Extragalactic Magnetism with SOFIA and ALMA

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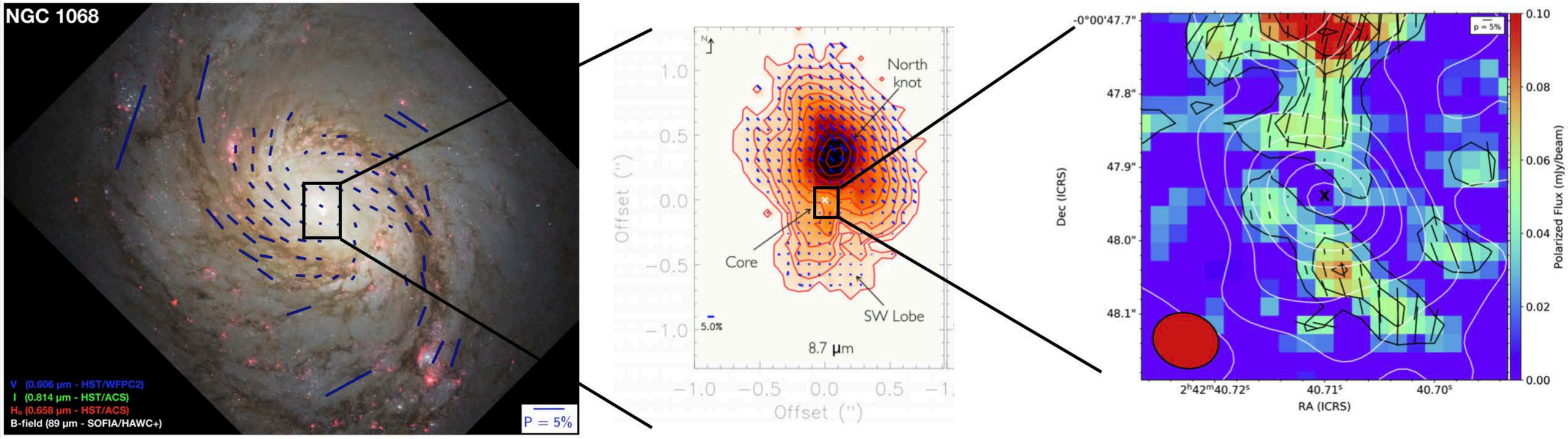
~3000 pc-scale galactic spiral magnetic field
(SOFIA/HAWC+: FIR polarimetric observations)

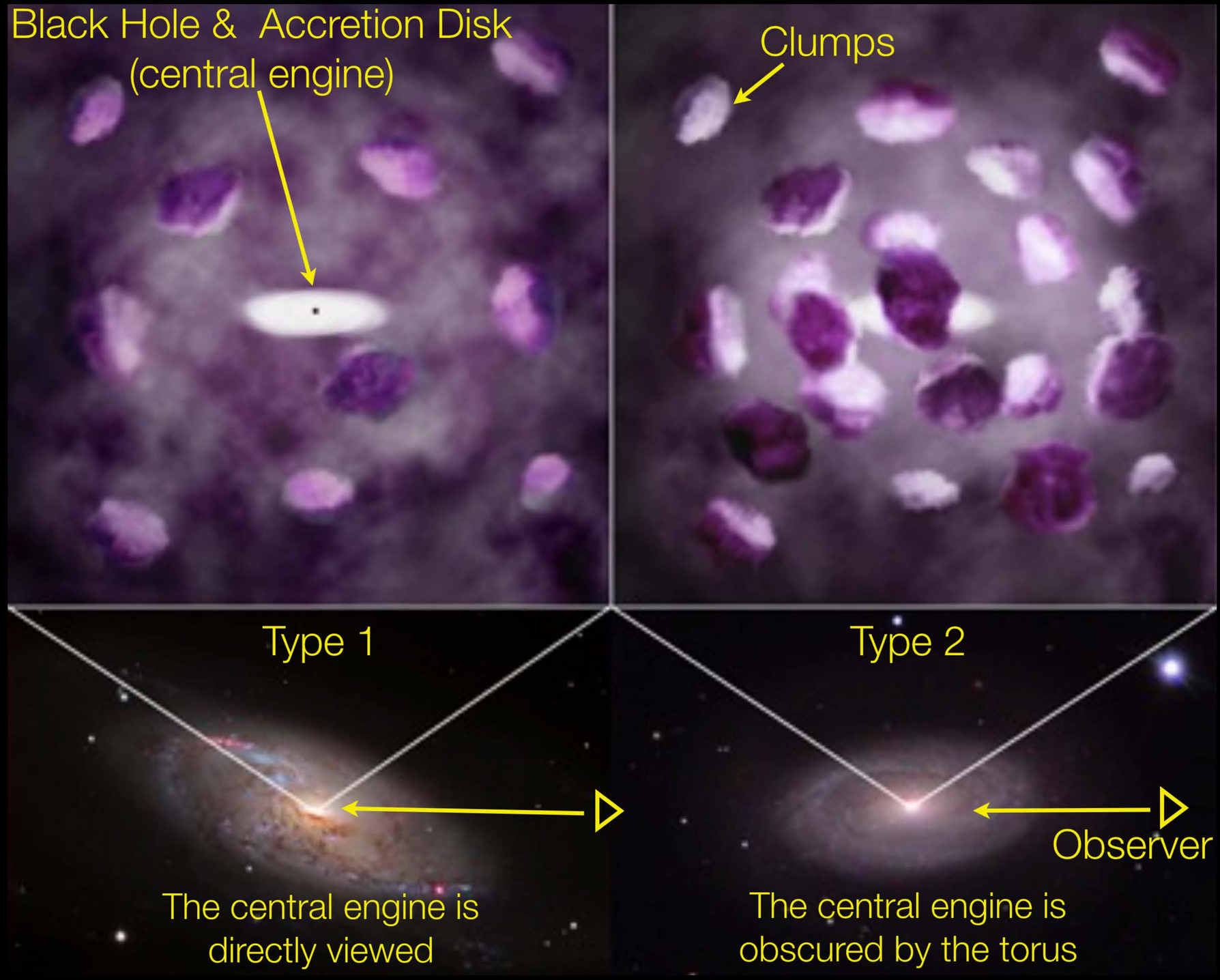
~100 pc-scale magnetic field in inner-bar
(GTC/CanariCam: MIR polarimetric observations)

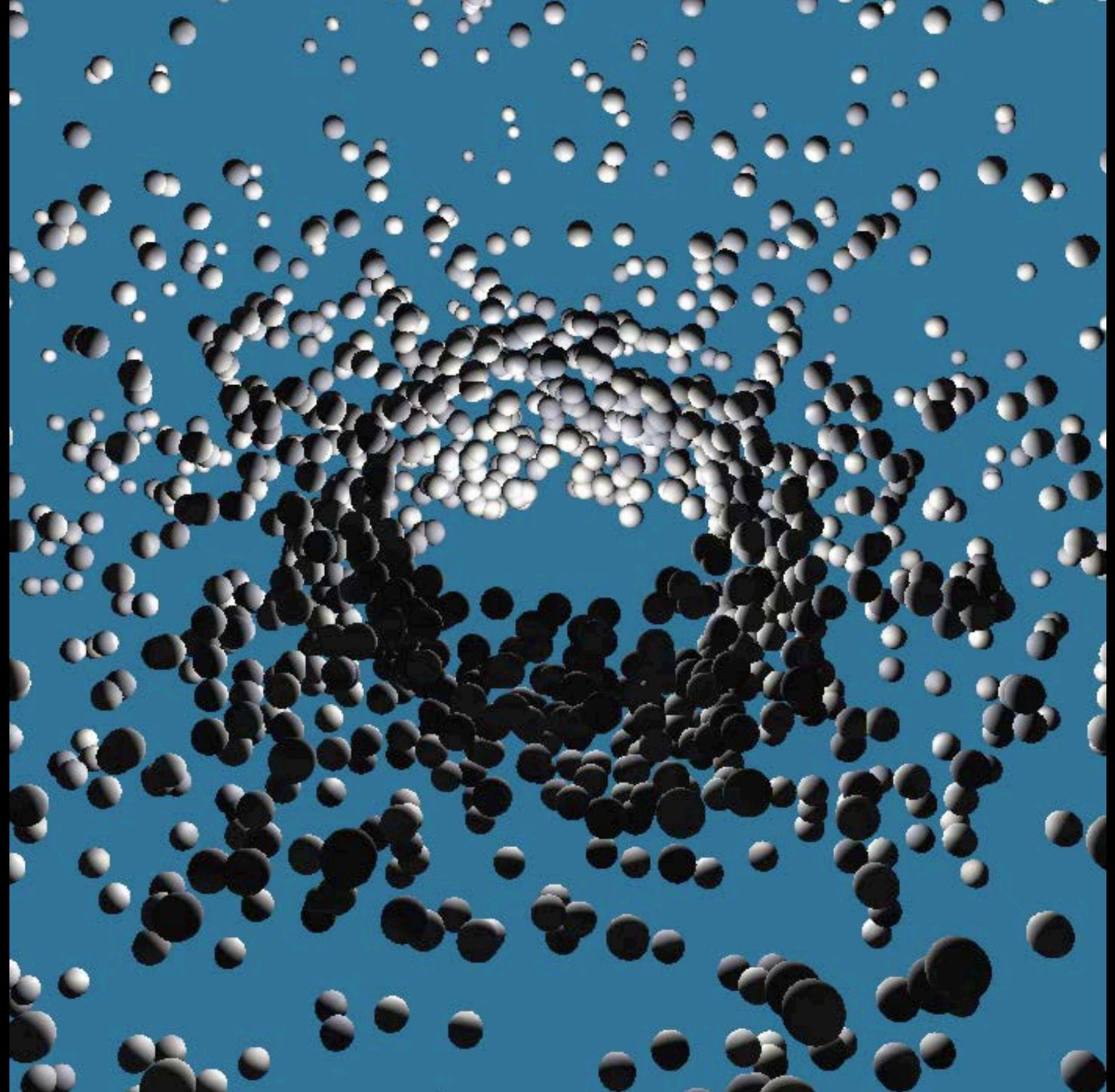
~10 pc-scale magnetic field in the torus
(ALMA: sub-mm polarimetric observations)



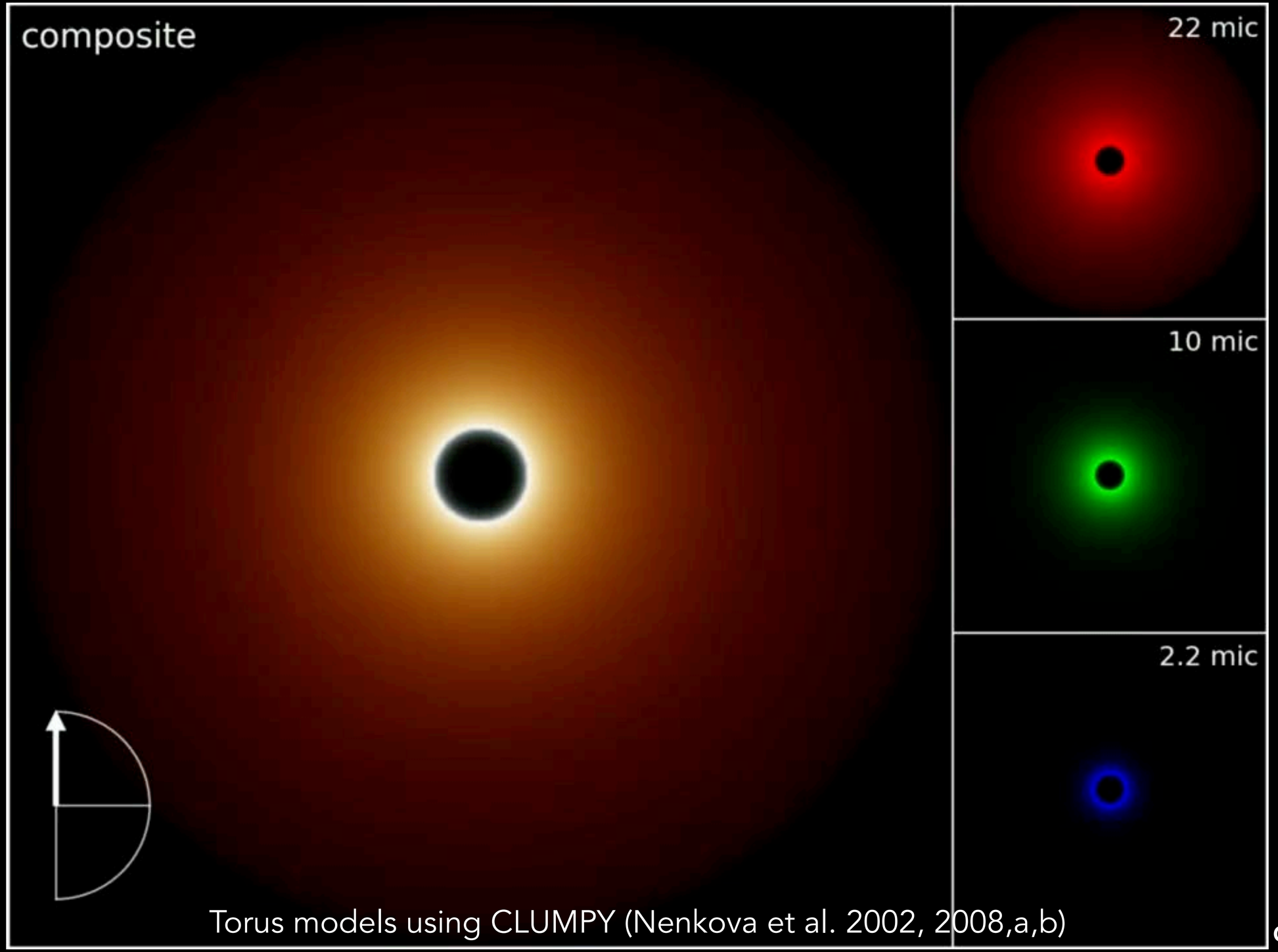
Disentangling the Thermal Emission of AGN Tori

SOFIA and ALMA: Total Intensity


Black Hole & Accretion Disk
(central engine)
Clumps
Type 1
Type 2
Observer
The central engine is
directly viewed
The central engine is
obscured by the torus



Credit: Robert Nikutta

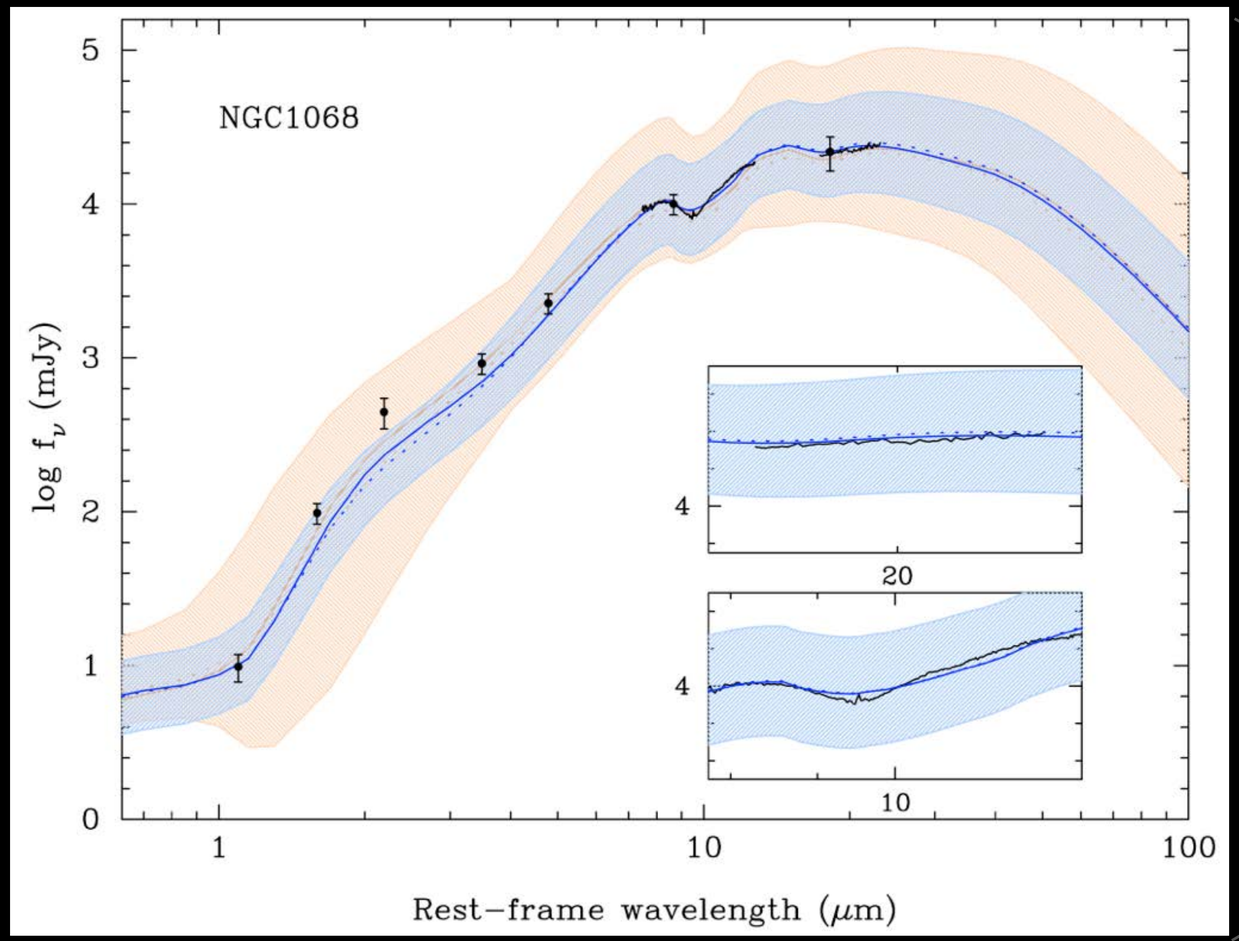


Torus models using CLUMPY (Nenkova et al. 2002, 2008,a,b)

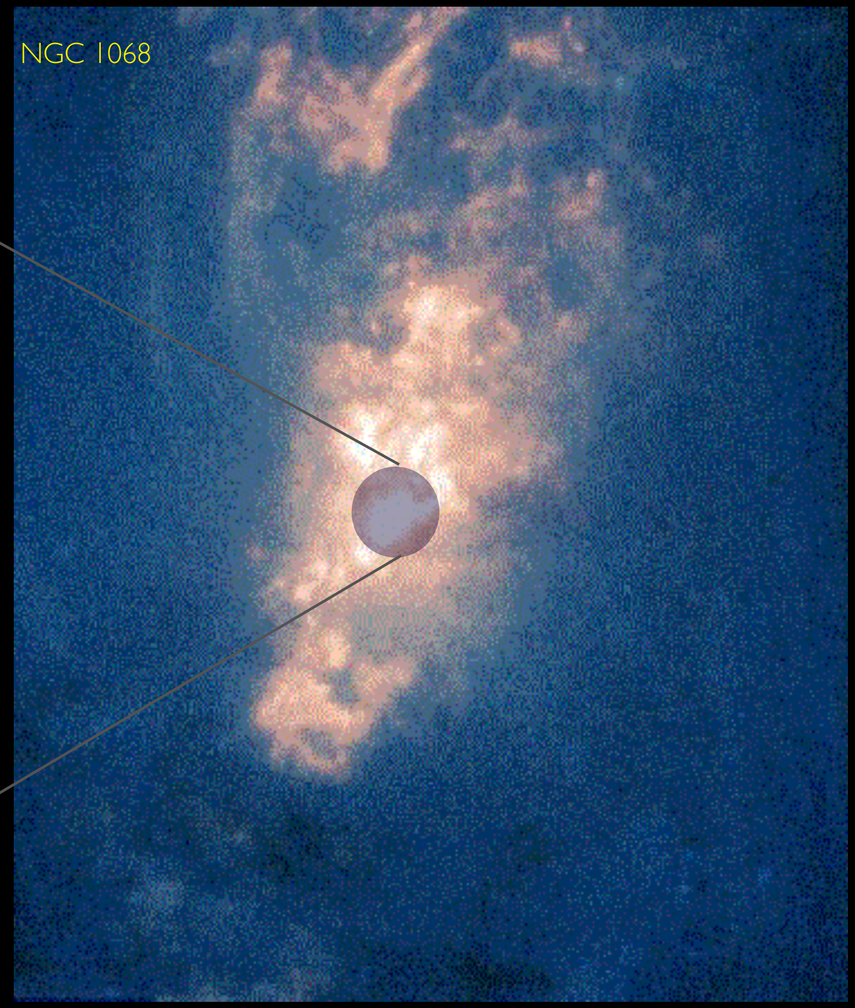
Credit: Robert Nikutta

AGN SEDs and CLUMPY Torus Models

Isolated thermal emission from 10-m class telescopes can be reproduced using CLUMPY torus models

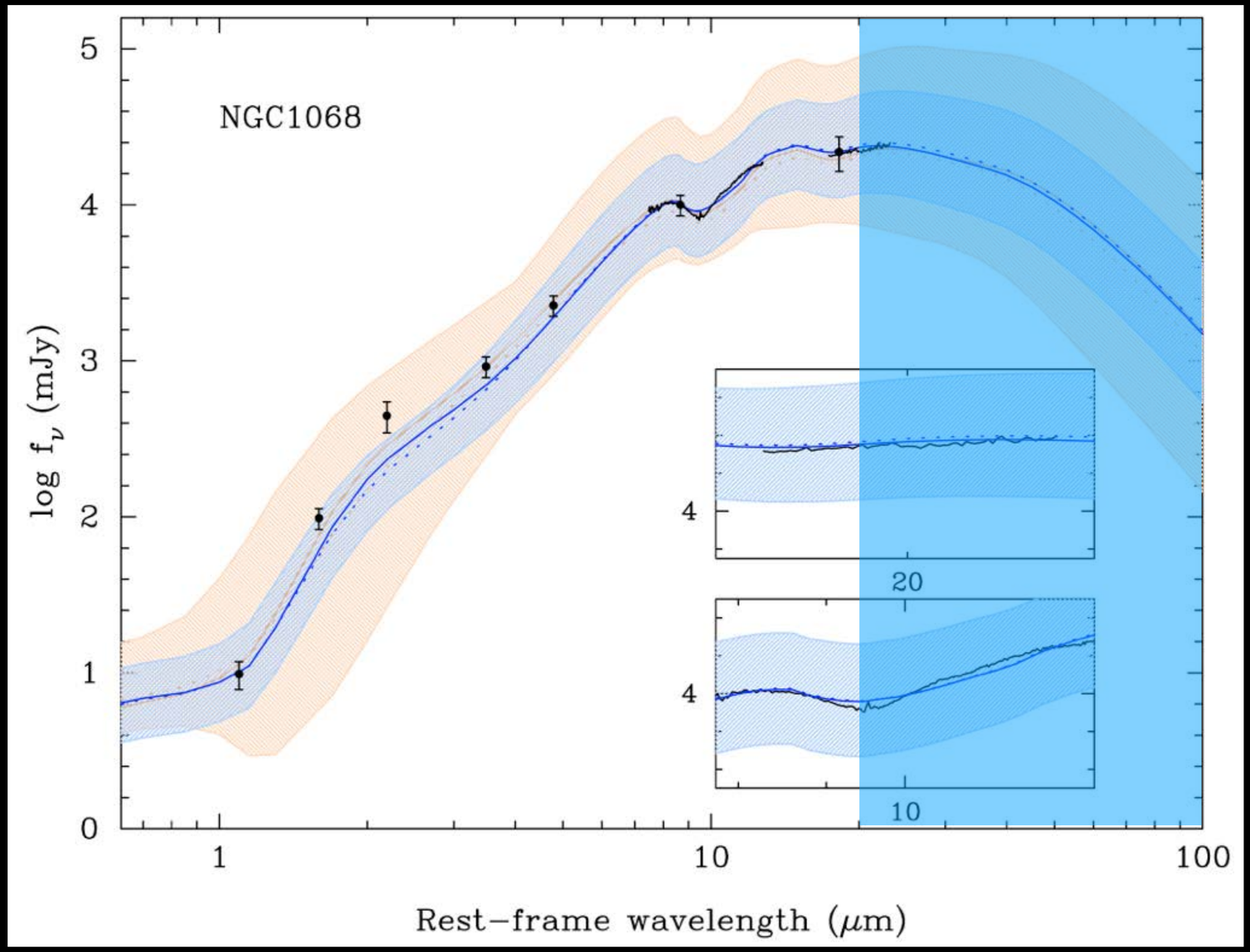


Alonso-Herrero et al. (2011)



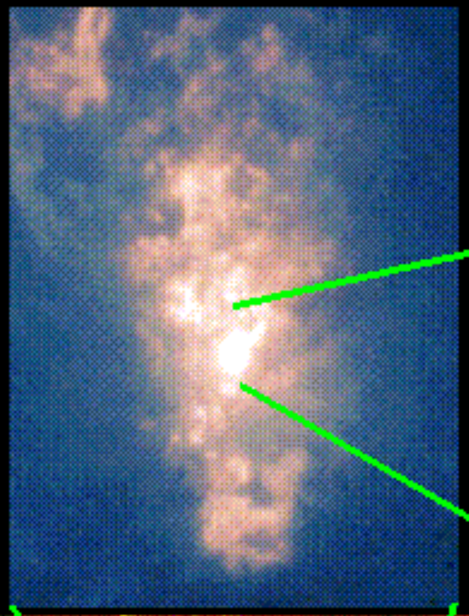
Torus models using CLUMPY (Nenkova et al. 2002, 2008,a,b)

Lack of FIR and Sub-mm observations and high-resolution (<0.1”) observations

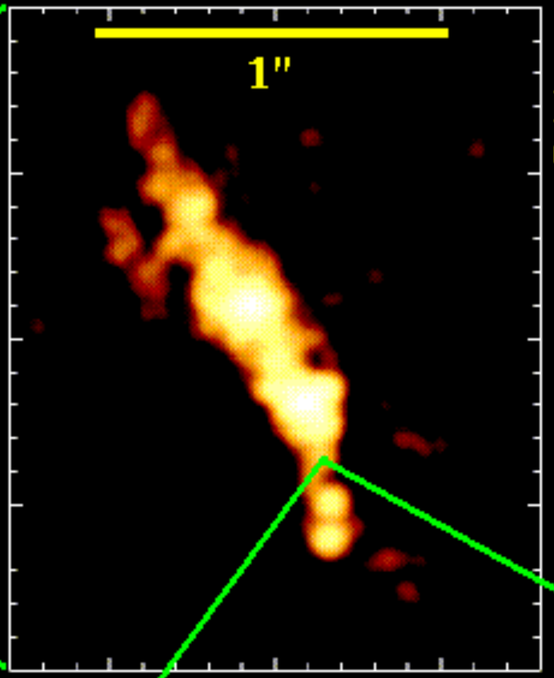


Alonso-Herrero et al. (2011)

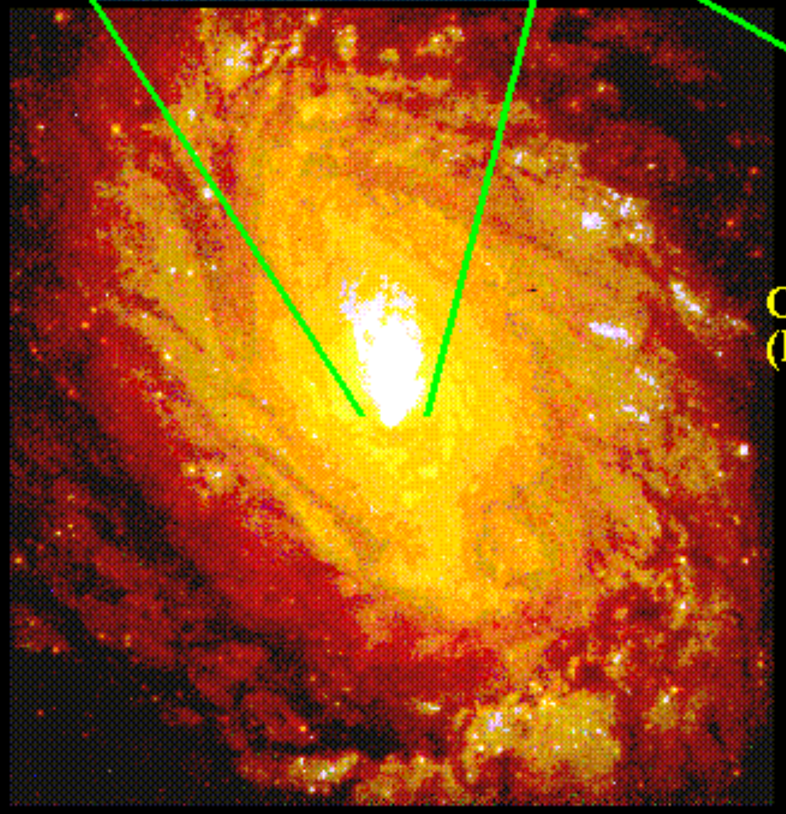
NGC 1068



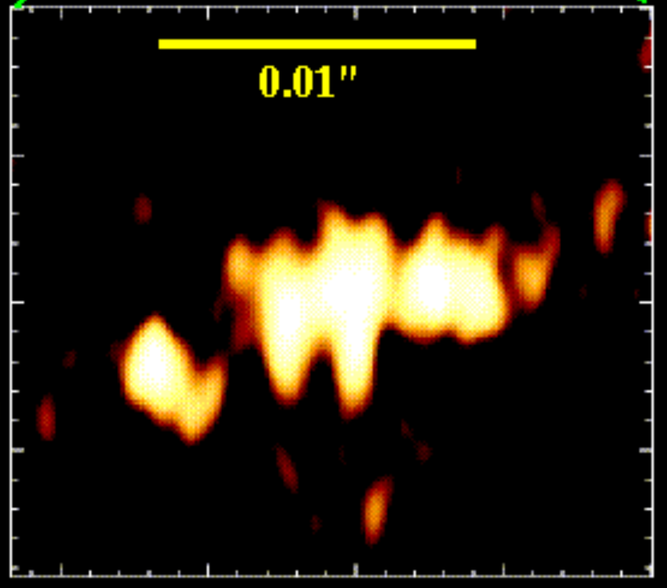
Nuclear reflection cone (HST/FOC)



Radio jet (MERLIN)

