Polarimetry Techniques in Radio Astronomy

A Gentle Introduction to Interferometric Polarimetry

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Black Hole Partnerships for International Research & Education – 2021

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Austin WN 2395 1:45 PM On Time 19
Baltimore US 085 12:20 PM On Time 11
Boise AS 2404 11:15 AM On Time 27
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Burbank WN 533 2:25 PM On Time 23
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Dallas/Ft. Worth AA 1184 12:55 PM On Time 9
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Y4 931 12:50 PM On Time 16
WN 2300 1:55 PM On Time 20
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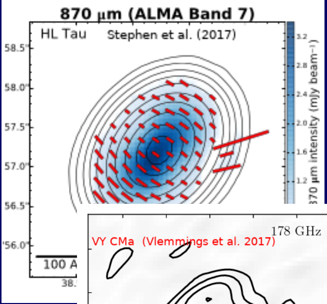
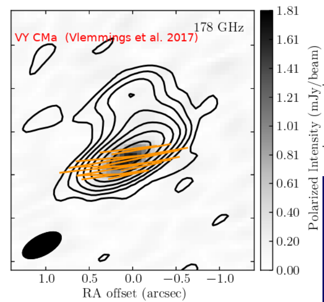
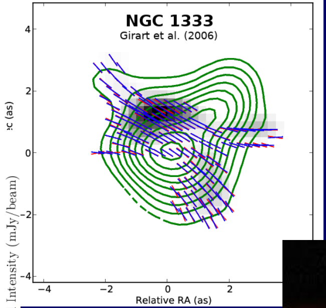
Polarized light carries a lot of information!







Polarized light in the Universe comes from very different scenarios.

There is a lot to discover!

Goals of this seminar

- Get familiar with the basics of polarimetry.
  - The different states of light polarization.
  - The Stokes parameters.
- Understand the processes that originate polarization in the Universe.
  - The role of magnetic fields.
  - From dust grains to AGN jets.
- Learn how polarization is measured in (Radio) Astronomy.
  - Polarization in Radio Astronomy.
  - Interferometers with coherent polarizers. The Measurement Equation.
  - The (very) basics of interferometric polarimetry calibration.

“Ordered” photons:

The polarization of light

Electromagnetic waves

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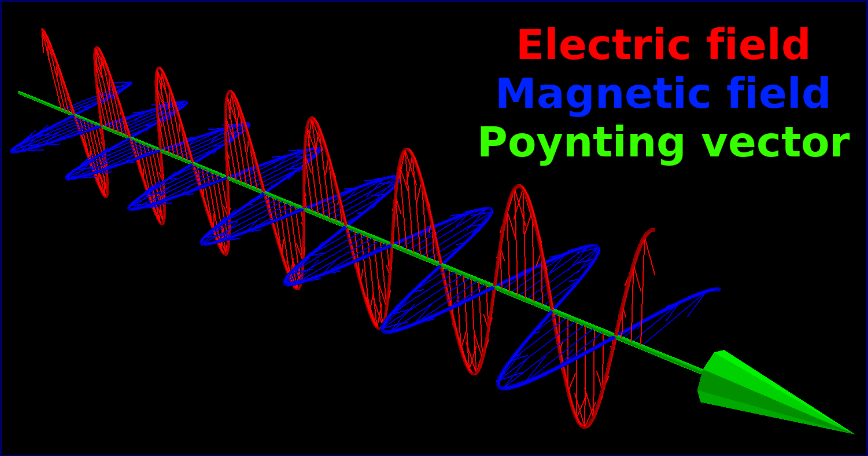


Unlike scalar waves, EM waves are characterized by wavelength, frequency and directionality of the oscillations (a.k.a., polarization).

Electromagnetic waves

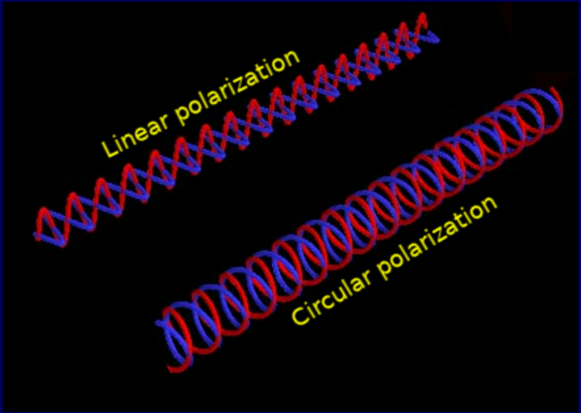
Ordinary light is made of photons with random $\vec{E}$ orientations (i.e, no *preferred* polarization).

Electromagnetic waves

But there are cases where propagation of light with certain $\vec{E}$ orientations may be favoured.

Polarization modes

- Linear polarization: $\vec{E}$ has a preferred direction of oscillation.
- Circular polarization: $\vec{E}$ rotates as the light ray propagates.



