Cadmium Zinc Telluride Imager (CZTI) calibration for polarization and Compton spectroscopy

Tanmoy Chattopadhyay et al

AstroSat Calibration Meeting, 23-24 August, 2022, Pune, India

CZTI calibration for polarization and Compton spectroscopy

On-axis polarimetry ground calibration
Post-launch on-board calibration

Off-axis Polarimetry calibration
>Mass model tuning
> charge sharing

sub-MeV spectral calibration

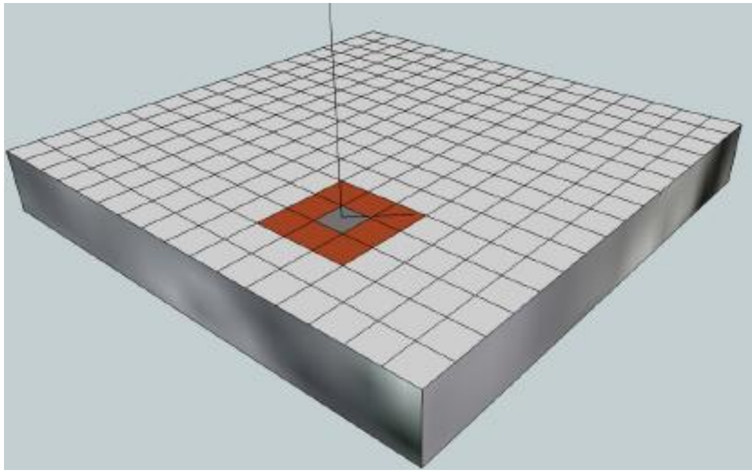
Hard X-ray Polarimetry with Astrosat - CZT-Imager

pixelated CZT detectors

Orbotech CZT modules

- Total 64 modules….
- each 4 x 4 cm^2 … ~1000 cm^2 collecting area
- further pixelated in 16 x 16 pixel (2.5 mm pixel size)

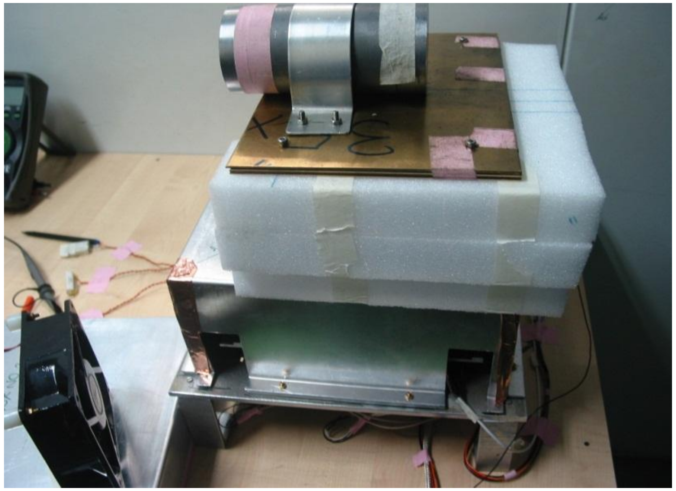
- 5 mm thick



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

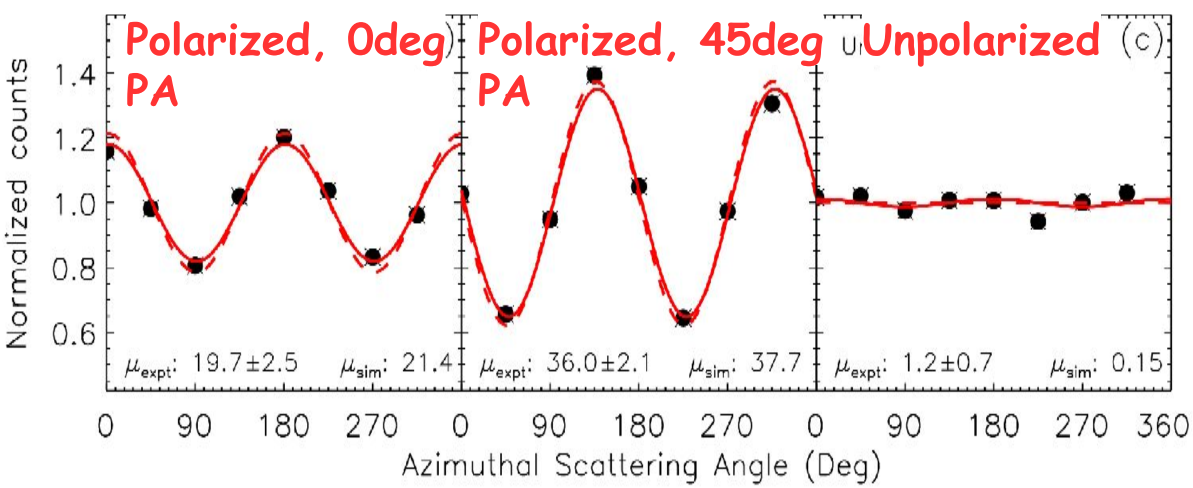
Polarimetric energy range : 100 – 380 keV

Realized this capability before launch …



Polarization expt with CZTI using Ba133 (356 keV) source

Observed azimuthal angle distributions (190-240 keV)

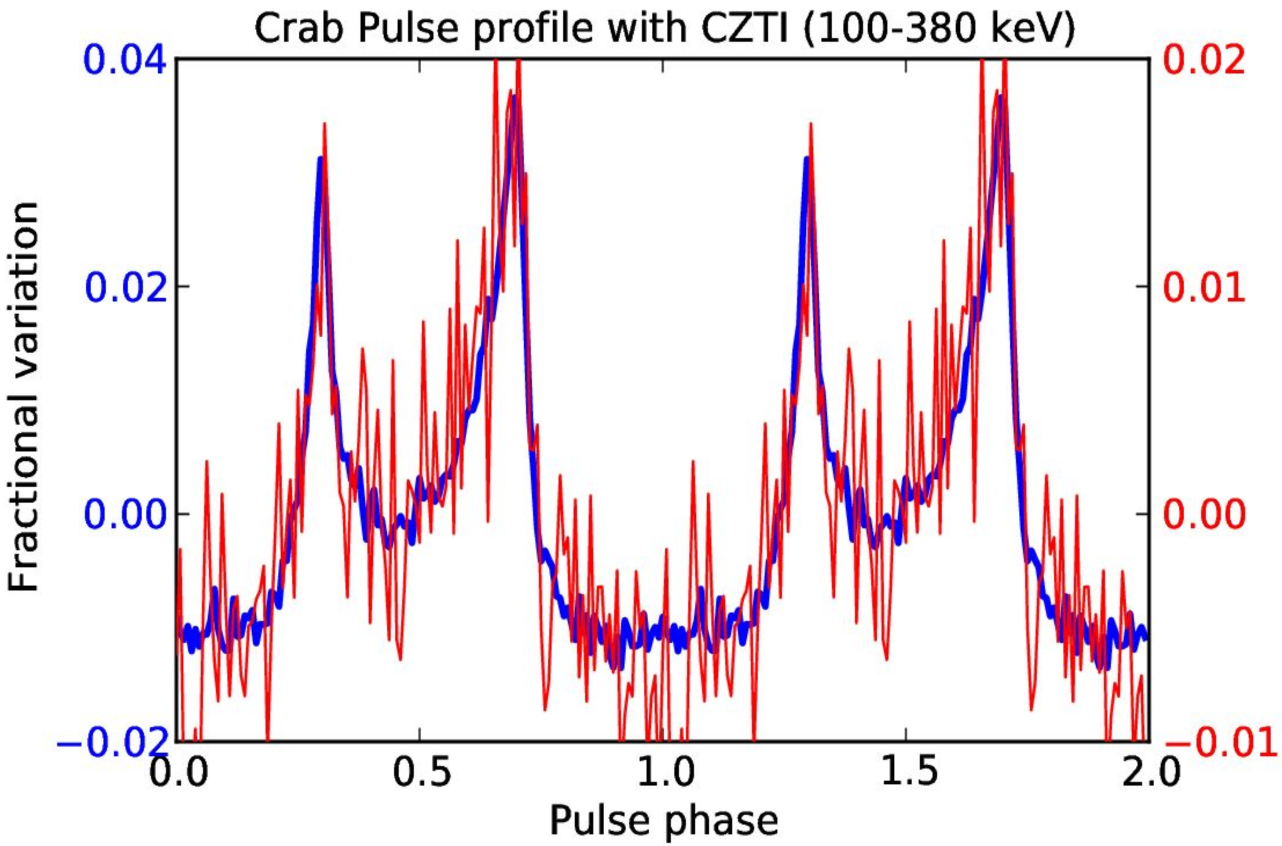


Chattopadhyay et al 2014 Vadawale et al 2015

CZTI does have polarization measurement capability!

Geant 4 simulations to calibrate for polarization

on-board calibration with Crab



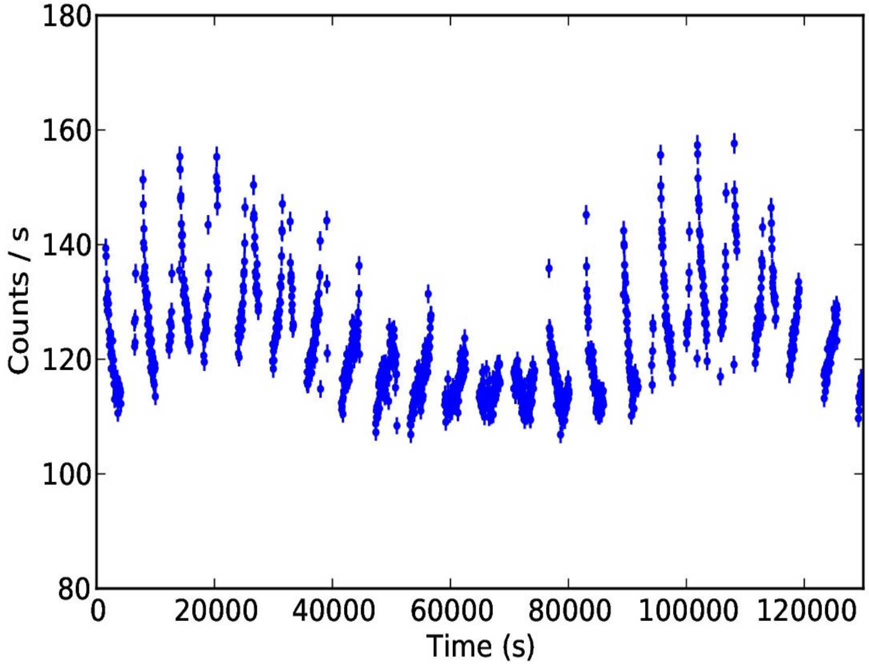
Total Exposure : **796 ks** (from September 2015 to January 2017)

RED : Compton events (adjacent double pixel events satisfying Compton criteria)

