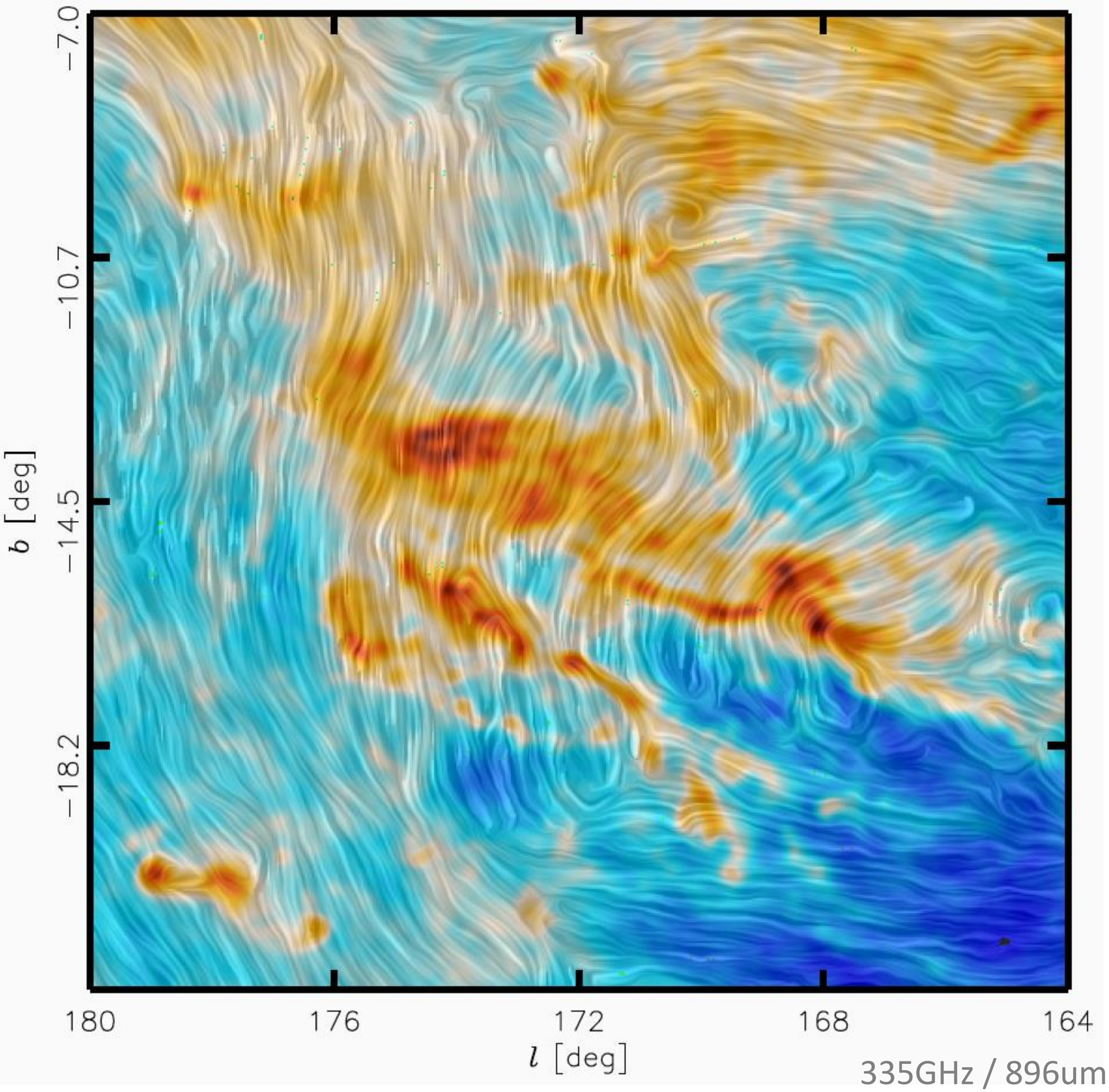
The potential of
Far-IR Polarimetry

Sebastian Wolf

Kiel University, Germany

Polarimetry – Magnetic fields



335GHz / 896um

Magnetic field and column density of the Taurus molecular cloud
(Planck Collaboration et al. 2016)

Overview

1. Motivation
2. Basics of polarimetry
3. Selected polarization mechanisms
4. Numerical simulations – Preparation and analysis of observations
5. Potential of polarimetry with SOFIA

1. Motivation

Magnetic fields in star formation

Giant molecular cloud scale: Magnetic fields in the interstellar medium (ISM)

- Magnetic fields observed on all astronomical scales permeating the entire galaxy and molecular clouds, ~few μG (e.g., Beck et al., 1996; Beck, 2001)

- Open debate (I)
  (a) Regulation of molecular clouds formation (e.g., Mouschovias & Ciolek, 1999) vs.
  (b) Almost unimportant (see e.g., Mac Low & Klessen, 2004)

- Open debate (II)
  (a) Magnetic fields inside molecular cloud cores: just dragged in from the large scale galactic field (e.g., Li et al., 2009) vs.
  (b) Generation inside clouds (e.g., Stephens et al., 2010)

Magnetic fields in star formation

Parsec to sub-parsec scale: Magnetic fields and star formation

Importance of role in star formation as well as in the formation process and evolution of protostellar disks?

- Models of magnetically regulated cloud and star formation:

  Molecular clouds are divided into two classes (e.g. Tomisaka et al., 1988):

  - Supercritical case: Cloud mass is large enough that gravitational collapse can proceed even against the outward force of magnetic pressure
  - Subcritical case: Magnetic field prevents compression perpendicular to the field lines by acting on the charged particles. As the cloud can only collapse parallel to the field, one might expect clouds to be flattened parallel to the field
  - Transition: Subcritical => Supercritical state in dense cores:

    Neutrals diffuse through the field (ambipolar diffusion)

(see, e.g., review by Vaillancourt, 2009)

Magnetic fields in star formation

Later stages: Outflows, jets, and accretion in circumstellar disks

- Most spectacular phenomenon:

  Jets (highly collimated, hydrodynamic disk winds):

  Sweep up ambient molecular gas and drive large-scale molecular outflows (e.g., Pudritz et al., 2007)

- Magnetospheric accretion:

  Disk material channeled from the disk inner edge onto the star along the magnetic field lines

  => Magnetospheric accretion columns (e.g., Bouvier et al., 2007)

2. Basics of polarimetry

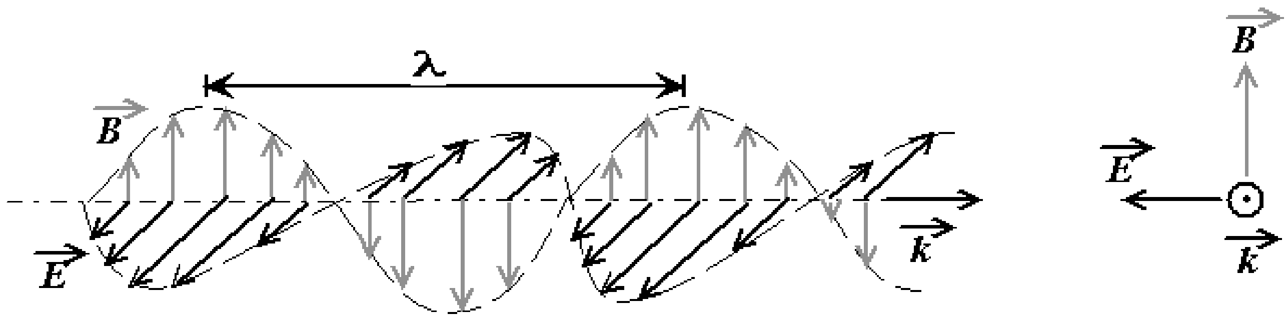
Electromagnetic radiation field

- **Primary quantities**
  - Intensity
  - Wavelength
  - Coherence (spatial, temporal)
  - Polarization

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

Vectorial nature: „**POLARIZATION**“

Electromagnetic radiation field



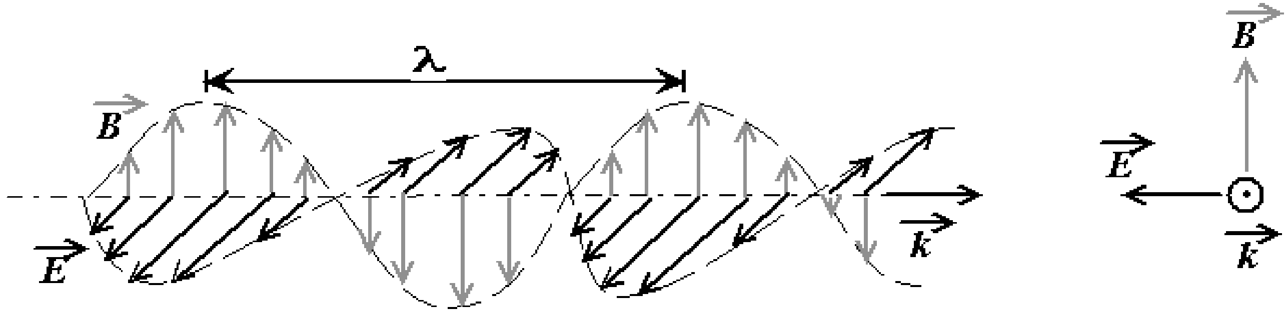
[Dang Ngoc Chan / wikipedia]

- **Concept of electromagnetic waves**
  - From non-zero solutions of Maxwell‘s equations in vacuum (i.e., absence of electric charges)
  - Oscillation of the electric/magnetic field perpendicular to direction of travel („transverse wave“)
  - Electric field of an electromagnetic wave traveling in *z* direction in Euclidean coordinates:

$$\underline{\mathbf{E}}(t,z) = \underline{\mathbf{E}}(0,0)\cos(\omega t - kz - \phi)$$

t	time
ω	angular frequency
$k=\omega/c$	absolute phase
ϕ	arbitrary phase

Electromagnetic radiation field



[Dang Ngoc Chan / wikipedia]

- **Polarization**
  - By convention: „Polarization of the Electric Field“

$$\underline{\mathbf{E}}(t,z) = \underline{\mathbf{E}}(0,0)\cos(\omega t - kz - \phi)$$

Location of $\underline{\mathbf{E}}(t,z)$ in the xy plane:

$$E_x(t) = E_x(0)\cos(\omega t - \phi_1)$$
$$E_y(t) = E_y(0)\cos(\omega t - \phi_2)$$

Polarization angle:
Angle between $\underline{\mathbf{E}}(t,z)$ and the positive x axis, counted in counterclockwise direction

Electromagnetic radiation field

$$E_x(t) = E_x(0)\cos(\omega t - \phi_1)$$
$$E_y(t) = E_y(0)\cos(\omega t - \phi_2)$$

- **Polarization**
  - General (if no preferential oscillation direction exists): **Elliptical polarization**
  - Special cases:
    a. Oscillation of these fields in one direction: $\phi_1 = \phi_2 = 0$

       Linear polarization

    b. Circular Rotation (with optical frequency): $\phi_2 = \phi_1 = +/- \pi/2$

       Circular polarization
  - Direction of rotation:
    Chirality / Handedness (clockwise „–“ / counter-clockwise „+“)

So far

Polarization of individual EM wave

(„Microscopic polarization“)

So far

Polarization of individual EM wave

(„Microscopic polarization“)

Now:

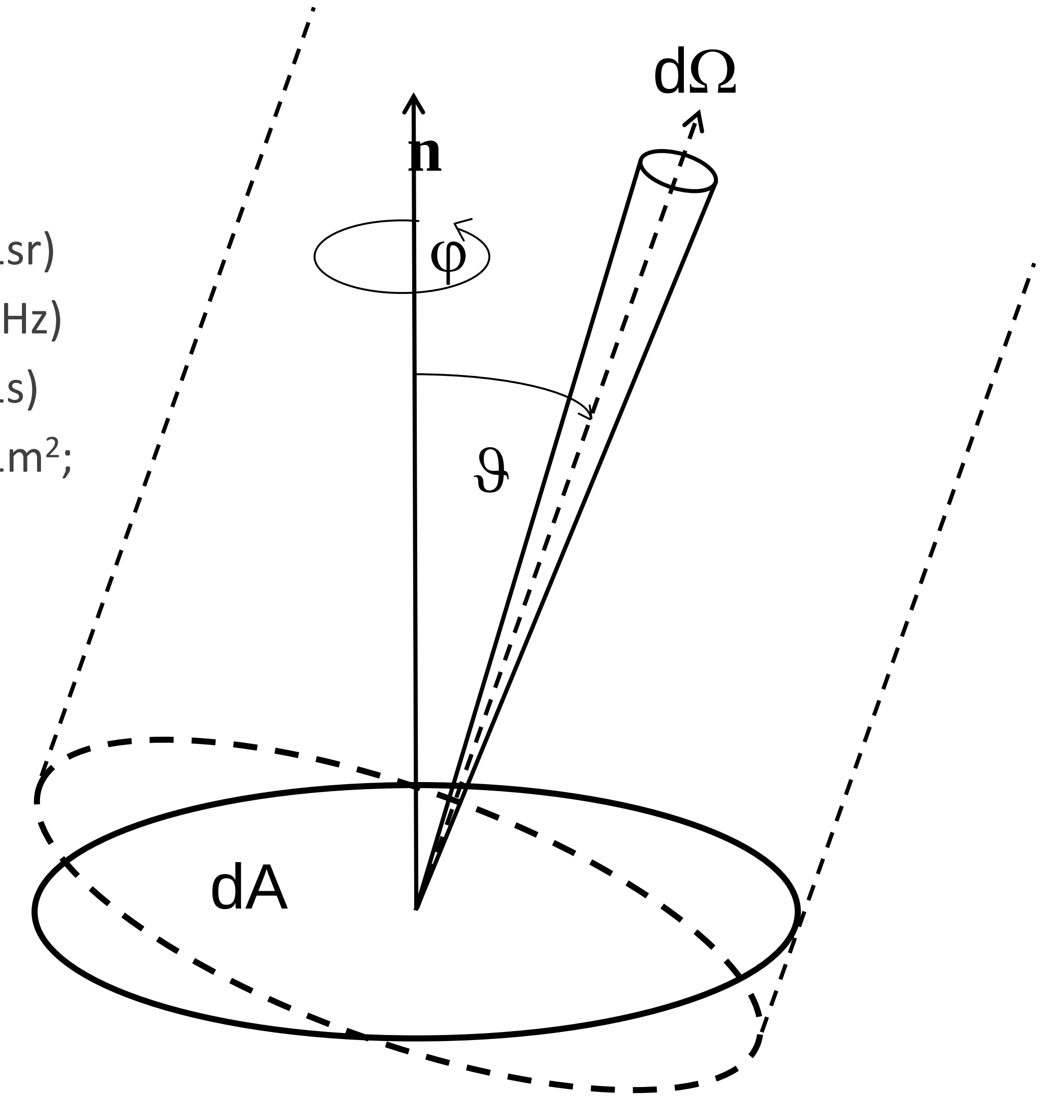
Astrophysical observations

(Usually) Incoherent superposition of very large number of EM waves

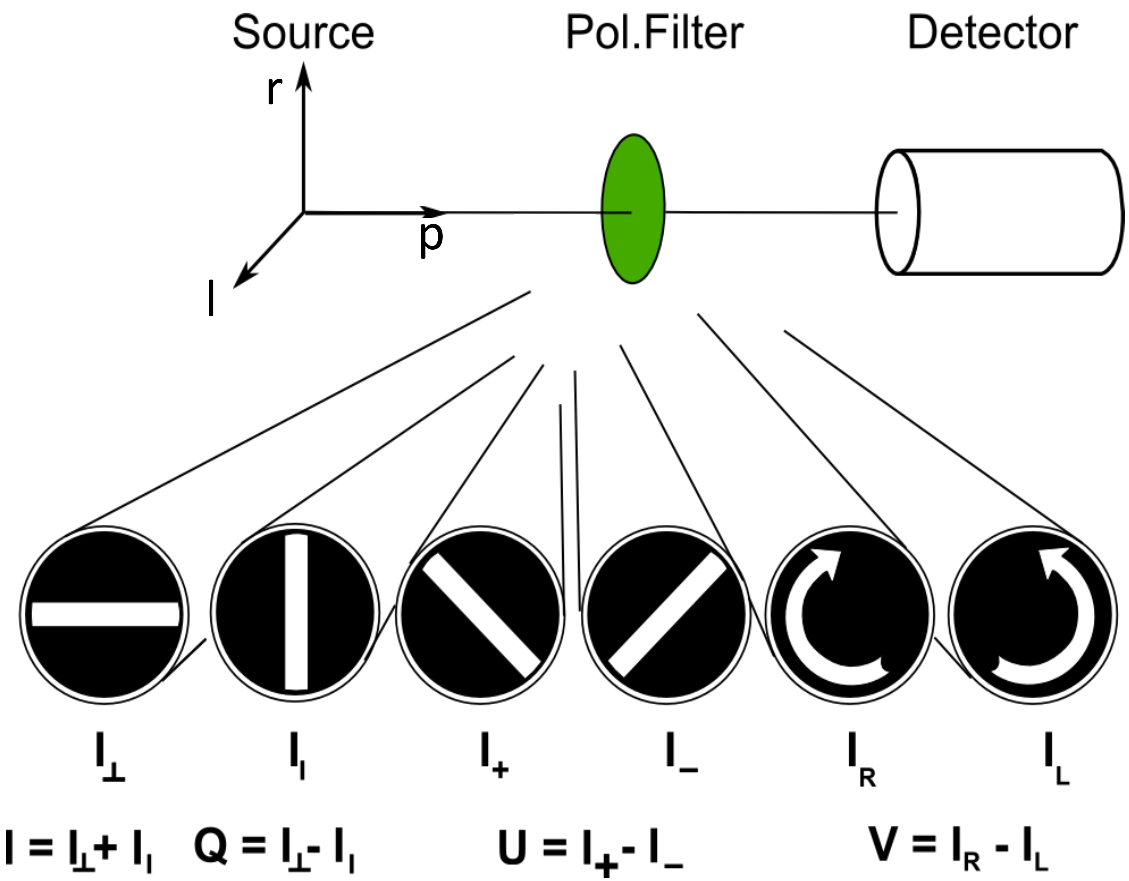
(Measurement: „Macroscopic polarization“)

