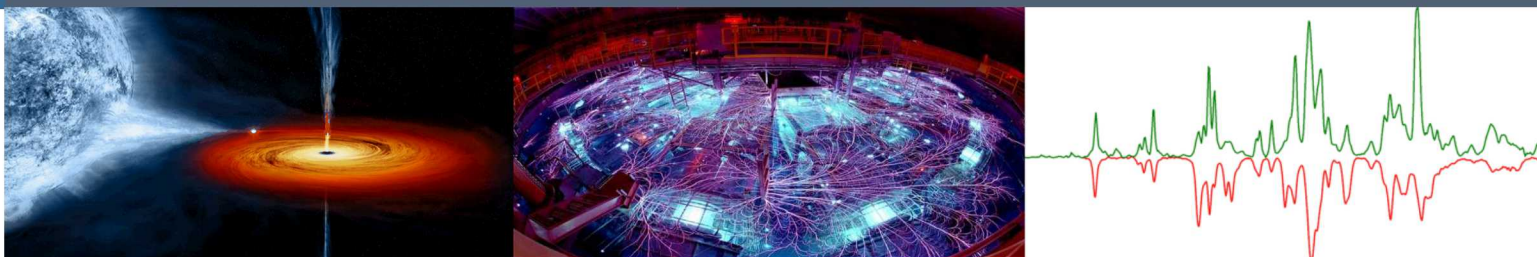SAND2019-4155C

A benchmark Experiment for X-ray Emission and Temperature Diagnostics in Accretion-Powered Photoionized Plasmas

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

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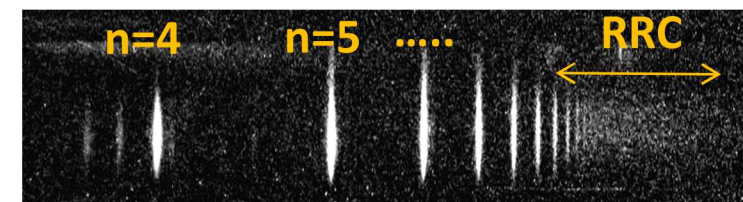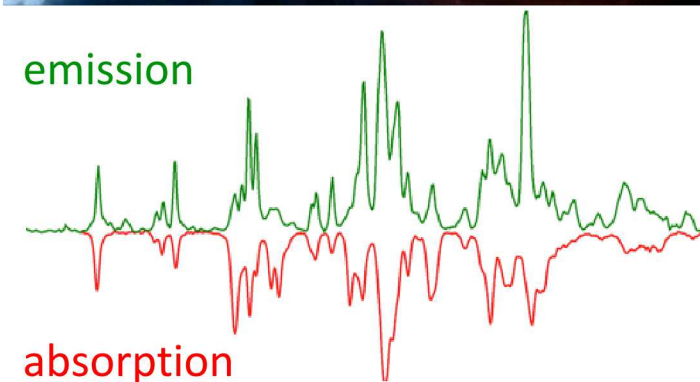
20th APiP
April 9–12th, 2019
Gaithersburg, MD

1

Summary: Z data can benchmark models of emission from photoionized accretion-powered plasmas
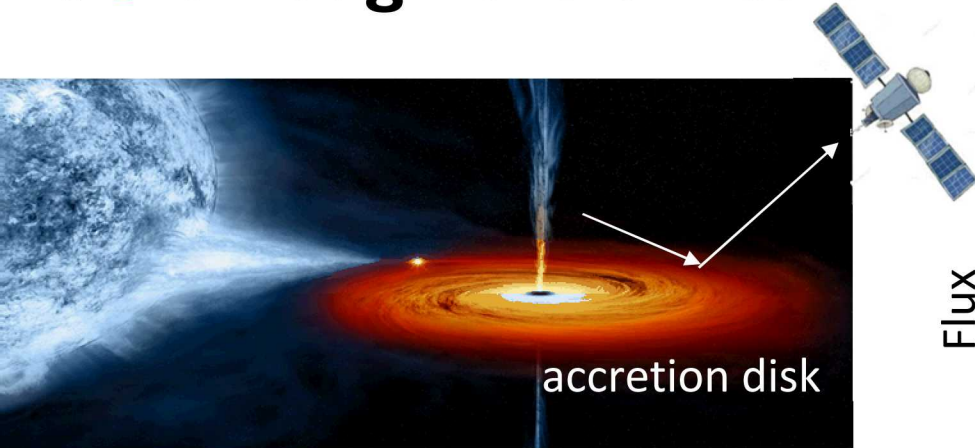
- Understanding X-ray Binaries and AGN accretion disks requires complex models that interpret observed spectra
  - → These models are largely untested in the laboratory
  - → Need benchmark quality data

- 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

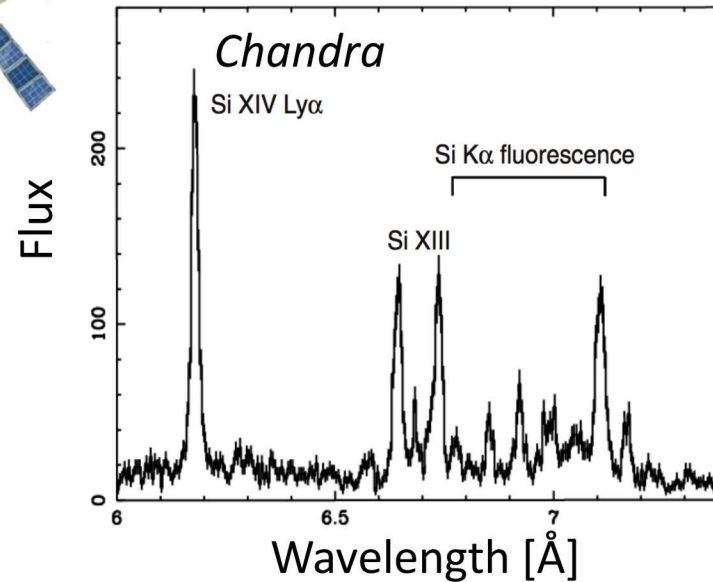**These results raise questions about the suitability of models used to interpret astrophysical observations**
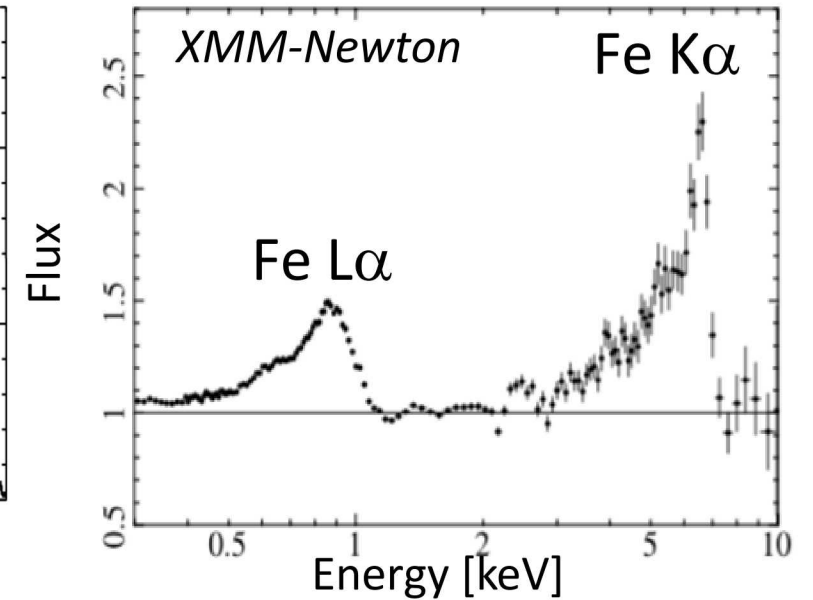
emission

absorption

n=4   n=5 .....   RRC

Si He-like emission

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

accretion disk

XMM-Newton - ESA

Suzaku – JAXA

Chandra - NASA

Neutron star Vela X-1

Chandra

Si XIV Lyα

Si Kα fluorescence

Si XIII

Flux

Wavelength [Å]

AGN 1H0707-495

*XMM-Newton*

Fe Kα

Fe Lα

Flux

Energy [keV]
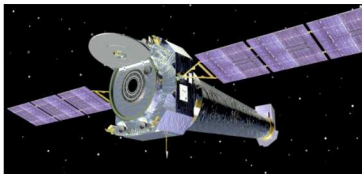
Challenges:
- Line identification
- Blended spectra from multiple elements
- Spatial and temporal integration
- Limited spectral resolution
- Limited signal-to-noise

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

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

Cygnus X-1 BH

Si
H-like
He-like
L-shell ions
λ [Å]
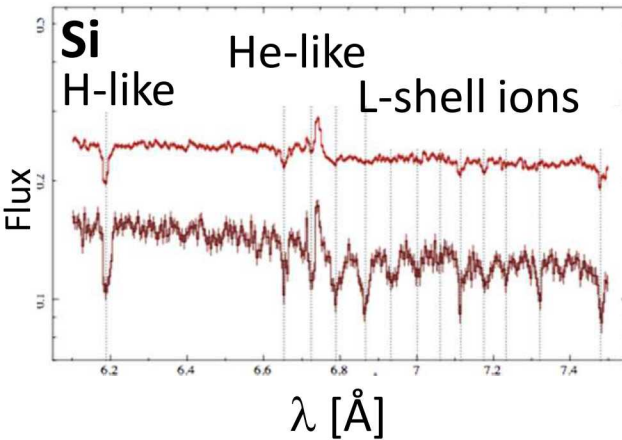
Absorption spectra

→ $\xi = 4\pi$flux/density
→ Column density
→ Accretion dynamics

Vela X-1 NS

Si
H-like
He-like
L-shell ions
λ [Å]
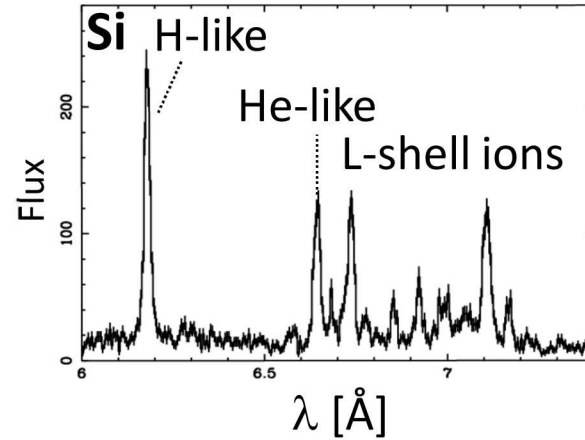
Emission spectra

Cygnus X-3 BHC

Cyg X-3
ASCA/SIS0
June 11, 1993

RRC   Si^{+13} S^{+15}
E [keV]
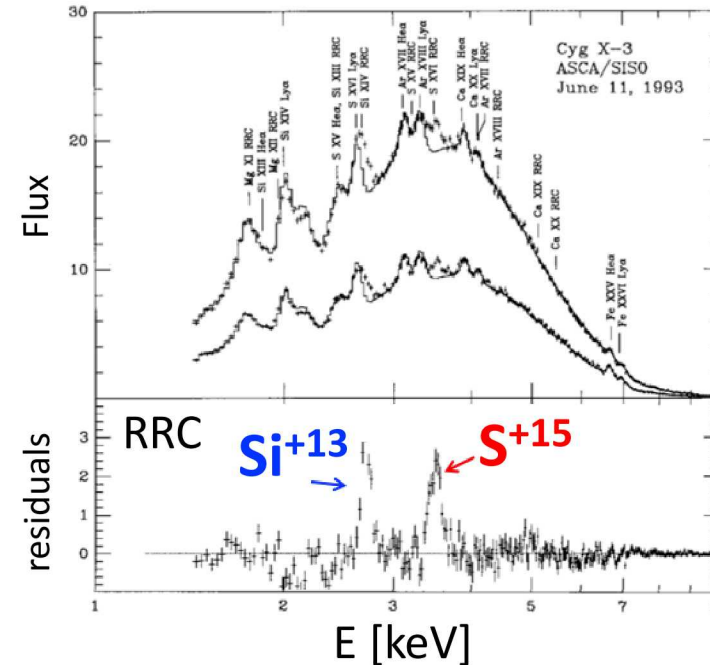
Radiative recombination continuum (RRC)

