Astrosat-CZTI

and

Hard X-ray Polarimetry

Santosh Vadawale
Physical Research Laboratory
Ahmedabad

On behalf of CZTI Team

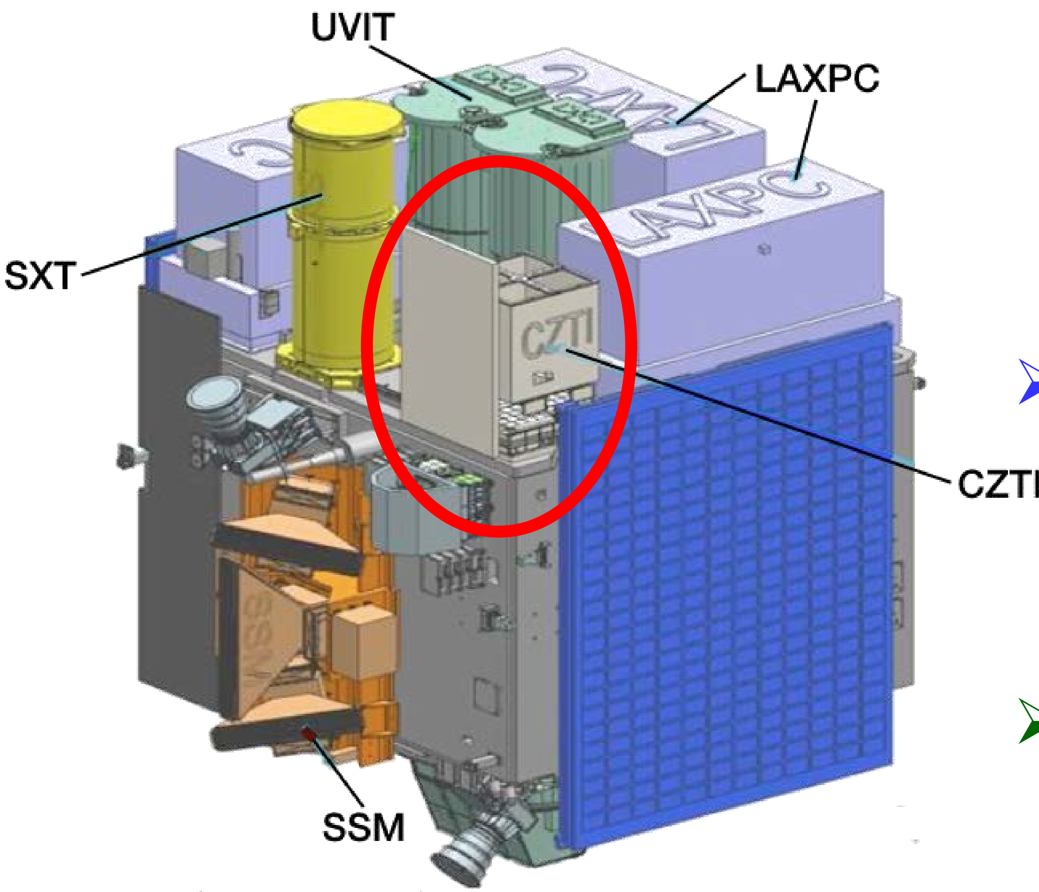
COSPAR Capacity Building Workshop
12 March 2019, IISER Mohali

CZTI Team

- TIFR: A. R. Rao, M. K. Hinger, A. P. K. Kutty, J. P. Malkar, Milind Patil, Rakesh Khanna, Yash Bhargava, Vikas Chand, Debdutta Paul, Ajay Ratheesh
- IUCAA: Dipankar Bhattacharya, Varun Bhalerao (now at IITB), Ajay Vibhute, G. C. Dewangan, Ranjeev Misra, Vedant, Shrikant, Sujay Mate, Vidushi Sharma
- PRL: Santosh Vadawale, Mithun N. P. S., Tanmoy Chattopadhyay (now at PSU), Aarthy E
- VSSC: S. Sreekumar, P. Vinod, Essy Samuel, Priya P
- SAC: Arvind Singh, Tanul Gupta

AstroSat Team

Outline



- Astrosat CZTI
  - Brief introduction
  - Imaging and Spectroscopy technique
  - Calibration
  - In-flight 'Observations'
- X-ray polarimetry
  - Brief Introduction
  - Hard X-ray polarimetry with CZTI
- CZTI as GRB detector
  - GRB polarimetry
  - EMGW monitoring → DKASHA
- Summary

Astrosat CZTI

Hard X-ray Spectroscopy and Imaging

Coded Mask imaging with pixilated CZT detectors

- Detector plane area: 976 cm^2
- Pixel size: 2.46 x 2.46 mm^2
- Total number of pixels: 16384
- Detector thickness : 5 mm

> Mask and support structure designed for shielding up to ~150 keV

> Detectors have significant efficiency upto ~400 keV

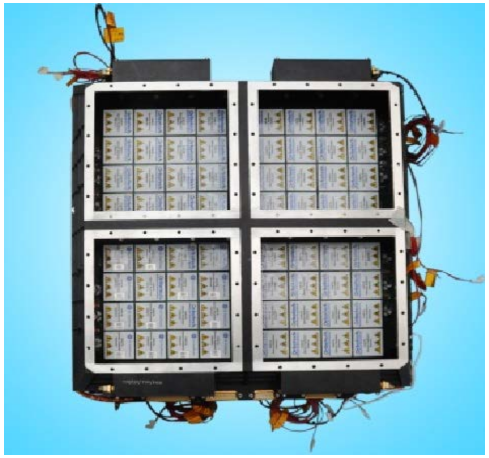
> Results in additional capabilities

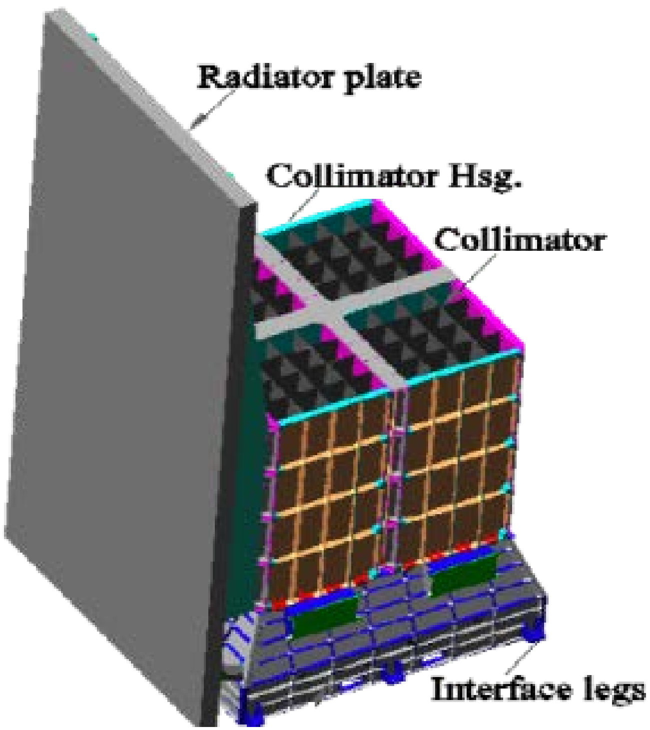
→ Hard X-ray transient monitoring

→ **Hard X-ray polarimetry**

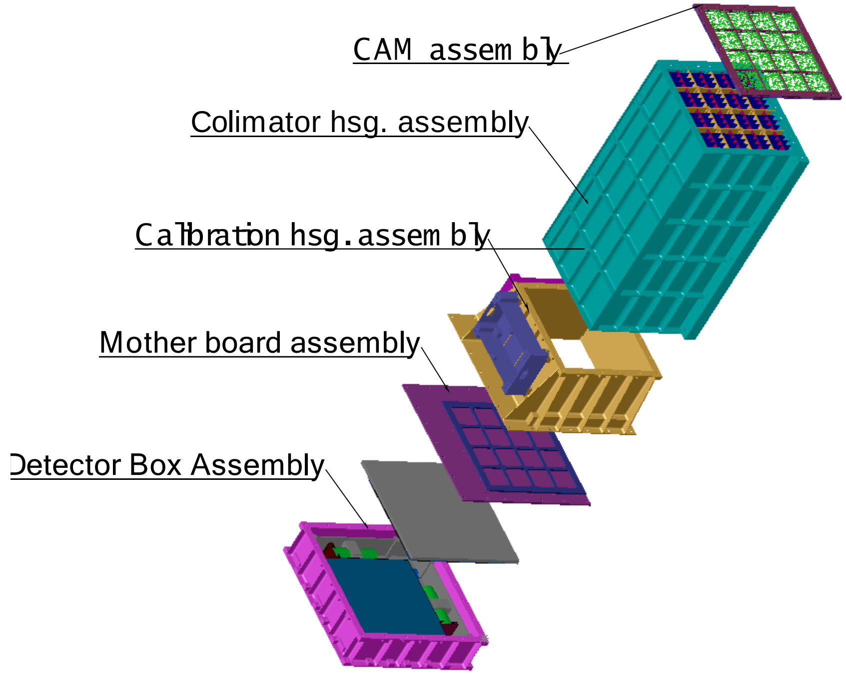
CZTI Configuration

Four Independent Quadrants





Details of a Quadrant

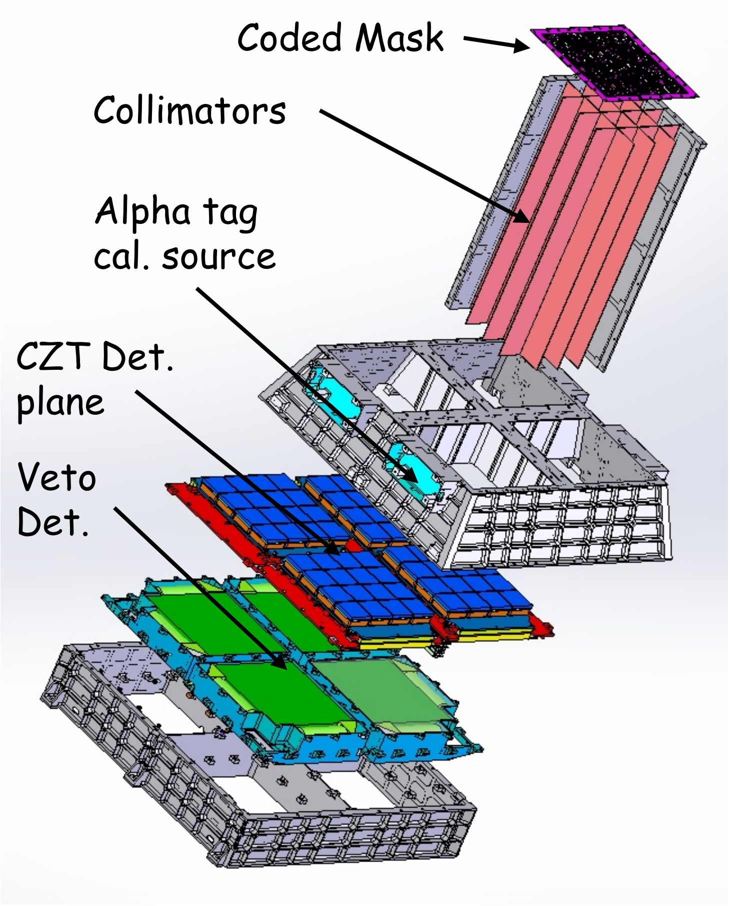


- Total 64 modules (16 in each quadrants)
- ASIC based readout (2 x 128 ch. ASIC)
- Two FOVs: 4.67° × 4.67; ~80° × 80°
- Size - 484 x 484 x 600 mm^3
- **Weight - 50 kg Power- 50 Watts**

CZTI Configuration

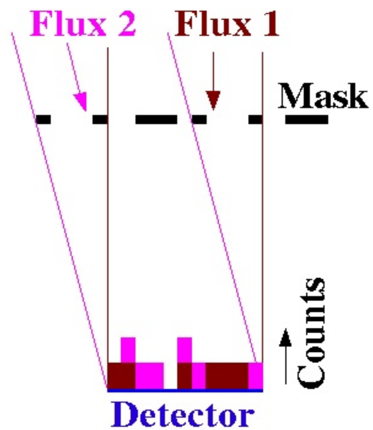
Salient Features

- Indirect imaging with coded aperture mask
- Mask and shielding designed up to 100 keV
  - Hard X-ray monitoring above ~100 keV
- Time tagged event data with 20 μs accuracy
  - Allows Compton spectroscopy and polarimetry



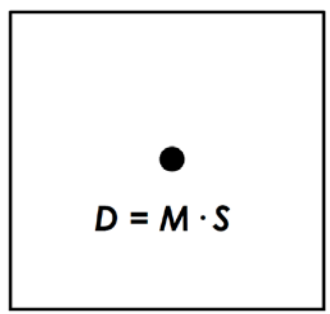
- Alpha-tagged detector for onboard calibration
- Veto detector for efficient background rejection
- Low inclination orbit
- Absolute time correlation with onboard SPS

Coded Mask Imaging

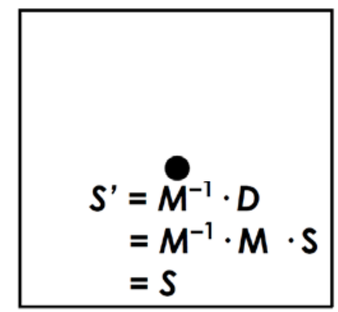


- In-direct imaging technique
- Uses mask shadow pattern, not focusing
- Only option at wavelengths which can not be focused →Hard X-ray / gamma-ray

