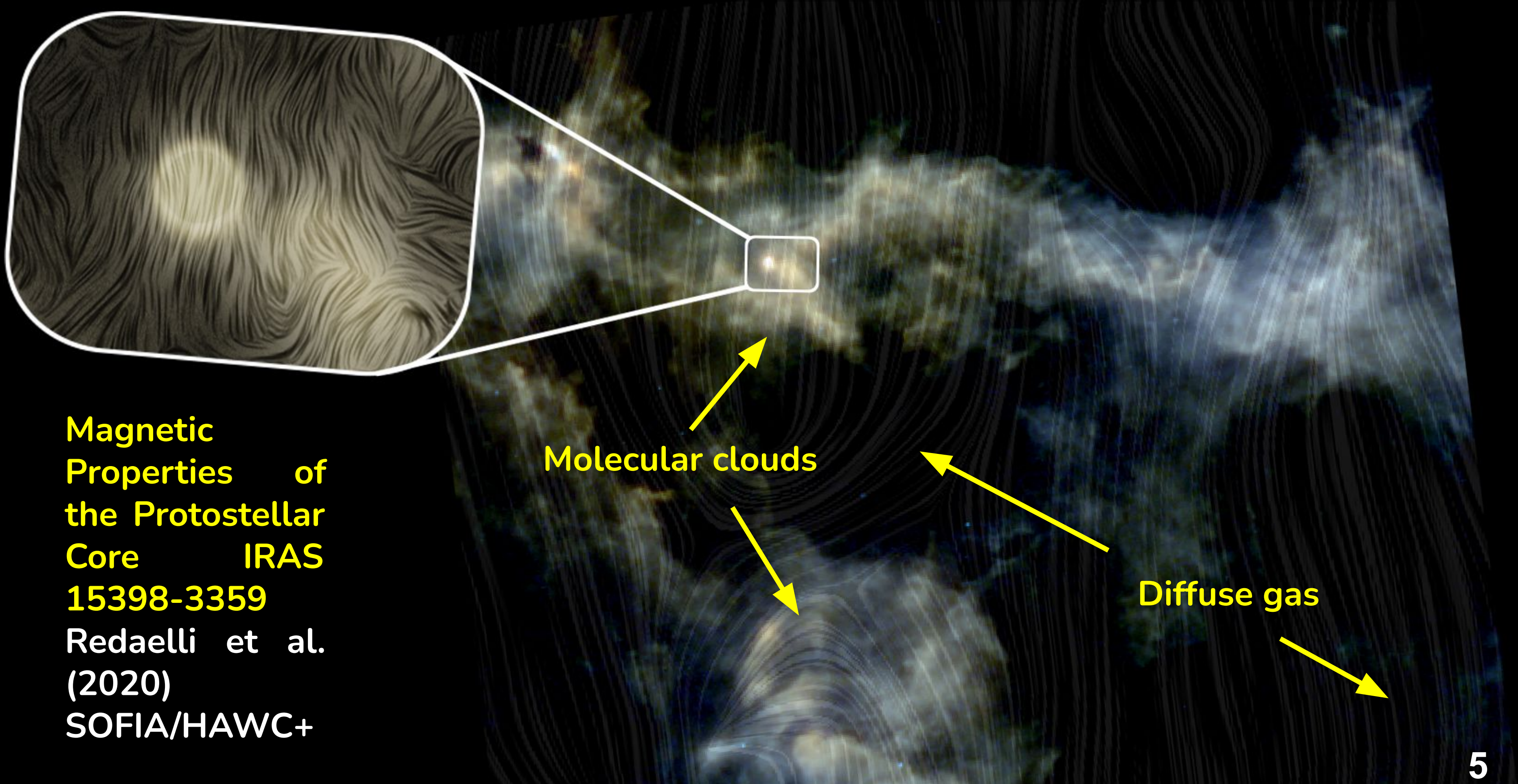


Illustris TNG50 simulation scaled to the real size of Malin 1



Illustris TNG50 simulation scaled to the real size of Malin 1

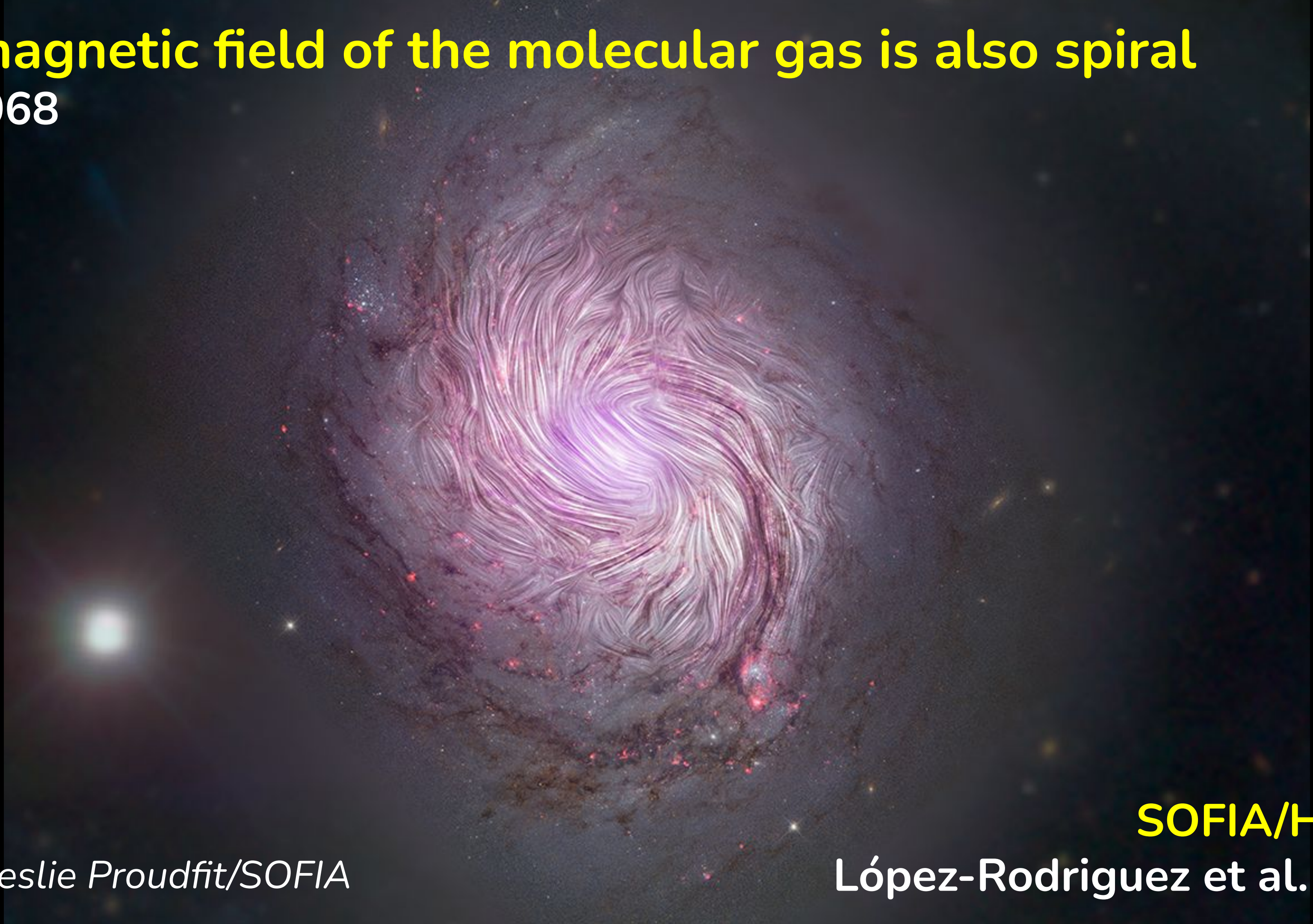
Magnetic fields are vital for star formation



