SiPM-based CubeSat for Measuring the Cosmic X-ray Background

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in collaboration with

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CONTENT

1 Introduction

◎ Rocket experiment: before 1962

- ○ X-ray emission from the Sun
- ○ rocket flight beyond atmospheric barrier (~100 km)
- ○ Geiger (gas) counters
- ○ one can see Sun X-rays modulation
- ○ no filtering of background
- ○ not able to find other sources

◎ Rocket experiment: since 1962

- ○ Geiger counter + active anticoincidence shield
- ○ was able to recognize discrete sources
- ○ the first extrasolar X-ray source Sco X-1
- ○ the CXB was revealed at the same time

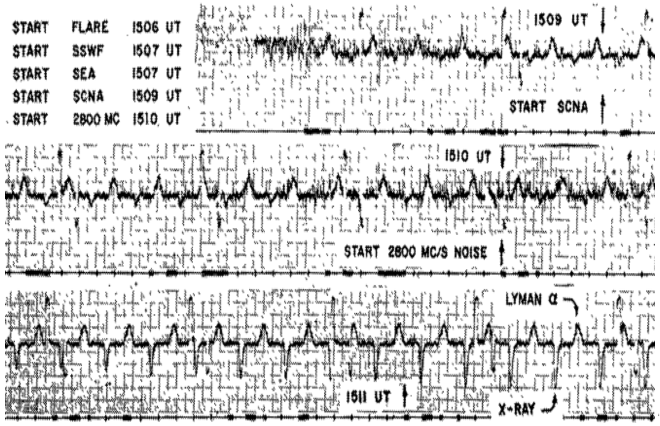
◎ *ROSAT* moon observation

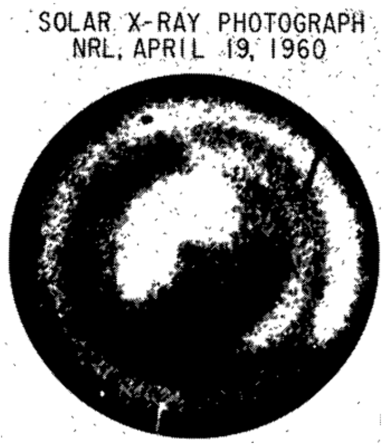
- ○ the bright side: solar X-ray reflection;
- ○ the dark side: a distinct shadow of CXB.
- ○ suggested an extrasolar origin

◎ CXB Intensity over the sky

- ○ measured by multi missions: *Uhuru*, *HEAO-1*, *ROSAT*, etc
- ○ nearly isotropy over the sky
- ○ suggested an extragalactic origin

V-2 Rocket, NRL @ NASA





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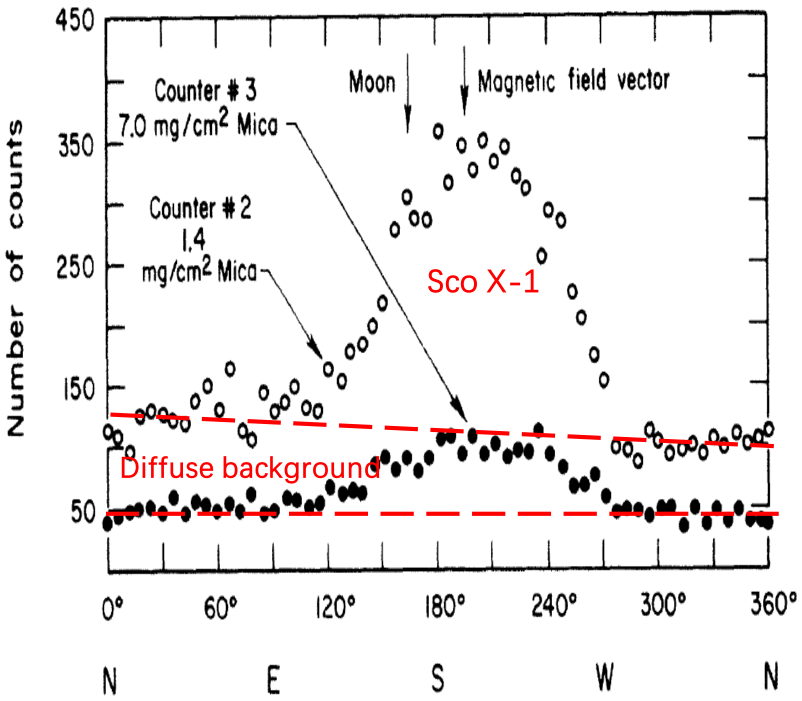
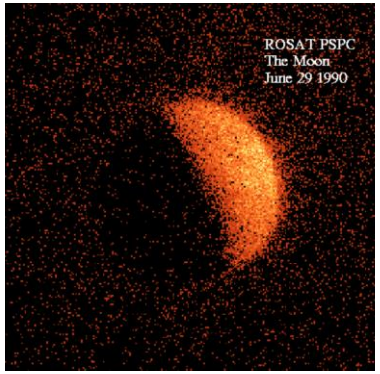
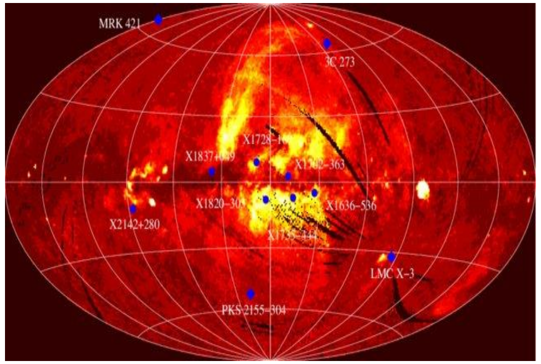


