THE SPIRAL MAGNETIC FIELD OF NGC1068

ENRIQUE LOPEZ-RODRIGUEZ

Scientist at the Stratospheric Observatory for Infrared Astronomy (SOFIA)
NASA Ames Research Center, Moffett Field, CA

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Collaborators:

Dowell, C. D. (JPL)
Harper, D. A. (UofChicago)
Jones, T. J. (UofMinnesota)
Berthoud, M. (UofChicago)
Chuss, D. (Villanova U.)
Dale, D. A. (UofWyoming)
Guerra, J. A. (Villanova U.
Hamilton, R. (Lowell Observatory)
Looney, L. W. (UofIllinois)
Michail, J. M. (Northwestern U.)
Nikutta, R. (NOAO)
Novak, G. (Northwestern U.)
Santos, F. P. (Max Planck Institute)
Sheth, K. (NASA)
Siah, J. (Villanova U.)
Staguhn, J. (NASA)
Stephens, I. W. (CfA-Harvard)
Tassis, K. (UofCrete)
Trinh, C. (SOFIA)
Ward-Thompson, D. (UofCentralLansashire)
Werner, M. (JPL)
Wollack, E. J. (NASA)
Zweibel, E. G. (UofWisconsin)
and
HAWC+ Science Team

ROLE OF MAGNETIC FIELDS IN GALAXIES

Main goal: Study the role of magnetic fields in the interstellar medium of nearby galaxies

Magnetic fields play important roles in:

- **dynamical evolution of the interstellar medium of galaxies,**
- **processes governing formation of stars, and**
- **dynamical evolution of galaxies.**

What is the geometry of these large-scale magnetic fields?
What are the dominant physical mechanisms of these large-scale magnetic fields?

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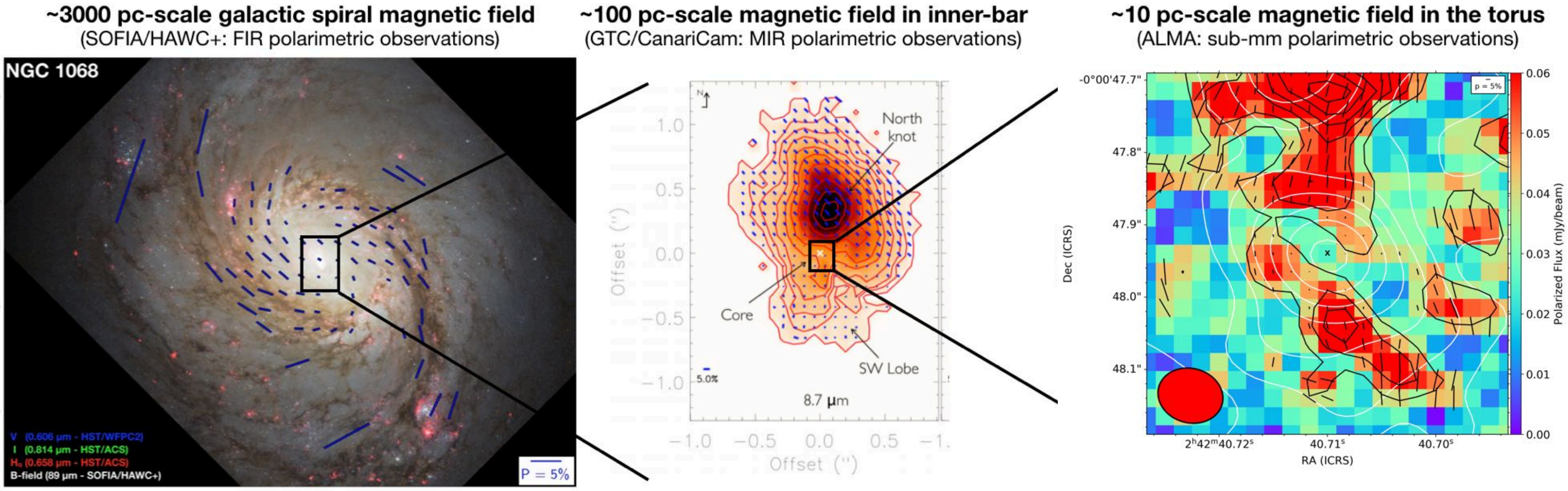
What is the geometry of these large-scale magnetic fields?
What are the dominant physical mechanisms of these large-scale magnetic fields?

IR-submm polarimetry has shown to be a powerful tool to study B-fields.



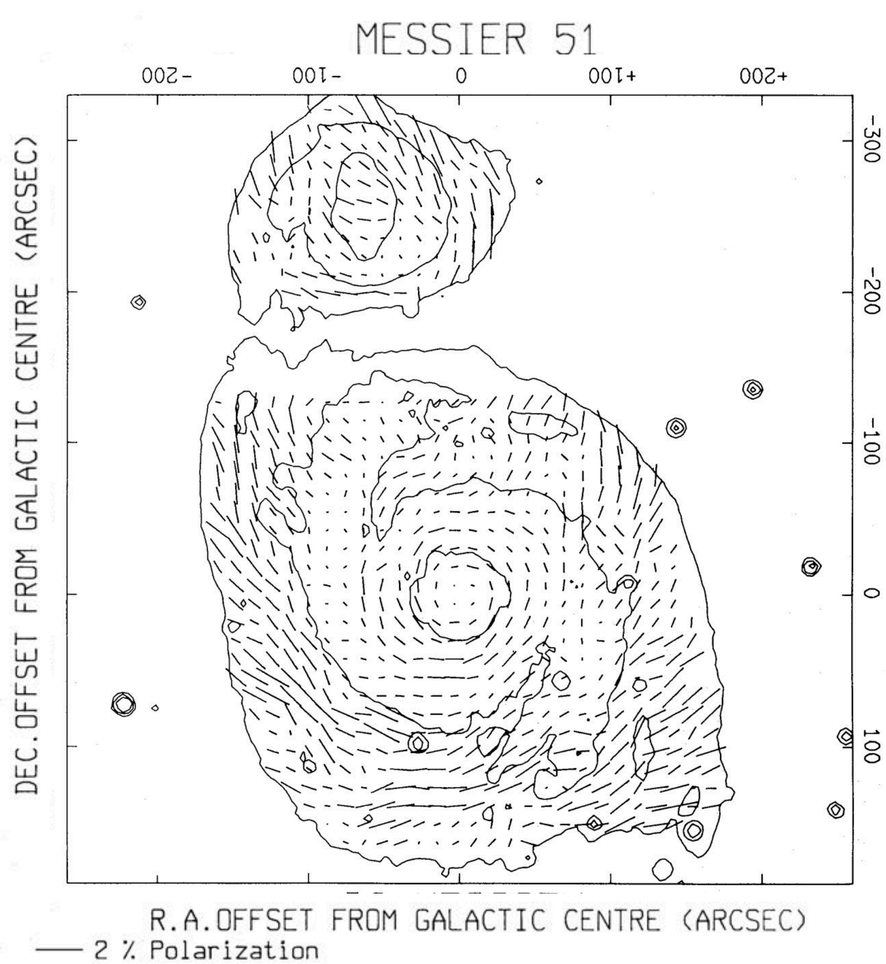
Lopez-Rodriguez et al. 2019a — Lopez-Rodriguez et al. 2015 — Lopez-Rodriguez et al. 2019b

Example:

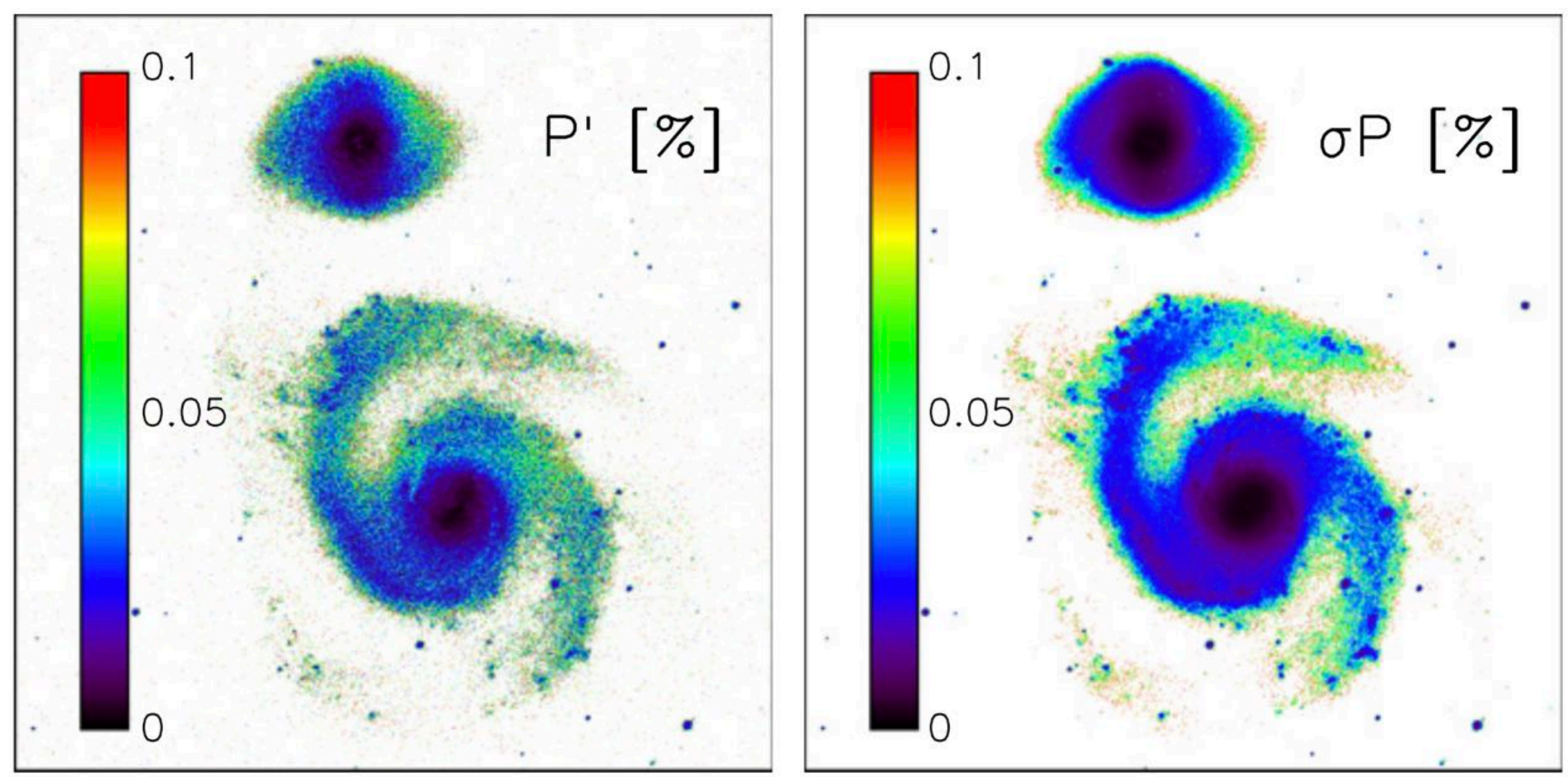
- M51 at optical shows an almost azimuthal polarization pattern with P<2% (Scarott et al. 1987)
- M51 at H-band shows P<0.05% across the host galaxy (Pavel et al. 2012))

The combination of Optical and NIR rules out a dichroic absorption polarization origin.

Optical-NIR polarimetry mainly suffers from dust/electron scattering.



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



Pavel & Clemens (2012)