BLUE : Single pixel events

Validation of the Compton Event selection

Background subtraction is tricky …

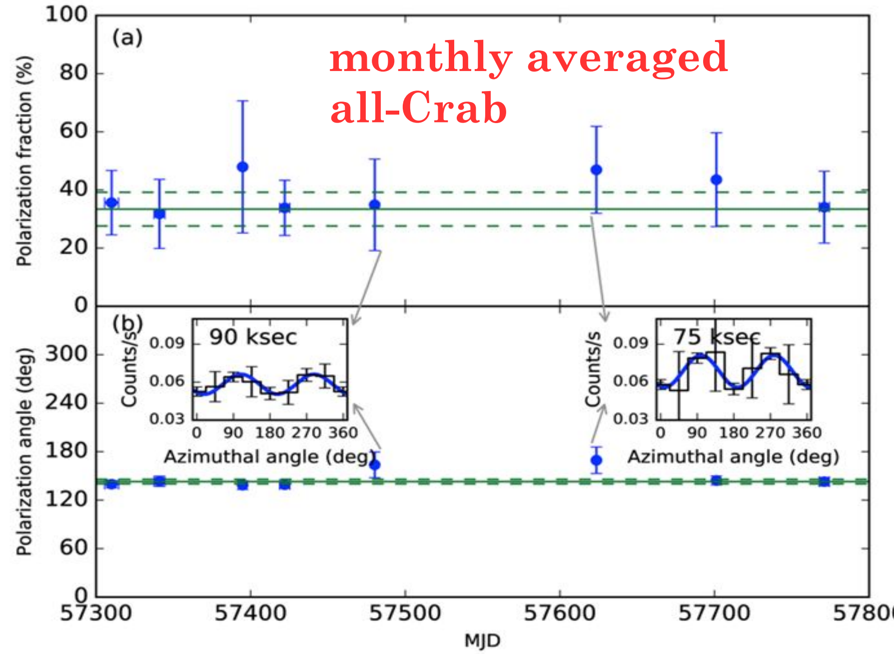


- Background rate varies with ground track
- Manually select background regions which are in same phase with Crab

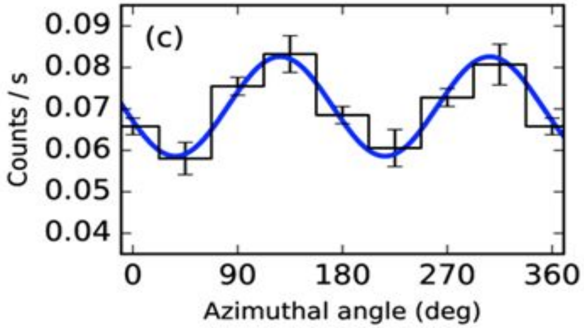
- Azimuthal distribution changes with DEC

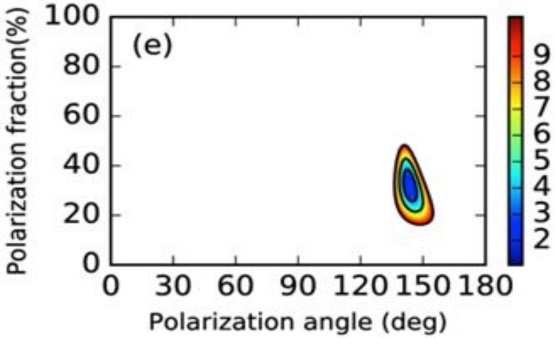
- Need to select blank sky observations with same DEC as Crab
- Both Crab and Cygnus X-1 should be more than 80° away

Crab results



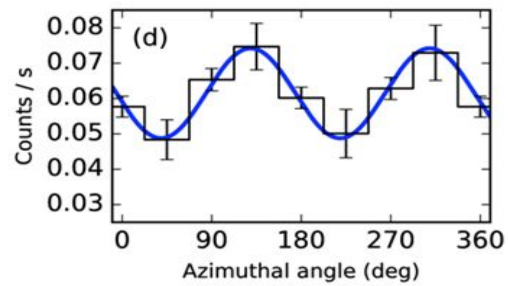
all-Crab

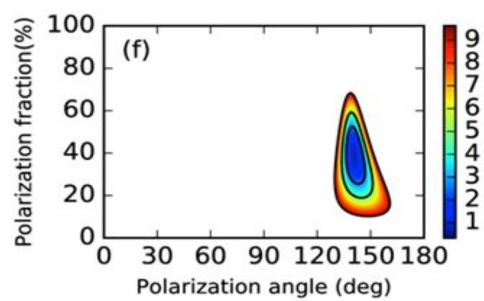




32.7 % +- 5.8 % at angle 143.5 deg +- 2.8 deg (North-East)

Nebula

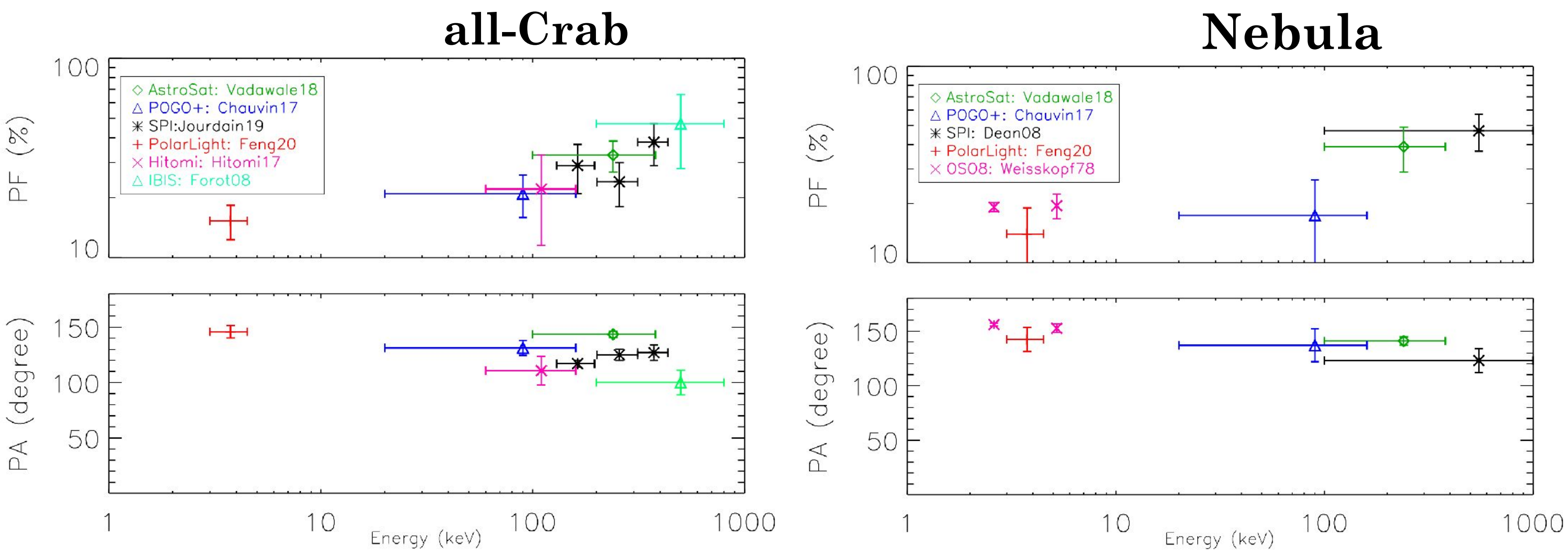




39 % +- 10 % at angle 140.9 deg +- 3.7 deg (North-East)

Vadawale, Chattopadhyay et al 2018, NatAs

Crab results



High polarization across the broad energy range → **synchrotron emission from a magnetically ordered compact emission site**

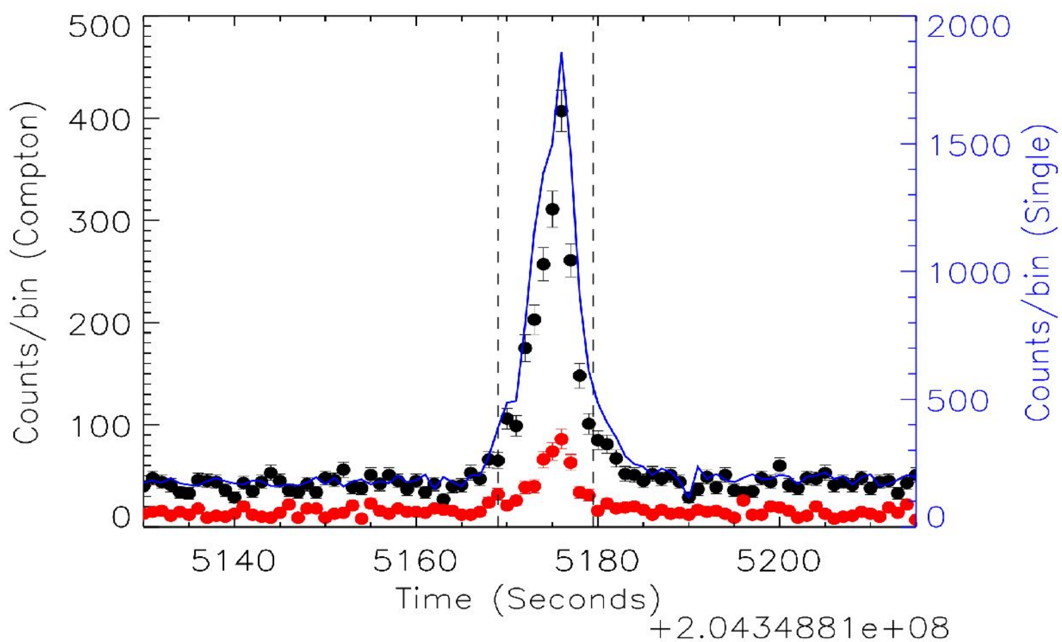
Polarization angle parallel to pulsar spin → **electrons trapped in the toroidal magnetic field produce synchrotron radiation with PA parallel to the spin axis of the pulsar**

CZTI also works as Open Detector in Hard X-rays – ~80 GRB detections/ year

CZTI supporting structures, collimators, mask, Spacecraft structures are transparent at higher energies

Regular detection of GRBs ~ 80 GRBs / year

Prompt emission polarization of GRBs using the same physics of interaction of photons?



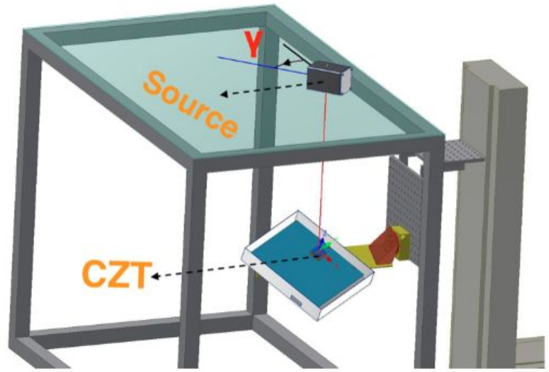
Chattopadhyay et al 2019, ApJ

well … GRB polarization is difficult…

Simultaneous background is available,
Better signal to noise … but …

1. Off-axis detection - does CZTI have off-axis polarization capability?
2. Interaction of photons with the satellite structure - how accurate is the mass model?
3. charge sharing between CZTI pixels - how to include charge sharing in the Geant4 simulation?

Characterized CZTI for off-axis polarization in lab …



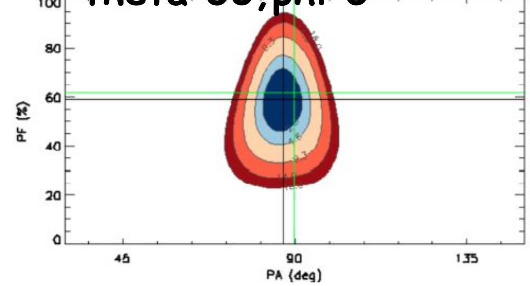
A Ba133 radioactive source to make polarized radiation.

