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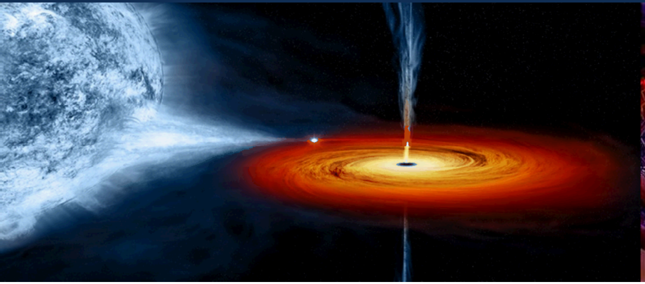

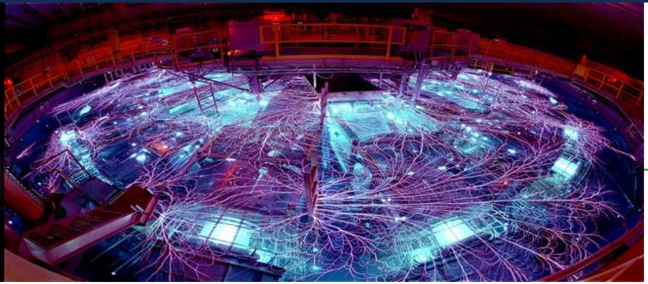

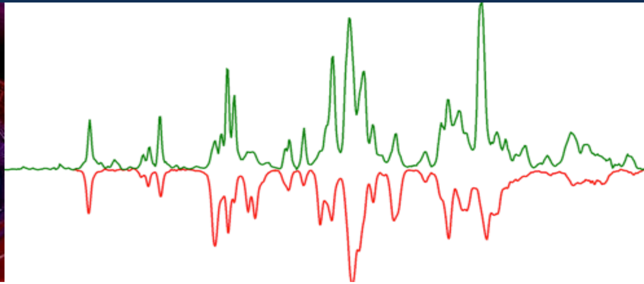

A benchmark experiment for photoionized plasma emission from accretion-powered x-ray sources

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R. Mancini — *University of Nevada, Nevada*

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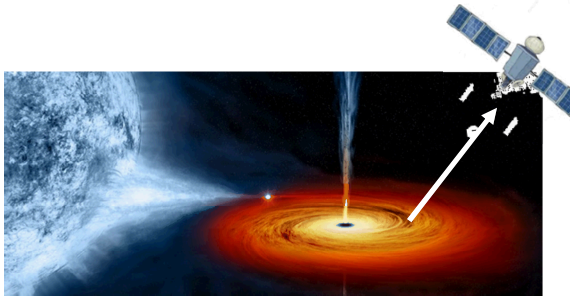
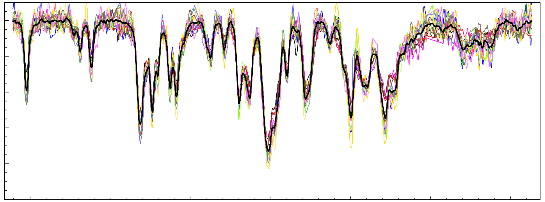
<u>Executive summary:</u> Z data can benchmark models of emission from photoionized accretion-powered plasmas

- Understanding X-ray Binaries and AGN accretion disks requires 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
- A key approximation used in astrophysical models of radiation transport appears to be inaccurate
- Models are unable to match the photoionized plasma emission and absorption spectra without invoking unidentified experimental errors, or model errors or both.

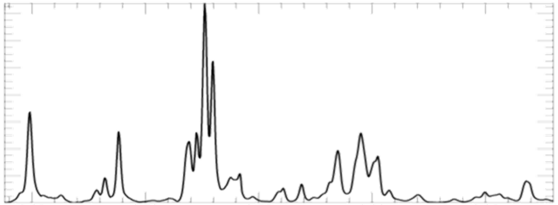
These results raise questions about the suitability of models used to interpret astrophysical observations



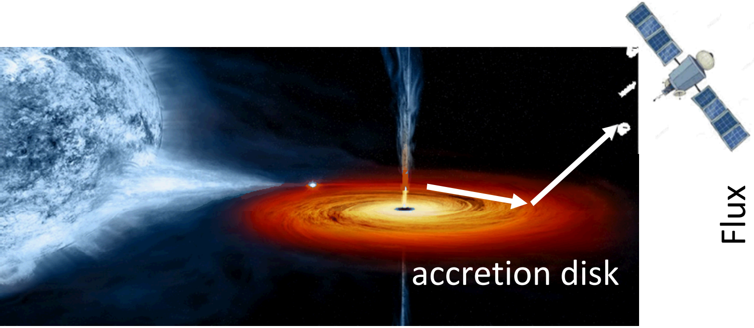
absorption spectrum



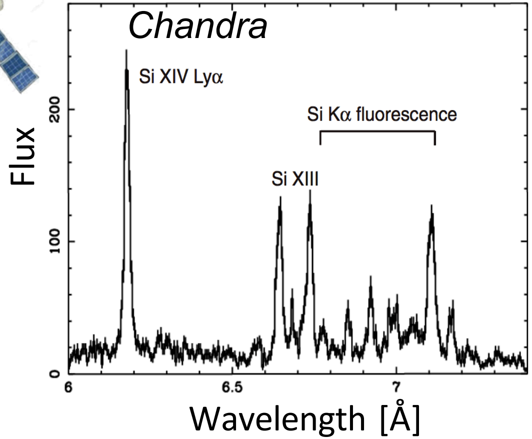
emission spectrum



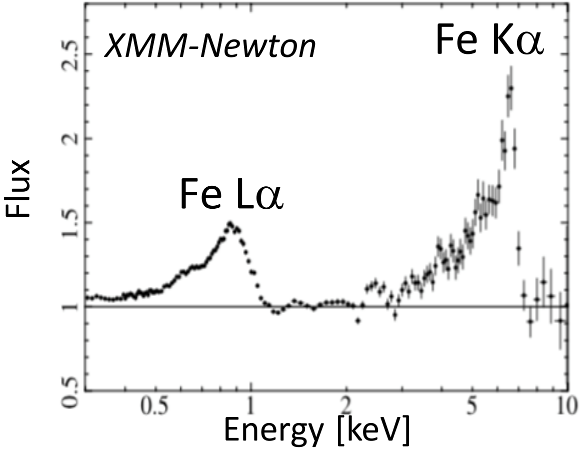
Active Galactic Nuclei and X-ray Binaries are revealed through the emission from their accretion disk



Neutron star Vela X-1

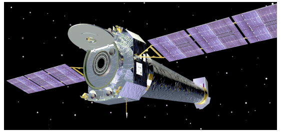


AGN 1H0707-495

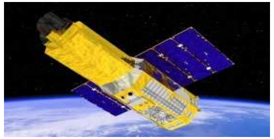


XMM-Newton - ESA

Chandra - NASA



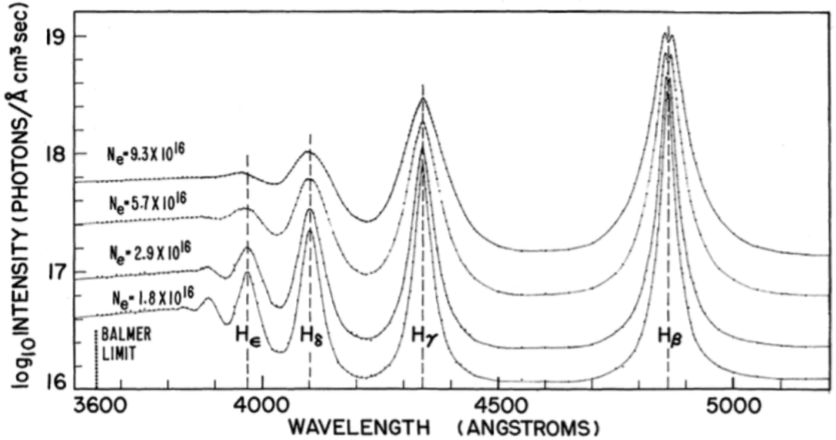
Suzaku – JAXA



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

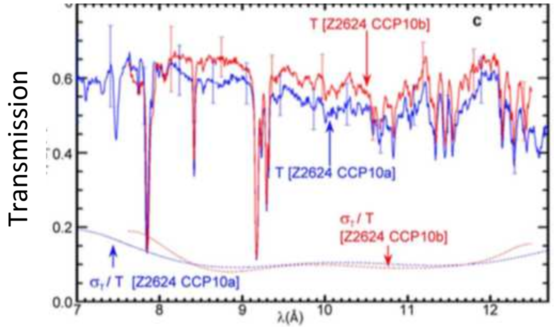
Benchmark experiments do exist for collisional plasmas