→ T_e temperature

AGN 1H0707 SMBH

Fe
Kα
Lα
E [keV]
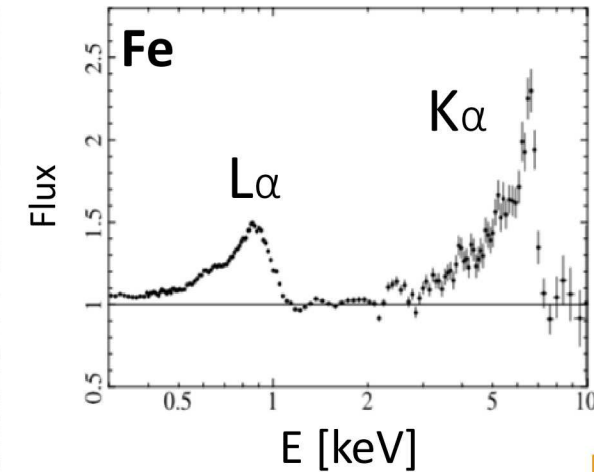
Broad Iron line

→ Radiation transport effects
→ Disk structure
→ General relativity effects

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

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, ξ > 1 erg.cm/s)
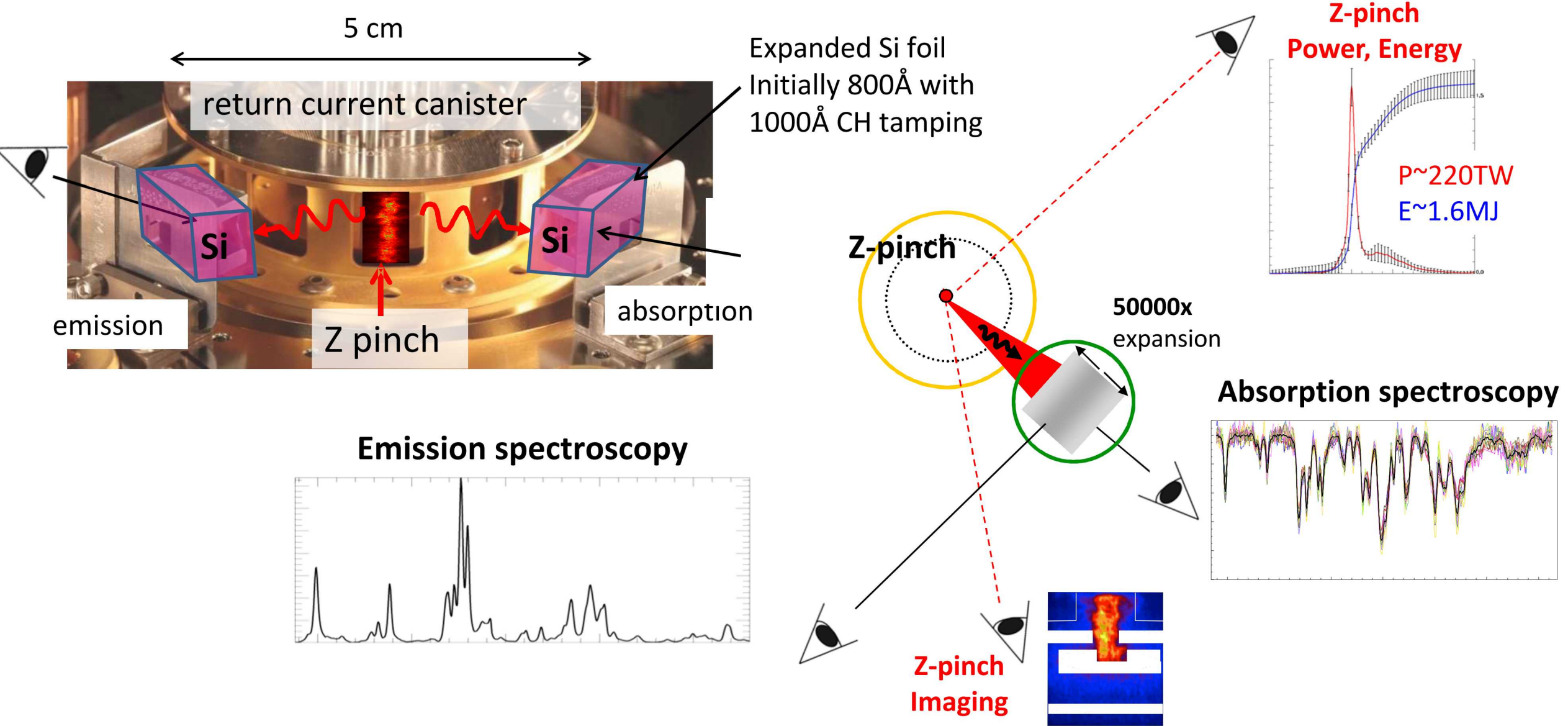
Specifically for *emission*:
- Large column density for high S/N

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

> **Experiments on the Z Facility can meet these criteria.**

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

5 cm

return current canister

Expanded Si foil
Initially 800Å with
1000Å CH tamping

Si

Si

emission

Z pinch

absorption

Z-pinch

**Z-pinch
Power, Energy**

P~220TW
E~1.6MJ

50000x
expansion

Absorption spectroscopy

Emission spectroscopy

**Z-pinch
Imaging**

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	$F \sim 1.3 \; 10^{19}$ erg/cm^2/s
	$T_{color} = [45, 80, 170]$ eV
Average charge	$Z^* \sim 10$, Si^{+10}
Electron density	$n_e = 8 \times 10^{18}$ e$^-$/cm^3
Photoionization parameter	$\xi \sim 20\text{-}300$ erg.cm/s
Column density (adjustable)	$N_i \sim 2.5 - 10 \; 10^{17}$ Si/cm^2
Electron temperature	$T_e = 26 - 40$ eV

Z-pinch Power, Energy

P~220TW
E~1.6MJ

Z-pinch

50000x expansion

Absorption spectroscopy

Emission spectroscopy

Z-pinch Imaging

G. Loisel, J. Bailey, D. Liedahl et al., PRL 119 (2017)
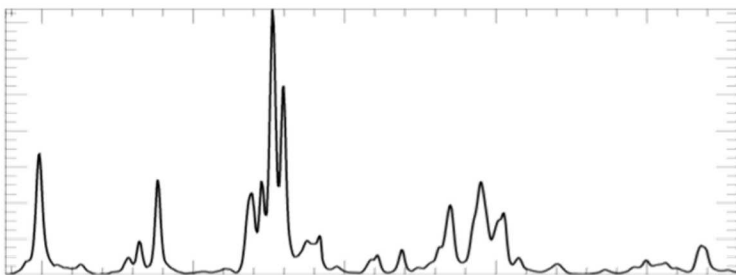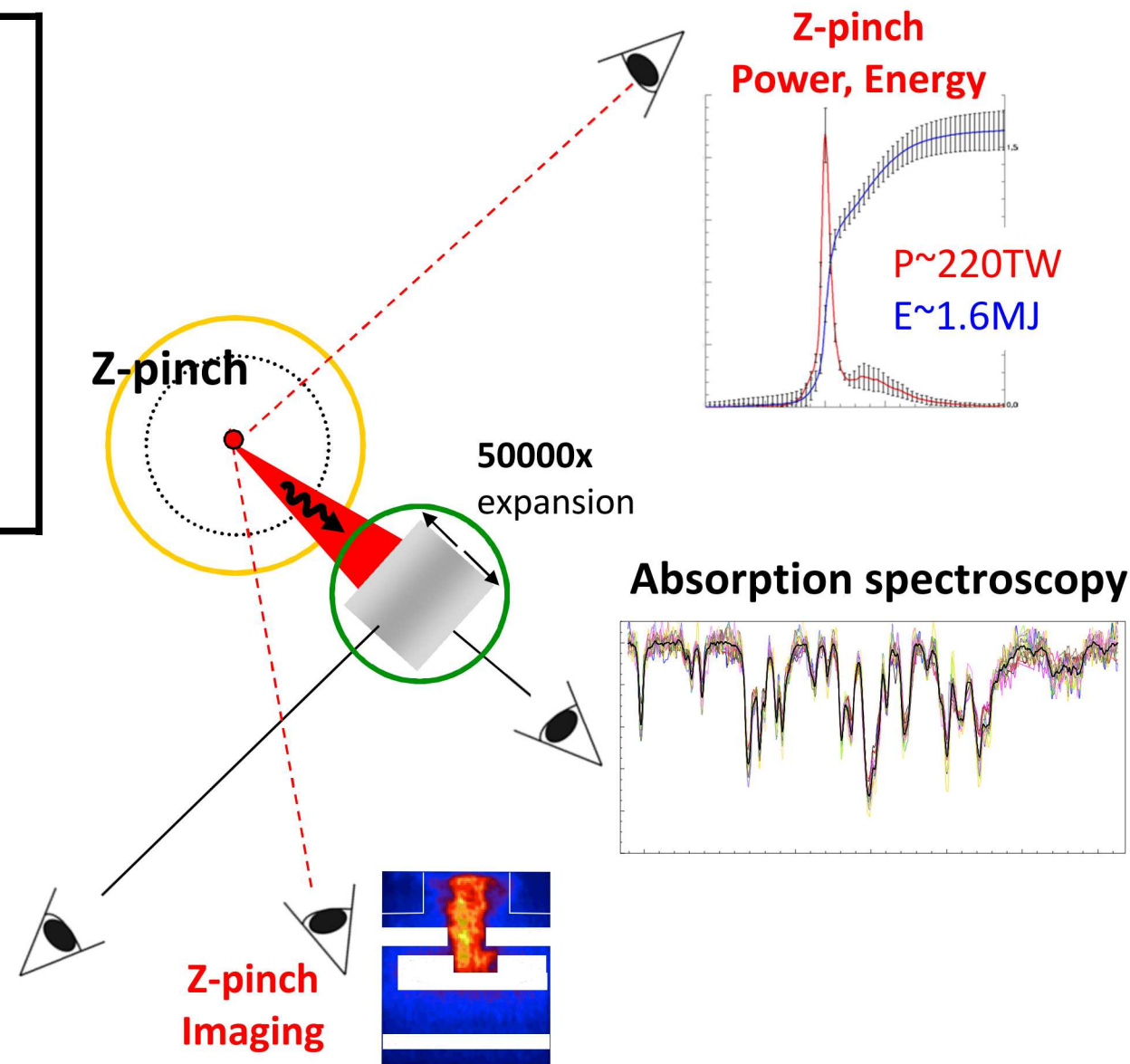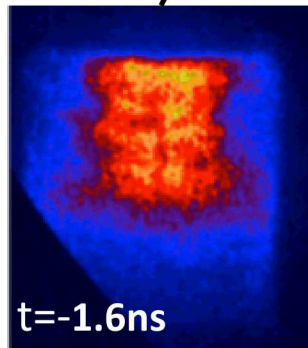
The radiation driving each sample is inferred from a combination of x-ray diagnostics

