H- and He-like X-ray emission due to charge exchange

RENATA CUMBEE

NPP FELLOW (GFSC, ROB PETRE)

PREVIOUSLY UNDER THE DIRECTION OF

P. C. STANCIL

Outline

Charge eXchange (CX): The basics

Why do we care? (CX in astrophysics)

Producing a CX theoretical spectrum:
- **Cross sections**
- **Radiative Cascade**

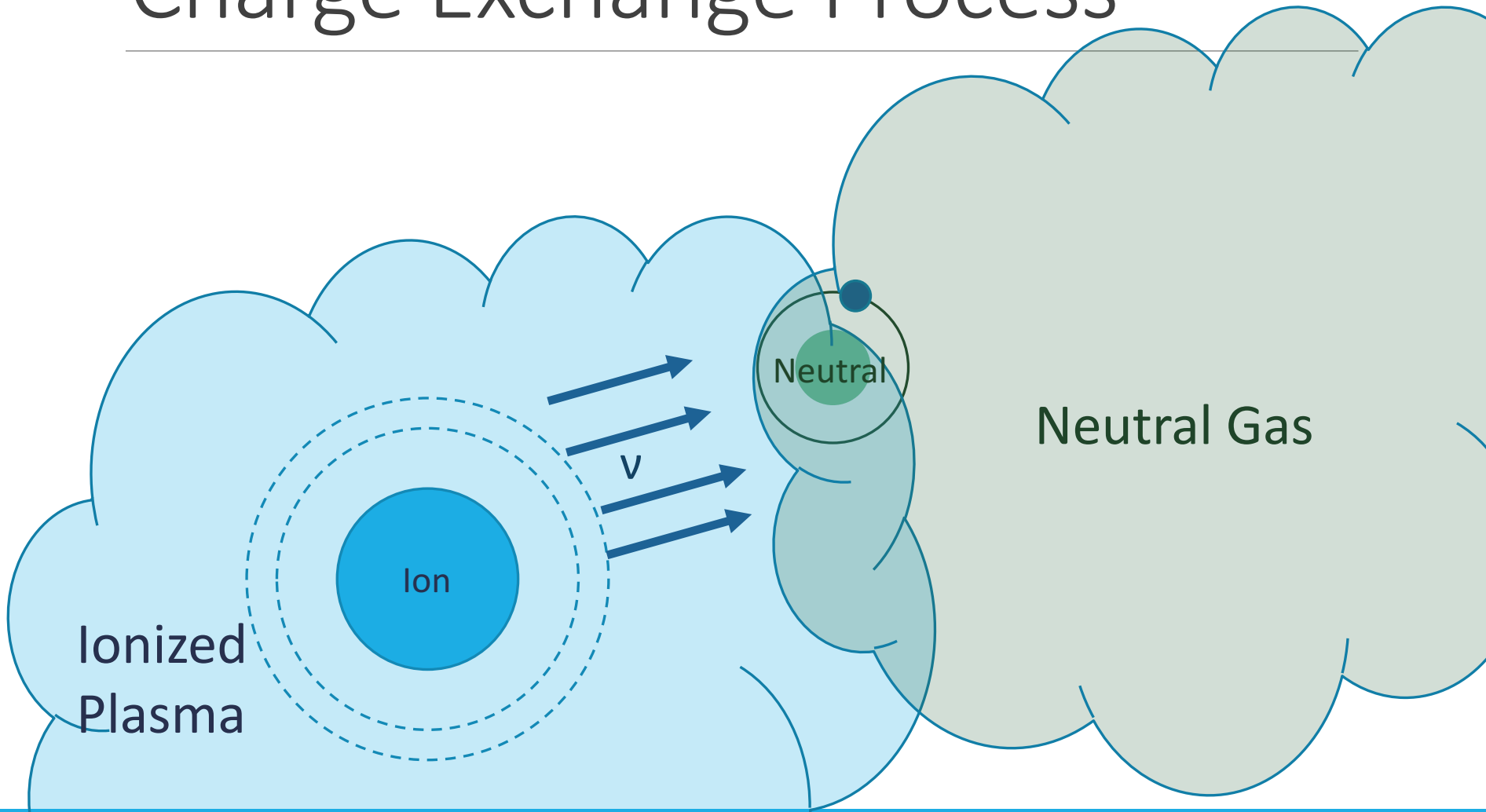
Theoretical Spectra
- Interesting features: Energy & Neutral target

How do we trust the theory?
- Benchmarking to experiments

CX Model
- Applications

Summary

Charge Exchange Process



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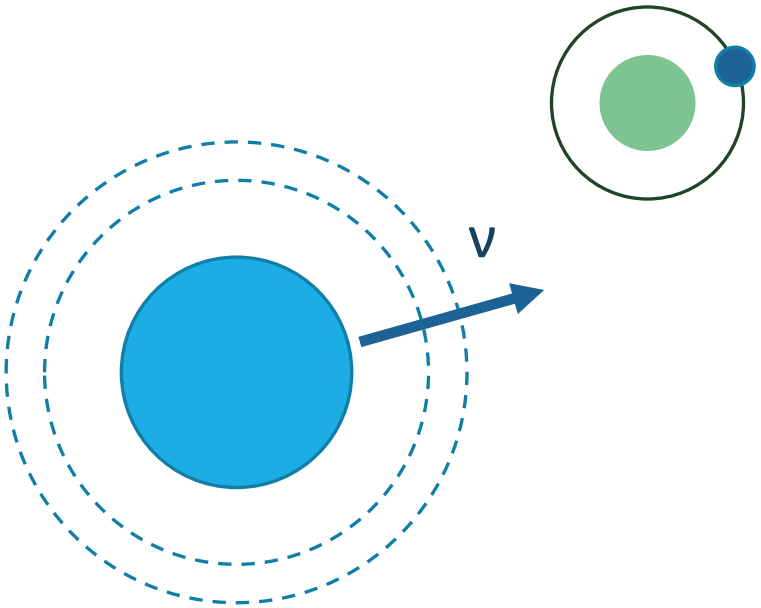

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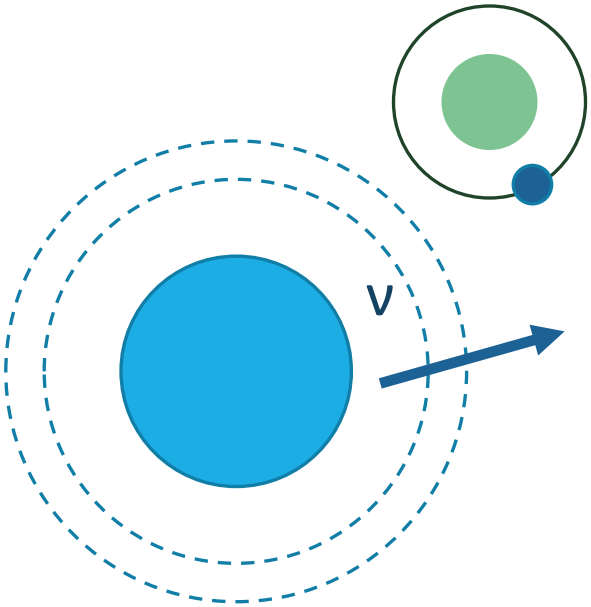

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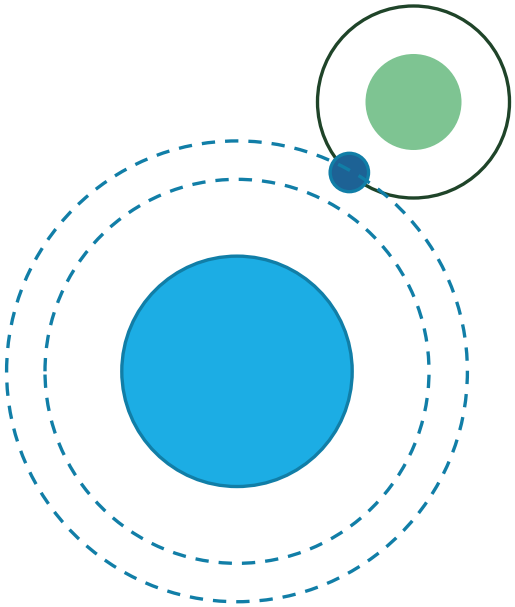

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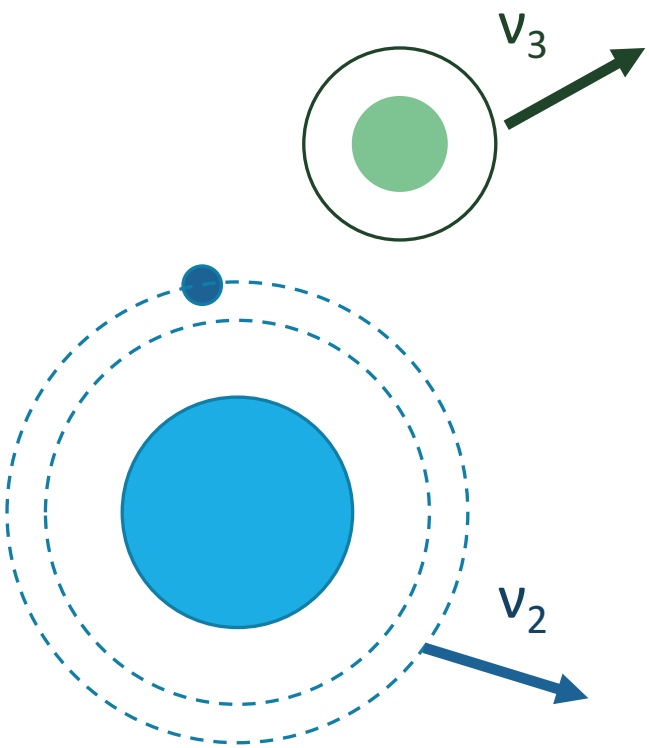

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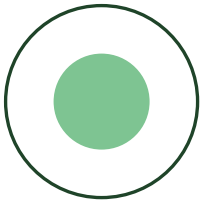
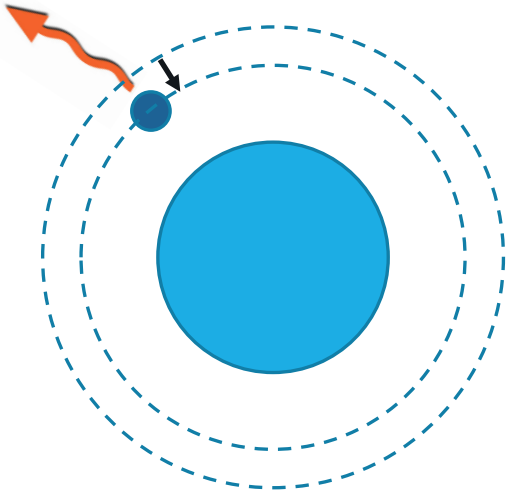
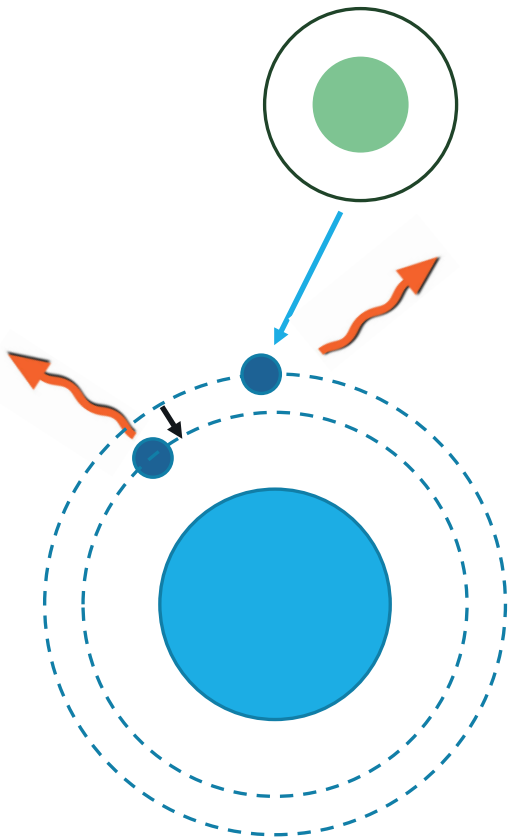




Charge Exchange Process

While single electron capture is significant for H-like and He-like system, multi electron capture (2 or more electrons are transferred) can be important for collision systems with more than one electron.



