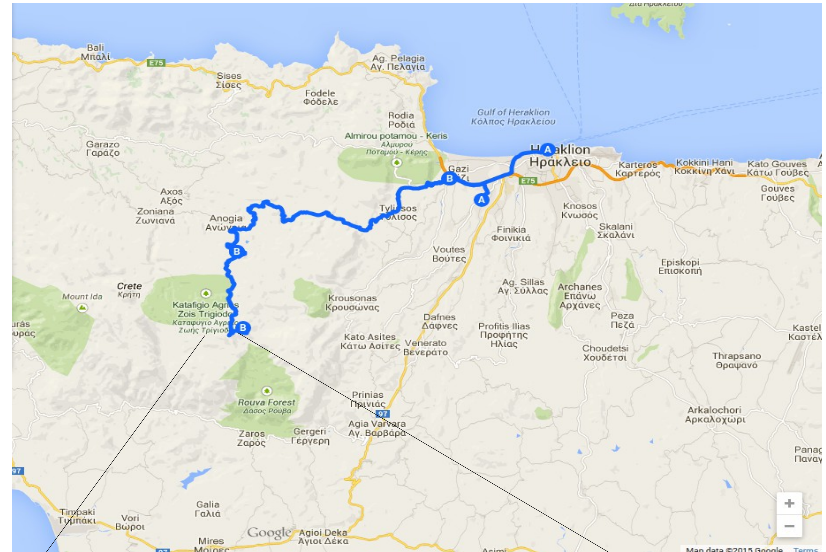
RoboPol: optical polarimetry in Crete

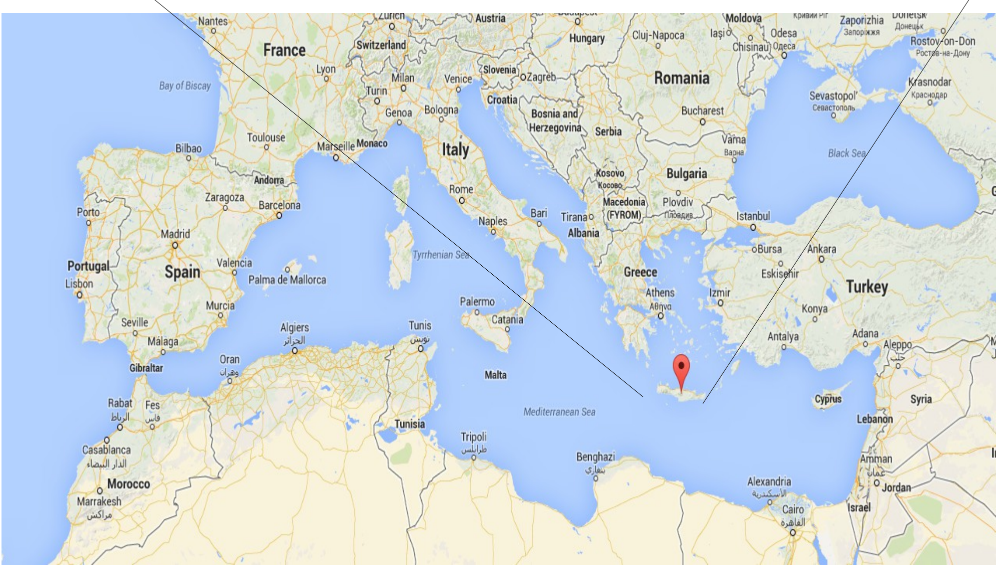
P. Reig (Foundation for Research & Technology-Hellas)
on behalf of the RoboPol collaboration

Outline

- Skinakas Observatory
- Robopol
  - the instrument
  - pipeline analysis & control system
  - science projects
- Future
  - Wide field polarimetry