X-ray power

t=-1.6ns   t=+0.3ns
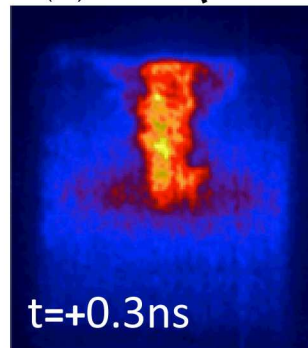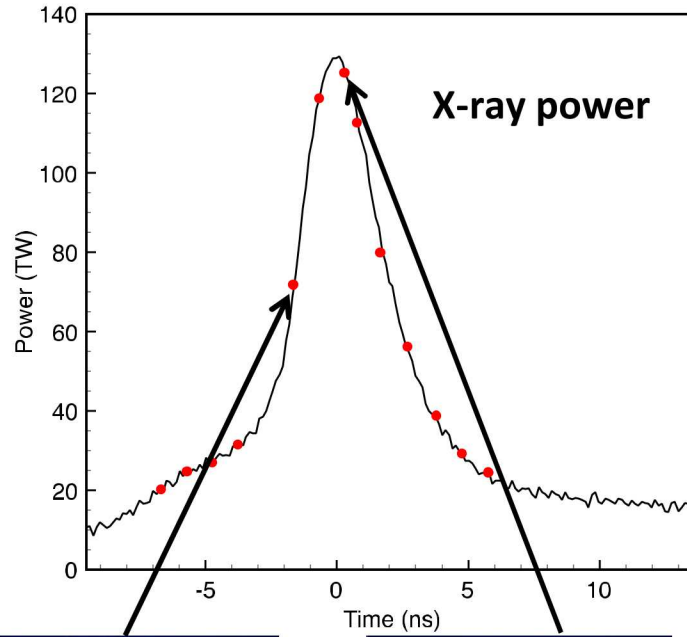
monochromatic images at 277 eV (also 528eV)

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 (hv=277 eV , hv=528 eV and hv>1keV)

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

x-ray power diagnostics

Multi-wavelength imager

incident flux: 2 TW/cm^2
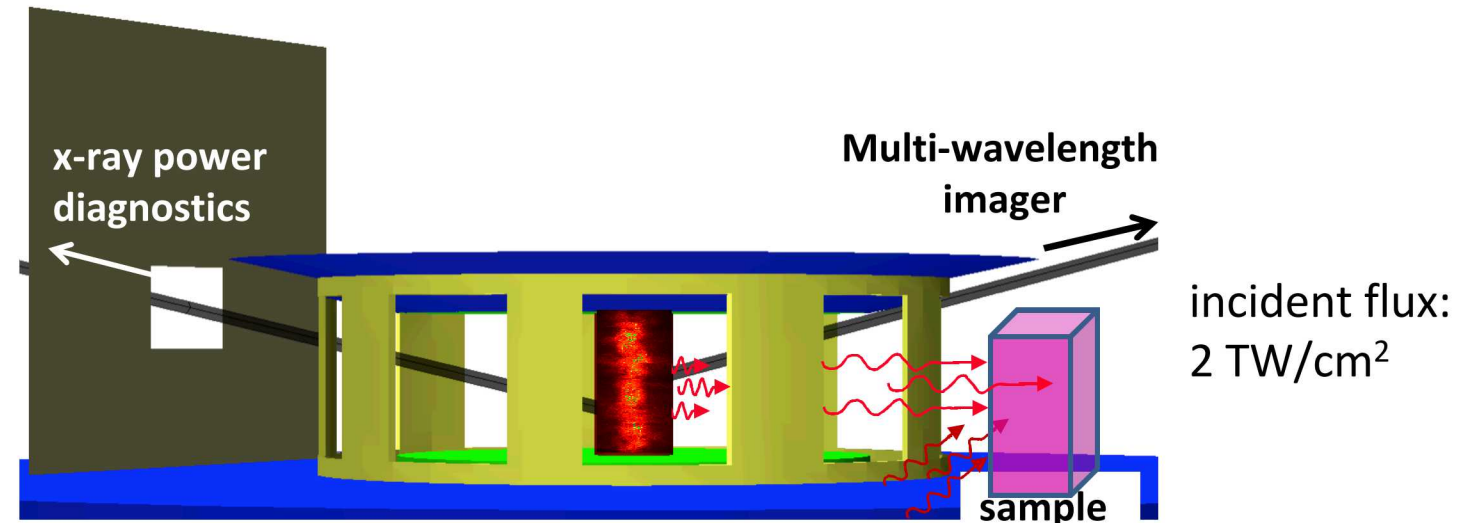
sample

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

target holder

Si

expansion

spatial resolution

spatial resolution
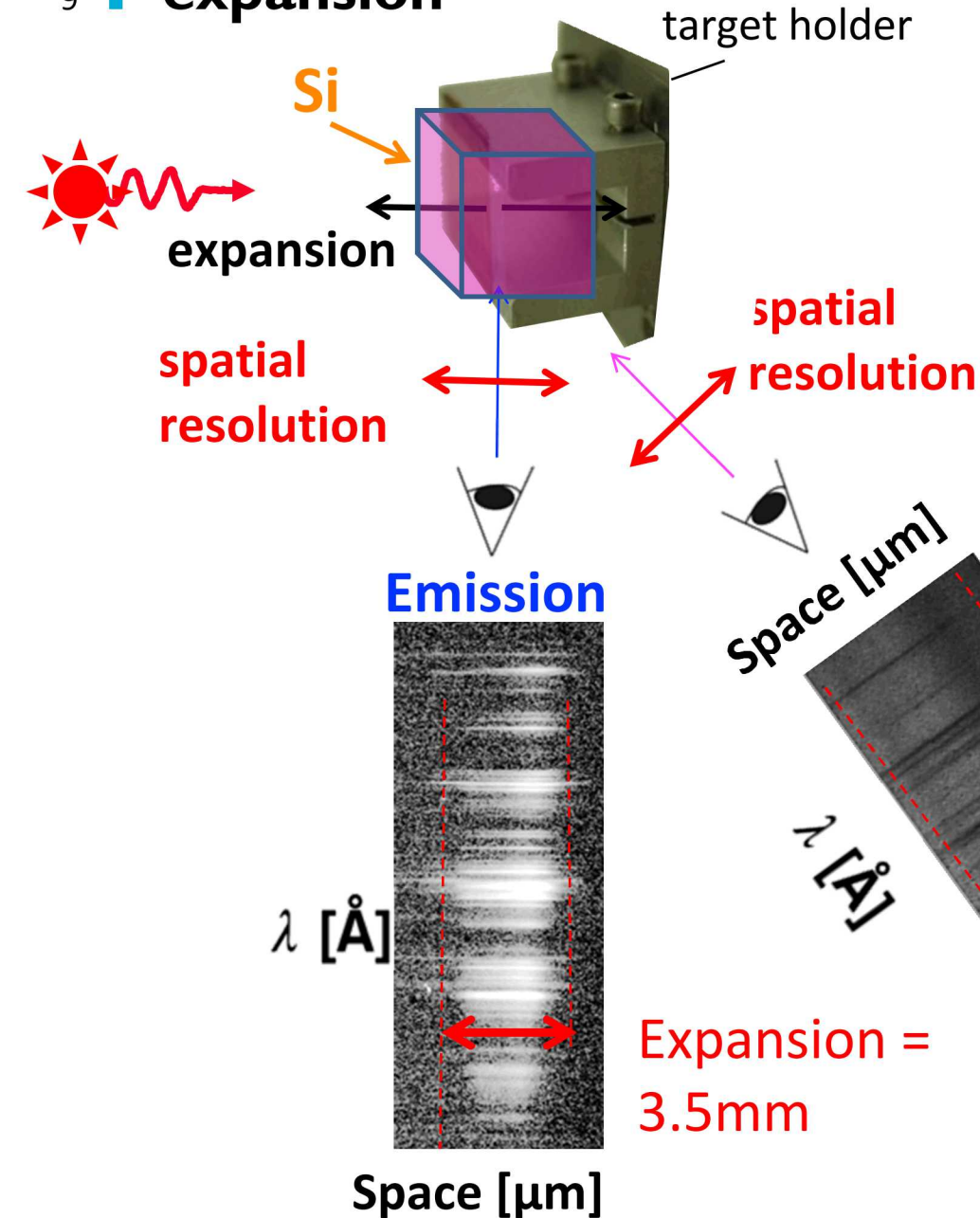
What is helping with uniformity?
- volumetric heating (line absorption)
- 2x 1000Å CH tamped along the heating direction →1D expansion
- 1mm CH tamping in the other dimension
- 3mm-apertured measurement over ~10mm plasma dimensions
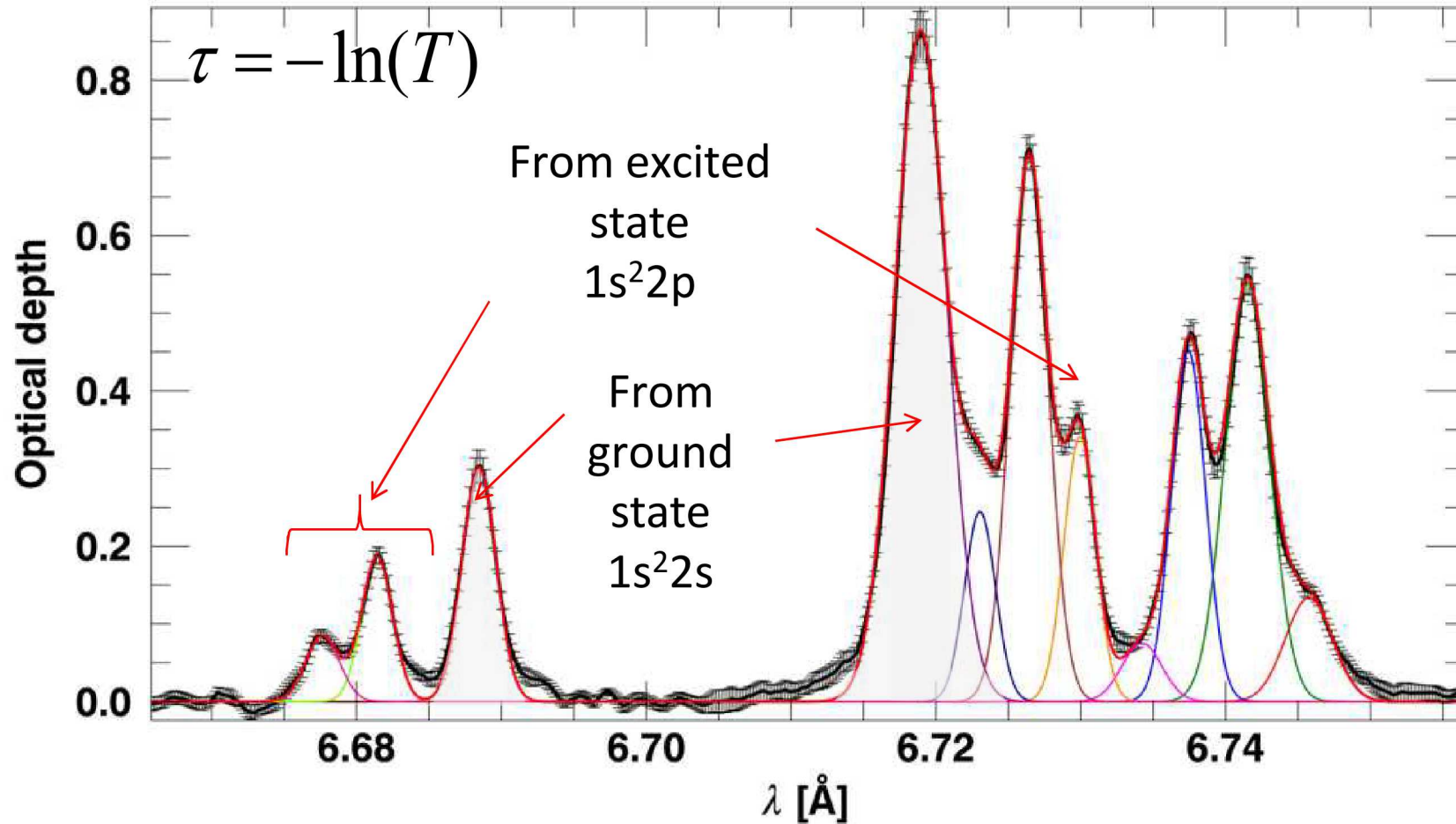
Emission

λ [Å]

Space [µm]

Expansion = 3.5mm

Space [µm]

