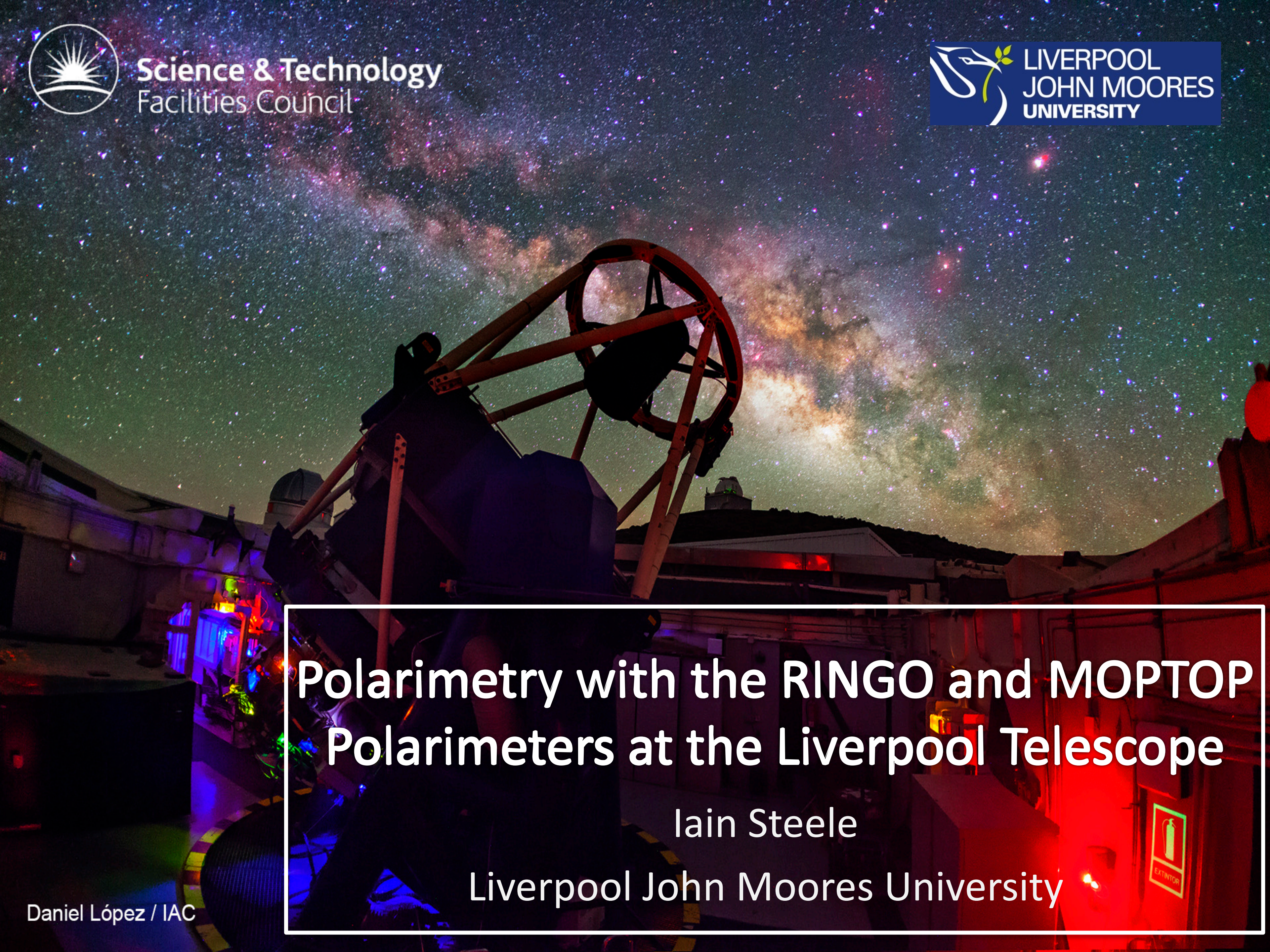

Daniel López / IAC

Science & Technology Facilities Council

LIVERPOOL JOHN MOORES UNIVERSITY

Polarimetry with the RINGO and MOPTOP Polarimeters at the Liverpool Telescope

Iain Steele

Liverpool John Moores University

LIVERPOOL TELESCOPE:

- First light in July 2003, robotic observations began in 2004 (La Palma)
- Clamshell design enclosure; two shutters, three separate portals (3 mins to open).
- Designed for *rapid* follow-up of transient sources such as novae, supernovae and GRBs.
- World's largest *fully autonomous*, robotic telescope. *Not* 'remote control'.

- 2m Ritchey-Chrétien Cassegrain optics (f/10)
- Altitude/azimuth mount
- Slew rate 2°/sec on all axes (mean time to target 3 minutes from alert)
- Acquisition and Guidance (A&G) box at Cassegrain focus gives one straight-through port and eight science fold ports accessed by deployable science fold mirror at 45°.

Instrumentation (change time <30s)

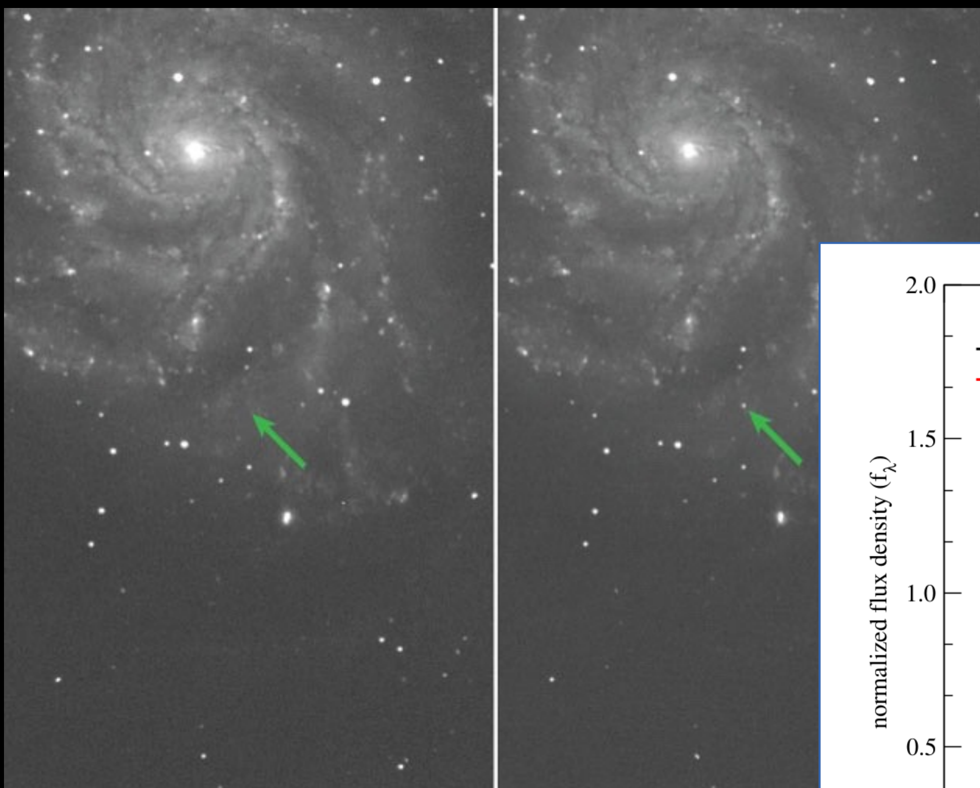
- **IO:O** – 10x10 arcmin optical imager (many filters)
- **SPRAT** – long-slit spectrometer
  - R~ 350, 400-800 nm wavelength coverage
- **RISE** – 9 arcmin diam. rapid-readout (0.8 sec) optical imager
- **MOPTOP** – 7 arcmin band polarimeter (BRVI filters)

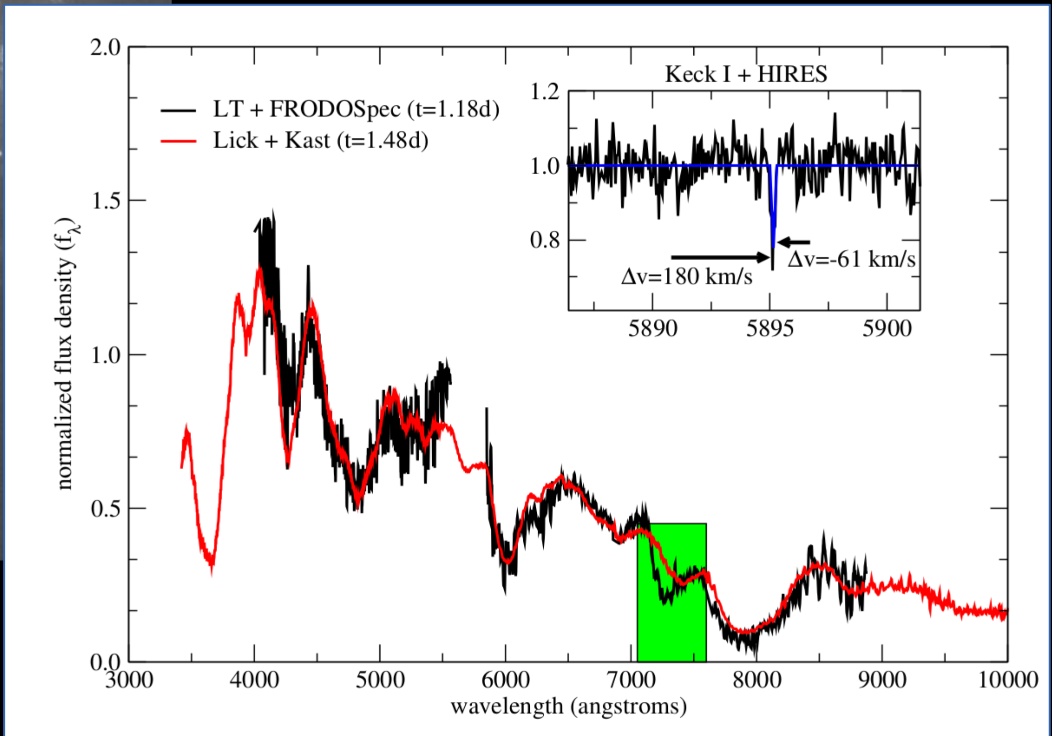
- FRODOspec – fibre-fed integral field spectrometer
  - R~2500/5500, 400-900nm
- RAPTOR – H band camera

Pipelines for all data (bias, flat, spectral extraction etc. in <10 minutes)

LT SCIENCE: Transient follow-up

- Diverse instrument suite and robotic control makes the LT a powerful tool for the follow-up of transient sources

