The spectral response of X-ray CCDs in the energy band around Si-K edge: a solution to the Si-K edge problem for the XIS onboard Suzaku

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See also Okazaki et al. , SPIE Proc. 10709, id. 107091F (2018)

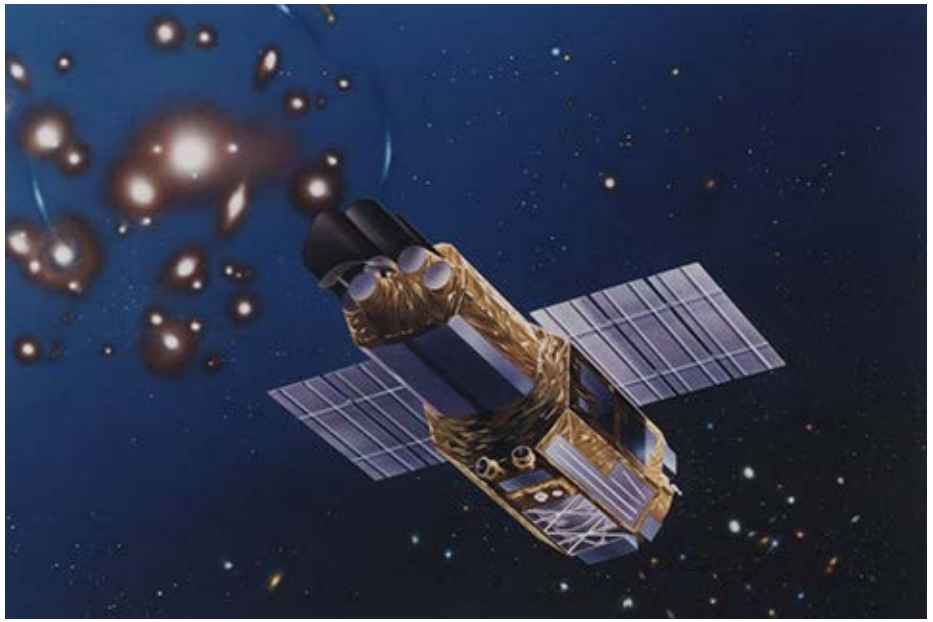
Outline

① Introduction
- Suzaku and XIS
- Si-K edge problem

② Solution of the Si-K edge problem
- Introduce discontinuity in PH_peak-Ex relation
- Application to several targets

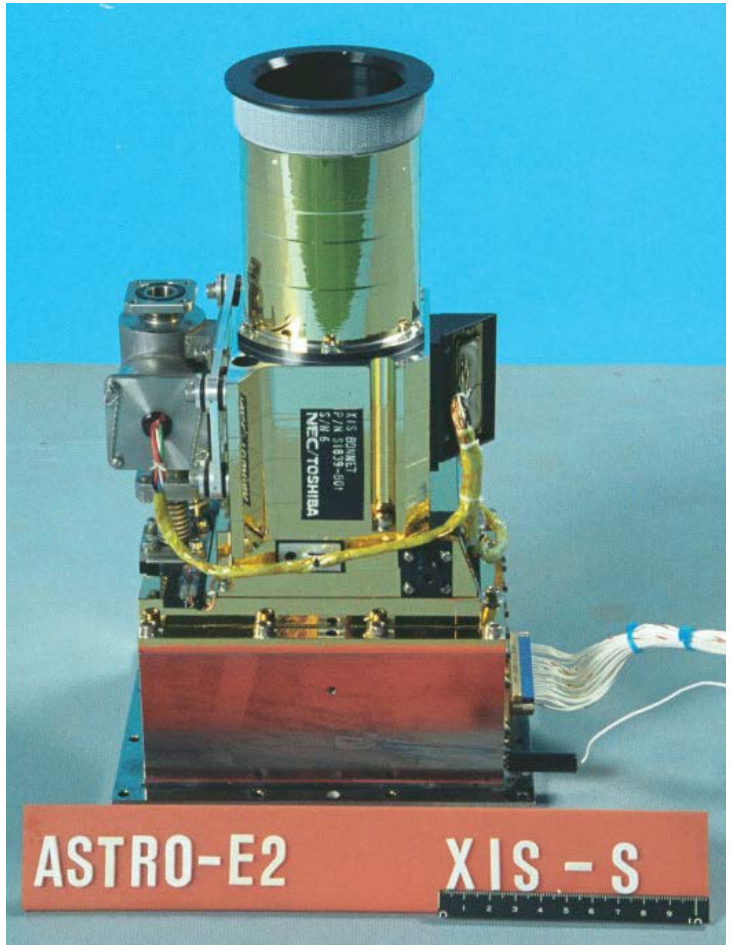
③ Discussion

The X-ray Astronomy Satellite “Suzaku”



(JAXA)

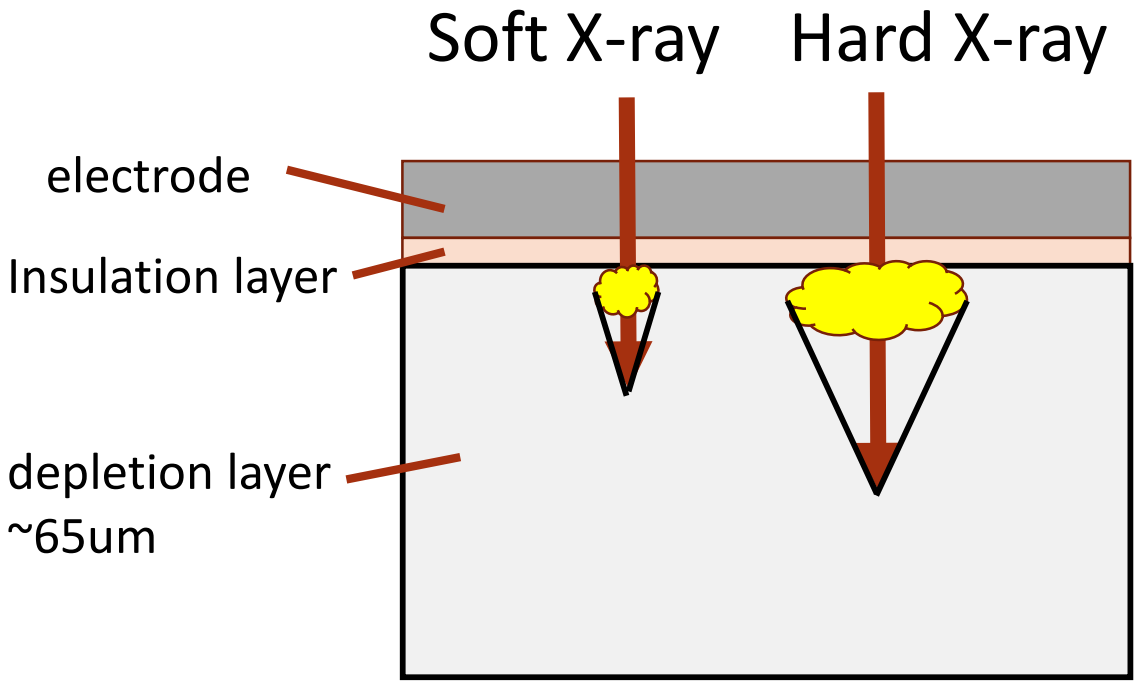
2005-2015



(Koyama et al. 2007)

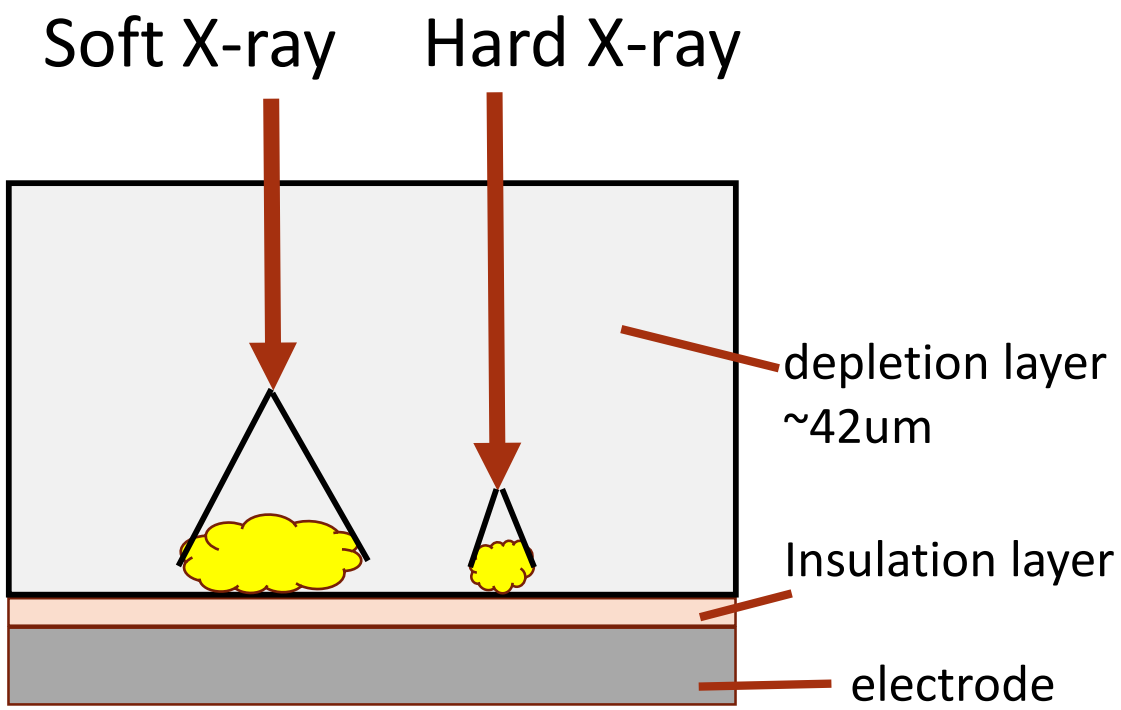
X-ray CCD Cameras
“X-ray Imaging Spectrometers (XIS)”
FI-CCD × 3 (XIS0, 2,3)
BI-CCD × 1 (XIS1)

