X-RAY EMISSION DUE TO CHARGE EXCHANGE IN THE CYGNUS LOOP?

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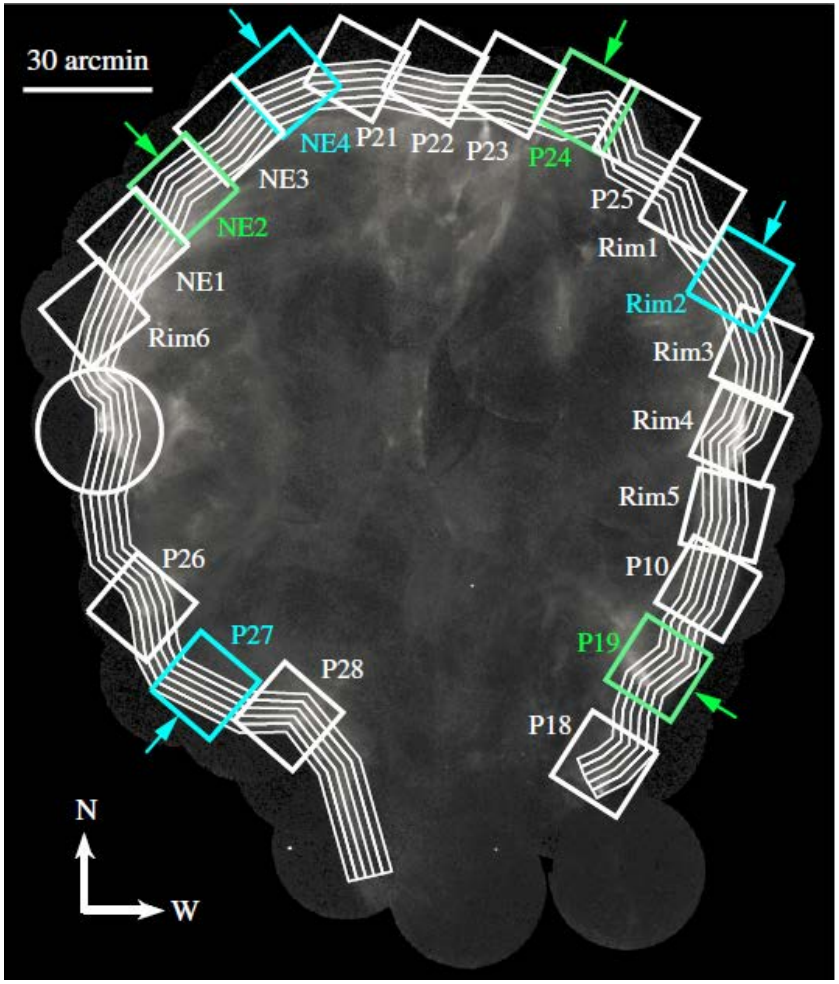
Outline

- Cygnus Loop
- Charge Exchange Model
  - Cascade
  - Cross Sections
  - Spectra
- XSPEC Modelling
  - Shock Model
  - CX Model
  - Future model
- Summary

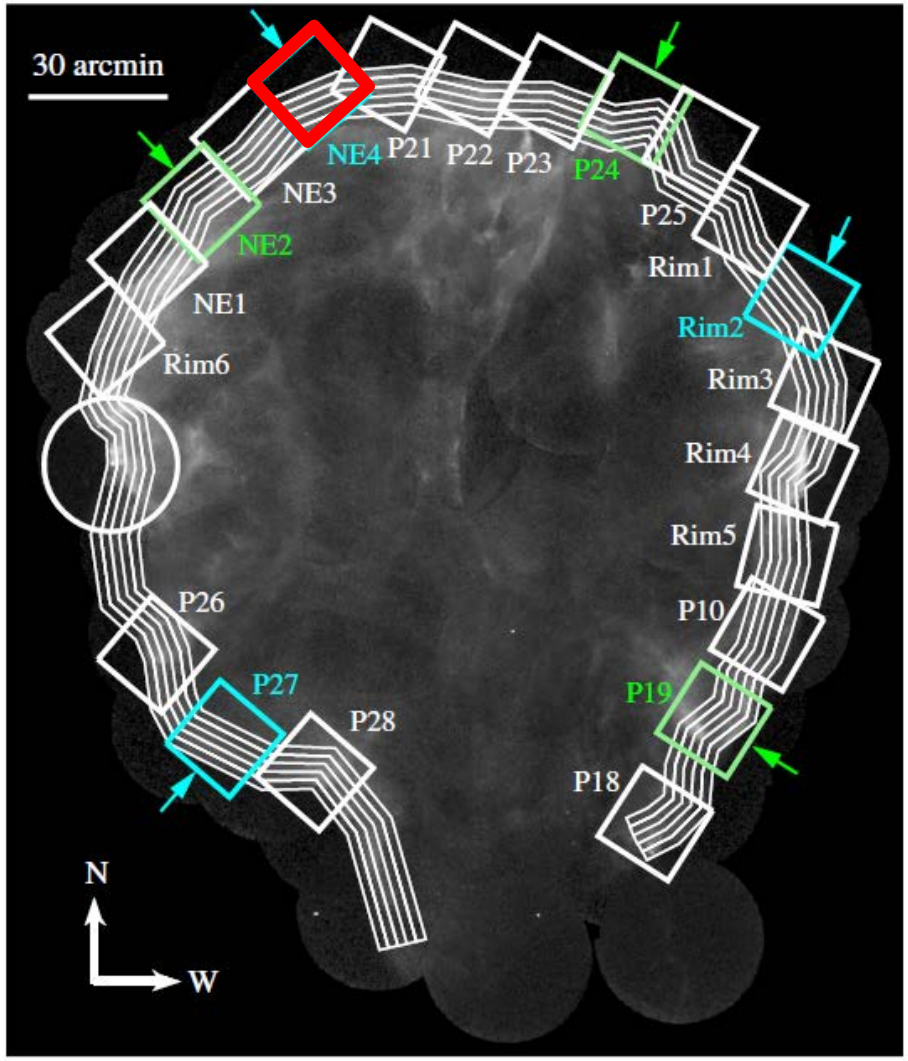
Cygnus Loop

- Supernova Remnant
- Cygnus Constellation
- Distance: ~1500 ly
- Size: ~90 ly
- Age: ~5000- 8000 years
- Shock Speed ~300 km/s



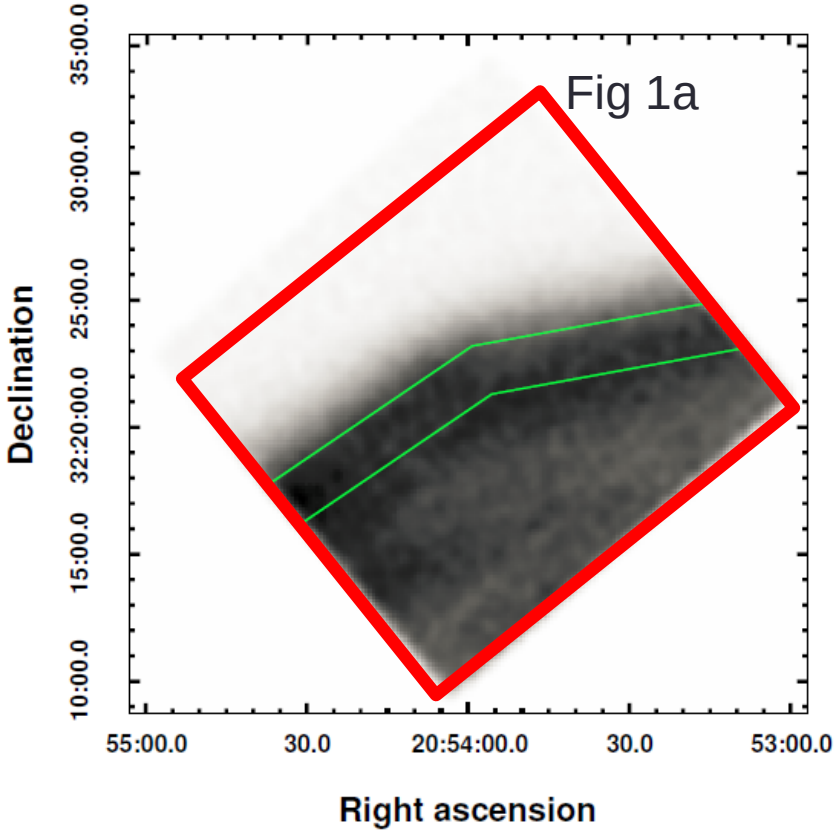
Katsuda et al. 2011

SNR: Cygnus Loop



Katsuda et al. 2011

Part of NE Rim
Significant neutral H fraction

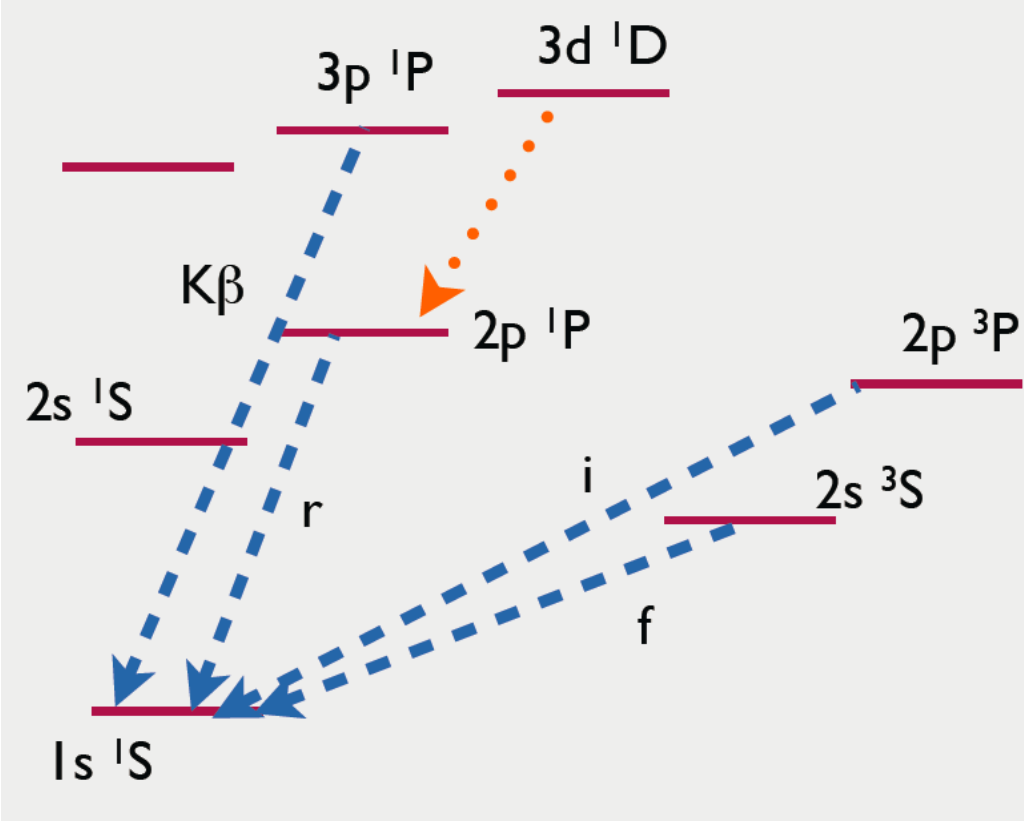


Suzaku ObsID 500023010

Charge Exchange Process

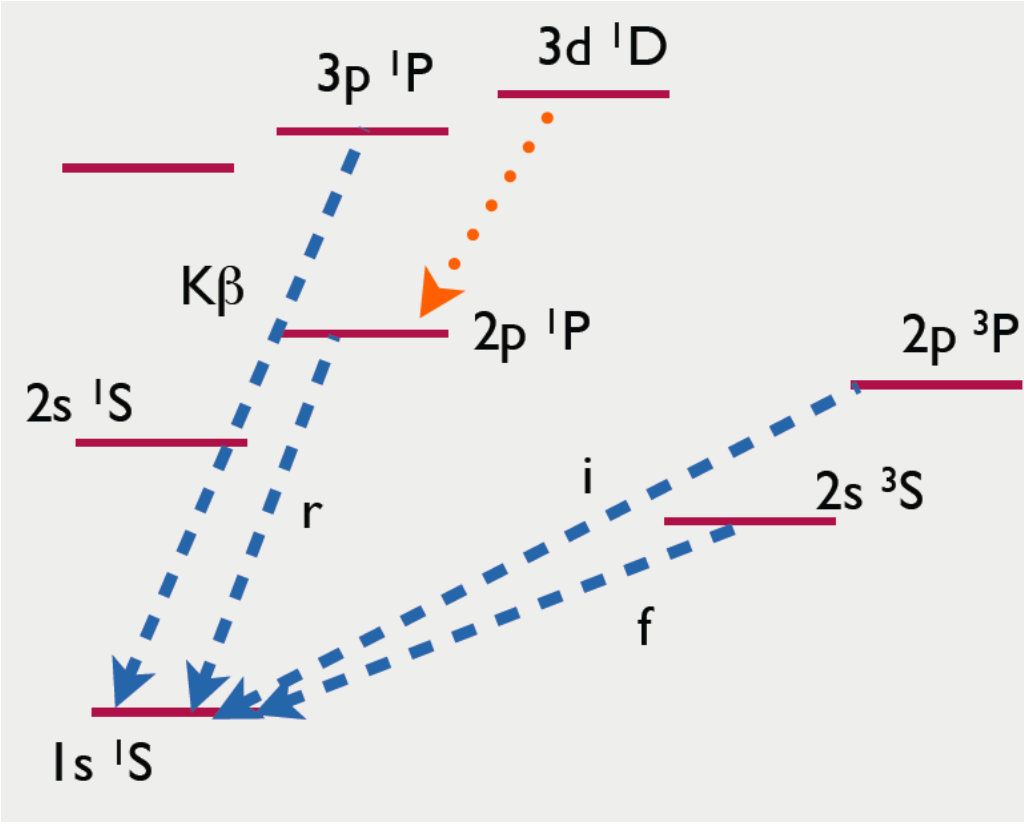
$$X^{q+} + Y \rightarrow X^{q-1}(nl^{2S+1}L) + Y^{+}$$

- Collision of
  - Highly charged ion X^{q+}
  - Neutral atom Y
- Produces highly excited, high charge state ions $X^{q-1}(nl^{2S+1}L)$
  - Cascade to lowest energy
    - Produce x-rays

