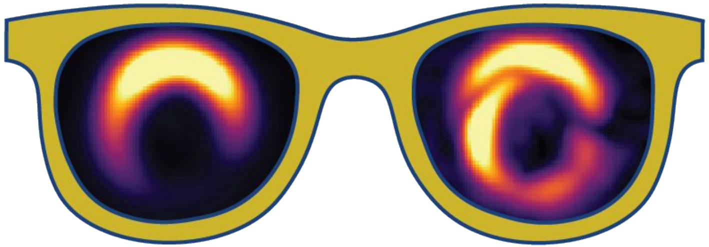
Basics of

Full Polarization with ALMA

Brief introduction to polarization theory with focus on mm-observations



I-TRAIN #7 Polarization observations with ALMA
European ARC Network, June 24, 2021

Outline

- Fundamentals of polarization
- ALMA operation and calibration
- Physical mechanisms generating polarization in the Universe

Credits

Rick Perley, Steven Meyers,
George Moellenbrock, Ivan Marti-Vidal,
Michiel Brentjens, Rainer Beck,
Richard Crutcher, Shane O'Sullivan,
Francesca Bacciotti, Cameron Van Eck

- Fundamentals of polarization

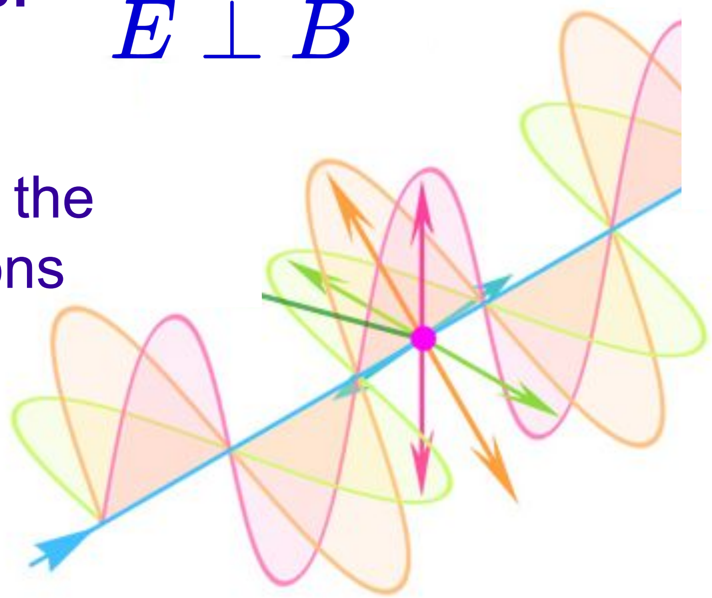
Electromagnetic radiation

Propagating sets of oscillating **vectors:**
Electric & Magnetic fields

$$\vec{E} \perp \vec{B}$$

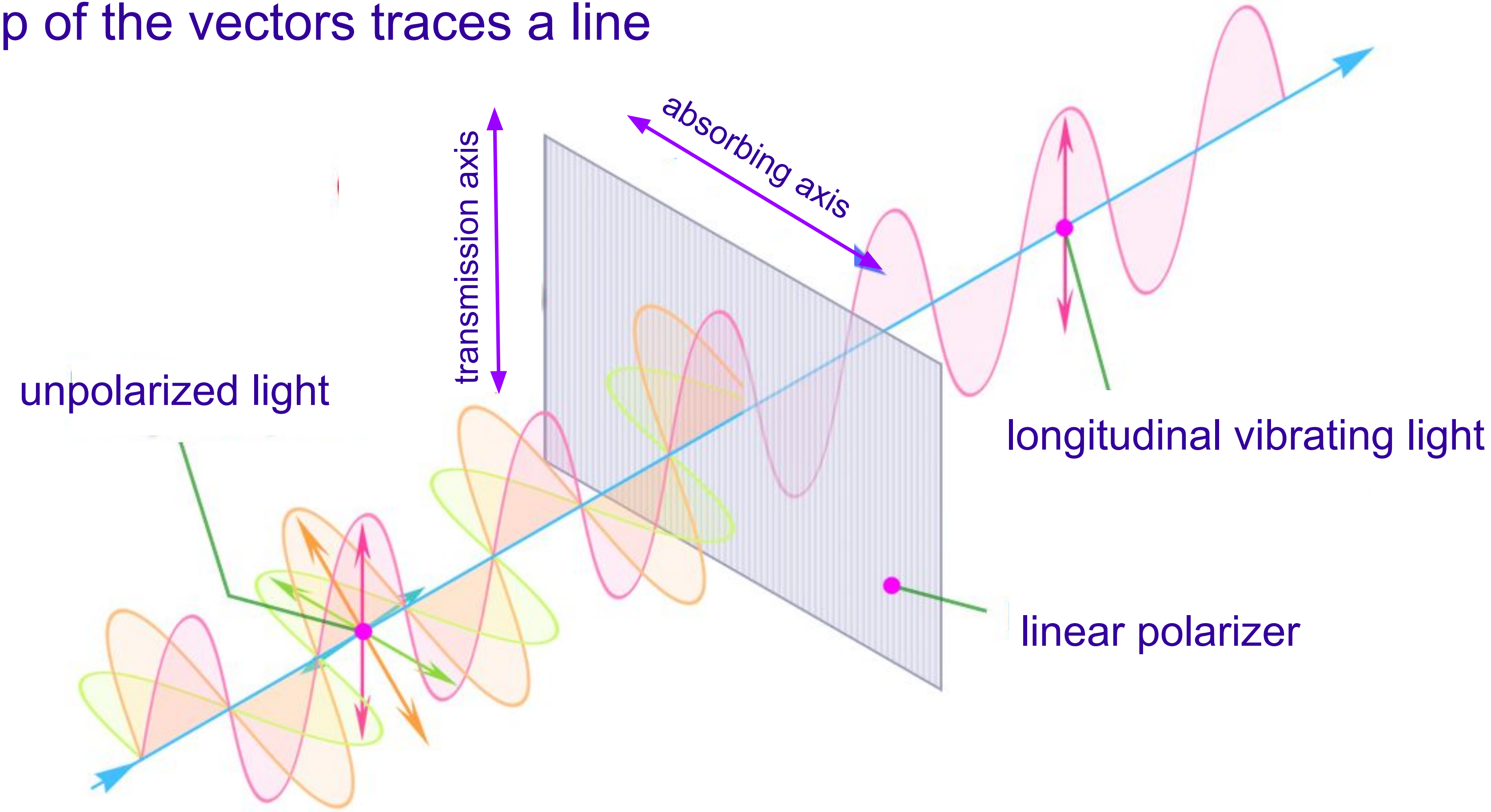
To properly describe it we need to add the geometrical orientation of the oscillations **(=polarization)**

Normal (unpolarized) light:
vectors vibrate in every direction
NO preferred polarization



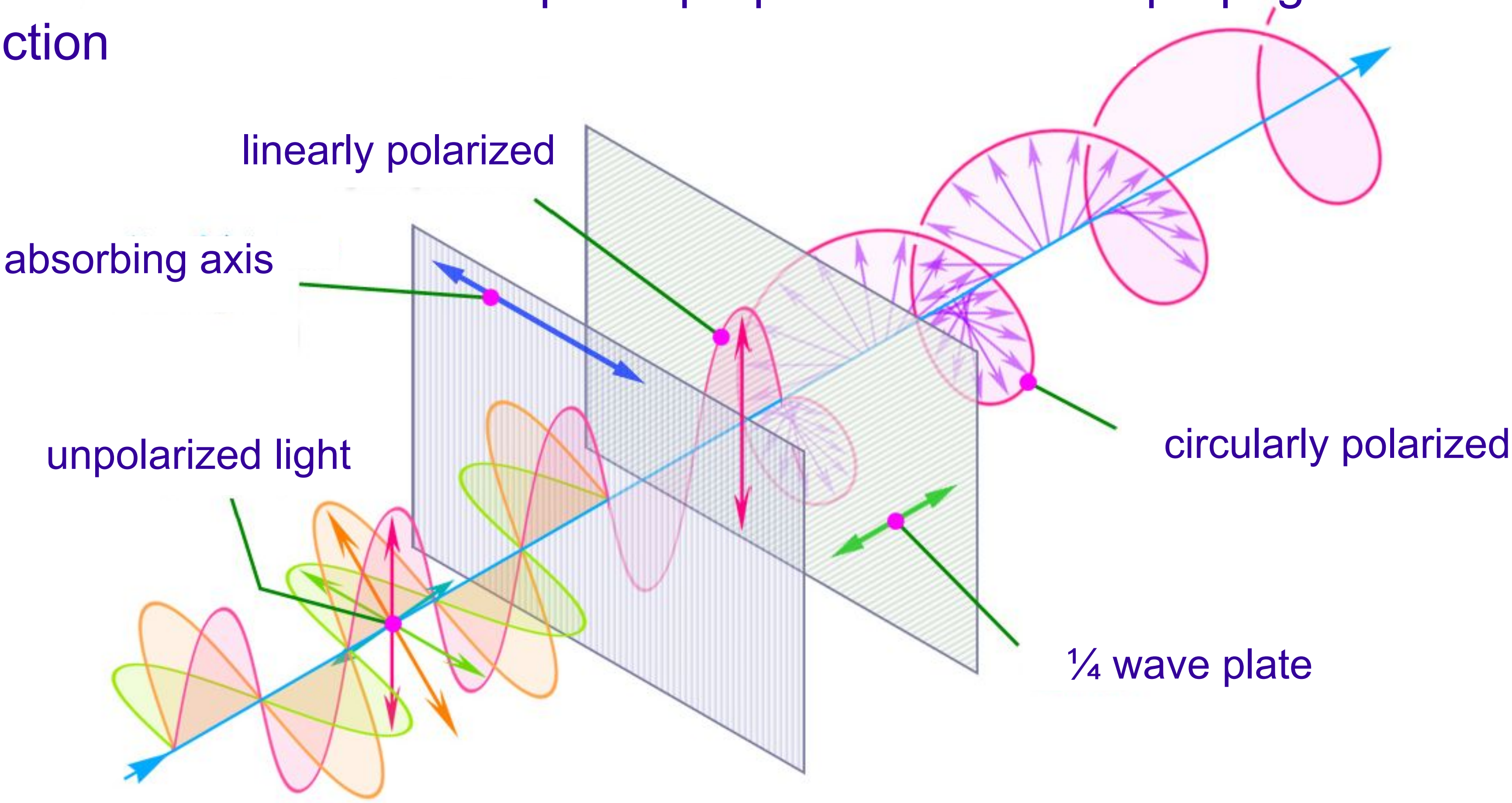
electric field only

Linearly polarized light:
the tip of the vectors traces a line



Circularly polarized light:

vectors trace a circle in the plane perpendicular to the propagation direction

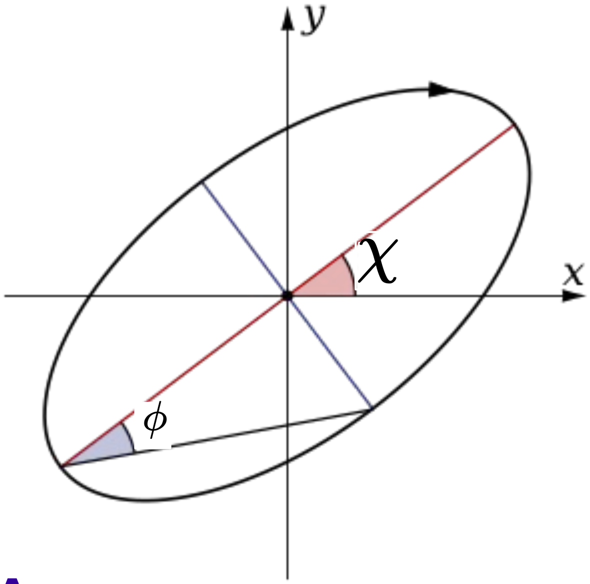


Most general polarized light:

a mixture of linear and circular polarization = **elliptical** polarization

Need to know:

- ellipticity **e = a/b ----> ϕ =arctan (1/e)**
- dimension a
- **azimuth** χ
- clockwise or counterclockwise



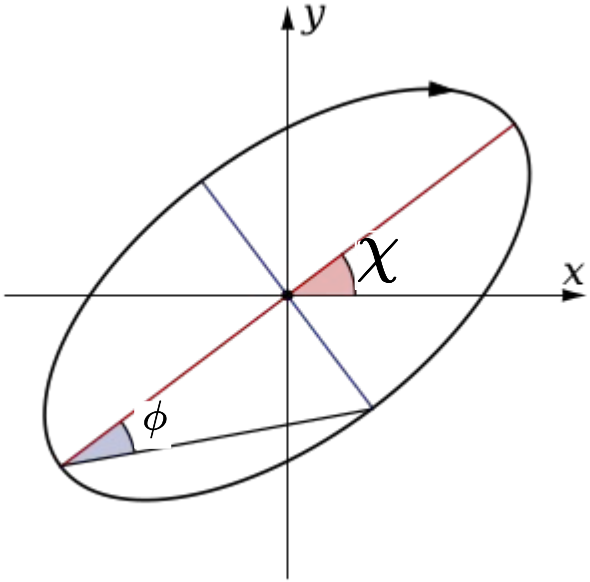
χ is the electric vector Position Angle **EVPA**

it has the symmetry $\chi + \pi \rightarrow \chi$ ⟶ **A** in the archive

Stokes parameters

$$I^2 = Q^2 + U^2 + V^2$$
$$Q = cos2\phi cos2\chi$$
$$U = cos2\phi sin2\chi$$
$$V = sin2\phi$$

(ideal full polarized case)



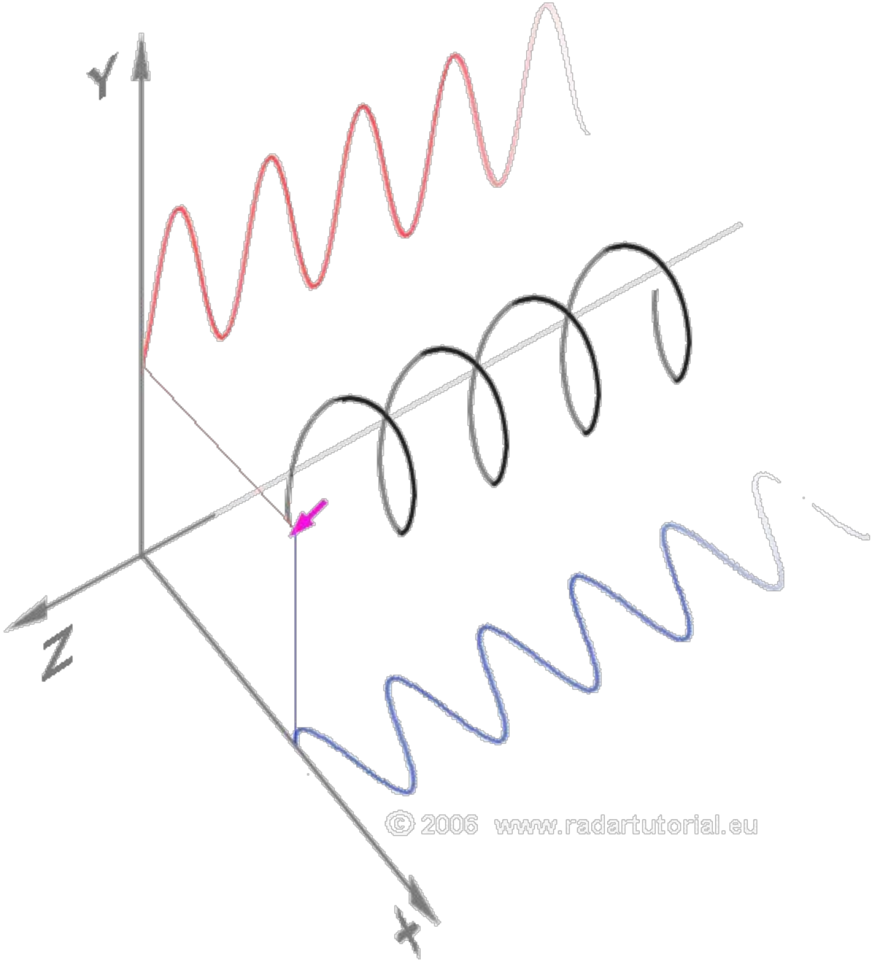
- I is the total intensity (polarized + unpolarized)
- Q and U describe linear polarization
- V gives the circular polarization

- ALMA operation and calibration

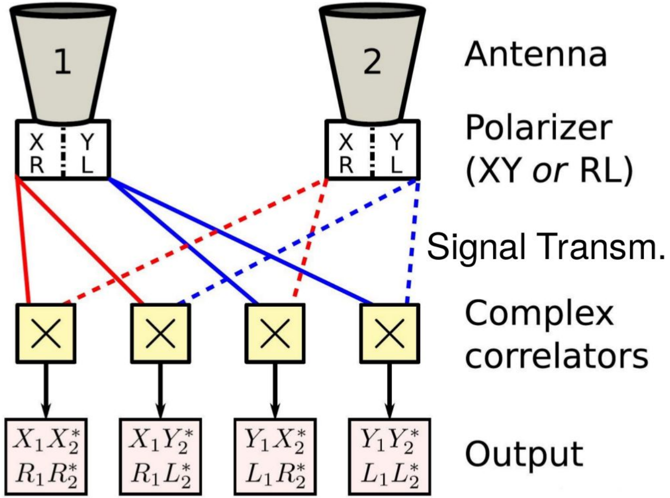
Radioastronomical feeds

every polarized wave can be decomposed using two orthogonal polarizers registering linear or circular polarization.

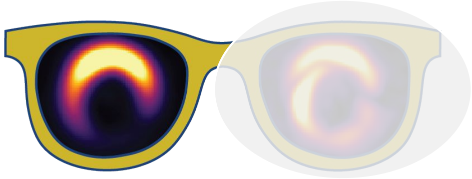
ALMA has linear feeds:
two orthogonal dipoles registering coherently two orthogonal polarization states



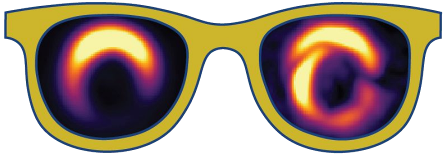
Interferometric polarization observations



- **single mode only XX**
- **dual mode only XX and YY** are registered → Stokes I only



- **full polarization mode** the four correlations
  XX YY YX XY are saved



Interferometric polarization observations

$$I = \frac{1}{2}(XX + YY)$$

$$Q = \frac{1}{2}(XX - YY)$$

$$U = \frac{1}{2}(XY + YX)$$

$$V = \frac{1}{2}(XY - YX)$$

In an ideal world we would get

- **total intensity ---> Stokes I**
- **circular polarization ---> Stokes V**
- **linear polarization** $$PI = \sqrt{Q^2 + U^2}$$
- **EVPA** $$tan 2\chi = \frac{U}{Q}$$

Interferometric polarization observations

In the real world

- feeds are not perfect ---> need to calibrate instrumental leakage

Interferometric polarization observations

In the real world

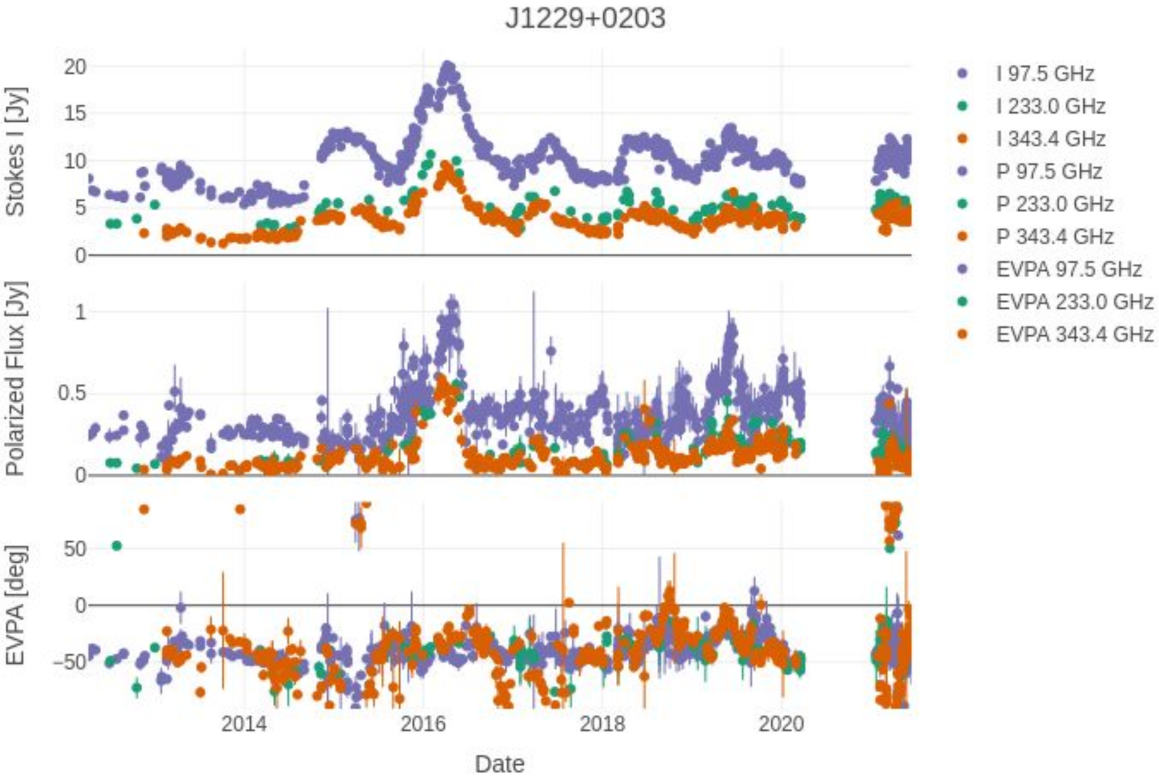
- feeds are not perfect ---> need to calibrate instrumental leakage
    - **calibrators properties are highly variable especially @ mm wavelengths**