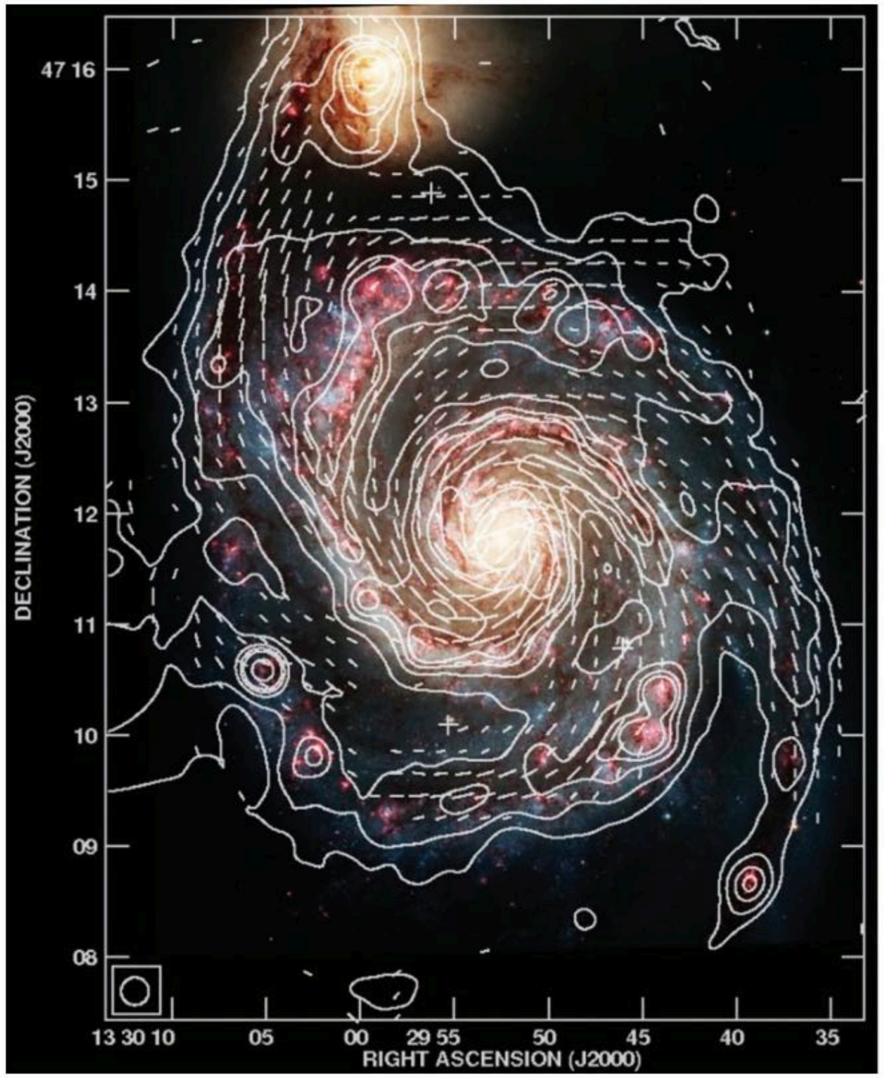
MAGNETIC FIELDS INFERRED BY POLARIMETRIC TECHNIQUES: RADIO

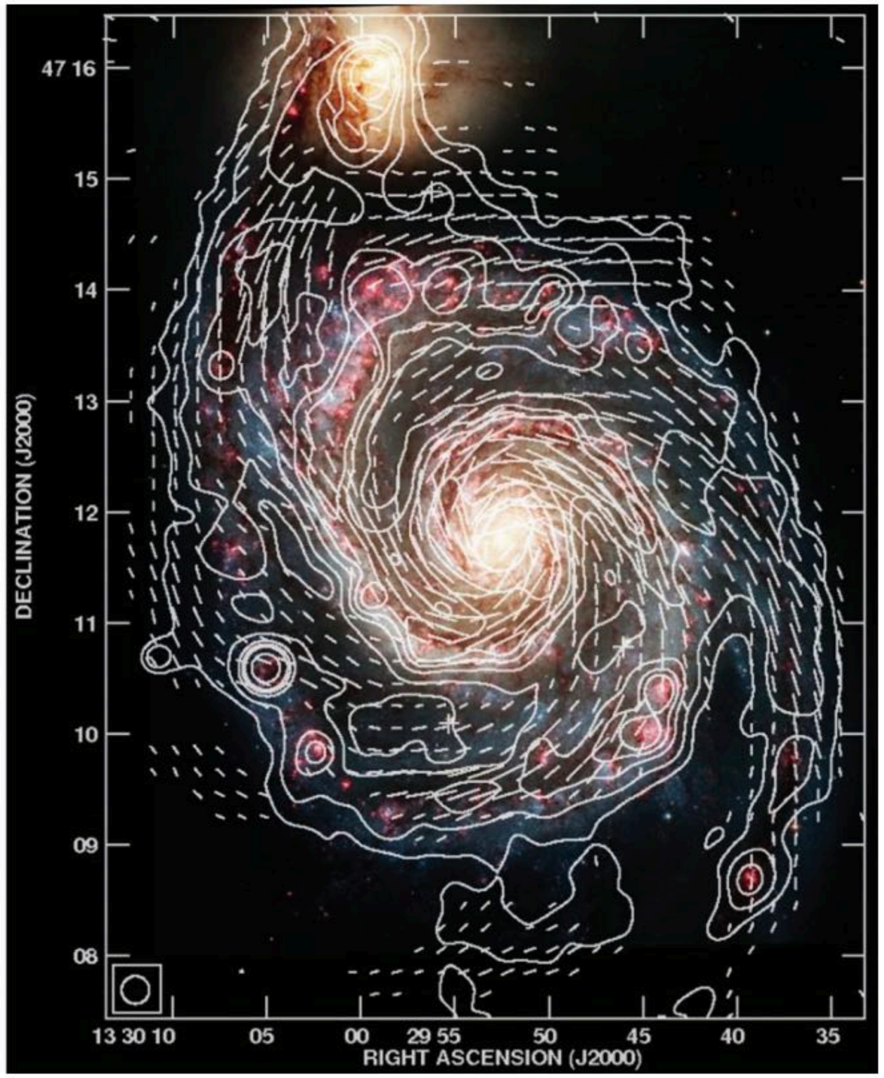
In the radio wavelength, the emission arises from non-thermal physical processes.

- Radio observations at cm measure the synchrotron radiation in the diffuse ISM from relativistic electrons (sensitive to the cosmic ray electron population).
- Radio polarimetry traces the magnetic fields 'illuminated' by relativistic electrons.

Example:

- M51 at radio cm wavelengths shows large-scale spiral magnetic fields (Fletcher et al. 2011)





Fletcher et al. (2011)

Optical-NIR polarization suffer of dust/scattering polarization

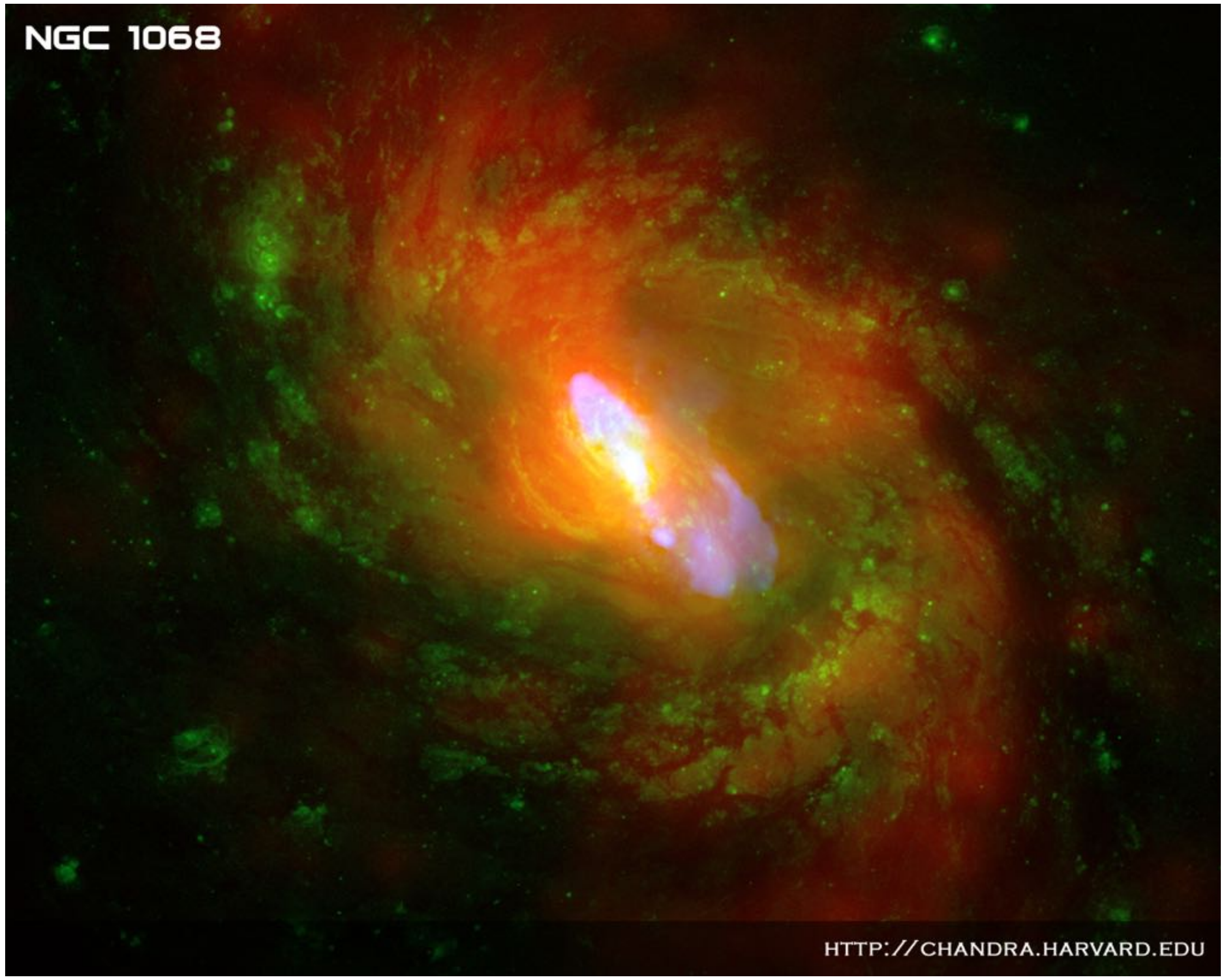
Radio wavelength traces the diffuse ISM and samples the relativistic electrons.

- Faraday rotation needs to be taken into account.

FIR wavelengths:

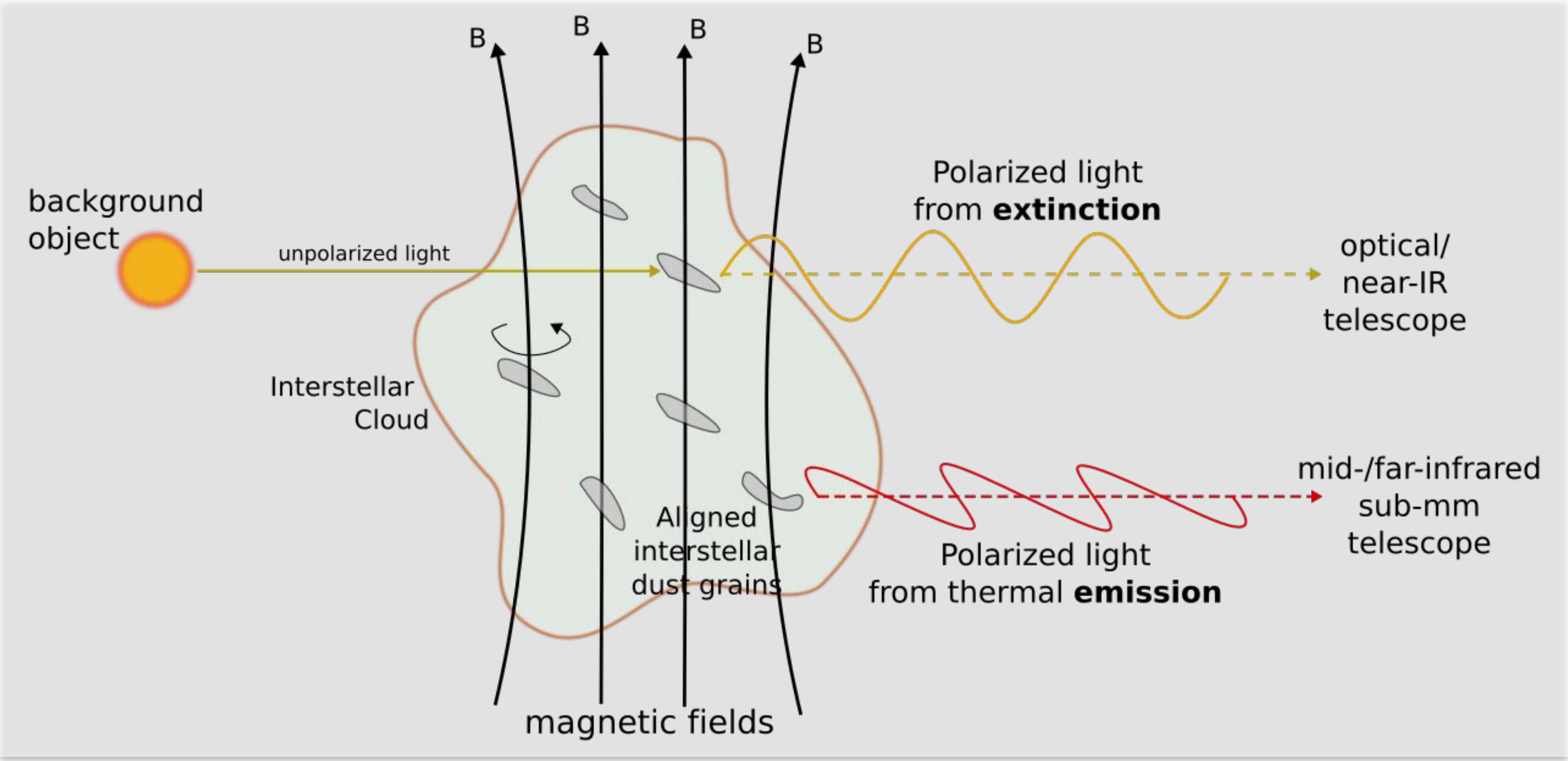
- Sensitive to temperature (helps to separate regions along the LOS)
- Traces the total gas and dust in the dense ISM.

The influence of magnetic field in the dust at several galactic scales is investigated using FIR polarimetric observations



UNDERSTANDING POLARIZATION ARISING BY MAGNETICALLY ALIGNED DUST GRAINS

Magnetic field can induce a preferential orientation of dust grains



Credit: Santos F.

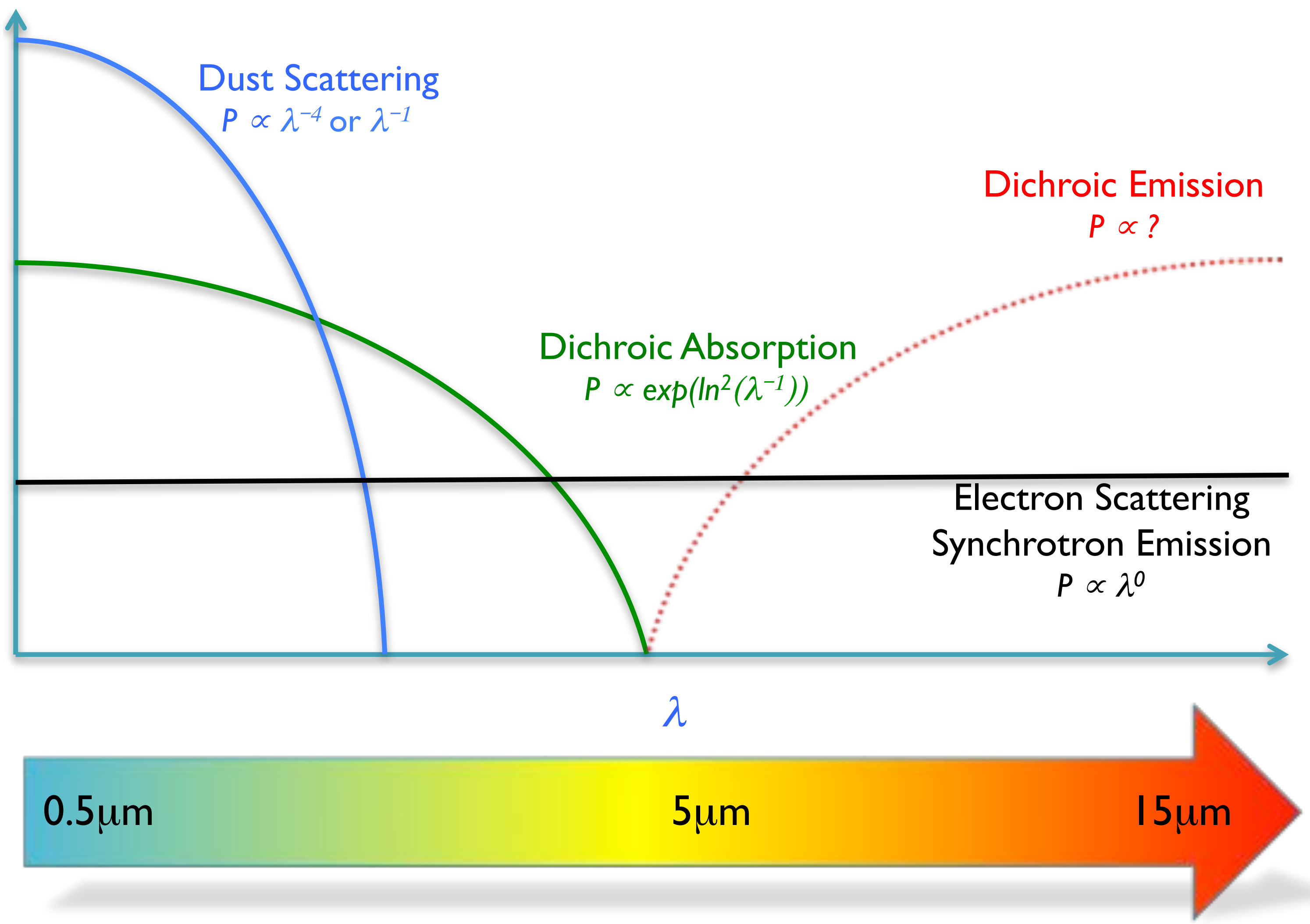
The PA of polarization from emission is perpendicular to the PA of polarization from extinction