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

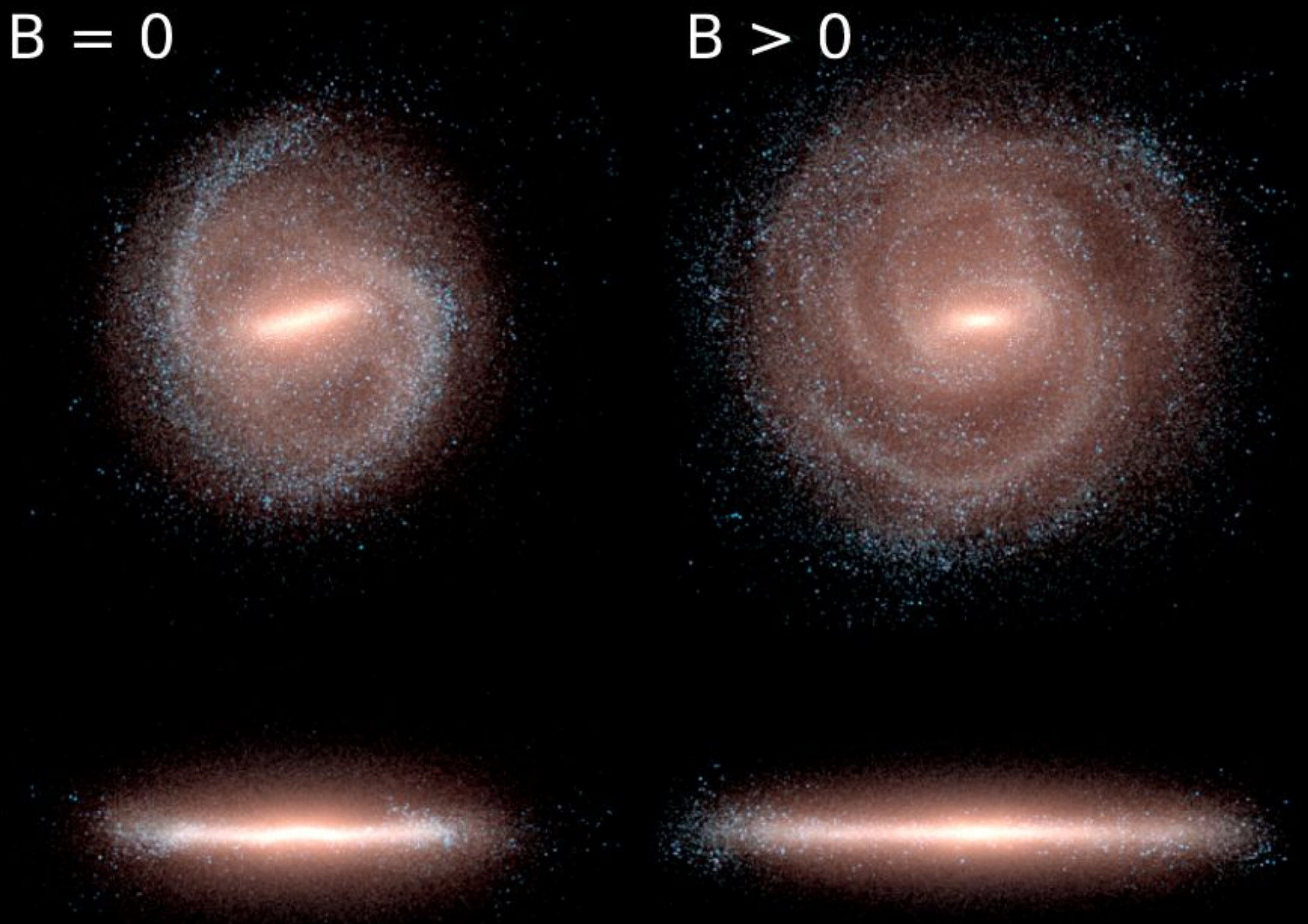
SOFIA/HAWC+

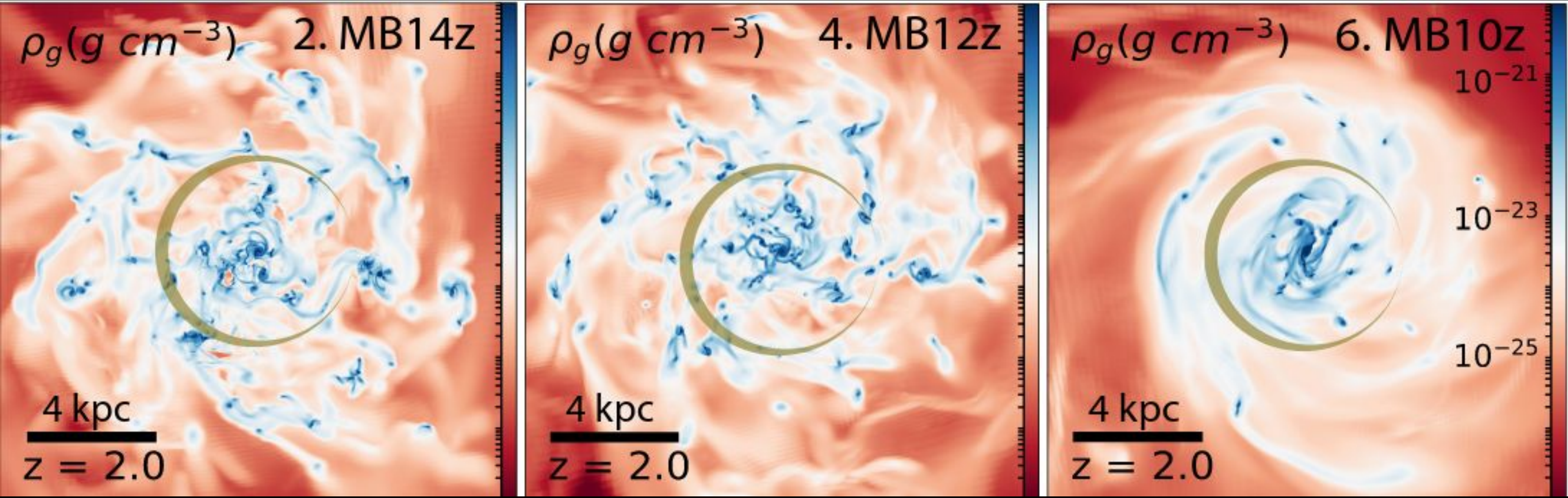
López-Rodriguez et al. (2020)

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



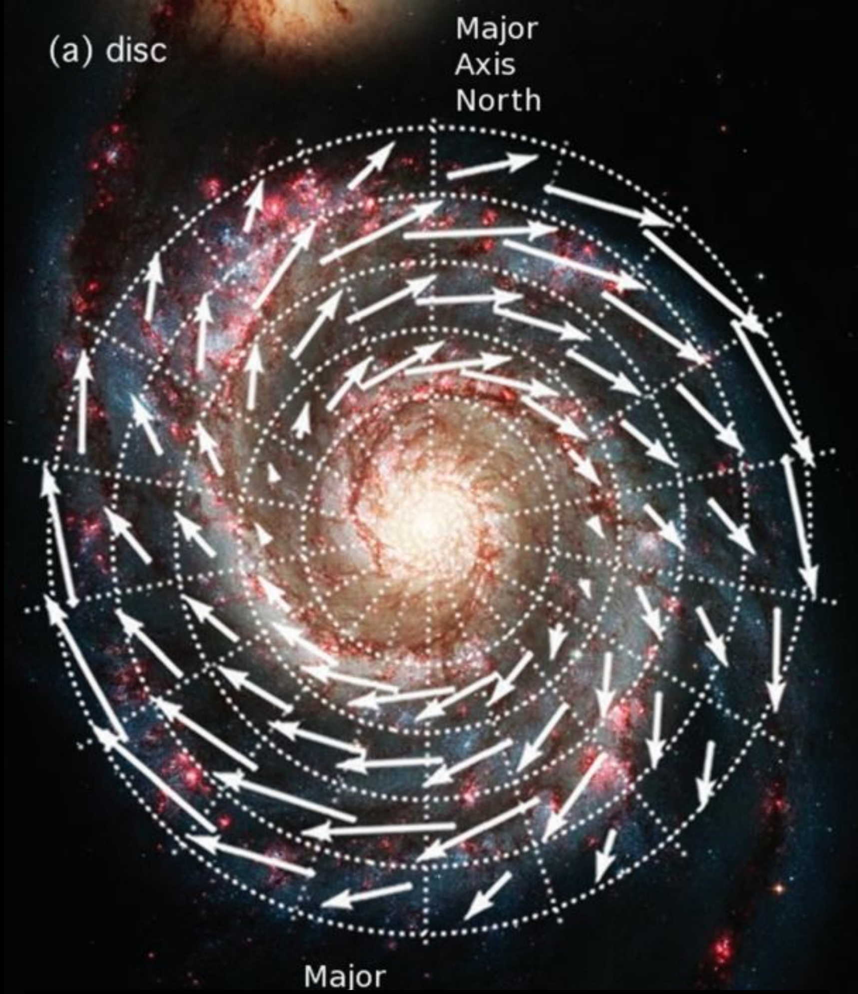


How primordial magnetic fields shrink galaxies - Martinez-Alvarez et al. (2020)

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?

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



Fletcher et al. 2011 **VLA/Effelsberg 100m (Radio)**

Diffuse warm 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 ?

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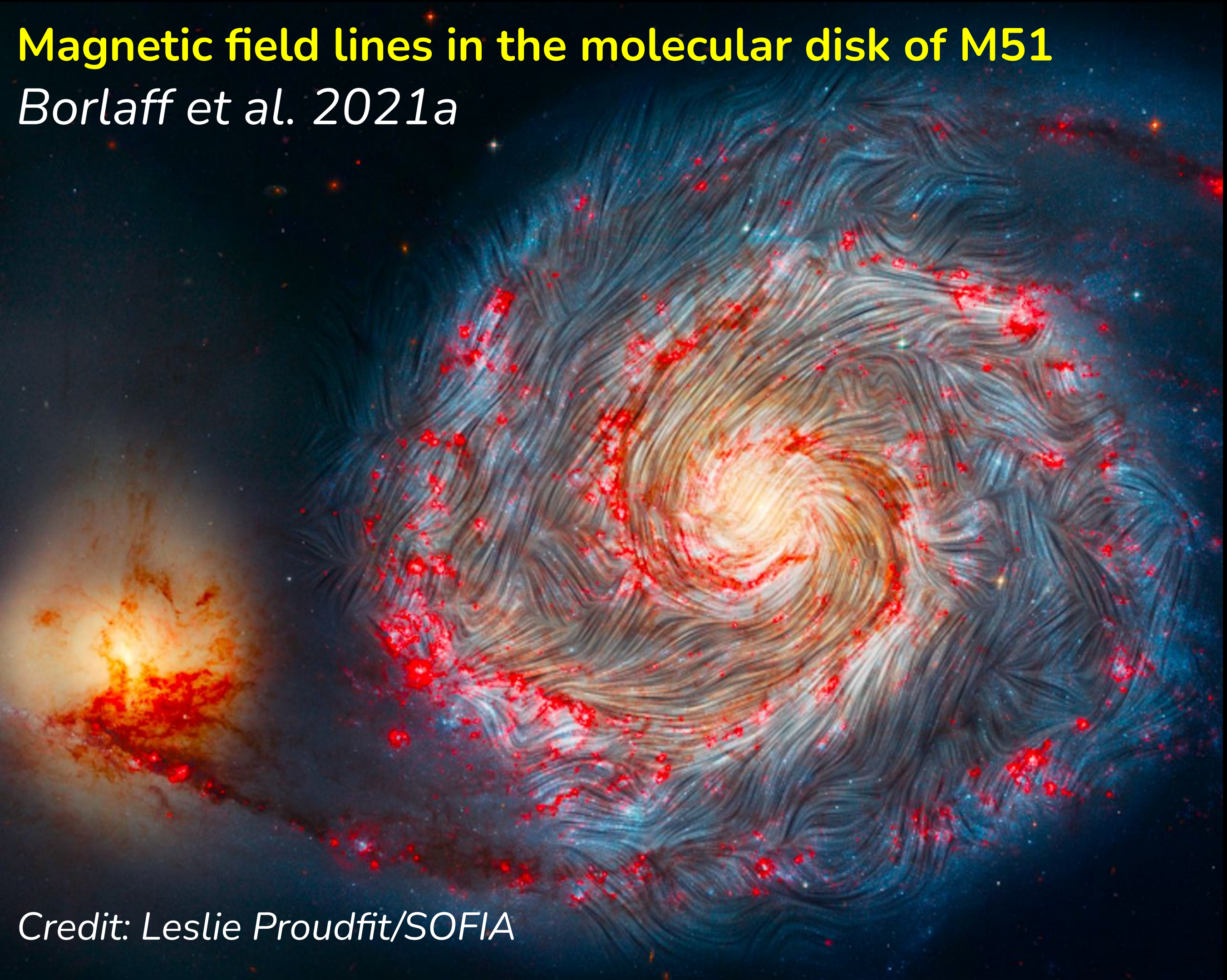
Magnetic field lines in the molecular disk of M51

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)

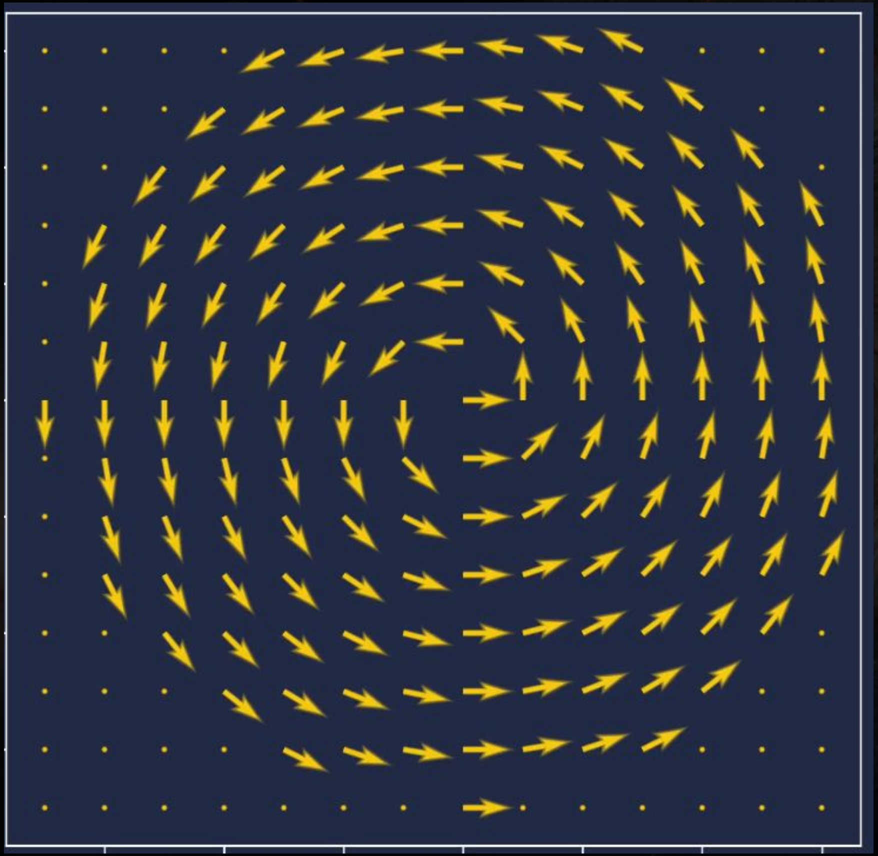
How?
Magnetic *pitch angle*

Magnetic field lines in the molecular disk of M51

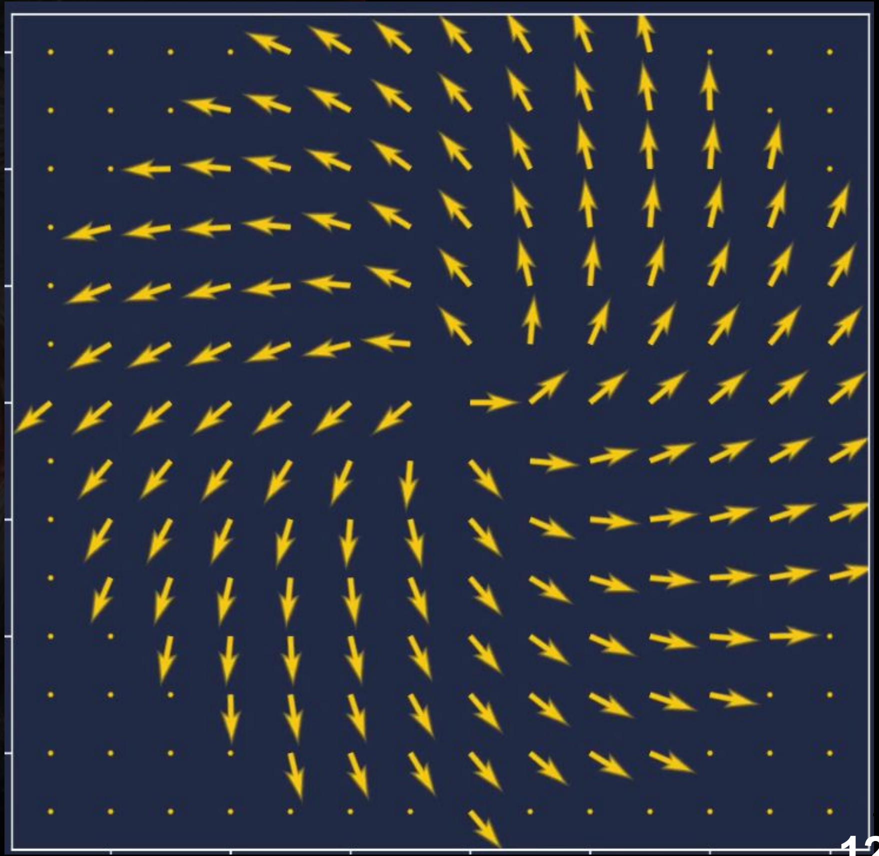
Borlaff et al. (in prep)

