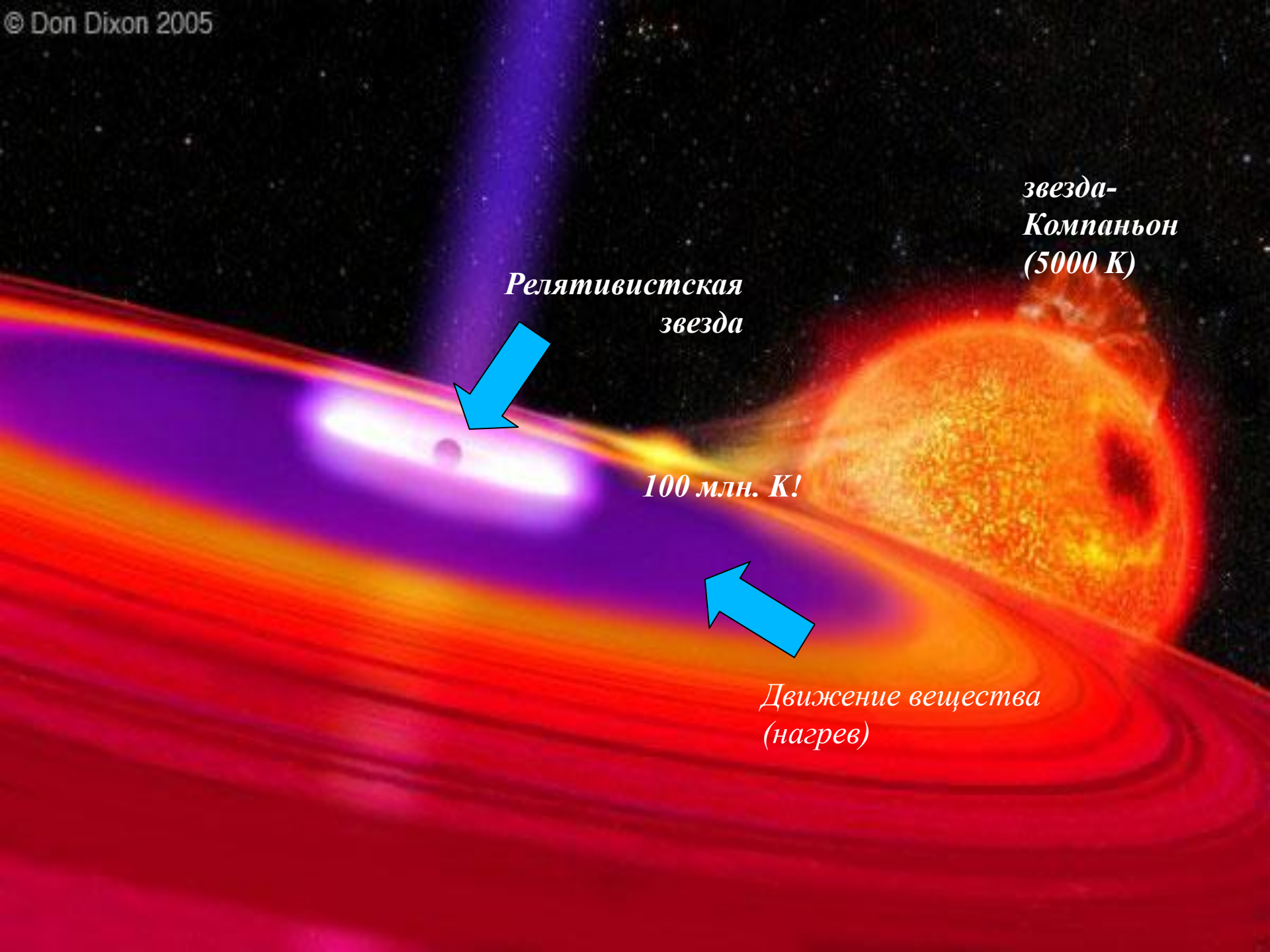




**От теории к практике:
о проявлениях сильной
гравитации
в рентгеновских наблюдениях**



звезда-
Компаньон
(5000 К)

Релятивистская
звезда

100 млн. К!

Движение вещества
(нагрев)

Почему рентгеновский диапазон?

$$L \sim \frac{GM_c \dot{M}}{R_c} \sim \left(\frac{2R_c}{R_s} \right)^{-1} \dot{M} c^2 = \eta \dot{M} c^2 \text{ — светимость}$$

$$R_s = \frac{2GM}{c^2} \text{ — радиус Шварцшильда } (= 3 \text{ км для } 1 M_{\text{Sun}})$$

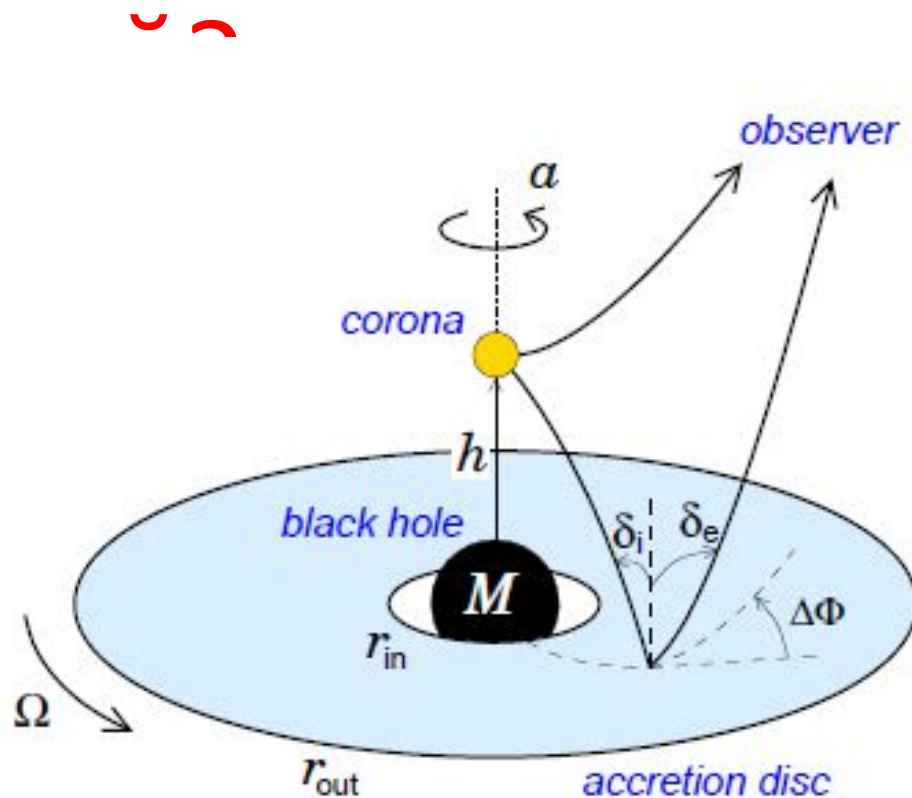
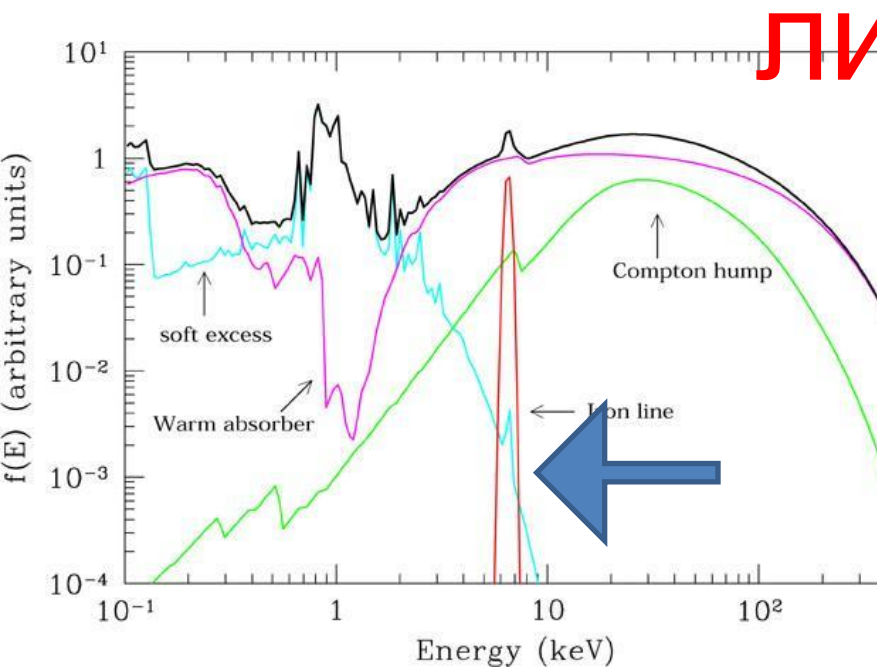
$$\eta = \left(\frac{2R_c}{R_s} \right)^{-1} \text{ — эффективность аккреции}$$

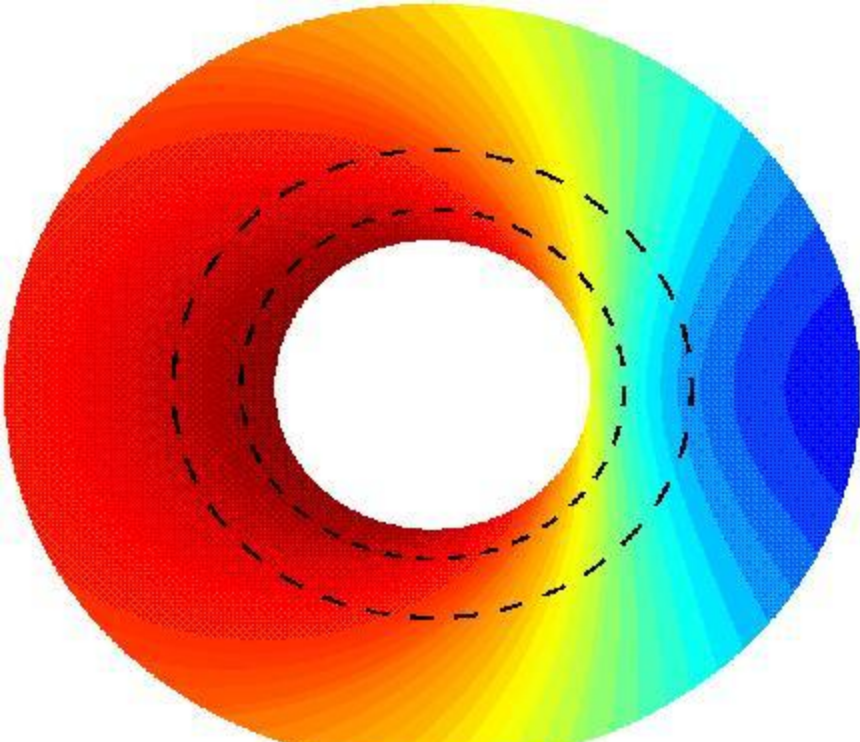
$$\left. \begin{array}{l} \dot{M} \sim 10^{-8} M_{\text{Sun}} / \text{Г} \\ L_x \sim 10^{38} \text{ эрг/с} \end{array} \right\} \Rightarrow \eta \sim 0.1, R_c \sim 5R_s \text{ } (\sim 15 \text{ км для } 1 M_{\text{Sun}})$$

$$\sigma T^4 4\pi R^2 \sim 10^{38} \text{ эрг / сек, } kT \sim 1 - 2 \text{ кэВ}$$

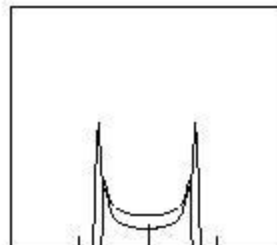
Пример 1.

Вращение черных дыр по искажениям эмиссионных





Newtonian



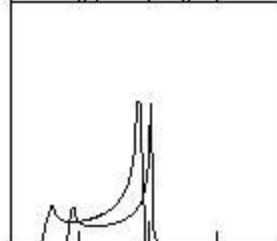
Special relativity



Transverse Doppler shift

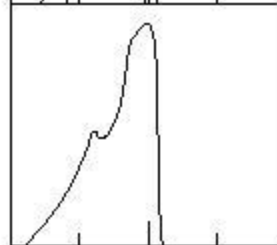
Beaming

General relativity

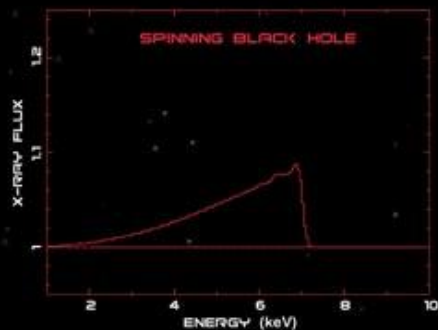
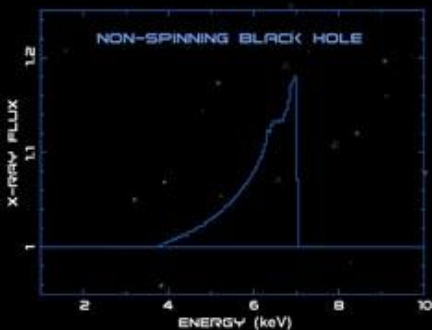
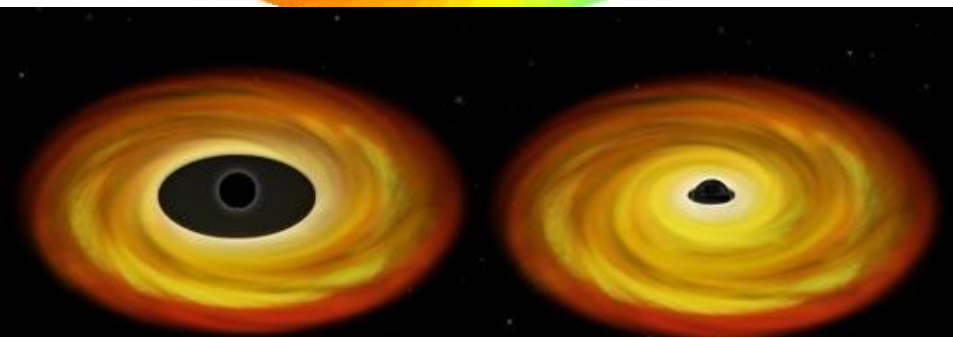


Gravitational redshift

Line profile

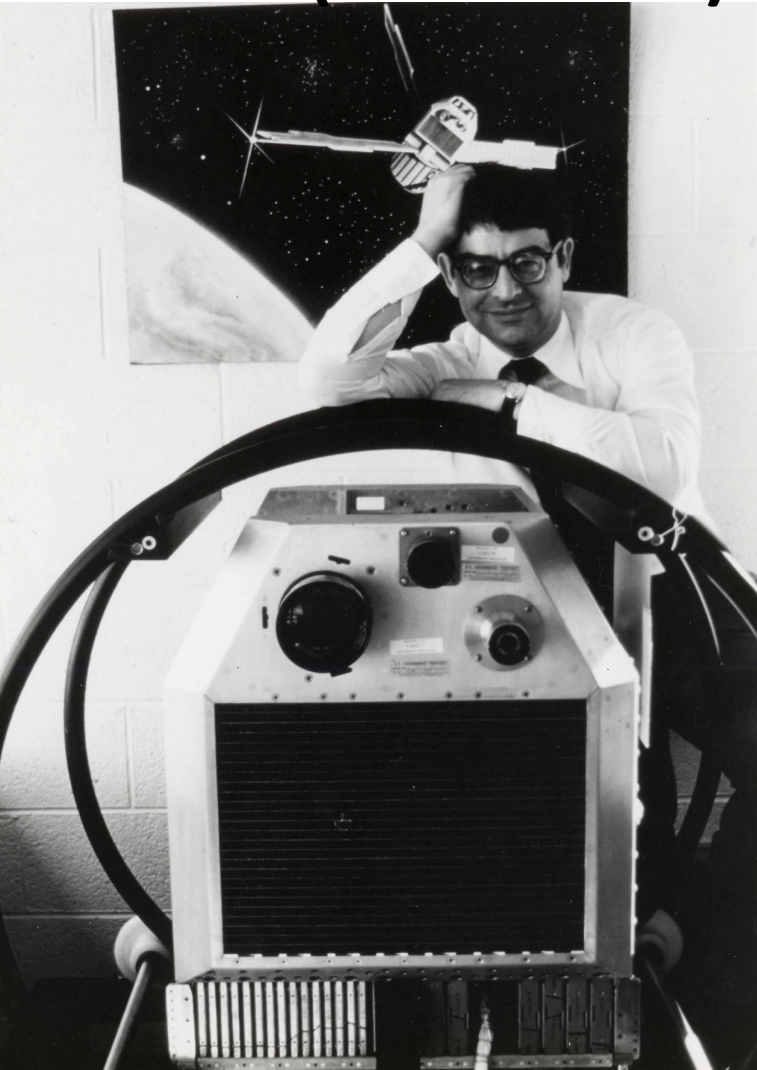


0.5 1 1.5
 $\nu_{\text{obs}}/\nu_{\text{em}}$

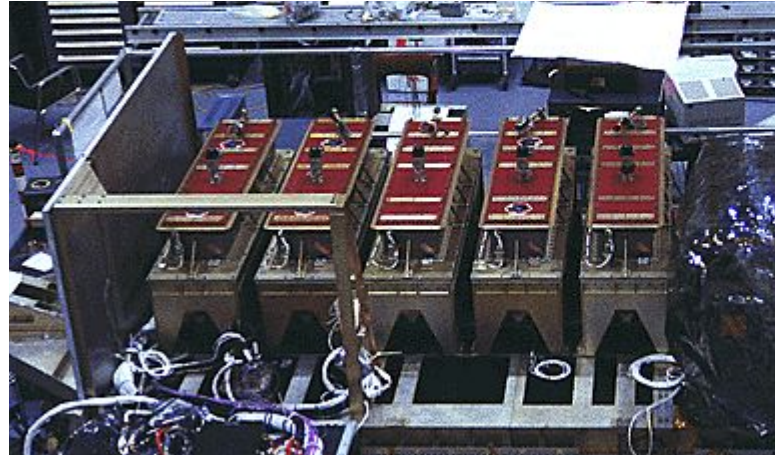


**Отражение от
быстровращ.
диска
находящегося**

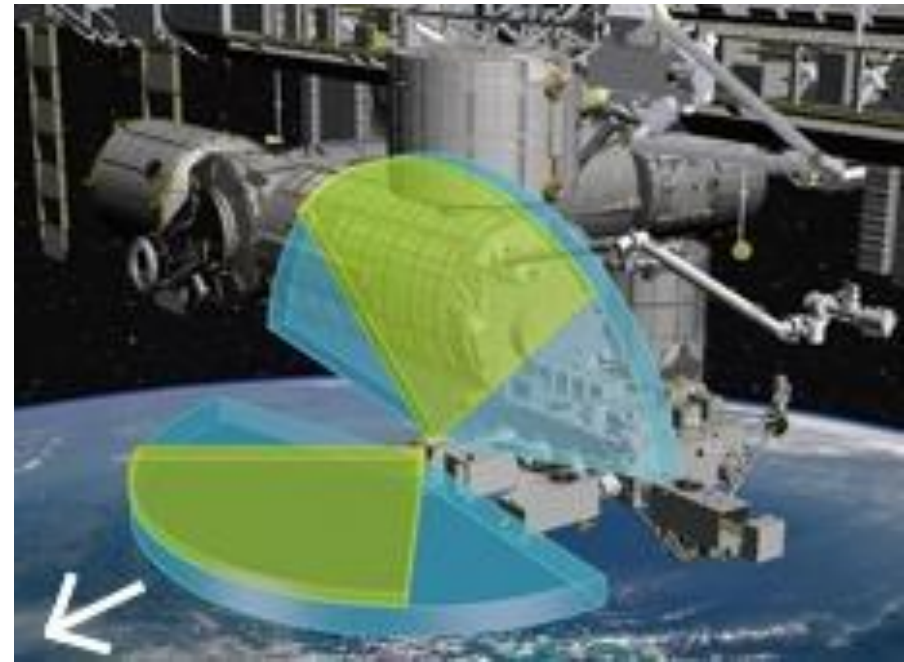
UHURU (1970-1973)



RXTE (1995-2012)

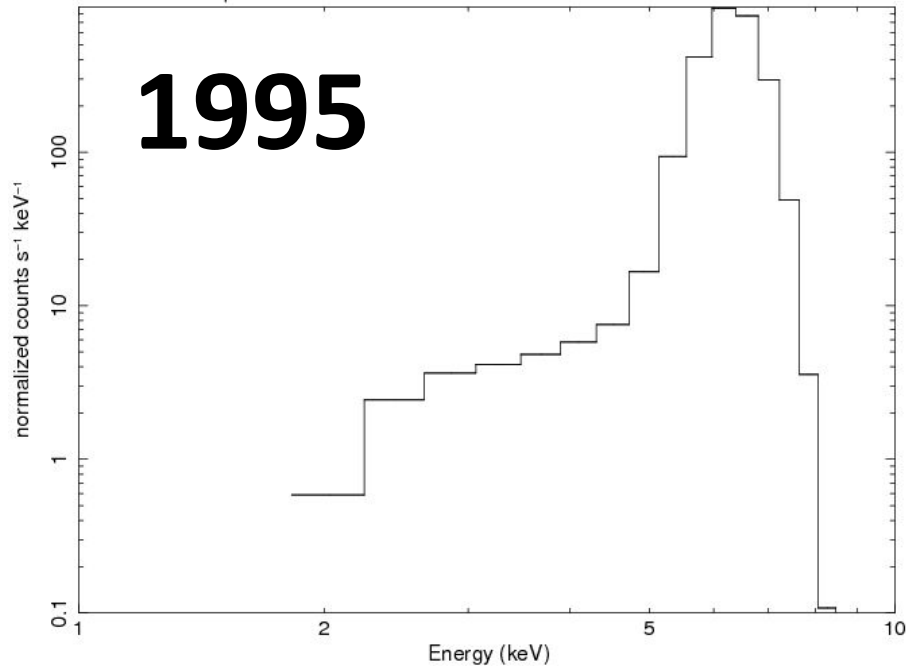


MAXI/ISS (2009-??)