λ [Å]

Absorption

Expansion = 3.6mm
(~50000x from 800Å)

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

Li-like Si^{+11} features

$$\tau = -\ln(T)$$

From excited state $1s^2 2p$

From ground state $1s^2 2s$

Optical depth

λ [Å]

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

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 − $1s^2 2p_{1/2}$	$T_e = 31.3 \pm 3.7$ eV	$T_e = 37.3 \pm 4.1$ eV
PRISM − $1s^2 2p_{3/2}$	$T_e = 33.3 \pm 4.0$ eV	$T_e = 36.8 \pm 3.8$ eV
CATS − $1s^2 2p_{1/2}$	$T_e = 27. \pm 2.7$ eV	$T_e = 31. \pm 3$ eV
CATS − $1s^2 2p_{3/2}$	$T_e = 30. \pm 3.2$ eV	$T_e = 32 \pm 3$ eV

→ T_e = 33 $\pm$ 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 emission data shows contributions from different charge states

Si^{+12}
He-like

Si^{+11}
Li-like

Si^{+10}
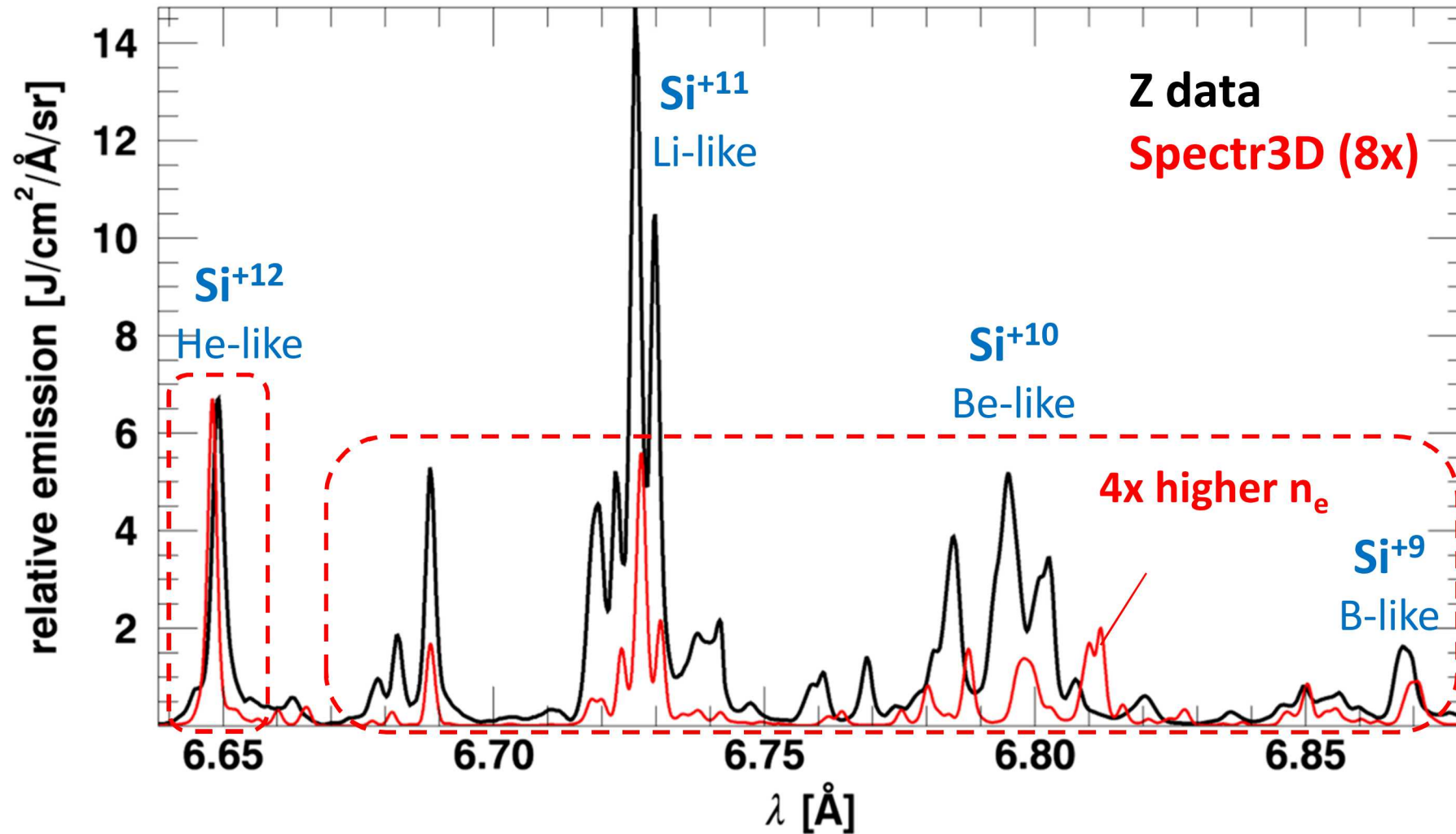Be-like

Si^{+9}
B-like

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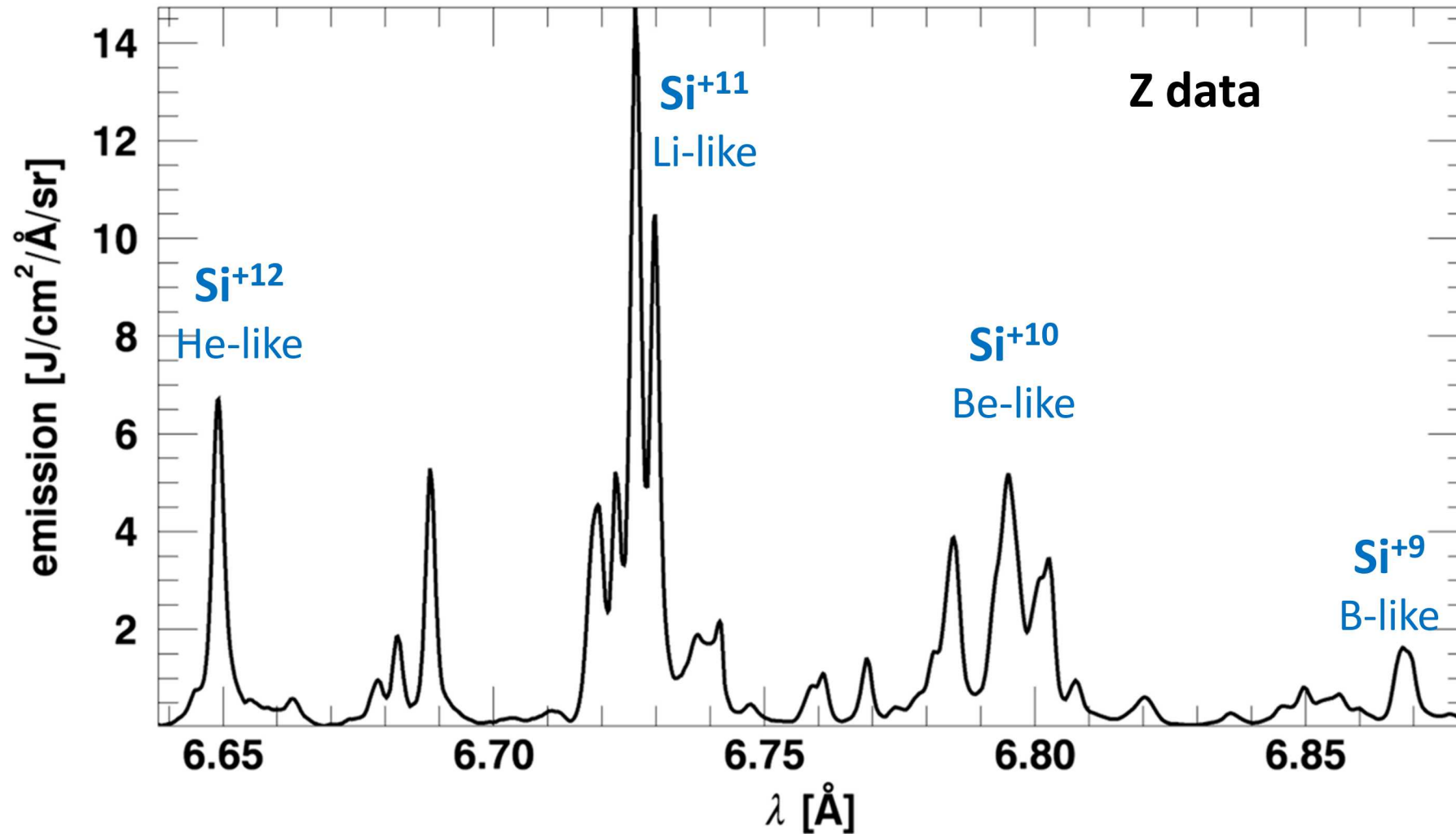
5.2% rel. unc.
$\lambda/\delta\lambda$ ~ 4400

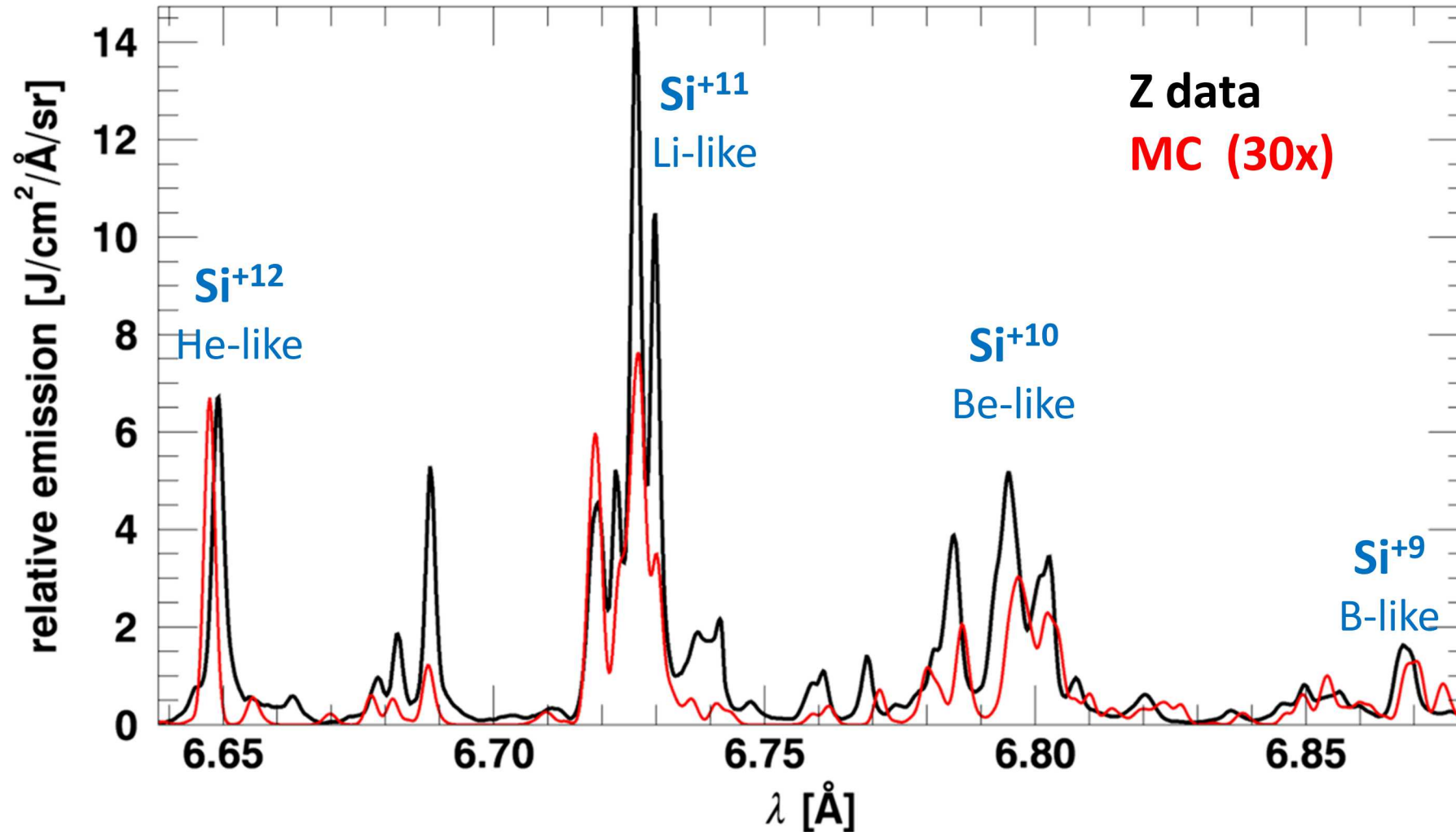**Simultaneous line observation contradicts an assumption used to interpret black hole spectra***