The diffuse gas and the molecular clouds feel the same

Low pitch angle (more circular)



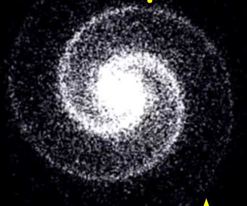
High pitch angle (more radial)

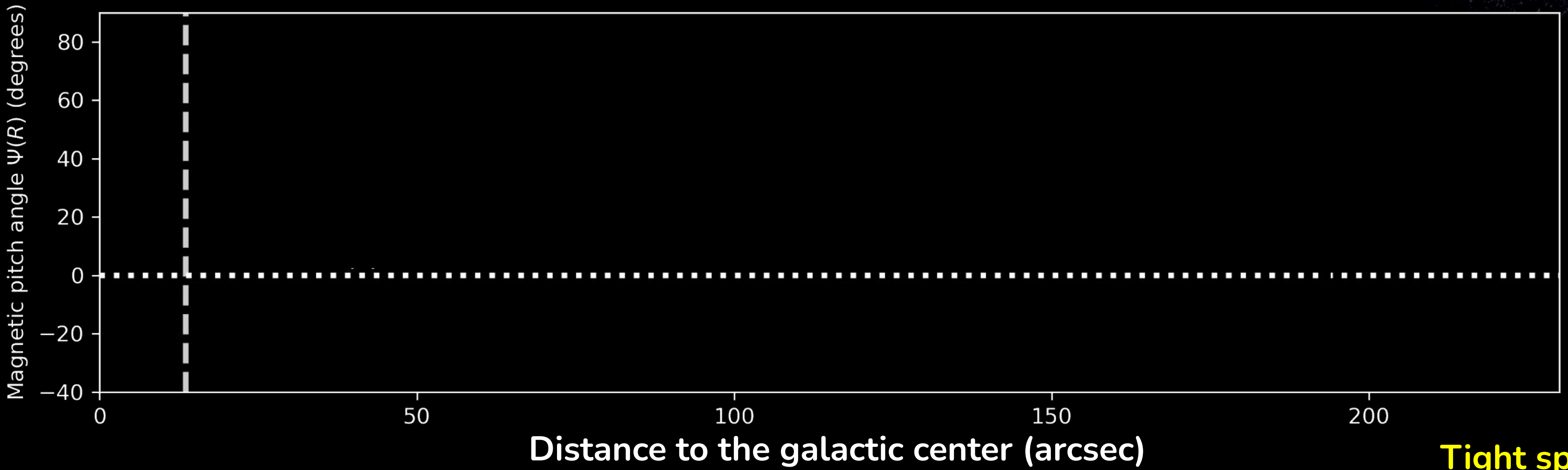


Radio vs. FIR magnetic pitch angle profiles

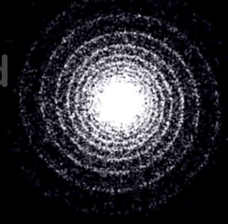
Borlaff et al. 2021a

Loose spiral





Tight spiral

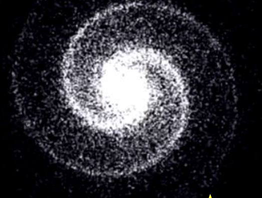


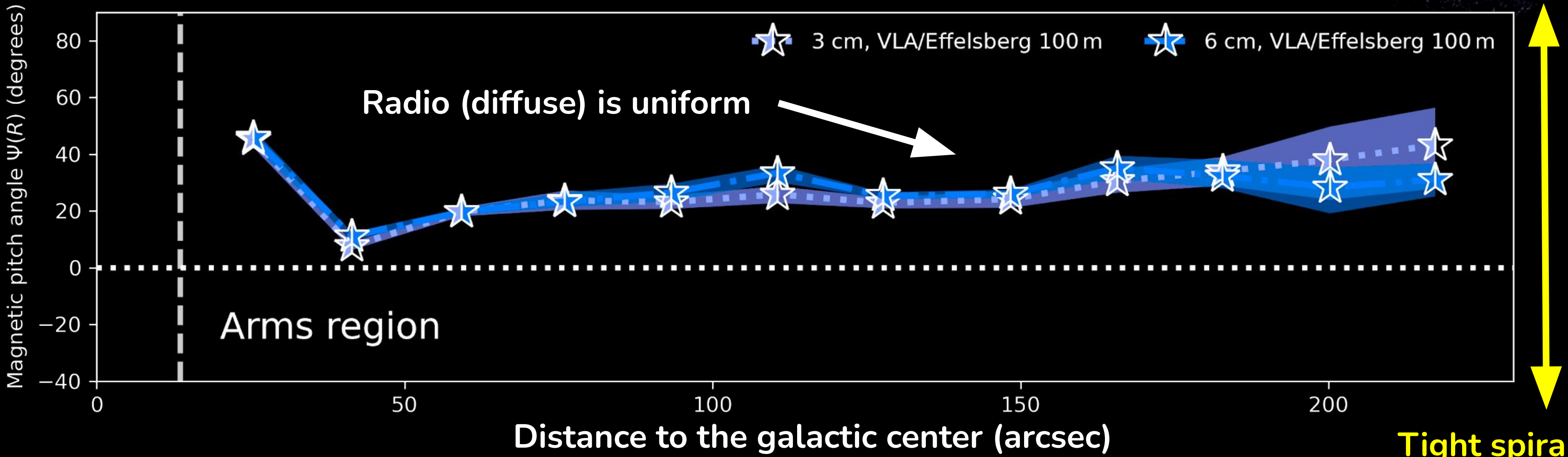
1 - The diffuse gas has a regular uniform spiral magnetic field

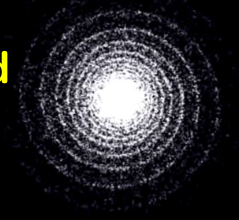
2 - The magnetic field of the outer molecular disk is highly distorted

Radio vs. FIR magnetic pitch angle profiles

Borlaff et al. 2021a







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Radio vs. FIR magnetic pitch angle profiles

Borlaff et al. 2021a

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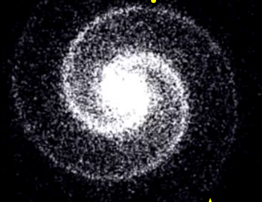

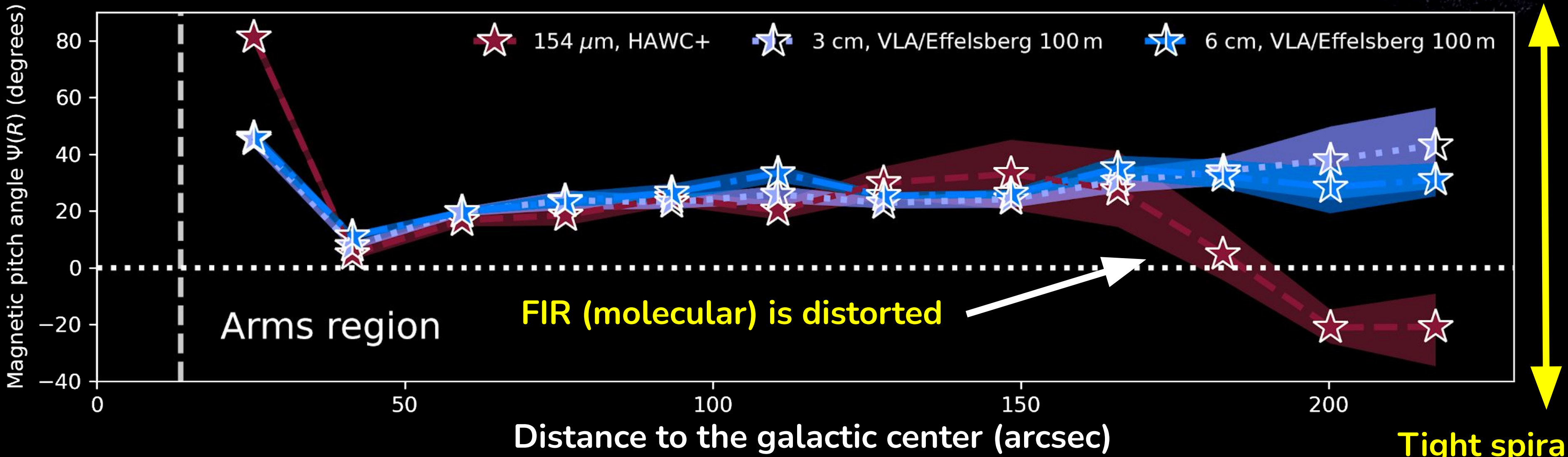

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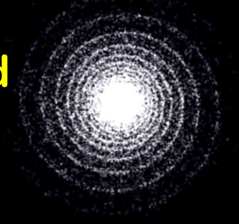

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Radio vs. FIR magnetic pitch angle profiles

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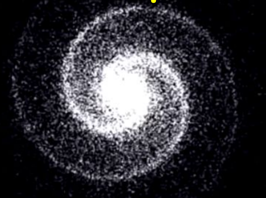

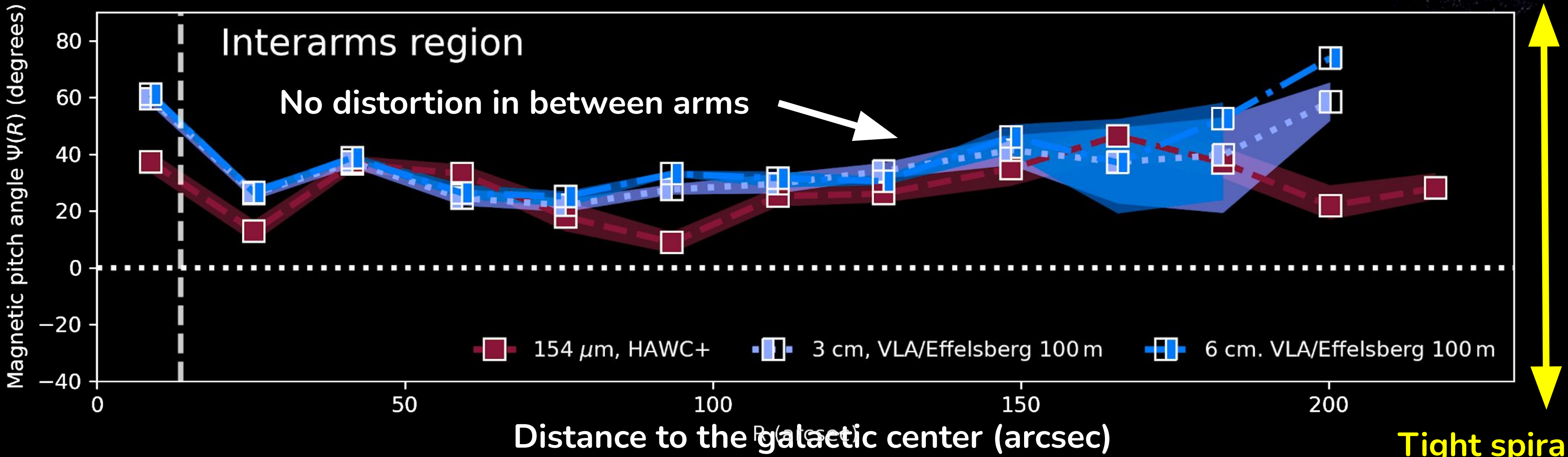

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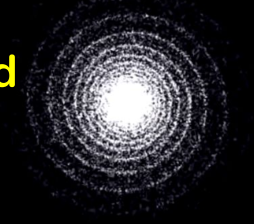

