Unveiling the Prompt Emission Mechanisms of Gamma-Ray Bursts: A Spectro-polarimetric perspective with *Fermi* and *AstroSat*

By

Rahul Gupta*

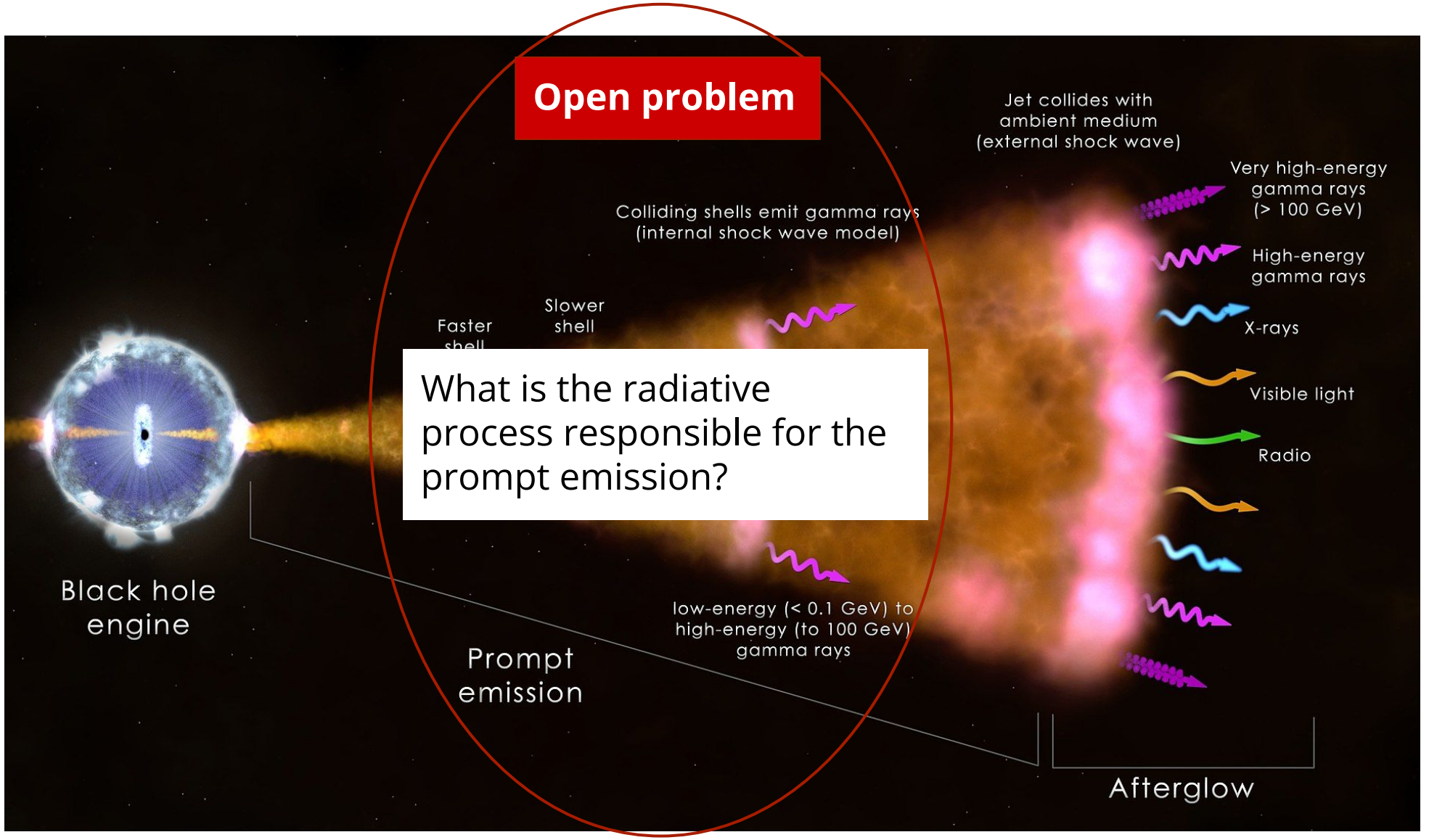
NASA GSFC

NAM 2025, July 10, 2025

In collaboration with: A. R. Rao, Dipankar Bhattacharya, Tanmoy Chattopadhyay, Judith Racusin, Vidushi Sharma, Shabnam Iyyani, Soumya Gupta, Varun Bhalerao, Shashi B. Pandey, and A. J. Castro-Tirado

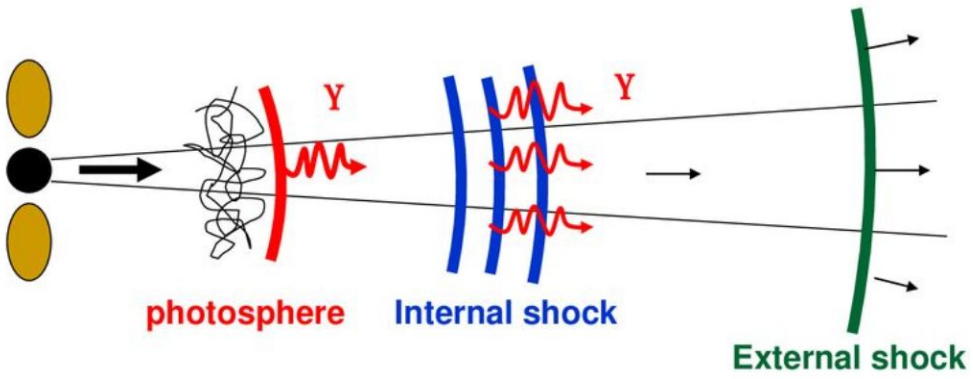
*rahulbhu.c157@gmail.com & rahul.gupta@nasa.gov