Skinakas Observatory



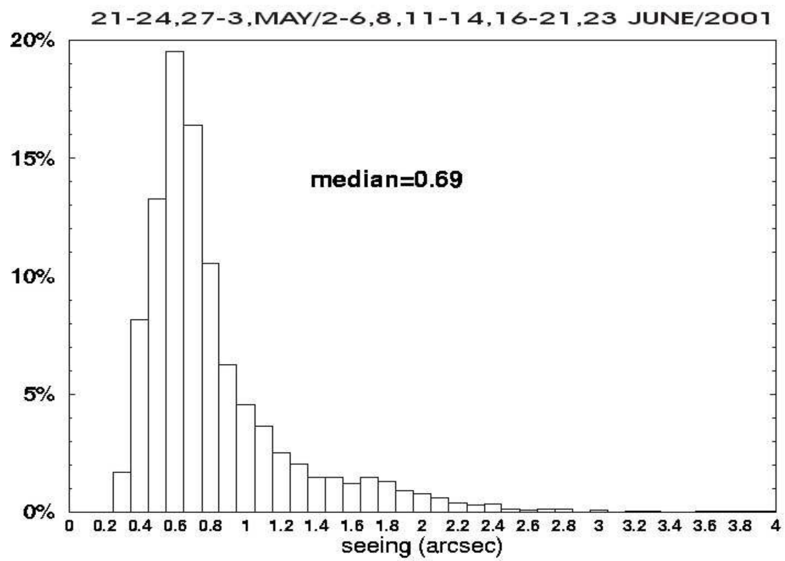


Equipment

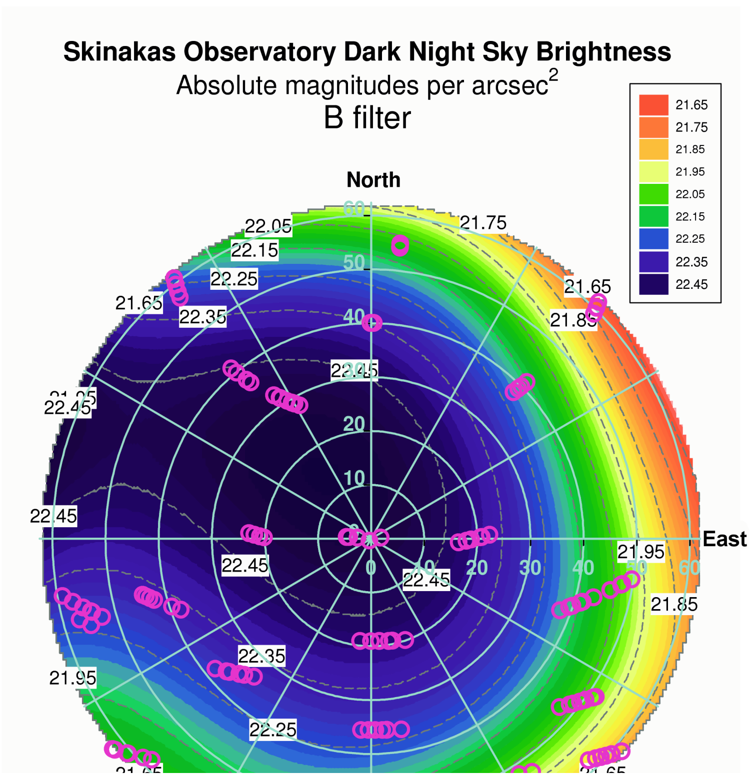
- Detectors
  - 2 ANDOR 2048X2048 13.5 μm
  - 2 PRINCETON PIXIS 2048 x 2048 13.5 μm
- Photometry
  - Optical: Jonhson, Strömgren and interference filters (OII, OIII, SII, NII, Hα, etc)
  - Infrared (J, H, K) and a set of narrow band filters (FeII 1644, H-2 2122, H-2 2144, BrG 2166, CO 2295)
- Spectroscopy
  - Set of gratings providing spectral resolution R=1000-8000
- Polarimetry
  - RoboPol photopolarimeter (BVRI)

Very good site

Seeing: Measurements with a DIMM give median of 0.5-1"