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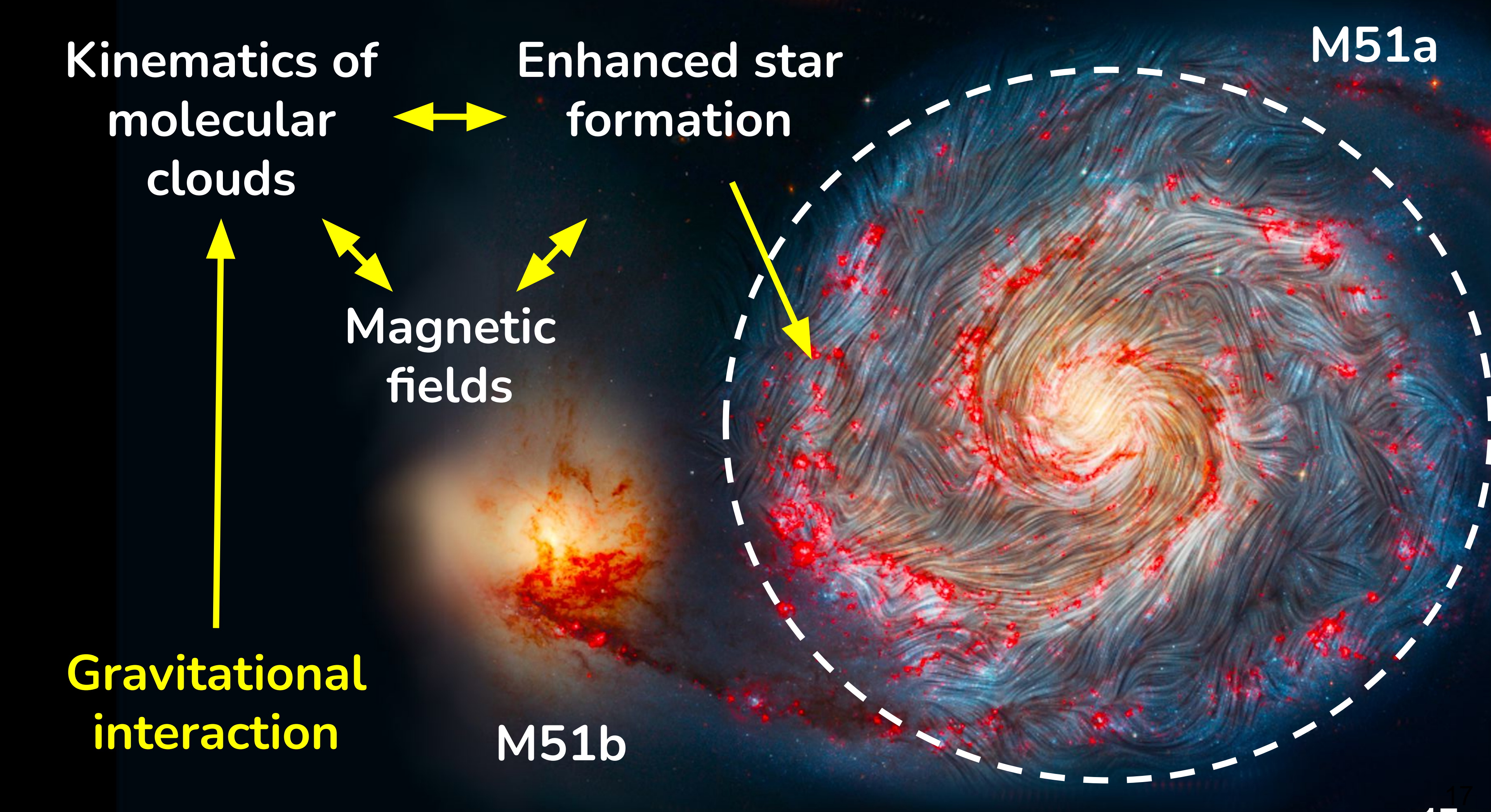
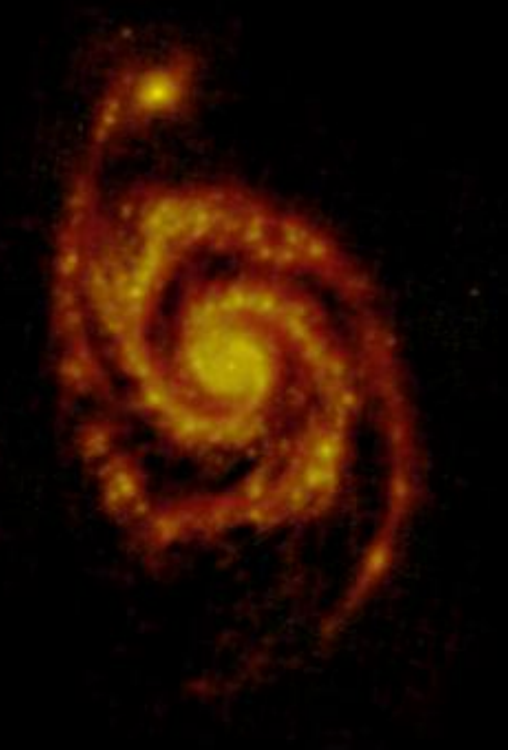
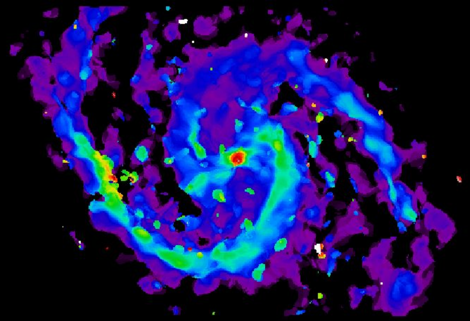

Kinematics of molecular clouds
Enhanced star formation
M51a
Magnetic fields
Gravitational interaction
M51b