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

Main results:

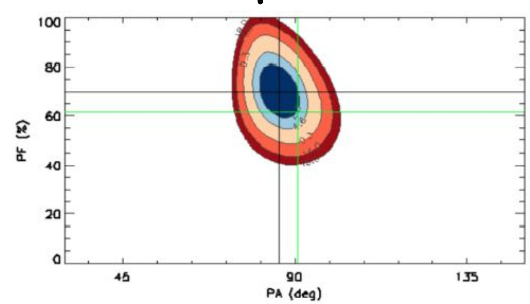
1. experimental and simulation results match within error
2. **>60 degree angles, the MDP is less and prone to systematics**

theta 30,phi 0



(a)

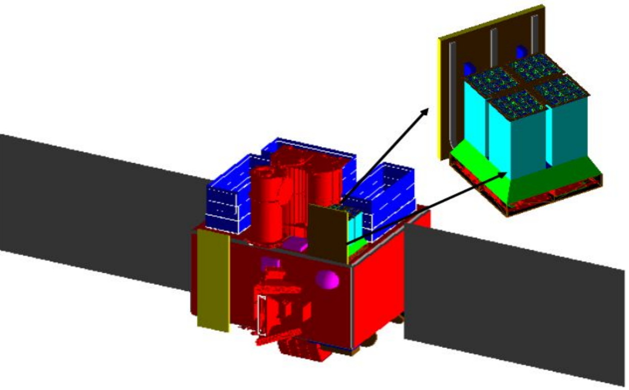
theta 30,phi -30



(c)

Vaishnava et al 2022, JATIS

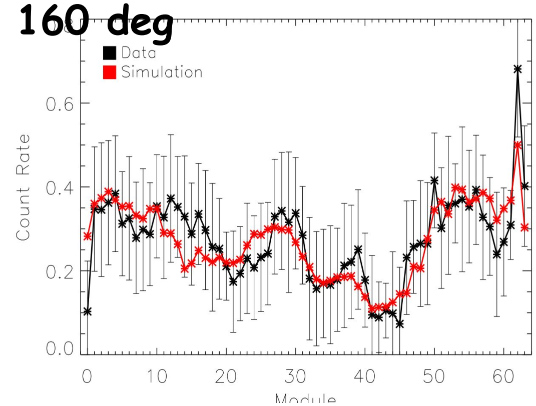
We validated the AstroSat mass model …



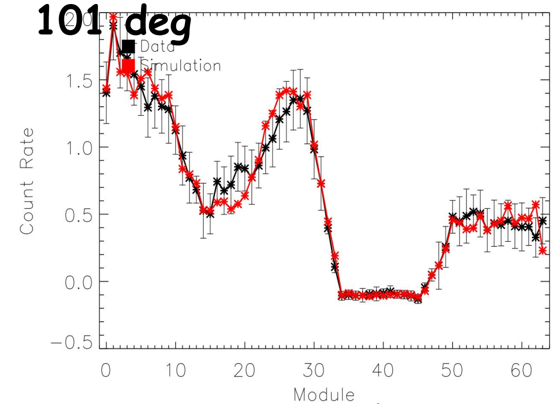
Mate et al 2021

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

GRB160325A, theta 0,phi 160 deg



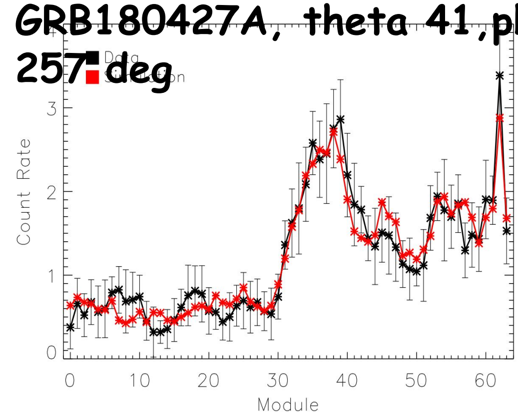
GRB170527A, theta 26,phi 101 deg



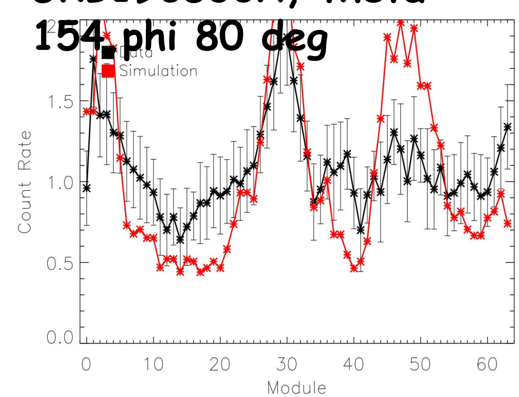
Validation:

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

GRB180427A, theta 41,phi 257 deg



GRB190530A, theta 154,phi 80 deg



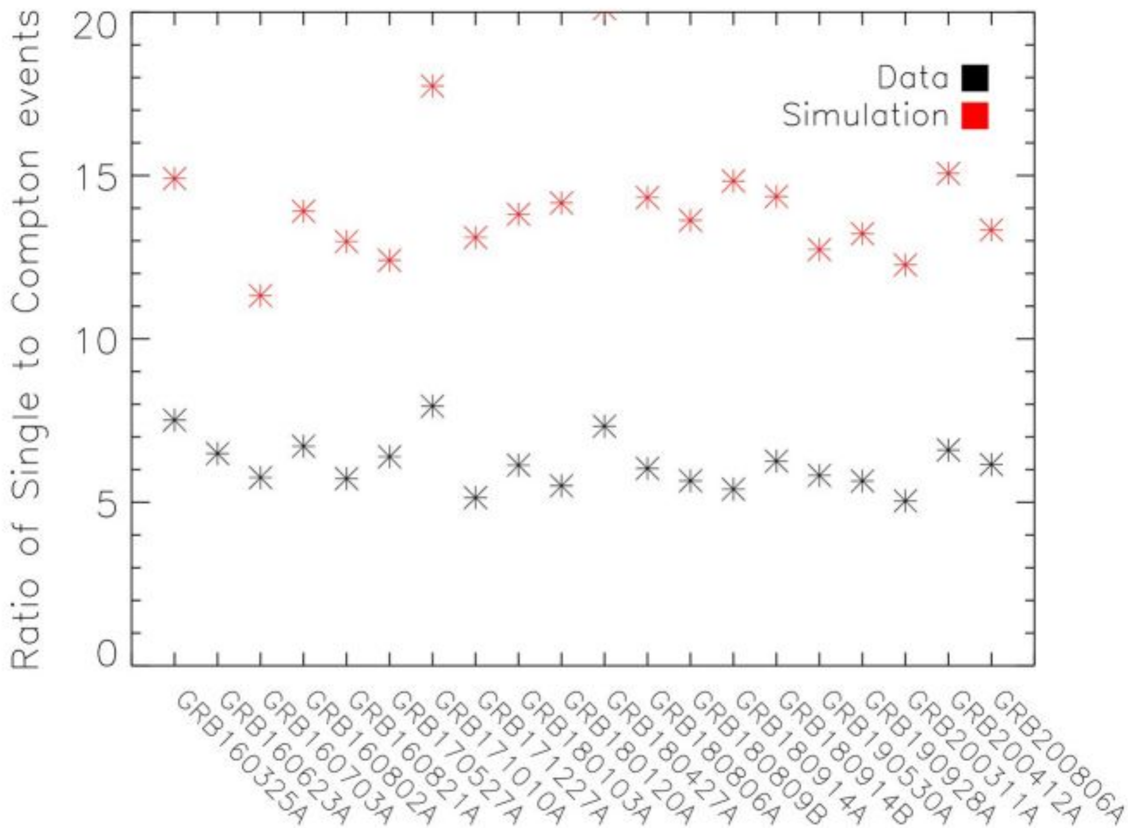
Chattopadhyay et al 2019, ApJ

Charge sharing in CZT pixels

- For single pixel spectroscopic events, CZTI 2.5 mm pixels are too big for significant effect of charge sharing

- However, Compton events are a factor 10-15 times lower. Therefore charge sharing events are significant.

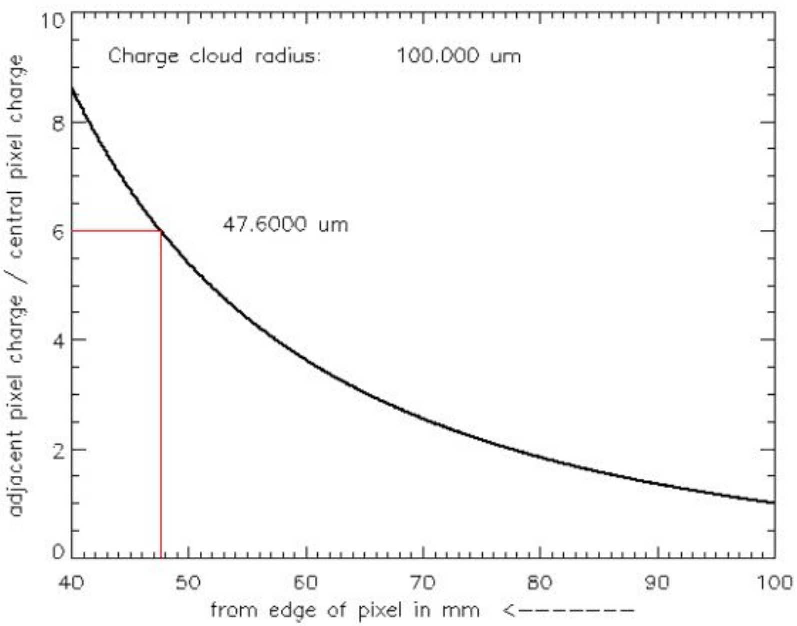
- We see the evidence of charge sharing in the ratio of single to Compton events
- Observed #Compton events = true Compton events + 2-pixel charge sharing events
- Observed #single events = true single events - 2-pixel charge sharing events

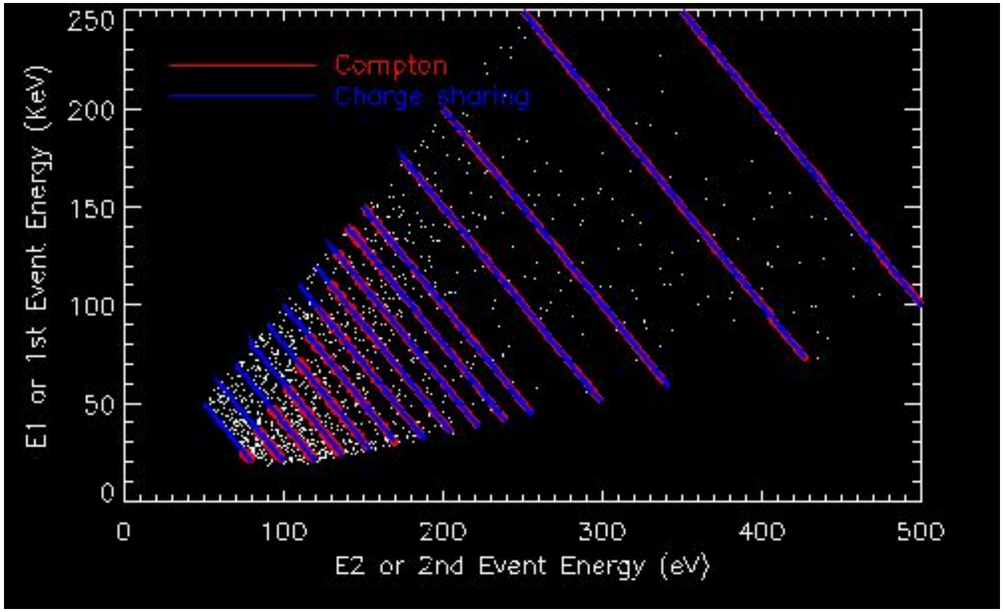


Chattopadhyay et al 2022, ApJ

Charge sharing in CZT pixels

- **CZTI efficiency > 200 keV is low.**
- **Estimated the weighted range of electrons in CZT crystal in 100-200 keV around 85 um. After diffusion, it will be 100 um for a 5 mm thick CZT**
- **Developed a model to estimate the shared charges between pixels. Charge sharing happens only at the edge upto 47 um due to the compton kinematic condition.**
- **Not possible to distinguish the charge sharing events from the Compton events at > 170 keV**
- **Need to include charge sharing in the simulation events**

