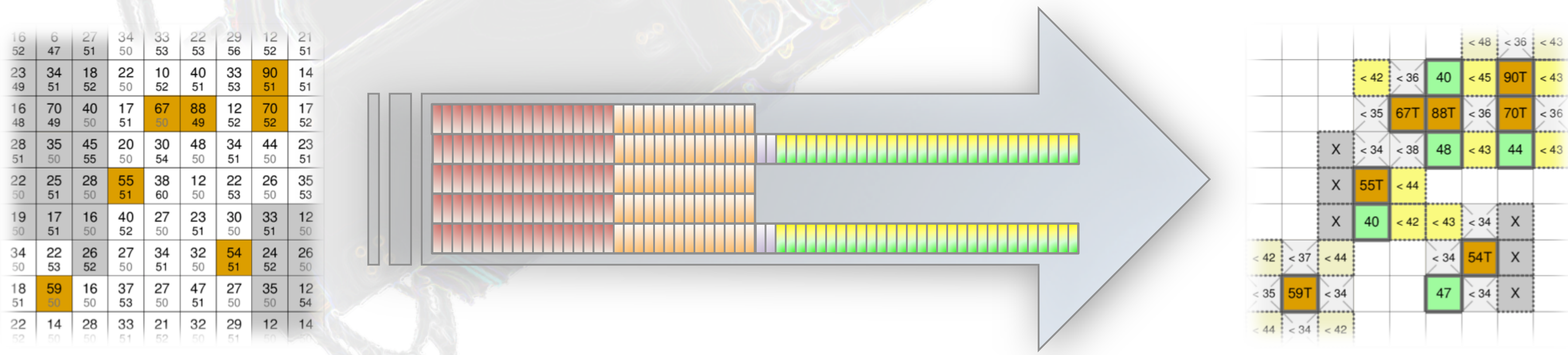
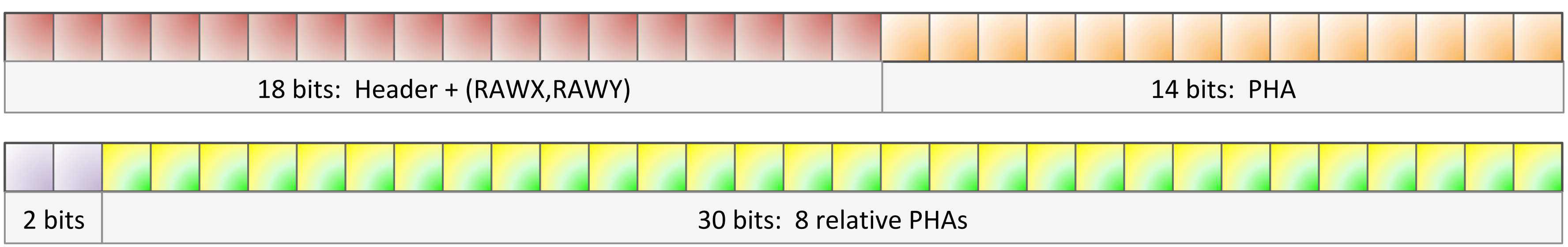
eROSITA Event Compression

a novel, fast, efficient compression method for maximizing the telemetry content





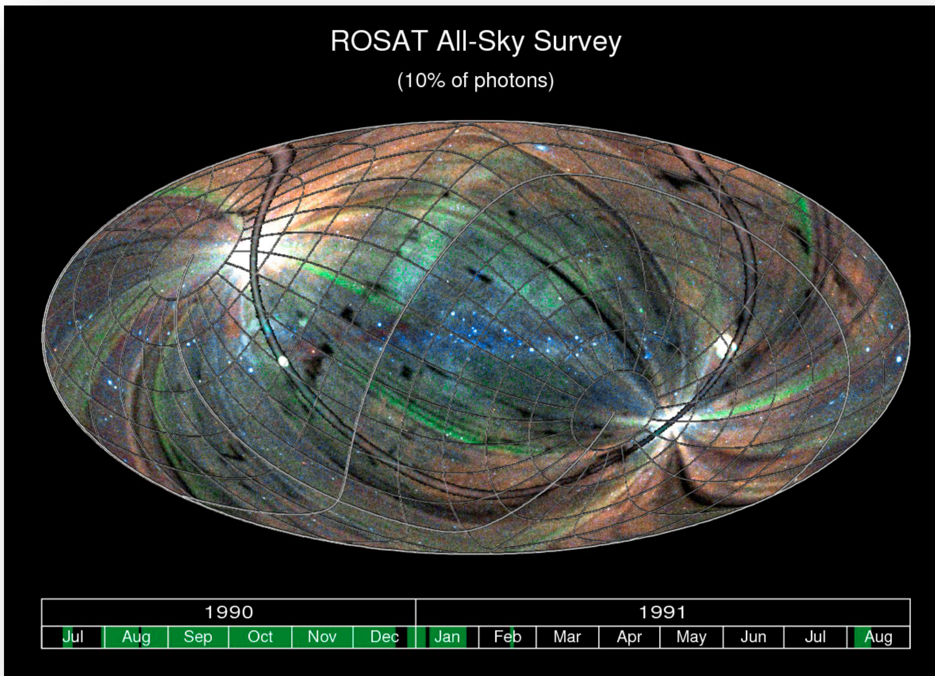
eROSITA
Event Compression

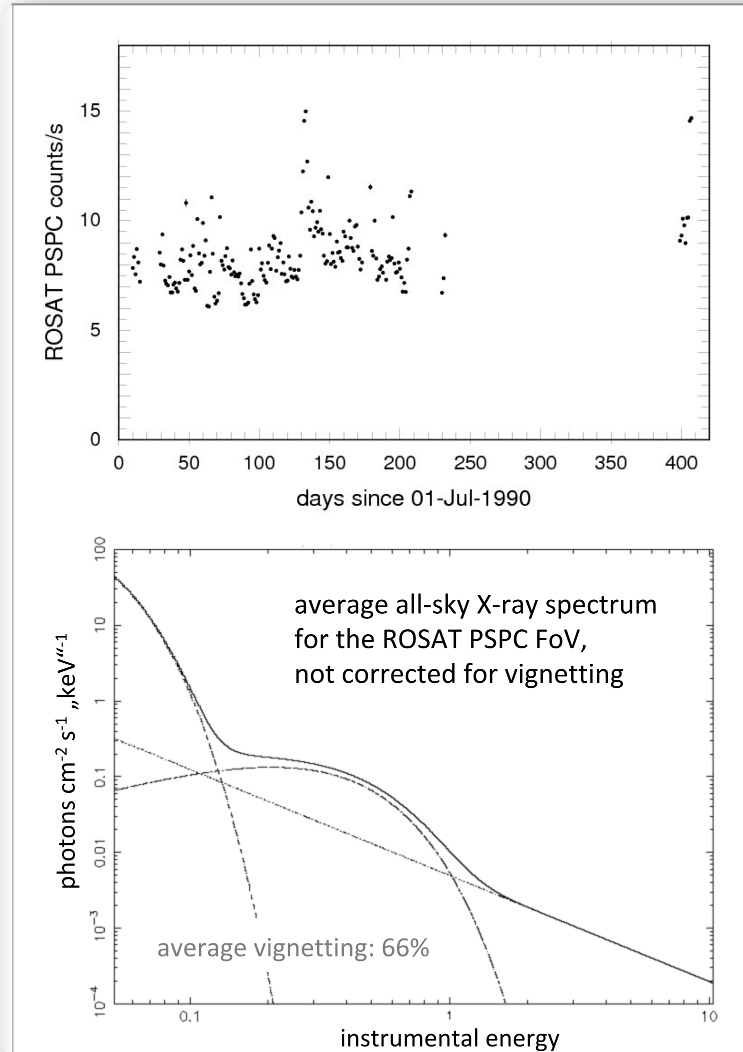
Expected event rate

caused by celestial X-ray photons

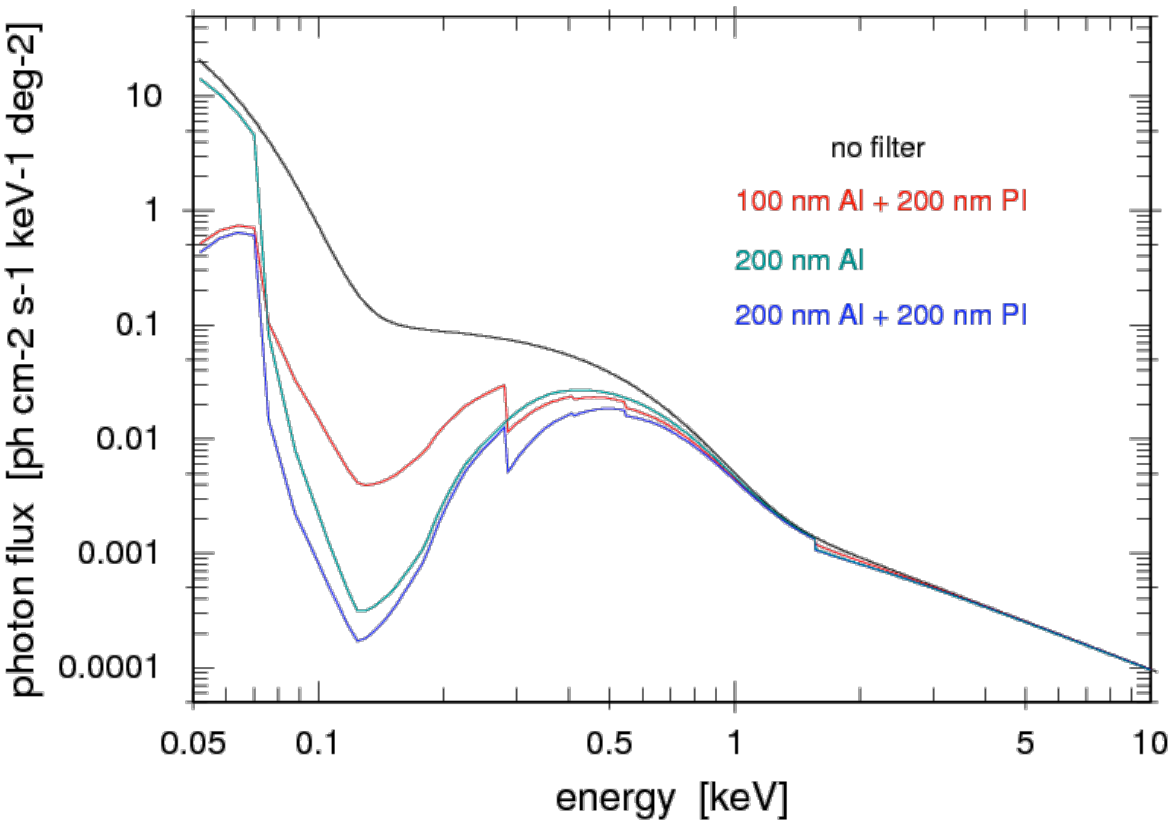
during the eROSITA all-sky survey

Expected event rate caused by celestial X-ray photons during the eROSITA all-sky survey





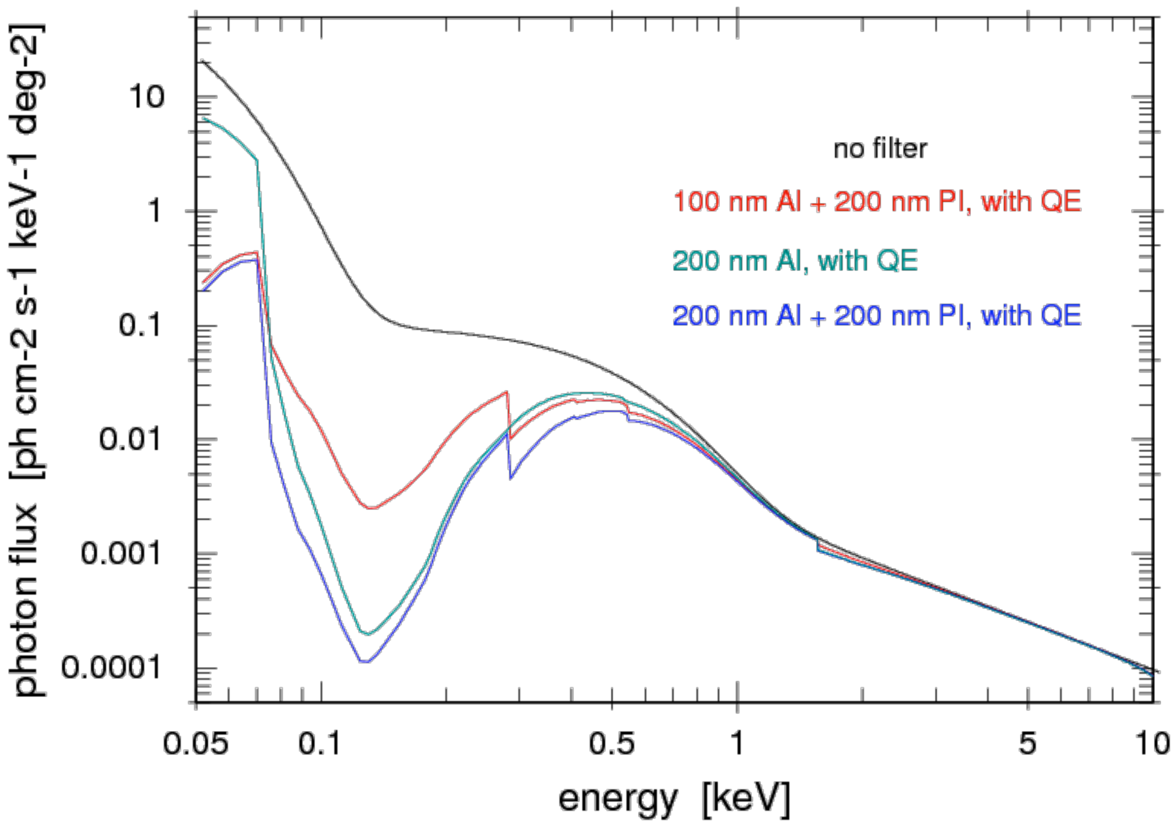
Expected event rate caused by celestial X-ray photons during the eROSITA all-sky survey



