Ground and in-flight calibration of the XSPECT instrument on-board XPoSat

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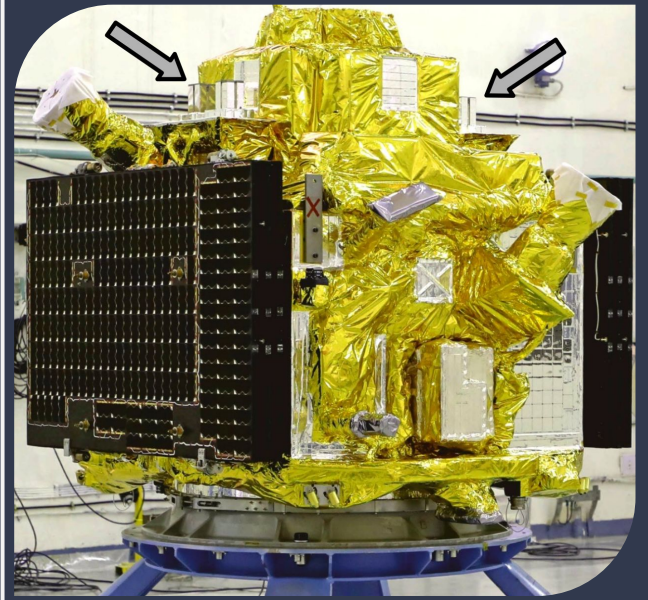

XPoSat ready for integration in launch vehicle (December 2023)

18th IACHEC Meeting, Pelham, Germany

Overview

- XPoSat and XSPECT: introduction
- Ground calibration
- On-board calibration
- Ongoing activities

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- Ground calibration
- On-board calibration
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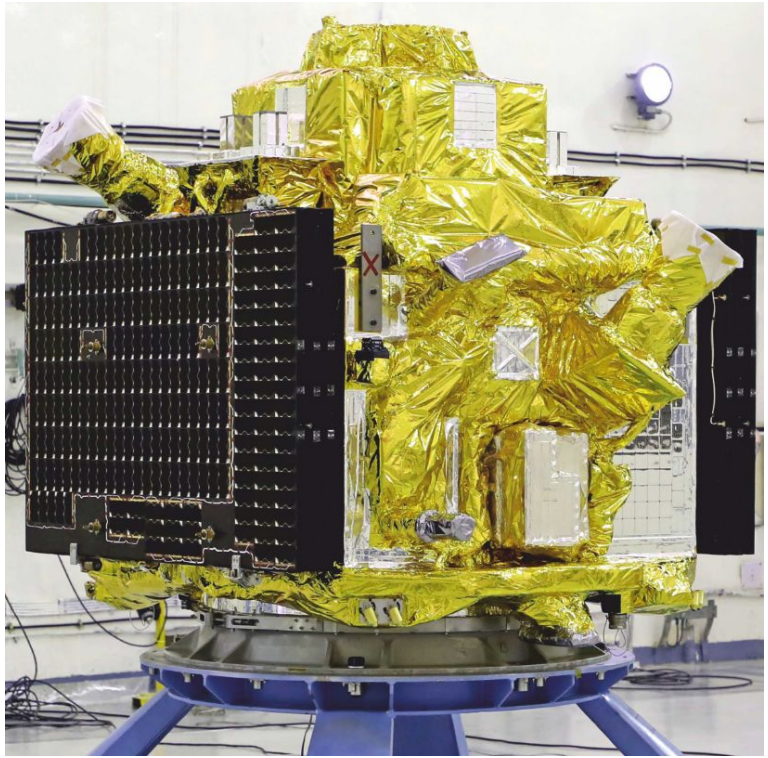
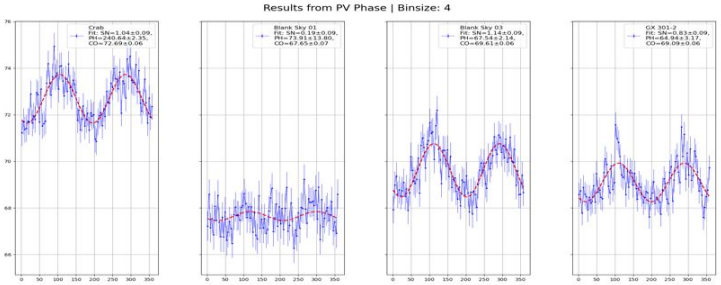
XPoSat: X-ray Polarimeter Satellite

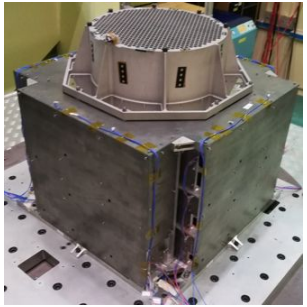


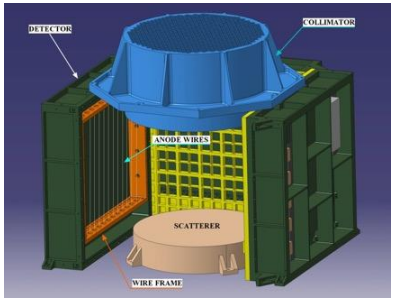
- **Launched**: Jan 1, 2024, (from Sriharikota, India)
- **Launch vehicle**: PSLV - C58
- **Orbit**: 650 km, 6 deg
- **Payloads**: Co-aligned POLIX & XSPECT
- **Long duration** observations for polarimetry
- Night side: source observation
- Day side: battery charging

Indian X-ray Polarimeter (POLIX) onboard XPoSat

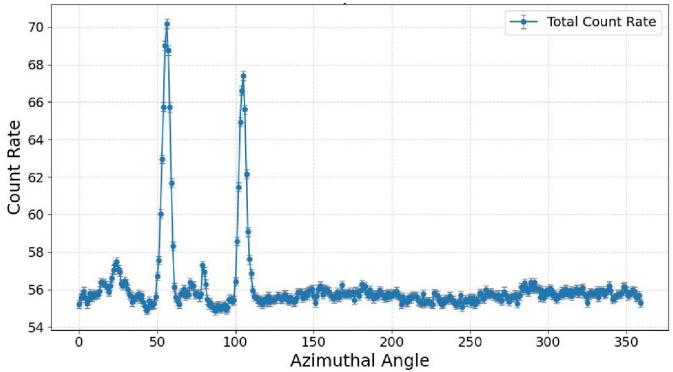


Variable background modulation do to anisotropic background radiation field

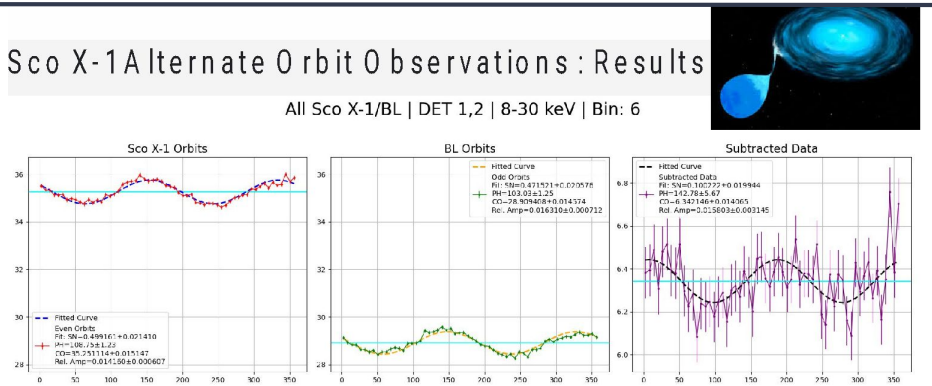




POLIX detector system



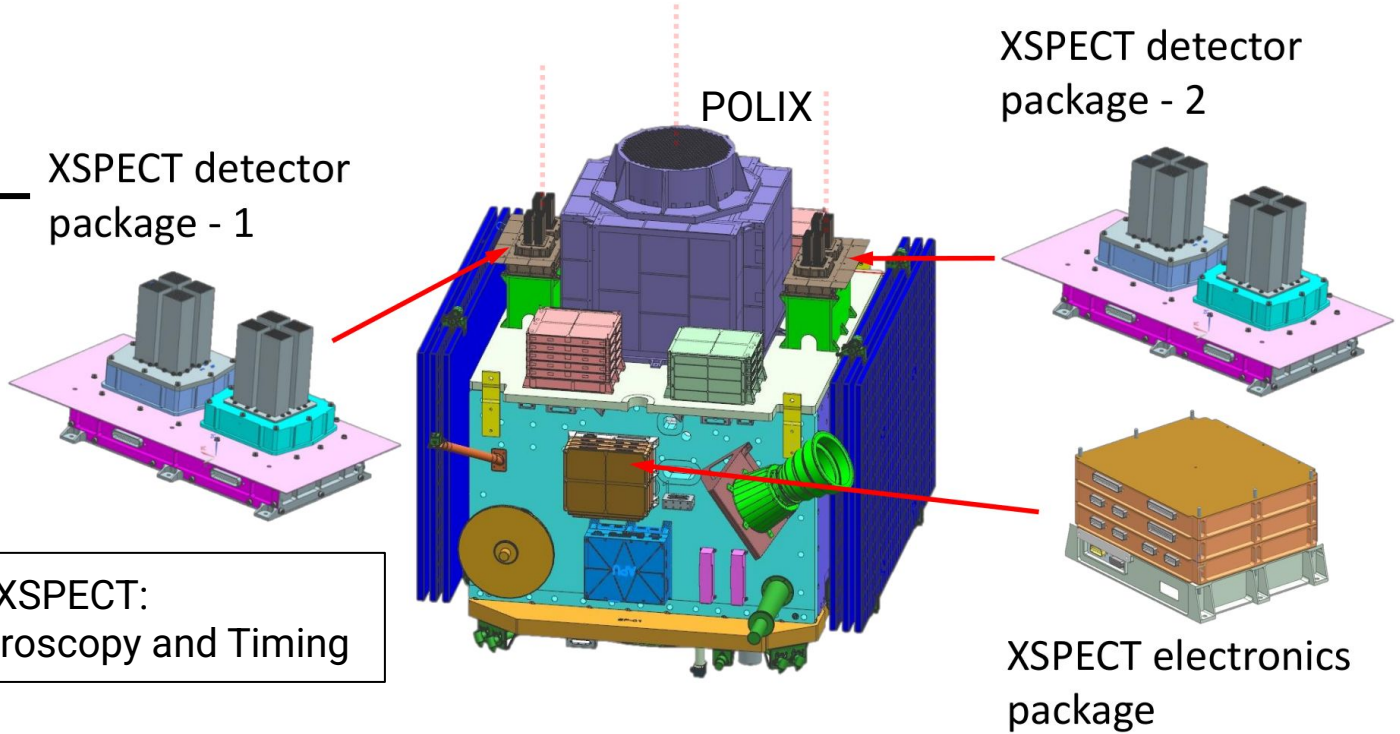
Spikes due to shield leakage in some observations



Polarisation measurement done with observation of nearby blank sky in alternate orbits. Reduced sensitivity

Credits: B. Paul, RRI

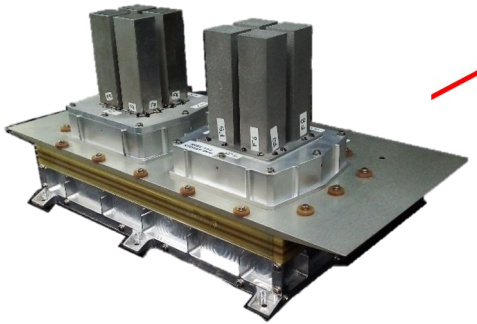
XSPECT: a soft X-ray spectrometer



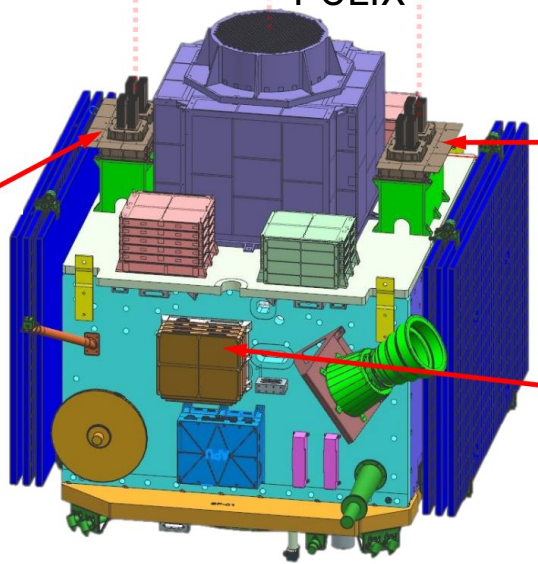
XSPECT:
X-ray SPECtroscopy and Timing

XPoSat: X-ray Polarimeter Satellite

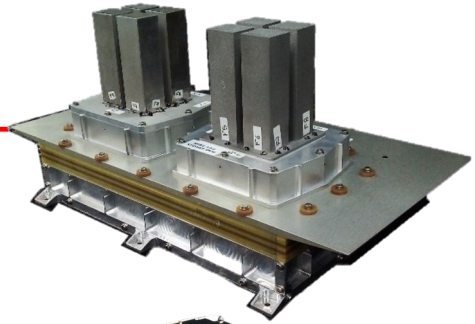
XSPECT: a soft X-ray spectrometer



XSPECT detector package - 1



POLIX



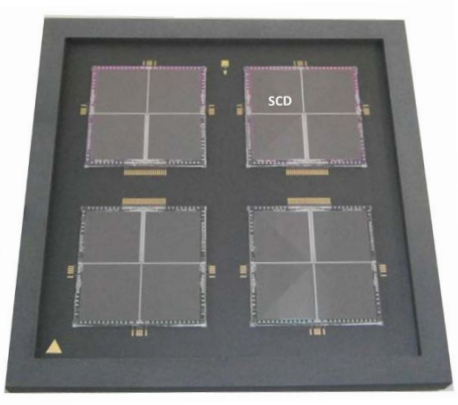
XSPECT detector package - 2

XSPECT electronics package

XSPECT:
X-ray SPECtroscopy and Timing

XPoSat: X-ray Polarimeter Satellite

XSPECT: Instrument



Swept Charge Device (SCD)
From Teledyne e2V

Pros:

- Large collecting area
- Fast readout: high count rate handling capacity
- Good resolution even with passive cooling

Cons:

- Non-imaging: no spatial information

Parameter	Specification
Detectors	SCD (16 nos)
Energy range	0.8 - 15 keV
Energy resolution	< 180 eV @ 6 keV (-20°C)
Time resolution	~ 1 ms
FOV	2° x 2°, 3° x 3°, 1 blocked
Area	60 cm^2 (G), 28 cm^2 (E)
5σ sensitivity	0.6 mCrab in 10 ks
Pile-up limit	< 1% upto 60 Crab

Previously flown in:

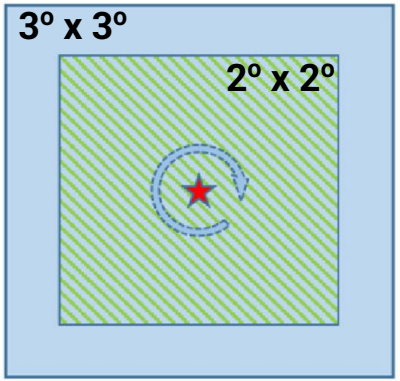
- ✓ C1XS (Chandrayaan-1)
- ✓ CLASS (Chandrayaan-2)
- ✓ LE telescope (Insight-HXMT)

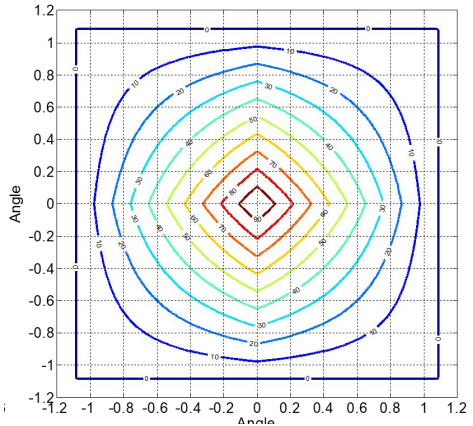
References:

- **Instrument:** *Vatedka R. et al. (2025), JATIS, 11, 035001*
- **Calibration:** *Chatterjee R. et al. (2025), JATIS, 11, 044007*

XSPECT: Instrument

- **Optical light filter**: aluminised polyimide (700 nm)
- **Collimators**: Al, square, co-aligned, 2° x 2° & 3° x 3°





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Science objectives:

- ➔ Spectral state changes in binaries
- ➔ Soft excess in XRPs
- ➔ Spin period, pulse profile evolution
- ➔ BH spin & mass
- ➔ LFQPOs

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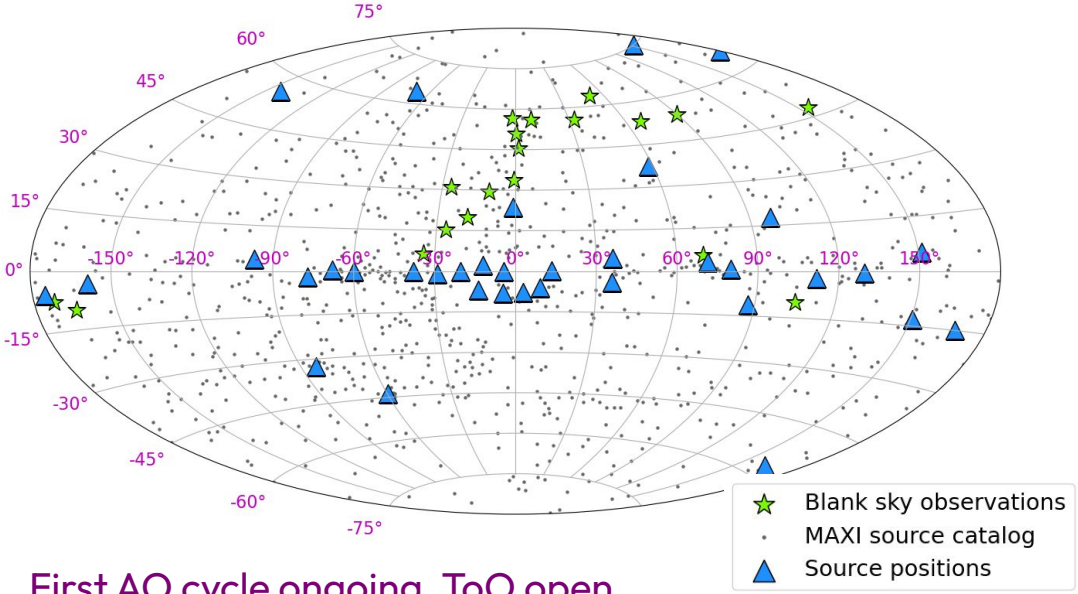
XSPECT: Current status



Source category	# of sources	# of days	Approx exposure (ks)
NS-LMXBs	17	210	3096
X-ray pulsars	10	209	3046
BH-XRB	4	128	1897
AGN	7	59	875
SNRs	2	25	386
T Tauri	2	12	191
Magnetar	1	10	162
Background	-	151	2293

- First AO cycle ongoing, ToO open (https://xpps.issdc.gov.in/web/)
  - XSPECT-based
- Data available @ ISSDC (pradan1.issdc.gov.in/x01)
- Dedicated XSPECT software for processing, User Handbook
- Response, background files for analysis

~28 months of operation completed...

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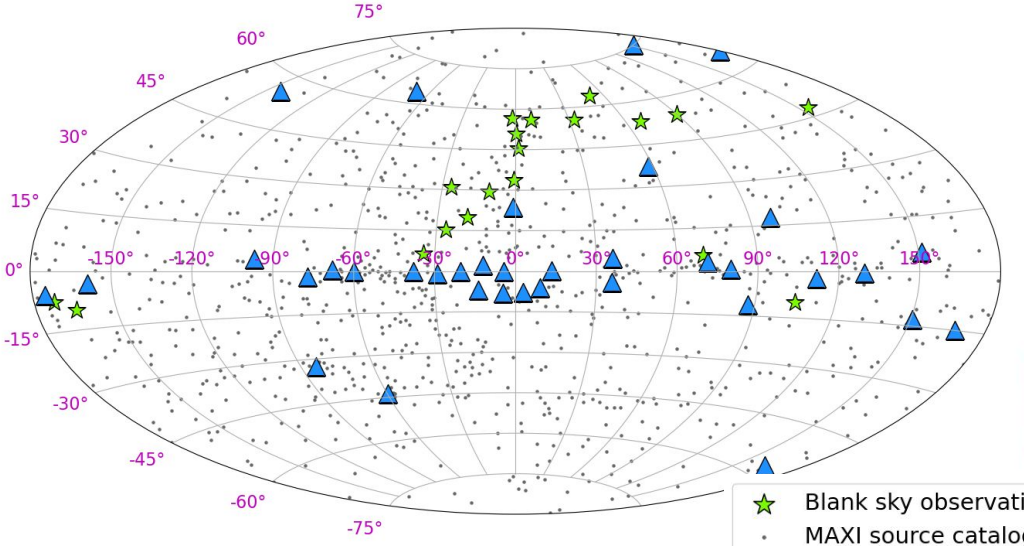

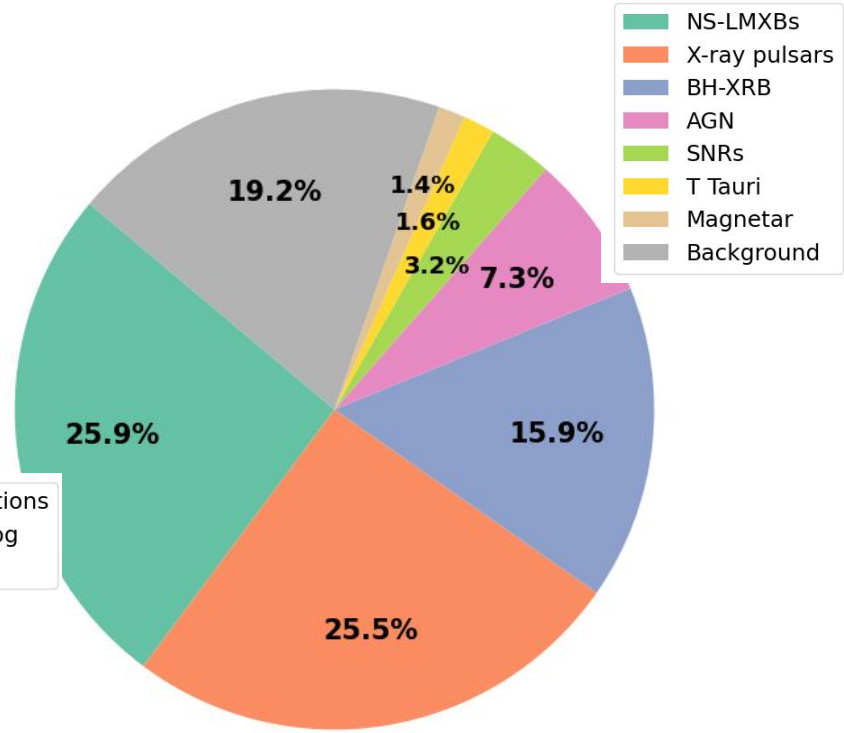

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- XPoSat and XSPECT: introduction
- **Ground calibration**
- On-board calibration
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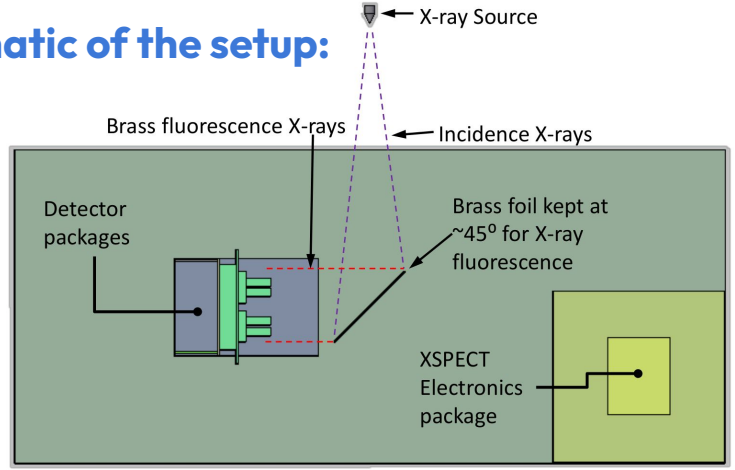
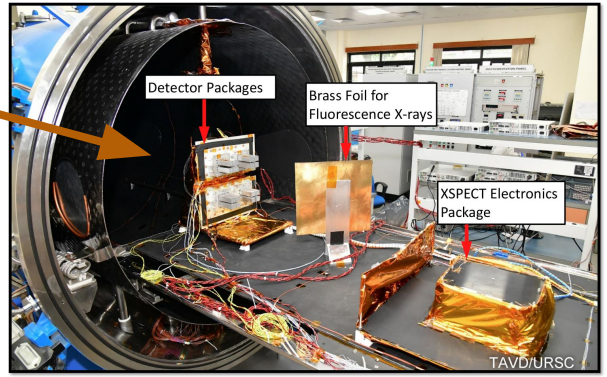
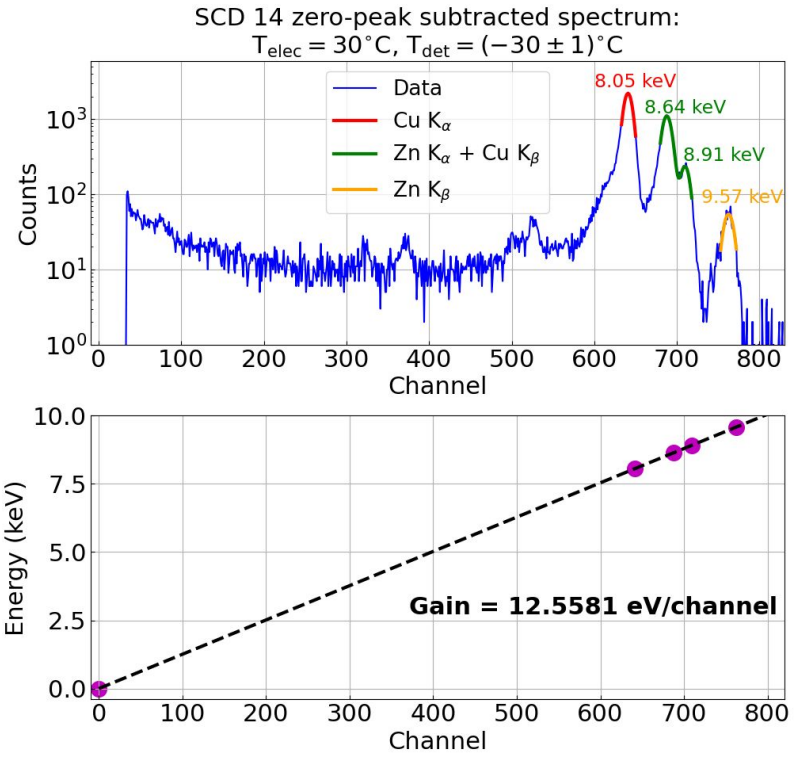
Ground Calibration: Gain

