SOFIA: FIR Polarimetry

Sebastian Wolf

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Christian Huygens
Propagation of light through crystals:
Light is *not* a scalar

Vectorial nature: „**POLARIZATION**“

EM waves
Non-zero solutions of Maxwell‘s equations in vacuum

Electromagnetic radiation

Intensity

Wavelength

Coherence (spatial, temporal)

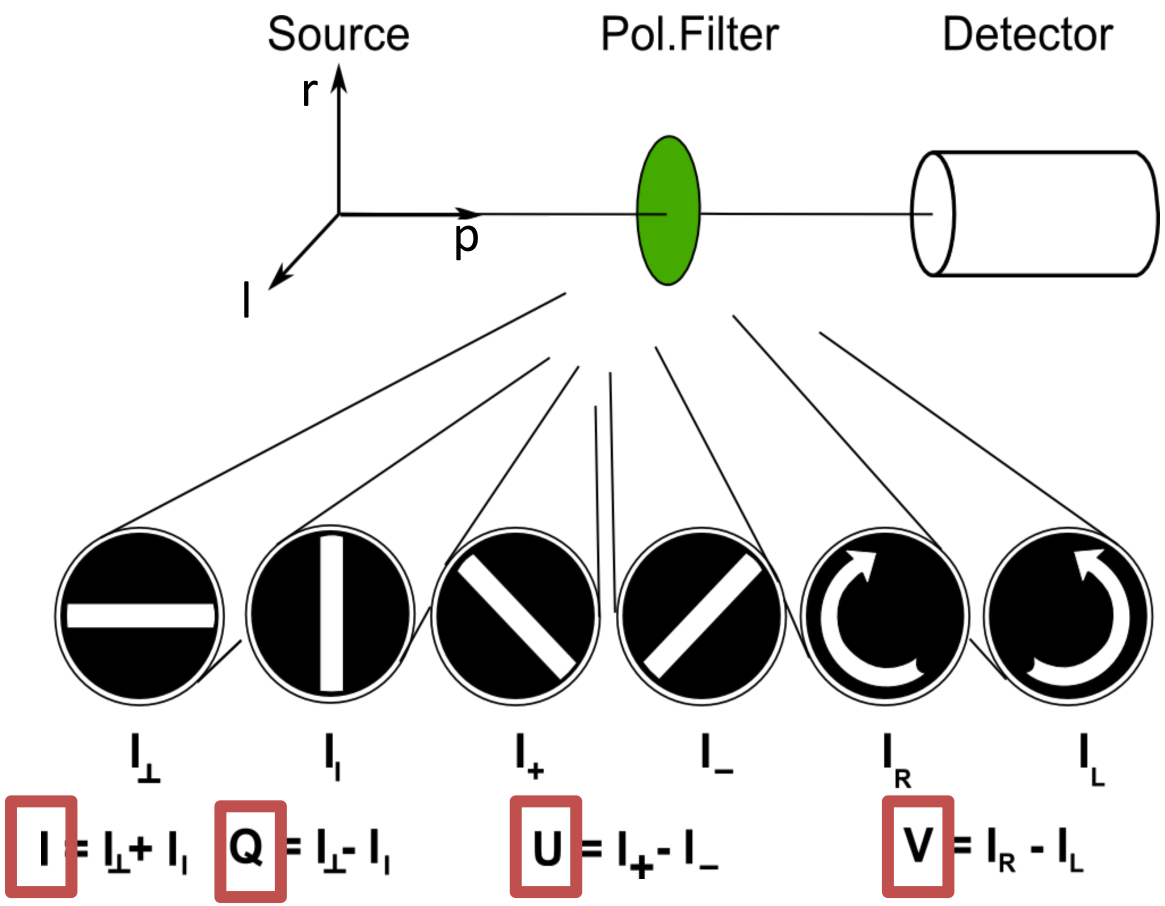
Polarization

Fundamental property of EM radiation

Polarization of individual EM waves

(„Microscopic polarization“)

Measuring & Describing polarization state: **Stokes vector**



[based on figure by G. Bertrang]

Degree of linear polarization

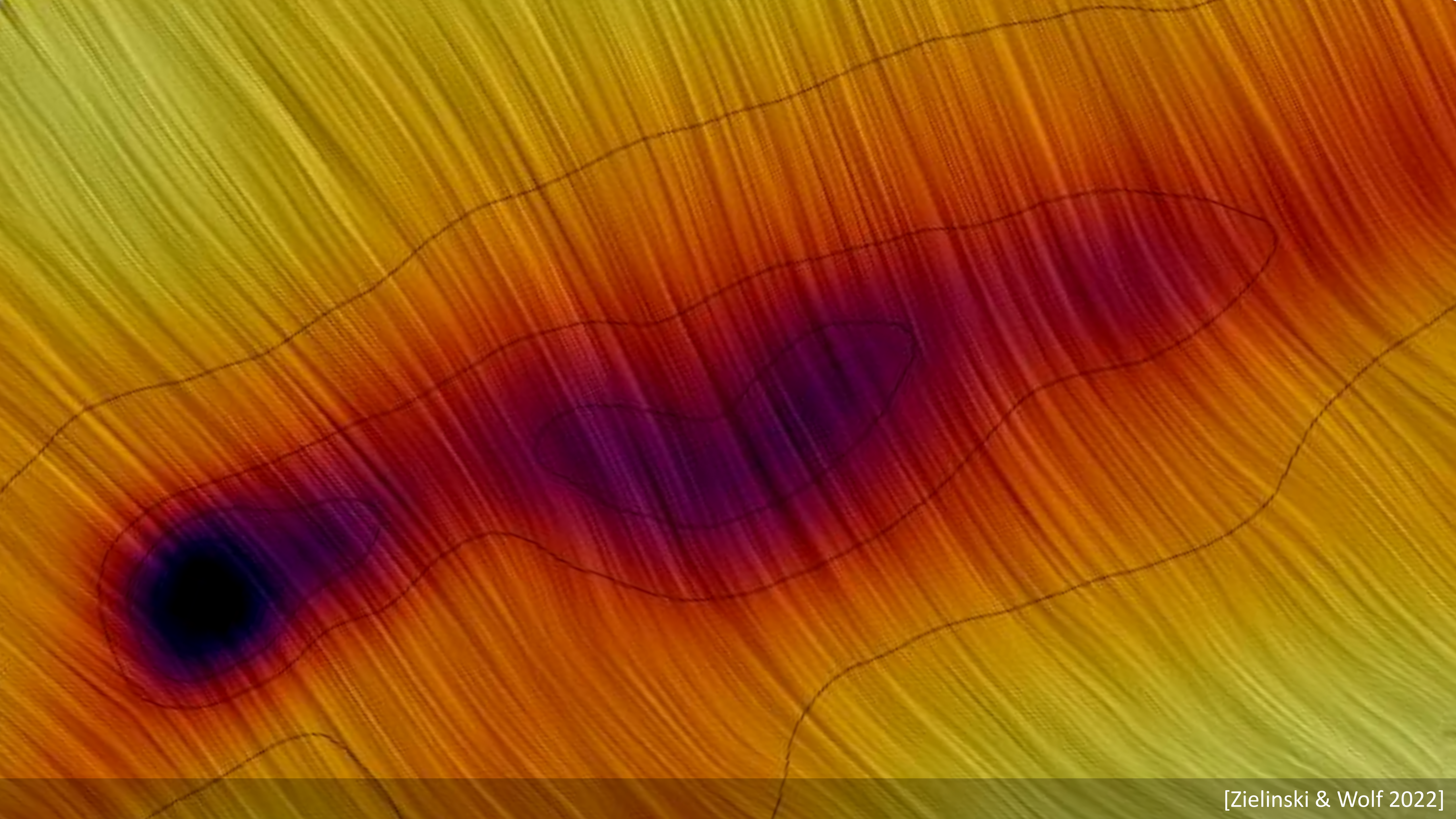
$$P_{\text{linear}} = \sqrt{\frac{Q^2 + U^2}{I^2}}$$

Degree of
circular polarization

$$P_{\text{circular}} = \frac{V}{I}$$

Orientation: $\tan 2\gamma = \frac{U}{Q}$

$$(0^\circ \leq \gamma \leq 180^\circ)$$



[Zielinski & Wolf 2022]

Polarimetry with SOFIA: Context

Polarization mechanisms

Astrophysical sources of polarized radiation

- Emission of polarized light
  - Synchrotron radiation
  - Molecular emission in external magnetic field => Zeeman effect
  - Thermal emission by aligned non-spherical dust grains
- Modification of polarization state
  - Absorption by aligned non-spherical dust grains
  - Scattering

- **Thermal emission / Absorpion of aligned, spinning grains**

  Various grain spin-up (e.g. radiative torques) / alignment mechanisms

- Selected alignment mechanisms:

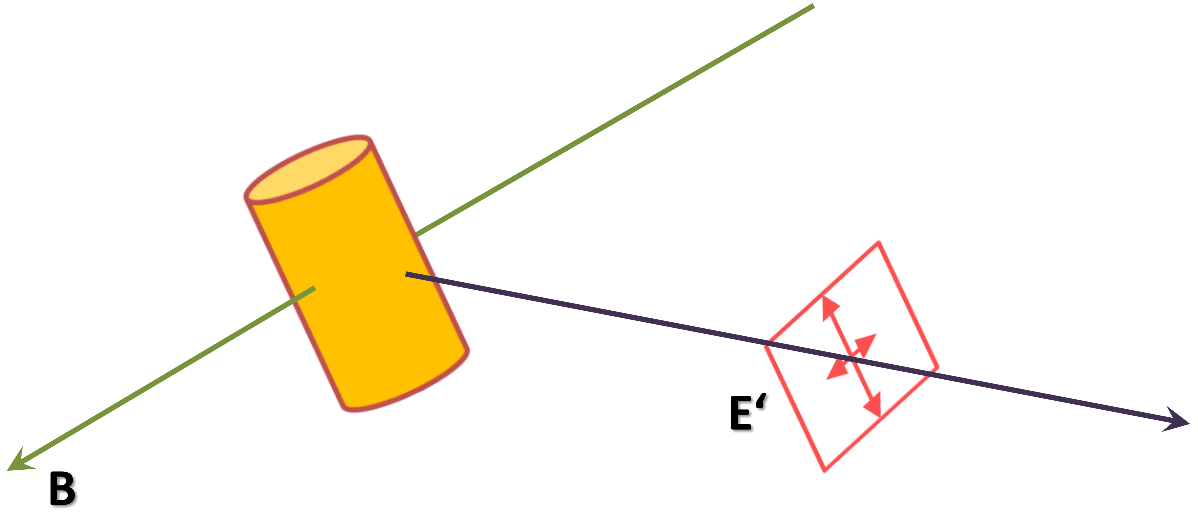
  Supersonic flows (=> constraints on gas flow)

  Barnett effect, Davis-Greenstein alignment

  (=> constraints on **B** field)

