

# **Identifying New Physics from High-Resolution Spectra**

**Hiroya Yamaguchi**

**ISAS/JAXA**

# Talk plan

(Target of this talk: students)

- \* Non-standard spectral analysis using XSPEC
  - Table model
    - Skip in this talk, see: [https://heasarc.gsfc.nasa.gov/docs/heasarc/ofwg/docs/general/ogip\\_92\\_009/](https://heasarc.gsfc.nasa.gov/docs/heasarc/ofwg/docs/general/ogip_92_009/)
  - Directly modify the AtomDB-based model FITS files in the /spectral/modelData directory
- \* Prospect for future emission line diagnostics with  $\mu$ -cal observations to identify new physics

**Be familiar with software and atomic physics.**

**Don't deal with them as blackboxes.**

# RGS study of the SNR N132D

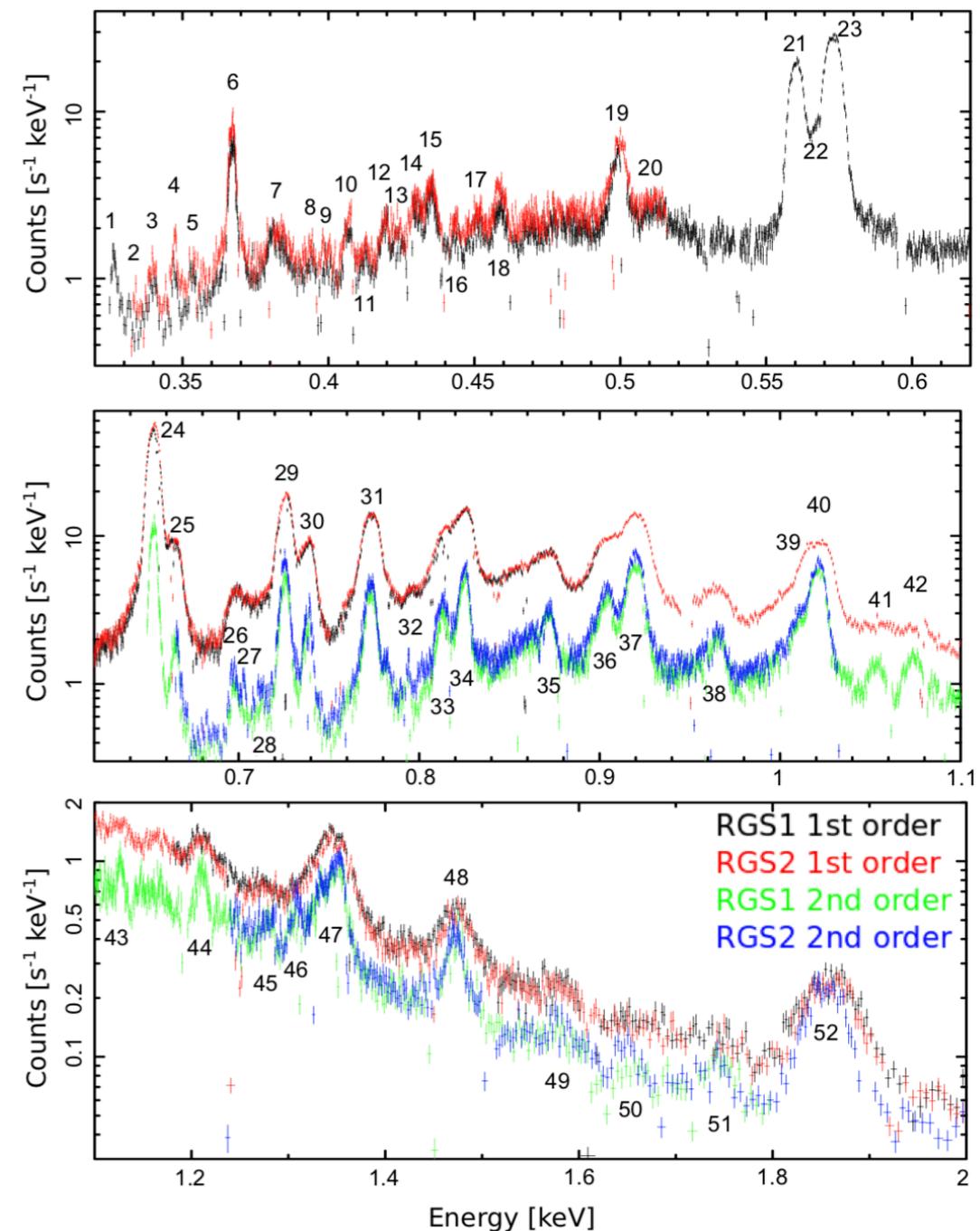
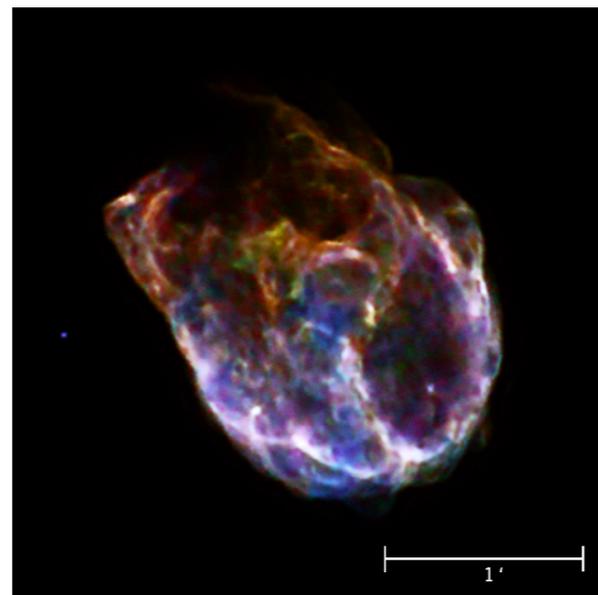
Suzuki, HY, et al. 2020, ApJ in press, arXiv:2007.06158

Plasma Diagnostics of the Supernova Remnant N132D Using Deep XMM–Newton Observations with the Reflection Grating Spectrometer

HITOMI SUZUKI,<sup>1,2</sup> HIROYA YAMAGUCHI,<sup>2,3</sup> MANABU ISHIDA,<sup>1,2</sup> HIROYUKI UCHIDA,<sup>4</sup> PAUL P. PLUCINSKY,<sup>5</sup> ADAM R. FOSTER,<sup>5</sup> AND ERIC D. MILLER<sup>6</sup>

N132D is...

- The X-ray Brightest SNR in LMC
- Calibration target for XMM-Newton
- Total exposure: ~ 300 ks (on-axis),  
~ 1 Ms (off-axis)



# RGS study of the SNR N132D

Suzuki, HY, et al. 2020, ApJ in press, arXiv:2007.06158

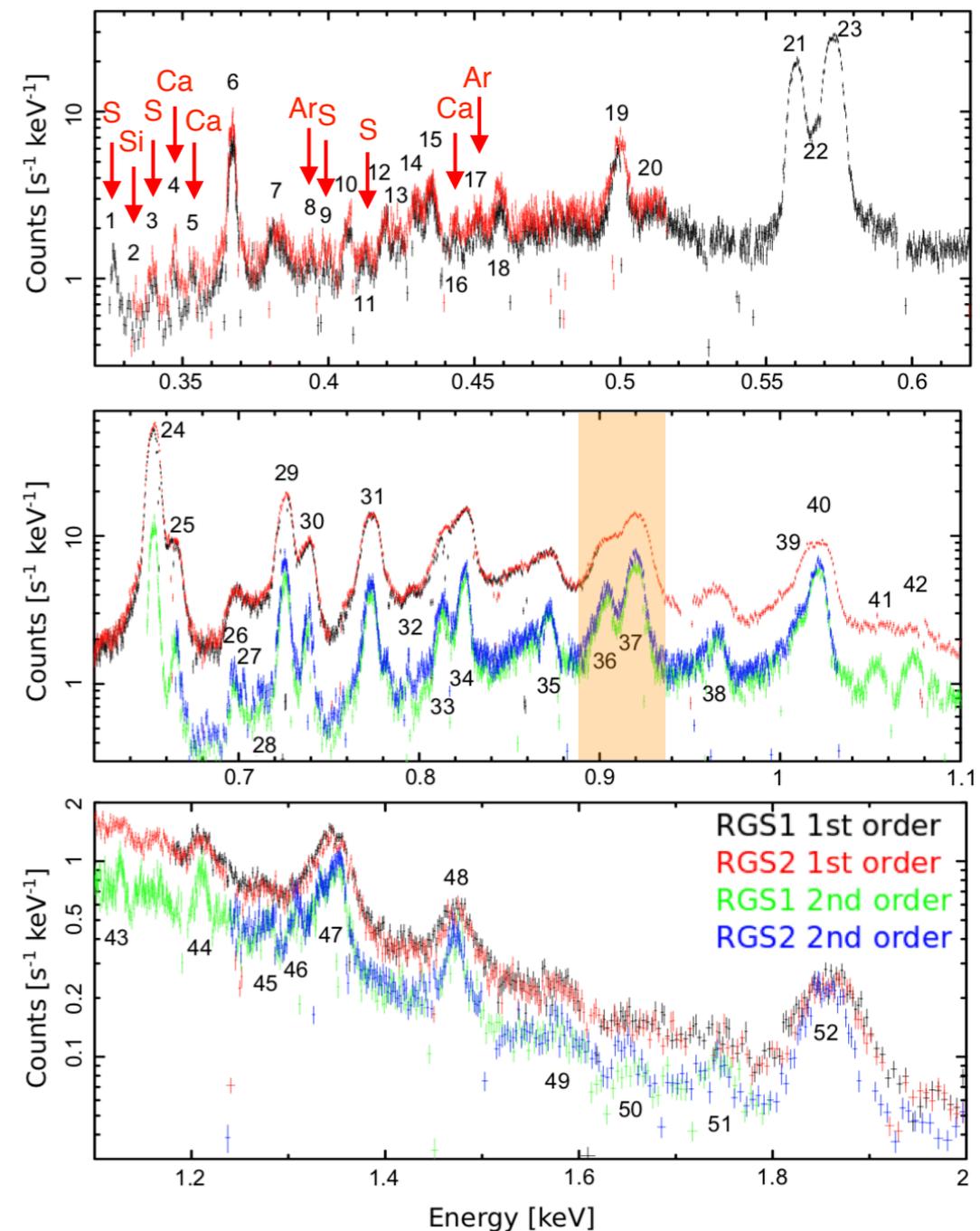
Plasma Diagnostics of the Supernova Remnant N132D Using Deep XMM–Newton Observations with the Reflection Grating Spectrometer

HITOMI SUZUKI,<sup>1,2</sup> HIROYA YAMAGUCHI,<sup>2,3</sup> MANABU ISHIDA,<sup>1,2</sup> HIROYUKI UCHIDA,<sup>4</sup> PAUL P. PLUCINSKY,<sup>5</sup> ADAM R. FOSTER,<sup>5</sup> AND ERIC D. MILLER<sup>6</sup>

## Main results:

- Newly detected a dozen weak lines
- Ne IX z (f) and w (r) lines resolved in the 2nd-order spectra
- Emission line diagnostics revealed:
  - evidence of non-equil ionization (for the first time for this object)
  - slightly enhanced z/w flux ratio (due to resonance scattering?)

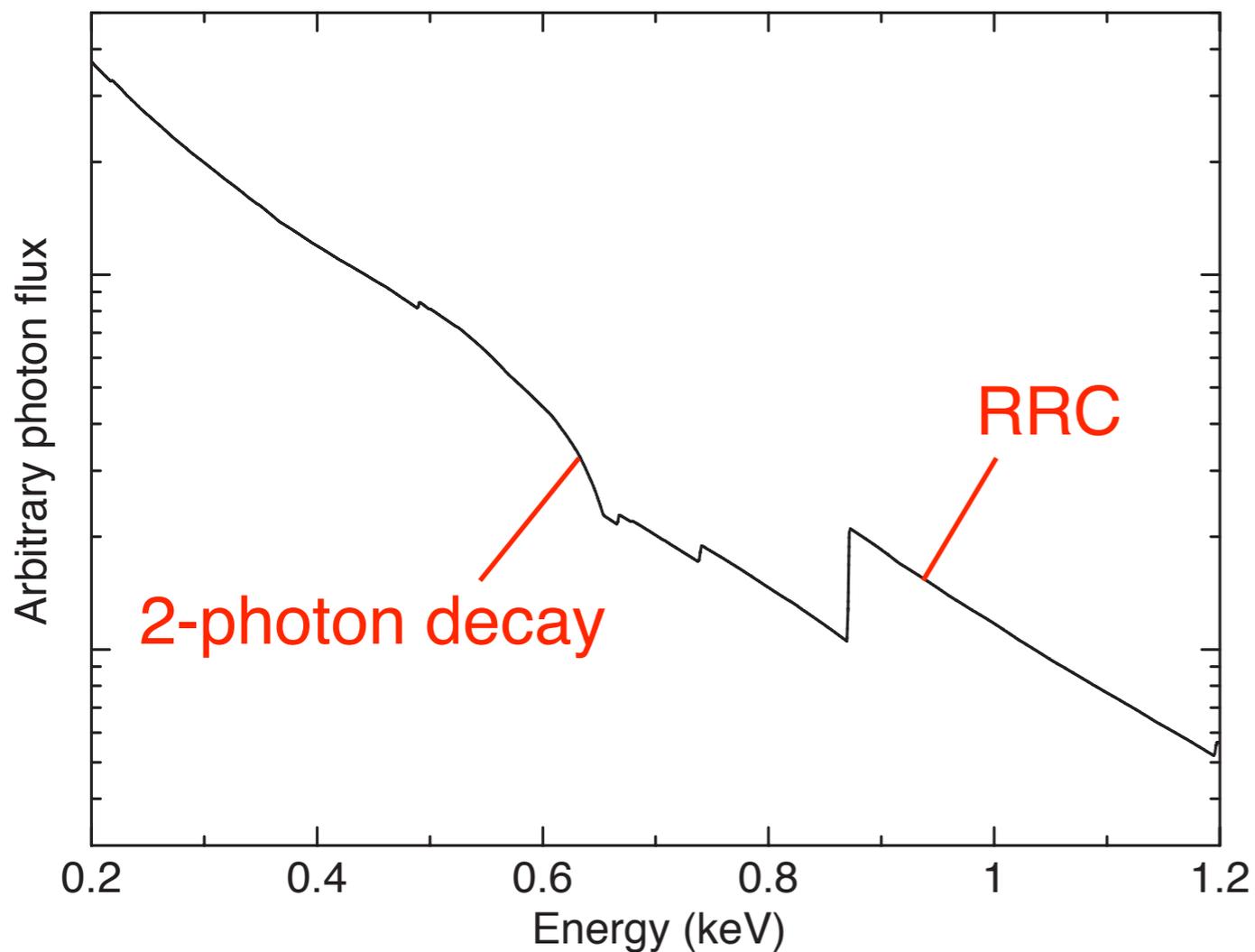
Question: how do you measure the the O VII and Ne IX line flux?



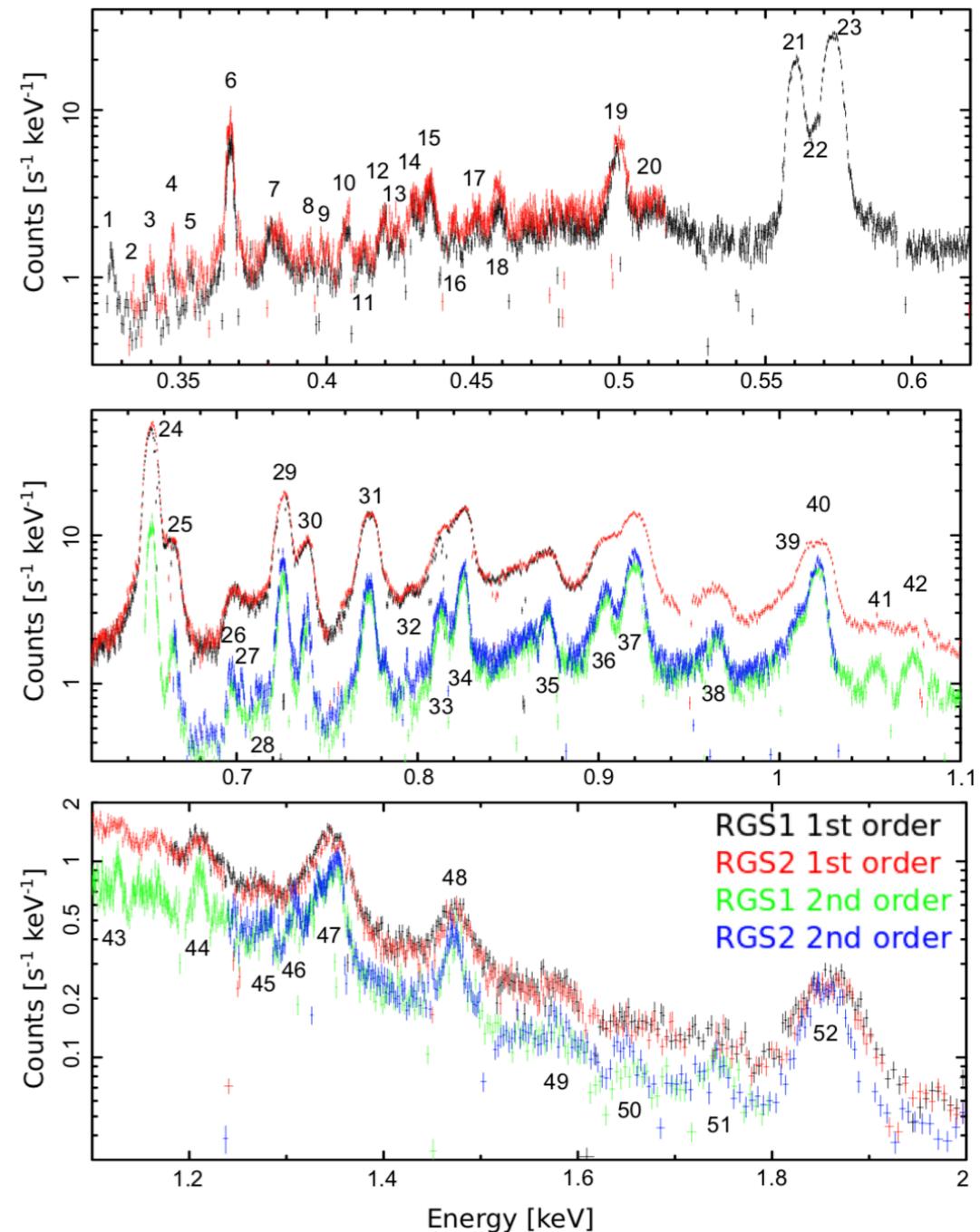
# How to measure line intensity

Fit with brems (for continuum) and many Gaussians (for lines)?  
... not recommended. Continuum is not just brems!

Continuum of 0.3 keV CIE plasma



These features are non-negligible especially in high-resolution spectra



# How to measure line intensity

## ATOMDB

ATOMIC DATA FOR  
ASTROPHYSICISTS

[WebGUIDE](#)[Features](#)[Comparisons](#)[Physics](#)[FAQ](#)[Download](#)[Contact Us](#)[iPad App](#)[Workshop](#)[Login/Register](#)

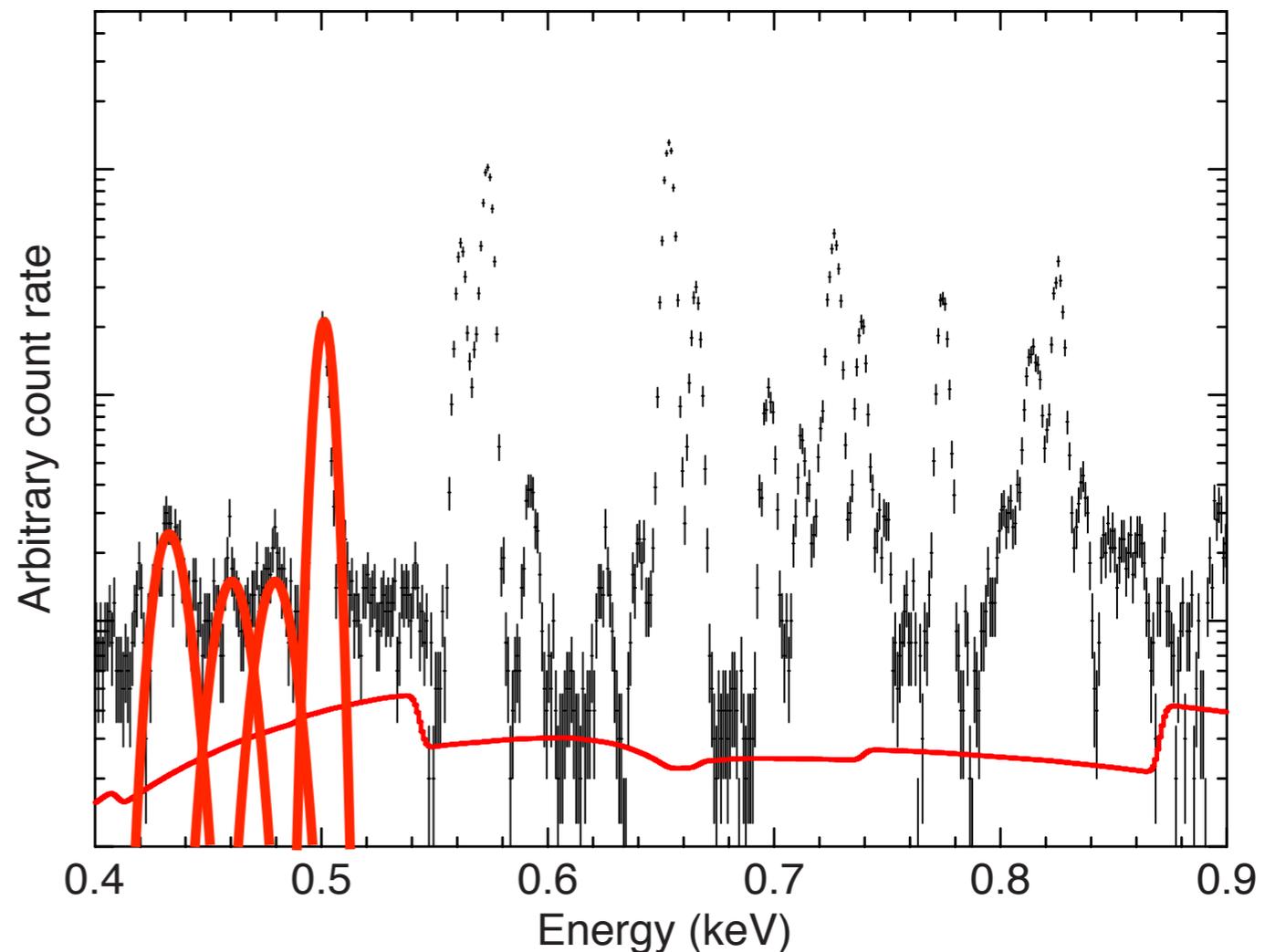
## AtomDB NoLine Model

The AtomDB NoLine model is produced by removing all emission lines from spectra calculated by APEC, producing a continuum spectrum which can be used as the user see fits. The processes which are included in this spectrum are:

- Bremsstrahlung
- Radiative Recombination Continuum
- Two Photon Emission from low-lying H- and He-like levels

The data can be downloaded here: [apec\\_v2.0.2\\_noline.tar.bz2 md5sum](#)

I'm too lazy to add hundreds of Gaussian components!