Mask (M)



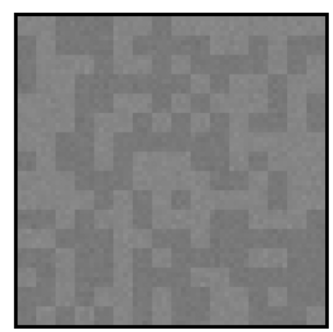
Sky (S)



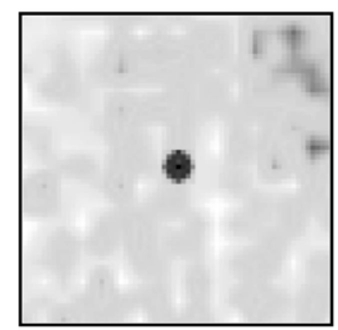
In real world

- Mask pattern is not invertible matrix
- Detector has significant background

→ Cross correlation with mask pattern



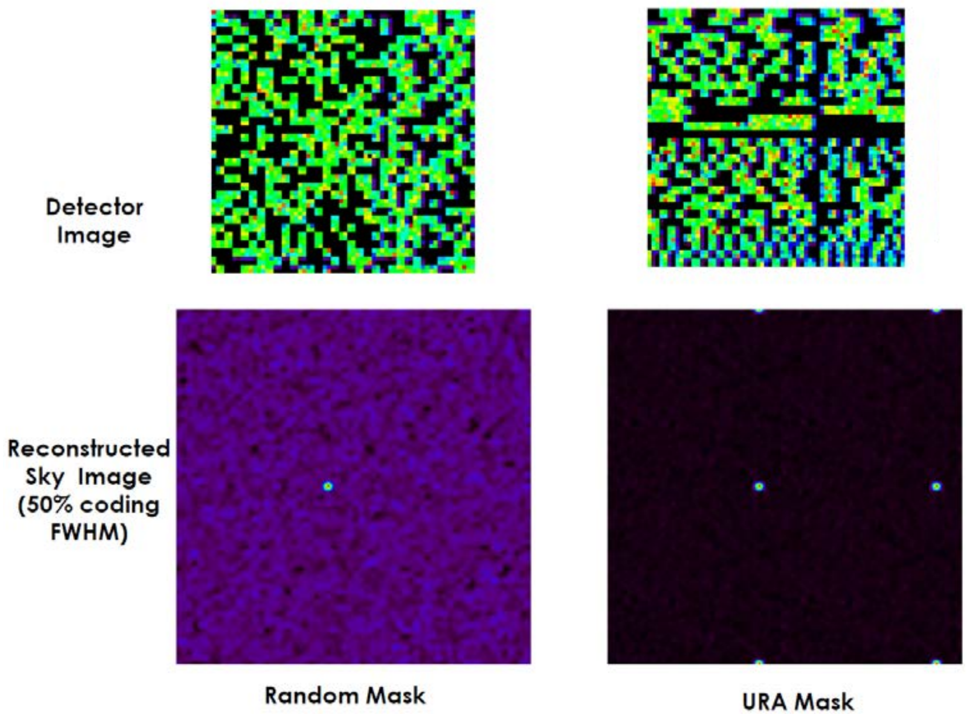
Detector Response (D)

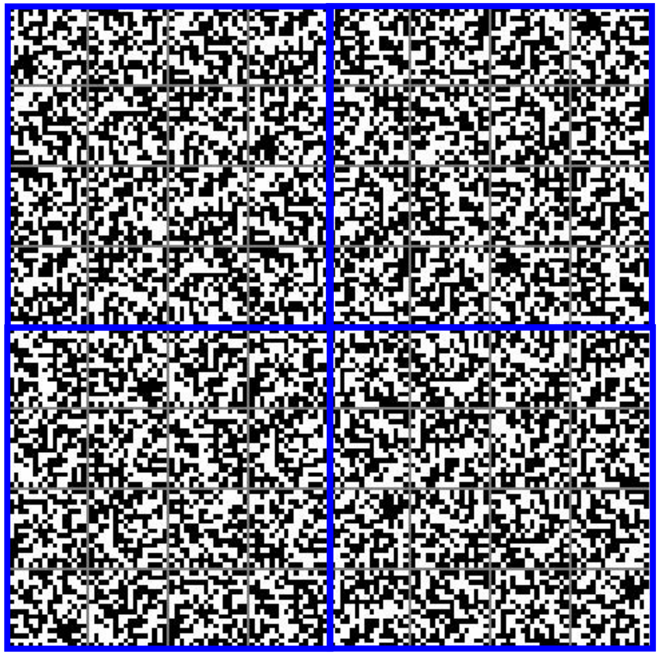


Reconstructed Sky Image (S')

Coded Mask Patterns

- Random pattern → simplest mask, ~50 % open fraction, slideloabs
- Uniformly Redundant Array (URA) → flat slidelobes, ghosts, varying open fraction





CZTI Coded Mask

- CZTI employs 16 x 16 URA variant → One for each detector module
- 7 different URA patterns are to make mask pattern for one quadrant.
- The same pattern is used for other quadrants with 90 deg. Rotation.
- Different methods of image reconstruction → FFT, cross correlation, back projection, Bayesian → CZTI Pipeline uses FFT

Spectroscopy with Coded Mask

Mask-weighting

- Data dominated by background events
- Simultaneous measurement of background from masked pixels
- Mask weighting technique for background subtracted source spectrum

Mask-weighted spectrum:
Background subtracted source spectrum per fully illuminated unit area on the detector plane (similar to Swift BAT)

$$f_i = \text{Mask open fraction of pixel } i$$
$$a_i = \text{Effective area including QE of pixel } i$$
$$B_i = \text{Relative background level of pixel } i$$
$$C_i = \text{Count in pixel } i$$

$$w_i{}' = 2f_i - 1$$

D → Renormalization factor

$$D = \sum_i w_i{}' a_i B_i / \sum_i a_i B_i$$

N → *Area rescaling for a given* pointing

$$w_i = w_i{}' - D$$

$$Flux = \sum_i w_i C_i / N$$

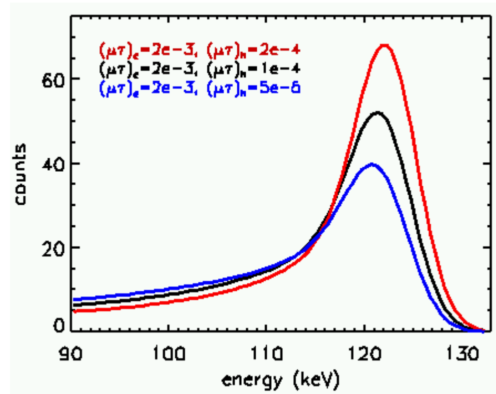
Recalculated when pointing offset changes by a fixed value (3')

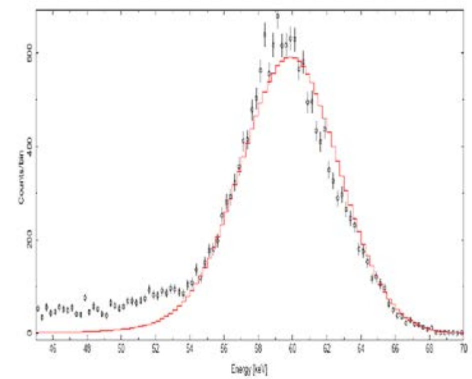
→To account for S/C jitter

$$N = \sum_i f_i a_i B_i \ [2 \sum_i f_i{}^2 a_i B_i / \sum_i f_i a_i B_i - (1 + D)]$$

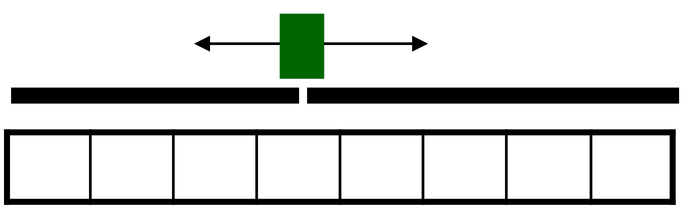
CZT Detector Response

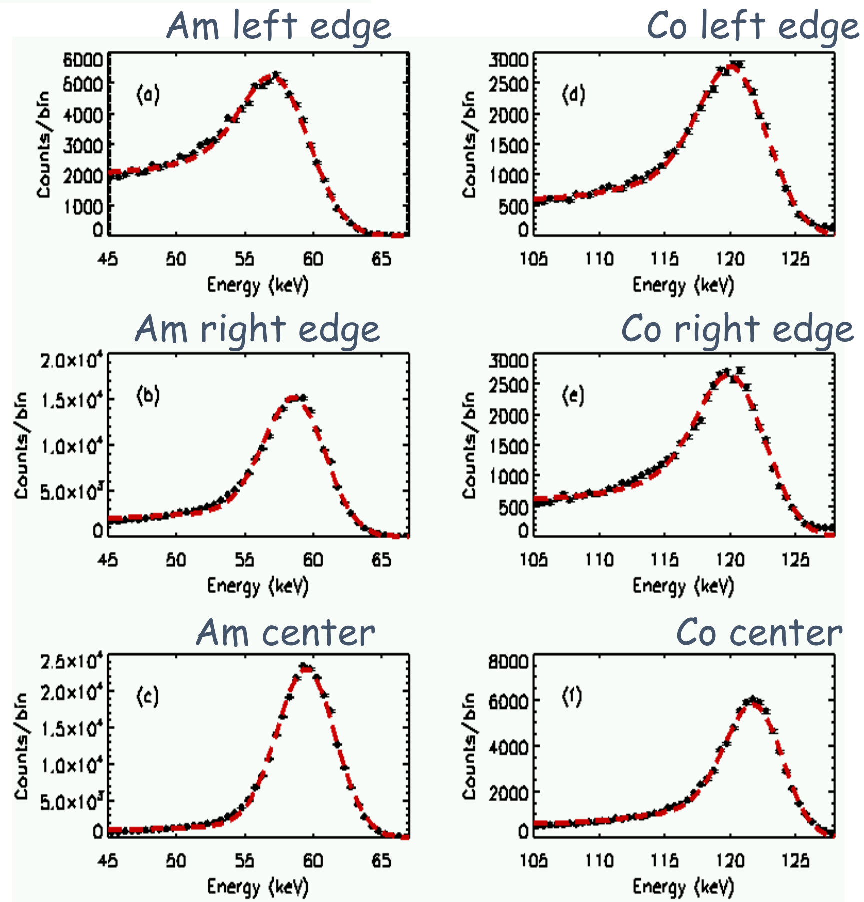
- CZTI line profile is not Gaussian
- Standard Hecht equation based model
  - under predicts tail at low energies for multi-pixel crystals
- Essential to consider charge sharing across pixels





New CZTI Line model validation

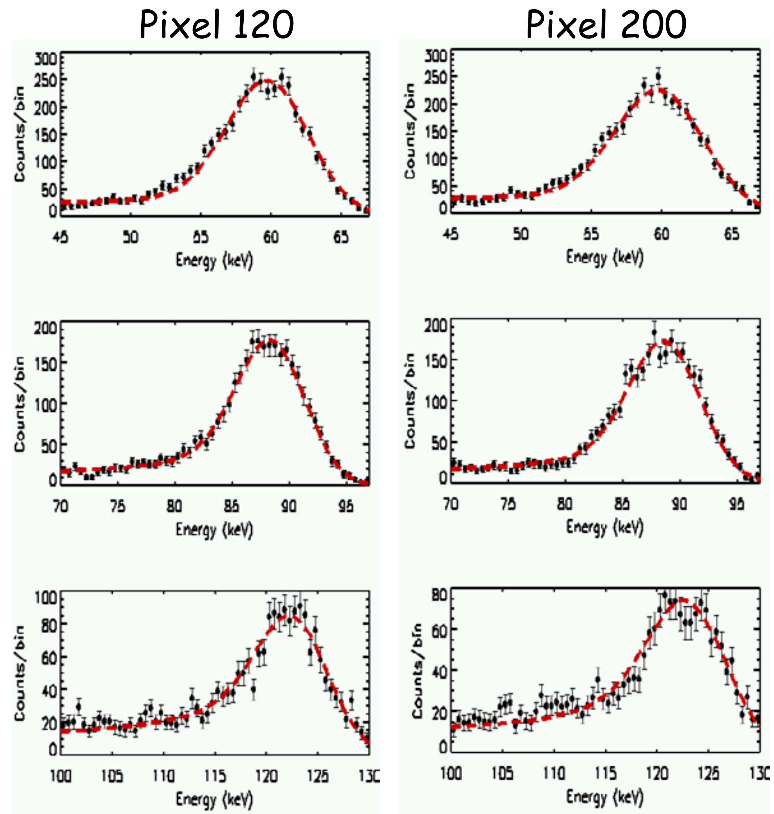




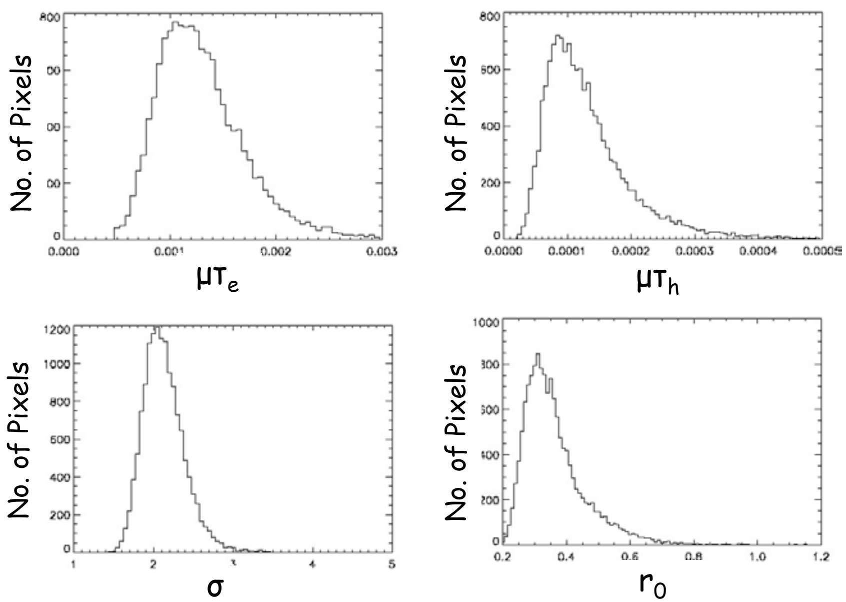
- Slide a 100 μm slit across pixels with accuracy of 50 μm
- Simultaneous fit of spectra at edges and center at two energies

