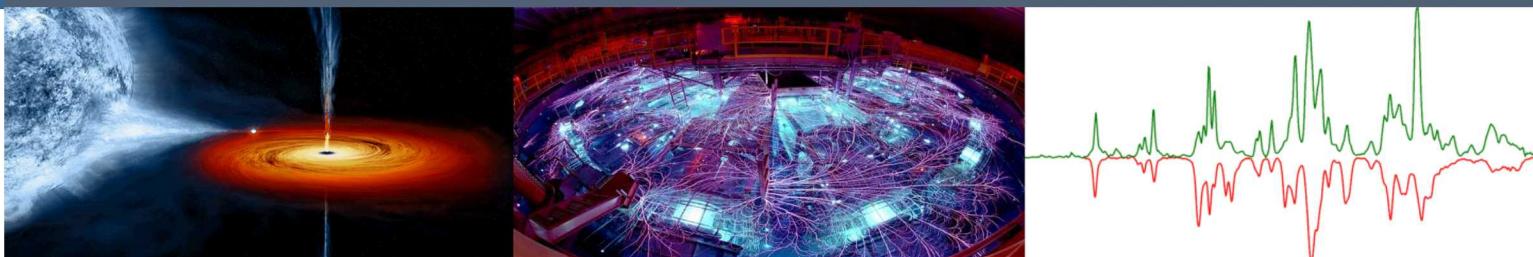


# Black hole accretion disc radiation



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

*Sandia National Laboratories, New Mexico*

*Lawrence Livermore National Laboratory, California*

*Los Alamos National Laboratory, New Mexico*

*University of Nevada Reno, Nevada*

*Goddard Space & Flight Center NASA, Maryland*



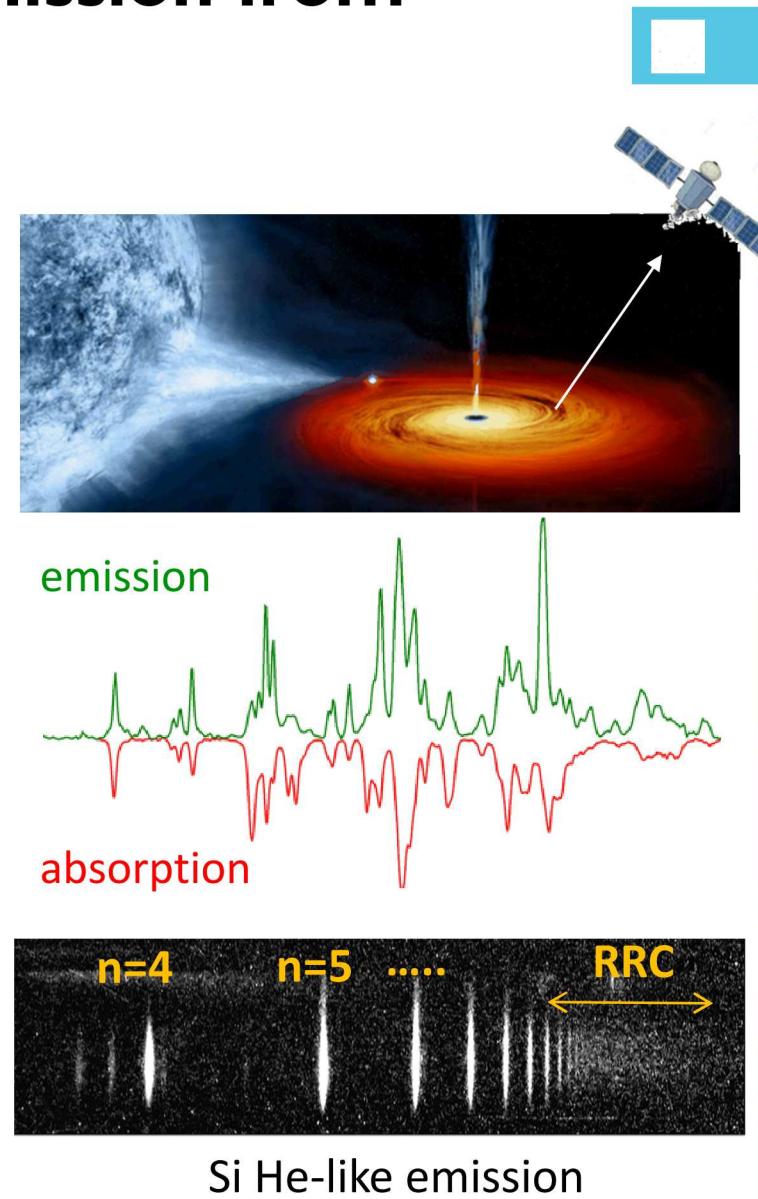
CSAC  
Jan 16<sup>th</sup> 2020  
Austin, TX



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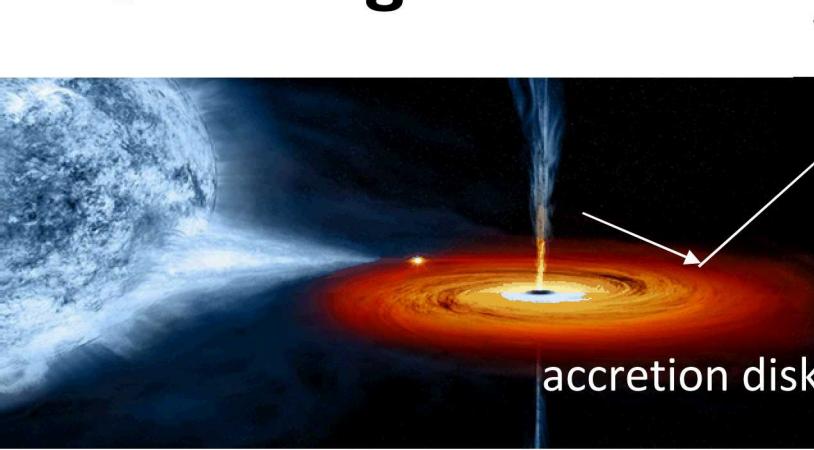
## Summary: Z data can benchmark models of emission from photoionized accretion-powered plasmas

- 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 from a photoionized plasma was obtained on Z enabling test of astrophysical temperature diagnostics

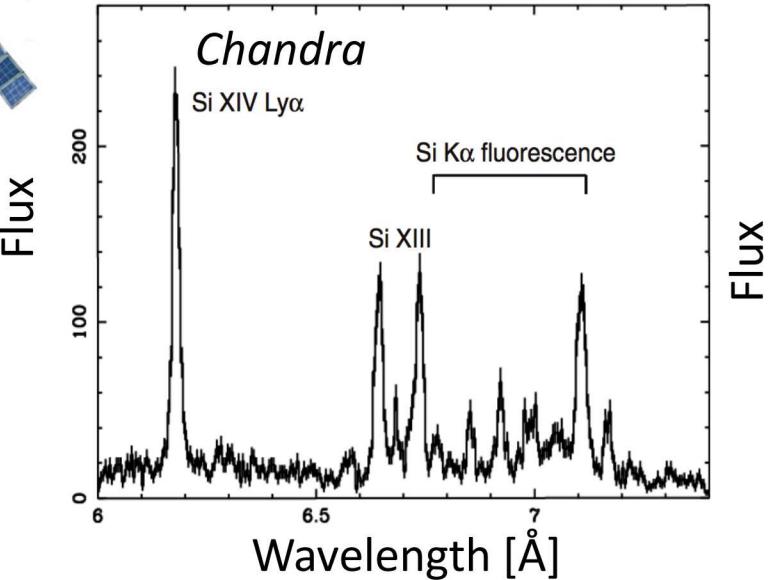


**The difficulty to model emission raises questions about the suitability of models used to interpret astrophysical observations**

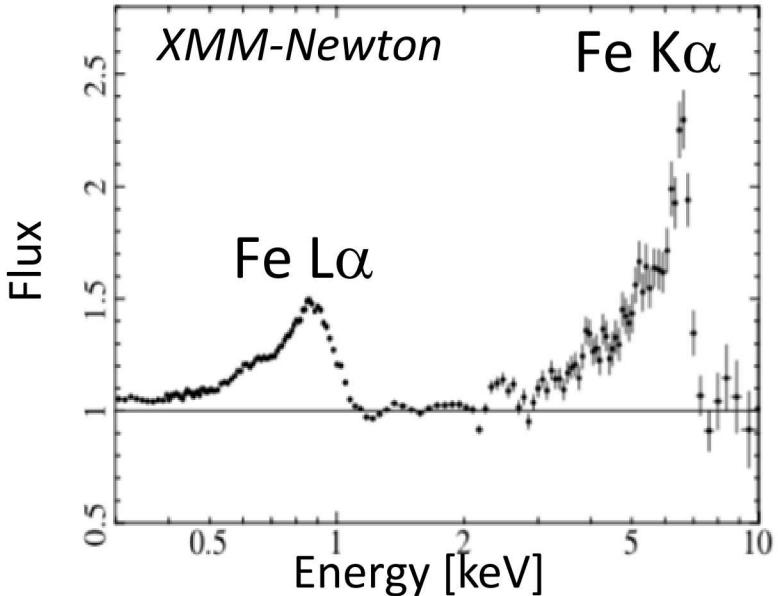
# Active Galactic Nuclei and X-ray Binaries are revealed through the emission from their accretion disk



Neutron star Vela X-1



AGN 1H0707-495



XMM-Newton - ESA



Chandra - NASA



Suzaku – JAXA

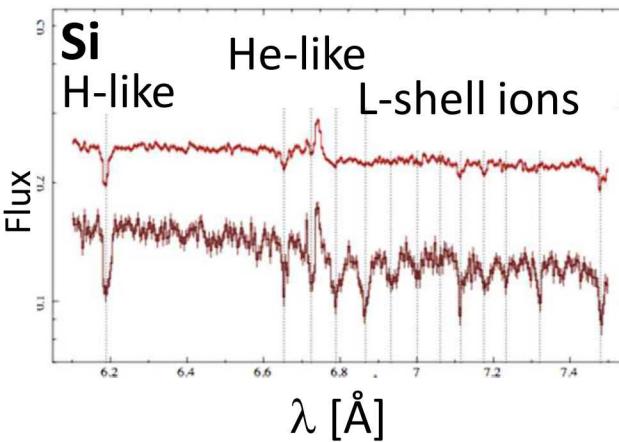


## Challenges:

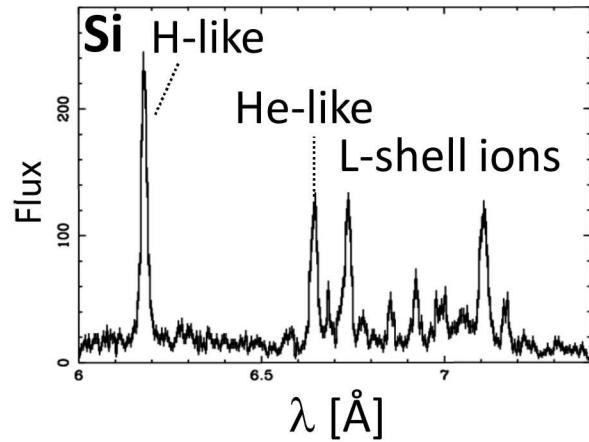
- Line identification
- Blended spectra from multiple elements
- Spatial and temporal integration
- Limited spectral resolution
- Limited signal-to-noise

# X-ray spectra are used to access a wide variety of the astrophysical object parameters

Cygnus X-1 BH



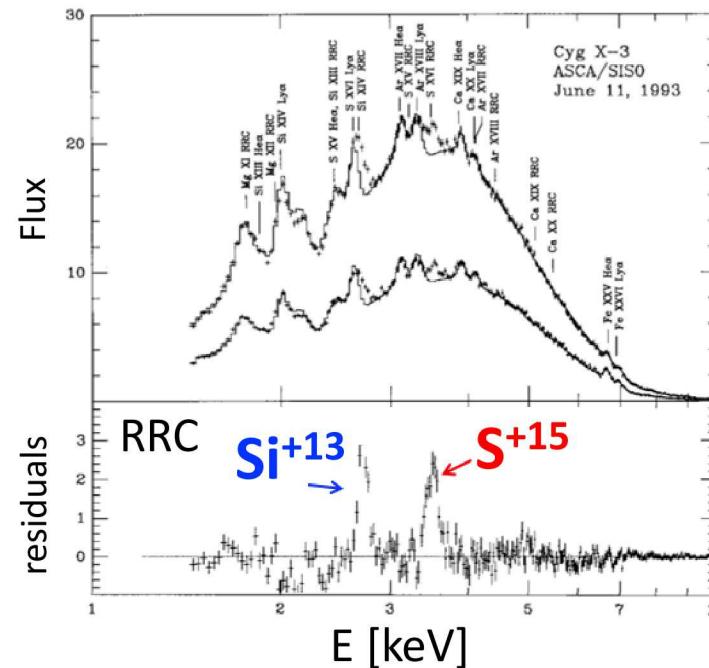
Vela X-1 NS



## Absorption spectra

- composition
- ionization  $\xi = 4\pi \text{flux}/\text{density}$
- Column density
- Accretion dynamics

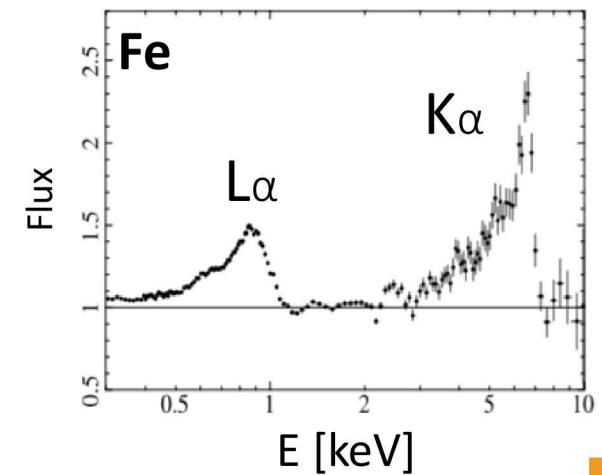
Cygnus X-3 BHC



## Radiative recombination continuum (RRC)

→  $T_e$  temperature

AGN 1H0707 SMBH



## Broad Iron line

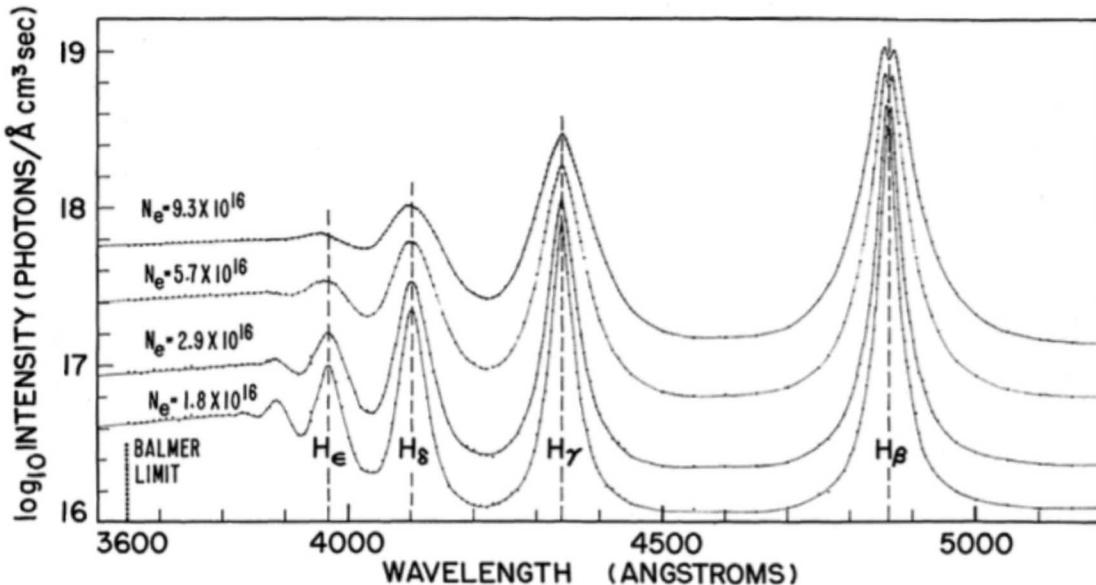
- Radiation transport effects
- Disk structure
- General relativity effects