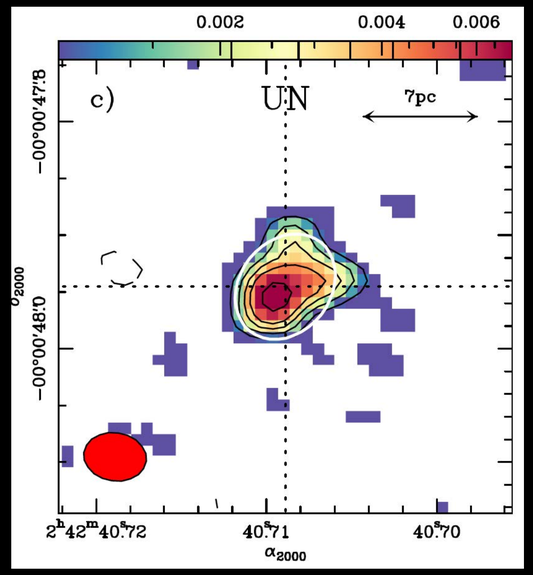


Optical galaxy (HST)



Obscuring torus ? (VLBA)

The Resolved Torus of NGC 1068: ALMA observations



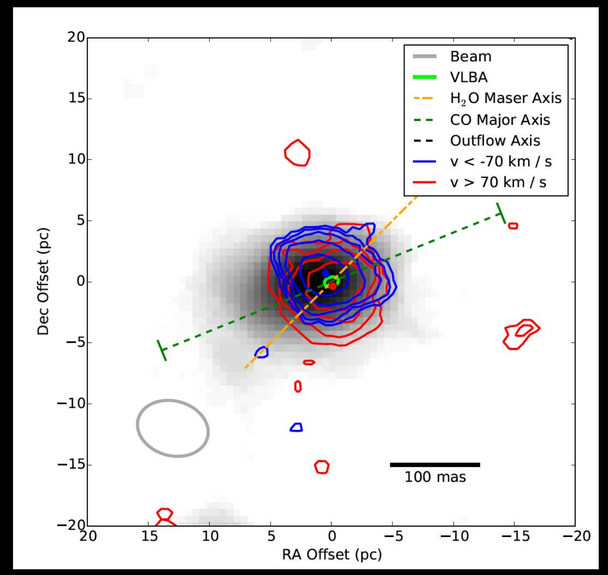
Garcia-Burrillo et al. (2016)

ALMA observations have put tight constraints on the morphology of the torus of NGC 1068:

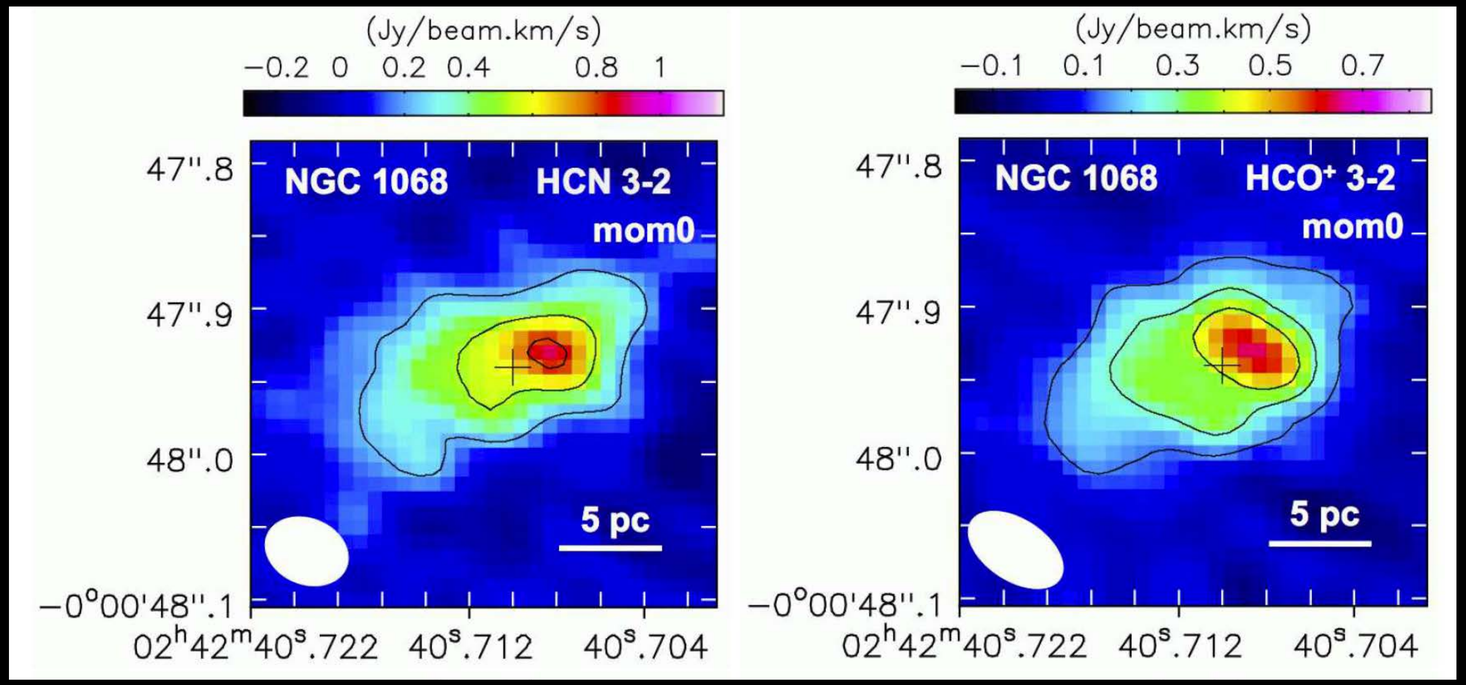
Torus size ~ 12x5 pc

Orientation of the torus ~ 110º

Highly inhomogeneous molecular torus

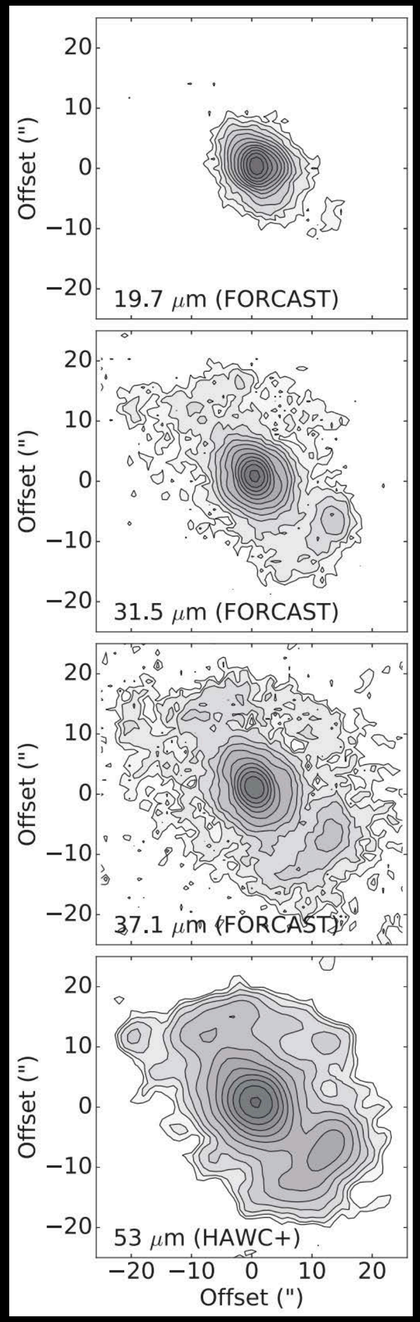


Gallimore et al. (2016)



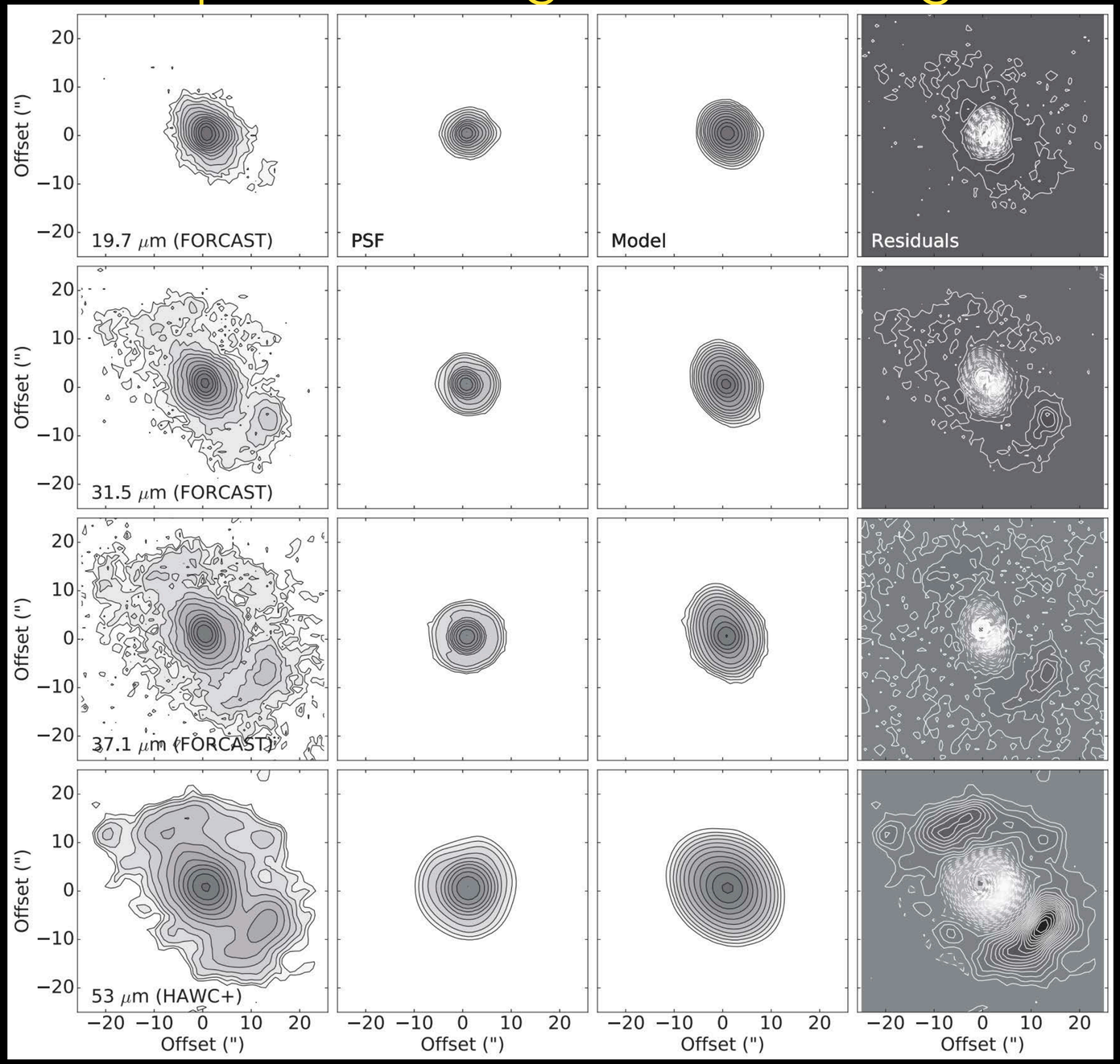
Imanishi et al. (2018)

Thermal emission using FORCAST/HAWC+/SOFIA



Lopez-Rodriguez et al. (2018a)

Nuclear decomposition using PSF and elongated Gaussian

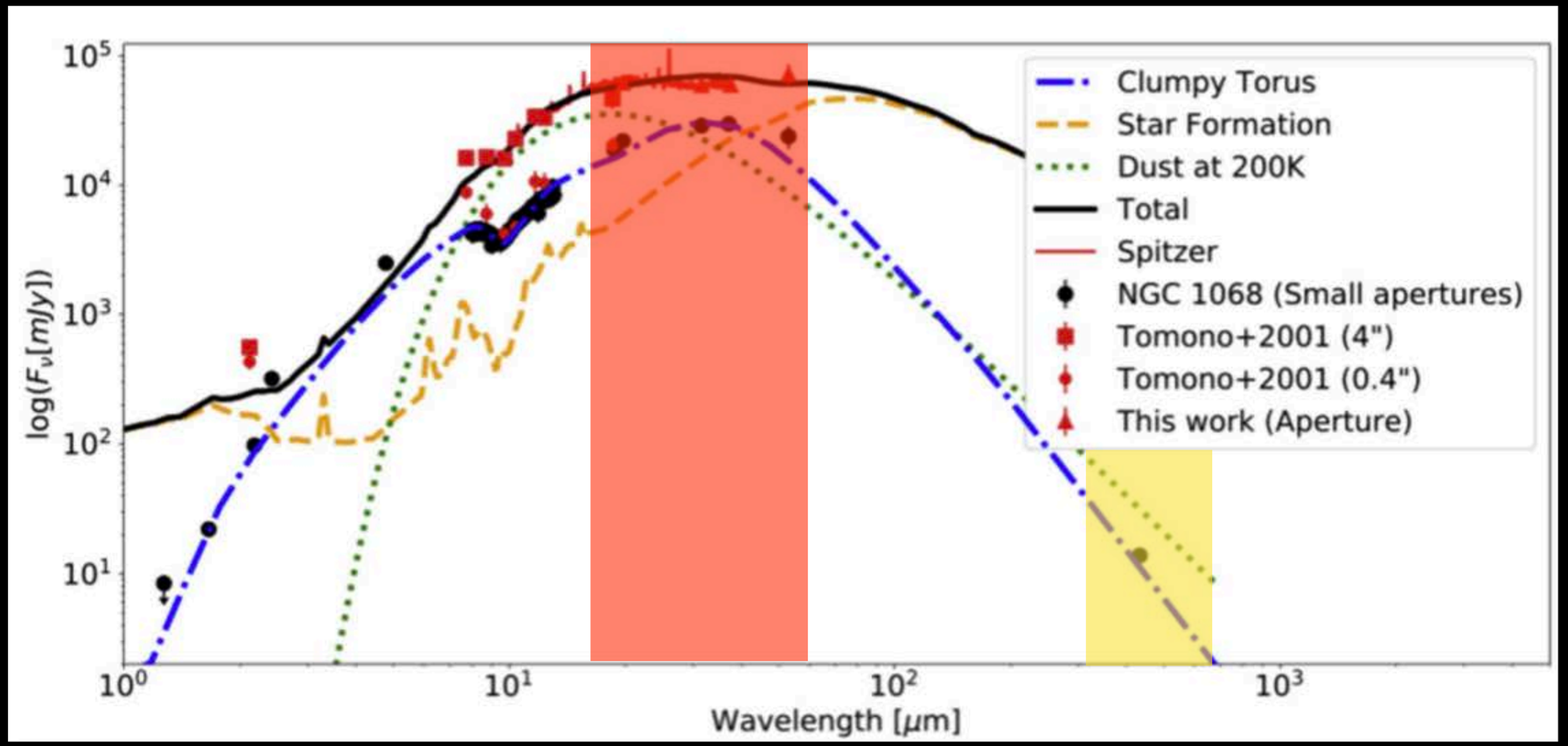


Lopez-Rodriguez et al. (2018a)

Spectral decomposition of the nuclear SED at several resolutions

SOFIA: 30-40 um FORCAST and 53 um HAWC+

ALMA: Continuum emission at Band 7 (Garcia-Burillo+2016)



Lopez-Rodriguez et al. (2018a)

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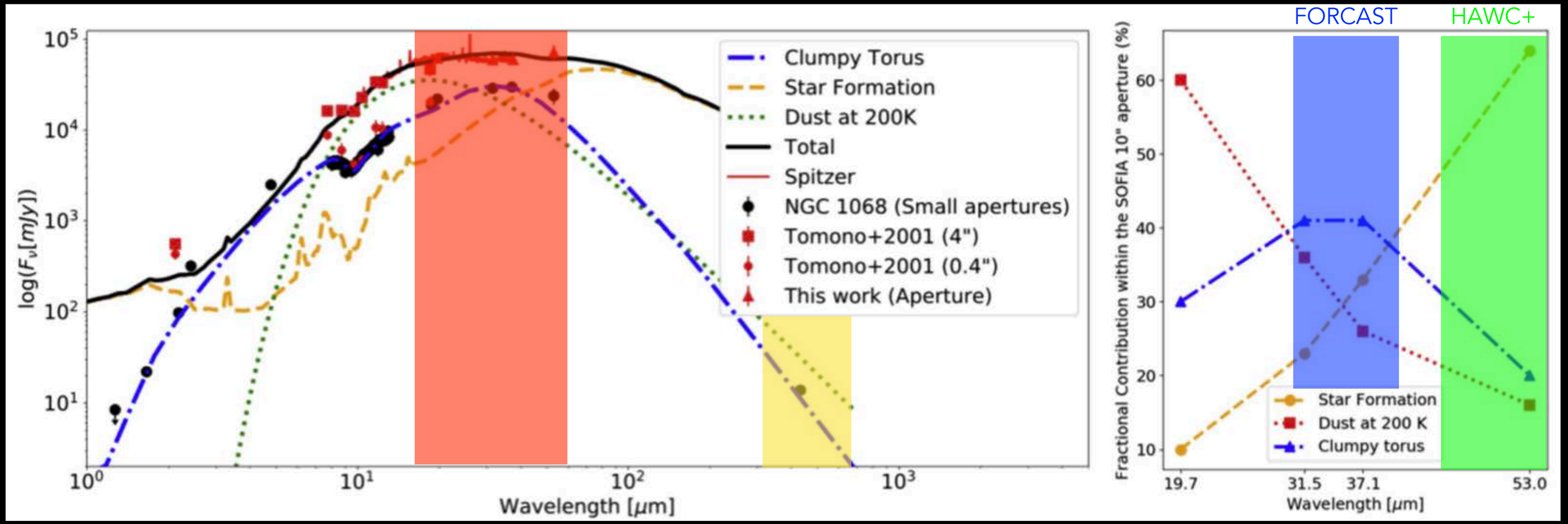
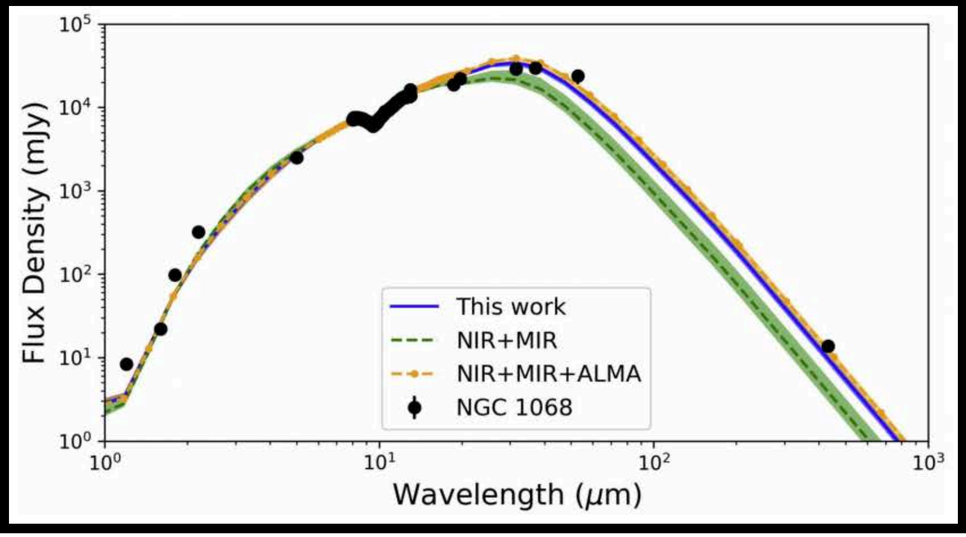
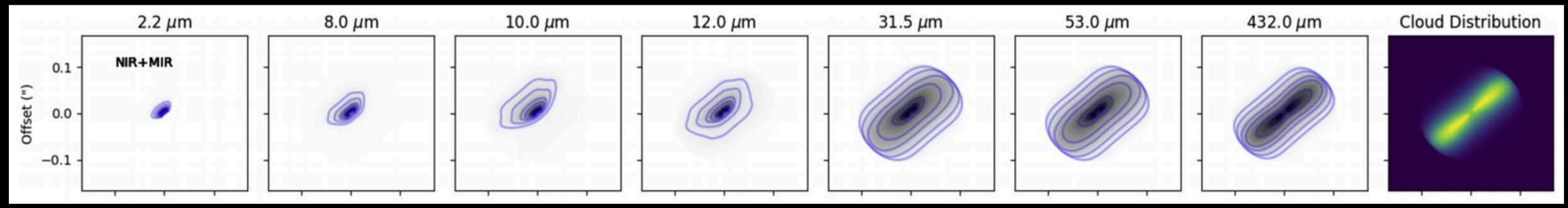


Lopez-Rodriguez et al. (2018a)

SED Fitting as a function of the wavelength coverage

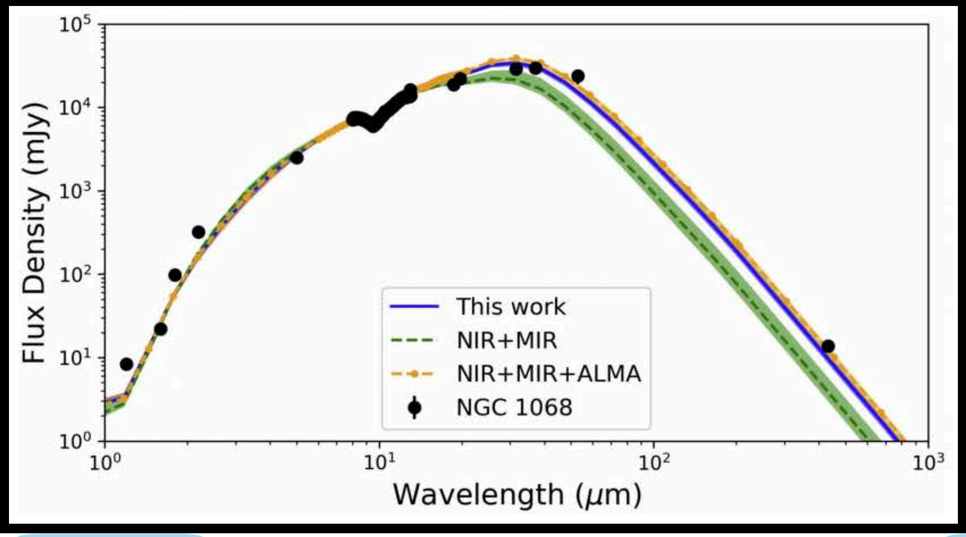


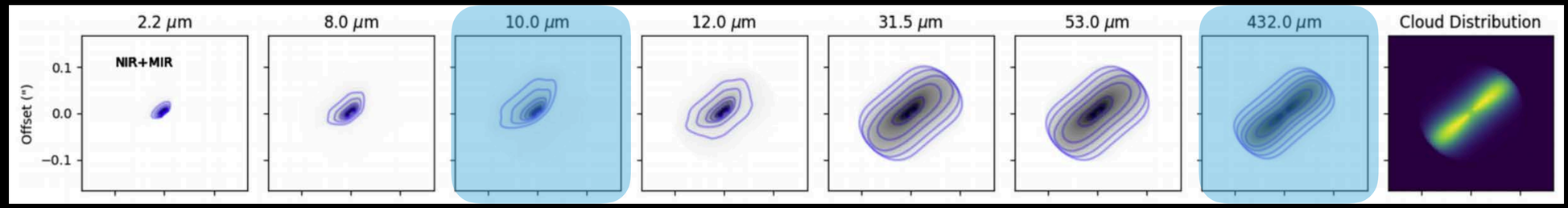


Thermal emission maps using CLUMPY and HyperCAT (Nikutta+2021a,b)

Lopez-Rodriguez et al. (2018a)

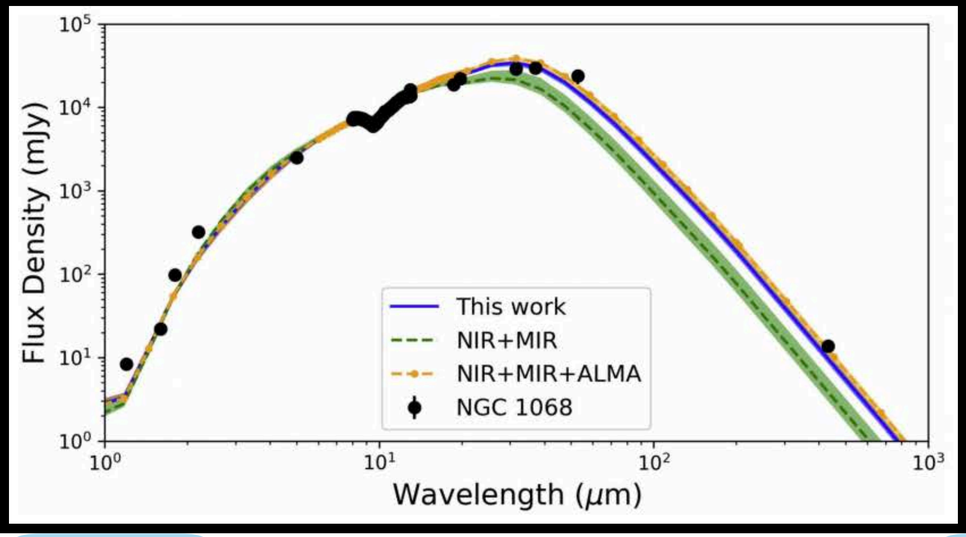
SED Fitting as a function of the wavelength coverage

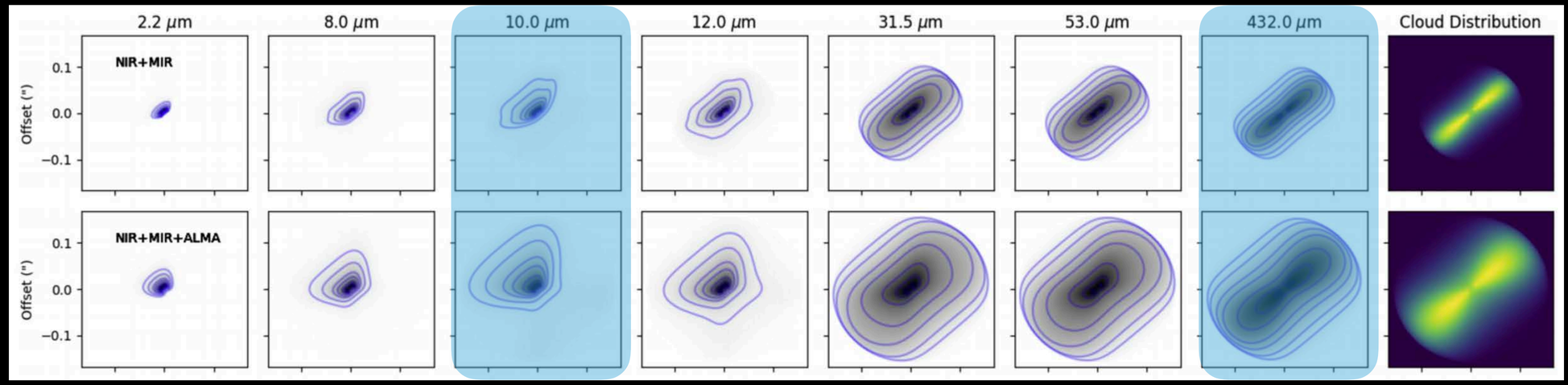




Lopez-Rodriguez et al. (2018a)

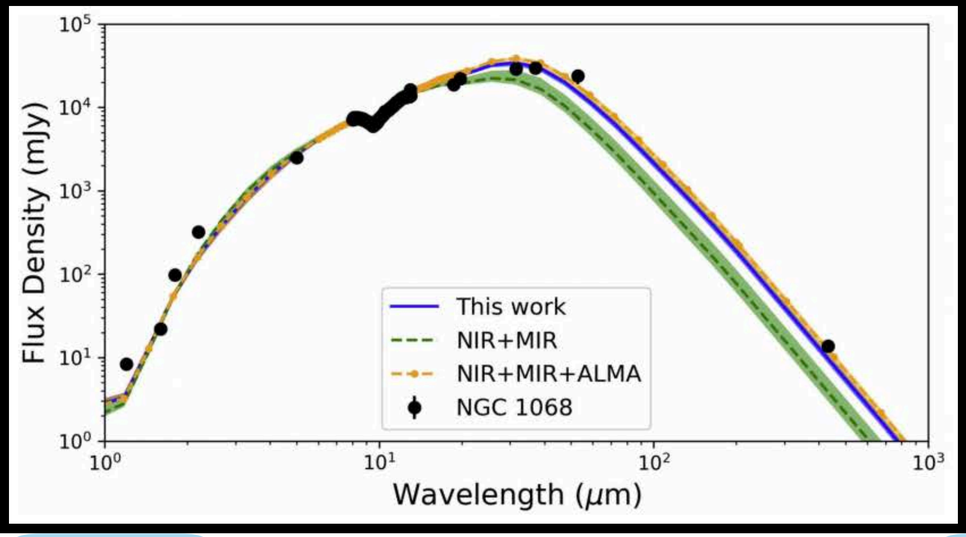
SED Fitting as a function of the wavelength coverage

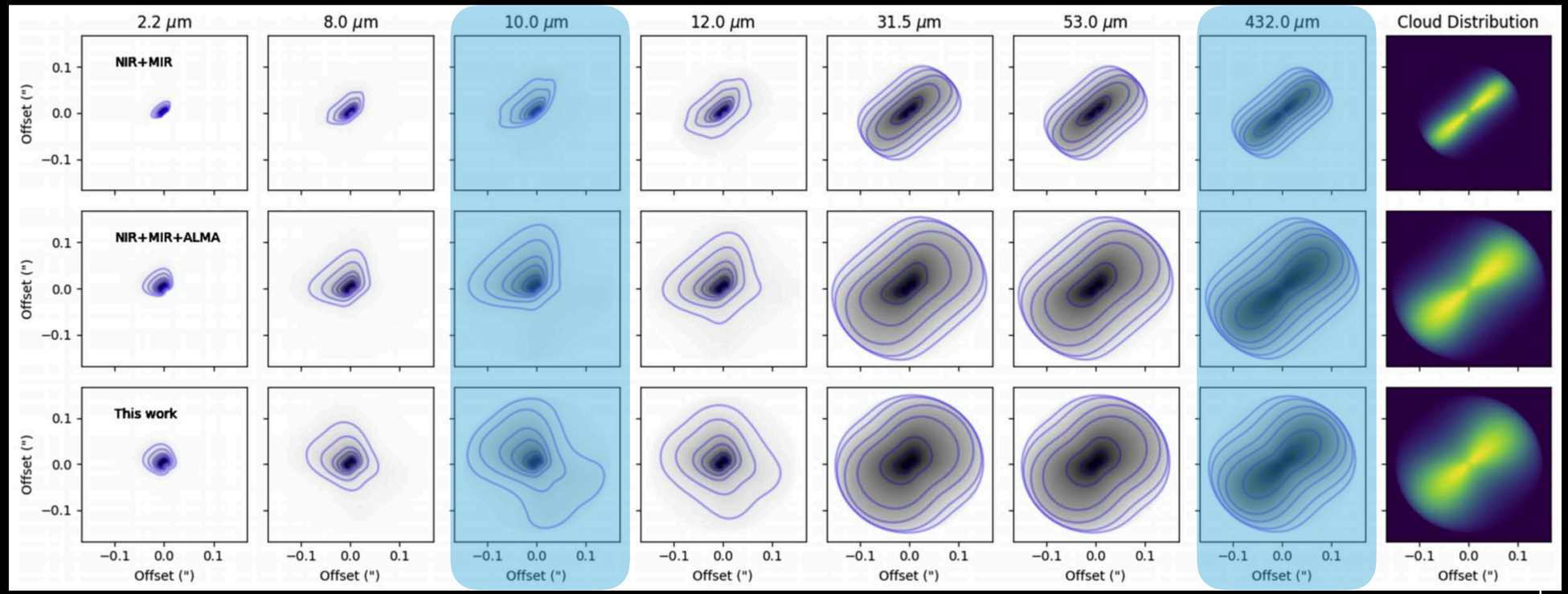




Lopez-Rodriguez et al. (2018a)