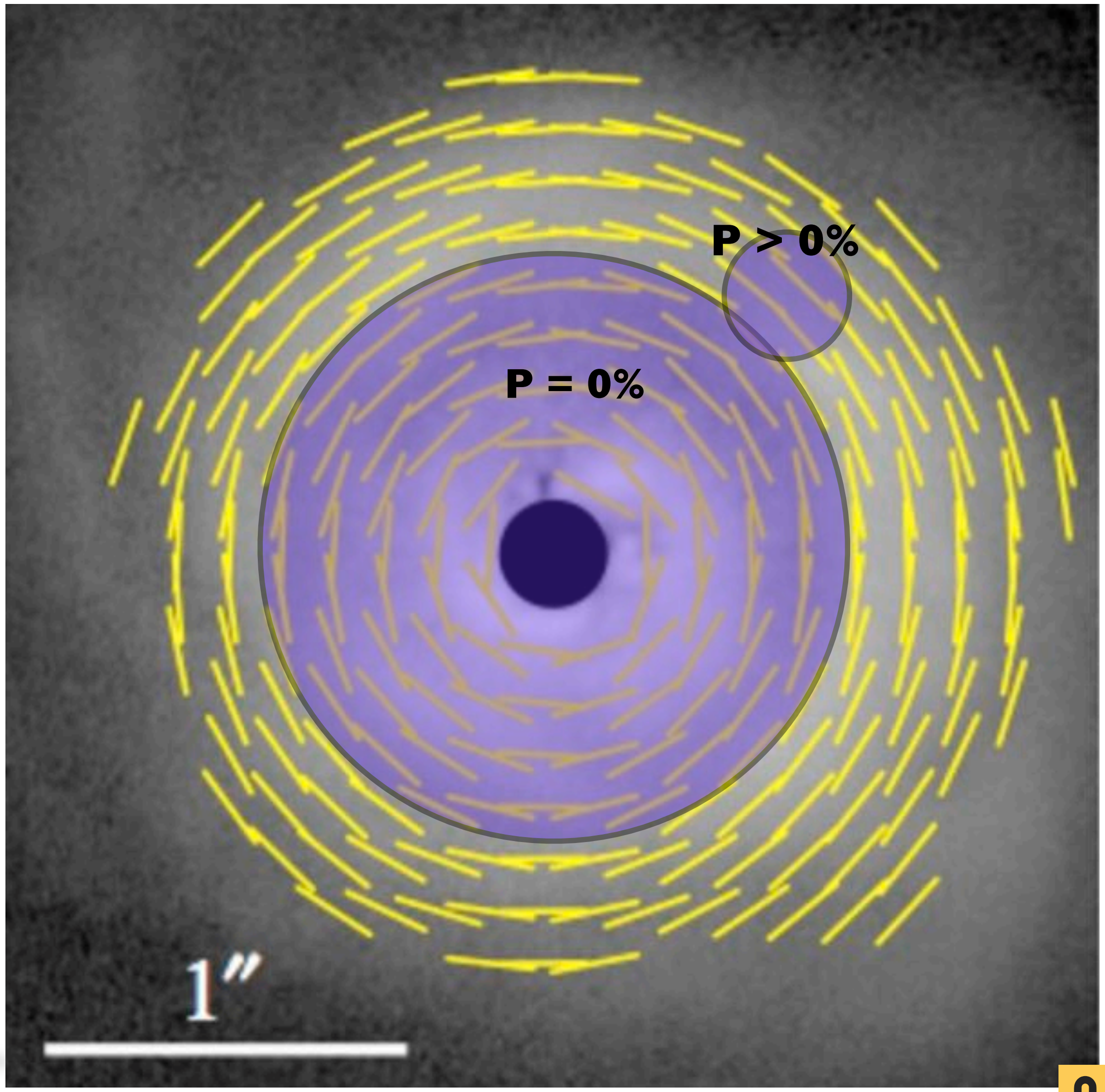
***Disclaimer: dust grain alignment theory can get very complex, we can talk later about the details.

We need:

- FIR observations to trace the polarized emission by magnetically aligned aligned dust grains.

- High-spatial resolution observations to obtain sensitive polarimetric measurements

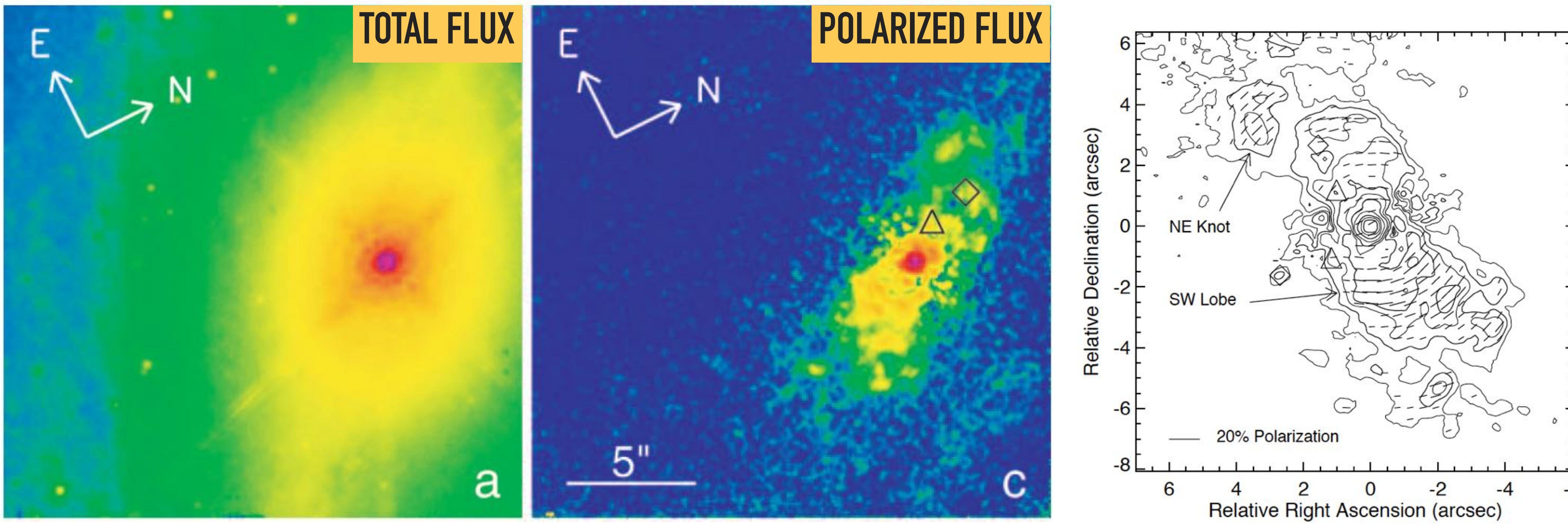




NGC 1068: NEAR-IR IMAGING POLARIMETRY

If dust grains are aligned, then we should measure some level of polarization and infer the B-field morphology.

HST/NICMOS 2 um



Simpson et al. (2002)

Polarization enhances the observed emission in the ionization cones and core

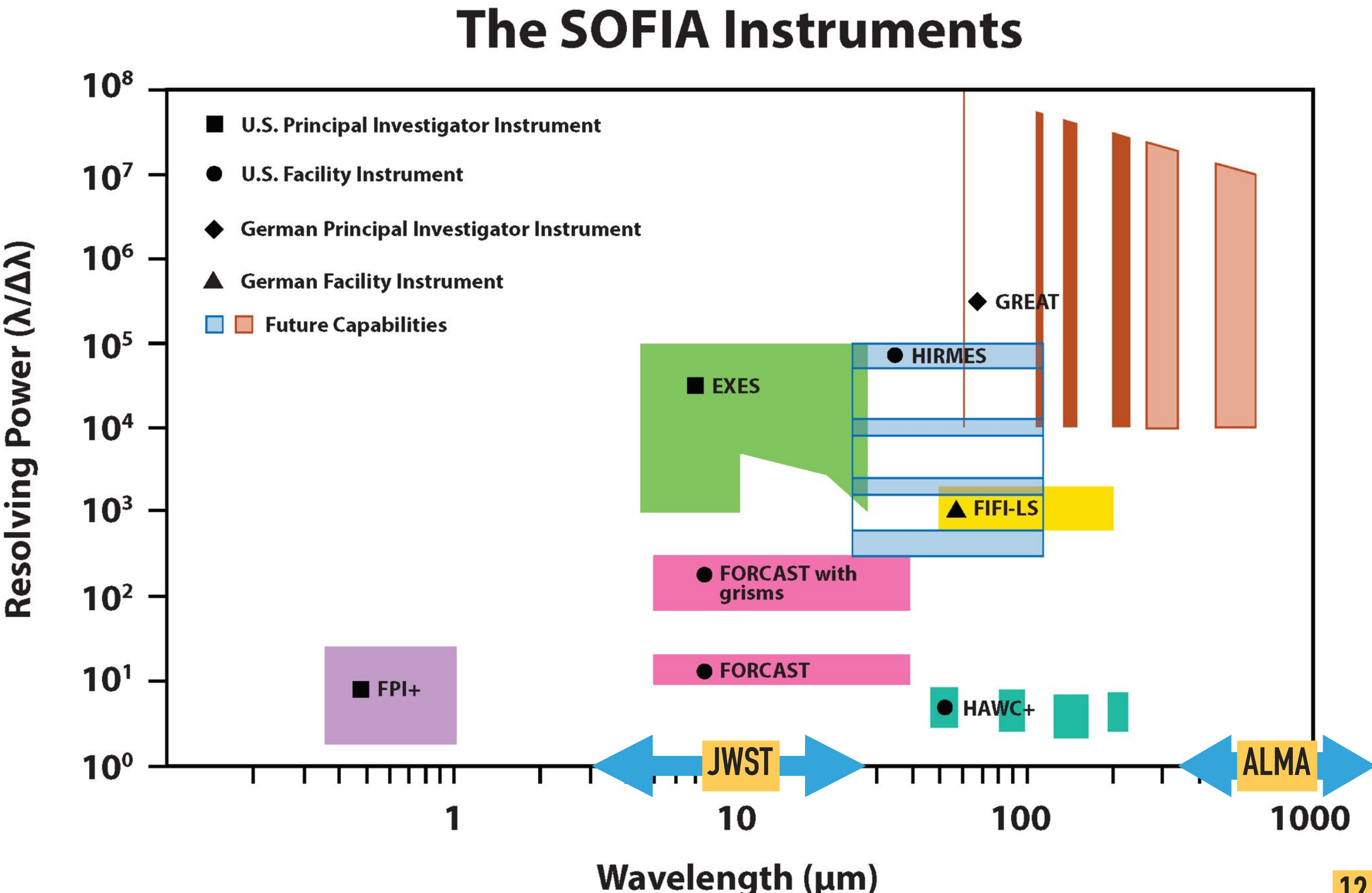
Ionization cone: dust scattering

Core: dichroic absorption

INSTRUMENTATION

SOFIA/HAWC+

SOFIA: 2.7-m telescope
WAVELENGTH RANGE: 0.3-300 microns
INSTRUMENTS: 7 First generation instruments: cameras, spectrometers & high-spectrometers. New instrument: imager-polarimeter at 50-200 microns (HAWC+)
AIRSPEED: Mach 0.85 (560 mph ~ 901 kmh)
OBSERVING ALTITUDE: 37,000 - 45,000 ft
ONBOARD STAFF: Flight crew 3; Mission crew 2-6, Scientist 1-3, Educators 5-15
AVERAGE SCIENCE FLIGHT LENGTH: 10 hours overnight


The SOFIA Instruments
Resolving Power (λ/Δλ)
Wavelength (µm)
U.S. Principal Investigator Instrument
U.S. Facility Instrument
German Principal Investigator Instrument
German Facility Instrument
Future Capabilities
GREAT
HIRMES
EXES
FIFI-LS
FORCAST with grisms
FORCAST
FPI+
HAWC+
JWST
ALMA
10⁸
10⁷
10⁶
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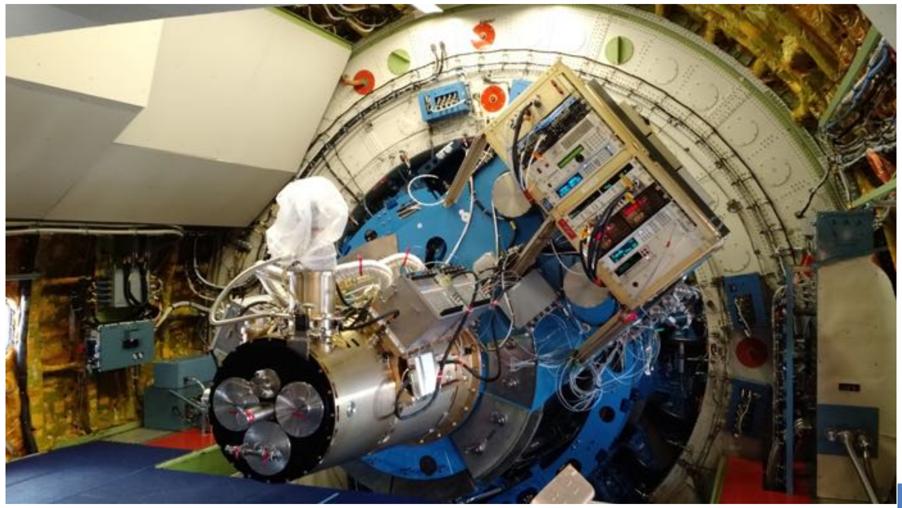
10⁰
1
10
100
1000

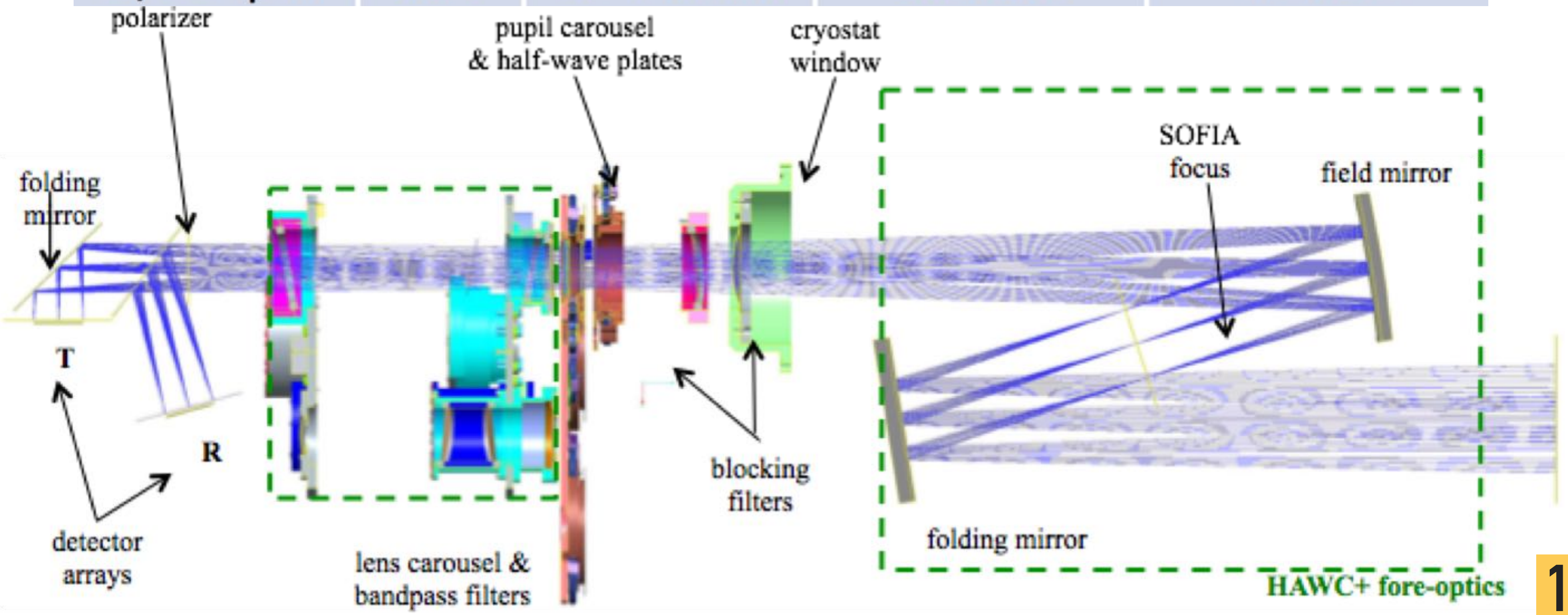


PI: Darren Dowell (JPL)

The far-infrared emission, detected by HAWC+, samples different dust temperatures in the range of 10K to 100K.