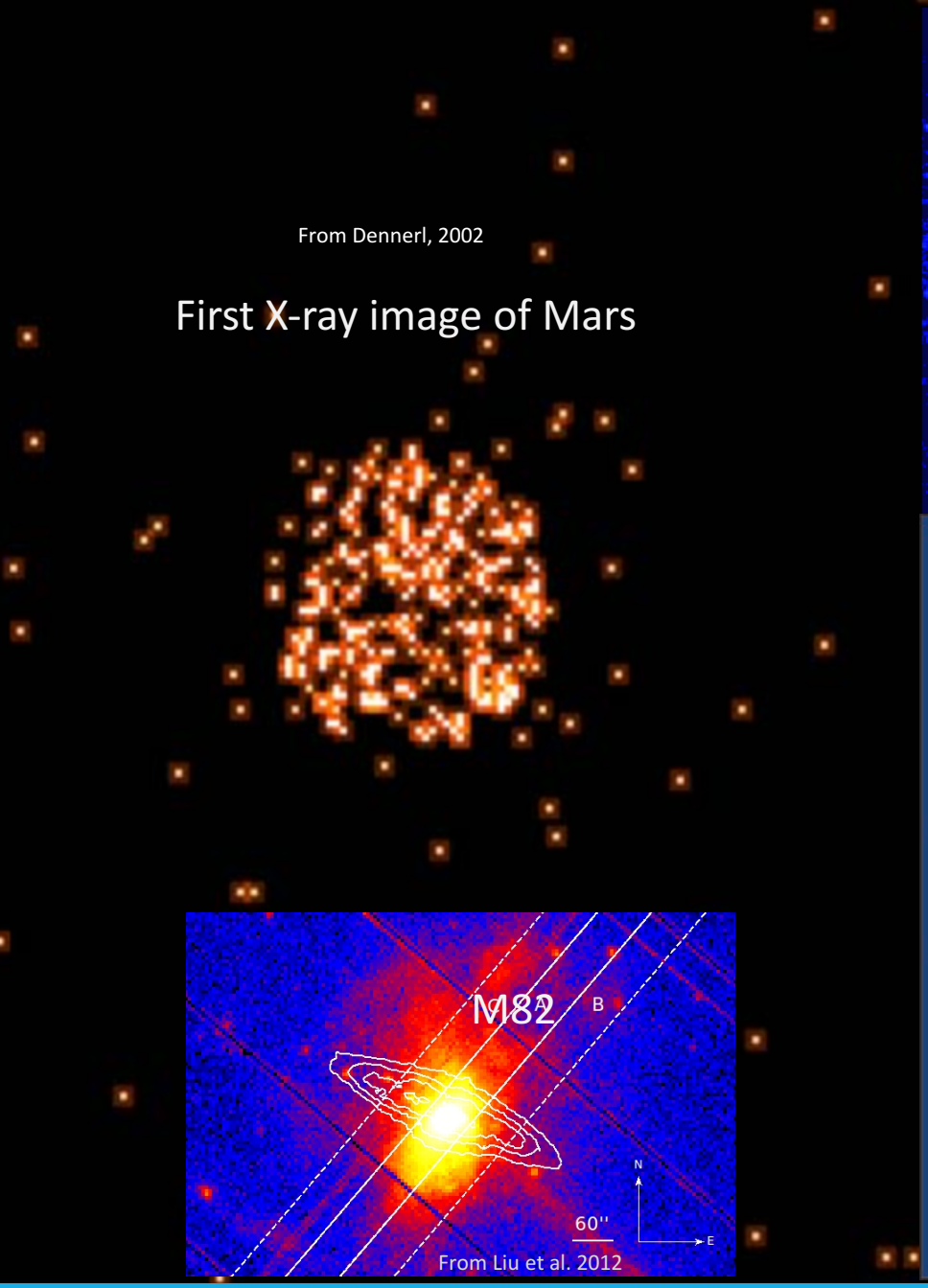
Astrophysical environments for CX

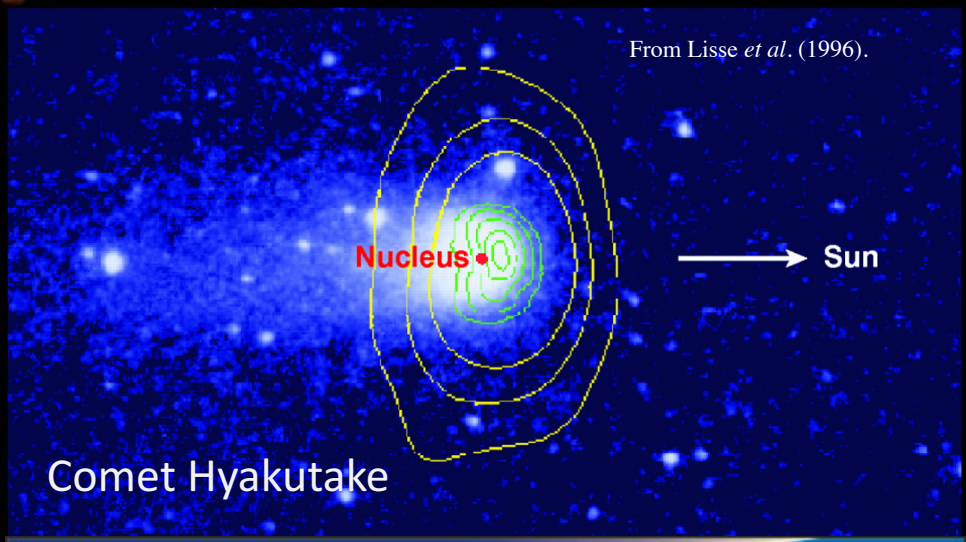
- Comae of comets (Bodewits et al. 2007, Mullen et al. 2017)
- Planetary atmospheres (Dennerl et al. 2006, Bhardwaj et al. 2007, +)
- Earth's exosphere (Freyberg 1998, Snowden et al. 2004)
- Heliosphere (Cravens 2000, Cravens et al. 2001)
  → contribution to diffuse soft X-ray background (Wargelin et al. 2004, Koutroumpa et al. 2009, Slavin et al. 2013, Galeazzi et al. 2014)

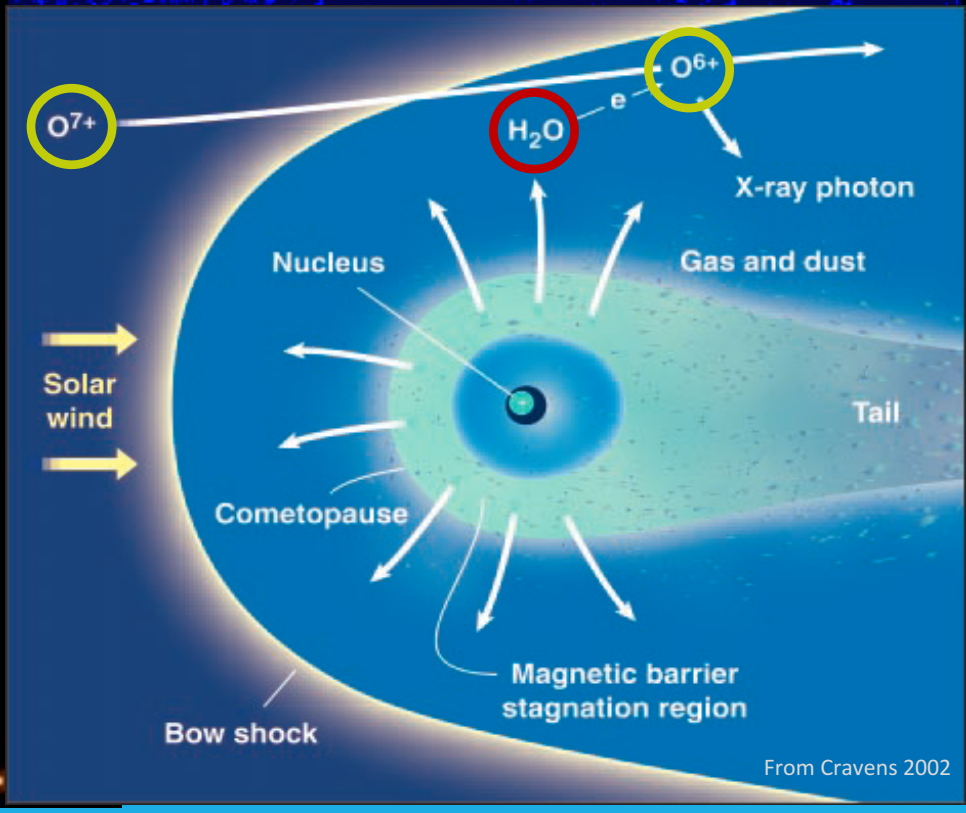
- Filaments in Perseus cluster? (Walker et al. 2015, Gu et al 2017)
- 3.5 keV line? (Gu et al. 2015)
- Rim of supernova remnants? (Katsuda et al. 2011, Cumbee et al. 2014)
- Starburst galaxies? (Zhang et al. 2014)

