

Photoionized silicon experiments on Z

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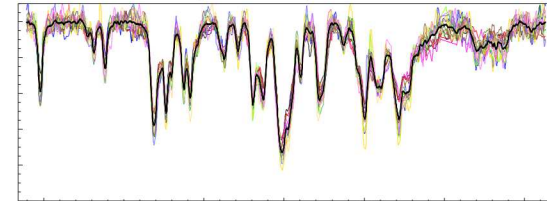
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Executive summary: Z data is suitable to benchmark photoionized plasma spectral models

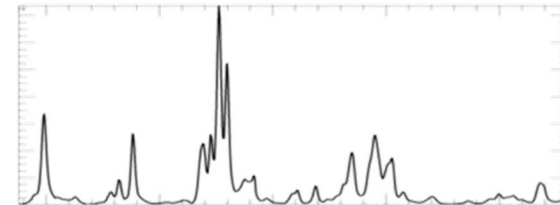
- Understanding X-ray Binaries and AGN accretion disks requires complex models that interpret observed spectra
→ These models are largely untested in the laboratory
- A photoionized silicon plasma with a measured drive radiation spectrum, density and temperature was created on Z
→ the column density is adjustable, testing radiation transport
- Models are unable to match the photoionized plasma emission and absorption spectra without invoking unidentified experimental errors, or model errors or both.



absorption spectrum

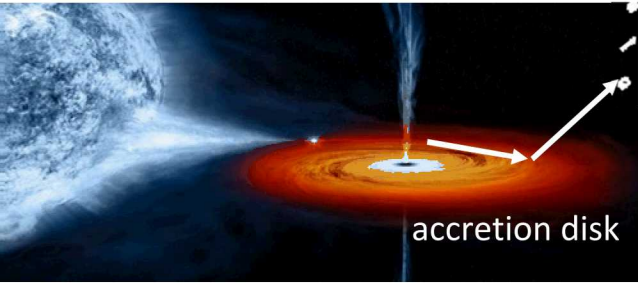


emission spectrum

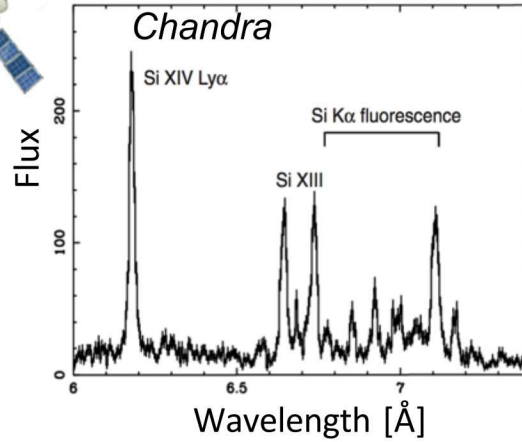


These results raise questions about the suitability of models used to interpret astrophysical observations

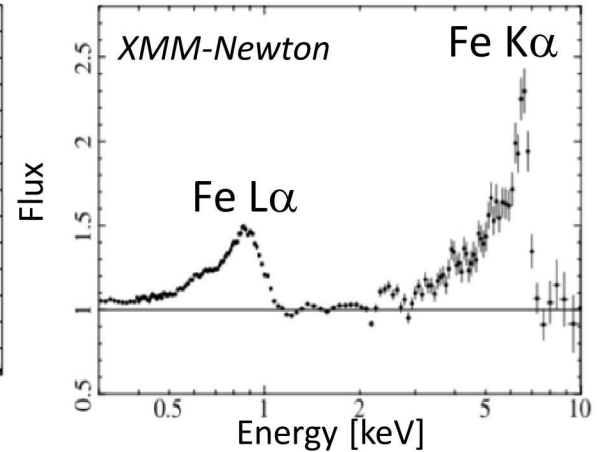
Active Galactic Nuclei and X-ray Binaries are revealed through the emission from their accretion disk



Neutron star Vela X-1



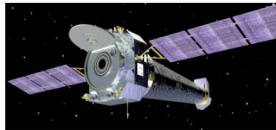
AGN 1H0707-495



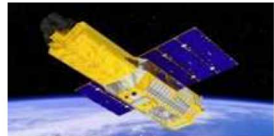
XMM-Newton - ESA



Chandra - NASA



Suzaku - JAXA



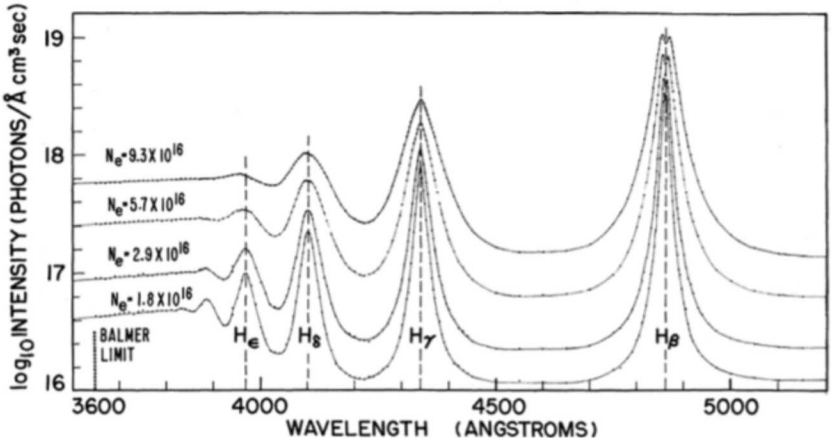
Challenges:

- Line identification
- Blended spectra from multiple elements
- Spatial and temporal integration
- Radiation transport
- Limited spectral resolution

Benchmark experiments do exist for collisional plasmas

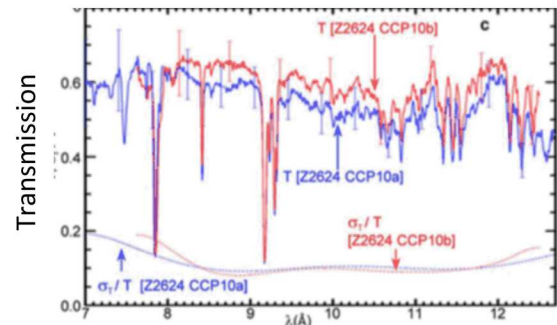


W. Wiese et al., Phys. Rev. A, **6**, (1972)

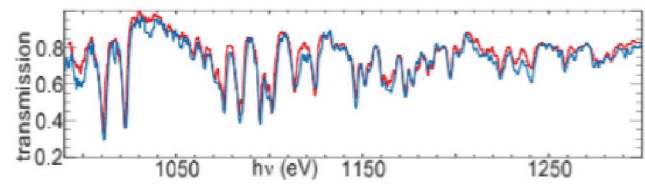


Balmer line shapes measured with 6% error

J. Bailey et al., Nature, **517** (2015)



J. Bailey et al., Phys. Rev. Lett., **99** (2007)



Transmission measured to 10% accuracy

There are numerous requirements for a benchmark emission experiment

For all photoionization experiments:

- large volumes for uniformity
- long duration for steady state
- demonstrated reproducibility
- independent diagnosis of plasma conditions *and* x-ray driving radiation
- demonstrated photoionization regime (CSD vs T_e , $\xi > 1 \text{erg.cm/s}$)

Specifically for *emission*:

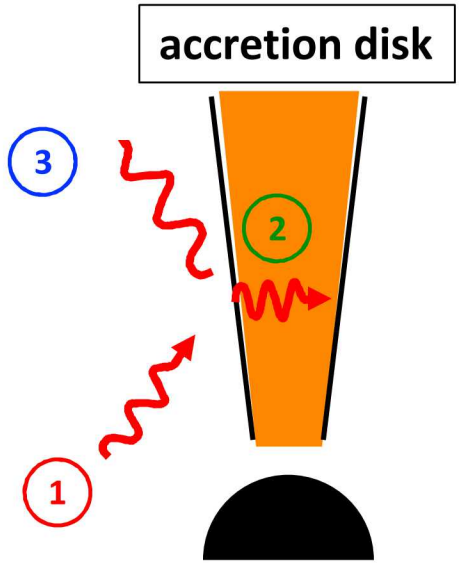
- Large column density for high S/N

But column = density x length , density $< 10^{19} \text{ e}^-/\text{cc}$ \rightarrow large $\sim 1\text{cm}$ plasma size

Experiments on the Z Facility can meet all these criteria.

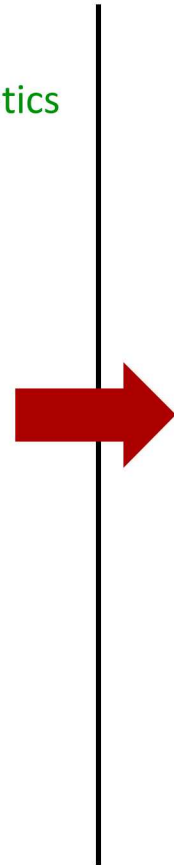
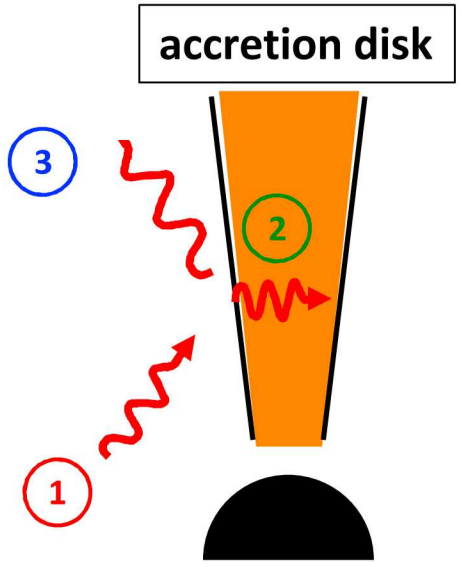
Goal: build a laboratory analog for accretion disk X-ray emission

- 1 X-ray illumination
- 2 Photon ionization and atomic kinetics
- 3 Plasma emission



Goal: build a laboratory analog for accretion disk X-ray emission

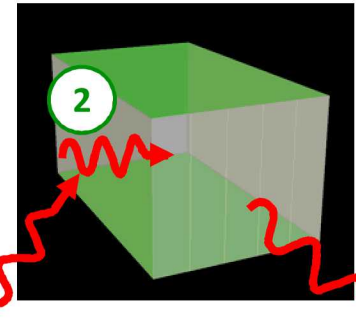
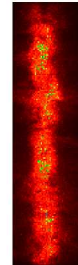
- 1 X-ray illumination
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laboratory

Temperature $T_e = 20-40 \text{ eV}$
 Density $n_i \sim 10^{17} - 10^{18} \text{ cm}^{-3}$

Z-pinch source
 $F > 1 \text{ TW/cm}^2$



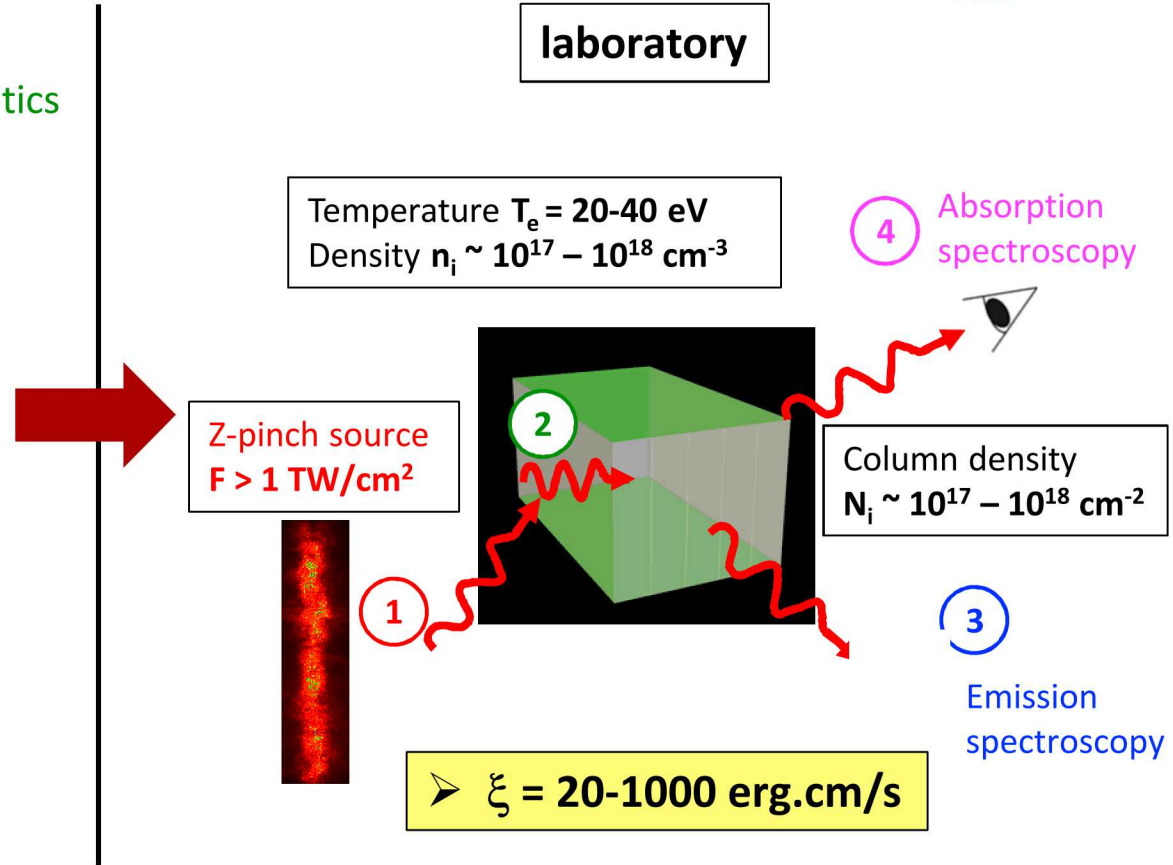
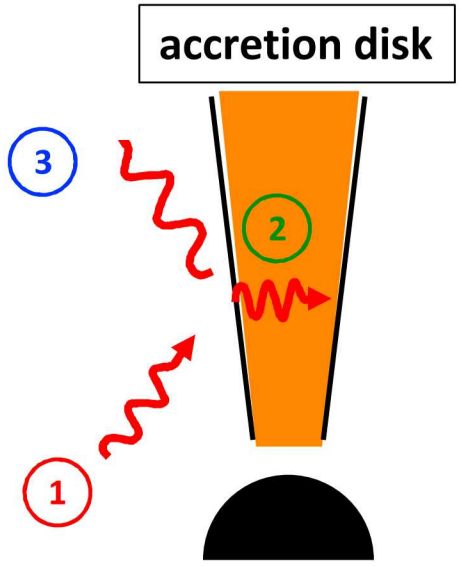
Column density
 $N_i \sim 10^{17} - 10^{18} \text{ cm}^{-2}$