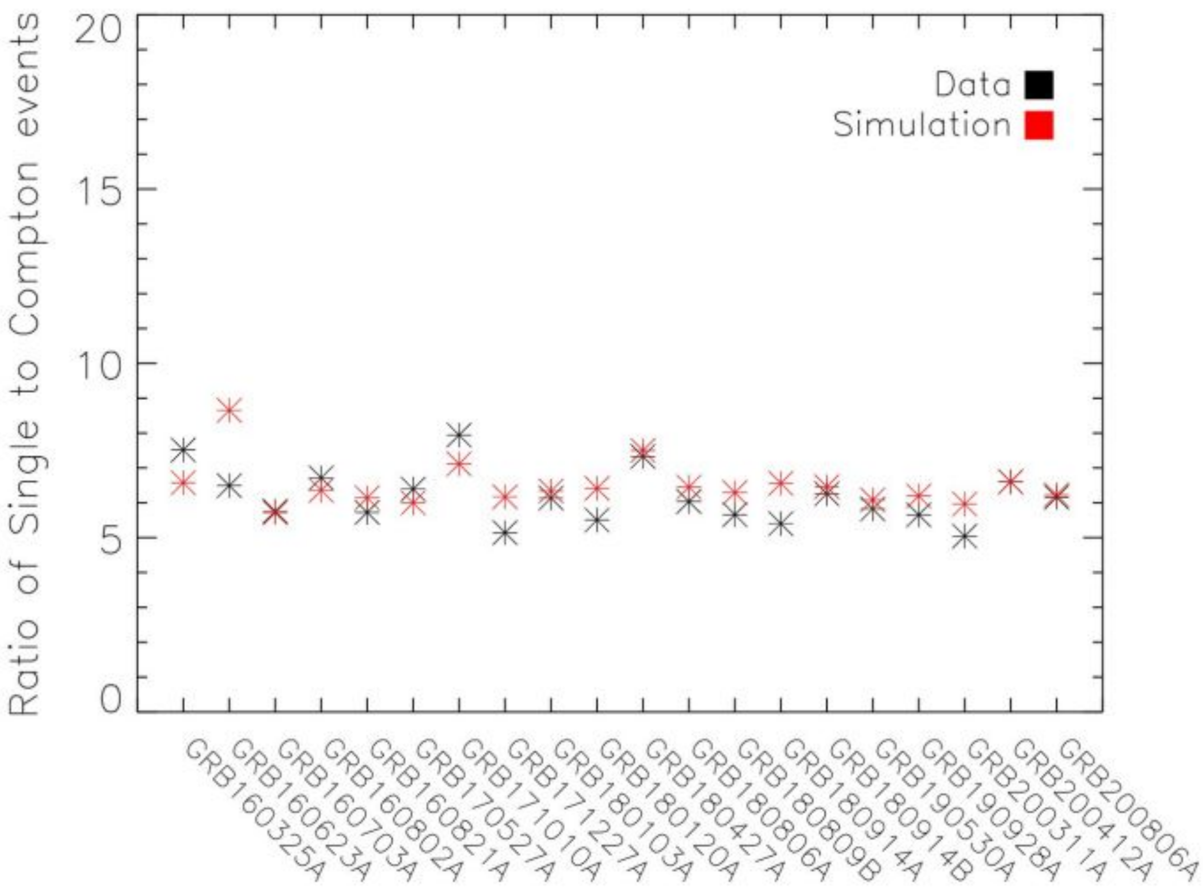




Chattopadhyay et al 2022, ApJ

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

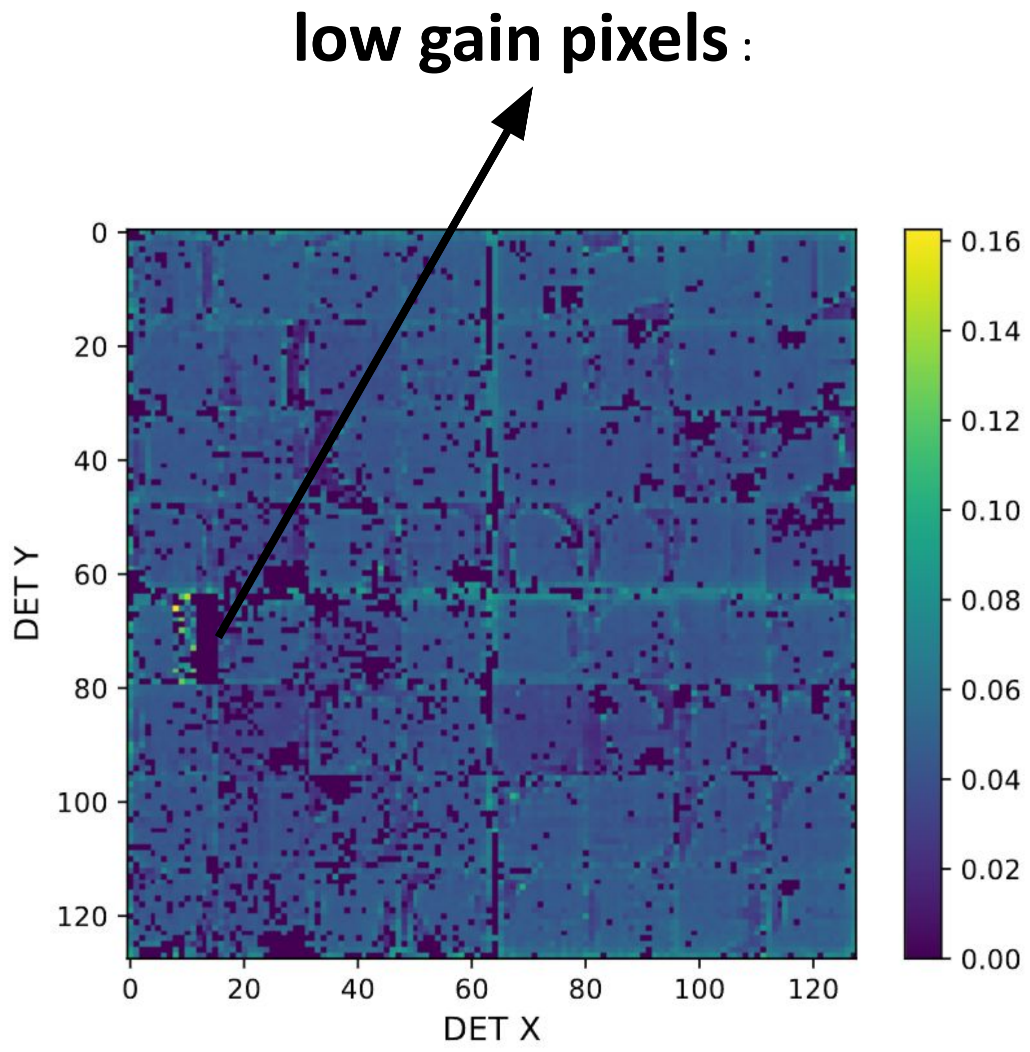
Extending the CZTI polarimetry and spectroscopic energy to sub-MeVs

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 and spectroscopic energy range to 600 and 900 keV** respectively.

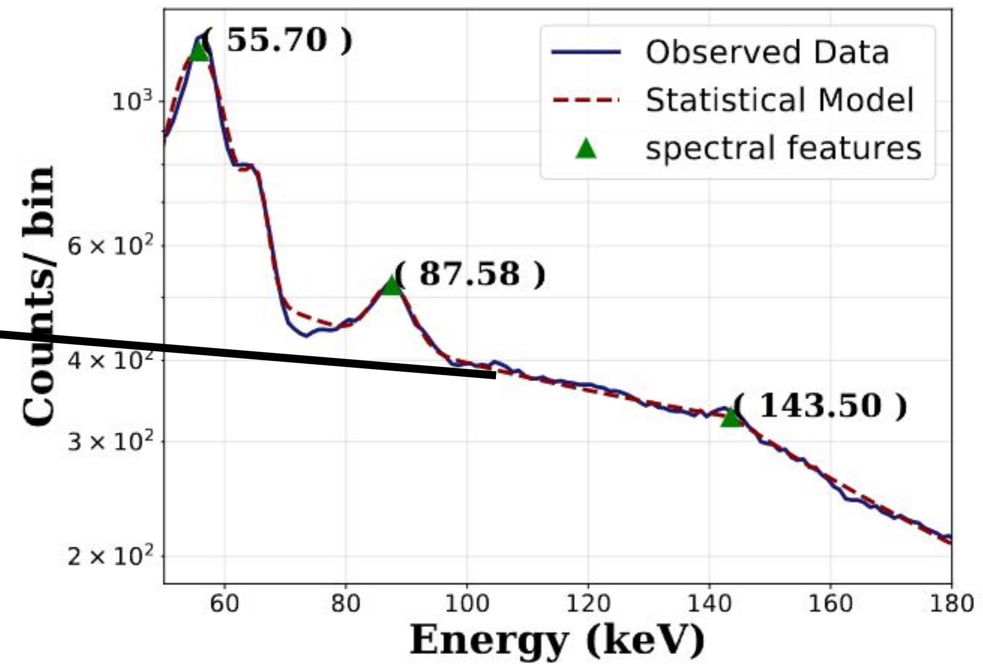
> calibration of the low gain pixels



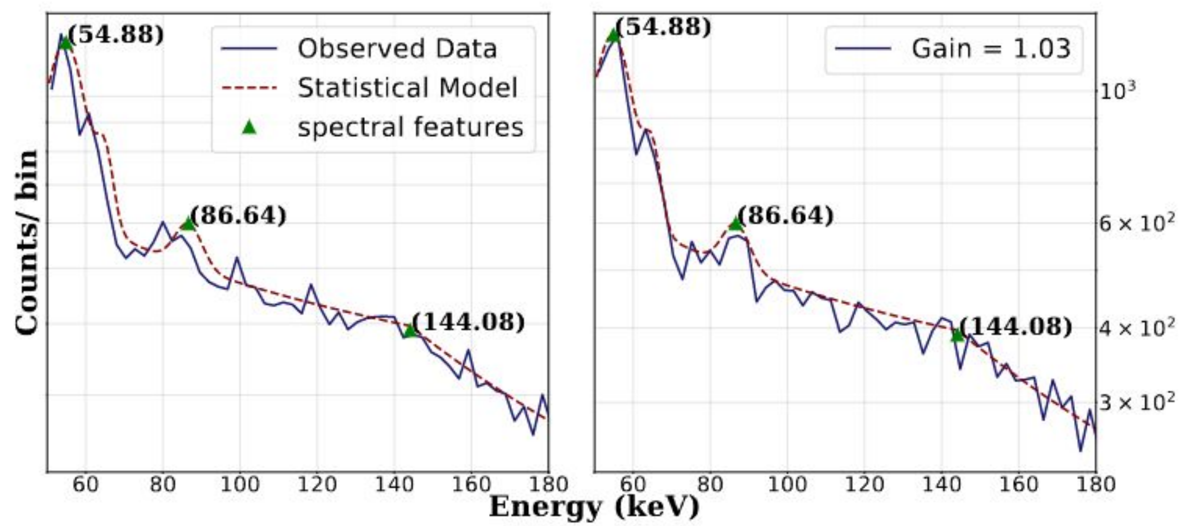
Low gain pixel calibration

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.