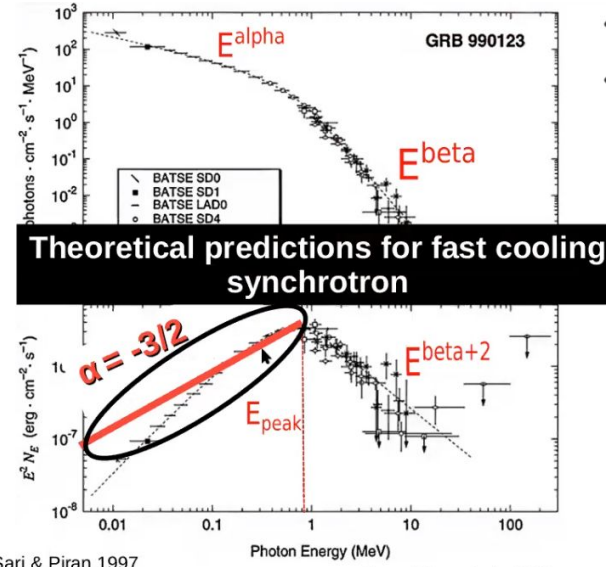
Gamma-Ray Burst: Radiation mechanisms?



Photospheric vs Synchrotron

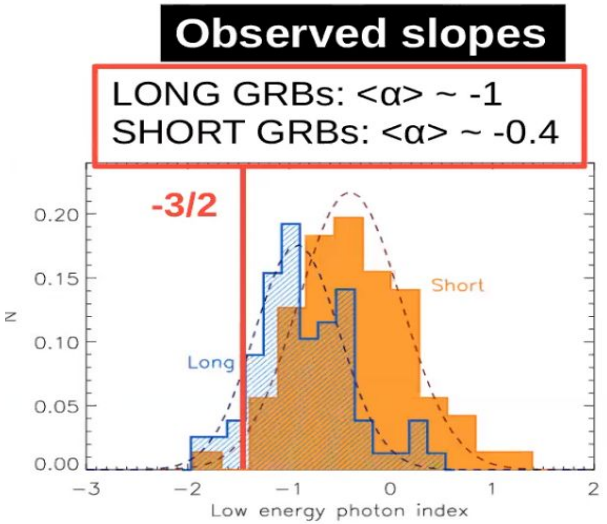
Spectrum	Quasi-thermal	Non-thermal
Spectral Shape	Hard Low-energy Slope (α)	α = -2/3 in the slow-cooling and α = -3/2 in the fast-cooling regime
Light Curve	Smooth, single-peaked	Rapid variability and complex
Energy Dissipation	~10^12 to 10^13 cm	~10^14 to 10^15 cm
Jet Composition	Optically thick, baryonic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





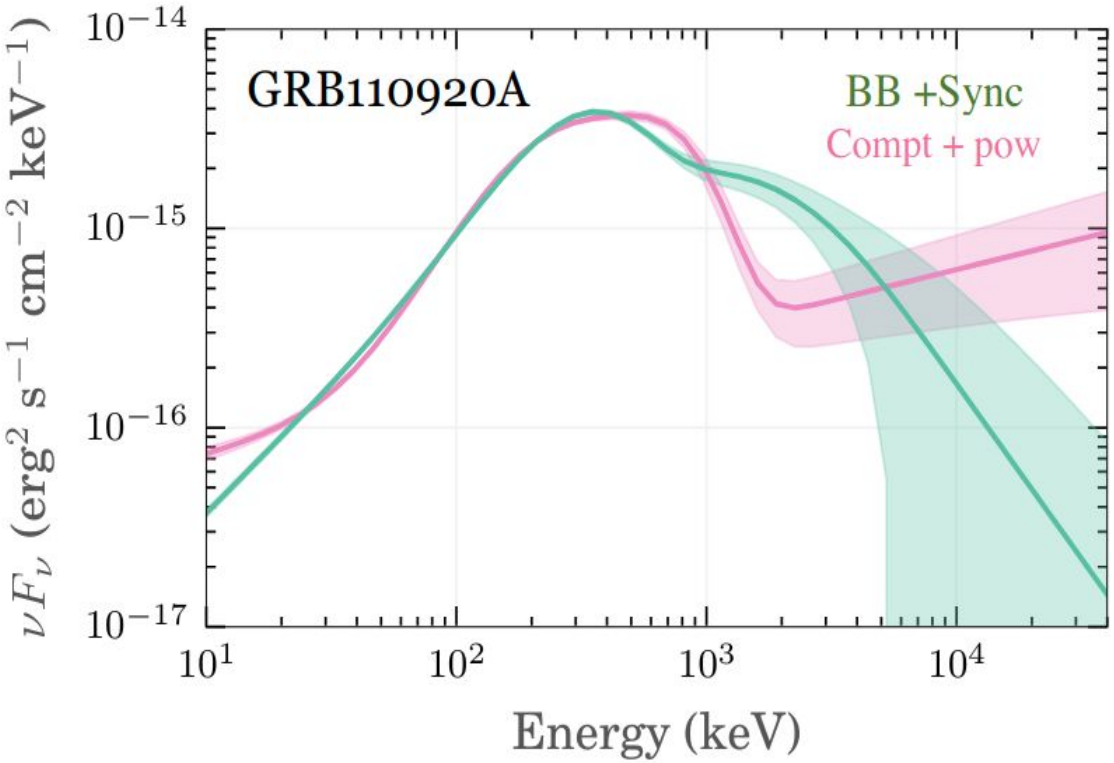
Sari & Piran 1997
Preece 1998
Ghisellini 2000