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

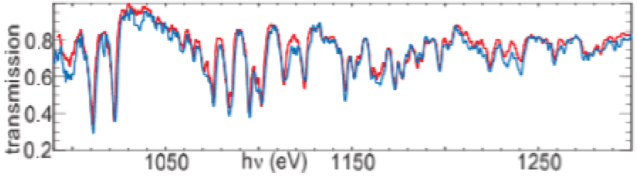


Balmer line shapes measured with 6% error

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



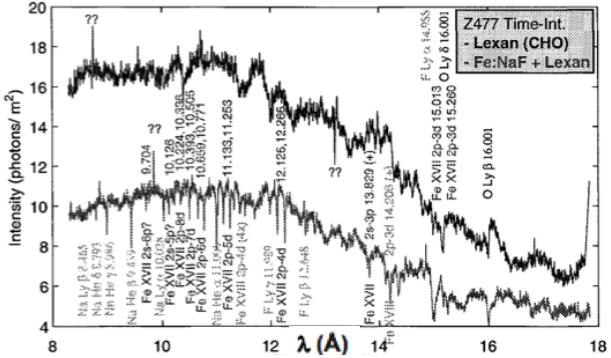
J. Bailey et al., Phys. Rev. Lett., **99** (2007)



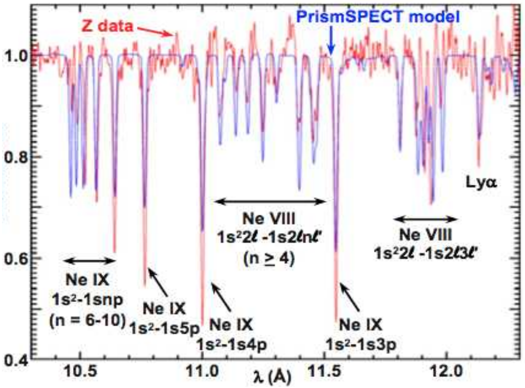
Transmission measured to 10% accuracy

Few photoionized plasmas experiments exist

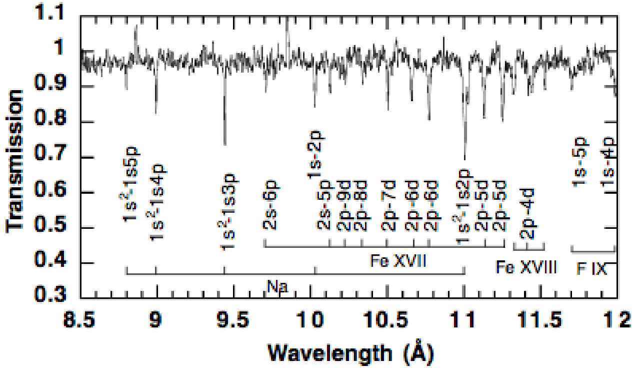
In absorption



R. F. Heeter, J. E. Bailey, M. E. Cuneo, *et al.*, AIP CP, **547**, (2000).

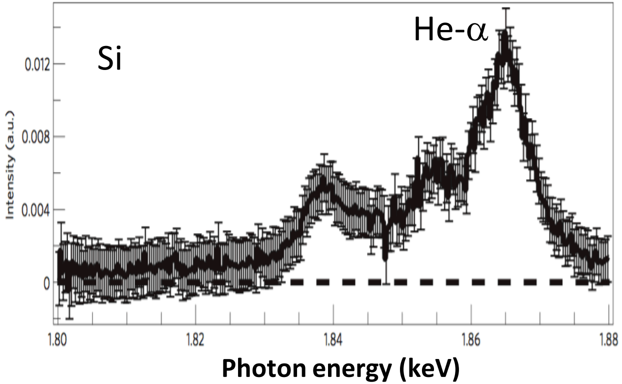


R. C. Mancini, J. E. Bailey *et al.*, *PoP*, **16**, (2009).



M. E. Foord, *et al.*, *PRL*, **93**, (2004).

In emission



S. Fujioka et al. Nature Phys. **5**, (2009)

→ **Absorption measurements revealed first photoionized plasma spectra and allowed test of ionization models.**
→ **Emission spectra was first observed in a laser experiment, although short timescale and important radiation dilution.**

There are numerous requirements for a benchmark emission experiment

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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, ξ > 1erg.cm/s)

Specifically for *emission*:

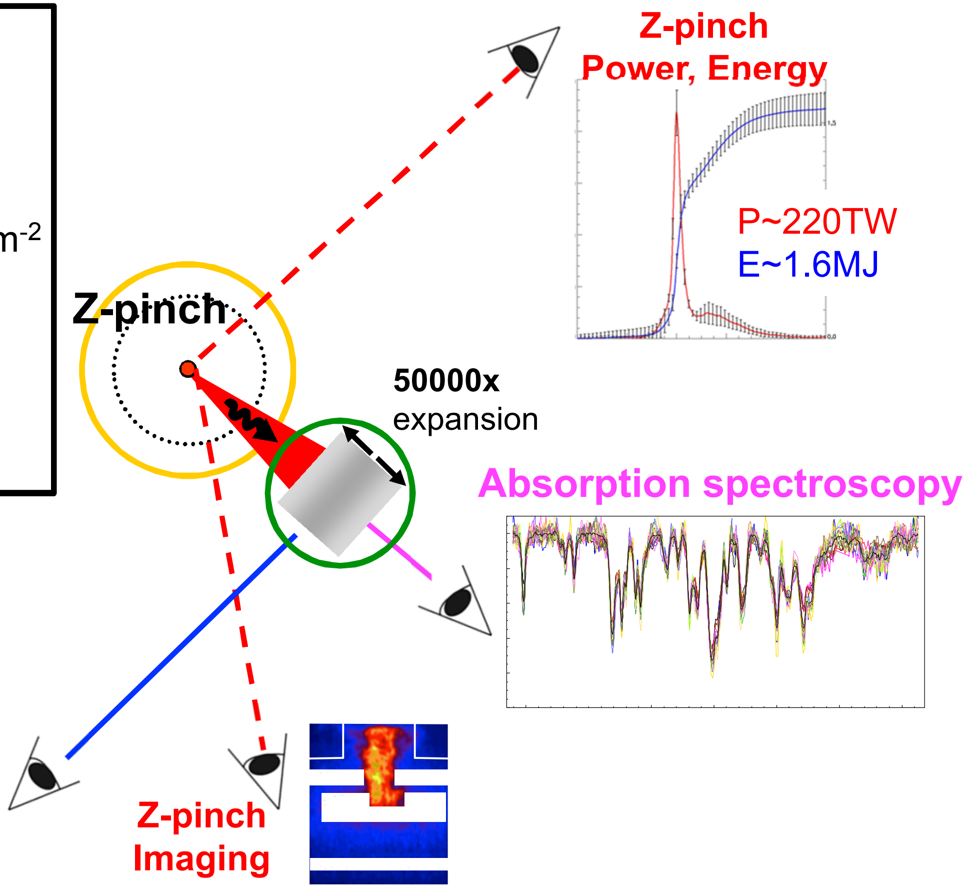
- Large column density for high S/N

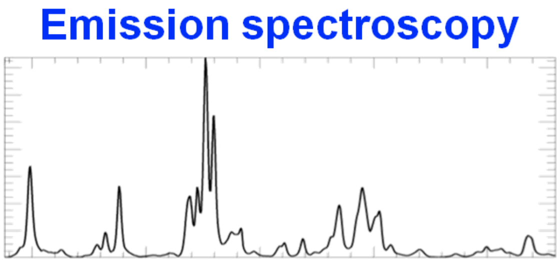
But column = density x length , density < 10^{19} e^-/cc → large ~1cm plasma size

Experiments on the Z Facility can meet all these criteria.

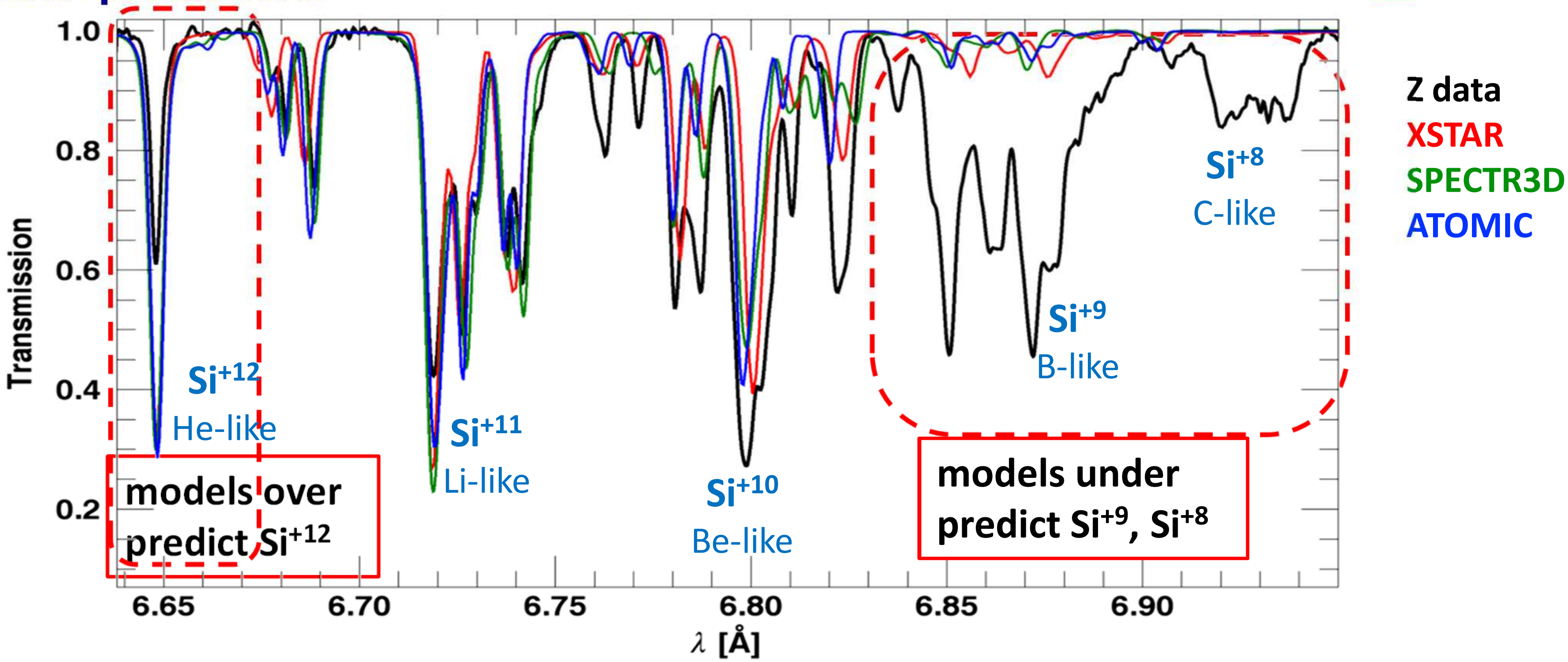
All required measurements are obtained on a single Z shot

