Measuring Gamma-ray Burst Polarisation with the *Daksha* mission

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On behalf of *Daksha* team

GRB Nanosat monthly – April 4, 2023

https://www.dakshasat.in

Daksha: Mission profile and design

- Two satellites on the opposite side of the positions in a low earth orbit (~600 km).
- Onboard real-time transient detection and localisation capability.

Parameter	Value
Energy coverage	1 – 1000 keV
Median effective area	1300 cm^2 single, 1700 cm^2 combined
Field of View*	12.6 sr
Localisation	~1° - 10° onboard ~5° ground
Time resolution	1 μs
Sensitivity**	4 x 10^{-8} $erg/cm^2/s$

* Two satellites combined.
** Single satellite 1s transient, 5 σ detection, 20 – 200 keV.

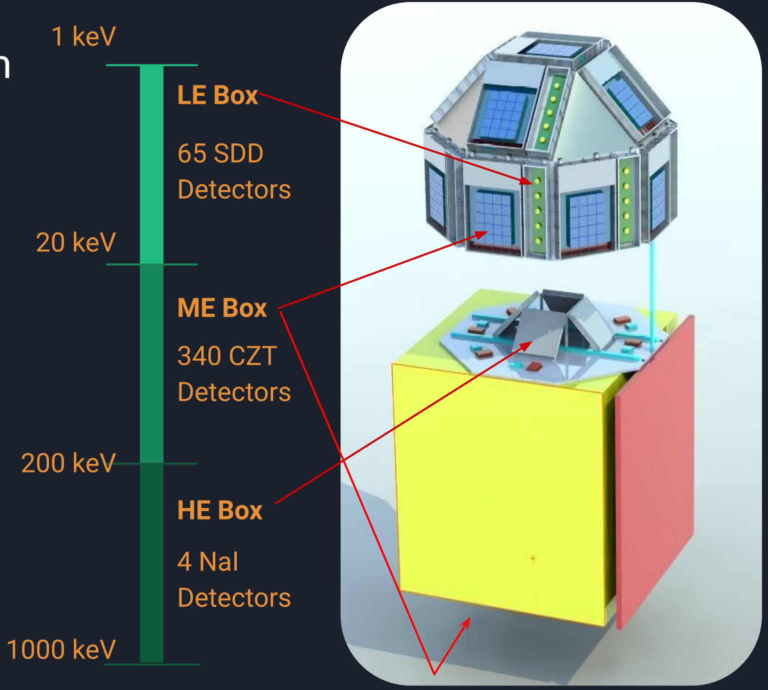
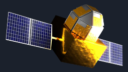


Figure: G. Waratkar (IIT Bombay)

Bhalerao et al 2022 (arXiv:2211.12055)



Daksha: Mission profile and design

- Two satellites on the opposite side of the positions in a low earth orbit (~600 km).
- Onboard real-time transient detection and

Table 1. Comparison of key parameters of GRB missions.

Mission name	Energy range (keV)	Effective area (cm^2)	FoV Sky fraction	FoV (sr)	Range Mpc	Volume Mpc^3	Sensitivity (1-s, 5σ) erg cm^{-2} s^{-1}	Sensitivity (1-s, 5σ) ph cm^{-2} s^{-1}	Reference
Daksha (single)	20–200	1300	0.7	8.8	76	1.27×10^6	4×10^{-8}	0.6	This work
Daksha (two)	20–200	1700	1	12.6	76	1.81×10^6	4×10^{-8}	0.6	This work
Swift-BAT	15–150	1400	0.11	1.4	67	0.14×10^6	3×10^{-8}	0.5	(a)
Fermi-GBM	50–300	420	0.7	8.8	49	0.35×10^6	20×10^{-8}	0.5	(b)
GECAM-B	6–5000	480	0.7	8.8	65	0.81×10^6	9×10^{-8}	—	(c)
SVOM/ECLAIRs	4–150	400	0.16	2	70	0.23×10^6	4×10^{-8}	0.8	(d)
~~*THESEUS*/XGIS~~	~~2–30~~	~~500~~	~~0.16~~	~~2~~	~~45~~	~~0.06×10^6~~	~~1.7×10^{-8}~~	~~—~~	~~(e)~~
~~*THESEUS*/XGIS~~	~~30–150~~	~~500~~	~~0.16~~	~~2~~	~~58~~	~~0.12×10^6~~	~~5×10^{-8}~~	~~—~~	~~(e)~~
~~*THESEUS*/XGIS~~	~~150–1000~~	~~1000~~	~~0.5~~	~~6.2~~	~~20~~	~~0.02×10^6~~	~~45×10^{-8}~~	~~—~~	~~(e)~~

Sensitivity**	4 x 10^{-8} erg/cm^2/s

Two satellites combined.

