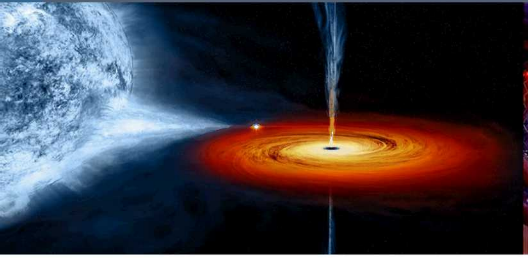
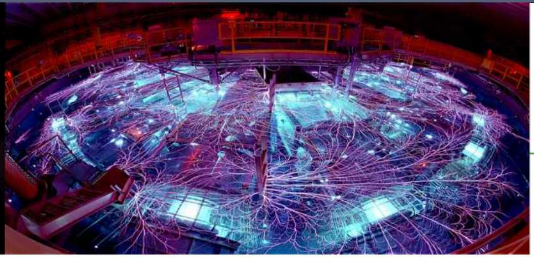
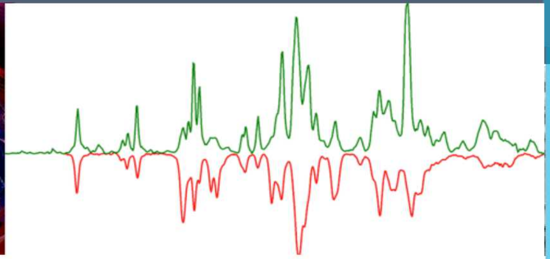
SAND2020-7947C

Photoionized plasma experiment for accretion-powered sources







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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Los Alamos National Laboratory, New Mexico

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Goddard Space & Flight Center NASA, Maryland

Also graduate student Patty Cho, University of Texas, Austin, NNSA LRGF fellow

WOOTTON CAPP

ZFSP workshop
August 2020

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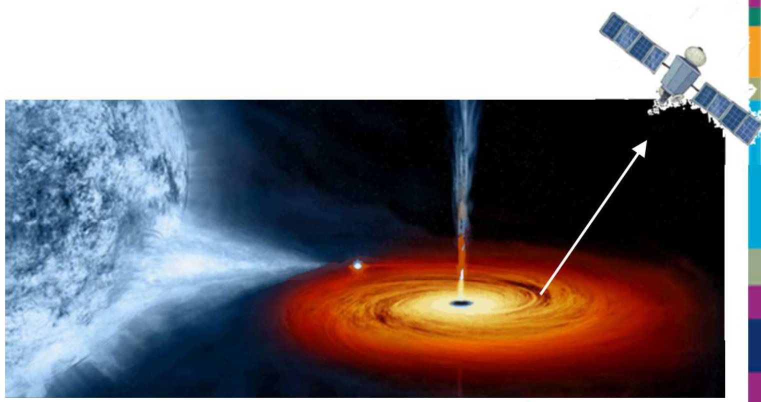
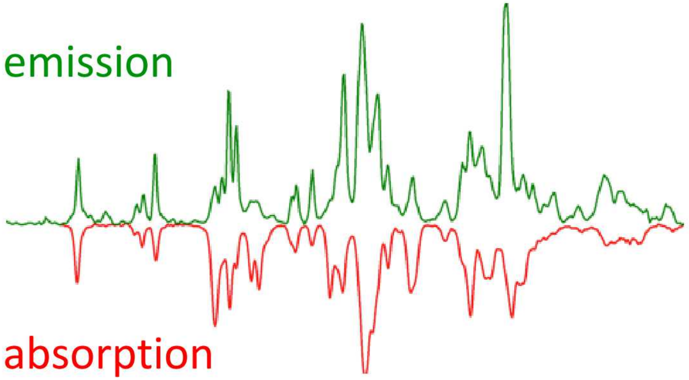
Summary: Z data can benchmark models of emission from photoionized accretion-powered plasmas

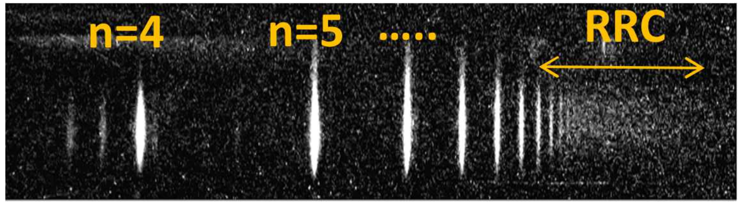
- Understanding X-ray Binaries and AGN accretion disks requires complex models that interpret observed spectra
  - → These models are largely untested in the laboratory
  - → Need benchmark quality data
- A photoionized silicon plasma with a measured drive radiation spectrum, density and temperature 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





Experimental developments:

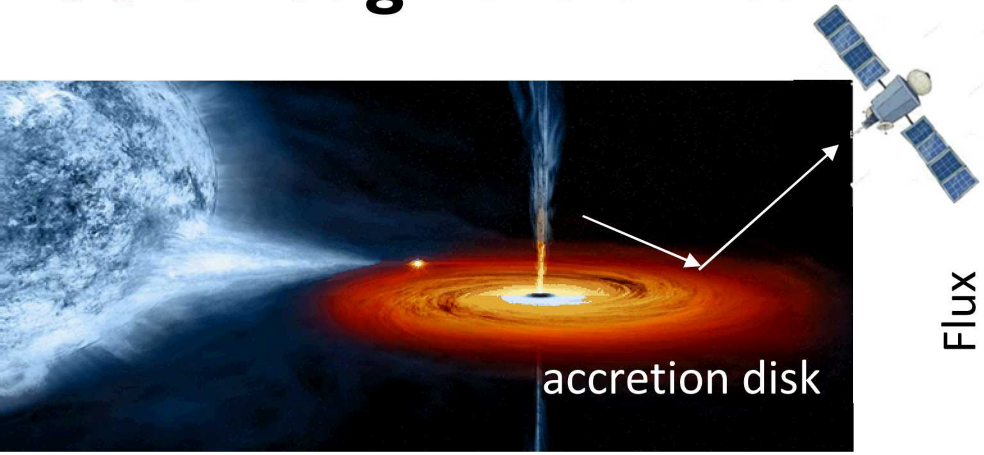
- First RRC from a photoionized plasma was obtained on Z
- First complete He-like line series
- Ultra high resolution emission spectra
- First Fe spectrum to address the super-solar abundance problem
- Time-resolved emission measurements design work



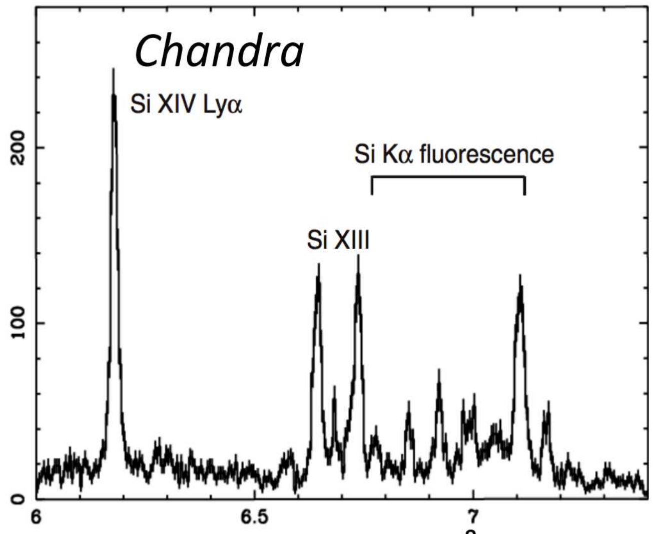
Si He-like emission

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

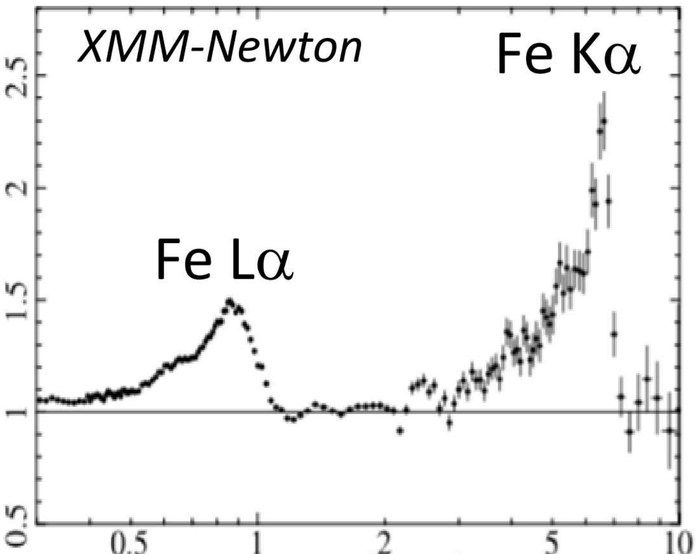
Active Galactic Nuclei and X-ray Binaries are revealed through the emission from their accretion disk