X-ray drive, flux and shape	$F \sim 1.3\ 10^{19}$ erg/cm^2/s T_{color}= [45, 80, 170] eV
Ion density	n_i = 8 x 10^{17} cm^{-3}
Column density (adjustable)	N_i = [2.5, 5, 10] x 10^{17} cm^{-2}
Average charge	$\overline{Z} \sim 10$, Si^{+10}
Electron temperature	T_e = 26 - 40 eV
Photoionization parameter	$\xi \sim$ 20-1000 erg.cm/s



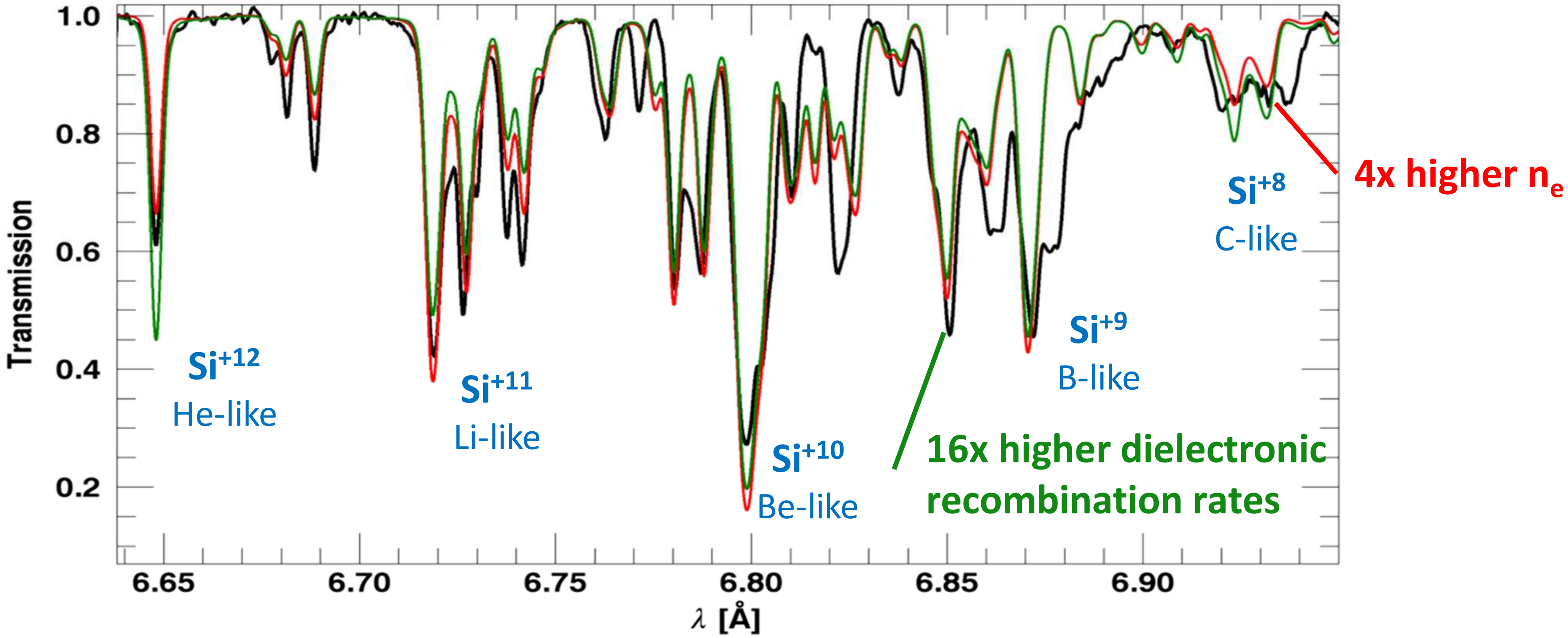


Measured relative absorption from different ion stages tests model ionization predictions



Z transmission data is reproducible to 4.7% with $\lambda/\delta\lambda$ ~2400.

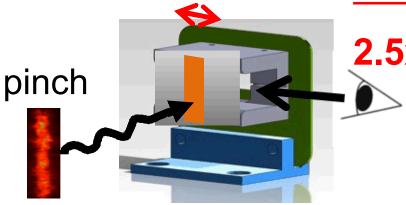
Agreement can be obtained by adjusting parameters that increase recombination



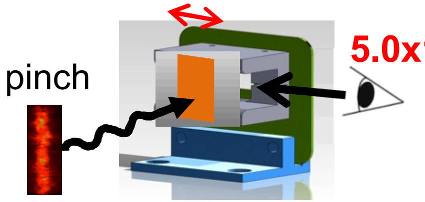
How accurately can models predict ionization?
→ NLTE-10 workshop, Dec. 2017