example : 1 pool of low gain pixels with gain 0.9- 1.5

Low gain pixel calibration

2nd pool of low gain pixels : gain correction factor between 1.5 and 5

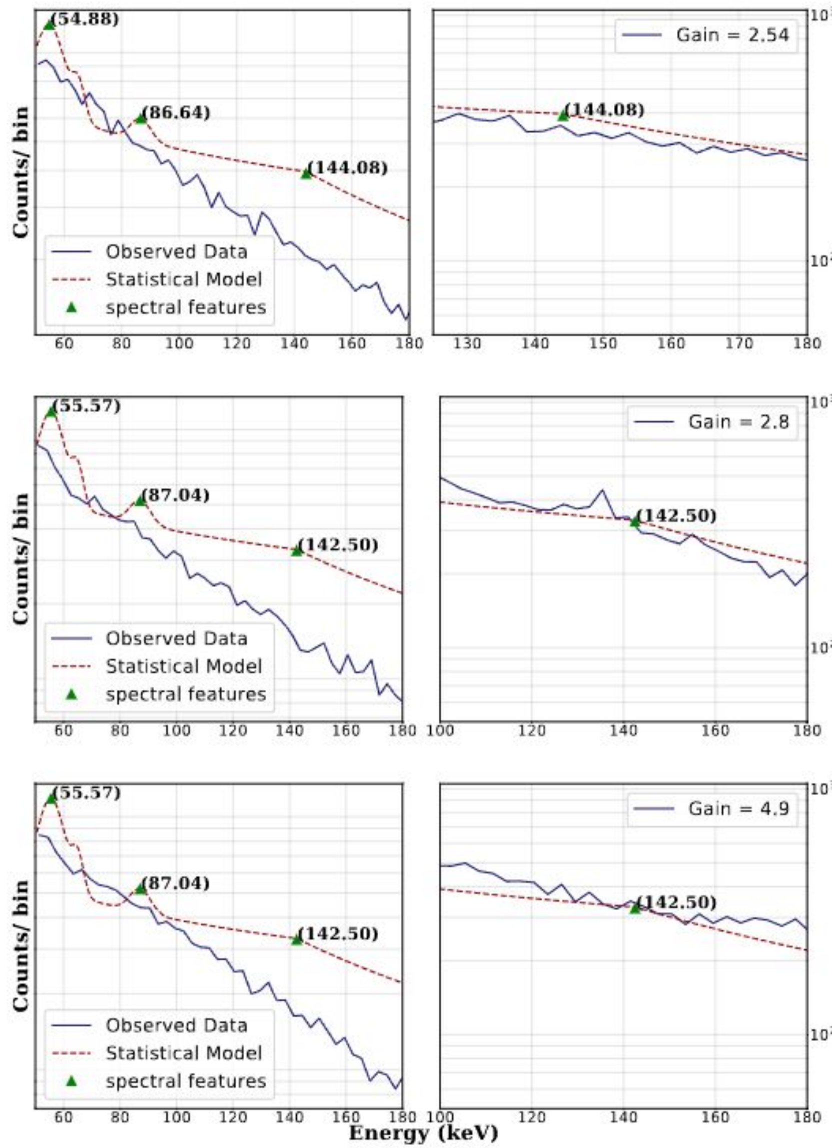
Pixels with no acceptable fit were removed.

Recovered around 15 % of the pixels

Gain is correct to 5-10 %

Compared 5 year background data - gain not changing !

before correction after correction

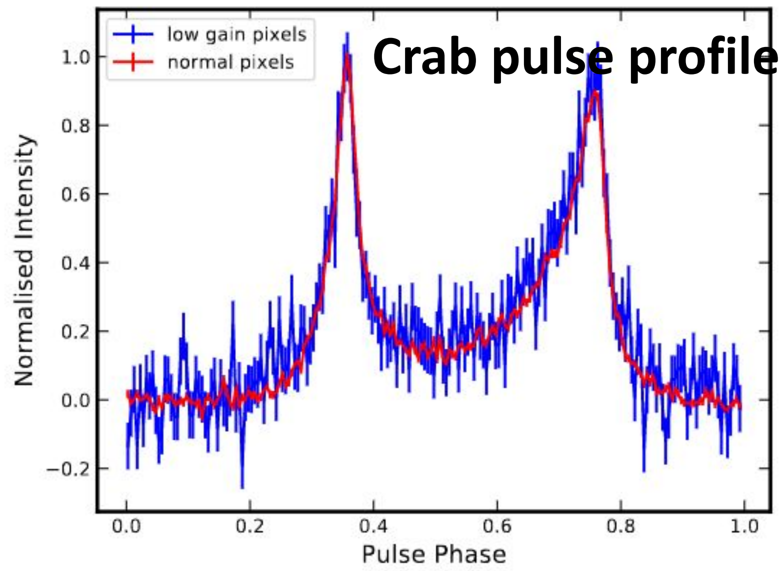


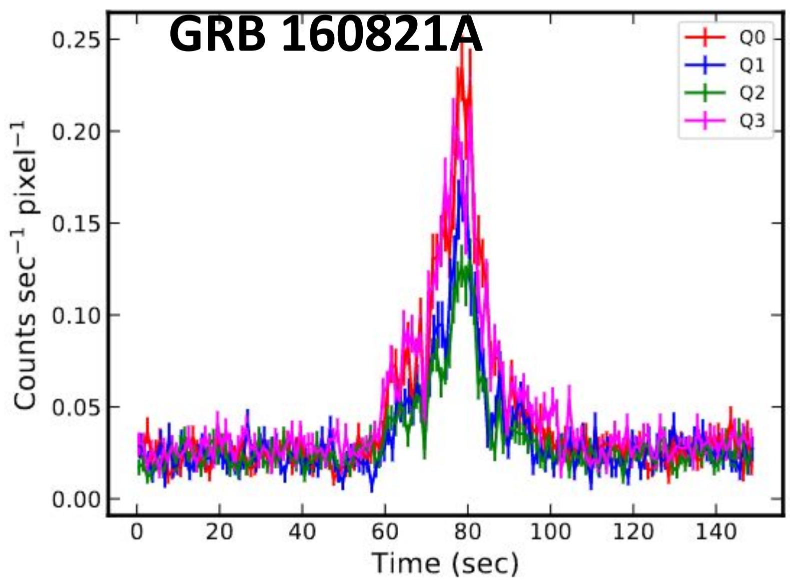
Validation of the Low gain pixel gains

Co-added the similar gain pixels and made sure we see the features like 88 keV or 145 keV break

Compared the Crab pulse profile in low gain pixels. Consistent with pulse fractions (p1 and p2) at those energies. See Anushree et al.

GRB prompt emission light curve reconstruction in low gain pixels.





Chattopadhyay et al 2021, JAA

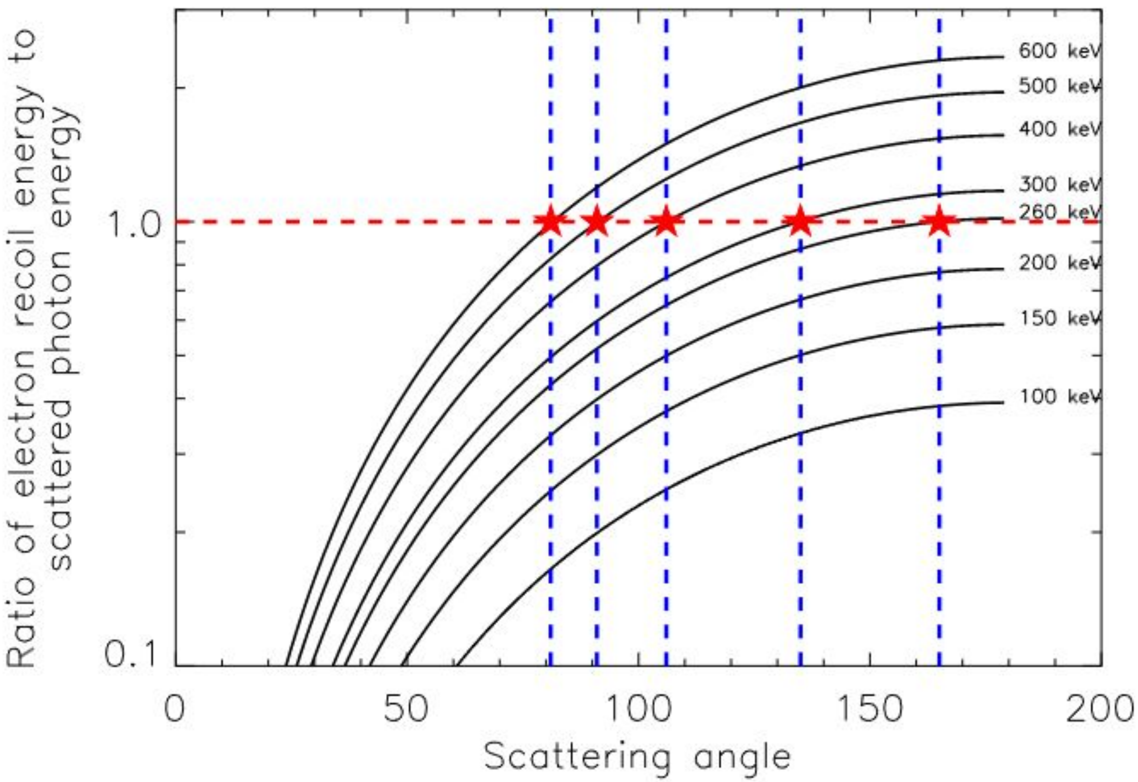
sub-MeV polarimetry for the GRBs …

Can we use the low gain pixels to enhance the polarimetric energy range?

Yes can be extended to 600 keV.
Above 600 keV, no intrinsic polarization analyzing power.