The Stokes parameters

- We need four quantities to fully describe the polarization state:
  - How much polarized vs. unpolarized light do we have?
  - How much circular polarization do we have? (and in which sense)
  - What is the strength and orientation (a.k.a. EVPA, χ) of the linear polarization?

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  - What is the strength and orientation (a.k.a. EVPA, χ) of the linear polarization?
- The Stokes parameters: I, Q, U, and V.
  - I: Total intensity (polarized and unpolarized).
  - Q and U: Strength and direction of the linear polarization.
  - V: Strength (and sense) of the circular polarization.

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But **beware**: The EVPA (χ) has the symmetry $\chi + \pi \rightarrow \chi$
(i.e., not the usual one, $\chi + 2\pi \rightarrow \chi$).

The Poincaré Sphere

A full rotation in azimuth corresponds to an EVPA change of 180°.

2χ is the azimuth angle;
2ϕ is the latitude:

$$\frac{Q}{I} = \cos(2\chi)\cos(2\phi)$$

$$\frac{U}{I} = \sin(2\chi)\cos(2\phi)$$

$$\frac{V}{I} = \sin(2\phi)$$

BEWARE in Astronomy!!:
Orientation convention for χ

The Poincaré Sphere

The latitude is related to the fractional circular polarization.

2χ is the azimuth angle;
2ϕ is the latitude:

$$\frac{Q}{I} = \cos(2\chi)\cos(2\phi)$$

$$\frac{U}{I} = \sin(2\chi)\cos(2\phi)$$

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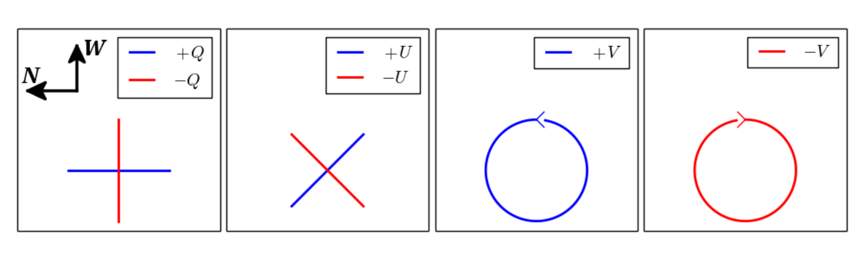
BEWARE in Astronomy!!:
Sign convention for V

The Stokes parameters

- The Stokes parameters: I, Q, U, and V (following IAU):



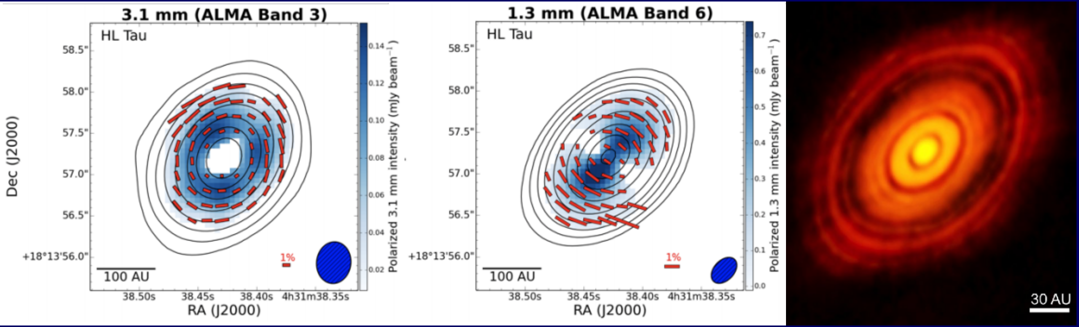
- Linear polarization: $P = \sqrt{Q^2 + U^2}$, $\quad \chi = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)$
- Unpolarized intensity: $I_u = \sqrt{I^2 - Q^2 - U^2 - V^2}$

Polarization in the Universe

Dust polarization

Elongated dust grains (with magnetic momenta) tend to align $\perp \vec{B}$. Depending on λ (i.e., absorption or emission), the final polarization relates to $\vec{B}$

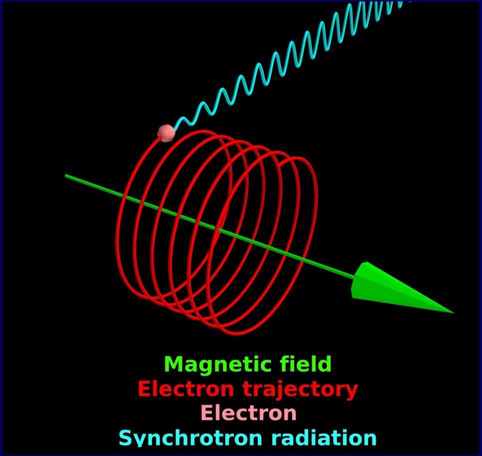
Example: dust in a proto-planetary disc.



