Polarimetry: a different window to the sky

even for small telescopes

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27TH FEBRUARY 2024

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- Basic Principles and Polarigenesis

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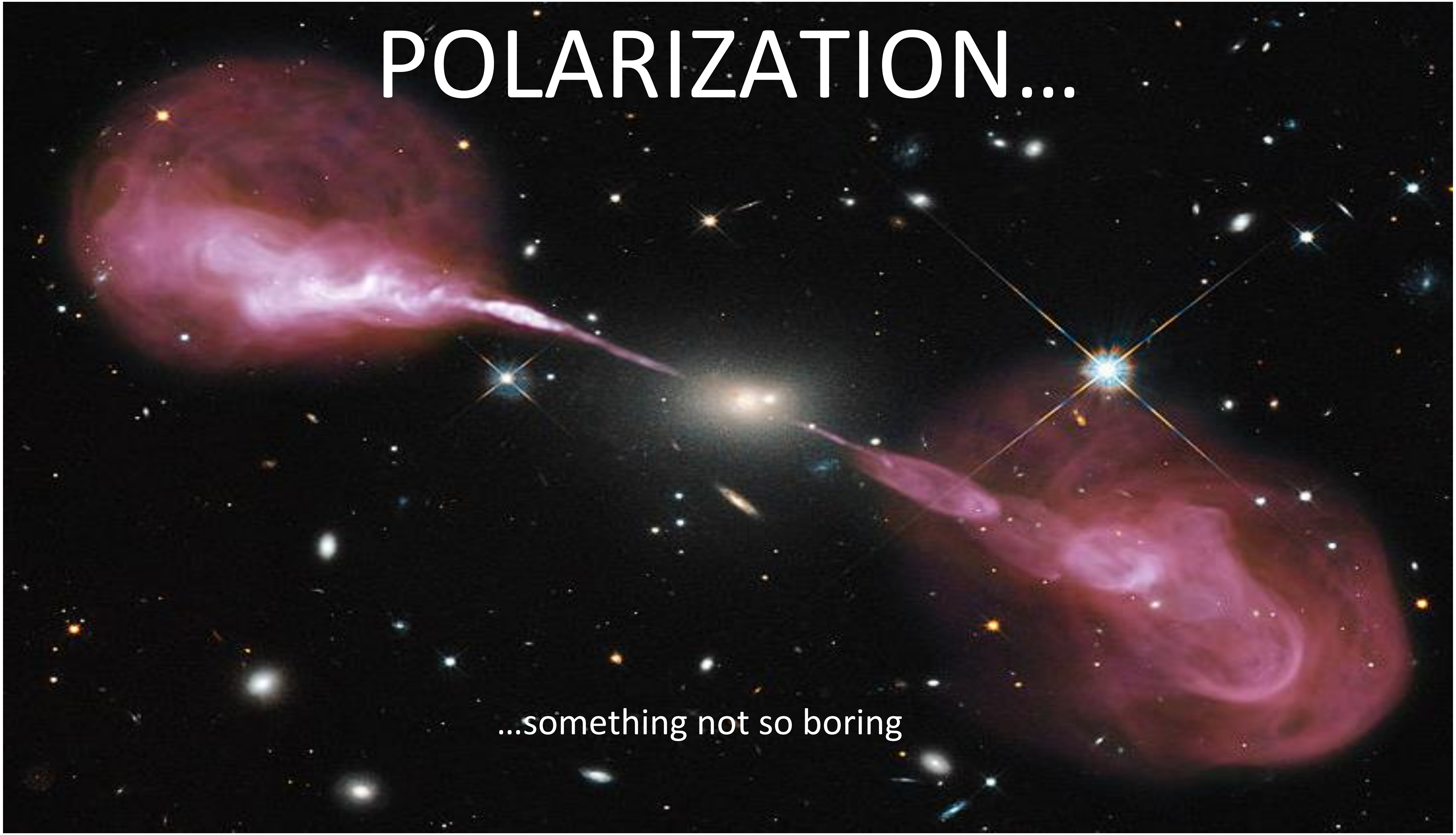
- Polarimetry with small telescopes: A **practical** example

POLARIZATION…



…something not so boring

Why studying polarization?

