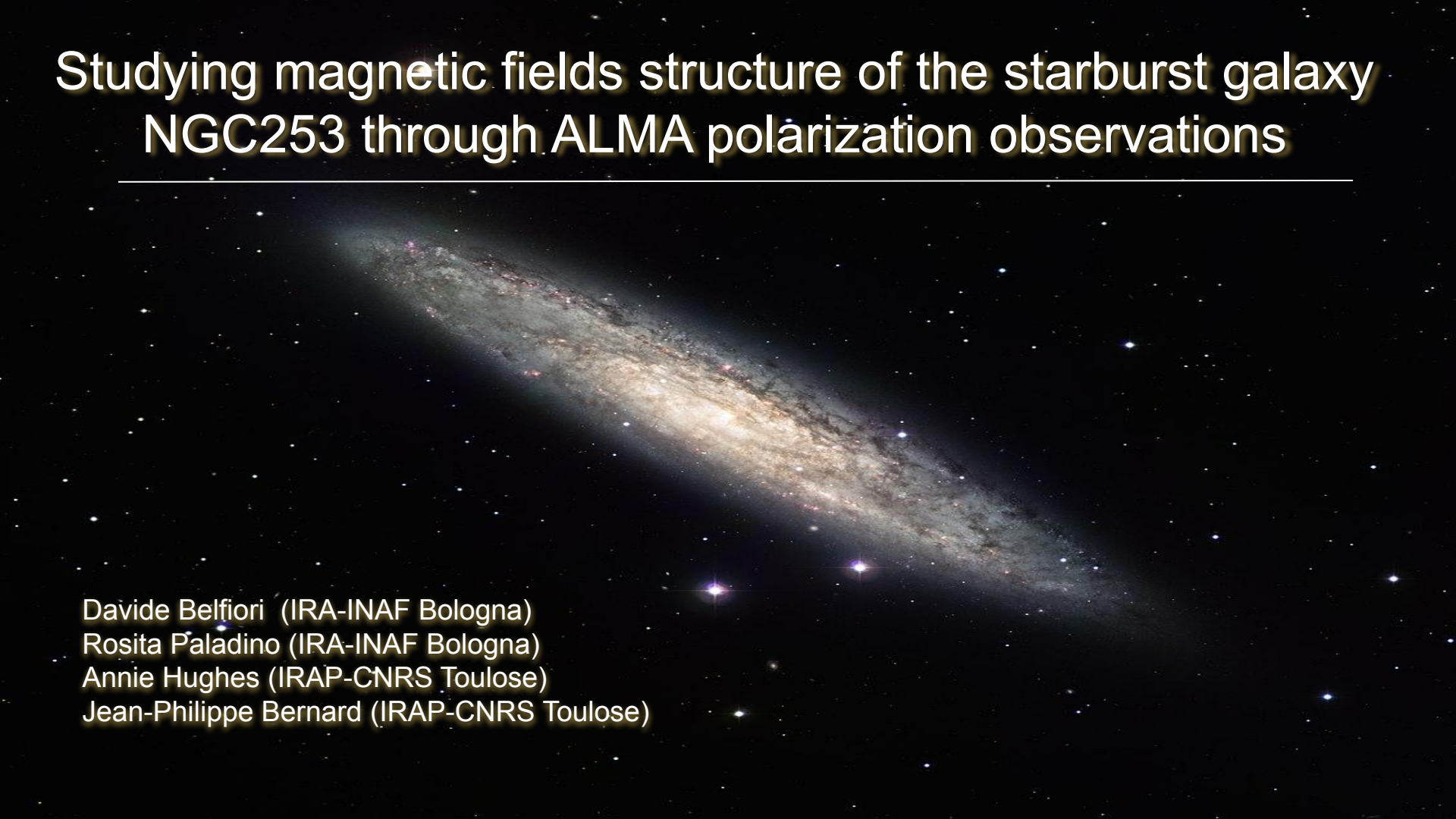
Studying magnetic fields structure of the starburst galaxy NGC253 through ALMA polarization observations



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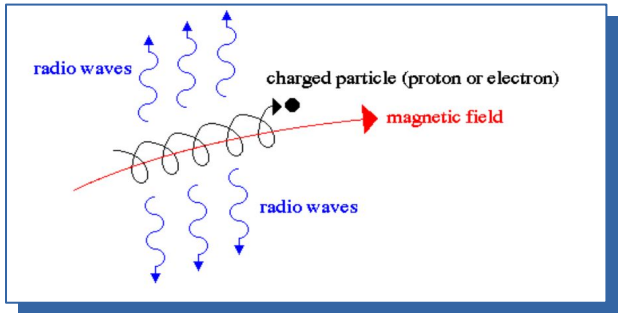
Magnetic fields in galaxies

They:

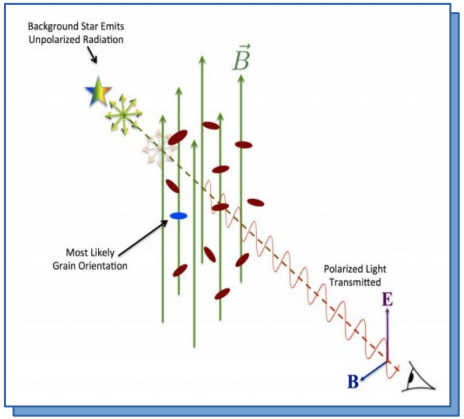
- Directly affect the mean gas density, which impacts significantly the star formation rate (Birnboim et al. 2015)
- Regulate Star Formation, both on the scale of individual stars and filaments and through the collapse and fragmentation of molecular clouds (Mac Low 2009; Crutcher 2012)
- Play an important role in launching galactic winds and outflows (Heesen et al. 2011)

Various methods to measure magnetic fields (dust polarization, Zeeman Effect, Faraday Rotation etc..)

Synchrotron Radiation

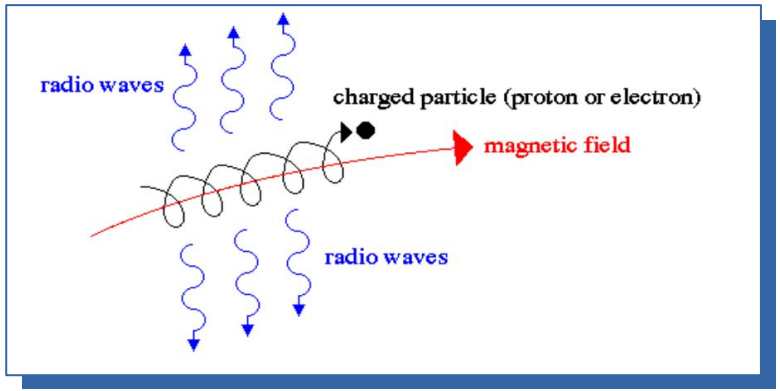


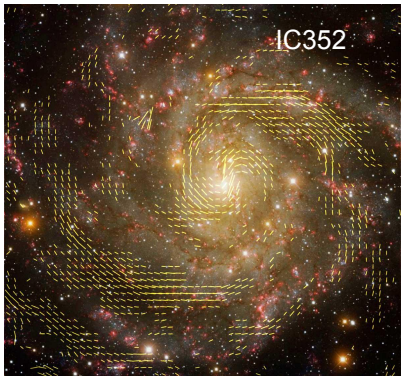
Dust polarization



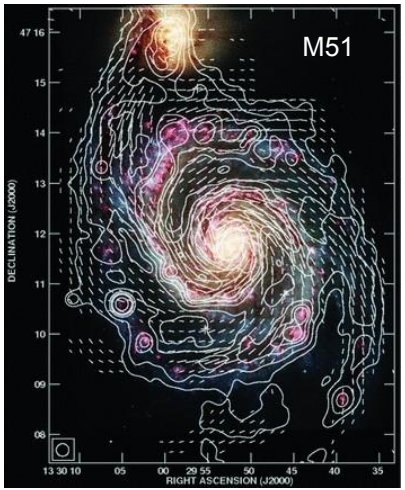
Synchrotron radiation and its polarization

Charged particles (mostly electrons) moving at relativistic speeds around magnetic fields lines on spiral trajectories generate electromagnetic waves.