Yet, largely untested physics models are used to interpret the observations

# Benchmark experiments do exist for collisional plasmas

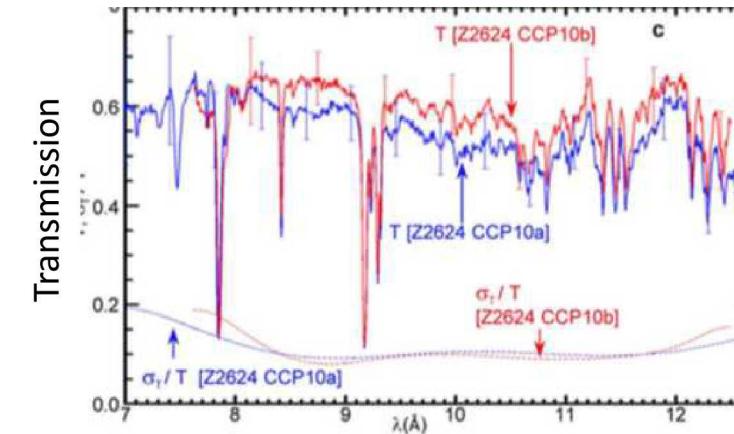
5

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

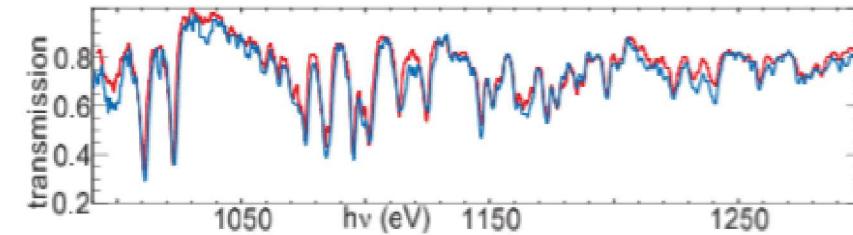


Balmer line shapes measured with 6% error

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



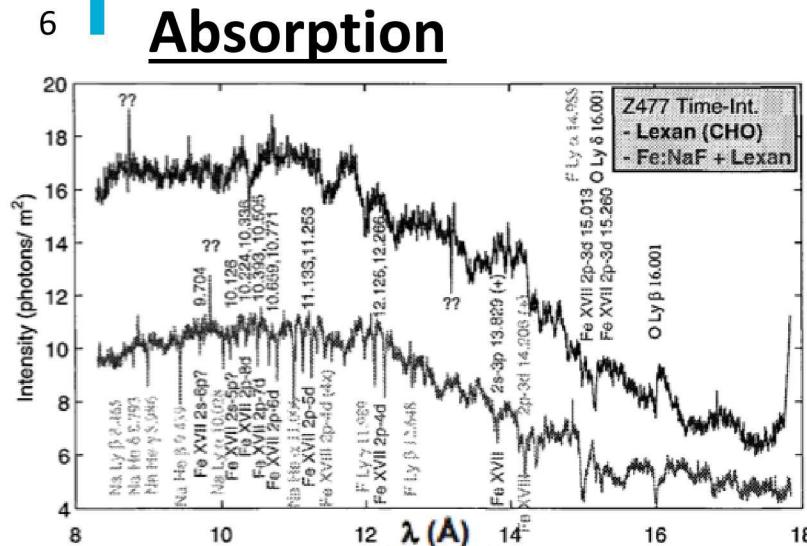
J. Bailey et al., Phys. Rev. Lett., 99 (2007)



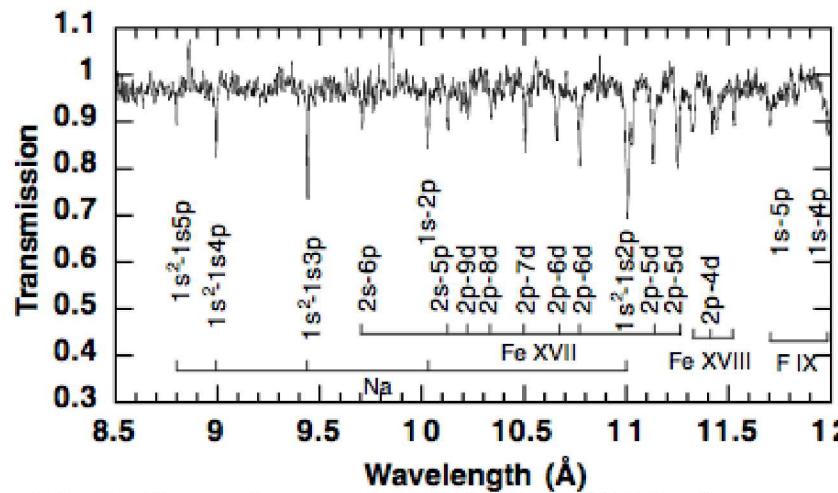
Transmission measured to 10% accuracy

# Few photoionized plasma experiments exist

## Absorption

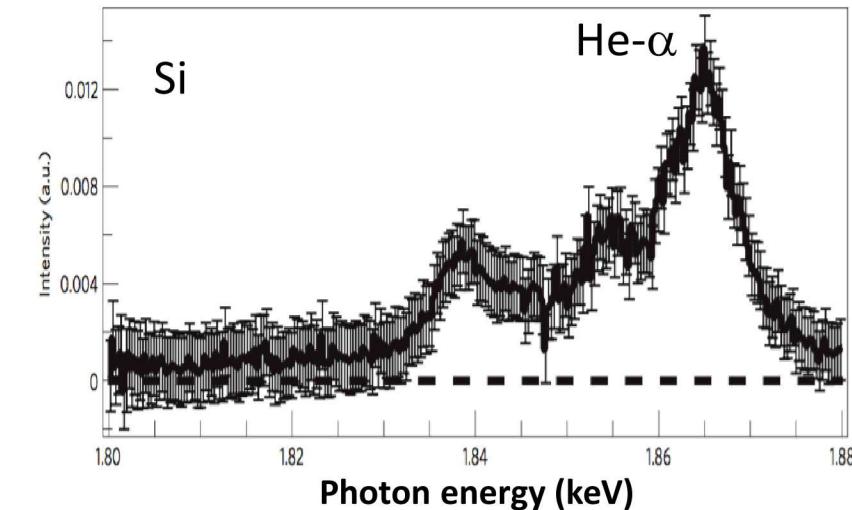


R. F. Heeter, J. E. Bailey, M. E. Cuneo, *et al.*, AIP CP, **547**, (2000).



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

## Emission



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

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.

# 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*:

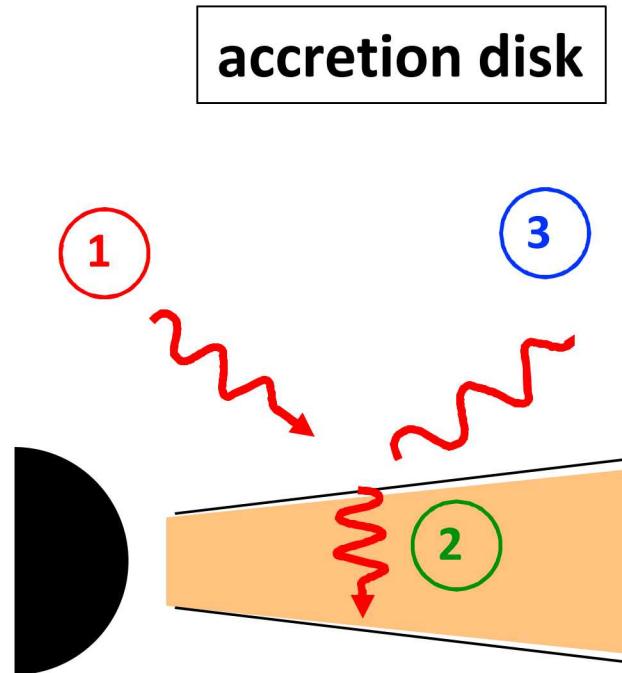
- Large column density for high S/N

Since column = density  $\times$  length , density  $< 10^{19}$  e<sup>-</sup>/cc  $\rightarrow$  large  $\sim$ 1cm plasma size

Experiments on the Z Facility can meet these criteria.

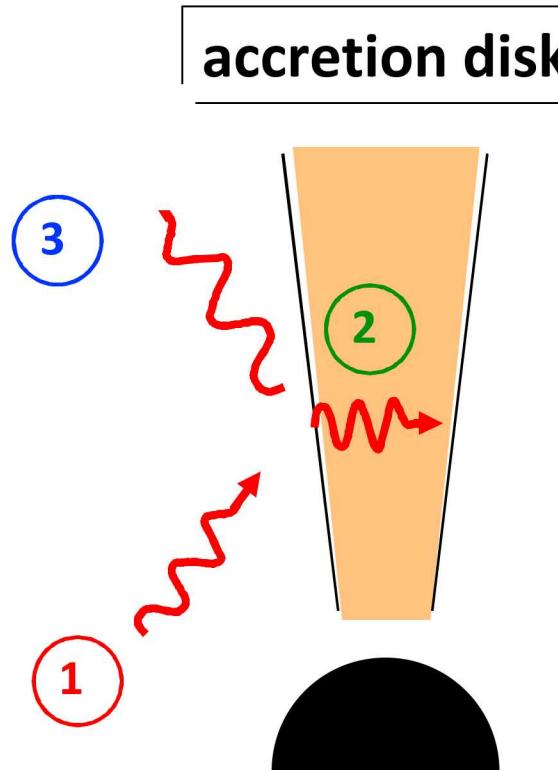
# Goal: build a laboratory analog for accretion disk X-ray emission

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



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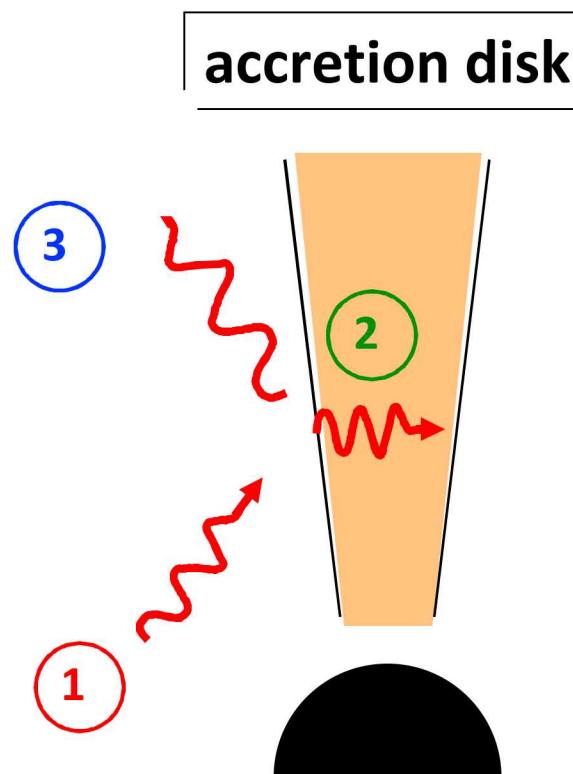
# Goal: build a laboratory analog for accretion disk X-ray emission

10

1 X-ray illumination

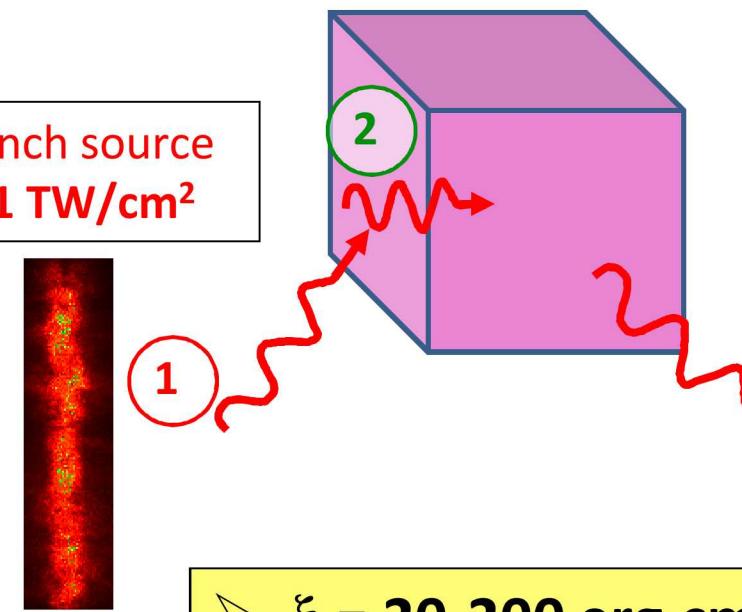
2 Photon ionization and atomic kinetics

3 Plasma emission



laboratory

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



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

$\rightarrow \xi = 20-200 \text{ erg.cm/s}$

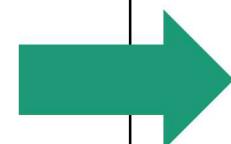
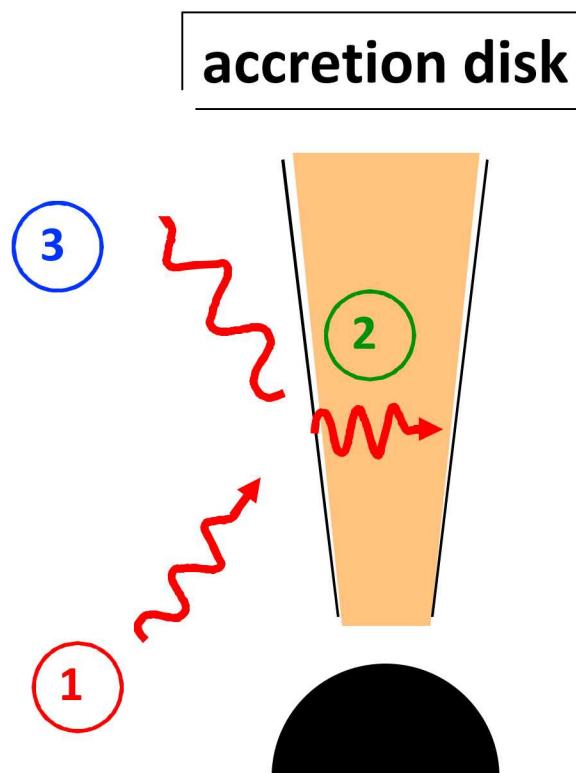
# Goal: build a laboratory analog for accretion disk X-ray emission

