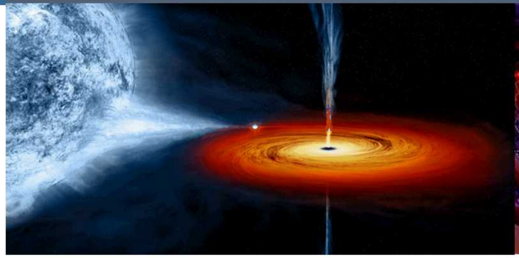
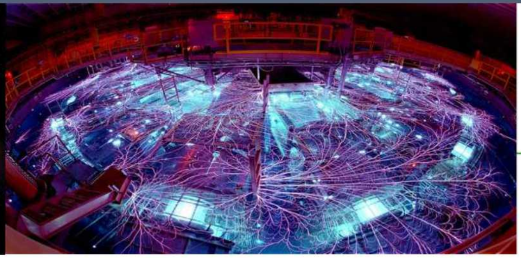
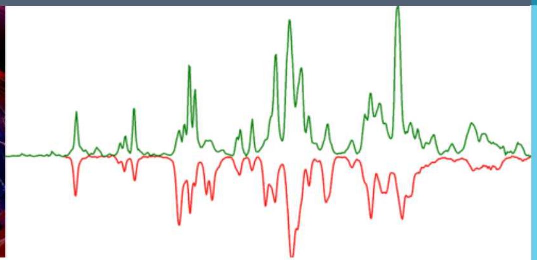
SAND2019-0146C

Experiments for Photoionized Plasma Emission from Accretion-Powered X-Ray Sources







G. Loisel, J. Bailey, G. Rochau, S. Hansen, T. Nagayama, E. Harding, D. Liedahl, C. Fontes, T. Kallman, R. Mancini

Sandia National Laboratories, New Mexico

Lawrence Livermore National Laboratory, California

Los Alamos National Laboratory, New Mexico

Goddard Space & Flight Center NASA, Maryland

University of Nevada Reno, Nevada

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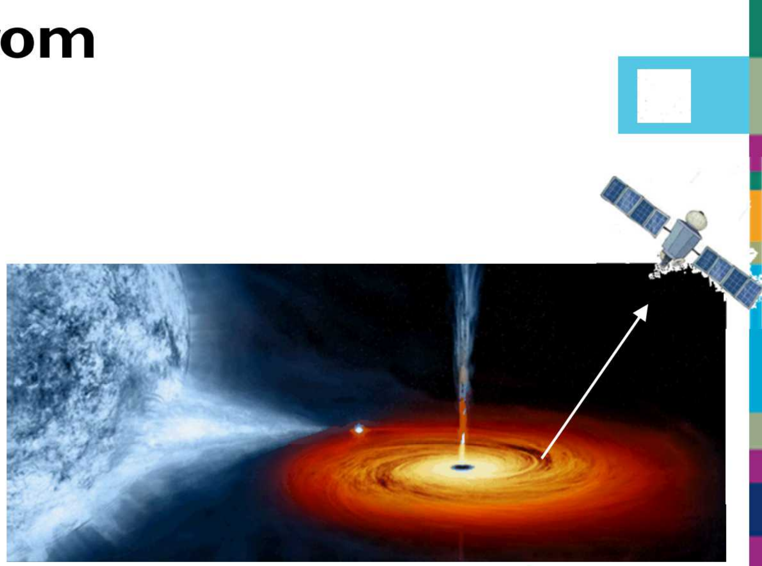
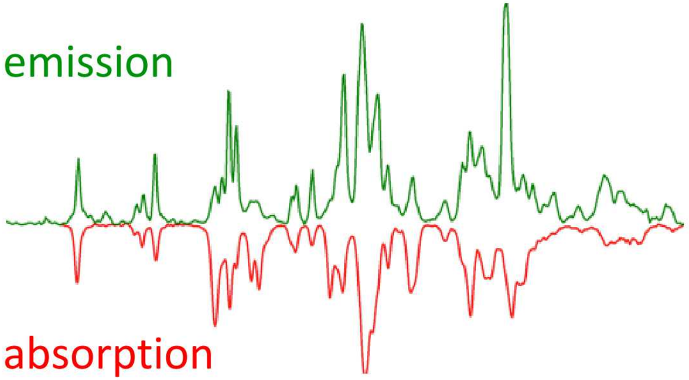
Summary: Z data can benchmark models of emission from photoionized accretion-powered plasmas

- Understanding X-ray Binaries and AGN accretion disks requires complex models that interpret observed spectra
  - → These models are largely untested in the laboratory
  - → Need benchmark quality data



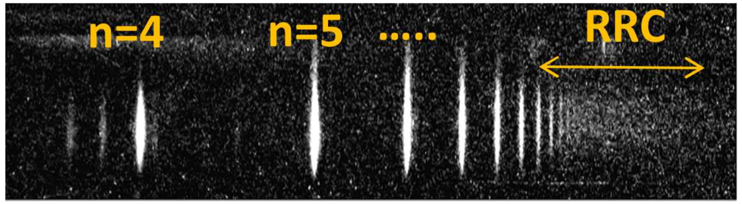
- A photoionized silicon plasma with a measured drive radiation spectrum, density and temperature was created on Z
  - → the column density is adjustable, testing radiation transport



- Spectral absorption and emission are measured to high reproducibility enabling benchmark code comparison

- Presently, models do not reproduce neither relative or absolute emission

- First terrestrial RRC for a photoionized plasma was obtained on Z enabling test of astrophysical temperature diagnostics

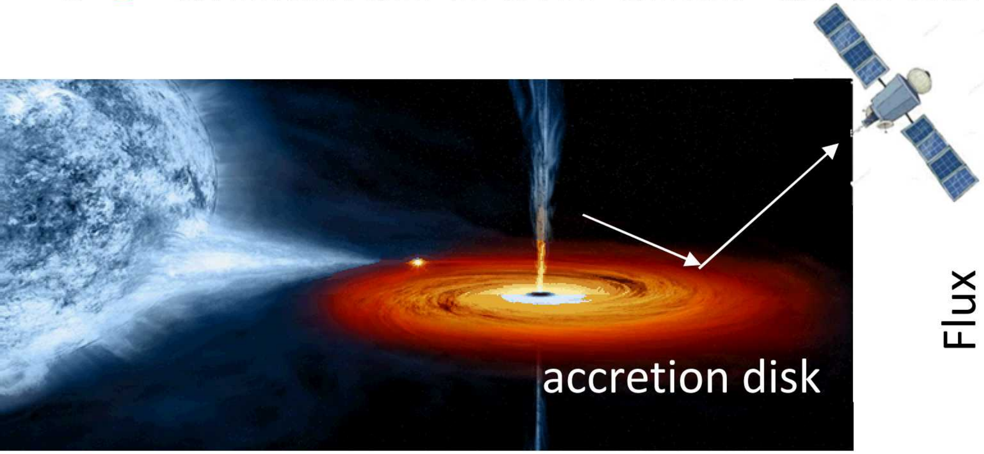


Si He-like emission

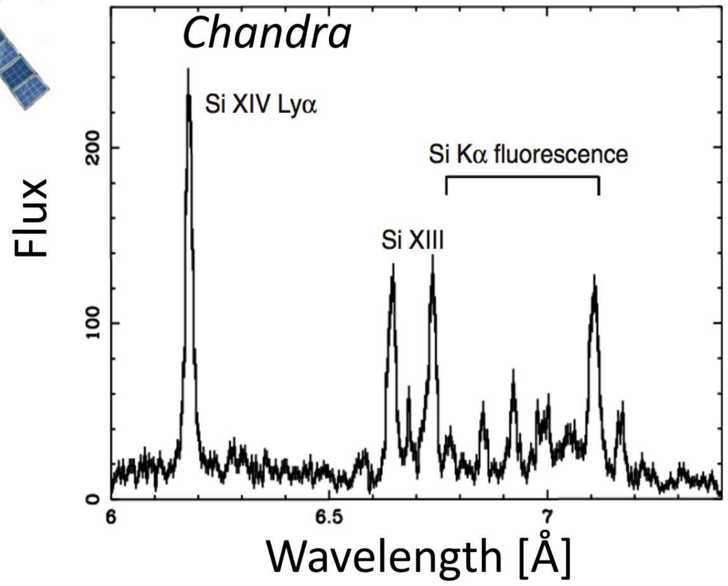
These results raise questions about the suitability of models used to interpret astrophysical observations

G. Loisel, J. Bailey, D. Liedahl et al., PRL 119 (2017)

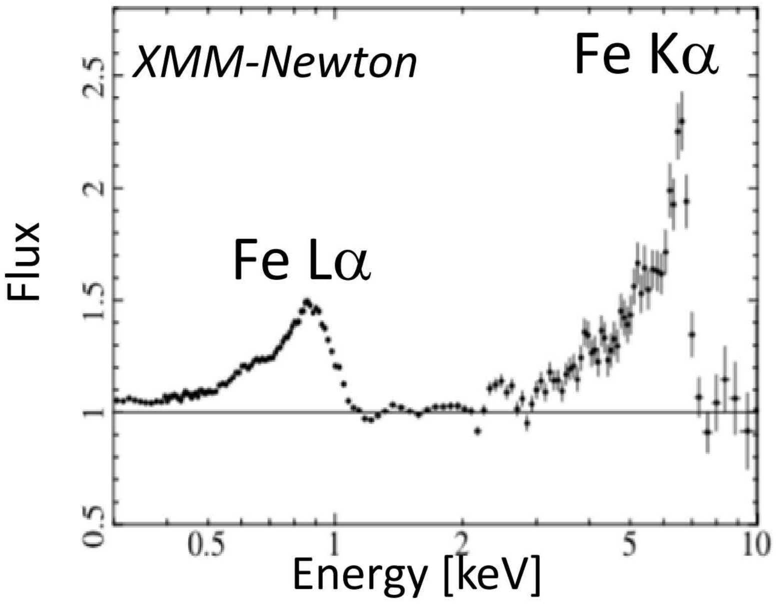
Active Galactic Nuclei and X-ray Binaries are revealed through the emission from their accretion disk



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
- Limited spectral resolution
- Limited signal-to-noise

Liedahl, X-ray Diagnostics of Astrophysical Plasmas (2005), Ross & Fabian, Nature (2009)

Benchmark requirements to emission experiment

Experimental requirements for model benchmarking:

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

Specifically for *emission*:

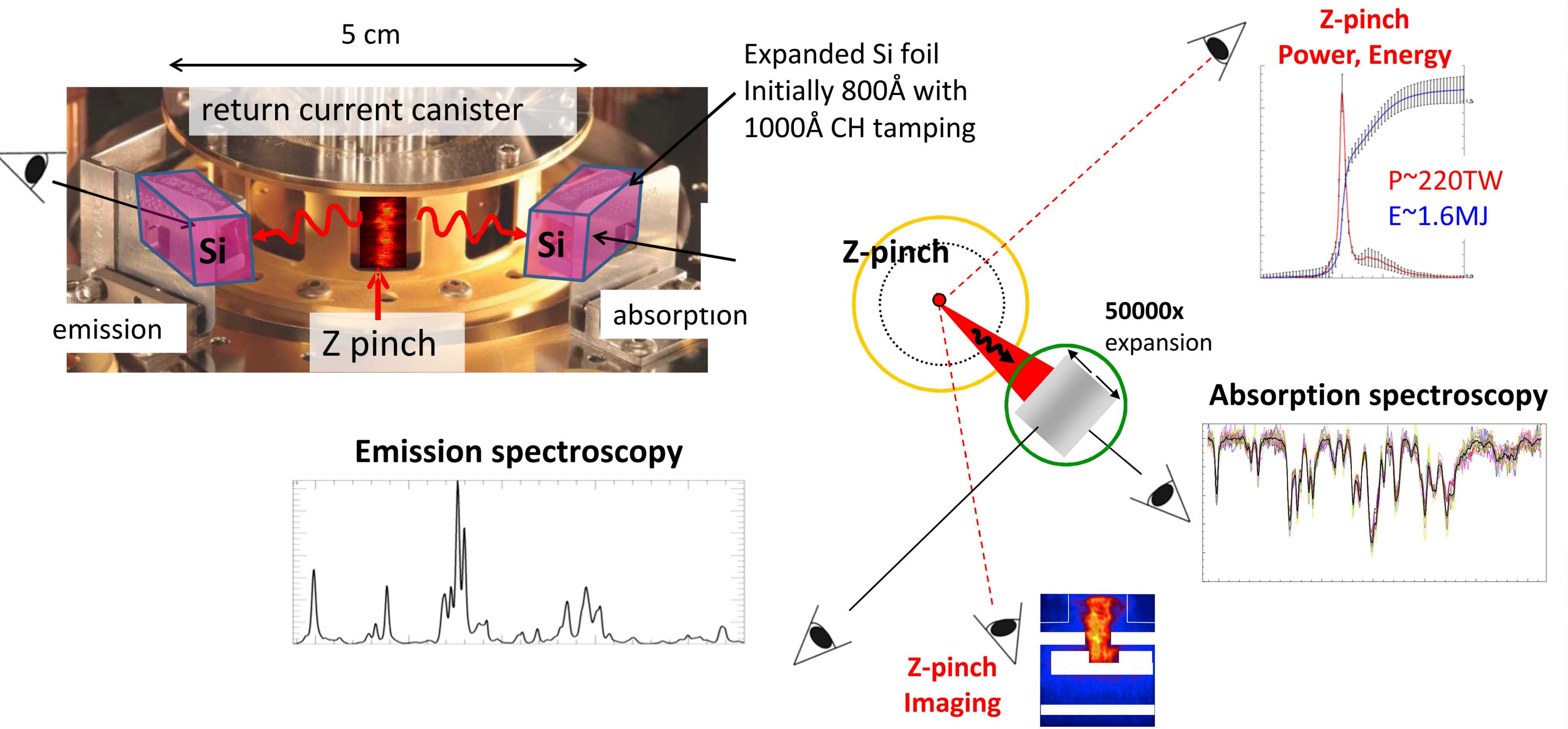
- Large column density for high S/N

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

Experiments on the Z Facility can meet these criteria.