Polarization calibrators

http://www.alma.cl/~skameno/AMAPOLA/

linear polarization
> 2% of Stokes I

selected by the observatory



Interferometric polarization observations

In the real world

- feeds are not perfect ---> need to calibrate instrumental leakage
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Interferometric polarization observations

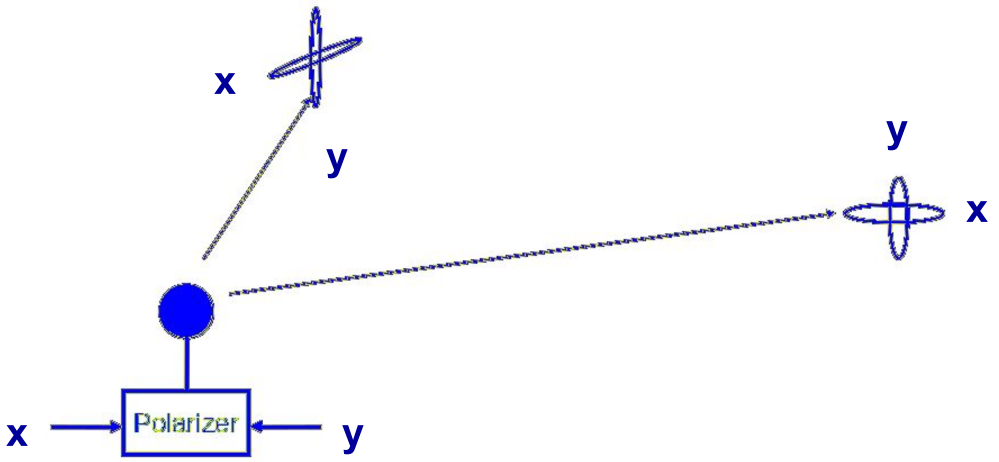
In the real world

- feeds are not perfect ---> need to calibrate instrumental leakage
  - calibrators properties are highly variable especially @ mm wavelengths ---> **No assumption on the calibrators properties**
  - **---> parallactic angle**

Parallactic angle

angle between the axis of the antenna mount and the source

While tracking the source the axis of the feeds is tied to the Earth, but it rotates on the sky --->
Parallactic angle variation



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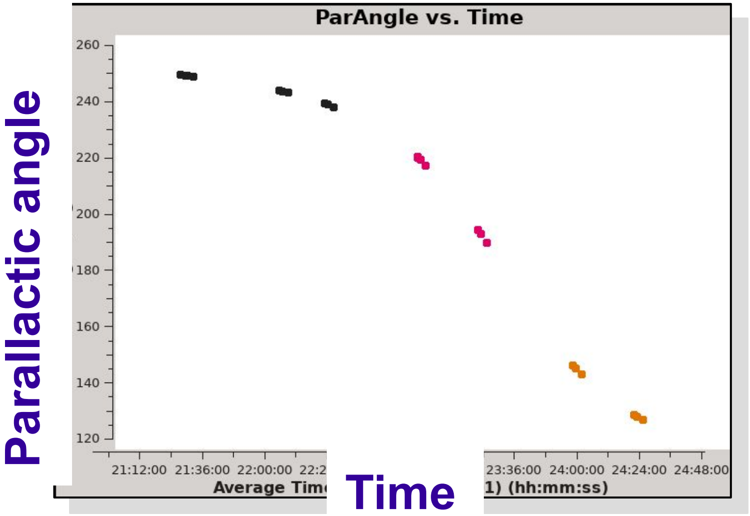
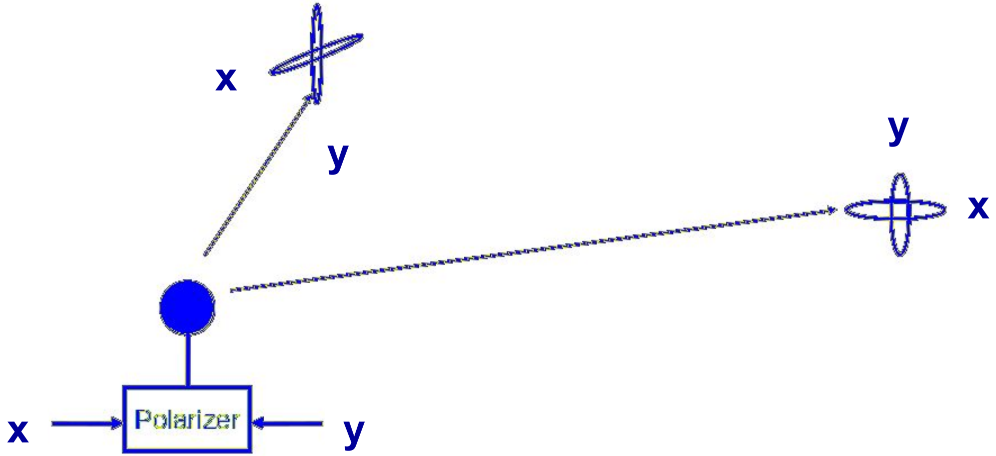
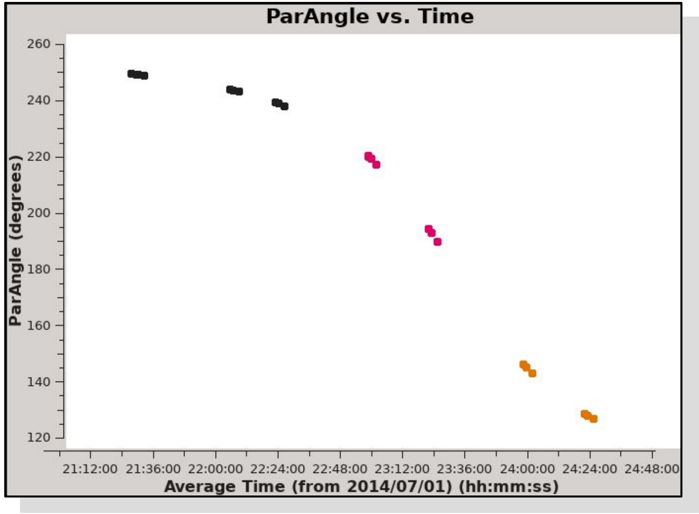


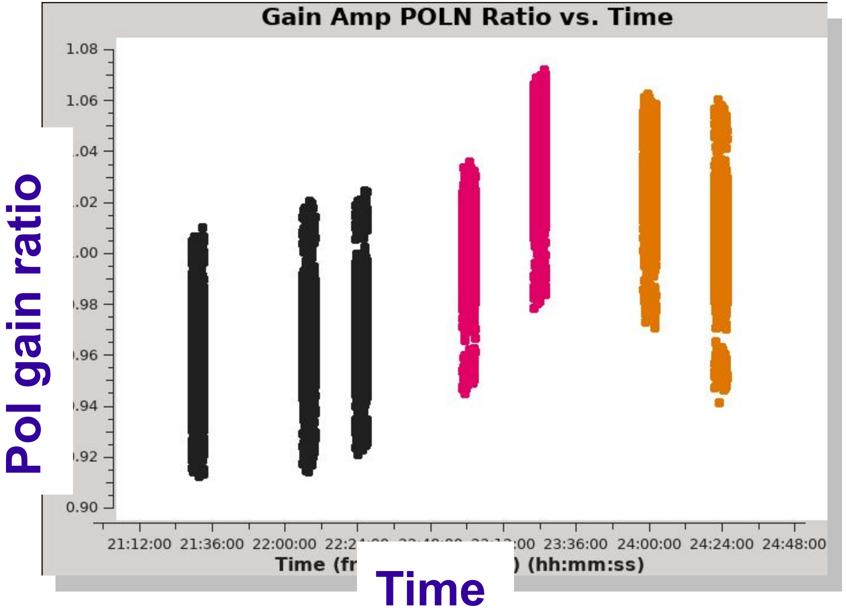


Parallactic angle

angle between the axis of the antenna mount and the source

the parallactic angle variation of the polarized signal allows us to disentangle instrumental from intrinsic polarization



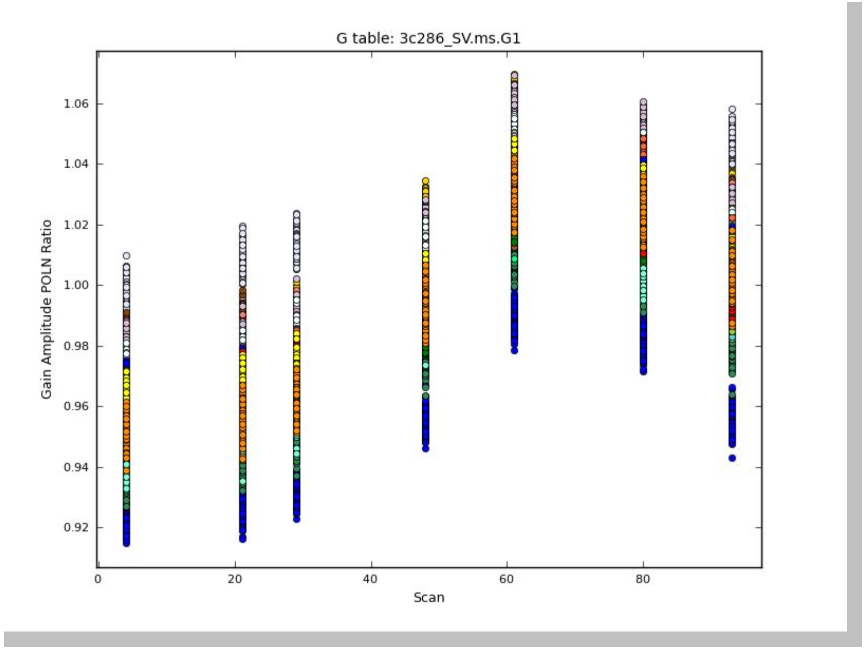


Polarization calibration

Current calibration scheme (Nagai et al. 2016) and
https://casaguides.nrao.edu/index.php?title=3C286_Polarization

- **No assumptions** on the linear polarization of the calibrator
- **Stokes V = 0**

