# Charge Exchange, from the laboratory to the sky

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# The story of Hyakutake: how we know that comets emit X-rays


Comet Hyakutake (with the Big Dipper) as seen from Chatsworth, New Jersey

# The story of Hyakutake: how we know that comets emit X-rays

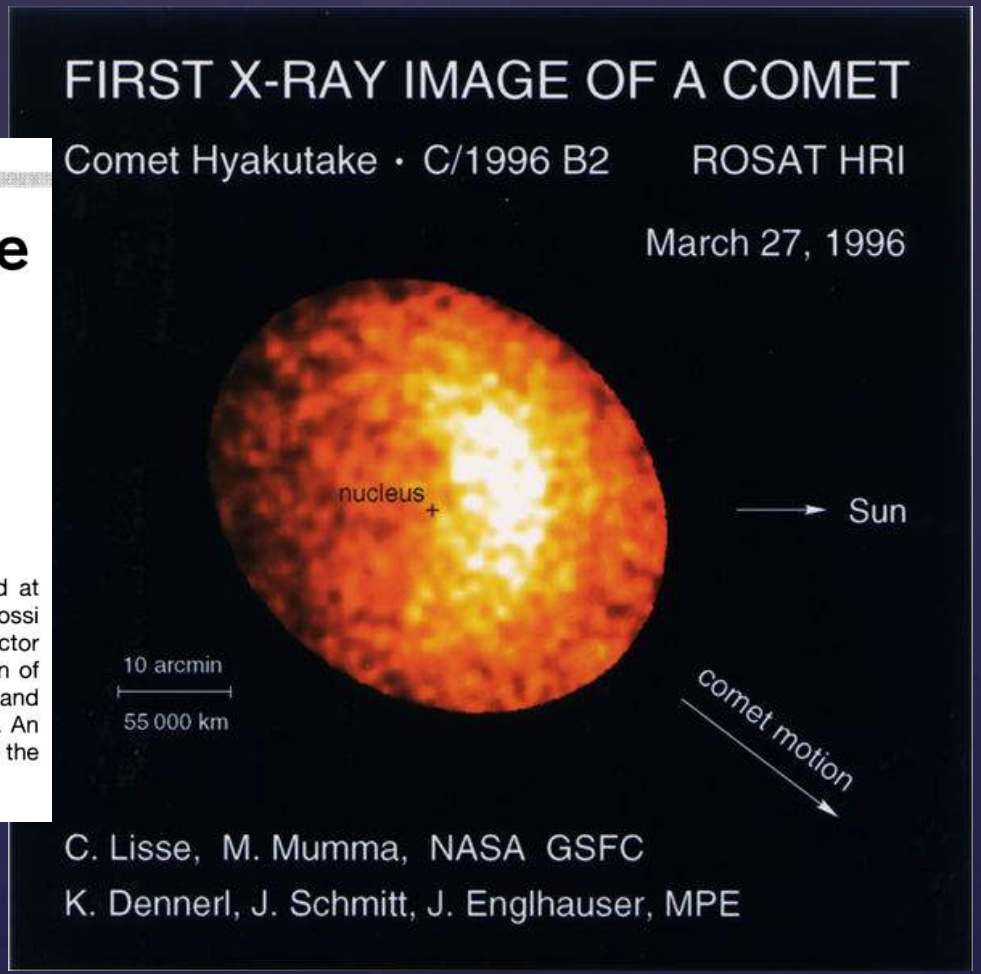
RESEARCH ARTICLES

## Discovery of X-ray and Extreme Ultraviolet Emission from Comet C/Hyakutake 1996 B2

C. M. Lisse, K. Dennerl, J. Englhauser, M. Harden, F. E. Marshall, M. J. Mumma, R. Petre, J. P. Pye, M. J. Ricketts, J. Schmitt, J. Trümper, R. G. West

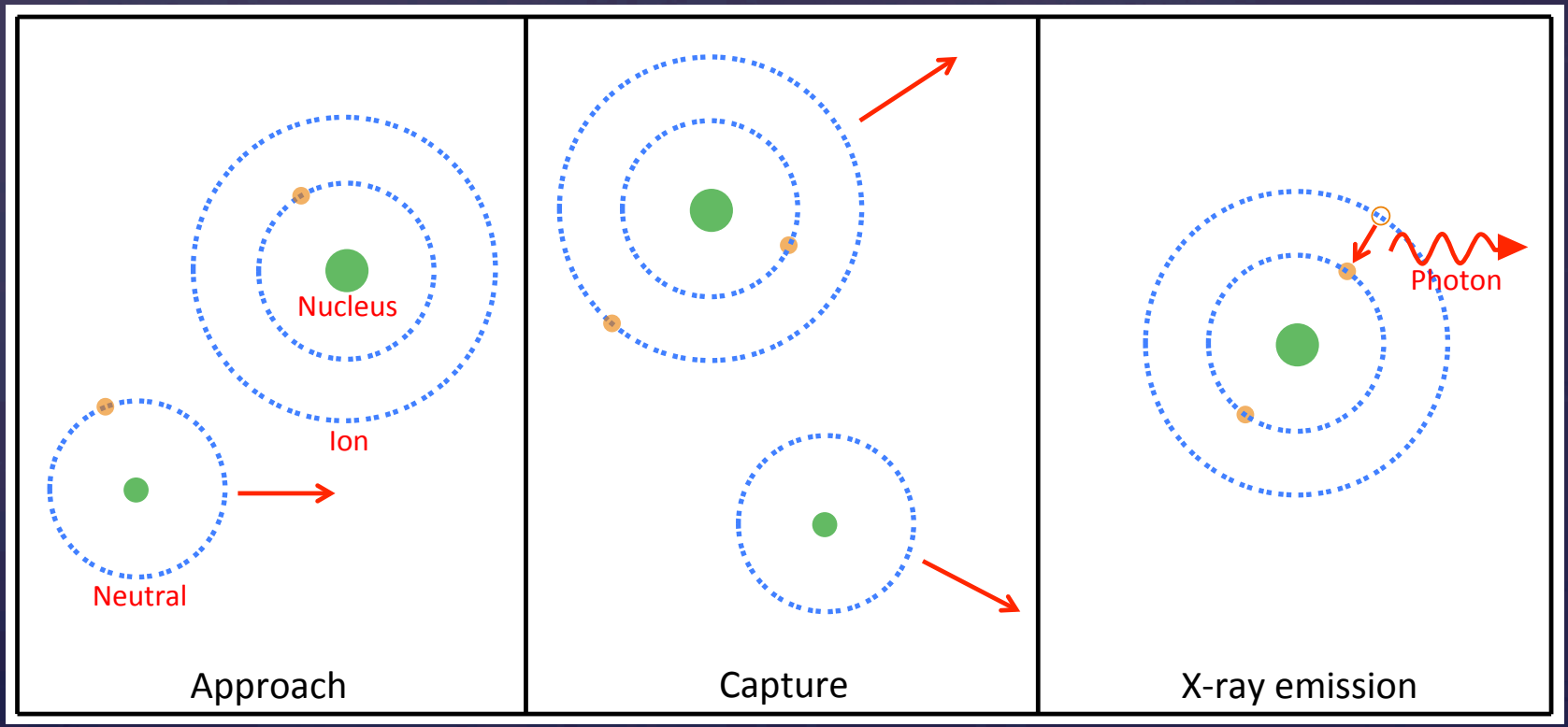
During its close approach to Earth, comet C/Hyakutake 1996 B2 was observed at extreme ultraviolet and x-ray wavelengths with the Röntgen X-ray Satellite and Rossi X-ray Timing Explorer. The emission morphology was symmetric with respect to a vector from the comet's nucleus toward the sun, but not symmetric around the direction of motion of the comet with respect to interplanetary dust. A slowly varying emission and a large impulsive event that varied on time scales of 1 to 2 hours were observed. An interaction between the comet and the solar wind/solar magnetic field seems to be the most likely mechanism for the observed emission.

Science, 11 October 1996



# Charge Exchange: a primer

A highly charged ion and a neutral interact after a close approach.



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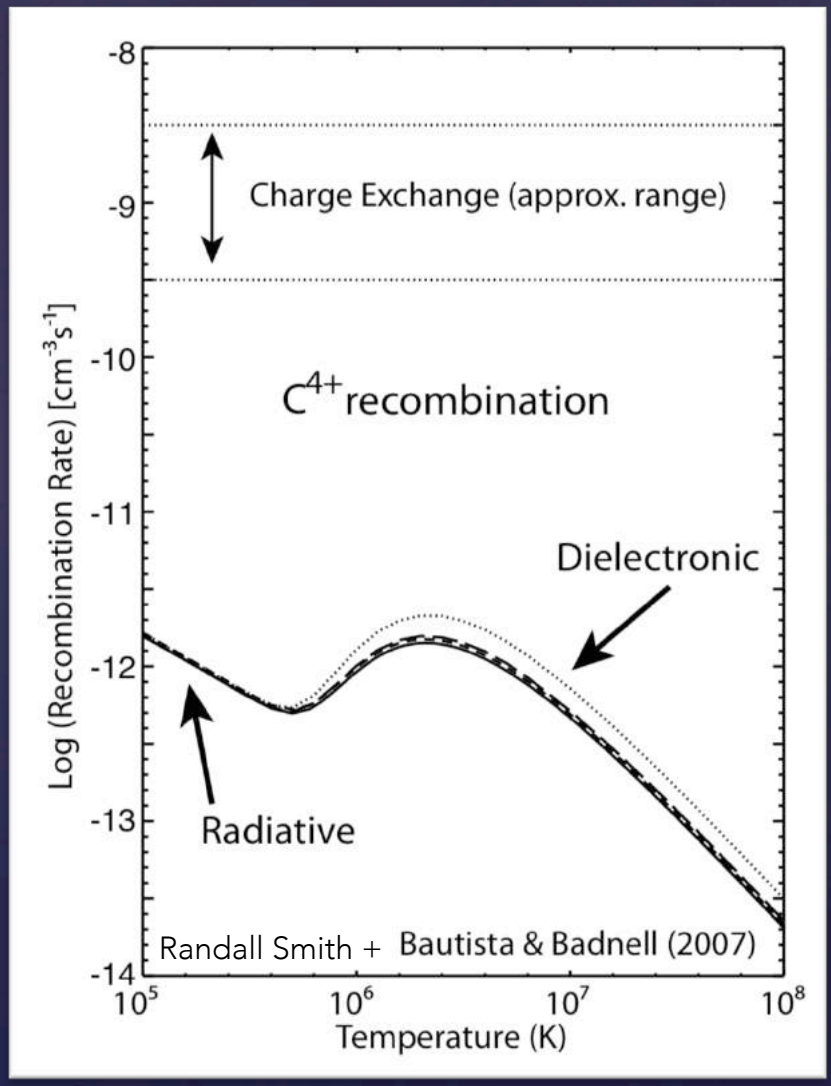


Cross sections are large: ~$10^{-15}$ cm$^2$

# Astrophysical environments for CX

- Comae of comets (Cravens 1997, +)
- Planetary atmospheres (Dennerl et al. 2006, Bhardwaj et al. 2007, +)
- Earth's exosphere (Freyberg 1998, Snowden et al. 2004)
- Heliosphere (Cravens 2000, Cravens et al. 2001)
  → contribution to diffuse soft X-ray background (Wargelin et al. 2004, Koutroumpa et al. 2009, Slavin et al. 2013, Galeazzi et al. 2014)

- Filaments in Perseus cluster? (Walker et al. 2015)
- 3.5 keV line? (Gu et al. 2015, Hitomi Collab. 2017)
- Rim of supernova remnants? (Katsuda et al. 2011, Cumbee et al. 2014)
- Nucleus, outflows of starburst galaxies? (Liu et al. 2011, Wang and Liu 2012)
- Stellar winds? (Wargelin and Drake 2001)
- Atmospheres of exoplanets? (Holmström et al. 2008)