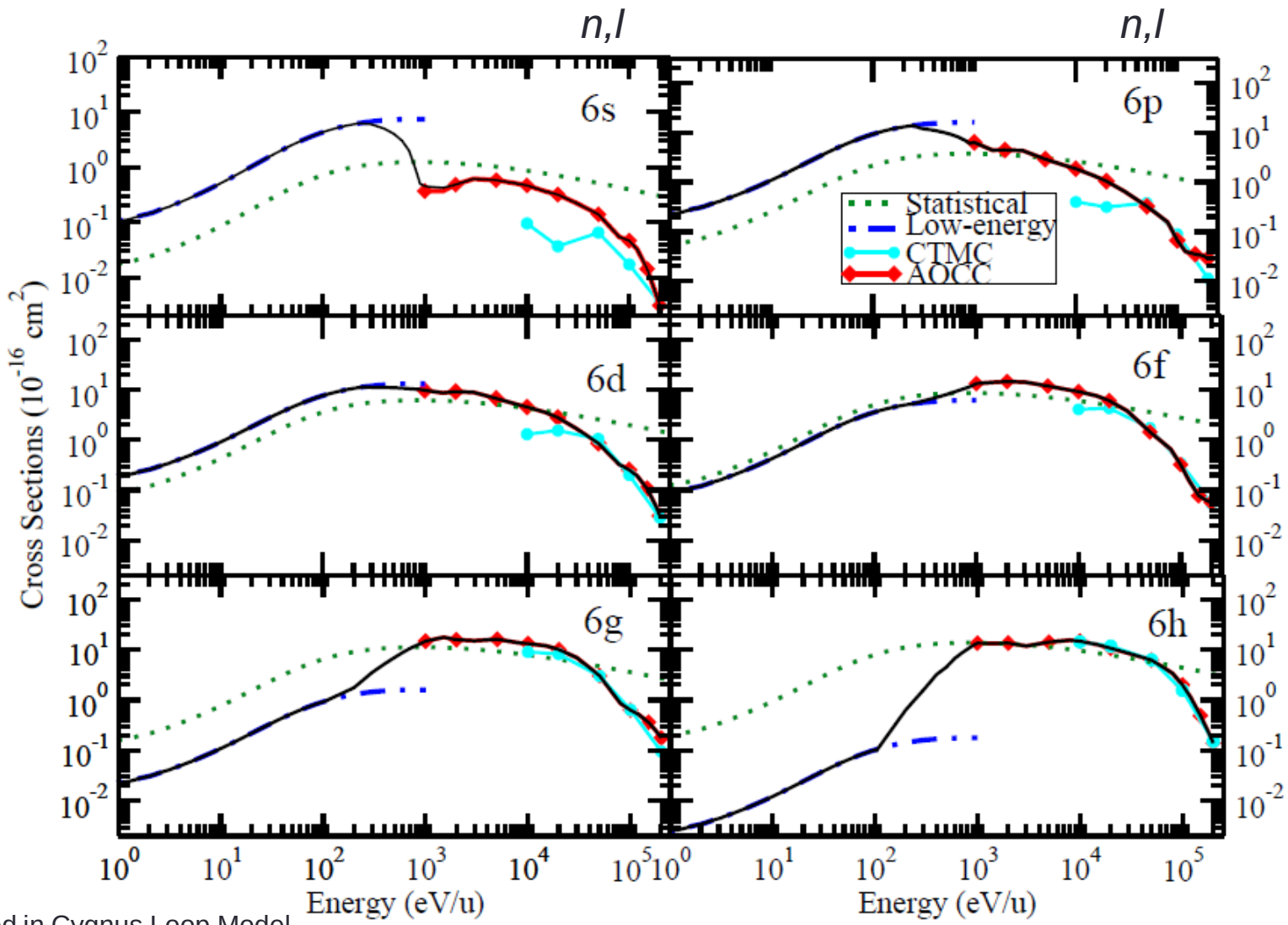


Cascade Model

- Low-density steady state cascade
  - Rigazio et al. (2002)
  - Initial state population proportional to CX cross sections
  - Cascade to lowest E-level results in X-rays



$Ne^{10+} + H \rightarrow Ne^{9+} + H^{+}$ Cross Sections

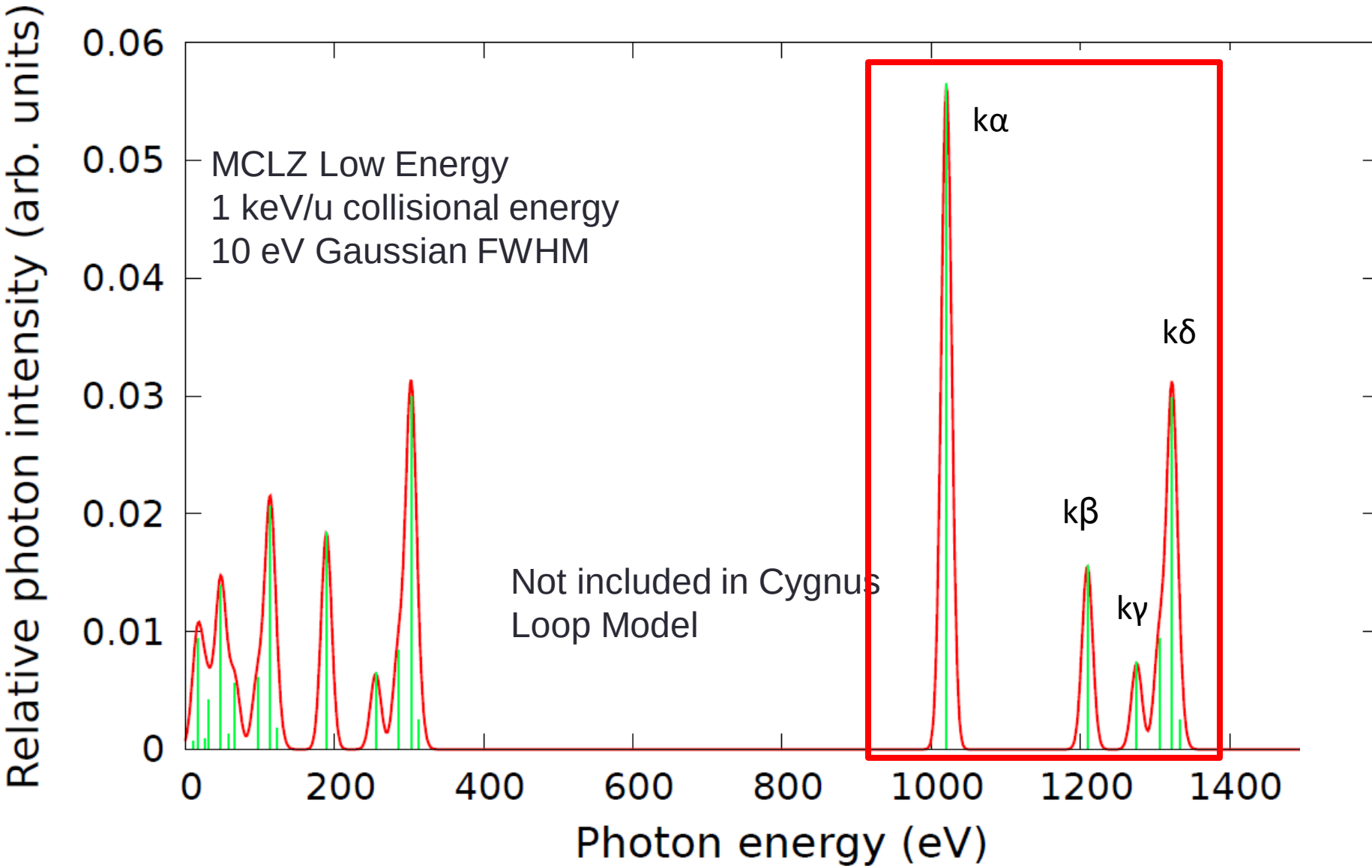


Not included in Cygnus Loop Model

Methods for Calculating Cross Section

- Multi-Channel Landau Zener
  - Fully stripped atoms:
    - Statistical l-distribution
    - Low-energy l-distribution
- Classical Trajectory Monte Carlo
- Atomic Orbital Close Coupling
- Quantum-Mechanical Molecular Orbital Close Coupling
  - Best method
  - Time consuming

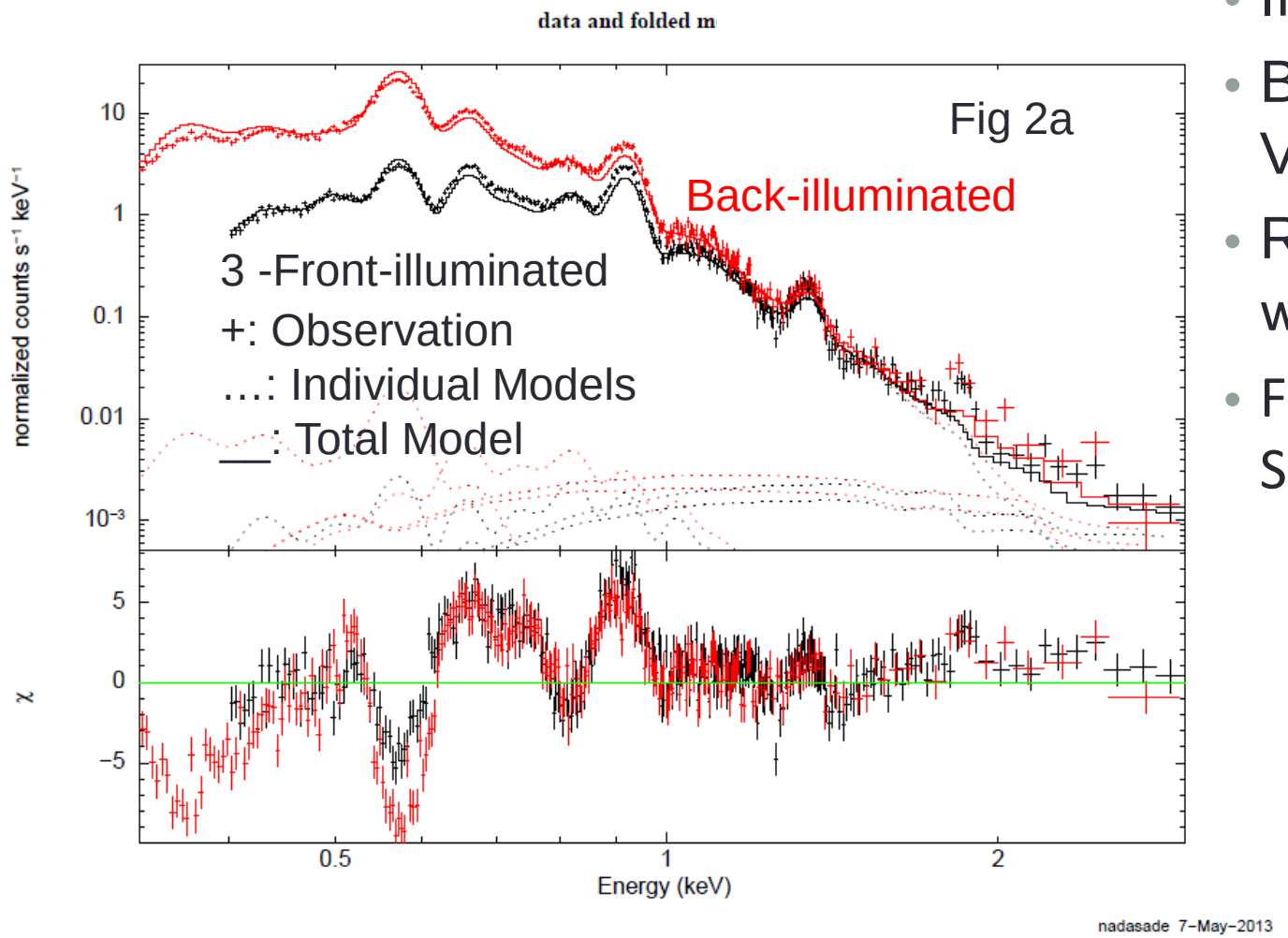
$Ne^{10+} + H \rightarrow Ne^{9+} + H^{+}$



XSPEC Model

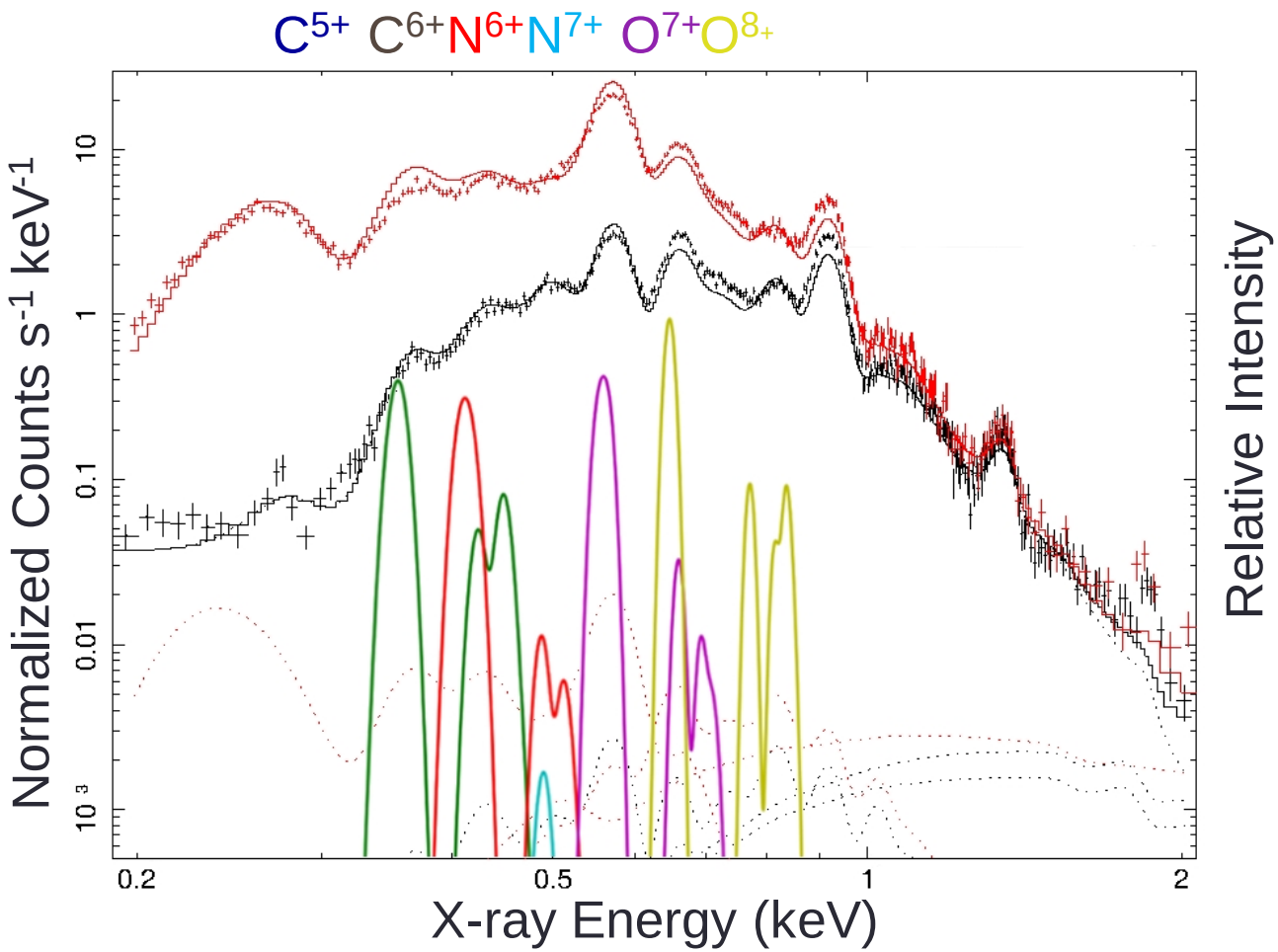
- Initial Model without CX spectra (SNR Shock)
  - VpShock Model
  - 2 APEC thermal Plasma Models
  - 2 broken power laws (X-ray background)
- CX Model (SNR + CX)
  - 35 separate emission lines
    - Tie separate lines together based on line ratios
  - Electron Temperature = 0.21 keV
  - Line intrinsic widths much smaller than instrumental line width
  - Collisional Energy of 1 keV/u
  - Input:
    - Line Energy
    - Line Ratios