- **Need a long observation ~ 3 hours to cover > 60 deg in parallactic angle**



Polarization calibration

Current calibration scheme (Nagai et al. 2016) and

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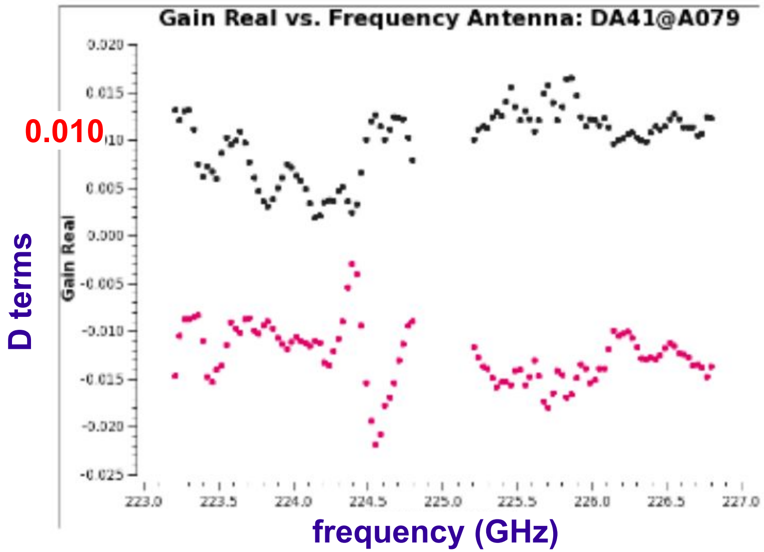
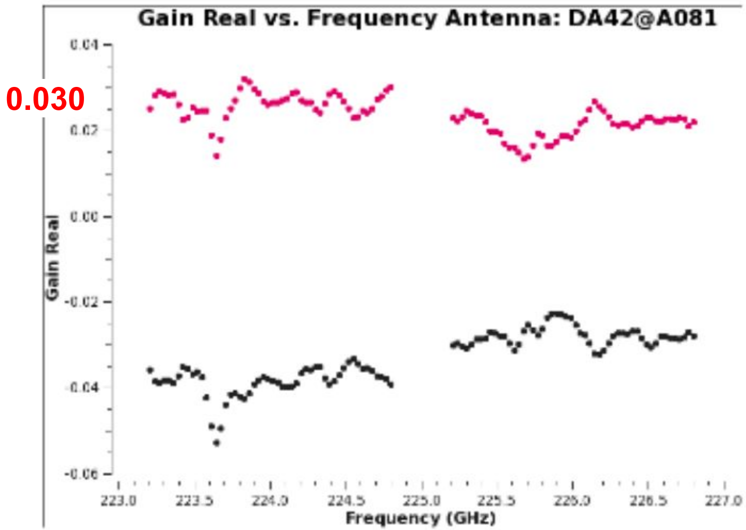
Instrumental polarization → D terms for each antenna ~ few % (<< 10 %)

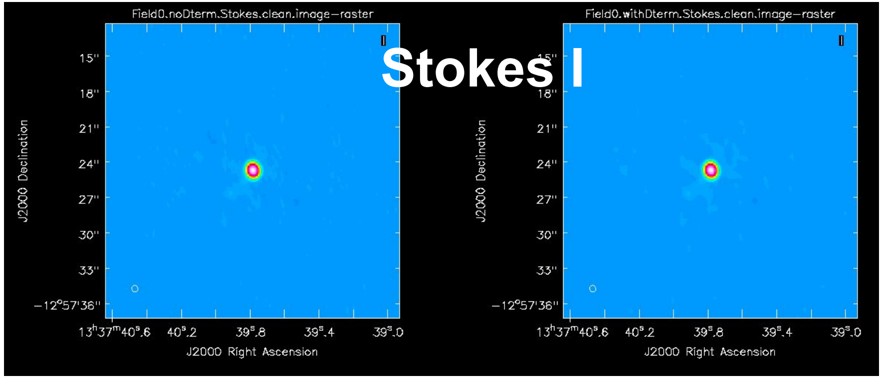


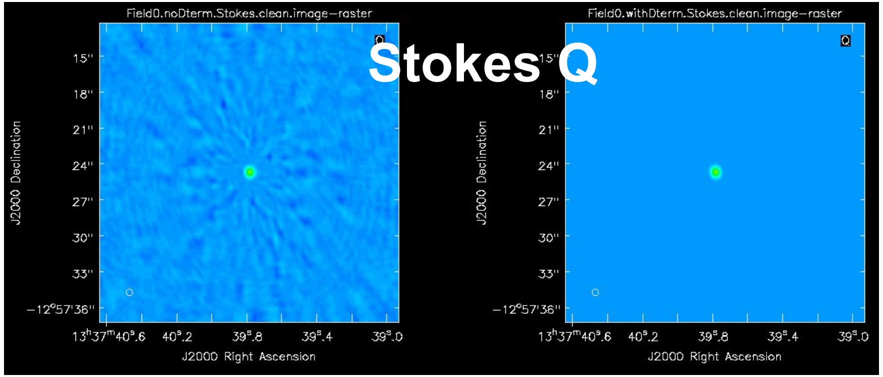


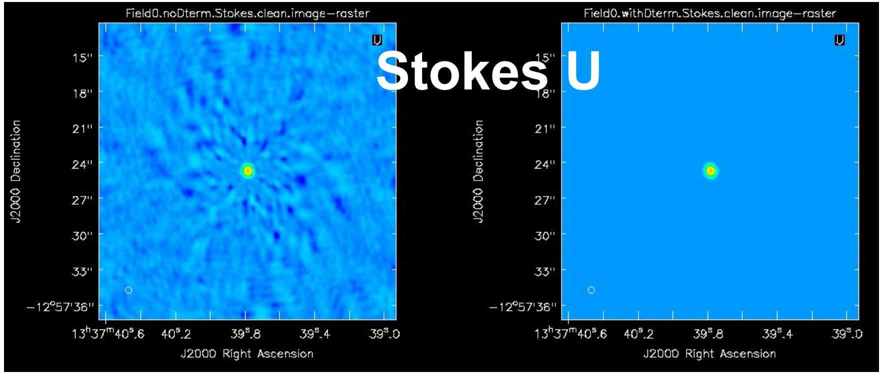
Calibration's results

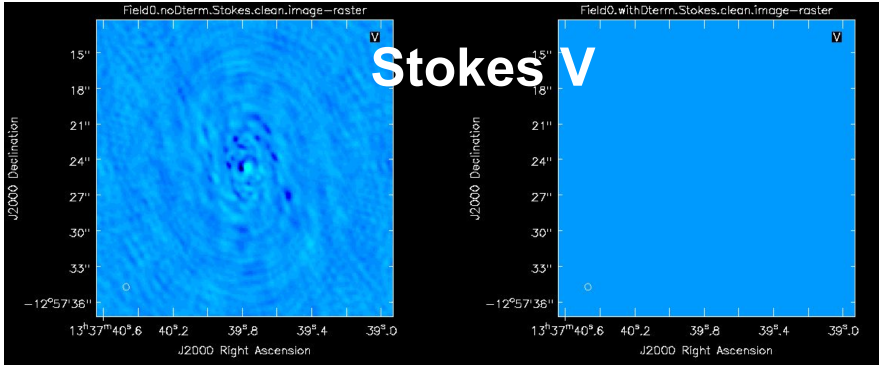
Comparison with and without leakage calibration applied

NOTE: the polarization calibrator Stokes I flux is normalized









Interferometric polarization observations

In the real world

- feeds are not perfect ---> need to calibrate instrumental leakage
    - calibrators properties are highly variable especially @ mm wavelengths
    - in alt-az antenna feeds rotate on the sky while tracking a target ---> parallactic angle

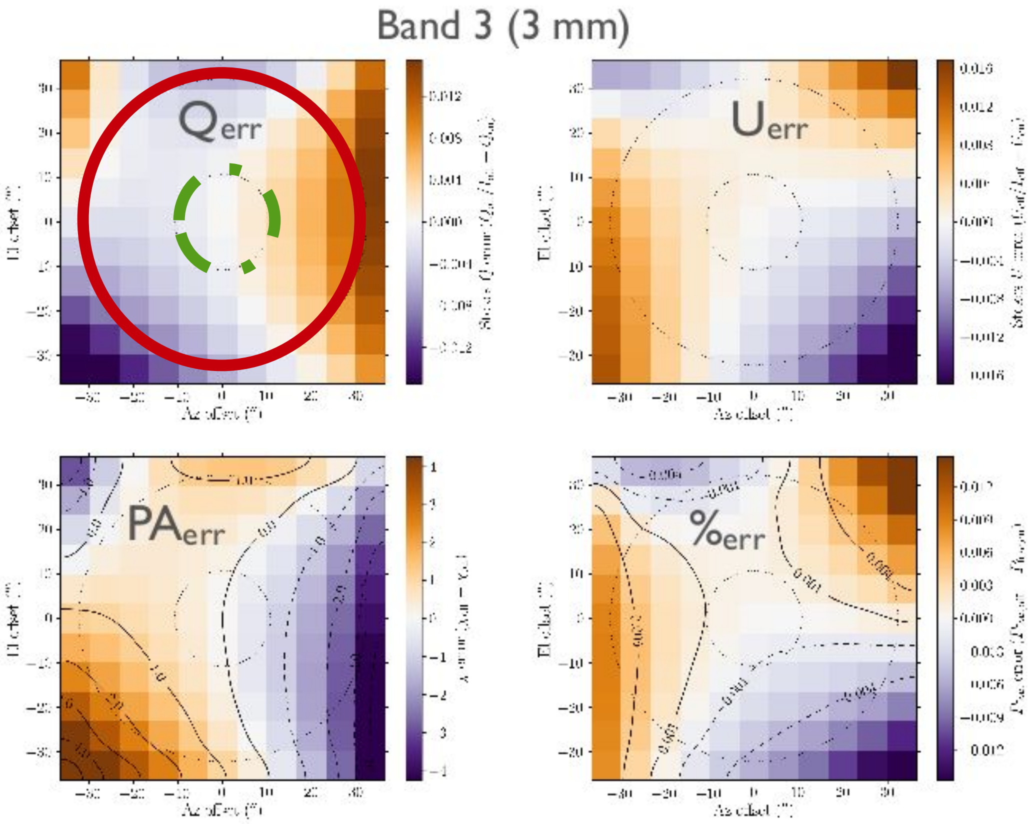
- **beam polarization due to antenna and feed geometry ---> need to know the antenna patterns for each Stokes**

Beam instrumental polarization

- Offset between receiver feeds and the reflector
- **off axis errors in linear and circular polarization evident**
- **Polarization observations limited to**

$$\frac{FOV}{3}$$ **for linear**

$$\frac{FOV}{10}$$ **for circular**



Band3 error maps.
Hull et al. 2020

Take home messages

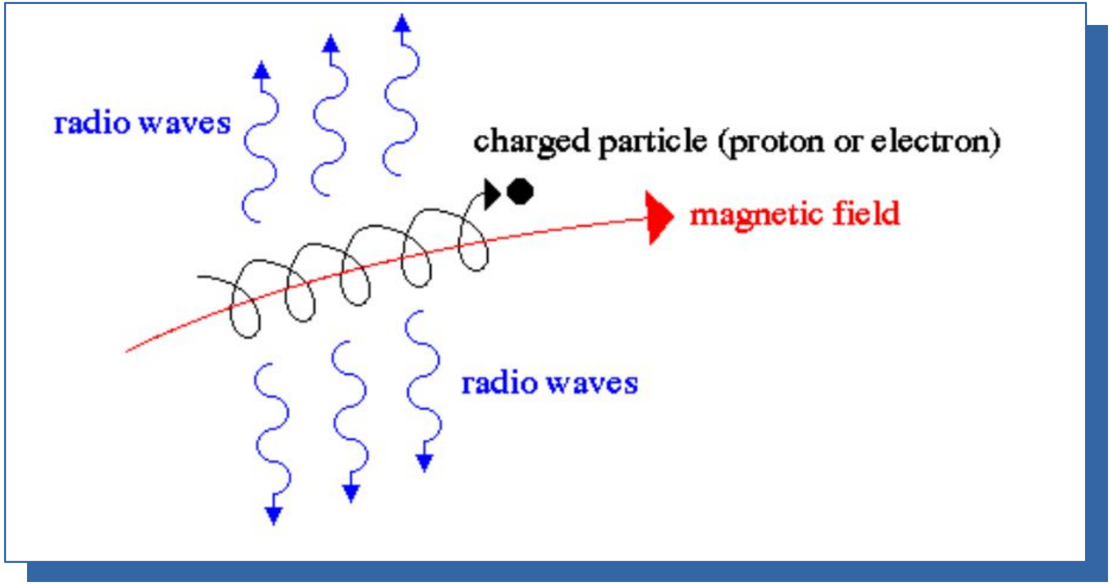
ALMA polarization observations

- **3hrs minimum observing time** – consecutive executions
- **limitations on the FOV (⅓ for linear, 1/10 for circular)**
- Systematic calibration uncertainty on axis
  0.03 % of Stokes I for linear polarization
  0.8 % of Stokes I for circular polarization

https://almascience.eso.org/documents-and-tools/cycle8/alma-technical-handbook

- Physical mechanisms generating polarization in the Universe (**@ ALMA frequencies**)