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

Si+12 He-like

Si+11 Li-like

Si+10 Be-like

Si+9 B-like

Z data

MC (30x)

relative emission [J/cm²/Å/sr]

λ [Å]

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

MC: Monte Carlo radiation transport code, D. Liedahl

Emission spectra are also measured at very high spectral resolution

Z data (no model)

Si^{+12} He-like

Si^{+11} Li-like

Si^{+10} Be-like

Si^{+9} B-like

Si^{+8} C-like

z2759 (12mm Si), $\lambda/\delta\lambda$ ~ 2800
z2792 (12mm Si), $\lambda/\delta\lambda$ ~ **9200**
or 60+ lines in 0.3Å or 80eV bandwidth

Film density

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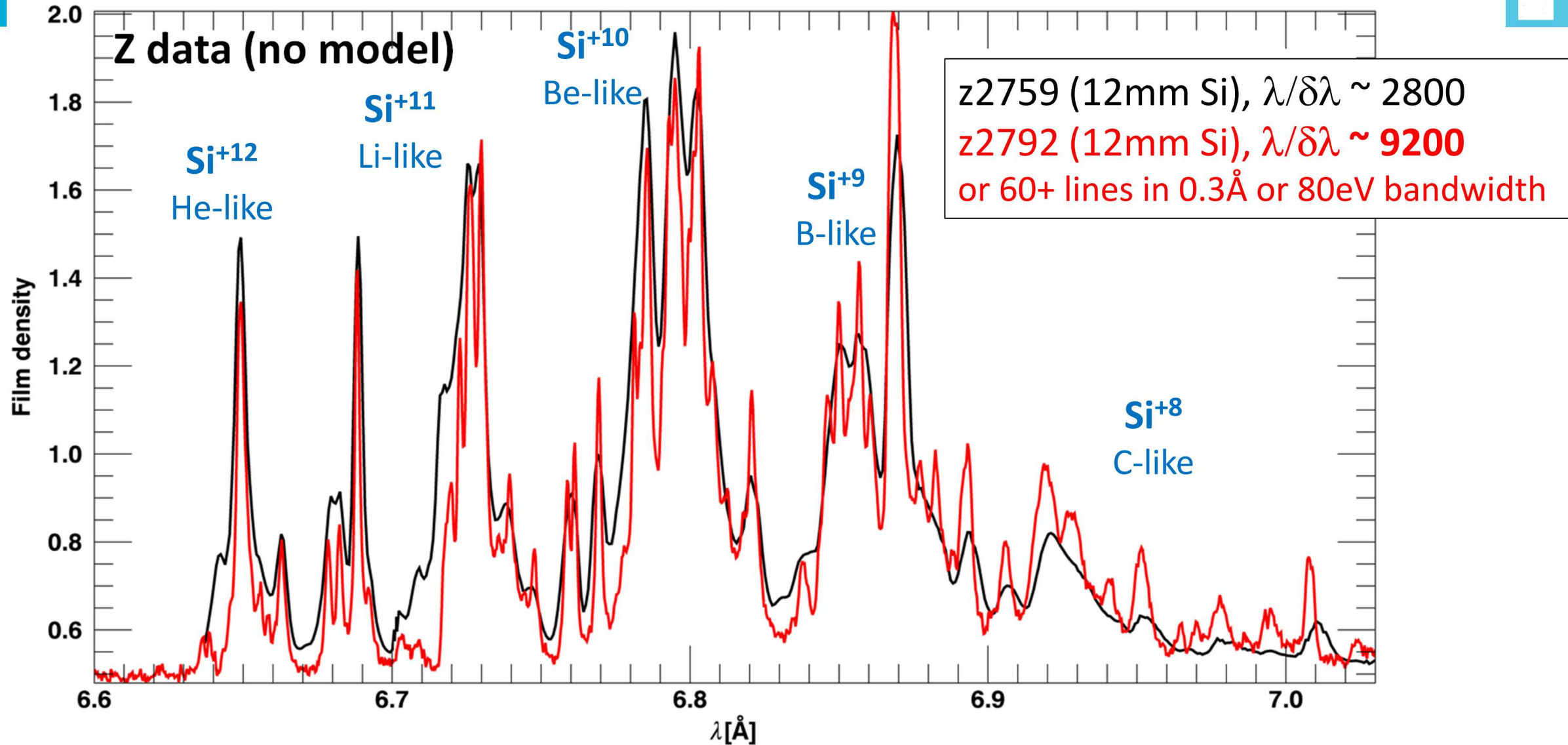
We can study very detailed level structure and more precise radiation transport effects on lines that have variable optical depth.

High-*n*, *n* ≤ 14, He-like transitions with merging into the continuum first obtained in a laboratory photoionized plasma
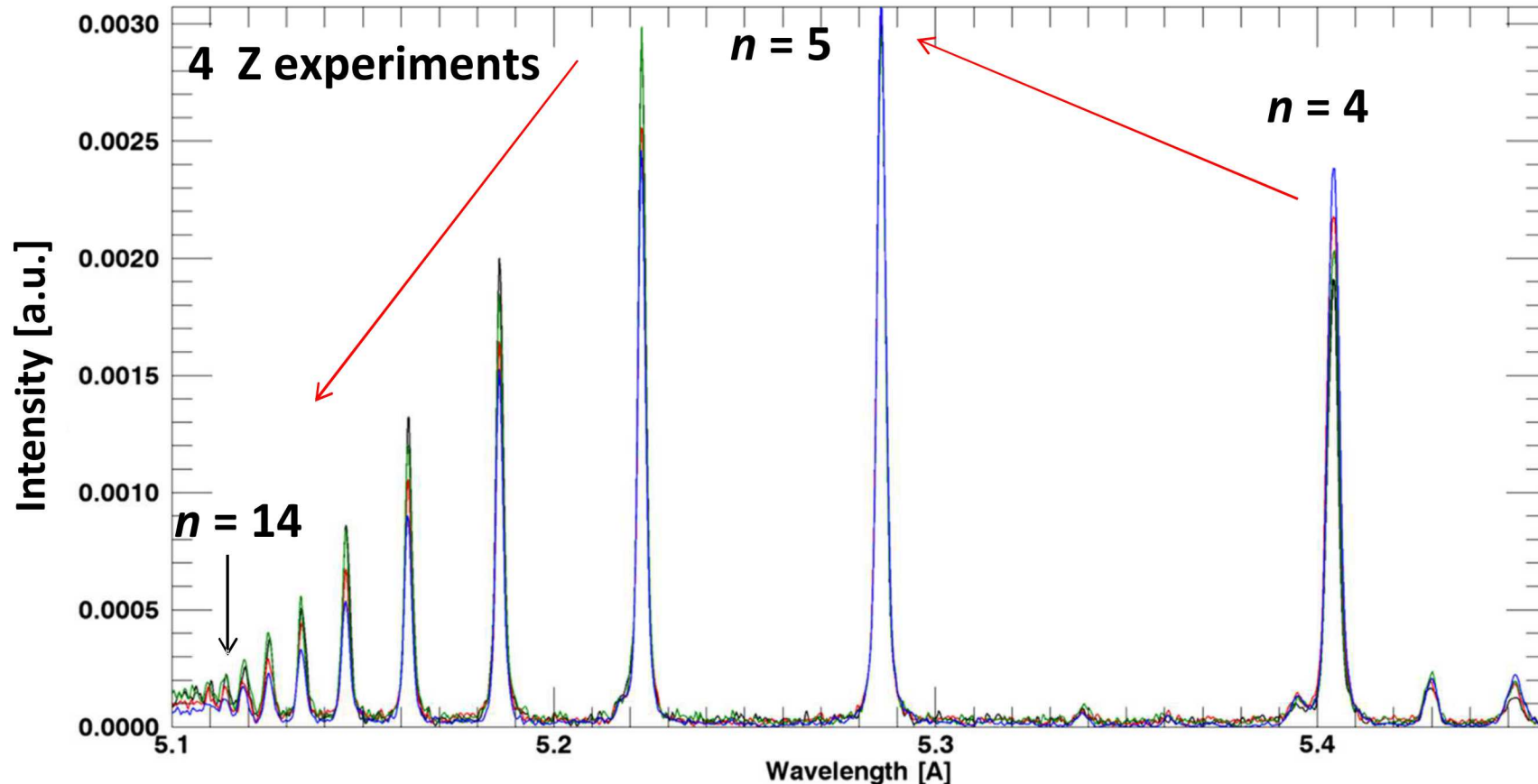
Silicon closer to the x-ray source
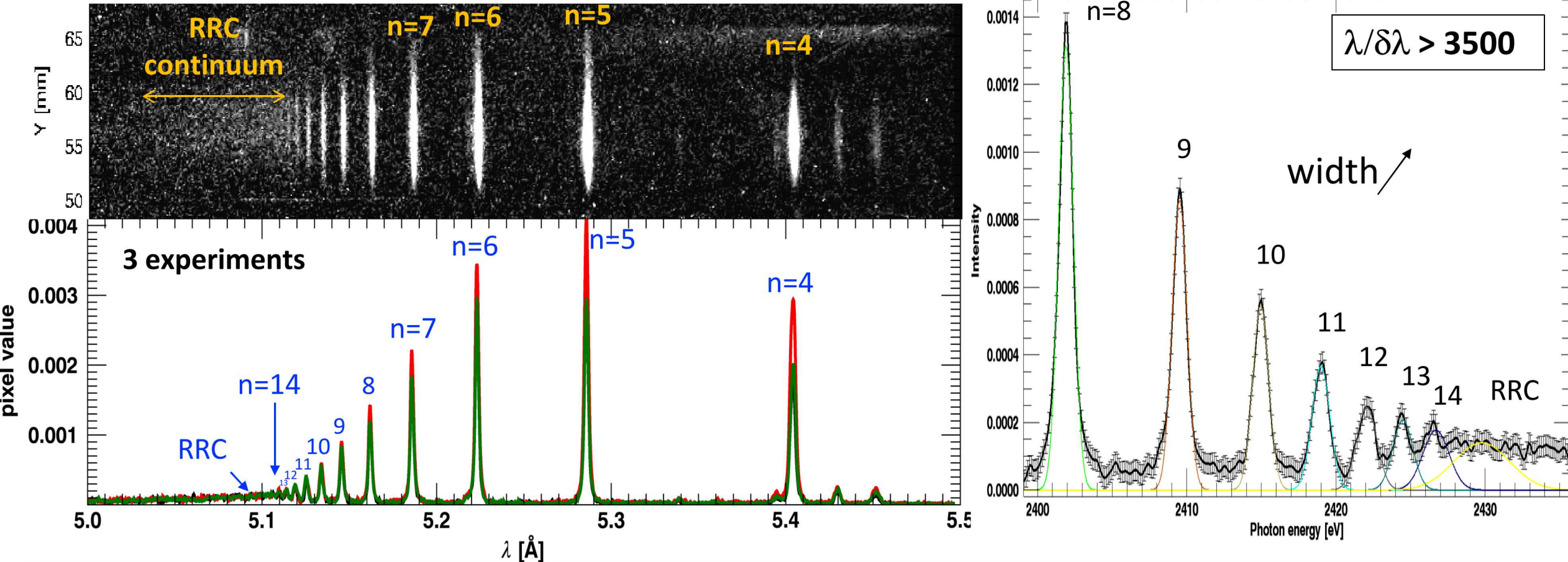
→ **Effect of line shape, line broadening, continuum lowering on the RRC can be studied. High-n lines getting broader with n → density sensitivity.**

