GEANT4 Simulations of the LAXPC Detectors

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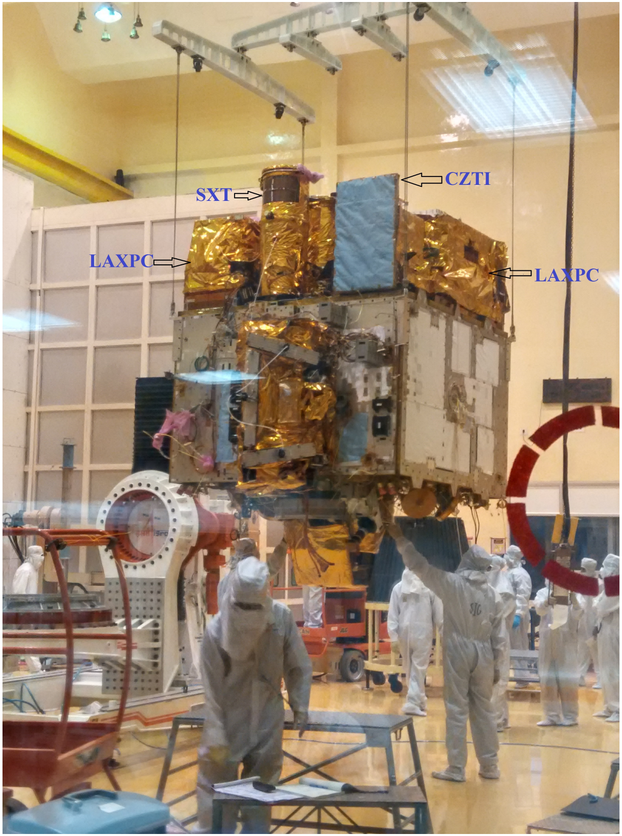


Integrated Astrosat satellite at ISAC, Bangalore
(21 May 2015)

GEANT4 simulations of LAXPC detector were used to estimate

- Field of view of detector
- Efficiency and effective area of the detector
- Efficiency of background rejection
- Resolution and channel No. as a function of energy by fitting observed spectra for radioactive sources
- Response matrix of the detector

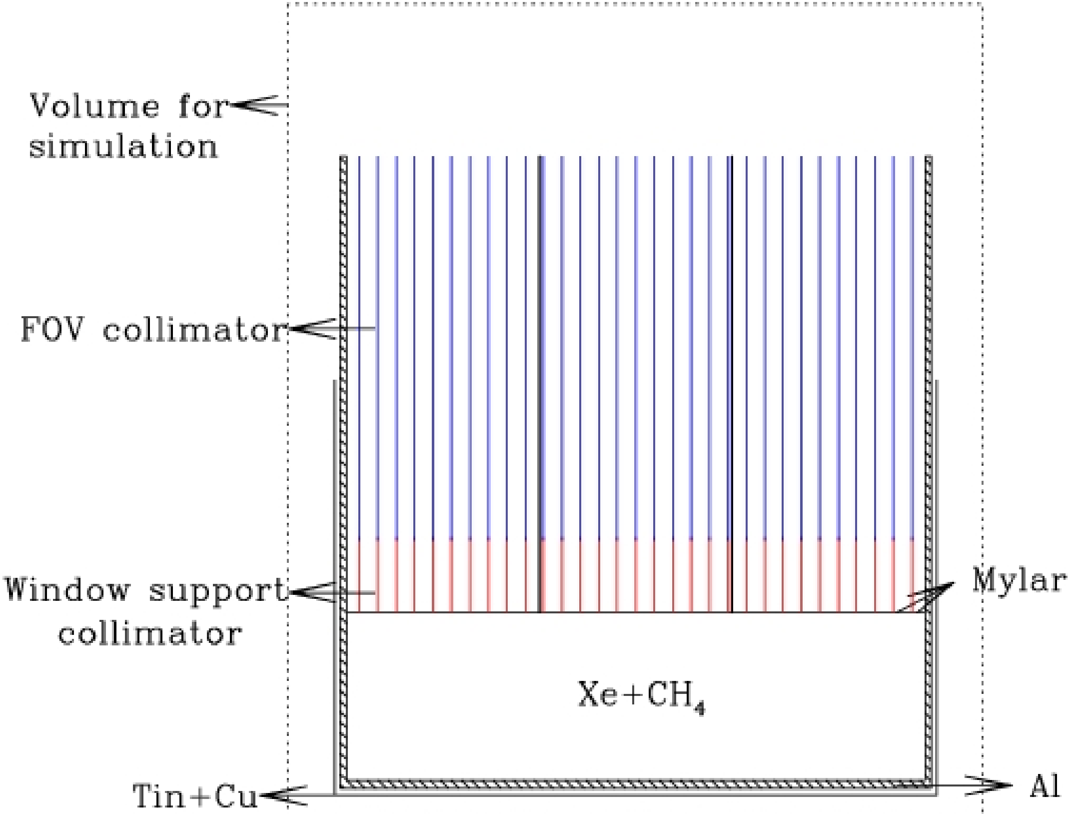
- LAXPC payload consists of 3 large area X-ray proportional counters

- Detector size: $100 \times 39 \times 16.5$ cm filled with a mixture of Xenon (90%) and Methane (10%) at a pressure of 2 atmospheres.

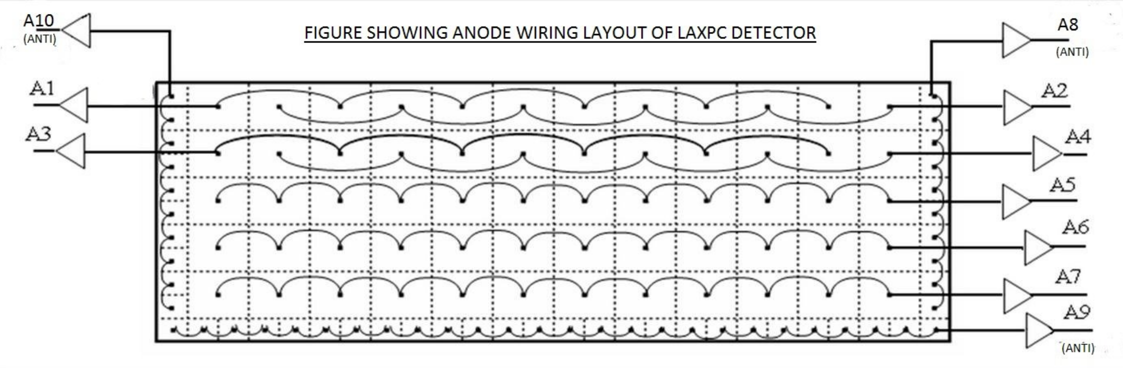
- Top of the detector is covered by a $50\ \mu$m thick Mylar window

- Above the Mylar window there is a window support collimator of height 7.5 cm and the field of view collimator of height 37 cm. These collimators have mesh with a pitch of 7 mm.

- Simulations use a volume of $120 \times 60 \times 80$ cm enclosing the entire detector.


Volume for simulation
FOV collimator
Window support collimator
Mylar
Xe+CH$_4$
Tin+Cu
Al

- Window support collimator is made of aluminium sheets
- The field of view collimator is made of tin sheet sandwiched between copper and aluminium sheets using epoxy
- Five sides of the detector are covered by Tin shield of thickness 1 mm, coated with Copper (50 μ)
- Each layer has 12 anode cells of size $100 \times 3 \times 3$ cm



Main Anodes : A1–A7 in 5 layers

Veto Anodes : A8, A9, A10 on 3 sides

No Veto Anodes on two small sides (39×16.5 cm)

Mylar and collimator on the top side

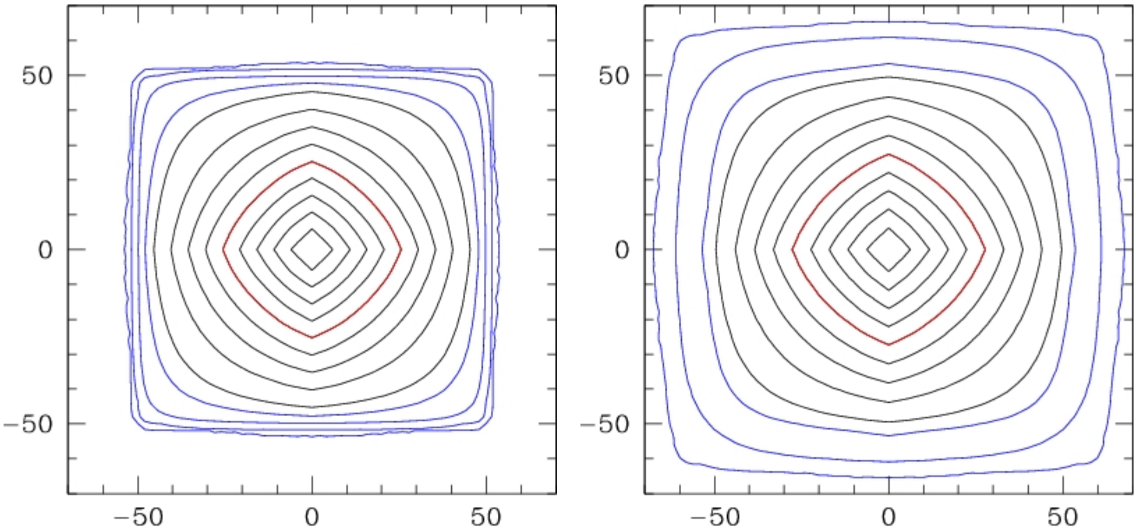
- GEANT4 simulation of 10^6 photons with fixed energy.
- Initial Photon trajectory is normal to detector top (except for FOV and background part)
- Uniformly distributed over detector area.
- Simulations with and without the collimators (and shield) are done.

  Collimator is required for FOV, effective area and background calculations.
- For background simulation the flux is assumed to be uniform and isotropic and energy uniformly distributed in a specified interval.

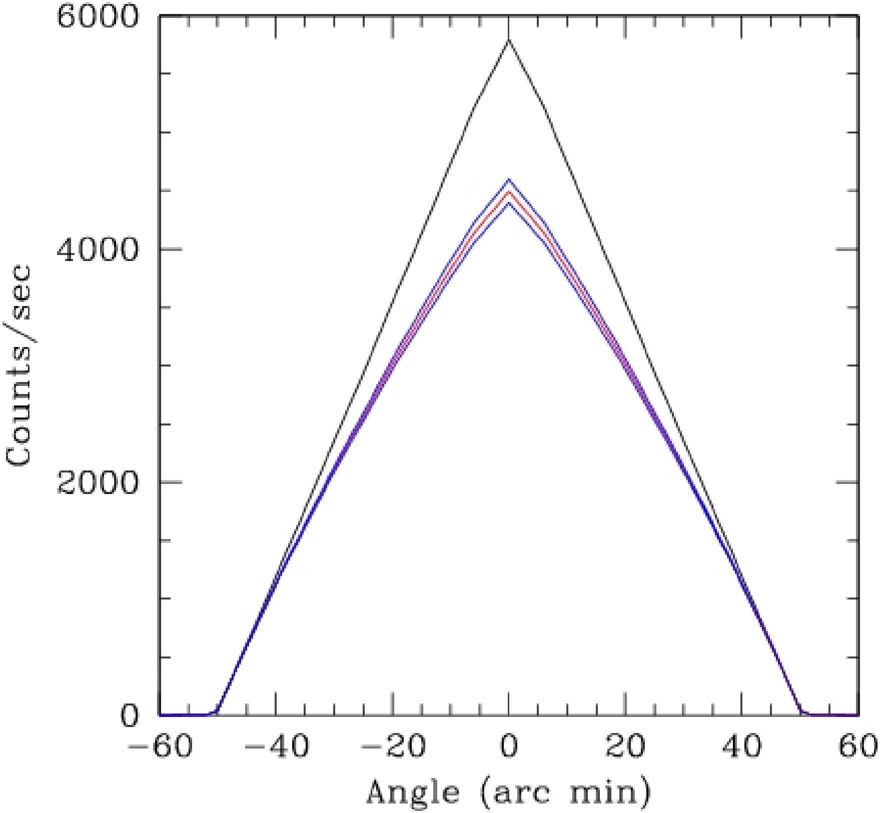
To reject background events the following logic is implemented which is consistent with the processing electronics:

- Any event that is recorded in veto-anodes (A8–A10)
- Any event that deposits more than an upper limit (80 keV) in any anode
- Any event that is recorded in more than 2 main anodes (A1–A7)
- If an event is recorded in two main anodes, then it is accepted only if at least one of the energy is in K-threshold for Xe (30 ± 4.5 keV). If the event is accepted the energies in two anodes are added and it is recorded as a single event of combined energy. Such events can exceed the upper limit of 80 keV.