Schematic of the setup:



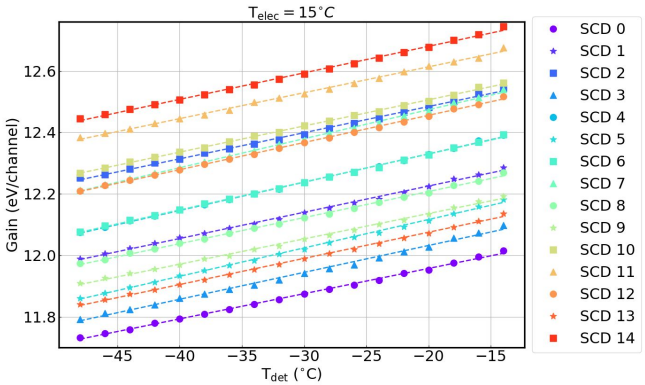
TVAC chamber



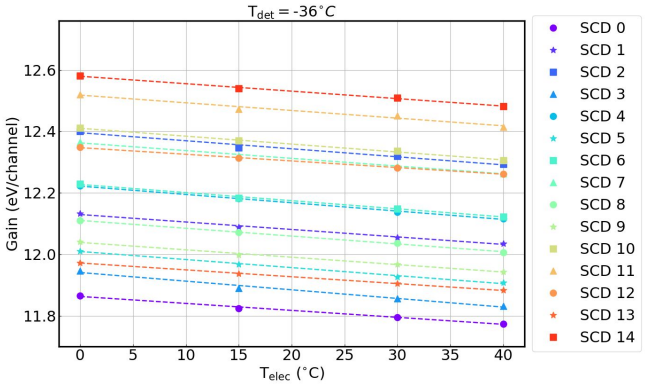


Ground Calibration: Gain

Gain vs T_{det}

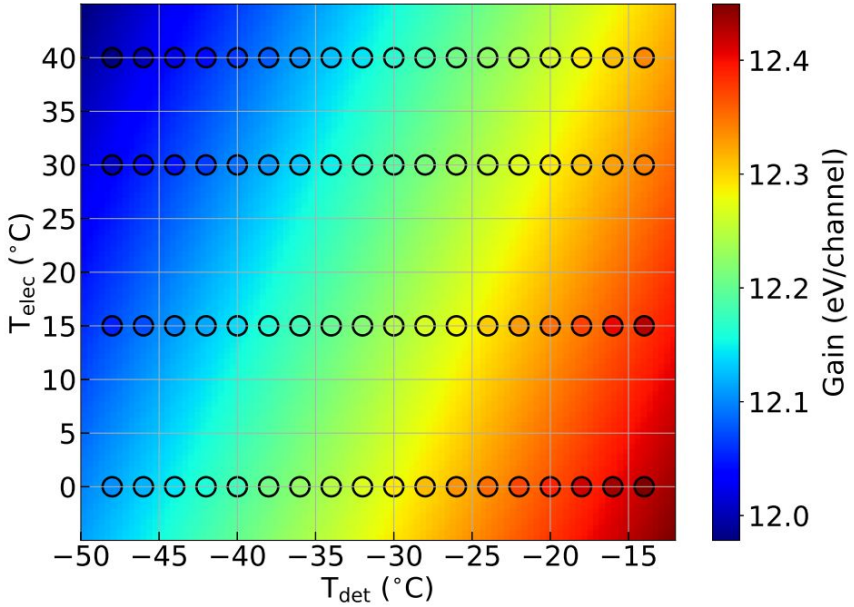


Gain vs T_{elec}



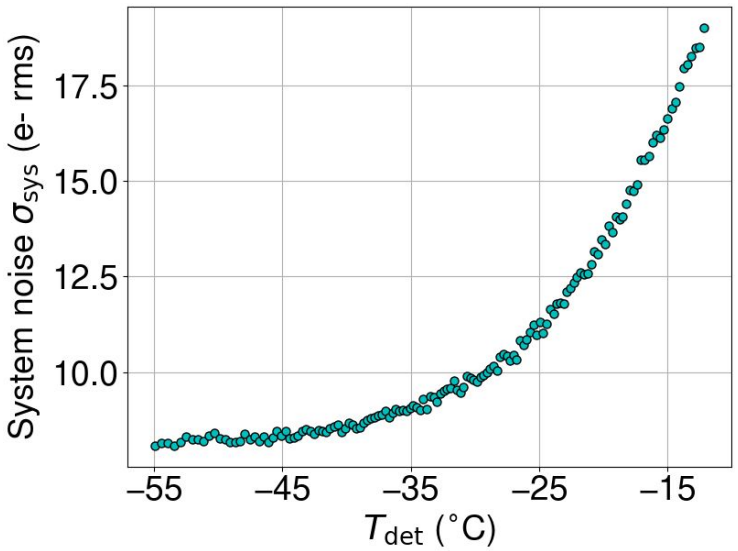
Gain depends on detector & electronics temperatures:

$$G_i = a_{0,i} + a_{1,i} T_{det} + a_{2,i} T_{elec}$$



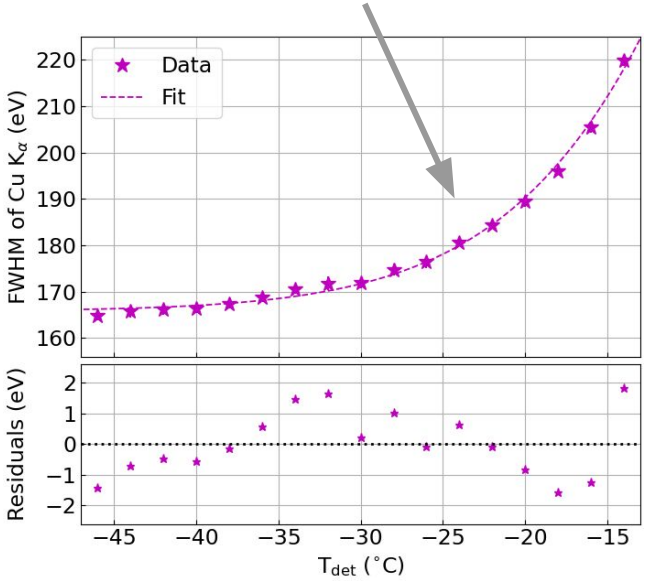
Ground Calibration: FWHM, noise

System noise variation with T_{det}



FWHM depends on detector temperature:

$$FWHM = \sqrt{a + b\,T_{det}^{3/2} \exp\left(\frac{-c}{T_{det}}\right)}$$



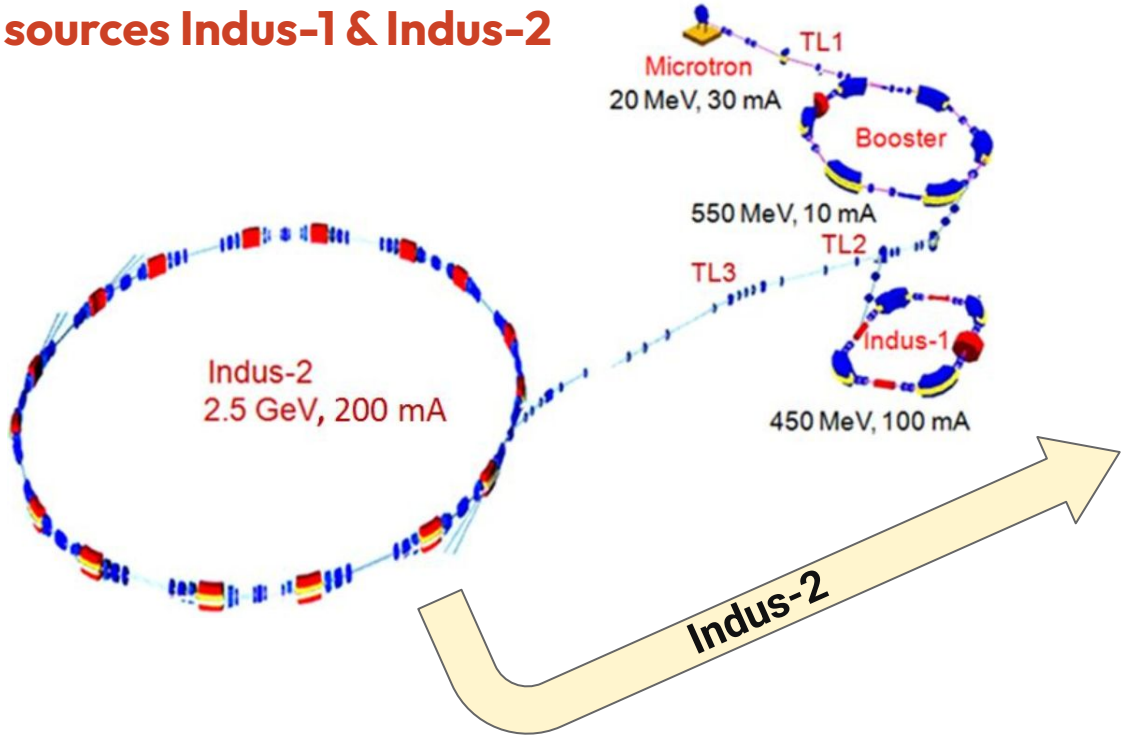
FWHM @ 8.04 keV

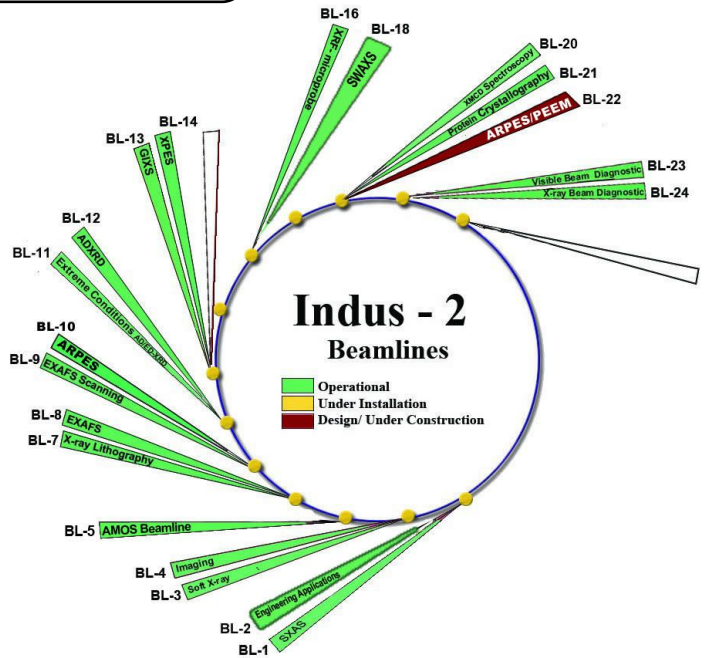
$$F = \frac{\left(\frac{\mathrm{FWHM}_{T,E}}{2.35}\right)^2 - \sigma^2_{\mathrm{sys},T}}{wE}$$