Beck+2015



Fletcher+2011

The **total intensity** of synchrotron emission ⟺ strength of the **total magnetic field** component in the sky plane

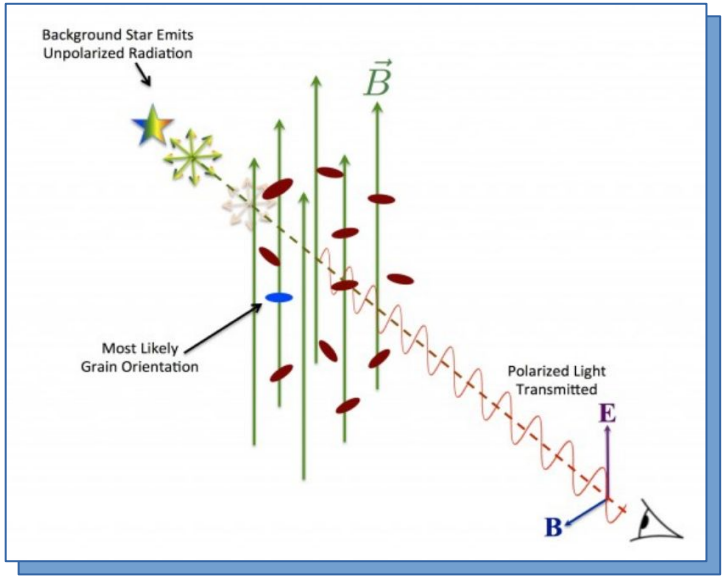
The **polarization** of synchrotron emission ⟺ orientation of the **ordered fields** in the sky plane

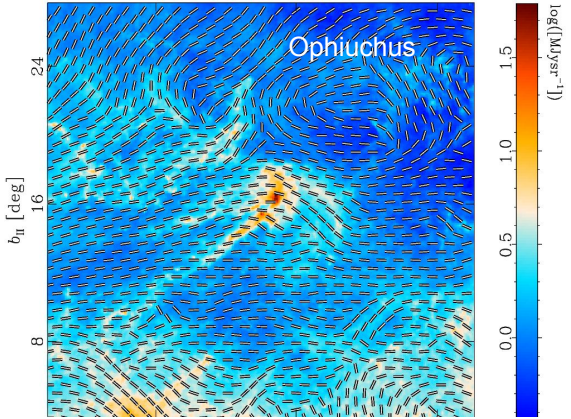
Traces the magnetic fields properties mostly in **warm and diffuse medium**, such as halos of galaxies, and reflects the average field structure over the full scale height explored by cosmic-rays

Dust polarization

Elongated dust grains can be oriented with their major axis perpendicular to the interstellar magnetic field lines by paramagnetic alignment or by radiative torque alignment.

When the dust particles are aligned perpendicular to the magnetic field lines, they emit polarized radiation, with the E-vectors pointing perpendicularly to the field.





Planck XIX 2015

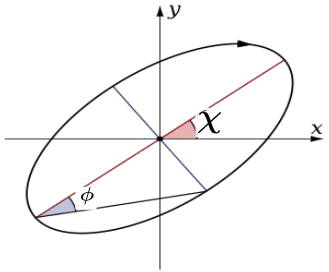
Traces the magnetic field in most **dense and cold regions** such as molecular clouds, where star formation actually happens.

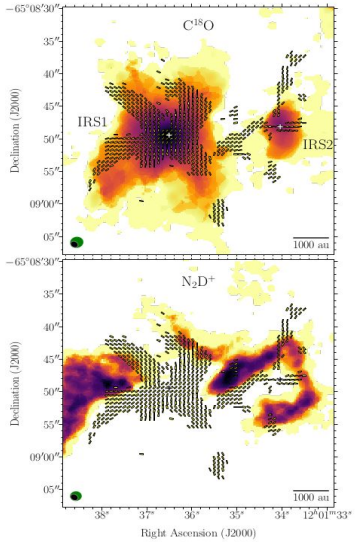
ALMA (Atacama Large Millimeter/submillimeter Array)

Full polarization mode in the range ~ 90 - 350 GHz frequency

Full polarization mode allows measures of Stokes parameters and informations on **polarization intensity** and **polarization angle**:

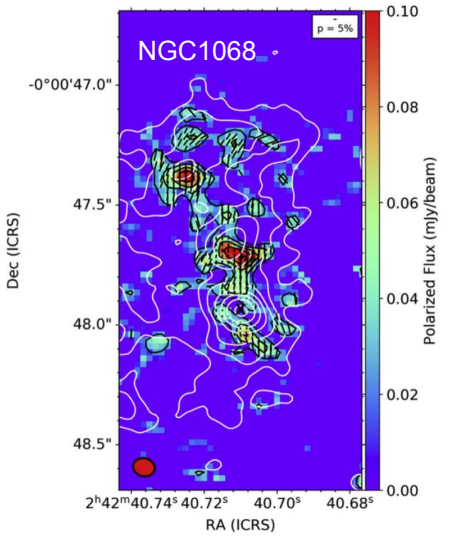
$$I^2 = Q^2 + U^2 + V^2$$
$$Q = cos2\phi cos2\chi$$
$$U = cos2\phi sin2\chi$$
$$V = sin2\phi$$





Hull et al. 2019

Ang. Res. = 140 AU



Lopez-Rodriguez et al. 2020

Ang. Res. = 4.2 pc

Polarization Angle

$$tan2\chi = \frac{U}{Q}$$

Polarized Intensity

$$PI = \sqrt{Q^2 + U^2}$$

Polarization Fraction

$$PF = \frac{\sqrt{Q^2+U^2}}{I}$$

NGC253

Nearby, highly inclined, starburst galaxy (D=3.5 Mpc, i ~ 78◦ , Rekola et al 2005, Pence 1980)

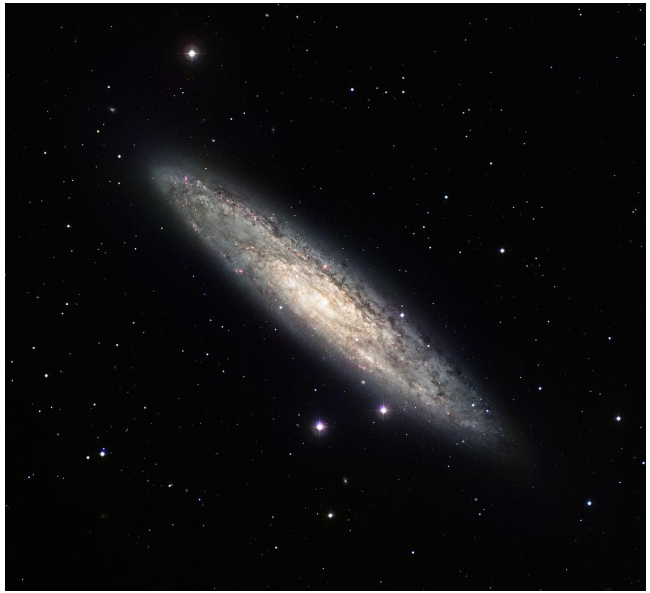


Image from the Wide Field Imager (WFI) of the MPG/ESO 2.2 m telescope at the La Silla Observatory.

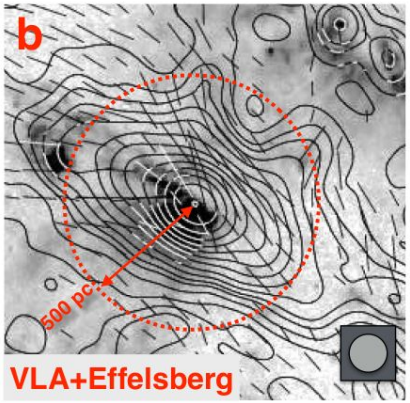
Extensively observed at many wavebands:
X-ray (Strickland et al. 2000), **Optical** (Watson et al. 1996), **Infrared** (Sugai et al. 2003), **Sub-/millimeter** (Bolatto et al. 2013), **GHz radio** including **polarisation** (Turner & Ho 1985; Heesen et al. 2009, 2011)

One of the nearest sources with an **extremely bright dust continuum** (17.4 Jy at 353 GHz, Planck Collaboration VII, 2011)

NGC253

Observations of the central starburst region

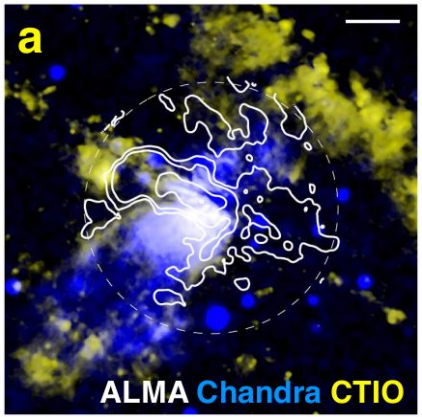
On large (> 0.5 kpc) scales, radio polarisation observations reveal a magnetic field in the disk that is parallel to the midplane, and an X-shaped halo field centered on the nucleus.