Synchrotron emission - continuum



- Intrinsically polarized $\perp \vec{\mathbf{B}}$

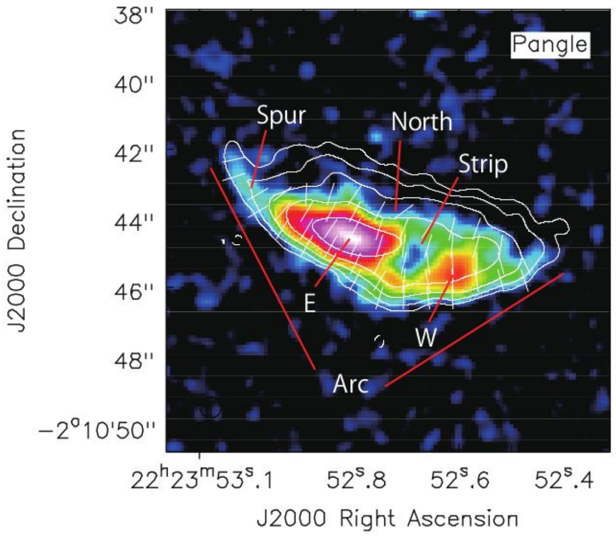
- From total intensity

  $$I_\nu \propto N_0 \, B^{(\delta+1)/2} \, \nu^{-\alpha}$$

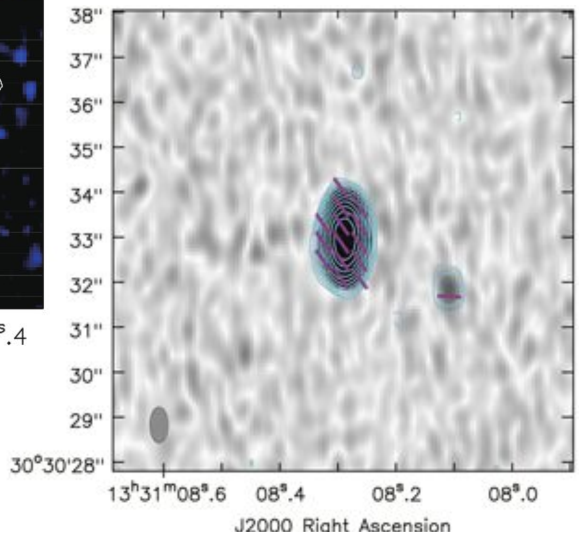
  B strength with assumptions (e.g. equipartition)

- From polarization angle ---> **orientation of B in the plane of the sky** fraction ---> **uniformity of B**

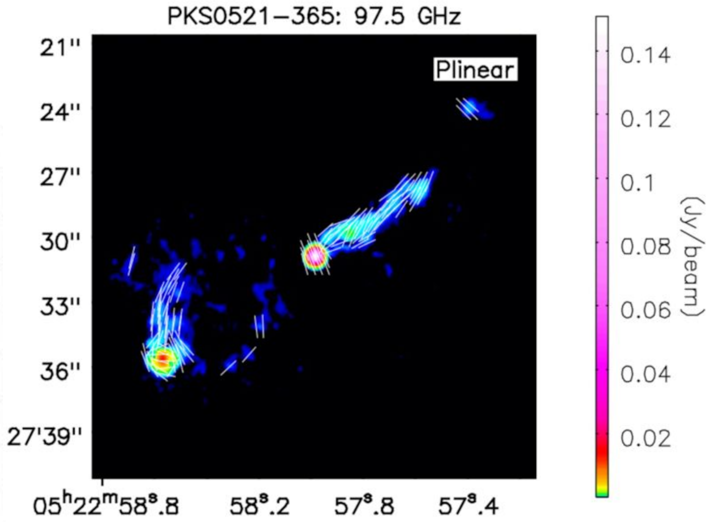
Synchrotron emission - continuum



Orienti et al. 2017

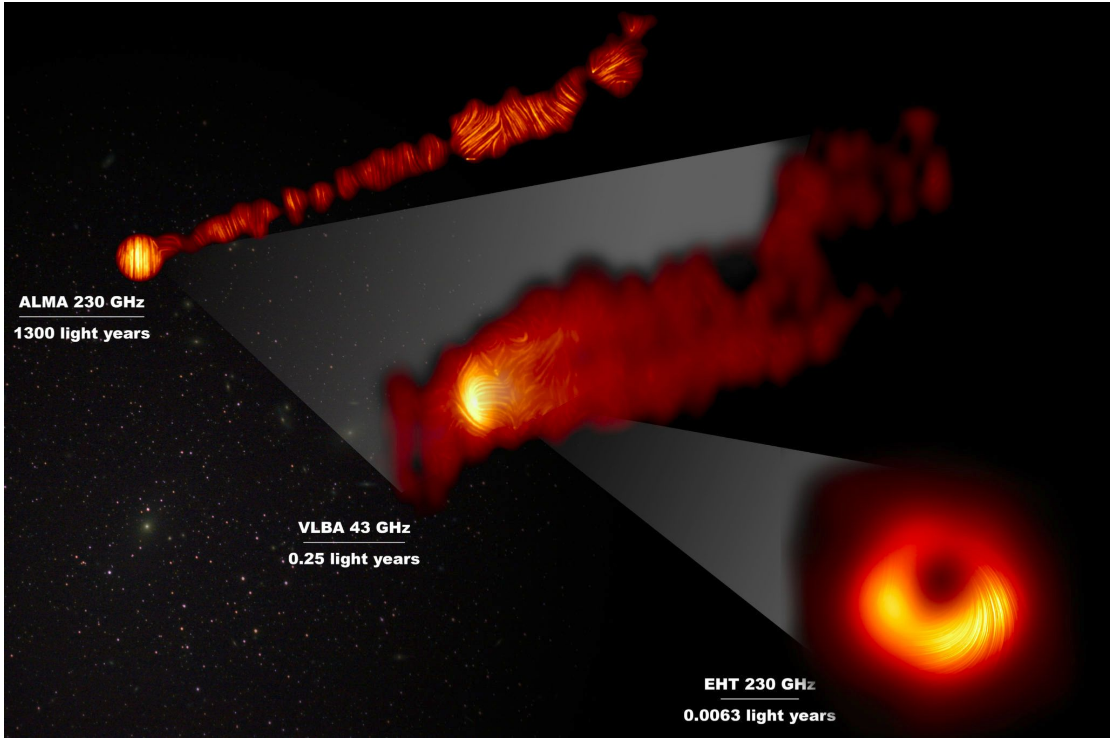


Nagai et al. 2016



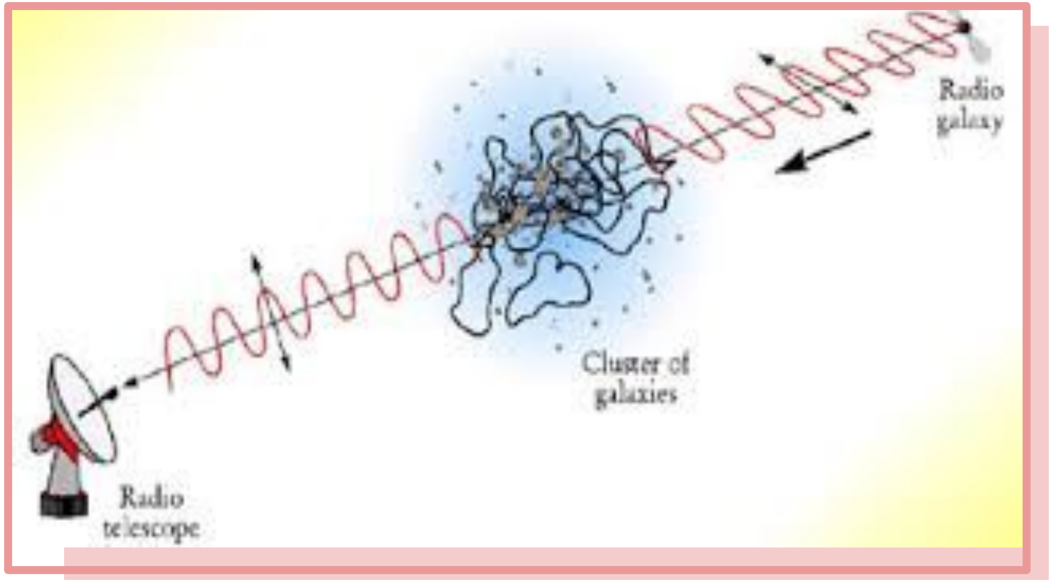
Galluzzi et al. 2019

Synchrotron emission - continuum



EHT collaboration. 2021

Faraday rotation - continuum



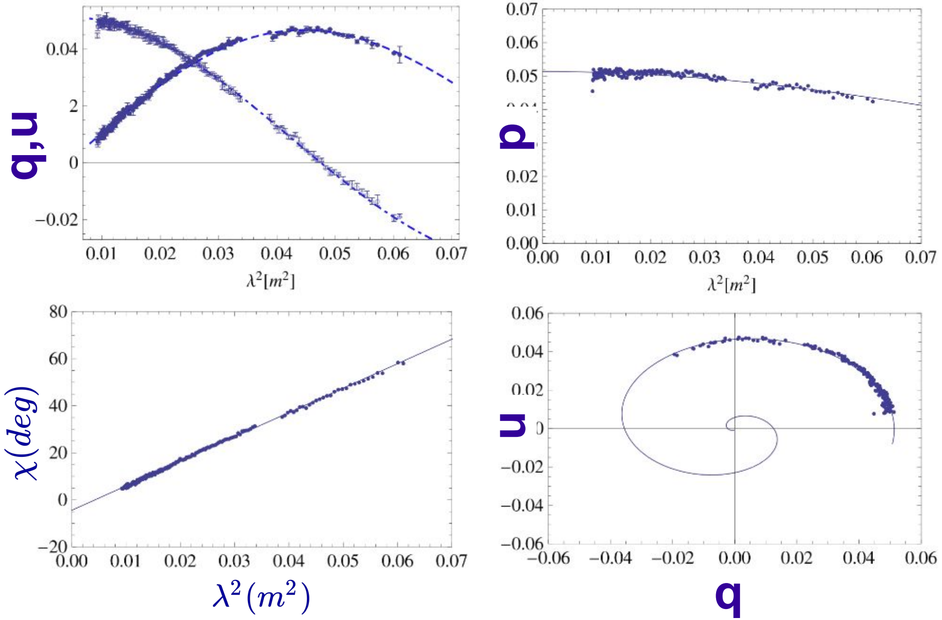
- Linearly polarized EM waves through magnetized plasma change the EVPA

