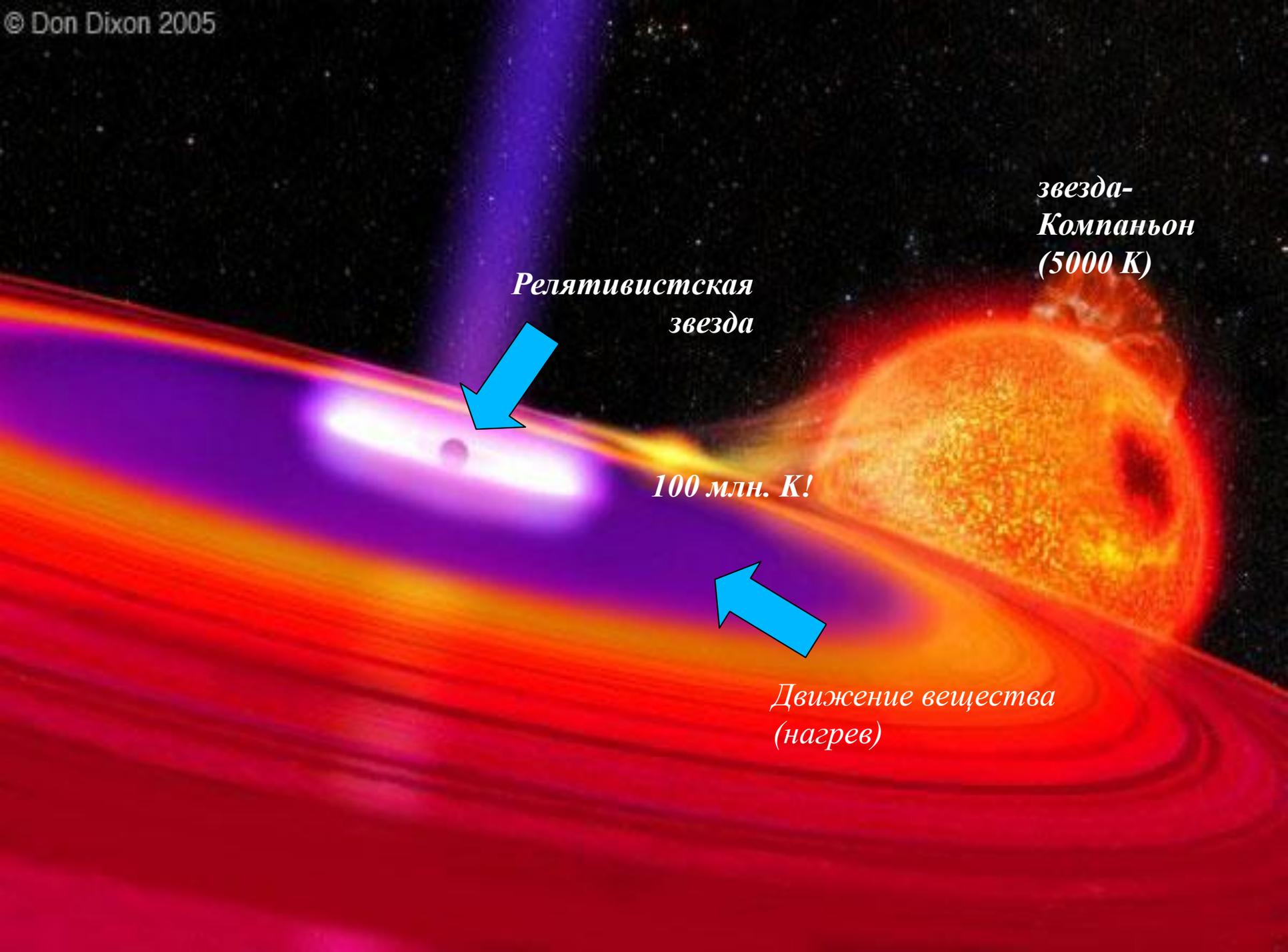




**От теории к практике:  
о проявлениях сильной  
гравитации  
в рентгеновских наблюдениях**



*Релятивистская  
звезда*

*звезда-  
Компаньон  
(5000 К)*

*100 млн. К!*

*Движение вещества  
(нагрев)*

# Почему рентгеновский диапазон?

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

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

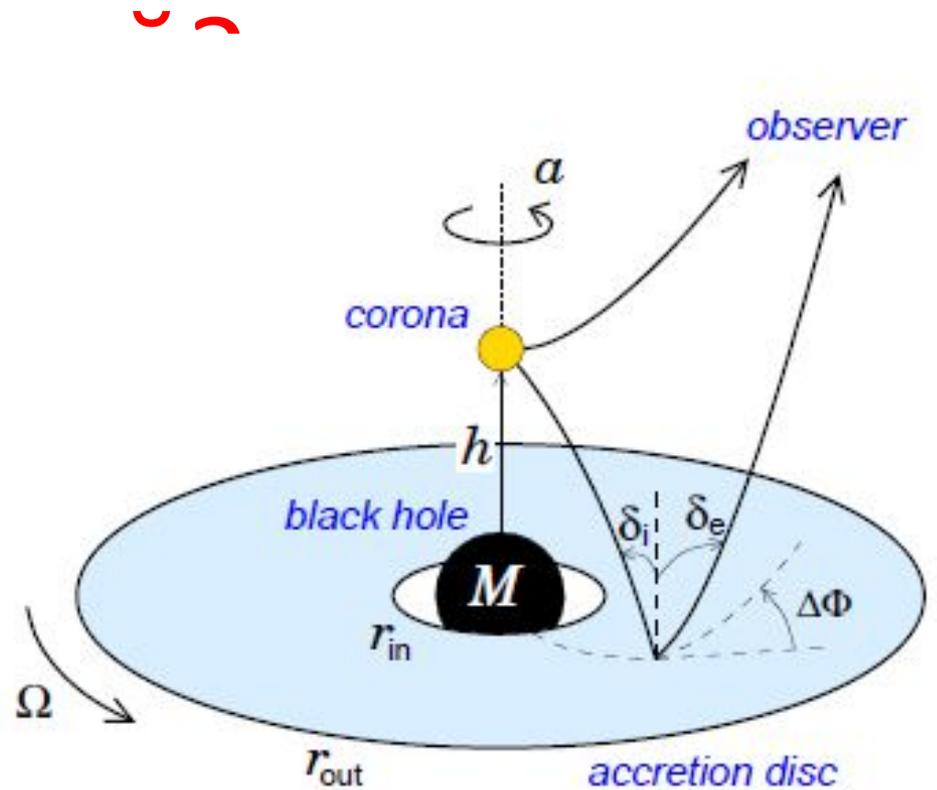
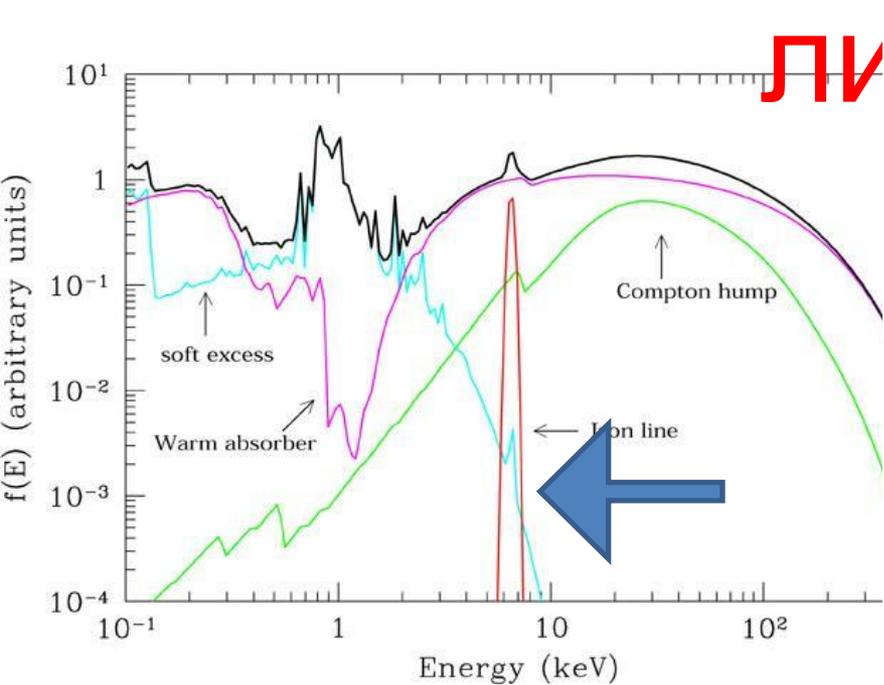
$$\eta = \left( \frac{2R_c}{R_s} \right)^{-1} \text{ — эффективность аккреции}$$

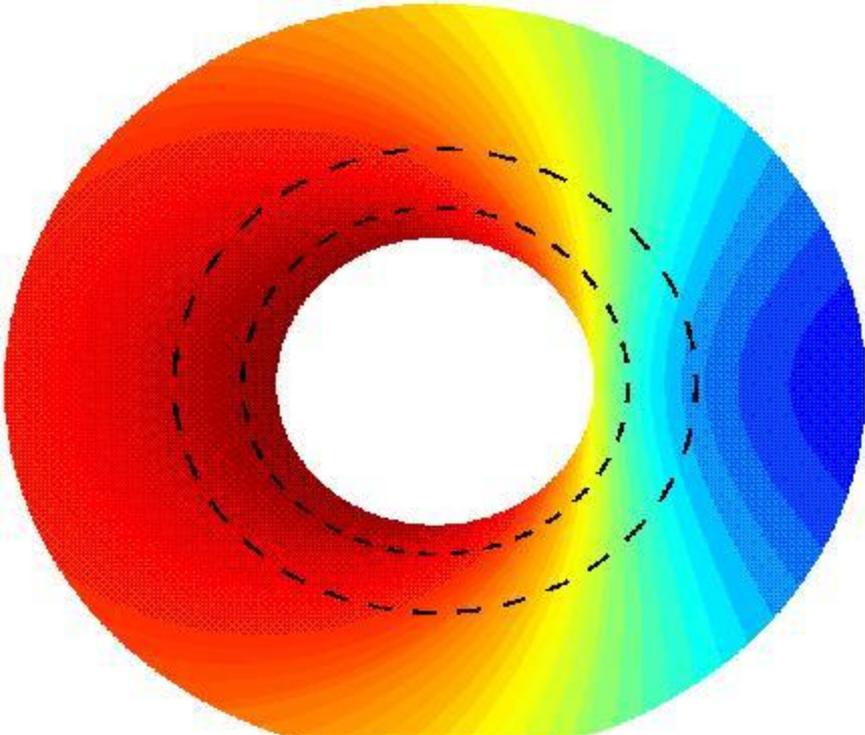
$$\left. \begin{array}{l} \dot{M} \sim 10^{-8} M_{\text{Sun}} / \text{Г} \\ L_x \sim 10^{38} \text{ эрг/с} \end{array} \right\} \Rightarrow \eta \sim 0.1, R_c \sim 5R_s \text{ } (\sim 15 \text{ км для } 1 M_{\text{Sun}})$$

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

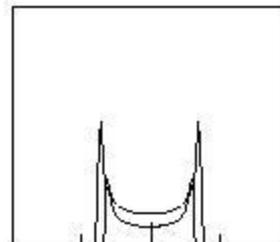
# Пример 1.

## Вращение черных дыр по искажениям эмиссионных

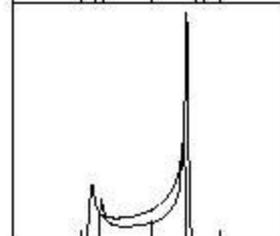




Newtonian

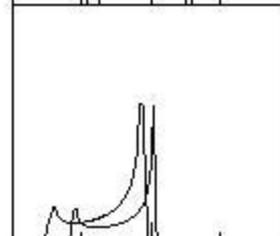


Special relativity



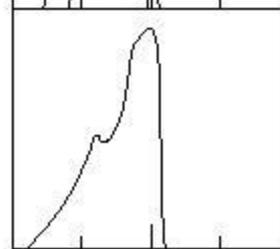
Transverse Doppler shift  
Beaming

General relativity

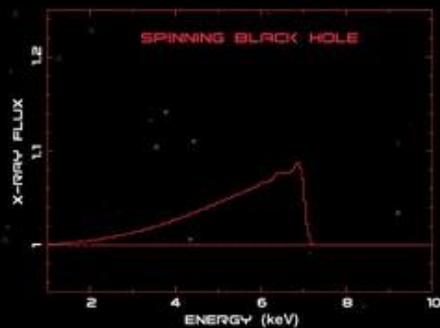
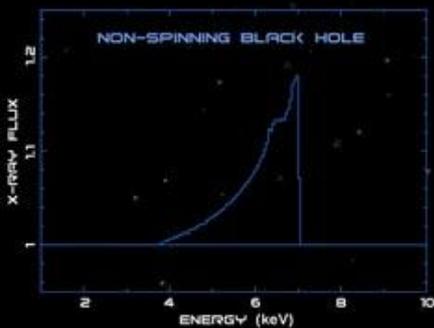
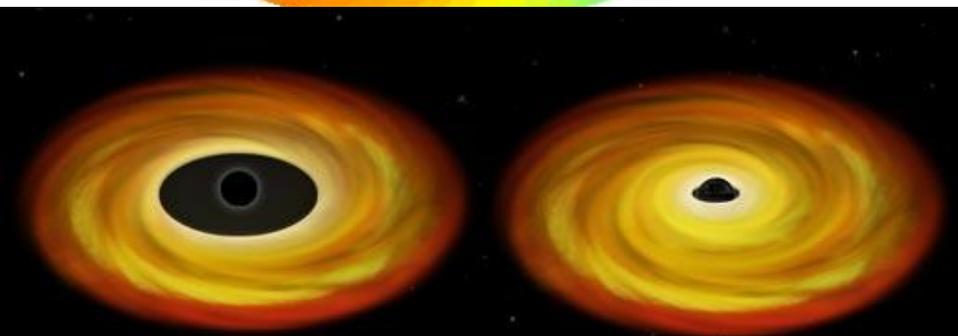


Gravitational redshift

Line profile

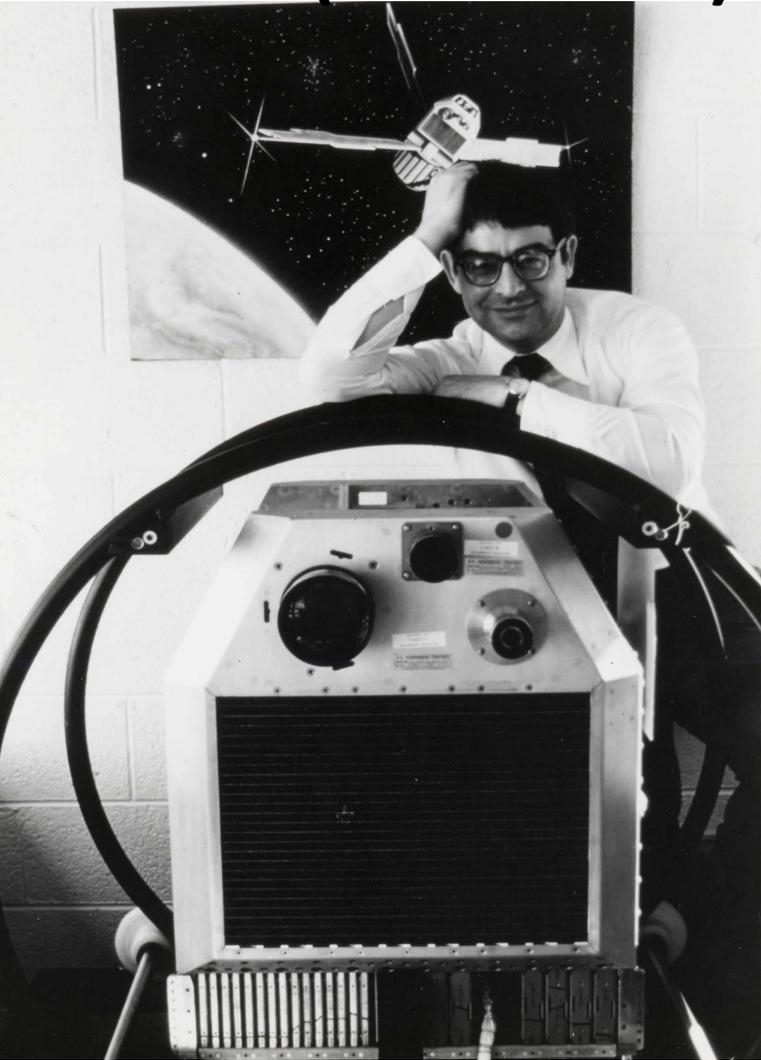


0.5 1 1.5  
 $\nu_{\text{obs}}/\nu_{\text{em}}$



**Отражение от  
быстровращ.  
диска  
находящегося**

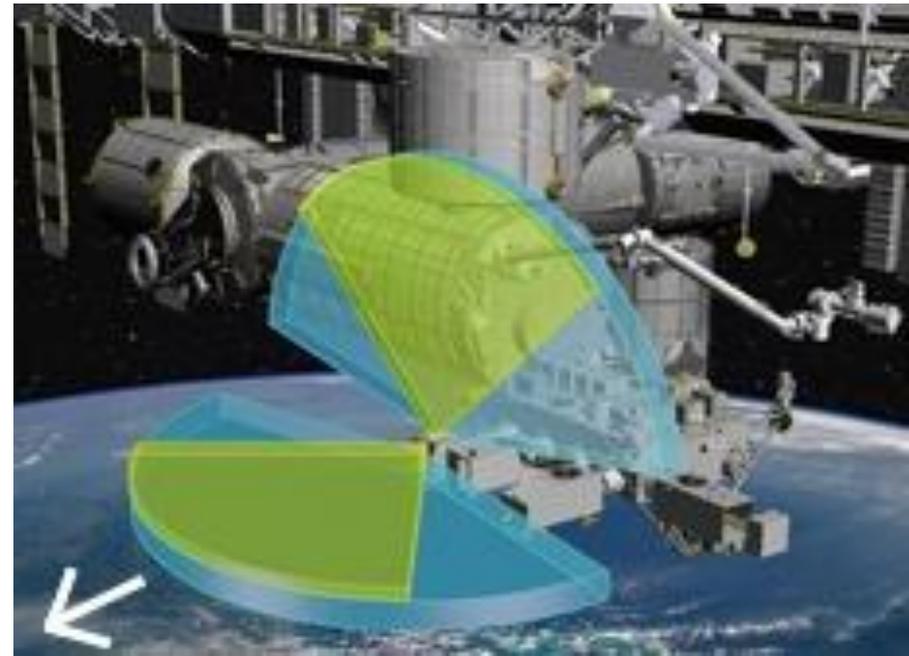
# UHURU (1970-1973)