Fano factor found ~ 0.149

Synchrotron facility at RRCAT, India

Synchrotron radiation sources Indus-1 & Indus-2

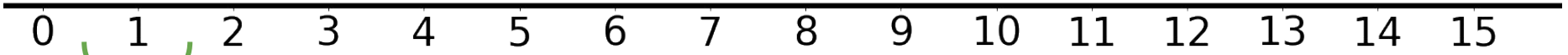




Multiple beamlines for different applications

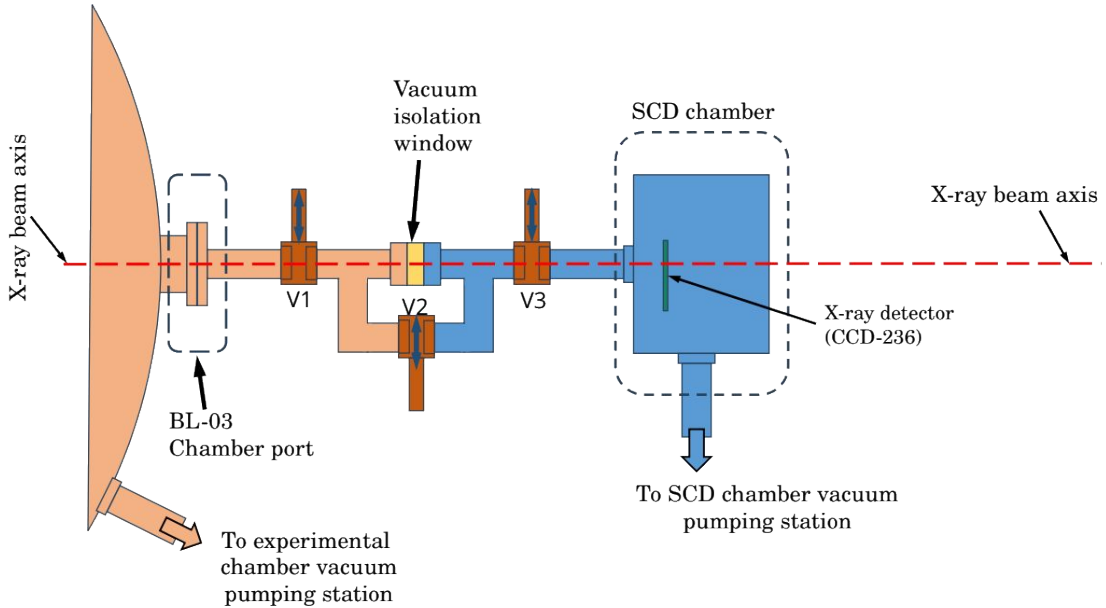
www.rrcat.gov.in

Ground Calibration: Spectral response



0.5 – 1.6 keV @ 0.1 keV steps

Monochromatic experiments @ lower energy range



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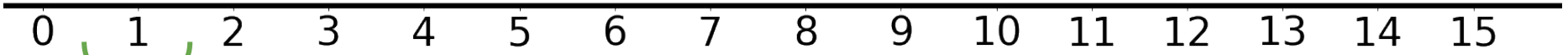

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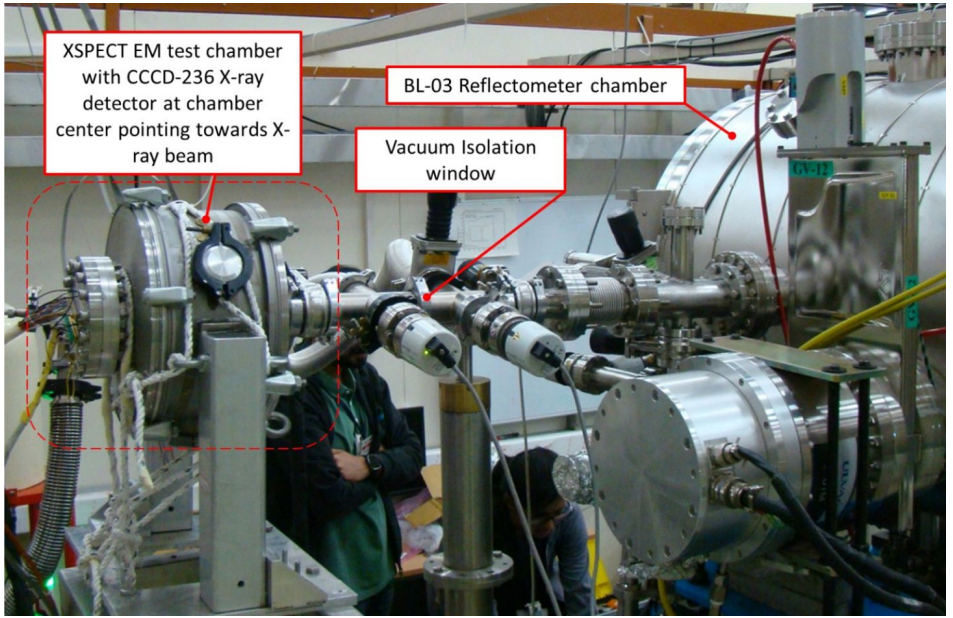

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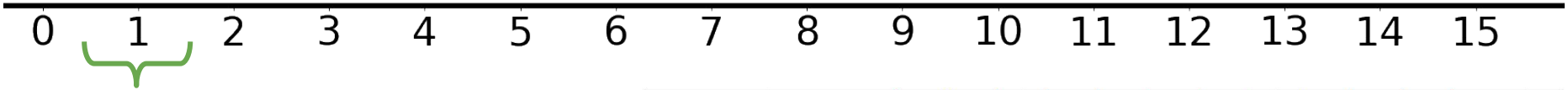

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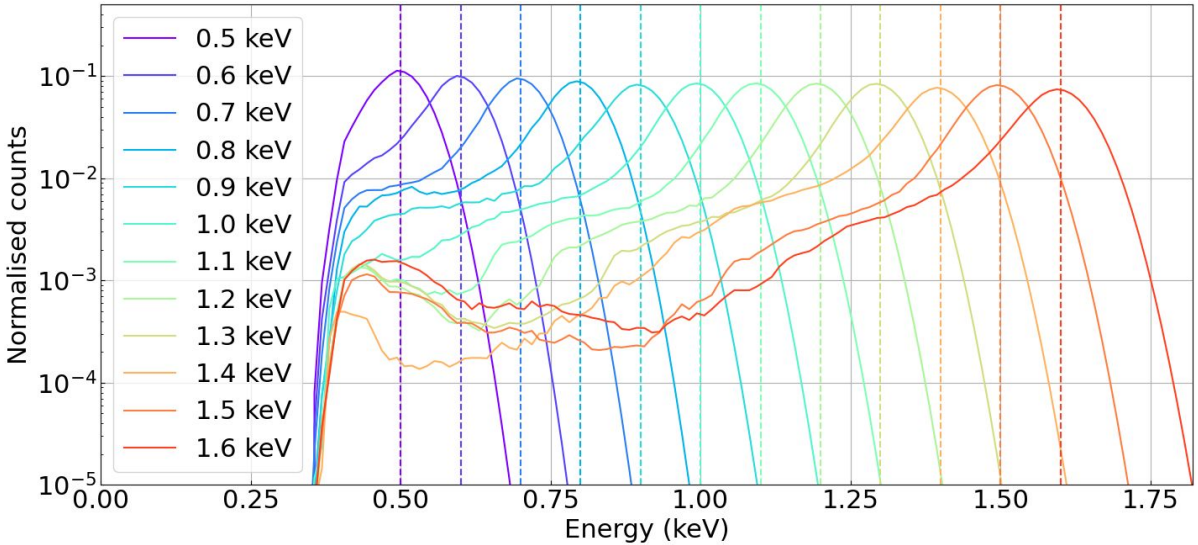

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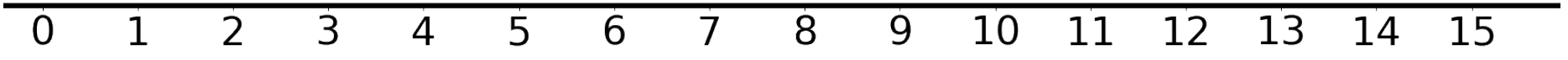
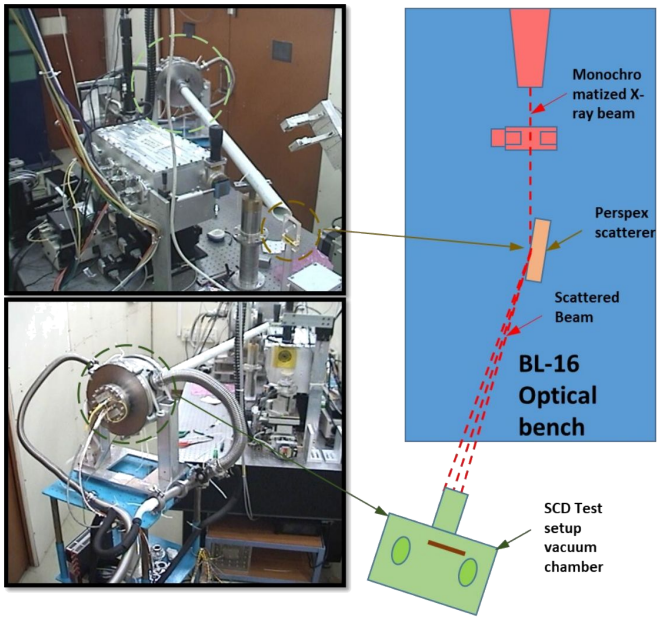
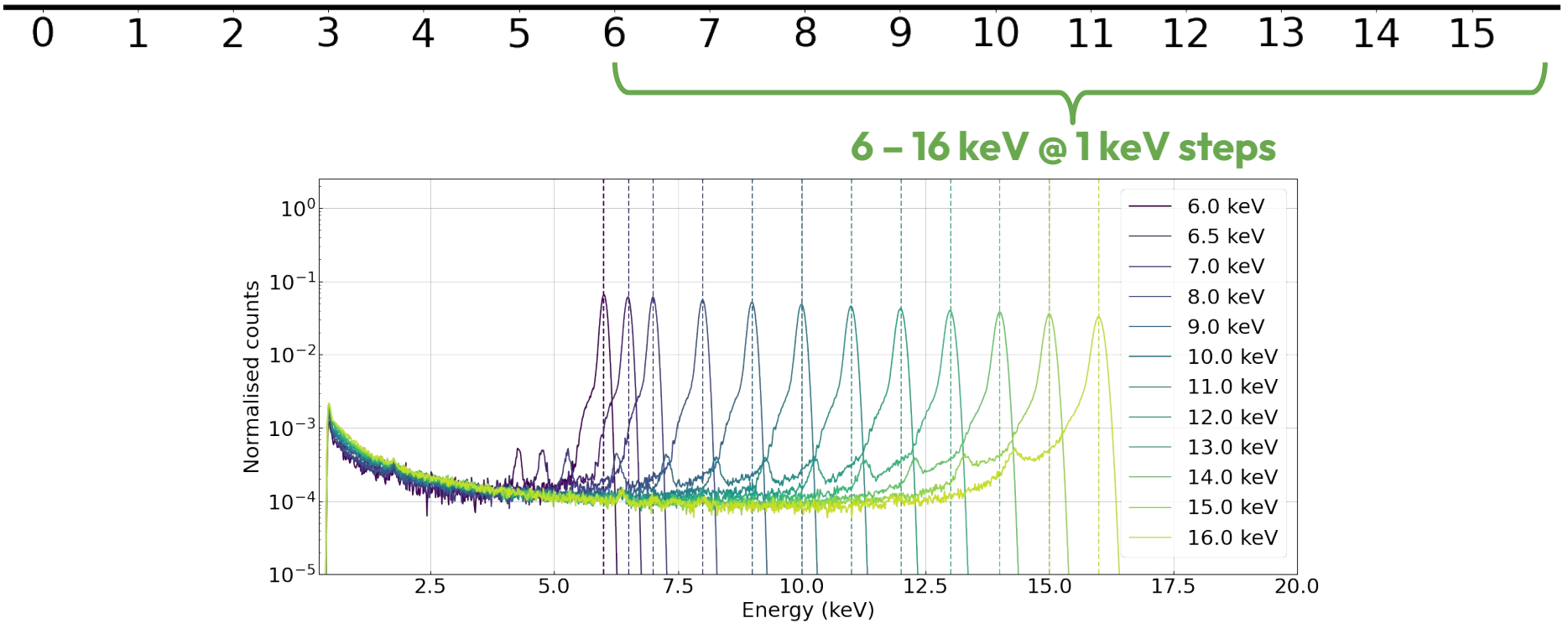


