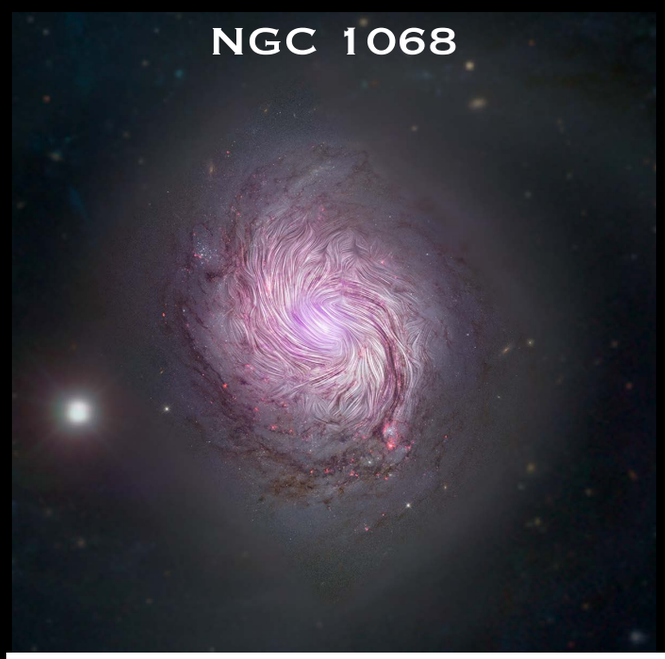
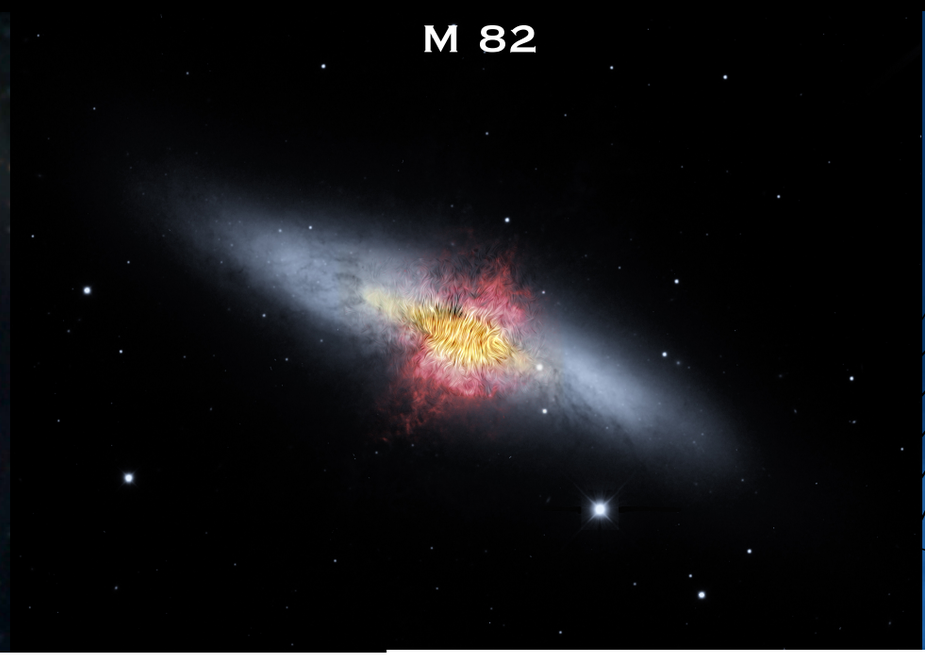
MAGNETIC FIELDS IN GALAXIES: A STUDY OF THE B-FIELD IN THE MULTI-PHASE ISM

ENRIQUE LOPEZ-RODRIGUEZ





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The work presented here has only been made possible through international collaborations with:

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and:
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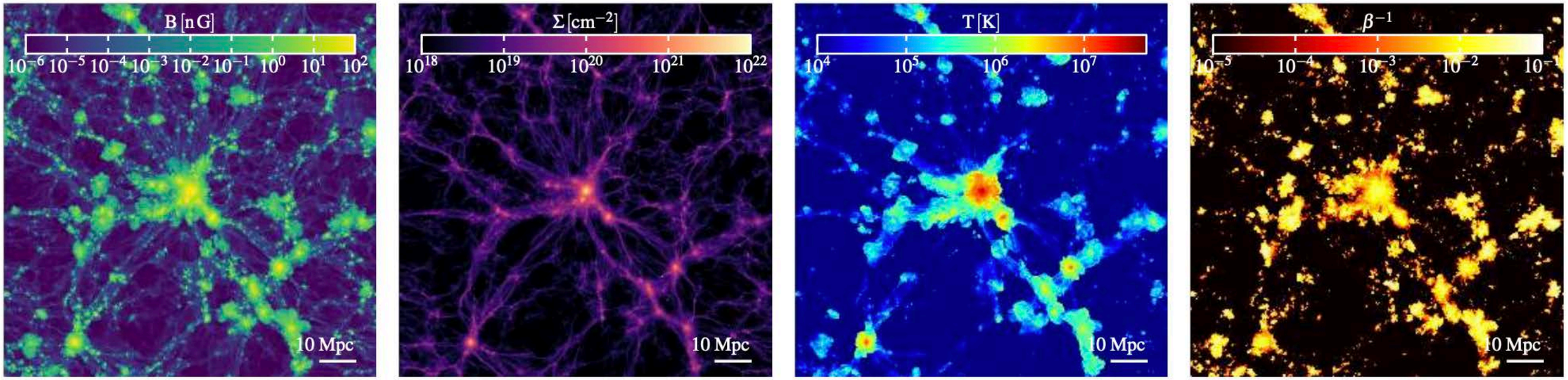
HAWC+ Science Team