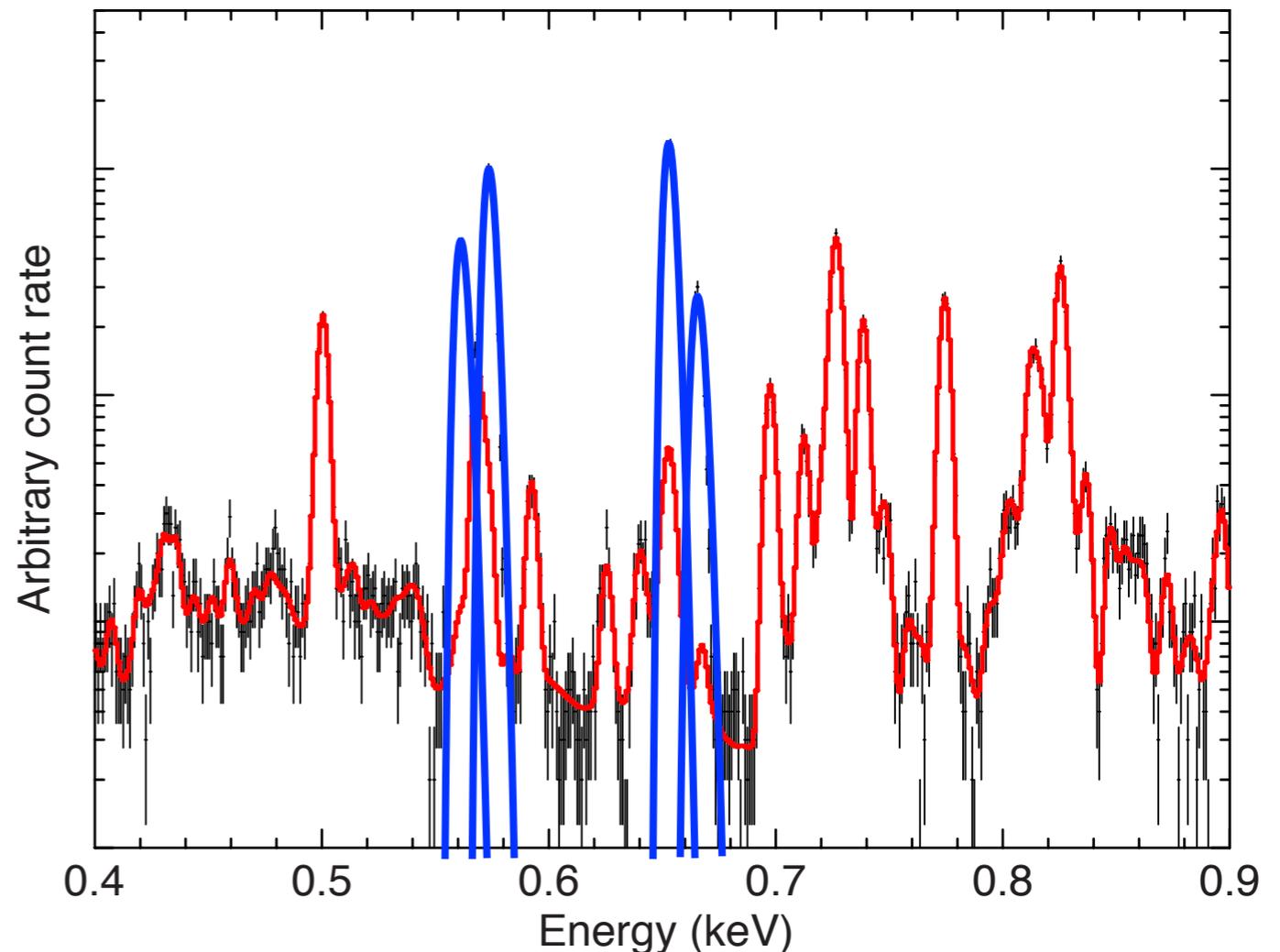


# What we did

Remove only diagnostic lines from APEC/NEI models and add Gaussians to measure the line flux directly.

Call “NoDiagnosticLine model” hereafter

If you understand how the software works and how the supporting files are structured, you can perform non-standard analysis as you want.



# Step 1 (Preparation)

Find the “levels” of the transitions you are interested in

## ATOMDB ATOMIC DATA FOR ASTROPHYSICISTS

Transition info?	Level Number	Electron Configuration	Energy [eV]	Energy Error [eV]	n	L	S	g
<input checked="" type="radio"/>	1	1s2	0.00000 [ref]	0	1	0	0.0	1
<input type="radio"/>	2	1s1 2s1	561.24900 [ref]	forbidden	2	0	1.0	3
<input type="radio"/>	4	1s1 2p1	568.81500 [ref]	0	2	1	1.0	1
<input type="radio"/>	5	1s1 2p1	568.86000 [ref]	0	2	1	1.0	3
<input type="radio"/>	6	1s1 2p1	568.95100 [ref]	0	2	1	1.0	5
<input type="radio"/>	3	1s1 2s1	569.68100 [ref]	0	2	0	0.0	1
<input type="radio"/>	7	1s1 2p1	574.79400 [ref]	resonance	2	1	0.0	3
<input type="radio"/>	8	1s1 3s1	662.45200 [ref]	0	3	0	1.0	3
<input type="radio"/>	10	1s1 3p1	664.48600 [ref]	0	3	1	1.0	1

Get transition information:

Select an element:      Select an ion:

Lower Level:     Upper Level:  (max=199)    Or list all levels in file:

FYI..., He-like series ... z: 2→1, y: 5→1, x: 6→1, w: 7→1, β1: 13→1, β2: 12→1  
 H-like series ... Lyα1: 4→1, Lyα2: 3→1, Lyβ1: 7→1, Lyβ2: 6→1  
 Fe XVII L-shell ... 15Å: 27→1, 17Å: 2→1 & 3→1

# Step 2 (Preparation)

## Modify “line file” for XSPEC

Don't forget to back up the original files.

```
cp /path/to/heasoft-6.27/spectral/modelData/apec_v3.0.9_nei_line.fits ./apec_v3.0.9_nodiagline_line.fits
cp /path/to/heasoft-6.27/spectral/modelData/apec_v3.0.9_nei_comp.fits ./apec_v3.0.9_nodiagline_comp.fits
```

Delete diagnostic lines from all the extensions of the `_line.fits` file.

Select	Lambda	Epsilon	Element	Ion	Ion_drv	UpperLev	LowerLev
1E	1E	1J	1J	1J	1J	1J	1J
All	A	photons cm <sup>3</sup> s <sup>-1</sup>					
Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify
9630	7.229827E+01	2.506400E-18	8	7	7		
9631	7.229827E+01	2.866599E-20	8	7	8		
9632	2.209772E+01	4.707906E-16	8	7	8	2	1
9633	2.209772E+01	1.744599E-14	8	7	7	2	1
9634	2.180364E+01	3.869052E-15	8	7	7	5	1
9635	2.180364E+01	1.083231E-16	8	7	8		
9636	2.180102E+01	2.926336E-17	8	7	7		
9637	2.180102E+01	7.594211E-19	8	7	8		
9638	2.160150E+01	6.756944E-14	8	7	7	7	1
9639	2.160150E+01	2.516472E-16	8	7	8	7	1
9640	1.977000E+01	1.972579E-18	8	7	8	10001	7
9641	1.939300E+01	4.568696E-17	8	7	8	10017	7
9642	1.934200E+01	2.811555E-20	8	7	8	10018	5
9643	1.933900E+01	1.532120E-18	8	7	8	10020	6
9644	1.933700E+01	5.107082E-19	8	7	8	10020	5

Index	Extension	Type	Dimension
0	Primary	Image	0
1	PARAMETERS	Binary	5 cols X 51 rows
2	EMISSIVITY	Binary	10 cols X 29627 rows
3	EMISSIVITY	Binary	10 cols X 28463 rows
4	EMISSIVITY	Binary	10 cols X 27727 rows
5	EMISSIVITY	Binary	10 cols X 27498 rows

⋮  
50 (or 200 in the latest version) extensions or temperature grids

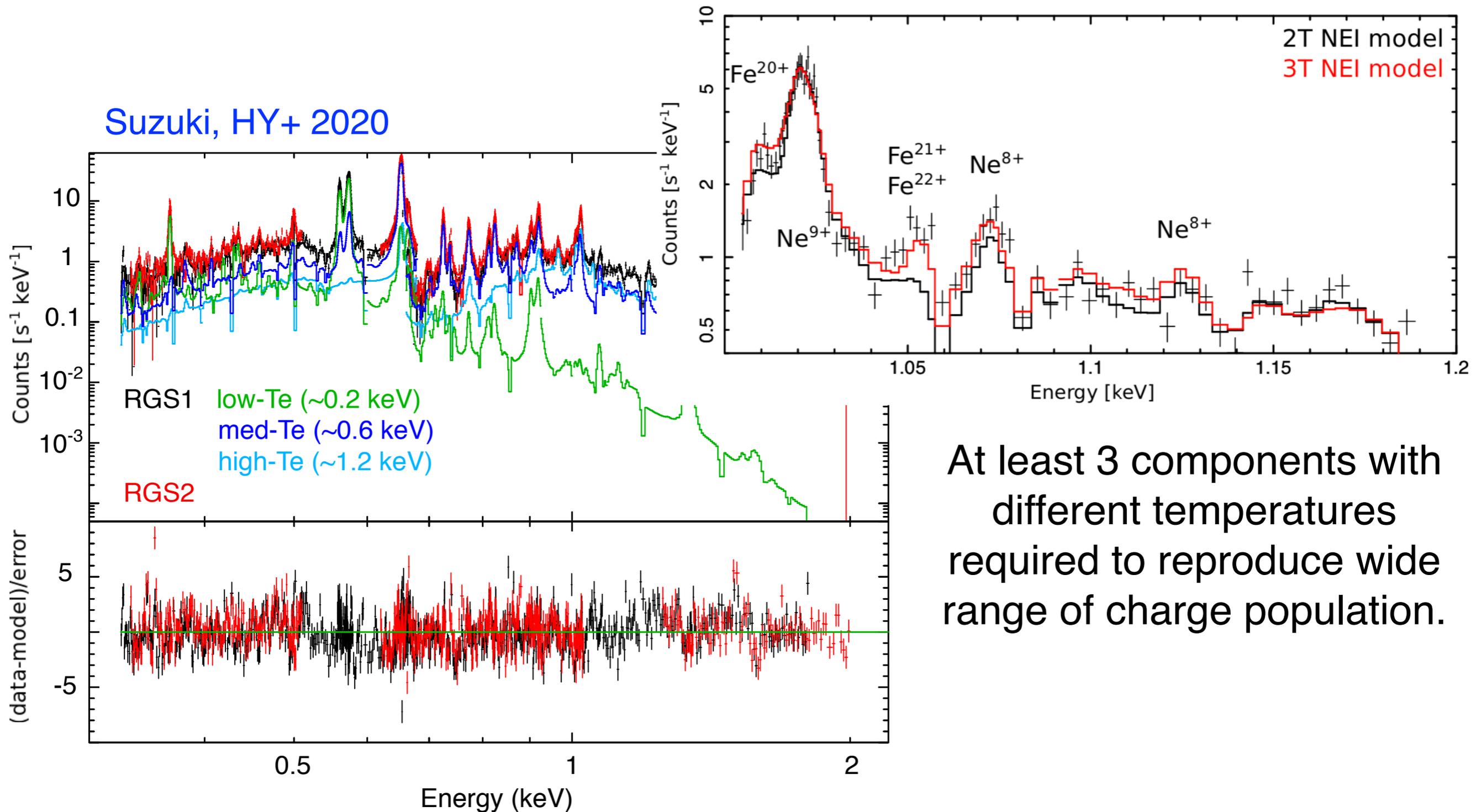
```
fselect infile[ext] outfile '!(Element==8 && Ion==7 && UpperLev==2 && LowerLev==1)'
```

```
fselect infile[ext] outfile '!(Element==8 && Ion==7 && UpperLev==7 && LowerLev==1)'
```

...

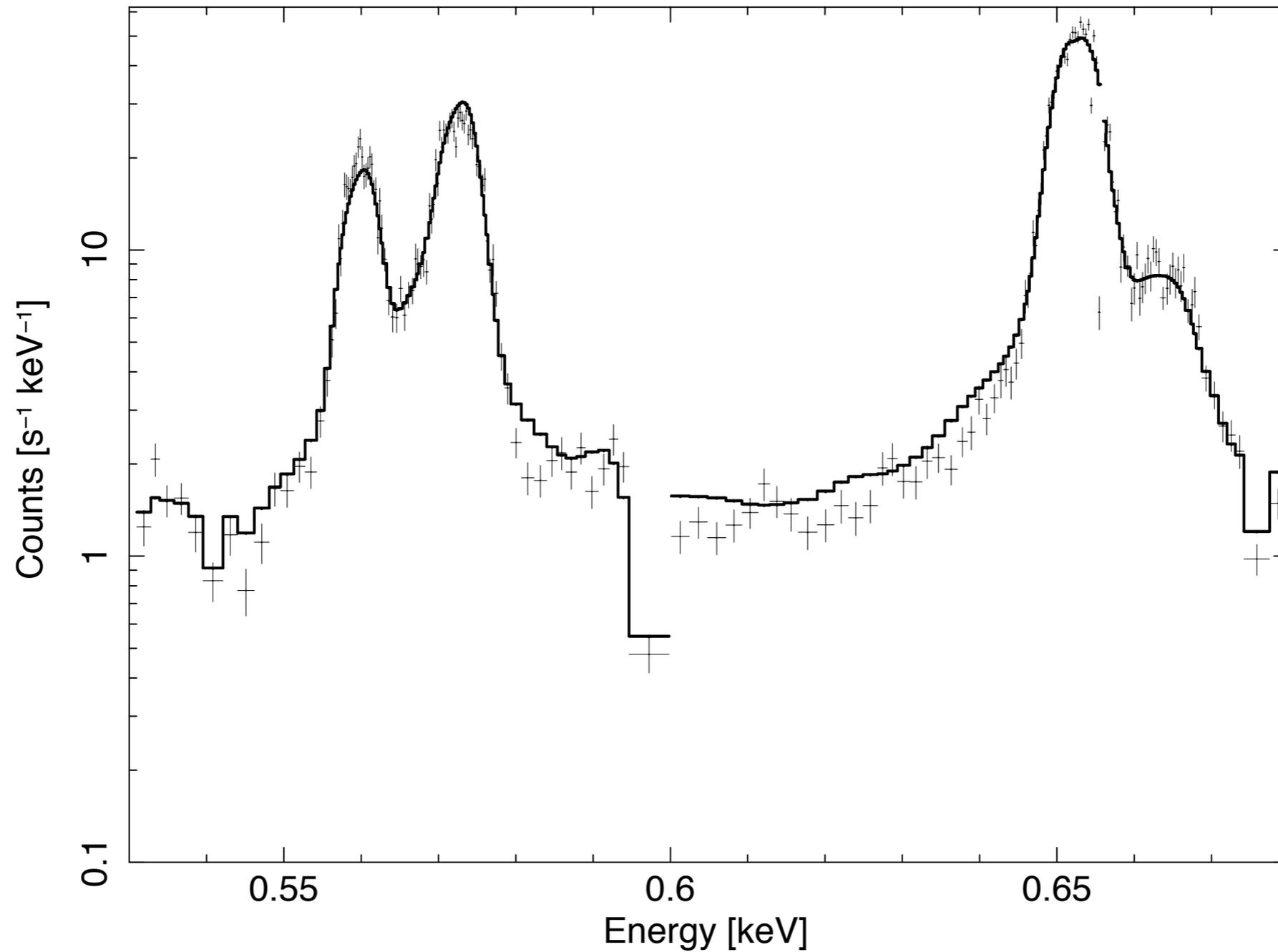
# Step 3

Find approx model to fit your spectra



# Step 4

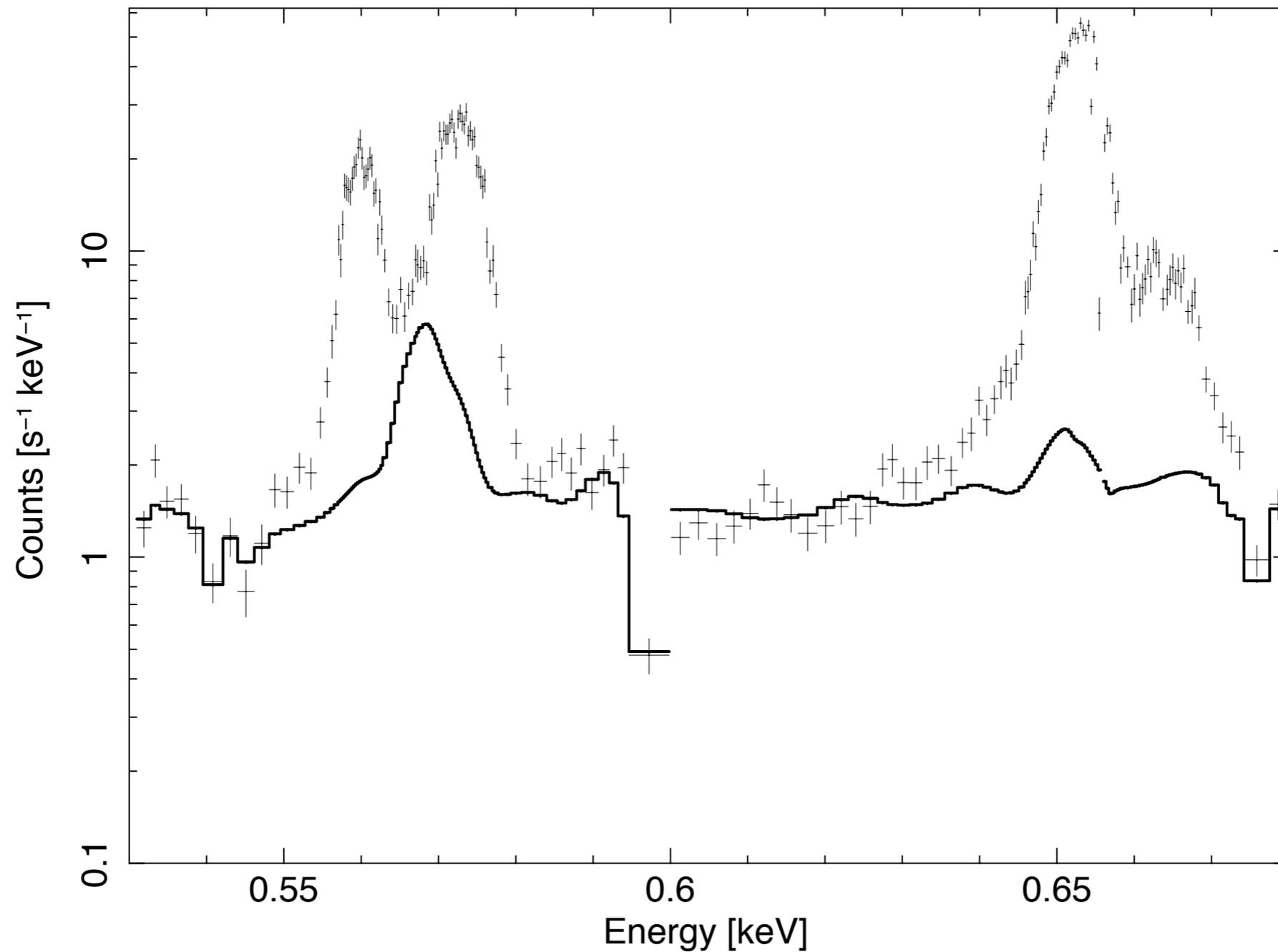
Replace NEI model with NoDiagnosticLine NEI



# Step 4

Replace NEI model with NoDiagnosticLine NEI

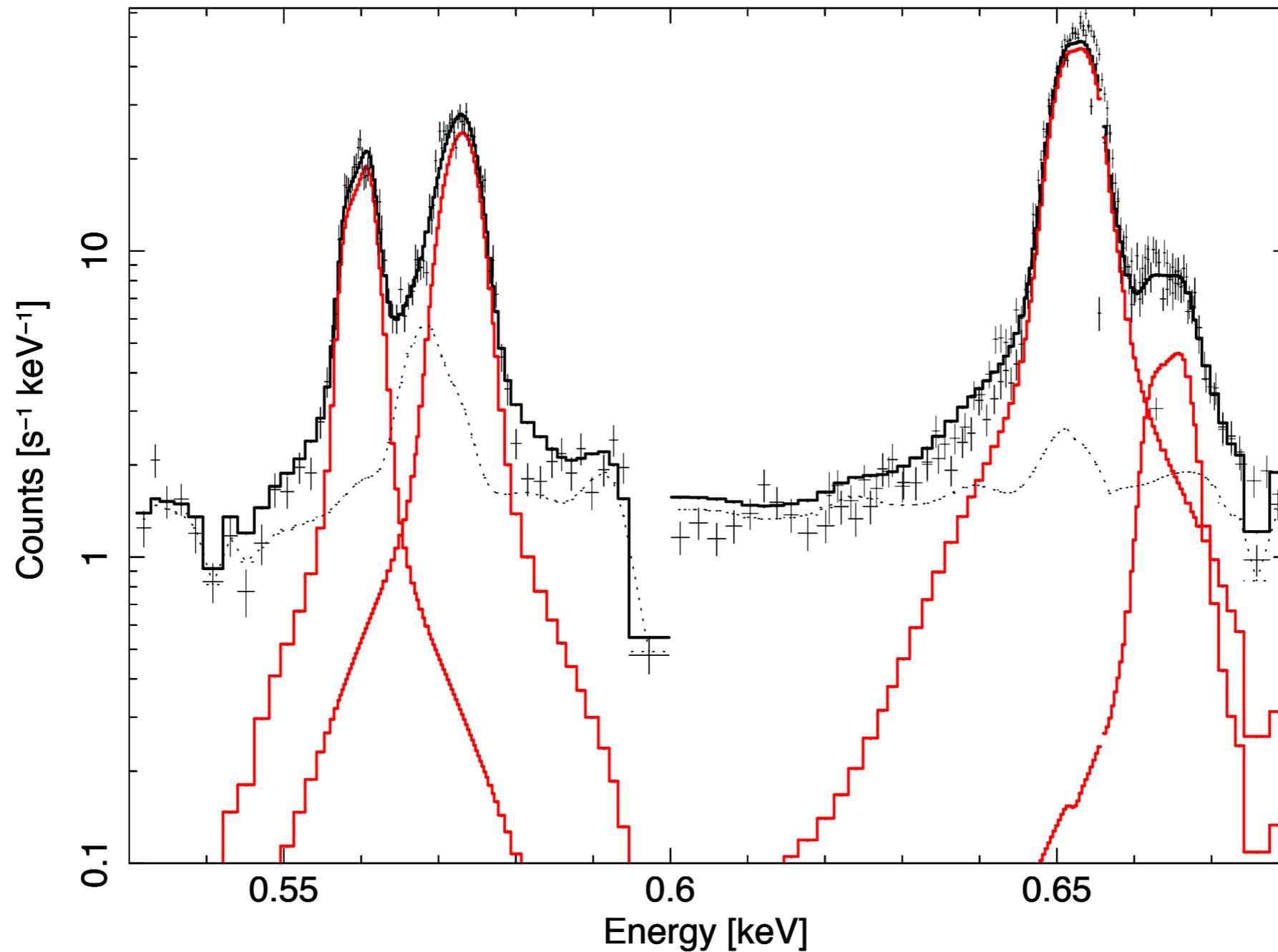
```
XSPEC> xset NEIAPECROOT ./apec_v3.0.9_nodiagline
```