6 – 16 keV @ 1 keV steps

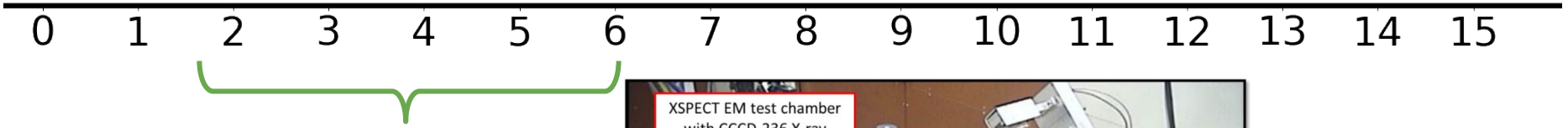


Monochromatic experiments @ higher energy range

Ground Calibration: Spectral response

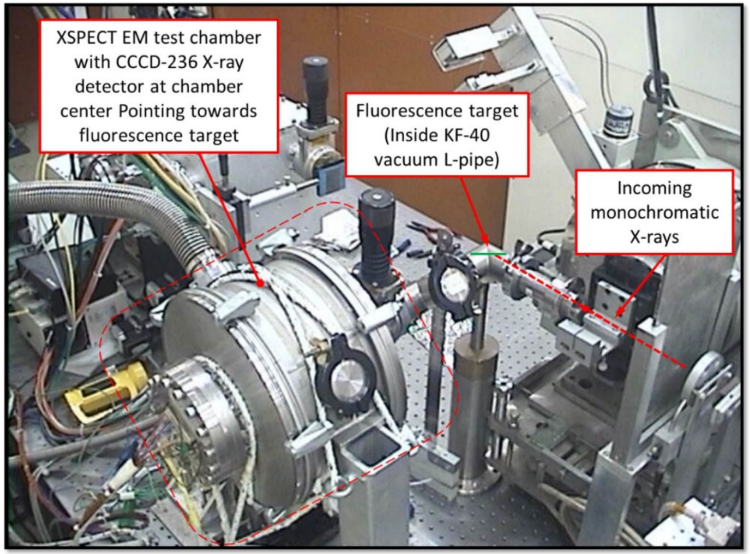


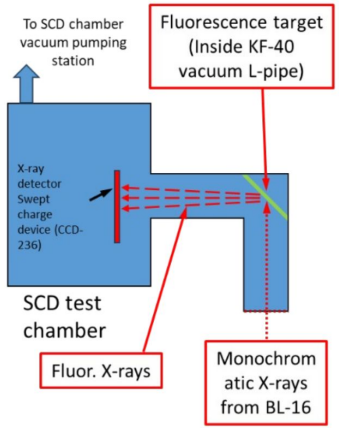
Ground Calibration: Spectral response



1.6 – 6 keV: discrete energies

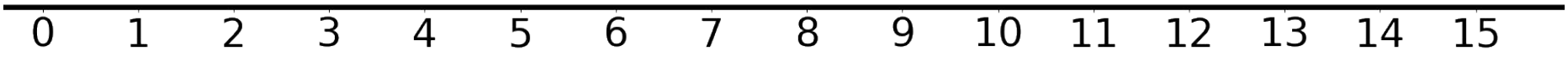
Fluorescence experiments @ mid-energy range





Ta $M\alpha$ (1.71 keV), Au $M\alpha$ (2.12 keV), Cl $K\alpha$ (2.62 keV), Silver $L\alpha$ (2.98 keV), Ca $K\alpha$ (3.69 keV), Ti $K\alpha$ (4.5 keV)

Ground Calibration: Spectral response



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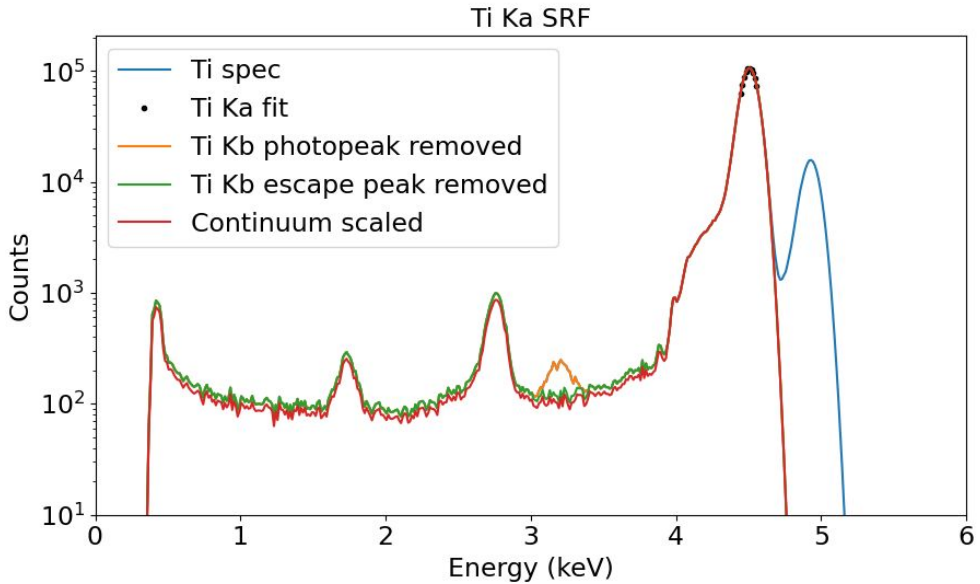

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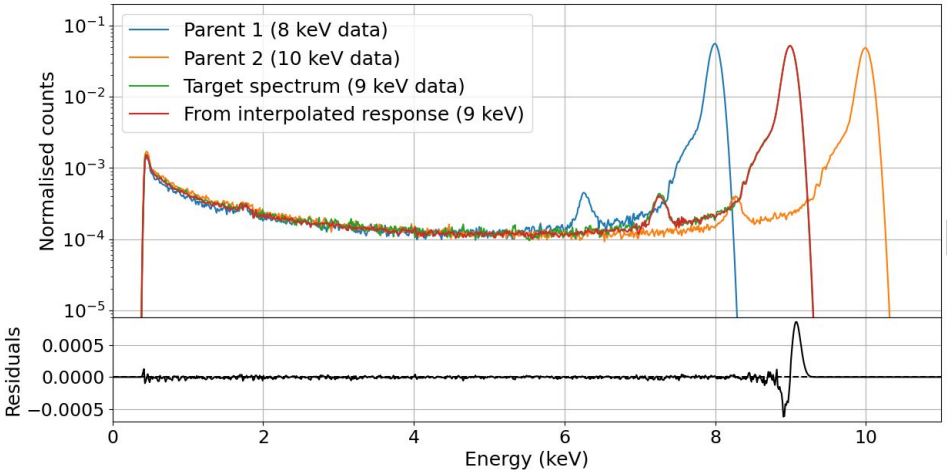
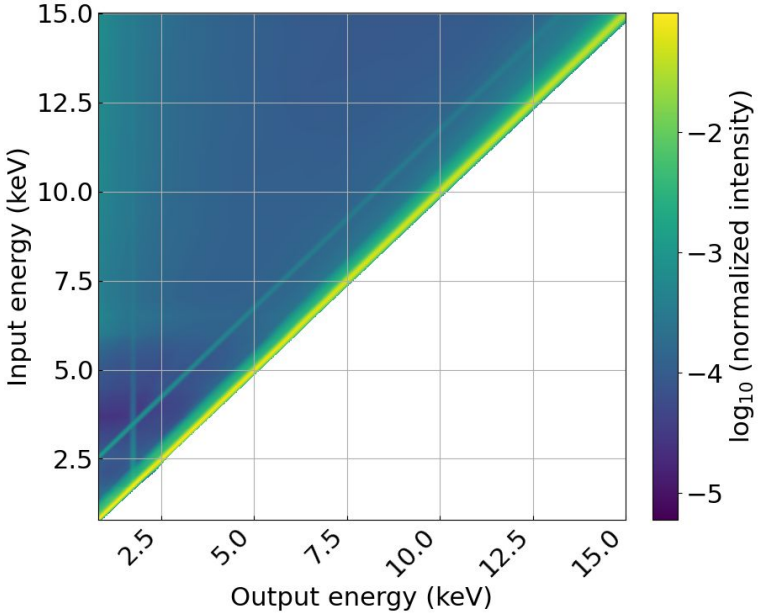
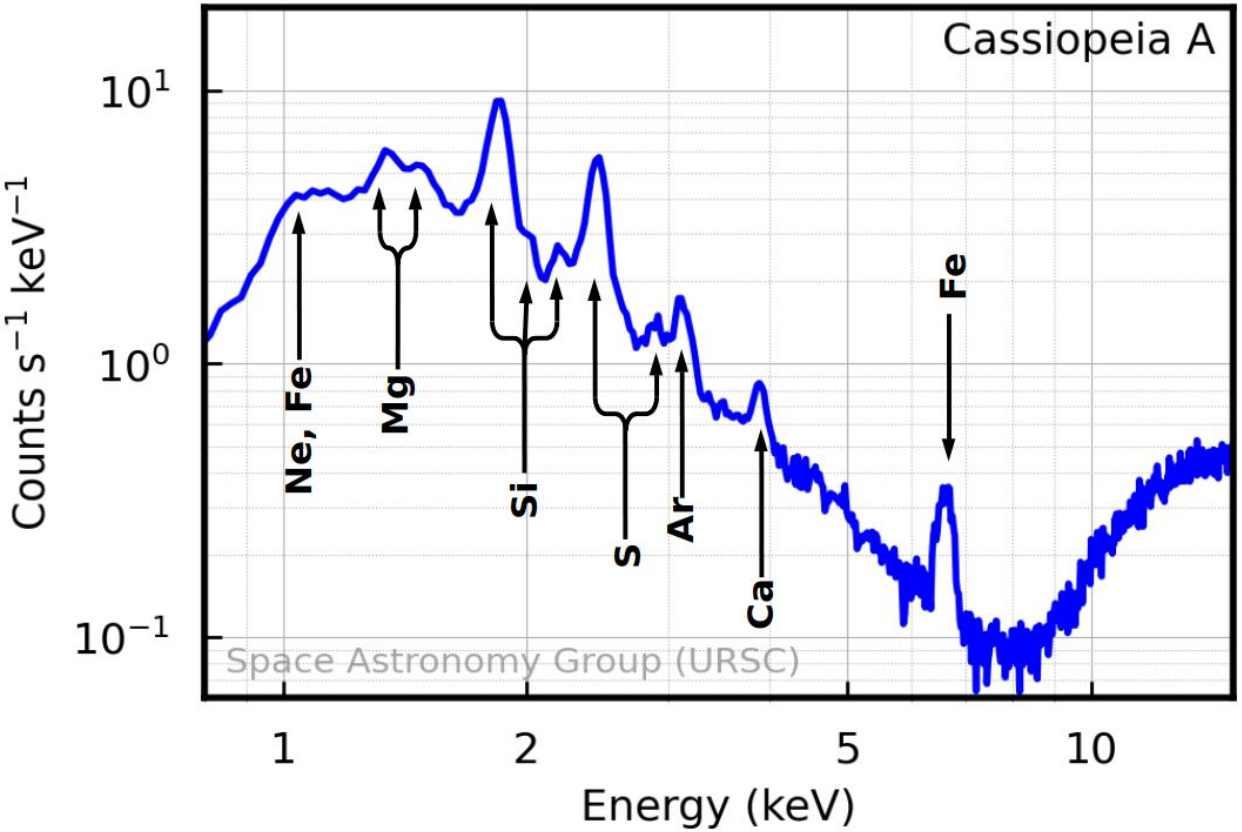




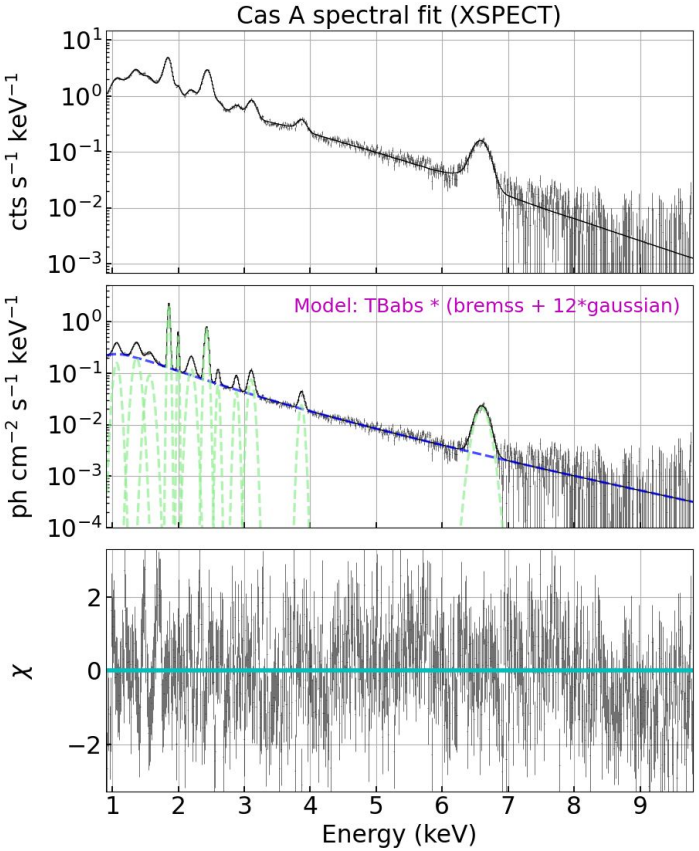
- **Decomposed into components**
- **Weighted interpolation on energy**