Electromagnetic radiation field

- **Intensity** $I_\nu(\theta,\phi)$
  - Amount of energy per
    unit solid angle (1sr)
    unit frequency interval (1Hz)
    unit time (1s)
    through unit area ($1m^2$; oriented perpendicular to direction (Θ,ϕ))
  - Note:
    This quantity does *not* depend on distance from radiation source



Measuring & Describing Polarization State: **Stokes vector**



[based on figure by G. Bertrang]

Degree of linear polarization

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

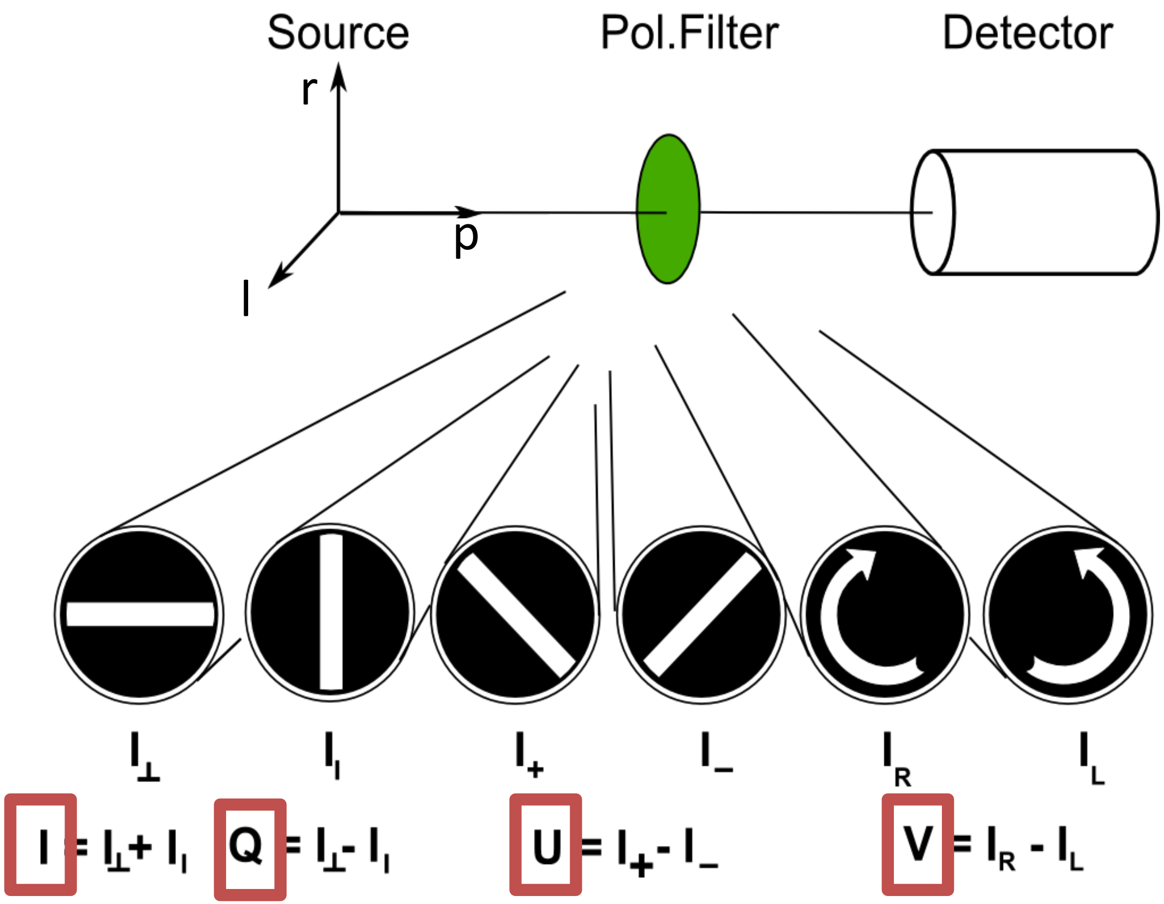
Degree of
circular polarization

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

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

$$(0° \leq \gamma \leq 180°)$$

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

$$(0° \le \gamma \le 180°)$$

3. Selected polarization mechanisms

Astrophysical sources of polarized radiation

- Intrinsically polarized light
  - Synchrotron radiation
  - Molecular emission in external magnetic field => Zeeman effect
  - Thermal emission by aligned non-spherical dust grains

- Unpolarized radiation => Modification of polarization state
  - Birefringence
  - Absorption by aligned non-spherical dust grains
  - Scattering

3.1 Sources of intrinsic polarization

Zeeman effect

Zeeman splitting of OH

- Frequency shift

$$\Delta\nu_Z = \frac{B\mu_b}{h}(g' M_F' - g'' M_F'')$$

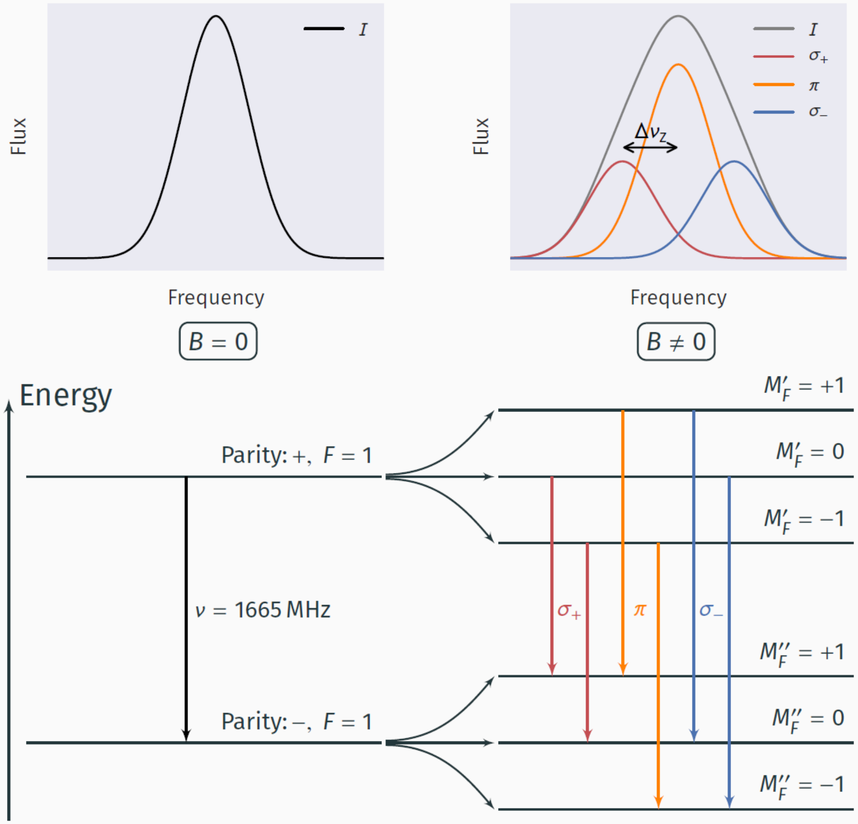
- Zeeman analysis (Crutcher et al. 1993)

$$V \propto \left(\frac{dI}{d\nu}\right) B_{LOS}$$

I: Intensity

V: Circular polarized fraction

B_{LOS}: Average B in the LOS direction



[Courtesy: R. Brauer]

Magnetic fields | Polarization | Dust particles

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

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

- Selected alignment mechanisms:

    Supersonic flows (=> constraints on gas flow)

    Barnett effect, Davis-Greenstein alignment

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

- **Long axes aligned perpendicular to the Magnetic field**

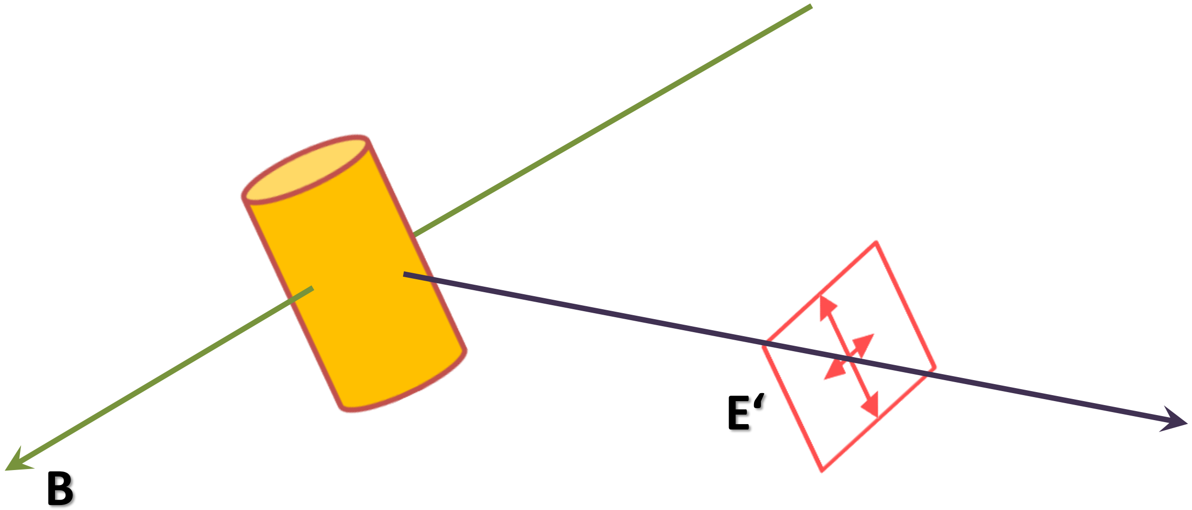
    [e.g., review by A. Lazarian:

    "Tracing magnetic fields with aligned grains", 2007, JQSRT, 106, 225]

Polarized thermal emission

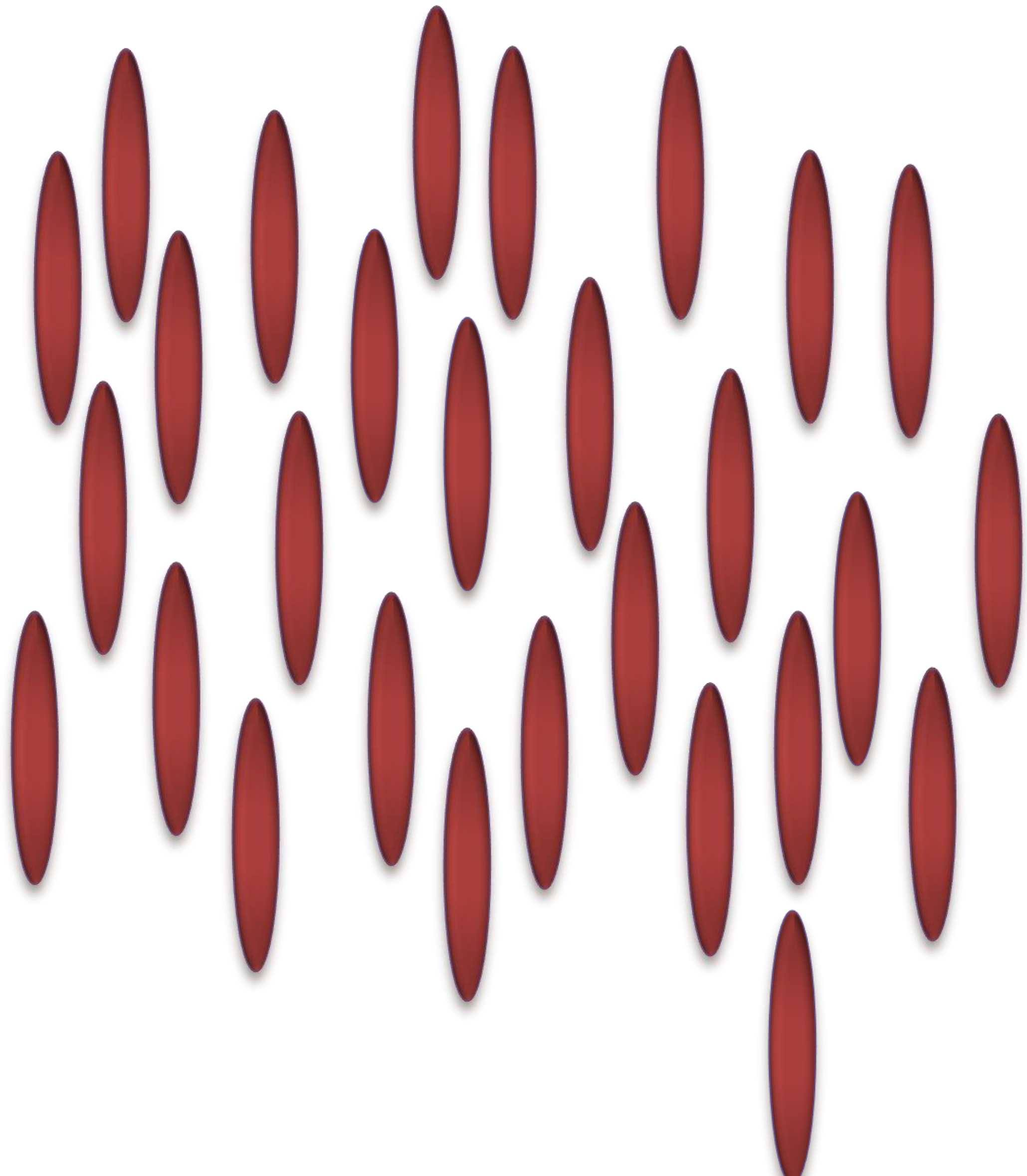
- Aligned non-spherical grains:

  Polarized thermal emission

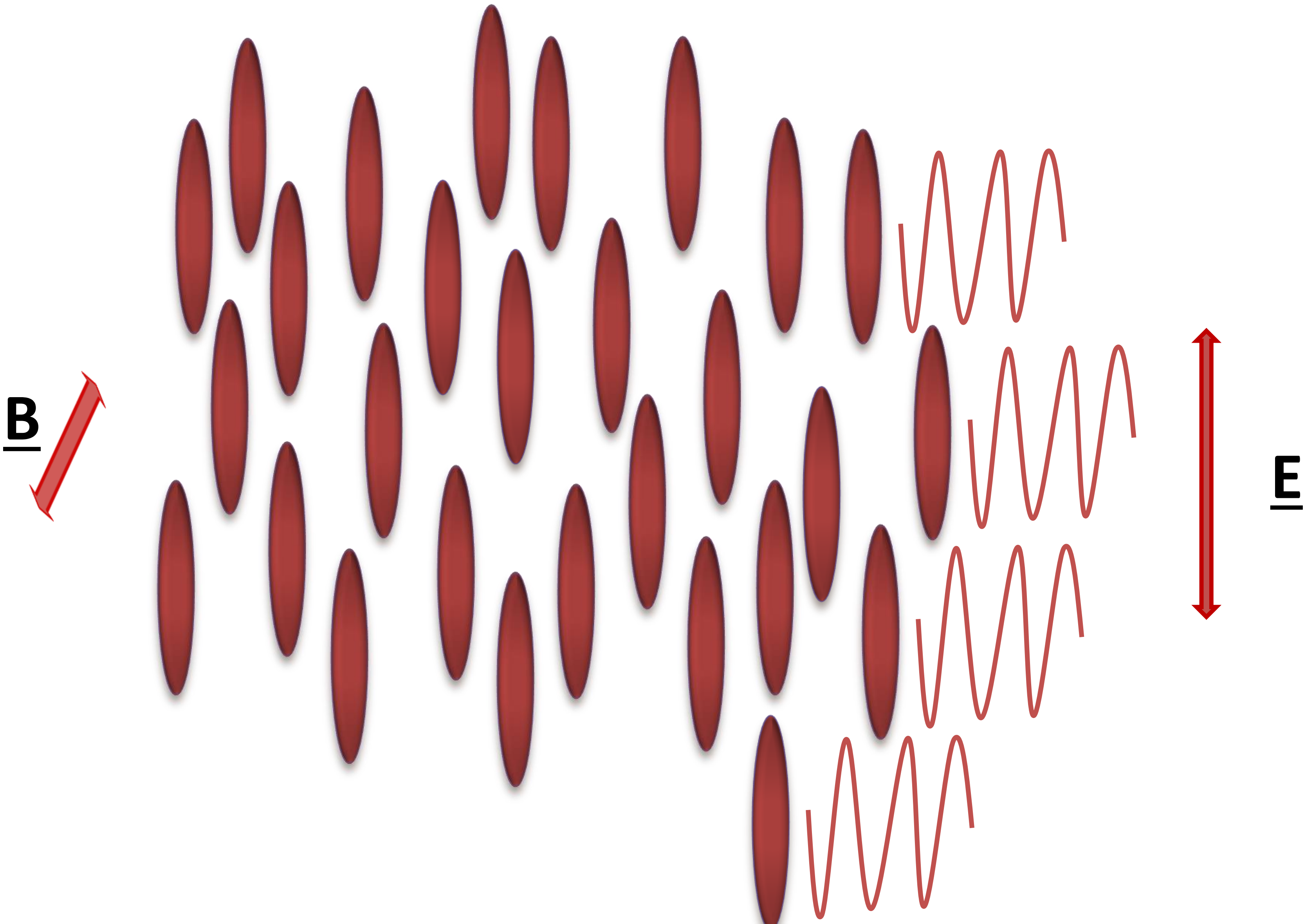


Thermal emission from grains at far-IR / mm wavelengths:
Partially linearly polarized (**P** perp. **B**)