Ang. Res. = 170 pc

Westmoquette+2011

Warm ionized phases of wind shown via soft X-ray (blue, Chandra) and Hα (yellow, CTIO) emission. **The white contours represent 12 CO(J = 1 → 0) emission detected by ALMA to highlight entrained cold gas in the outflow.**



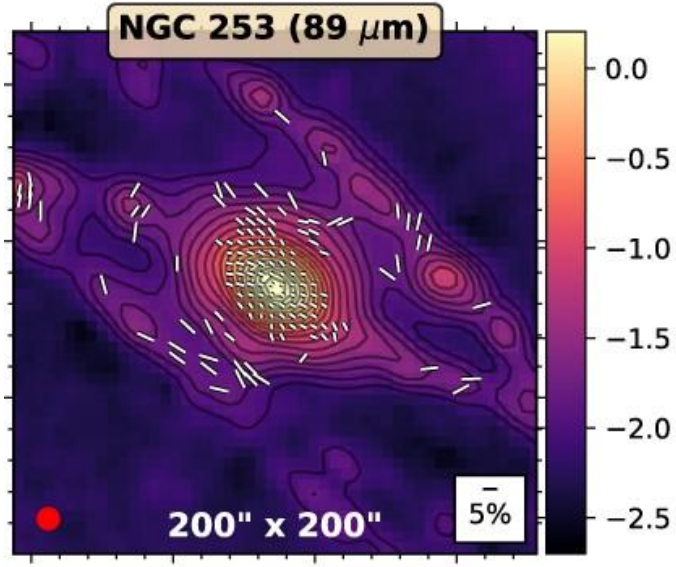
Ang. Res. = 50 pc

Bolatto+2013

NGC253

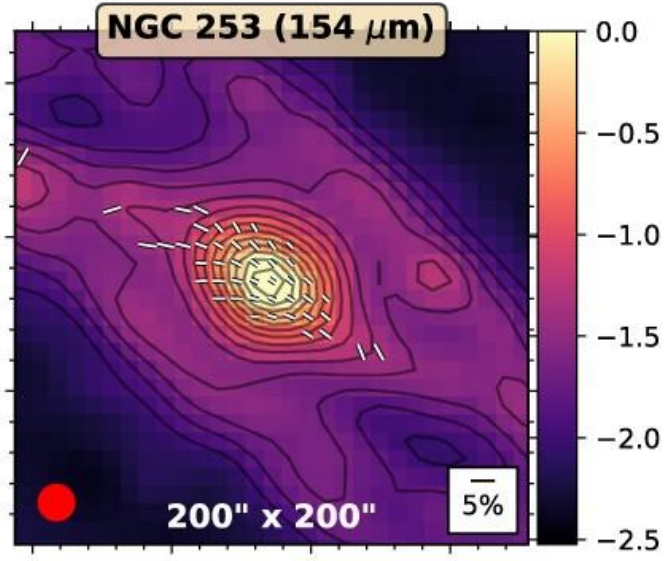
$$PF = \frac{\sqrt{Q^2+U^2}}{I}$$

Recent SOFIA FIR polarization observations
(Lopez-Rodriguez+2022b)



Ang.res. = 7.8'' (~ 130 pc)

Polarization fraction **PF ≅ 1.5 %**



Ang.res. = 13.6'' (~ 230 pc)

Polarization fraction **PF ≅ 1.0 %**

NGC253

ALMA polarization observations in Band 4 and 7:

Parsec-scale map of the magnetic field structure in the dense gas at the heart of a starburst system.

REPRESENTATIVE SCIENCE GOALS (UP TO FIRST 30)						
SCIENCE GOAL	POSITION	BAND	ANG.RES.(")	LAS.(")	ACA?	NON-STANDARD MODE
B7 Polarisation C43-4	J2000 00:47:33.1079, -25:17:18.386	7	0.300	3.200	N	Y
B4 polarisation C43-1	J2000 00:47:33.1079, -25:17:18.386	4	2.200	12.000	N	Y

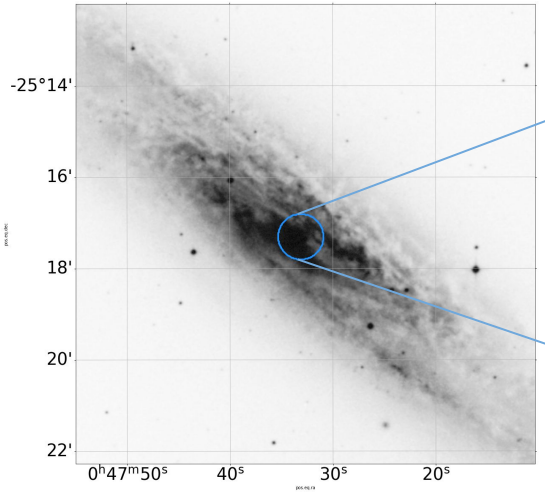
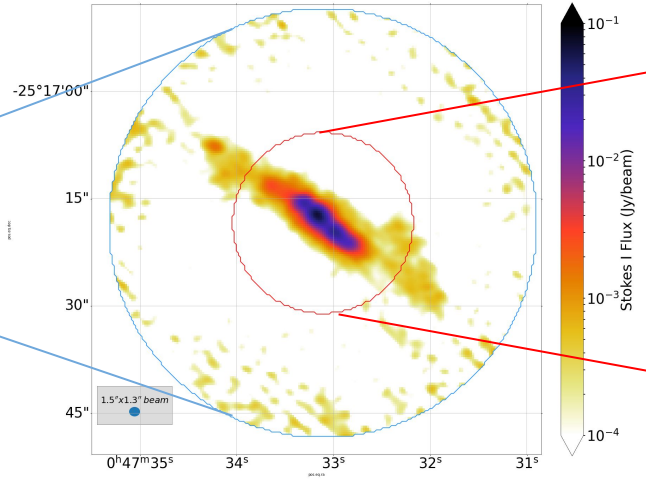
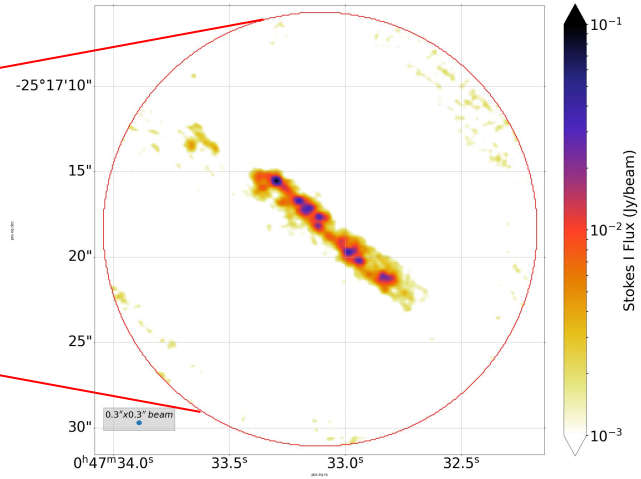


Image from ESO Digitized Sky Survey 2



Band 4 (~ 150 GHz)
Ang. Res = ~ 40 pc



Band 7 (~ 350 GHz)
Ang. Res = ~ 0.5 pc

Noise analysis

Non linear quantities:

$$PF = \frac{\sqrt{Q^2+U^2}}{I} \qquad PI = \sqrt{Q^2+U^2} \qquad \chi = \frac{1}{2} arctan(\frac{U}{Q})$$

rotation by 90° ⟹ $\vec{B}$

Full use of the covariance matrix:

$$\Sigma \equiv \begin{pmatrix} \sigma_{\mathrm{II}} & \sigma_{\mathrm{IQ}} & \sigma_{\mathrm{IU}} \\ \sigma_{\mathrm{IQ}} & \sigma_{\mathrm{QQ}} & \sigma_{\mathrm{QU}} \\ \sigma_{\mathrm{IU}} & \sigma_{\mathrm{QU}} & \sigma_{\mathrm{UU}} \end{pmatrix}$$

$$\sigma^2_{PF} = f(I, Q, U, \sigma_{II}, \sigma_{IQ}, \sigma_{IU}, \sigma_{QQ}, \sigma_{UU}, \sigma_{QU})$$

$$\sigma^2_{PI} = f(Q, U, \sigma_{QQ}, \sigma_{UU}, \sigma_{QU})$$

$$\sigma^2_{\chi} = f(Q, U, \sigma_{QQ}, \sigma_{UU}, \sigma_{QU})$$

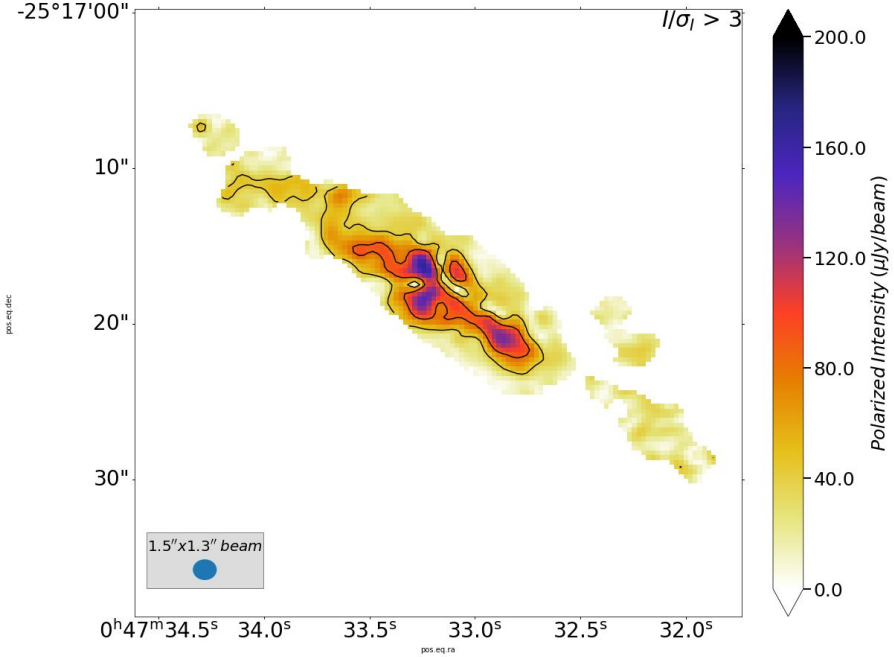
No assumptions on correlation noise on I, Q, U and relative polarization quantities