** Single satellite 1s transient, 5 σ detection, 20 – 200 keV.

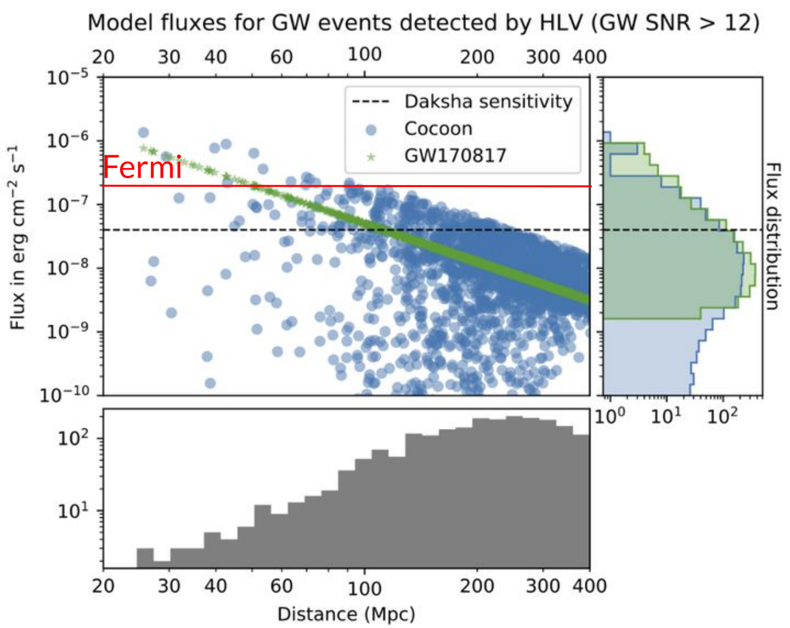
Figure: G. Waratkar (IIT Bombay)

Bhalerao et al 2022 (arXiv:2211.12055)

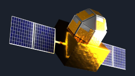
Daksha mission: Science

- Primary science:
  - Detect and localise 1 – 20 BNS mergers and ~500 classical GRBs.
  - Broadband spectroscopy of high-energy transients.
  - Hard X-ray polarimetry of bright transients.

- Secondary science:
  - Magnetar giant flares
  - Compton imaging of high-energy sky
  - Terrestrial Gamma-ray Flashes
  - Solar flares



Bhalerao et al 2022 (arXiv:2211.12052)



GRB polarimetry: Science case

- Timing and spectroscopic studies of prompt emission are not enough to understand GRB the jet physics completely.

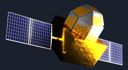
- Polarisation measurements can answer some of the open questions about the GRB jet
  - Composition and dynamics of the jet
  - Energy dissipation and emission mechanism
  - Magnetic field orientation and geometric structure

Toma et. al. 2013, Gill et. al. 2021, Tyler et. al. 2020

MODELS	Polarization degree (PD) %								
	$\Gamma^{-1} \ll \theta_j$			$\Gamma^{-1} \simeq \theta_j$			$\Gamma^{-1} \gg \theta_j$		
	$\theta_v < \theta_j$	$\theta_v \approx \theta_j$	$\theta_v > \theta_j$	$\theta_v < \theta_j$	$\theta_v \approx \theta_j$	$\theta_v > \theta_j$	$\theta_v < \theta_j$	$\theta_v \approx \theta_j$	$\theta_v > \theta_j$
SO	~40	40-50	10-15	<30	40-60	<20	<10	12-20	>50
SR	0	~30	0	0	<20	10-40	0	<10	10-40
CD	0	40-50	0	0	40-70	20-30	0	~40	50-90
PH	0	4-20	-	0	5-15	~20	0	-	~14

SO: Synchrotron Ordered; SR: Synchrotron Random
CD: Compton Drag; PH: Photospheric

Table credits: S. Bala (IIT Bombay), D. Saraogi (IIT Bombay)