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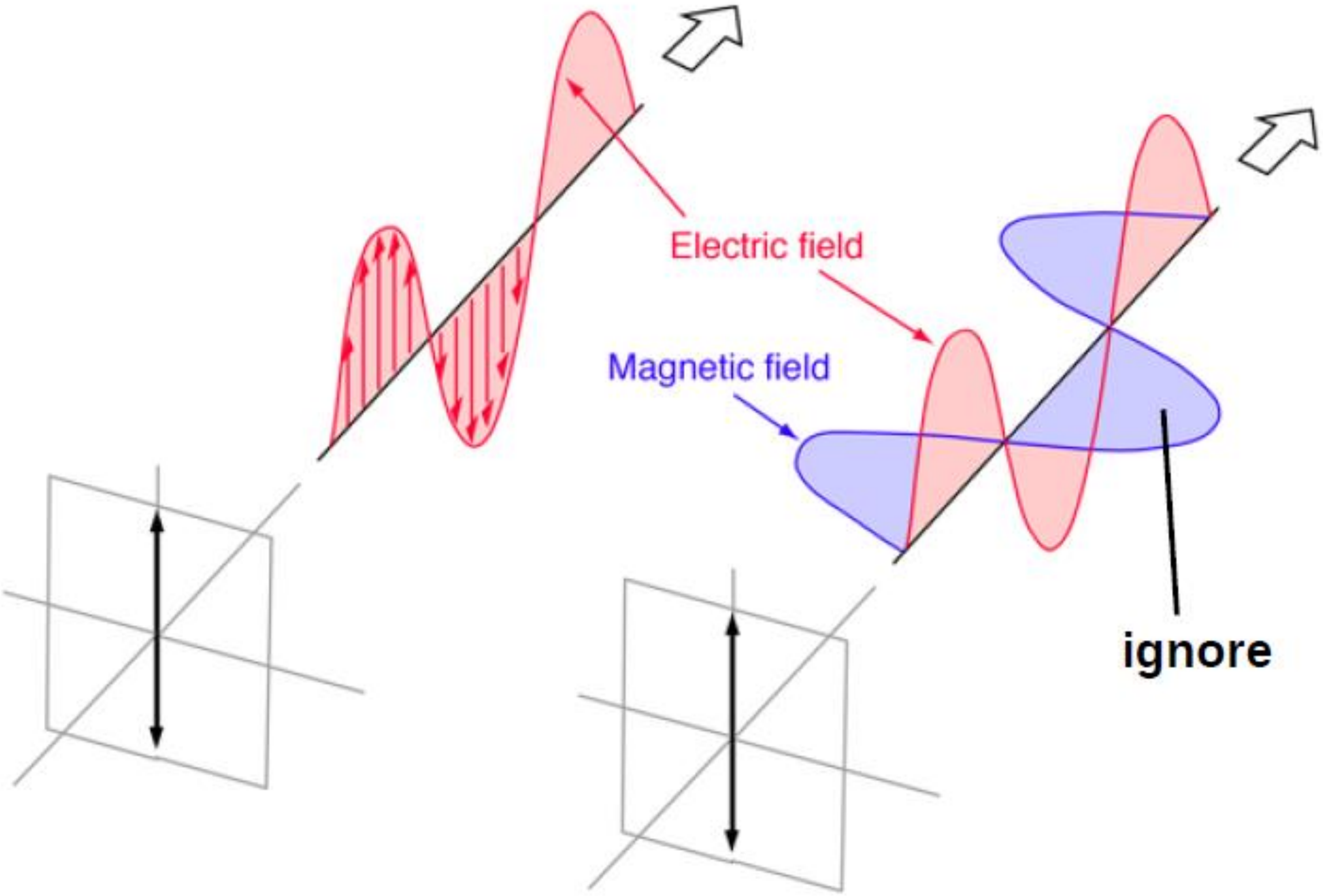
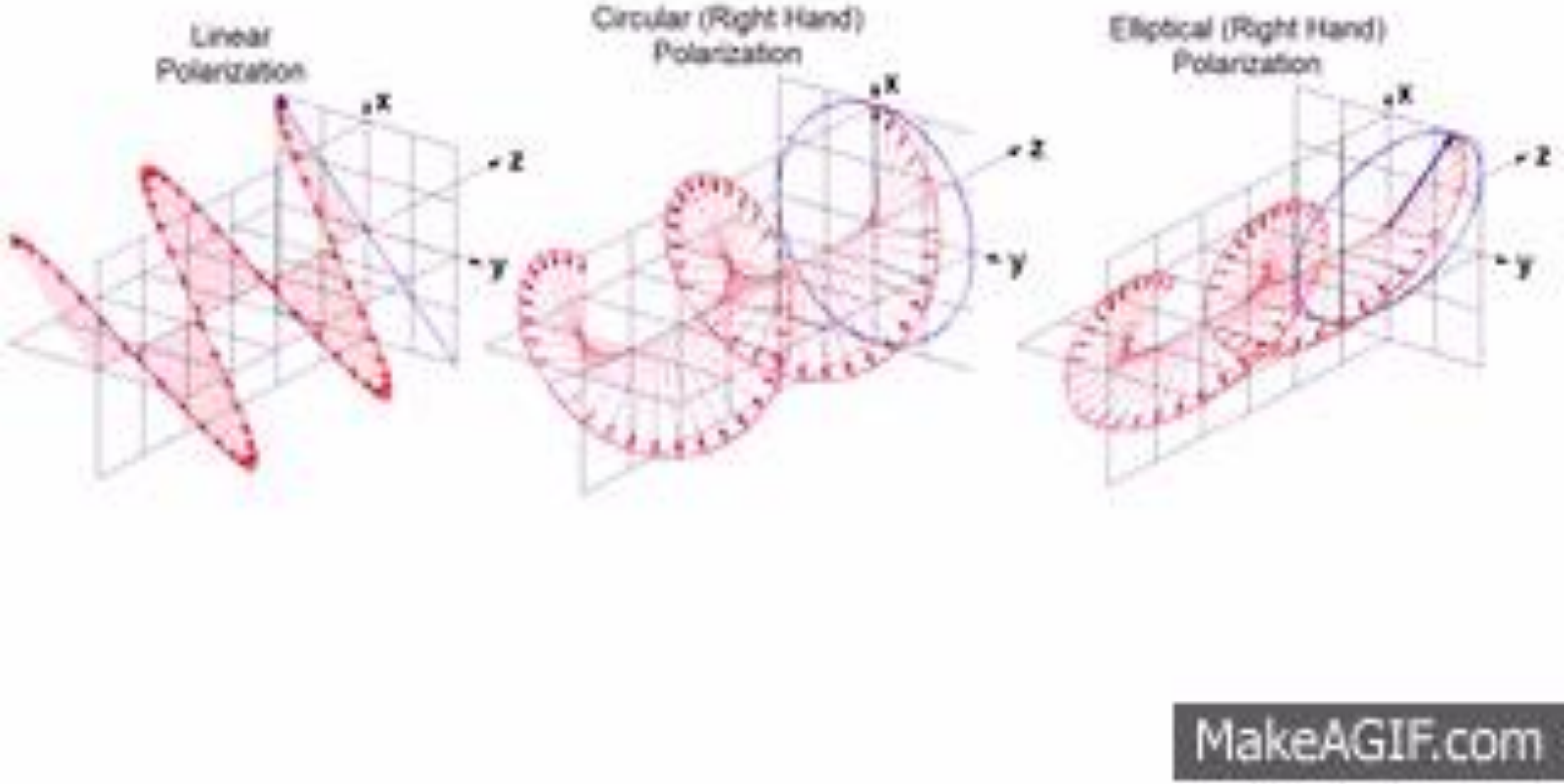
- Mapping of the magnetic field (**STRUCTURE !**)

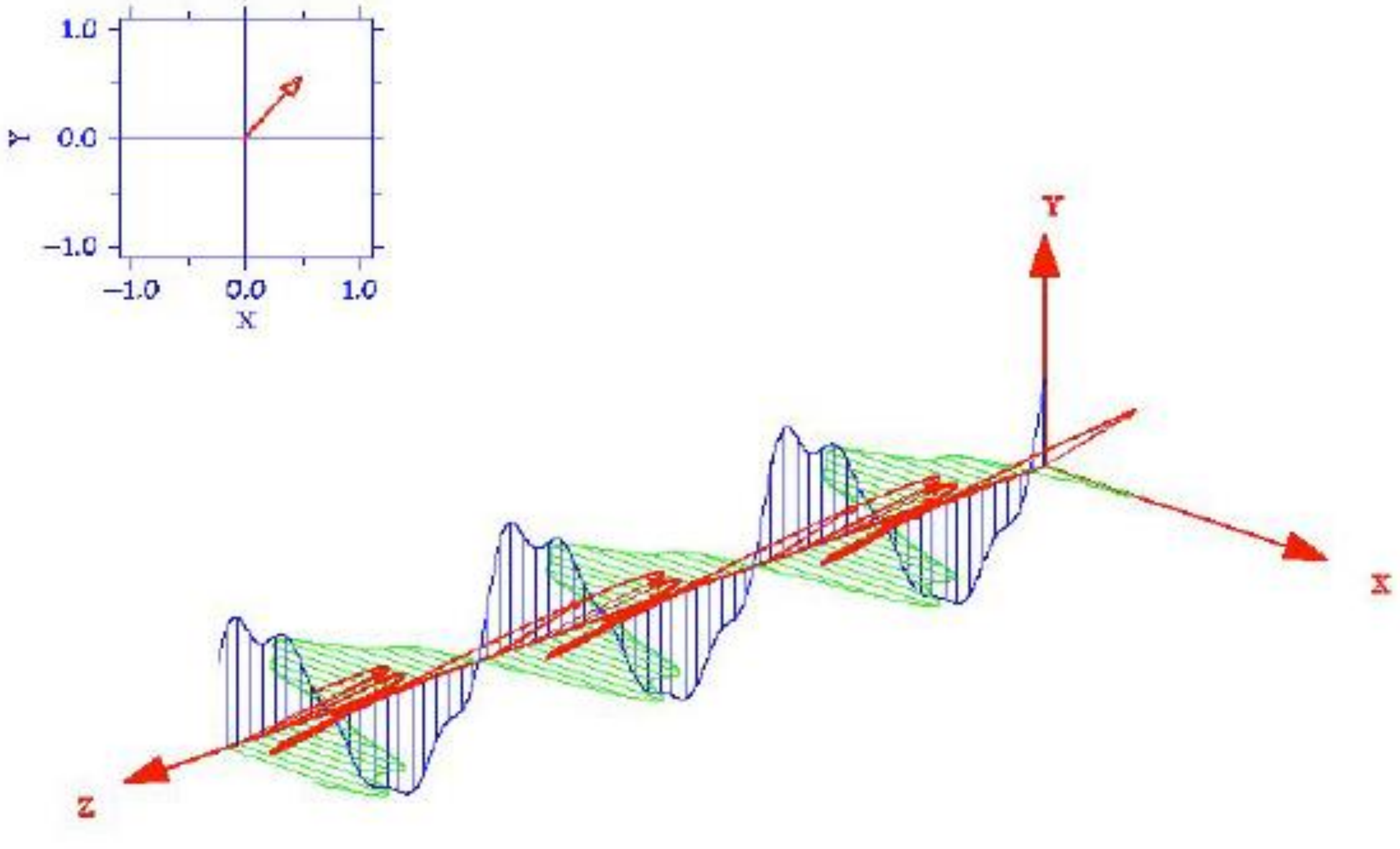
- Detailed study of nonthermal processes and associated emission regions (Synchrotron, Inverse Compton)