Band 4 (~ 150 GHz, ~ 40 pc)

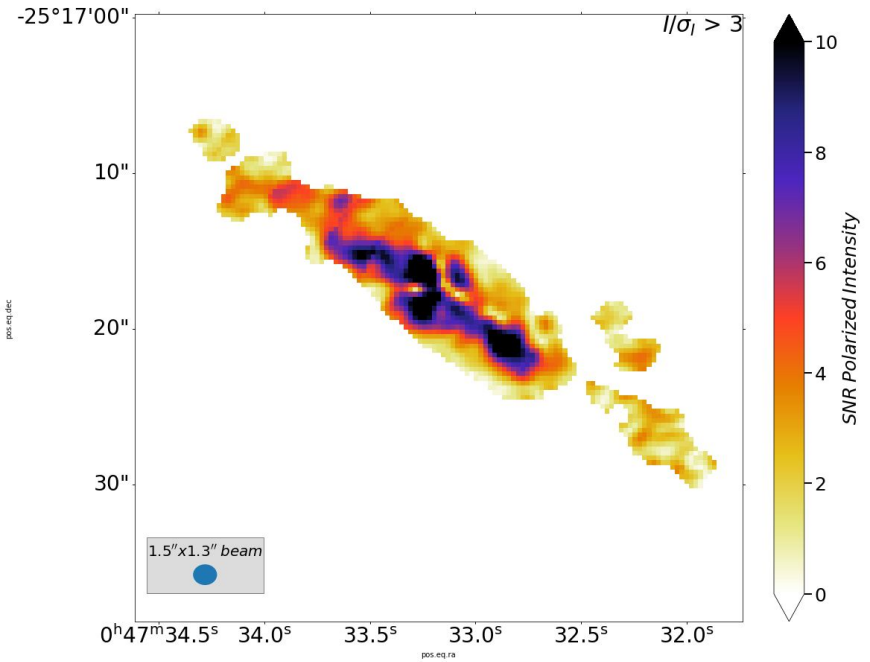
$$PI = \sqrt{Q^2 + U^2}$$

SNR = PI/σ_{PI}

Polarized Intensity



SNR Polarized Intensity



Band 4 (~ 150 GHz, ~ 40 pc)

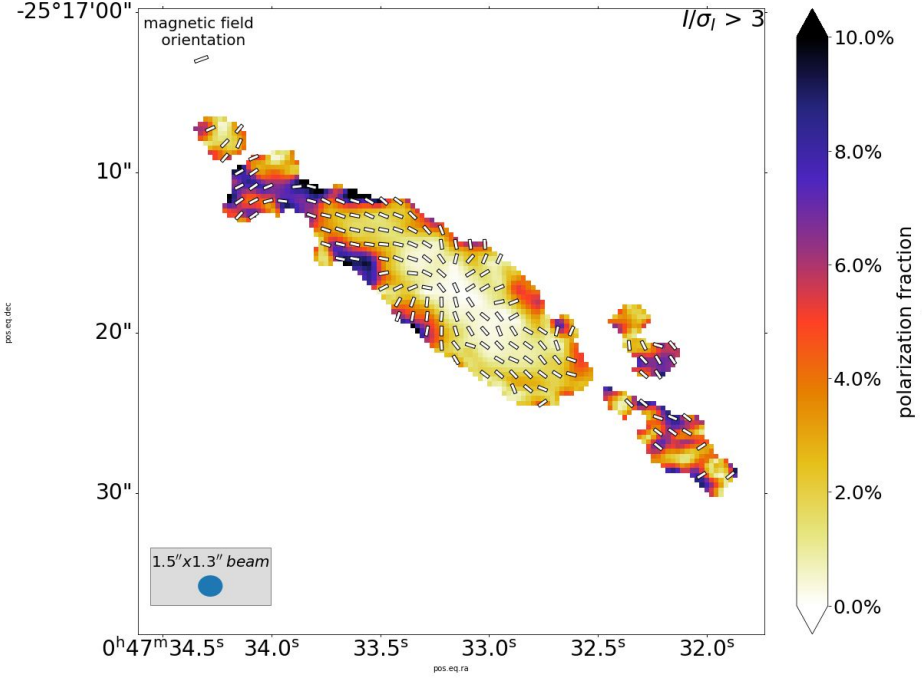
Median PF ~ 2.6%

$$PF = \frac{\sqrt{Q^2+U^2}}{I}$$

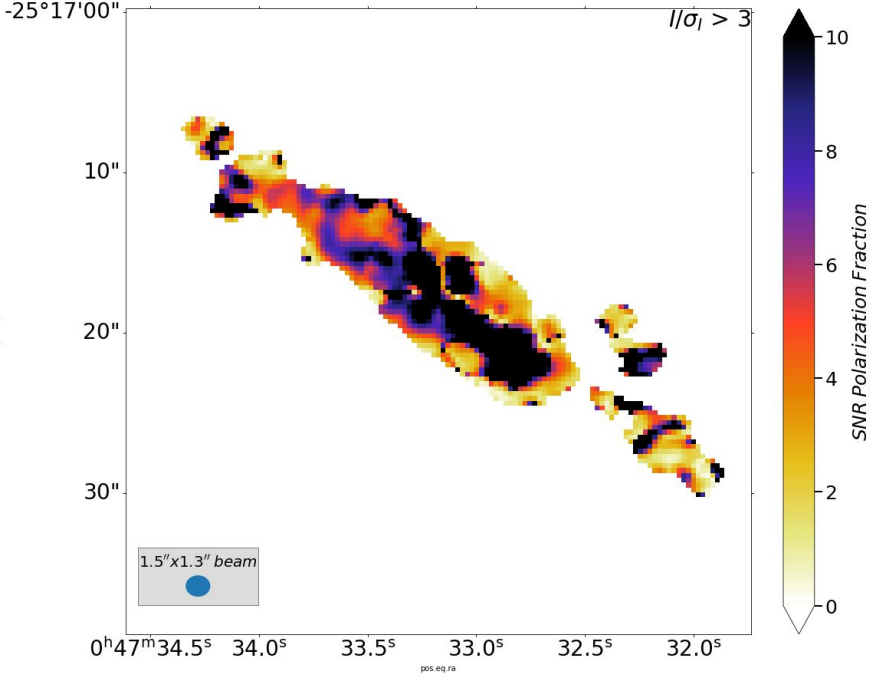
SNR = PF/σ_{PF}

High SNR at PF ~ 1%

Polarization Fraction



SNR Polarization Fraction



Band 4 (~ 150 GHz, ~ 40 pc)