3
 Emission spectroscopy

➤ $\xi = 20-1000 \text{ erg.cm/s}$

Goal: build a laboratory analog for accretion disk X-ray emission

- ① X-ray illumination
- ② Photon ionization and atomic kinetics
- ③ Plasma emission



Goal: build a laboratory analog for accretion disk X-ray emission

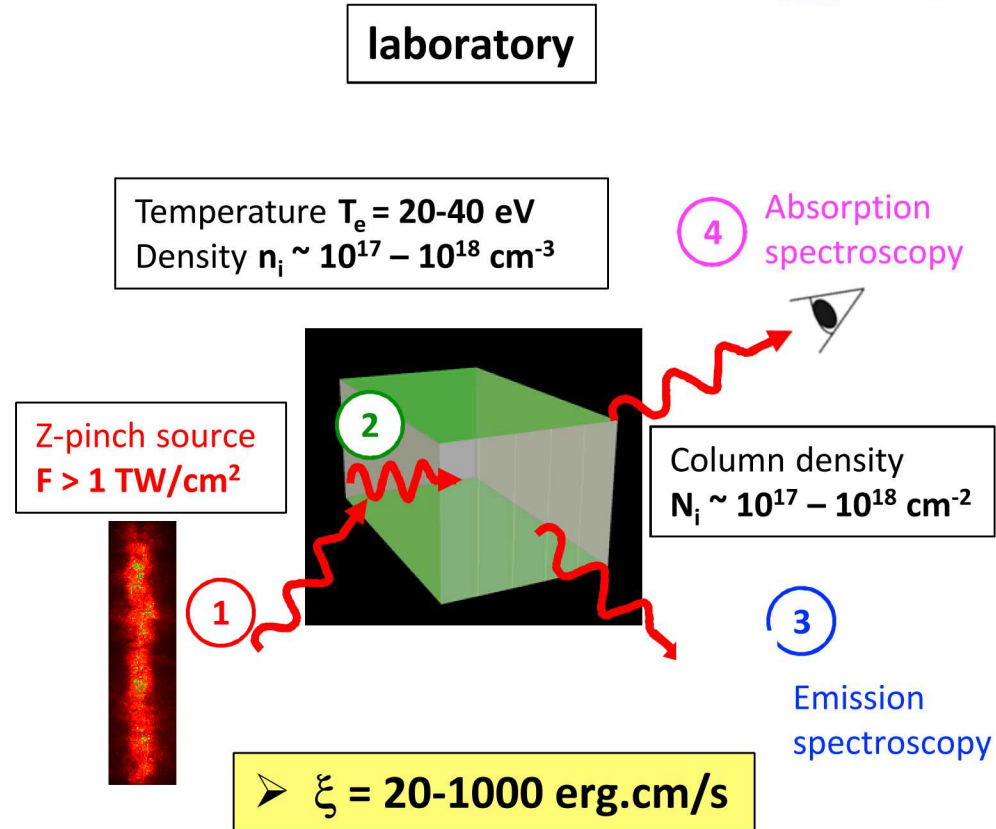
- ① X-ray illumination
- ② Photon ionization and atomic kinetics
- ③ Plasma emission

Advantages

- study individual process ① ② ③
- single element
- known drive
- controlled uniform plasma size
- higher spectral resolution
- higher signal to noise

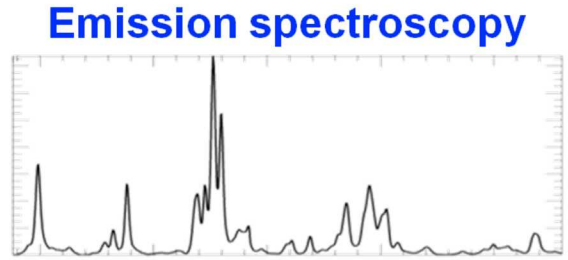
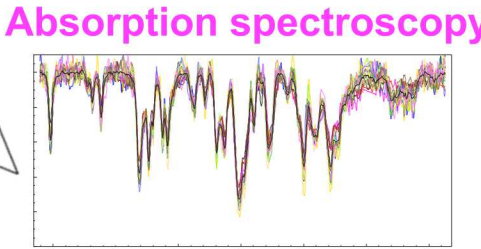
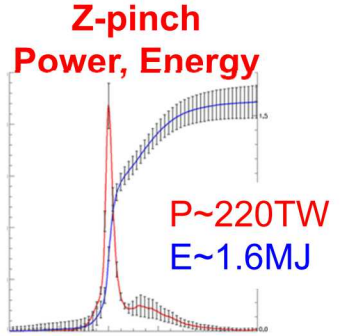
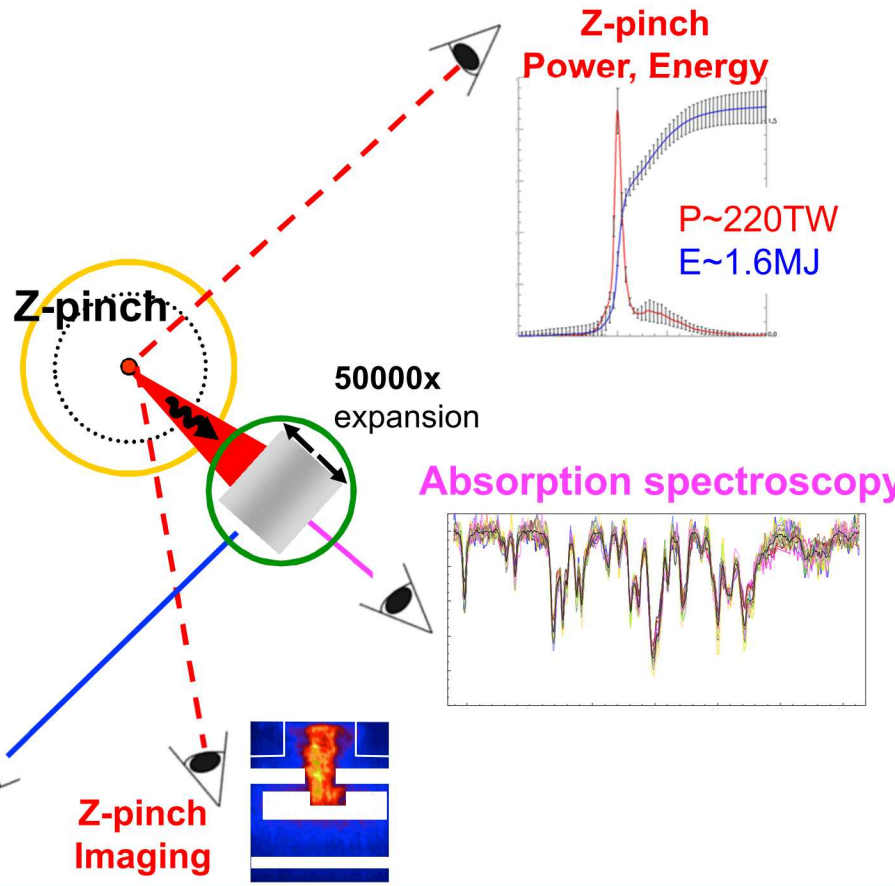
Challenges

- dynamic evolution
- ensure higher density doesn't impact results
- measurements accuracy
- residual non-uniformities



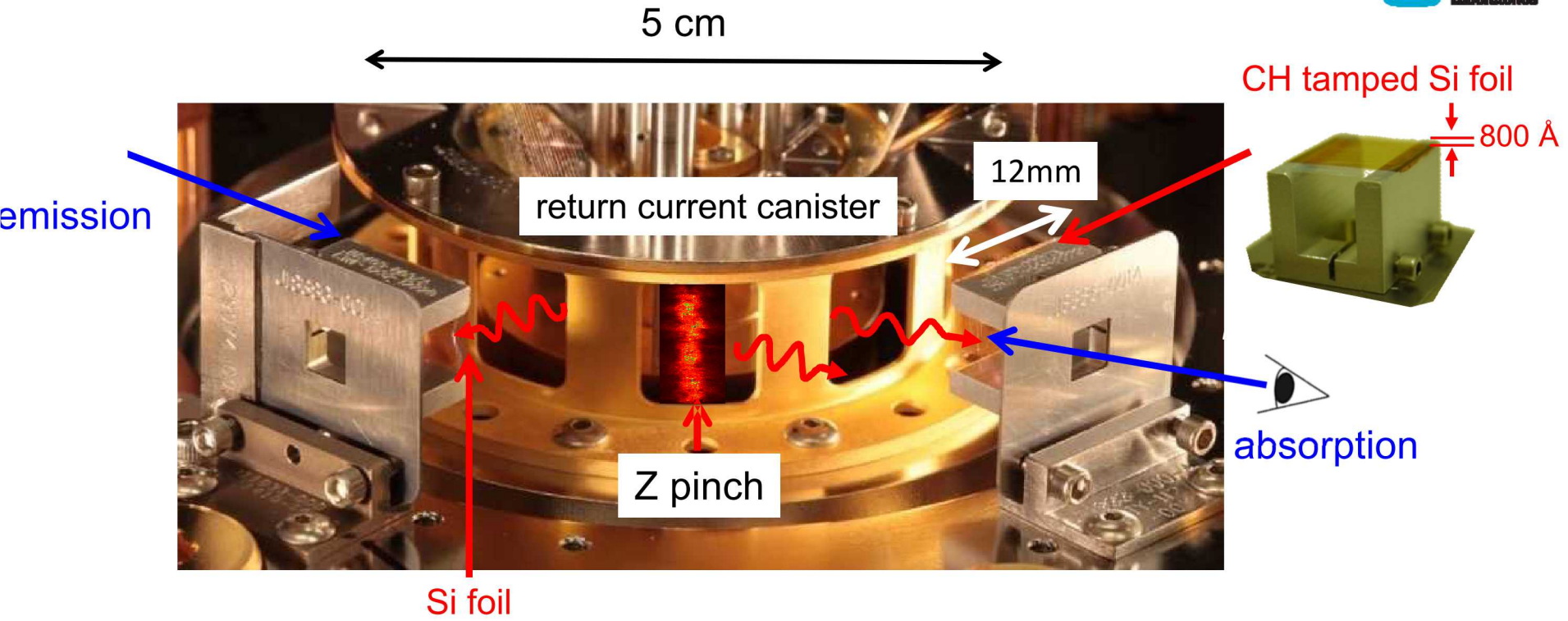
All required measurements are obtained on a single Z shot

X-ray drive, flux and shape	$F \sim 1.3 \cdot 10^{19} \text{ erg/cm}^2/\text{s}$ $T_{color} = [45, 80, 170] \text{ eV}$
Ion density	$n_i = 8 \times 10^{17} \text{ cm}^{-3}$
Column density (adjustable)	$N_i = [2.5, 5, 10] \times 10^{17} \text{ cm}^{-2}$
Average charge	$\bar{Z} \sim 10, \text{ Si}^{+10}$
Electron temperature	$T_e = 26 - 40 \text{ eV}$
Photoionization parameter	$\xi \sim 20-200 \text{ erg.cm/s}$



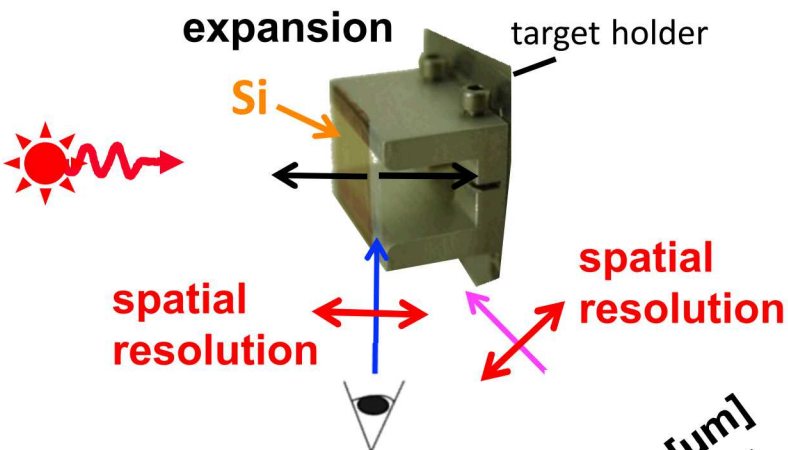
Z-pinch Imaging

Emission and absorption spectra are measured on the same shot

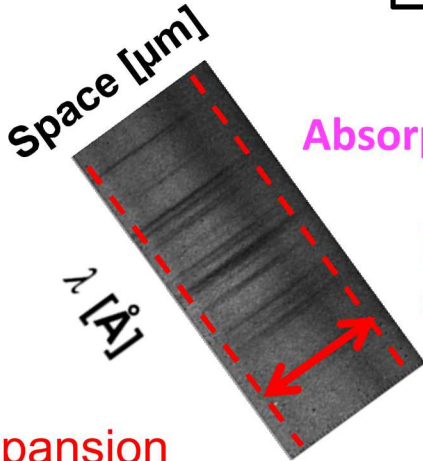
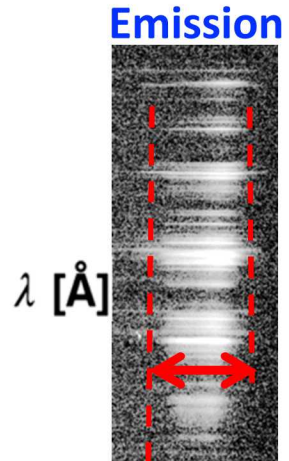


The sample can be fielded edge-on (lying flat) so the expansion can be observed with the absorption spectrometer