11

1 X-ray illumination

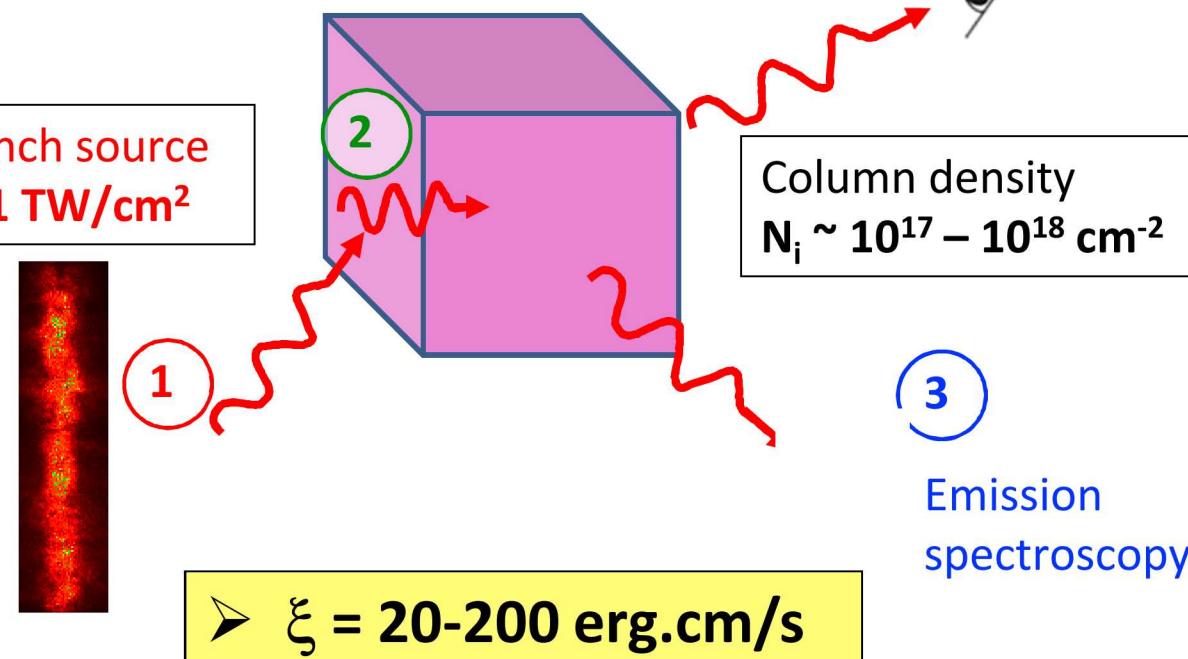
2 Photon ionization and atomic kinetics

3 Plasma emission



laboratory

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



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

12

1 X-ray illumination

2 Photon ionization and atomic kinetics

3 Plasma emission

laboratory

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

4 Absorption spectroscopy

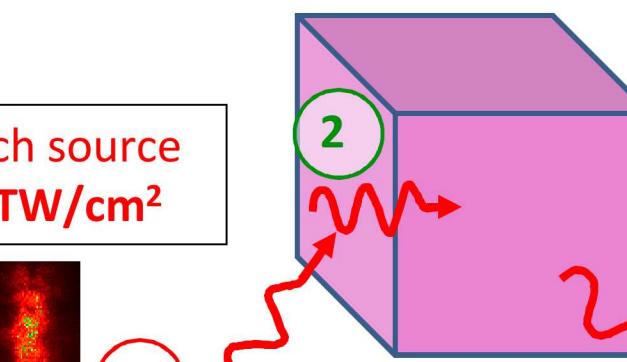
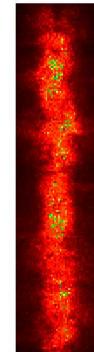
## Advantages

- 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

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

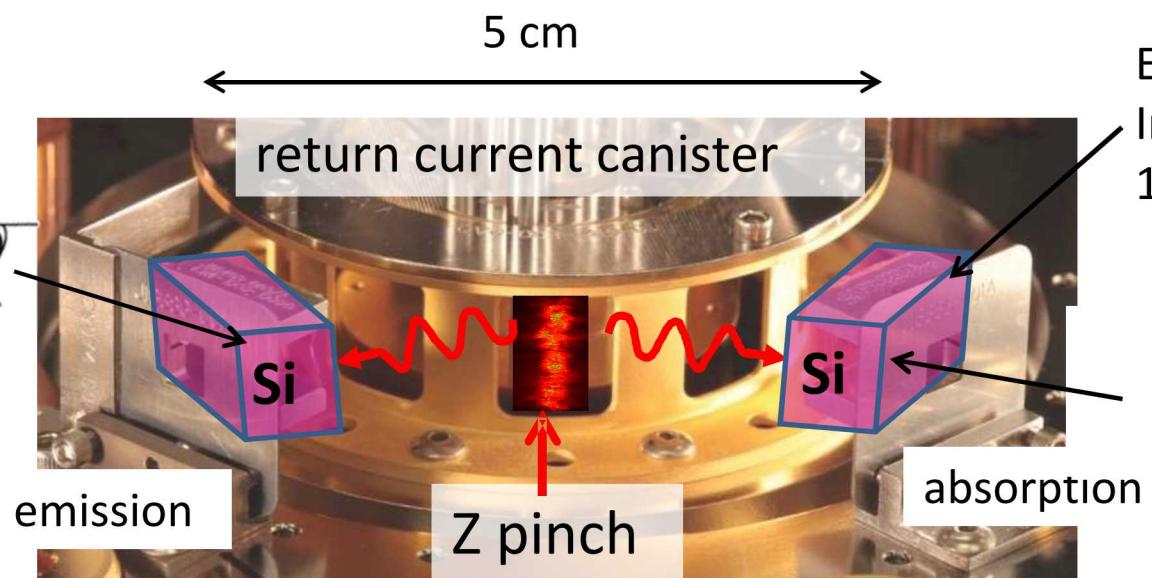


Column density  
 $N_i \sim 10^{17} - 10^{18} \text{ cm}^{-2}$

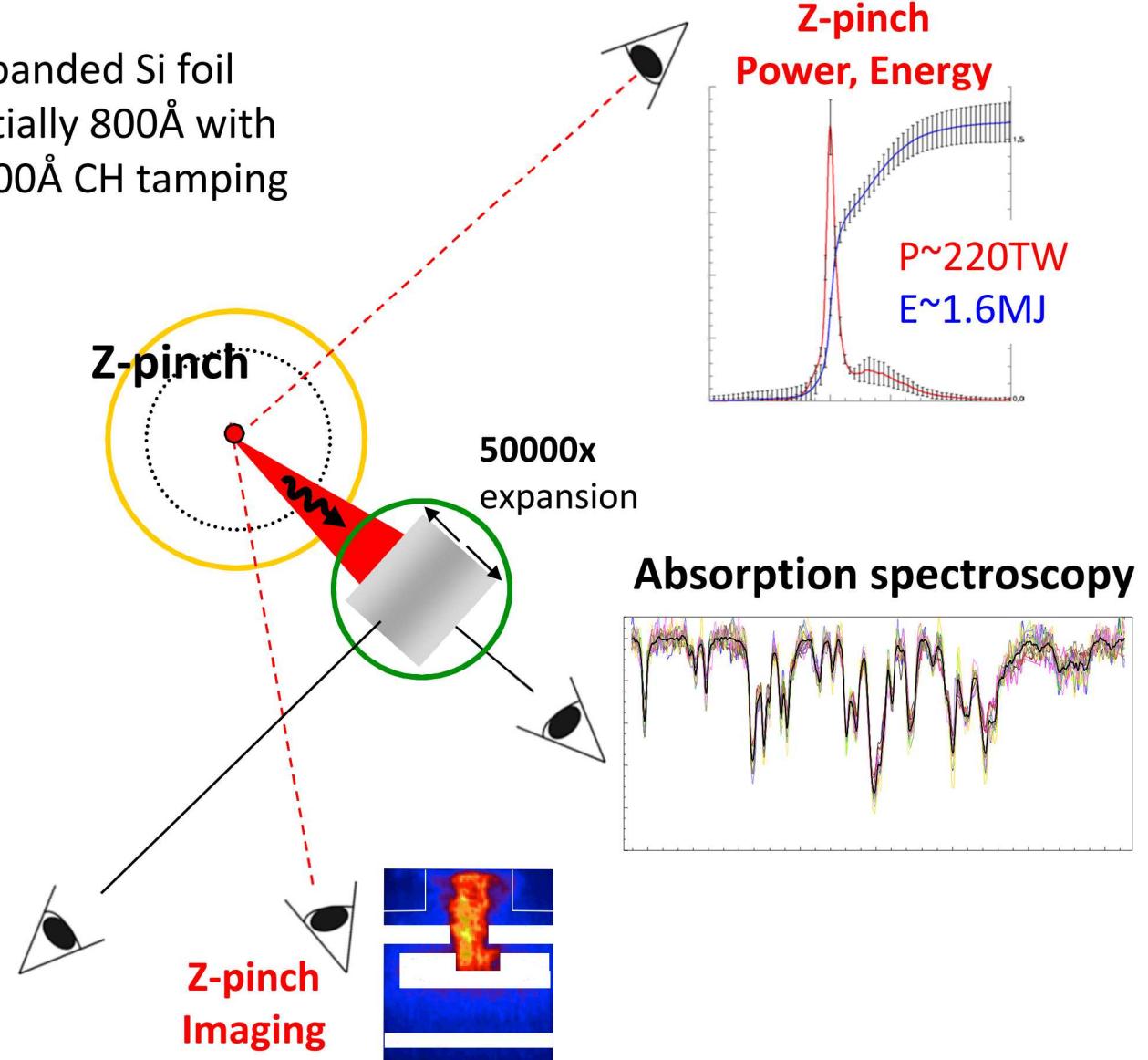
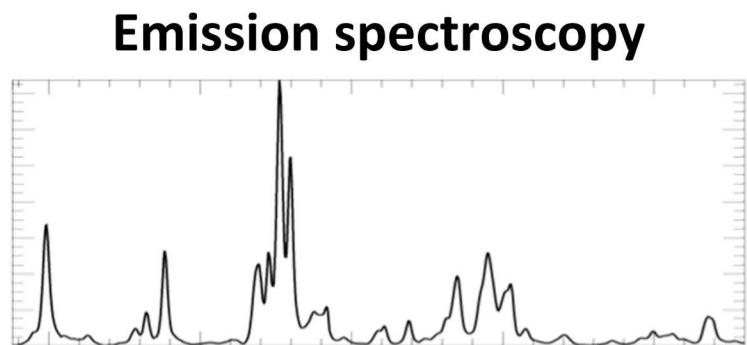
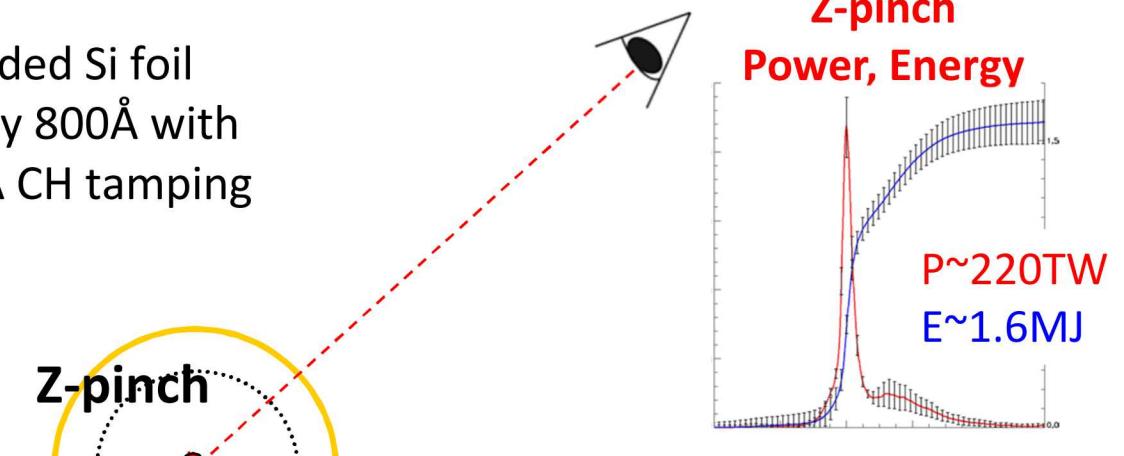
3 Emission spectroscopy