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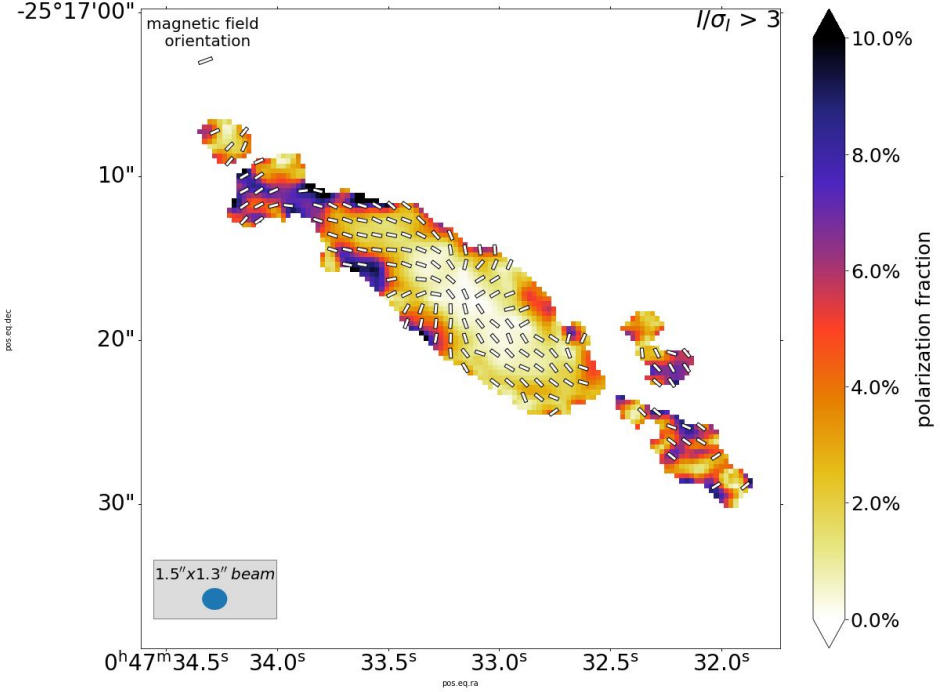
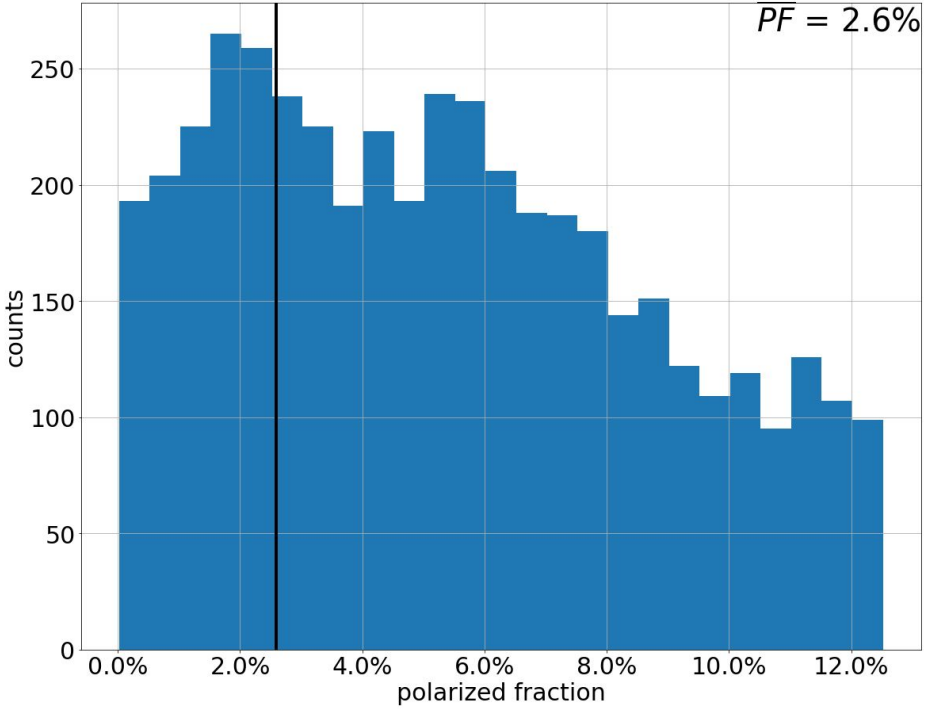
High SNR at PF ~ 1%

Polarization Fraction



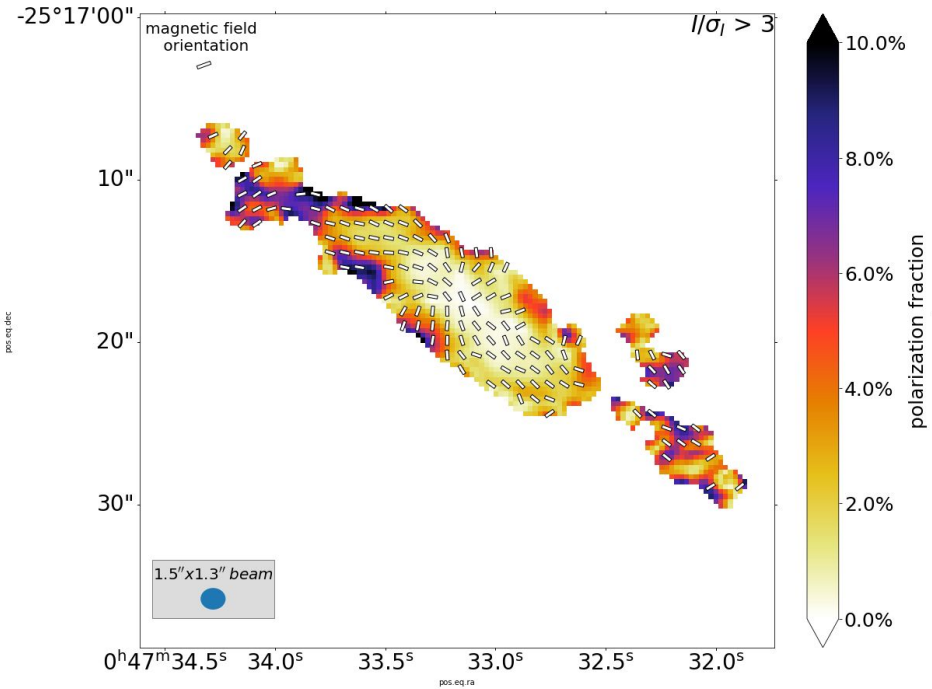
Polarization Fraction distribution



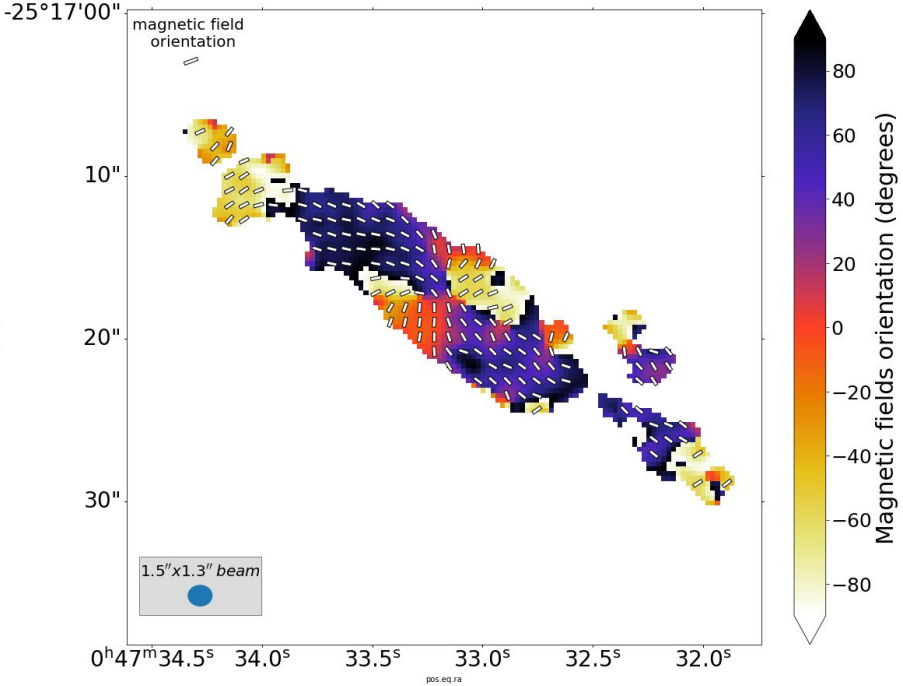
Band 4 (~ 150 GHz, ~ 40 pc)