Thermal emission: Non-spherical dust grains



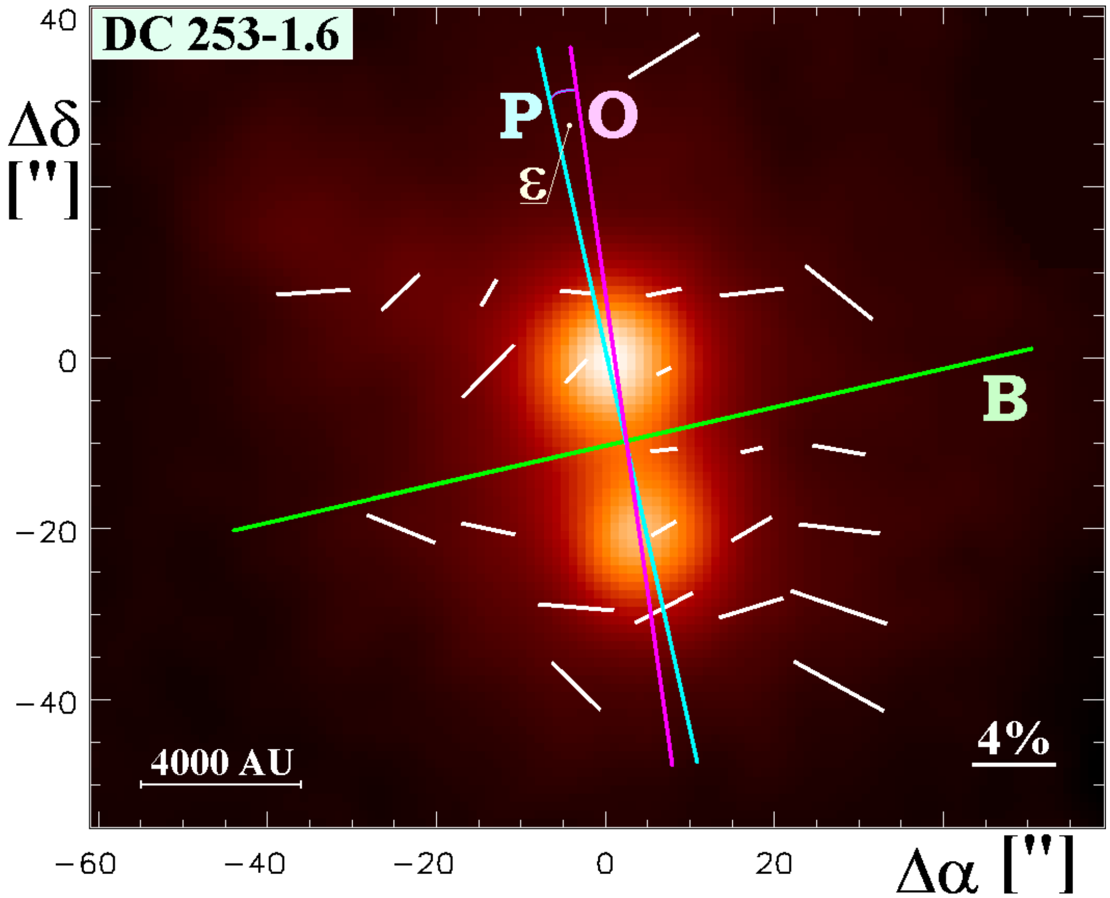
Thermal emission: Non-spherical dust grains



Polarized thermal emission: Example

- Aligned non-spherical grains:

  Polarized thermal emission



Intensity map &

Polarization map

@

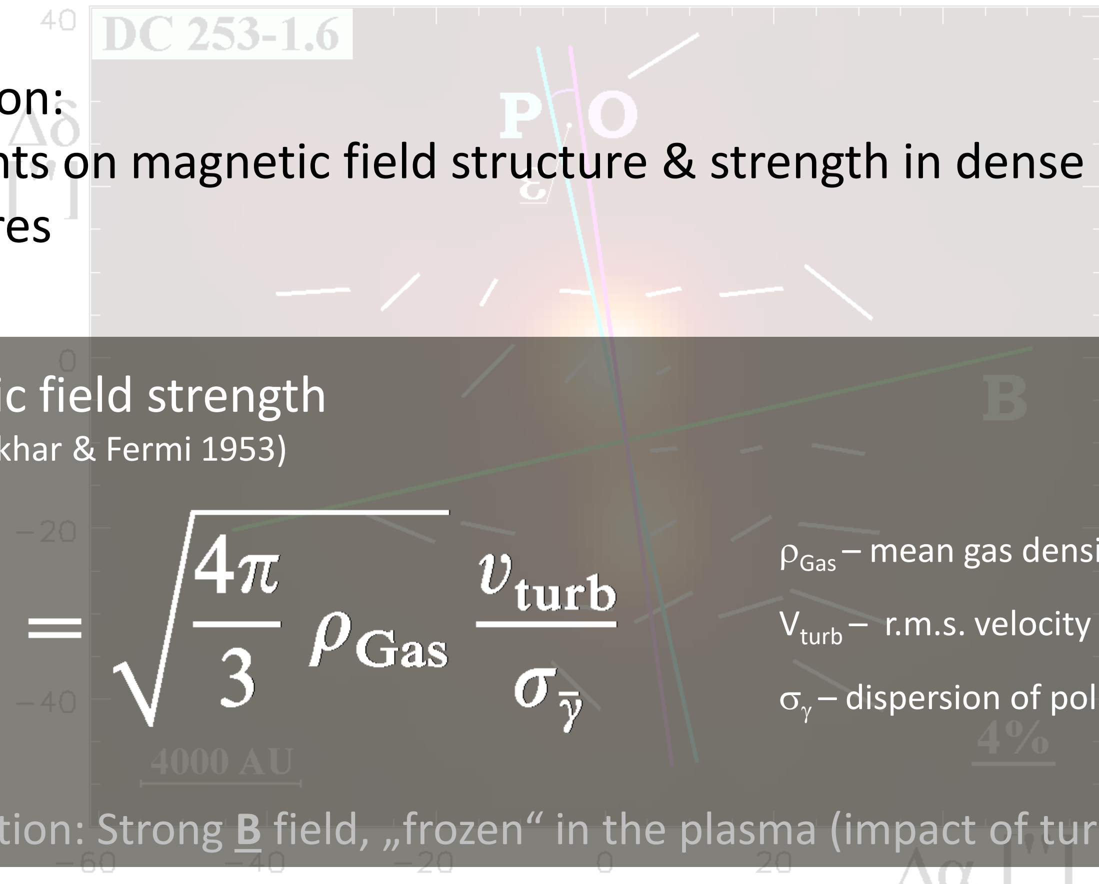
850 μm

[Wolf 2001]

Polarized thermal emission: Example

- Aligned non-spherical grains:
  Polarized thermal emission

- Application:
  Constraints on magnetic field structure & strength in dense molecular cloud cores



Magnetic field strength

(Chandrasekhar & Fermi 1953)

$$|\boldsymbol{B}| = \sqrt{\frac{4\pi}{3}\,\rho_{\mathrm{Gas}}}\;\frac{v_{\mathrm{turb}}}{\sigma_{\bar{\gamma}}}$$

ρ_{Gas} – mean gas density

V_{turb} – r.m.s. velocity dispersion

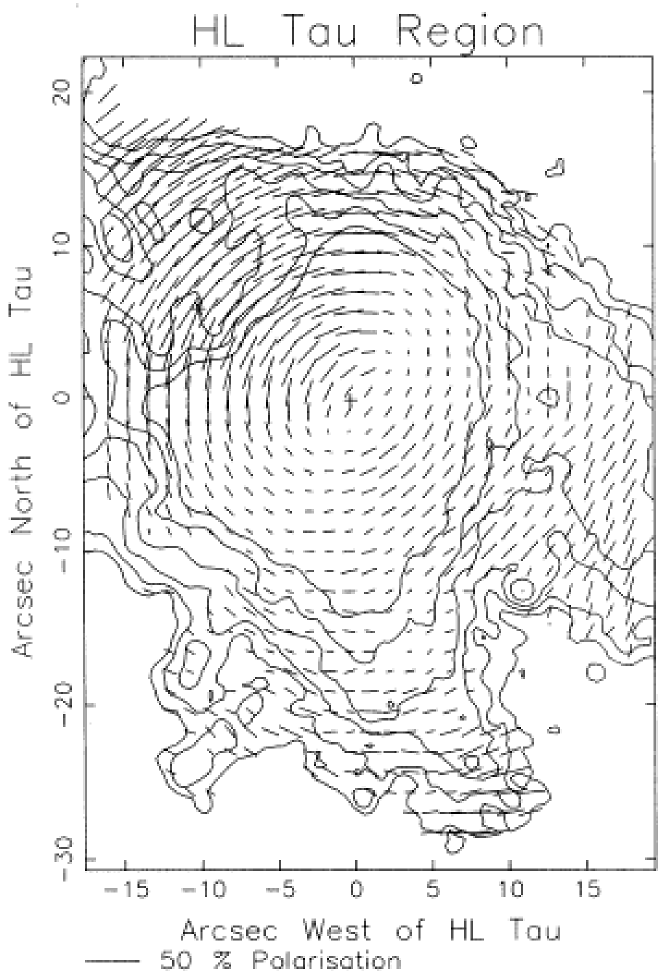
σ_{γ} – dispersion of polarization angles

Assumption: Strong **B** field, „frozen“ in the plasma (impact of turbulence small)

3.2 Intrinsically unpolarized sources:

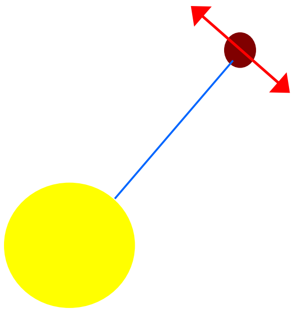
Mechanisms for subsequent polarization

Scattering



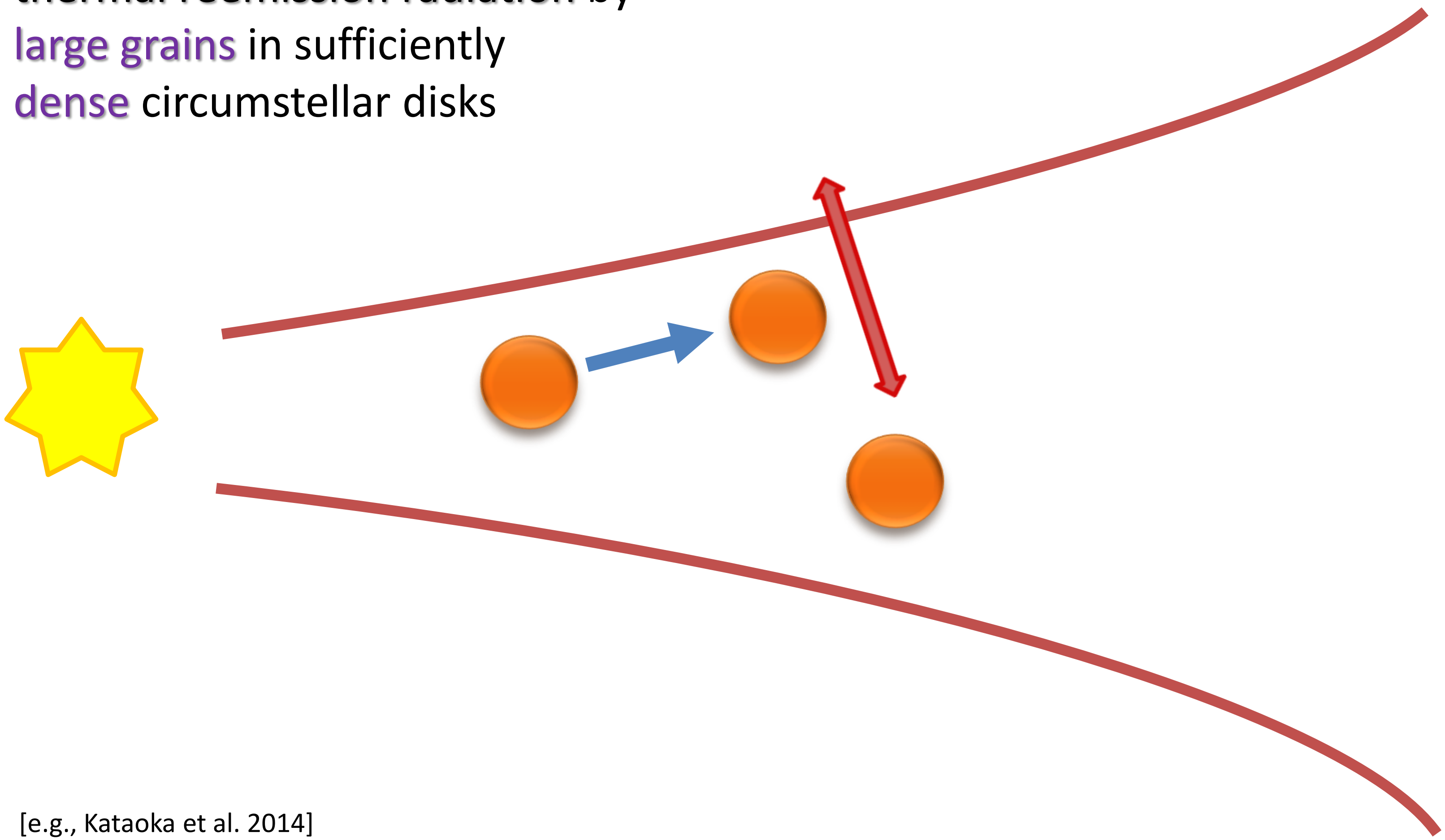
[Gledhill & Scarrott 1989]

- **Light Scattering**
  - Most important in the near-IR and shorter wavelength range
  - Spherical dust grains: Polarization vector oriented perpendicular to the radius vector towards the illuminating source
  - Deviations from the centro-symmetric polarization pattern caused by multiple illuminating sources and / or scattering by aligned non-spherical grains



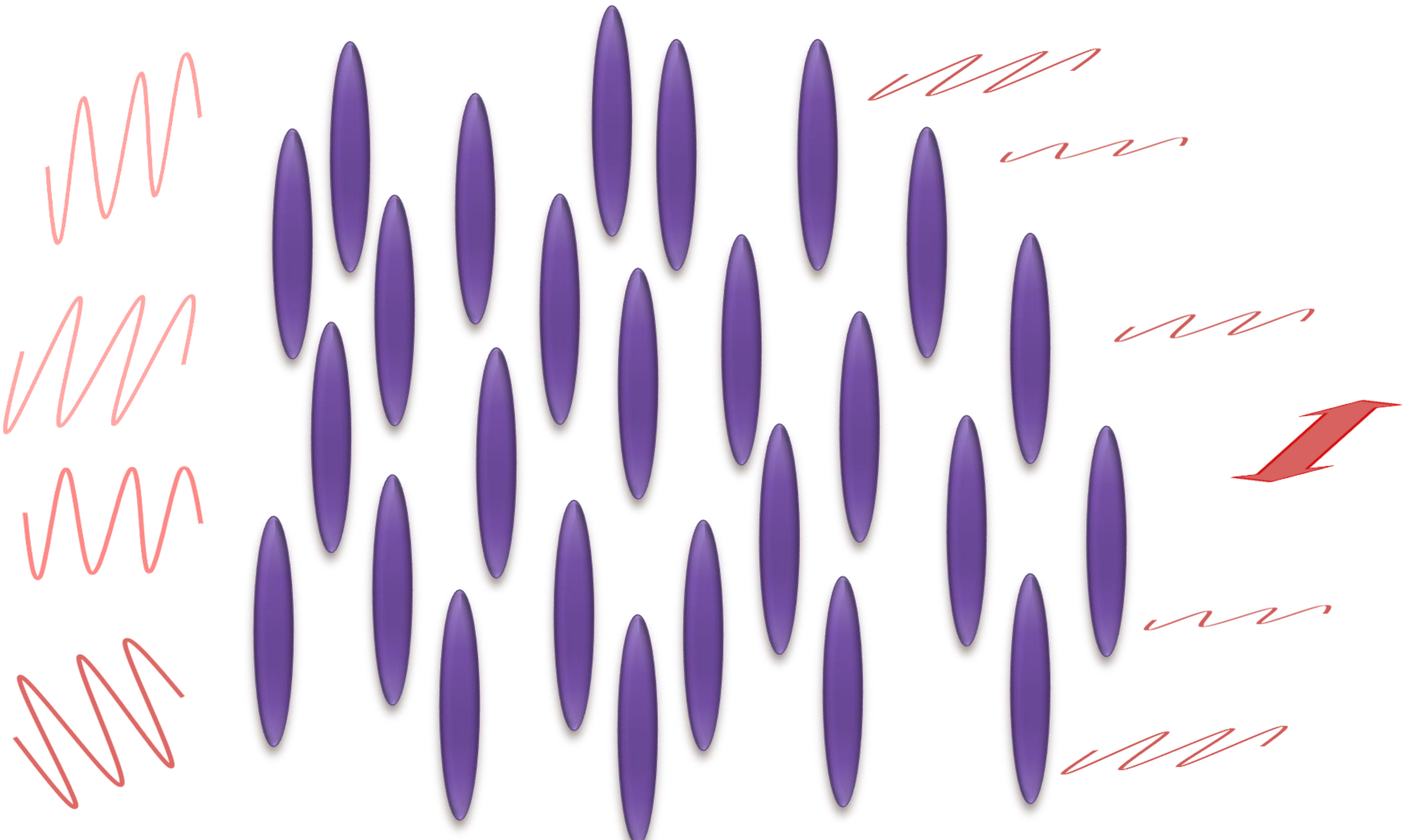
Polarization due to scattering @ FIR wavelengths

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



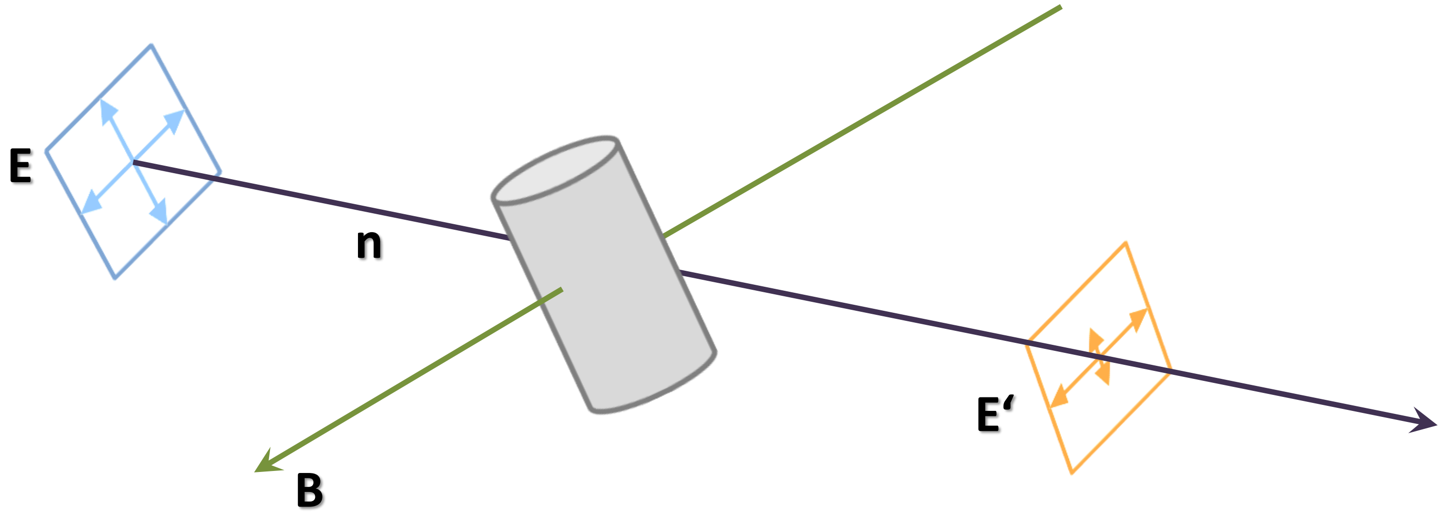
[e.g., Kataoka et al. 2014]