Electromagnetic waves: Look at E field only




Linear
Polarization
Circular (Right Hand)
Polarization
Elliptical (Right Hand)
Polarization
x
z
y
x
z
y
x
z
y
MakeAGIF.com

Unpolarized Light



When integrating over time, the net polarization is null

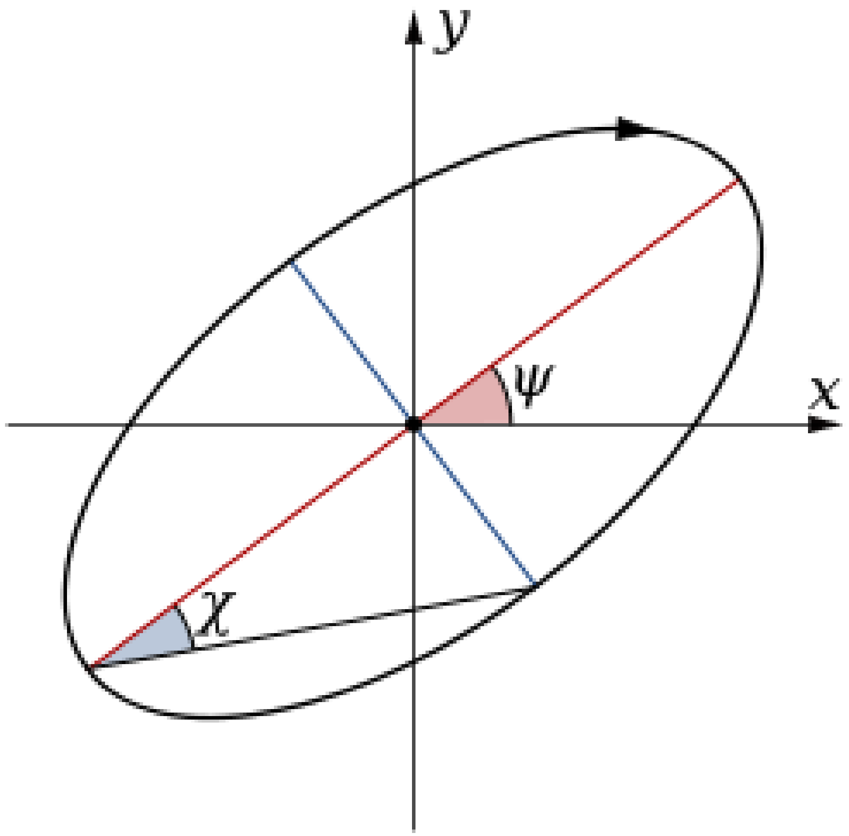
Stokes Parameters

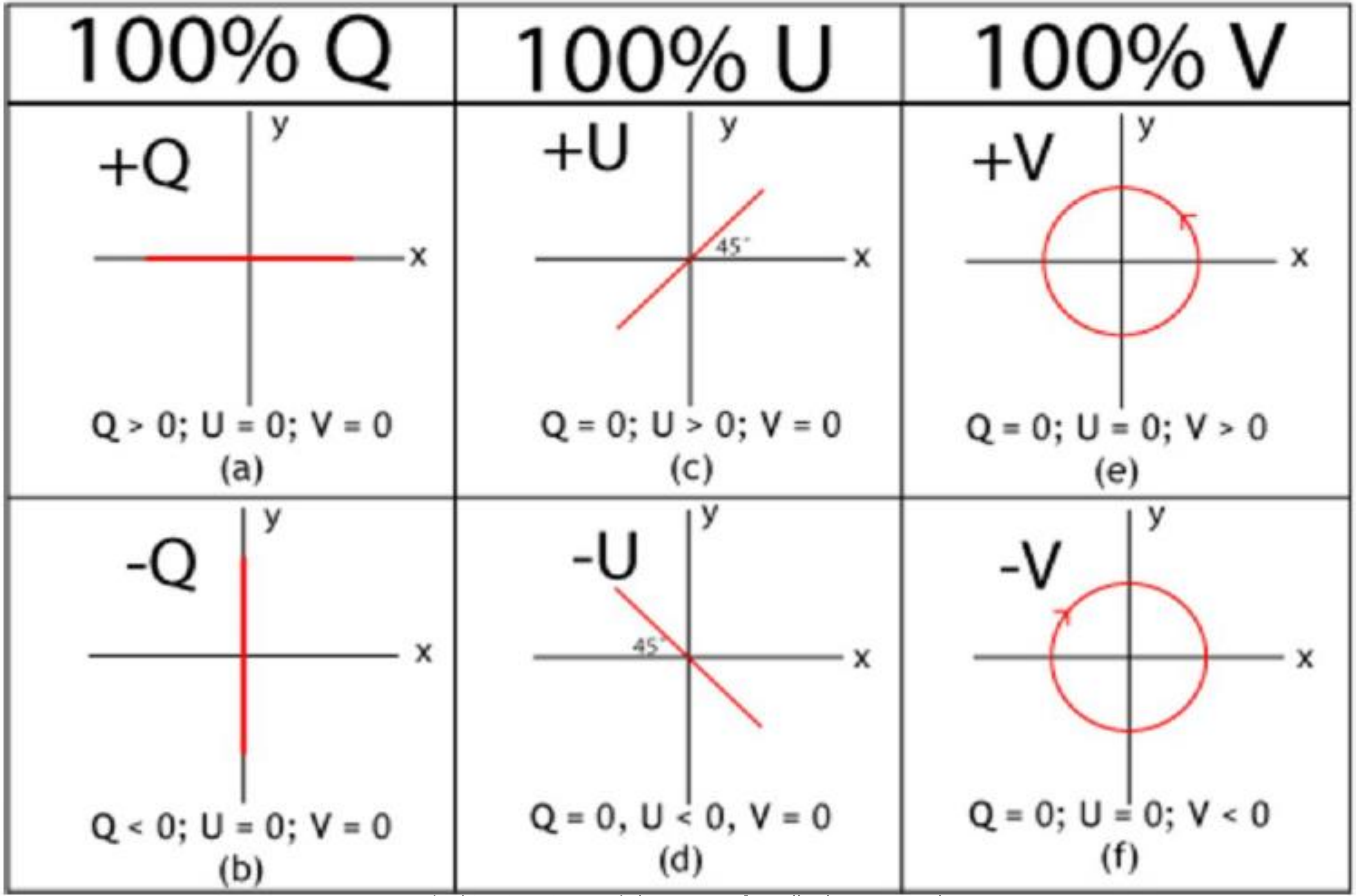
I ⟷ $S_0 = I$

Q ⟷ $S_1 = Ip\cos 2\psi \cos 2\chi$

U ⟷ $S_2 = Ip\sin 2\psi \cos 2\chi$

V ⟷ $S_3 = Ip\sin 2\chi$




100% Q
100% U
100% V
+Q
y
x
Q > 0; U = 0; V = 0
(a)
+U
y
45°
x
Q = 0; U > 0; V = 0
(c)
+V
y
x
Q = 0; U = 0; V > 0
(e)
-Q
y
x
Q < 0; U = 0; V = 0
(b)
-U
y
45°
x
Q = 0, U < 0, V = 0
(d)
-V
y
x
Q = 0; U = 0; V < 0
(f)

In general, the light that we will measure **is always partially polarized**, therefore:

$$\sqrt{Q^2 + U^2 + V^2} \leq I$$

$$P = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}, P_C = \frac{V}{I}$$

$$PA_L = \frac{1}{2}\tan^{-1}\frac{U}{Q}$$

$$PA_C = \frac{1}{2}\tan^{-1}\frac{V}{\sqrt{Q^2 + U^2}}$$

→ *PRESERVING QUADRANT TANGENT*

(USUALLY V<<Q, U IN OPTICAL OBSERVATIONS)