Two Types of CCDs



FI (Front-Illuminated)-CCD
XIS0, XIS2, XIS3

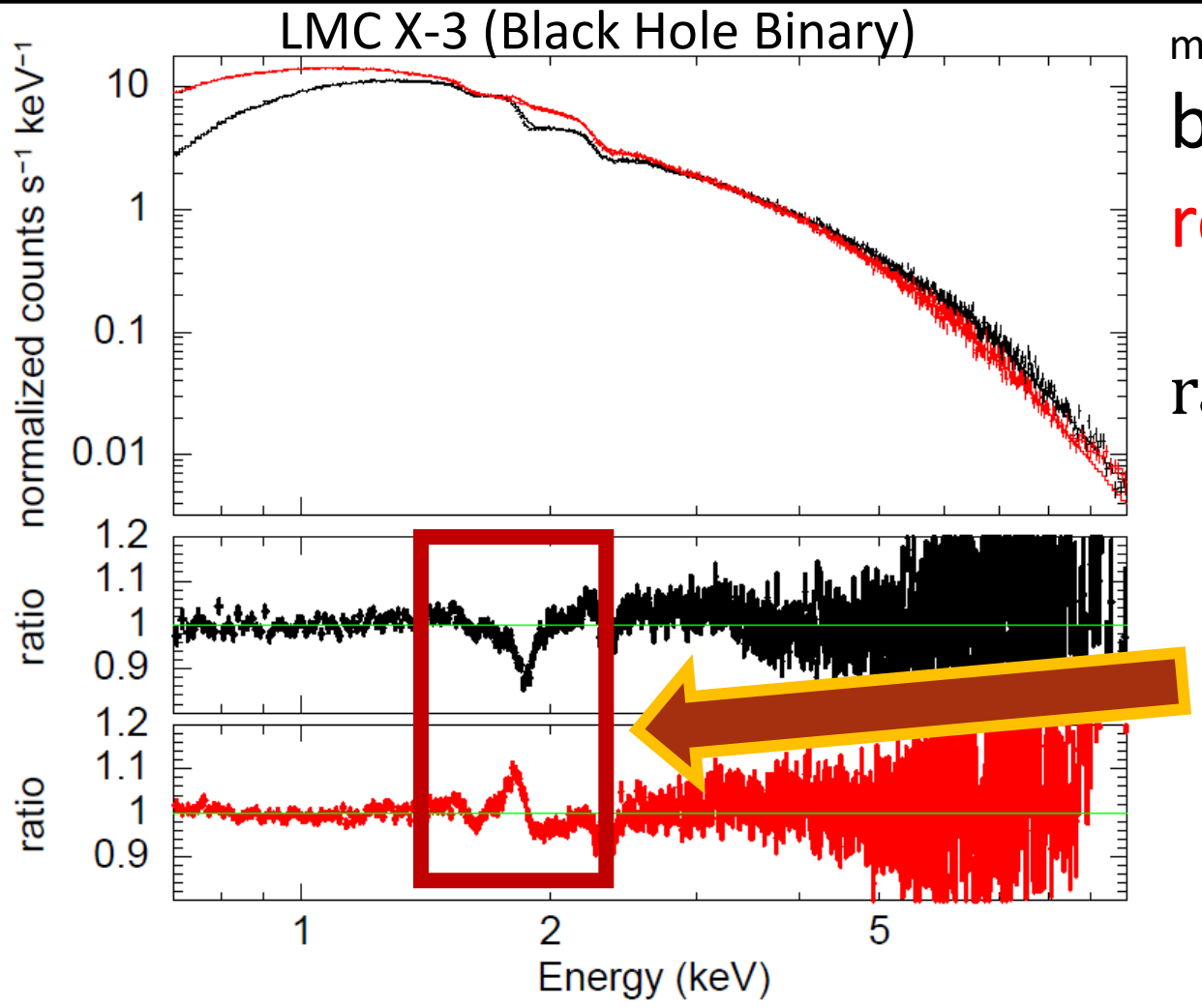
Note: XIS2 was stopped on 2006



BI (Back-Illuminated)-CCD
XIS1

XISs were sensitive in 0.3-12 keV

Si-K Edge Problem



model: phabs*(diskbb + powerlaw)

black: FI-CCD

red: BI-CCD

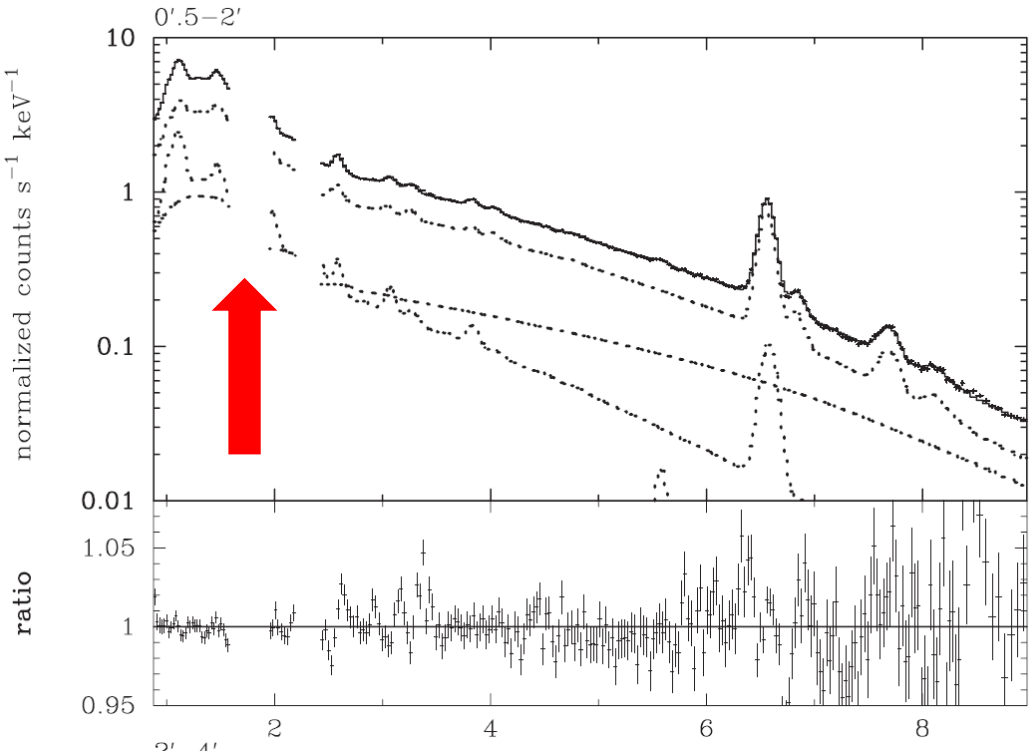
$$\text{ratio} = \frac{\text{data}}{\text{model}}$$

about 10 % residual around Si-K edge (1.839 keV)

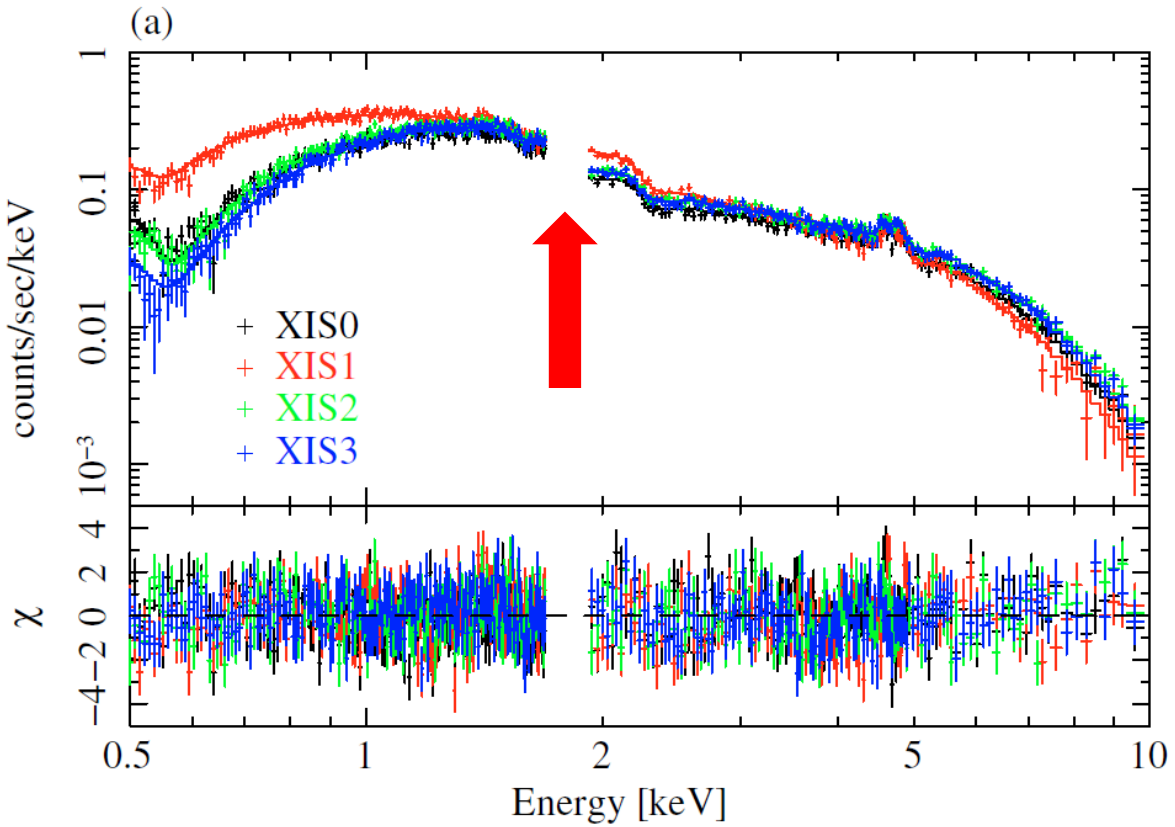
different

- direction
- peak energy

Si-K Band was ignored in the analysis



Perseus Cluster (Tamura et al. 2009)



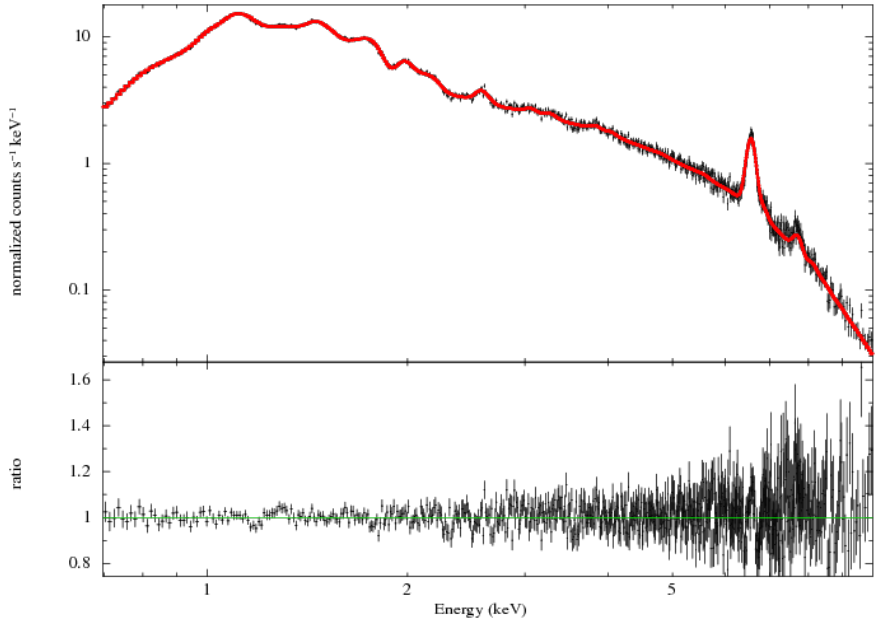
RX J1347.5 (Ota et al. 2008)

Response Matrix

$$\begin{pmatrix} S_{PI[0]} \\ S_{PI[1]} \\ \vdots \\ \vdots \\ S_{PI[n-1]} \end{pmatrix} = \begin{pmatrix} R_{0,0} & R_{0,1} & \cdots & & R_{0,m-1} \\ R_{1,0} & R_{1,1} & & & \\ \vdots & & & & \\ & & & & \\ R_{n-1,0} & & & & R_{n-1,m-1} \end{pmatrix} \begin{pmatrix} M_{E[0]} \\ M_{E[1]} \\ \vdots \\ \vdots \\ M_{E[m-1]} \end{pmatrix}$$