Cygnus Loop: Shock Model



- Initial Model
- Background + VpShock
- Reduced χ^2= 8.9 with 592 dof
- FI and BI fitted Simultaneously

Astrophysical Modeling: Using Xspec

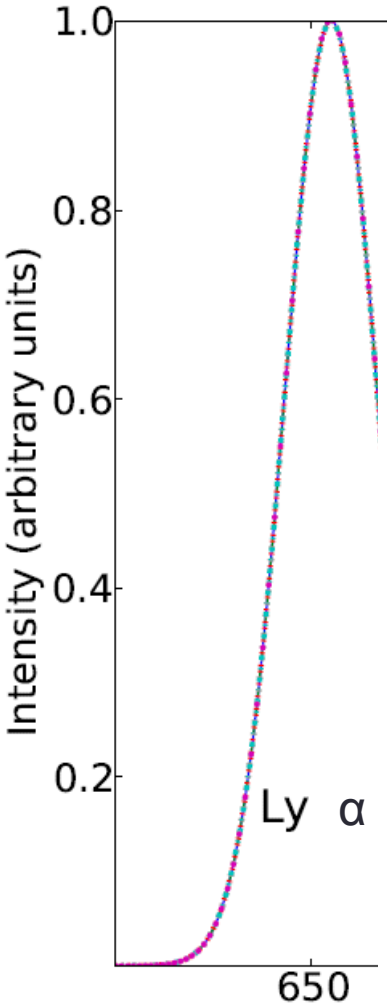


Cygnus Loop

Relative Intensity

- C^{5+} +H
  - (Nolte et al. 2012)
- C^{6+} +H
  - (Janev et al. 1993)
- N^{6+} +H
  - (Wu et al. 2011)
- N^{7+} +H
  - (Harel et al. 1998)
- O^{7+} +H
  - (Nolte et al. 2013)
- O^{8+} +H
  - (Janev et al. 1993)

$O^{8+} + H \rightarrow O^{7+} + H^{+}$



Collision Energy: 1 keV/u

(Janev et al. 1993)

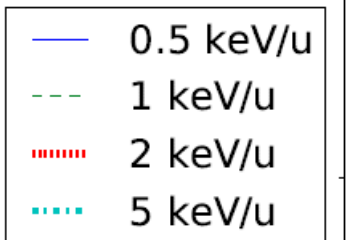
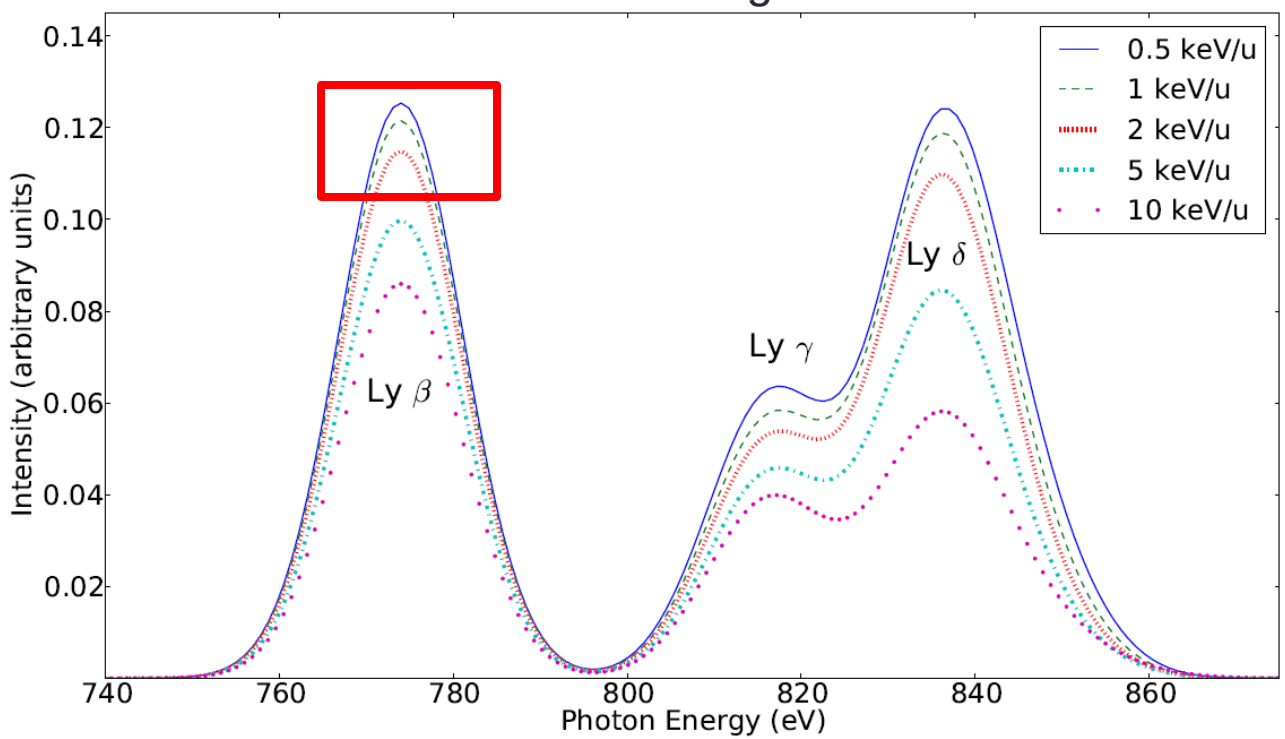
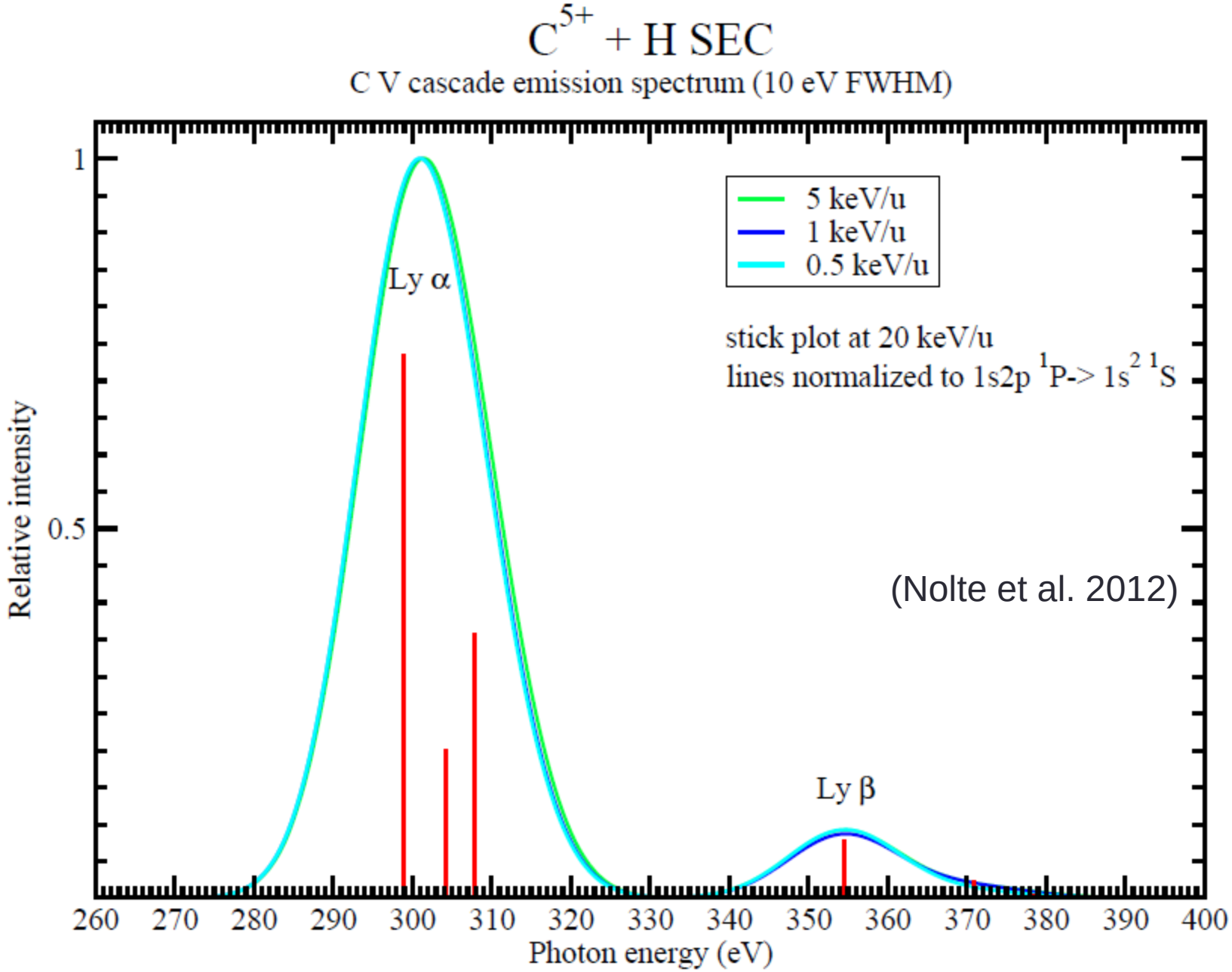
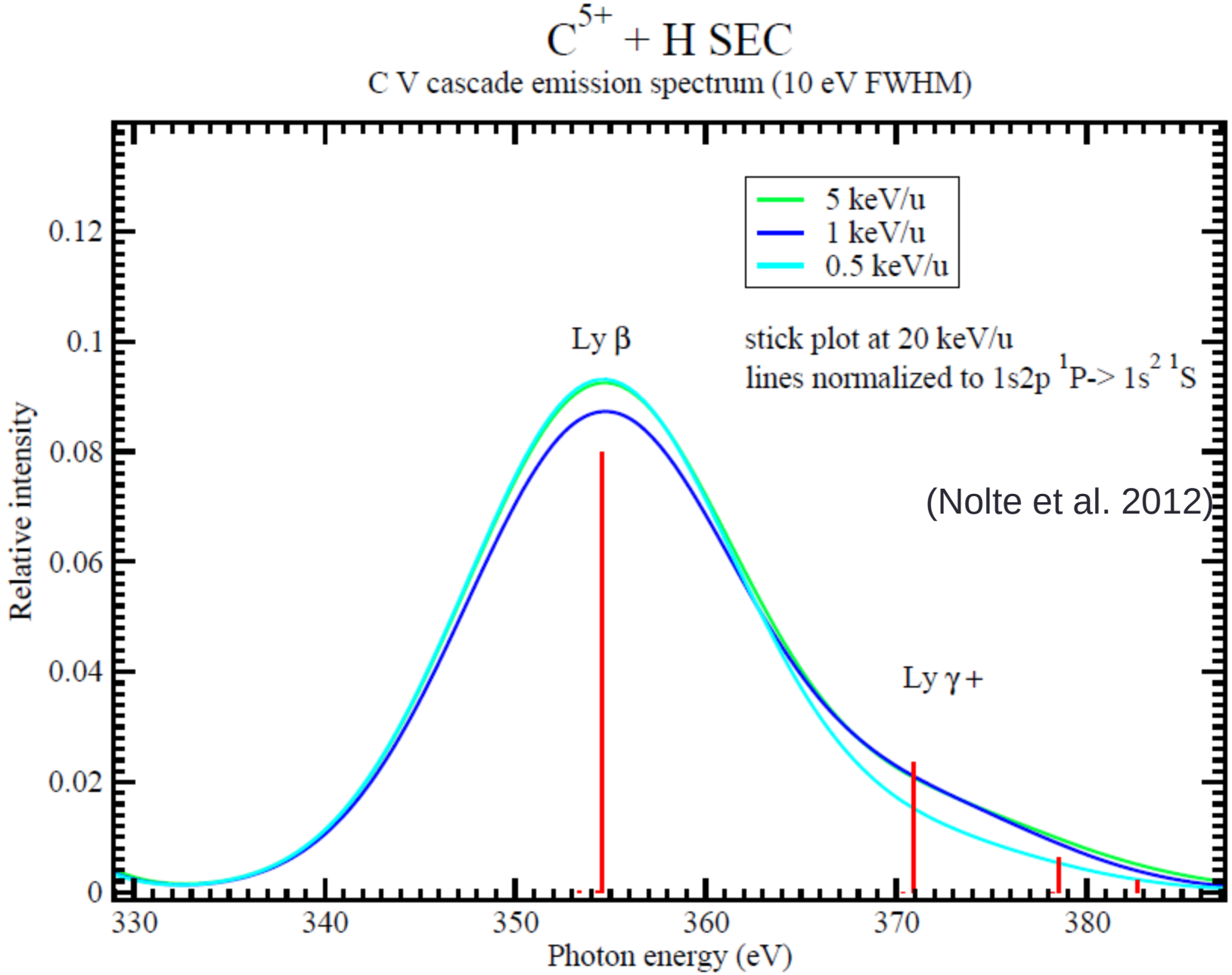