HAWC+ observes **total** and **polarized** emission of dust grains at five different wavelengths in the range of 50-250 micrometers.

Band / Wavelength	Δλ/λ	Angular Resolution	Total Intensity FOV (arcmin)	Polarization FOV (arcmin)
A / 53 μm	0.17	4.7" FWHM	2.7 x 1.7	1.3 x 1.7
B[a] / 63 μm	0.15	5.8" FWHM	4.2 x 2.6	2.1 x 2.6
C / 89 μm	0.19	7.8" FWHM	4.2 x 2.6	2.1 x 2.6
D / 154 μm	0.22	14" FWHM	7.3 x 4.5	3.6 x 4.5
E / 214μm	0.20	19" FWHM	8.0 x 6.1	4.0 x 6.1



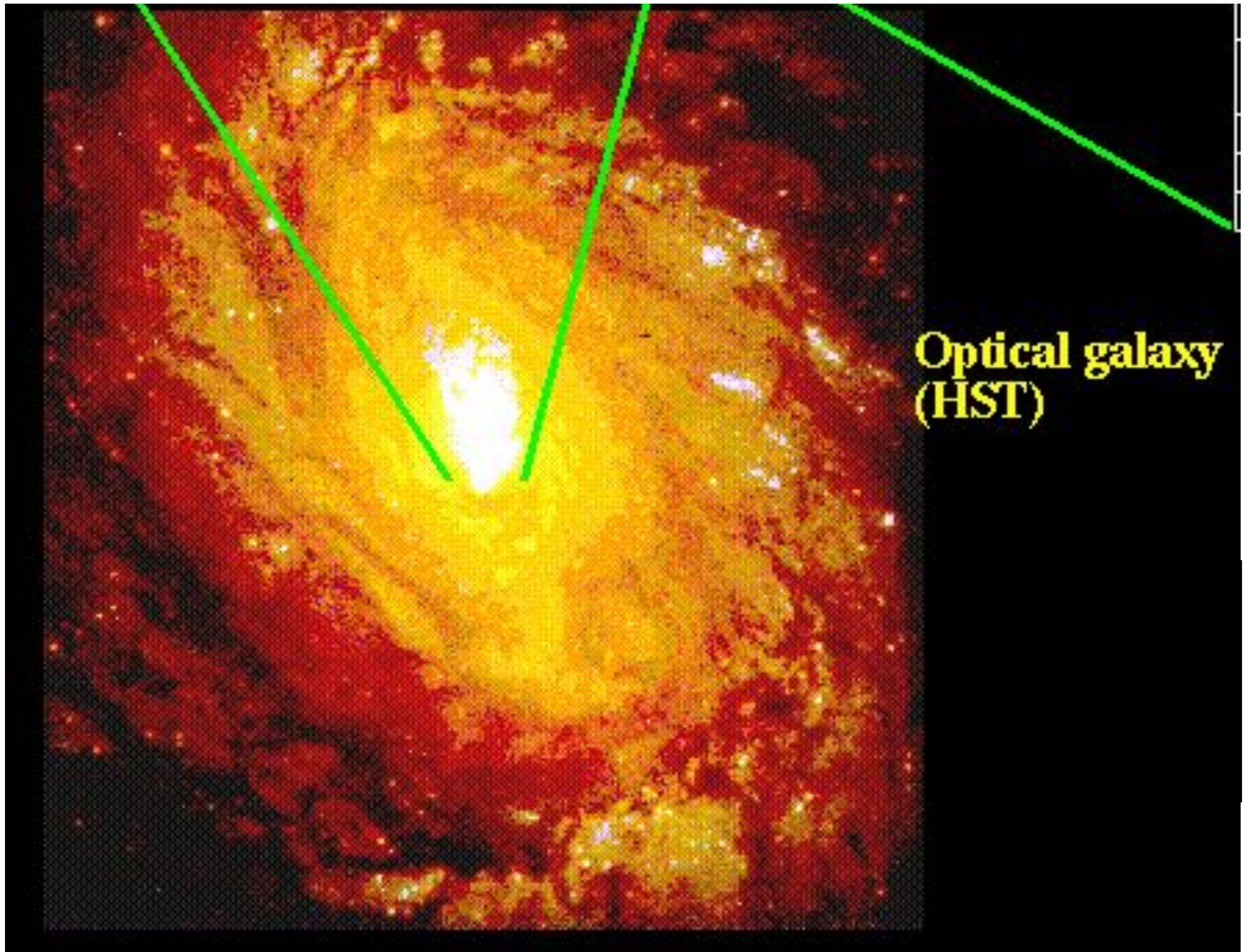
SOFIA POLARIMETRIC OBSERVATIONS OF NGC 1068

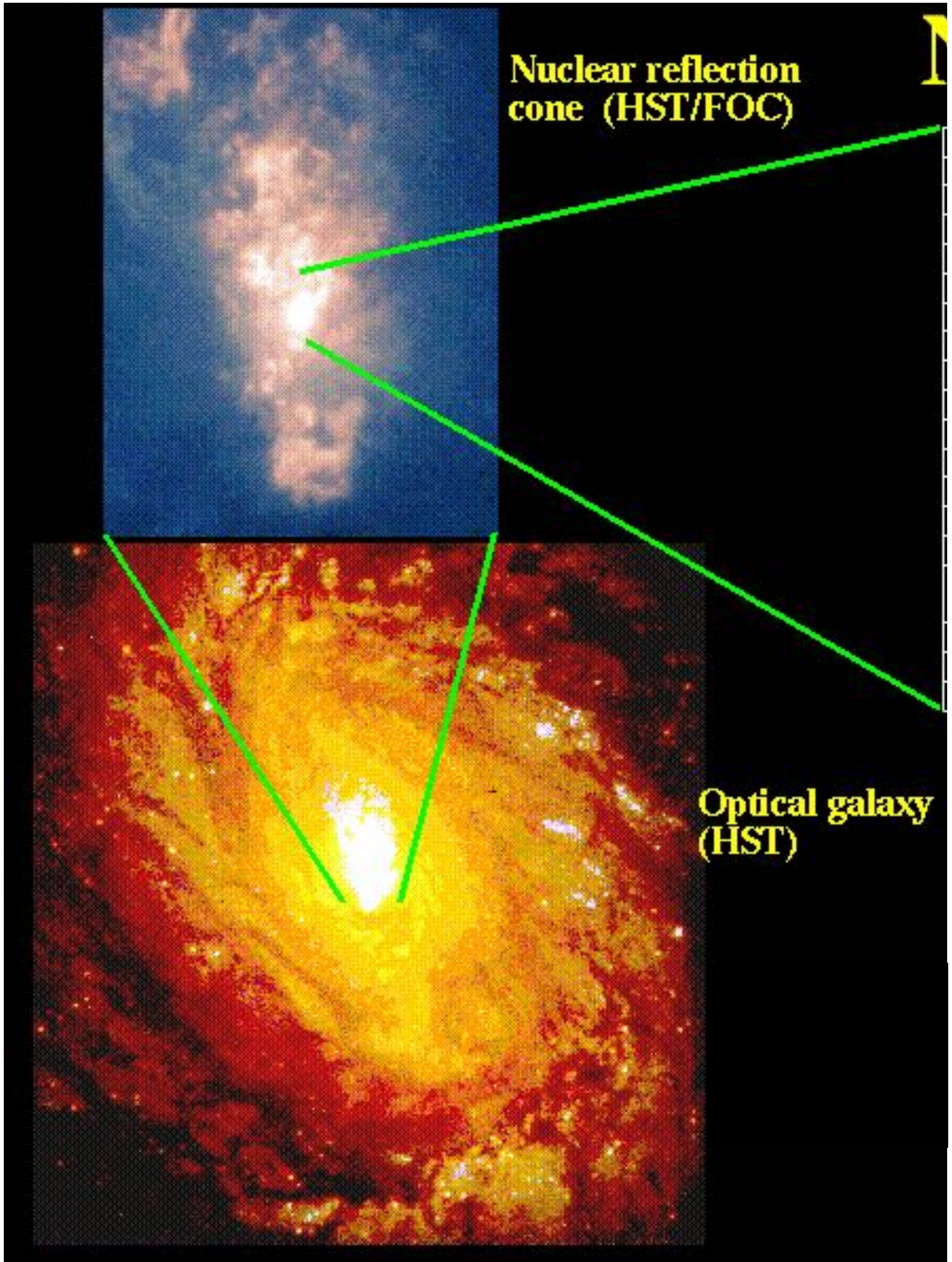
THE SPIRAL MAGNETIC FIELD

Lopez-Rodriguez et al. (2019b)

PHYSICAL STRUCTURES OF NGC 1068: HOST GALAXY

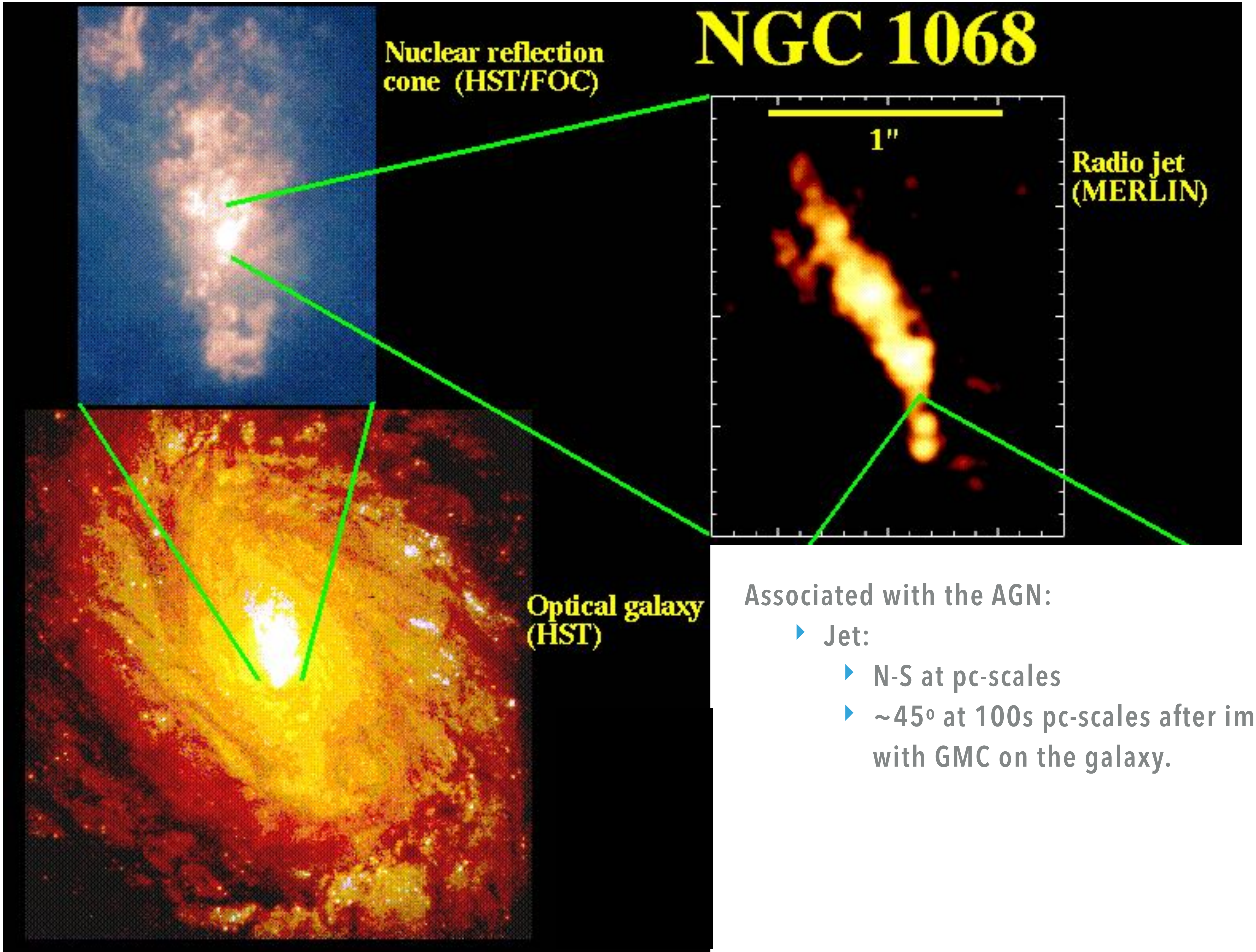
- Grand-design spiral galaxy at 13.5 Mpc (1″ = 65 pc)
  - Active galactic nuclei (Seyfert 2)
  - Circumnuclear starburst





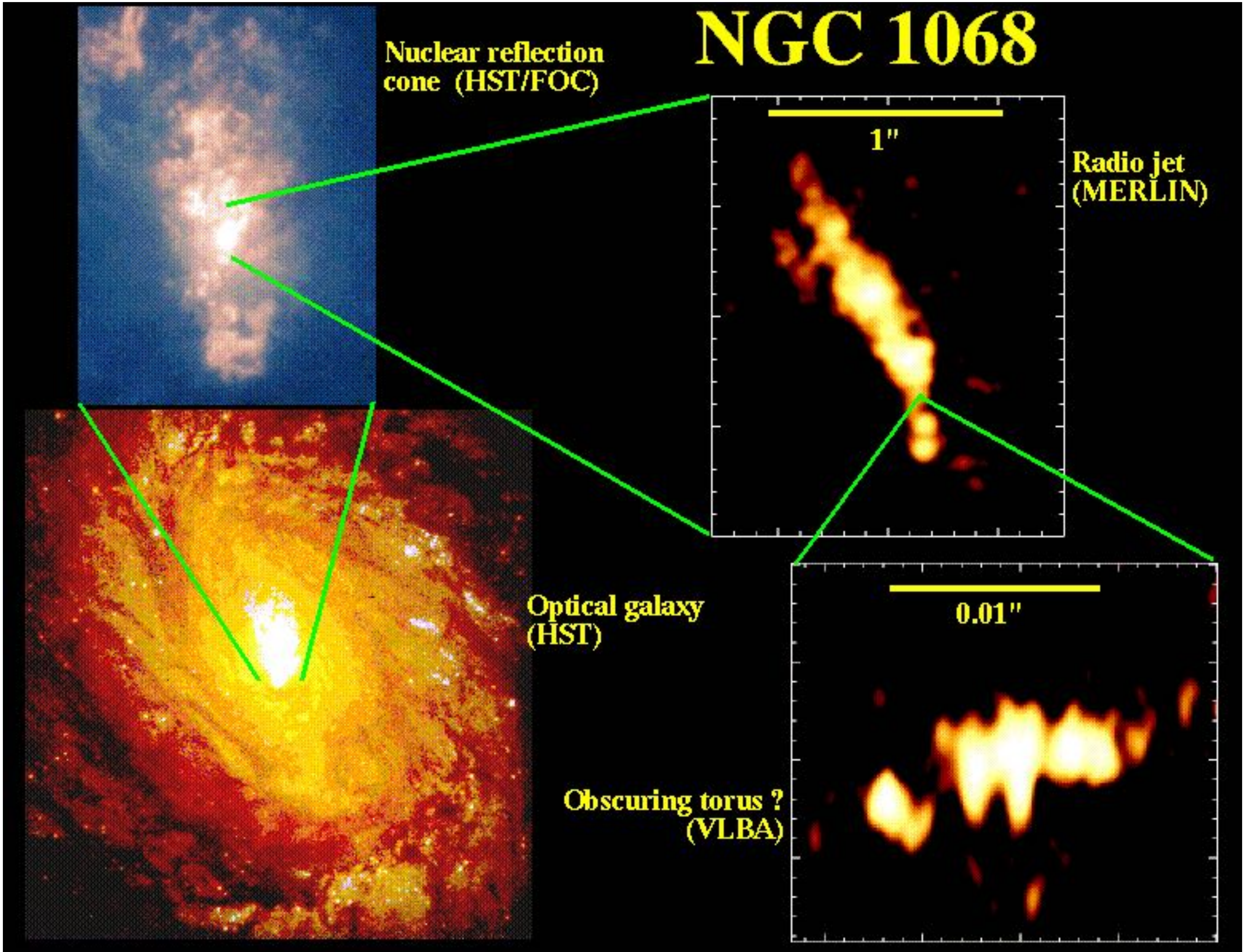
Associated with the AGN:

- Narrow line-region (ionization cone)
- ~1.3 kpc (20″) at PA~40°
- North protruding toward us out of the plane of the galaxy.