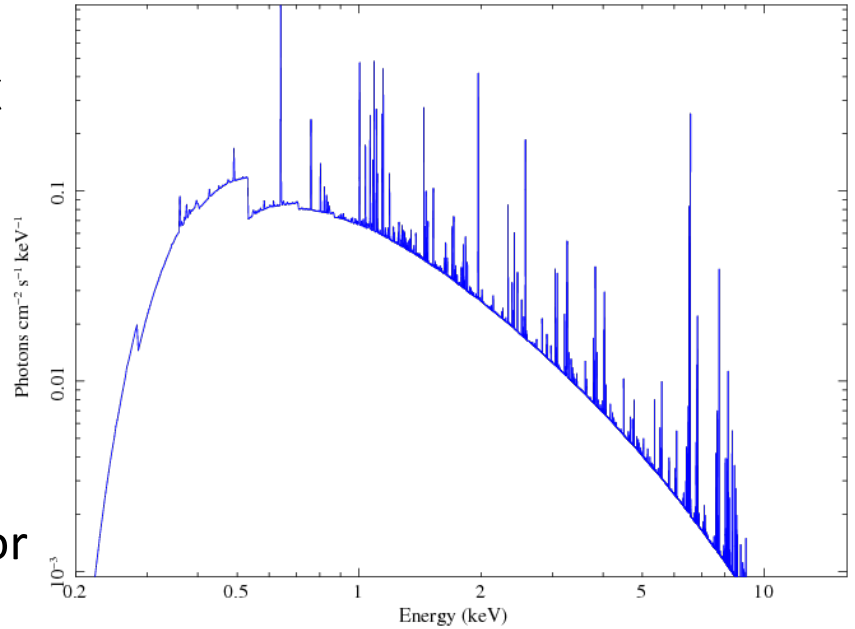
PI spectrum

incident X-ray energy spectrum



response matrix

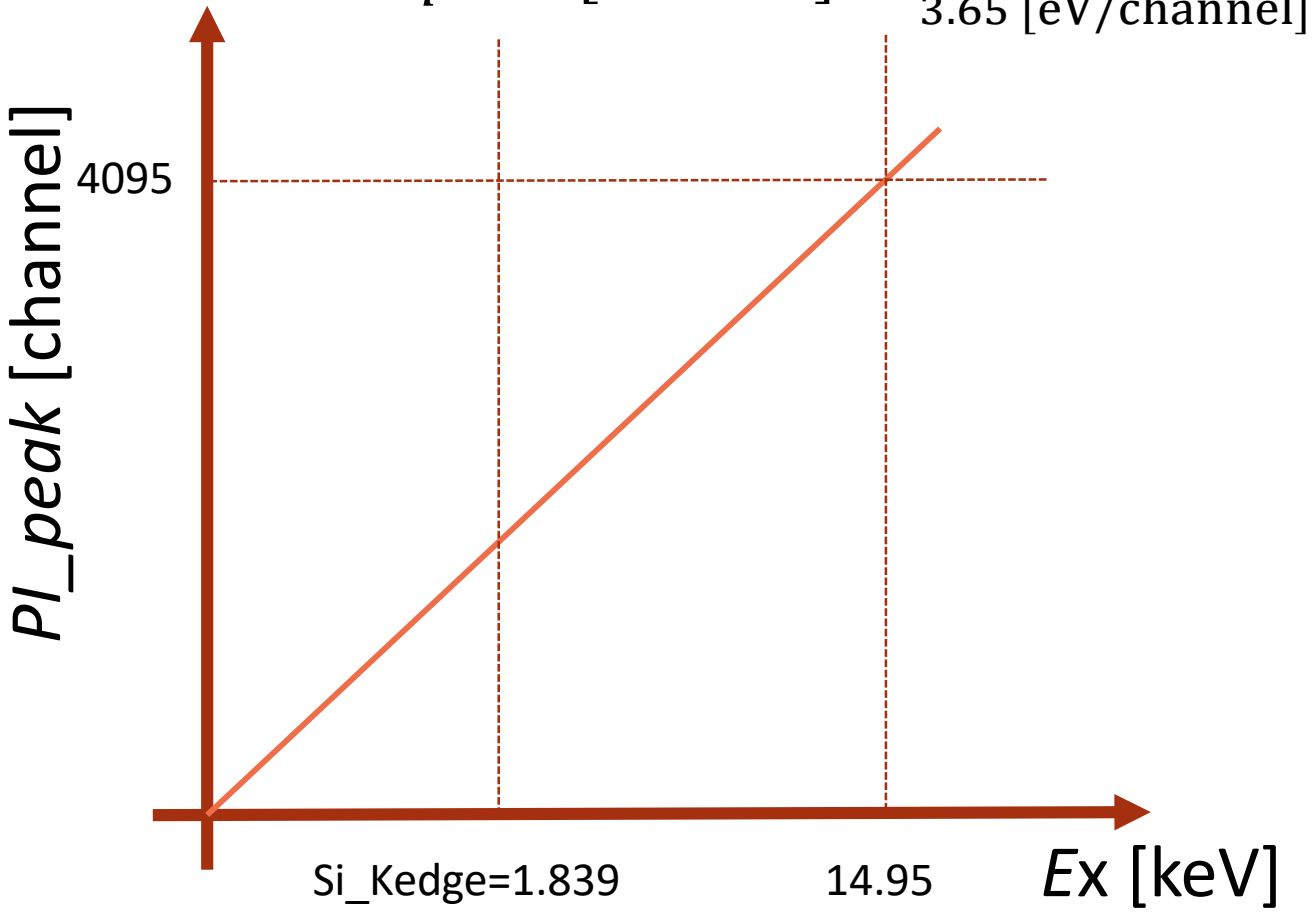
The software “xisrmfgen” makes response matrixes for XIS.



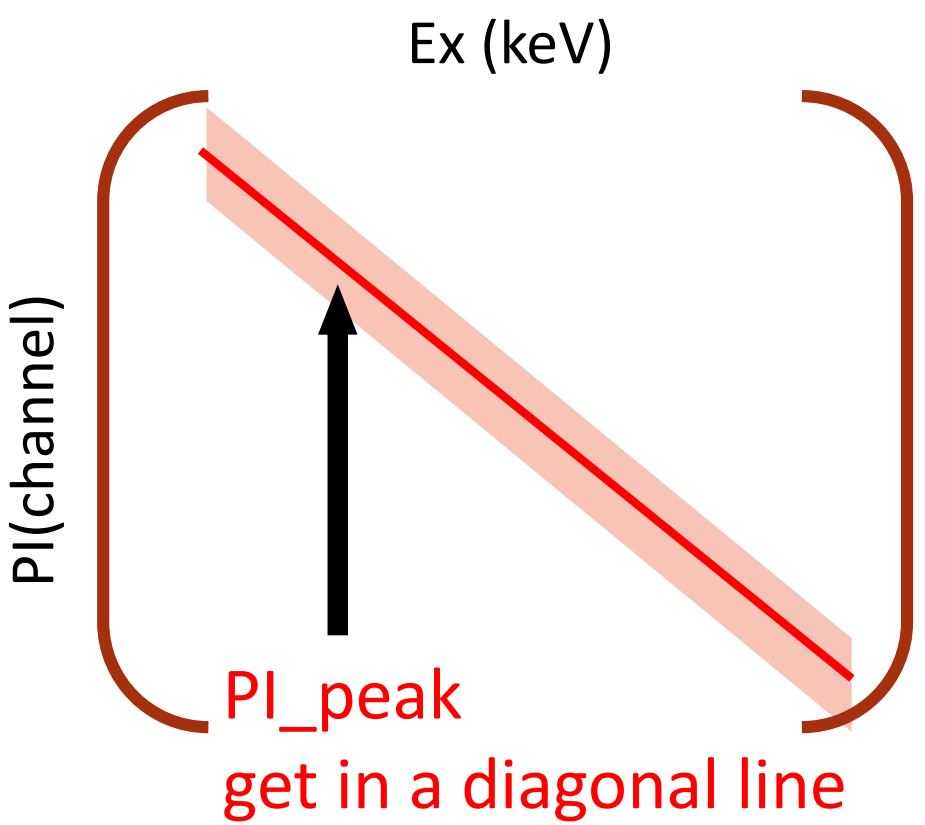
PI_peak-Ex Relation

PI_peak:
peak PI when a monochrome X-ray enters CCD
Ex: incident X-ray energy

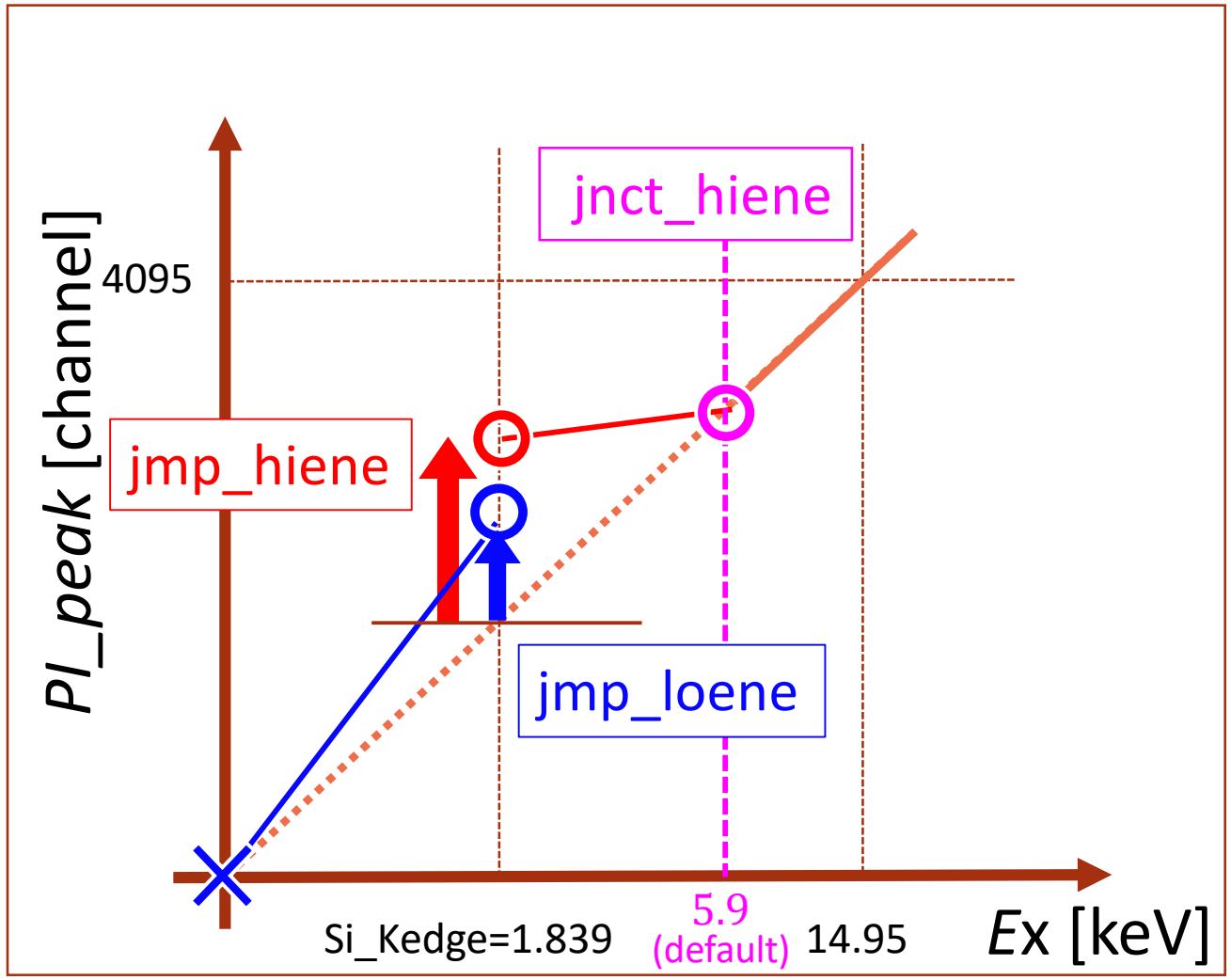
assumed PI_peak [channel] $= \frac{E_x \text{ [eV]}}{3.65 \text{ [eV/channel]}}$