# Step 4

Replace NEI model with NoDiagnosticLine NEI

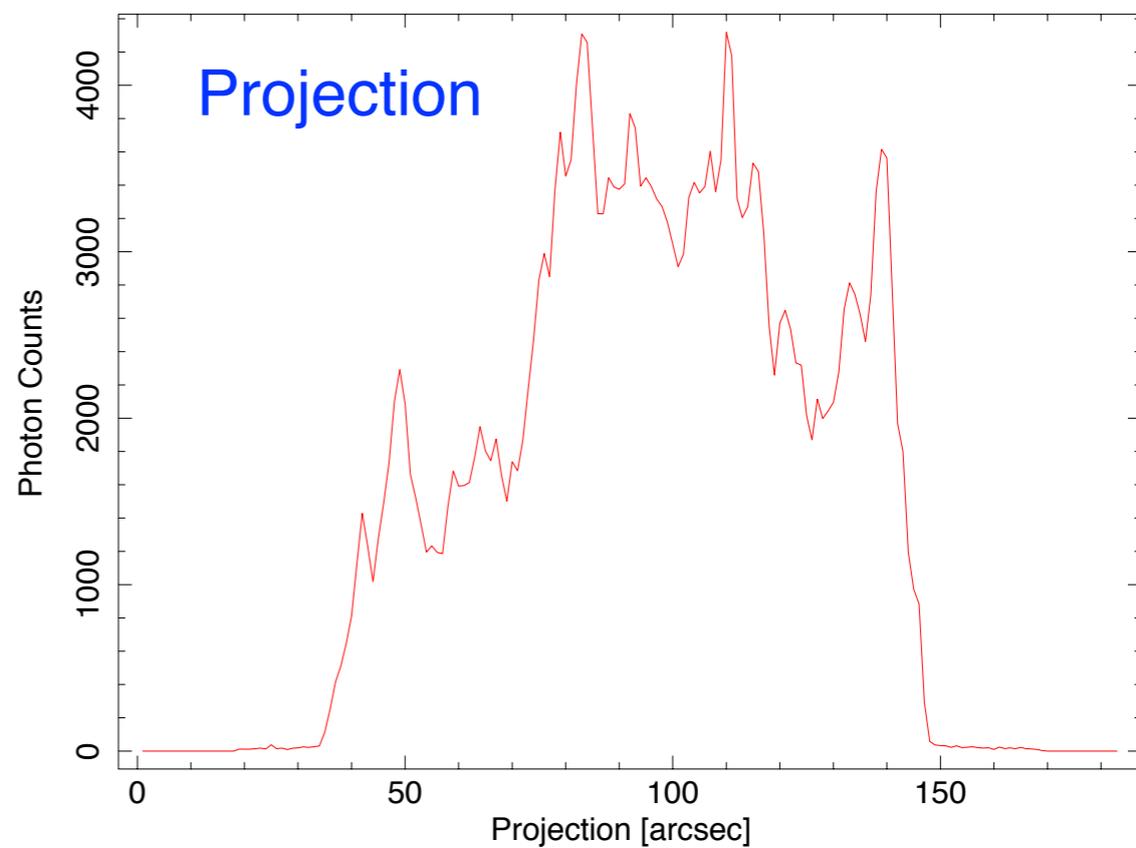
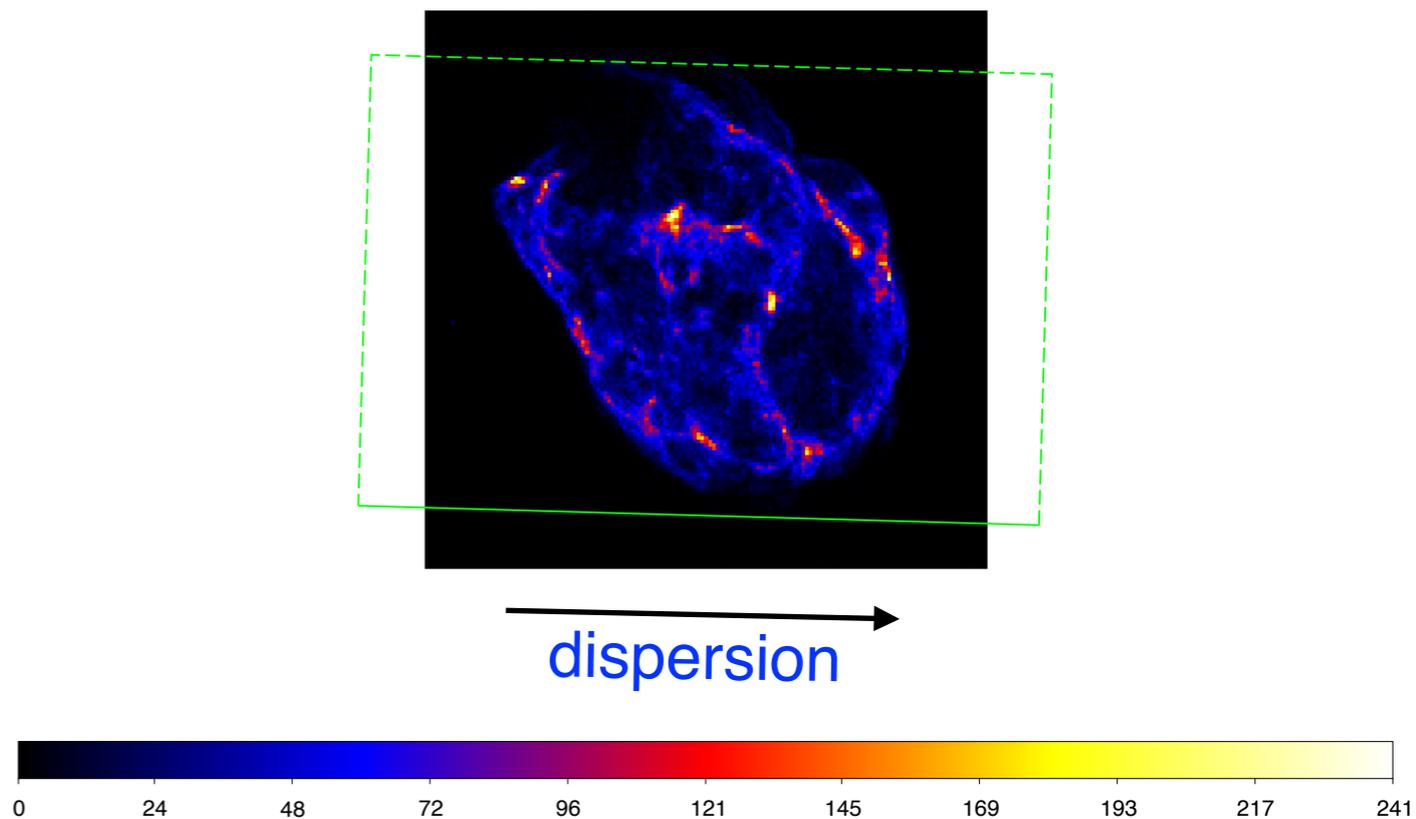
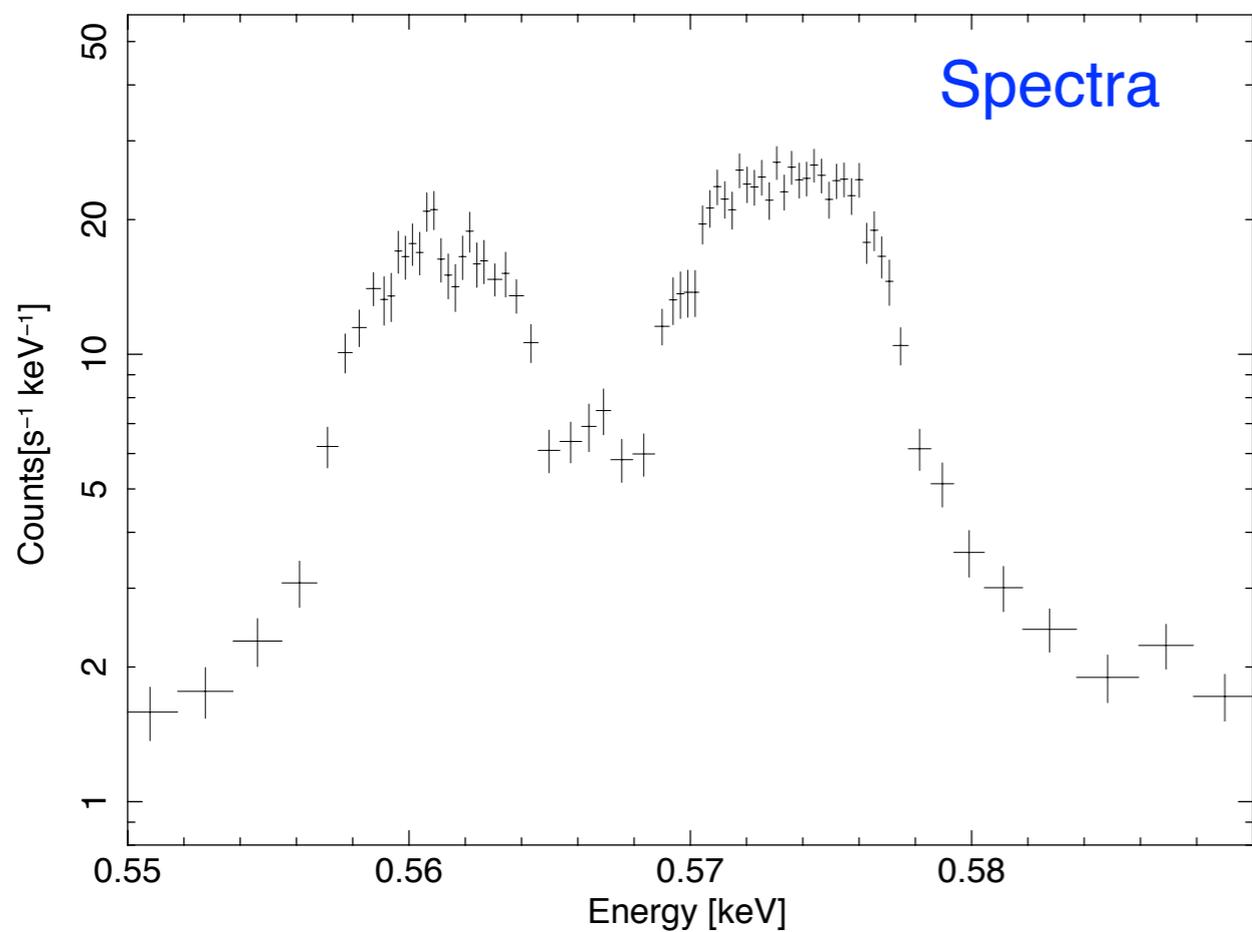
```
XSPEC> xset NEIAPECROOT ./apec_v3.0.9_nodiagline
```



# Our data consisted of 9 observations with different roll angles

obsID	Roll angle	ontime (ksec)
137551101	88.759	16.161
129341301	88.837	25.457
157160601	152.293	26.849
157160801	160.347	33.158
157161001	180.553	29.951
157360201	196.818	26.293
157360501	251.66	32.482
125100201	339.77	23.904

obsID	PA-PNT	ontime(ksec)	GTI(ksec)
129341301	88.837	25.457	20.340



obsID

157160801

PA-PNT

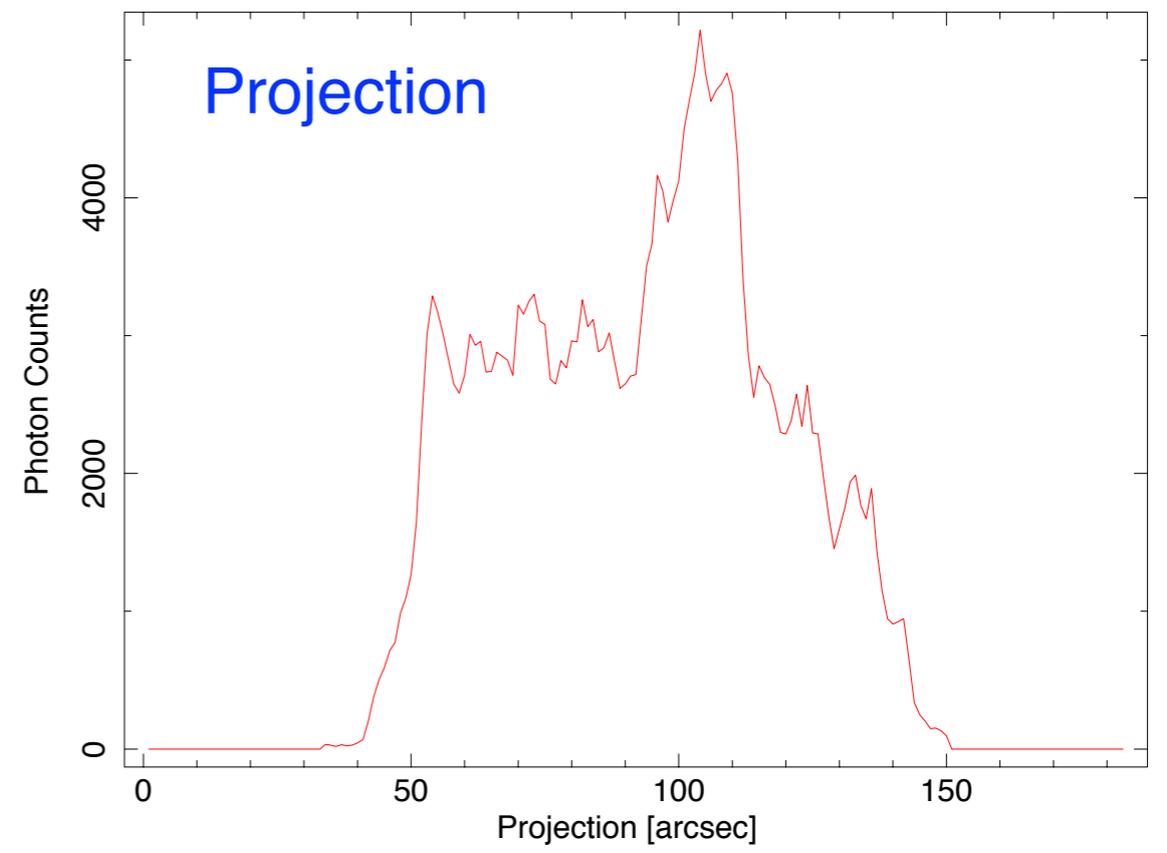
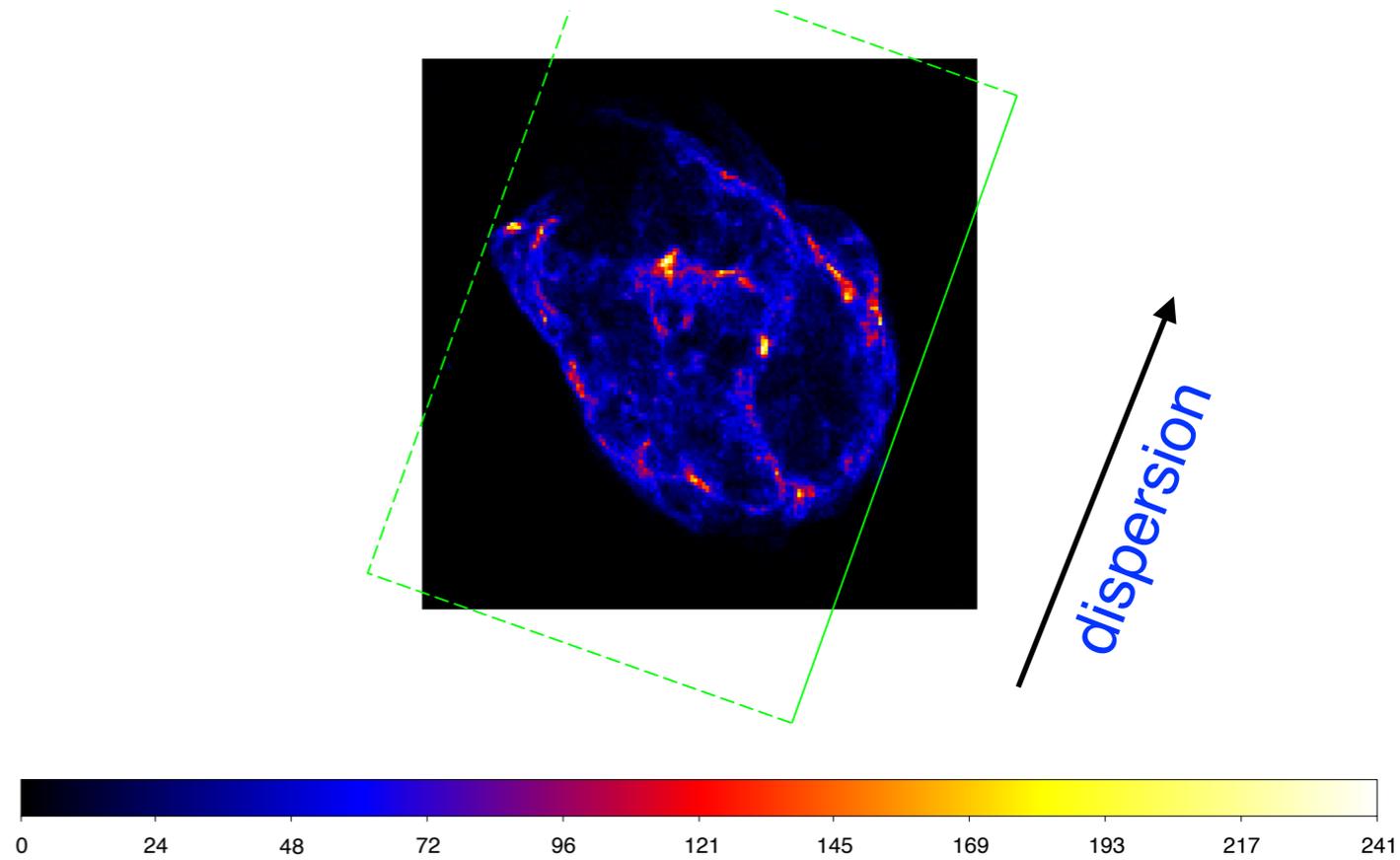
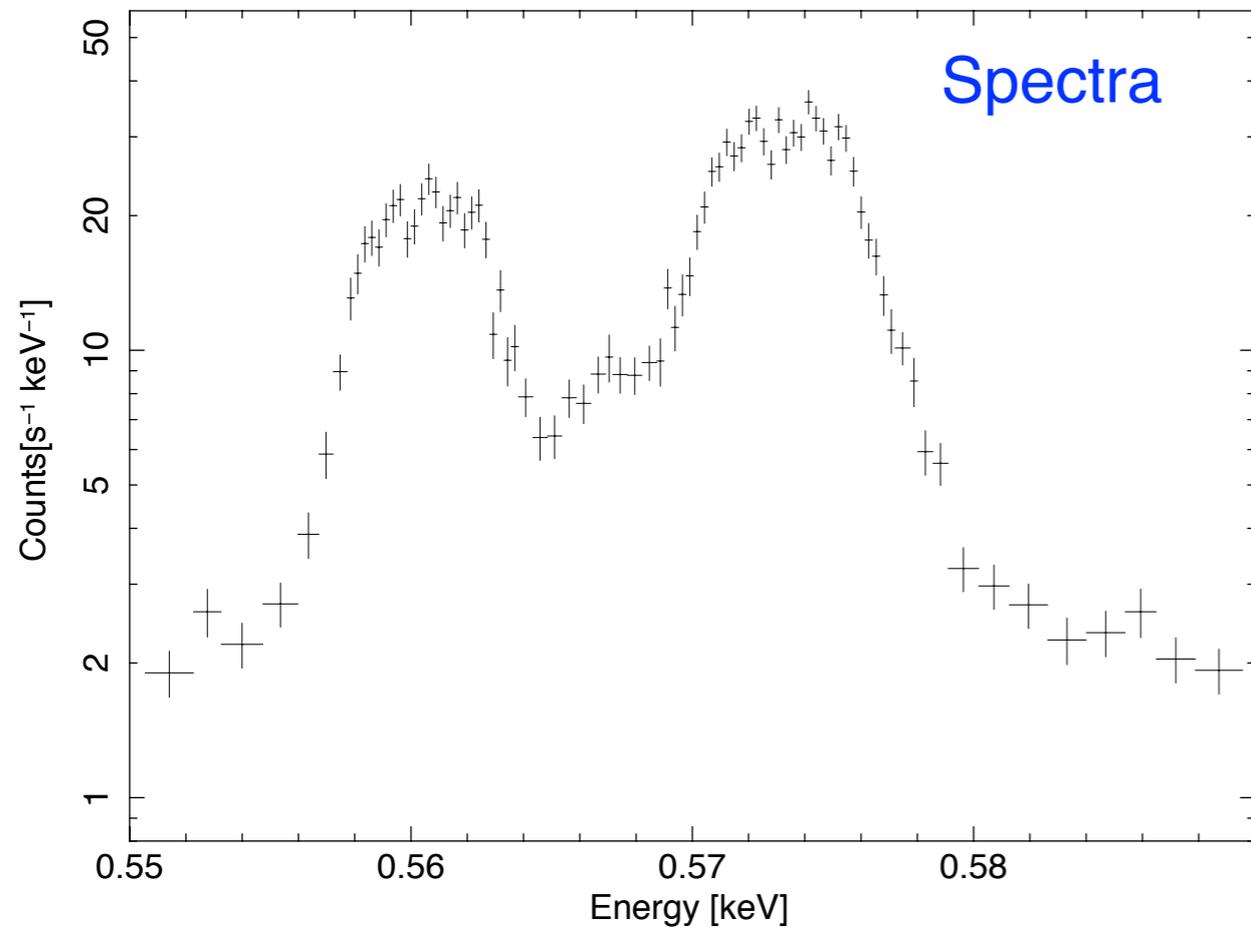
160.347

ontime(ksec)