photon spectrum

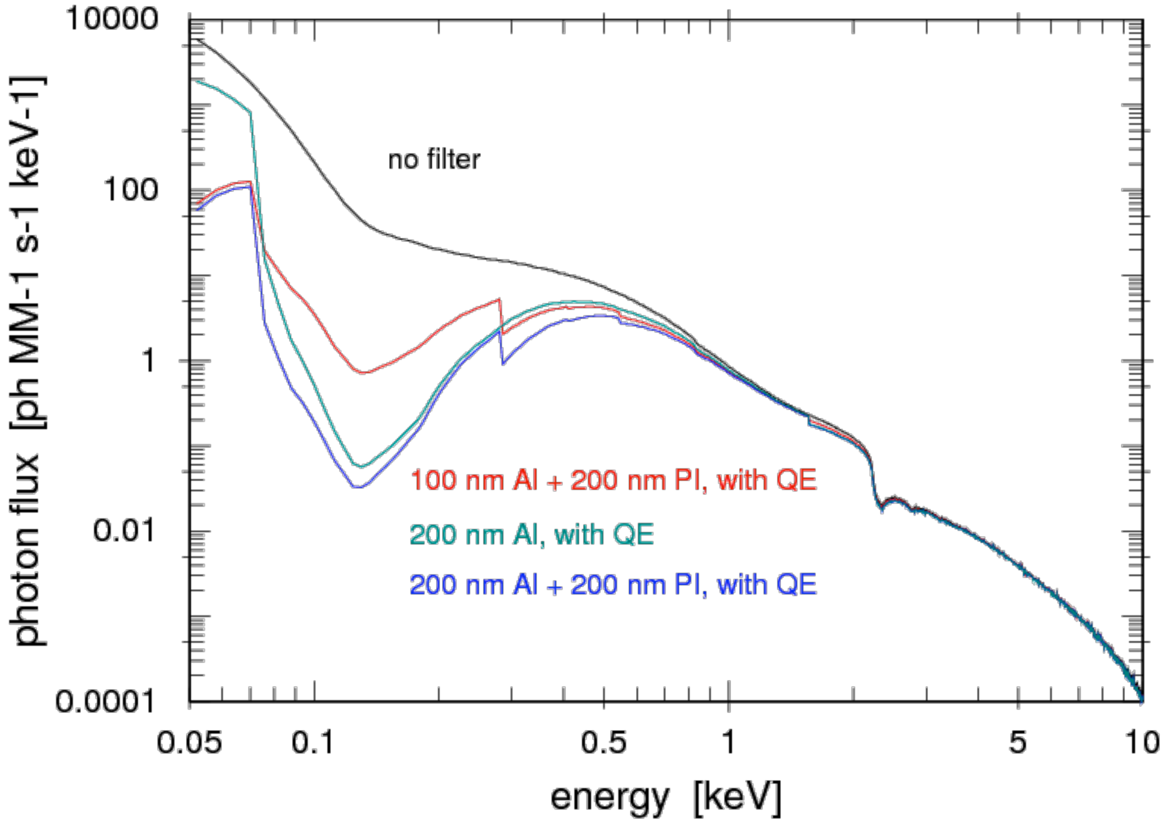
before and after filter passage

Expected event rate caused by celestial X-ray photons during the eROSITA all-sky survey



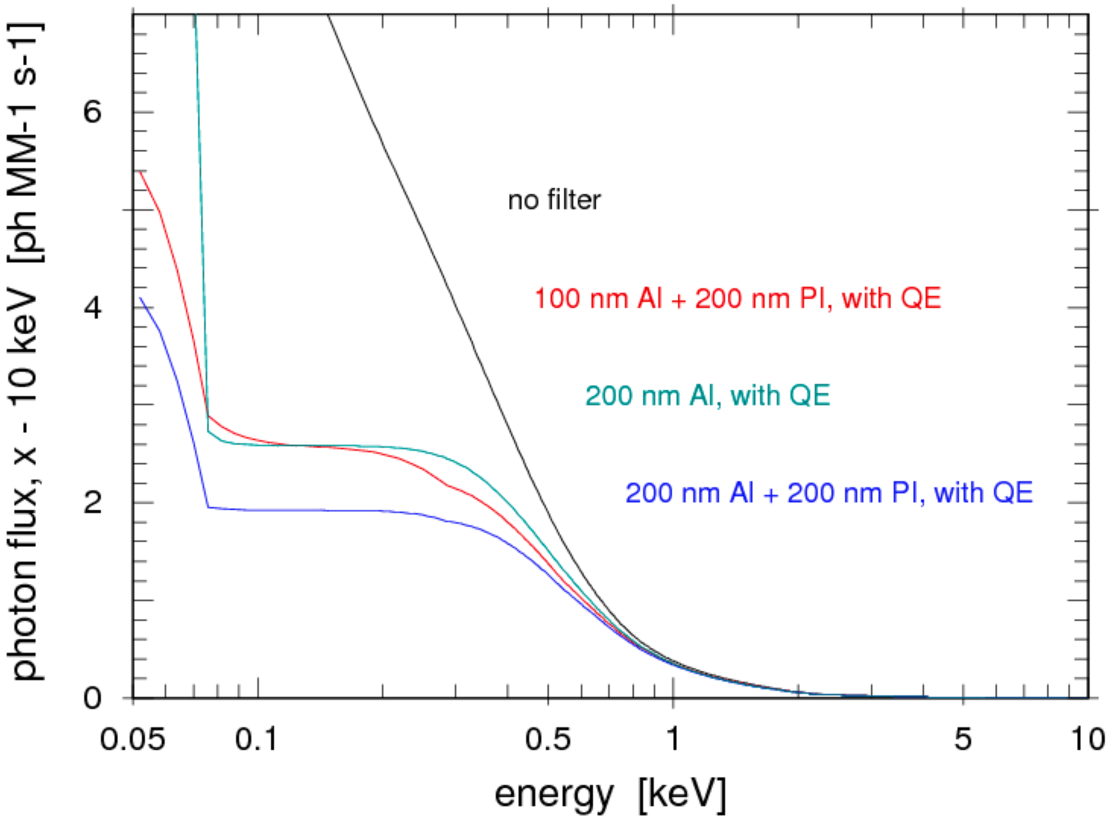
detected photon spectrum (including QE) before and after filter passage

Expected event rate caused by celestial X-ray photons during the eROSITA all-sky survey



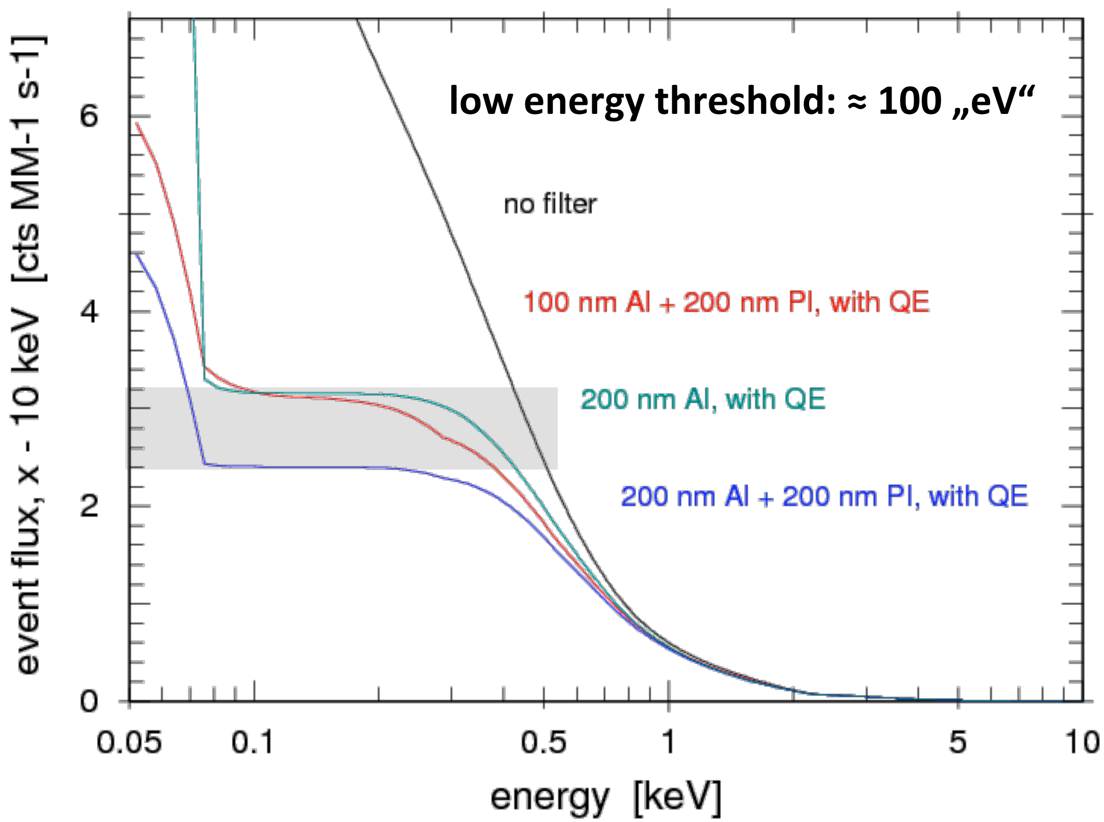
detected photon spectrum (including QE) before and after filter passage and after mirror passage per mirror module (MM)

Expected event rate caused by celestial X-ray photons during the eROSITA all-sky survey



→ integrated photon flux from <energy> to 10 keV per mirror module (MM)

Expected event rate caused by celestial X-ray photons during the eROSITA all-sky survey

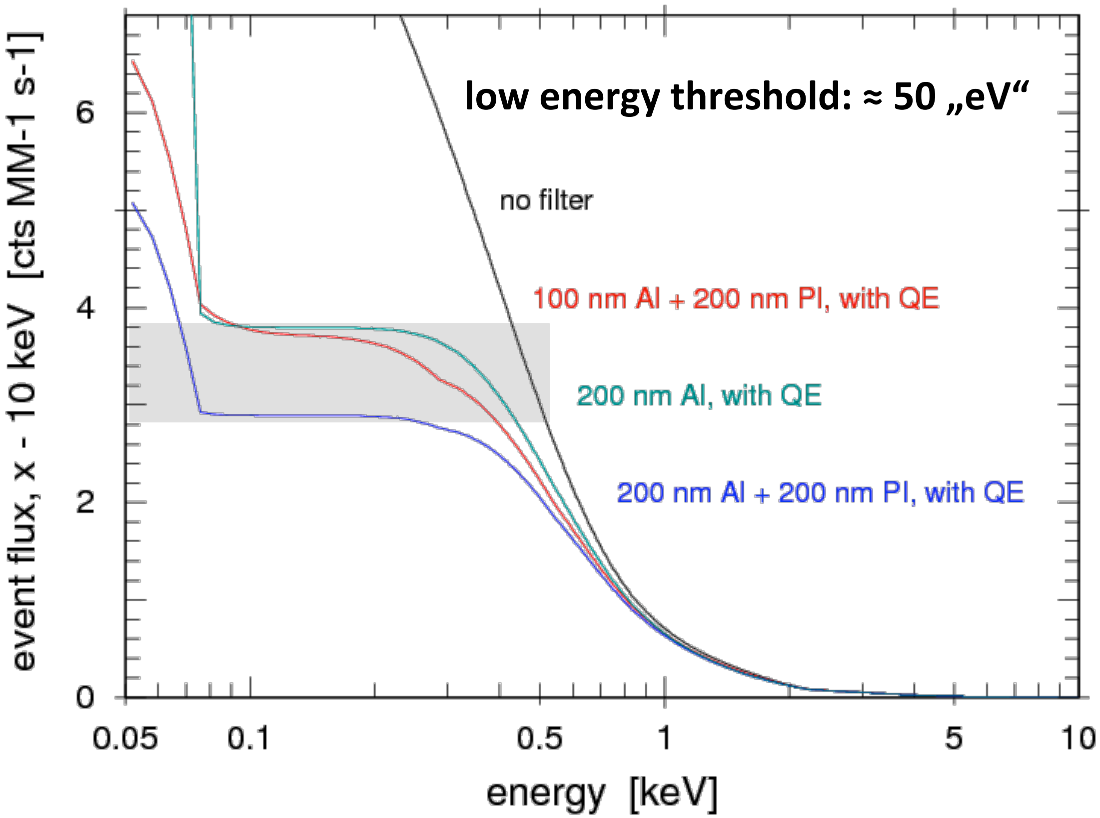


→ integrated event flux from <energy> to 10 keV per mirror module (MM)

for a low energy threshold of ≈ 100 „eV“:

→ 2.4 – 3.2 events/camera/s
→ 0.34 – 0.46 events/camera/frame

Expected event rate caused by celestial X-ray photons during the eROSITA all-sky survey