R. Giacconi et al 1962





Copyright @ ROSAT

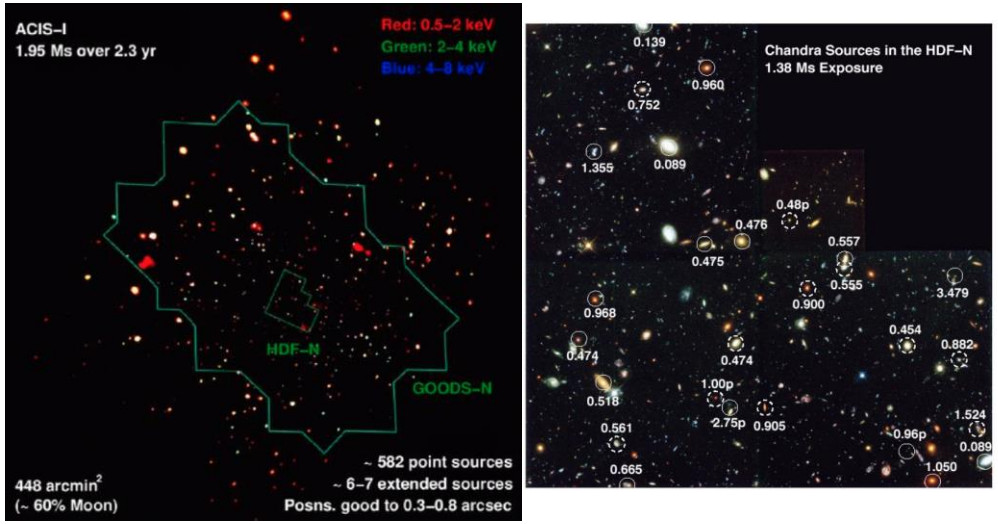
2 Synthesis model of the CXB

◎ Deep-field observations:
- ○ *Chandra*, *XMM-Newton*, etc.
- ○ resolve the CXB into discrete sources
- ○ below 2 keV, 80-90% are already resolved
- ○ resolved fraction decreases with increasing energy

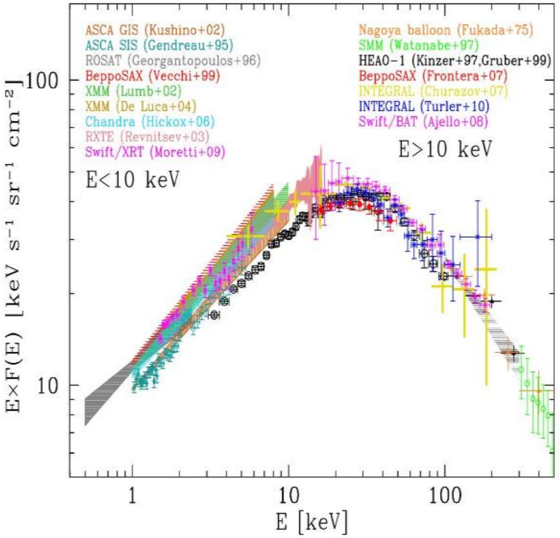
◎ Active galactic nucleus (AGN) population
- ○ unobscured AGN (N_H~0), most observed
- ○ mildly obscured AGN
- ○ Compton-thick AGN (N_H>10^{25}), later proposed