Measured emission at 3 column densities enables radiation transport tests

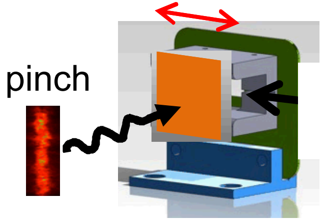
Column density



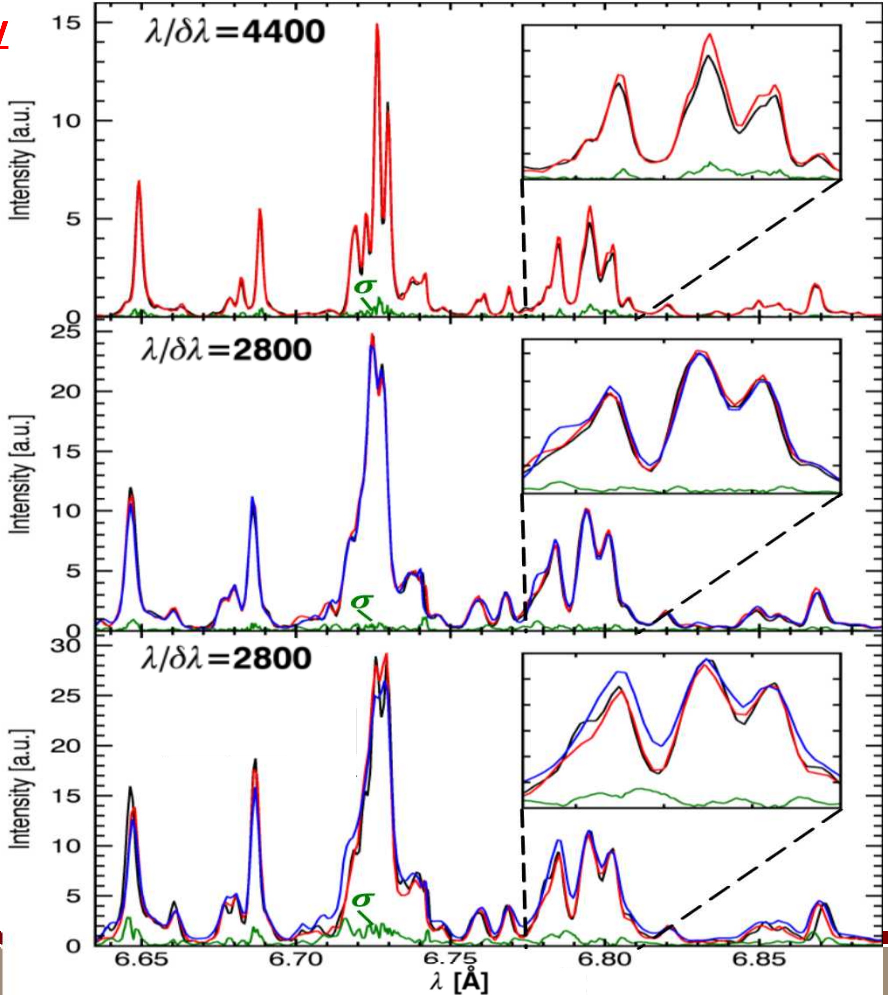
2.5×10^{17} Si/cm^2



5.0×10^{17} Si/cm^2



10×10^{17} Si/cm^2



2 separate Z experiments

std. dev. = 5.7%

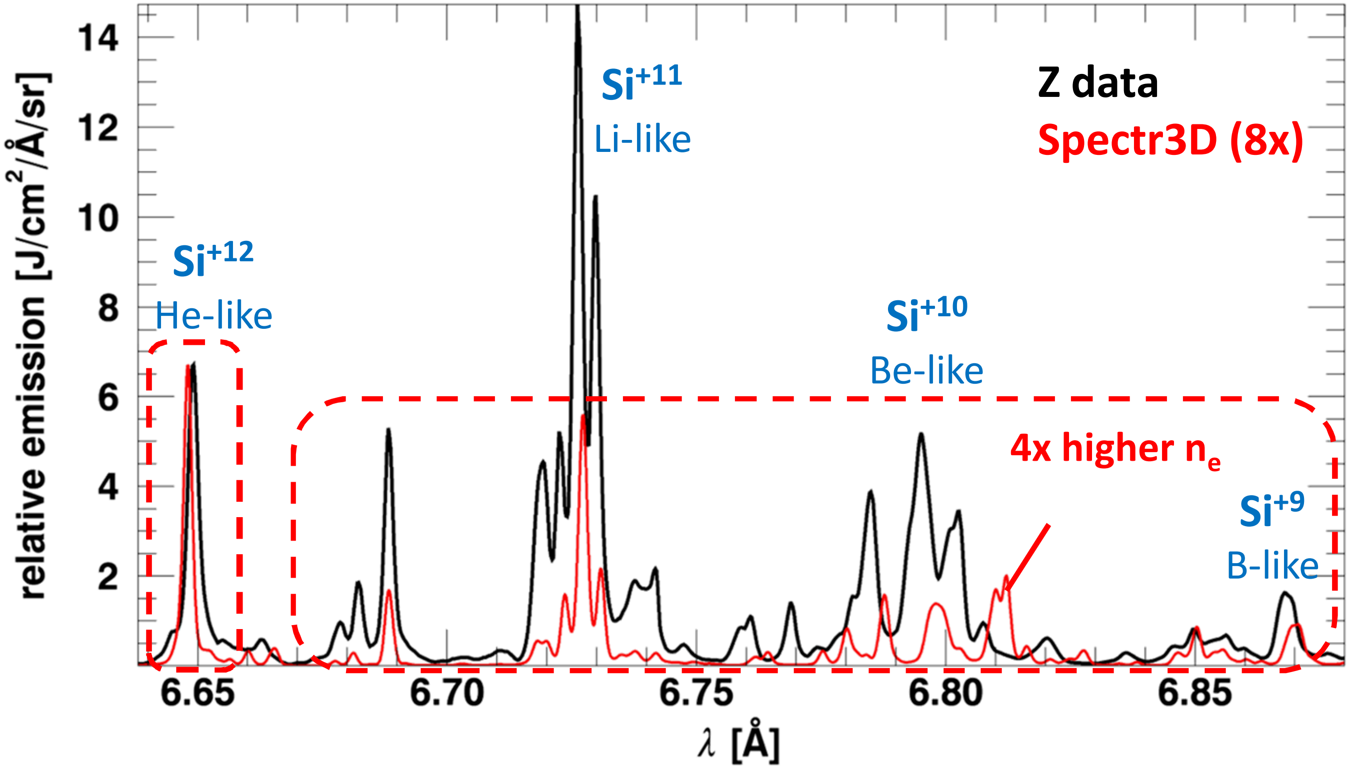
3 separate Z experiments

std. dev. = 5.2%

3 separate Z experiments

std. dev. = 11.2%

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

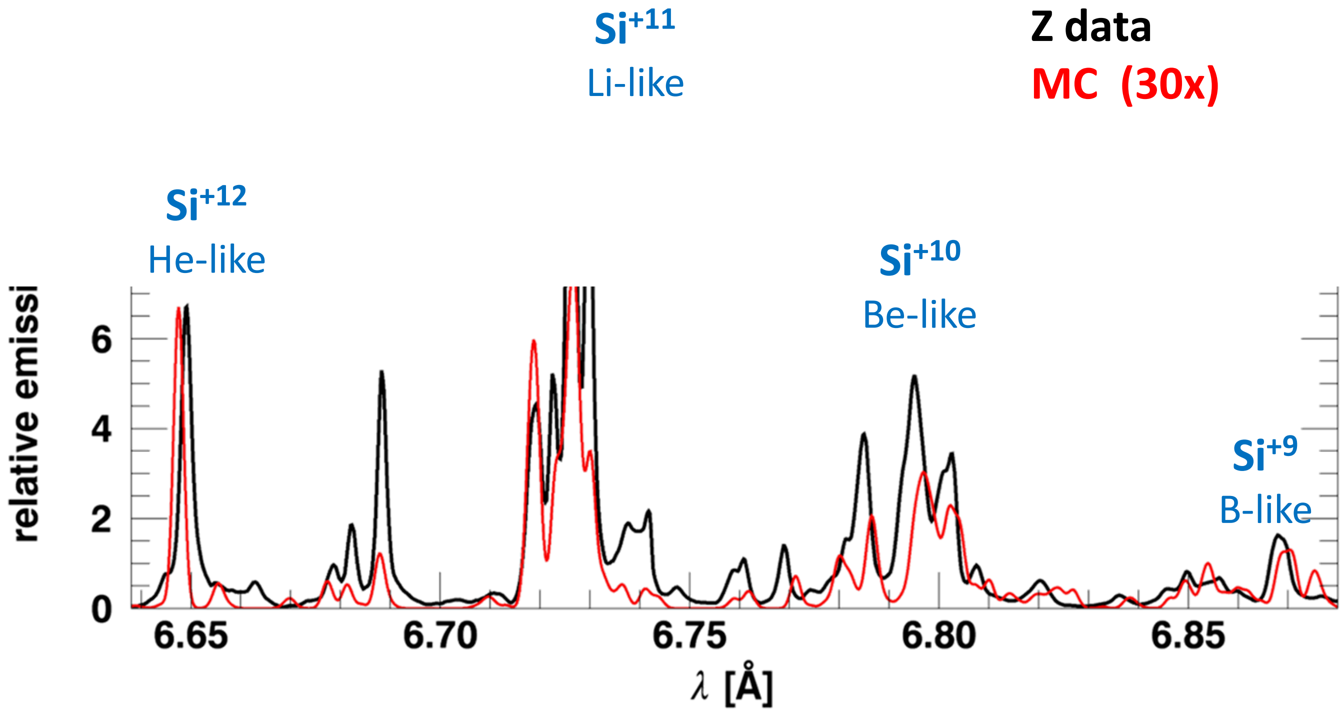


5.7% rel. unc.
$\lambda/\delta\lambda$ ~ 4400

With normalization to Si^{+12} (Heα) models under predict lines from lower charge state.

Comparison with a Monte Carlo radiation transport code exhibit improved but n

5.7% rel. unc.
λ/δλ ~ 4400



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

Open questions

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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

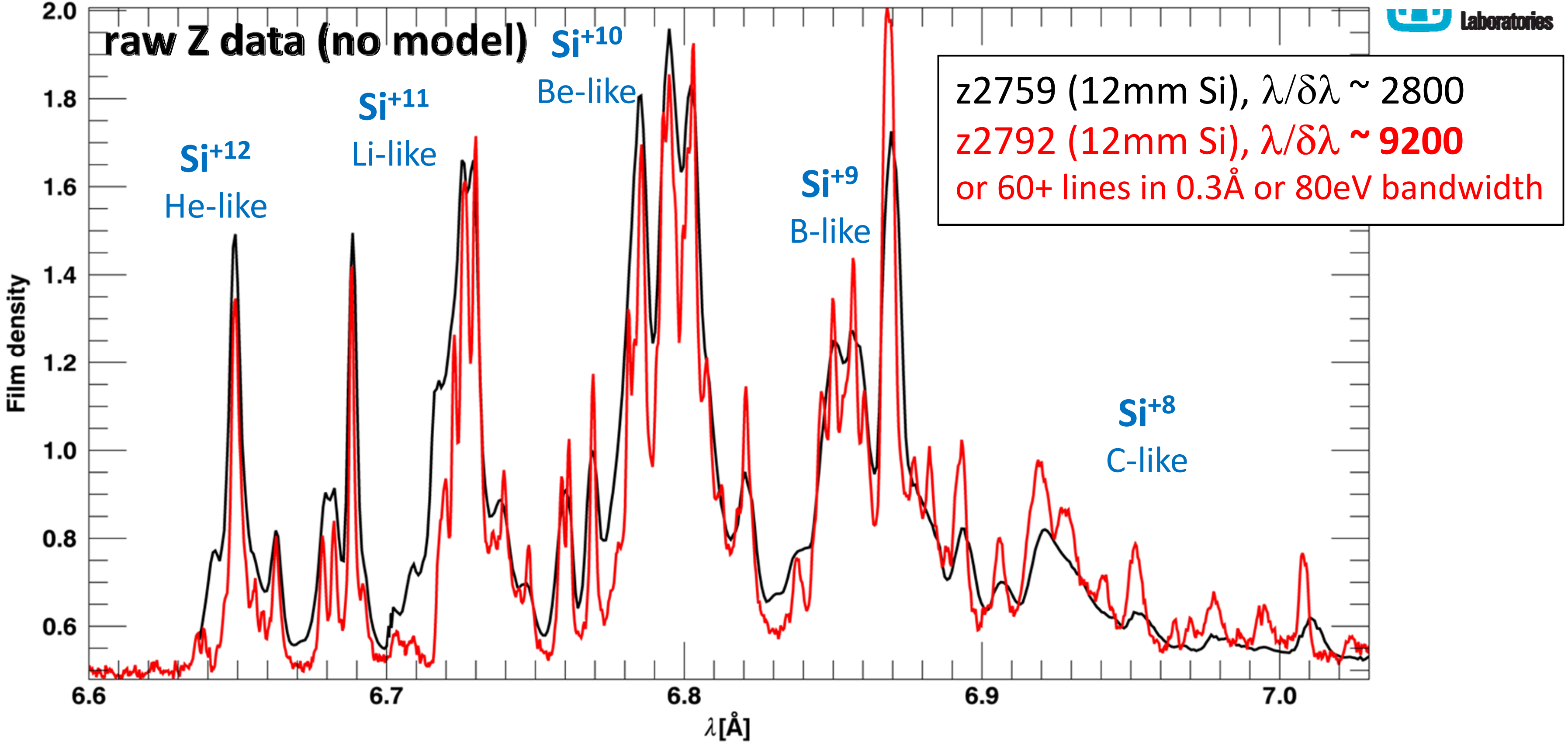
- Could electron density be higher than the value measured with radiography?
- Transient kinetics appear relatively unimportant, but further evaluation is needed
- The bulk of x-ray drive in 0.1 -1keV is measured to ±20%, but accuracy in >1.7keV photon spectrum needs more evaluation.
- Accounting for 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?