# RXTE (1995-2012)

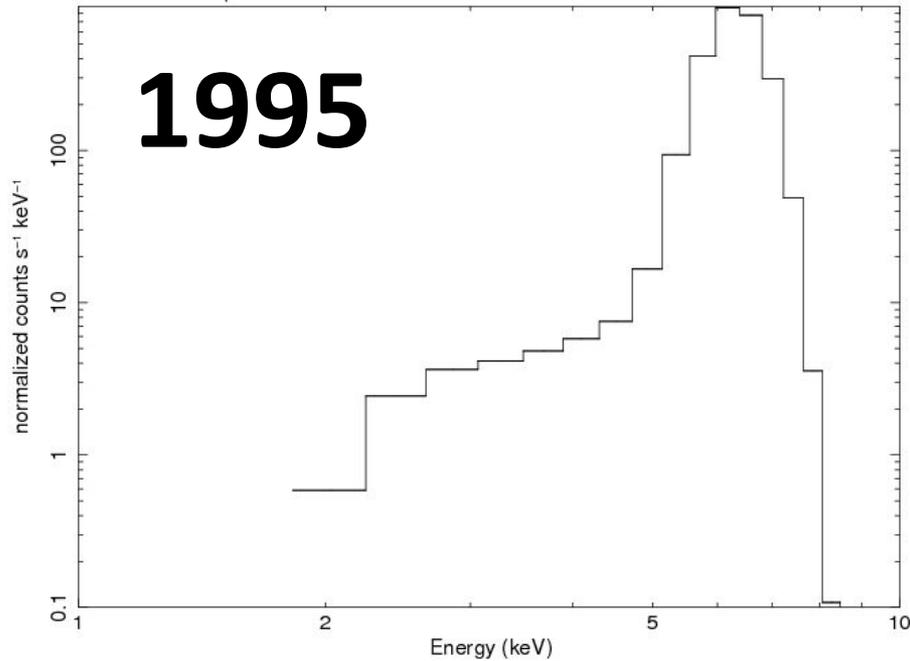


# MAXI/ISS (2009-??)



RXTE/PCA

6.4 keV line response



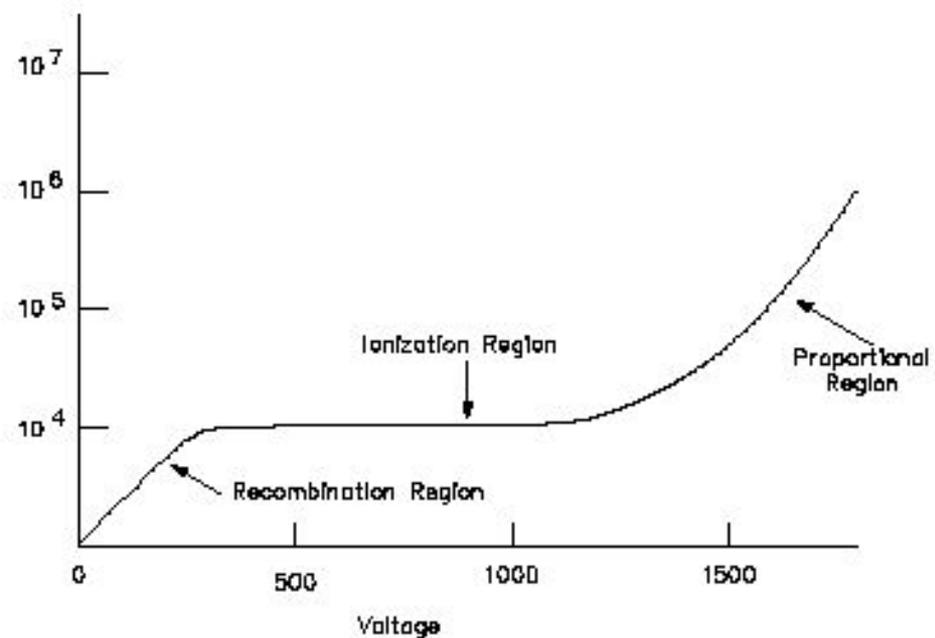
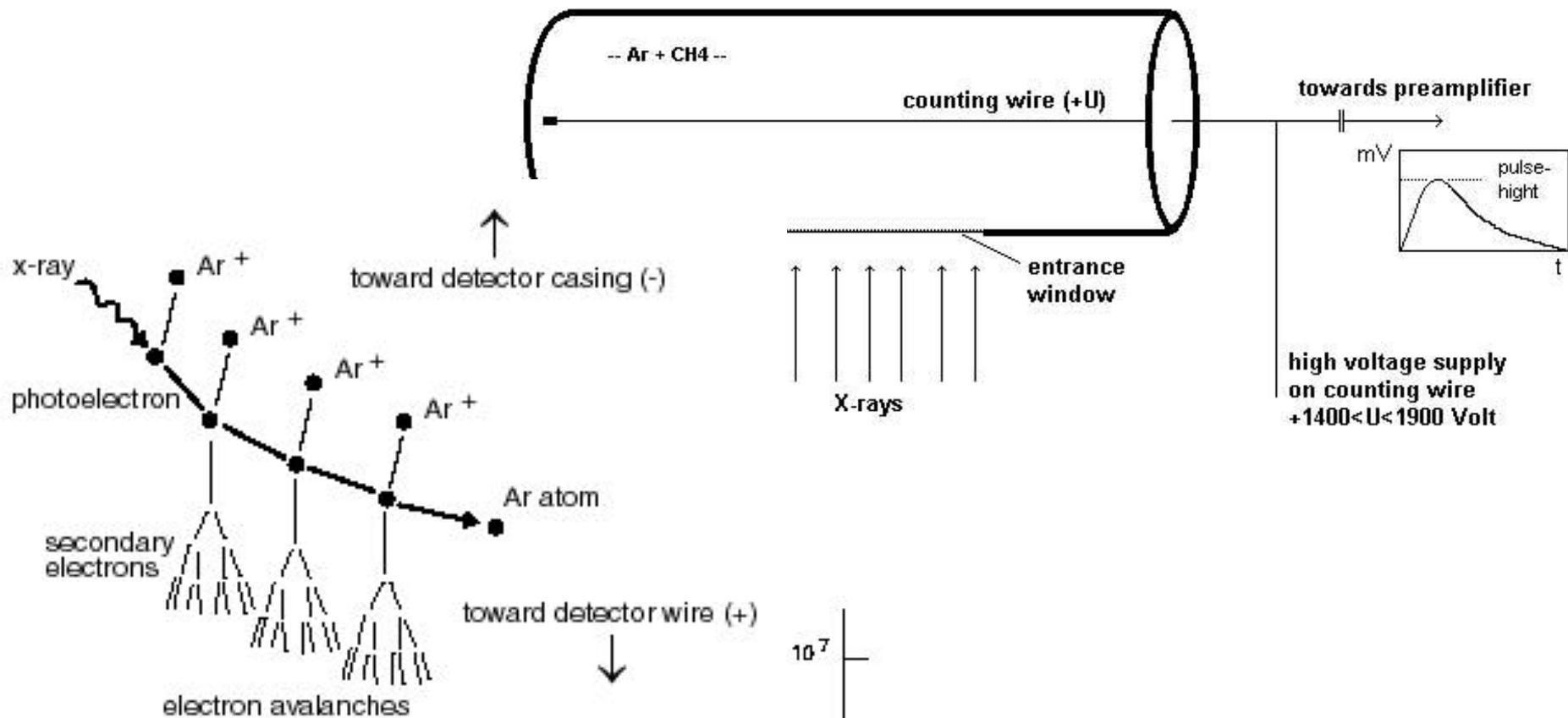
HEAO1/A2/H1

6.4 keV line response



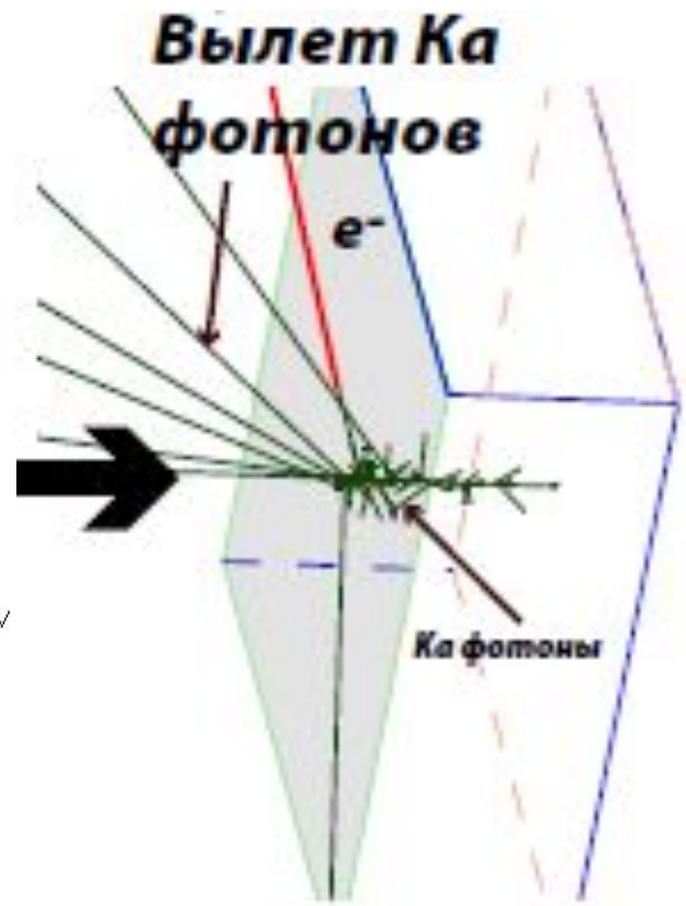
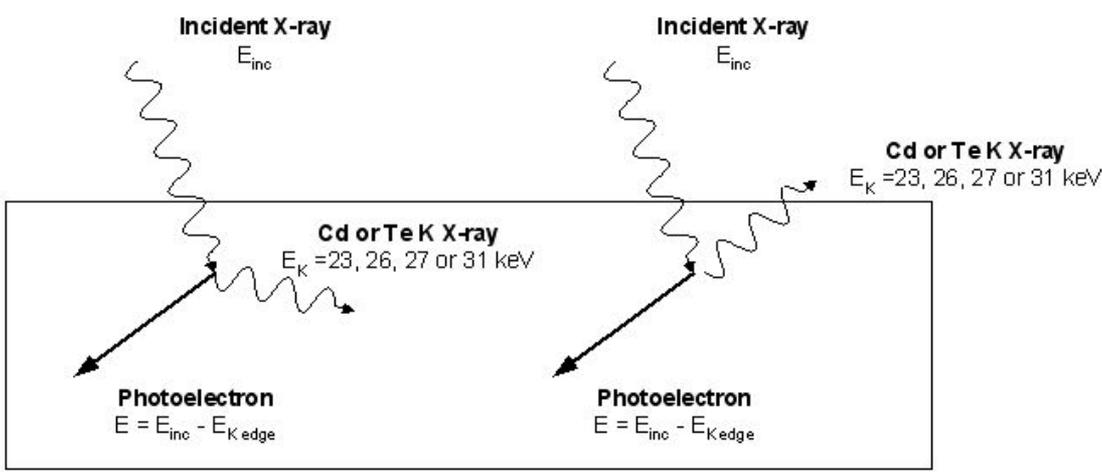
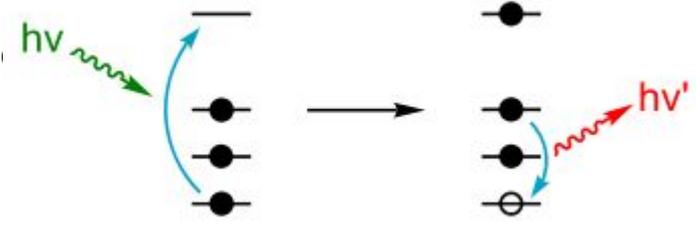
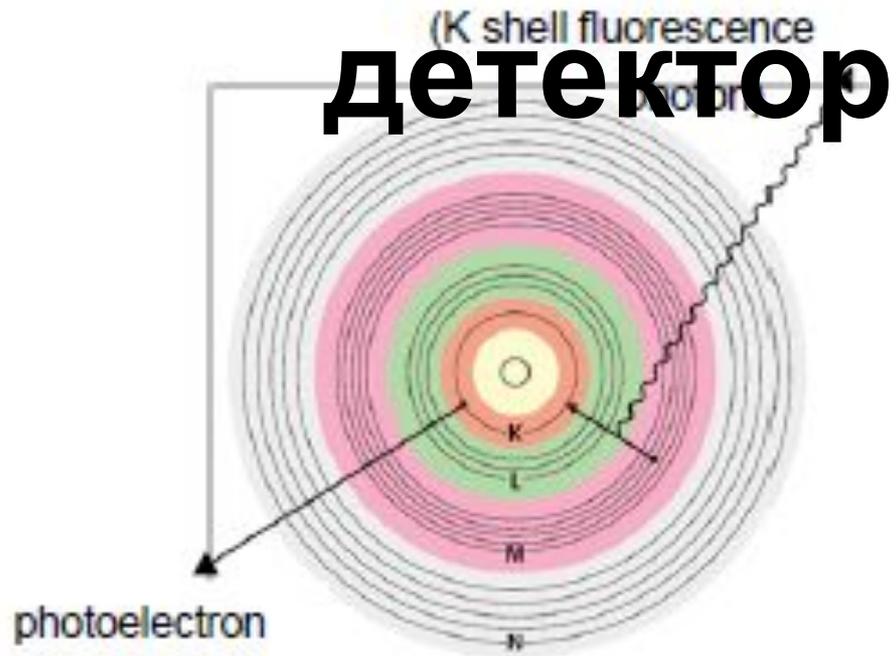
**Отклик  
газовых  
счетчик  
ОВ**

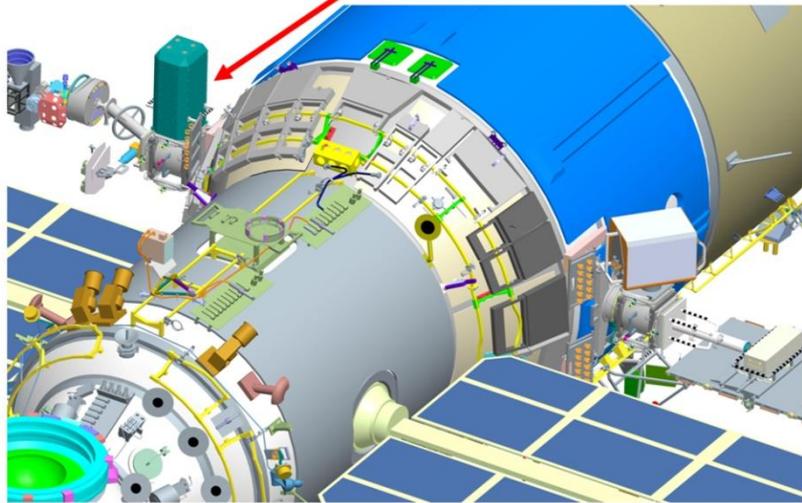
**Разрешение  
ограничено  
количеством  
собираемых  
электронов**



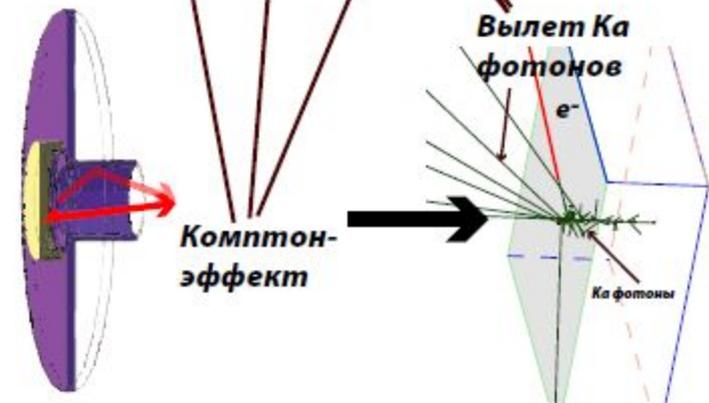
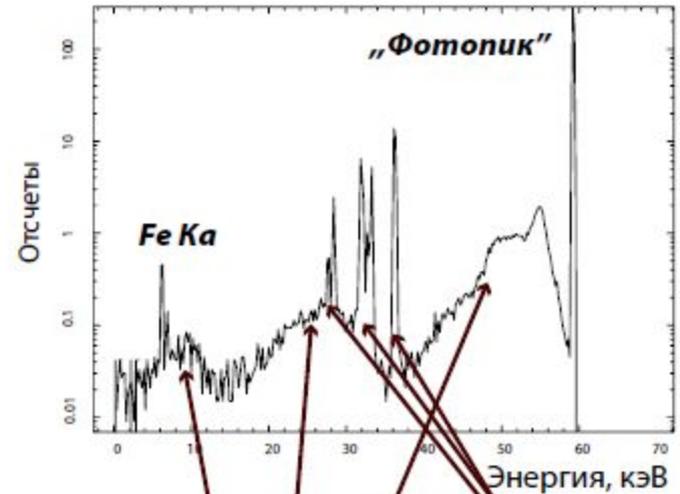
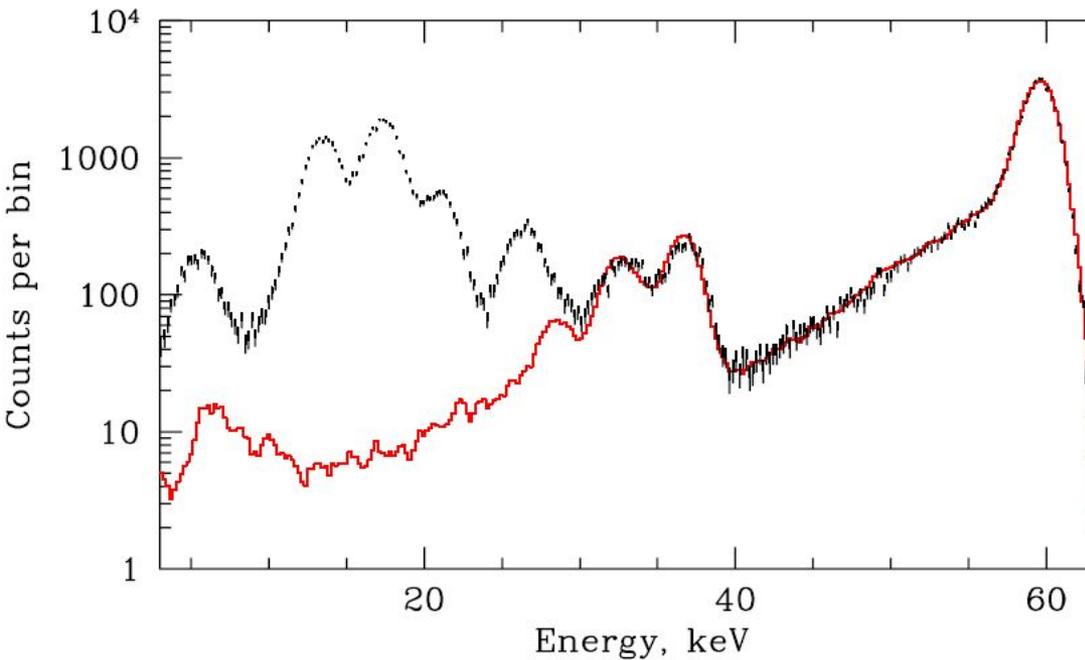
**Электроны,  
выбитые  
рентгеновскими  
фотонами формируют**

# 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
TDEF2 = '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<br>b10000010<br>b00001001 |
| 2 | 5.629222840016069E+08 | b10000000<br>b01000010<br>b00010000 |
| 3 | 5.629222840031948E+08 | b10000000<br>b01000010<br>b00000111 |

# Достижение для спектроскопии пропорциональных счетчиков

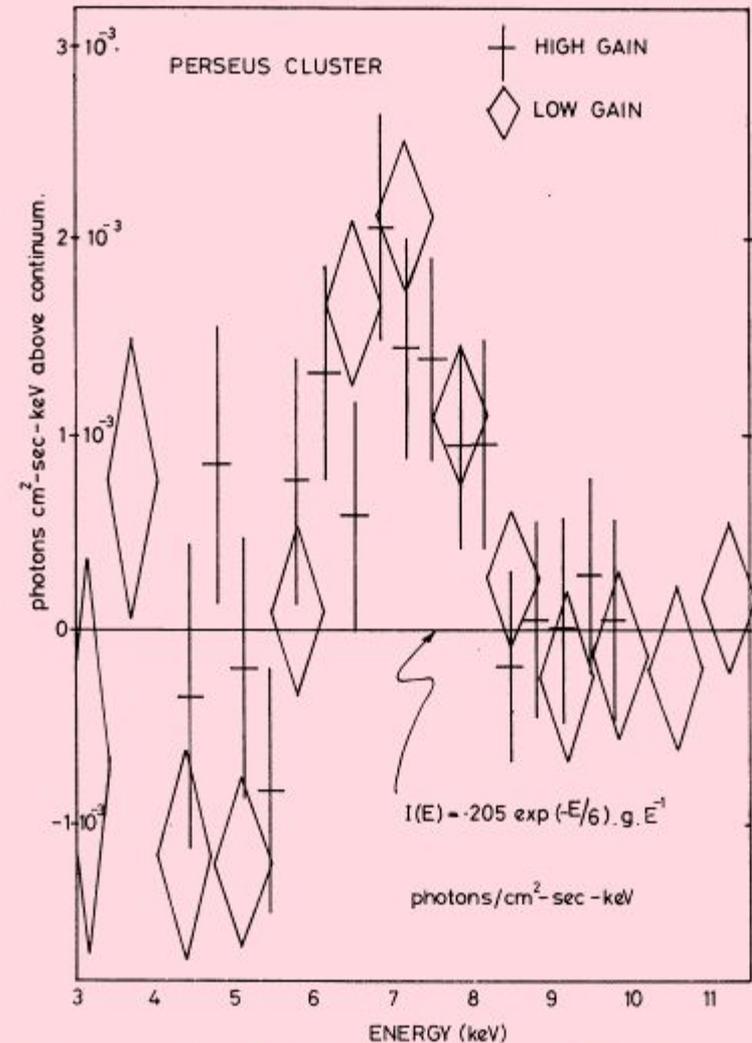
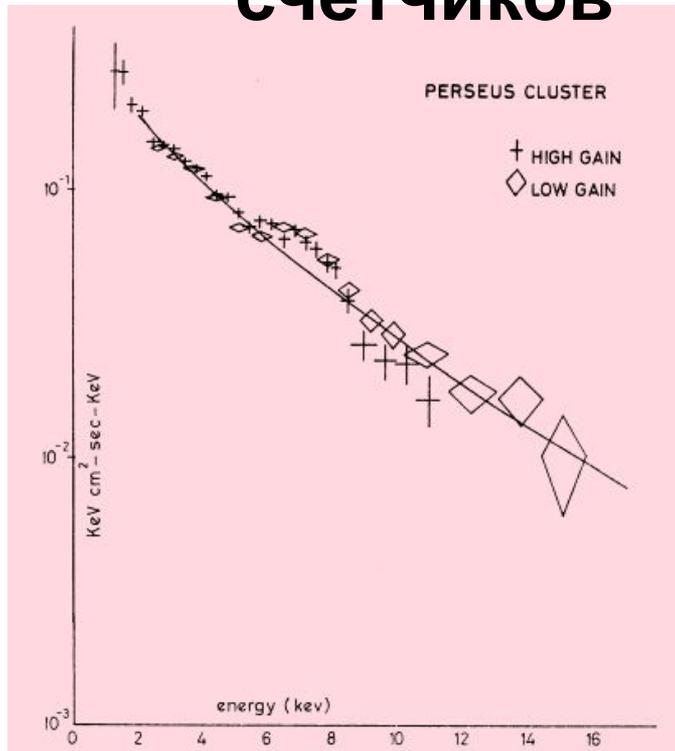


FIG. 2. The deviation of the flux in each energy channel from that predicted by the best-fitting single temperature continuum is plotted for the range 3–11 keV. Data from both gain modes show a systematic departure from the continuum in the energy range around 6.9 keV. The width of the feature is consistent 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  $\sigma$  levels.