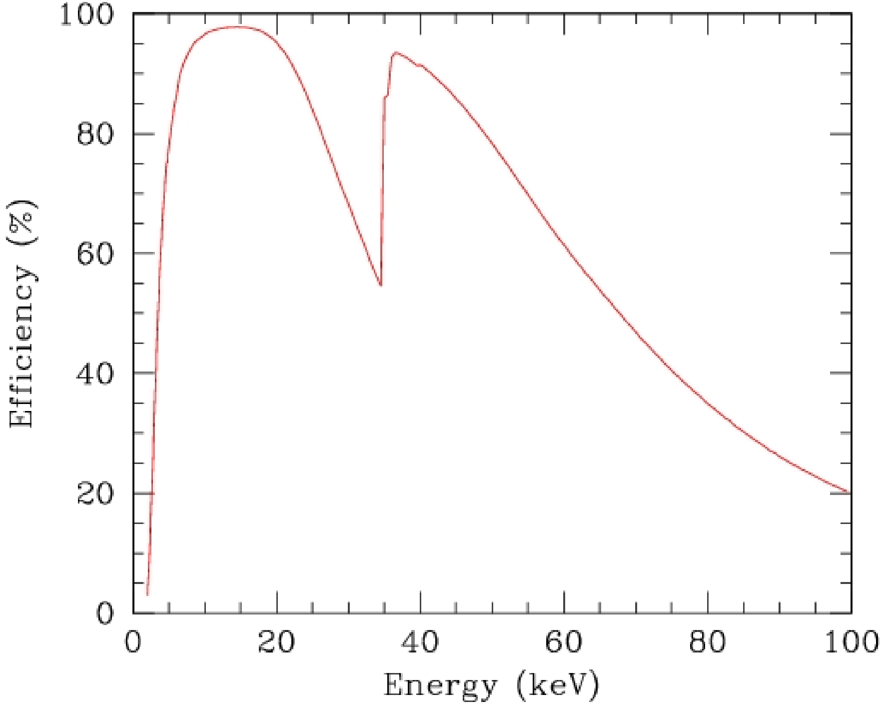
Calibration of the Field of View



15 keV: FWHM $= 43' = 0.72°$ 50 keV: FWHM $= 47' = 0.78°$


6000
4000
2000
0
Counts/sec
−60
−40
−20
0
20
40
60
Angle (arc min)

Detector Efficiency



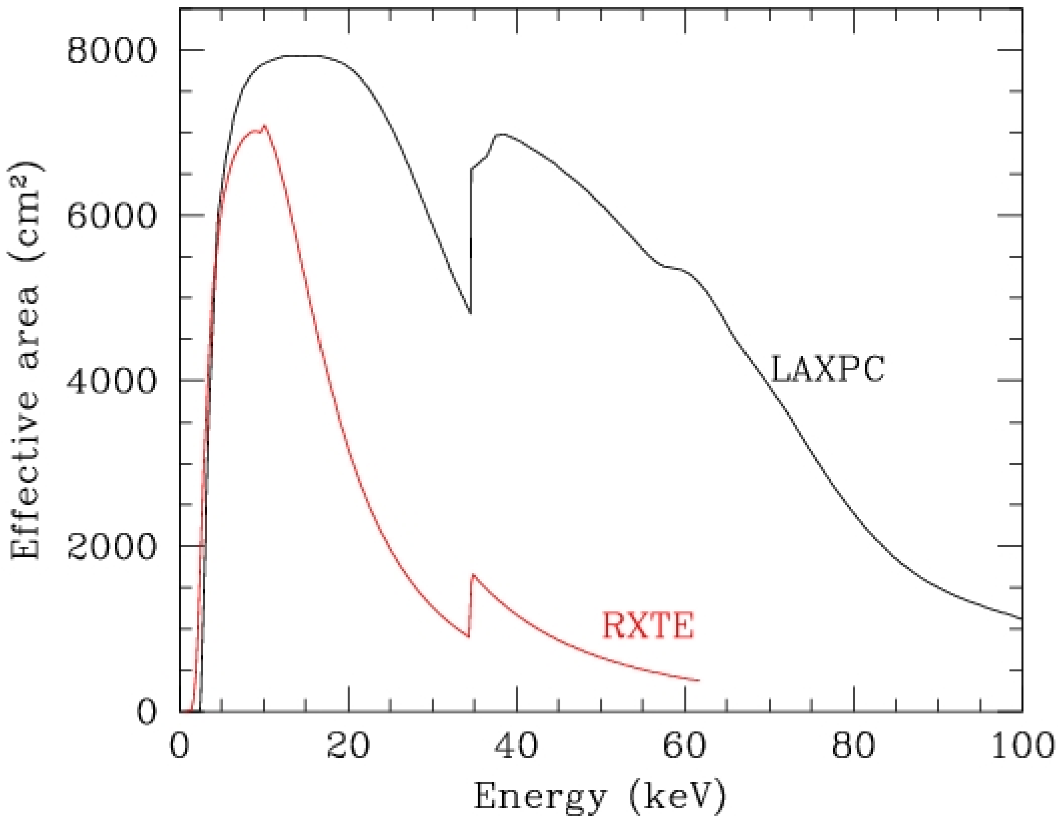
Effective Area

- Geometric area $= 3 \times 100 \times 36 = 10800$ cm^2
- Collimator blocks about 20% of area
- Detector efficiency and imperfections in collimator reduce it further to about 8000 cm^2 at 10–15 keV.
- At lower limit of 3 keV, effective area ≈ 2000 cm^2
- At upper limit of 80 keV, effective area ≈ 2400 cm^2
- Beyond 80 keV events can still register because

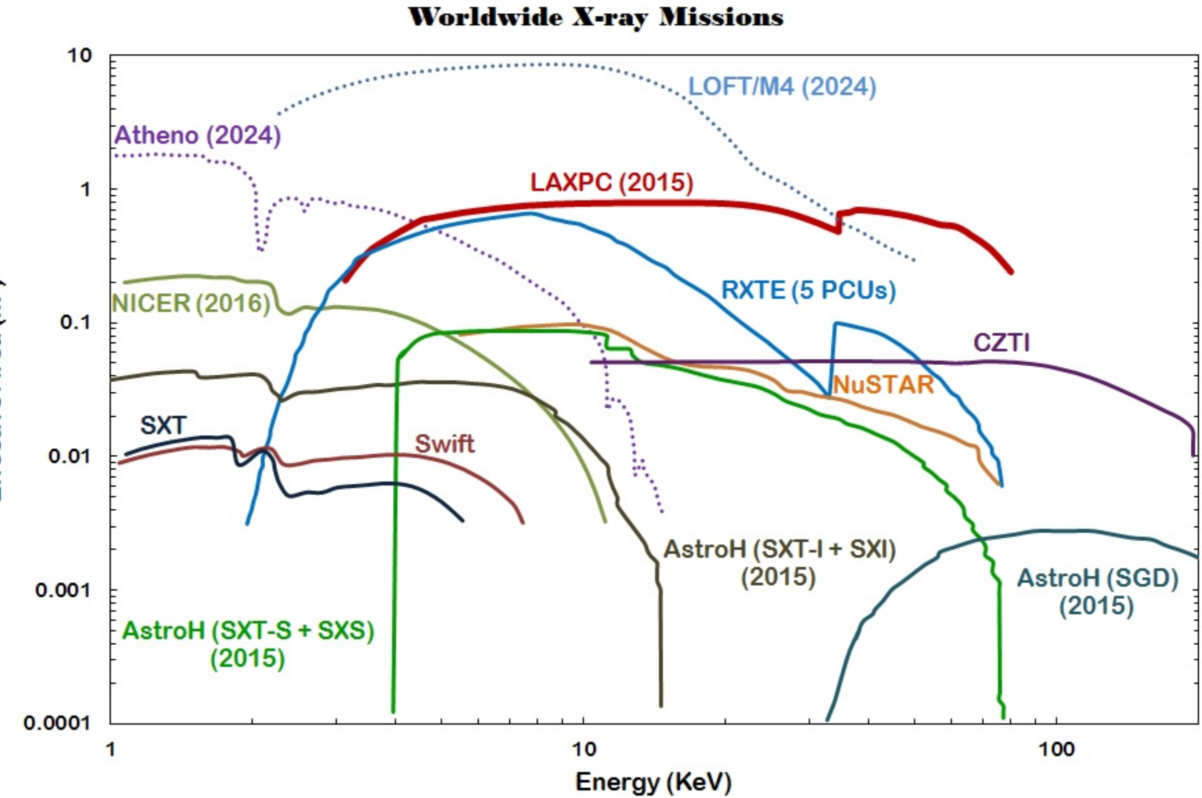
  finite resolution

  K-escape peak at $E - 30$ keV

  double events

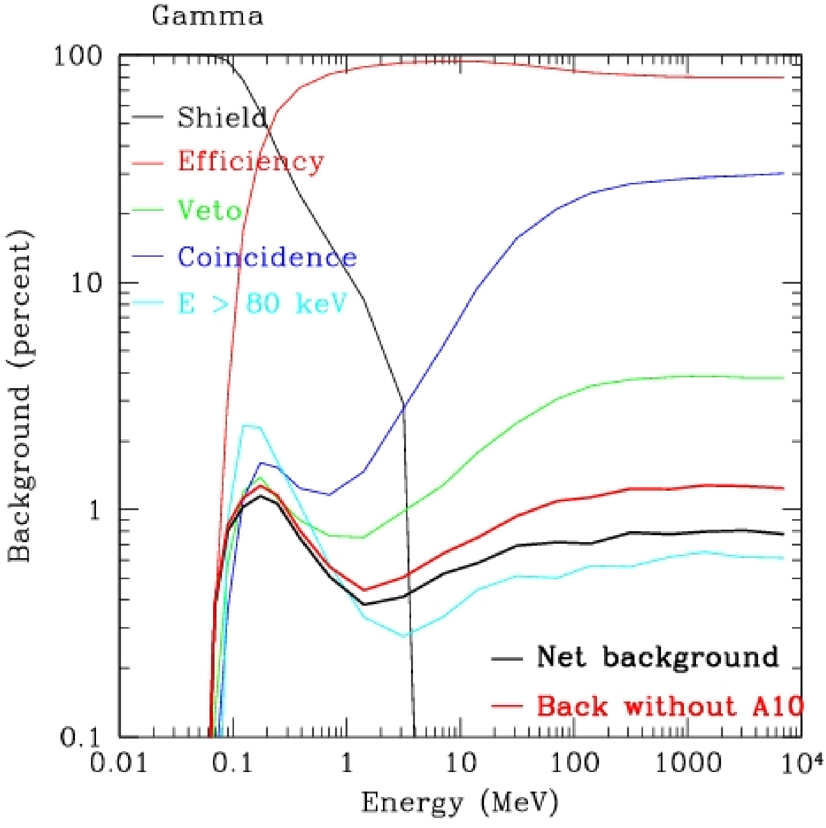


8000
6000
4000
2000
0
Effective area (cm²)
0
20
40
60
80
100
Energy (keV)
LAXPC
RXTE

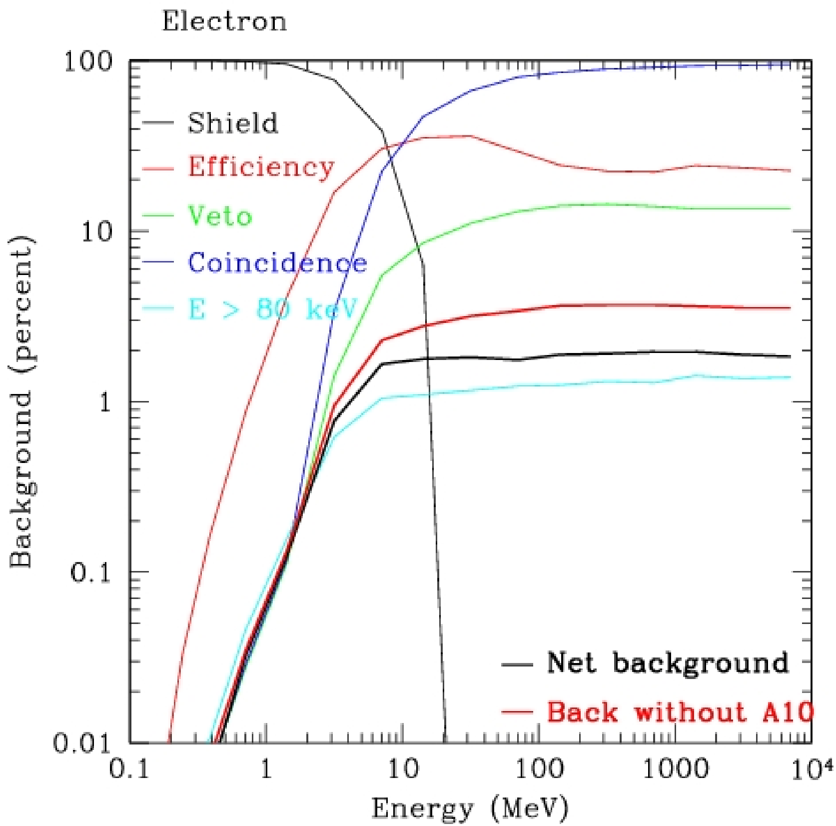

Worldwide X-ray Missions
LOFT/M4 (2024)
Atheno (2024)
LAXPC (2015)
RXTE (5 PCUs)
NICER (2016)
CZTI
NuSTAR
SXT
Swift
AstroH (SXT-I + SXI)
(2015)
AstroH (SGD)
(2015)
AstroH (SXT-S + SXS)
(2015)
10
1
0.1
0.01
0.001
0.0001
1
10
100
Energy (KeV)

Simulation of background

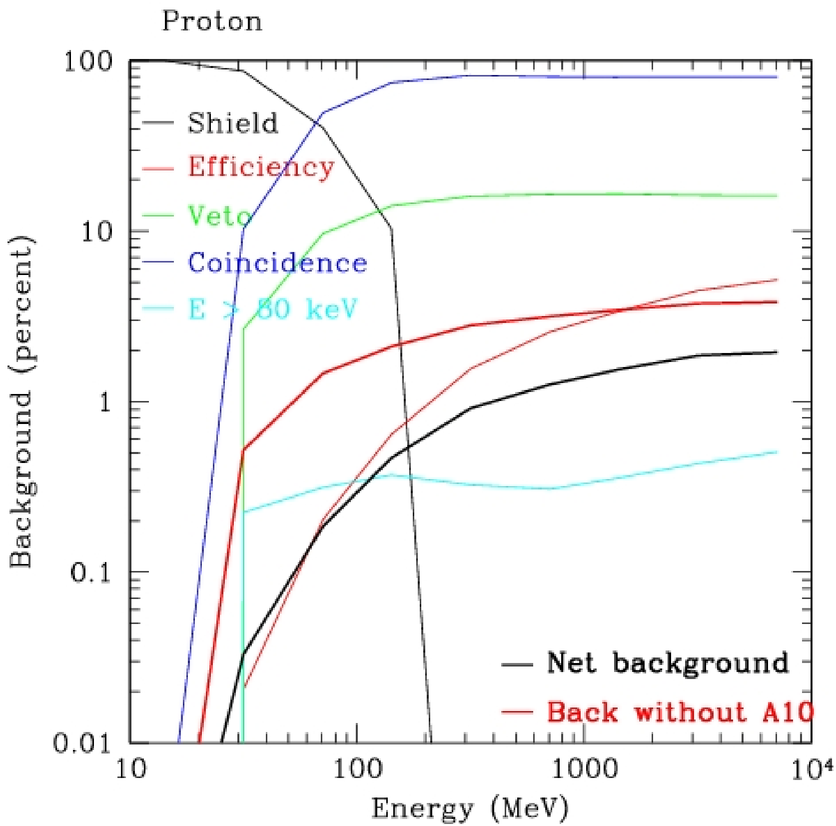
- 10^6 particles uniformly distributed over entire surface area $120 \times 60 \times 80$ cm and in 2π solid angle
  about 233333 ± 1177 particle reach active detector volume $100 \times 39 \times 16.5$ cm
- Following factors contribute to background rejection
  1. The Shield
  2. The Detector efficiency
  3. Coincidence
  4. Veto layers
  5. Energy deposited > 80 keV
- Simulation were done with and without veto-anode A10 as in LX10 detector A10 has been disabled.



