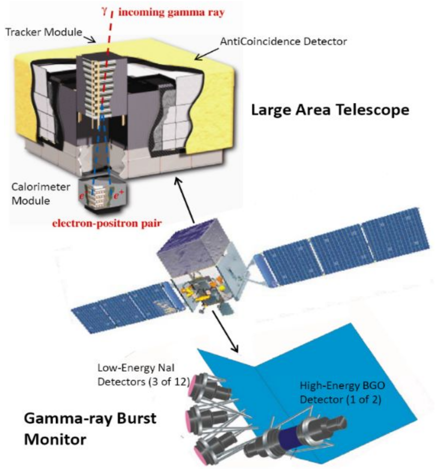
A detailed time-resolved spectro-polarimetric study of bright GRBs observed using *Fermi* and *AstroSat*



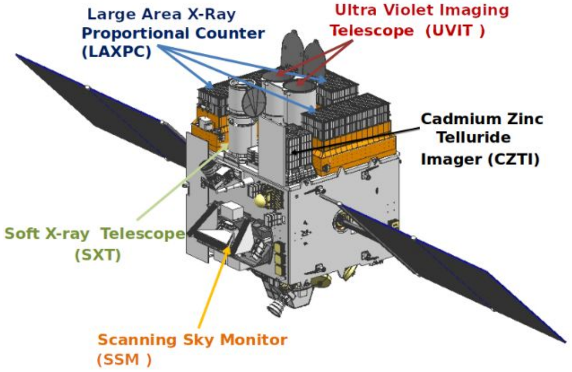
By

Rahul Gupta*

NASA GSFC

11th International Fermi Symposium, 09-13 September 2024

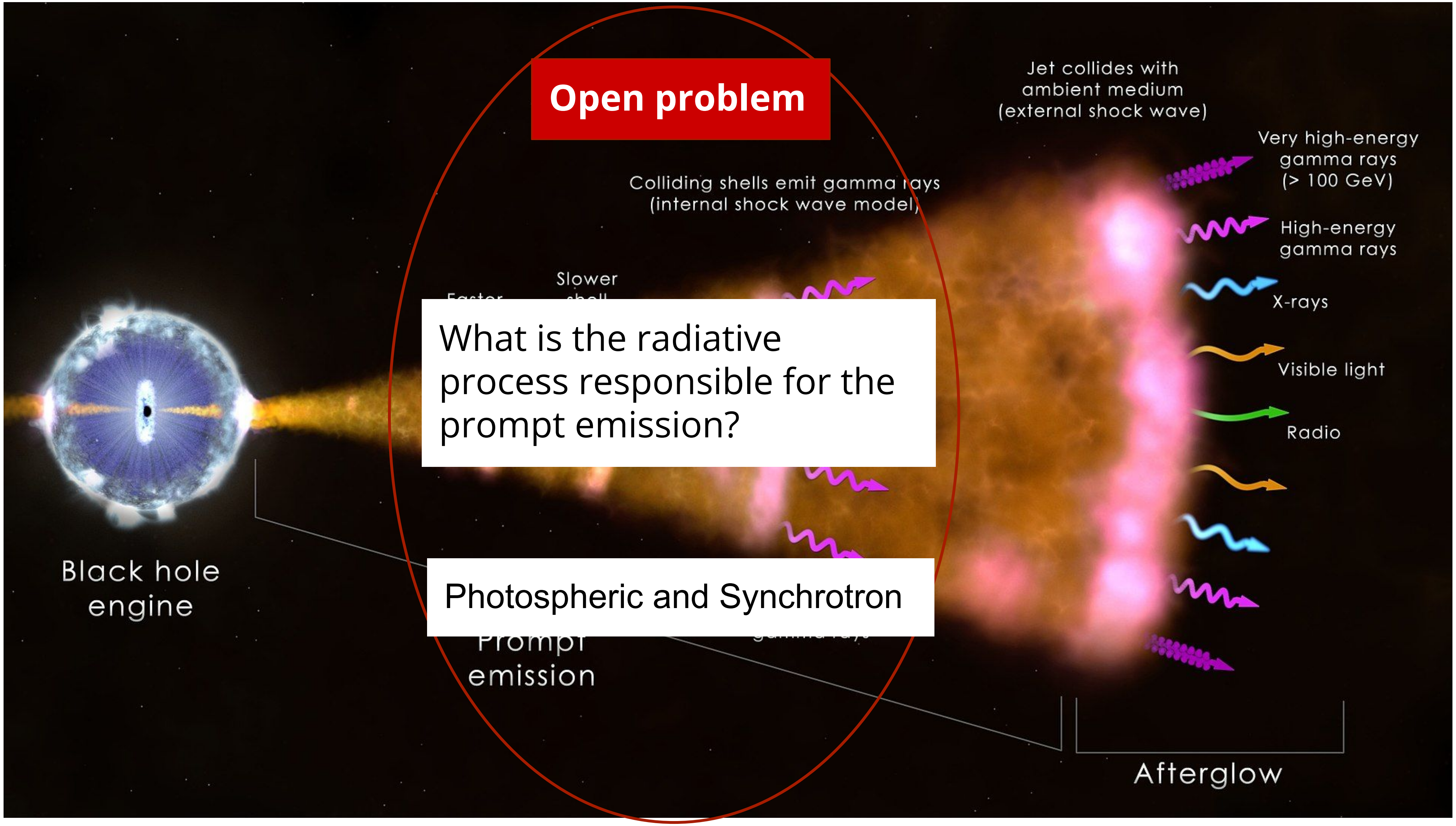
NASA Postdoctoral Program



In collaboration with: A. R. Rao, D. Bhattacharya, T. Chattopadhyay, S. Iyyani, V. Sharma, S. Gupta, V. Bhalerao, S. B. Pandey, Judith Racusin, A. J. Castro-Tirado, + AstroSat CZTI team

*rahulbhu.c157@gmail.com & rahul.gupta@nasa.gov

Gamma-Ray Burst: standard model



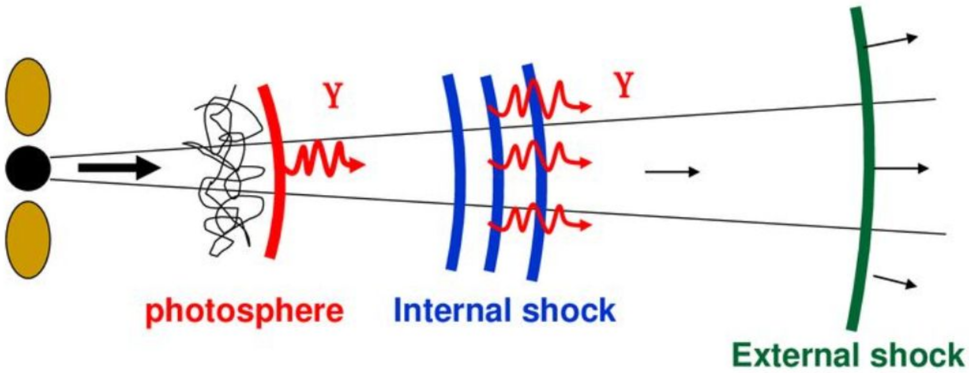
Open problem

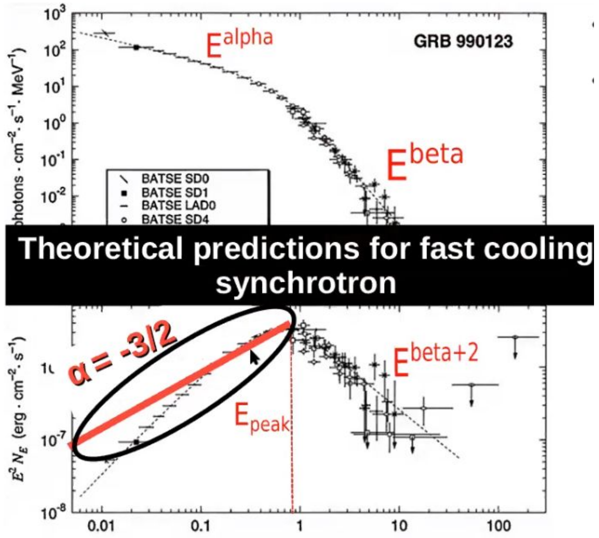
What is the radiative process responsible for the prompt emission?

Photospheric and Synchrotron

Photospheric vs Synchrotron

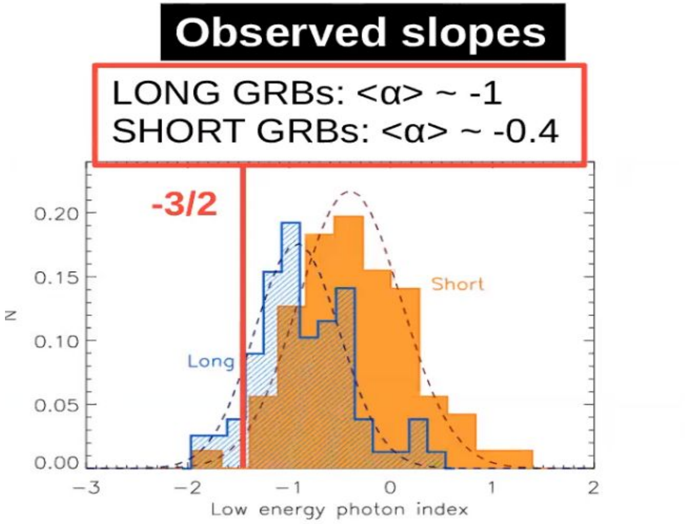
Spectrum	Quasi-thermal	Non-thermal
Spectral Shape	Hard Low-energy Slope (α)	α = -2/3 in the slow-cooling and α = -3/2 in the fast-cooling regime
Light Curve	Smooth, single-peaked	Rapid variability and complex
Energy Dissipation	~10^12 to 10^13 cm	~10^14 to 10^15 cm
Jet Composition	Optically thick, baryonic dominated	Optically thin, magnetically dominated
Polarization	Low or no polarization	High polarization





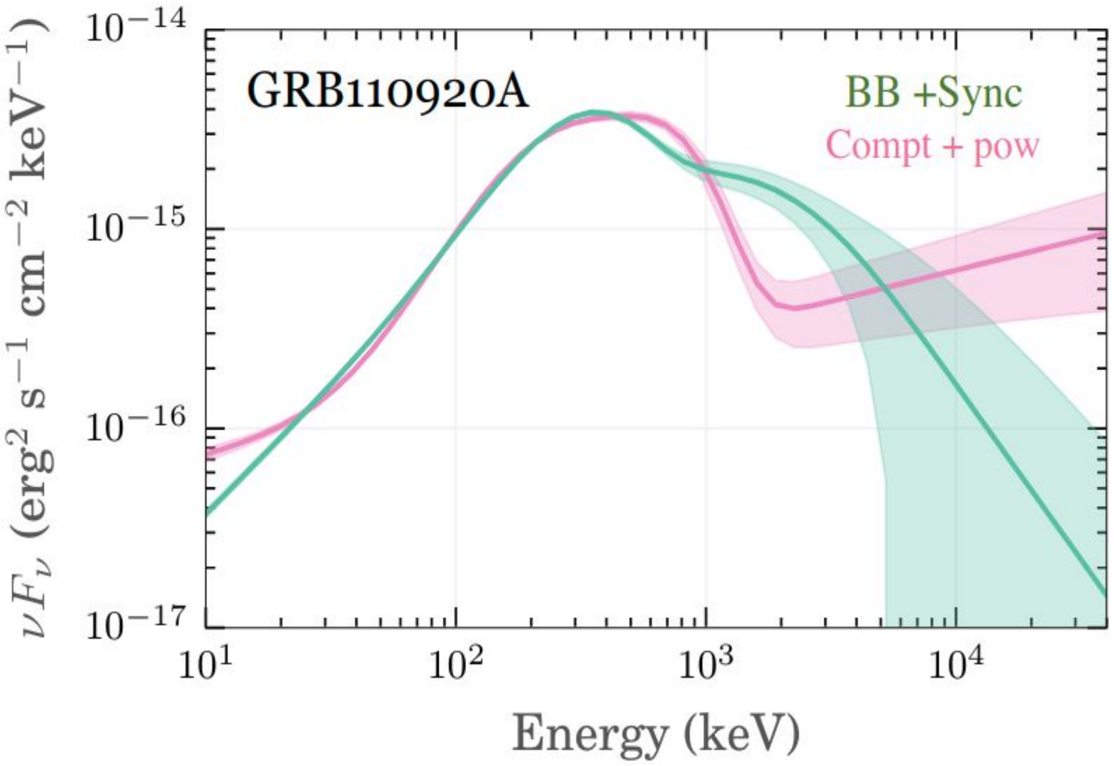
Sari & Piran 1997
Preece 1998
Ghisellini 2000

From Briggs et al., 1999



From Ghirlanda et al., 2009
(see also Preece 1998, Kaneko 2006, Nava 2011, Goldstein 2012, Gruber 2014)

Limitation: Degeneracy between spectral models



> 6000 GRBs in 30 years ! (BATSE, FERMI, SWIFT)
Detailed spectroscopy for most of GRBs (bright)

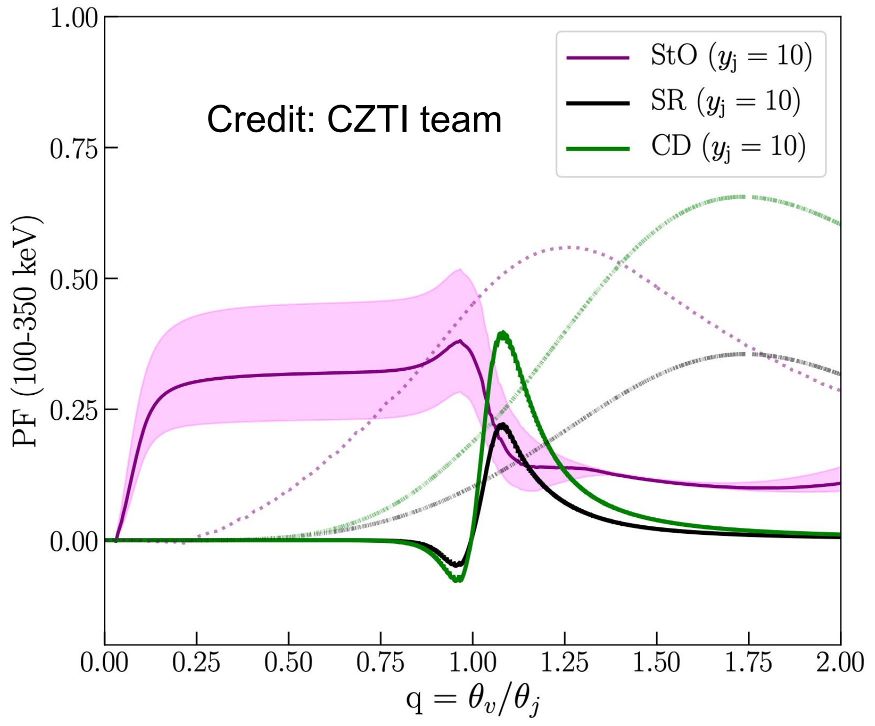
Emission mechanism of prompt emission is still unknown!

Two Models: Two completely different spectral shape

Iyyani et al. 2016, 2018

Constraining Observables: GRB polarimetry

Toma et al. 2009



Polarization measurement for a large sample of GRBs might be useful to understand the prompt emission mechanism.

Polarization measurement by different mission:

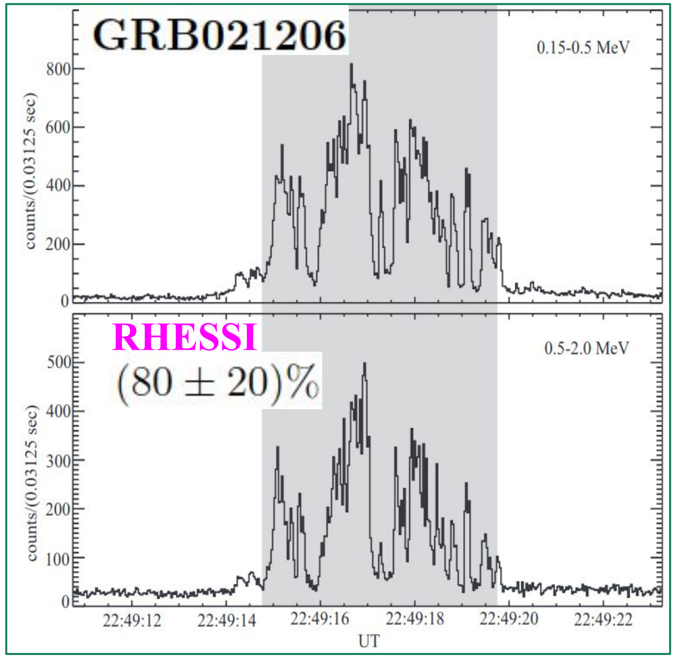
- **RHESSI 1 GRB**
- **BATSE 2 GRBs**
- **INTEGRAL 6 GRBs**
- **Fermi/GBM 1 GRB**
- **GAP 3 GRBs**
- **COSI Balloon Borne 1 GRB**
- **POLAR 14 GRBs**
- **AstroSat 20 GRBs (upto 2020)**

BATSE: GRB 930131 and GRB 960924
$\Pi > 35\%$ and $\Pi > 50\%$

INTEGRAL

GRB	Π (68% c.l.)
041291A	65±26%
06122	>60%
100826A	25±15%
110301A	70±22%
110721	$84^{+16}_{-28}\%$
140206A	>48%

see Gill et al. 2021 for review



Fermi/GBM

GRB 180720B PD= $72^{+24}_{-30}\%$ (1σ)

VERES et al. 2024

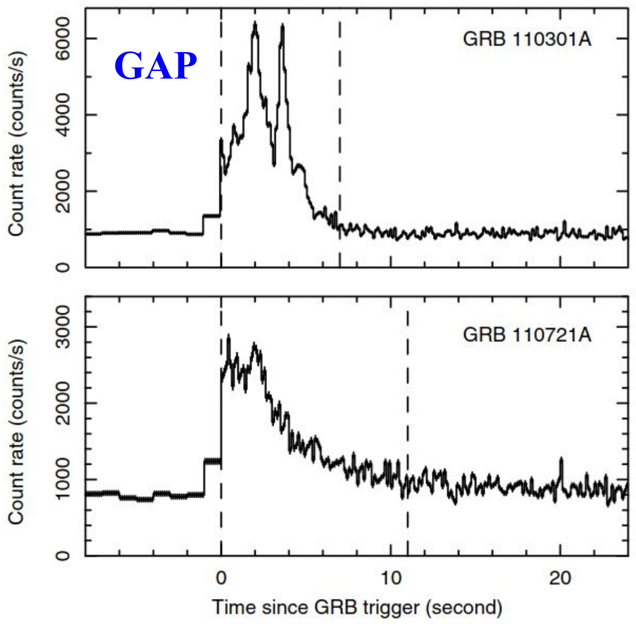
Polarisation depends on the jet viewing geometry:

On axis viewing

High Polarisation fraction:
Synchrotron emission in ordered magnetic field.