# На самом деле...

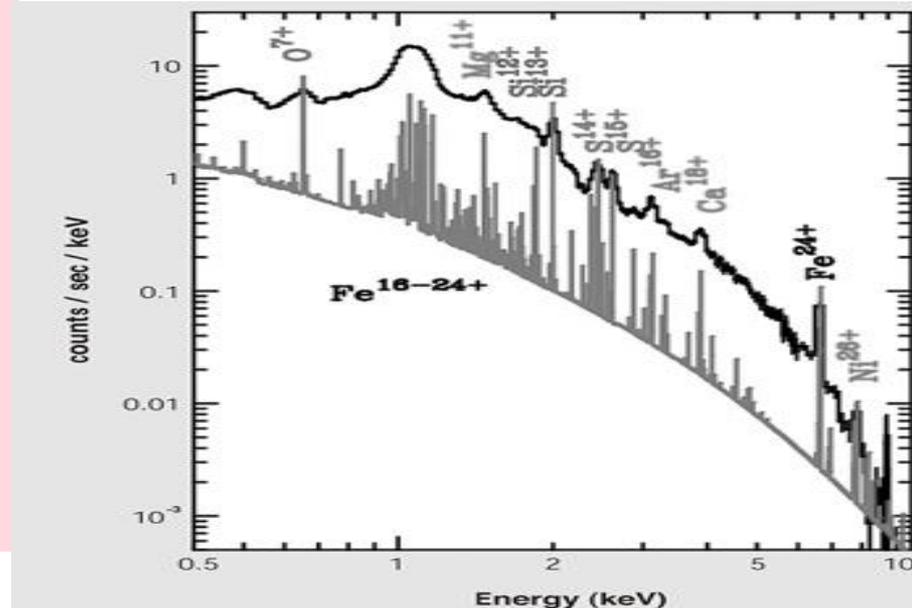
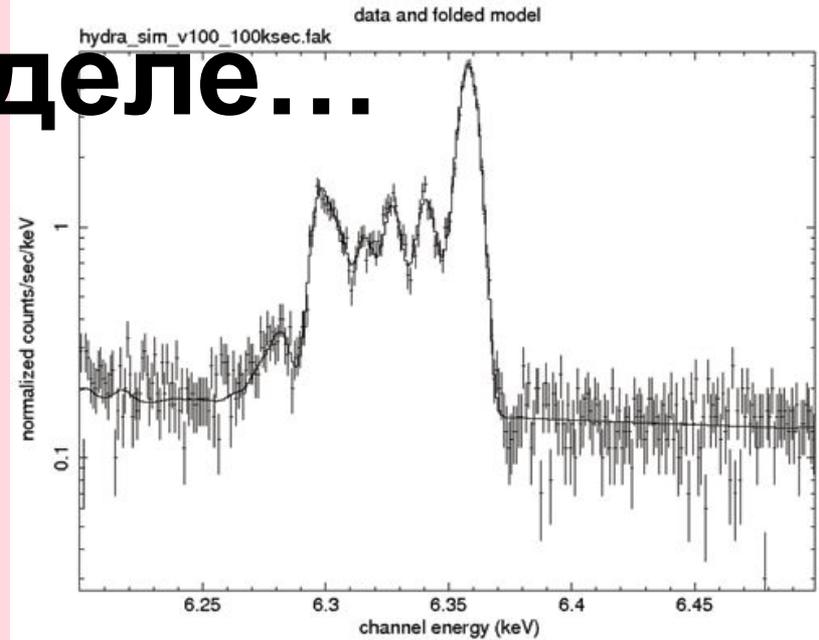
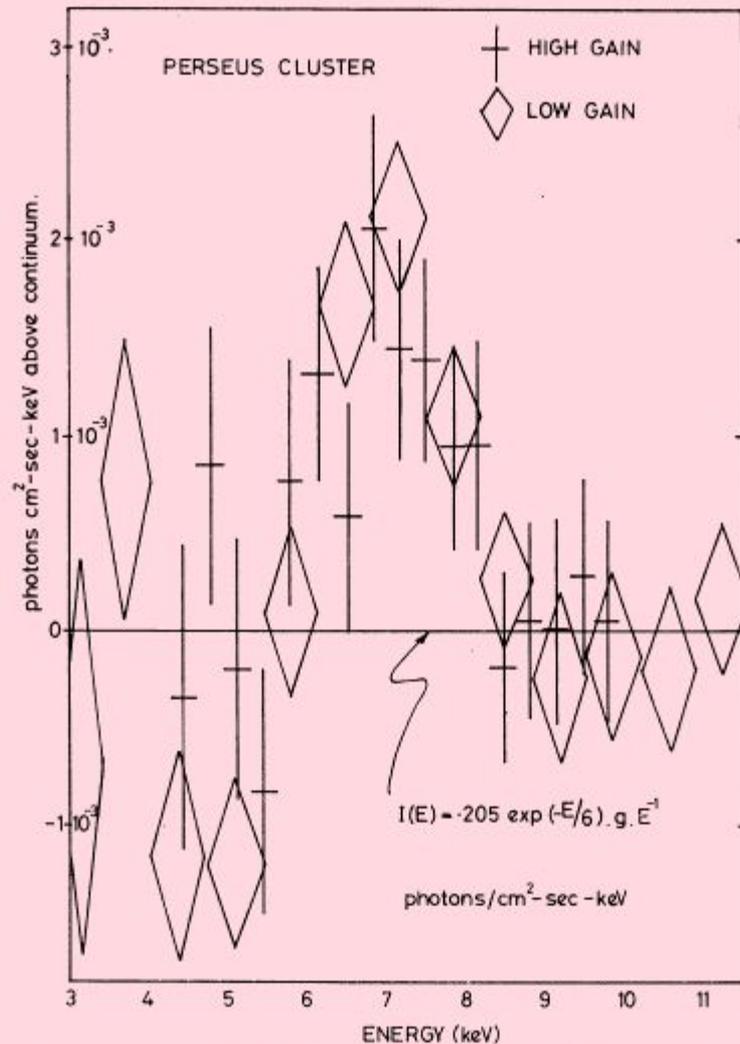


FIG. 2. The deviation of the flux in each energy channel from that predicted by the best-fitting single temperature continuum is plotted for the range 3–11 keV. Data from both gain modes show a systematic departure from the continuum in the energy range around 6.9 keV. The width of the feature is consistent 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  $\sigma$  levels.

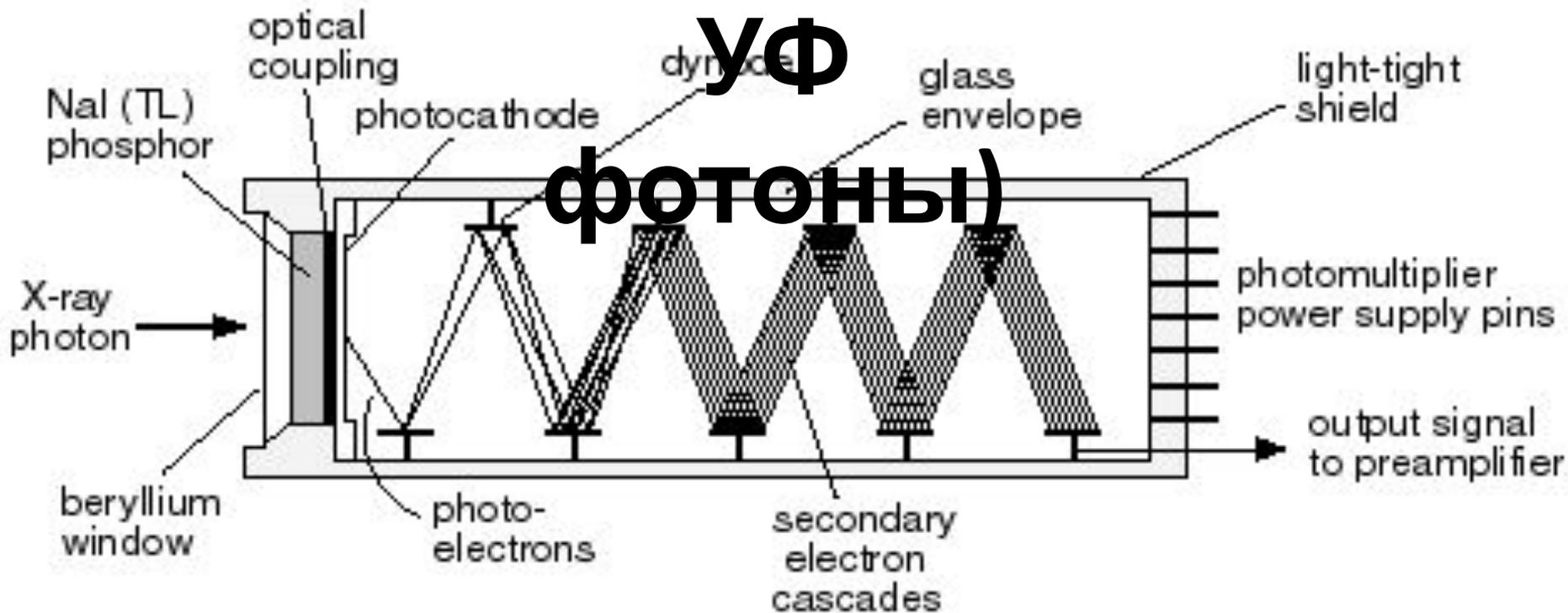
# СЦИНТИЛЛЯТОР

р

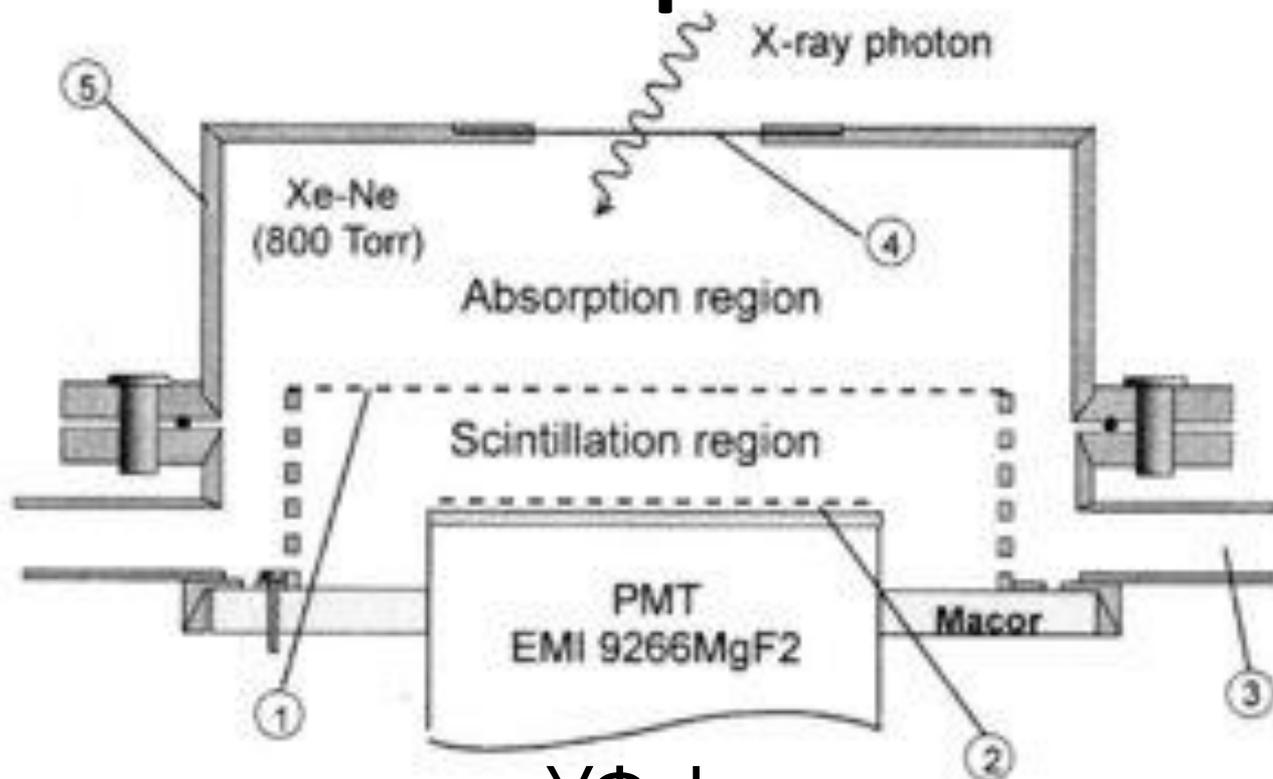
(измеряются

УФ

ФОТОНЫ)



# Gas Scintillation Proportional Counter



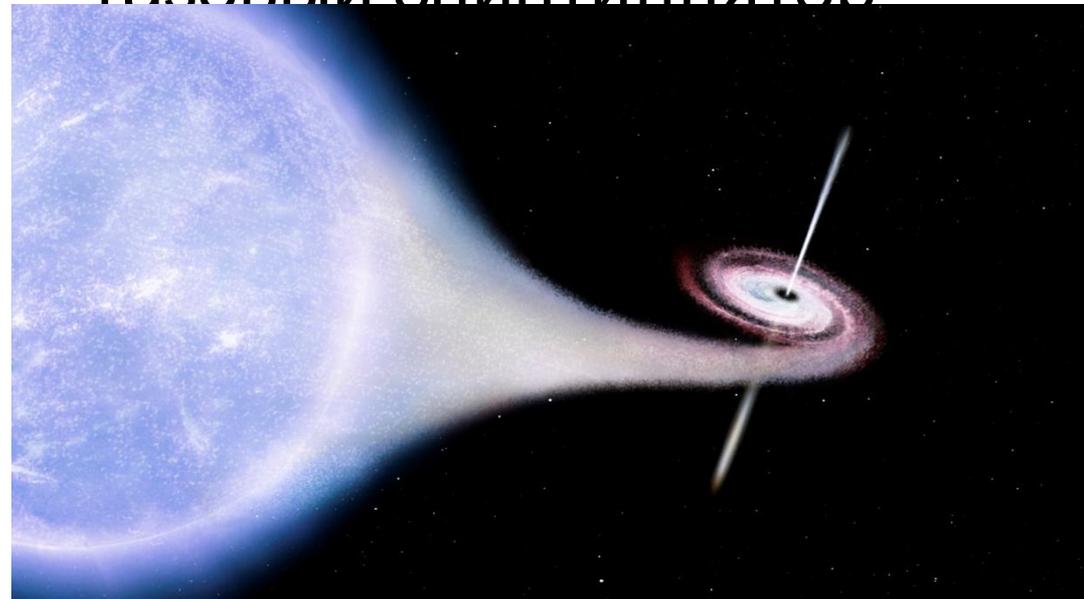
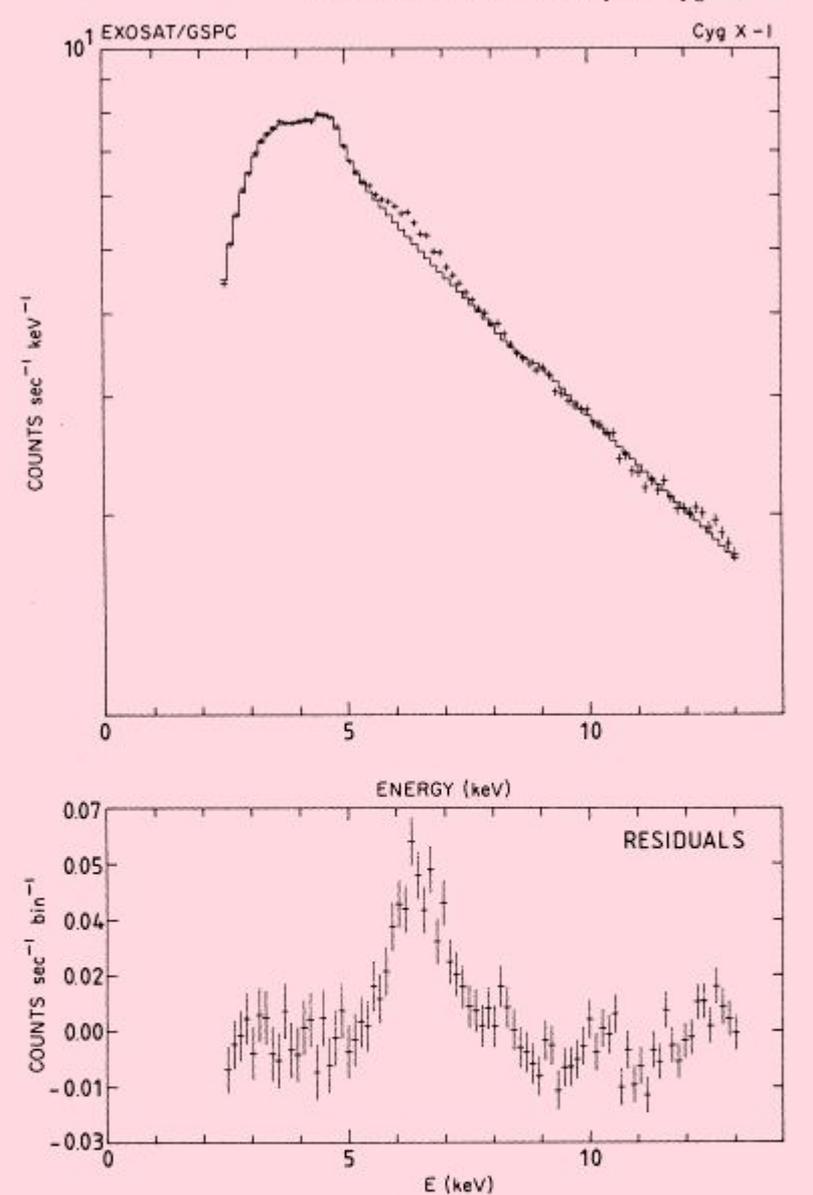
Электроны создают УФ фотоны  
(сцинтилляция)