G. Loisel, J. Bailey, D. Liedahl et al., PRL 119 (2017)

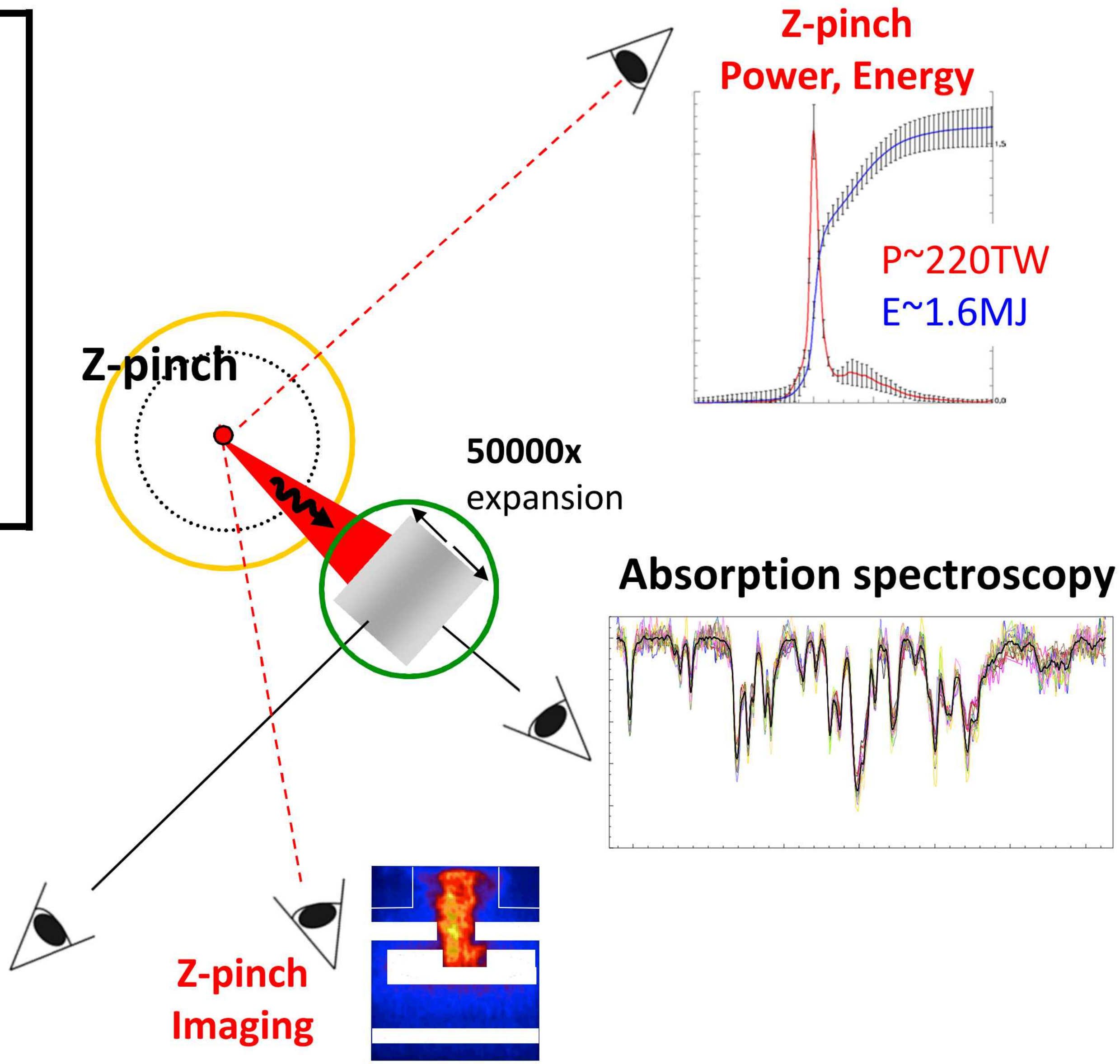
All required inputs are obtained on a single Z shot, confirm the plasma is photoionized and at relevant regime

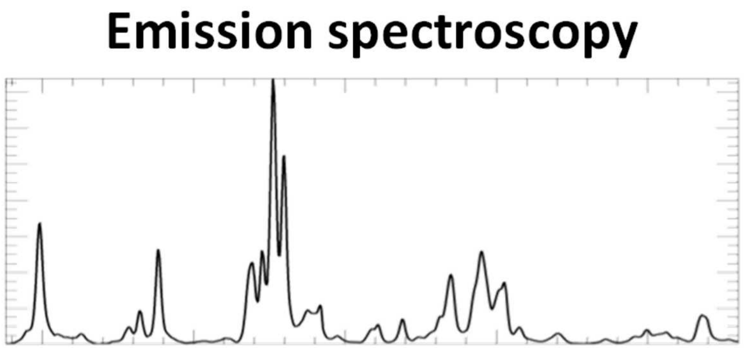


G. Loisel, J. Bailey, D. Liedahl et al., PRL 119 (2017)

All required inputs are obtained on a single Z shot, confirm the plasma is photoionized and at relevant regime

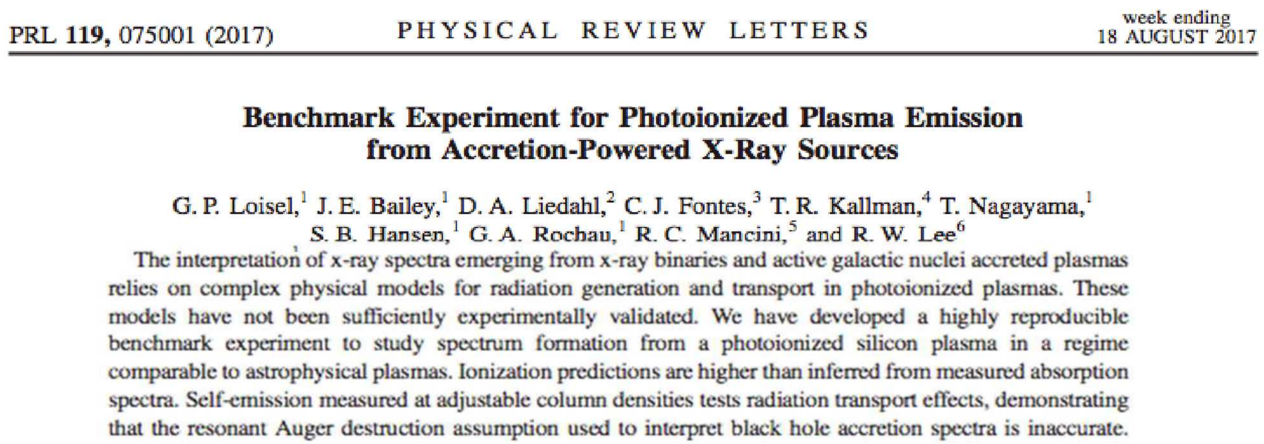
X-ray drive, flux and shape	F ~ 1.3 10^{19} erg/cm^2/s T_{color}= [45, 80, 170] eV
Average charge	Z* ~ 10 , Si^{+10}
Electron density	n_e = 8 x 10^{18} e^-/cm^3
Photoionization parameter	ξ ~ 20-300 erg.cm/s
Column density (adjustable)	N_i ~ 2.5 - 10 10^{17} Si/cm^2
Electron temperature	T_e = 26 - 40 eV





G. Loisel, J. Bailey, D. Liedahl et al., PRL 119 (2017)

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



PRL 119, 075001 (2017) PHYSICAL REVIEW LETTERS week ending 18 AUGUST 2017

Benchmark Experiment for Photoionized Plasma Emission from Accretion-Powered X-Ray Sources

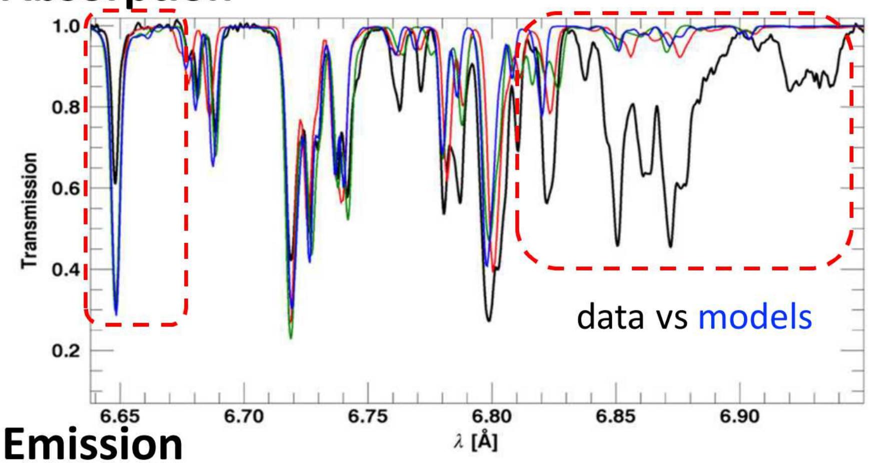
G. P. Loisel,[1] J. E. Bailey,[1] D. A. Liedahl,[2] C. J. Fontes,[3] T. R. Kallman,[4] T. Nagayama,[1] S. B. Hansen,[1] G. A. Rochau,[1] R. C. Mancini,[5] and R. W. Lee[6]

The interpretation of x-ray spectra emerging from x-ray binaries and active galactic nuclei accreted plasmas relies on complex physical models for radiation generation and transport in photoionized plasmas. These models have not been sufficiently experimentally validated. We have developed a highly reproducible benchmark experiment to study spectrum formation from a photoionized silicon plasma in a regime comparable to astrophysical plasmas. Ionization predictions are higher than inferred from measured absorption spectra. Self-emission measured at adjustable column densities tests radiation transport effects, demonstrating that the resonant Auger destruction assumption used to interpret black hole accretion spectra is inaccurate.

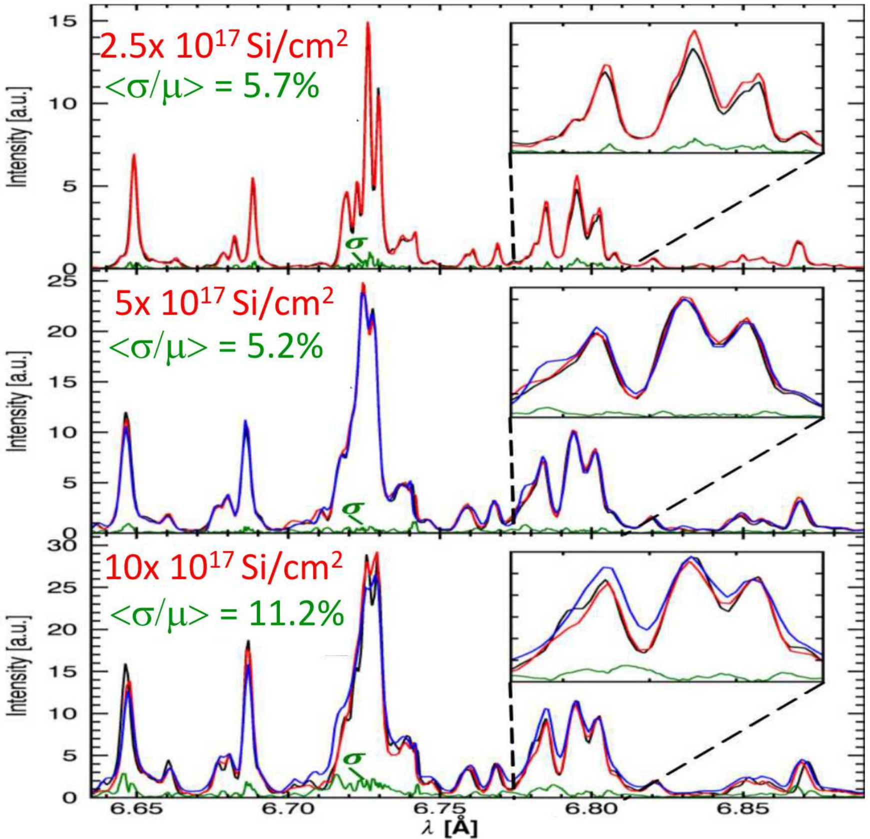
1. Transmission was measured with 4.7% reproducibility enabling test of ionization predictions
2. Models over-predict ionization at measured conditions
3. Emission is measured down to 5.2% reproducibility and at three column densities thus enabling test of radiation transport
4. Resonant Auger Destruction 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.