RXTE/PCA

6.4 keV line response



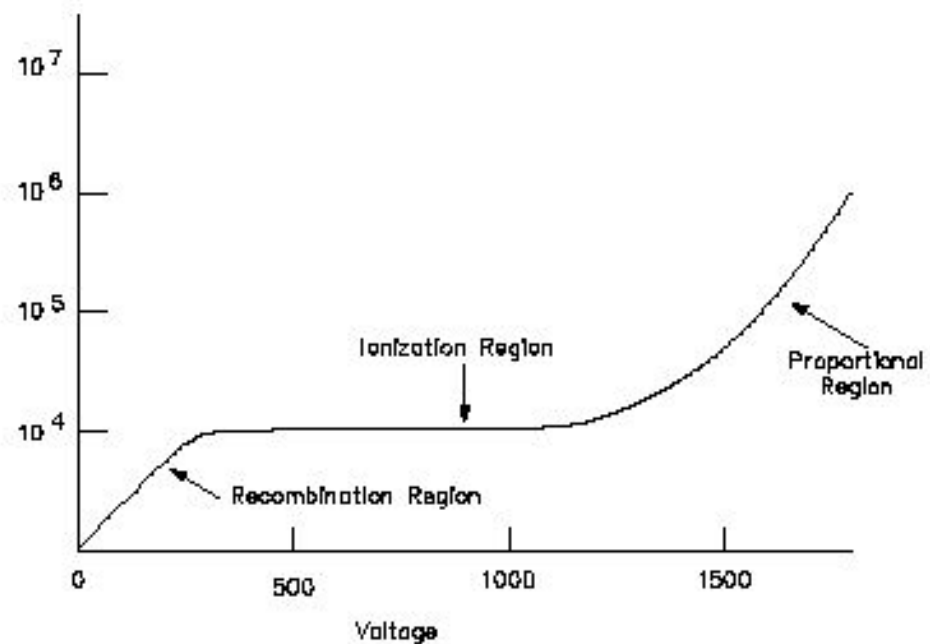
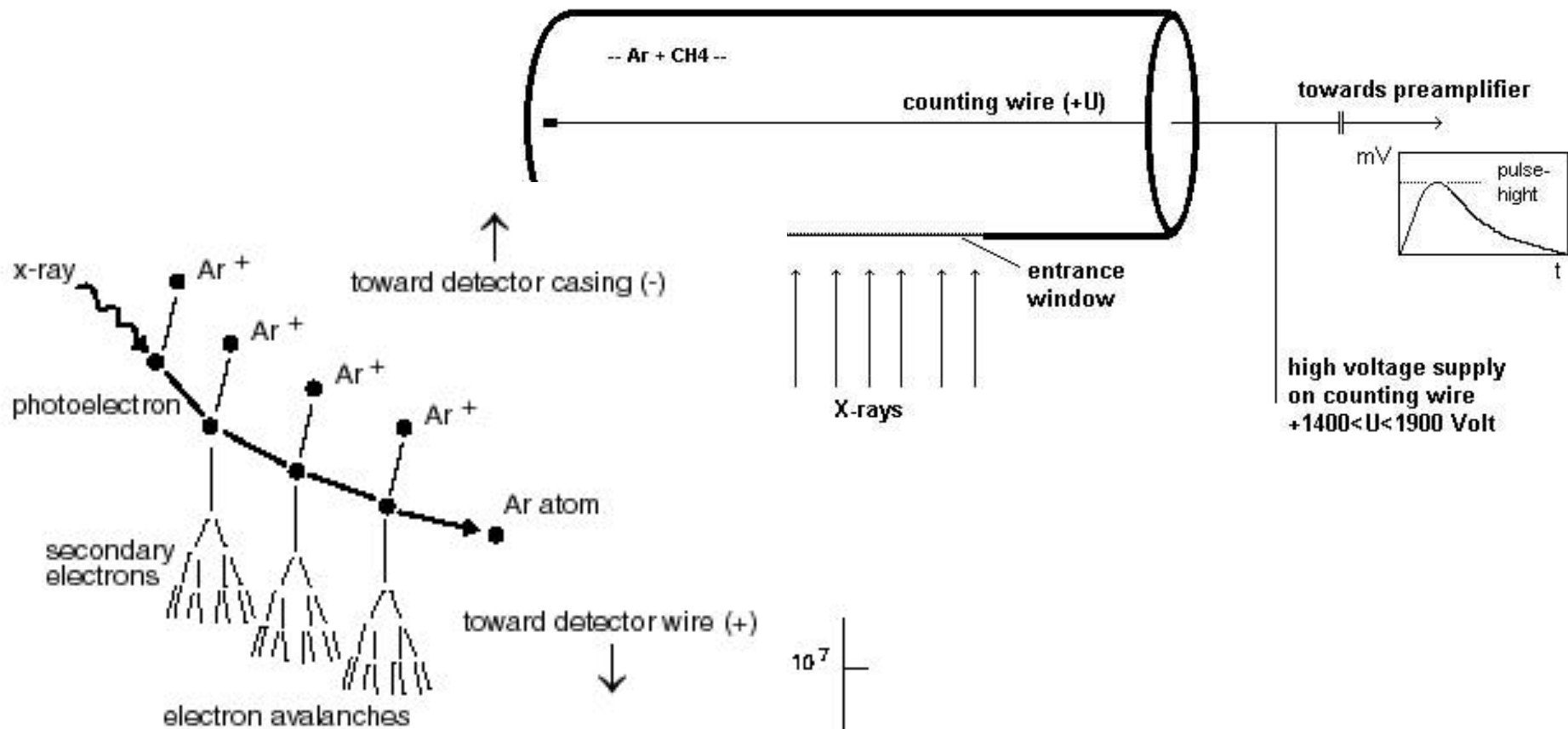
HEAO1/A2/H1

6.4 keV line response



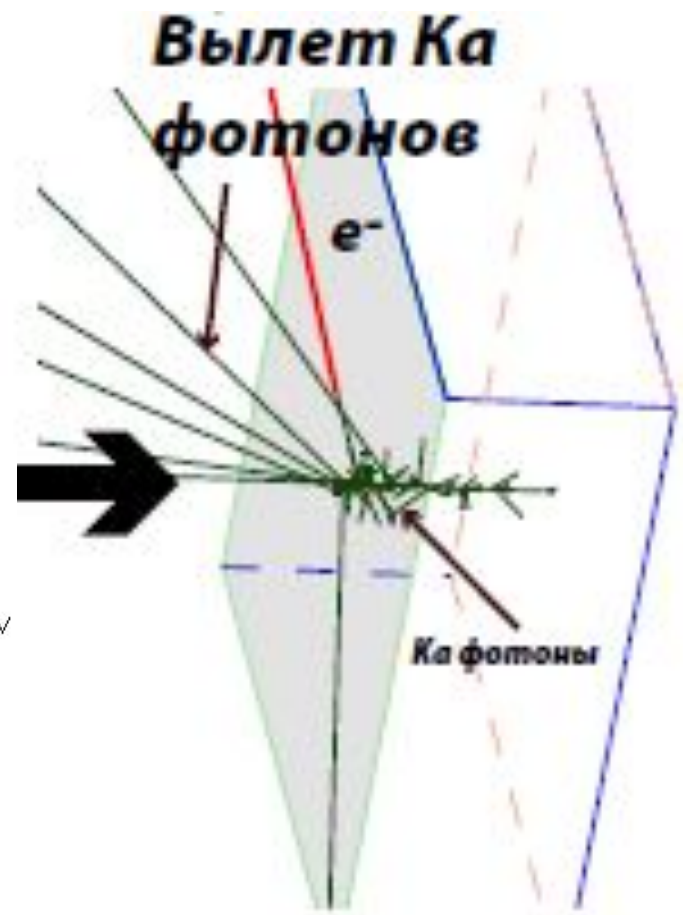
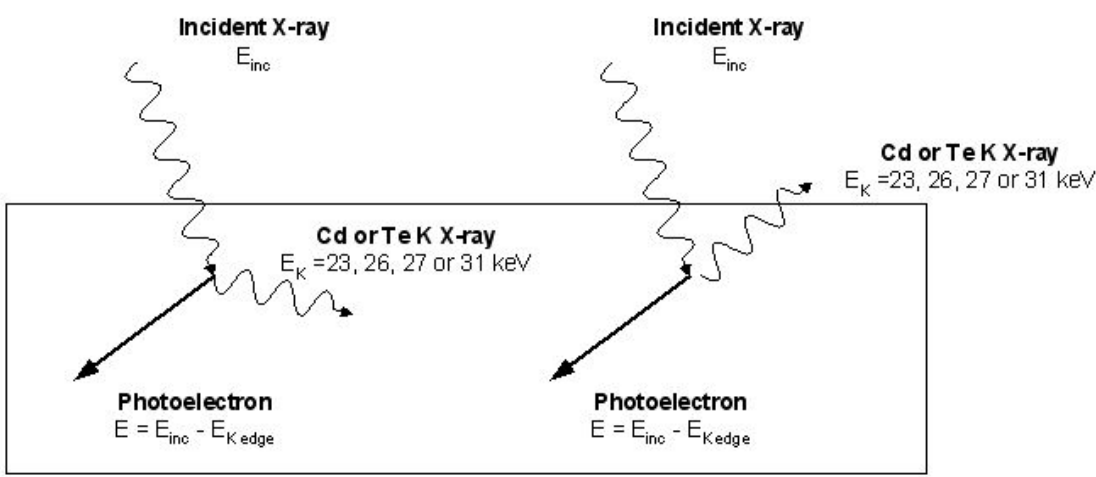
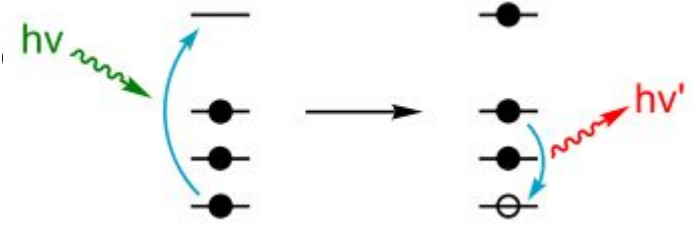
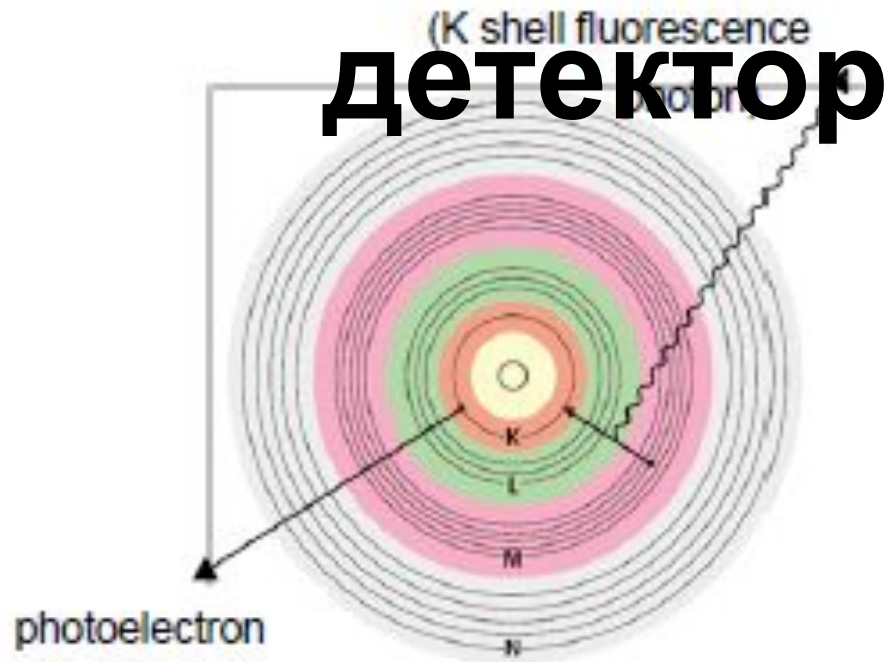
**Отклик
газовых
счетчик
ОВ**

**Разрешение
ограничено
количеством
собираемых
электронов**

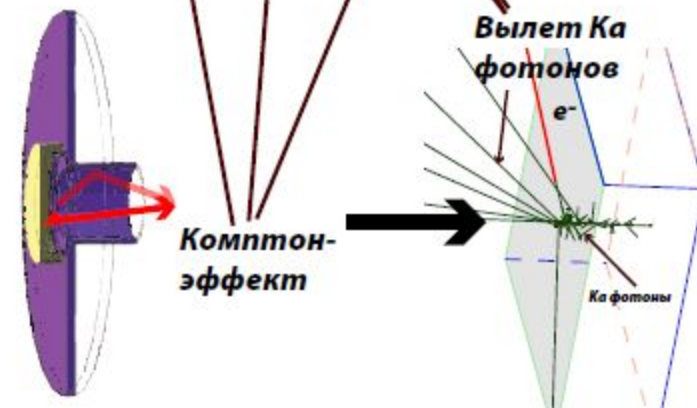
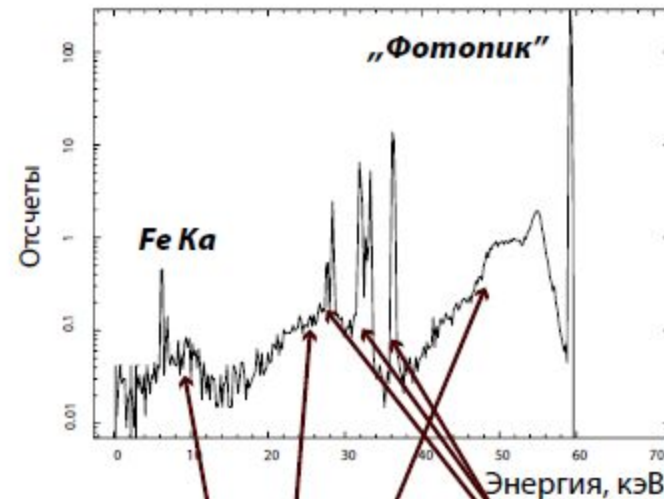
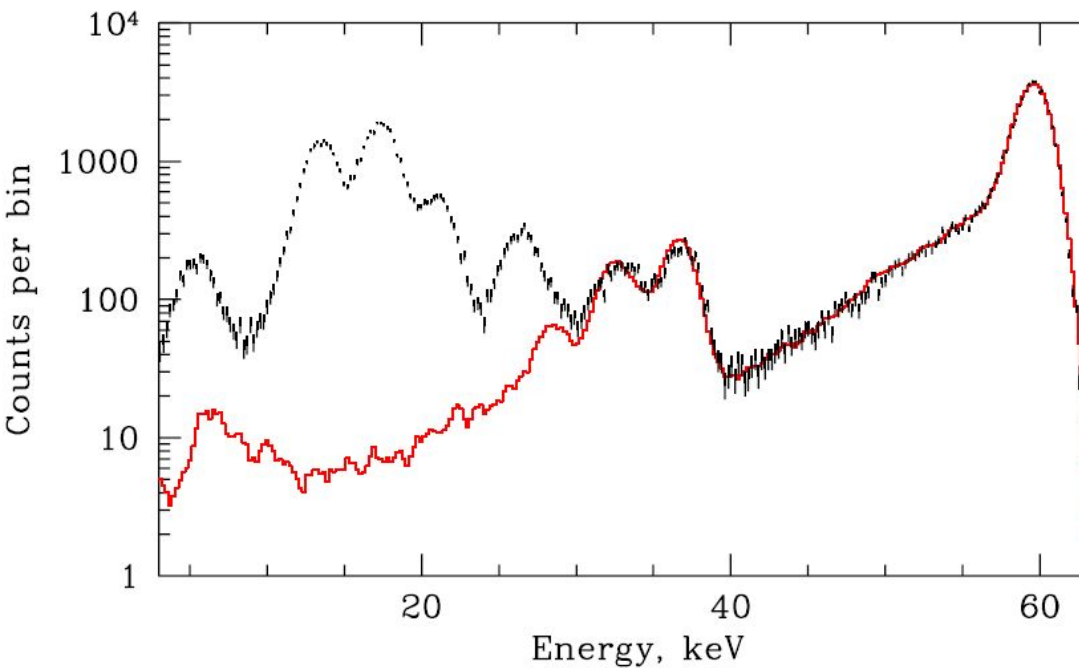
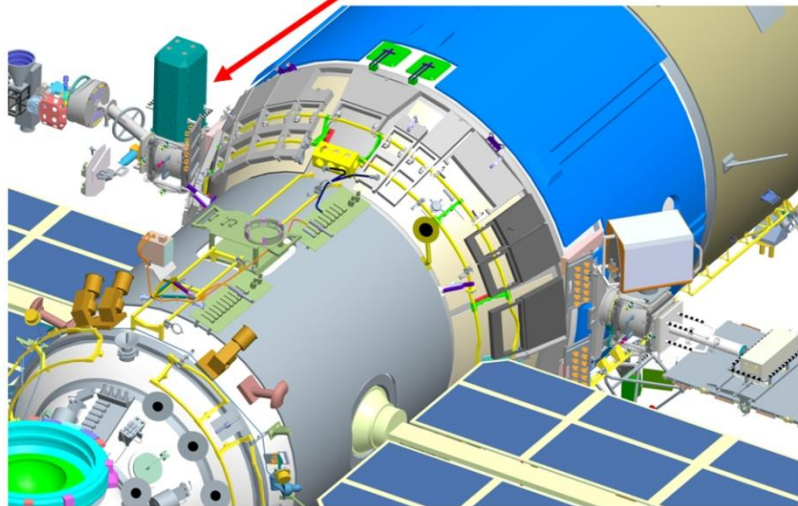


**Электроны,
выбитые
рентгеновскими
фотонами формируют**

Процессы в детекторе



Пример отклика реального детектора, изготавливаемого в ИКИ РАН



Пример файла событий со спектрометра

ordinate reference frame
interval
ation
clock stability
recision of clock correction
) expressed in TT (integer part)
) expressed in TT (fractional part)

```
TIMEZERO= 5.57842846000E+00 / Clock correction
TIMEORZ= 5.62922284000E+08 / As in the "TIME" column: raw space craft clock
TIMEOFF= 5.62922284000E+08 / add TIMEZERO and MJDREF for absolute TT
OBJECT = 'GALACTIC_DISK' / Source information block-----
TPACK2 = '8,3' / Data is packed
TDISP2 = '28,2' / Display format
TDEF52 = 'D[0~4] & E[X1L^X1R^X2L^X2R^X3L^X3R] & C[0~255]'
```

LONGSTRN= 'UGIP 1.0' / The HEASARC Long String Convention may be used.
COMMENT This FITS file may contain long string keyword values that are
COMMENT continued over multiple keywords. The HEASARC convention uses the &
COMMENT character at the end of each substring which is then continued
COMMENT on the next keyword which has the name CONTINUE.
COMMENT E[VPR] is the Propane bit
COMMENT It is either TRUE or FALSE
More?[Yes]

COMMENT E[0:63]{6} stands for E[X3R,X3L,X2R,X2L,X1R,X1L] layers.
COMMENT Thus the bit pattern is: 5 , 4 , 3 , 2 , 1 , 0
COMMENT so the bit value is: 32 ,16 , 8 , 4 , 2 , 1
COMMENT Thus X3R=32, X3L=16, X2R=8, X2L=4, X1R=2, X1L=1
COMMENT If only X2R is desired, E[0:63] == 8.
COMMENT If X1R and X3R is desired, E[0:63] == 2 & E[0:63] == 32
COMMENT If all layers are desired, do not filter on this parameter.

```
TEVTB2 = '(M[1]{1},S[Zero]{5},E[VPR]{1},D[0:4]{3},E[0:63]{6},C[0:255]{8})' / Ev
CHECKSUM= '94CFD39F93AFA39F' / HDU checksum updated 2012-02-28T10:59:35
DATASUM = '2996004570' / data unit checksum updated 2012-02-28T10:59:35
END
```

	TIME	Event
	s	
1	5.629222840008841E+08	b10000000 b10000010 b00001001
2	5.629222840016069E+08	b10000000 b01000010 b00010000
3	5.629222840031948E+08	b10000000 b01000010 b00000111

Достижение для спектроскопии пропорциональных счетчиков

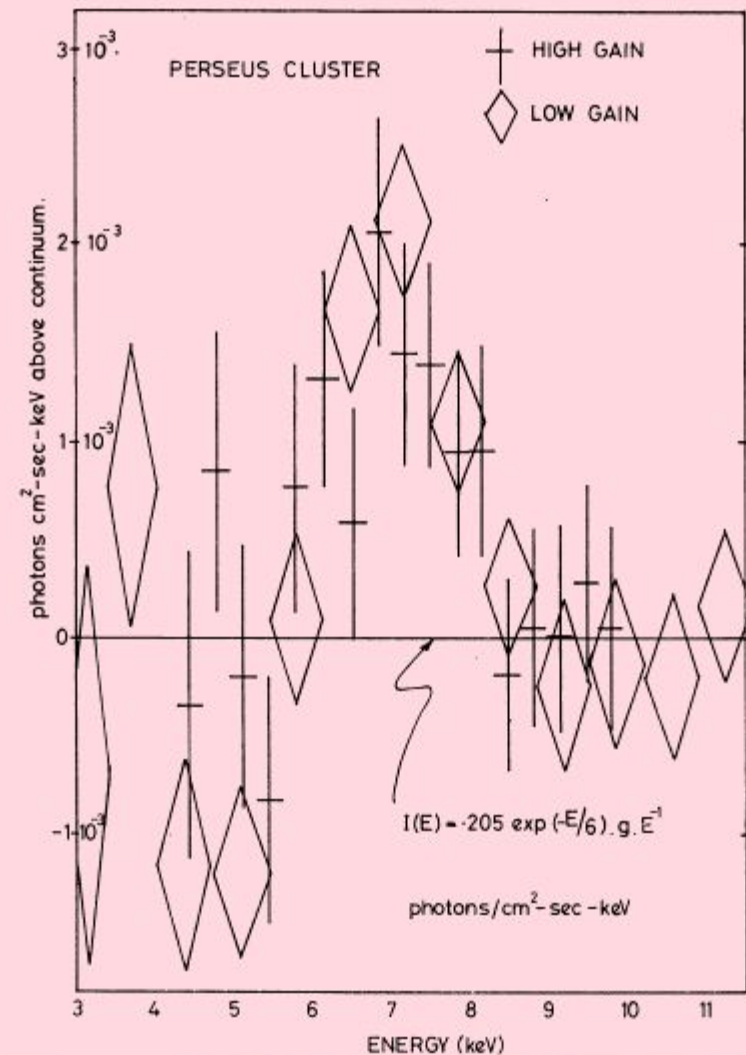
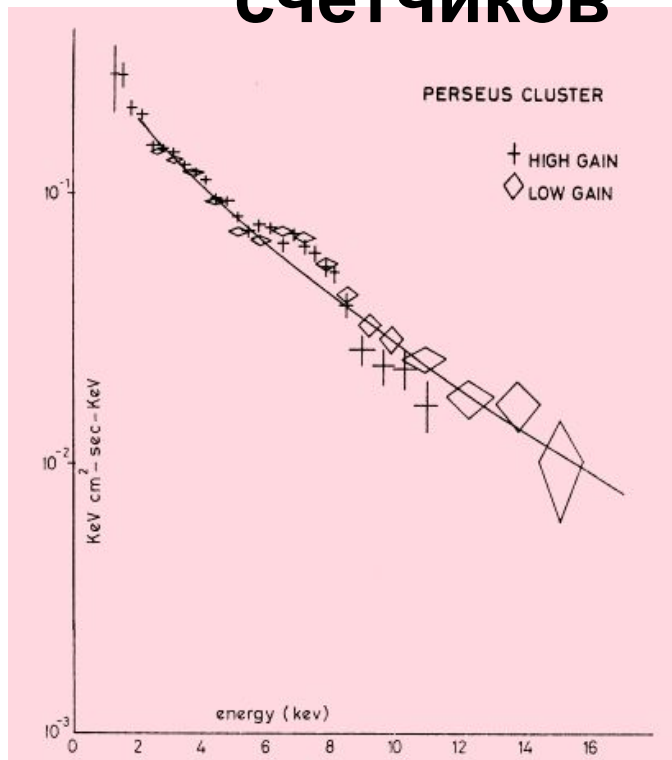


FIG. 2. The deviation of the flux in each energy channel from that predicted by the best-fitting single temperature continuum is plotted for the range 3–11 keV. Data from both gain modes show a systematic departure from the continuum in the energy range around 6.9 keV. The width of the feature is consistent with that of the gaussian energy resolution function for the detector at 7 keV. Each gain mode shows departures from continuum that are significant at the 5.6 and 6 σ levels.