◎ Synthesis model of the CXB
- ○ superposition of AGN population

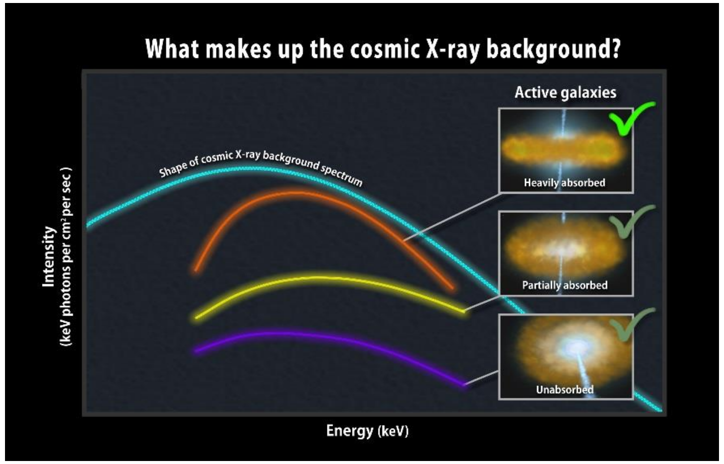
◎ Challenge of the modelling:
- ○ poor knowledge of obscured AGN
- ○ measured CXB spectrum uncertainty: ~ 20%.



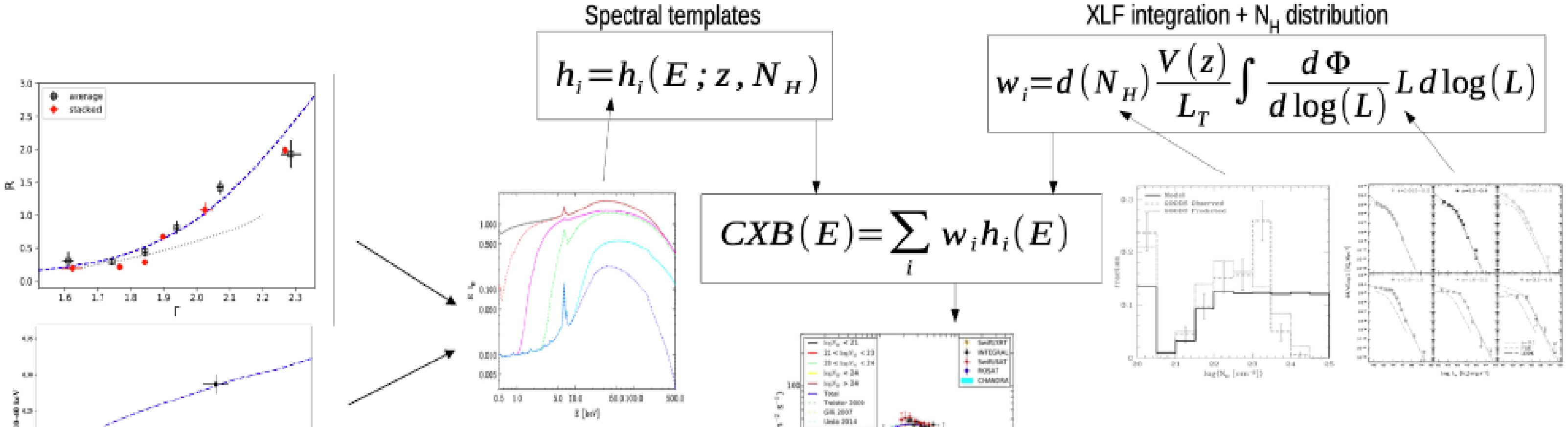
Chandra deep-field observations



CXB spectrum by multi-missions



Credit: NASA



Method based on works of
Comastri et al 1995, Gilli et al 2007

Esposito, V. and Walter, R. 2016

3 CXB measuring approaches

◎ General idea:

- expose the sky regions (preferably blank sky),
- filter out relevant contamination:
  non-X-ray background and known discrete sources;
- distinguish all components registered in the detector.