Neutron star Vela X-1



AGN 1H0707-495



XMM-Newton - ESA

Chandra - NASA

Suzaku – JAXA

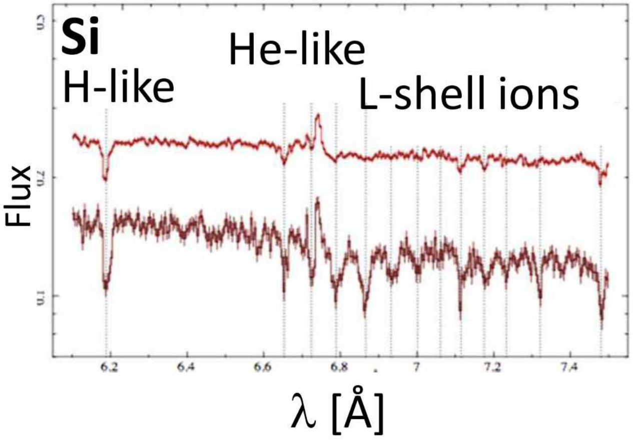
Challenges:

- 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)

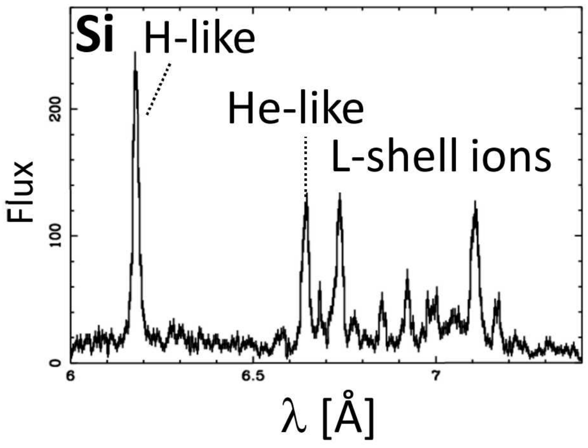
X-ray spectra are used to access a wide variety of the astrophysical object parameters

Cygnus X-1 BH



Absorption spectra

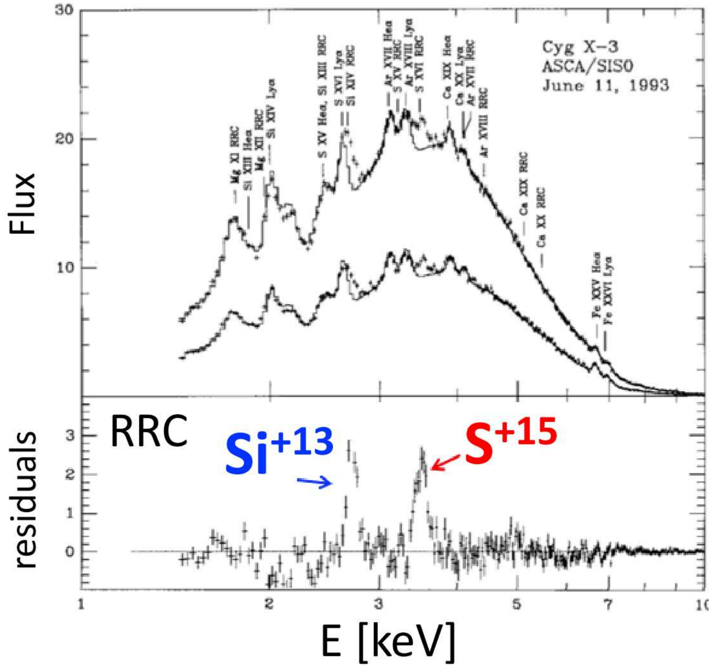
Vela X-1 NS



Emission spectra

→ composition
→ ionization ξ=4πflux/density
→ Column density
→ Accretion dynamics

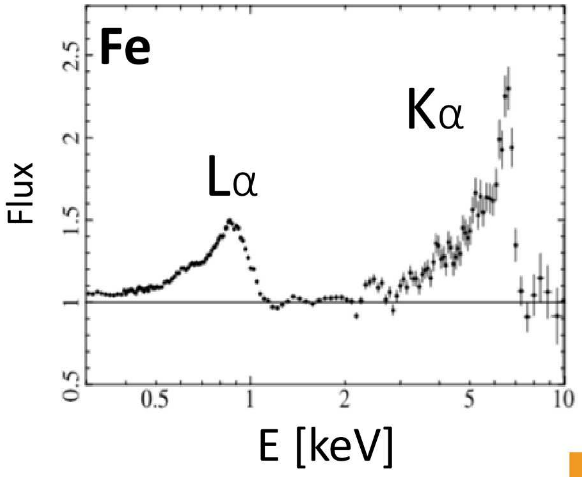
Cygnus X-3 BHC



Radiative recombination continuum (RRC)

→ T_e temperature

AGN 1H0707 SMBH



Broad Iron line

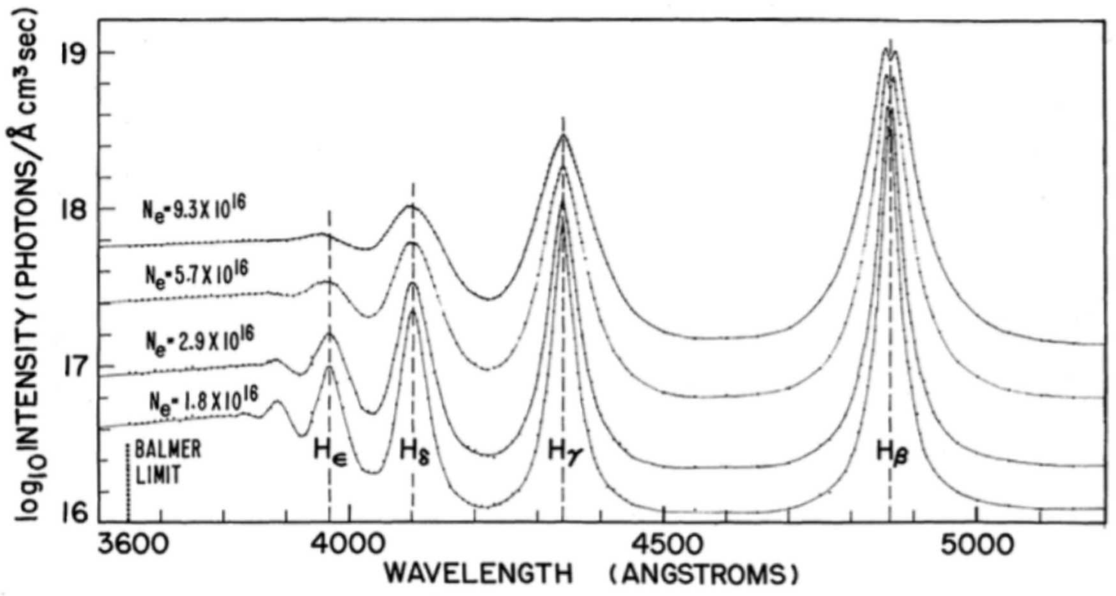
→ Radiation transport effects
→ Disk structure
→ General relativity effects

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

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

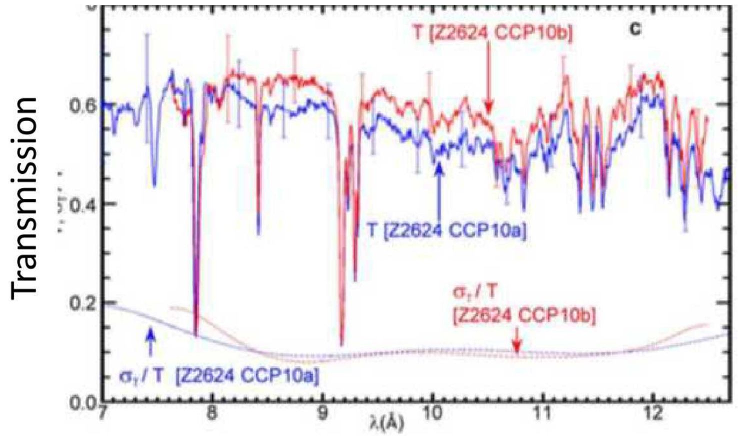
Benchmark experiments do exist for collisional plasmas

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

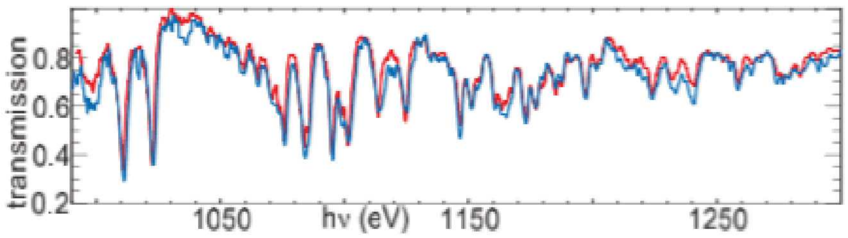


Balmer line shapes measured with 6% error

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



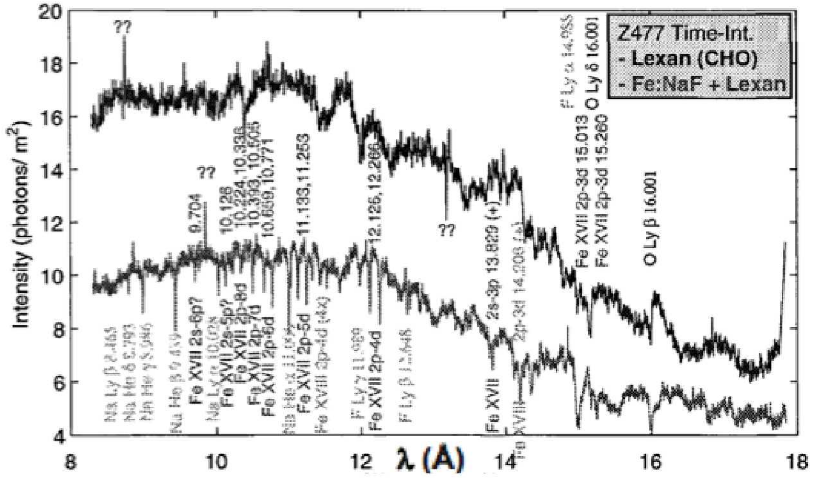
J. Bailey et al., Phys. Rev. Lett., **99** (2007)