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



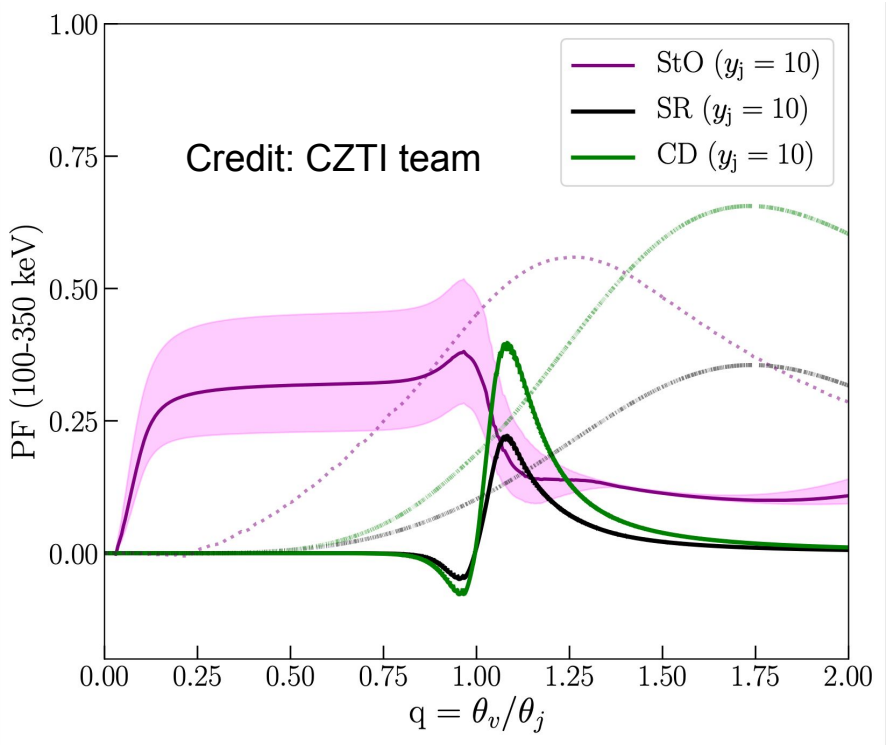
> 6000 GRBs in 30 years ! (BATSE, FERMI, SWIFT)
Detailed spectroscopy for most of GRBs (bright)

Emission mechanism of prompt emission is still unknown!

Two Models: Two completely different spectral shape

Iyyani et al. 2018

Constraining Observables: GRB polarimetry



Toma et al. 2009

Polarisation depends on the jet viewing geometry:

On axis viewing

High Polarisation fraction:
Synchrotron emission in ordered magnetic field.

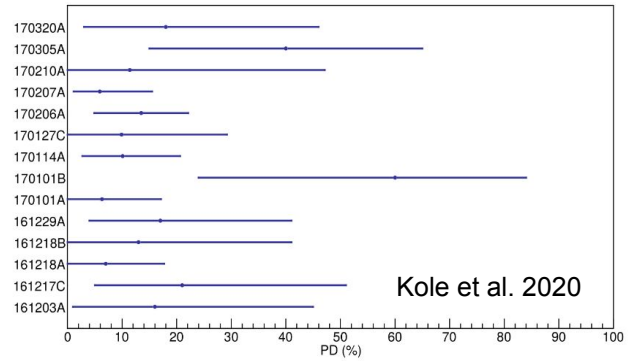
Nearly, null Polarisation fraction:
Synchrotron emission in random magnetic field.
Photospheric emission: Compton scattering

see Gill et al. 2021 for review

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

Polarization measurement by different mission: (Time-integrated Polarisation measurements)

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)