◎ Approach 1: ASCA/SIS, Beppo-SAX and RXTE/PCA

- deep exposure on high latitude blank sky regions
  to register the CXB flux;
- same level of exposure on the dark side of the Earth
  employed as an estimation of the instrumental background.

◎ Approach 2: HEAO-1

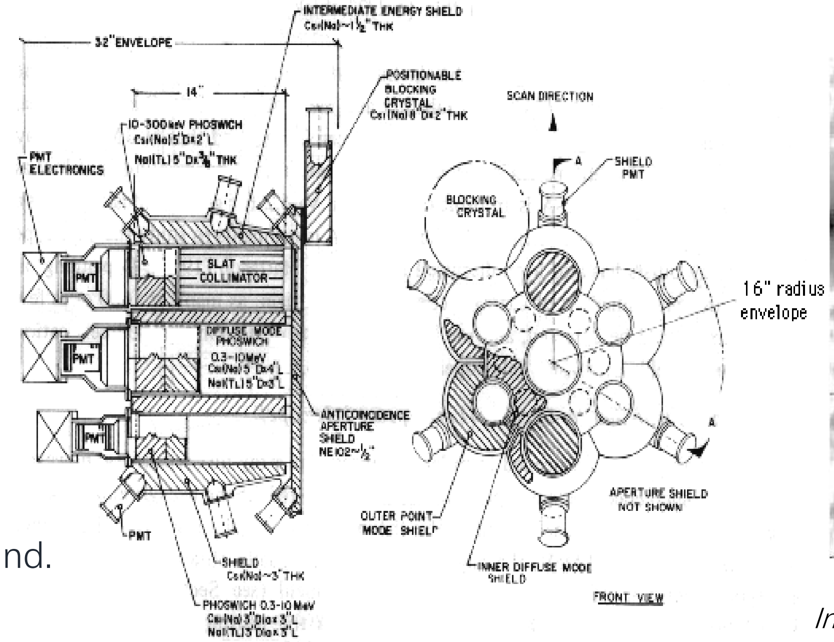
- active collimator: CsI active anticoincidence shield;
- movable shutter (CsI/NaI) to introduce modulation.

◎ Approach 3: INTEGRAL, Swift/BAT

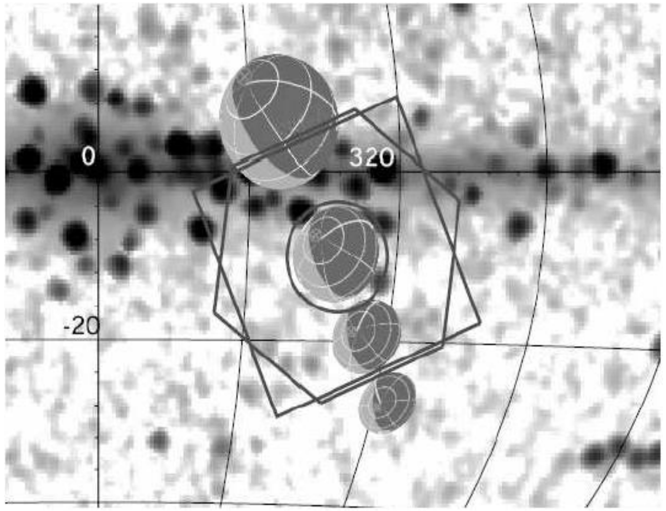
- Earth occultation to modulate all components.