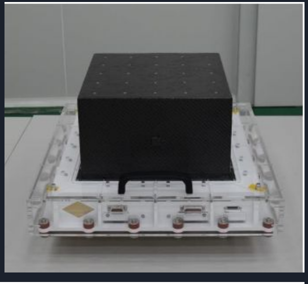


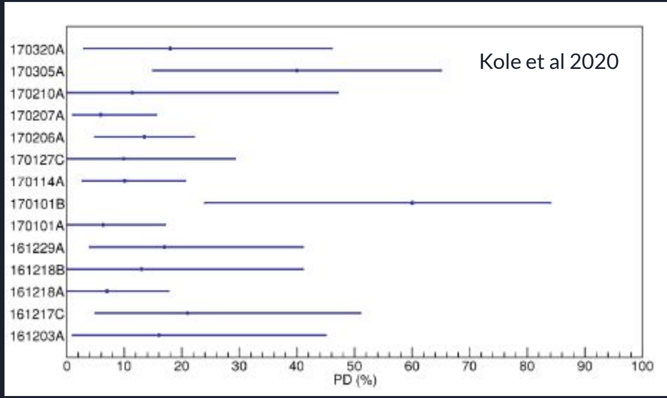
Recent GRB polarimeters

POLAR

Onboard Chinese space station

14 GRBs in one year

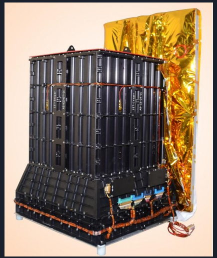




CZTI

Onboard AstroSat

20 GRBs in 7 years



GRB Name	N_{compt}	Bayes Factor	PF (%)[a]	CZTI PA (°)[b]	sky PA (°)
GRB 160325A	764	1.72	< 45.02	–	–
GRB 160623A	1714	1.02	< 56.51	–	–
GRB 160703A	433	0.76	< 62.64	–	–
GRB 160802A	1511	0.69	< 51.89	–	–
GRB 160821A	2851	0.87	< 33.87	–	–
GRB 170527A	1638	0.79	< 36.46	–	–
GRB 171010A	3797	0.98	< 30.02	–	–
GRB 171227A	1249	0.84	< 55.62	–	–
GRB 180103A	4164	8.52	71.43 ± 26.84	34.67 ± 7.00	122.13
GRB 180120A	705	3.95	62.37 ± 29.79	−3.65 ± 26.00	61.21
GRB 180427A	986	9.25	60.01 ± 22.32	16.91 ± 23.00	47.22
GRB 180806A	555	0.86	< 95.80	–	–
GRB 180809B	3294	0.98	< 24.63	–	–
GRB 180914A	2276	1.2	< 33.55	–	–
GRB 180914B	7765	3.52	48.48 ± 19.69	26.99 ± 19.00	68.41
GRB 190530A	1859	3.08	46.85 ± 18.53	43.58 ± 5.00	154.05
GRB 190928A	4492	1.77	< 33.10	–	–
GRB 200311A	1082	0.86	< 45.41	–	–
GRB 200412A	911	0.89	< 53.84	–	–
GRB 200806A	534	0.71	< 54.73	–	–

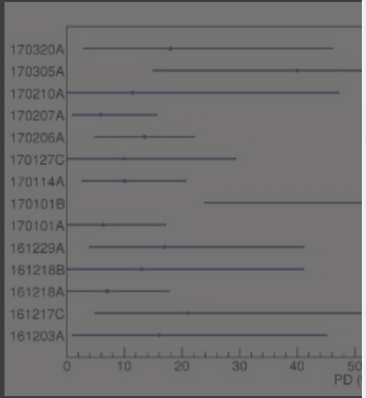
Chattopadhyay et al 2022

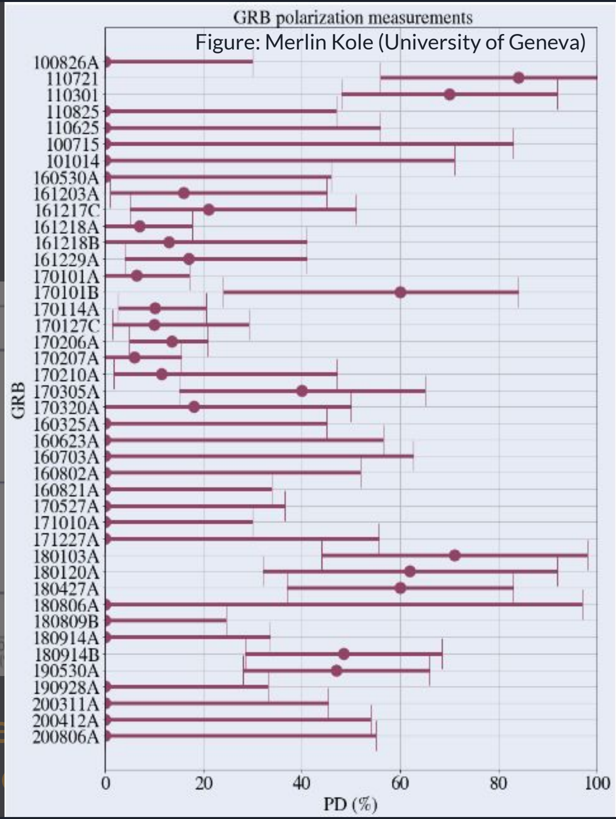
In addition to these, measurements by some other missions (RHESSI, BATSE, INTEGRAL, GAP) take the number to about 50 out of > 5000 GRBs detected till now