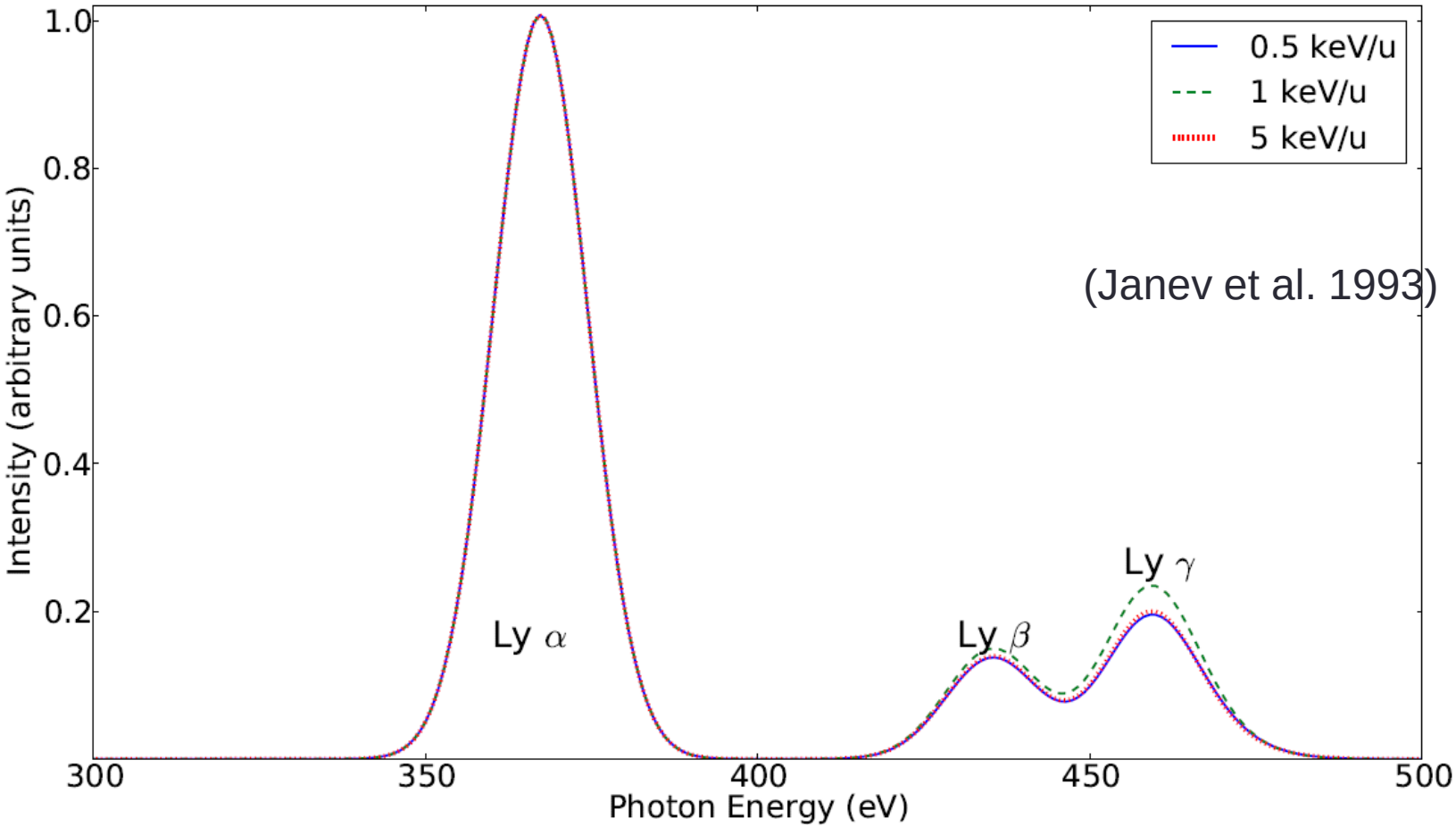
Fig 1b



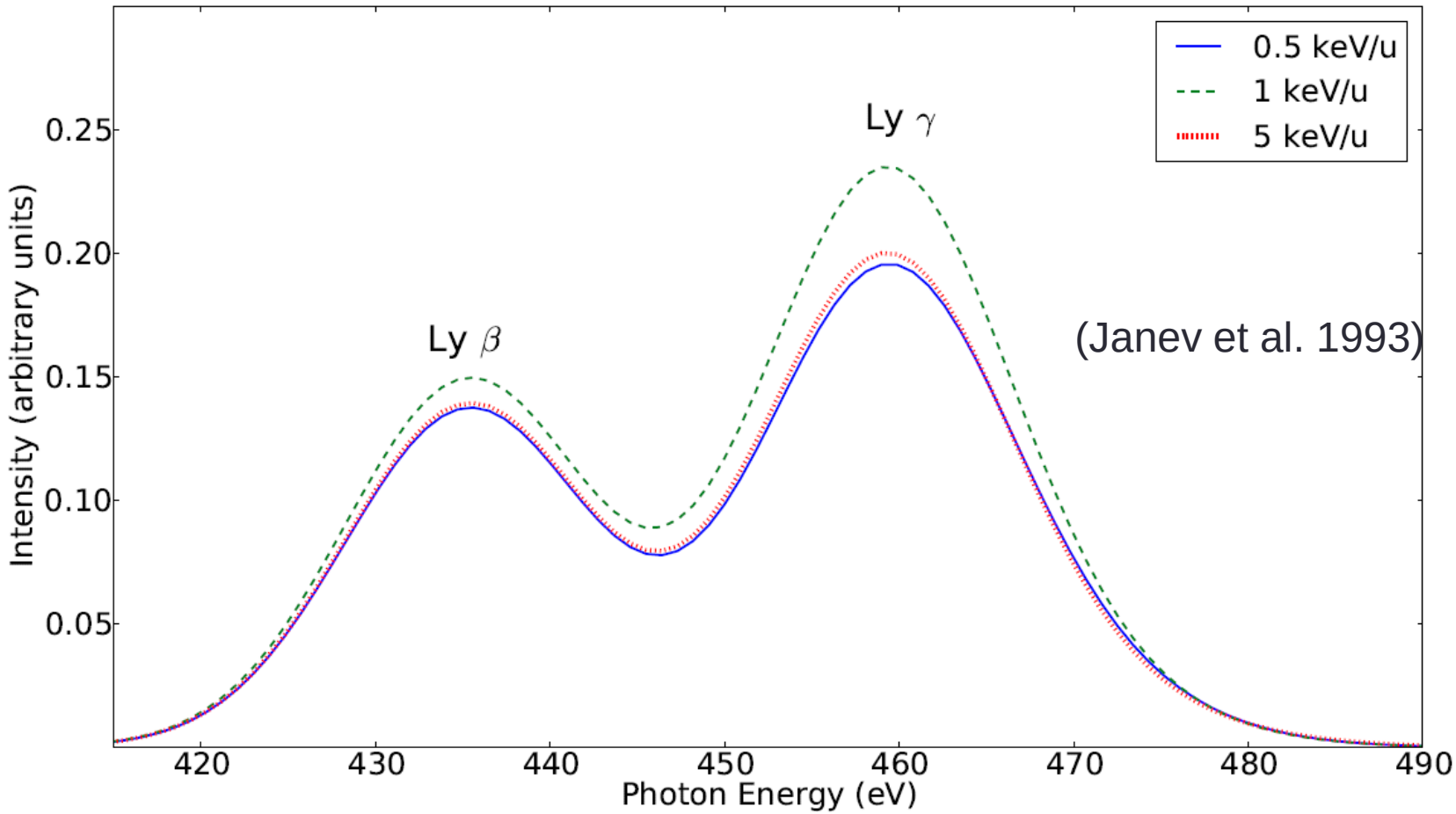

C^{5+} + H SEC
C V cascade emission spectrum (10 eV FWHM)
5 keV/u
1 keV/u
0.5 keV/u
stick plot at 20 keV/u
lines normalized to 1s2p ^{1}P-> 1s^2 ^{1}S
Ly α
Ly β
(Nolte et al. 2012)
Relative intensity
1
0.5
260
270
280
290
300
310
320
330
340
350
360
370
380
390
400
Photon energy (eV)


C^{5+} + H SEC
C V cascade emission spectrum (10 eV FWHM)
5 keV/u
1 keV/u
0.5 keV/u
Ly β
stick plot at 20 keV/u
lines normalized to 1s2p ^{1}P-> 1s^2 ^{1}S
(Nolte et al. 2012)
Ly γ +
Relative intensity
0.12
0.1
0.08
0.06
0.04
0.02
0
330
340
350
360
370
380
Photon energy (eV)

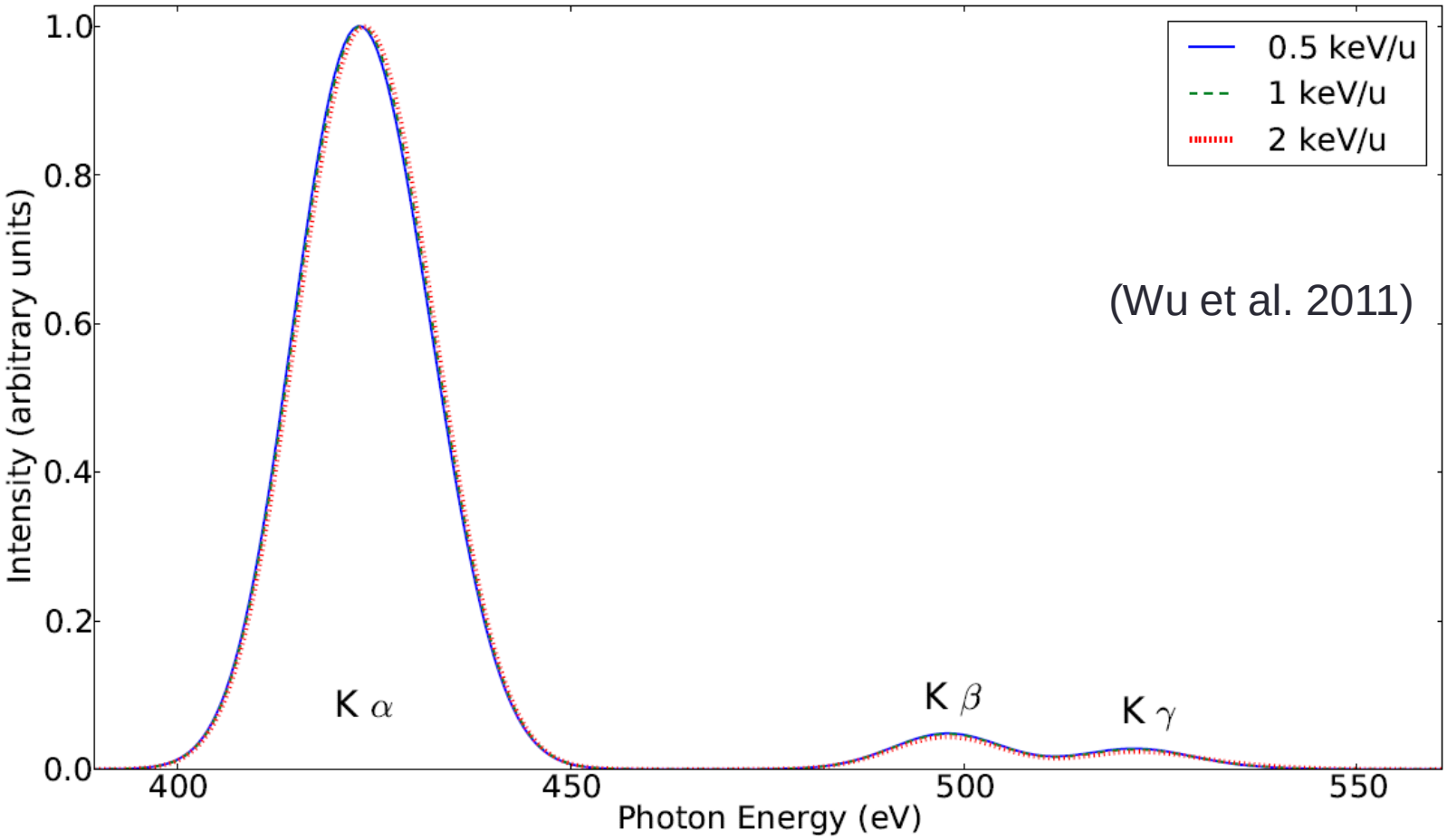
C^{6+} +H


0.5 keV/u
1 keV/u
5 keV/u
(Janev et al. 1993)
Ly α
Ly β
Ly γ
Intensity (arbitrary units)
Photon Energy (eV)
1.0
0.8
0.6
0.4
0.2
300
350
400
450
500