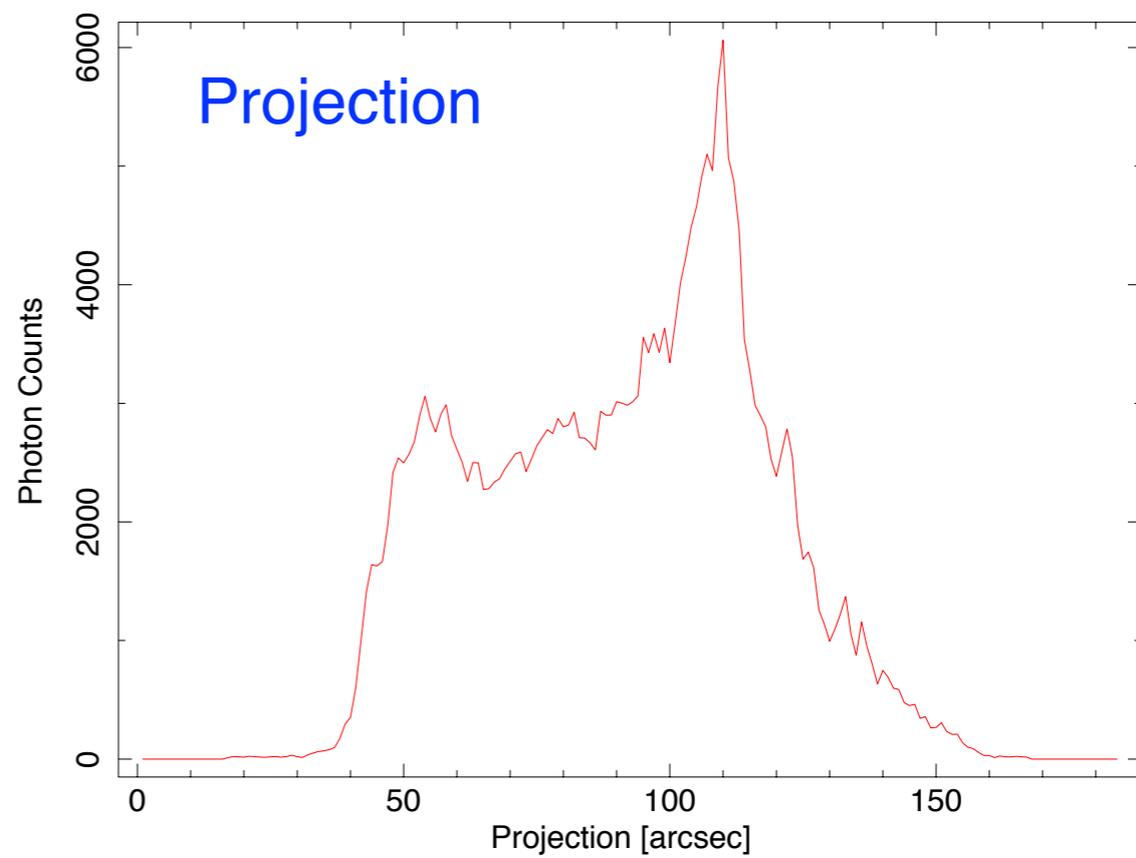
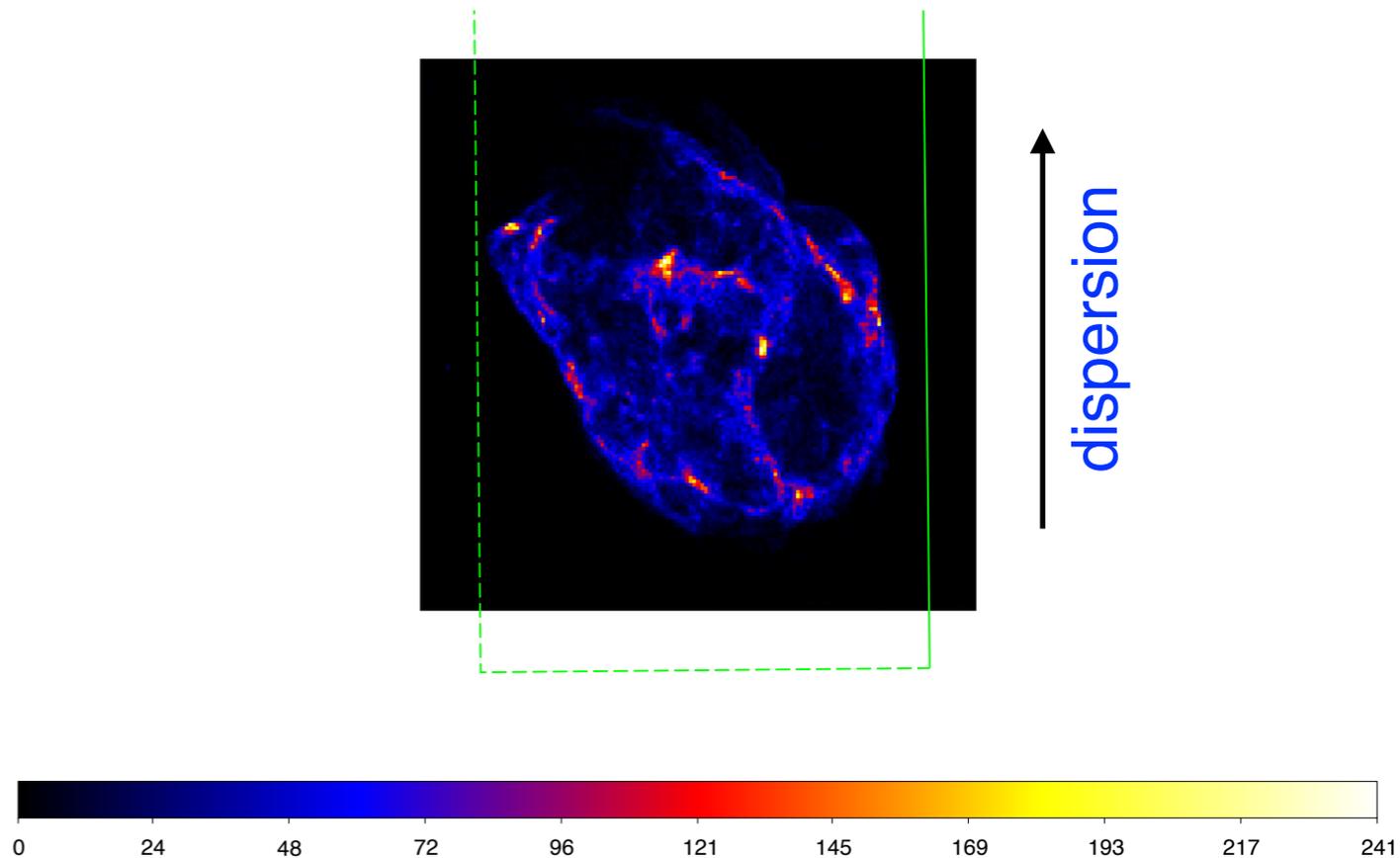
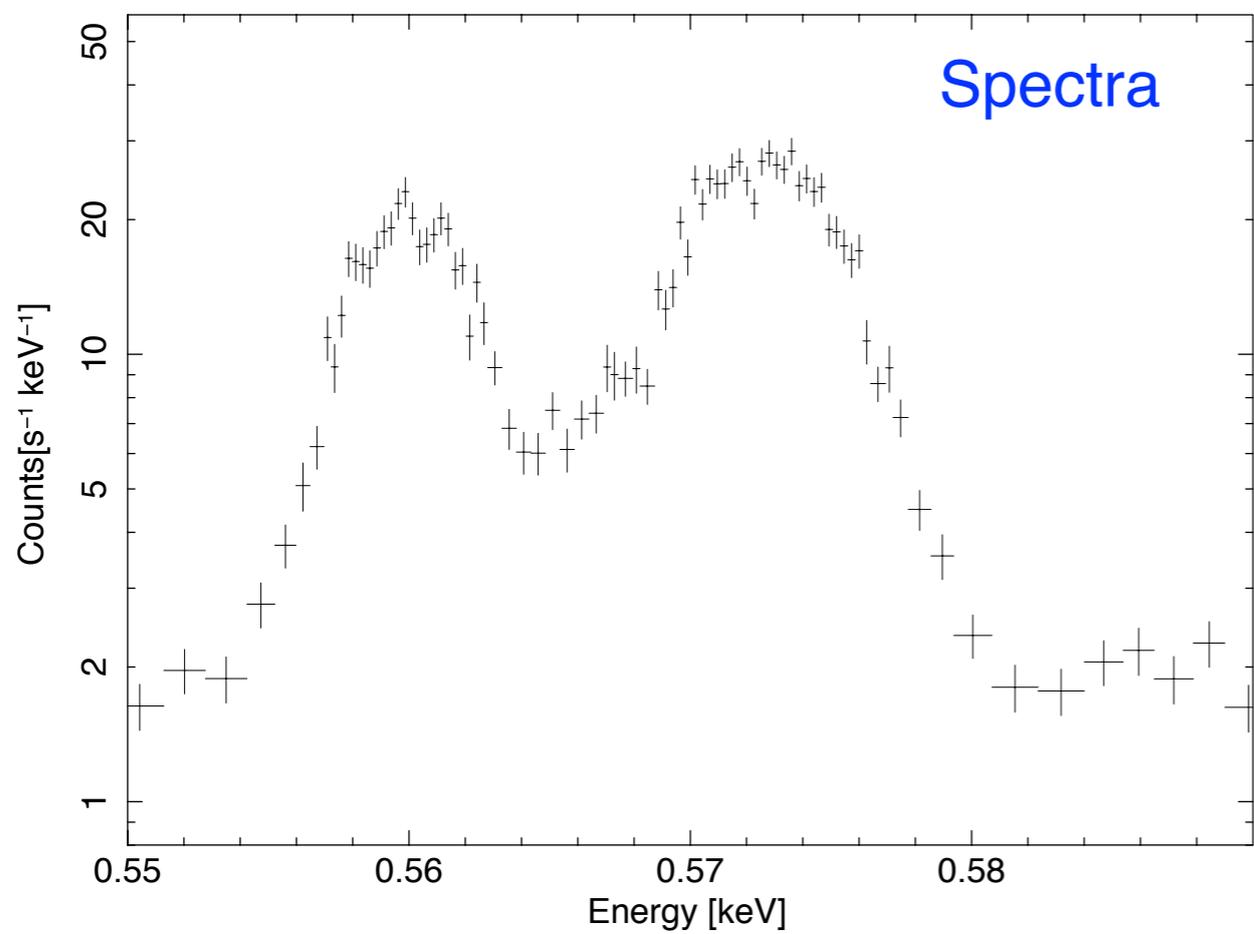
33.158

GTI(ksec)

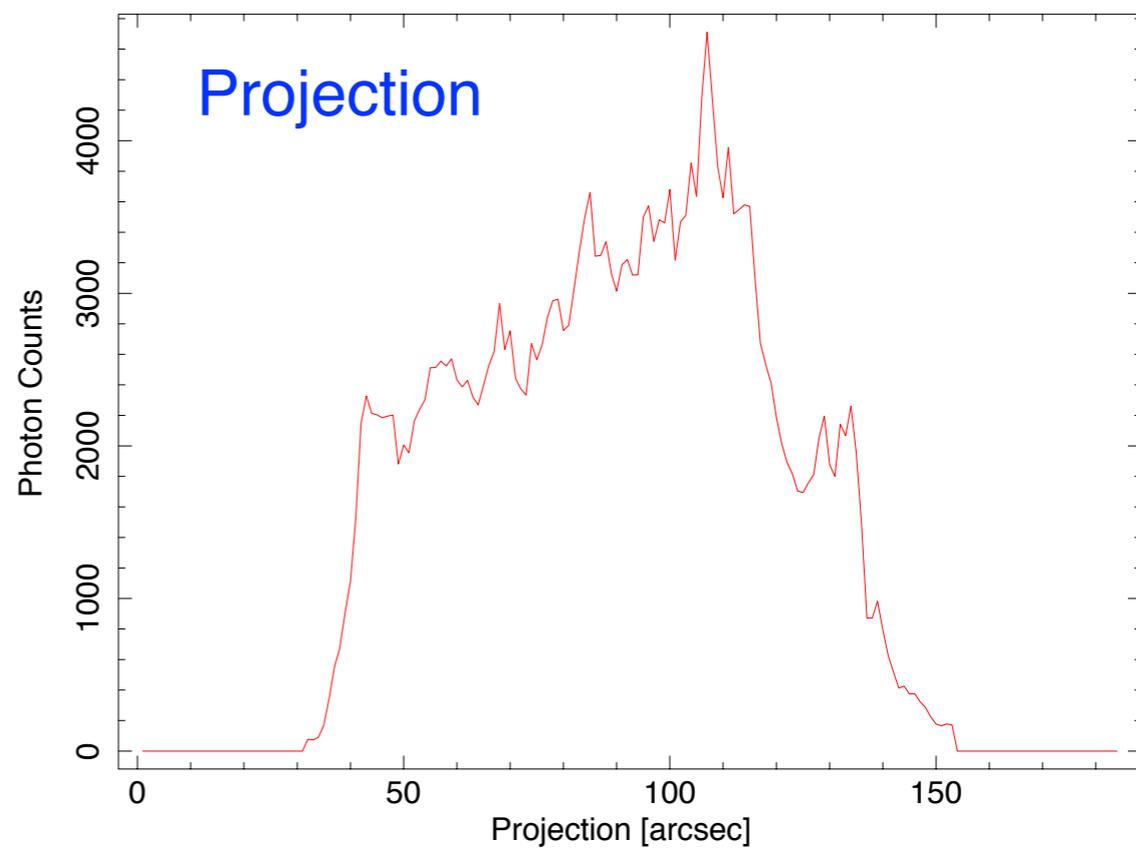
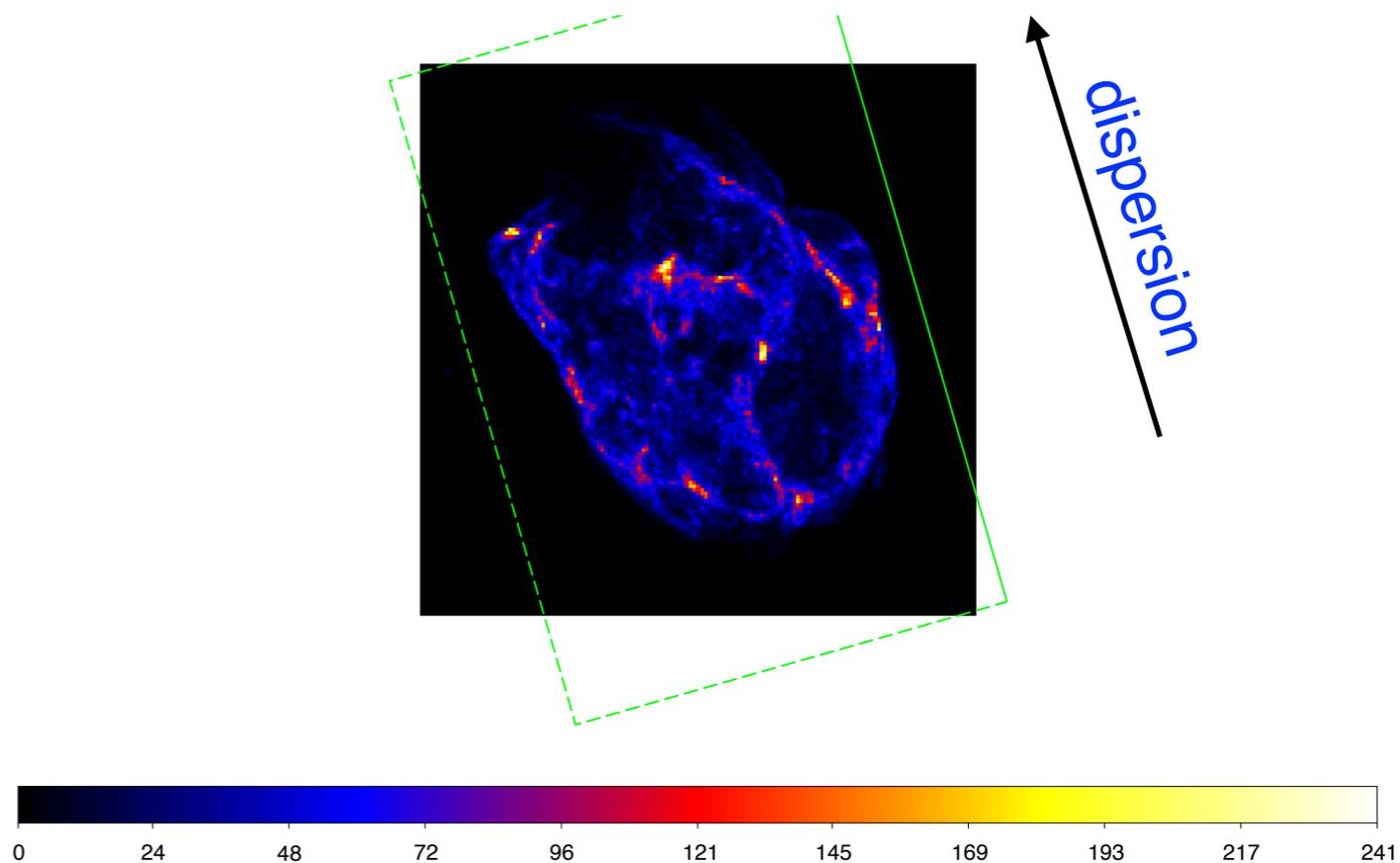
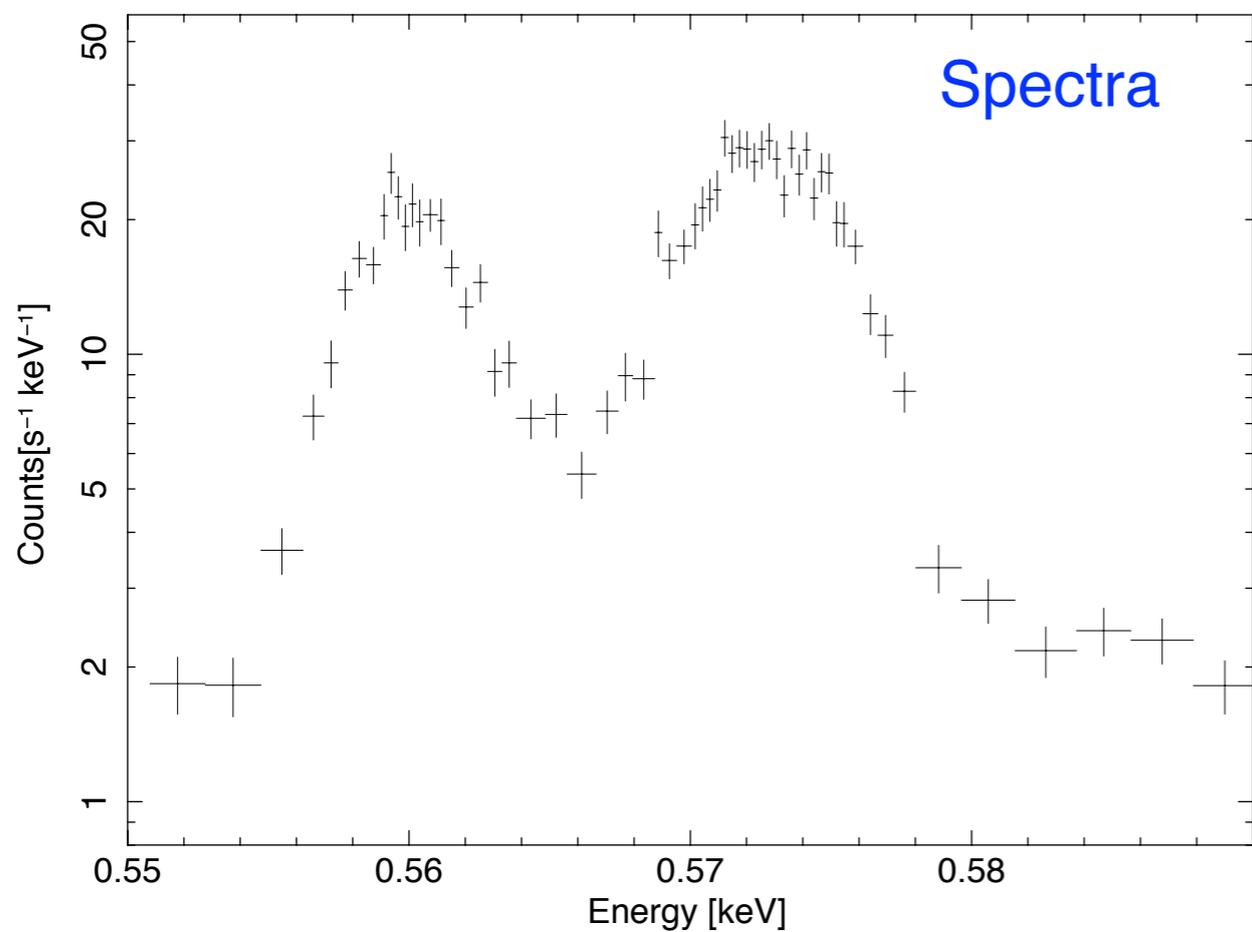
29.090