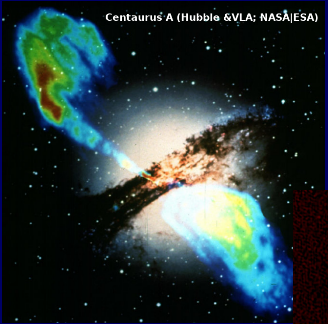
Magnetic fields and dust alignment in HL Tauri (e.g., Stephens et al. 2017)

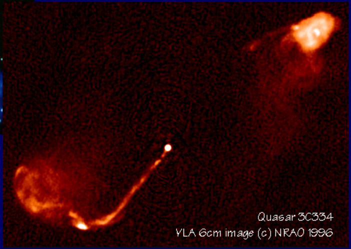
Non-thermal emission.

Synchrotron light originates from relativistic particles in presence of strong magnetic fields.
It is *intrinsically polarized* and $\perp \vec{B}$.



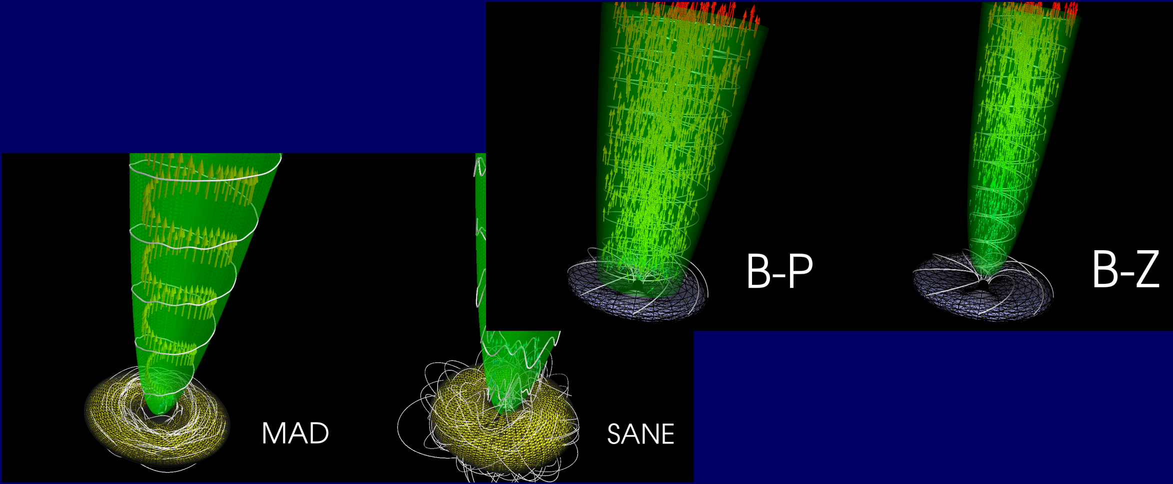
Jets in AGN: Escaping from the Jaws of the Beast





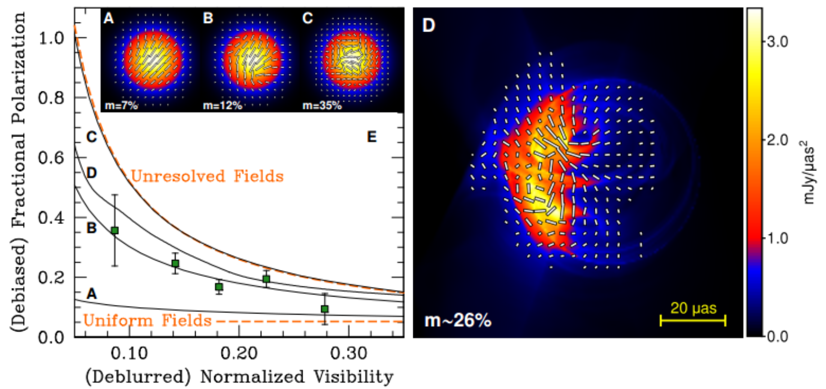
Relativistic plasma & strong $\vec{B}$ are present in AGN jets.

Relativistic jets. How do they form?



Different models with a critical role of $\vec{B}$. We need observations!

Example (event-horizon scales): SgrA*



$\vec{B}$ substructures in the accretion disc of Sgr A*; Johnson et al. *Science*, (2015)

Measuring Polarization

(in Radio Astronomy)

Light polarizers

Devices that filter light depending on its polarization

At radio wavelengths, a polarizer may be something as simple as a dipole.

Detecting source polarization

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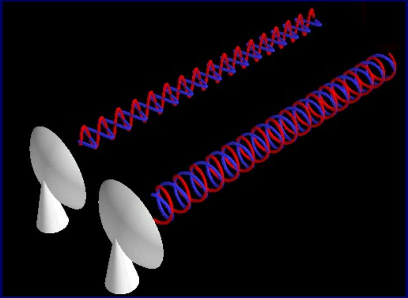
- The Stokes parameters describe the polarization state of light. But how do we measure them?