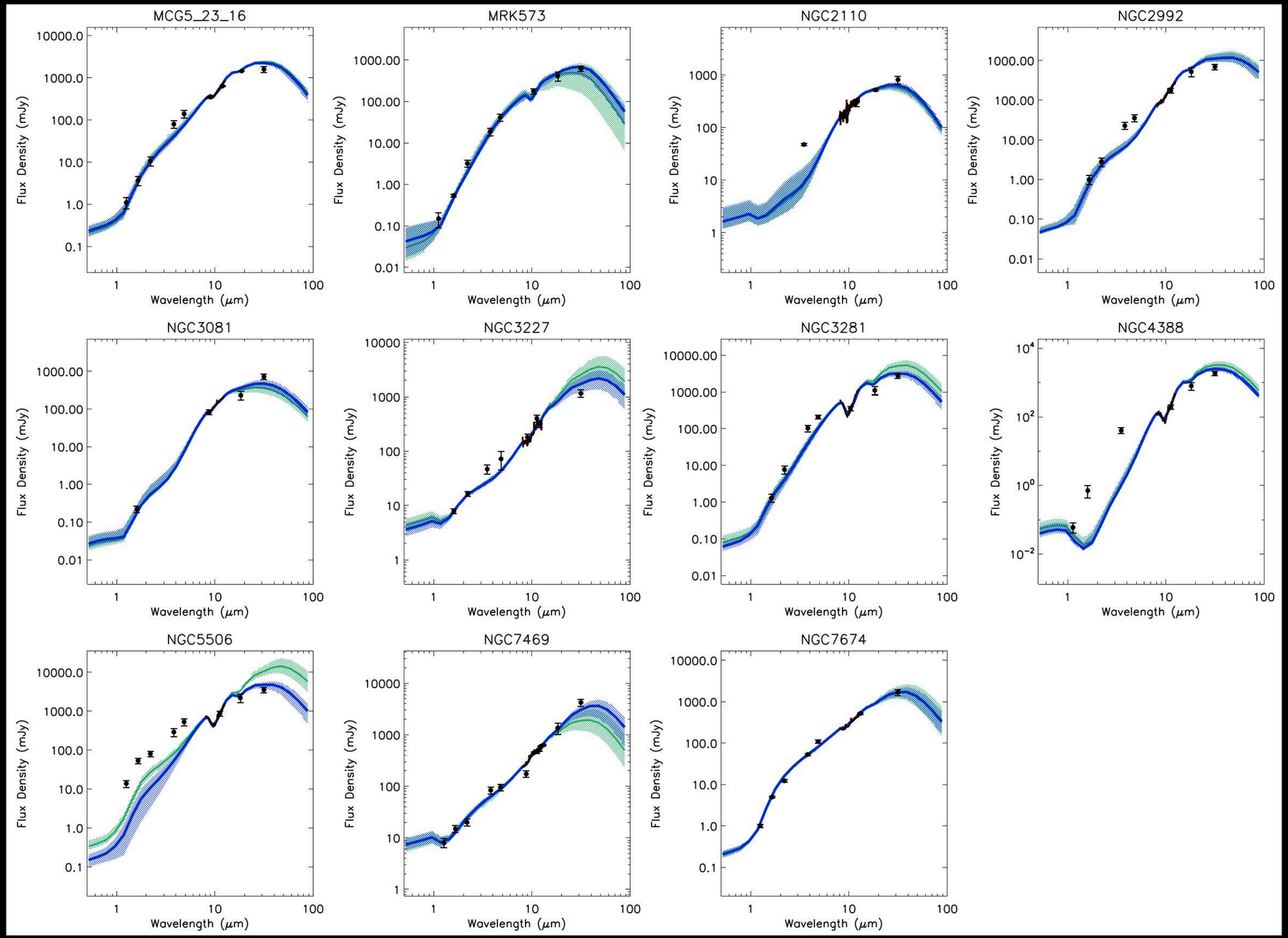
SED Fitting as a function of the wavelength coverage





Lopez-Rodriguez et al. (2018a)

Torus emission peaks at 30-50 um and torus radial extend < 9pc



Fuller et al. (2016, 2018)

ALMA Band 7 and CO observations of nearby (<28 Mpc) AGN

Angular resolution: 0.1" (7-13 pc)

Contours: 870 um continuum emission

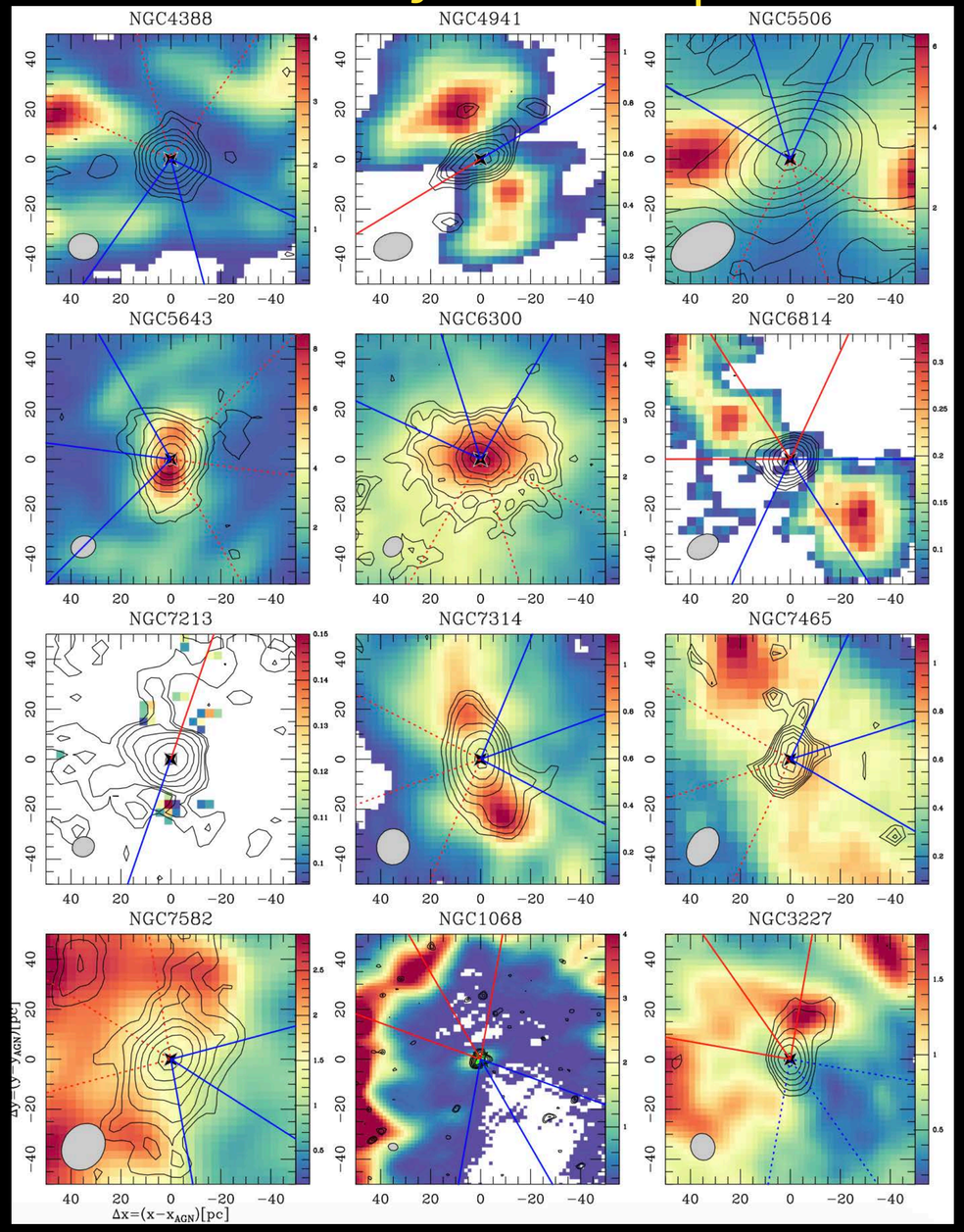
Colorscale: Velocity integrated CO(3-2) map

Continuum emission:

- Thermal emission from dusty molecular torus.
- Elongated disk mostly perpendicular to the AGN winds.
- Median diameter ~42 pc
- Median mass ~6×10^5 $M_\odot$

Line emission:

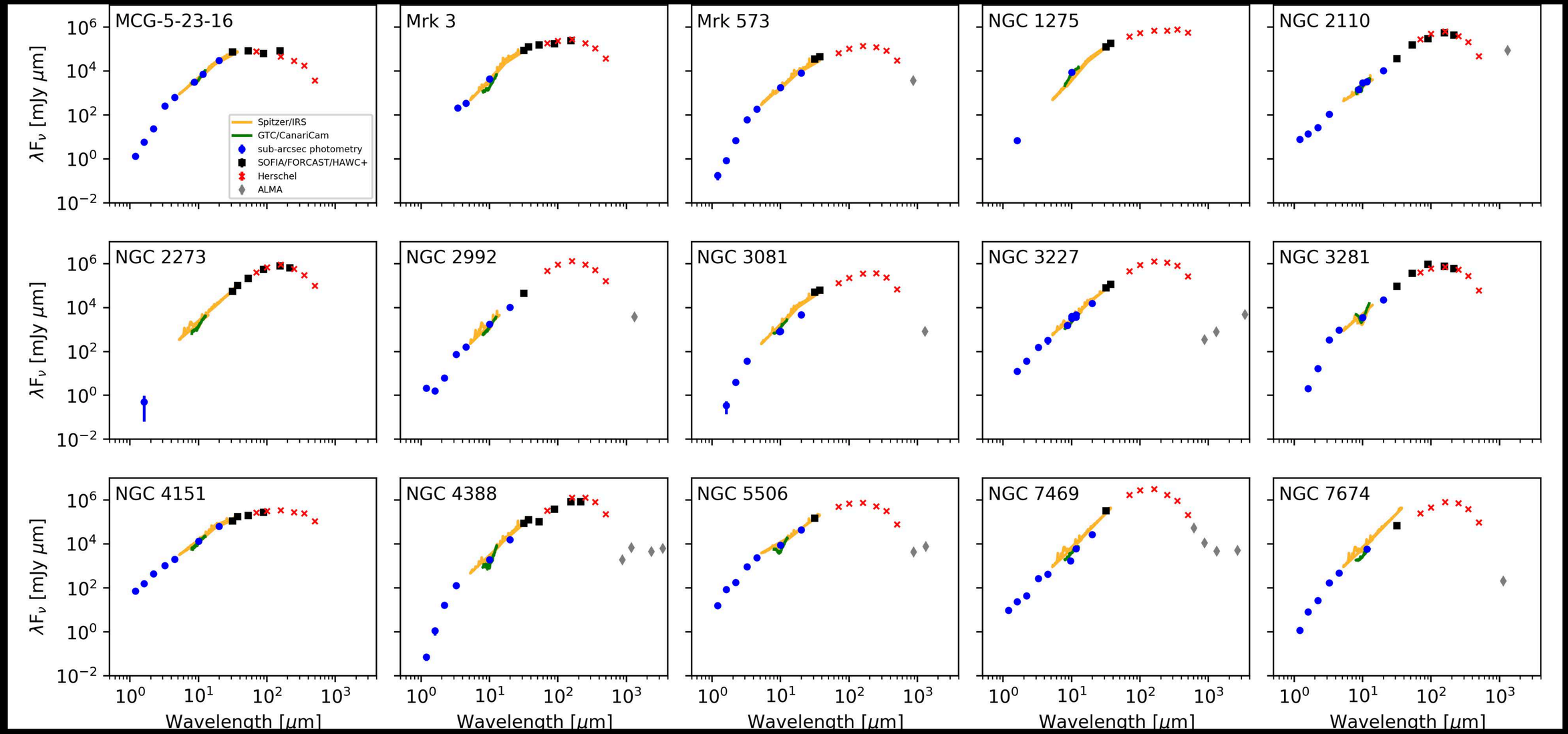
- Highly inhomogeneous tori across the long axis.



http://gatos.strw.leidenuniv.nl/

Garcia-Burillo et al. (2021, Gatos I)

AGN SEDs of the objects observed with SOFIA Cycle 2-8 and ALMA

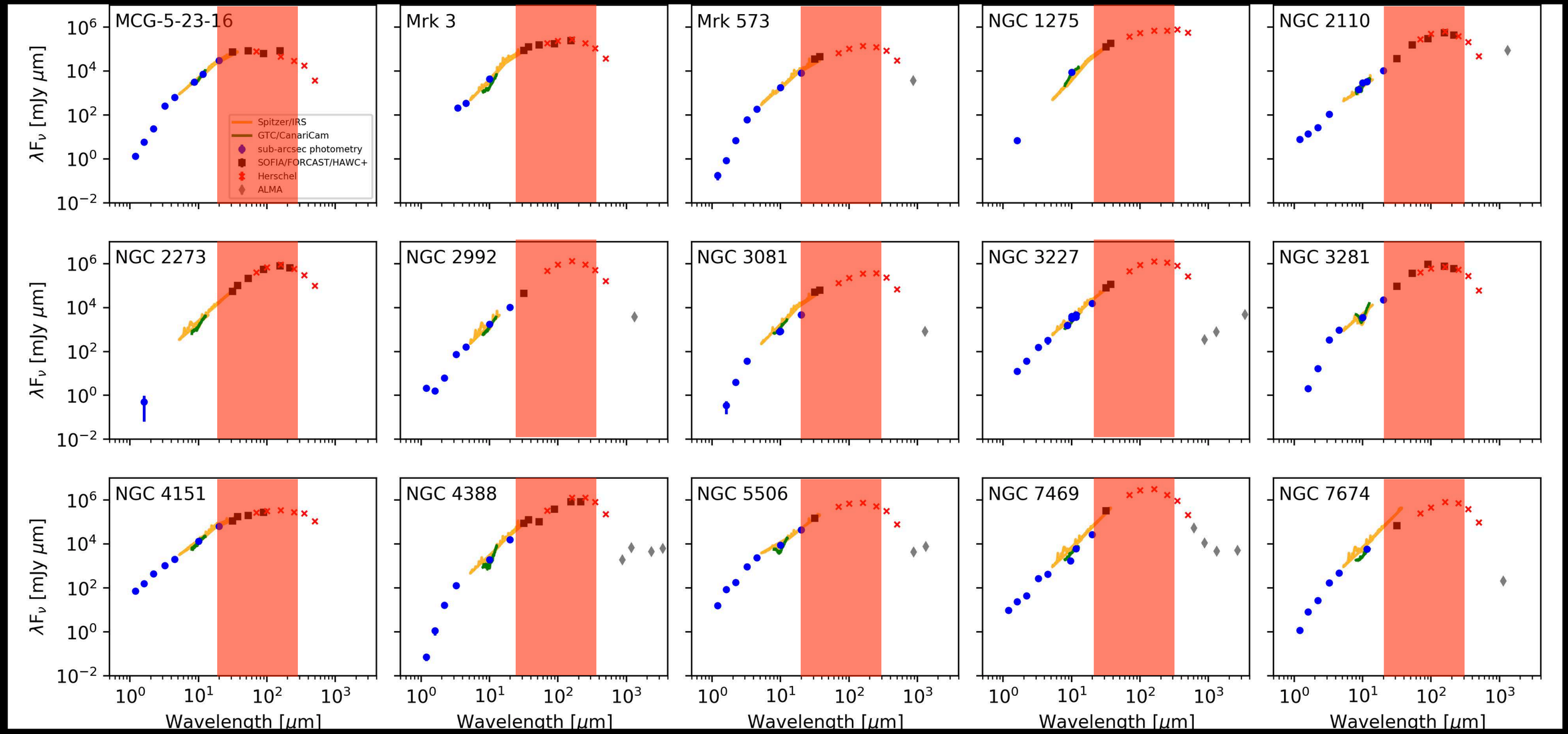


Fuller et al. (in prep.)

AGN SEDs of the objects observed with SOFIA Cycle 2-8 and ALMA

SOFIA: 30-40 um FORCAST and 50-214 um HAWC+

Thermal emission (torus, SF, host galaxy)



Fuller et al. (in prep.)

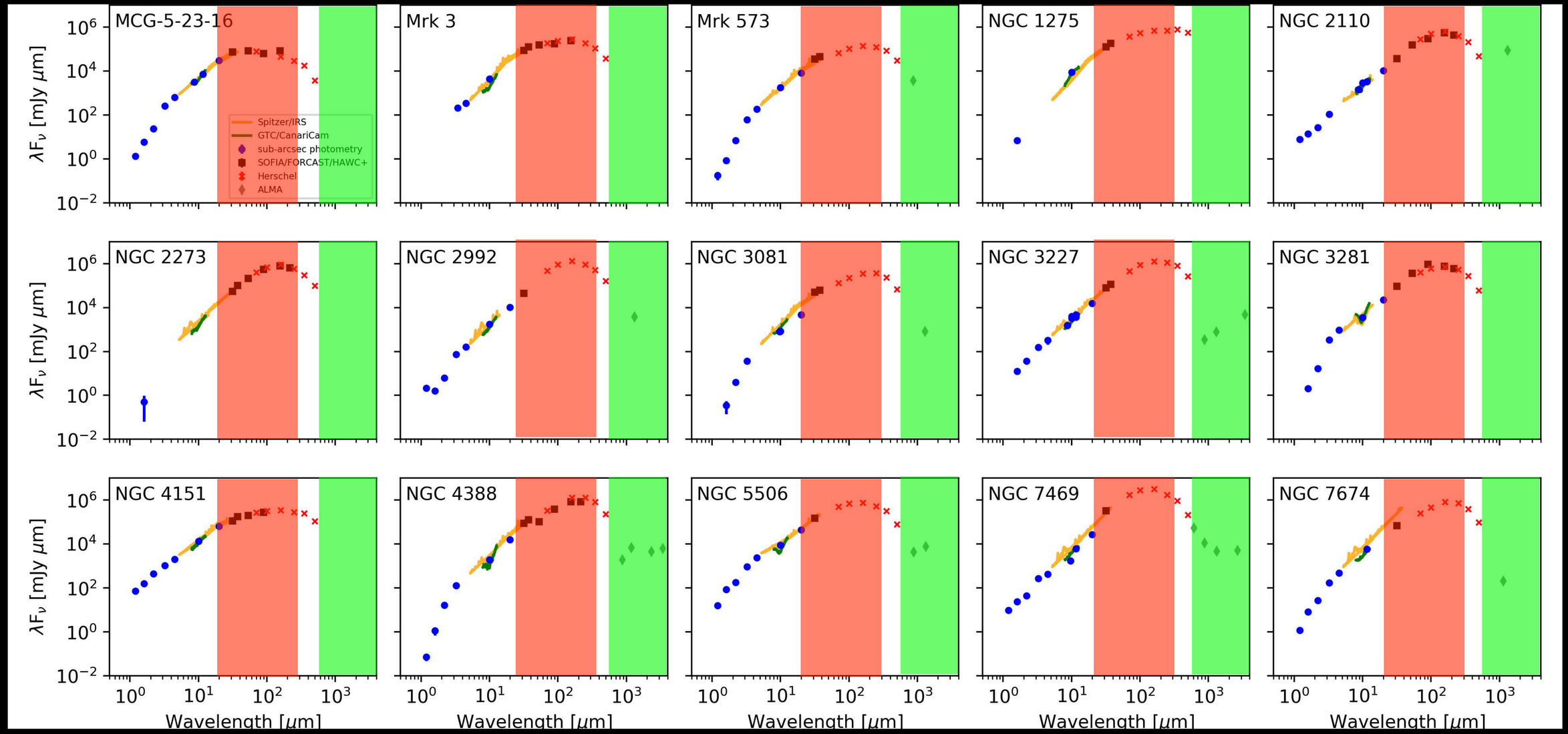
AGN SEDs of the objects observed with SOFIA Cycle 2-8 and ALMA

SOFIA: 30-40 um FORCAST and 50-214 um HAWC+

ALMA: Continuum emission and Band 3-7 (+Archival data)

Thermal emission (torus, SF, host galaxy)

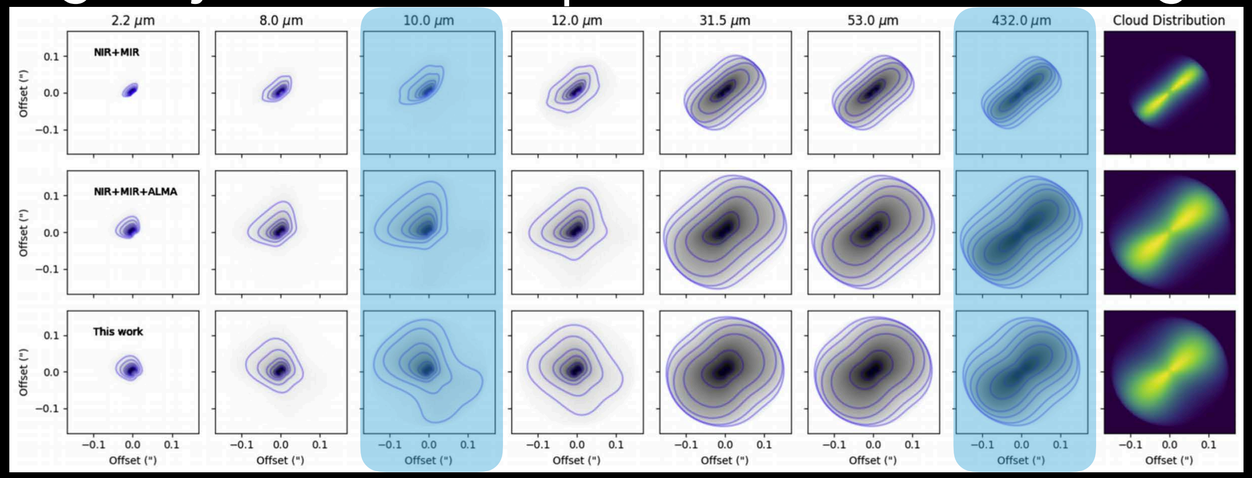
Synchrotron emission + thermal emission



Fuller et al. (in prep.)

Summary

- Thermal emission morphology of the torus highly depends on the wavelength coverage.
  - NIR+MIR: cannot probe the full extent of the torus observed by ALMA.
  - NIR+MIR+ALMA: cannot reproduce the IR extended emission observed by IR interferometry.
  - 1-900 um: reproduces IR extended emission and full extend of the torus.
- ALMA is the only facility that can resolve AGN tori
  - Empirically constrain the total intensity of the torus
- SOFIA can resolve the extended emission from SF and host galaxy
  - 30-40 um: AGN tori peak
  - 50+ um: SF and host galaxy emission components can be disentangled from SED decomposition.



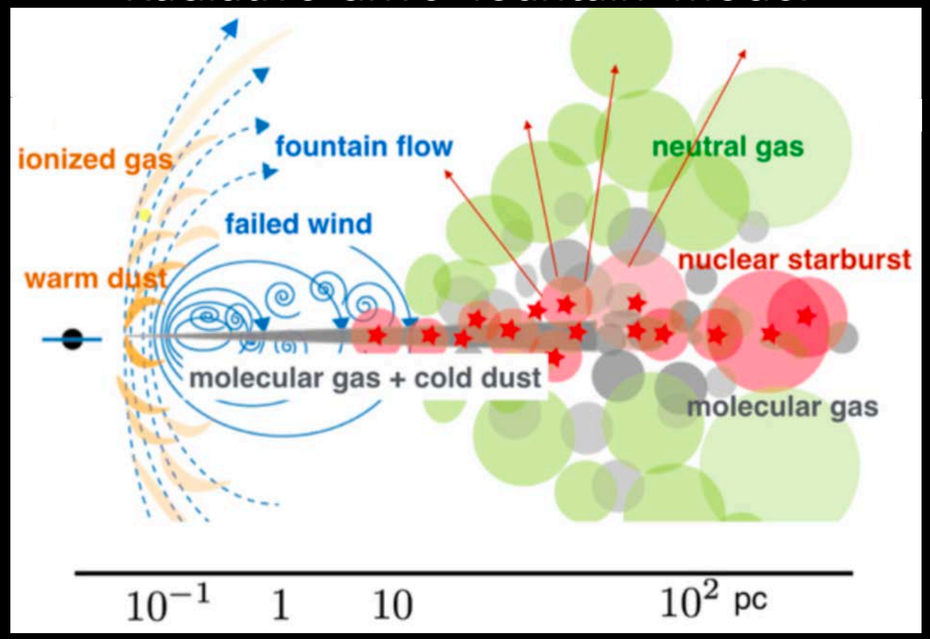
Lopez-Rodriguez et al. (2018a)

AGN Tori as an MHD Wind

SOFIA and ALMA Polarimetry

Towards a Hydromagnetic ‘torus’: formation and evolution

Radiative-drive ‘fountain’ model

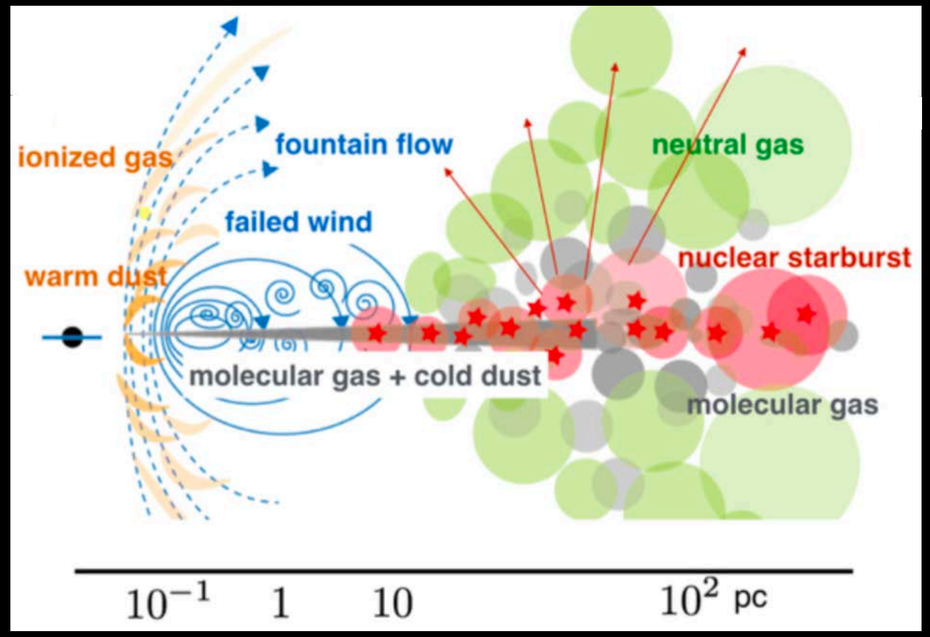


Credit: Wada, K.

Towards a Hydromagnetic ‘torus’: formation and evolution

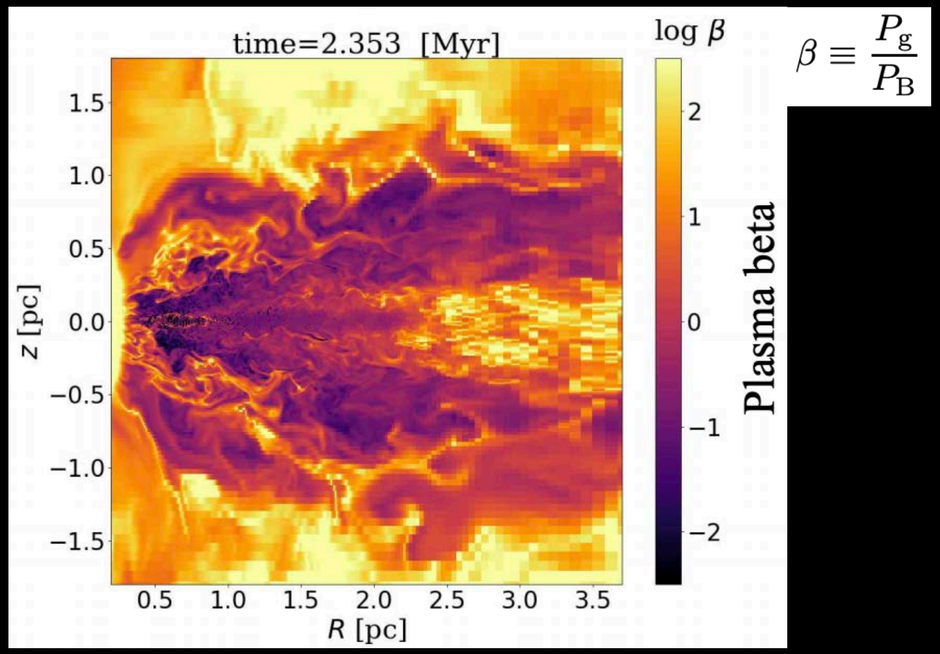
The ‘torus’ is a particular region of an inflow/outflow where the dust is located in optically thick regions influenced by the B-fields of the AGN

Radiative-drive ‘fountain’ model



Credit: Wada, K.