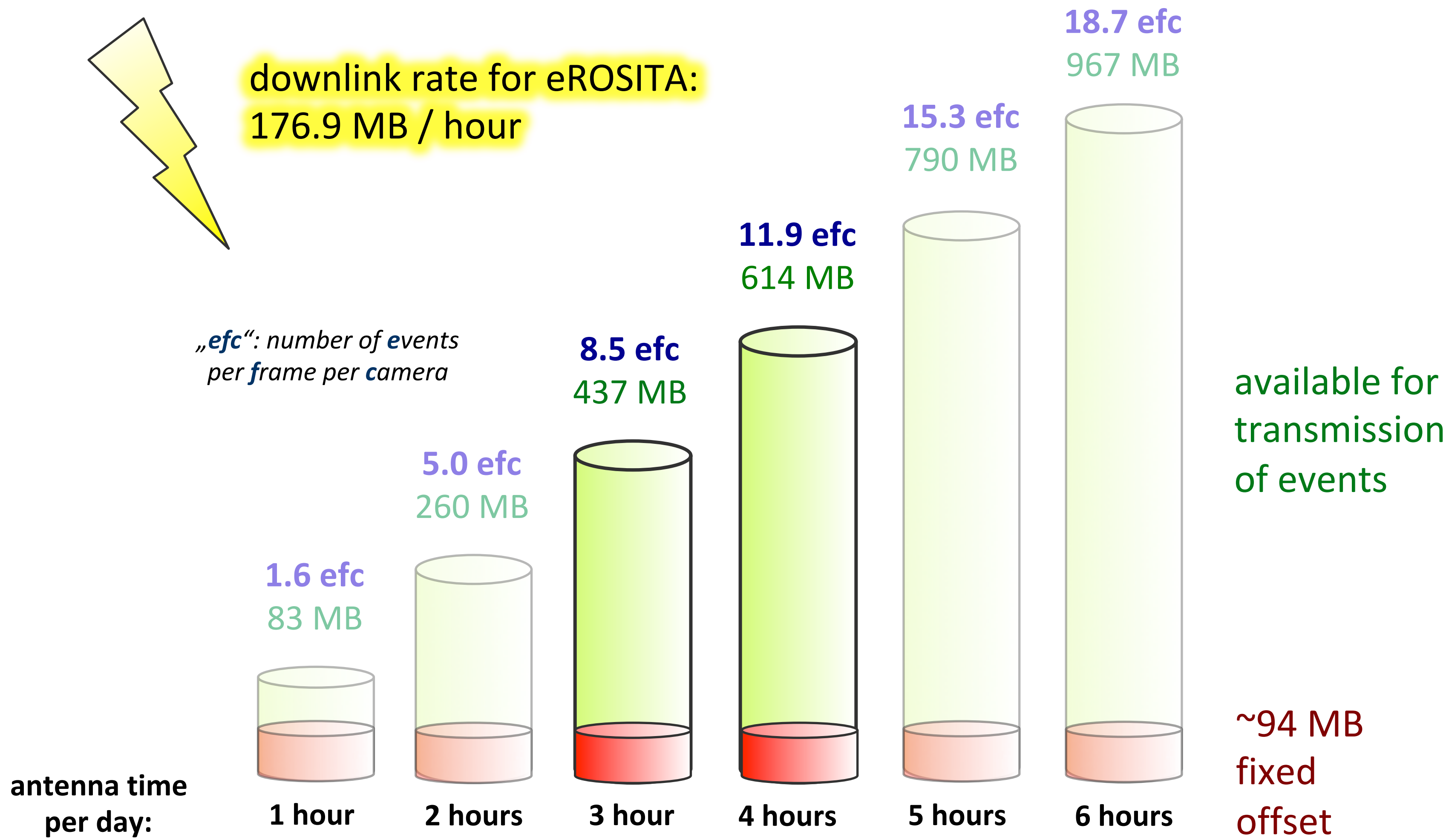
→ integrated event flux from <energy> to 10 keV per mirror module (MM)

for a low energy threshold of ≈ 50 „eV":

→ 2.8 – 3.8 events/camera/s
→ 0.40 – 0.54 events/camera/frame

What can be transmitted per day:

each event requires 4.27 Bytes of telemetry (including record overhead)



eROSITA Event Compression

Why do we deal with compression ?

Motivation for event compression

We expect to be able to transmit on average ~10 ecf (events/camera/frame), while the average survey rate is unlikely to exceed 0.6 ecf.

Where is the problem ?

The X-ray detectors are CCDs, which have two generic properties:

1. pixelized charge traps
2. low energy „detector“ noise

Therefore,

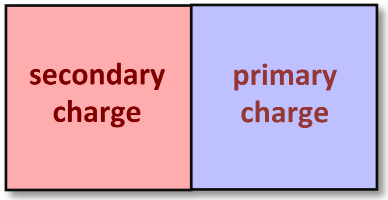
1. the charge released by the absorption of a photon may spread over several pixels
2. some charge components may be as low as the detector noise

For good spectroscopy it is necessary to make the charge collection as complete as possible, i.e., to collect charges down to the detector noise.

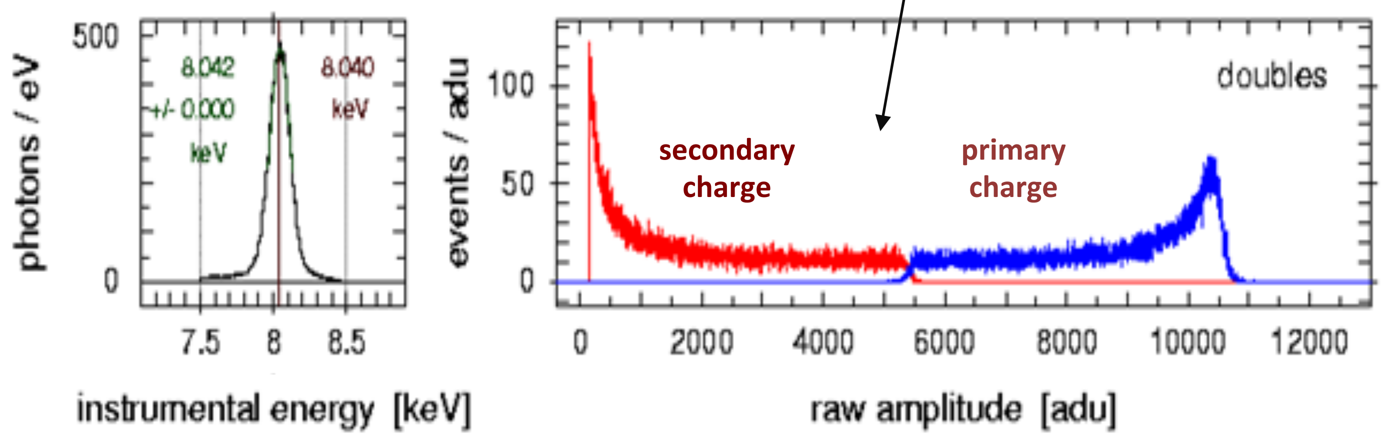
At ideal conditions (no photons, no particles), the detector produces 10 ecf at a low energy threshold of ~56 adu (about 47 eV).

In space, the noise is expected to be considerably higher.

Charge distributions and the importance of the low energy threshold



distribution of the charge generated by 8 keV photons over two pixels



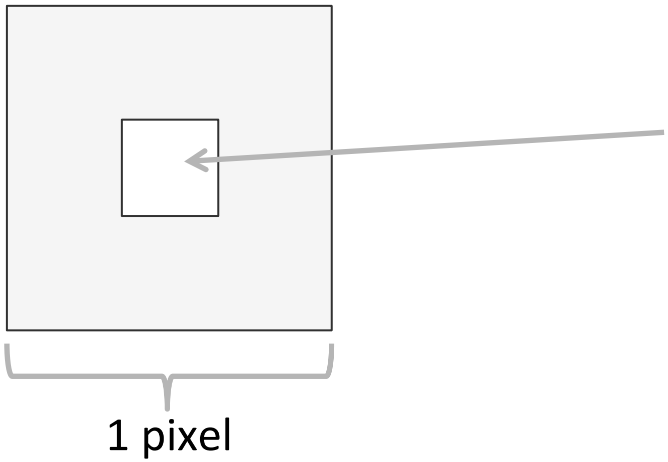
→ unequal charge splittings are preferred

→ the **spectroscopic quality** improves if the small secondary charge is recovered

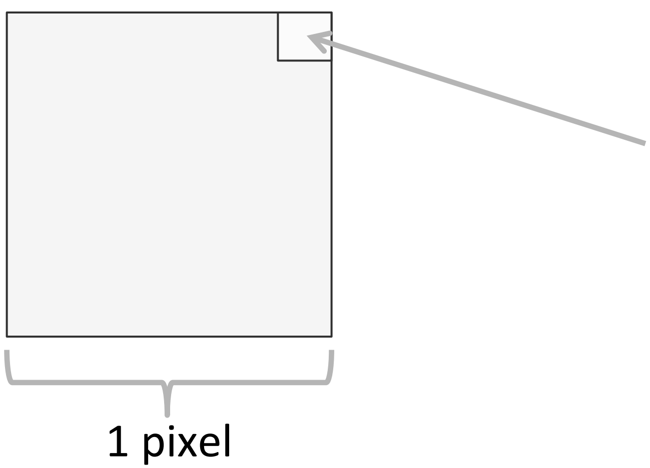
→ even at 8.0 keV, the spectral quality for doubles is improved by a low split threshold

→ a low split threshold implies that also some noise gets transmitted

Importance of the low energy threshold

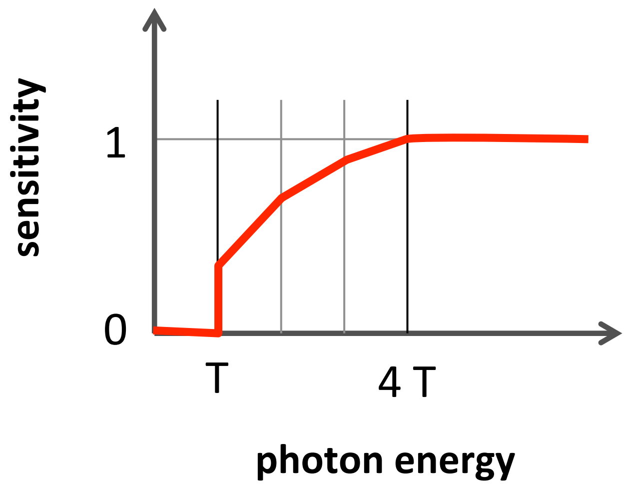


When the charge released by the absorption of a photon is only slightly above the low energy threshold, it will be included into the telemetry only if the photon hits the pixel centrally enough to ensure that the charge will be confined to this pixel.

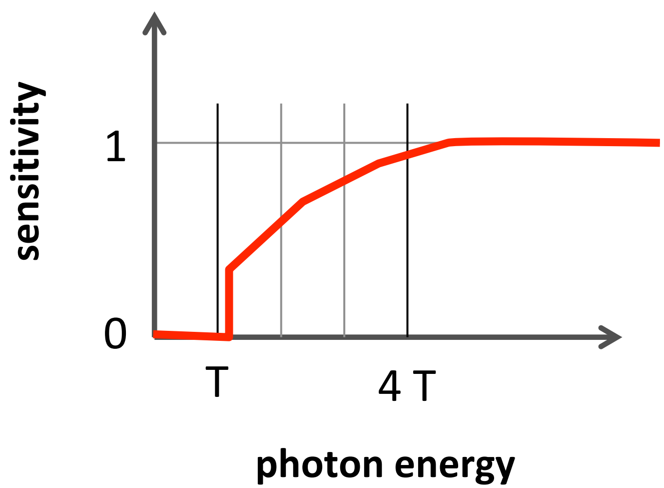


The full sensitivity will not be reached before the energy of the incident photon is large enough to ensure that even when the released charge is equally distributed among 4 pixels the low energy threshold will be exceeded.

Importance of the low energy threshold



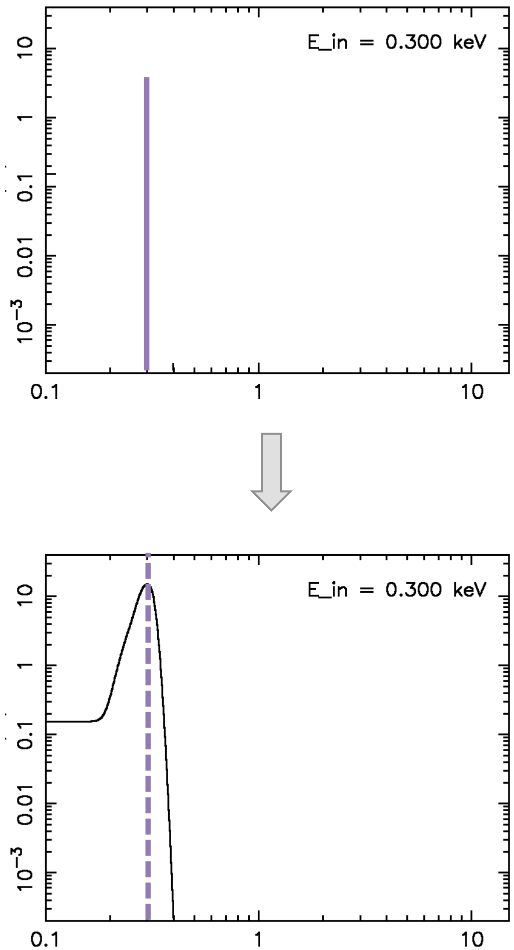
schematic sensitivity curve
for an ideal detector
(CTI = 0, gain = 1,
perfect energy resolution)

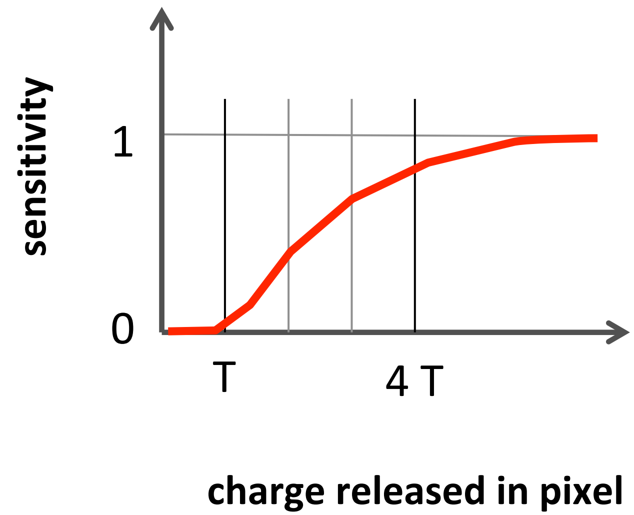


schematic sensitivity curve
for a detector with
CTI > 0 and gain < 1, but
perfect energy resolution

Importance of the low energy threshold

real detector: finite energy resolution (redistribution..)