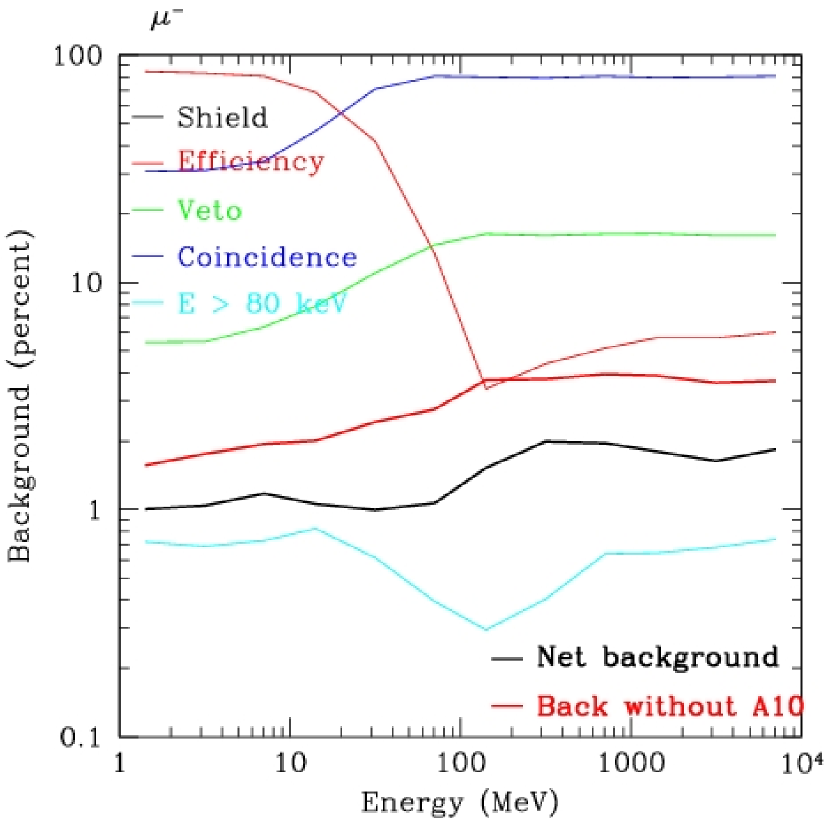
Gamma
Shield
Efficiency
Veto
Coincidence
E > 80 keV
Net background
Back without A10
Background (percent)
Energy (MeV)
100
10
1
0.1
0.01
0.1
1
10
100
1000
10^4



Electron
Shield
Efficiency
Veto
Coincidence
E > 80 keV
Net background
Back without A10
Background (percent)
Energy (MeV)
100
10
1
0.1
0.01
0.1
1
10
100
1000
10⁴



Proton
Shield
Efficiency
Veto
Coincidence
E > 50 keV
Net background
Back without A10
Background (percent)
100
10
1
0.1
0.01
10
100
1000
10^4
Energy (MeV)

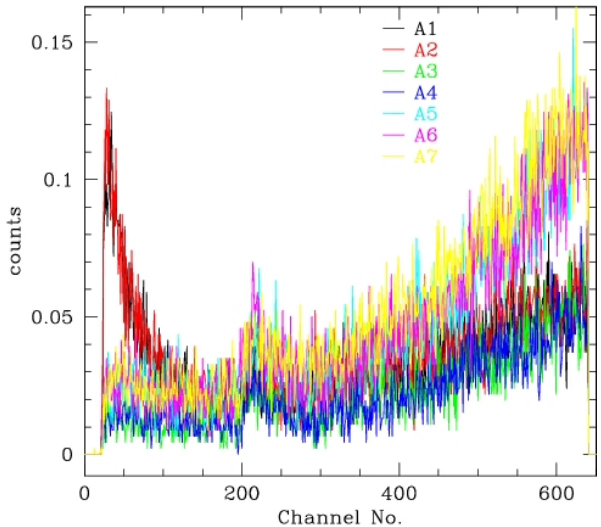


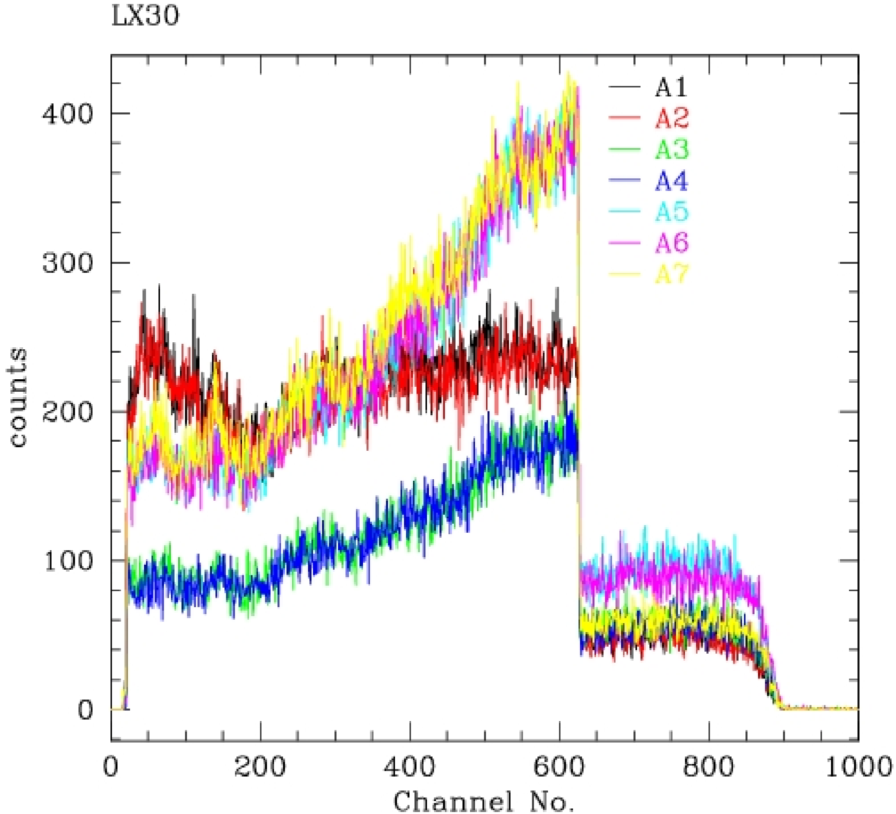
μ⁻
Shield
Efficiency
Veto
Coincidence
E > 80 keV
Net background
Back without A10
Background (percent)
Energy (MeV)
100
10
1
0.1
1
10
100
1000
10⁴

- Background from cosmic diffuse X-ray background

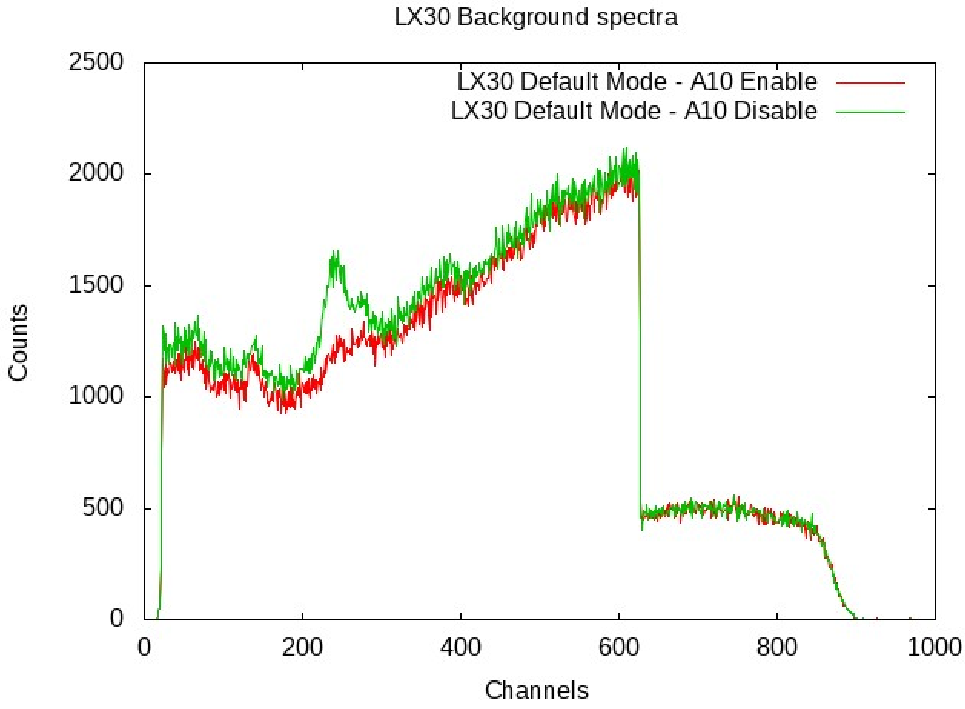
$$\frac{dN}{dE} = 87.4\, E^{-2.3}\ \mathrm{cm^{-2}s^{-1}keV^{-1}steradian^{-1}}$$

gives background 165 s^{-1} in 1 detector





LX30
A1
A2
A3
A4
A5
A6
A7
counts
0
100
200
300
400
0
200
400
600
800
1000
Channel No.



A10 enabled : 146 s^{-1}, A10 disabled : 156 s^{-1}

Detector Response for Radioactive Sources

- Three radioactive sources were used for calibration.
  For Fe^{55} energy of 5.96 keV
  For Cd^{109} energies of 22.1 keV (54.5%), 21.9 keV (28.8%), 24.9 keV (16.7%)
  For Am^{241} energy of 59.6 keV

- For each source, energy deposited in each cell (60 main anodes and 3 veto anodes) during each event is recorded.

- To account for finite resolution, a random number with Normal distribution with 0 mean and $\sigma = E_p \sigma_i$ is added.

- Effective energy in all cells in an anode are added.
  For LX10: For C1, $0.95E_p$ and for C12, $1.05E_p$ was used.

  For A4 C1, $0.74E_p$ was used.

  A10 is disabled.

  For LX20, LX30: For C1 and C12, $0.95E_p$ is used
- Rejection and K-escape logic as used in PE is applied and total energy in each anode is converted to channel No.

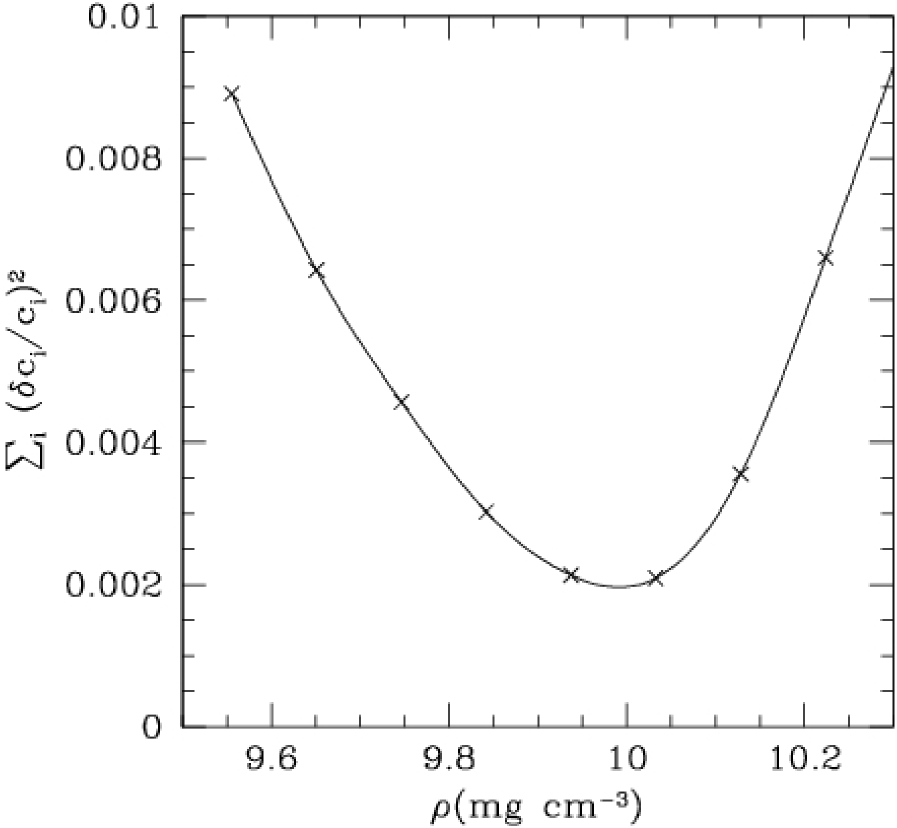
$$n_c = e_1 E_p (1 + e_2 E_p)$$

- The simulated spectrum is compared with observed spectrum after subtracting the background. For normalisation the simulated spectrum is multiplied by a constant to match the total counts under one peak.