G. Loisel, J. Bailey, D. Liedahl et al., PRL 119 (2017)

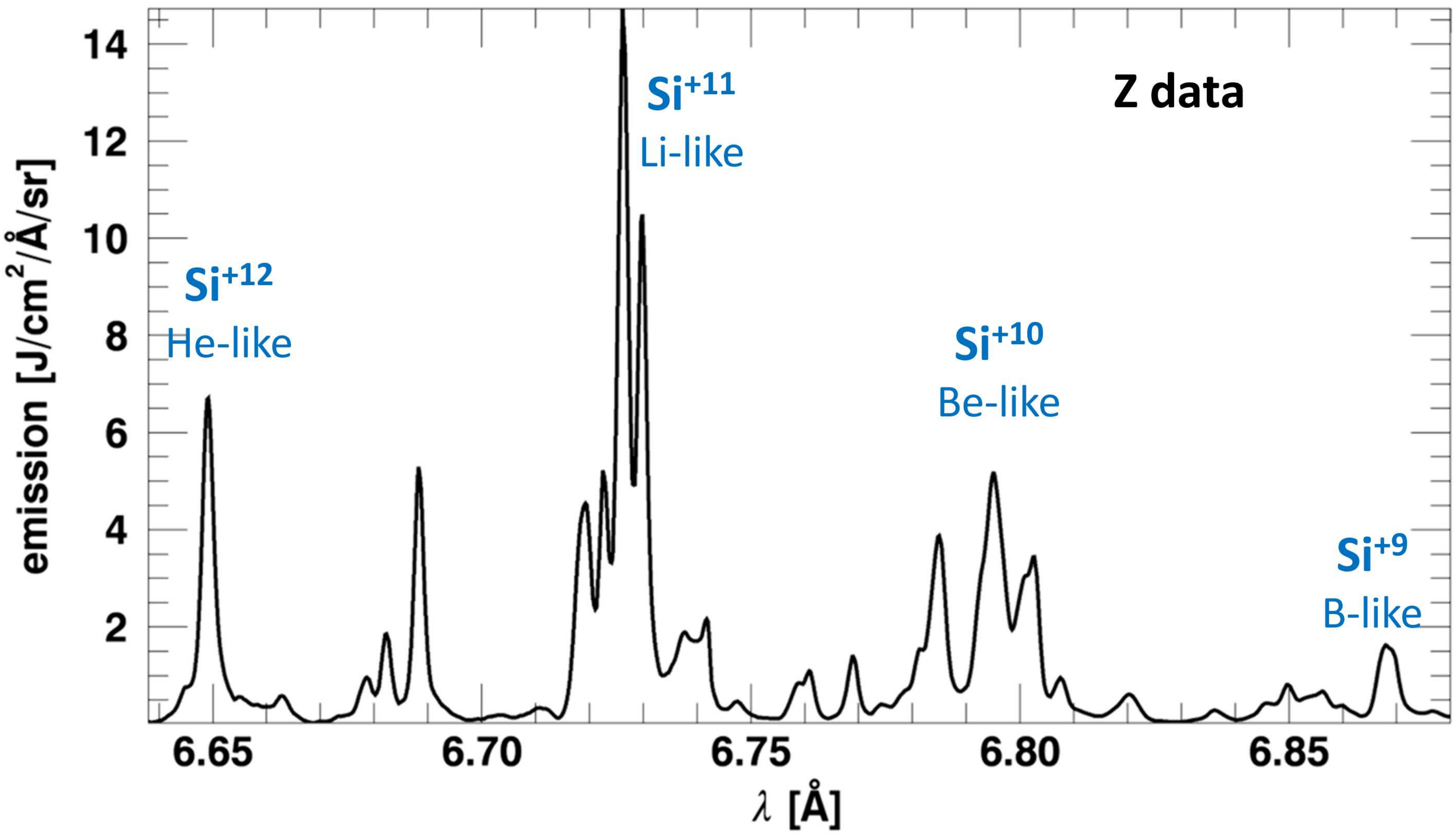
Absorption



Emission



The emission data shows contributions from different charge states

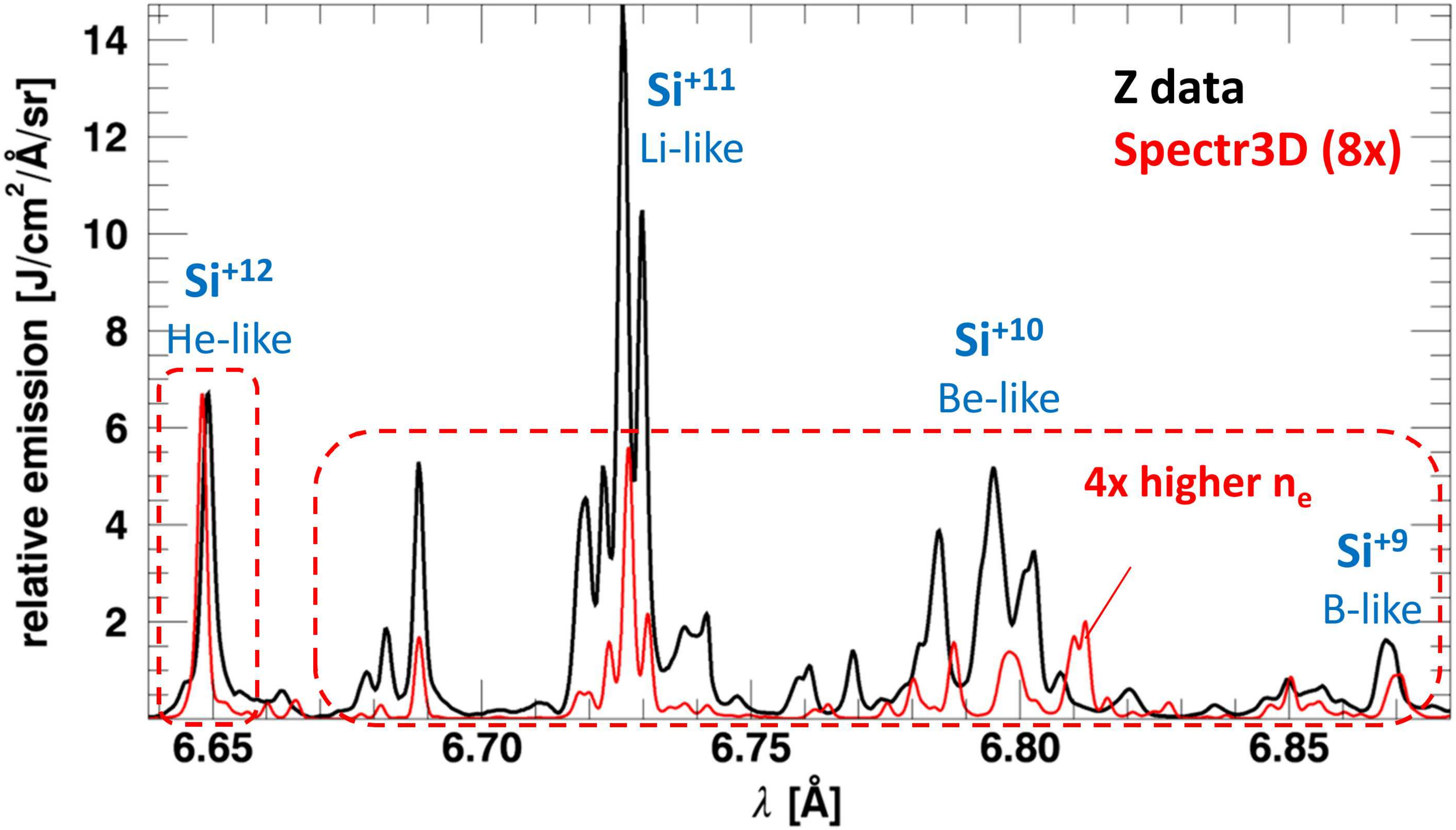


5.2% rel. unc.
$\lambda/\delta\lambda$ **~ 4400**

Simultaneous line observation contradicts an assumption used to interpret black hole spectra*

Ross and Fabian, MNRAS, 278 (1996), Loisel et al., PRL 119 (2017)

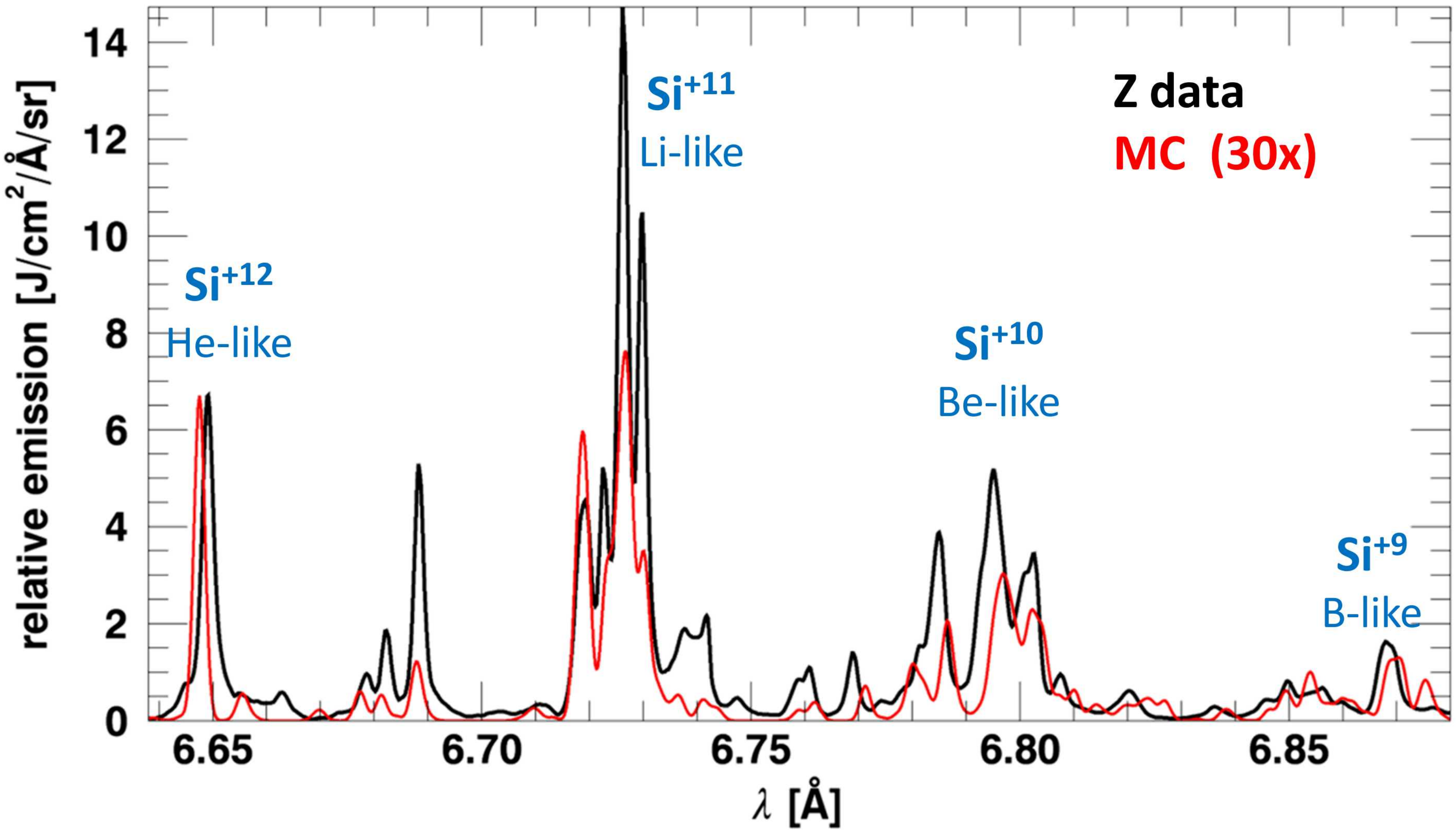
The emission is not reproduced by any model even with conditions adjusted to match absorption spectra



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

Spectr3D: Prism Computational Software

Comparison with a Monte Carlo radiation transport code exhibits improved agreement