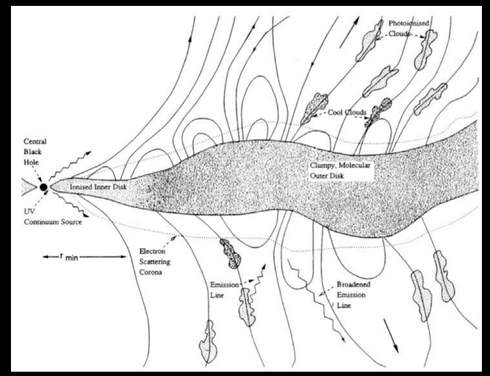
MHD-driven wind



$$\beta \equiv \frac{P_{\rm g}}{P_{\rm B}}$$

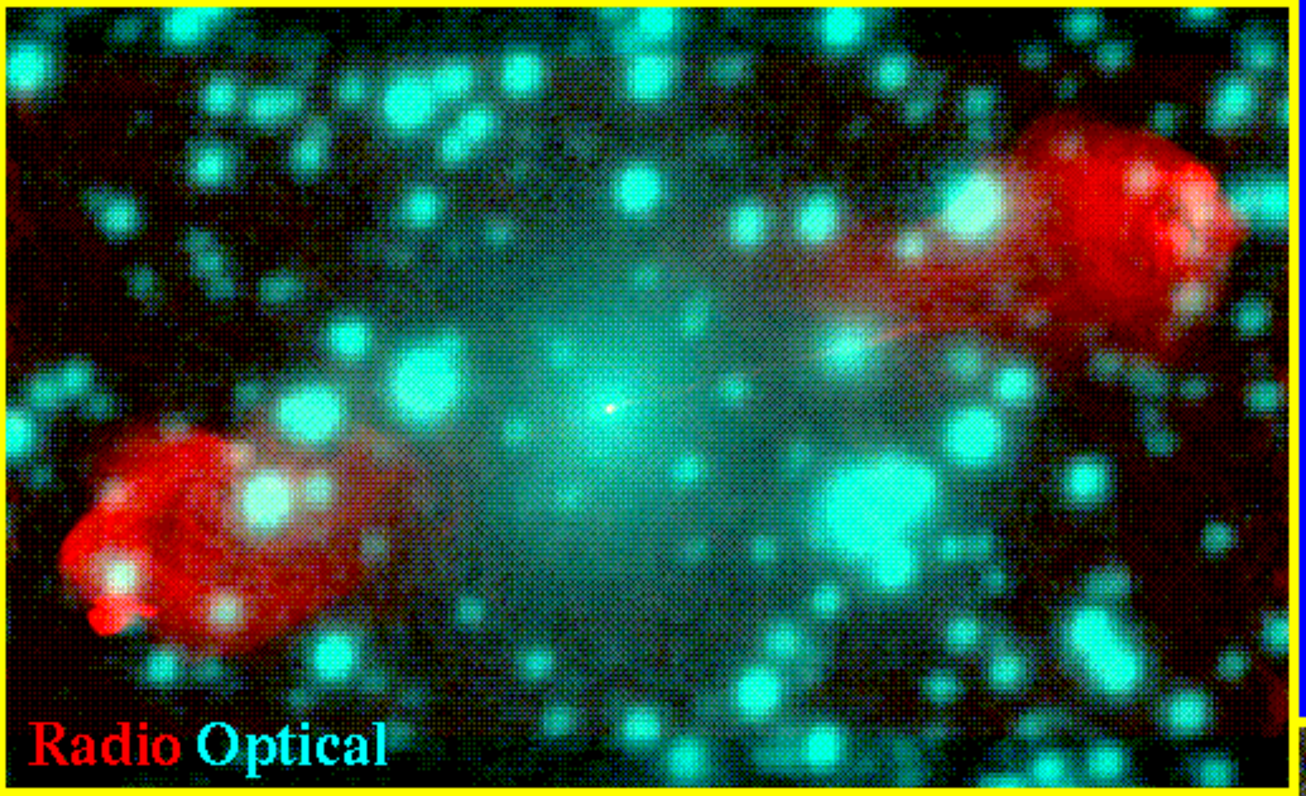
Kudoh, Wada & Norman (2020)

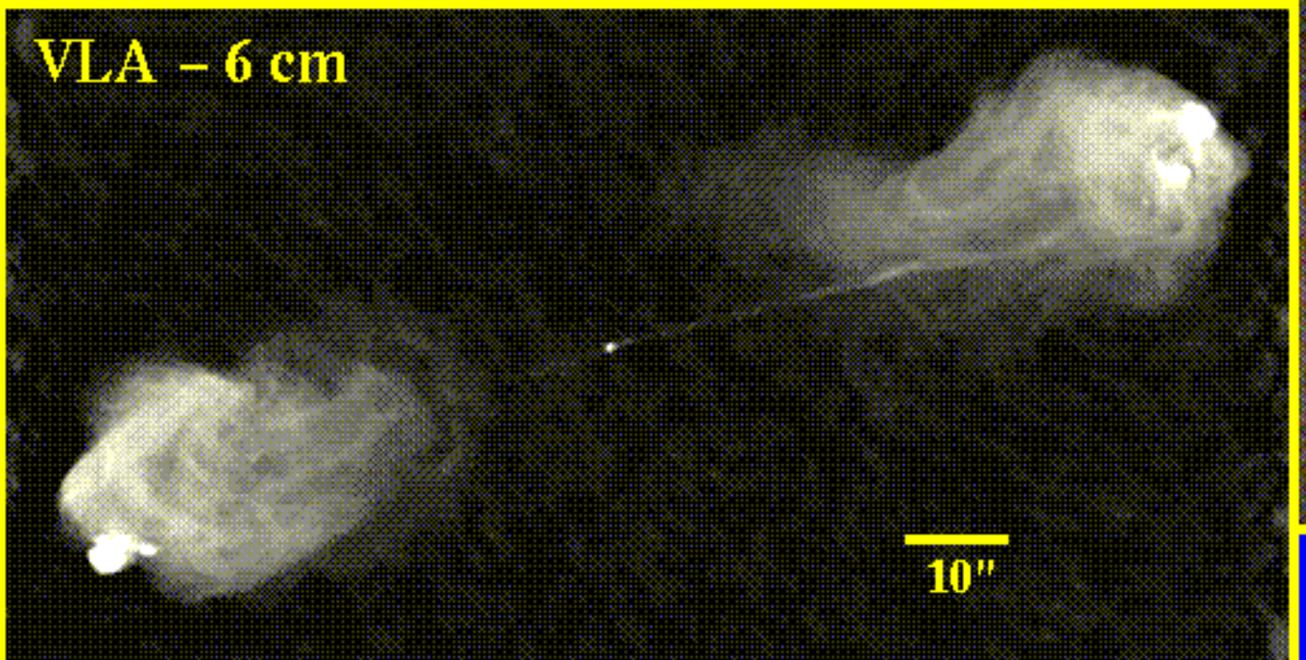
Bipolar outflows (‘polar dust’) can be dynamically associated with an inflowing disk
—> polar dust is a natural structure from the release of angular momentum removed magnetically by the inflowing material.



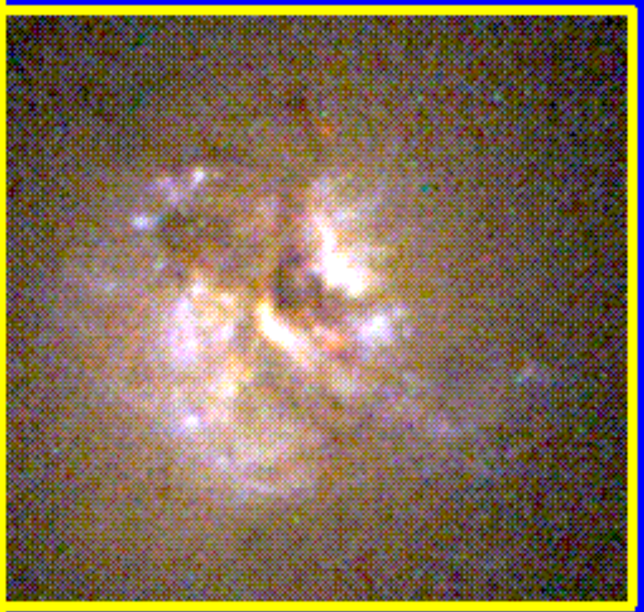
Emmering, Blandford & Shlosman (1992)

Cygnus A (3C 405)



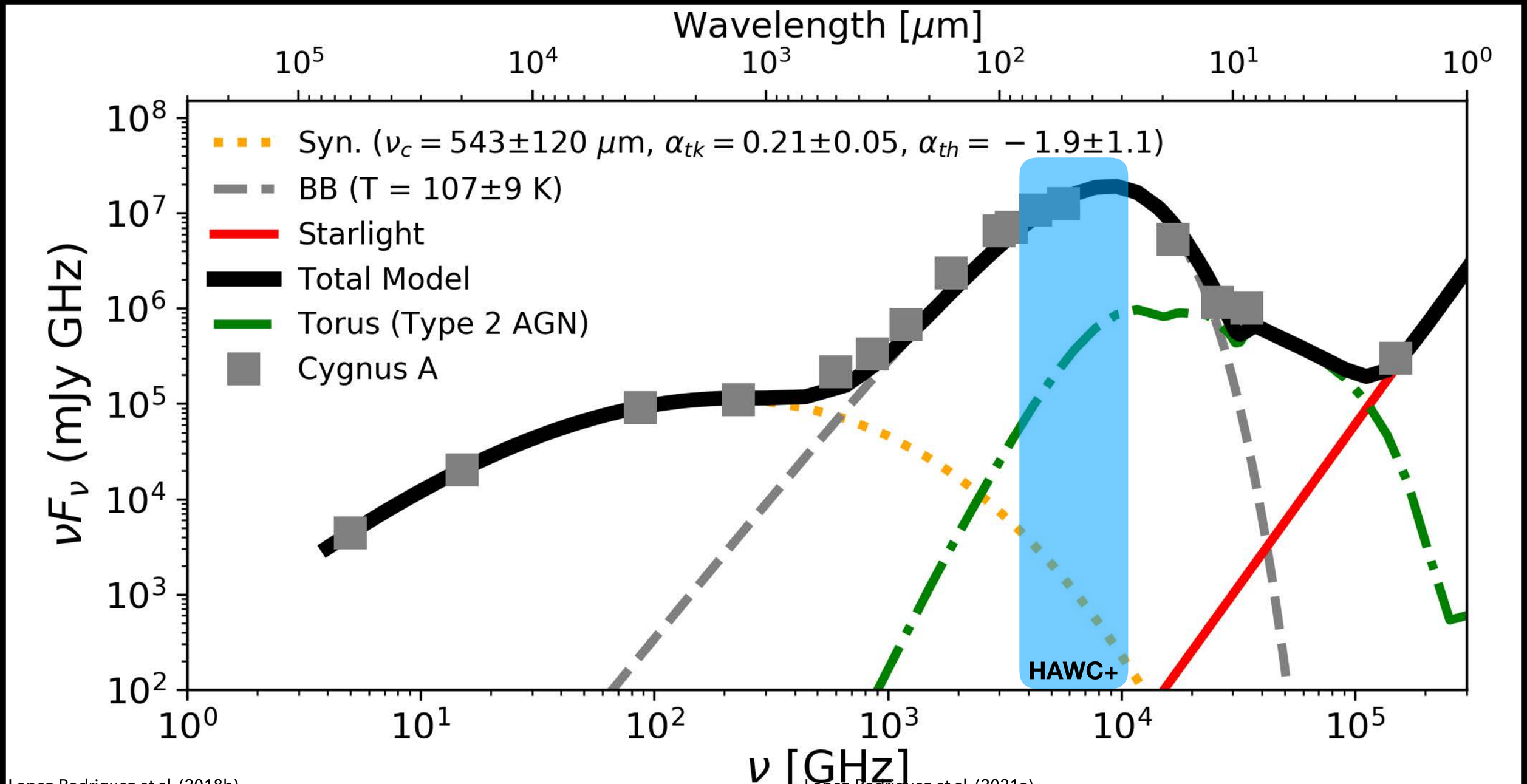


HST closeup



5"

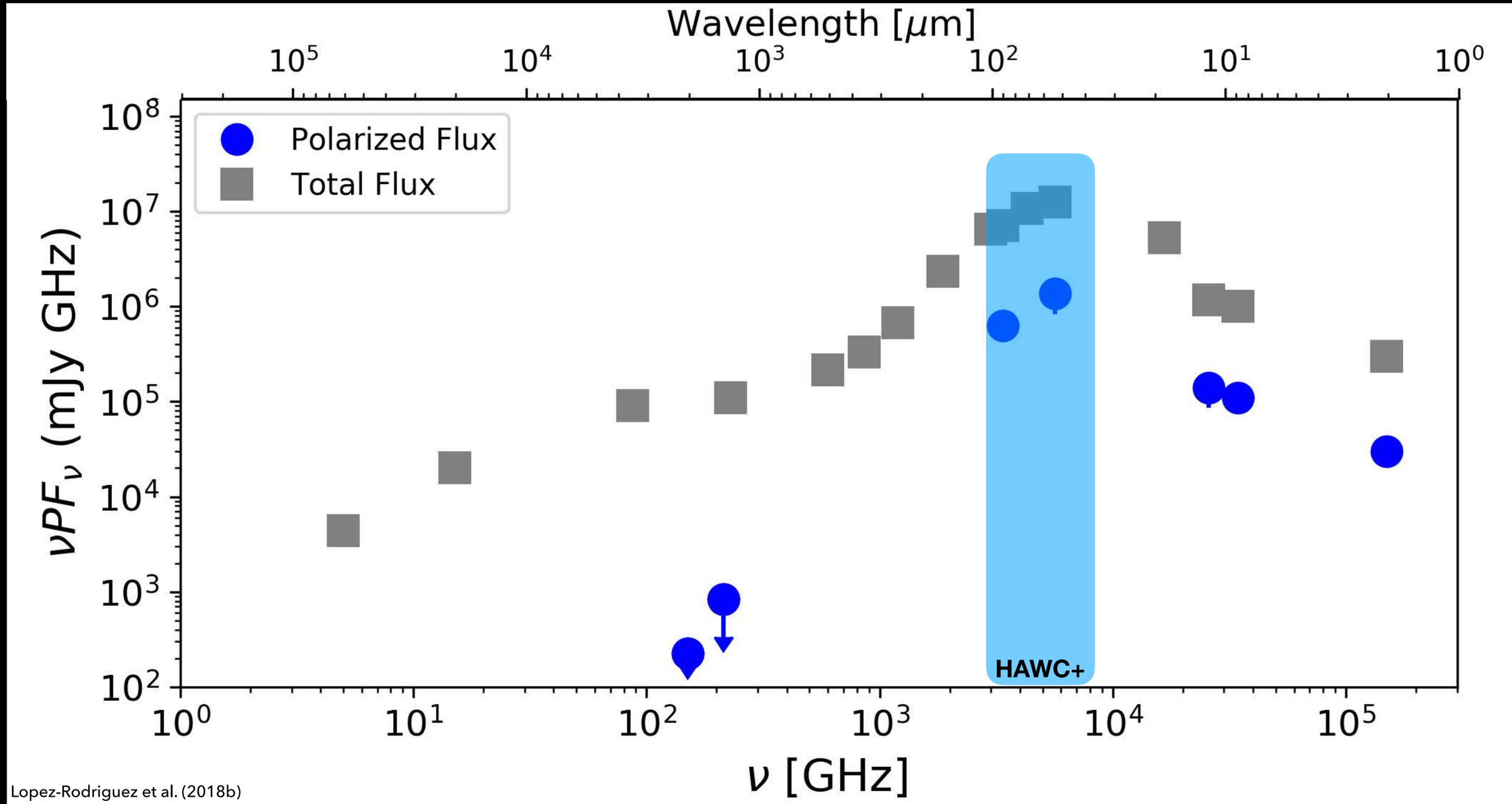
Total Flux



Lopez-Rodriguez et al. (2018b)

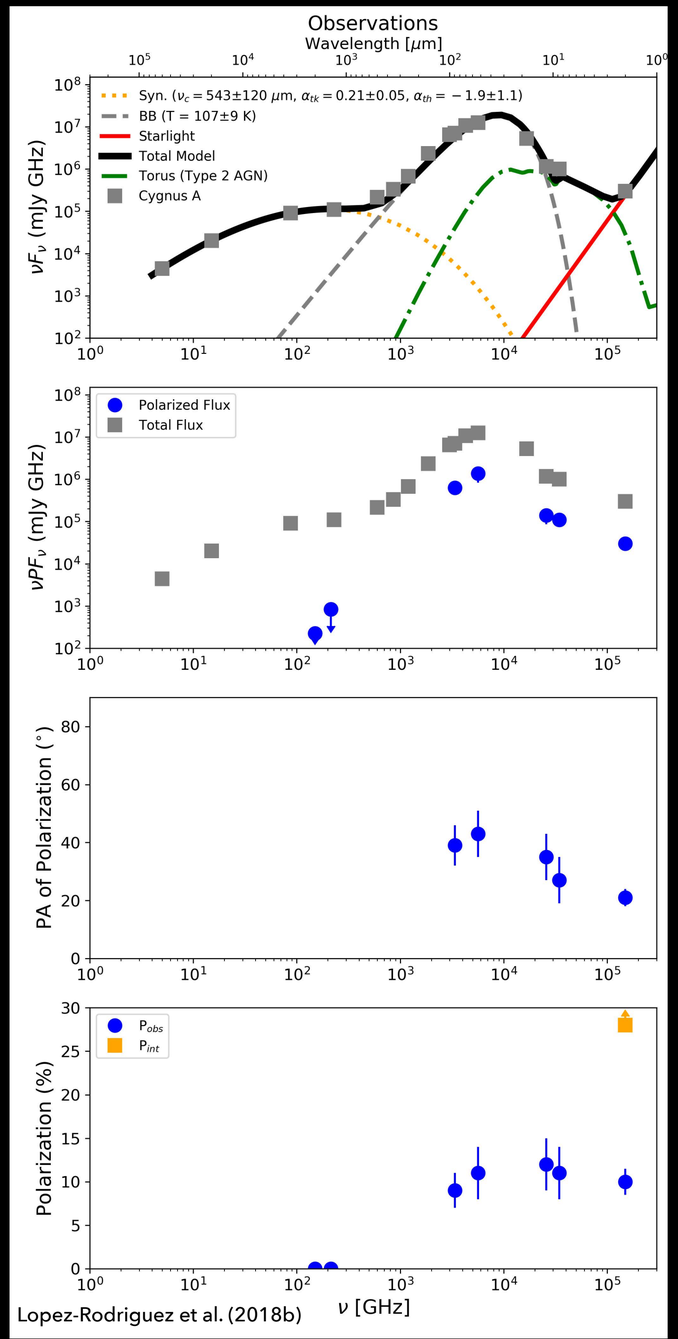
Lopez-Rodriguez et al. (2021a)

Polarized Flux



Lopez-Rodriguez et al. (2018b)

Polarized SED



Lopez-Rodriguez et al. (2018b)

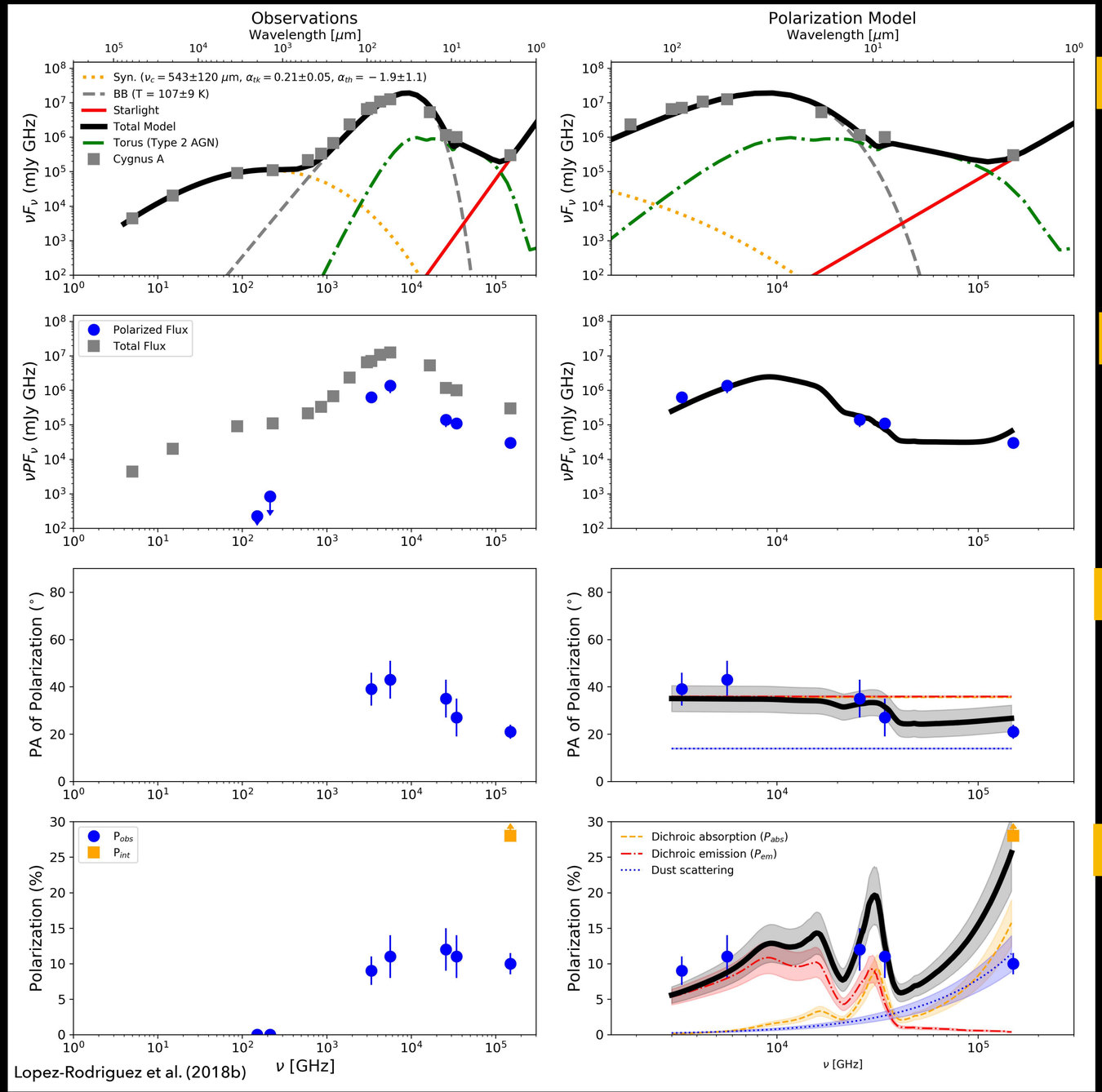
Total Intensity

1) Synchrotron emission is insignificant at infrared wavelengths.
2) IR bump dominated by dust emission in the torus and extended structures.

Polarized flux

The polarized flux follows the infrared bump of the total flux SED.

Polarization Model



Lopez-Rodriguez et al. (2018b)

Total Intensity

1) Synchrotron emission is insignificant at infrared wavelengths.
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Polarized flux

The polarized flux follows the infrared bump of the total flux SED.

Position Angle of Polarization

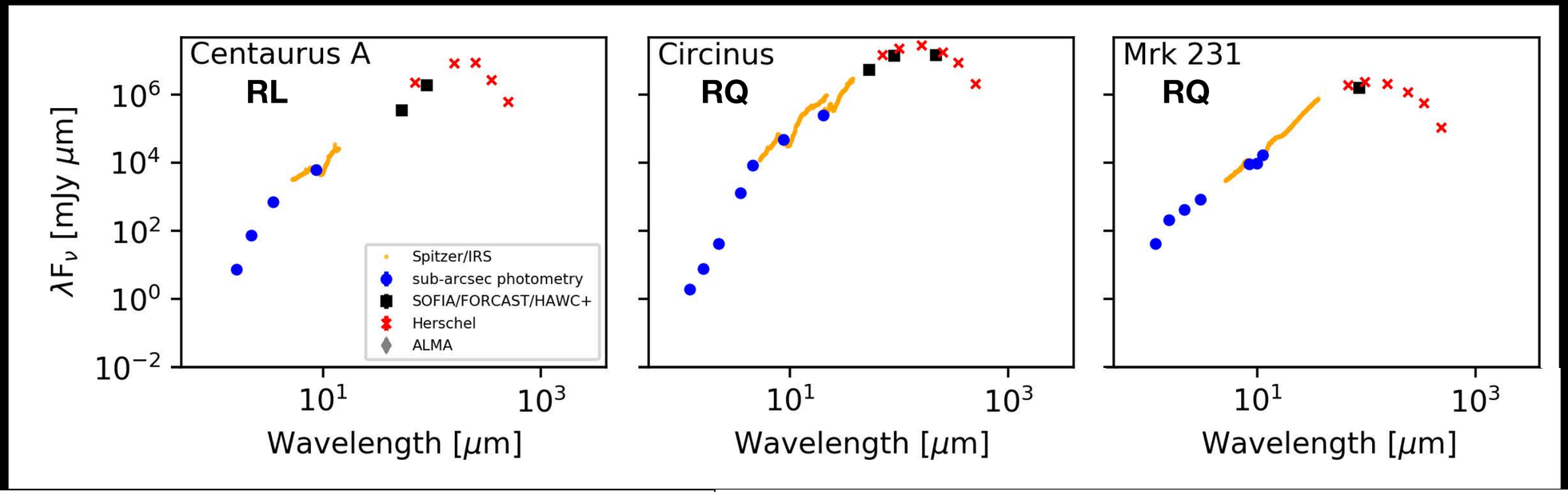
Change of PA of polarization due to a change in polarization mechanisms.

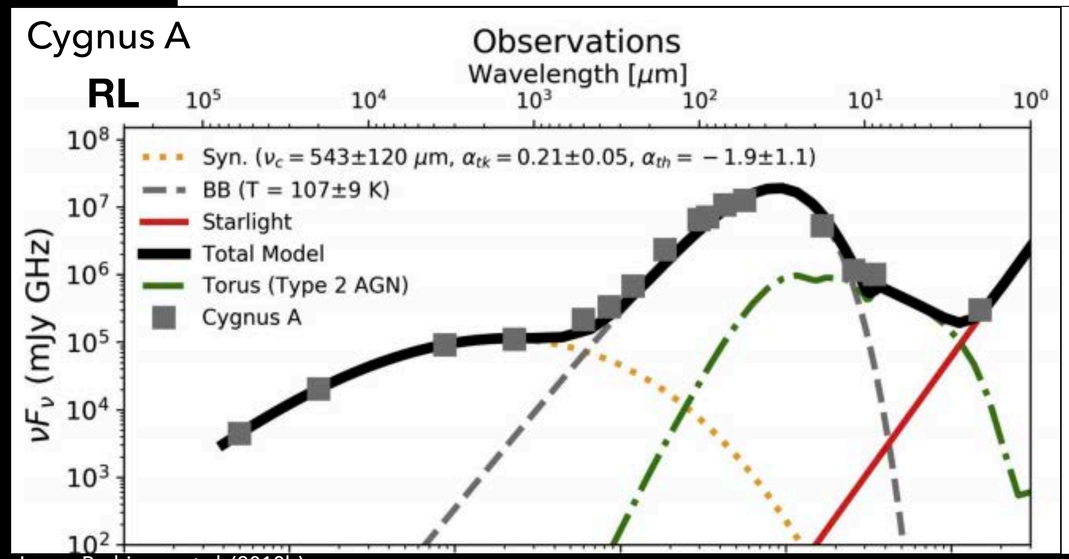
Degree of Polarization

- FIR: Polarization from dust emission of aligned dust grains in a very compact, ~20 pc, dusty structure.
- MIR: Dust emission and absorption competes.
- NIR: dust scattering from surrounding dust.