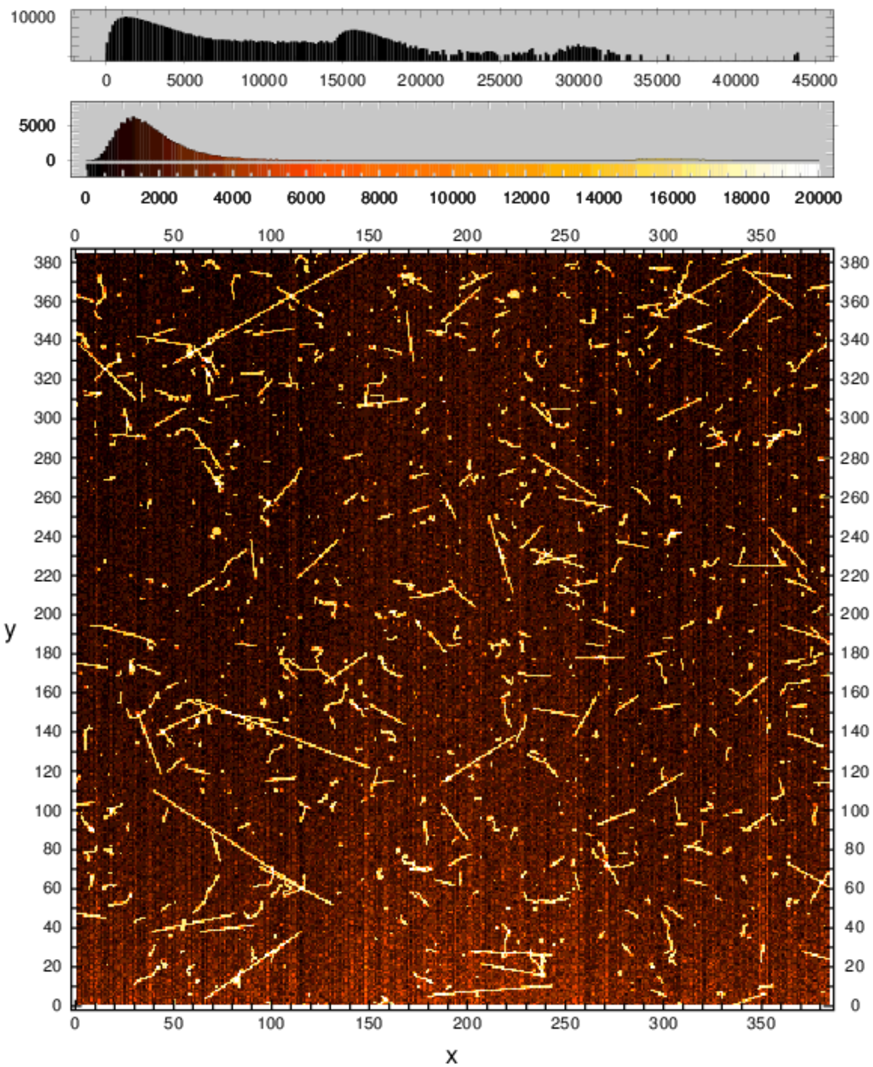


→ the full sensitivity will only be reached above 4 times the low energy threshold !

eROSITA Event Compression

Properties of the detector noise

Properties of the detector noise



Motivation: what is the „pure“ detector noise ?

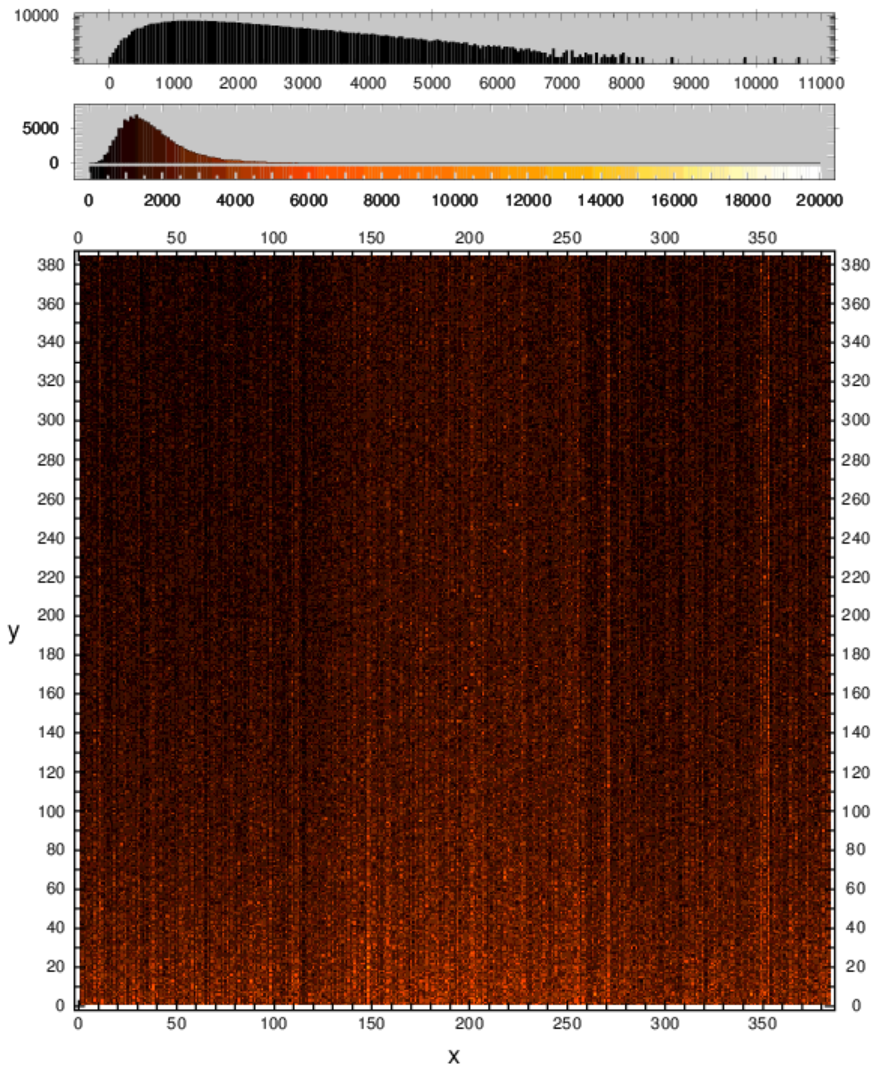
→ lower limit to „the noise“ in space

→ analyse data from a „dark“ exposure

Total accumulated charge in 45 min at „dark“ conditions

(CA-FM6, PUMA, HK160630 0012)

Properties of the detector noise



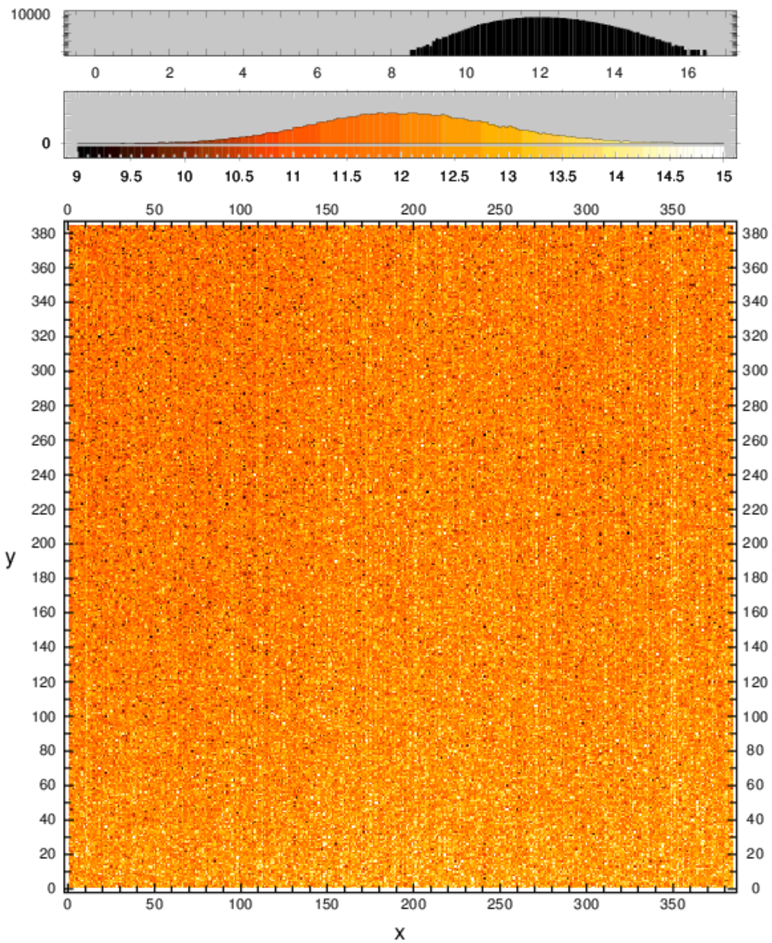
Total accumulated charge,
after rejecting all frames
where at least one pixel
contained charge > 1000 adu.

This happened in 2.1% of all frames.

(the expected MIP rate in space
is ~2 MIPs/frame, so this is likely
to happen in ~100% of all frames!)

Properties of the detector noise

Noise map of CA-FM6, obtained during ground calibration, scaled to σ
→ mean value: **σ = 12.0 adu**



In the case of a Gaussian noise, a value of **5.73 σ** should be exceeded with a probability of **10^{-8}**.

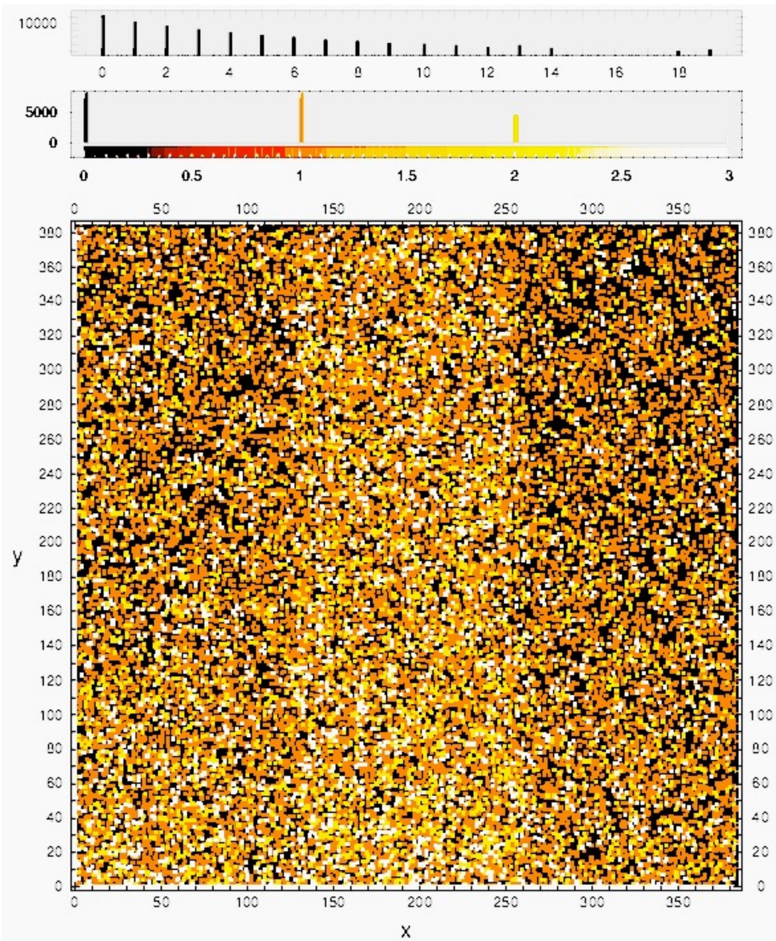
For 53 552 frames and 147 456 pixels, this should happen only **79 times**.

The noise map is derived by applying to each pixel a common mode correction, subtracting its mean offset, and computing the 1σ value of the remaining fluctuations from 128 samples (which remain from 134 samples after rejecting the three smallest and the three largest values)

Properties of the detector noise

Intensity map of all events which exceeded the PHA values in the noise map by 5.73 σ

(CA-FM6, 45 min dark exposure, PUMA, HK160630 0012)



In the case of a Gaussian noise, a value of **5.73 σ** should be exceeded with a probability of $\mathbf{10^{-8}}$.