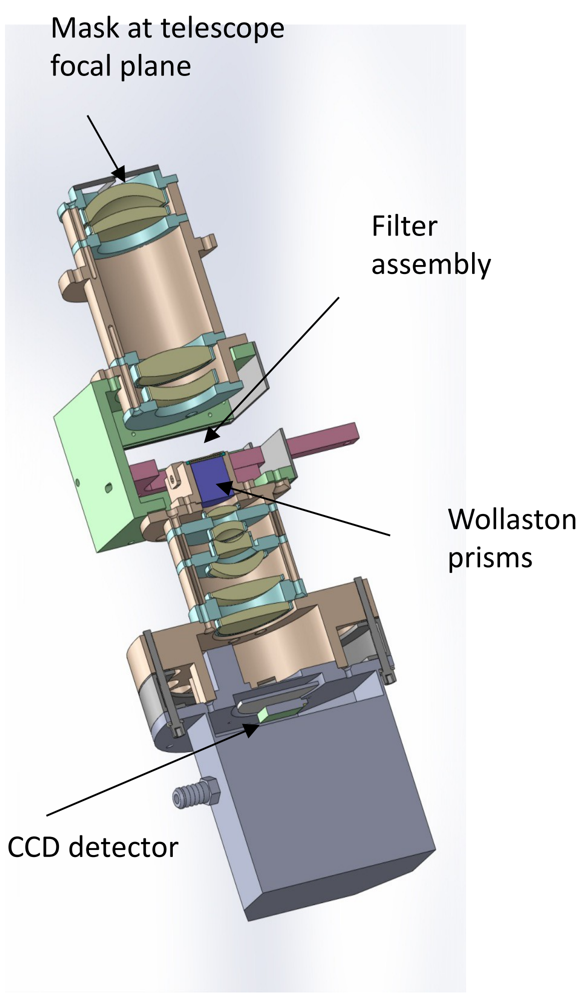
Sky brightness



- Operation period: April-November

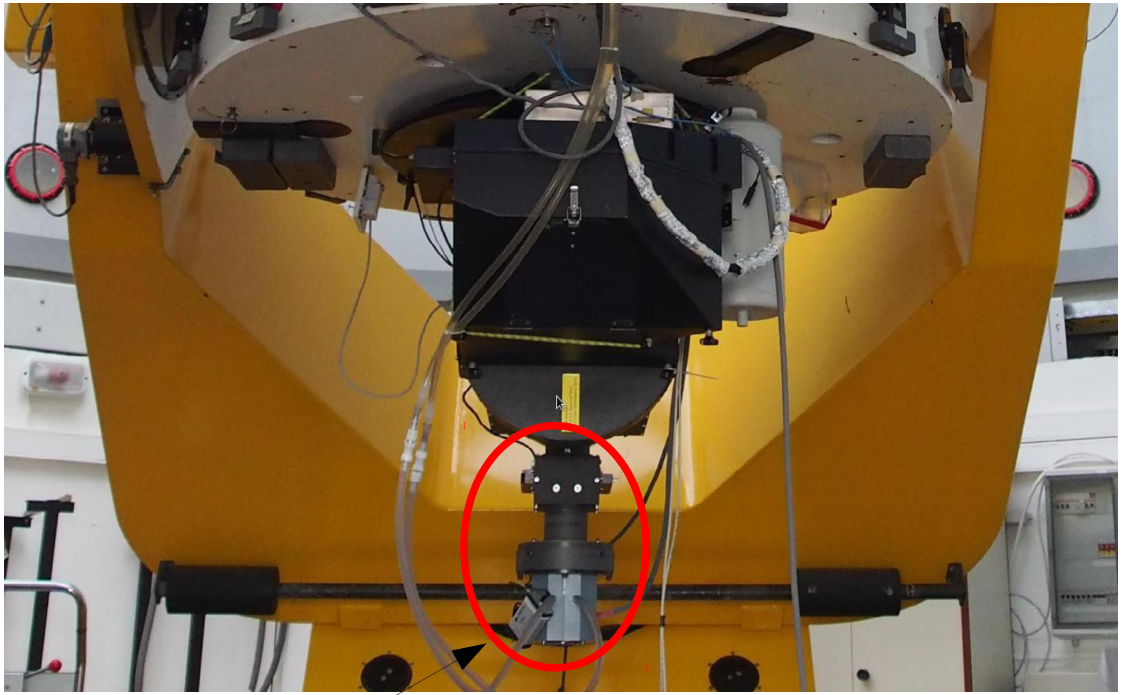


RoboPol: a novel instrument

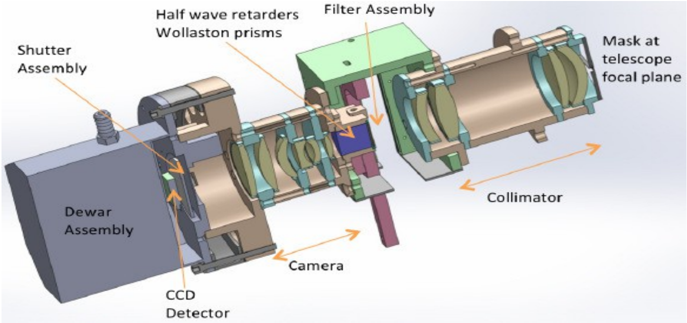


- The RoboPol polarimeter is an imaging photopolarimeter that measures the linear polarization and magnitude of all sources in the 13 × 13 arcmin field of view.
- Two distinct characteristics:
  - An optical polarimeter that can measure simultaneously Stokes I,Q,U parameters of celestial objects with no moving parts.
  - Robotic design: Designed for automated observing, data reduction and scheduling so as to maximize observing efficiency.
- Chronology
  - May 2010: First discussions
  - Mid-late 2011: funding found, MoU signed
  - 2012: instrument design and built
  - 13 May 2013: first light