STRUCTURE FORMATION AMPLIFIES MAGNETIC FIELDS

Galaxy evolution is controlled by a delicate interplay between dark matter, gravity, feedback, turbulence, and magnetic fields



Illustris-TNG Team

Stage 1: Field seeds

- Generation of seed fields by Biermann battery, Weibel instability, or plasma fluctuations. ($B \sim 10^{-18}$ - 10^{-6} G)

Stage 2: Field Amplification

- Amplification of seed fields by turbulent gas flows, i.e. small-scale dynamo ($B \sim 10^{-5}$ G).
- Turbulence is driven by accretion flows and SN explosions.

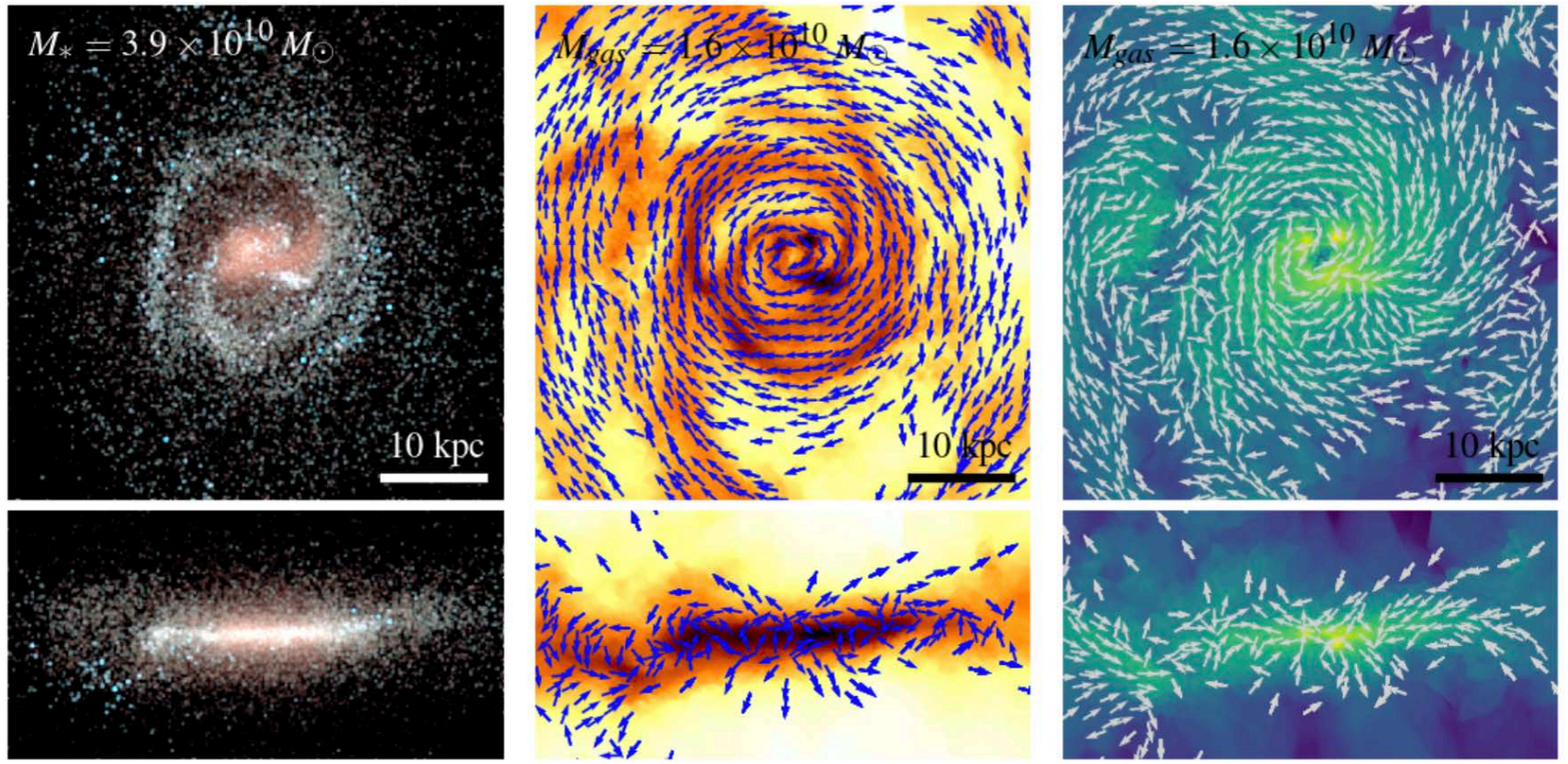
Stage 3: Field ordering

- Field ordered (stretched) by shear and by large-scale dynamo ($t \sim 10^{9}$ yr)
- Turbulence driven by SN explosions and MRI in galaxy disks.

MAGNETIC FIELDS IN GALAXIES

Disk galaxies (spiral galaxies) have large-scale coherent magnetic fields.