Recent GRB polarimeters

POLAR

Onboard Chinese space station
14 GRBs in one year





CZTI

Onboard AstroSat
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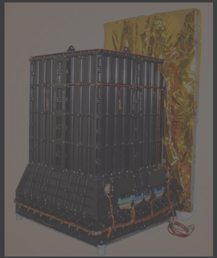

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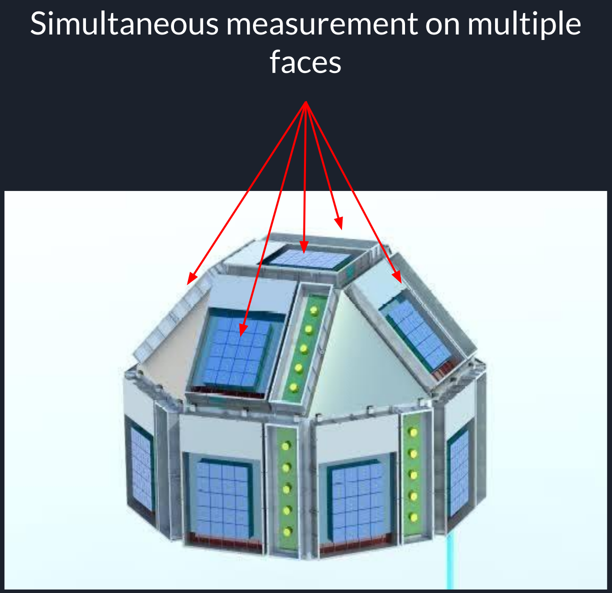
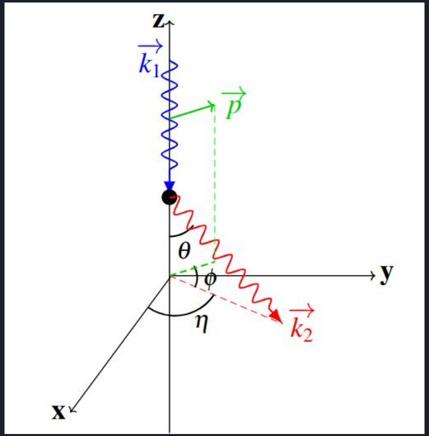
GRB Polarimetry with Daksha

- Advantages:
  - Large effective area, simultaneous and independent measurement with each face.
  - At least 4-5 times more GRB detections / year than CZTI.
  - No shielding ⇒ Less reprocessing of photons due to scattering
- Disadvantages:
  - No shielding ⇒ Higher background (but simultaneous background measurement available + higher time resolution).

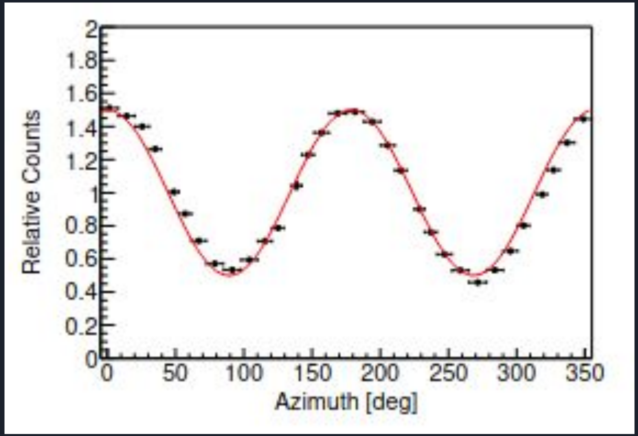


Hard X-ray polarimetry: Basic concept

- Based on the principle of Compton scattering.
- Polarised photons are Compton scattered in direction ⊥ to the E field.
- Polarisation shows up as modulation at 2ϕ, the amplitude of the modulation gives the polarisation fraction / degree (PA or PD) and the phase gives the polarisation angle (PA).