Nearly, null Polarisation fraction:
Synchrotron emission in random magnetic field.
Photospheric emission: Compton scattering

GAP, COSI (Balloon Borne), & POLAR



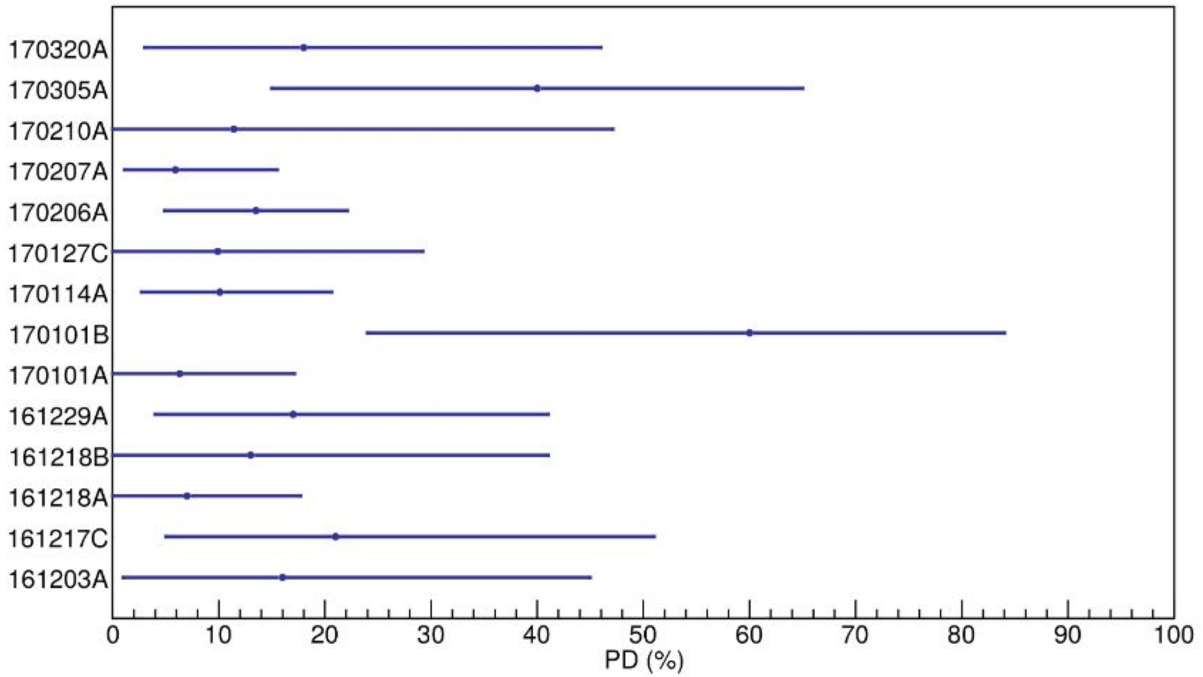
110721A [236]	GAP/IKAROS	84^{+16}_{-28}
110301A [236]	GAP/IKAROS	70 ± 22
100826A [237]	GAP/IKAROS	27 ± 11

GRB 160530A: Balloon Borne Compton Spectrometer and Imager

Π 90% upper limit	46%

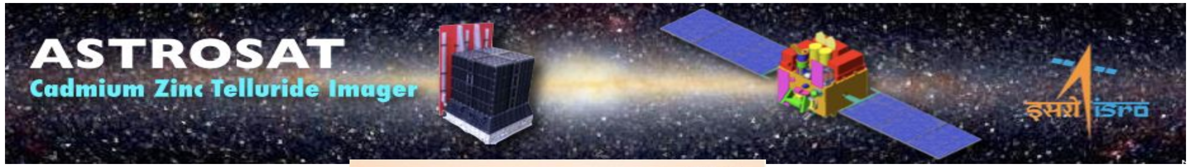
Lowell et al. 2017

POLAR

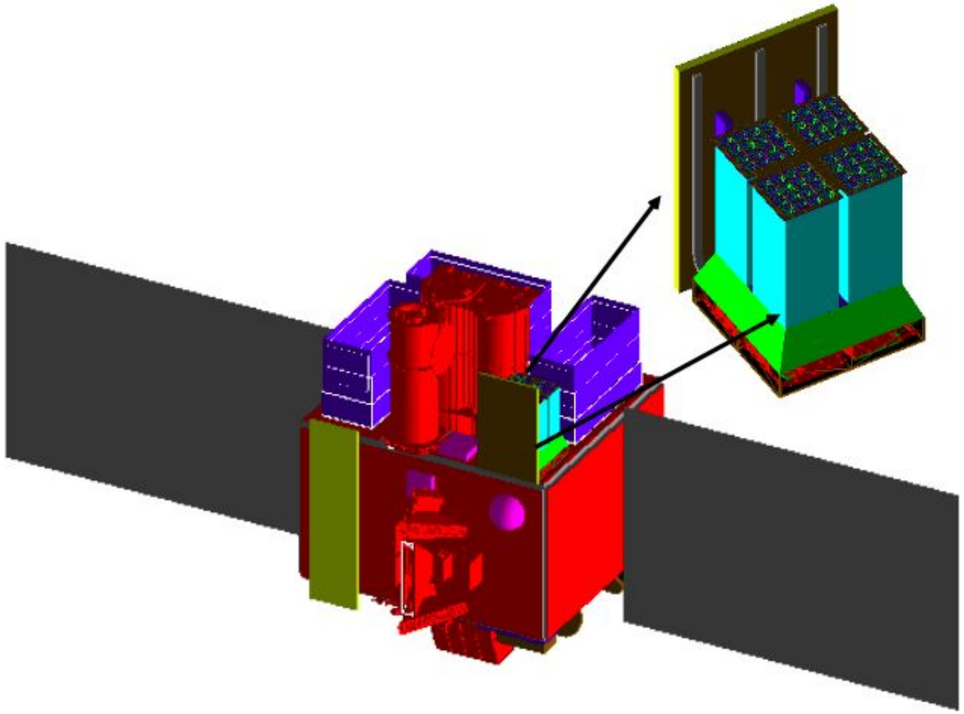


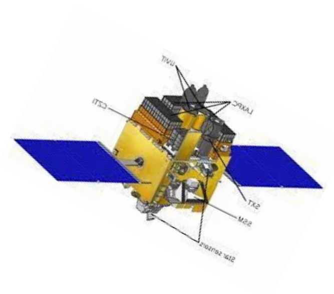
Kole et al. 2020

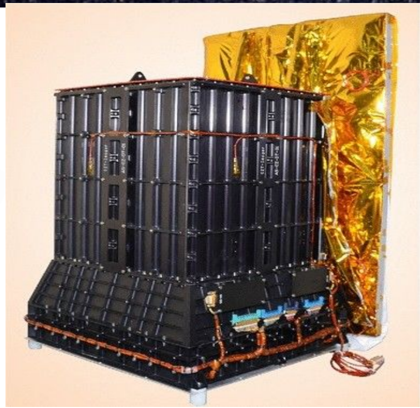
AstroSat and X-ray Polarimetry with CZT-Imager (CZTI)

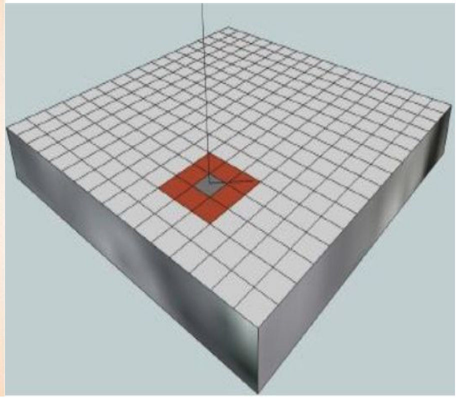


Launched in 28th September 2015.
-Five science payloads onboard.



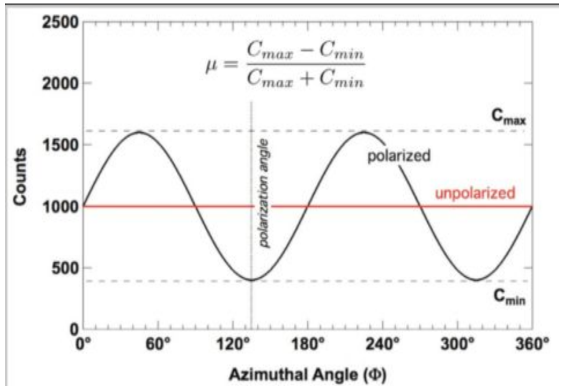


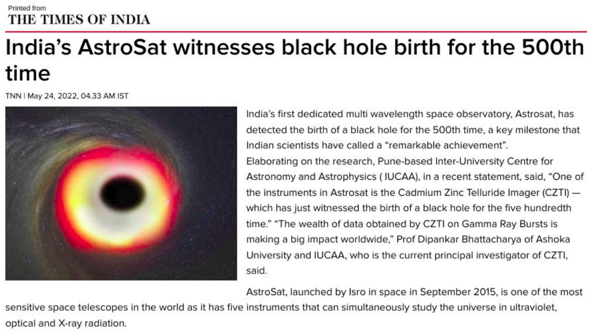




Compton scattering in one pixel and absorption of the scattered photon in another pixel constitute the **8 bin azimuthal angle distribution.**

Aim: To measure the azimuthal distribution of scatter angles about the incident photon direction.





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THE TIMES OF INDIA

India's AstroSat witnesses black hole birth for the 500th time

TNN | May 24, 2022, 04.33 AM IST

India's first dedicated multi wavelength space observatory, Astrosat, has detected the birth of a black hole for the 500th time, a key milestone that Indian scientists have called a "remarkable achievement".
Elaborating on the research, Pune-based Inter-University Centre for Astronomy and Astrophysics (IUCAA), in a recent statement, said, "One of the instruments in Astrosat is the Cadmium Zinc Telluride Imager (CZTI) — which has just witnessed the birth of a black hole for the five hundredth time." "The wealth of data obtained by CZTI on Gamma Ray Bursts is making a big impact worldwide," Prof Dipankar Bhattacharya of Ashoka University and IUCAA, who is the current principal investigator of CZTI, said.

AstroSat, launched by Isro in space in September 2015, is one of the most sensitive space telescopes in the world as it has five instruments that can simultaneously study the universe in ultraviolet, optical and X-ray radiation.

Polarization - 100 - 600 keV

https://astrosat.iucaa.in/czti/grb

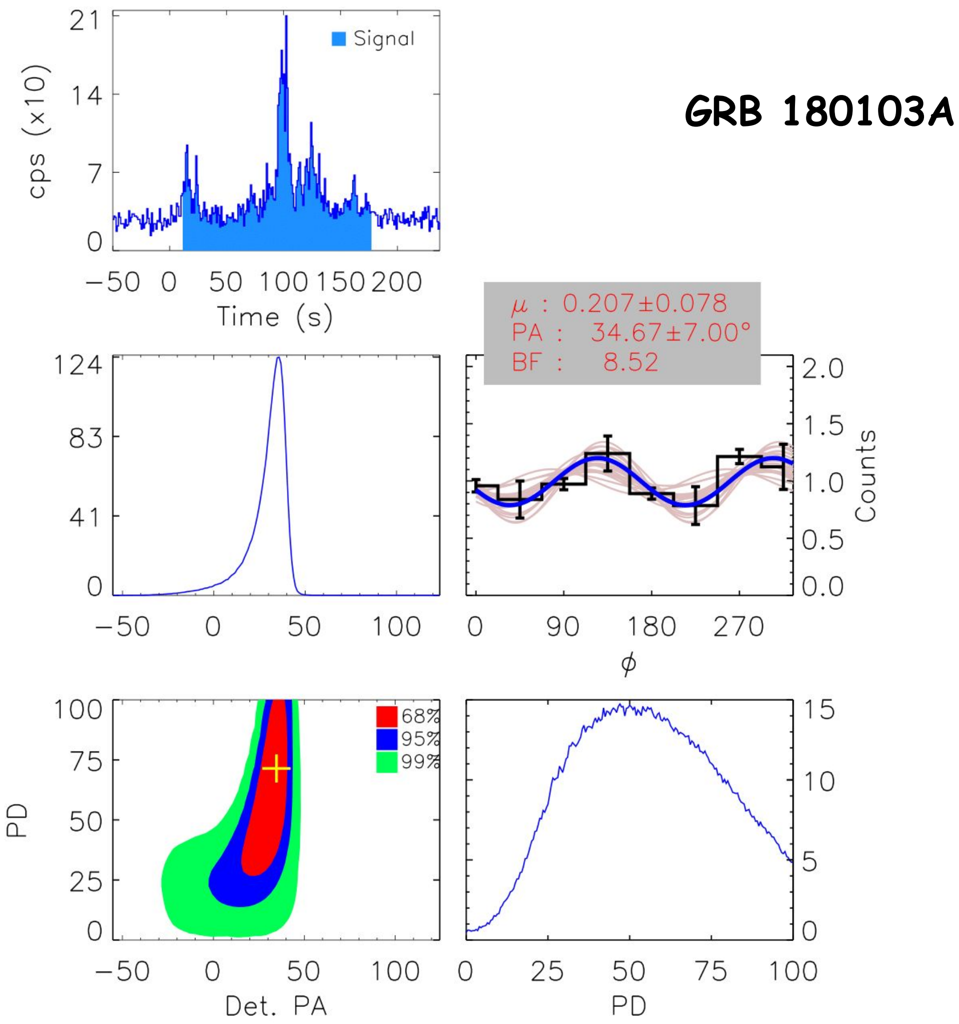
Credit: CZTI team

Finally - GRB polarization for a 5 year sample

2015-2020

Shortlisted 20 GRBs for polarization analysis

- bright
- localized
- <60 degree from detector normal

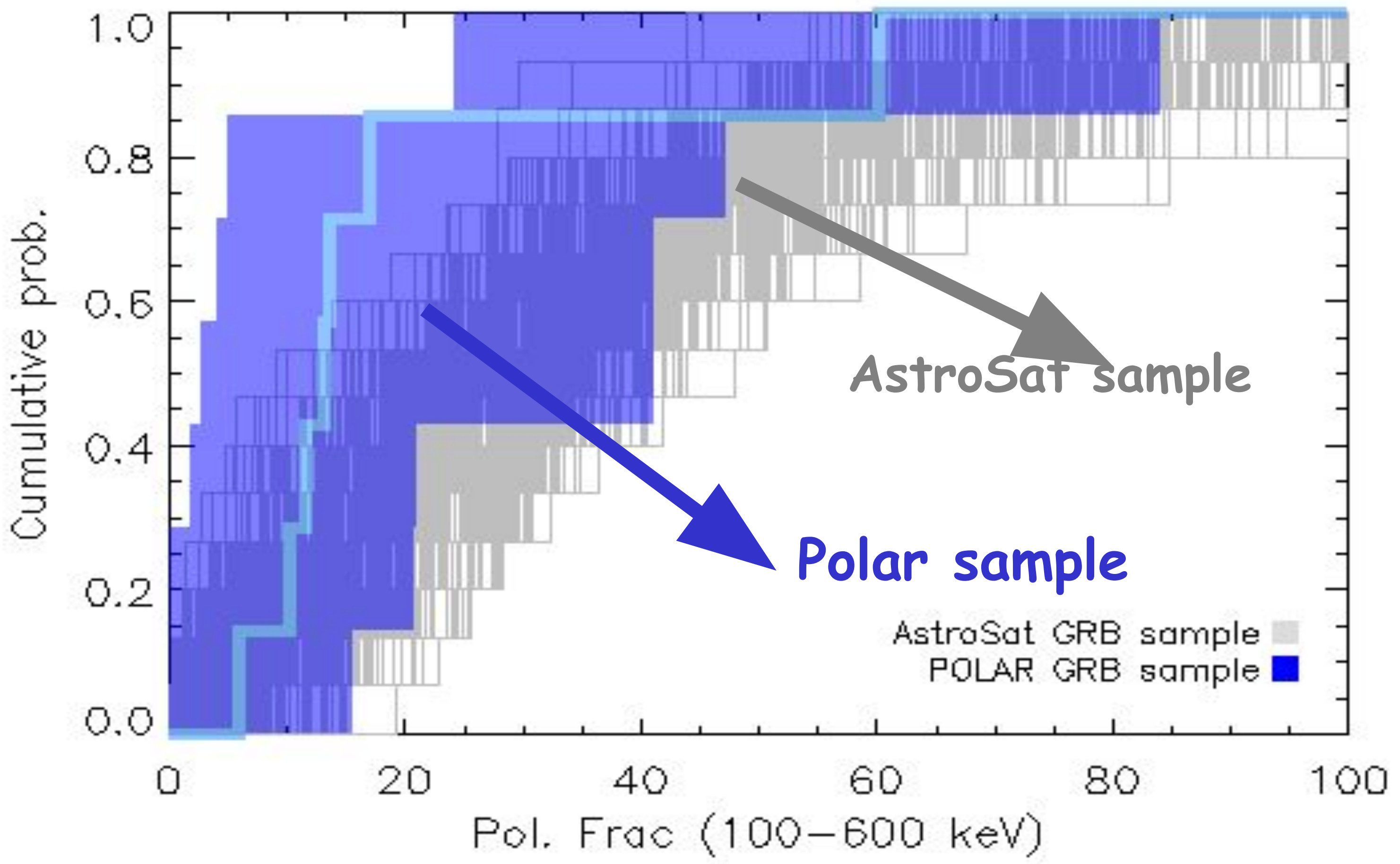


Results (100-600 keV, full burst)