- Low velocity dispersion (low turbulence field)
- Late-type galaxies with enough time for the dynamo to take place and amplify the fields



Illustris-TNG Team

OPEN QUESTIONS:

How did fields affect the evolution of galaxies in mergers?

Is the intergalactic medium magnetized?

How have the fields been amplified in galaxies?

RESEARCH GOAL

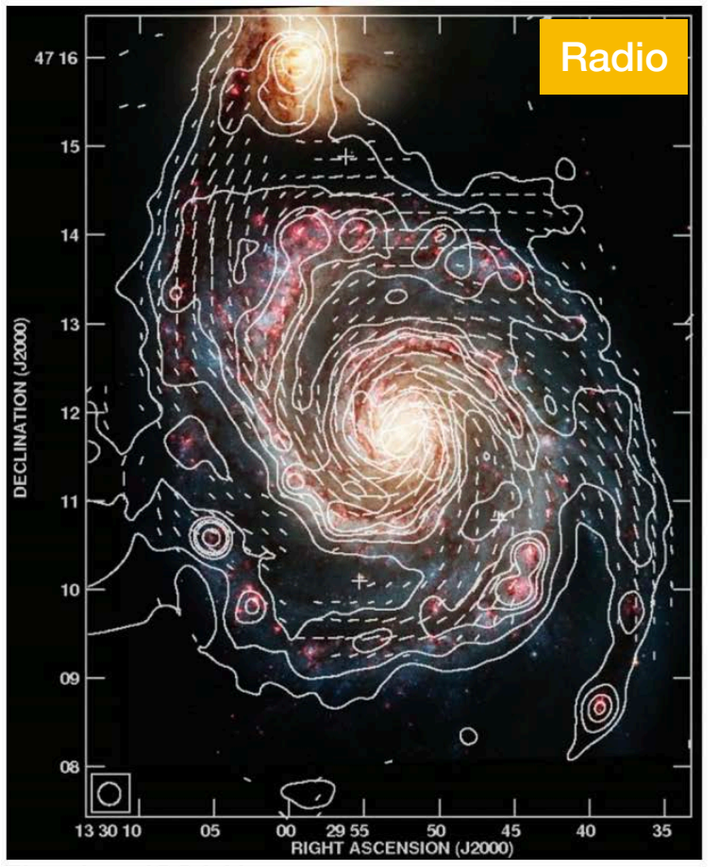
Characterizing the role of magnetic fields in the multiphase interstellar medium of nearby galaxies.

Pilot SOFIA Legacy Program (co-PIs: Lopez-Rodriguez & Mao)

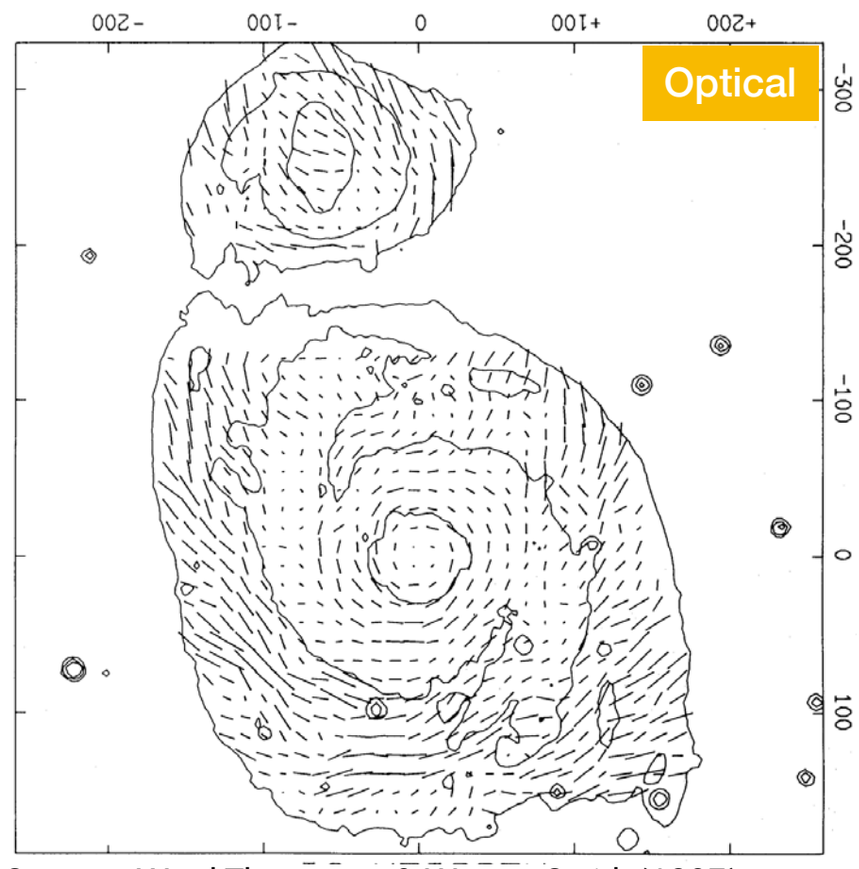
MULTI-WAVELENGTH POLARIZATION ANALYSIS: OPTICAL VS RADIO VS FIR

- Optical-NIR polarization suffers of dust/scattering polarization.
- Radio wavelength traces 'illuminated' magnetic fields by relativistic electrons in the diffuse ISM (sensitive to the cosmic ray electron population).
  - Faraday rotation needs to be taken into account.
  - Traces ordered and turbulent magnetic fields
- FIR wavelengths:
  - Sensitive to temperature and dust density (helps separate regions along the LOS)
  - Traces the total gas and dust in the dense ISM.
  - Traces turbulent fields and only B-field orientation.