CZTI Response Matrix

- ➢ Model implemented in ISIS
- ▪ Simultaneous fit to spectra at three energies for all pixels at five temp.
- ➢ Total ~80000 spectral fits Using PRL Vikram-100 HPC cluster
- ➢ Proper Fitting ~90% of the pixels to obtain model parameters
- ▪ Rest flagged spectroscopicallly bad



Key parameter for all pixels



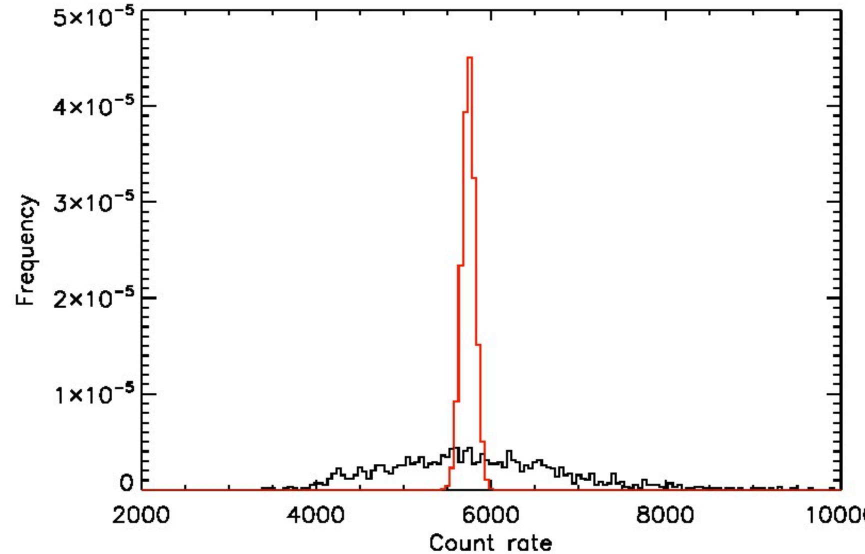
- ➢ Group similar pixels
  - ▪ Compute redistribution matrix for each group
- ➢ All parameters and matrices stored in CALDB
- ➢ Final multi-pixel response matrix ➔ Weighted addition

CZTI In-flight observations

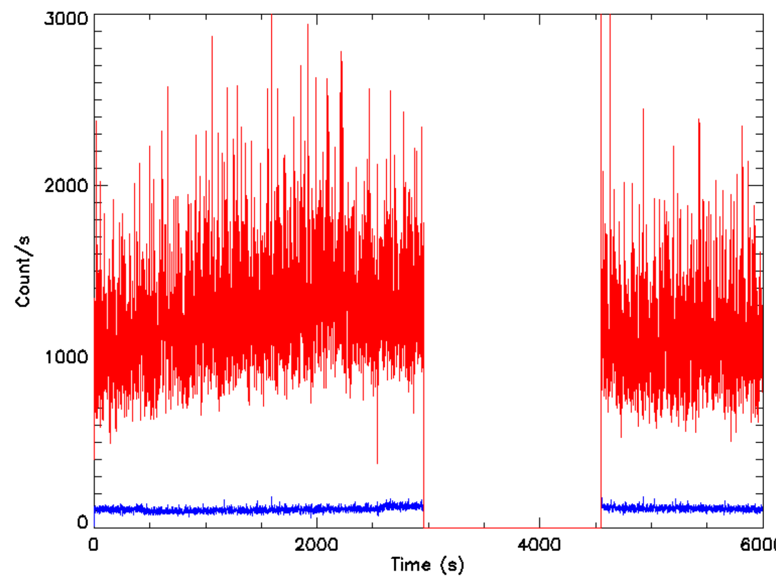
CZTI In-flight 'Observations'

'Bunch' Events

- ➢ First observations showed ~10 times higher count rate
- ➢ Variance is not Poissonian
- ▪ All events are not "independant", both temporally and spatially
- ▪ There are "bunch" of events (shower events) produced by single high energy particle event



- ➢ Similar effect in other missions → Integral (PICsIT)
- ➢ Possible to identify by clever algorithm



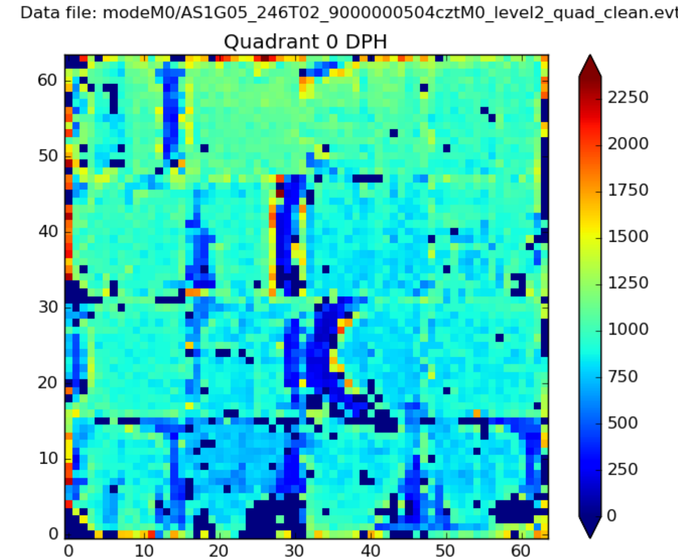
➔ Advantage of having time tagged event information unlike earlier experiments (RT-2/Chronos-Photon, HEX/Ch-1)!!

Onboard bunch cleaning from Feb 16 by a firmware patch

CZTI In-flight 'Observations'

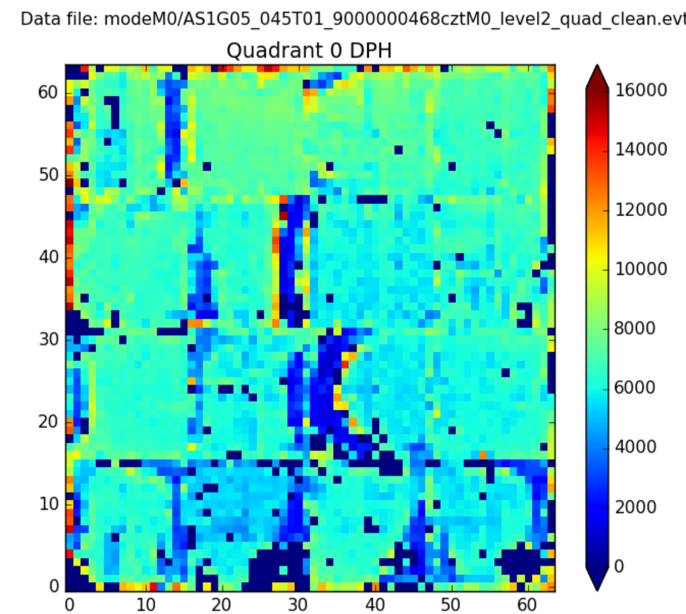
Anomalous pixels

- A fraction of pixels have anomalously low count rates since first day
- Tantalum lines and 60 keV line are not seen in the same pixels
- Gain of those pixels changed drastically–threshold ~70 keV !!
- ~20% of pixels ➔ flagged as spectroscopically bad in CALDB



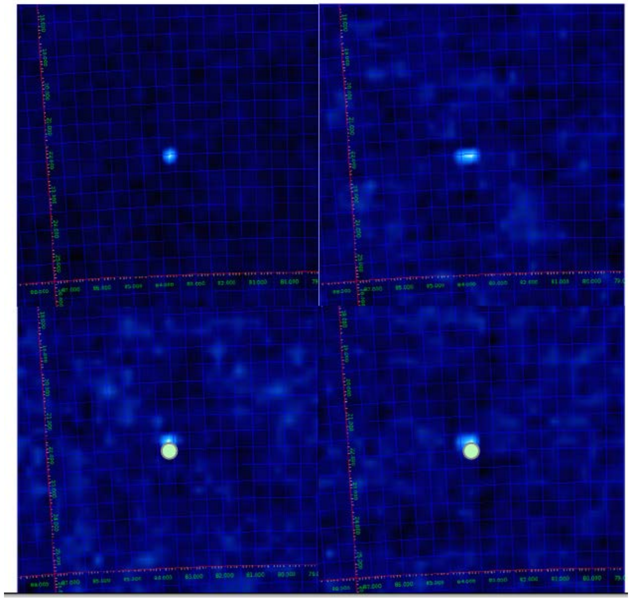
Background non-uniformity

- Background not expected to be uniform by design
- Knowledge of this non-uniformity important for effective background subtraction
- Multiple blank sky observations used to derive the fixed patterns of background in the detector plane



CZTI In-flight 'Observations'

Different images in all of quadrants



Indicates mask shifts or quadrant tilts

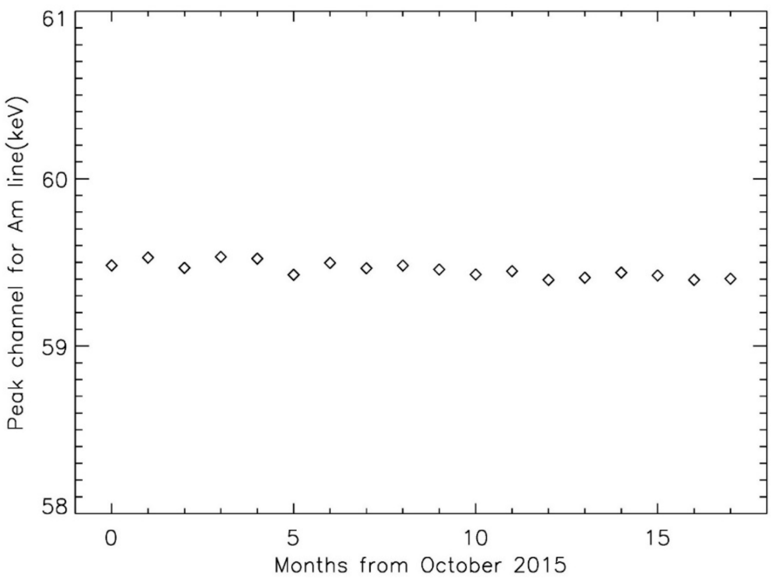
- Imaging by cross-correlation of different crab observations
- Module level imaging to identify the image shifts – measure boresight
- Consistent results across multiple observations
- Account for flux discrepancy

Quadrant	Shift in TX (deg)	Shift in TY (deg)
Q0	0.015	-0.025
Q1	-0.125	-0.025
Q2	-0.08	0.205
Q3	0.035	0.215

CZTI In-flight 'Observations'

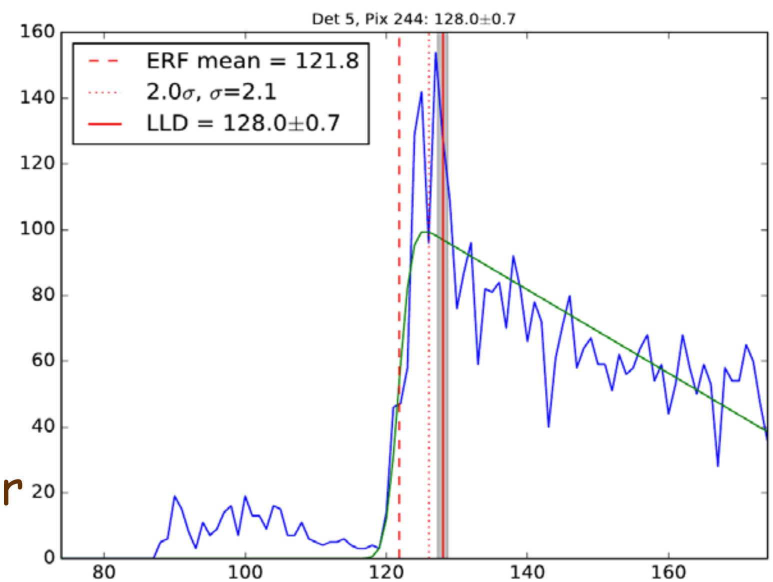
In-flight gain calibration

- Alpha-tag source → Am-241 source encapsulated in CsI crystal
- Spectrum of 59.6 keV line using alpha tagged events
- Background spectrum has Ta K-alpha and K-beta peaks
- Three lines for in-flight calibration
- Pixel gain measurement