➤  $\xi = 20-200 \text{ erg.cm/s}$

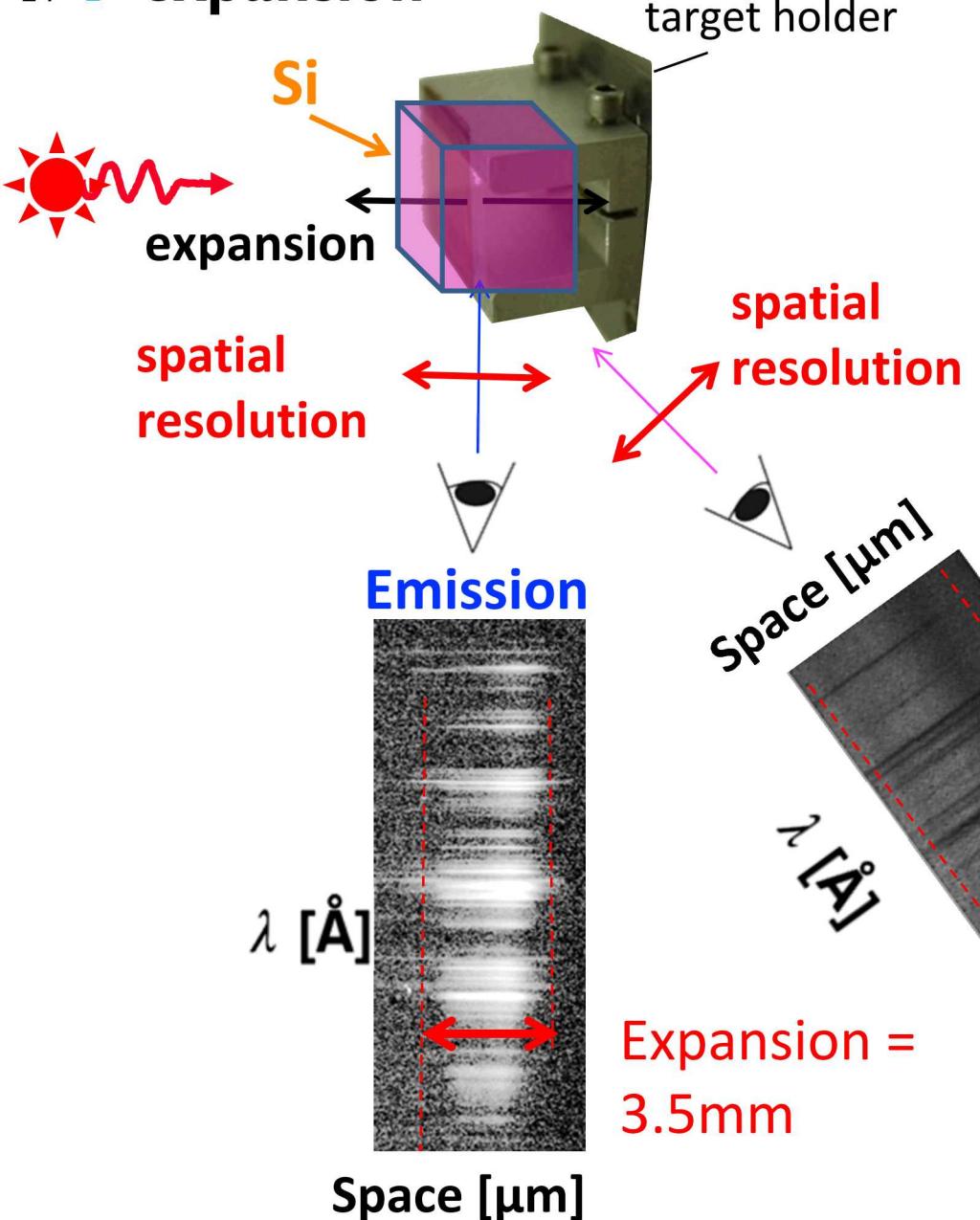
# All required inputs are obtained on a single Z shot, confirm the plasma is photoionized and at relevant regime



Expanded Si foil  
Initially 800Å with  
1000Å CH tamping



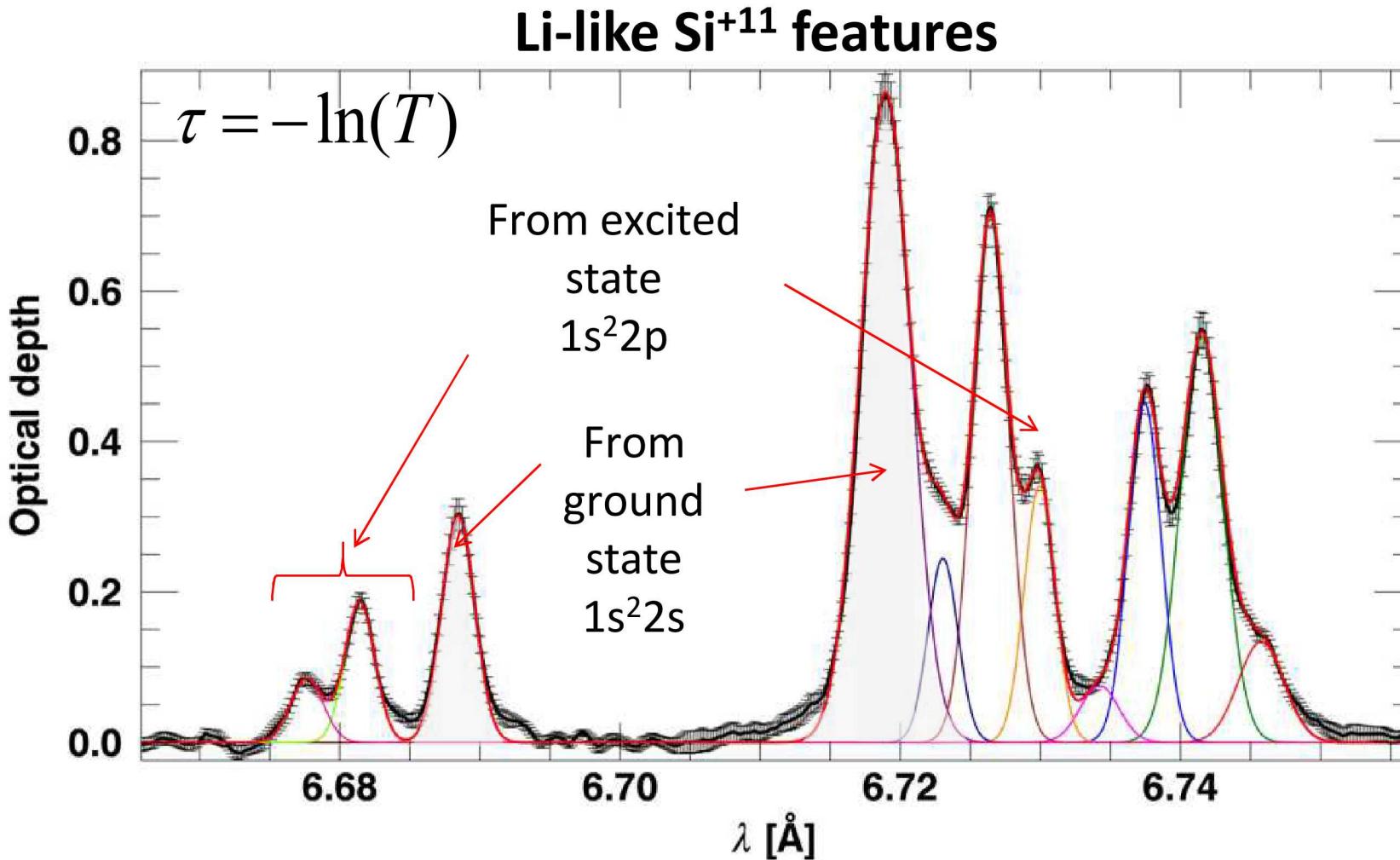
# Ion density is measured from the sample areal mass and sample expansion



## 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

# 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

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

$$\bar{Z} = 10.3 \quad \text{with radiation}$$

$$\bar{Z} = 5.3 \quad \text{without radiation}$$

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

# 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

$$F \sim 1.3 \cdot 10^{19} \text{ erg/cm}^2/\text{s}$$

$$T_{\text{color}} = [45, 80, 170] \text{ eV}$$

## Average charge

$$Z^* \sim 10, \text{ Si}^{+10}$$

## Electron density

$$n_e = 8 \times 10^{18} \text{ e}^-/\text{cm}^3$$

## Photoionization parameter

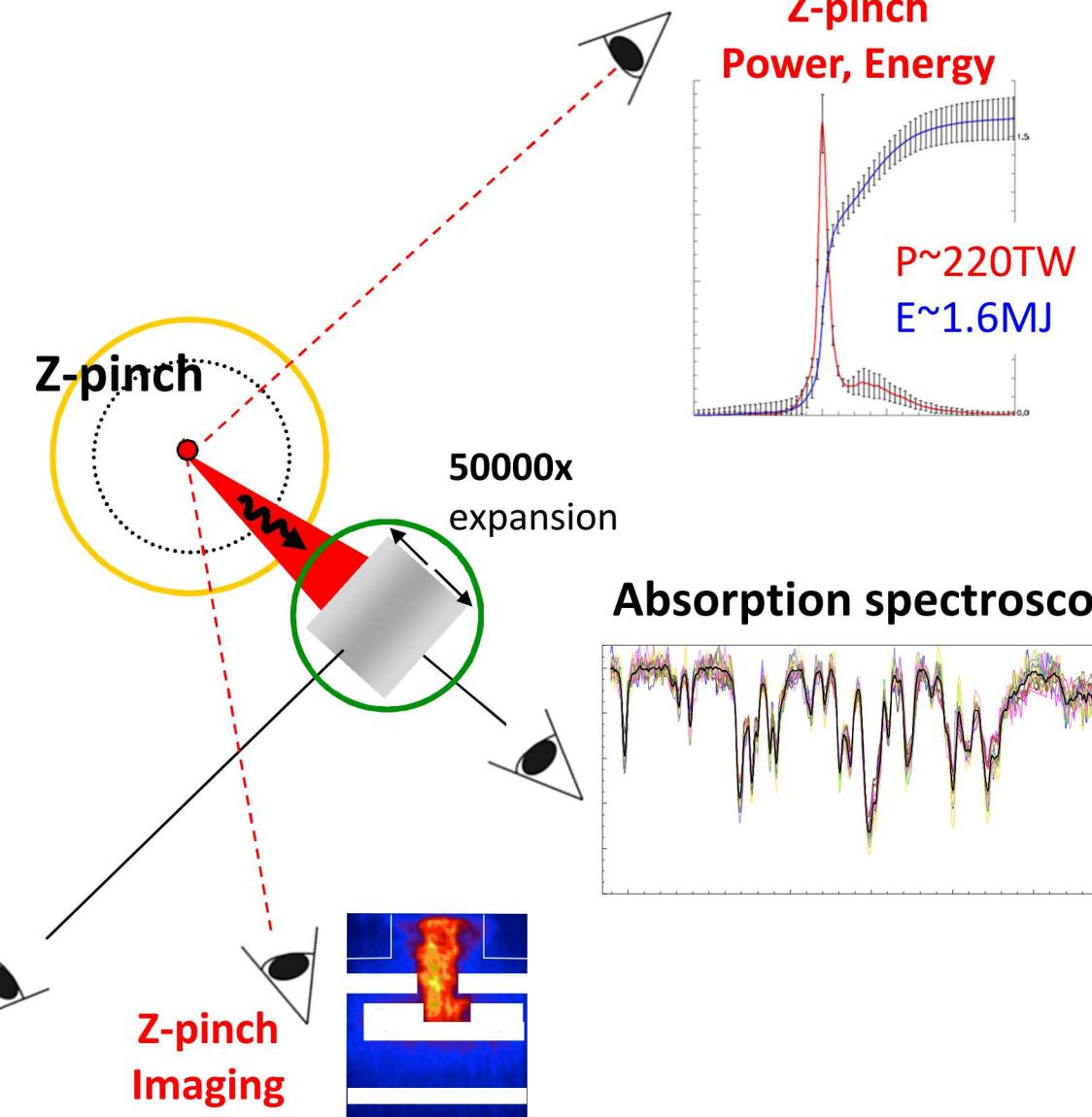
$$\xi \sim 20-300 \text{ erg.cm/s}$$

## Column density (adjustable)

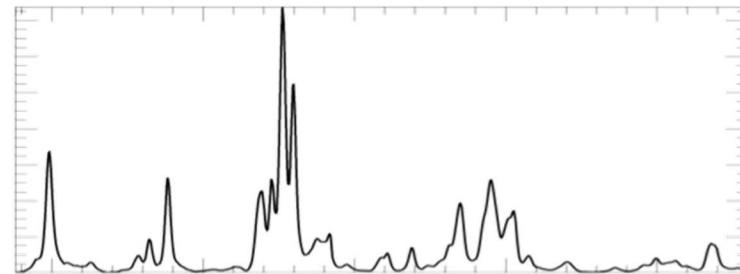
$$N_i \sim 2.5 - 10 \cdot 10^{17} \text{ Si/cm}^2$$