Question - how to identify the first and second event to estimate the azimuthal angle for the Compton event? Above 600 keV, can't distinguish

Developed a model based on Compton kinematics and MC simulation to distinguish the events.



sub-MeV spectroscopy for the GRBs

Used the low gain pixels

extended the single pixel events to 900 keV

Compton spectroscopy in 100-700 keV (without low gain pixels 100-380 keV)

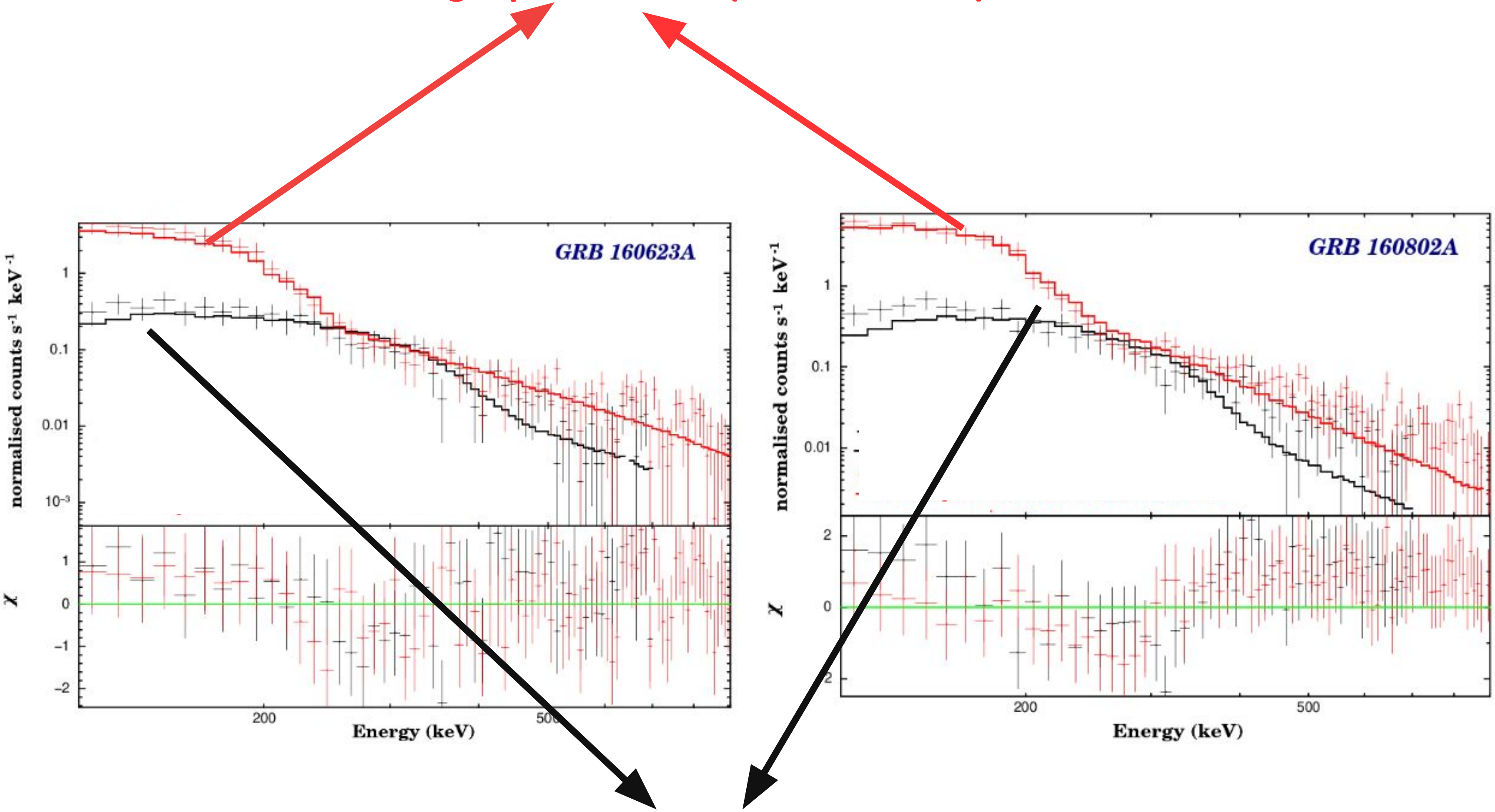
Response matrix generated using AstroSat mass model.

Monenergetic X-ray photons from 100 - 2000 keV ~ each 10^9 photons

We used a sample of Fermi detected GRBs fixed the alpha, beta and epeak at the fermi values and kept the norm free in xspec fitting

sub-MeV spectroscopy for the GRBs

single pixel events (100 - 900 keV)



2-pixel Compton events (100 - 700 keV)

also used the veto data for sub-MeV spectroscopy

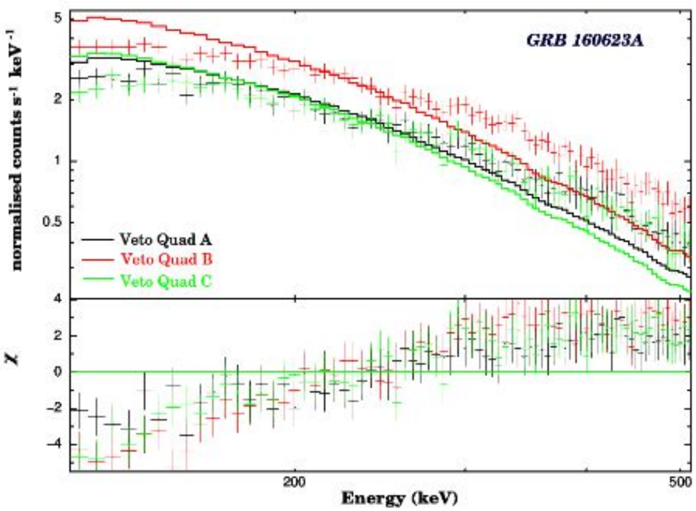
Veto is sensitive in 100-500 keV

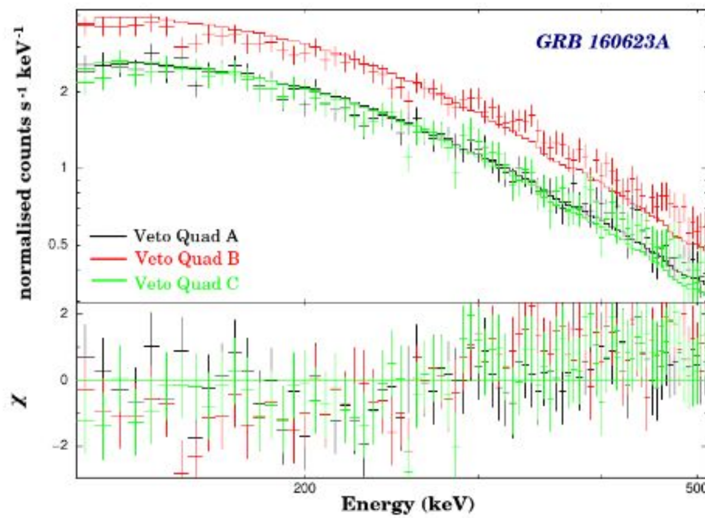
We had to use a correction term in the response 1-e^(-p. E). P is significant for back side GRBs.