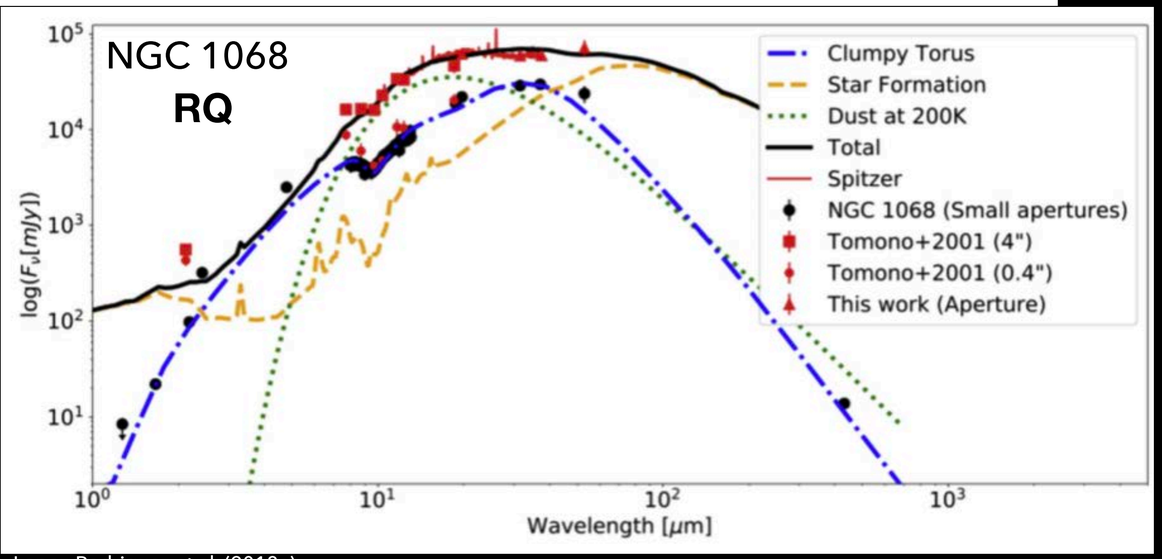
SED of Radio-Quiet (RQ) and Radio-loud (RL) AGN

Despite the radio emission, the IR emission from the AGN is quite similar for both RL and RQ AGN





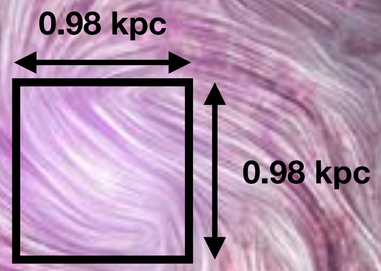
Lopez-Rodriguez et al. (2018b)

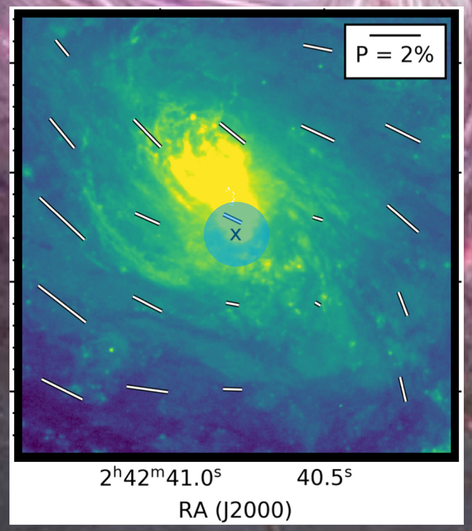


Lopez-Rodriguez et al. (2018a)


NGC 1068
Radio Quiet
89 um (HAWC+)
Lopez-Rodriguez et al. (2020a)

NGC 1068
Radio Quiet



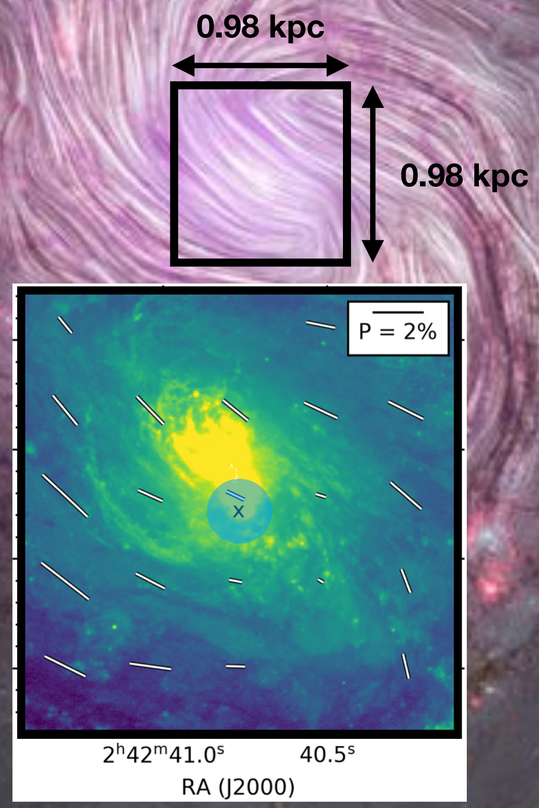


Unpolarized Core

89 um (HAWC+)

Lopez-Rodriguez et al. (2020a)

NGC 1068
Radio Quiet



Unpolarized Core

89 um (HAWC+)

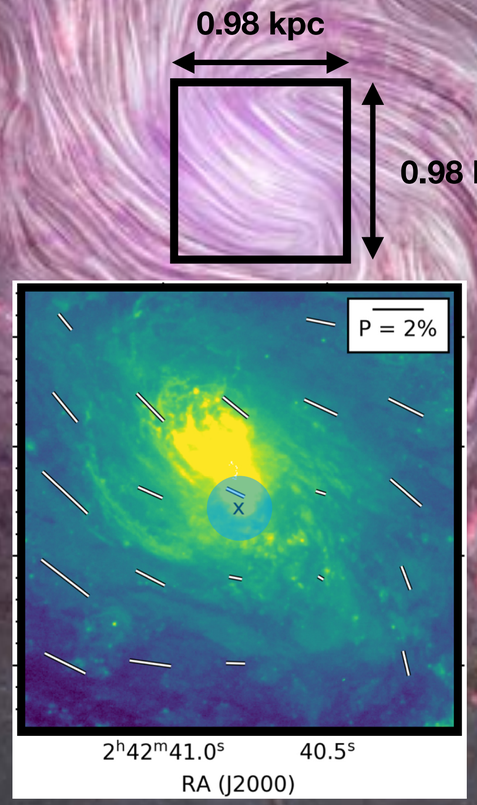
Lopez-Rodriguez et al. (2020a)

Centaurus A
Radio Loud

89 um (HAWC+)

Lopez-Rodriguez (2021a)

NGC 1068
Radio Quiet

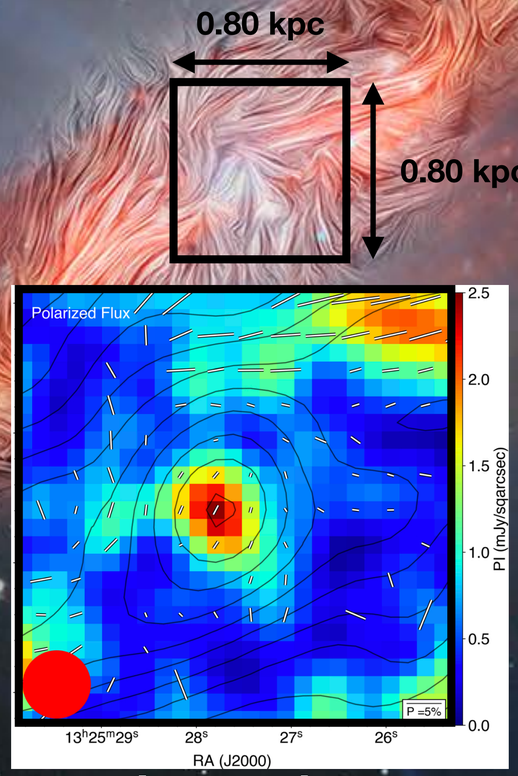


Unpolarized Core

89 um (HAWC+)

Lopez-Rodriguez et al. (2020a)

Centaurus A
Radio Loud



Polarized Core

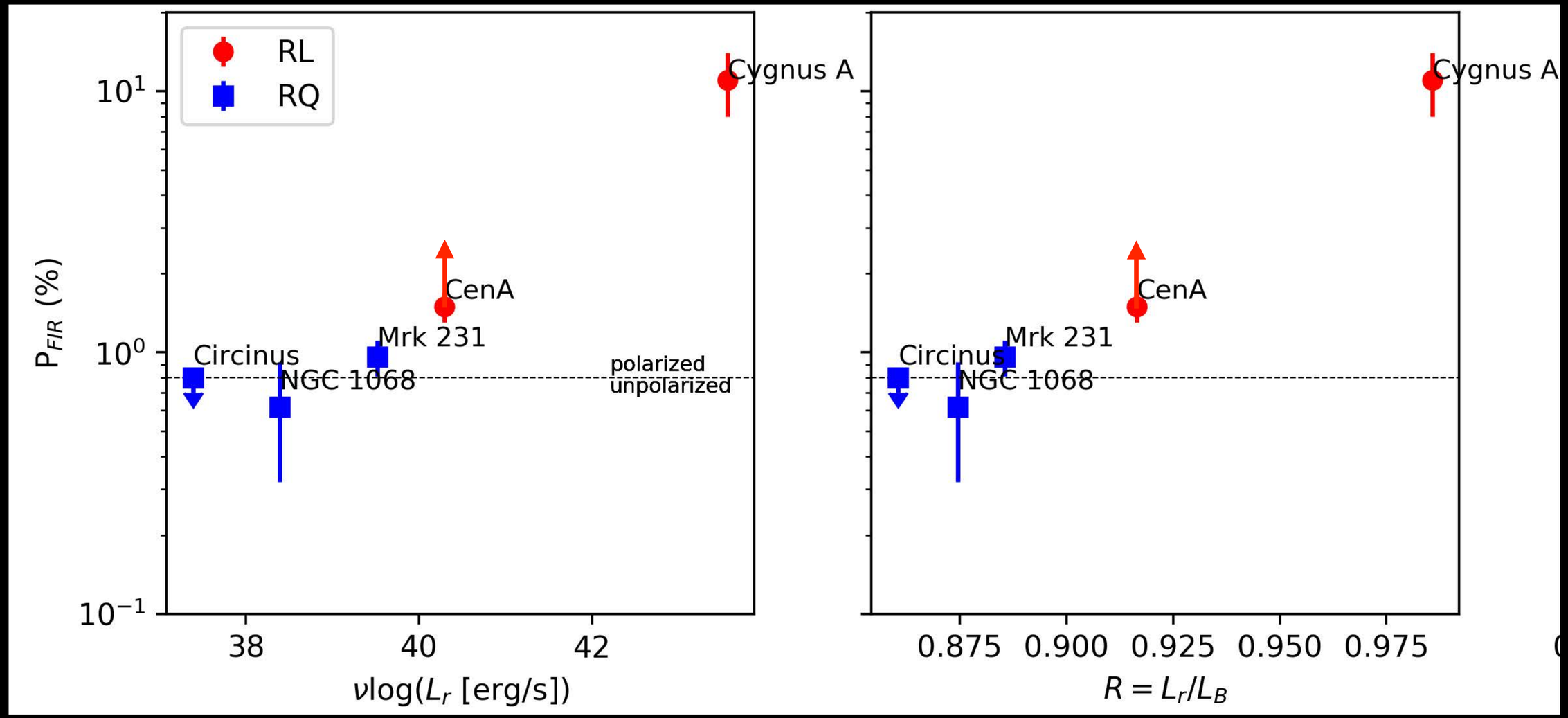
89 um (HAWC+)

Lopez-Rodriguez (2021a)

Radio Quiet vs Radio Loud (in prep.)

RL AGN are:

- Highly polarized (P>2%)
- B-field orientation perpendicular to the jet axis.

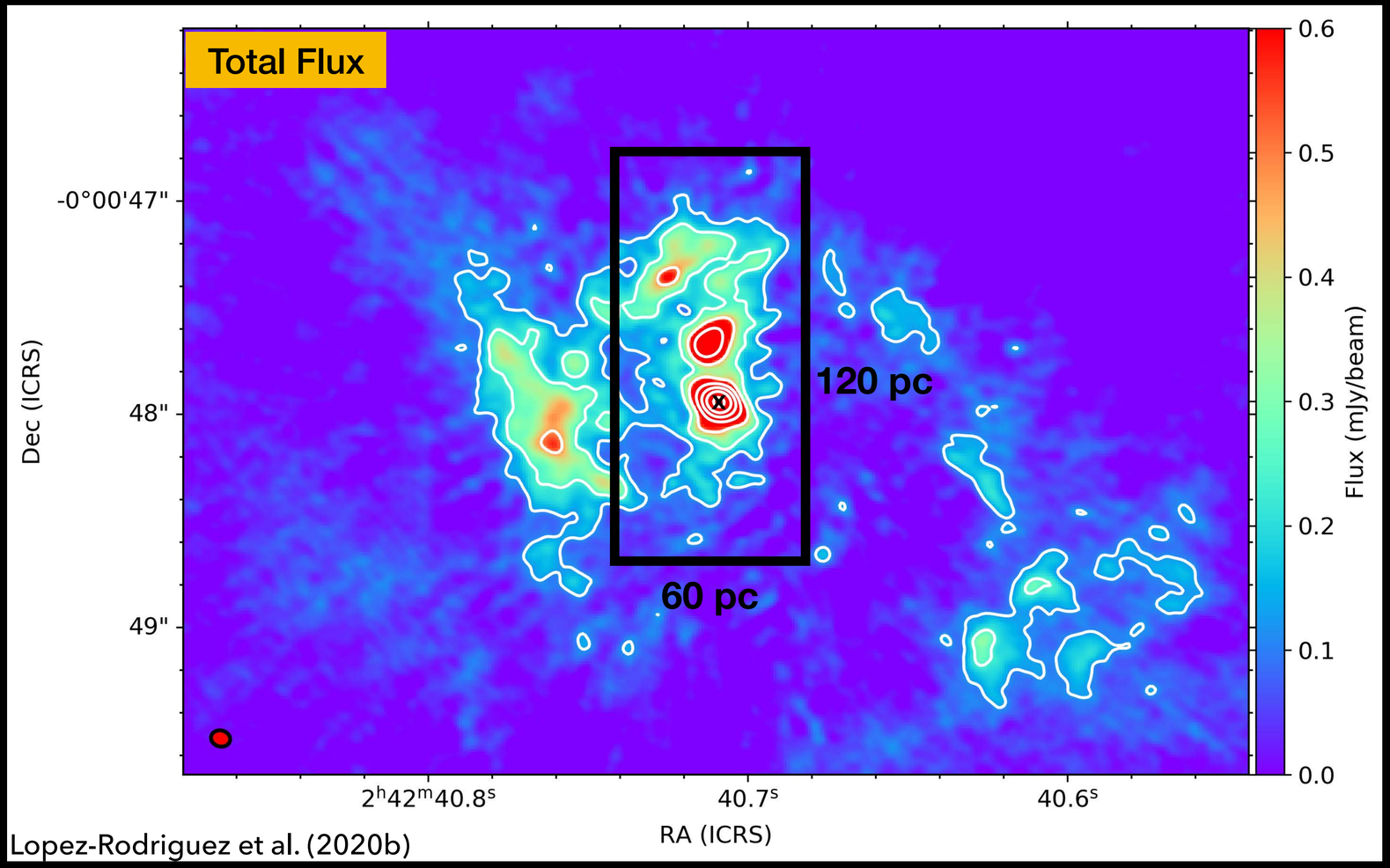


Radio jet luminosity

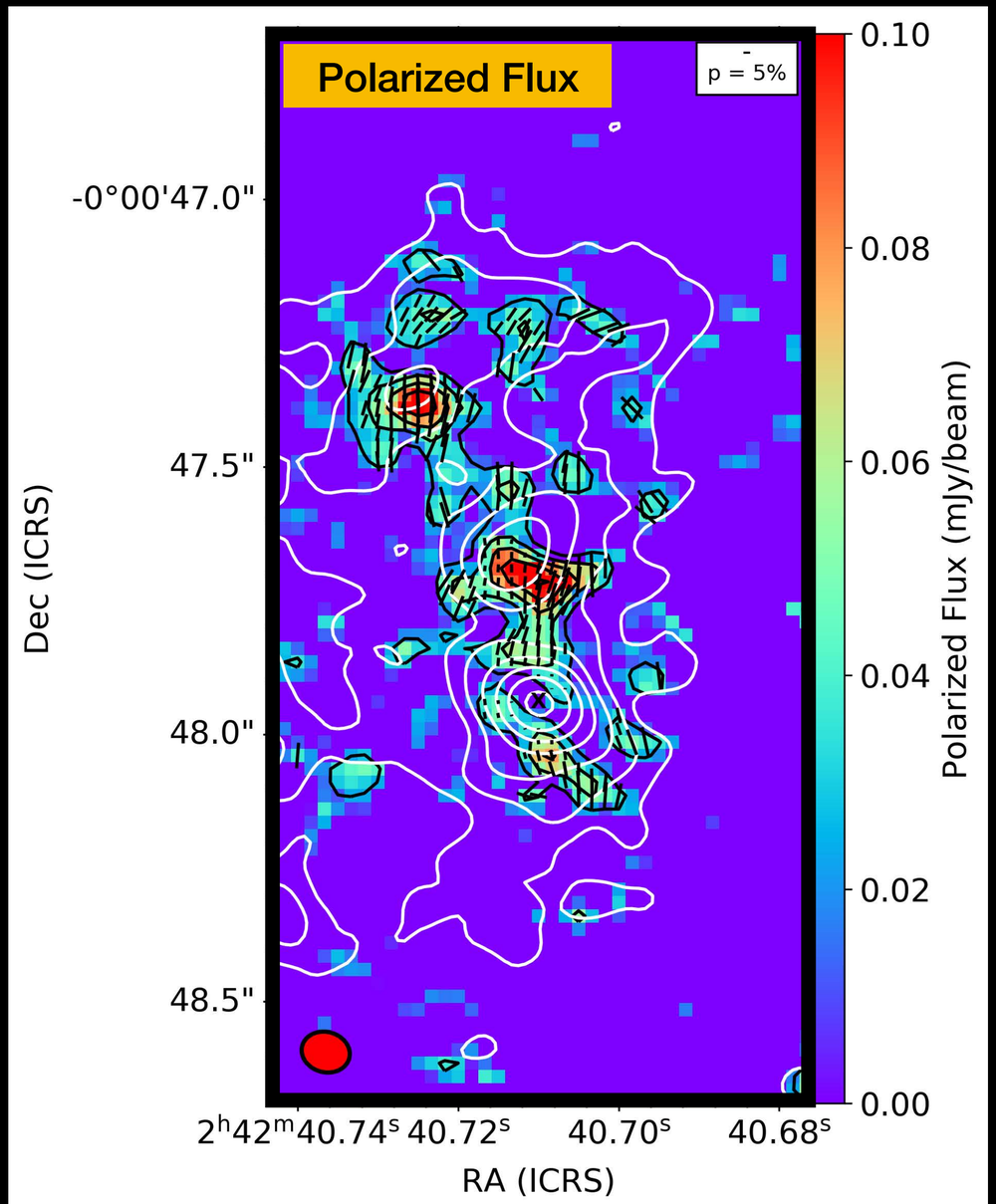
Radio 'loudness'

ALMA Polarimetry

Band 7 (348.5 GHz, 860 μm) - Dust continuum
Resolution: 0.07” (4.1 pc)
Execution time: 9.17h

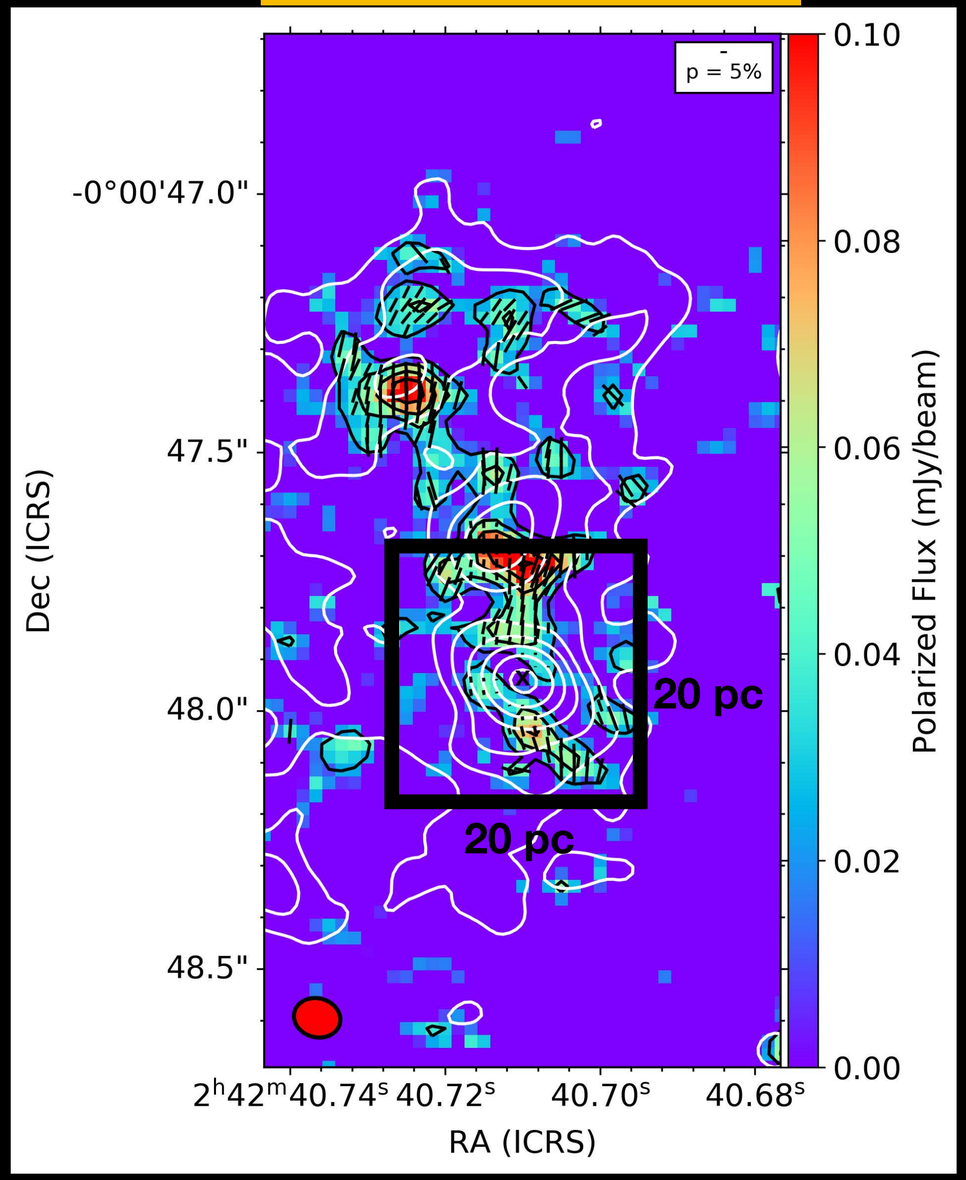


Lopez-Rodriguez et al. (2020b)

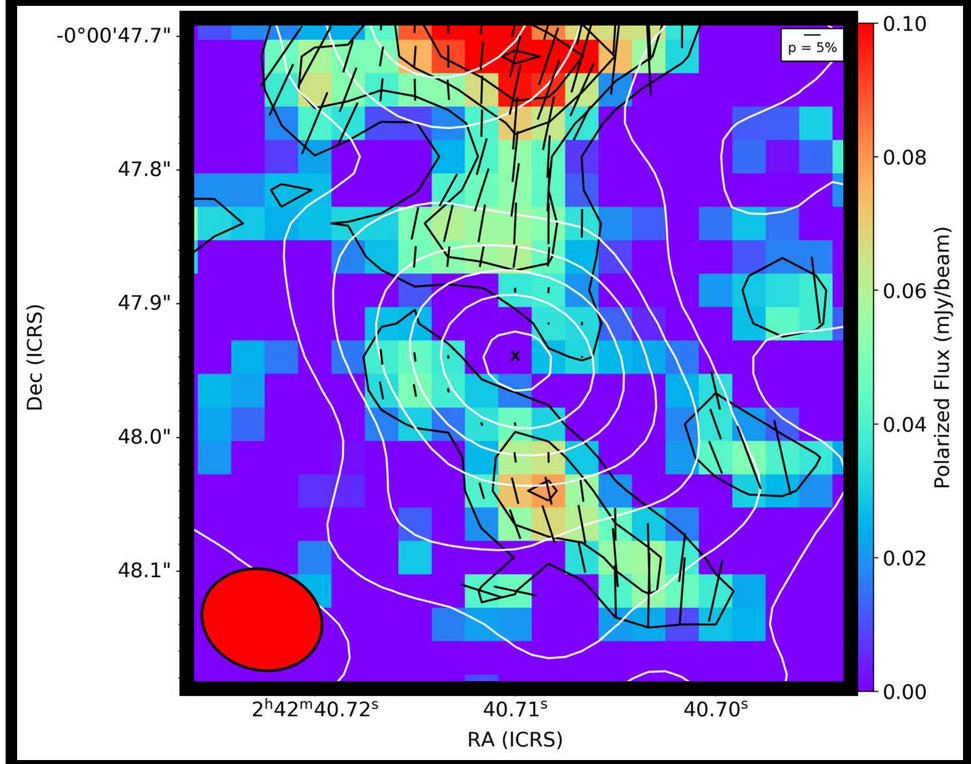


ALMA resolved the B-field of the torus of NGC 1068

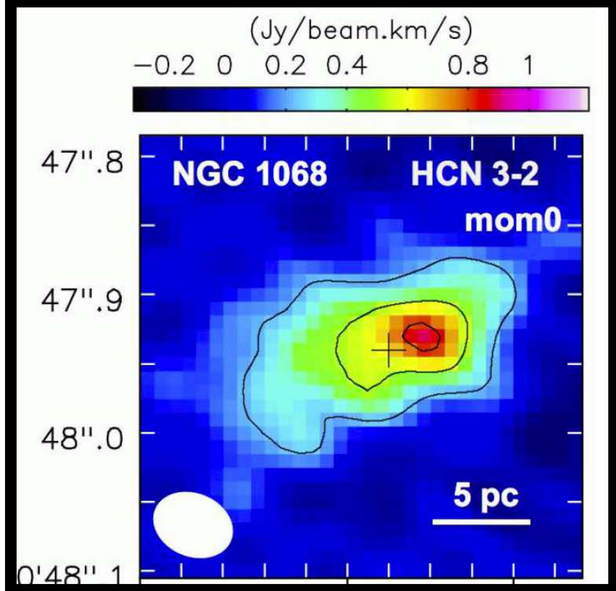
100-pc scale polarized flux



10 pc-scale polarized flux



10 pc-scale HCN 3-2



Imanishi et al. (2018)

Lopez-Rodriguez et al. (2020b)

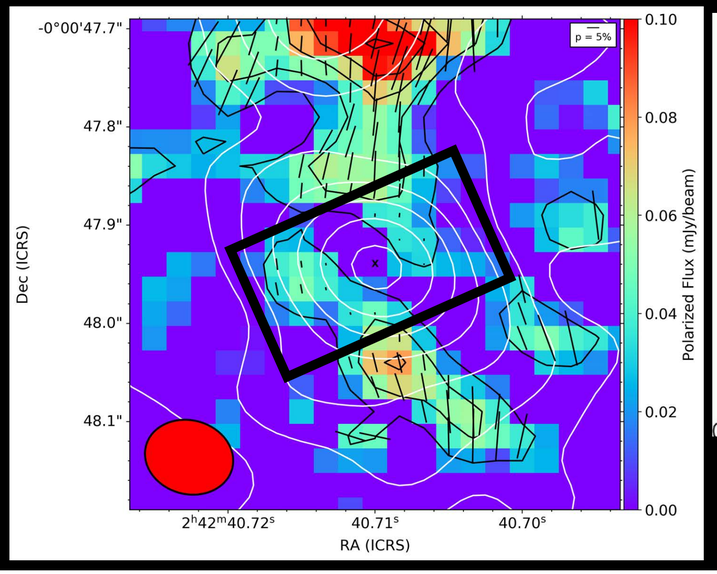
Polarization properties of the torus

1. The outer regions of the torus are polarized.

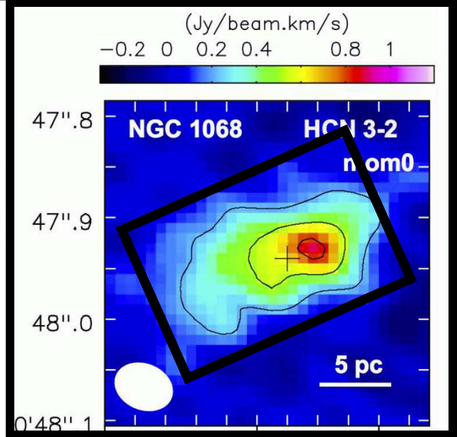
2. The polarization angle is parallel to the equatorial axis of the torus.