На самом деле...

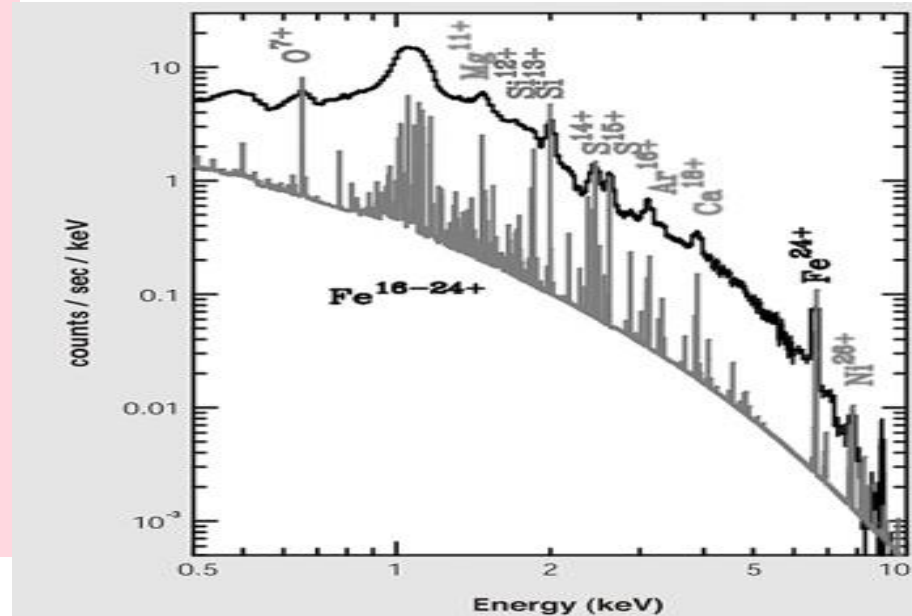
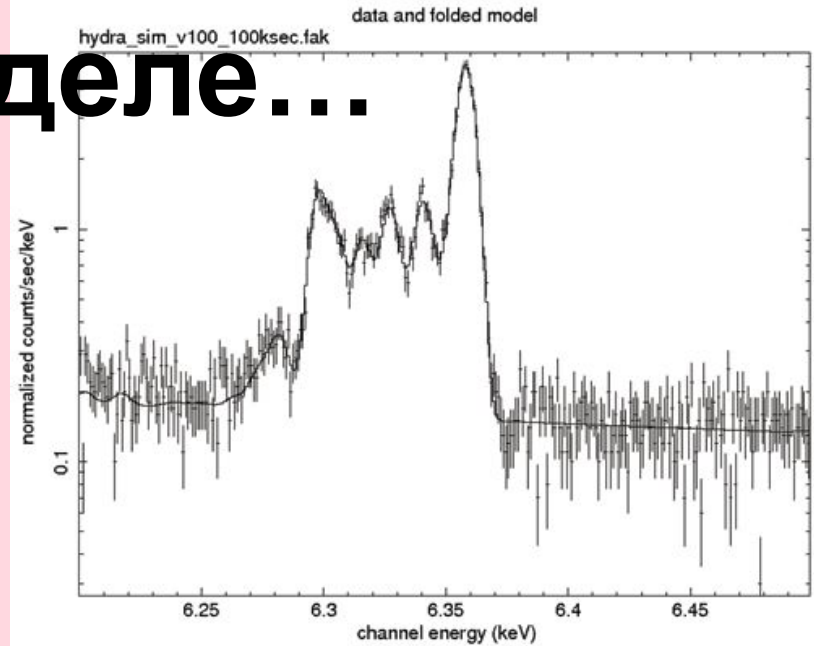
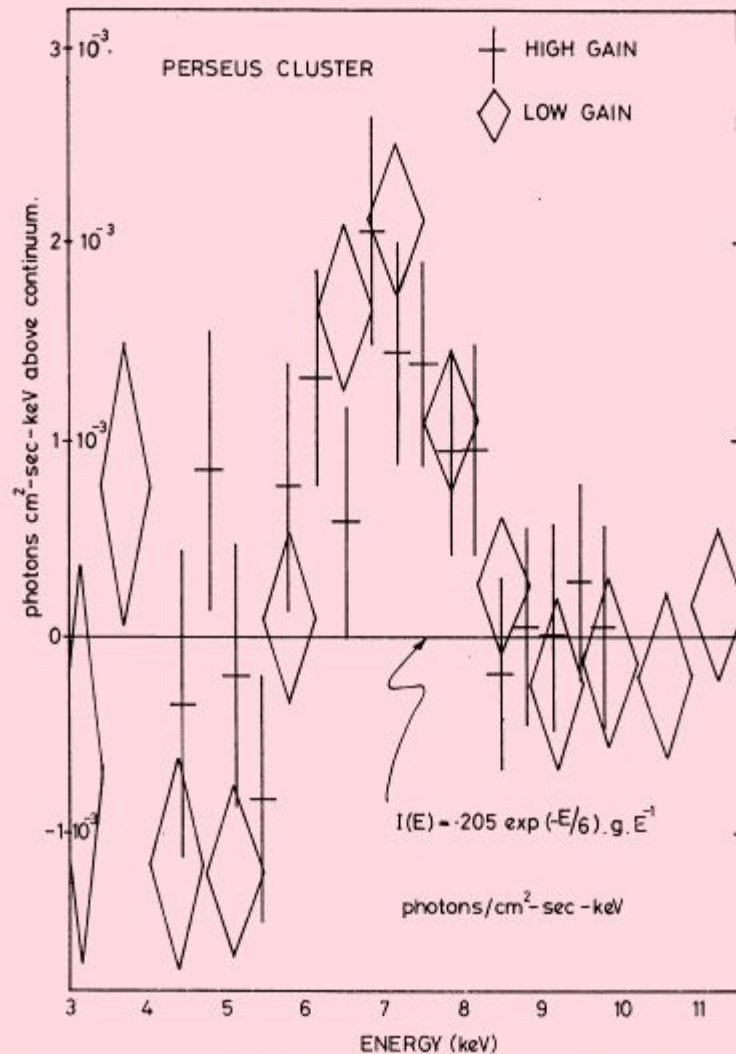


FIG. 2. The deviation of the flux in each energy channel from that predicted by the best-fitting single temperature continuum is plotted for the range 3–11 keV. Data from both gain modes show a systematic departure from the continuum in the energy range around 6.9 keV. The width of the feature is consistent with that of the gaussian energy resolution function for the detector at 7 keV. Each gain mode shows departures from continuum that are significant at the 5.6 and 6 σ levels.

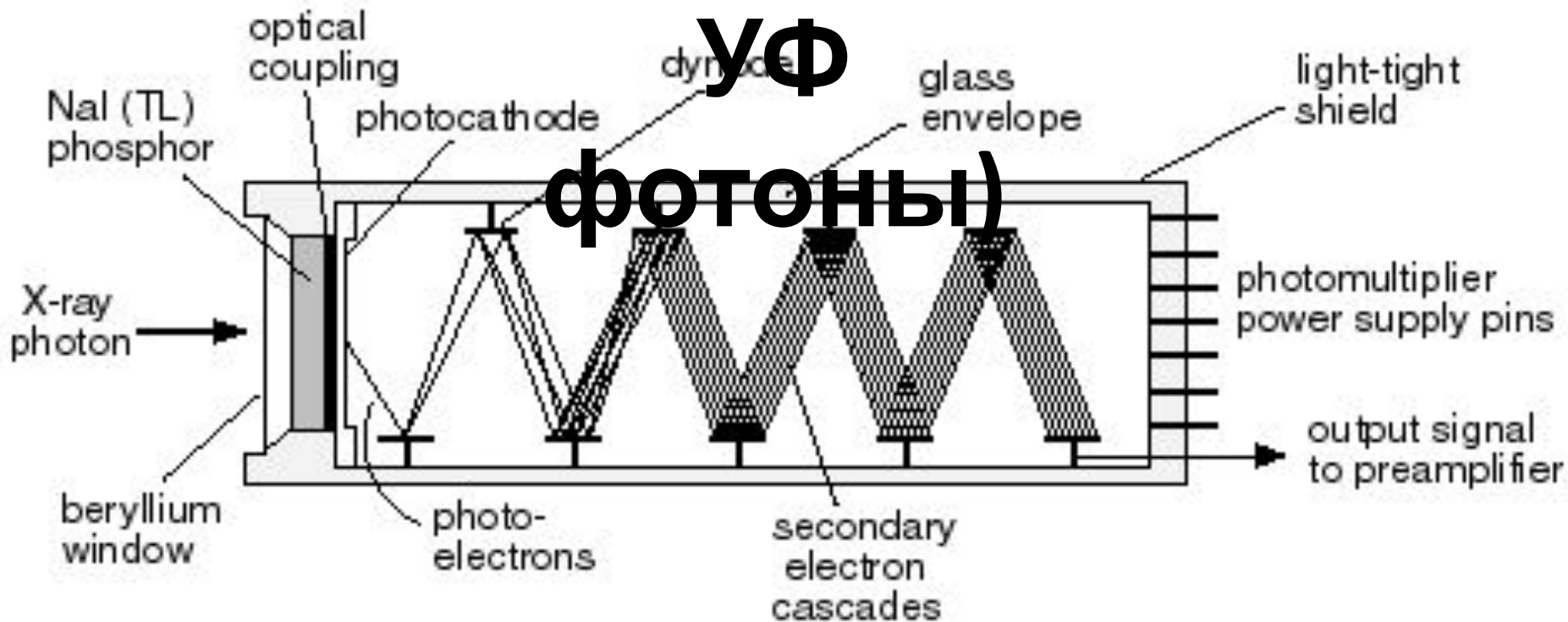
СЦИНТИЛЛЯТОР

р

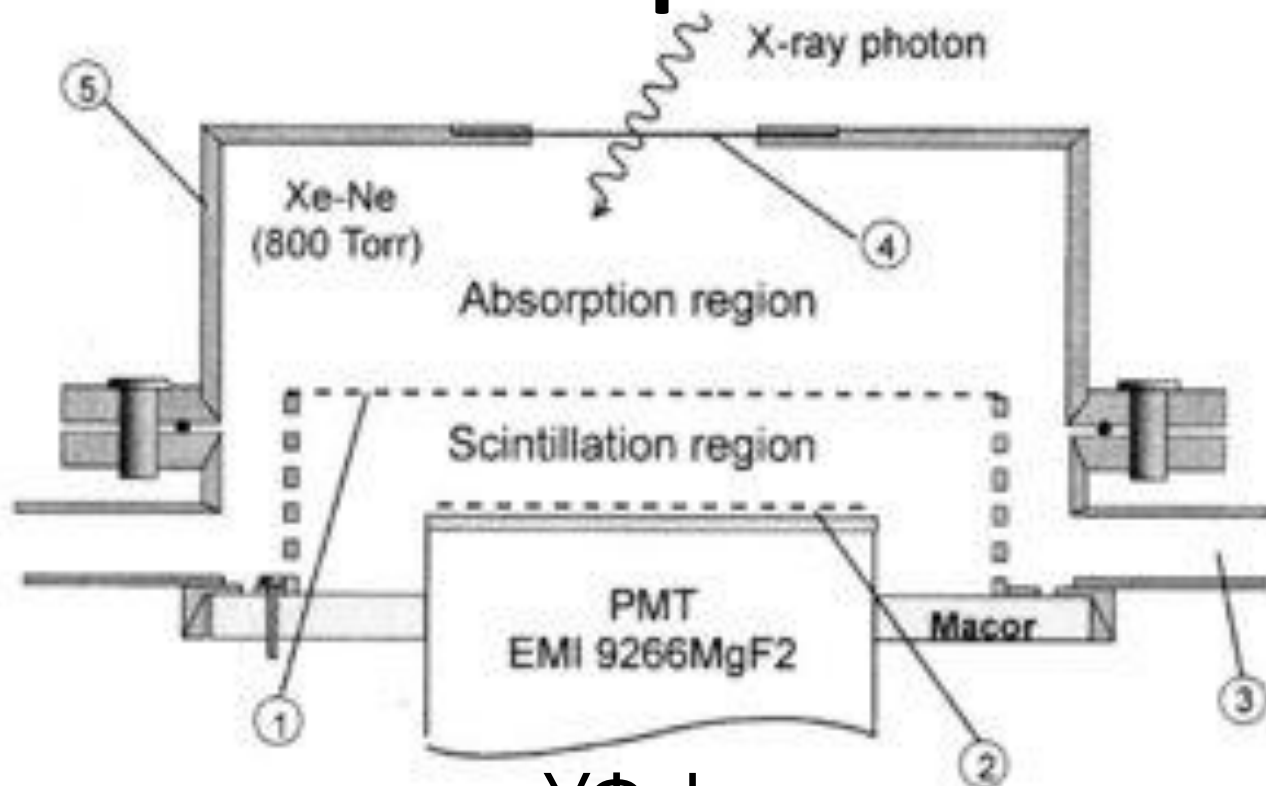
(измеряются

УФ

ФОТОНЫ)



Gas Scintillation Proportional Counter



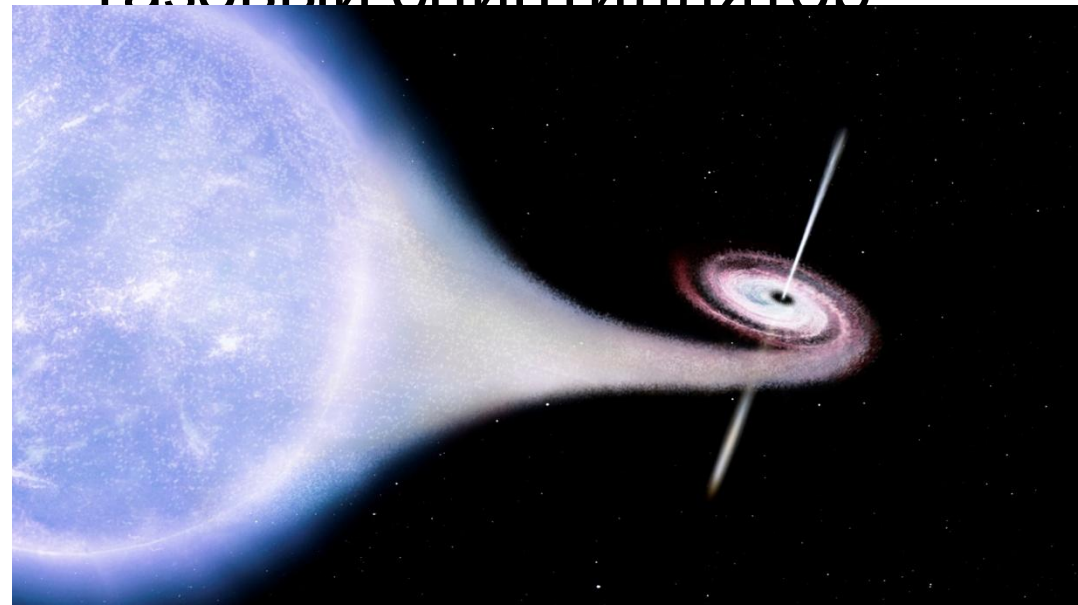
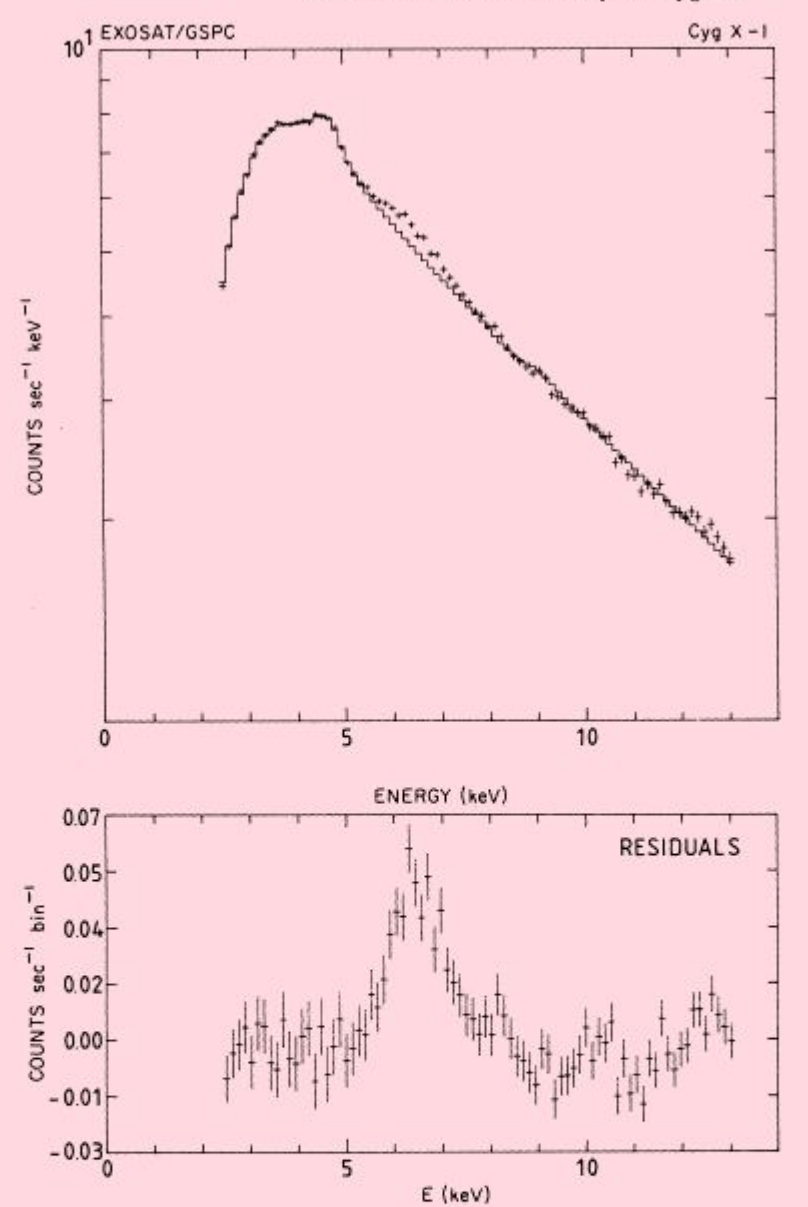
Электроны создают УФ фотоны
(сцинтилляция)

фотоны “видятся” фотоумножителем

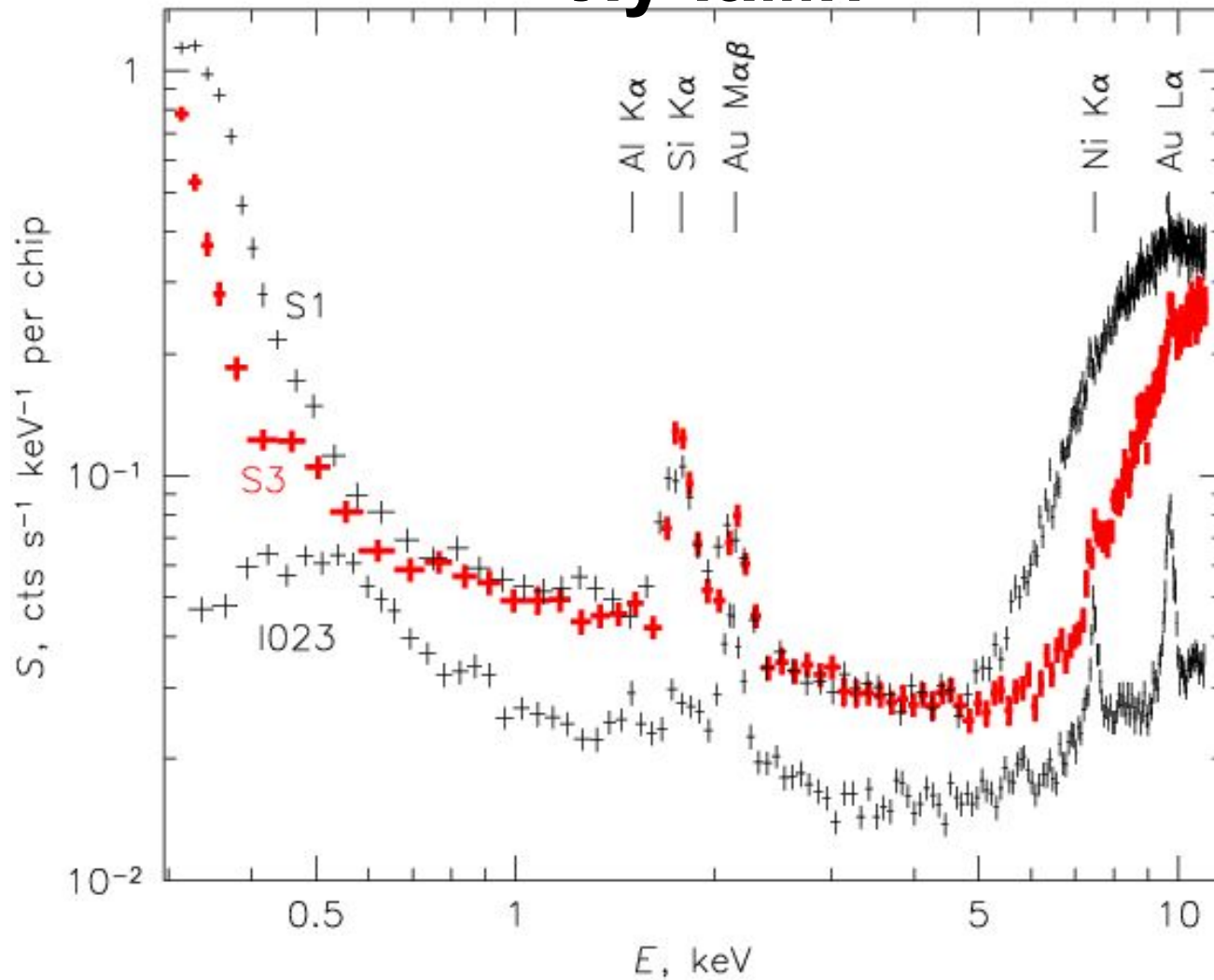
**Разрешение увеличилось в ~2
раза**

Обнаружена флуоресцентная линия нейтрального железа 6.4 кэВ (1985)