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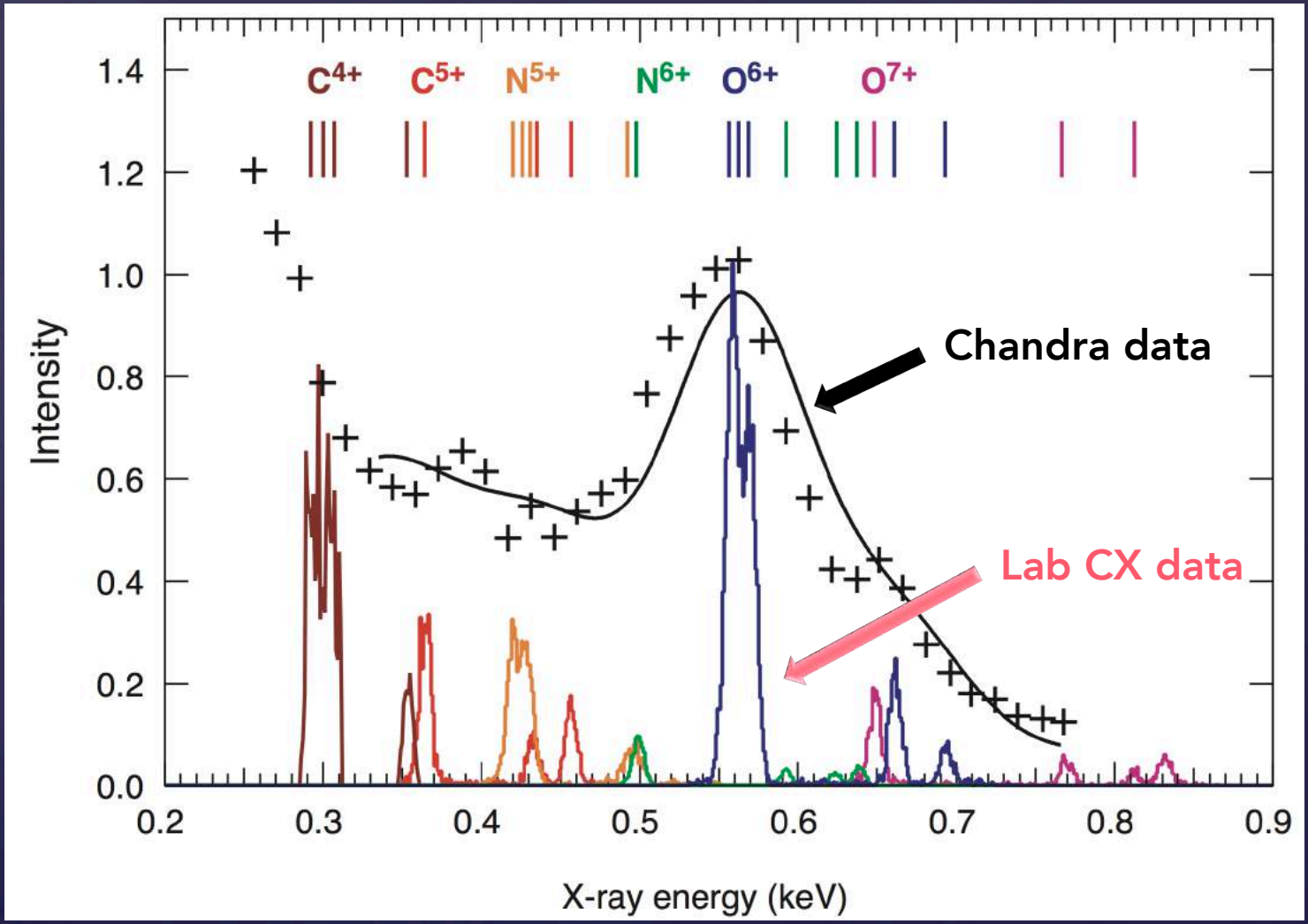
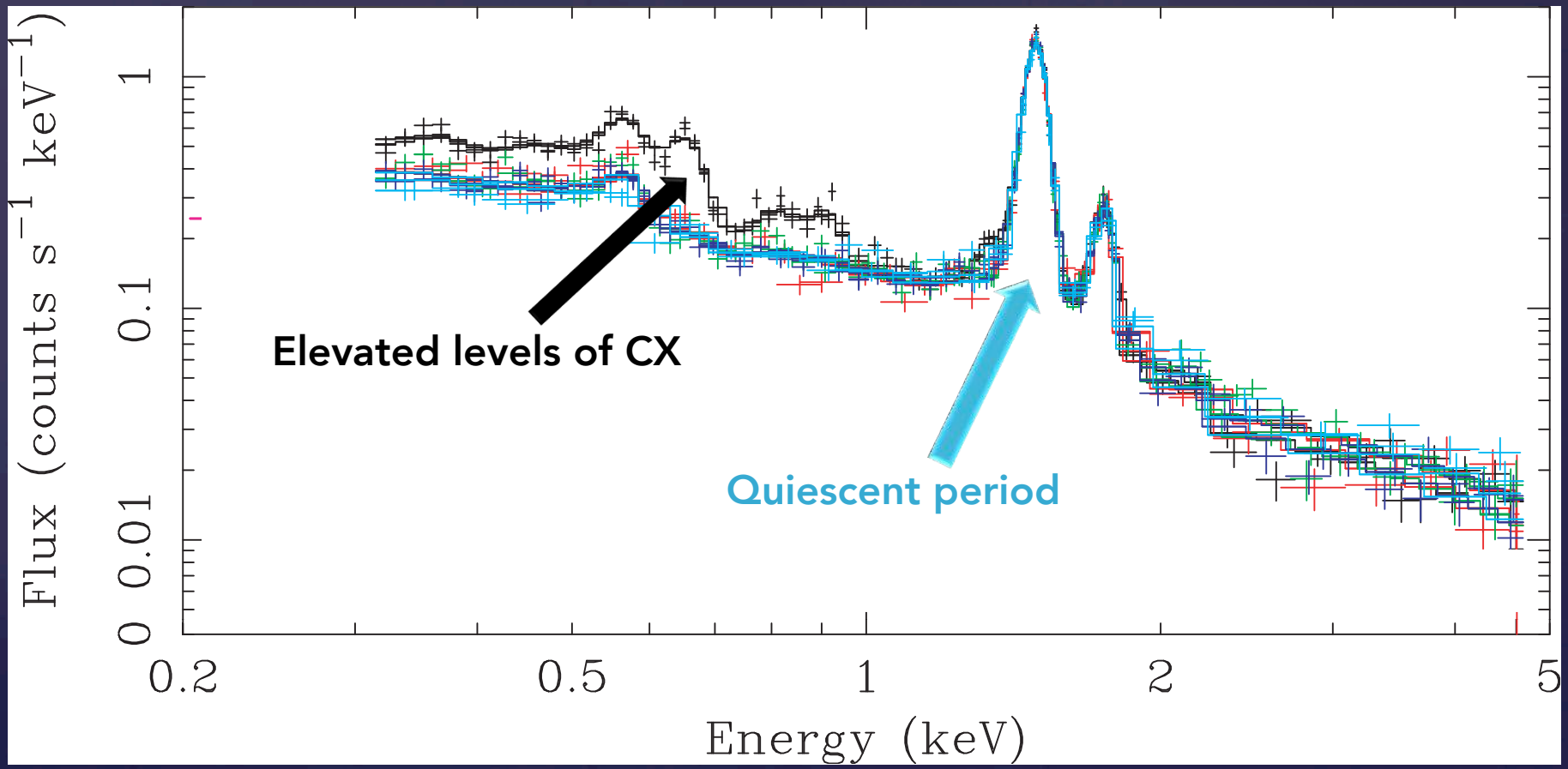
# Cometary CX



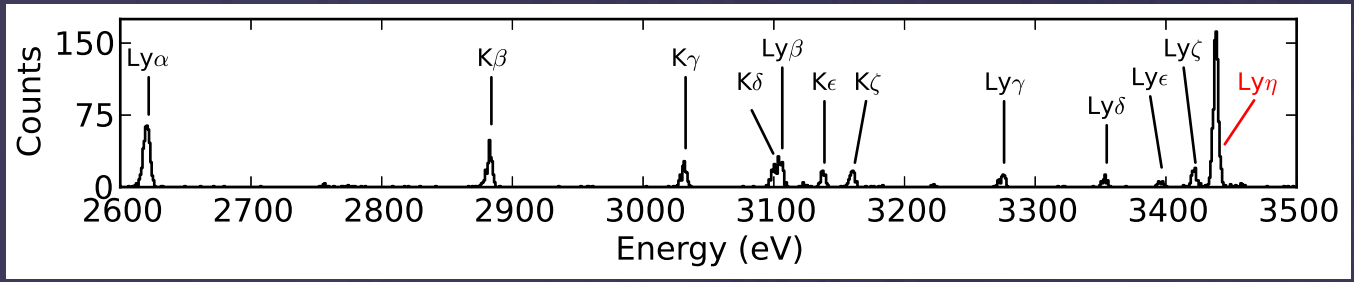

Beiersdorfer et al. (Science, 2003)

# Exospheric/Heliospheric CX

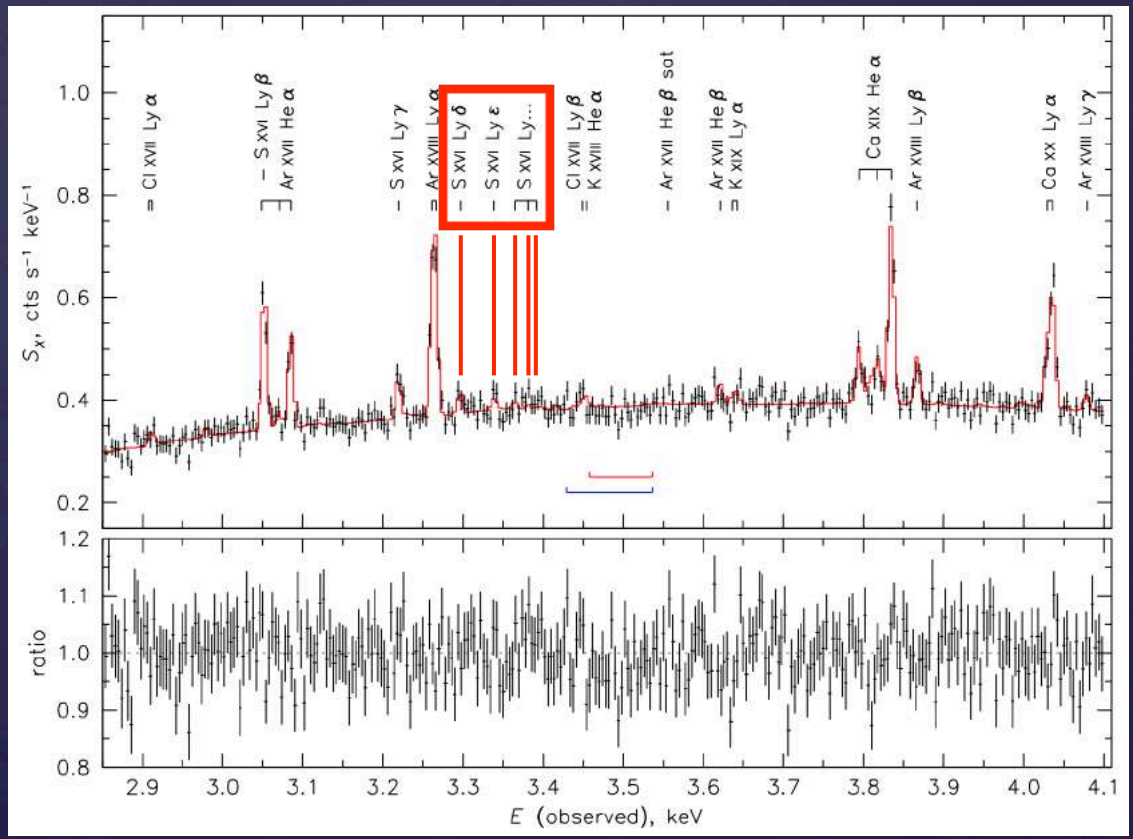



Snowden et al. (2004)

# Sulphur CX in Perseus Cluster?

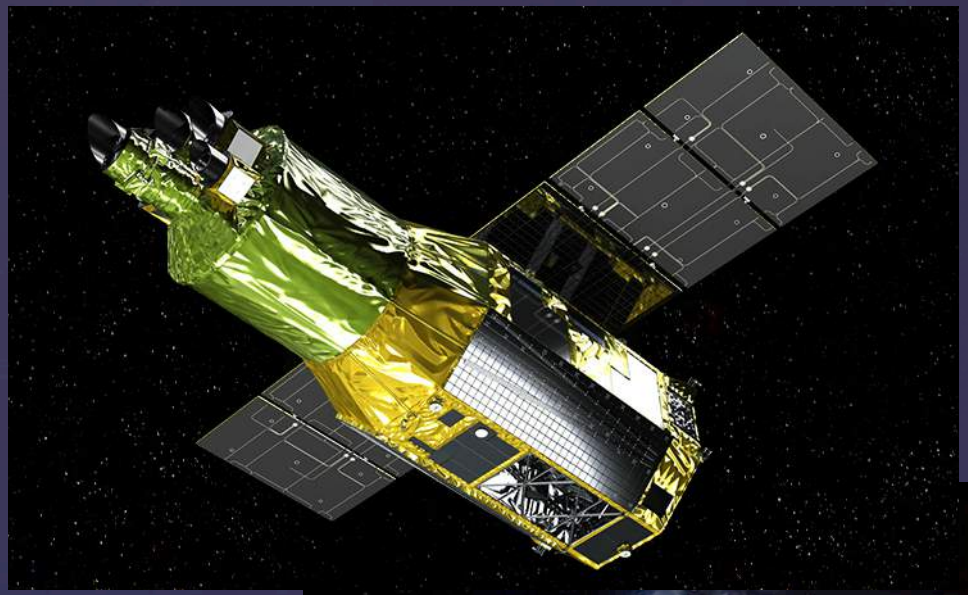


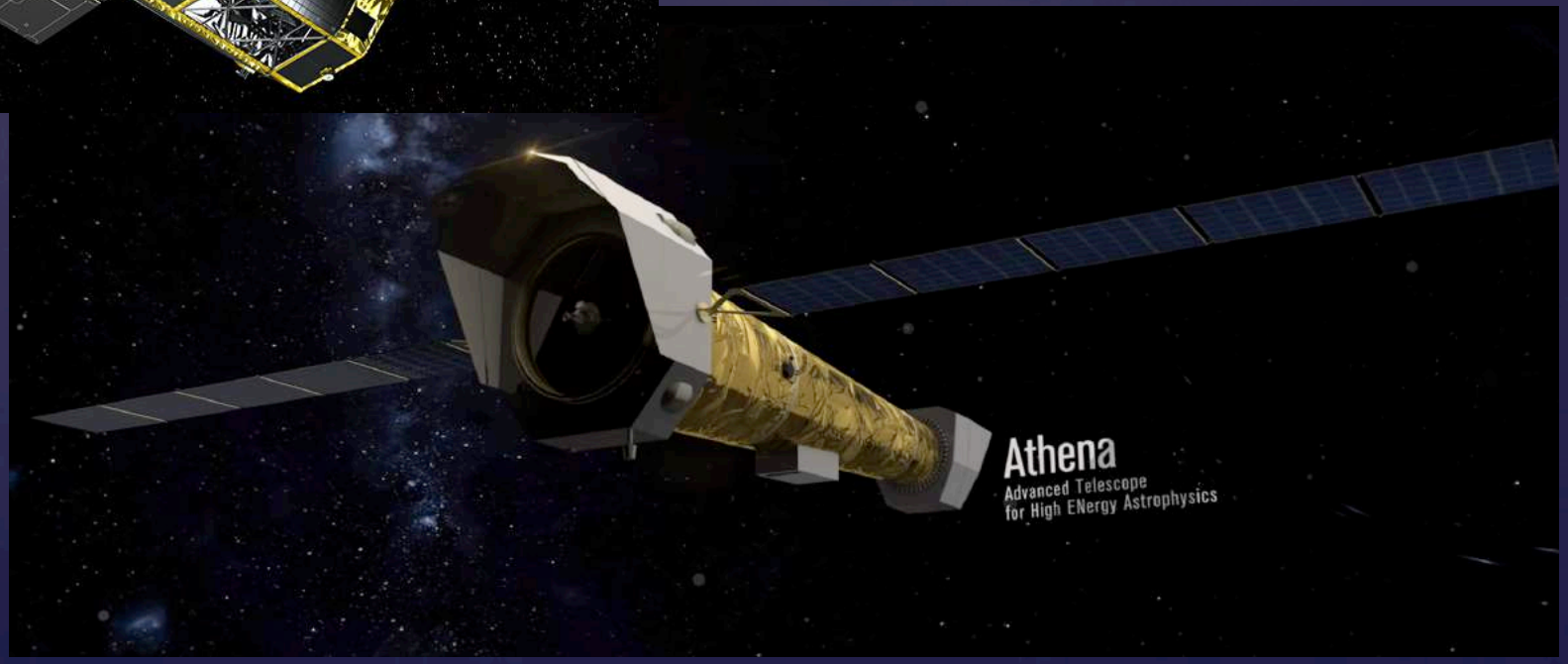

Betancourt-Martinez et al. (2014)




Hitomi Collab. (2017)