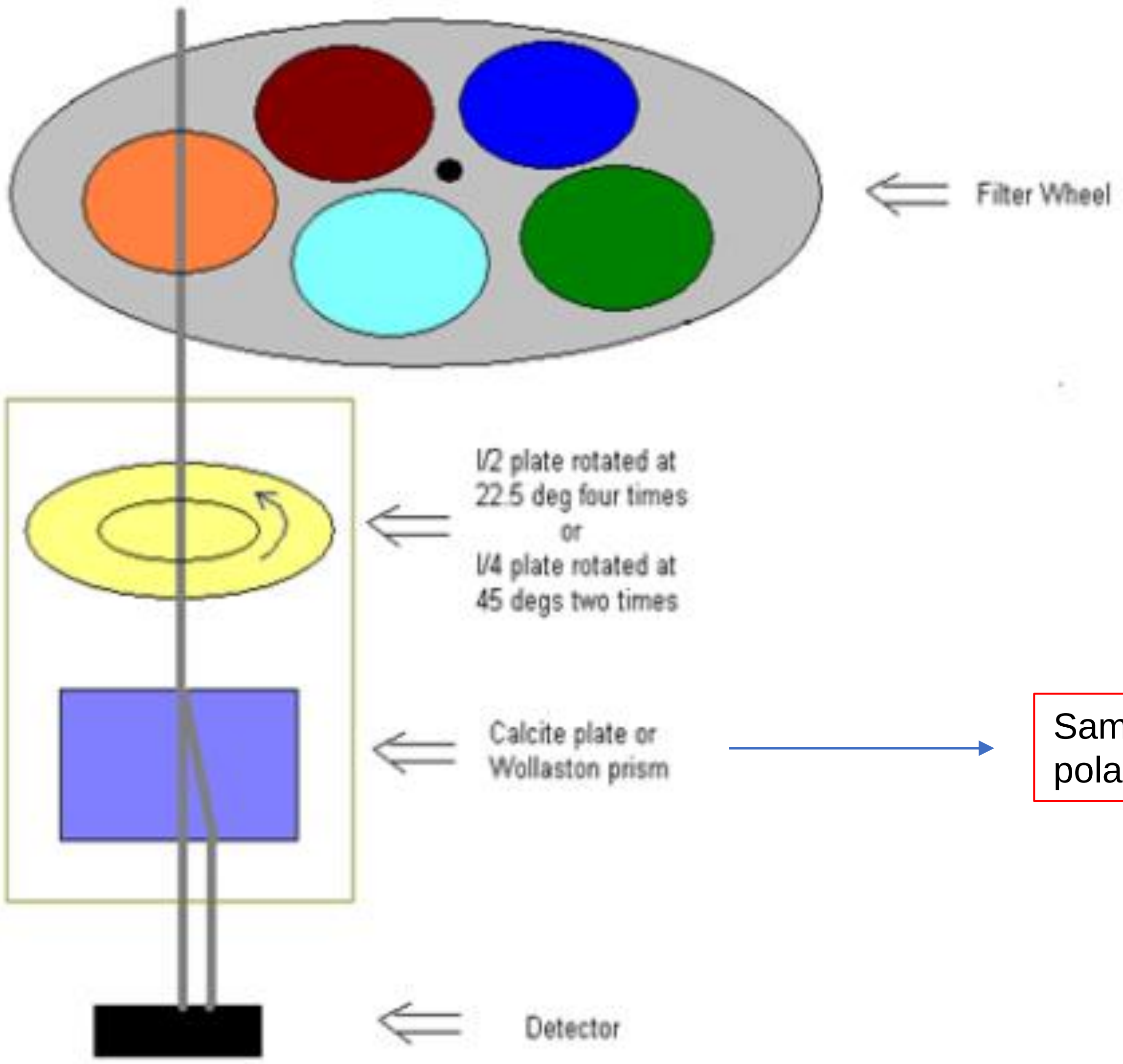
- Stokes parameters fully describe the polarization state of a light beam, regardless if it’s partially polarized/unpolarized.

- Stokes parameters describe the polarization state of a light beam irrespective of its spectrum (monochromatic or polychromatic).

- Stokes vectors are additive (Chandrasekhar 1950). The polarization status of a beam resulting from two beams is due to the sum of two beams. This is true if the two beams **are not** correlated (no phase dependence)! (**Use Jones calculus otherwise**).

Polarimeters design

The basic type of polarimeter that can be installed on a small telescope



Same sky conditions for both polarization states!