Ion density is measured from the sample areal mass and sample expansion



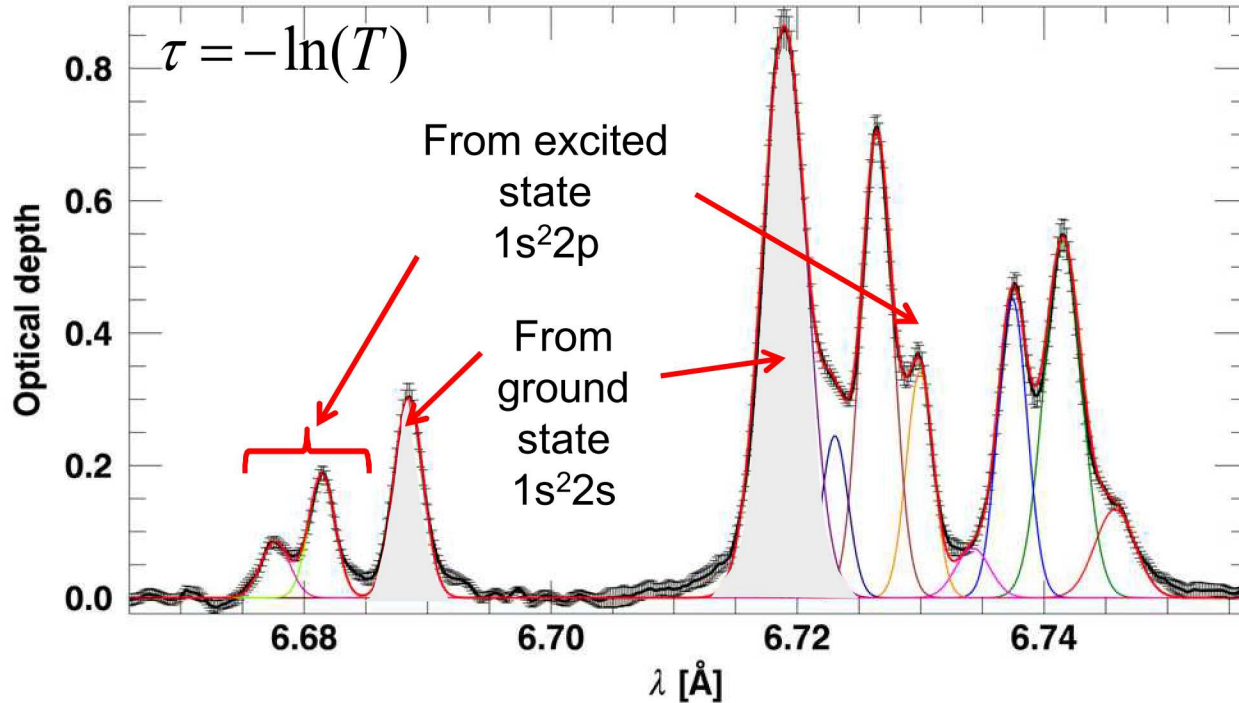
- Rutherford backscattering : 3.1×10^{17} Si/cm²
 - 1-D expansion over 3.5mm
- $$\rightarrow \begin{cases} n_i = 8.5 \times 10^{17} \text{ Si/cm}^3 & (12\% \text{ rel. unc.}) \\ n_e = \bar{Z} n_i = 8.5 \times 10^{18} \text{ e}^-/\text{cm}^3 & (20\% \text{ rel. unc.}) \end{cases}$$



Space [μm]

The temperature is obtained from Li-like absorption from low-lying state assuming partial LTE

Li-like Si^{+11} features



The ratio of lines from ground state and low lying states is a temperature diagnostic

$$\rightarrow T_e = 33 \pm 7 \text{ eV}$$

$\bar{Z} = 10.3$ with radiation

$\bar{Z} = 5.3$ without radiation

The plasma is over-ionized compared to collisional plasma at the same temperature

The temperature inferred relies on the partial LTE assumption, oscillator strengths and energy level separation (~28eV)

$$\frac{N_2(1s^22p)}{N_1(1s^22s)} \sim \frac{g_2}{g_1} \exp\left(-\frac{E_2 - E_1}{kT_e}\right)$$

oscillator strength source / initial level	Silicon EDGE-ON	Silicon FACE-ON
PRISM – 1s ² 2p _{1/2}	T _e = 31.3 ± 3.7 eV	T _e = 37.3 ± 4.1 eV
PRISM – 1s ² 2p _{3/2}	T _e = 33.3 ± 4.0 eV	T _e = 36.8 ± 3.8 eV
CATS – 1s ² 2p _{1/2}	T _e = 27. ± 2.7 eV	T _e = 31. ± 3 eV
CATS – 1s ² 2p _{3/2}	T _e = 30. ± 3.2 eV	T _e = 32 ± 3 eV

→ T_e = 33 ± 7 eV

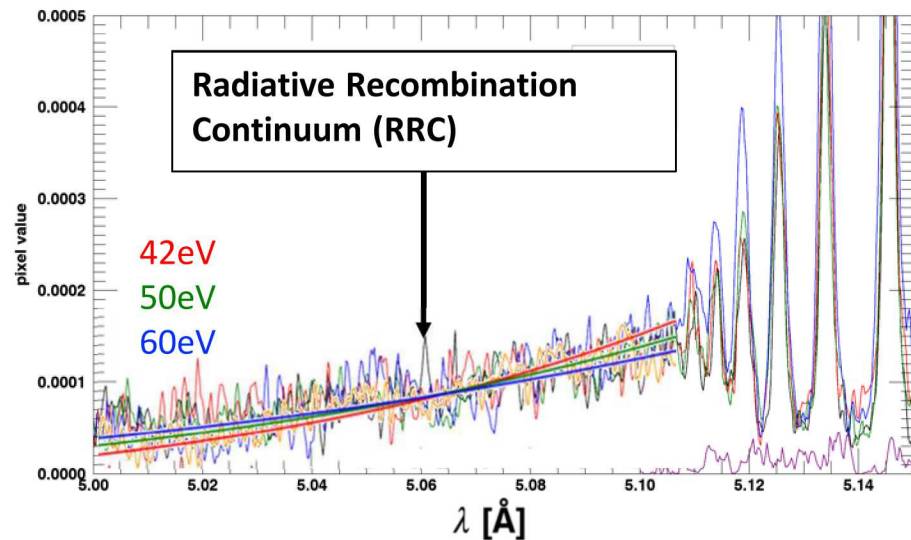
statistical error from data

Half of the 7eV error bar comes from the oscillator strength variation (used average/std over PRISM, CATS and XSTAR)

The temperature inferred when the silicon closer to the x-ray source (on canister) agrees with the RRC slope (on-going work)

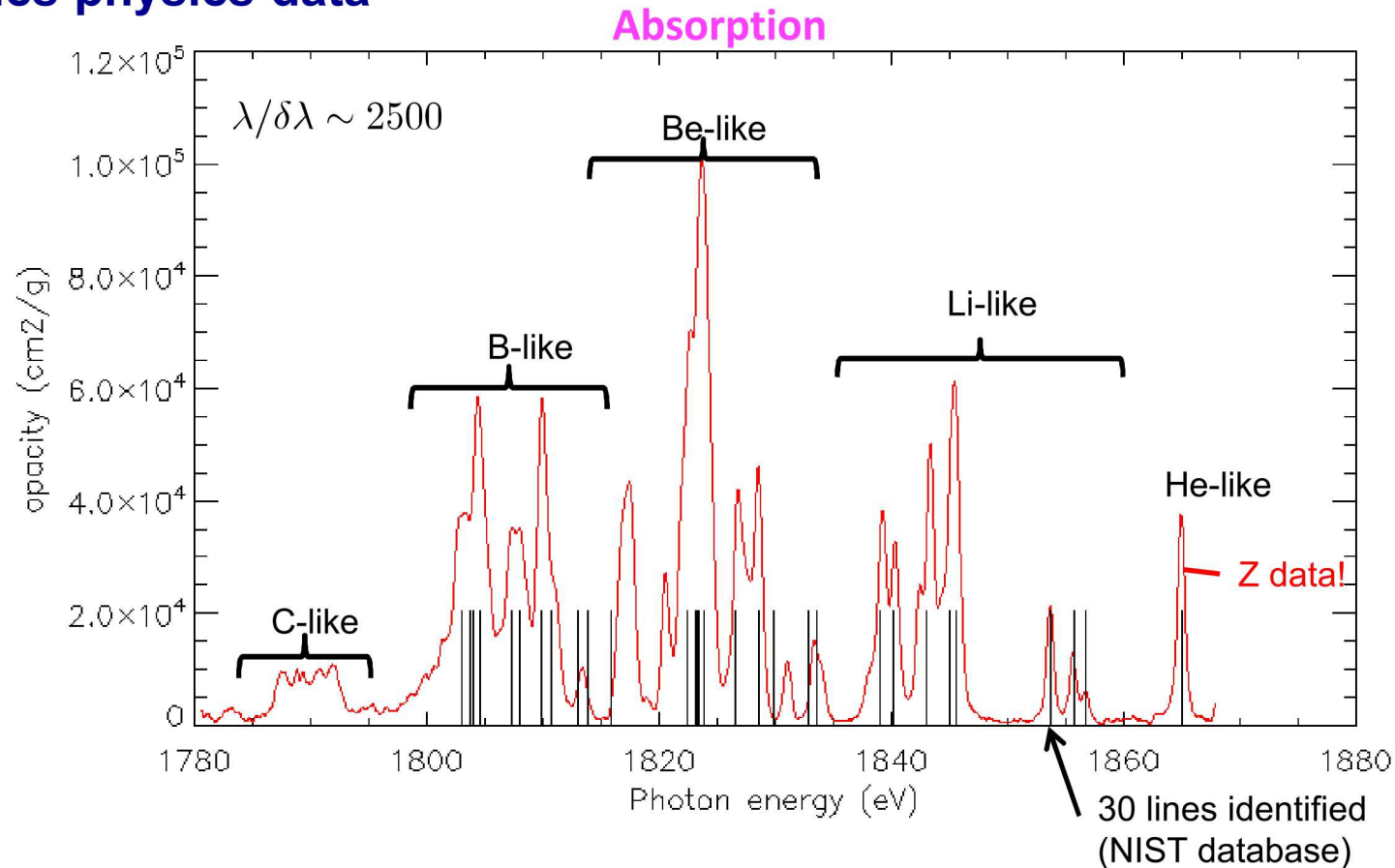
oscillator strength source / initial level	Silicon ON CAN (z3092)
PRISM – $1s^2 2p_{1/2}$	$T_e = 51 \pm 21$ eV
PRISM – $1s^2 2p_{3/2}$	$T_e = 57 \pm 19$ eV
CATS – $1s^2 2p_{1/2}$	$T_e = 39 \pm 13$ eV
CATS – $1s^2 2p_{3/2}$	$T_e = 55 \pm 35$ eV

Silicon on can - emission



RRC slope $\rightarrow T_e \sim 42 - 60$ eV

The high reproducibility and resolution impose strong constraints on atomic physics data



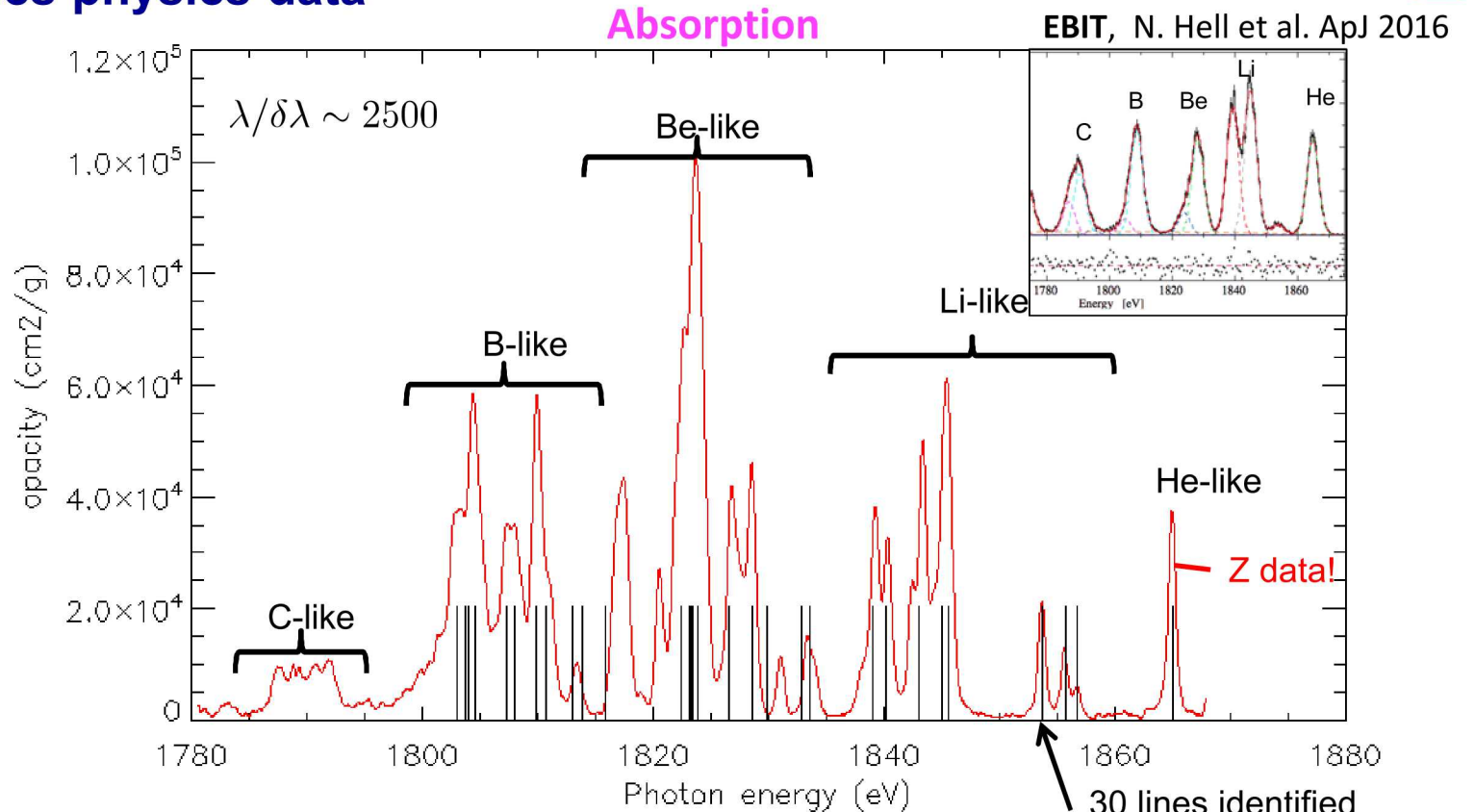
Absorption data enables detailed line identification



Lines in spectral range $\Delta\lambda \sim 0.23\text{\AA}$ or $\Delta E \sim 64\text{eV}$