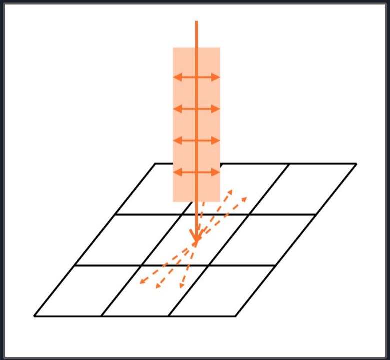


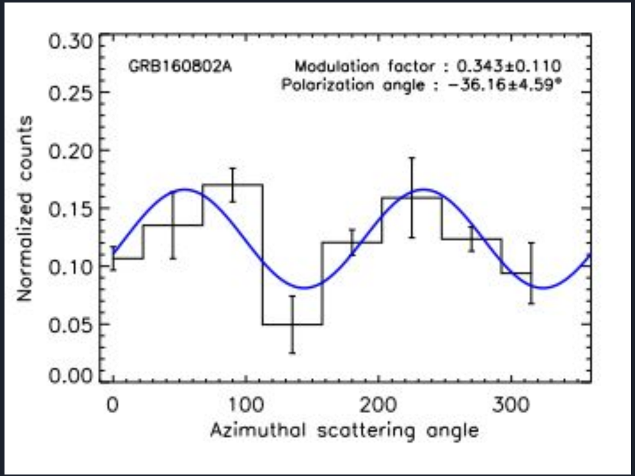
Bernard et. al 2022



X-ray polarimetry with pixelated CZT detector

- Pixelated detector → 8 azimuthal pixel bins
- Compton scattering dominant in 100 - 400 keV range.
- Successfully demonstrated with AstroSAT/CZTI.
- Modulation curve fitting can introduce additional systematics for off-axis incidences.





Chattopadhyay et. al 2019

Template Matching

Create azimuthal histogram templates for different Polarisation Angle (PA) / Polarisation Fraction (PF) values and match them (using chi sq. fitting) with observed azimuthal histogram (Vaishnava et. al. 2022)

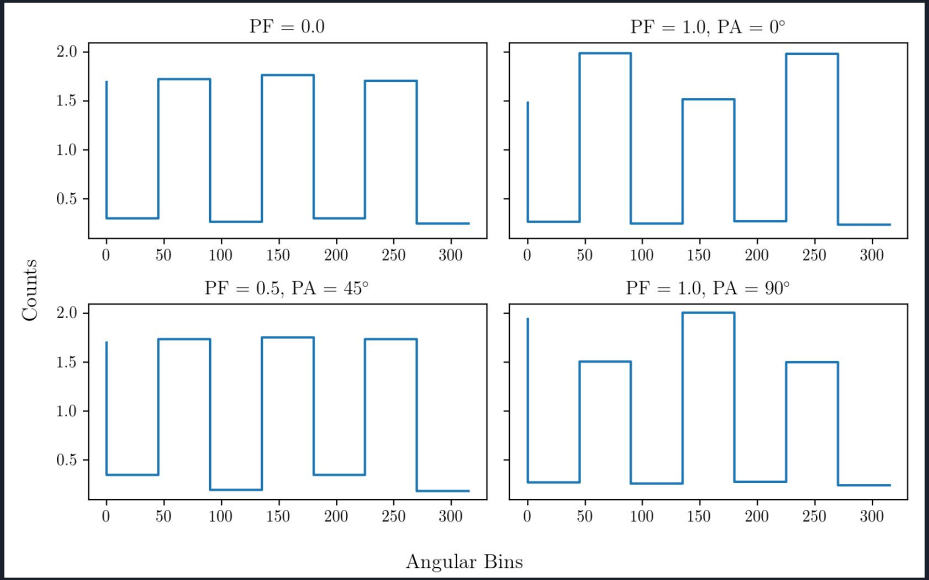
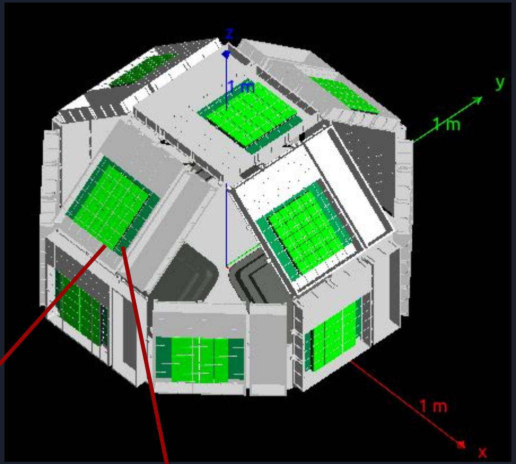
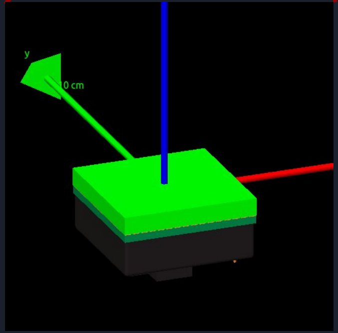


Figure: A. Mehla (IIT Bombay)

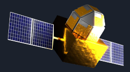
Daksha mass model

- ME Box: CZT detectors + support structure modelled with ~few percent accuracy
- HE Box: Only the shield and NaI crystal modelled
- LE Box: Only the support structure modelled.
- Dome frame without satellite bus.
- Only CZT crystal is an active volume.