1.3m telescope

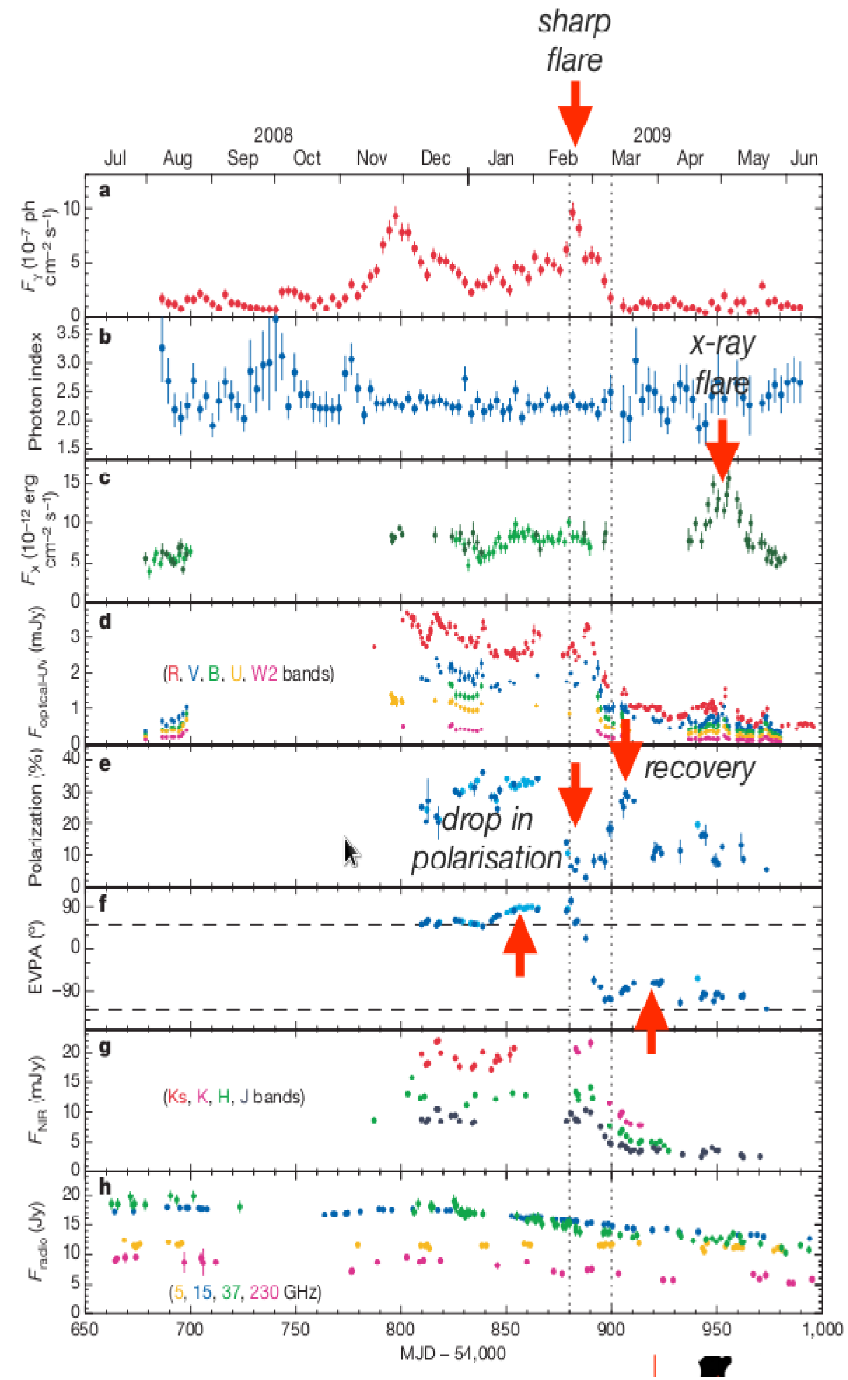


RoboPol



Robopol main science goal

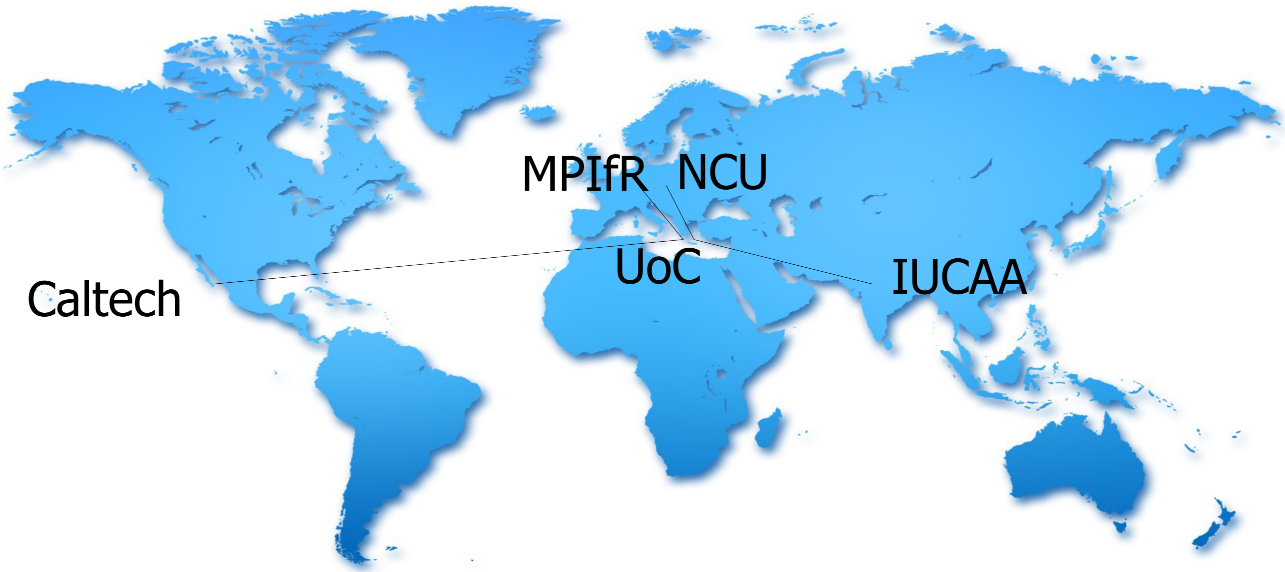
- to understand the link between optical polarization behaviour of AGN blazars, particularly the EVPA and gamma-ray flares. This is done by
- monitoring a large (~100 sources), well-defined sample of blazars in linear polarization with high cadence.
- Apply rigorous statistical methods to identify rotation events and study correlations with optical, radio, and γ-ray flares.
- also monitored by Fermi/NASA (in **γ-rays**) and by OVRO/CalTech in **radio**.