HI + H2 column density



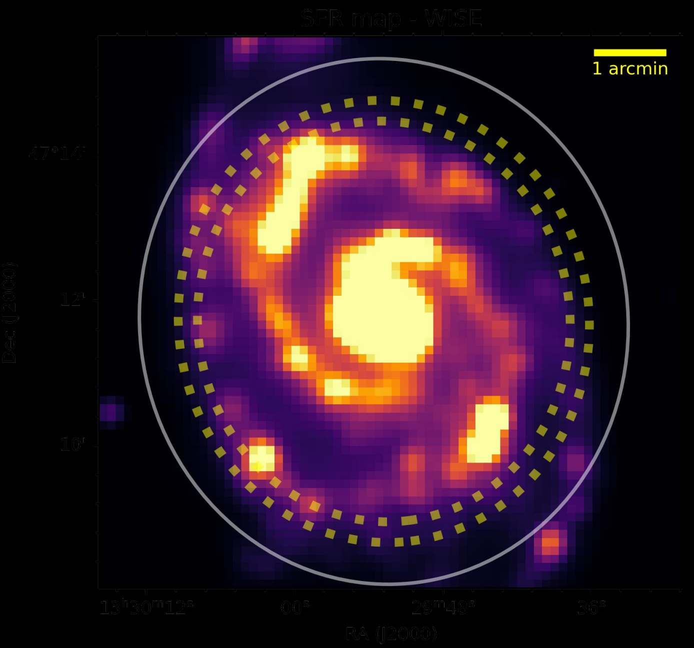
Herschel PACS/SPIRE
PID/Wilson 2007

^{12}CO velocity dispersion



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

Star Formation Rate

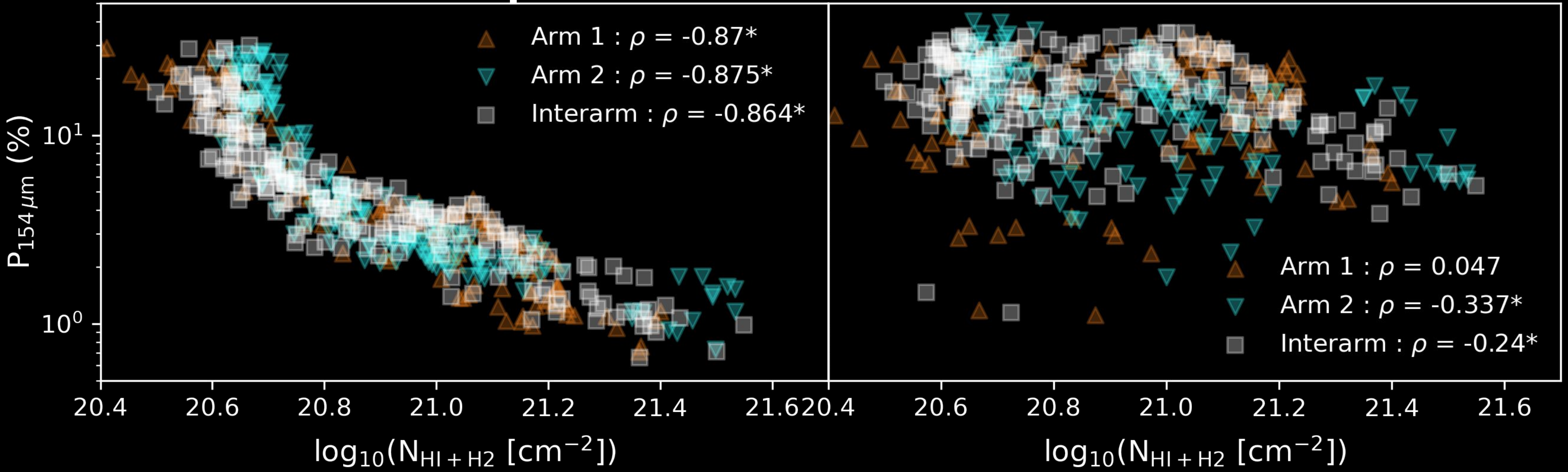


WISE
Leroy et al. 2019

Polarization fraction vs. Column density

Borlaff et al. 2021a

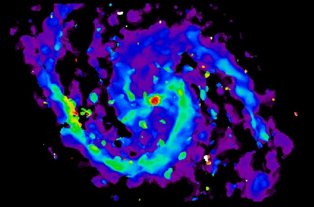
FIR 154 μm | **Radio 3 cm**

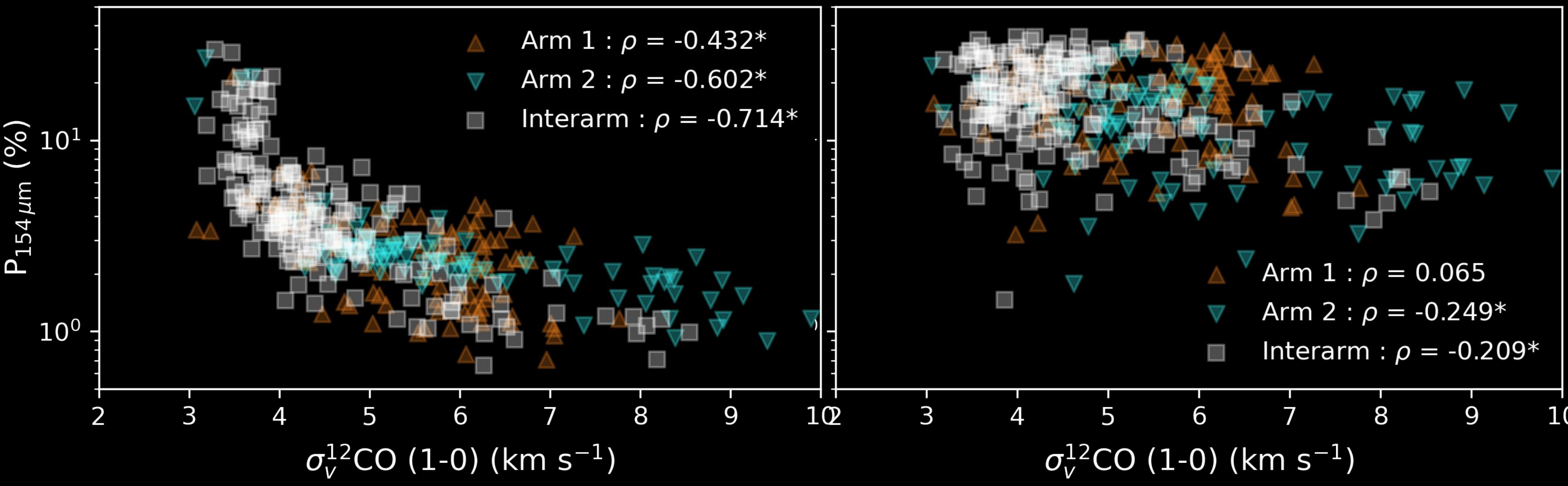


Higher density → **Lower FIR P(%)**, **Same radio P(%)**

Polarization fraction vs. ^{12}CO velocity dispersion

Borlaff et al. 2021a

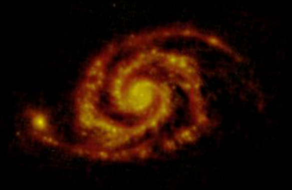




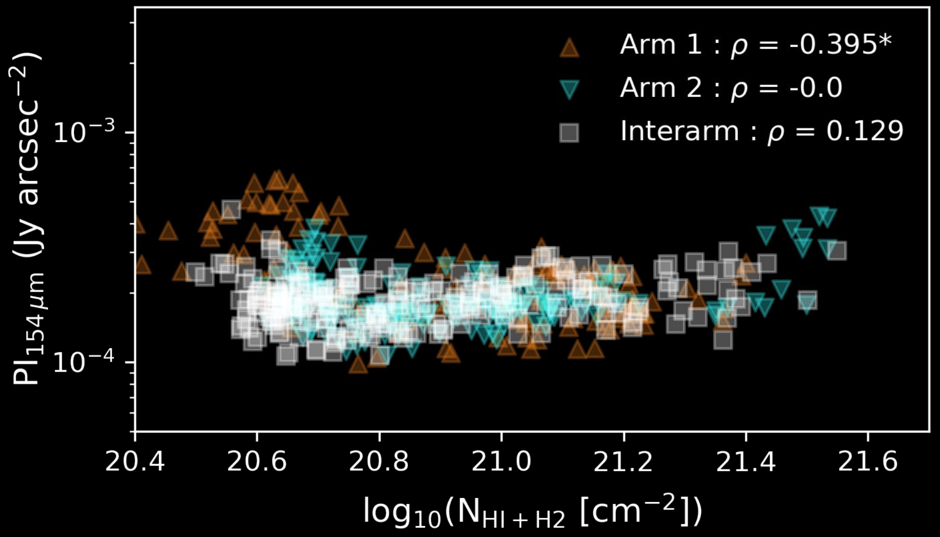
Higher density → **Higher molecular gas turbulence** → **Lower FIR P(%)** / **Same radio P(%)**

Polarized intensity vs. Column density

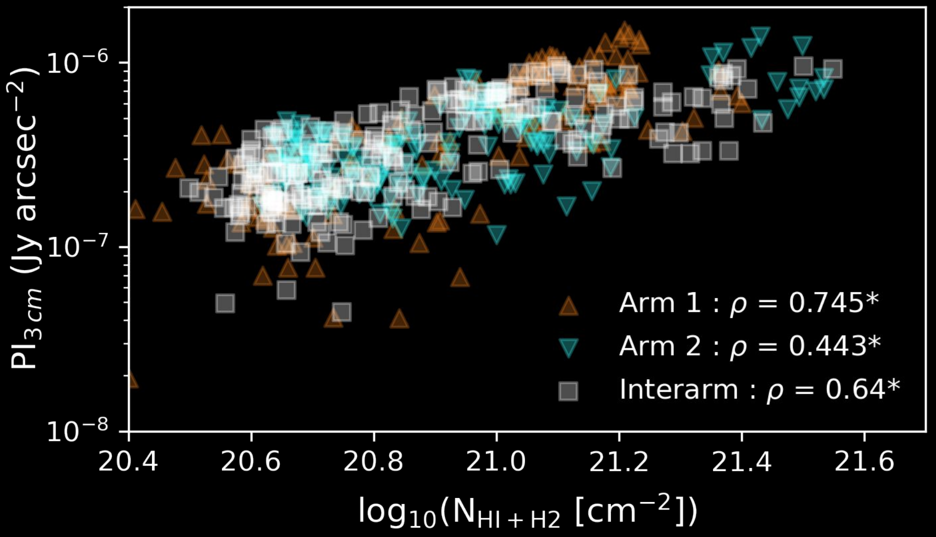
Borlaff et al. 2021a



FIR 154 µm



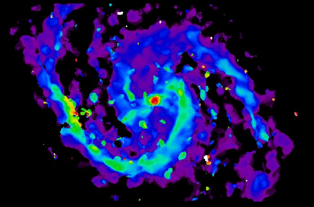
Radio 3 cm



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

Polarized intensity vs. ^{12}CO velocity dispersion

Borlaff et al. 2021a



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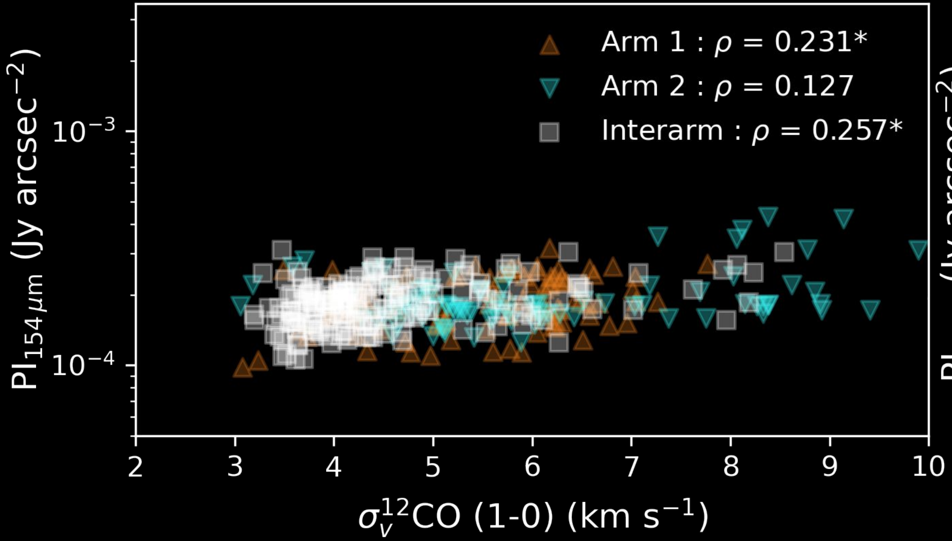
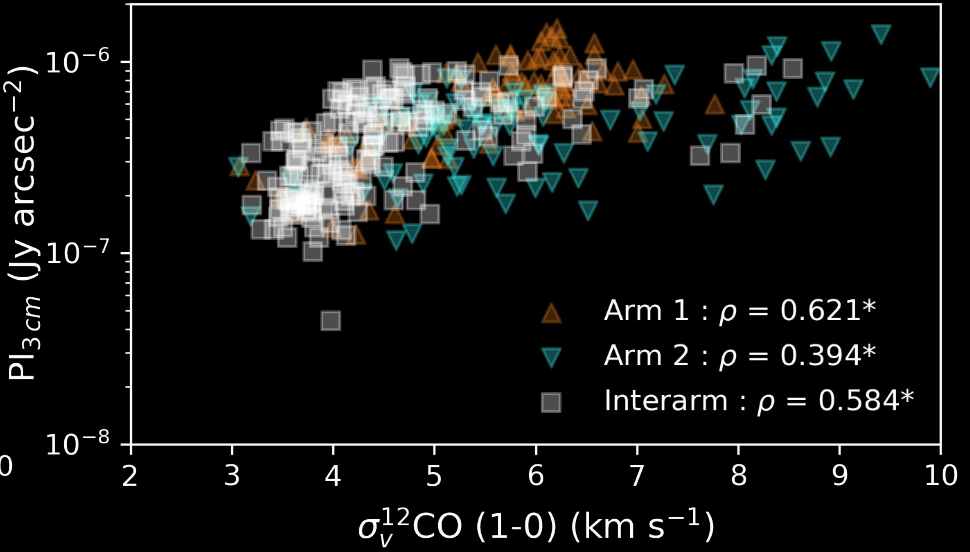