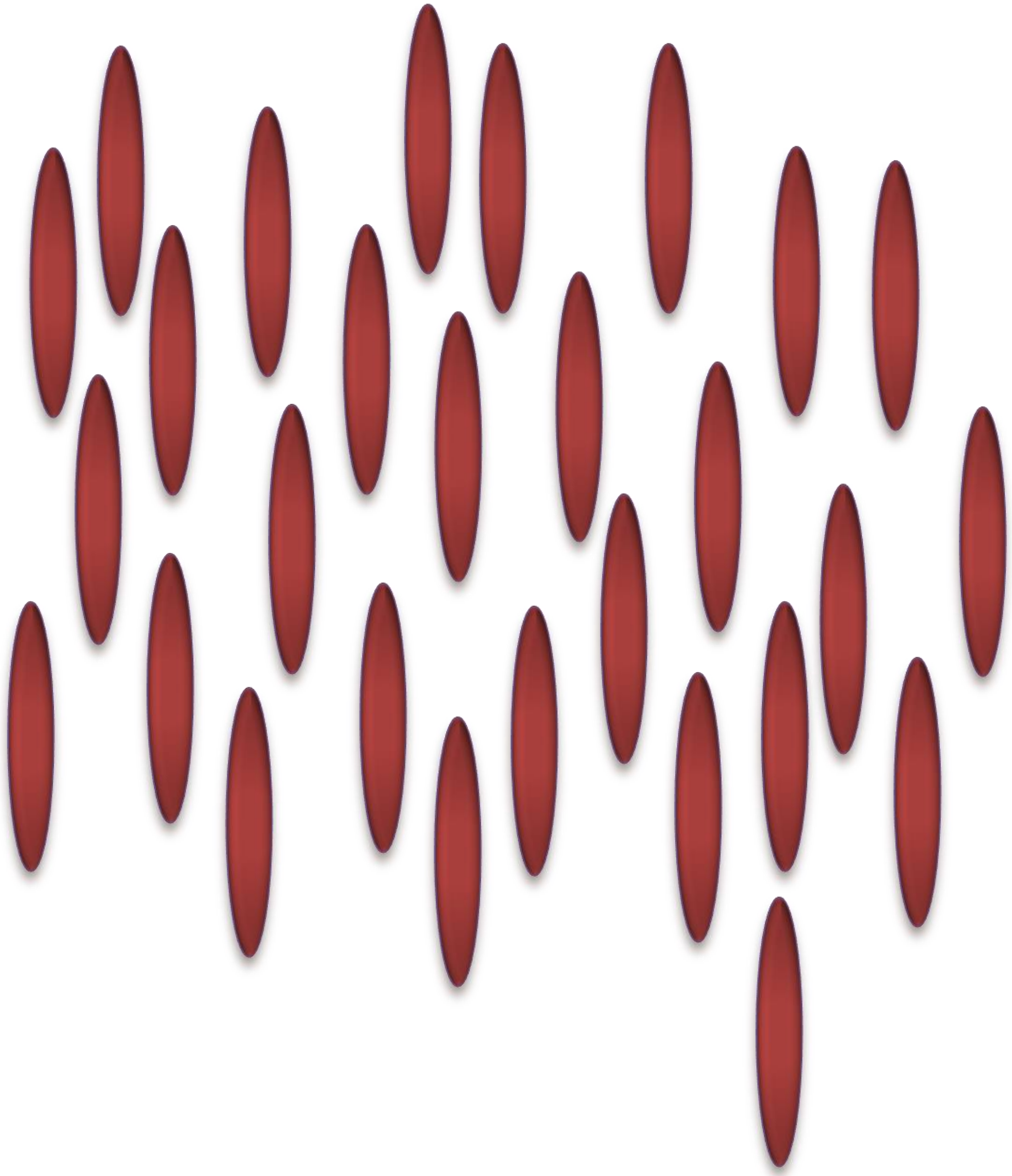
(A) Polarized thermal emission

- Aligned non-spherical grains:
  Polarized thermal emission

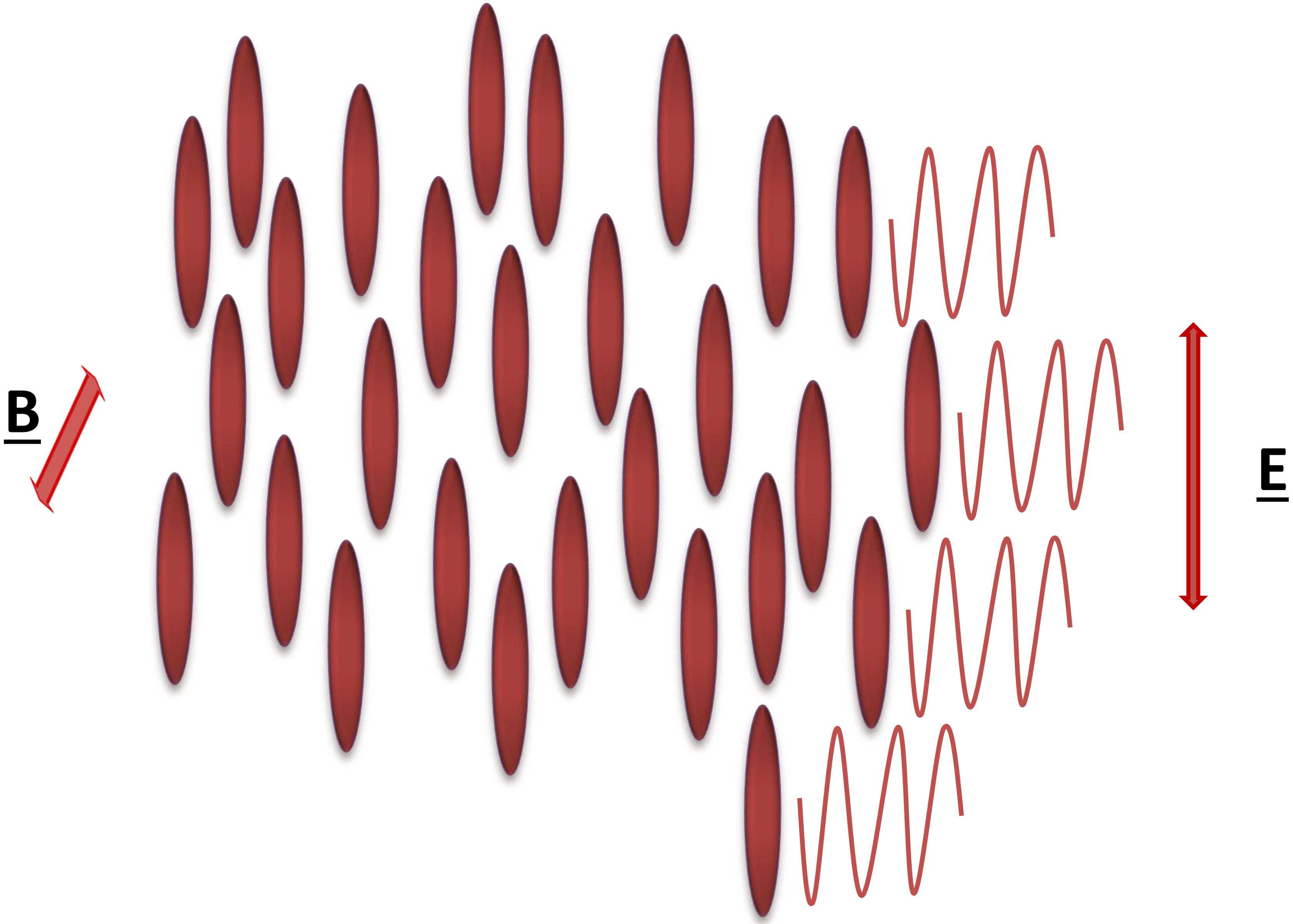


Thermal emission from grains at far-IR / mm wavelengths:
Partially linearly polarized (**P** perp. **B**)

(A) Polarized thermal emission

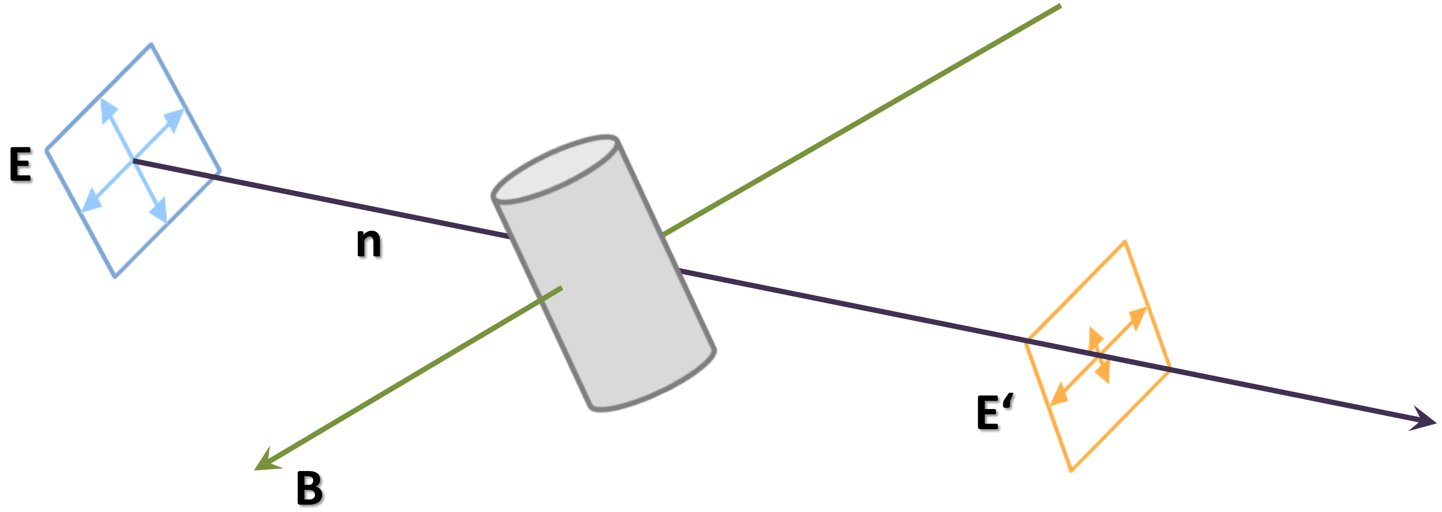


(A) Polarized thermal emission



(B) Dichroic extinction

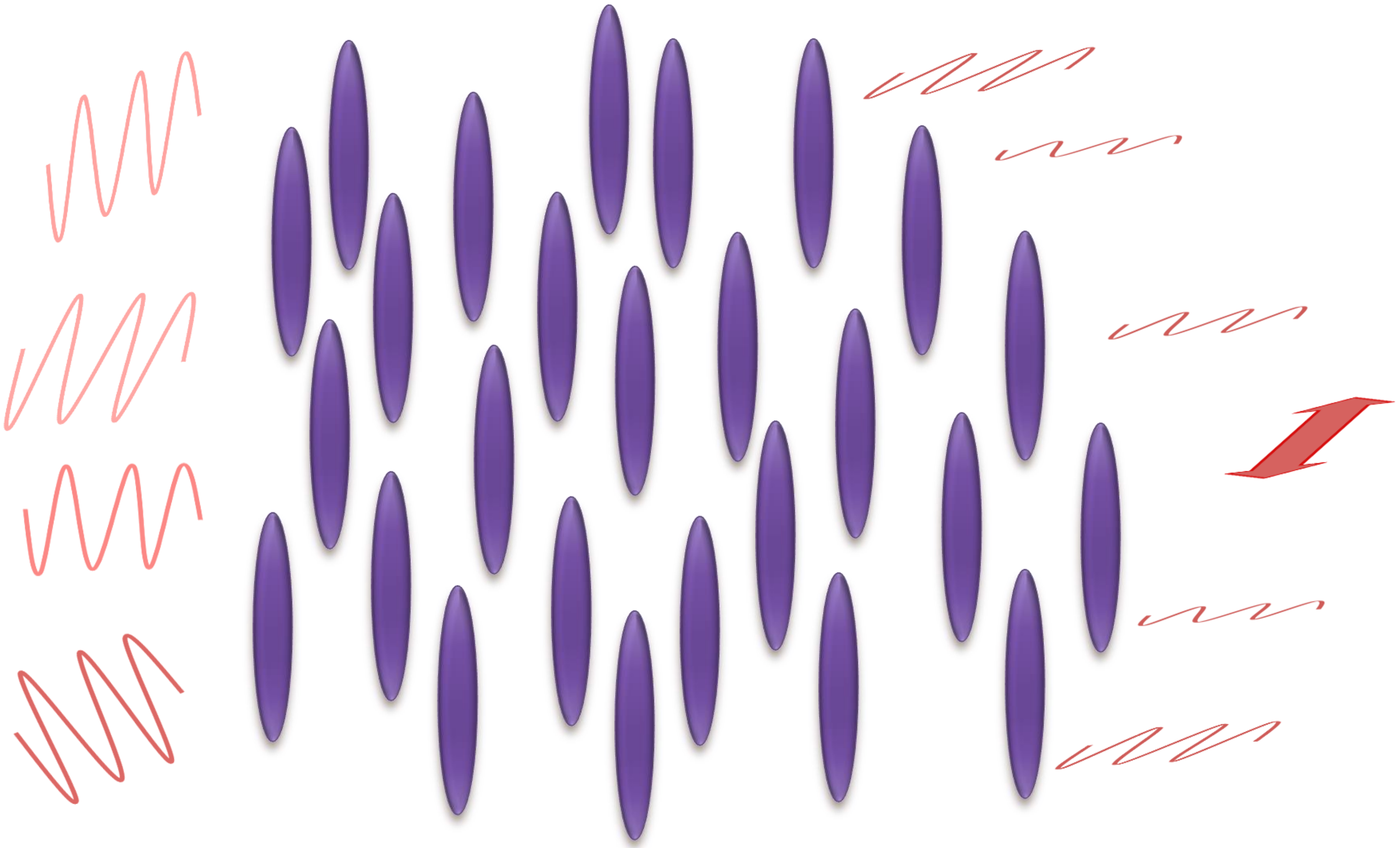
- Aligned non-spherical grains: **Dichroic extinction**



Observed polarization degrees (ISM): < 5%

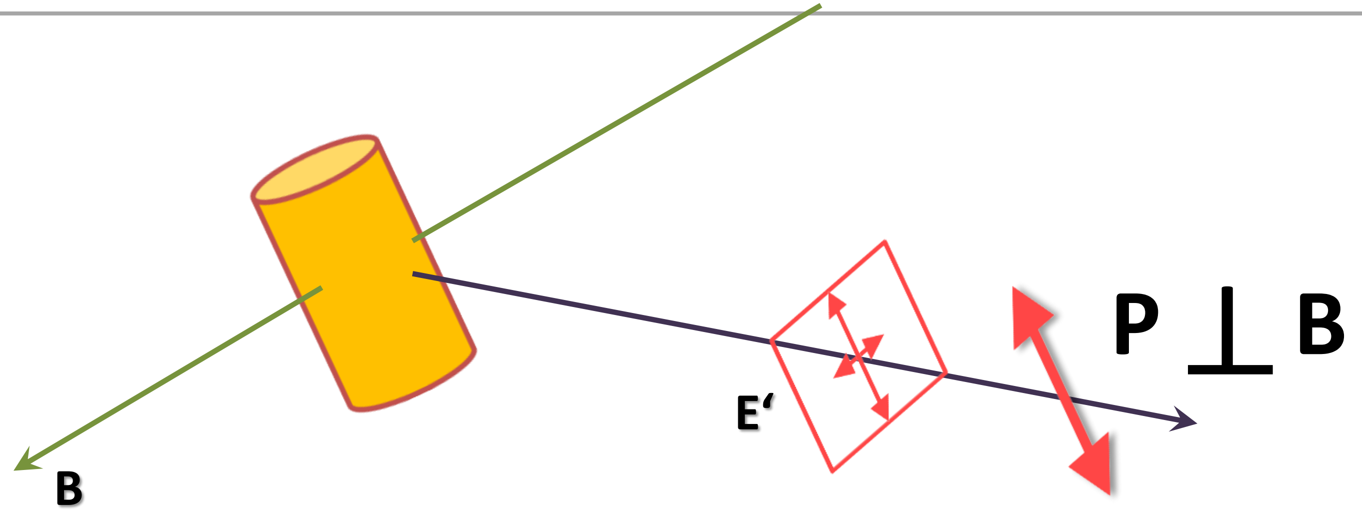
(optical / infrared wavelength range)