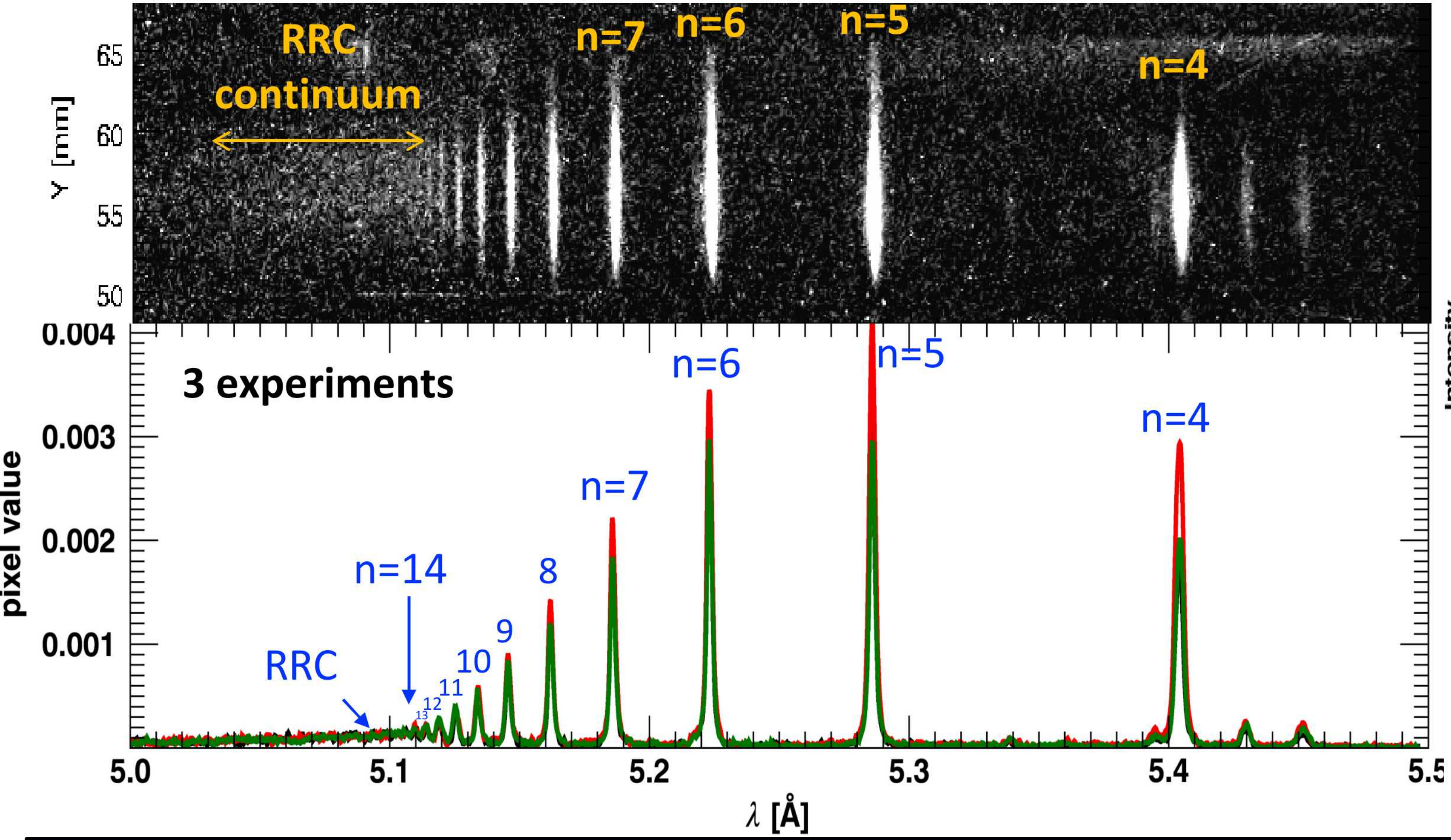


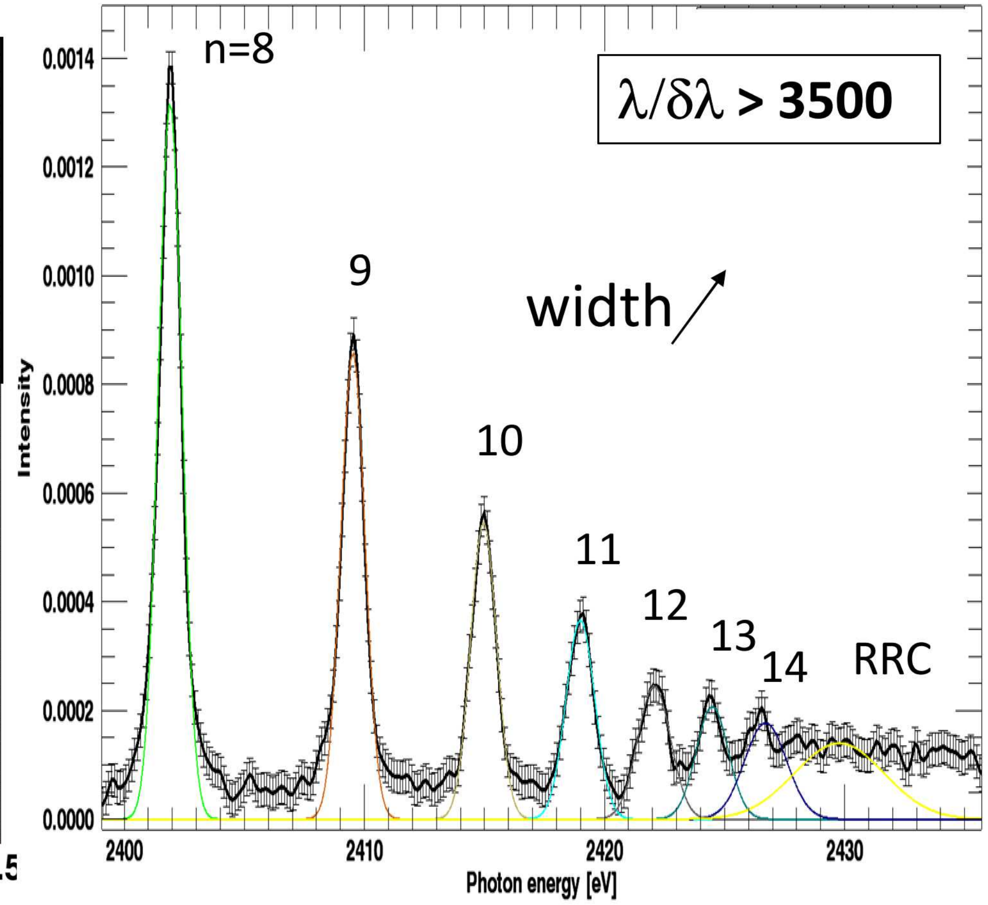
The effect of the different atomic physics data must also be evaluated

MC: Monte Carlo radiation transport code, D. Liedahl

High-*n*, *n*≤14, He-like transitions with merging into the continuum first obtained in a laboratory photoionized plasma

Silicon closer to the x-ray source

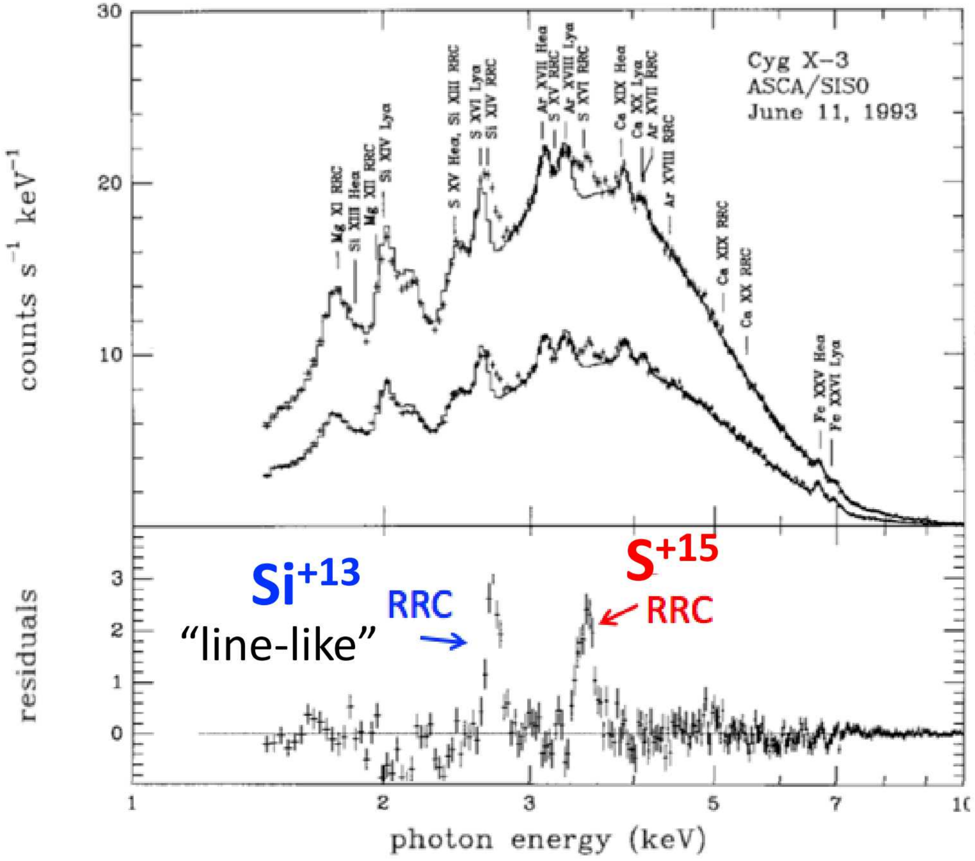




→ **Effect of line shape, line broadening, continuum lowering on the RRC can be studied. High-n lines getting broader with n → density sensitivity.**

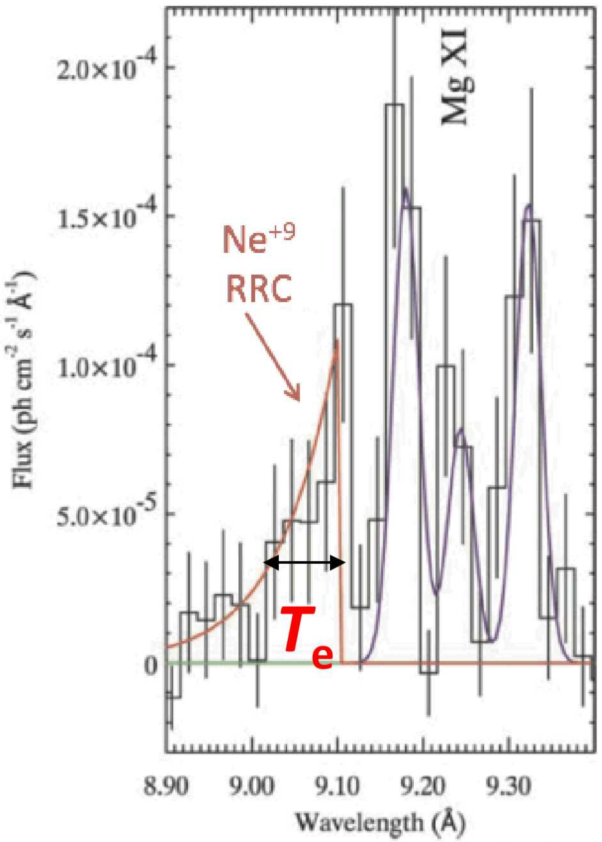
The radiative recombination continuum (RRC) is considered the most reliable temperature diagnostics for accretion-powered objects

Cygnus X-3



T_e = 5-50 eV [1]

Vela X-1



$T_e = 10 \pm 2$eV [2]

$T_e = 6.6 \pm 2$eV [3]

RRC = emission following the capture of electron by plasma ions above recombination threshold energy

Requirements to observe RRC:

1. low temperature $T_e << I_p$ (ionization potential)
2. Overionized recombining plasma
3. High sensitivity instrument (overcome x-ray drive radiation)
4. Spectral resolution better than T_e
5. Little contamination from line and/or other continuous emission

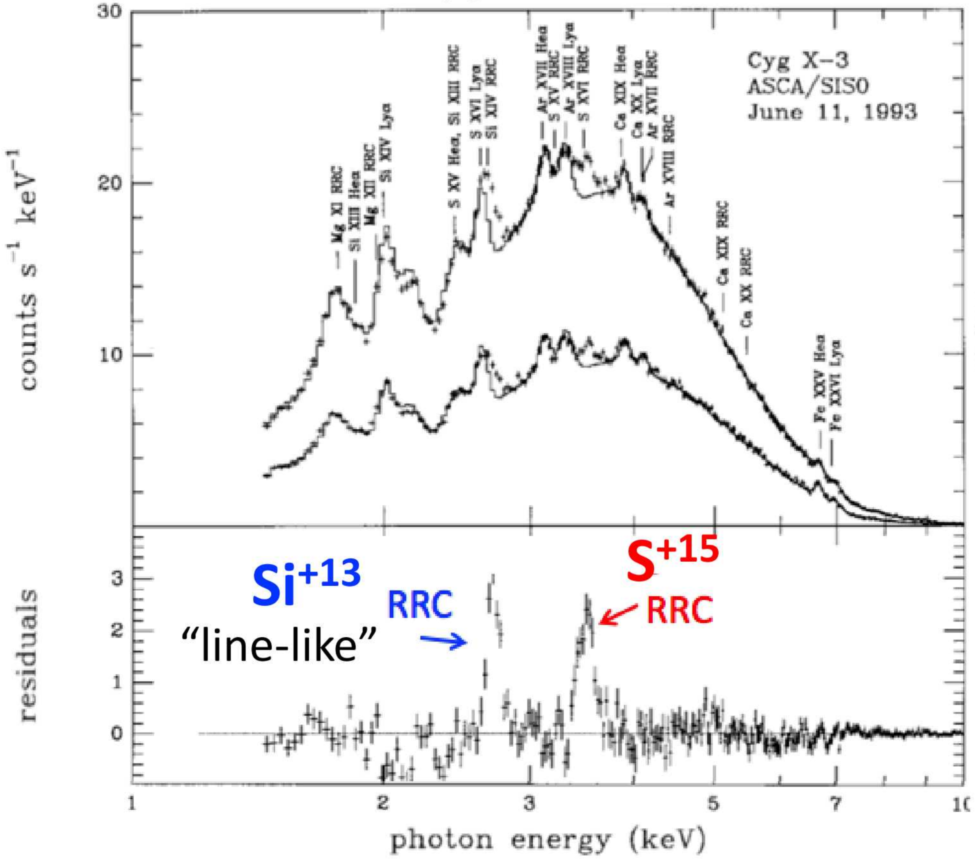
→ RRC visibility with highly charged ions supports the photoionized nature of the accreted matter

→ Untested in the laboratory in a well-characterized photoionized plasma.