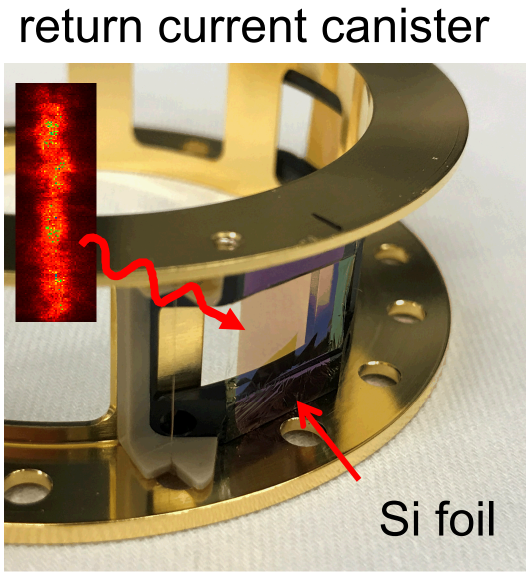
  e.g. escape factors, escape geometry, self-consistency…

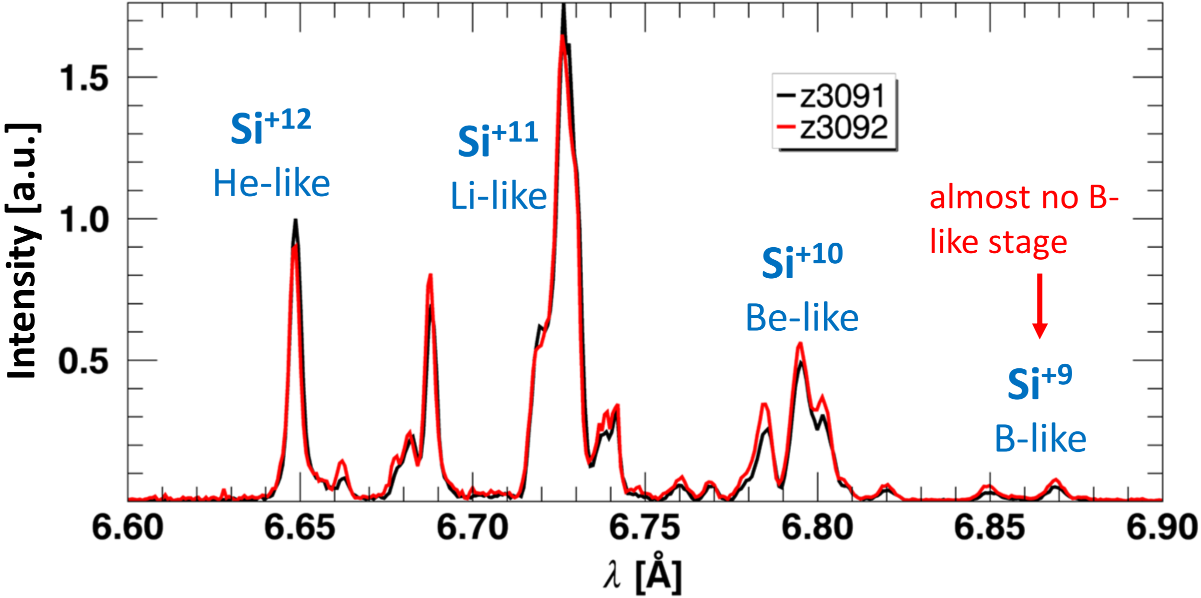
Announcement 1: We measured emission at very high spectral resolution



We can study very detailed level structure and more precise radiation transport effects on lines that have variable optical depth.

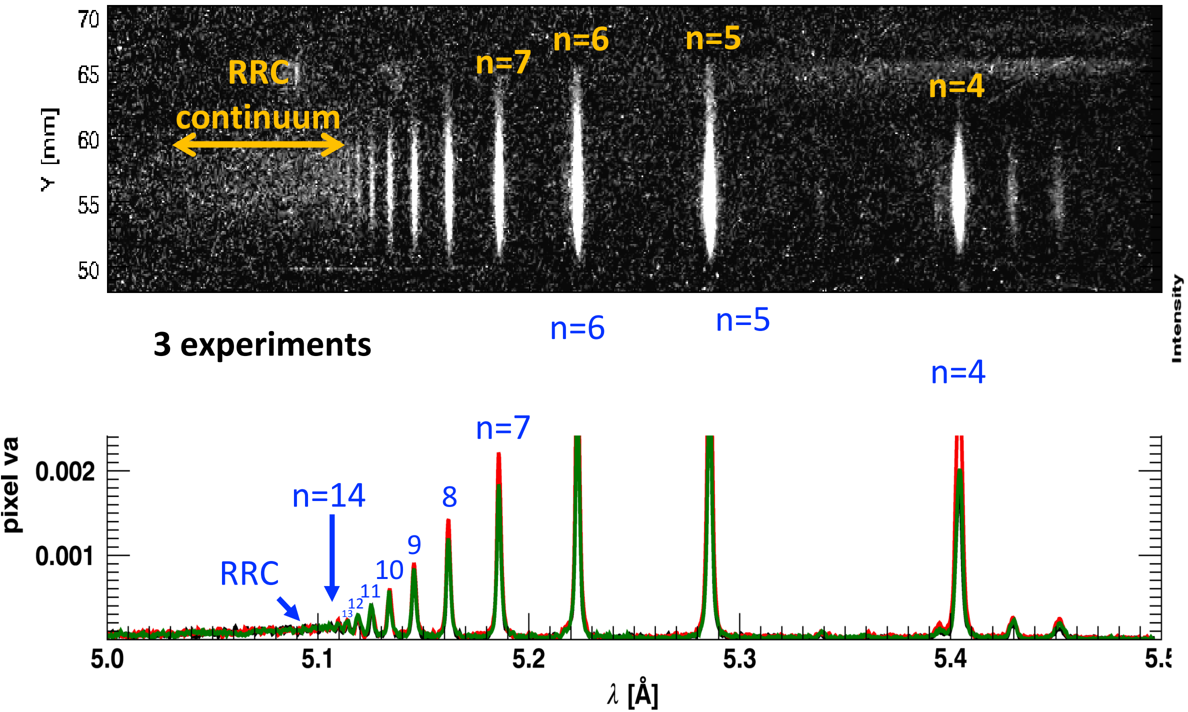
Announcement 2: We successfully fielded a Si sample closer to the source, providing higher photoionization regime (~*10x* ξ)

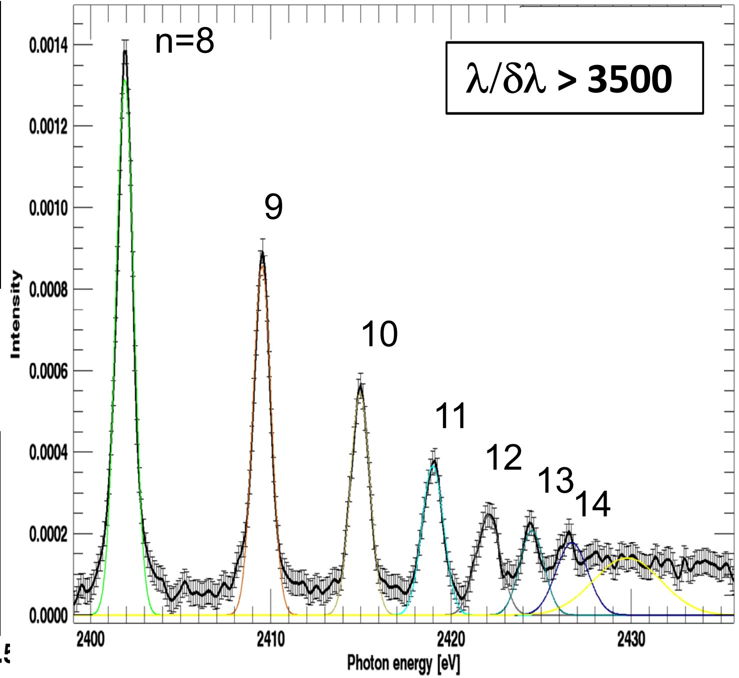




→ **Higher ionization was obtained, testing ionization at different ξ.**
→ **This experiment is a surrogate to study Fe in the laboratory.**