(B) Dichroic extinction

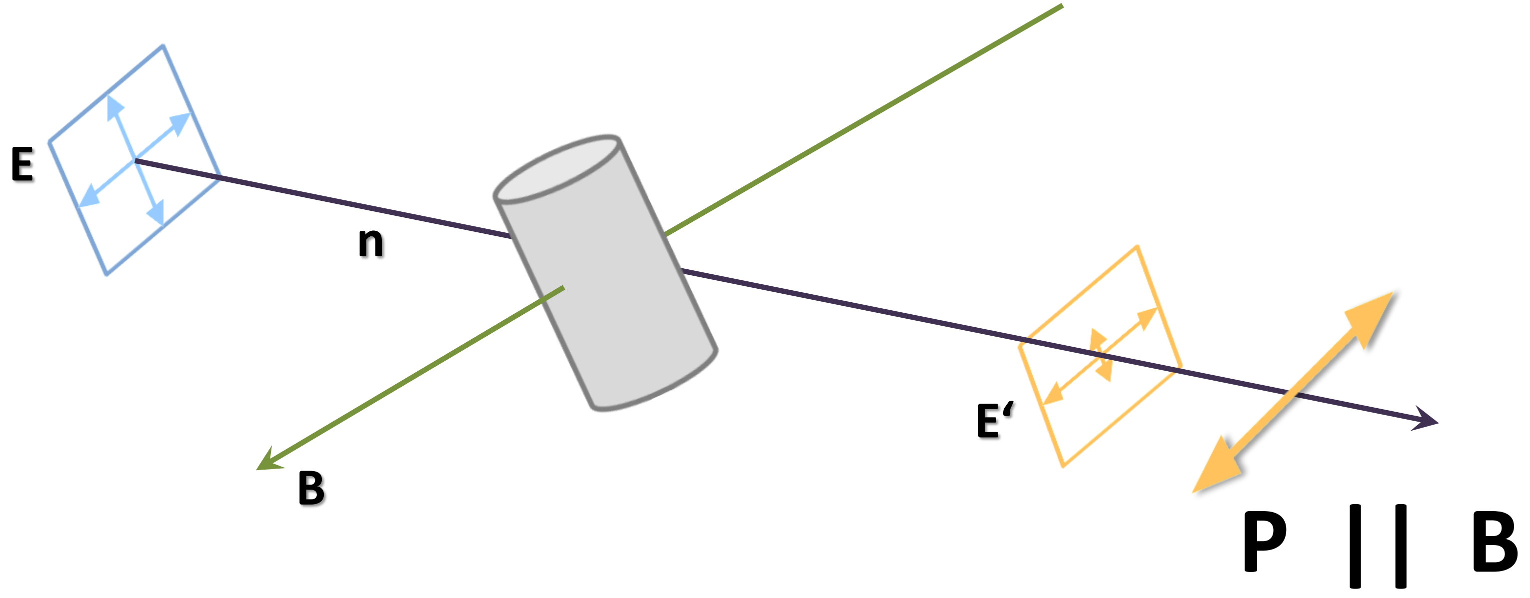


(A) Polarized emission / (B) Dichroic absorption: Comparison

- Polarized emission



- Dichroic extinction

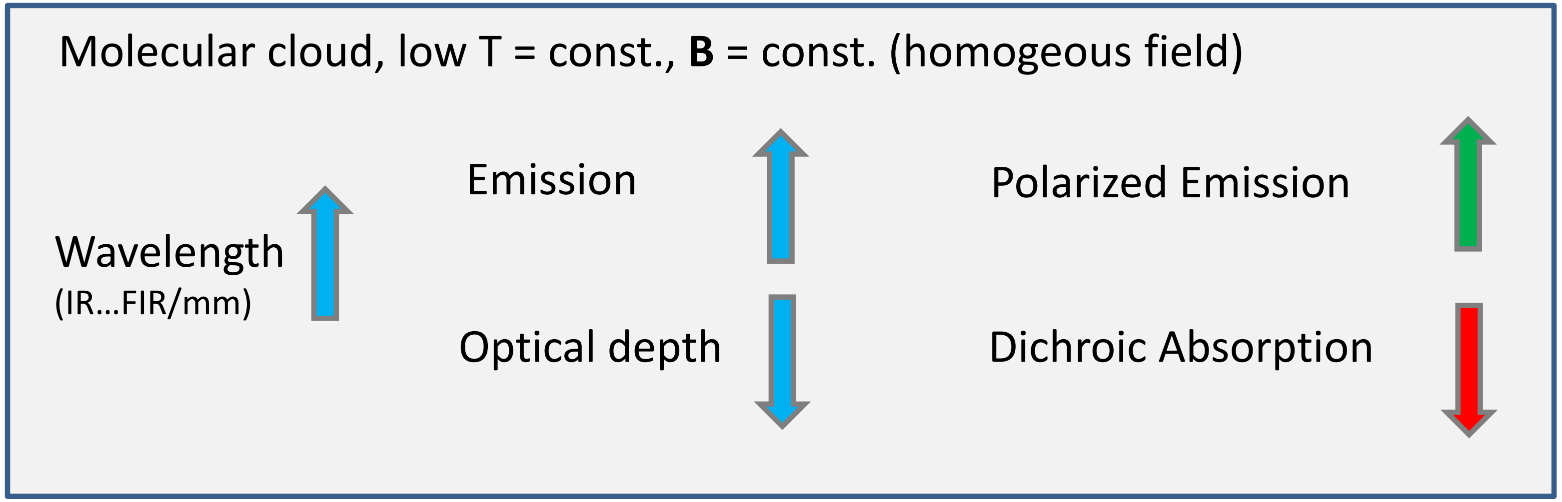


(A) Polarized emission / (B) Dichroic absorption: Comparison

Importance of **multi-wavelength polarization** measurements

(1) Dichroic extinction => Polarized emission: **90° flip**

= f(wavelength, temperature)

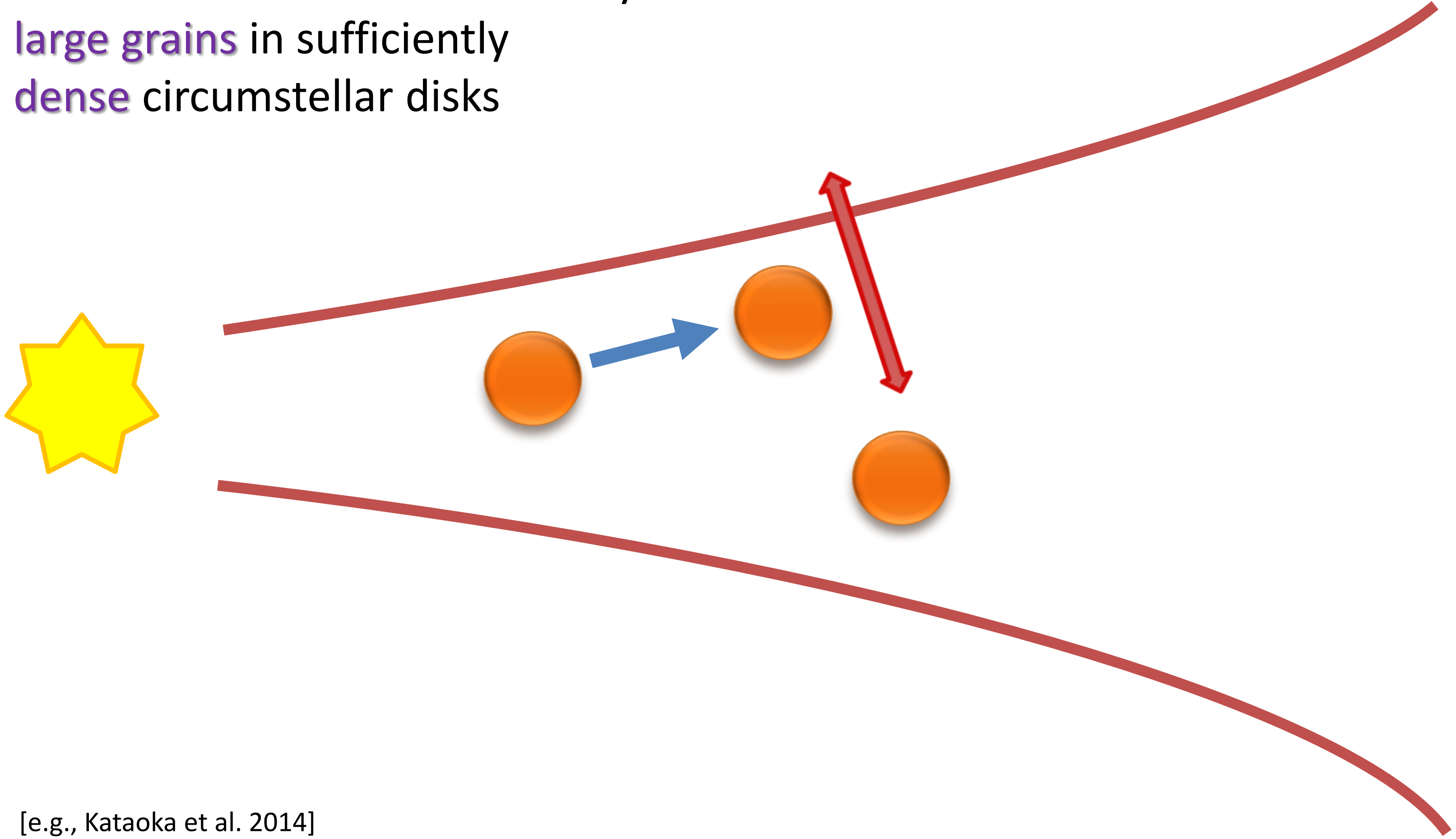


(2) Inhomogenous magnetic field structure along line of sight: **Continuous rotation**

= f(wavelength, temperature)

(C) Polarization due to scattering @ FIR wavelengths

Scattering of
thermal reemission radiation by
large grains in sufficiently
dense circumstellar disks



[e.g., Kataoka et al. 2014]

Polarimetry with SOFIA
Unique potential

SOFIA/HAWC+:

A unique instrument for measuring polarization (=> magnetic fields, …)

- 5 channels: **53 um … 216 um**
- Angular resolution of **5.4" - 22"**

  => **best angular resolution** and **only polarimetric capability** in this wavelength range
- Bridges the sub-mm and mid-infrared regimes for the first time:

NIR/MIR @ 8-10m class telescopes
(diffraction limited; e.g.,
a) *SPHERE / ZIMPOL*, Beuzit et al. (2008); Thalmann et al. (2008): imaging polarimeter at the VLT/ESO
b) *CanariCam / Gran Telescopio CANARIAS*, Telesco et al. (2003); Packham et al. (2005): MIR imager and spectrometer)

⇔

(Sub)mm regime
Atacama Large submillimeter / Millimeter Array (ALMA):
Most advanced observatory allowing polarimetric observations:
Much smaller scales than possible with SOFIA/HAWC+ (ALMA: 10 mas)

ESA/Planck satellite:
Lower sampling than SOFIA/HAWC+ (Planck: 5').

SOFIA/HAWC+:

A unique instrument for studying magnetic fields

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- Angular resolution of 5.4” - 22”

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Atacama Large submillimeter / Millimeter Array (ALMA): Most advanced observatory allowing polarimetric observations. Much smaller scales than possible with …

ESA/Planck satellite: Lower sampling than SOFIA/HAWC+ (Planck: 5’).

> SOFIA/HAWC+ : Perfectly suited to study phenomena at intermediate angular resolution, providing the link between NIR/MIR and ALMA/Planck observations

SOFIA/HAWC+:

A unique instrument for studying magnetic fields

- 5 channels: 53 um … 216 um
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  => best angular resolution and only polarimetric capability in this wavelength range
- Bridges the sub-mm and mid-infrared regimes for the first time:

NIR/MIR @ 8-10m class telescopes ⟺ **(Sub)mm regime**

Relative contribution of different polarization mechanisms (scattering, dichroic extinction,dichroic absorption) /
Resulting polarization of each individual polarization mechanism:

Wavelength-dependent

Wavelength-range targeted by SOFIA/HAWC+
covers the transition region between
the different polarization mechanisms.

FIR Polarimetry with SOFIA

Selected results

Large-scale **B**-fields in AGNs

NGC 1068:

Magnetized spiral arms

Interplay:

Dust grain alignment

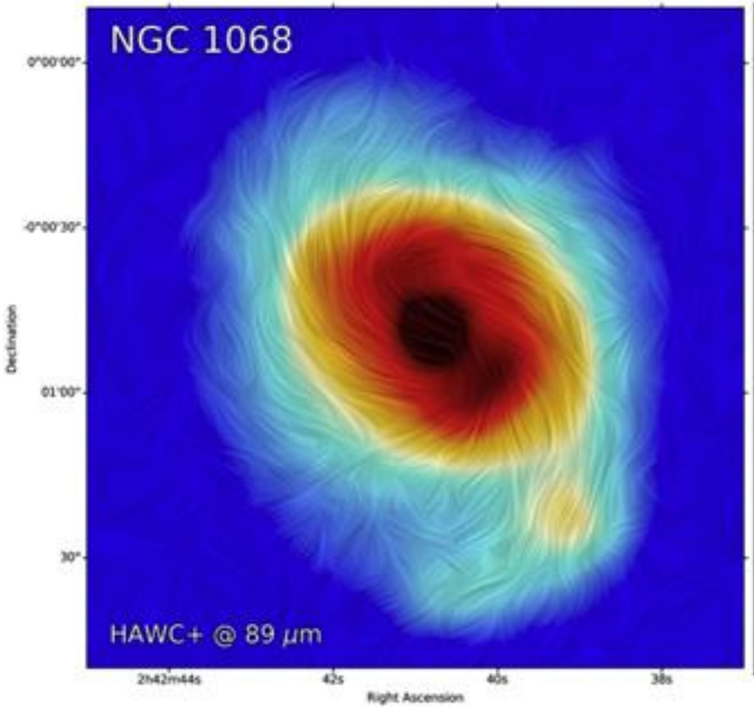
⇔

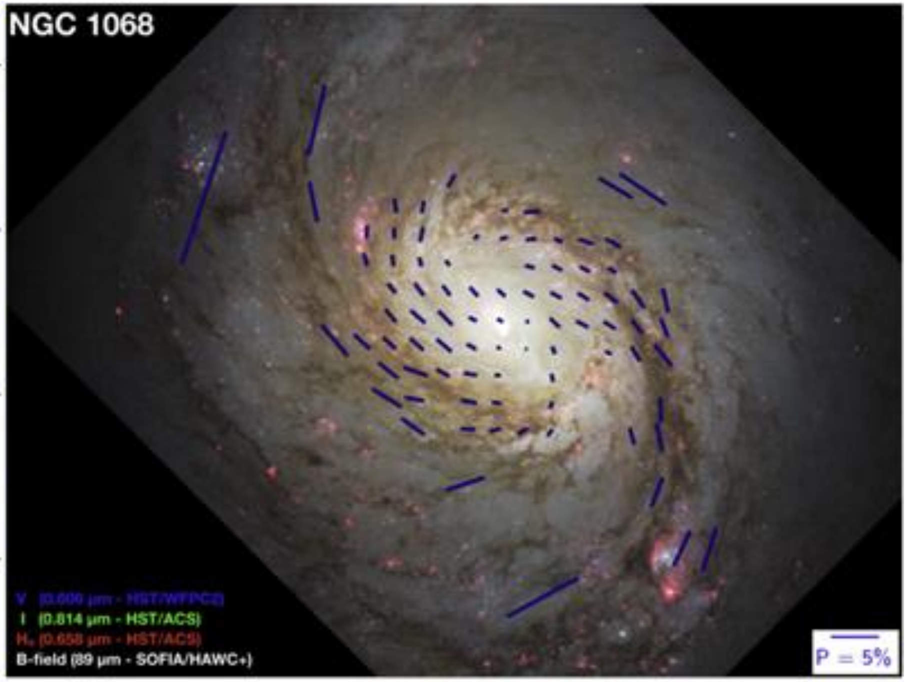
Magnetic field

Magnetic field

⇔

Disk morphology

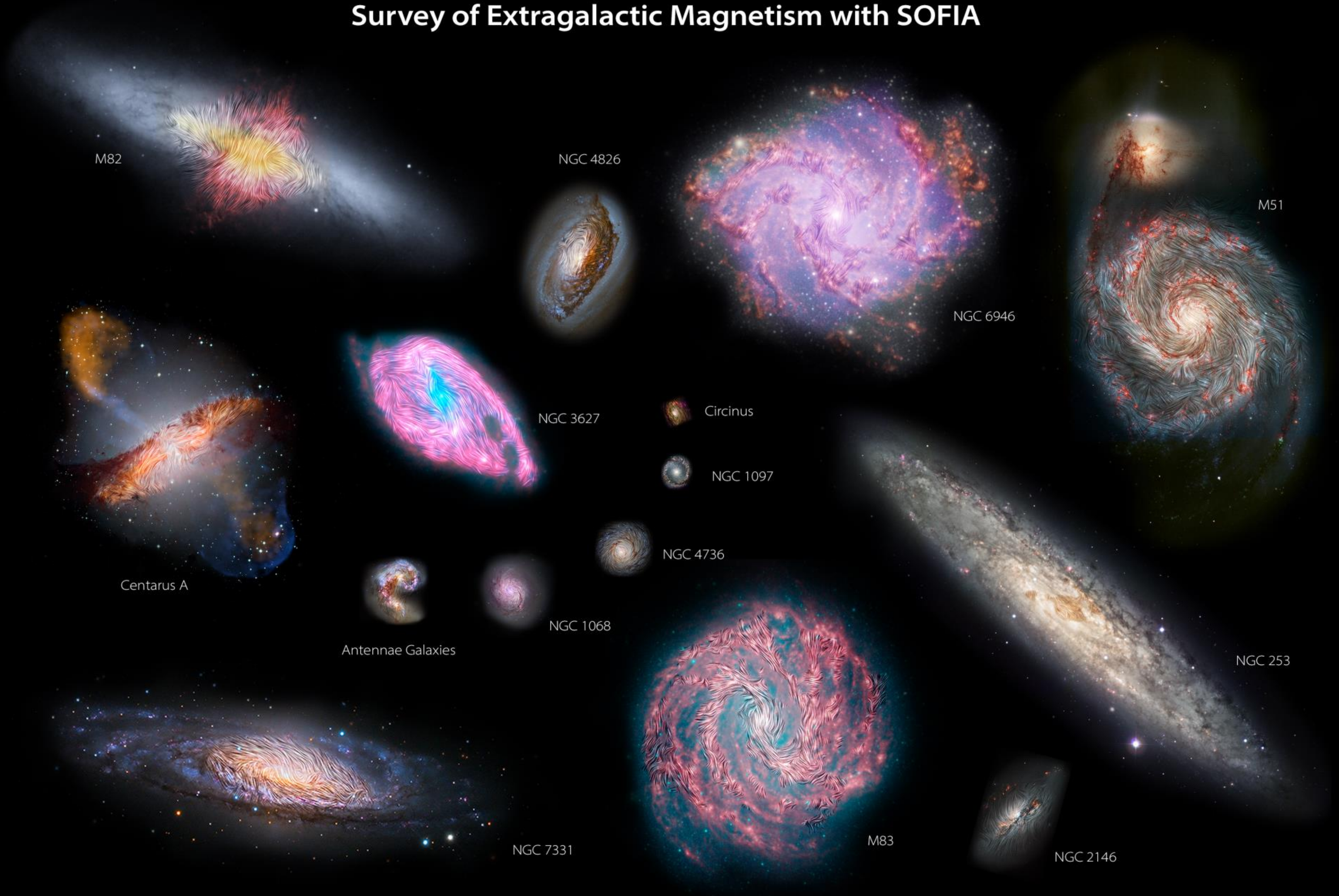




[SOFIA/HAWC+/E. Lopez-Rodriguez]

SALSA

Survey of Extragalactic Magnetism with SOFIA

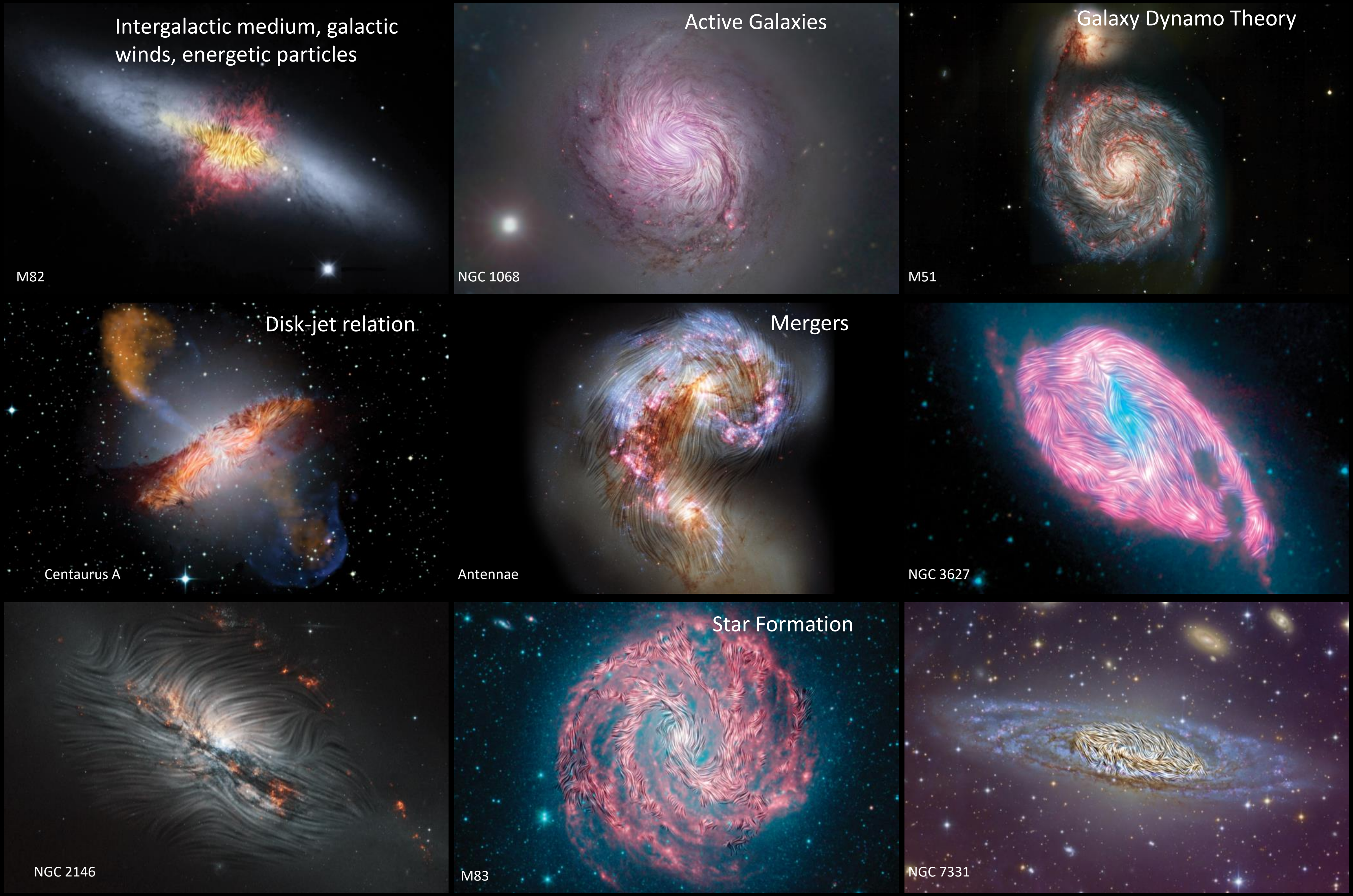


galmagfields.com

[E. Lopez-Rodriguez]

RESULTS:

B-FIELDS PERMEATE THE DENSE AND COLD INTERSTELLAR AND CIRCUMGALACTIC MEDIUM

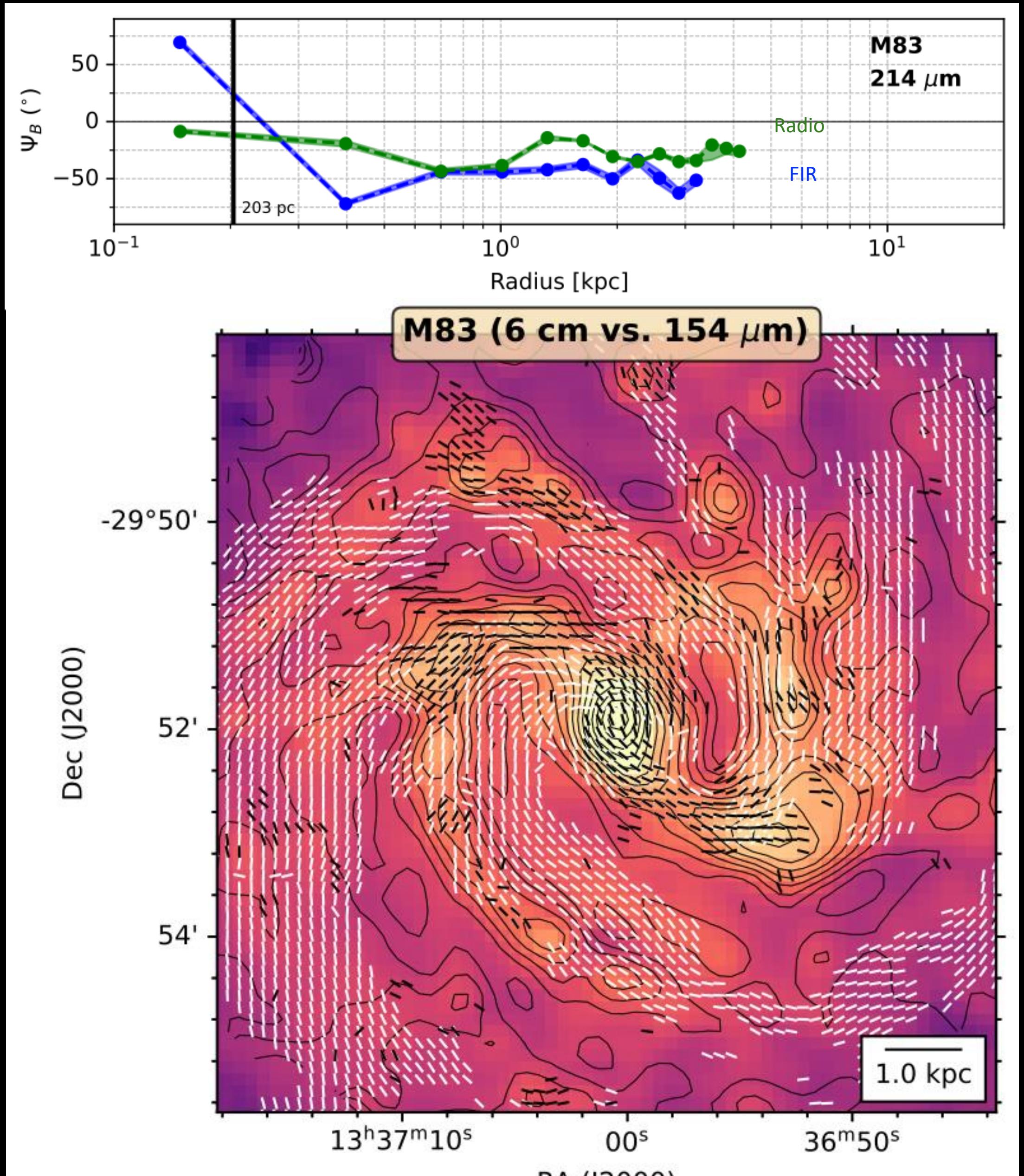


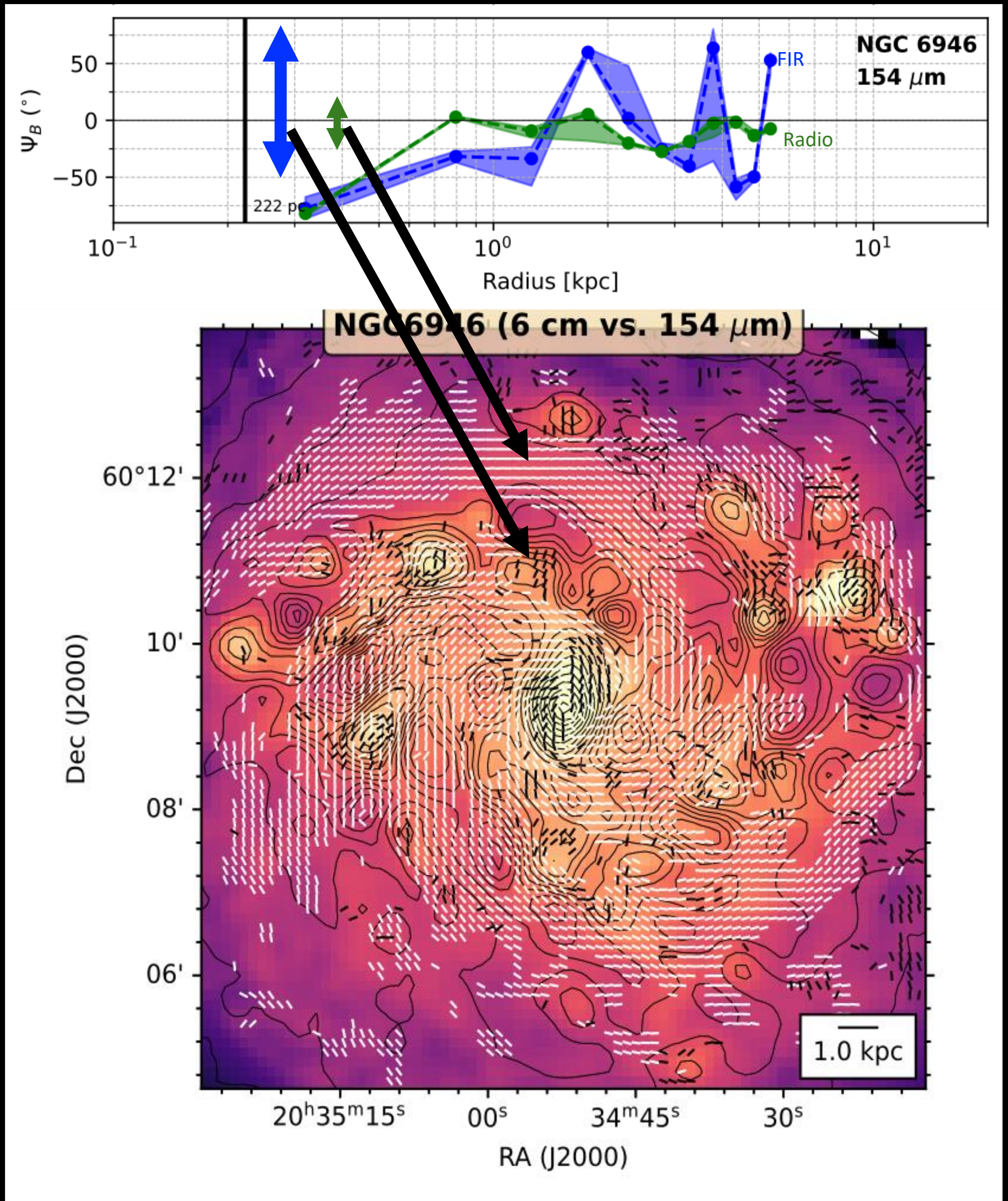
Borlaff et al. (2021, 2023), Martin-Alvarez et al. (2024), Lopez-Rodriguez (2020, 2021a,b, 2022b,c, 2023a,c)