ГАЗОВЫЙ СЦИНТИЛЛЯТОР



Проблемы для слабых источников фон, наведенный космическими лучами



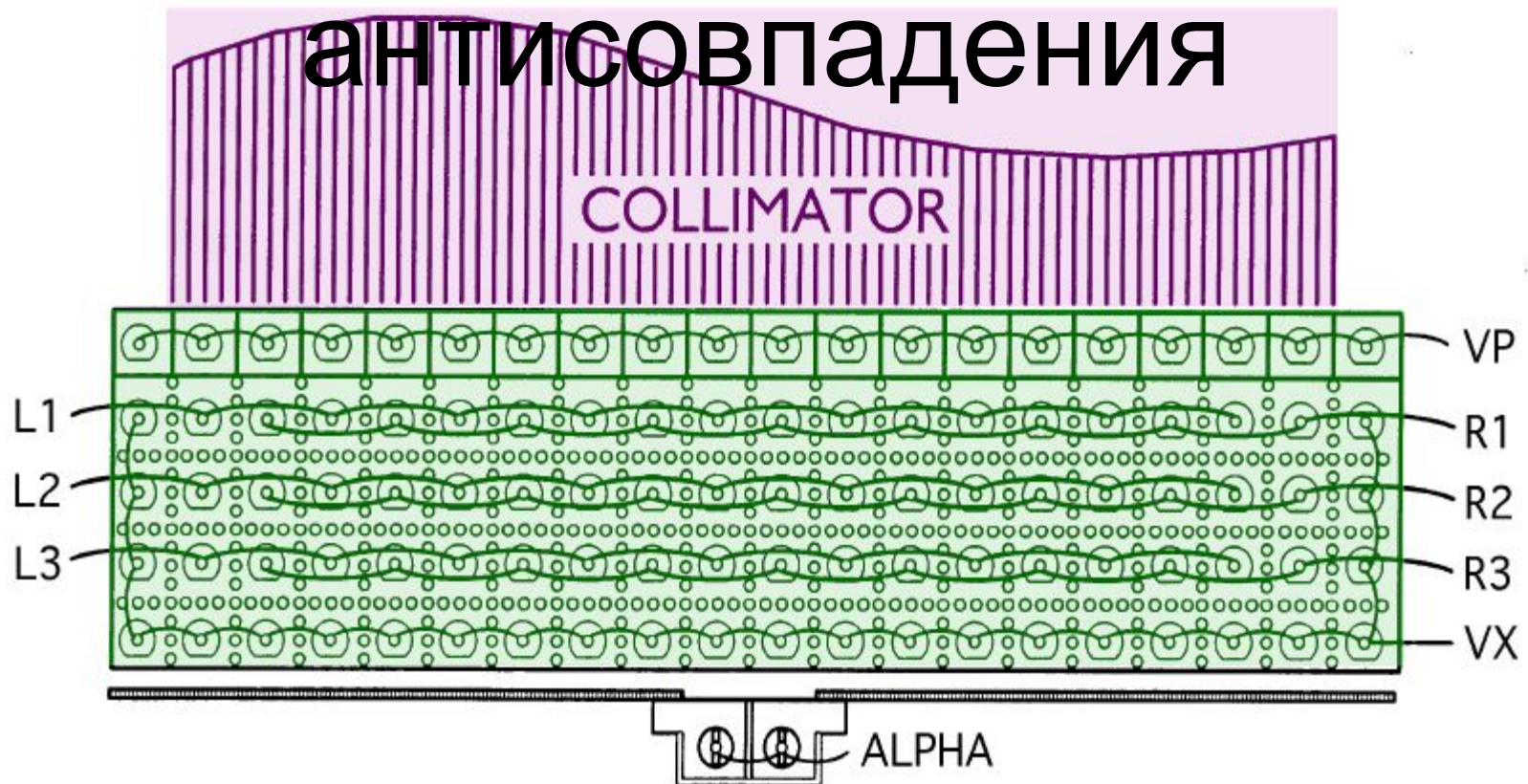
пример:

Проблемы для слабых источников фон, наведенный космическими

лучами Активная система

защиты:

антисовпадения

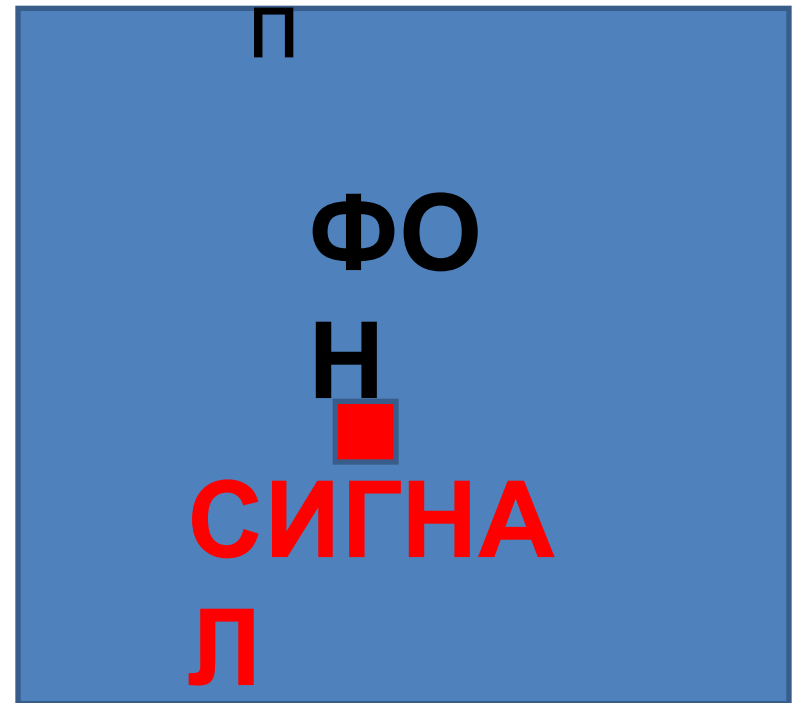


Преимущество построения изображений для слабых источников

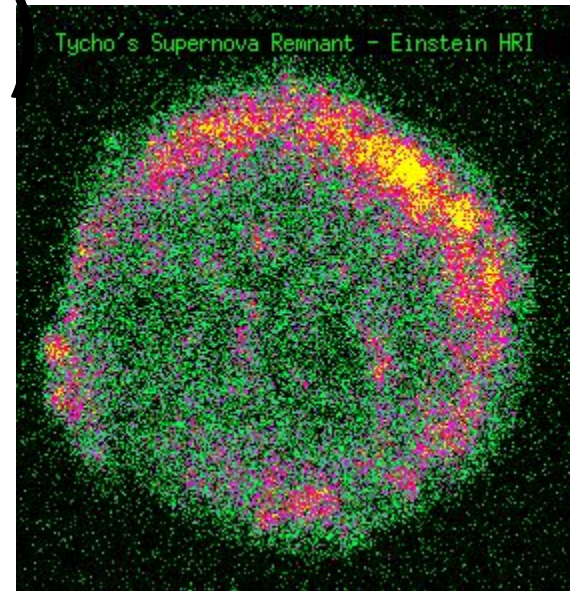
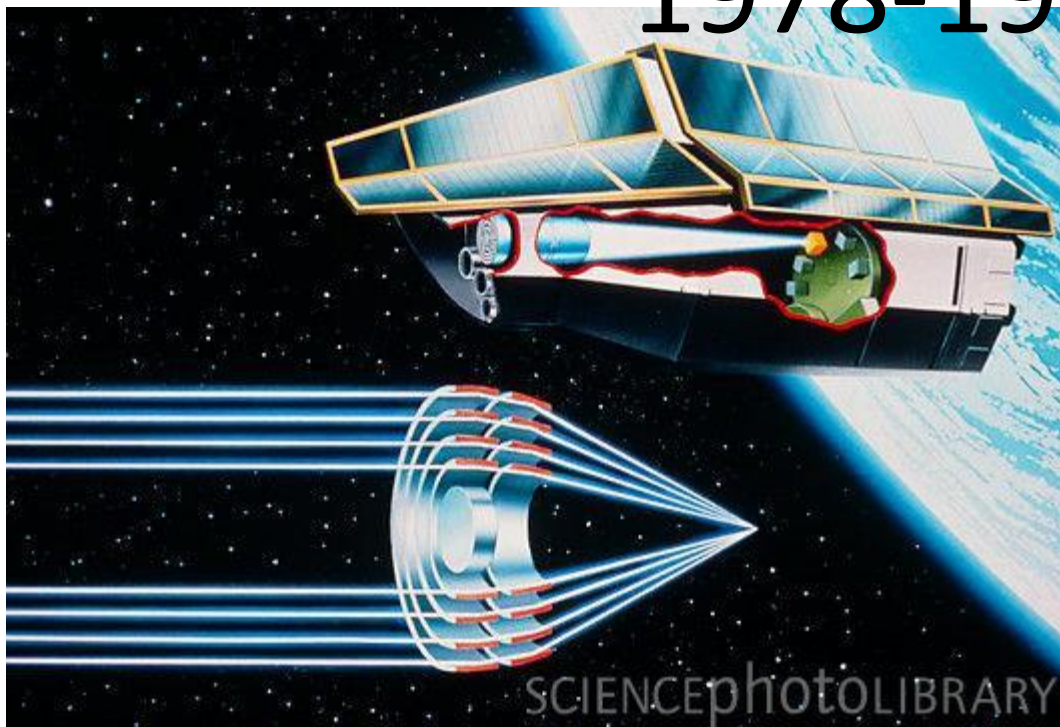
Спектрометр



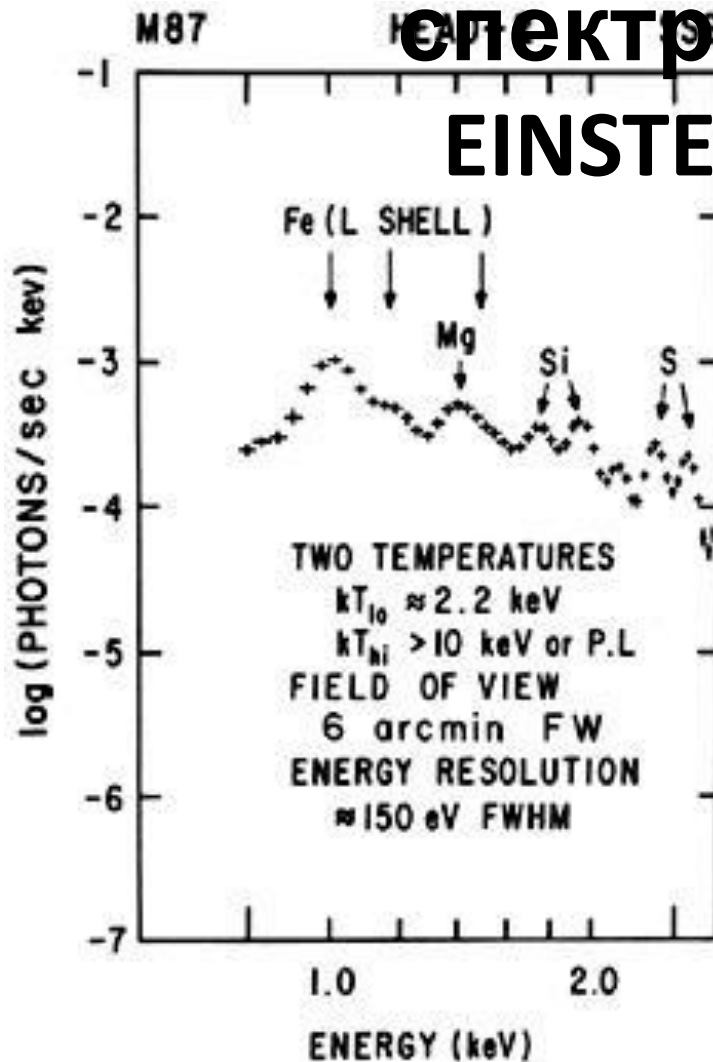
Телескоп



Первые рентгеновские изображения астрофизических объектов (HEAO2/EINSTEIN 1978-1981)



Первый твёрдотельный спектрометр: EINSTEIN/SSS



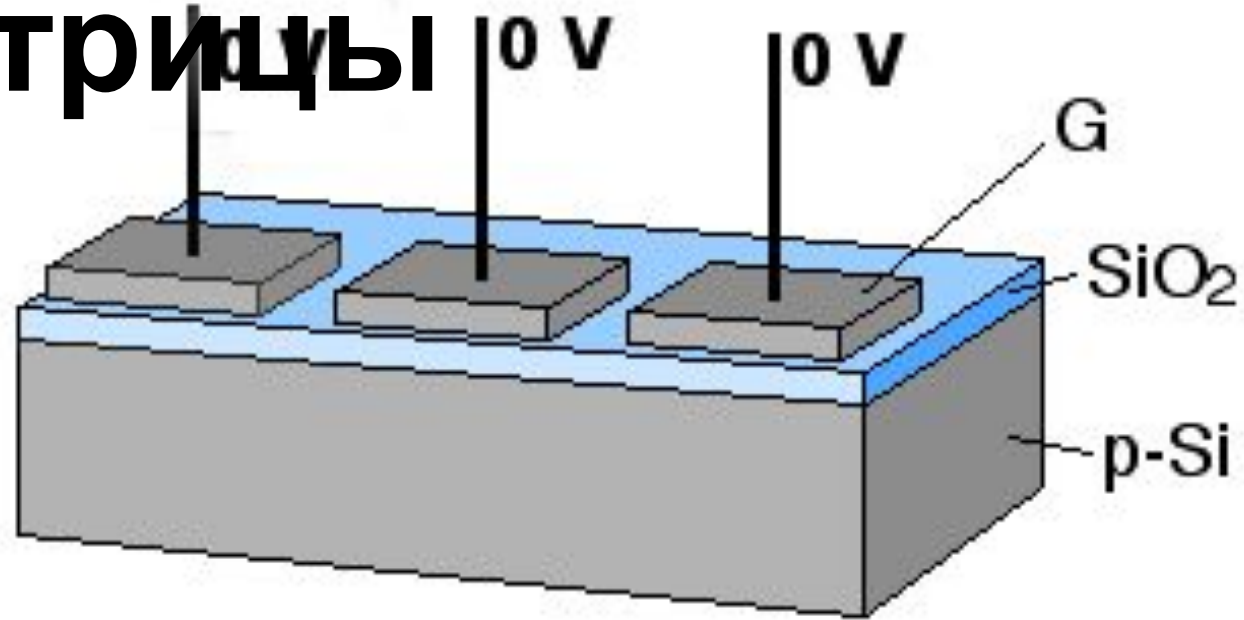
Работал на
энергиях <4
кэВ

Энергия
линии

жёлтого цвета

ПЗС

матрицы



Two Phase CCD Clocking

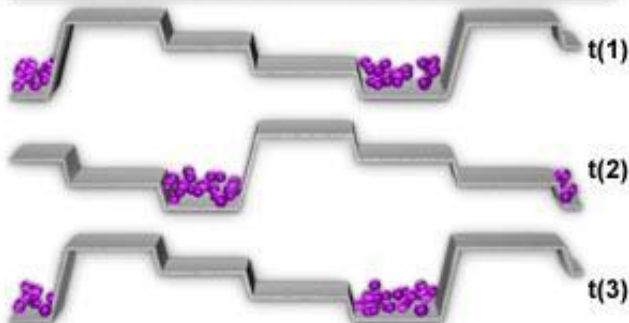
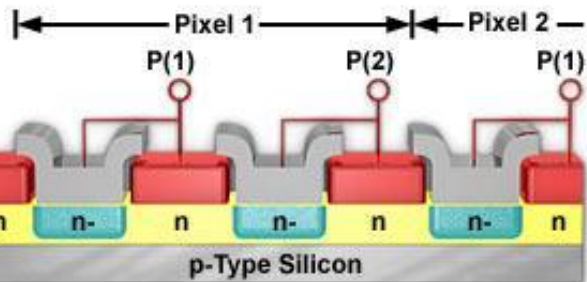
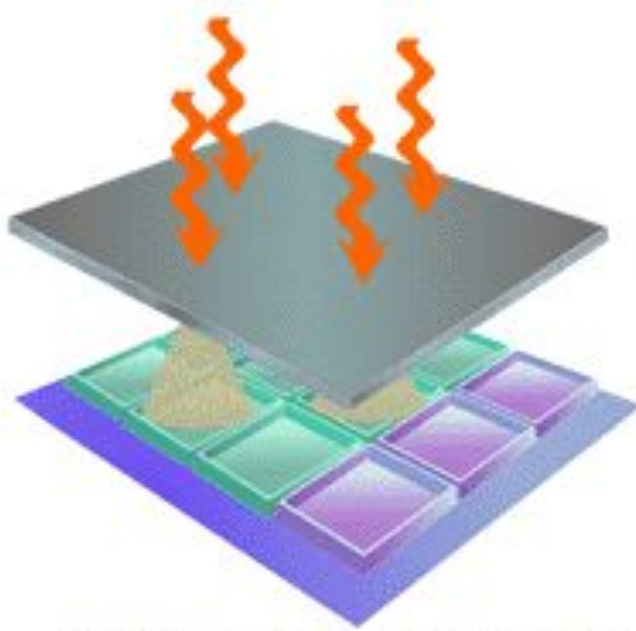
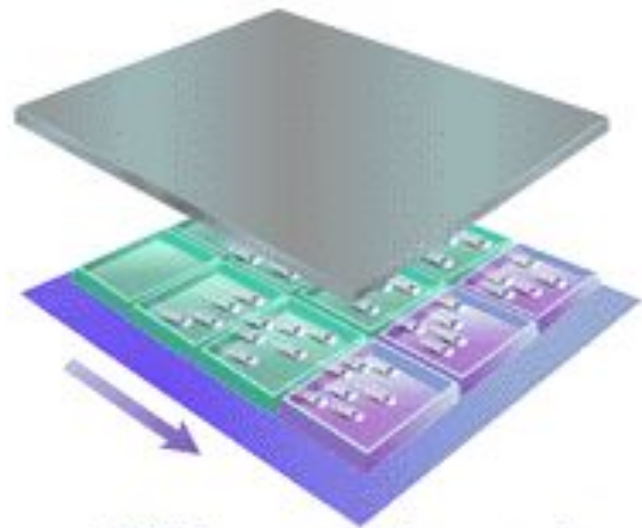


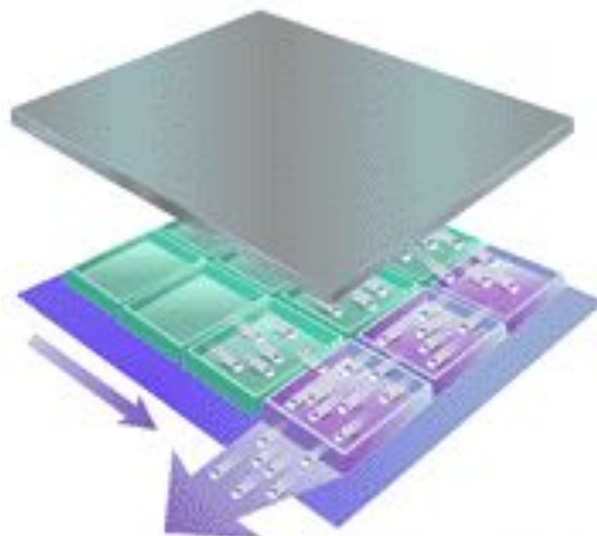
Figure 1



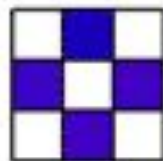
(1) Incident x-ray produces shower of electrons in selected pixels



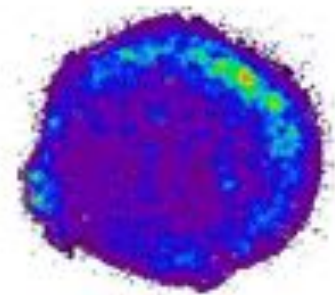
(2) Voltage moves electrons to the right to "count-out" row



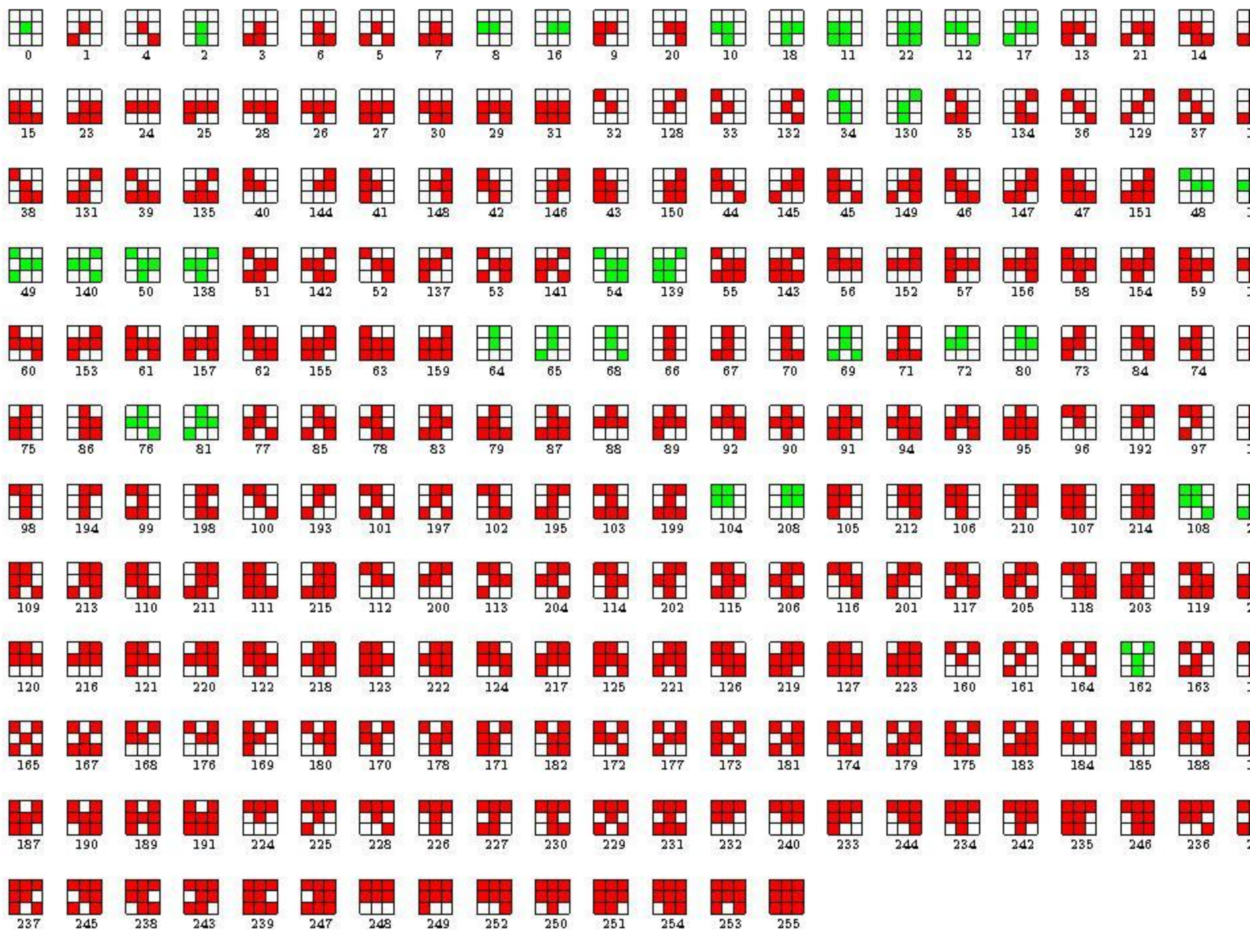
(3) Clocked voltage moves electrons out of count-out row