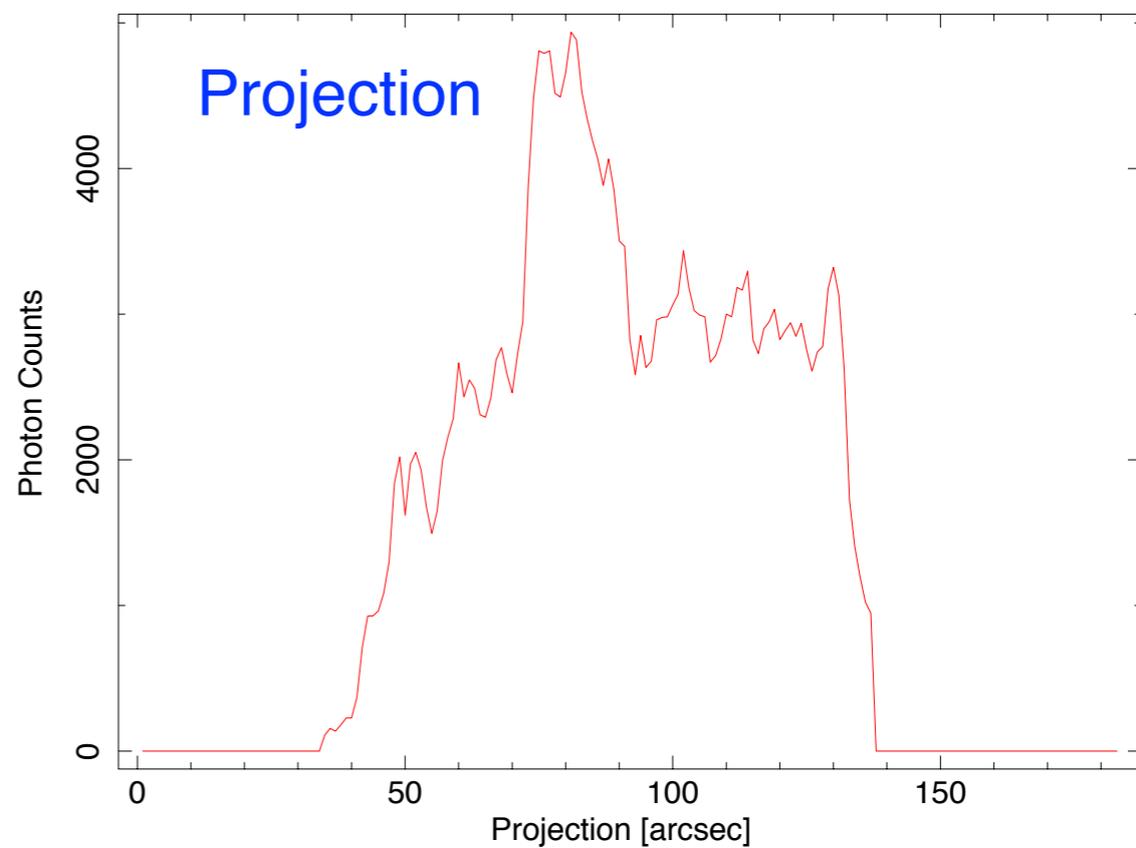
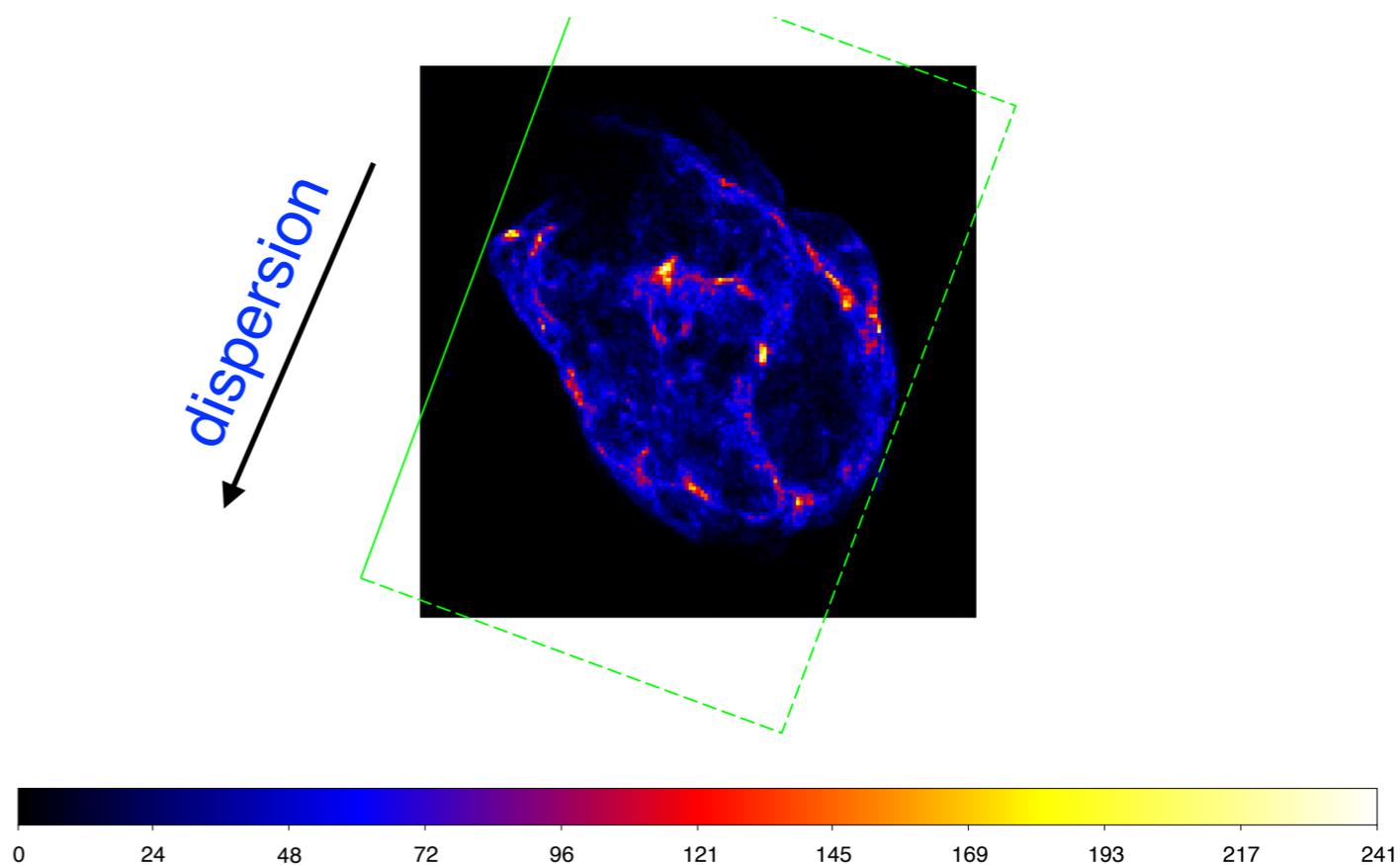
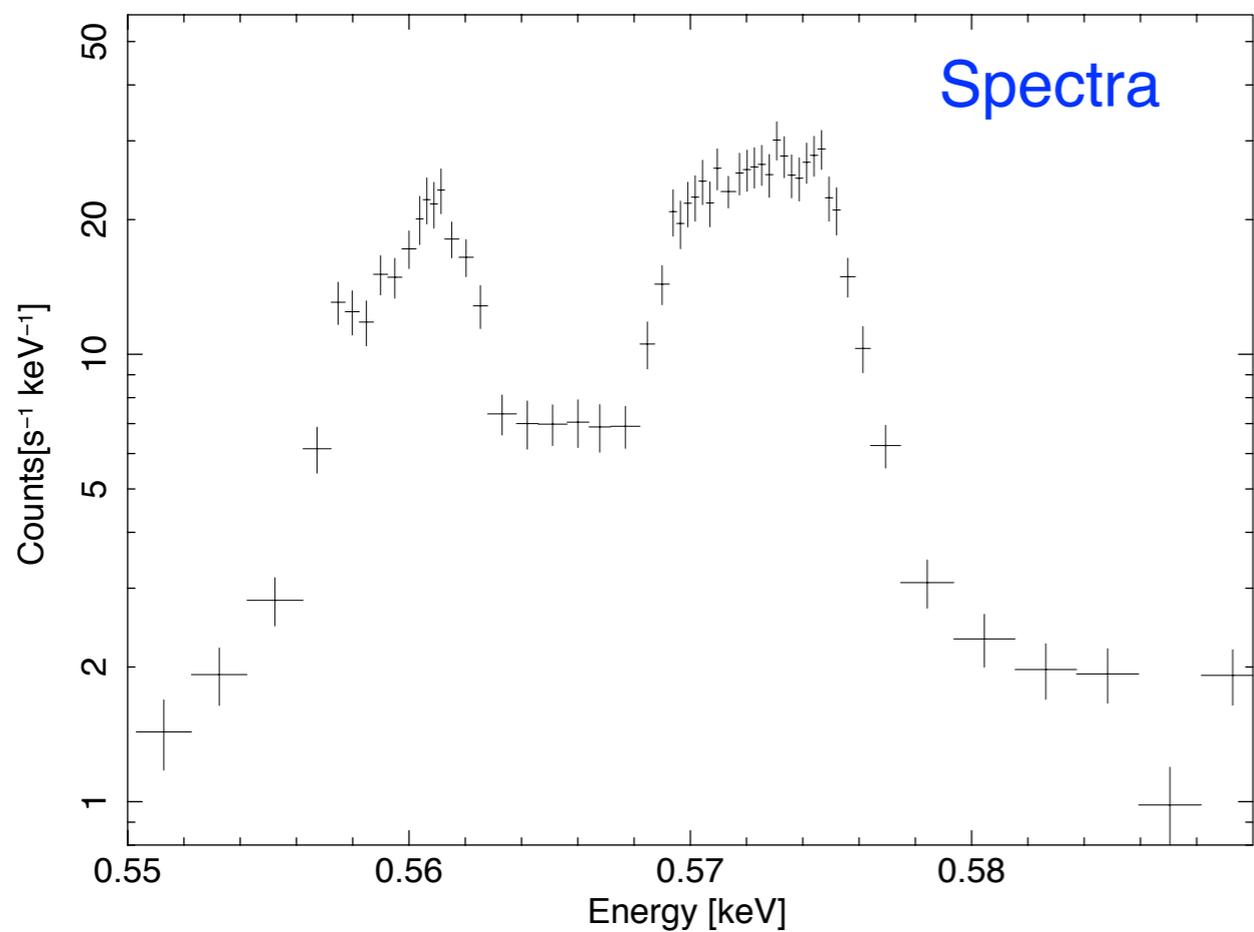
obsID	PA-PNT	ontime(ksec)	GTI(ksec)
157161001	180.553	29.951	29.910



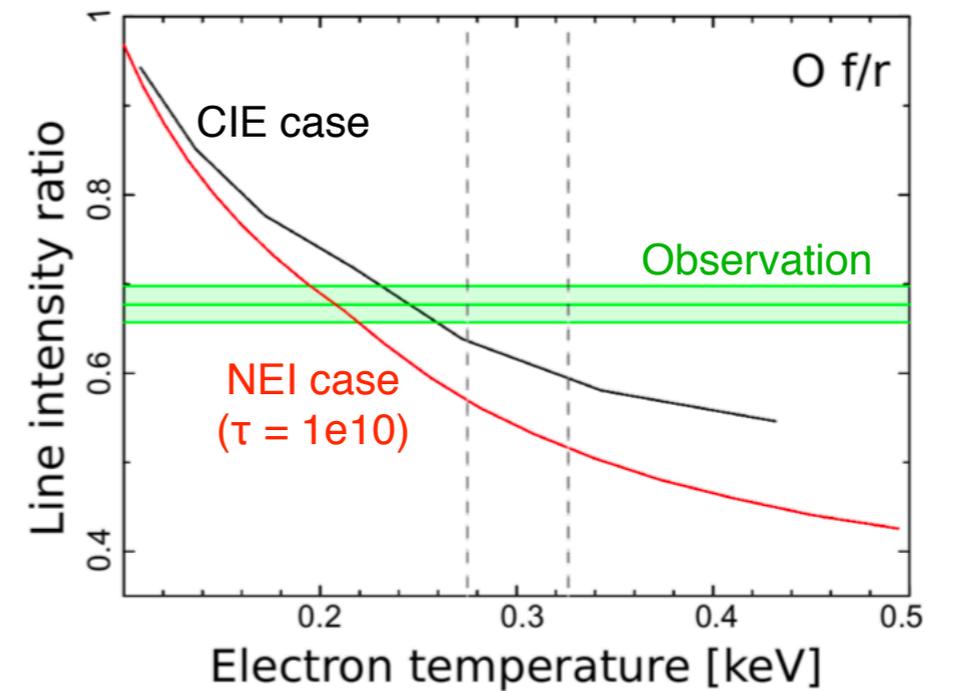
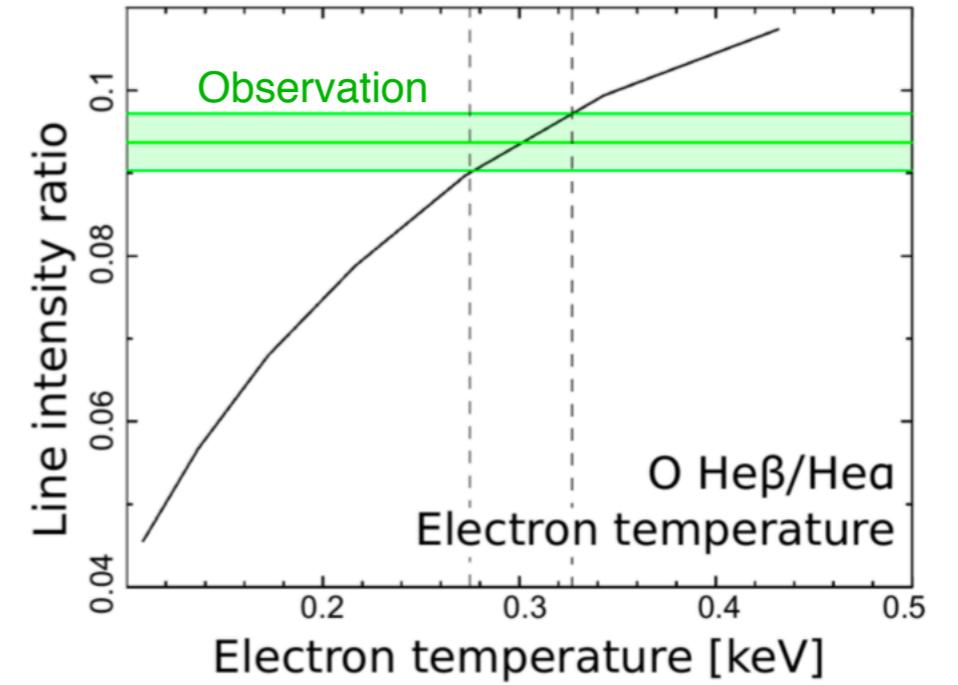
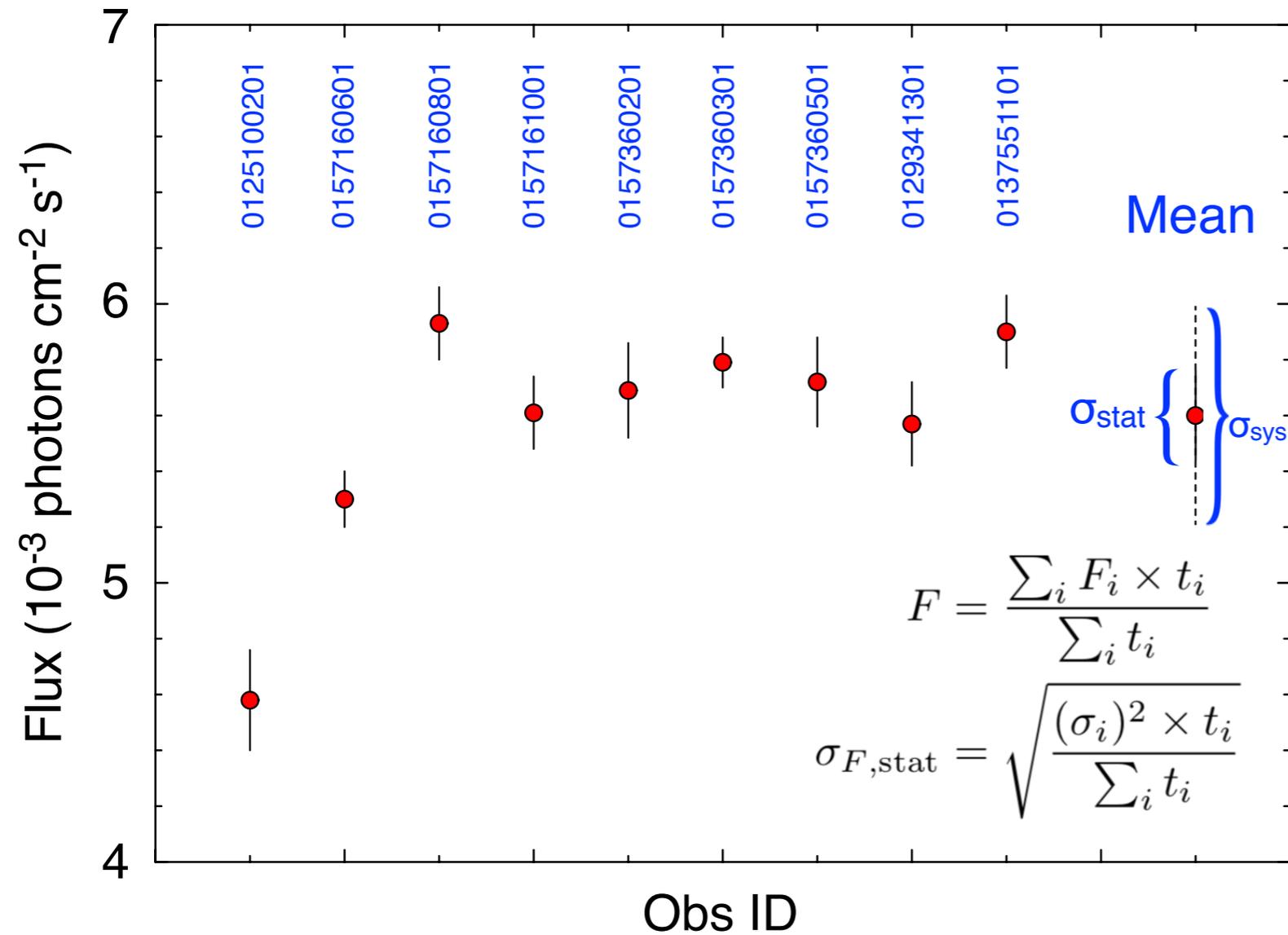
obsID PA-PNT ontime(ksec) GTI(ksec)  
157360201 196.818 26.293 15.020



obsID	PA-PNT	ontime(ksec)	GTI(ksec)
125100201	339.77	23.904	13.63



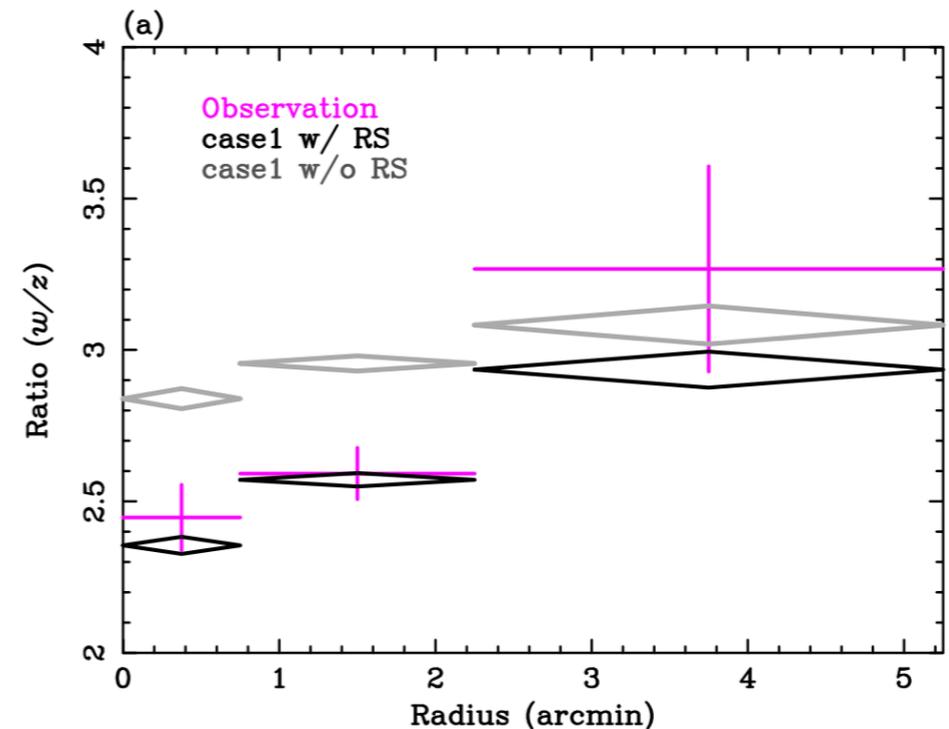
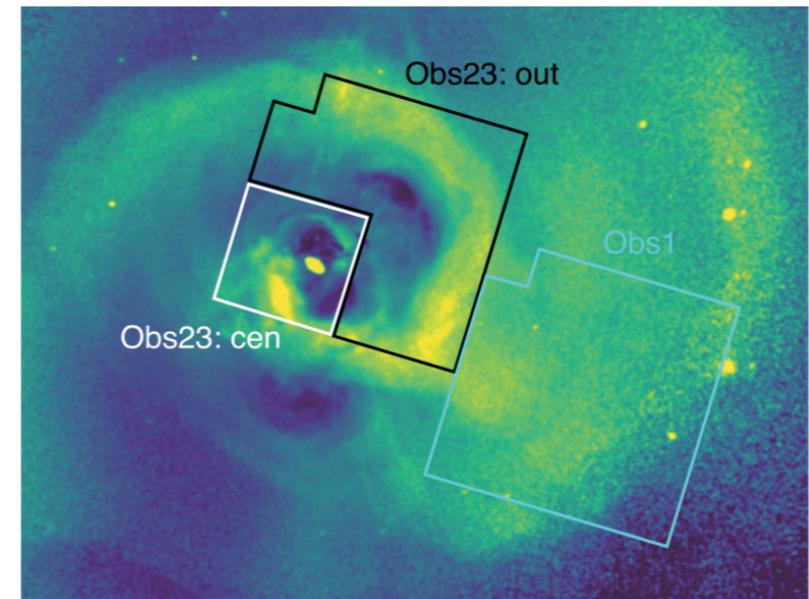
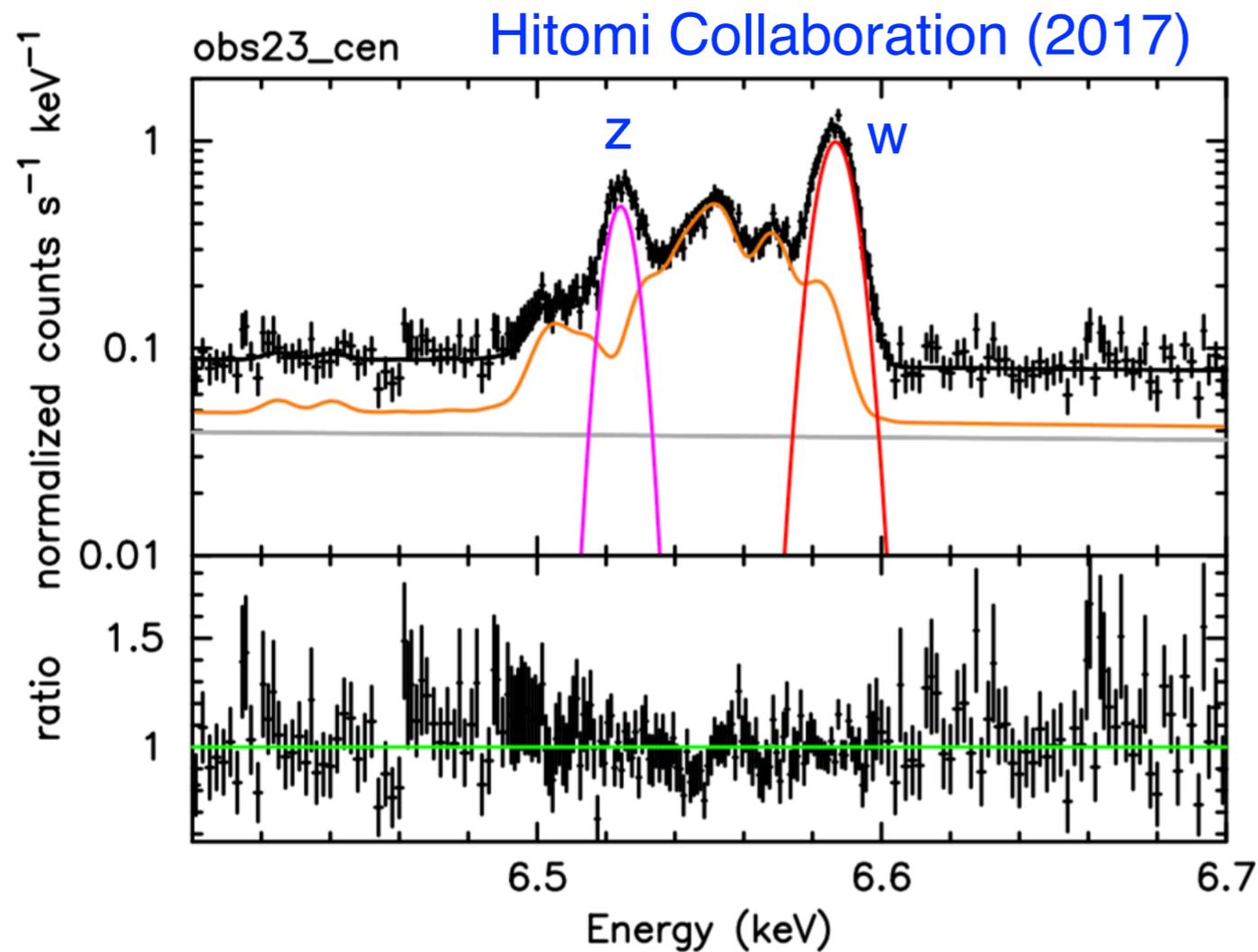
# Results



Mean of multiple observations can easily be calculated

# Hitomi observation of Perseus cluster

Applied the same method to confirm resonance scattering



Ideally, software should allow users to do such analysis more easily.