„ISM polarizing screens“



Dichroic extinction

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

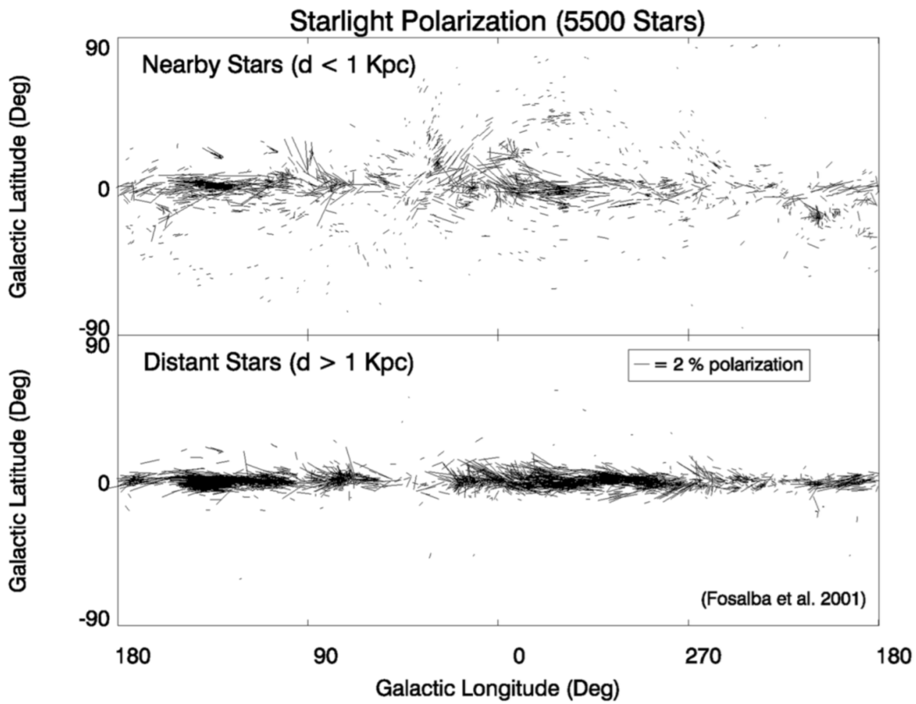


Observed polarization degrees (ISM): < 5%

(optical / infrared wavelength range)

Dichroic extinction: Example

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



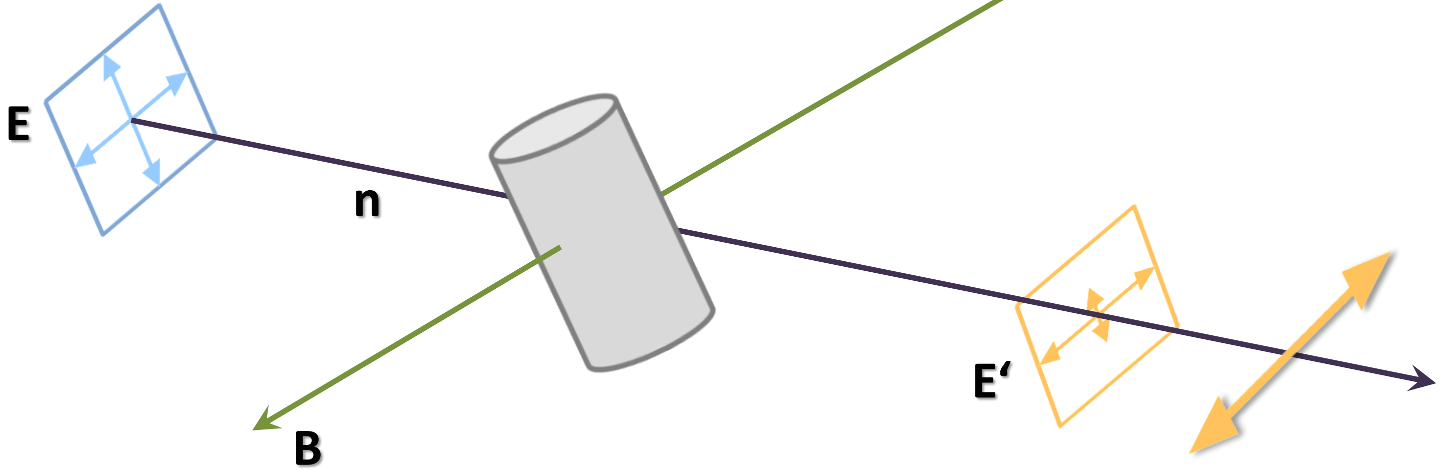
<u>Application:</u>
Particle alignment by galactic magnetic field
=>
Dichroic extinction of background starlight traces large-scale magnetic field structure in the interstellar medium
(highest polarization degrees close to the galactic equator)

Figure 33 Starlight polarization vectors in the galactic coordinates for a sample of 5513 stars. For nearby stars (upper panel), the polarization is mainly produced in single local clouds, while the lower panel displays polarization averaged over many clouds in the galactic plane. The length of the vectors is proportional to the polarization degree and the scale used is shown in the lower panel. After Fosalba *et al.* (2001).

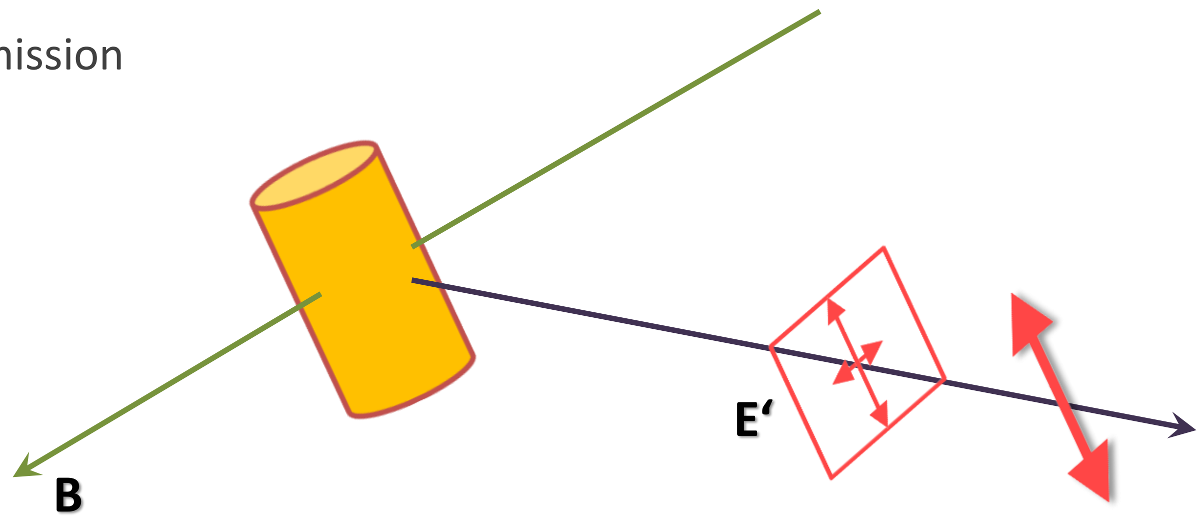
[Voshchinnikov 2004]

(3) Dichroic extinction / absorption

- As mentioned earlier:
  - Dichroic extinction



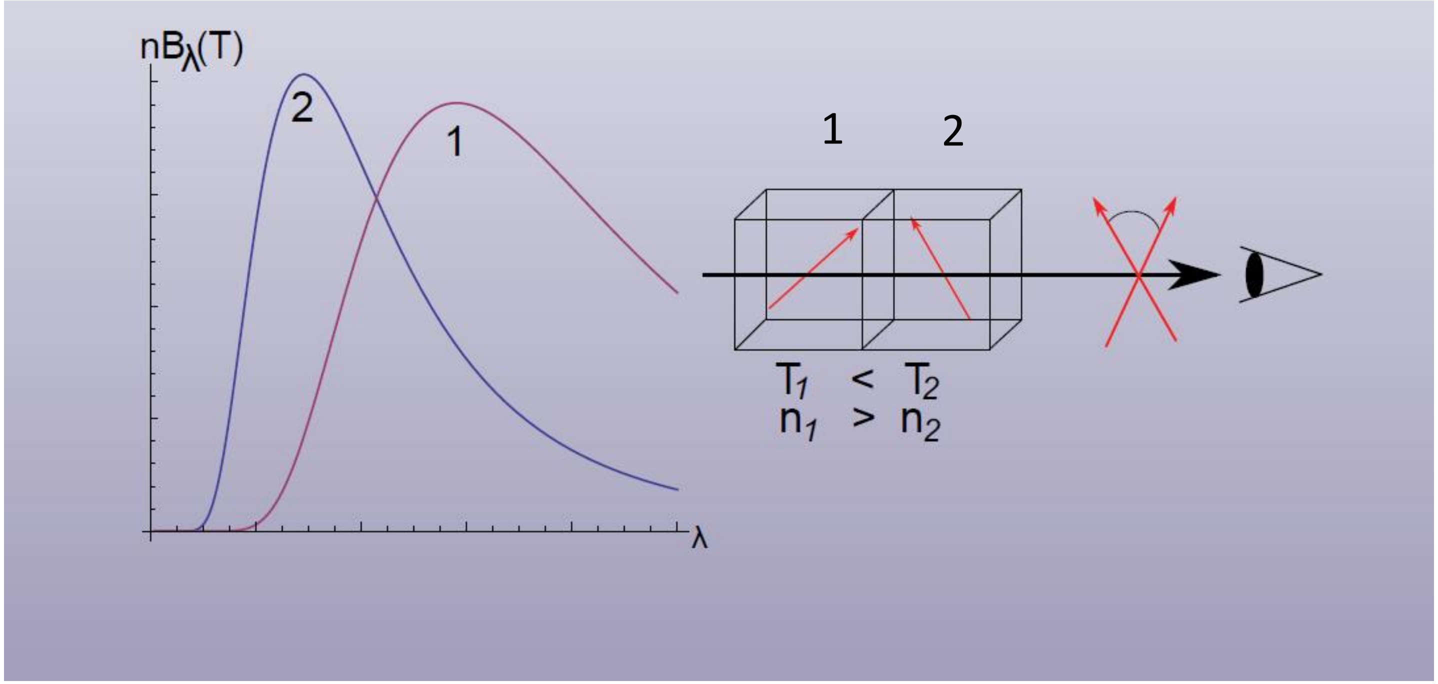
  - Dichroic emission



Importance of **multi-wavelength polarization** measurements

(1) Dichroic extinction => Dichroic emission: **90° flip**
= f(wavelength, temperature)

(2) Imhomogenous magnetic field structure => **Continuous rotation**
= f(wavelength, temperature)

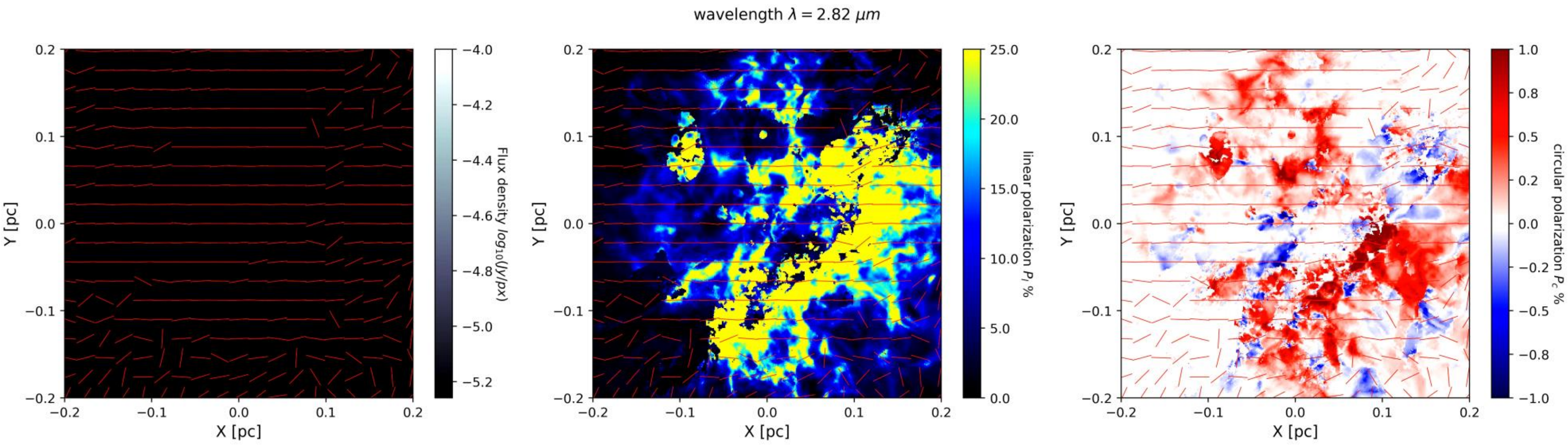


[S. Reissl, et al.]

Multi-wavelength observations

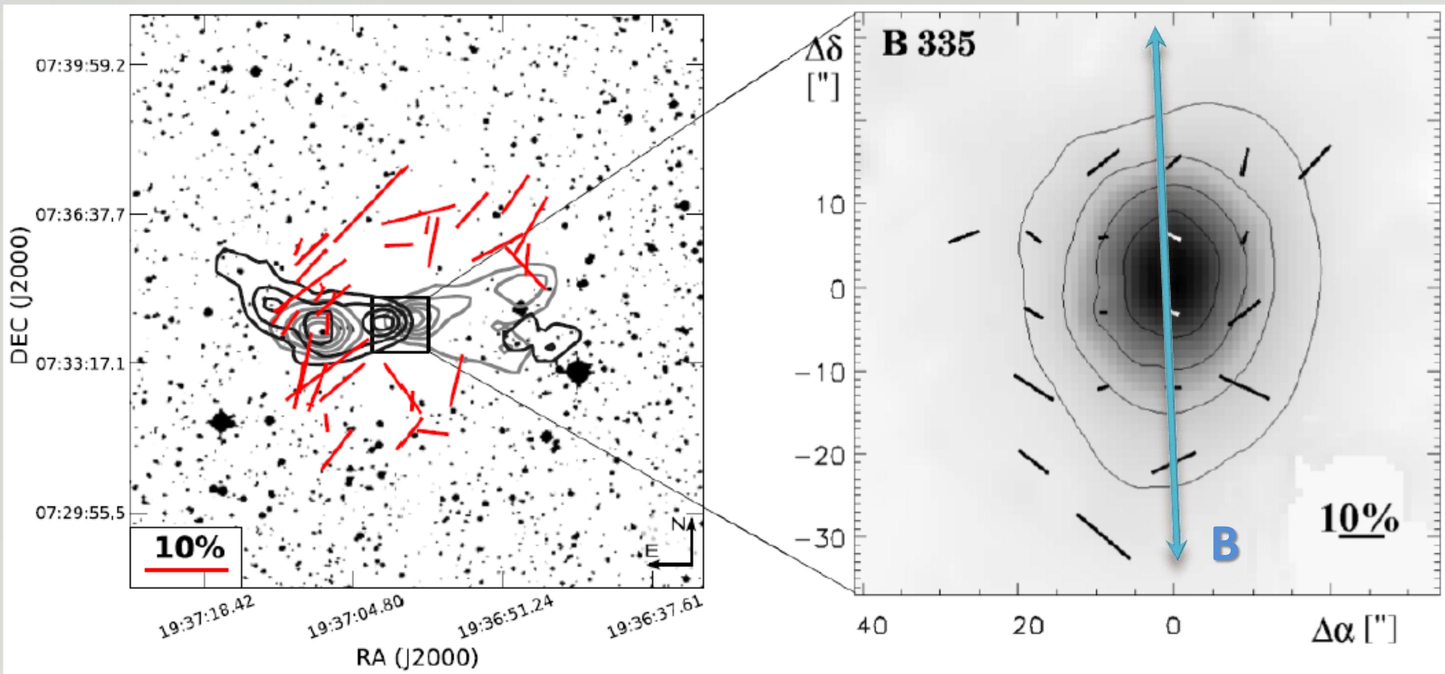
[Reissl et al. 2014, 2016, Brauer et al. 2017]

http://www1.astrophysik.uni-kiel.de/~polaris/



Importance of **multi-wavelength polarization** measurements

B335



a) **near-IR**
($P > 3\sigma_P$,
ISAAC/VLT,
Bertrang+ 2013, in prep.)

b) **sub-mm**
(SCUBA/JCMT,
Henning+ 2001)

[Bertrang, et al.]