For 53 552 frames and 147 456 pixels, this should happen only **79 times**.

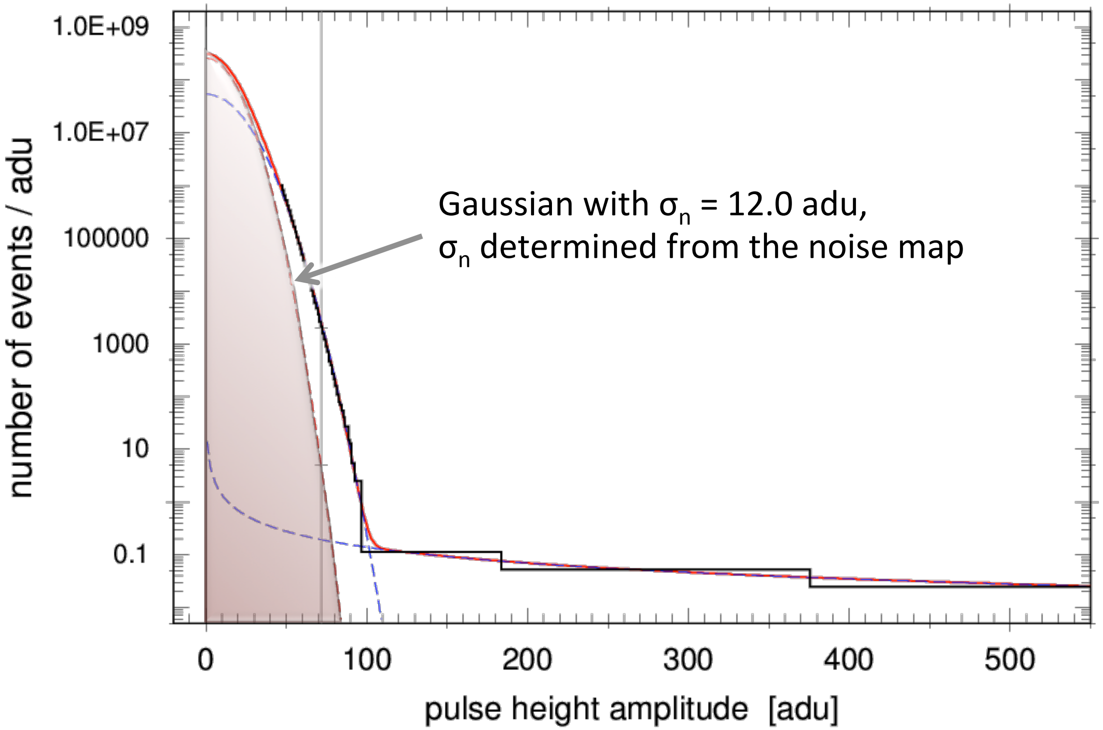
However, this happened **58 993 times**.

→ the spectral distribution of noise is not Gaussian

→ **the noise is substantially higher than the „σ“ suggests (even on ground)**

Properties of the detector noise

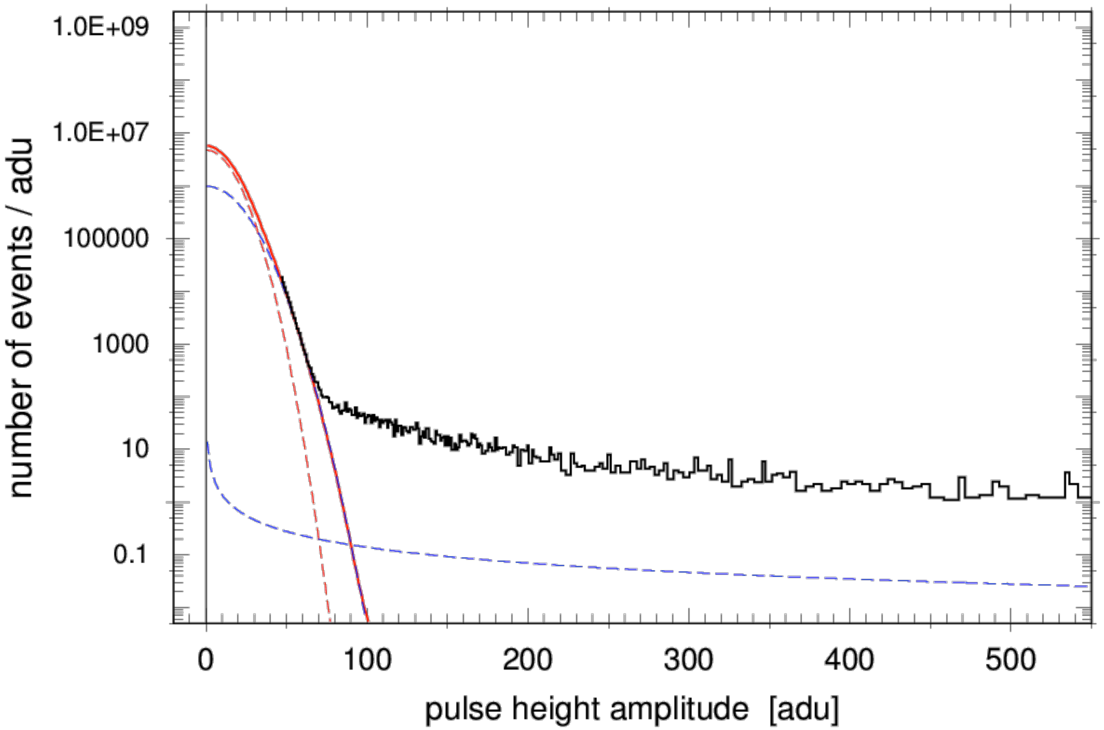
45 min „dark“ exposure, CA-FM6, PUMA, HK160630 0012



spectral distribution of all events after rejecting all frames where at least one pixel contained charge > 1000 adu

Properties of the detector noise

45 min „dark“ exposure, CA-FM6, PUMA, HK160630 0012

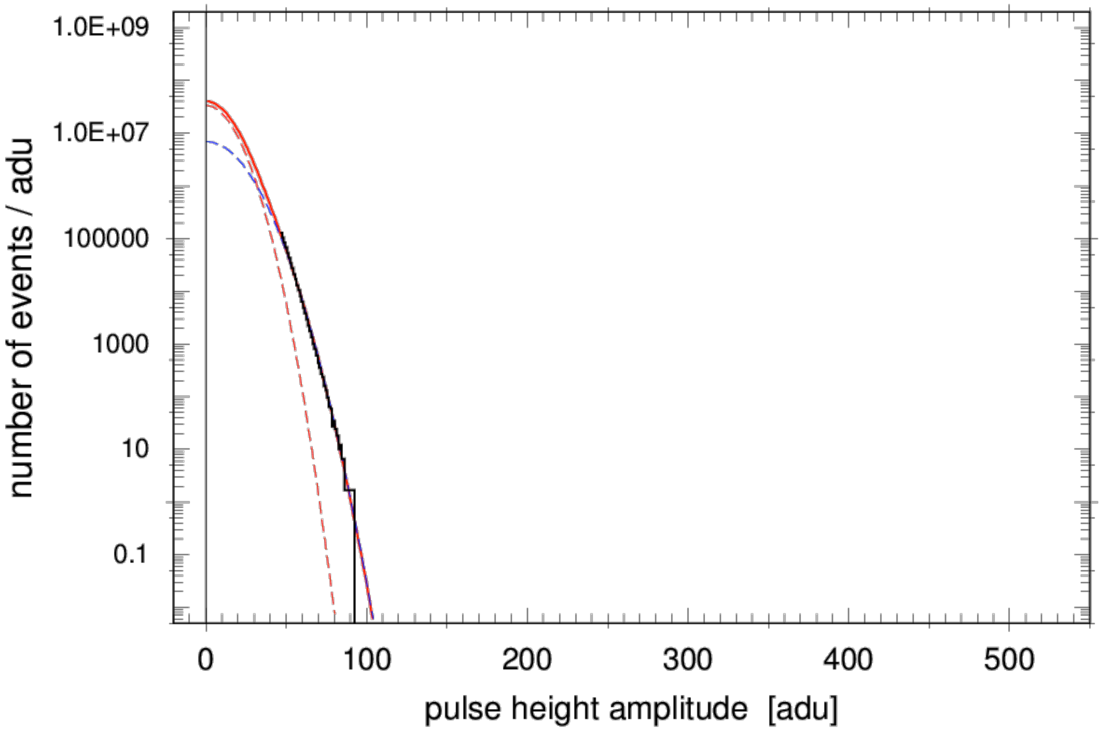


spectral distribution of all the rejected events

(all events in the frames where at least one pixel contained charge > 1000 adu)

Properties of the detector noise

45 min „dark“ exposure, CA-FM6, PUMA, HK160630 0012

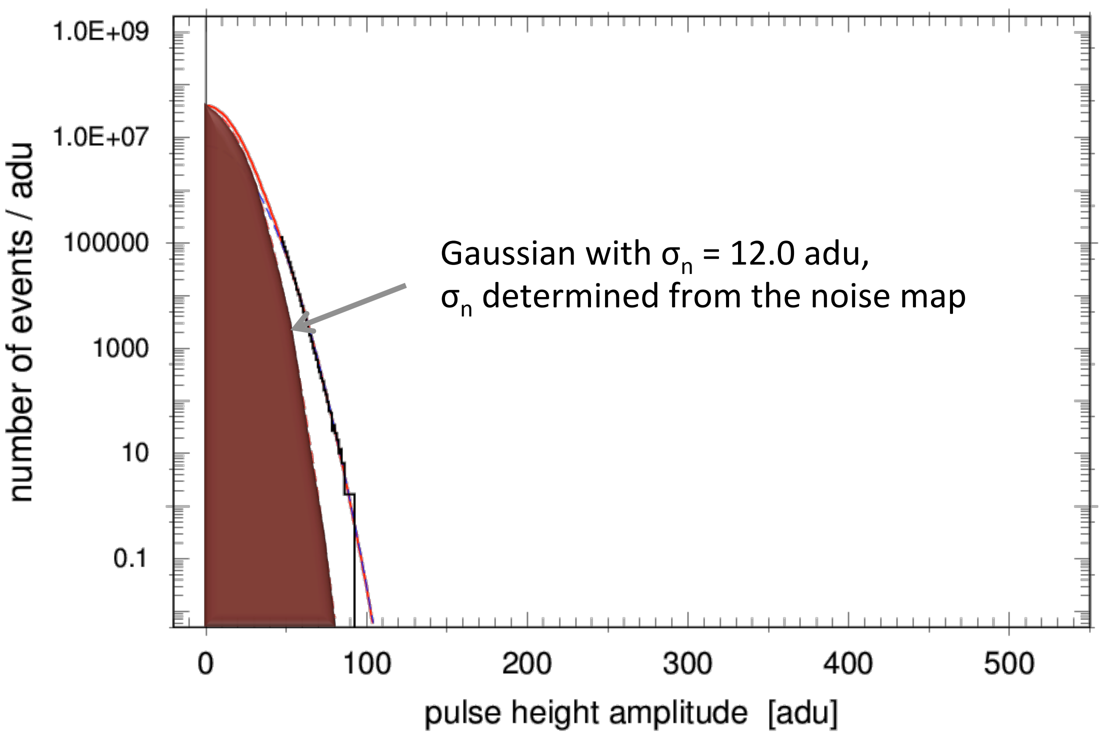


spectral distribution of all events after excluding all frames where at least one pixel contained charge > 1000 adu **and also the subsequent 100 frames (5 s)**

→ spectrum of internally generated events („detector noise“)

Properties of the detector noise

45 min „dark“ exposure, CA-FM6, PUMA, HK160630 0012

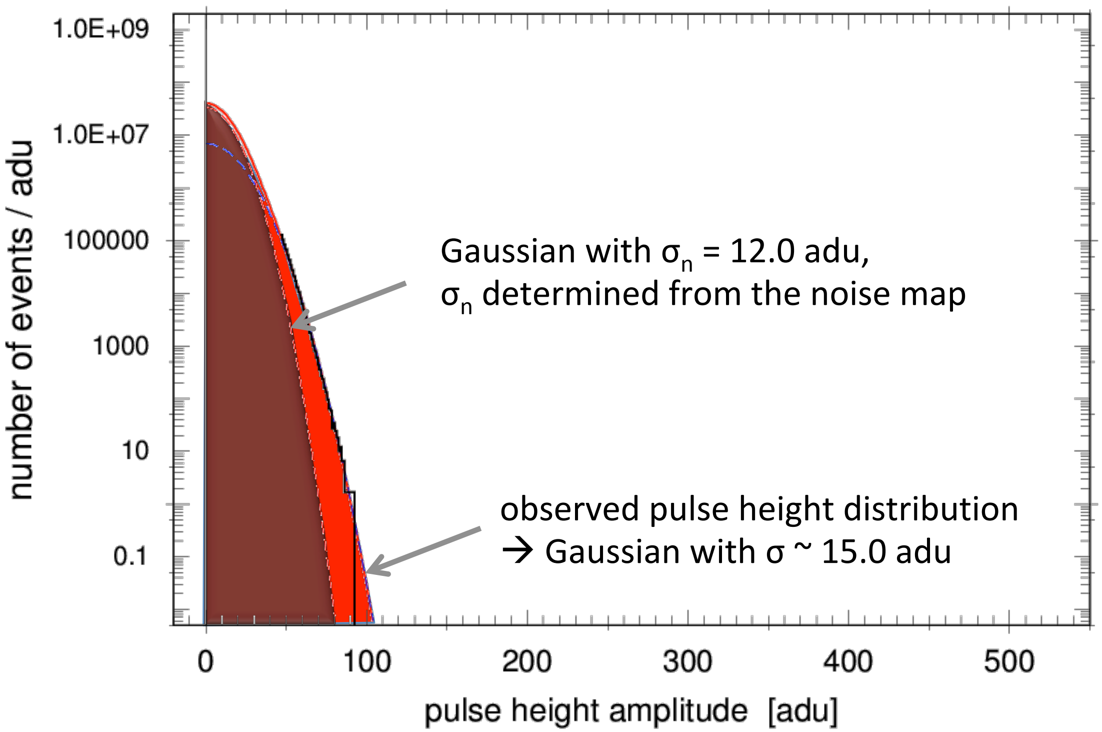


spectral distribution of all events after excluding all frames where at least one pixel contained charge > 1000 adu **and also the subsequent 100 frames (5 s)**