Median PF ~ 2.6%

Polarization Fraction



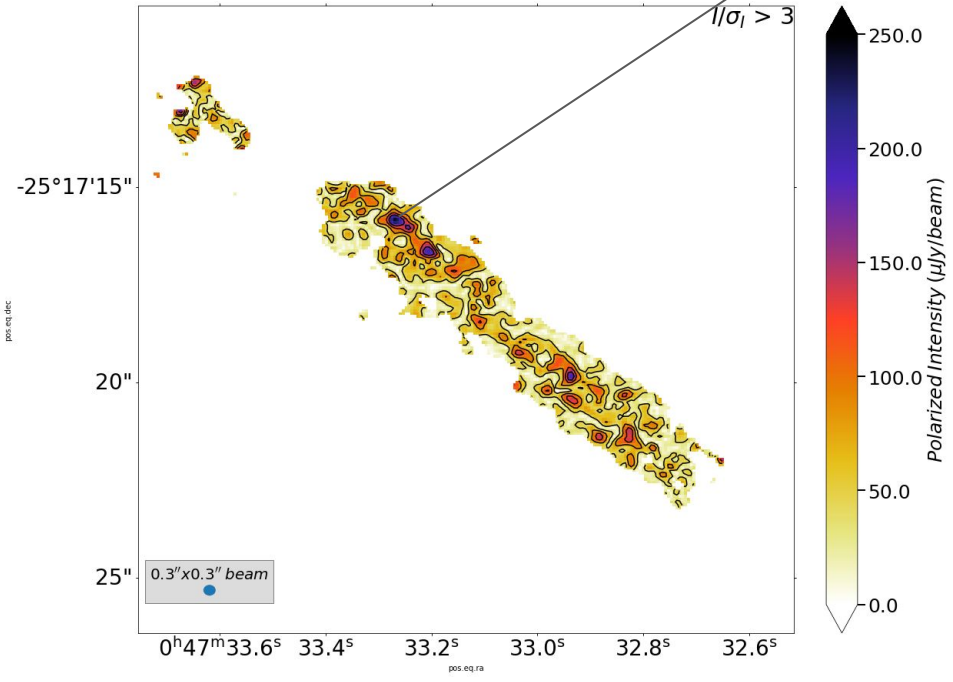
Magnetic Field Orientation



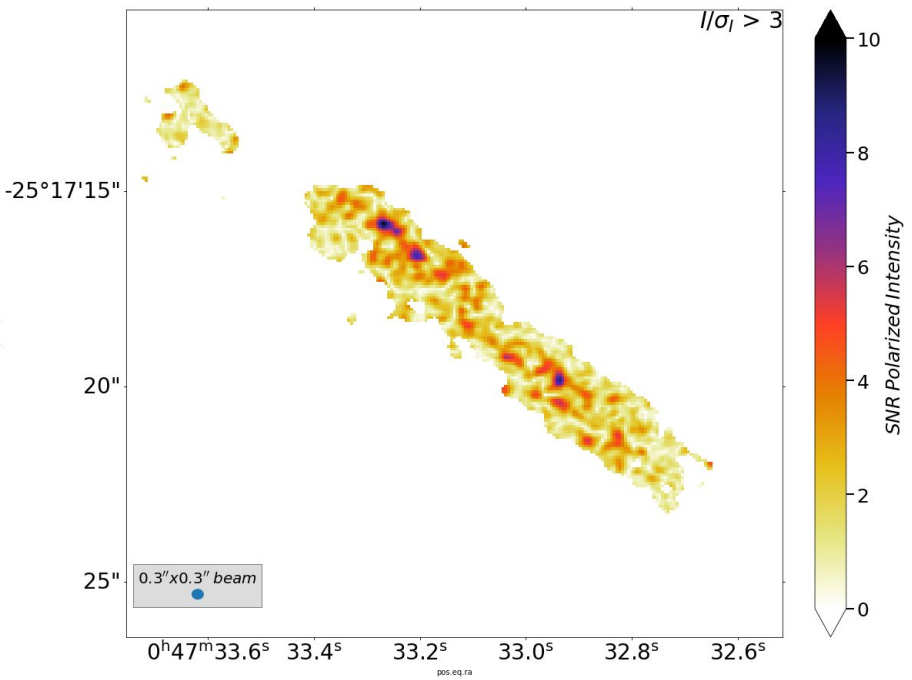
Band 7 (~ 350 GHz, ~ 0.5 pc)

Local maxima of Polarized Intensity near starcluster (Leroy et al. 2018)

Polarized Intensity



SNR Polarized Intensity

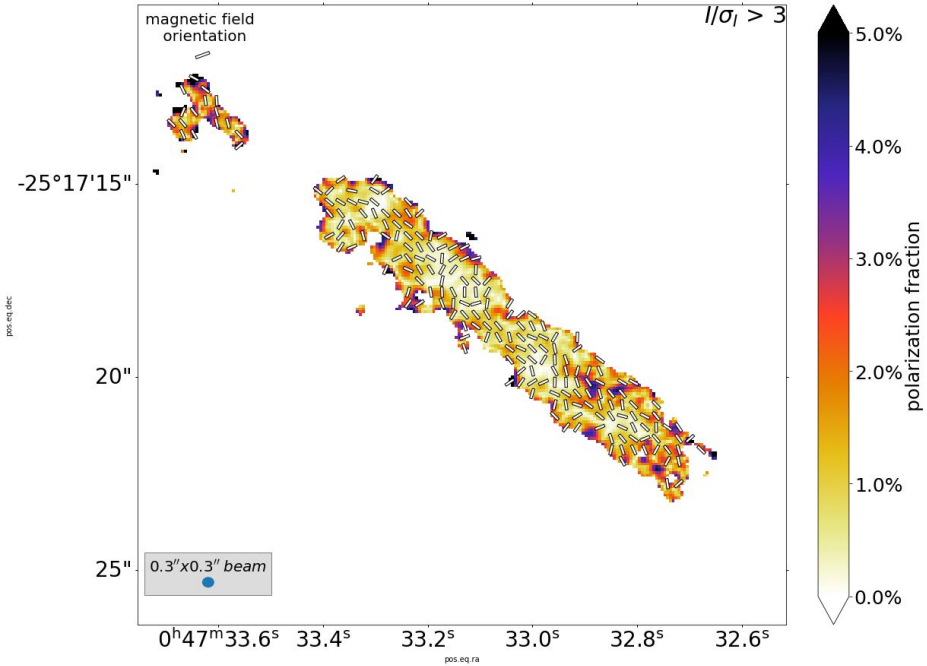


Band 7 (~ 350 GHz, ~ 0.5 pc)

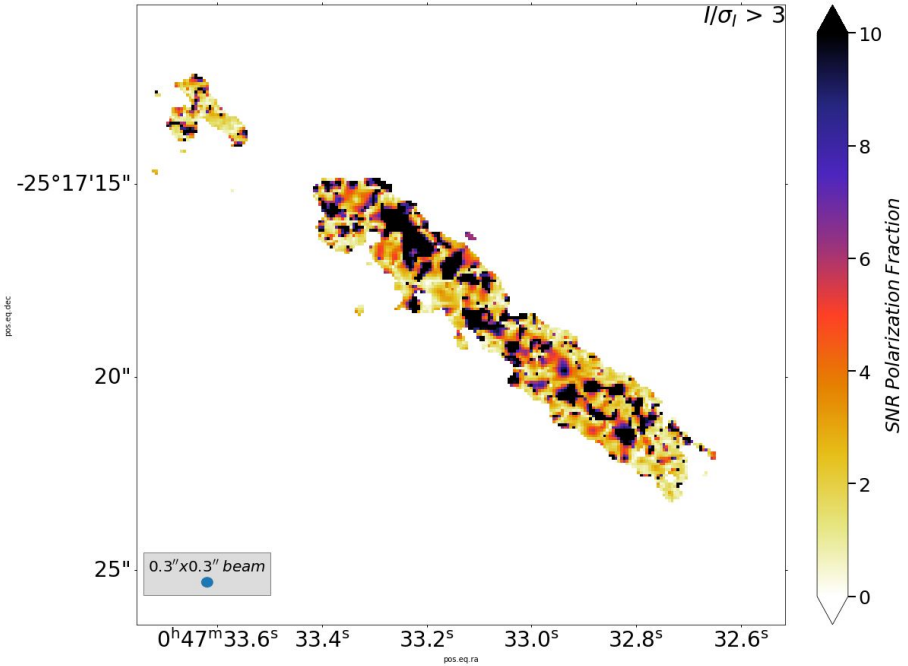
High SNR at PF < 1%

Median PF ~ 1.1%

Polarization Fraction



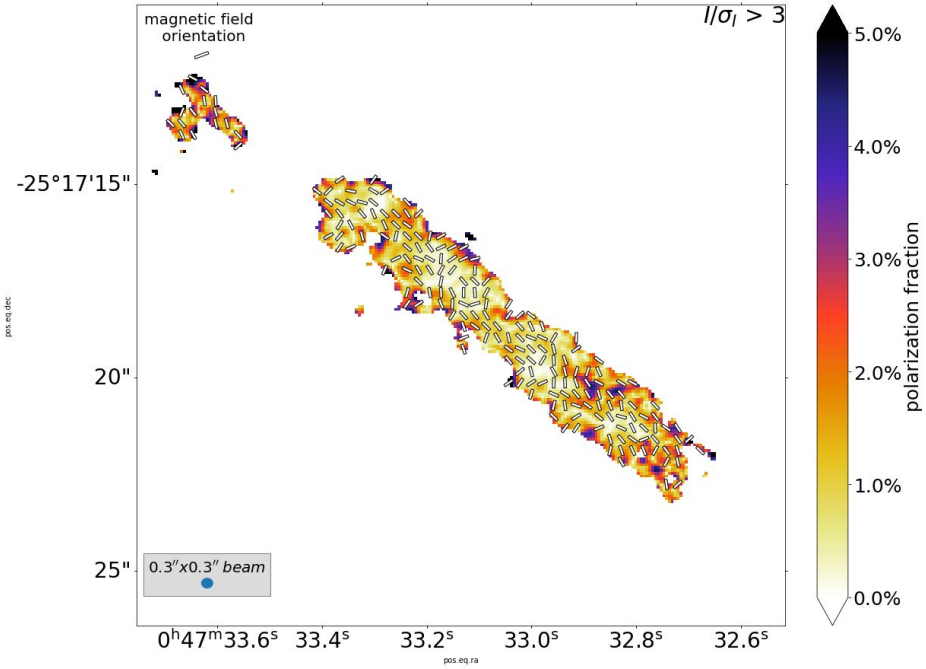
SNR Polarization Fraction



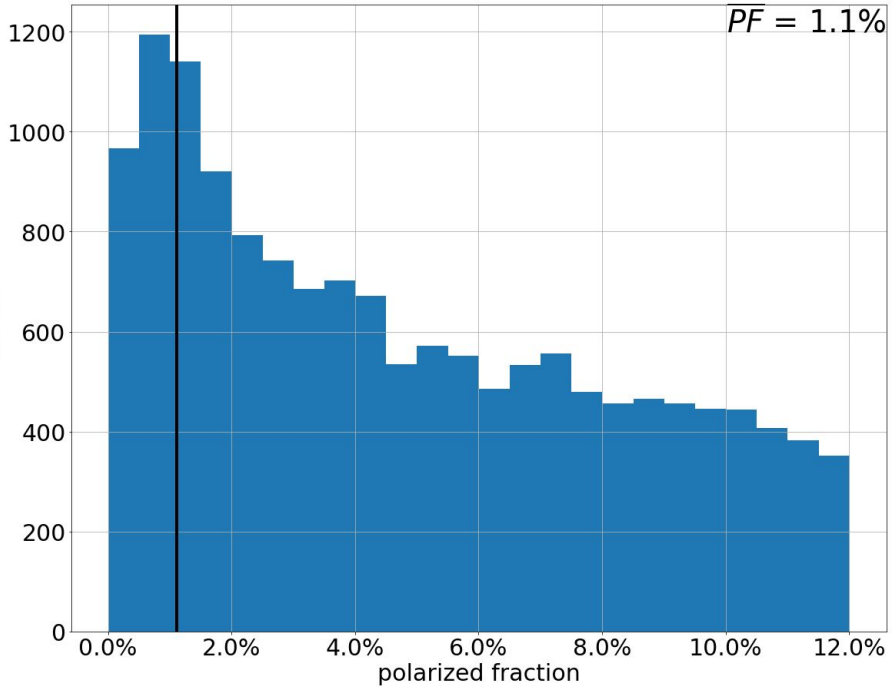
Band 7 (~ 350 GHz, ~ 0.5 pc)