Kole et al. 2020

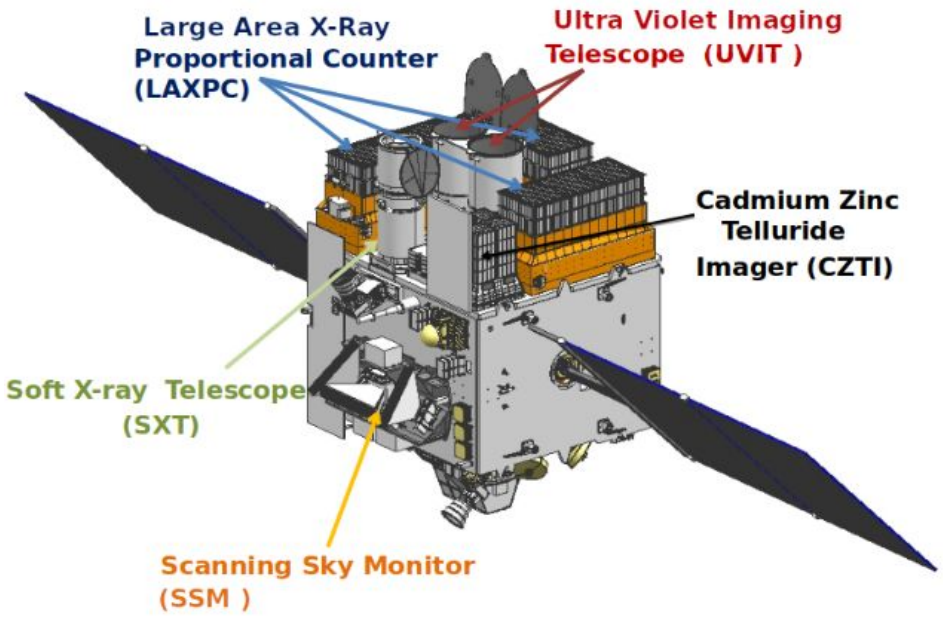
Fermi/GBM

GRB 180720B PD= 72^{+24}_{-30}% (1σ)

VERES et al. 2024

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

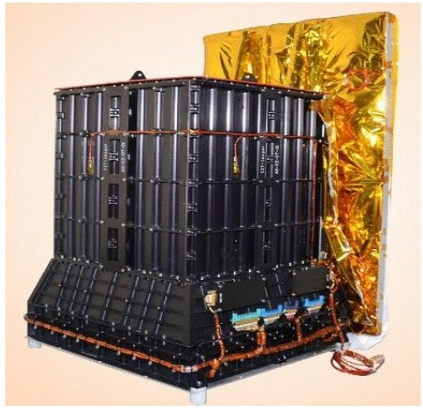
Launched in 28th September 2015.
-Five science payloads onboard.

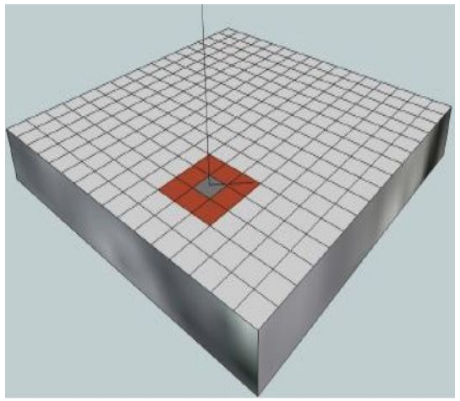


~ 700 GRBs

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

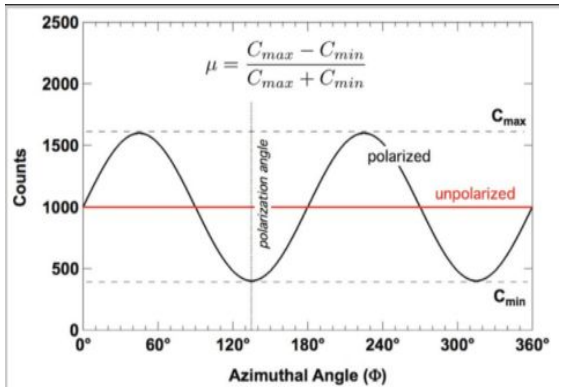
CZT-Imager (CZTI)





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.