- To adjust the density of gas the square of relative difference in total counts for each anode layer for Cd^{107} is minimised

$$\sum_{i=1}^{5} \left(\frac{O_i - S_i}{O_i} \right)^2$$

This corrects for difference in temperature or pressure


0.01
0.008
0.006
0.004
0.002
0
9.6
9.8
10
10.2
$\sum_i (\delta c_i / c_i)^2$
ρ(mg cm^{-3})

- Since the peak position in simulation may not exactly match that in observed spectra for each anode, while comparing a small shift by a few channels in simulated spectra is made to get best match.

- Parameters to be determined : $e_1, e_2, \sigma_1, \sigma_2, \sigma_3, \sigma_4$

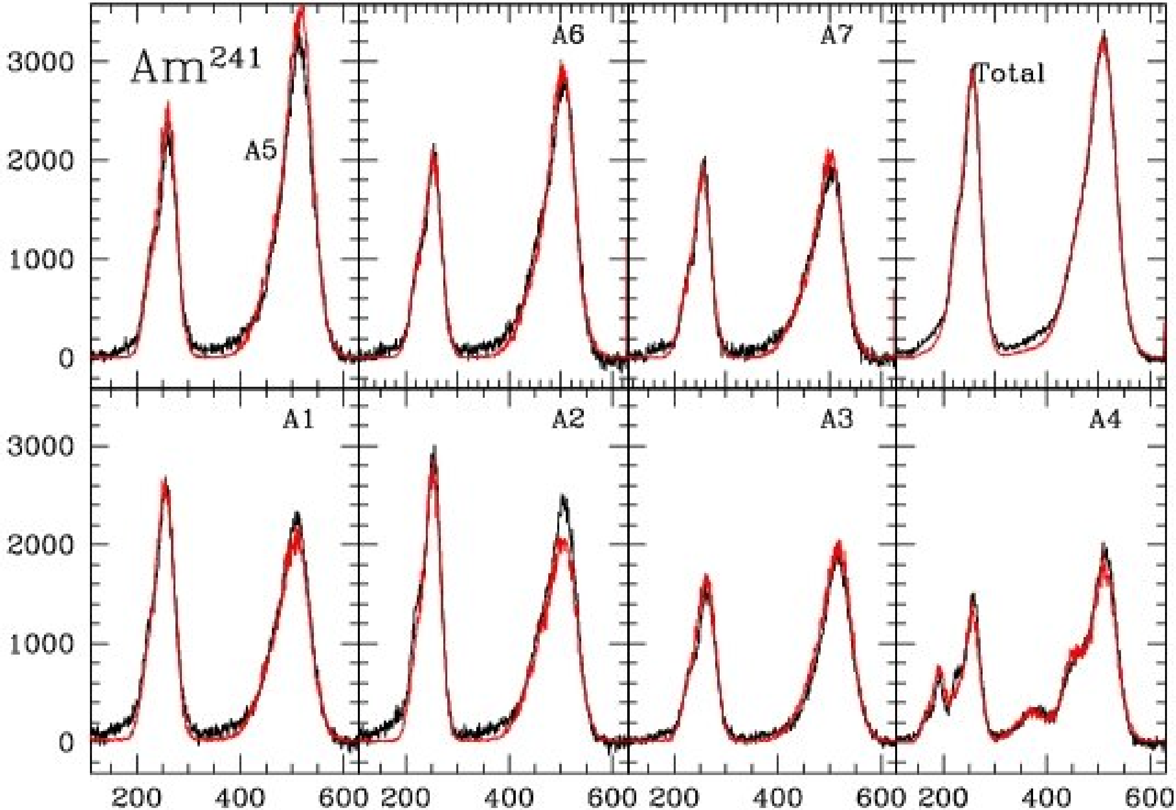
  $e_1, e_2, \sigma_3, \sigma_4$ are determined by best fit to Am^{241} spectrum

  σ_1, σ_2 are determined by best fit to Fe^{55} and Cd^{109} respectively, keeping e_1, e_2 fixed.

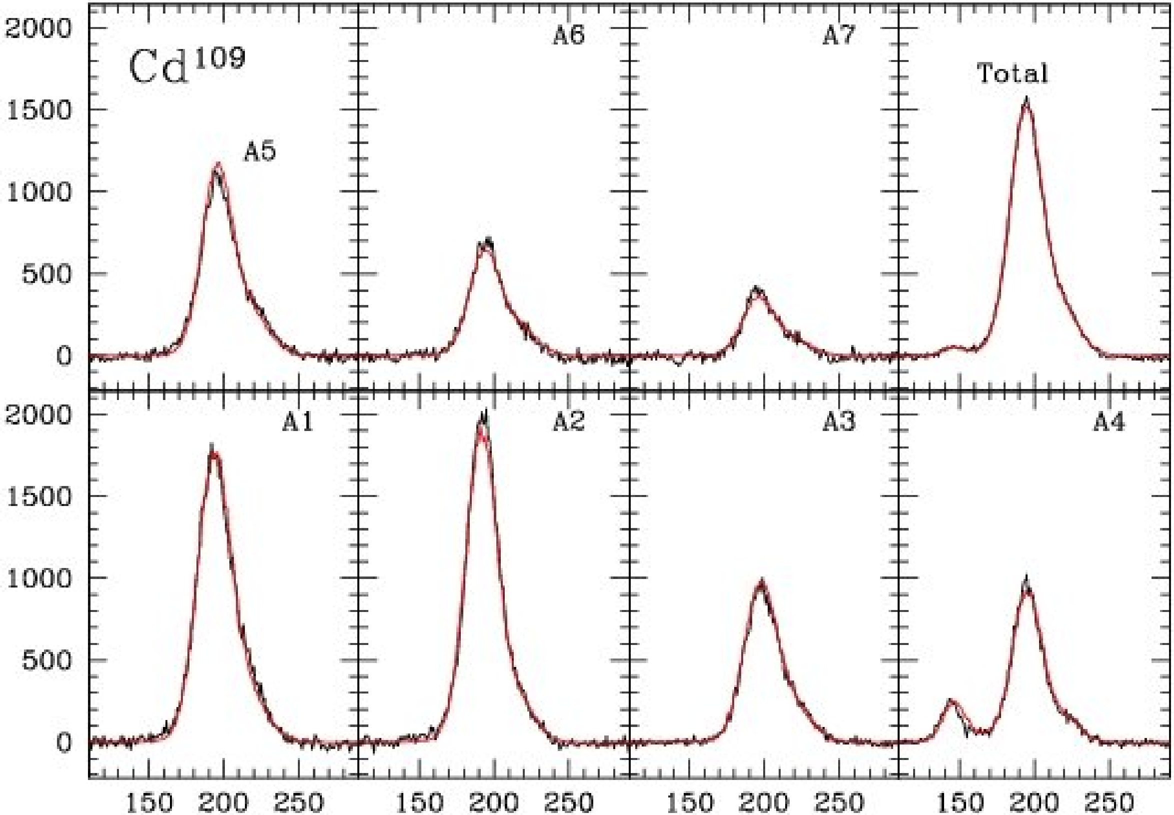
- Finally the channel to energy mapping is determined by fitting

$$n_c = e_0 + e_1 E_p (1 + e_2 E_p)$$

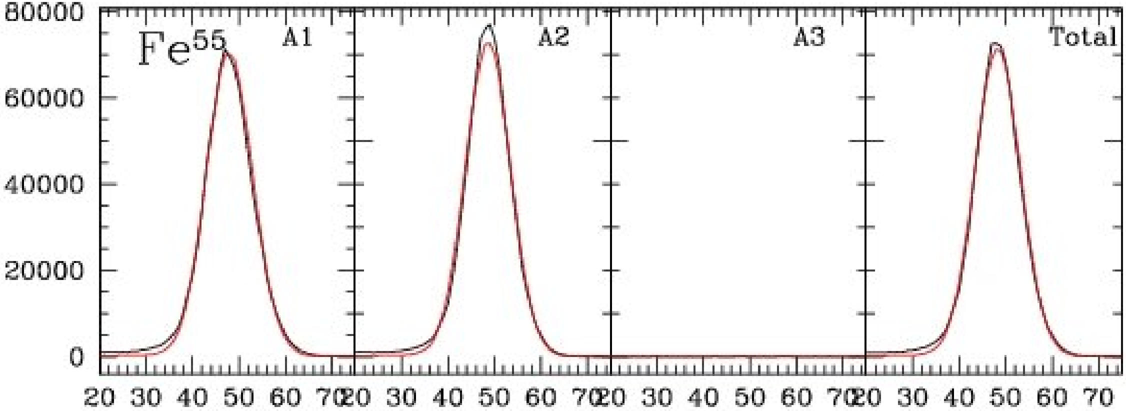
  Here, only e_0, e_1 are fitted as e_2 is determined earlier.



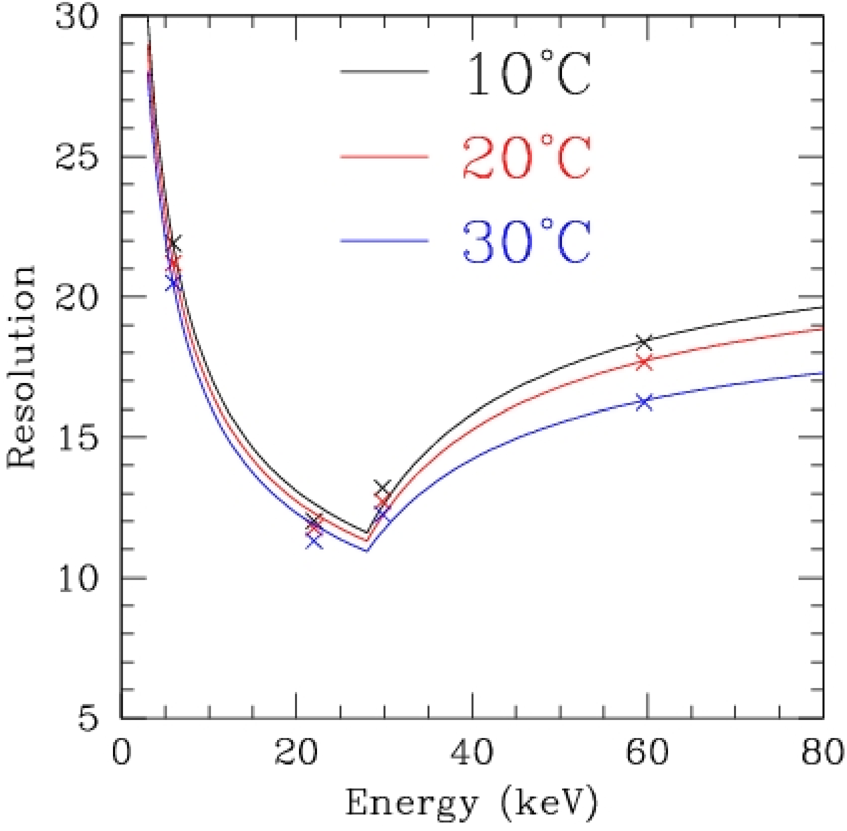
Am^{241}
A5
A6
A7
Total
A1
A2
A3
A4
3000
2000
1000
0
200
400
600



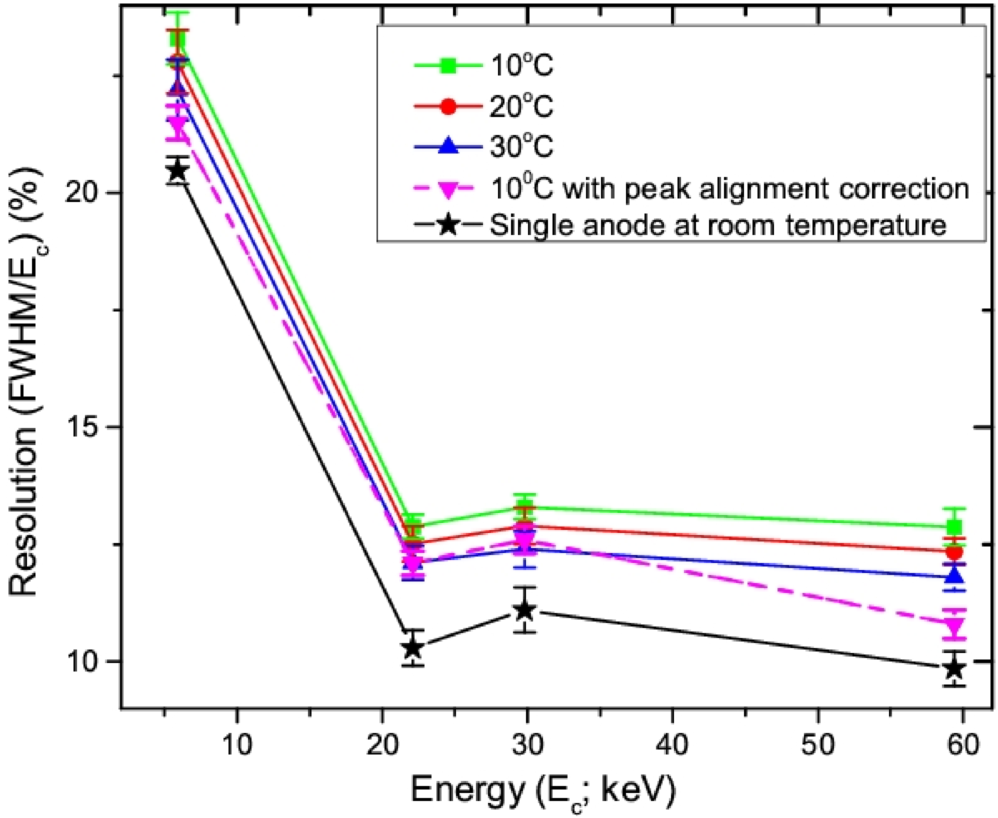
Cd^{109}
A5
A6
A7
Total
A1
A2
A3
A4
2000
1500
1000
500
0
150
200
250