Detecting source polarization

- The Stokes parameters describe the polarization state of light. But how do we measure them?
- Polarizing receivers (polarizers). The signal is split coherently into two orthogonal polarization states.
  - Linear polarizers (horizontal / vertical linear polarization).
  - Circular polarizers (left / right circular polarization).



Linear polarizers

Decomposing linear pol. with linear polarizers (no phase offset)

Linear polarizers

Decomposing circular pol. (left) with linear polarizers (90° offset)

Linear polarizers

Decomposing circular pol. (right) with linear polarizers (270° offset)

Linear polarizers

Decomposing elliptical pol. (right) with linear polarizers (any phase offset)

Circular polarizers

Decomposing linear pol. with circular polarizers (phase offset gives EVPA)

Circular polarizers

Decomposing elliptical pol. with circular polarizers (R/L ampl. diff.)

Polarization and interferometry

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  - R^a, L^a, R^b, L^b

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  - R^a, L^a, R^b, L^b
- We compute all combinations of polarization cross-correlations (a.k.a. *visibilities*):
  - The so-called "parallel hands": $V_{RR}^{ab} =< R^a \times (R^b)^* >$ and $V_{LL}^{ab} =< L^a \times (L^b)^* >$.
  - The so-called "cross hands": $V_{RL}^{ab} =< R^a \times (L^b)^* >$ and $V_{LR}^{ab} =< L^a \times (R^b)^* >$

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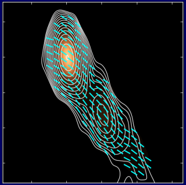
- These cross-correlations can be related to the Stokes parameters of the observed source.

The RIME (e.g., Smirnov 2011)



This is what we measure:

$R^a, \quad L^a, \quad R^b, \quad L^b$

This is what we want:

$\mathcal{I}(\alpha,\delta), \quad \mathcal{Q}(\alpha,\delta), \quad \mathcal{U}(\alpha,\delta), \quad \mathcal{V}(\alpha,\delta)$

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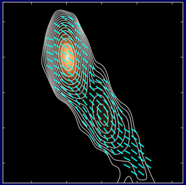

This is what we measure:

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Visibility Matrix:

$$V^{ab}_{\odot} = \begin{bmatrix} V^{ab}_{RR} & V^{ab}_{RL} \\ V^{ab}_{LR} & V^{ab}_{LL} \end{bmatrix}$$

This is what we want:

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Brightness Matrix:

$$B_{\odot} = \begin{bmatrix} \mathcal{I}+\mathcal{V} & \mathcal{Q}+j\mathcal{U} \\ \mathcal{Q}-j\mathcal{U} & \mathcal{I}-\mathcal{V} \end{bmatrix}$$

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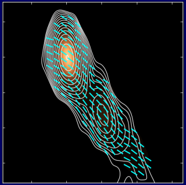

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Radio Interferometer Measurement Equation (VLBI case):

$$\int_{\Omega} B_{\odot}(\vec{\Omega}) \exp\left[2\pi j \frac{\vec{B}\vec{\Omega}}{\lambda}\right] d\vec{\Omega} = {J_a}^{-1} V^{ab}_{\odot} ({J_b}^{H})^{-1}$$

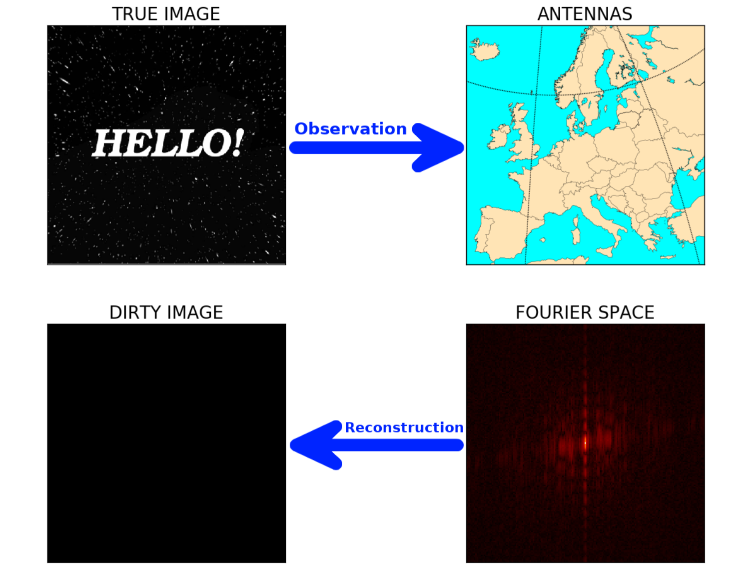
where J_a and J_b are *Calibration matrices.*