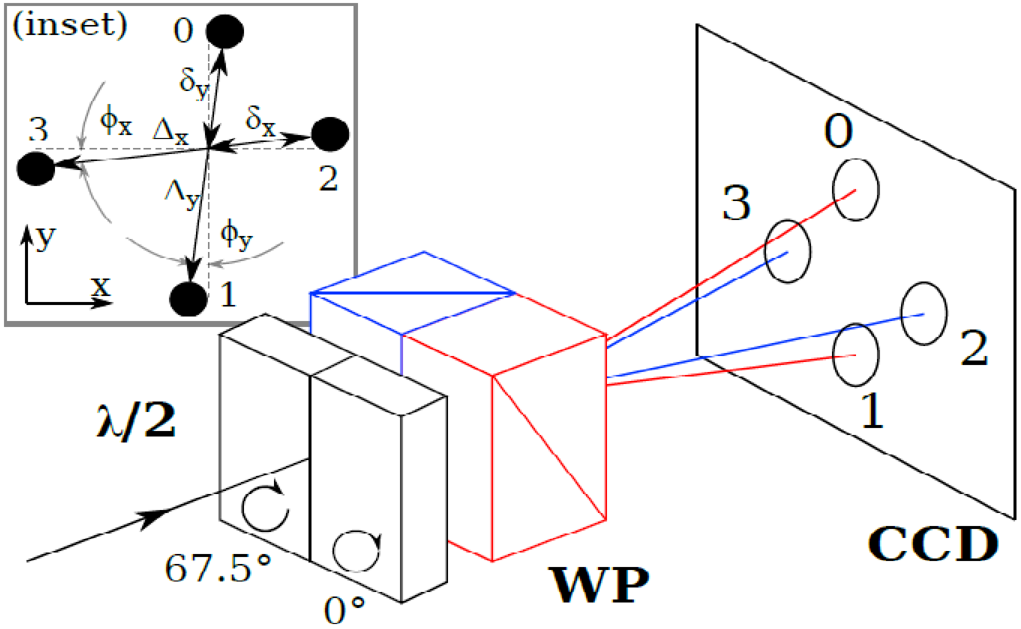
Abdo et al. 2010

Collaboration

- **California Institute of Technology, <u>USA</u>**: O. King, M. Baloković, T. Hovatta, T. Pearson, A. Readhead, A. Mahabal
- **University of Crete & FORTH, <u>Greece</u>**: V. Pavlidou, D. Blinov, N. Kylafis, G. Panopoulou, I. Papadakis, I. Papamastorakis, P. Reig, K. Tassis, I. Liodakis
- **Max-Planck Institute for Radioastronomy, <u>Germany</u>**: E. Angelakis, I. Myserlis, L. Fuhrmann, S. Kiehlmann, J. A. Zensus
- **Inter-University Centre for Astronomy and Astrophysics, <u>India</u>**: A. Ramaprakash, P. Khodade, C. Rajarshi, R. Rouneq
- **Nicolaus Copernicus University, <u>Poland</u>**: A. Kus, A. Marecki, B. Pazderska, E. Pazderski



Basic operation



- The incident light is split in two beams, each half incident on a half-wave retarder followed by Wollaston prisms, with differing fast axis and prism orientations.
- The fast axis of the half-wave retarder in front of the first prism is rotated by 67.5◦ with respect to the other retarder.
- One prism splits the rays in the horizontal plane (blue prism and rays)
- The other prism’s orientation splits them in the vertical plane

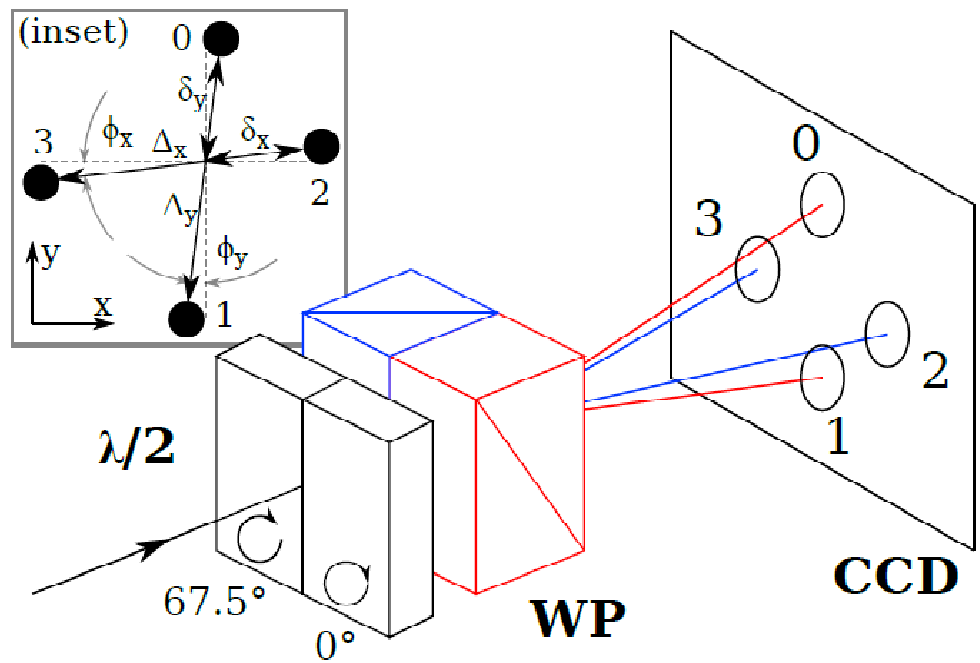
- **Every point in the sky is projected to four points on the CCD.**

- The linear polarization parameters are then calculated

$$q = \frac{N_1 - N_0}{N_0 + N_1}, \quad \sigma_q = \sqrt{\frac{4(N_1^2\sigma_0^2 + N_0^2\sigma_1^2)}{(N_0 + N_1)^4}},$$

$$u = \frac{N_2 - N_3}{N_2 + N_3}, \quad \sigma_u = \sqrt{\frac{4(N_3^2\sigma_2^2 + N_2^2\sigma_3^2)}{(N_2 + N_3)^4}},$$

where N_0,N_1,N_2,N_3 are the intensities of the upper, lower, right and left spots



Lather et al. (2012)

$$\sigma_i = \sqrt{N_i + \sigma_{\rm sky}^2 A_{\rm phot} + \frac{\sigma_{\rm sky}^2 A_{\rm phot}^2}{A_{\rm sky}}},$$