Announcement 3: First observation of high-n, up to n=14, He-like transitions with merging into the continuum in a photoionized plasma



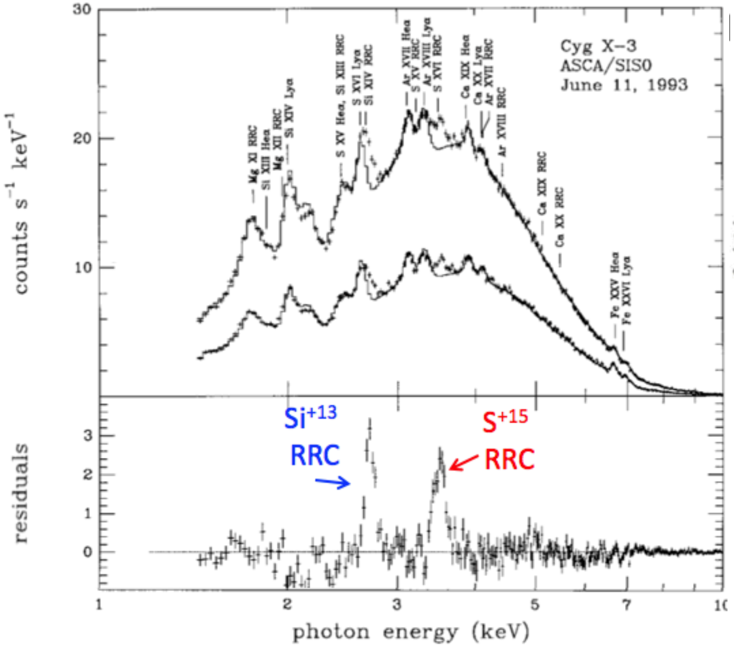


→ **We can test the relative importance of photoexcitation vs photoionization**

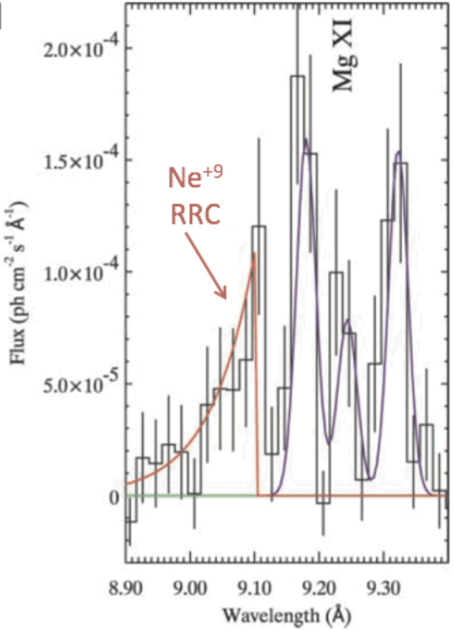
→ **Effect of line shape, line broadening, continuum lowering can be studied. High-n lines getting broader with n (preliminary).**

Announcement 4: First observation of RRC (~10^{-8} Z-pinch energy) in a photoionized plasma

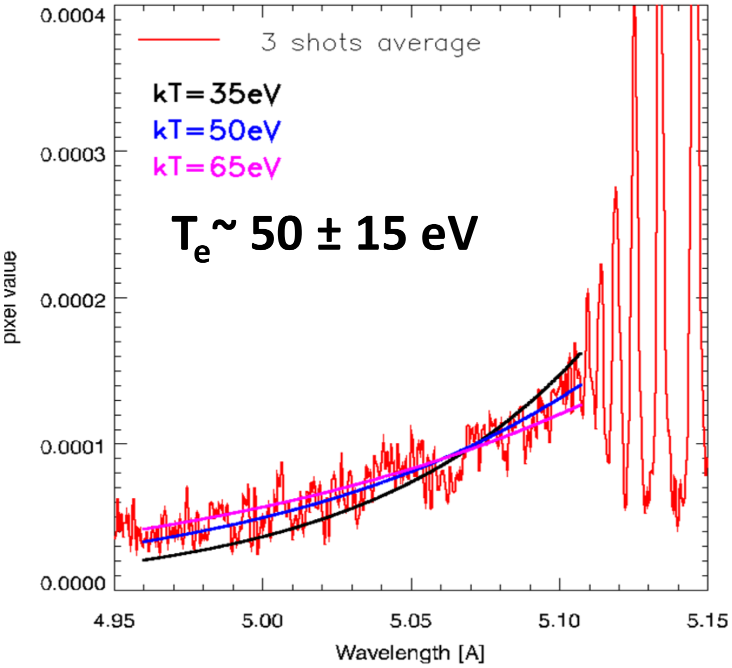
Cygnus X-3



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

- Understanding X-ray Binaries and AGN accretion disks requires 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
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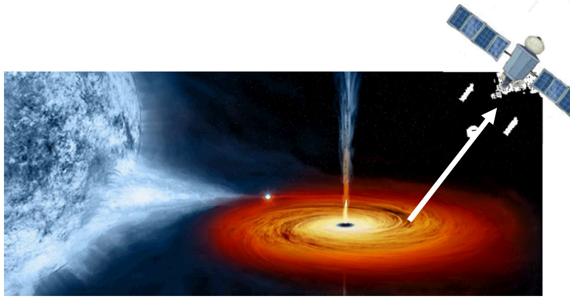
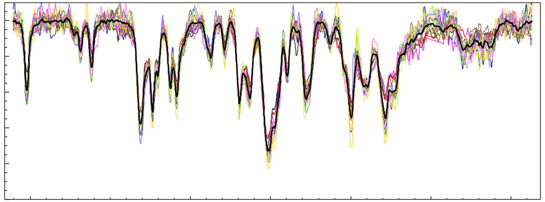
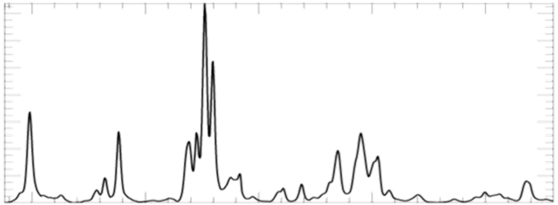


absorption spectrum

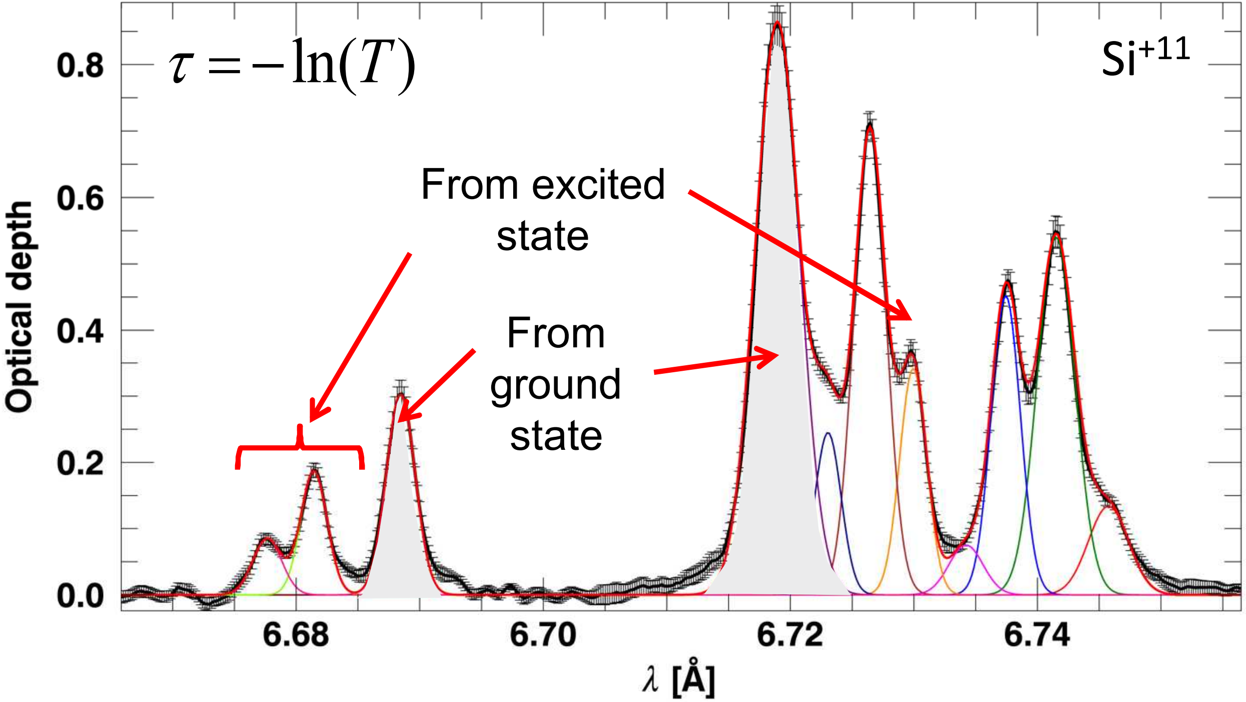


emission spectrum



Backup slides

The measured ionization balance and the electron temperature inferred from the data confirm Si plasma is *photoionized*