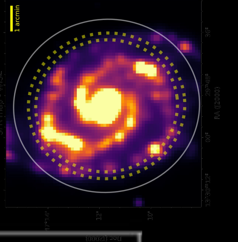
Radio 3 cm

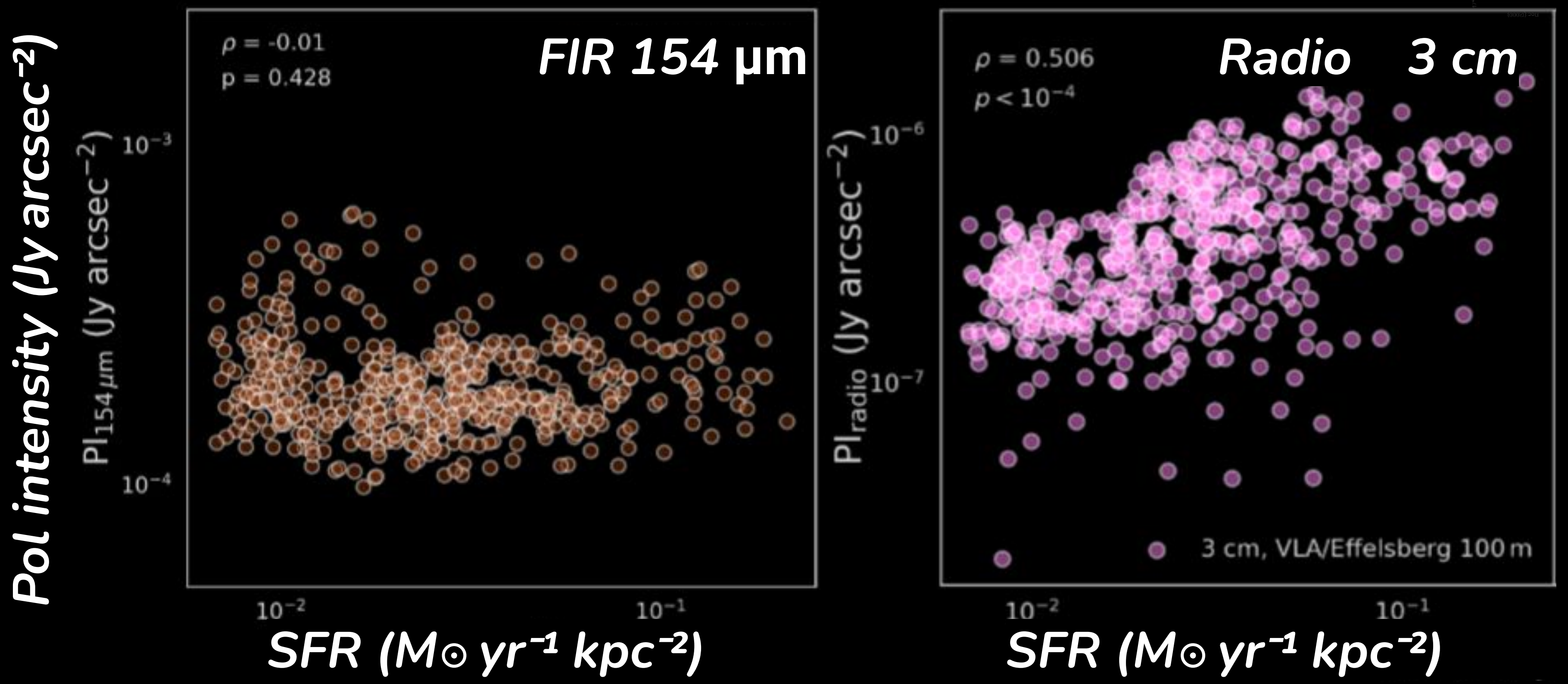


PI in radio traces B-field strength **Regular or Anisotropic fields?**

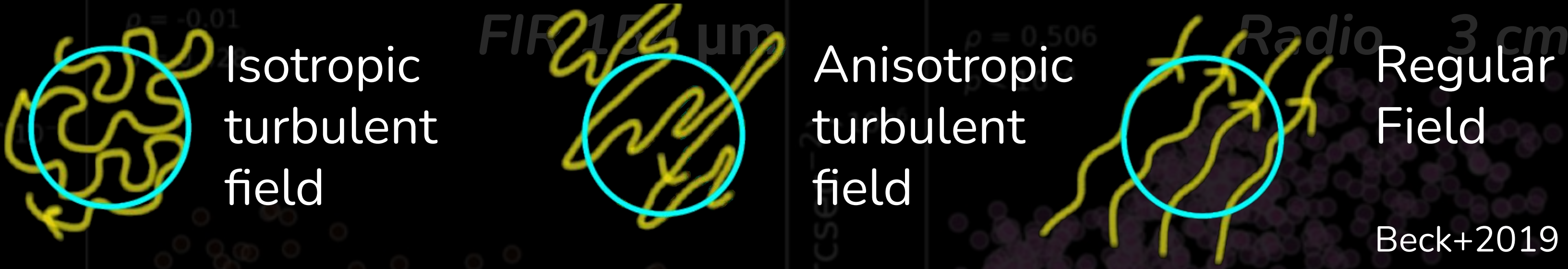
Polarized intensity vs. Star Formation Rate

Borlaff et al. 2021a





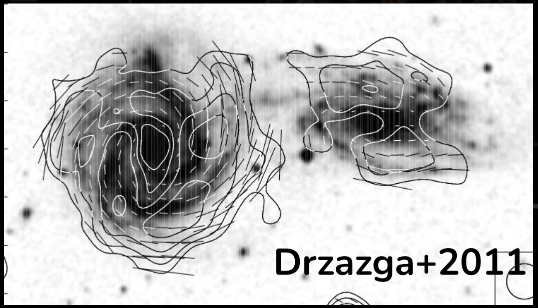
1 - Complex molecular clouds structure inside each beam - FIR **depolarization** dense ISM (Fissel et al. 2016)



Beck+2019

2 - PI **increases** with Column density / velocity dispersion / SFR

Turbulence generates isotropic B-fields → **Shear? Merger? Shocks?**



Drzazga+2011

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

Conclusions

Magnetic field diffuse gas ≠ Magnetic field molecular gas

Star formation, magnetic fields and galaxy mergers are interlinked factors that dominate the outskirts of M51

Borlaff et al. (2021a) -

Extragalactic Magnetism with SOFIA (Legacy Program) I: The magnetic field in the multi-phase interstellar medium of M 51

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Stratospheric Observatory for Infrared Astronomy

Special thanks to:

Kassandra Bell   Joan Schmelz   Mahboubeh Asgari-Targhi   Rick Fienberg

and the rest of SOFIA team!

SOFIA/M51 team members:

Alejandro S. Borlaff, Enrique López-Rodríguez,
Pamela M. Marcum, Rainer Beck, Lucas Grosset,
Eva Ntormousi, Annie Hughes, Rodion Stephanov, John E. Beckman,
Kostas Tassis, Ann Mao, Leslie Proudfit

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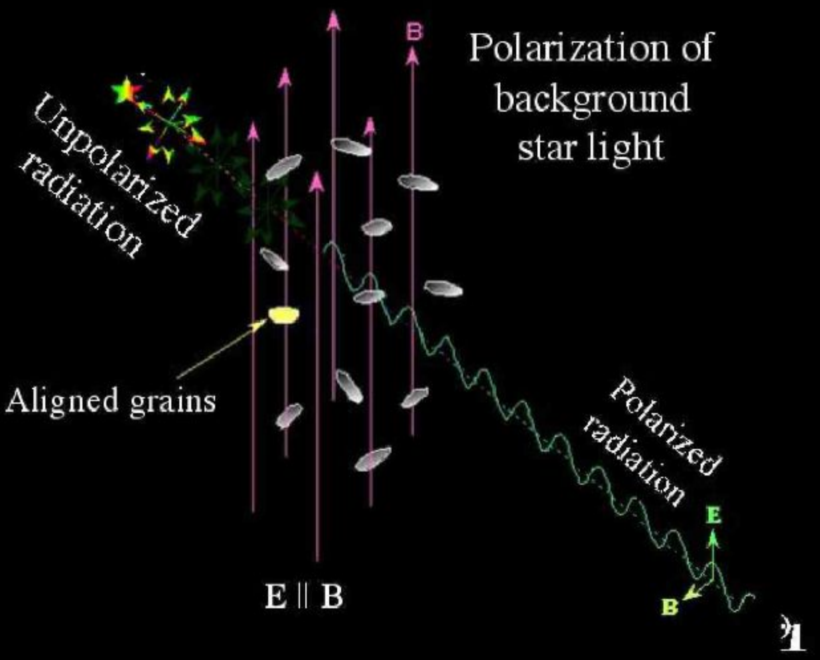
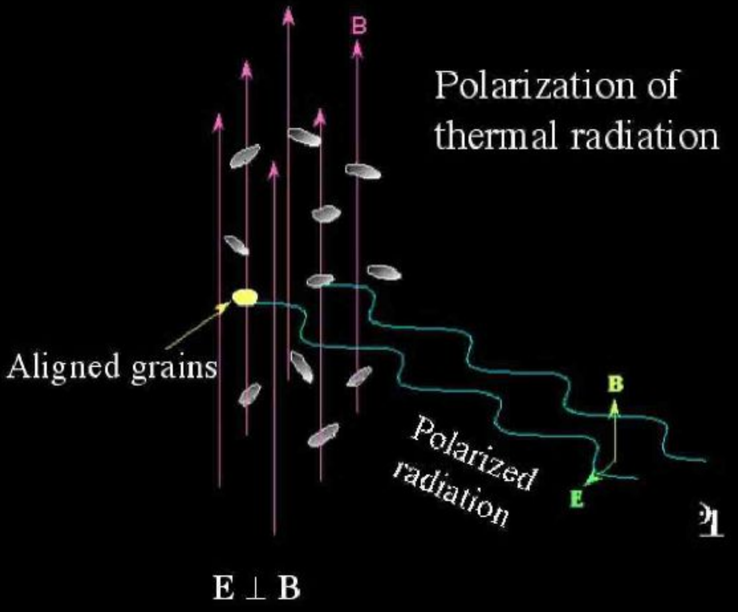
Optical starlight polarization

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)

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!

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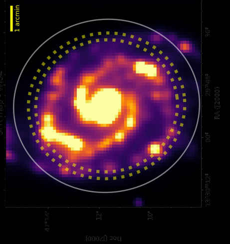
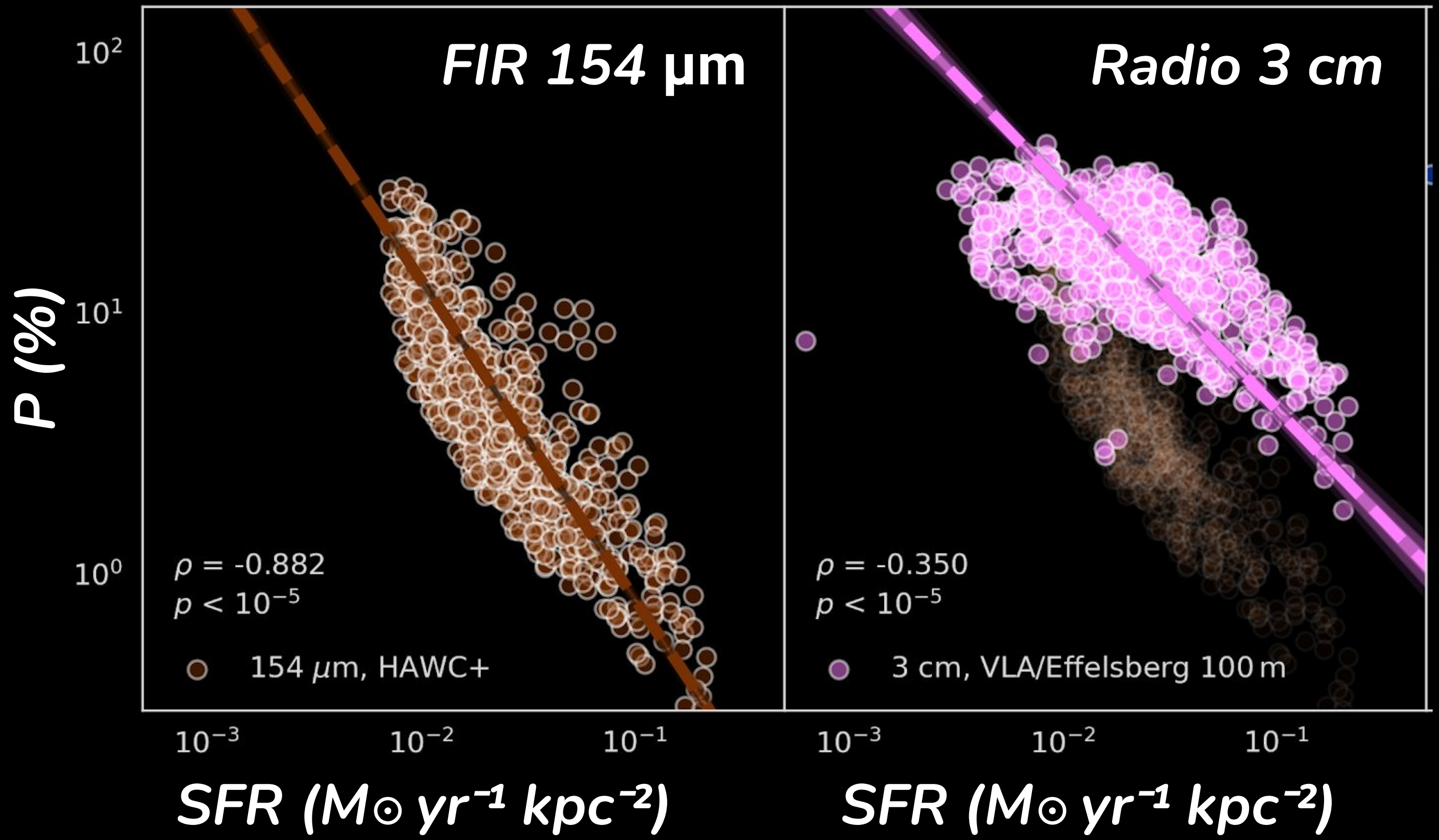
Polarization fraction vs. Star Formation Rate