From Dennerl, 2002

First X-ray image of Mars

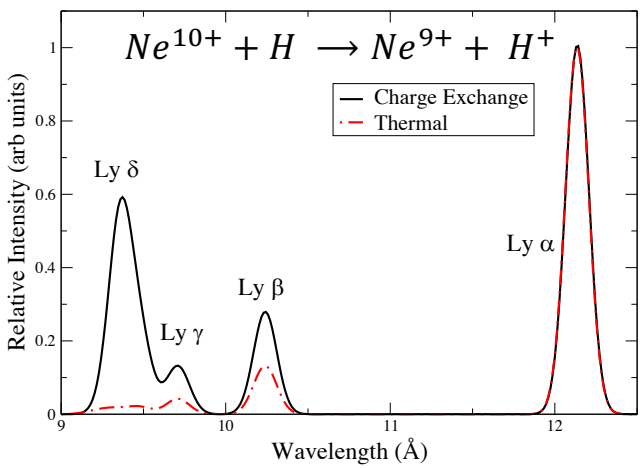


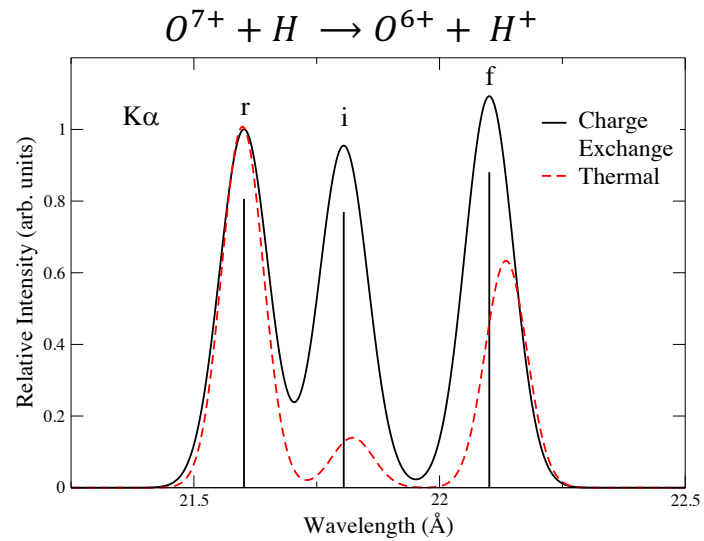


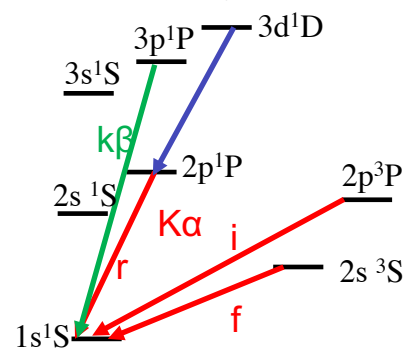


CX Emission vs Thermal Emission

- X-ray emission from charge exchange produces a very distinct spectrum compared to thermal emission.
- With high resolution spectra, it is plausible to disentangle CX from thermal emission!







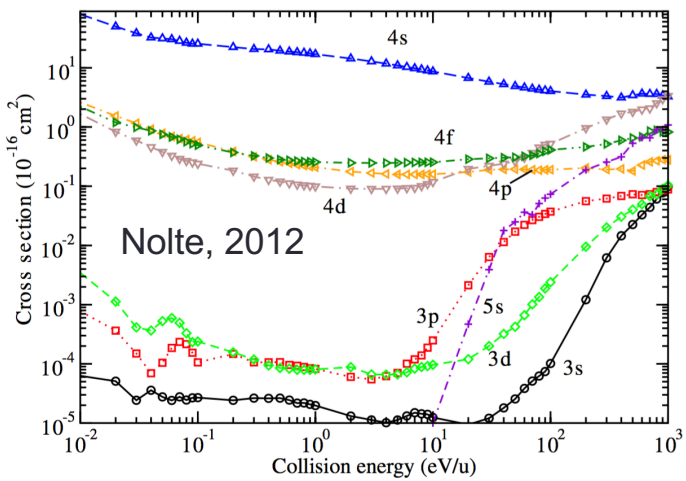
Charge Exchange Theory

Two steps are required to produce charge exchange X-ray emission spectrum:

- 1)Calculate cross-section (Not easy!)
- 2)Radiative cascade (easier!)

Charge Exchange Cross Section (σ)

The *probability* of an electron to transfer from the neutral atom into a specific excited state (n, l, S) of the ion.



For charge exchange calculations:

- σ depends on the
  - **n** (principle quantum number)
  - **l** (orbital angular momentum quantum number
  - **S** (spin quantum number)
  - **v** (collision velocity)
- $\boldsymbol{\sigma_{nlS}(v)}$ is required to produce reliable theoretical CX X-ray emission spectra

"Effective area" that quantifies the likelihood of a scattering event to occur

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

Recommended Cross-sections for the n=6 quantum levels

Accuracy & difficulty

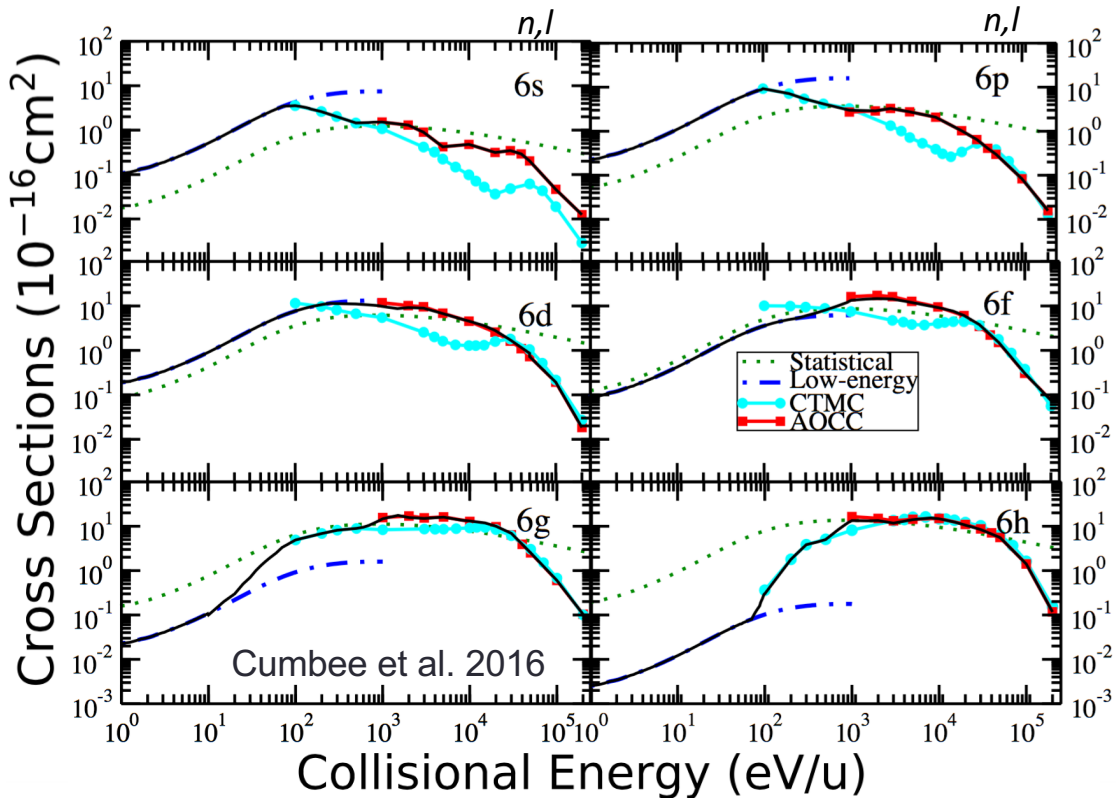
Multi-channel Landau-Zener
- Statistical l-distribution
- Low energy l-distribution

Classical Trajectory Monte Carlo

Atomic Orbital Close Coupling

~~Quantum Mechanical Molecular orbital Close Coupling~~

All available cross-sections for H-like and He-like CX collisions are implemented in Kronos Database



Radiative Cascade

To produce theoretical CX X-ray emission spectra, these n and l levels are given an initial population that is directly proportional to the cross-section σ_{nl} for that given state.

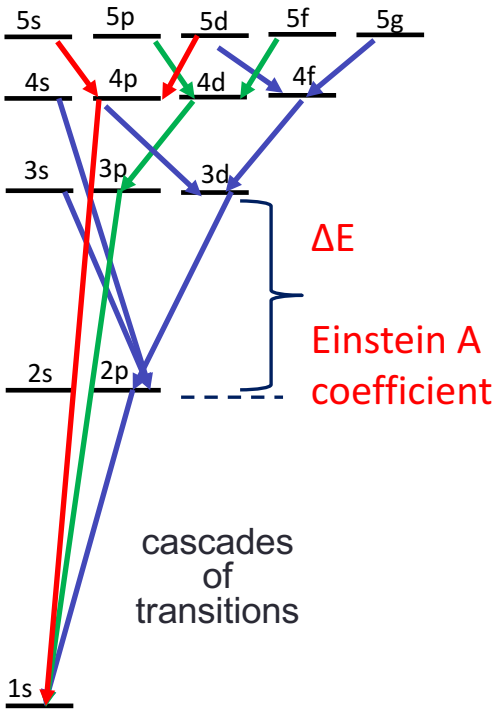
$$i.e. \quad Population_{2s} \propto \sigma_{2s}$$

The electron then transitions to a lower energy level, obeying quantum mechanical selection rules,

$$\Delta l = \pm 1,$$

until it reaches the ground state

Photons are emitted



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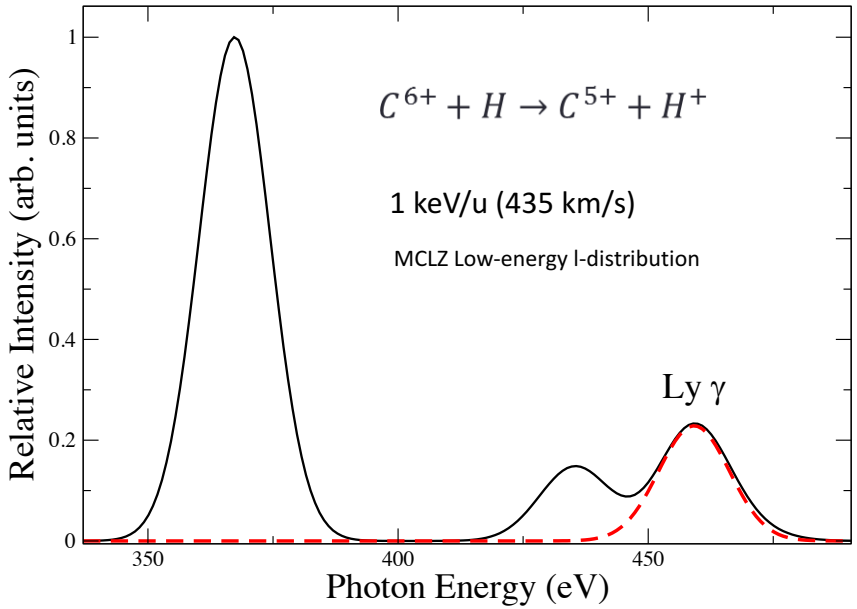
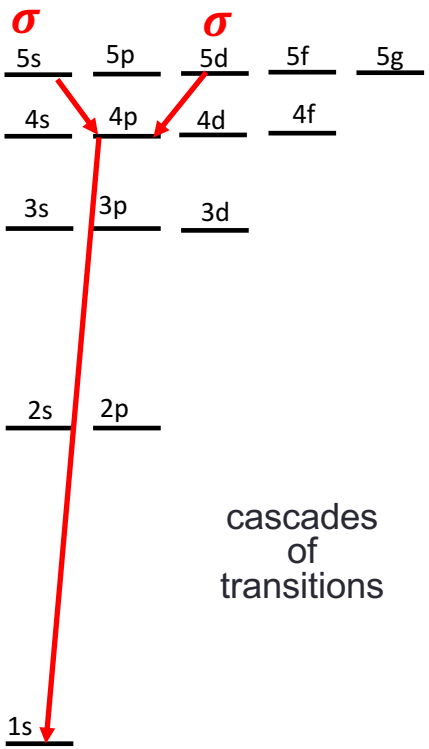