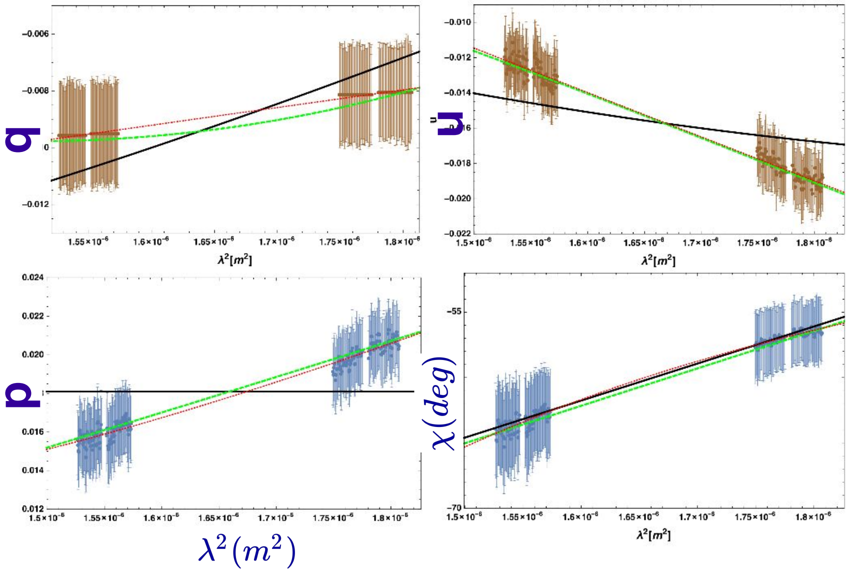
$$\chi_{obs} = \chi_0 + RM\lambda^2$$

$$RM \propto \int n_e \vec{B} dl$$

- **magnetic field along the line of sight**

Faraday rotation - continuum

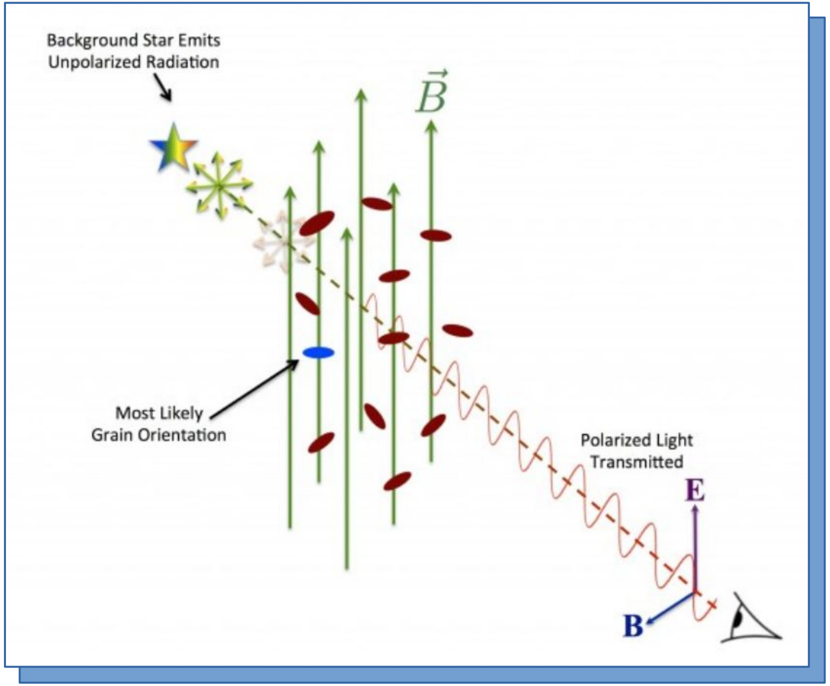




Hovatta et al. 2019

ATCA data
O'Sullivan et al. 2012

Dust polarization - continuum



- Dust grains align minor axis with the magnetic field

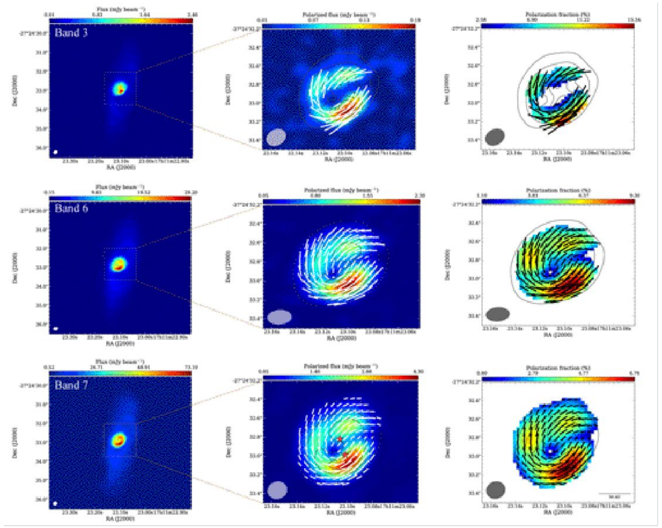
- Different λ sample different grain size

- Polarization determines the **orientation of the field in the sky plane**

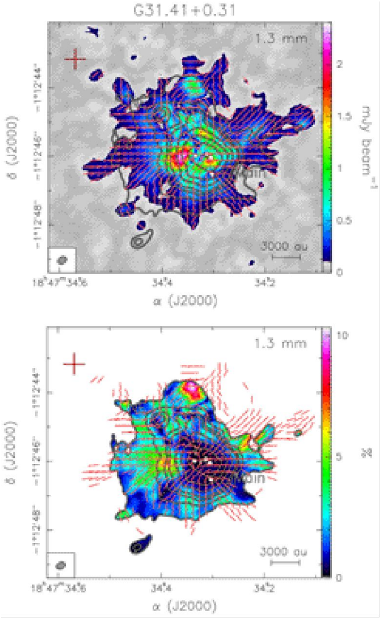
- Davis, 1951, Chandrasekar - Fermi 1953
  A statistical method
  B strenght

$$B \propto \sqrt{4\pi\rho}\,\frac{\delta V_{los}}{\delta\theta}$$

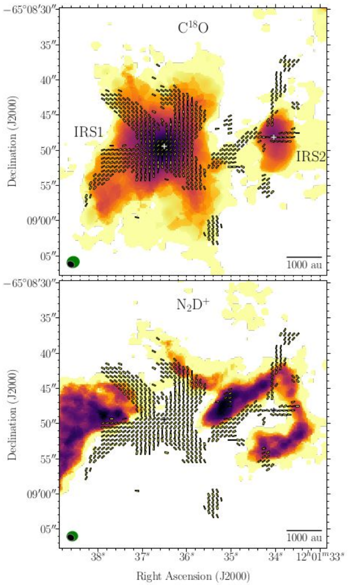
Dust polarization - continuum



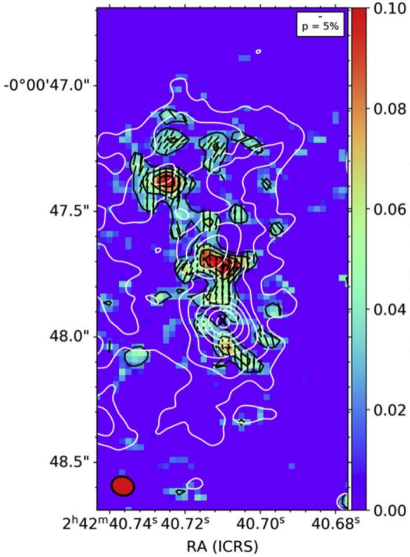
Alves et al. 2018



Beltran et al. 2019

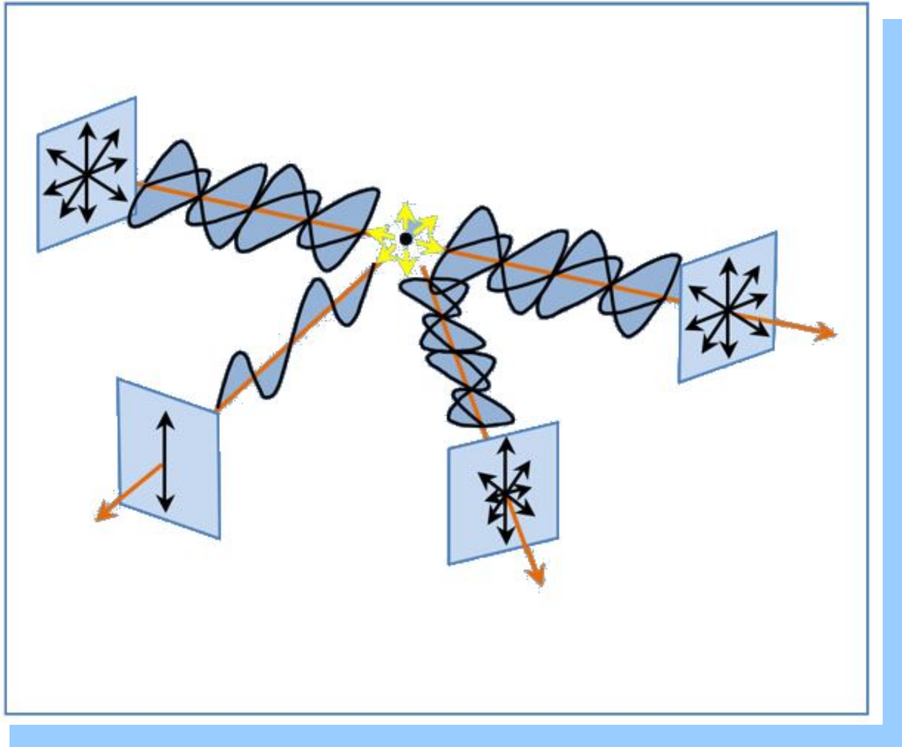


Hull et al. 2019



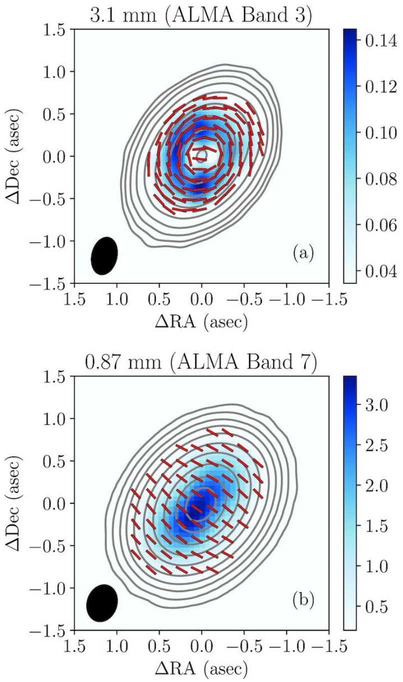
Lopez-Rodriguez et al. 2020

Scattering - continuum

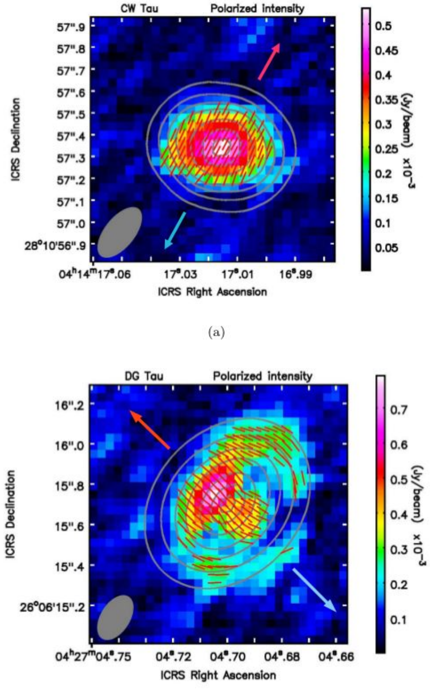


- Polarized (sub) mm wave emission can be produced partially or completely by the **self-scattering** of dust emission from (sub) mm-sized grains