# More to come with XRISM, Athena





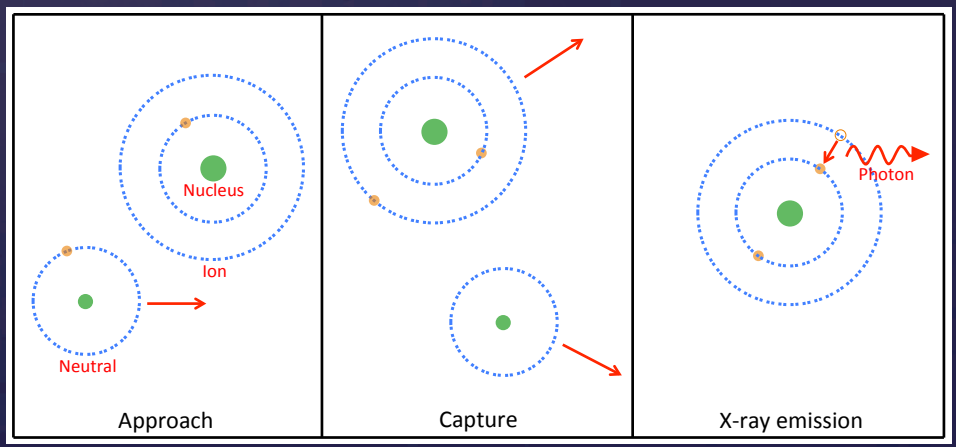
# Challenge:

1. Get the atomic physics right
2. Get this into models

# Challenge:

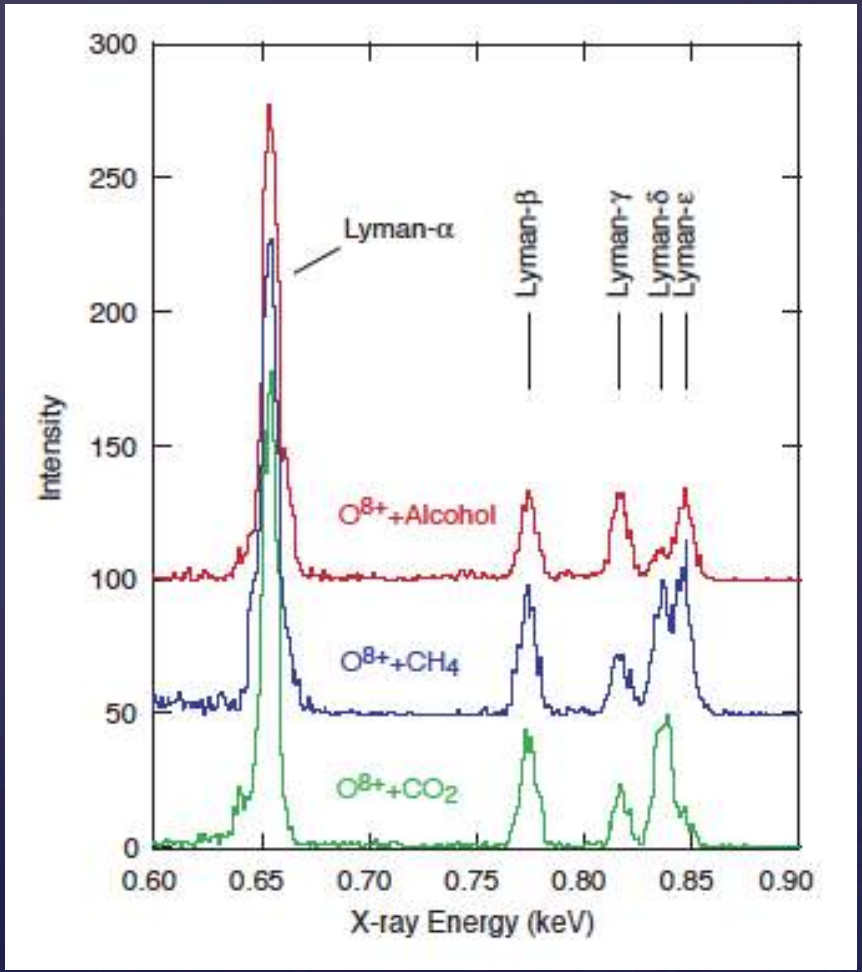
1 Get the atomic physics right

- *n*, *l* (etc.) - resolved cross sections
- radiative cascade



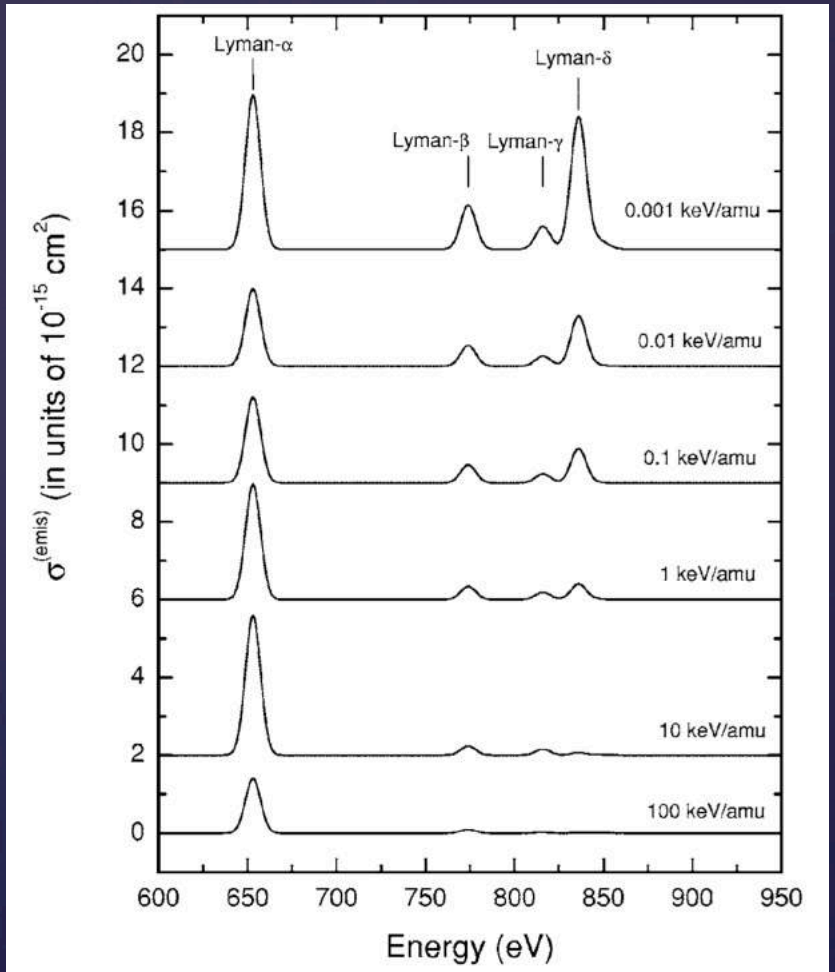
# Challenge ⟺ diagnostic power

Neutral species



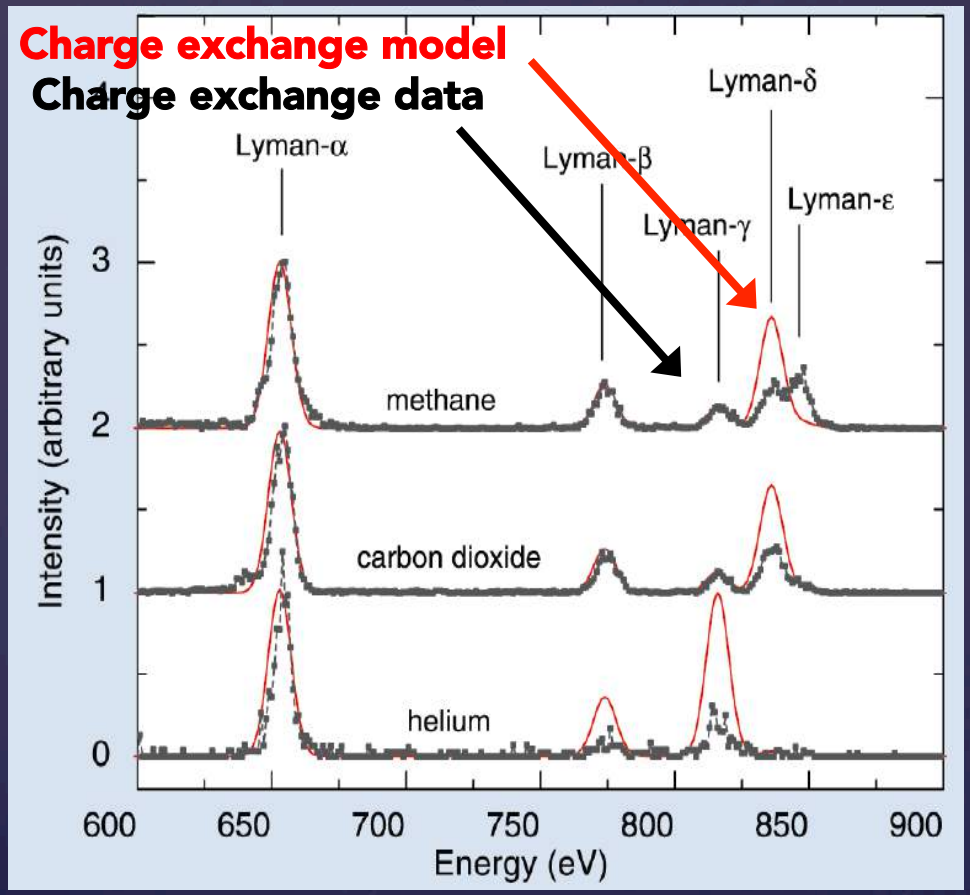

Beiersdorfer et al. (Science, 2003)

Collision velocity

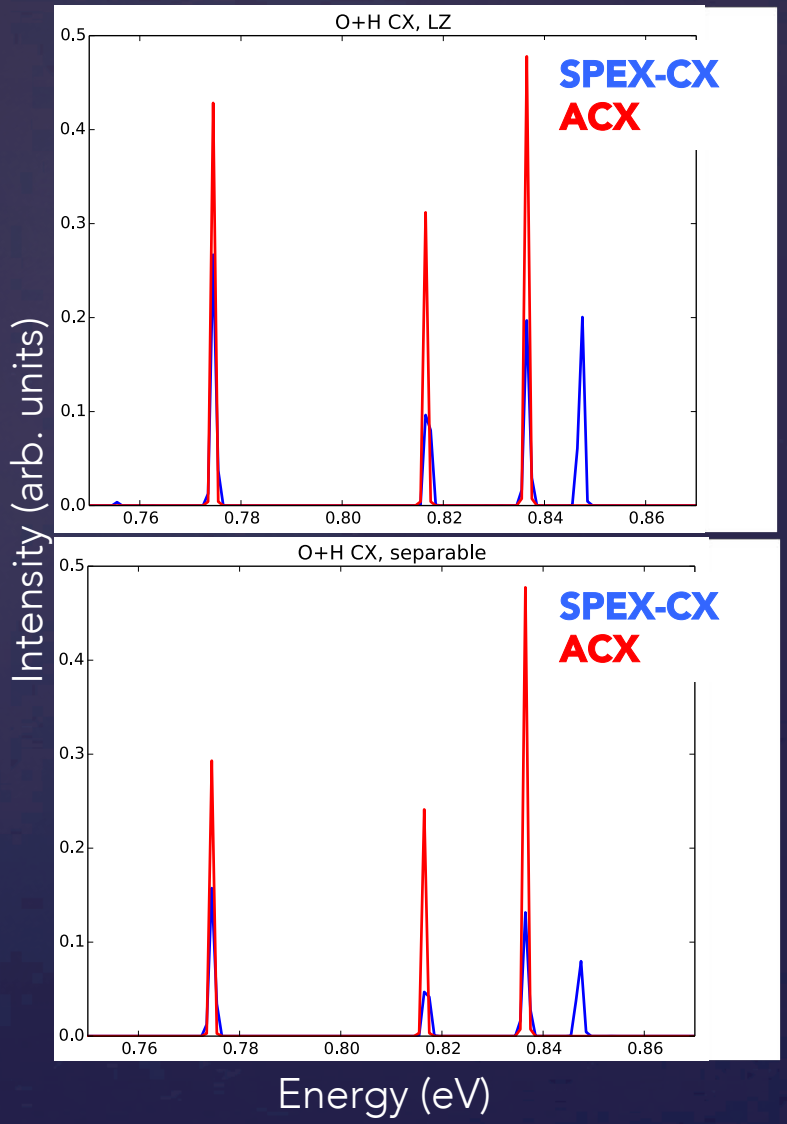



Otranto et al. 2006

# Challenge: hard to model!




Otranto et al. (2006)