	ID- Ion lower state - upper state - wavelength (\AA)		ID- Ion lower state - upper state - wavelength (\AA)
He-like	1- He 1s2 [1S0] - 1s 2p [1P1] - 6.64802		
Li-like	2- Li 1s2 2p [2P1/2] - 1s 2p2 [2S1/2] - 6.67756	B-like	16- B 1s2 2s 2p2 [2D3/2] - 1s 2s {2D} 2p3 [2D5/2] - 6.83523
	3- Li 1s2 2p [2P3/2] - 1s 2p2 [2S1/2] - 6.68119		16- B 1s2 2s 2p2 [2D5/2] - 1s 2s {2D} 2p3 [2D5/2] - 6.83553
	4- Li 1s2 2s [2S1/2] - 1s 2s {1S} 2p [2P3/2] - 6.68804		16- B 1s2 2s2 2p [2P3/2] - 1s 2s2 2p2 [2S1/2] - 6.83832
	5- Li 1s2 2s [2S1/2] - 1s 2s {3S} 2p [2P3/2] - 6.71804		17- B 1s2 2s2 2p [2P1/2] - 1s 2s2 2p2 [2P3/2] - 6.84708
	5- Li 1s2 2s [2S1/2] - 1s 2s {3S} 2p [2P1/2] - 6.72001		17- B 1s2 2s2 2p [2P3/2] - 1s 2s2 2p2 [2P3/2] - 6.85037
	6- Li 1s2 2p [2P3/2] - 1s 2p2 [2P3/2] - 6.72730		18- B 1s2 2s2 2p [2P1/2] - 1s 2s2 2p2 [2D3/2] - 6.85757
	7- Li 1s2 2p [2P1/2] - 1s 2p2 [2D3/2] - 6.73776		18- B 1s2 2s2 2p [2P3/2] - 1s 2s2 2p2 [2D5/2] - 6.86045
	8- Li 1s2 2p [2P3/2] - 1s 2p2 [2D5/2] - 6.74197		19- B 1s2 2s 2p2 [2D5/2] - 1s 2s {2D} 2p3 [2D5/2] - 6.87076
Be-like	9- Be 1s2 2s 2p [3P1] - 1s 2s 2p2 [3S1] - 6.76198		19- B 1s2 2s 2p2 [4P3/2] - 1s 2s 2p3 [4D5/2] - 6.87243
	9- Be 1s2 2s 2p [3P2] - 1s 2s 2p2 [3S1] - 6.76434		19- B 1s2 2s 2p2 [4P5/2] - 1s 2s 2p3 [4D7/2] - 6.87392
	10- Be 1s2 2p2 [1D2] - 1s 2p3 [1P1] - 6.77535		19- B 1s2 2p3 [4S3/2] - 1s 2p4 [4P5/2] - 6.87625
	11- Be 1s2 2s2 [1S0] - 1s 2s2 2p1 [1P1] - 6.78021		
	12- Be 1s2 2s 2p [1P1] - 1s 2s 2p2 [1P1] - 6.78782		
	13- Be 1s2 2s 2p [3P2] - 1s 2s {3P} 2p2 [3P2] - 6.79801		
	13- Be 1s2 2s 2p [3P1] - 1s 2s {3P} 2p2 [3P0] - 6.79932		
	13- Be 1s2 2s 2p [3P1] - 1s 2s 2p2 [3D1] - 6.79995		
	13- Be 1s2 2s 2p [3P2] - 1s 2s {3P} 2p2 [3P1] - 6.80018		
	13- Be 1s2 2s 2p [3P1] - 1s 2s 2p2 [3D2] - 6.80029		
	14- Be 1s2 2s 2p [3P2] - 1s 2s 2p2 [3D3] - 6.80309		
	15- Be 1s2 2p2 [1S0] - 1s 2p3 [1P1] - 6.82789		

The high reproducibility and resolution impose strong constraints on atomic physics data



➤ many of these lines have never been seen in any experiment

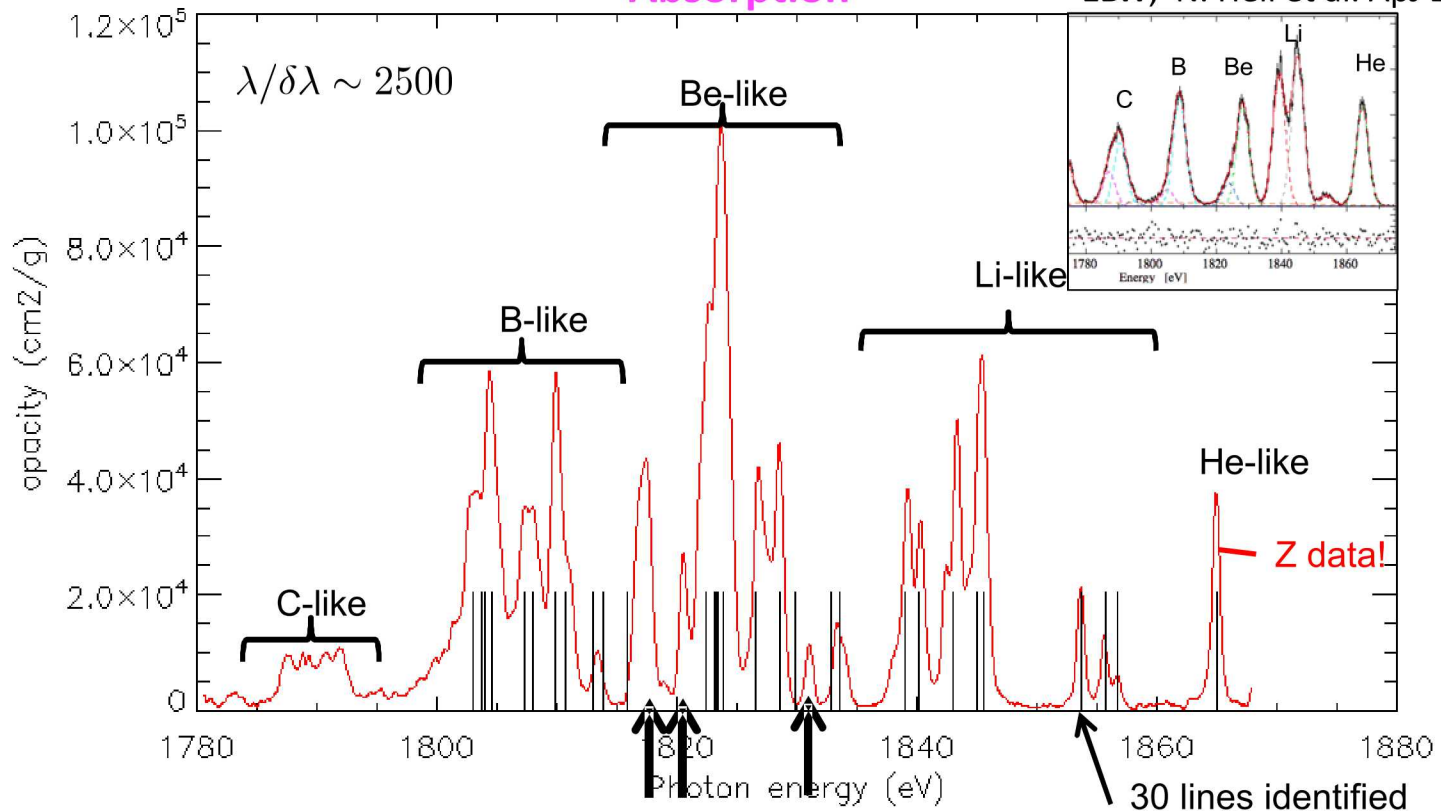
30 lines identified (PRISM, NIST database)

The high reproducibility and resolution impose strong constraints on atomic physics data



Absorption

EBIT, N. Hell et al. ApJ 2016



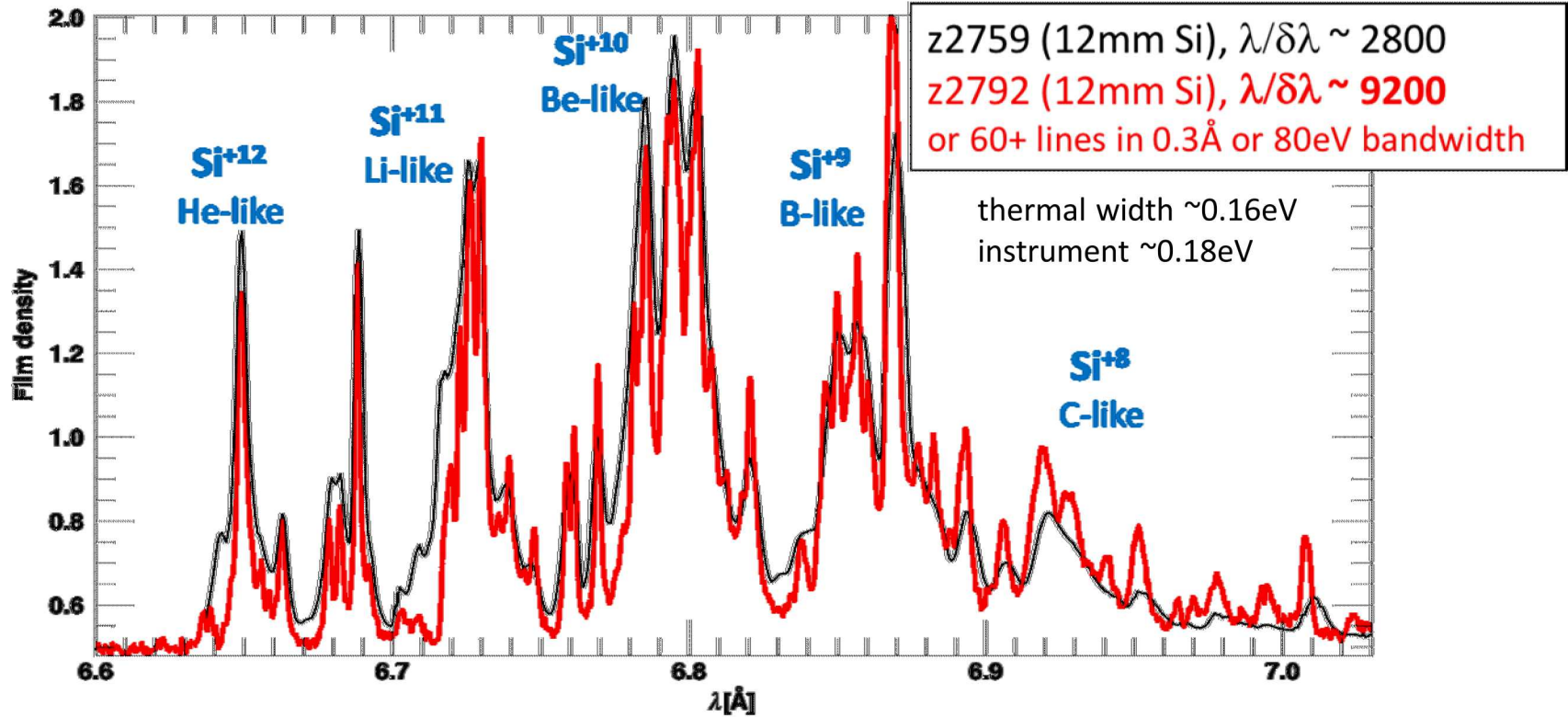
lines mismatch

30 lines identified (PRISM, NIST database)

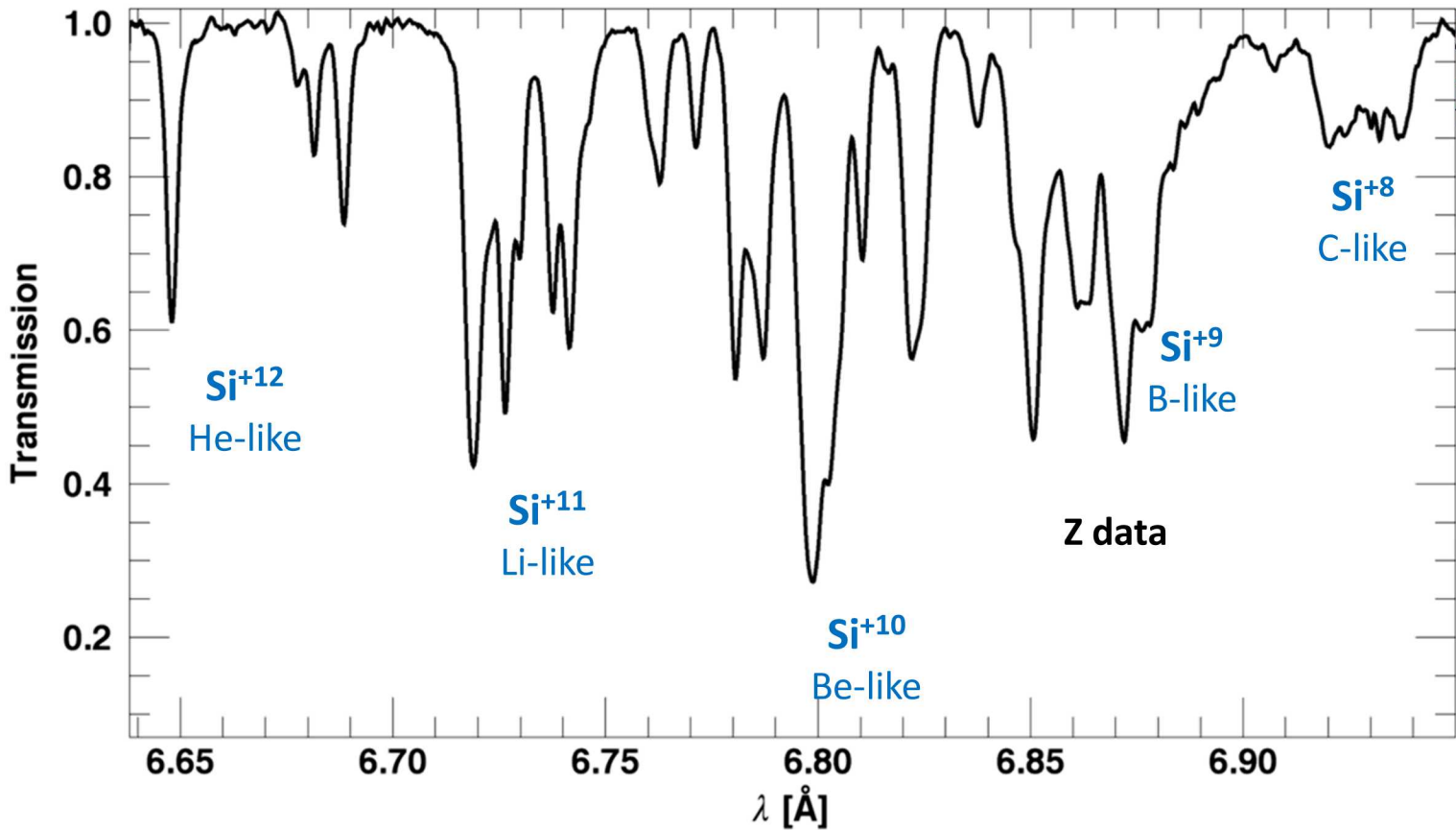
The high reproducibility and resolution impose strong constraints on atomic physics data

raw Z data (no model)