1. Most GRBs are unpolarized in the full burst
2. **25 % of the sample polarized (50 - 70 %)**
3. the total sample size is now more than 40

Chattopadhyay et al 2022, ApJ

GRB polarization for a 5 year sample



Slightly higher polarization (around 20%) in Astrosat sample (100-600 keV) than POLAR (50-500 keV)

Changing PA across the burst ?

narrower sampling region at the higher energies (>100 keV) in case of AstroSat, less chance of mixing

Chattopadhyay et al 2022, ApJ

Time-resolved spectro-polarimetric

THE ASTROPHYSICAL JOURNAL, 972:166 (32pp), 2024 September 10 https://doi.org/10.3847/1538-4357/ad5a92

CrossMark

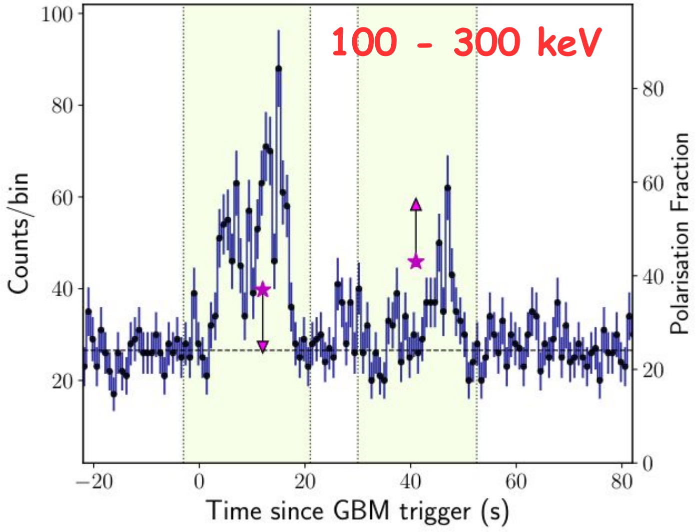
A Detailed Time-resolved and Energy-resolved Spectro-polarimetric Study of Bright Gamma-Ray Bursts Detected by AstroSat CZTI in Its First Year of Operation

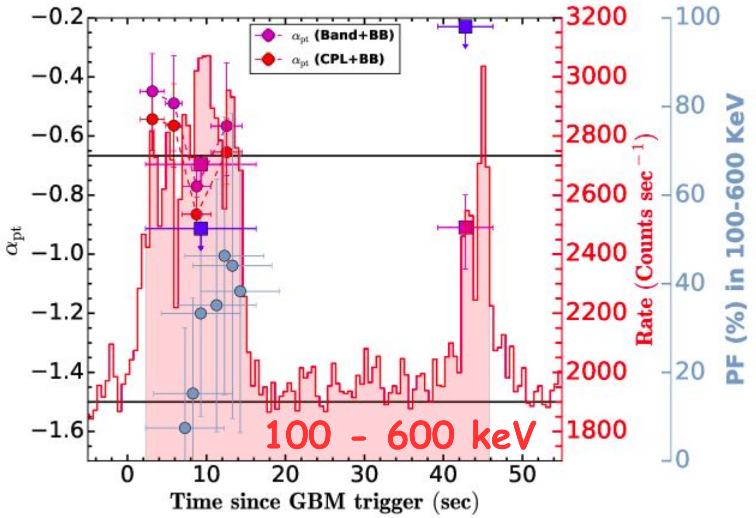
Rahul Gupta[1,2,16], S. B. Pandey[2], S. Gupta[3,4], T. Chattopadhayay[5], D. Bhattacharya[6], V. Bhalerao[7], A. J. Castro-Tirado[8,9], A. Valeev[10], A. K. Ror[2], V. Sharma[1,11,12], J. Racusin[1], A. Aryan[2,13], S. Iyyani[14], and S. Vadawale[15]

[1] Astrophysics Science Division, NASA Goddard Space Flight Center, Mail Code 661, Greenbelt, MD 20771, USA; rahulbhu.c157@gmail.com, rahul.gupta@nasa.gov

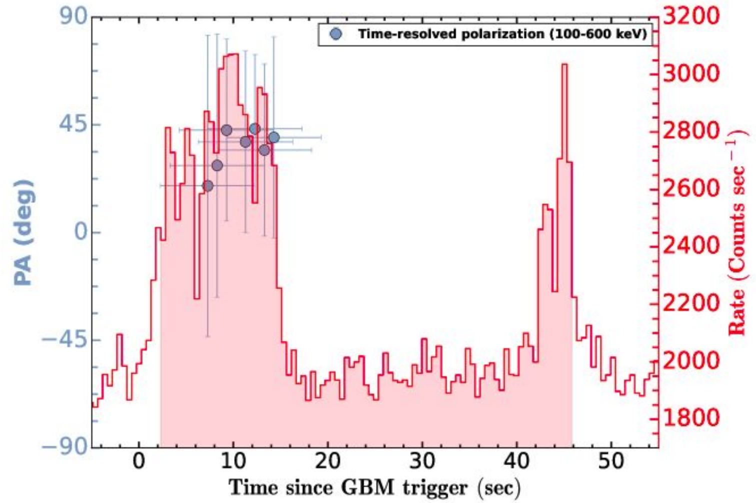
Available in today’s arxiv!

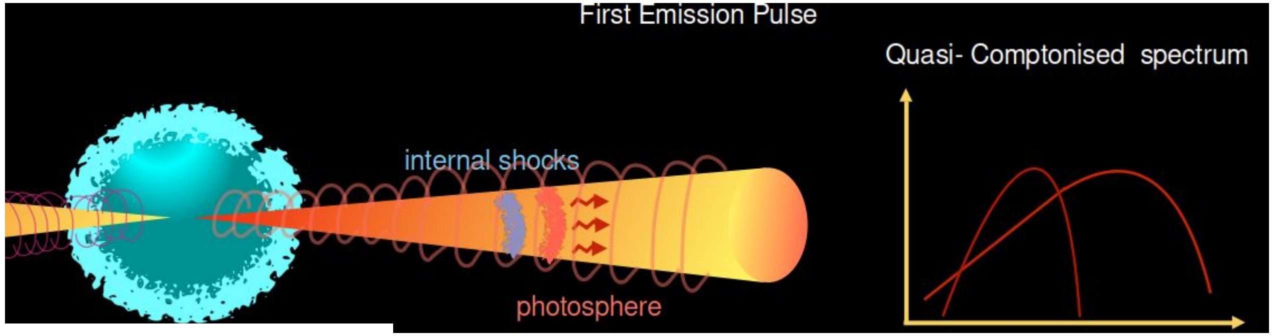
GRB 160325A



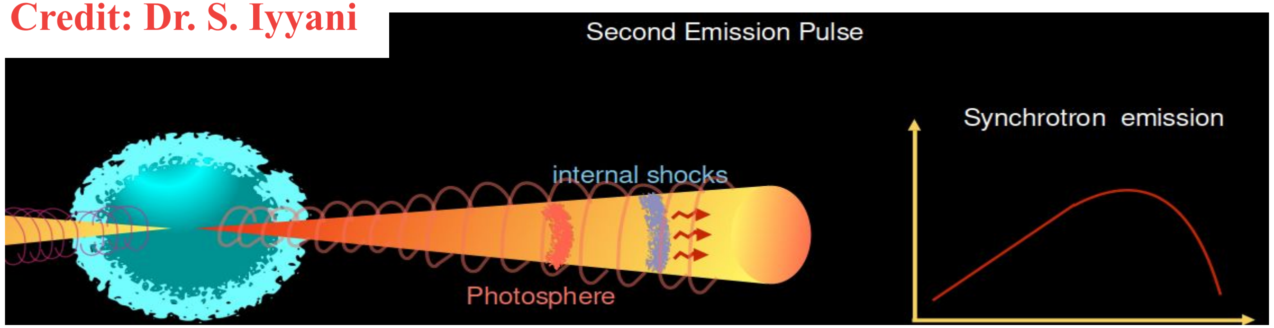


100 - 600 keV





Credit: Dr. S. Iyyani



First Pulse: Best fit Spectrum: Blackbody + Cutoff power law

Second Pulse: Best fit Spectrum: Cutoff power law

Physical scenario: Baryonic dominated jet with mild magnetisation

Gupta et al. 2024, ApJ & Sharma et al. 2020

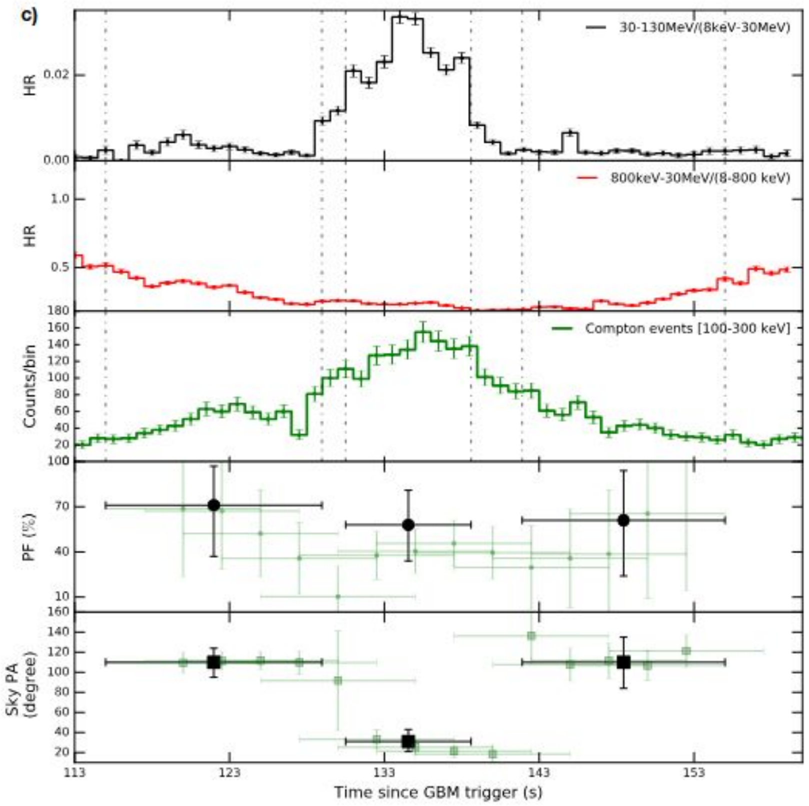
GRB 160821A

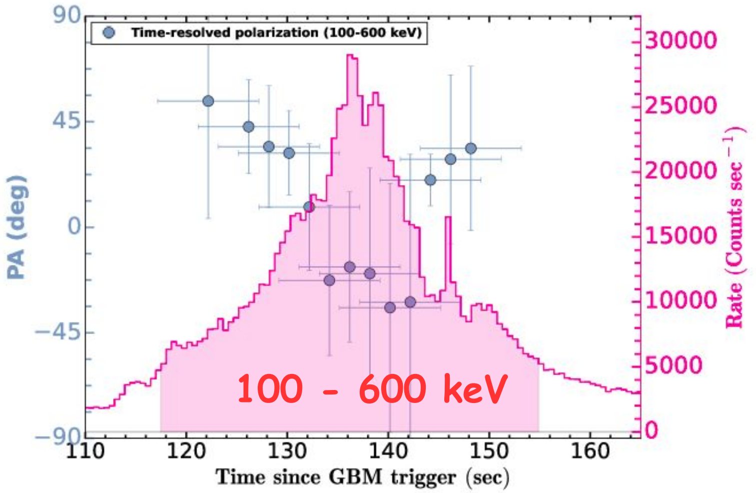
A rapid change in polarization angle by ~ 90 degrees within the main pulse!

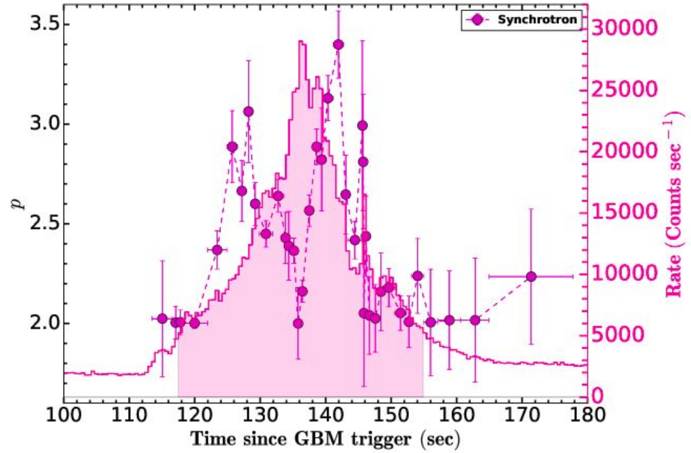
Main features:
Precursor emission ~ 100 s.
Main episode of ~ 88 s duration.
One of the brightest GRB detected by Fermi.

Among highest known values of Eiso ~ 10^{53} -10^{55} erg, for redshift z = 0.4 - 2.

100 - 300 keV





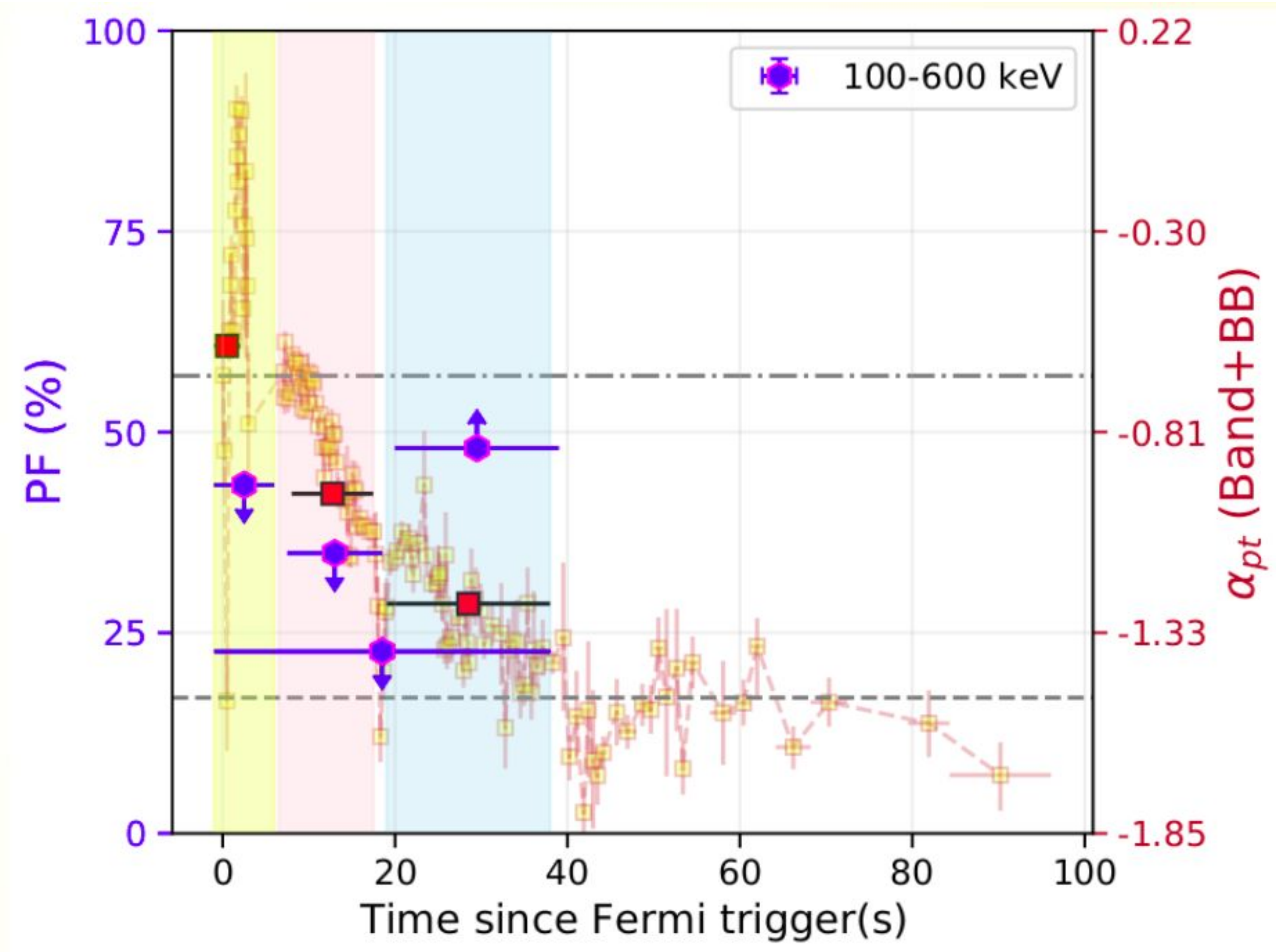


Gupta et al. 2024, ApJ & Sharma et al. 2021 ApJL

Optically thin Synchrotron

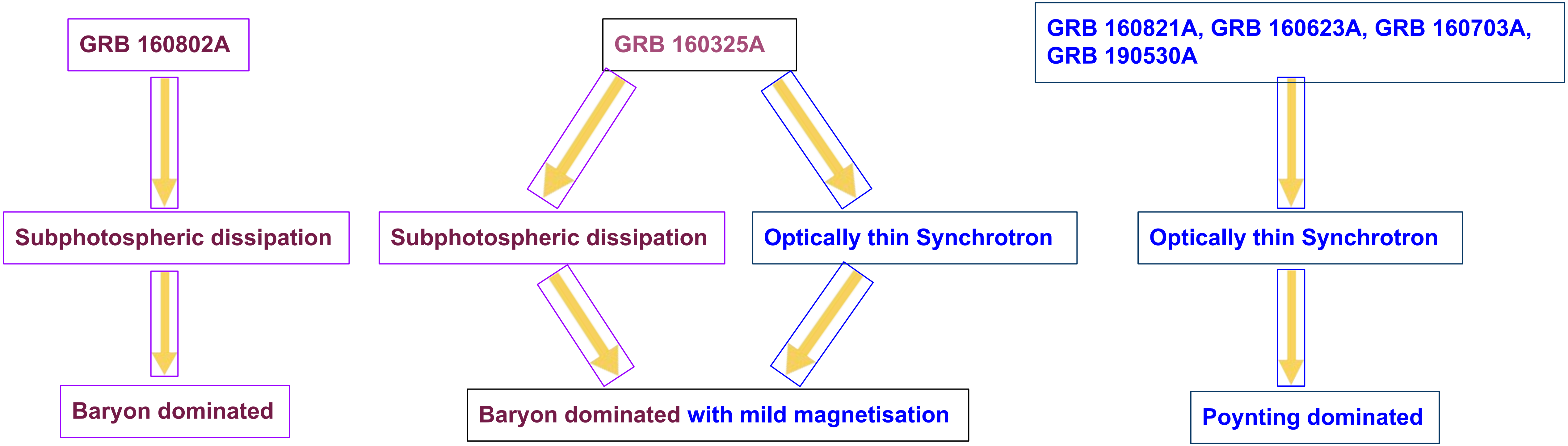
GRB 230307A: Evidence of transition from Baryonic to Poynting flux-dominated jet composition?