фотоны “видятся” фотоумножителем

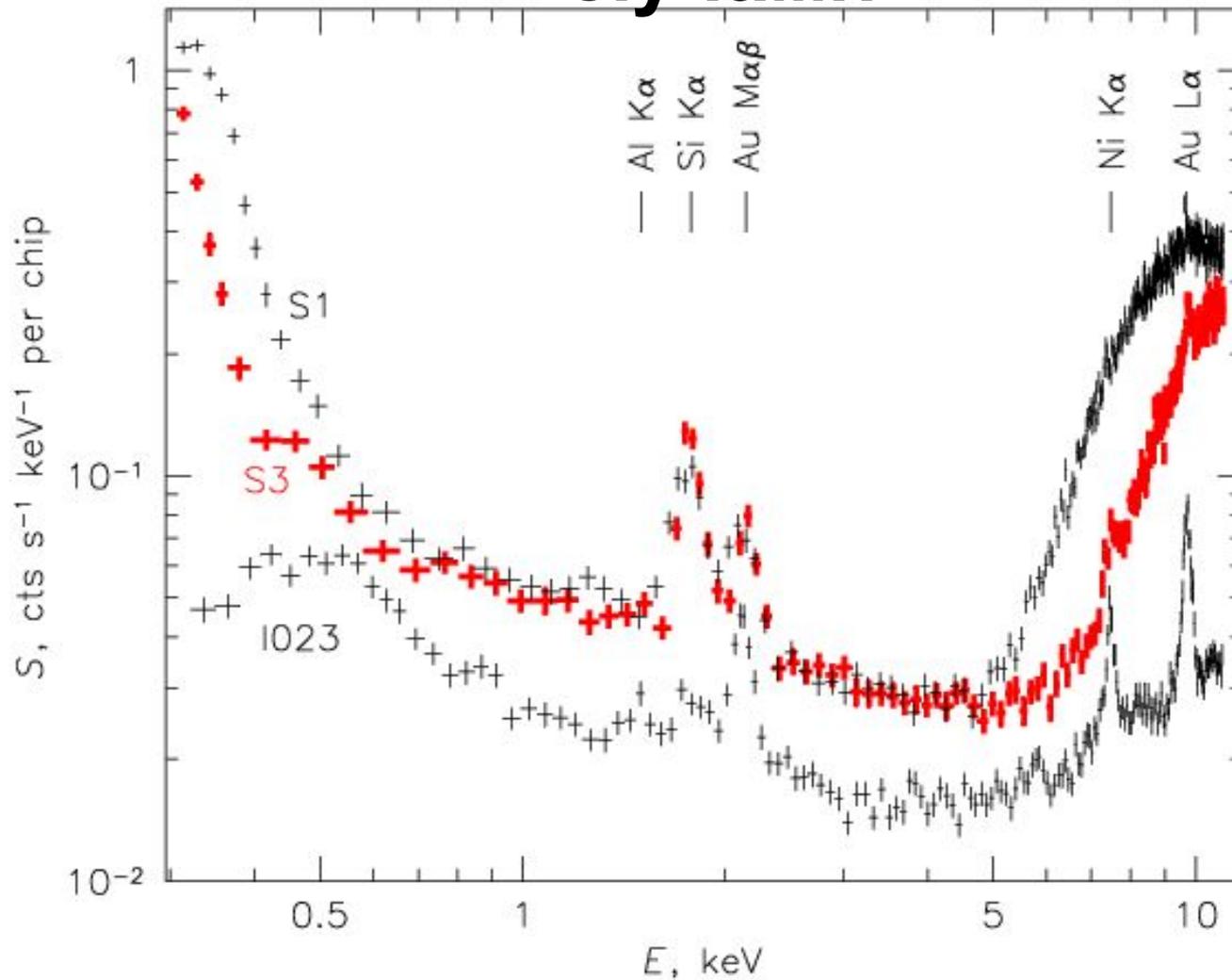
**Разрешение увеличилось в ~2  
раза**

# Обнаружена флуоресцентная линия нейтрального железа 6.4 кэВ (1985)

ГАЗОВЫЙ СЦИНТИЛЛЯТОР



# Проблемы для слабых источников фон, наведенный космическими лучами



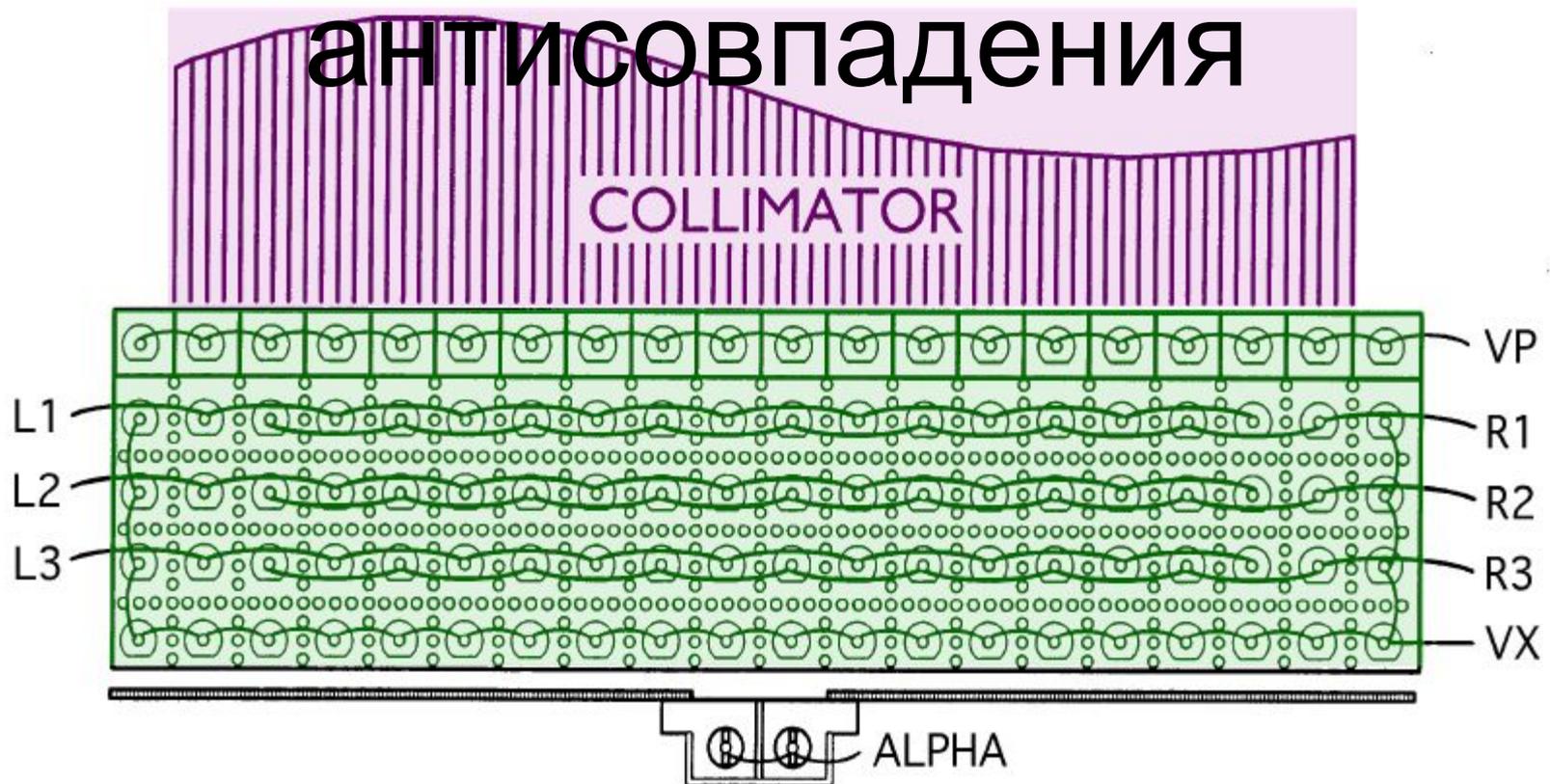
пример:

# Проблемы для слабых источников фон, наведенный космическими

## лучами Активная система

### защиты:

#### антисовпадения

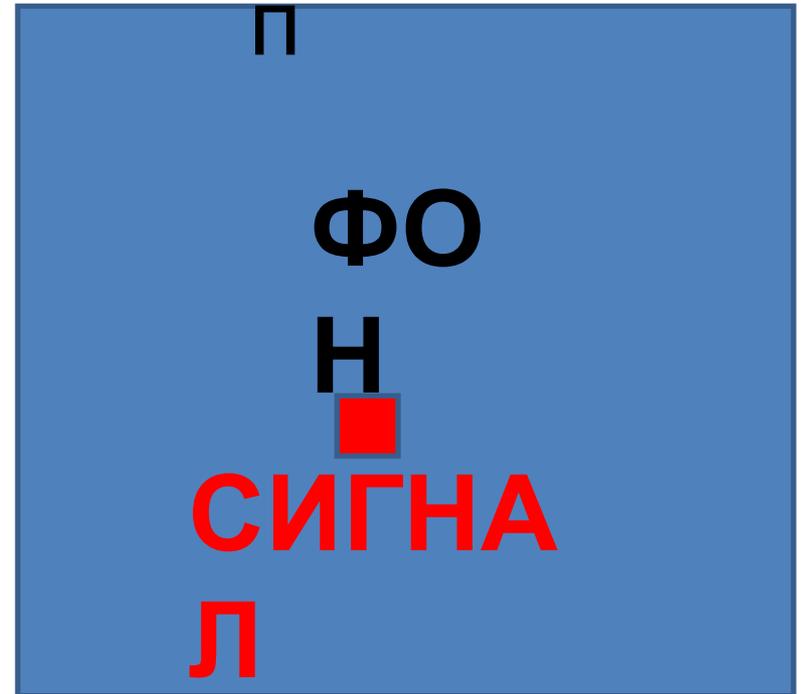


# Преимущество построения изображений для слабых источников

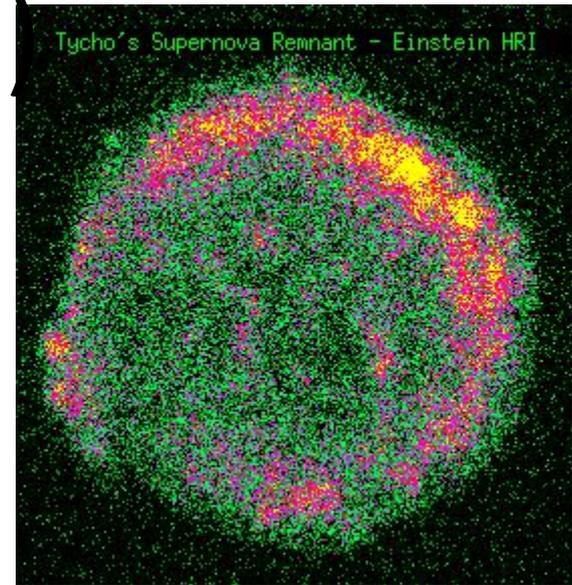
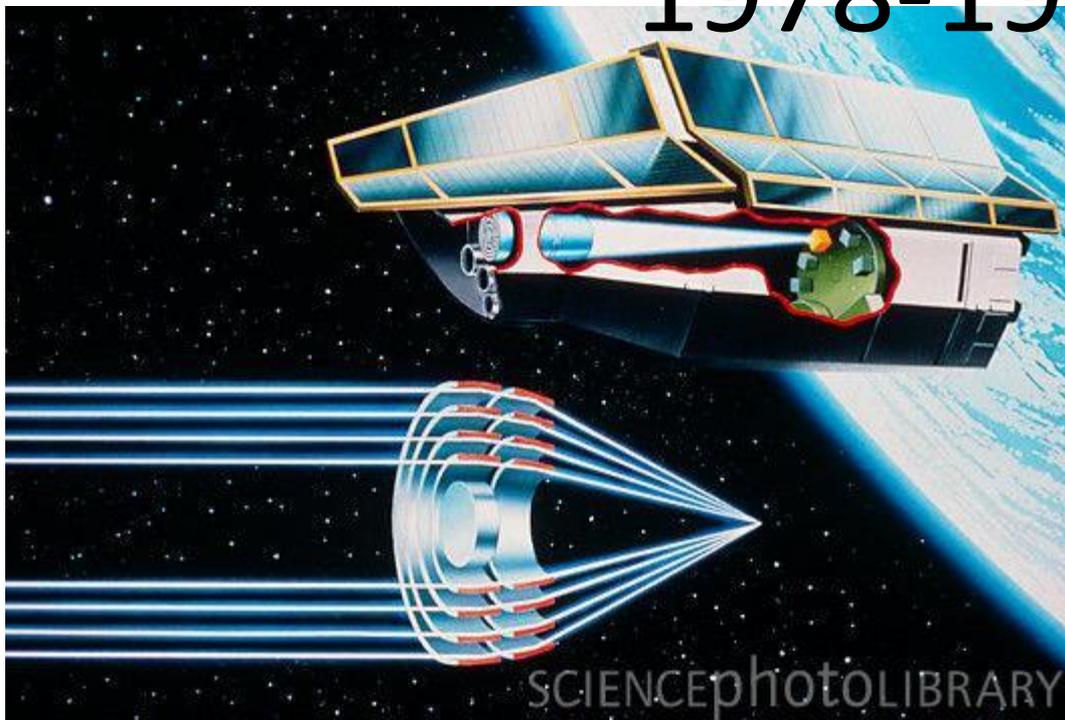
Спектрометр



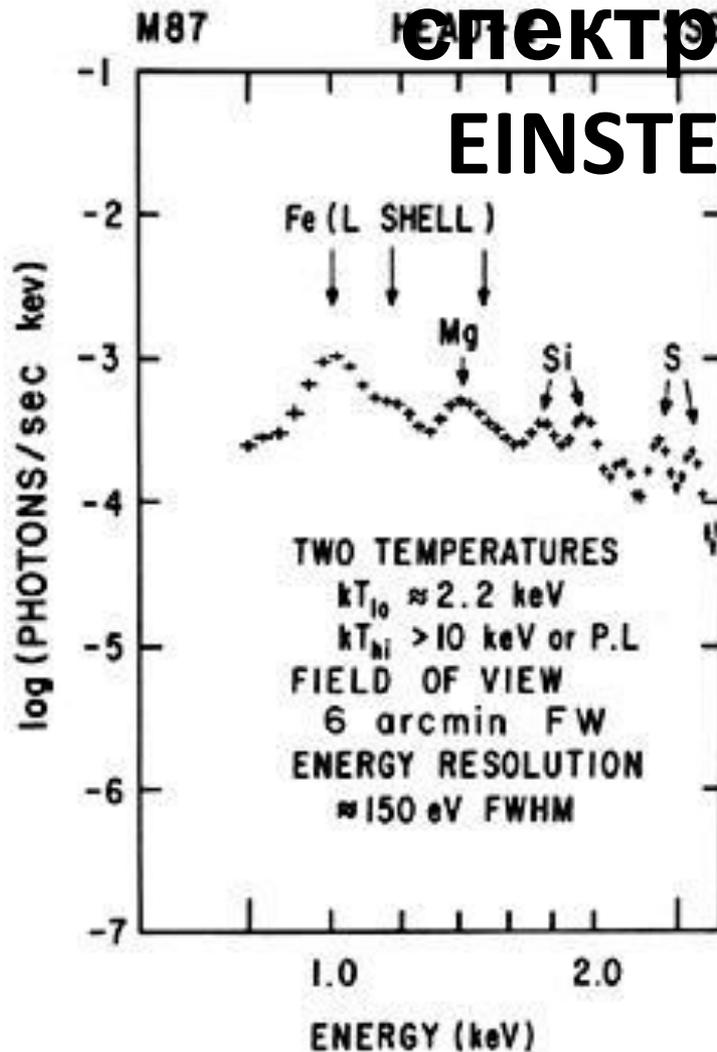
Телескоп



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



# Первый твердотельный спектрометр: EINSTEIN/SSS



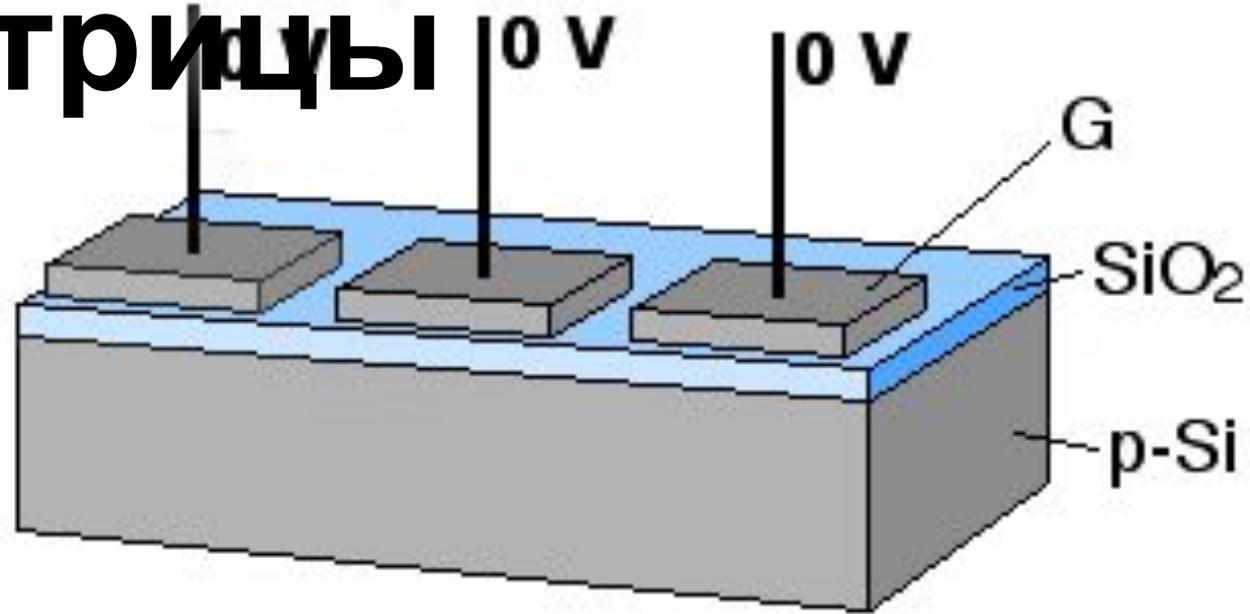
Работал на  
энергиях <4  
кэВ

Энергия  
линии

жесткое  $\gamma$

# ПЗС

## матрицы



### Two Phase CCD Clocking

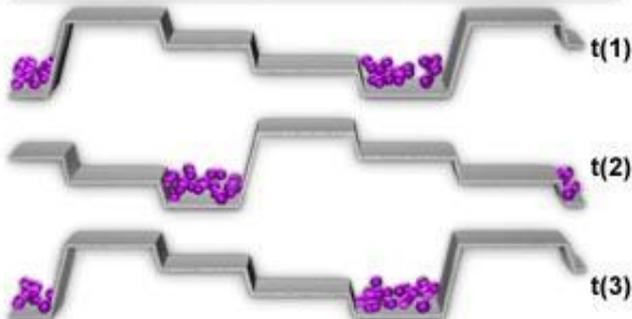
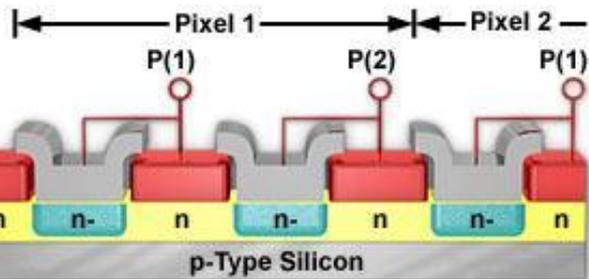
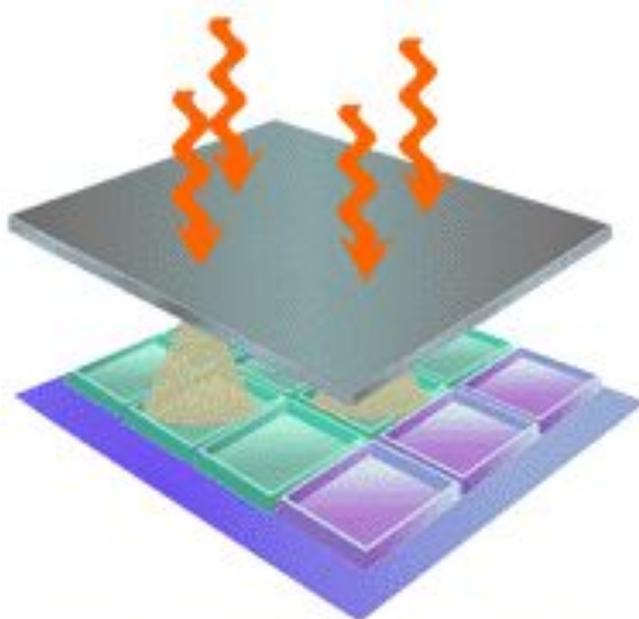
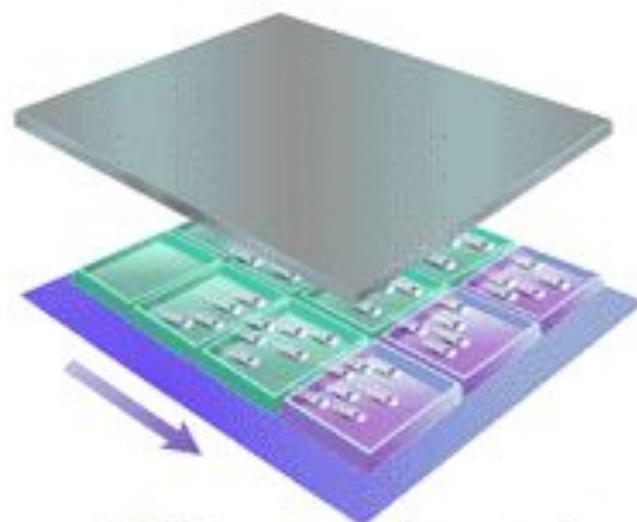


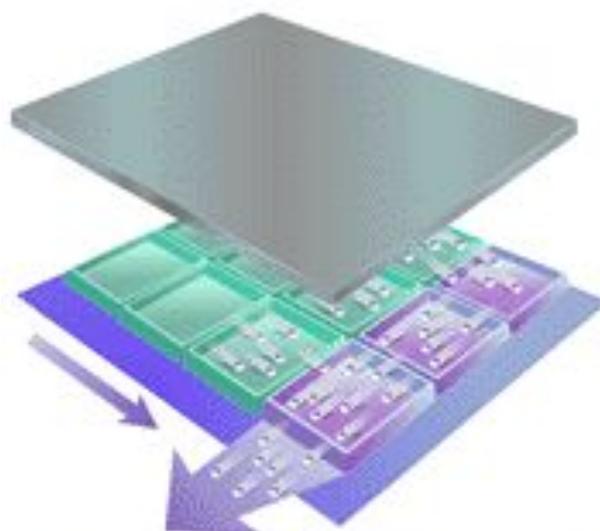
Figure 1



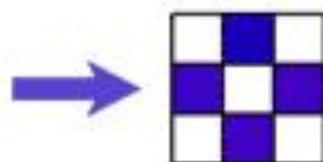
(1) Incident x-ray produces shower of electrons in selected pixels



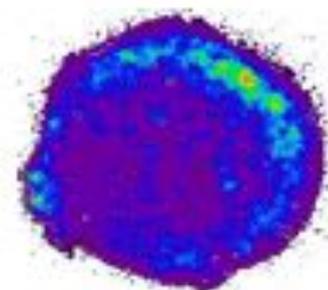
(2) Voltage moves electrons to the right to "count-out" row



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



(4) Computer reconstructs image (9 pixels)