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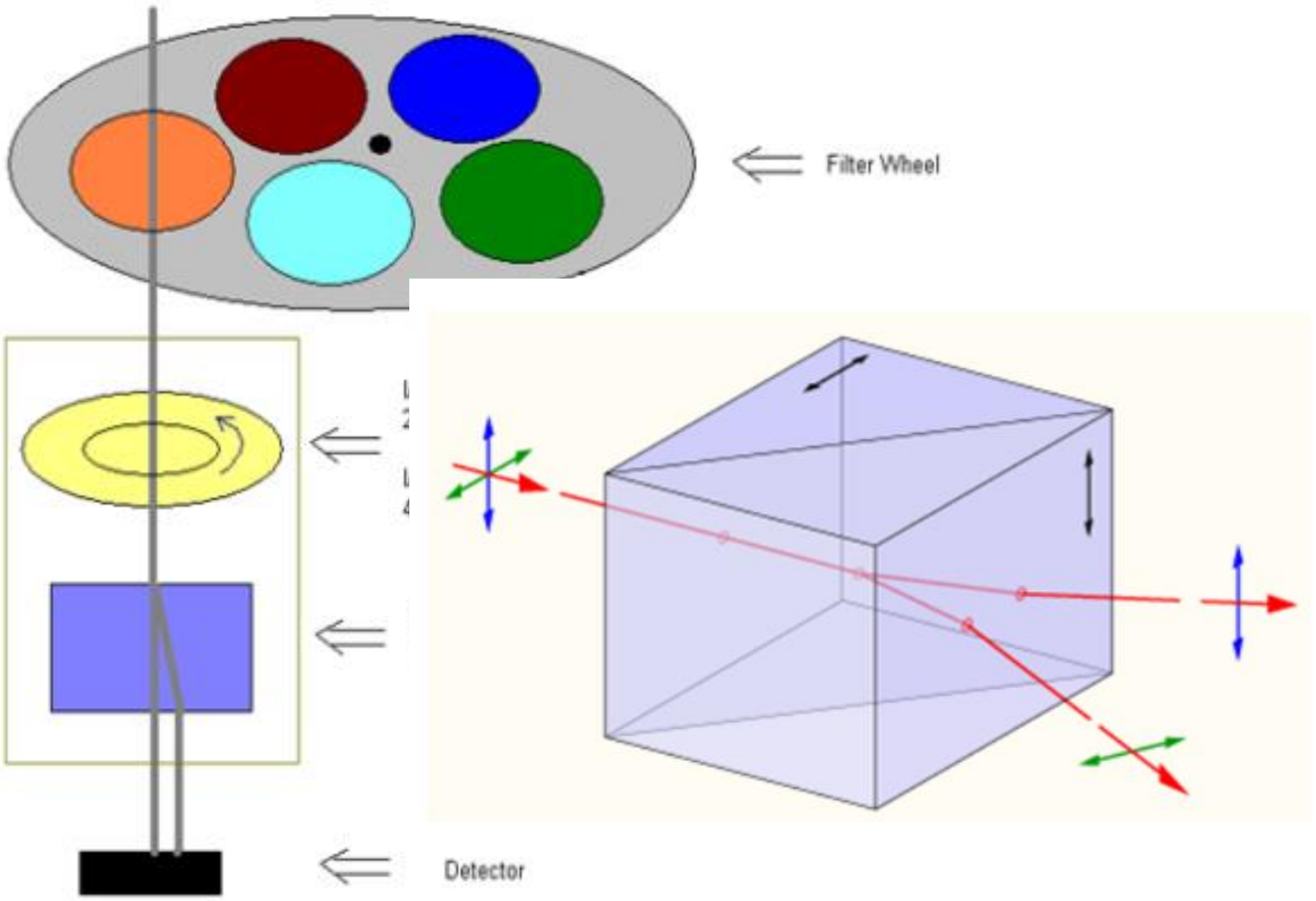
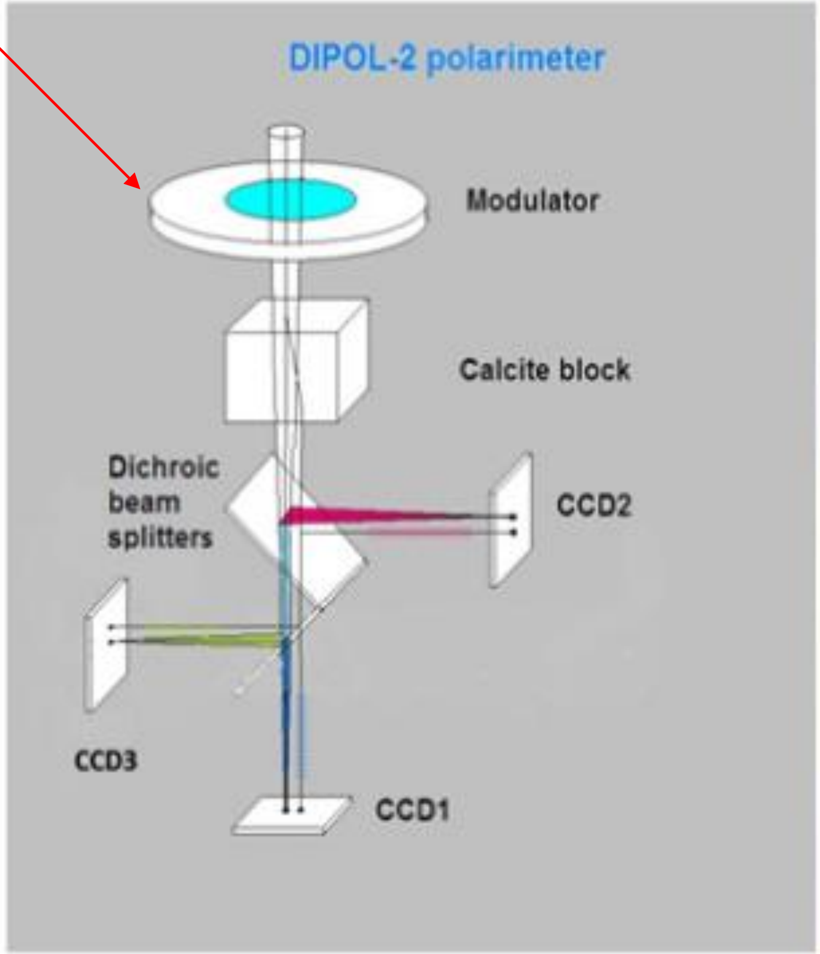
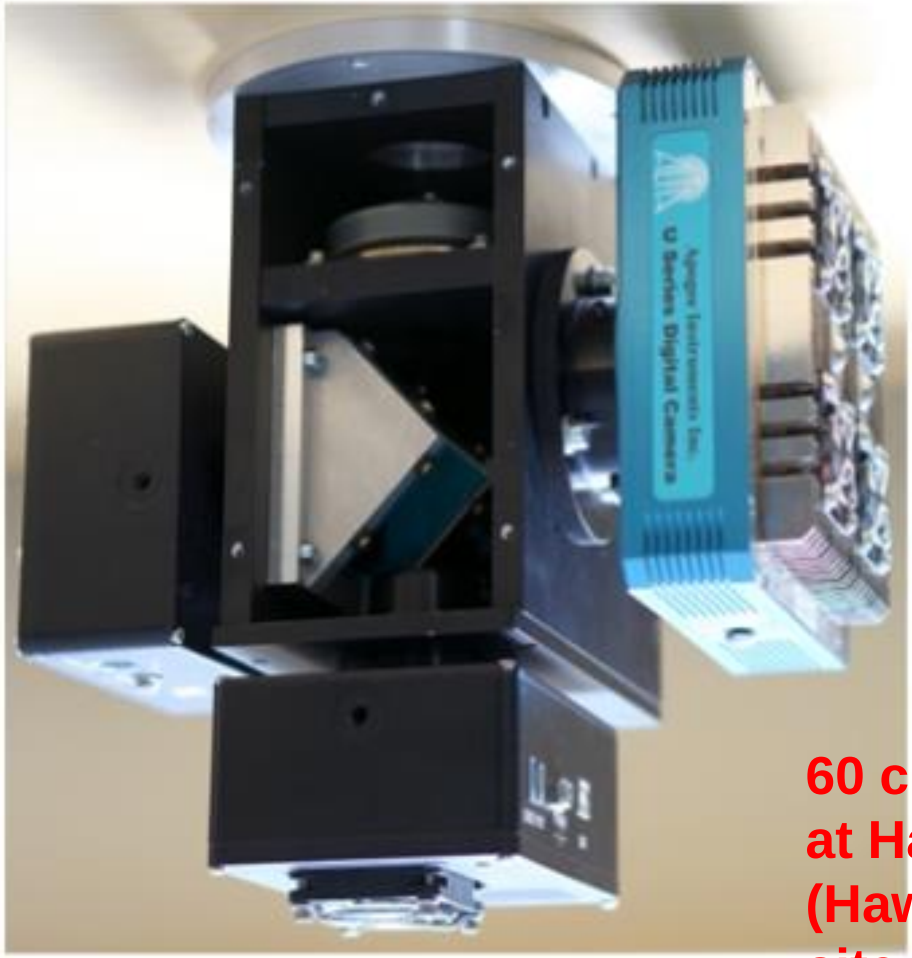


Another polarimeter: more sensitivity without so much effort...

SUPER-ACHROMATIC!





60 cm Telescope at Haleakala (Hawaii) telescope site.

Piirola et al. (2014), SPIE Vol. 9147

Data analysis

- N HWP positions (4, 8, 16...) are taken, so we have a **set of 2N equations** to be solved. Even if two positions would be sufficient to find Q and U, at least 4 positions are considered. Redundancy helps in reducing systematics errors and dispersions in the measurements!

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- If one has a polarimeter with a Wollaston prism, on the CCD they will compare two images of the target: these are the so-called ordinary (I_o) and extraordinary rays (I_e). This double-beam approach has the advantage of taking into account seeing variations in both polarization beams.

$$I_o = \frac{1}{2}(\, I + Q \cdot \cos(2\theta) + U \cdot \sin(2\theta)\,)$$

$$I_e = \frac{1}{2}(\, I - Q \cdot \cos(2\theta) - U \cdot \sin(2\theta)\,)$$

$$F_i = \frac{I_o - I_e}{I_o + I_e}$$

$$I = I_o + I_e$$

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$$\begin{cases} Q = \frac{2}{N}\sum_i^N F_i \cos(\frac{\pi}{2} i) \\ U = \frac{2}{N}\sum_i^N F_i \sin(\frac{\pi}{2} i) \end{cases}$$

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- If one has a good polarimeter, usually **4 angles are sufficient**. In this case, one can obtain Q and U in the following way
- $r = \frac{I_e}{I_o}; r_{TOT} = r_0 + r_{22,5°} + r_{45°} + r_{67,5°}$
- $\begin{cases} Q = \frac{r_{0°} - r_{45°}}{r_{TOT}} \\ U = \frac{r_{22,5°} - r_{67,5°}}{r_{TOT}} \end{cases}$

ERROR ANALYSIS

Remember that what one measures are the Stokes Parameters, while usually, from the scientific point of view, P and PA are considered.

If Q, U follows gaussian distributions, P and PA do not!!

$$P = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$PA = \frac{1}{2}\tan^{-1}\frac{U}{Q}$$

$$\sigma_P = \sqrt{\frac{Q^2}{P^2}\sigma_Q^2 + \frac{U^2}{P^2}\sigma_U^2}$$

$$\sigma_\chi = \frac{\sigma_P}{2P}$$

First order and no correlation!