4p – 1s



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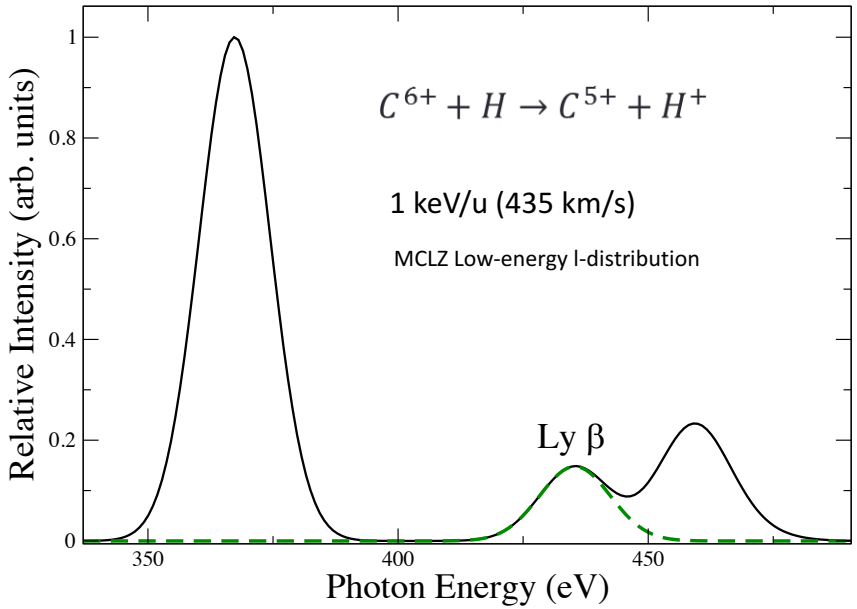
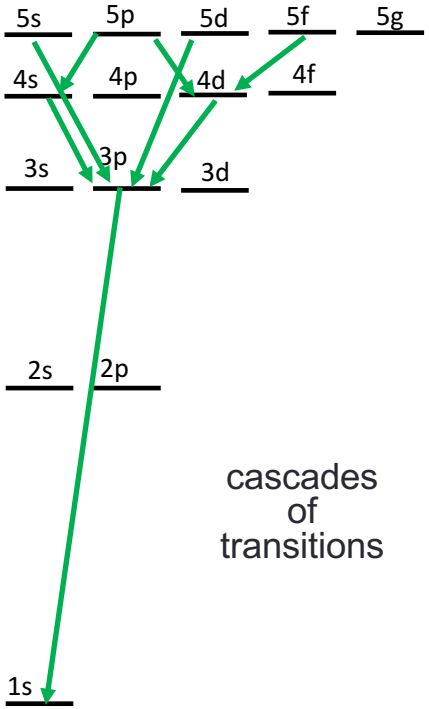


3p - 1s



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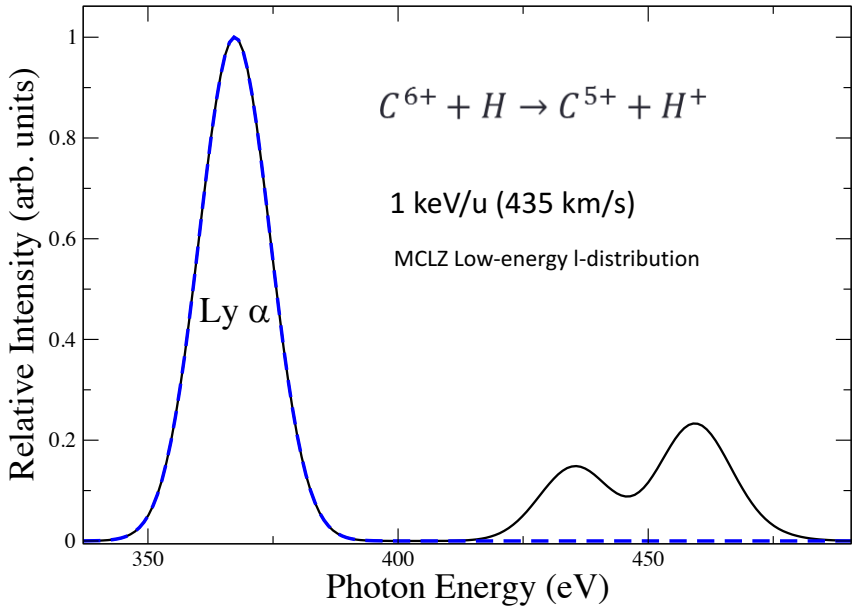
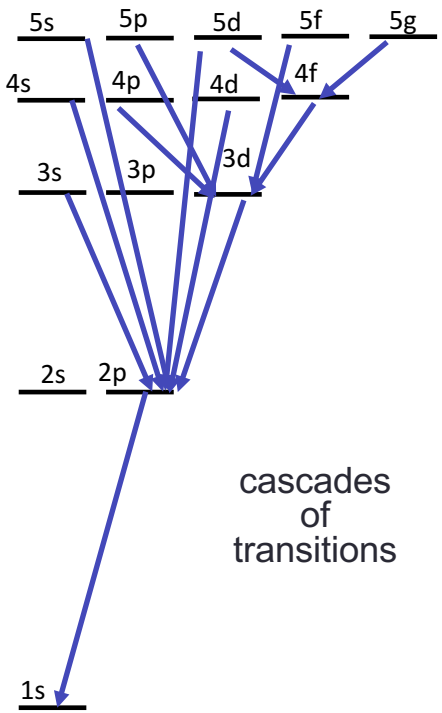
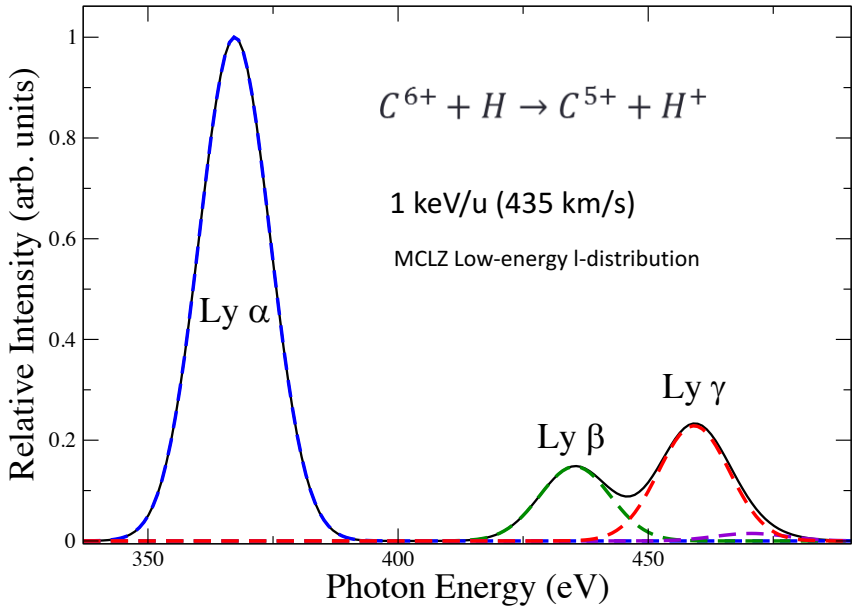


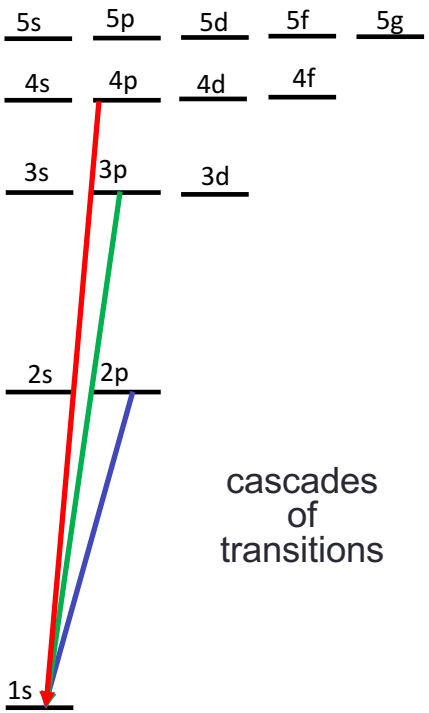


2p – 1s

The 2p-1s transition is dominant due to the cascade from higher excited states (3s, 3d, 4s, 4d, 4f).

Radiative Cascade





2p – 1s > 3p - 1s & 4p – 1s

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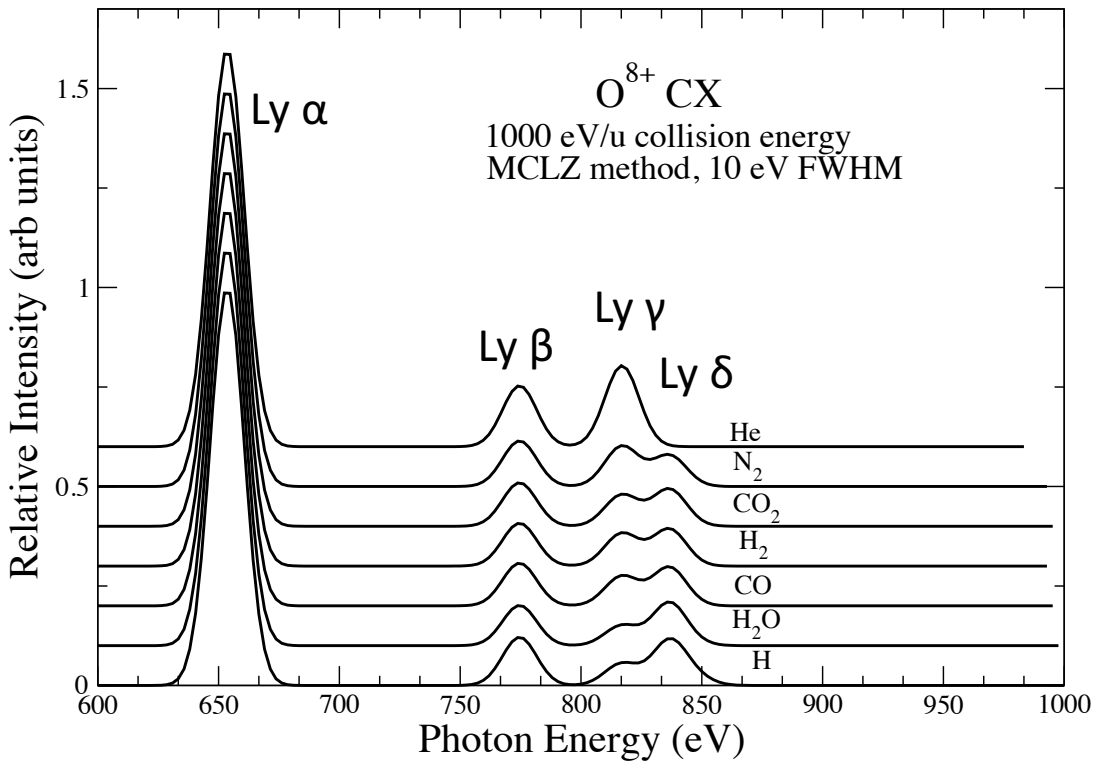
CX as a diagnostic