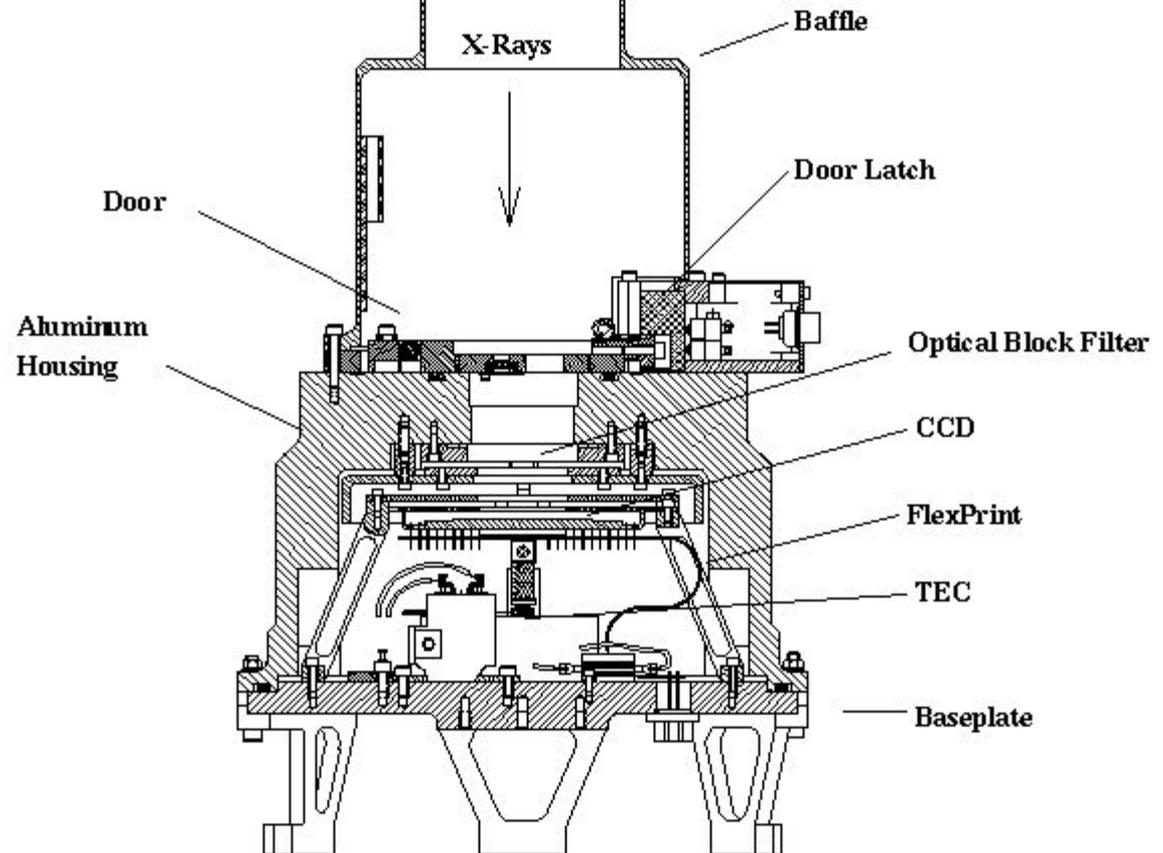


CXC CCD's will have ~ 1 million pixels



| time<br>s                    | ccd_id | node_id | expro | chipx<br>pixel | chipy<br>pixel | tdetx<br>pixel | tdety<br>pixel | detx<br>pixel | dety<br>pixel | x<br>pixel    | y<br>pixel    | phas<br>adu   | pha<br>adu | pha_ro<br>adu | energy<br>eV | pi<br>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<br>-1<br>-1<br>-2<br>371<br>-4<br>-3<br>4<br>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<br>-2<br>-1<br>3<br>335<br>-2<br>0<br>4<br>1<br>0   |            | 384           | 335          | 1.5000878E+03 | 103  |
| 3.268654370767151E+08<br>es] | 3      | 2       | 3     | 654            | 703            | 4429           | 3715           | 4.4130879E+03 | 4.3971841E+03 | 4.4570464E+03 | 3.8171567E+03 | 0<br>-3<br>-4<br>2<br>1076<br>2<br>1<br>10<br>-1<br>-1<br>-2<br>0<br>-2<br>1394<br>-4<br>0<br>10<br>1<br>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<br>-1<br>0<br>-2<br>1394<br>-4<br>0<br>10<br>1<br>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<br>0<br>1<br>2<br>4<br>600<br>-1<br>3<br>5<br>-1<br>0<br>5<br>-2<br>-2<br>765<br>1<br>0<br>588<br>-3<br>-3<br>-3<br>-5<br>-3<br>1591<br>-6<br>-2<br>11<br>-3<br>-1<br>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<br>5<br>-2<br>-2<br>765<br>1<br>0<br>588<br>-3<br>-3<br>-3<br>-5<br>-3<br>1591<br>-6<br>-2<br>11<br>-3<br>-1<br>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<br>-3<br>-3<br>-5<br>-3<br>1591<br>-6<br>-2<br>11<br>-3<br>-1<br>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<br>-1<br>3   |            | 1058          | 902          | 4.1399751E+03 | 284  |

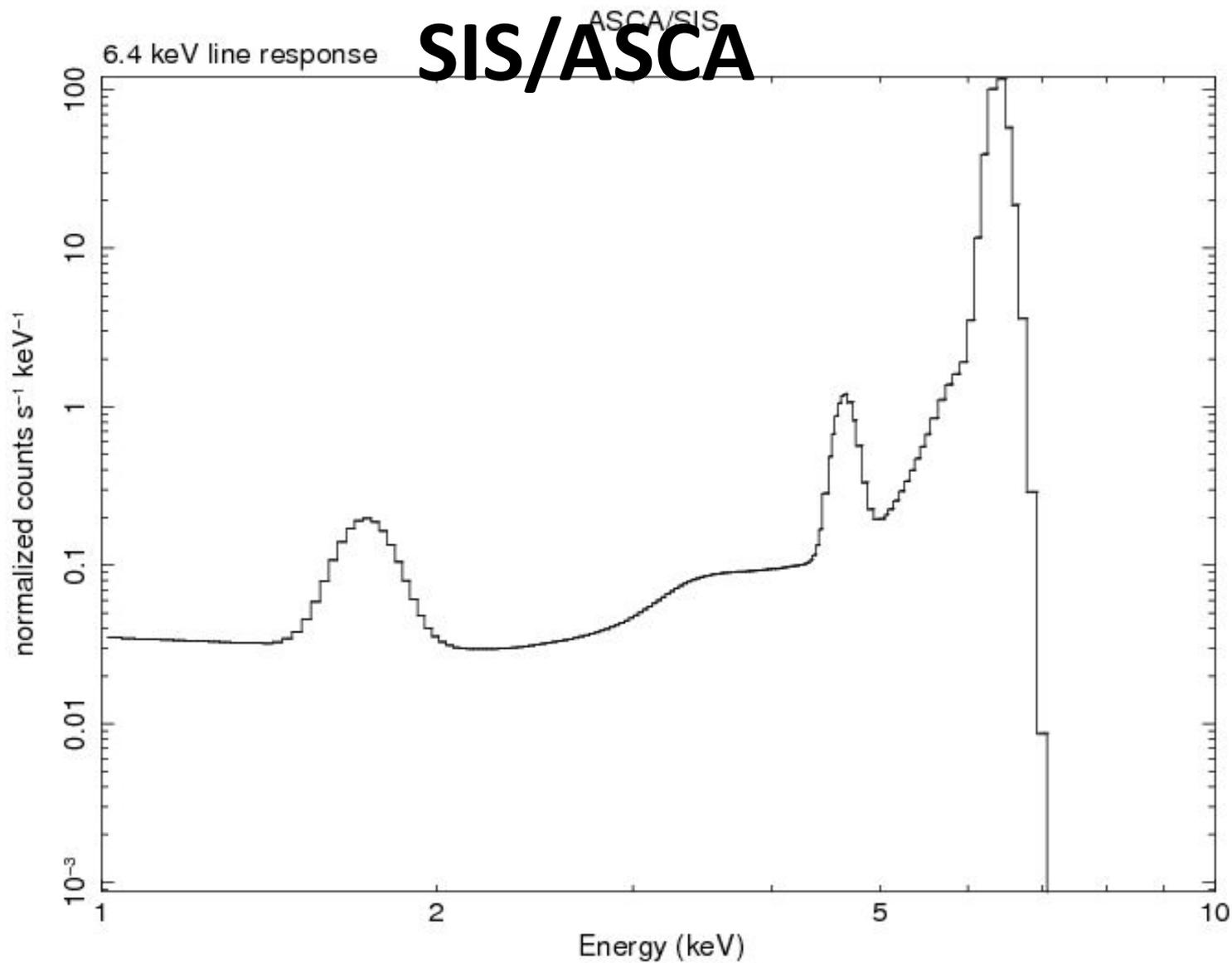
# Первая ПЗС матрица для рентгеновских фотонов в космосе : ASCA/SIS



# Отклик ПЗС

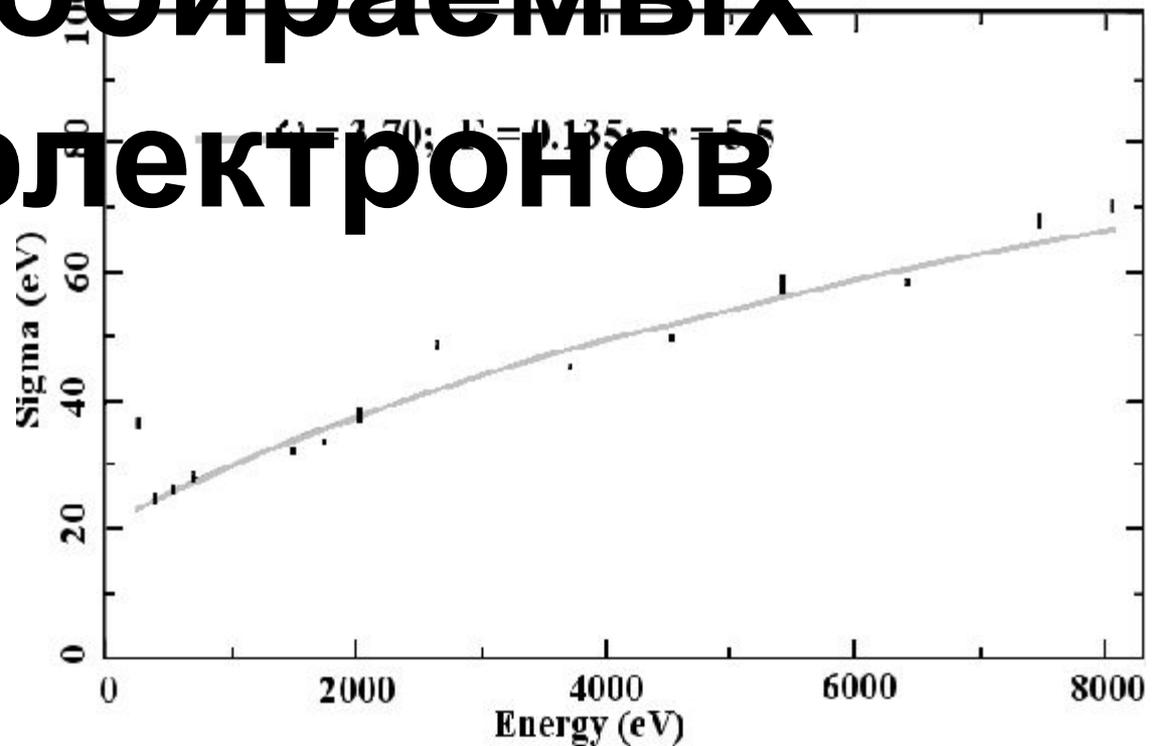
матрицы

SIS/ASCA

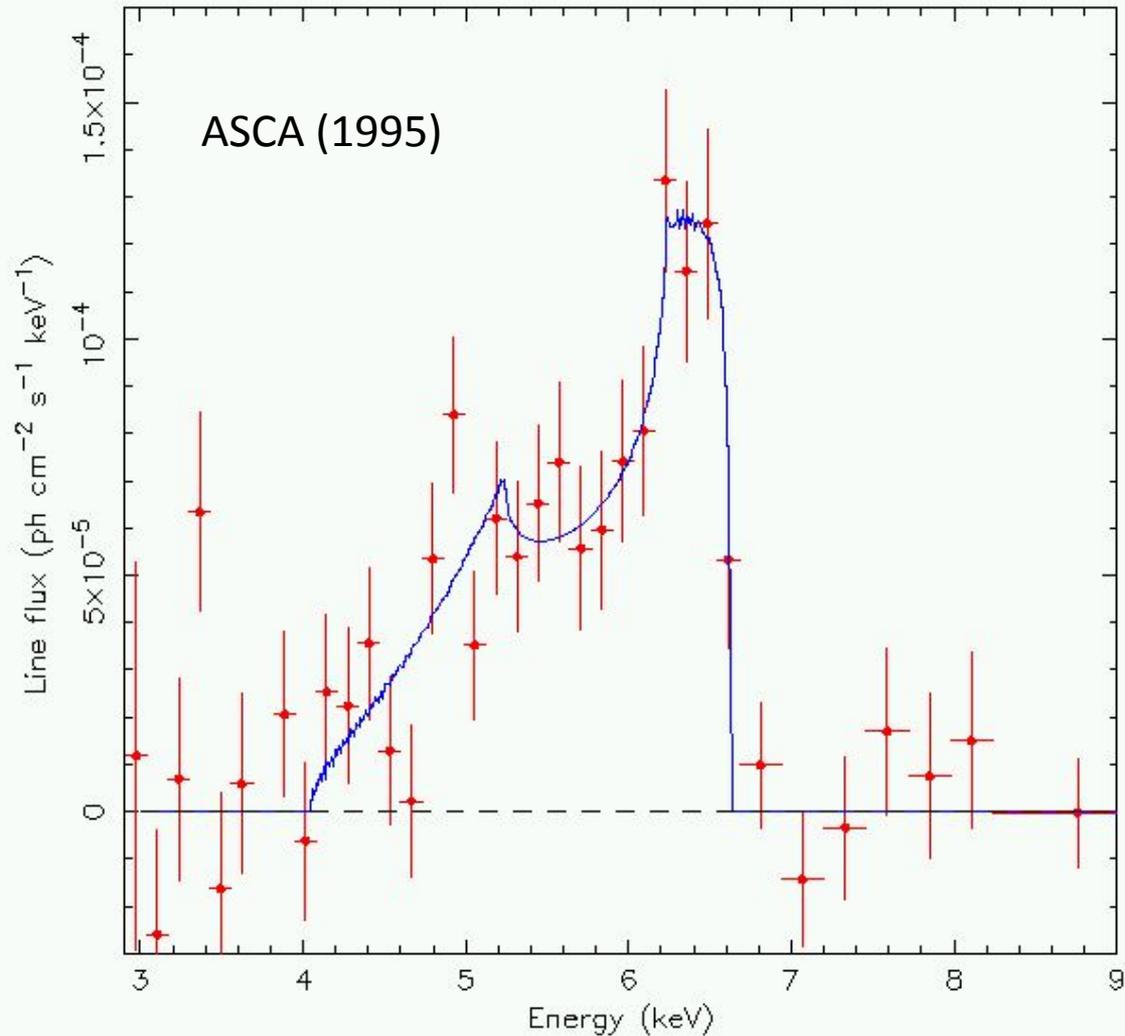


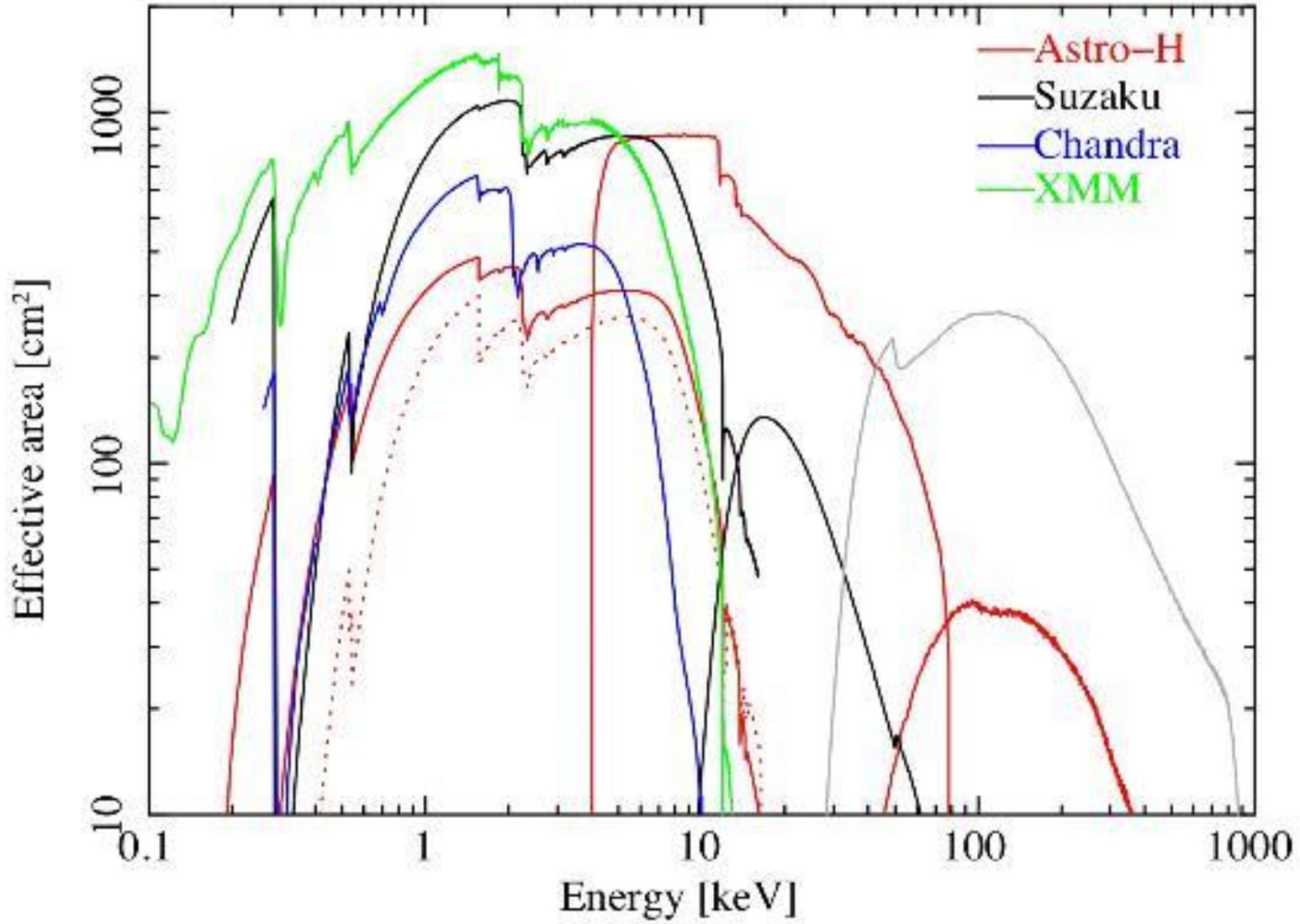
# Разрешение ограничено количеством собираемых электронов