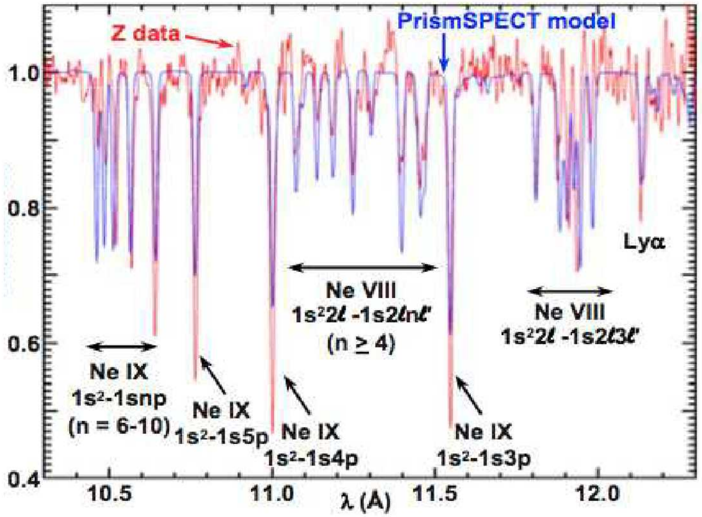
Transmission measured to 10% accuracy

Few photoionized plasma experiments exist

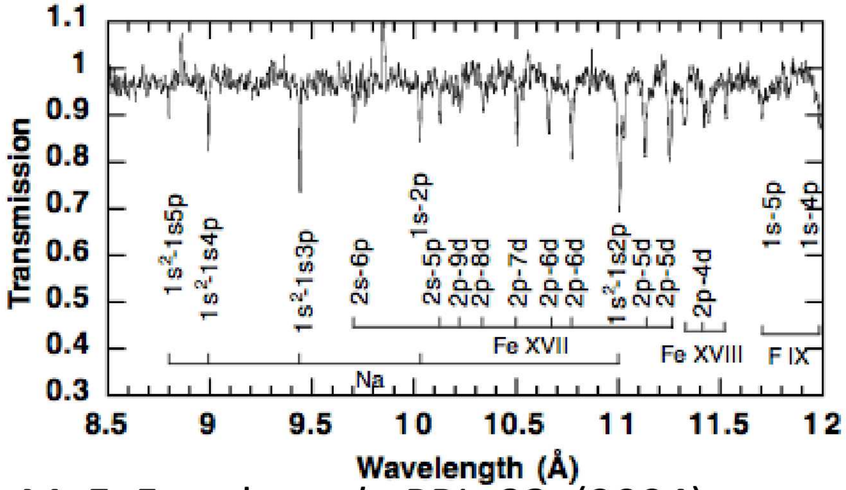
Absorption



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

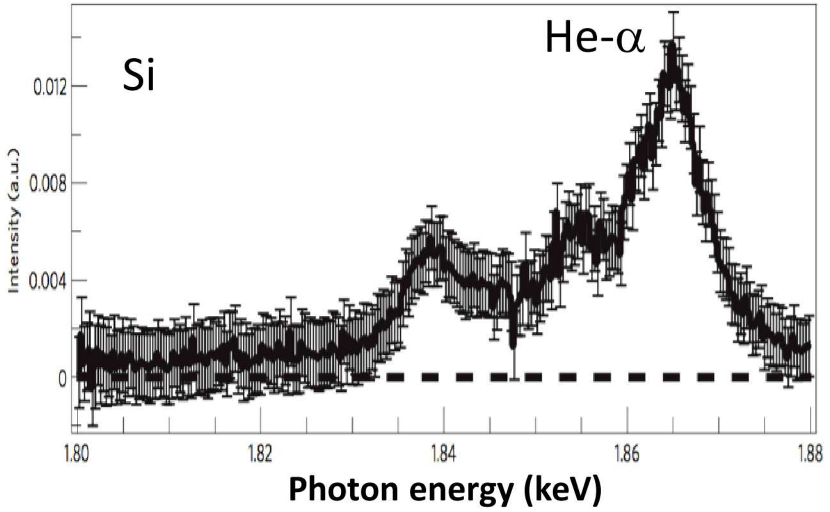


R. C. Mancini, J. E. Bailey *et al.*, *PoP*, **16**, (2009).



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

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.**

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.

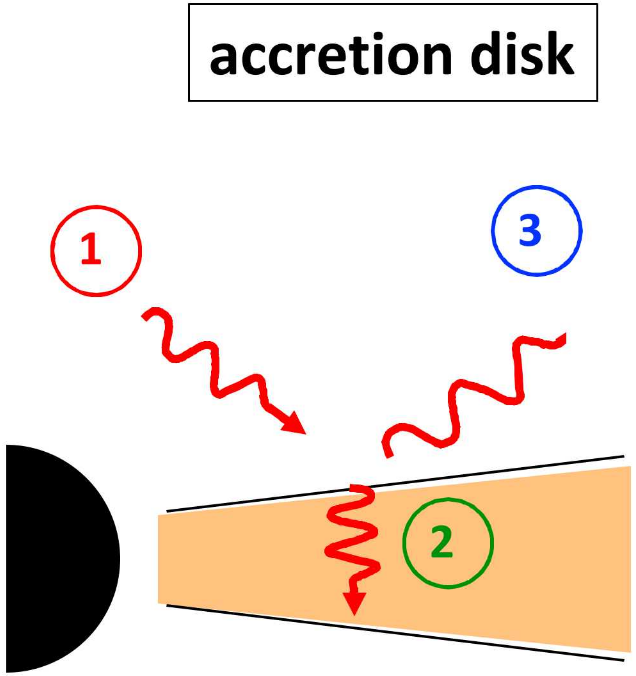
G. Loisel, J. Bailey, D. Liedahl et al., PRL 119 (2017)

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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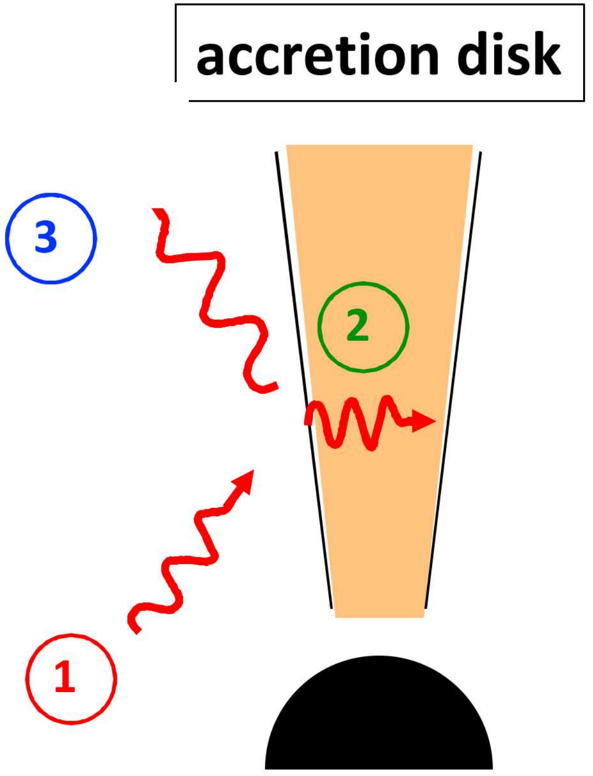

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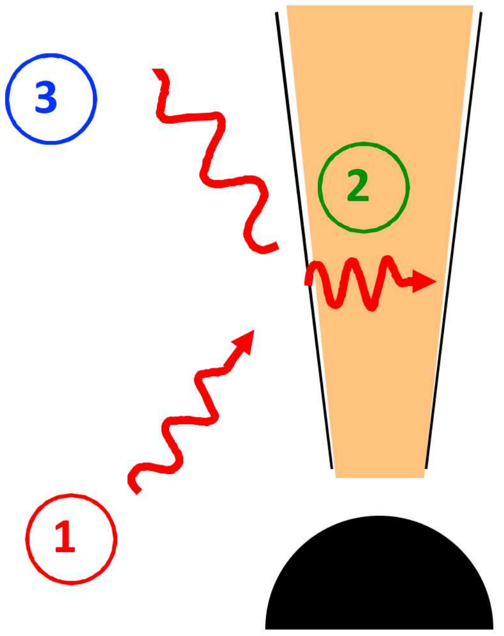
1. X-ray illumination
2. Photon ionization and atomic kinetics
3. Plasma emission