CX is highly dependent on:

- Ion stage (O^{8+}, O^{7+})
- Neutral target (H, He, CO_2)
- Velocity of the collision



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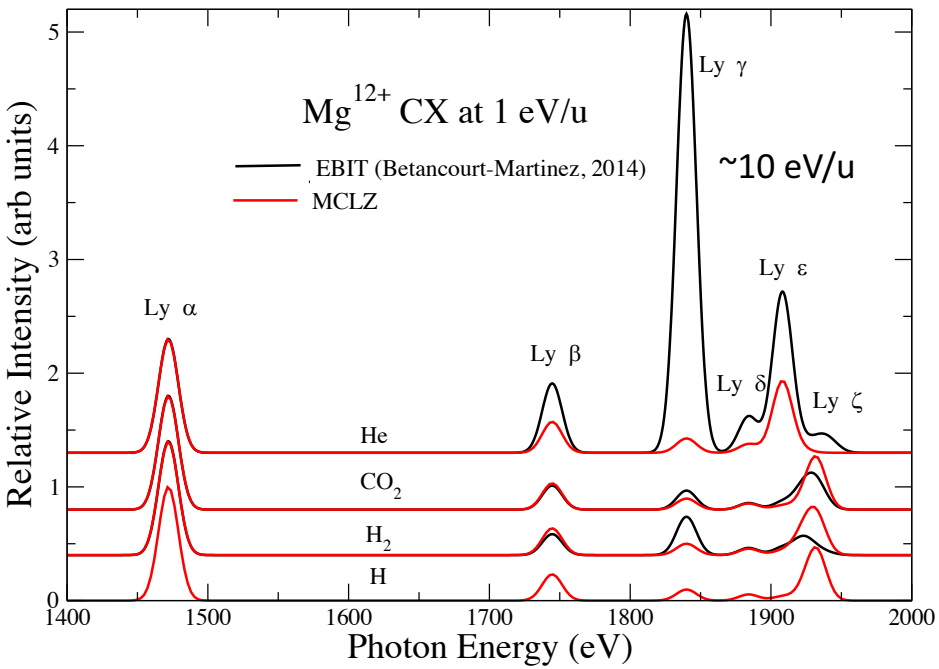

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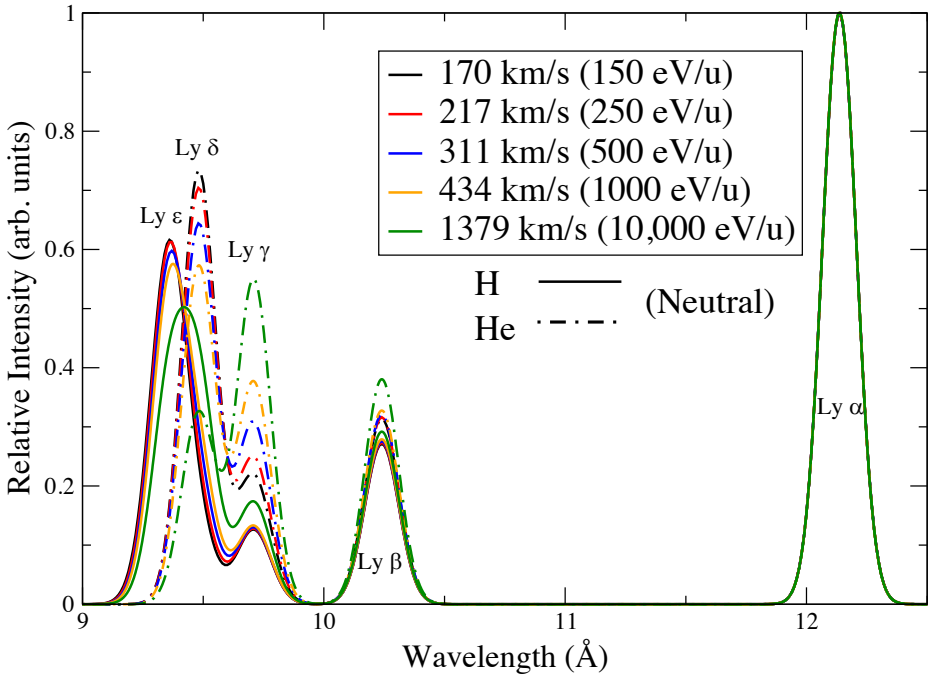

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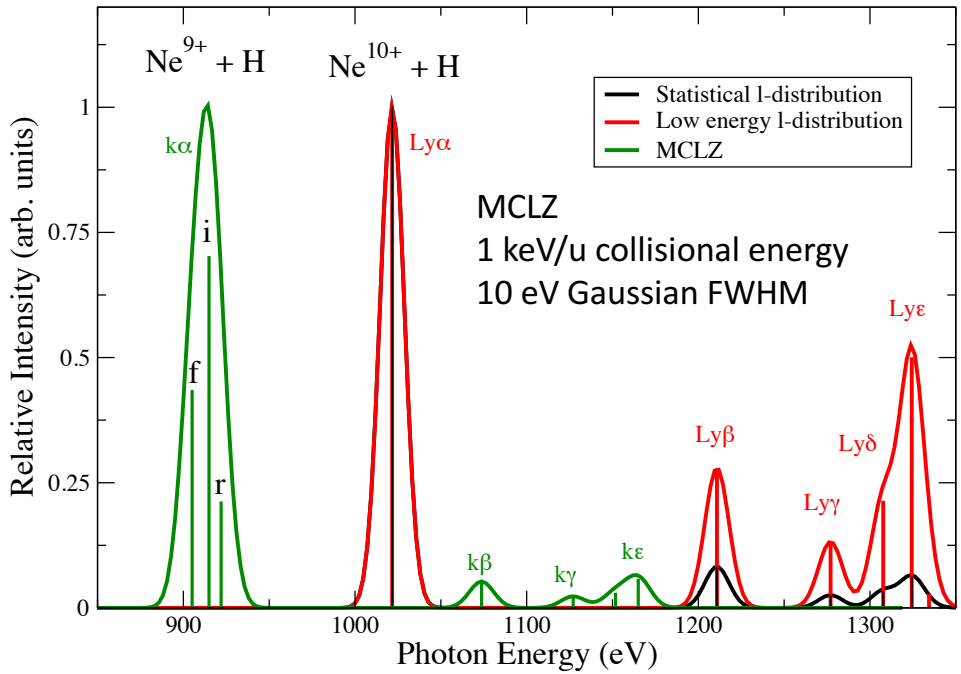

CX as a diagnostic: Hardness Ratios (H_2)

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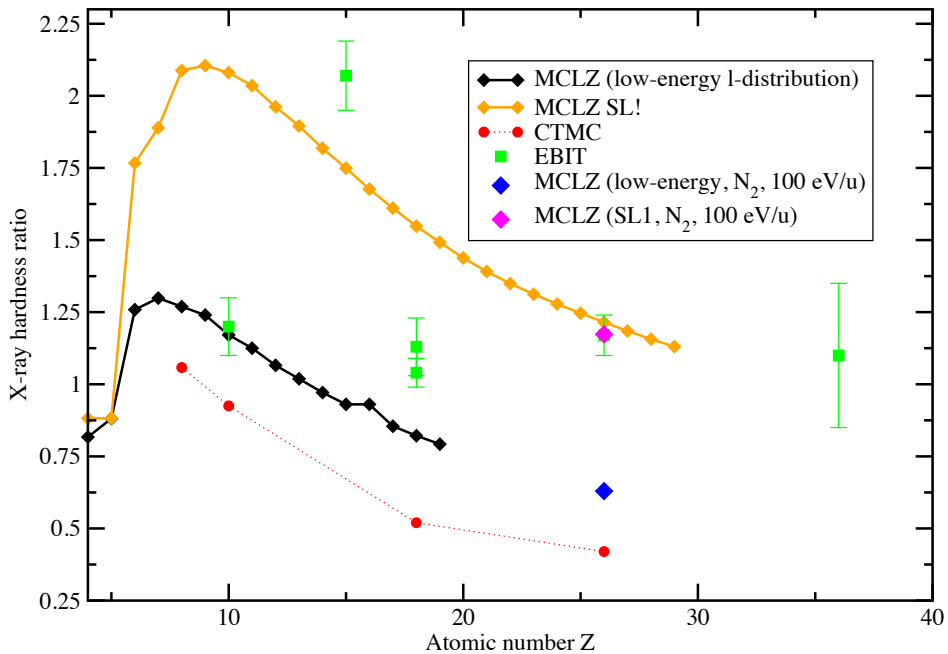
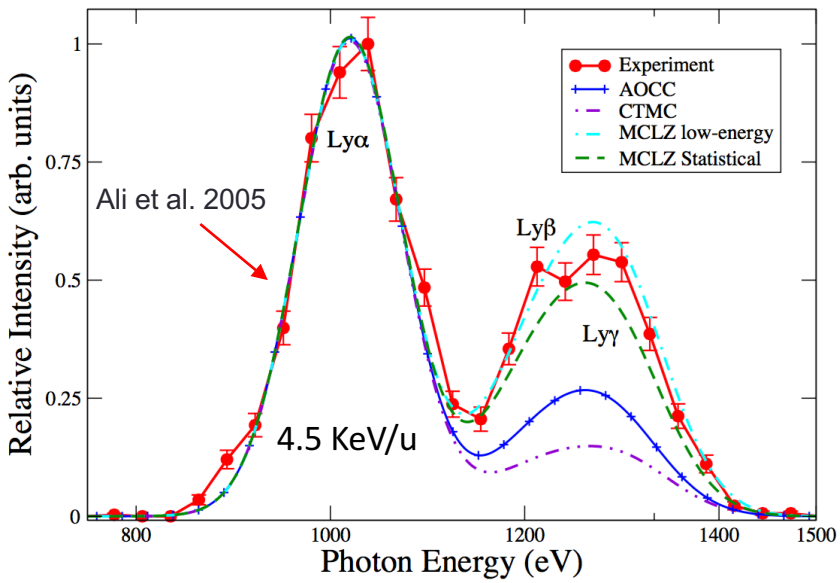
$$H = \frac{Ly_\beta + Ly_\gamma + \cdots}{Ly_\alpha}$$