Polarization - 100 - 600 keV

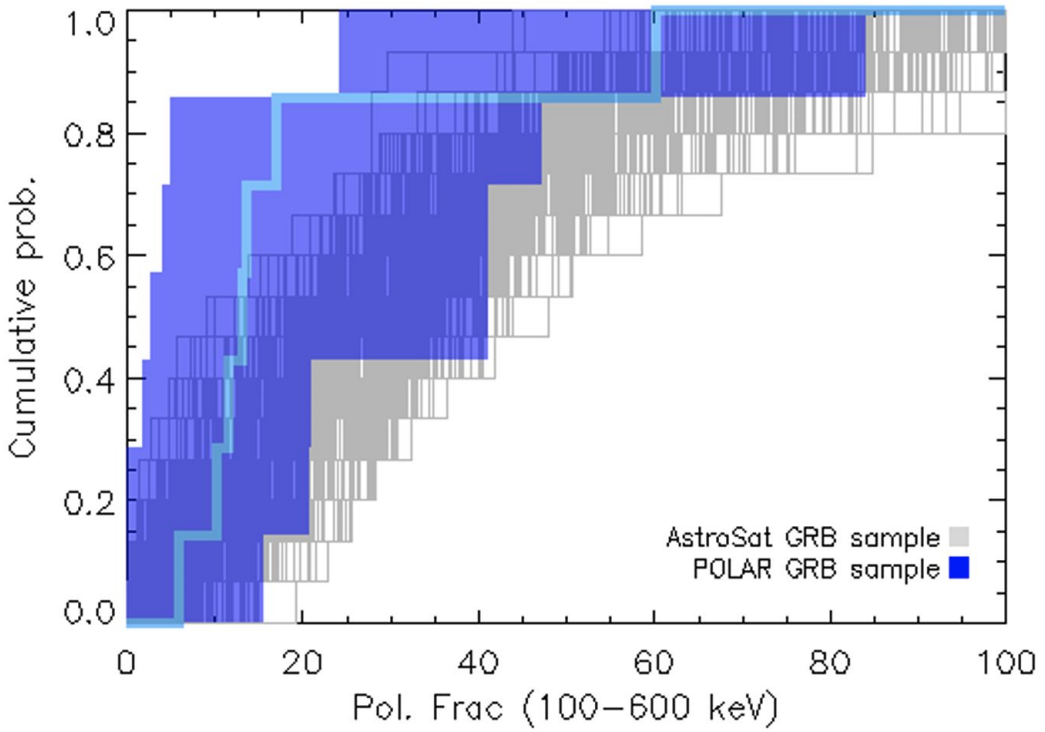
Credit: CZTI team

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

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

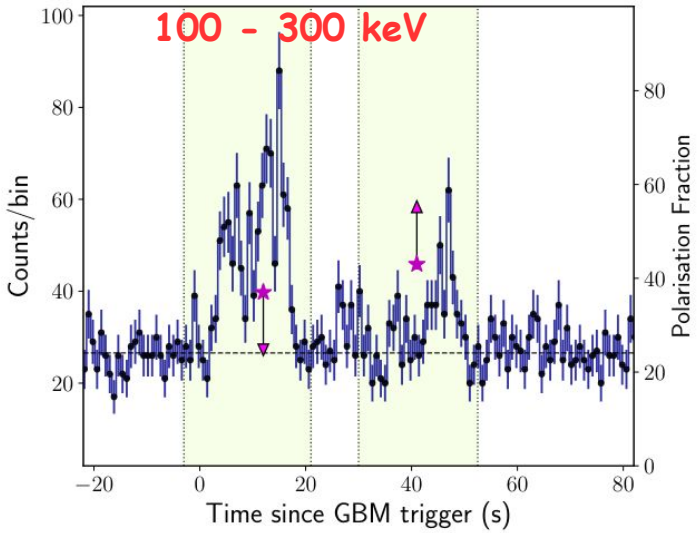
Time-resolved spectro-polarimetric

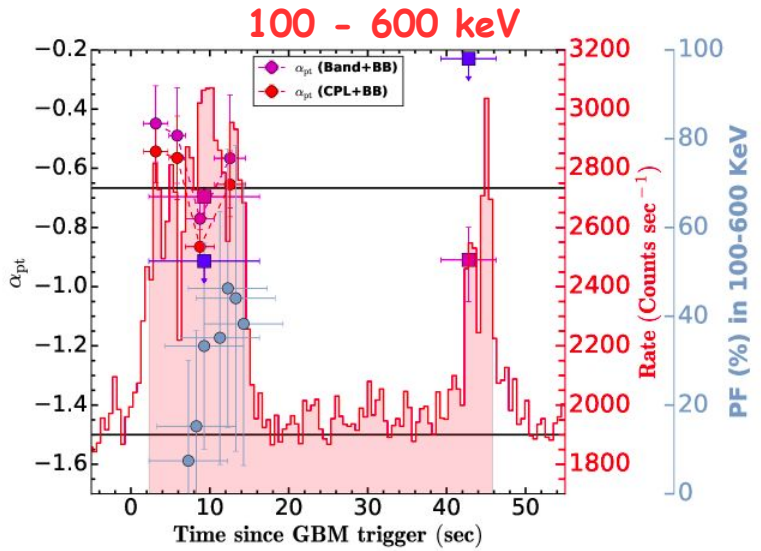
The Astrophysical Journal, 972:166 (32pp), 2024 September 10 https://doi.org/10.3847/1538-4357/ad5a92