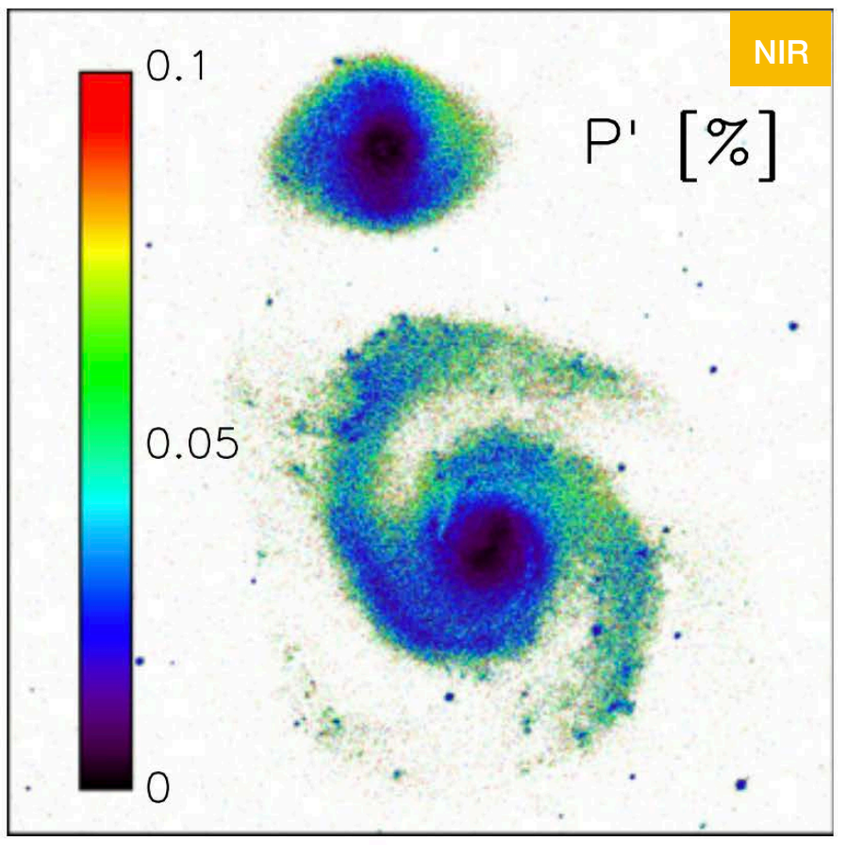
The influence of magnetic fields in the dense ISM at several galactic scales can be characterized using FIR polarimetric observations.



Fletcher (2011)



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



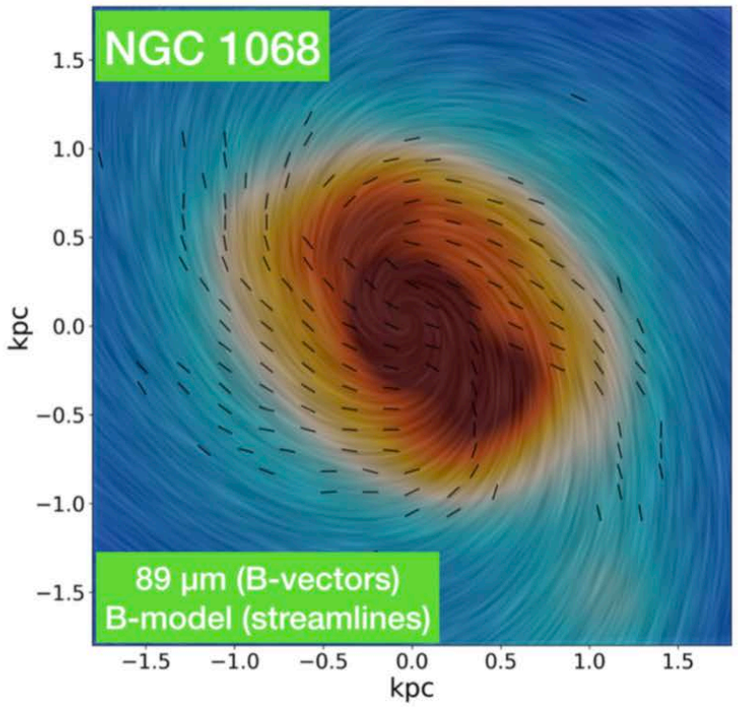
Pavel & Clemens (2012)