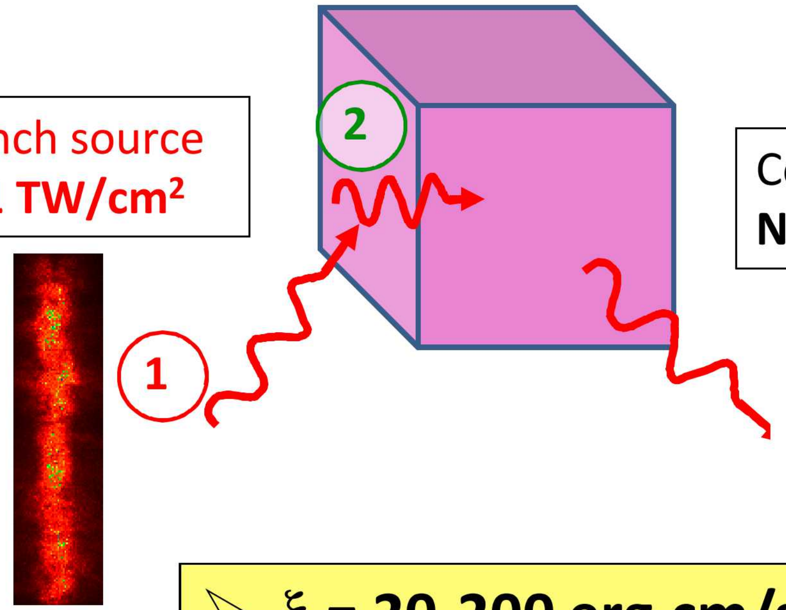
accretion disk



laboratory

Temperature T_e **= 20-40 eV**
Density n_i **~ 10^{17} – 10^{18} cm^{-3}**

Z-pinch source
F > 1 TW/cm²



Column density
N_i **~ 10^{17} – 10^{18} cm^{-2}**

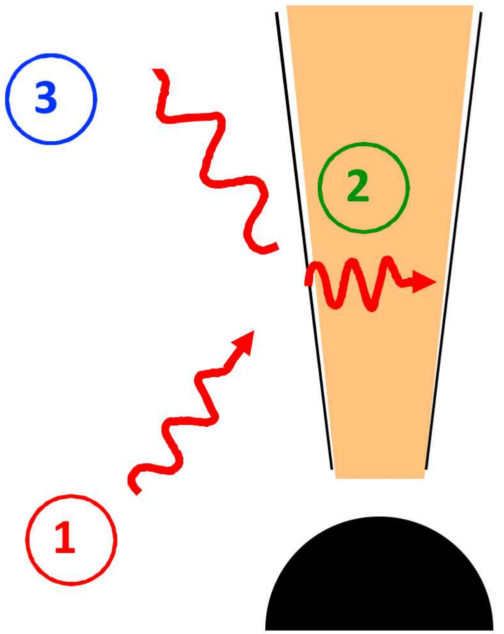
3 Emission spectroscopy

➢ **ξ = 20-200 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

accretion disk



laboratory

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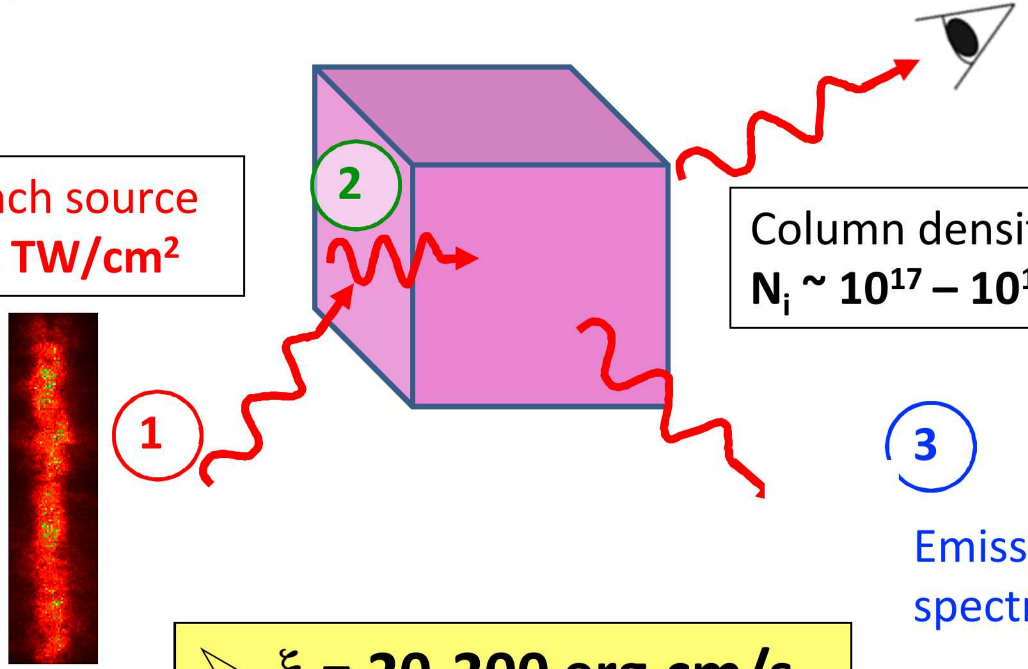