Emission

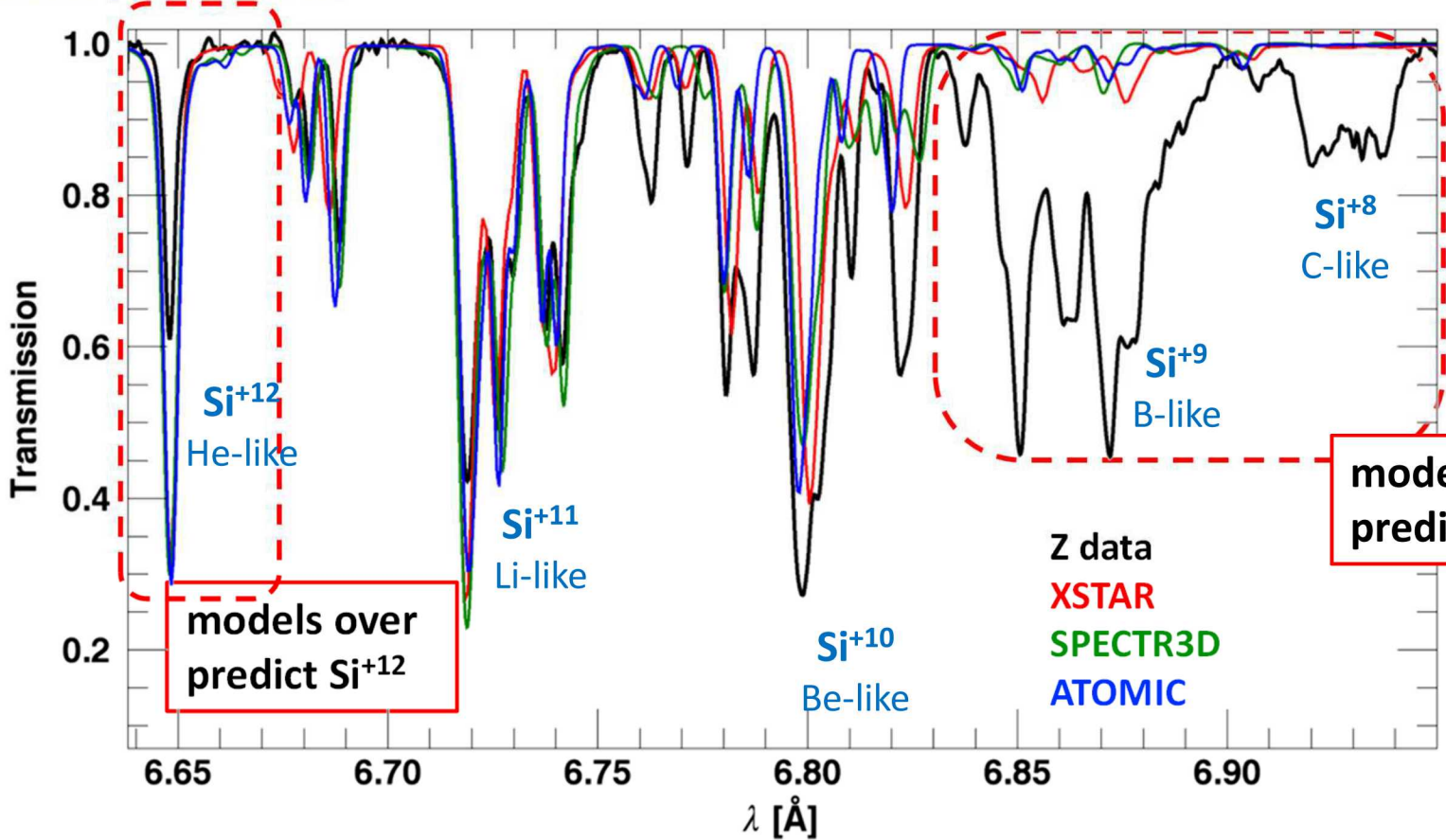


Measured relative absorption from different ion stages tests model ionization predictions

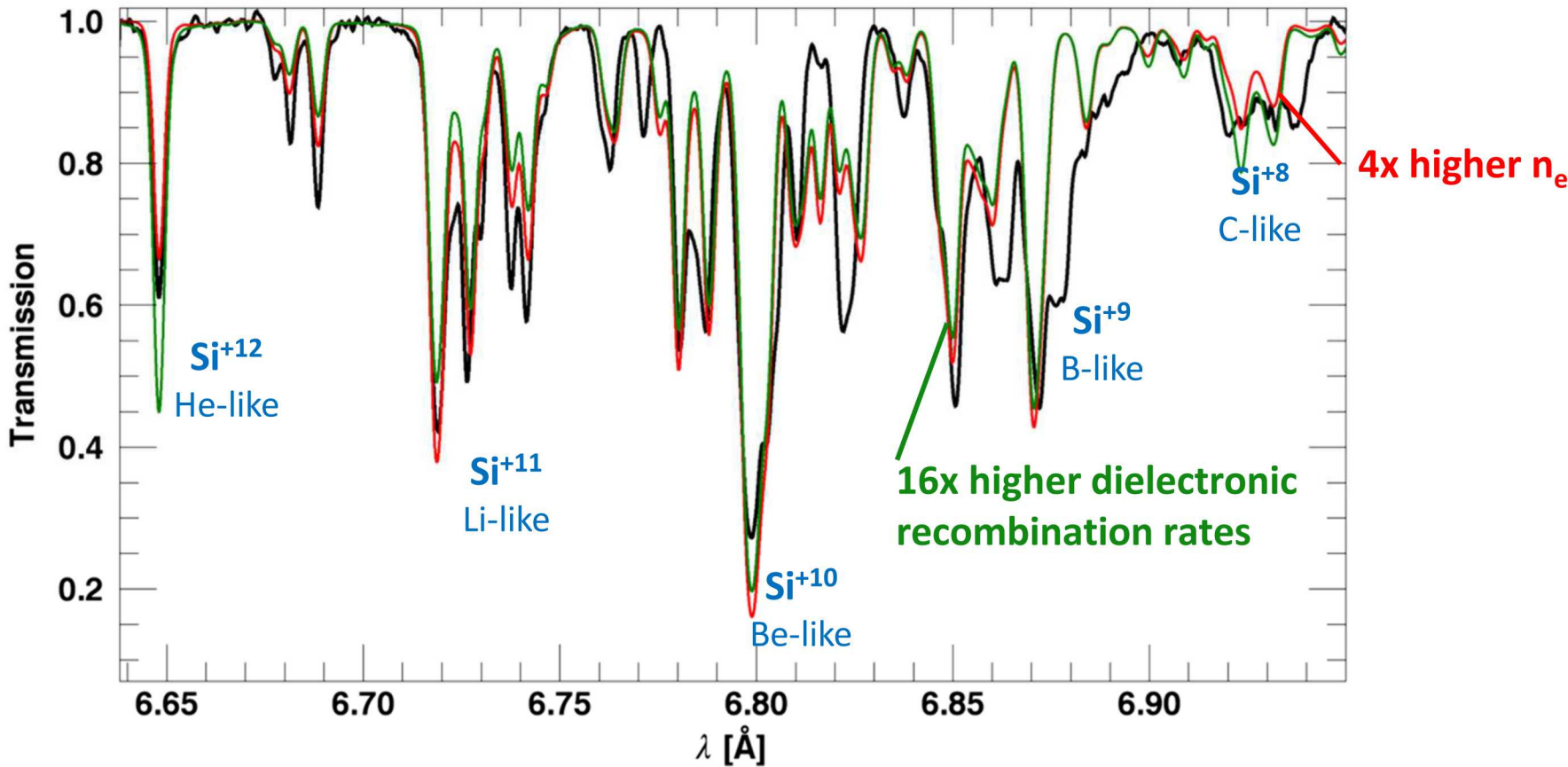


4.7% rel. unc.
 $\lambda/\delta\lambda \sim 2400$

Measured relative absorption from different ion stages tests model ionization predictions



Agreement can be obtained by adjusting parameters that increase recombination



Can models predict the charge state distribution?



Either:

the experiment electron density is 4x higher than the measured value

or:

model recombination rates need revision

The uncertainty in the measured electron density is ~20%

but

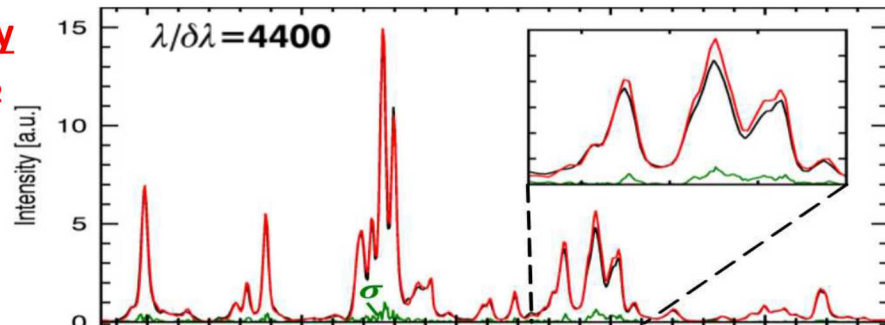
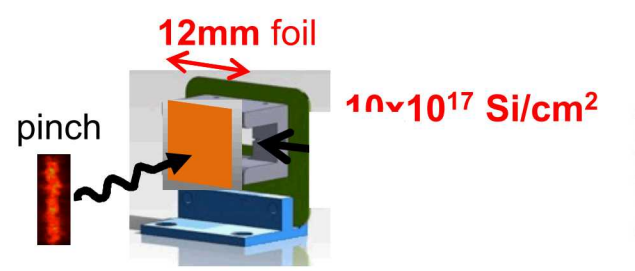
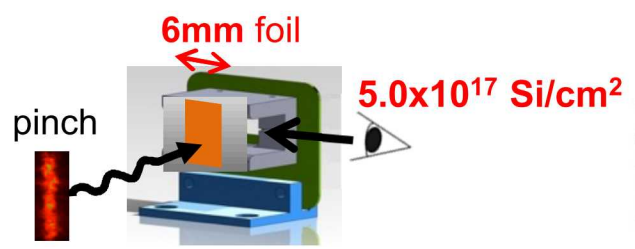
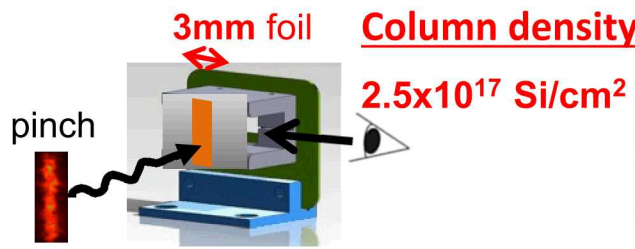
this assumes the CH tamper plasma does not mix with the Si plasma.
Preliminary tests indicate CH mixing does not resolve the discrepancy.

or:

something else?

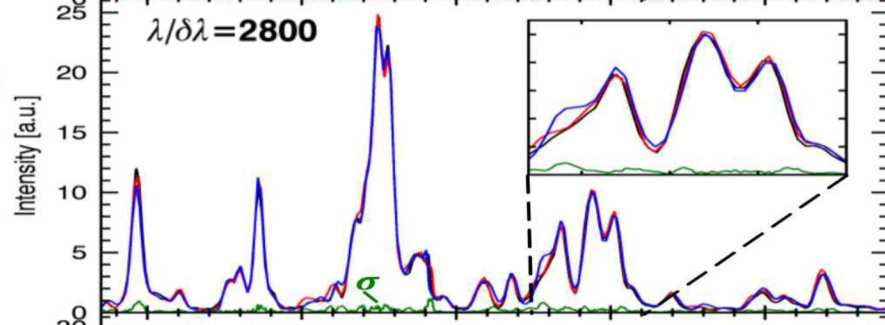
→ we need an improved electron density diagnostic