[1] Liedahl, Paerels et al. (1996), [2] Schulz et al., Ap. J. Letters 564 (2002). [3] Watanabe et al., Ap. J. 651 (2006)

We recorded first RRC (~10^{-8} Z-pinch energy) in a photoionized plasma in a terrestrial laboratory

Cygnus X-3



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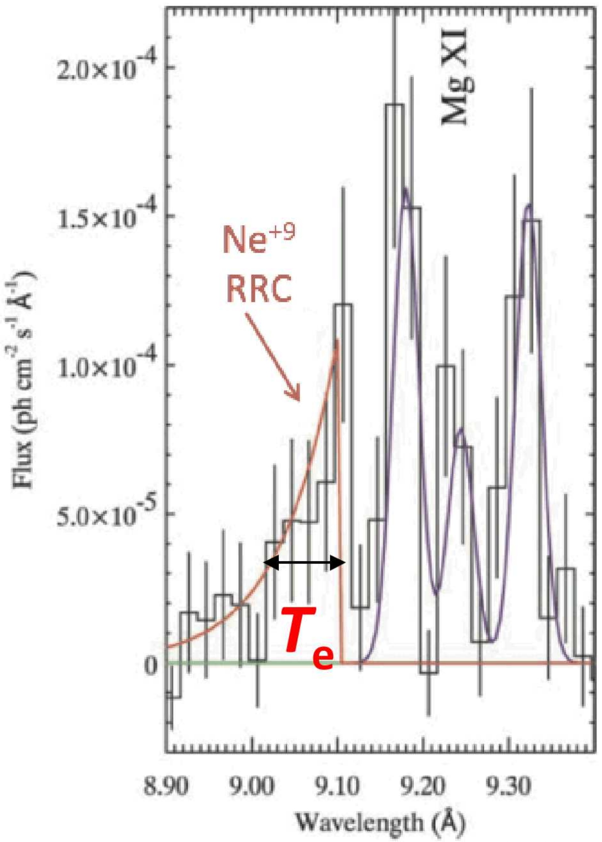
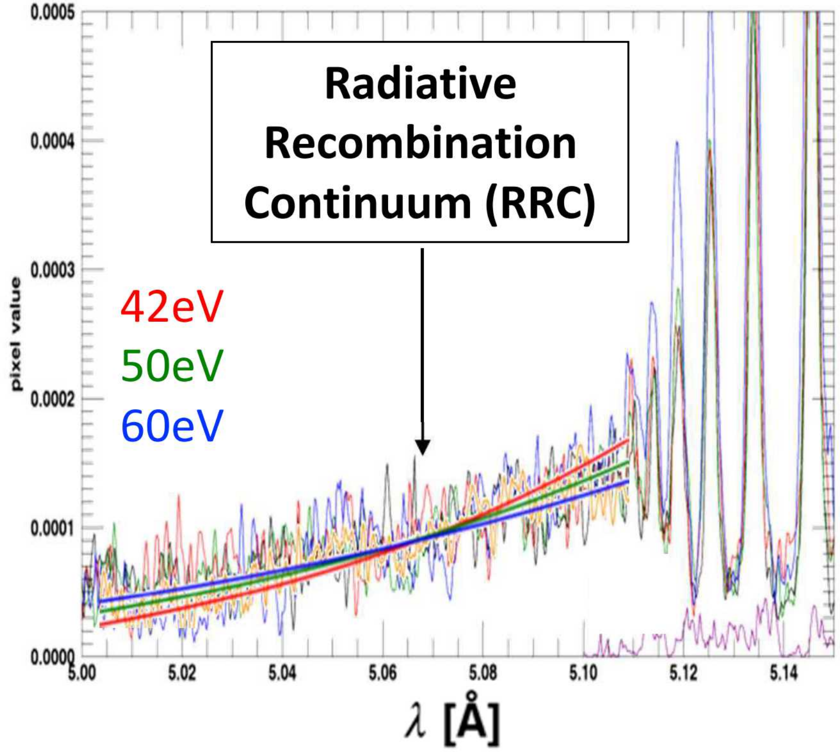
Vela X-1



T_e = 10 ± 2eV [2]
T_e = 6.6 ± 2eV [3]

Earth: Z plasma



→ T_e~ 50 ± 15 eV
→ ~Maxwellian e$^-$ distribution

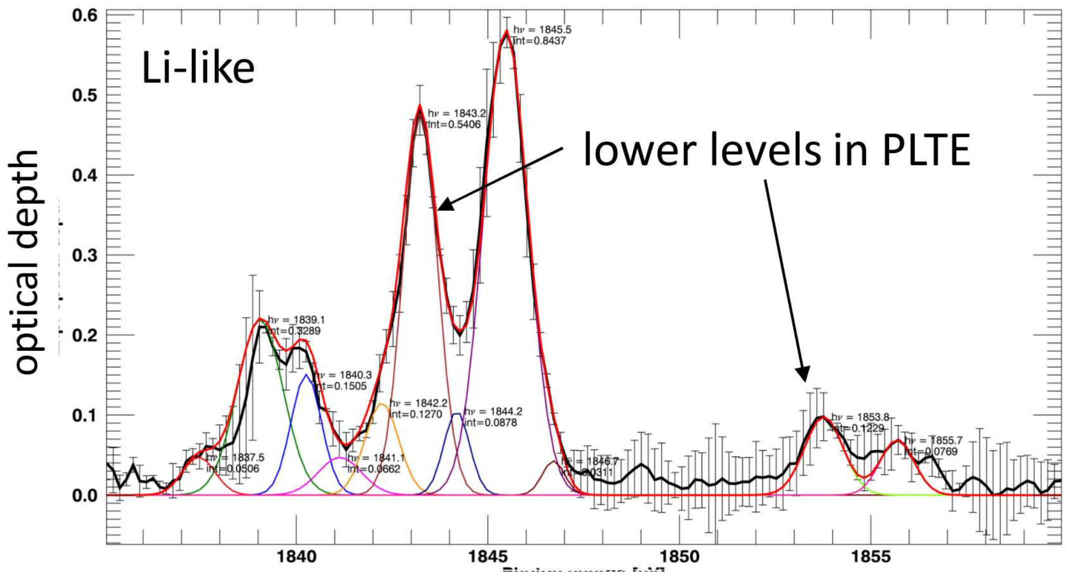
→ **RRC visibility with highly charged ions supports the photoionized nature of the accreted matter**
→ **Untested in the laboratory in a well-characterized photoionized plasma.**

[1] Liedahl, Paerels et al. (1996), [2] Schulz et al., Ap. J. Letters 564 (2002). [3] Watanabe et al., Ap. J. 651 (2006)

Preliminary: temperature inferred from line absorption agrees with the RRC slope

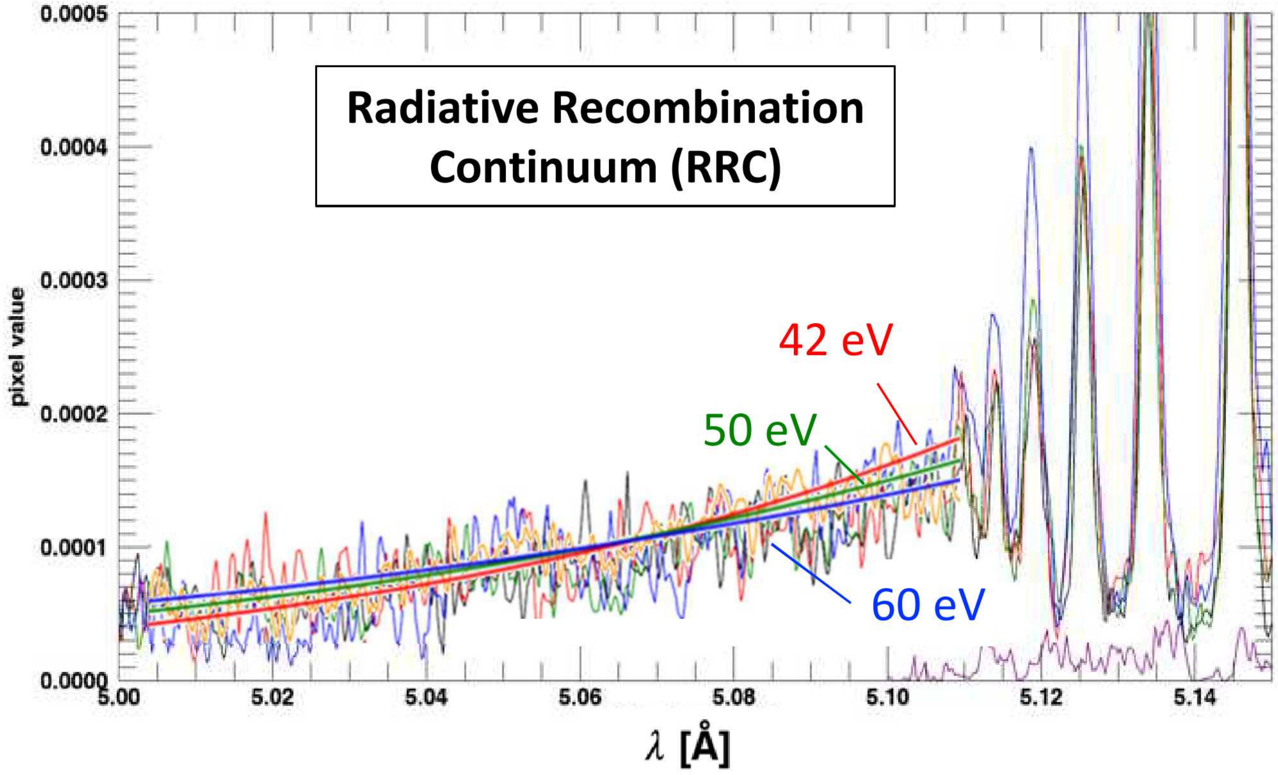
Silicon closer to the x-ray source

Absorption



Absorption initial level	Oscillator strength code	Temperature T_e [eV]
$1s^2 2p_{1/2}$	PRISM	51 ± 21
$1s^2 2p_{3/2}$	PRISM	57 ± 19
$1s^2 2p_{1/2}$	CATS	39 ± 13
$1s^2 2p_{3/2}$	CATS	55 ± 35

Emission



RRC slope → T_e ~ 42 – 60 eV
Li-like sat. ratio → T_e ~ 39 – 60 eV

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

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

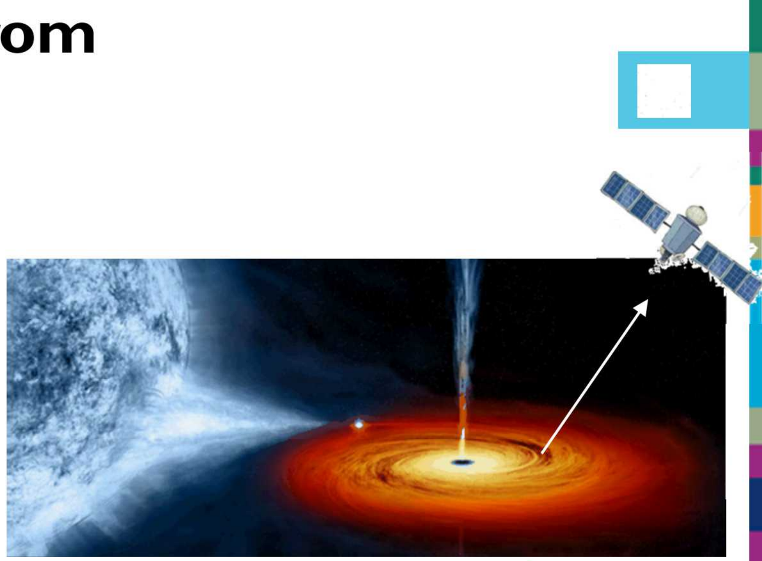
- Accuracy of the recombination rates? dielectronic recombination rates?
- Is the atomic data complete?
- Are approximations in the radiation transport valid?

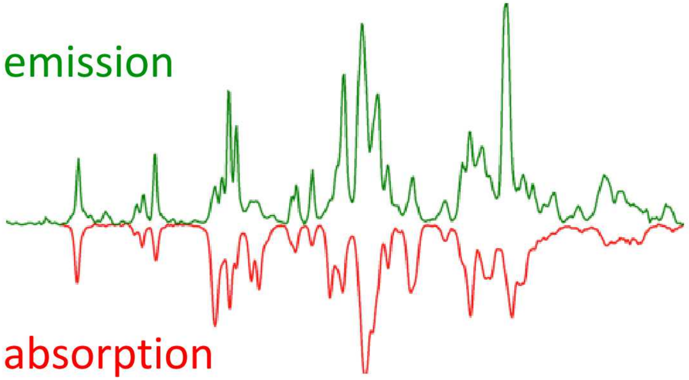
  e.g. escape factors, escape geometry, self-consistency…

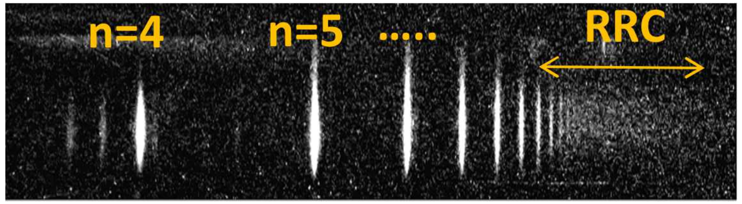
We will scrutinize some of these for the 2018-2020 Z fundamental science proposal

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

- Understanding X-ray Binaries and AGN accretion disks requires complex models that interpret observed spectra
  - → These models are largely untested in the laboratory
  - → Need benchmark quality data
- 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
- Spectral absorption and emission are measured to high reproducibility enabling benchmark code comparison
- Presently, models do not reproduce neither relative or absolute emission
- First terrestrial RRC for a photoionized plasma was obtained on Z enabling test of astrophysical temperature diagnostics







