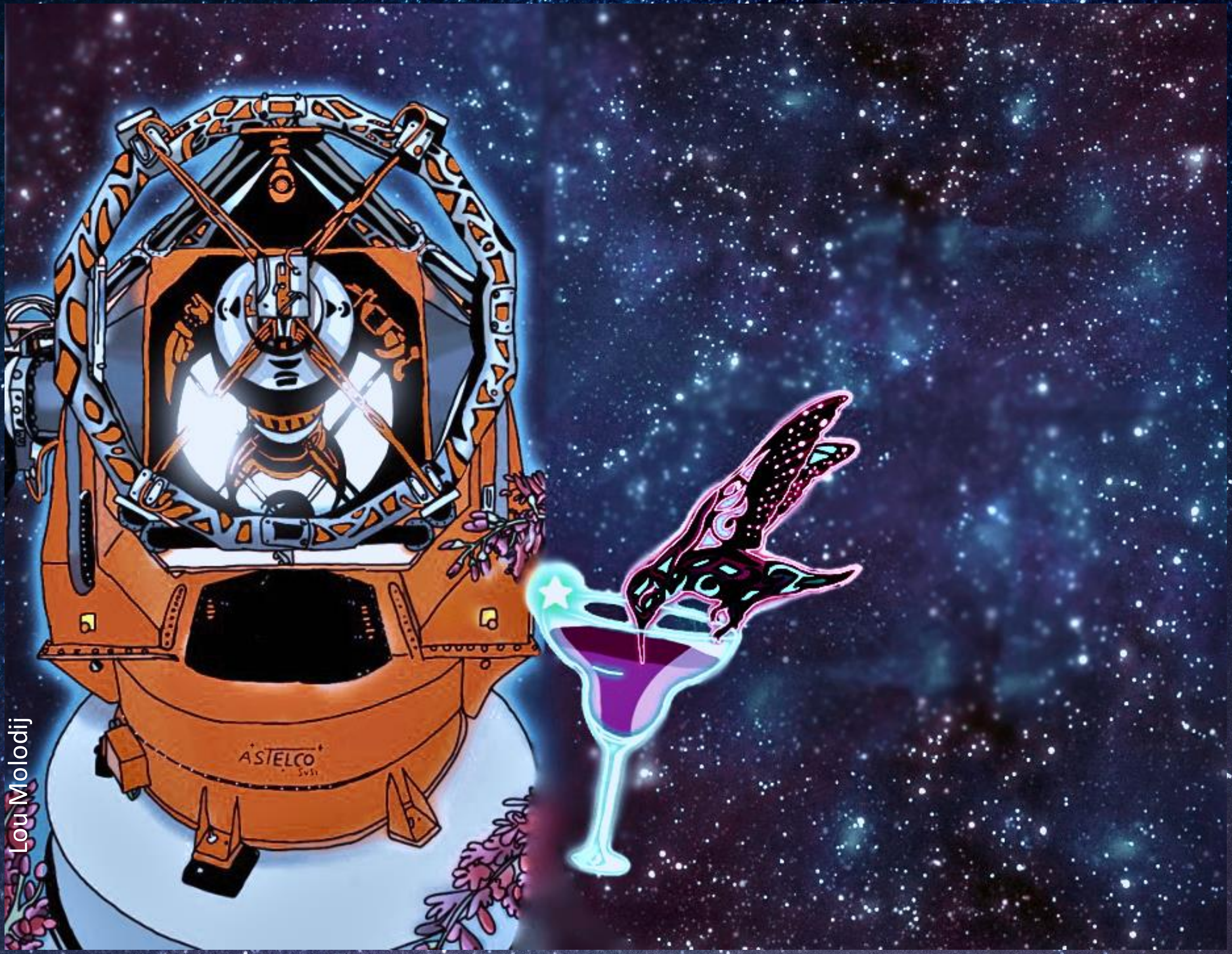
TEQUILA status

Noémie Globus & Alan Watson



What’s TEQUILA?

- **TEQUILA** (**T**ransient **E**vents **Q**, **U,** and **I**, **L**ight **A**nalyzer) is a polarimetric imager for the second Nasmyth focus of COLIBRÍ.

- **In March 2025, Alan and I proposed to replace the OGSE test camera with a polarization camera with a new technology**, a sensor developed by Sony which is mainly targeting the industrial equipment, Sony Polarsens™.

- This sensor capture the light polarization with a single acquisition over the entire image, pixel by pixel and can calculate **real-time information about the direction and degree of polarization.**

- **Goals**:
    - **Scientific:** to monitor in real time the optical linear (Q, U, I) polarization of bright, early GRB afterglows and other transients
    - **Technological:** to test for low-cost polarimetry solutions for astronomy. The system has no mechanisms or moving parts.

- **Funding:**

SIMONS FOUNDATION

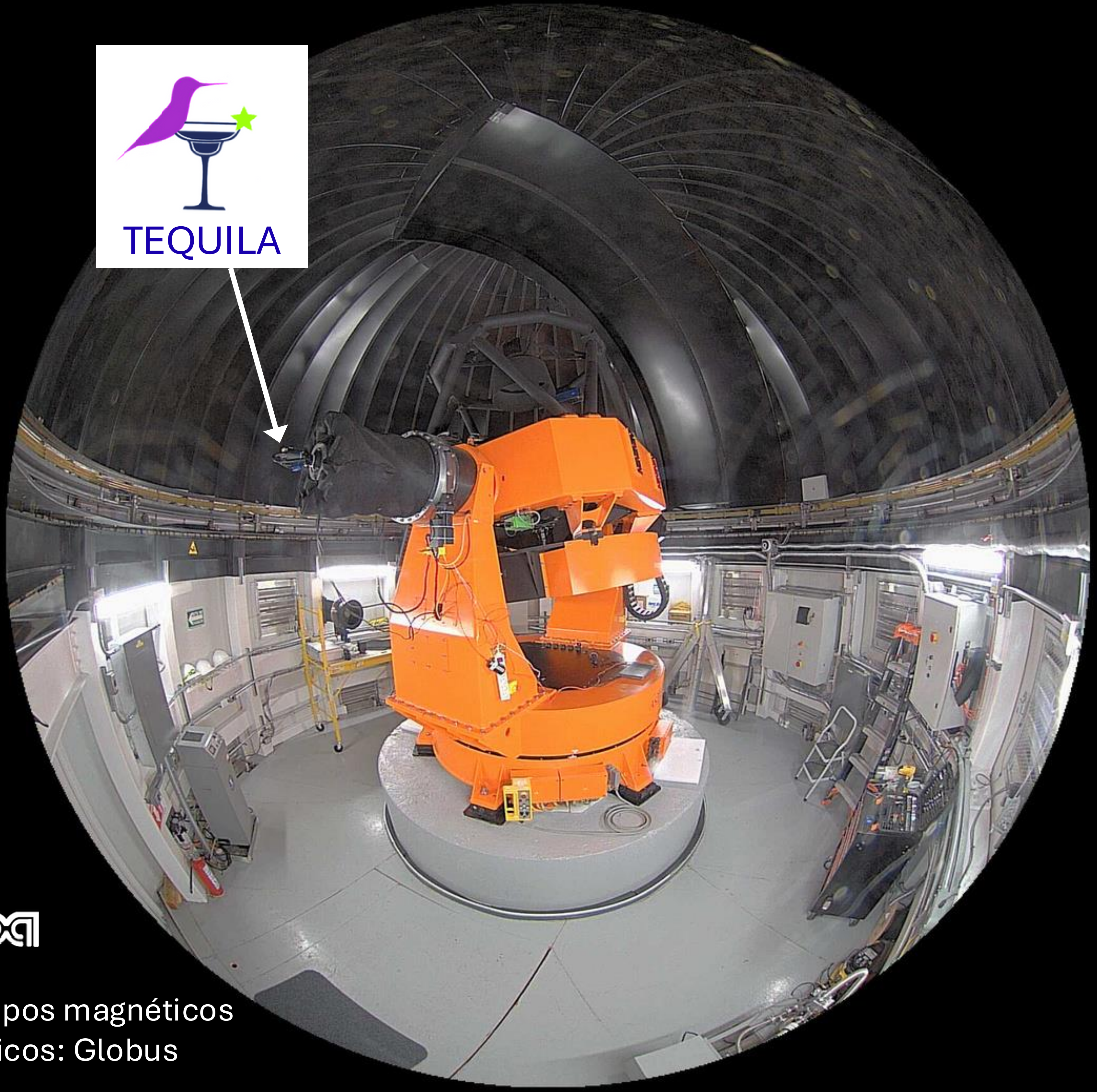
SCEECS grant: Globus (camera+)

Ciencia y Tecnología
Secretaría de Ciencia, Humanidades, Tecnología e Innovación

Grant: Lee (optics)

dgapa

PAPIIT Ver lo invisible: campos magnéticos en transitorios astrofísicos: Globus



Science

What creates polarized light?

For continuum radiation:

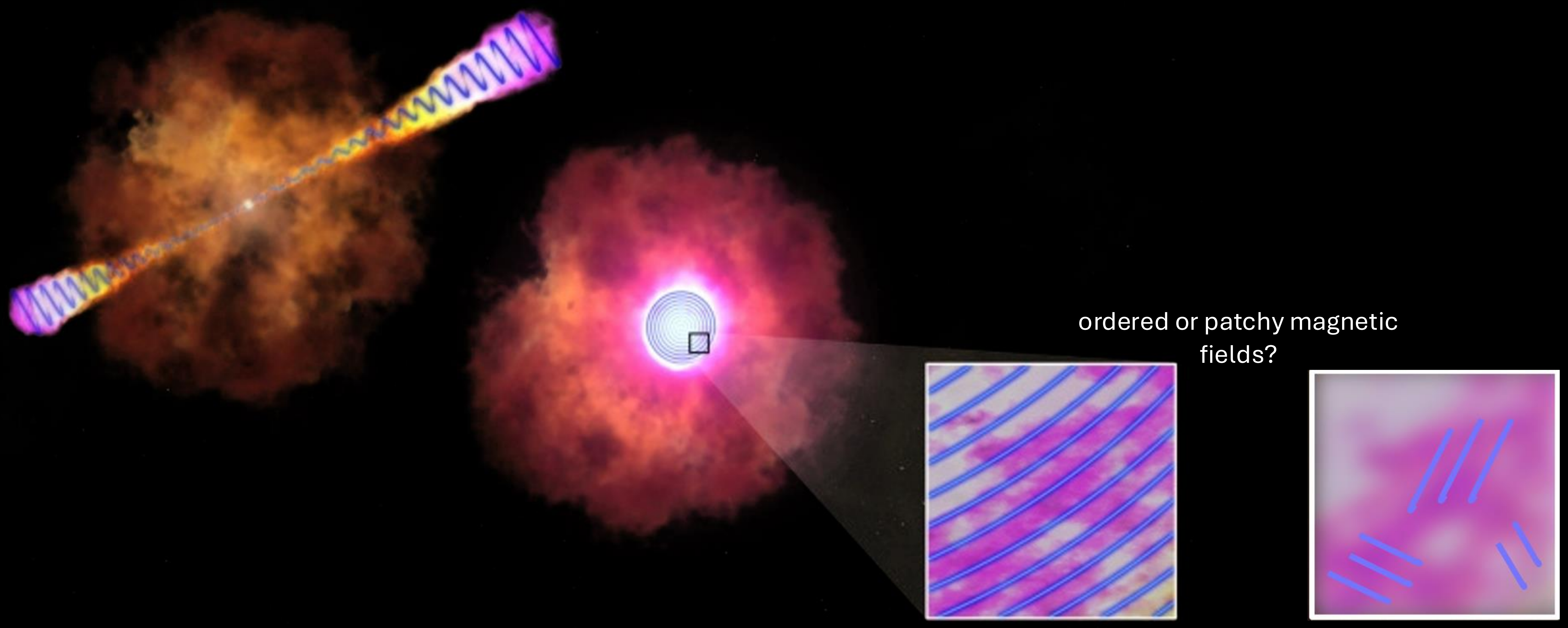
- Anisotropic scattering or reflection of continuum radiation. For instance Rayleigh scattering in the Earth's (or another planet's) atmosphere, Mie scattering by large particles, or Thomson scattering by free electrons.
- Differential absorption or scattering by magnetically aligned non-spherical dust grains (particularly in the infrared range).
- Synchrotron radiation from charged particles in a magnetic field exhibits continuum polarization. For synchrotron radiation in a well-aligned magnetic field, the polarization degree is expected to be ~69% at maximum (for electron distribution index p = 2).

For line radiation:

- Anisotropic scattering of line radiation (the emergent polarization depends largely on the quantum numbers of the transition).
- Zeeman effect. Magnetic field splits atomic energy levels into magnetic sublevels (changes allowed transitions). Line polarization may be modified by magneto-optical effects (i.e. birefringence of the medium due to the magnetic field; the Faraday effect and the Voigt effect).
- Electric fields can produce a similar line polarization (the Stark effect).
- Depolarization of line polarization due to scattering through the Hanle effect.

Polarization in Gamma-Ray Bursts

Polarization is one of the best direct diagnostics of magnetic-fields in relativisitc jets — knowing whether the field is ordered or tangled has big implications for the central engine models, particle acceleration models and can help breaking the degeneracy in jet structures models.