◎ Remaining difficulties:

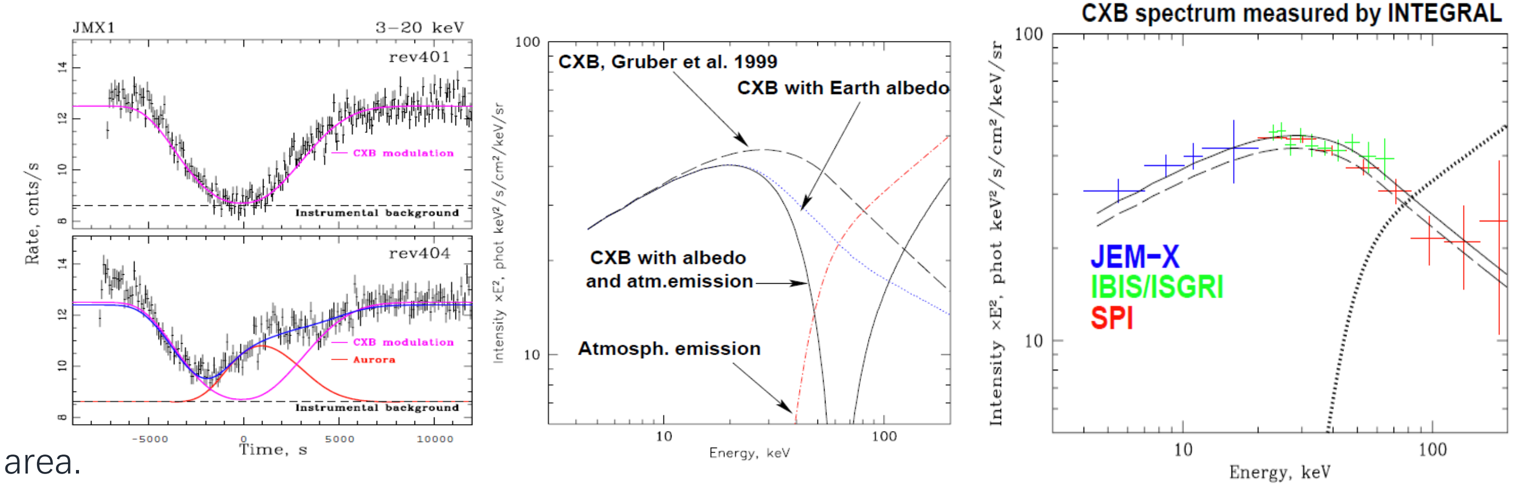
- residual background;
- inaccurate energy calibration;
- poor knowledge of detection efficiency and collecting area.



HEAO-1 A4 instrument layout @ HEASARC



Integral Earth occultation @ E. Churazov et al 2007



Integral Earth occultation @ E. Churazov et al 2007

4 EQUATOR CXB detector

◎ Monitor Vsego Neba (MVN) proposed to the ISS

- passive collimator / shutter : Sn-Cu-Al sandwich;
- 1 mm CdTe crystal (6-70 keV) + charge amplifier ASICs;
- 4 tubes, ARF~4.5 cm^2/tube at 30 keV, FoV 8.55 deg^2.

◎ Equator (inspired by MVN)

- same idea of passive collimator / shutter;
- 2 cm $CeBr_3$ crystal (10-100 keV) + SiPM readout;
- 18 tubes, ARF ~4.5 cm^2/tube at 30 keV, FoV 26 deg^2.

◎ Improvements:

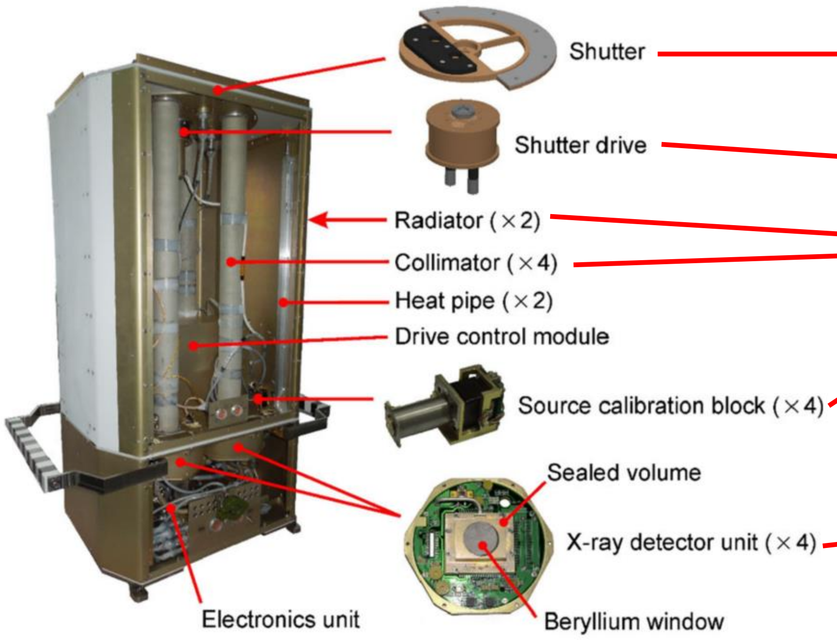
- bigger collecting area, more active exposure;
- 2 counter-rotating shutters: compensate the torque;
  reveal the emissivity of shutter/collimator; and handle calibration sources;
- wider energy coverage, possible extending to 511 keV even to MeV.