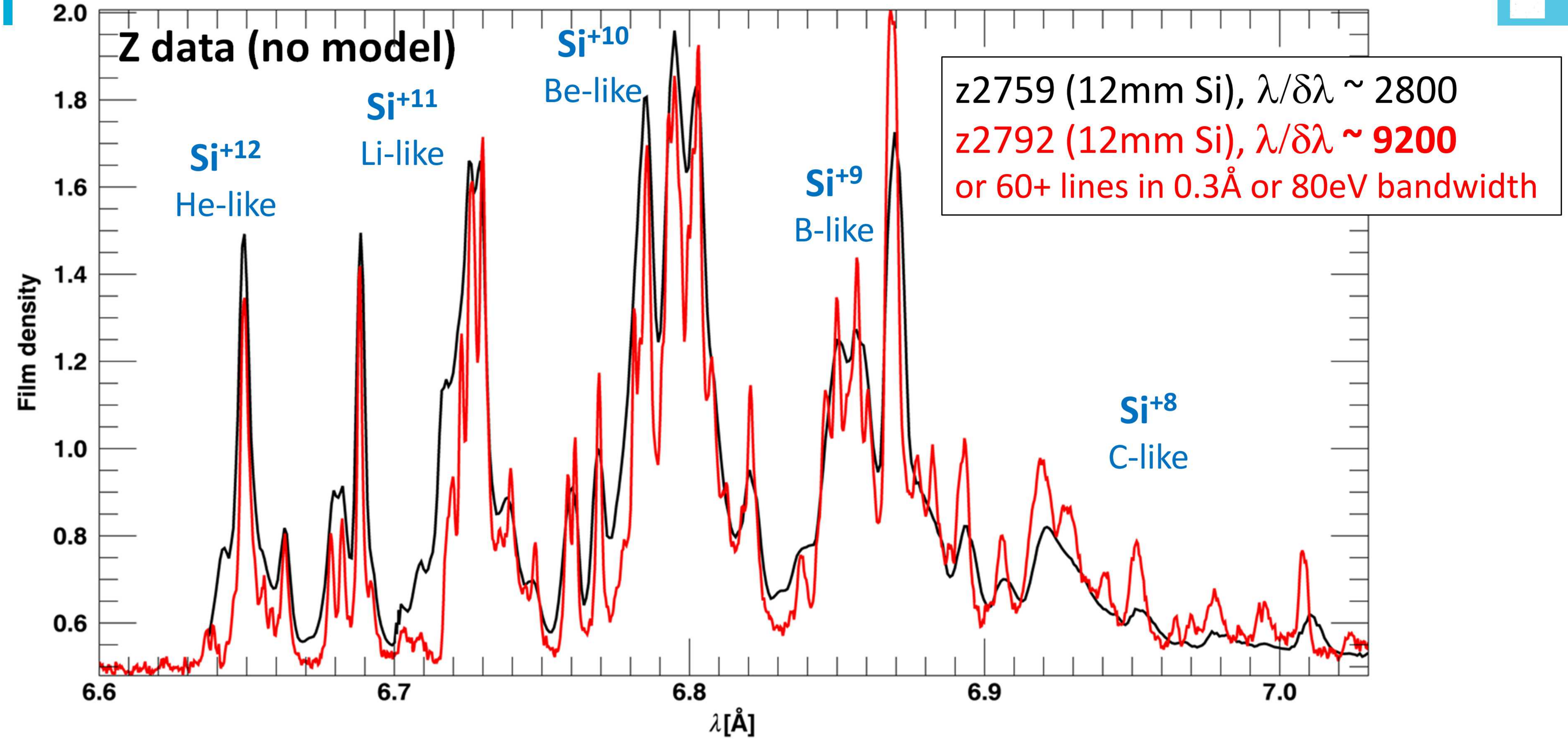
Si He-like emission

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

G. Loisel, J. Bailey, D. Liedahl et al., PRL 119 (2017)

Extra slides

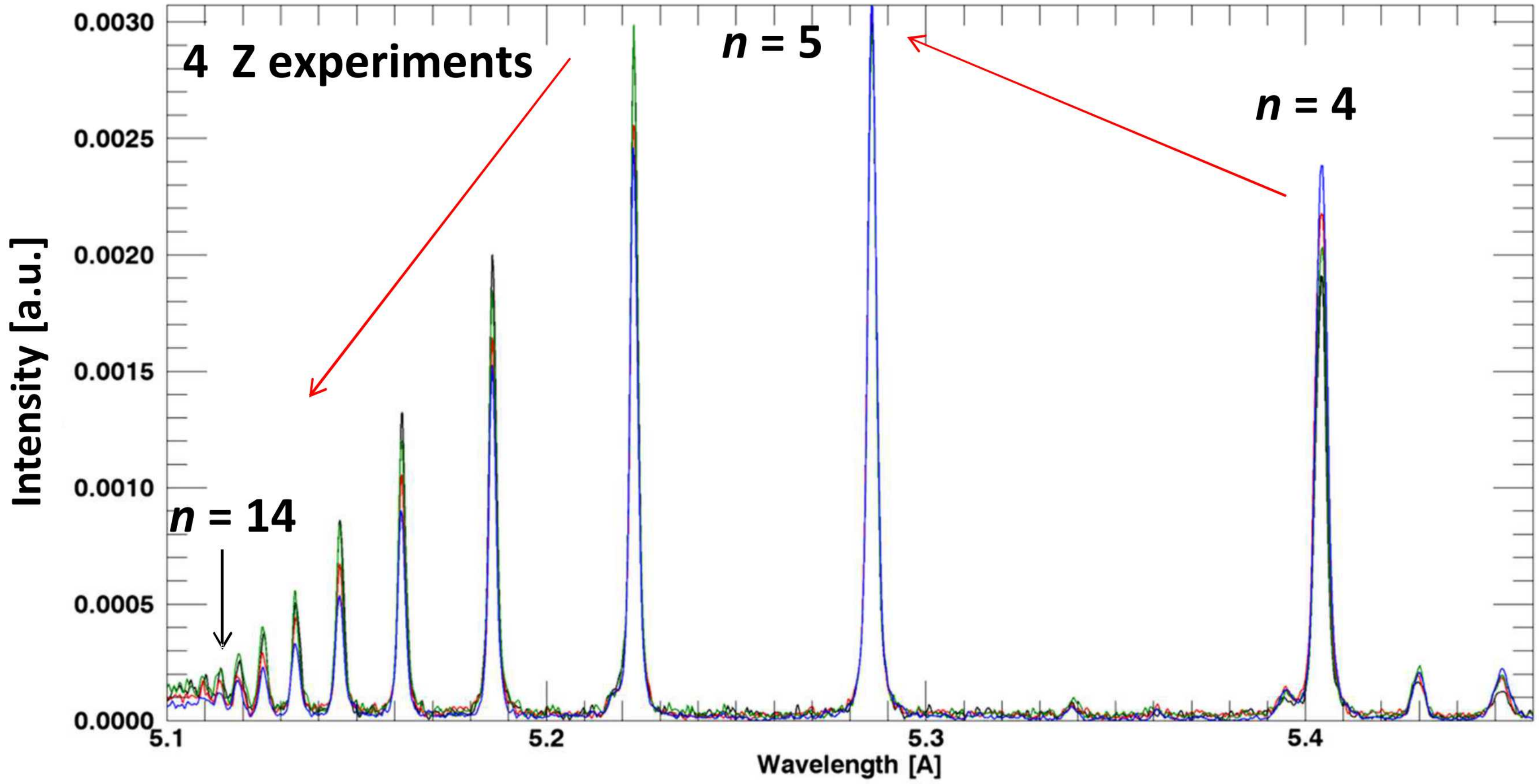
Emission spectra are also measured at very high spectral resolution



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

The high-n lines are not systematically decreasing with principal quantum number

Silicon closer to the x-ray source



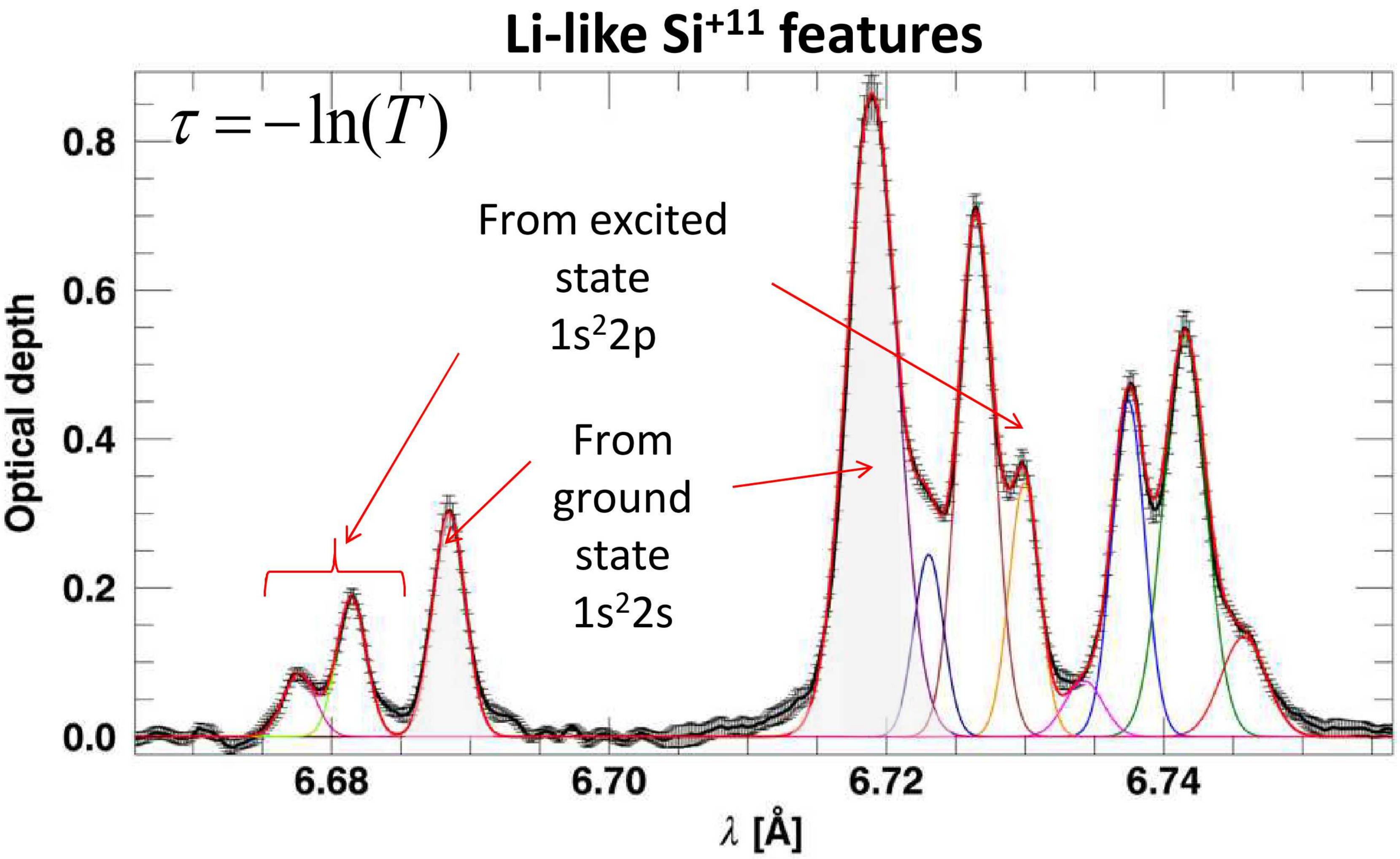
Initial upper states can be populated either by:

- **recombination following photoionization**
- **or photoexcitation**

Also line intensity is affected by radiation transport.