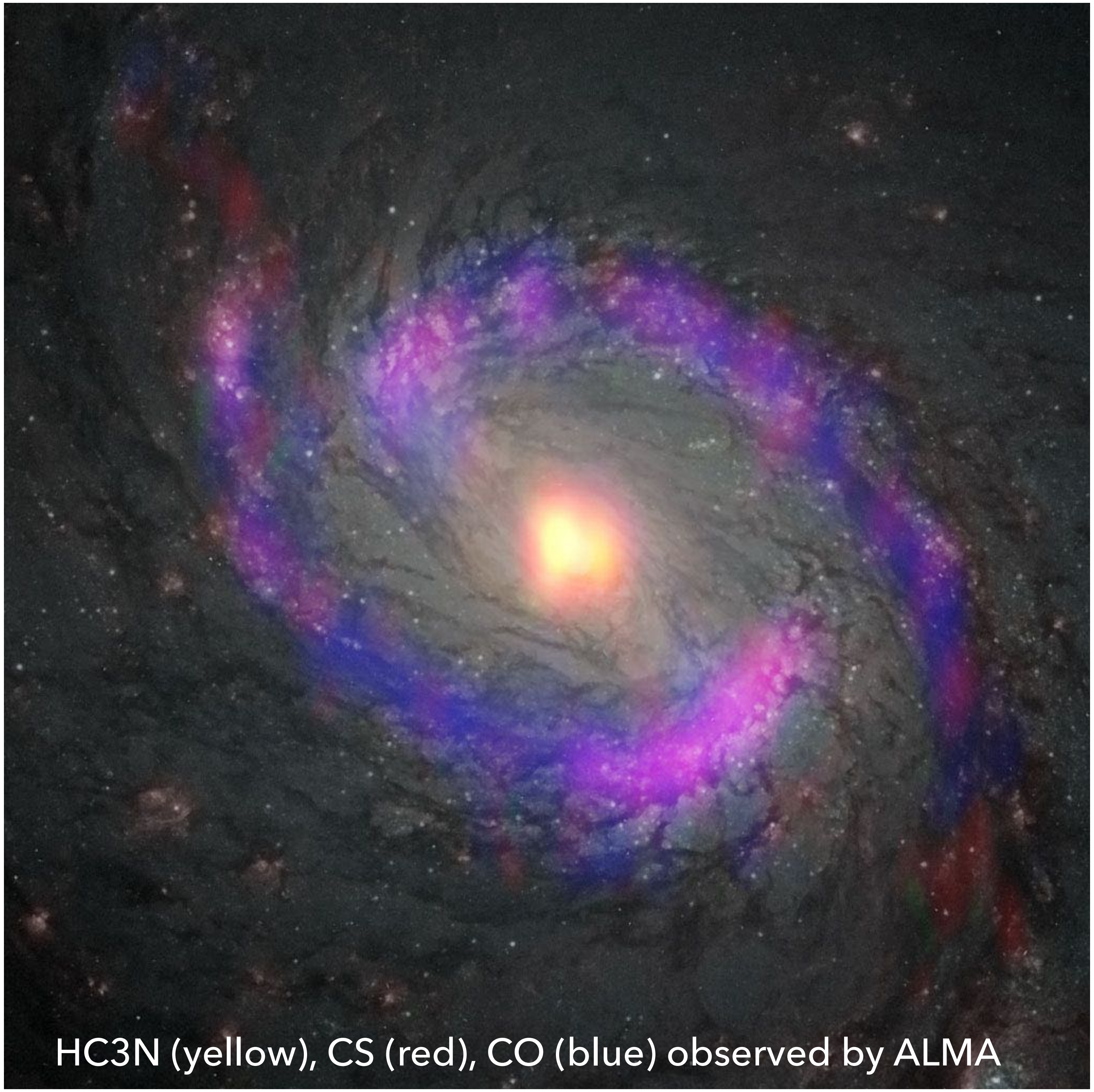
Associated with the AGN:

- Jet:
  - N-S at pc-scales
  - ~45º at 100s pc-scales after impact with GMC on the galaxy.


NGC 1068
Nuclear reflection cone (HST/FOC)
1"
Radio jet (MERLIN)
Optical galaxy (HST)
0.01"
Obscuring torus ? (VLBA)

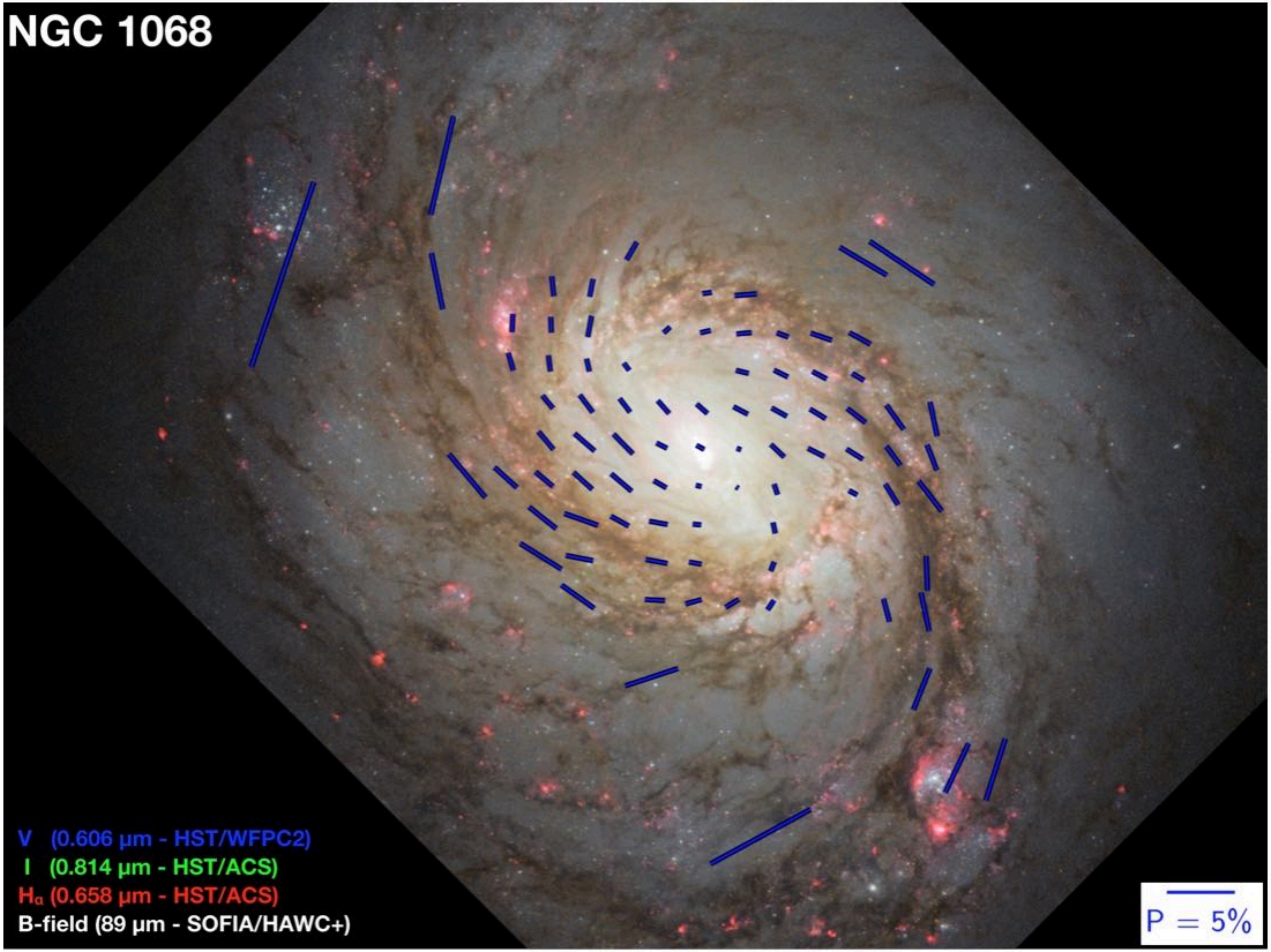
PHYSICAL STRUCTURES OF NGC 1068: CO STARBURST RING

- CO is mainly distributed in the starburst ring.
- HC3N is abundant in the CND
- CS is distributed both in CNS and starburst ring.


HC3N (yellow), CS (red), CO (blue) observed by ALMA

Takano et al. (2014)

HAWC+ 89 um OBSERVATIONS: RESULTS



SPIRAL MAGNETIC FIELD: AXISYMMETRIC SPIRAL STRUCTURE MODEL I

Logarithmic spiral B-field (Ψ: pitch angle):

$$B_x = -B_0(r)\sin(\phi + \Psi)\cos\chi(z)$$
$$B_y = B_0(r)\cos(\phi + \Psi)\cos\chi(z)$$
$$B_z = B_0(r)\sin\chi(z)$$

B-field viewed at inclination, i, and tilt, θ, angles:

$$B_{x^s} = B_x\cos\theta + (B_y\cos i - B_z\sin i)\sin\theta$$
$$B_{y^s} = -B_x\sin\theta + (B_y\cos i - B_z\sin i)\cos\theta$$
$$B_{z^s} = B_y\sin i + B_z\cos i$$

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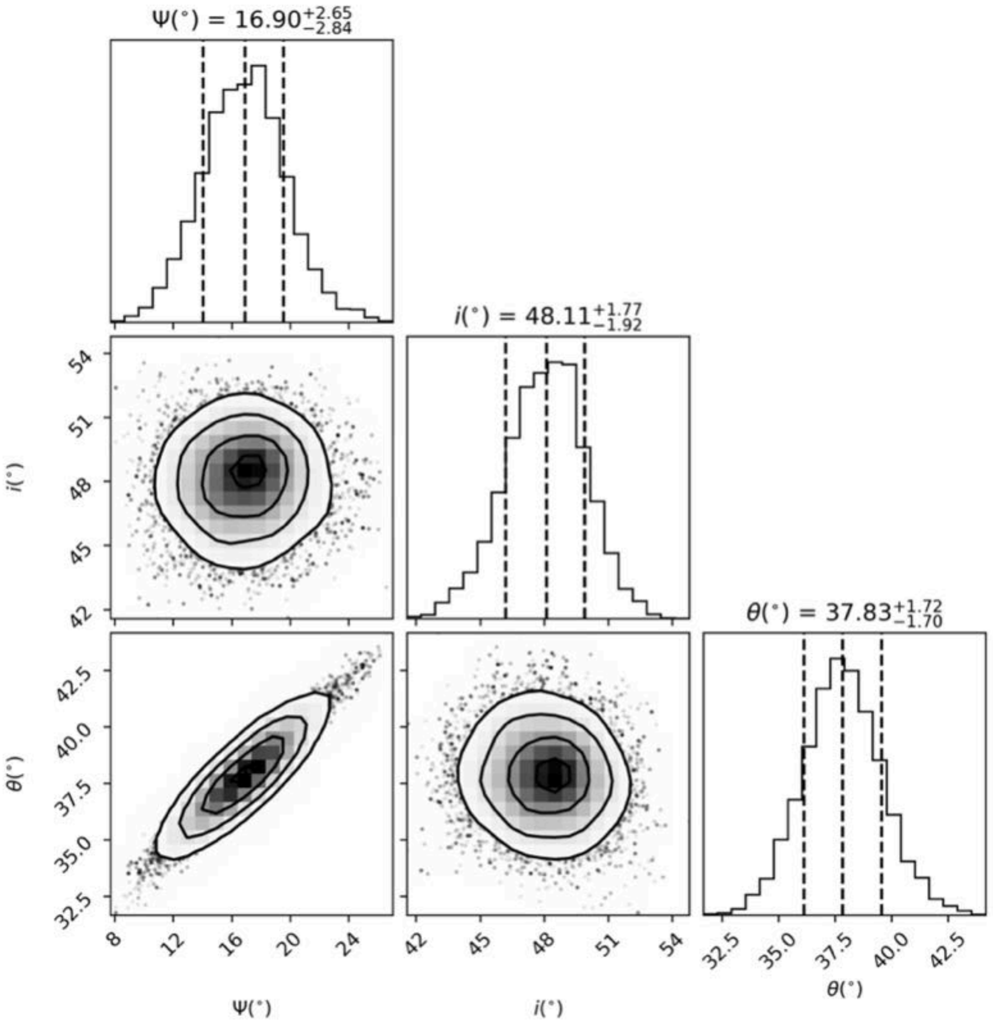
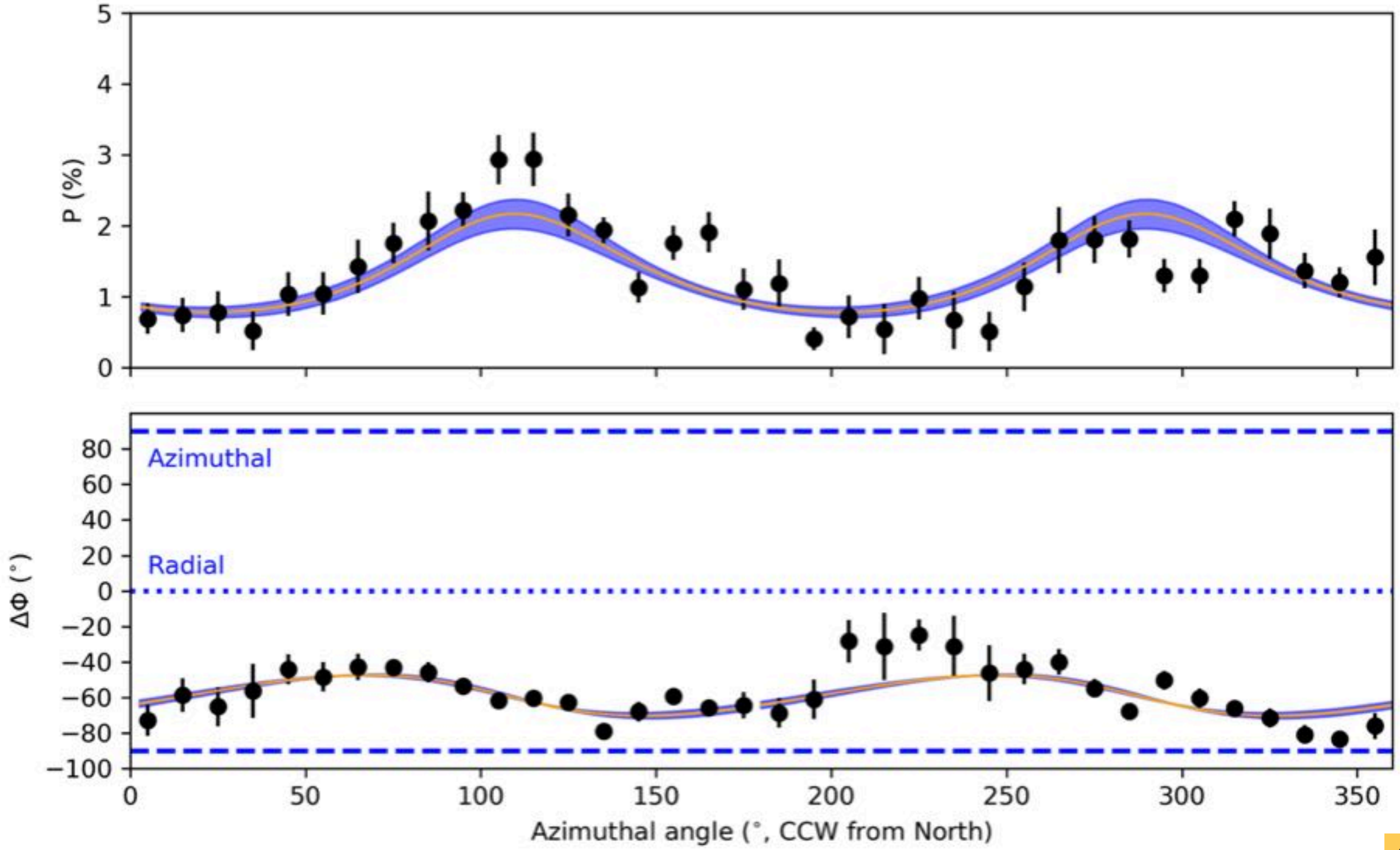
Bayesian inferred angles:

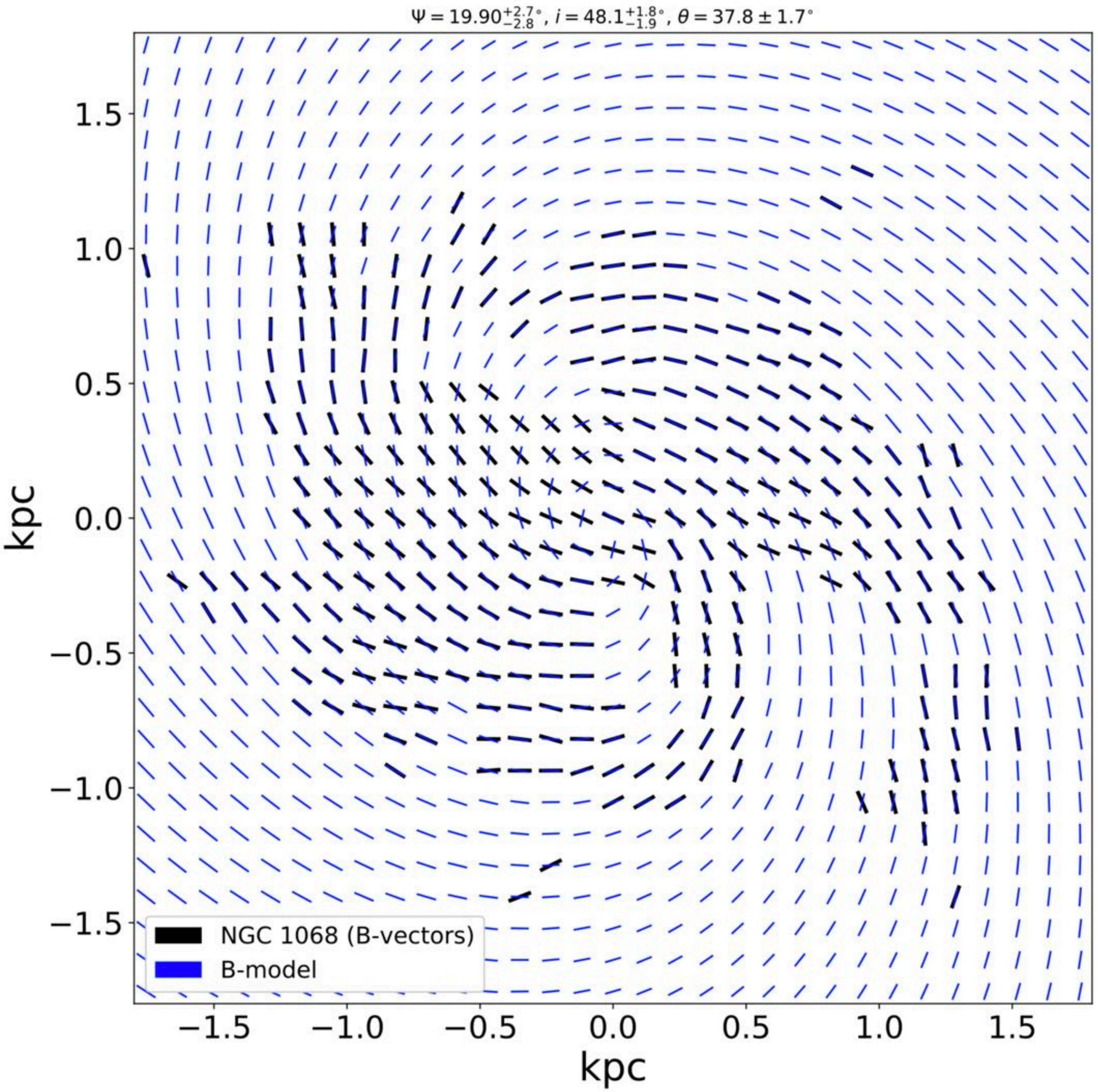


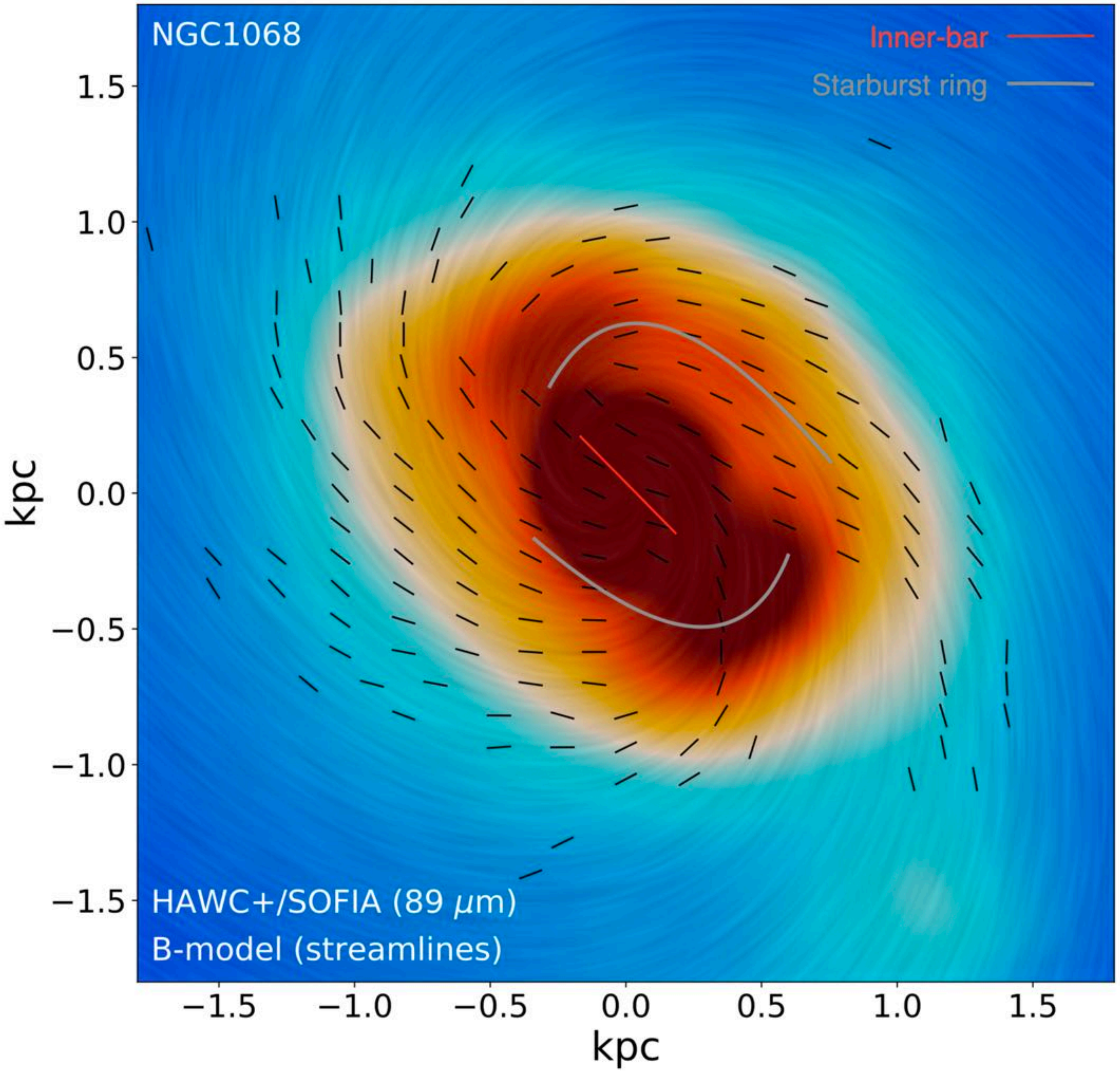
Best family of solutions:

- P and PA varies as a function of the azimuthal angle, which arises from the projection and inclination of the disk field component in the plane of the sky



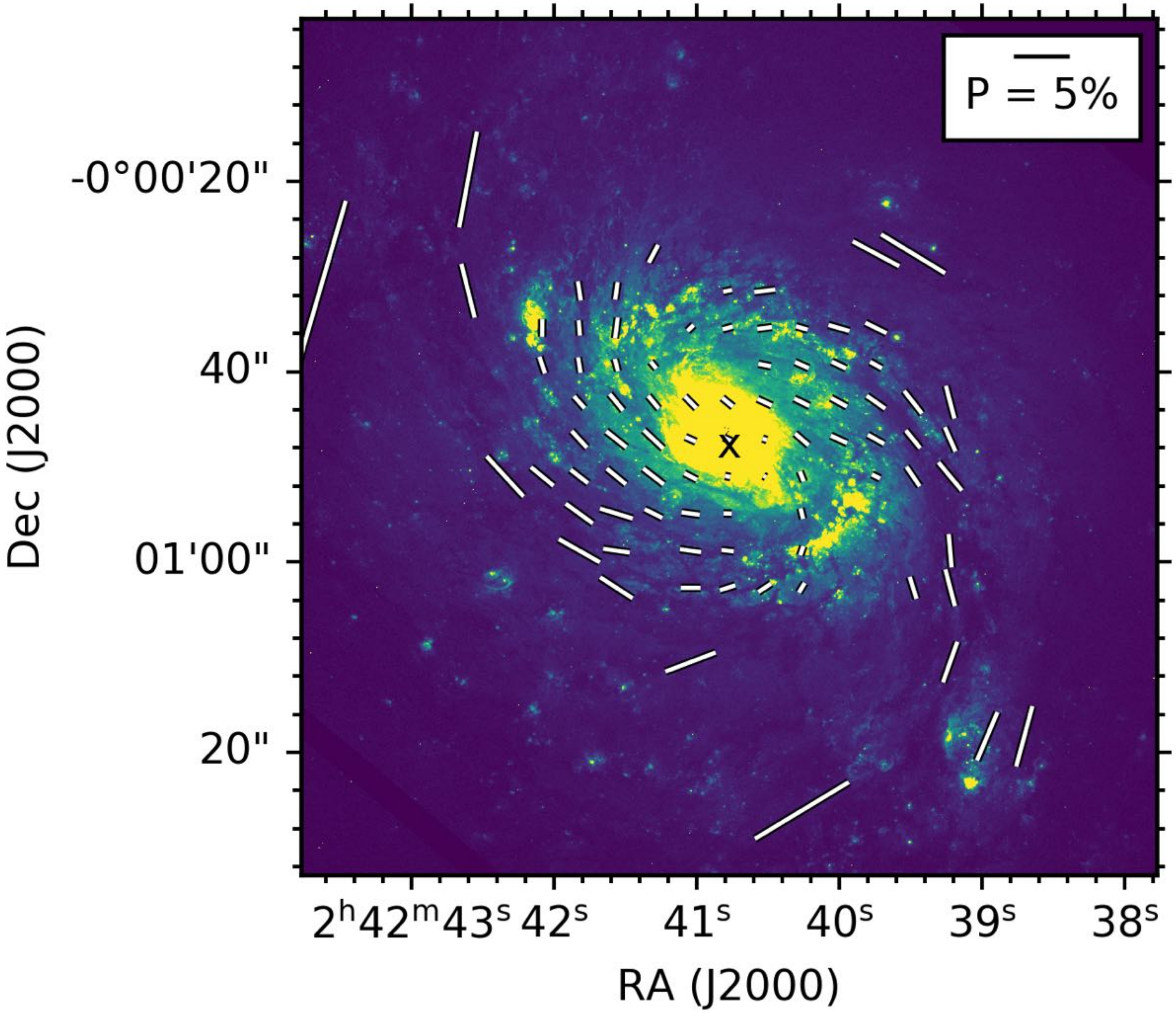
SPIRAL MAGNETIC FIELD: AXISYMMETRIC SPIRAL STRUCTURE MODEL II





89 um: The logarithmic spiral model traces the star-forming regions along the spiral arms.