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

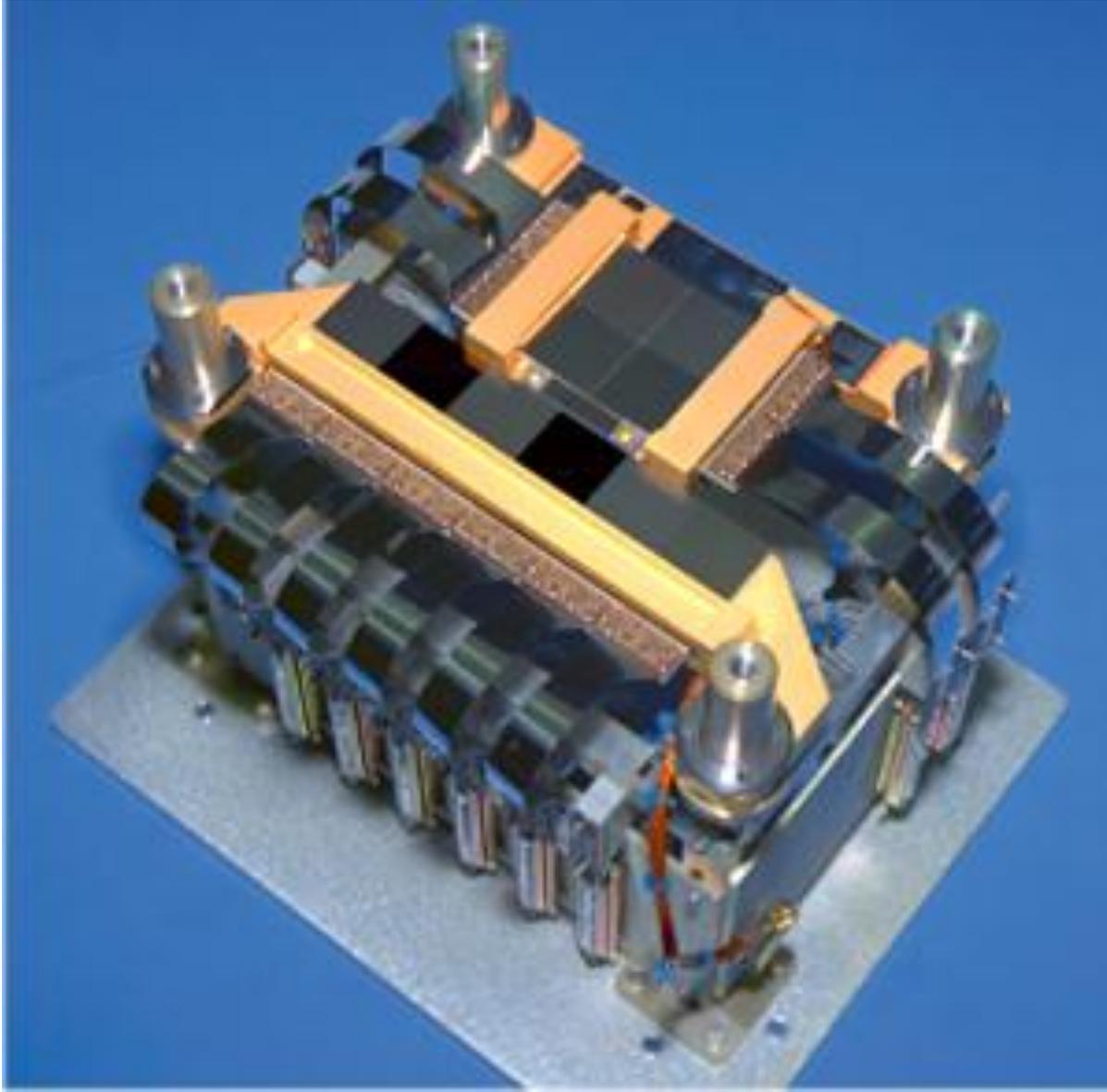


# Релятивистская линия в АЯГ MSG-6-30-15?





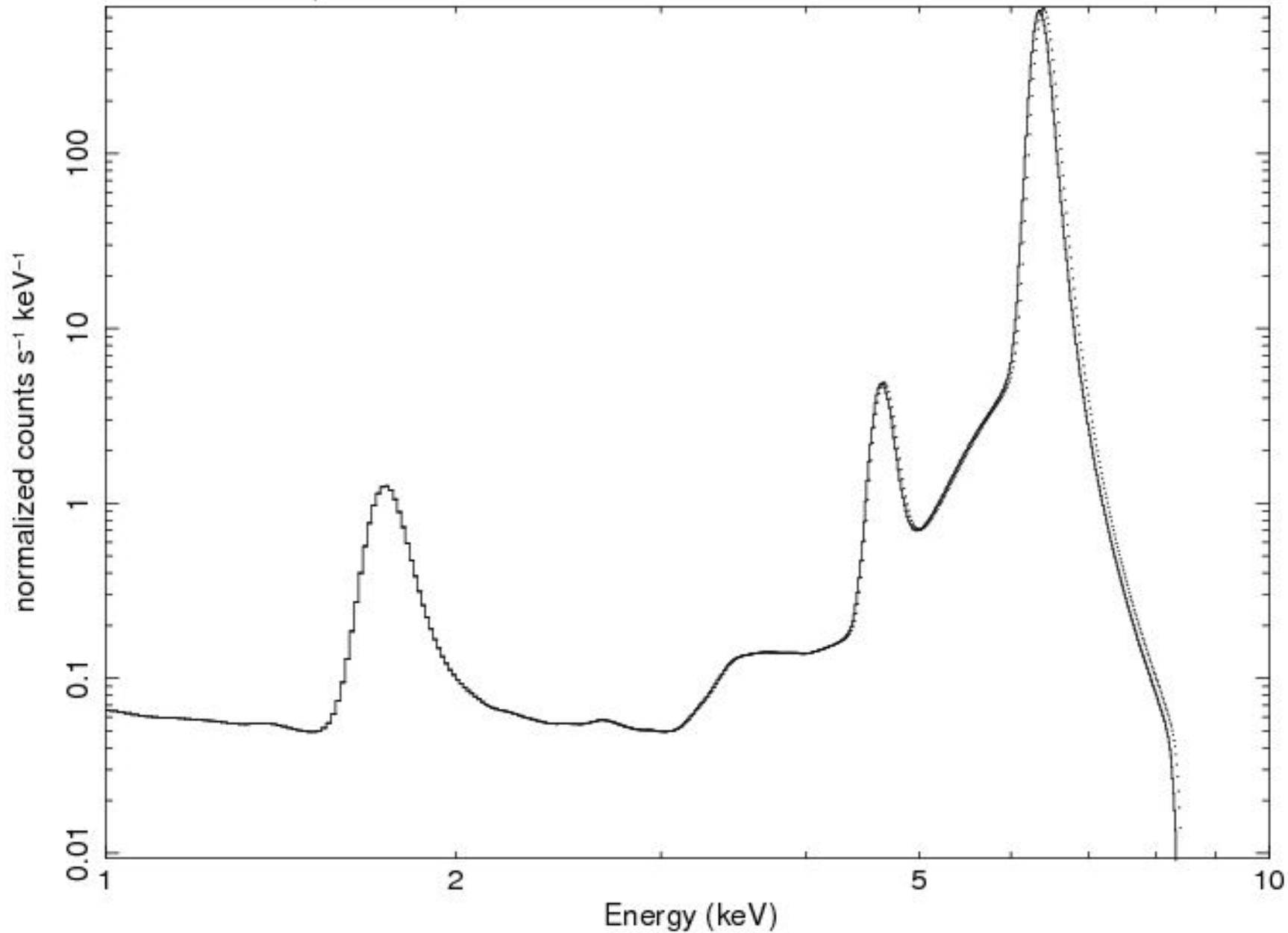
# CHANDRA/ACIS



| time<br>s                    | ccd_id | node_id | expro | chipx<br>pixel | chipy<br>pixel | tdetx<br>pixel | tdety<br>pixel | detx<br>pixel | dety<br>pixel | x<br>pixel    | y<br>pixel    | phas<br>adu  | pha<br>adu | pha_ro<br>adu | energy<br>eV | pi<br>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<br>-1<br>-1<br>-2<br>371<br>-4<br>-3<br>4<br>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<br>-2<br>-1<br>3<br>335<br>-2<br>0<br>4<br>1<br>0  |            | 384           | 335          | 1.5000878E+03 | 103  |
| 3.268654370767151E+08<br>es] | 3      | 2       | 3     | 654            | 703            | 4429           | 3715           | 4.4130879E+03 | 4.3971841E+03 | 4.4570464E+03 | 3.8171567E+03 | 0<br>-3<br>-4<br>2<br>1076<br>2<br>1<br>10<br>-1<br>-1<br>-2<br>0<br>-2<br>1394<br>-4<br>0<br>10<br>1<br>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<br>-1<br>0<br>-2<br>1394<br>-4<br>0<br>10<br>1<br>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<br>0<br>1<br>2<br>4<br>600<br>-1<br>3<br>5<br>-1<br>0<br>5<br>-2<br>-2<br>765<br>1<br>0                  |            | 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 | -1<br>0<br>5<br>-2<br>-2<br>765<br>1<br>0  |            | 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<br>-3<br>-3<br>-5<br>-3<br>1591<br>-6<br>-2<br>11<br>-3<br>-1<br>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<br>-1<br>3  |            | 1058          | 902          | 4.1399751E+03 | 284  |

CHANDRA/ACIS-I

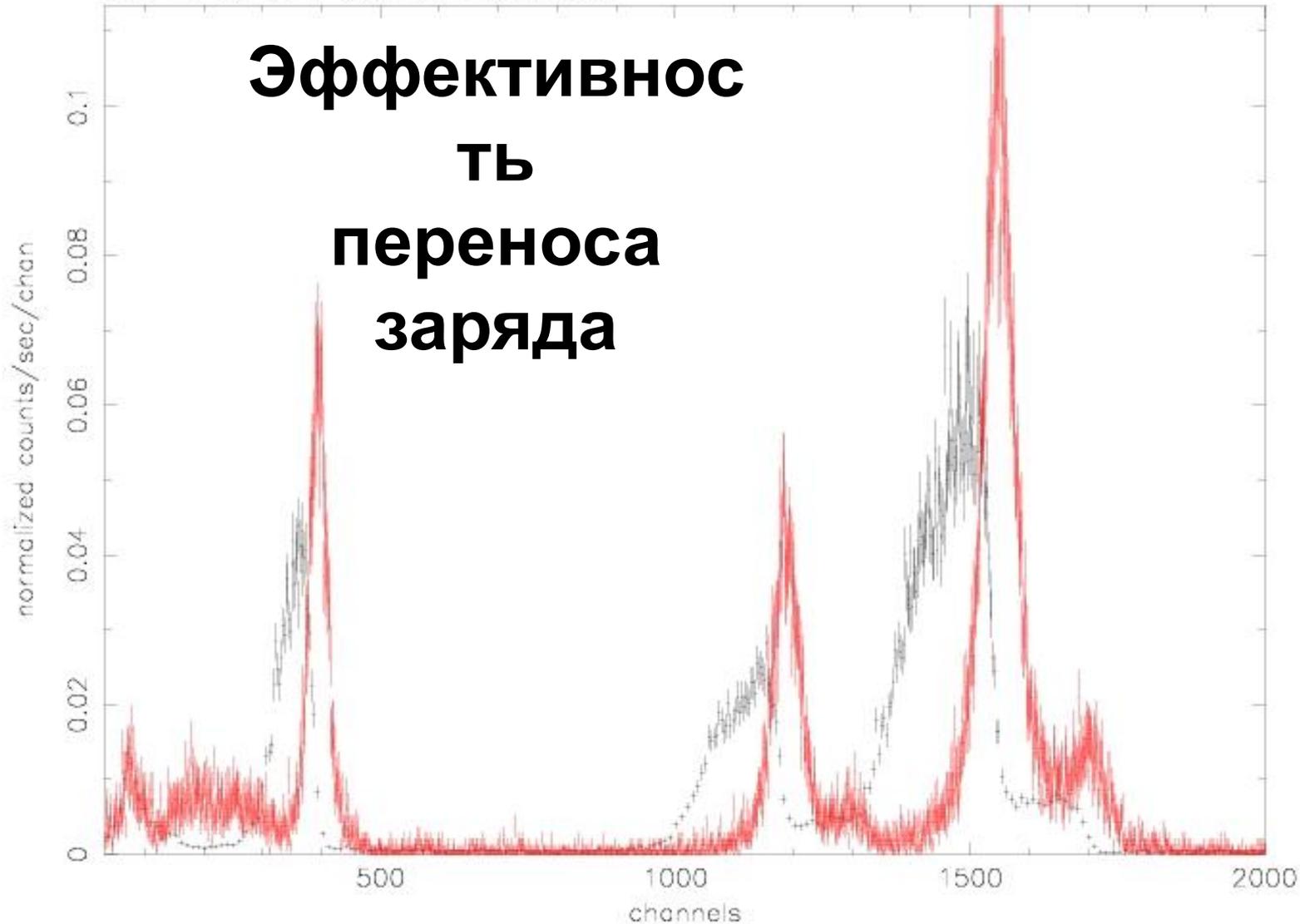
6.4 keV line response



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

S2c1\_uncorr.pha S2c1\_corr\_no66.pha

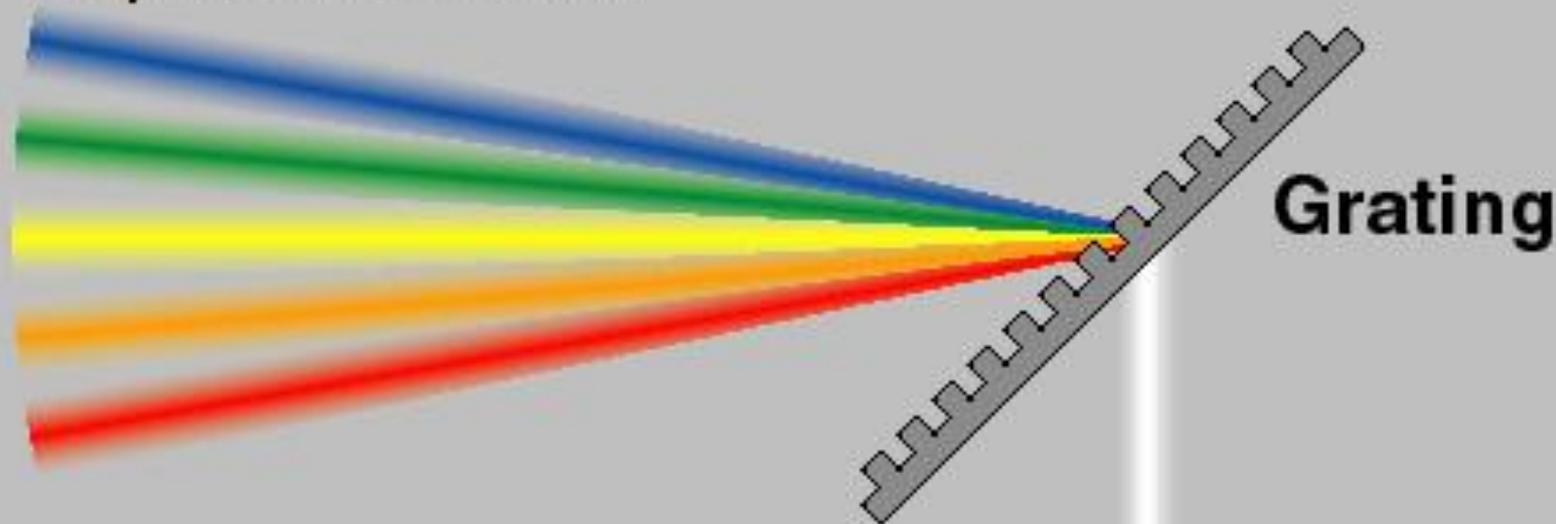
# Эффективнос ть переноса заряда



# Диффракционн ый

## спектрометр

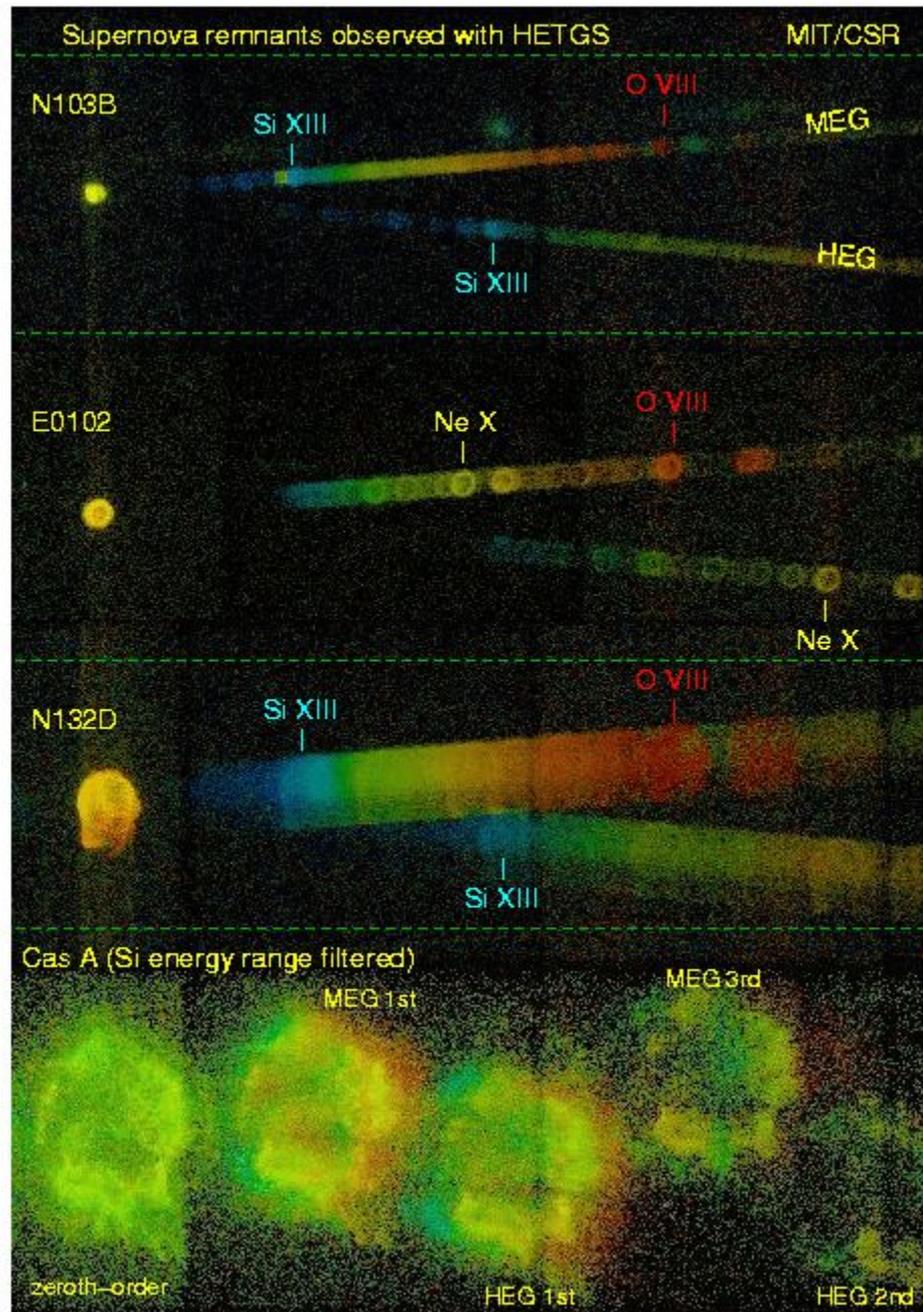
*Separated colors*



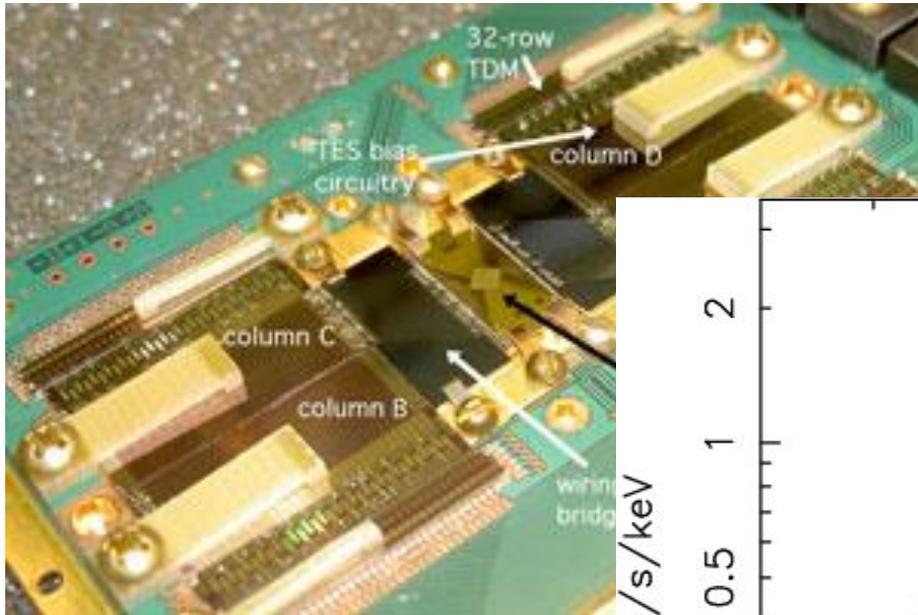
**Grating**

*Light*

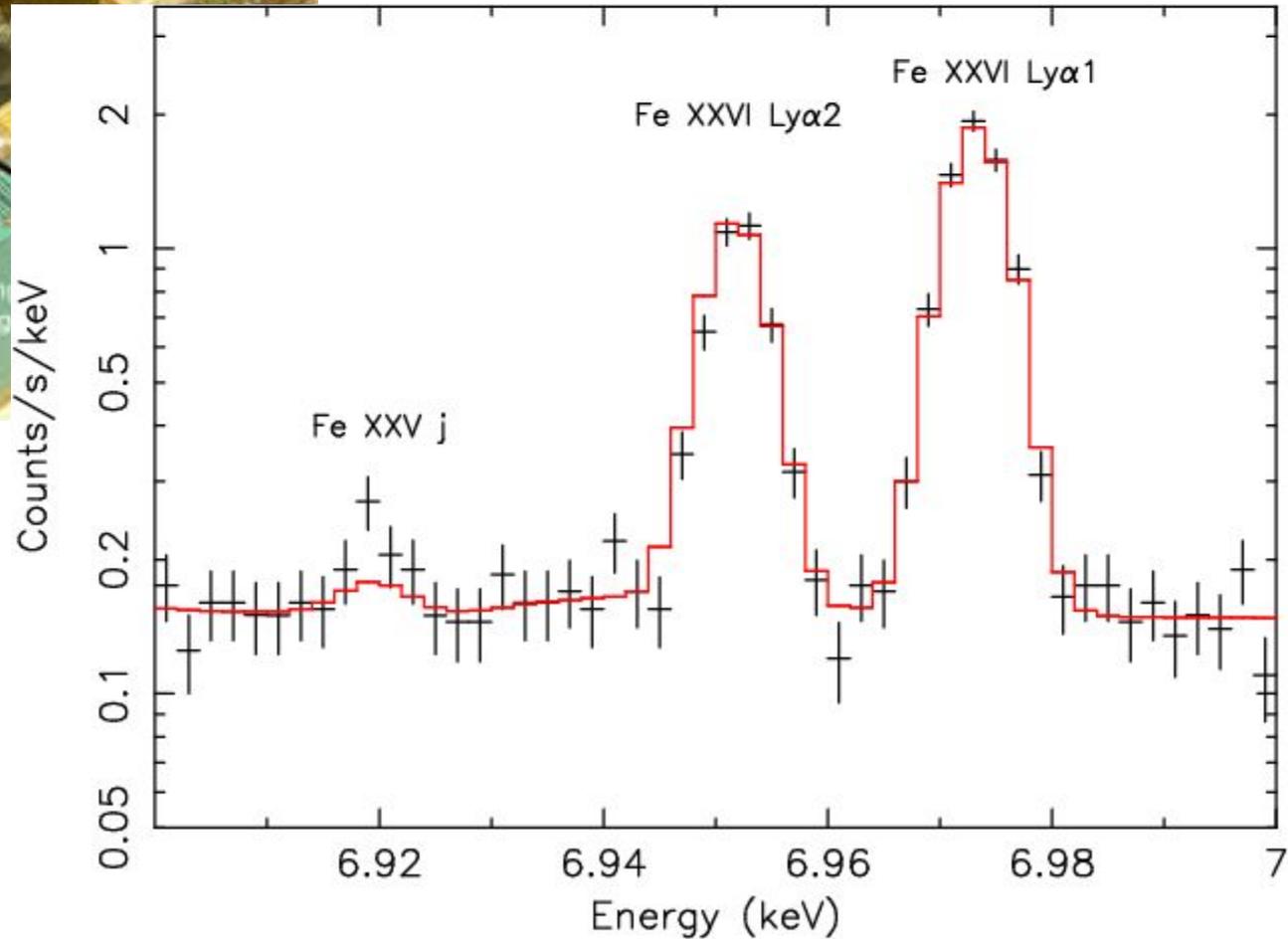
**Spectrometer**



# Следующий шаг -

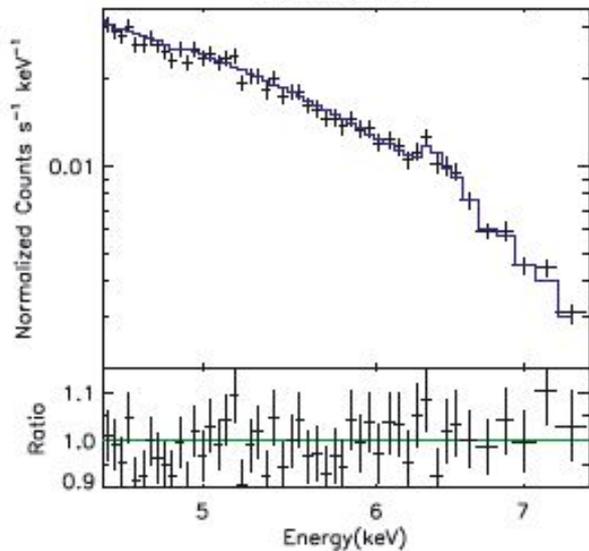


тры

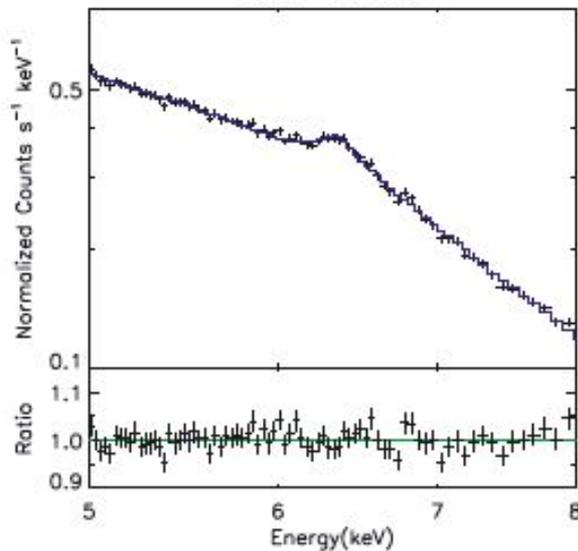


Astro-H(Япония)