→ Test predominance of photoexcitation versus photoionization in populating He-like states

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



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

→ T_e= 33 ± 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

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

$$\frac{N_2(1s^2 2p)}{N_1(1s^2 2s)} \sim \frac{g_2}{g_1} \exp\left(-\frac{E_2 - E_1}{kT_e}\right)$$

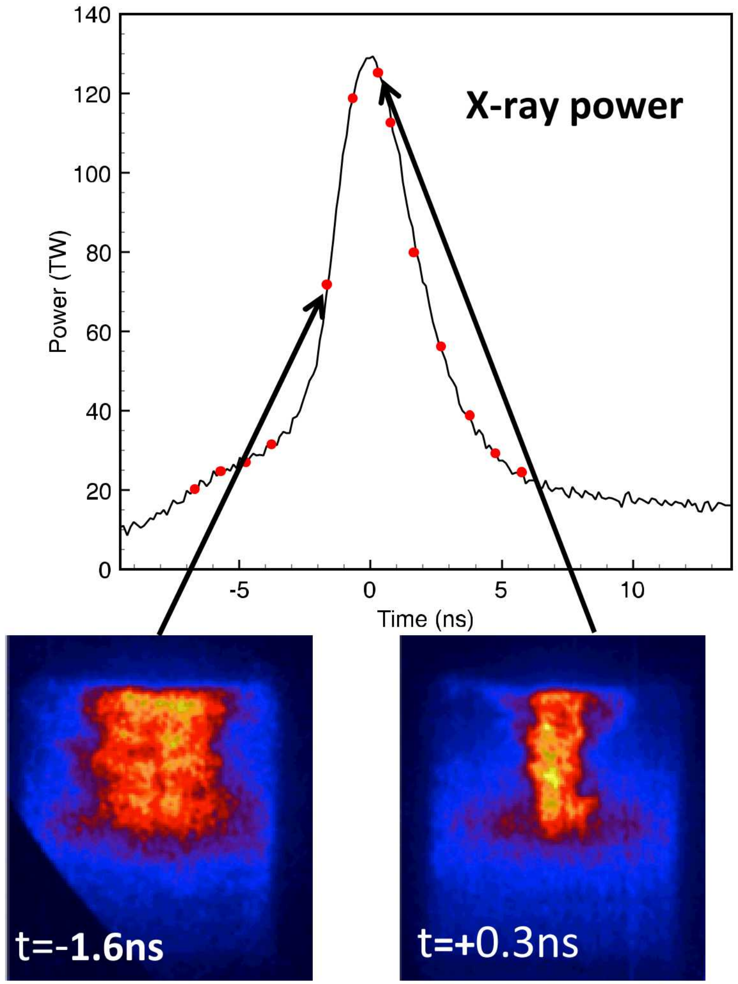
oscillator strength source / initial level	Silicon EDGE-ON	Silicon FACE-ON
PRISM – $1s^2 2p_{1/2}$	T_e = 31.3 ± 3.7 eV	T_e=37.3 ± 4.1 eV
PRISM – $1s^2 2p_{3/2}$	T_e=33.3 ± 4.0 eV	T_e=36.8 ± 3.8 eV
CATS – $1s^2 2p_{1/2}$	T_e=27. ± 2.7 eV	T_e = 31. ± 3 eV
CATS – $1s^2 2p_{3/2}$	T_e=30. ± 3.2 eV	T_e = 32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

statistical error from data

→ T_e= 33 ± 7 eV

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

The radiation driving each sample is inferred from a combination of x-ray diagnostics

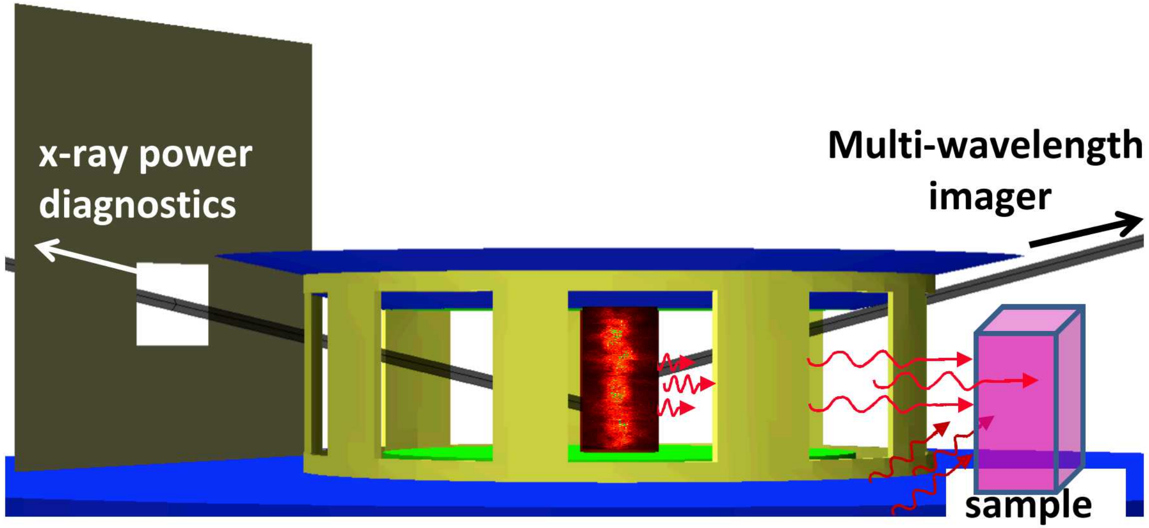


monochromatic images
at 277 eV (also 528eV)

1) Samples are exposed to multiple radiation source contributions

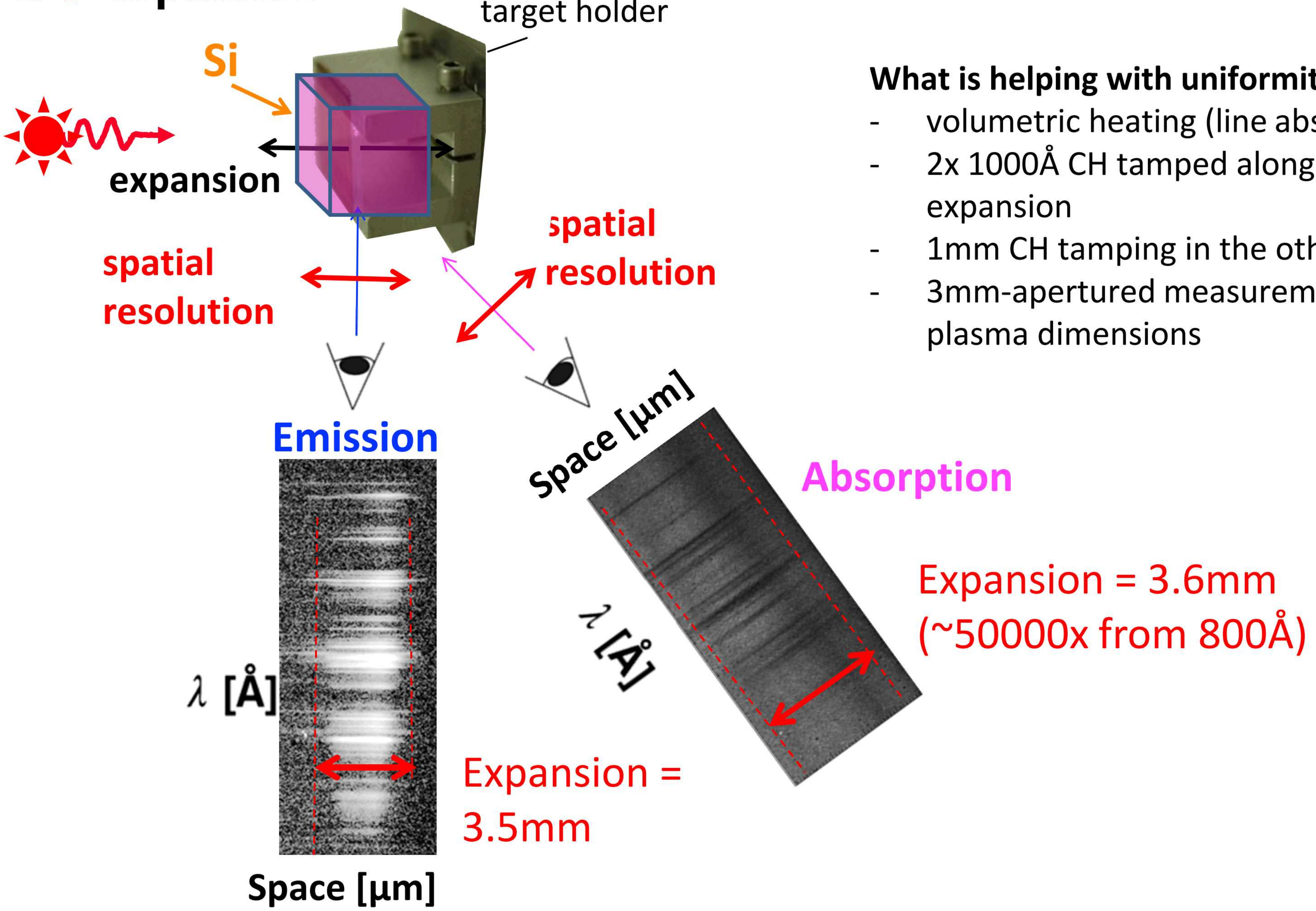
2) X-ray emission from the pinch and the surrounding apparatus is measured with absolute power diagnostics and a gated imager with three photon energies ($h\nu$=277 eV , $h\nu$=528 eV and $h\nu$>1keV)

3) A view factor code is used to infer the spectral irradiance at the sample



incident flux:
2 TW/cm^2

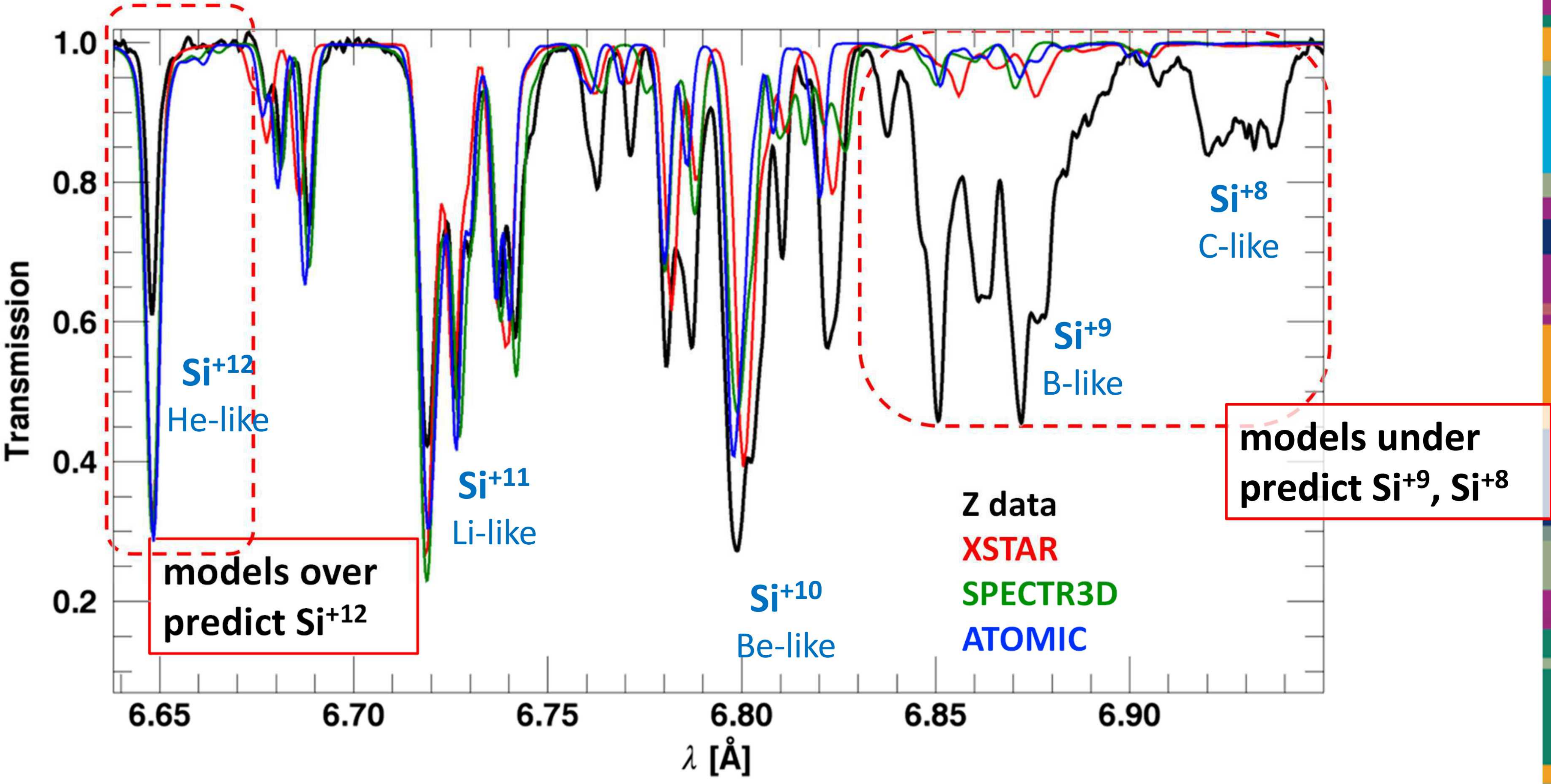
Ion density is measured from the sample areal mass and sample expansion