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

GRB 160325A



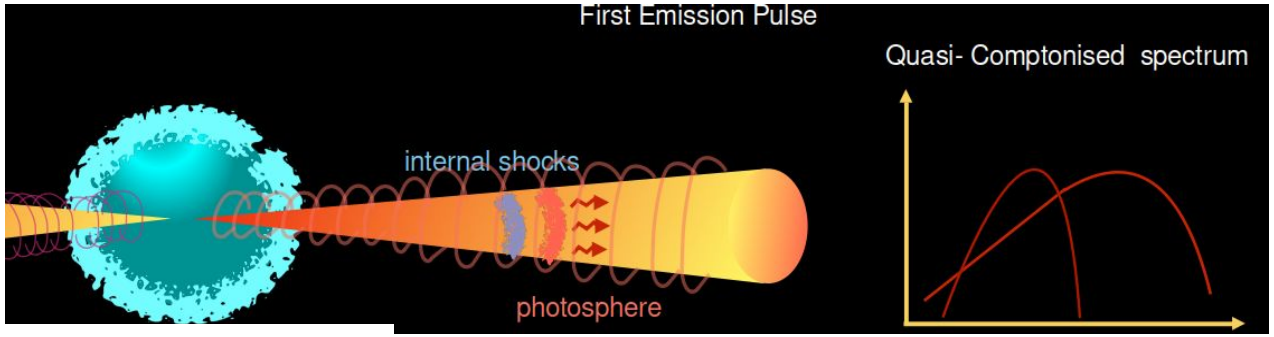


First Pulse: Best fit Spectrum: Blackbody + Cutoff power law

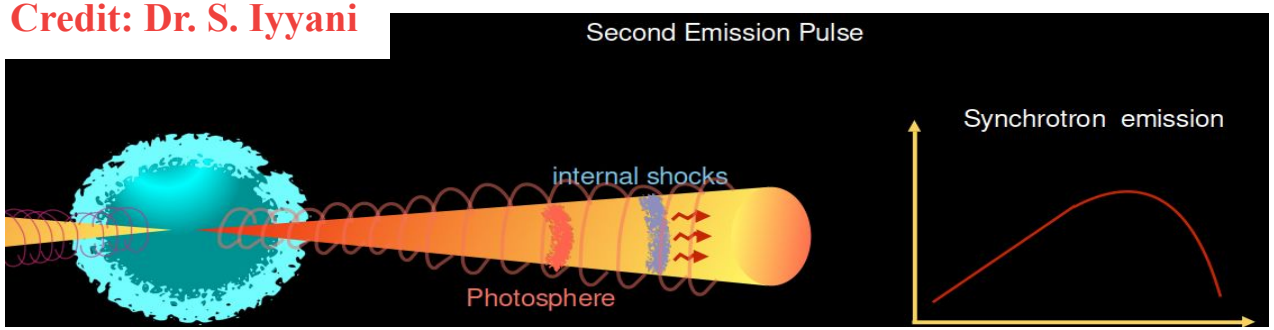
Second Pulse: Best fit Spectrum: Cutoff power law

Physical scenario: Baryonic dominated jet with mild magnetisation

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



Credit: Dr. S. Iyyani

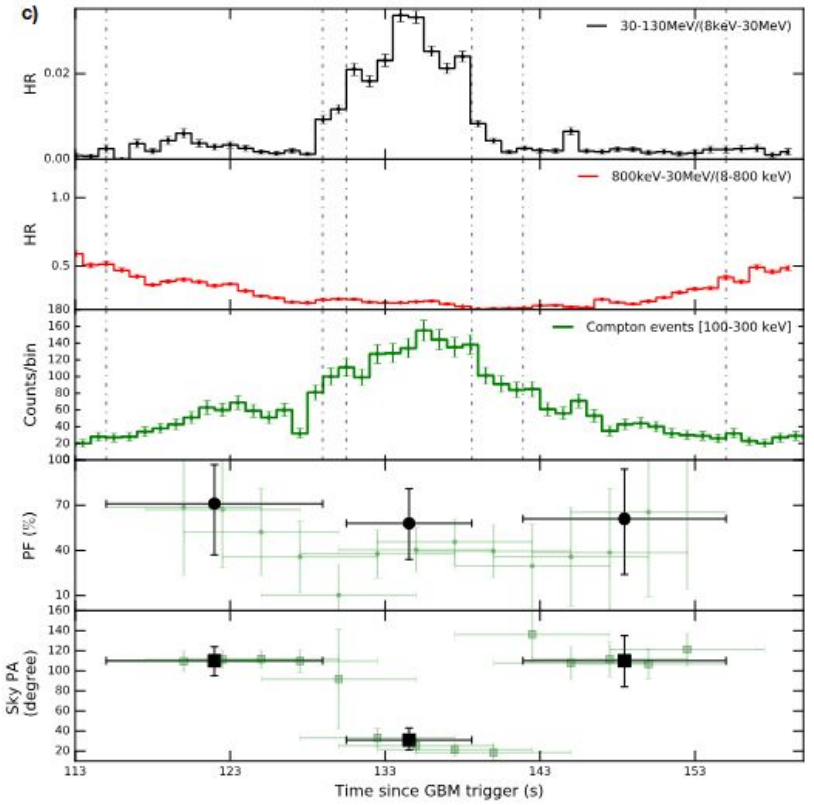


GRB 160821A

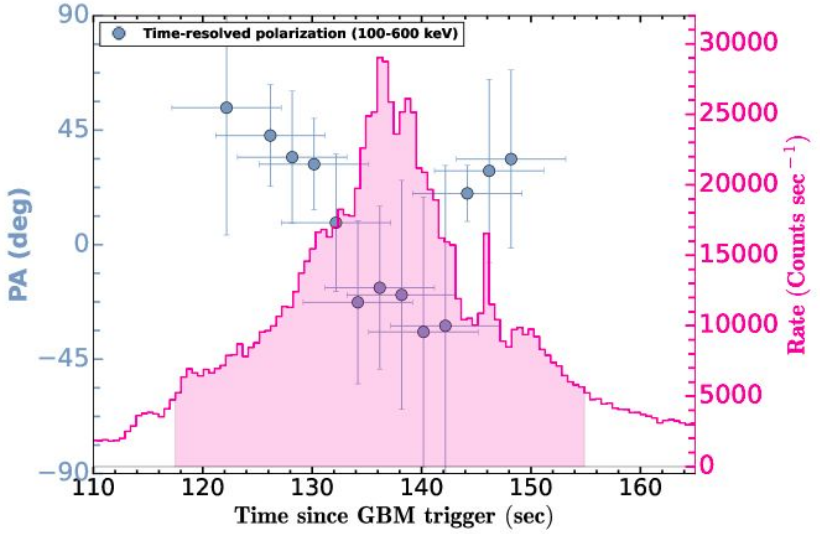
Main features:
Precursor emission ~ 100 s.
Main episode of ~ 88 s duration.
One of the brightest GRB detected by Fermi.