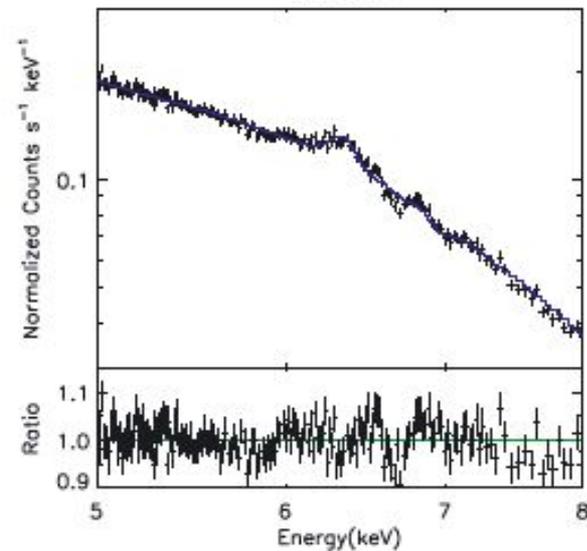
Chandra HEG



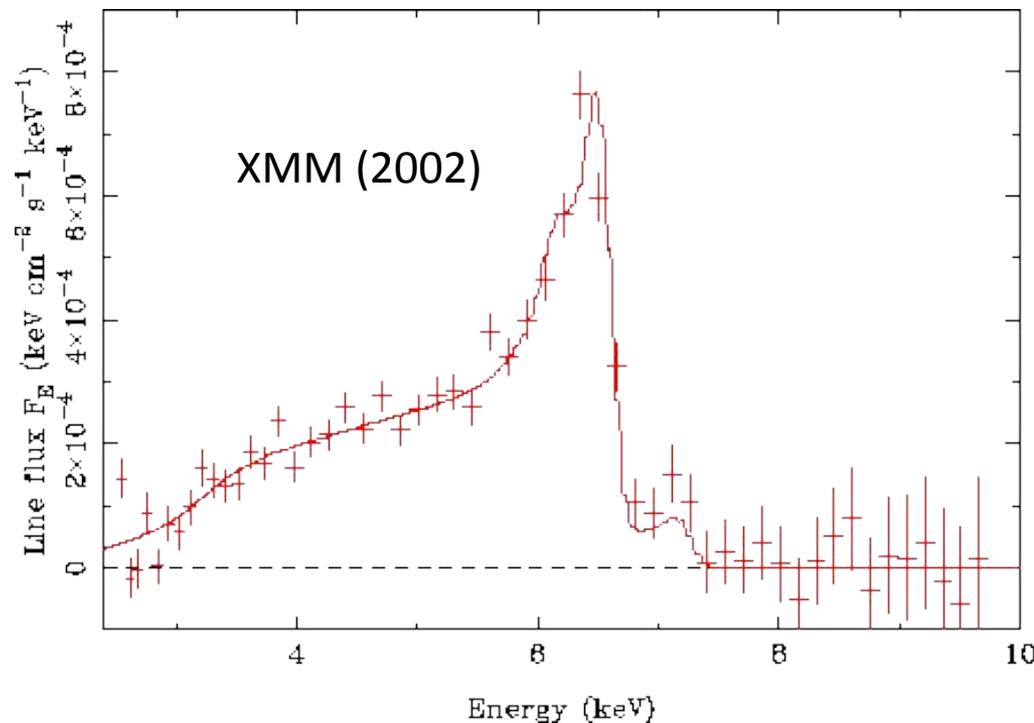
XMM-Newton



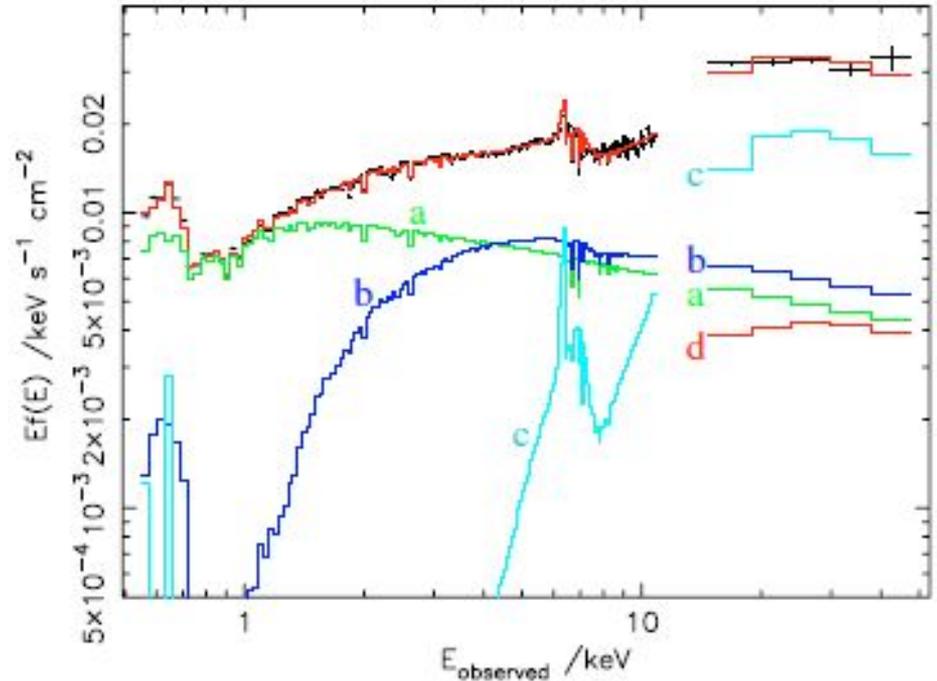
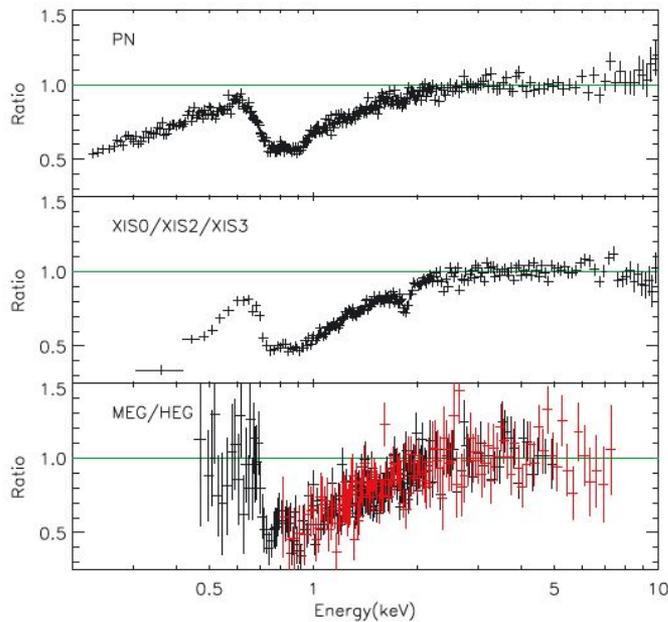
Suzaku



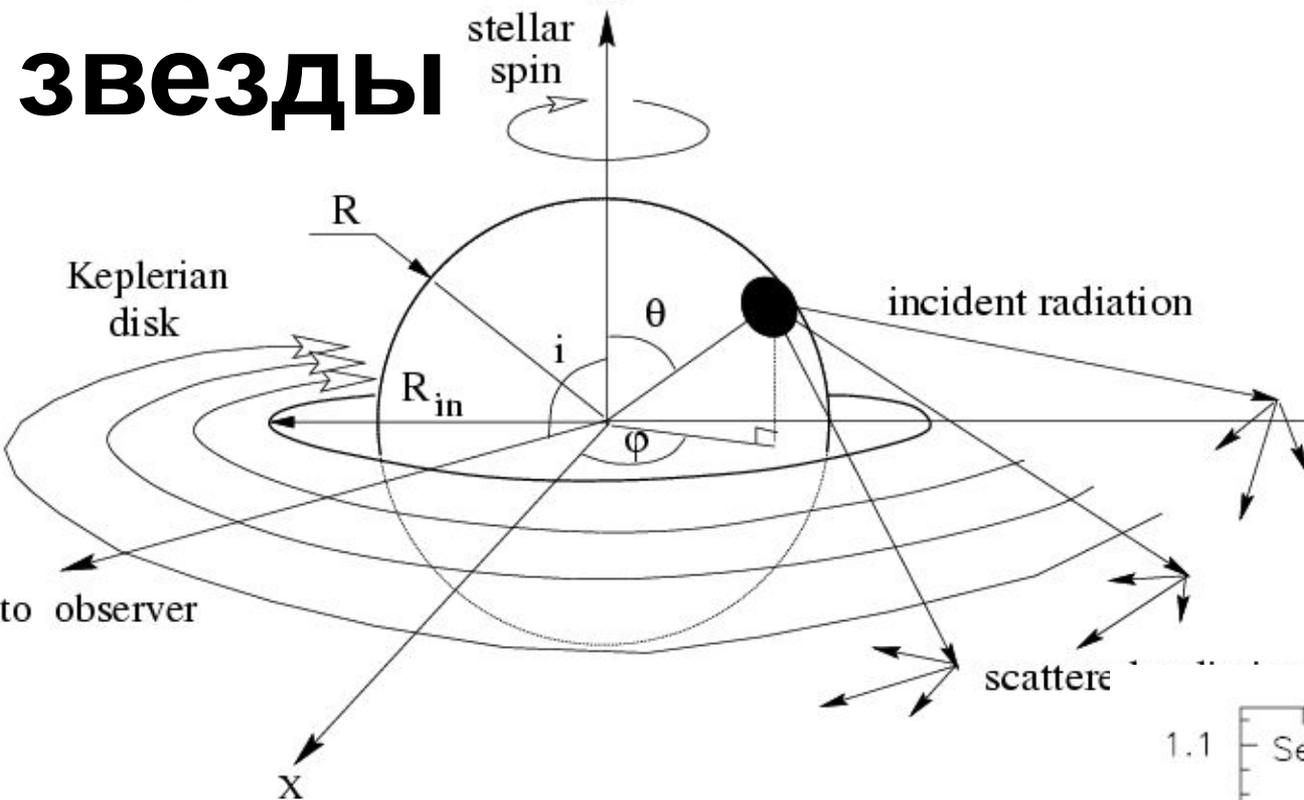
# MCG-6-30-15



# Проблемы интерпретации: поглощение на луче зрения?

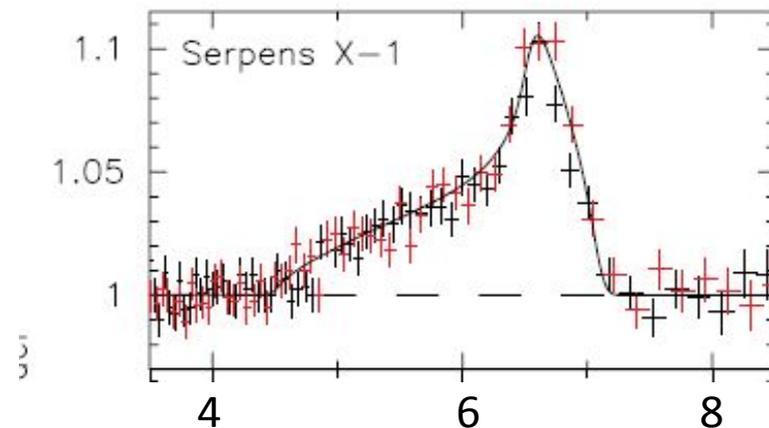


# Другой случай: нейтронные звезды



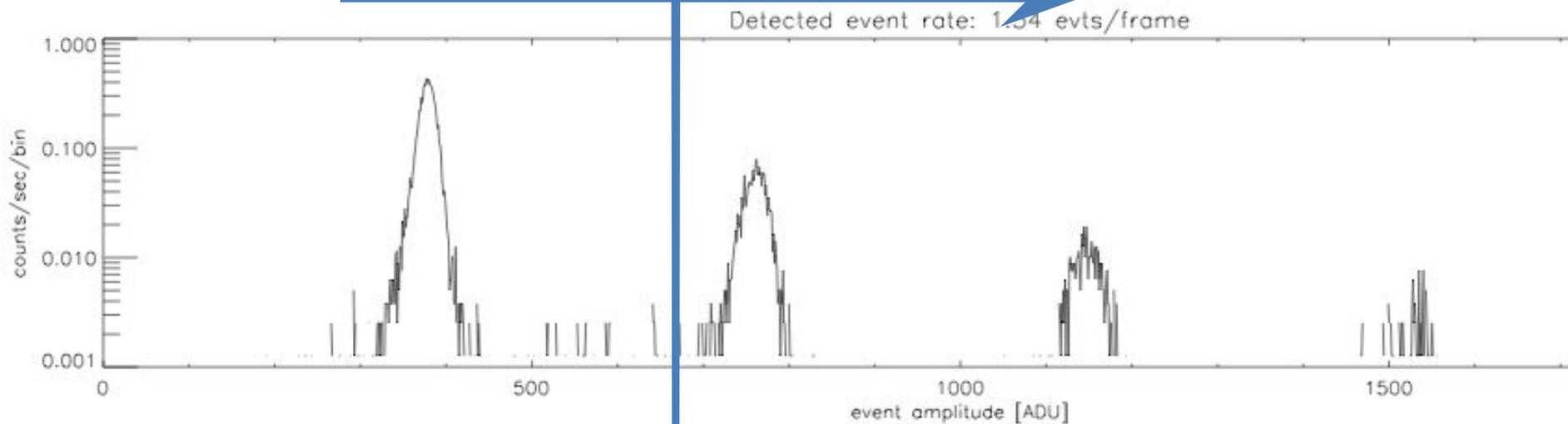
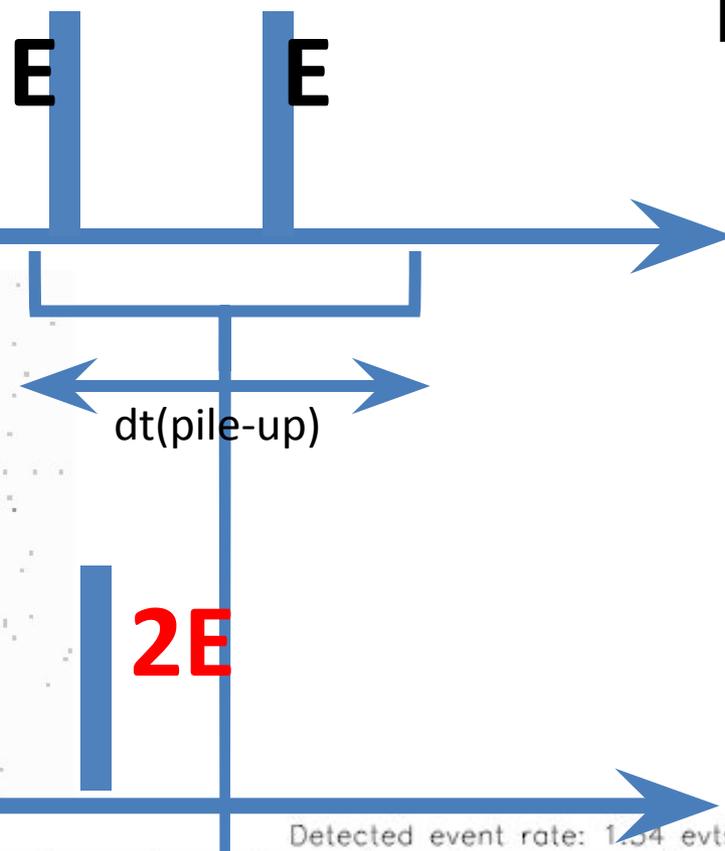
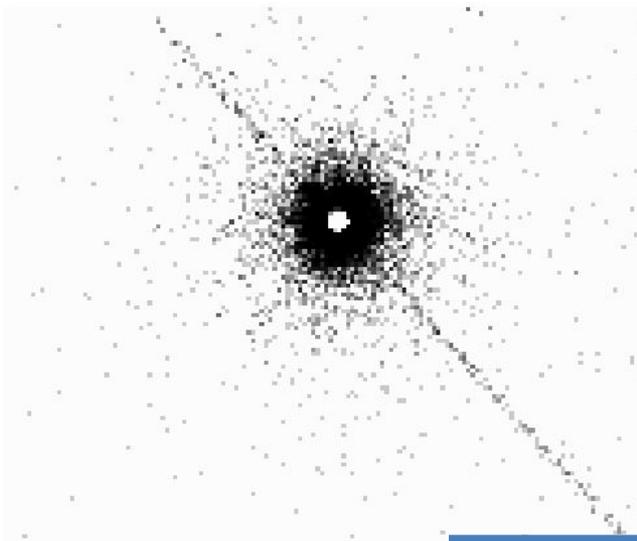
Метрика Керра  
не так важна