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

Silicon closer to the x-ray source

4 Z experiments

n = 14

n = 5

n = 4

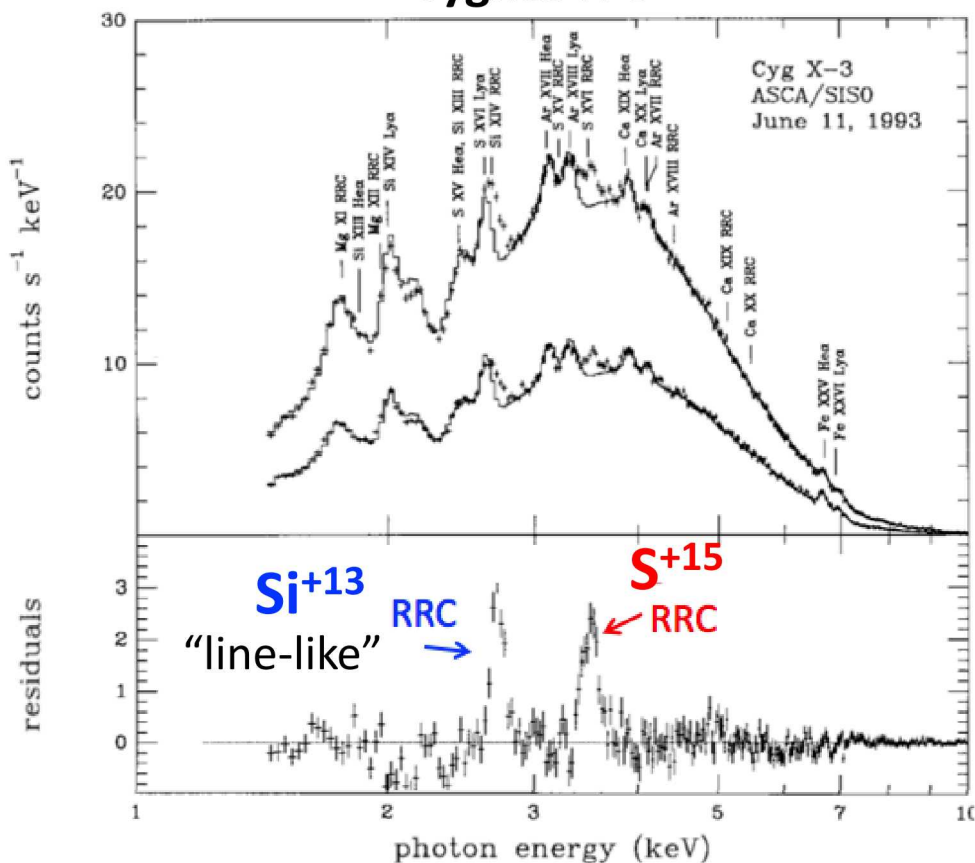Initial upper states can be populated either by:
- recombination following photoionization
- or photoexcitation

Also line intensity is affected by radiation transport.

→ **Test predominance of photoexcitation versus photoionization in populating He-like states**
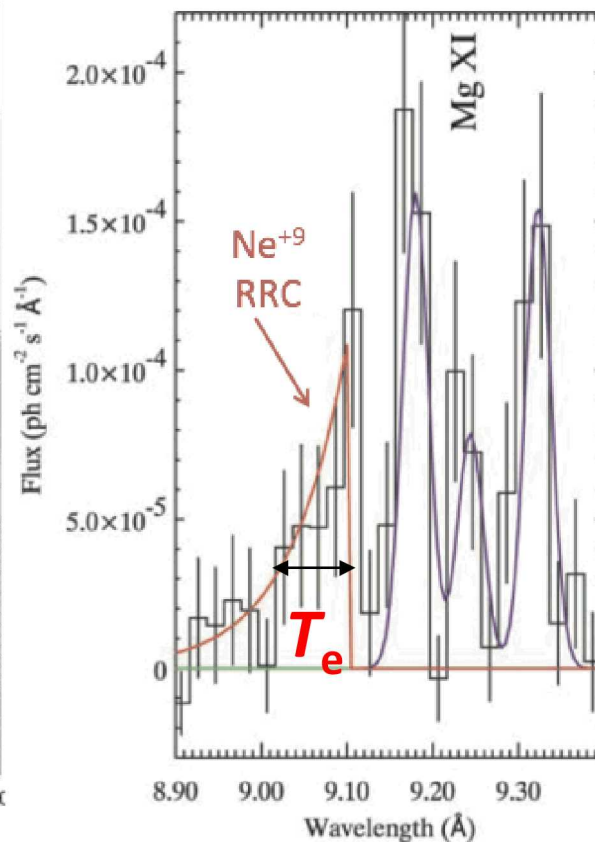
The radiative recombination continuum (RRC) is considered the most reliable temperature diagnostics for accretion-powered objects

Cygnus X-3

Vela X-1

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

T_e = 5-50 eV [1]

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

→ **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
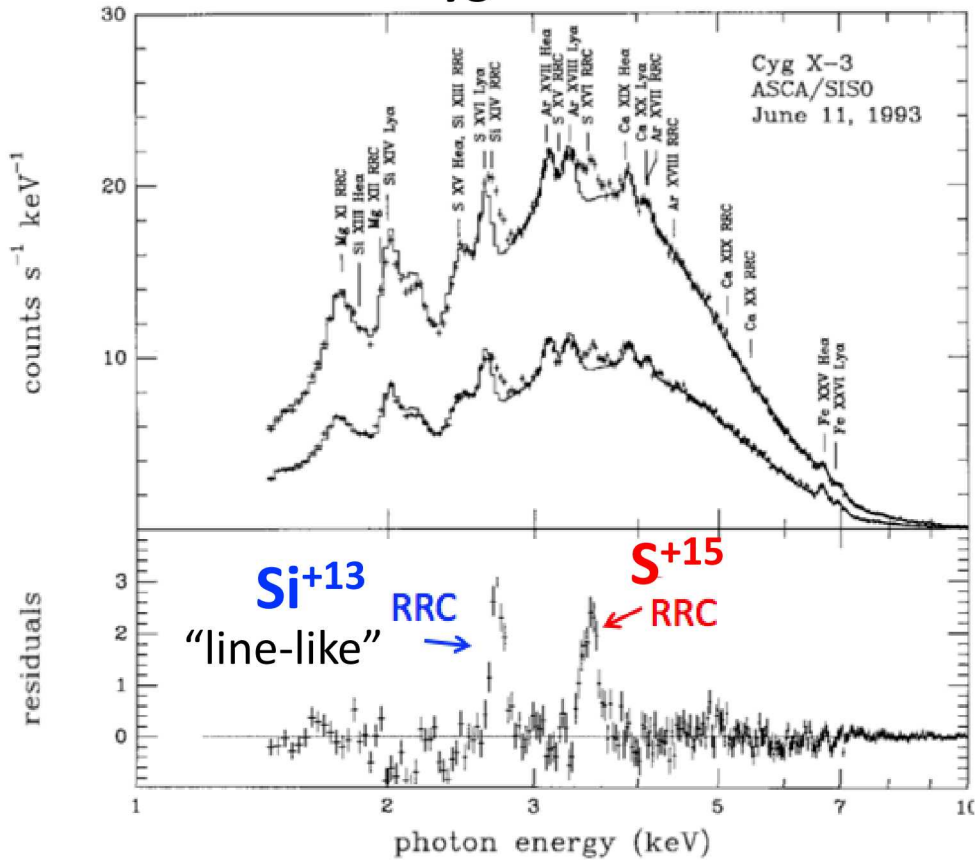
T_e = 5-50 eV [1]

Vela X-1

T_e = 10 $\pm$ 2eV [2]
T_e = 6.6 $\pm$ 2eV [3]

Earth: Z plasma

Radiative Recombination Continuum (RRC)

42eV
50eV
60eV
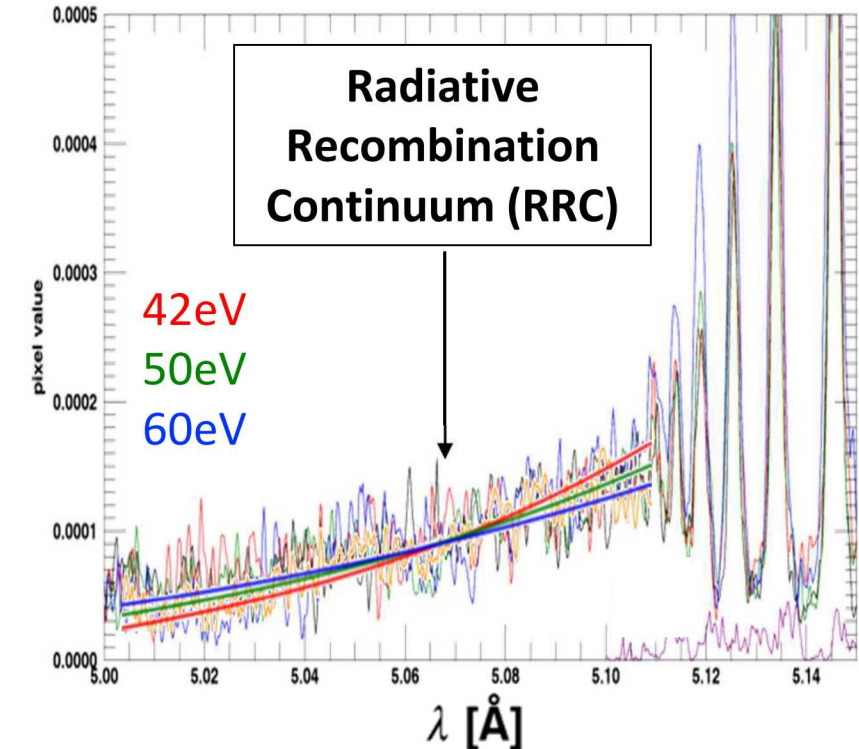
→ T_e ~ 50 $\pm$ 15 eV
→ ~Maxwellian e⁻ distribution

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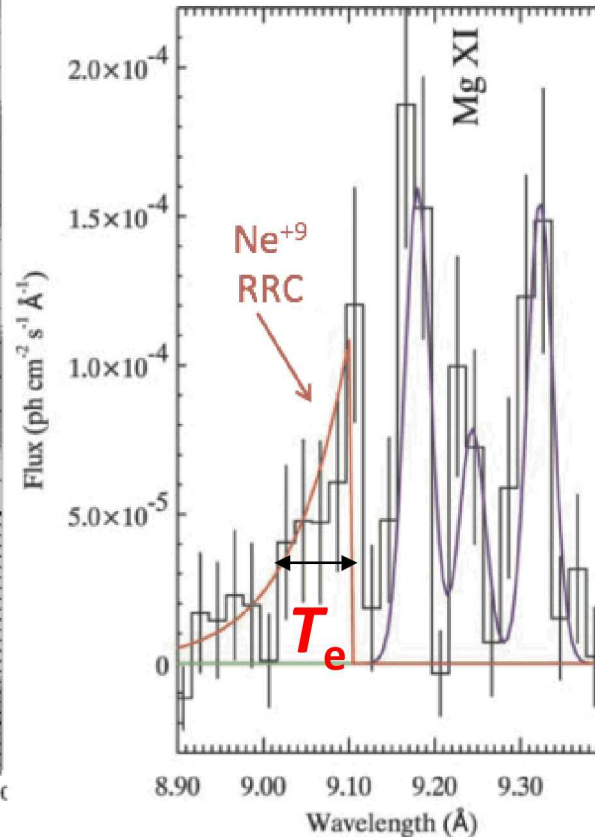→ Untested in the laboratory in a well-characterized photoionized plasma.