SPEX has a function to eliminate emission from certain 'ions'.

SPEX> ions ignore ion 8 7 — to eliminate O VII emission

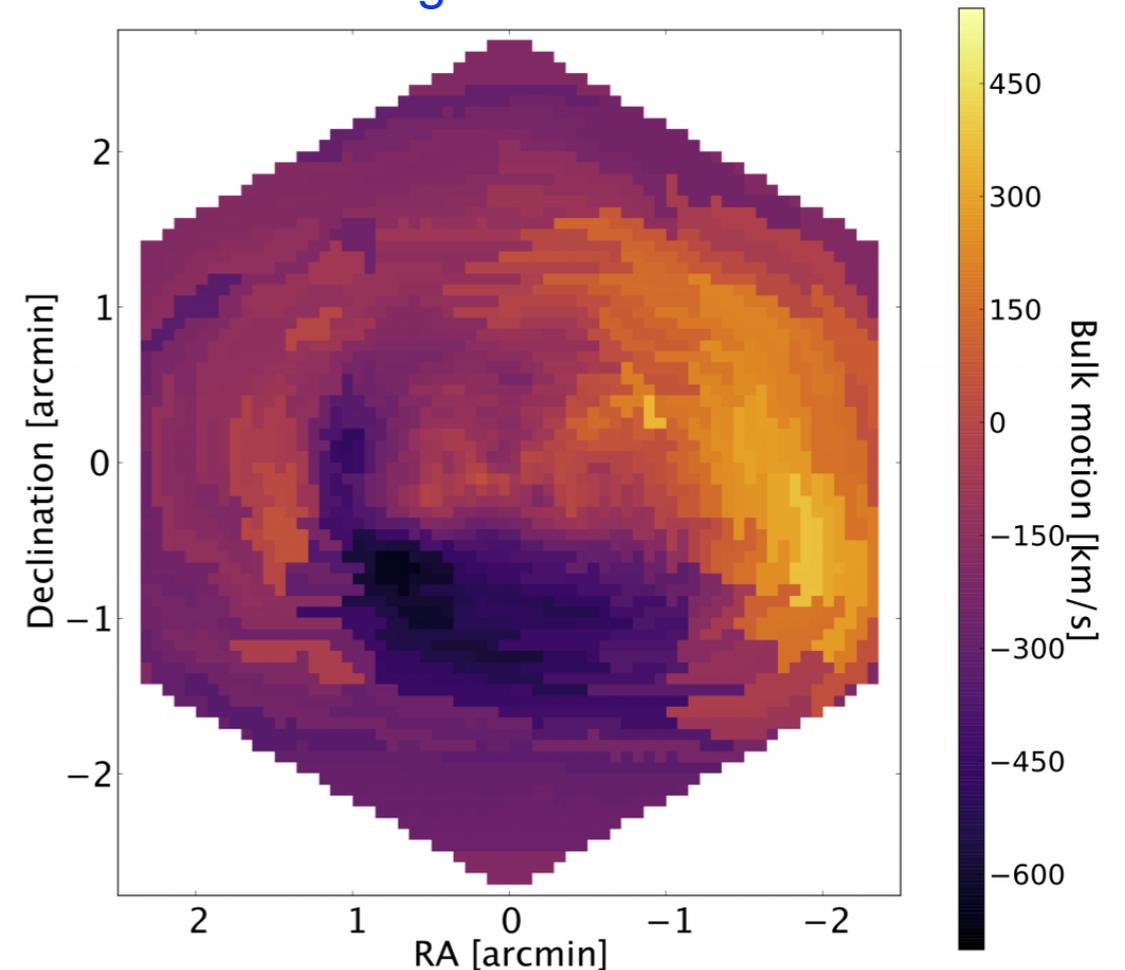
# Prospects for emission line diagnostics with $\mu$ -calorimeters

Non-dispersive spectrometer

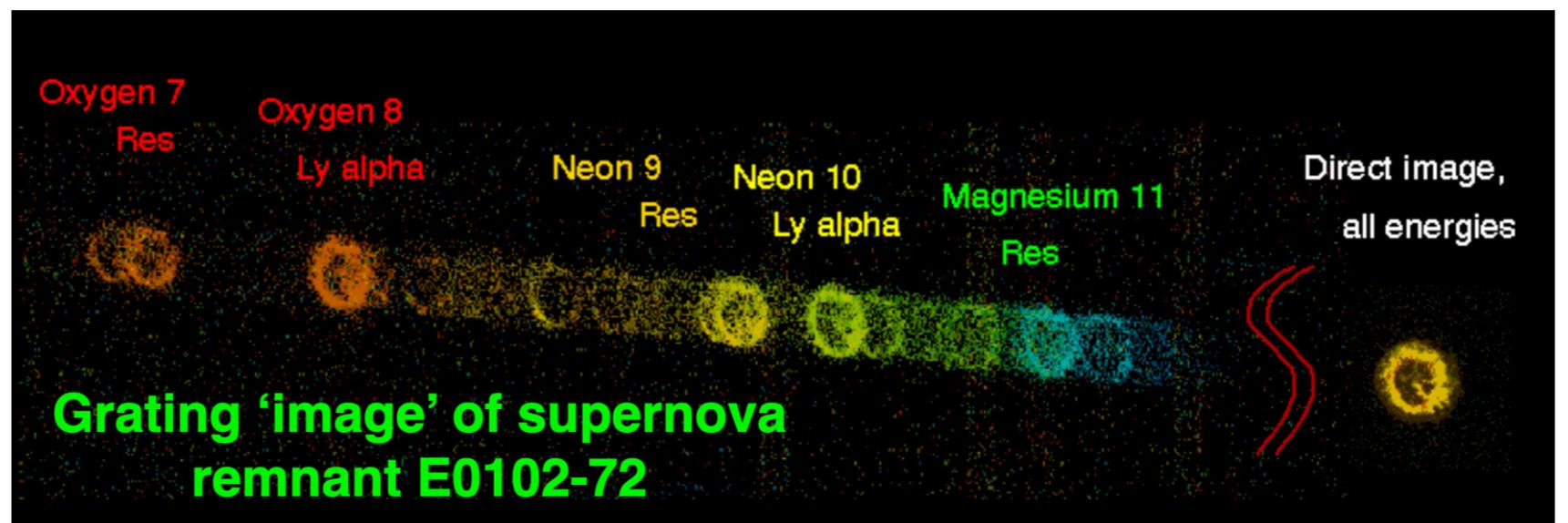
Spectra and images obtained simultaneously.

Great advantage for extended objects, e.g., clusters, SNRs

X-IFU mock image of the Perseus cluster



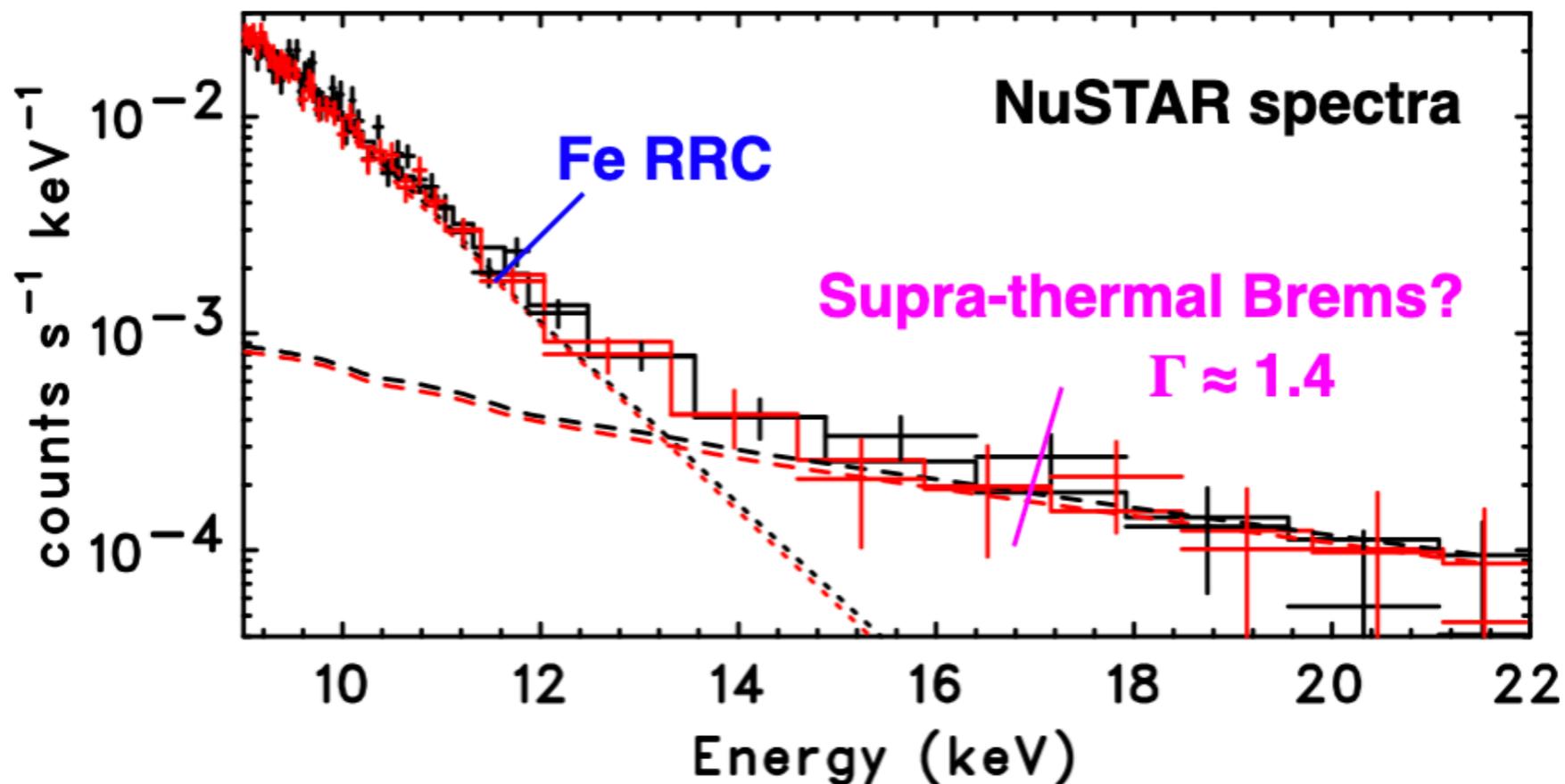
Spectral and imaging information degenerated in grating data



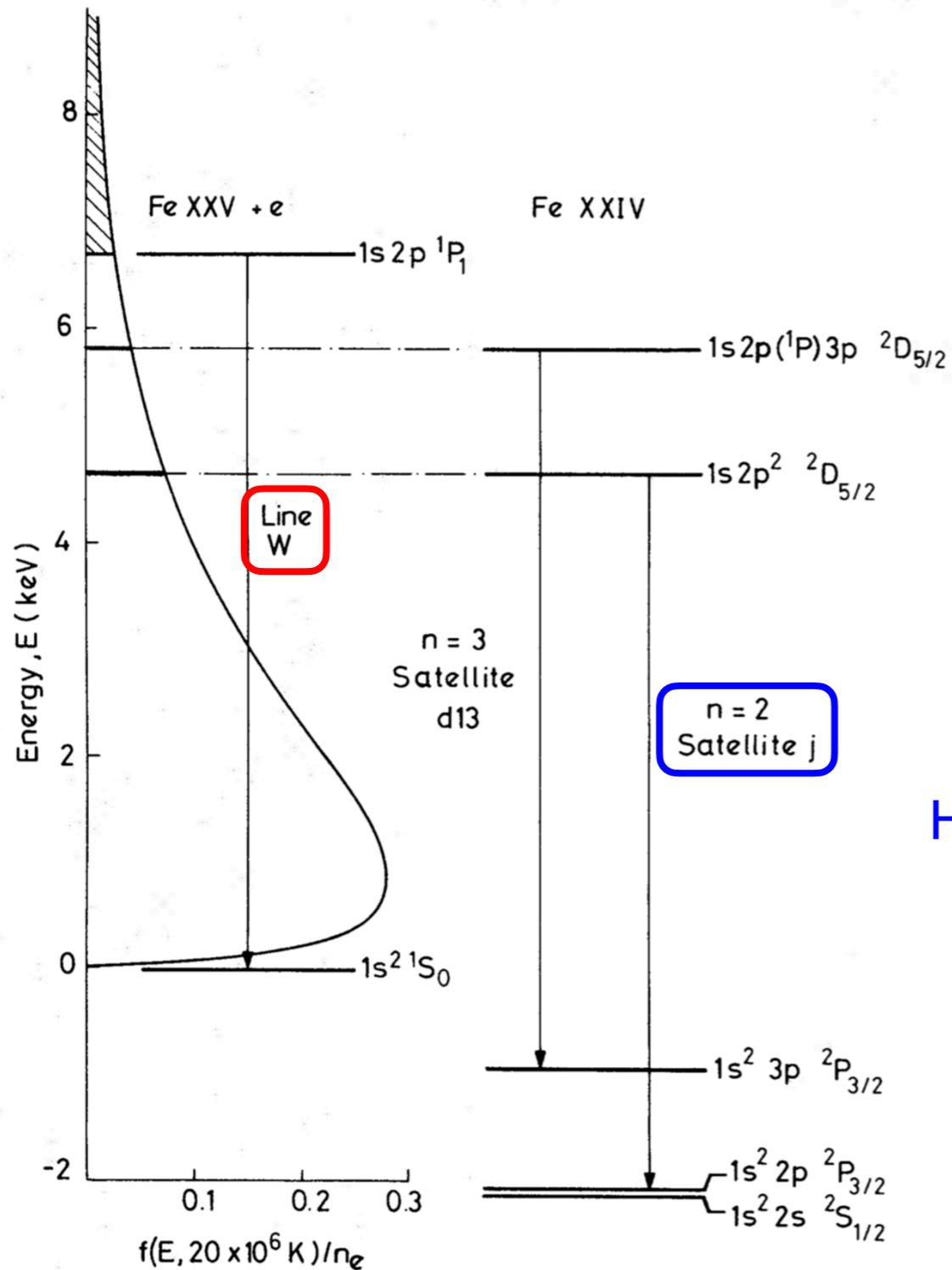
# Search for evidence of non-Maxwellian electron energy distribution in W49B

XRISM observation planning led by Makoto Sawada

- Most prominent recombining plasma (e.g., HY+2018)
- NuSTAR detected possible supra-thermal bremsstrahlung (Tanaka, HY+2018)



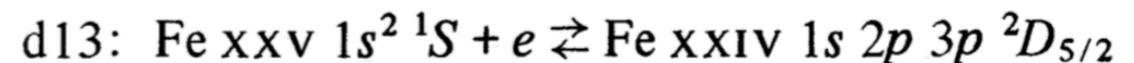
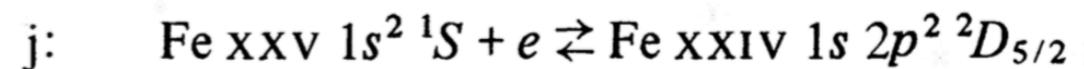
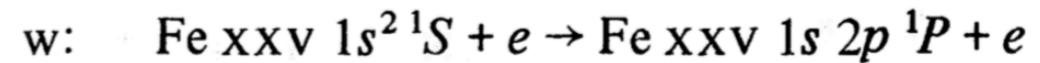
# Diagnostic for non-Maxwellian



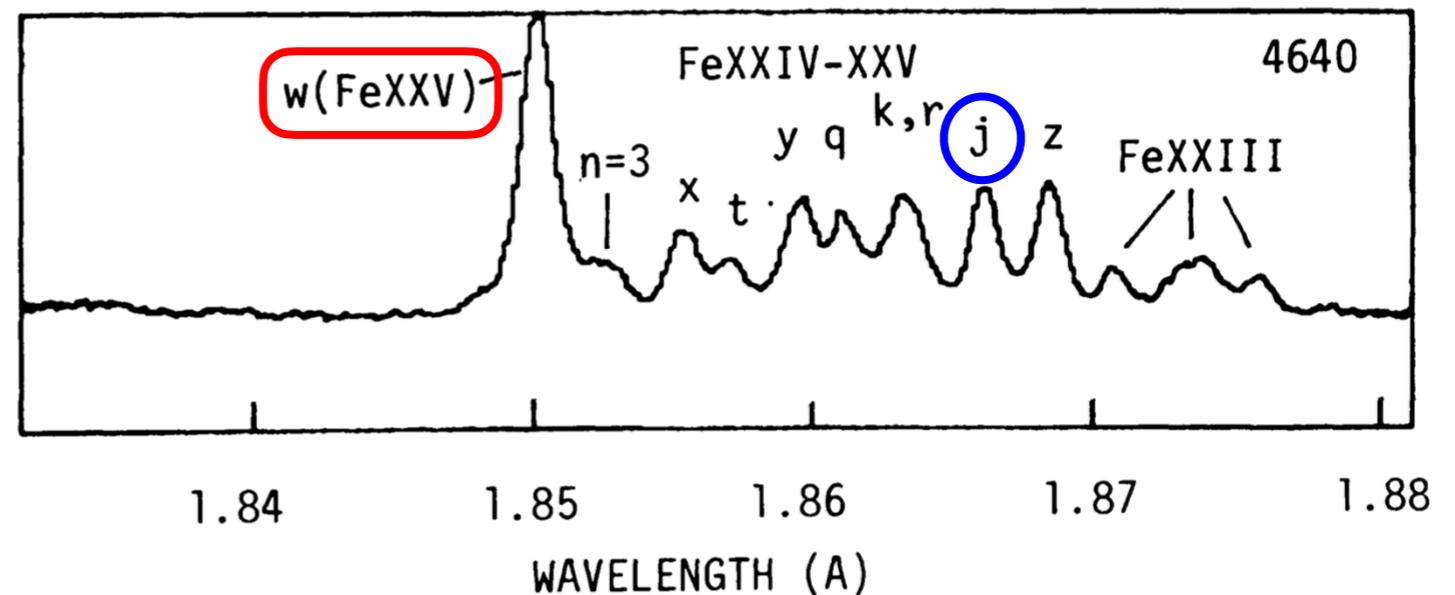
Gabriel and Phillips 1979

Both w and j (and d13) originate predominantly from He-like ions

→ Ratio sensitive to electron energy distribution

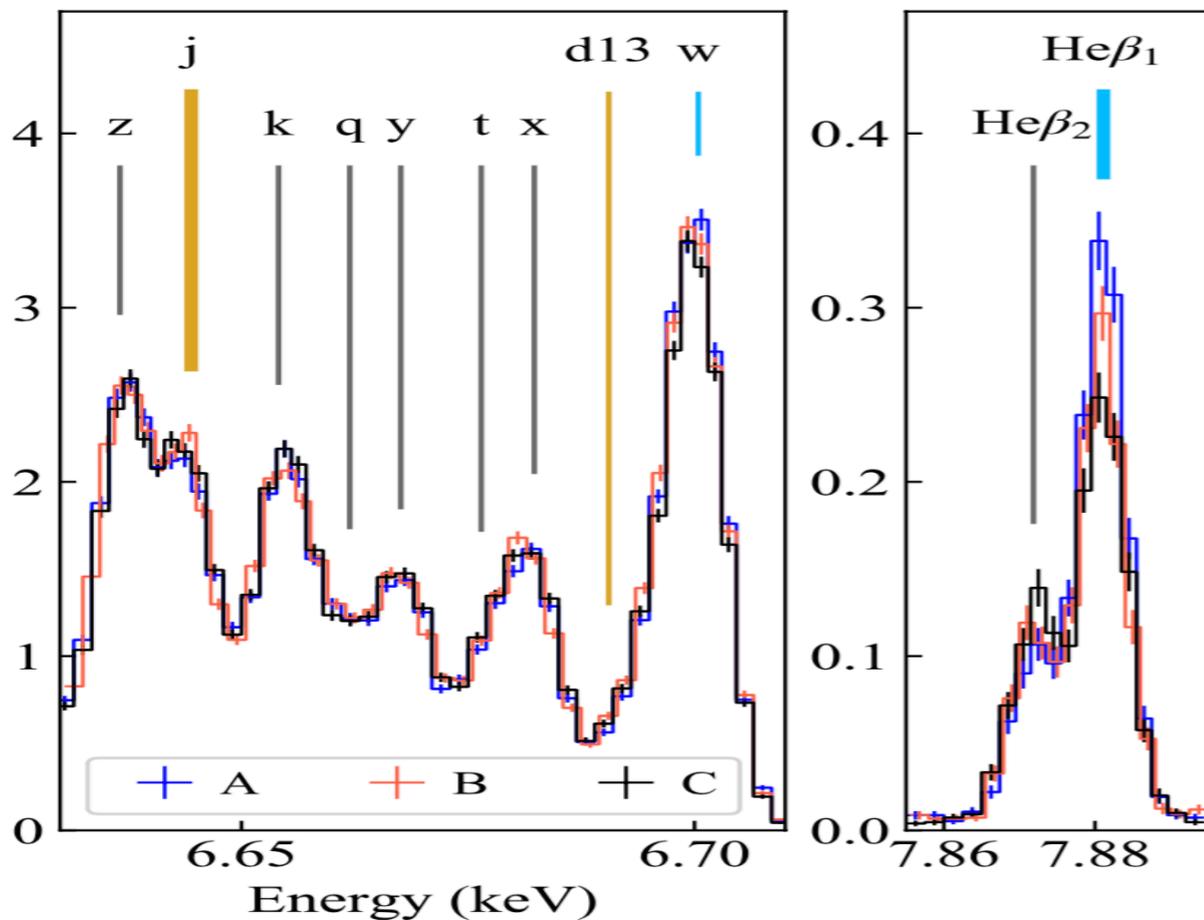
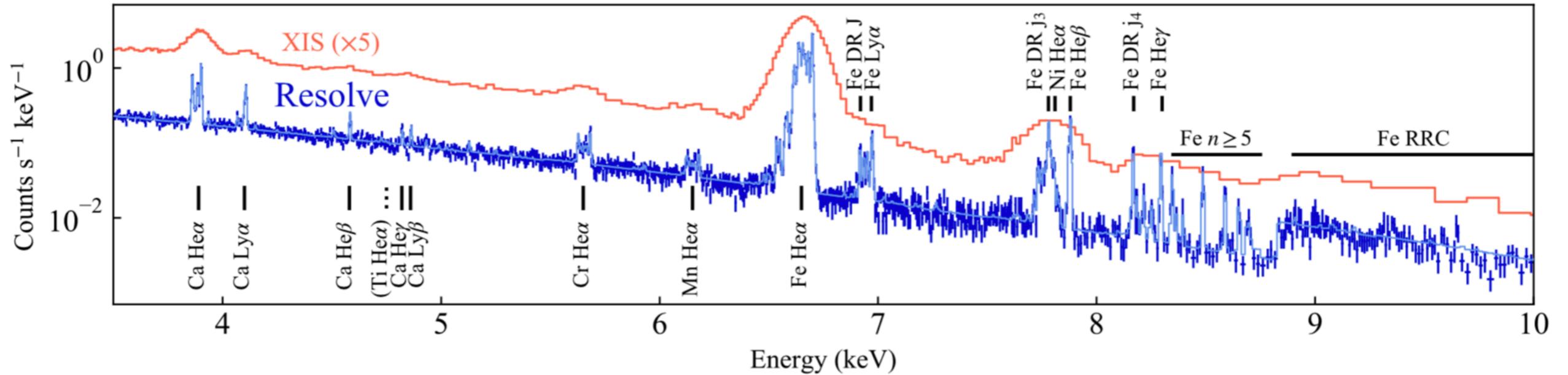