Credit: NASA's Goddard Space Flight Center/S. Wiessinger

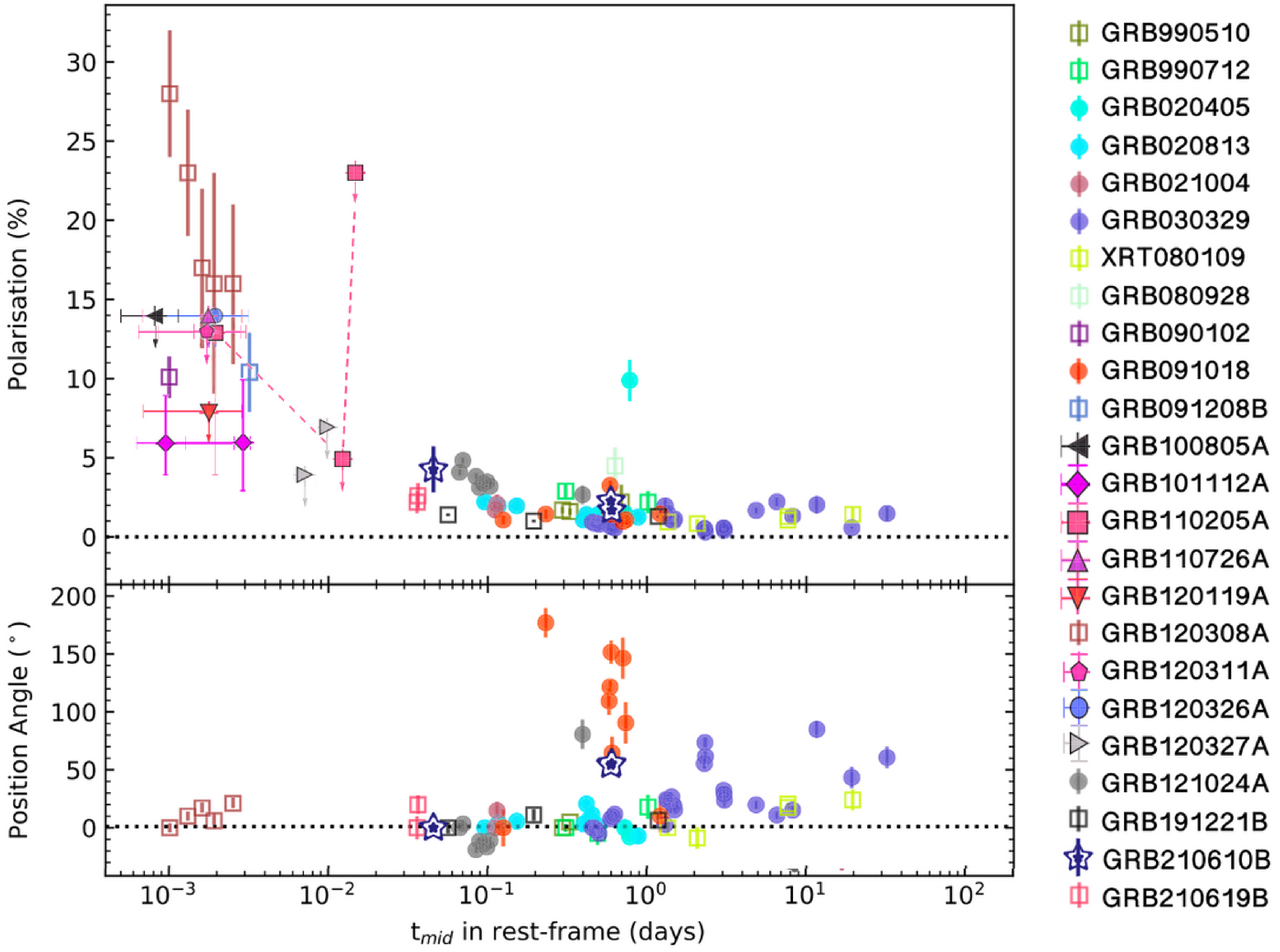
Optical Polarimetry is a Tracer of Jet Structure in Gamma-Ray Bursts

RS – central engine

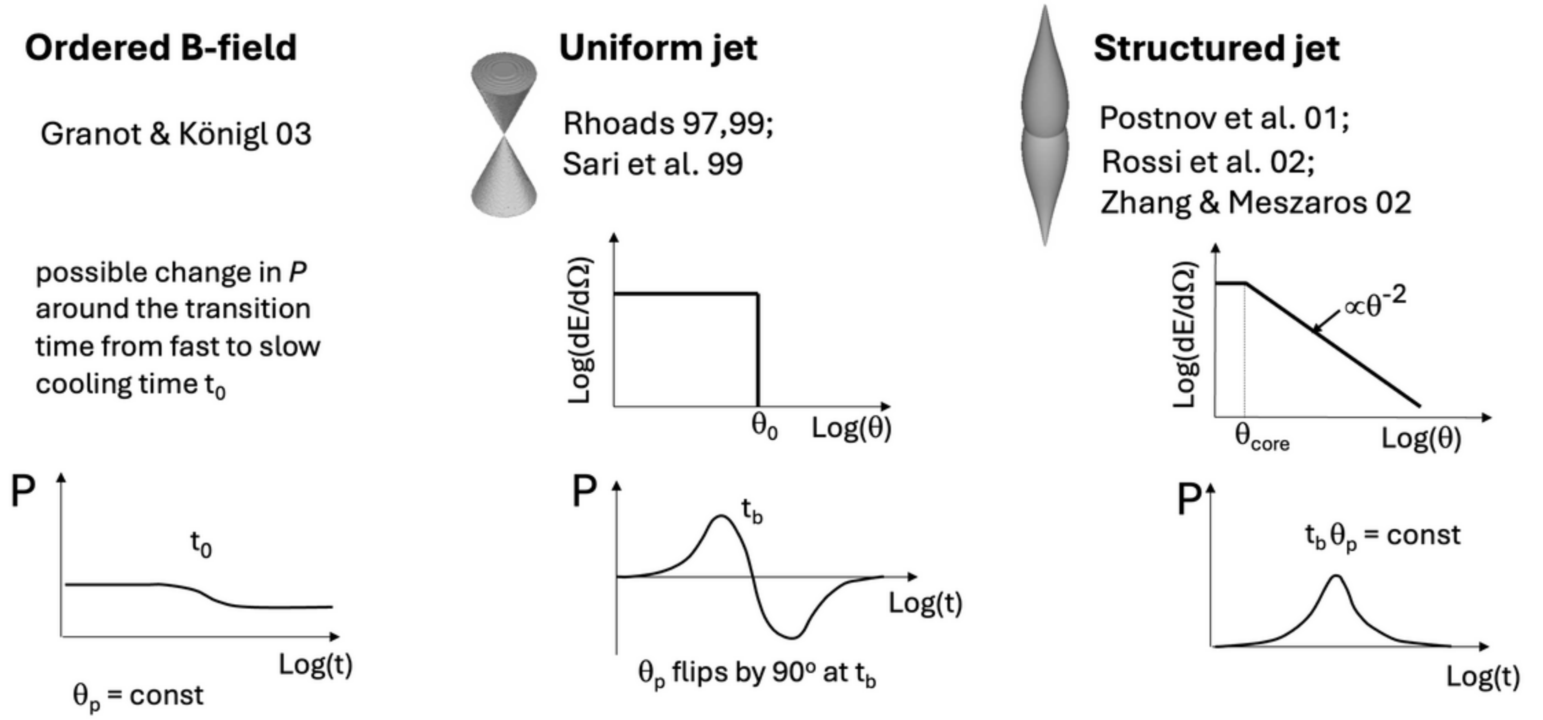
Reverse shock dominates optical emission at early times

FS -- jet structure

In most GRB AGs: Optical polarization degree is 5% or less at late times



Predictions of polarization for different jet structure



A 90 degree change in in the mean polarization angle is expected :

- Near a jet break in FS emission for a uniform top-hat like) jet
- At the RS-> FS transition (see e.g. Arimoto et al.+ Gill R. 2024)

cf. Asuka's talk

GRB Compilation figure adapted from:
Steele et al. (2017) and Agüí Fernández et al. (2024)

Slides retired because these are theoretical works in progress:

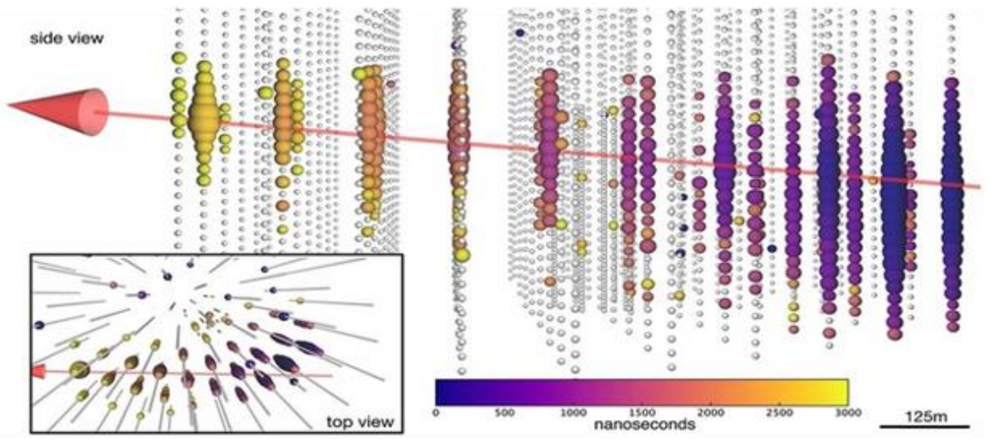
Optical Polarimetry is a Tracer of the GRB Central Engine

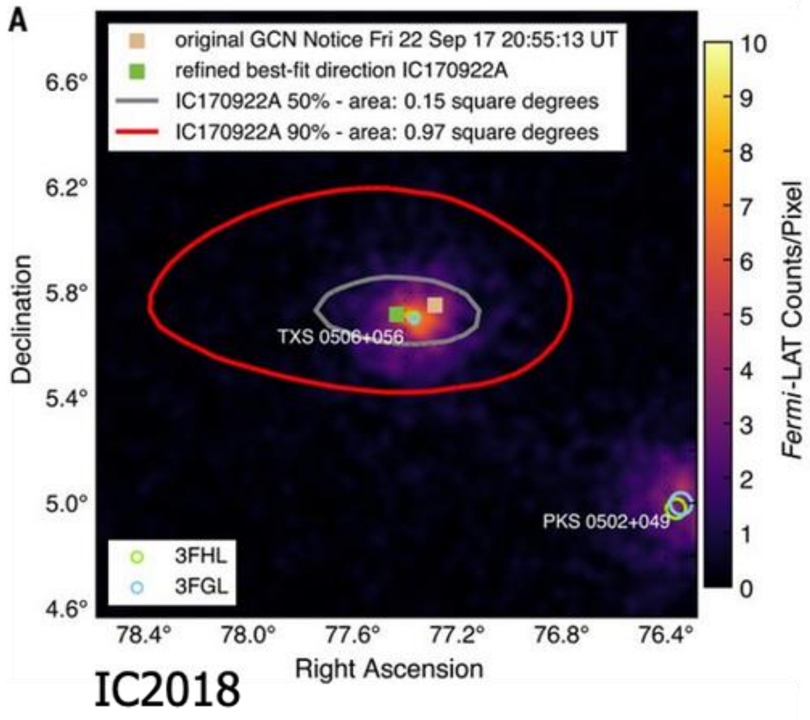
Optical Polarimetry is a Tracer of Microlensing in Gamma-Ray Bursts

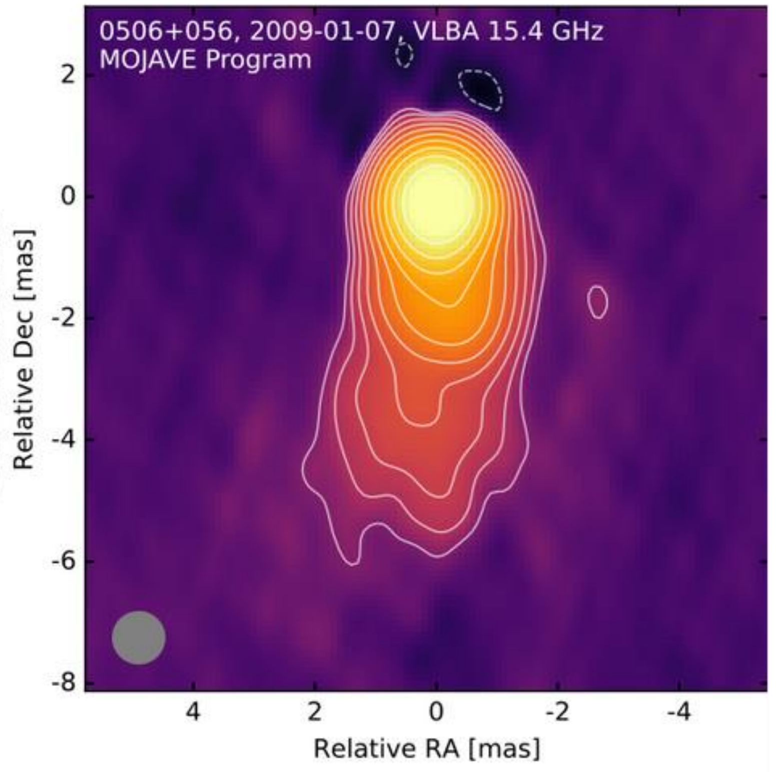
Optical Polarimetry is a Tracer of Magnetic Activity in Blazars

Neutrino-blazar association:

- The overall significance is still rather weak (2.64σ; post-trial)
- It is driven by two associations: TXS 0506+056 and J0211+1051
- Based on these results:
  - BLLs (especially IBLs) are favored over FSRQs
  - Peak of major flares are favored