◎ Calibration: sources attached beneath the top shutter

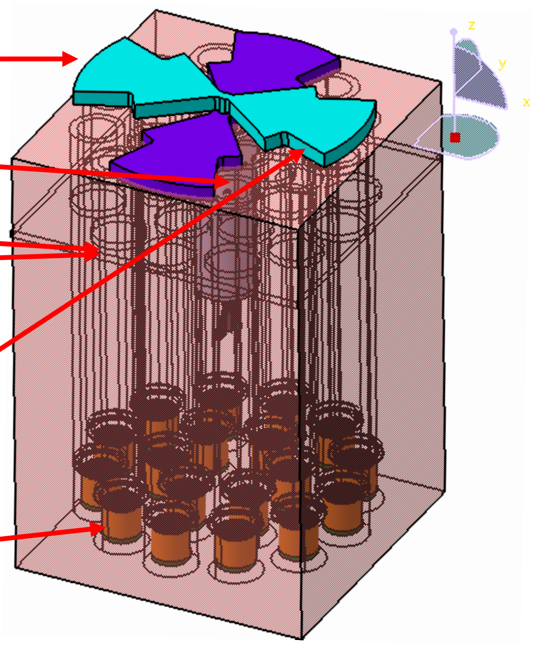
- AM-241+ tagged β^+ source -> energy, detection efficiency calibration.

◎ Resource requirements

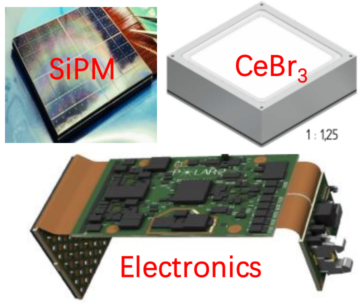
- dimension: 12-16 Units (CubeSat standard);
- mass: ~16 kg;   mission time: 2-5 years;
- power: ~20 Watts;   data volume: 2 GB / day;
- orbit preference: equatorial / low-inclination orbit;
- readiness: 1-1.5 year-> flight model (ground calibration + space qualification).