[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

Li-like

lower levels in PLTE

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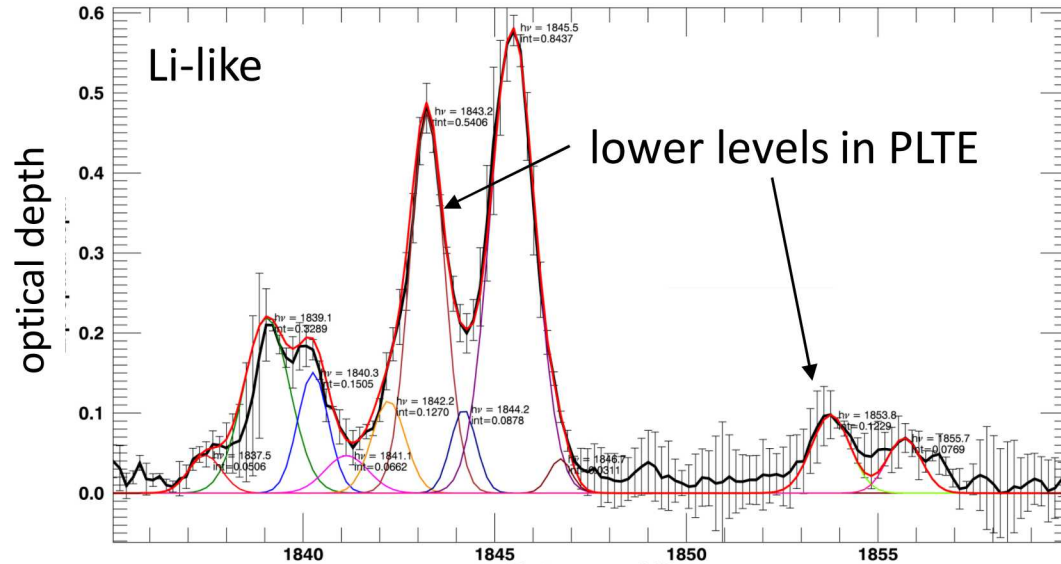
Absorption initial level	Oscillator strength code	Temperature T_e [eV]
$1s^2 2p_{1/2}$	PRISM	51 ± 21
$1s^2 2p_{3/2}$	PRISM	57 ± 19
$1s^2 2p_{1/2}$	CATS	39 ± 13
$1s^2 2p_{3/2}$	CATS	55 ± 35

Emission

Radiative Recombination Continuum (RRC)

pixel value

42 eV

50 eV

60 eV

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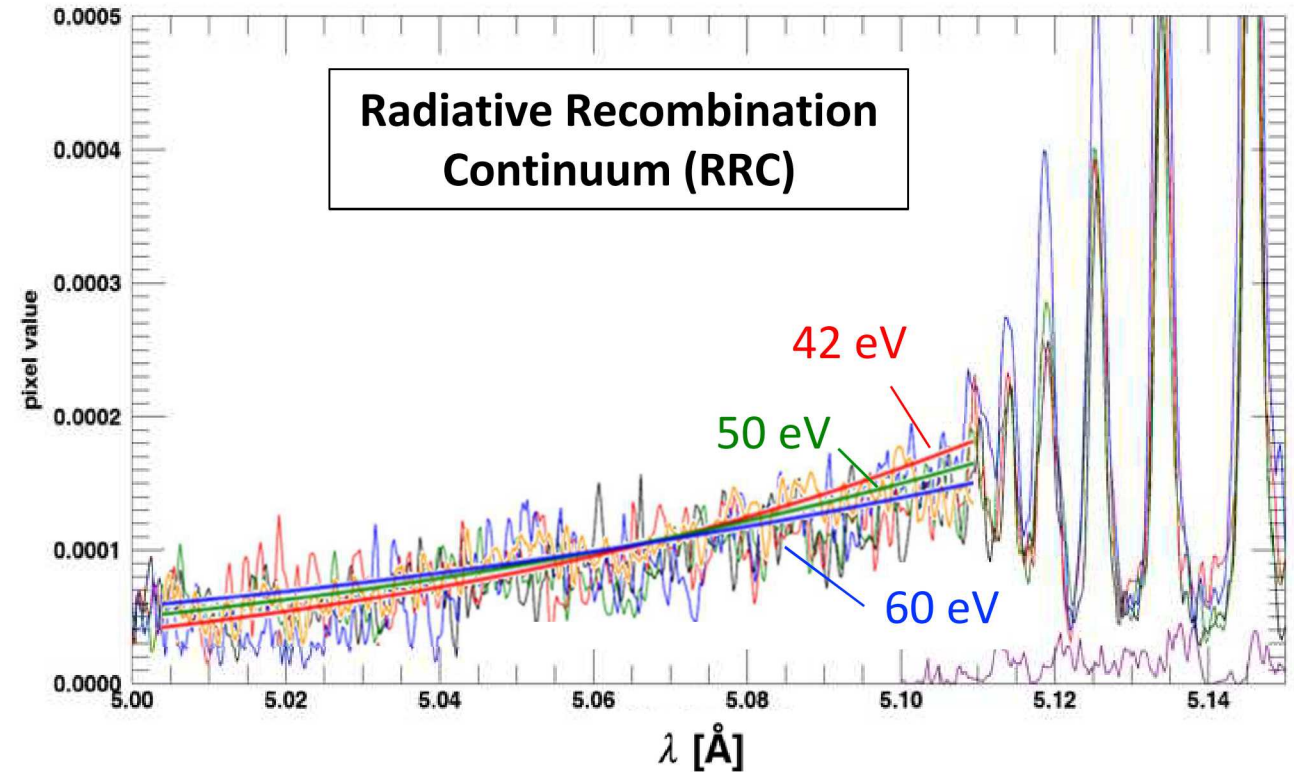
RRC slope → T_e ~ 42 – 60 eV
Li-like sat. ratio → T_e ~ 39 – 60 eV

Nine shot absorption average

Li-like opt. depth

Si on can – 9 shots average (03/2019)
Si on can – 9 shots average mul by 1.47
using IDL *com* procedure
Si at 44mm (PRL)
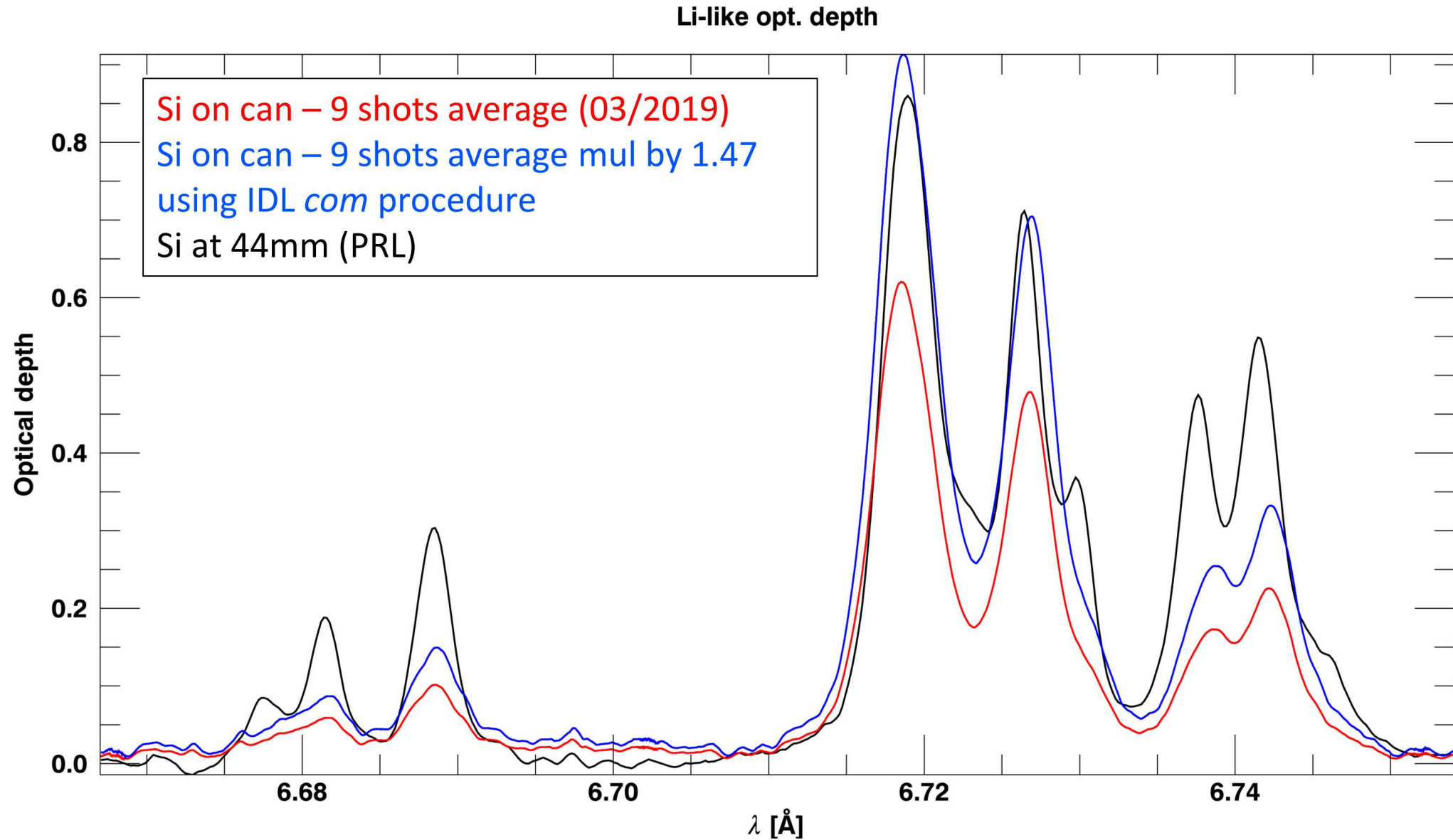
The broadband spectrum measurements include all He-like lines (He α to He-14)

Silicon closer to the x-ray source

B   Be   Li   Heα Heβ γ δ ε **7**   14

rrc

z3287

z3364 (April 4th)

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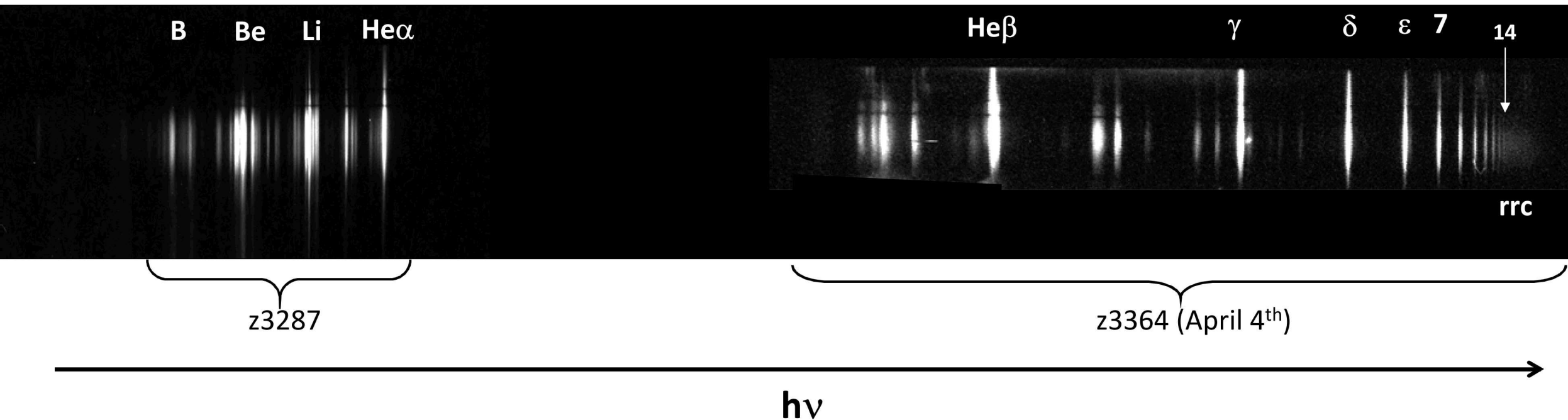
How much of the predictive difficulty is unique to our experiments and how does it impact astrophysical objects?