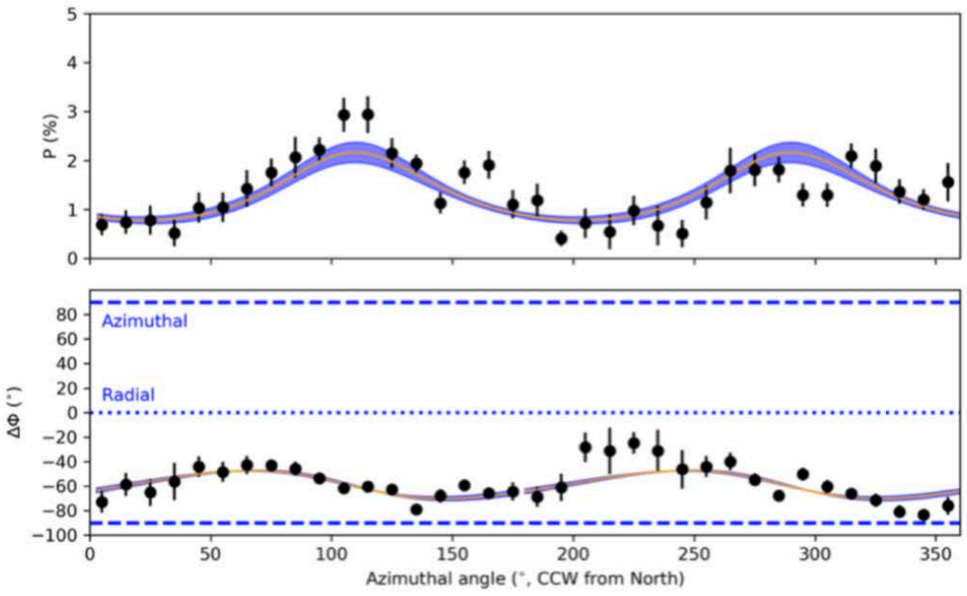
The spiral magnetic field of NGC 1068

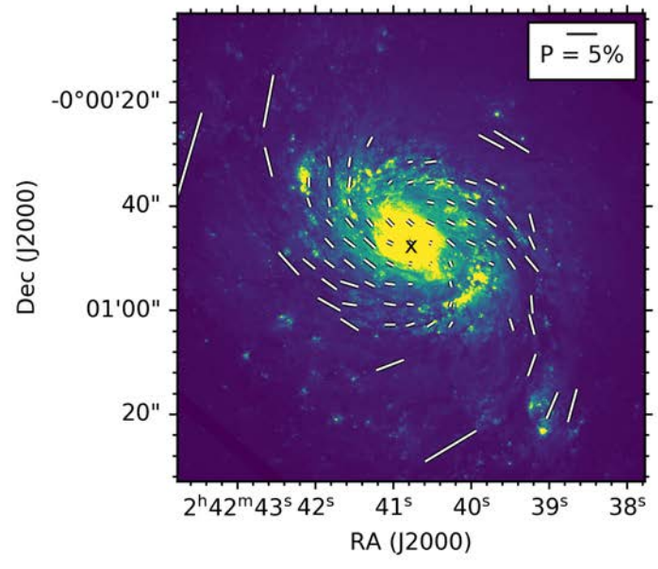
Lopez-Rodriguez et al. (2020a)

THE SPIRAL MAGNETIC FIELD OF NGC1068

- ~3 kpc large-scale spiral magnetic fields are 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 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

Lopez-Rodriguez et al. (2020a)