(4) Computer reconstructs image (9 pixels)

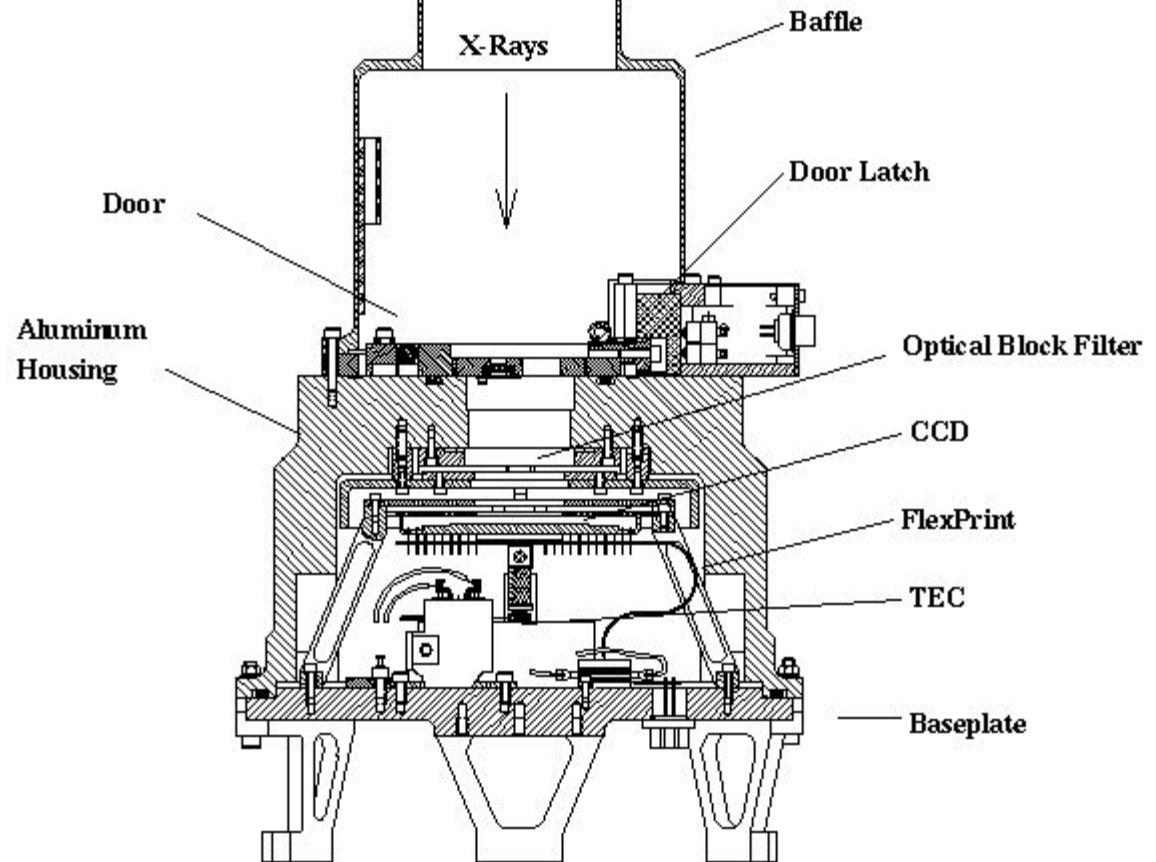


CXC CCD's will have ~ 1 million pixels



time s	ccd_id	node_id	expro	chipx pixel	chipy pixel	tdetx pixel	tdety pixel	detx pixel	dety pixel	x pixel	y pixel	phas adu	pha adu	pha_ro adu	energy eV	pi chan	flte
3.268654370767151E+08	3	0		3 176	268	4864	3237	4.8459023E+03	4.8736860E+03	4.9909937E+03	3.4575977E+03	-1 -1 -1 -2 371 -4 -3 4 0		404	371	1.5798693E+03	109
3.268654370767151E+08	3	3		3 793	402	4730	3854	4.7134795E+03	4.2587075E+03	4.3633457E+03	3.4999329E+03	1 -2 -1 3 335 -2 0 4 1 0		384	335	1.5000878E+03	103
3.268654370767151E+08 es]	3	2		3 654	703	4429	3715	4.4130879E+03	4.3971841E+03	4.4570464E+03	3.8171567E+03	0 -3 -4 2 1076 2 1 10 -1 -1 -2 0 -2 1394 -4 0 10 1 0		1226	1076	4.8969058E+03	336
3.268654370767151E+08	3	0		3 41	783	4349	3102	4.3315703E+03	5.0082827E+03	5.0499971E+03	3.9859653E+03	-1 -1 -2 0 -2 1394 -4 0 10 1 0		1558	1394	6.1048931E+03	419
3.268654370767151E+08	3	3		3 822	784	4348	3883	4.3325566E+03	4.2292041E+03	4.2792075E+03	3.8726165E+03	1 0 1 -2 4 600 -1 3 5 -1 0 5 -2 -2 765 1 0 588 -3 -3 -3 -5 -3 1591 -6 -2 11 -3 -1 3		718	600	2.8072107E+03	193
3.268654370767151E+08 es]	3	1		3 319	909	4223	3380	4.2063193E+03	4.7314810E+03	4.7580234E+03	4.0699814E+03	0 5 -2 -2 765 1 0 588 -3 -3 -3 -5 -3 1591 -6 -2 11 -3 -1 3		1502	1353	5.9133271E+03	406
3.268654370767151E+08	3	2		3 591	954	4178	3652	4.1622480E+03	4.4600366E+03	4.4830610E+03	4.0744390E+03	-3 -3 -3 -5 -3 1591 -6 -2 11 -3 -1 3		1860	1591	7.4303926E+03	509
3.268654370767151E+08	3	3		3 983	981	4151	4044	4.1358848E+03	4.0685471E+03	4.0918628E+03	4.0440593E+03	-1 -1 3		1058	902	4.1399751E+03	284

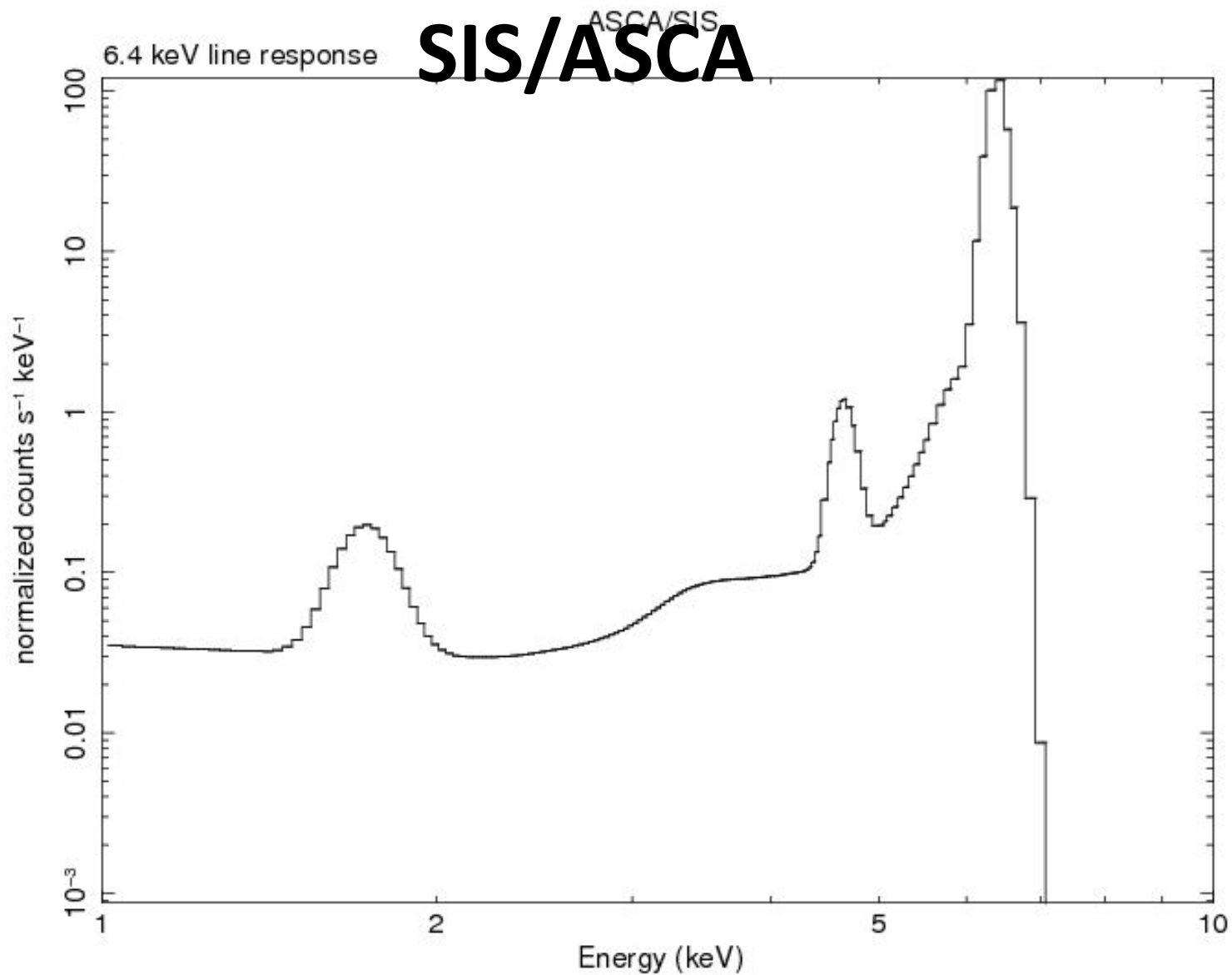
Первая ПЗС матрица для рентгеновских фотонов в космосе : ASCA/SIS



Отклик ПЗС

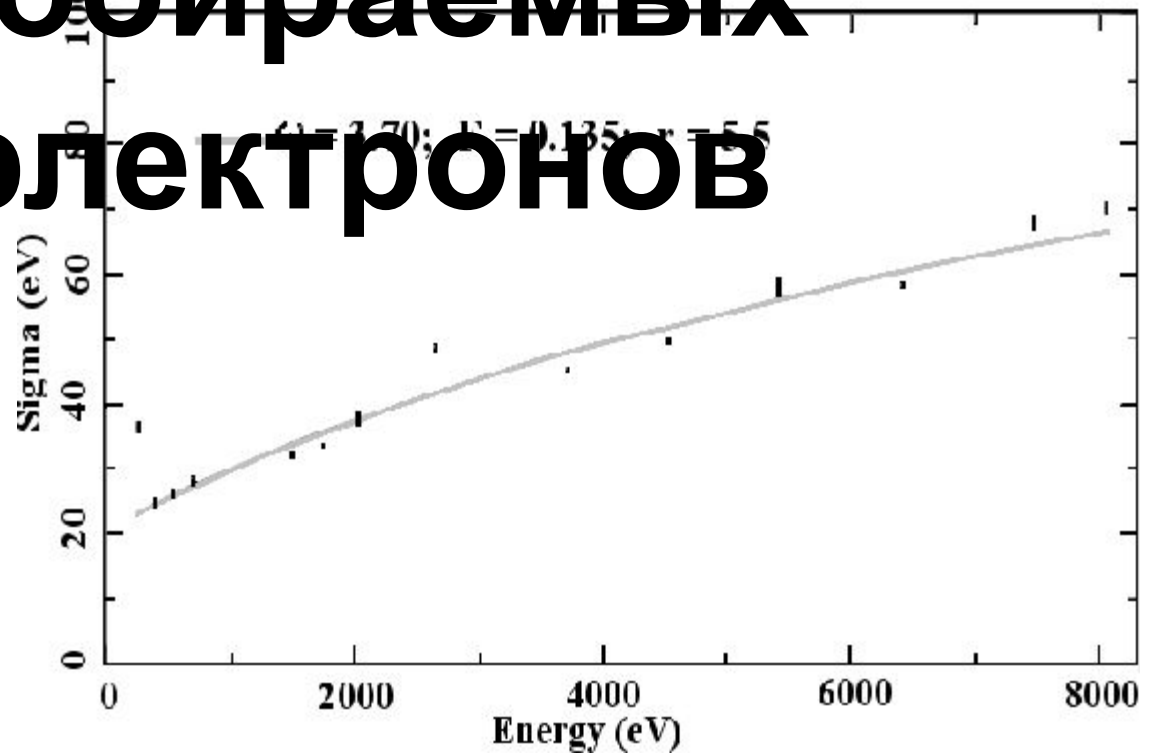
матрицы

SIS/ASCA

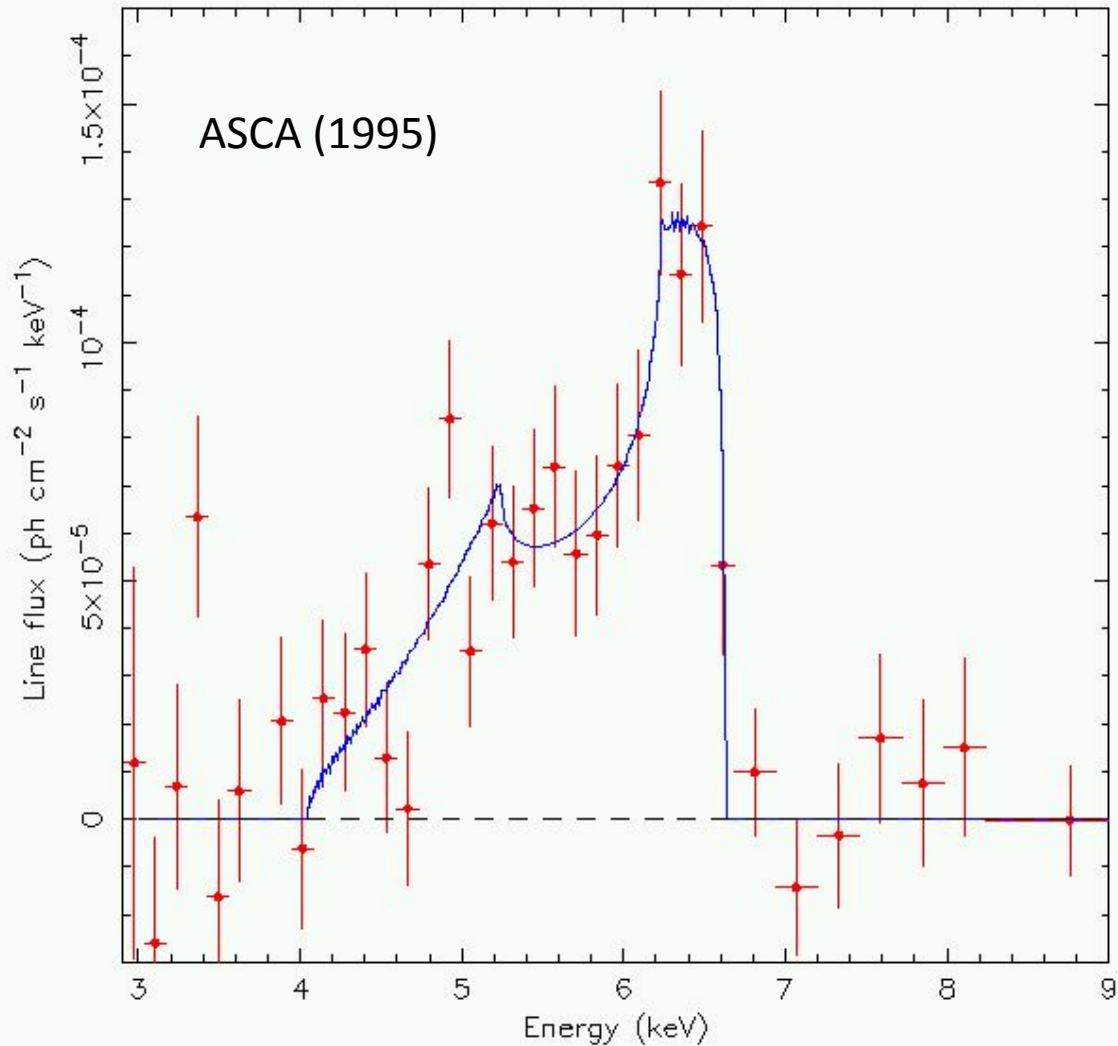


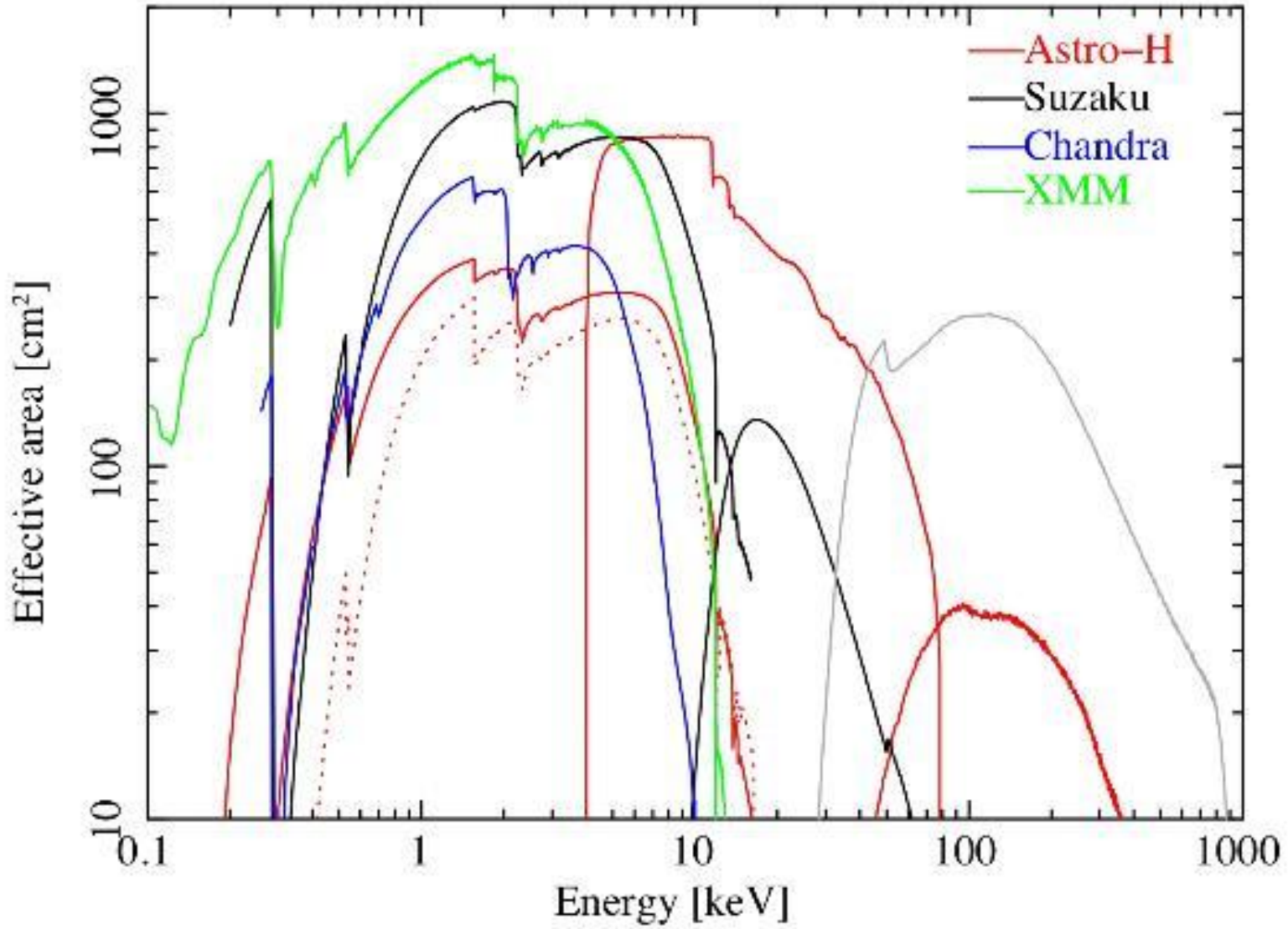
Разрешение ограничено количеством собираемых электронов

$$\sigma = \omega \sqrt{\frac{FE}{\omega} + r^2}$$

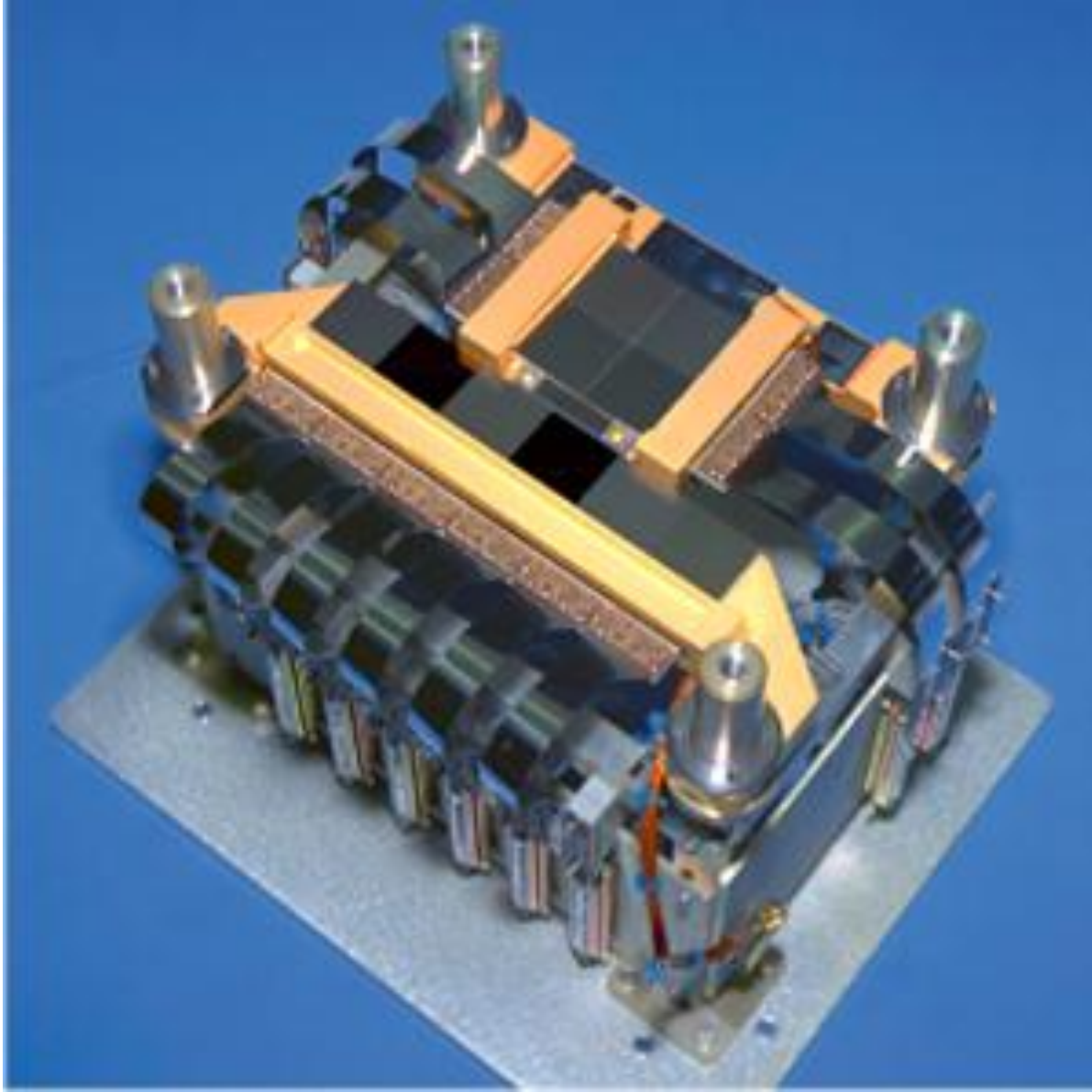


Релятивистская линия в АЯГ МСГ-6-30-15?