→ spectrum of internally generated events („detector noise“)

Properties of the detector noise

The detector noise is considerably higher than the noise map suggests:

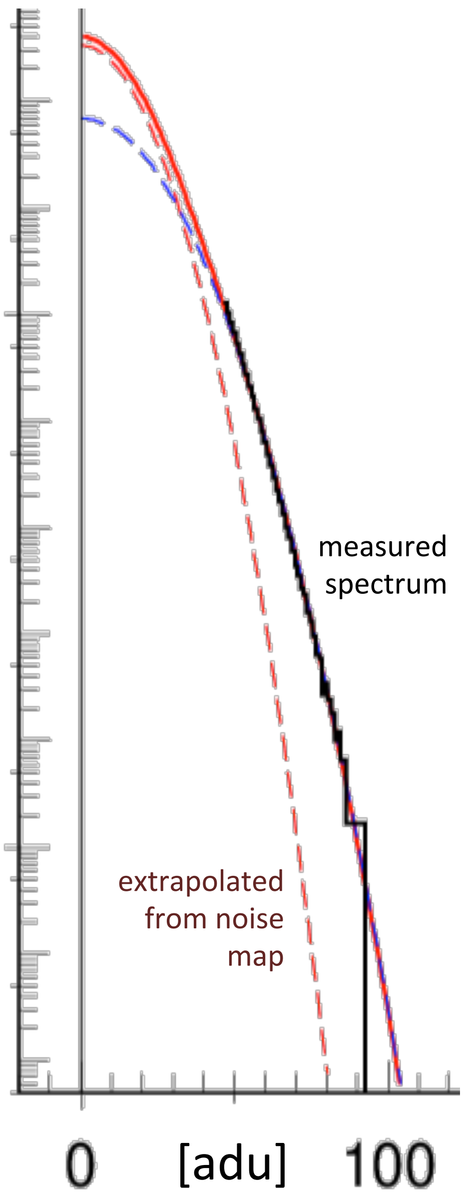


spectral distribution of all events after excluding all frames where at least one pixel contained charge > 1000 adu **and also the subsequent 100 frames (5 s)**

→ spectrum of internally generated events („detector noise“)

for a Gaussian distribution with σ_n = 12.0 adu, only 5 events would be expected above 72 adu, but ~2000 are observed

Spectral properties of noise events on ground*



low energy threshold [adu] ↑

thr [adu]	rate [efc]
65	1.08
64	1.41
63	1.84
62	2.39
61	3.11
60	4.03
59	5.21
58	6.73
57	8.66
56	11.2
55	14.2
54	18.2
53	23.8
52	29.5
51	37.3
50	47.2
49	59.5
48	74.8
47	93.7

event rate [events / frame / camera] ↓

*after rejecting all frames where at least one pixel contained charge > 1000 adu

(FM6, 45 min „dark“, PUMA, HK160630 0012)

→ **lower limit to the situation in space**

reducing the low energy threshold by 9-10 adu (≈11-12 eV) increases the telemetry rate by one order of magnitude

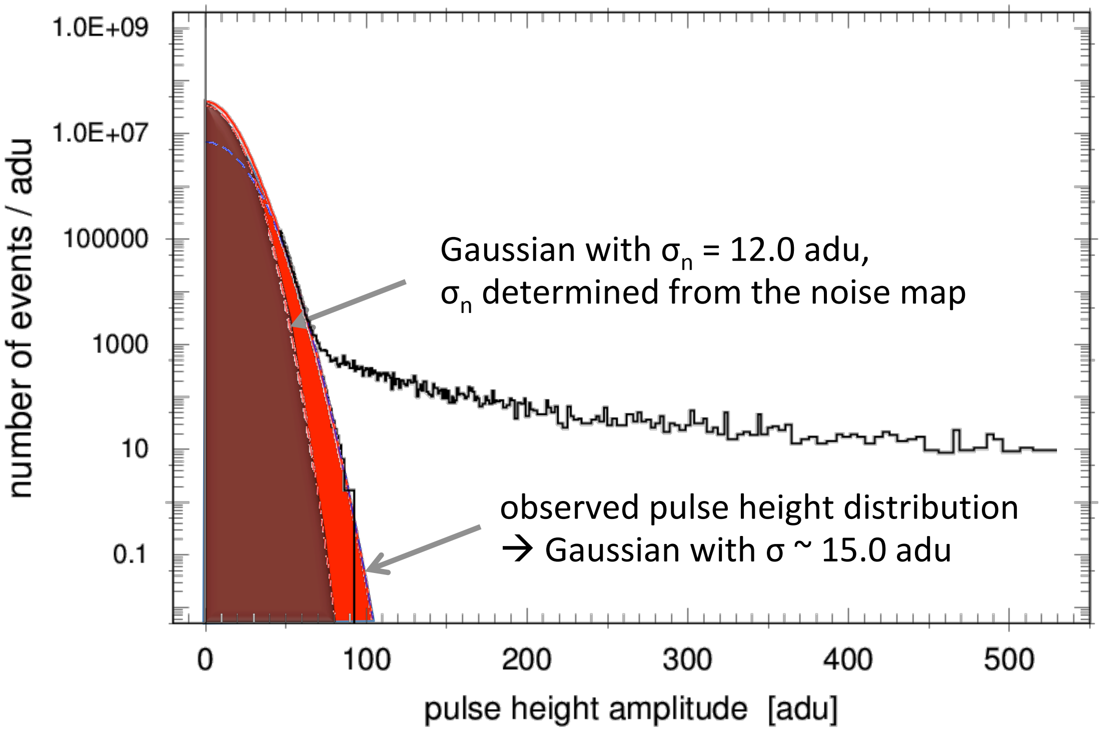
1 adu ≈ 0.84 eV

10 eV ≈ 12 adu

Properties of the detector noise

The detector noise is considerably higher than the noise map suggests

.. and there will be a MIPs induced component .. plus a component caused by soft protons



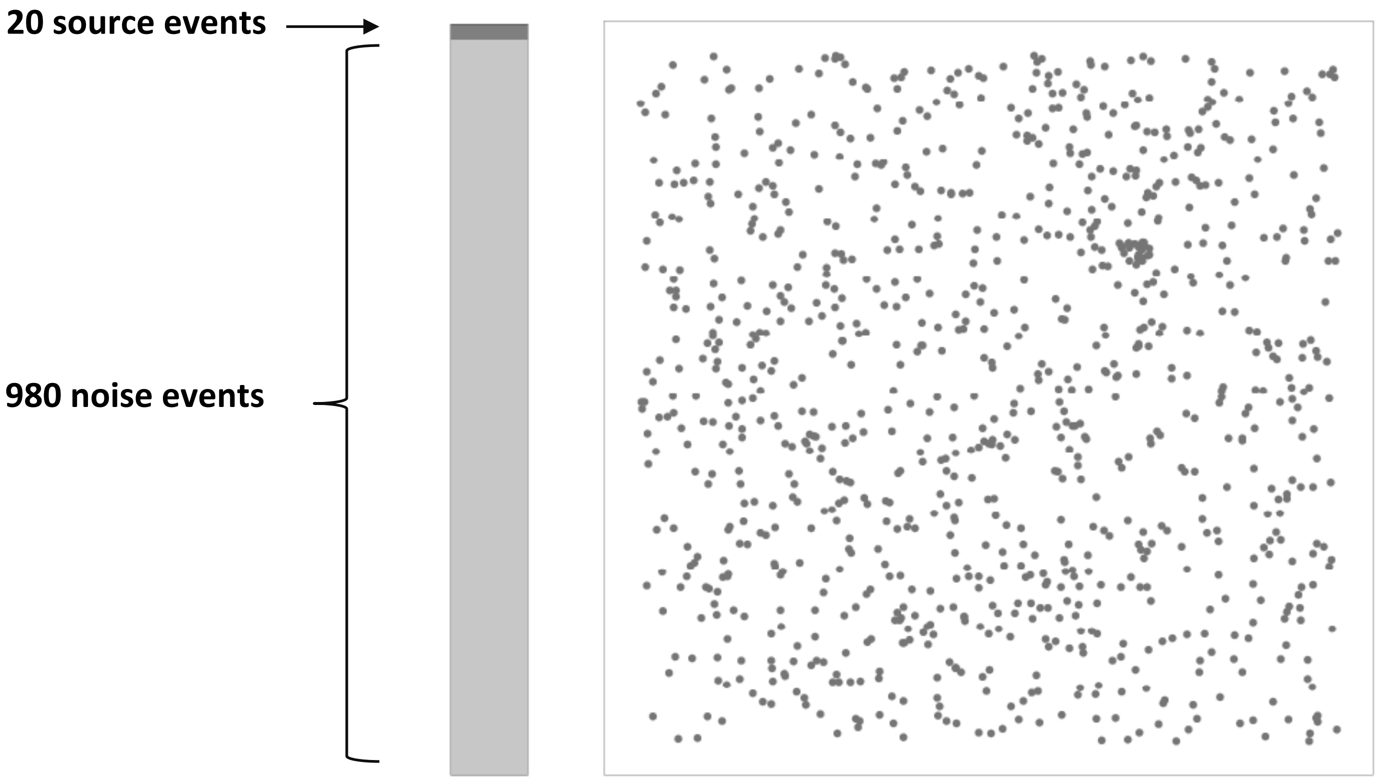
spectral distribution of all events after excluding all frames where at least one pixel contained charge > 1000 adu **and also the subsequent 100 frames (5 s)**

→ spectrum of internally generated events („detector noise“)

At low energies, the signal will merge with detector noise

simple example:

1000 randomly distributed points, 980 uniformly distributed, 20 over a small region
→ 20 source photons among 1000 photons



→ to some degree it does make sense to transmit primarily noise

eROSITA Event Compression

General concept

Event compression: general concept

Save telemetry by transmitting only the „important“ regions, i.e. the regions around charges which are likely to have been released by X-ray photons

→ concept of „event islands“
(also applied in other X-ray missions, but not in XMM-Newton)

→ concept of **two** low energy thresholds:

1. a trigger threshold for locating a major charge
2. a split threshold for locating secondary (= minor = supplementary) charges around a major charge

good to know:
in the case of eROSITA, the maximum pattern size which can be created by an X-ray photon is 2 x 2 pixels

Event compression: strict requirements

1. the compression has to be achieved during readout
2. the compression needs to be fast
3. events have to be placed into 4 Byte blocks (32-bit „words“)
4. each word needs to start with a 2 bit header

→ 30 bits available

→ for **singles** and the **main pixel** in doubles, triples, and quadruples, no compression is possible:

→ the compression is restricted to secondary pixels

Event compression: early ideas

- **singles** and **main pixel** in doubles, triples, and quadruples: use **full information**
- **secondary pixels** in doubles, triples, and quadruples: use **compressed information**

compression method: use relative coordinates with respect to the main pixel

compression requirement: perform simple pattern recognition on-board

pattern type	uncompressed	compressed
single	1 word	1 word
double	2 words	2 words
triple	3 words	2 words
quadruple	4 words	3 words

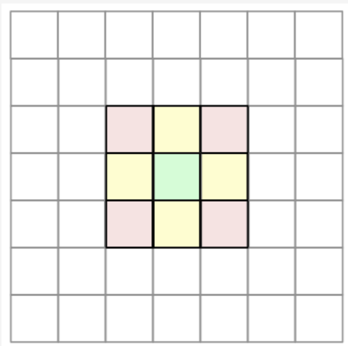
however: most photons will appear as singles or doubles; **the contribution of triples and quadruples will be < 8%**

→ **weakness:**

- compression is restricted to valid triples and quadruples
- compression does not save much telemetry
- finding the appropriate split threshold may be challenging (save margins required)

Event compression: novel concept

It is generally beneficial to sample the charge distribution in an „event island“ as completely as possible, because this enables a subsequent thorough analysis on ground



Idea: transmit the **whole 8 pixel environment** of each major pixel in just one 32-bit word whenever this is „worthwhile“.

This is feasible!