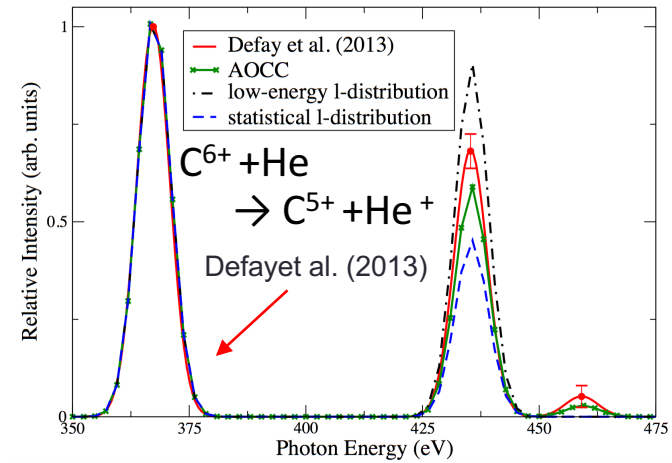
A. Miller, In Prep

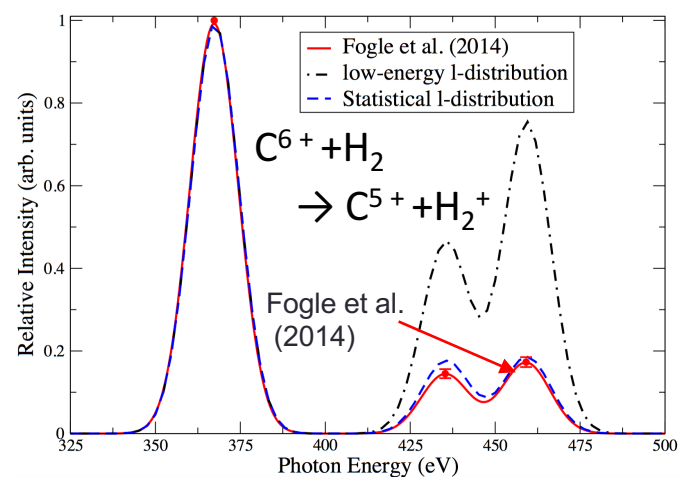
Benchmarking Theory to Experiments

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



Cumbee et al. 2016





Cumbee et al. 2017, accepted

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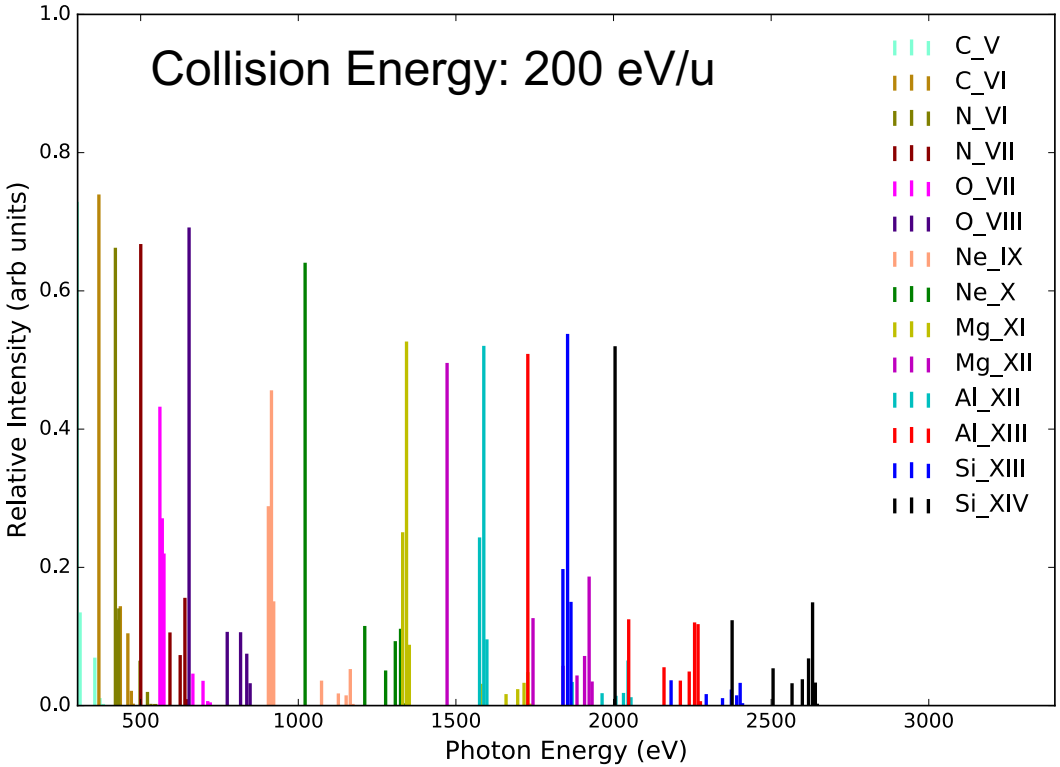

Methods:
- QMOCC
- CTMC
- AOCC
- MCLZ

Neutrals:
- H
- He(10%)

Each spectrum is normalized to a relative intensity of 1

*relative abundance not considered

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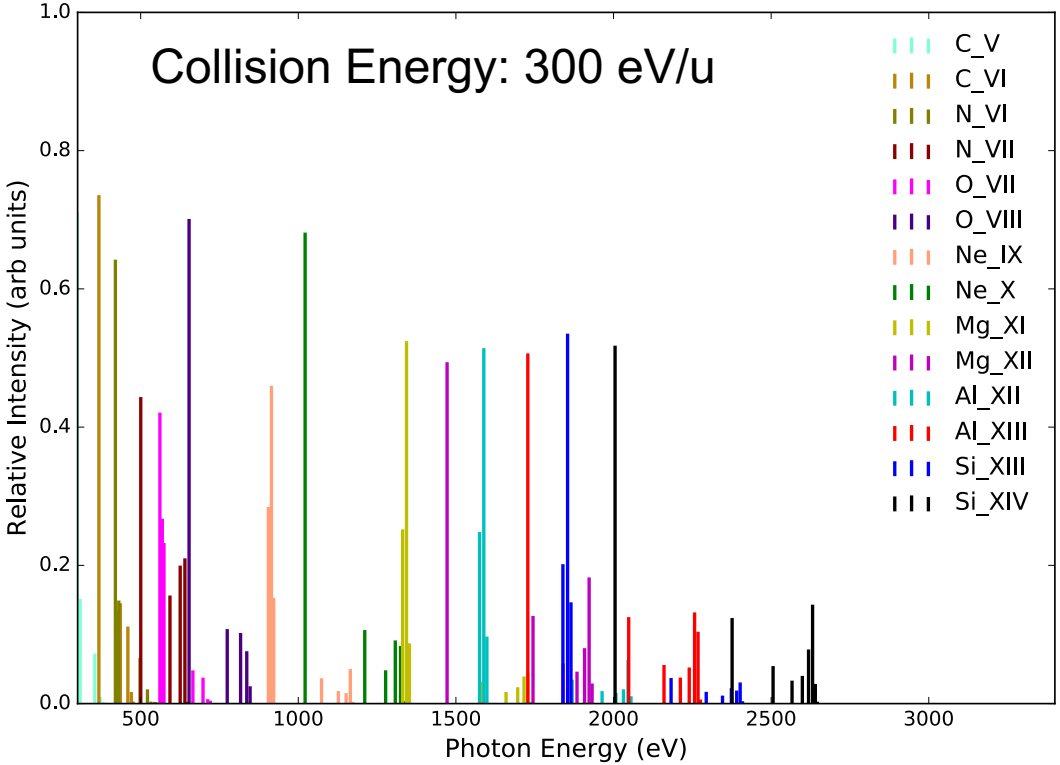

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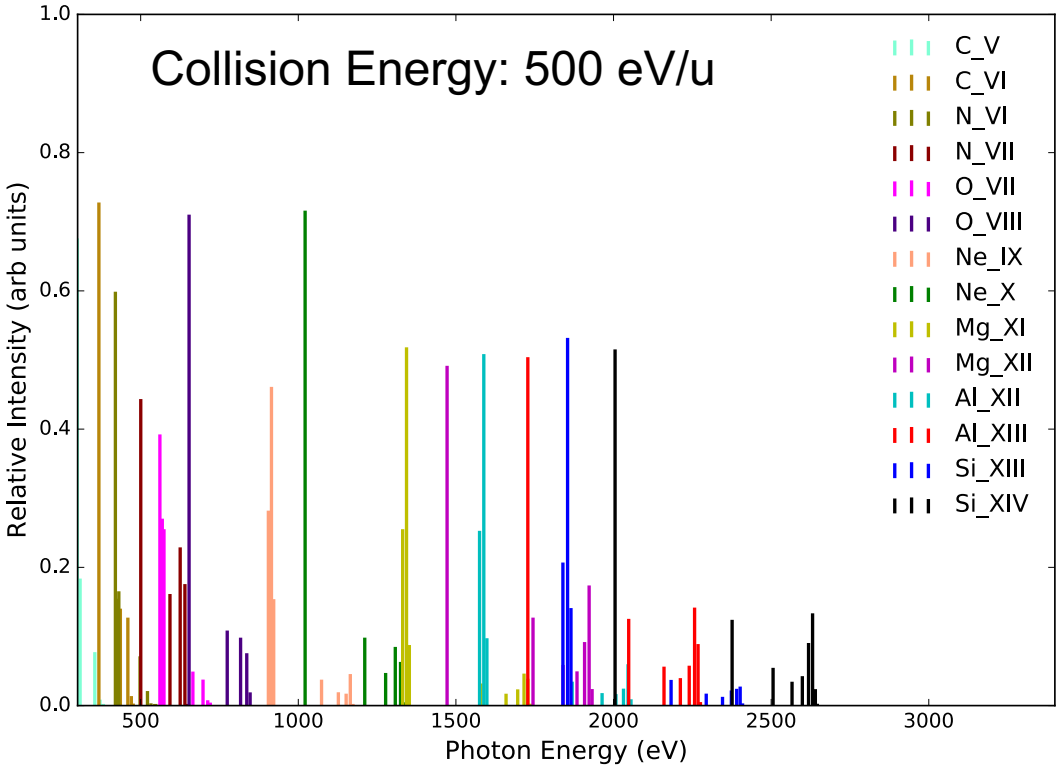