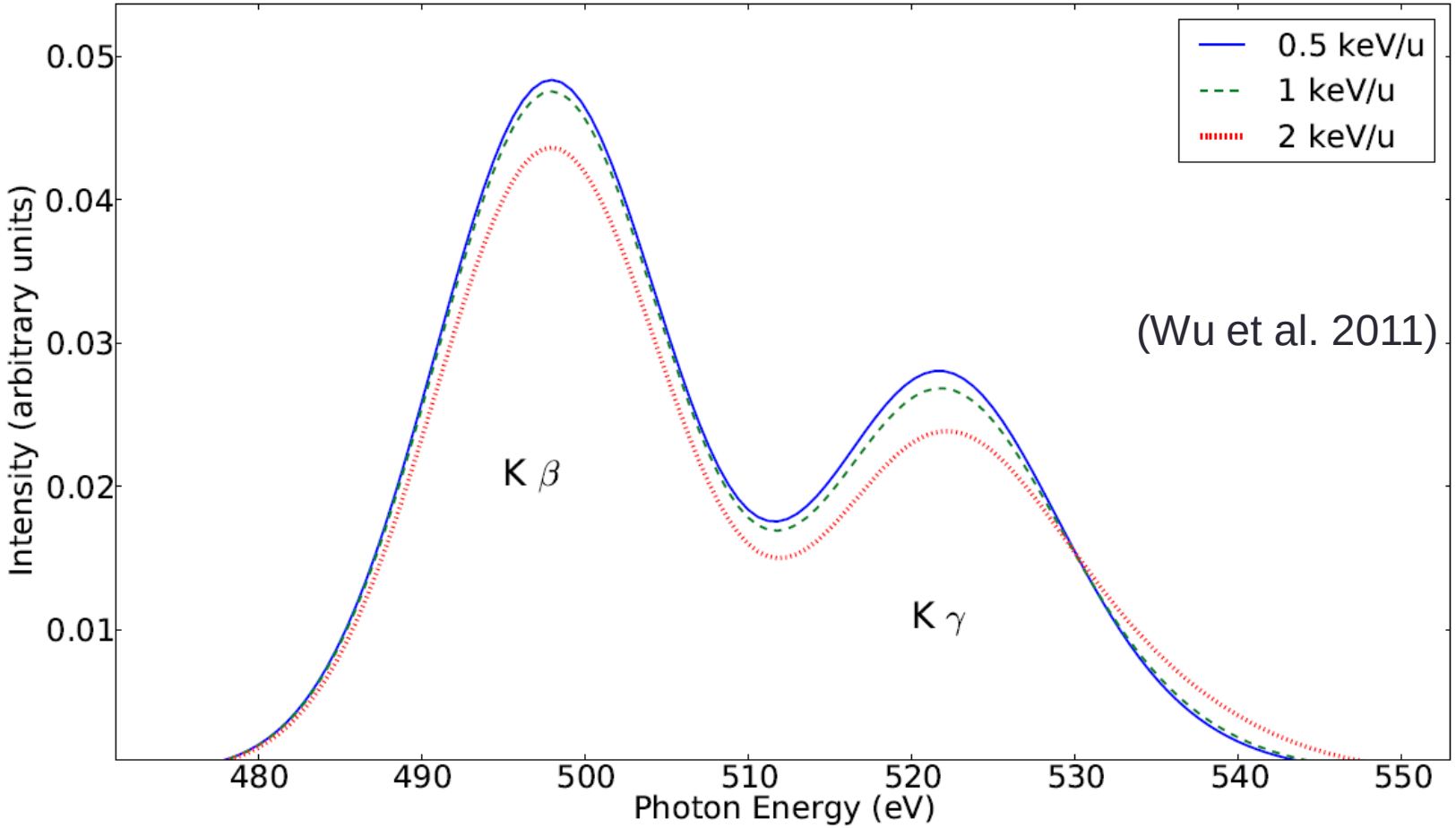
C^{6+} +H


0.5 keV/u
1 keV/u
5 keV/u
Ly γ
Ly β
(Janev et al. 1993)
Intensity (arbitrary units)
0.25
0.20
0.15
0.10
0.05
420
430
440
450
460
470
480
490
Photon Energy (eV)

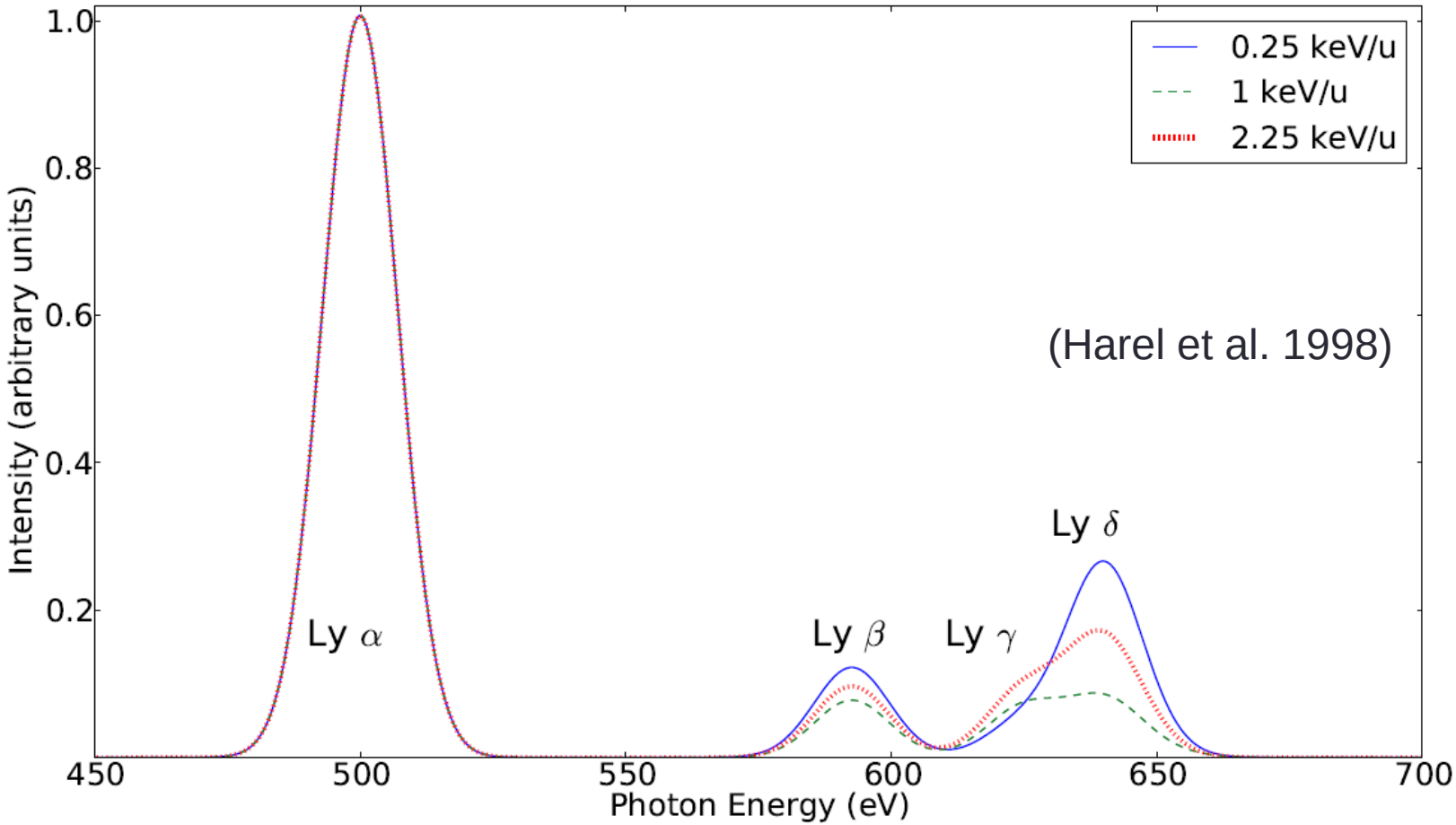
N^{6+} +H


0.5 keV/u
1 keV/u
2 keV/u
(Wu et al. 2011)
Intensity (arbitrary units)
Photon Energy (eV)
K α
K β
K γ
0.0
0.2
0.4
0.6
0.8
1.0
400
450
500
550

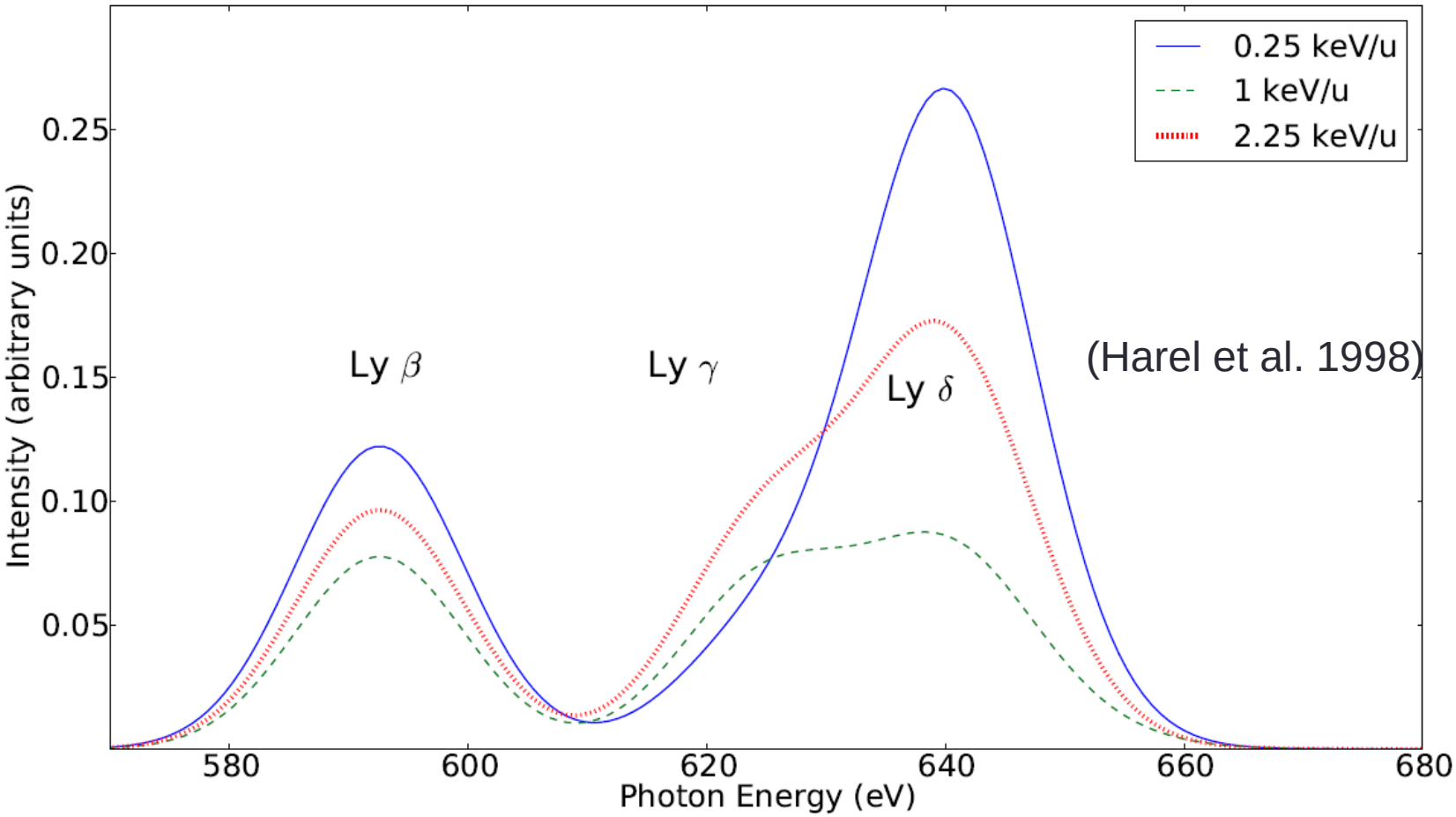
N^{6+} +H


0.5 keV/u
1 keV/u
2 keV/u
(Wu et al. 2011)
K β
K γ
Intensity (arbitrary units)
Photon Energy (eV)
0.05
0.04
0.03
0.02
0.01
480
490
500
510
520
530
540
550

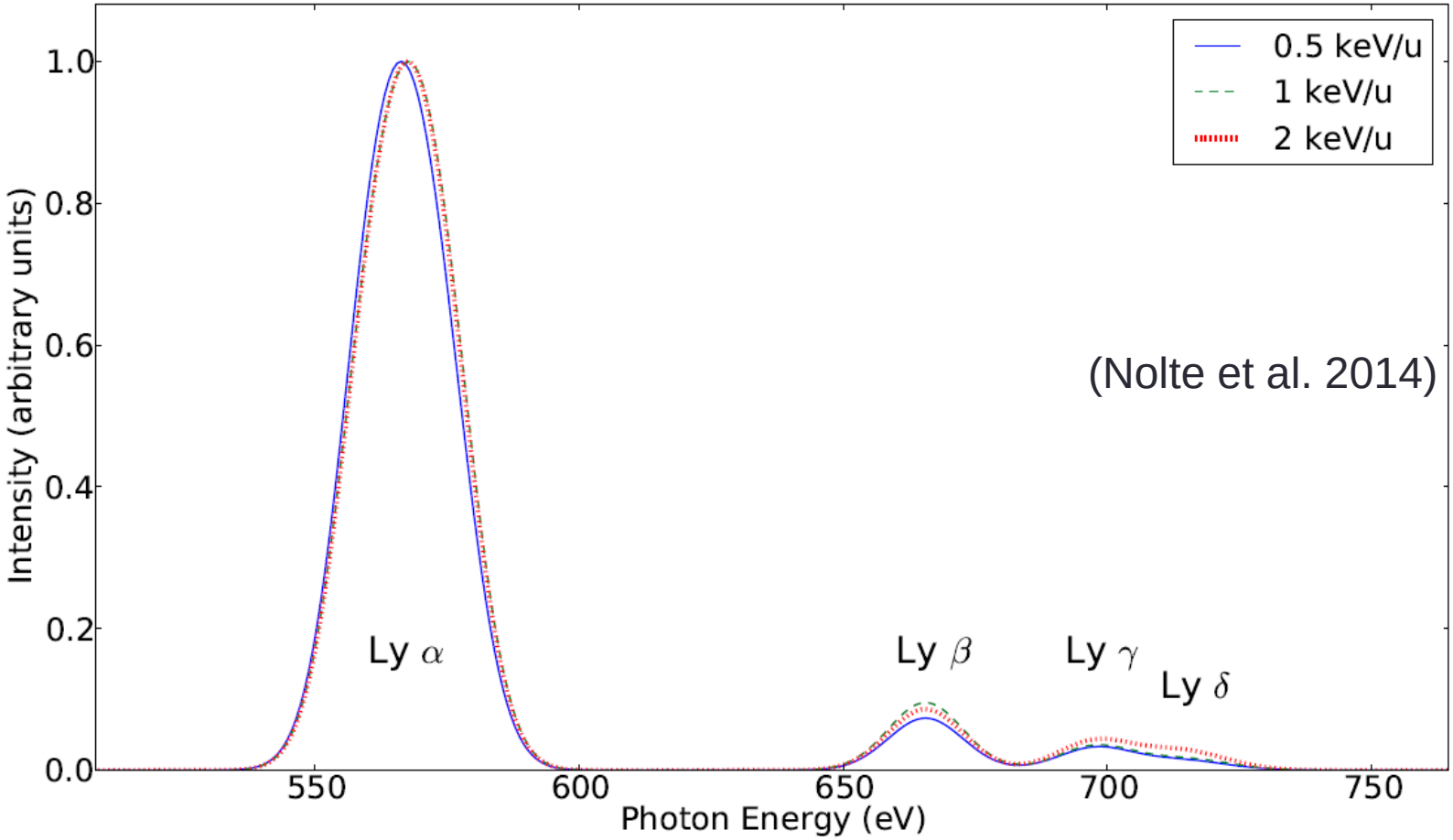
N^{7+} +H


0.25 keV/u
1 keV/u
2.25 keV/u
(Harel et al. 1998)
Ly α
Ly β
Ly γ
Ly δ
Intensity (arbitrary units)
Photon Energy (eV)
1.0
0.8
0.6
0.4
0.2
450
500
550
600
650
700