How much photons do we require? →

$$\sigma_P = \frac{1}{\sqrt{N/2} \cdot SNR}$$

This means that with **SNR=100** and N=4, we obtain a **RMS error of 0,7%** in P**.**

If we want a precision of 0,1%, a SNR~700 is needed!

- All of these results are valid if the Stokes Parameters (and P and χ) follow Gaussian distributions.

- For Q and U this is valid for SNR~3, but NOT for P and χ!

- The reason for this is that P is the quadrature sum of Q and U and therefore statystical errors always sum in the positive direction.

- The error distribution tends to the Rayleigh function

$$R \sim R_M'\left[1 - \left(\frac{\sigma'}{R_M'}\right)^2\right]^{1/2}$$

Wardle&Cronberg, ApJ (1974)

$$f(P) = \frac{P}{< P >^2}\left\{1 - \exp[-\frac{1}{2}\left(\frac{P}{< P >}\right)^2]\right\}$$

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Other problems arise when dealing with polarization observations: Wollaston defects, HWP angle errors, sky polarization, background subtraction…but all of these can be controlled and calibrated

POLARIMETRY: OBSERVATIONS WITH SMALL TELESCOPES

(< 2 m)

- Stellar Physics (Radiative transfer, Be Stars, YSO, WRs, stellar/disk-winds, circumstellar matter...).
- Exoplanets (atmospheres)
- Galactic maps of the ISM (caveat: high-resolution instruments and very good observing site needed).

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Why a small telescope?

- Polarimetry require a lot of time (and photons), so the use of this technique is more difficult to obtain on very large telescopes ⟶ A small telescope has less constraint from this point of view (even if has its limitations on low magnitudes objects).
- Usually, it is crucial to map how a given structure changes in time, to constrain the physical processes going on that are affecting the polarization state ⟶ a small telescope can tackle this objective (with a dedicated instrument for example).
- If there's a transient one can map the polarization change of the source. A small telescope can have fast reaction times if no time is allocated.
- Last but not least: can provide new (and very good!) data to students for their theses or PhD project, permitting a more open science without trying to have time on high-end telescopes (see next example!).

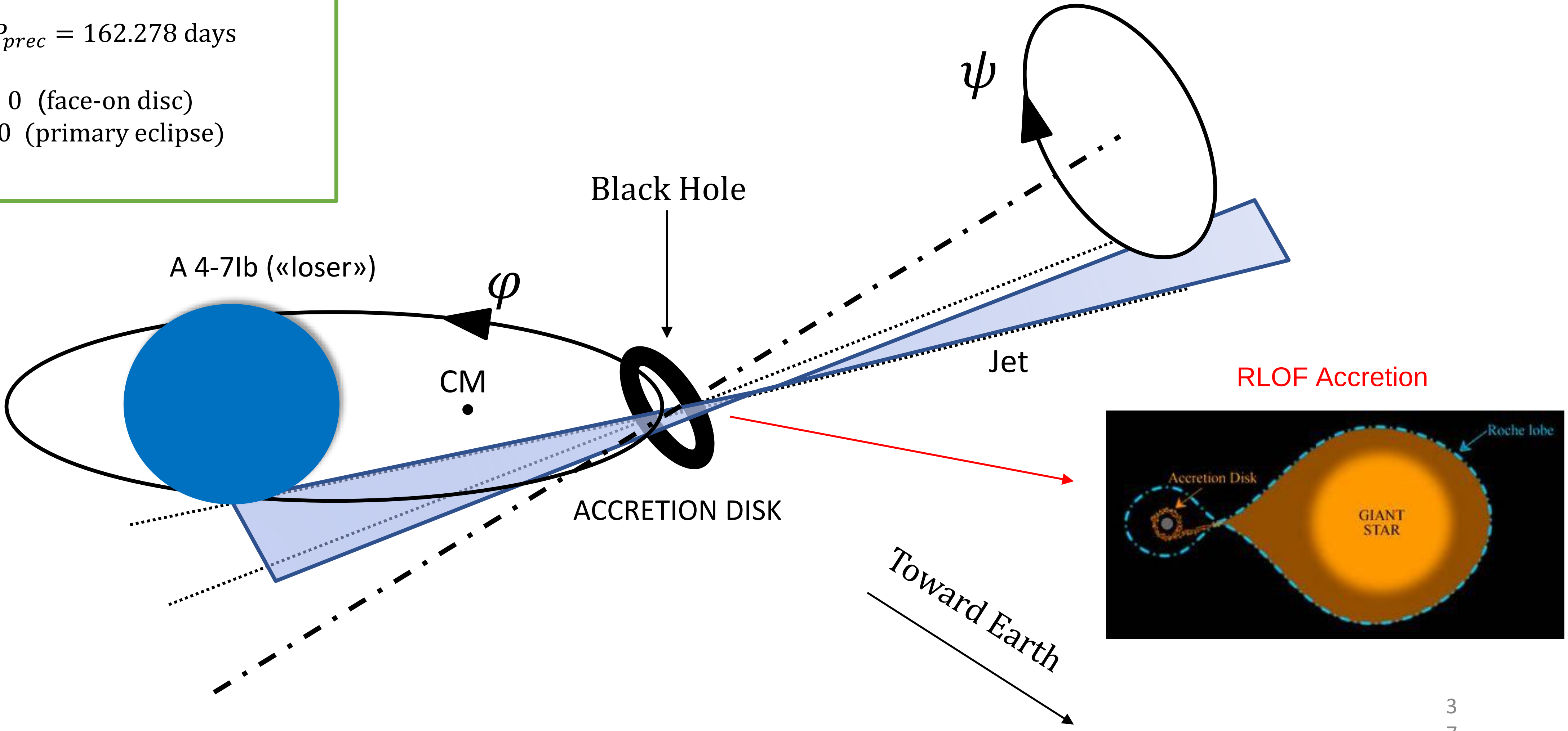
POLARIMETRY WITH SMALL TELESCOPES:
A PRACTICAL EXAMPLE.

SS 433: the prototype among microquasars.