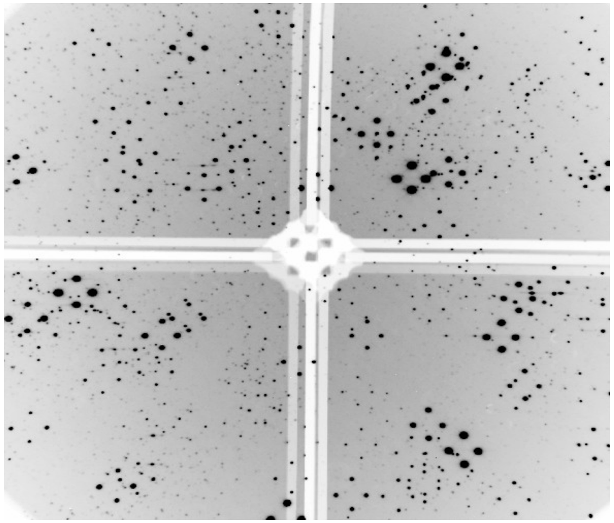
where N_i is the spot intensity, $\sigma_{sky} = n_{sky}$ is the sky intensity (background) in a single pixel, A_{phot} is the area (in pixels) of the photometry aperture, and A_{sky} is the area of the background estimation annulus.

$$p = \sqrt{q^2 + u^2}, \quad \sigma_p = \sqrt{\frac{q^2\sigma_q^2 + u^2\sigma_u^2}{q^2 + u^2}}$$

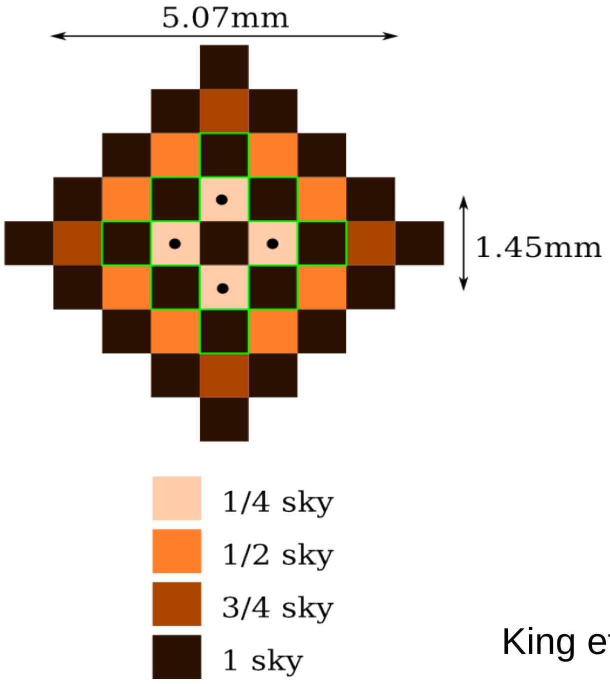
$$\chi = \frac{1}{2}\tan^{-1}\left(\frac{u}{q}\right), \quad \sigma_\chi = \frac{1}{2}\sqrt{\frac{u^2\sigma_q^2 + q^2\sigma_u^2}{(q^2 + u^2)^2}}$$

This design eliminates the need for multiple exposures with different half-wave plate positions hence minimizing the potential sources of error due to sky changes between measurements and imperfect alignment of rotating optical elements.

The Mask



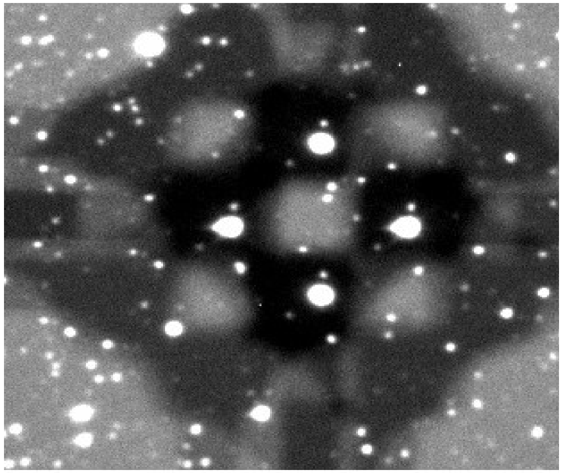
CCD sky brightness

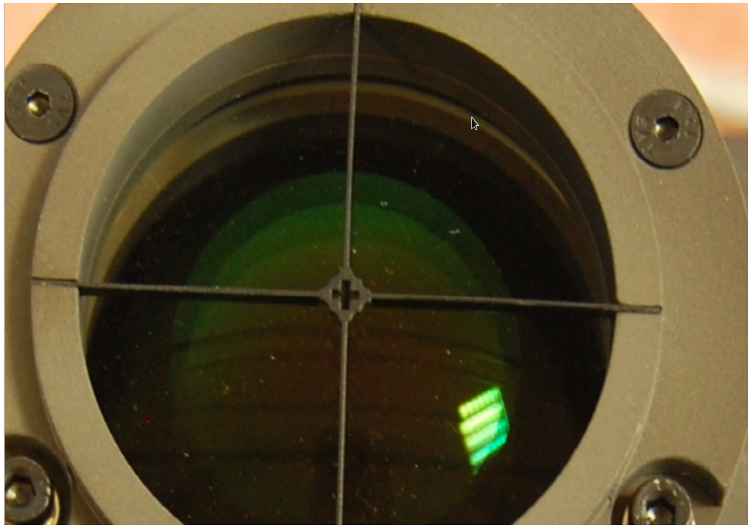


King et al. (2014)

A focal plane mask, held in place by four support legs:

- blocks unwanted photons from near-by sky and sources and prevents those photons from overlapping with the photons from the source
- reduces the sky background level for the central target.