## Electron temperature

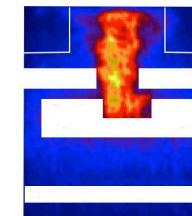
$$T_e = 26 - 40 \text{ eV}$$



## Emission spectroscopy

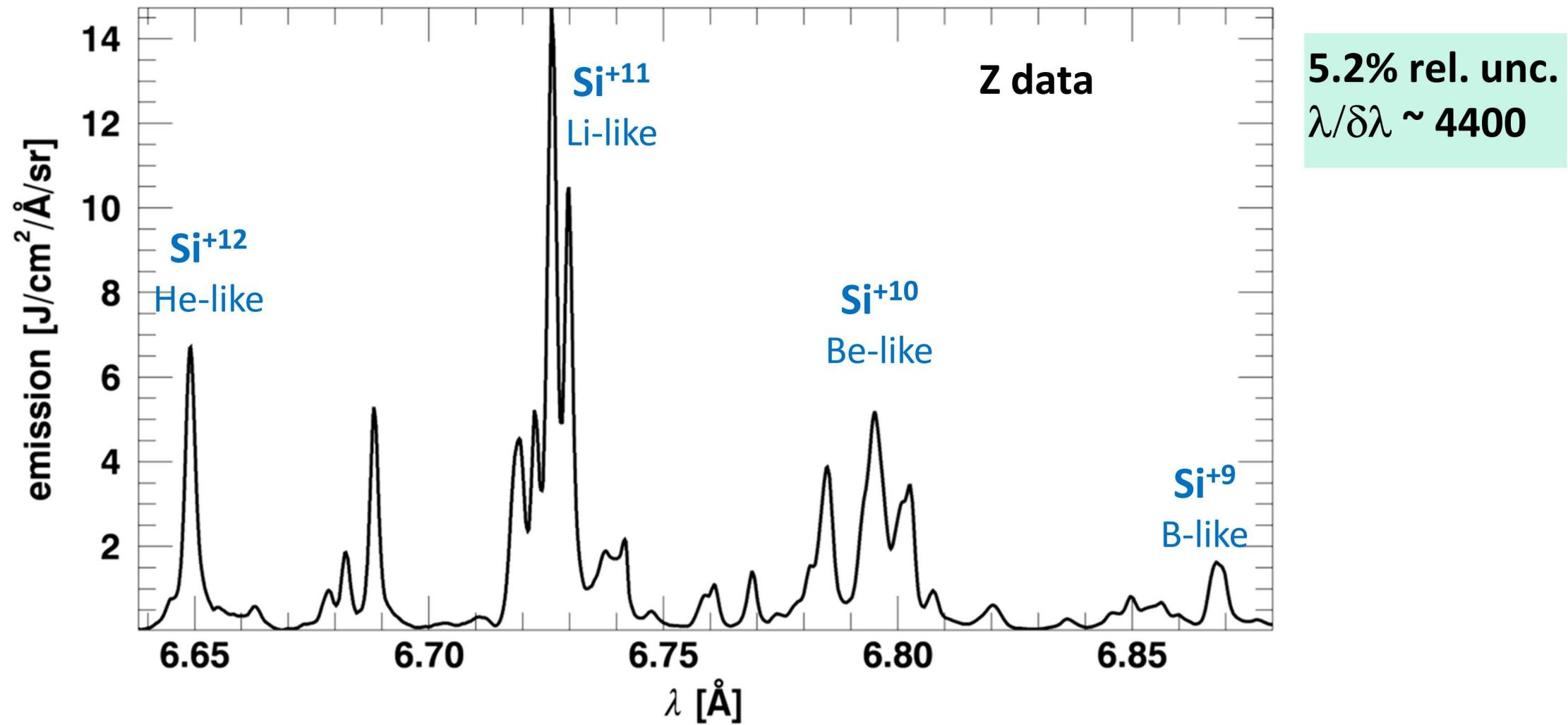


## Z-pinch Imaging



# The emission data shows contributions from different charge states

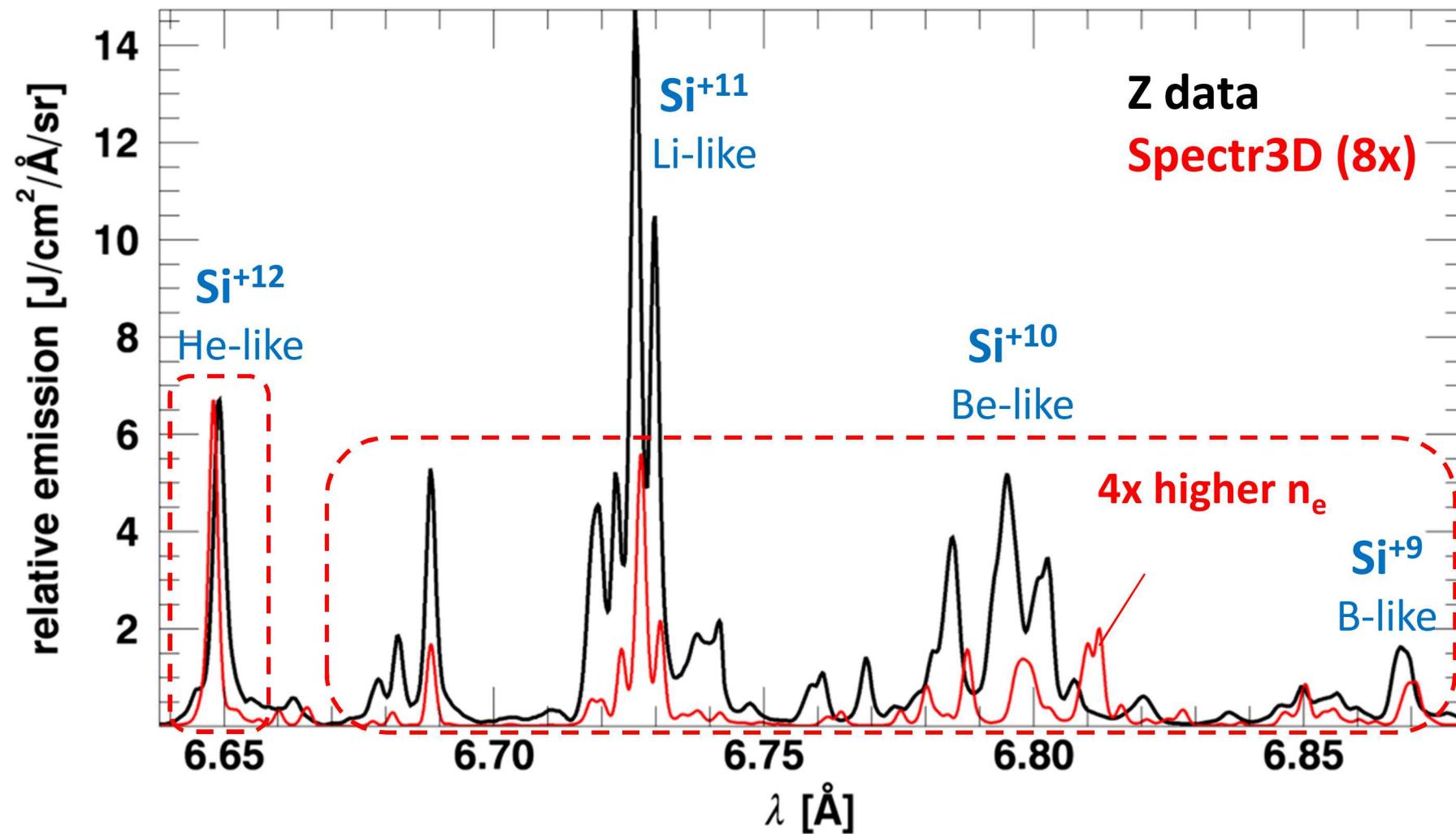
17



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

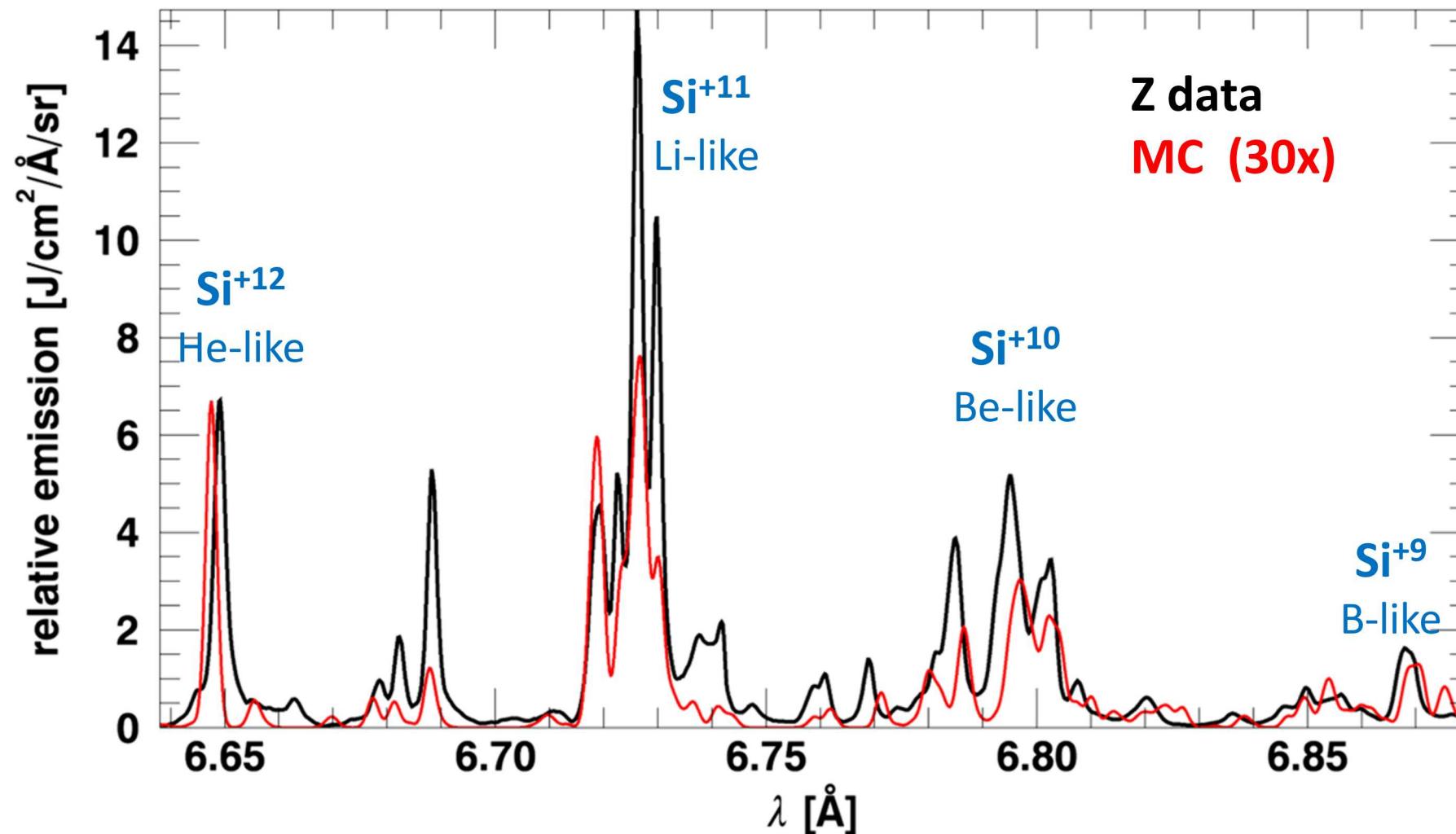
\*Ross and Fabian, MNRAS, 278 (1996), Loisel et al., PRL 119 (2017)

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



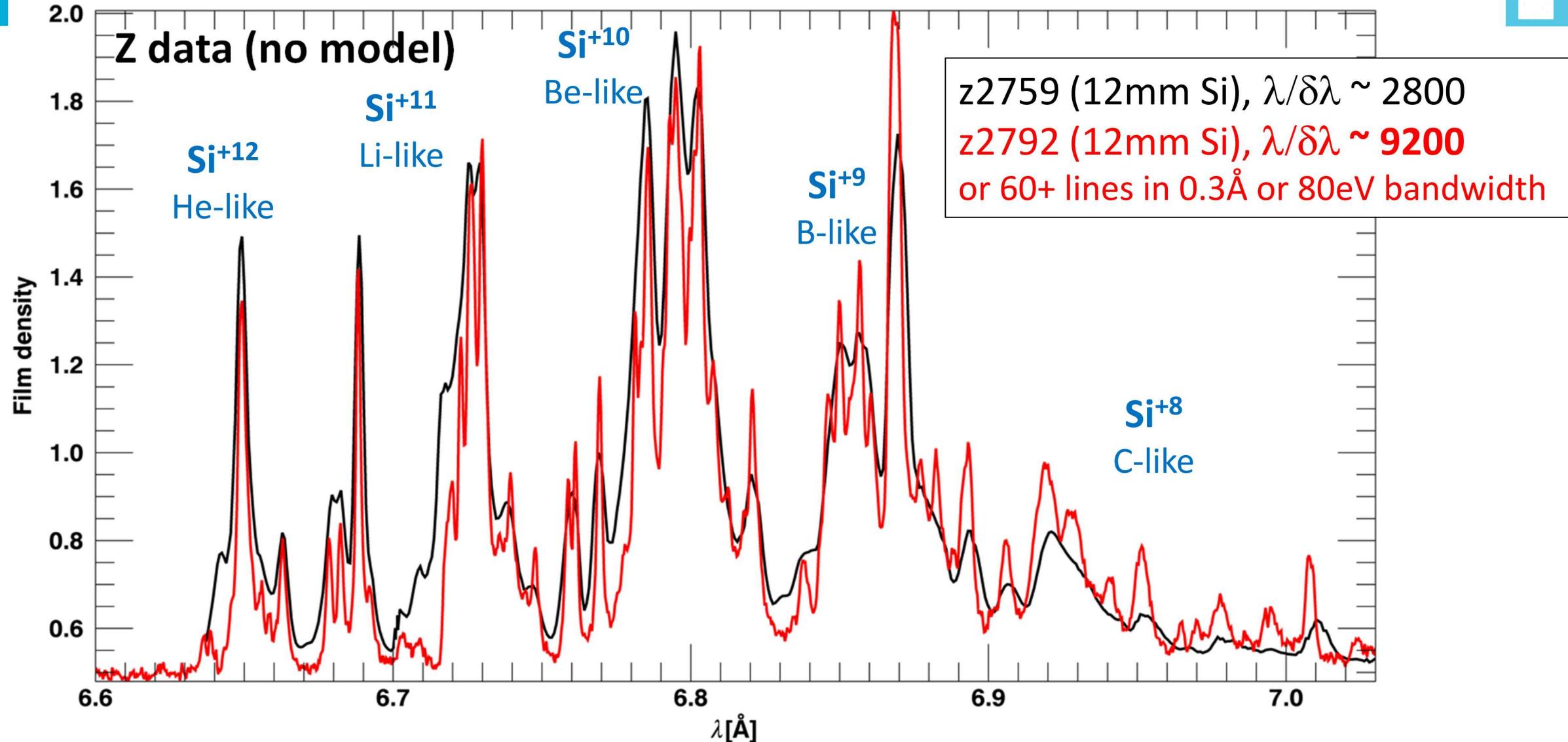
With normalization to  $\text{Si}^{+12}$  ( $\text{He}\alpha$ ) models under predict lines from lower charge state