[E. Lopez-Rodriguez]

FIR B-FIELDS ARE MORE DISORDERED THAN RADIO B-FIELDS

[E. Lopez-Rodriguez]





Borlaff et al. (2023, SALSA V)

THE COSMIC HISTORY OF THE B-FIELDS IN GALAXY EVOLUTION USING FIR POLARIMETRY

Mergers


Lopez-Rodriguez 2022c

Active galaxies


Lopez-Rodriguez 2021b

Galactic outflows


Lopez-Rodriguez 2021a

Interaction, star formation, galactic dynamo


Borlaff et al. 2021

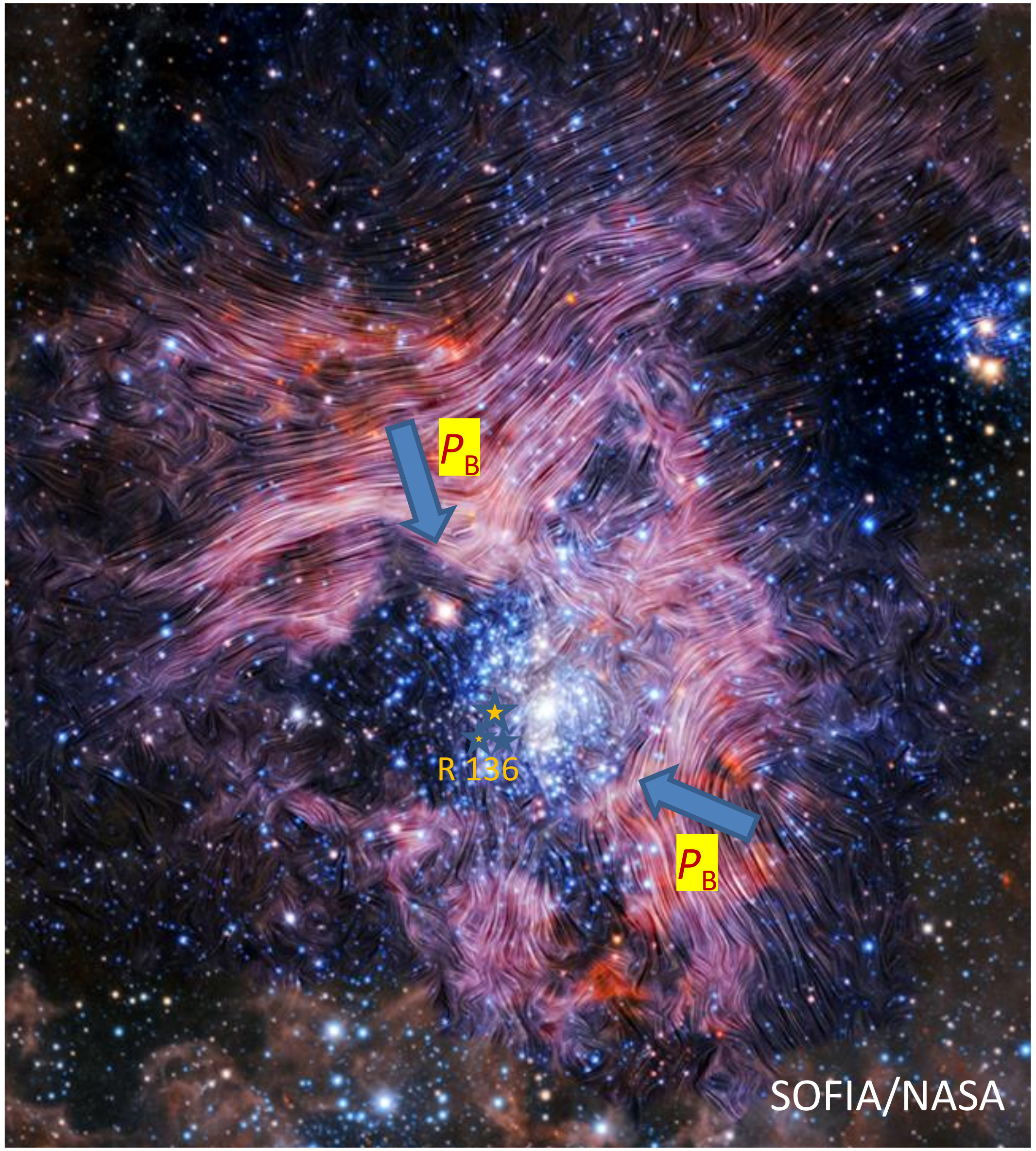
AGN, star formation, galactic dynamo


Lopez-Rodriguez et al. 2020

How did the evolution of galaxies in mergers affect magnetic fields?
Is the circumgalactic medium magnetized?
How has the magnetic field been amplified by interaction/SF in galaxies?
What is the structure of the magnetic field around an active nucleus?

[E. Lopez-Rodriguez]

30 Doradus @ Large Magellanic Cloud



Pol. Measurements @ 89, 154 and 214 μm

Magnetic fields:

Key to maintain integrity of 30 Doradus

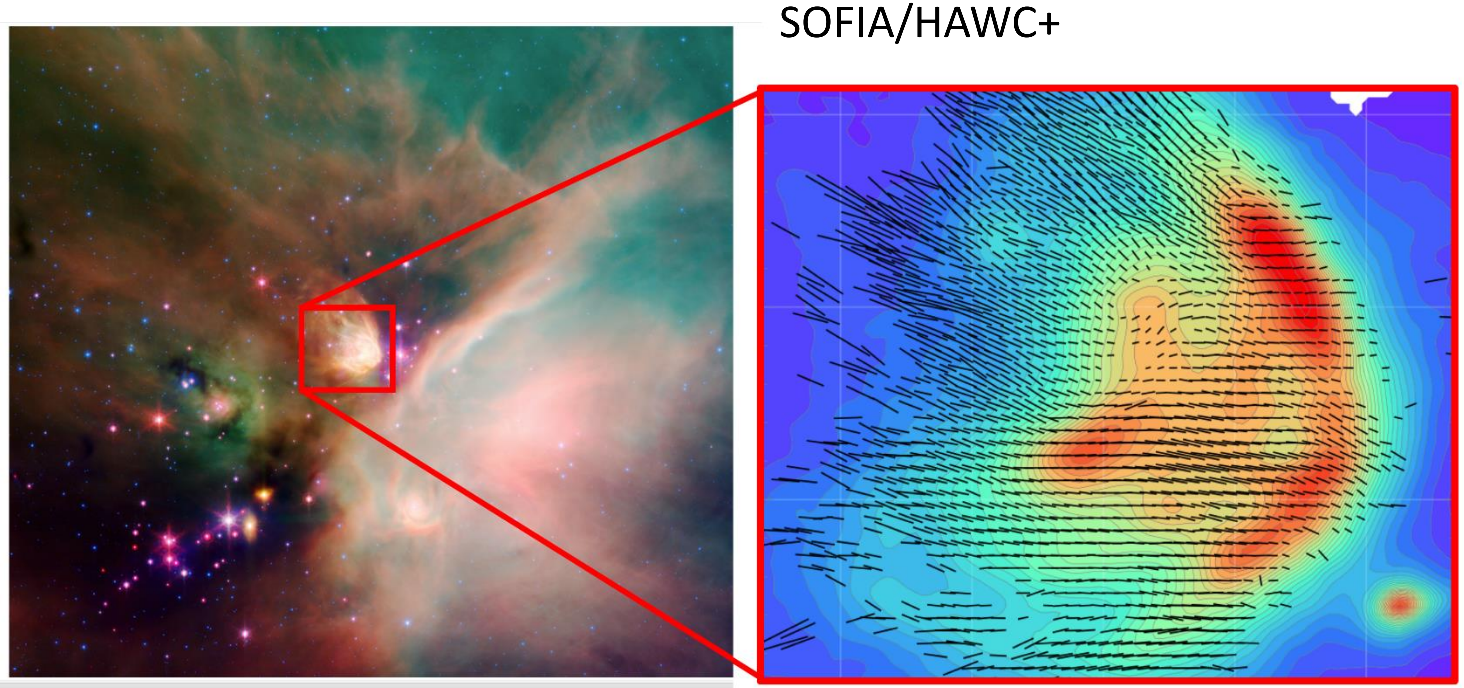
Correlation between magnetic field structure, transport of material

=> Triggered star formation

- B-fields' strength varies across the cloud
- Relatively strong field: few hundreds μG
- Miminal at the peak flux intensity

[Le Ngoc Tram, nle@mpifr-bonn.mpg.de]

Magnetic fields: Star-forming clouds



Rho Ophiuchi (~131pc):

Systematic variations of the far-infrared polarization spectrum exist within the interstellar environment

[NASA/JPL-Caltech/Harvard-Smithsonian CfA. SOFIA/ HAWC+/ Northwestern University /F. Pereira Santos]

Rho Ophiuchi A (Santos+ 2019)

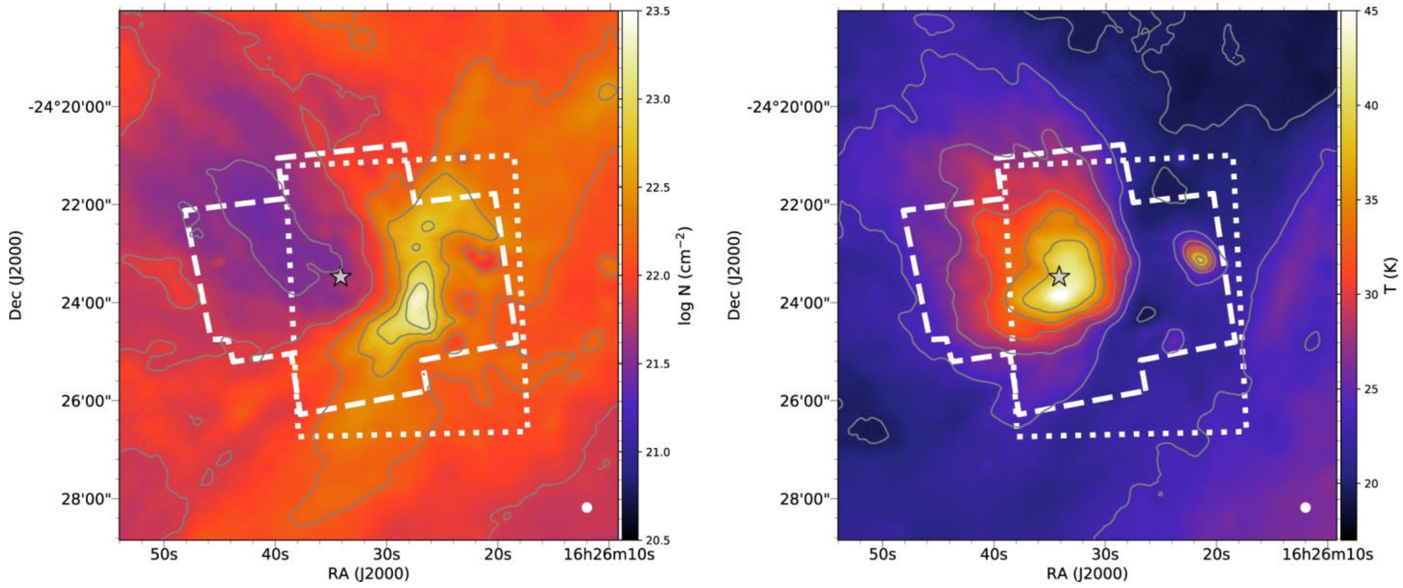
HAWC+ @ 89 μm / 154 μm

(1) Warm grains at the cloud outskirts, which are efficiently aligned by the abundant exposure to radiation from Oph S1 (as proposed in the radiative torques theory)

(2) Cold grains deep in the cloud core, which are poorly aligned due to shielding from external radiation

=> Constraints on grain alignment efficiency

Magnetic fields: Star-forming clouds



ρ Oph A maps of the inferred molecular hydrogen (H_2) column density (*N*, left), and dust temperature (*T*, right), as derived from *Herschel* fluxes

Rho Ophiuchi A (Santos+ 2019)