3. The core (<0.07”, 4.1 pc) is unpolarized.

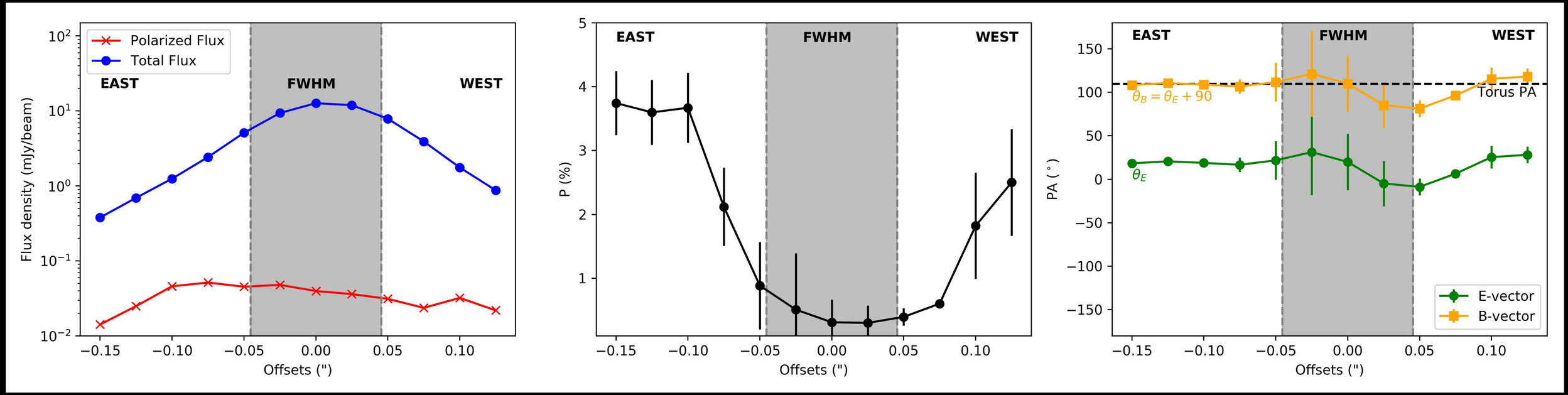
10 pc-scale polarized flux



10 pc-scale HCN 3-2



Imanishi et al. (2018)



Lopez-Rodriguez et al. (2020b)

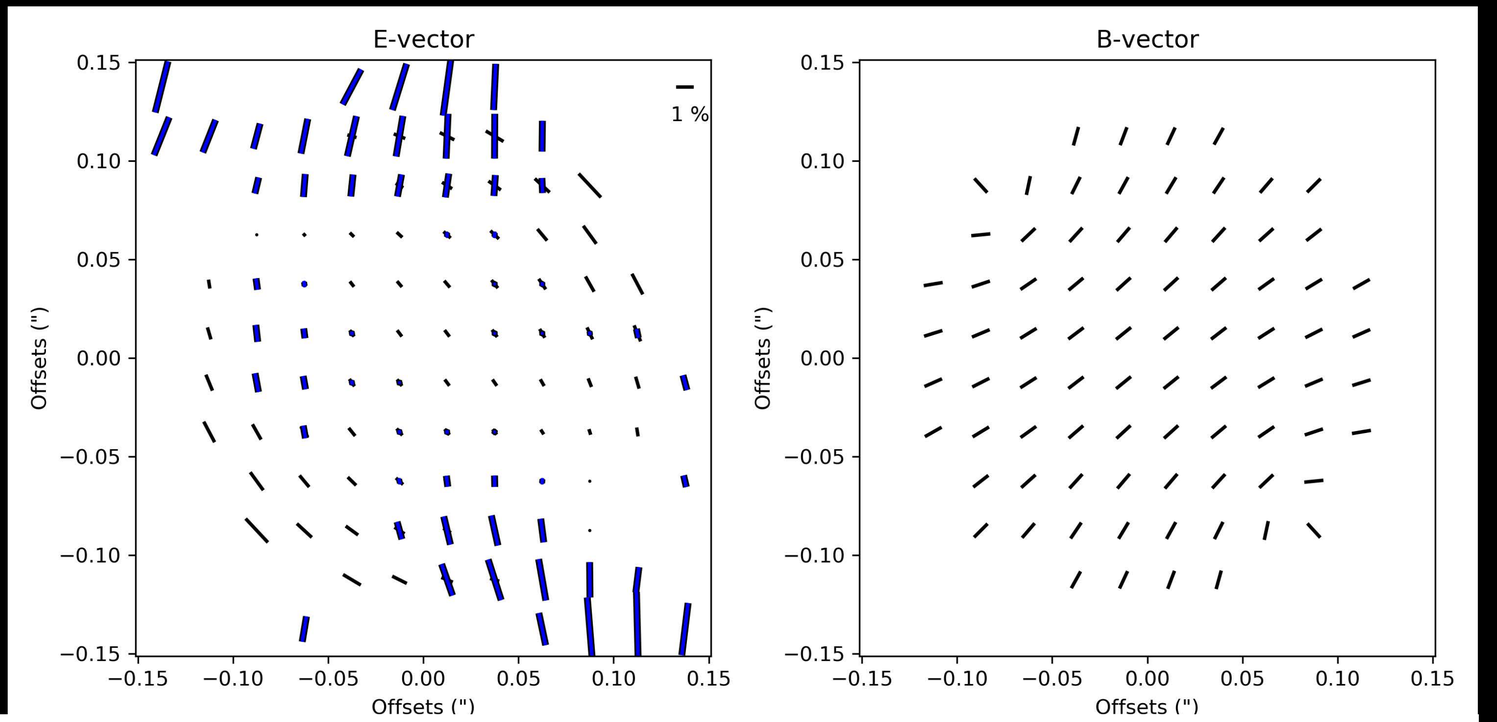
Synthetic observations of the polarized dust emission

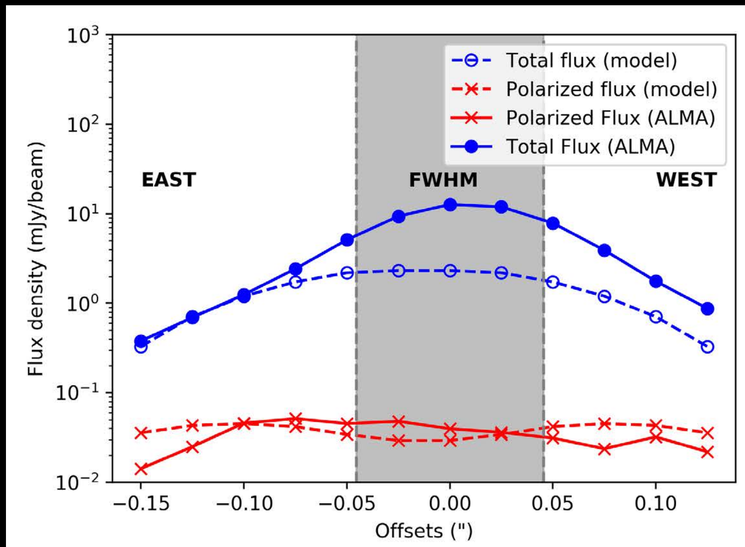
Synthetic observations:

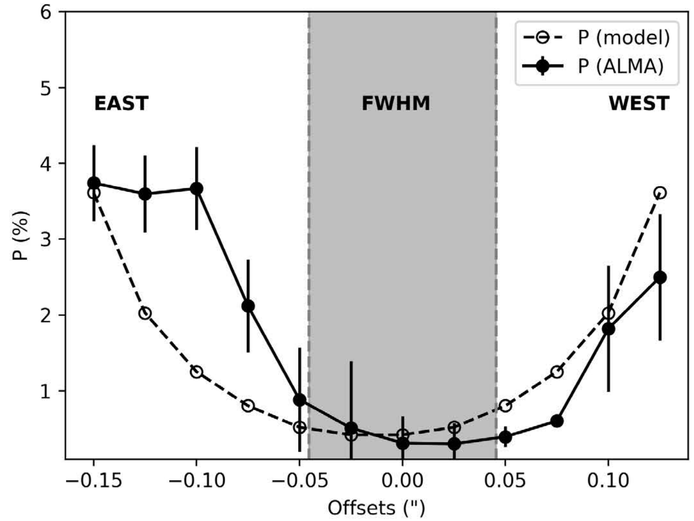
- Toroidal magnetic field
- Homogeneous grain alignment
- Radiative transfer model of the dust emission using the torus SED from 1 to 800 um (HyperCAT, Nikutta+2021a,b)

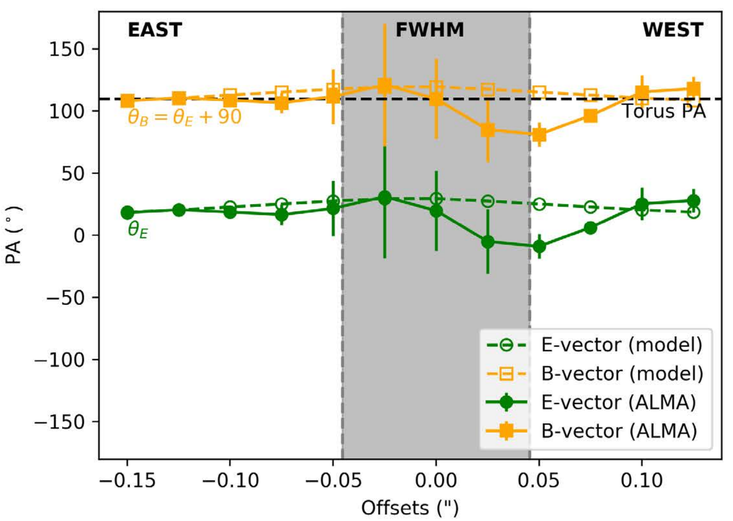
We found:

- ***Toroidal magnetic field is viewed at an inclination of 75° with a size of up to 18 pc.***





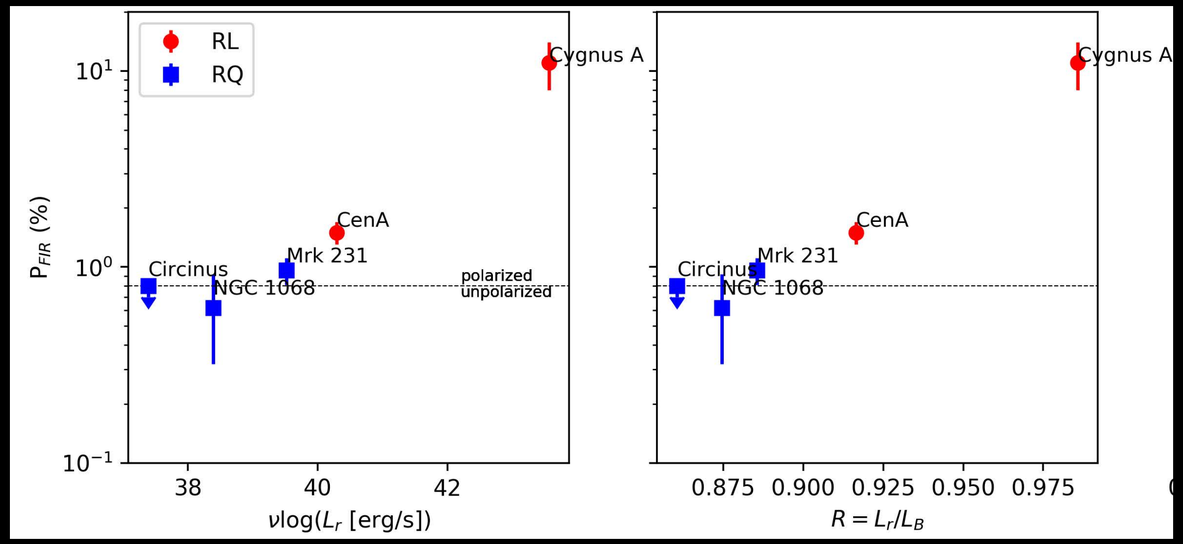




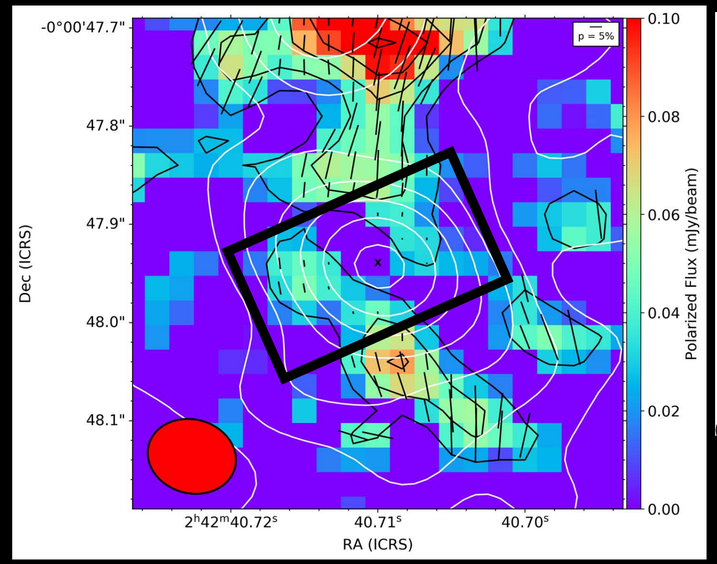
Lopez-Rodriguez et al. (2020b)

Summary

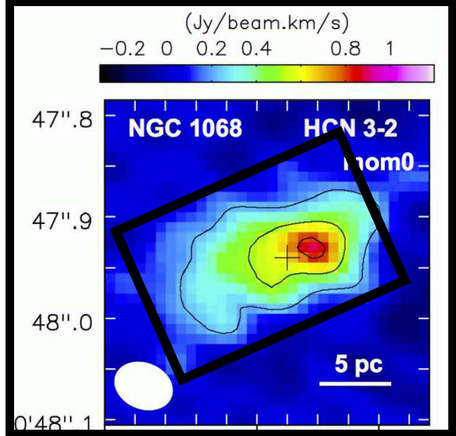
- ALMA and SOFIA trace thermal polarized emission by means of magnetically aligned dust grains.
- SOFIA suggests a potential difference from RL and RQ AGN at <100 pc scales.
  - RQ AGN have high polarized cores (P>2%) with B-field along the equatorial axis of the torus
    - This B-field may be the large-scale component from the central engine supporting accretion flow
- ALMA is the only facility that can resolve the B-field in AGN tori.
  - Torus flux emission and gas dynamics can be constrained.
  - The core of NGC1068 (RQ) is still unpolarized (extinction, multi-component velocities)
  - The outer part of the torus is polarized and consistent with a toroidal B-field.



10 pc-scale polarized flux



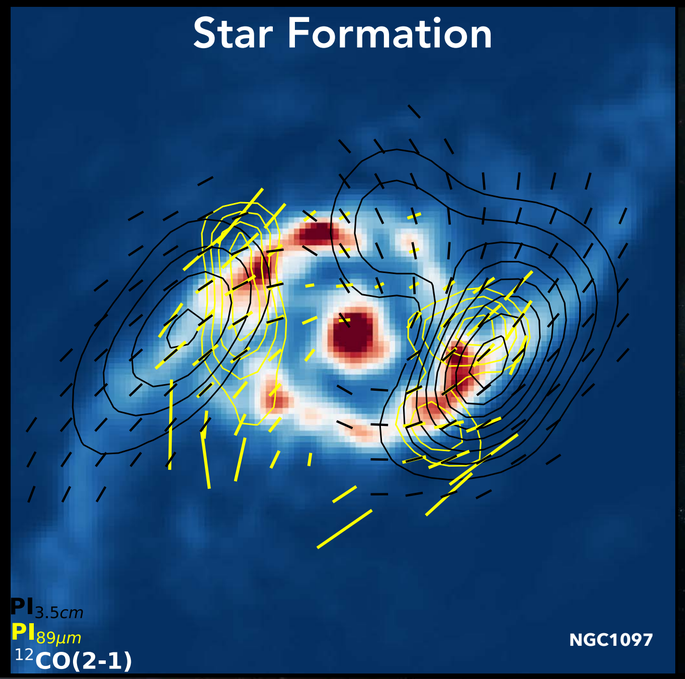
10 pc-scale HCN 3-2

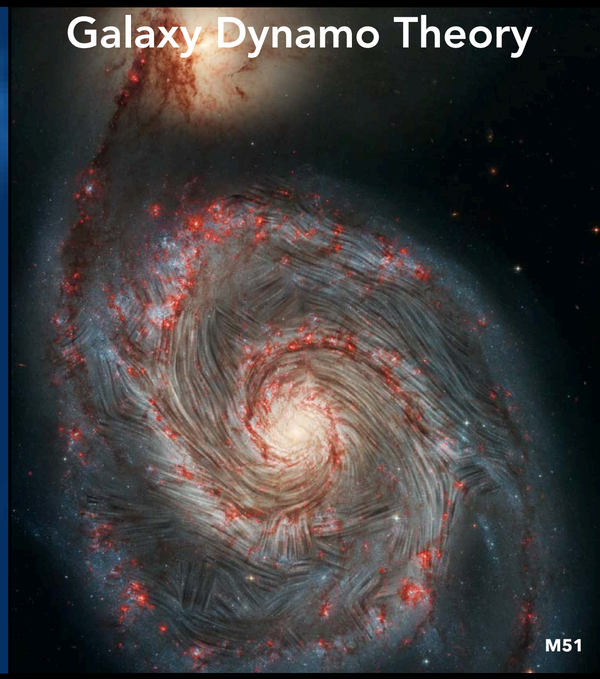


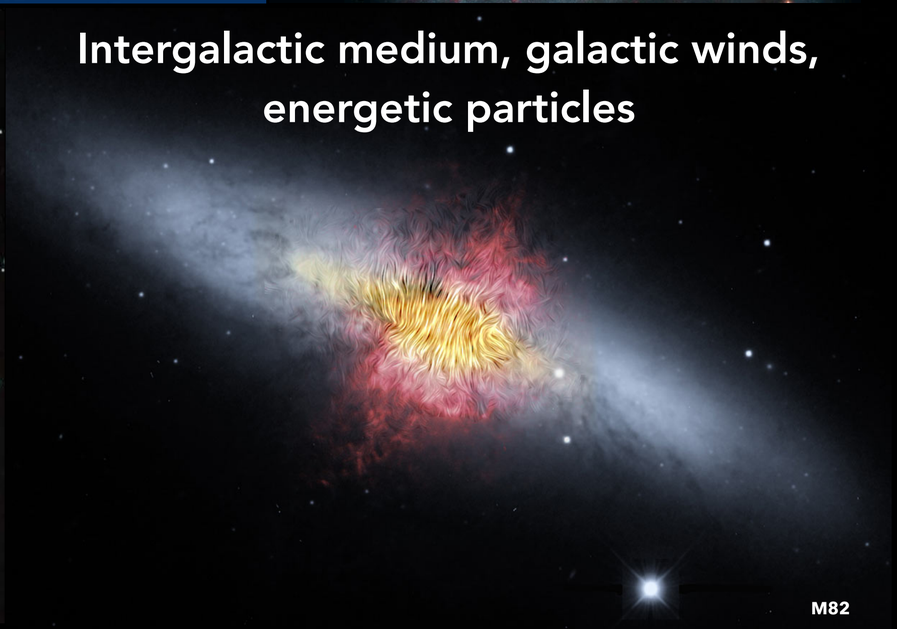
Extragalactic Magnetic Fields

SOFIA Polarimetry and ALMA Line Emission & Polarimetry

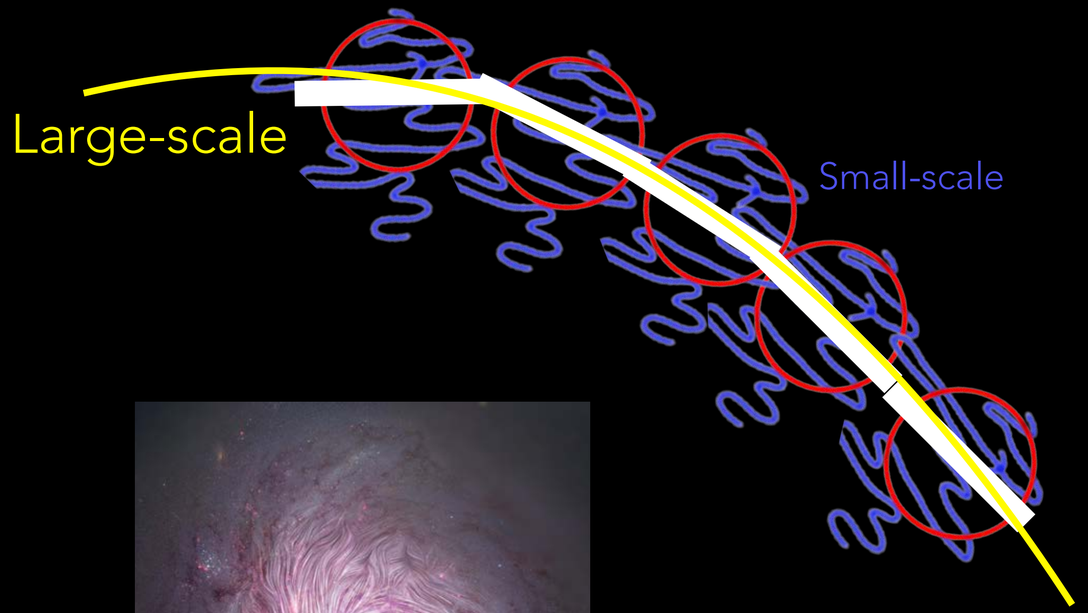
Key science topics of the legacy program







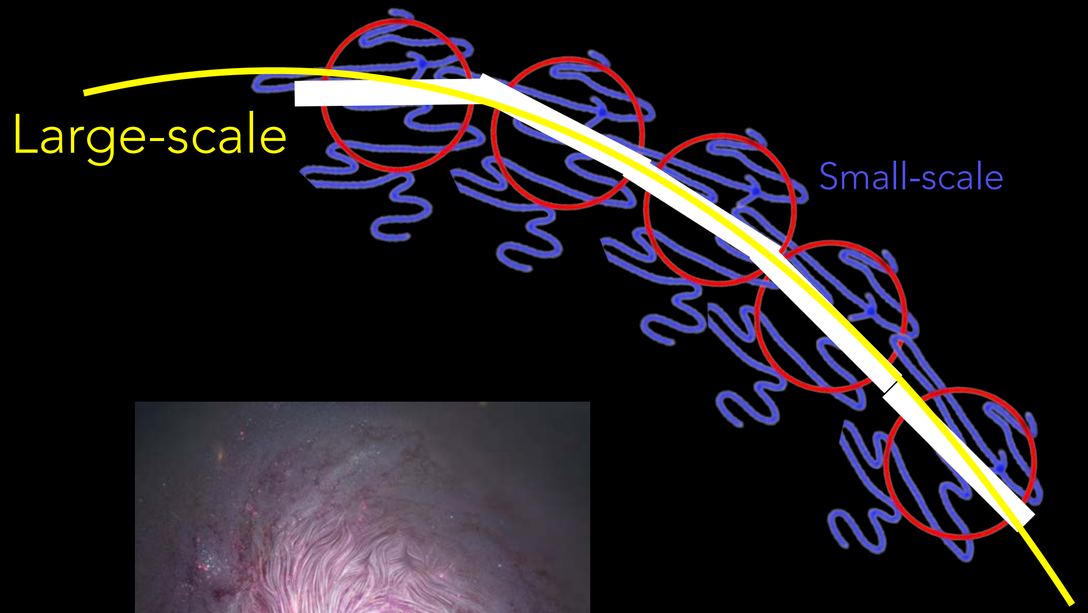
NGC 1068: large-scale field dominates



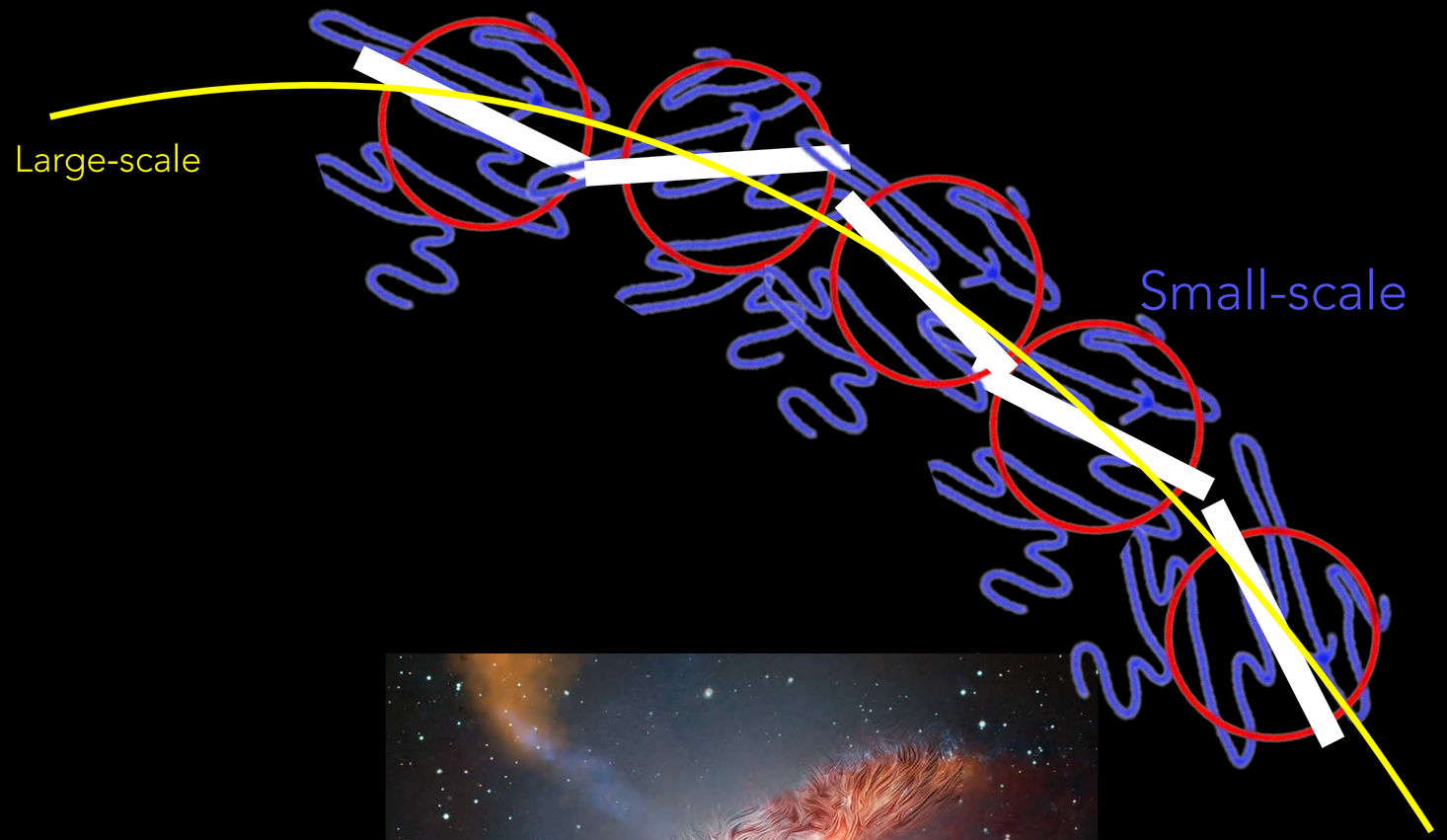
NGC 1068

Lopez-Rodriguez et al. (2020a)

Centaurus A: small-scale turbulent field dominates

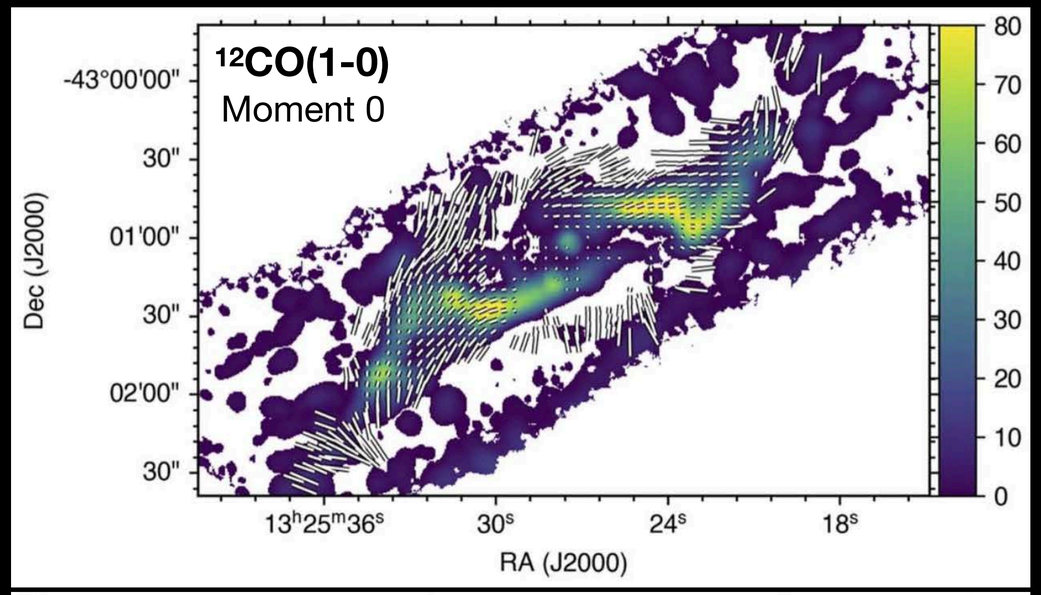


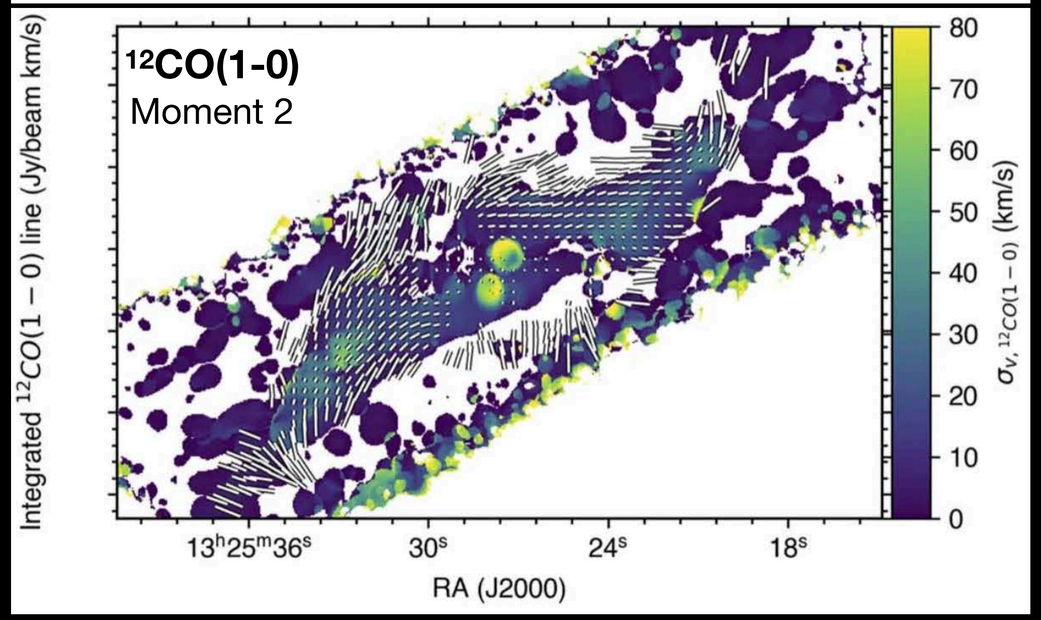
NGC 1068



Centaurus A

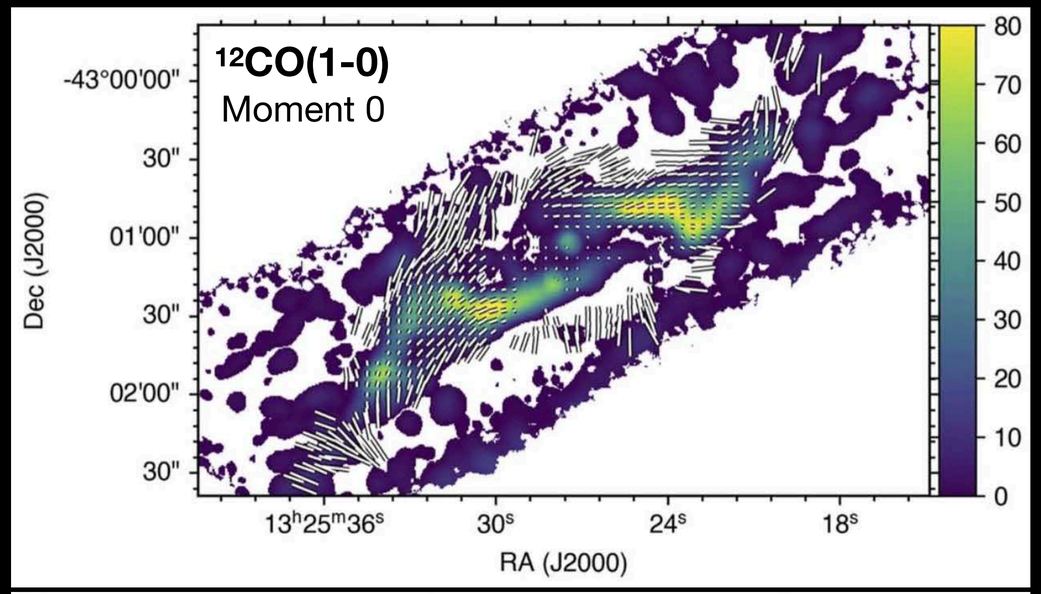
ALMA provides the information about the kinetic energy of the molecular gas