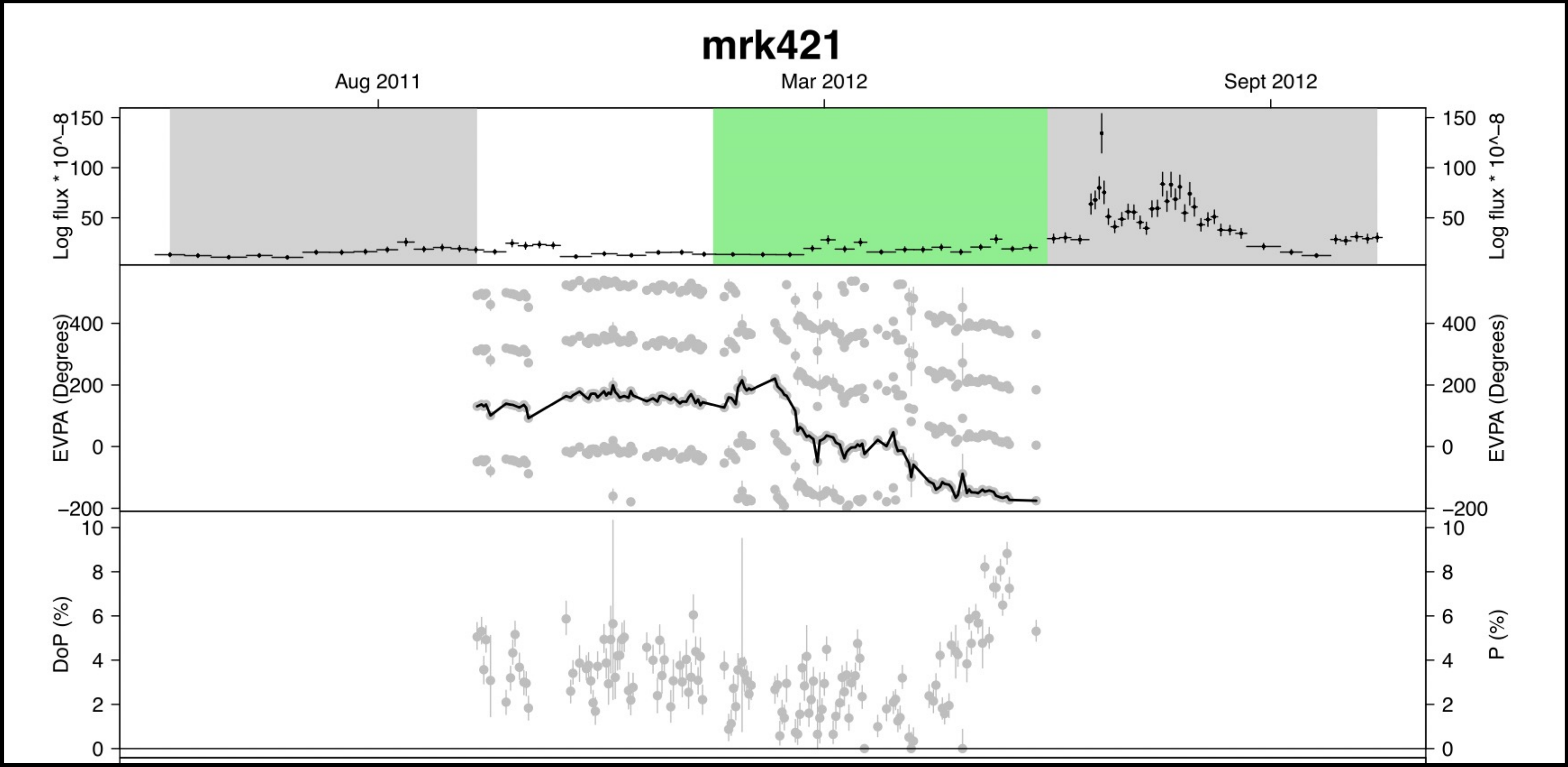




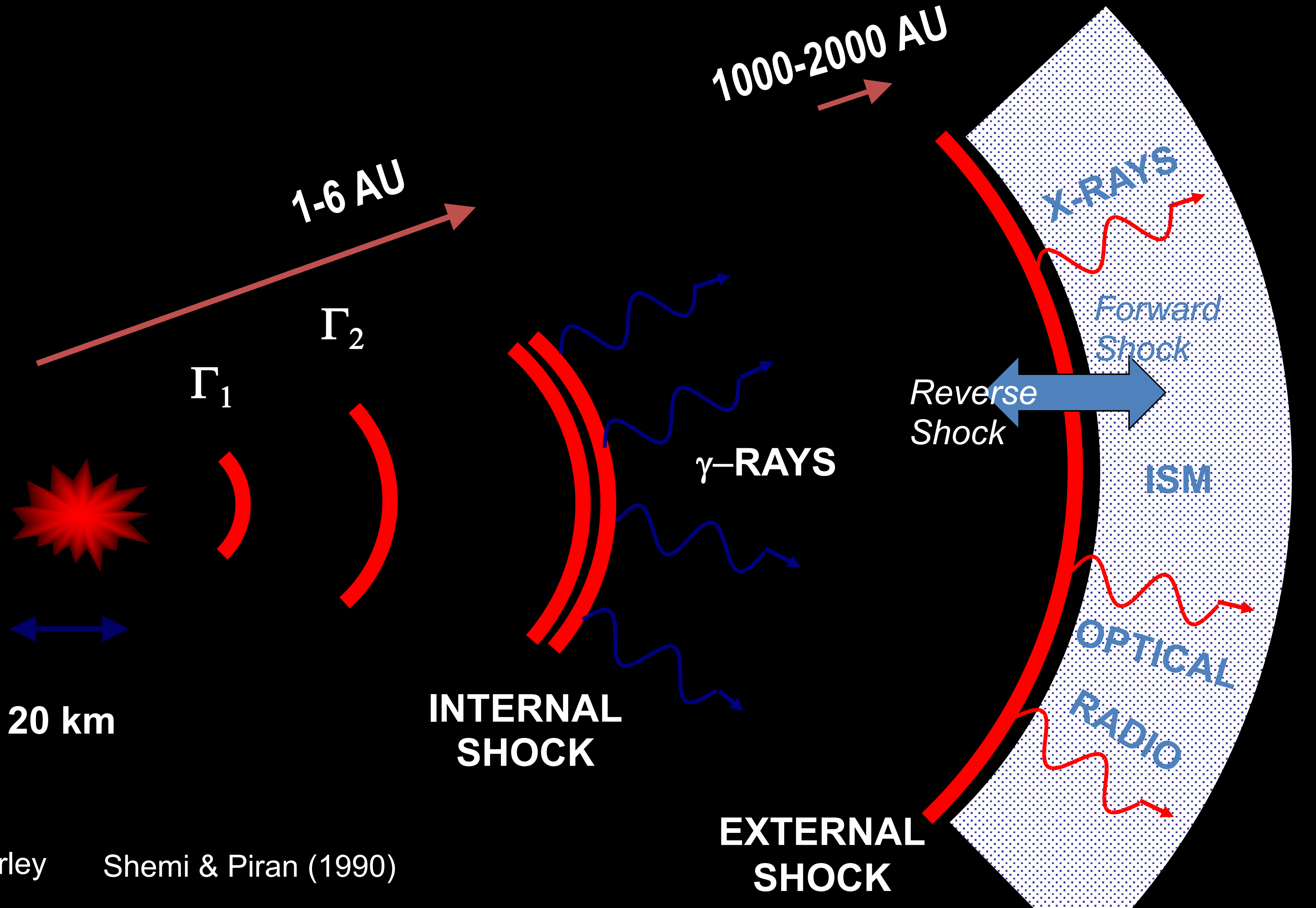
SN 2011fe:
Nugent et al. (Nature, 2011)

Optical Polarimetry of GRBs

- RINGO1/2/3 "Single shot" polarimeters
- Designed for GRB follow-up but in use for other programmes (e.g. Blazars – Jermak et al, 2016)



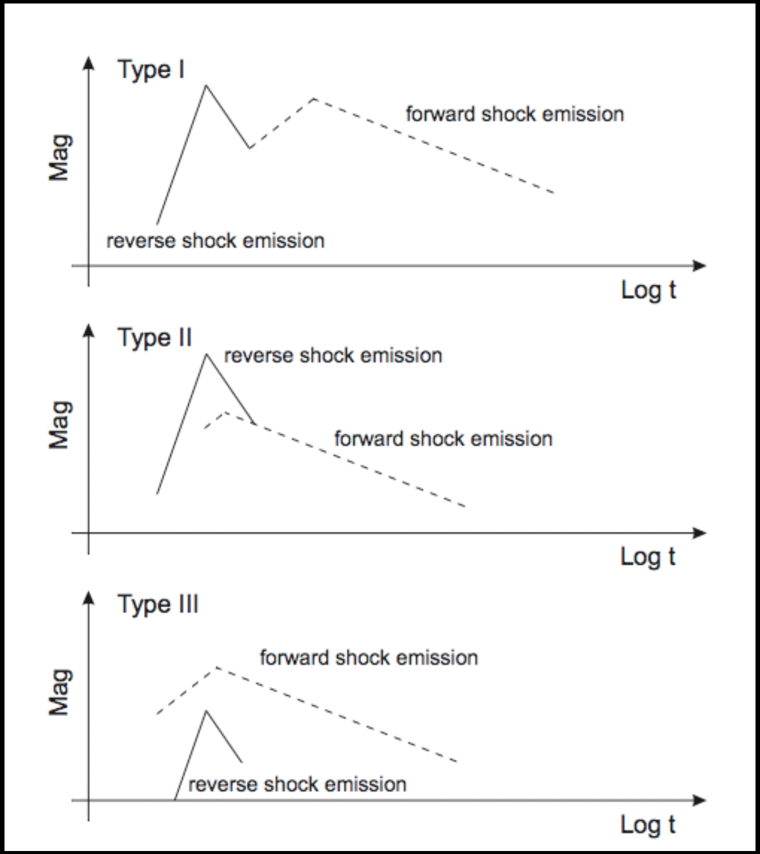
GRB Fireball Model



Hurley Shemi & Piran (1990)

Fireball Magnetization

- **Indirect diagnostics**
  - Bright optical flashes predicted from reverse shocks
  - Bright forward shock emission *only* e.g. GRB 061007, 060418
  - Typical synchrotron frequency below optical band (Mundell et al. 2007)
  - Magnetized, but baryon-dominated fireball in few GRBs with optical reverse shock emission (GRB061126 - Gomboc et al. 2008, ApJ, 687, 443; Gomboc et al. 2009)
  - Magnetic suppression of reverse shocks in others?



GRBs 990123, 021211, 060111B, 060117, 061126, 080319B (Gomboc et al. 2009)

Fireball Magnetization

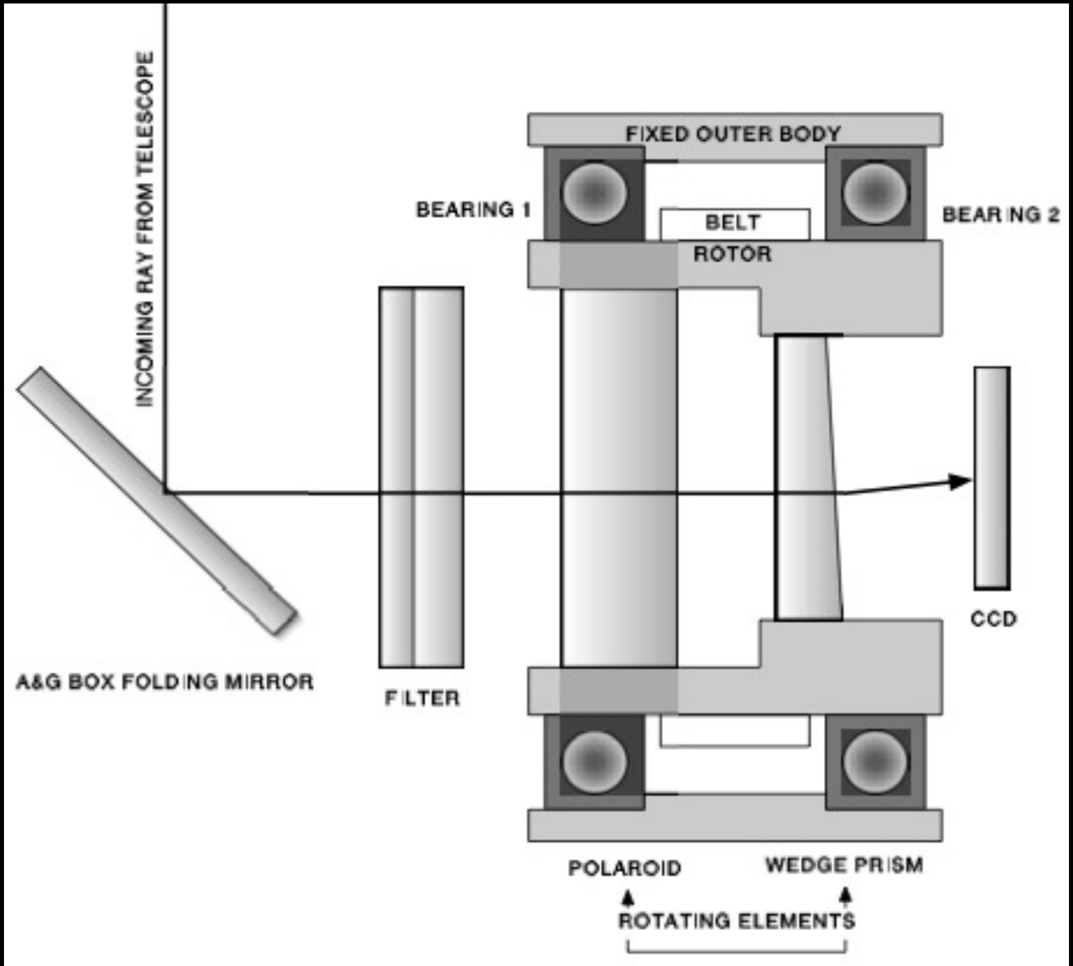
- **Direct diagnostics**
  - Synchrotron emission → intrinsic polarization
  - Fading signal and spatially unresolved
  - Expect reverse shock to be polarized
  - Expect forward shock to be unpolarized
  - Early time optical polarisation powerful

Challenges of Rapid GRB Polarimetry

- Source is generally quite faint (R=15-21)
- Initial Localization (SWIFT) is ~4 arcmin
- Source is rapidly variable and fading
- Only one chance!