Potential of Circular Polarization

- Complex helical organic molecules (e.g. amino acids):

  Homochirality

  (out of two helix orientations possible, only one is used exclusively)

  Discussion:

  – Preferred orientation in pre-biotic chemistry

  – Explanation(?):

  Circularly polarized light in star forming regions, leading to preferential photo-dissociation of organic molecules with specific orientation (De Marcellus et al 2011, Kwon et al. 2013)

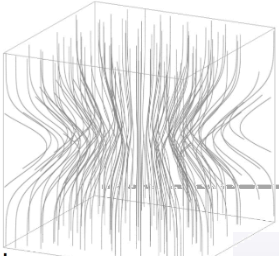
Highly speculative

- Radiation reflected on biological surfaces: Circular polarization (due to homochirality)

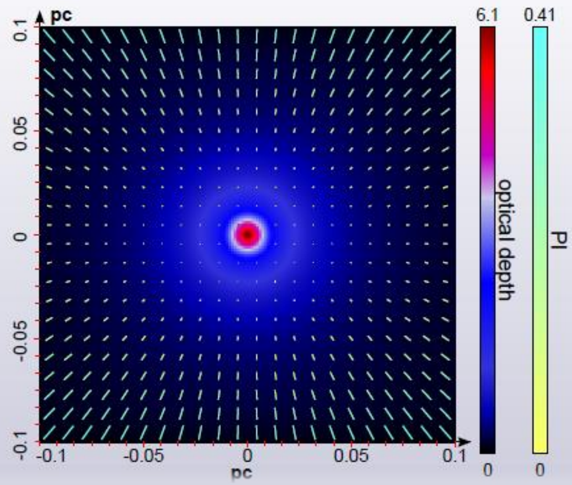
  => Search for tracers of life

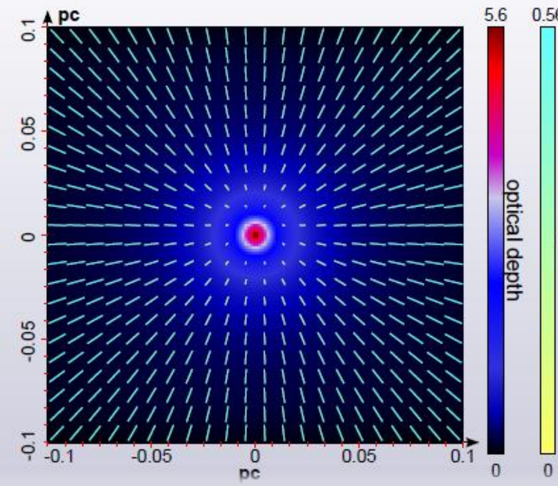
Highly speculative

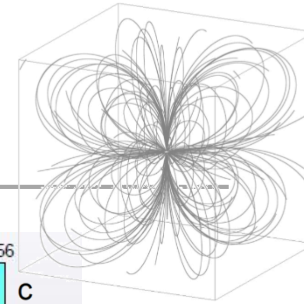
Potential of Circular Polarization



hourglass







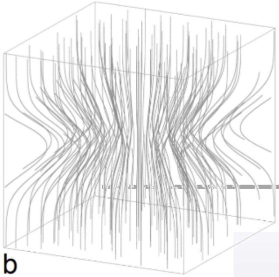
quadrupol

Optical depth, linear polarization $\mathbf{P}_l$ and circular polarization $\mathbf{P}_C$ with a **hourglass** magnetic field morphology

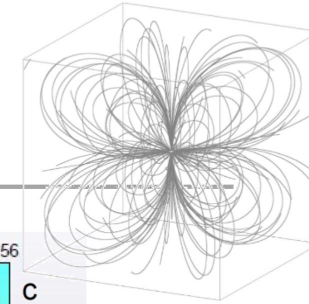
Optical depth, linear polarization $\mathbf{P}_l$ and circular polarization $\mathbf{P}_C$ with a **quadrupole** magnetic field morphology

[S. Reissl]

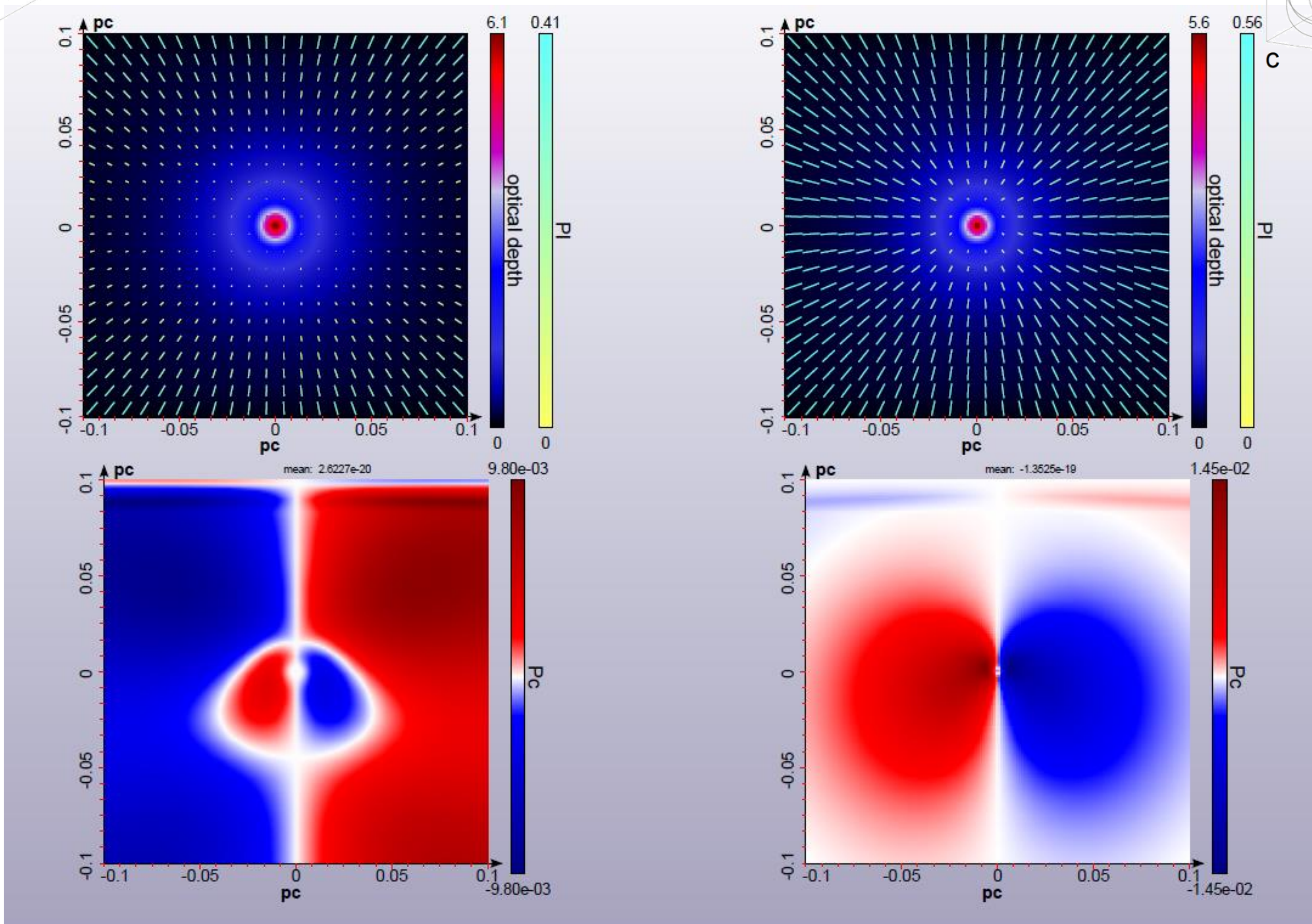
Potential of Circular Polarization



hourglass



quadrupol



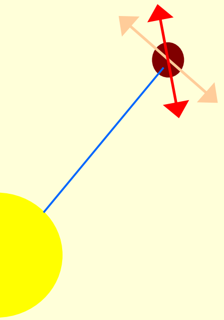
Optical depth, linear polarization $\mathbf{P}_l$ and circular polarization $\mathbf{P}_C$ with a **hourglass** magnetic field morphology

Optical depth, linear polarization $\mathbf{P}_l$ and circular polarization $\mathbf{P}_C$ with a **quadrupole** magnetic field morphology

[S. Reissl]

Scattering by non-spherical grains

- What tells us that grains are non-spherical?
  - Interstellar polarization, Polarized thermal emission
  - Deviations of the polarization vectors from the direction perpendicular to the illuminating star
  - Wavelength dependence of the positional angle of polarization *(Red Giants, AGB stars, bipolar reflection nebulae)*
  - High degrees of circular polarization *(Orion molecular cloud – Chrysostomou et al. 2000)*



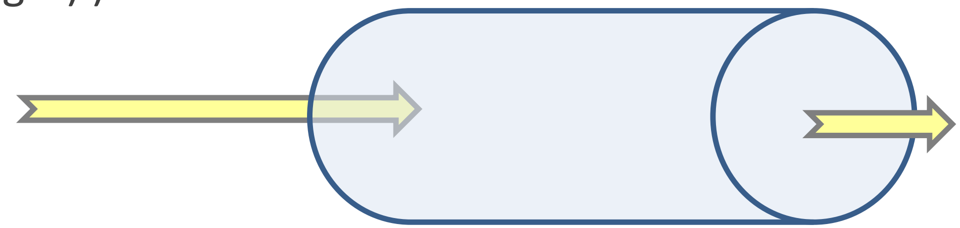
1. Azimuthal dependence of the scattered radiation
2. Linear Polarization (>0) in the forward + backward directions
3. Deviation of the positional angle of linear polarization after first scattering from the direction perpendicular to the illuminating source
4. Circular polarization after first scattering

4. Simulation tools

How to prepare (simulate)
polarization observations?

Reality check

- Simplification:
  - Smooth density distribution
  - Pure absorption (= f(wavelength))
  - Intensity only



- Reality
  - Clumpy media
  - Scattering
  - Embedded sources
  - Heating / Reemission
  - Polarization
  - …

[„Orion Nebula“, Credit: NASA, ESA, T. Megeath (University of Toledo) and M. Robberto (STScI)]

Radiative transfer in a nutshell: „Mainstream solutions"

1. Grid-based discretization and iterative solution of the RT equation

$$\vec{n}\,\nabla I_\nu(\vec{r},\vec{n}) = -\left[\kappa_\nu(\vec{r}) + \sigma_\nu(\vec{r})\right] I_\nu(\vec{r},\vec{n}) + \kappa_\nu(\vec{r})\, B_\nu(T(\vec{r}))$$

$$+ \frac{1}{4\pi}\sigma_\nu(\vec{r}) \oint p_\nu(\vec{n},\vec{n}')\, I_\nu(\vec{r},\vec{n}')\, \mathrm{d}\vec{n}'$$

- Advantage: Full control (e.g., measure of errors)
- Disadvantage: Very time-consuming (in 2D/3D)

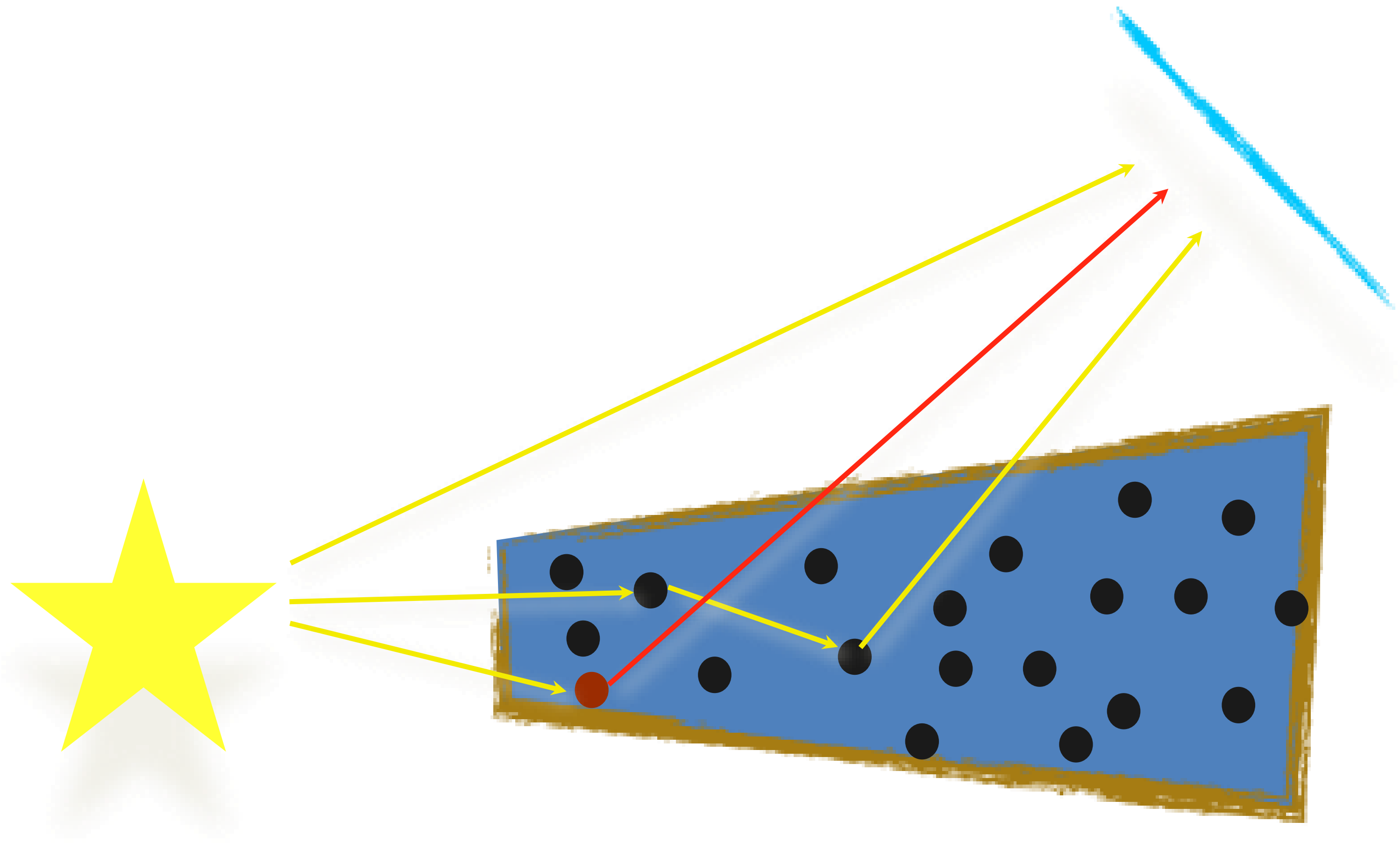
1D/2D/3D

2. Monte-Carlo simulation of the RT process
   - Advantage:

     Easy handling of complex density distributions and many types of interaction processes (e.g., anisotropic scattering, polarization)
   - Disadvantage: Less control (reliable error estimation difficult)

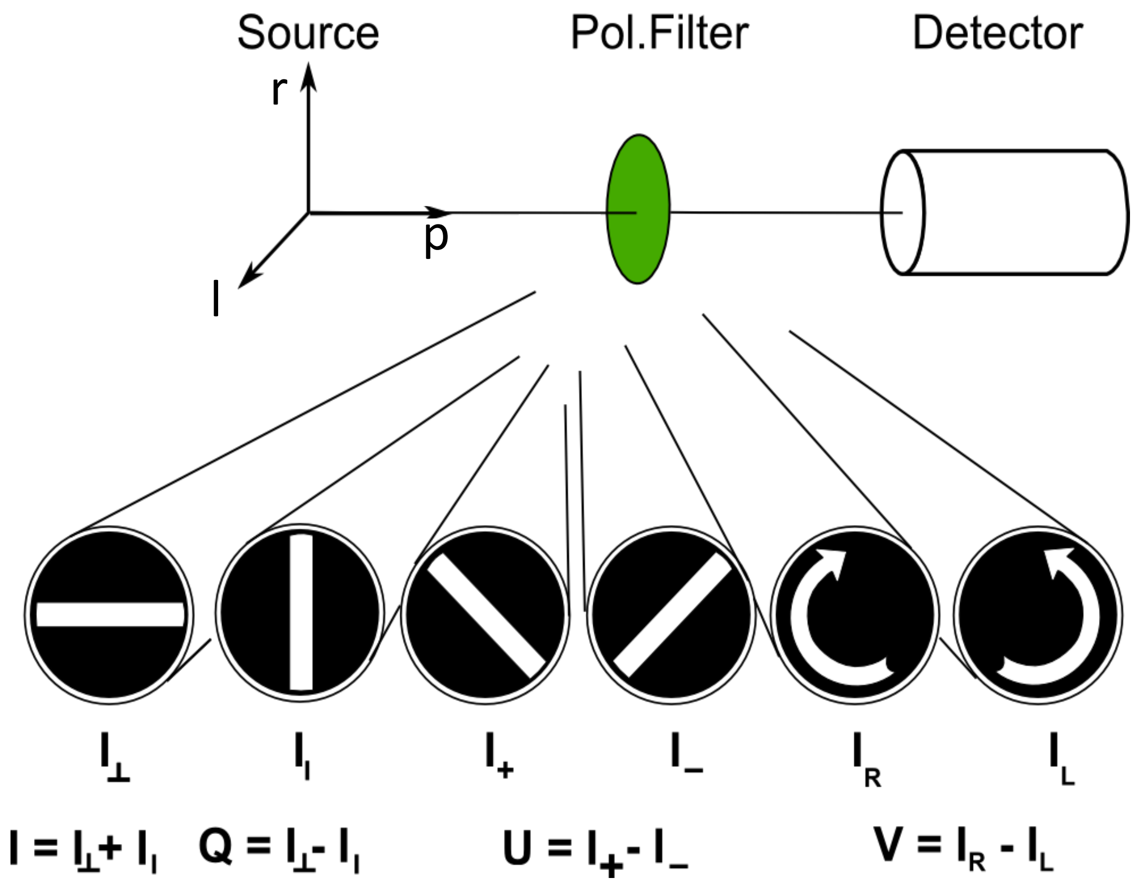
1D/2D/3D

Monte-Carlo technique



[Courtesy: J. Sauter]

Stokes vector



[based on figure by G. Bertrang]