Minimum Detectable Polarisation (MDP)



- Minimum polarization fraction above which the probability of observed modulation being attained by unpolarized photons by chance is less than 1%.

$$\mathrm{MDP} = \frac{4.29}{\mu_{100}\, R_s}\left[\frac{R_s + R_b}{T}\right]^{1/2}$$

μ_{100} = Modulation factor for 100% polarised light
R_s = Source count rate
R_b = Background count rate
T = Total exposure

- Only valid for on-axis incidence as it is derived from the expected sinusoidal variation (Weisskopf et. al. 2010).
- Off-axis incidence ⇒ Azimuthal variation deviates from pure sinusoidal variation.

MDP estimation with Monte Carlo method

- We define a Monte-Carlo based approach to compute the MDP for off-axis incidences.
- We call it MC-MDP and it is computed as follows:
  - For a given direction and fluence, simulate large no. of realisations of Unpolarised Azimuthal Histograms.
  - Measure the Polarisation Angle (PA) and Polarisation Fraction (PF) for all the realisations.
  - Obtain the cumulative distribution of measure PF and the 99th percentile of this distribution gives the MDP.

$$H_{i,o}(0) = P\left(\overline{H_i^{grb} T_{grb}}\right) + P\left(\overline{H_i^{bkg} T_{grb}}\right) - P\left(\overline{H_i^{bkg} T_{bkg}}\right) \frac{T_{grb}}{T_{bkg}}$$