Calibration matrices. Examples

- Gain, $G = \begin{pmatrix} A_x(t)\, e^{j\phi_x(t)} & 0 \\ 0 & A_y(t)\, e^{j\phi_y(t)} \end{pmatrix}$
- Delay, $K = \begin{pmatrix} e^{j\tau_x(\nu-\nu_0)} & 0 \\ 0 & e^{j\tau_y(\nu-\nu_0)} \end{pmatrix}$
- Bandpass, $B = \begin{pmatrix} A_x(\nu)\, e^{j\phi_x(\nu)} & 0 \\ 0 & A_y(\nu)\, e^{j\phi_y(\nu)} \end{pmatrix}$

The calibration matrices are multiplicative, e.g.: $J = G \times B \times K$, but care must be taken, since matrices generally do not commute.

VLBI in a nutshell (Stokes I)



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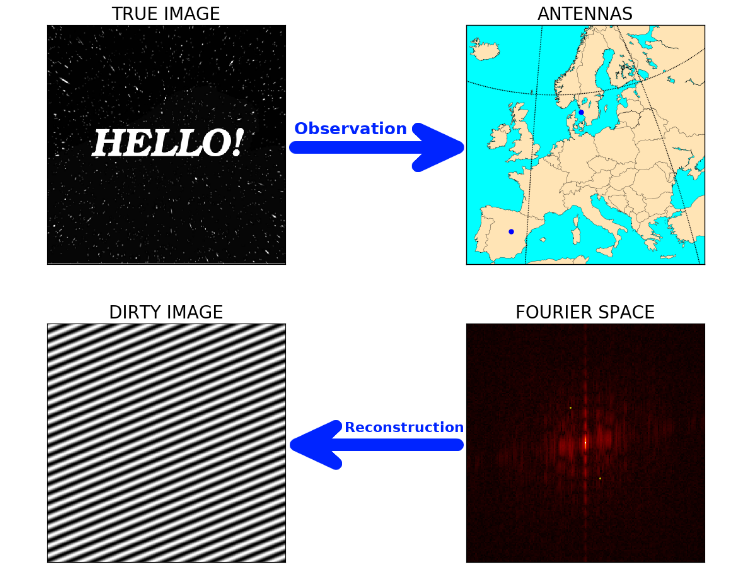

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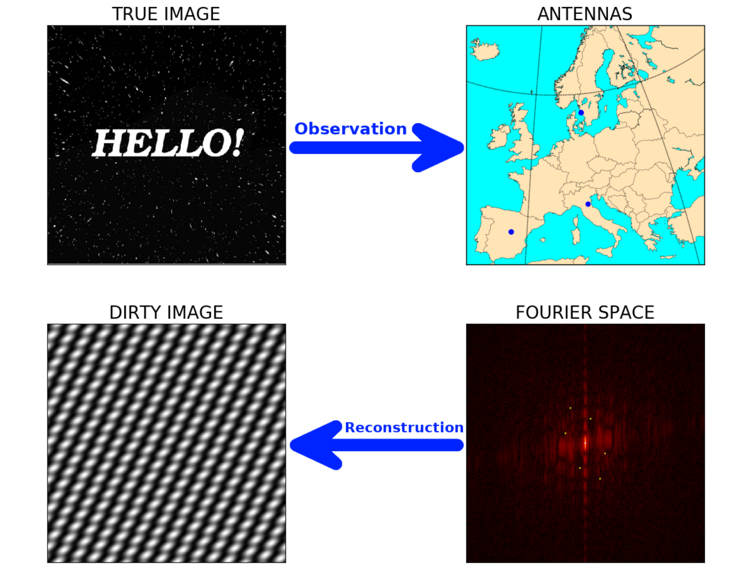

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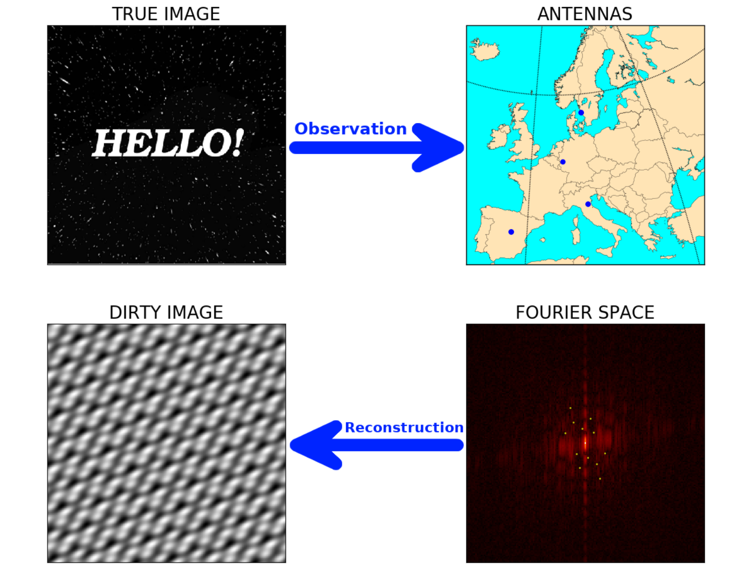