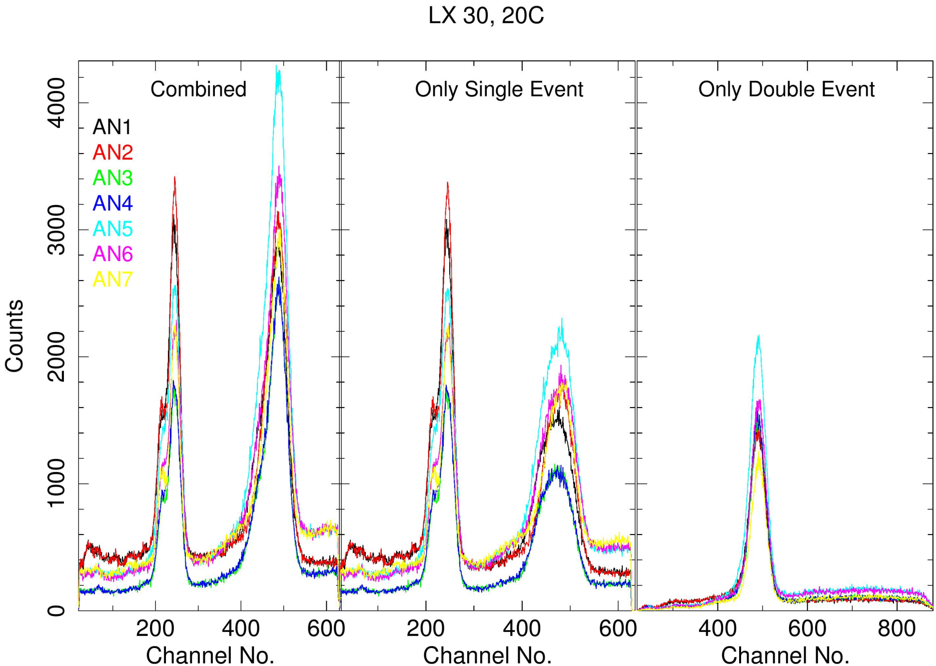
The resolution as a function of energy is determined by fitting a linear spline with 3 knots to $\sigma^2(E^{-1})$

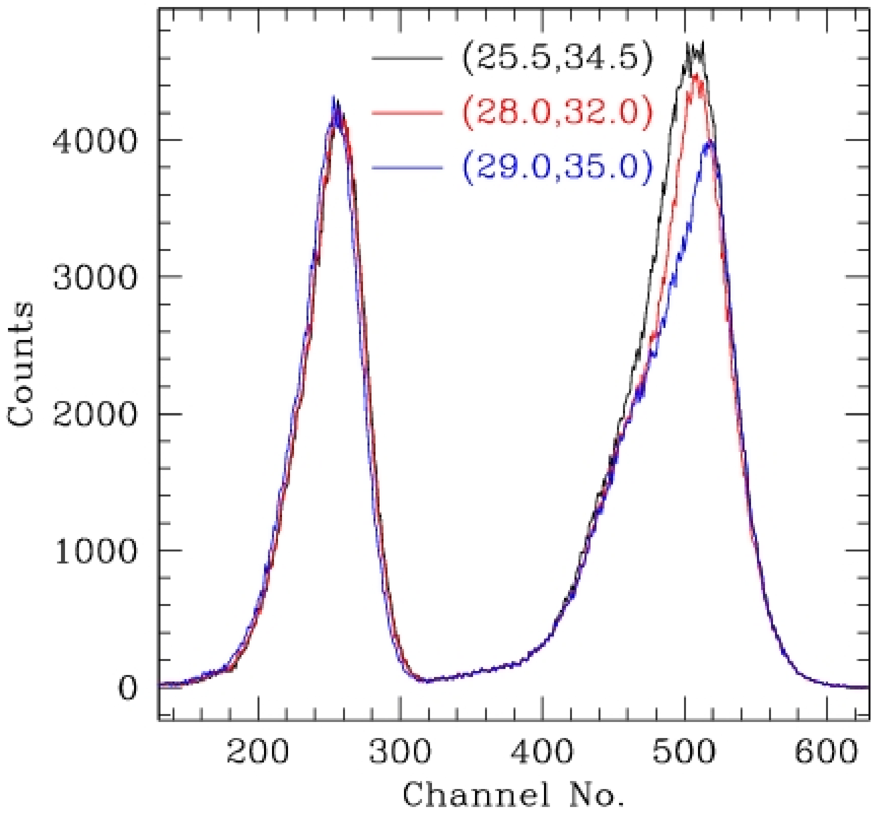


10°C
20°C
30°C
Resolution
Energy (keV)
30
25
20
15
10
5
0
20
40
60
80



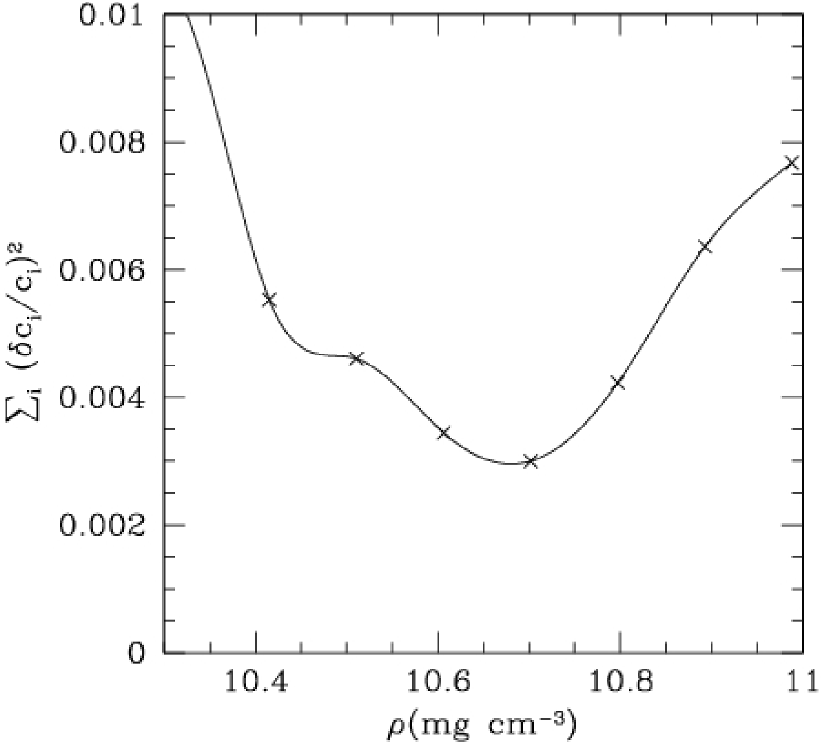
10°C
20°C
30°C
10°C with peak alignment correction
Single anode at room temperature
Resolution (FWHM/E$_c$) (%)
20
15
10
10
20
30
40
50
60
Energy (E$_c$; keV)

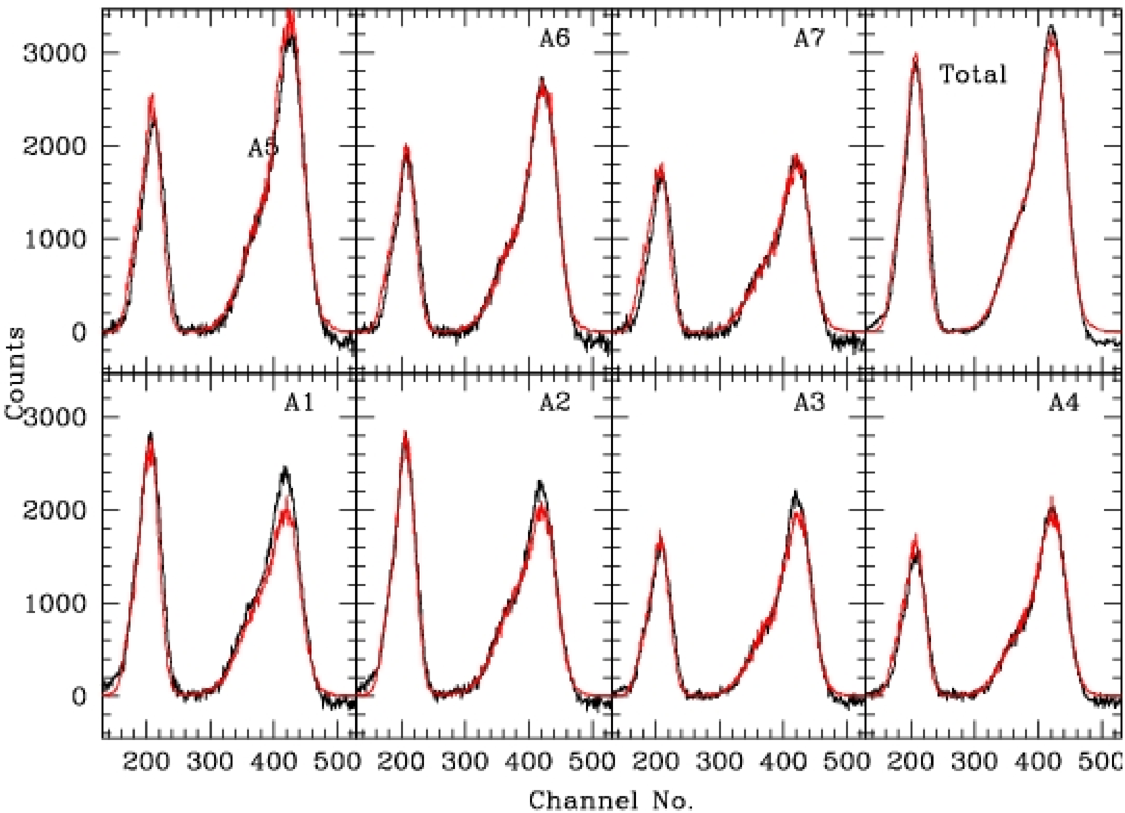

LX 30, 20C
Combined
Only Single Event
Only Double Event
AN1
AN2
AN3
AN4
AN5
AN6
AN7
Counts
0
1000
2000
3000
4000
200
400
600
200
400
600
400
600
800
Channel No.
Channel No.
Channel No.



(25.5,34.5)
(28.0,32.0)
(29.0,35.0)
Counts
4000
3000
2000
1000
0
200
300
400
500
600
Channel No.