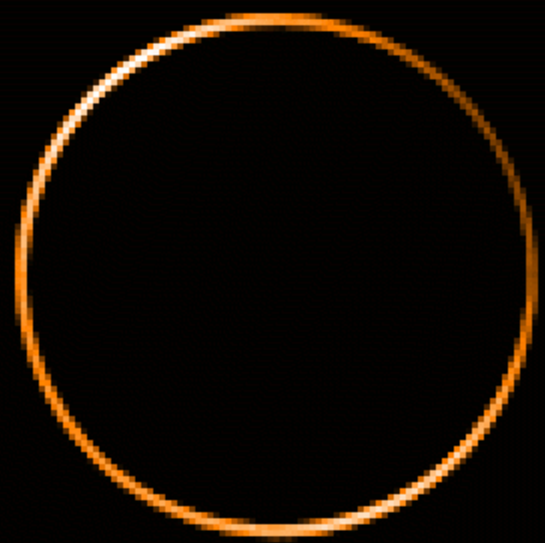
RINGO Polarimeter

- Novel design (D. Clarke): rotating polaroid (500rpm) in telescope beam
- CCD field of view ~5 arcmin
- Variable signal for polarised sources
- Time variable signal → spatial signal by small angle wedge prism rotating with polaroid
- Signal recorded on CCD

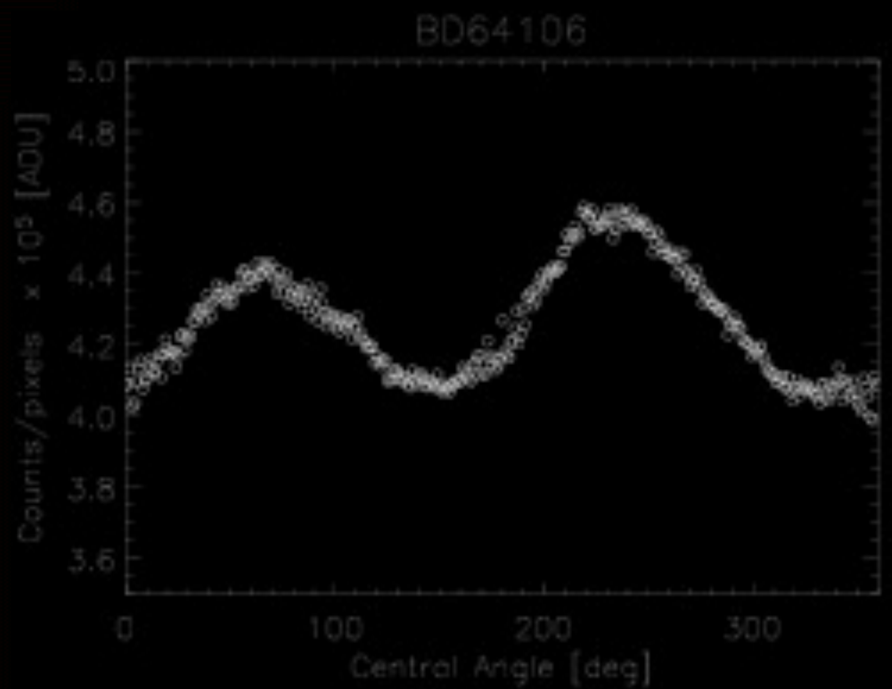


RINGO Polarimeter

- Each source is a ring
- Polarisation signal mapped x2 round ring

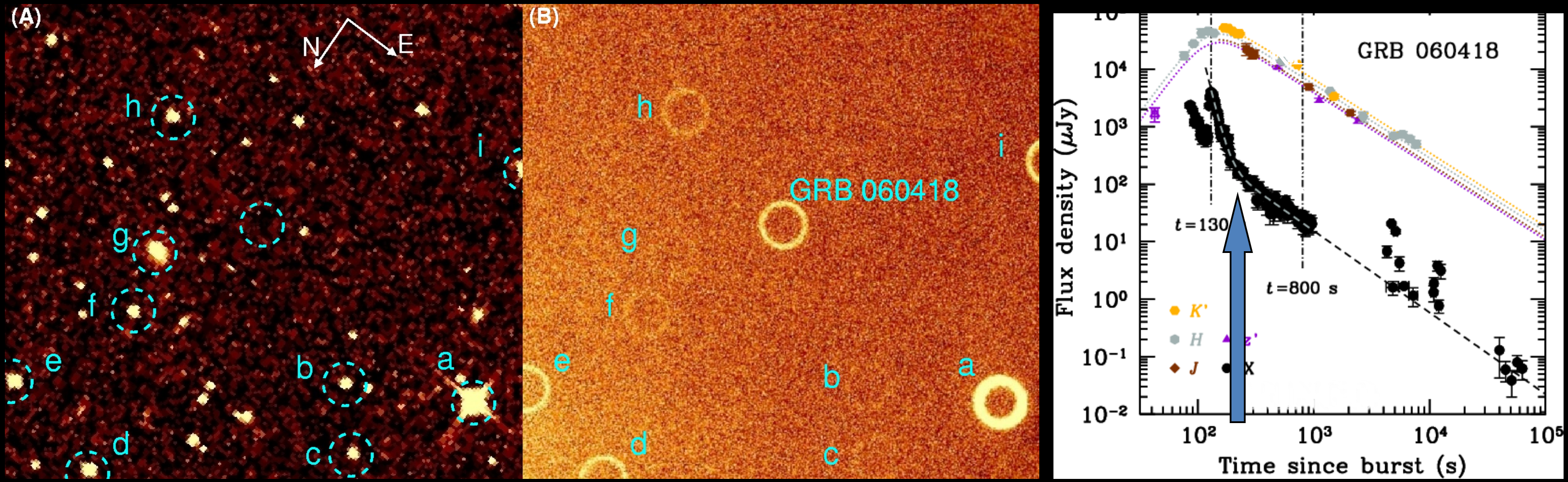


30 second RINGO exposure of BD +64 106



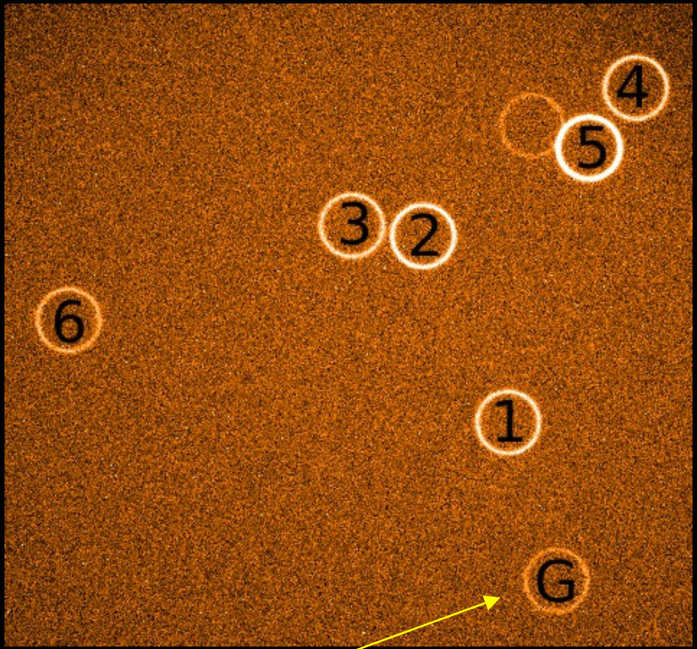
GRB 060418: P<8%

- RINGO polarimetry of GRB 060418 at ***t = 203 sec***
  - Measurement coincided with deceleration of fireball
    - (Γ_0~400; R_{dec}~ 10^{17}) cm
  - Equal contribution from forward and reverse shocks

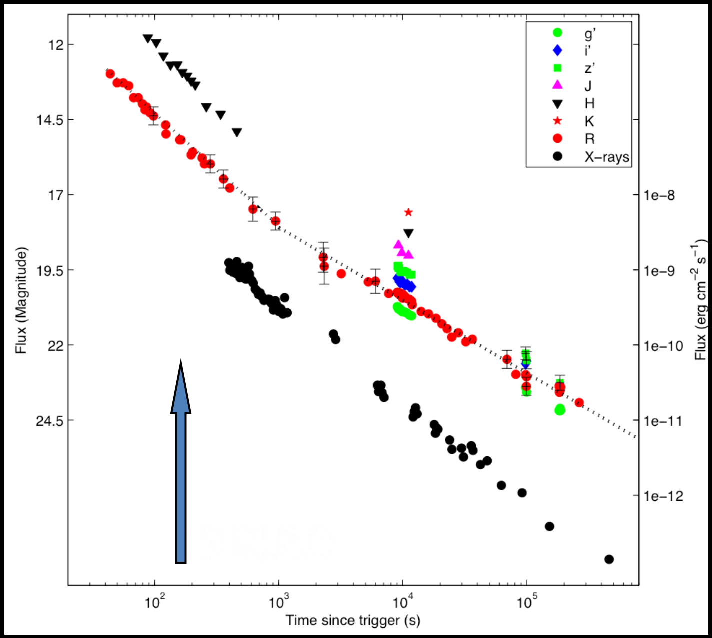


Steele et al. 2006, SPIE, 6269 ,179;
Mundell et al. 2007, Science, 315, 1822

GRB 090102 (P=10%)



GRB 090102



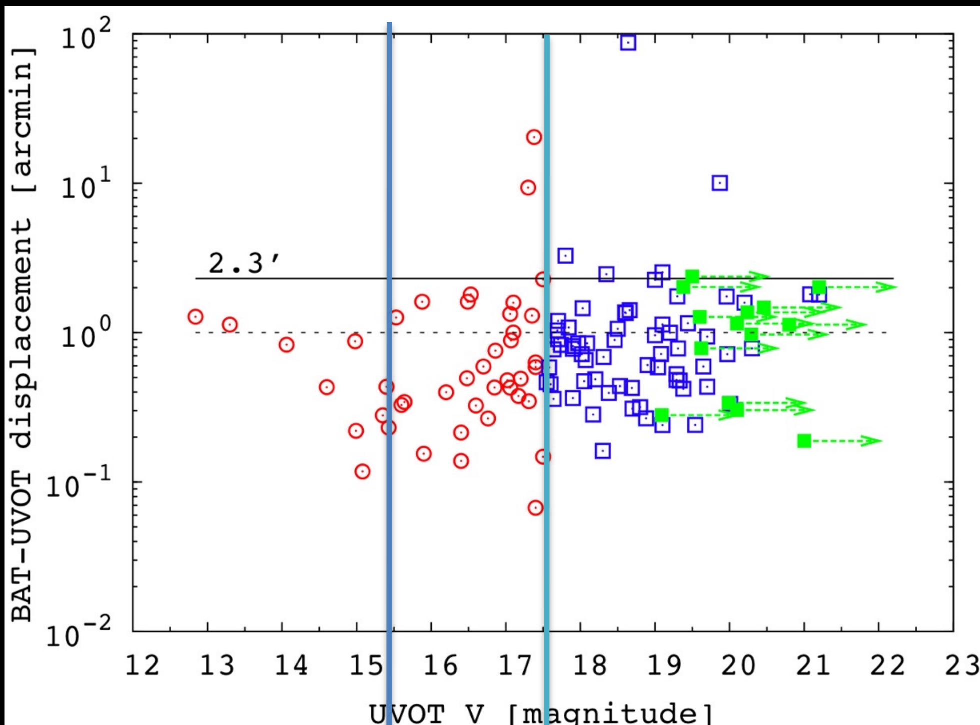
- 60-s RINGO exposure began ***t = 160 s*** post-burst
- Stars in field provide additional calibration