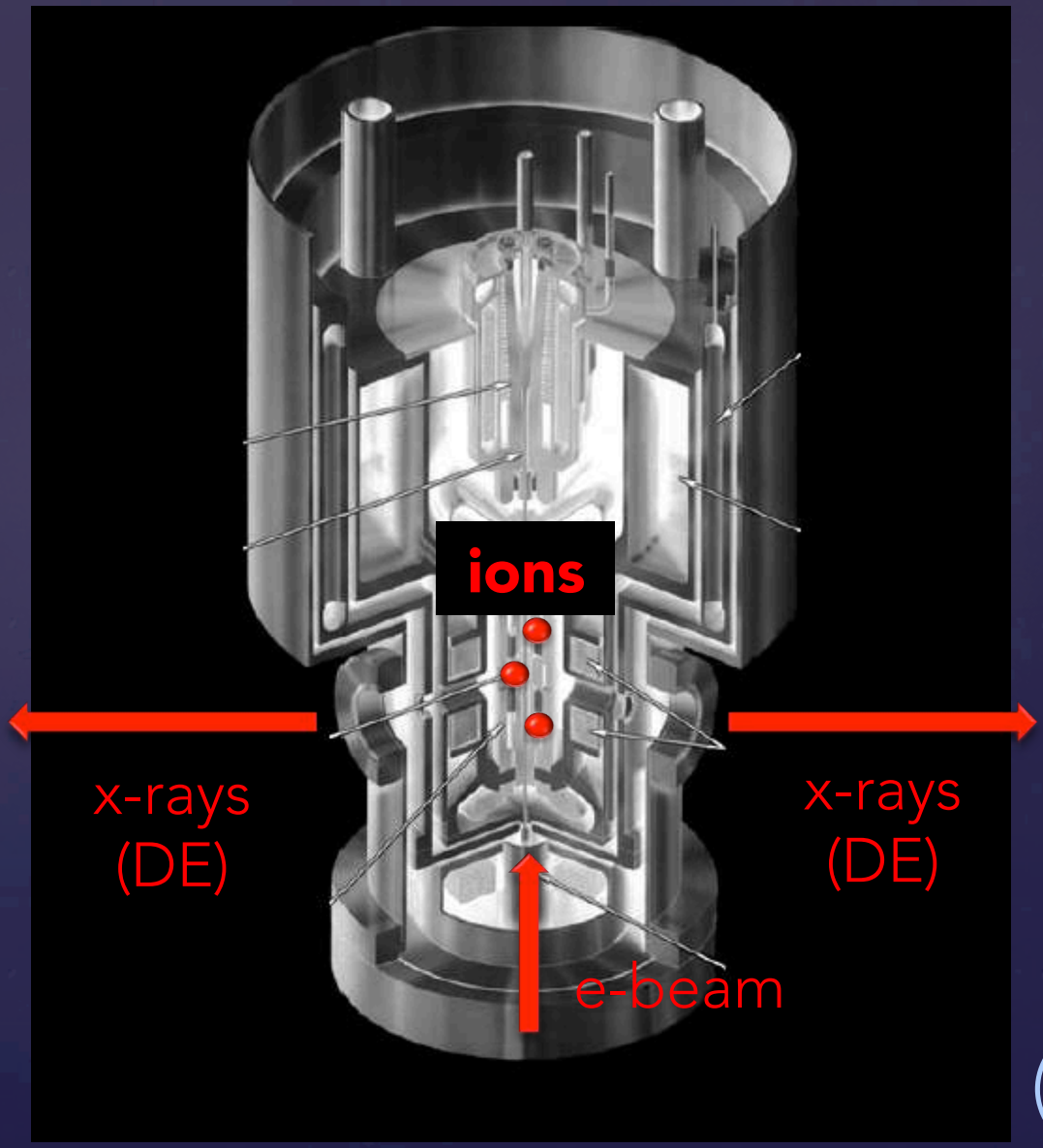
# Laboratory Astrophysics can help

experiment

theory

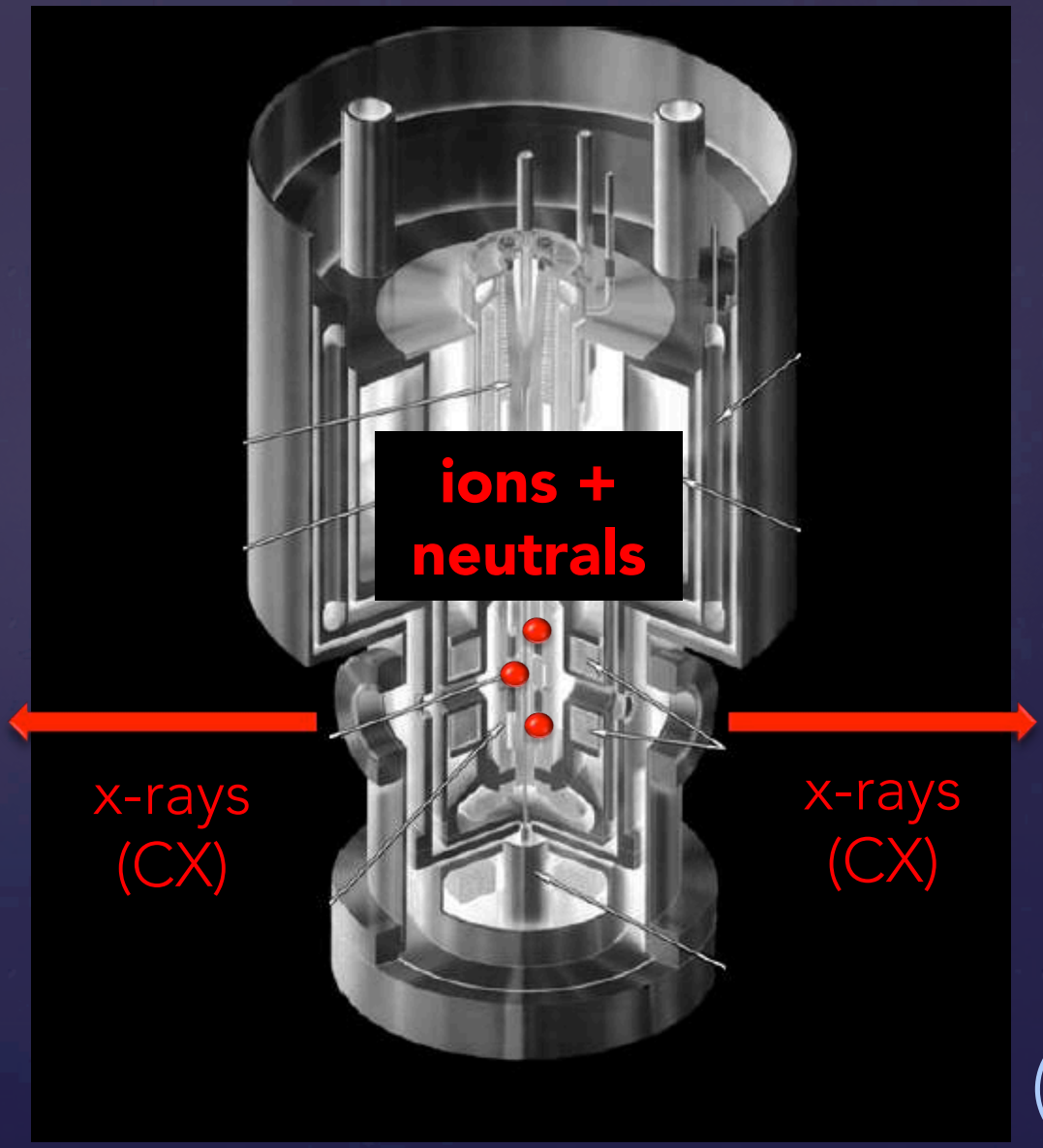
- Merged beam experiments
  - ion beam + gas cell
  - Ion beam + neutral beam
- COLTRIMS
- Electron Beam Ion Traps (EBITs)

# The LLNL Electron Beam Ion Trap



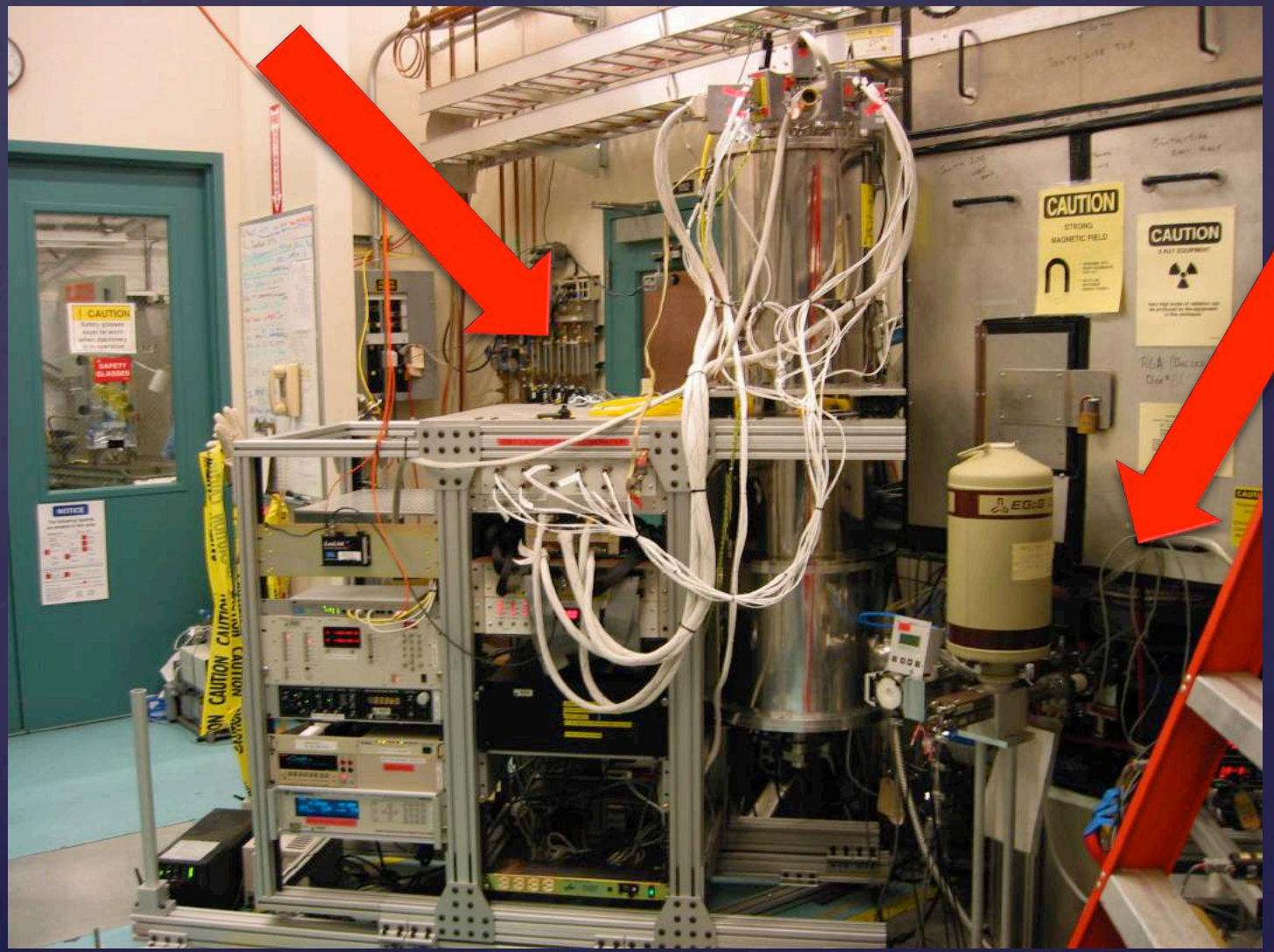

(EBIT)

# The LLNL Electron Beam Ion Trap

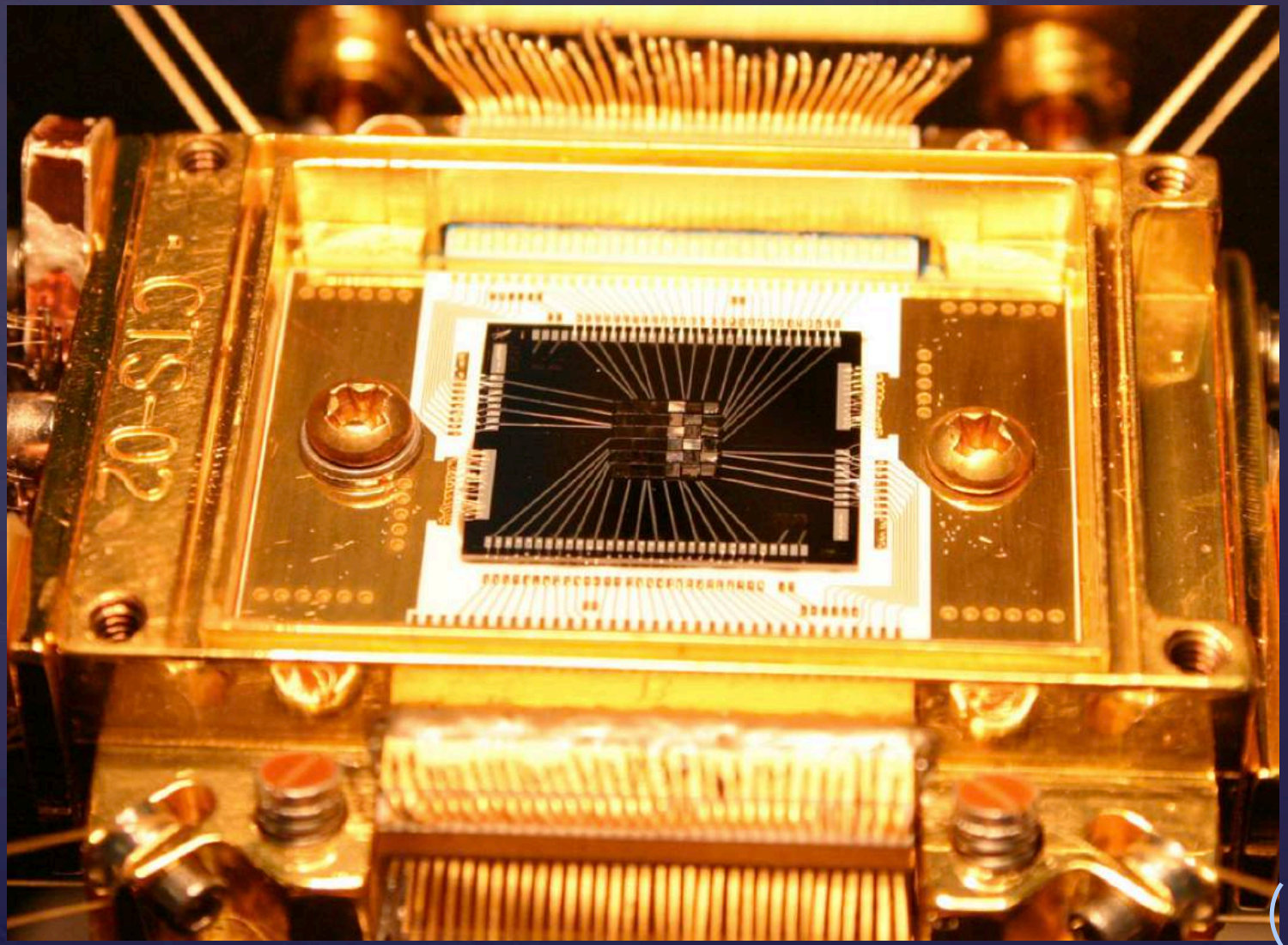



(EBIT)