Hinotori SOX2 spectrum of solar flare (Tanaka+1982)



# XRISM mock spectra

Led by Makoto Sawada



He-like  $\beta$  emission is even more sensitive to supra-thermal  $e^-$

Blue: supra-thermal electrons completely associated with hot plasma

Black: not associated with hot plasma but with ambient cold gas

# Another advantage of $\mu$ -cal

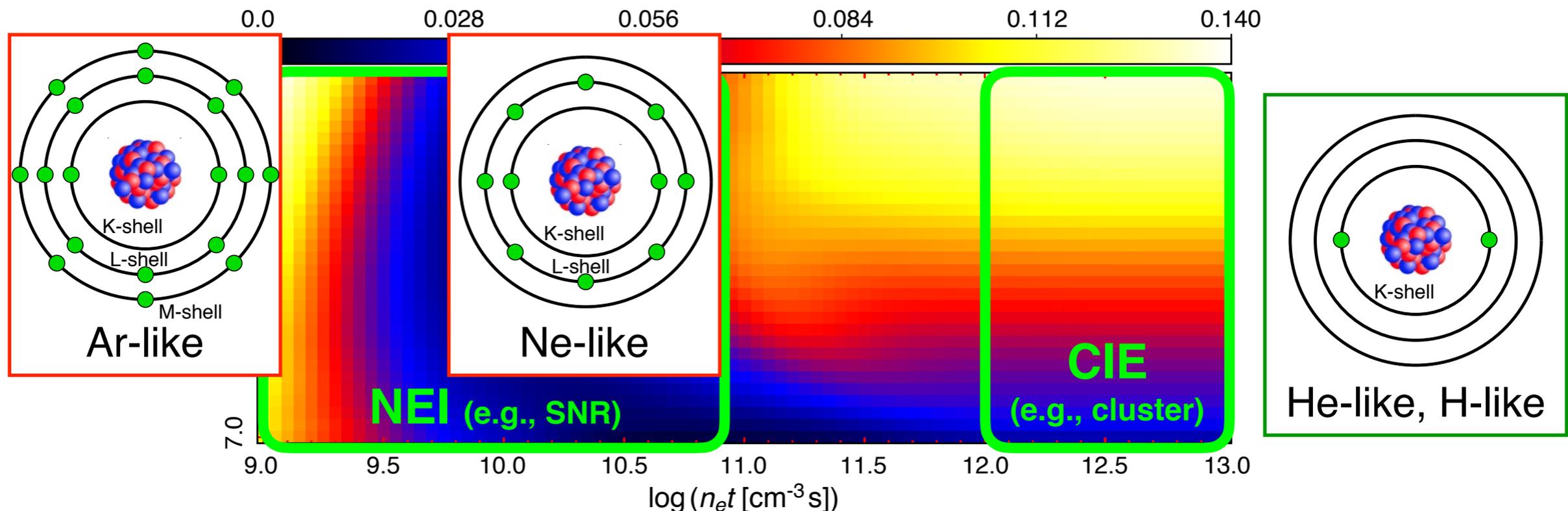
Wide bandpass (0.3-12 keV) with constant resolution ( $\Delta E \sim 5$  eV)

→ Enables high-resolution spectroscopy using both Fe K-shell and L-shell emission simultaneously

In young SNRs,  $T_e$  measurement for Fe ejecta is challenging

- Continuum is dominated by synchrotron emission
- $K\beta/K\alpha$  ratio is more sensitive to charge state

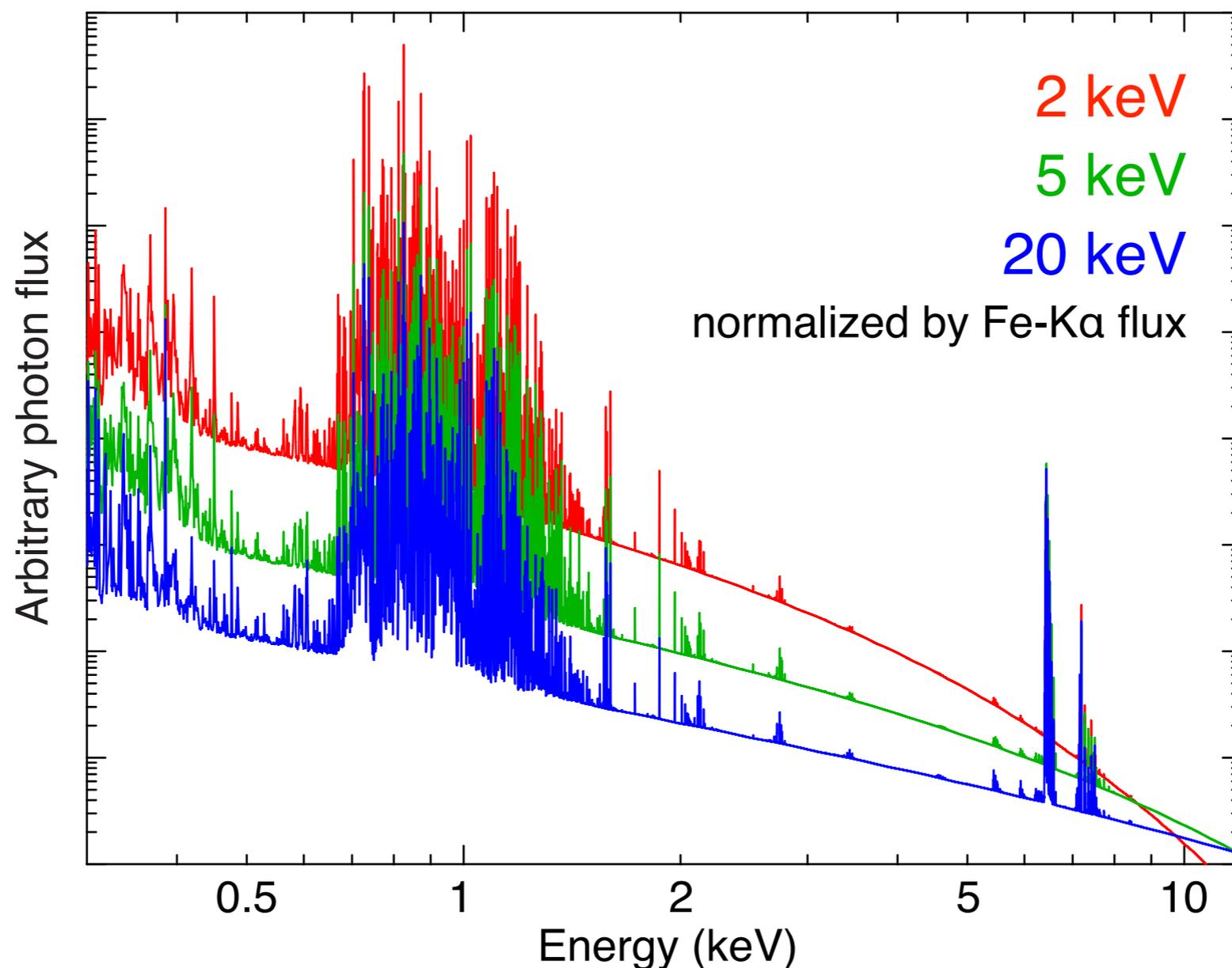
**Fe  $K\beta(3p-1s)/K\alpha(2p-1s)$  intensity ratio (HY+14, 17)**



# Another advantage of $\mu$ -cal

Wide bandpass (0.3-12 keV) with constant resolution ( $\Delta E \sim 5$  eV)

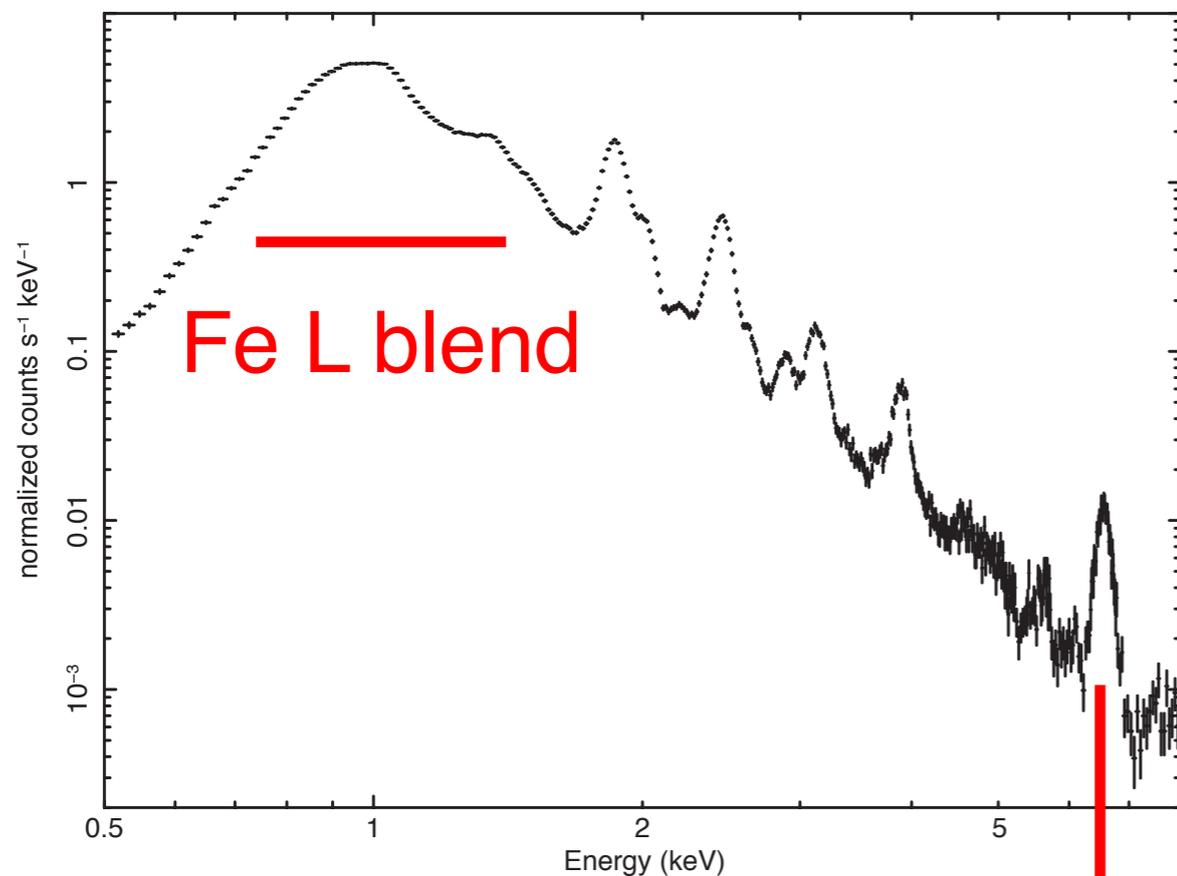
→ Enables high-resolution spectroscopy using both Fe K-shell and L-shell emission simultaneously



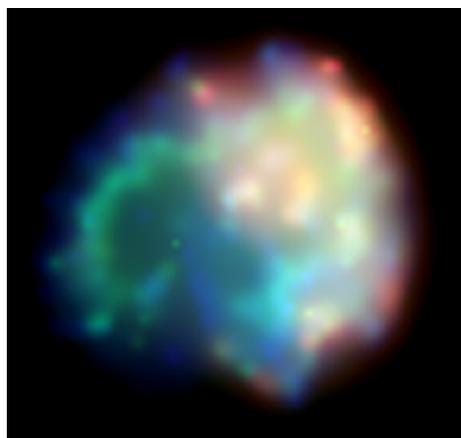
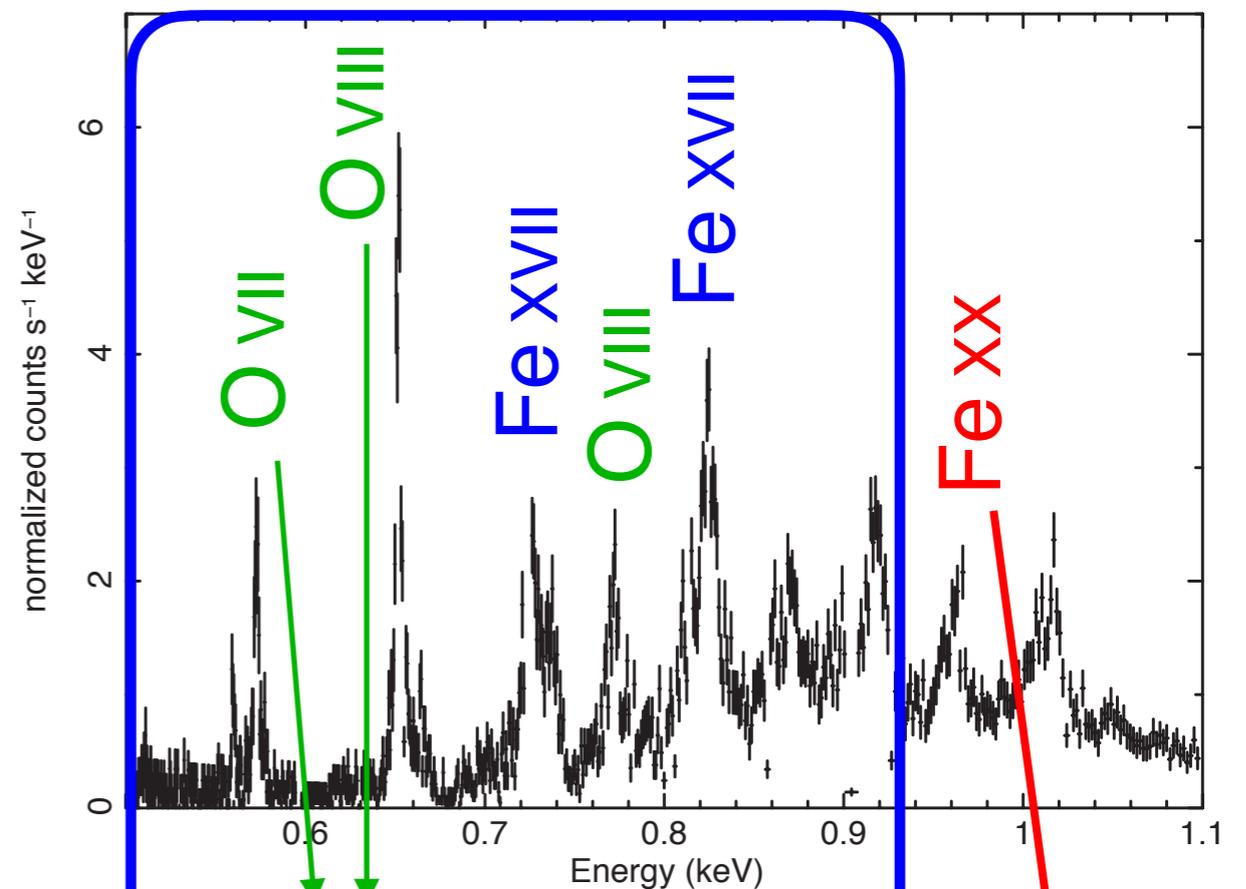
# Case SNR N103B

Type Ia SNR in LMC interacting with CSM (e.g., Williams+2014)

Chandra/ACIS



XMM/RGS



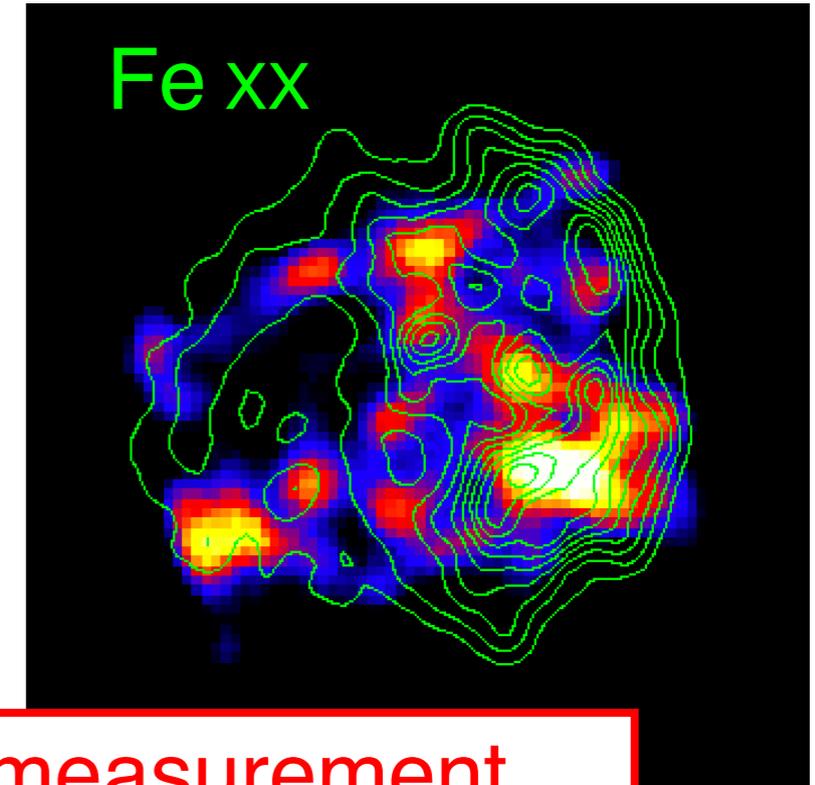
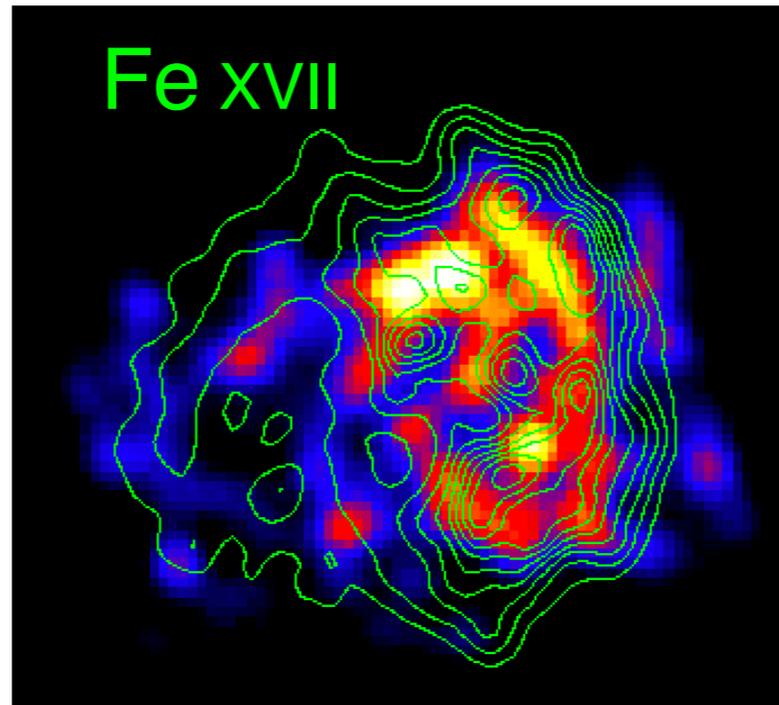
~ 6.54 keV  
→ Fe XX-XXII  
originating from  
Fe ejecta

likely associated  
with Fe K

# Case SNR N103B

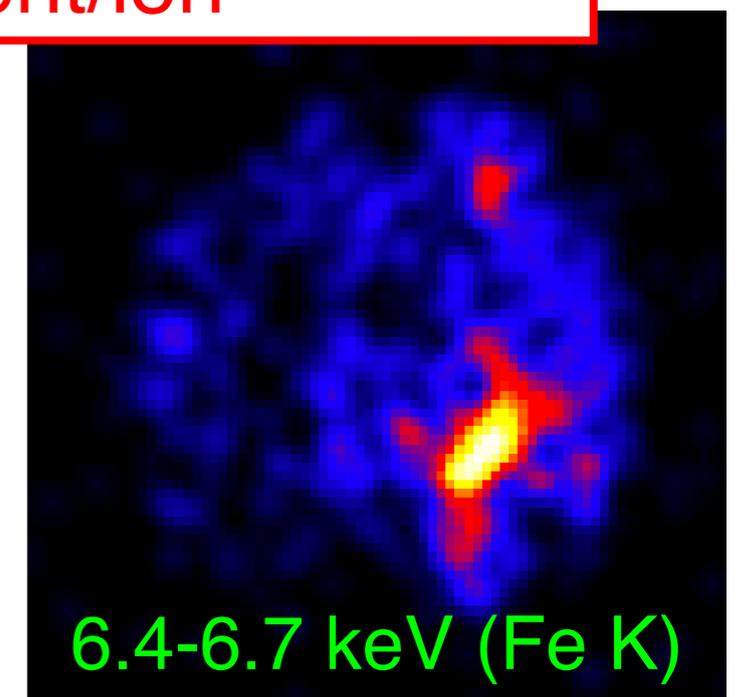
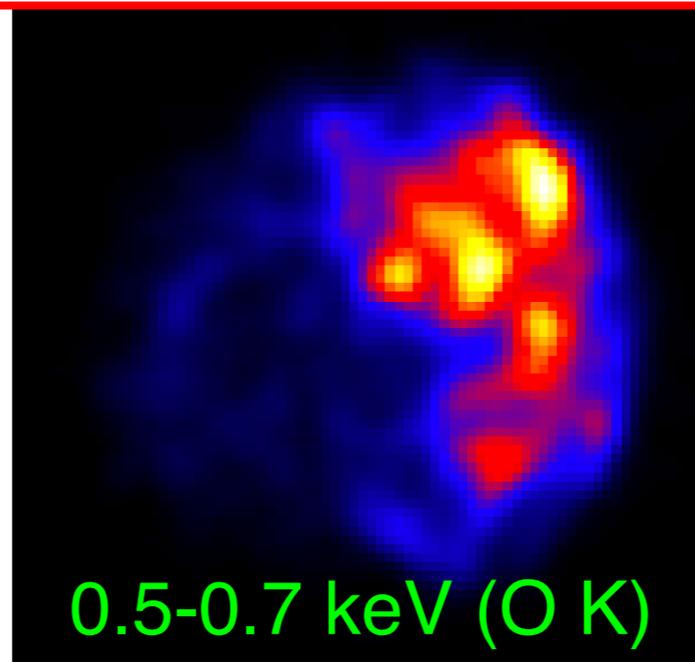
very preliminary

**HETG 1st order  
images**



$\mu$ -cal observations enable ion-by-ion  $T_e$  measurement,  
discriminating origin of each element/ion

**ACIS narrow band  
images**



# Conclusions

What is needed to identify new physics?