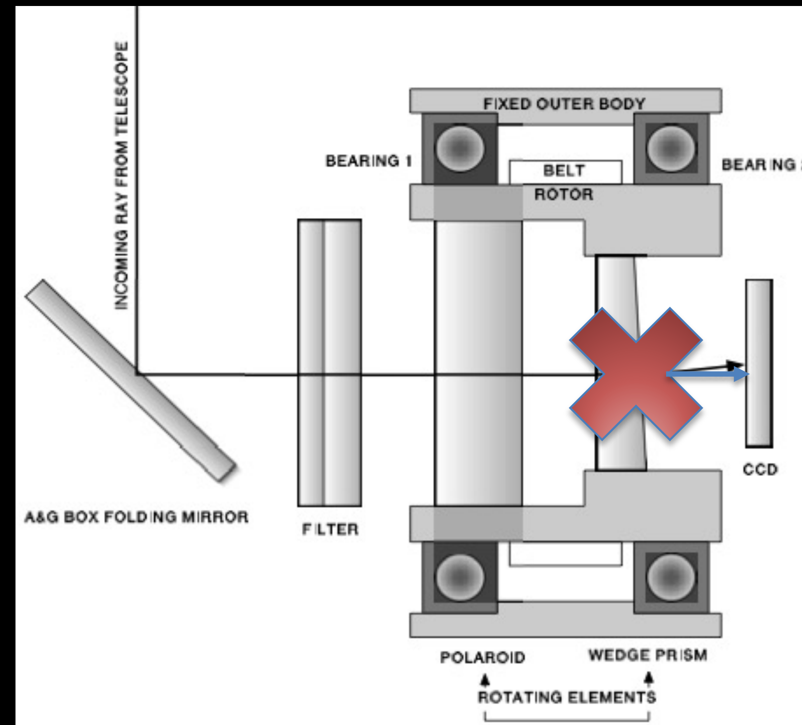
Steele et al. Nature 2009

RINGO problems

- Overlapping rings – complex, “hands on” reduction
- Large Sky Signal affects SNR for faint sources
- Effective limiting magnitude V~15 in 30 seconds
- Only 2 successful observations in 3 years!

RINGO2



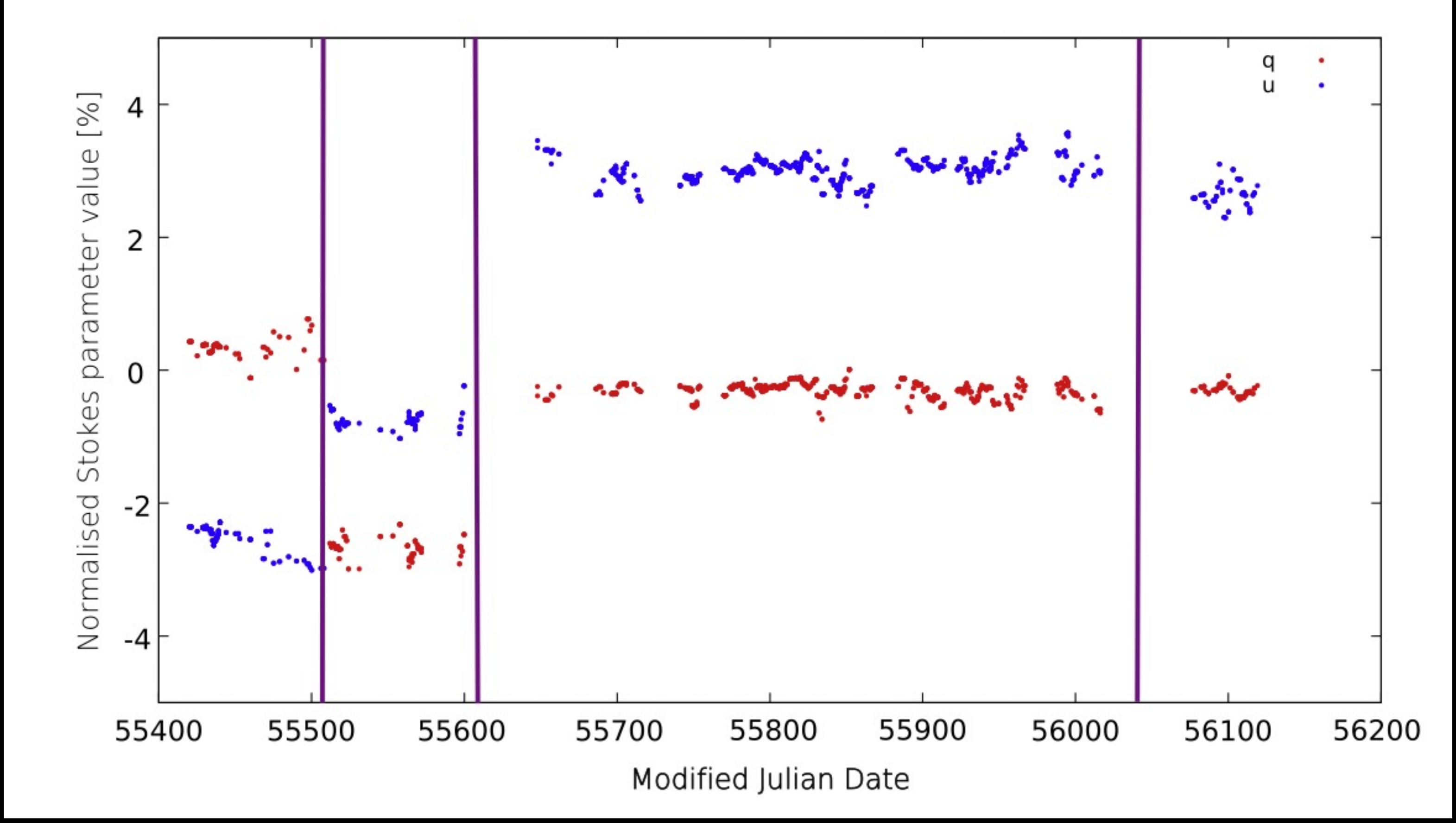


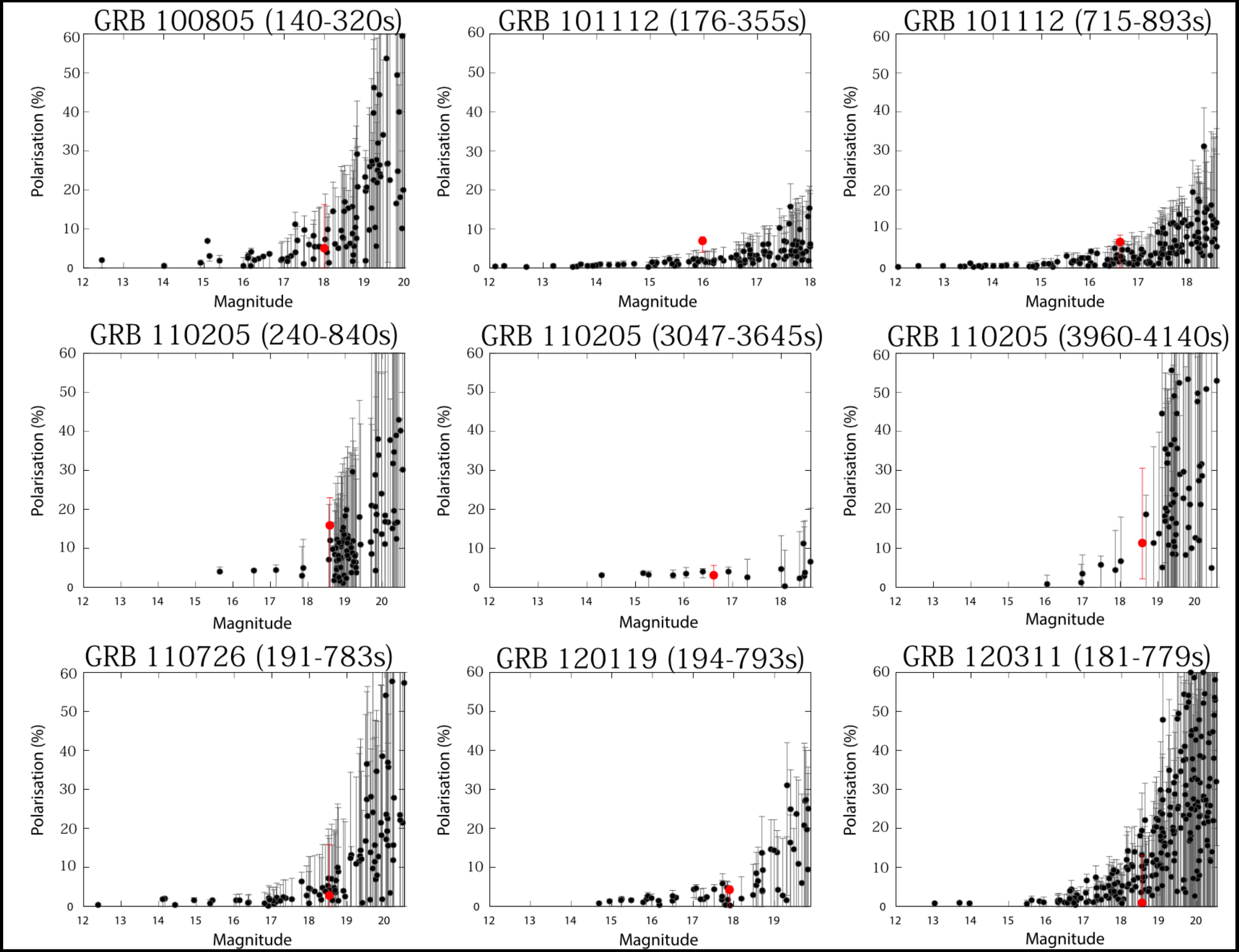
RINGO RINGO2

- Slower rotation (60 rpm), no wedge
- Fast EMCCD detector (8 frames/s)
- Point sources – rapid photometry
- Fewer sky photons – improved sensitivity