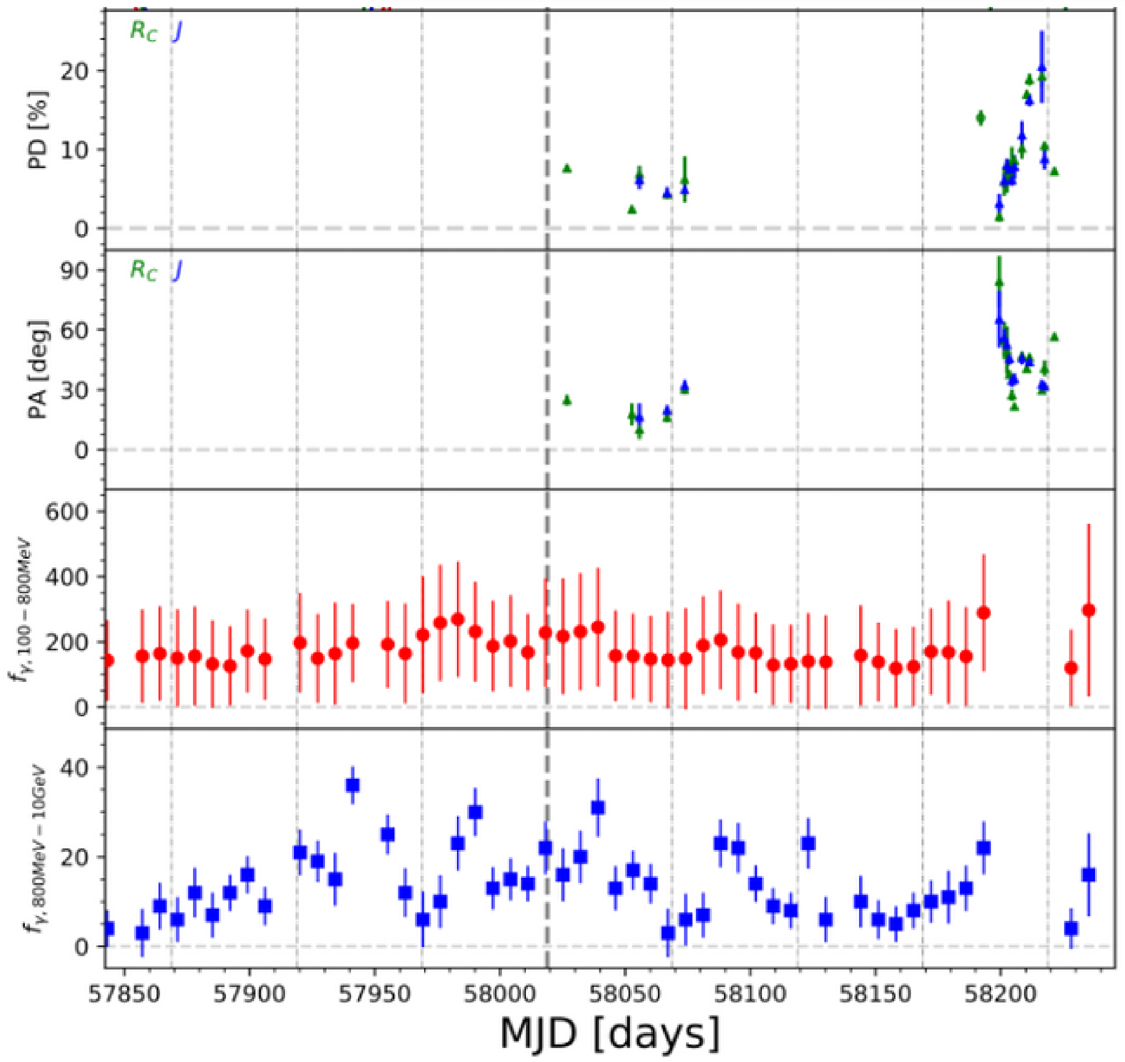


- Polarimetry can probe magnetic activity in blazar jets (see plot on the right for TXS 0506+056)

- If ~10 PeV protons acceleration and hence, ~1 PeV neutrino production, occurs during magnetically disturbed, high-energy states, then time-resolved polarimetry would be essential to identifying neutrino-emitting blazars (this would be detectable through changes in polarization angles and fractions)

- Acceleration sites:

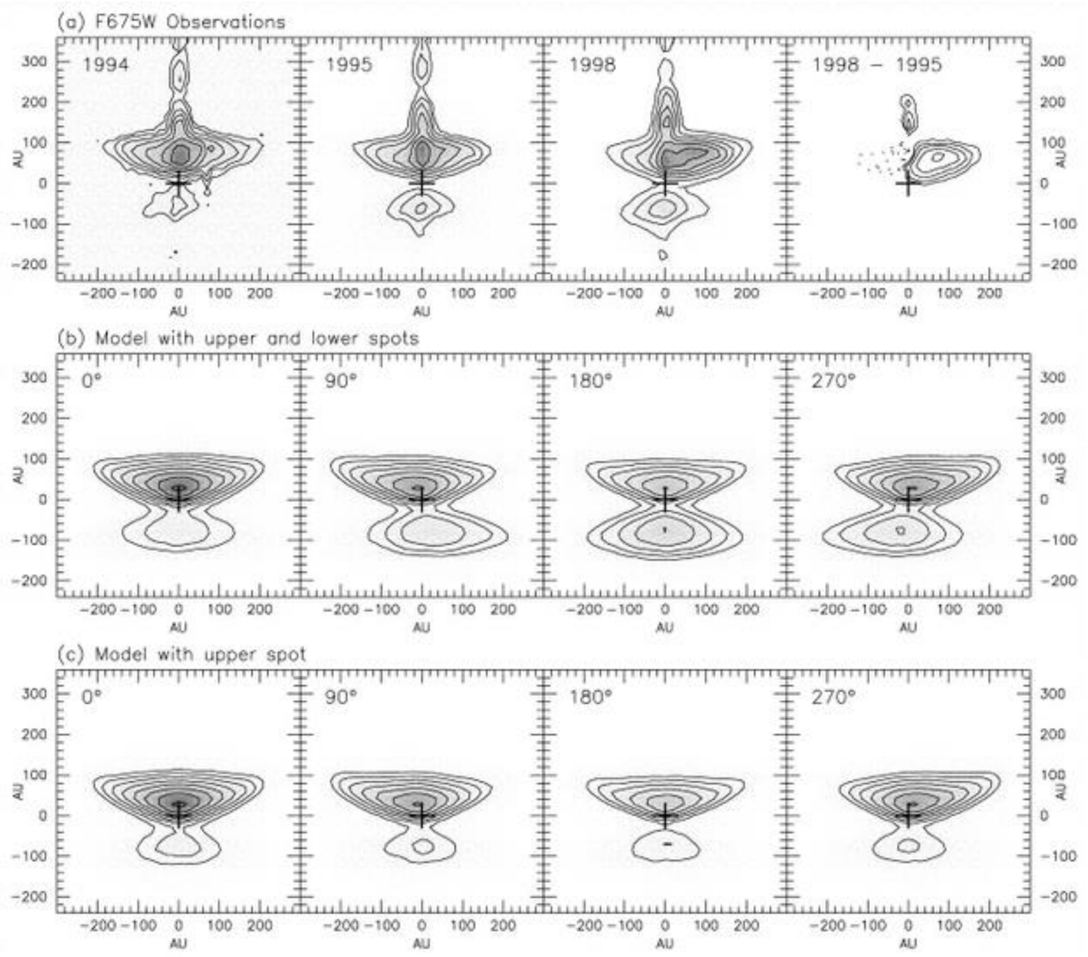
  - Not related to the beamed jet: corona, magnetic reconnection.
  - Related to beamed jet: shocks in jets (acceleration due to DSA); spine – sheath surface (acceleration due to velocity shear).



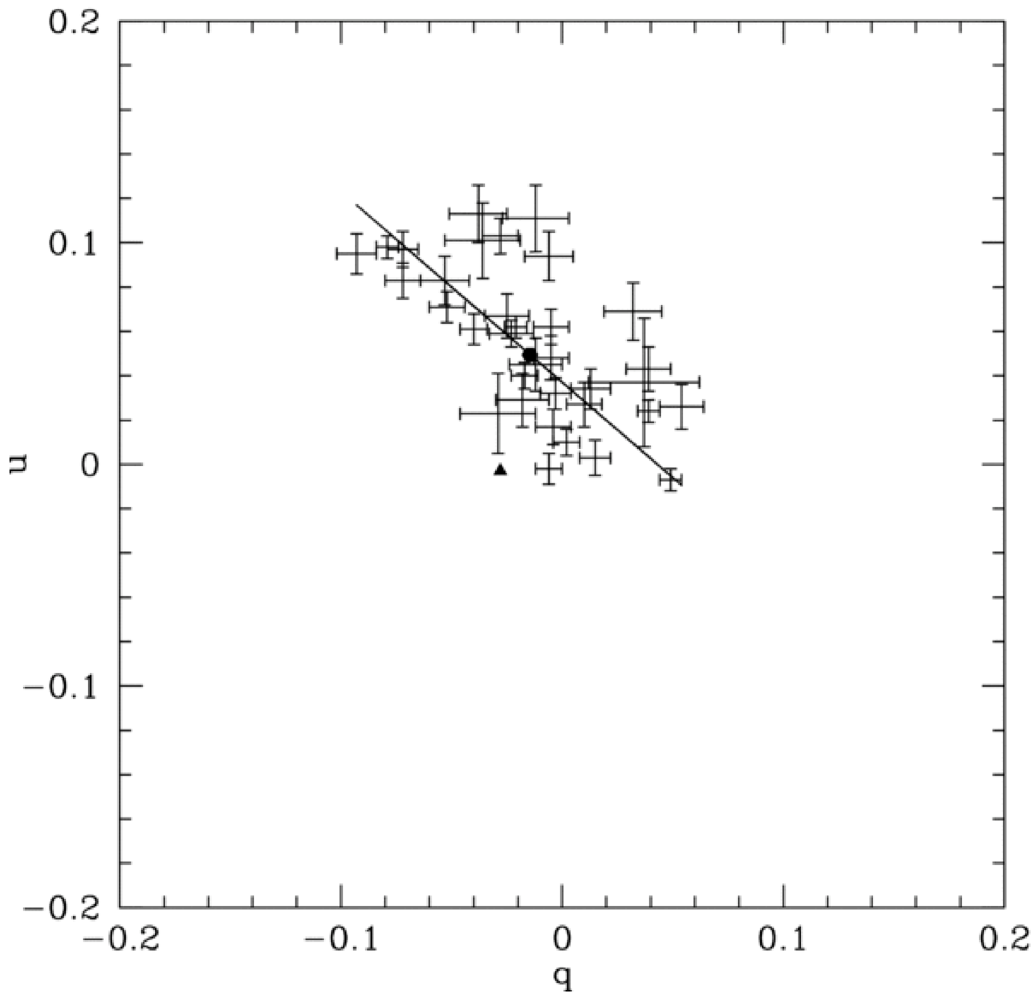
Edge-On YSO Disks

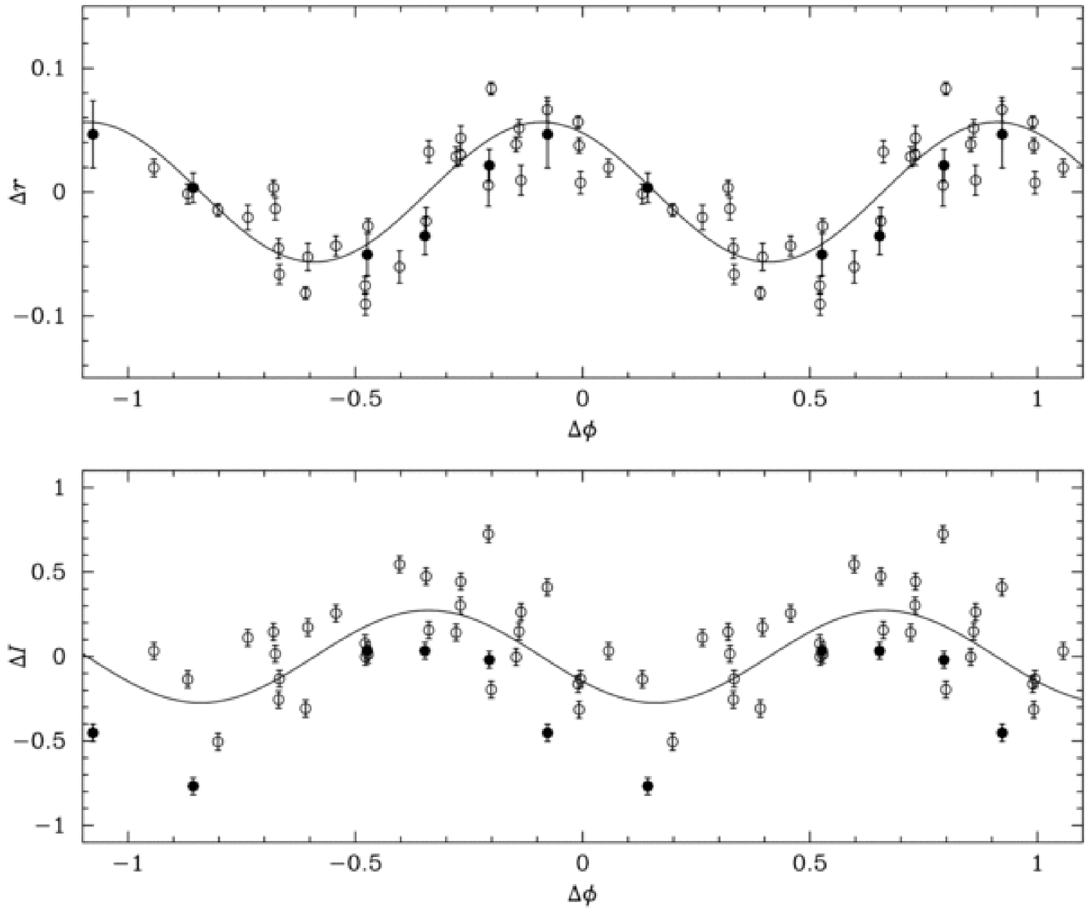
ACS image of HH30 and HL Tau

Optical Polarimetry is a Tracer of Asymmetric Illumination of Edge-On YSO Disks



Variable asymmetry in WFPC2 imaging of HH30
Stapelfeldt et al. (1999)





Variable linear polarization from asymmetric illumination and scattering
Period = 7.5 days
Consistent with hot spots or clumps in the inner disk
Durán-Rojas et al. (2009)

PhD thesis of Carolina Durán-Rojas
72 nights of in-person observation at OAN/SPM 84-cm
TEQUILA opens the possibility of expanding the sample beyond one object!