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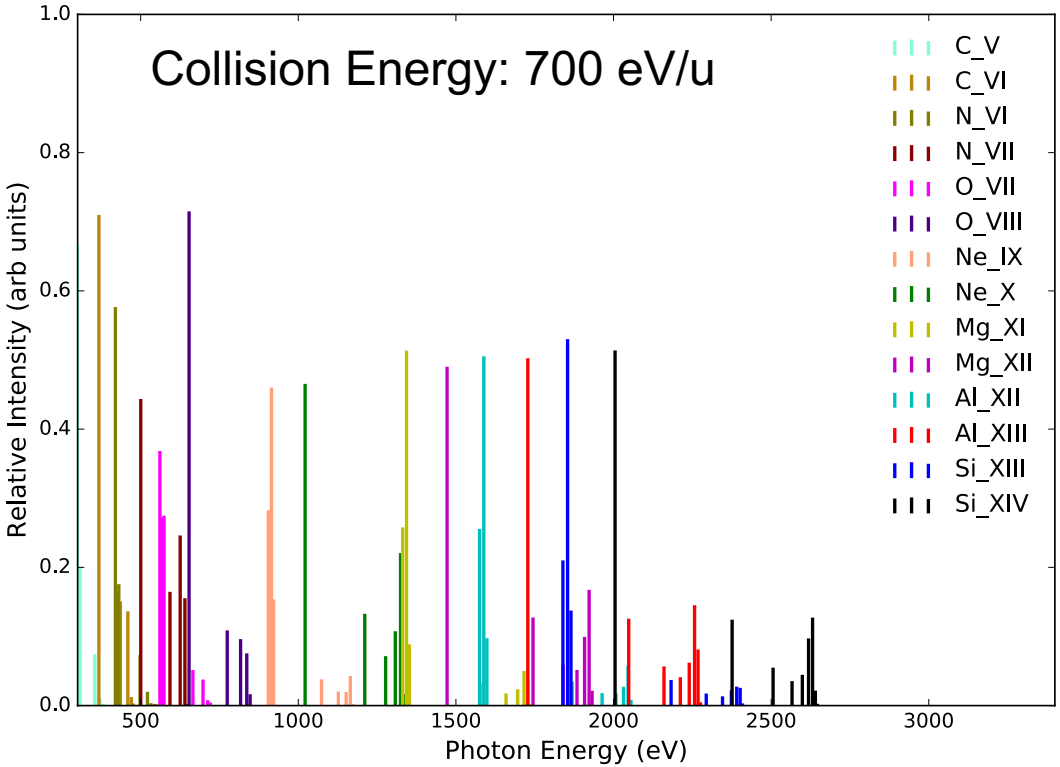

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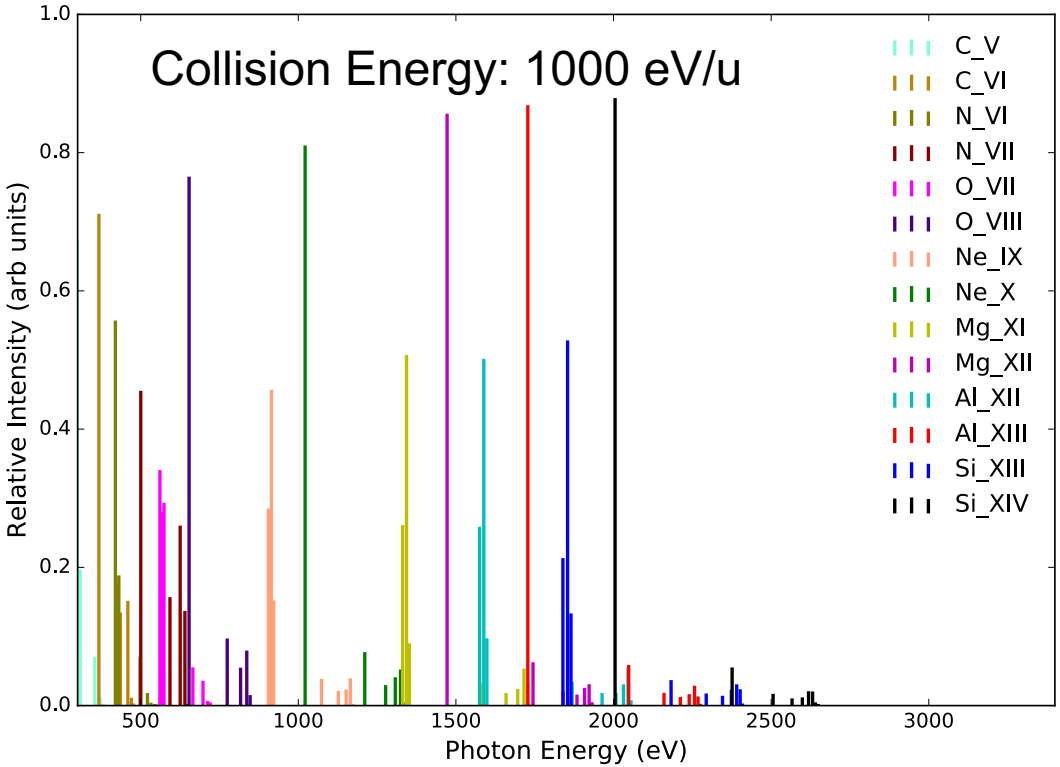

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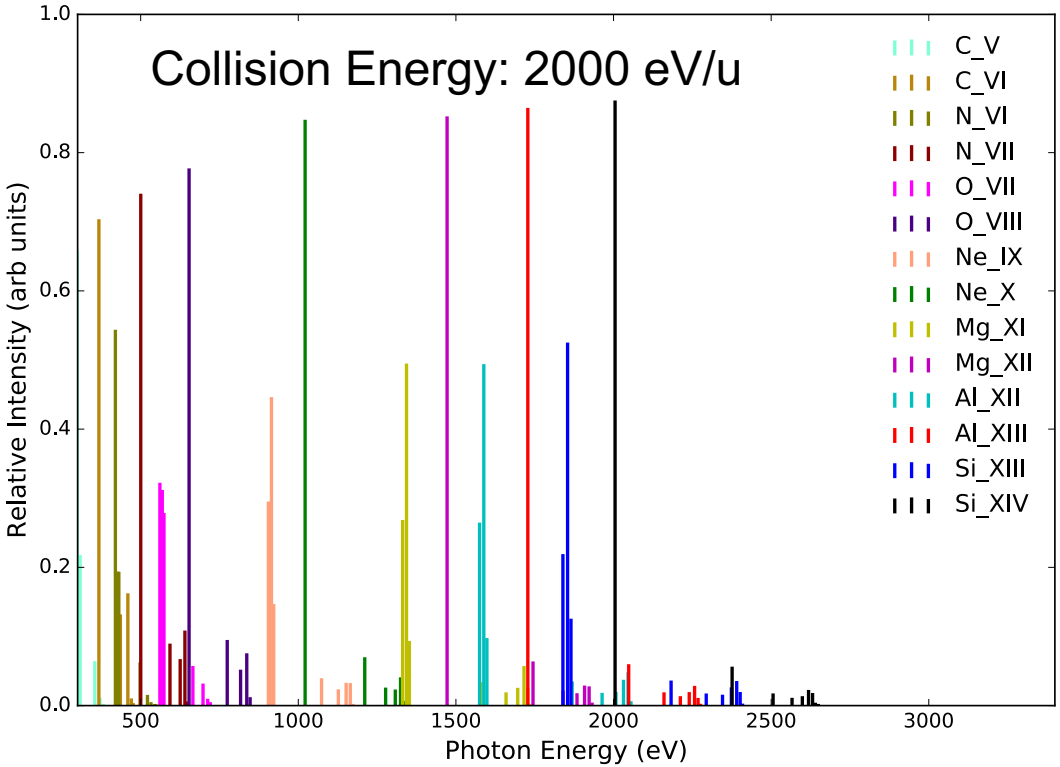

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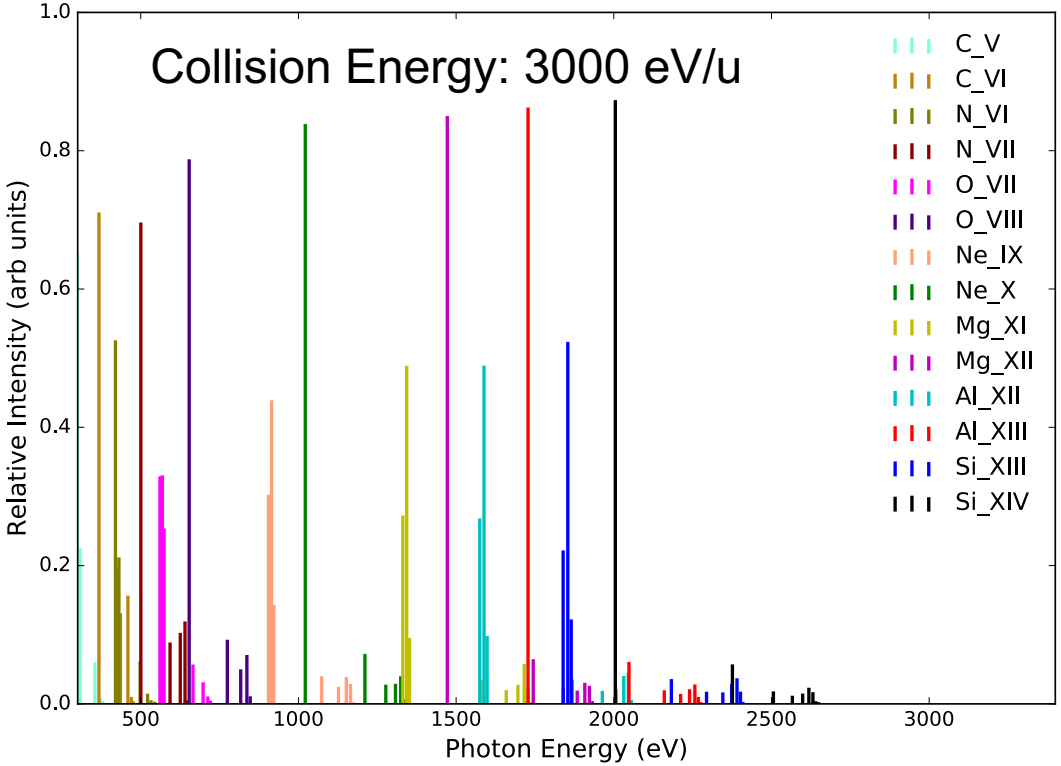

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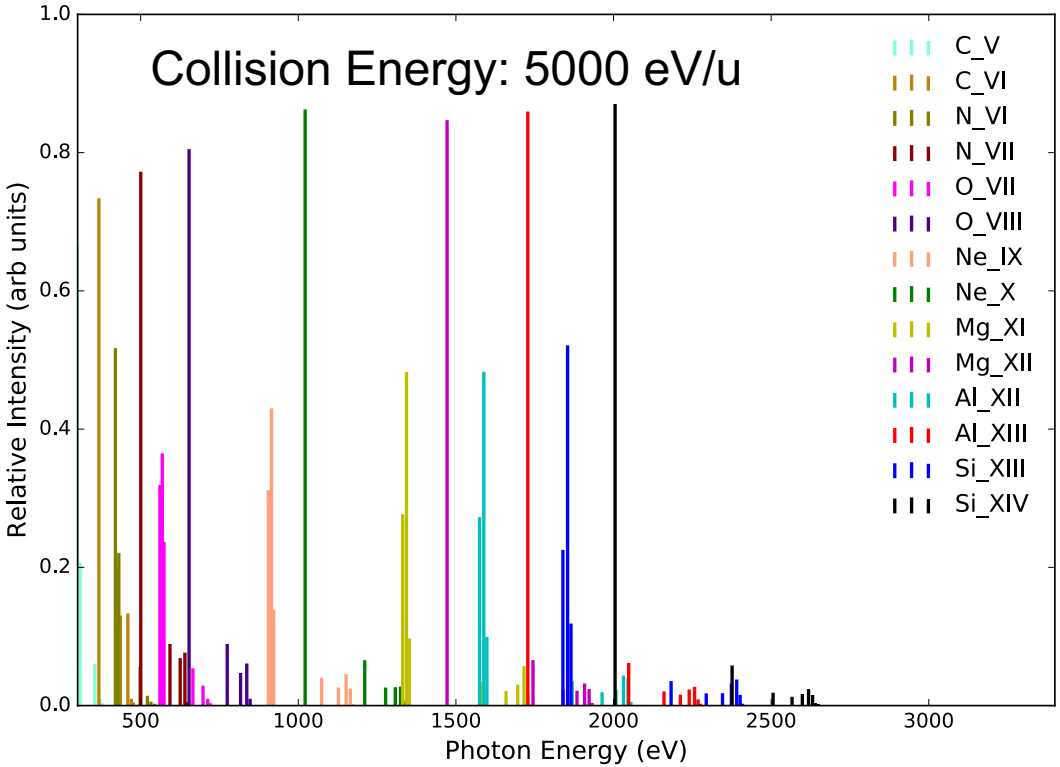