The brightest burst for which Spectro-polarimetry analysis has been attempted ever!



See the next talk by Soumya!

Spectro-polarimetric results of CZTI GRBs



GRB 230307A: Evidence of transition from Baryonic to Poynting flux-dominated jet composition

Our study suggests that the jet composition of GRBs may exhibit a wide range of magnetization, which can be revealed by utilizing spectro-polarimetric investigations of the bright GRBs.

Sharma et al. 2019, 2020; Chand et al. 2018, 2019; Chattopadhyay et al. 2021, 2022; Gupta et al. 2022, 2024; S. Gupta et al. (in prep.)

Summary

- **Time-integrated polarization results, while pointing to lower polarization, are potentially an artifact of summing over the changing polarization signal and thus washing out the true moderate/high polarization.**

- **Time-resolved spectro-polarimetry of the bright GRBs give hint of time-dependent nature of polarization properties…POLAR 2/COSI/DAKSHA?**

- **AstroSat will be the only GRB polarimeter till 2027 at least**
  - Another 20 GRB polarization measurement expected (2021-2025).
  - **after localization of the GRBs, the number may go to total 50 GRBs (20+20+10)**

A detailed cookbook and pipeline for GRB polarization measurements using AstroSat/CZTI is going to be public soon!

Thank you for your attention!

*rahulbhu.c157@gmail.com & rahul.gupta@nasa.gov

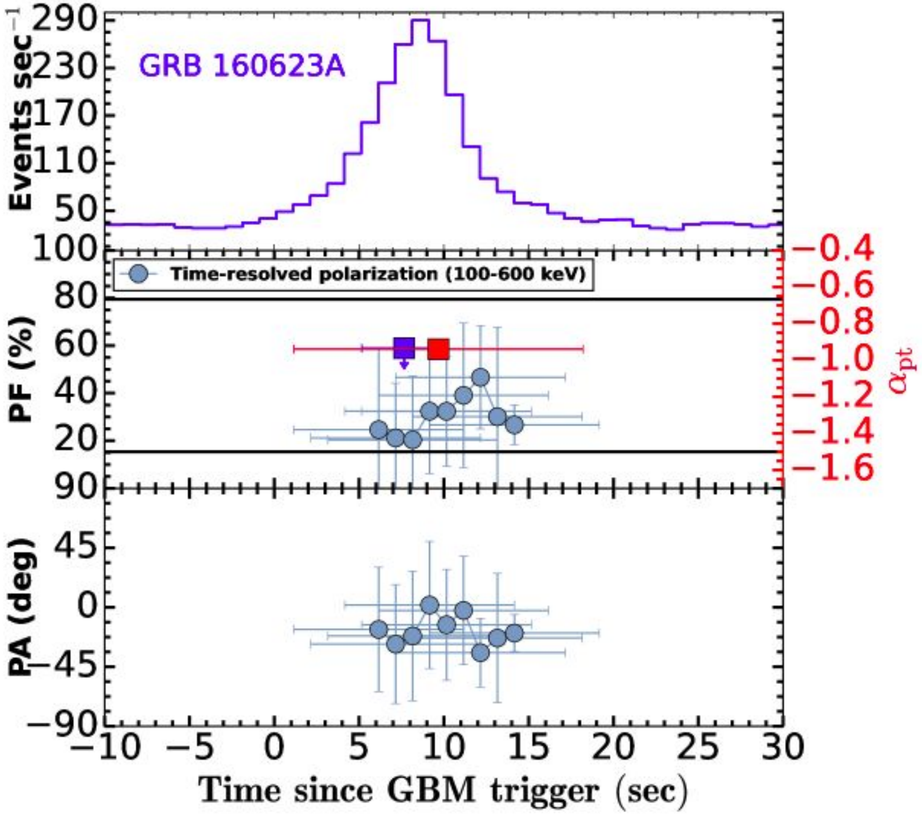
Backup Slides

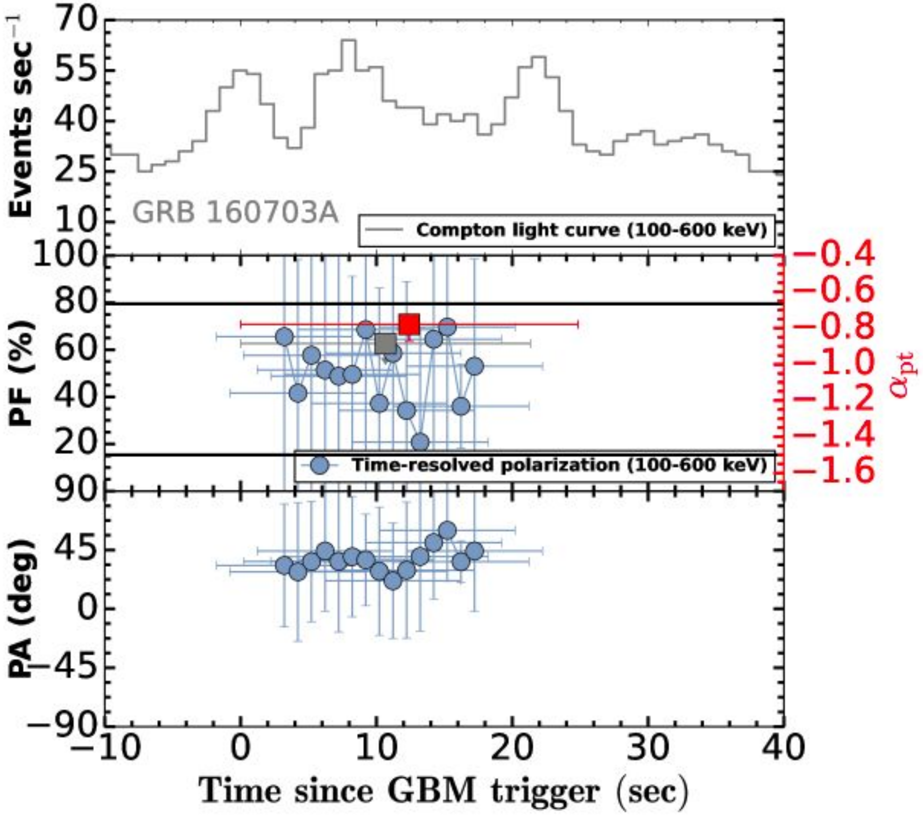
GRB 160623A and GRB 160703A

GRB 160623A (main emission episode) and GRB 160703A were occluded for *Fermi* mission.

The observed value of alpha using the time-integrated Konus-Wind spectrum lies within the synchrotron slow and fast cooling prediction.

Hint of higher PF in time-averaged/time-resolved measurements?



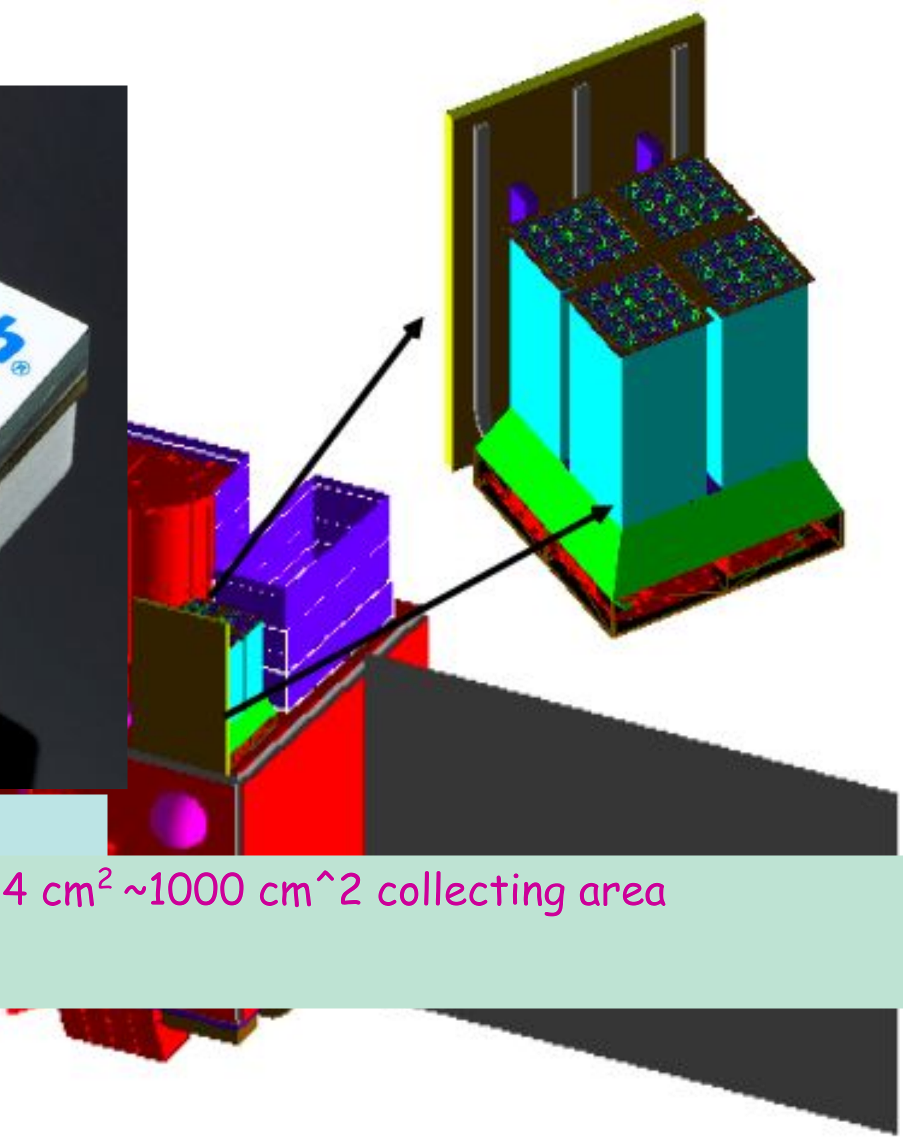


Optically thin Synchrotron

Gupta et al. 2024, ApJ

The possibility of no significant polarization cannot be entirely ruled out based on the current measurements.

AstroSat and X-ray Polarimetry with CZT-Imager



Orbotech CZT modules

- Total 64 modules …. each 4 x 4 cm^2 ~1000 cm^2 collecting area
- 5 mm thick

Credit: CZTI team

AstroSat and X-ray Polarimetry with CZT-Imager

Each Module is pixelated in 16 x 16 pixel ~ pixel size of 2.5 mm

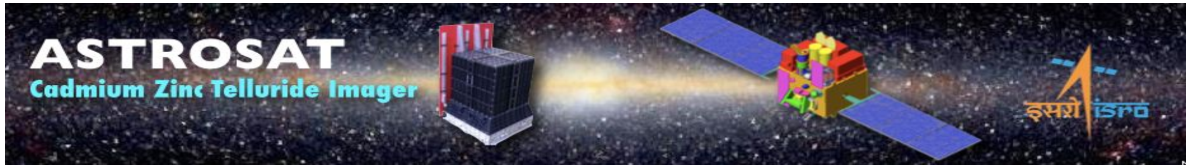
Timing resolution ~ 20 us

Orbotech CZT modules

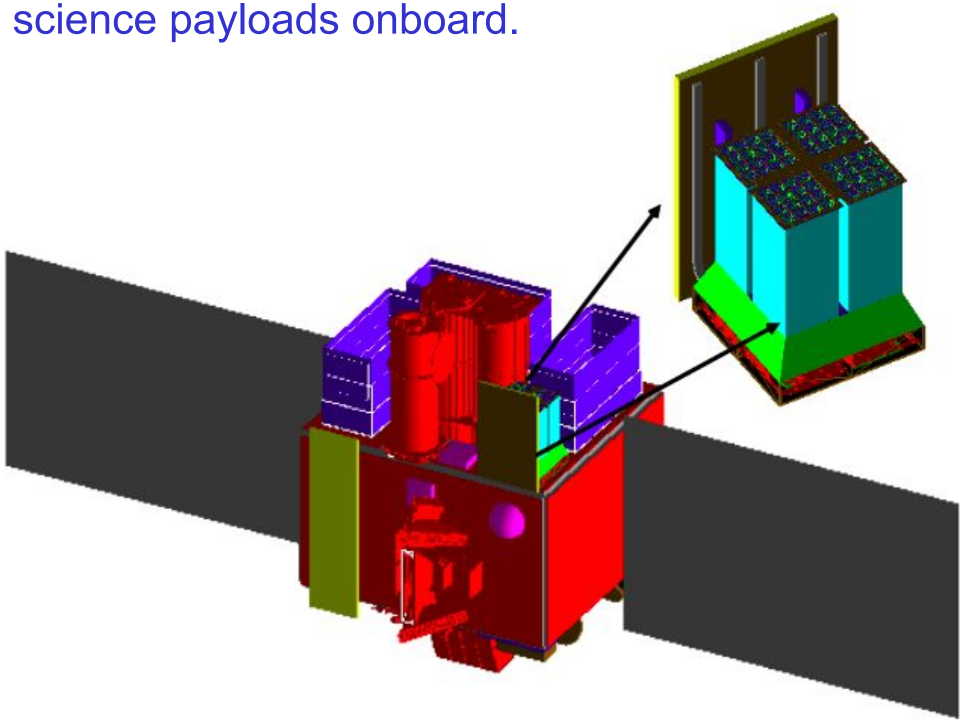
- Total 64 modules … ~1000 cm^2 collecting area …. each 4 x 4 cm^2
- 5 mm thick

Credit: CZTI team

AstroSat and X-ray Polarimetry with CZT-Imager (CZTI)



Launched in 28th September 2015.
-Five science payloads onboard.



The passive shielding around CZTI becomes transparent above 80 keV

CZTI works as open detector in hard X-rays: ~80 GRB detections/ year

EDITION IN

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NEWS / INDIA NEWS / India's AstroSat Witnesses Black Hole Birth For The 500th Time

THIS STORY IS FROM MAY 24, 2022

India's AstroSat witnesses black hole birth for the 500th time

SURENDRA SINGH / TNN / May 24, 2022, 04:33 IST

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ARTICLES

India's AstroSat witnesses black hole birth for the 500th time

'Bachpan Yaad Aa Jaye': The success story of One Kitchen, a 95-yea...