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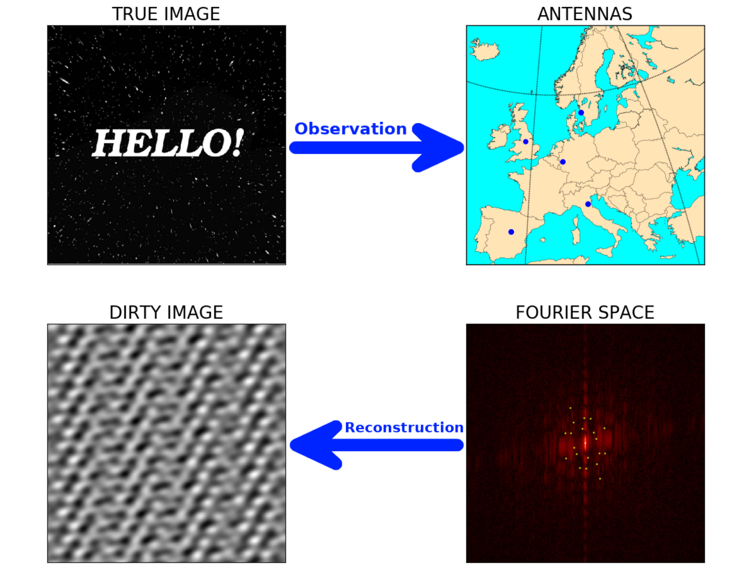

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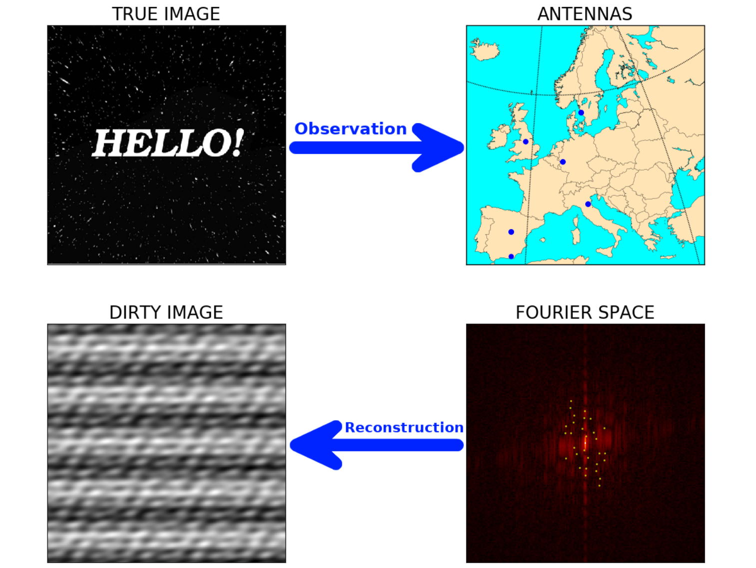

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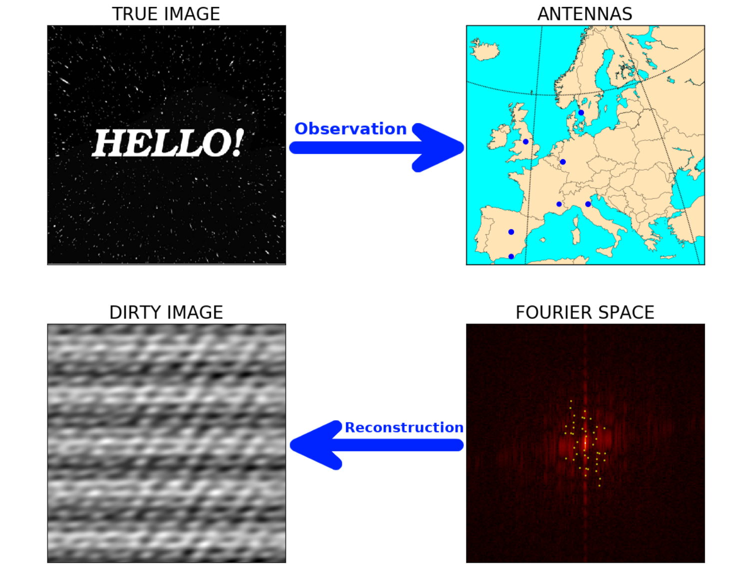