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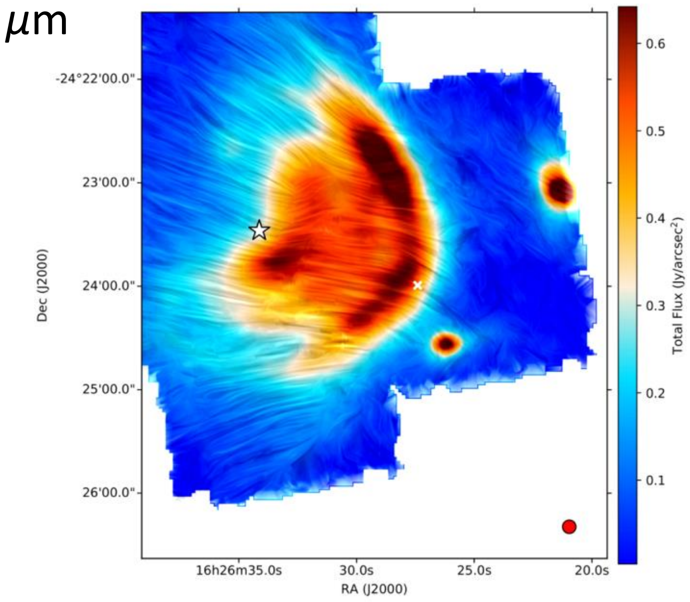
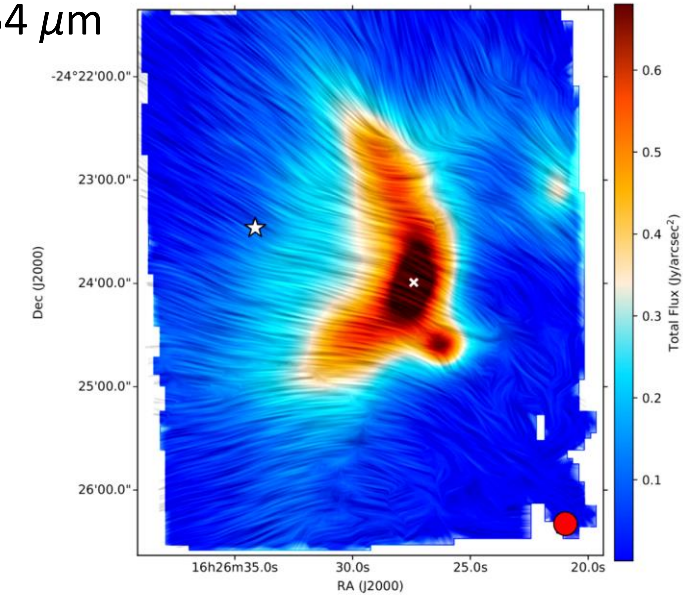
Magnetic fields: Star-forming clouds

89 μm

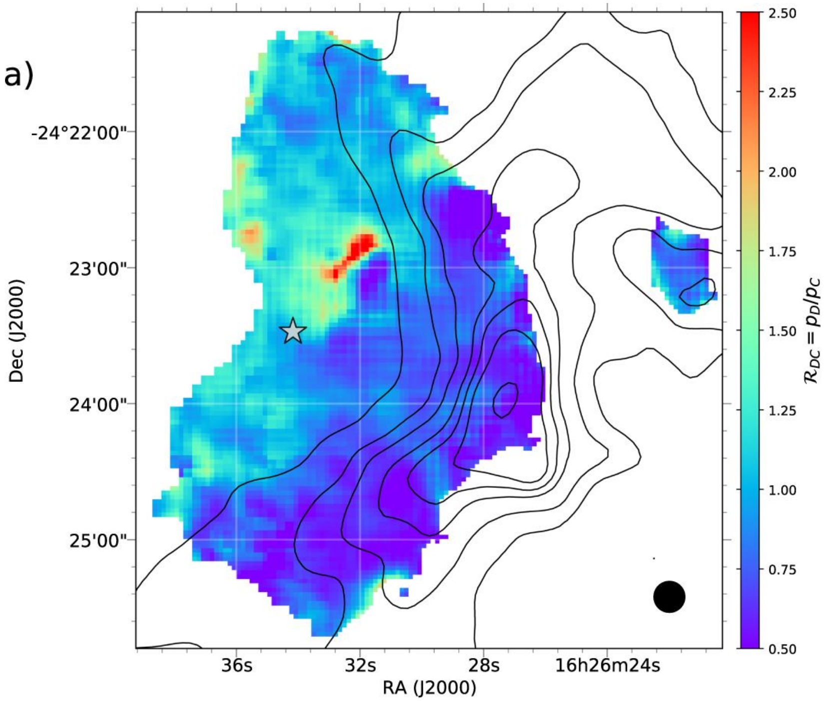


154 μm



Magnetic field structure

Polarization spectrum



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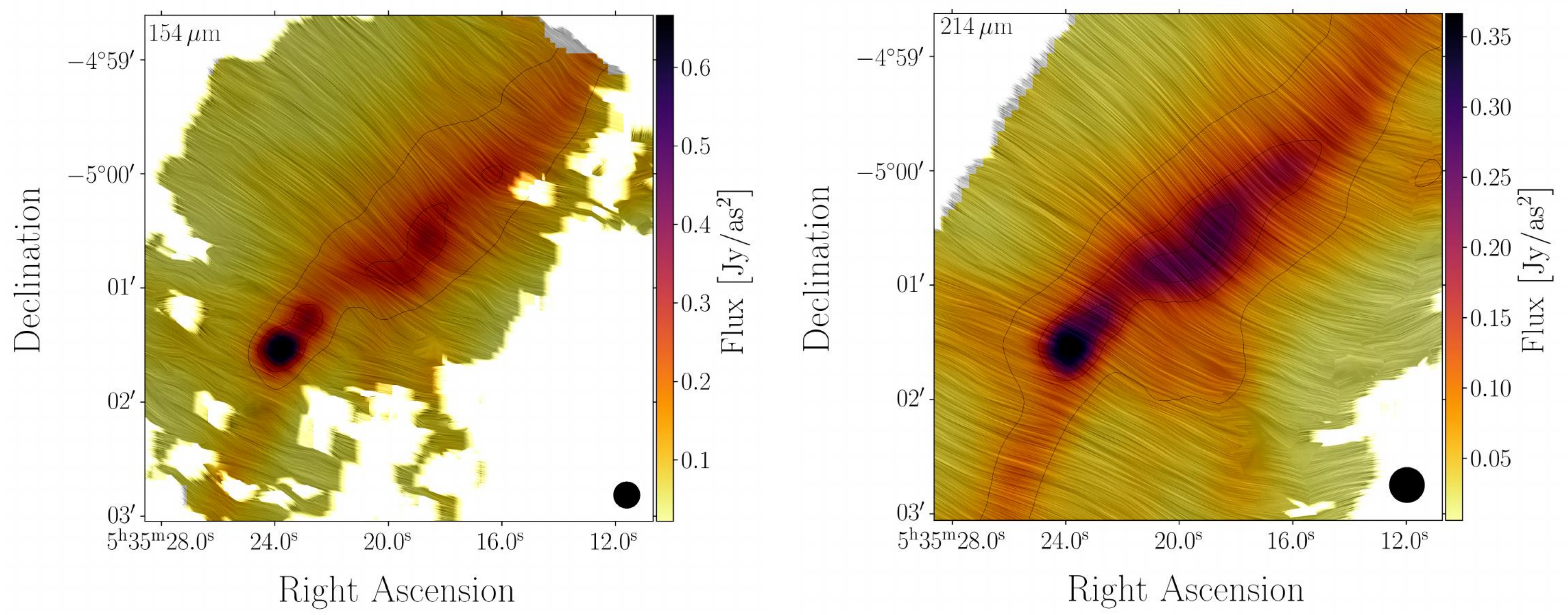
Magnetic fields: Filaments

[Zielinski & Wolf 2022, 2024]

OMC 3



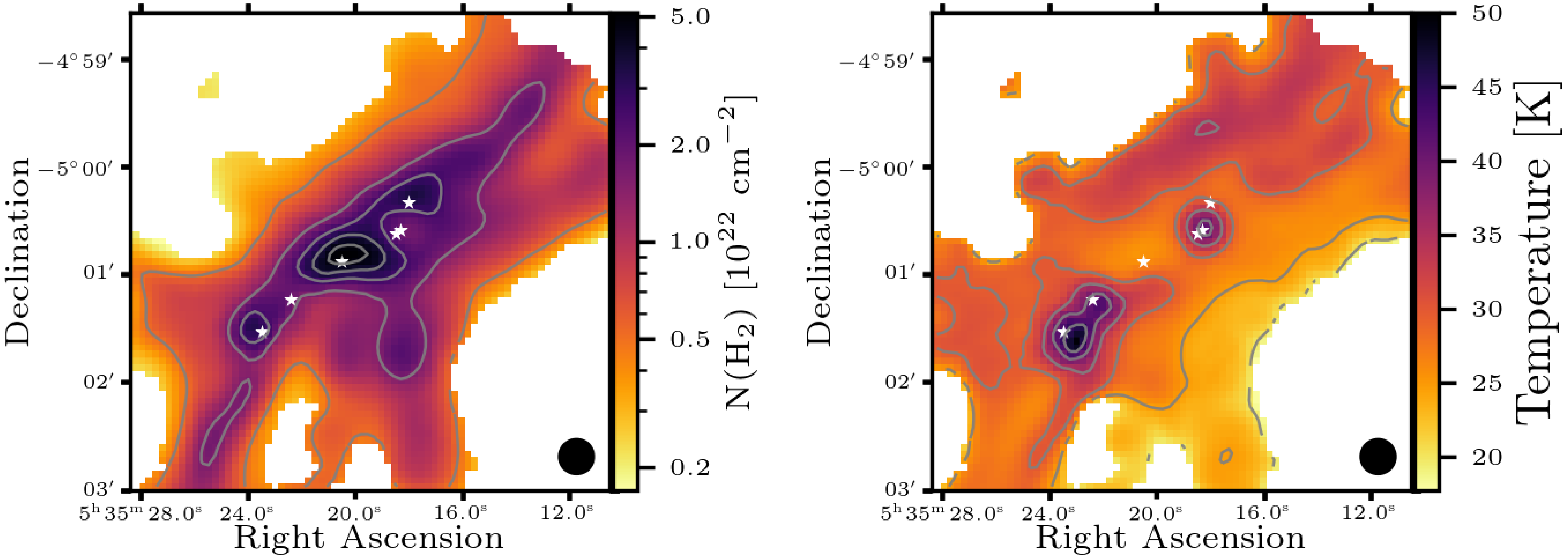
B field: uniform, oriented perpendicular to the filament

B = 202 (261) μG @ 154 (214) μm

Magnetic fields: Filaments

[Zielinski & Wolf 2022, 2024]

OMC 3

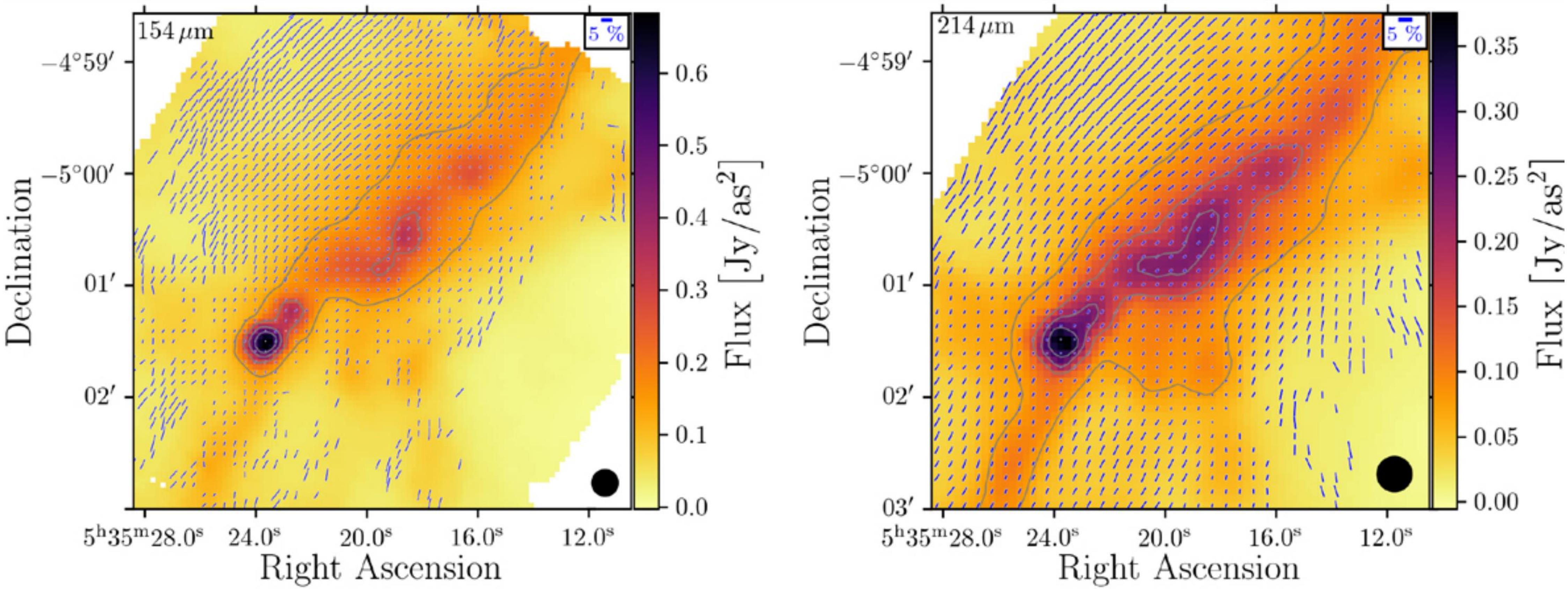


FIR polarization spectrum: no clear correlation with column density, $N(H_2)$, and temperature, T

Magnetic fields: Filaments

[Zielinski & Wolf 2022, 2024]

OMC 3



Decrease of polarization: Impact of dichroic extinction

Limitations

Limitations of the modified blackbody fit method (Zielinski & Wolf 2024)

- Derivation of dust temperature T, column density $N(H_2)$ and dust emissivity index β using a SED fitting process (Hildebrand 1983; Chuss et al. 2019):

$$I_\nu = (1 - \exp(-\tau(\nu))\ B_\nu(T)$$

$$\tau(\nu) = \epsilon \left(\frac{\nu}{\nu_0}\right)^\beta$$

$$I_\nu = \left(1 - \exp\left(-\kappa_{\nu_0}\ \mu\ m_H\ N(\mathrm{H_2})\ (\nu/\nu_0)^\beta\right)\right) \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

- Potential limitations: e.g., different observing wavelengths, unknown dust properties, optically thick regimes
- Goal: Determine impact of these limitations on the parameter estimates