**Аналогичные  
искажения?**

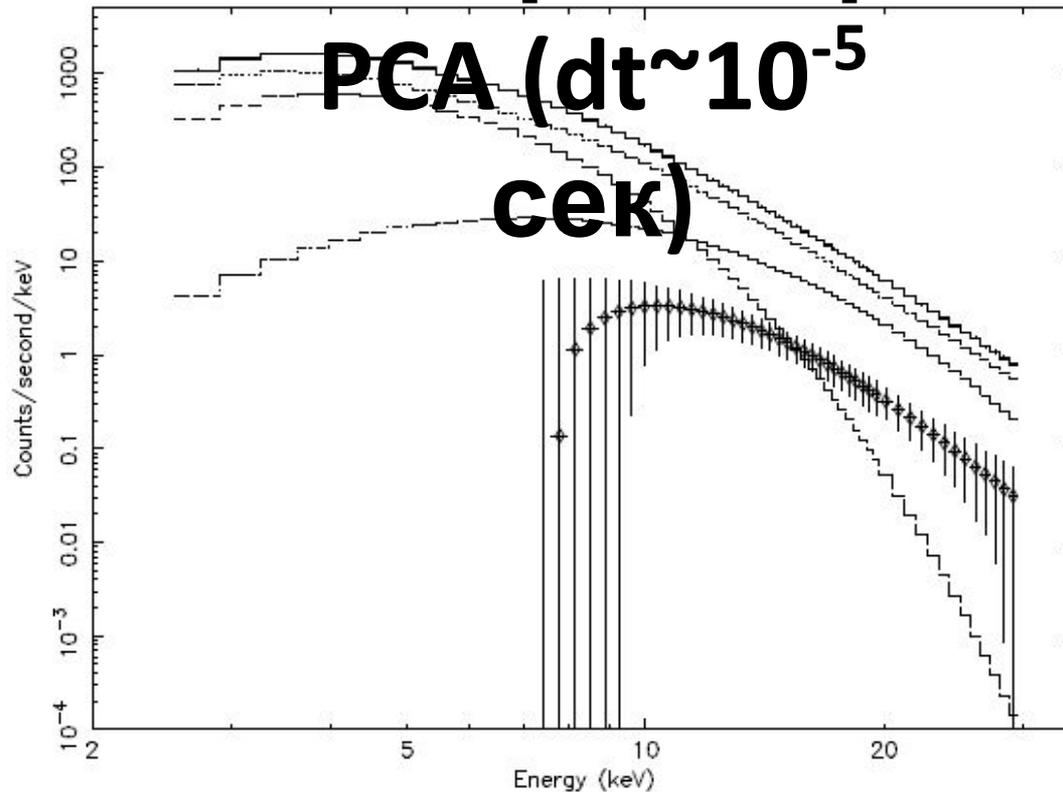


Энергия,

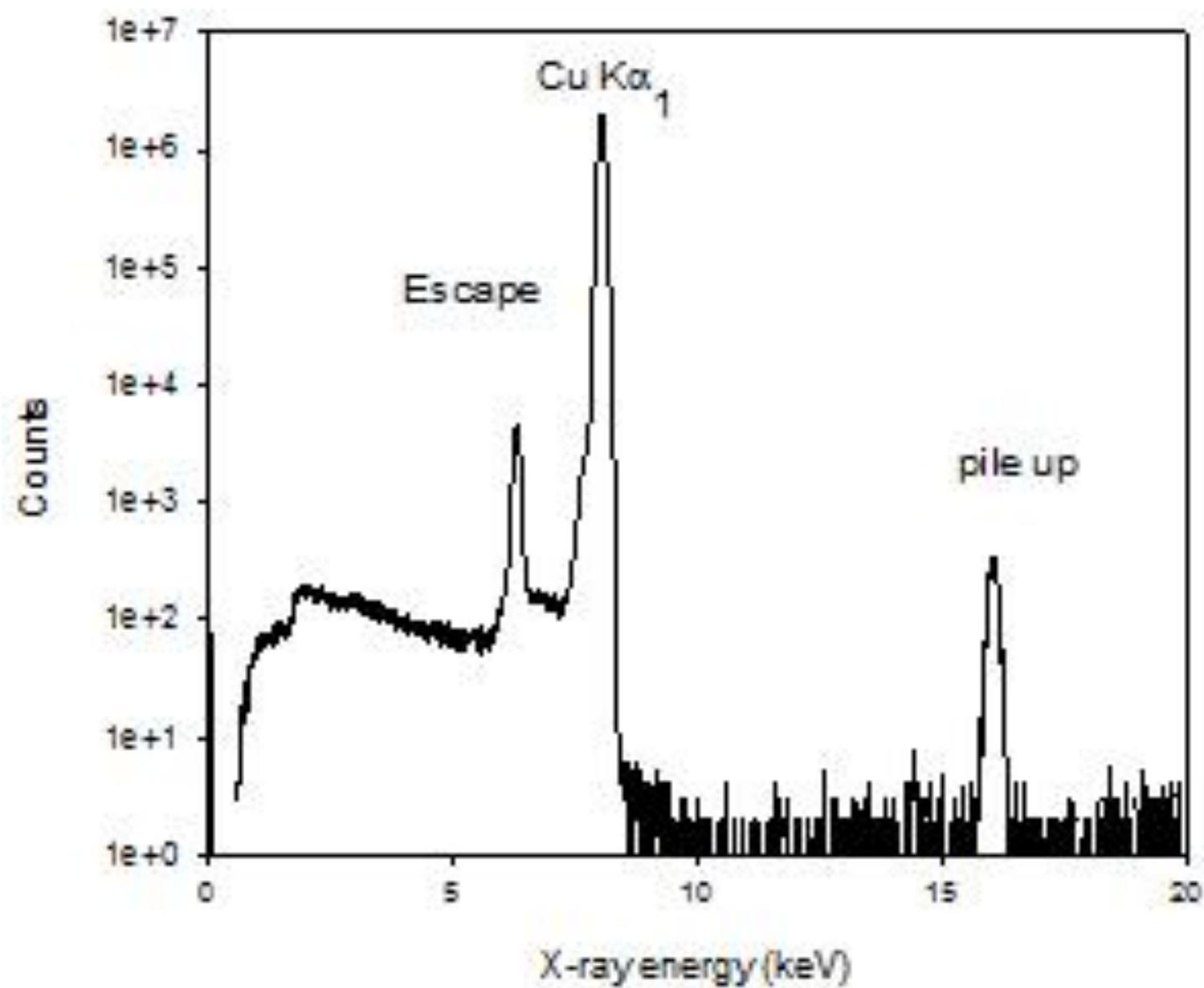
# Проблема pile-up



# Pile up в случае спектрометра



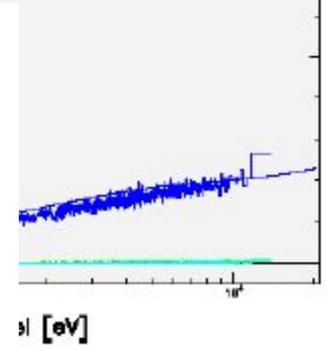
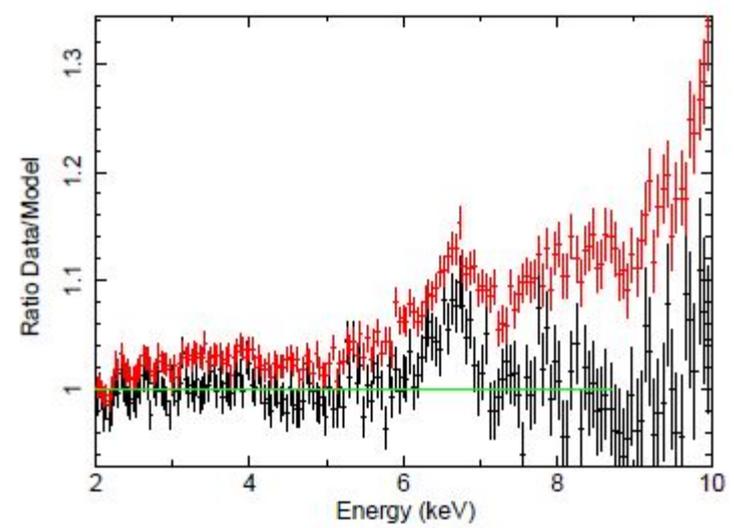
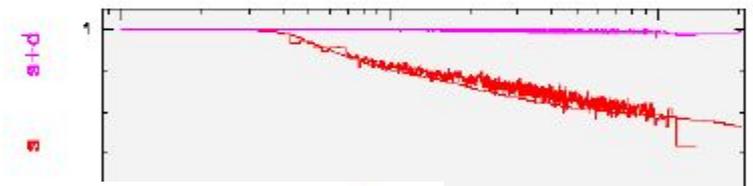
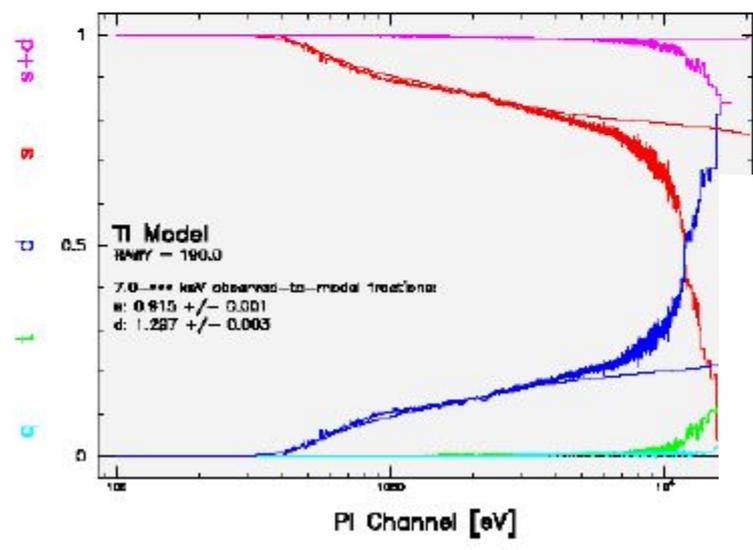
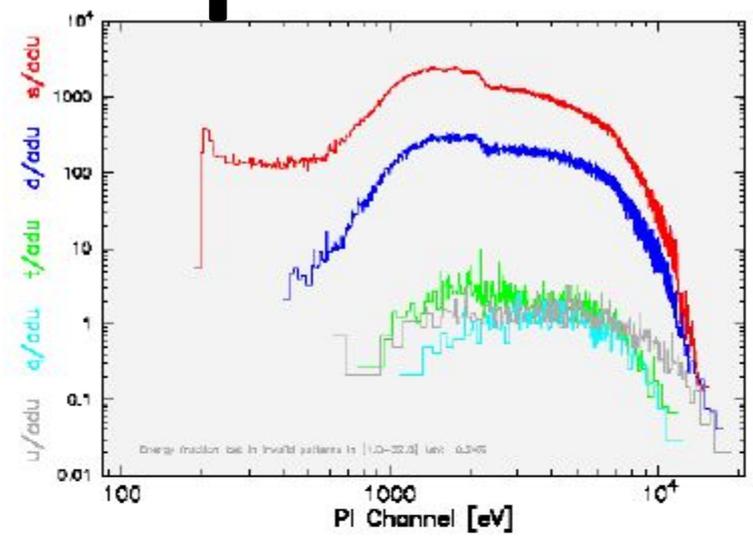
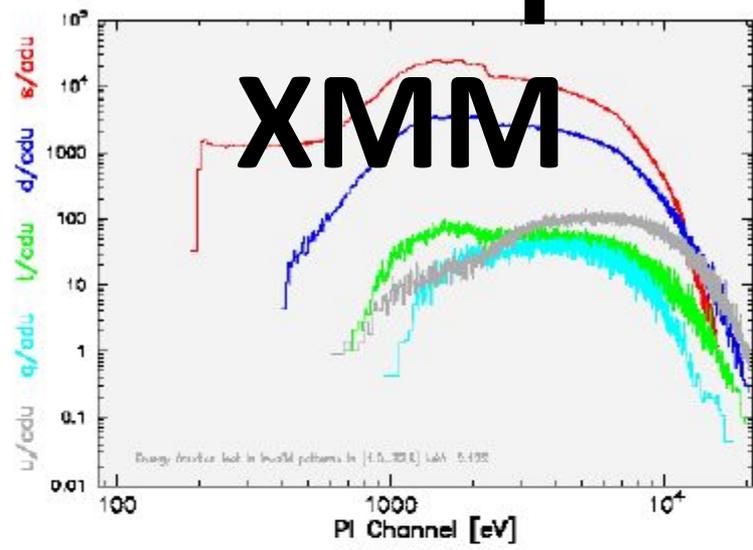
Для ПЗС  $dt \sim 0.1-1$   
сек



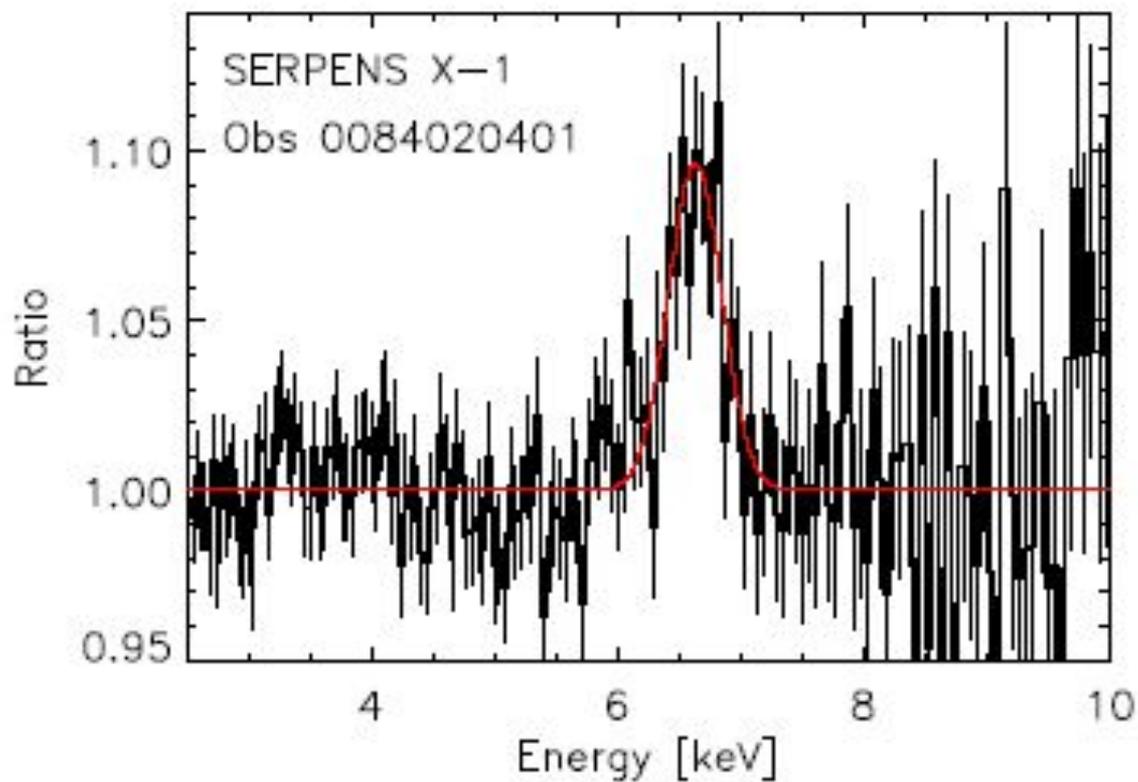
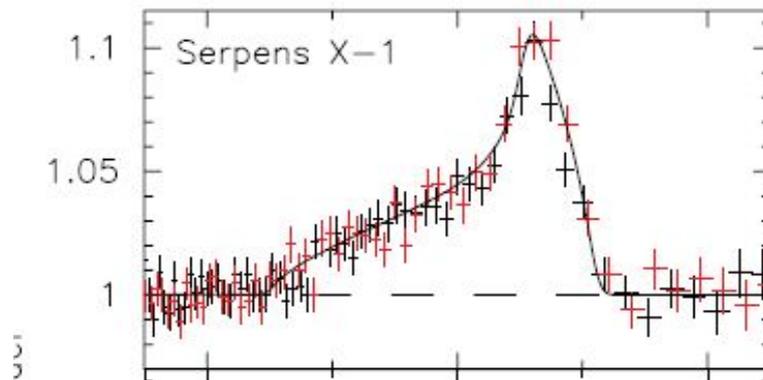
# Поправки pile-up

## XMM

## 2011



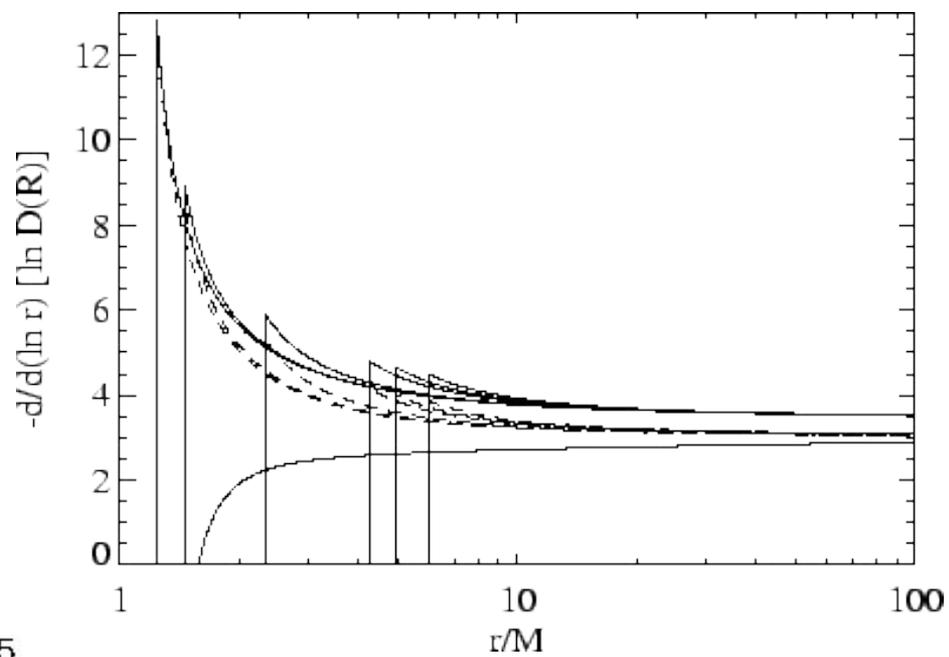
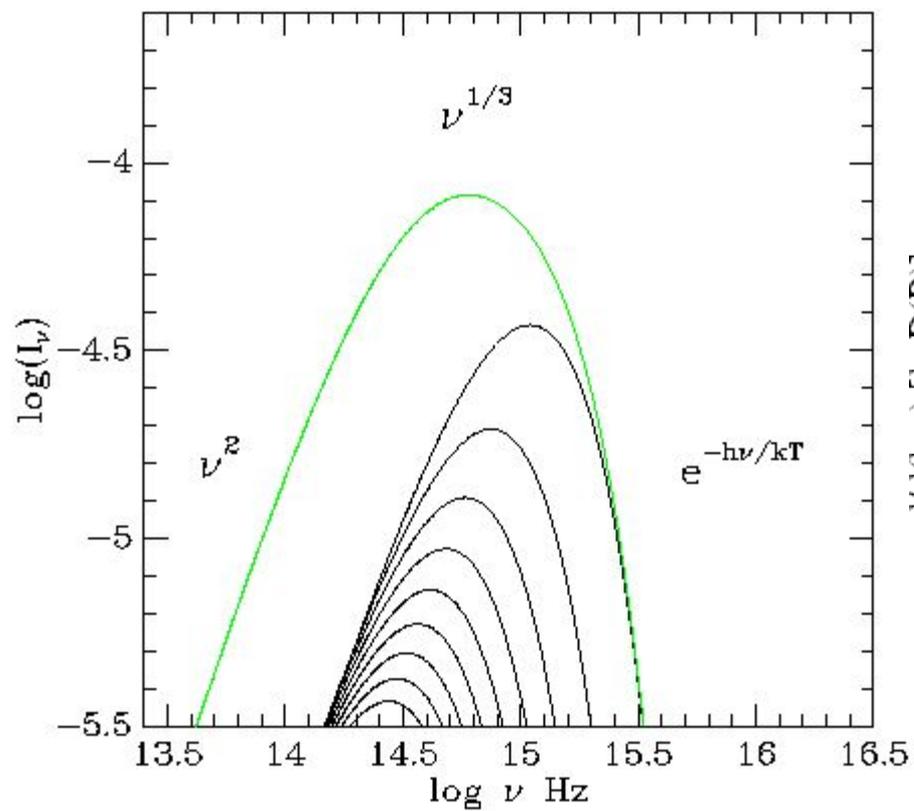
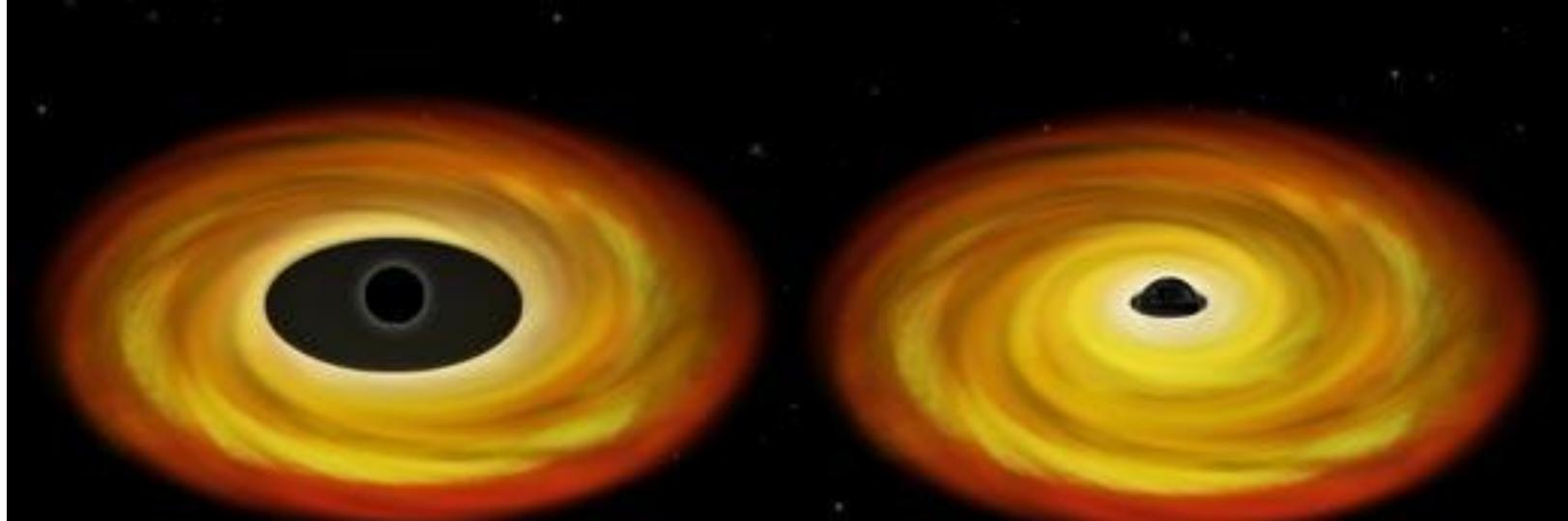
С  
неправильной  
коррекцией

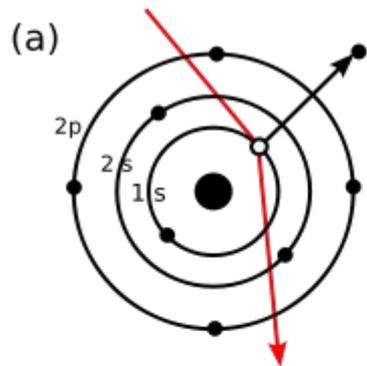


С  
правильной  
коррекцией

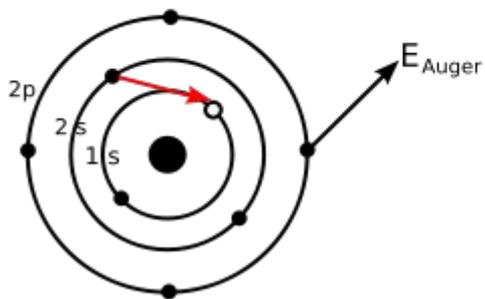
## Пример 2.

Вращение черных дыр  
по  
характерной  
температуре  
аккреционного диска?





Electron collision



Auger electron emission