Degree of linear polarization

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

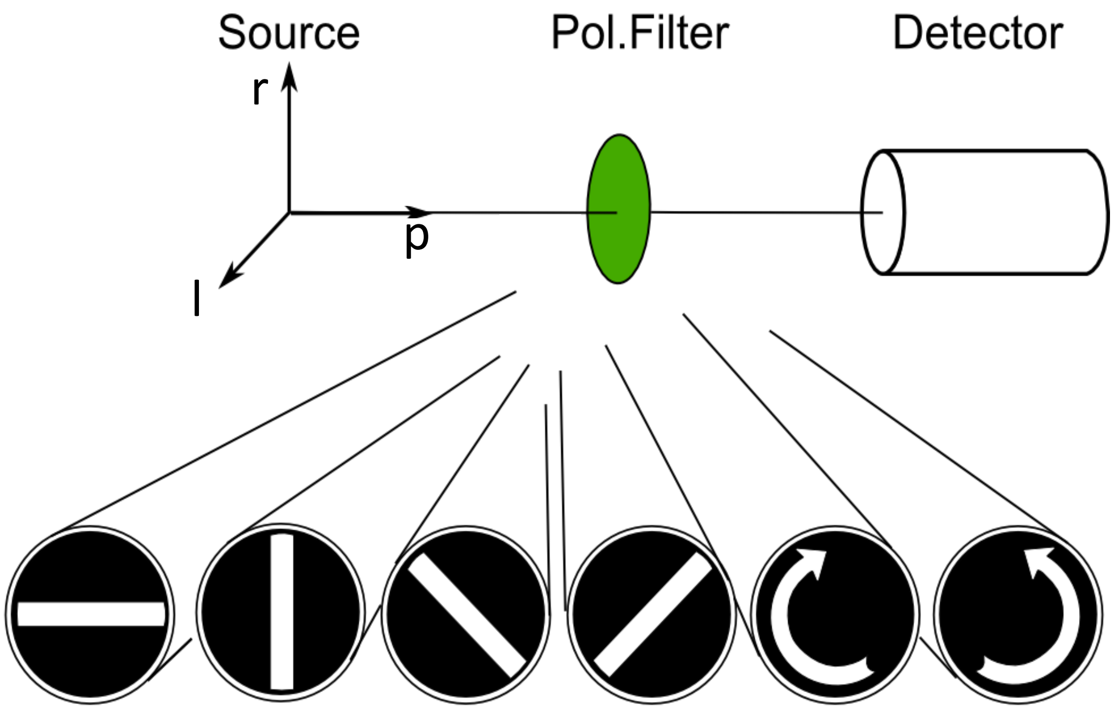
Degree of circular polarization

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

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

$$(0° \leq \gamma \leq 180°)$$

Stokes vector



$I_\perp$ $I_\parallel$ I_+ I_- I_R I_L

I $= I_\perp + I_\parallel$ **Q** $= I_\perp - I_\parallel$ **U** $= I_+ - I_-$ **V** $= I_R - I_L$

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

$$(0° \leq \gamma \leq 180°)$$

(1) Scattering by spherical grains

Scattering: $\hat{I}_i \propto \hat{S}(\Theta)\,\hat{I}_{i-1}$

$$\hat{I}_0 = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_0 = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Scattering matrix
(special Müller matrix)

(1) Scattering by spherical grains

Scattering: $\hat{I}_i \propto \hat{S}(\Theta)\,\hat{I}_{i-1}$

Spherical Dust Grains:

$$\hat{S}(\theta) = \begin{pmatrix} S_{11}(\theta) & S_{12}(\theta) & 0 & 0 \\ S_{12}(\theta) & S_{11}(\theta) & 0 & 0 \\ 0 & 0 & S_{33}(\theta) & S_{34}(\theta) \\ 0 & 0 & -S_{34}(\theta) & S_{33}(\theta) \end{pmatrix}$$

where

$$\begin{aligned} S_{11}(\theta) &= \tfrac{1}{2}(|S_1(\theta)|^2 + |S_2(\theta)|^2 + |S_3(\theta)|^2 + |S_4(\theta)|^2) \\ S_{12}(\theta) &= \tfrac{1}{2}(|S_2(\theta)|^2 - |S_1(\theta)|^2 + |S_4(\theta)|^2 - |S_3(\theta)|^2) \\ S_{33}(\theta) &= \mathrm{Re}\{S_1(\theta)S_2^*(\theta) + S_3(\theta)S_4^*(\theta)\} \\ S_{34}(\theta) &= \mathrm{Re}\{S_2(\theta)S_1^*(\theta) + S_4(\theta)S_3^*(\theta)\}\ . \end{aligned}$$

S1…S4: wavelength-dependent scattering amplitudes (Mie theory)

(1) Scattering by spherical grains

Scattering: $$\hat{I}_i \propto \hat{S}(\Theta)\, \hat{I}_{i-1}$$

Electrons
(Thomson Scattering)

$$\hat{S}(\theta) = \begin{pmatrix} S_{11}(\theta) & S_{12}(\theta) & 0 & 0 \\ S_{12}(\theta) & S_{11}(\theta) & 0 & 0 \\ 0 & 0 & S_{33}(\theta) & S_{34}(\theta) \\ 0 & 0 & -S_{34}(\theta) & S_{33}(\theta) \end{pmatrix}$$

where

$$S_{11}(\theta) = S_{22}(\theta) = (\cos^2(\theta) + 1)/2$$
$$S_{12}(\theta) = S_{21}(\theta) = (\cos^2(\theta) - 1)/2$$
$$S_{33}(\theta) = S_{44}(\theta) = \cos(\theta)$$
$$S_{13} = S_{31} = S_{23} = S_{32} = 0$$
$$S_{14} = S_{24} = S_{34} = S_{43} = 0$$

θ: scattering angle

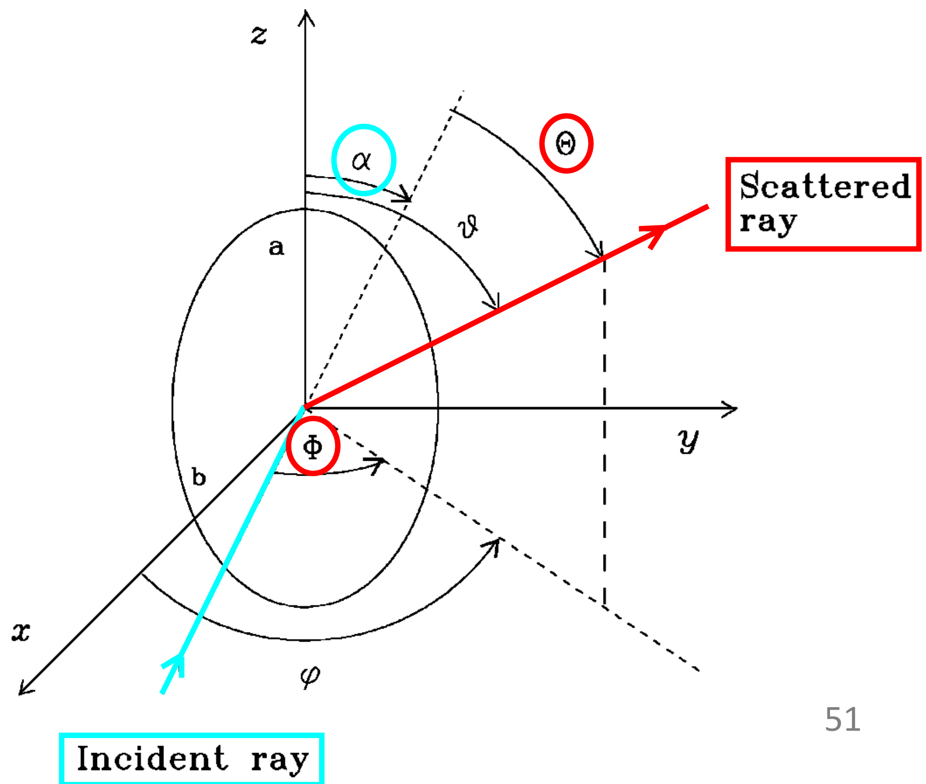
(2) Scattering by non-spherical grains

Scattering: $$\hat{I}_i \propto \hat{S}(\alpha,\Theta,\Phi)\,\hat{I}_{i-1}$$

Computationally demanding(!)

[e.g., α, Θ, Φ discretized
in 180 bins per angle
=> 6 x 10^6 scattering matrices]

Significantly more complex treatment of the radiative transfer (in particular in the case of multiple scattering)



(2) Scattering by non-spherical grains

Absorption:

$$\hat{I}_{\mathrm{after}} = \hat{R}^{-1}\,\hat{\Lambda}_{\mathrm{part.}}\,\hat{R}\,\hat{I}_{\mathrm{before}}$$

rotation matrix
(laboratory frame => particle frame)

$$\hat{R} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\Psi & \sin 2\Psi & 0 \\ 0 & -\sin 2\Psi & \cos 2\Psi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Ψ: angle between particle frame and laboratory frame

albedo matrix

$$\hat{\Lambda}_{\mathrm{part.}} = \begin{pmatrix} \tilde{l}_1 & \tilde{l}_2 & 0 & 0 \\ \tilde{l}_2 & \tilde{l}_1 & 0 & 0 \\ 0 & 0 & \tilde{l}_1 & 0 \\ 0 & 0 & 0 & \tilde{l}_1 \end{pmatrix}_{\mathrm{part.}}$$

where

$$\tilde{l}_1 = \frac{\Lambda^{\mathrm{TM}}}{1 + C_{\mathrm{ext}}^{\mathrm{TM}}/C_{\mathrm{ext}}^{\mathrm{TE}}} + \frac{\Lambda^{\mathrm{TE}}}{1 + C_{\mathrm{ext}}^{\mathrm{TE}}/C_{\mathrm{ext}}^{\mathrm{TM}}}$$

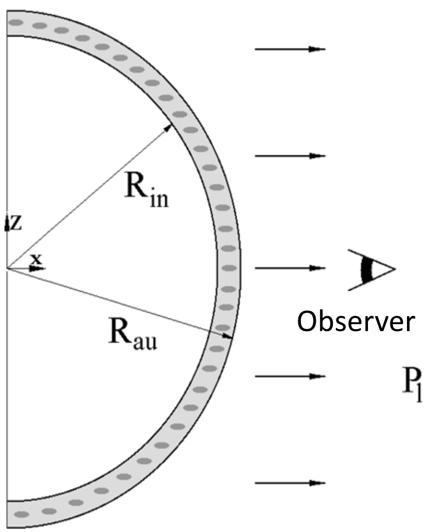
$$\tilde{l}_2 = \frac{\Lambda^{\mathrm{TM}}}{1 + C_{\mathrm{ext}}^{\mathrm{TM}}/C_{\mathrm{ext}}^{\mathrm{TE}}} - \frac{\Lambda^{\mathrm{TE}}}{1 + C_{\mathrm{ext}}^{\mathrm{TE}}/C_{\mathrm{ext}}^{\mathrm{TM}}}$$

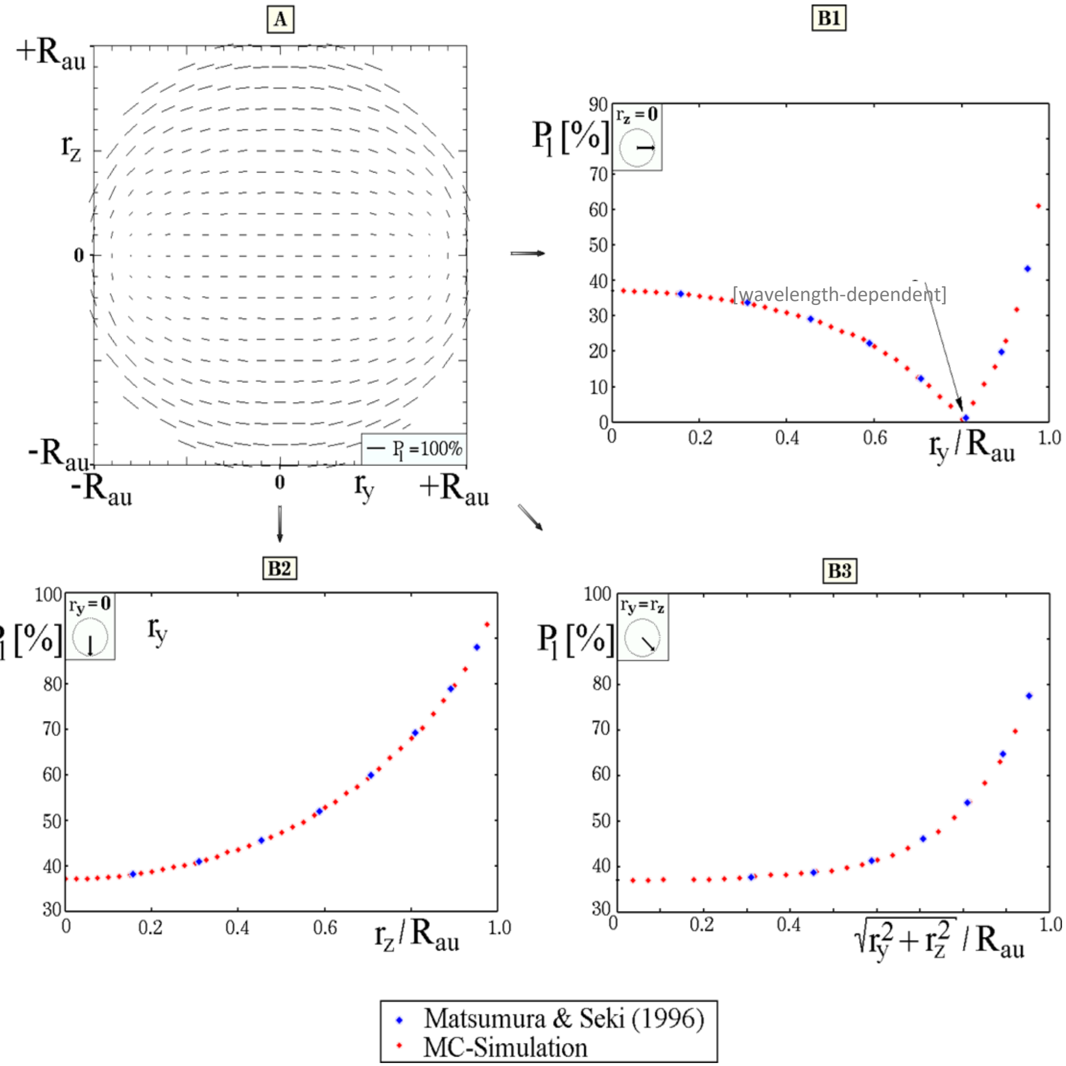
albedo

$$\Lambda^{\mathrm{TM,TE}}(m, r_{\mathrm{V}}, a/b, \alpha) = \frac{C_{\mathrm{sca}}^{\mathrm{TM,TE}}(m, r_{\mathrm{V}}, a/b, \alpha)}{C_{\mathrm{ext}}^{\mathrm{TM,TE}}(m, r_{\mathrm{V}}, a/b, \alpha)}$$

(2) Scattering by non-spherical grains: Example

Model



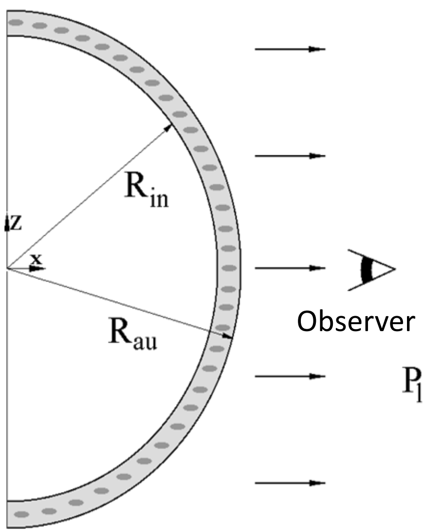


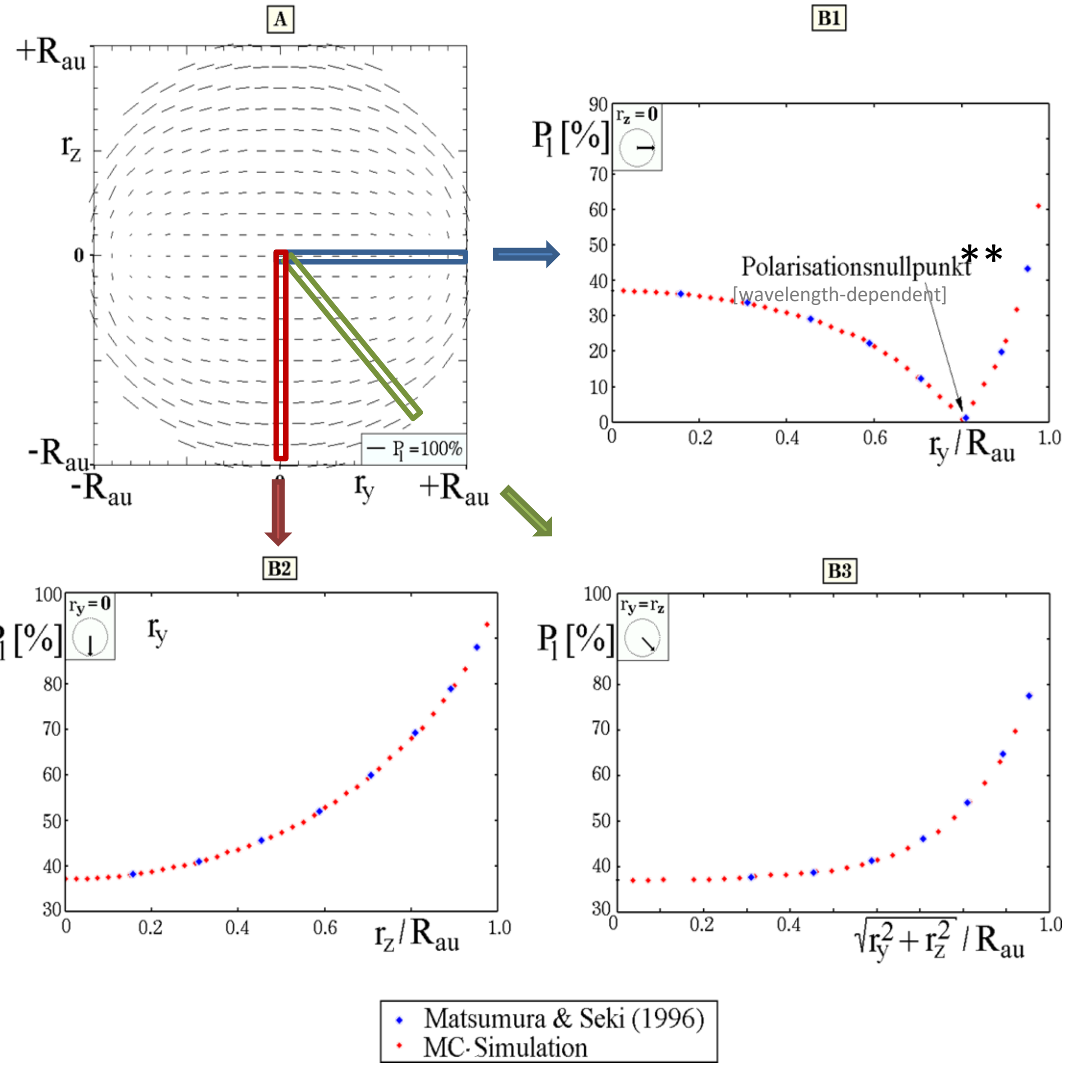
[Wolf et al. 2002]