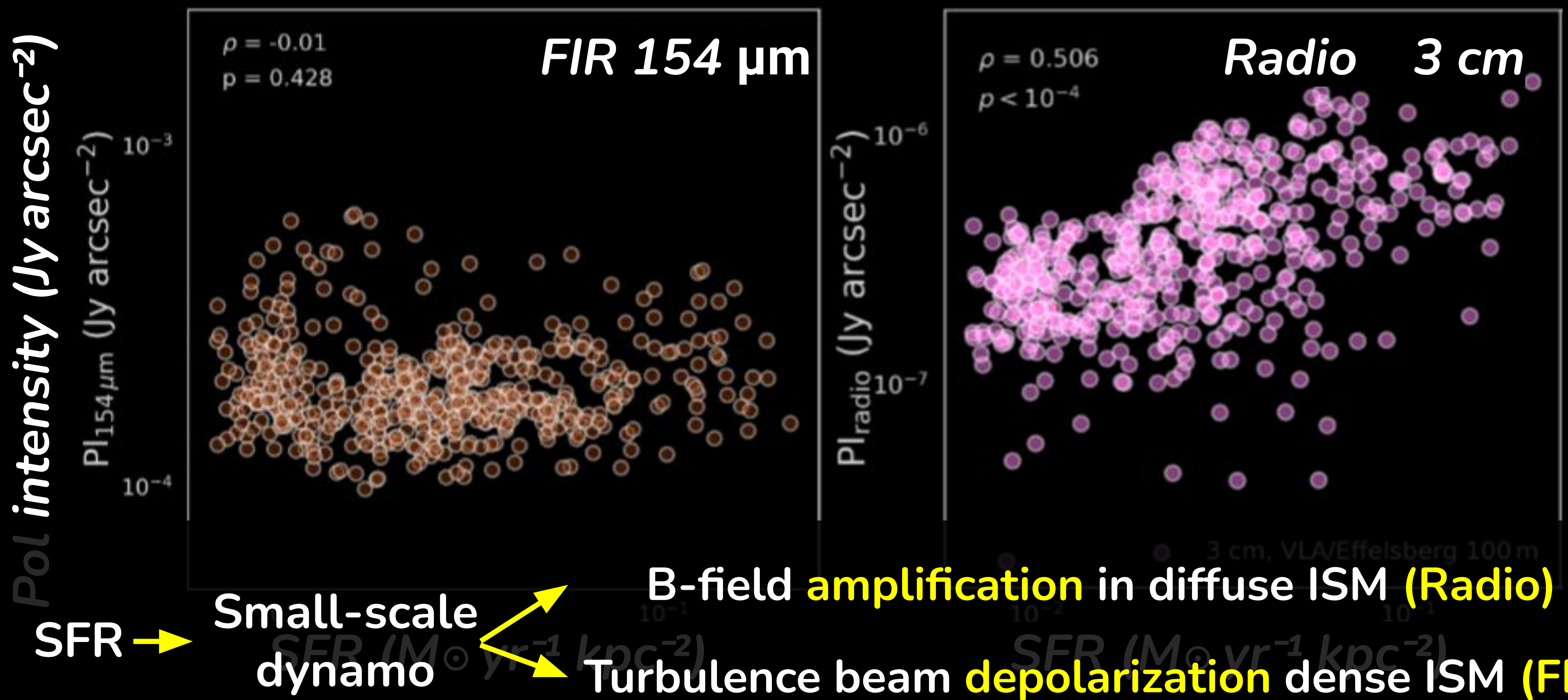
Borlaff et al. 2021a





Polarized intensity vs. Star Formation Rate

Borlaff et al. 2021a



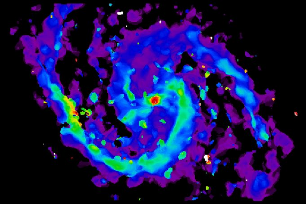
SFR → Small-scale dynamo

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

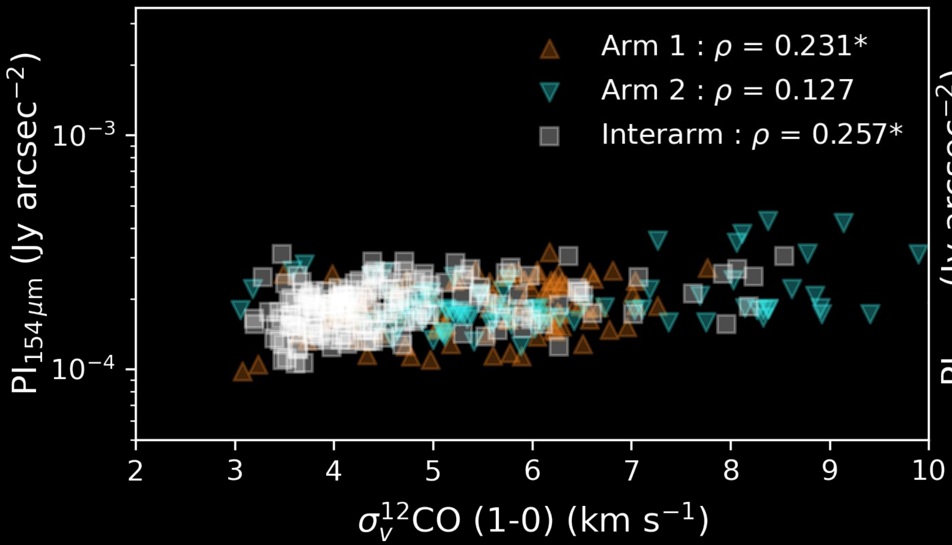
→ Turbulence beam **depolarization** dense ISM **(FIR)**