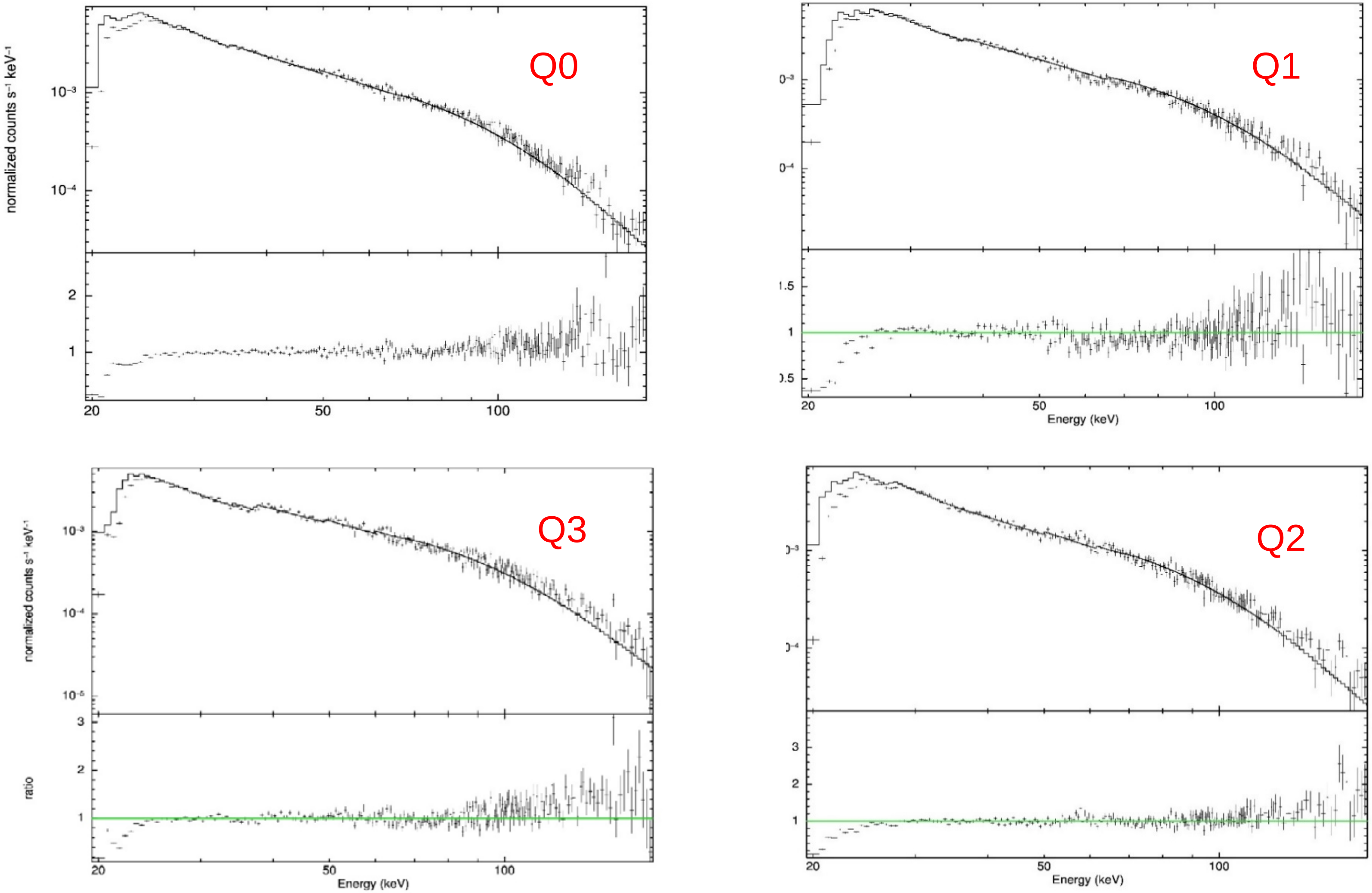
Low energy threshold (LLD)

- Each of the detector module has a configurable LLD
- Pixel to pixel gain vairiations will make actual LLDs in PI space for each pixel different
- Pixel wise LLD measurement required for response → automated measurements



All parameters stored in CALDB → Standard HEASARC Caldb file structure

Crab spectrum: All Quadrants



Cross calibration with NuSTAR

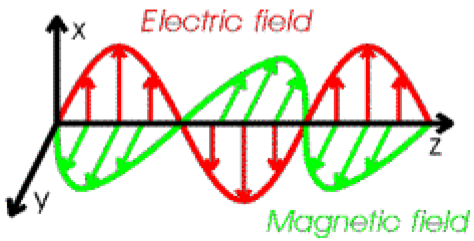
- PI: 2.09+- 0.0015; Norm (FPMA) – 7.97455+- 0.025
- CZTI Q0 norm – 0.87 * NuSTAR FPMA

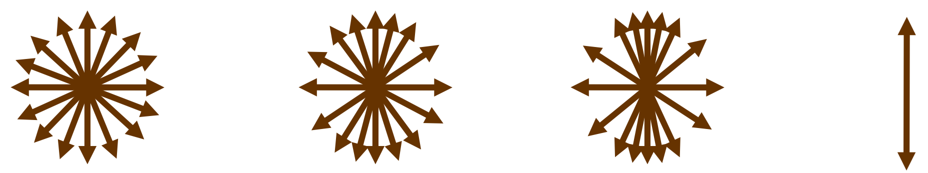
X-ray Polarimetry

Specific Details of CZTI data analysis by Shah Alam

X-ray polarimetry

- **X-ray astronomy ➔ single photon detection**
- Properties of an X-ray photons
  - Energy, position, arrival time
  - Polarization (electric field vector) direction





- Polarized X-ray beam
  - Having preferential direction of electric field vector
- X-ray polarimetry
  - Measure the degree and angle of the polarization
  - **Almost completely unexplored so far!!**
  - No dedicated experiments in last ~40 years old

Measurement techniques

- **Brag reflection**

$$2d_1 sin(\theta) = n\lambda \qquad E = \frac{nhc}{2d_1 \sin 45^o}$$

  - Very narrow energy band pass, effective < 2 keV

- **Photo-electron tracking**

$$\frac{\partial\sigma}{\partial\Omega} = r_o^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$

  - Most effective at low energies 2 – 15 keV
  - Good sensitivity if coupled with mirror

- **Scattering**

$$d\sigma = r_e^2 (1-\sin^2\theta\cos^2\varphi) d\theta d\varphi$$

$$d\sigma = \frac{r_e}{2}\left(\frac{\nu'}{\nu}\right)^2 \left(\frac{\nu}{\nu'} + \frac{\nu'}{\nu} - 2\sin^2\theta\cos^2\varphi\right) d\theta d\varphi$$

  - **Rayleigh**

    → high background, poor sensitivity, ~5 – 50 keV

  - **Compton**

    → low background, better sensitivity, Effective at >100 keV

  - Can be used with / without optics

All three techniques are applicable in different energy ranges and hence are complementary to each other

Why X-ray polarimetry

X-ray polarimetry is very powerful tool

- It opens a completely new window to the high energy universe!
- Dominated by Compact objects (un-resolvable in near future!)
- In this case, X-ray astronomy essentially deals with properties of two parameter space → time and energy
- X-ray polarimetry doubles the parameter space
  - Can uniquely probe geometry and magnetic field structure in the vicinity of the compact objects

- Astrophysical X-ray polarization can arise due to →
  - Emission processes themselves:
    - cyclotron, synchrotron, non-thermal bremmstrahlung
  - Scattering on aspherical accreting plasmas:
    - disks, blobs, columns.
  - Fundamental physics
    - GR space time curvature, Vacuum birefringence through extreme magnetic fields (LIV)

X-ray Polarimetry is Difficult

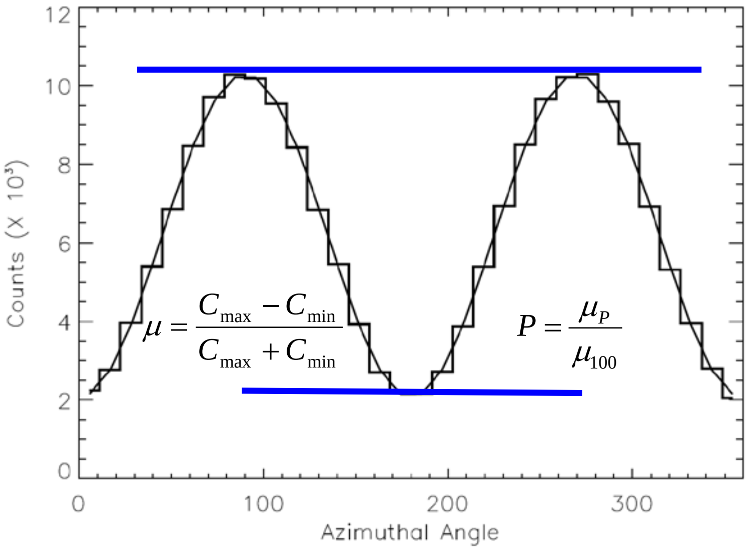
Minimum Detectable Polarization

$$MDP = \frac{4.29}{\mu_{100} R_{src}} \sqrt{\frac{(R_{src} + R_{bkg})}{T}}$$

If Background is negligible (!)

Number of photons required for -

		Detection	Measurement
Flux		10	100
Spectral slope		100	1000
Polarization	10 %	10000	100000
	3 %	100000	1000000
	1 %	1000000	10000000



- For time, energy dependent study
  - similar number of photons required per bin

- Not all sources are expected to be highly polarized
- Typical exposure times ➔ ~100 ks (~ 2 days) to ~1 Ms (~25 days)
- Extremely prone to systematic effects → Measured parameter is positive definite, even in absence of polarization

X-ray Polarimetry: Present status

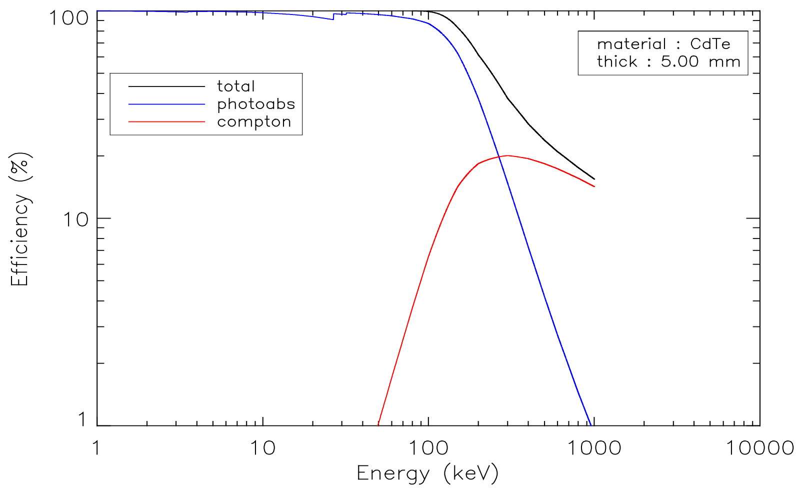
- Large number of excellent science cases
- Still almost completely unexplored in last 40 years
  - Far behind timing/imaging/spectroscopy in terms of sensitivity
- Only confirmed measurement is for Crab
- Many attempts to salvage polarization information from non-optimized instruments (RHESSI / INTEGRAL)
- Many proposals and 'concept studies'
  - GRAPE, Polarix, XTP, Pogo, Polar, PLEXAS, Castor, PheniX, X-Calibur
  - Balloon flights for GRAPE, PoGOLite, **X-Calibur**, **POGO+**
- A small GRB polarimeter is launched onboard Japanese satellite
  - Measured highly polarized emission from 3 GRBs
- Two likely missions ➔
  - Indian Polarimetry experiment (XPoSat) → by 2020
  - NASA IXPE → by 2021

Possibility of a dedicated polarimetry mission

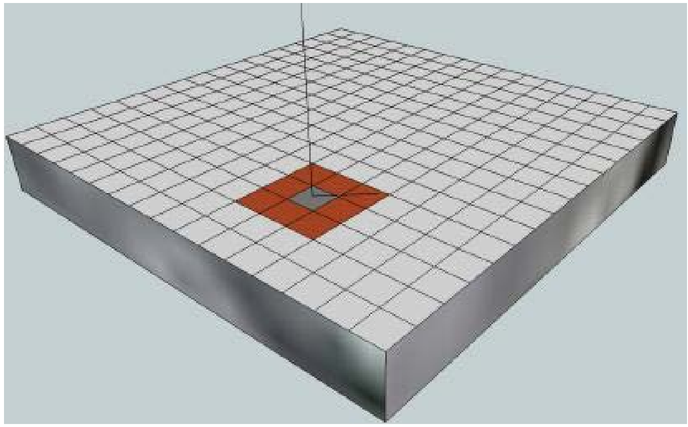
➔ But fresh measurements are still few years away, Any additional inputs are useful