Science requirements

- TEQUILA trigger goal: <1min after any alert occuring during the night
- The magnitude cut is estimated to be r ~17
- TEQUILA polarization uncertainty goal ~1% or less

Instrument

Early March 2025

- Noémie: “I want to put a polarimeter on COLIBRÍ.”
- Alan: “Polarimeters need mechanisms. I love polarimetry, but I hate mechanisms, and they hate me.”
- Noémie: “I can do this without mechanisms.”
- Alan: !!!!!!

TEQUILA is an imaging photopolarimeter without mechanisms.

What do we mean by imaging photopolarimetry?

We mean measurement of

- **intensity** and
- **linear polarization**
- over the **focal plane** of the telescope
- but at **one wavelength**.

In terms of the Stokes' parameters:

- I = **intensity**
- Q = **linear polarization** at 0 degrees (positive) or 90 degrees (negative)
- U = **linear polarization** at 45 degrees (positive) or 135 degrees (negative)

We will not be concerned with **circular polarization**:

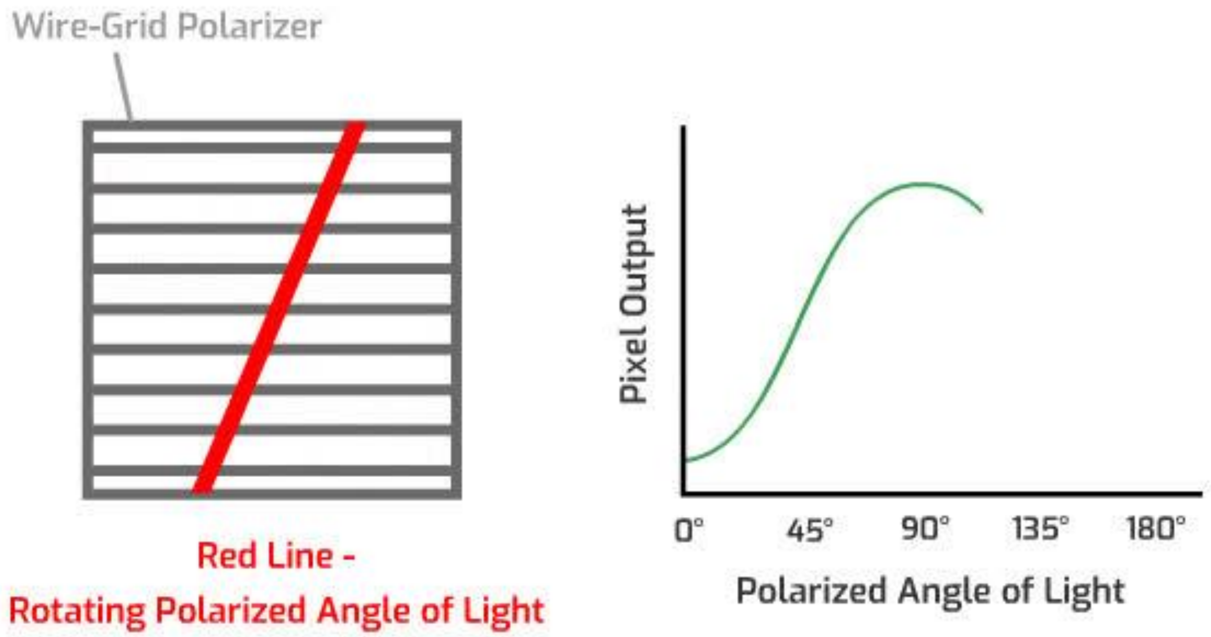
- V = left-hand polarization (positive) or right-hand polarization (negative)

Why? We wanted to measure *V*, but there is no V in TEQUILA, so we can't.

Simple Linear Analyzer

The simplest polarimetric analyzer is a filter that preferentially transmits light in one polarization: a polarizing filter.

The simplest polarizing filter is a wire-grid polarizer. When light hits the grid, the electric field component parallel to the wires excite electrons in the wires, causing them to oscillate and absorb the energy of that polarization.



Credit: Lucid Vision Lab

The transmitted intensity varies as the sine of the angle between the grid and the polarization between Tmax and Tmin. For an ideal polarizar Tmax = 1 and Tmin = 0.

Problem: To measure the intensity, degree of polarization, and direction of polarization (or equivalently the Stokes' parameters *I*, *Q*, and *U*), we need measurements at three or more rotations of the polaroid. So we need mechanisms, and Alan hates mechanisms, and they hate him.

Sony Polarsens™ wire grid polarization sensor

In 2018, Sony released its first CMOS-based polarization imaging sensors, which integrated patterned wire-grid polarizers on-chip onto the pixels.

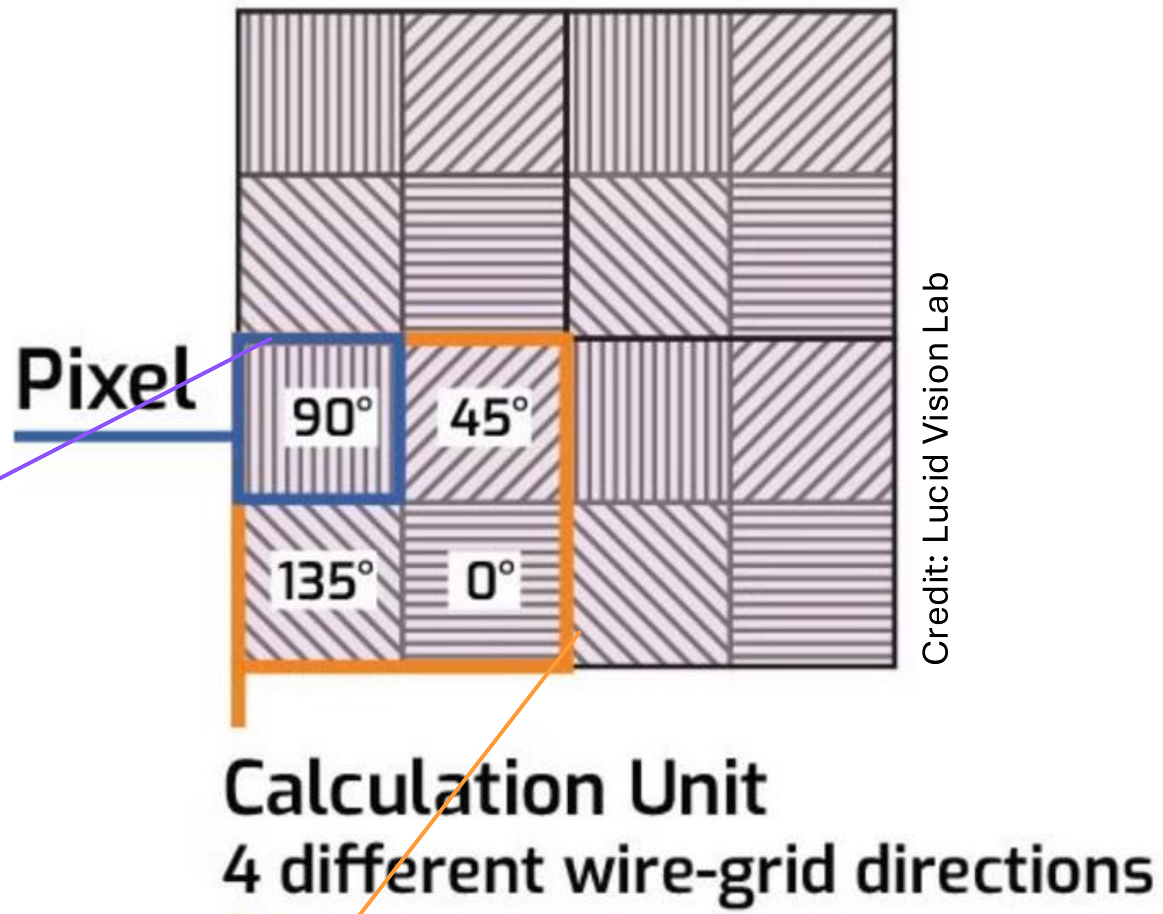
The polarizer array is comprised of four different angled polarizers (0°, 45°, 90°, and 135°).

Every super-pixel block of 2x2 pixels makes up a calculation unit.

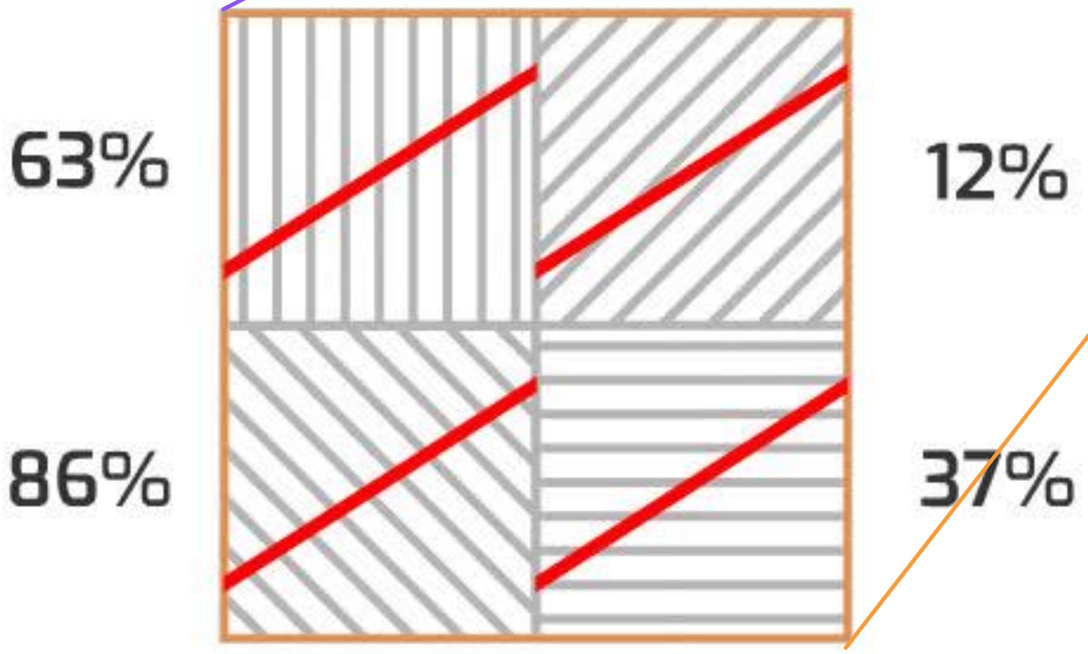
We have, effectively, analyzers at four different angles spread over the detector.

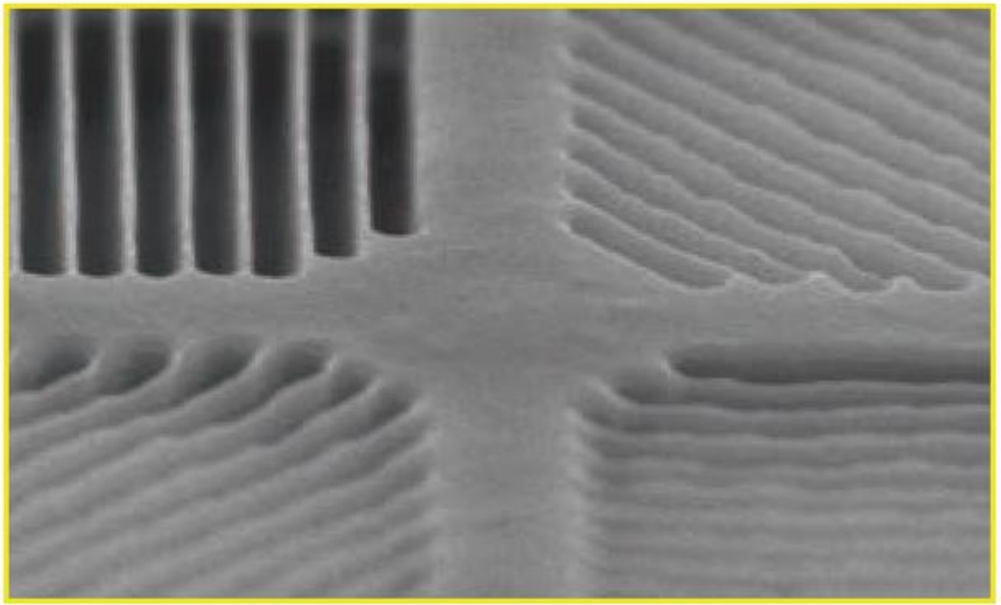
We can calculate *I*, *Q*, and *U* — intensity and linear polarization — from a single image at the resolution of 2x2 pixels with no mechanisms.

Disadvantages:
- We cannot (yet) measure *V* — circular polarization
- We lose half the light compared to other approaches (in theory)



Credit: Lucid Vision Lab





Polarizer image
Source: Sony, IEDM2016, Lecture number 8.7

$$\vec{S} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} \frac{I_0 + I_{45} + I_{90} + I_{135}}{2} \\ I_0 - I_{90} \\ I_{45} - I_{135} \\ \cancel{I_R - I_L} \end{bmatrix}$$

Design

- **Focus:** TEQUILA will directly image the f /7.2 beam of the 1.3-meter telescope with a CMOS-camera with a Polarsens™ sensor.