# The EBIT + spectrometer

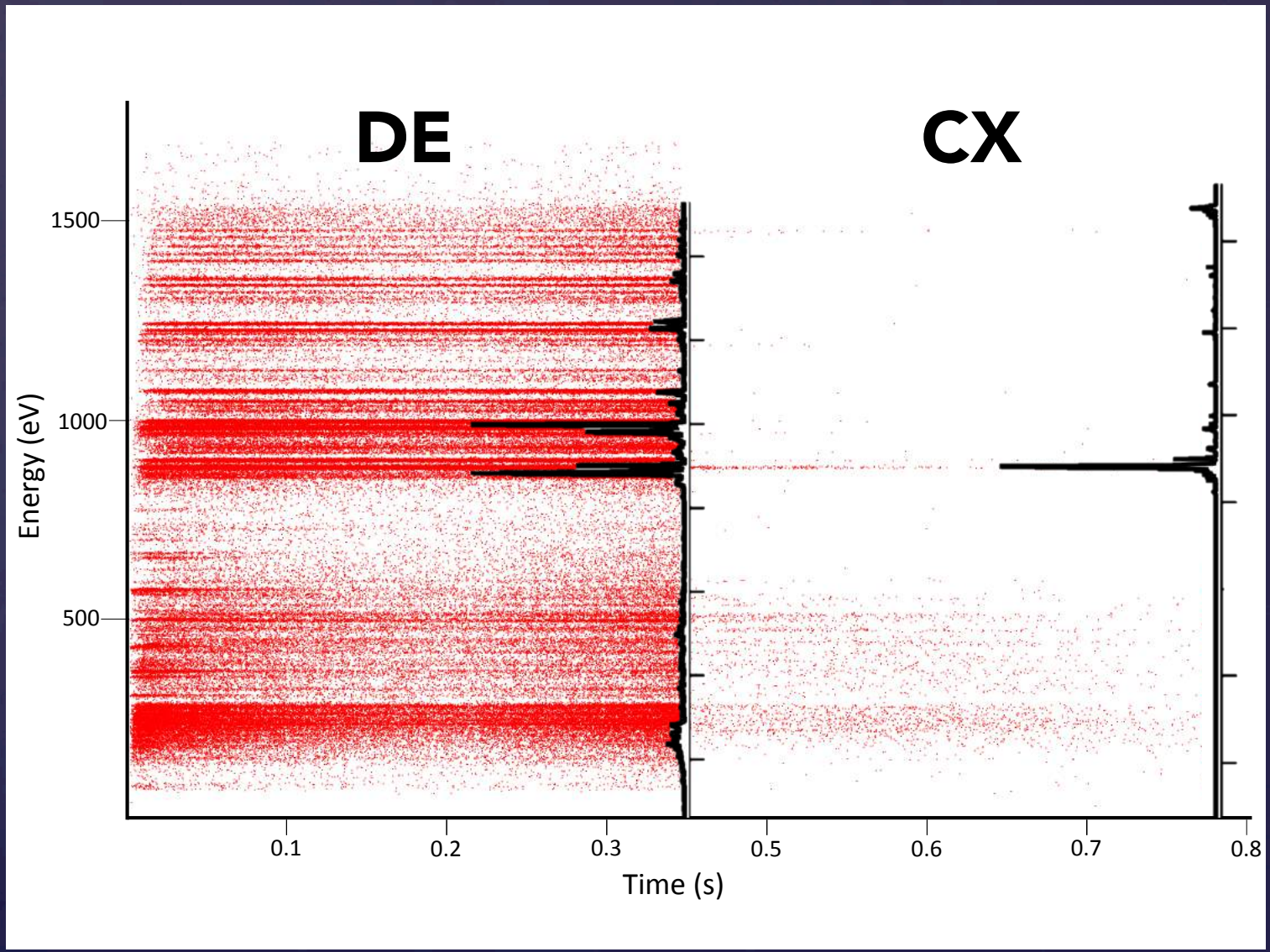


# The EBIT Calorimeter Spectrometer




(ECS)

# Time-resolved experiments



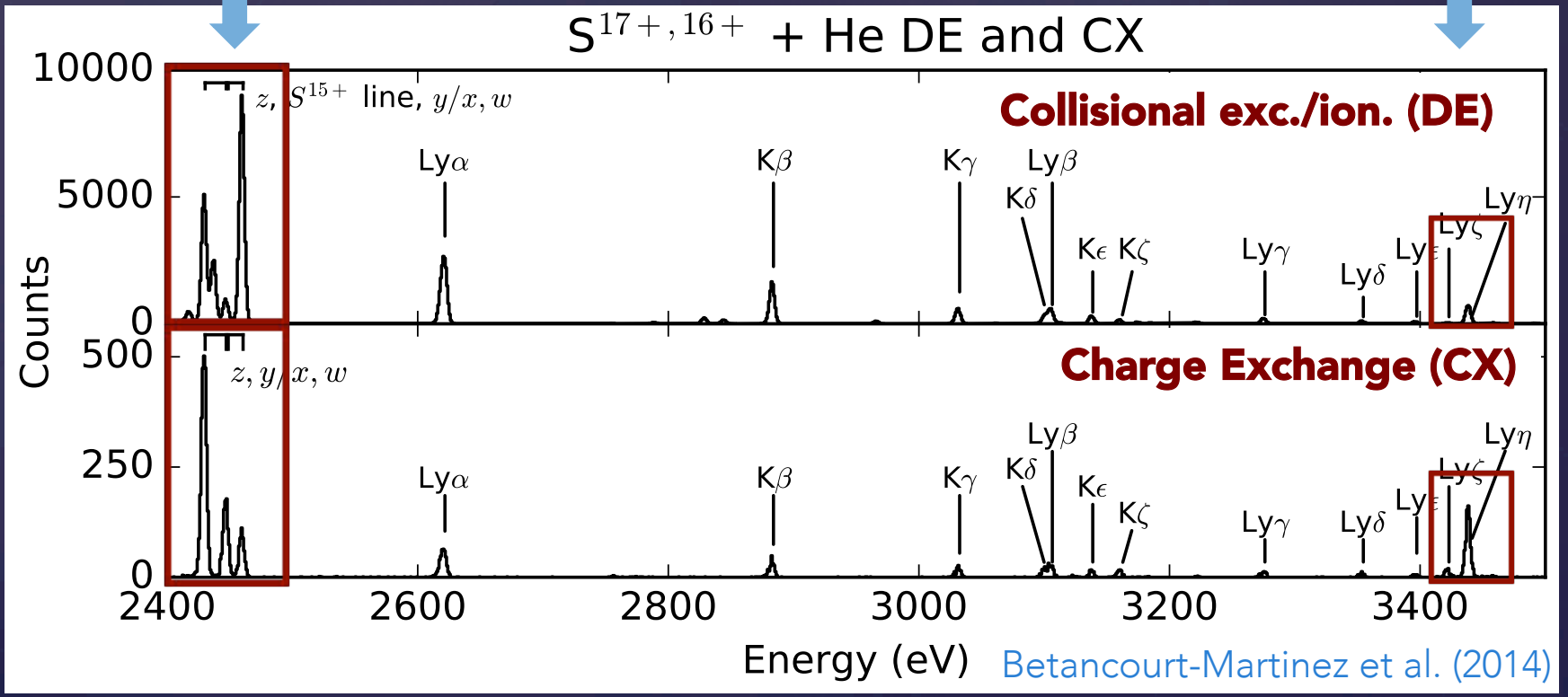
# EBIT/ECS + model comparison: results

1. Get the atomic physics right
2. Get this into models
    1. K-shell
    2. L-shell

# K-shell CX diagnostics

K-alpha complex
(He-like ions)

High-n Lyman line
(H-like ions)




Betancourt-Martinez et al. (2014)

Identifying features in K-shell: strong He-like *z* line; strong emission from H-like high-*n* Lyman lines

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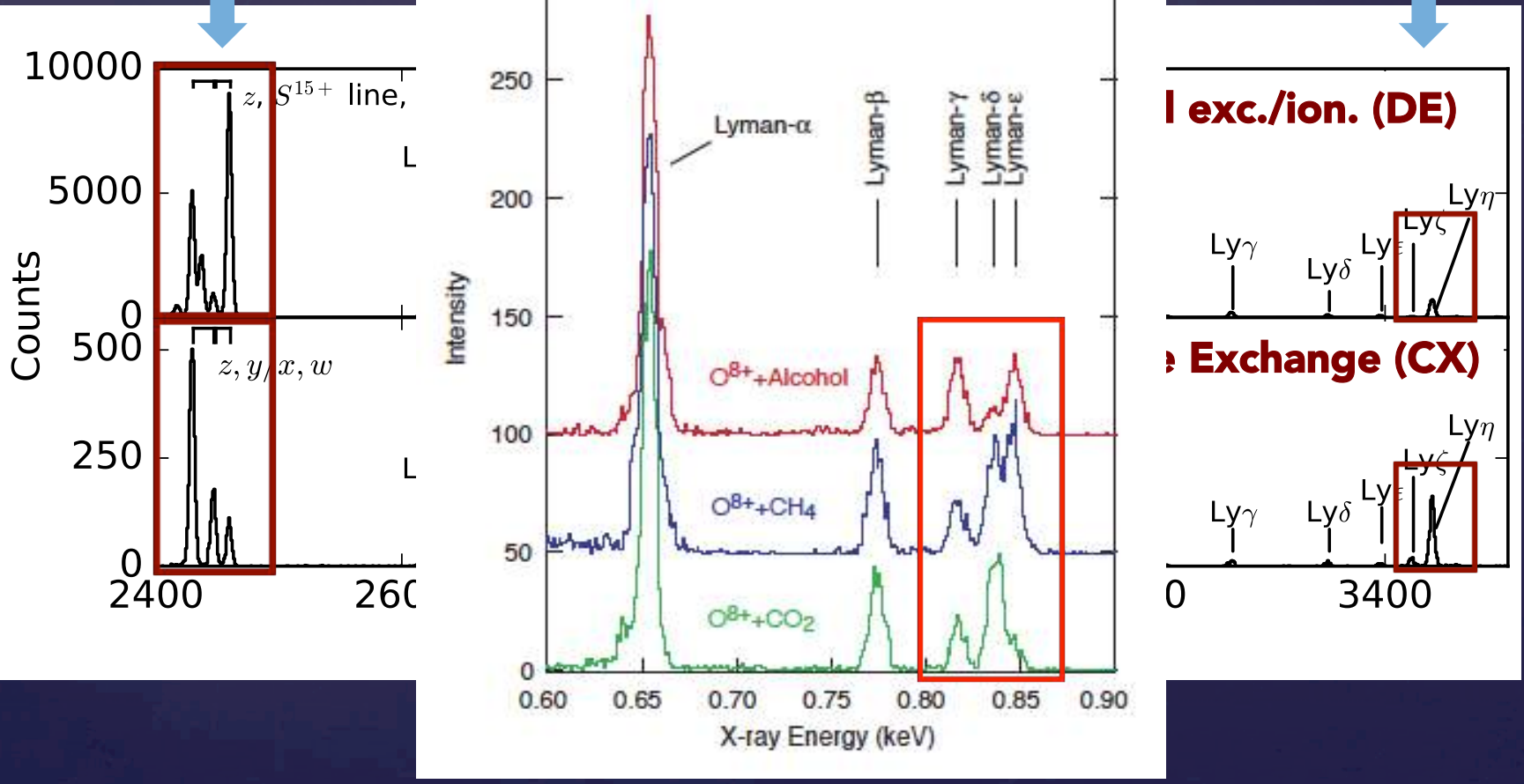
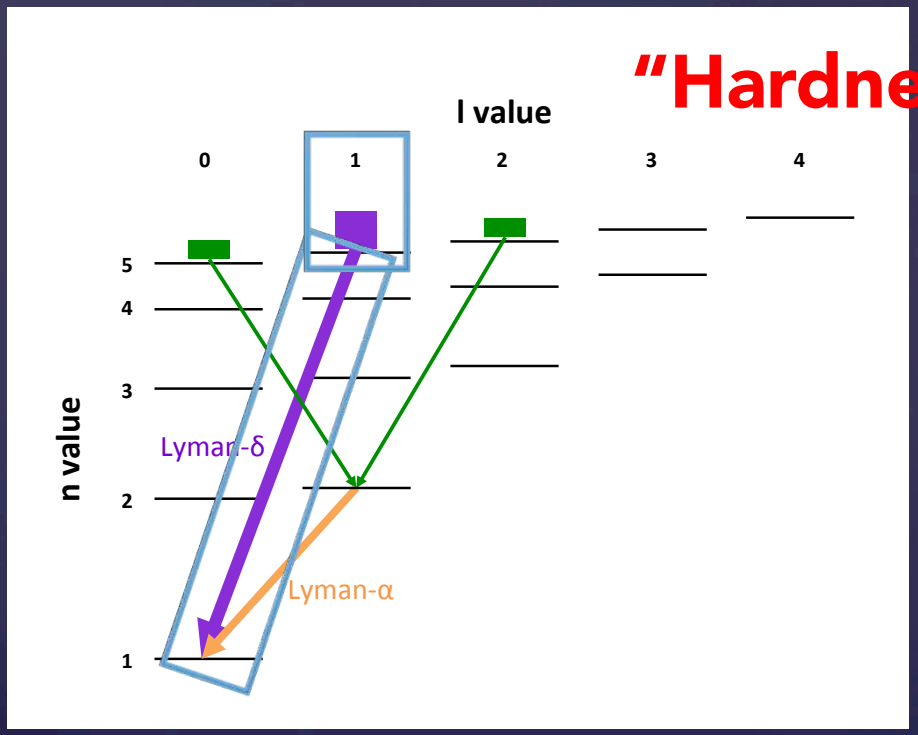


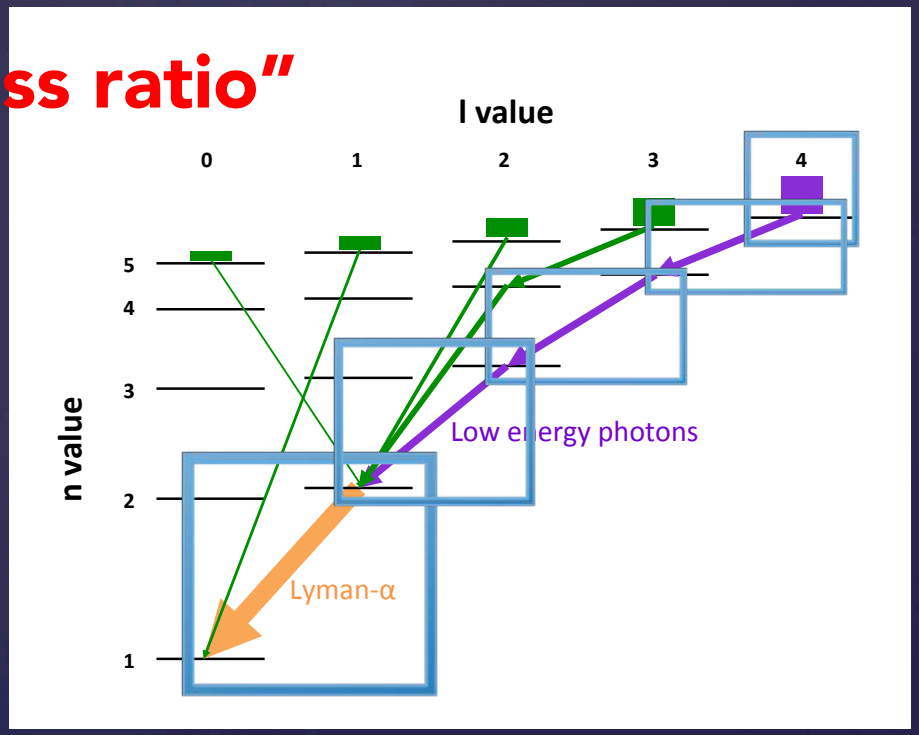

Beiersdorfer et al. (Science, 2003)