Considered instruments:

- SOFIA/HAWC+
- Herschel/PACS
- JCMT/SCUBA-2

- Dust emissivity index derived from this method:
  Not suitable as an indicator of dust grain size

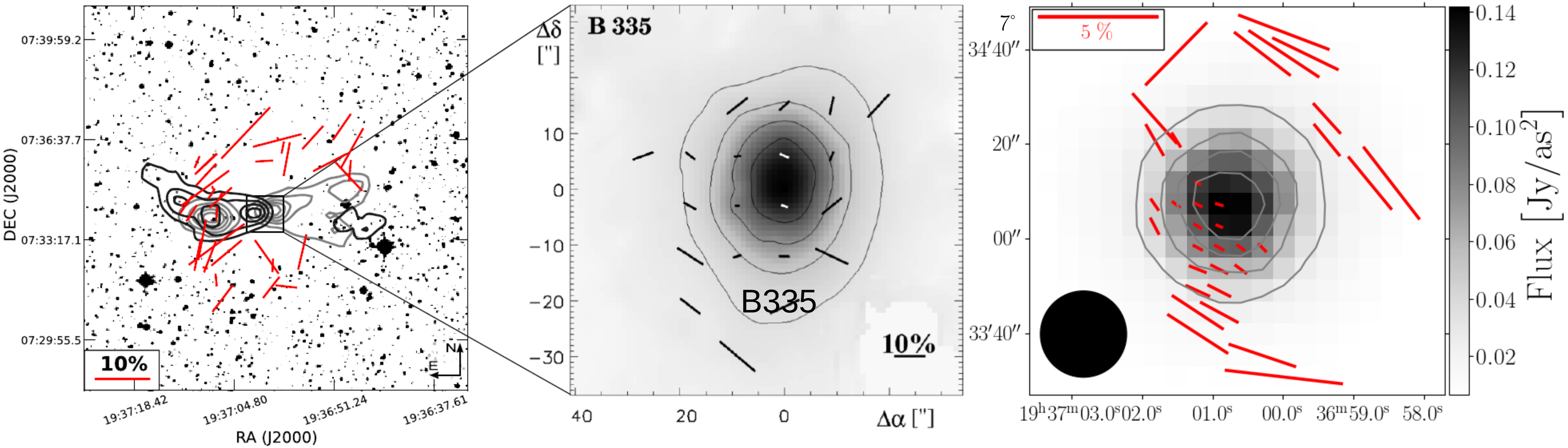
- Highest uncertainty:
  Often poorly constrained dust properties

- Proposed approach:
  First derive the optical depth;
  Subsequently the column density with the help of a suitable dust model as the optical depth can be obtained with high accuracy, especially at longer wavelengths

Magnetic fields: Molecular cloud cores

[Wolf et al. 2003 | Bertrang, Wolf, et al. 2014
Brauer, Wolf, et al. 2016 | Zielinski, Wolf, et al. 2021]

Example: B335



SOFI/NTT: K band **SCUBA/JCMT: 850µm** **SOFIA/HAWC+: 255µm**

First multi-wavelength (optical-submm), multi-scale polarization studies of the Bok-globules

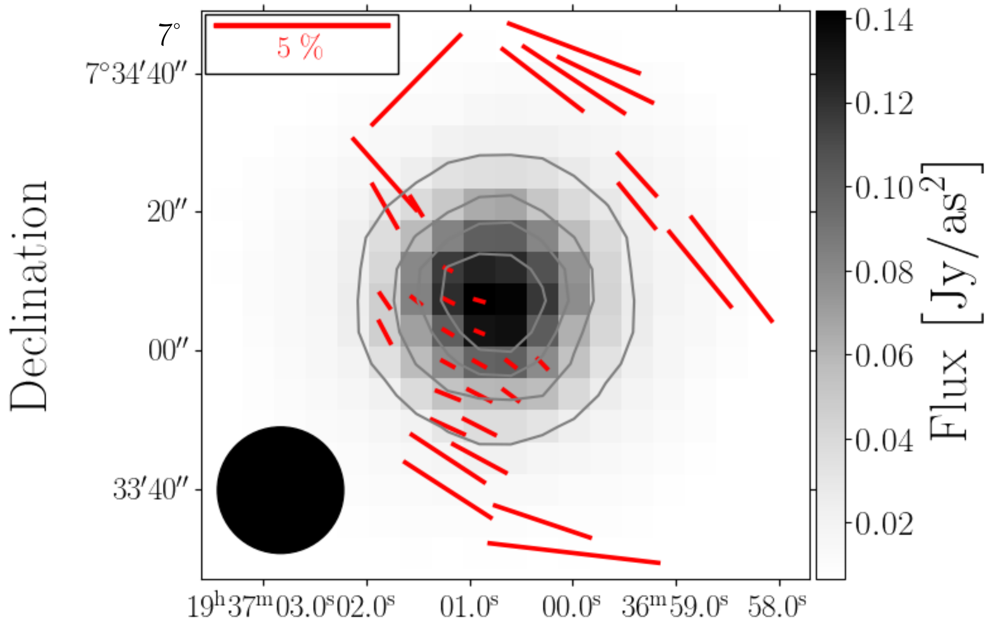
Correlation between large-scale (10^5AU) and small-scale (10^2AU) magnetic field structures in low-mass star-forming regions

Origin of "polarization holes"

Magnetic fields: Molecular cloud cores

[Wolf et al. 2003 | Bertrang, Wolf, et al. 2014
Brauer, Wolf, et al. 2016 | Zielinski, Wolf, et al. 2021]

Example: B335



SOFIA/HAWC+: 255µm

Column density towards the center of B335 is too low to cause the observed polarization hole in B335 via dichroic absorption

Effect of self-scattering has no significant impact on the observed polarization

Adopting dust-grain alignment via the radiative torque mechanism, a combination of the interstellar radiation field and the central star as radiation sources is consistent with the decrease in polarization degree at the outer regions of B335

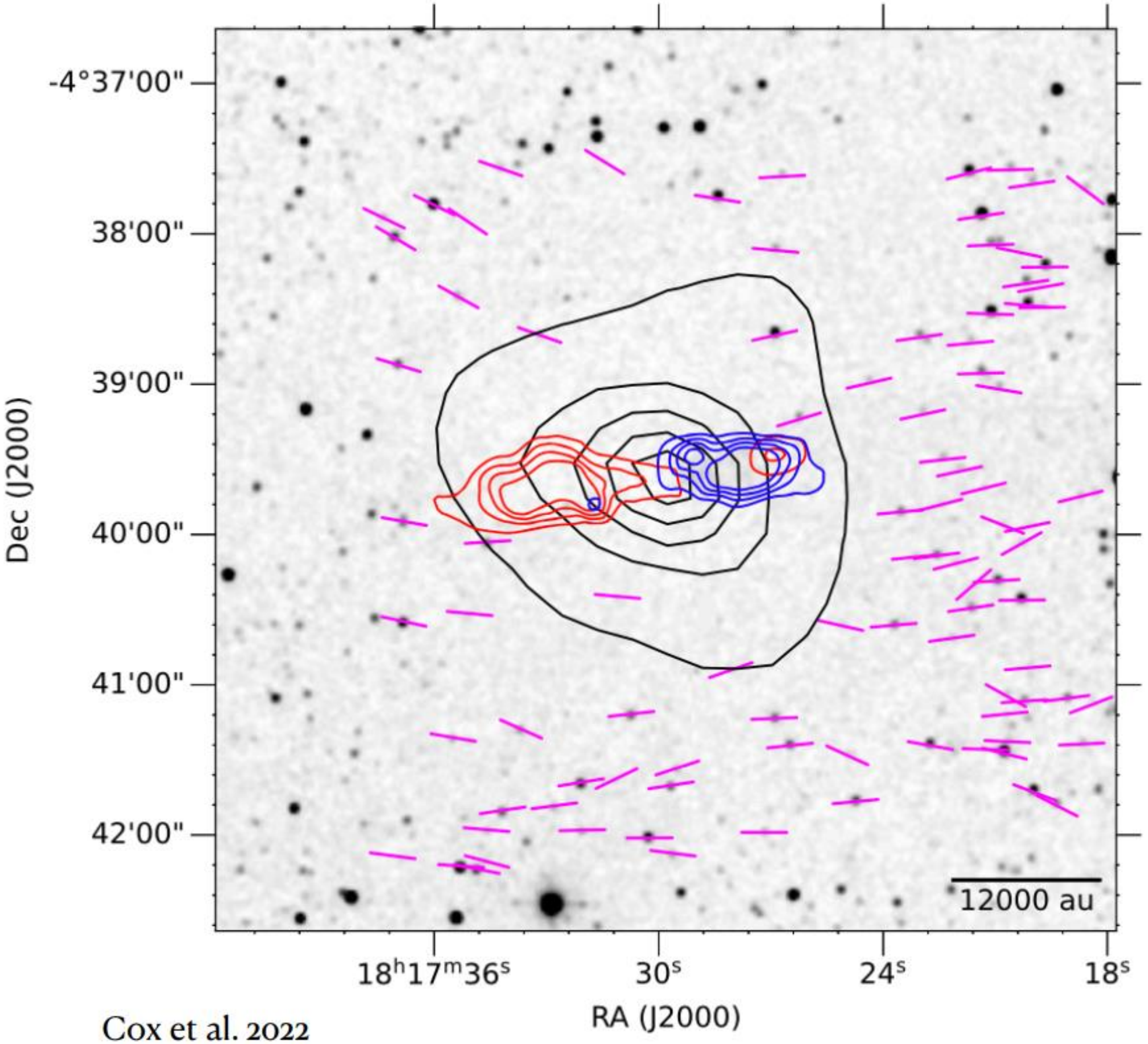
First multi-wavelength (optical-submm), multi-scale polarization studies of the Bok-globules

Correlation between large-scale (10^5AU) and small-scale (10^2AU) magnetic field structures in low-mass star-forming regions

Origin of "polarization holes"

Multi-scale Magnetic Field of L483

Protobinary molecular cloud core



Cox et al. 2022

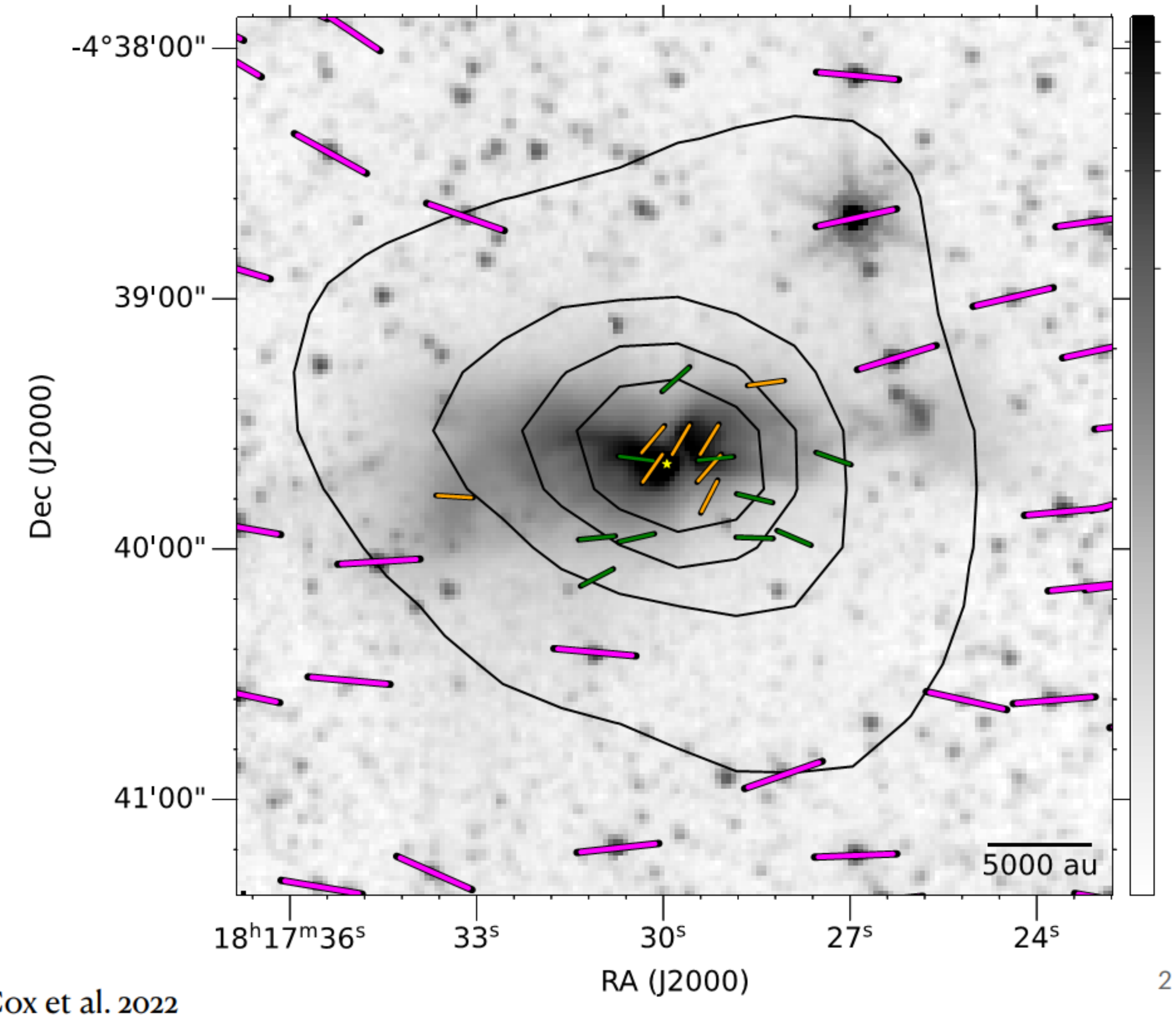
10,000 au magnetic field (magenta) parallel to the large-scale outflow