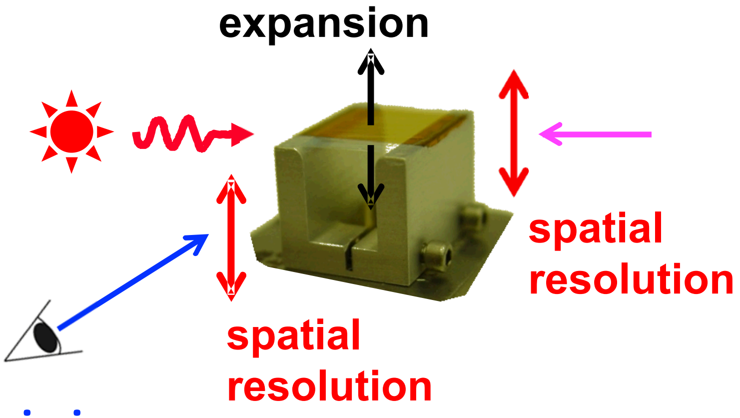
The ratio of lines from ground state and low lying states is a temperature diagnostic

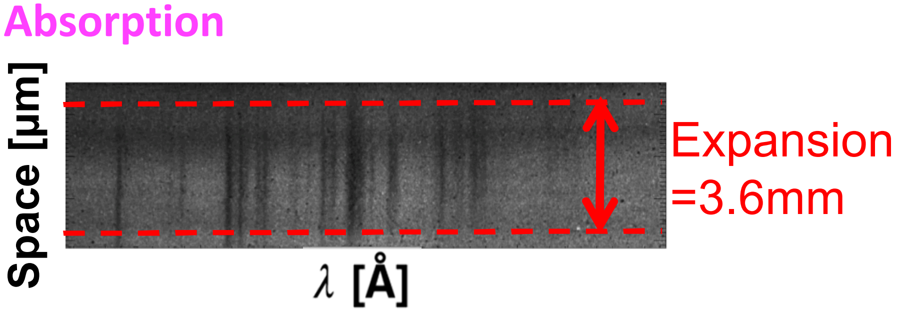
→ $T_e = 33 \pm 7$ eV

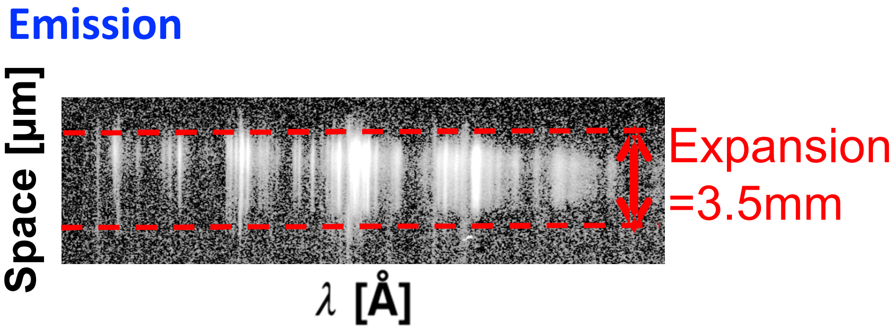
$\bar{Z} = 10.3$ with radiation
$\bar{Z} = 5.3$ without radiation

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

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



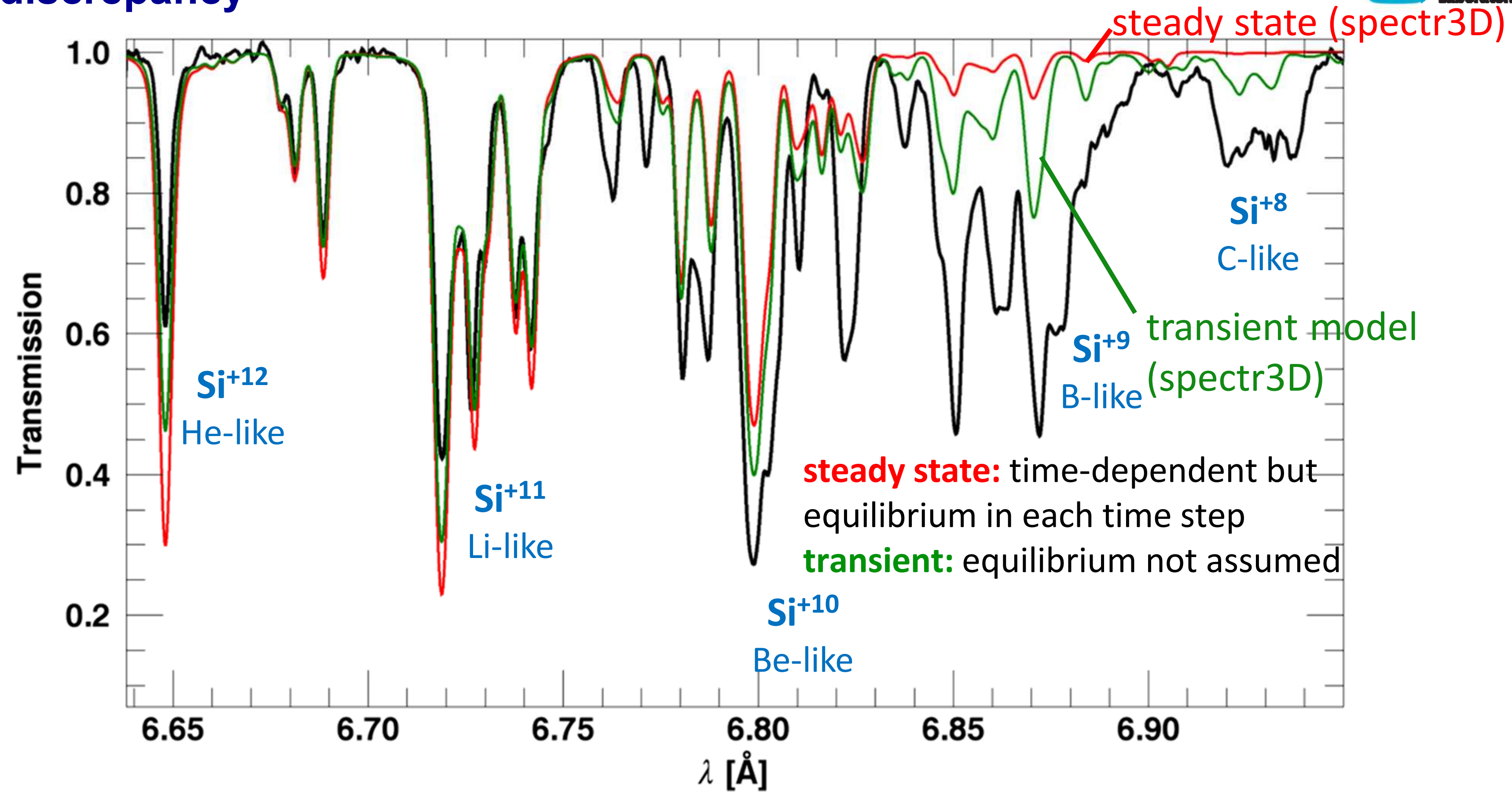




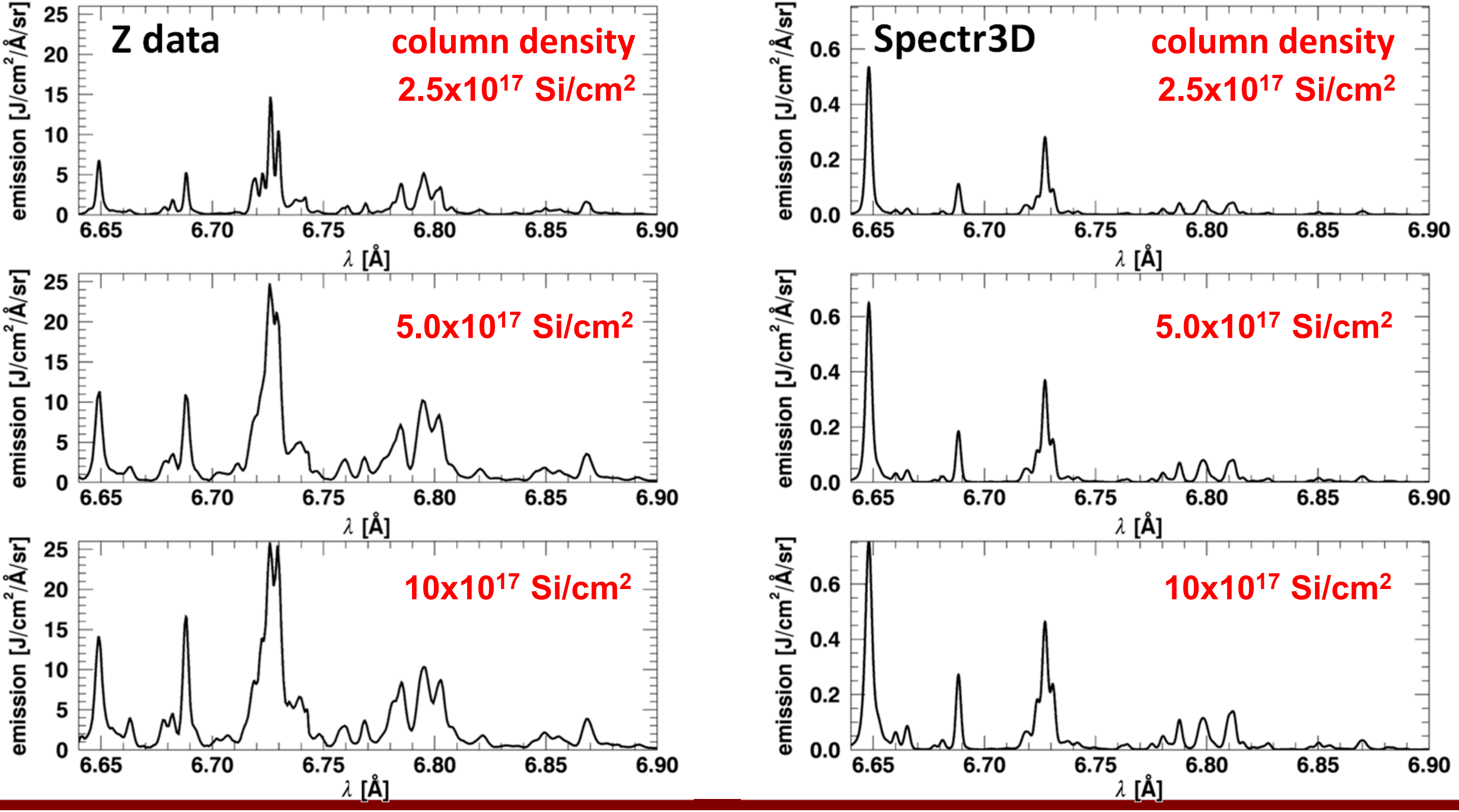
- Rutherford backscattering : 3.1×10^{17} Si/cm^2
- 1-D expansion over 3.5mm