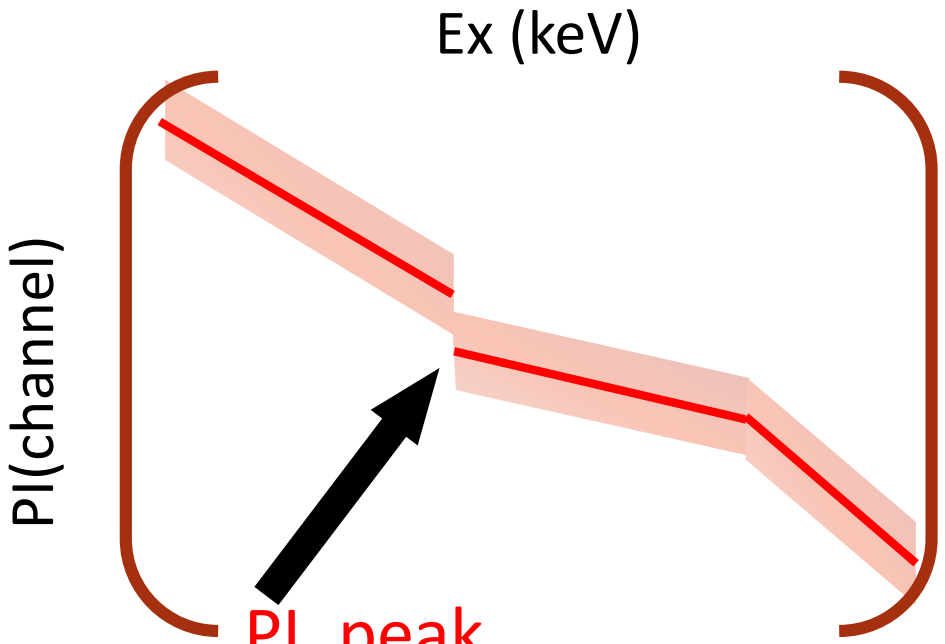
response matrix



Introduce New Parameters in PI_peak-Ex relation



response matrix



jmp: gap from the original linear relation at Si-K edge
junct: the energy where the relation returns original

Search for Best Jump Values

Calibration target : LMC X-3 (black hole binary)

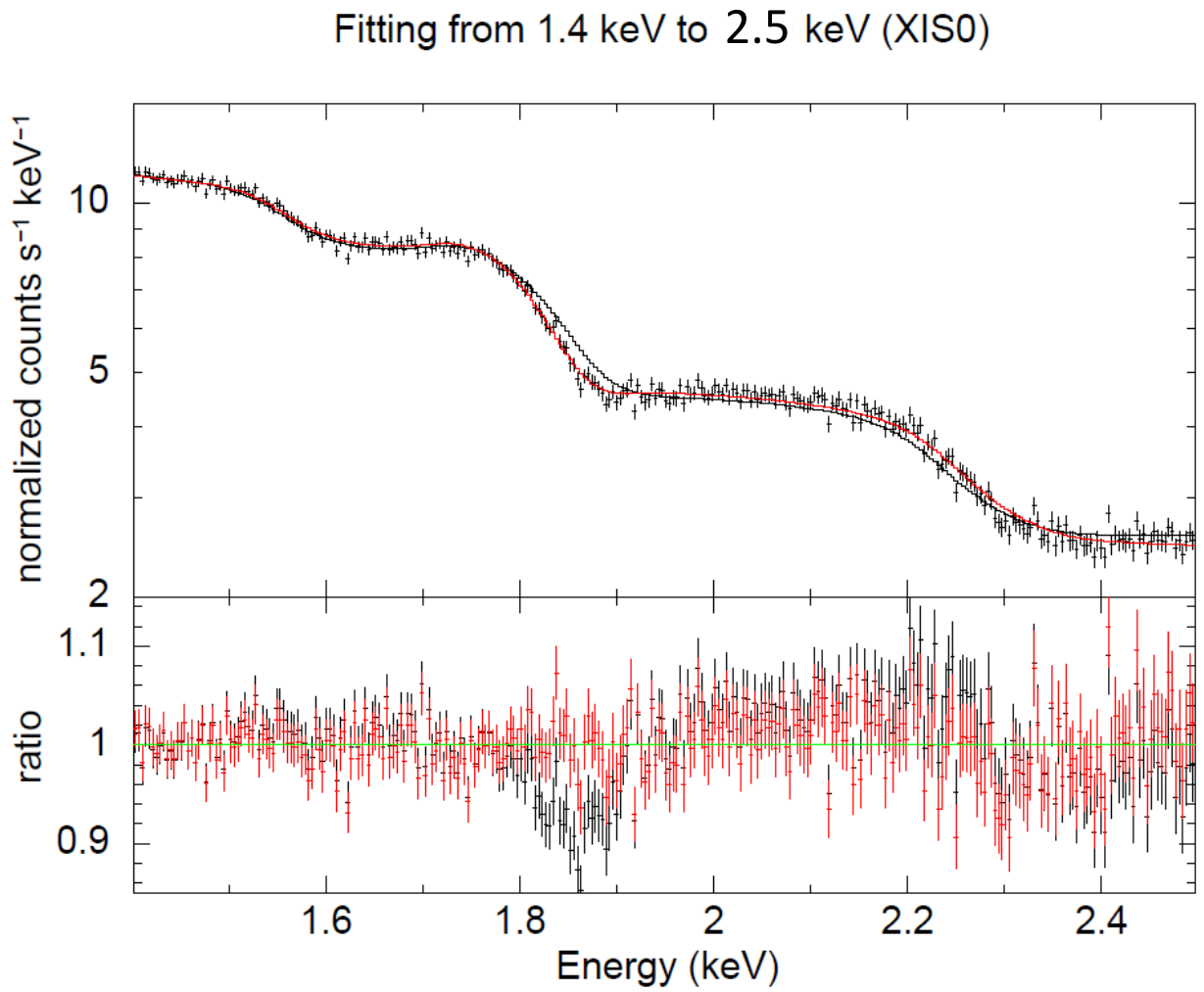
1. Use model: phabs*(diskbb + powerlaw)
2. Fit in 0.7-10.0 keV
3. Fix N_H and Γ
4. Refit in 1.4-2.5 keV

search the jump values which make reduced-chi square (χ_r^2) minimum

Search Range (step 0.1 channel)

	XIS0	XIS3	XIS1
jmp_loene [channel]	-2.0 - $+2.0$	-2.0 - $+2.0$	-3.0 - $+1.0$
jmp_loene [channel]	-1.0 - $+5.0$	$+2.0$ - $+5.5$	-5.0 - $+1.0$

Best Jump Values for XIS0 (FI)



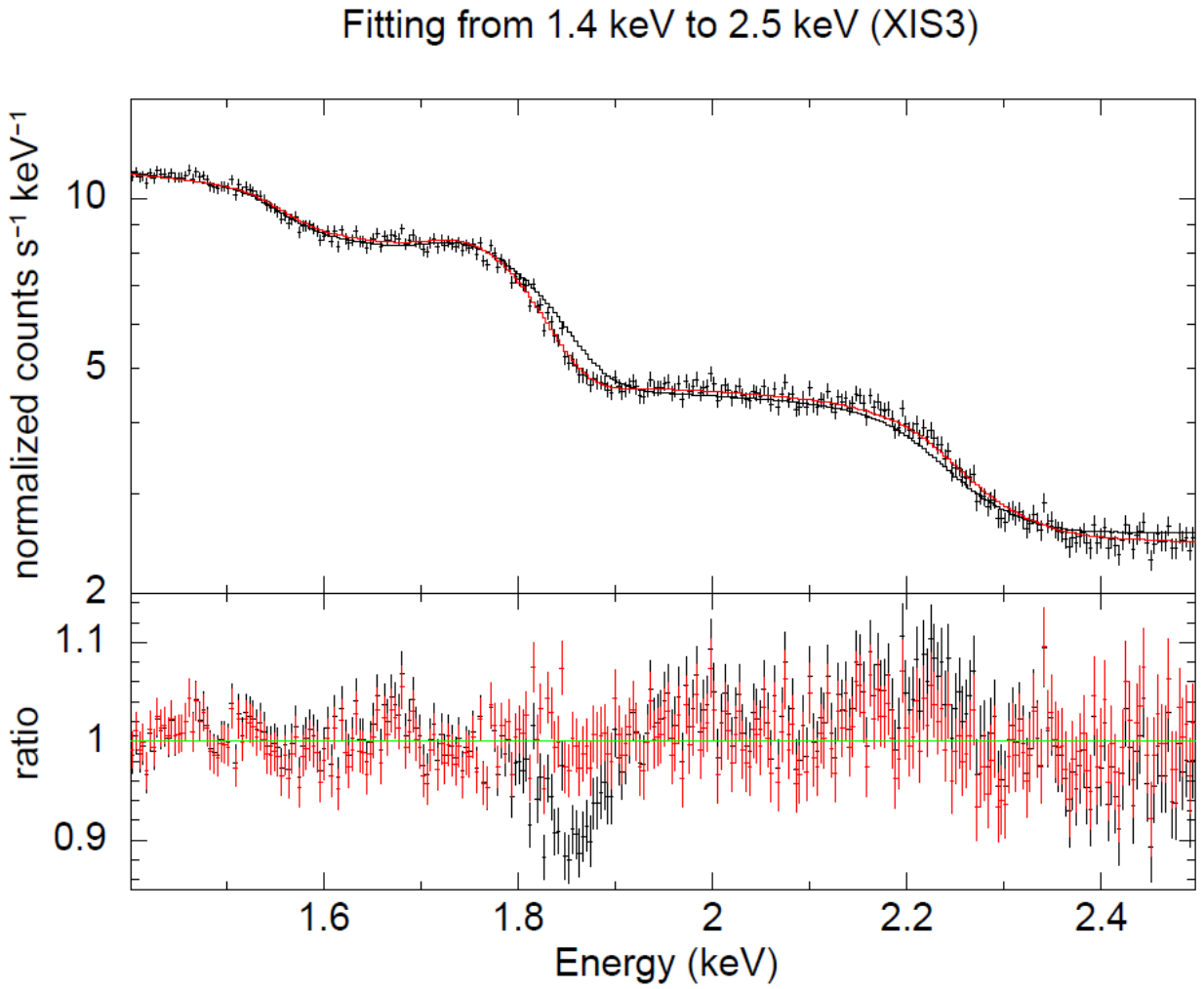
black: response without jump

$\chi_r^2 = 2.3159$ for 297 d. o. f

red: response with jump
jmp_loene=+0.7,
jmp_hiene=+4.9

$\chi_r^2 = 1.1468$ for 297 d. o. f

Best Jump Values for XIS3 (FI)