Scattering - continuum



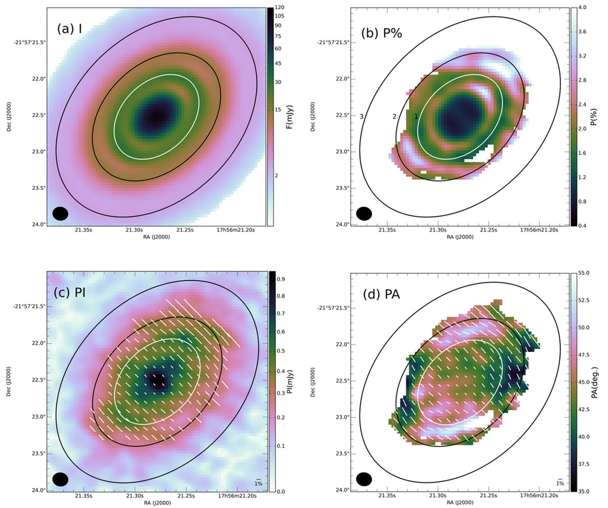
Kataoka et al. 2017
Stephens et al. 2017



(a)

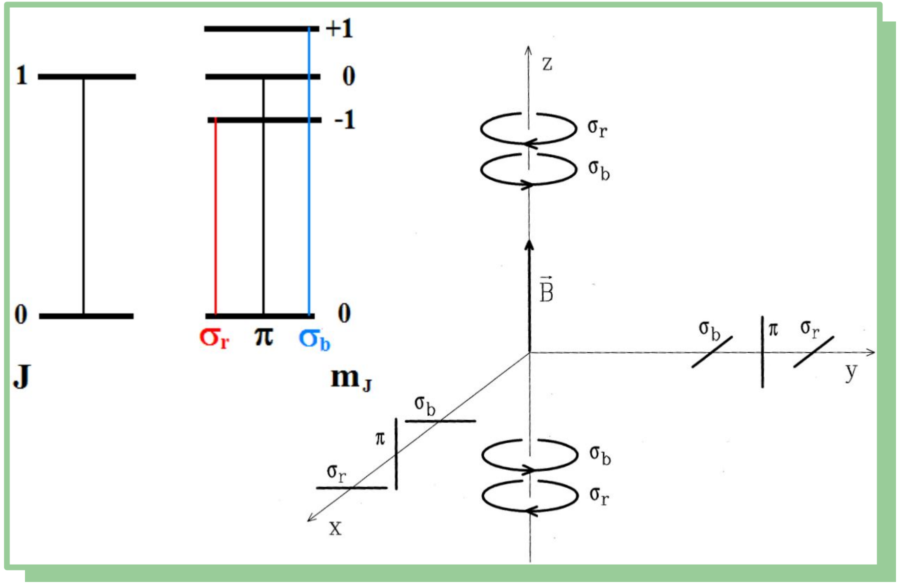
(c)

Bacciotti et al. 2018



Dent et al. 2018

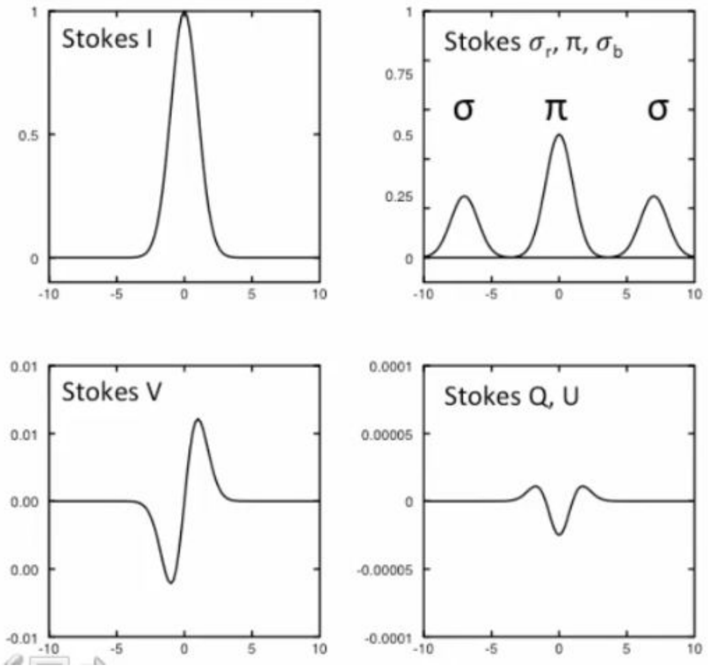
Zeeman effect – spectral lines



- Magnetic fields split the levels of a molecular line, and the distance between sublevels:

$$\delta\nu_z \propto ZB$$

Zeeman effect – spectral lines

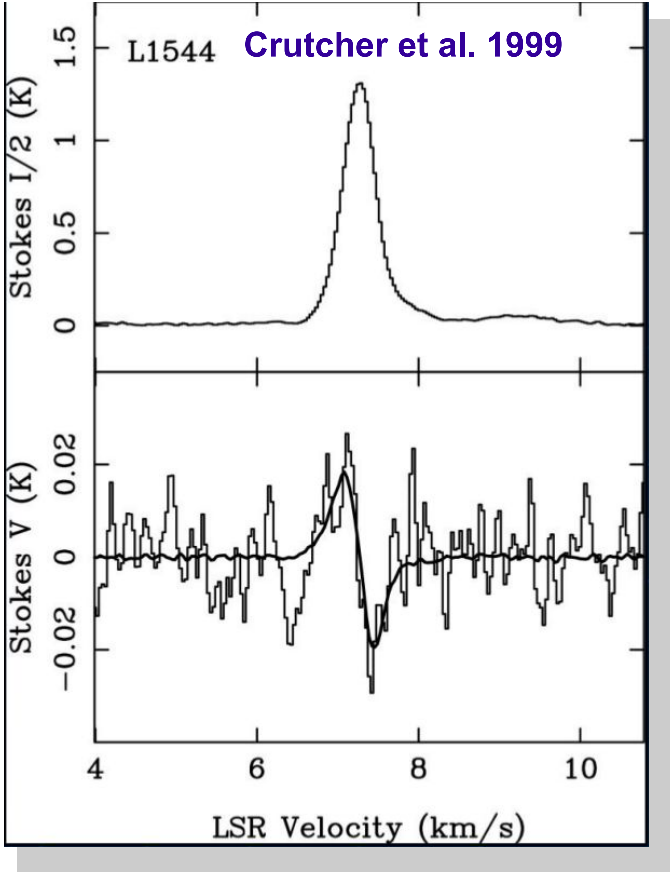


- Magnetic fields split the levels of a molecular line, and the distance between sublevels:

$$\delta\nu_z \propto ZB$$

- **Parallel to the field --->**
  only 2 σ components circularly polarized
  Perpendicular to B --->
  3 components linearly polarized

Zeeman effect – spectral lines



Typically only circular polarization is visible:
due to the blending of the three components the linear polarization is very faint.

CN Zeeman effect in a molecular cloud

Zeeman effect – spectral lines

Possible Zeeman lines

Species	Frequency GHz	ALMA Band
CN	113.5 226.3	3 6
CCH	87.4	3
SO	99.3 138.2 159.0 220.0 236.5	3 4 4 6 6

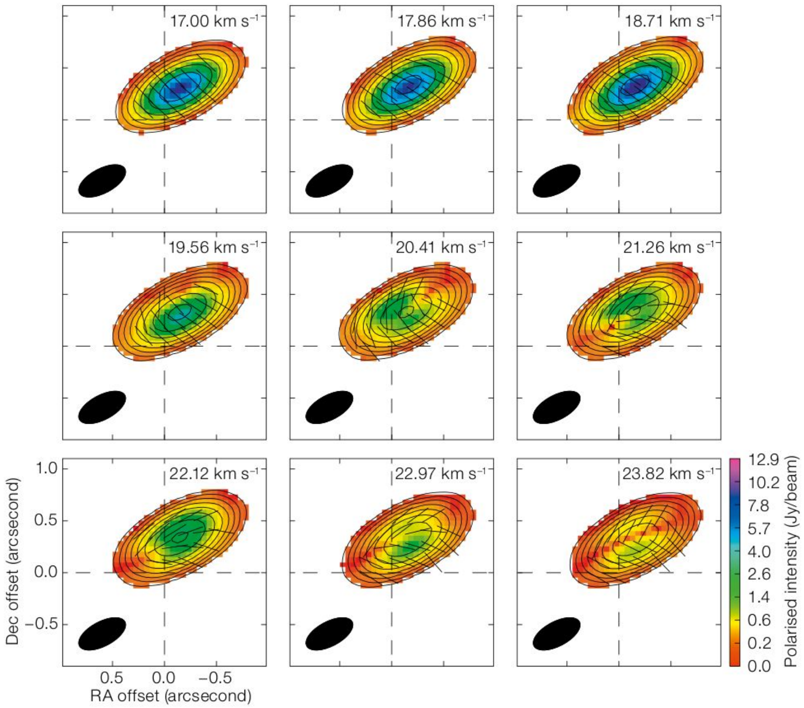
Perez-Sanchez & Vlemmings 2013

and Maser lines

Species	Frequency GHz	ALMA band
SiO	86.24 129.363 172.481 215.596 258.707	3 4 5 6 6
H2O	83.310 325.153 439.151	3 7 8
HCN	89.0877 177.238 267.199 354.461	3 4 6 7