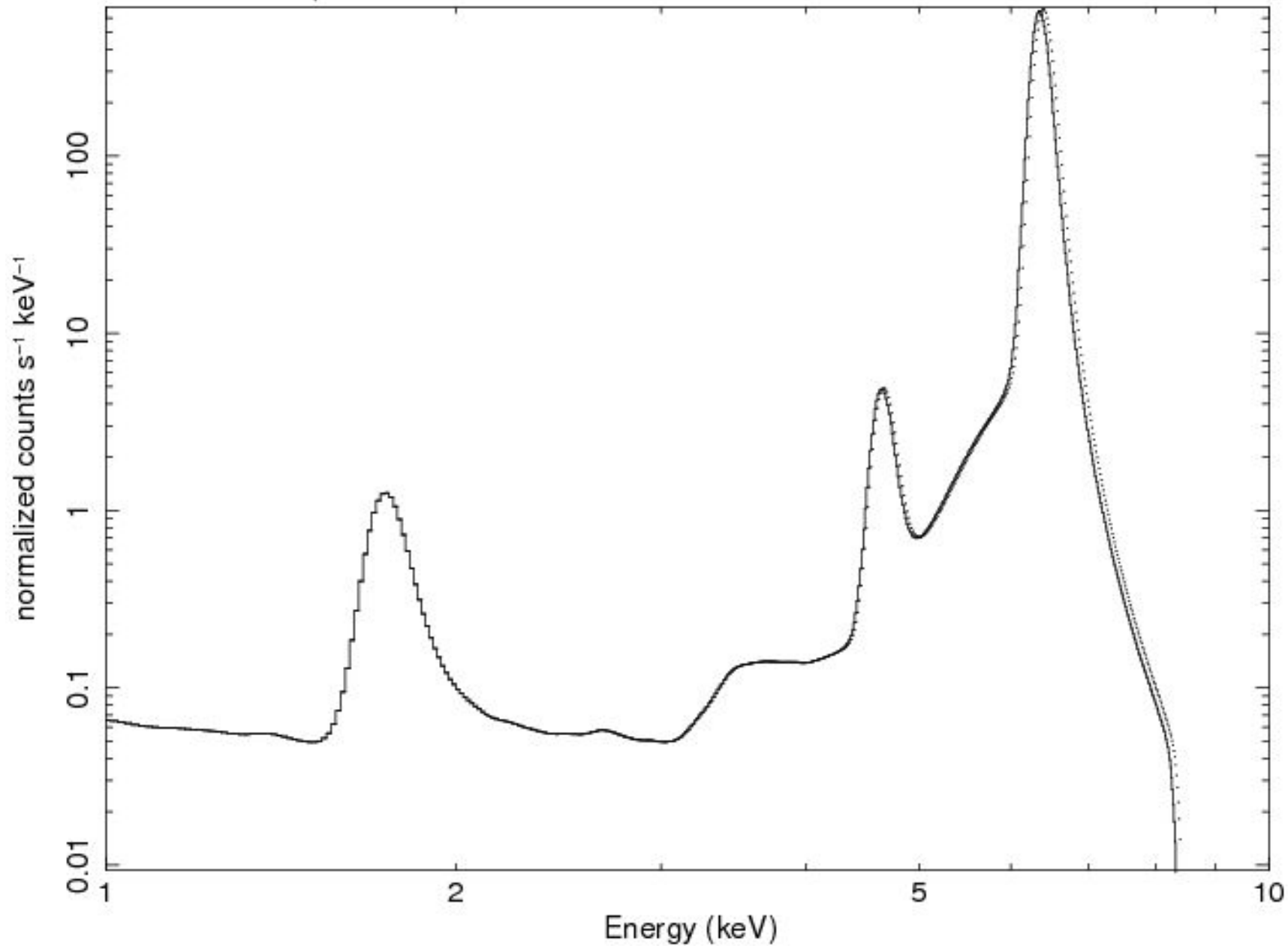
CHANDRA/ACIS



time s	ccd_id	node_id	expro	chipx pixel	chipy pixel	tdetx pixel	tdety pixel	detx pixel	dety pixel	x pixel	y pixel	phas adu	pha adu	pha_ro adu	energy eV	pi chan	flte
3.268654370767151E+08	3	0	3	176	268	4864	3237	4.8459023E+03	4.8736860E+03	4.9909937E+03	3.4575977E+03	-1 -1 -1 -2 371 -4 -3 4 0		404	371	1.5798693E+03	109
3.268654370767151E+08	3	3	3	793	402	4730	3854	4.7134795E+03	4.2587075E+03	4.3633457E+03	3.4999329E+03	1 -2 -1 3 335 -2 0 4 1 0		384	335	1.5000878E+03	103
3.268654370767151E+08 es]	3	2	3	654	703	4429	3715	4.4130879E+03	4.3971841E+03	4.4570464E+03	3.8171567E+03	0 -3 -4 2 1076 2 1 10 -1 -1 -2 0 -2 1394 -4 0 10 1 0		1226	1076	4.8969058E+03	336
3.268654370767151E+08	3	0	3	41	783	4349	3102	4.3315703E+03	5.0082827E+03	5.0499971E+03	3.9859653E+03	-1 -1 0 -2 1394 -4 0 10 1 0		1558	1394	6.1048931E+03	419
3.268654370767151E+08	3	3	3	822	784	4348	3883	4.3325566E+03	4.2292041E+03	4.2792075E+03	3.8726165E+03	1 0 1 2 4 600 -1 3 5 -1 0 5 -2 -2 765 1 0 588 -3 -3 -3 -5 -3 1591 -6 -2 11 -3 -1 3		718	600	2.8072107E+03	193
3.268654370767151E+08	3	1	3	319	909	4223	3380	4.2063193E+03	4.7314810E+03	4.7580234E+03	4.0699814E+03	0 5 -2 -2 765 1 0 588 -3 -3 -3 -5 -3 1591 -6 -2 11 -3 -1 3		1502	1353	5.9133271E+03	406
3.268654370767151E+08	3	2	3	591	954	4178	3652	4.1622480E+03	4.4600366E+03	4.4830610E+03	4.0744390E+03	-3 -3 -3 -5 -3 1591 -6 -2 11 -3 -1 3		1860	1591	7.4303926E+03	509
3.268654370767151E+08	3	3	3	983	981	4151	4044	4.1358848E+03	4.0685471E+03	4.0918628E+03	4.0440593E+03	-1 -1 3		1058	902	4.1399751E+03	284

CHANDRA/ACIS-I

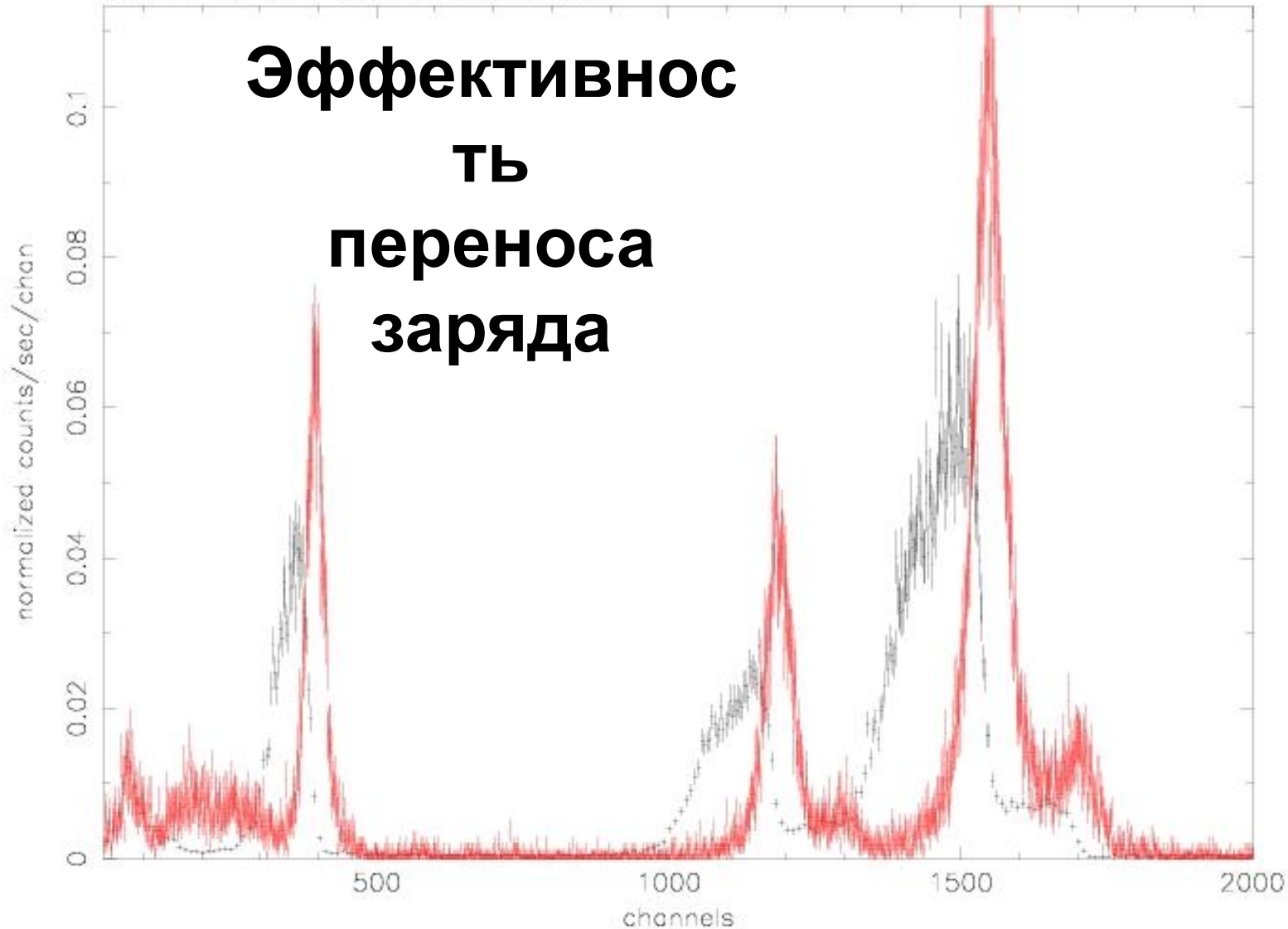
6.4 keV line response



uncorrected (black), toy CTI correction (red)
obsids 58358 58318 58309 S2c1

S2c1_uncorr.pha S2c1_corr_no66.pha

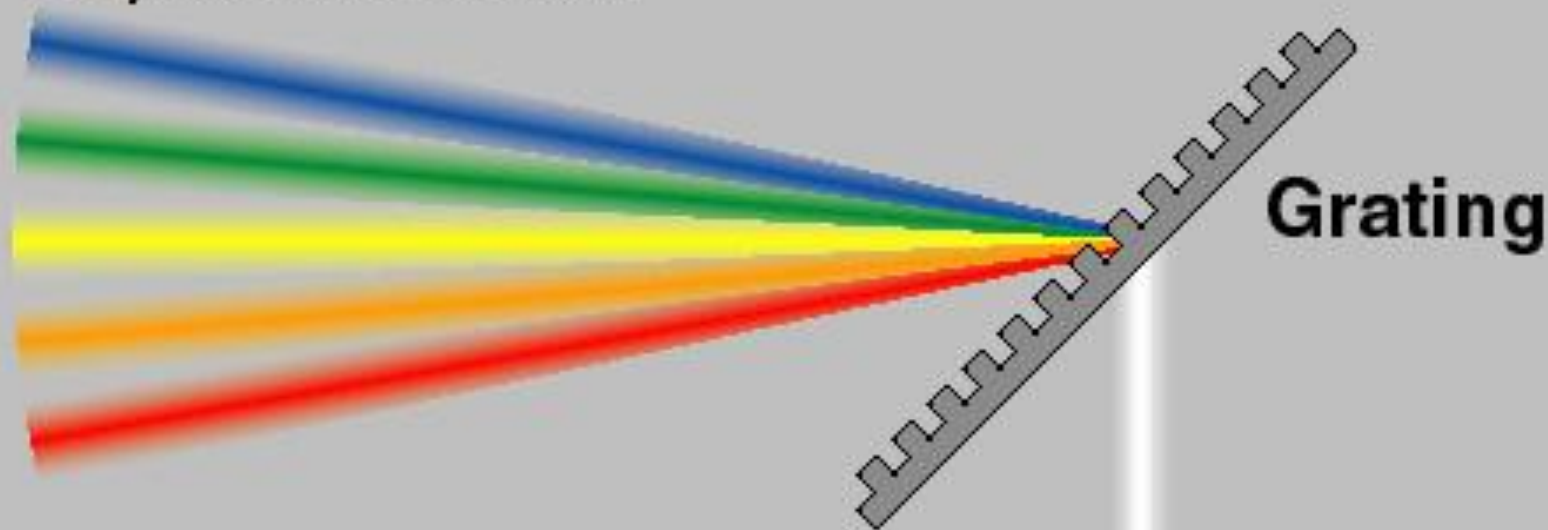
Эффективнос ть переноса заряда



Диффракционн ый

спектрометр

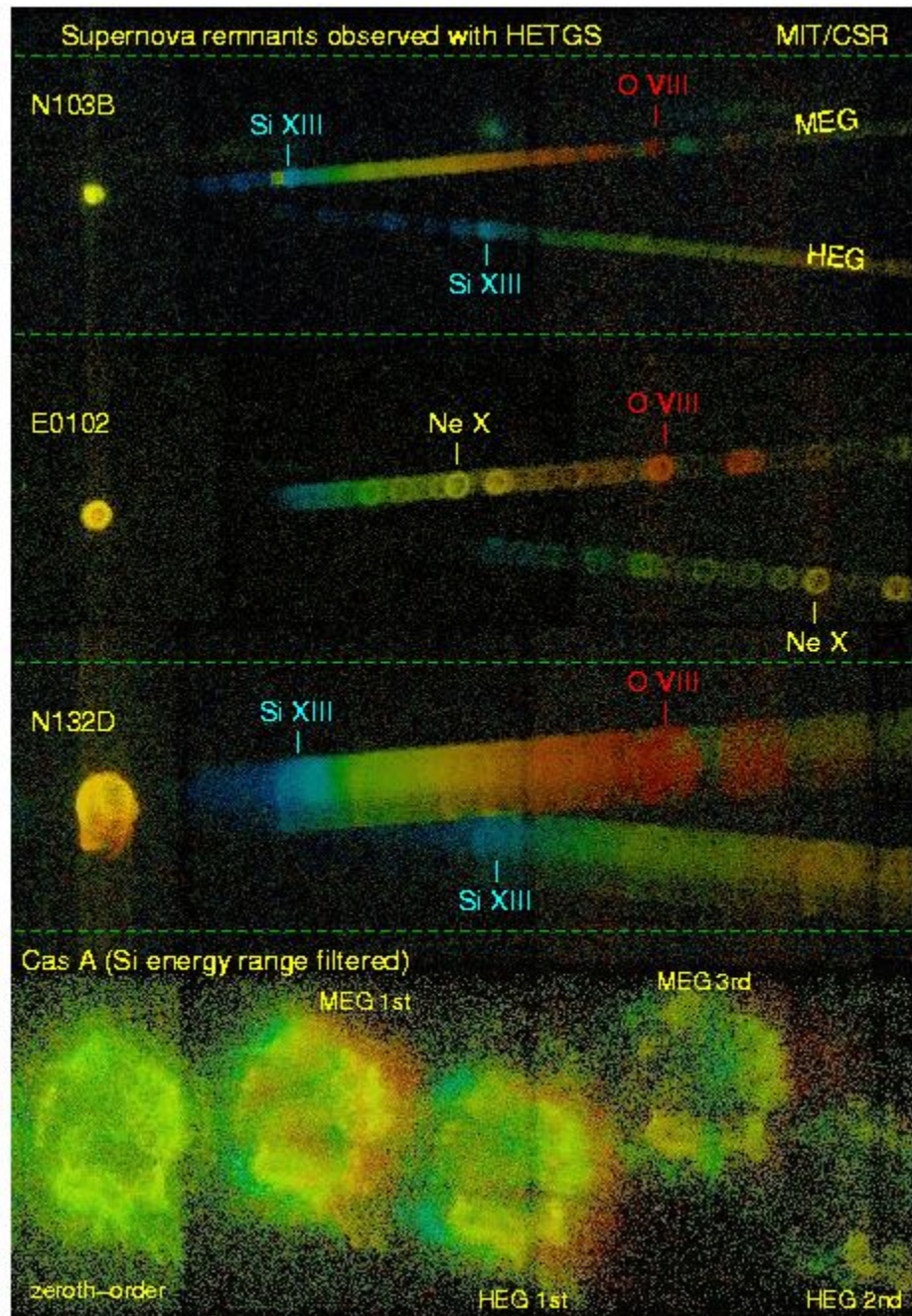
Separated colors



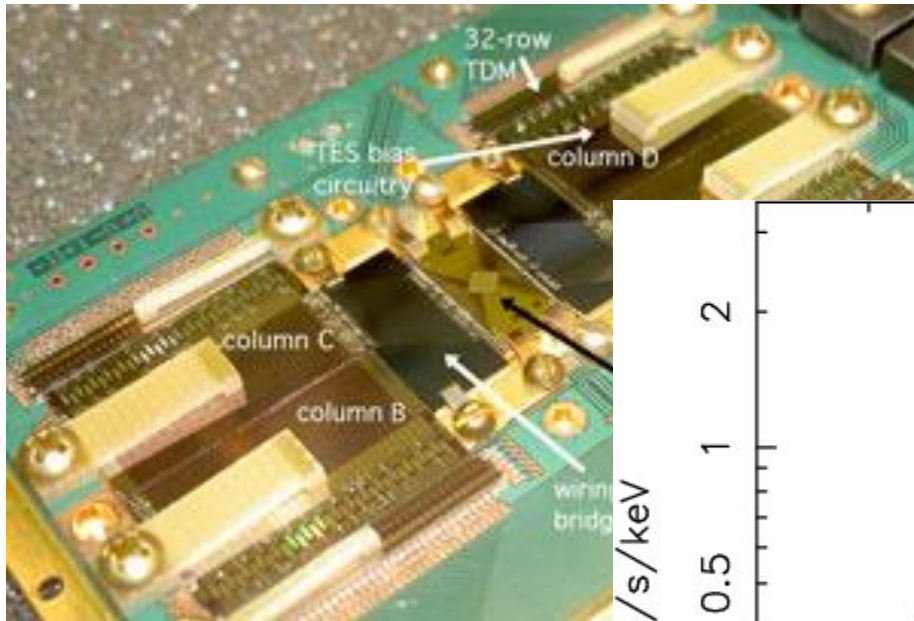
Spectrometer

Light

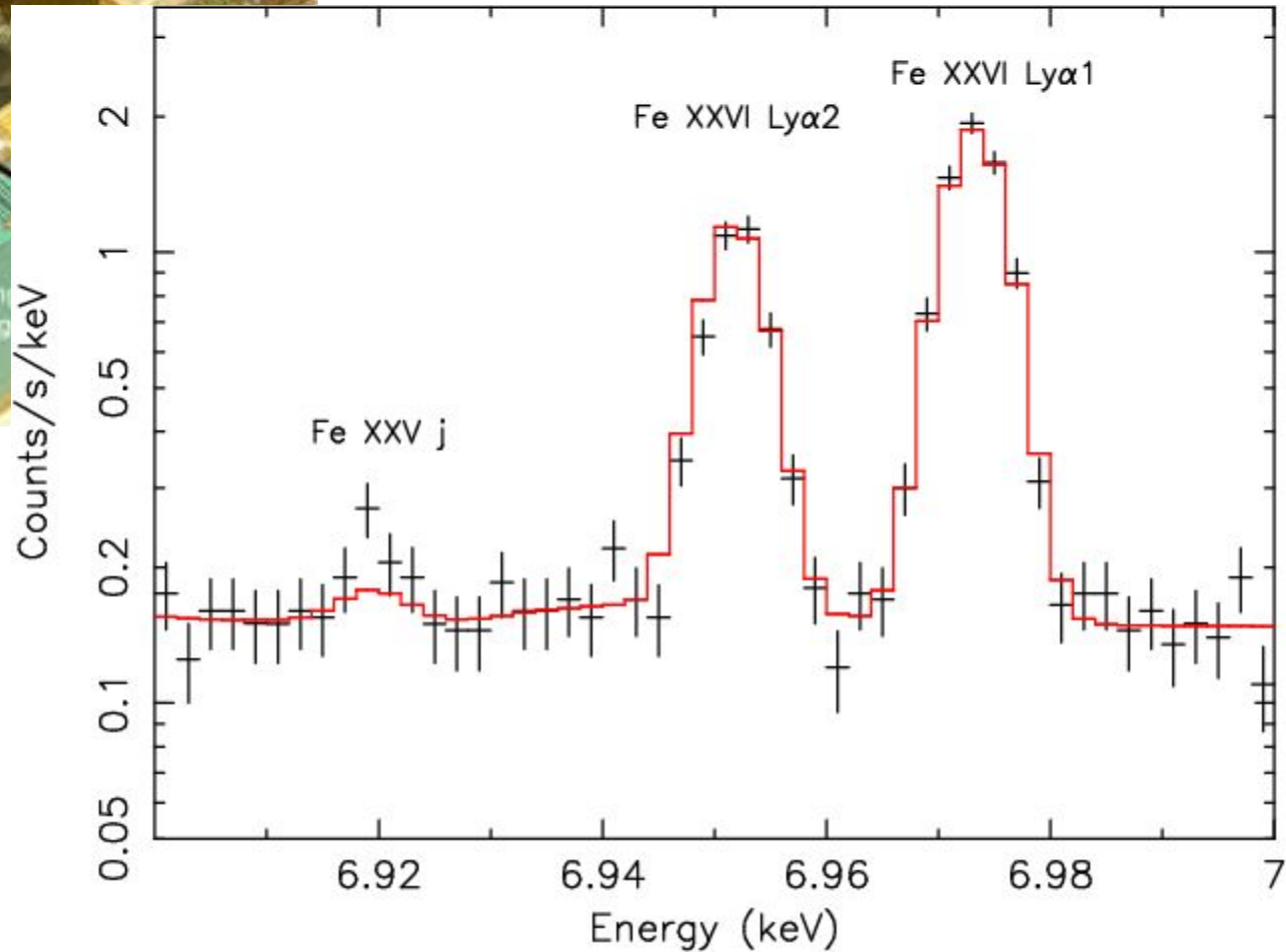
Grating



Следующий шаг -

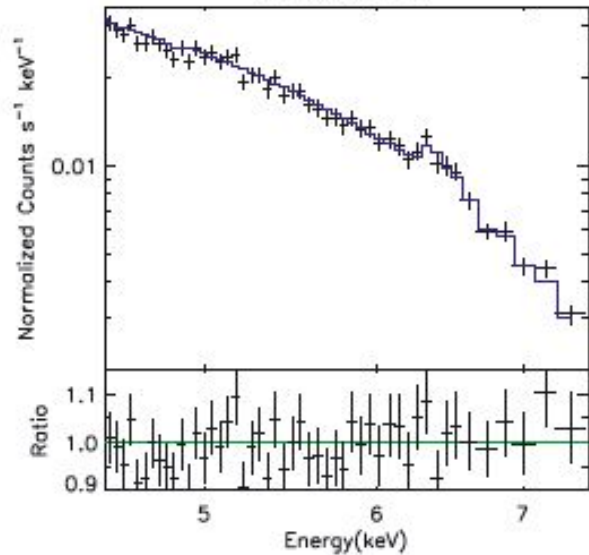


тры

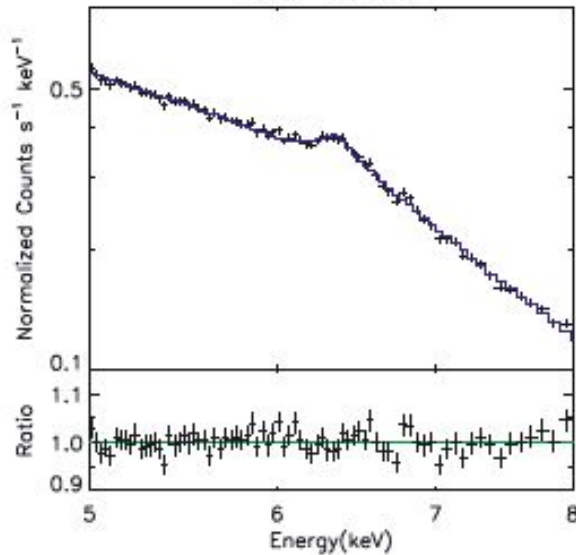


Astro-H(Япония)