# H-like decay schemes

low angular momentum

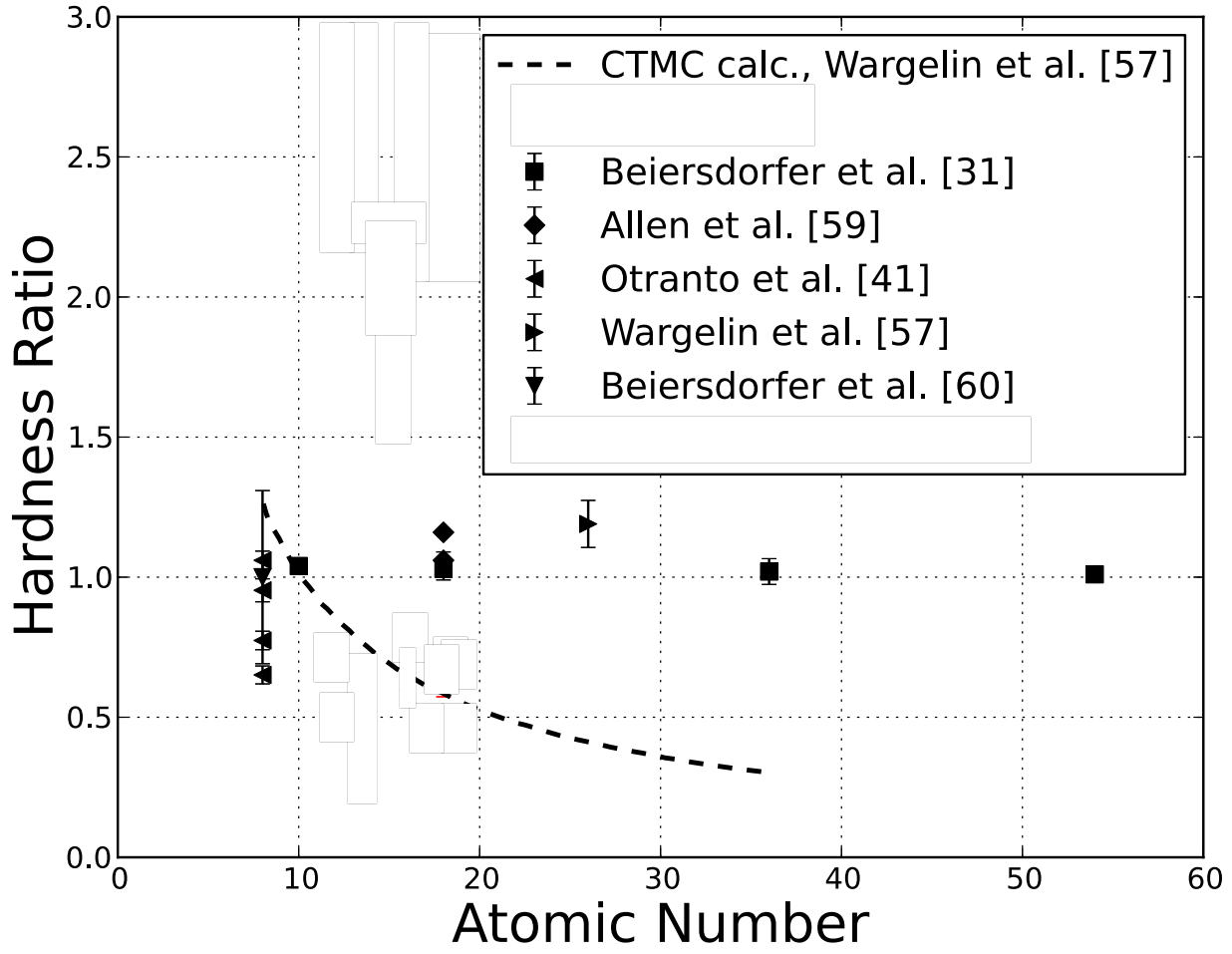
high angular momentum




Betancourt-Martinez, Ph.D. thesis (2017)

# Hardness ratio: correlation with Z?

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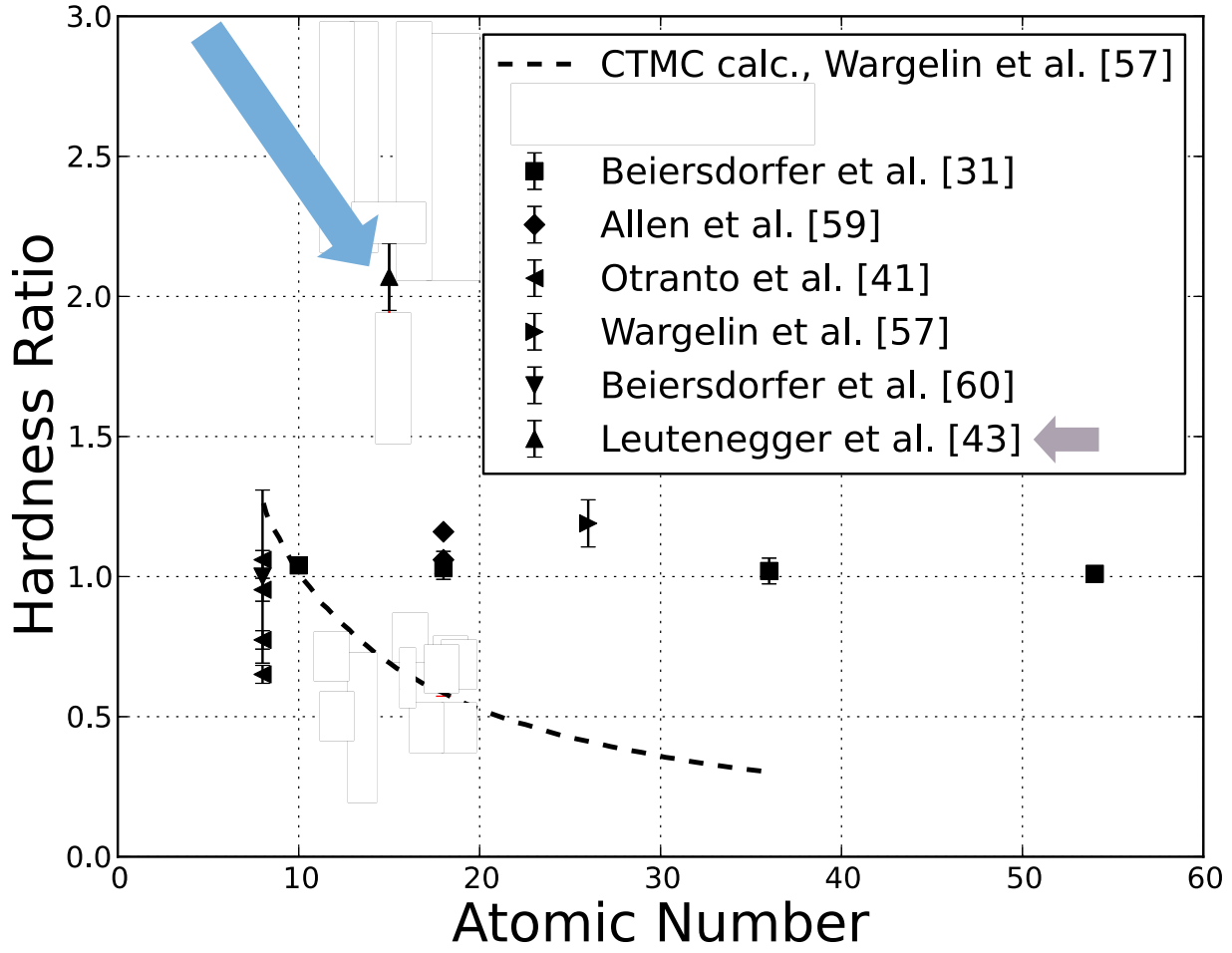


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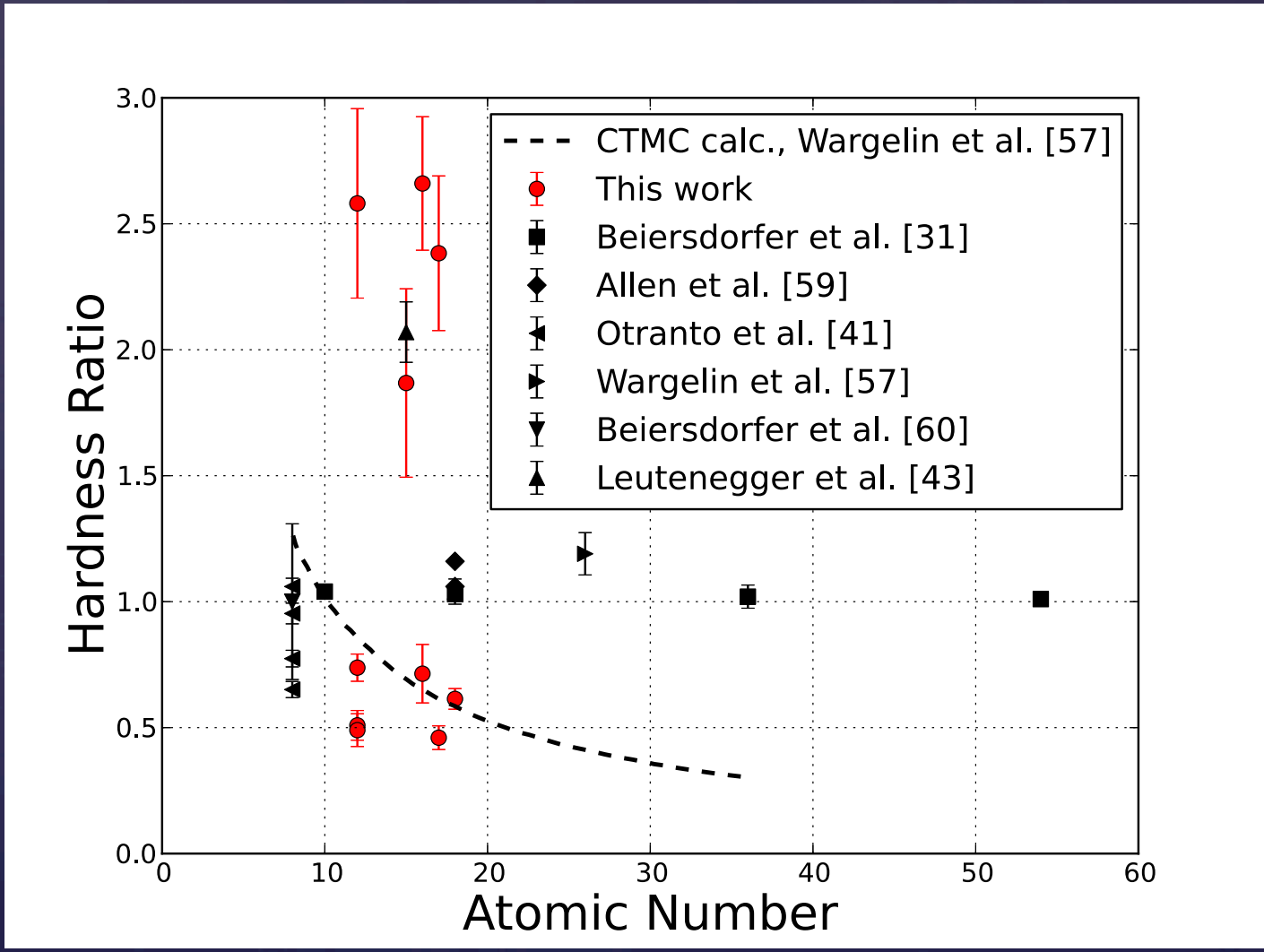
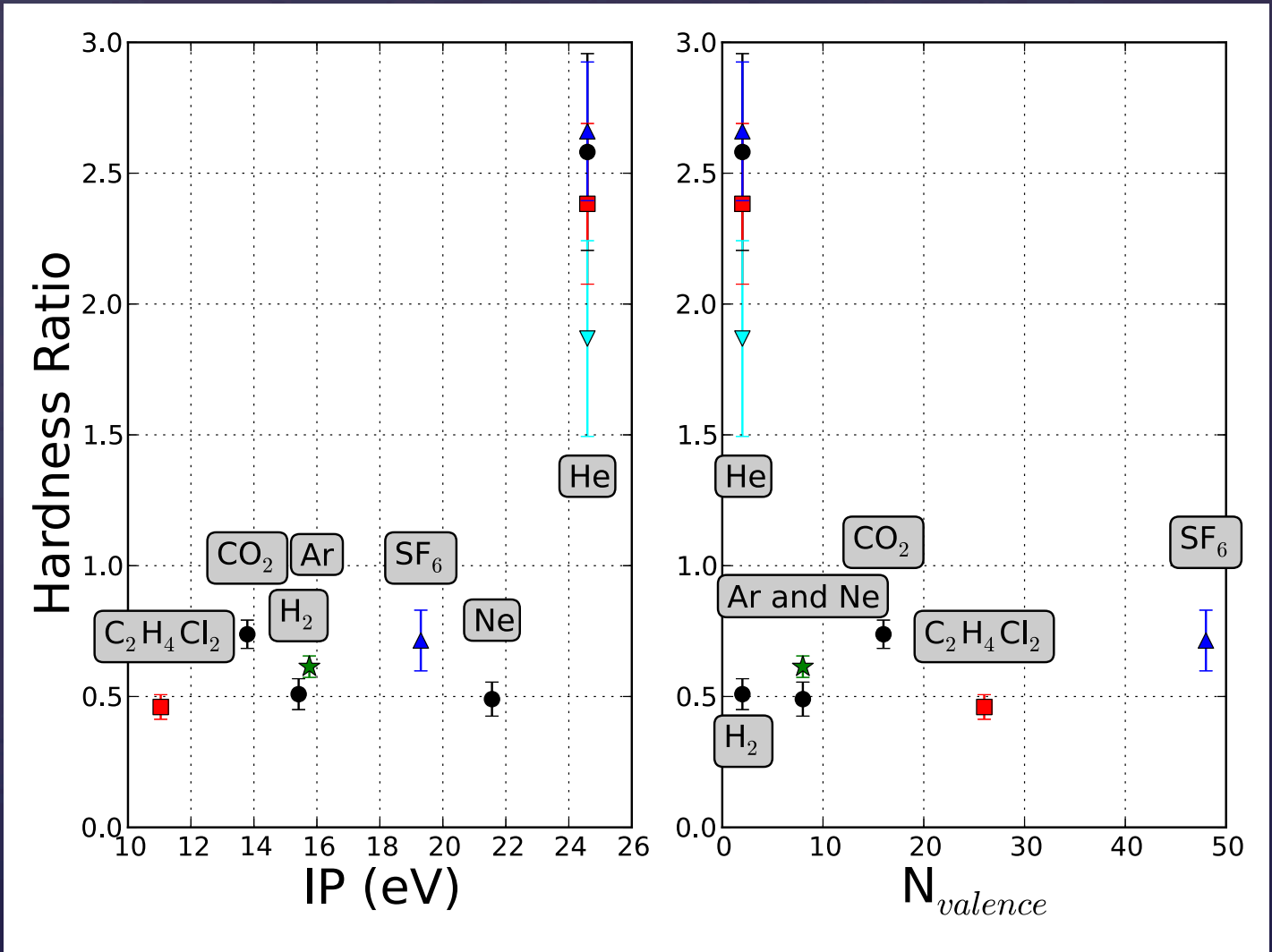