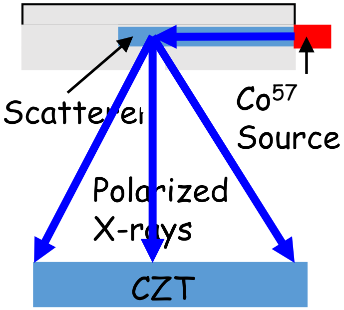
Hard X-ray polarimetry with CZTI

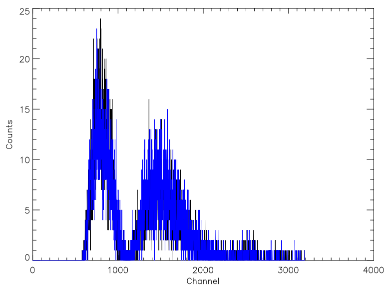
X-ray polarimetry with CZT-Imager



- Significant Compton scattering probability in 100 – 300 keV
- Pixilated detectors in principle can measure polarization
- CZTI can detect multi-pixel events
- **Can Astrosat CZTI measure X-ray polarization?**
  - Multi-pixel capability in the Orbotech CZT modules? ✓
  - Polarimetric information preserved by data processing? ✓
  - Will it have meaningful sensitivity? ✓





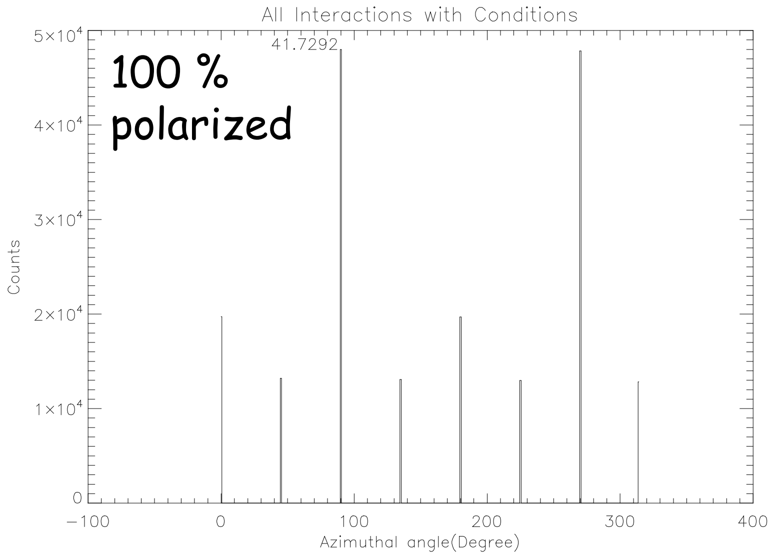


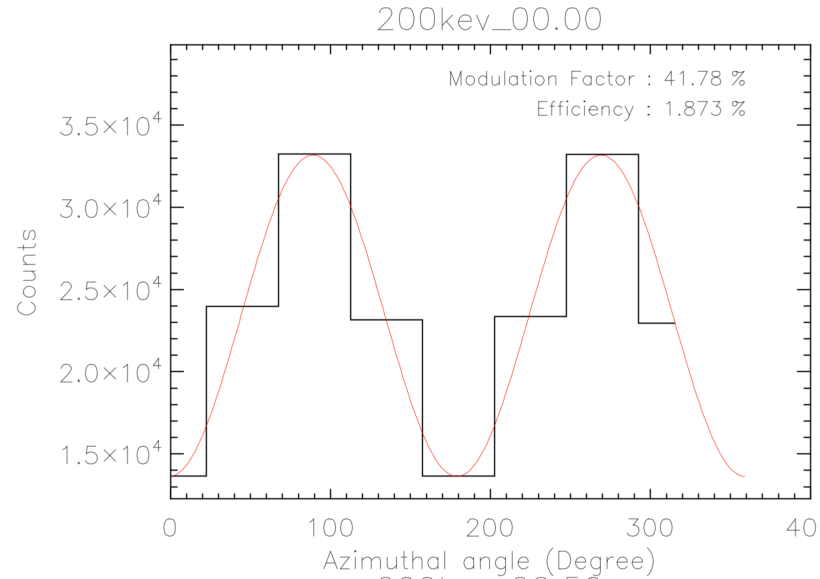
Simulations for CZTI show that 20 % to 60 % polarization for 1 Crab source can be detected in ~100 to 50 ks

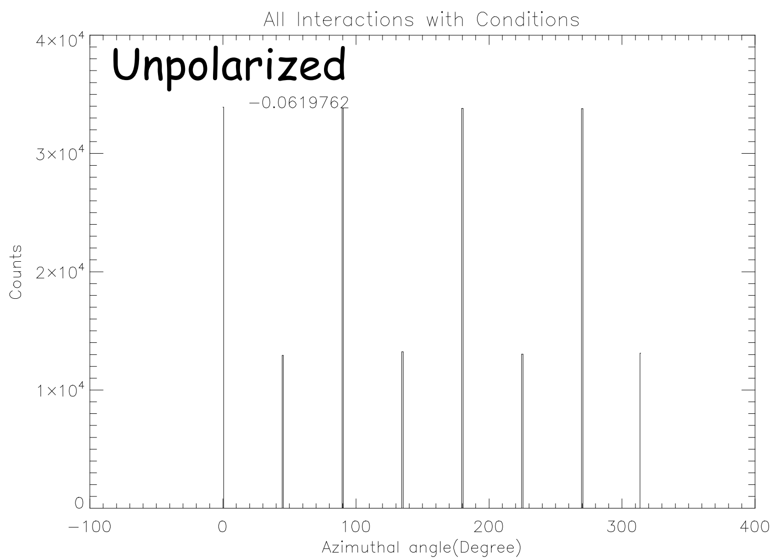
CZTI Modulation Curves

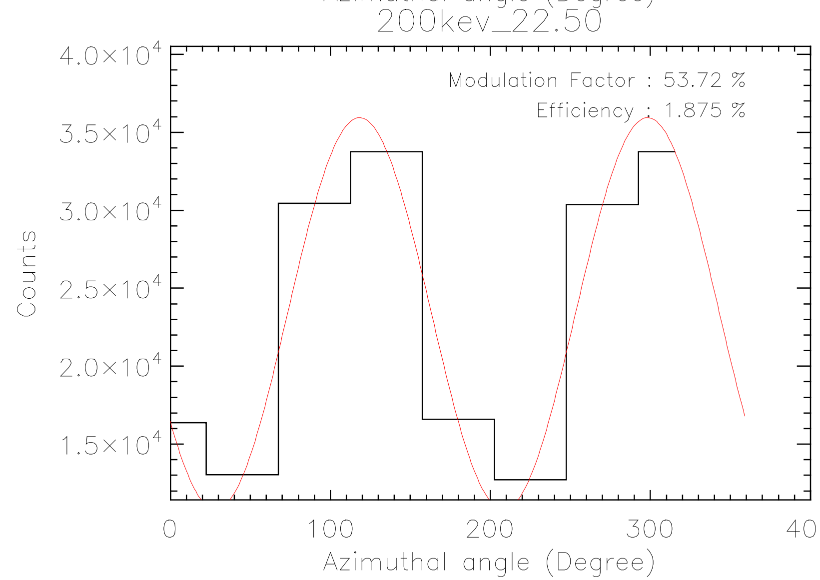
8 bin azimuthal histogram with low energy pixel as scattering pixel

2 sets of 4 equal azimuthal bins ➔ self geometry correction

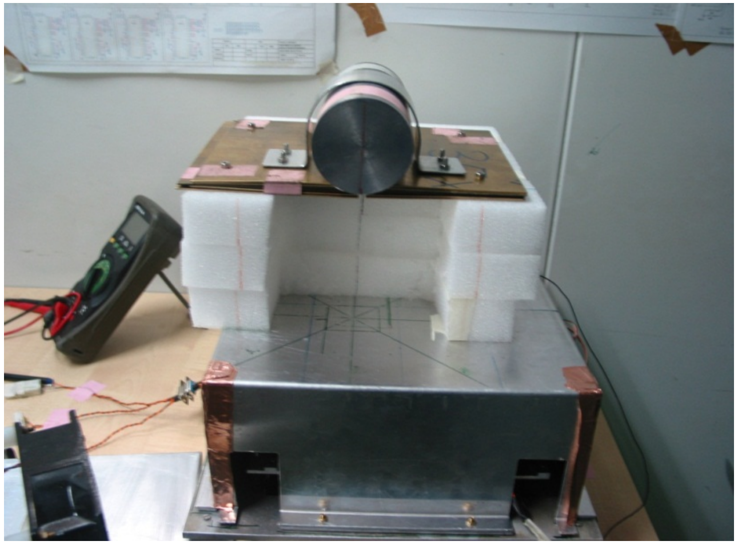


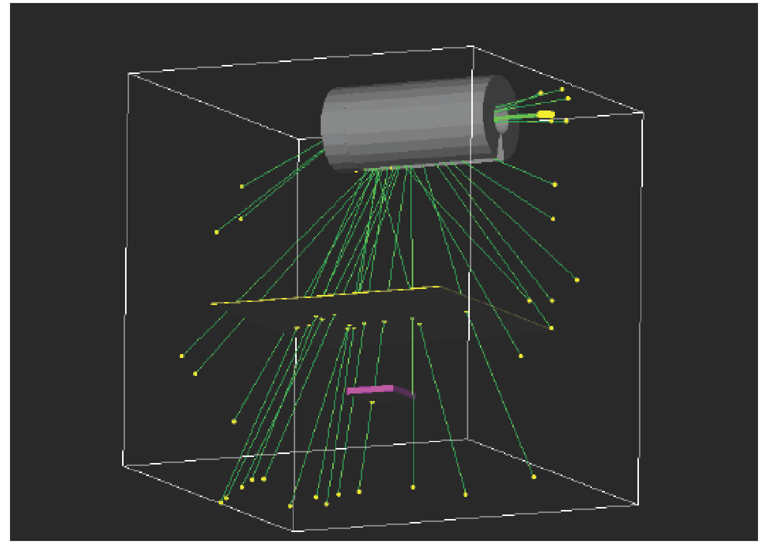






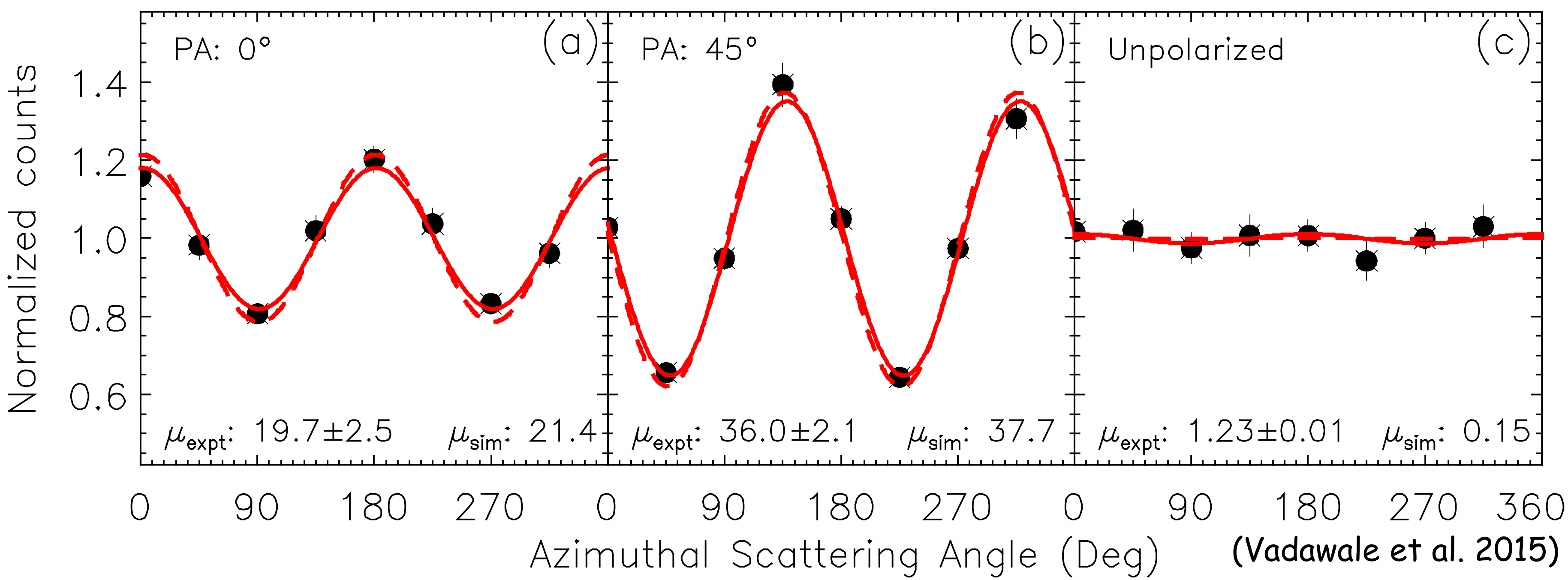
X-ray polarimetry with CZTI: Experimental Confirmation