$$P_{orb} = 13.08221 \text{ days}$$

$$P_{prec} = 162.278 \text{ days}$$

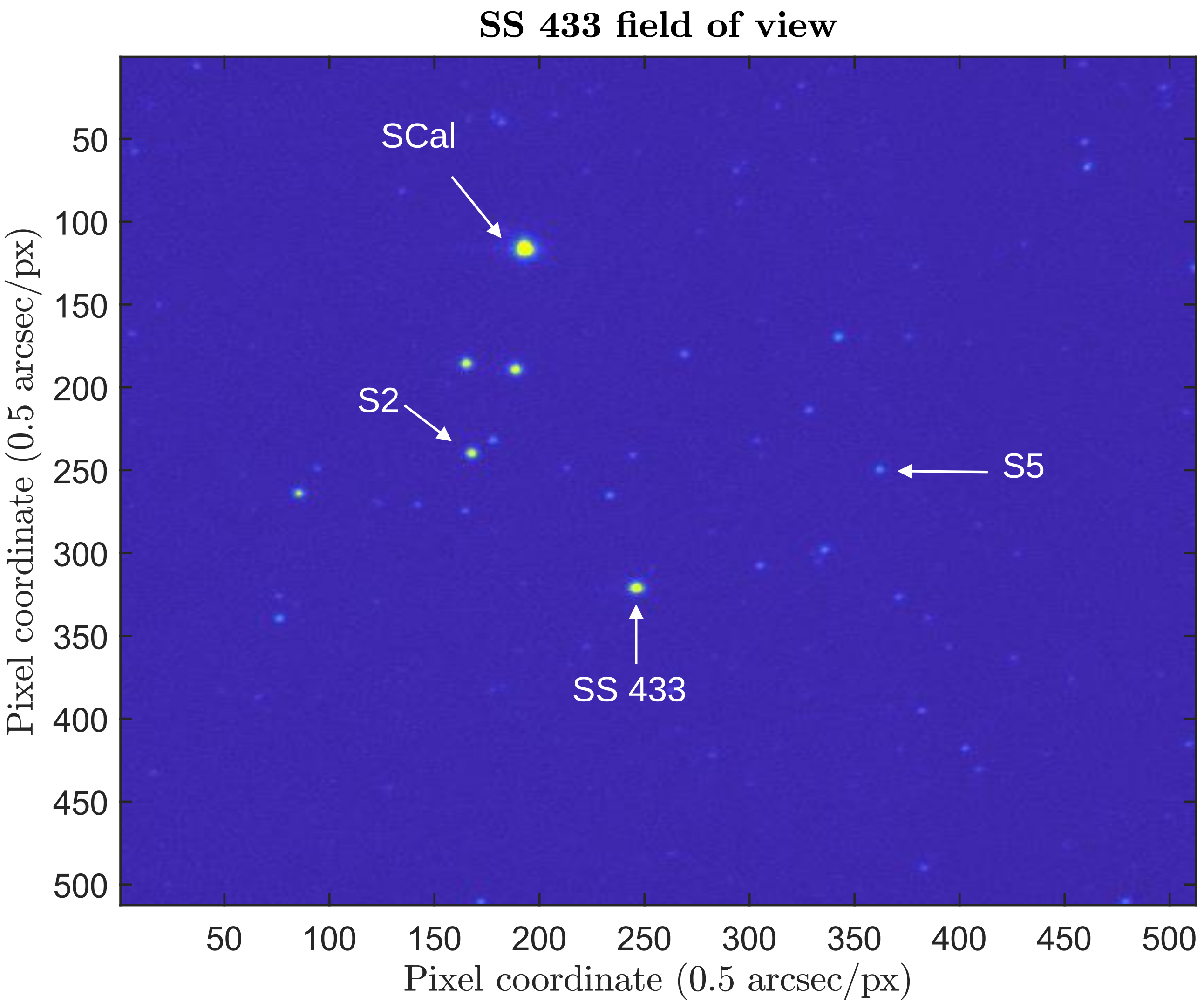
$\psi = 0$ (face-on disc)
$\varphi = 0$ (primary eclipse)



Once the data are calibrated you still cannot work on the data...ISM!!

METHOD APPLIED FOR SS 433

The ISM contributes to the measured polarisation!



$$q_{obs} = q_{SS433} + q_{ISM}$$

$$u_{obs} = u_{SS433} + u_{ISM}$$

Serkowski law:

$$p(\lambda) = p_{max}\exp(-1.13\ln^2\frac{\lambda}{\lambda_{max}})$$

Filter	$P(\%)$	PA (°)
$B\ S2$	1.91 ± 0.06	49.2 ± 1.0
$B\ S5$	1.10 ± 0.20	51.7 ± 5.2
$B\ SCal$	4.29 ± 0.20	176.3 ± 1.3
$V\ S2$	1.86 ± 0.06	48.0 ± 0.9
$V\ S5$	1.58 ± 0.21	52.6 ± 3.7
$V\ SCal$	4.37 ± 0.07	176.1 ± 0.5
$R\ S2$	1.78 ± 0.03	48.0 ± 0.4
$R\ S5$	1.27 ± 0.09	49.7 ± 2.0
$R\ SCal$	4.46 ± 0.03	176.9 ± 0.2

Picchi, P. et al, 2020, A&A, Vol 640

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Parallaxes and fit parameters
for the Serkowski law

Star	*Parallax (mas)* (GAIA DR2)	P_{max} (%)	λ_{max} (Å)	$\frac{\chi^2}{dof}$
S2	0.98 ± 0.03	1.93 ± 0.04	5082.5 ± 192.2	0.82
S5	1.51 ± 0.06	1.33 ± 0.08	5786 ± 1059	1.98
SCal	0.25 ± 0.08	4.48 ± 0.03	6065.3 ± 207.0	3.49

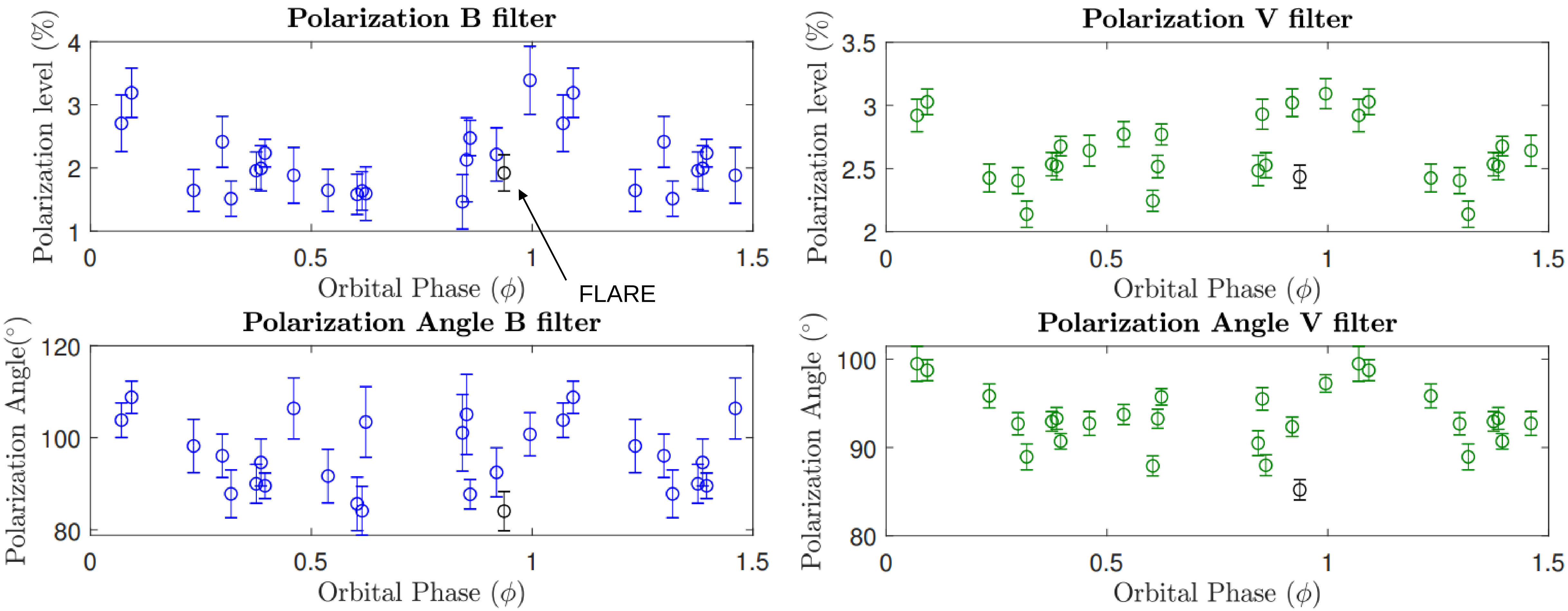
$\text{Parallax}_{SS433} = 0.22 \pm 0.06\ mas$

One needs to find the Serkowski law,
corresponding to the ISM in proximity of SS433.