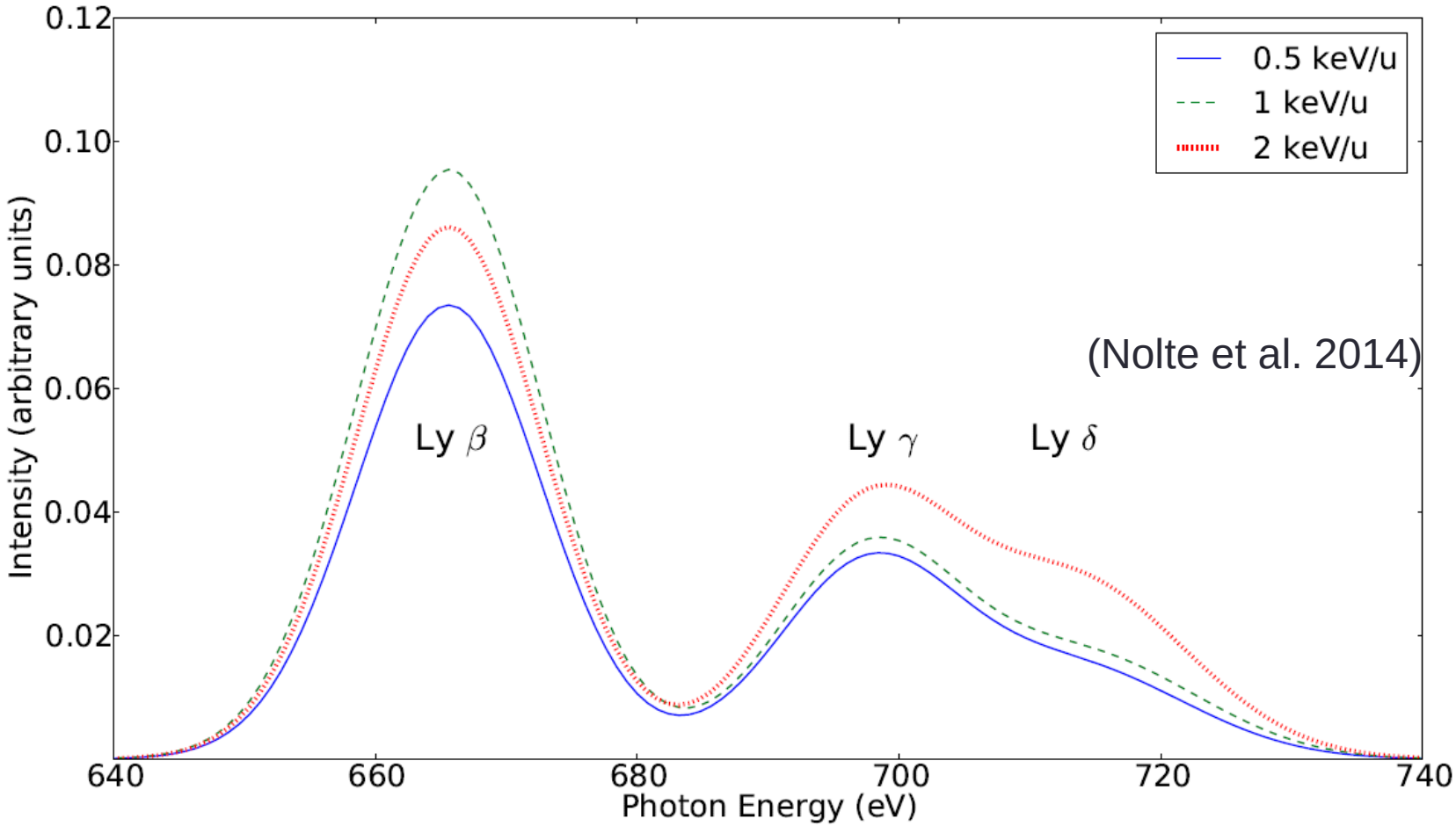
N^{7+} +H


0.25 keV/u
1 keV/u
2.25 keV/u
Ly β
Ly γ
Ly δ
(Harel et al. 1998)
Intensity (arbitrary units)
0.25
0.20
0.15
0.10
0.05
580
600
620
640
660
680
Photon Energy (eV)

O^{7+} +H

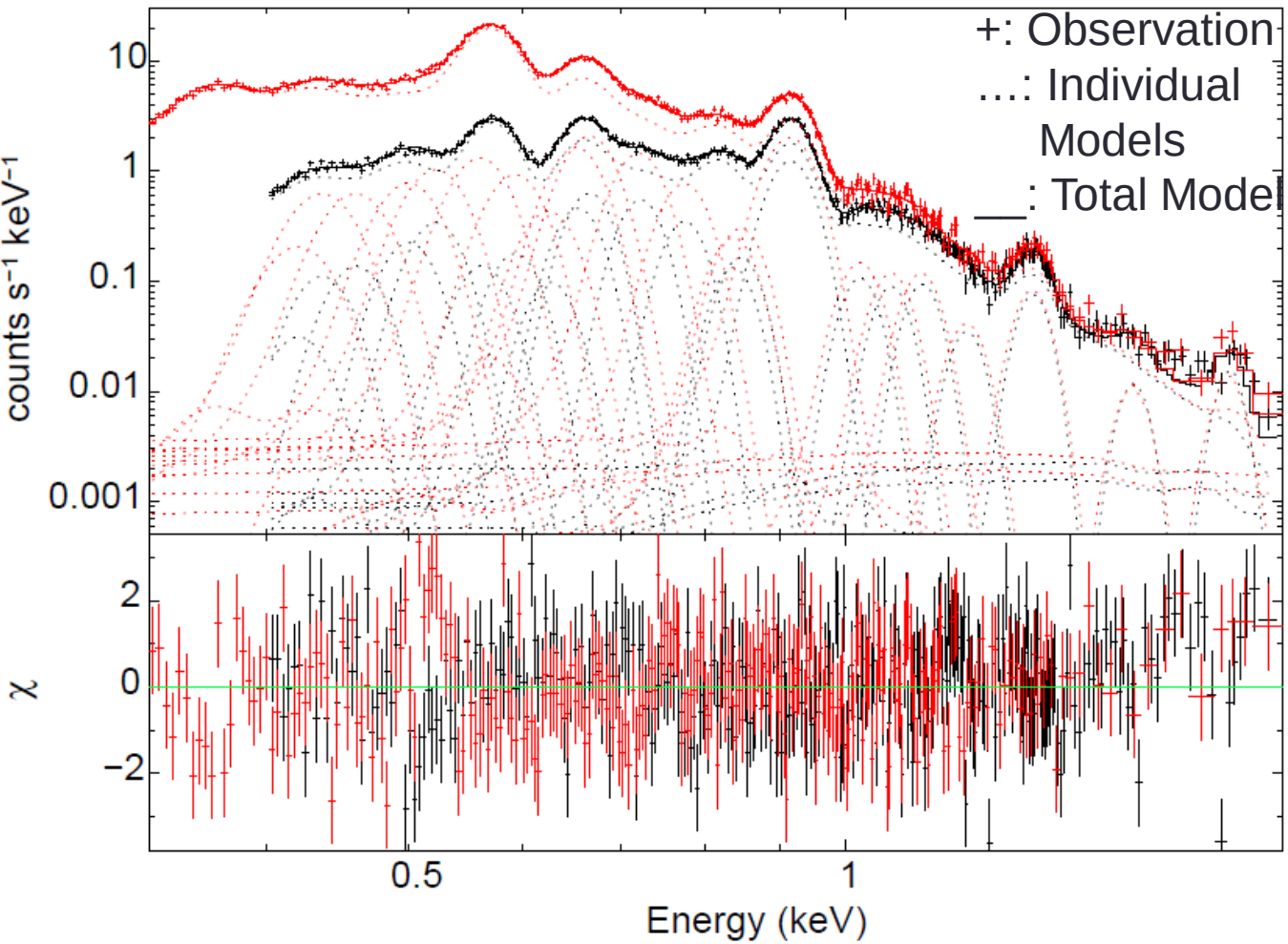

0.5 keV/u
1 keV/u
2 keV/u
(Nolte et al. 2014)
Ly α
Ly β
Ly γ
Ly δ
Intensity (arbitrary units)
Photon Energy (eV)
0.0
0.2
0.4
0.6
0.8
1.0
550
600
650
700
750

O^{7+} +H


0.12
0.10
0.08
0.06
0.04
0.02
Intensity (arbitrary units)
640
660
680
700
720
740
Photon Energy (eV)
0.5 keV/u
1 keV/u
2 keV/u
Ly β
Ly γ
Ly δ
(Nolte et al. 2014)

Cygnus Loop: Free normalizations

Fig 2b



Model with CX

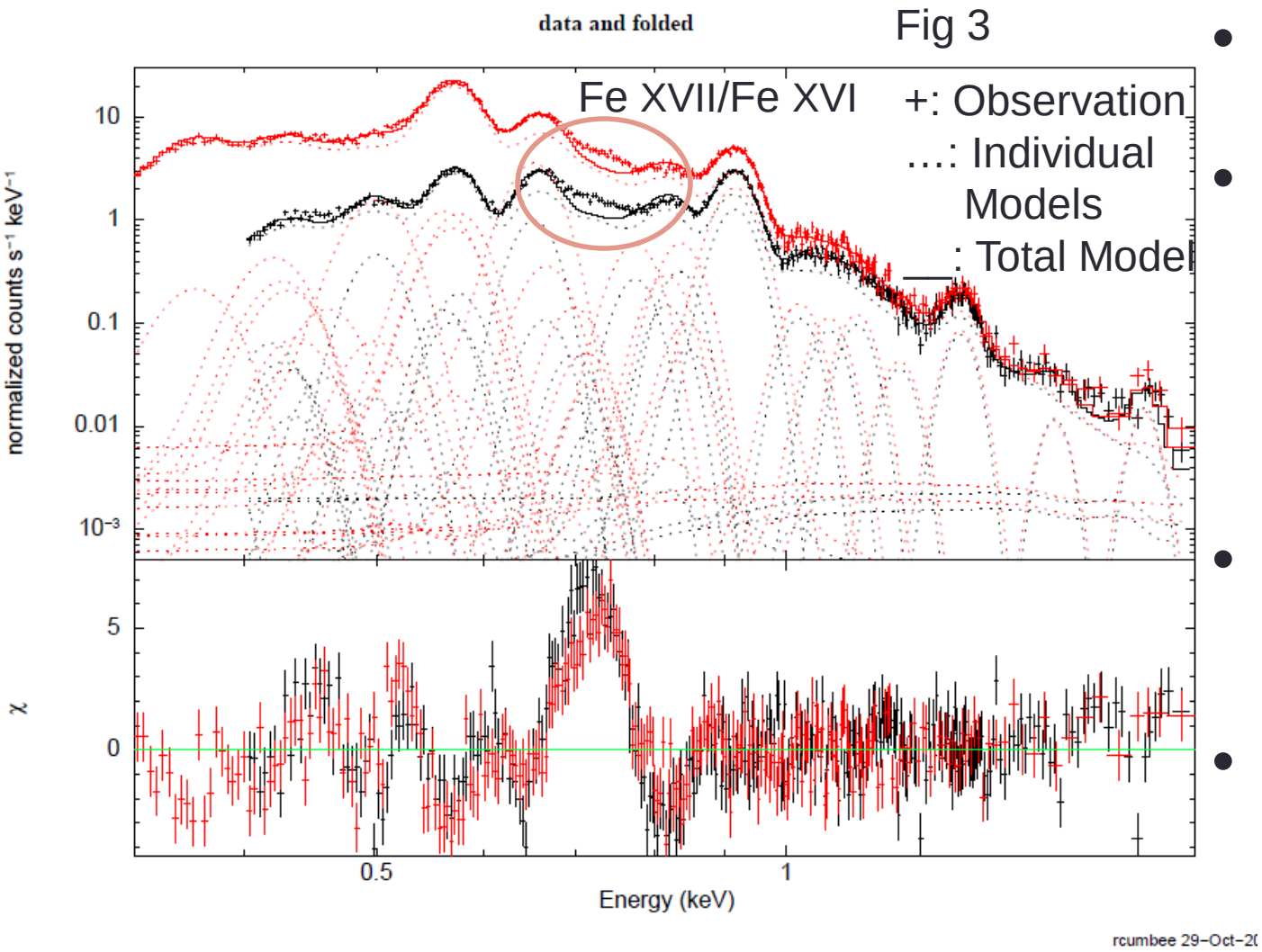
Background + VpShock + 33 CX lines

- Intensities vary independently
- No line ratios

Reduced χ^2= 1.36 with 533 dof.