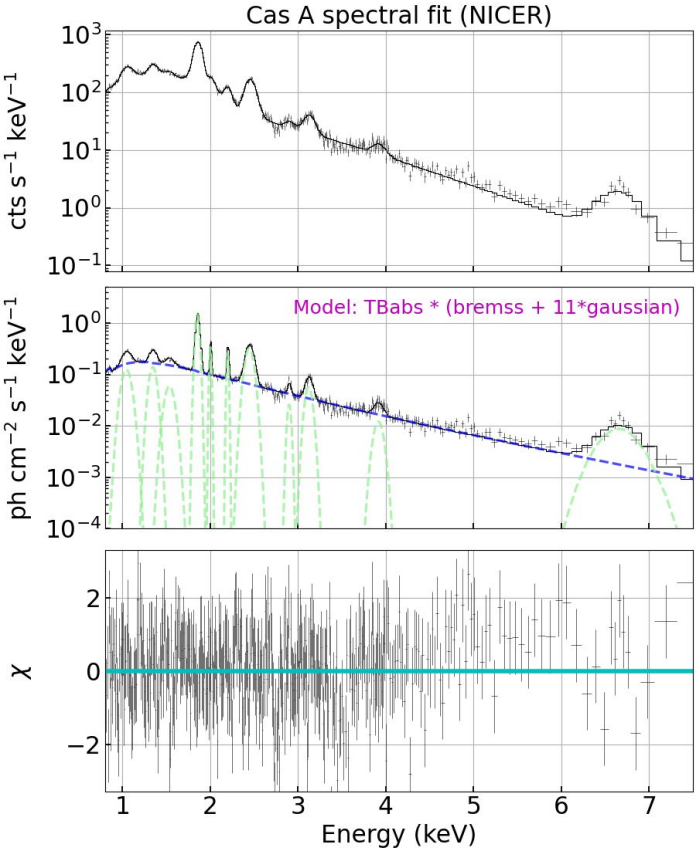
- XPoSat and XSPECT: introduction
- Ground calibration
- **On-board calibration**
- Ongoing activities

First light...


Cassiopeia A
Counts s^{-1} keV^{-1}
10^{1}
10^{0}
10^{-1}
Ne, Fe
Mg
Si
S
Ar
Ca
Fe
Space Astronomy Group (URSC)
1
2
5
10
Energy (keV)

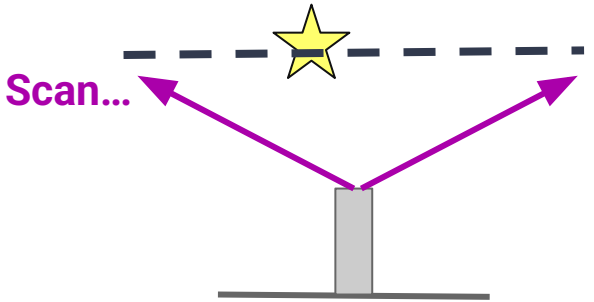
On-board Calibration: verification

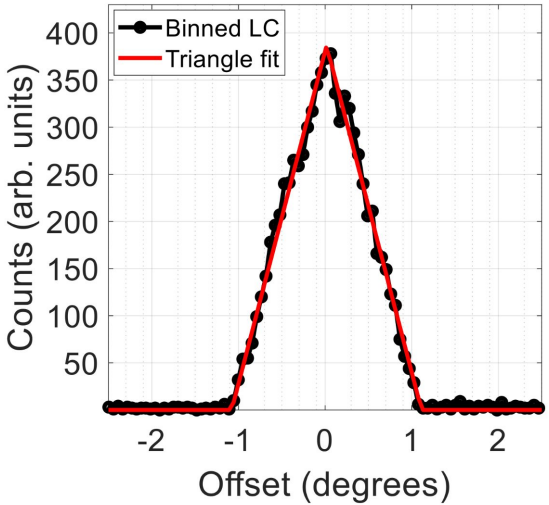




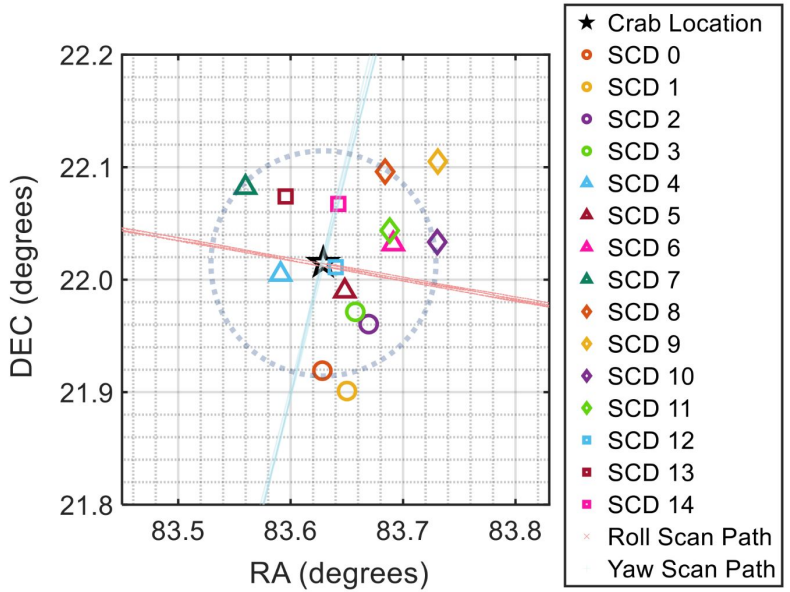
- **Fitted lines:** Ne, Mg, Si, S, Ar, Ca, Fe
- **Gain** & **FWHM** verified

On-board Calibration: alignment

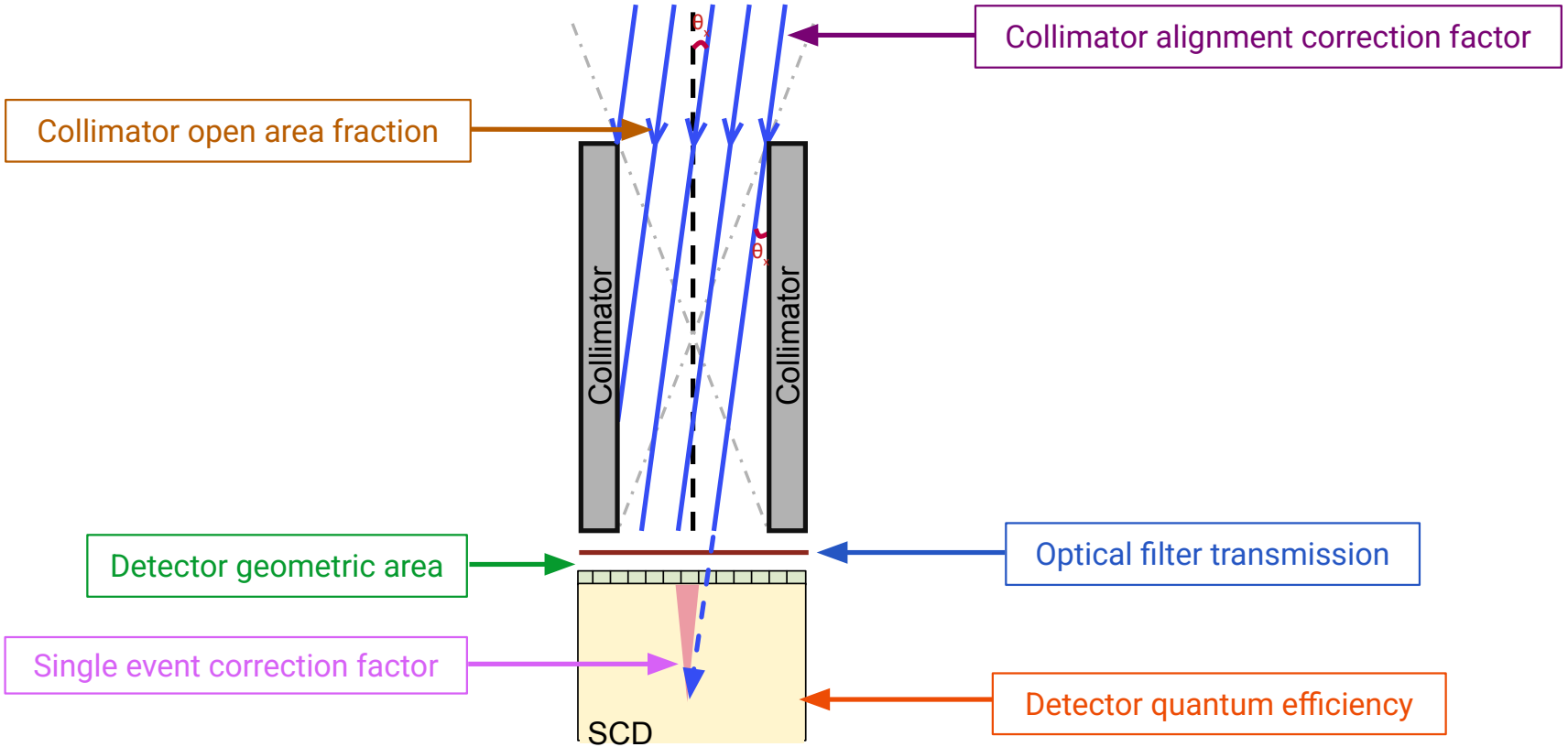




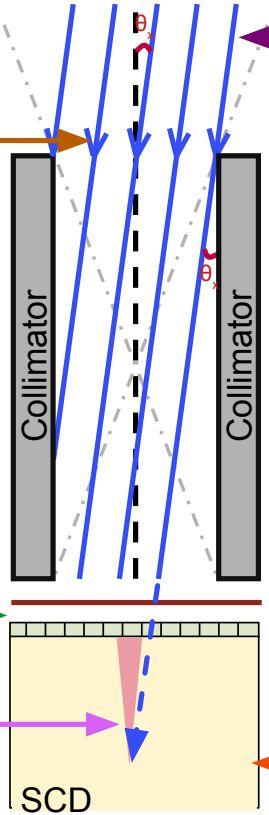
- Launch stresses, vibrations may have changed the alignment
- <~ 0.1 deg max misalignment



On-board Calibration: effective area



On-board Calibration: effective area



Collimator alignment correction factor

Offsets measured on-board (Crab scan);
Collimator response measured on-ground

Collimator open area fraction

Known from design;
Verified in lab

Known from vendor

Detector geometric area

Known from design

Optical filter transmission

Single event correction factor

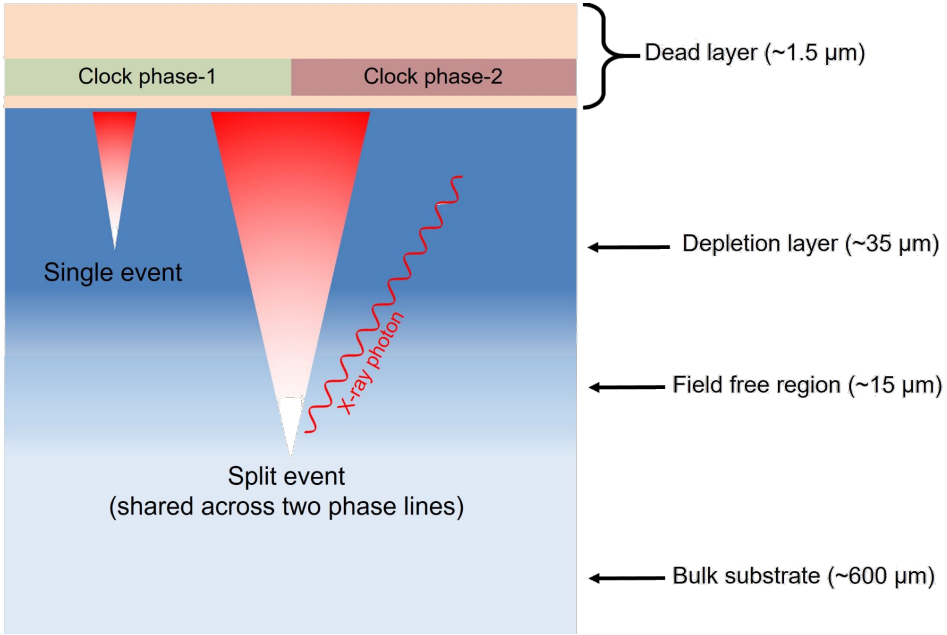
Measured at RRCAT

Uncertain...