Experimentally verified simulations

Confirmation with un-polarized X-rays

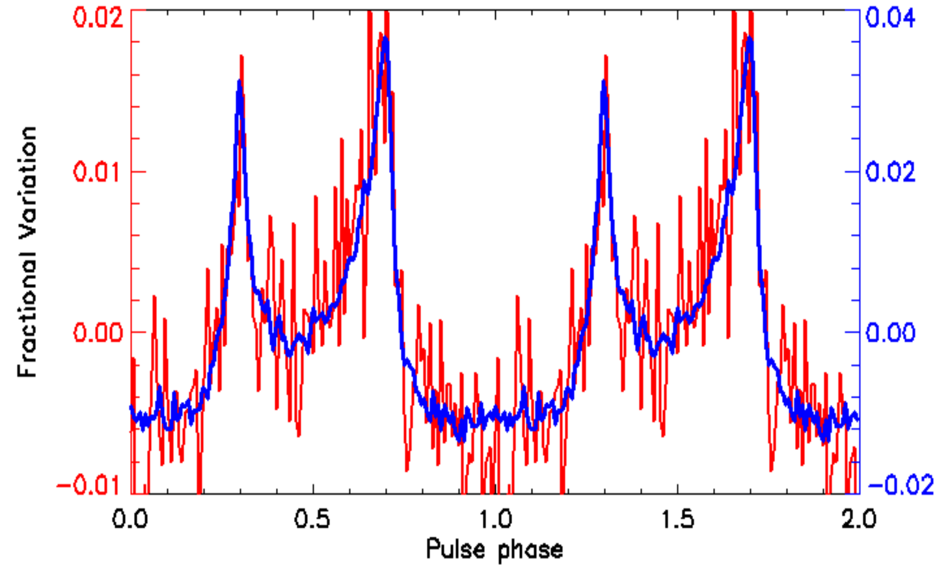


(Vadawale et al. 2015)

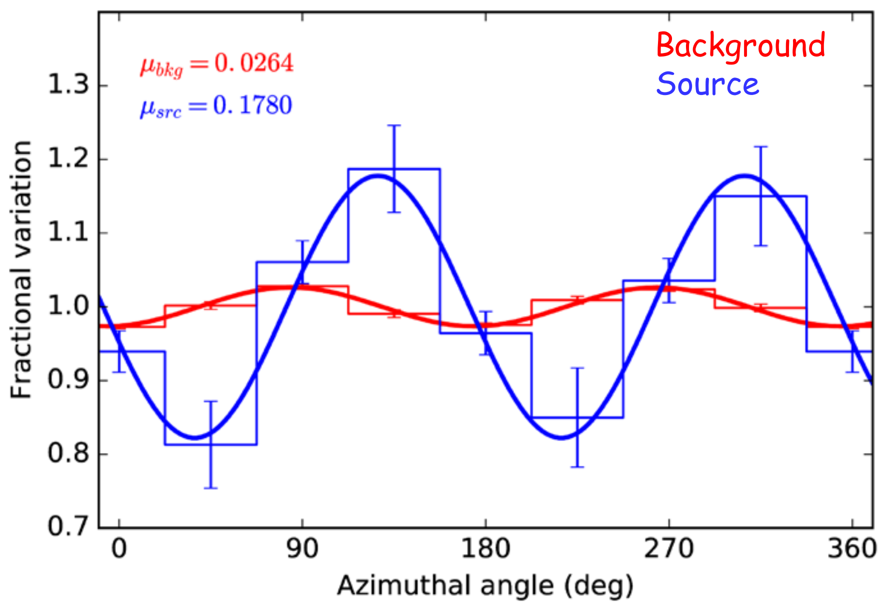
CZTI Polarization Analysis

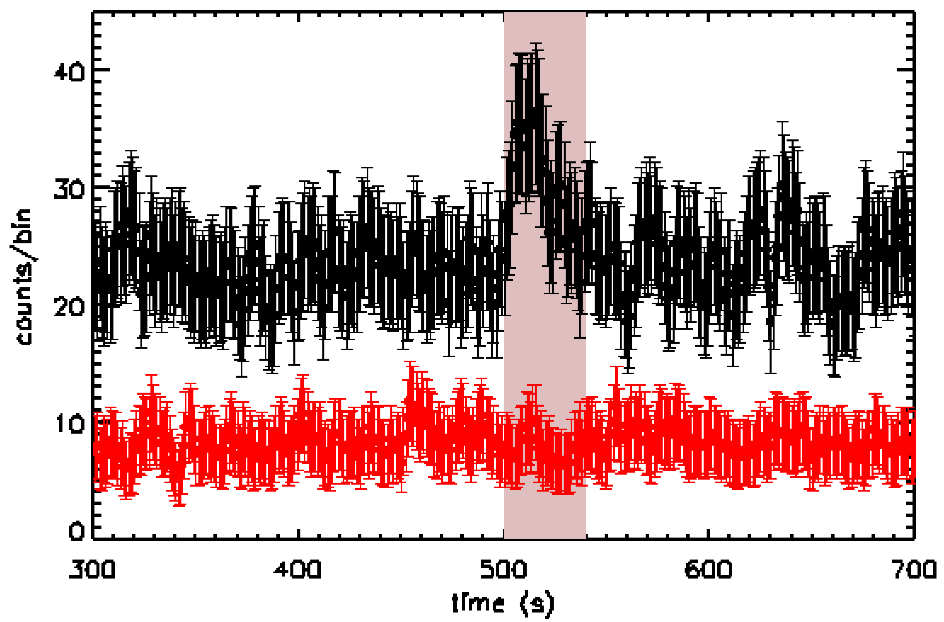
Event selection:

Adjacent double pixel events satisfying Compton criteria



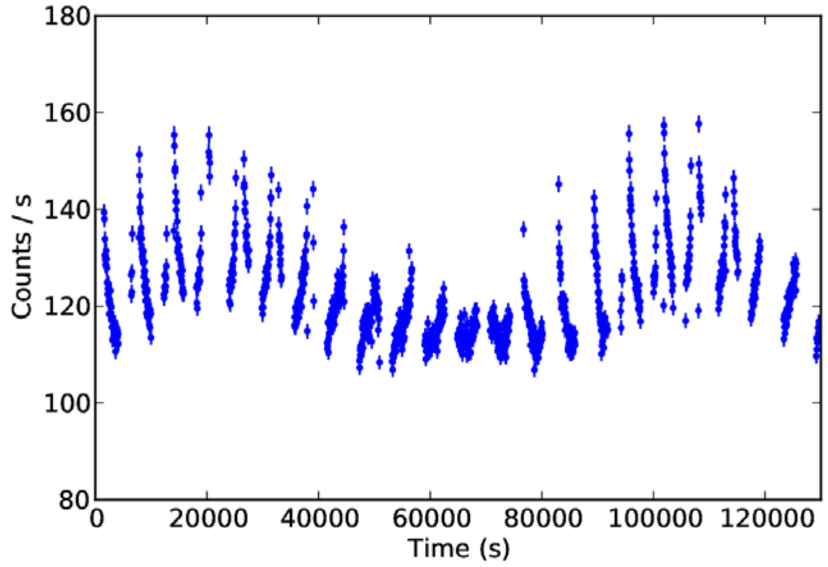
- **Validation of event selection**
  - Crab pulse profile
  - GRB Compton events light curve
  - Source vs. background modulation

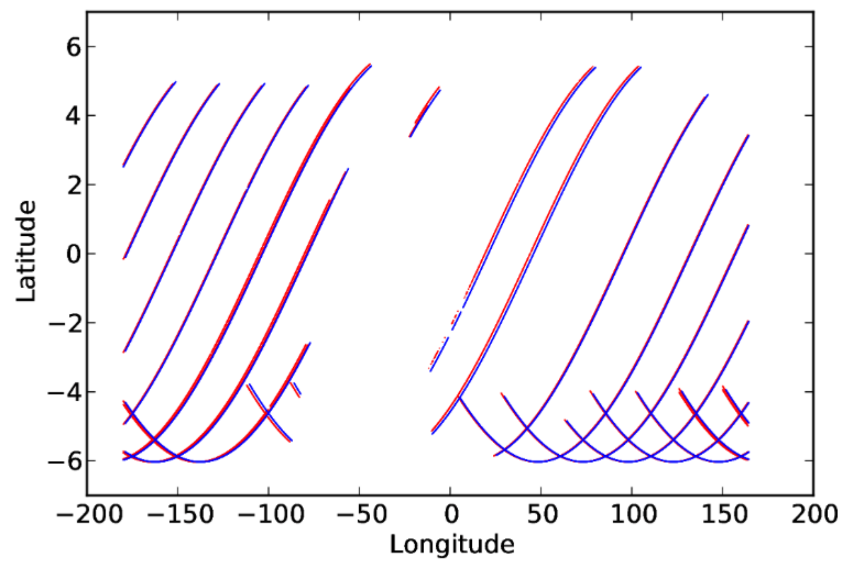




Background analysis

- Background pattern changes with DEC
- Need to select blank sky observations with same DEC as Crab
- Both Crab and Cygnus X-1 should be more then 80° away
- Small region of sky suitable for Crab background
- Background rate varies with ground track
- Selecting only similar tracks result in significant reduction in exposure
- Manually optimize back ground regions and correct for exposure
- Rate difference does not affect modulation or polarization angle
- It may only affect the polarization fraction → systematic uncertainty ~10%

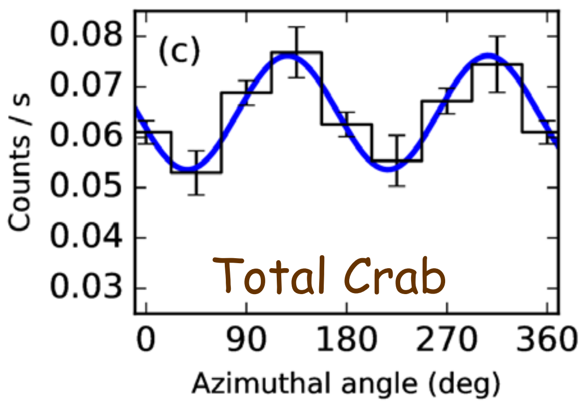


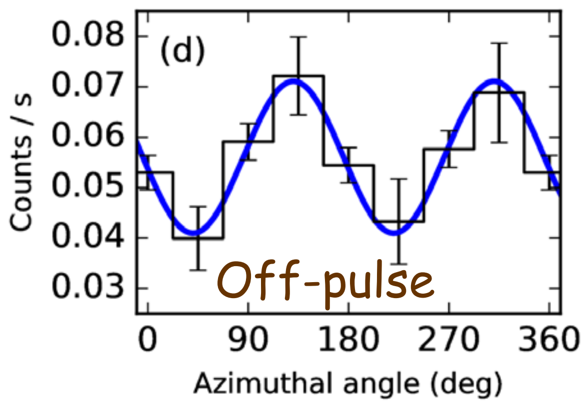


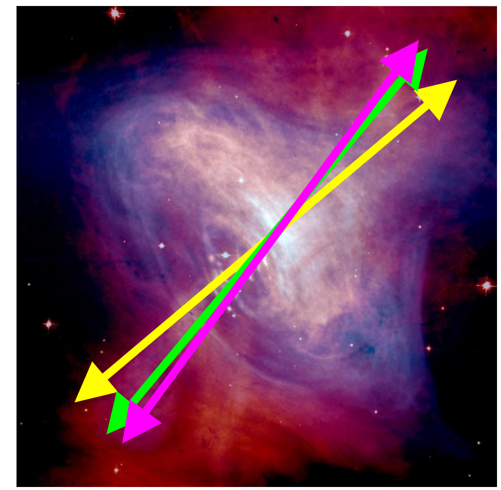
Crab Polarization

All data added → Total exposure ~800 ks

- Most sensitive measurement of hard X-ray polarization for Crab nebula and pulsar so far
- First polarization measurement in last 40 years with ground-calibrated instrument







Polarization Fraction →
33.8 % ± 5.8 %
~6σ Measurement

Polarization angle →
143.0° ± 2.8°

Polarization Fraction →
50.4 % ± 12.0 %
~4σ Measurement

Polarization Angle →
139.5° ± 3.2°

Polarization Angle

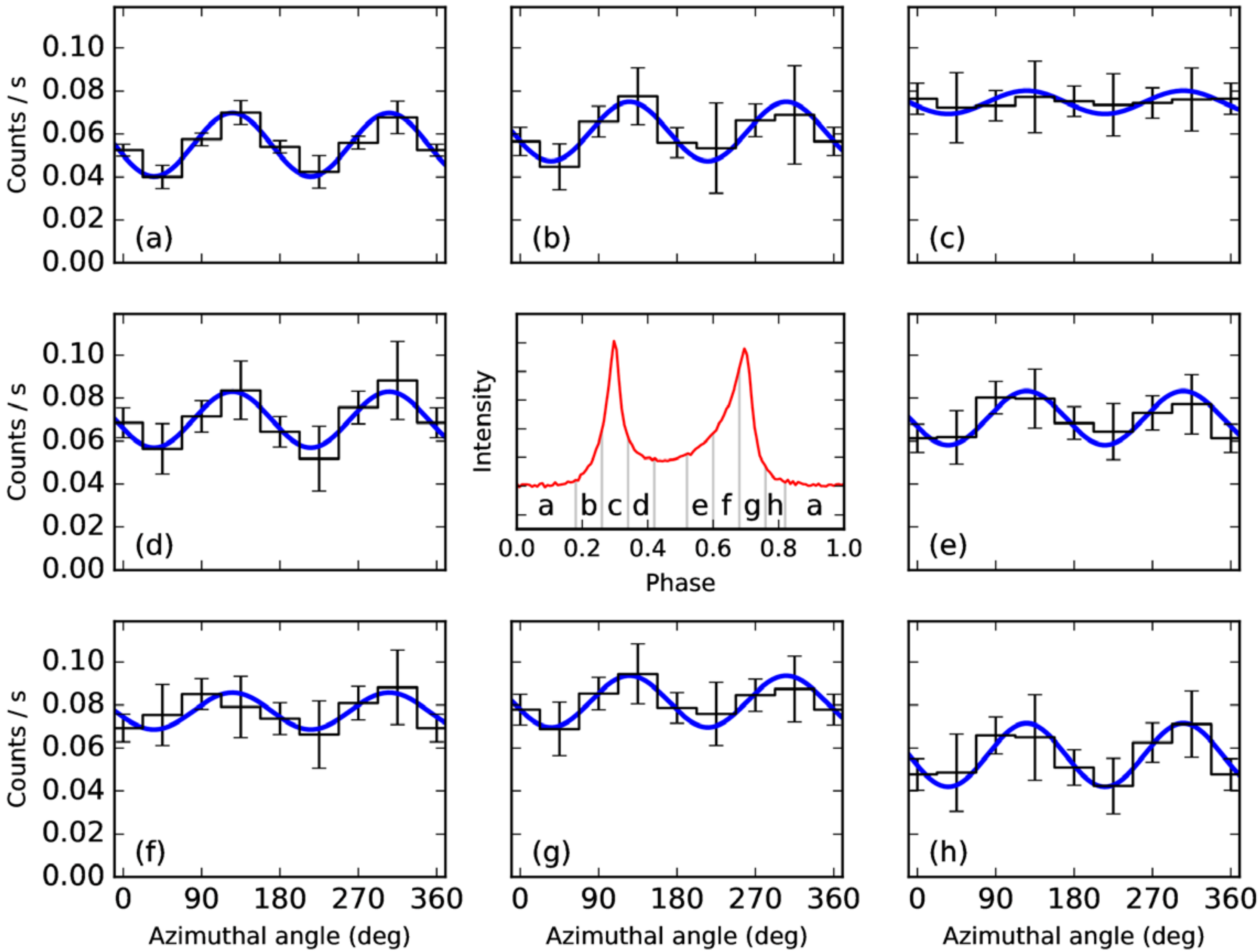
In general direction of the rotation axis