Steele et al. SPIE 2010

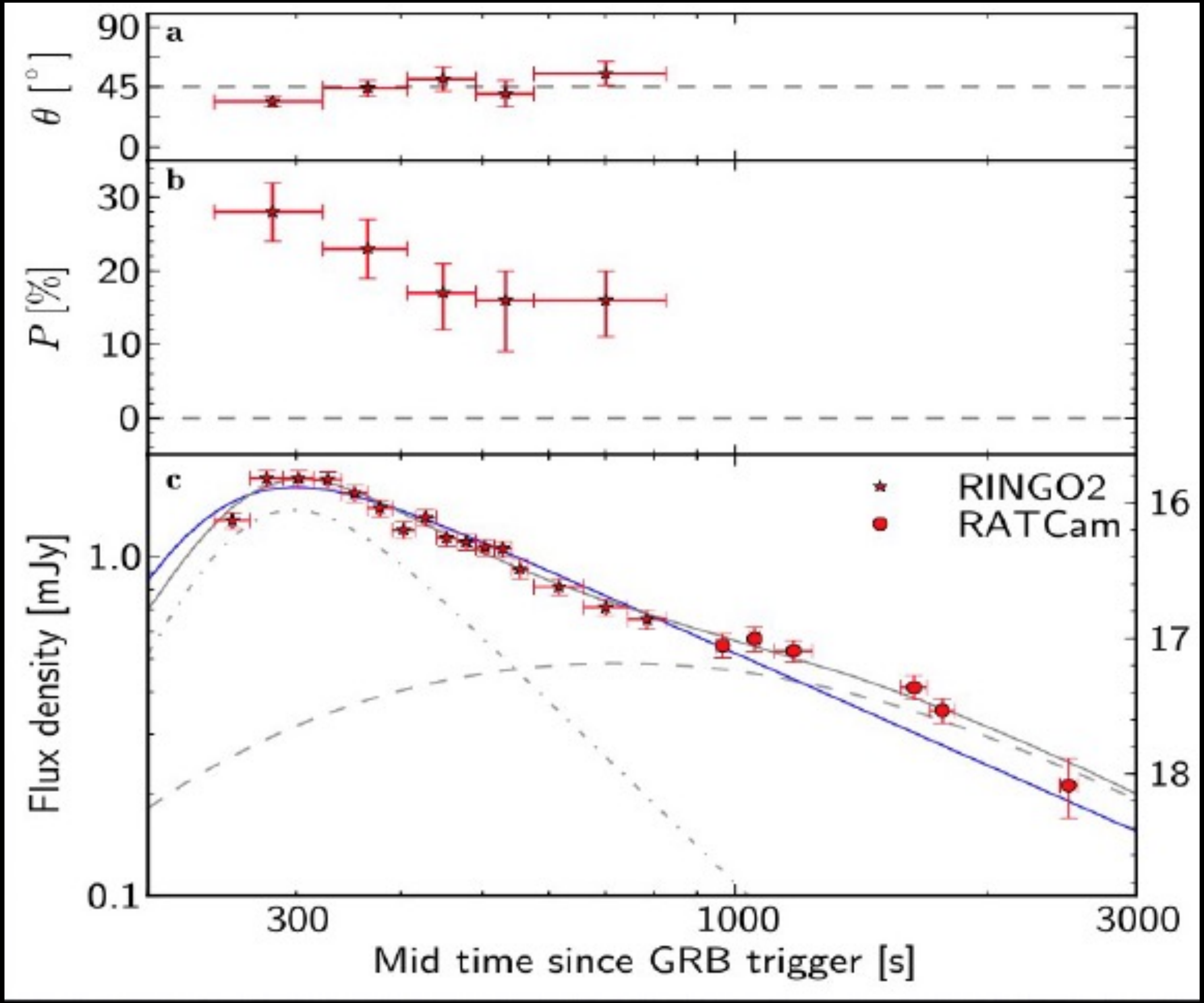
Instrumental Polarization ~4%, stable to 0.5%





Steele et al, 2017, ApJ

GRB120308A



(Mundell et al. 2013, Nature; Steele et al, 2017 ApJ)

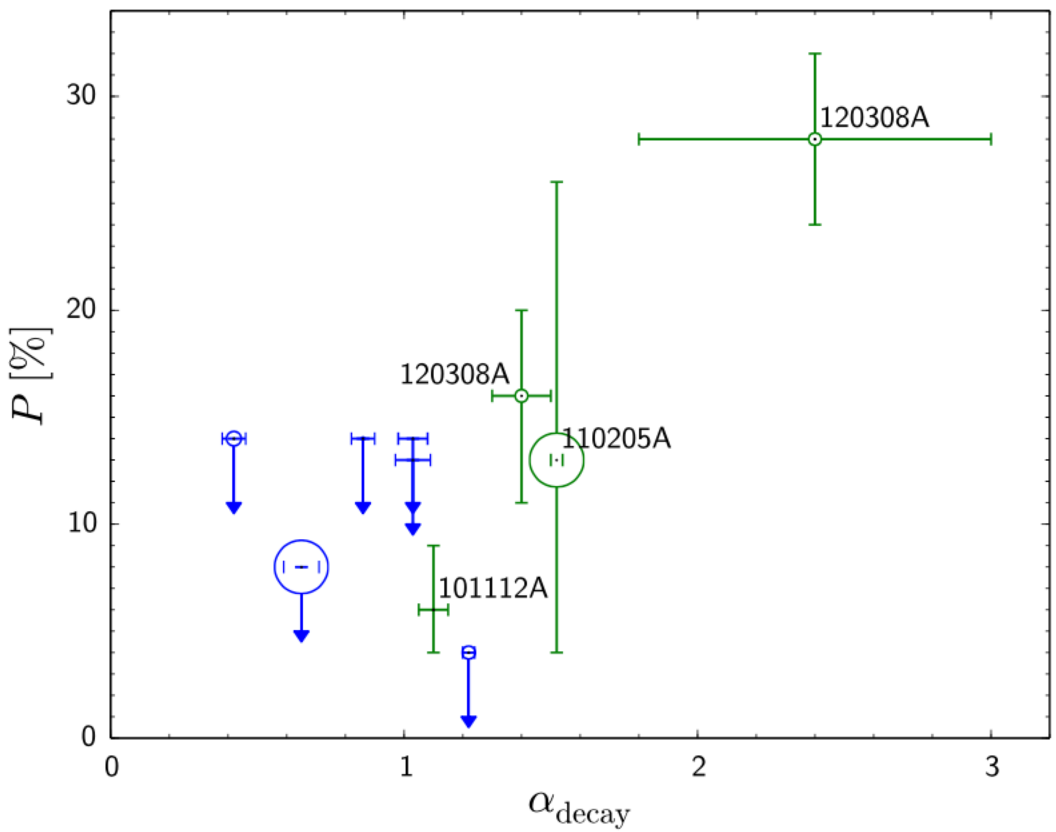
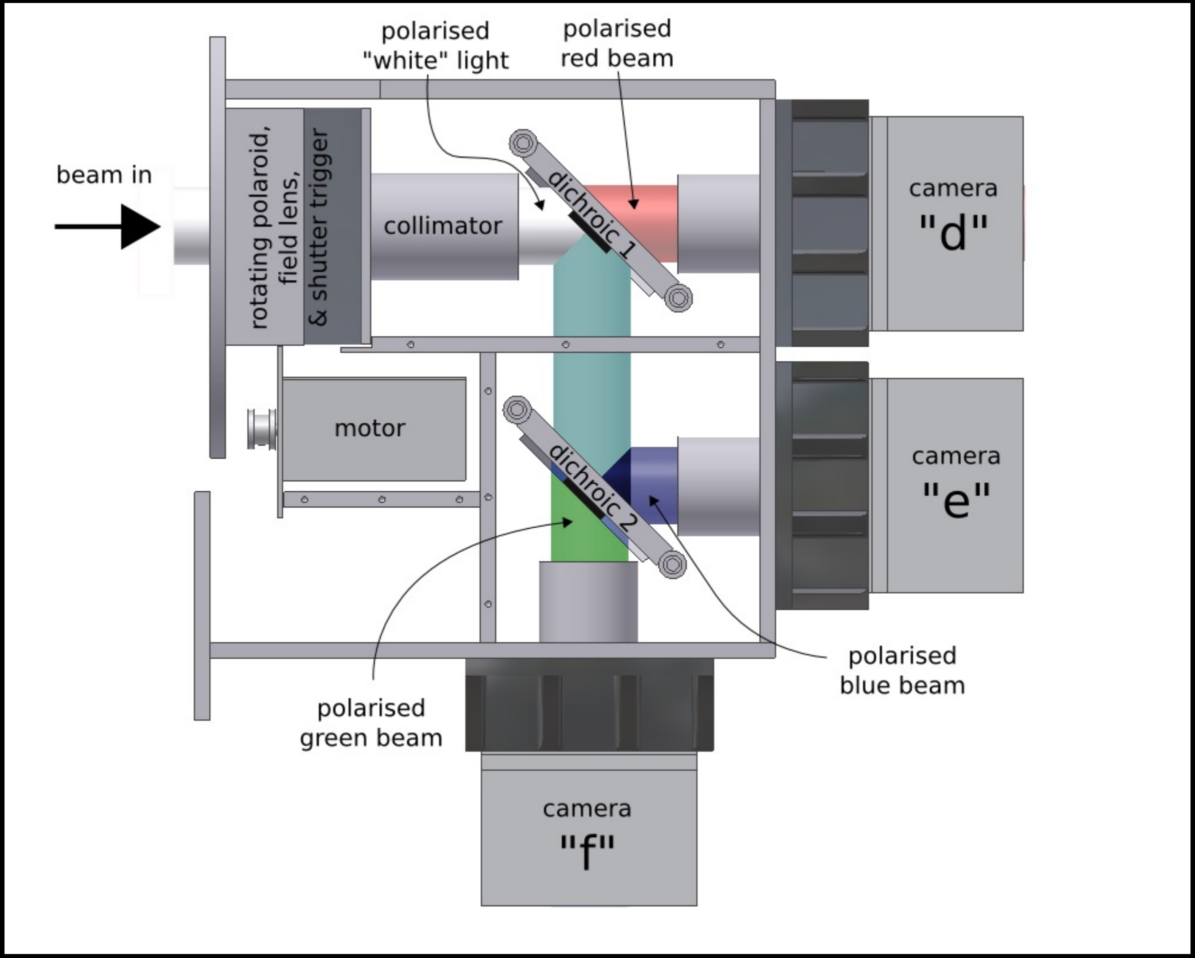


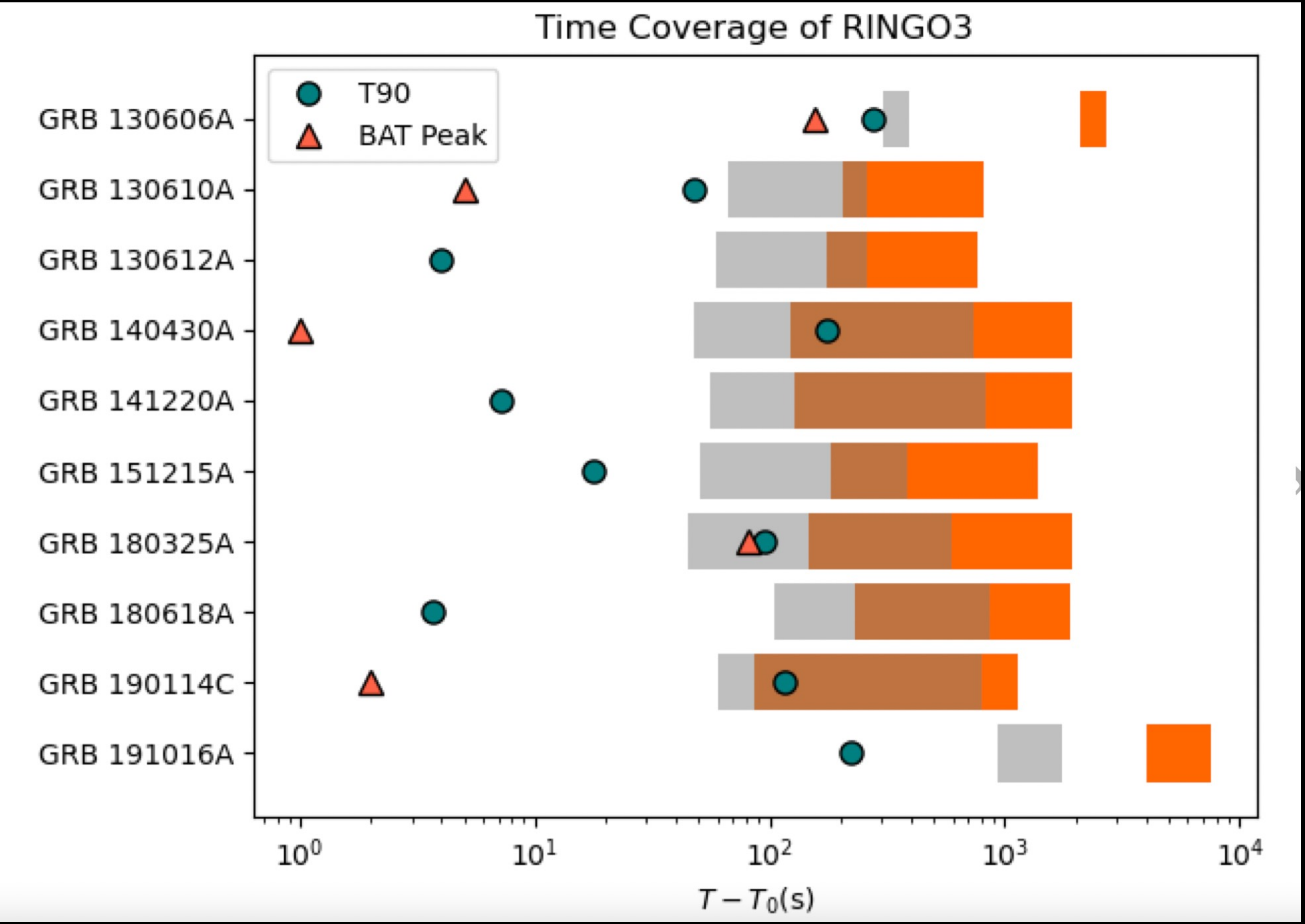
Figure 13. . PL decay index (α) vs. degree of polarization. The green points in the plot are measurements, while blue points are upper limits. The relative size of the point is the T90 value (which shows no correlation with α or and P). For GRB120308A we plot two epochs: (240–323 s, $P = 28\%$) and (575–827 s, $P = 16\%$).