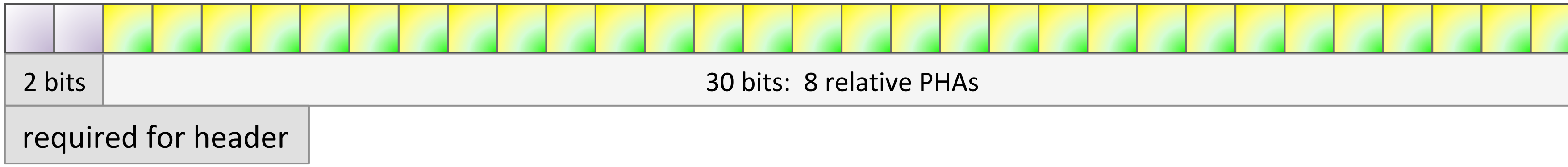
Method:

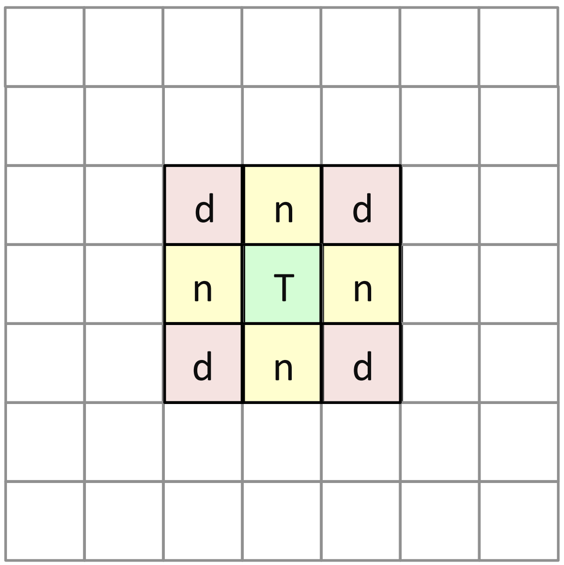
1) transmit the 8 PHAs **in a pre-defined sequence**
→ no additional coordinates necessary at all → costs no telemetry

2) express these 8 PHAs **relative to the local threshold**
→ numeric values small → few bits are sufficient

3) assign a higher dynamic range to direct neighbour pixels than to diagonal pixels
→ higher spectroscopic quality for singles and doubles (lower for triples and quadruples)

eROSITA event compression





30 bits available → 2^{30} = 1 073 741 824 values

4 diagonals and 4 neighbours = 4 d + 4 n = 4 (d + n)

→ 30/4 bits or $2^{7.5}$ = 181 values (V_d,V_n) for each (d,n) pair

→ $V_d \times V_n \leq 181$

→ possible combinations for d and n:

$$\begin{aligned}&13\cdot13=169,\ 12\cdot15=180,\ 11\cdot16=176,\ 10\cdot18=180,\\ &9\cdot20=180,\ \ 8\cdot22=176,\ \ 7\cdot25=175,\ \ 6\cdot30=180,\\ &5\cdot36=180,\ \ 4\cdot45=180,\ \ 3\cdot60=180,\ \ 2\cdot90=180.\end{aligned}$$

only PHA values lower than the local threshold need to be coded:

PHA = threshold - 1 .. threshold - V

two values need to be reserved for special meanings:

- upper PHA limit (outside dynamic range)
- PHA unknown or unreliable (MIP region)

→ PHA = threshold - 1 .. threshold − V + 2

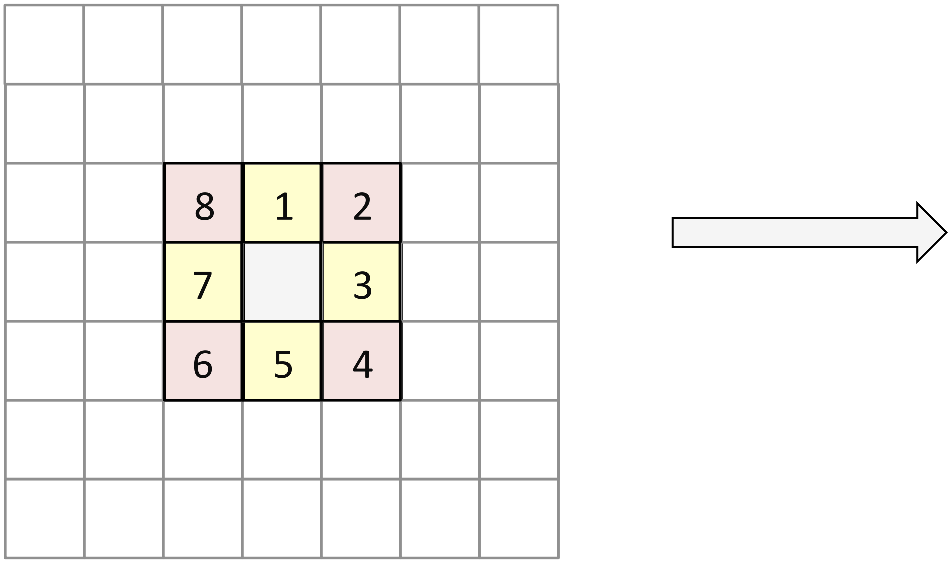
Challenge:

how to squeeze the 8 relative adu values into 30 bits ?

Solution:

consider them as coordinates

in an 8 dimensional fractal bit coordinate system



$(i_1, i_2, i_3, i_4, i_5, i_6, i_7, i_8)$

Example: coding all possible combinations of (i_1,i_2,i_3) with i_1=0..3, i_2=0..2, i_3=0..1 requires 4.585 bits

(2.000 bits for i_1, 1.585 bits for i_2, 1.000 bit for i_3, $2^{4.585} \approx 24$)

(0,2,1) (1,2,1) (2,2,1) (3,2,1)

(0,1,1) (1,1,1) (2,1,1) (3,1,1)

(0,0,1) (1,0,1) (2,0,1) (3,0,1)

(0,2,0) (1,2,0) (2,2,0) (3,2,0)

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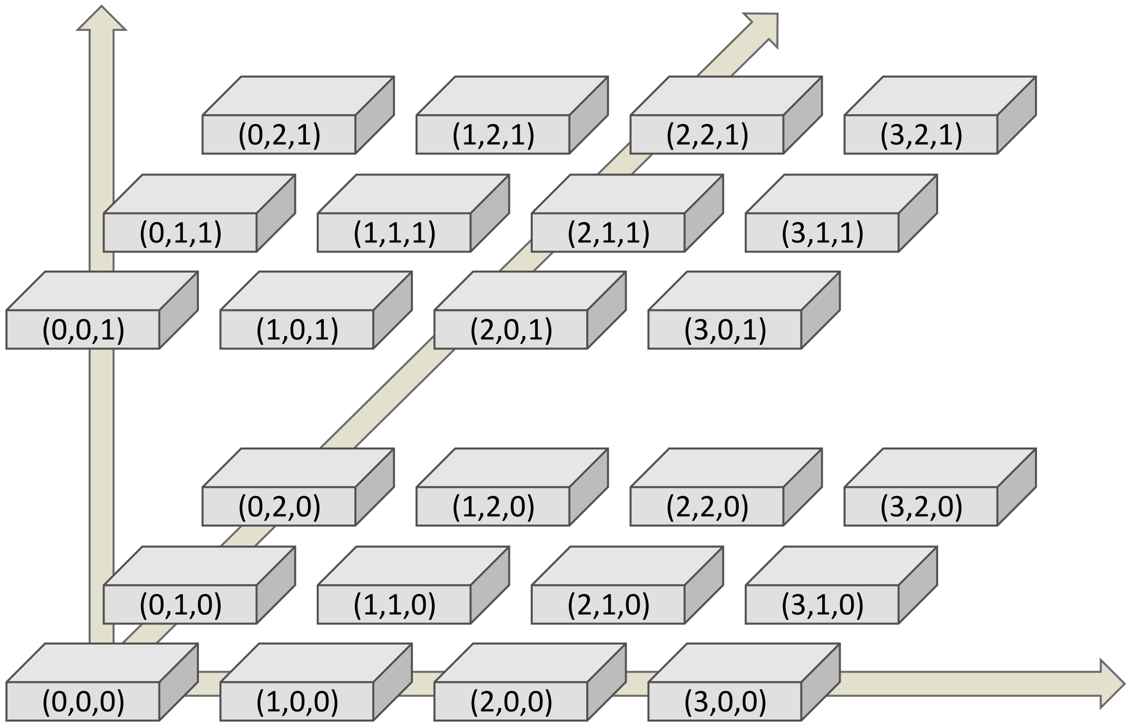

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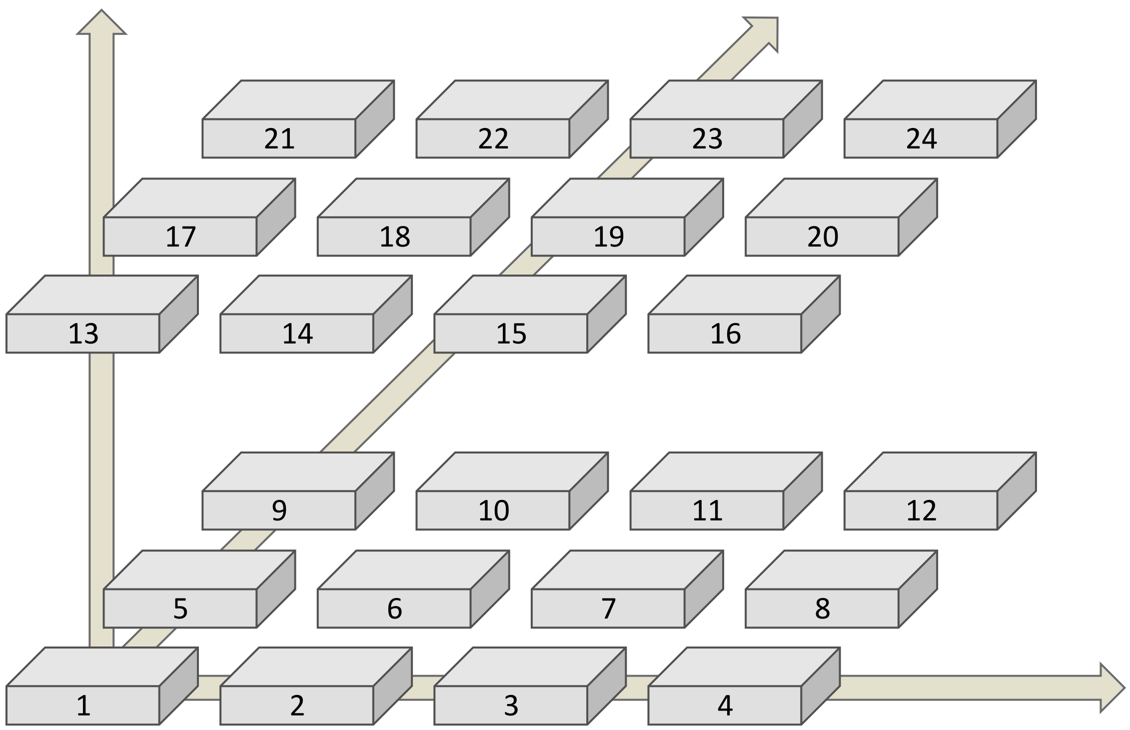
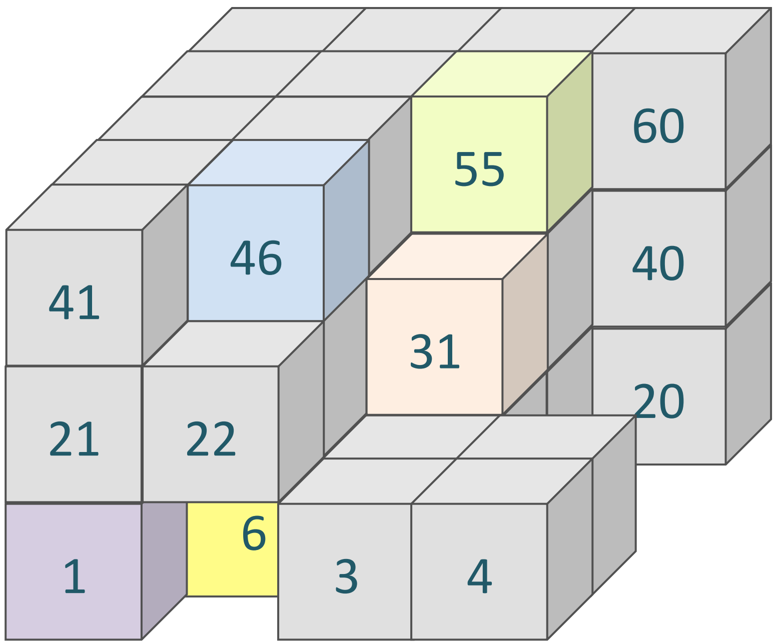


Assigning running numbers to coordinates

example: 4 x 5 x 3 array

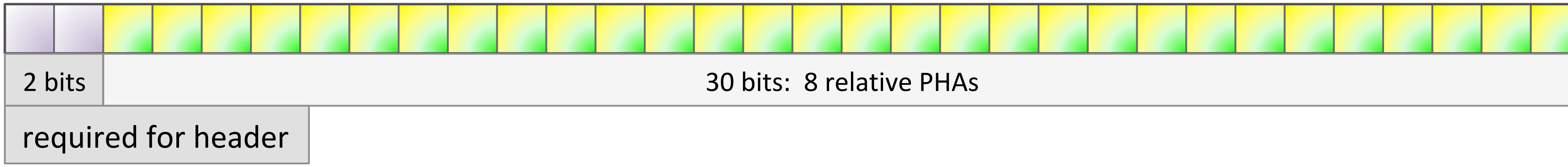


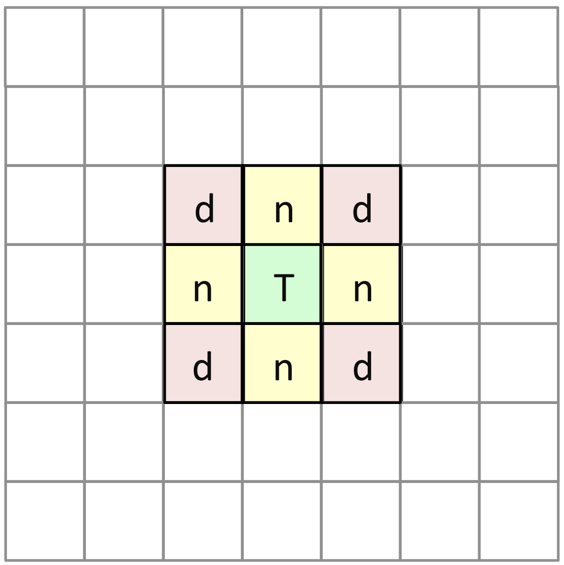
$$\# j = i_x + (i_y - 1) n_x + (i_z - 1) n_x n_y$$