black: response without jump

$\chi_r^2 = 2.2799$ for 297 d. o. f

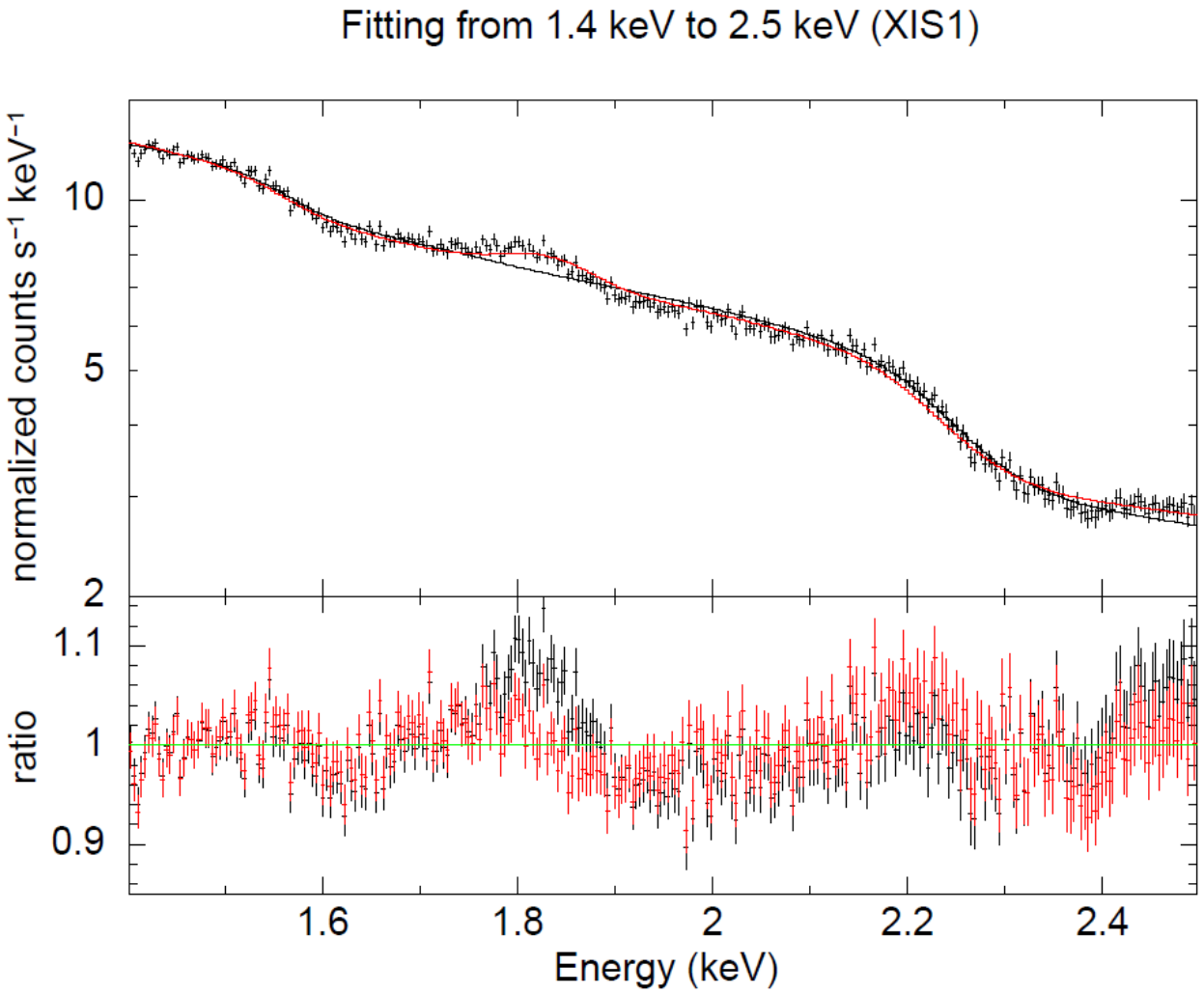
red: response with jump

jmp_loene=+0.2,

jmp_hiene=+4.2

$\chi_r^2 = 1.1046$ for 297 d. o. f

Best Jump Values for XIS1 (BI)



black: response without jump

$\chi_r^2 = 2.6515$ for 297 d. o. f

red: response with jump

jmp_loene=−1.0,

jmp_hiene=−4.1

$\chi_r^2 = 1.7205$ for 297 d. o. f

Summary of Best Jump Values

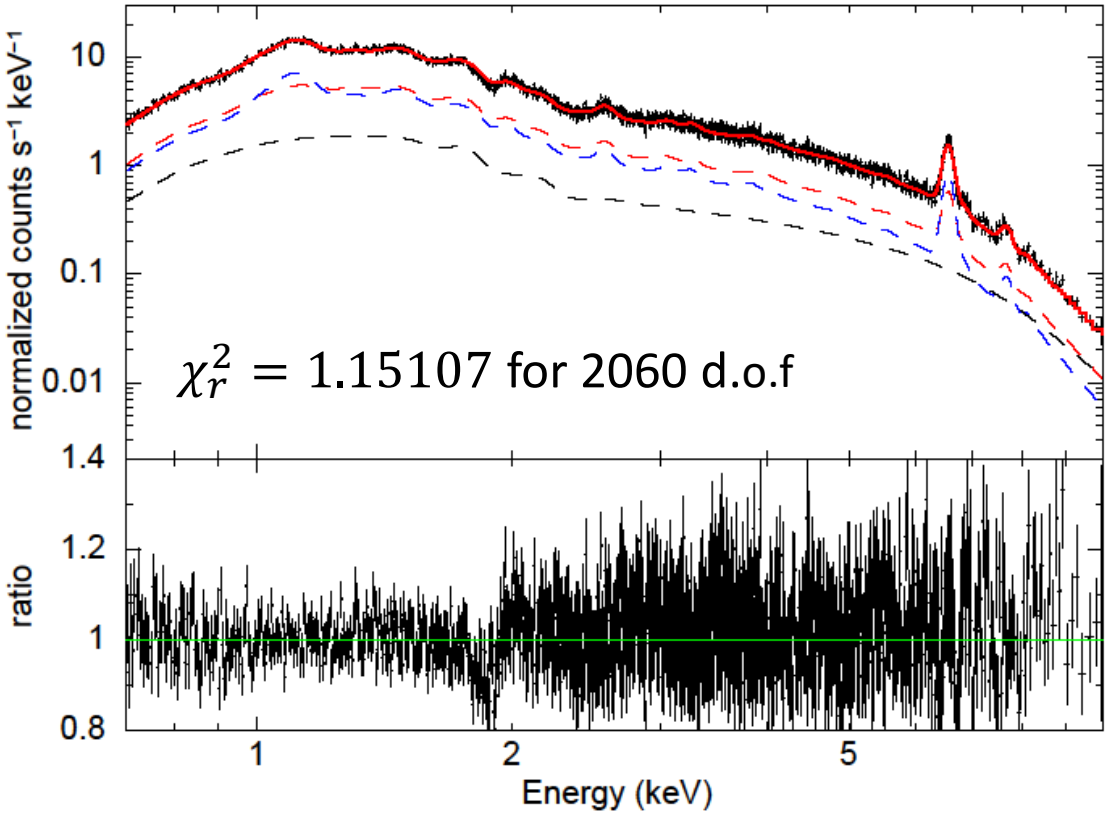
	jmp_loene [channel]	jmp_hiene [channel]	χ_r^2 [for 297 d.o.f]	without jump χ_r^2
XIS0 (FI)	$+0.7$	$+4.9$	1.1468	2.3159
XIS3 (FI)	$+0.2$	$+4.2$	1.1046	2.2799
XIS1 (BI)	-1.0	-4.1	1.7205	2.6515

Perseus Cluster (XIS0)

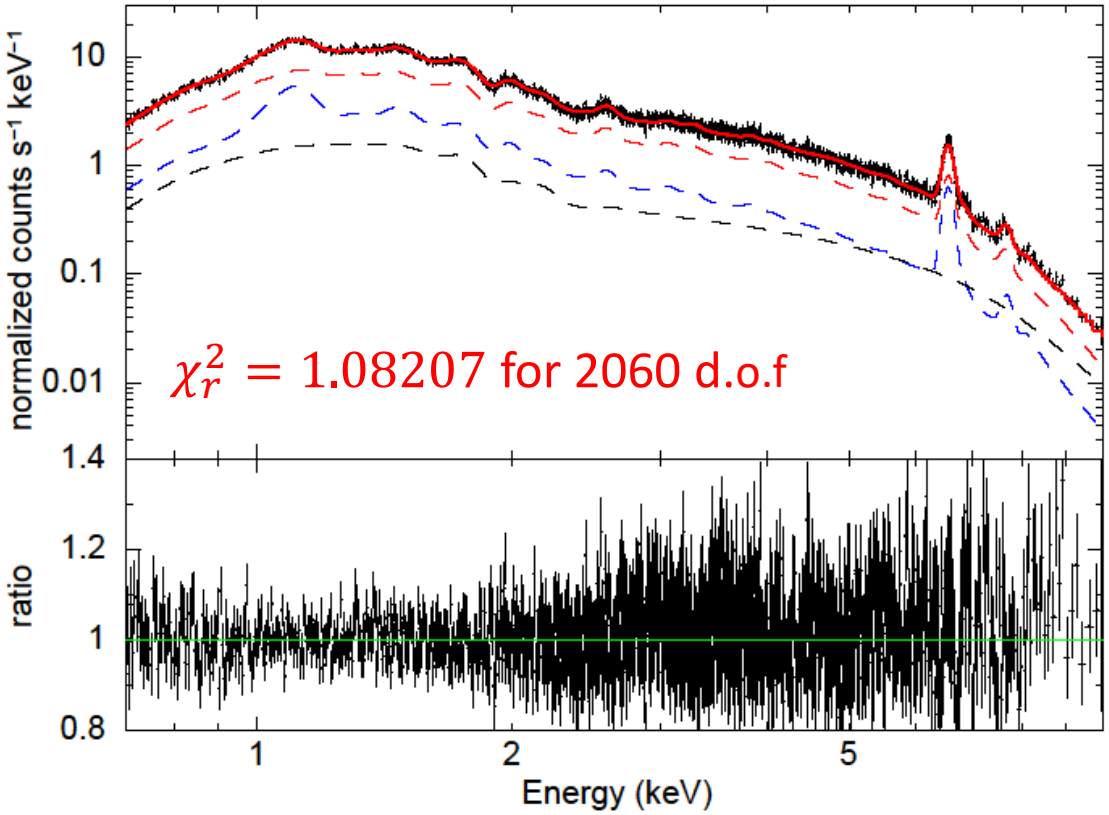
w/o jump -> “before”
w/ jump -> “after”

model : phabs*(vapec1 + vapec2 + powerlaw)

before



after



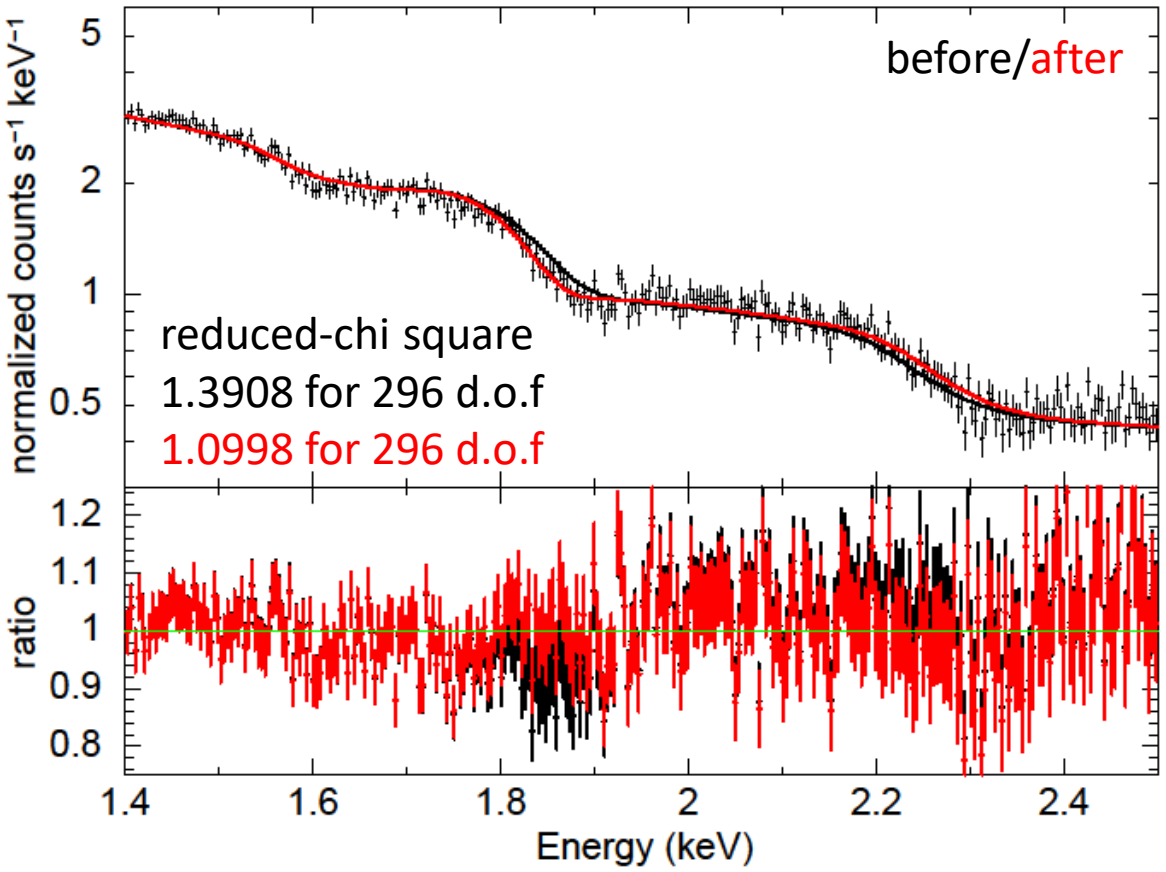
PKS2155-304 (XIS0)