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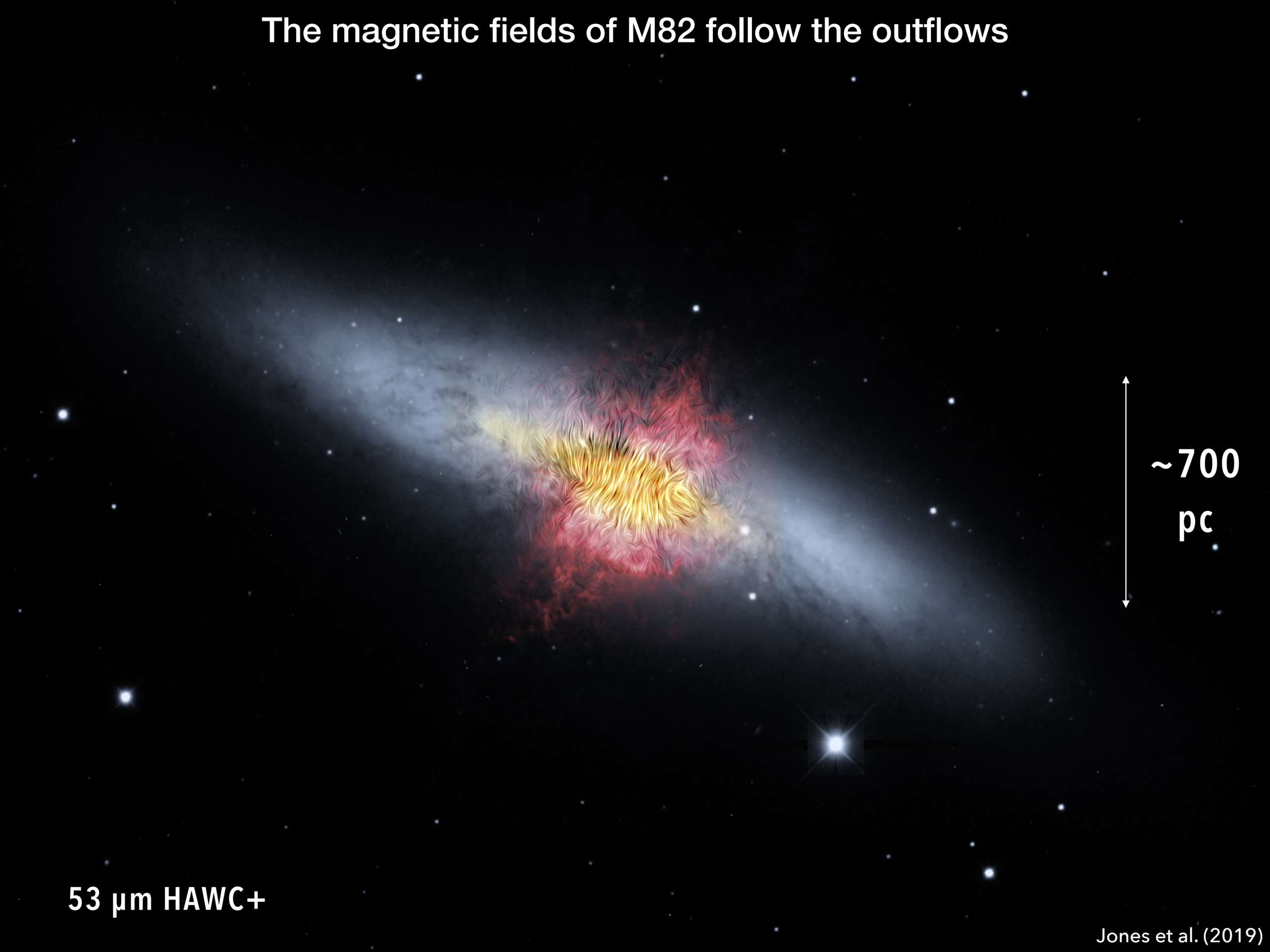
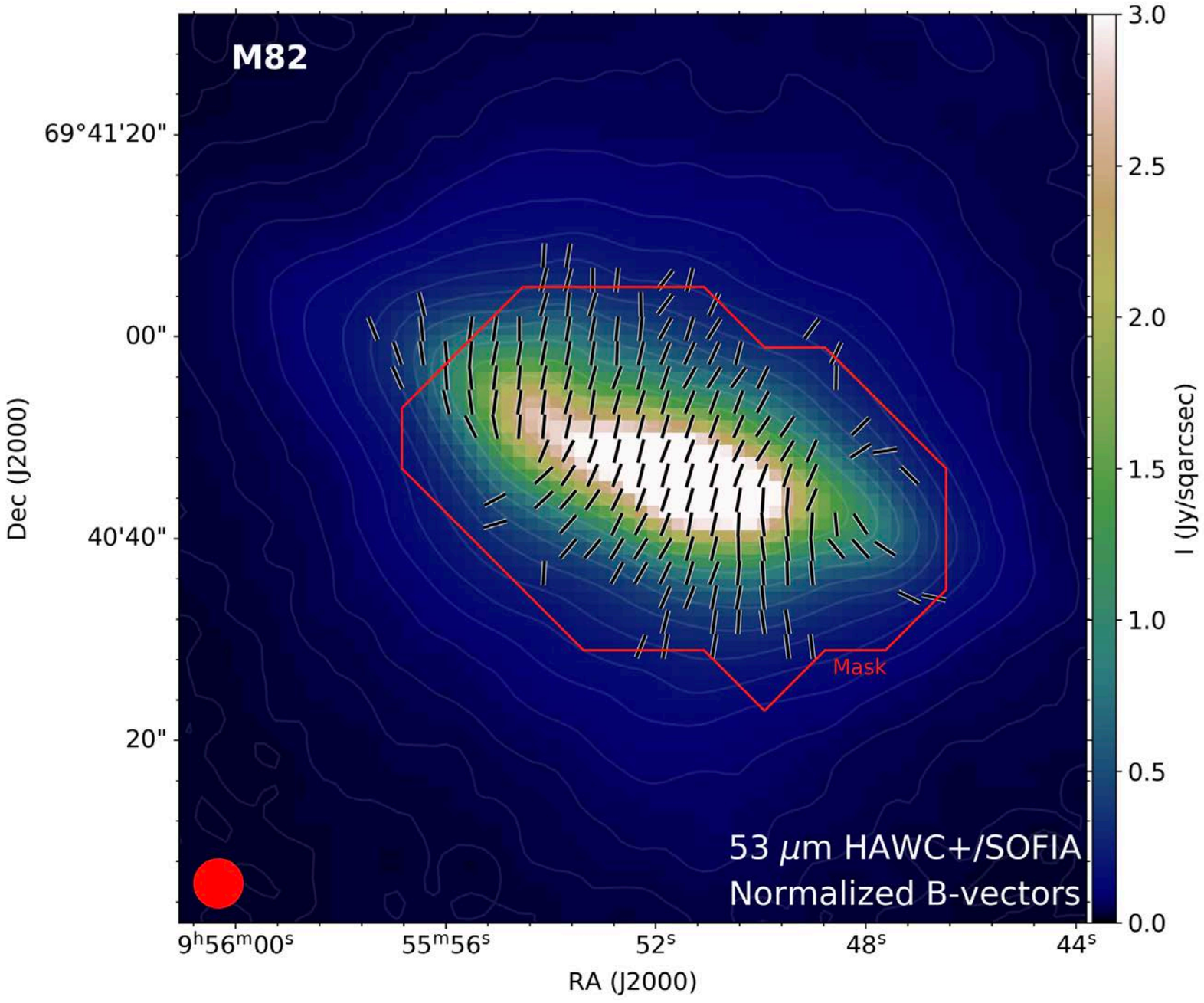
The magnetic fields of M82 follow the outflows



Jones et al. (2019)

THE MAGNETIC FIELD OF A GALACTIC OUTFLOW

- Bipolar magnetic field distribution is perpendicular to the disk.
- Outflow is driven by star formation and extends beyond the galactic plane.
- Dust grains are aligned in the outflow due to large-scale magnetic fields that have been dragged from the mid-plane of the galaxy by the outflow.