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

100 - 300 keV



100 - 600 keV



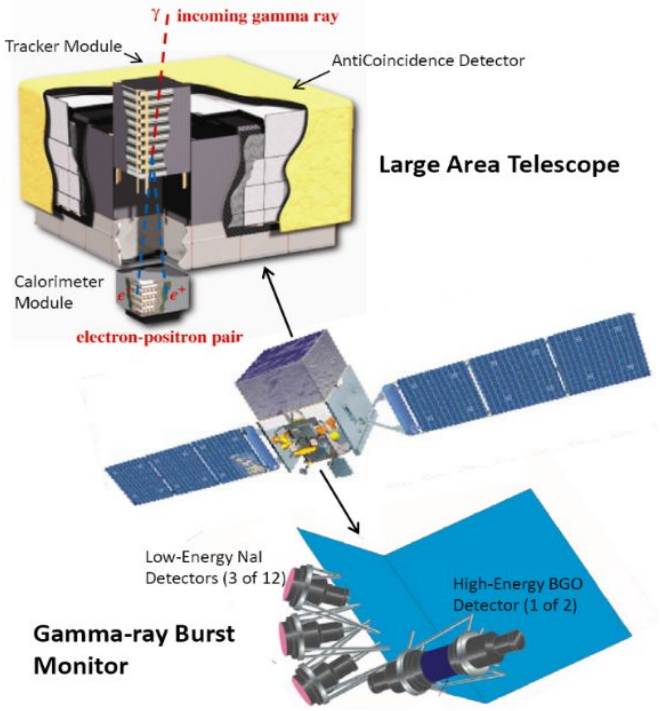
Among highest known values of Eiso ~ 10^{53} -10^{55} erg, for redshift z = 0.4 - 2.

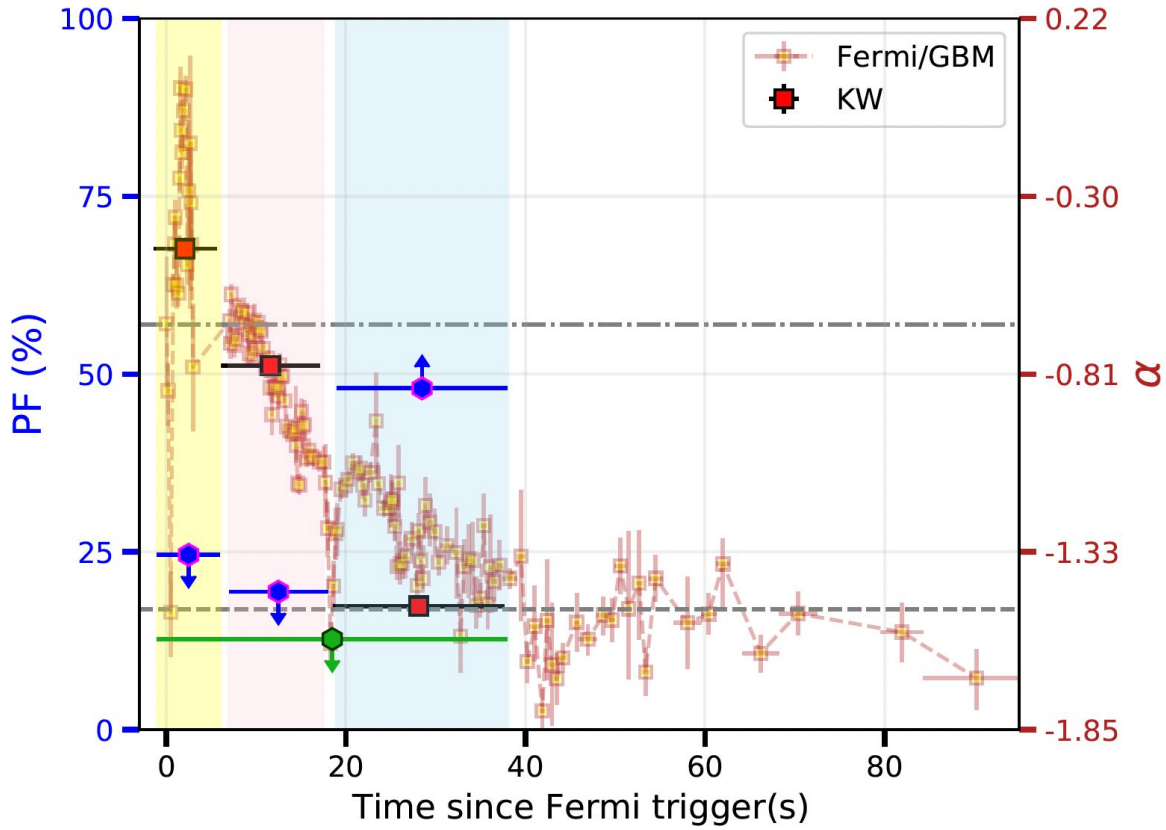
Gupta et al. 2024, ApJ & Sharma et al. 2021 ApJL

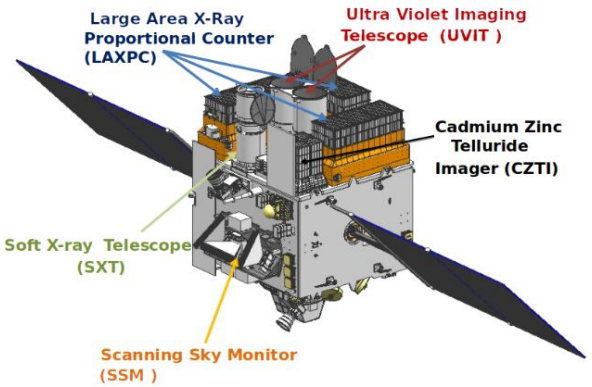
Optically thin Synchrotron

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!