Median PF ~ 1.1%

Polarization Fraction



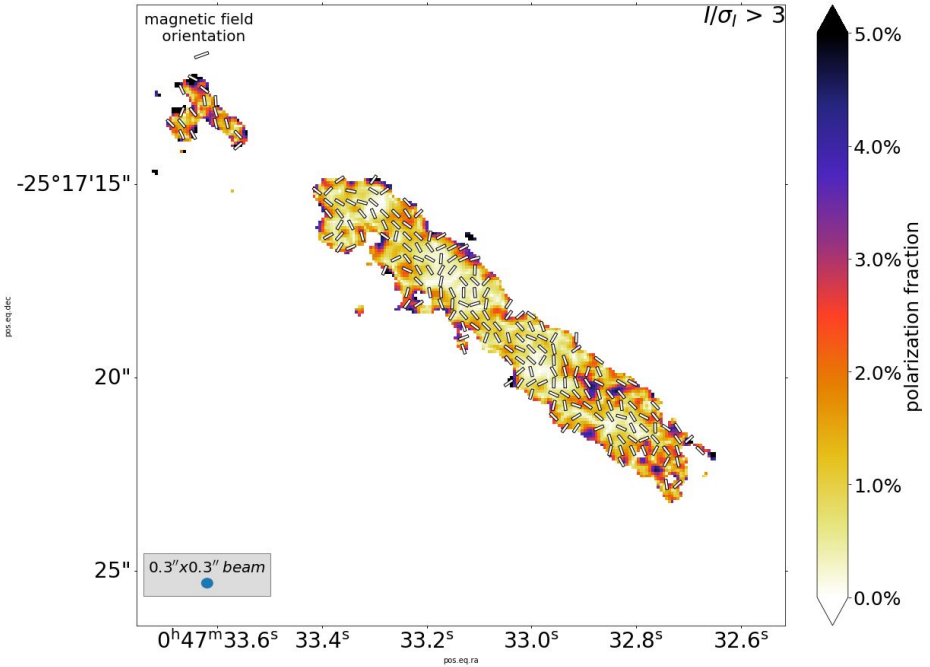
Polarization Fraction distribution



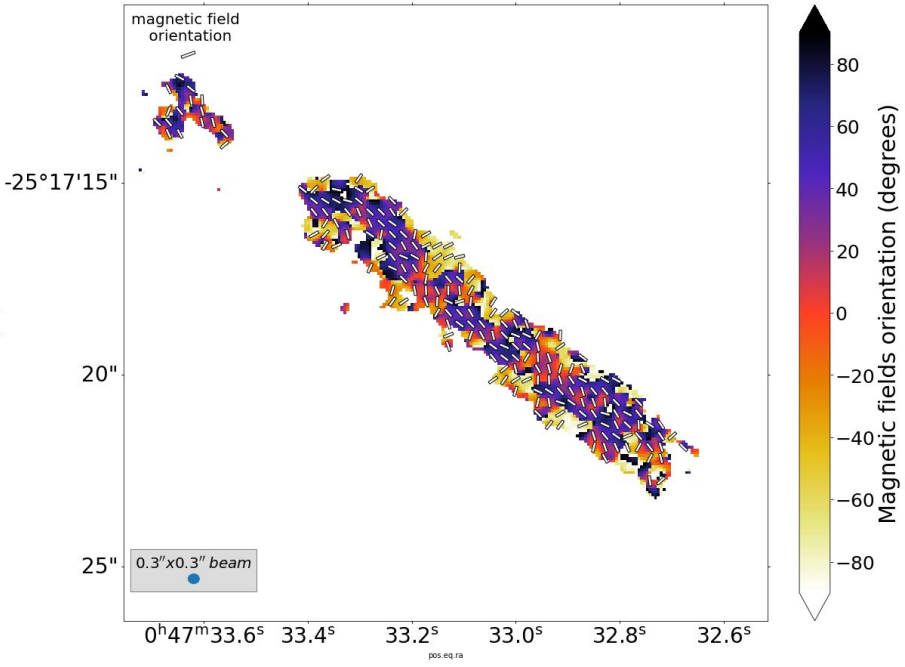
Band 7 (~ 350 GHz, ~ 0.5 pc)

Median PF ~ 1.1%

Polarization Fraction



Magnetic Field Orientation



Band 4 and Band 7 comparison

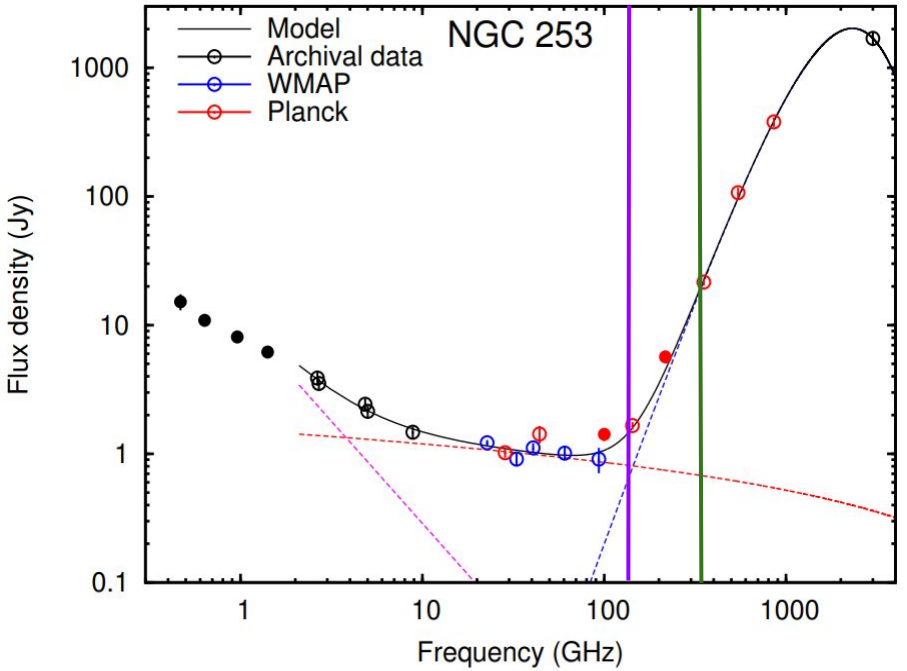
Band 4:

Frequency: ~ 150 GHz
Ang. Res: ~ 40 pc
PF: ~ 2.6 %

Band 7:

Frequency: ~ 350 GHz
Ang. Res: ~ 0.5 pc
PF: ~ 1.1 %

Total Intensity SED computed on the whole galaxy suggested a negligible synchrotron contribution at Band 4



Band 7
Band 4

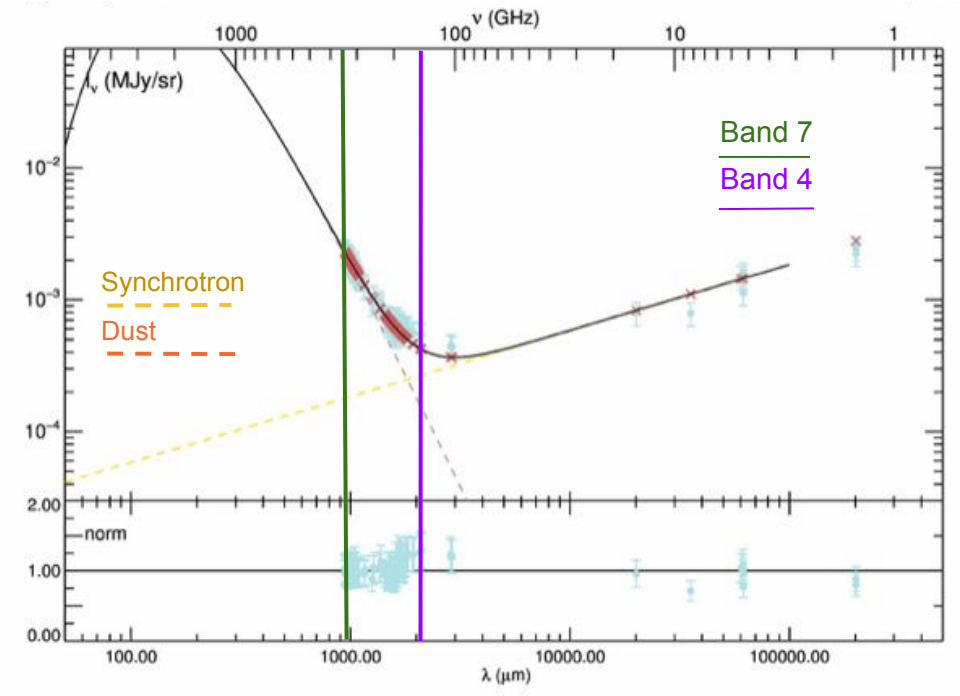
Peel+2011

Total Intensity SED analysis

Unexpected PF values in Band 4 and 7

Spectral energy distribution decomposition:

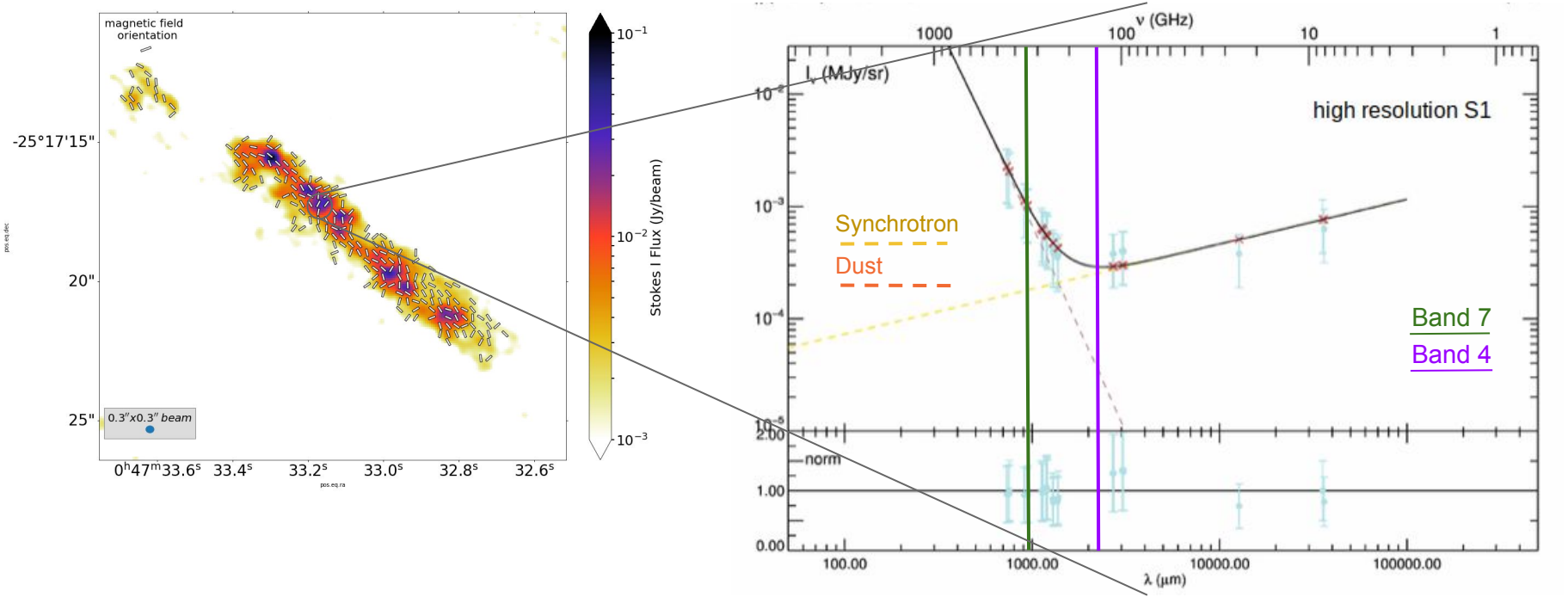
- Archival VLA and ALMA data
- Ang. Res. between 0.9″ and 2.2″
- Similar contribution of dust and synchrotron radiation at 150 GHz



Total Intensity SED analysis

High resolution archival data (Ang. Res. between 0.1″ and 0.5″)

SED in starcluster region **S1** (Leroy et al. 2018)

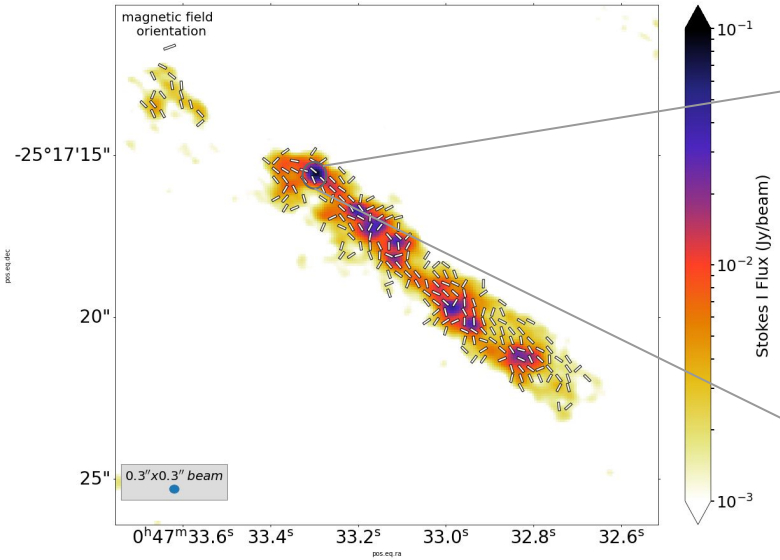


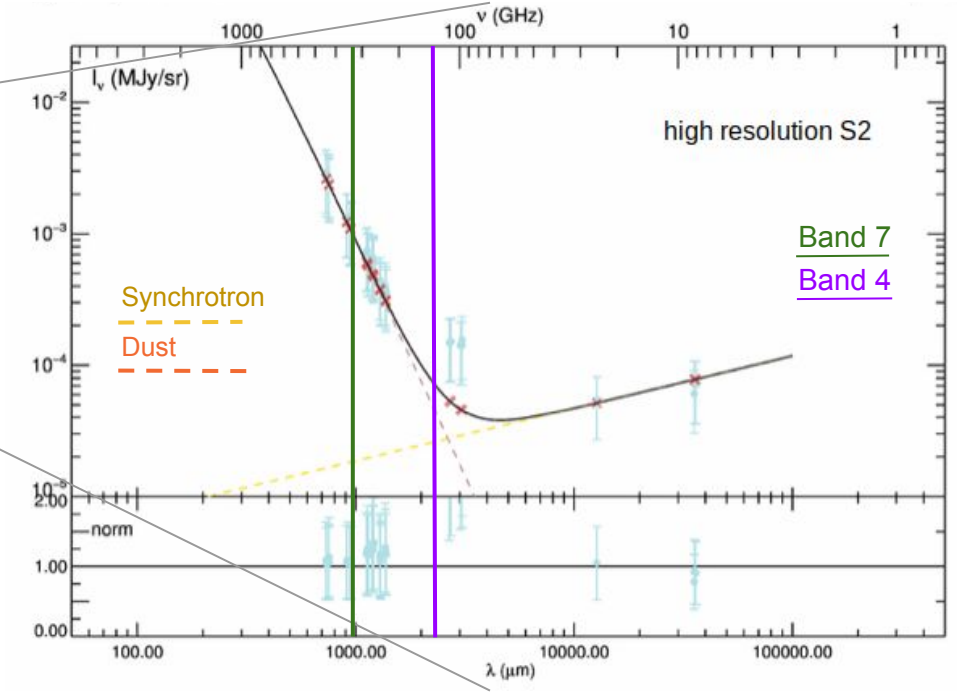
The fit of the S1 SED is very similar to the low-resolution one.

Total Intensity SED analysis

High resolution archival data (Ang. Res. between 0.1″ and 0.5″)

SED in starcluster region **S2** (Leroy et al. 2018)





Flatter synchrotron spectrum or even a free-free only spectrum

Bump at 100 GHz which is not easy to fit with the available data, giving the little frequency coverage in the range 10-100 GHz

Summary and conclusions

- Band 4 and Band 7 PF, PI, and PA map with relative pixel by pixel uncertainty map.
- Two main magnetic field orientations in Band 4.
    - one parallel to the disk, the other roughly orthogonal, possibly connected to the molecular outflows (further investigations ongoing).
- Band 7 PI show local maxima coincident with super starclusters.
- PF ~ 2.6 % for Band 4 and PF ~ 1.1% for Band 7
    - **Complex polarization emission in the starburst region**: While we can be confident that the B7 data is almost purely dust emission, at B4 the contribution of synchrotron and free-free is not negligible.

New high resolution ALMA observations requested