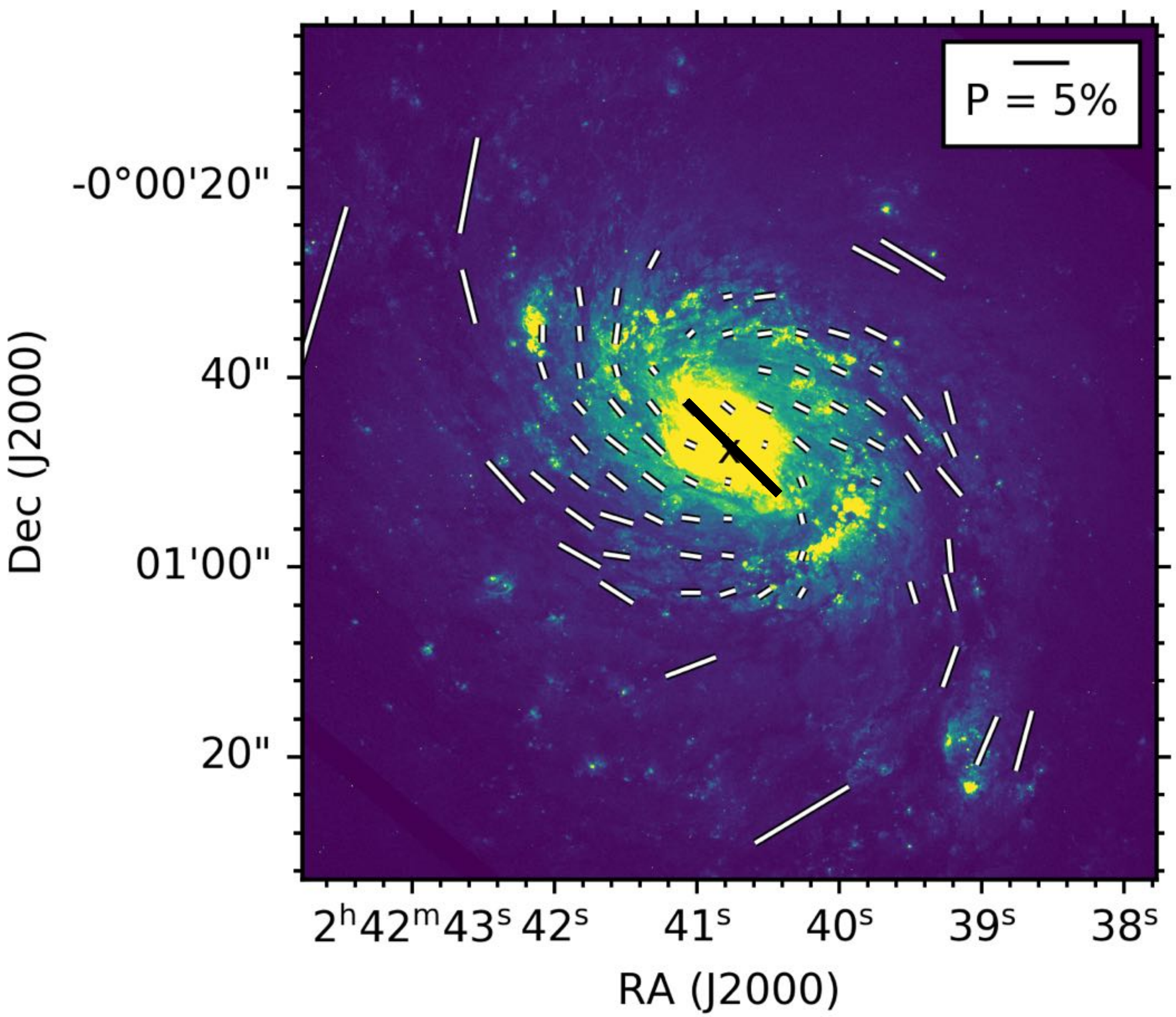
- Spiral between the optical at 0.46 um and the CO (J=1-0) emission (table).
- Spiral spatially coincident with the H_{α} velocity field and HII regions
    - HII regions were enhanced by a burst in the past 30 Myr (Davies, Sugai & Ward 1998)

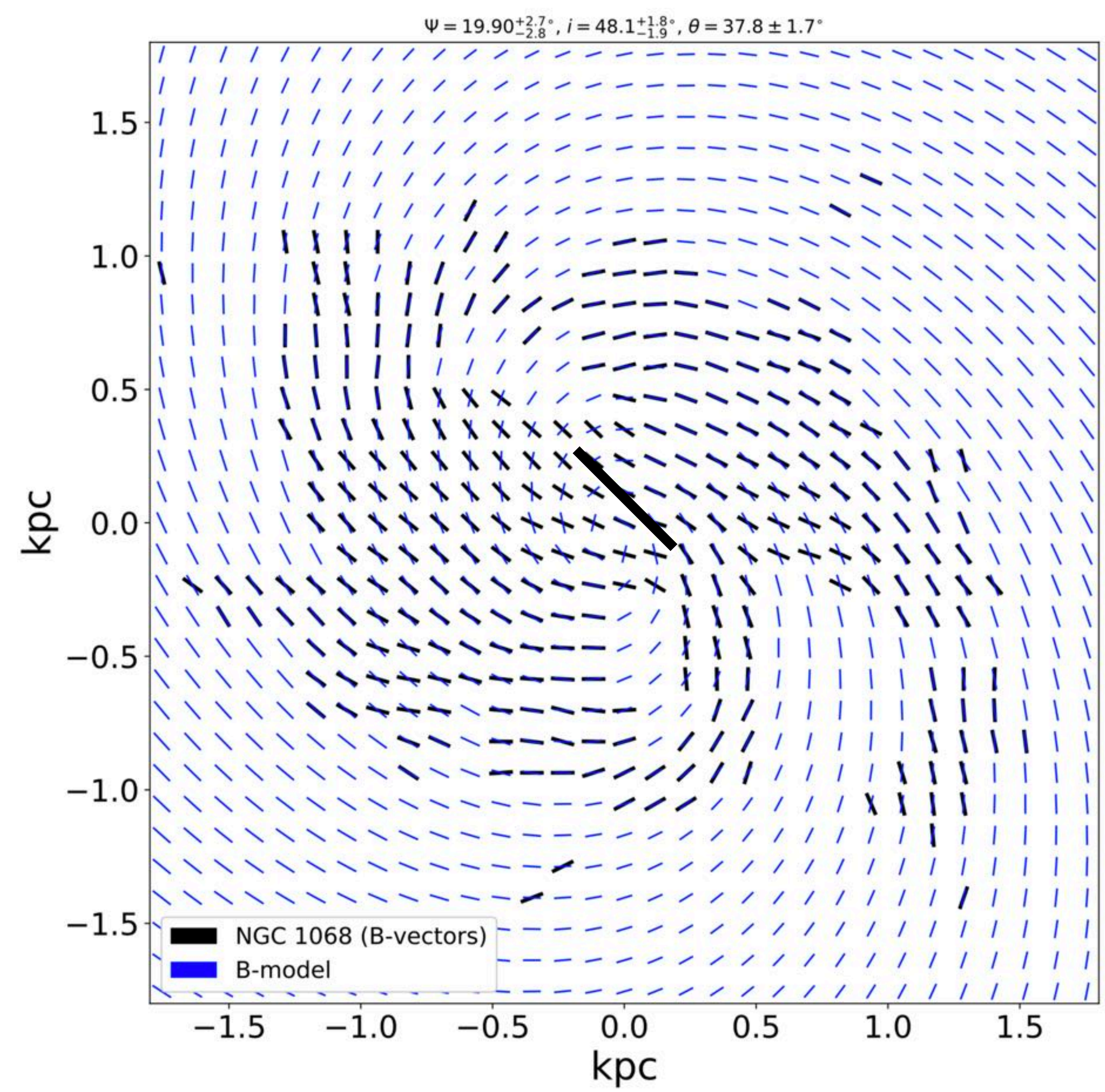


Tracer	Pitch angle (°)
0.46 um	20.6 ± 4.5°
R-band	17.3 ± 2.2°
Ha velocity field	15°
CO (J=1-0)	7-10°
89 um (HAWC+)	16.9 ± 2.8°

THE CENTRAL REGION: INNER-BAR

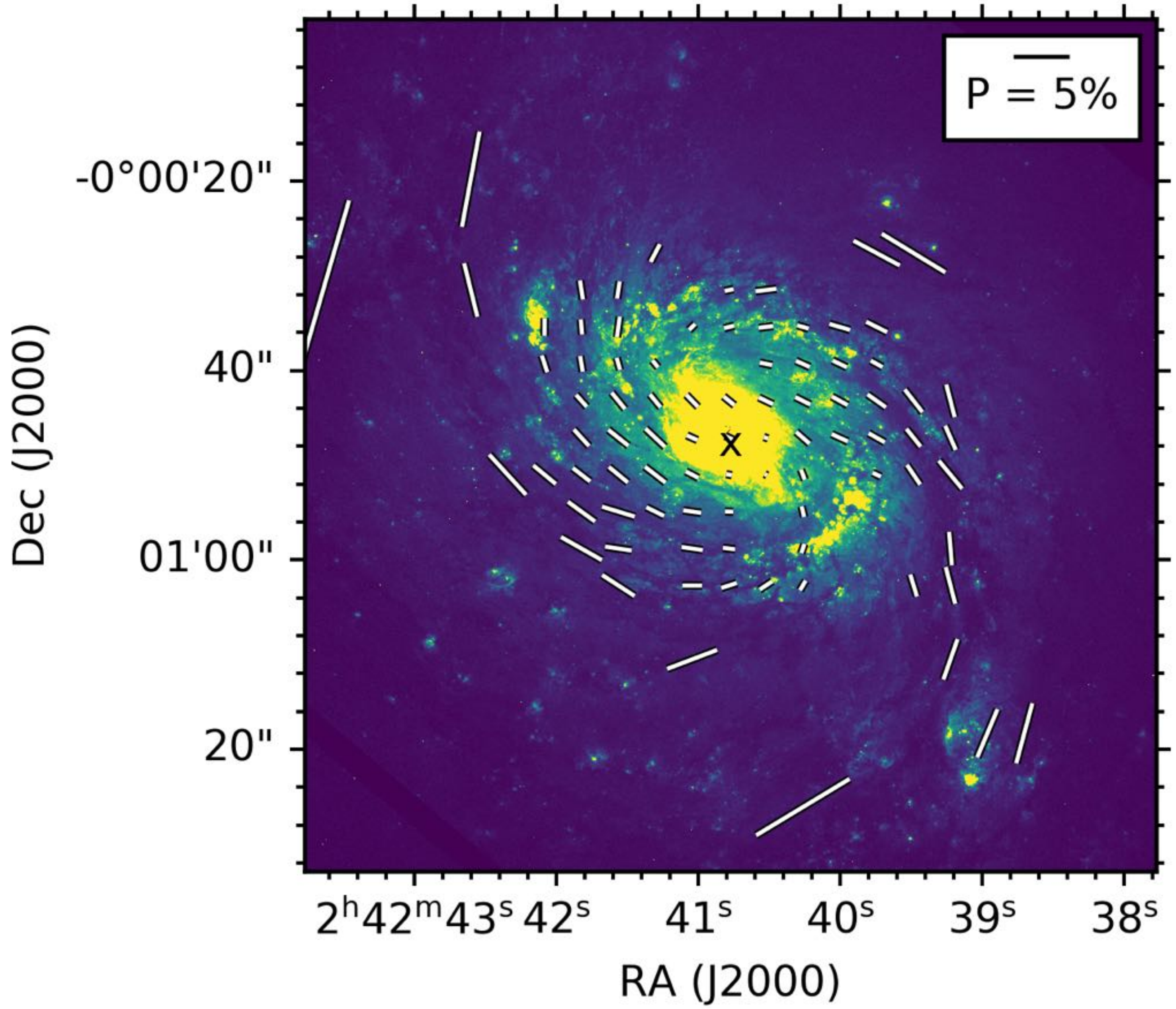
- Within the central region (<2 kpc):
  - Large-scale coherent magnetic field aligned with the inner-bar (black line)
    - Spiral model cannot explain this area because the model does not fulfill the divergence-free requirement and/or the different magnetic field morphology.