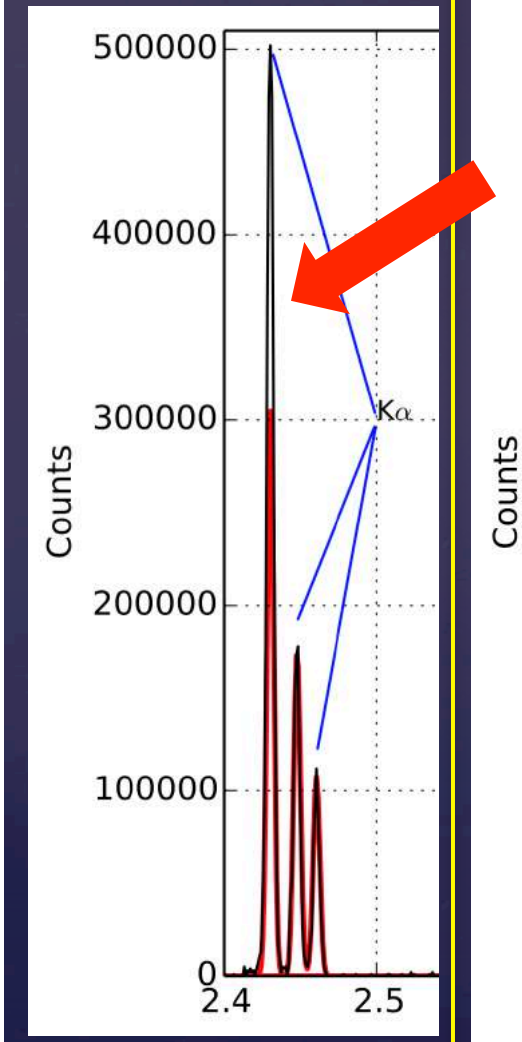

Betancourt-Martinez et al. (2014)

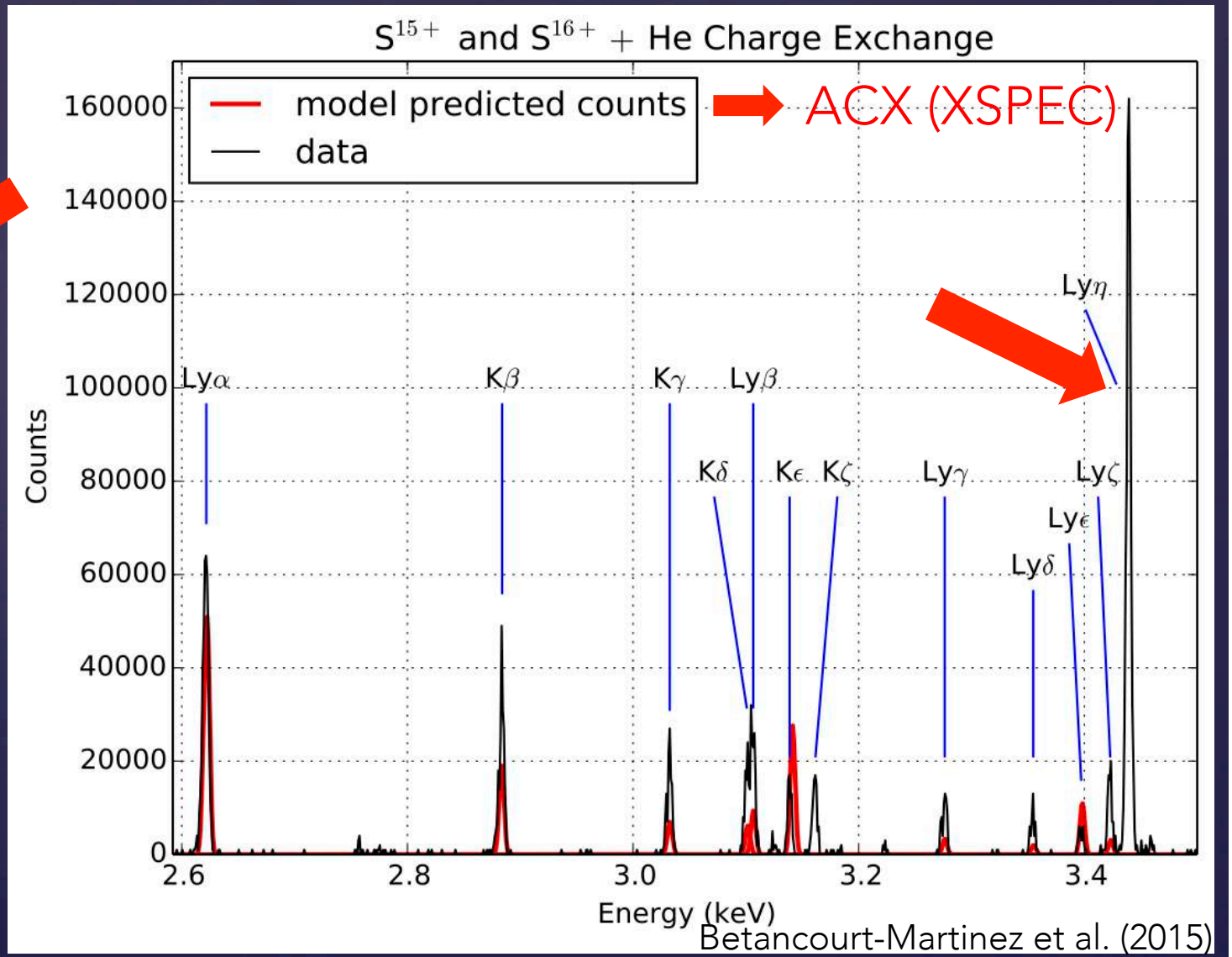
# Hardness ratio: correlation with IP, $N_{val}$?




Betancourt-Martinez et al. (2014)

# Model comparison: K-shell

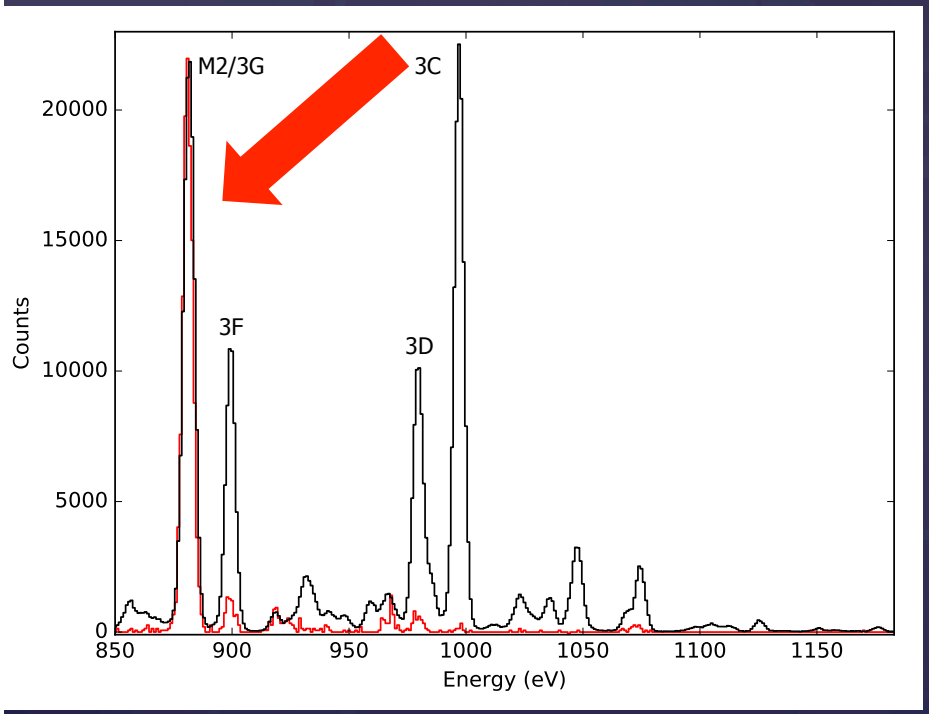


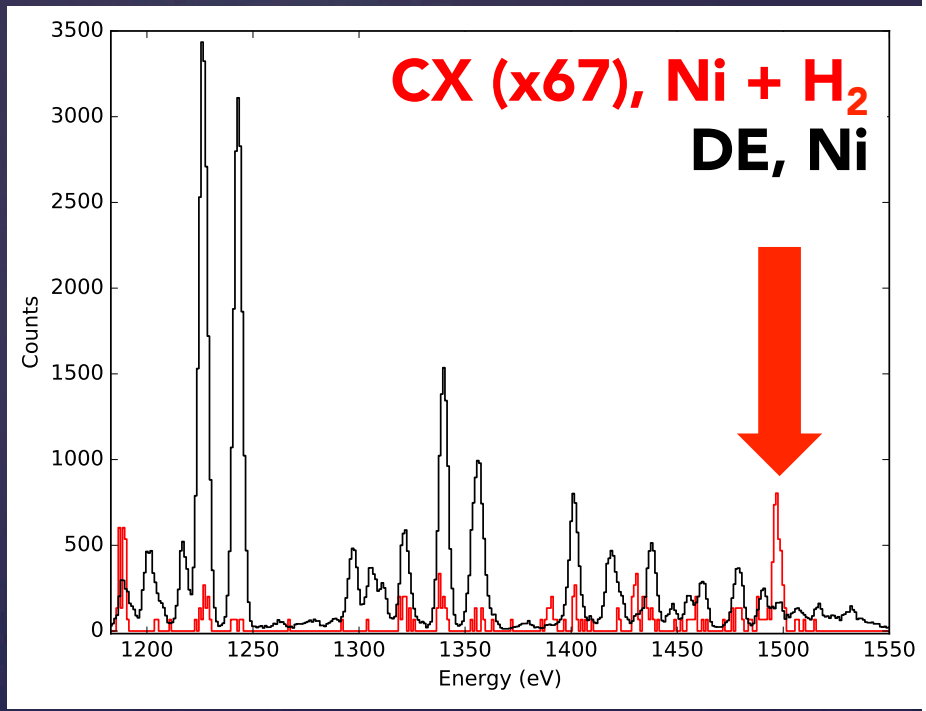




Betancourt-Martinez et al. (2015)

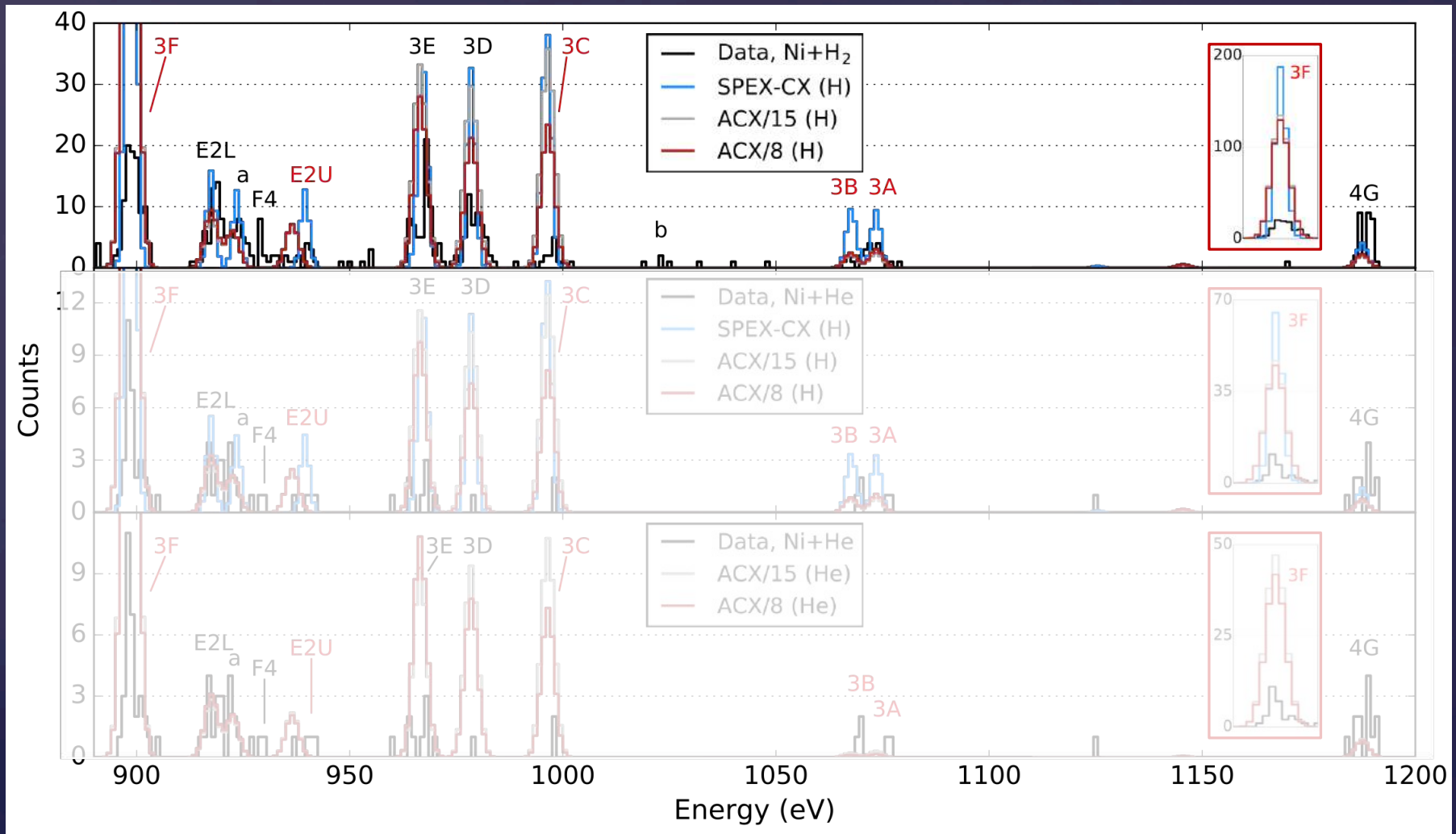
# L-shell CX spectra: Ne-like Ni

# L-shell CX diagnostics



# Model comparison (SPEX-CX, ACX)




Betancourt-Martinez et al. (2018)