4 Absorption spectroscopy

Column density
N_i **~ 10^{17} – 10^{18} cm^{-2}**

3 Emission spectroscopy

➢ ξ **= 20-200 erg.cm/s**

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

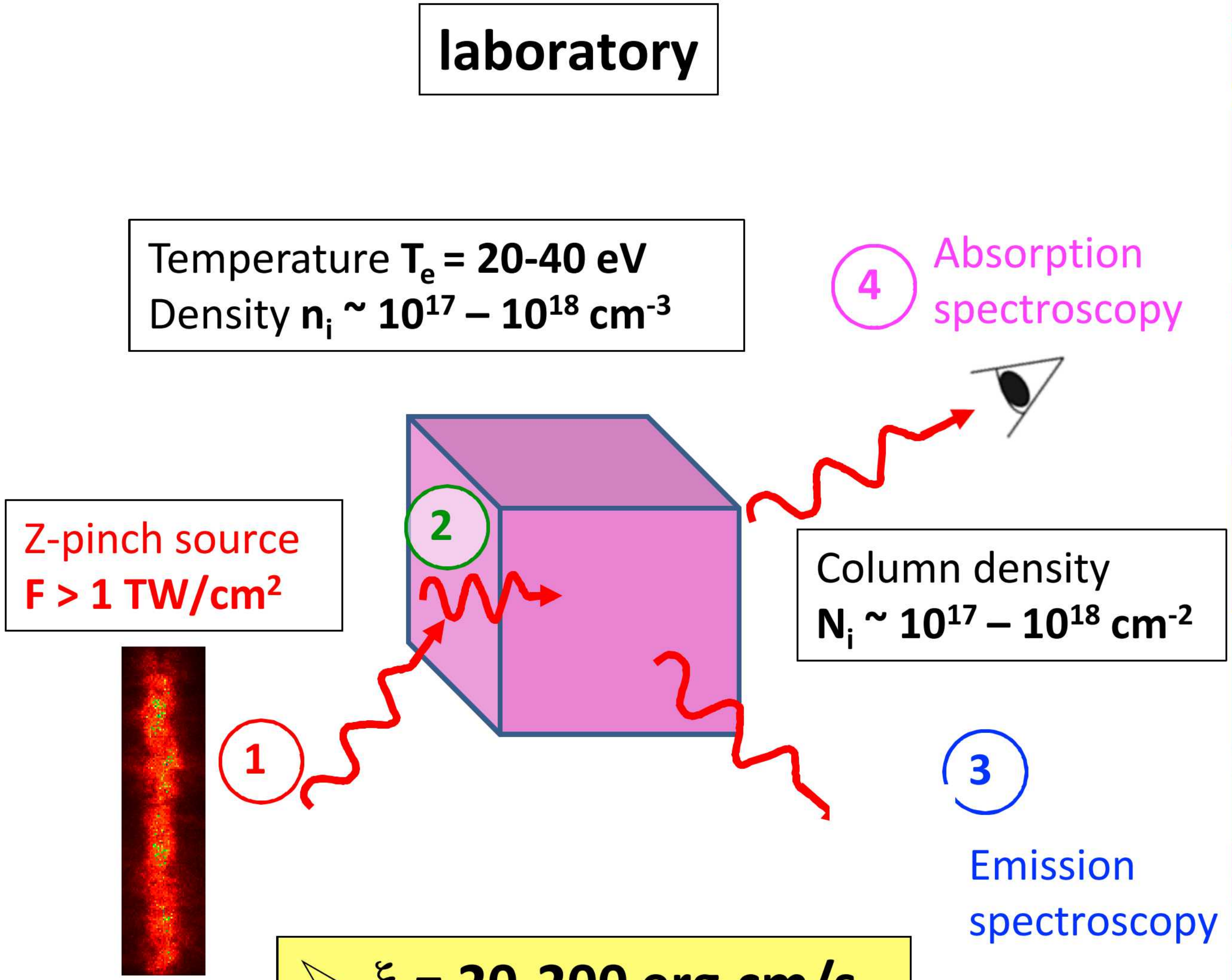
1 X-ray illumination

2 Photon ionization and atomic kinetics

3 Plasma emission

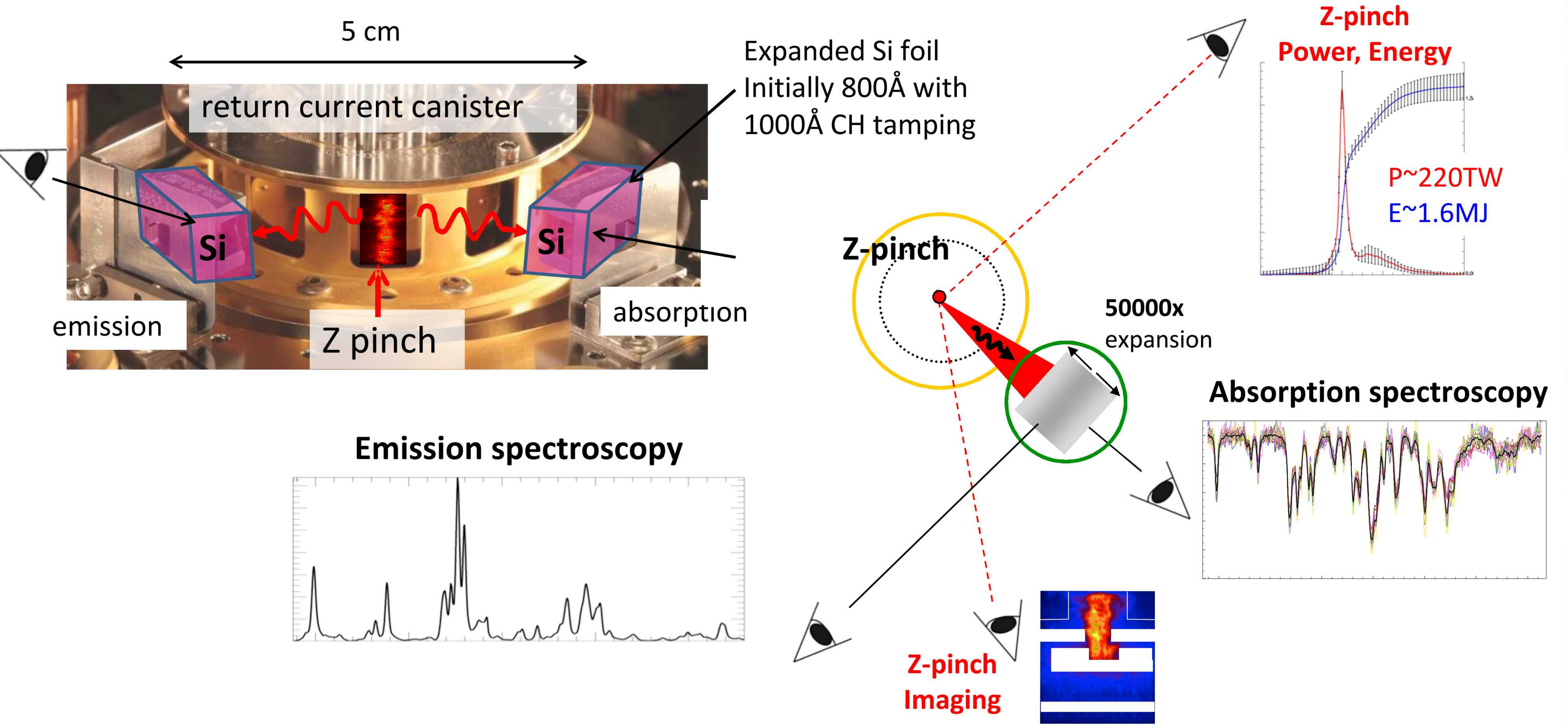
Advantages
- study individual process 1 2 3
- single element
- known drive
- controlled uniform plasma size
- higher spectral resolution
- higher signal to noise

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



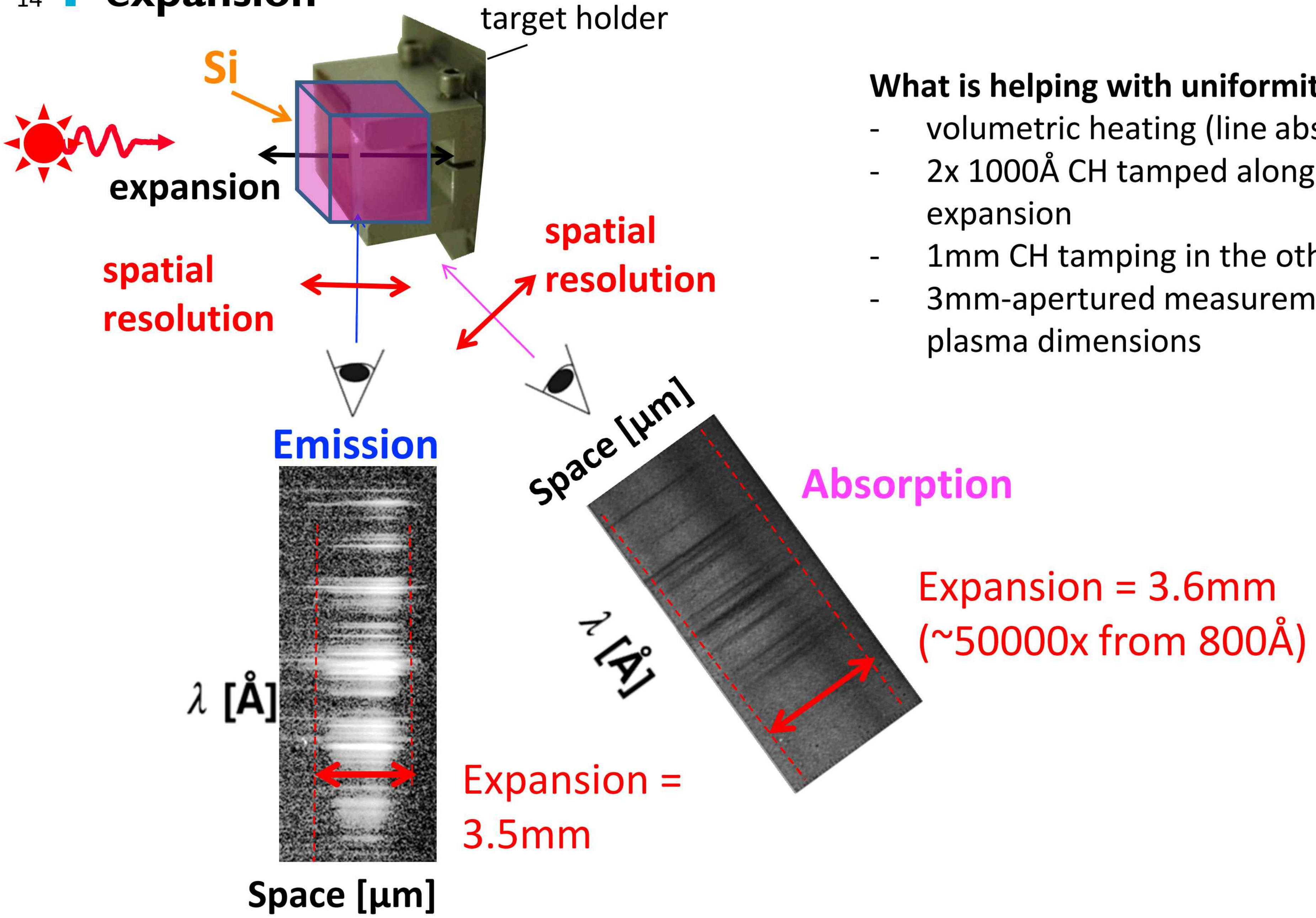
➢ ξ = 20-200 erg.cm/s

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)