# Comparison with a Monte Carlo radiation transport code exhibits improved agreement



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

## Emission spectra are also measured at very high spectral resolution

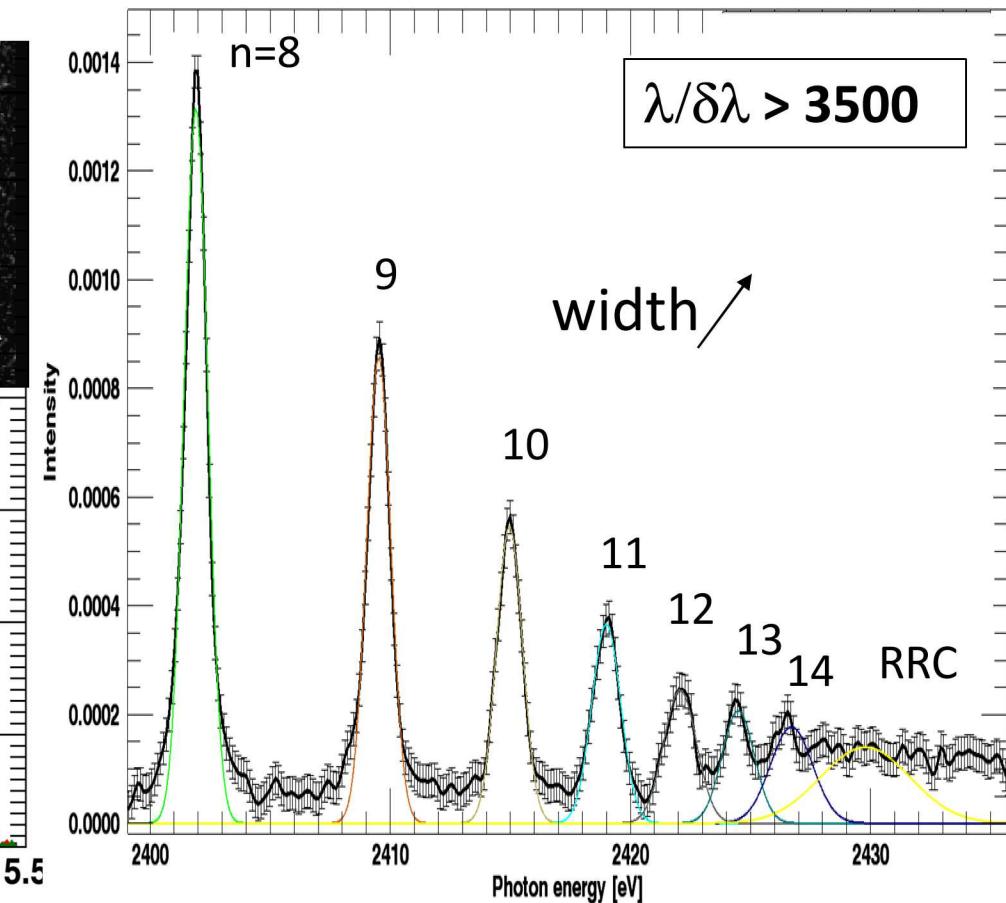
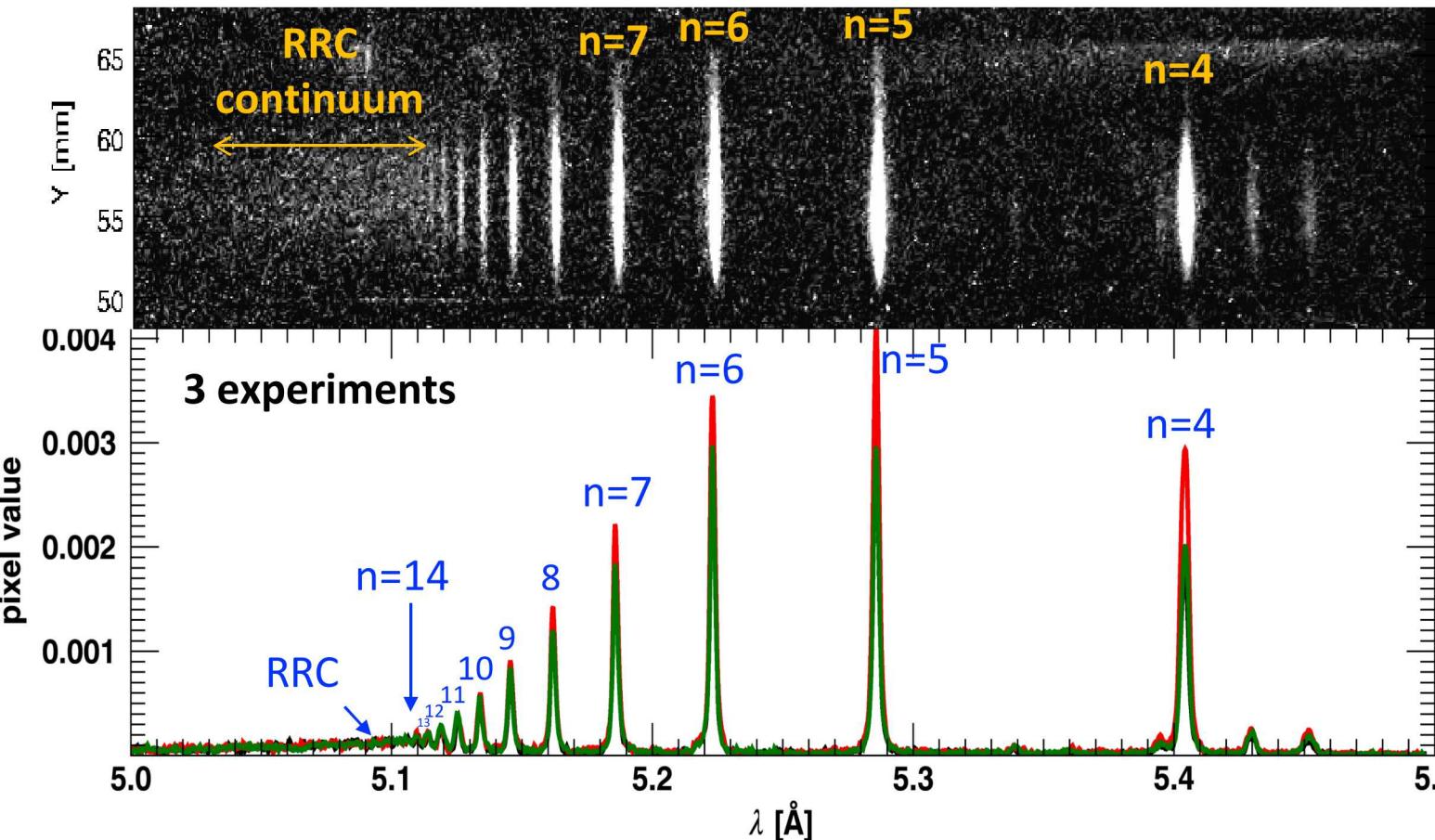


We can study very detailed level structure and more precise radiation transport effects on lines that have variable optical depth.

# High- $n$ , $n \leq 14$ , He-like transitions with merging into the continuum first obtained in a laboratory photoionized plasma



## Silicon closer to the x-ray source

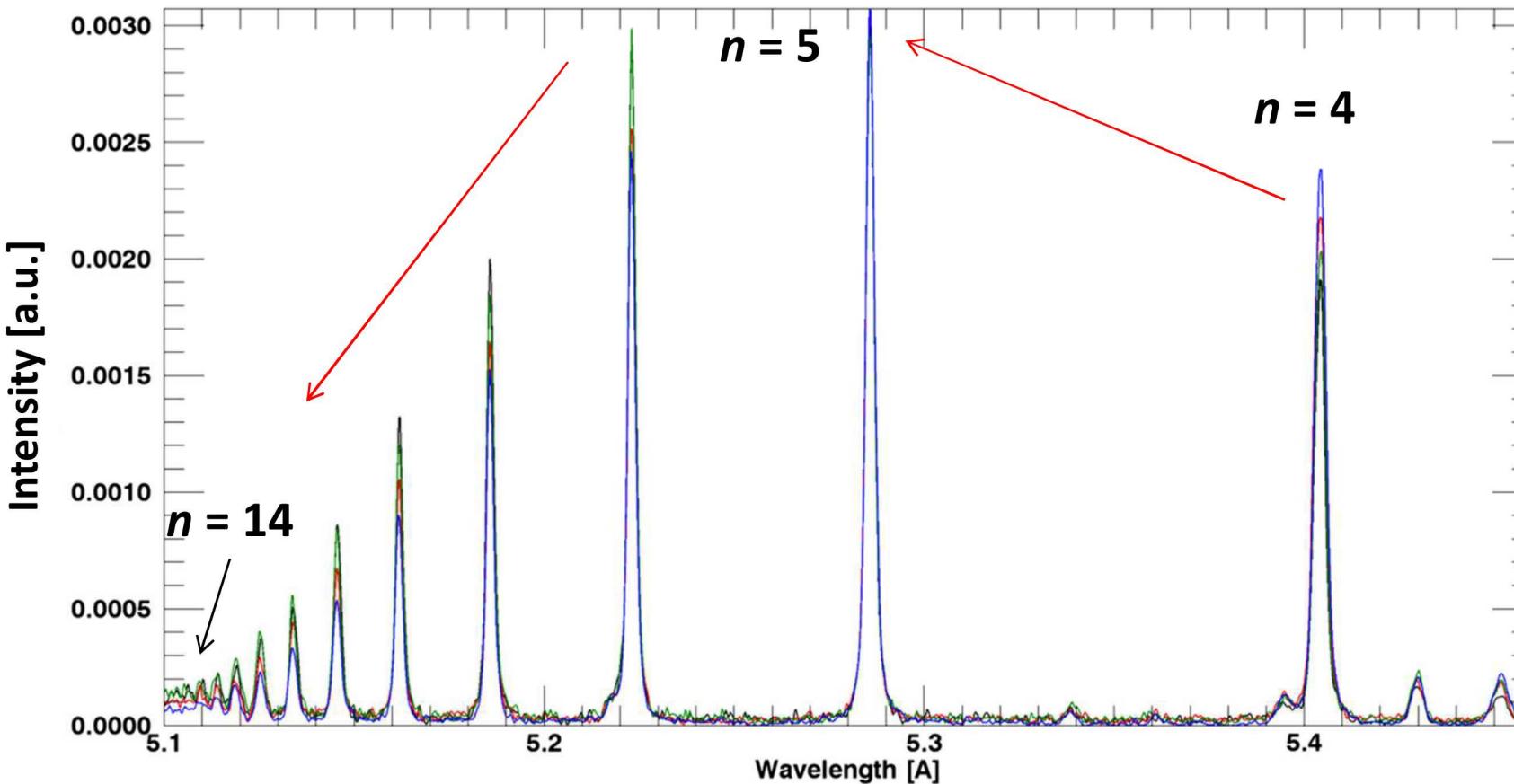


→ Effect of line shape, line broadening, continuum lowering on the RRC can be studied. High- $n$  lines getting broader with  $n \rightarrow$  density sensitivity.

# 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:

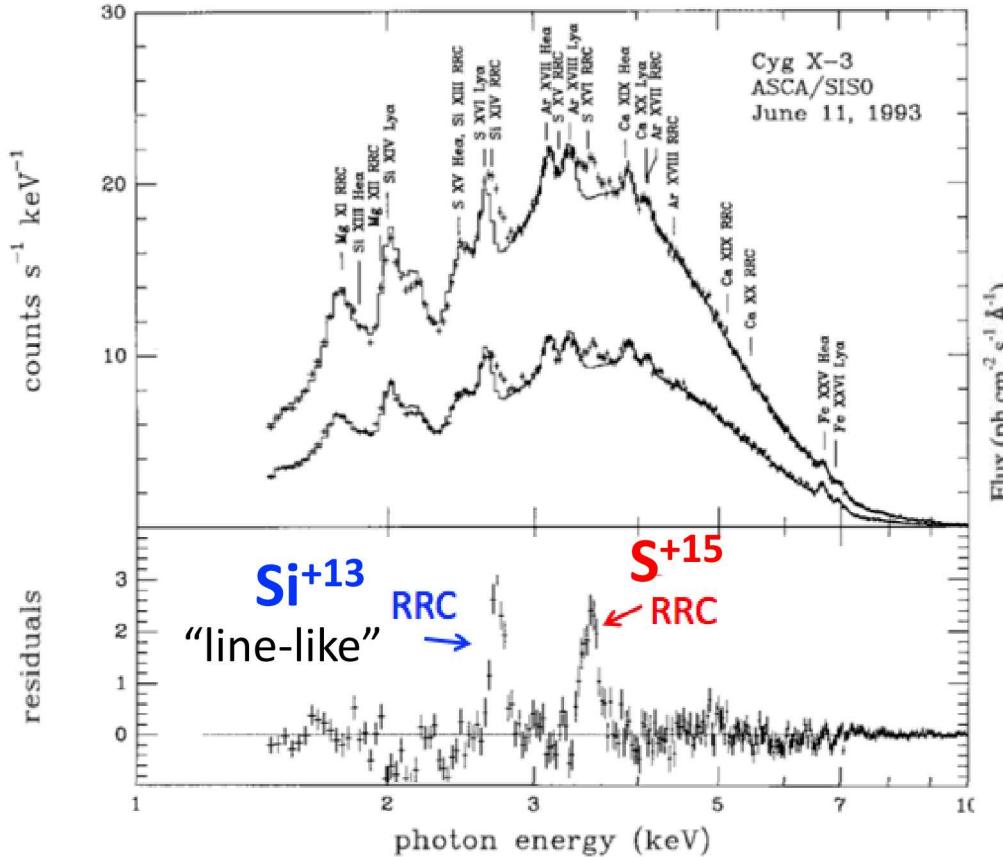
- recombination following photoionization
- or photoexcitation

Also line intensity is affected by radiation transport.

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

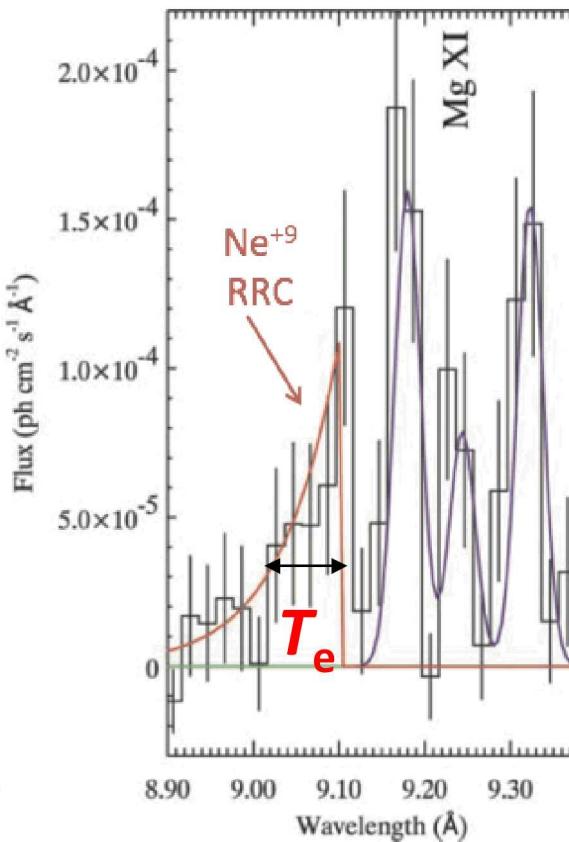
# The radiative recombination continuum (RRC) is considered the most reliable temperature diagnostics for accretion-powered objects

Cygnus X-3



$$T_e = 5-50 \text{ eV} [1]$$

Vela X-1



$$T_e = 10 \pm 2 \text{ eV} [2]$$

$$T_e = 6.6 \pm 2 \text{ eV} [3]$$

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

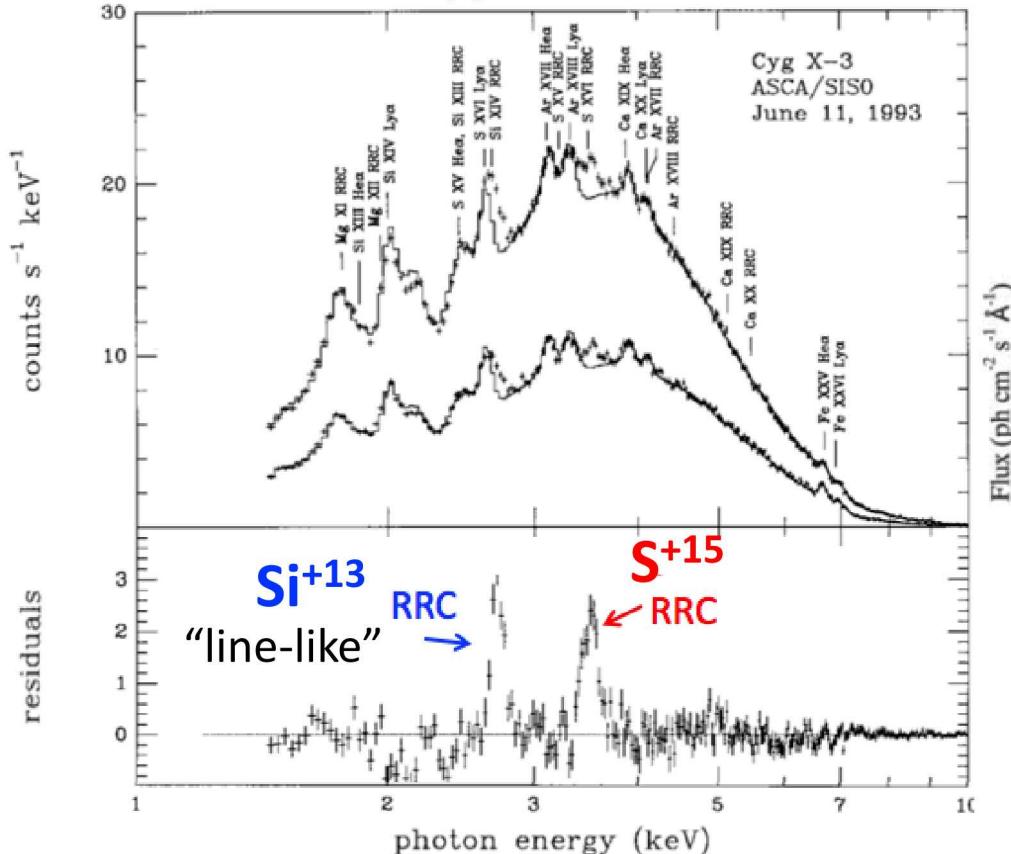
## Requirements to observe RRC:

1. low temperature  $T_e \ll I_p$  (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.