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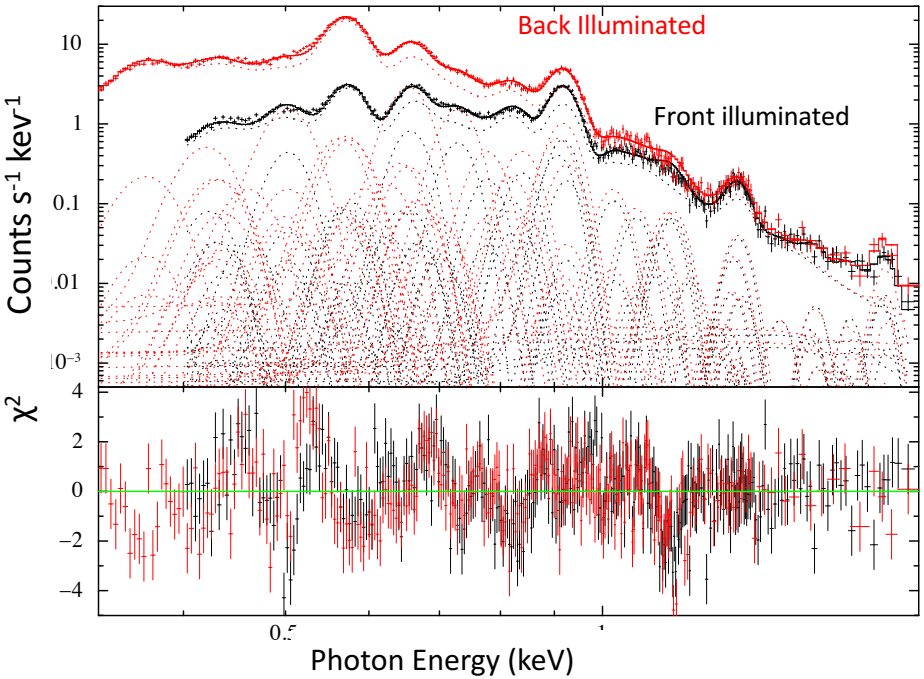
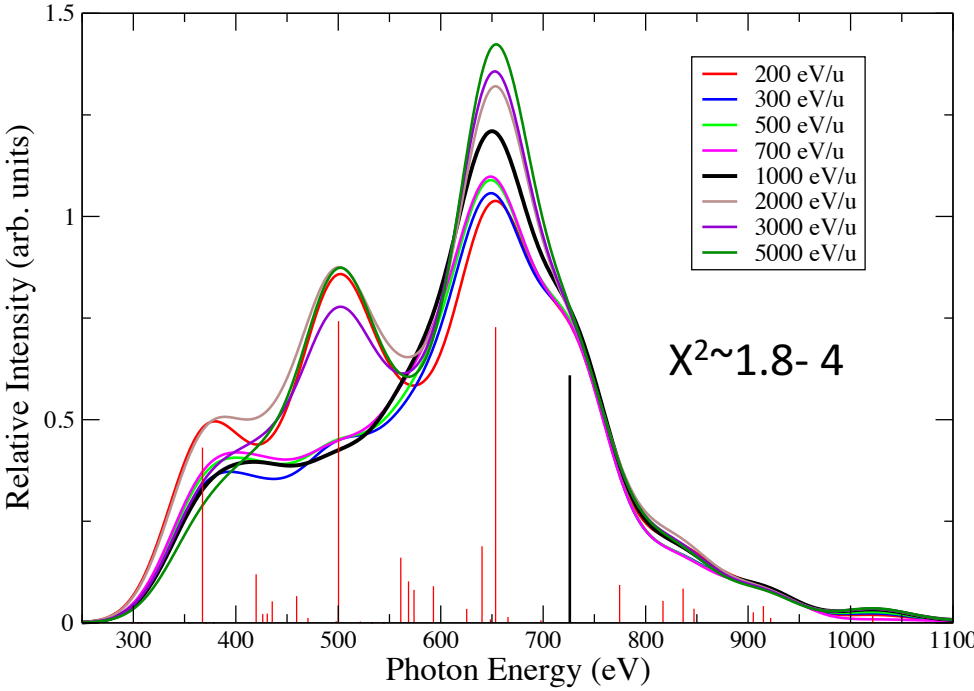
Charge eXchange Model: Cygnus Loop Supernova Remnant

XSPEC model of CX in Cygnus Loop

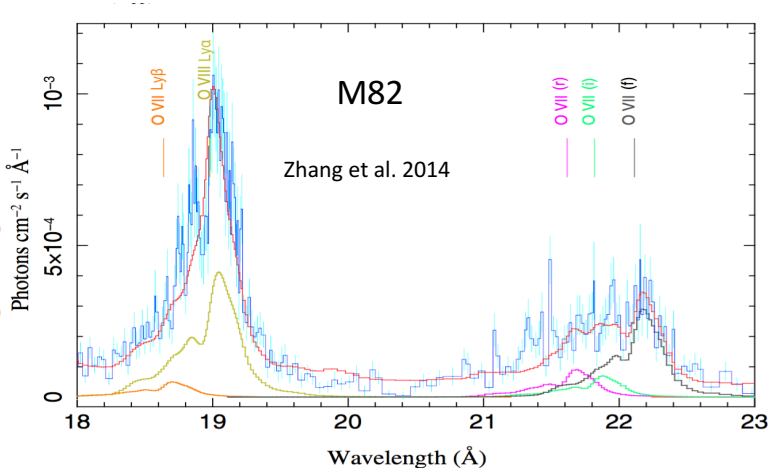


CX contribution in XSPEC model

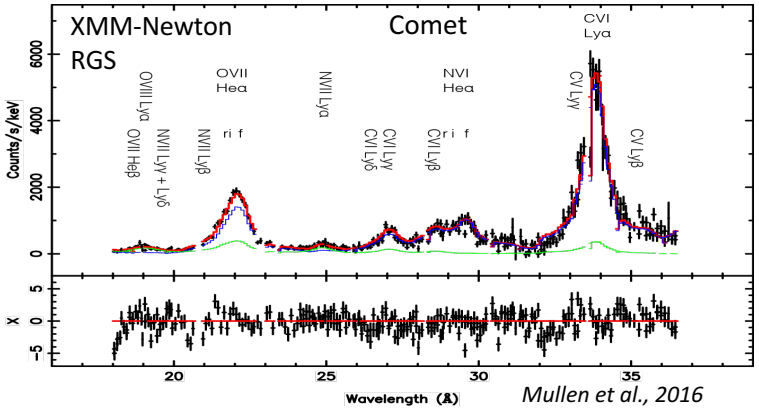


CX Modeling

AtomDB CX
ACX2.0

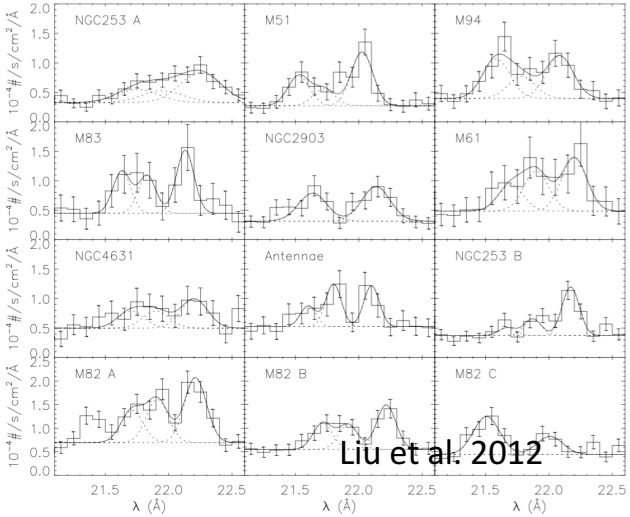


SPEX



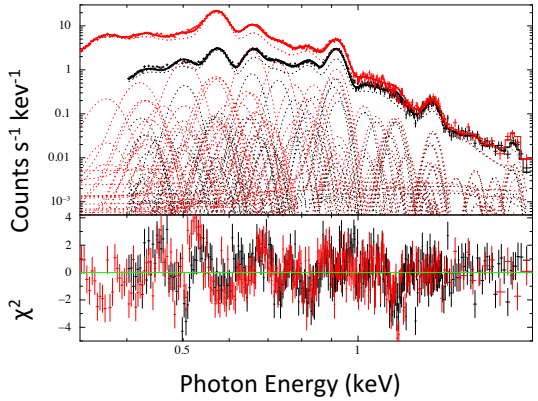
Mullen et al., 2016

Lnie Ratio
Direct Comparisons



Liu et al. 2012

Lnie Ratio
Modeling



Limitations

- In comets, more ionization stages (other than H-like and He-like) are significant
- Multi-electron capture, in which 2 or more electrons is transferred can be significant for collisions with neutrals with more than 1 electron
- Current theory needs to be benchmarked to experiment for a variety of collision energies
- MCLZ is relatively easy to calculate, but requires more approximations than QMOCC or AOCC.

Summary

Cross-sections are calculated for various ion-atom collisions

- H-like and He-like C, N, O, Ne, Mg, Al, and Si
- H and He targets
- 200-1000 km/s
- QMOCC, AOCC, CTMC, and MCLZ methods

CX model is applied to a region on the Northeast rim of the Cygnus Loop Supernova remnant

- Including all ions calculated and a fraction of 10% He
- For 8 energies

For a proper solar wind model

- More ionization stages (O^{6+}, etc)
  - In the works

All data available in Kronos Database
https://www.physast.uga.edu/research/stancil-group/atomic-molecular-databases/kronos
Google search: UGA Stancil Kronos

Zach Dorsey: Li-like CX
Liyi Gu : Astrophysical CX
Jason Terry: Double Electron Capture
Ruitan Zhang: Fully stripped ions
Mike Fogle: COLTRIMS measurements