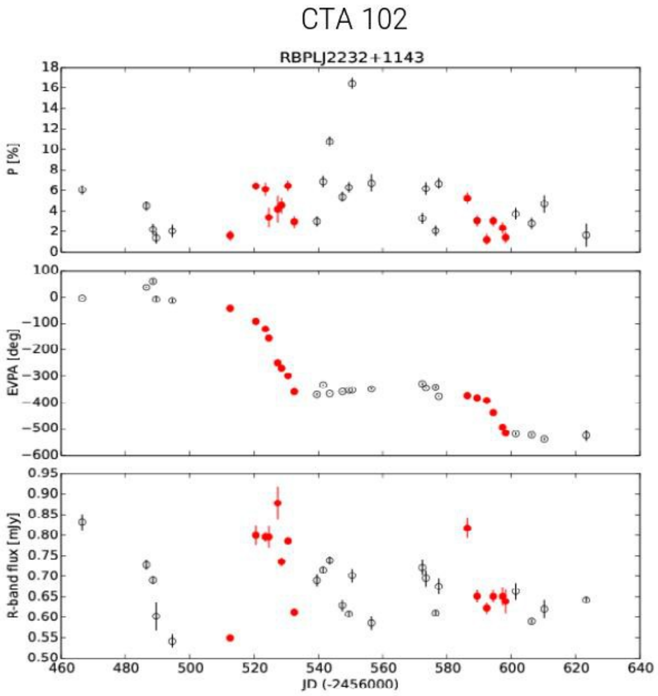


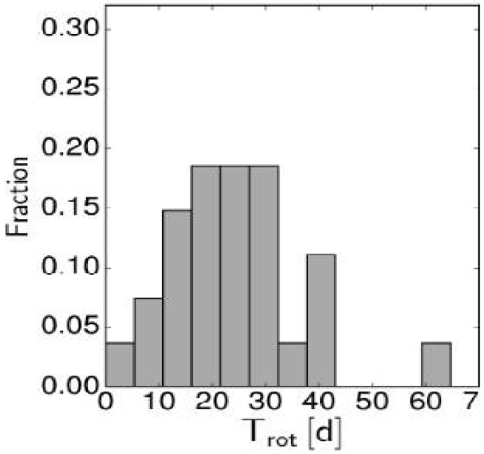


Automated operation & analysis

- Large amount of data (observing time: four nights a week on average)
  - High cadence – once every two/three days
- Fast response to events
  - Adaptive cadence for targets that become interesting

fully automated data reduction **pipeline** and observing procedure





Blinov et al. 2015, in prep

Blinov et al. (2015, in prep.)

Pipeline

- The main pipeline steps:
  - ➡ 1. source identification: find all the spots on the CCD and reverse the 1-4 mapping
  - ➡ 2. photometry: perform aperture photometry on each of the spots
  - ➡ 3. calibration: apply instrument model to correct spot intensities
  - ➡ 4. polarimetry: measure the linear polarization of every source in the field
  - ➡ 5. relative photometry: measure the R-band magnitude of every source using field sources and the Palomar Transient Factory catalog

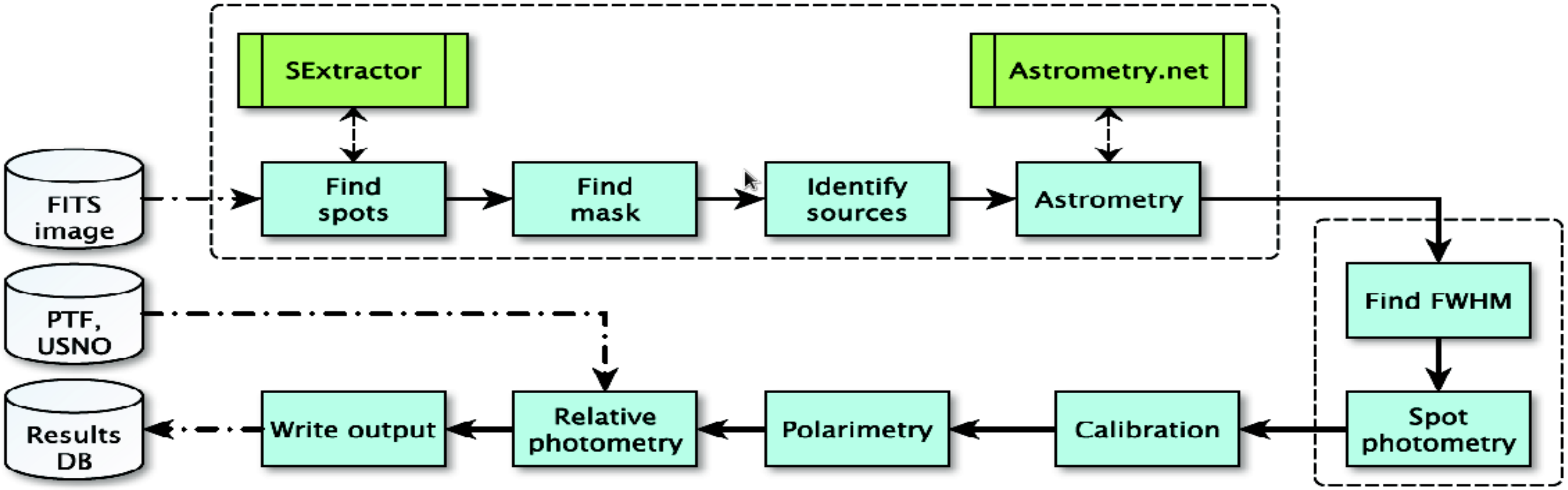
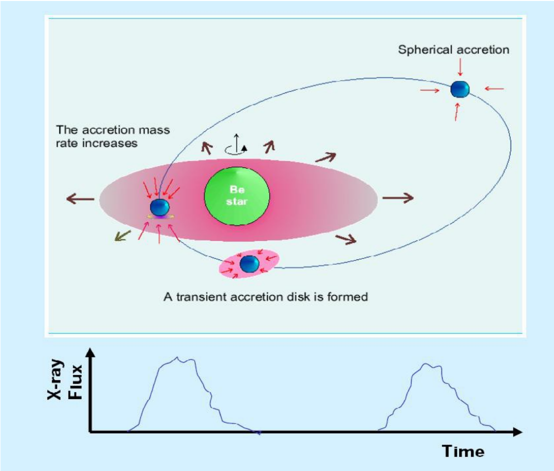
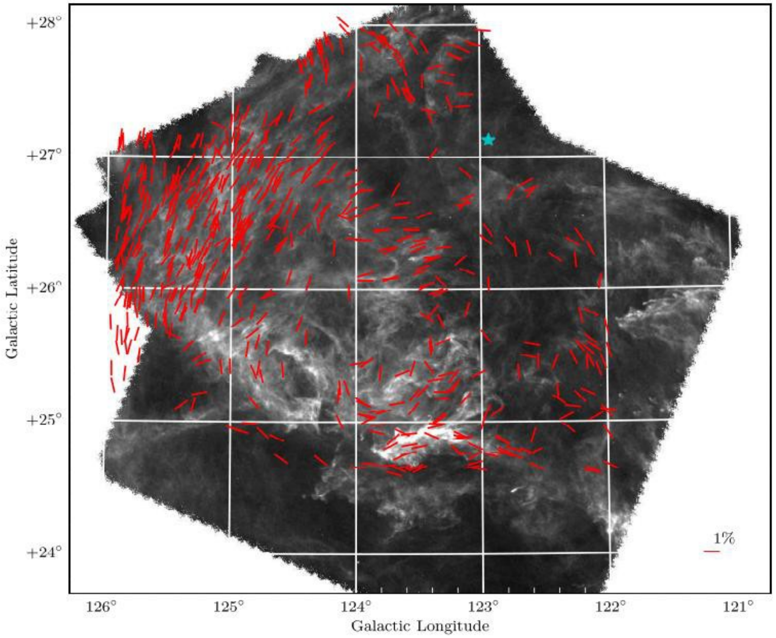