- Analysis beyond standard software usage
- Knowledge of atomic physics

Of course, the latter is more important!

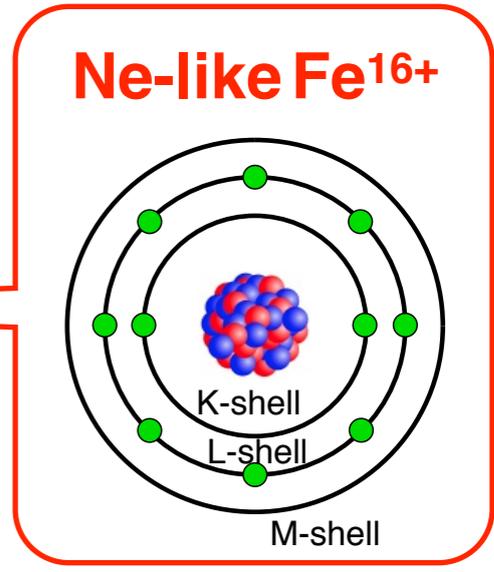
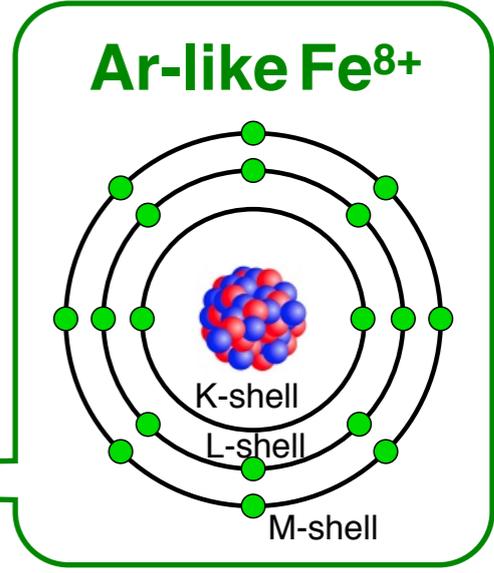
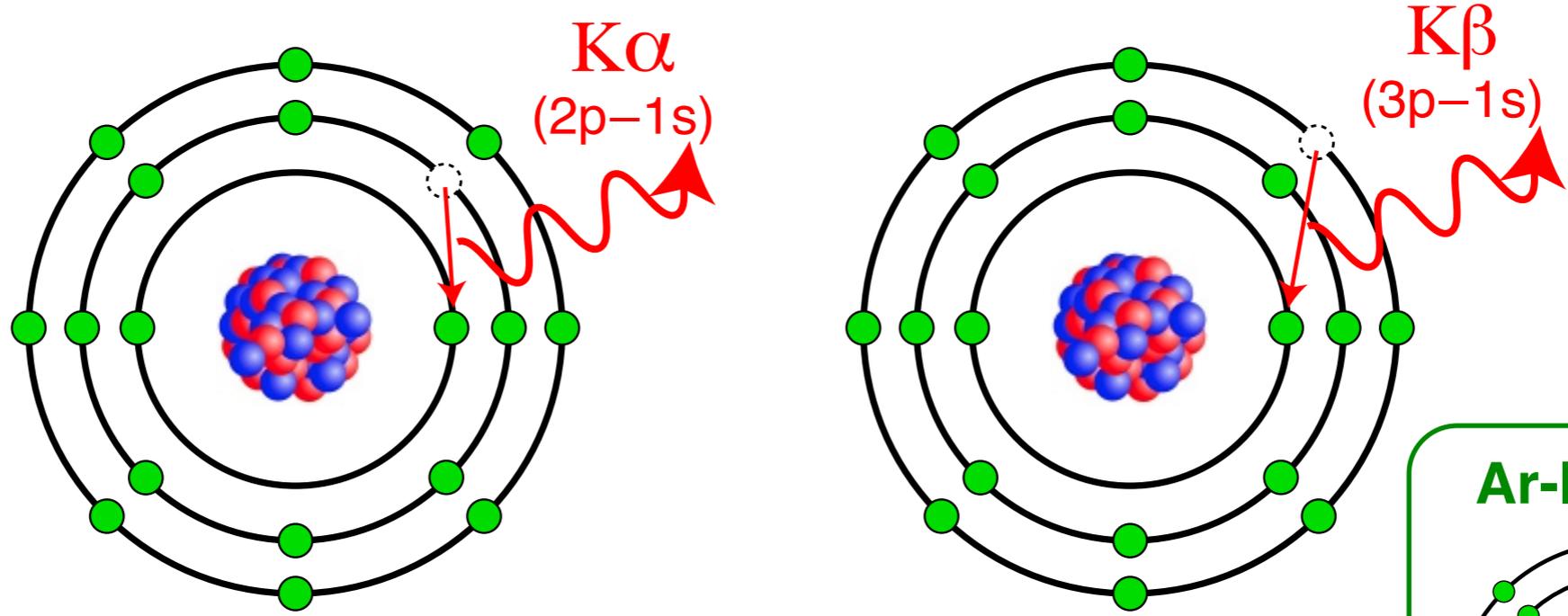
Related topics I couldn't cover today:

- Fluorescence line diagnostics for low-ionized plasma (HY+2014, ApJ, 780, 136)
- Recombining plasma (HY+2018, ApJL, 868, L35)

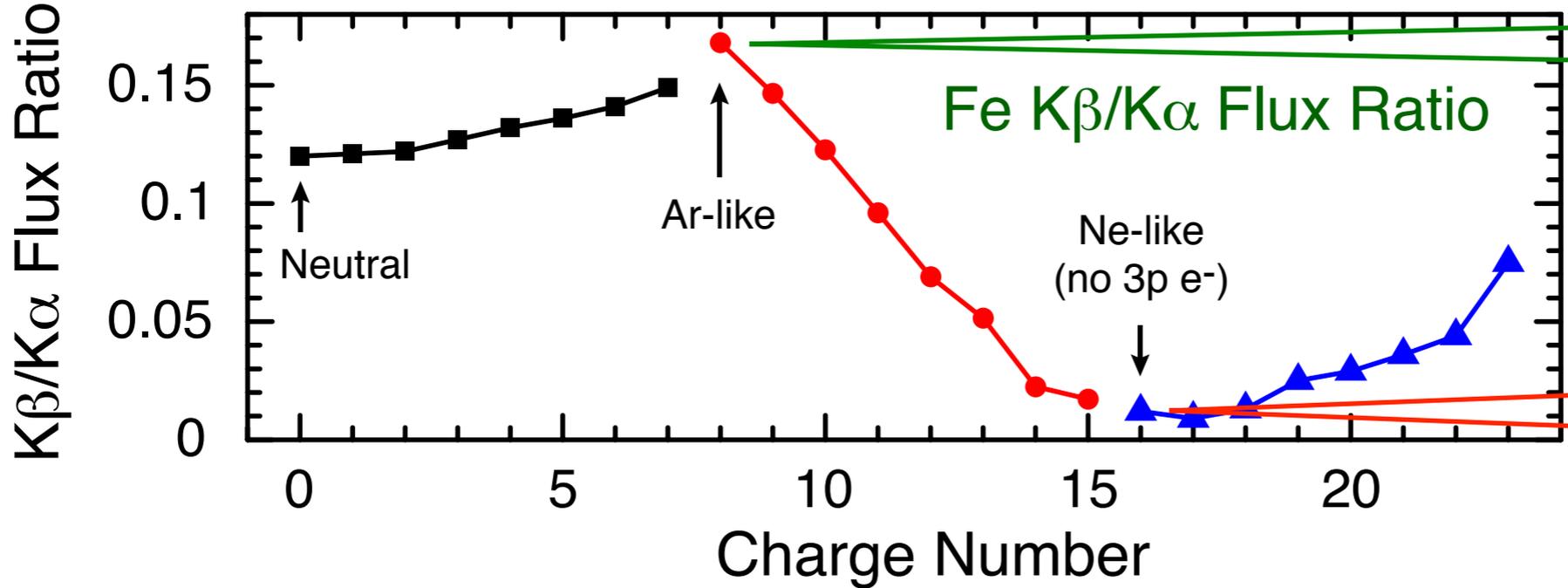




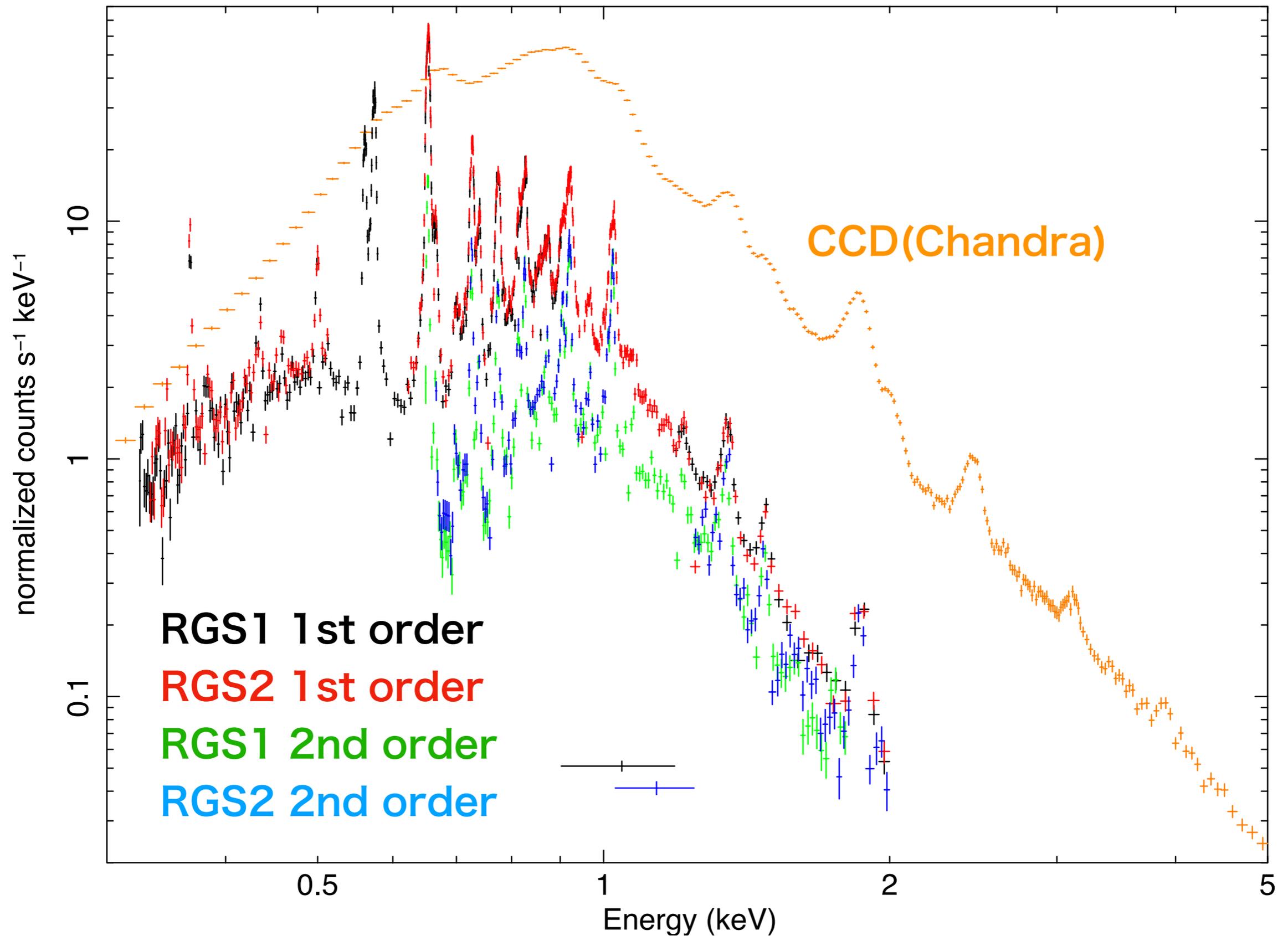
# Theoretical calculations of line ratios



Yamaguchi et al. 2014, ApJ, 780, 136



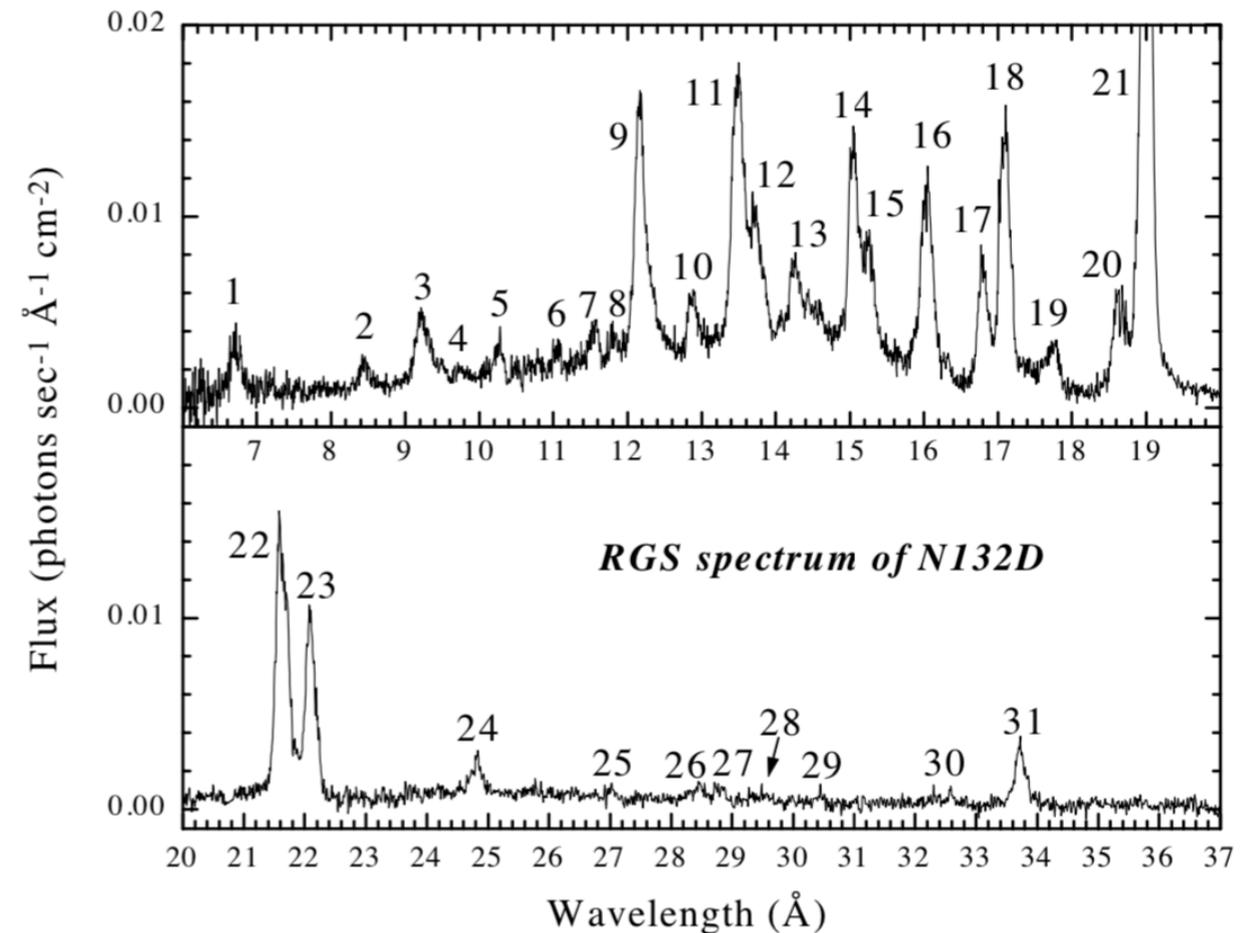
# Comparison with CCD



# Preceding work

Behar et al. 2001

- Only first  $\sim 50$  ks observations in May 2000 reported
- 1st- and 2nd-order spectra merged, dominated by former
- No detailed analysis performed
  - CIE or NEI not distinguished



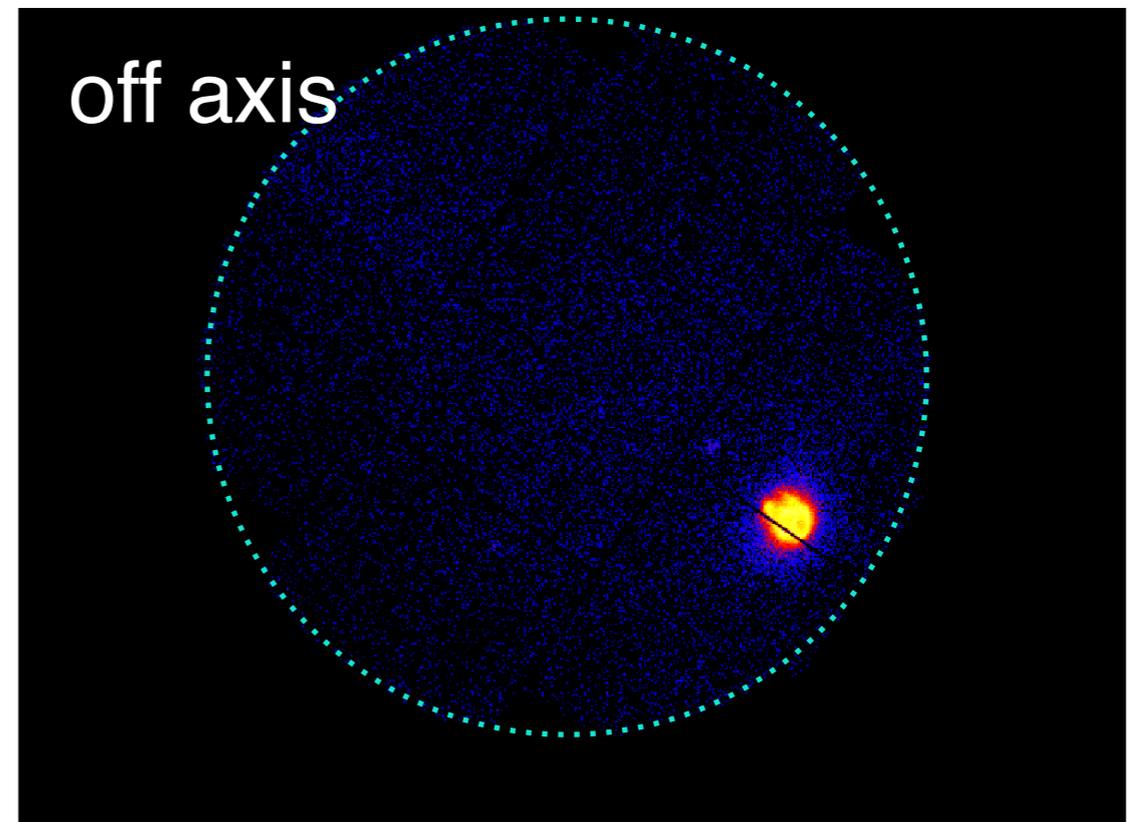
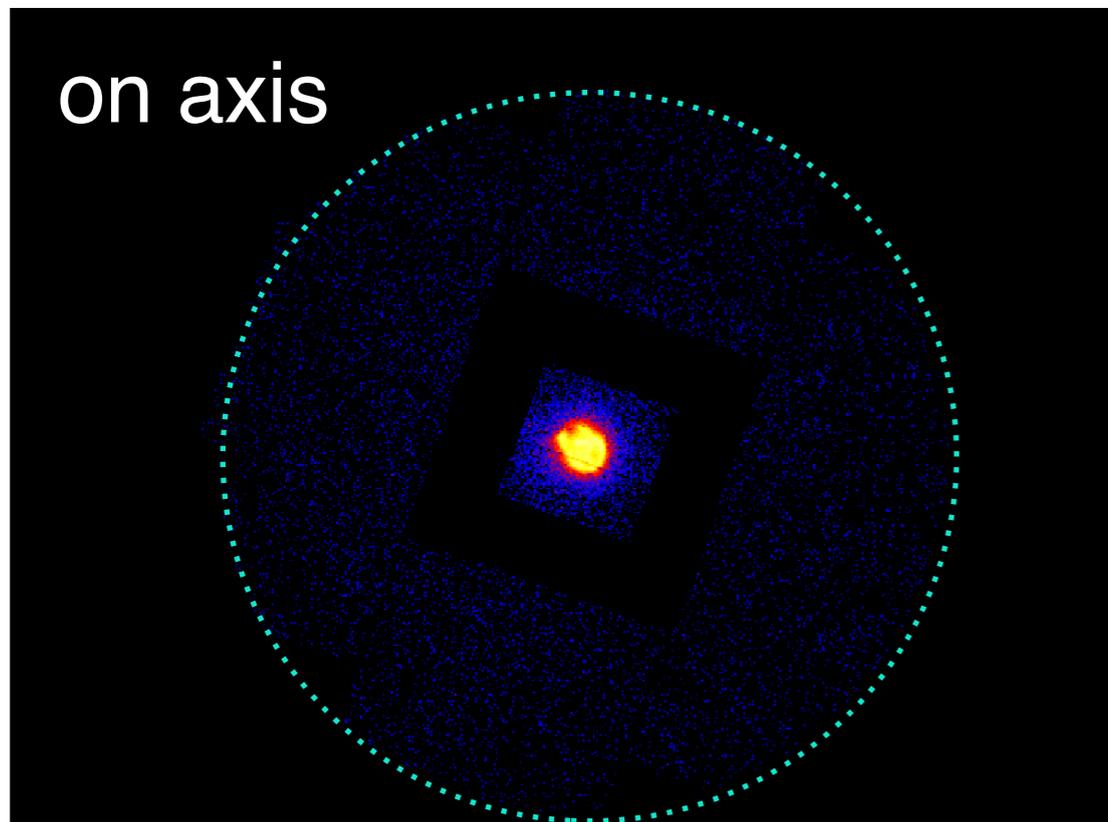
## Our goals:

- Fully exploit the long exposure RGS data
- Utilize higher-resolution 2nd-order spectra
- Constrain plasma condition

# Data selection

Use on-axis observations only

EPIC MOS2 image



~300 ks  
(9 observations)



~200 ks after bgd flare cut

~800 ks