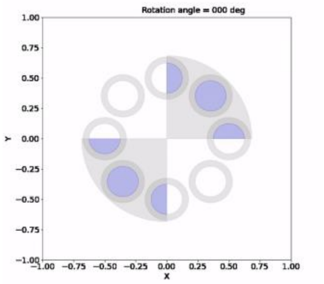


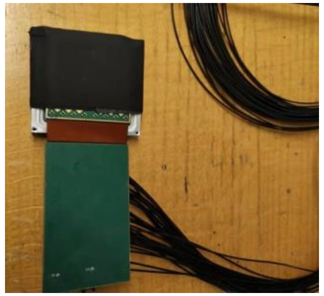
MVN : Serbinov, D. V. et al. 2021



Equator integrated CAD model







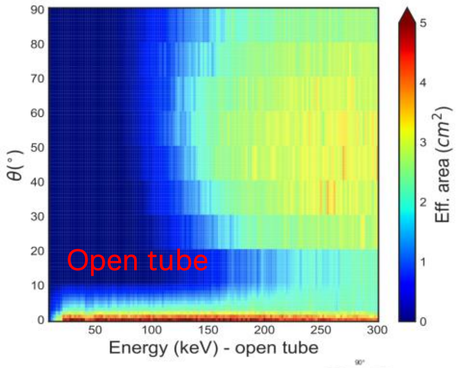
Spectrometer prototype

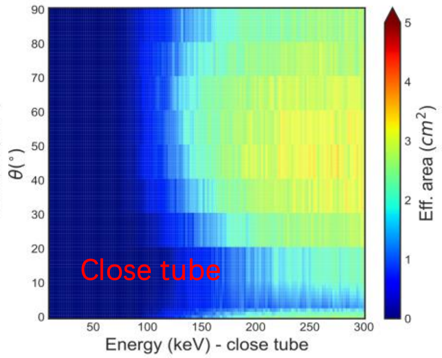
Collimator tube prototype

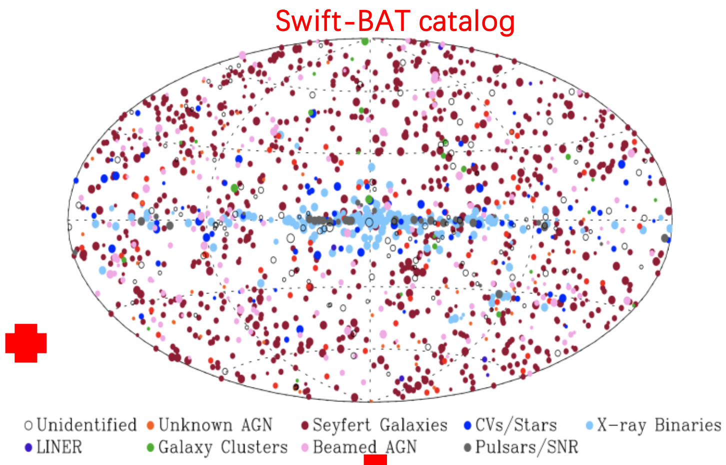
Wheel system prototype

4 EQUATOR CXB detector

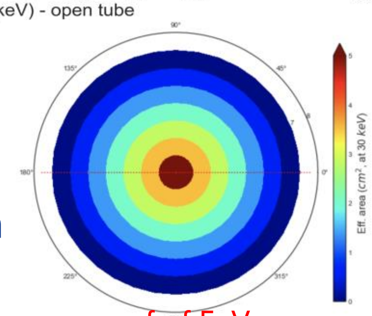
◎ Effective area (arf)
- ○ maximum arf ~5 cm^2;
- ○ collimator cut < 100 keV off-axis photons;
- ○ shutter cut < 150 keV on-axis photons.

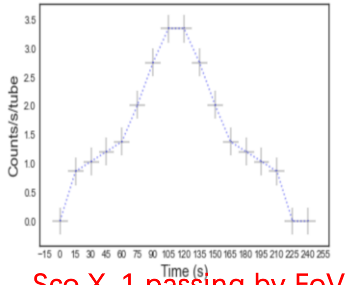


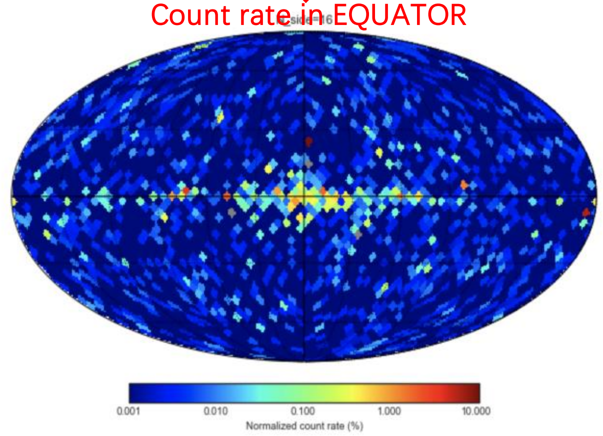




◎ How to measure/subtract Background (B)
- ○ close tubes monitoring B constantly;
- ○ open tubes minus close tubes;
- ○ simulation: 0.2 cnts/cm^2/s/keV/tube.