Measured emission at 3 column densities enables radiation transport tests



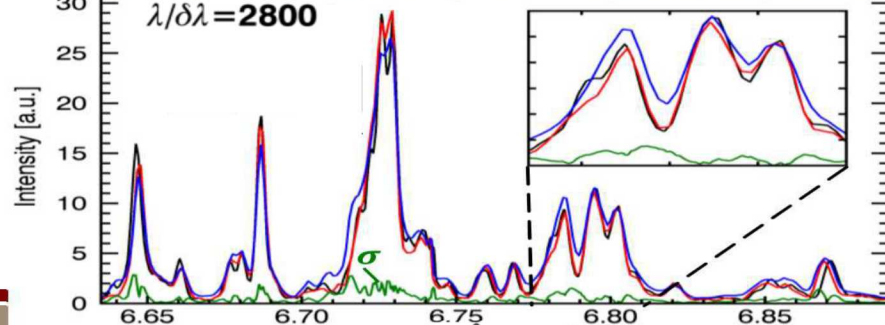
2 separate
Z experiments

std. dev. = 5.7%



3 separate
Z experiments

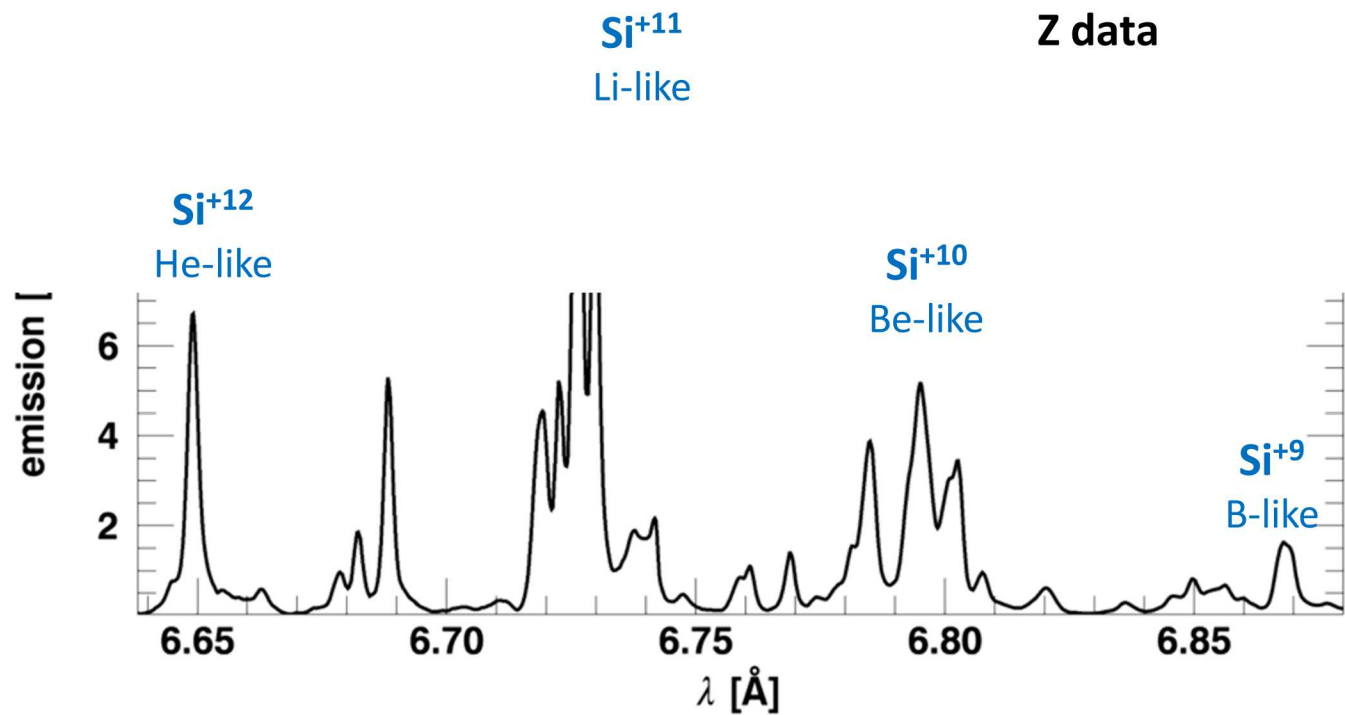
std. dev. = 5.2%



3 separate
Z experiments

std. dev. = 11.2%

The emission data shows contributions from different charge states

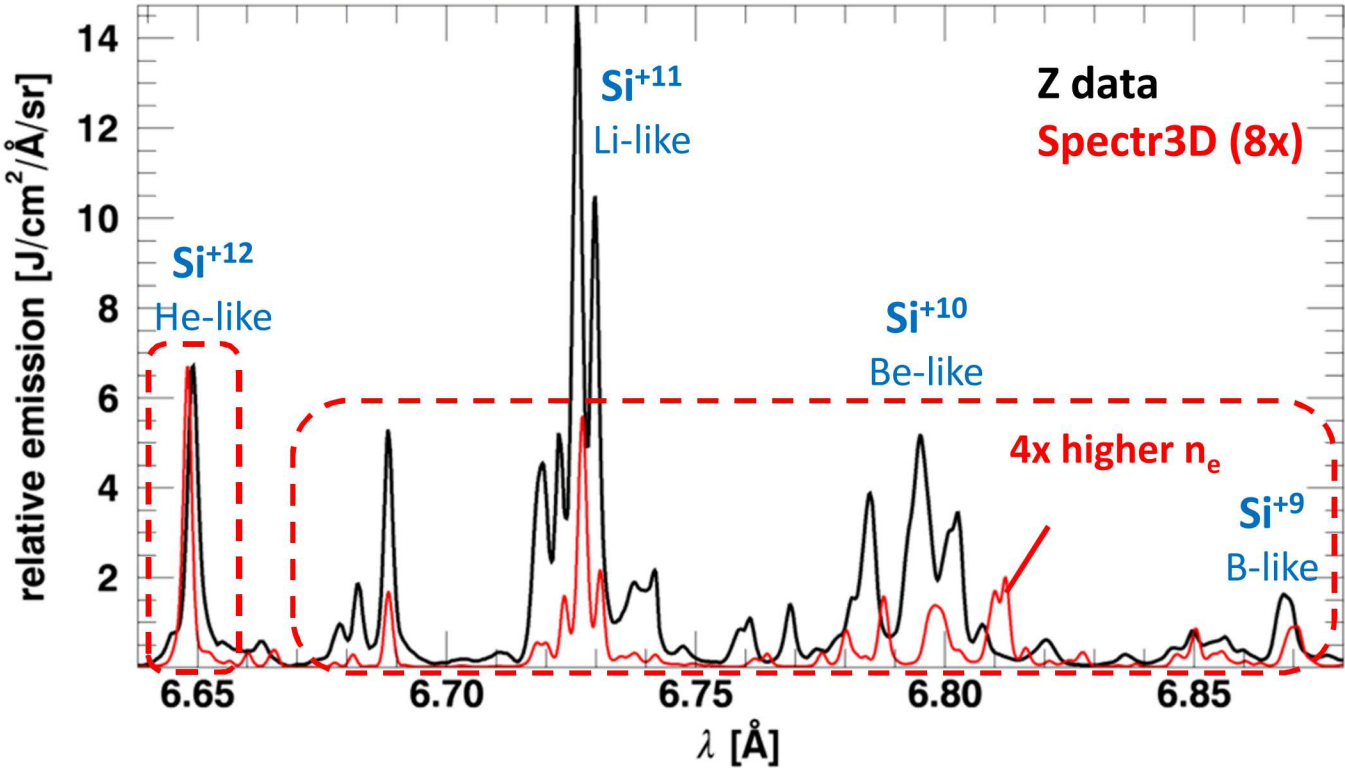


Z data

5.7% rel. unc.
 $\lambda/\delta\lambda \sim 4400$

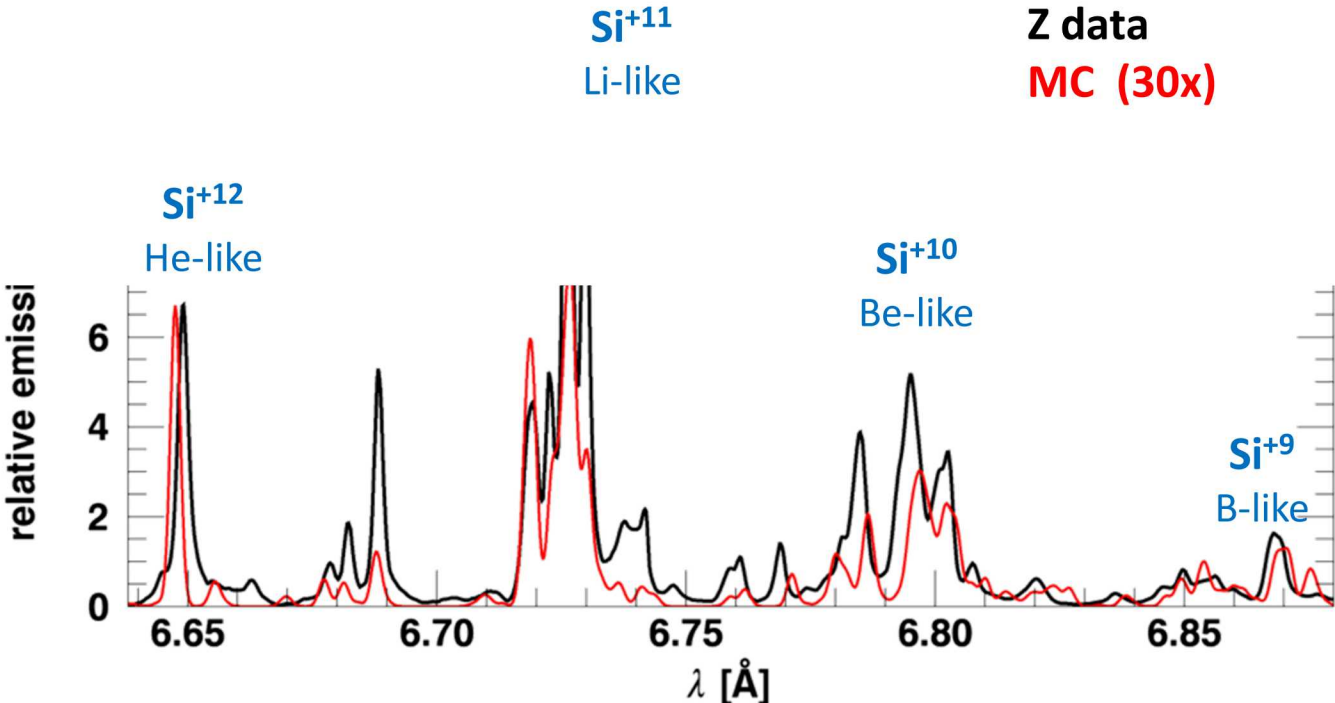
RAD is not 100% efficient at destroying from Si^{+11} to Si^{+9}

The emission is not reproduced by any model even with conditions adjusted to match absorption spectra



With normalization to Si^{+12} ($\text{He}\alpha$) models under predict lines from lower charge state

Comparison with a Monte Carlo radiation transport code exhibit improved but not



The effect of the different atomic physics data must also be evaluated

How much of the predictive difficulty is unique to our experiments and how does it impact astrophysical models?

Possible needed improvements in understanding the experiment

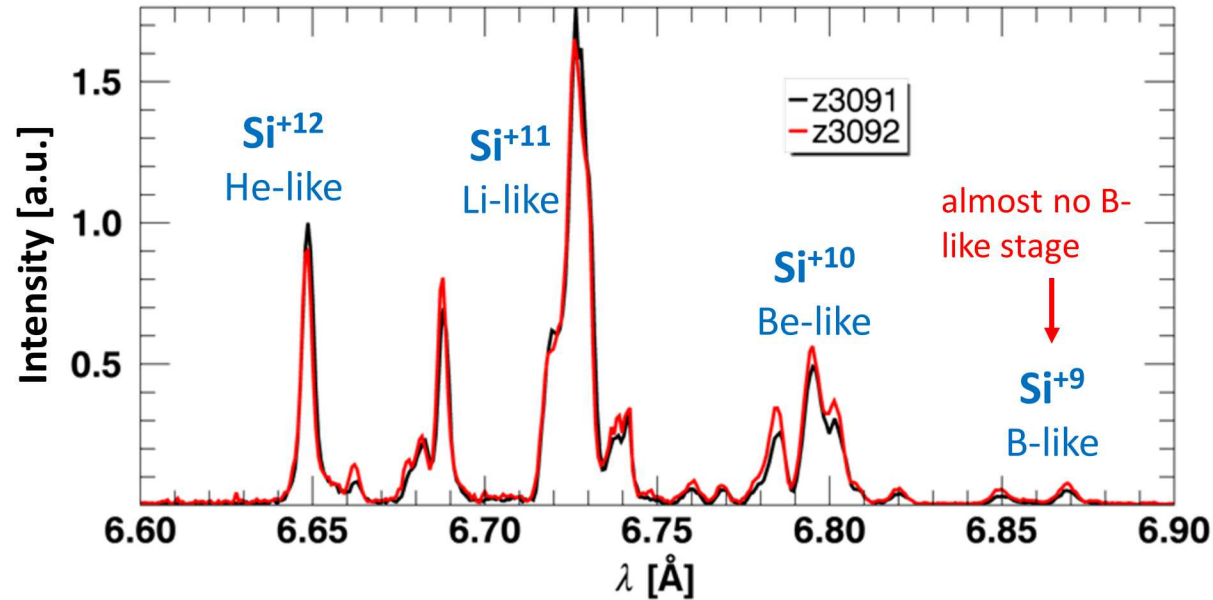
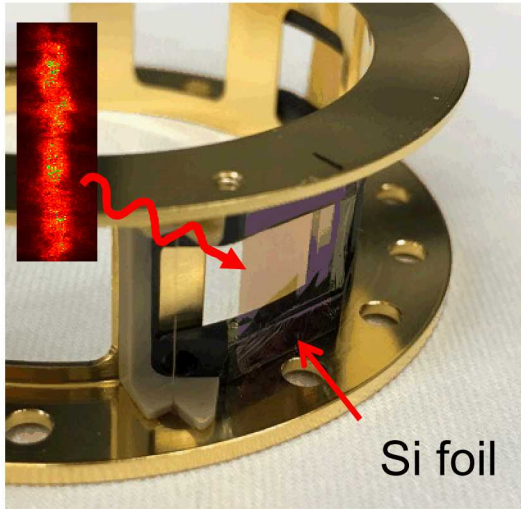
- Could electron density be higher than the value measured with radiography?
- Transient kinetics appear relatively unimportant, but further evaluation is needed
- The bulk of x-ray drive in 0.1 -1keV is measured to $\pm 20\%$, but accuracy in $>1.7\text{keV}$ photon spectrum needs more evaluation.
- Accounting for geometrical dilution of drive requires attention
- Velocity impact on line optical depths appears small, but further investigation needed

Scrutiny is required for the models

- Accuracy of the recombination rates? dielectronic recombination rates?
- Is the atomic data complete?
- Are approximations in the radiation transport valid?
e.g. escape factors, escape geometry, self-consistency...

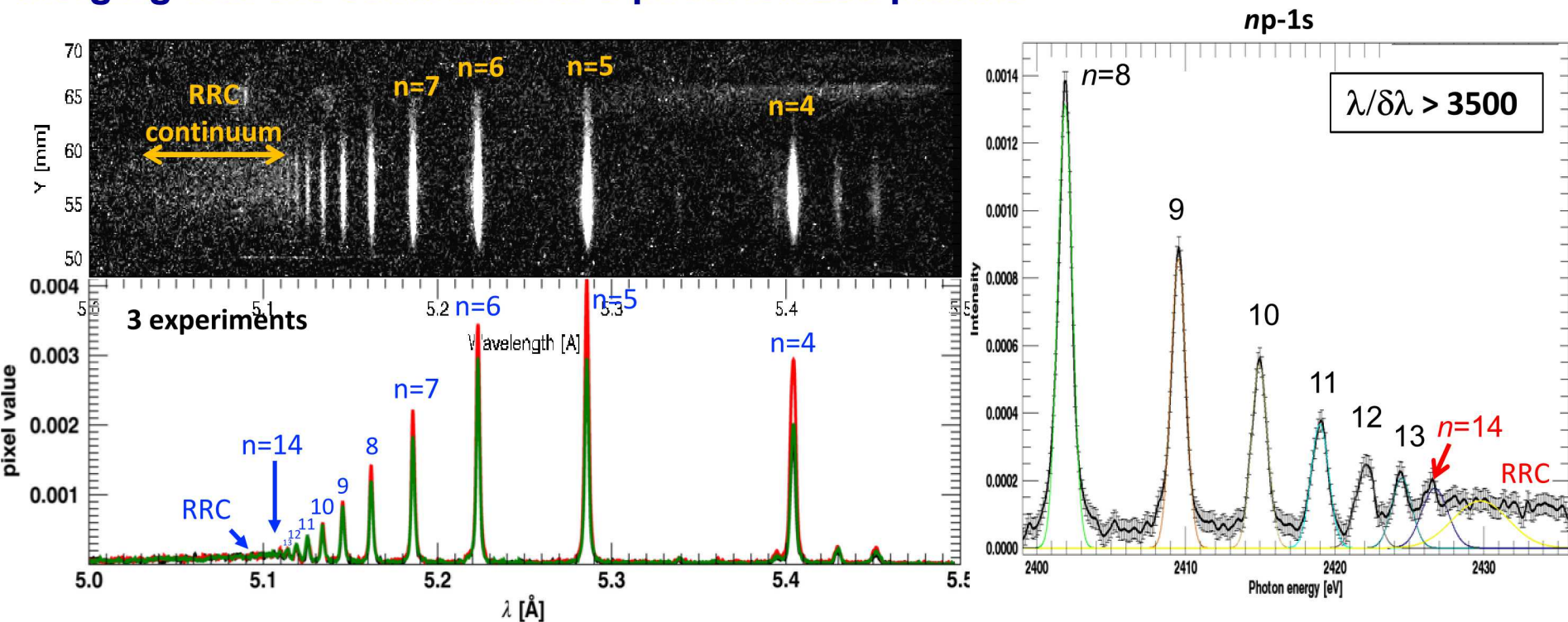
Announcement 1: We successfully fielded a Si sample closer to the source, providing higher photoionization regime ($\sim 10\times \xi$)

return current canister



→ Higher ionization was obtained, testing ionization at different ξ .