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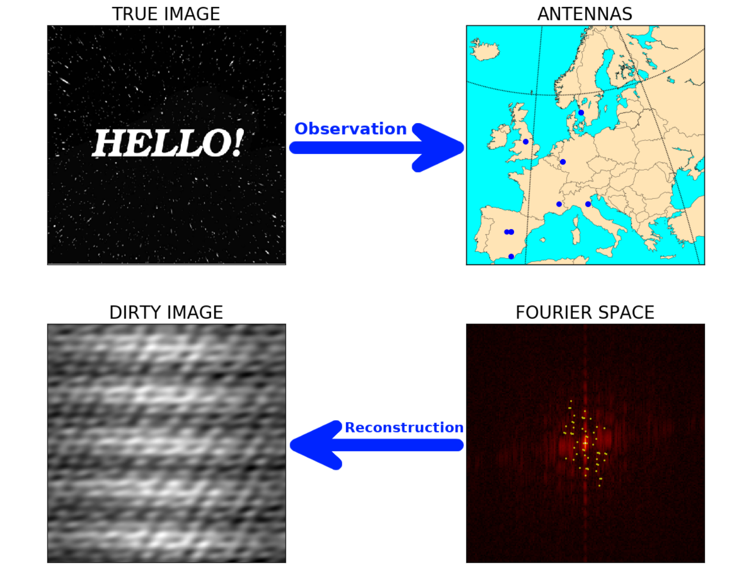

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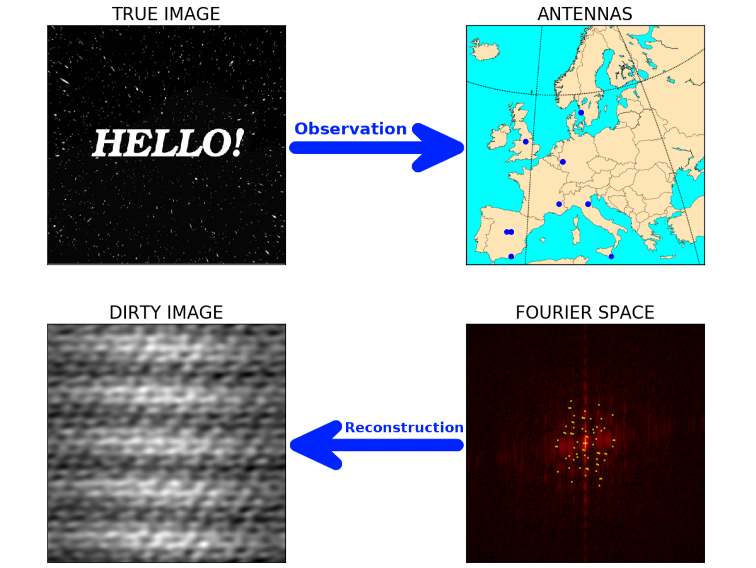

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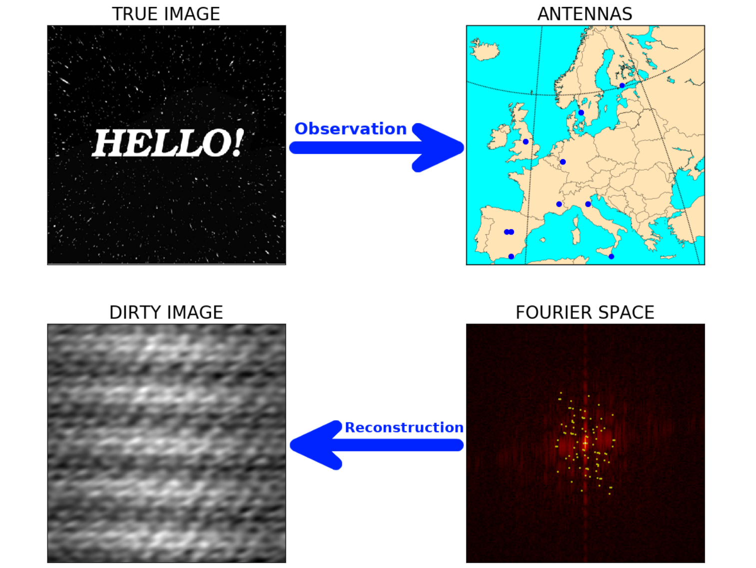