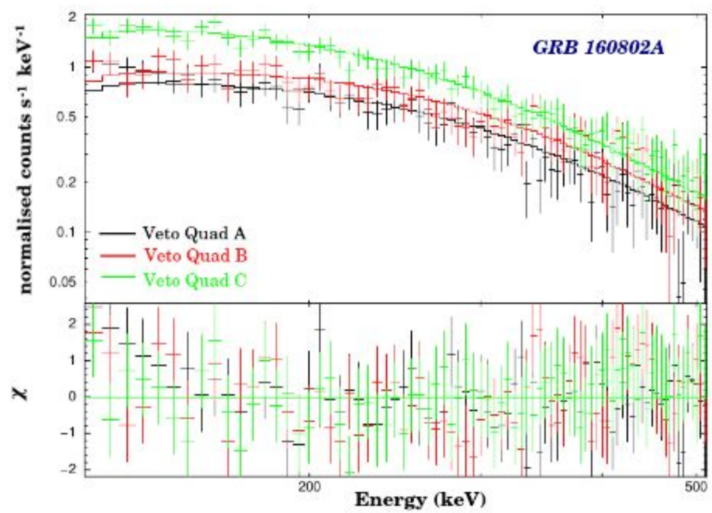
Response from the mass model

neglected the 4th quadrant

back side GRB

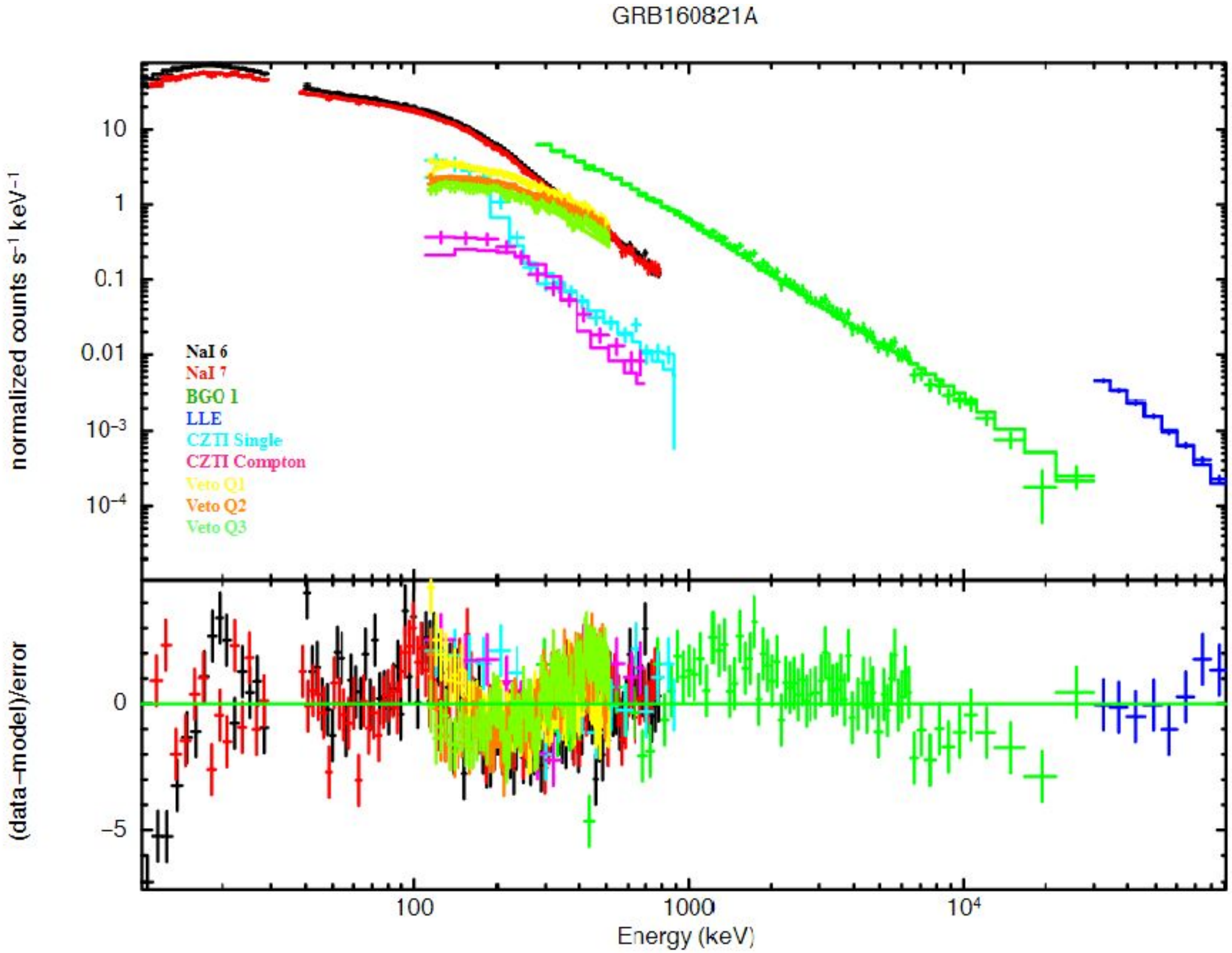






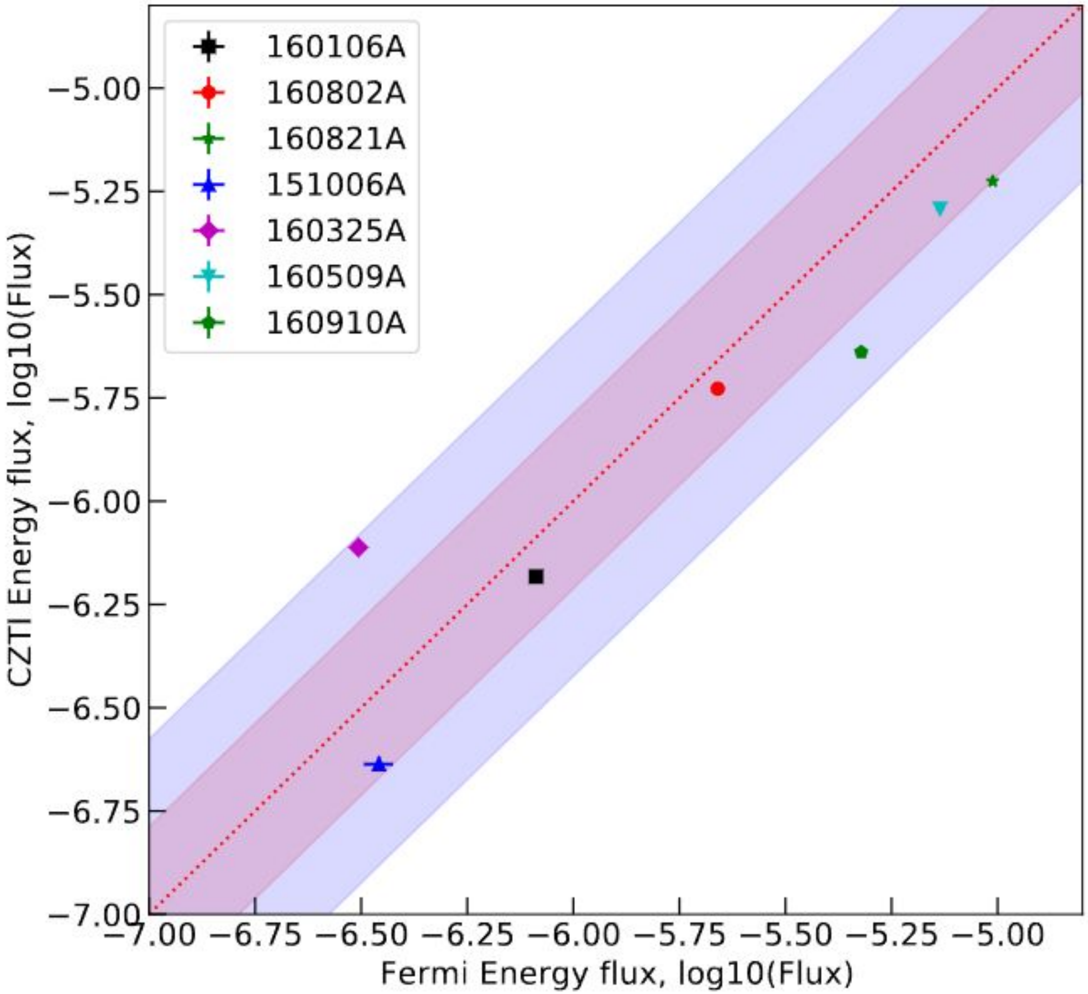
front side GRB

An example of broad band spectroscopy with Fermi + CZTI



Chattopadhyay et al 2021, JAA

And the CZTI obtained flux is consistent with Fermi flux



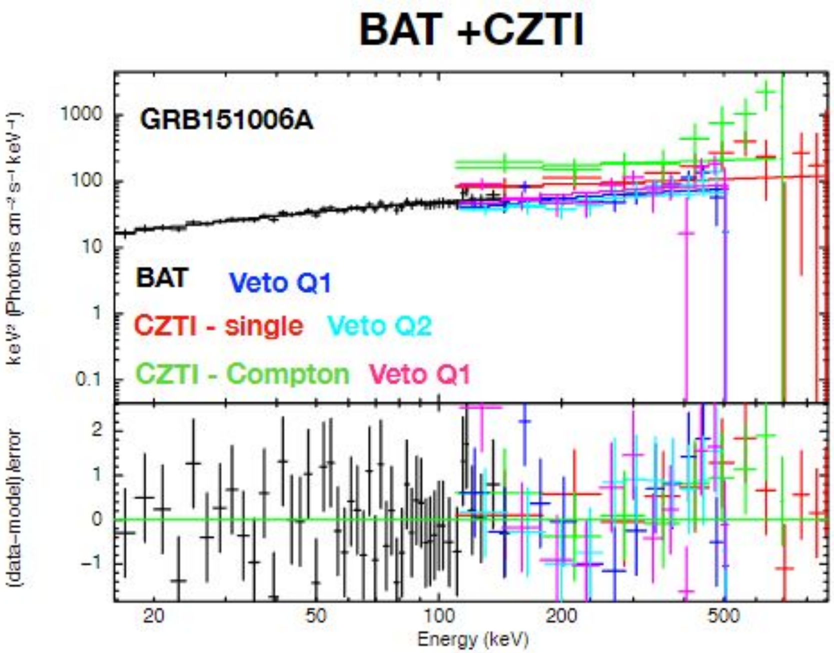
alpha, beta, epeak parameters are fixed at Fermi values. Norm free.

Flux is estimated in 100-1000 keV from fermi and CZTI

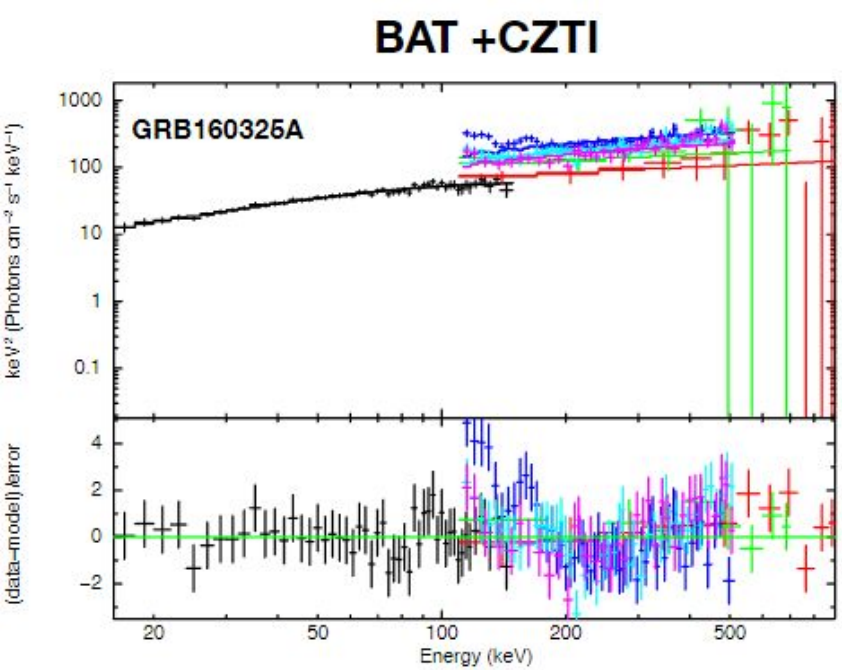
Consistent flux at 2 sigma level.

Effective area in the response is correct

Chattopadhyay et al 2021, JAA



So, we can do spectroscopy for non-Fermi detected GRBs



GRB name	Band Parameters	BAT	BAT + CZTI	Fermi
GRB151006A	α	$-1.25^{+0.07}_{-0.14}$	$-1.23^{+0.15}_{-0.12}$	$-1.08^{+0.12}_{-0.13}$
	β	$-9.37^{+19}_{-0.0}$	$-1.79^{+0.18}_{-0.17}$	$-1.89^{+0.11}_{-0.20}$
	E_{peak} (keV)	288^{+257}_{-117}	262^{+44}_{-24}	350^{+400}_{-126}
	$Norm$	$0.007^{+0.001}_{-0.0009}$	$0.007^{+0.002}_{-0.001}$	$0.008^{+0.002}_{-0.001}$
	χ^2_{red}	0.68	0.69	1.02
GRB160325A	α	$-0.87^{+0.13}_{-0.12}$	$-0.82^{+0.08}_{-0.16}$	$-0.77^{+0.10}_{-0.09}$
	β	$-10^{+1e-15}_{-0.0}$	$-1.74^{+0.06}_{-0.09}$	$-2.63^{+0.42}_{-2.36}$
	E_{peak} (keV)	137^{+54}_{-27}	124^{+44}_{-24}	214^{+53}_{-43}
	$Norm$	$0.02^{+0.003}_{-0.002}$	$0.01^{+0.002}_{-0.003}$	$0.01^{+0.002}_{-0.001}$
	χ^2_{red}	0.55	0.91	0.81

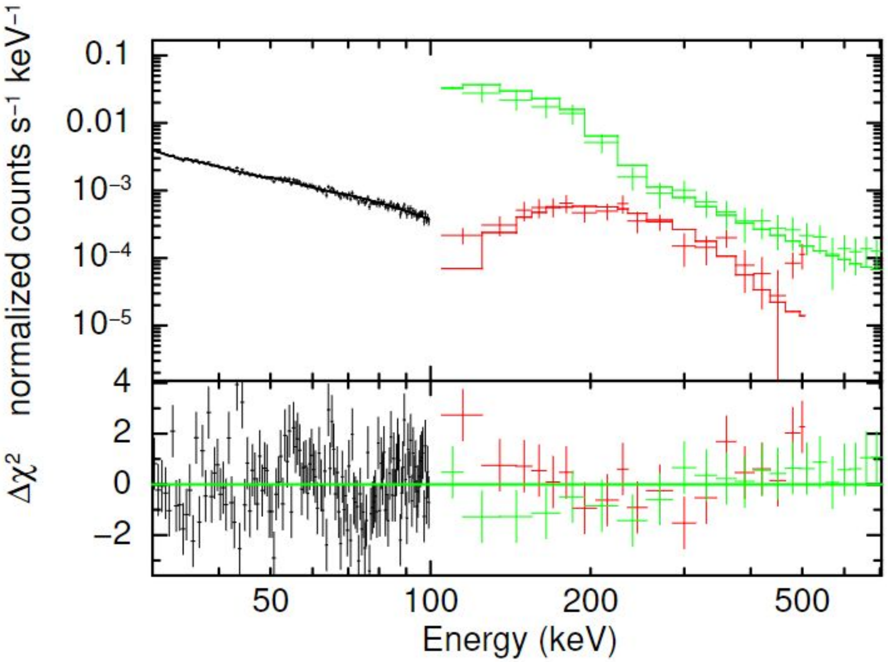
sub-MeV spectroscopy for on-axis sources without low gain pixels

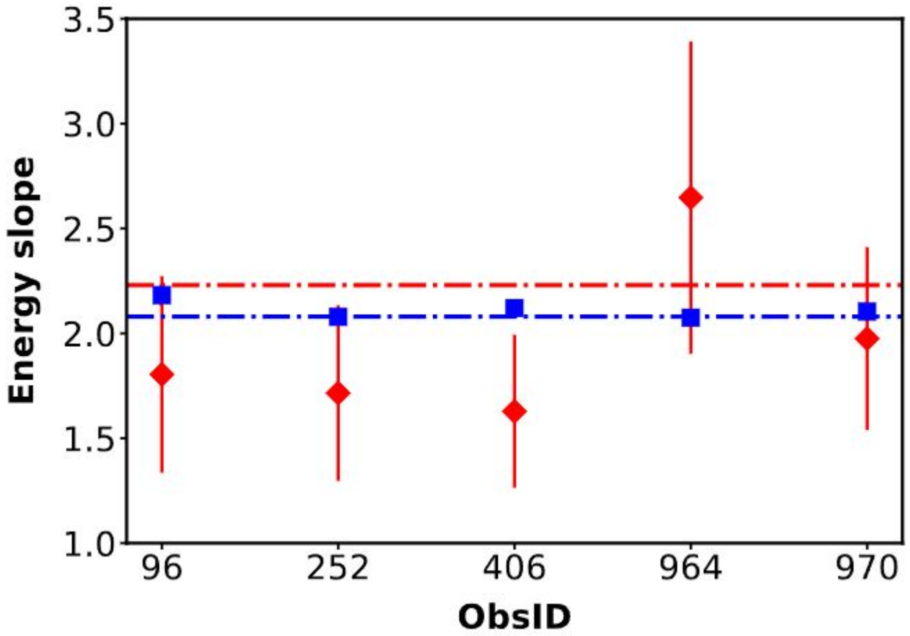
We just used the Compton spectrum (100-380 keV) to get the broadband spectroscopy

2nd powerlaw index is inconsistent.