NOT set jump -> “before”
set jump -> “after”

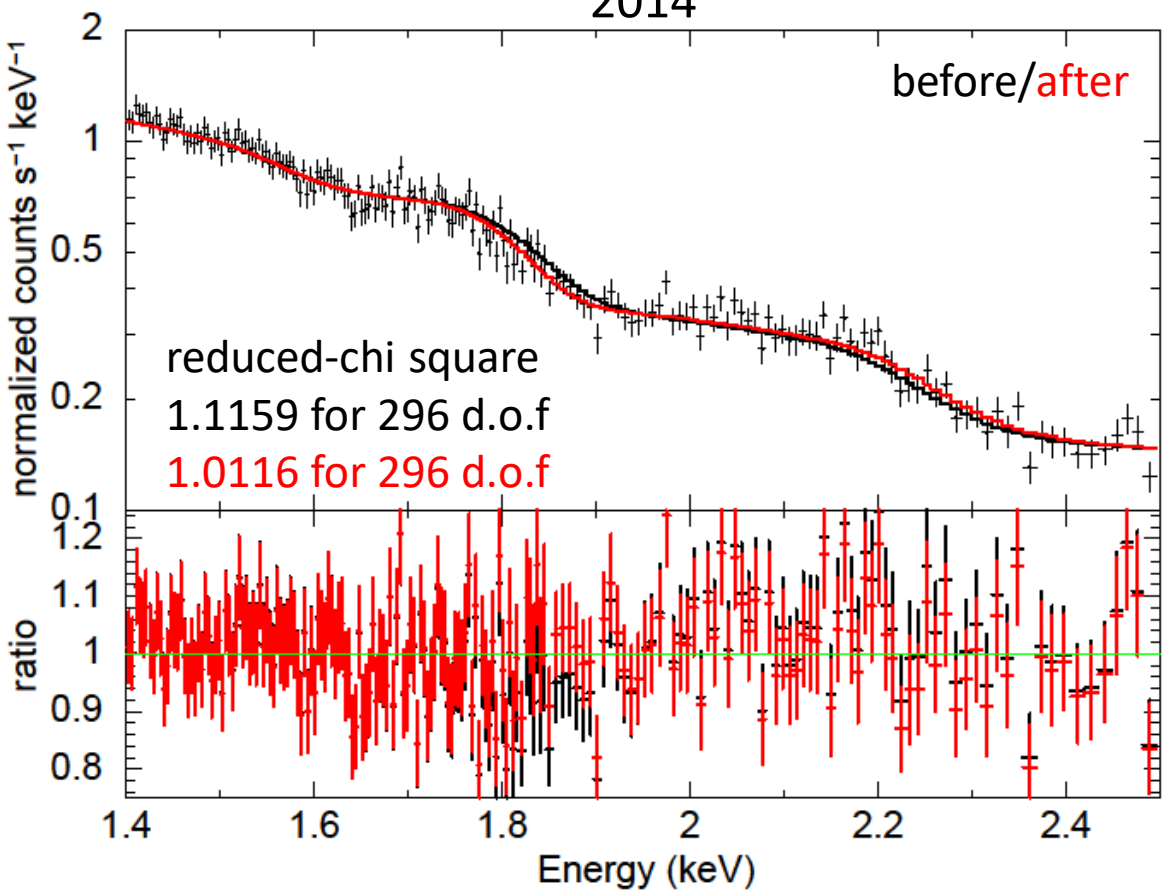
model : phabs*logpar

!!! We fitted in 0.7-10.0 keV and zoomed 1.4-2.5 keV

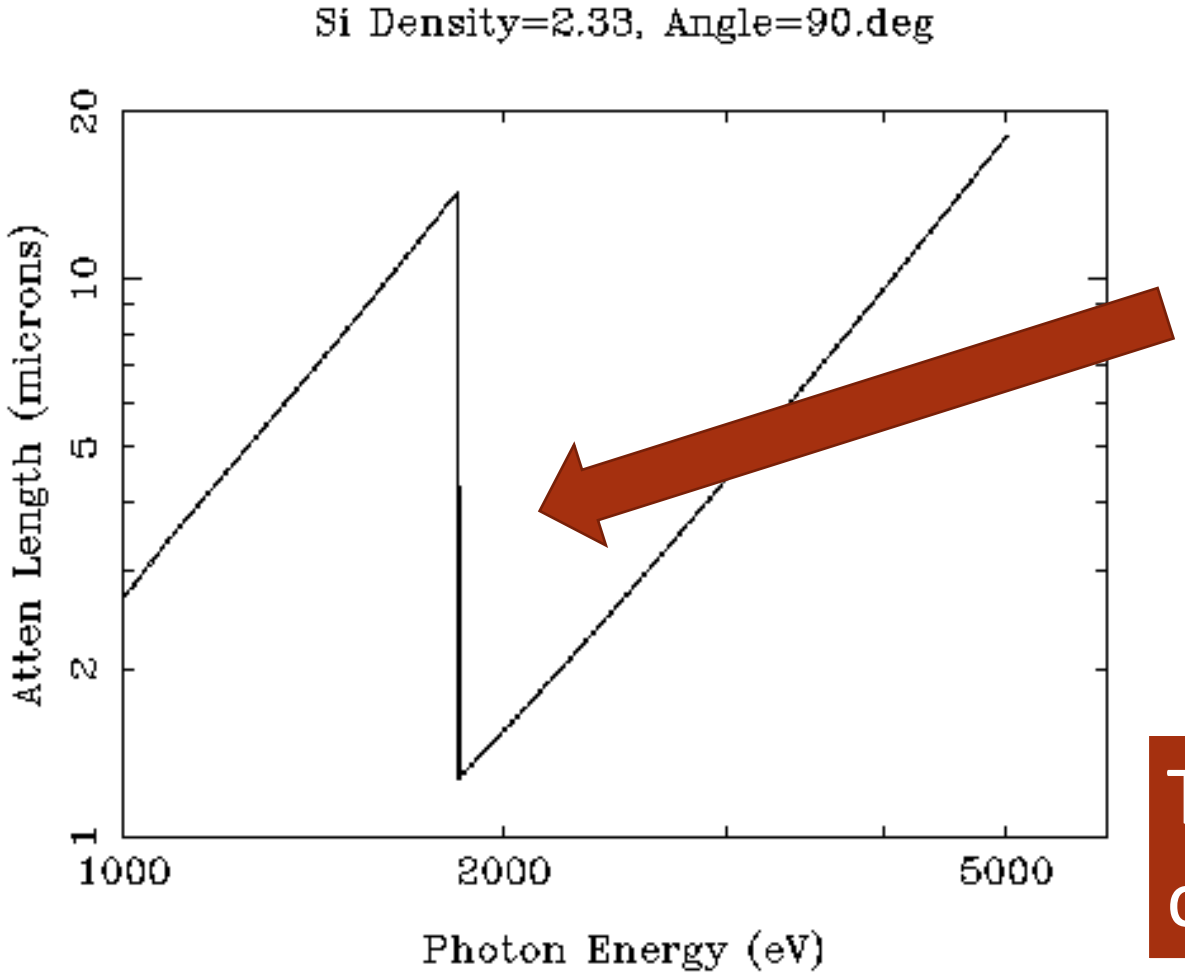
2005



2014



X-ray Attenuation Length in Silicon



(http://henke.lbl.gov/optical_constants/atten2.html)

The attenuation length is discontinuous at Si-K edge(1838.9 eV)

14.3 μm at 1838.5 eV (= E_{below})
1.3 μm at 1839.1 eV (= E_{above})

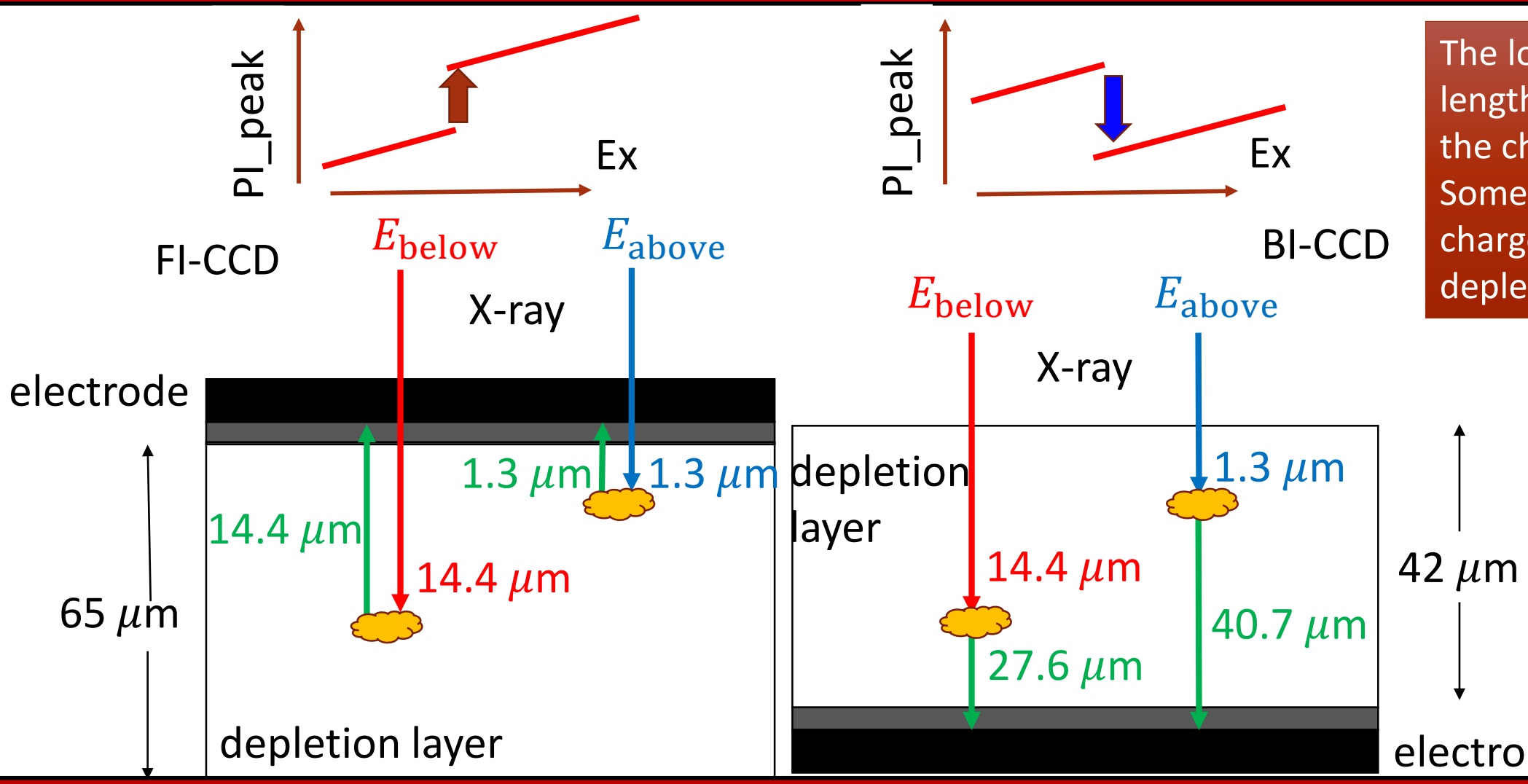
The path length of the electron cloud changes discontinuously at Si-K edge.