→ $n_i = 8.5\ 10^{17}$ Si/cm^3 **(12% rel. unc.)**
  $n_e = \bar{Z}\, n_i = 8.5\ 10^{18}$ e$^-$/cm^3 **(20% rel. unc.)**

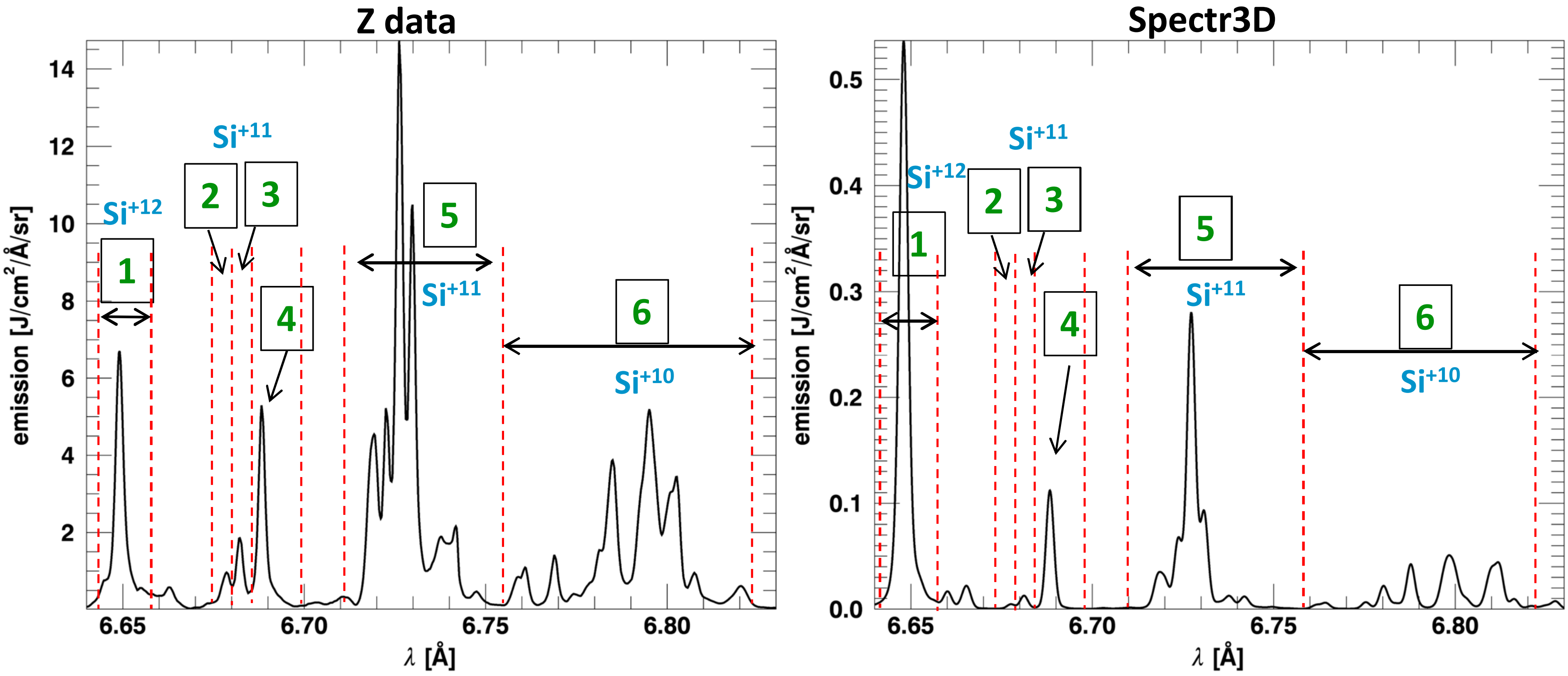
Accounting for transient effects helps but does not resolve the model-data discrepancy



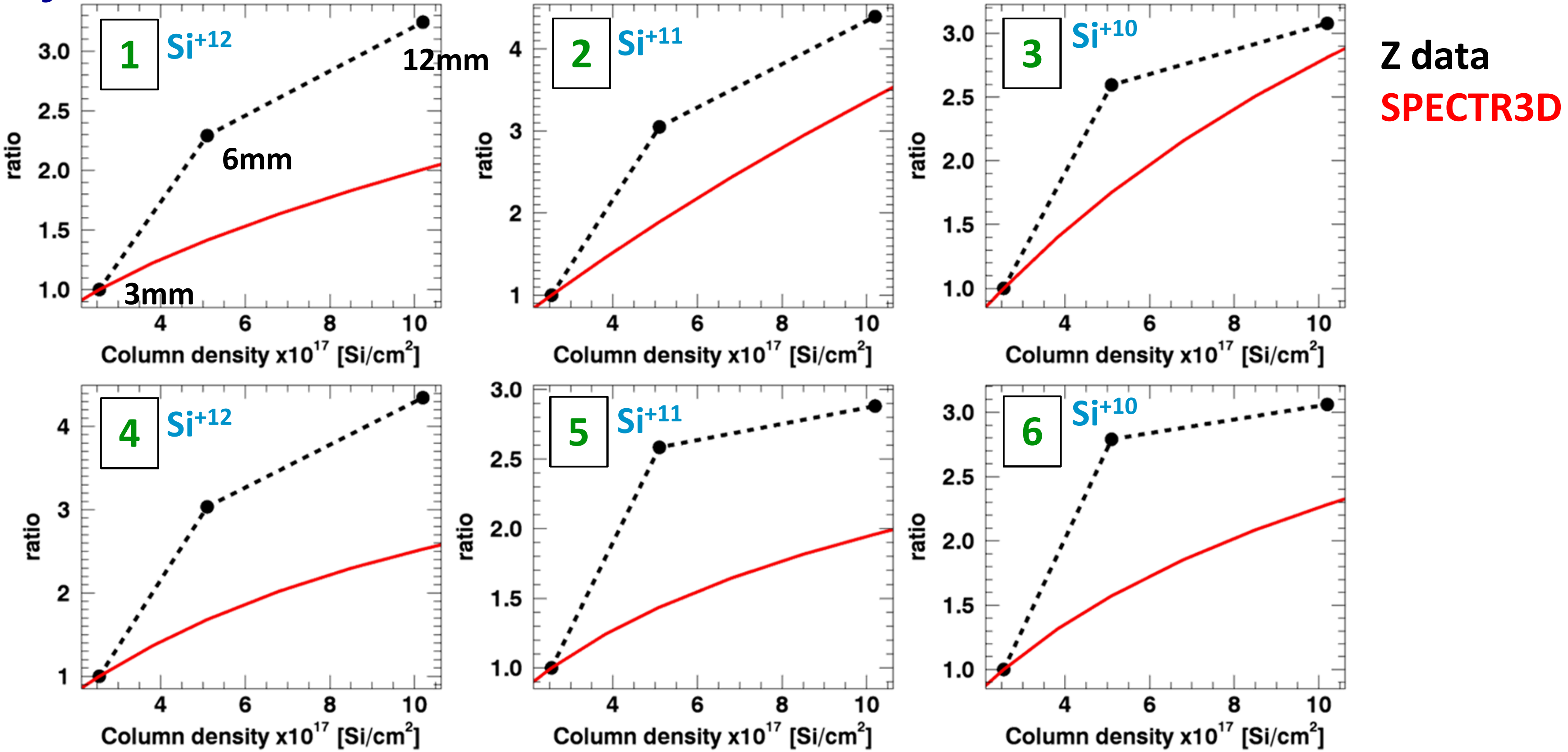
Measured emission variations with plasma column density test model radiation transport predictions



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



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