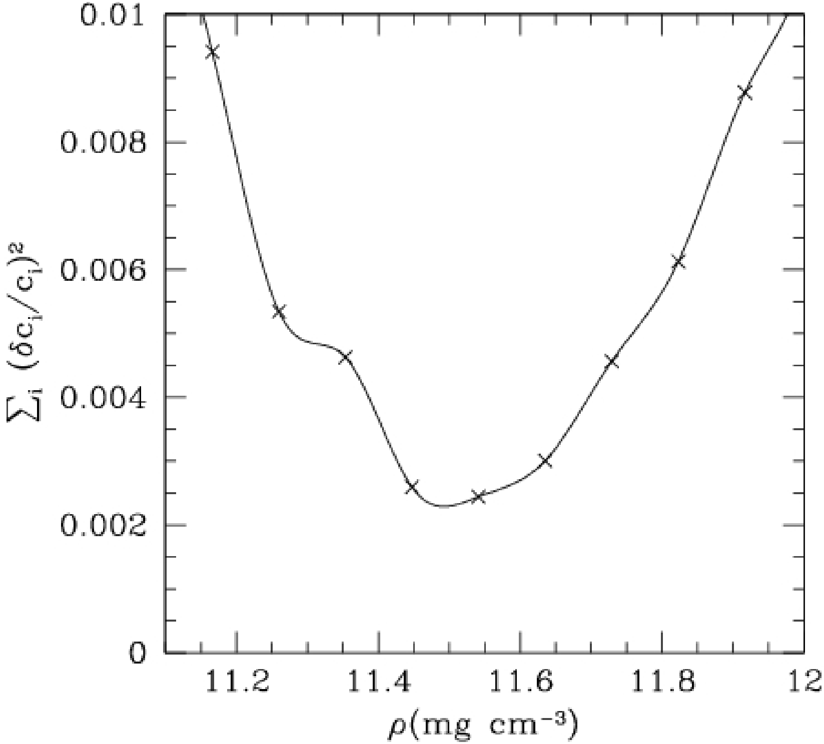
LX20 Detector

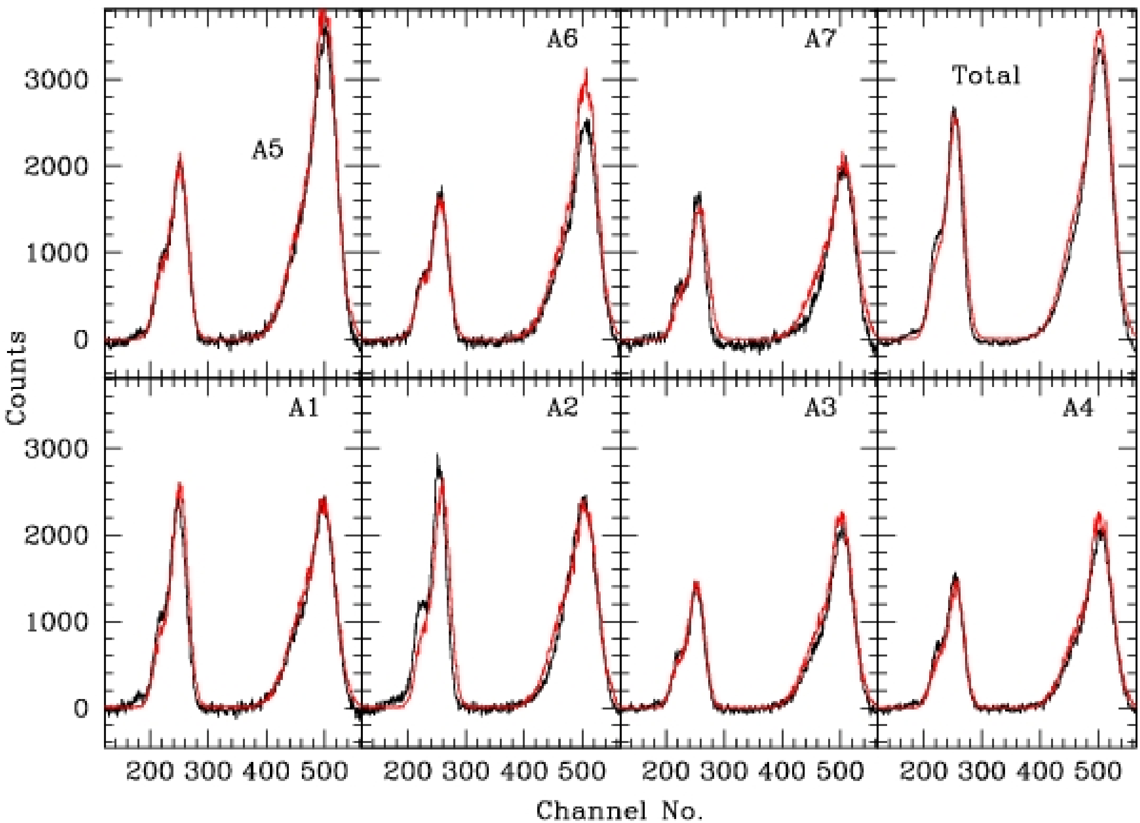




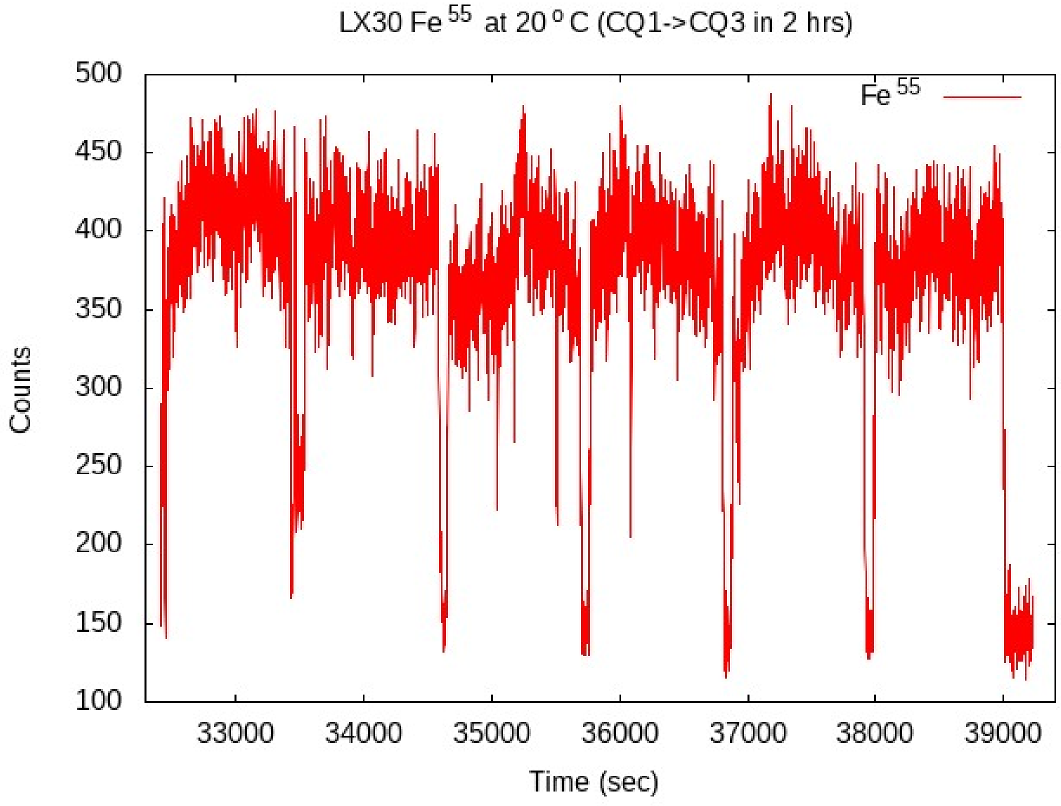
A5
A6
A7
Total
A1
A2
A3
A4
Counts
3000
2000
1000
0
200
300
400
500
Channel No.

LX30 Detector

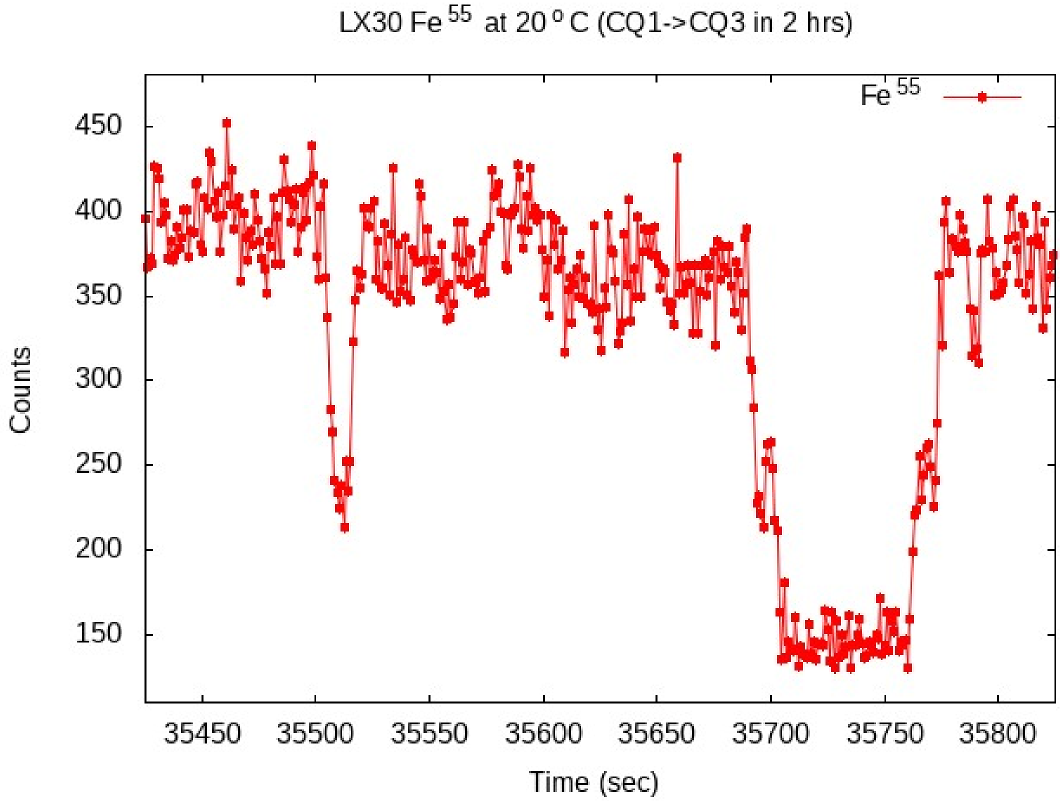




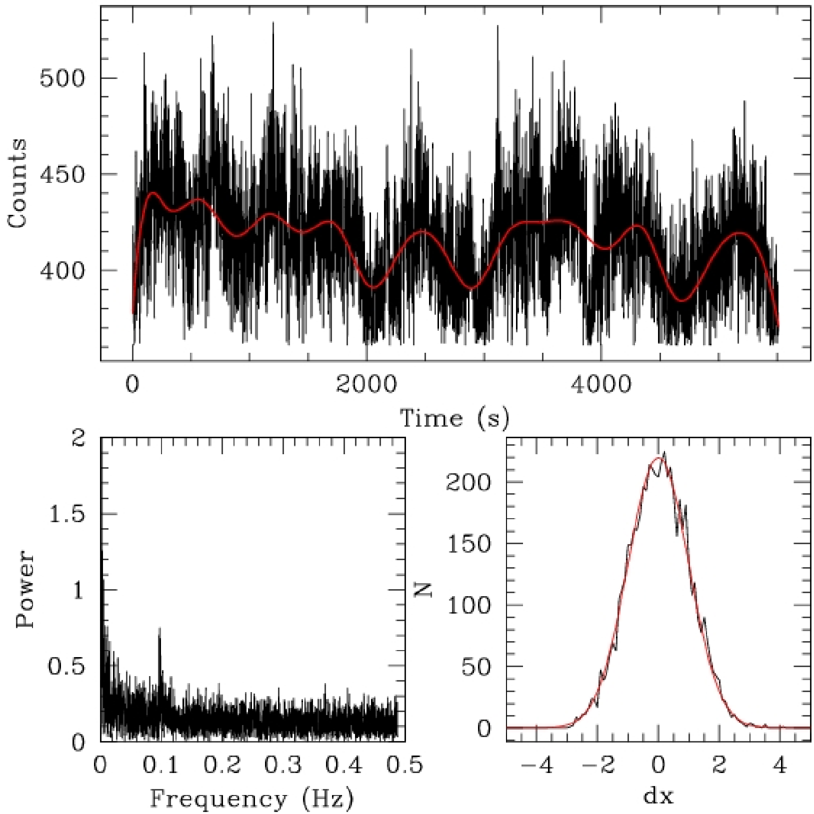
A5
A6
A7
Total
A1
A2
A3
A4
Counts
0
1000
2000
3000
200
300
400
500
Channel No.



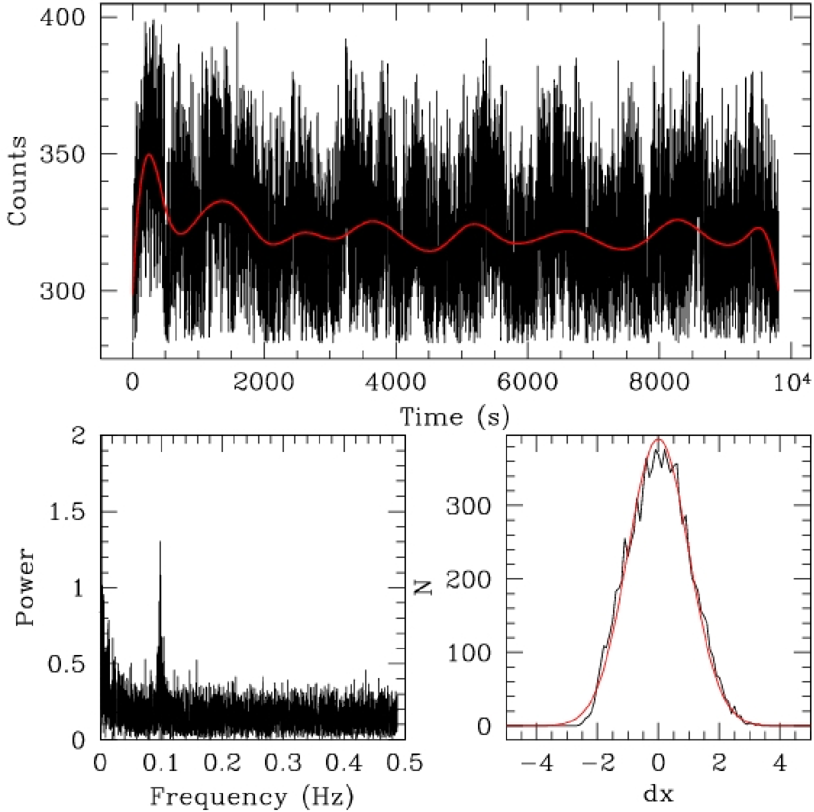
LX30 Fe 55 at 20 o C (CQ1->CQ3 in 2 hrs)
Fe 55
Counts
Time (sec)
500
450
400
350
300
250
200
150
100
33000
34000
35000
36000
37000
38000
39000



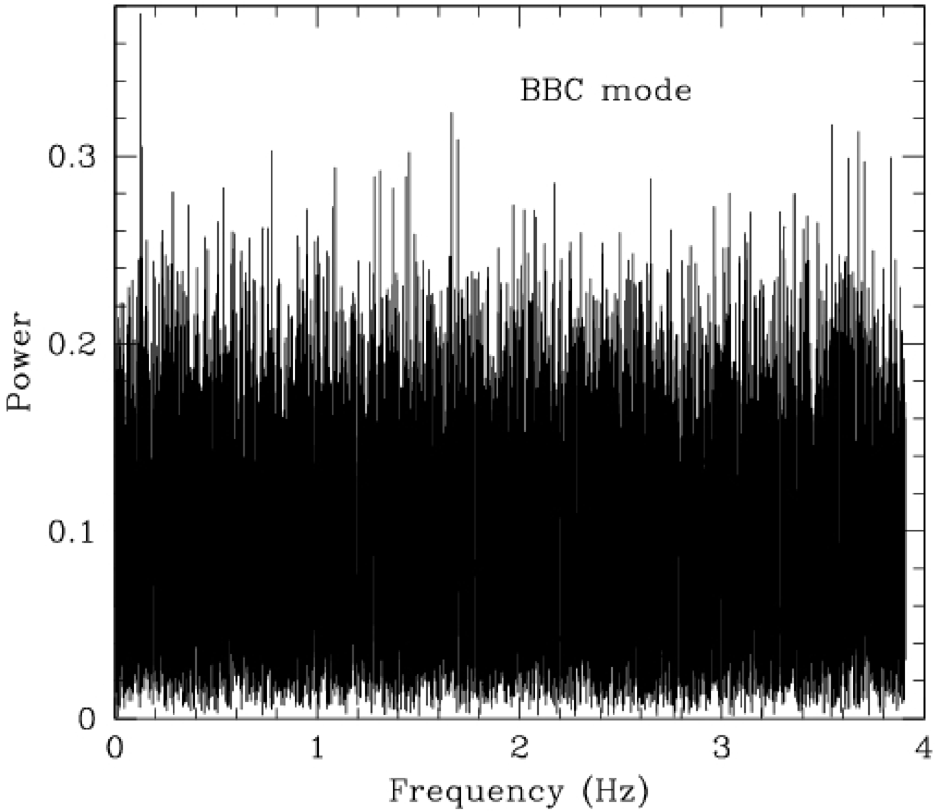
LX30 Fe 55 at 20 o C (CQ1->CQ3 in 2 hrs)
Fe 55
450
400
350
300
250
200
150
Counts
35450
35500
35550
35600
35650
35700
35750
35800
Time (sec)