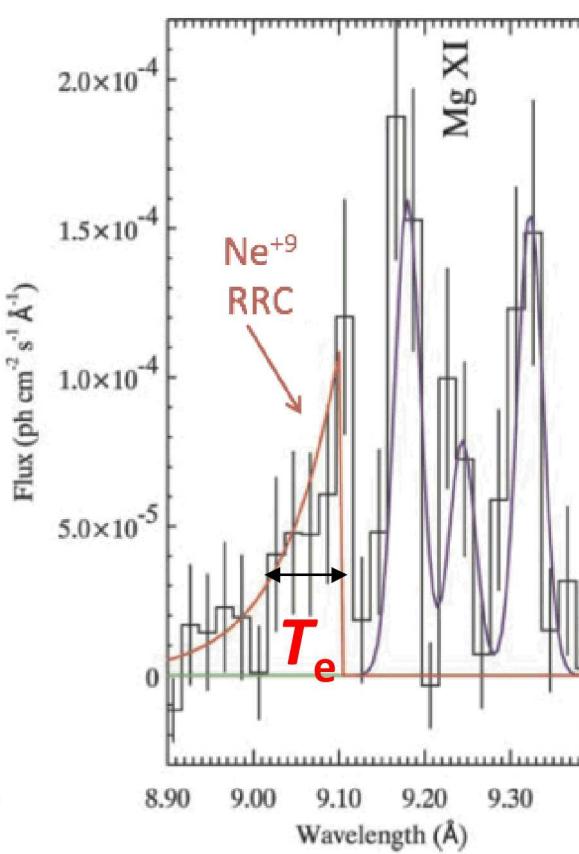
# First RRC ( $\sim 10^{-8}$ Z-pinch energy) in a photoionized plasma in a terrestrial laboratory was recorded

Cygnus X-3



$$T_e = 5-50 \text{ eV} [1]$$

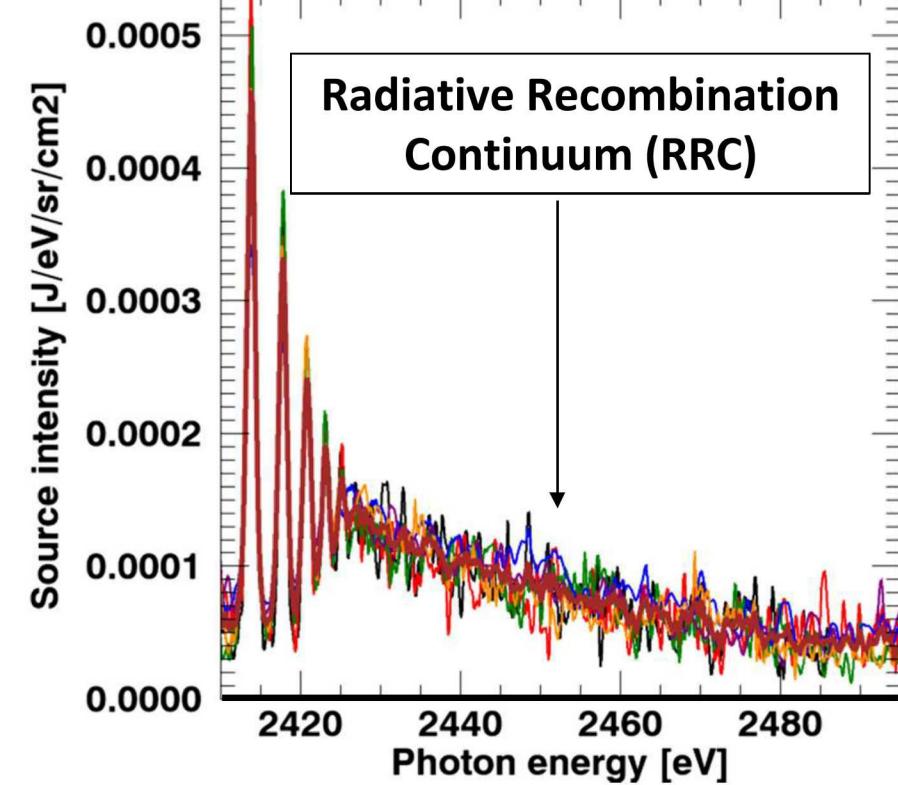
Vela X-1



$$T_e = 10 \pm 2 \text{ eV} [2]$$

$$T_e = 6.6 \pm 2 \text{ eV} [3]$$

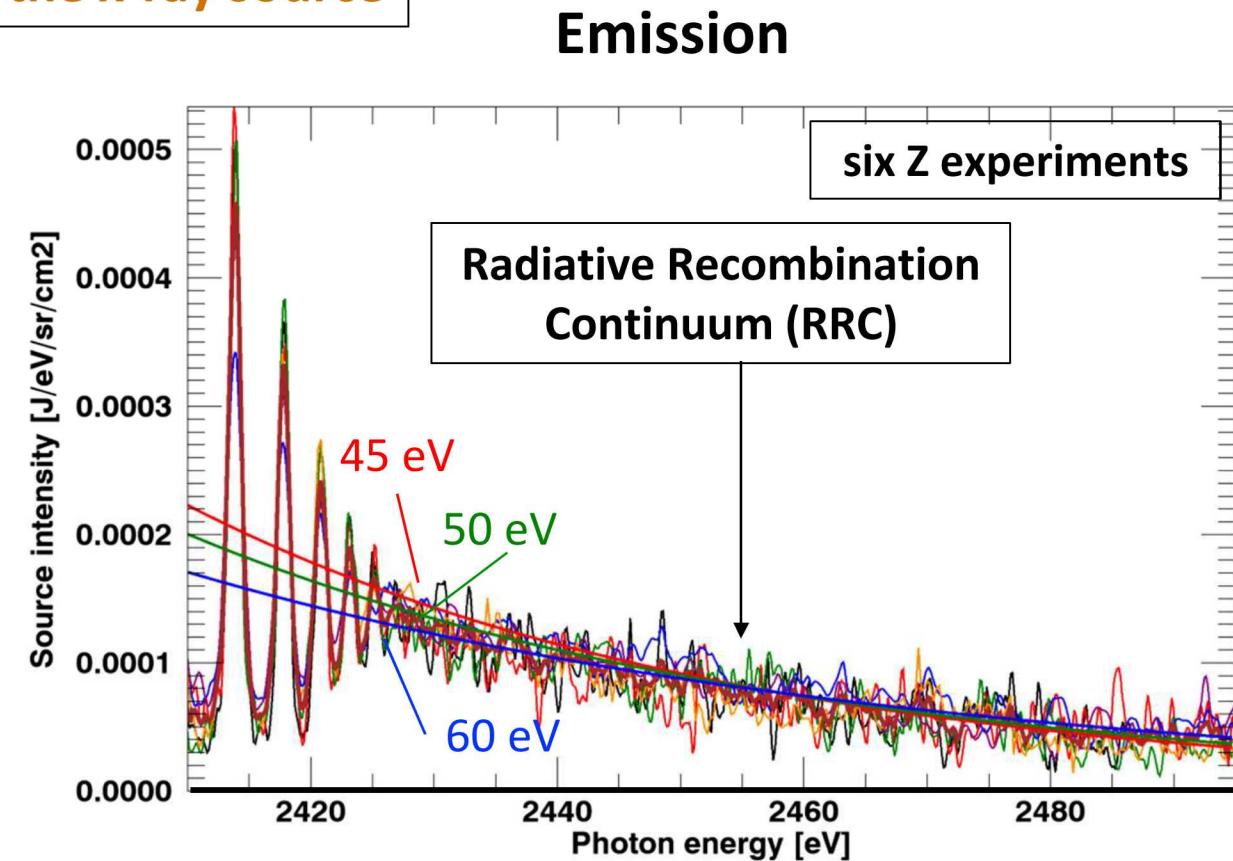
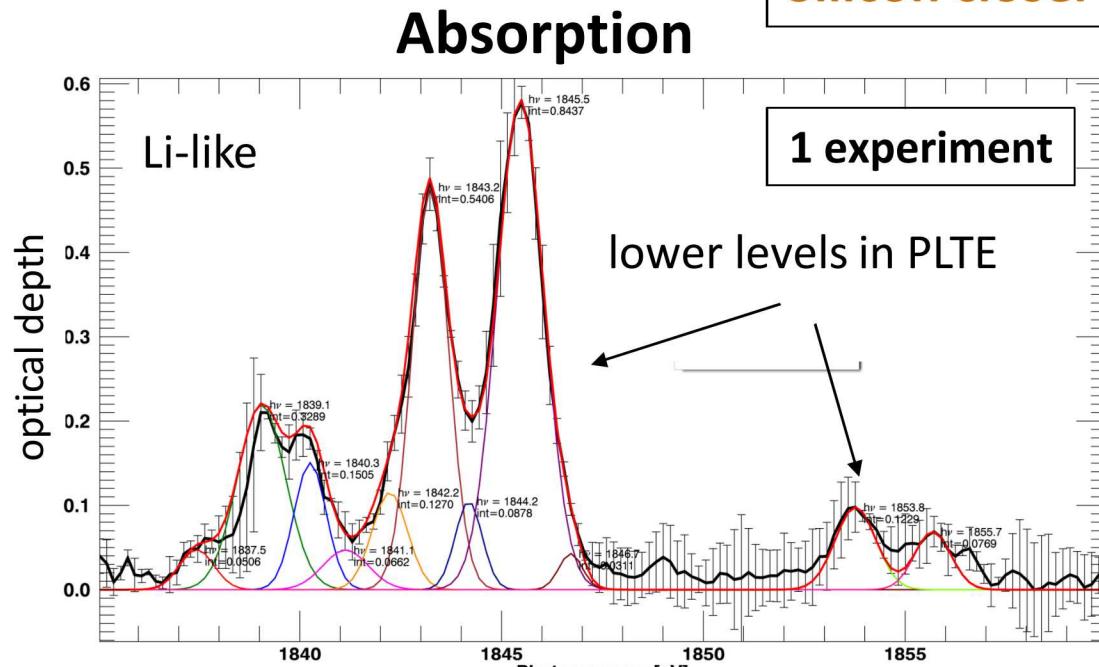
Earth: Z plasma

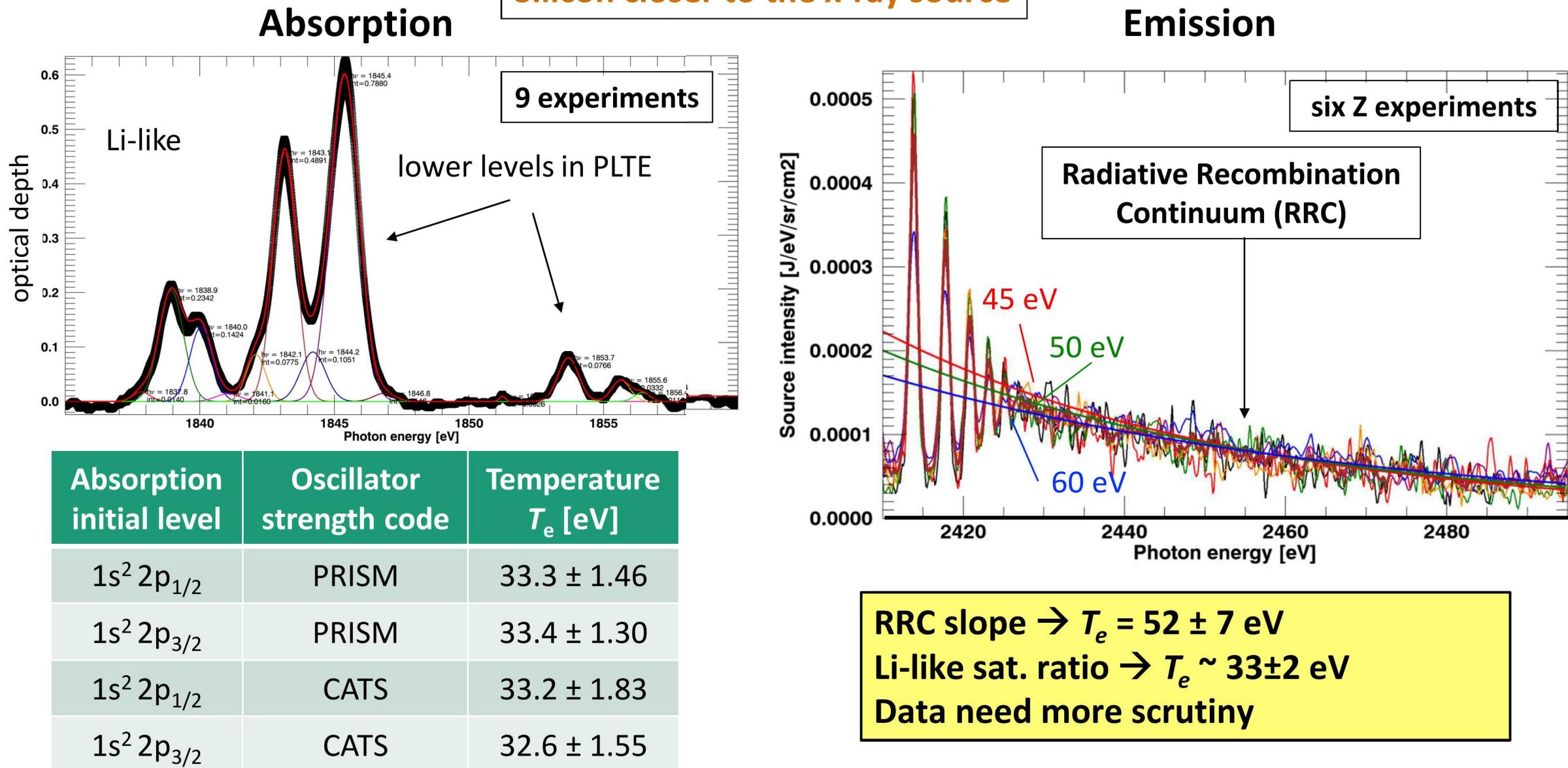


exp. slope  $\Rightarrow T_e$   
 $\rightarrow \sim$ Maxwellian  $e^-$  distribution