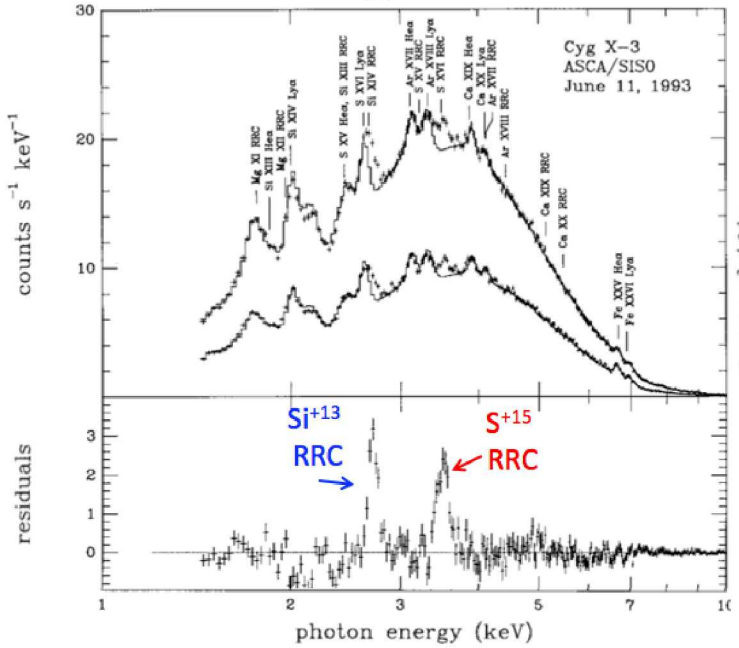
Announcement 2: First observation of high-n, up to n=14, He-like transitions with merging into the continuum in a photoionized plasma



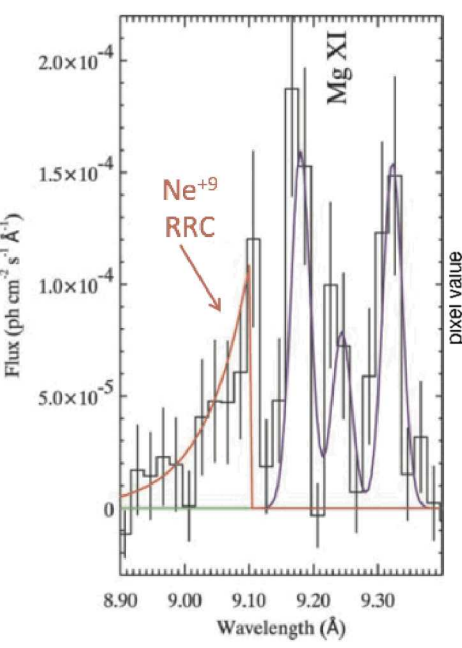
- We can test the relative importance of photoexcitation vs photoionization
- Effect of line shape, line broadening, continuum lowering can be studied. High-n lines getting broader with n (preliminary).

Announcement 3: First observation of RRC ($\sim 10^{-8}$ Z-pinch energy) in a photoionized plasma

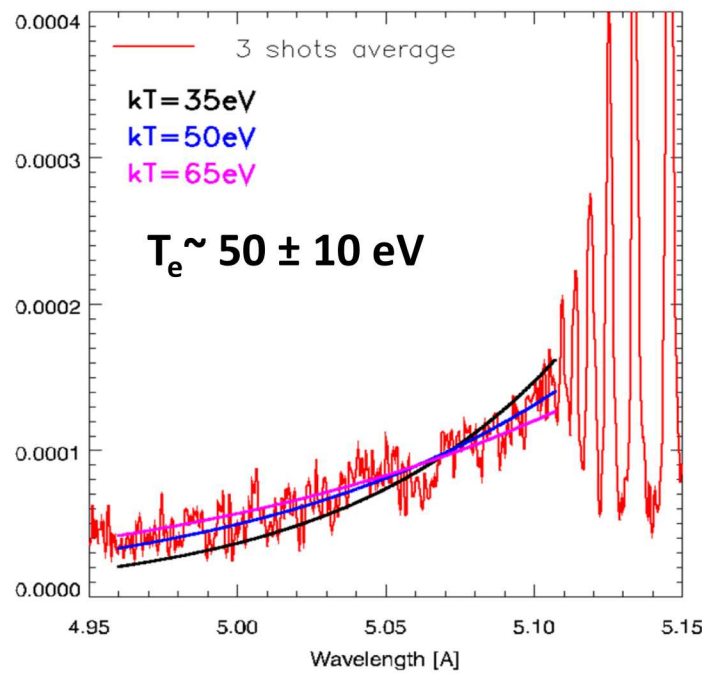
Cygnus X-3



Vela X-1



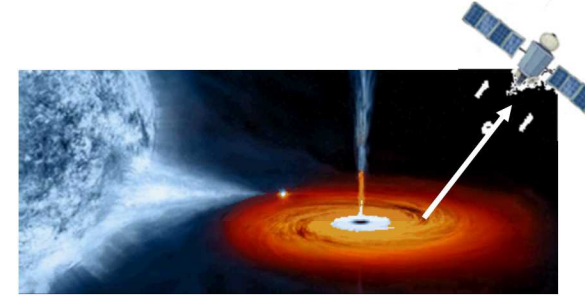
Earth: Z data



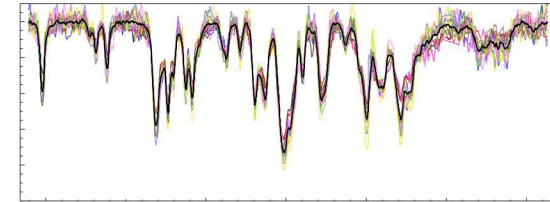
→ The RRC is considered the most reliable temperature diagnostic, untested in the laboratory in the photoionization regime.

→ We can test RRC accuracy at inferring temperature and the PLTE assumption in absorption.

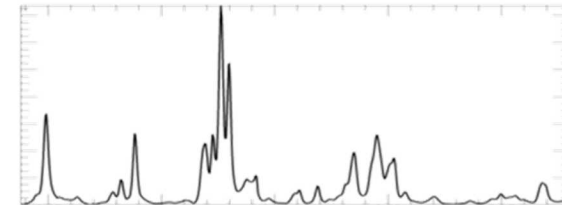
Executive summary: Z data can benchmark models of emission from photoionized accretion-powered plasmas



absorption spectrum



emission spectrum



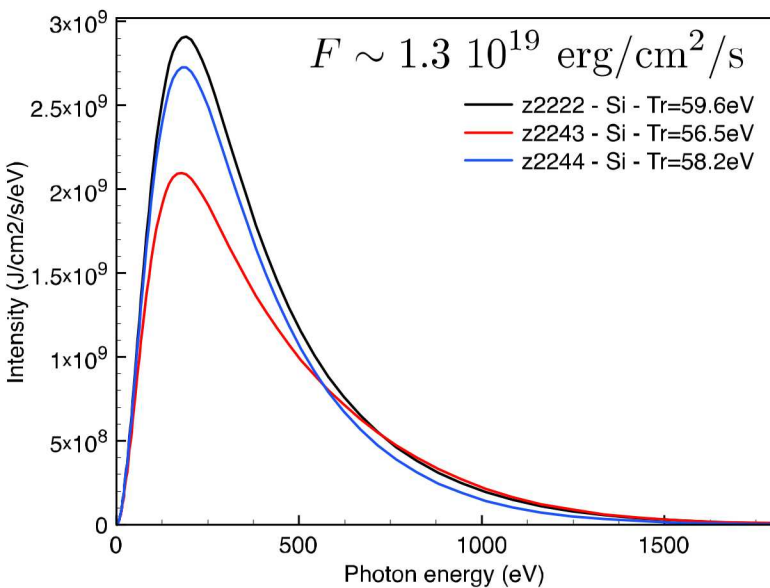
- Understanding X-ray Binaries and AGN accretion disks requires complex models that interpret observed spectra
→ These models are largely untested in the laboratory
- A photoionized silicon plasma with a measured drive radiation spectrum, density and temperature was created on Z
→ the column density is adjustable, testing radiation transport
- Models are unable to match the photoionized plasma emission and absorption spectra without invoking unidentified experimental errors, or model errors or both.

These results raise questions about the suitability of models used to interpret astrophysical observations

Back-up slides

A calibrated 3D-view factors model is used to infer spectral irradiance on the sample