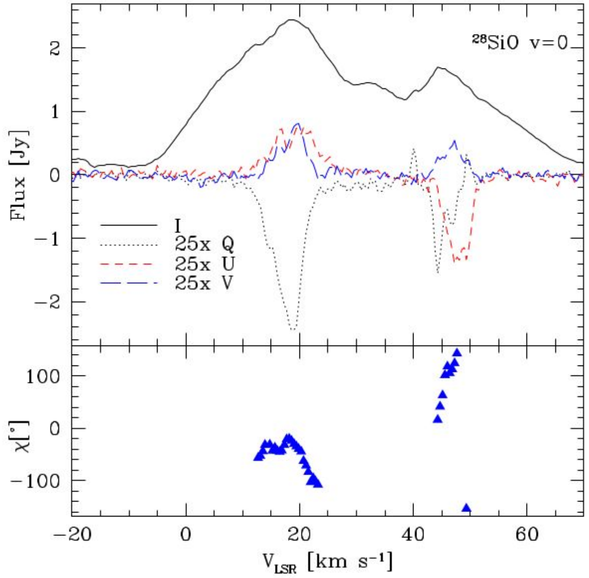
require strong Z

Zeeman effect – spectral lines

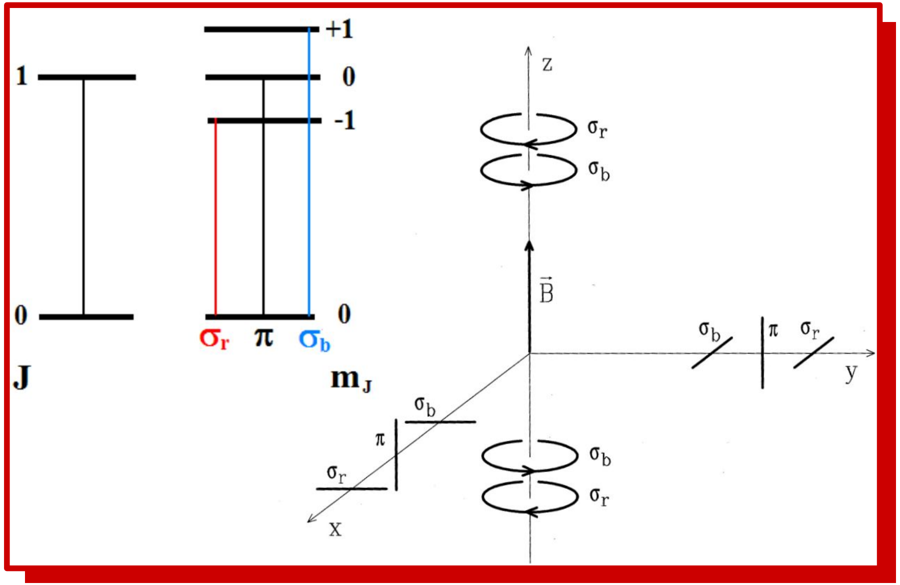


Vlemmings et al. 2017

SiO maser polarization



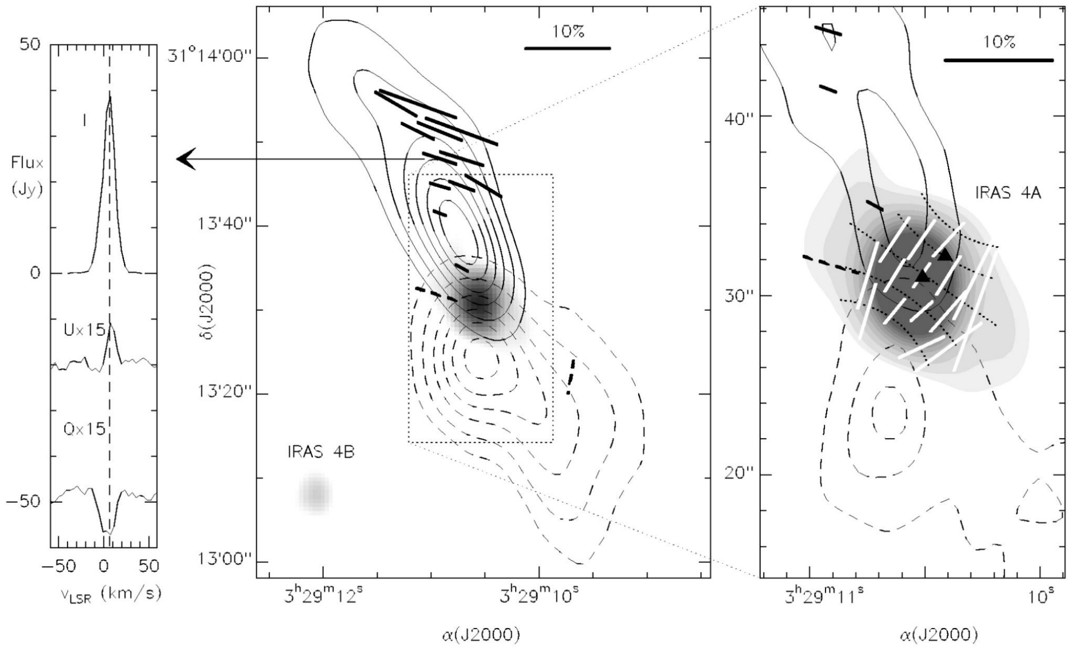
Goldreich-Kylafis (G-K) effect – spectral lines



- Local anisotropy in line optical depths or in radiation fields
- Population imbalance of the **π** and **σ** transitions
- **Linear polarization of spectral lines, parallel or orthogonal to magnetic fields**
- **Direction of B in the plane of the sky**

Goldreich-Kylafis (G-K) effect – spectral lines

CO line linear polarization on NGC1333



Girart et al., 1999

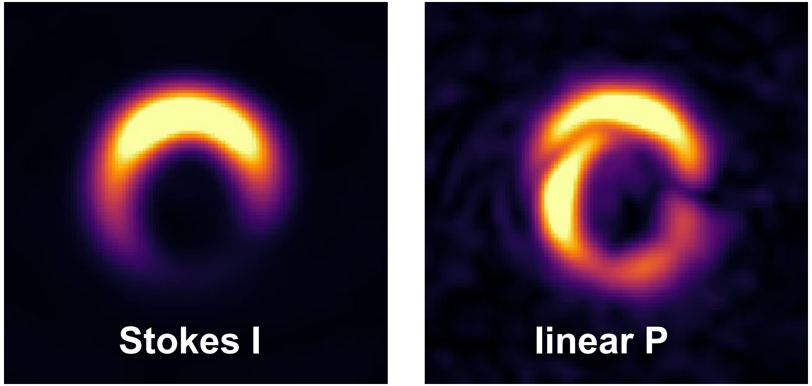
Archival dataset for the hands-on

Stephens et al. 2020

https://ui.adsabs.harvard.edu/link_gateway/2020ApJ...901...71S/doi:10.3847/1538-4357/abaef7

- ALMA Band 6 observations of two protoplanetary disks
- both continuum and spectral lines (CO(2-1), $^{13}CO(2-1)$, $C^{18}O(2-1)$)
- full polarization

HD 142527



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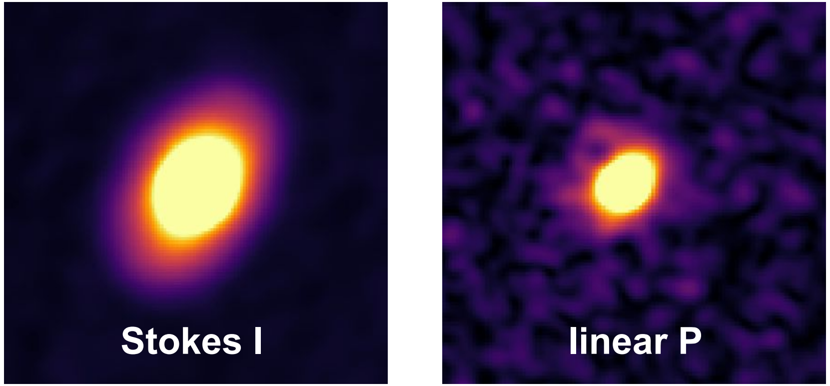
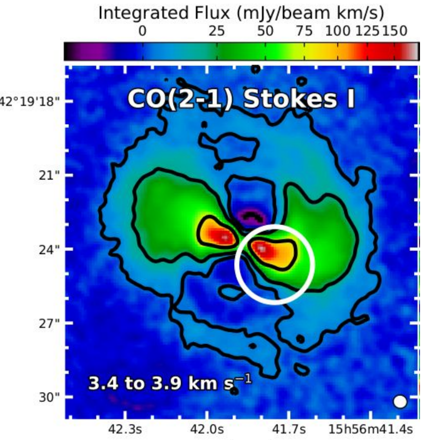


Continuum emission -- Origin still unclear: possibly dust scattering

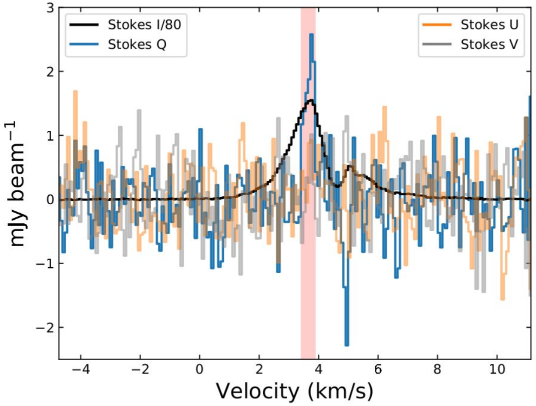
Stephens et al. 2020

https://ui.adsabs.harvard.edu/link_gateway/2020ApJ...901...71S/doi:10.3847/1538-4357/abaef7

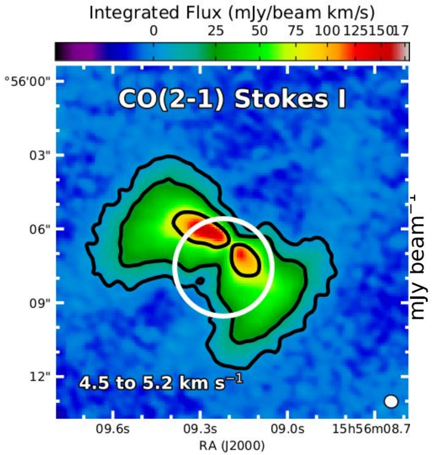
HD 142527



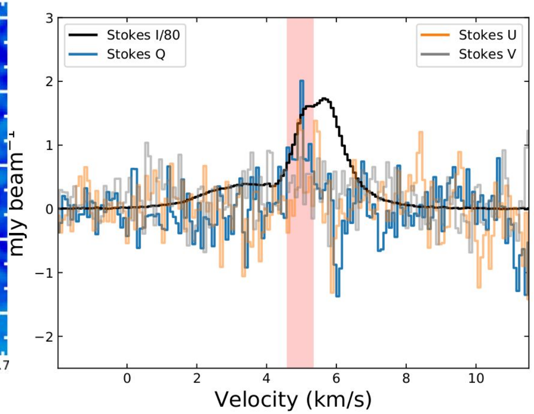
Stokes I/80



IM Lup



Stokes I/80

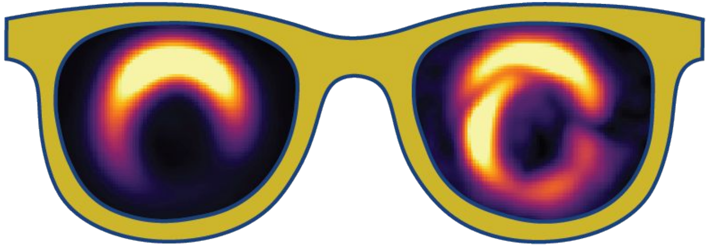


Line emission

- 13CO(2-1) and C18O(2-1) expected to be optimal to probe **G-K effect ---> NO detections**
- **CO(2-1) polarization marginal signal for Stokes Q** ---> peculiar result

Grazie

Enjoy exploring the archive



I-TRAIN #7 Polarization observations with ALMA
European ARC Network, June 24, 2021