- **Camera model:** After discussing with several companies, Noémie decided for **QHYCCD - QHY1253P Polarize CMOS Monochrome Camera - Professional Version** that was purchased from Woodland Hills Camera & Telescope, Woodland Hills, California on May 23, 2025.

- **Cooling system:** QHY1253 has built-in two stage TEC cooler. It can cool the sensor to -35C below ambient to reduce and stabilize the dark current. This is important for calibration, as uncorrected dark current dilutes the polarization signal. None of the other cameras Noémie considered have cooling.

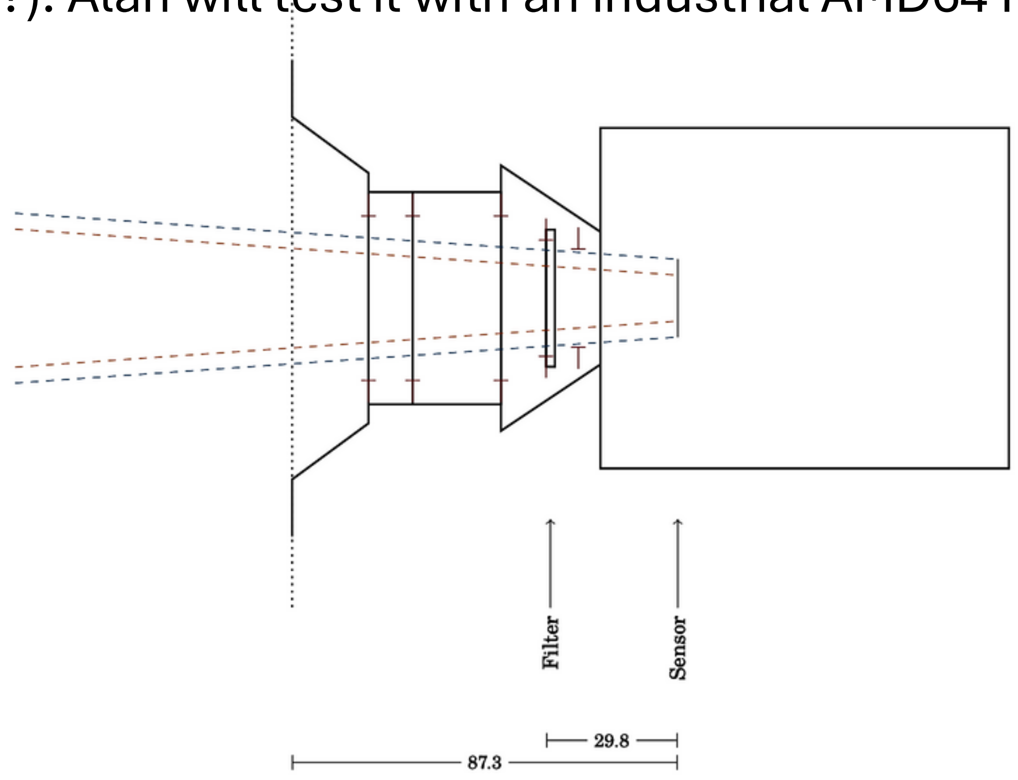
- **Field of View:** The total field of the detector will project to 5.2 × 3.8 arcmin with 0.076 arcsec pixels or 0.152 arcsec super-pixels.

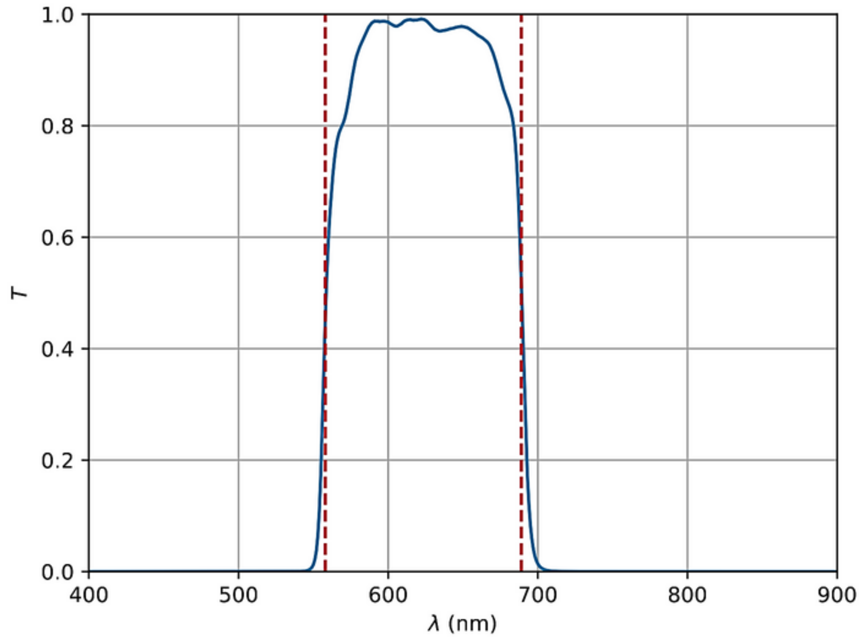
- **Filter:** Fixed SDSS *r* filter**.**

- **Mounting:** Commercial T-mount and C-mount parts (Celestron, Edmund, Baader). Mounted on the second Nasmyth focus in place of the FLI test CCD.

- **Integration into TCS:** QHY provide a C++ SDK. Alan has written a driver for TCS. It works like any other detector.

- **Control:** The interface is USB3.0. We had hoped to run this from a Raspberry Pi in the fork arm, however it does not seem to be stable enough (too much current on USB bus?). Alan will test it with an industrial AMD64 PC in December.



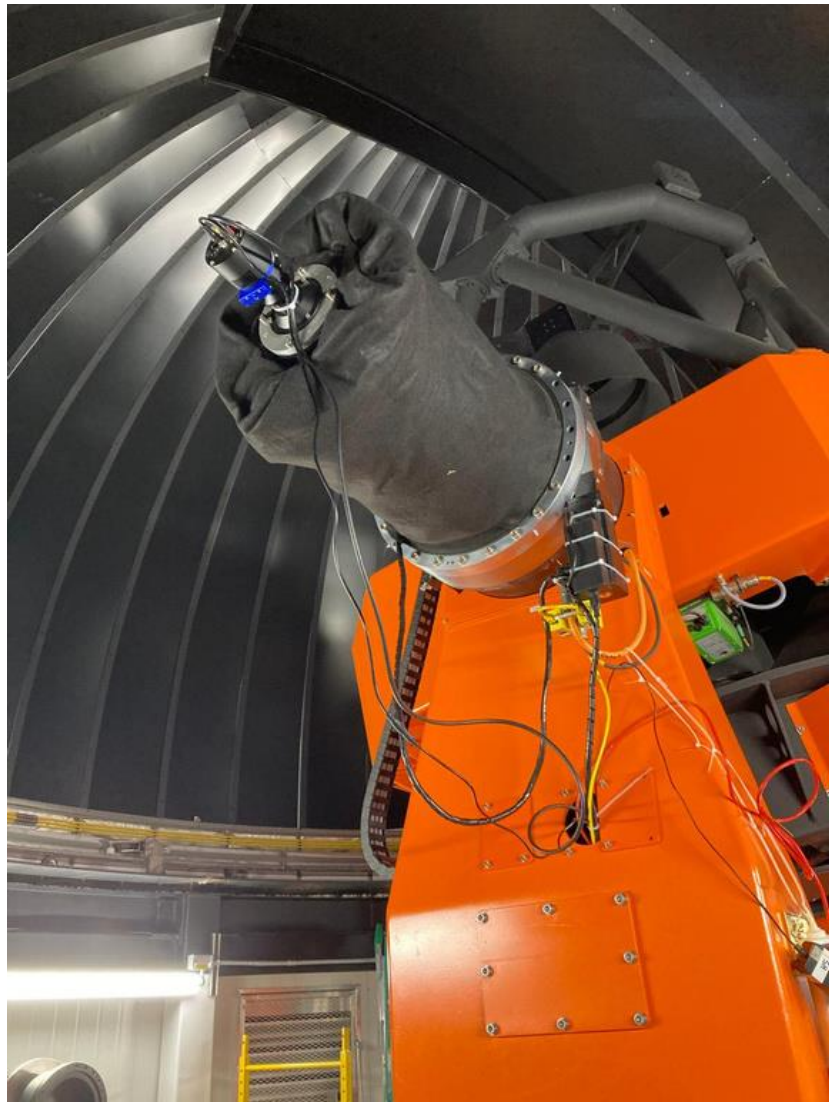


Assembly and testing at OAN-SPM, Nov.12-14, 2025

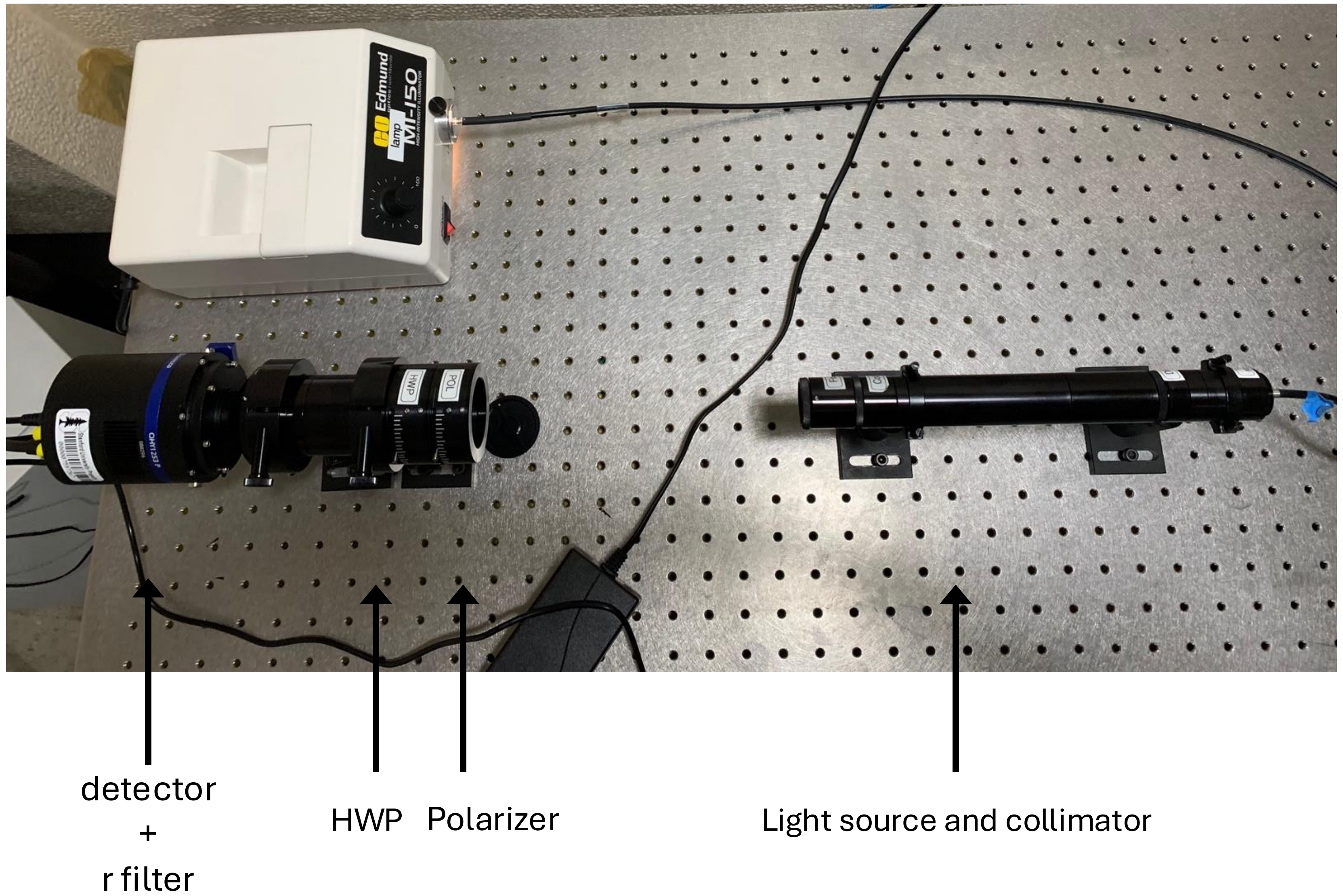
Read noise = 2.5 electrons
Full well ≈ 10k electrons