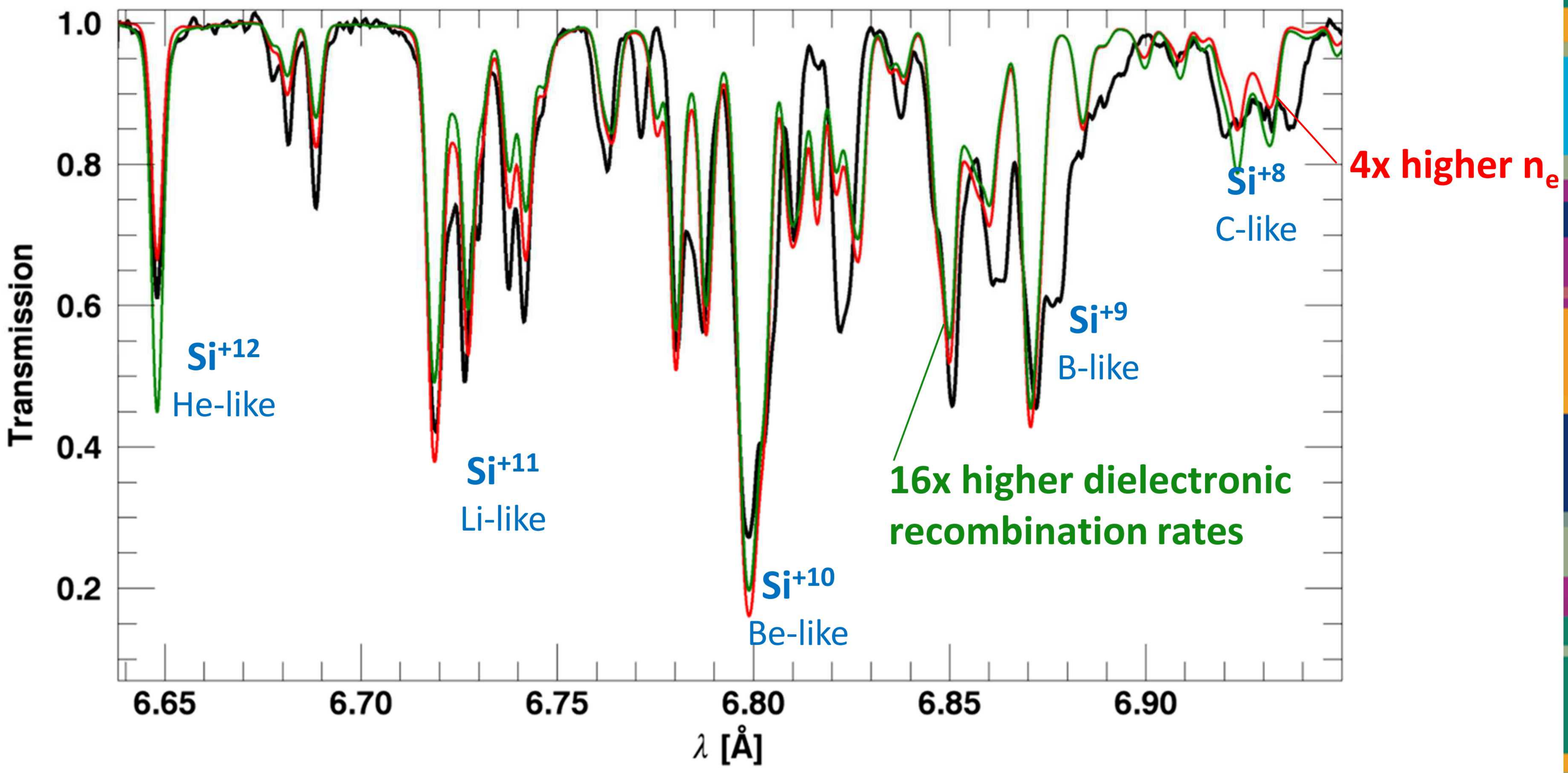
What is helping with uniformity?

- volumetric heating (line absorption)
- 2x 1000Å CH tamped along the heating direction →1D expansion
- 1mm CH tamping in the other dimension
- 3mm-apertured measurement over ~10mm plasma dimensions

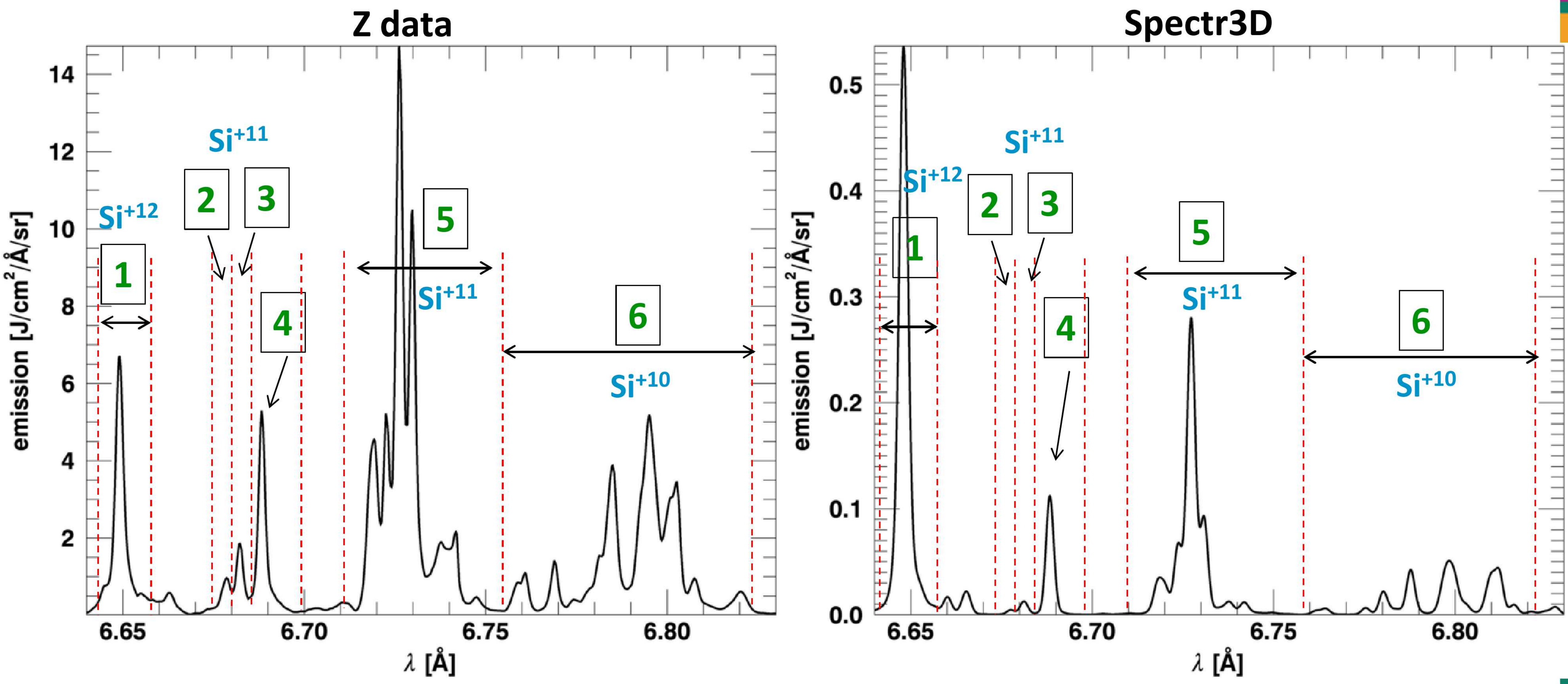
Measured relative absorption from different ion stages tests model ionization predictions



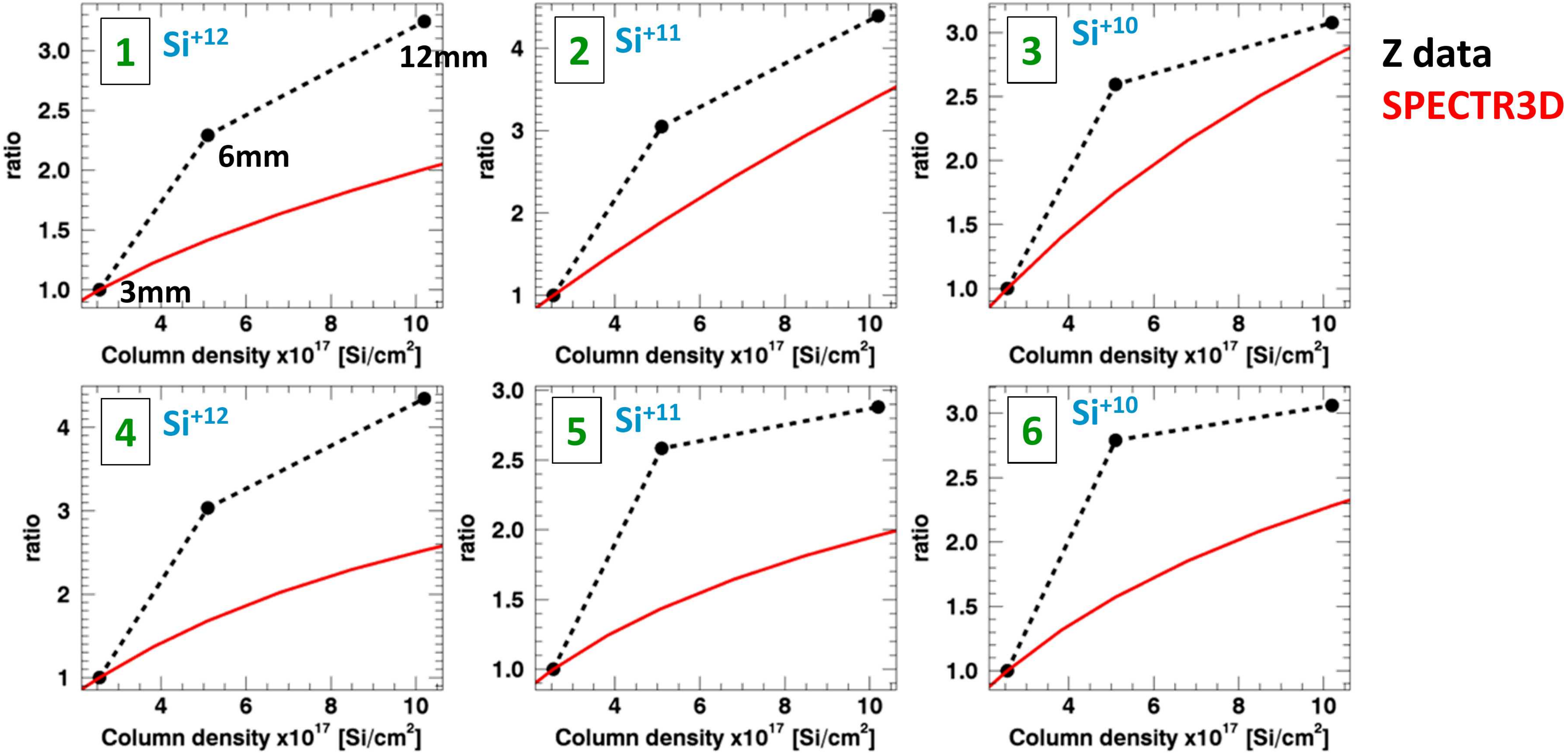
Agreement can be obtained by adjusting parameters that increase recombination



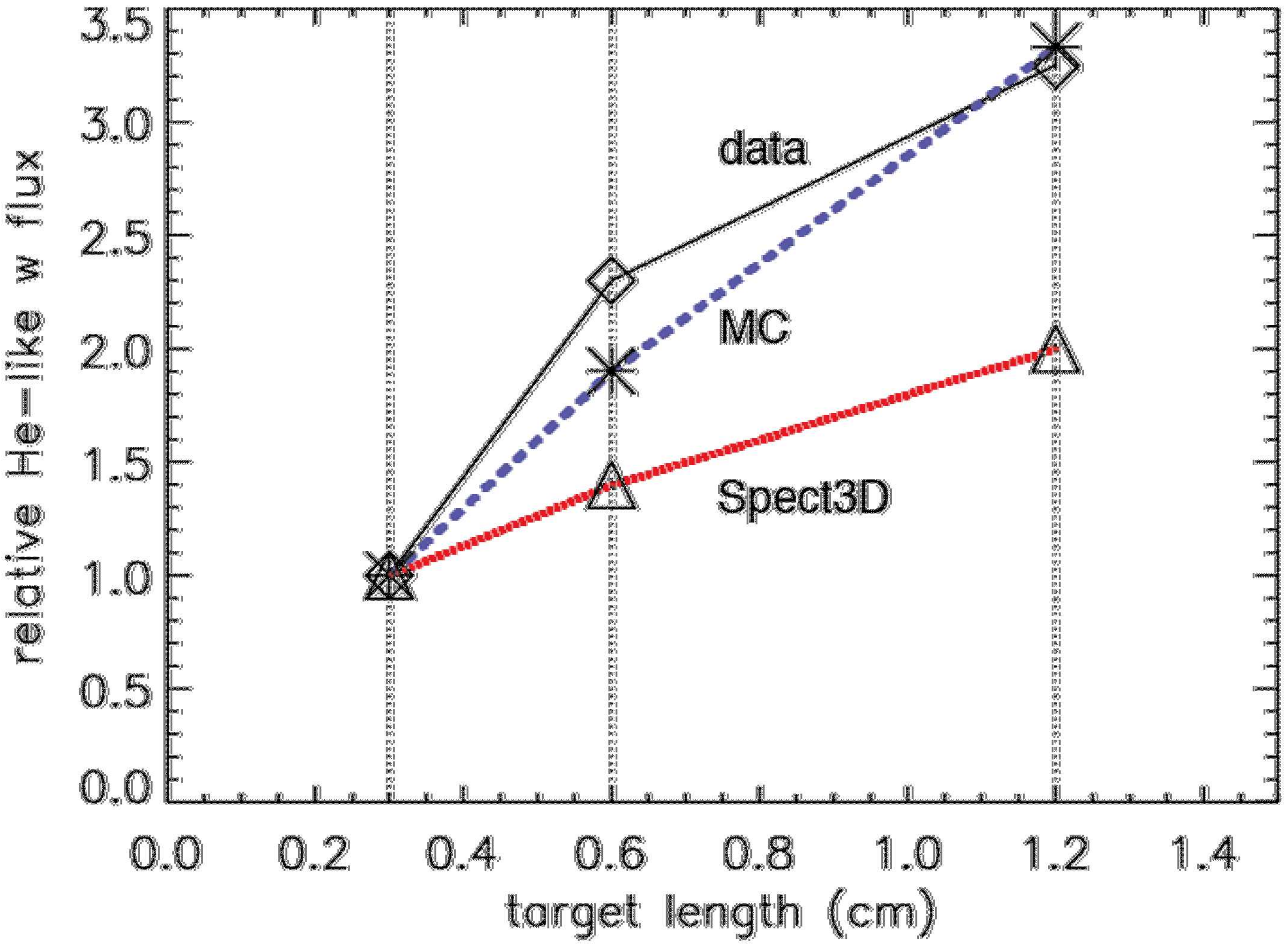
Dividing spectra into segments according to charge states facilitates model radiation transport tests



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



Preliminary result
MC simulation D. Liedahl 05/2018