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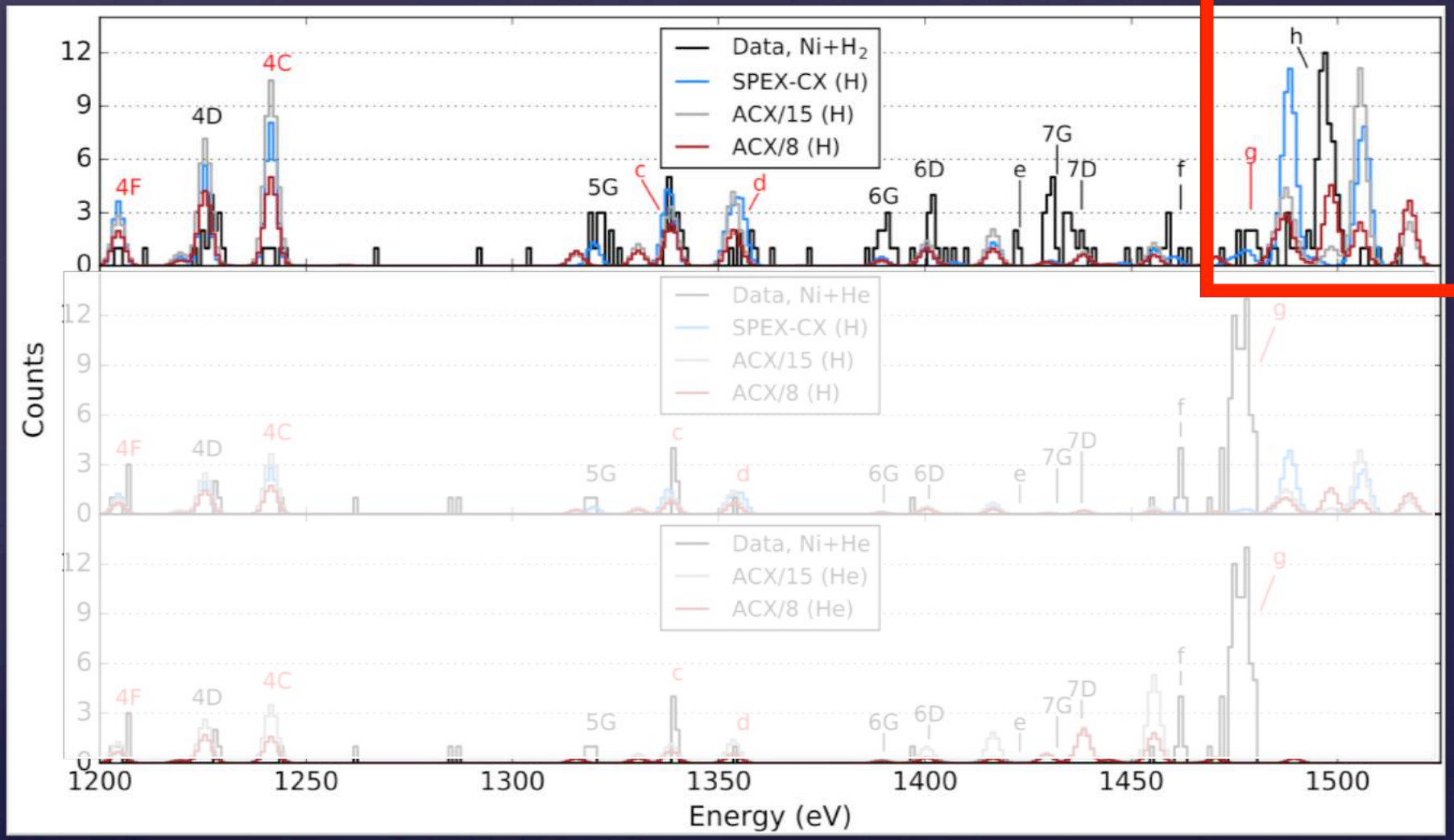
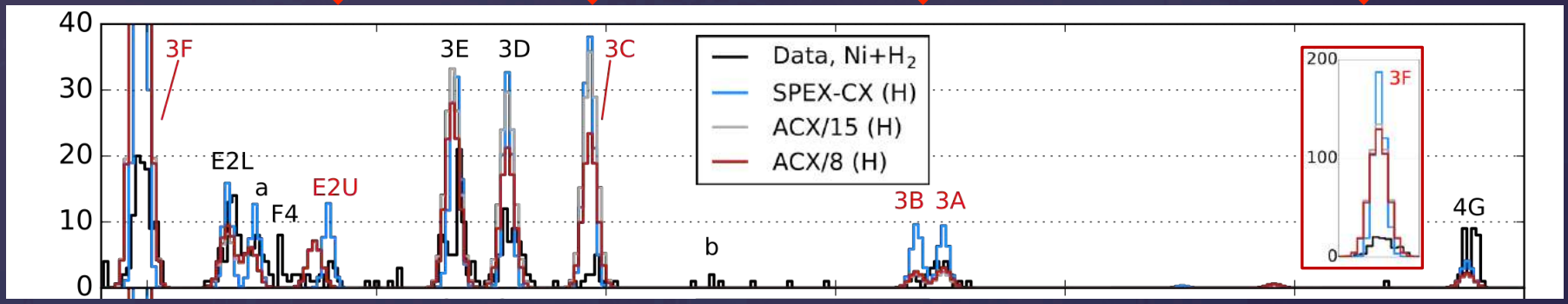
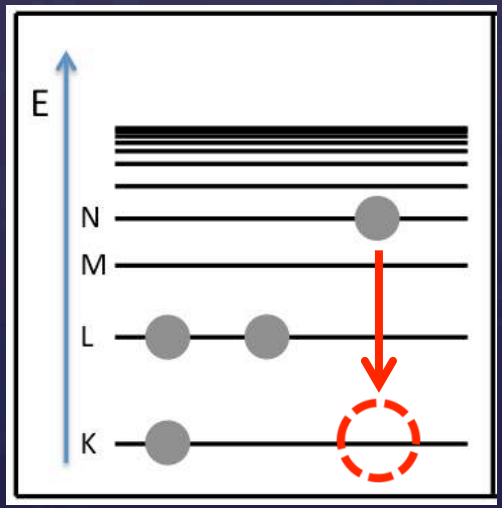


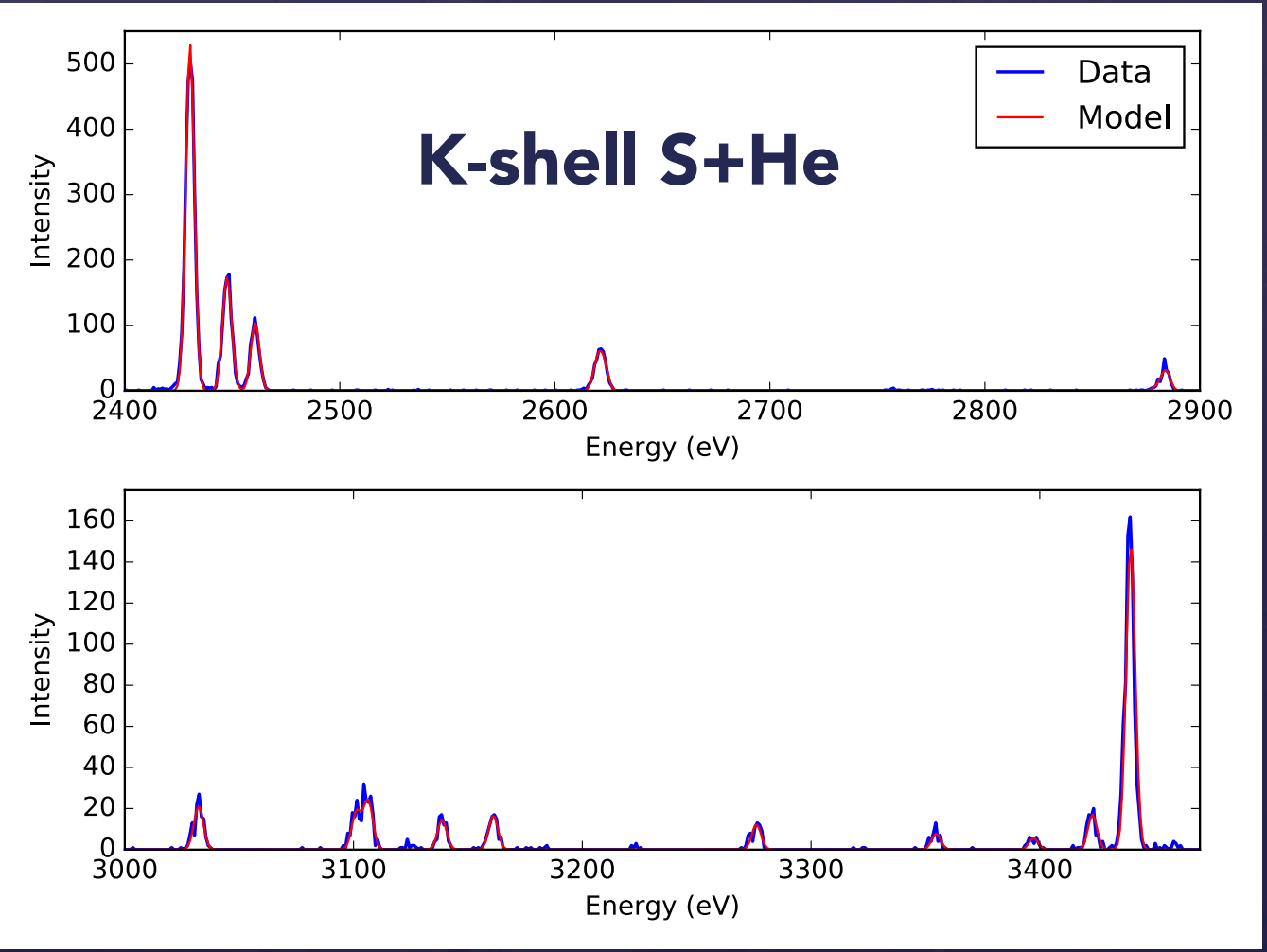

Betancourt-Martinez et al. (2018)

# Configuration mixing important



# Use high-resolution spectra to probe atomic physics




Betancourt-Martinez, Ph.D. thesis (2017)

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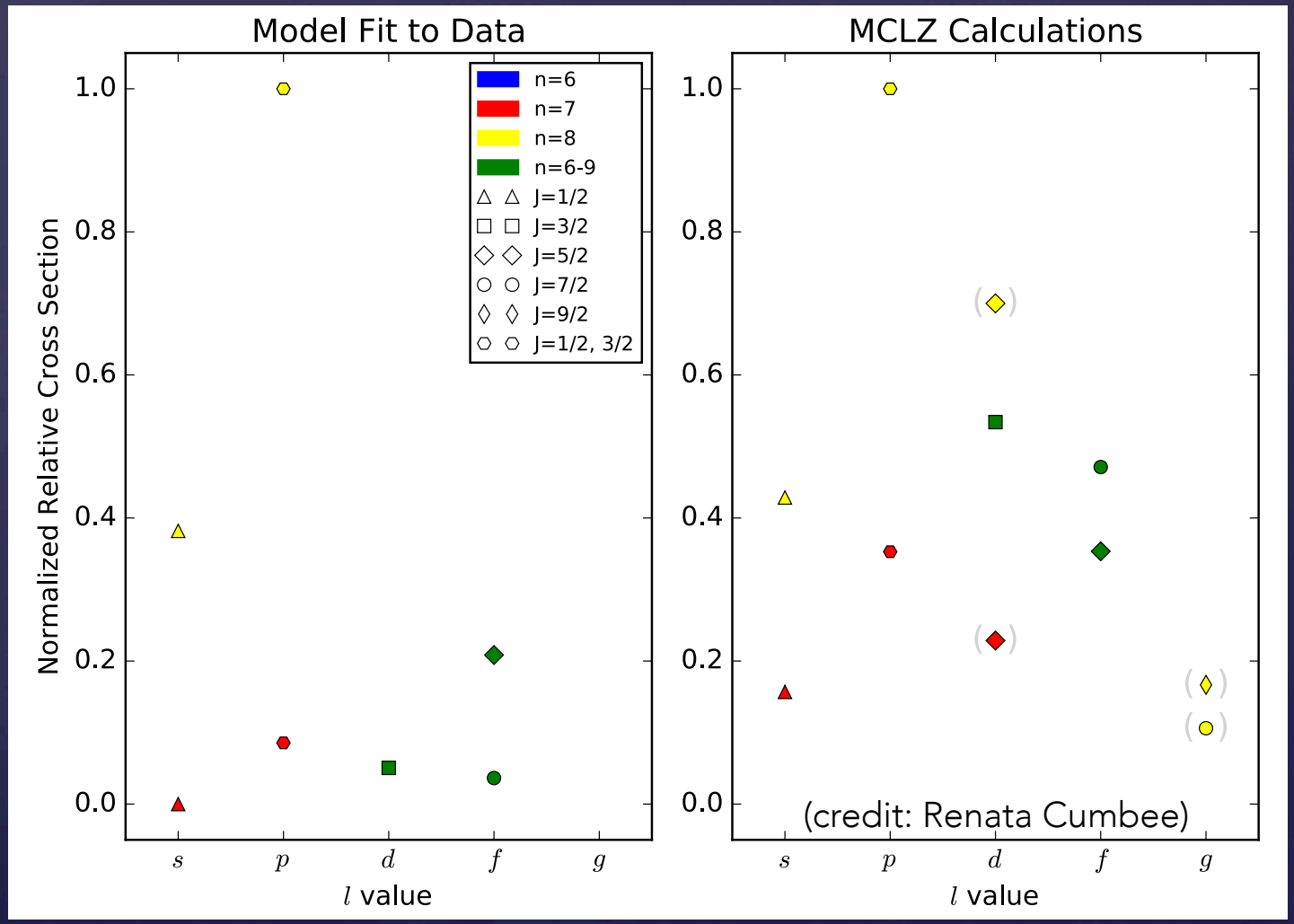


Betancourt-Martinez, Ph.D. thesis (2017)

# Conclusions

1. Charge exchange is relevant to many aspects of X-ray astronomy, but CX theory is complex

2. We are doing experiments in the lab to address this challenge

3. Through laboratory astrophysics, we can
   a. Understand atomic physics from spectra
   b. Directly benchmark, improve models
   c. Extract state-selective cross sections from data to compare to theory

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Comet Hyakutake / Big Dipper, 3/25/96, 05:57 UT
50mm f/2.8, 5 min, Hypered Fujicolor Super G 800 Plus
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