Jones et al. (2019)

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NGC 2146: The magnetic field of the galactic outflow

~1.5 kpc

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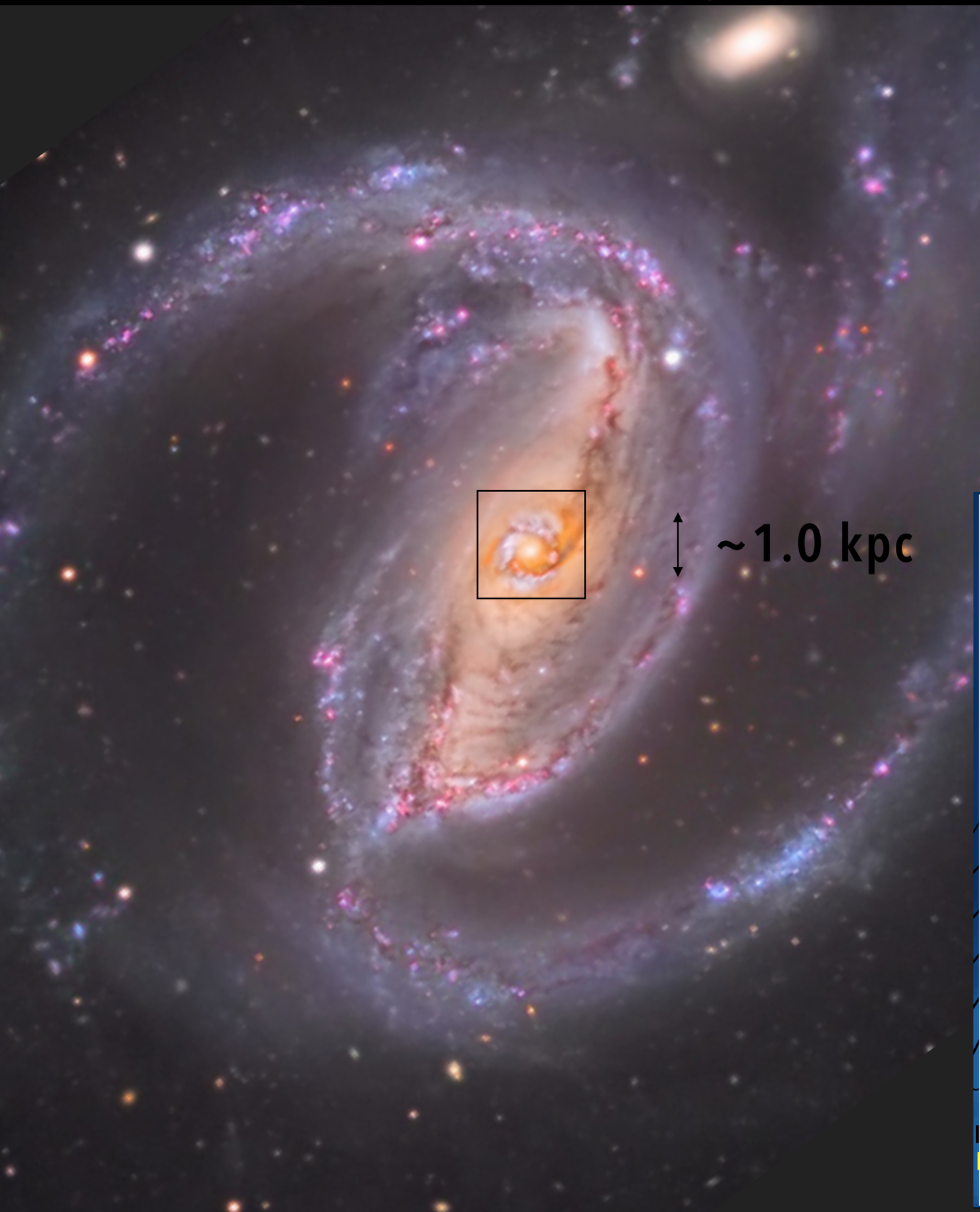
Multi-wavelength analysis of the B-field across the galactic outflow of NGC 2146