Gupta et al. 2025 (minor revision to A&A)

Summary

- **Detailed spectro-polarimetric observations and analysis of bright GRBs using Fermi and AstroSat provide a valuable approach to constraining the radiation mechanisms of GRBs.**

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

- **AstroSat will be the only GRB polarimeter till 2027 at least**
  - 10 year GRB polarization catalogue in prep (2015-2025).

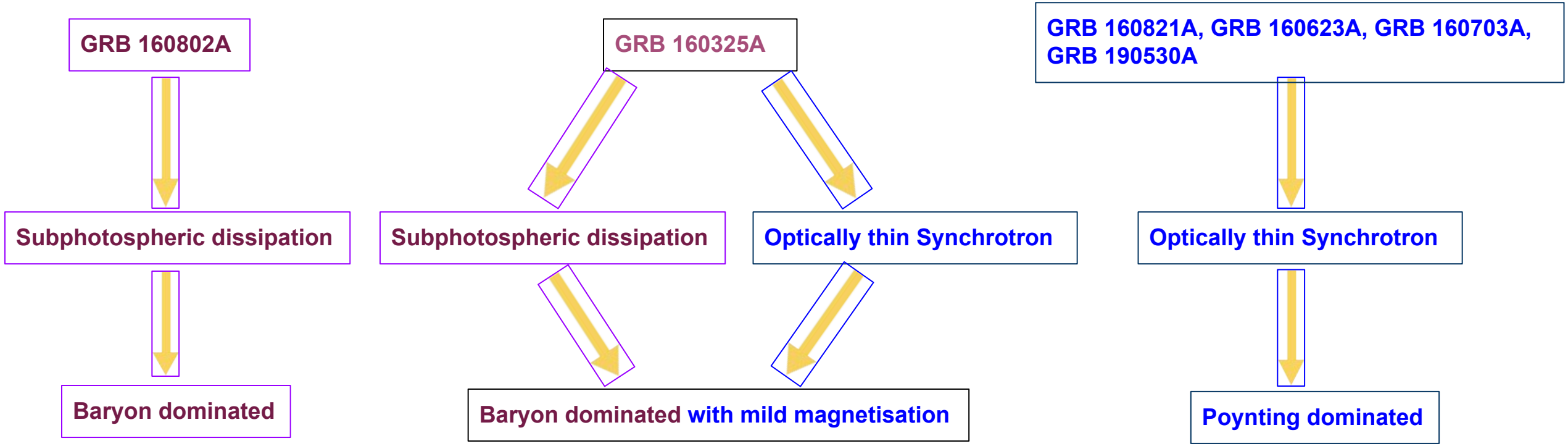
https://astrosat.iucaa.in/czti/

Thank you for your attention!

*rahul.gupta@nasa.gov

Backup Slides

Spectro-polarimetric results of CZTI GRBs



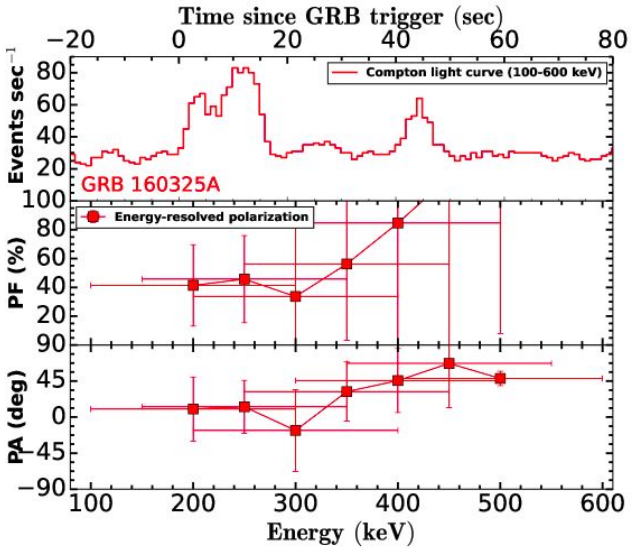
GRB 230307A: Evidence of transition from Baryonic to Poynting flux-dominated jet composition

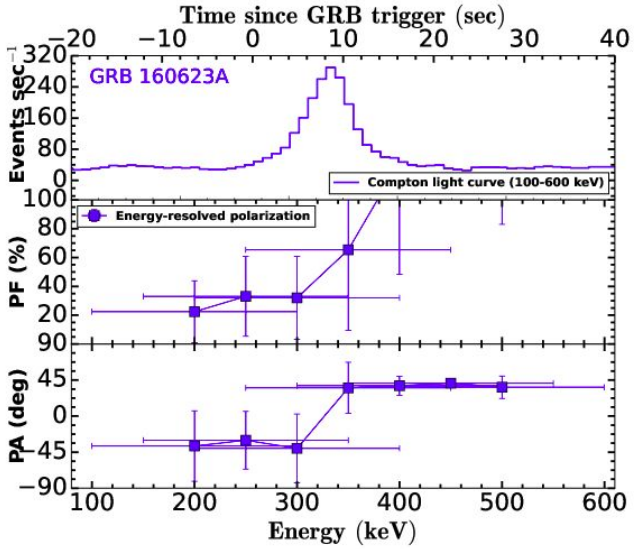
Our study suggests that the jet composition of GRBs may exhibit a wide range of magnetization, which can be revealed by utilizing spectro-polarimetric investigations of the bright GRBs.

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.)

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