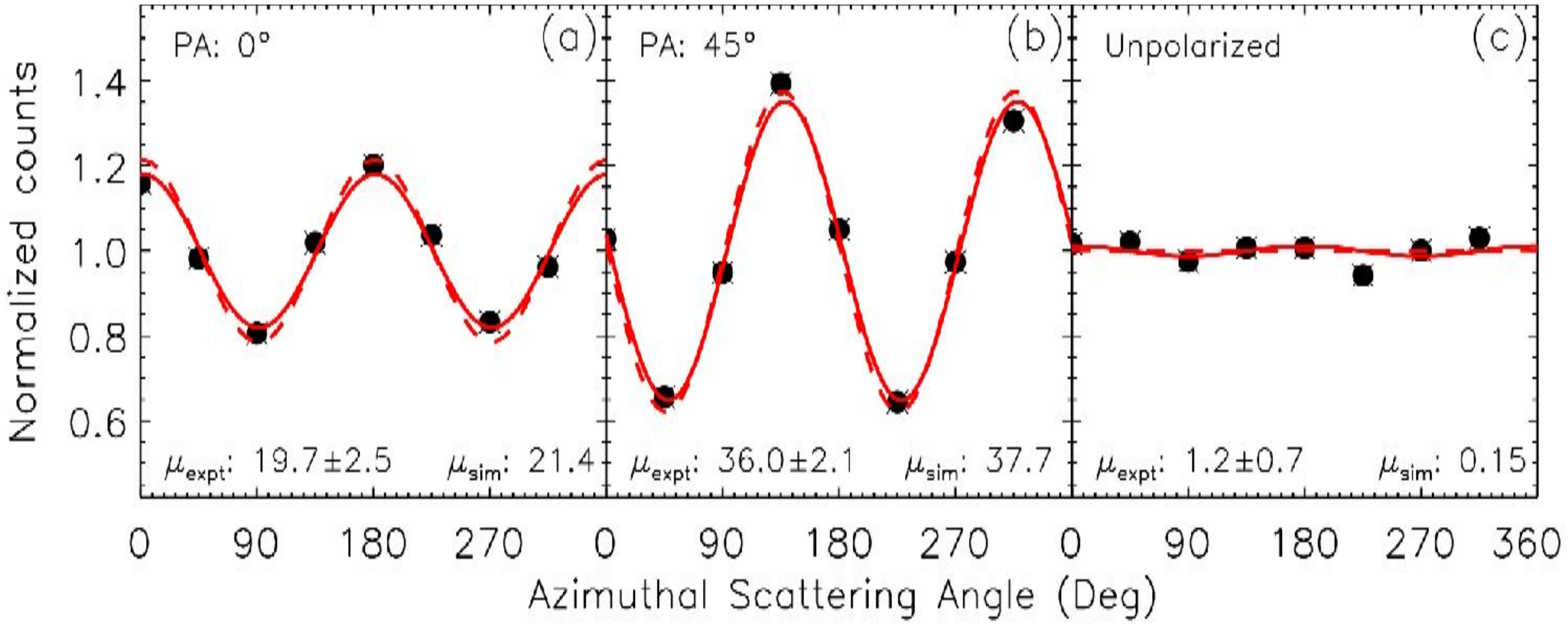
Biggest ever: BEST places Rs 3,675 crore order for 2,100 e-buses

At PM Modi's museum, Amit

Prompt emission polarization of GRBs?

Credit: CZTI team

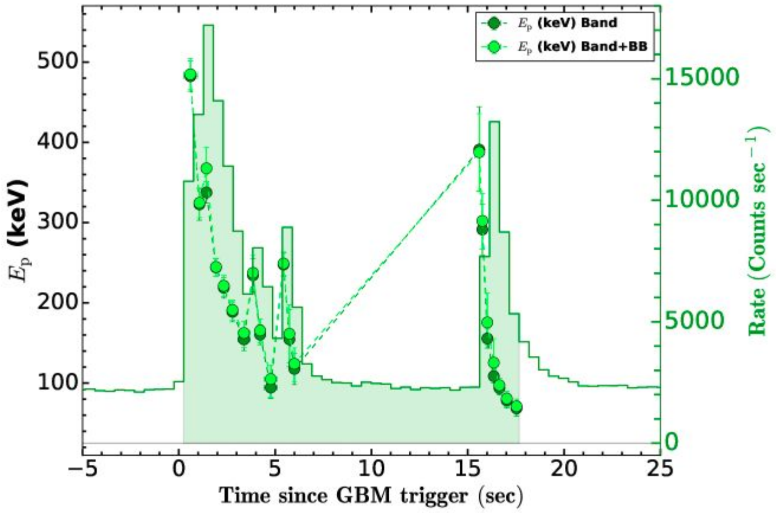
AstroSat and X-ray Polarimetry with CZT-Imager

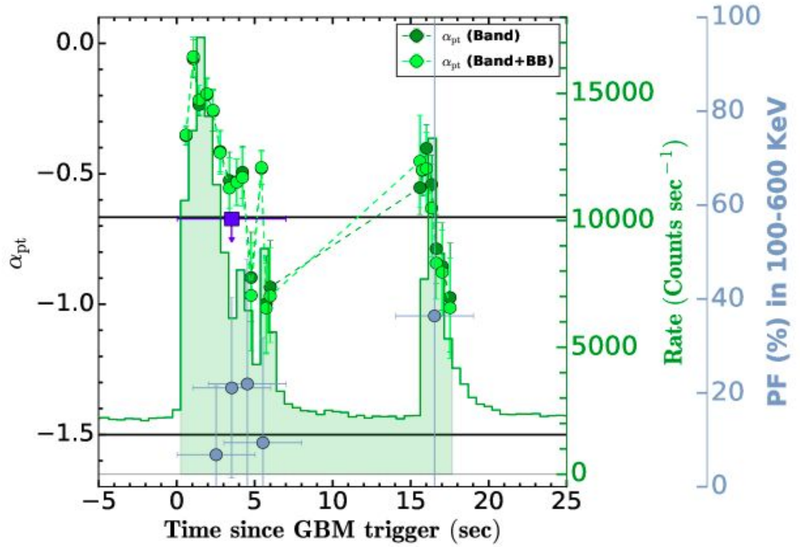


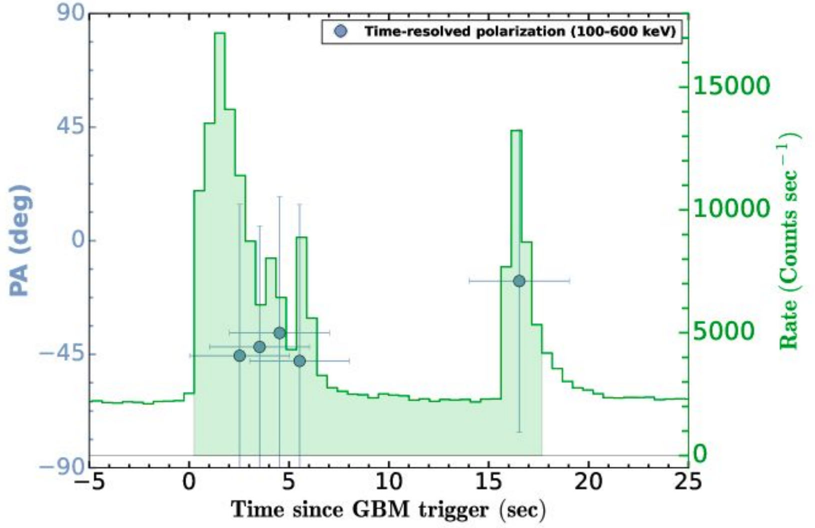
Pre-flight calibration using on-axis laboratory sources

Credit: CZTI team

GRB 160802A







The light curve of GRB 160802A displays two distinct emission episodes separated by a quiescent period.

First Pulse

Hard alpha values > line of death of synchrotron

Time-resolved polarization measurements (sliding mode analysis) during this episode constrain the polarization fraction to low values.

Top hat jet viewed on axis

Physical scenario: Baryonic dominated jet ?

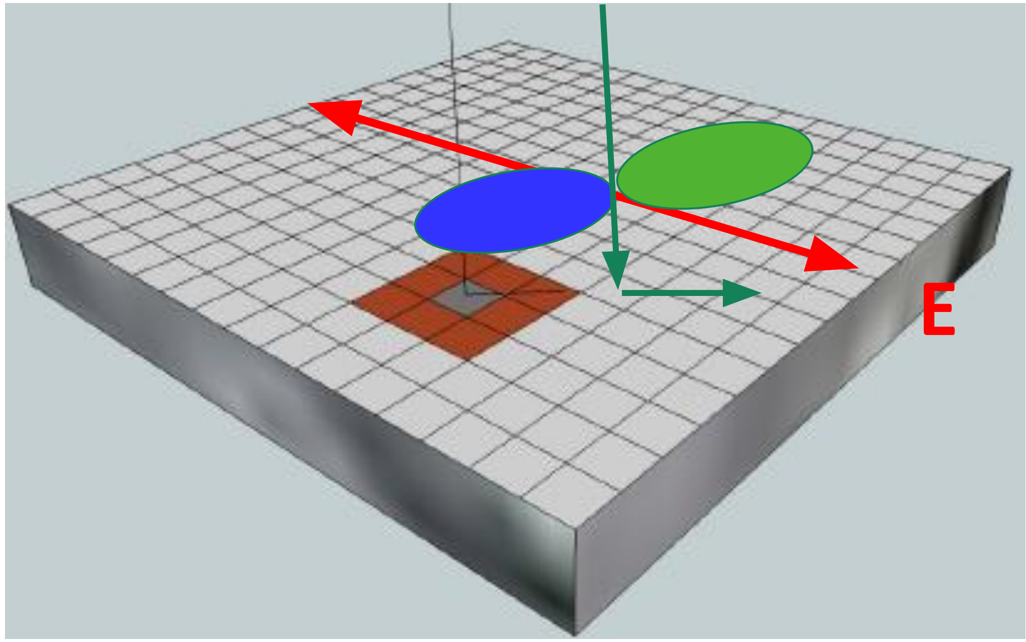
Second Pulse

Relatively softer alpha values but still crossing the line of death of synchrotron in most of the bins.

No precise polarization measurement due to the low number of Compton counts during this episode.

Gupta et al. 2024, ApJ

AstroSat and X-ray Polarimetry with CZT-Imager



5 mm CZT has ~10 % Compton scattering probability > 100 keV

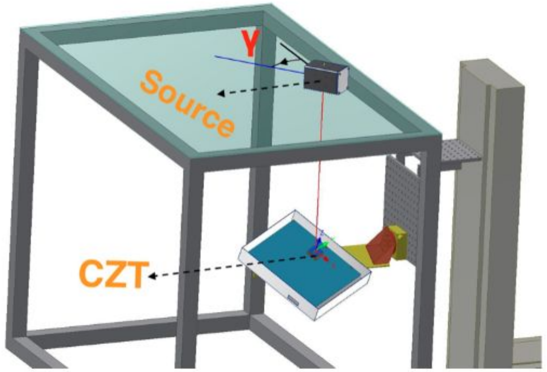
Photons are preferentially Compton scattered at angles perpendicular to the polarization direction – asymmetry in the azimuthal angle distribution

Polarization - 100 - 600 keV

Compton scattering in one pixel and absorption of the scattered photon in another pixel constitute the **8 bin azimuthal angle distribution.**

Credit: CZTI team

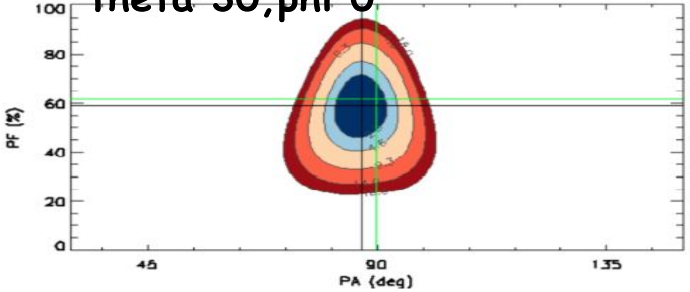
Also recently characterized CZTI detectors for off-axis polarization in lab ...



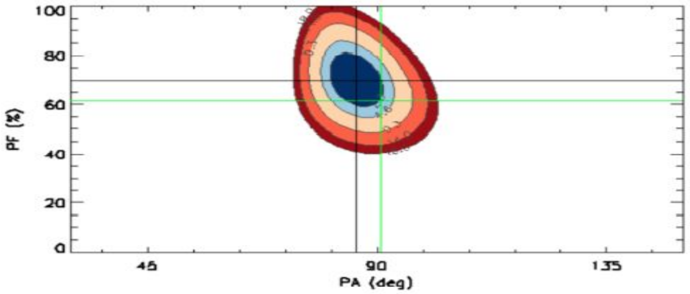
A Ba133 radioactive source to make polarized radiation.

Expt done at multiple off-axis angles - 30,45, 60 degree

theta 30,phi 0



theta 30,phi -30



(c)

Main results:

1. experimental and simulation results match within error
2. **>60 degree angles, the MDP is less and prone to systematics**

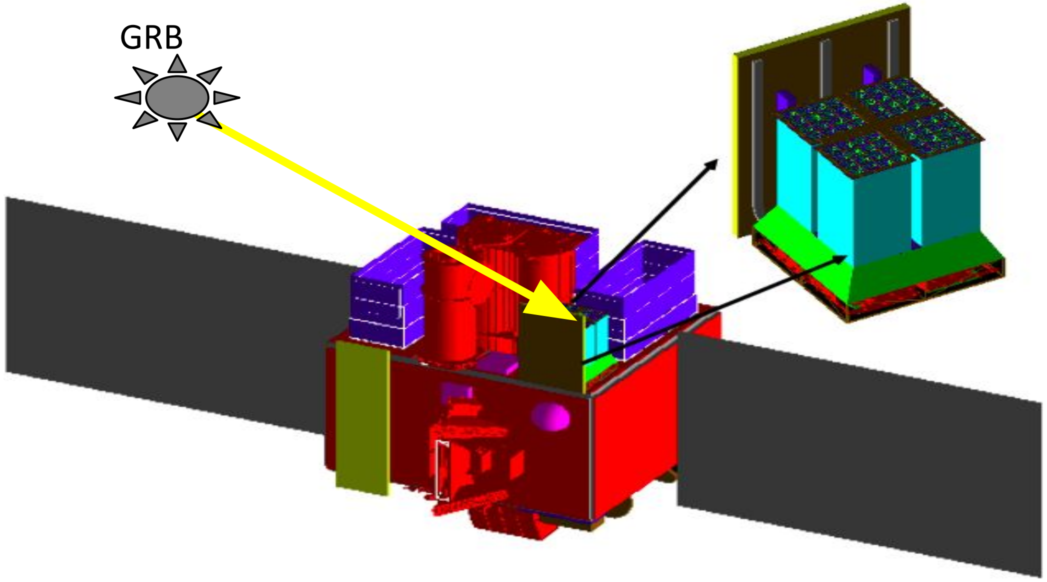
Vaishnava et al 2022, JATIS

Over the years, we have done several improvements in polarimetric analysis pipeline such as increasing the effective area and bandwidth (by using data from low-gain pixels), using an improved event selection logic to reduce noise in the double events and extend the spectral bandwidth.

well … GRB polarization is difficult…

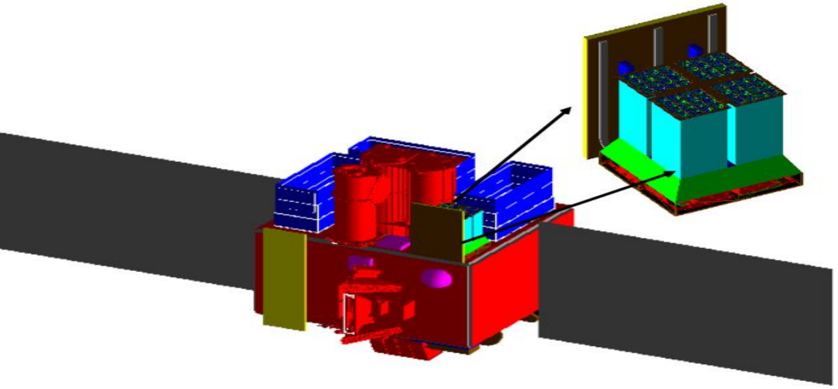
1. Interaction of photons with the satellite structure - how accurate is the mass model?

1. charge sharing between CZTI pixels - how to include charge sharing in the Geant4 simulation?



We need Strong theoretical models with clear predictions
&
More constraining unambiguous observations!

We validated the AstroSat mass model …

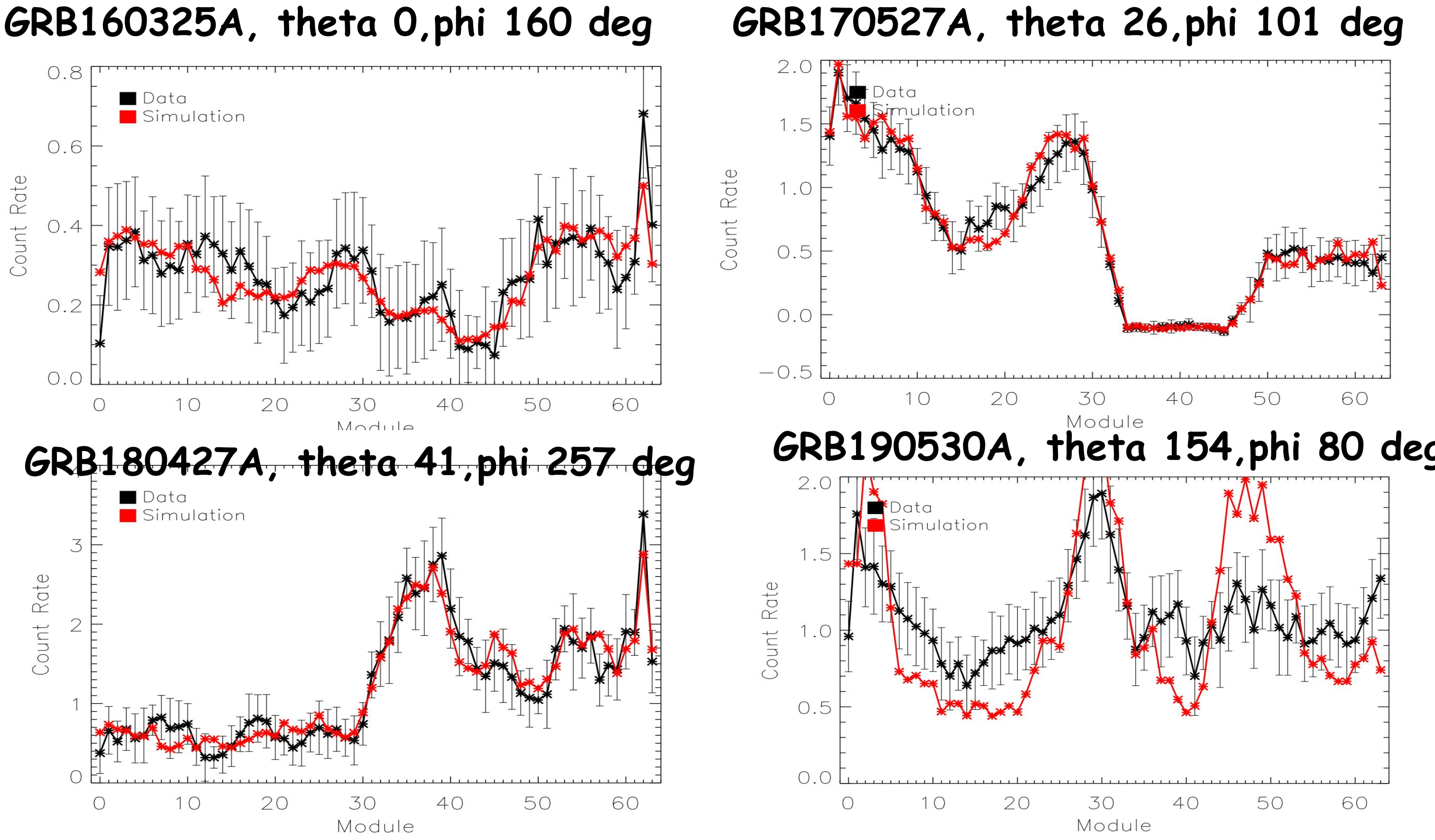


Mate, Chattopadhyay et al 2021

- A mass model including all instruments, spacecraft in Geant4.
- Some parts hard coded
- Some parts in Cadmesh

Validation:

- the collimators, mask, supporting structures, veto cast shadow on the CZTI modules
- compared the simulated and observed DPH
- matching reasonable well!