Detector quantum efficiency

On-board Calibration: QE

- × Only approximate layer thicknesses known
- × Incomplete charge collection regions?
- × Poor fit to Crab spectrum

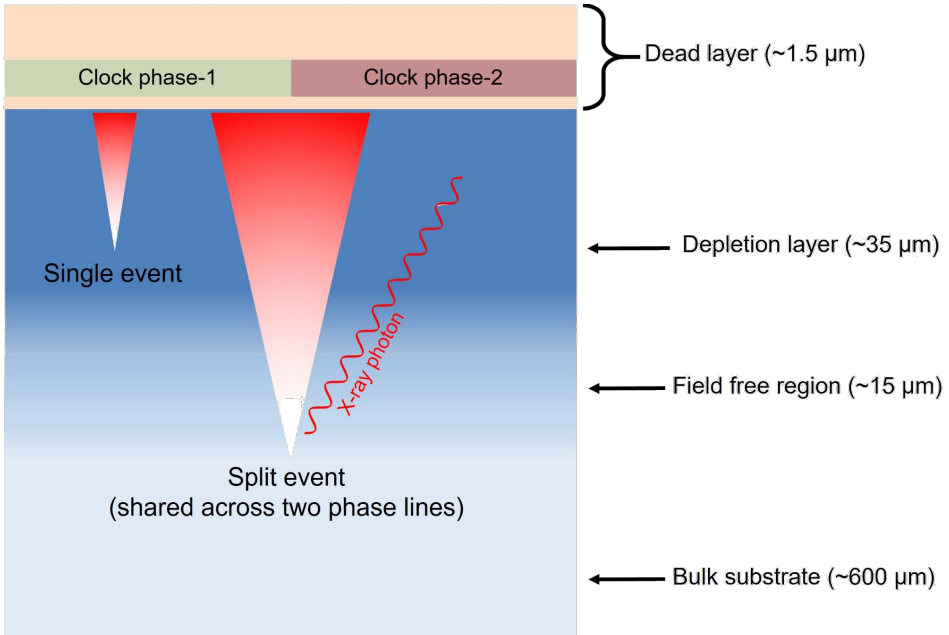


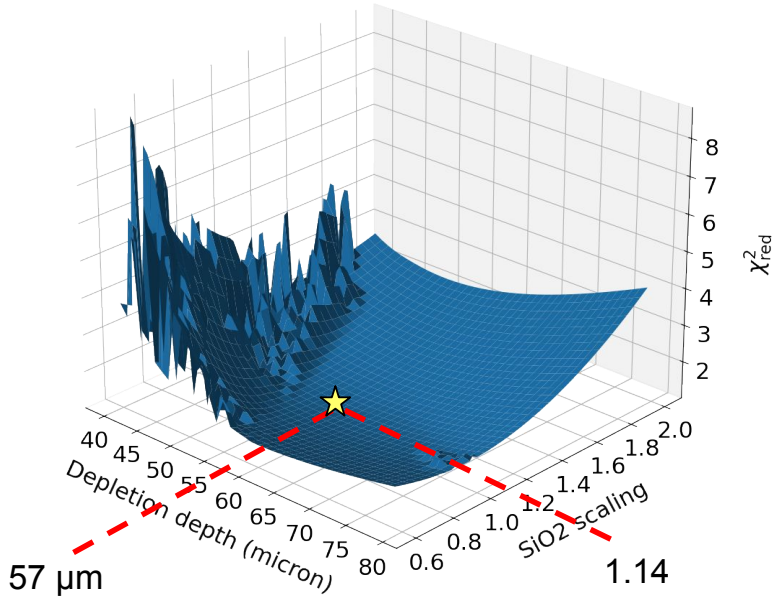
On-board Calibration: QE

- × Only approximate layer thicknesses known
- × Incomplete charge collection regions?
- × Poor fit to Crab spectrum

→ On–board Crab observations used: Iterative fitting

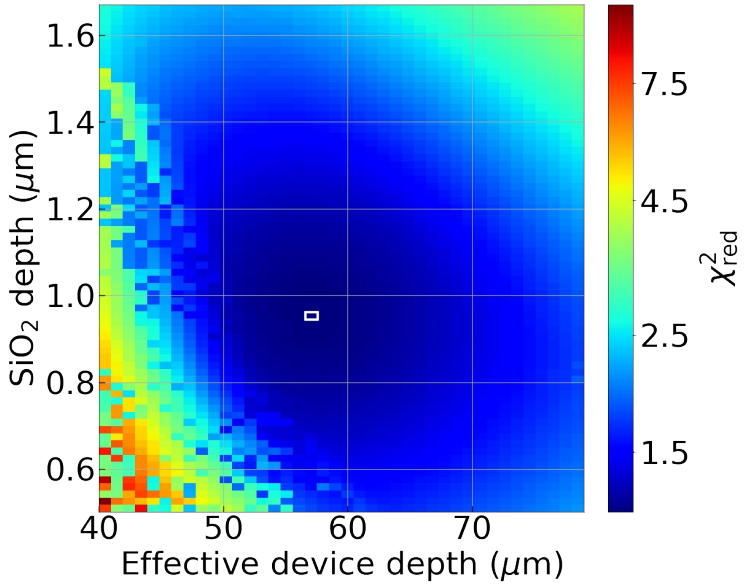
$N_H \sim 0.3 \times 10^{22}$ cm^{-2}
$\Gamma \sim 2.1$
Norm ~ 9.5

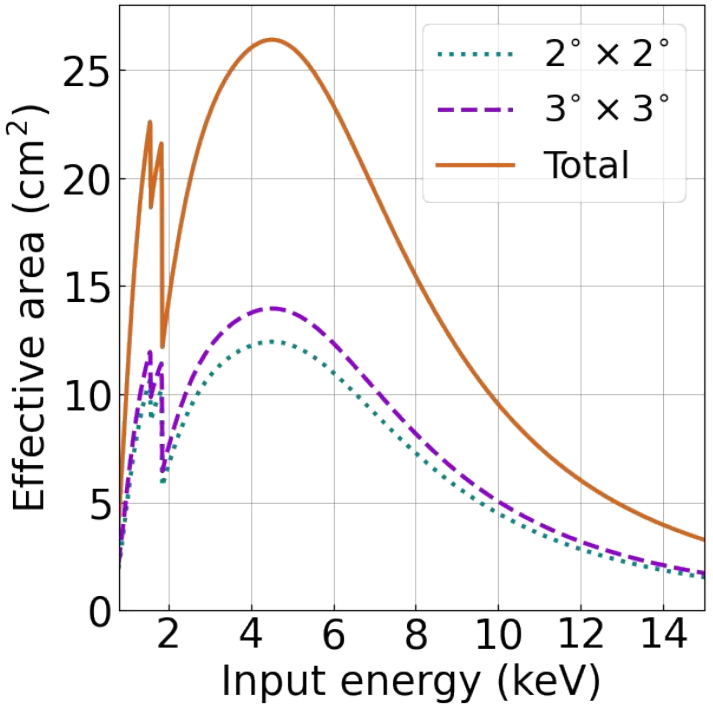




On-board Calibration: QE

Iterative fitting of Crab spectra...