** no hybrid models required for explanation

(2) Scattering by non-spherical grains: Example

Model

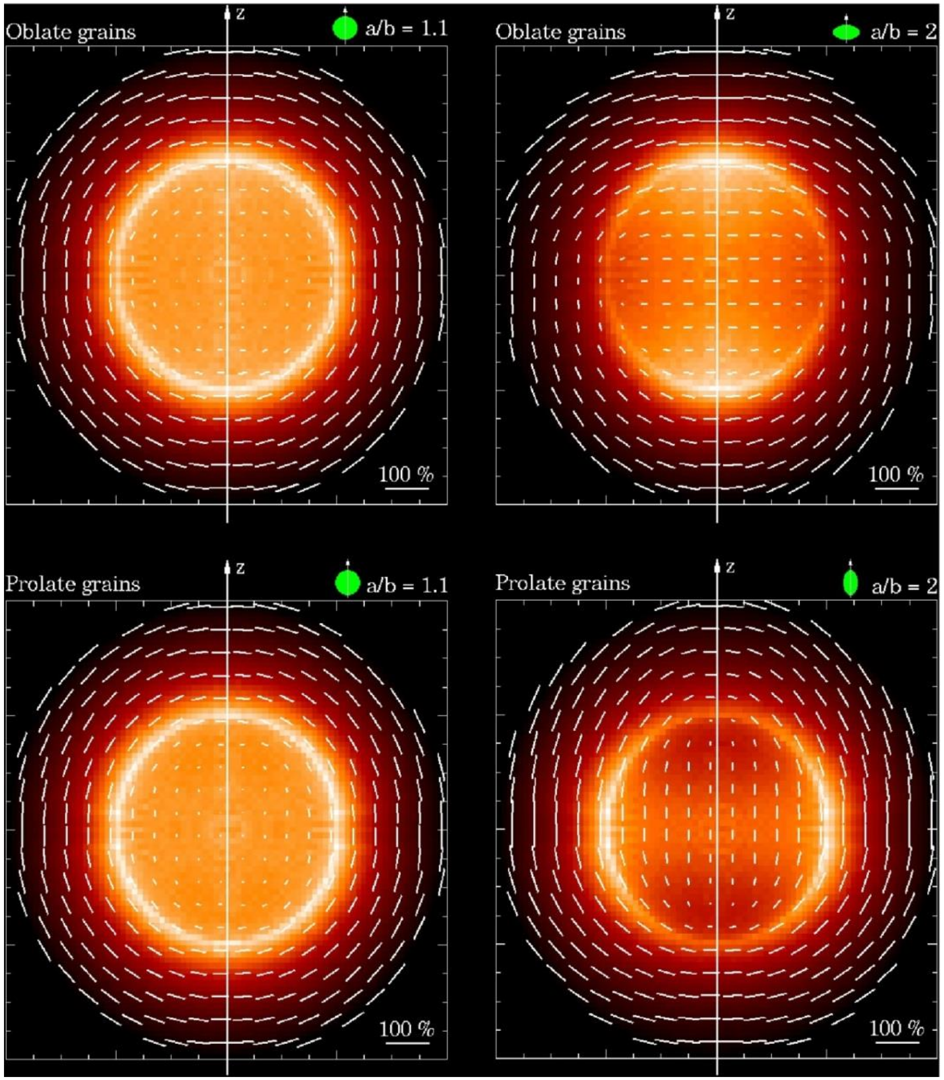




[Wolf et al. 2002]

** no hybrid models required for explanation

(2) Scattering by non-spherical grains: Example

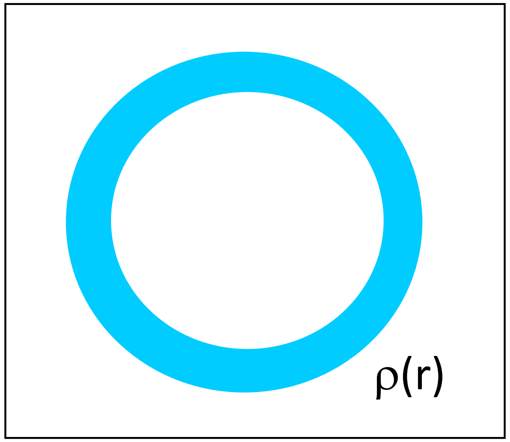


[Wolf et al. 2002]

Non-centro-symmetric

Intensity

Profile



POLARIS

[Reissl et al. 2014, 2016, Brauer et al. 2017]

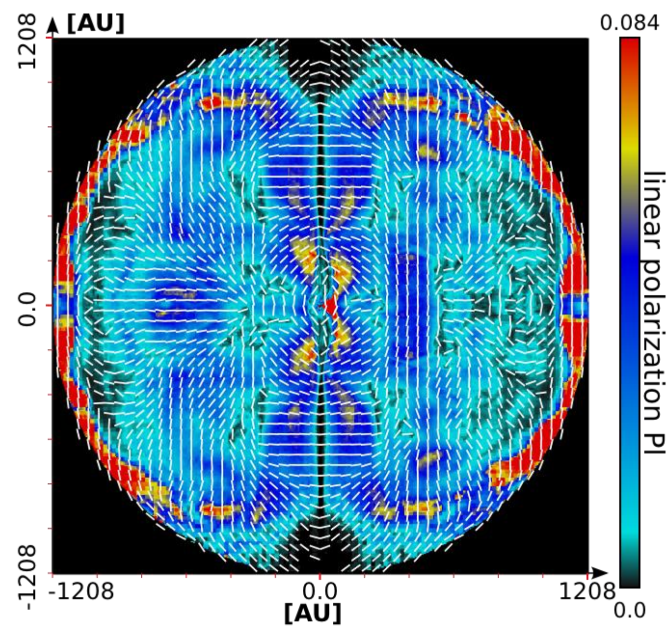
1.
MHD simulations of selected scenarios of the star-formation process

4.
Evaluation: Potential to constrain the impact of magnetic fields

2. Radiative transfer

3. Polarization map

Simulated image

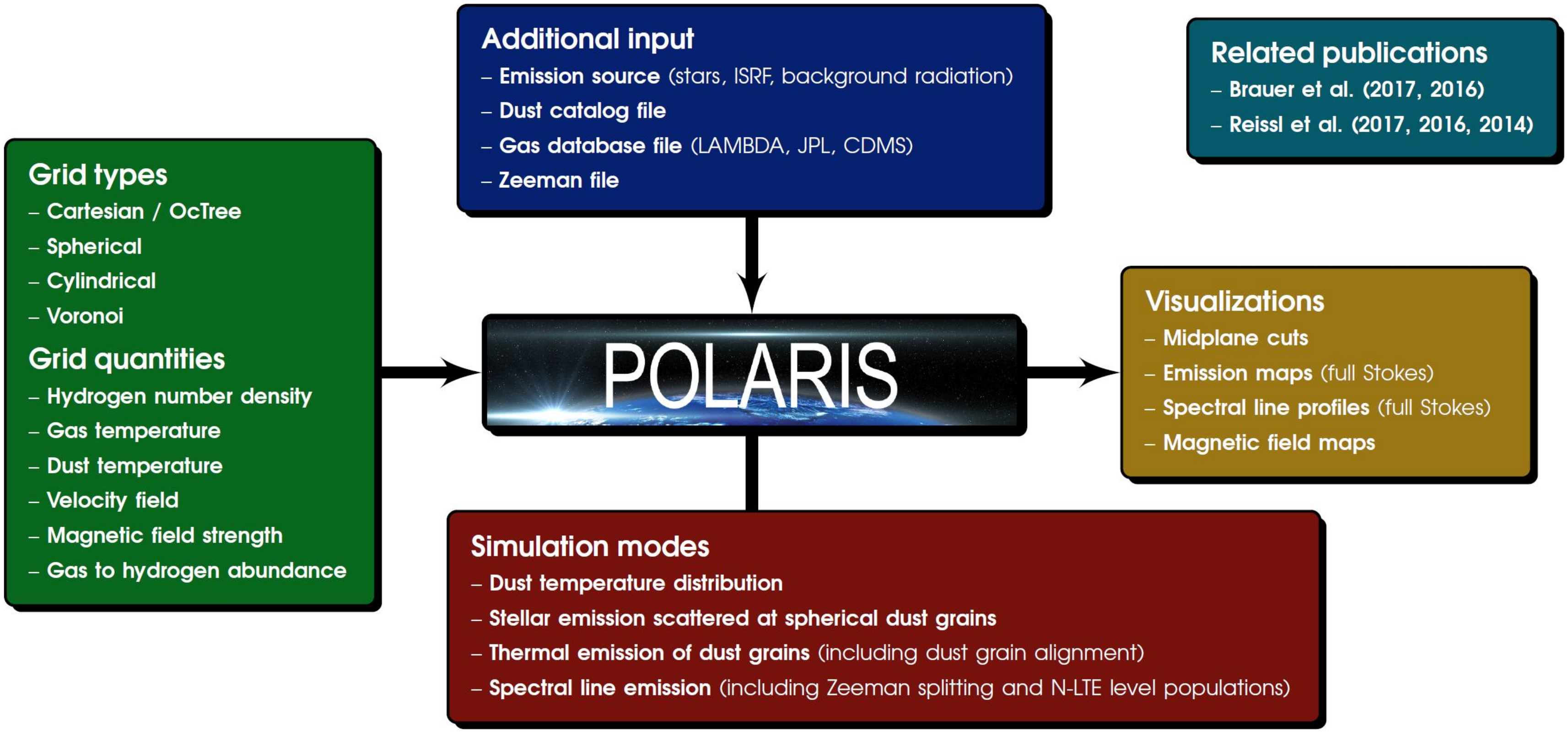


Simulated polarization map

POLARIS

[Reissl et al. 2014, 2016, Brauer et al. 2017]

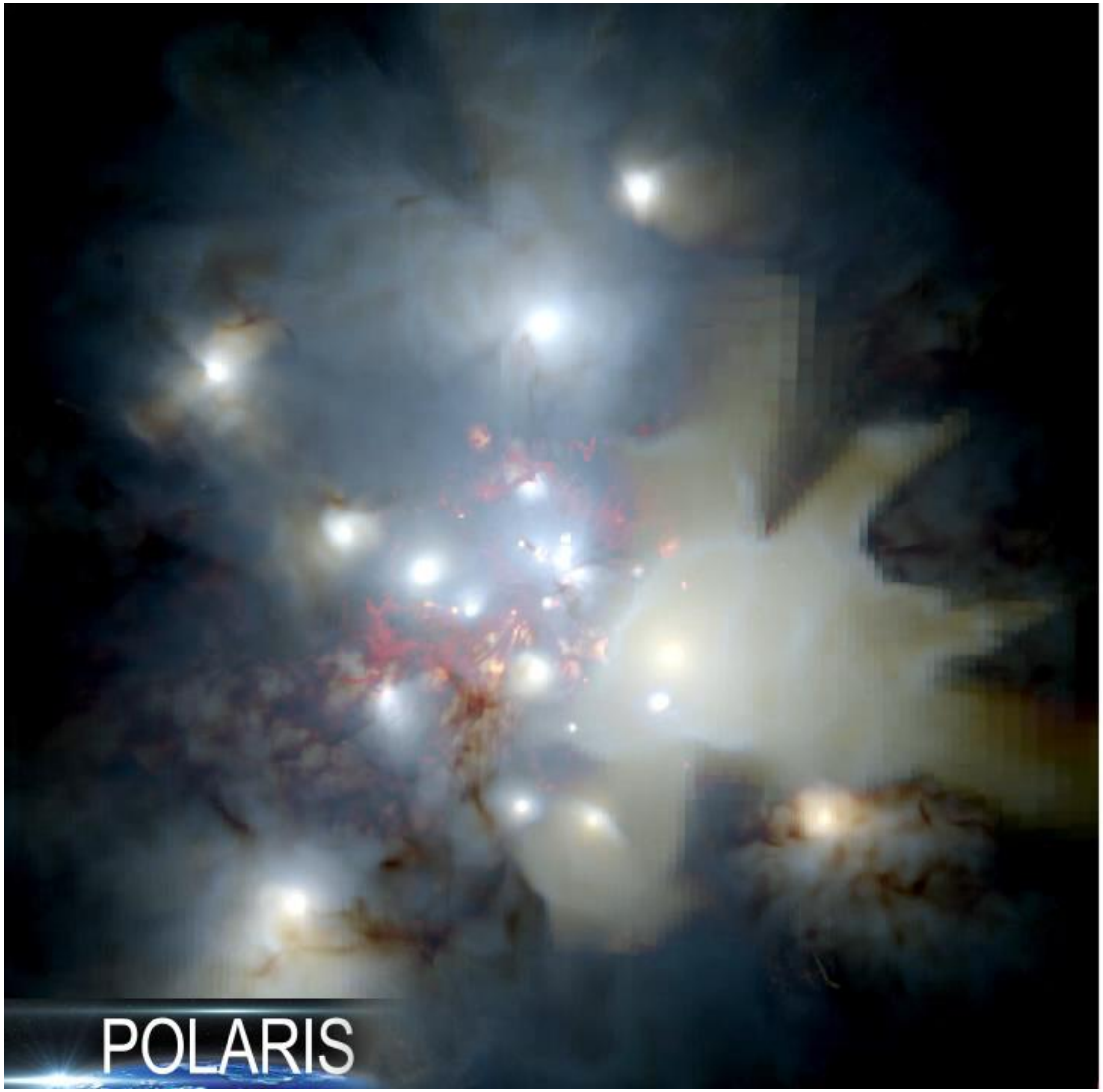
http://www1.astrophysik.uni-kiel.de/~polaris/

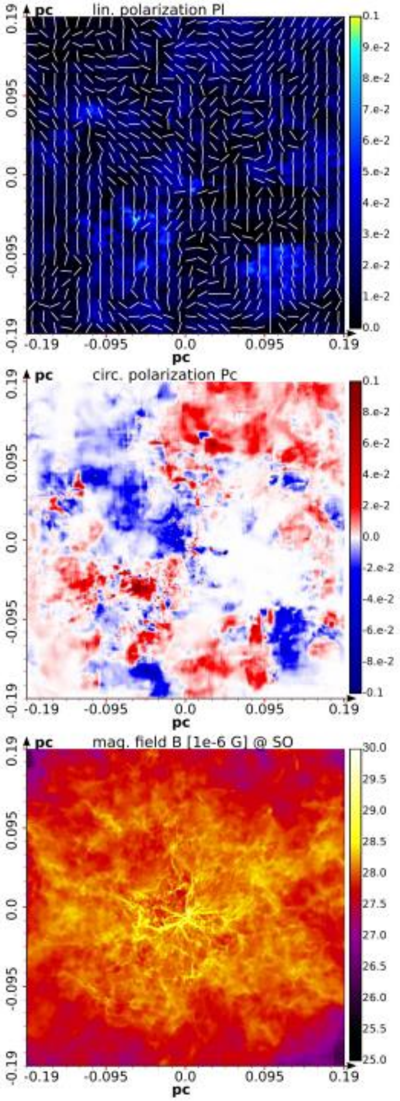


POLARIS

[Reissl et al. 2014, 2016, Brauer et al. 2017]

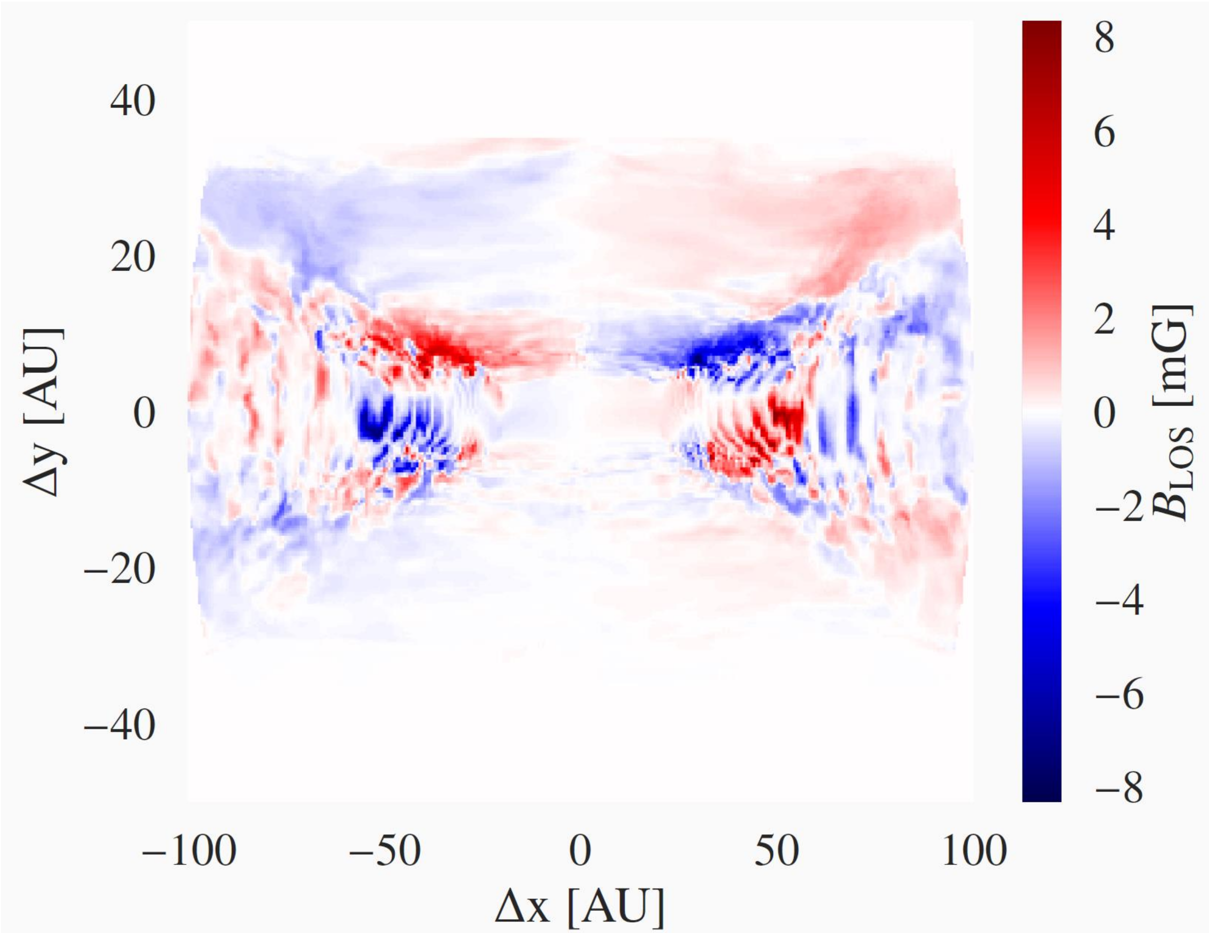
http://www1.astrophysik.uni-kiel.de/~polaris/





Tracing the **B** field (molecular lines)

[Brauer et al. 2017]



LOS B field derived from Zeeman splitting of CN

ν = 113.144 GHz
(Falgarone et al. 2008)

$\Delta v_{resolution}$ = 60kHz
(ALMA Partnership 2016)

Abundance:
CN/H = 4 x 10^{-9}
(Falgarone et al. 2008)

- With $\Delta x \sim 1\,\mathrm{AU} \Rightarrow \Delta F \sim 0.01\,\mu\mathrm{Jy}$
  (ALMA: $\Delta F \sim 10$ mJy / 3 hours)

⇒ Spatially unresolved observations?