RINGO3

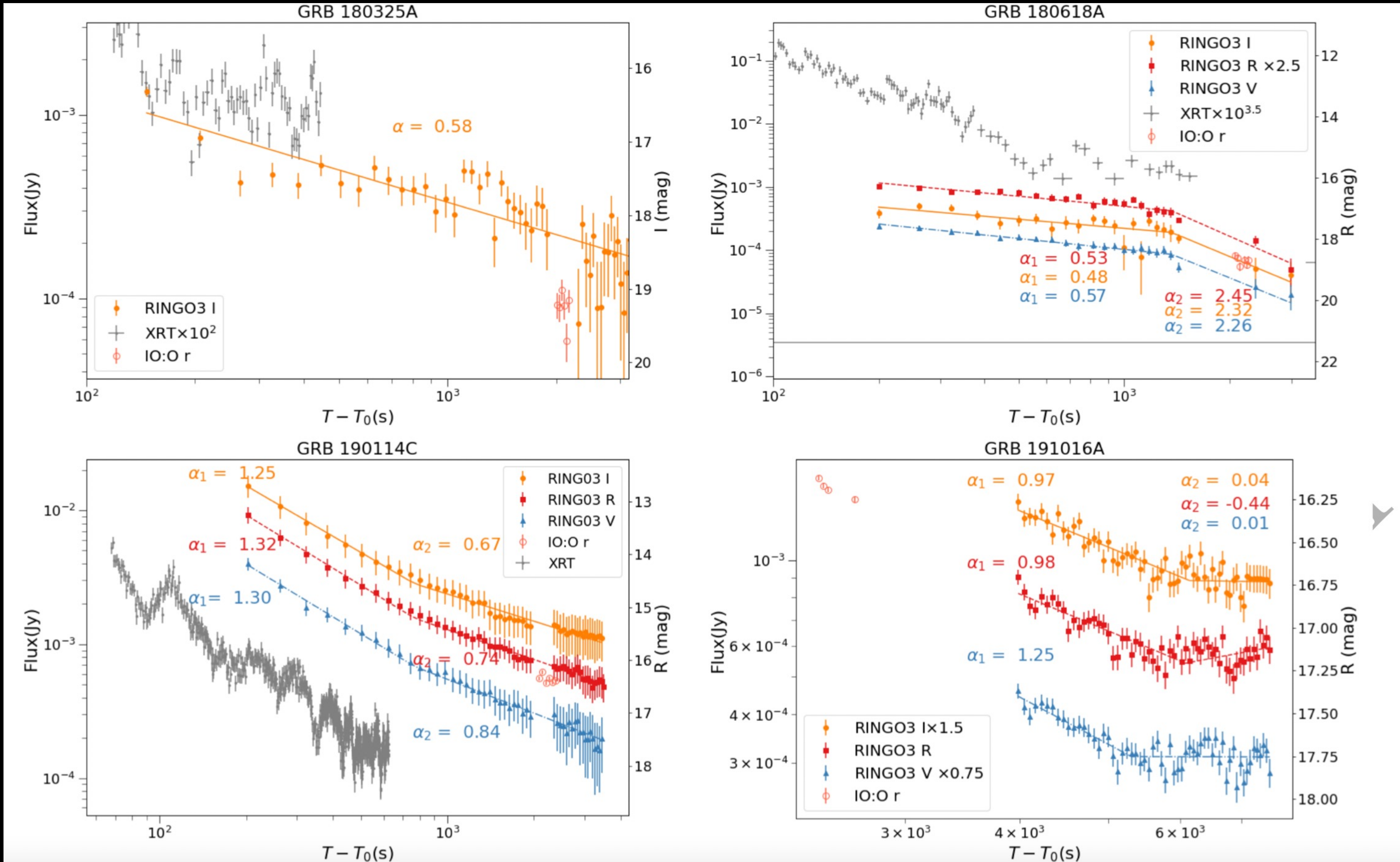
Red: 760-1000 nm
Green: 650-750 nm
Blue: 350-640 nm



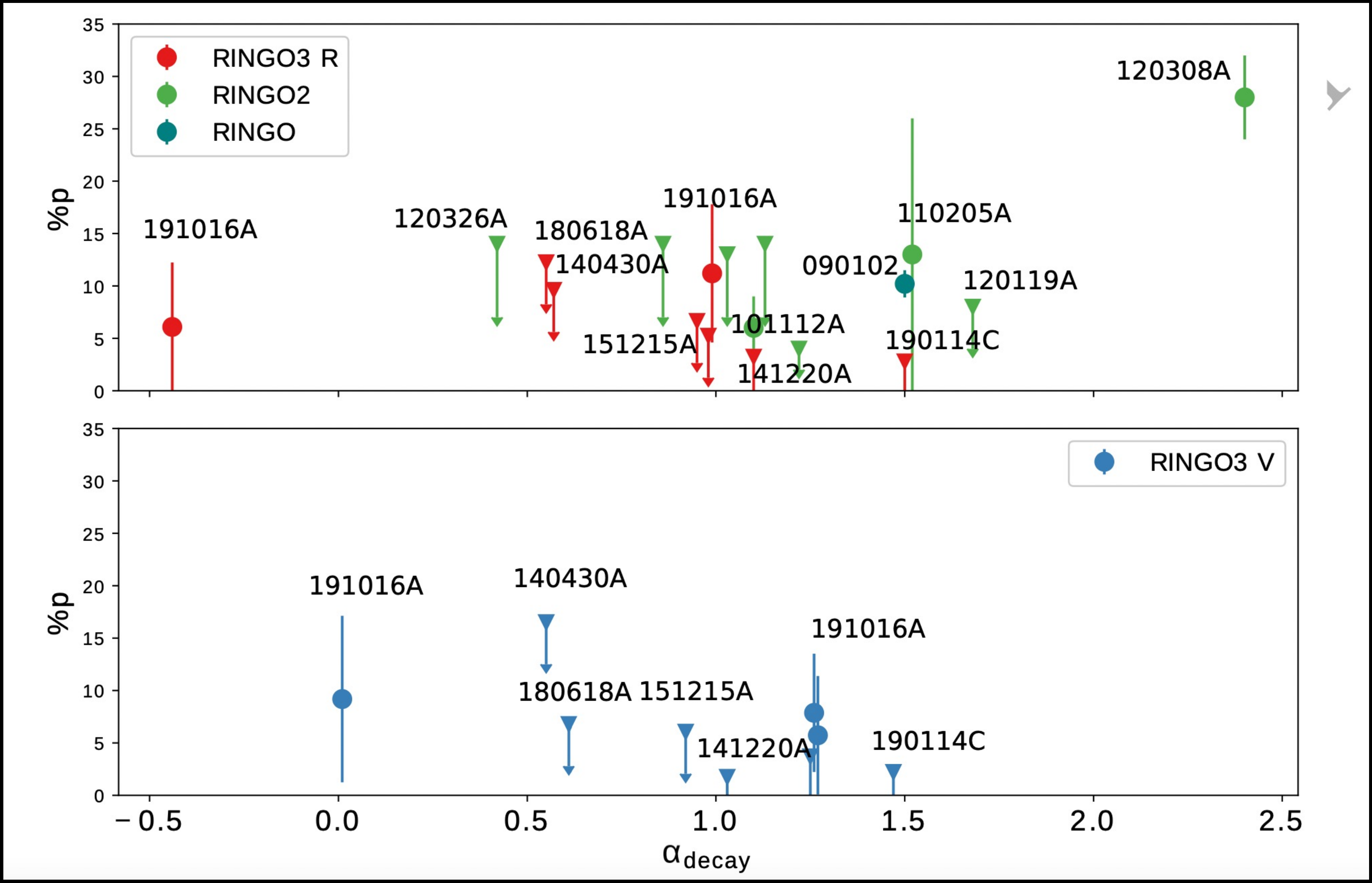
RINGO3



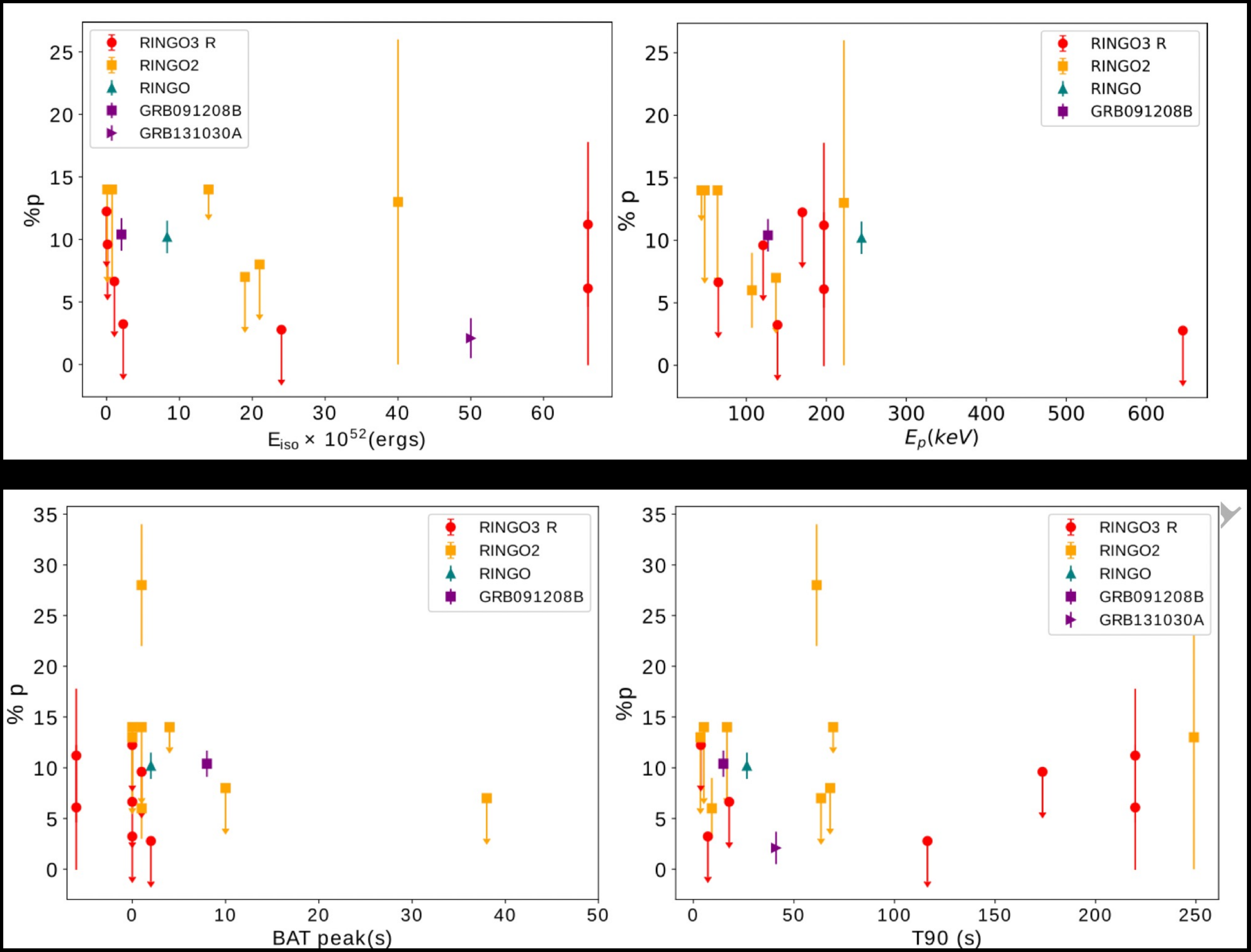
Time Coverage of RINGO3
T90
BAT Peak
GRB 130606A
GRB 130610A
GRB 130612A
GRB 140430A
GRB 141220A
GRB 151215A
GRB 180325A
GRB 180618A
GRB 190114C
GRB 191016A
10^0
10^1
10^2
10^3
10^4
$T - T_0(s)$