Unphysical Line Ratios

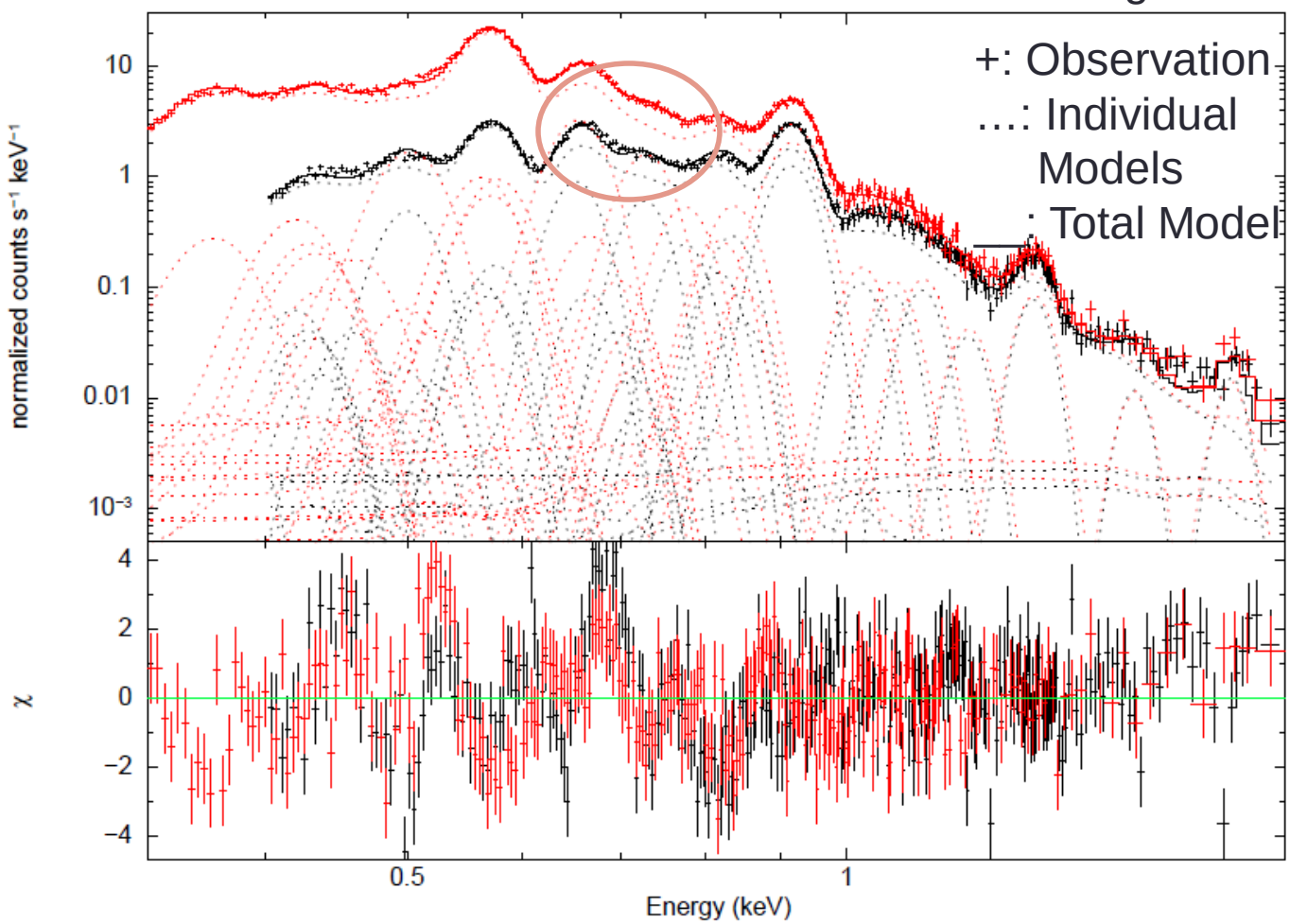
Cygnus Loop: With CX Data



- Model with CX
- Background + VpShock + 33 CX lines
  - Tied to respective Kα line
- Reduced χ^2= 3.95 with 555 dof.
- Physically Reasonable Line Ratios

Cygnus Loop: With CX Data + Fe Lines

Figure 4

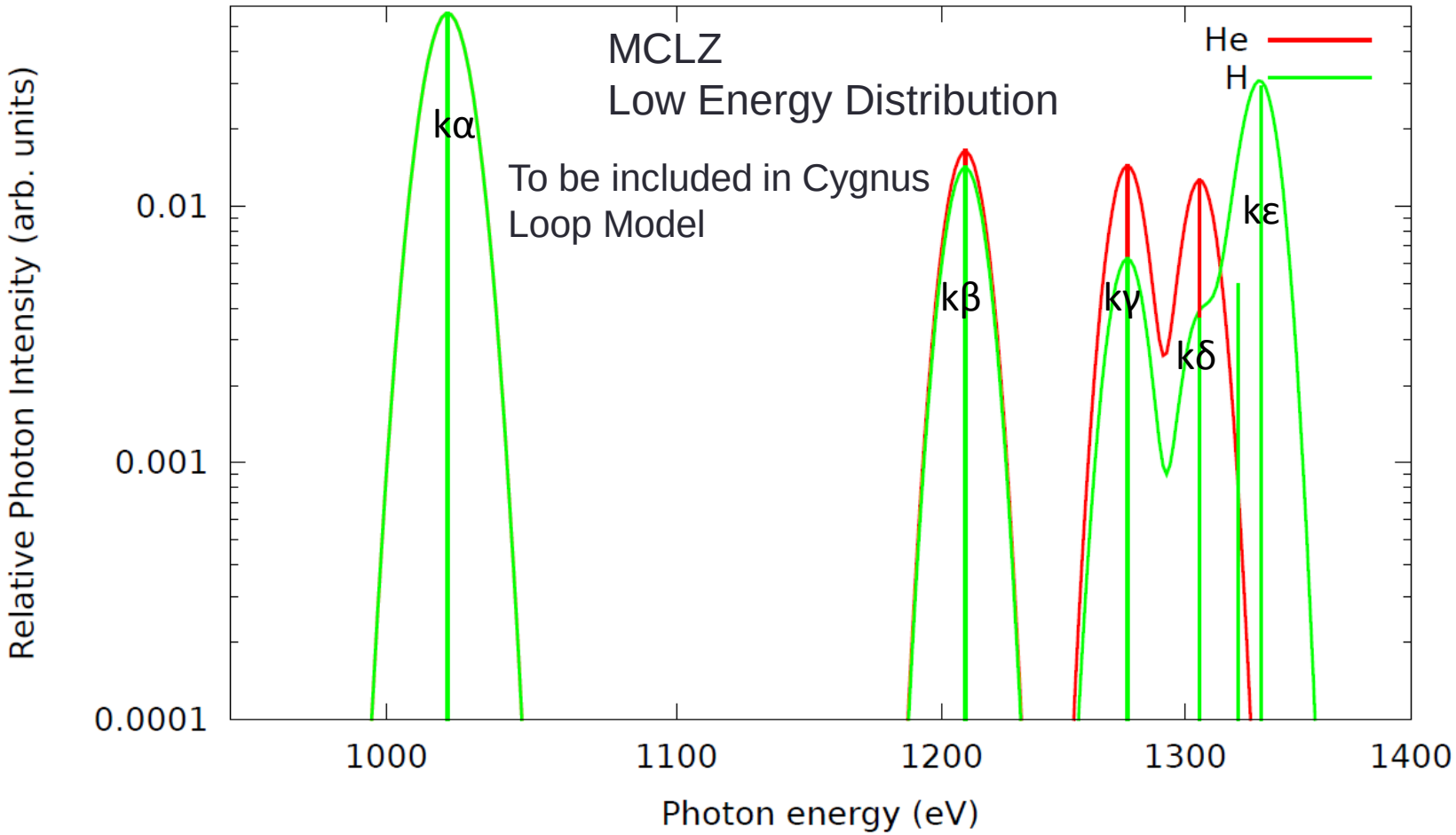


rcumbee 2

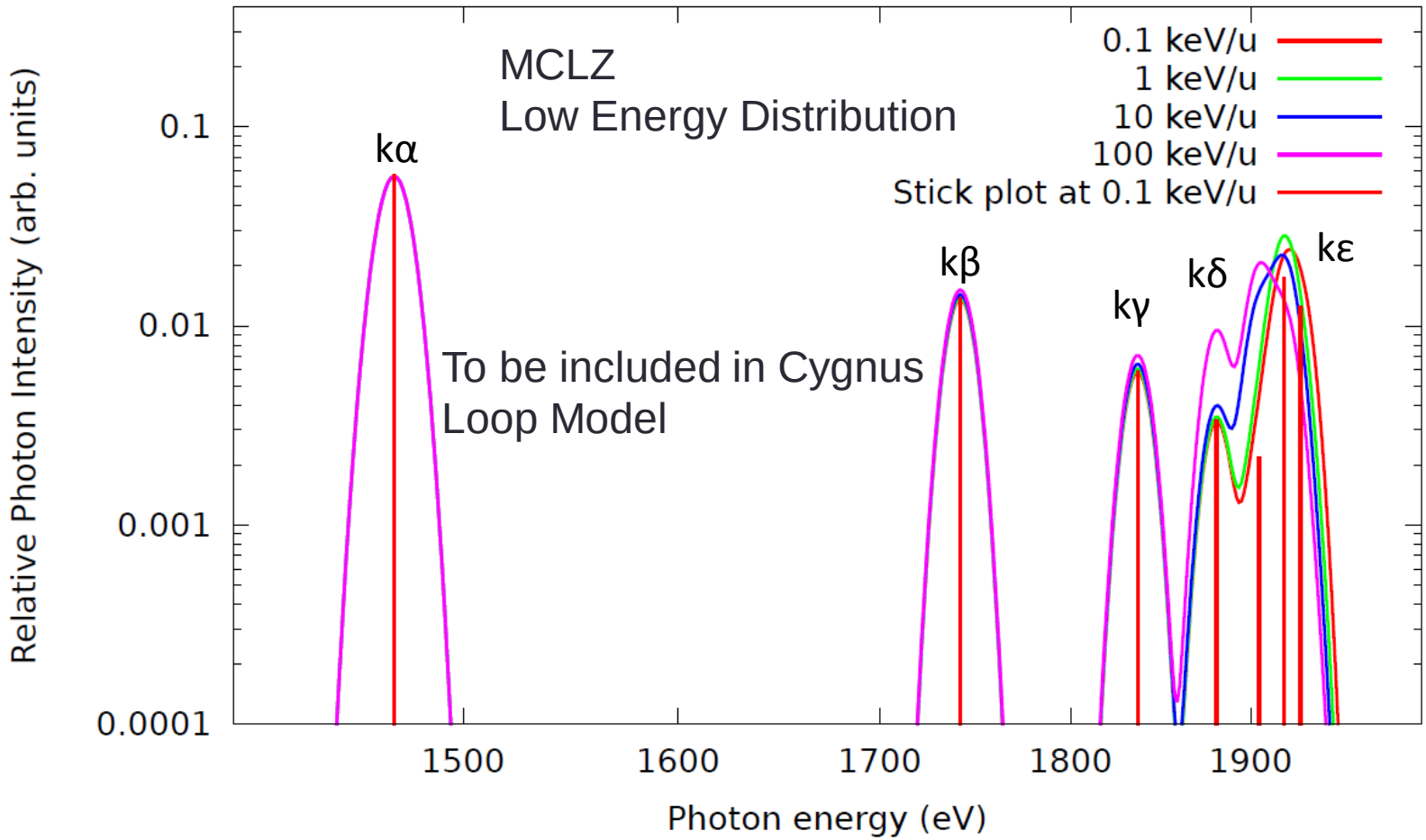
- Model with CX
- Background + VpShock + 35 CX lines
  - Tied to respective Kα line
- + .725 keV & .826 keV Fe lines
- Reduced χ^2= 1.83 with 553 dof.

$Ne^{10+} + H \rightarrow Ne^{9+} + H^{+}$

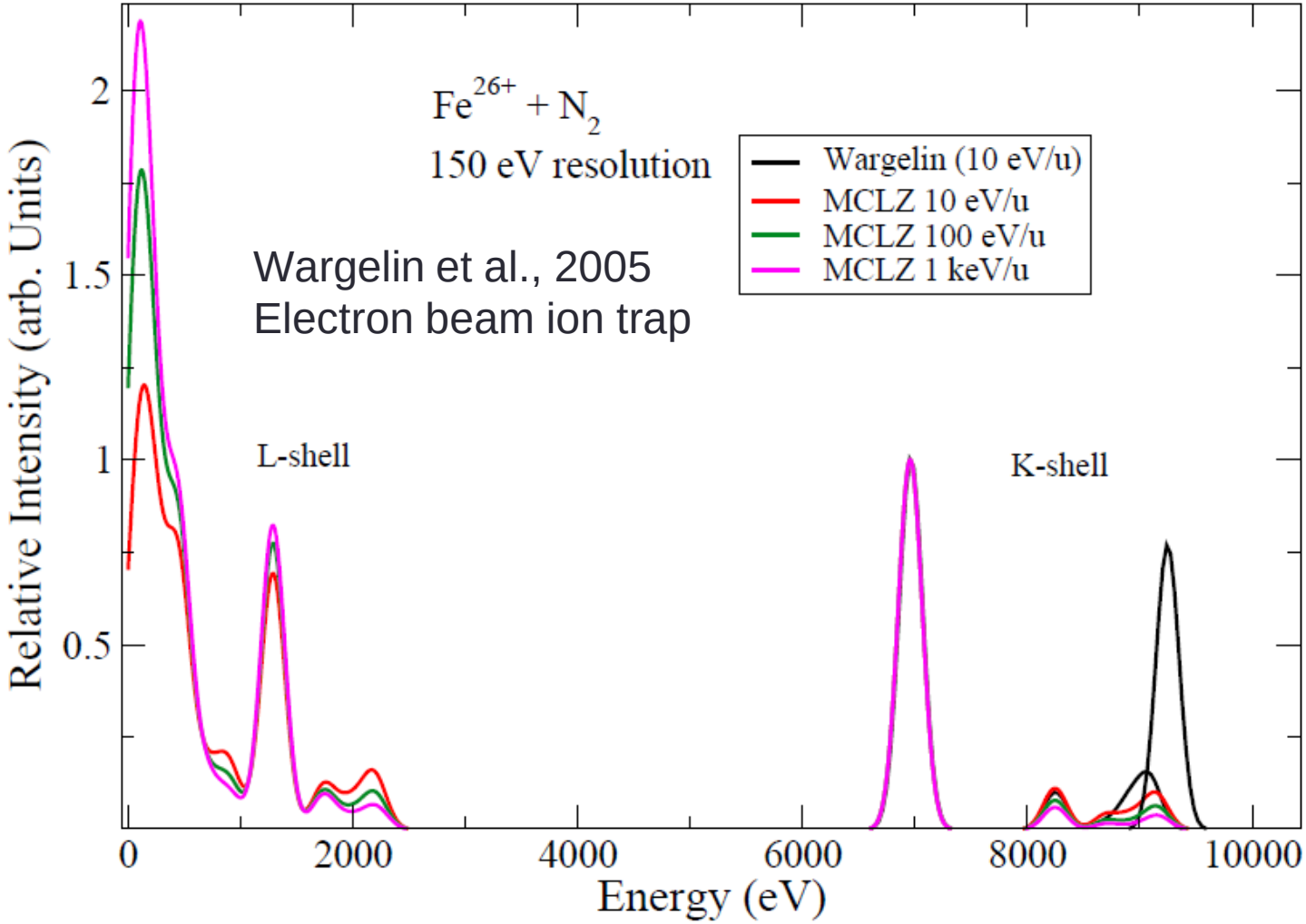
$Ne^{10+} + He \rightarrow Ne^{9+} + He^{+}$