Filter	q (%)	u (%)
U	3.21 ± 0.20	-0.42 ± 0.23
B	4.26 ± 0.20	-0.55 ± 0.19
V	4.33 ± 0.07	-0.60 ± 0.08
R	4.43 ± 0.03	-0.48 ± 0.03

Picchi, P. et al, 2020, A&A, Vol 640

RESULTS: Polarization



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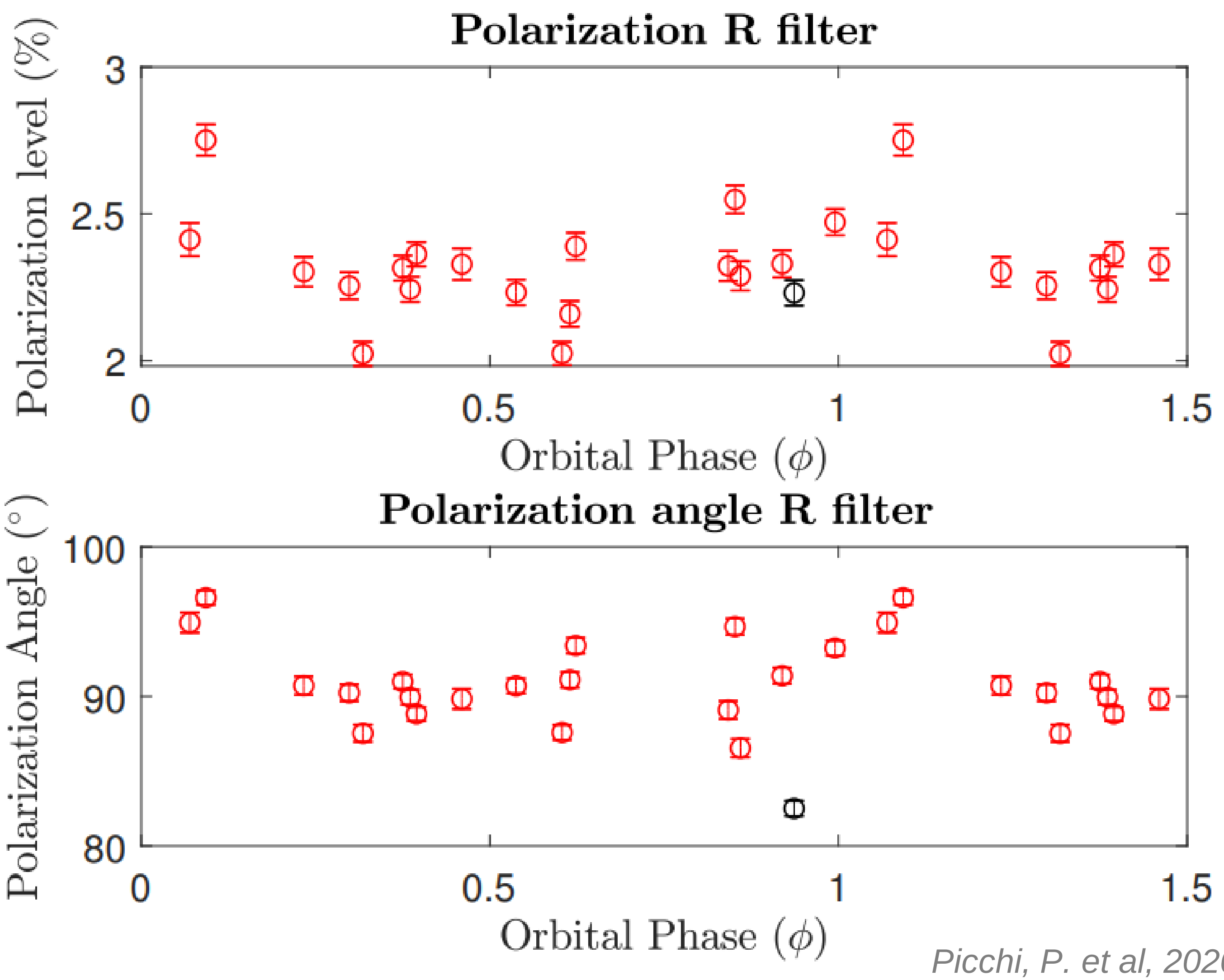


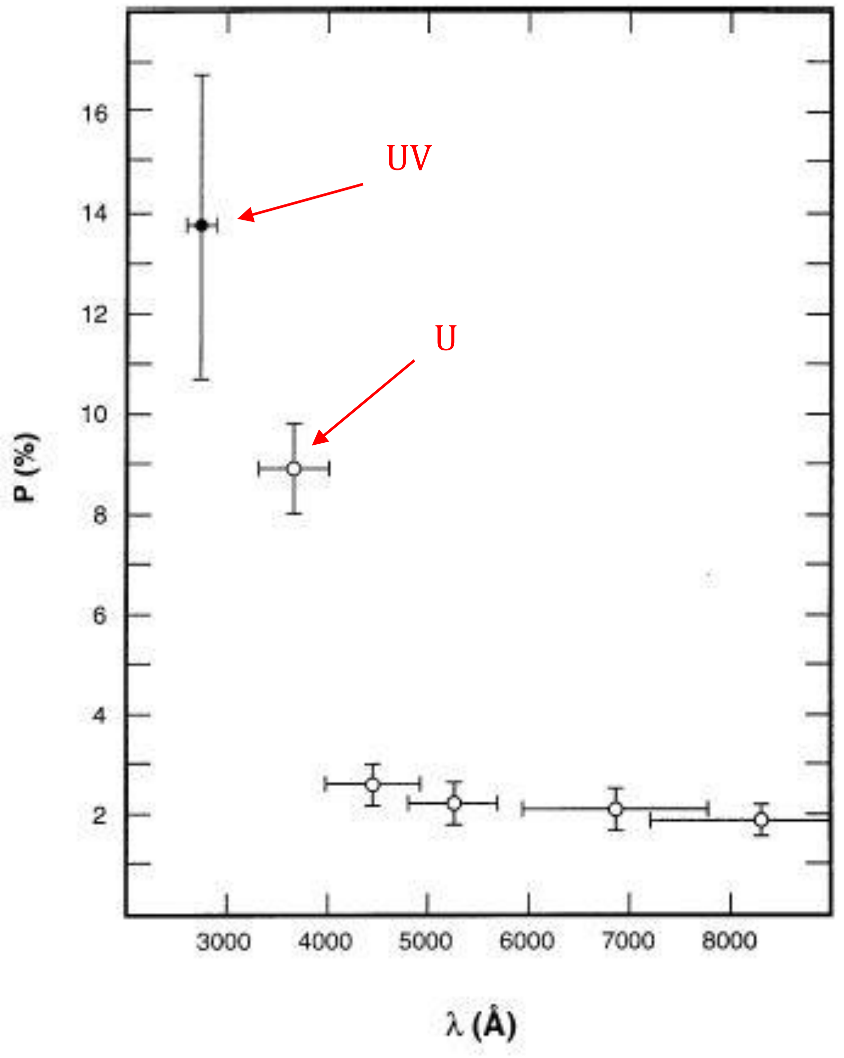
Picchi, P. et al, 2020, A&A, Vol 640

JUST THOMSON SCATTERING?

Dolan et al. (1997) took Hubble UV polarimetry measurements (with HSP instruments) of SS433 at 2772 A and in U, B, V, R, I bands.

Rayleigh scattering? $\sigma_R = \sigma_T \left(\frac{\lambda_0}{\lambda}\right)^4$

They measured a dramatic increase in PL toward UV, but strange shift in PA! They raised problems for calibration issues!



Dolan *et al.* (1997)

Polarization angle (°)					
DOLAN			PICCHI		
U	B	V	U	B	V
90 ± 10	141 ± 16	92 ± 18	90.9 ± 2.2	91.7 ± 7.5	92.3 ± 2.7

N.B. The jet position angle is of 100°!

CONCLUSIONS

- High quality polarimetric data have been taken with a small aperture telescope (60 cm) on a highly reddedned source ($B \sim 16$ mag, $R \sim 12$ mag)
- First intrinsic polarization measurements of SS433 have been obtained → understanding of intrinsic polarization process in the UV-optical region
- Confirmed the structure of the disk-wind as indicated also by spectroscopic data

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WHEN STUDYING HIGHLY COMPLEX SYSTEMS (AS OFTEN HAPPENS IN ASTROPHYSICS) IT IS CRUCIAL TO HAVE COMPLEMENTARY DATASETS THAT CAN DISENTANGLE THE MULTIPLE DEGENERACIES PRESENT IN THE SYSTEM.

«I read in the *Moniteur*, a few months ago, that Biot had read at the Institut a very interesting memoir on the *polarization of light*. No matter how much I rack my brain, I have no idea what that means.»

Augustin-Jean Fresnel to his brother, Léonor, May 1814.

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Questions, Comments, Concerns

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