GRB duration

Background duration

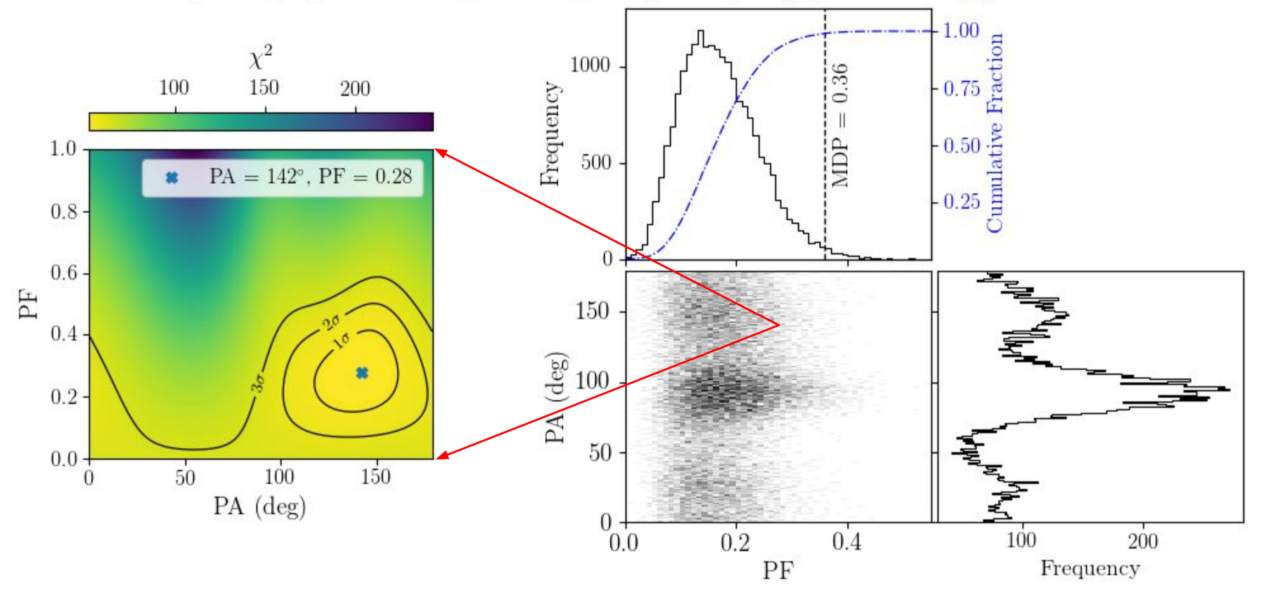
One realisation of observed histogram

Poisson sampling

Time-averaged GRB histogram

Time-averaged background histogram

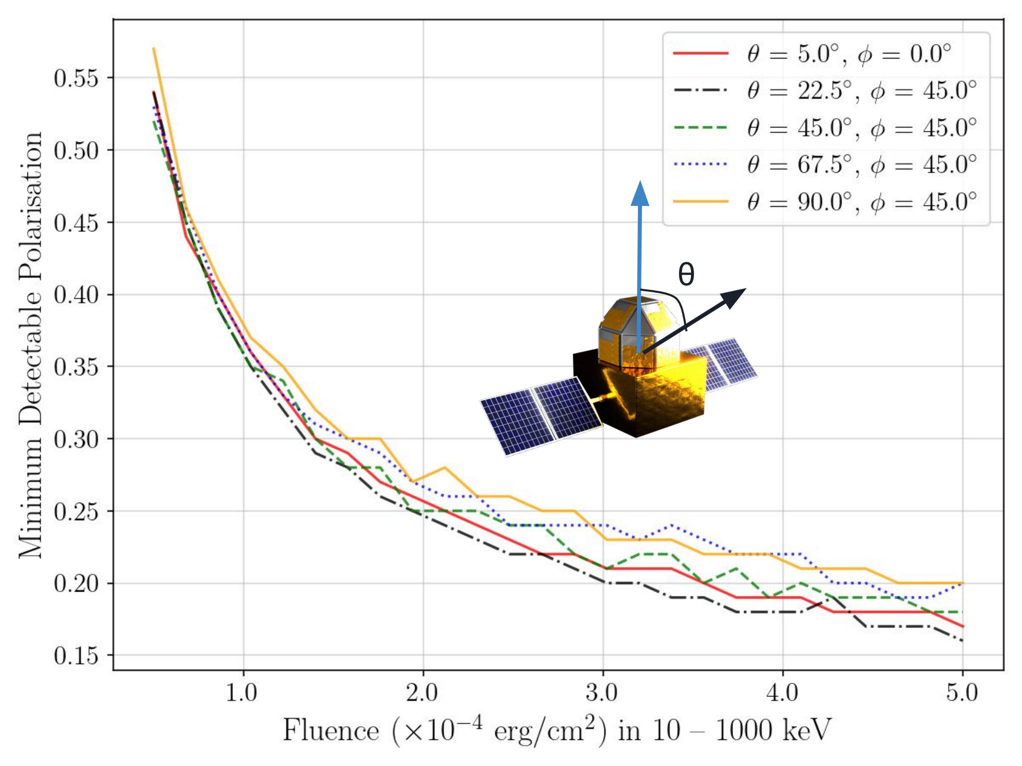
Daksha MDP computation: One example



Near on-axis incidence, fluence = 1 x 10^{-4} erg/cm^2 (10 – 1000 keV)

Bala et al 2023, in prep.

Daksha Polarisation Measurement Sensitivity



For a fluence of 1×10^{-4} erg/cm^2 (in 10 – 1000 keV) we expect to have MDP of 36%

If GRBs are highly polarised, *Daksha* can measure polarisation of about 5 GRBs per year

Bala et al 2023, in prep.

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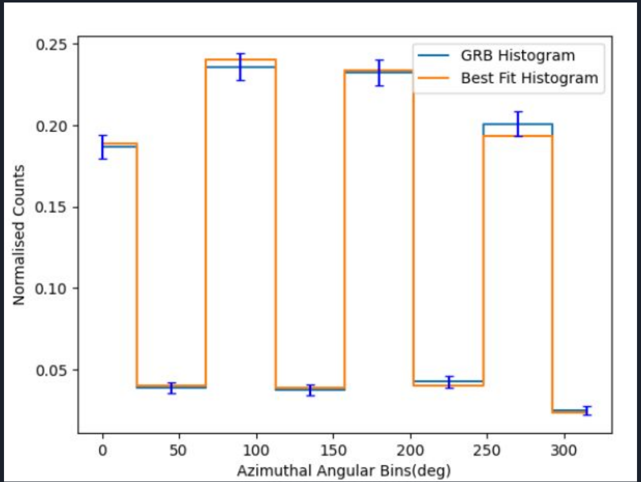
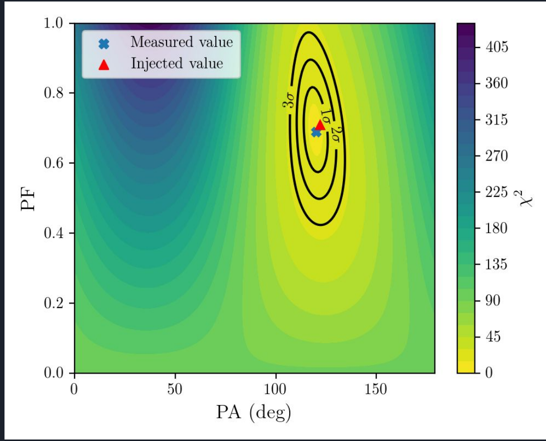
Polarisation measurement cross-check

- Check using injected GRBs.