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

# Preliminary: temperature inferred from line absorption agreed with the RRC slope

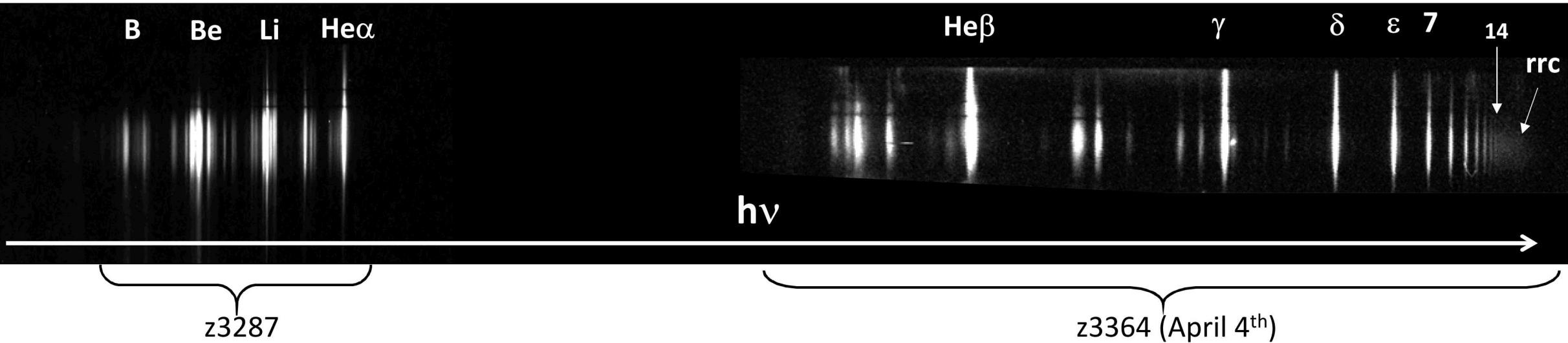




# The complete He-like series up to n=14 can be obtained for a single target thanks to the new XRS3 extended range design



## Photoionized Silicon plasma emission on Z



Extended range XRS3 spectrometer data

The complete He-like series will facilitate the comparison between data and model for photoionized plasma emission.

# 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 - 1 keV is measured to  $\pm 20\%$ , 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

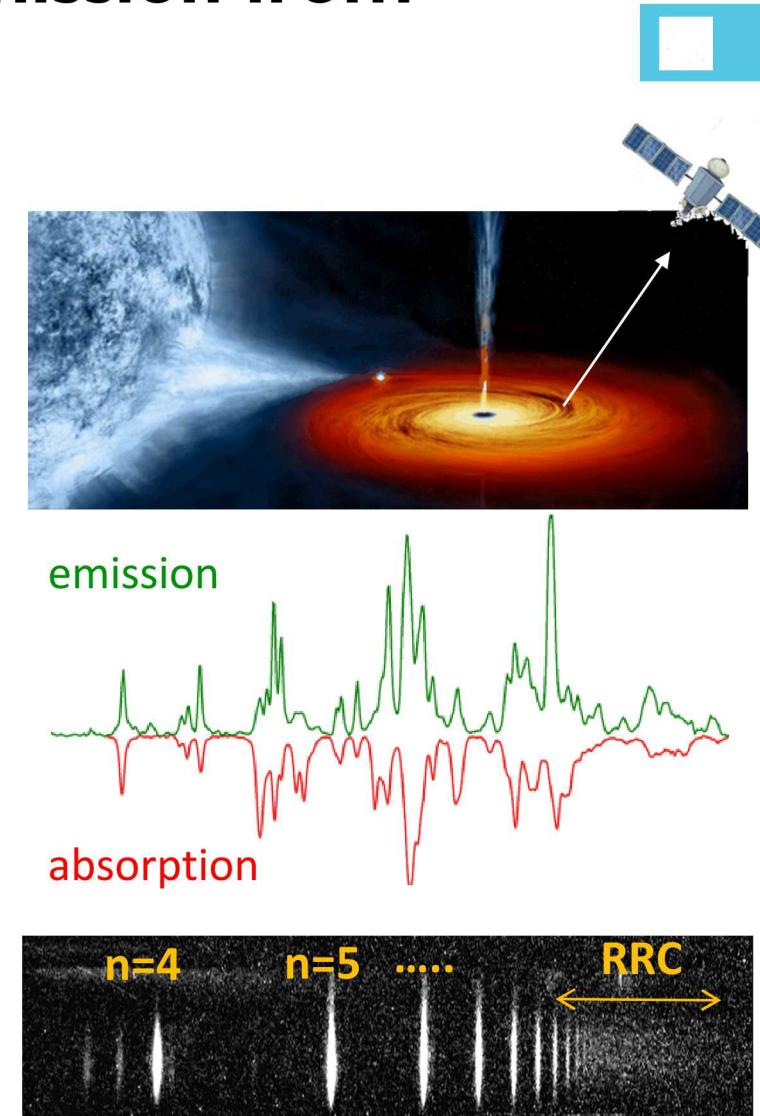
## Scrutiny is required for the models

- 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...
- XSTAR revisions have been carried: angular distribution of the drive, updated oscillator strengths. Future: treatment of radiation transport will be scrutinized.

# 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

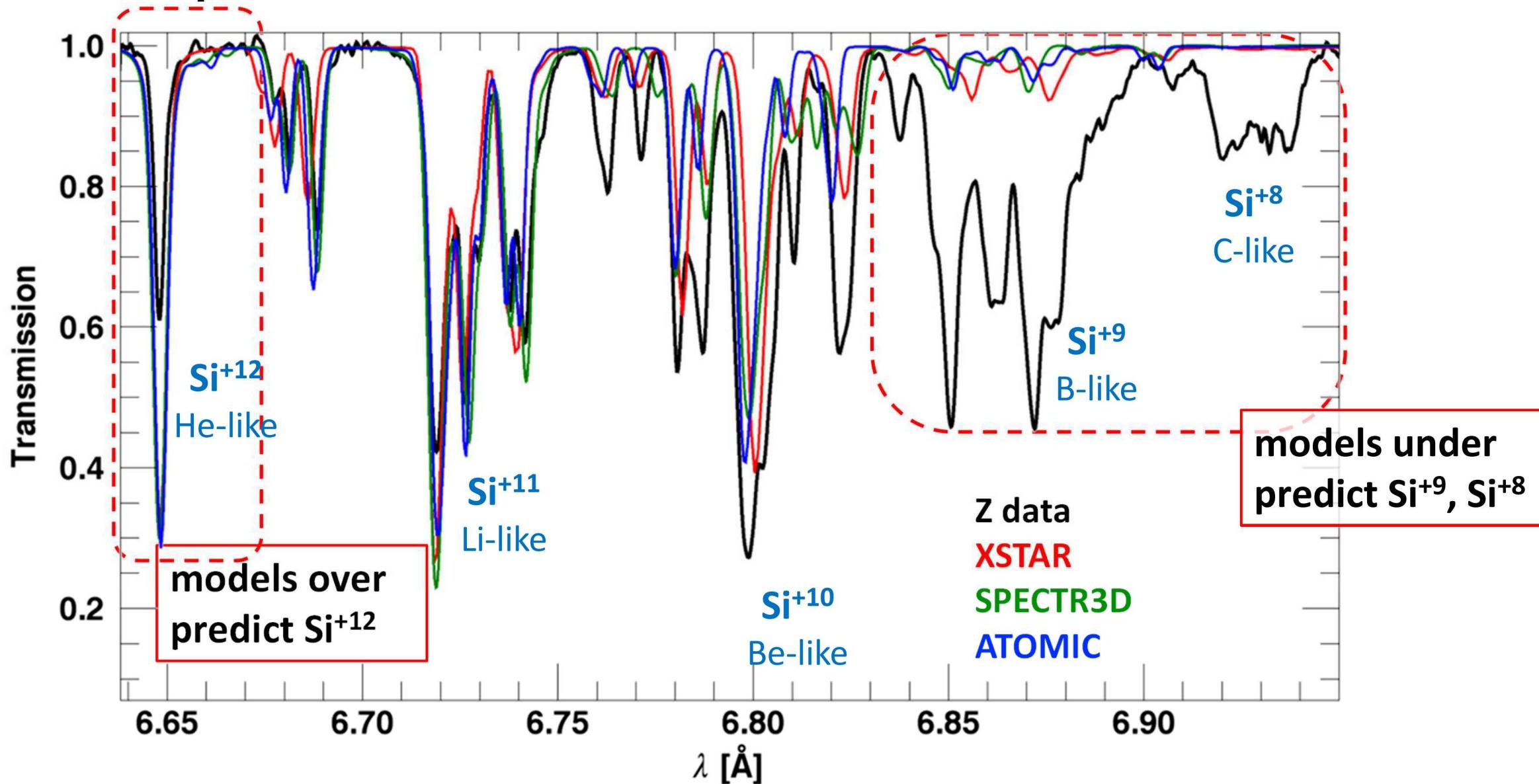
These results raise questions about the suitability of models used to interpret astrophysical observations



# Extra slides

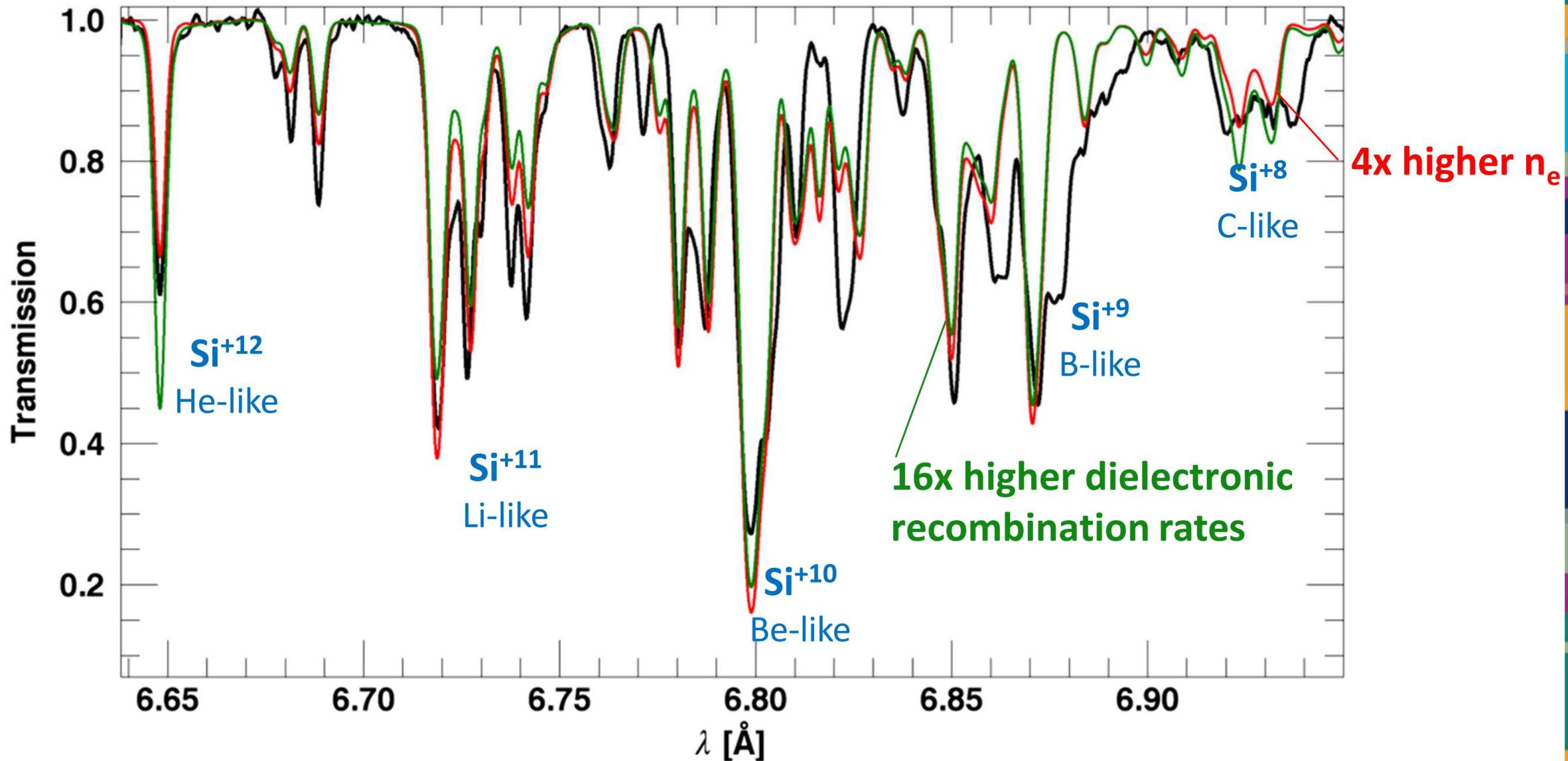
# Measured relative absorption from different ion stages tests model ionization predictions

31



# Agreement can be obtained by adjusting parameters that increase recombination

32



# Results and puzzles are documented

33

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,<sup>1</sup> J. E. Bailey,<sup>1</sup> D. A. Liedahl,<sup>2</sup> C. J. Fontes,<sup>3</sup> T. R. Kallman,<sup>4</sup> T. Nagayama,<sup>1</sup> S. B. Hansen,<sup>1</sup> G. A. Rochau,<sup>1</sup> R. C. Mancini,<sup>5</sup> and R. W. Lee<sup>6</sup>

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.