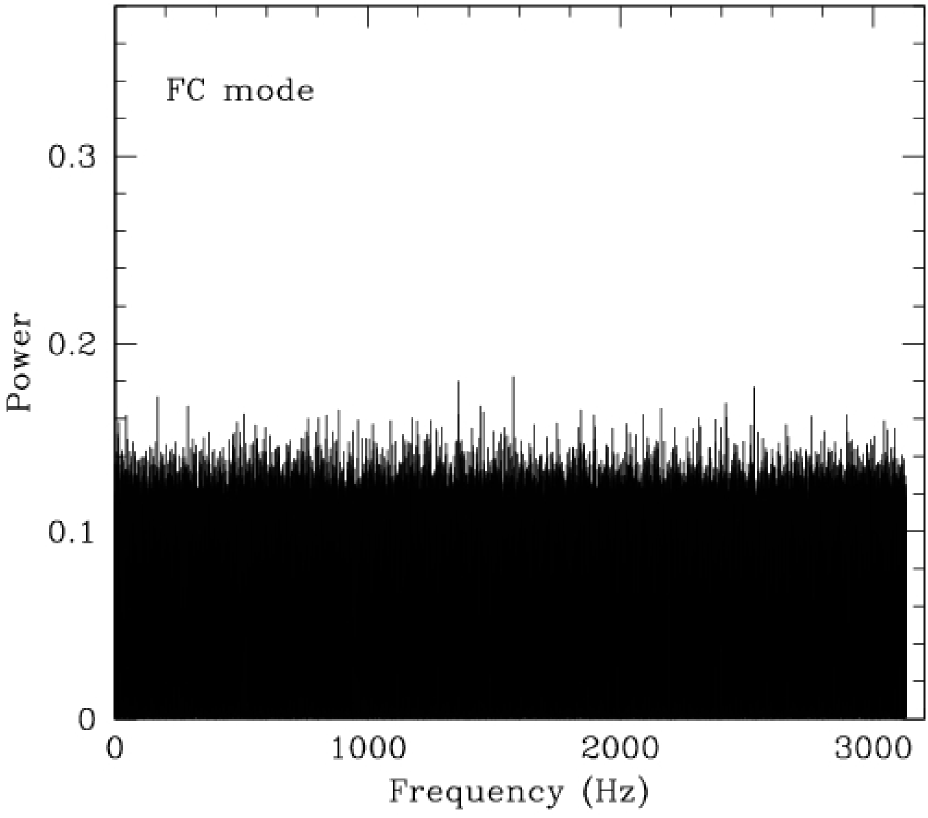


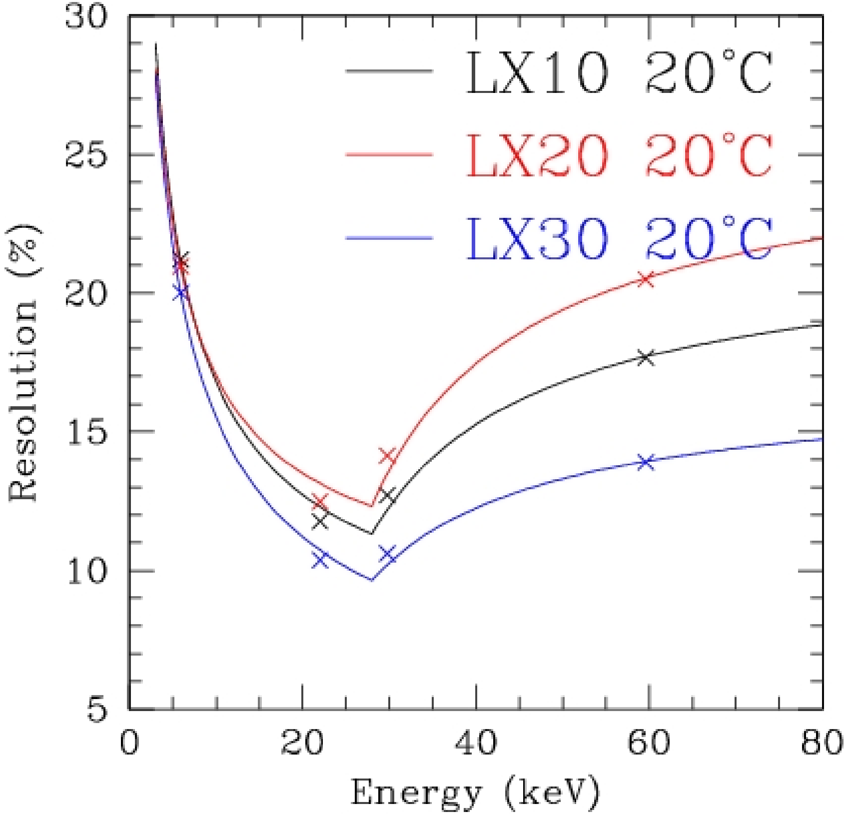
Counts
500
450
400
0
2000
4000
Time (s)
Power
2
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
Frequency (Hz)
N
200
150
100
50
0
−4
−2
0
2
4
dx



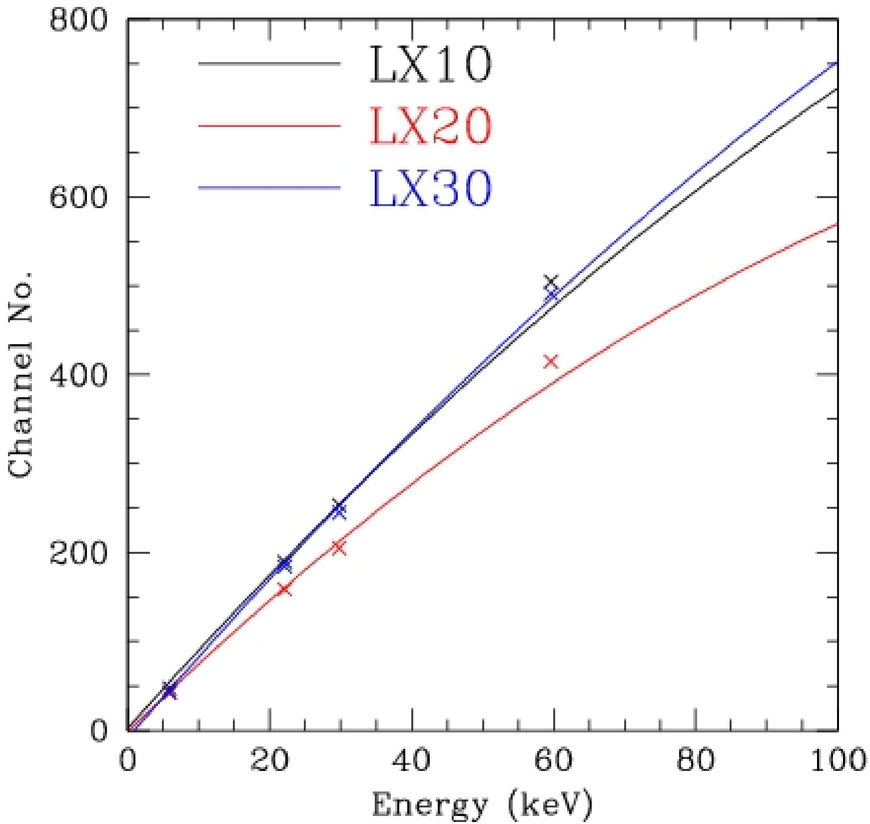
400
350
300
Counts
0
2000
4000
6000
8000
10⁴
Time (s)
2
1.5
1
0.5
0
Power
0
0.1
0.2
0.3
0.4
0.5
Frequency (Hz)
300
200
100
0
N
−4
−2
0
2
4
dx


BBC mode
Power
0.3
0.2
0.1
0
0
1
2
3
4
Frequency (Hz)

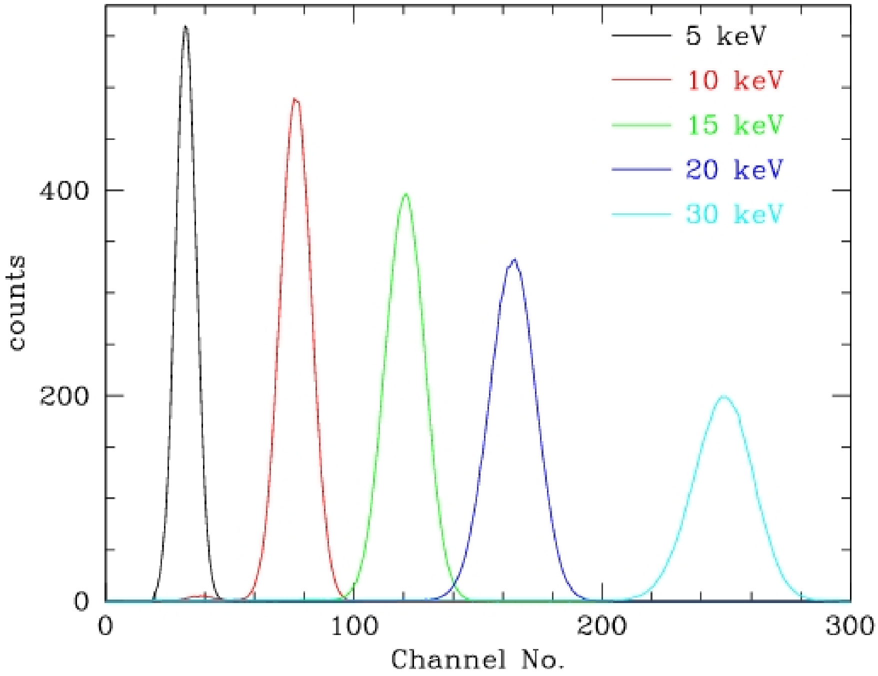

FC mode
Power
0.3
0.2
0.1
0
0
1000
2000
3000
Frequency (Hz)

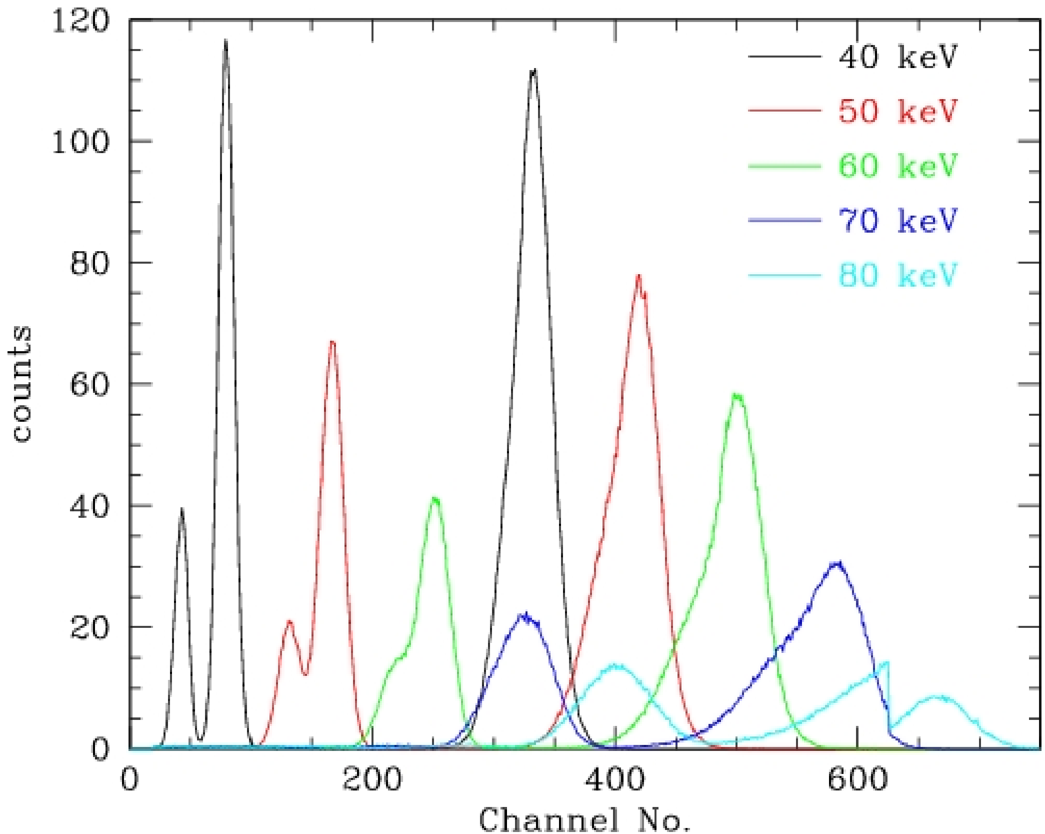


LX10 20°C
LX20 20°C
LX30 20°C
Resolution (%)
Energy (keV)
30
25
20
15
10
5
0
20
40
60
80