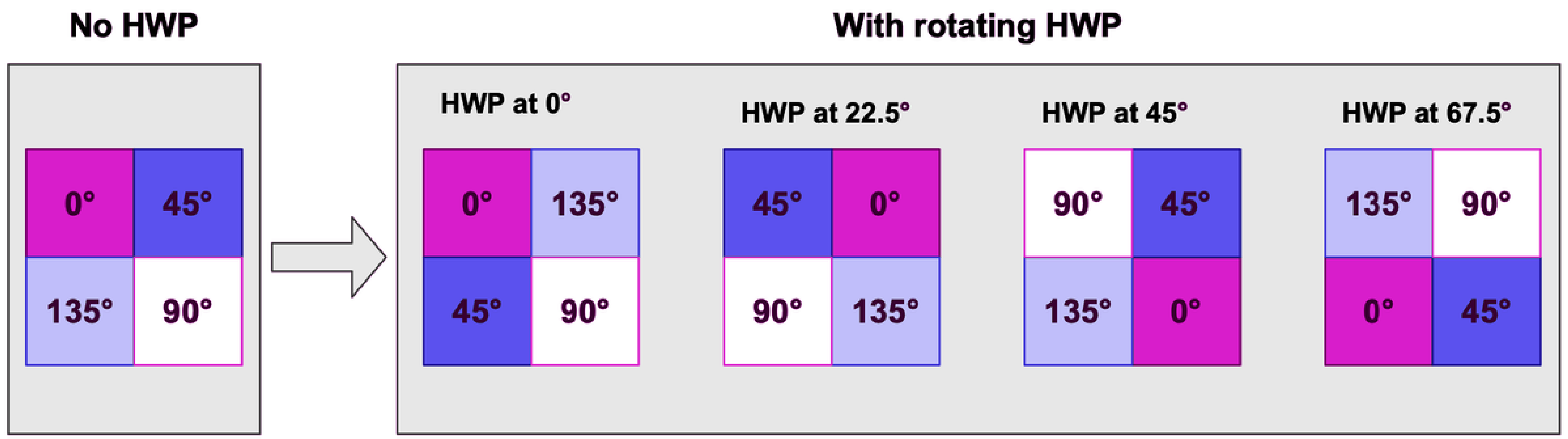
Test Fitting on Telescope

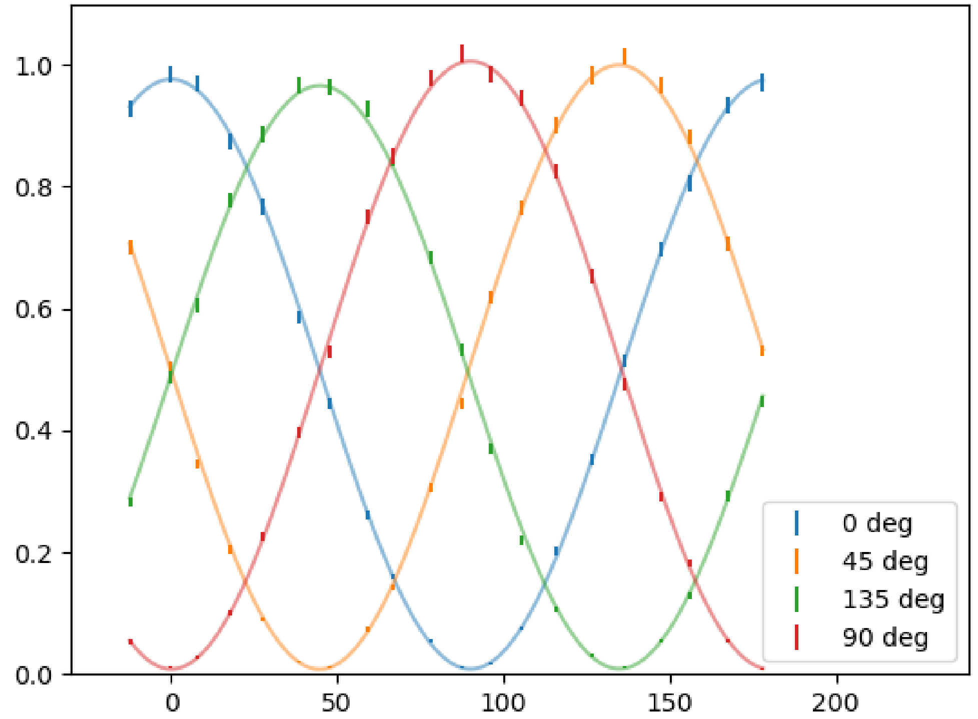
We checked that we could install TEQUILA in the place of the FLI detector, with the help of Johan Floriot and Samuel Ronayette. There were no surprises.



Calibration - laboratory setup





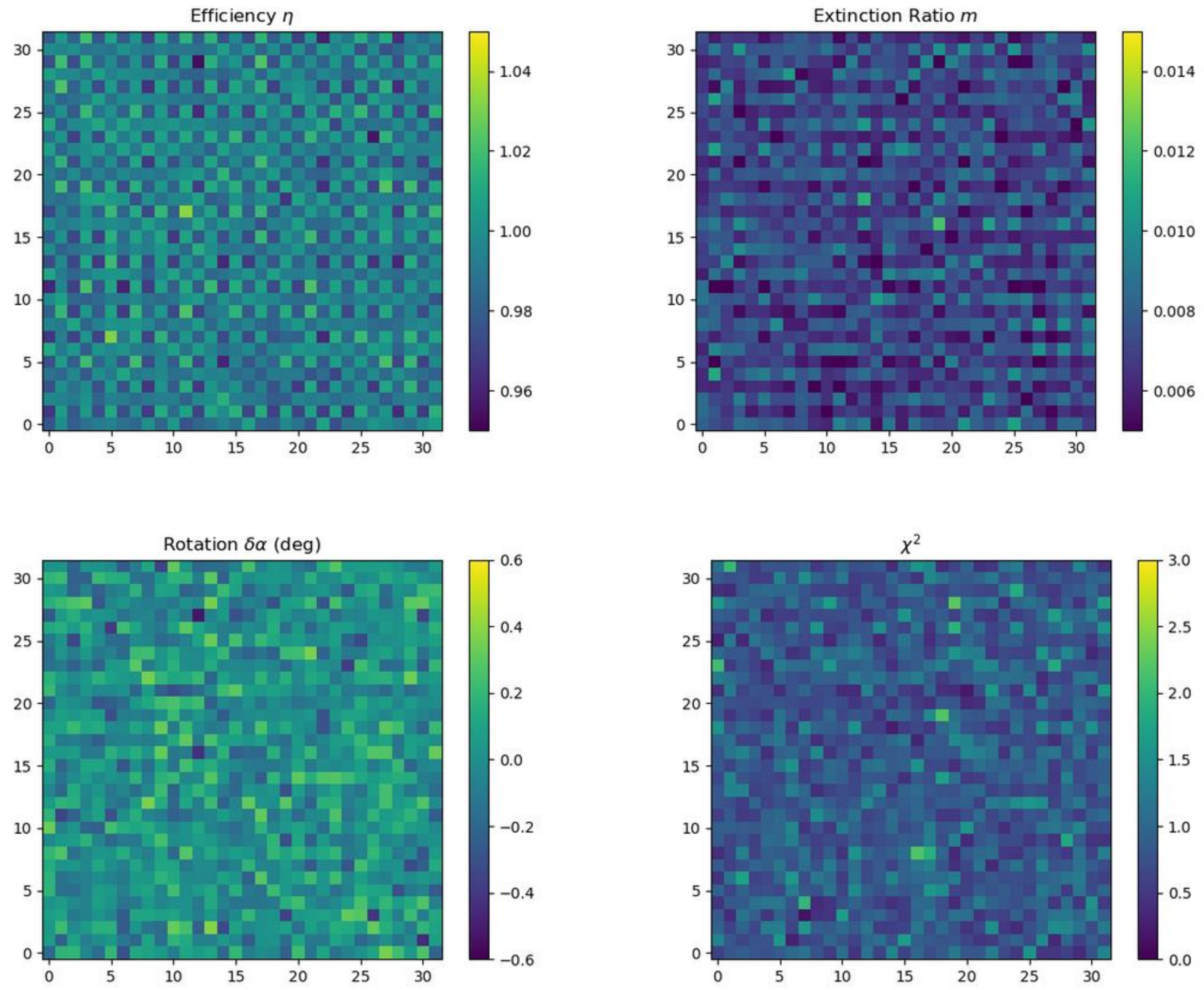


Measured quantity:

$$z_i(\beta) \;=\; \frac{1}{2} z_0 \eta_i \left[(1+m_i) S_0 + (1-m_i) \left(S_1 \cos 2\theta_i + S_2 \sin 2\theta_i \right) \right] \quad \text{with} \quad \theta_i = \beta + \alpha_i$$

- ***η*: *Pixel-specific throughput efficiency. This accounts for pixel-to-pixel variation in responsivity (normalized to the average gain).***
- ***m*: Pixel-specific extinction ratio leakage.** This is the minimum transmission of the micro-polarizer when light is orthogonal to its axis.
- ***α*: Pixel-specific polarizer orientation.** The physical angle of the micro-polarizer placed above pixel *i*.

Calibration - measurements



We find:

- η = 0.993 ± 0.015
- m = 0.007 ± 0.001
- α = +0.01 ± 0.14
- χ^2 = 1.06

Our model is adequate.

The detector is very uniform and has an adequate extinction ratio for our purposes.

Calibration - inversion method

- index a pixel in a superpixel as $i \in \{0, 45, 90, 135\}$ (or $i = 1..4$).
- measured intensity for pixel i at HWP/polarizer angle β is $z_i(\beta)$.
- microgrid orientation α_i (nominal $0, 45, 90, 135^\circ$ plus small error). $\boldsymbol{\alpha_i = A_i + \delta\alpha_i}$ **where** $\boldsymbol{A_i \in \{0°, 45°, 90°, 135°\}}$
- extinction ratio $m_i = I_{\text{min}}/I_{\text{max}} \in [0, 1]$.
- diattenuation $d_i = \dfrac{1 - m_i}{1 + m_i}$.
- per-pixel gain/efficiency η_i and global scale z_0.
- incoming Stokes vector $\mathbf{S} = [S_0, S_1, S_2]^\top$ (we ignore circular S_3 here).

The Mueller matrix of an imperfect linear polarizer **aligned to 0°** is:

$$M_{\text{pol}}(d) = \frac{1}{2}\begin{bmatrix} 1 & d & 0 & 0 \\ d & 1 & 0 & 0 \\ 0 & 0 & \sqrt{1-d^2} & 0 \\ 0 & 0 & 0 & \sqrt{1-d^2} \end{bmatrix}.$$

Now rotate it by α_i:

$$\boxed{M_i = R(-\alpha_i)\ M_{\text{pol}}(d_i)\ R(\alpha_i)}$$

This gives the full Mueller matrix.

$$M_i = \frac{1}{2}\begin{bmatrix} 1 & d_i \cos 2\alpha_i & d_i \sin 2\alpha_i & 0 \\ d_i \cos 2\alpha_i & \cos^2 2\alpha_i + d_i^2 \sin^2 2\alpha_i & (1-d_i^2)\cos 2\alpha_i \sin 2\alpha_i & 0 \\ d_i \sin 2\alpha_i & (1-d_i^2)\cos 2\alpha_i \sin 2\alpha_i & \sin^2 2\alpha_i + d_i^2 \cos^2 2\alpha_i & 0 \\ 0 & 0 & 0 & \sqrt{1-d_i^2} \end{bmatrix}$$

We can then invert the pixel values to get the Stokes' vector:

$$\hat{\mathbf{S}} = \mathbf{M}^{-1}\mathbf{z}$$

$$DoLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}, \qquad AoLP = \frac{1}{2}\arctan\left(\frac{S_2}{S_1}\right)$$

Calibration - On Telescope

M3 has a reflection at about 45 degrees.

This will impart an instrumental linear polarization of about 4% (and also mix some circular polarization into linear polarization).

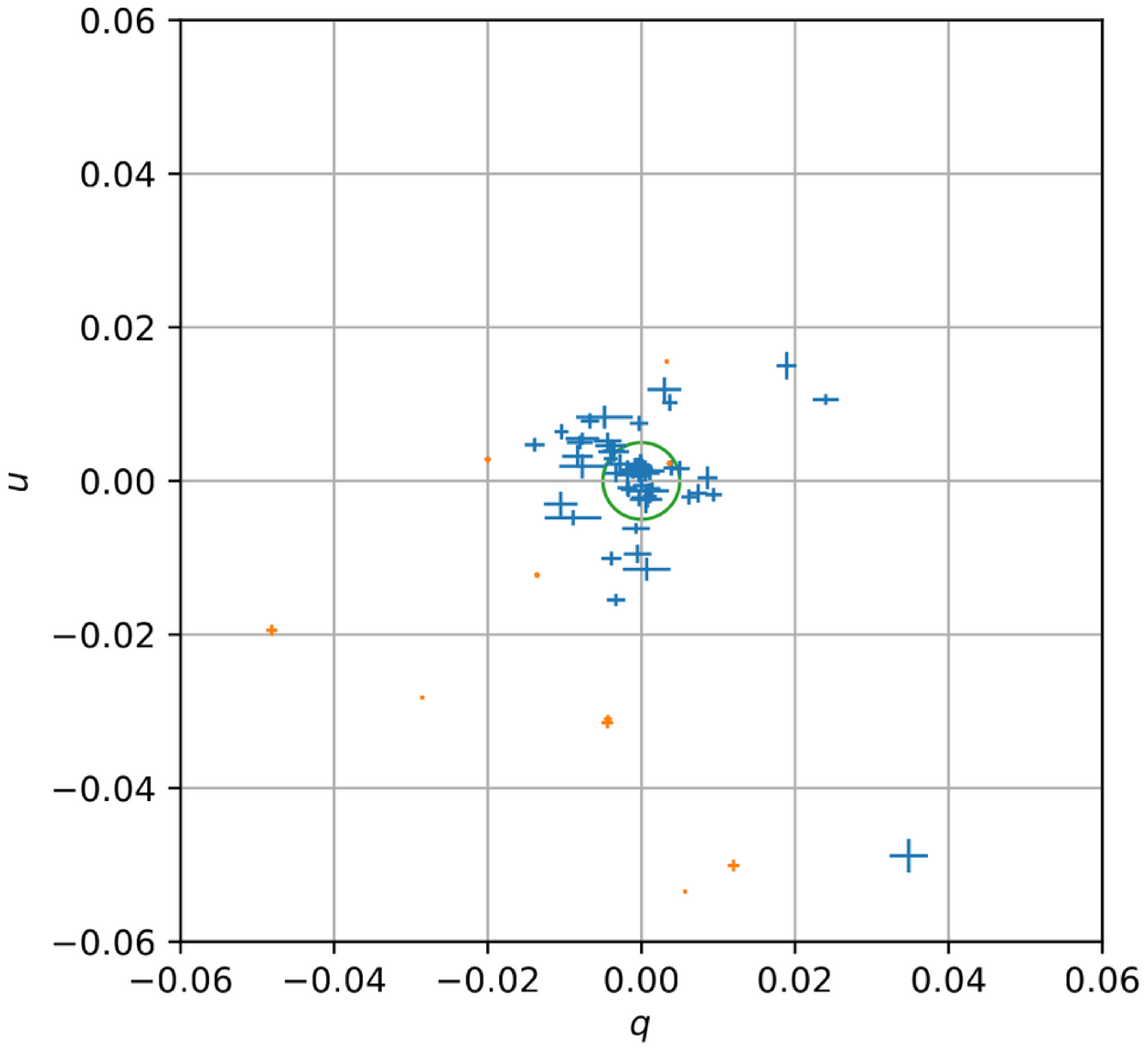
Worse, the instrumental polarization rotates on the sky.