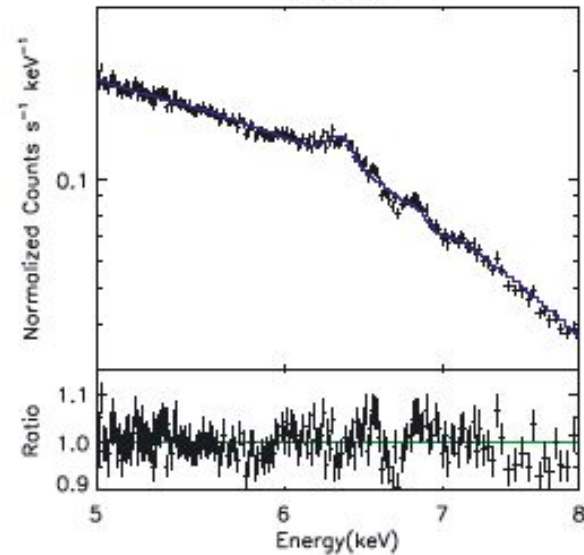
Chandra HEG



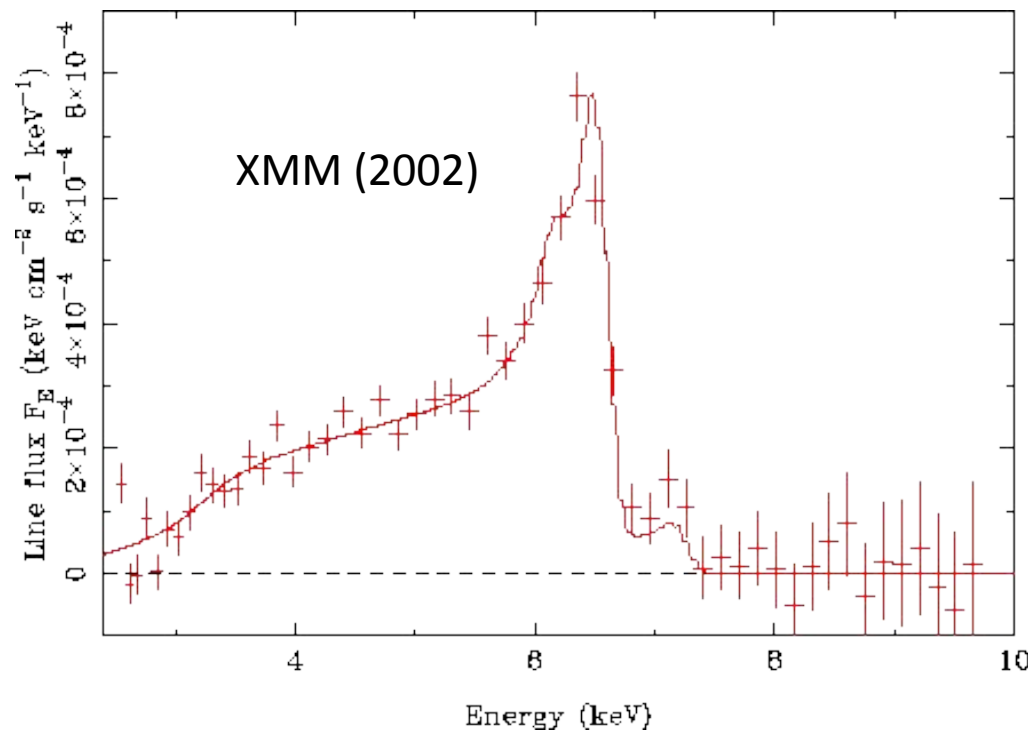
XMM-Newton



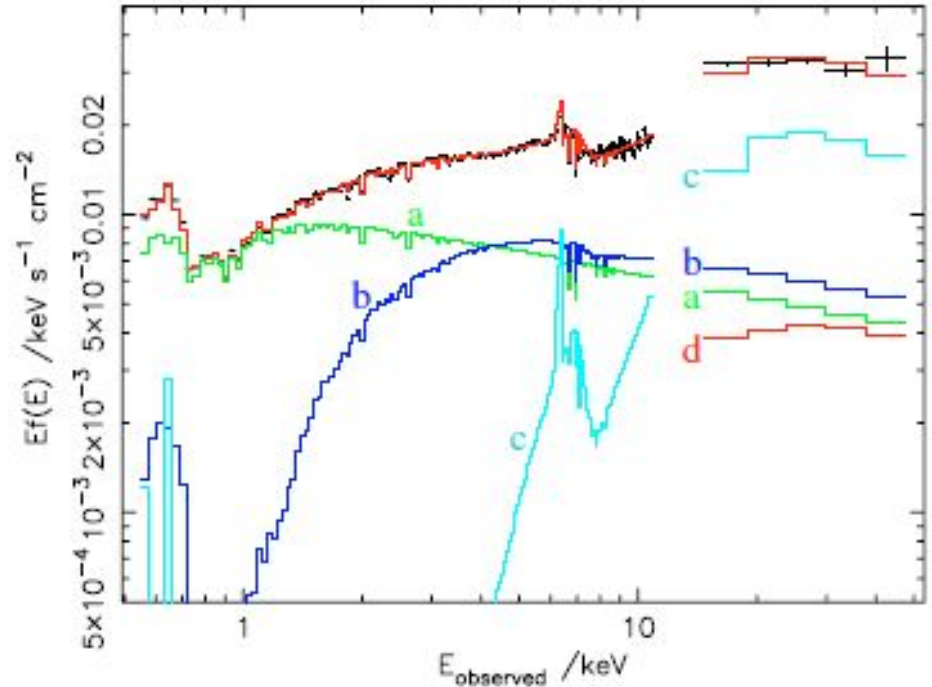
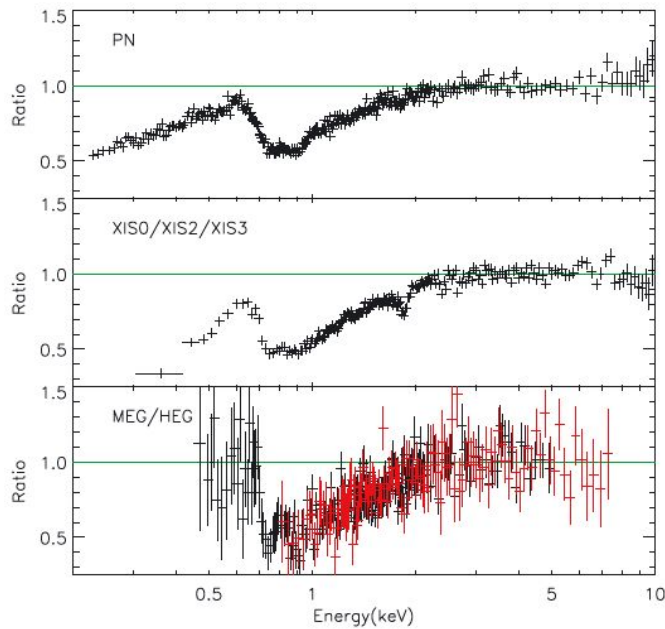
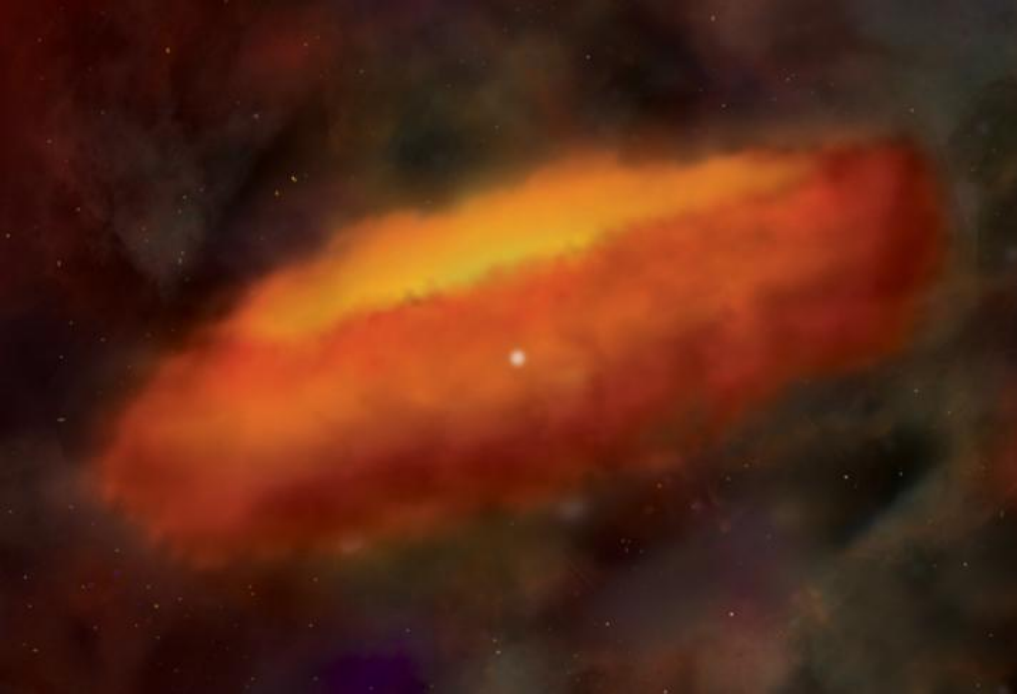
Suzaku



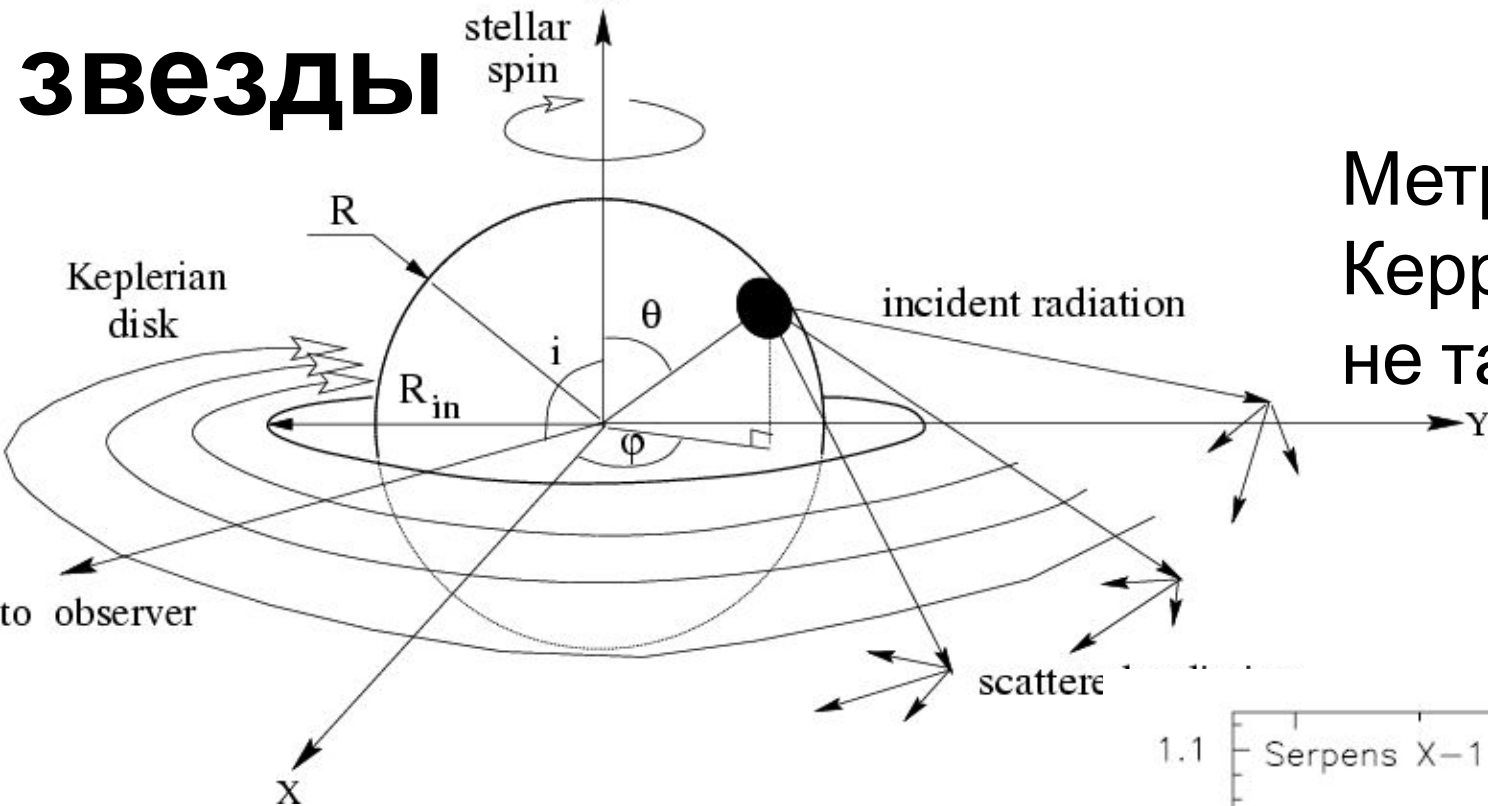
MCG-6-30-15



Проблемы интерпретации: поглощение на луче зрения?

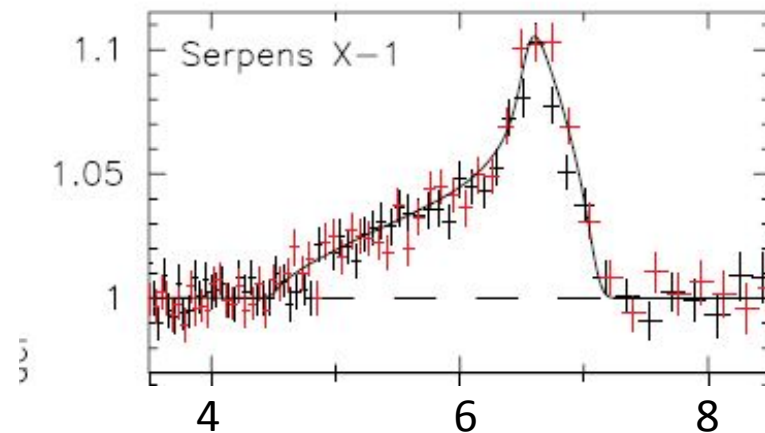


Другой случай: нейтронные звезды



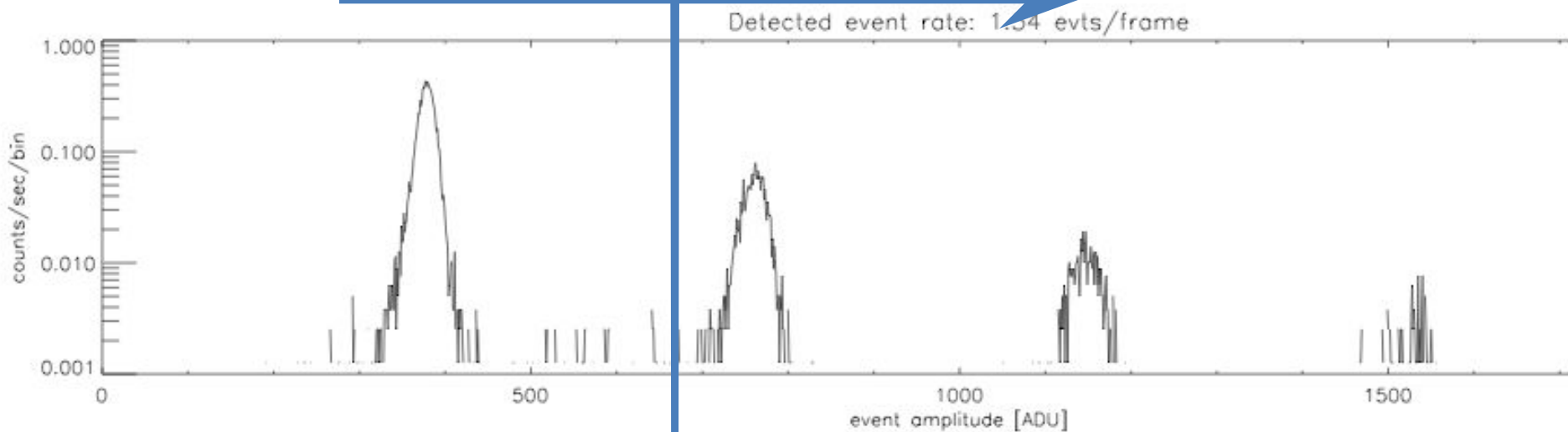
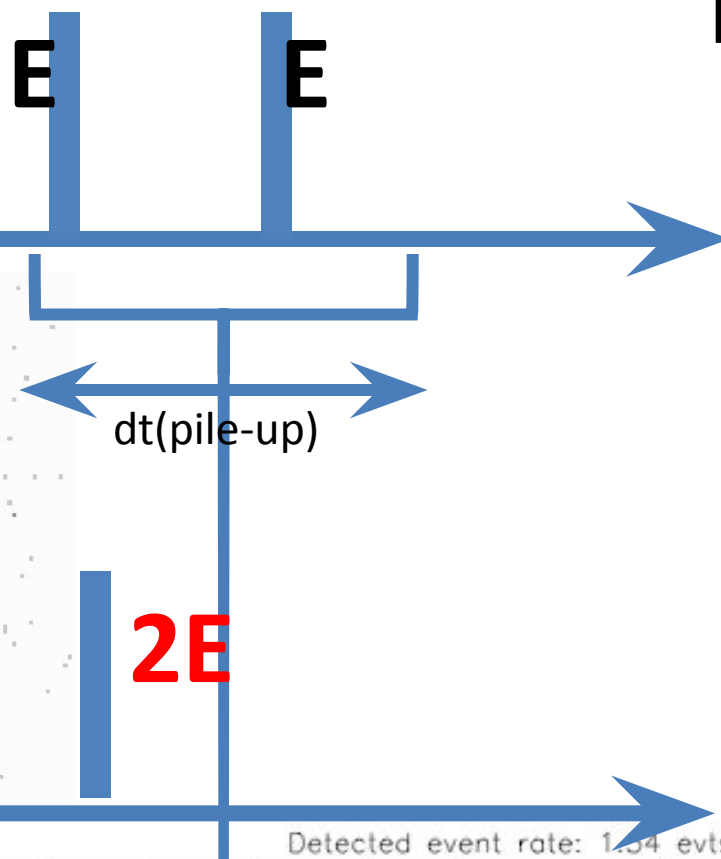
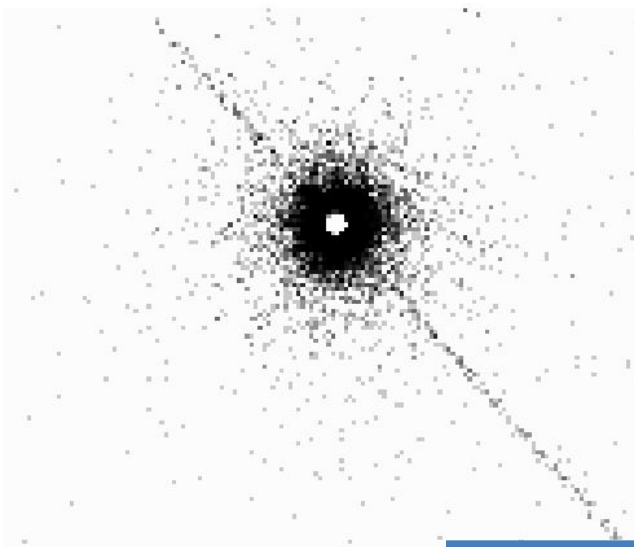
Метрика Керра не так важна

Аналогичные искажения?