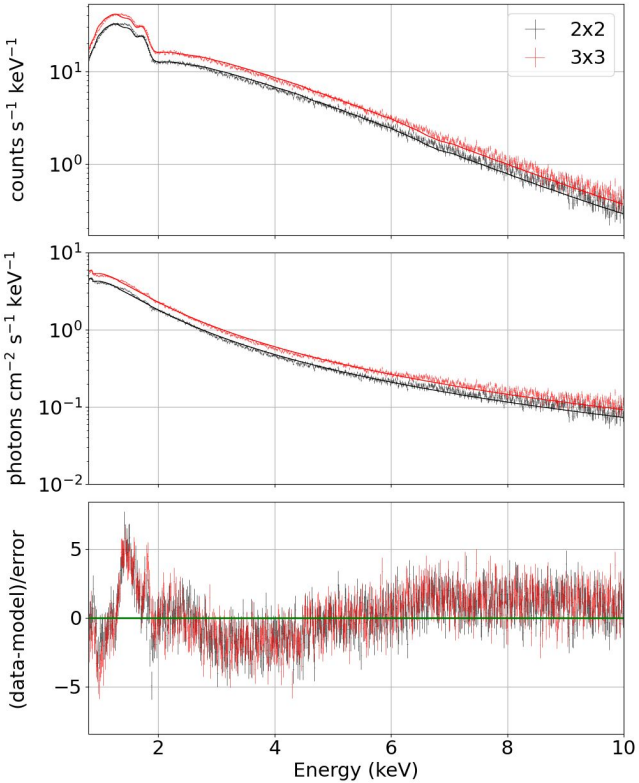




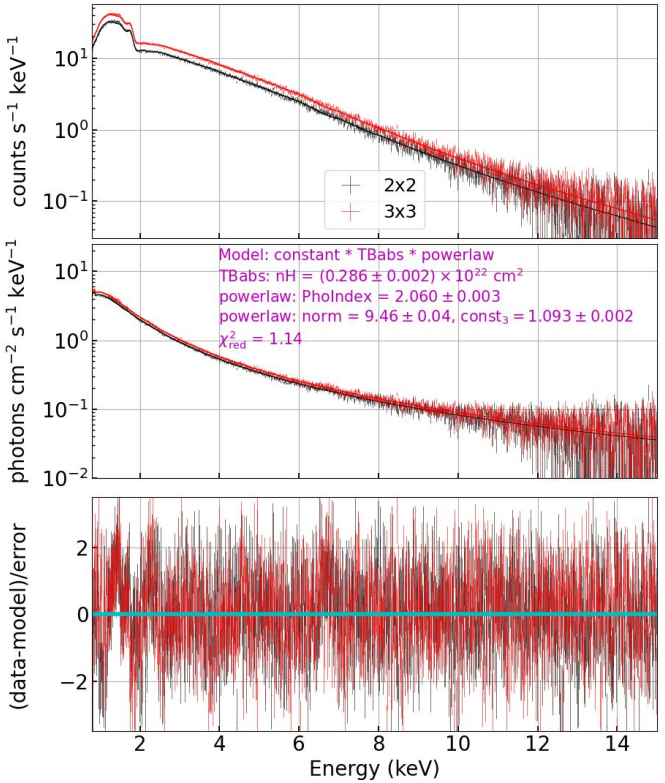
✓ **Effective depth ~ 57 µm**

✓ **Dead layer depth ~ 952 nm**

On-board Calibration: Crab fitting

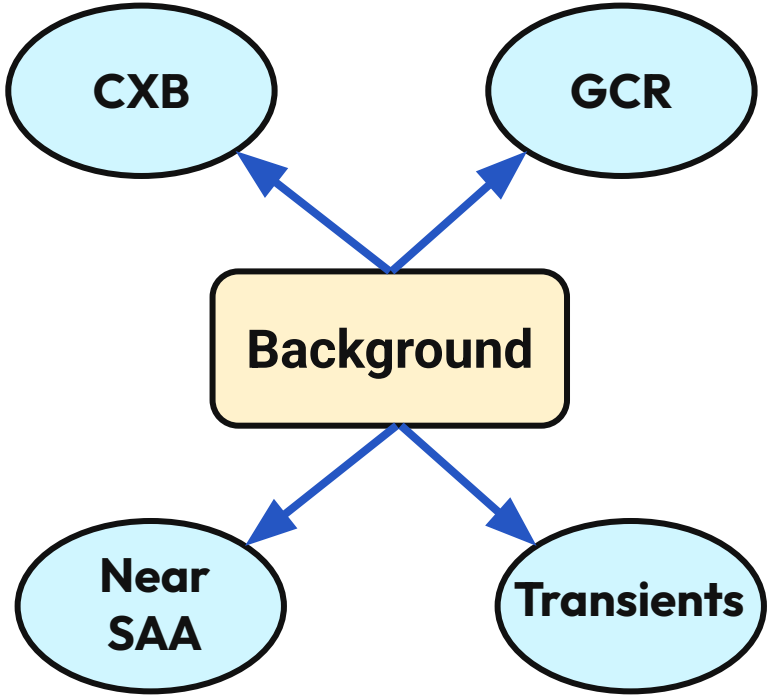


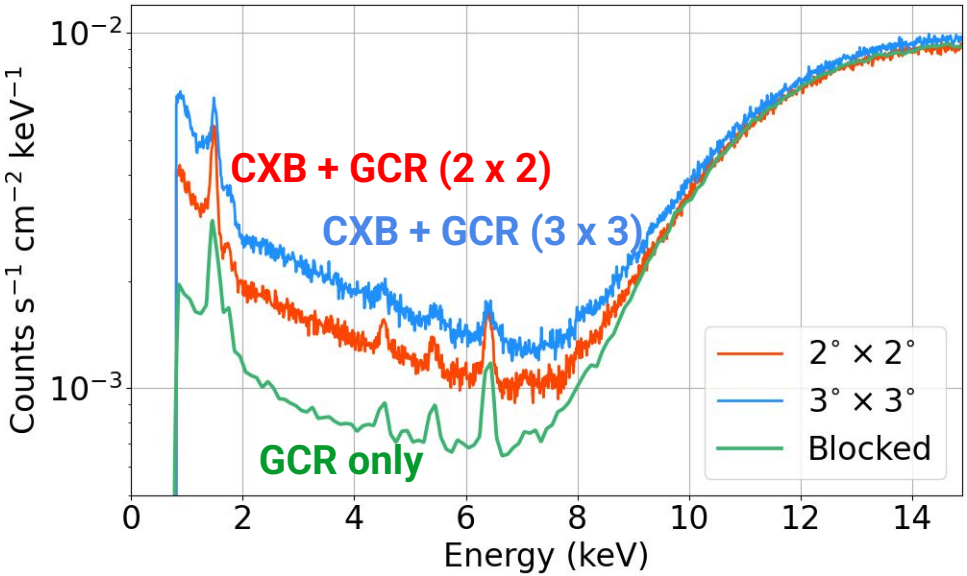
Using QE with approx depths



Using QE with fitted depths

On-board Calibration: background

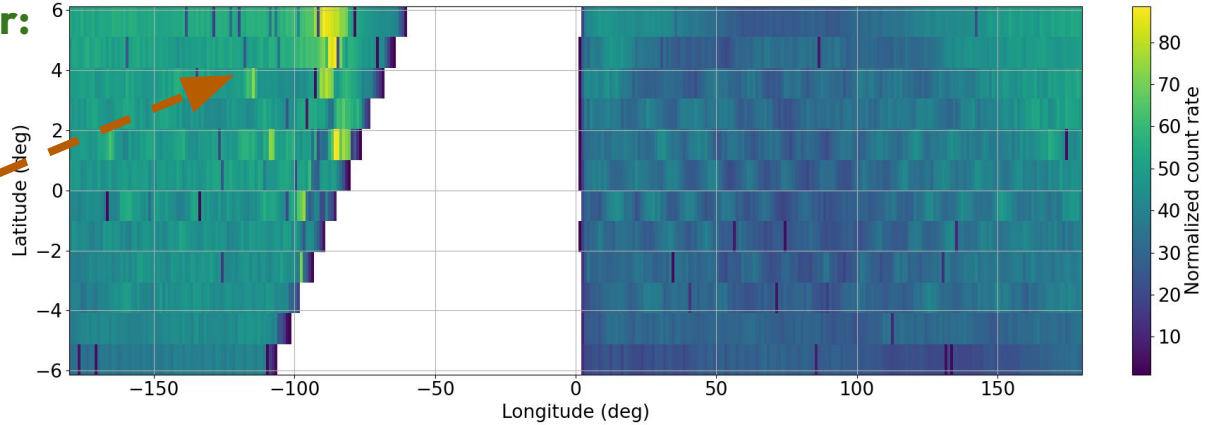




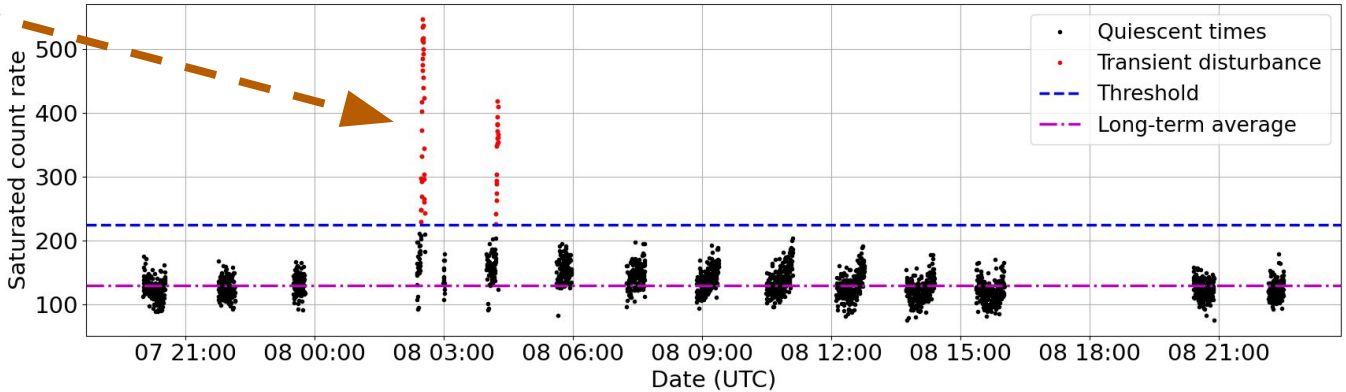
Approx bkg count rate: ~ 2.6 cps / 15 SCD

On-board Calibration: background

Saturation counter:
Events > 16 keV

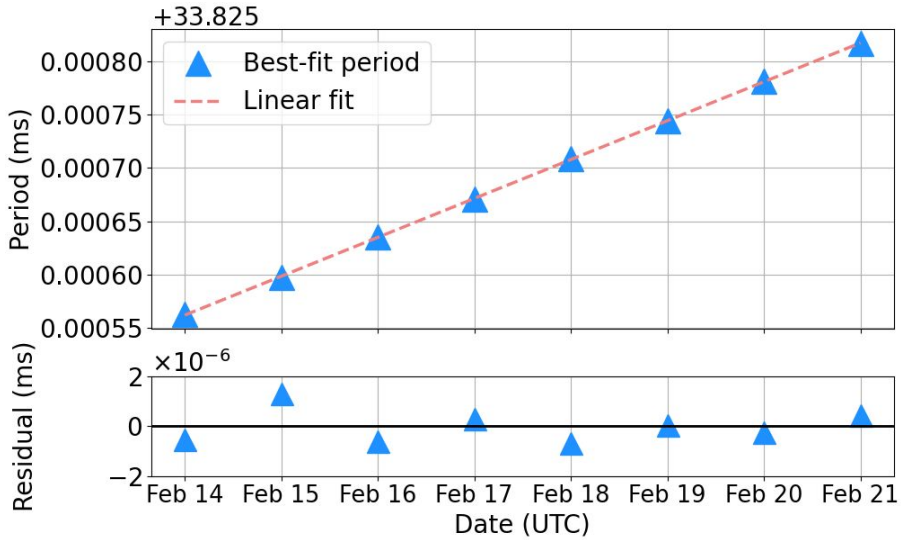


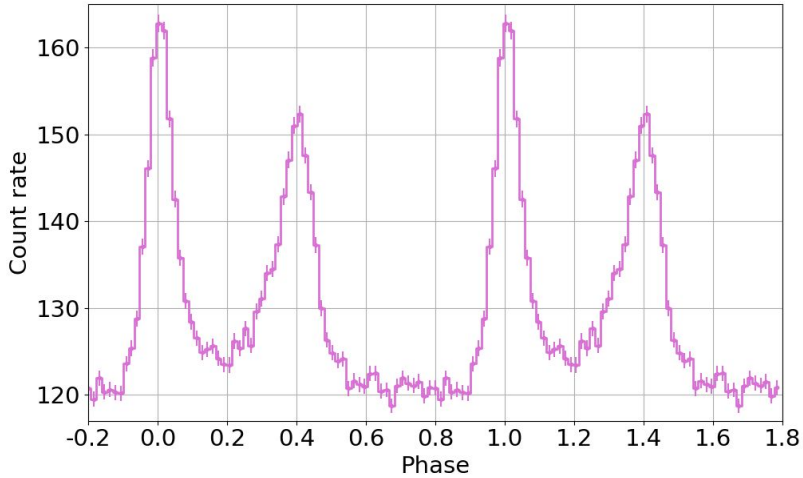
Enhancements seen near SAA



On-board Calibration: timing

~270 ns



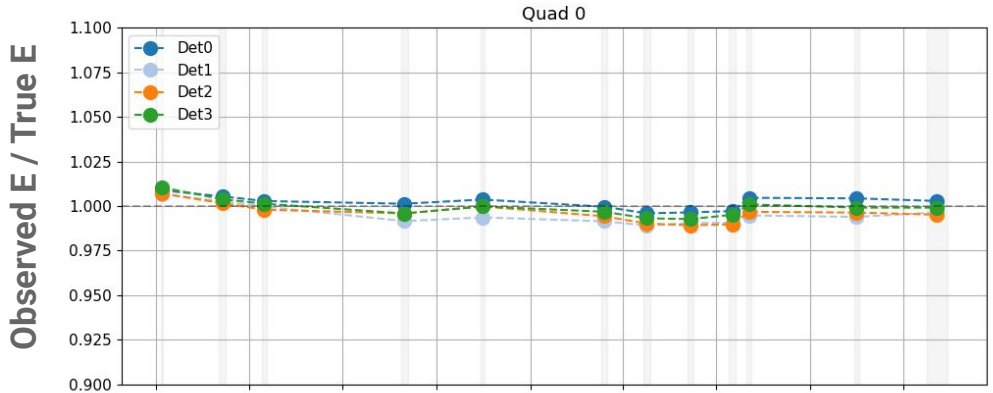


- Average period difference from Jodrell Bank ~ 0.59 μs
- P_dot determined ~ 4.22 x 10^{-13} s/s, consistent with literature

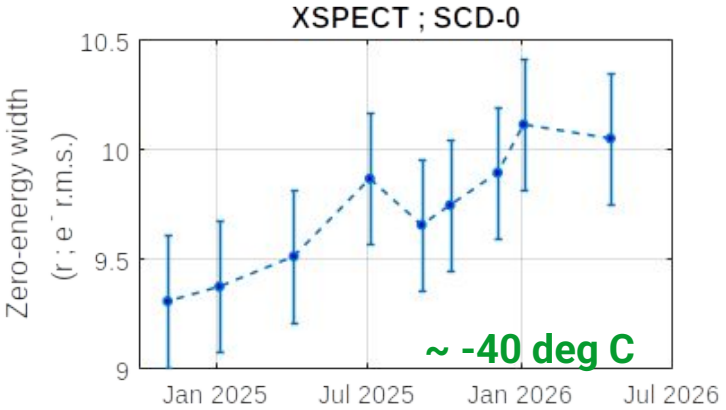
- XPoSat and XSPECT: introduction
- Ground calibration
- On-board calibration
- Ongoing activities

Ongoing: gain, FWHM monitoring

- Regular gain cal observations carried out (Cas A, GX 301-2)
- Gain caldb periodically updated to account for shifts



- Regular noise monitoring observations
- No significant deviation from ground performance till date

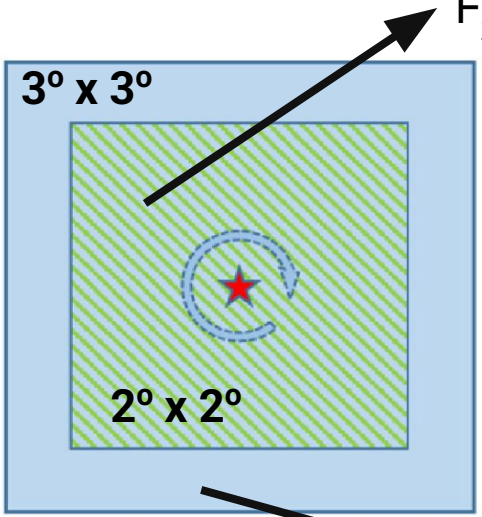


Ongoing: FOV-wise background

Observable: ★ + **CXB** + **GCR**

Unknowns: S_0 B_0 P_0

$$F_2 = (S_0 \times A_{geom,2} \times QE) + (0.25 \times B_0 \times A_{geom,2} \times FOV_2 \times QE) + (P_0 \times A_2)$$



Blocked

$$F_{15} = (P_0 \times A_{15})$$

$$F_3 = (S_0 \times A_{geom,3} \times QE) + (0.25 \times B_0 \times A_{geom,3} \times FOV_3 \times QE) + (P_0 \times A_3)$$

3 unknowns & 3 equations

Ongoing: Response modeling efforts

WHY?

- Interpolation may not hold
  - Ignores physical origin of response components
  - Breaks down near absorption edges
  - May introduce uncertainties
- Gaps in experimental coverage
- Understanding of device physics
  - Evolution of SRF on-orbit
- Further improvement in spectral fits
  - Low energies improvement
  - Remove the need for systematics

HOW?

- Empirical fitting
  - Describe the functional form of SRF
  - Interpolate the parameter trends
- Physical models
  - Possible improvements (include more physics; tweak parameters)
- Hybrid model
  - Charge collection fraction vs depth

THANK YOU