This is inconvenient, but it can be calibrated, e.g., the polarimeters at Nasmyth focus at TNG and VLT.

We will calibrate it by regularly observing unpolarized standards from the RoboPol standards list.

Rule of thumb: systematic effects routinely can be calibrated to 10% which means we can work to about 0.5%. This is adequate for our science cases and for many others. However, if you need better precision, TEQUILA is probably not the instrument for you.

We will also determine the rotation from the instrumental coordinate system to the equatorial coordinate system by observing highly polarized RoboPol standards.



Proposed operation

We can switch from DDRAGO/CAGIRE to TEQUILA by rotating M3. This takes less than 25 seconds.

- Changing between the two will be fast.
- We can satisfy our requirement to start observing an alert with DDRAGO/CAGIRE in less than 30 seconds even when using TEQUILA.

What happens when we observe a new GRB with DDRAGO/CAGIRE?

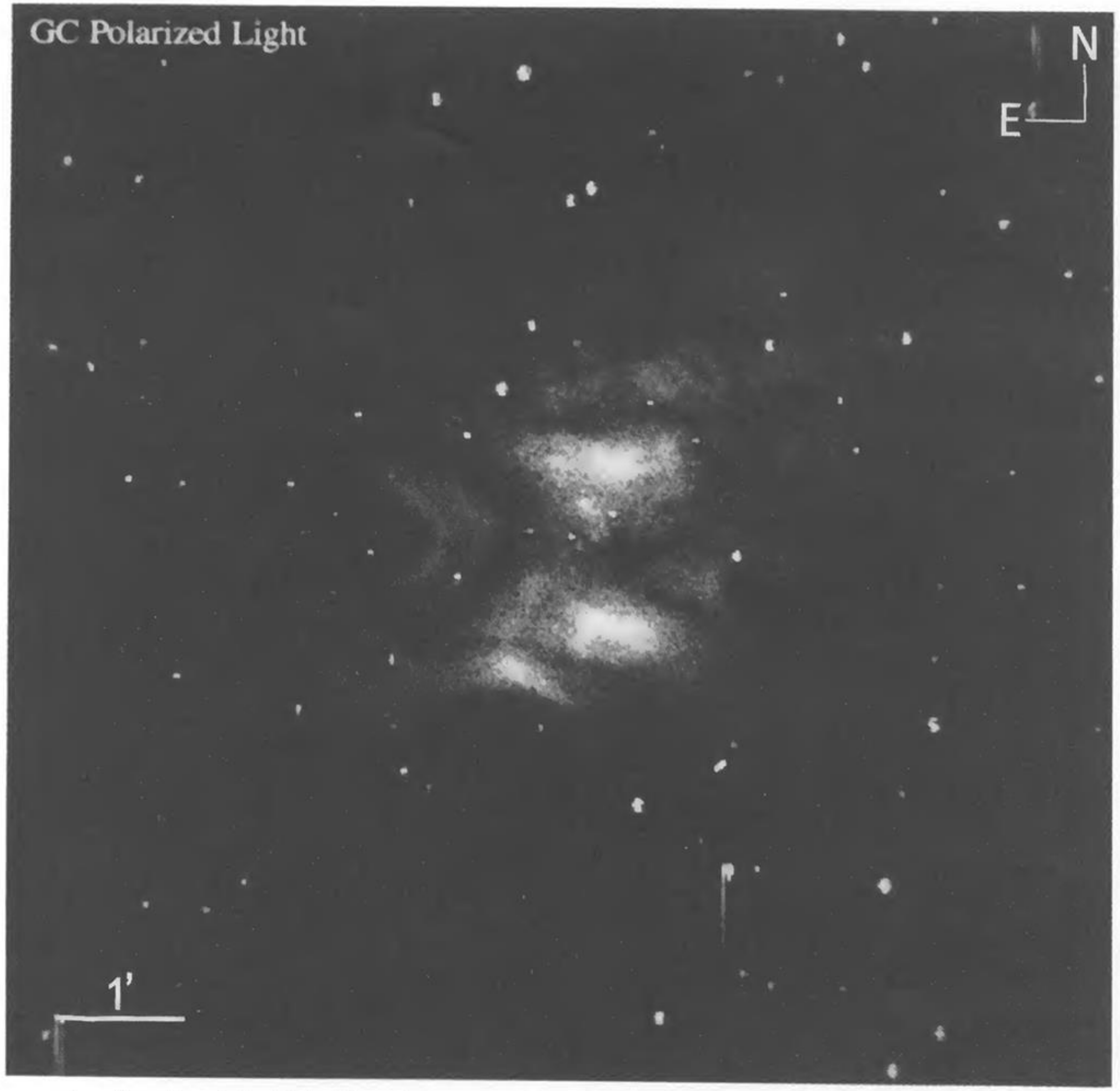
Alan is working with two high-school students (Sabina Miranda and Liam Watson) to implement a trigger system

- **SANGRITA**: **S**earching with **A**lacrity for **N**ew **GR**Bs in **I**mages **T**aken **A**lready
- Looks at first 10 second or 60 second image in *r*.
- Find point sources brighter than r = 18 that are not in Pan-STARRS/SkyMapper and are not in SkyBot.
- This is much easier than the general case.
- Aim is to run in less than 10 seconds.

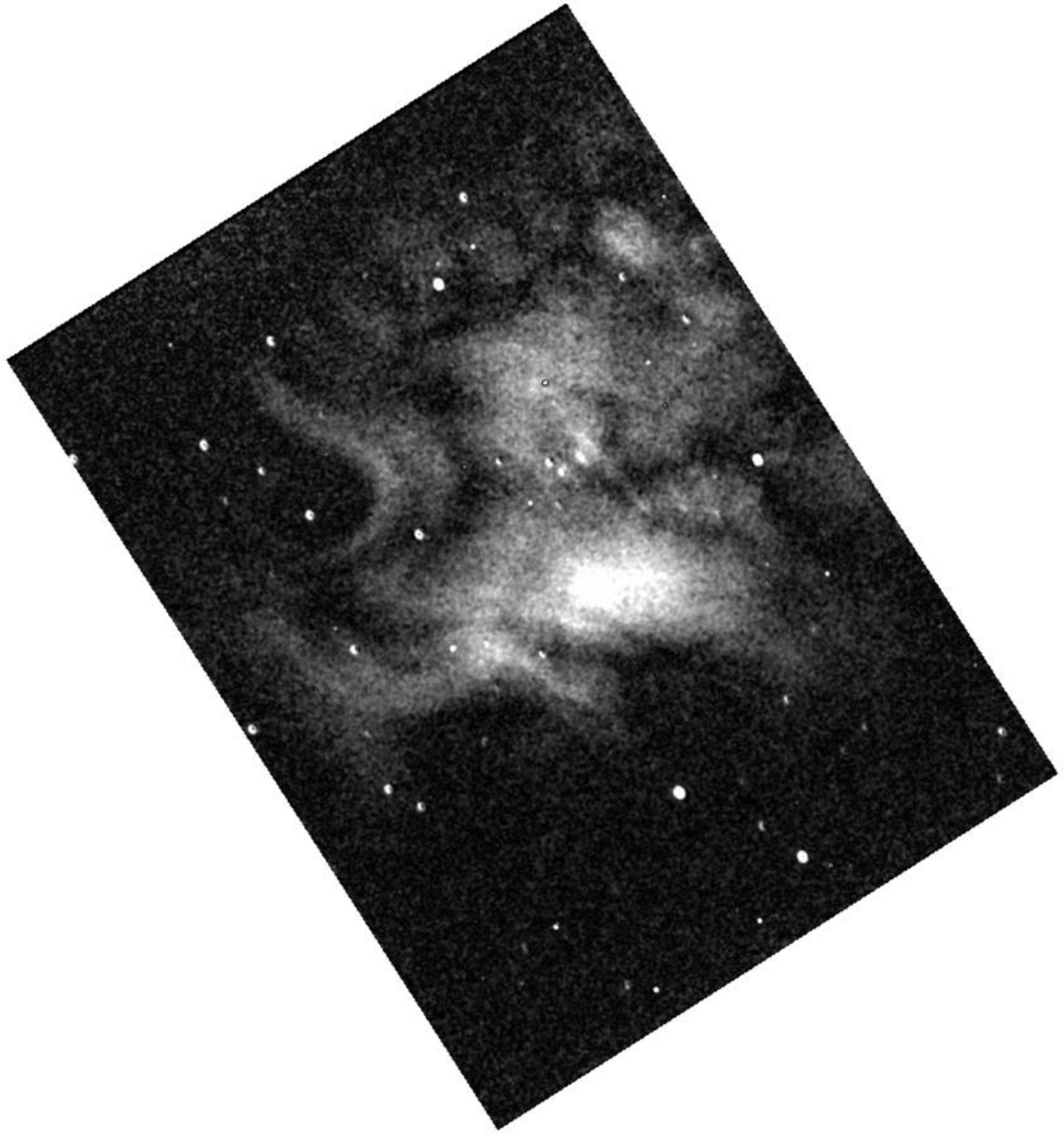
If we find a bright enough source, we propose to switch from DDRAGO/CAGIRE to TEQUILA.