5. Potential of polarimetry with SOFIA

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

- 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 ⟺ **(Sub)mm regime**

(diffraction limited; e.g.,
a) *SPHERE / ZIMPOL*, Beuzit et al.
VLT/ESO
b)
CANARIAS, Telesco et al. (2003);
Packham et al. (2005): MIR imager and spectrometer)

Atacama Large submillimeter / Millimeter Array (ALMA):

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 ALMA and ESA/Planck observations

SOFIA/HAWC+:

A unique instrument for studying 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 ⟺ (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.

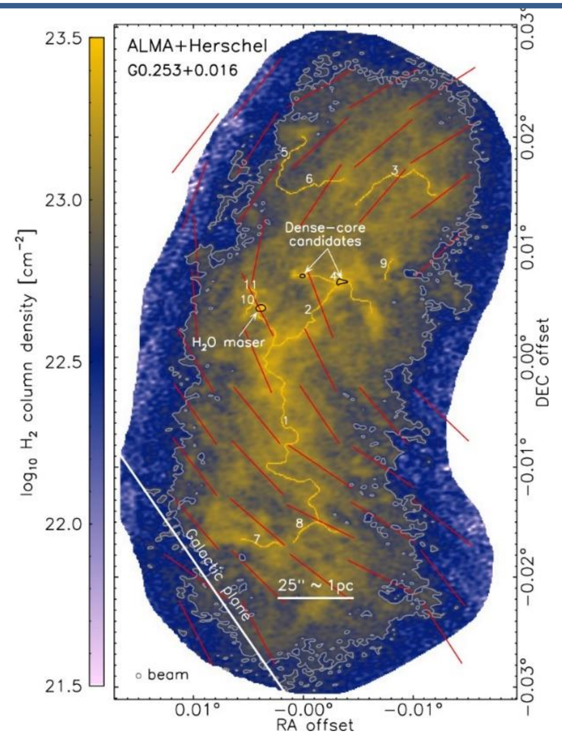
Selected science cases

Molecular clouds

Earliest stages of star formation: Dense cores embedded in molecular clouds

Impact of magnetic fields on the structure and dynamics of molecular clouds:

Spatially resolved polarization maps @ IR … mm wavelengths



H_2 column density maps of the central molecular zone cloud G0.253+0.016 from Herschel + ALMA.

Herschel / ALMA: large/small-scale structures

Large-scale magnetic field direction from polarization measurements @ 350um / CSO.

[Federrath et al., 2016]

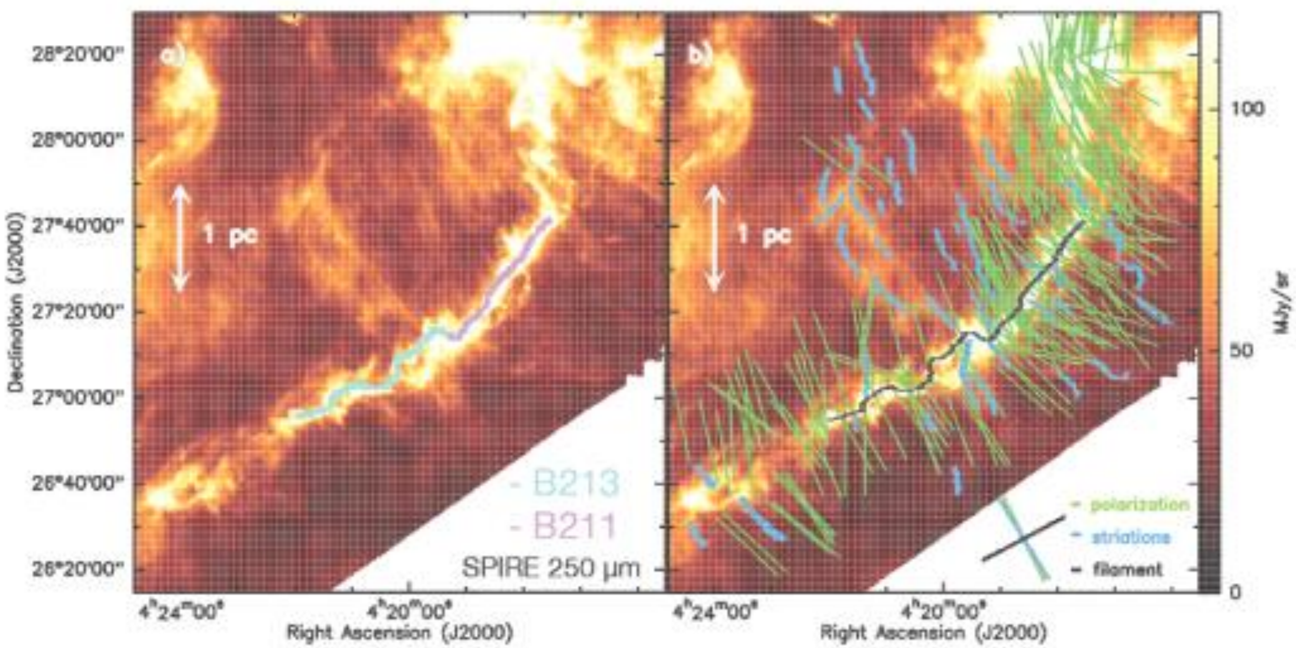
Goals

– Relation: Structure of the *ambient* magnetic field and that *inside the core*
– Constrain the *mass-to-magnetic flux ratio*

=> Impact of the magnetic field on potential fragmentation and core collapse

Magnetic fields and filaments

- Common feature in molecular clouds (irrespective of their star formation activity, e.g. André et al. 2014) => directly related to the evolution of the clouds themselves

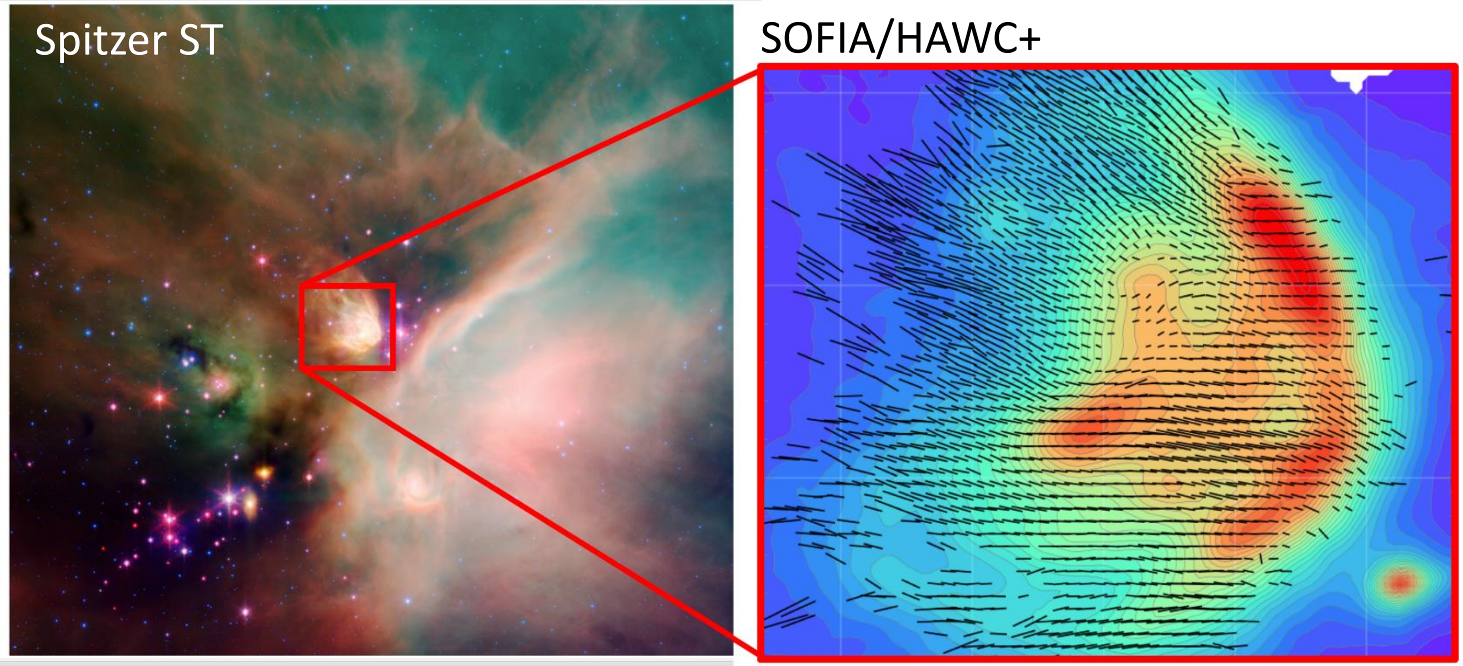


- Goal: Dynamics, Magnetic field structure and strength

Left: Herschel/SPIRE 250um image of the B211/B213/L1495 region in Taurus; Right: Display of optical and **infrared** polarization vectors overlaid on the Herschel/SPIRE image. *[Palmeirim et al. 2013]*

SOFIA/HAWC+: Magnetic field inside the filaments

Magnetic fields in star formation



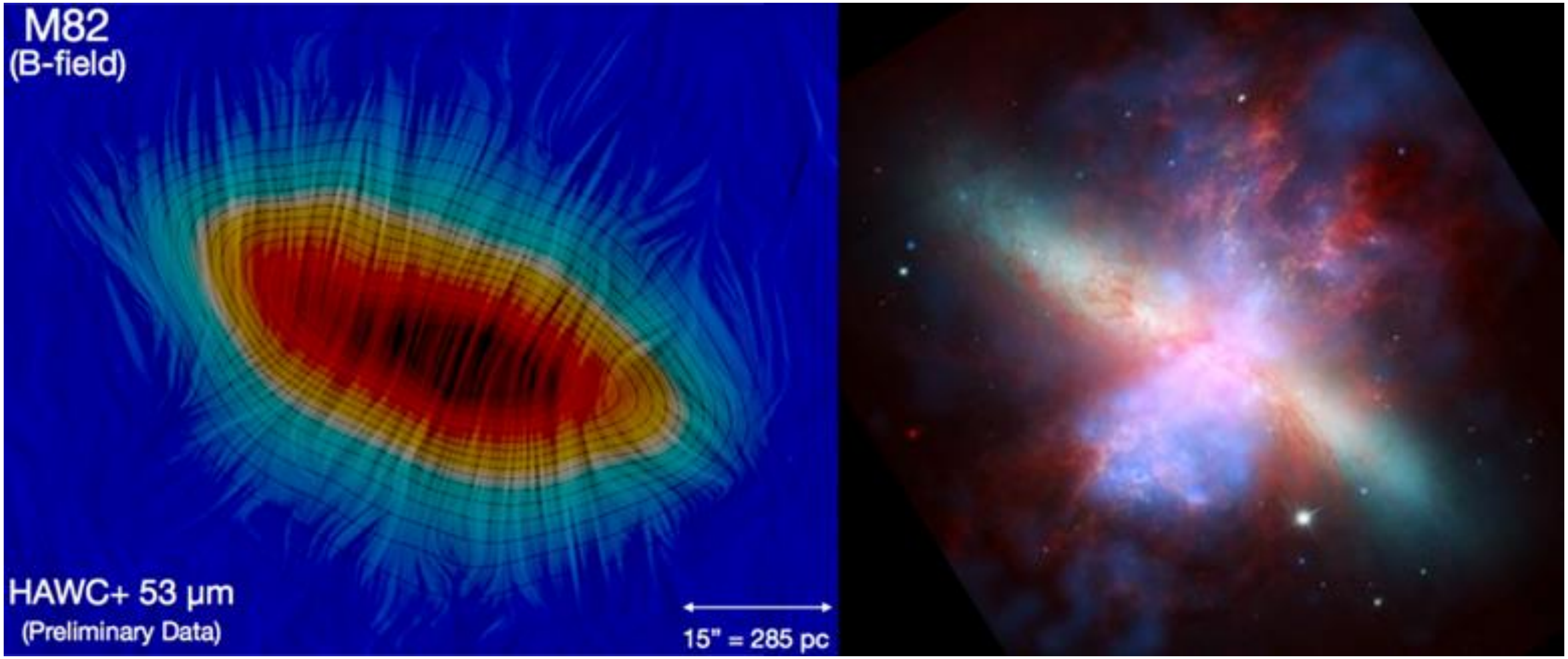
Rho Ophiuchi (~131pc):

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]

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

Magnetic field in extragalactic sources, such as in AGNs:



M82: Constraints on the galactic magnetic wind at scales of few hundred parsecs

[Left: SOFIA/HAWC+/E. Lopez-Rodriguez; Right: X-ray: NASA/CXC/JHU/D.Strickland;
Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht]

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

NGC 1068:

Magnetized spiral arms

Interplay:

Rotation of the disk

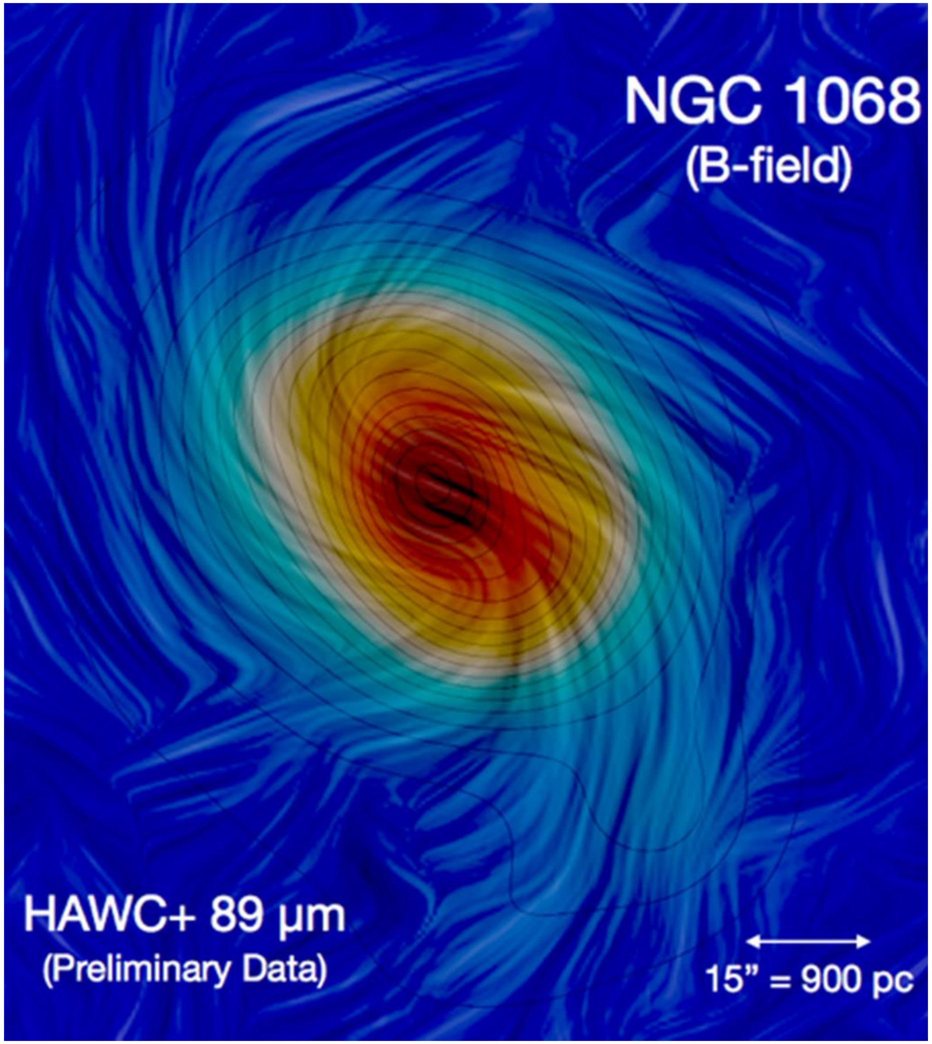
⇔

Magnetic field

Magnetic field

⇔

Dust grain alignment



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

Selected Literature

1. S. Trippe „Polarization and Polarimetry: A Review“, Journal of the Korean Astronomical Society, 2014, in press
2. D.A.Weintraub, A.A.Goodman, R.L.Akeson „Polarized light from star-forming regions“, Protostars & Planets IV, 2000, 247
3. J.H. Hough “New opportunities for astronomical polarimetry”, Journal of Quantitative Spectroscopy & Radiative Transfer (2007) 106, 122

Thank you!

&

Don't be afraid of polarimetry ;-)