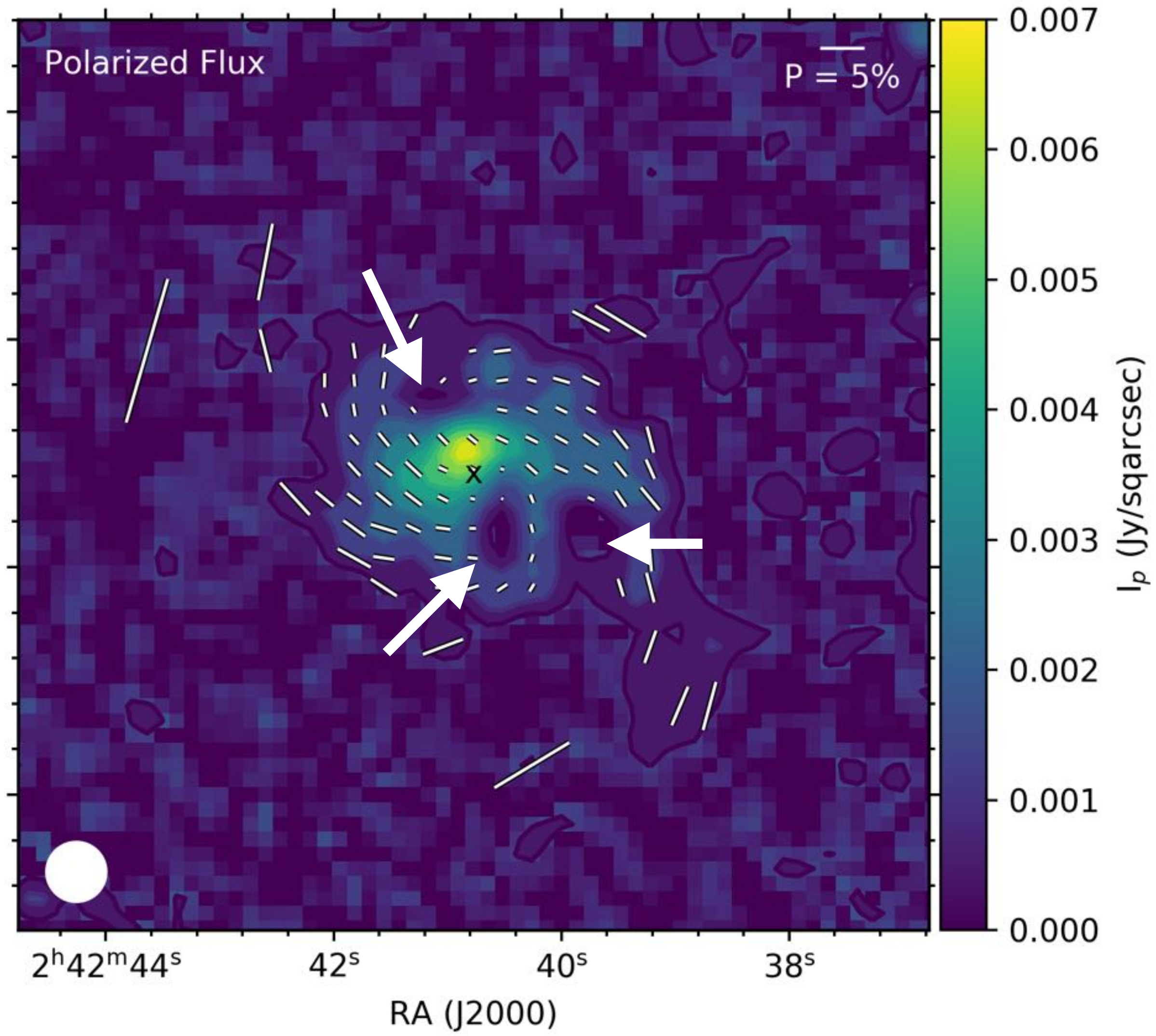




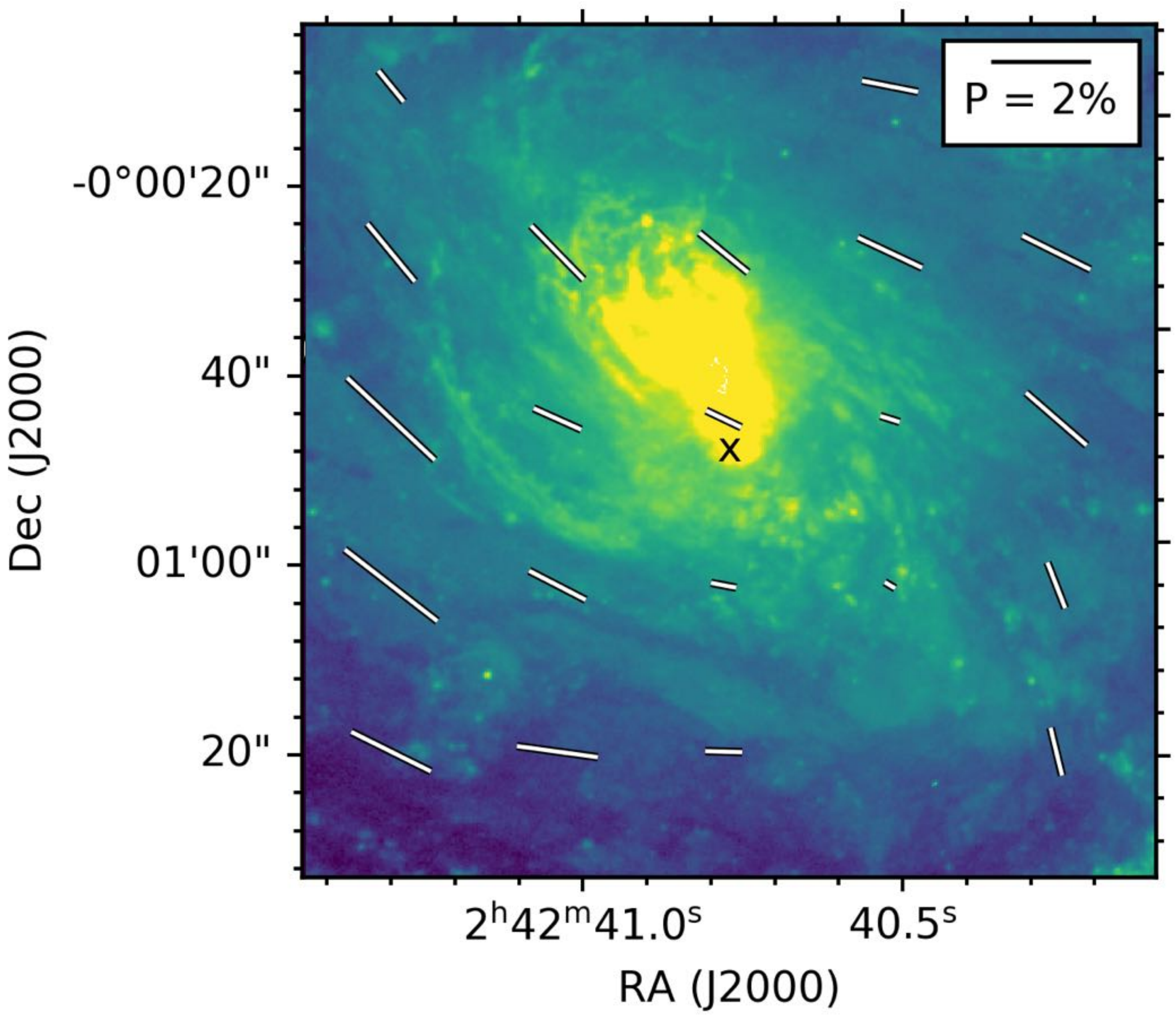
THE CENTRAL REGION: STAR FORMING REGIONS

- Within the central region (<2 kpc):
  - Zero-polarization occurs between the regions of most active star formation and the points at which the other spiral arms diverge from the starburst ring.
  - The B-field directions from the model are in the sense of a larger radial component in the observed vectors.
    - If B-field traces the gas flow, these results would be consistent with inward transport of gas at the leading edge of the inner-bar, with the highest present-day flow rates occurrent along the NE branch of the bar.

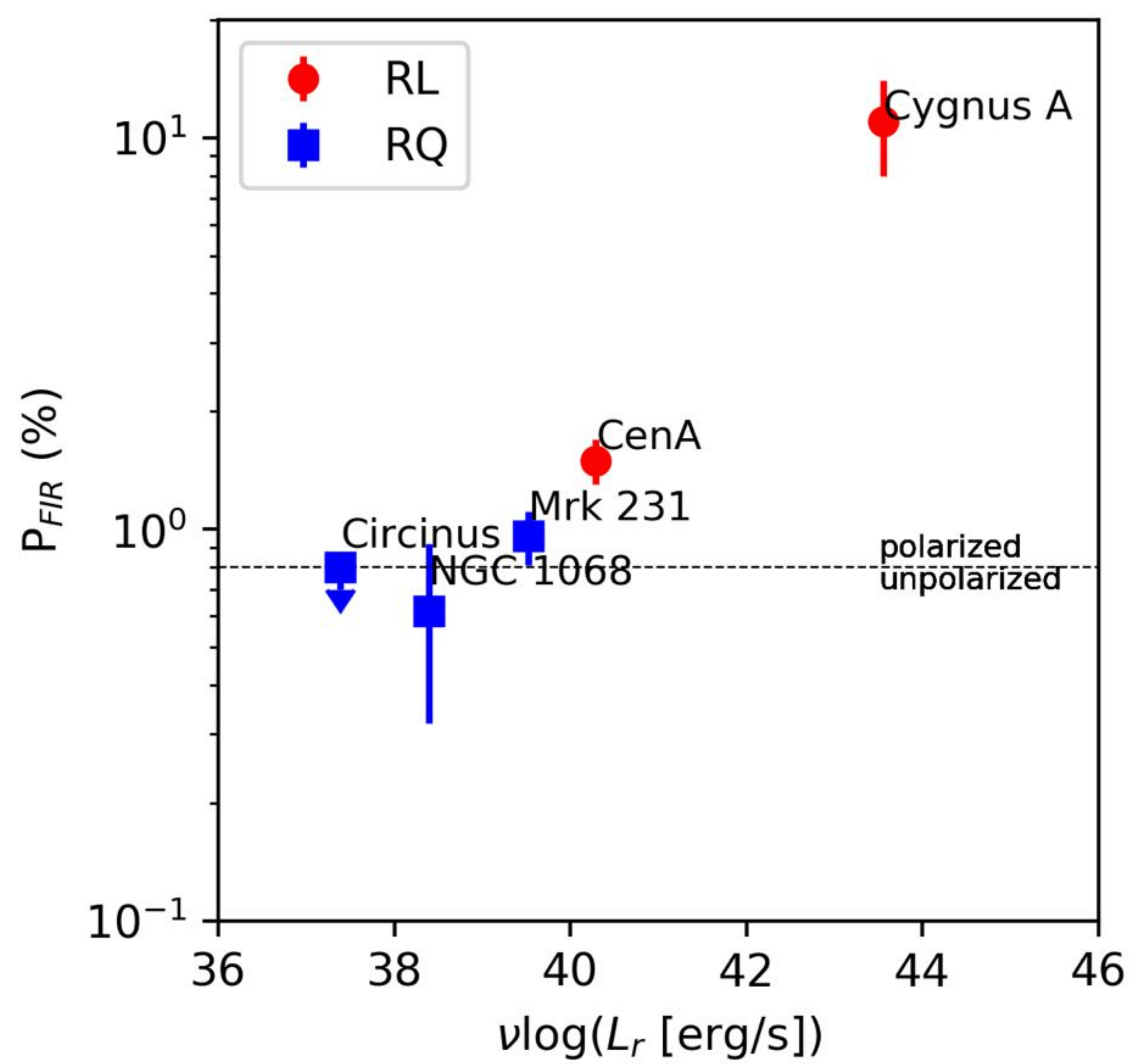




- Within the central region (<2 kpc):
  - Low-polarized AGN (black cross):
    - P ~0.6 ± 0.3% (89 um), 1.3±0.3% (53 um).

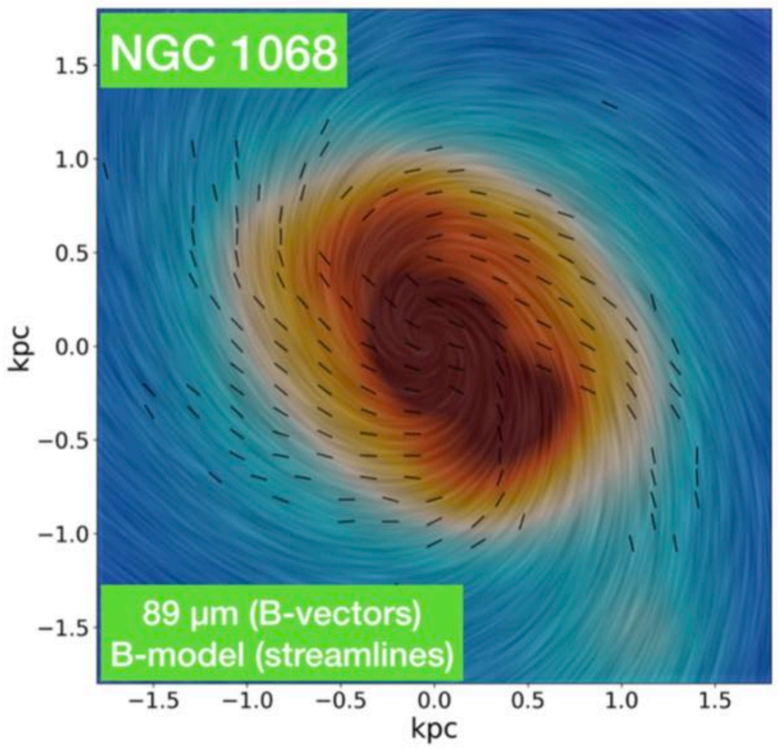


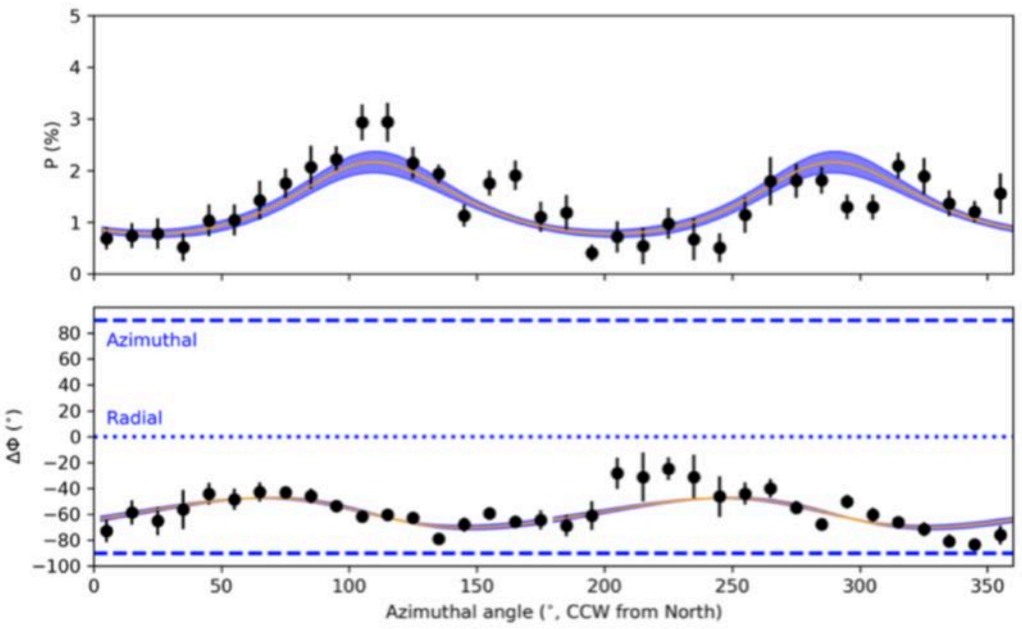
Radio-Loud AGN are highly polarized
Radio-quiet AGN are low polarized

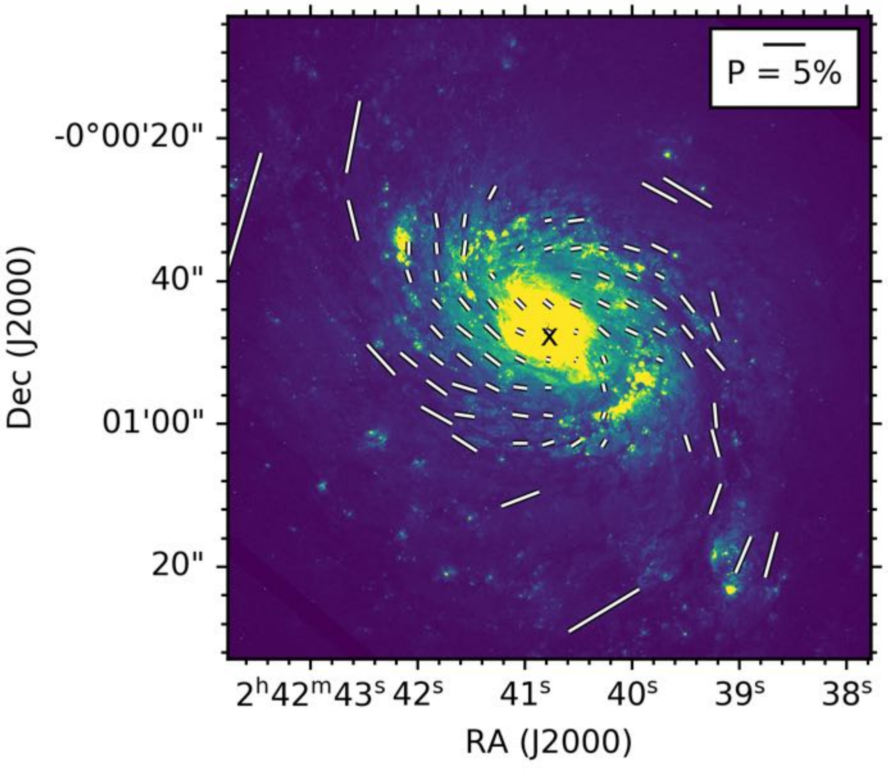


Lopez-Rodriguez et al. (in prep.)

- FIR polarimetric observations allow to trace the magnetic field in the dense ISM.
  - Optical-NIR suffers of electron/dust scattering
  - Radio polarimetry traces synchrotron polarization from relativistic electrons in the diffuse ISM







- A ~3 kpc large-scale spiral magnetic fields is measured on the disk of the galaxy.
  - A logarithmic spiral model with a pitch angle tracing the star-forming regions along the spiral arms can explain the large-scale spiral structure.
- Within the central region (<2 kpc):
  - Large-scale coherent magnetic field aligned with the inner-bar
  - Zero-polarization at the location of star-forming regions at the edges of the inner-bar.
  - Low-polarized AGN.