$n_x = 4$, $n_y = 5$, $n_z = 3$

(1,1,1) = # 1 = 1 + (1-1) x 4 + (1-1) x 4 x 5
(2,2,1) = # 6 = 2 + (2-1) x 4 + (1-1) x 4 x 5
(3,3,2) = #31 = 3 + (3-1) x 4 + (2-1) x 4 x 5
(2,2,3) = #46 = 2 + (2-1) x 4 + (3-1) x 4 x 5
(3,4,3) = #55 = 3 + (4-1) x 4 + (3-1) x 4 x 5

eROSITA event compression





30 bits available → 2^{30} = 1 073 741 824 values

4 diagonals and 4 neighbours = 4 d + 4 n = 4 (d + n)

→ 30/4 bits or $2^{7.5}$ = 181 values (V_d,V_n) for each (d,n) pair

→ $V_d \times V_n \leq 181$

→ possible combinations for d and n:

$$\begin{aligned}&13\cdot13=169,\ 12\cdot15=180,\ 11\cdot16=176,\ 10\cdot18=180,\\ &9\cdot20=180,\ \ 8\cdot22=176,\ \ 7\cdot25=175,\ \ 6\cdot30=180,\\ &5\cdot36=180,\ \ 4\cdot45=180,\ \ 3\cdot60=180,\ \ 2\cdot90=180.\end{aligned}$$

only PHA values lower than the local threshold need to be coded:

PHA = threshold - 1 .. threshold - V

two values need to be reserved for special cases:

- upper PHA limit (outside dynamic range)
- PHA unknown or unreliable (MIP region)

→ PHA = threshold - 1 .. threshold − V + 2

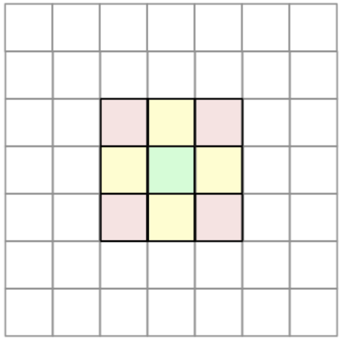
eROSITA event compression

When is the transmission of the environment „worthwhile" ?

- when there is at least one pixel in the environment with a PHA inside the available dynamic range

or

- when there is at least one direct neighbour pixel located in a MIP affected area



an overlapping environment is only transmitted if it contains additional information

Important consequence: the lack of any transmitted environment contains valuable information at no telemetry cost !

Event compression: general features

- ✓ coding is faster than decoding

- ✓ lack of environment transmission contains valuable information and does not cost any telemetry at all

- ✓ 12 options for PHA range allocations are available, emulating a dynamic split threshold:

(13,13)	(12,15)	(11,16)	(10,18)
(9,20)	(8,22)	(7,25)	(6,30)
(5,36)	(4,45)	(3,60)	(2,90)

- ✓ for an appropriate setting of the event threshold, the telemetry cannot get saturated by whatever happens below this threshold

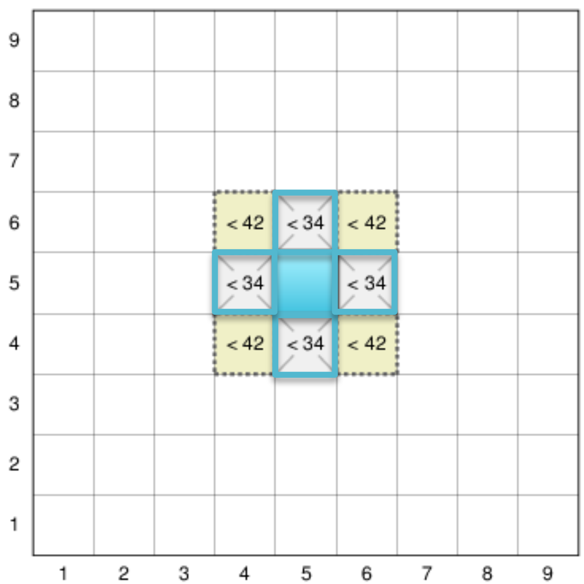
- ✓ later in the mission: singles will migrate into vertical doubles (due to increased reemission) → patterns will get larger

- ✓ additional benefit: information about the spectroscopic quality of a pattern

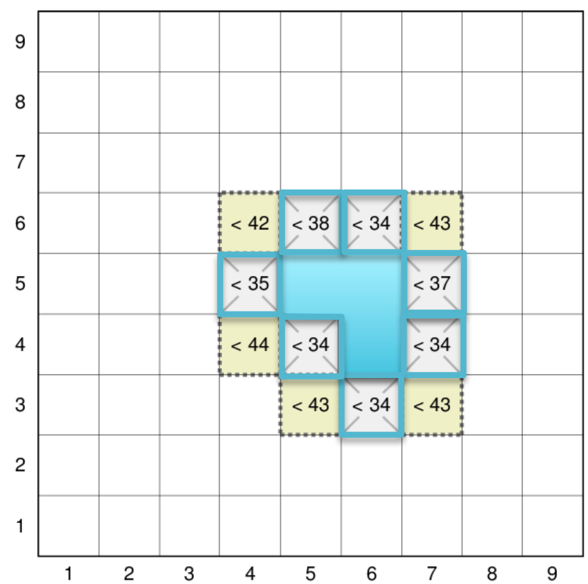
Event compression: information about the spectroscopic quality

The presence of the environmental information makes it possible to assign an **additional spectral quality flag to the reconstructed pattern** which counts the number of direct neighbour pixels which might contain (with a low likelihood) PHA values of at least the threshold applied in the pattern recognition.

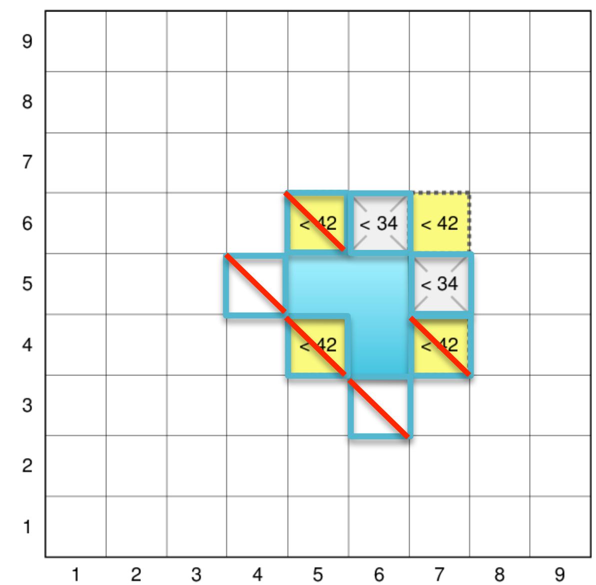
The following examples show the quality which results for a pattern recognition threshold of 40 adu:



→ single of (highest) quality 0



→ triple of (highest) quality 0



→ triple of quality 5

Event compression: information about the spectroscopic quality

The **additional spectral quality flag of the reconstructed pattern** makes it possible to adjust the photon selection according to the specific scientific goal:

- if **sensitivity** is of prime importance (e.g. source detection, variability studies), then this flag can be ignored

- if **spectroscopy** is of prime importance and if the photon statistics is sufficient, then low values of this flag should be useful for increasing the spectral resolution

A new version of the PATTERN recognition program provides a lot of additional information about the individual patterns; this is described in a detailed help file.

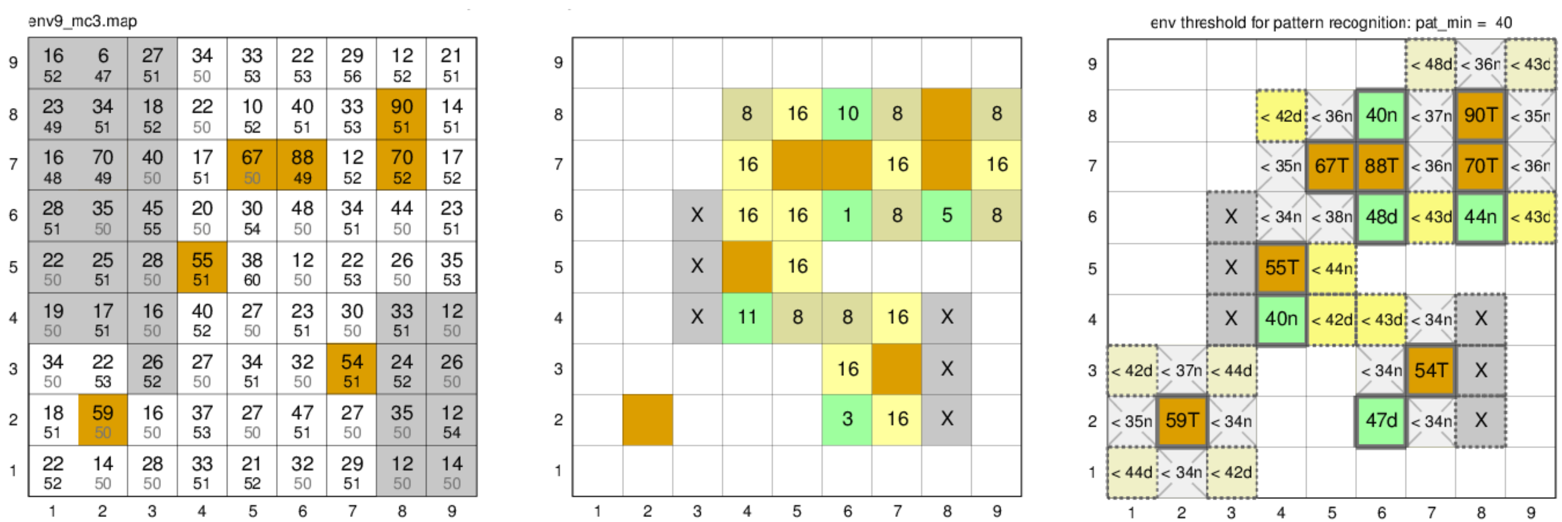
eROSITA Event Compression

Tests

Event compression: first tests

1. compression software developed and tested in Fortran on workstation
2. onboard version, written in C (by Walter Kink), installed on workstation
3. both versions used to code „invented data“ (including pathological cases)

   → subsequent decoding produced identical results ✓



original and threshold values [adu] | transmitted environment values | reconstructed values [adu]

telemetry stream:

```
|008_008_00090|
|005_007_00067|08_16_08_16_00_08_16_01|
|006_007_00088|08_10_08_00_16_08_01_08|
|008_007_00070|08_00_08_16_16_08_05_08|
|004_005_00055|09_16_08_17_16_09_11_08|
|007_003_00054|08_16_09_16_17_03_16_09|
|002_002_00059|
```

statistics:

```
number of pixels with
- adu ignored due to MIPs:   6
- rough upper limits:       11
- sensitive upper limits:   17
- known adu values:         12
                           ---
                            46

number of 32-bit words:     12
```

reconstructed event list: (46 entries)

```
 1: (007,009) 2   47 adu or less (or missing)
 2: (008,009) 1   35 adu or less (or missing)
 3: (009,009) 2   42 adu or less (or missing)
 4: (004,008) 4   41 adu or less
 5: (005,008) 3   35 adu or less
 6: (006,008) 5   40 adu
 7: (007,008) 1   36 adu or less (or missing)
 8: (008,008) 7   90 adu
 9: (009,008) 1   34 adu or less (or missing)
10: (004,007) 3   34 adu or less
11: (005,007) 7   67 adu
12: (006,007) 7   88 adu
.........................................
```

Event compression: test with real data

26.03.2018

FM8 camera, exposure with ^{55}Fe, simultaneous output of raw data and compressed telemetry stream

→ **614 697 triggering pixels, 46 816 (7.6 %) of them with 8 pixel environments**

→ 661 513 „words“ of 32 bits each → 2.69 MB (including overhead) of „events data“

→ 614 697 * 9 = 5 532 273 pixels after expansion, with 2 357 344 in overlapping regions

→ **3 174 929 entries** after removing multiple cases → 0.89 Byte per entry

Compressed telemetry stream decoded and FITS converted in Bamberg by Ingo Kreykenbohm, then decoded at MPE and compared with the raw data → **no single disagreement** !

FLAG	PHA property	pixel property	in telemetry	number of pixels
0	PHA unreliable	in insensitive area	yes	30 (0.0 %)
1	upper limit to PHA	direct neighbour	**no**	1 407 949 (44.3 %)
2	upper limit to PHA	diagonal pixel	**no**	911 003 (28.7 %)
3	upper limit to PHA	direct neighbour	yes	95 146 (3.0 %)
4	upper limit to PHA	diagonal pixel	yes	97 778 (3.1 %)
5	PHA known	direct neighbour	yes	42 291 (1.3 %)
6	PHA known	diagonal pixel	yes	6 035 (0.2 %)
7	PHA known	triggering pixel	yes	614 697 (19.4 %)

73.0 % for „free“ (flags 1 and 2)

eROSITA Event Compression

a novel, fast, efficient compression method for maximizing the telemetry content