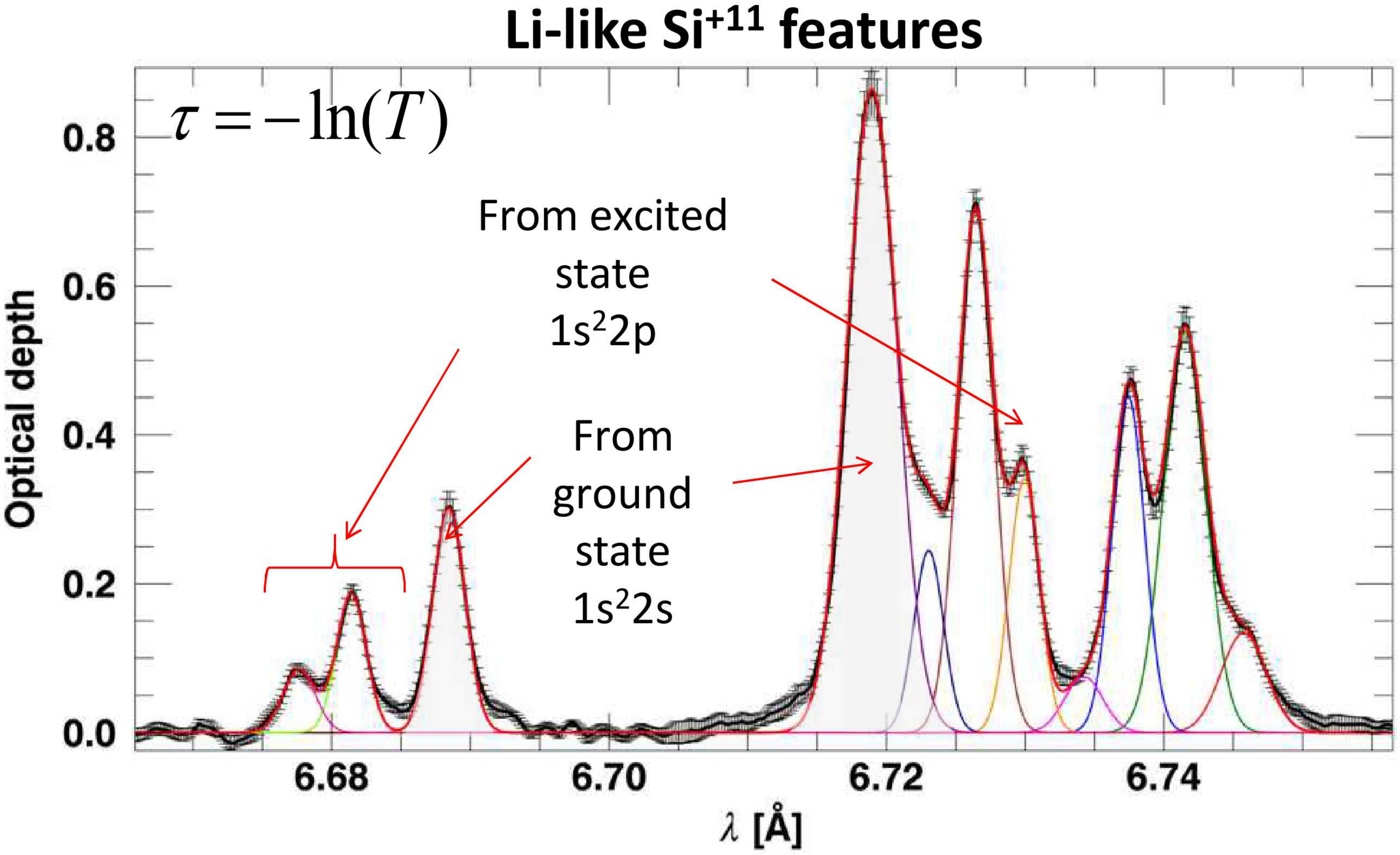
Ion density is measured from the sample areal mass and sample expansion



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

→ T_e = 33 ± 7 eV

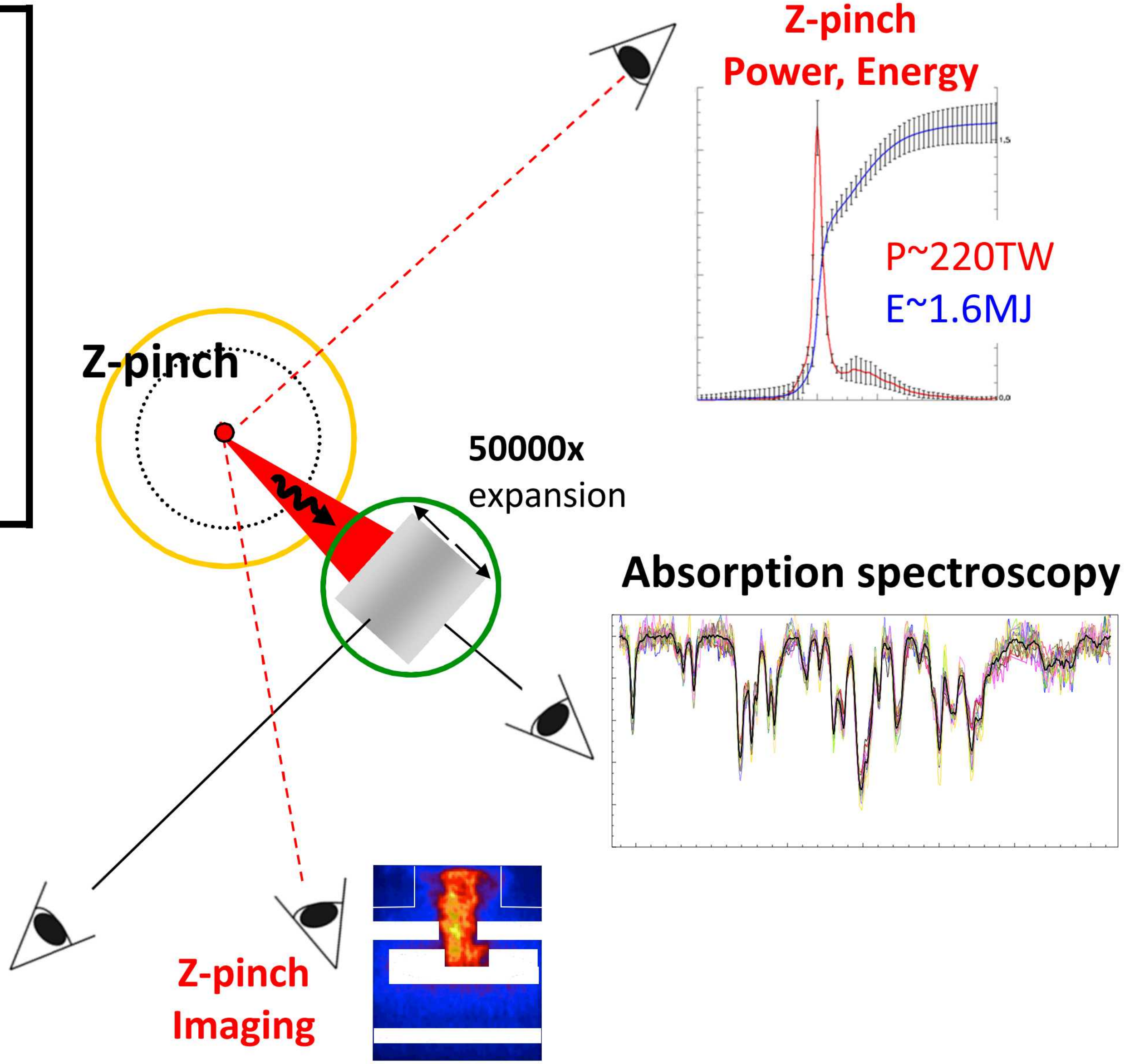
$\bar{Z} = 10.3$ with radiation

$\bar{Z} = 5.3$ without radiation

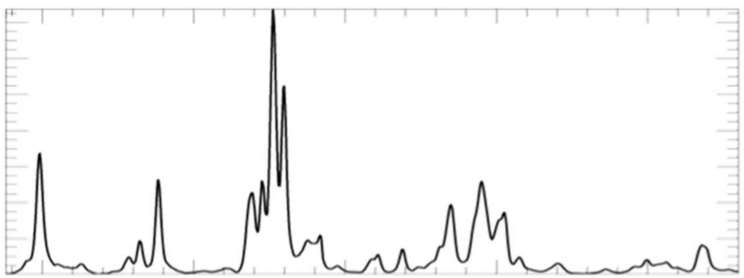
The plasma is over-ionized compared to collisional plasma at the same temperature