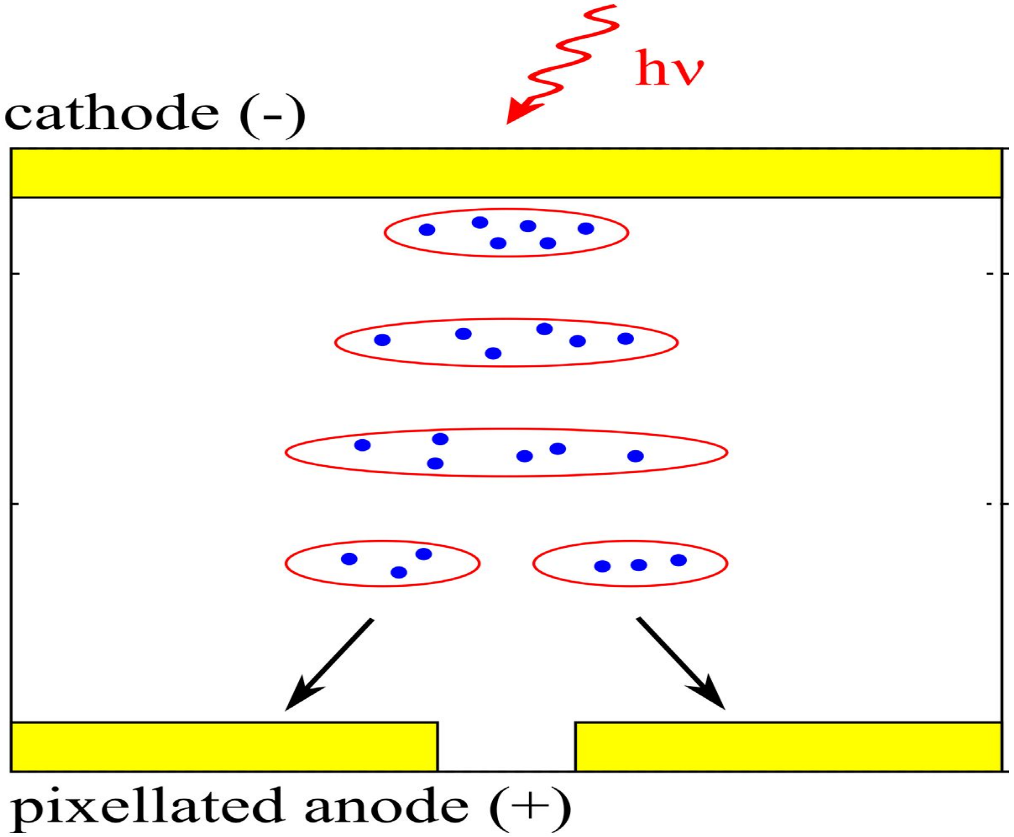
Chattopadhyay et al 2019, ApJ

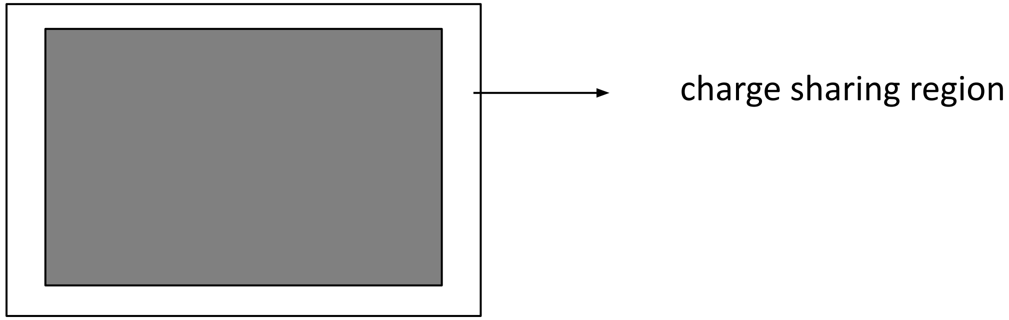
Charge sharing in CZT pixels

- Charge sharing in any pixelated detector– **f(thickness, temp, bias, energy)**

- **In large pixel size ~2.5 mm, charge sharing not significant in case of single pixel spectroscopy**

- **However, Compton events are a factor ~12 times lower. Therefore charge sharing events are significant in Compton polarimetry and spectroscopy**





Evidence of charge sharing in case of GRBs

- Expected single / Compton in CZT ~ 12
- Observed single / Compton ~ 6

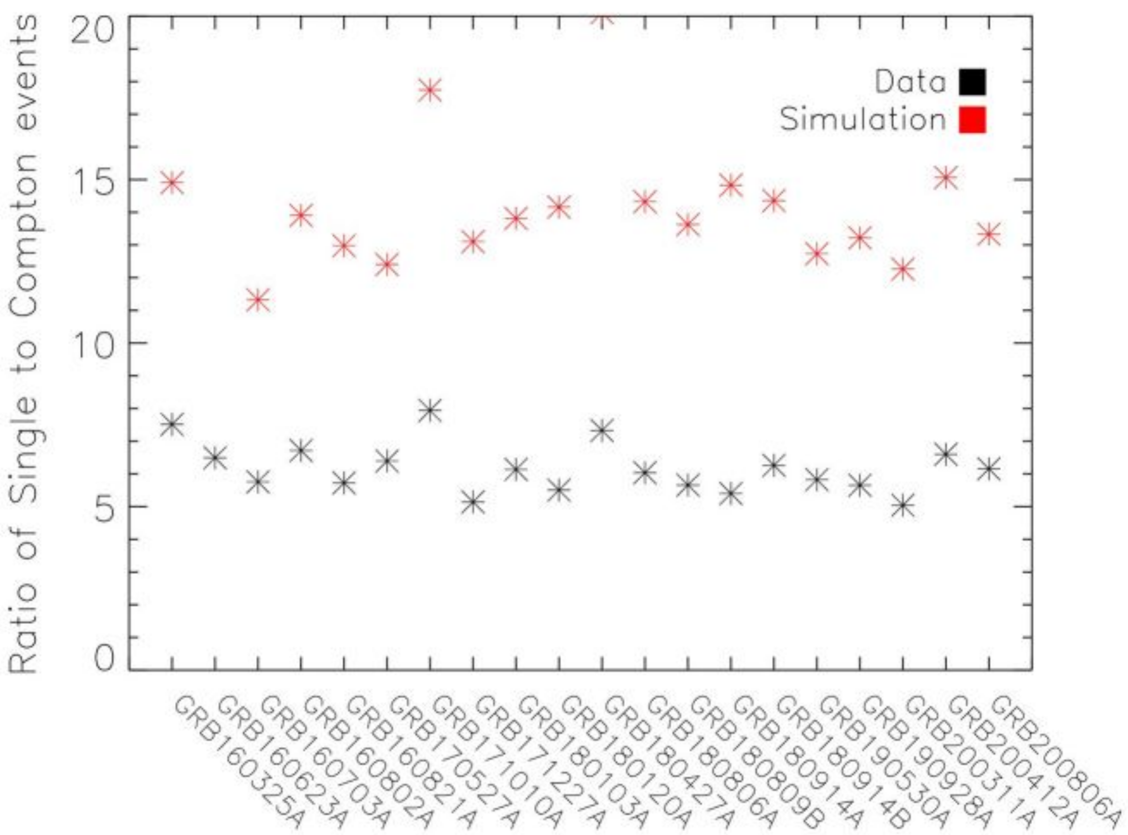
- Why?

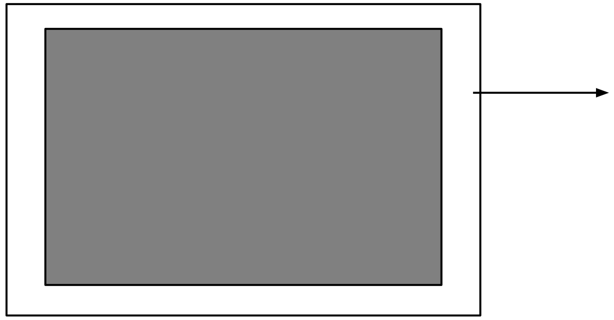
Obs Compton > Simulated Compton by charge sharing events

- How to correct?

Calculate the charge sharing region

Calculate the events in the charge sharing
> add it to the simulated Compton events
> subtract from the simulated single pixel events





charge sharing region

Evidence of charge sharing in case of GRBs

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Calculate the char

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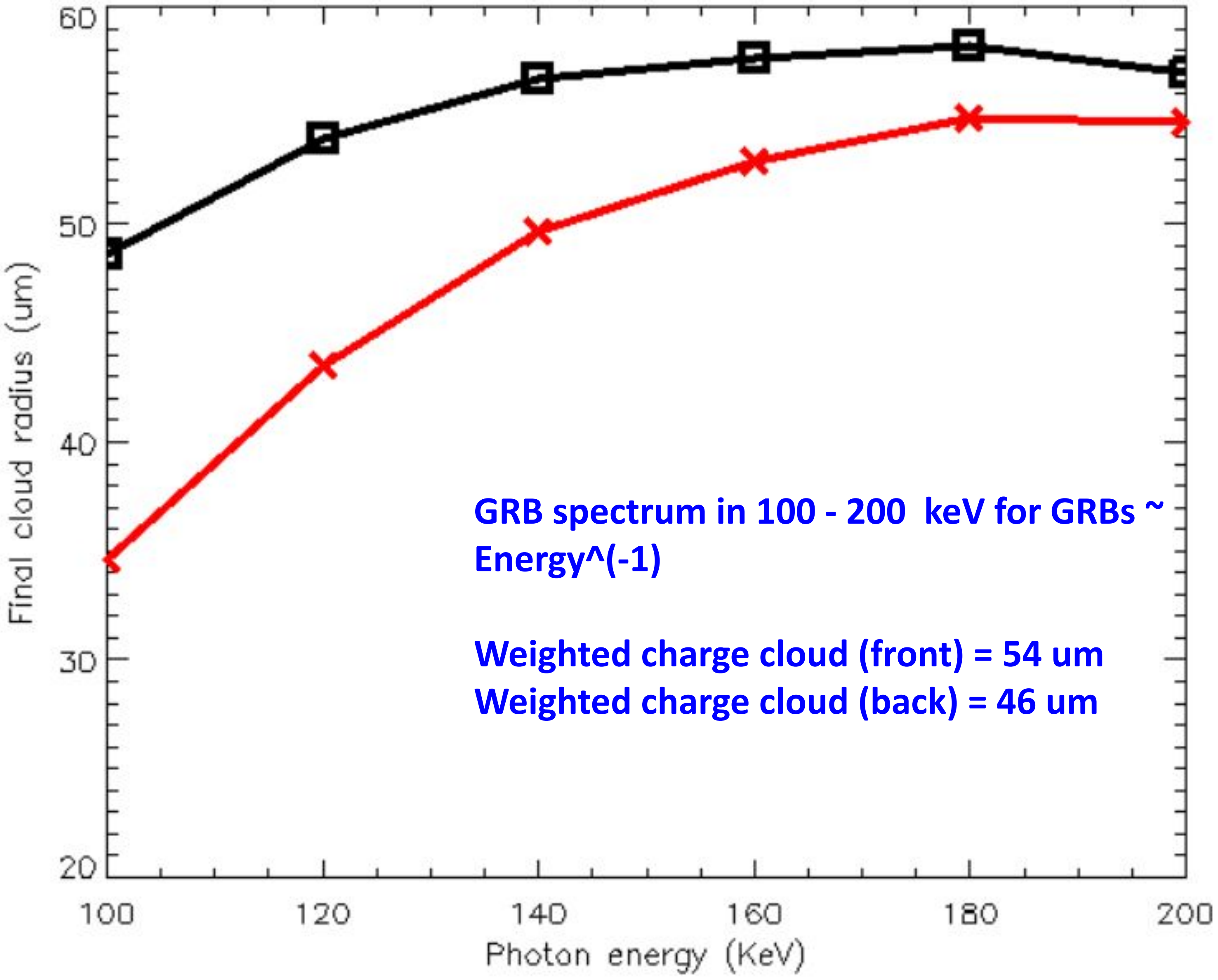
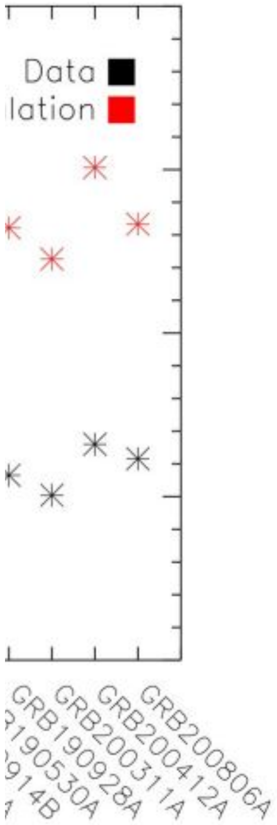
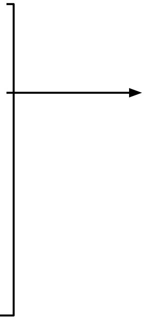


GRB spectrum in 100 - 200 keV for GRBs ~ Energy^(-1)

Weighted charge cloud (front) = 54 um
Weighted charge cloud (back) = 46 um

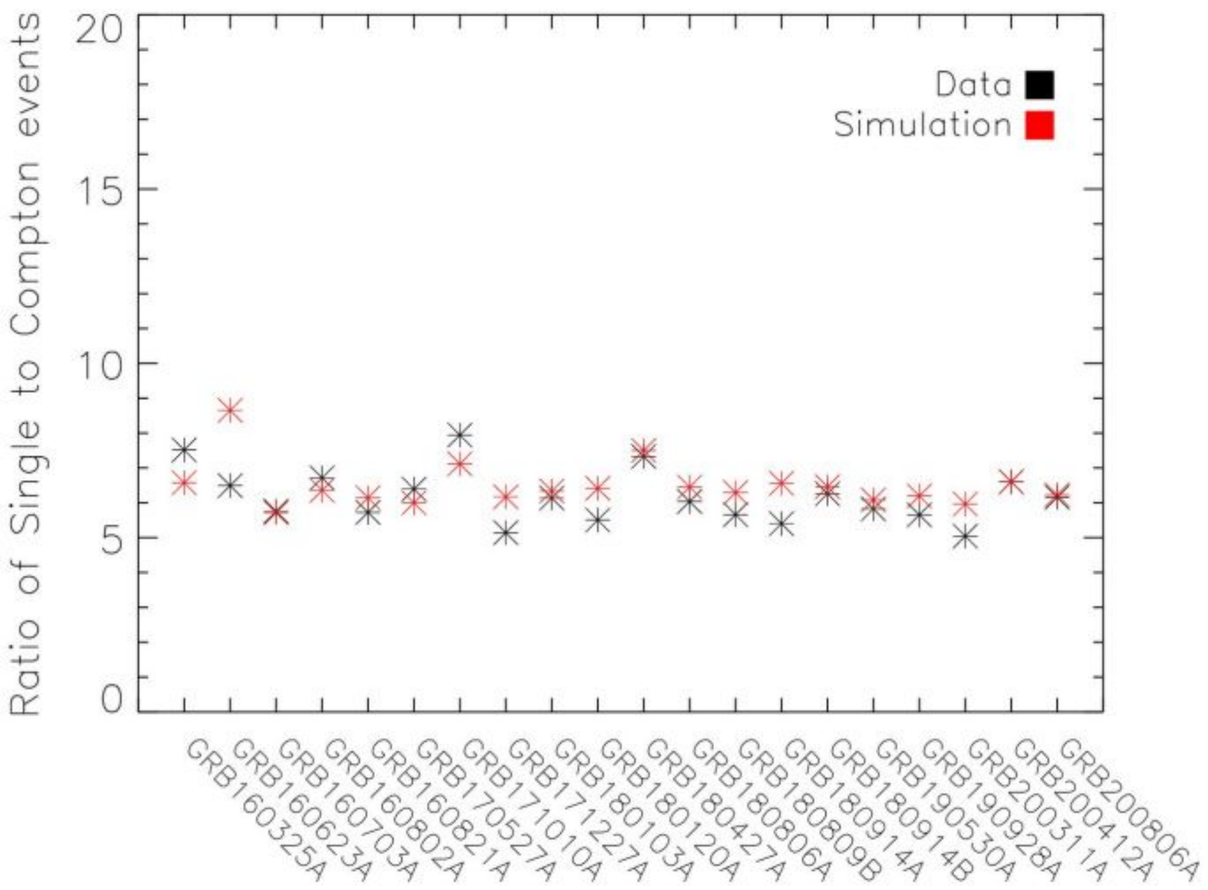




Charge sharing corrected in CZT pixels

- **We applied the charge sharing model to the simulated events and corrected them for charge sharing.**

We also developed a semi-empirical model to correct the simulated azimuthal angle distributions. — next talk.