- Confirmation of earlier results with INTEGRAL satellite
- With more scrupulous measurements and analysis

Phase Resolved Polarization

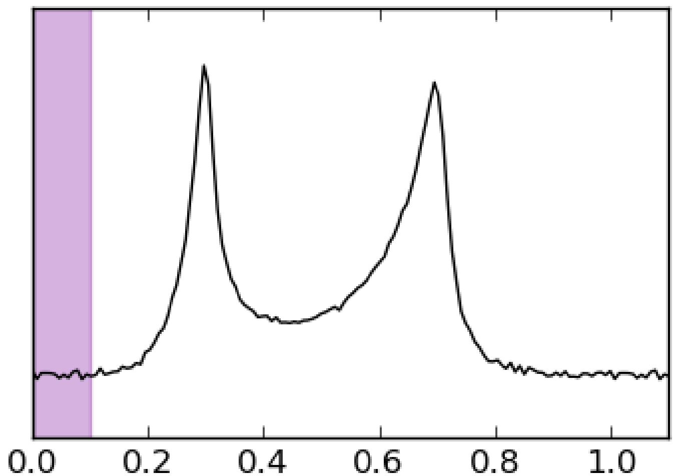
Both peaks show lower polarization as found by Integral

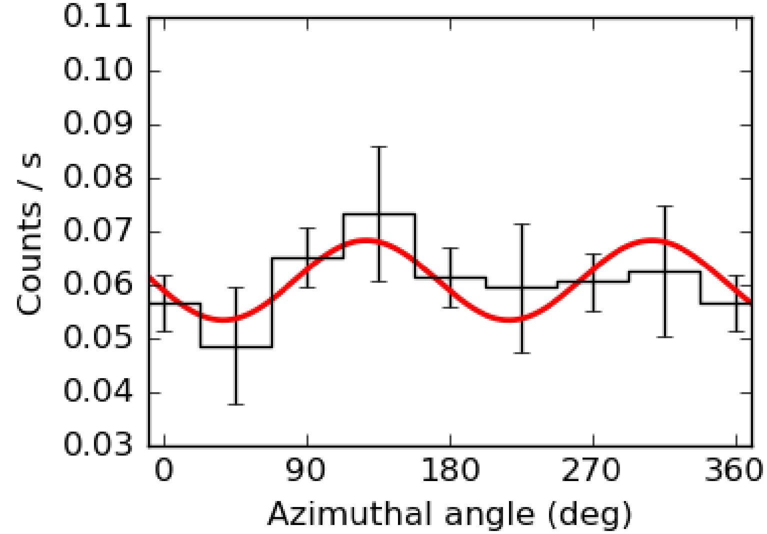
Finer phase bins show more interesting variations

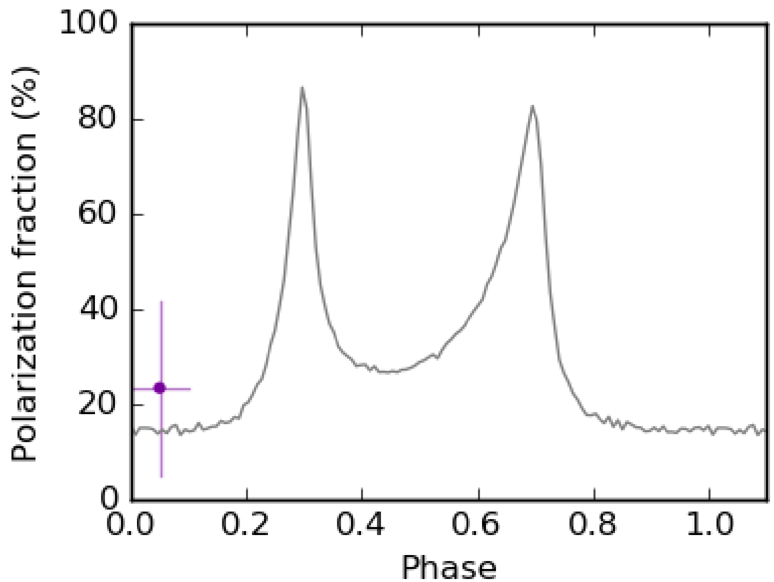


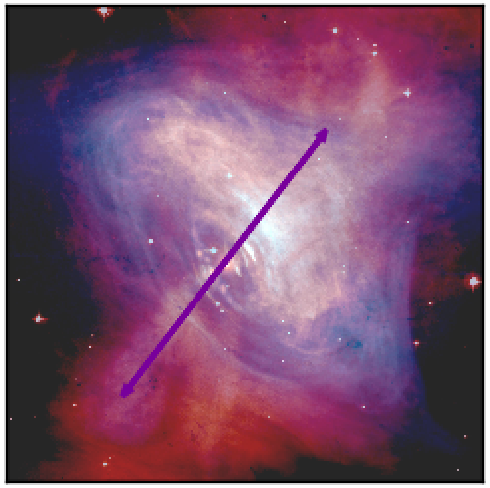
Dynamic Pulse Phase Resolved Polarization

Sliding window of with width of 0.1 phase and slide at 0.01 step



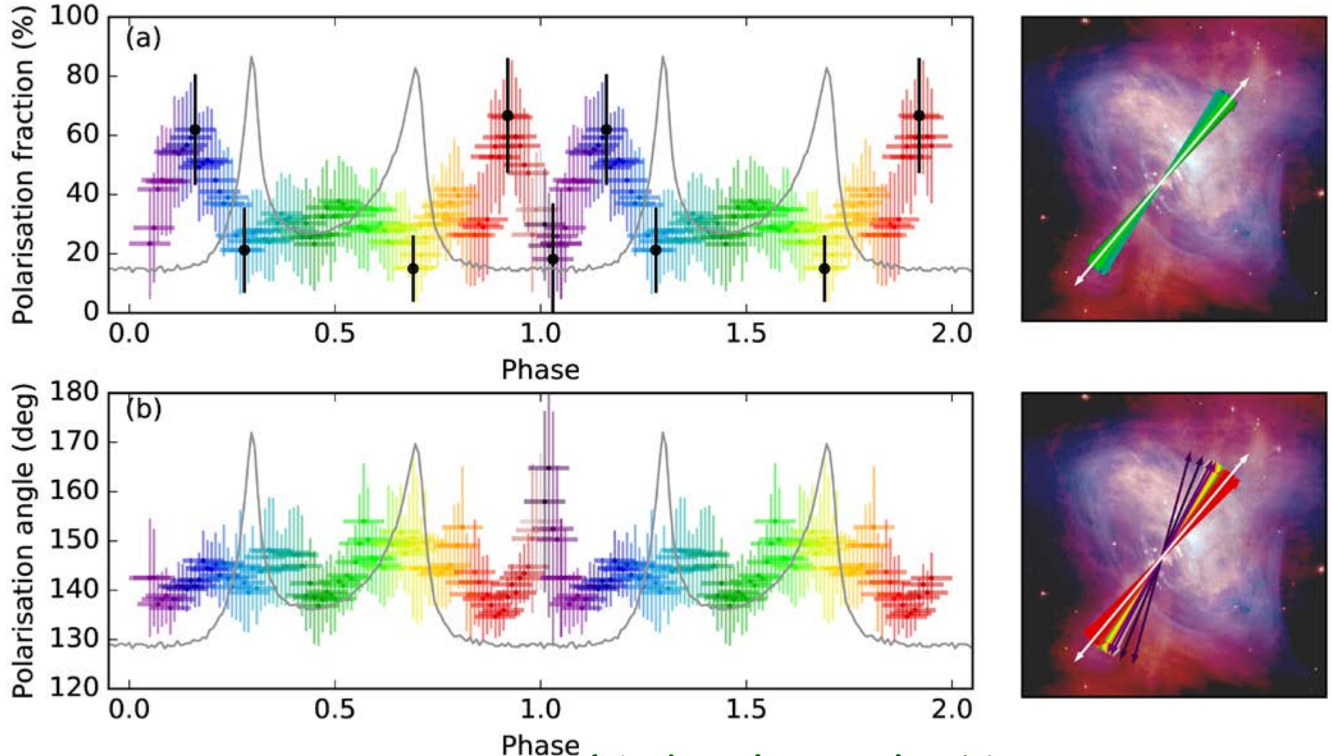






X-ray Polarization with Astrosat-CZTI

- First measurement of phase resolved polarization for Crab pulsar
- Reveal huge contribution of the pulsar during 'off-pulse' region



(Vadawale et al., Nature Astronomy, 2018)

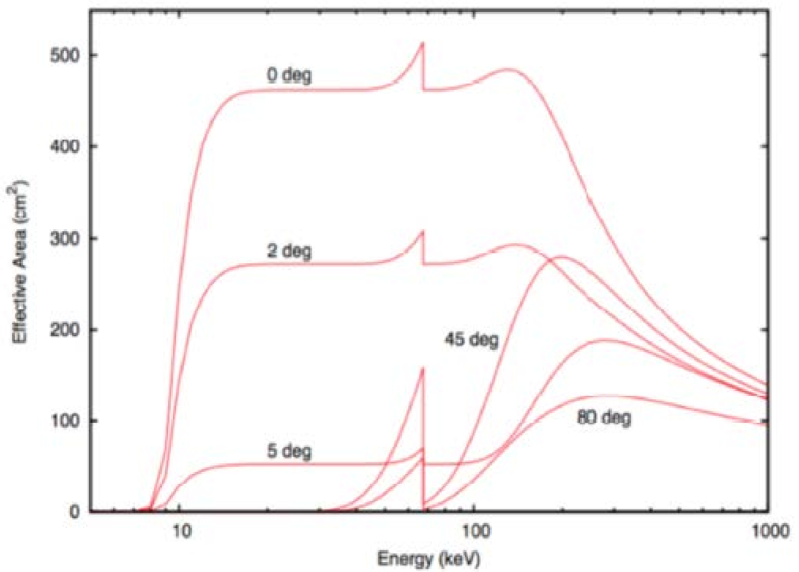
- No current pulsar emission models can explain these observations
- Usher a new paradigm in understanding of pulsar magnetosphere
- First manifestation true potential of X-ray polarimetry → so far all attempts were to measure polarization of astrophysical sources