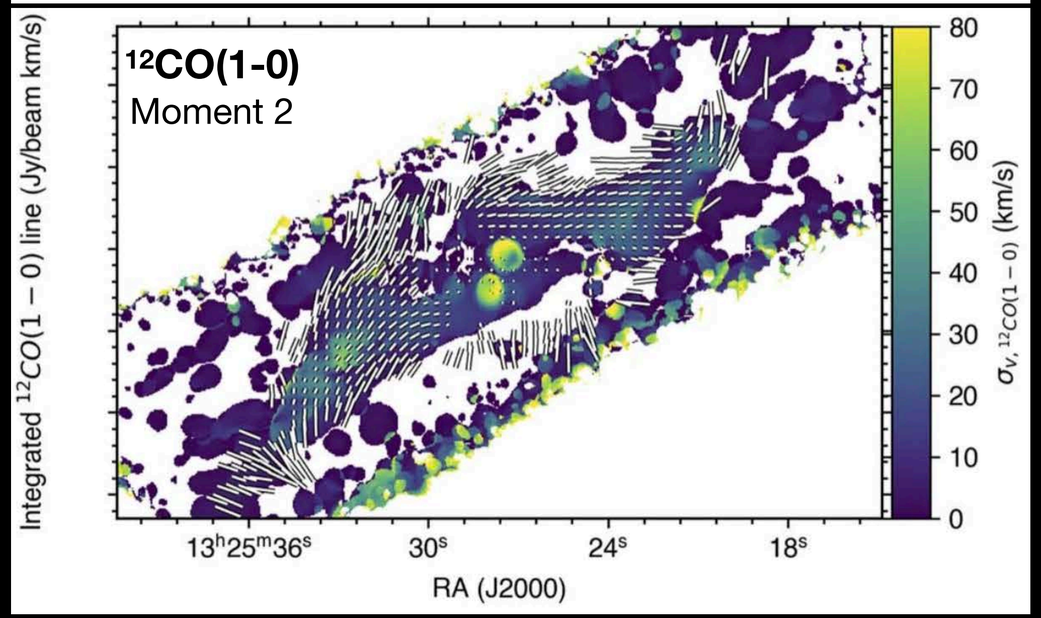




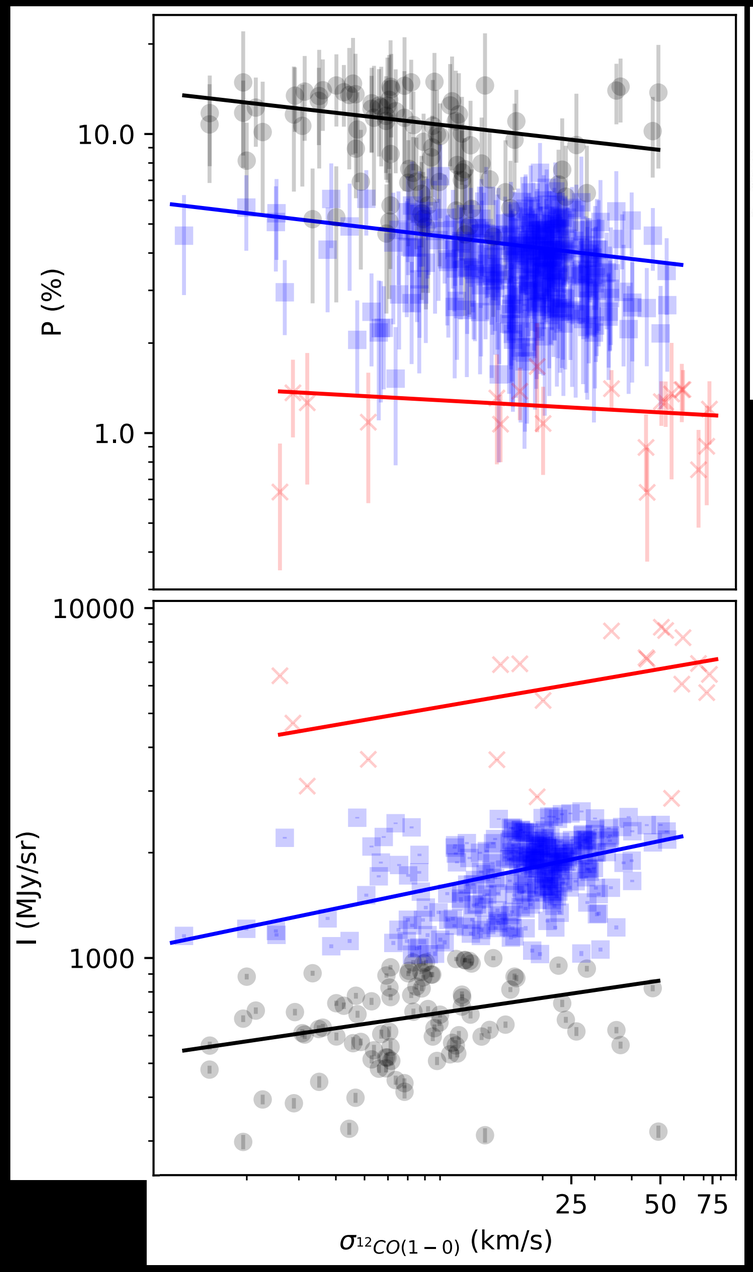
CO data from Espada et al. (2019)

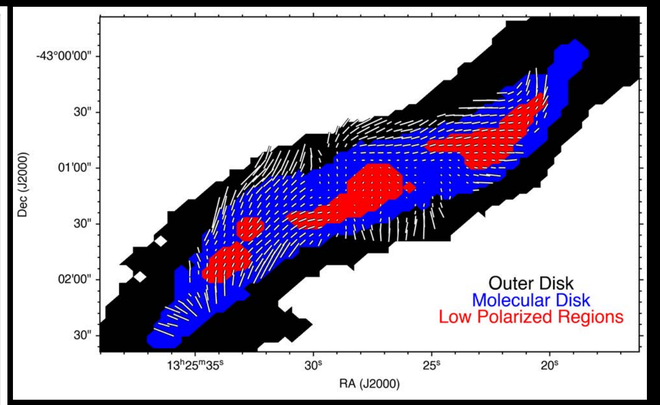
Polarization decreases with increasing turbulent kinetic energy





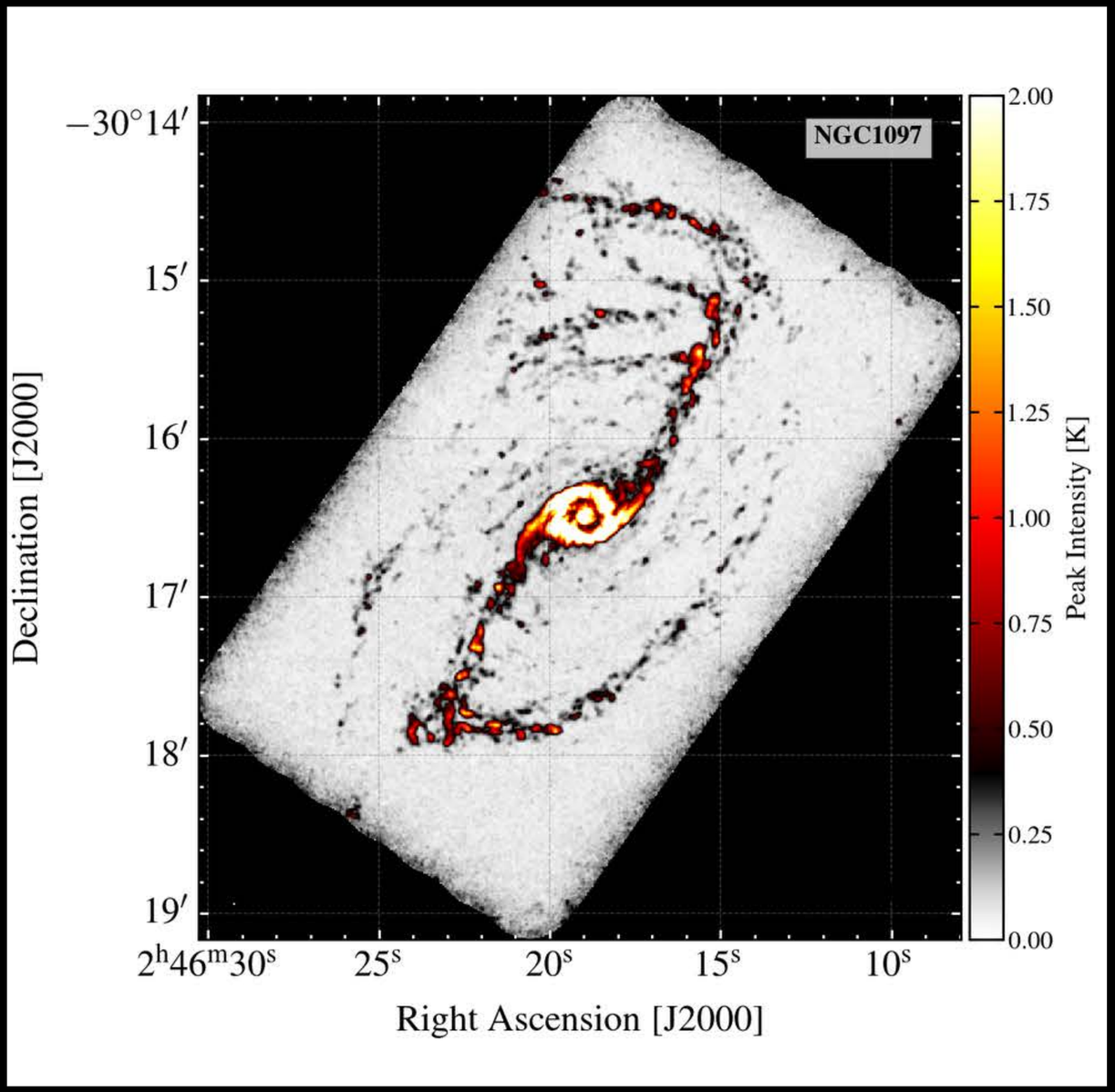
CO data from Espada et al. (2019)





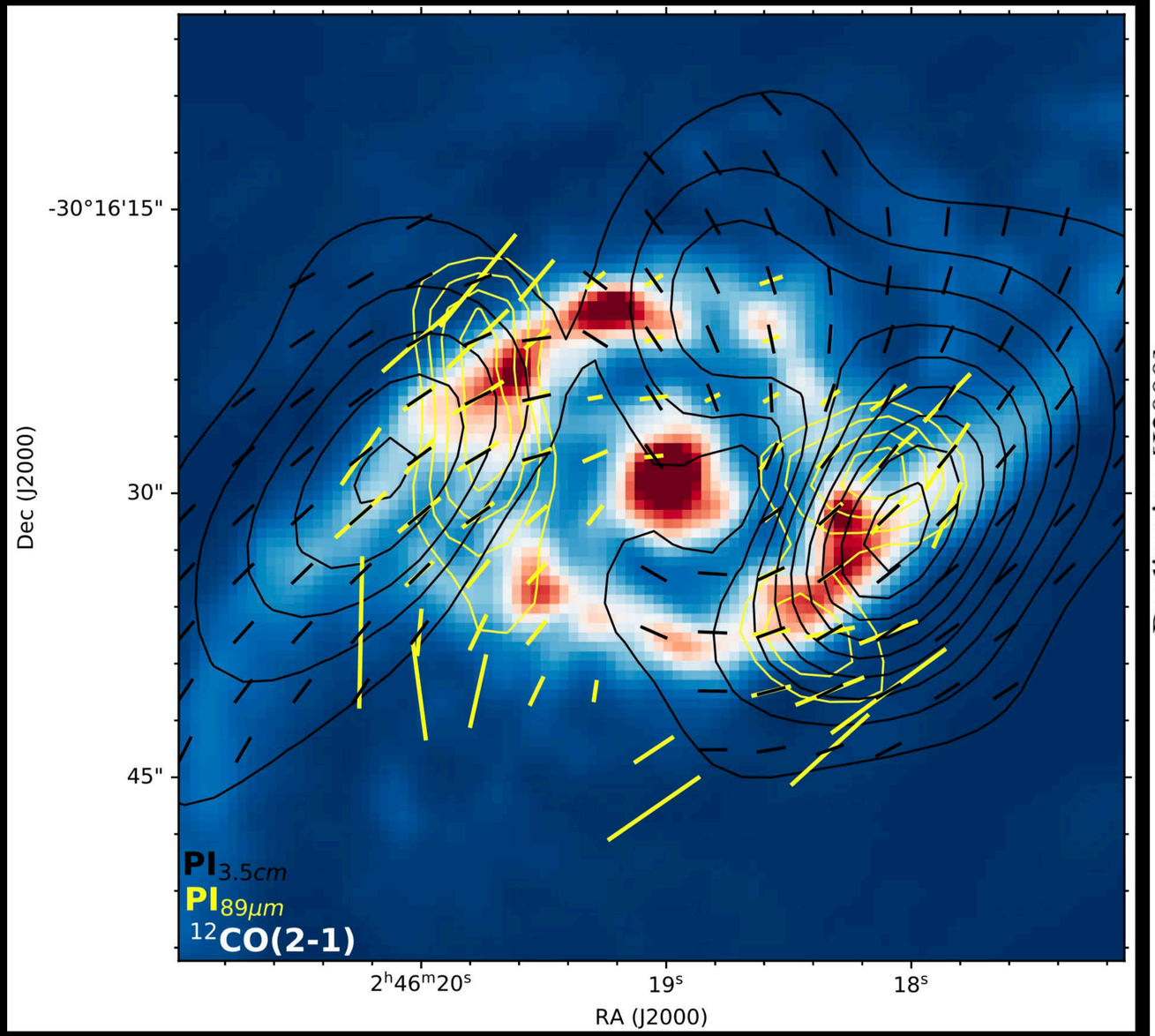
Lopez-Rodriguez (2021a)

NGC 1097: PHANGS-ALMA ^{12}CO(2-1)

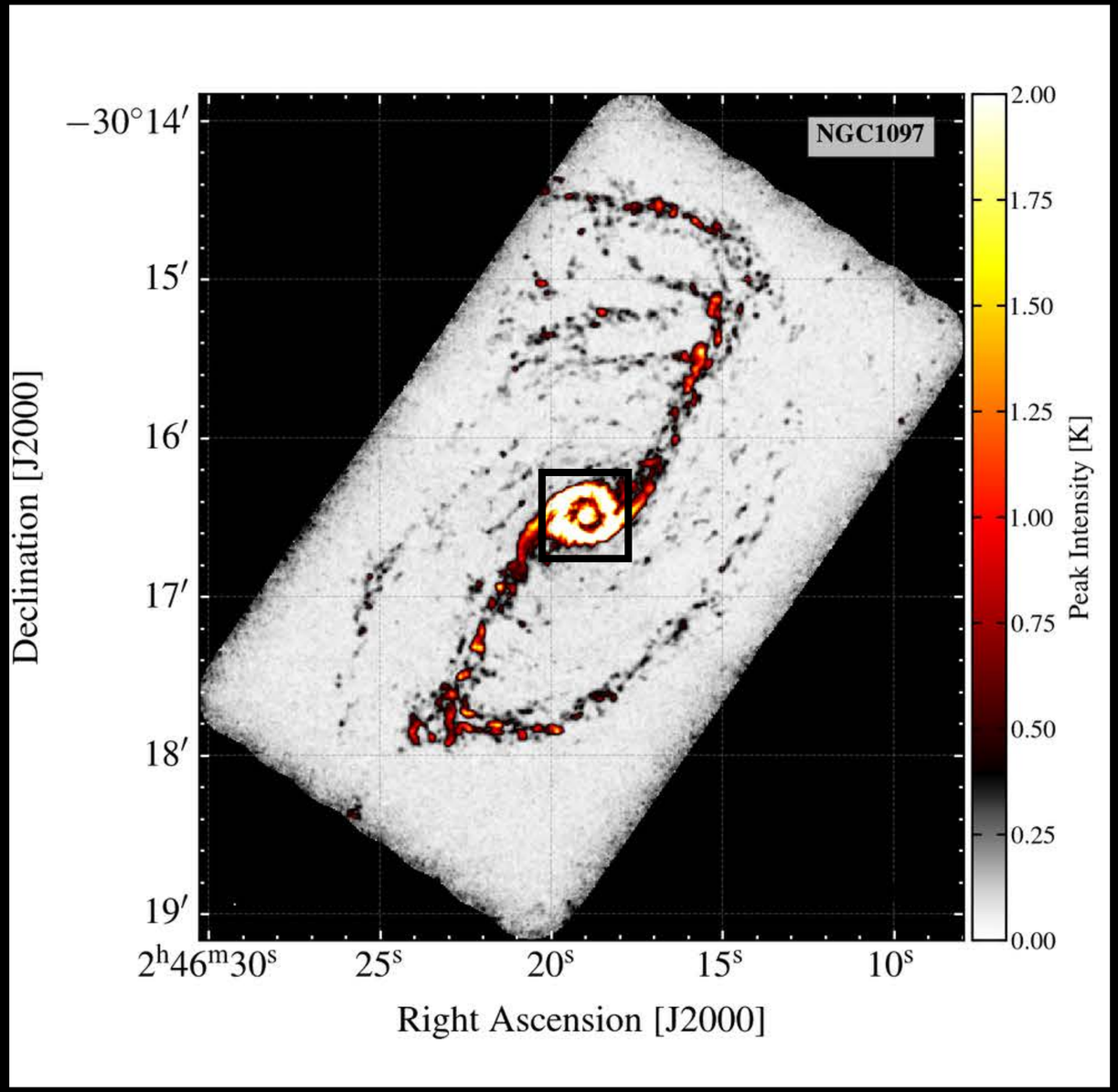


Leroy et al. (2021)

NGC 1097: PHANGS-ALMA ^{12}CO(2-1) + SOFIA + Radio

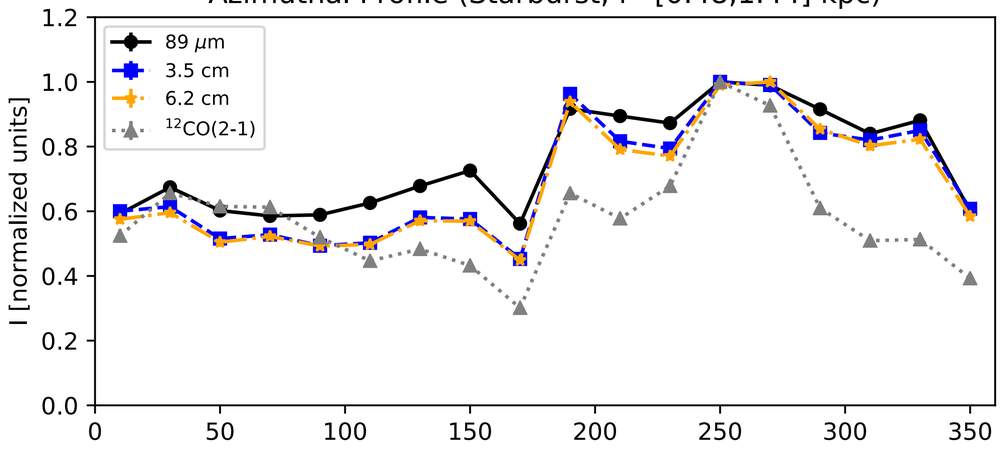


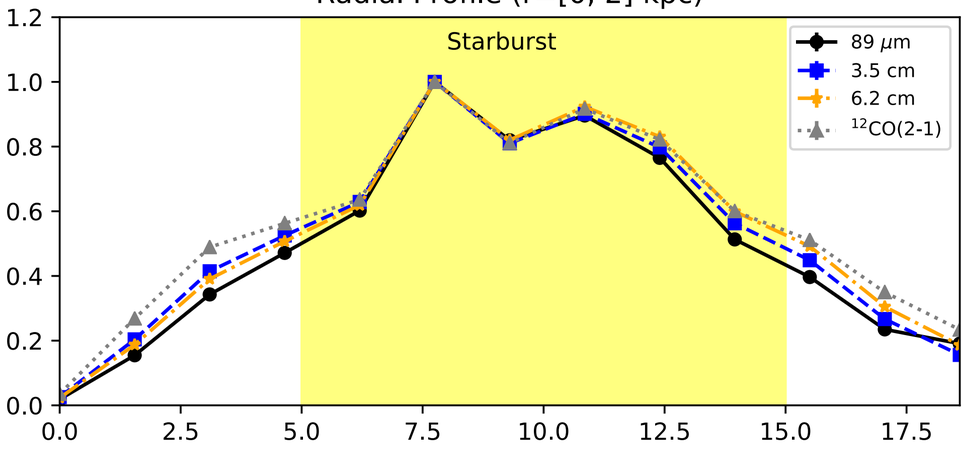
Lopez-Rodriguez et al. (in prep. Legacy Program paper II)

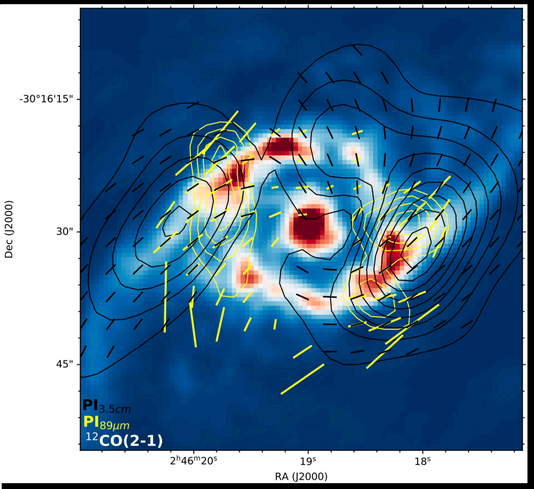


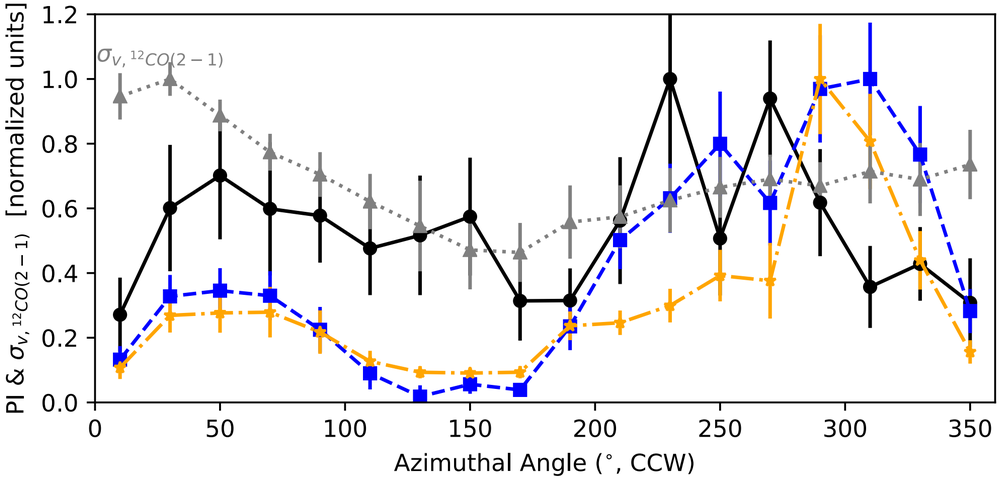
Leroy et al. (2021)

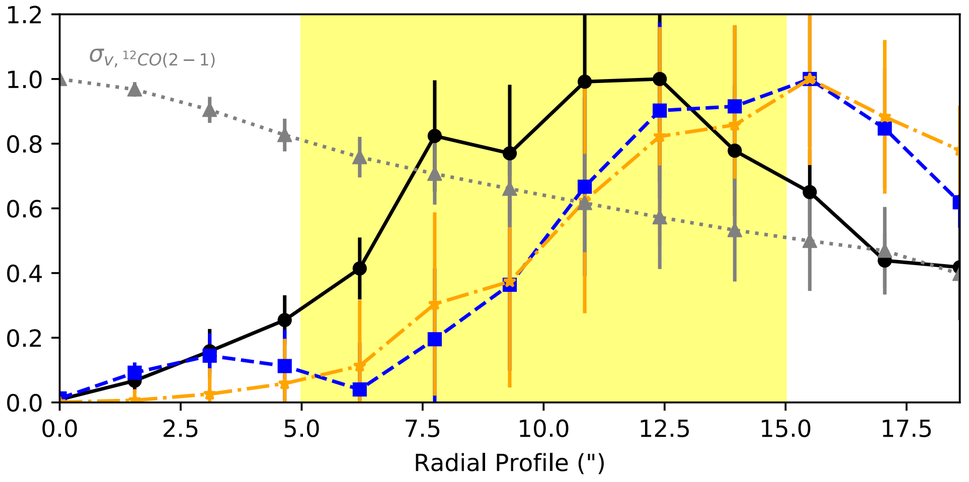
NGC 1097: Radial and Azimuthal profiles







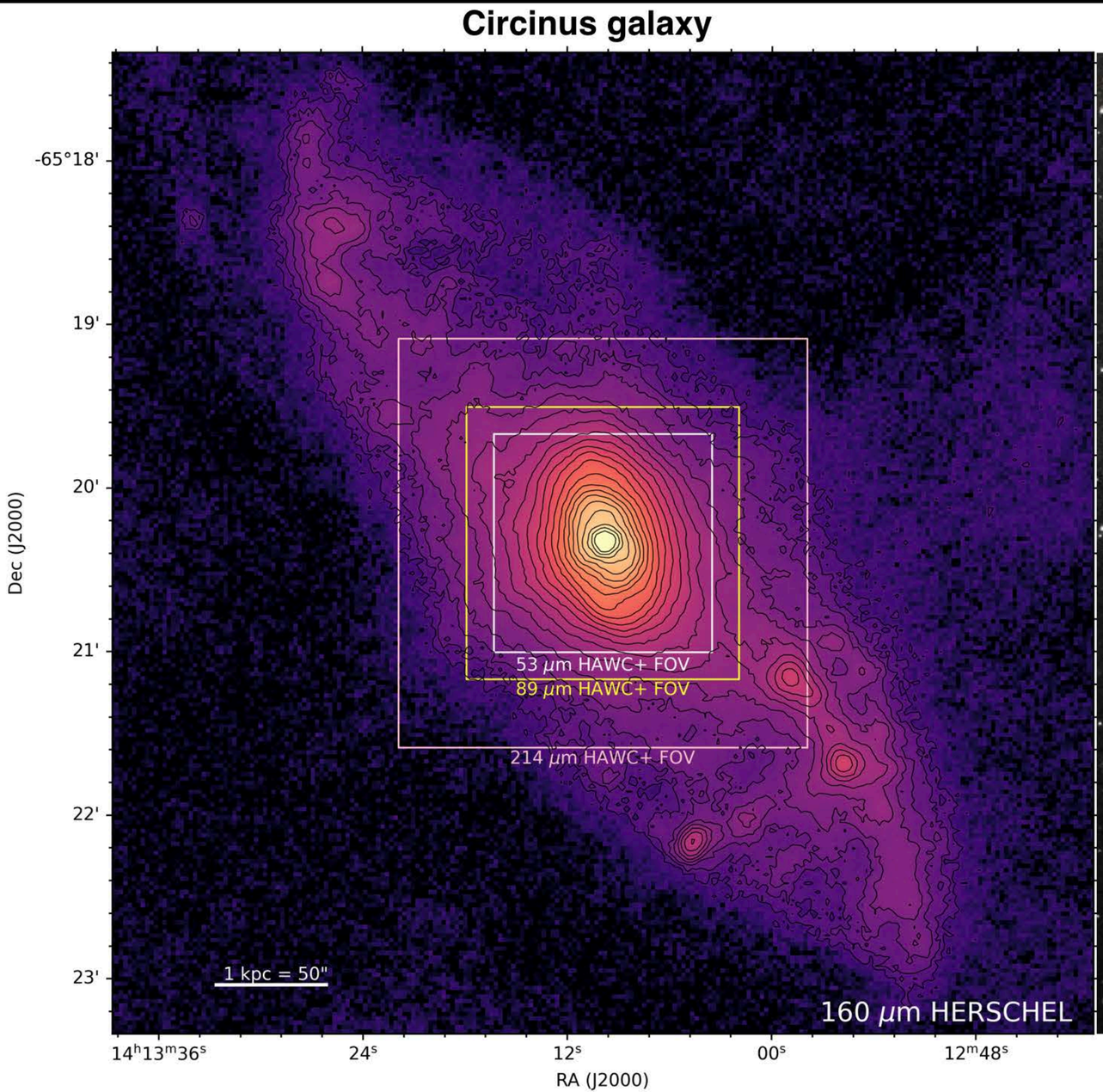


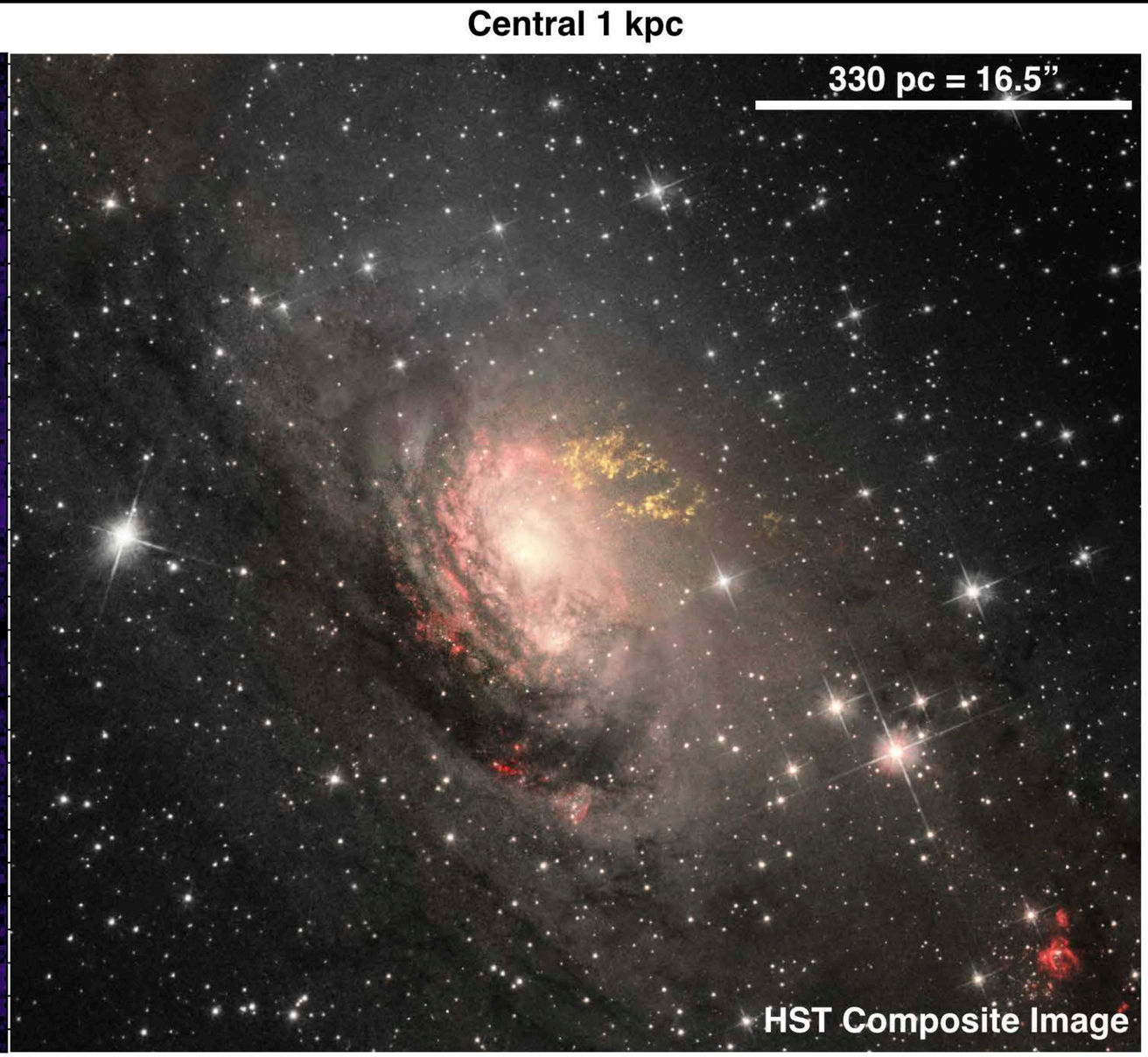


Lopez-Rodriguez et al. (in prep. Legacy Program paper II)