NGC 1097: The Magnetic Field of the Starburst Ring



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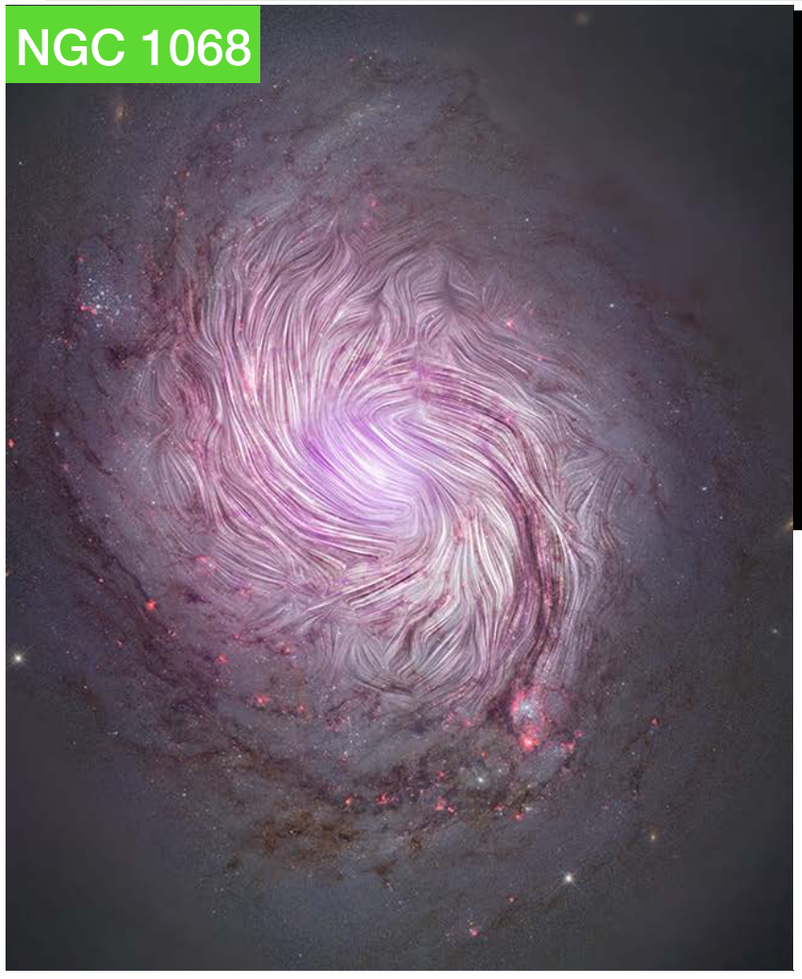
A NEW ERA OF MEASURING MAGNETIC FIELDS IN GALAXIES



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SOFIA Legacy Program is a great opportunity to:

- Enhance German+U.S. scientific collaborations throughout the Joint Programs
- Mentoring early-career astronomers (most of papers and new data analysis are lead by post-docs or early-career)
- New observing modes have been developed to enable this program to achieve their goals.
- As soon as observations gets collected and reduced, most data will be publicly available

Upcoming work offers many opportunities for the community to participate:

- **SOFIA Legacy Program (co-PI: Lopez-Rodriguez, E. & Mao, A.):**
  - ~180h of FIR polarimetry of nearby galaxies (~20h as a Pilot Program)
  - Program includes: ~20 Starburst, Spirals, Edge-on, and Merge galaxies, as well as ~ 10 AGN.
- **M51 deep observations (PI: Darren, D.):**
  - ~30h of polarimetric observations at 154 um.

http://galmagfields.com

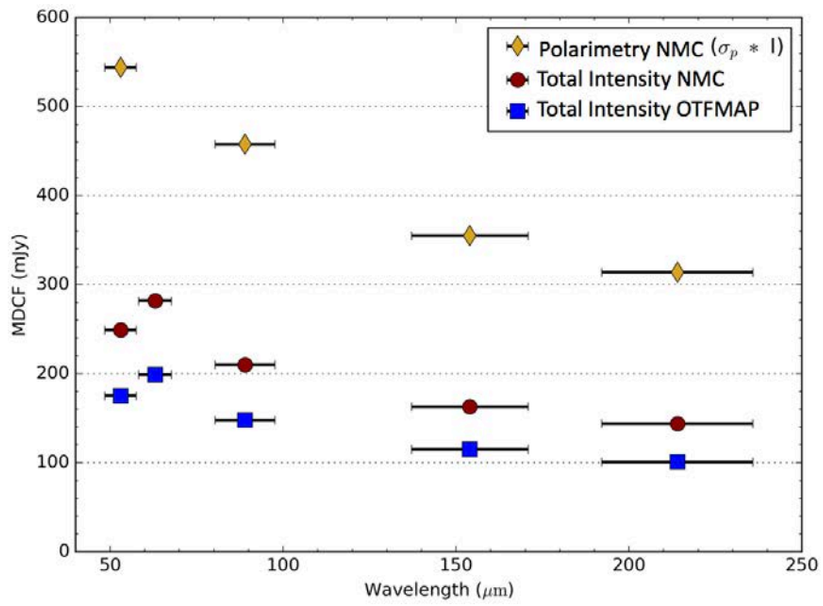
FUTURE UPGRADES

HAWC+:

- Development of new observing modes, such as scan-polarimetry and/or scan+chop-polarimetry
  - Requires resources to characterize it, software development, and testing -> Eng. time
    - Potential improvement of a factor ~2 in overheads and ~1.6 in sensitivity.
      - Note that the Legacy program would have taken 422h using chop-nod, instead of the 175h, and it would have had only 60% of the requested galaxy sample.
- New arrays + higher sensitivity:
  - Faster scan speeds and larger FOV.
    - Excellent for galaxies like NGC6946, M83, which are larger than Band E FOV.
  - It will greatly decrease the observing time per object (current: typically 15-20h).
  - It will increase the sample size (current: ~20 objects)
    - Can sensitivity be increased by a factor of 2-4? (Question for instrument builders)

Synergies:

- ALMA to obtain dust continuum polarization and CO maps of nearby galaxies
- Radio polarimetry to obtain synchrotron emission of those galaxies without radio observations yet.



Magnetic fields in galaxies measured by polarized emission of magnetically aligned dust grains with HAWC+/SOFIA can raise new discussions in galactic dynamics for the next few decades.

… which can only be surpassed by a space FIR polarimeter (SPICA, Origins).