Shrestha et al 2022

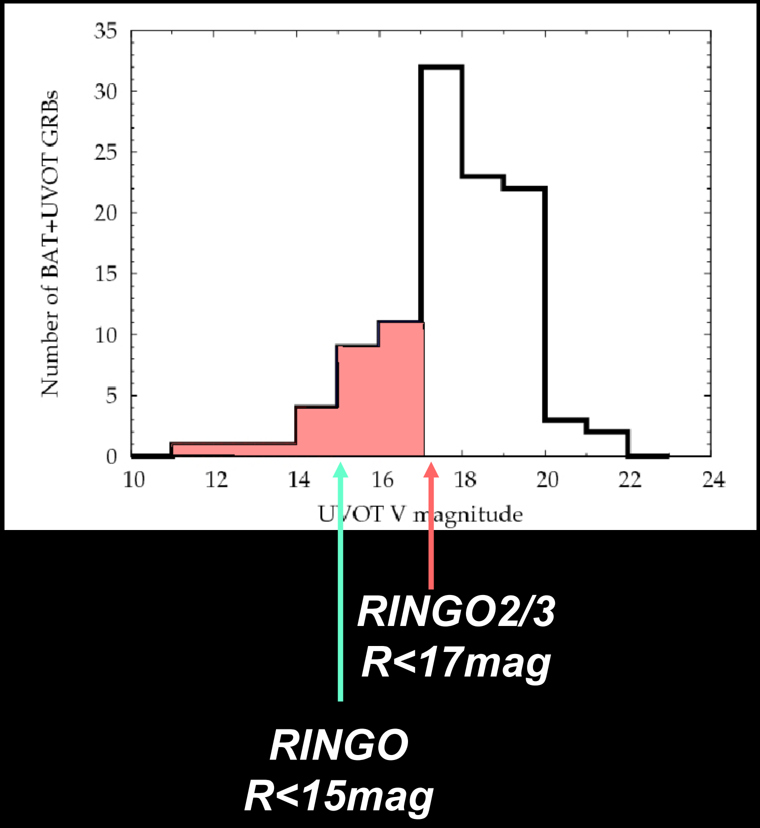


Shrestha et al 2022



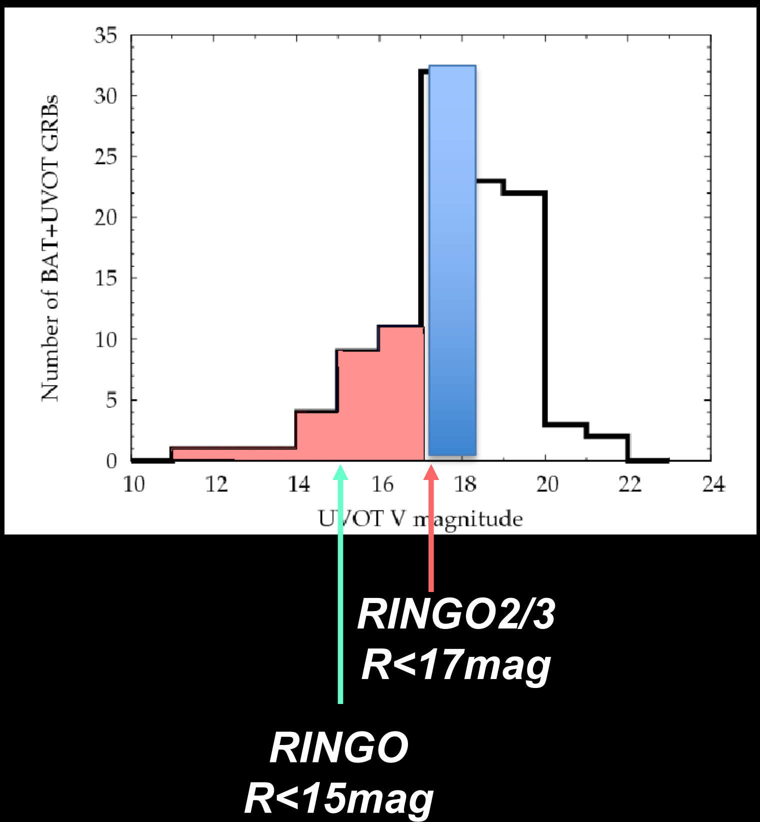
Shrestha et al 2022

Early Time Polarization – we are still missing most of the bursts



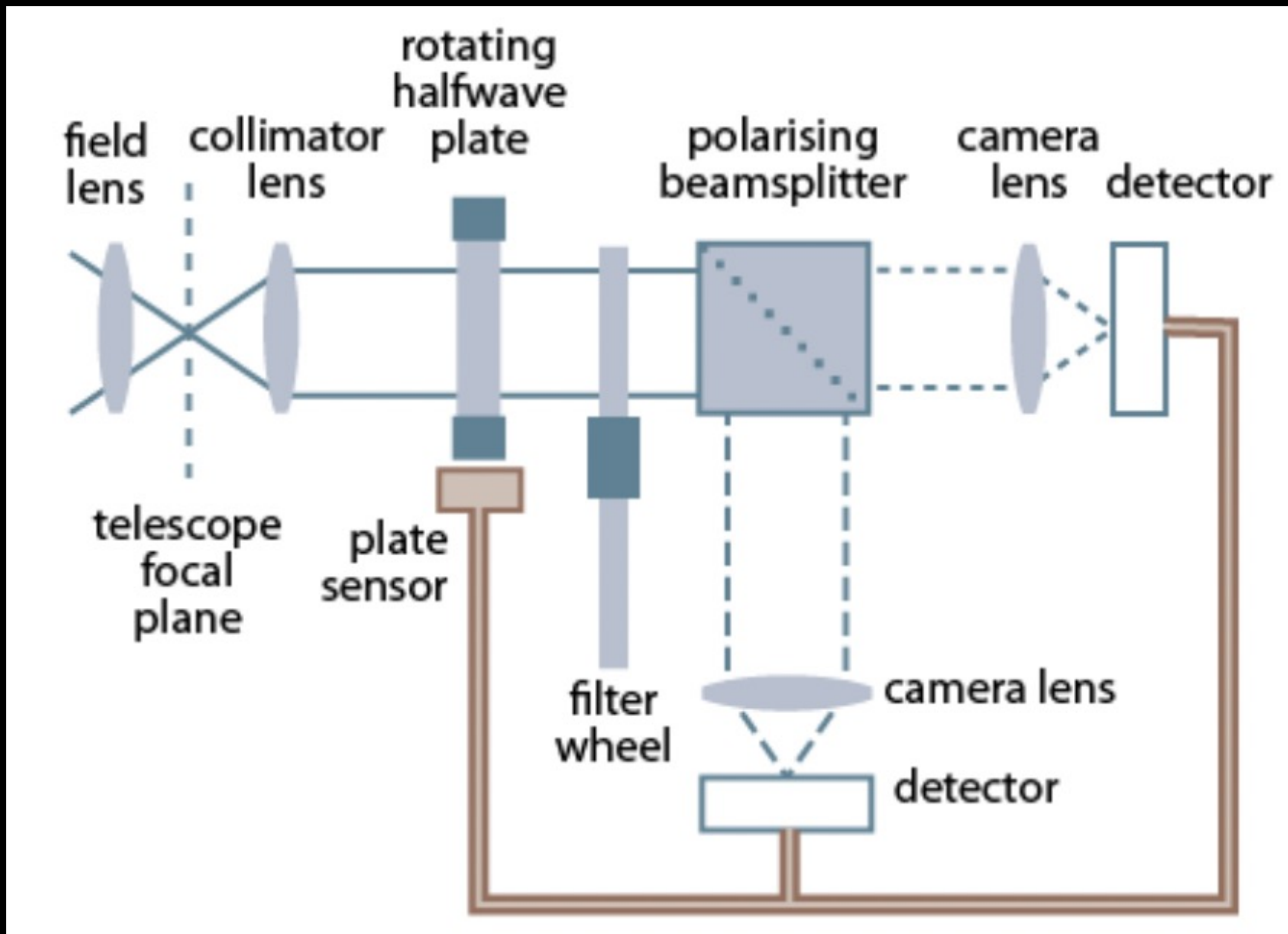
- *After 11 years, still only about 20 GRBs with polarization constraints from RINGO series*
- *Time evolution* of polarisation
- Population statistics (selection effects?)
- Redshift evolution
- New understanding of GRB physics
- Foundation for future X-ray polarization experiments
- WE NEED A MORE SENSITIVE POLARIMETER

MOPTOP – a (sort of) change of approach



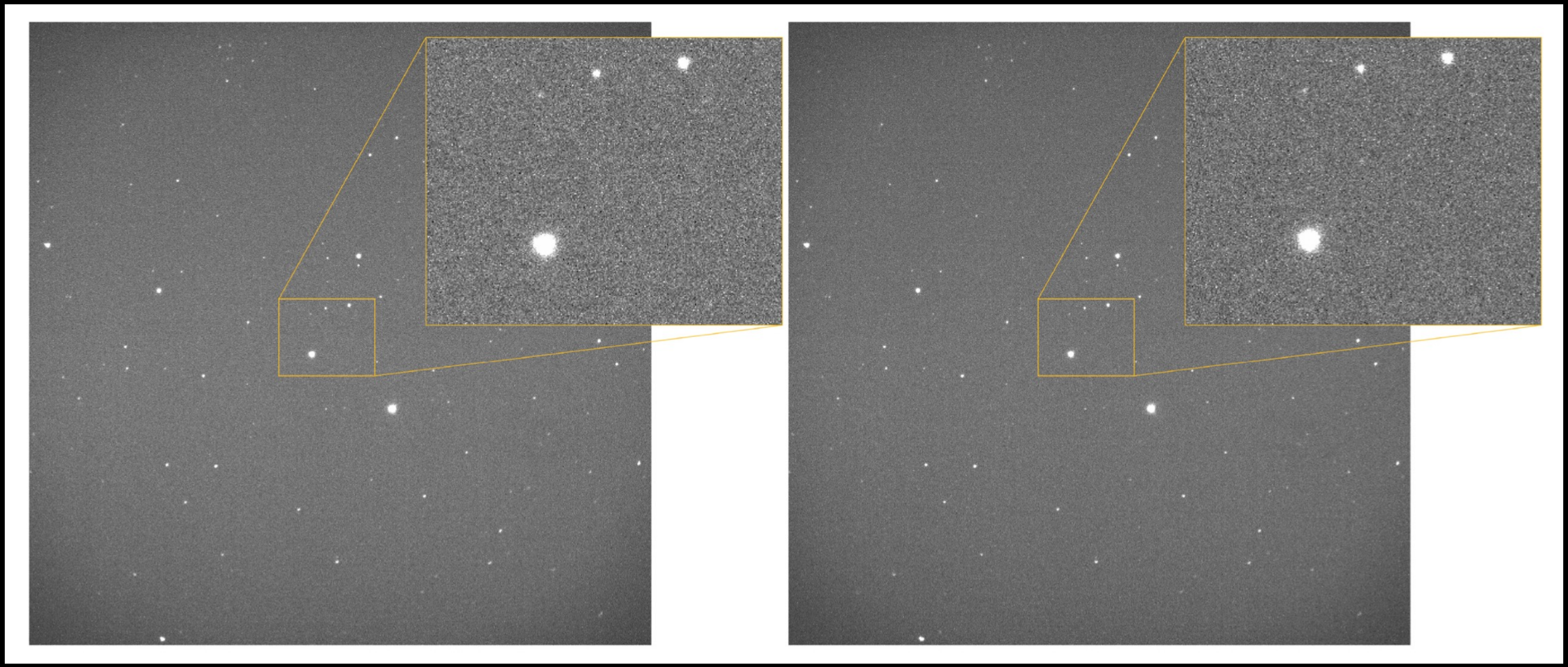
- Greater sensitivity
- Greater accuracy (non synchrotron sources)
- Retain wide, unconfused field of view
- Retain ability to measure rapidly variable source