Summary of Jump

	jmp_loene [channel]	jmp_hiene [channel]	jump = jmp_hiene –jmp_loene	
			[channel]	[eV]
XIS0 (FI)	$+0.7$	$+4.9$	4.2	15
XIS3 (FI)	$+0.2$	$+4.2$	4.0	15
XIS1 (BI)	-1.0	-4.1	-3.1	-11

Possible Origin of Jumps

※Si-K edge : 1838.9 eV
E_{below} : 1.838.5 eV
E_{above} : 1.839.1 eV



The longer the path length is, the larger the charge loss is. Some amount of charges is lost in the depletion layer?

Conclusion (Okazaki et al. SPIE proc. 2018)

- Introduction of “jump” in response PI_peak-Ex relation, the residual around Si-K edge was reduced.
- Jump parameters were determined by fitting LMC X-3.
- The reduction of the residual was confirmed also for other targets; Perseus Cluster with emission lines, PKS2155 observed a few times.
- Jumps are $\sim$**4 channel (15 eV)** for XIS0 and 3, and $\sim -$**3 channel (11 eV)**.
- We speculate some amount of charges is lost in the depletion layer; the longer the path length is, the larger the charge loss is.
- “xisrmfgen” in which jumps are implemented with their optimized values was released on Oct. 2018 as a part pf HEASOFT v6.25.

Further Optimization after HEASOFT v6.25

- Jump values are tuned also with M87 and Perseus Cluster in which line emissions are present.

	in V6.25		after	
	loene (ch)	hiene (ch)	loene (ch)	hiene (ch)
XIS0	+0.2	+4.5	-1.9	2.4
XIS1	-2.0	-4.7	-0.1	-2.9

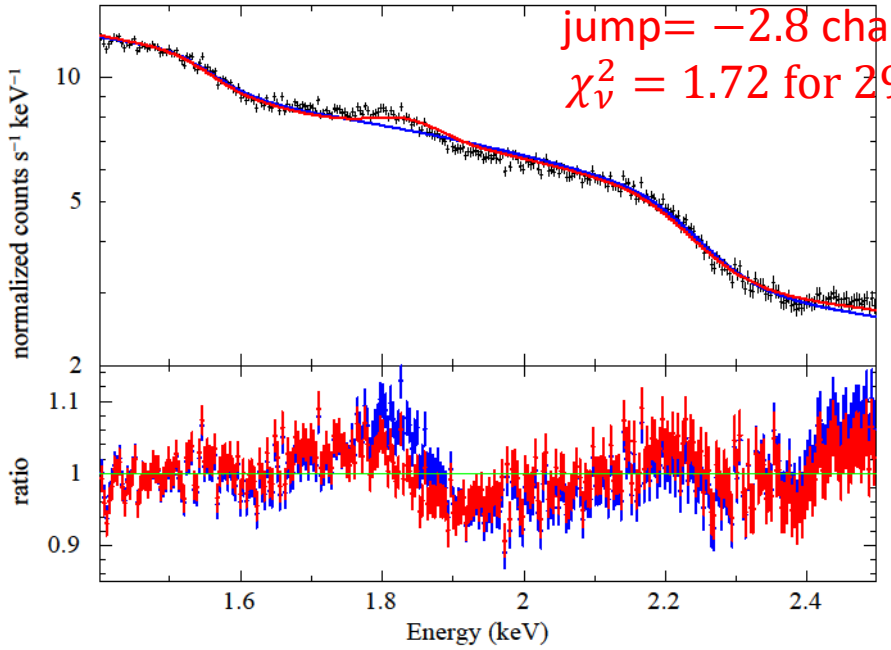
- However, significant residual remains for the BI.

LMC X-3 (XIS1)

red: response w/ jump

jump= -2.8 channel

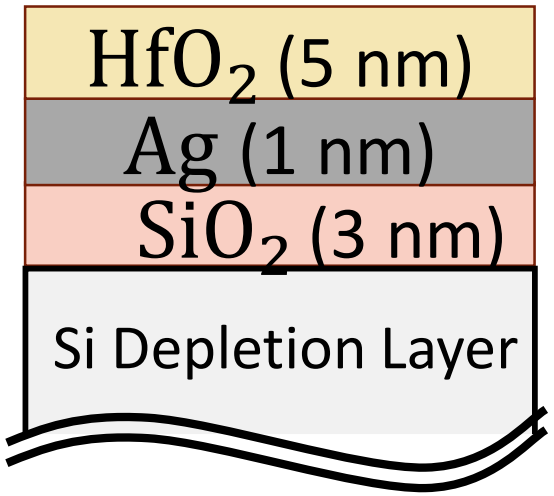
$\chi^2_\nu = 1.72$ for 297 d. o. f

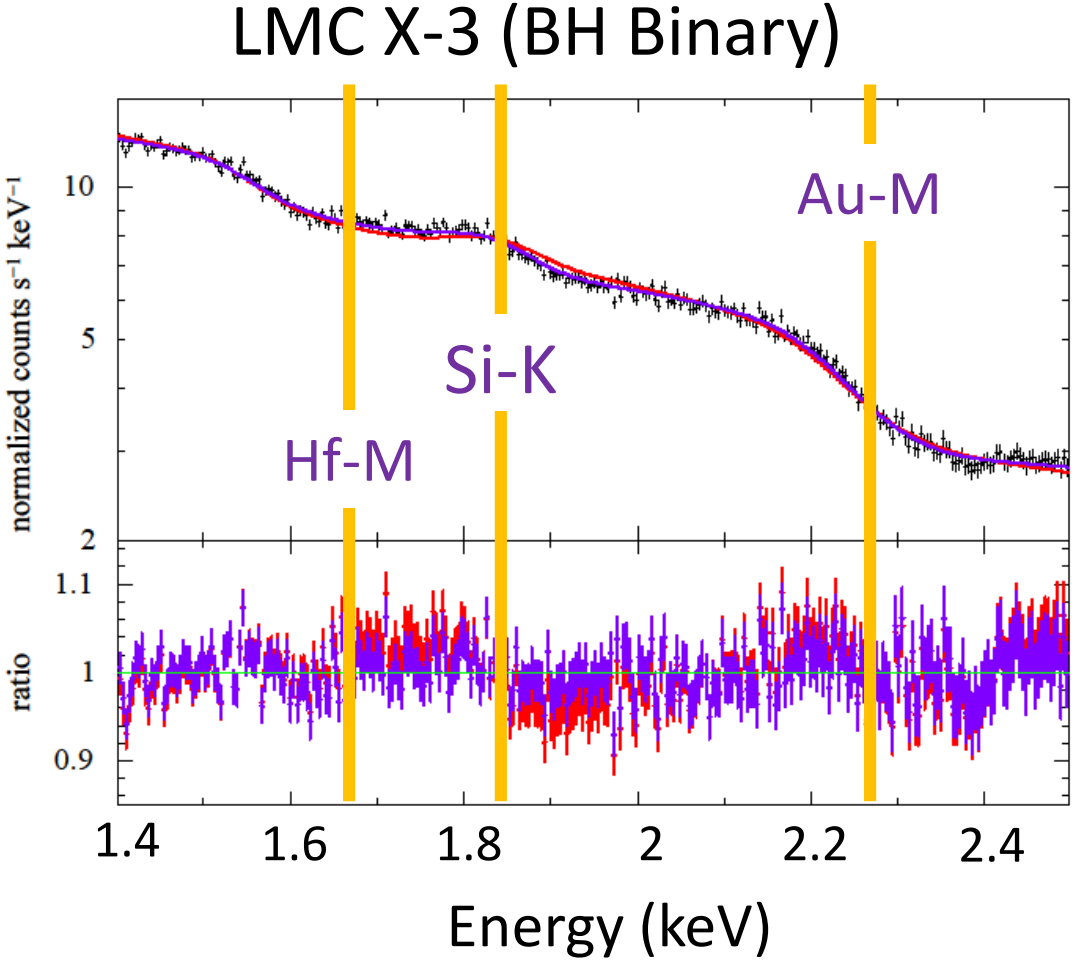


Further Optimization after HEASOFT v6.25

- QE of BI-CCD is reconsidered.