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

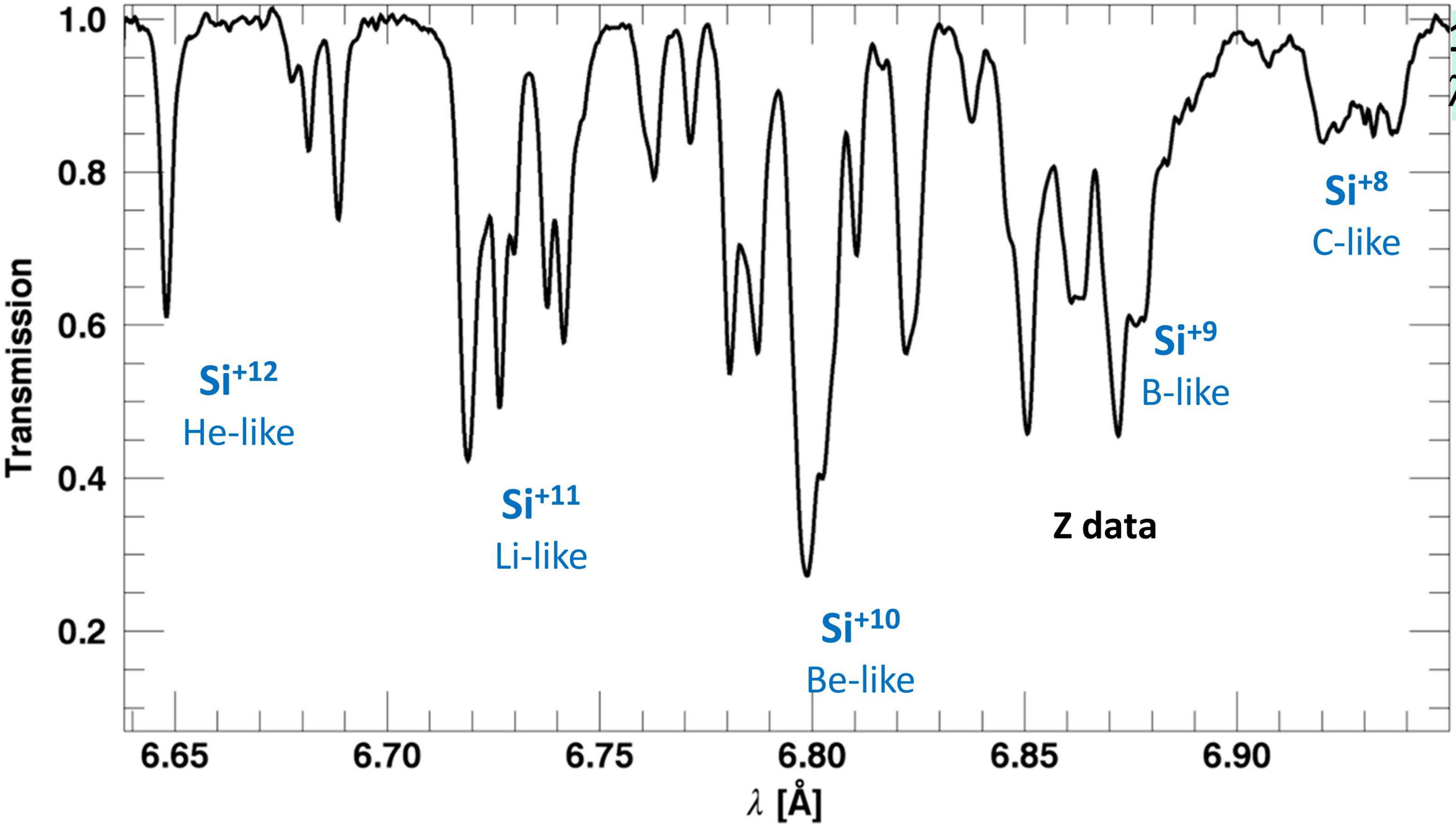


Emission spectroscopy



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

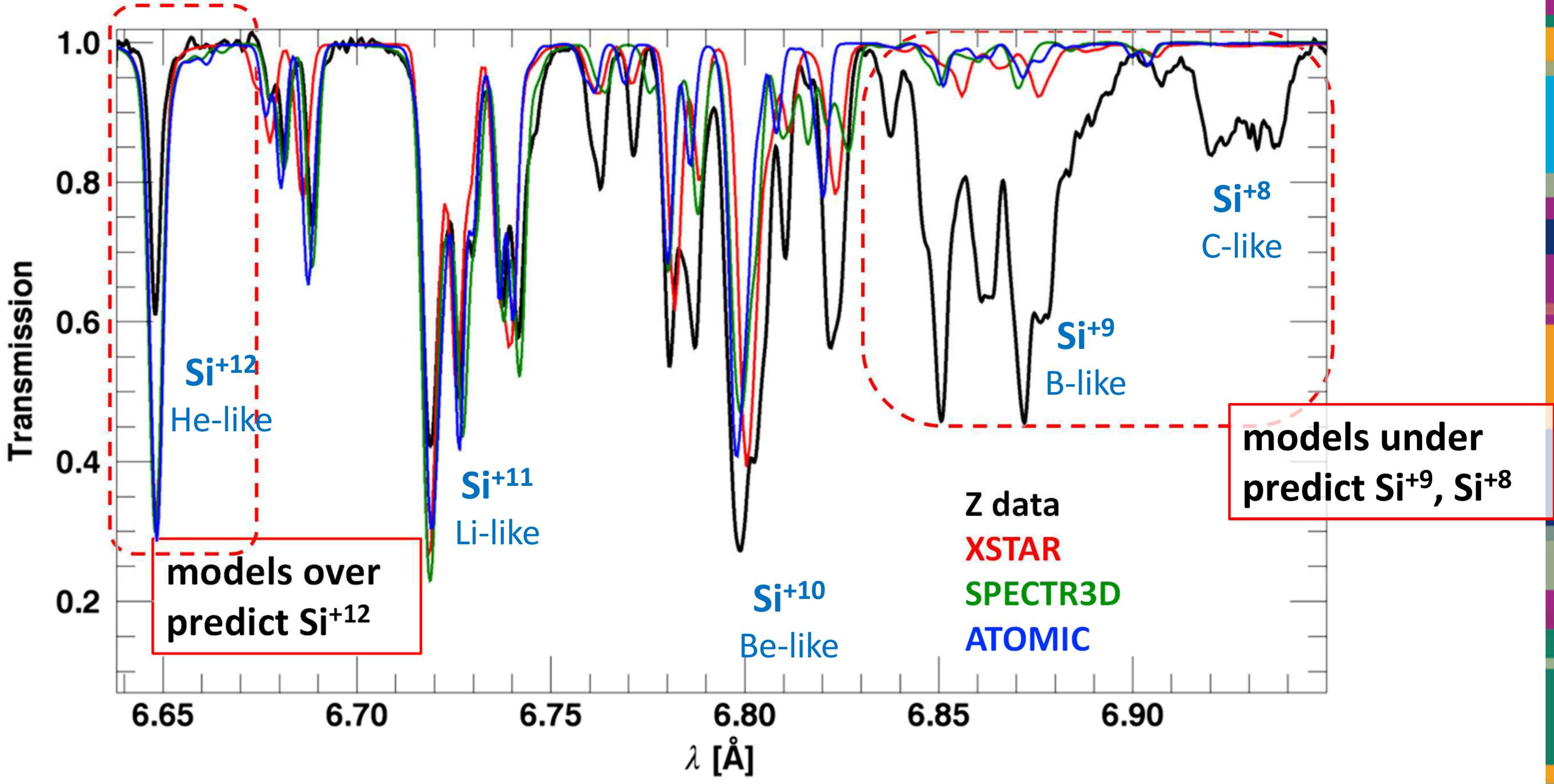
Measured relative absorption from different ion stages test ionization predictions



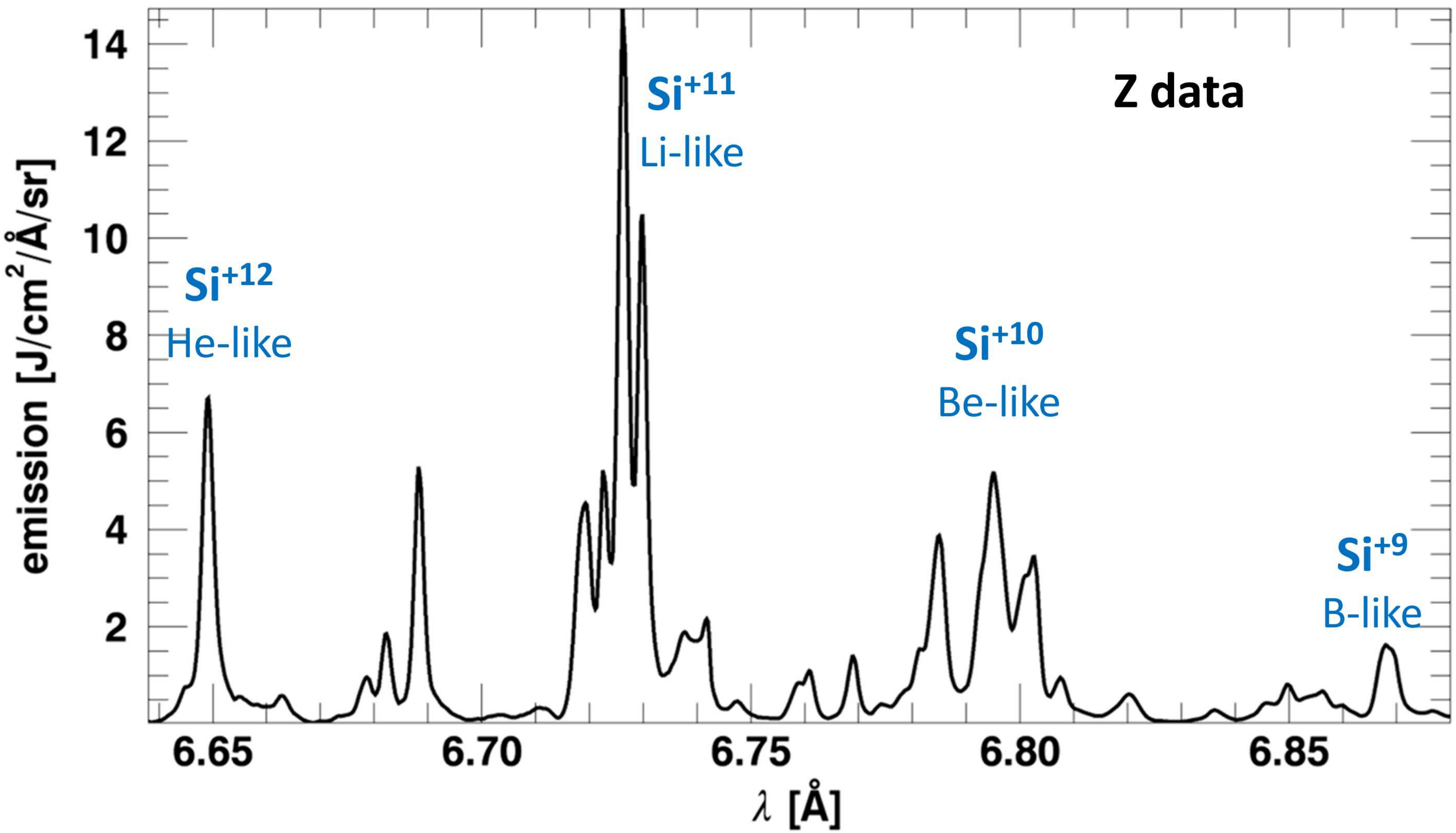
1.2% rel. unc.