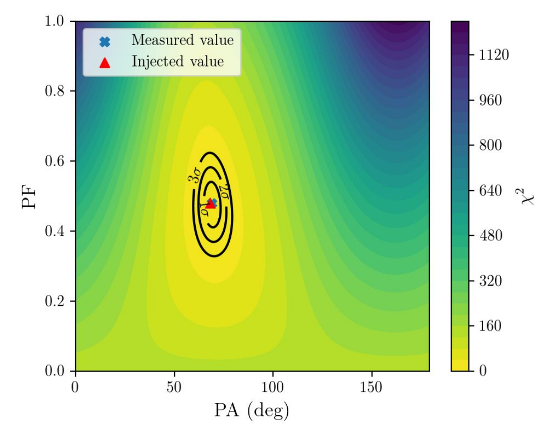


GRB180103A



Injected PA/PF = 122°, 71%
Recovered PA/PF = 120°, 69%

GRB180914B



Injected PA/PF = 68°, 48%
Recovered PA/PF = 69°, 48%

Bala et al 2023, in prep.

Thank You

Template Matching

Observed histogram

Template histogram

Best 5 faces (in terms of det. counts)

$$\chi_j^2(p,\,\psi) = \sum_{i=0}^{i=7} \frac{\left(H_{i,o}(p_0,\,\psi_0) - H_{i,e}(p,\,\psi)\right)^2}{\sigma_{i,o}^2(p_0,\,\psi_0)} \longrightarrow \chi_{tot}^2(p,\,\psi) = \sum_{i=0}^{i=5} \chi_j^2(p,\,\psi)$$

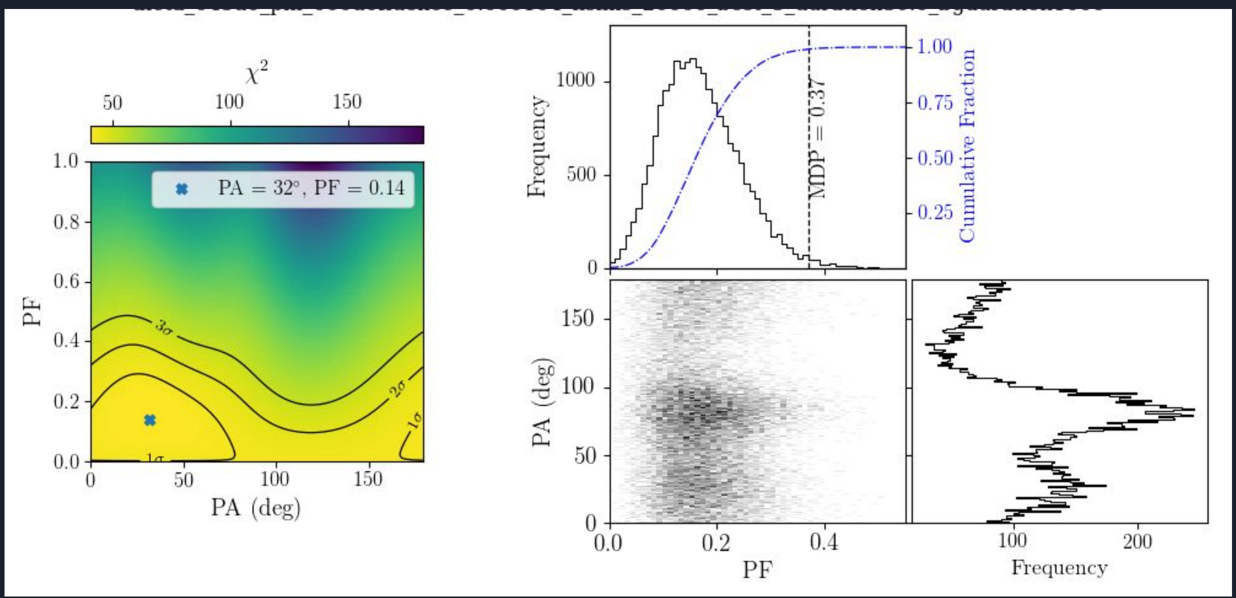
Face ID

Azimuthal bin

Observed variance

Minimise

Daksha MDP computation: One example



45 deg incidence, fluence = 1 x 10^{-4} erg/cm^2 (10 – 1000 keV)

Bala et al 2023, in prep.