Polarized intensity vs. ^{12}CO velocity dispersion

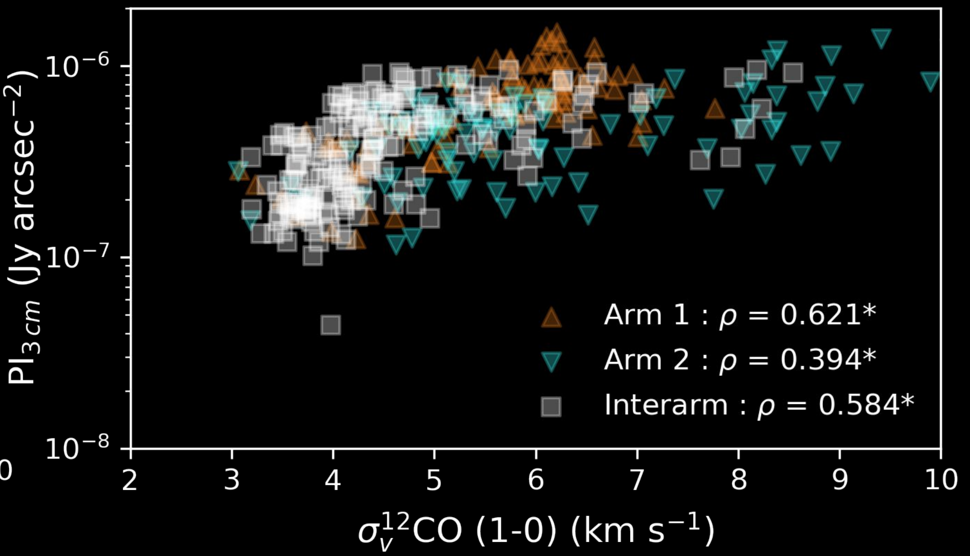
Borlaff et al. 2021a



FIR 154 µm



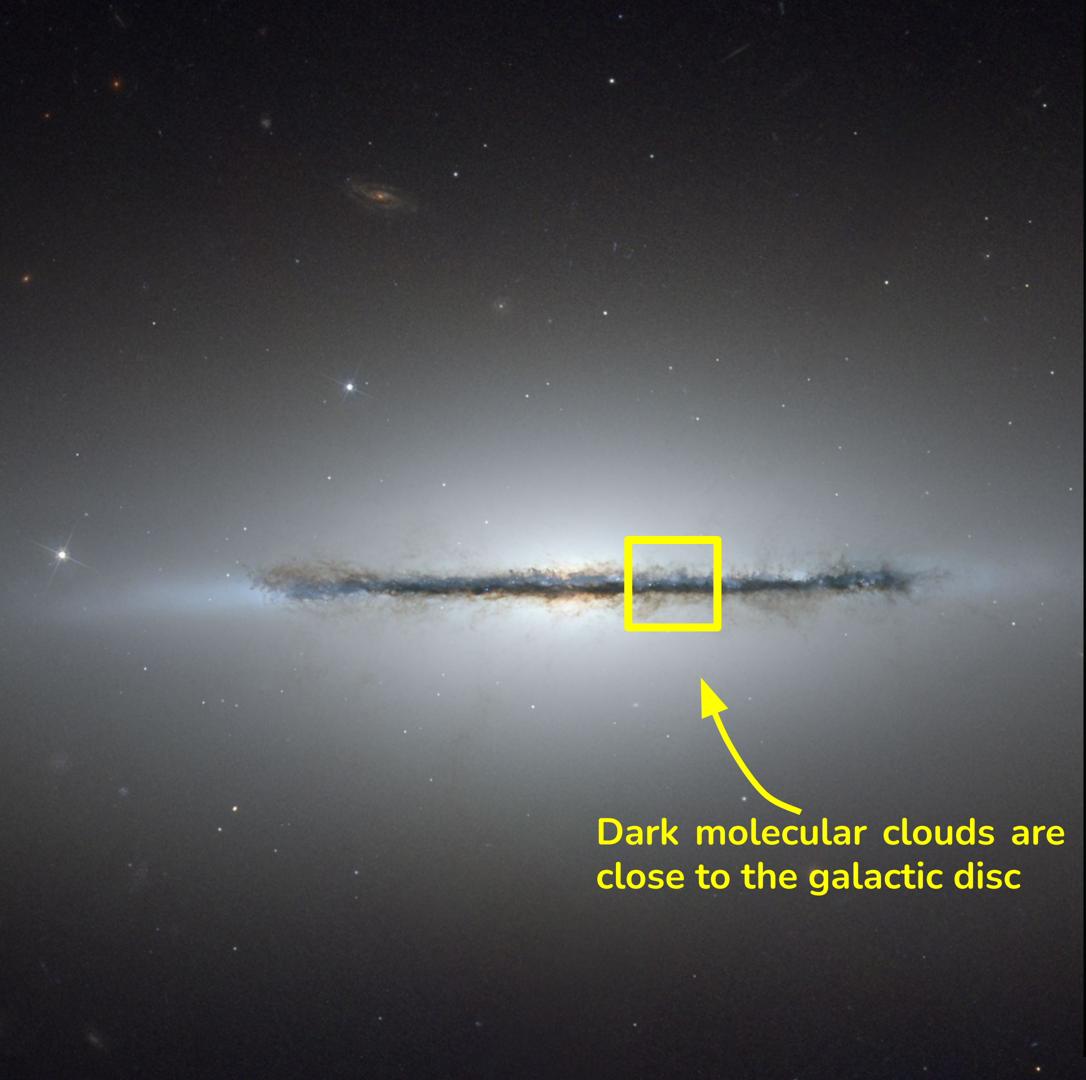
Radio 3 cm



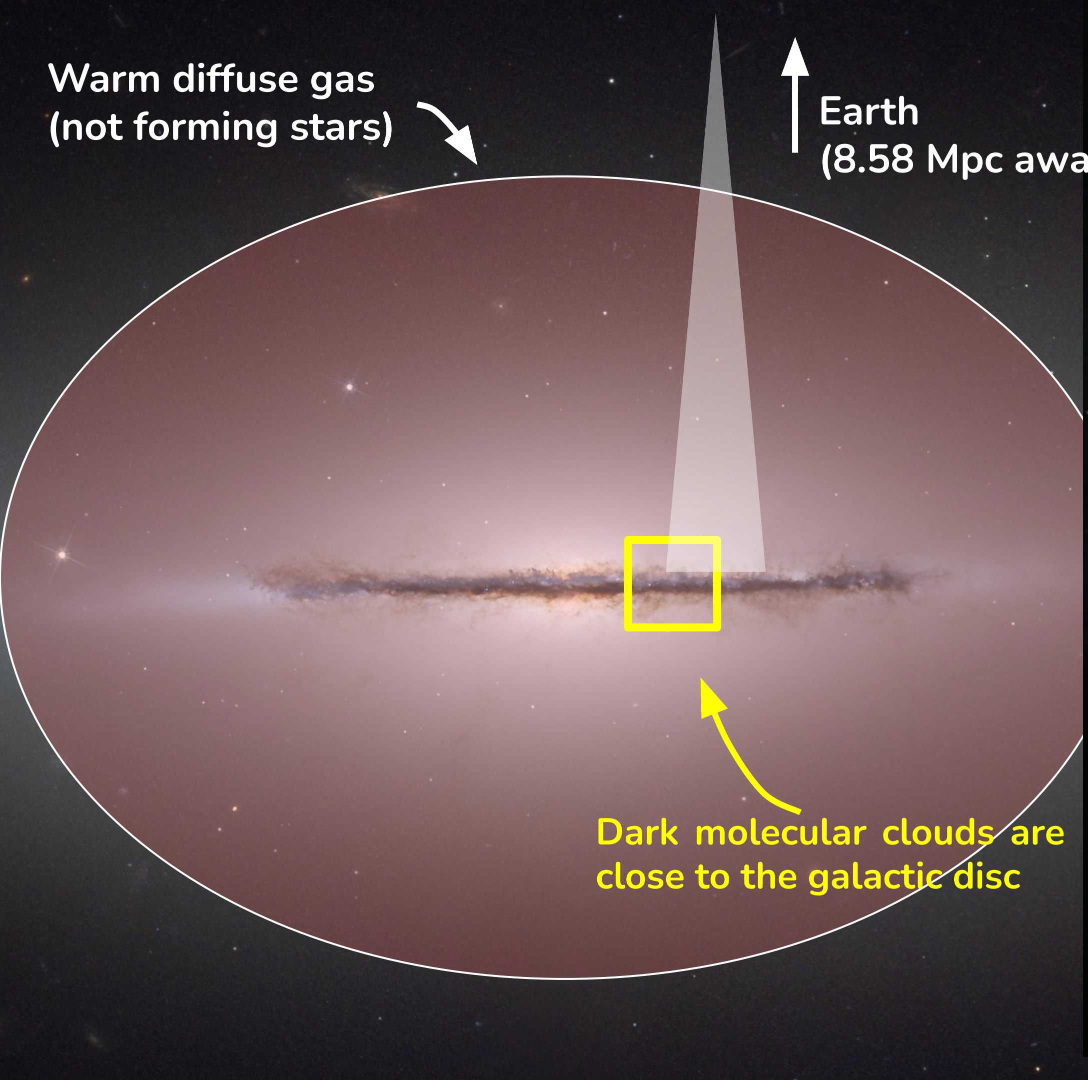
Anisotropic turbulent field

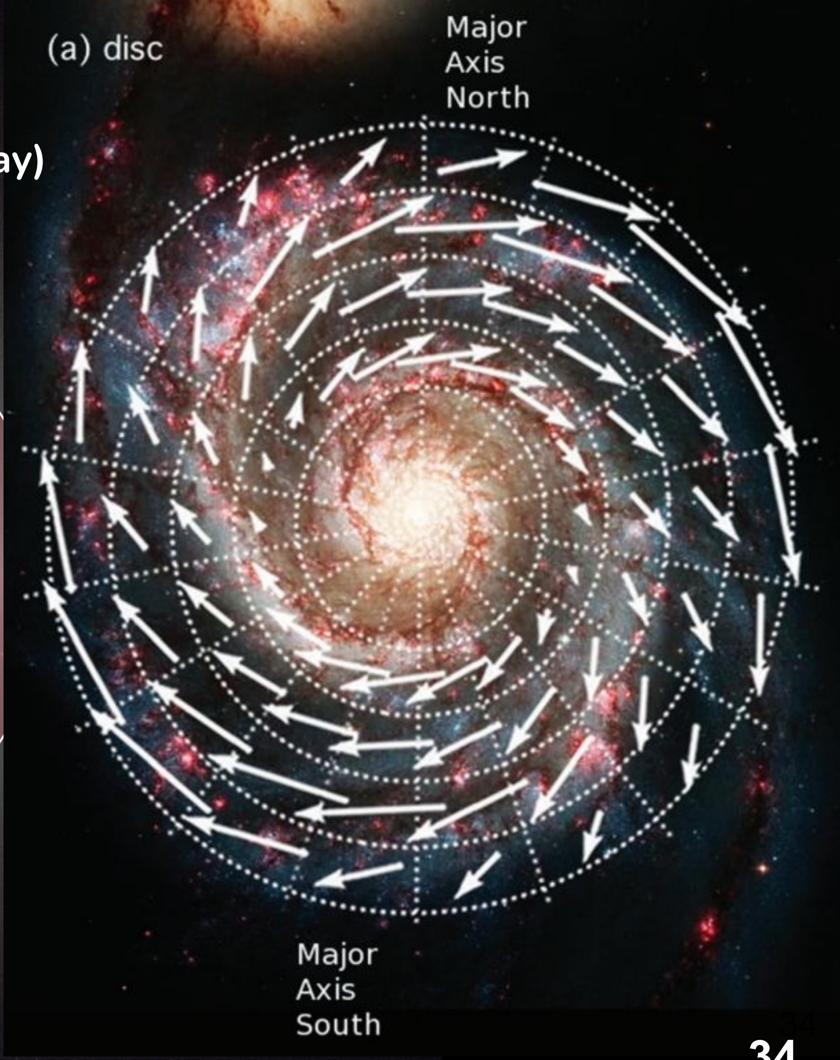
B-field amplification in diffuse ISM (Radio)

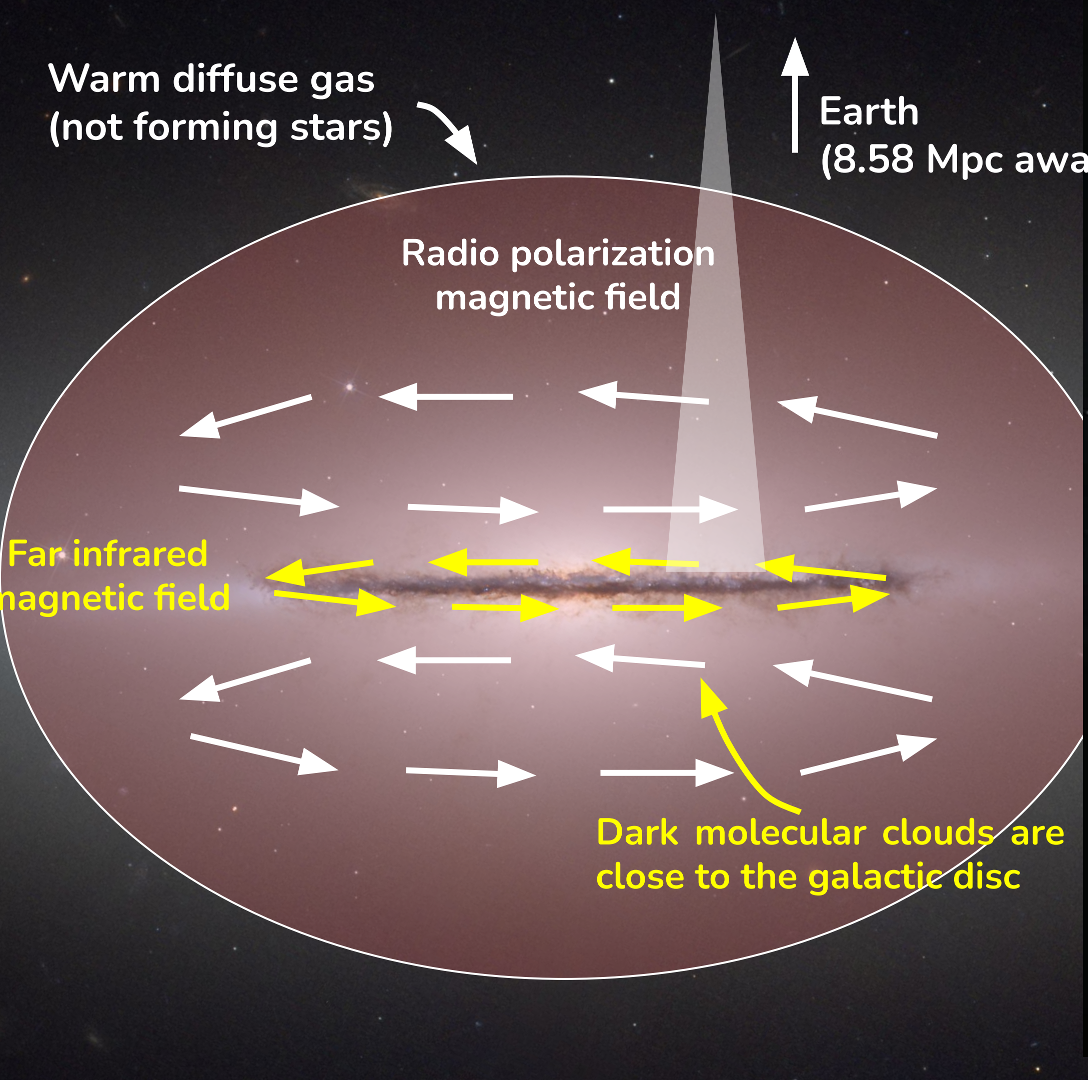
Turbulence beam depolarization dense ISM (FIR)


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)
Dark molecular clouds are
close to the galactic disc


(a) disc
Major
Axis
North
Major
Axis
South


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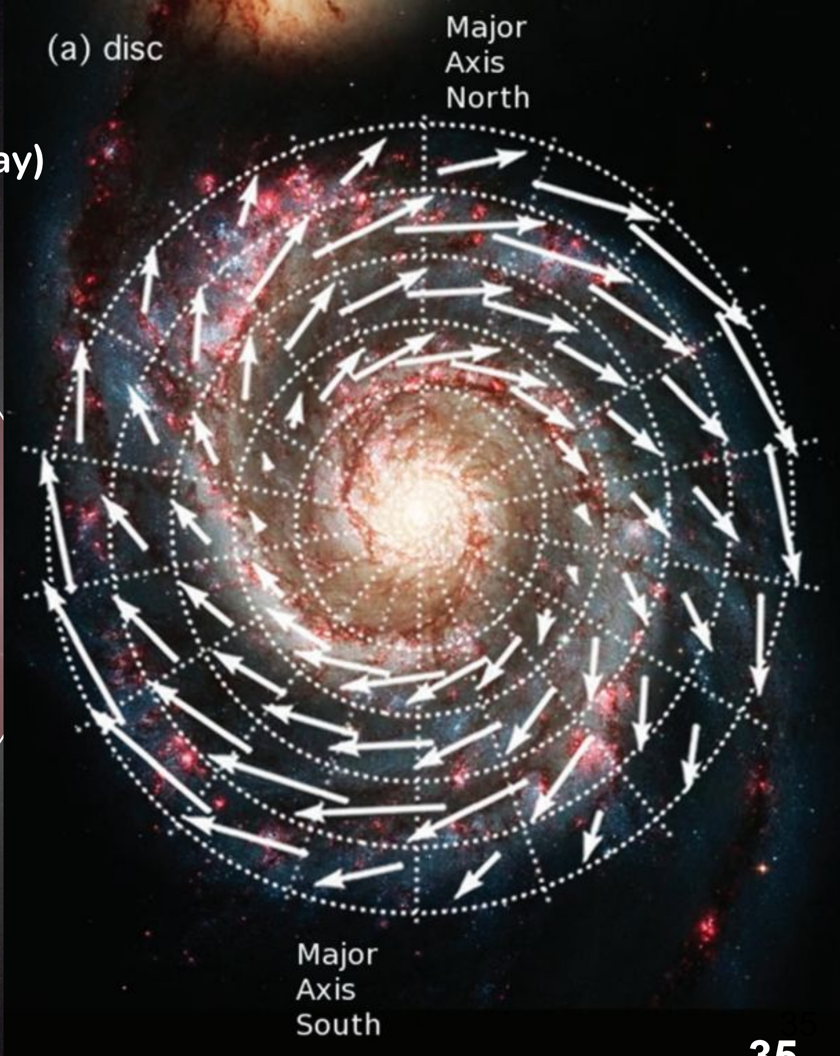
Radio polarization
magnetic field
Far infrared
nagnetic field
Dark molecular clouds are
close to the galactic disc


(a) disc
Major
Axis
North
Major
Axis
South