BI surface design





red: w/o edge model

$\chi^2_\nu = 1.72$ for 297 d. o. f

purple: w/ edge model

$\chi^2_\nu = 1.16$ for 297 d. o. f

HfO2: 4nm

SiO2+Si deadlayer: 160nm

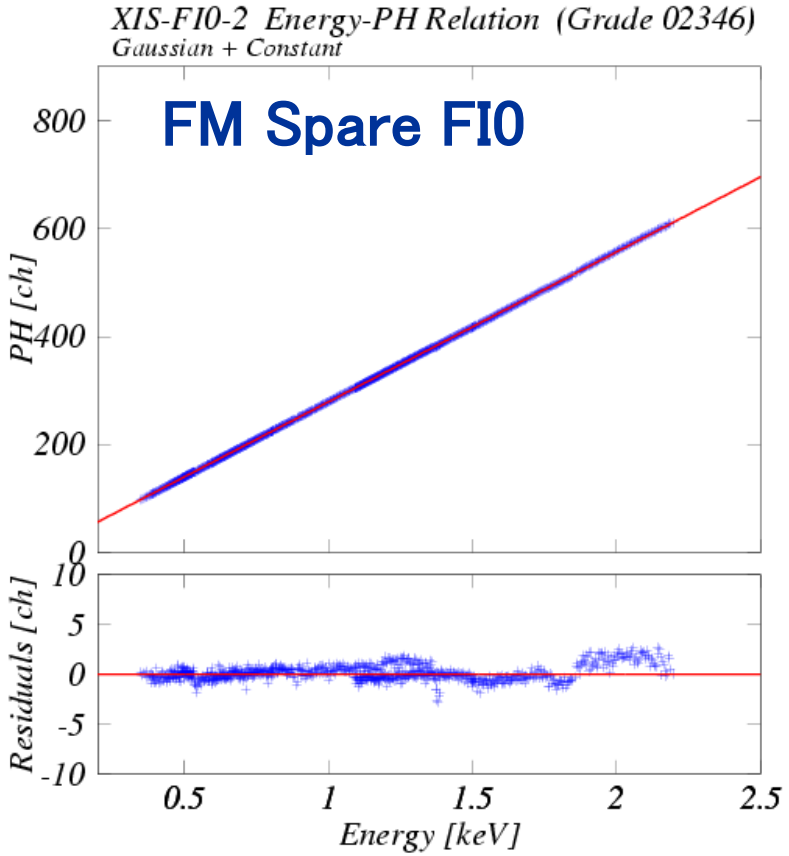
For XRISM Xtend

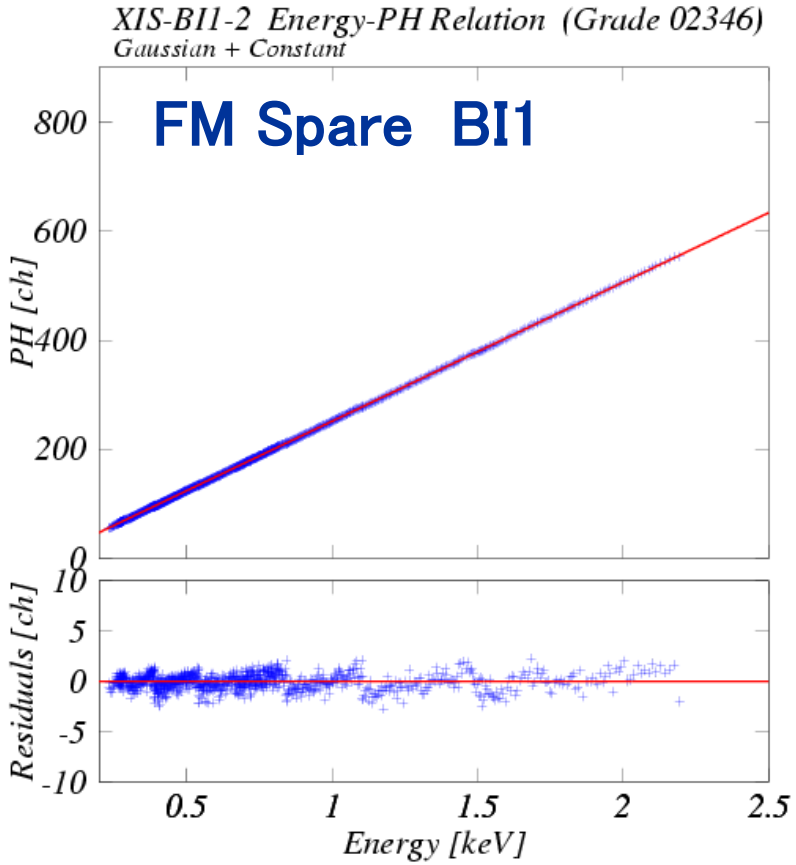
- Response generator is being updated from that for Hitomi SXI so as to implement possible jumps in the Ex – PI_peak relation.
- Note: PH->PI conversion should not have jumps. We need matrices to implement a jump.
- Experiments around Si-K edge performed with a test CCD before the Hitomi launch have been investigated in detail.
- Irradiation of continuum X-rays are considered.

Backup Slide

XIS Experiments on Ground with a Grating

Gaussian Fit (Response Profile is NOT taken into account)
W-M line contamination makes analysis around Si-K edge difficult





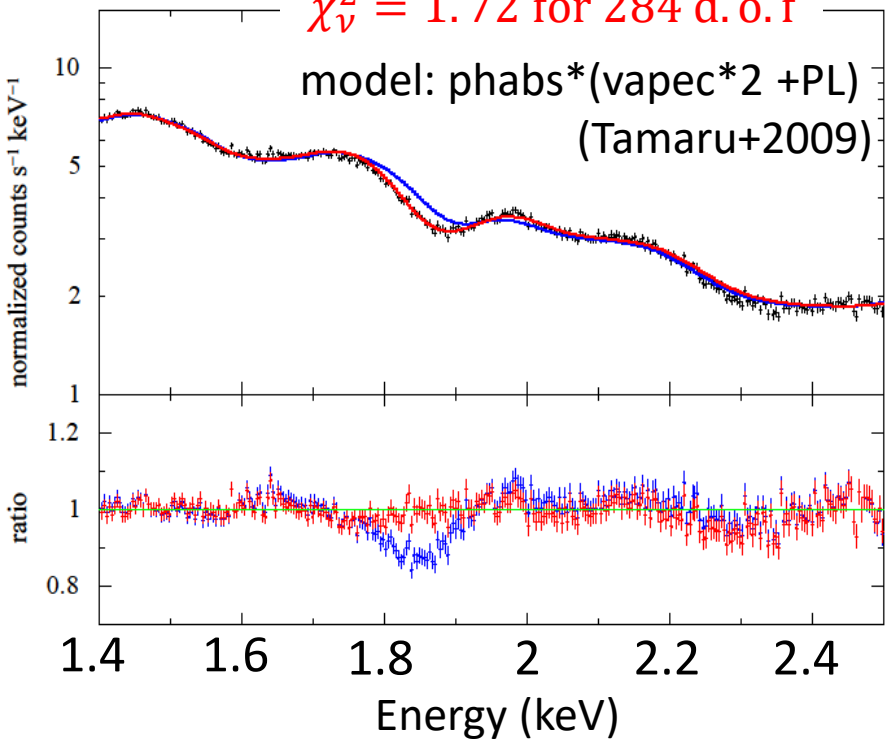
Application to Cluster and SNR Spectra

Perseus Cluster

$\chi_\nu^2 = 5.06$ for 284 d.o.f

$\chi_\nu^2 = 1.72$ for 284 d.o.f

model: phabs*(vapec*2 +PL)
(Tamaru+2009)

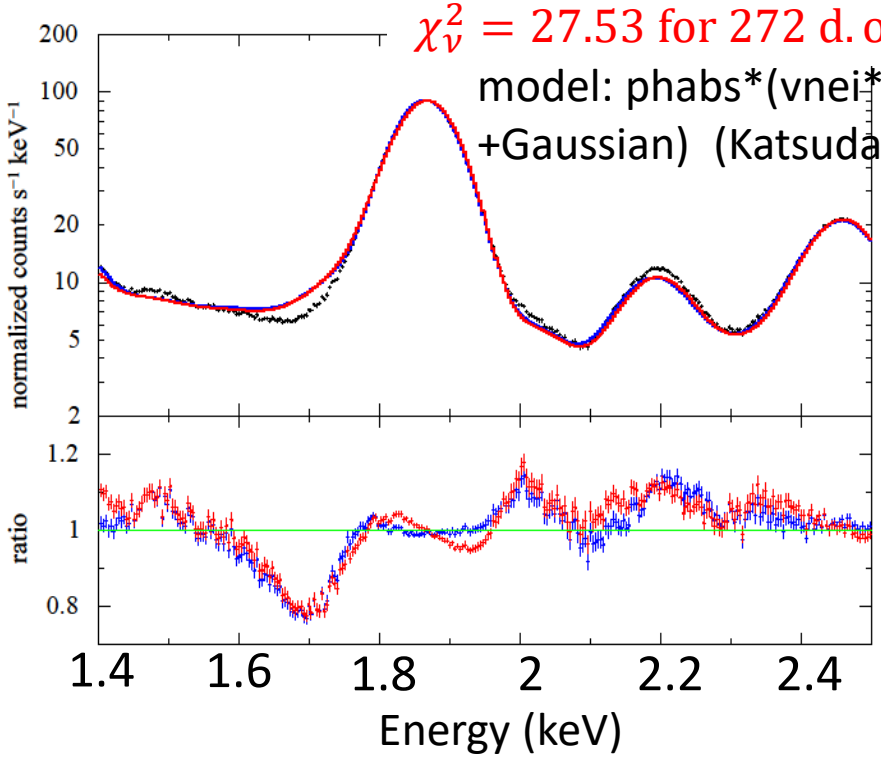


Tycho (SNR)

$\chi_\nu^2 = 22.91$ for 272 d.o.f

$\chi_\nu^2 = 27.53$ for 272 d.o.f

model: phabs*(vnei*3 + PL
+Gaussian) (Katsuda+2015)



We need to Update Emission model for this case.

Study of Si-K edge response in 1994

Theory (Fraser et al., NIMA, 1994)

- W-value jump by +0.2%

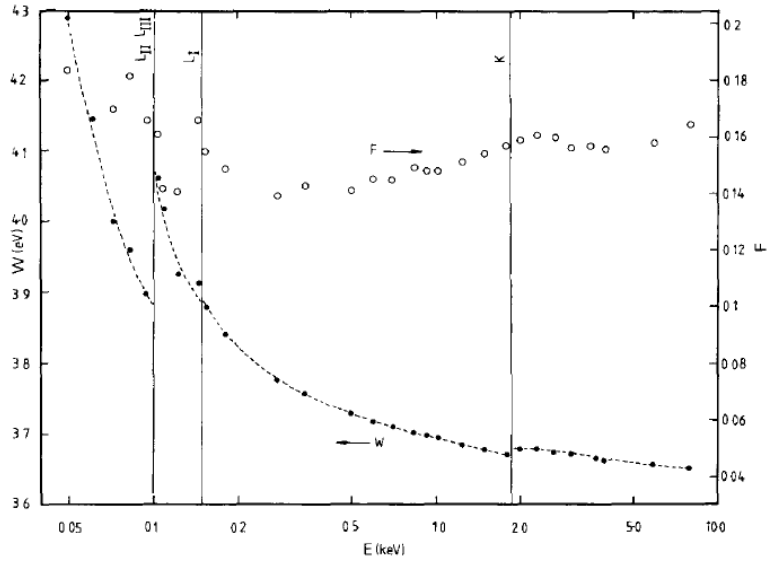


Fig. 7. Variation of the mean electron–hole pair creation energy W (filled circles; left hand scale) and Fano factor F (open circles; right hand scale) with X-ray energy E, $E_g = 1.15$ eV (operating temperature $T = 170$ K). The curve through the $W(E)$ values is drawn to guide the eye.

Experiment (Owens et al., NIMA, 1994)

- W-value jump by +0.5%

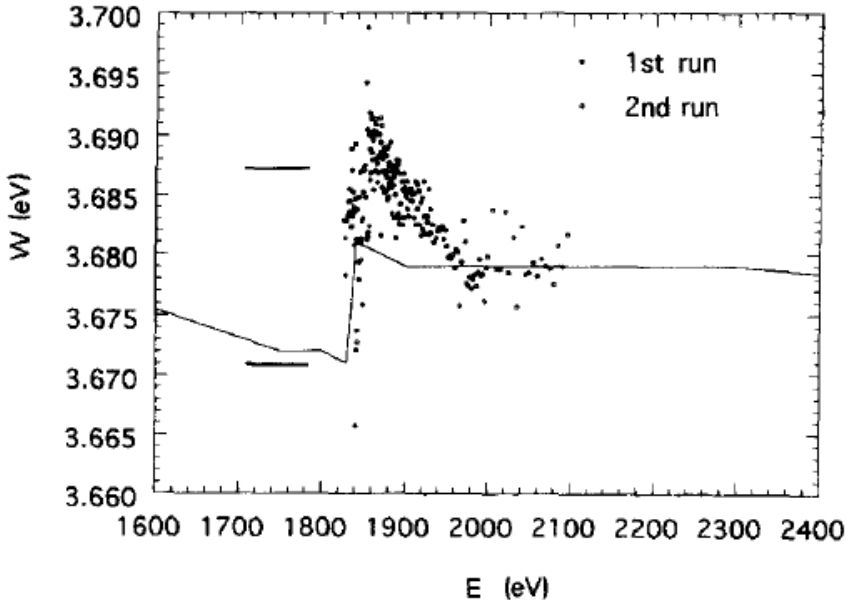


Fig. 3. Comparison of measured and calculated pair creation energies in the vicinity of the silicon K edge. Individual symbols – synchrotron data. Light curve – calculations from Table 1. Bold horizontal lines – white line calculation (see text).