Background selection, subtraction are the tricky factors

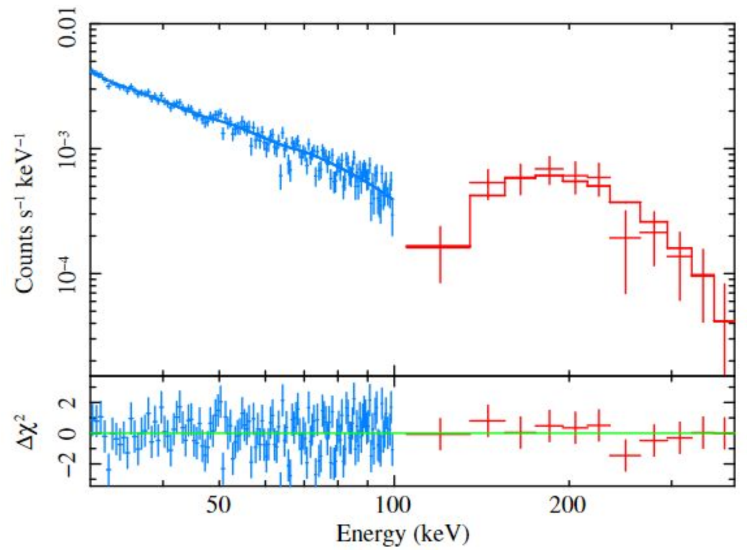
work under progress!

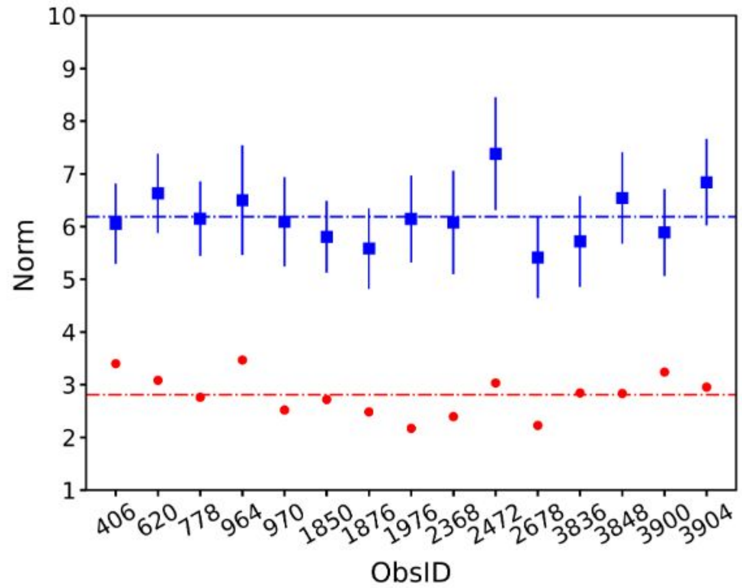




Abhay et al 2022, MNRAS

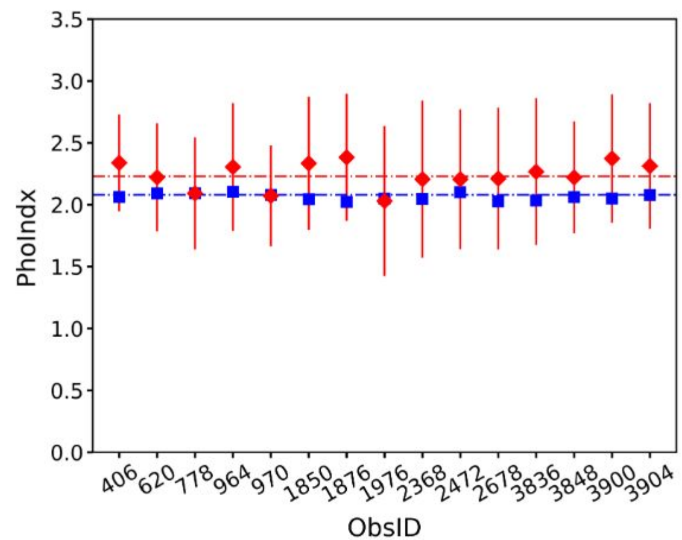
sub-MeV spectroscopy for on-axis sources …





We used Compton events in 100-380 keV to extend the spectroscopic energy range

Applied for Crab for calibration. The results are consistent with the Integral results. 2nd power law ~2.23 with break energy ~100 keV



Abhay et al 2022, MNRAS

Plans …

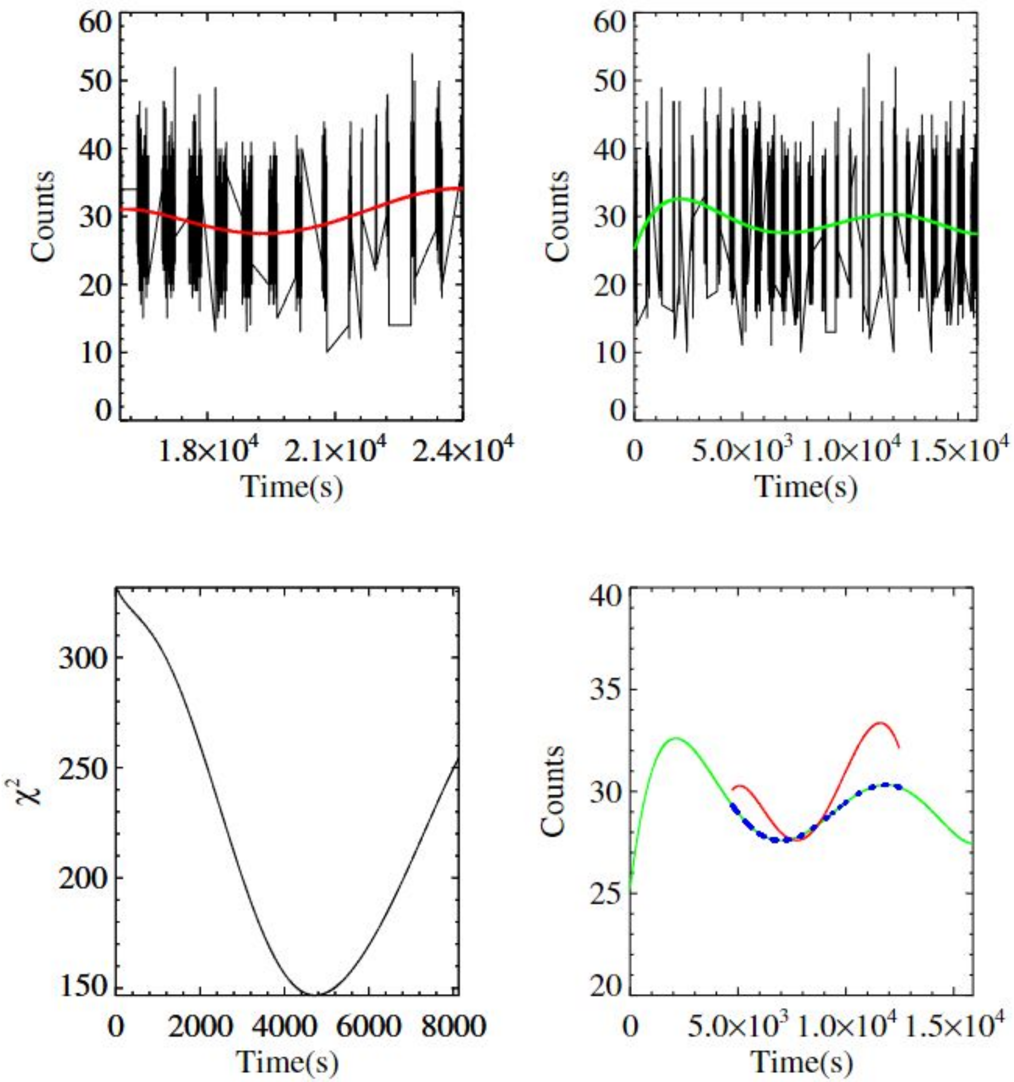
Sub-MeV polarization and spectroscopy is working well for GRBs.

- POLAR+CZTI cross calibration for 2 common GRBs
- Develop methods to do simultaneous spectroscopy and polarization (3ML)
- The first version cookbook and pipeline to be published soon
- We will include charge sharing in the response to get even better constraints
- Spectroscopy cookbook and pipeline under progress

Sub-MeV spectro-polarimetry for ON axis sources in currently limited to 100 - 380 keV

- The background selection and subtraction are difficult because of low S/N
- Use of low gain pixels to extend the energy range require more work …

sub-MeV spectroscopy for on-axis sources …



sub-MeV spectroscopy for on-axis sources …

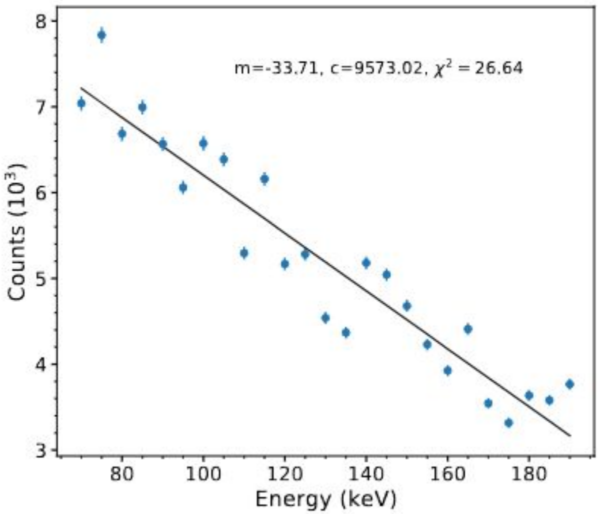
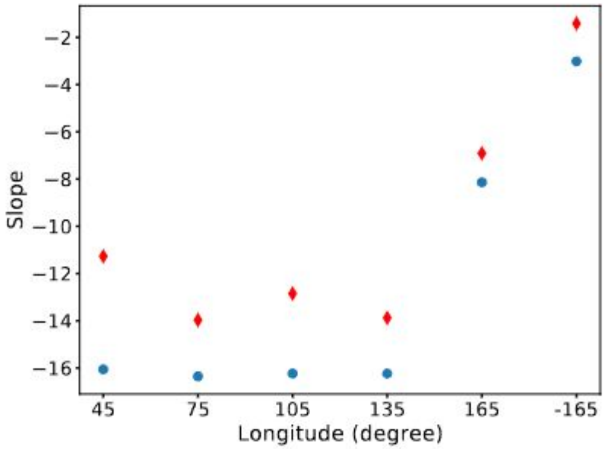


Figure 6. Spectral hardness using a straight line fit in 70 to 190 keV .



sub-MeV spectroscopy for on-axis sources …