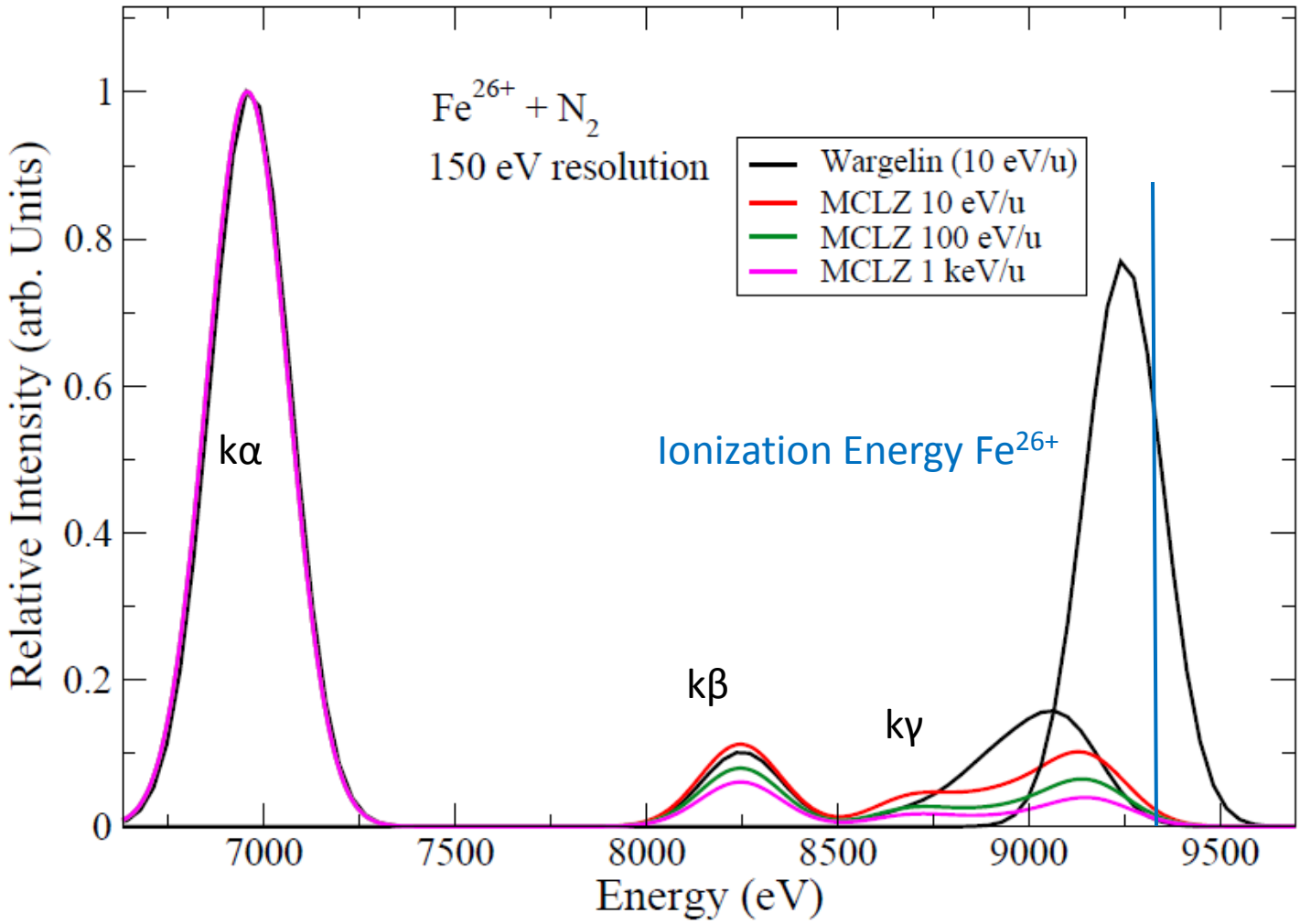
$Mg^{12+} + H \rightarrow Mg^{11+} + H^{+}$



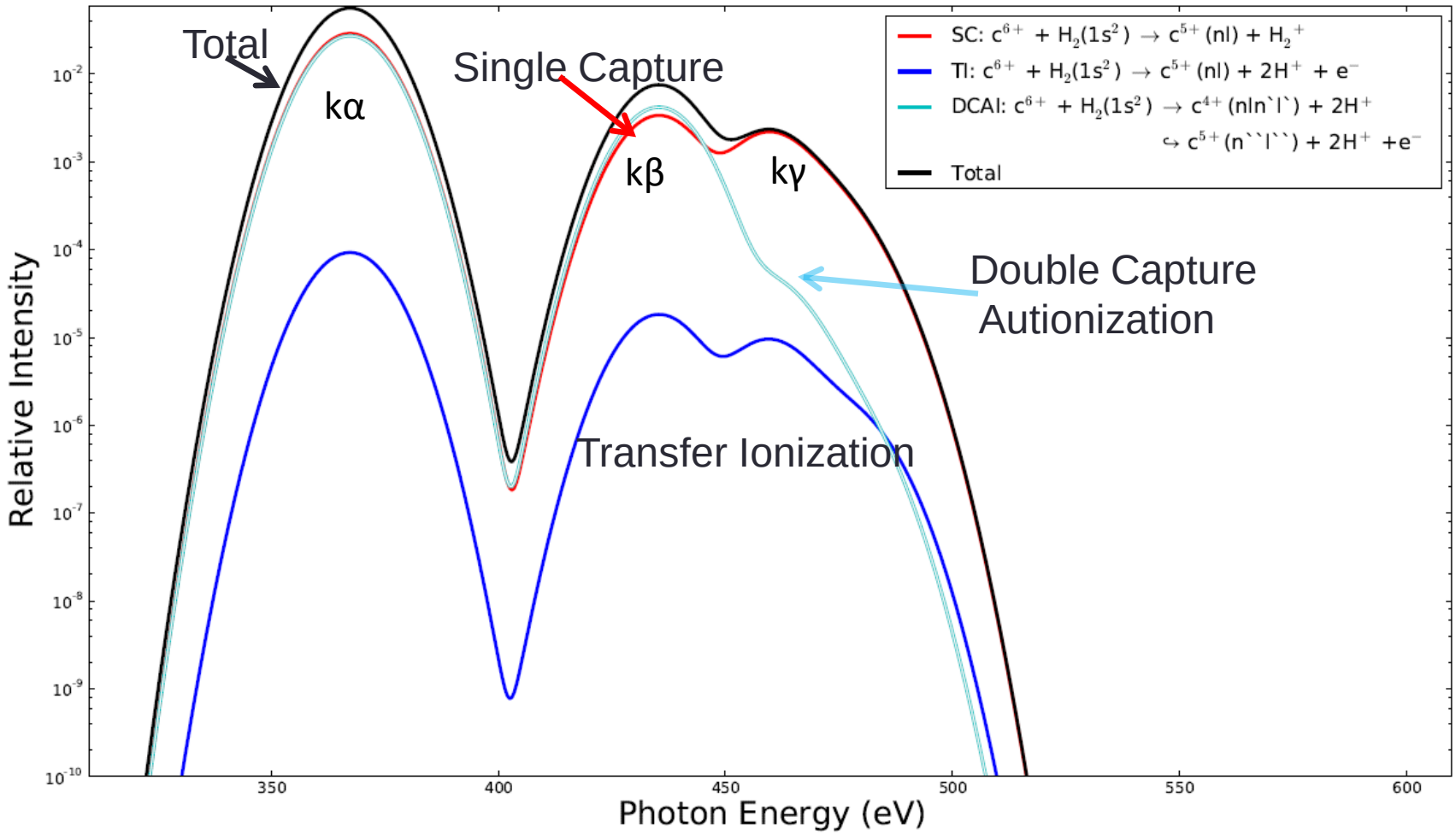
$Fe^{26+} + N_2 \rightarrow Fe^{25+} + N_2^+$



$Fe^{26+} + N_2 \rightarrow Fe^{25+} + N_2^+$



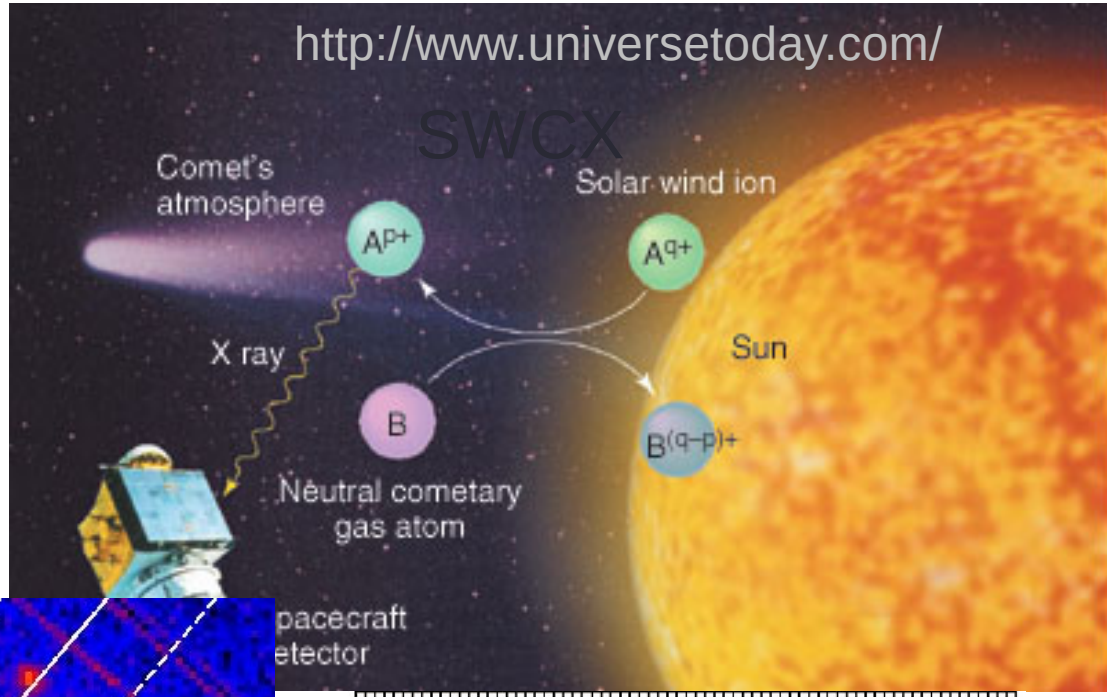
$C^{6+} + H_2 \rightarrow C^{5+} + H_2^{+}$: CTMC



Summary

- CX often invoked in observations with anomalous X-ray features
  - Often with unrealistic CX data
- Cygnus Loop:
  - Can improve spectrum from NE4 with CX model
  - 0.7 keV region still difficult to model
  - Consider only ion interactions with Neutral H
    - Would like to consider He
  - Need more:
    - Ions: Ne, Mg, Fe, si
    - Ionization stages
    - Neutral species (he, H_2)
  - Future: Apply to other Observations

In the Future



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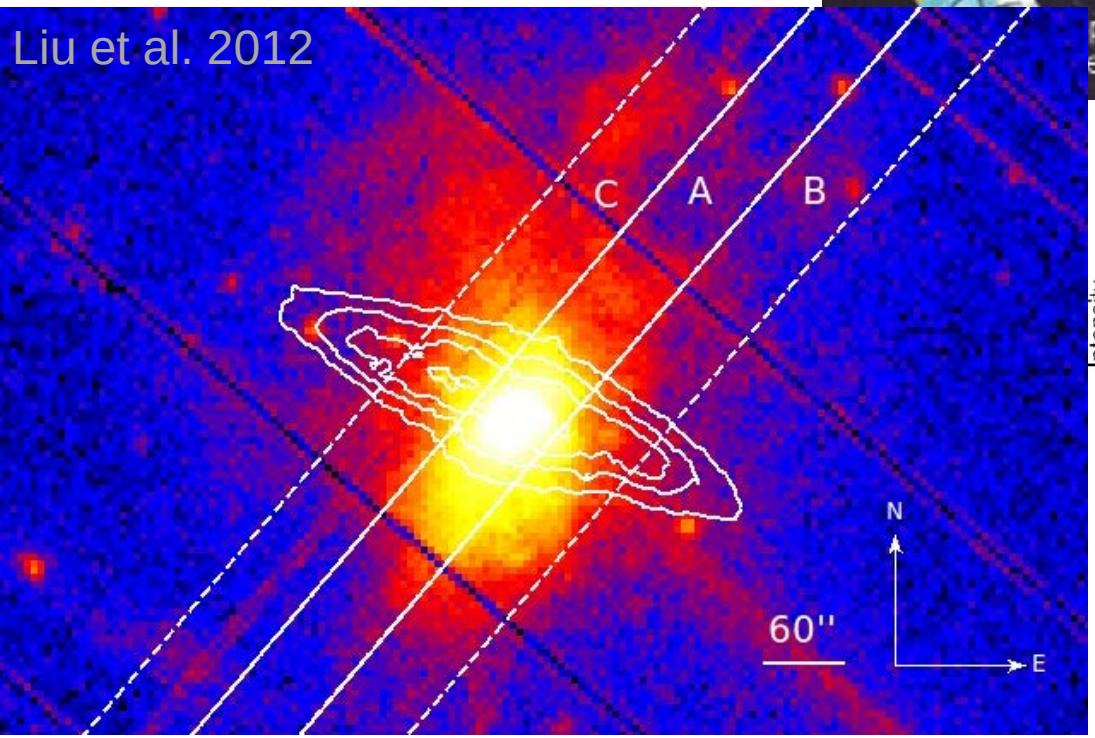

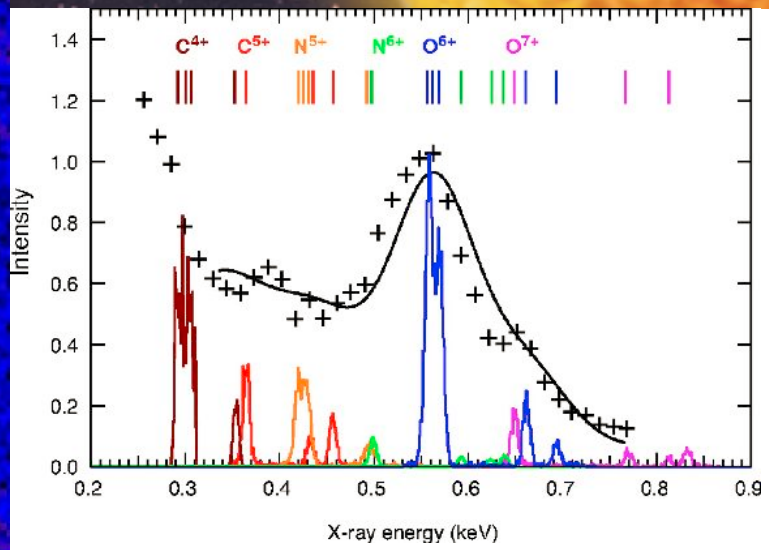

Comet Linear: Beiersdorfer et al, Science, 200