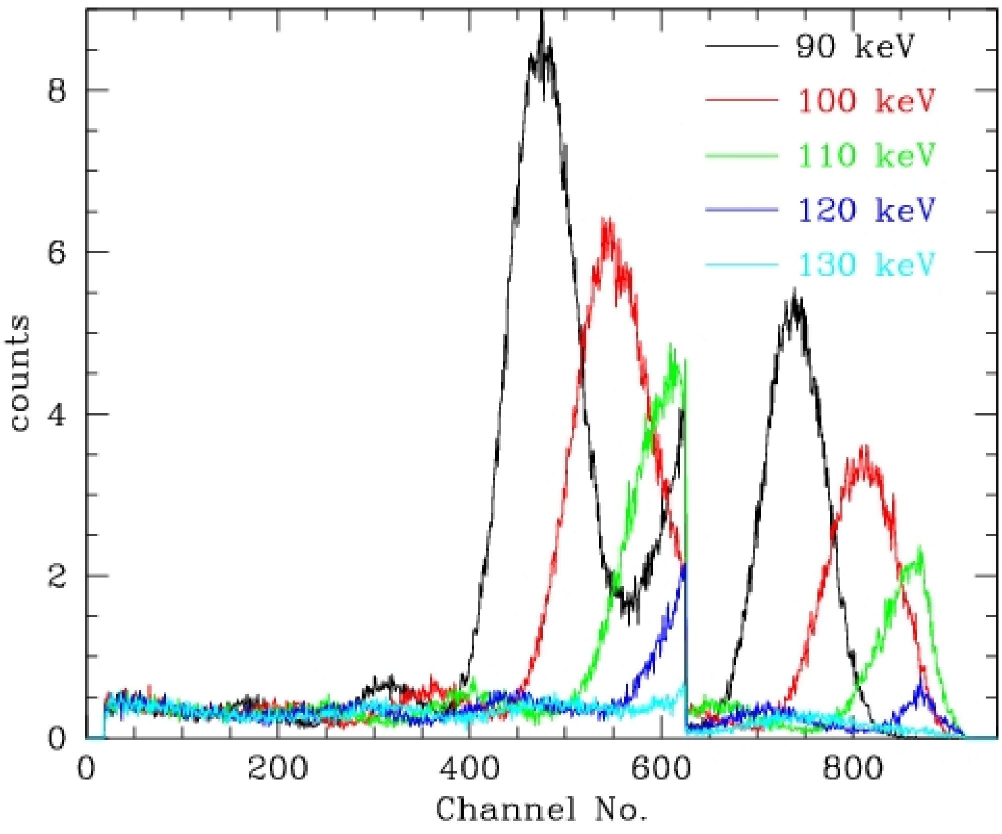

LX10
LX20
LX30
Channel No.
Energy (keV)
0
200
400
600
800
0
20
40
60
80
100

- To calculate detector response for other energies we need to get $\sigma(E, T), n_c(E, T)$





40 keV
50 keV
60 keV
70 keV
80 keV
counts
Channel No.
0
20
40
60
80
100
120
0
200
400
600

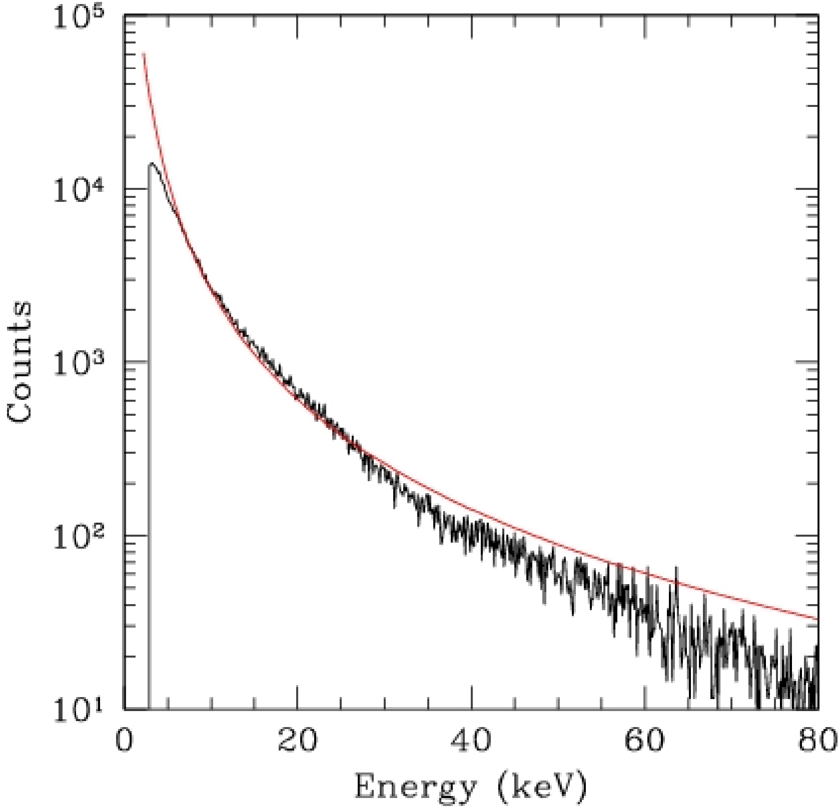

90 keV
100 keV
110 keV
120 keV
130 keV
counts
Channel No.
0
2
4
6
8
0
200
400
600
800

- For Crab X-ray source, the simulated spectrum calculated when the input spectrum of $N(E) = N_0 E^{-2.1}$
- The expected count rate is about 6000 s^{-1} in each detector. At this rate the dead-time of the system will reduce the count rate by about 25%.

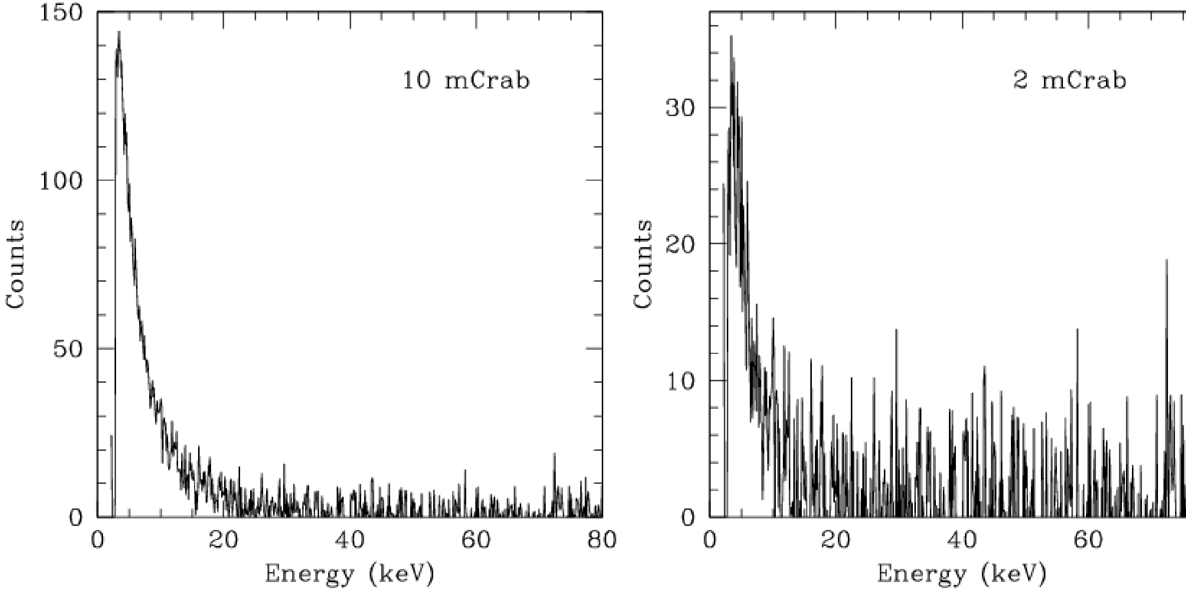
  Net count rate is expected to be about 13000 s^{-1}.
- For 1 mCrab source in 100 s the detection is at level of 8σ in total counts.

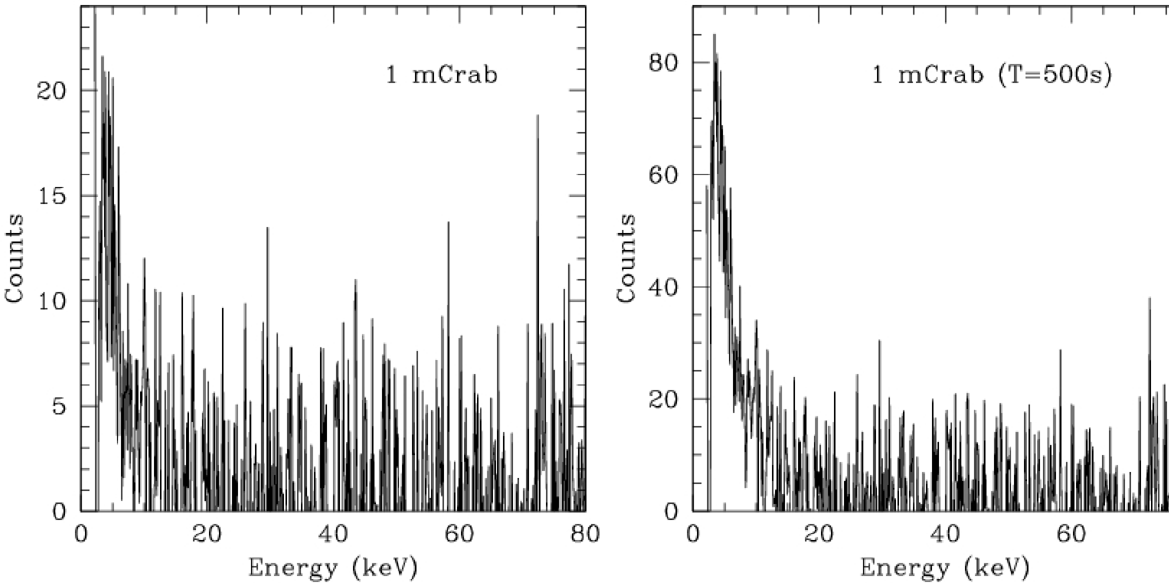
  If counts in 3–20 keV are used it improves to 16σ.

  is shown in Fig.

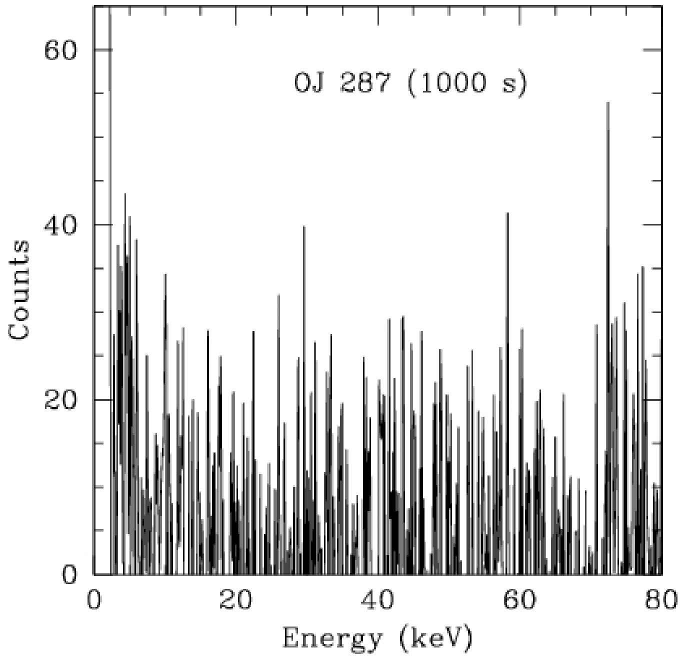


10⁵
10⁴
10³
10²
10¹
Counts
0
20
40
60
80
Energy (keV)

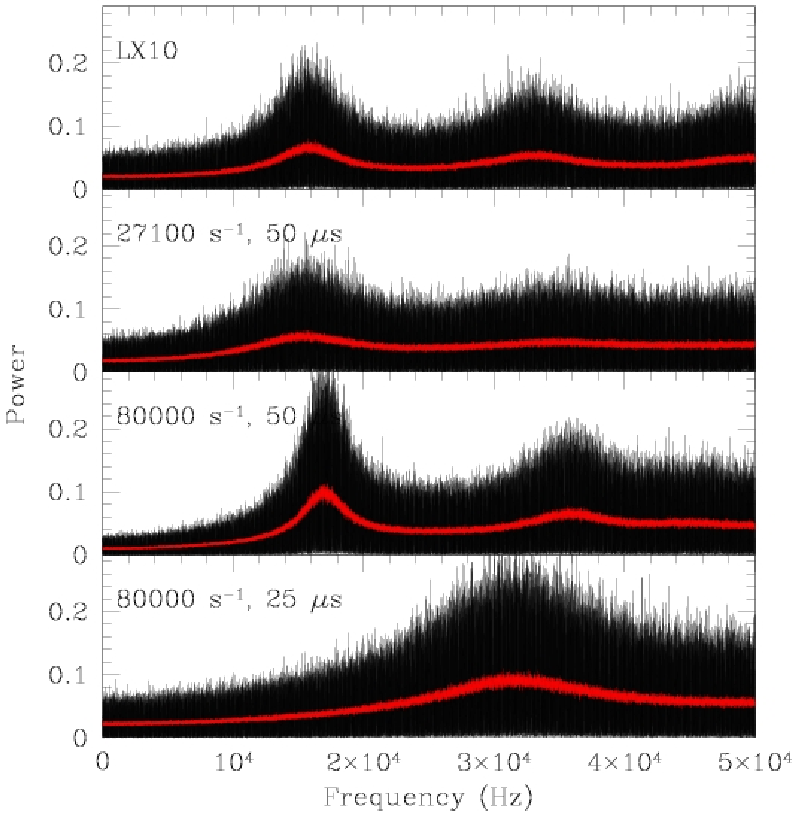

10 mCrab
Counts
Energy (keV)
0
50
100
150
0
20
40
60
80
2 mCrab
Counts
Energy (keV)
0
10
20
30
0
20
40
60


1 mCrab
Counts
Energy (keV)
0
5
10
15
20
0
20
40
60
80
1 mCrab (T=500s)
Counts
Energy (keV)
0
20
40
60
80
0
20
40
60

OJ 287 $\alpha = 1.65$



Counts: 0.6 s^{-1}, 3.7σ detection in 1000 s (3–20 keV)



LX10
27100 s^{-1}, 50 μs
80000 s^{-1}, 50 μs
80000 s^{-1}, 25 μs
Power
0
0.1
0.2
0
10^4
2×10^4
3×10^4
4×10^4
5×10^4
Frequency (Hz)

Summary

- Field of view: $43'$ at 15 keV, $47'$ at 50 keV
- Effective area: 0.8 m^2 at 10–20 keV, 0.24 m^2 at 80 keV
- For LX30 in lab background increased by 10% when A10 was disabled
- Simulated spectra for all 3 radioactive sources match the observed spectra
- Using the resolution and channel number as a function of energy the detector response matrix has been generated.
- Using the Fourier Transform of data at high count rate it is possible to estimate the dead-time of the detector
- For Crab source about 13000 s^{-1} is expected.
- 1mCrab source can be detected with 100 s observation.