Irradiance near x-ray peak

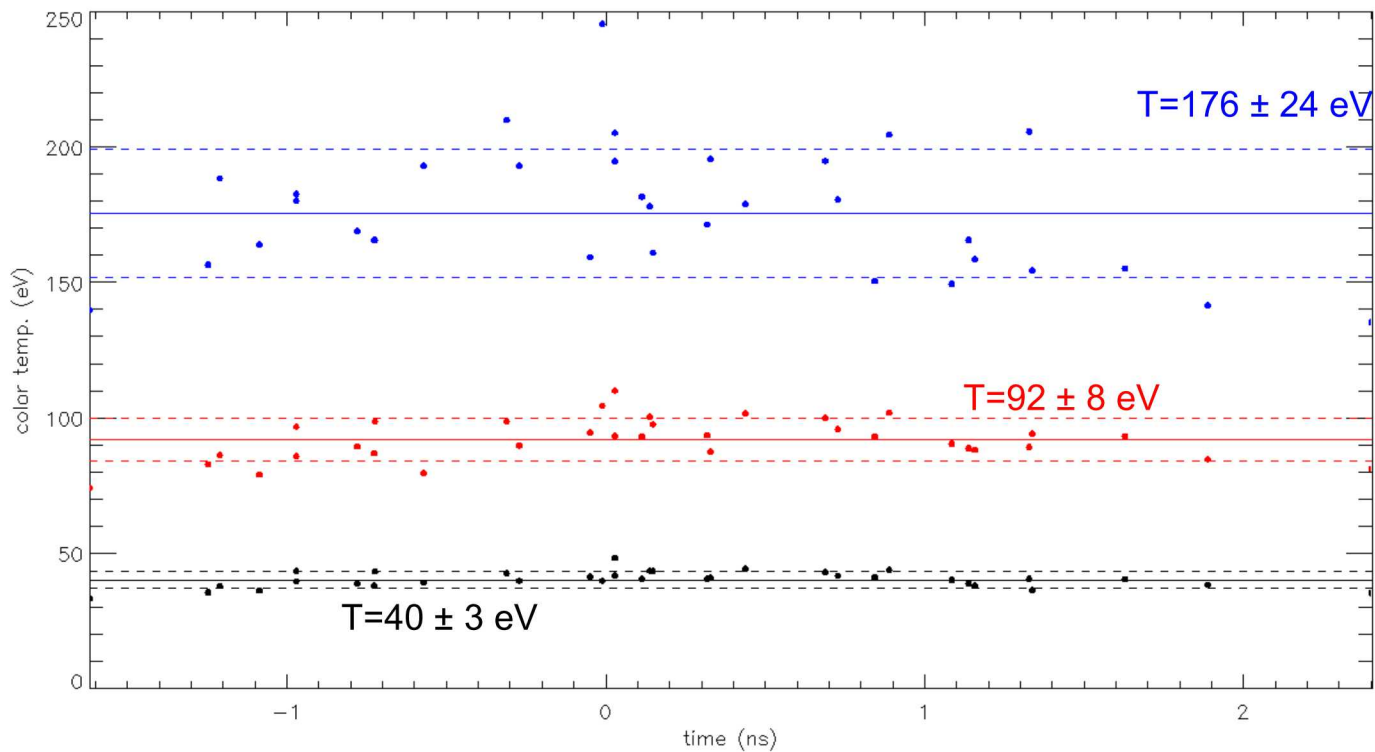


z-pinch

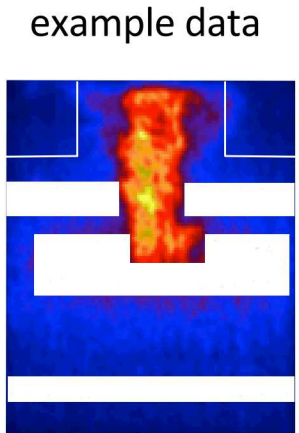
Si foil

3-planckian color temperatures on silicon sample

3-T fits summary - Color temperatures

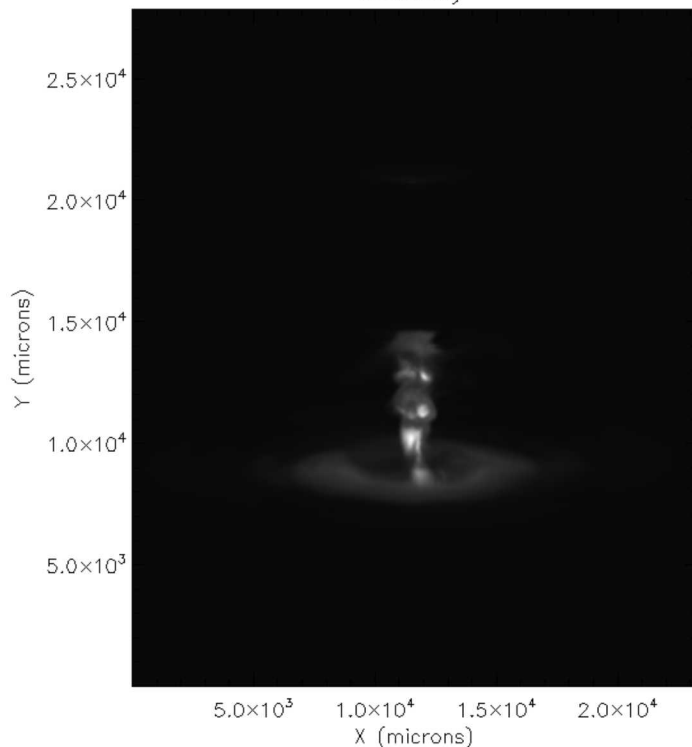


3D simulation of the z-pinch dynamic hohlraum



Linear scale

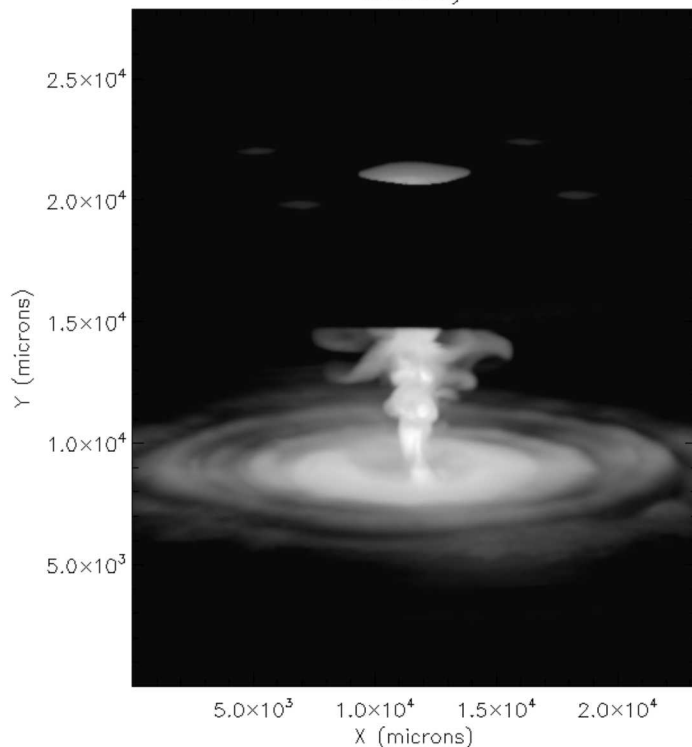
Intensity



Plot: Jun 4 15:29 2014

Log scale

Intensity

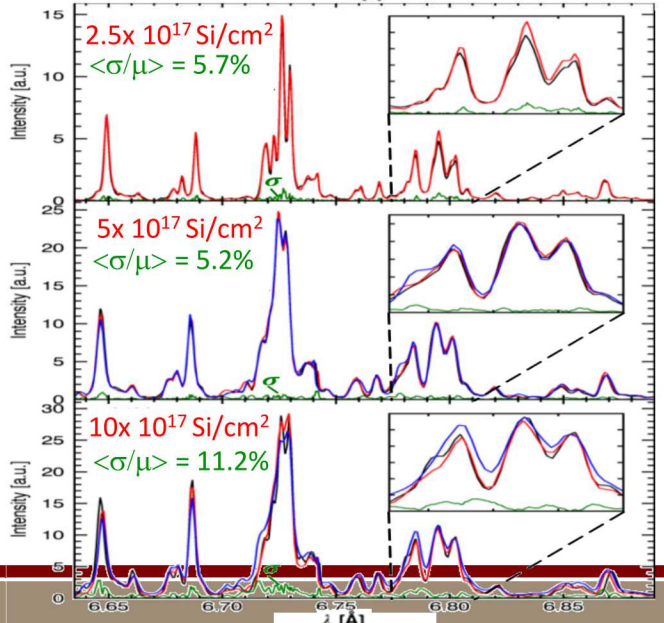
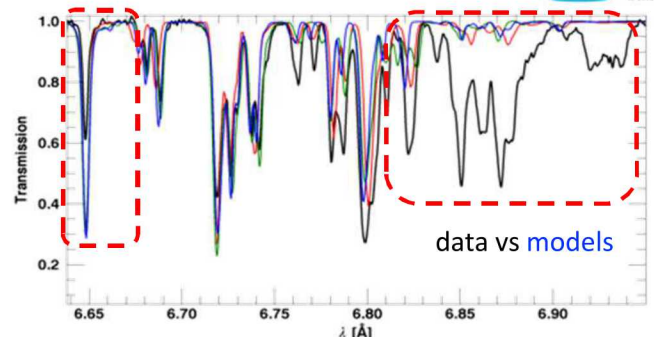


Plot: Jun 4 15:28 2014

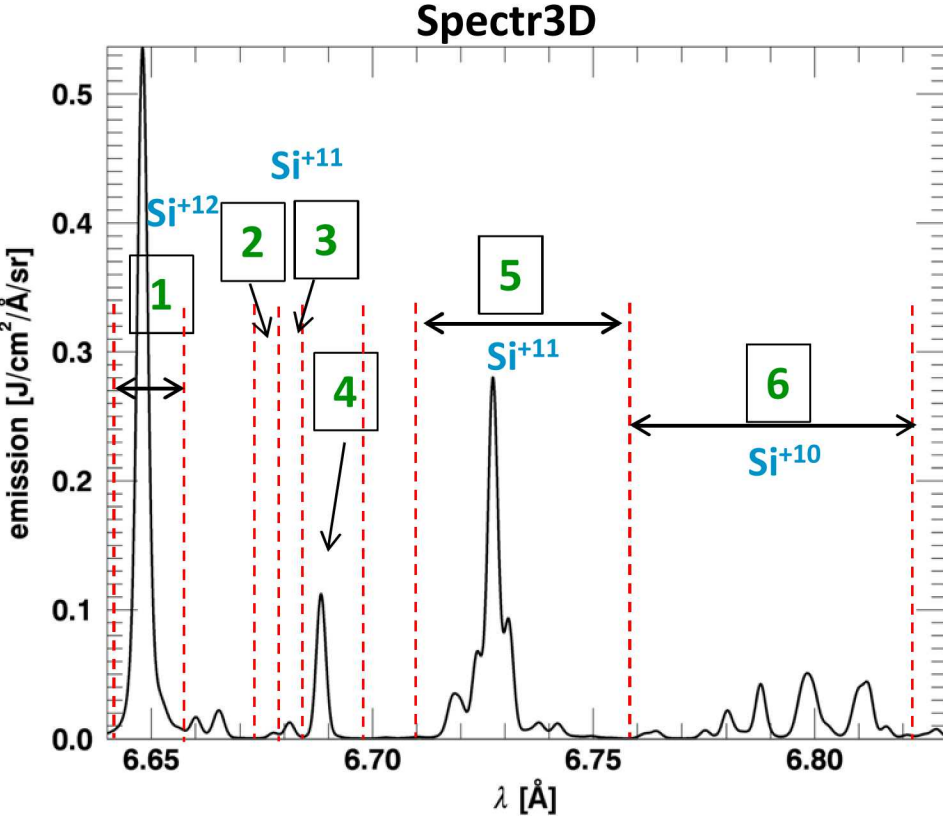
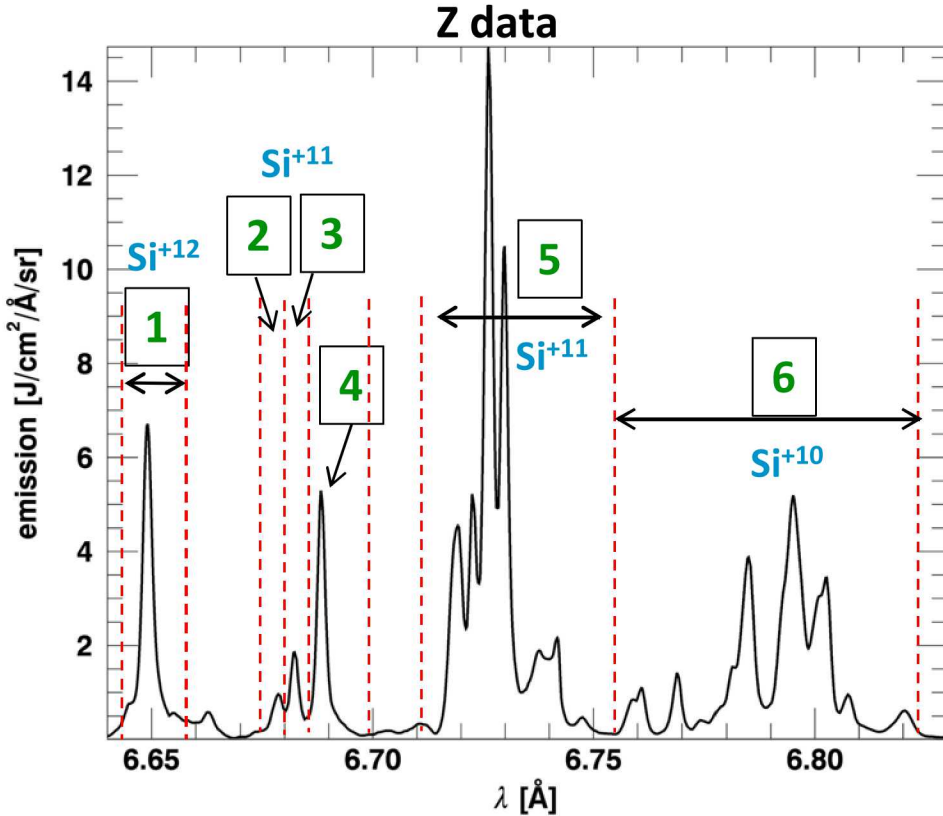
Results and puzzles are documented in Loisel et al., PRL (2017)



- 1. Transmission was measured with 4.7% reproducibility enabling test of ionization predictions
- 2. Models over-predict ionization at measured conditions → Case study at NLTE-10, Dec. 2017
- 3. Emission is measured down to 5.2% reproducibility and at three column densities thus enabling test of radiation transport
- 4. Resonant Auger Destruction is not 100% effective at quenching L-shell ion K emission
- 5. Emission predictions don't match measurements even at conditions that favor transmission agreement.



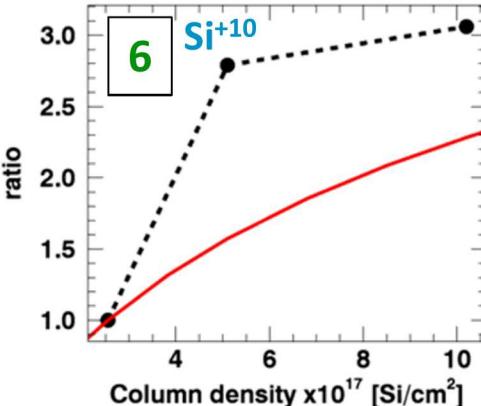
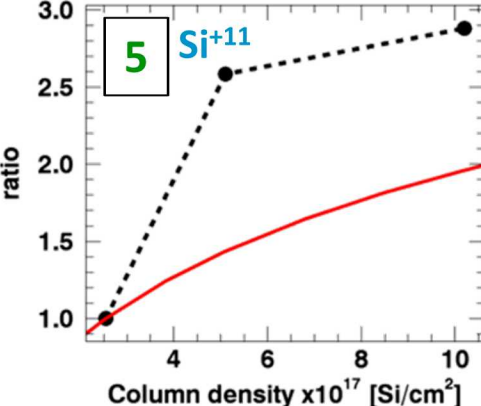
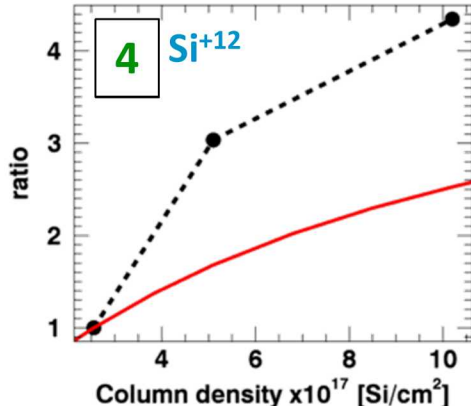
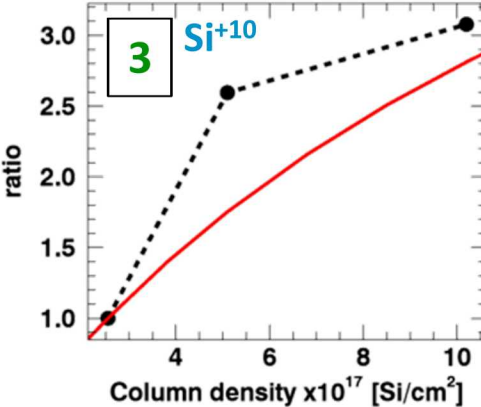
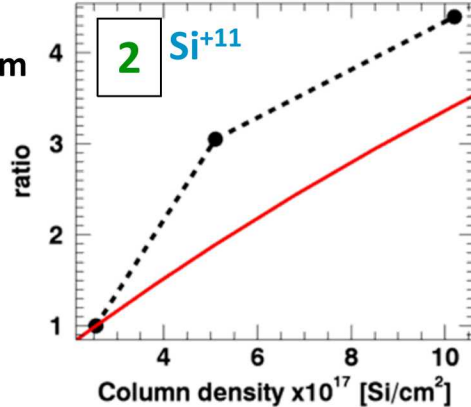
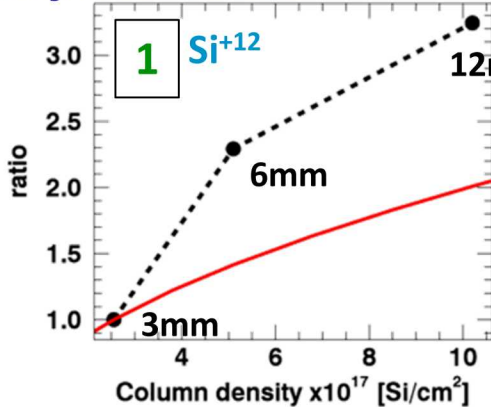
Dividing spectra into segments according to charge states facilitates model radiation transport tests



The line intensity grows faster than code predicts as plasma column density increases



Z data
SPECTR3D



An evaluation of the differences in line optical depths that contribute is in progress