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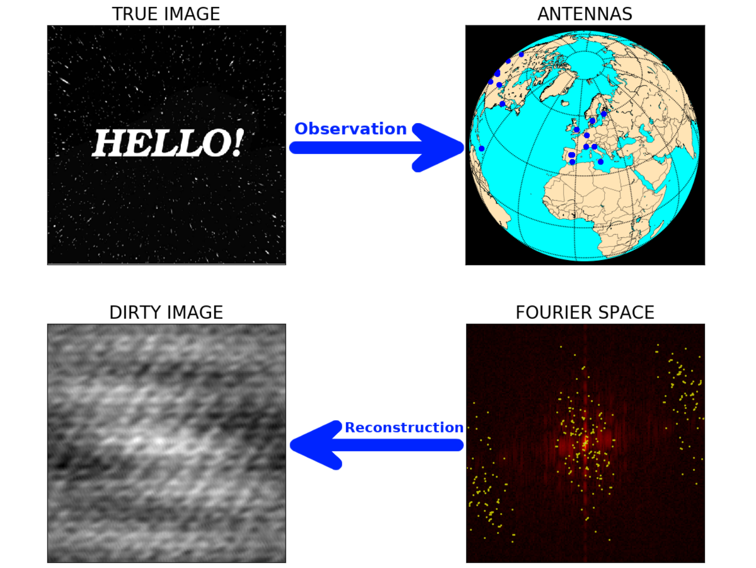

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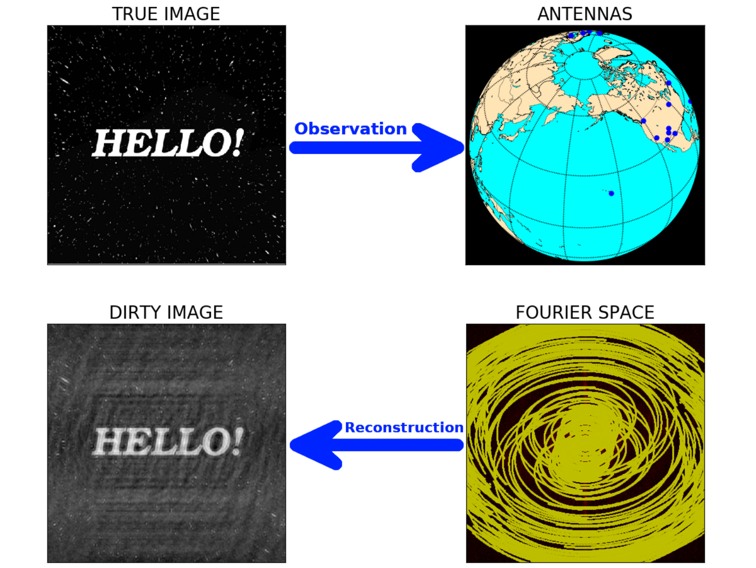

Polarization calibration in a nutshell

- The axes of the antenna mounts are "tied" to the Earth (green).
  So are their polarizers.
- The source orientation is tied to the sky (yellow).
- Since the signal in a polarizer depends on its orientation w.r.t. the source, the Earth rotation allows us to decouple instrumental effects from the source polarization.

Polarization calibration matrices

- Parallactic angle (orientation of the source w.r.t. the antenna). $P_{rl} = \begin{pmatrix} e^{j\phi} & 0 \\ 0 & e^{-j\phi} \end{pmatrix}$
- Polarization leakage (cross-talk between the orthogonal polarizers). $D_{xy} = \begin{pmatrix} 1 & D_R(\nu) \\ D_L(\nu) & 1 \end{pmatrix}$
- Cross-Delay/phase (difference in optical path between polarizers). $K_c = \begin{pmatrix} 1 & 0 \\ 0 & e^{j(\tau_c(\nu-\nu_0)+\phi_c)} \end{pmatrix}$
- Amplitude ratio (difference in gain between polarizers). $G_a = \begin{pmatrix} 1 & 0 \\ 0 & A_c \end{pmatrix}$

VLBI Polarimetry Software

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Nearly all the polarization calibrator sources have resolved structures in VLBI.
The problem of using spatially-resolved polarization calibrators is that we need to estimate the D and (complex) $B_{\odot}$ matrices at the same time.

- **Inverse Modelling.**
  - **LPCAL** (Leppänen et al. 1995). Pretty old, but well established and tested.
  - **GPCAL** (Park et al. 2020). Overcomes some LPCAL limitations.
  - **PolSolve** (Marti-Vidal et al. 2020). Overcomes some LPCAL limitations.
- **Forward Modelling.**
  - **EHTim** (A. Chael et al. 2018, 2020)
- **MCMC.**
  - **DMC** (D. Pesce 2020) and **THEMIS** (Broderick et al. 2020)

SUMMARY

- We have reviewed basic concepts of polarization.
  - Modes of polarization.
  - Stokes parameters.
- We have discussed about the origin of polarization in the Universe.
  - Absorption (and emission) of dust grains inmmersed in $\vec{B}$ fields.
  - Synchrotron emission.
- We have discussed about the different kinds of polarizers in radioastronomical receivers.
  - Linear polarizers (X-Y).
  - Circular polarizers (R-L).
- We have studied how to deal with polarization in interferometric observations.
  - The Measurement Equation.
  - The matrices for polarization calibration.
  - The (tricky) polarimetry calibration in VLBI.

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THANKS Please, give feedback! `http://bit.ly/Polarimetry-I`