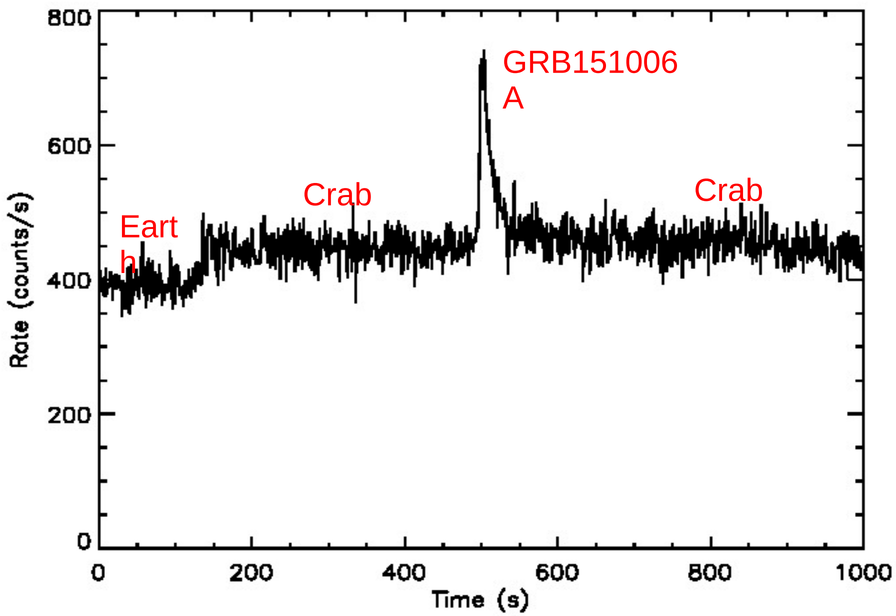
CZTI as GRB Detector

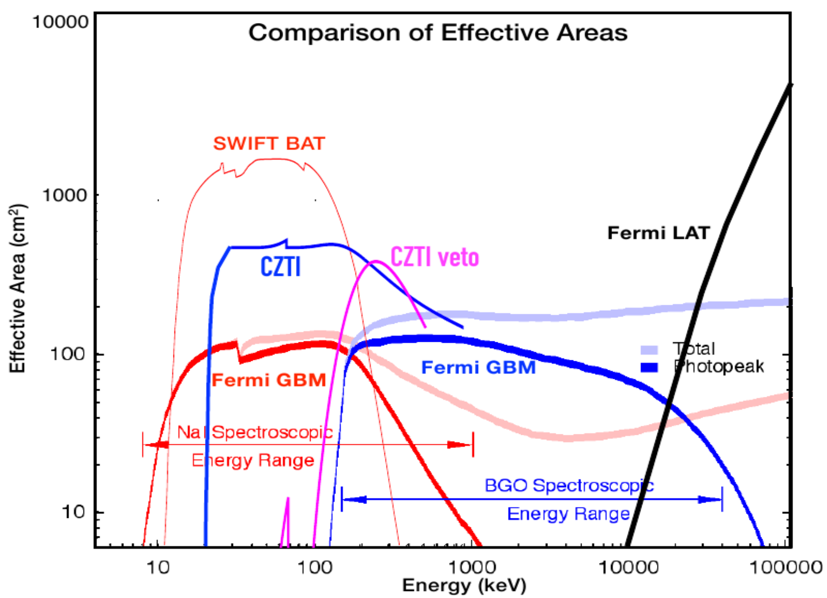
GRBs with CZTI

- CZTI mask, collimators support structure designed up to 150 keV
- CZTI has good sensitivity to GRBs in 150 to 400 keV energy range
- First GRB on first day / first observation
- More then 220 GRBs till now
- Rudimentary localization possible
  - Useful when no other option!

CZTI Effective Area

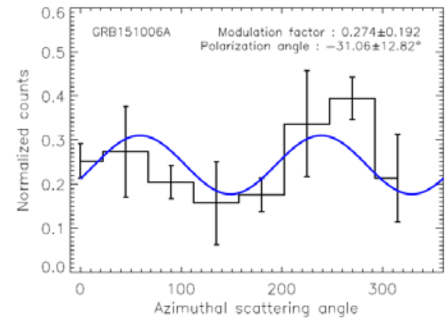


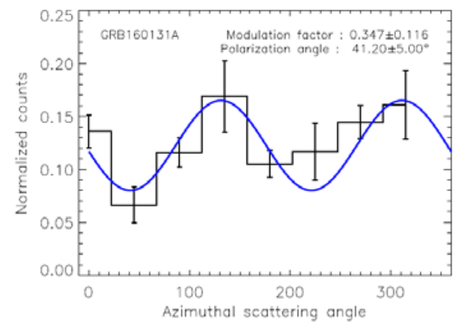


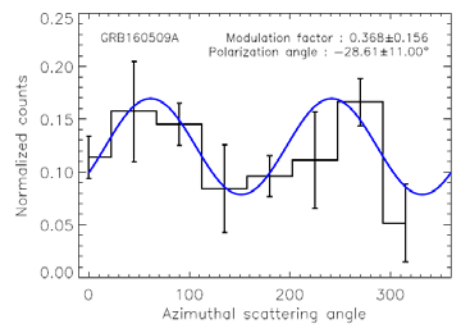


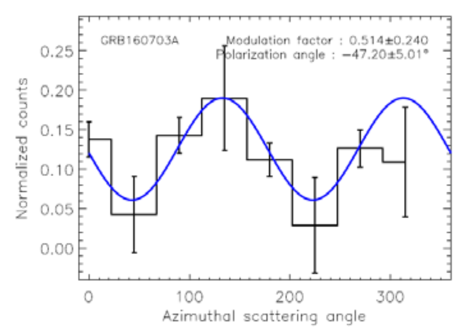
GRB Polarization

- CZTI had detected more then 50 GRBs during first year
  - 11 are suitable for polarization analysis
  - Selected based on number of Compton events (> 350)
- Modulation detection in GRB is relatively easy
  - Accurate background available pre / post GRB
  - High signal-to-noise
  - Optimize signal by ignoring shadowed regions.
- Estimation of accurate polarization fraction is difficult as GRBs are highly off-axis
  - Requires modulation curves for both 100% and completely unpolarised X-rays from the location of GRB
  - Obtained by extensive Geant4 simulations with the mass model of full spacecraft
  - Require extensive computing effort









GRB Polarization

Doubling the sample within one year

Under review in ApJ

GRB Name	Compton events	PF (%)	PA (°)
GRB 151006A	459	<79.2 ($\alpha = 0.05, \beta = 0.5$)	-
GRB 160106A	950	68.5±24	-22.5±12.0°
GRB 160131A	724	94±31	41.2±5.0°
GRB 160325A	835	58.75±23.5	10.9±17.0°
GRB 160509A	460	96±40	-28.6±11.0°
GRB 160607A	447	<75 ($\alpha = 0.05, \beta = 0.5$)	-
GRB 160623A	1400	<46.4 ($\alpha = 0.05, \beta = 0.5$)	-
		<57.1 ($\alpha = 0.01, \beta = 0.5$)	
GRB 160703A	448	<54.5 ($\alpha = 0.05, \beta = 0.5$)	-
		<68.1 ($\alpha = 0.01, \beta = 0.5$)	-
GRB 160802A	901	85±29	-36.1±4.6°
GRB 160821A	2549	48.7±14.6	-34.0±5.0°
GRB 160910A	832	93.7±30.92	43.5±4.0°

Fluence(erg/cm^2)	T90 (Sec)	Peak energy (keV)
1.15E-5	203.9	227
4.526E-5	39.43	205
3.26E-4	325	1152
1.91E-5	64.9	235
2.90E-4	33.4	288
4.12E-5	379.65	176
6.6E-4	90.46	562
2.7E-5	44.4	327
1.04E-4	16.4	284
1.0E-5	43	968
8.41E-5	24.3	347

More measurements expected at the same rate ➔ ~50 GRBs in years

- ~20 more GRBs in last two years suitable for polarization analysis
- Heavy dependence on Geant4 simulations
  - Independent experimental validation with CZTI QM in progress
- Validation of Mass model is critical → for both polarmetry and localization
  - Under progress… to be published soon.

CZTI for EM-GW follow-up

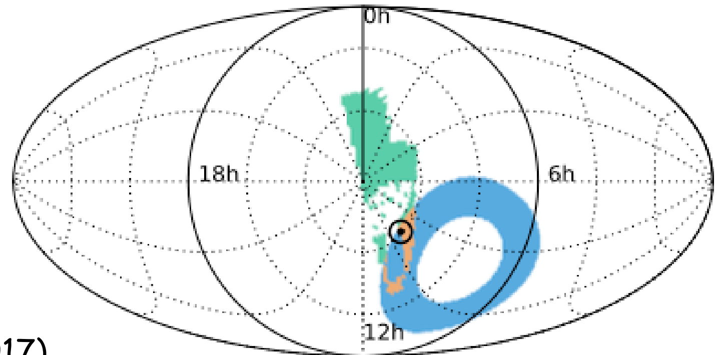
Contributed to EM counterpart studies for at least two GW sources

- GW170104 → Prevented false alarm
- GW170817 → Enhanced confidence

ATLAS17aeu→

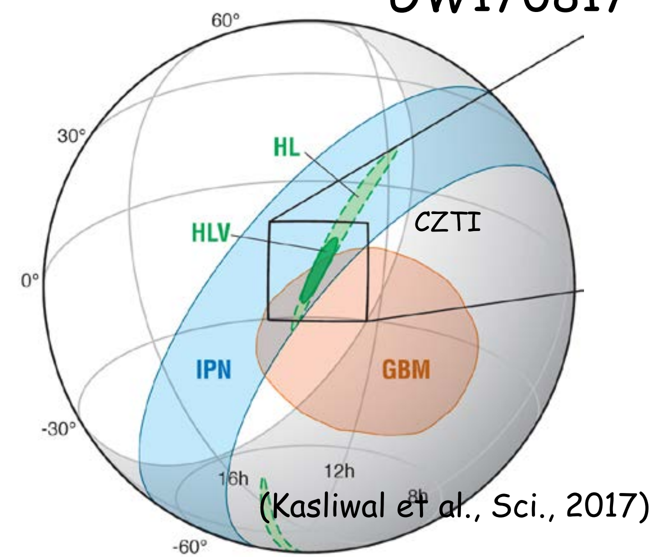
GRB170105A ✓

GW170104 ✗



(Bhalerao et al., ApJ, 2017)

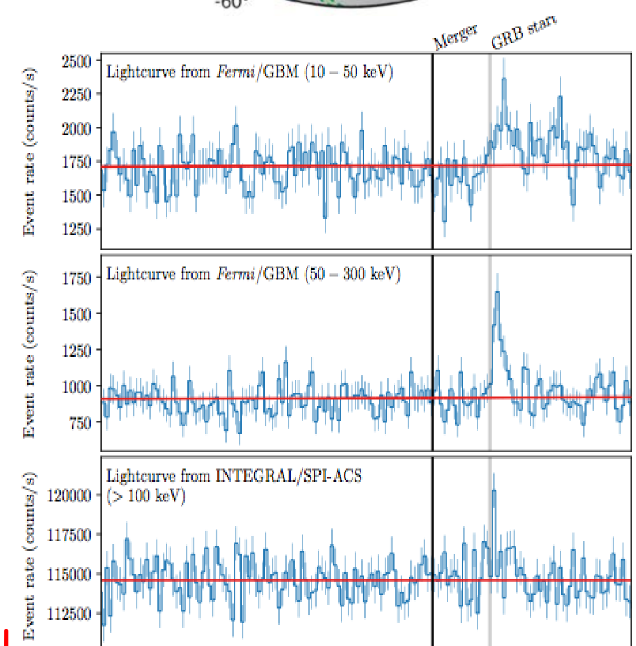
GW170817



(Kasliwal et al., Sci., 2017)

GW170817 → BNS merger

- EM-counterpart was just on the sensitivity limit of present detectors
- Daily detection of such events in GW waves expected with network of 5 GW detectors
- Most of events likely to be missed by present / planned GRB detector
  - Sensitivity in EM band lagging behind GW!!

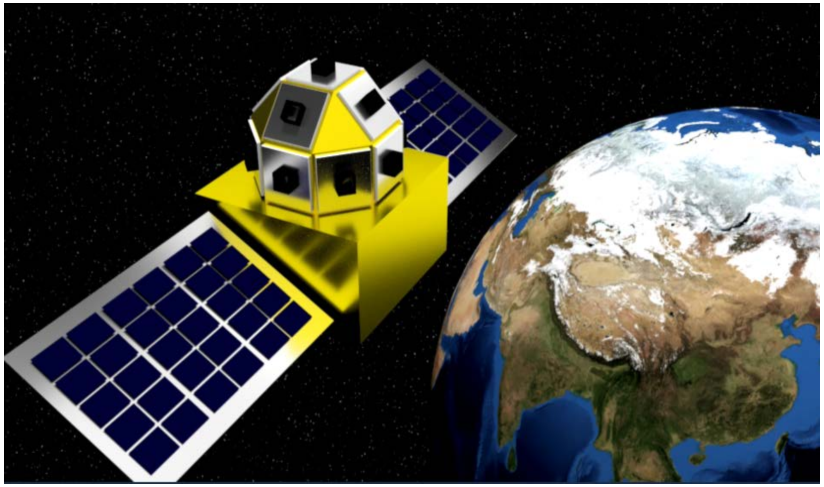


(LIGO Collaboration, ApJ, 2017)

DAKSHA – On Alert for High Energy Transients

- Small but ambitious mission on short time scale (~4 years)
- IIT-Bombay-PRL-TIFR-IUCAA joint program
  - ➔ Reviewed highly favorably by ADCOS

Scientific objectives:



- ***Detecting EM-counterparts of the Gravitational Wave sources***
- ***Wide band studies of GRB***

DAKSHA Key features:

- Order of magnitude more sensitive
- Continuous full Sky coverage (two S/C on LEO or one S/C in HEO)
- Sensitive GRB observations over wide spectral band (1 keV to 1 MeV) with three different types of detectors
  - SDD array with total effective area ~100 cm2 covering 1 – 40 keV
  - CZT detectors with effective area ~2000 cm2 covering 20 – 300 keV
  - Scintillator with eff. area of ~1600 cm2 covering 100 keV – 1 MeV

Summary

- CZTI is operating perfectly for more then three years now
  - Imaging / spectroscopy up to ~150 keV for bright sources
- CZTI is showing fantastic performance in its 'additional' capabilities
  - Proven to have good polarimetric capabilities in extended energy range of 100 – 300 keV
  - Accurate measurement of Crab hard X-ray polarization
  - First time phase resolved polarimetry of Crab
  - Interesting results on Cygnus X-1 in near future
- CZTI is also a prolific GRB detector
  - Very good GRB Polarimeter, large sample of GRBs

Thanks…