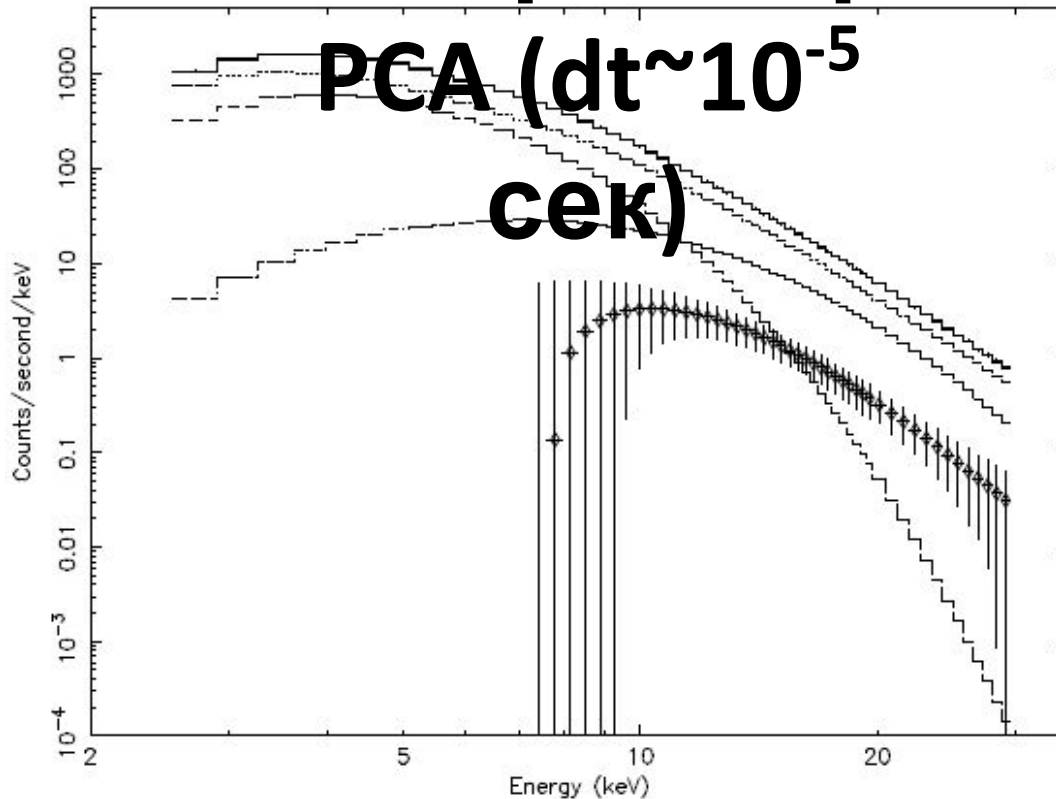


Энергия,

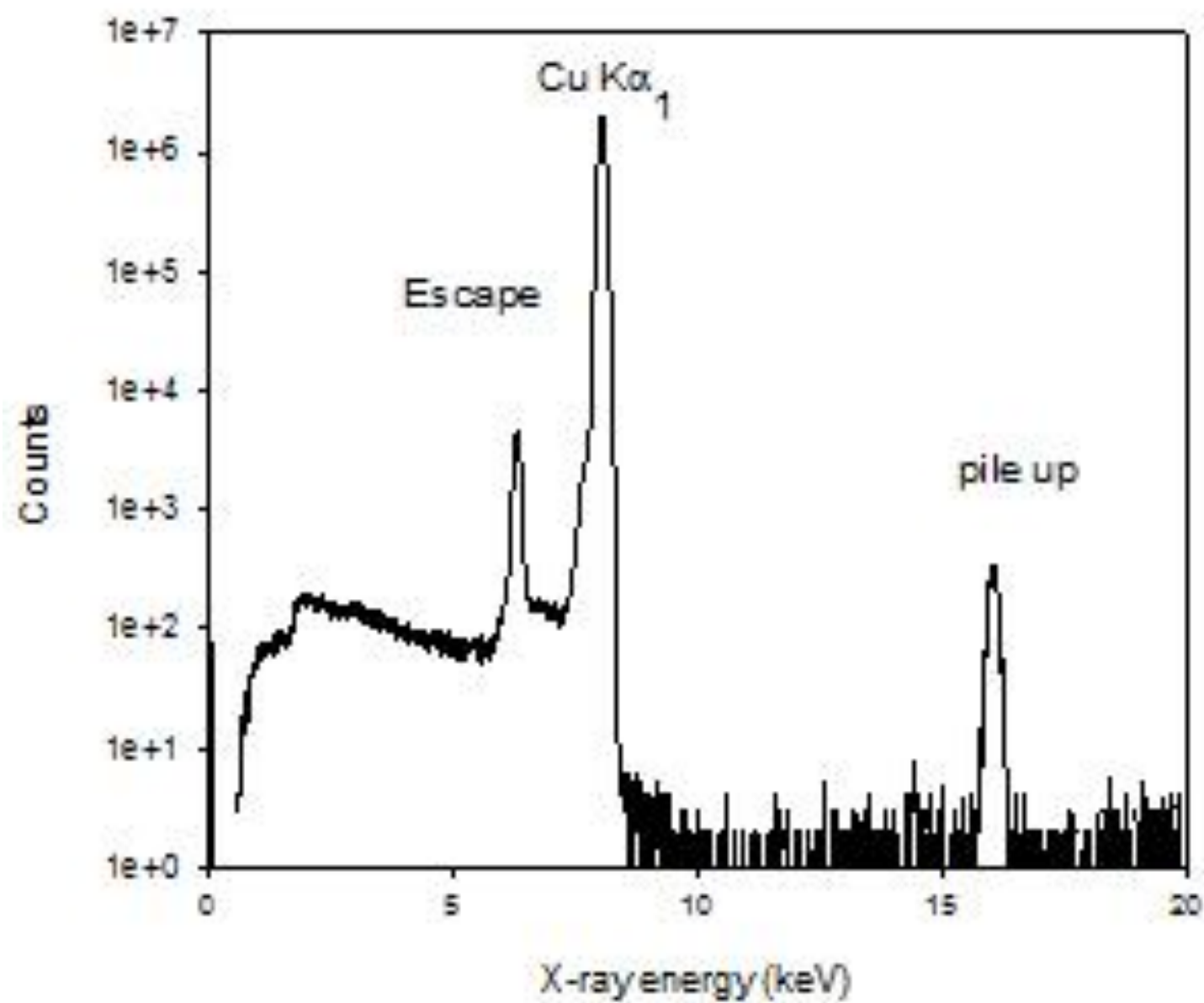
Проблема pile-up



Pile up в случае спектрометра



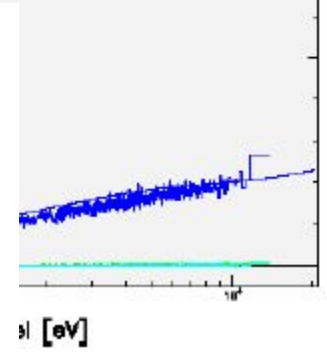
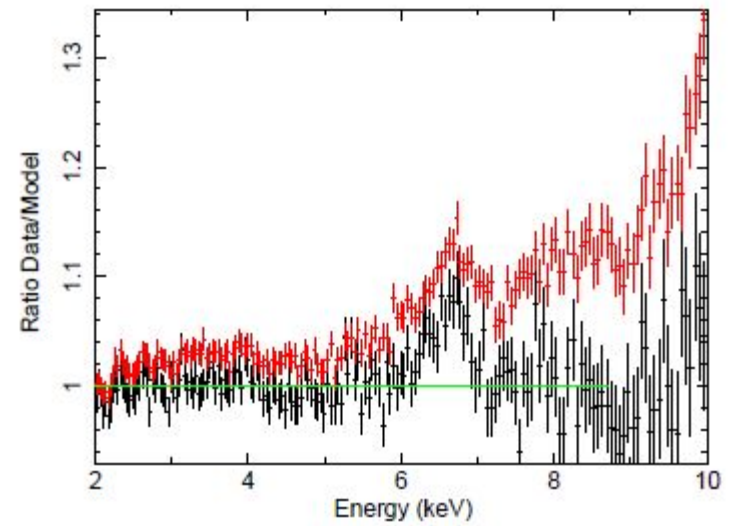
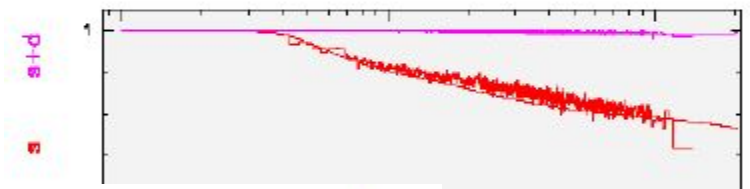
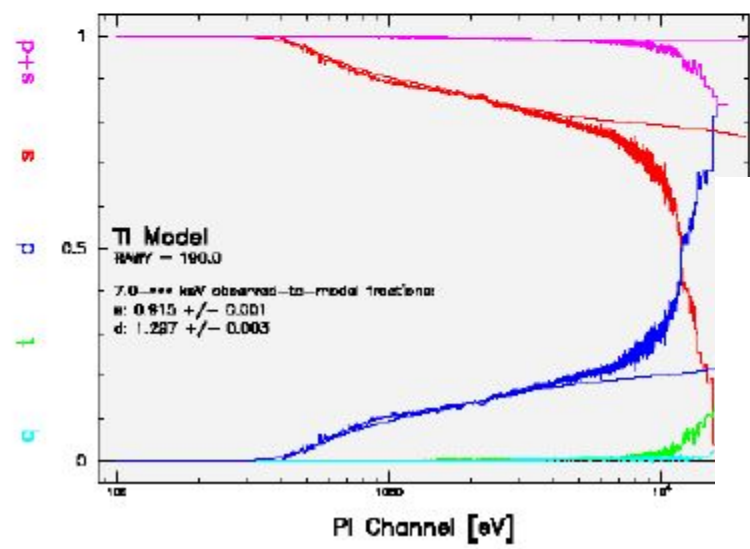
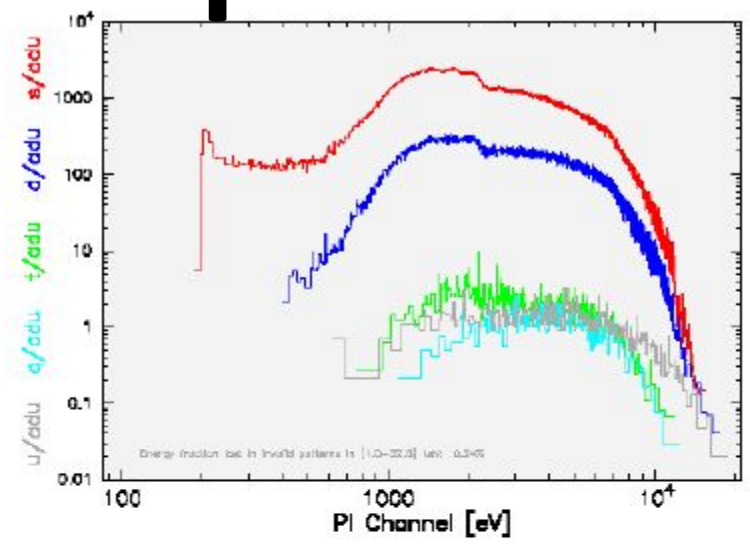
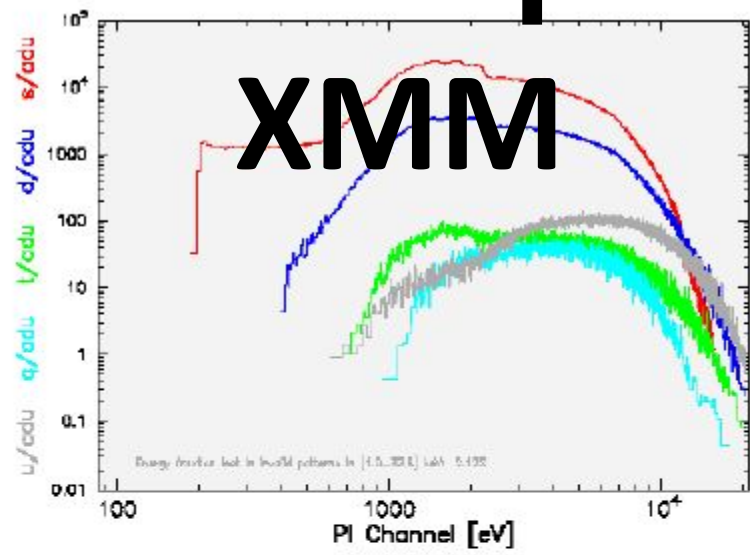
Для ПЗС $dt \sim 0.1-1$
сек



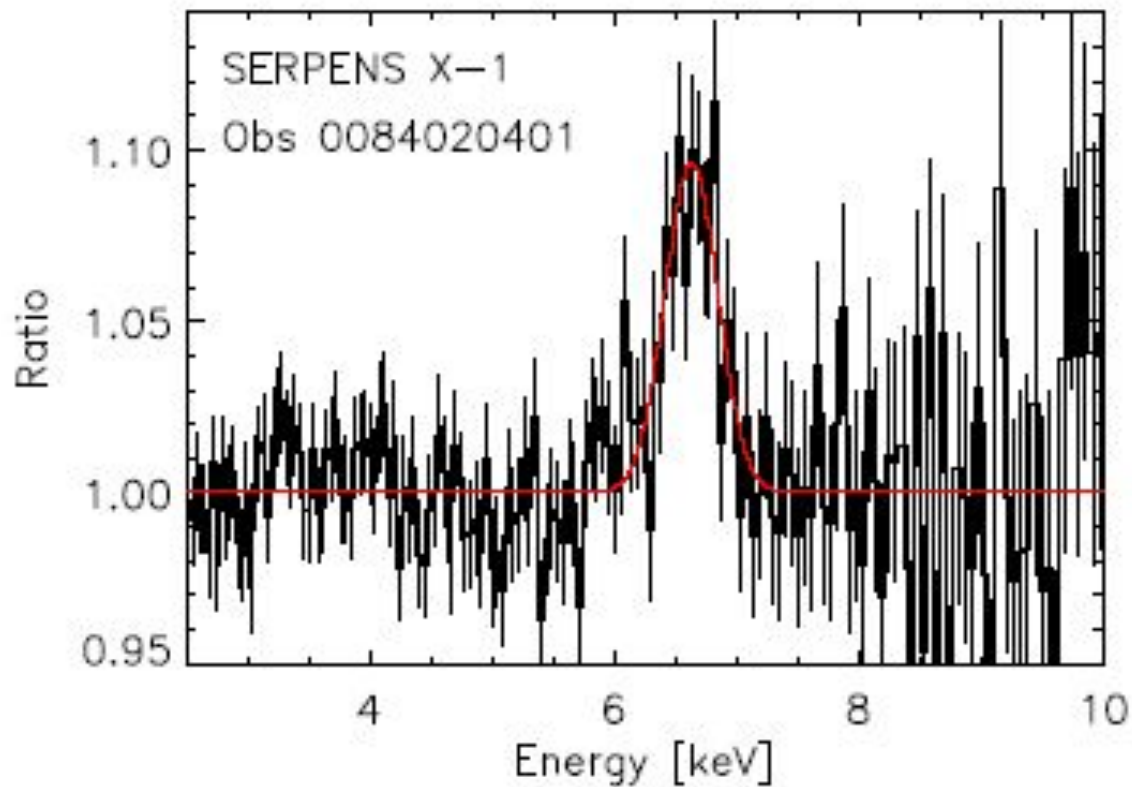
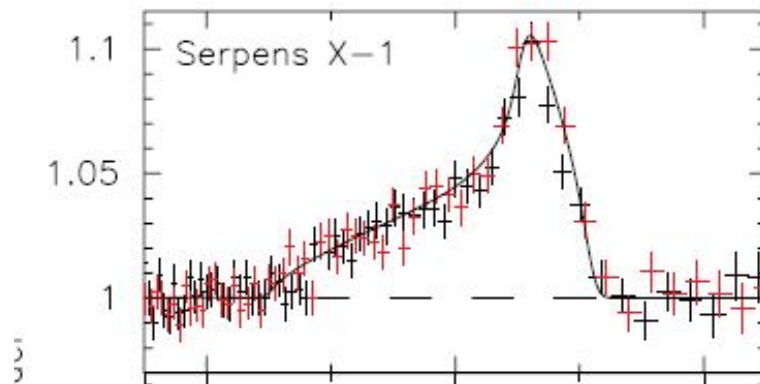
Поправки pile-up

XMM

2011



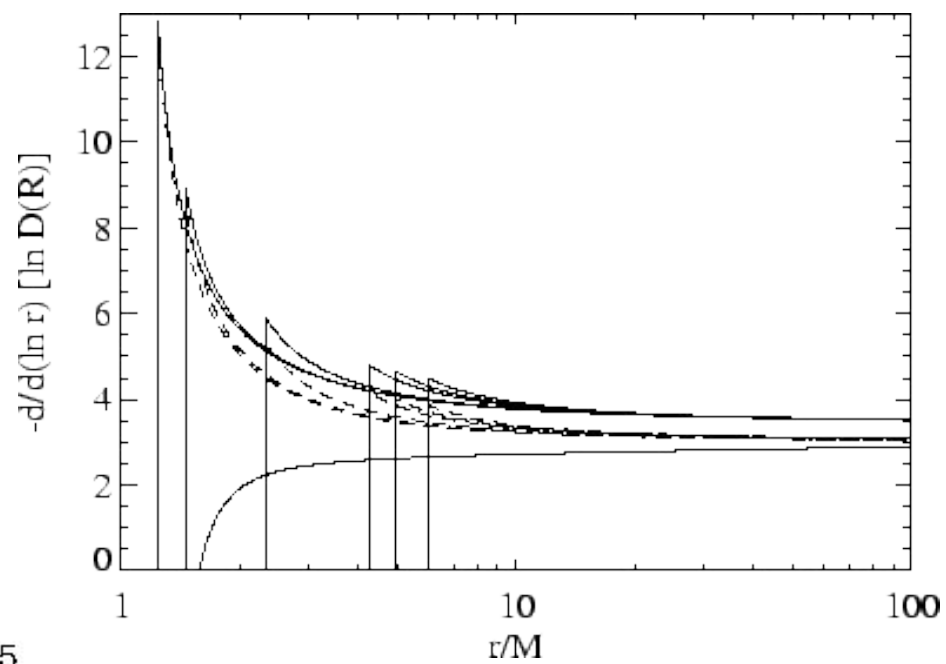
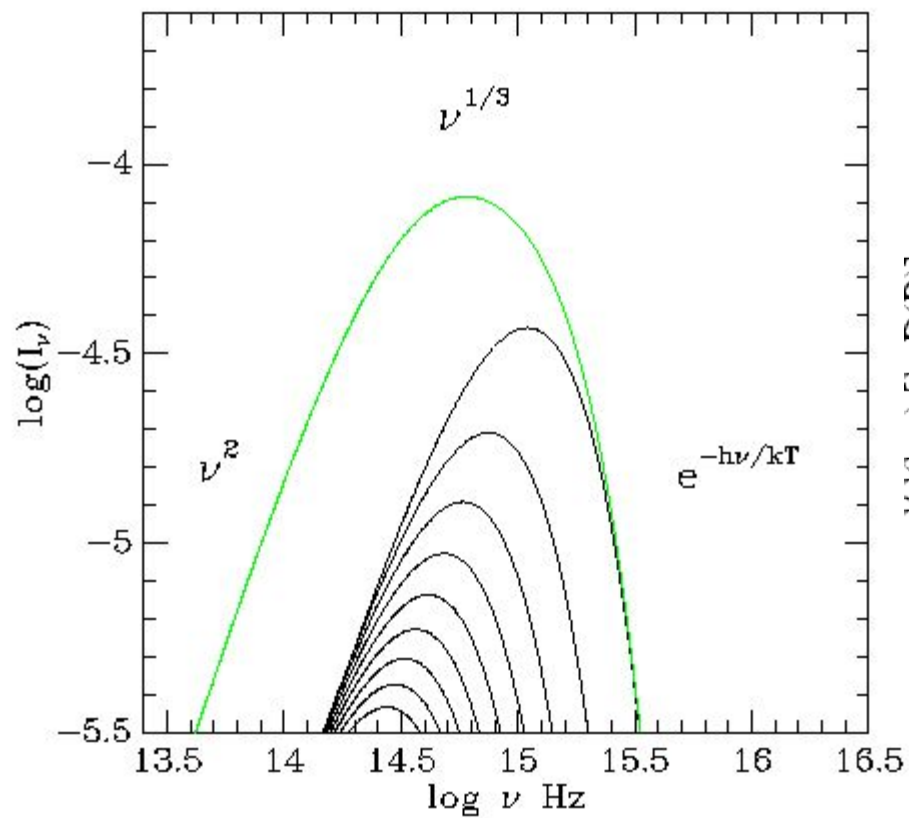
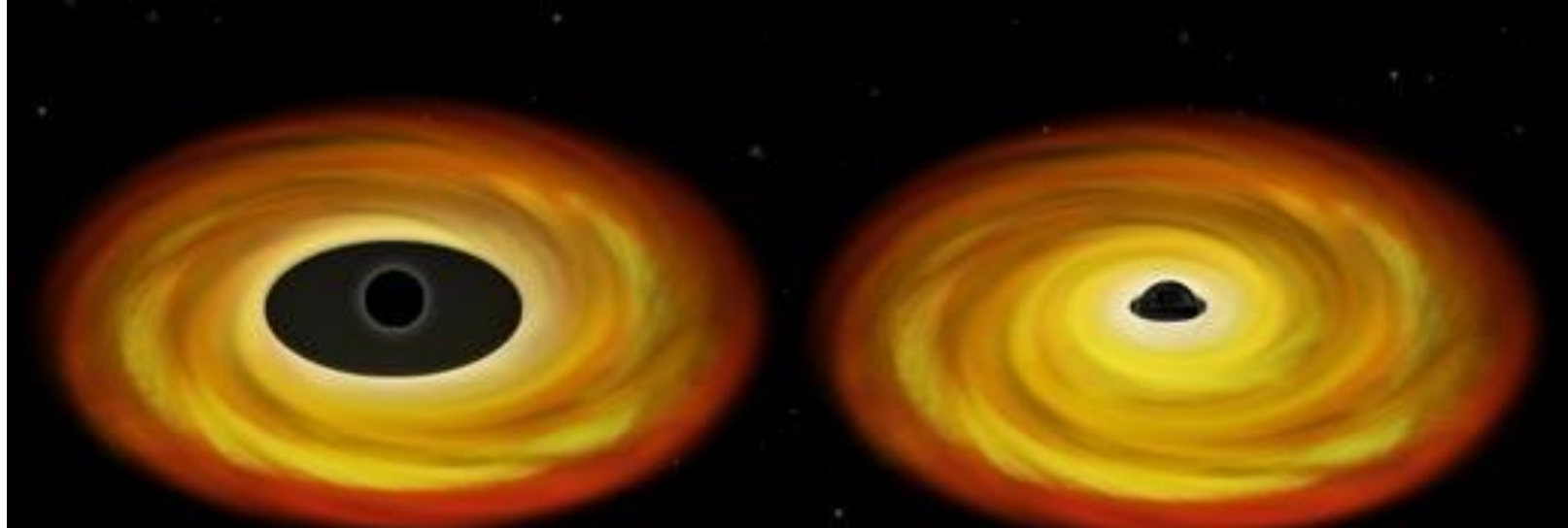
С
неправильной
коррекцией

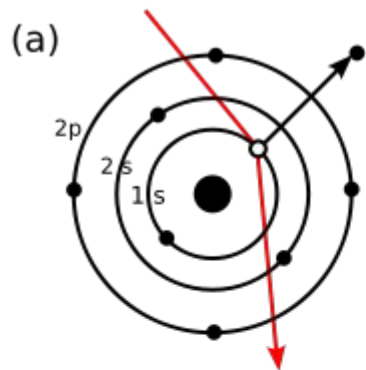


С
правильной
коррекцией

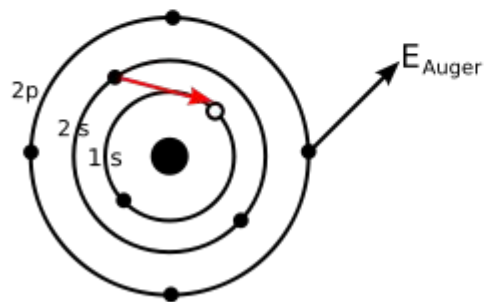
Пример 2.

Вращение черных дыр
по
характерной
температуре
аккреционного диска?





Electron collision



Auger electron emission