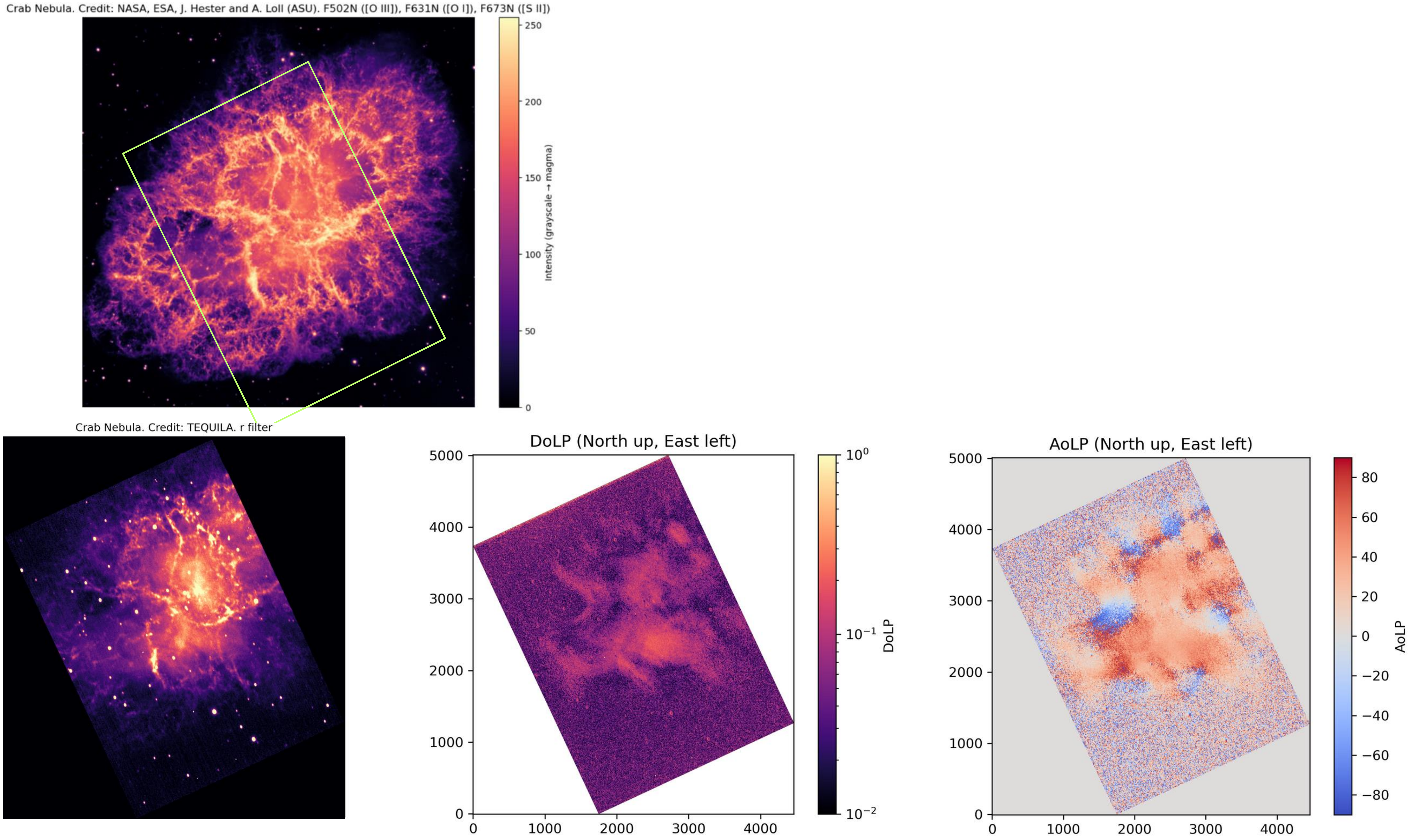
First light

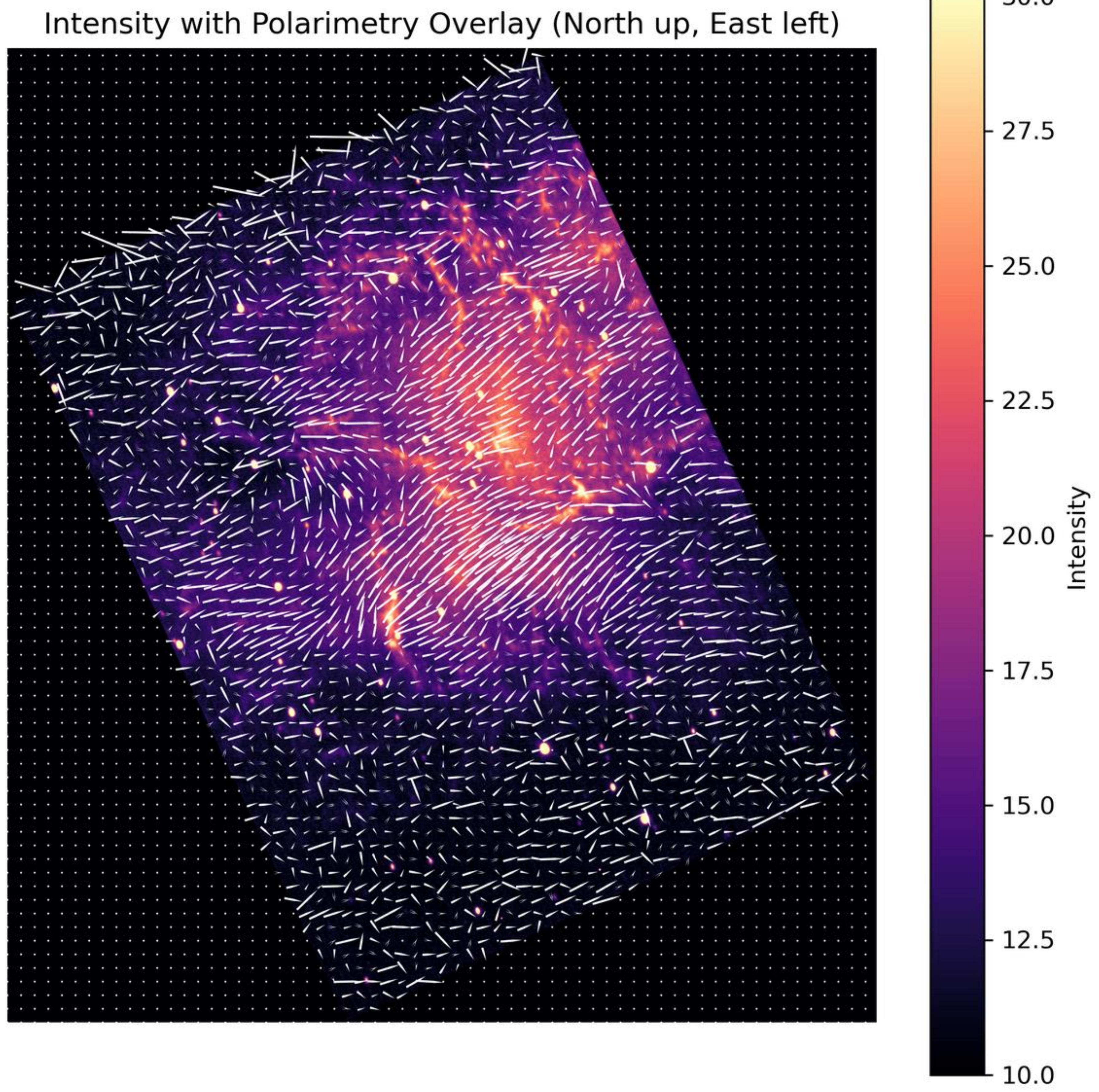
Michel et al. 1991 ApJ 368:463



TEQUILA 14 NOVEMBER 2025

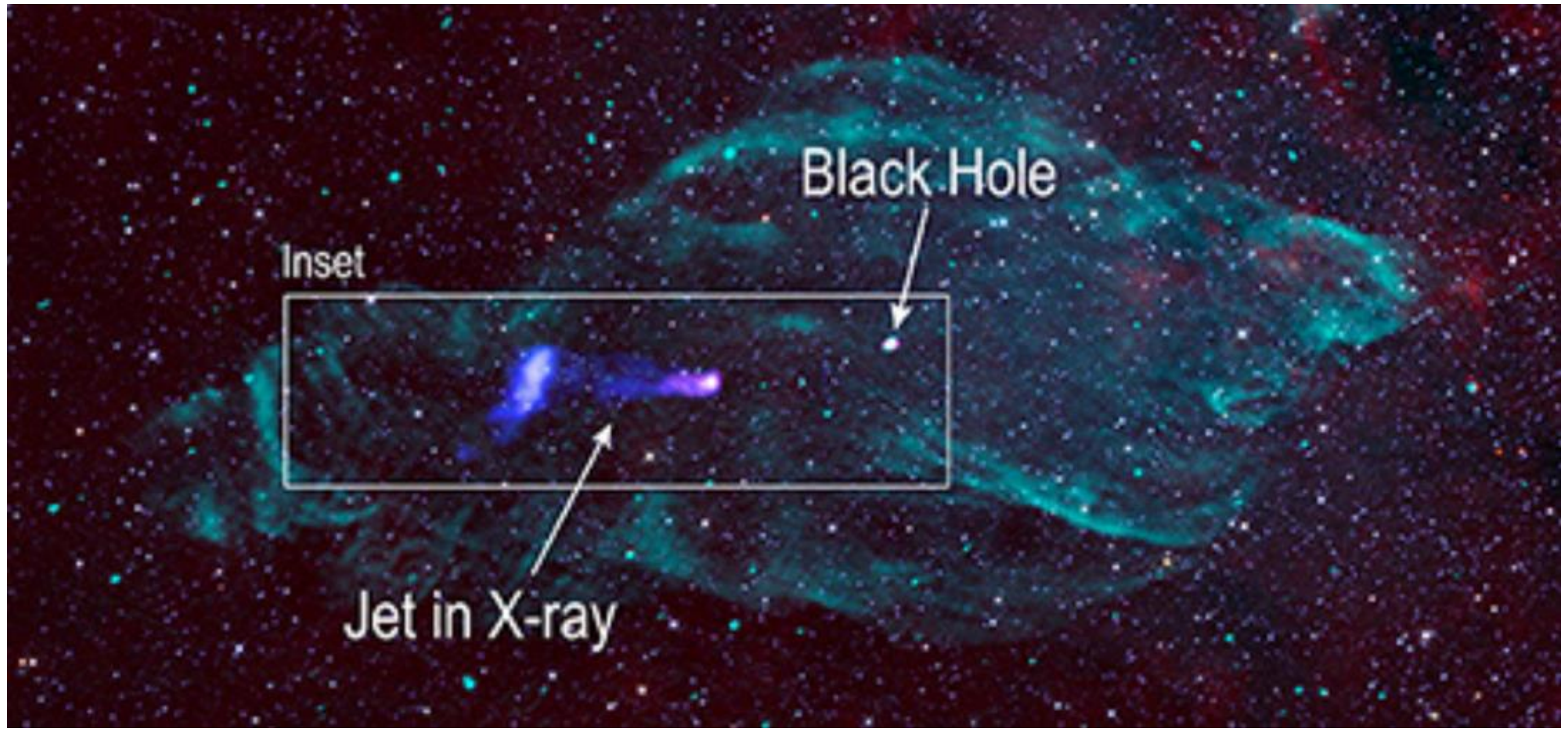



Crab Nebula. Credit: NASA, ESA, J. Hester and A. Loll (ASU). F502N ([O III]), F631N ([O I]), F673N ([S II])
Intensity (grayscale → magma)
0
50
100
150
200
250
Crab Nebula. Credit: TEQUILA. r filter
DoLP (North up, East left)
DoLP
10^{-2}
10^{-1}
10^{0}
0
1000
2000
3000
4000
5000
AoLP (North up, East left)
AoLP
−80
−60
−40
−20
0
20
40
60
80

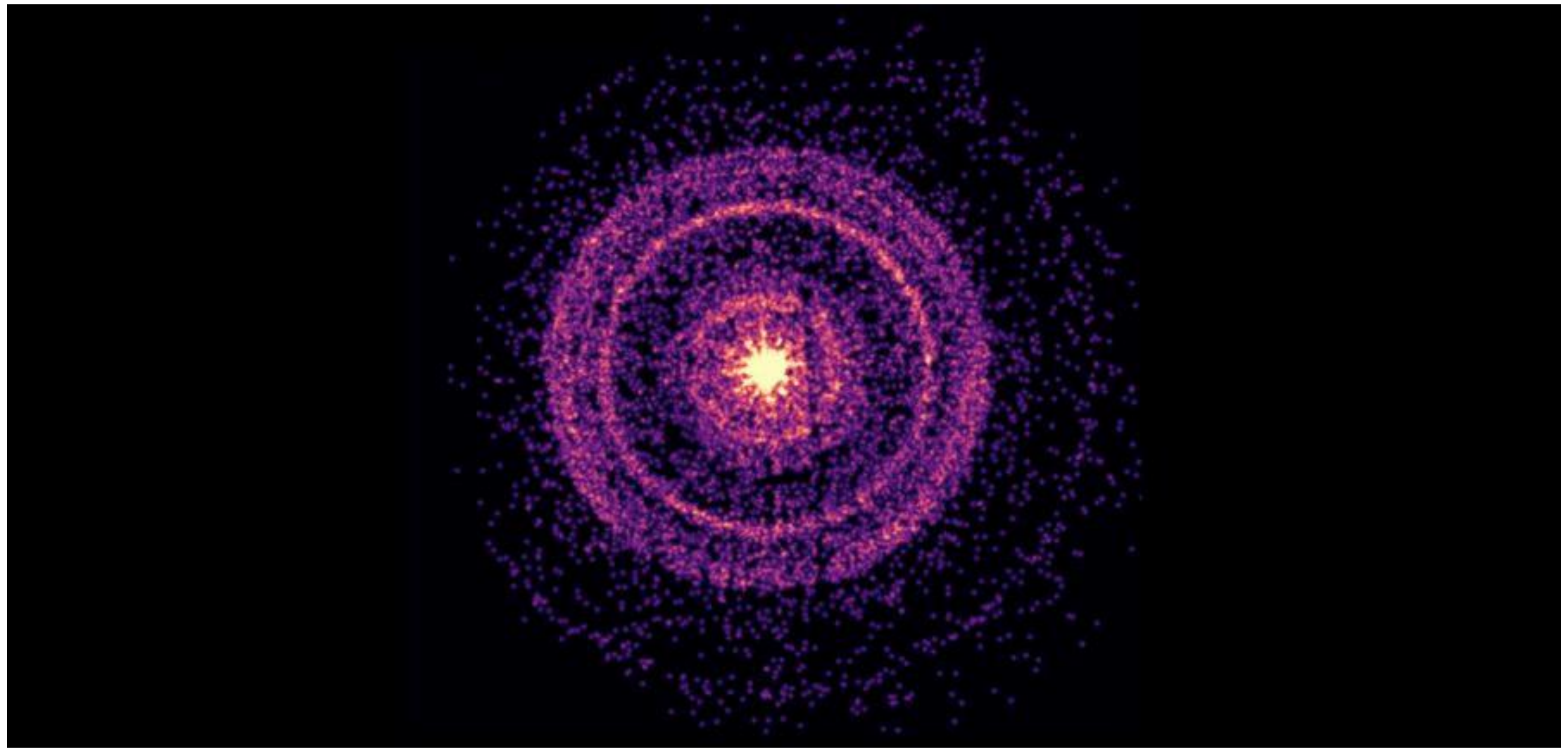

Intensity with Polarimetry Overlay (North up, East left)
Intensity
30.0
27.5
25.0
22.5
20.0
17.5
15.0
12.5
10.0

Next plans

- We plan to put TEQUILA back on the telescope as soon as possible.
- On-sky calibration with RoboPol standards.
- We plan to (not necessarily in this order):
  - Use the Crab (PWN) as benchmark and do a polarimetric mapping of SS 433 + W50 (a "BWN"!) (lead by Noémie)
  - Polarimetric monitoring of edge-on YSOs (including HH30) and measure variations (lead by Alan)
- Test the possibility of detecting circular polarization with QWP ("SALT" for TEQUILA: Simple Analysis of Light Twist)
- Collaborate with Yannis Liodakis to install sister instrument (RAKI: Radiation Anisotropy Kosmic Instrument) at Skinakas
- Sony has a very recent patent (granted Jan 21, 2025) for a "sensor with long wavelength infrared polarization sensitive pixels
  - motivation: IR polarization to study dusty environments
  - preparation for a double channel TEQUILA
- Teaching & outreach are important components of this project
  - development of a polarimetry master course at IA-UNAM
- We propose that Fredd Sánchez Álvarez will do his PhD thesis at UNAM on the calibration and science use of TEQUILA.



Credit: X-ray: (IXPE): NASA/MSFC/IXPE; (Chandra): NASA/CXC/SAO; (XMM): ESA/XMM-Newton; IR: NASA/JPL/Caltech/WISE; Radio: NRAO/AUI/NSF/VLA/B. Saxton. (IR/Radio image created with data from M. Goss, et al.); Image Processing/compositing: NASA/CXC/SAO/N. Wolk & K. Arcand



An X-ray image of GRB 221009A's emission scattering off of dust.

Adapted from Williams et al. 2023

It was worth a shot!