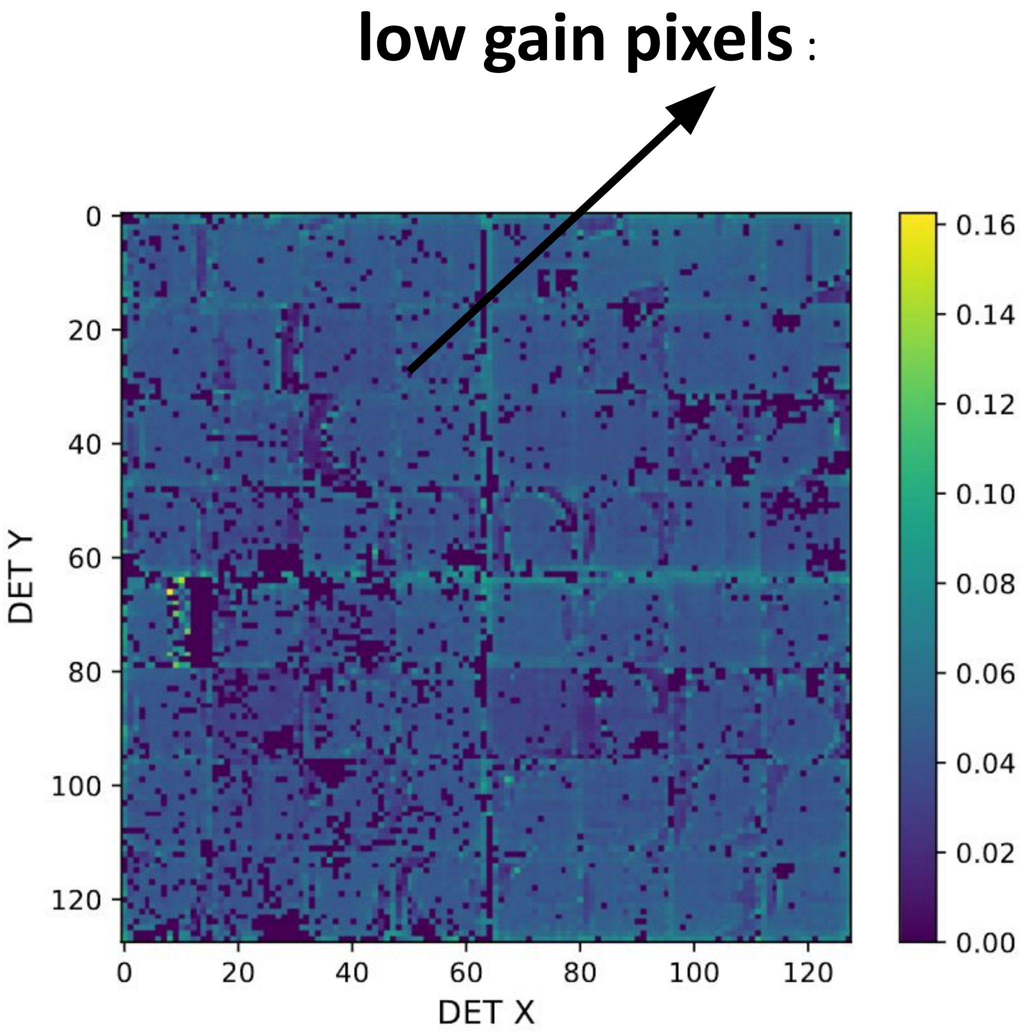
Chattopadhyay et al 2022, ApJ

Extending the CZTI polarimetry energy to sub-MeVs

low gain pixels : post-launch
~20 % of the pixels in the CZTI plane found to have lower counts due to shift in the electronic gain

We have utilized the low gain pixels in CZTI to enhance the **polarimetric energy range to 600 kev** with 30-40 % increase in Compton counts.

> calibration of the low gain pixels were done using particle induced activation lines at 88 keV and ~150 keV



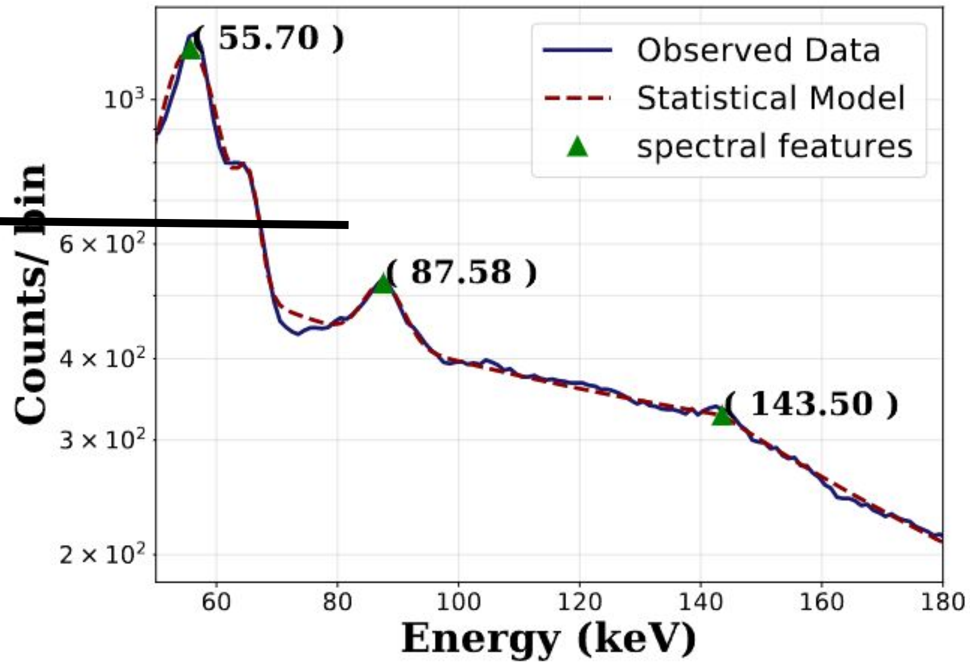
Chattopadhyay et al 2021, JAA

Low gain pixel calibration

spectrum of the good pixels in a detector module ~ 1 month of data July 2016

model -> **Gaussian 1 (54 keV** Tantalum kalpha + **Gaussian 2 (88 keV** proton induced Te activation) + **power law with break at 150 keV** due to break in CZTI detection efficiency)

Used this template model and compared the spectrum of each of the low gain pixels. The shift needed in the ground calibrated gain is the correction factor.



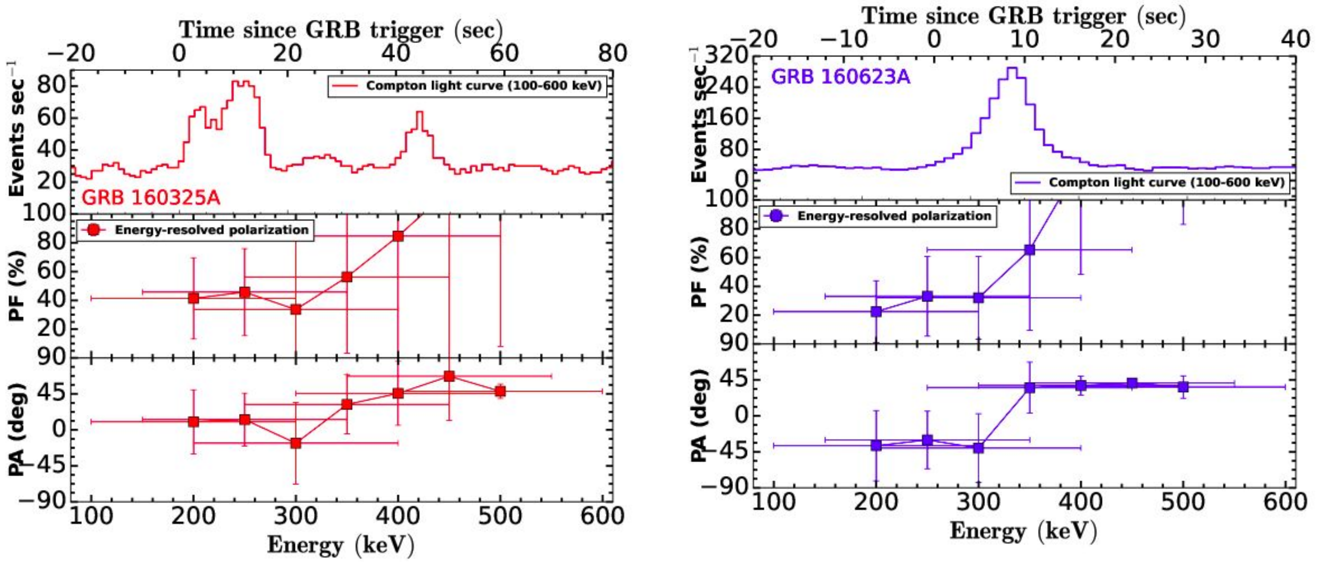
The polarimetric energy range is extended to 600 keV (otherwise it's limited to 380 keV). Above 600 keV, no intrinsic polarization analyzing power.

~ 20-30 % more Compton events.

Chattopadhyay et al 2021, JAA

Energy-resolved polarisation analysis using *AstroSat* CZTI

Energy sliding mode:



100-300 keV
(sliding of 50 keV)

Hint of energy-dependent polarization ?

Gupta et al. 2024, ApJ

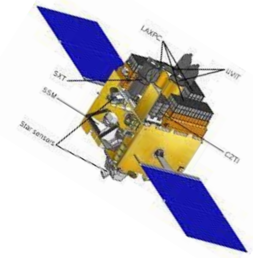
GRB name	Energy range (keV)	No. of Compton events	PF (%)	BF
GRB 160325A	100-187	391	< 70.54	1.41
GRB 160325A	187-600	380	< 33.28	0.80
GRB 160623A	100-300	1428	< 24.42	0.74
GRB 160623A	300-600	277	unconstrained	2.82
GRB 160703A	100-351	376	< 18.64	0.73
GRB 160703A	351-600	51	unconstrained	1.02
GRB 160802A	100-363	1360	< 27.92	0.70
GRB 160802A	363-600	152	< 69.97	0.69
GRB 160821A	100-300	2387	< 20.03	0.85
GRB 160821A	300-600	468	unconstrained	2.27

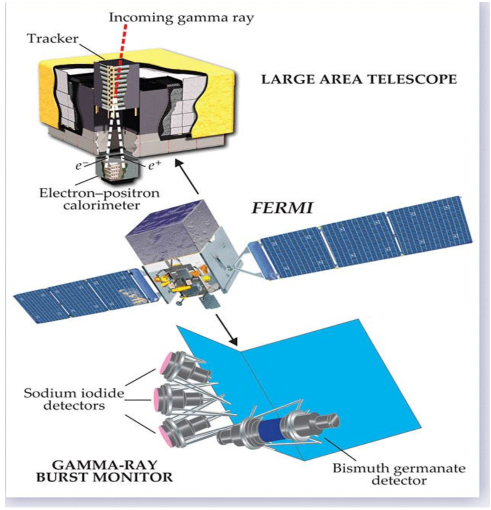
Multiwavelength Observations of GRB 190530A

Prompt Observations :

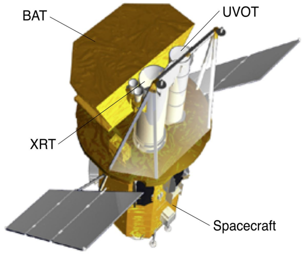
Detected by *Fermi* GBM and LAT on 30 May 2019 at 10:19:08 UT. (GCNs 24676, 24679)

Also detected by *AstroSAT* CZTI, KW, and AGILE. (GCNs 24694, 24678)





Afterglow Observations :



The XRT observed GRB from ~ 33.8 ks after the trigger time. (GCN 24689)

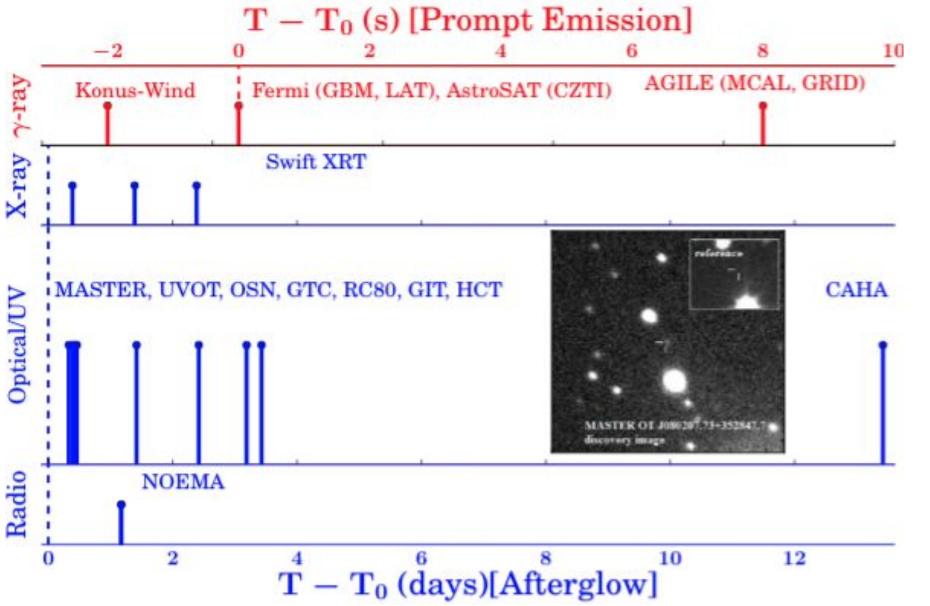
MASTER detected the afterglow ~ 8 hrs after the trigger. (GCN 24703)

The UVOT detected a optical afterglow in U, B, V, UVW1, UVW1, and UVM2 filters.

Several Optical/ NIR telescopes performed the follow-up observations.
(https://gcn.gsfc.nasa.gov/other/190530A.gcn3)

Afterglow spectroscopy using 10.4m GTC : on 31st May 2019, and measured the redshift of the burst.

Millimeter observations using NOEMA



Ground Based Telescopes

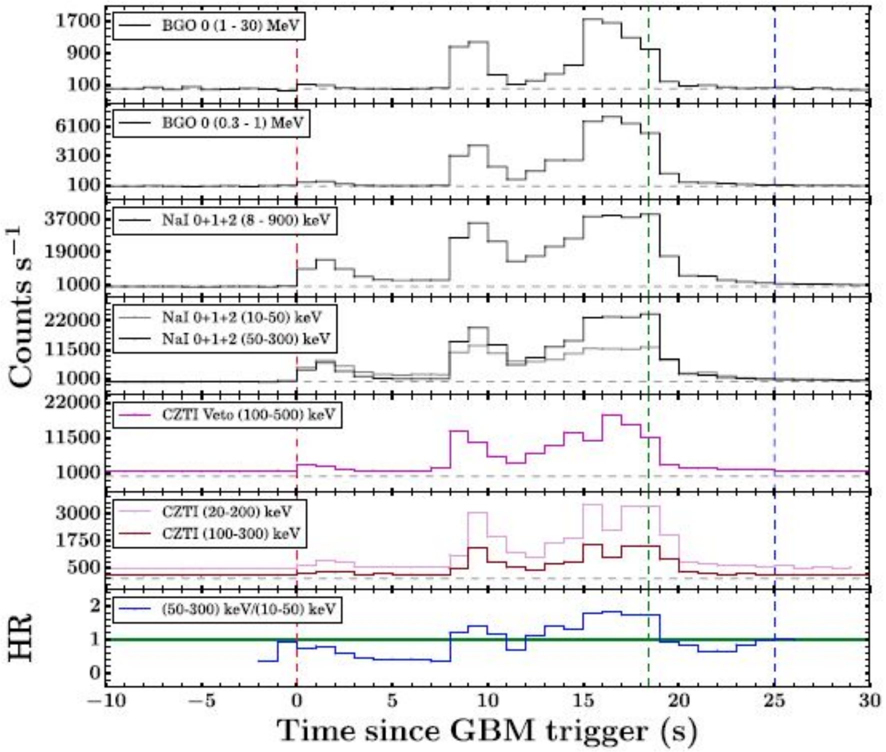
Host Observations :

Host photometric observations (UBVRI) using 3.6m DOT.

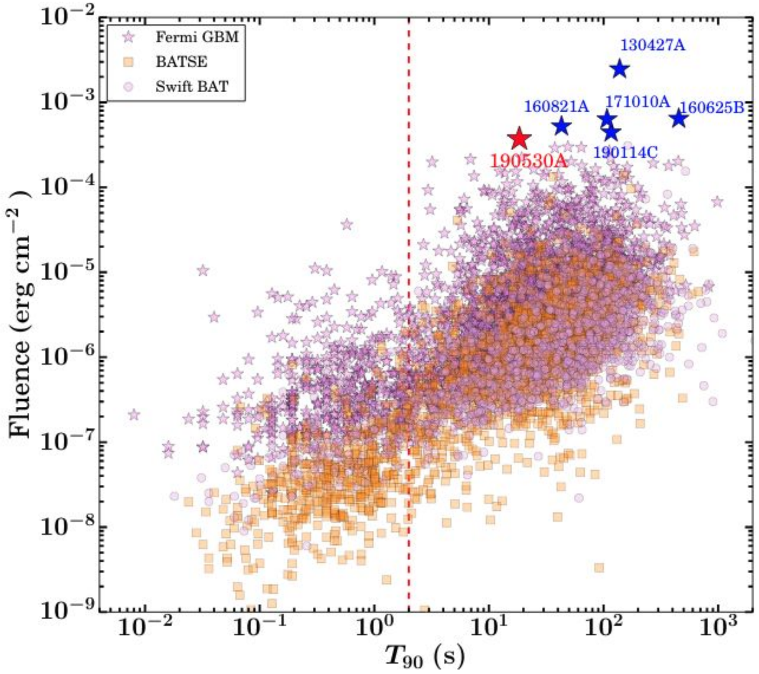
Deep observations using 10.4m GTC.