Dual Beam, Dual Camera Design



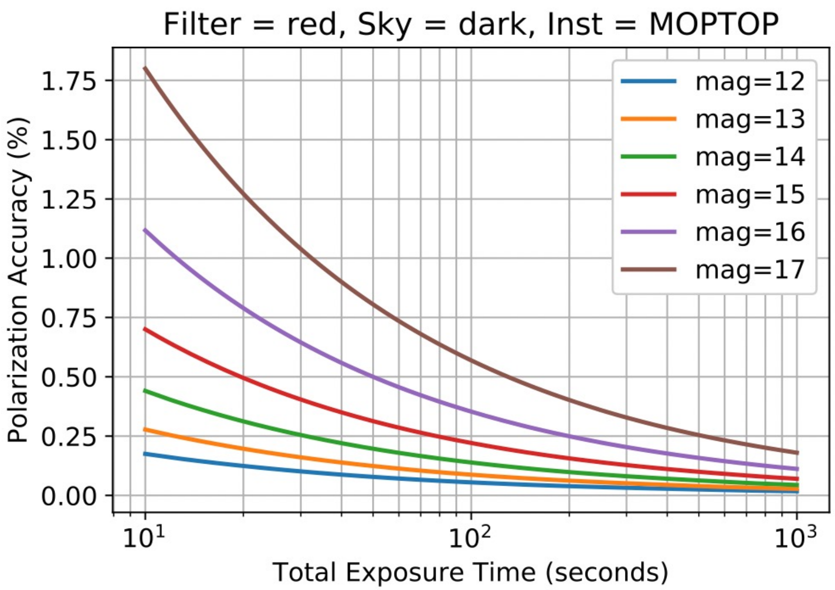
Jermak et al, Proc SPIE (2016, 2018)

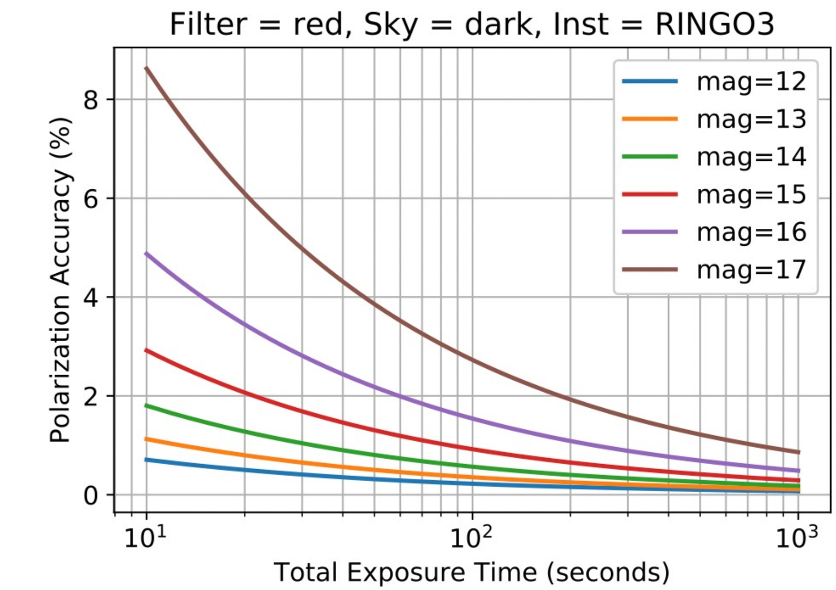
Dual Beam, Dual Camera Design



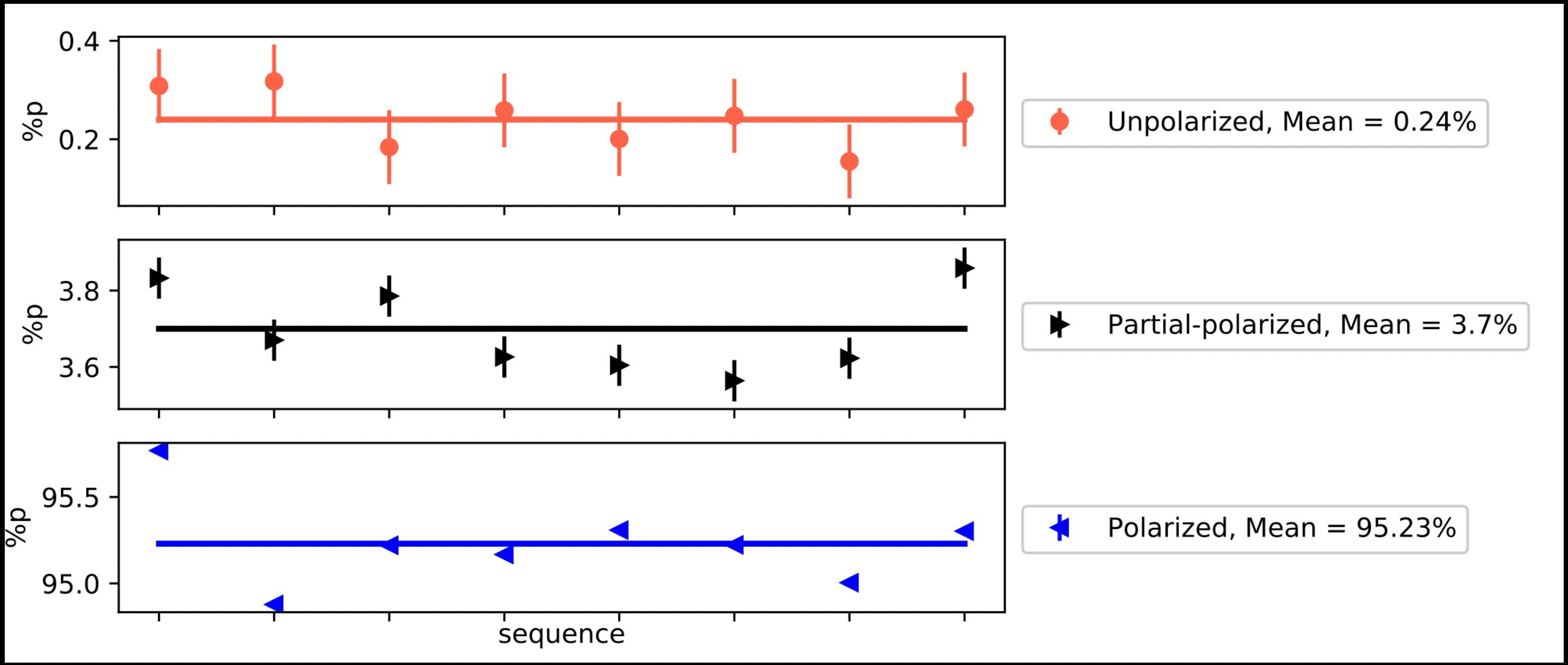
4 x Sensitivity Gain

- Polaroid –> Beam Splitter = 2x gain
- EMCCD -> CMOS= 2 x gain
- [Each Image only has its own sky contribution]





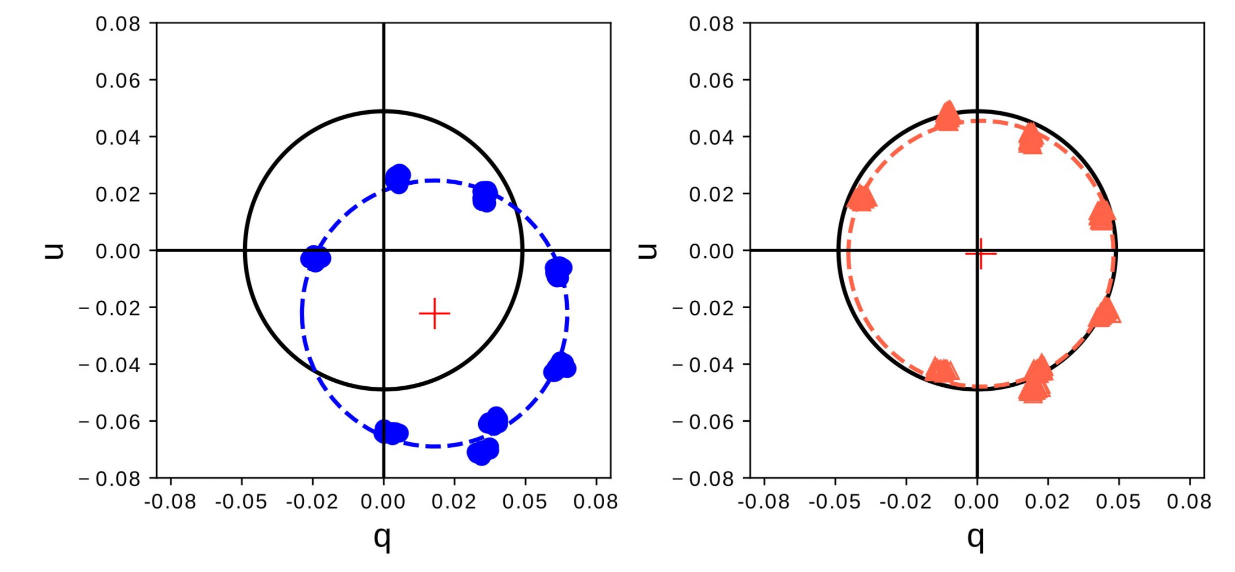
5-10 x Stability Gain



Shrestha et al, MNRAS (2022)

On Sky

Filter	Wavelength (nm)	q_0 (%)	u_0 (%)	K (°)	D
B	380 – 520	0.12 ± 0.02	−1.19 ± 0.03	124.7 ± 0.5	0.86 ± 0.02
V	490 – 570	0.56 ± 0.02	−2.33 ± 0.02	122.8 ± 0.2	0.87 ± 0.01
R	580 – 795	1.07 ± 0.07	−3.08 ± 0.05	124.1 ± 0.2	0.91 ± 0.01
I	695 – 830*	1.17 ± 0.02	−3.38 ± 0.02	124.1 ± 0.2	0.81 ± 0.01



Shrestha et al, MNRAS (2022); Steele et al. MNRAS (submitted 2022)

Summary

Instrument	Wavelength	Sensitivity	Stability	Field of View
RINGO 2006 - 2009	450 – 700 nm	R=15	0.5%	5 x 5 arcmin
RINGO2 2010 - 2013	400 – 700 nm	R=17	0.5%	4 x 4 arcmin
RINGO3 2014 - 2020	Simultaneous 350 – 640 nm 650 – 760 nm 770 – 1000 nm	R=17	0.5%	4 x 4 arcmin
MOPTOP 2021 -	Filter Wheel B, V, R, I	R=18.5	0.1%	7 x 7 arcmin
MOPTOP2 ?	Simultaneous B, V, R	R=18.5	0.1%	7 x 7 arcmin