==> magnetic fields important in initial collapse

H band polarimetry

Multi-scale Magnetic Field of L483

Protobinary molecular cloud core



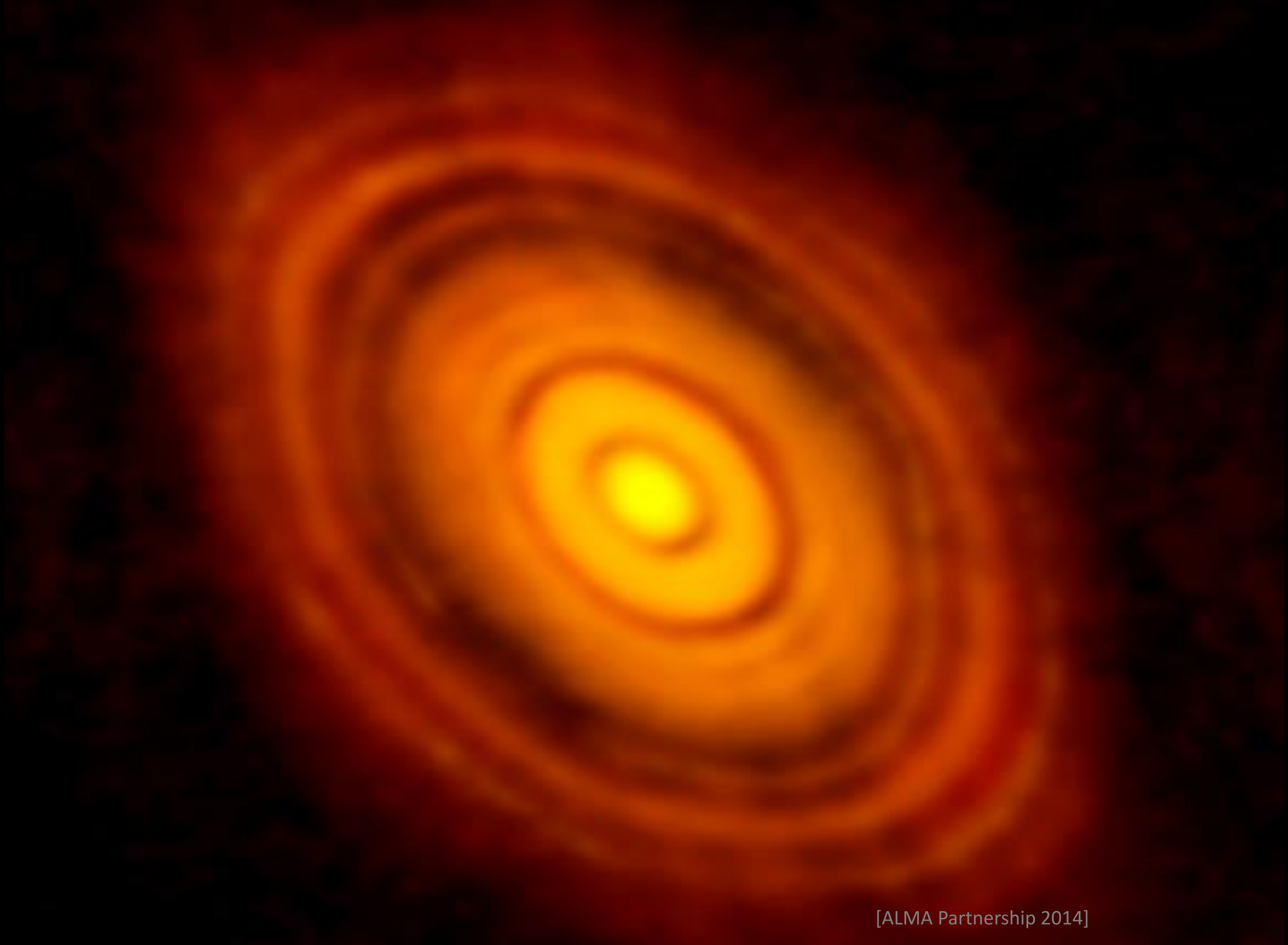
Cox et al. 2022

350 μm vectors (Chapman et al. 2013) at 2000 au (green) match larger scale field consistent with a strong magnetic field

SOFIA vectors (orange) show consistency with this larger field in the outer two vectors and a twist in the central inner envelope

— weaker field?

— event that changed the field direction?

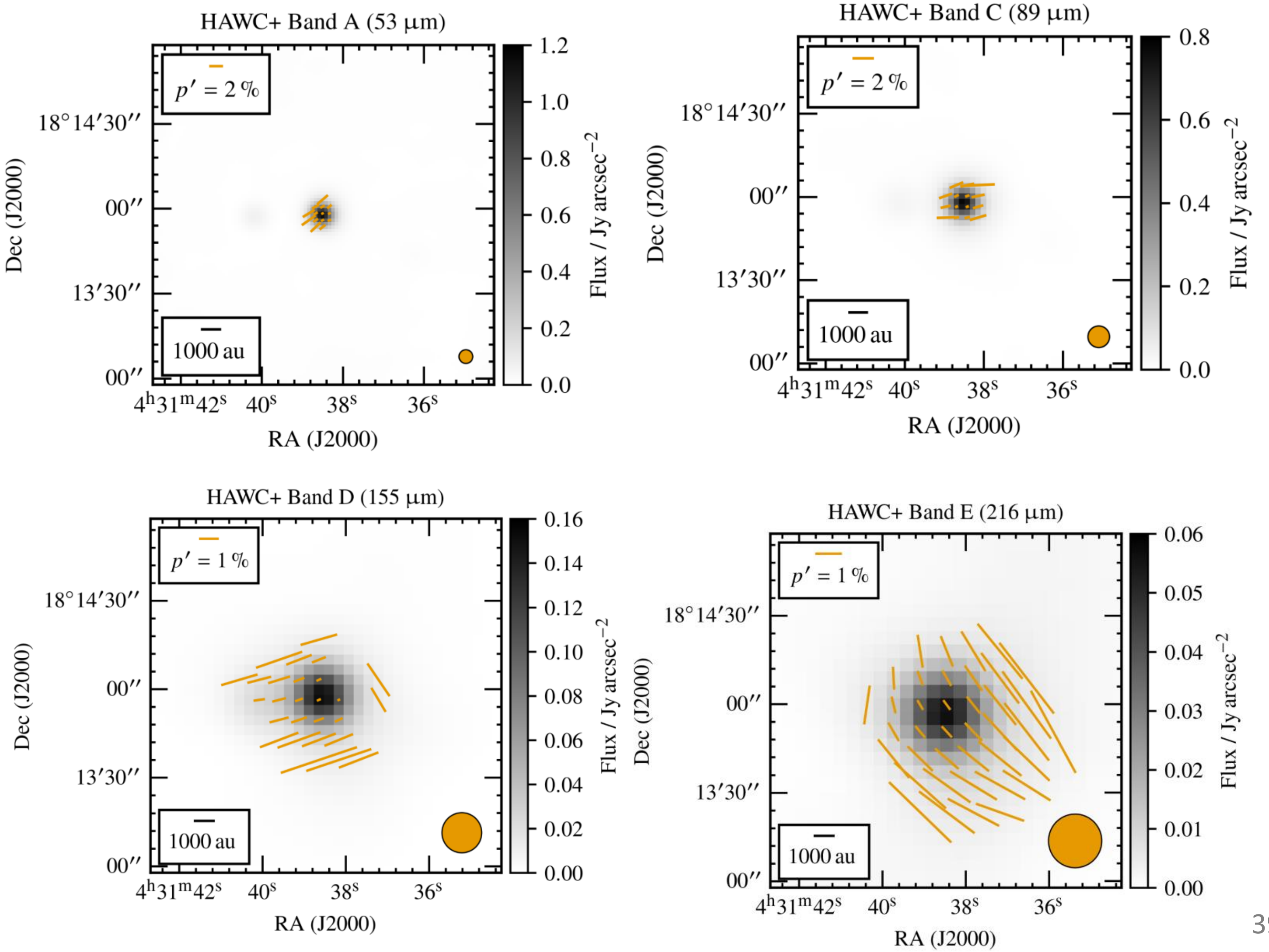


[ALMA Partnership 2014]

Magnetic fields: Protoplanetary disk

[Lietzow+, subm.]

- **HL Tauri**
  Protoplanetary disk
  Inclination ~47°, Position angle ~138°
- **Bands A, C, D**
  Polarization vectors parallel to major disc axis
- **Band E**
  Polarization vectors parallel to minor disc axis



Magnetic fields: Protoplanetary disk

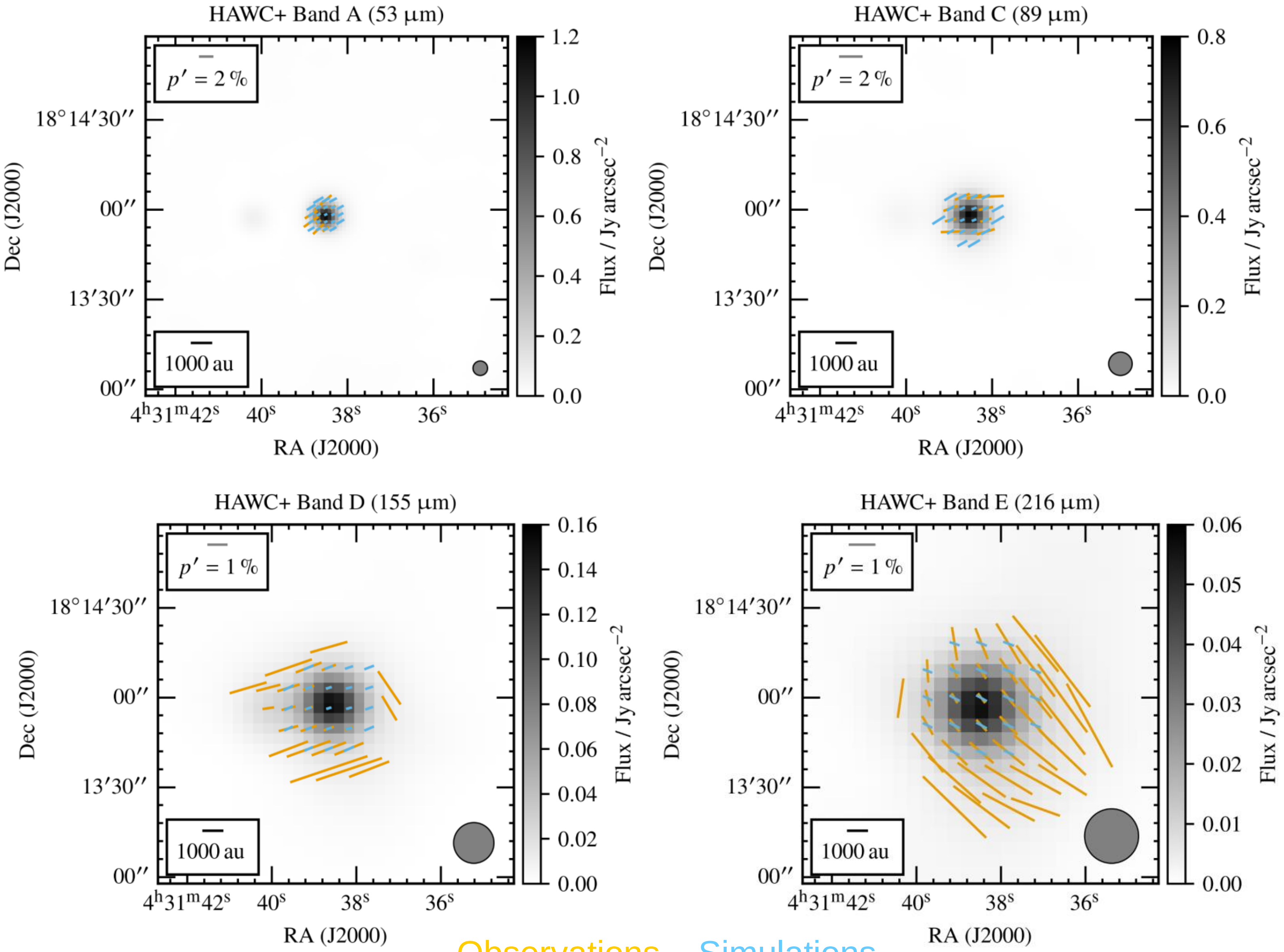
[Lietzow+, subm.]

- **Bands A, C, D**
  Polarization due to emission of aligned non-spherical grains

→ Magnetic field lines perpendicular to polarization vectors

- **Band E**
  Polarization due to self-scattering

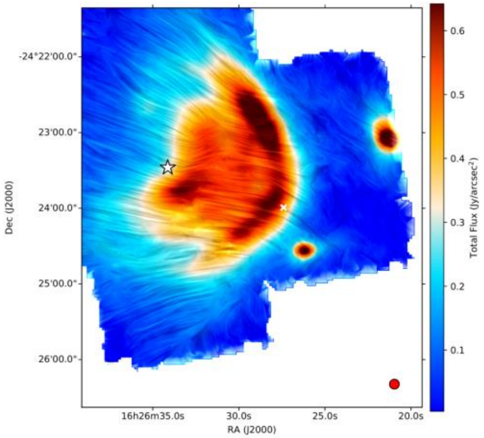
→ Dust grain size up to 25 µm

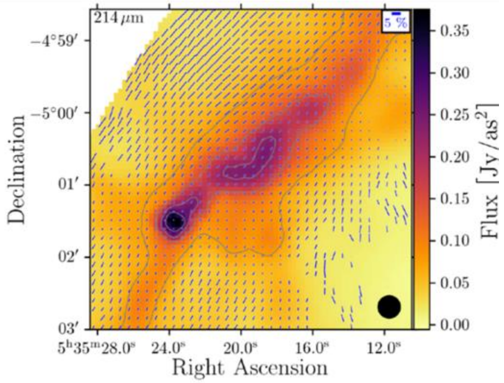


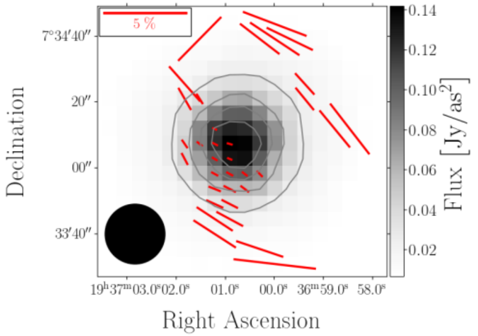
Observations – Simulations

Summary

Thank you!







- Unique constraints on parameters that determine polarization mechanisms
  (emission – absorption – scattering)

- Covers transition region between different polarization mechanisms

- Magnetic field strength / structure + related physical effects on a vast range of scales
  Galaxies … Molecular cloud cores & filaments … Protoplanetary disks