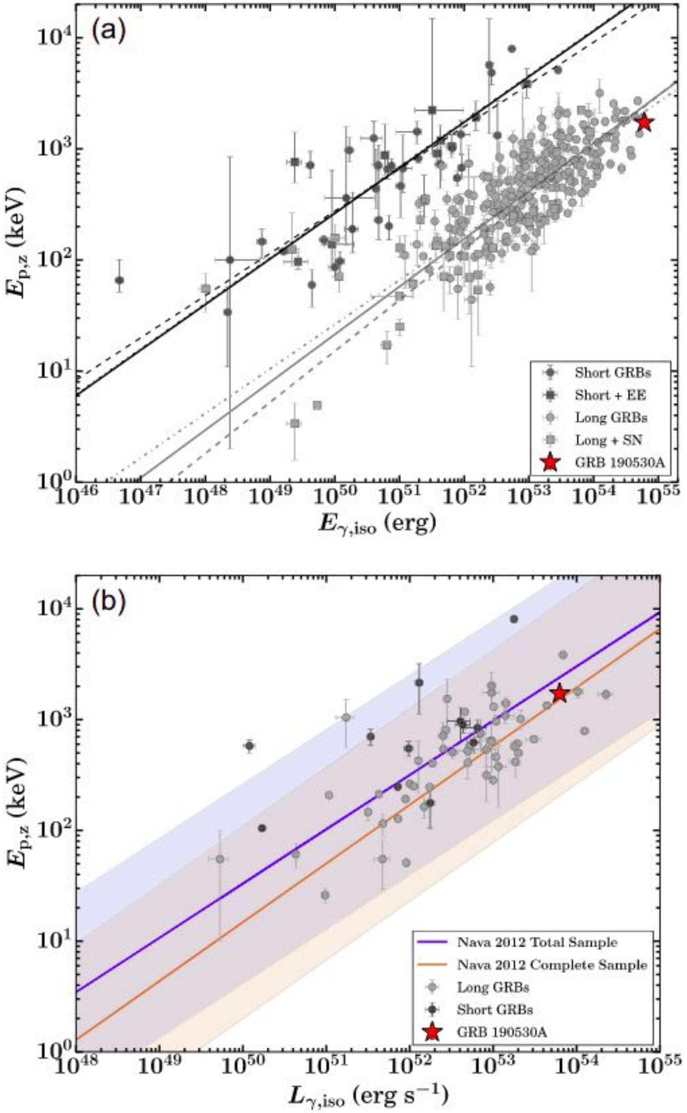
Prompt emission properties of GRB 190530A

Energy-resolved prompt emission LC



Prompt properties	GRB 190530A	Detector
T_{90} (s)	18.43 ± 0.36	GBM
$t_{\rm mvts}$ (s)	~ 0.50	GBM
HR	1.35	GBM
$E_{\rm p}$ (keV)	$888.36^{+12.71}_{-11.94}$	GBM + LAT
$F_{\rm p}$	135.38	GBM
$E_{\gamma,\rm iso}$ (erg)	6.05×10^{54}	–
$L_{\rm p,iso}$ (erg s^{-1})	6.26×10^{53}	–
Redshift z	0.9386	GTC

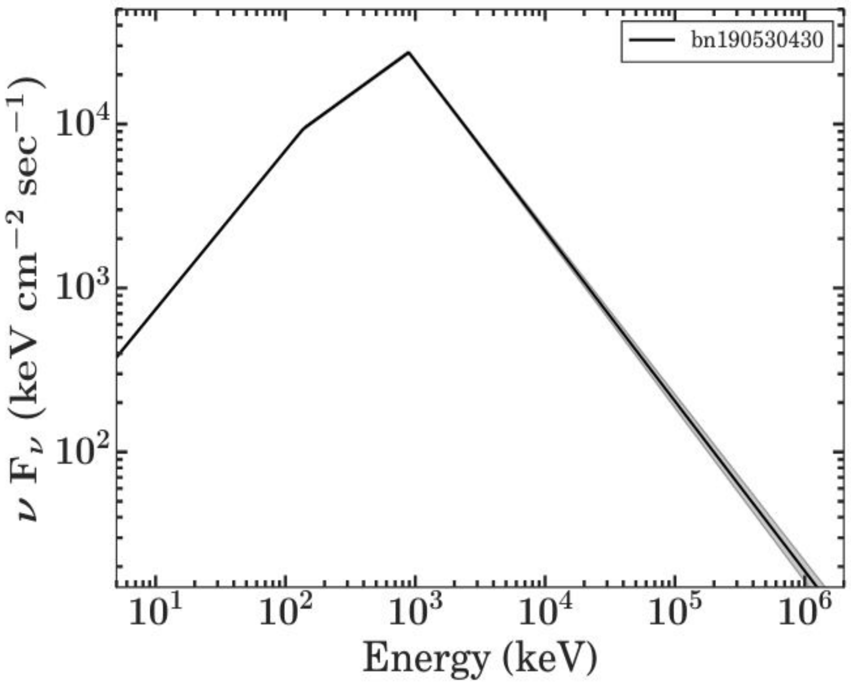




Gupta et al 2022, MNRAS

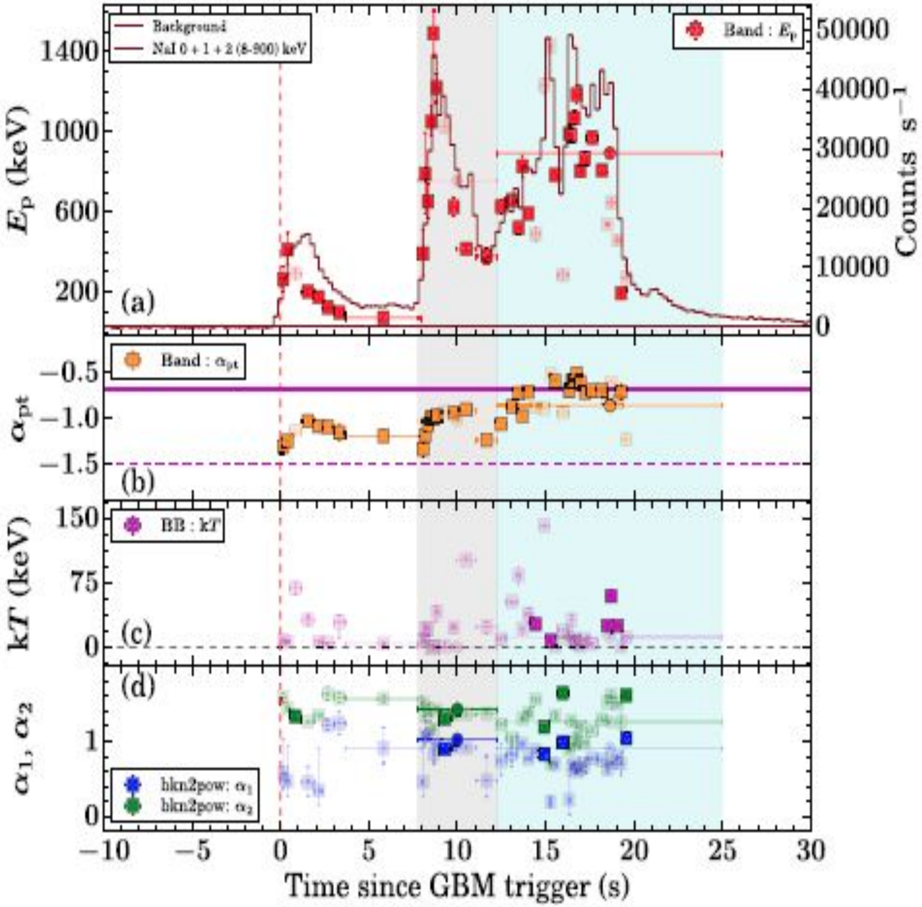
Prompt emission Spectral Properties

The time-integrated best fit energy spectrum in model space.

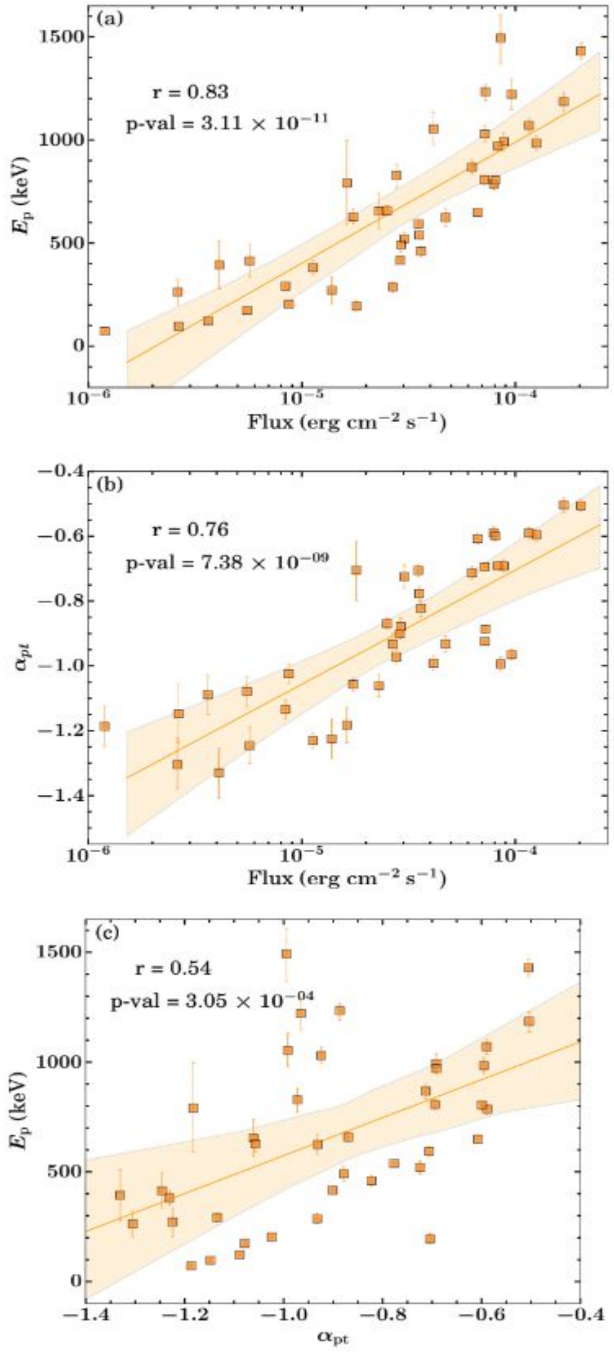


$<\alpha_1>= 0.77 \pm 0.06$
$<\alpha_2>= 1.43 \pm 0.05$

Evolution of spectral parameters



Double tracking Characteristic !



Polarisation measurement using *AstroSat* CZTI

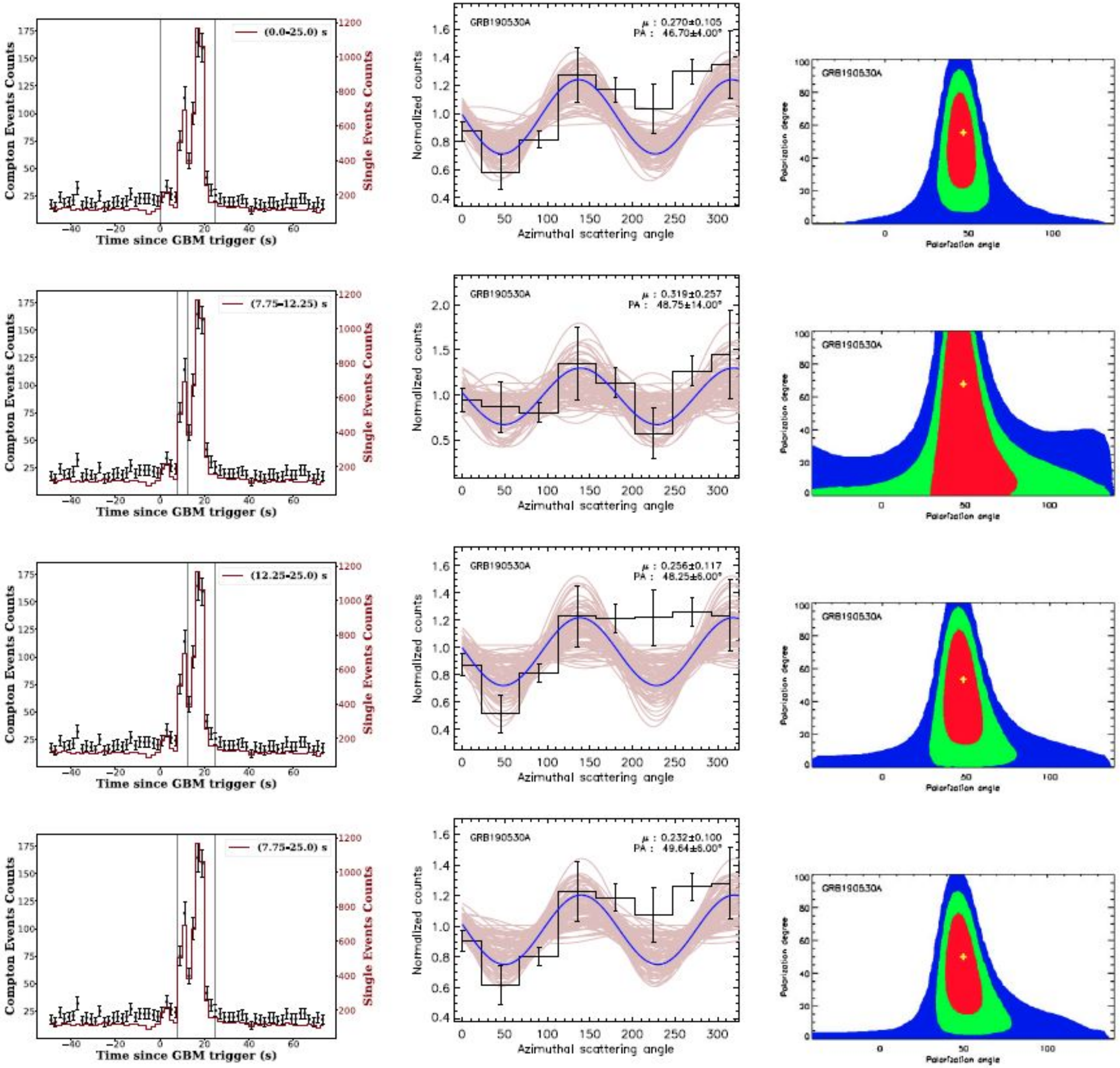
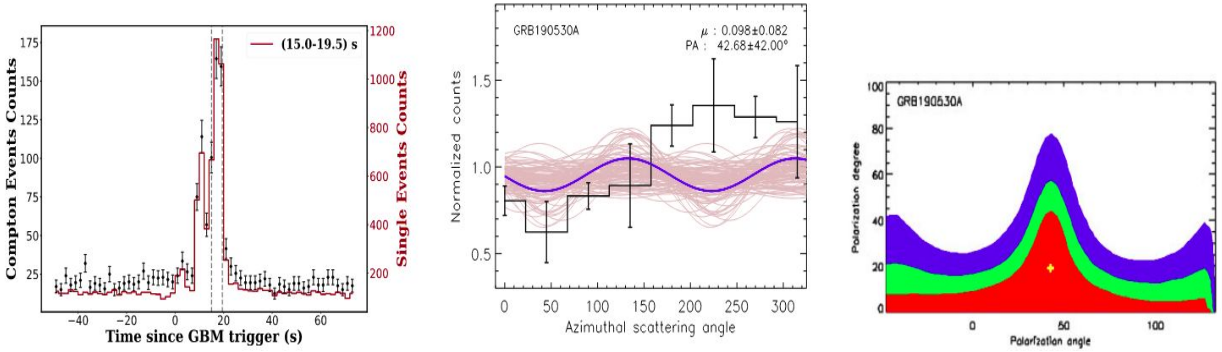


Table 3. The *AstroSat*-CZTI polarimetry results of GRB 190530A in the time-integrated and time-resolved temporal window in the 100–300 keV energy range.

Burst interval (s)	Energy (keV)	No. of Compton events	Modulation amplitude (μ)	Polarization angle (°)	Bayes factor	Polarization fraction
0.0–25.0	100–300	1246	0.27 ± 0.10	46.74 ± 4.0	3.51	55.43 per cent ± 21.30 per cent
7.75–12.25	100–300	319	0.32 ± 0.26	–	1.08	<64.40 per cent (95 per cent)
12.25–25.0	100–300	870	0.26 ± 0.12	48.17 ± 6.0	2.11	53.95 per cent ± 24.13 per cent
7.75–25.0	100–300	1189	0.23 ± 0.10	49.61 ± 6.0	2.52	49.99 per cent ± 21.80 per cent
15.0–19.5	100–300	577	0.09 ± 0.08	–	0.71	<65.29 per cent (95 per cent)



Synchrotron emission in ordered magnetic field.

Gupta et al 2022, MNRAS