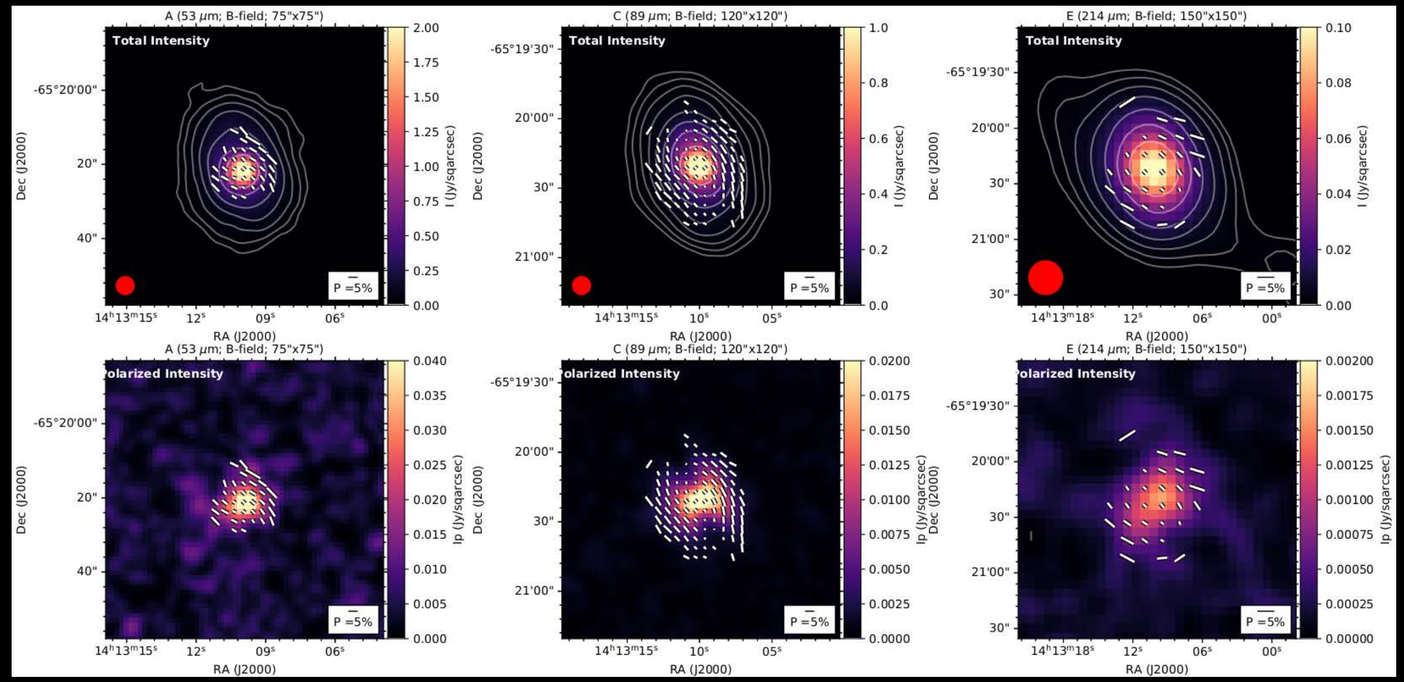
CIRCINUS: SPIRAL GALAXY & ACTIVE NUCLEI

SPIRAL MAGNETIC FIELD AND CIRCUMNUCLEAR STAR FORMATION





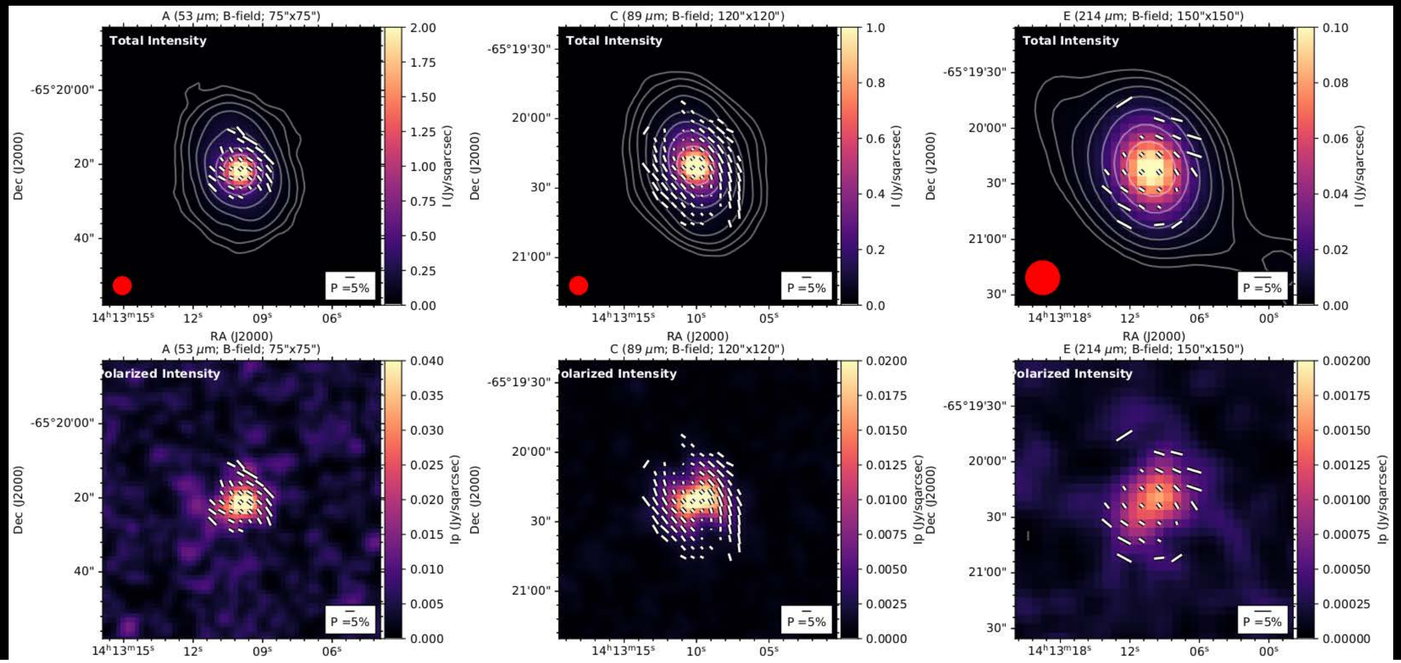
The multi-scale spiral B-field in the central 1 kpc

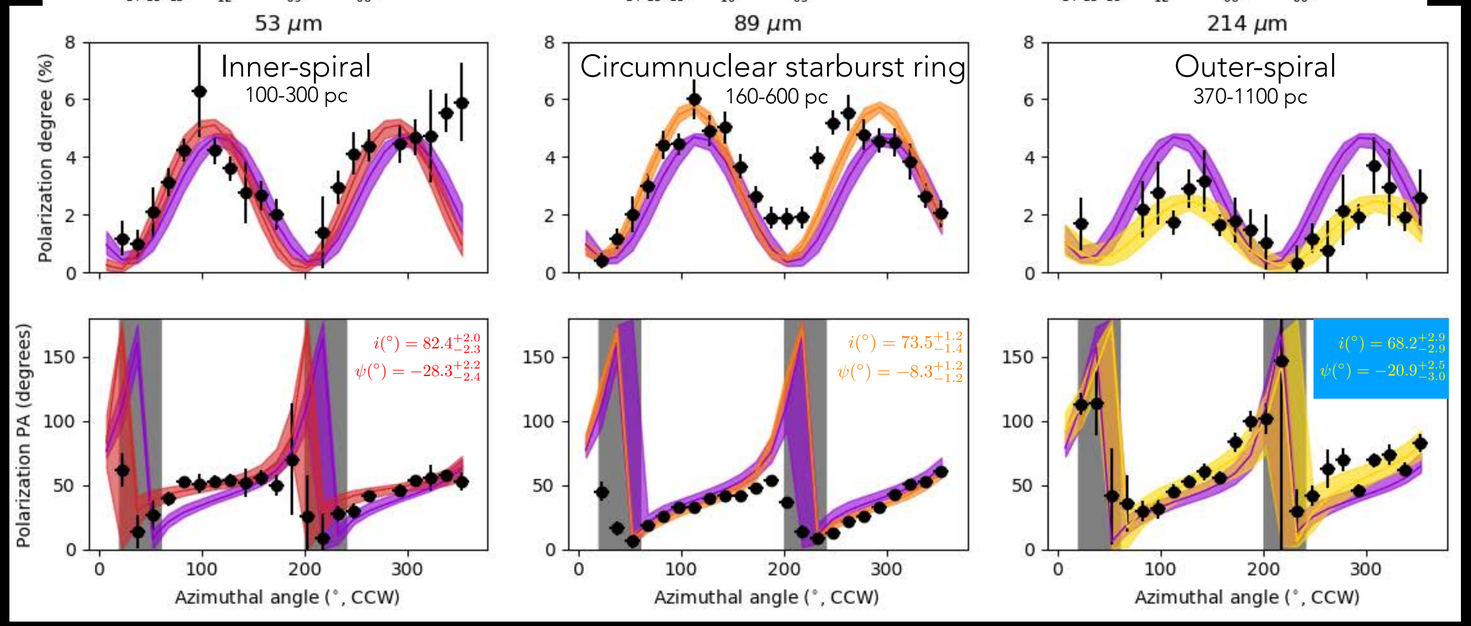


Lucas Grosset's work

(in prep. Legacy Program Paper III)

The multi-scale spiral B-field in the central 1 kpc





Lucas Grosset's work

(in prep. Legacy Program Paper III)

A 3D axisymmetric spiral and helical model shows changes across different spatial scales. Variations are due to:

- Inclination of the physical components along the LOS.
- Pitch angles of the inner-spiral, starburst ring, and npc-scale inner-bar.

*B-model: Inclined and tilted 3D axisymmetric logarithmic spiral and helical component.

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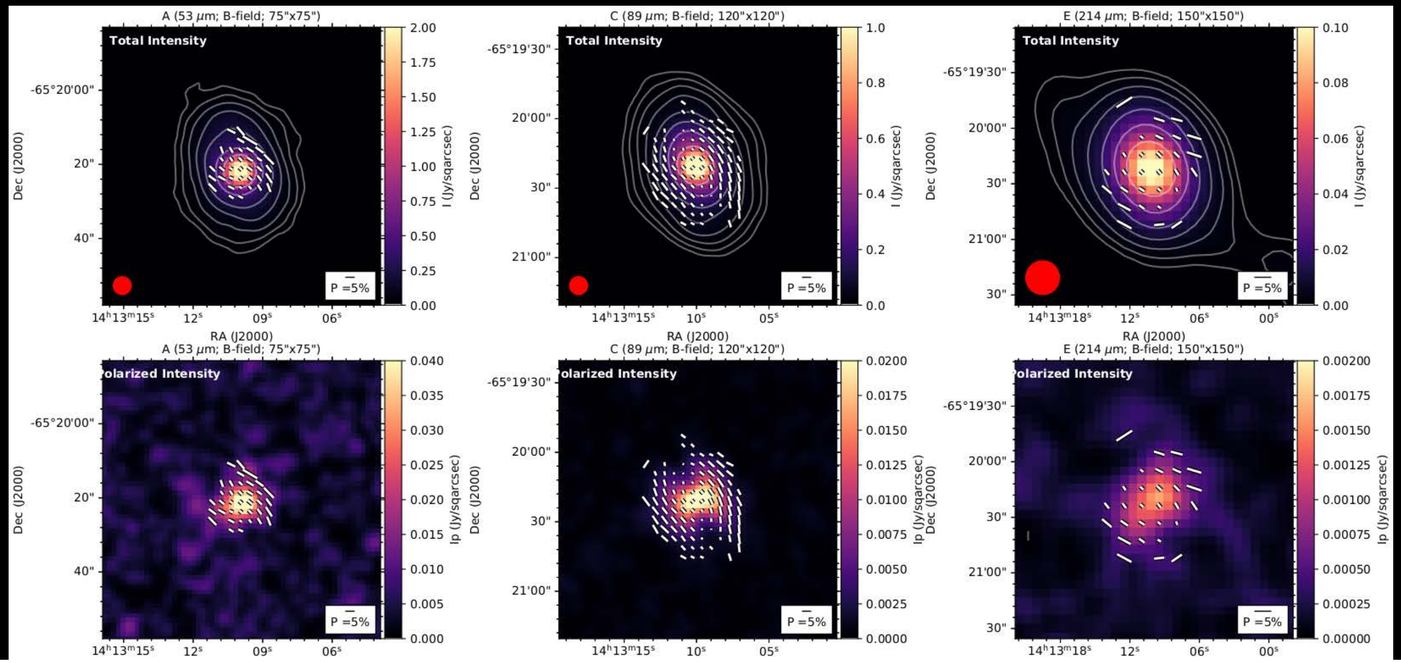

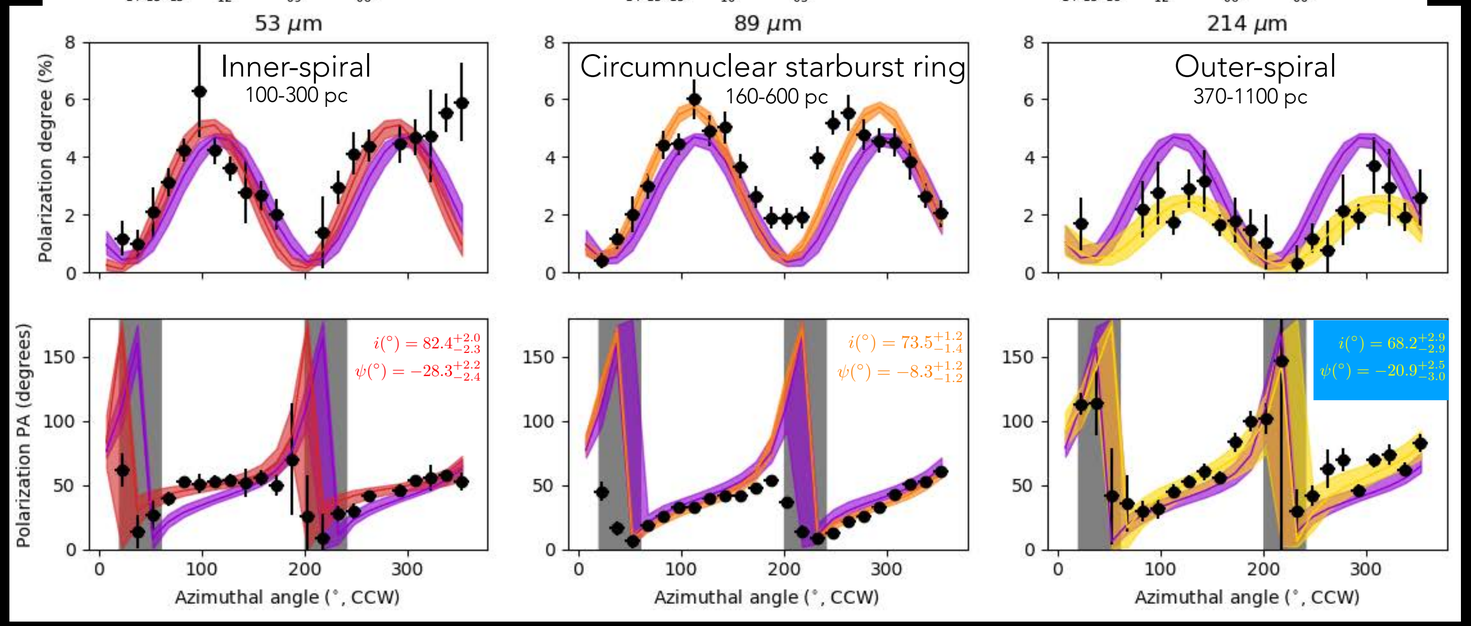

*B-model: Inclined and tilted 3D axisymmetric logarithmic spiral and helical component.

Lucas Grosset's work

(in prep. Legacy Program Paper III)

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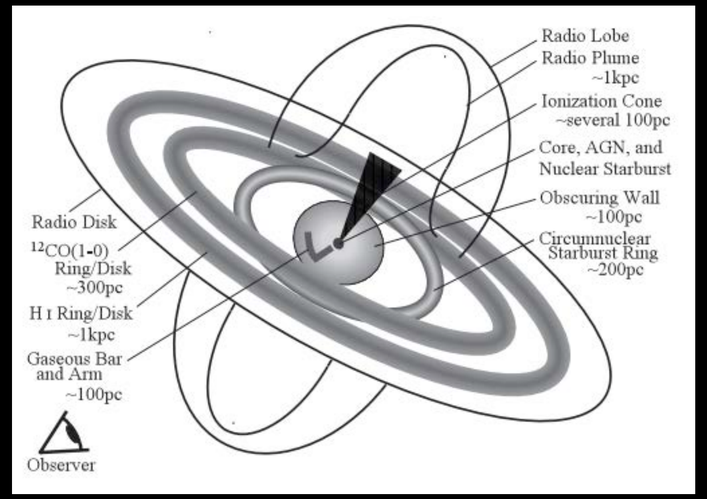
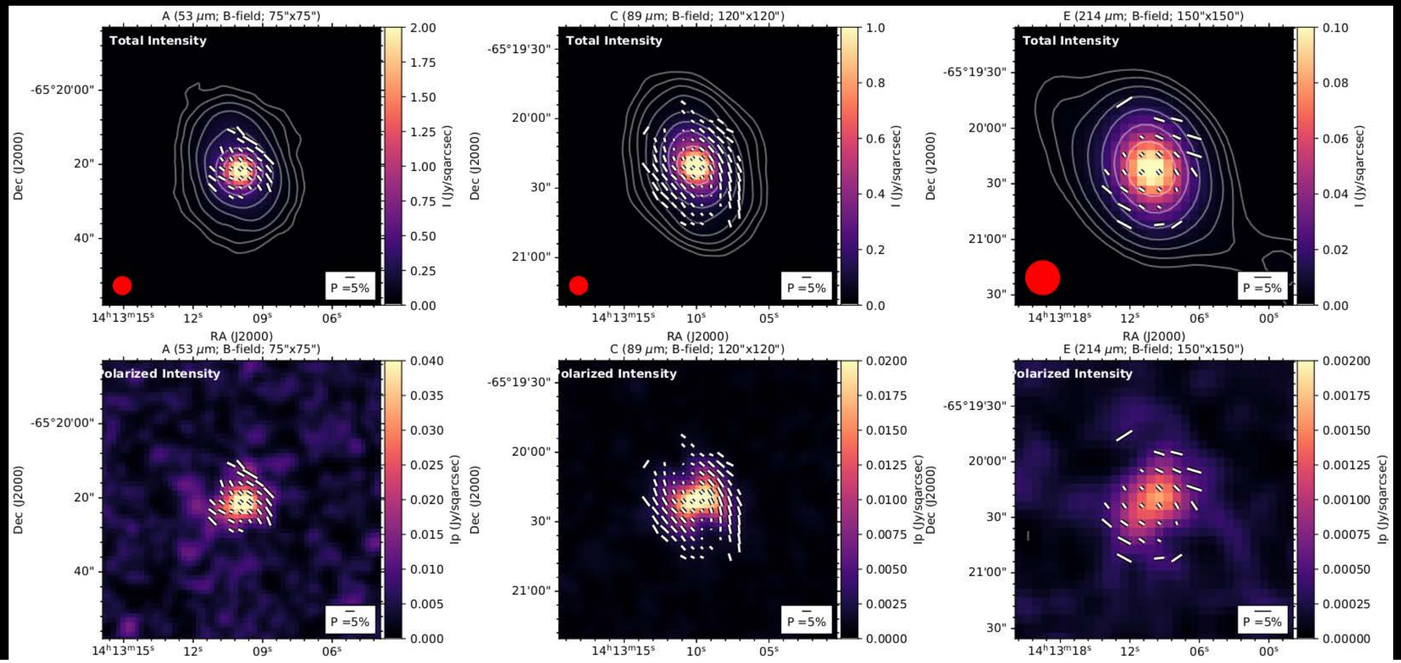
- Pitch angles of the inner-spiral, starburst ring, and npc-scale inner-bar.

Physical sketch of the central ~1 kpc of Circinus.



Ohsuga & Memura (2001)

The multi-scale spiral B-field in the central 1 kpc



Lucas Grosset's work

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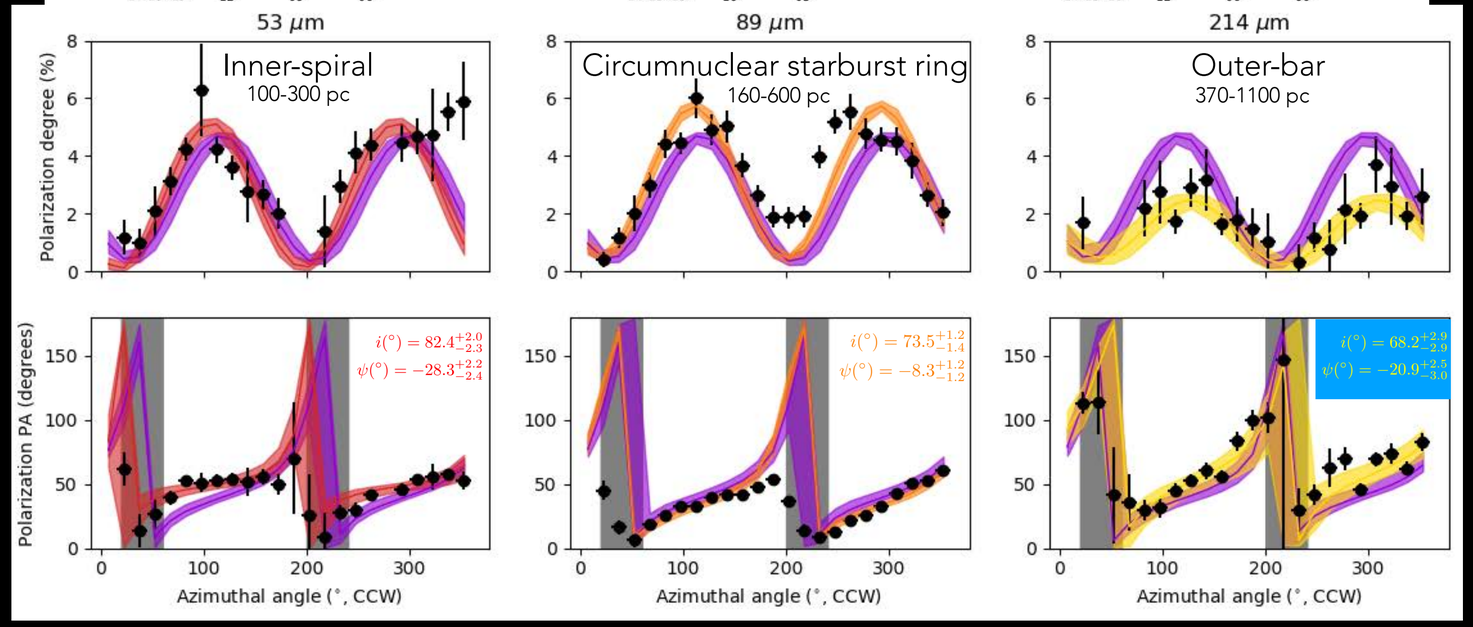
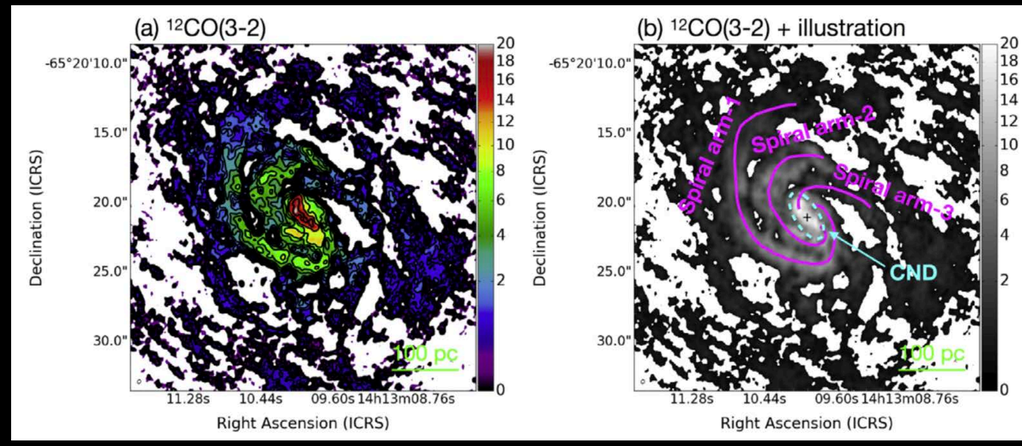


ALMA (central 300 pc)

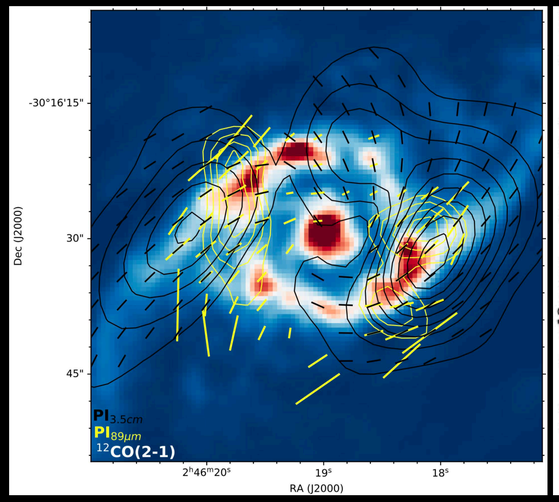


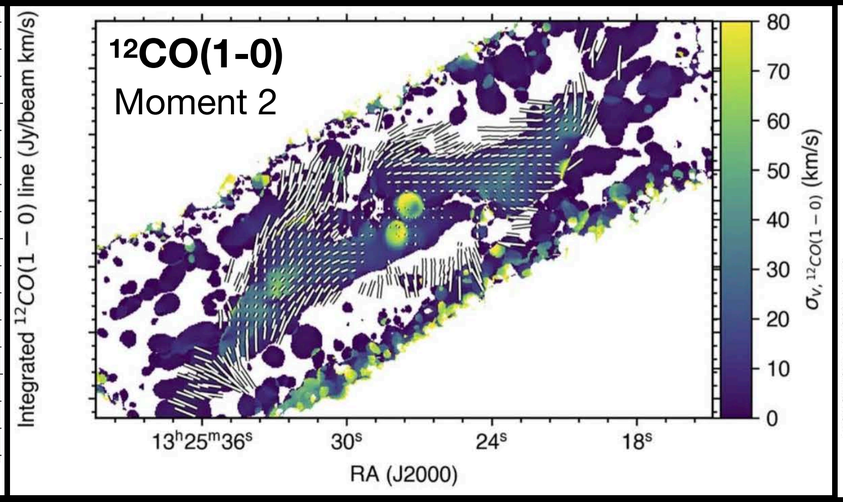
Izumi et al. (2018)

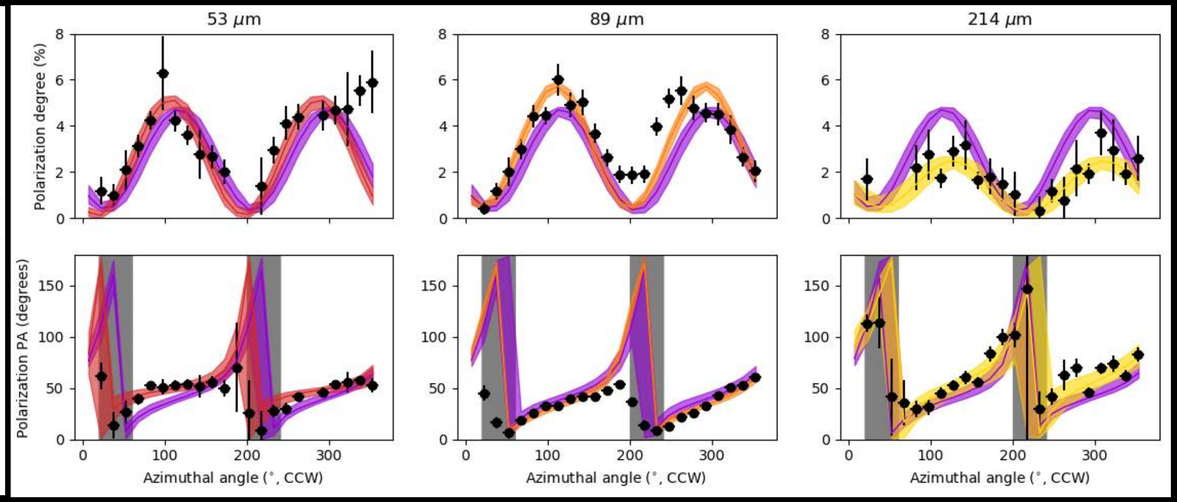
*B-model: Inclined and tilted 3D axisymmetric logarithmic spiral and helical component.

Summary

- SOFIA traces the thermal polarized emission by means of magnetically aligned dust grains.
- SOFIA provides the information about the morphology of the B-field in the plane of the sky.
  - It needs supporting data from radio and emission lines of several gas tracers.
- ALMA provides information about the gas dynamics of the molecular gas.
  - ^{12}CO(1-0) and ^{12}CO(2-1) are almost co-spatial with the B-field along the host galaxy (M51: Borlaff+2021)
  - Molecular gas provides a proxy of the turbulent kinetic energy within the SOFIA's beam.







ALMA polarimetry of external galaxies is under explored!

- What is the connection between small- and large-scale magnetic fields?
  - ➡ Circinus, NGC1068, others provide excellent objects for SOFIA+ALMA at 1 pc to 1 kpc scales.

- What is the morphology and strength of the B-field at the base of starburst galaxies?
  - ➡ Check the work by Annie Hughes on NGC253 using ALMA polarimetry (spectacular!)

- How do interacting galaxies affect the B-field of their original galaxies?
  - ➡ Centaurus A, Arp 220, Antennae, others are excellent objects.

- How does star formation in the spiral arms change the B-field in the molecular gas?
  - ➡ NGC1068, NGC 1097, others are excellent objects for a SOFIA+ALMA project.