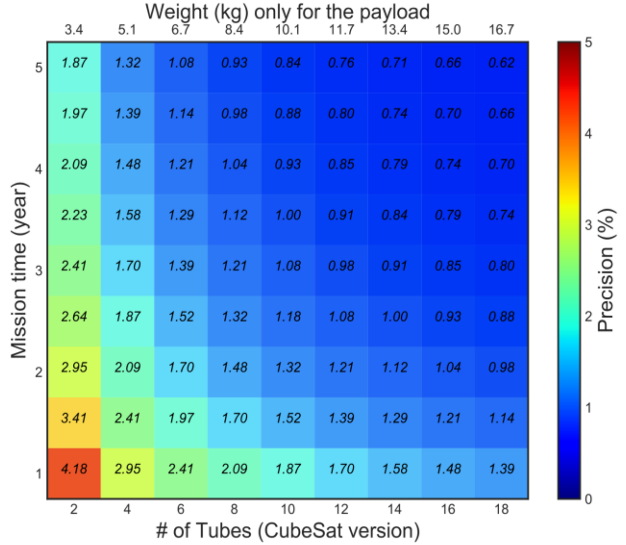


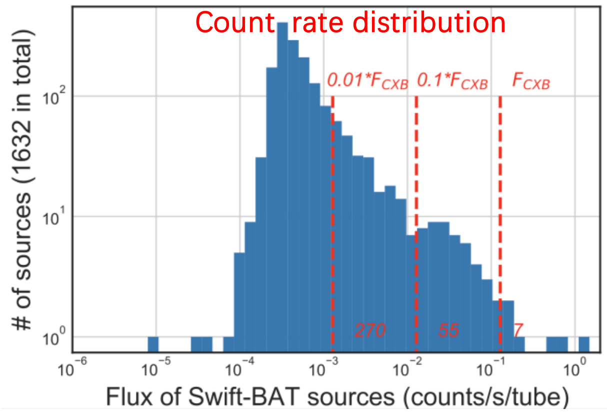


◎ How to measure/subtract Sources (S) contamination
- ○ passing by FoV leaves modulation of the sources;
- ○ simulation: Swift-BAT 105-month catalogue;
  cut |Glat| < 10; cut SNR > 200.

◎ How to measure/extract CXB (C)
- ○ All registered counts (A)
- ○ C ≅ A-B-S (systematics can be well studied by tube array)
- ○ Simulation: 0.128 counts/s/tube

◎ Statistical/systematic precision (P): 1% ⇐ $\frac{\sqrt{C+B+S}}{C}$
- ○ Mission time (T), Number of tubes (N)
- ○ Gradient: P~ a/sqrt(T) / P~ a/sqrt(N)





4 EQUATOR CXB detector

◎ Isotropic CXB measurement:

- reach 1% precision for 10-100 keV :
  resolving the CXB into AGNs + improve cross-calibration precision among instruments;
- observation at >100 keV, up to MeV :
  offering a sight on the CXB contribution of time-integrated Hawking radiation (HR) of primordial black holes (PBHs);
- measuring 511 keV from the Galactic center/plane and its vicinity region :
  a wealth of information on the temperature, density, composition, and dynamics of the source region.

◎ Anisotropic CXB measurement (dipole):

- Compton-Getting effect (dipole amplitude $\Delta = 0.0042$);
- remaining large-scale structure of the local Universe ($0.0023 \lesssim \Delta \lesssim 0.0085$).

◎ Monitoring luminous X-ray sources:

- monitoring variability of sources -> to gain knowledge about fundamental astrophysics;
- calibrate “standard candle” (like the Crab) for cross-calibration

◎ Gamma-Ray Burst (GRB) detection

- Short GRBs have generally harder spectra and peak energies (~490 keV)
- possibly associated with Gravitational Wave event (like Binary Neutron Star merger, 2017ApJ...848L..13A);
- such GRBs could penetrate the platform structure/instrument housing, and reach the sensitive detector;
- Missions like Integral and Insight-HXMT have successfully employed this idea to monitor GRBs with nearly omnidirectional FoV

Summary and outlook

- Measuring CXB requires precise instrumental calibration and background modelling
- Science topics behind gain us knowledge of the accretion power in the Universe
- EQUATOR will employ collimated spectrometer with moving shutter approach
- A 12-16 U CubeSat mission with >2 year could reach 1% precision of the CXB measurement
- We need 1-1.5 year to be prepared for launching such a CubeSat mission