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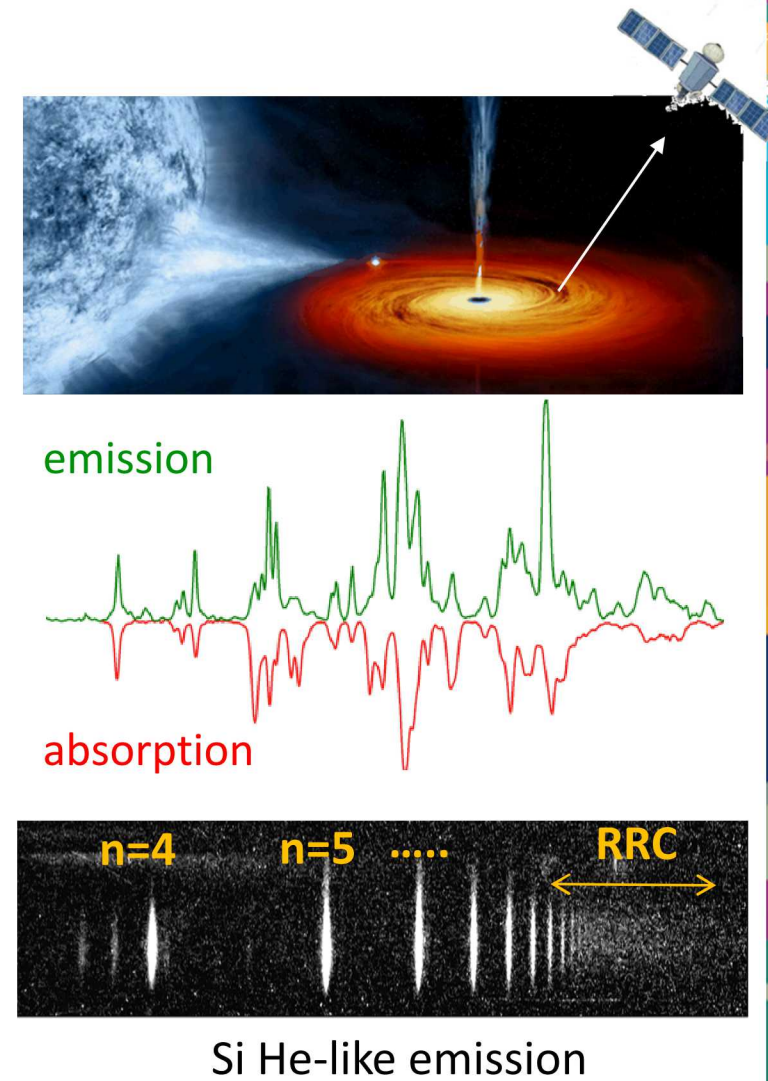 - e.g. escape factors, escape geometry, self-consistency…

Scrutiny 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

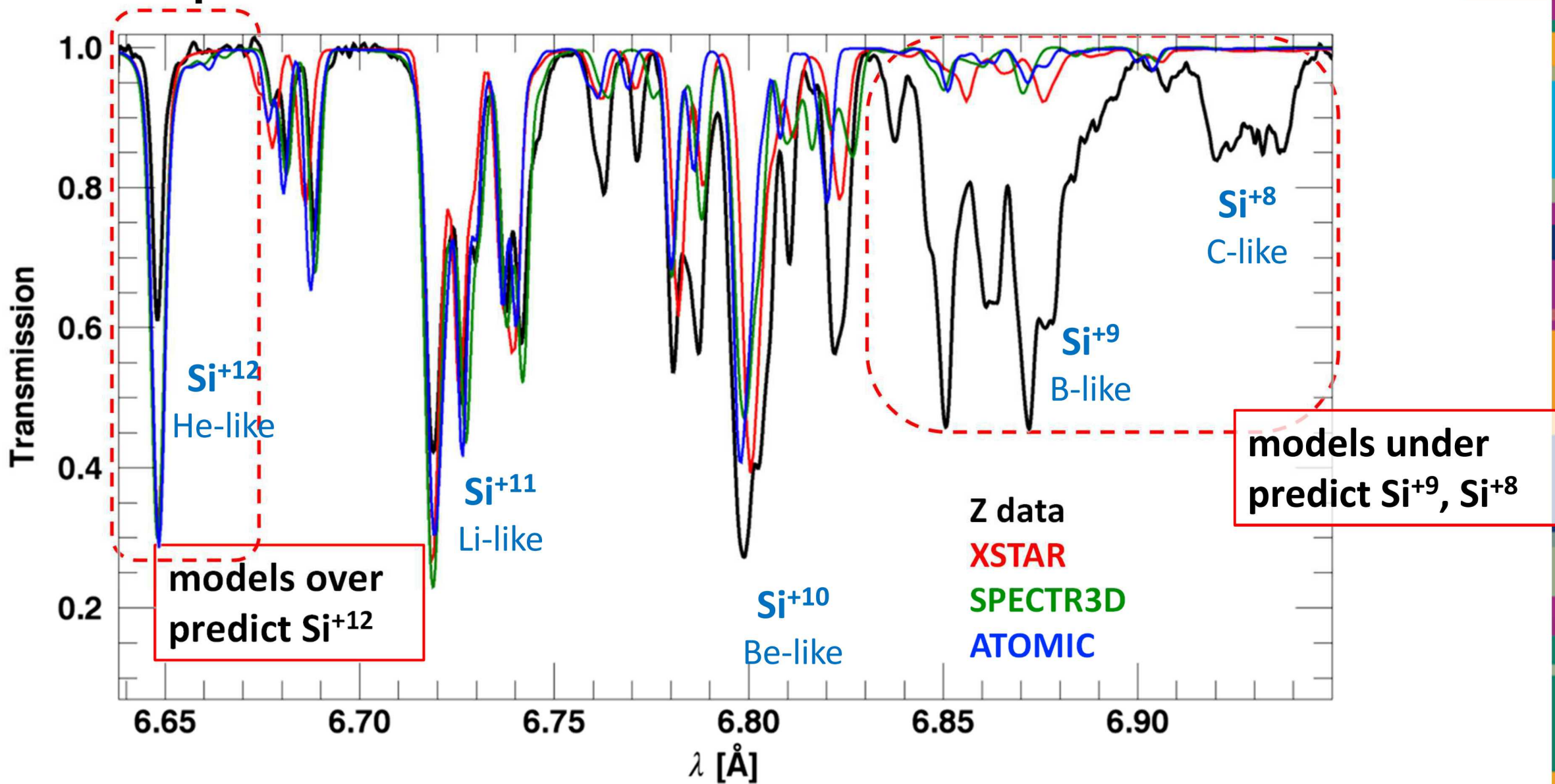**These results raise questions about the suitability of models used to interpret astrophysical observations**

emission

absorption

n=4   n=5 .....   RRC

Si He-like emission

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

Extra slides

Measured relative absorption from different ion stages tests model ionization predictions

Si^{+12}
He-like

Si^{+11}
Li-like

Si^{+10}
Be-like

Si^{+9}
B-like

Si^{+8}
C-like

models over predict Si^{+12}

models under predict Si^{+9}, Si^{+8}

Z data
XSTAR
SPECTR3D
ATOMIC

Agreement can be obtained by adjusting parameters that increase recombination
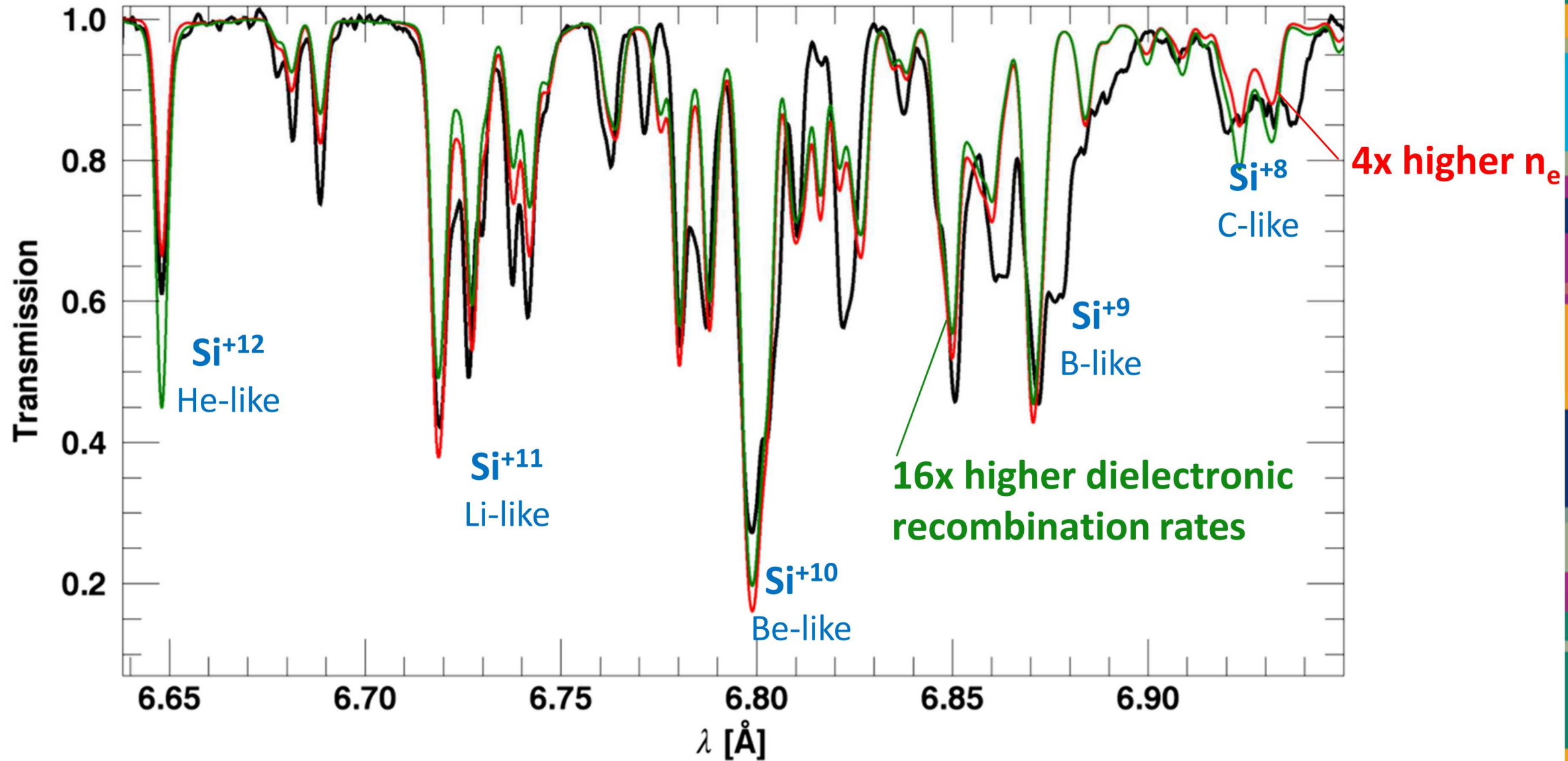
Results and puzzles are documented

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 — data vs models

Emission — 2.5×10^{17} Si/cm^2, $\langle \sigma/\mu \rangle = 5.7\%$; 5×10^{17} Si/cm^2, $\langle \sigma/\mu \rangle = 5.2\%$; 10×10^{17} Si/cm^2, $\langle \sigma/\mu \rangle = 11.2\%$