Figure 3. Flow chart representation of the operation of the pipeline. The FITS image from the CCD is first processed in a source identification step (Section 3.2), in which we match spots to sources in the sky and calculate their astronomical coordinates. We then perform photometry on all the identified sources (Section 3.3). The measured spot counts are corrected for instrumental errors in the calibration step (Section 3.4) before we measure the linear polarization (Section 3.5) and relative photometry (Section 3.6).

Projects

- **AGN Blazars**
  - Rotation and γ-ray flares
  - Host galaxies of blazars
  - Monitoring of TeV blazars
- **Monitoring of Be/X-ray binaries**
  - Polarimetric properties of Be stars in X-ray binaries
- **The interstellar medium**
  - Map the magnetic field in molecular interstellar clouds to understand the initial stages of star formatio
- Potential for new discoveries (wide field)
  - Polarization of field objects: classification, identification of different types of objects, especially quasar candidates
  - Light curves: search for optical transients
  - Polarimetric standards





Polaris cloud: a map of 609 polarization segments showing the magnetic field structure of the cloud as projected on the plane of the sky. Median p=1.3%.

Panopoulou et al. (2015)

Publications

- **Robopol**
  - King et al. 2014, MNRAS, 442, 1706 *The RoboPol pipeline and control system*
- **Blazars**
  - Pavlidou et al. 2014, MNRAS, 442, 1693 *The RoboPol optical polarization survey of gamma-ray-loud blazars*
  - *Blinov et al. 2015, MNRAS, 453, 1669 RoboPol: First season rotations of optical polarization plane in blazars*
- **ISM**
  - Panopoulou et al. 2015, MNRAS, 452, 715 *Optical polarization map of the Polaris Flare with RoboPol*
- **BeXB**
  - Reig et al. 2014, MNRAS, 445, 4235 *The high optical polarization in the Be/X-ray binary EXO 2030+375*
- **Other**
  - King et al. 2014, MNRAS, 445, L114 *Early-time polarized optical light curve of GRB 131030A*

- Plus 4 PhD thesis projects using Robopol as main source of data

COST STSM

- Dr. Talvikki Hovatta
  - April 20-30, 2014: Optical polarization of blazars and the effect of host galaxy dilution
  - November 2-10, 2014: Polarization Monitoring of TeV Blazars
- Dr. Agnieszka Słowikowska
  - August 24-September 7, 2013: observations and analysis of BeXB
  - June 7-14, 2014: observations and analysis of BeXB; orbital polarimetric variability of BeXB
- Dr. Krzysztof Krzeszowski
  - August 24-September 7, 2013: development of software
  - June 7-14, 2014: development of software
- M.Sc. Michał Żejmo
  - October 19-31, 2014: polarimetric observations of WD and orbital polarimetric variability of BeXB

- Dr. Pablo Reig (outgoing)
  - September 1-7, 2015: polarimetric observations of Be star in open clusters

Future

- Plans for a "RoboPol South"
- Wide field polarimetry (PASIPHAE/WALOP)
  - RoboPol mask accuracy in the field
    - How? new polarimeter design: each of 4 spots projected on a different CCD:
      - No confusion
      - High sensitivity
      - Flat-fielding possible
    - Run concurrently in north (Skinakas)

    and south (SAAO)
    - cost driver: 8 CCDs