$\lambda/\delta\lambda$ **~ 2400**

Measured relative absorption from different ion stages test ionization predictions



The emission data shows contributions from different charge states

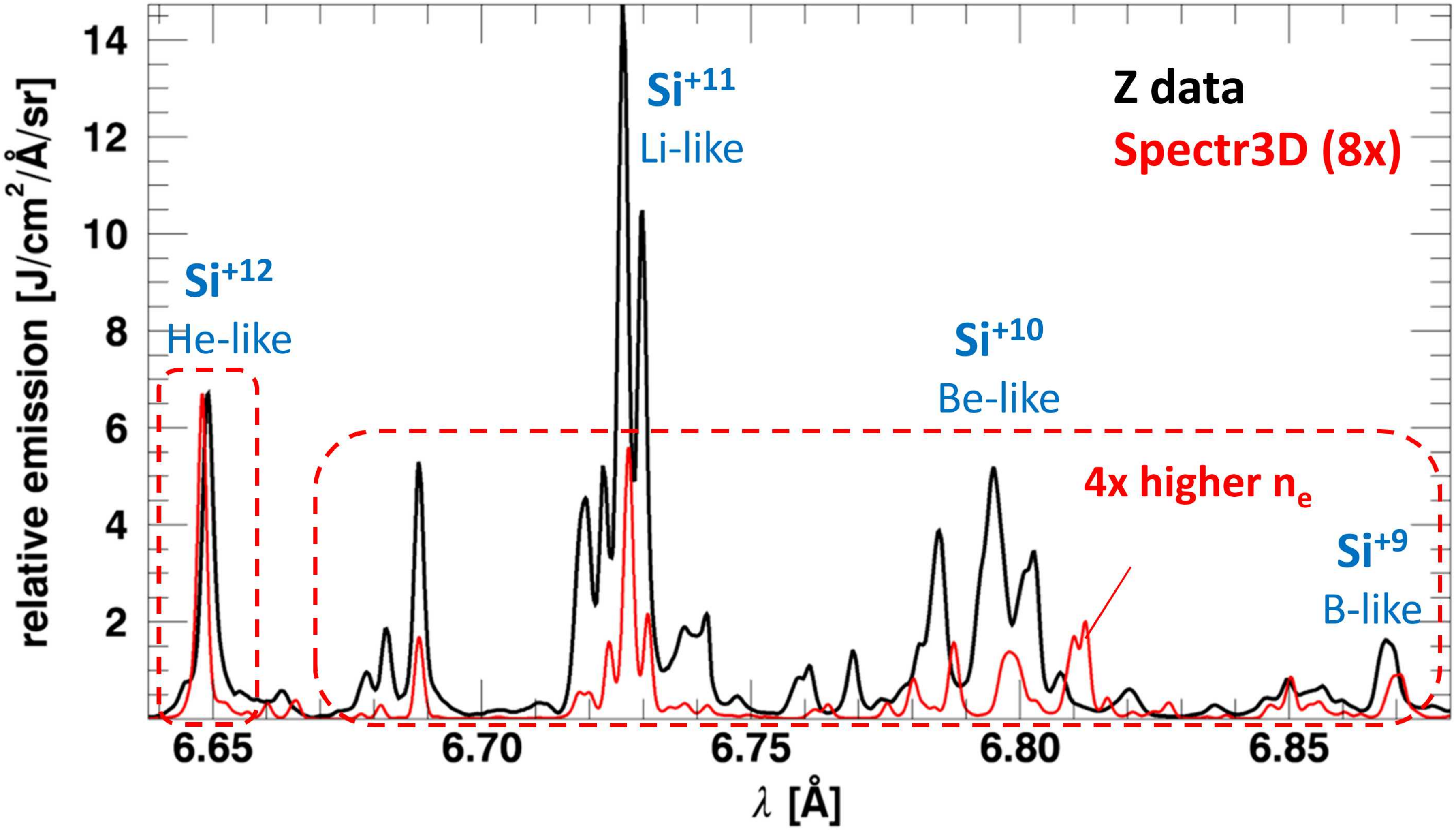


5.2% rel. unc.
$\lambda/\delta\lambda$ ~ 4400

Simultaneous line observation contradicts an assumption used to interpret black hole spectra = Resonant Auger Destruction (RAD)* is not 100% effective.

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

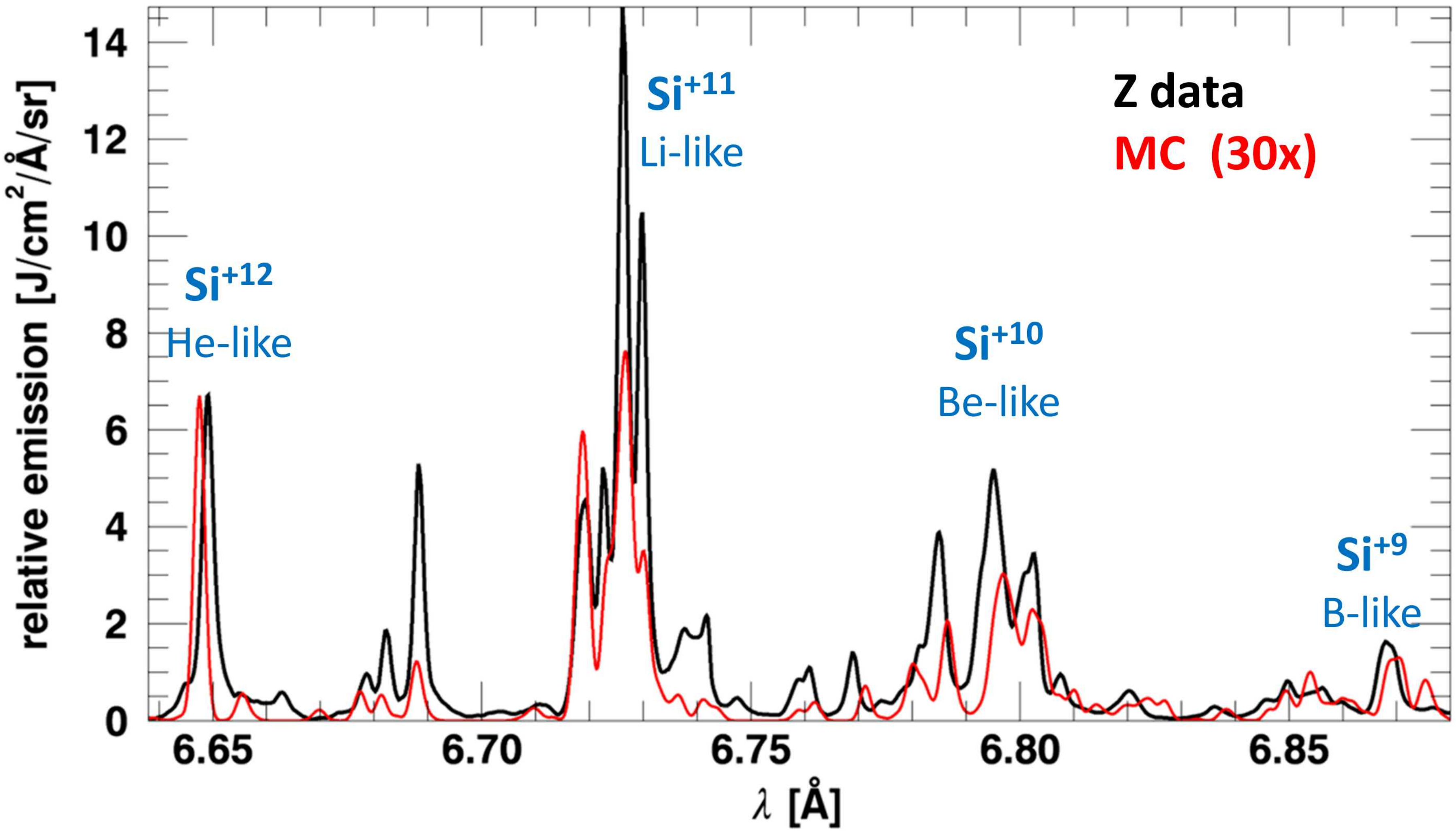
The emission is not reproduced by any model even with conditions adjusted to match absorption spectra



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

Spectr3D: Prism Computational Software

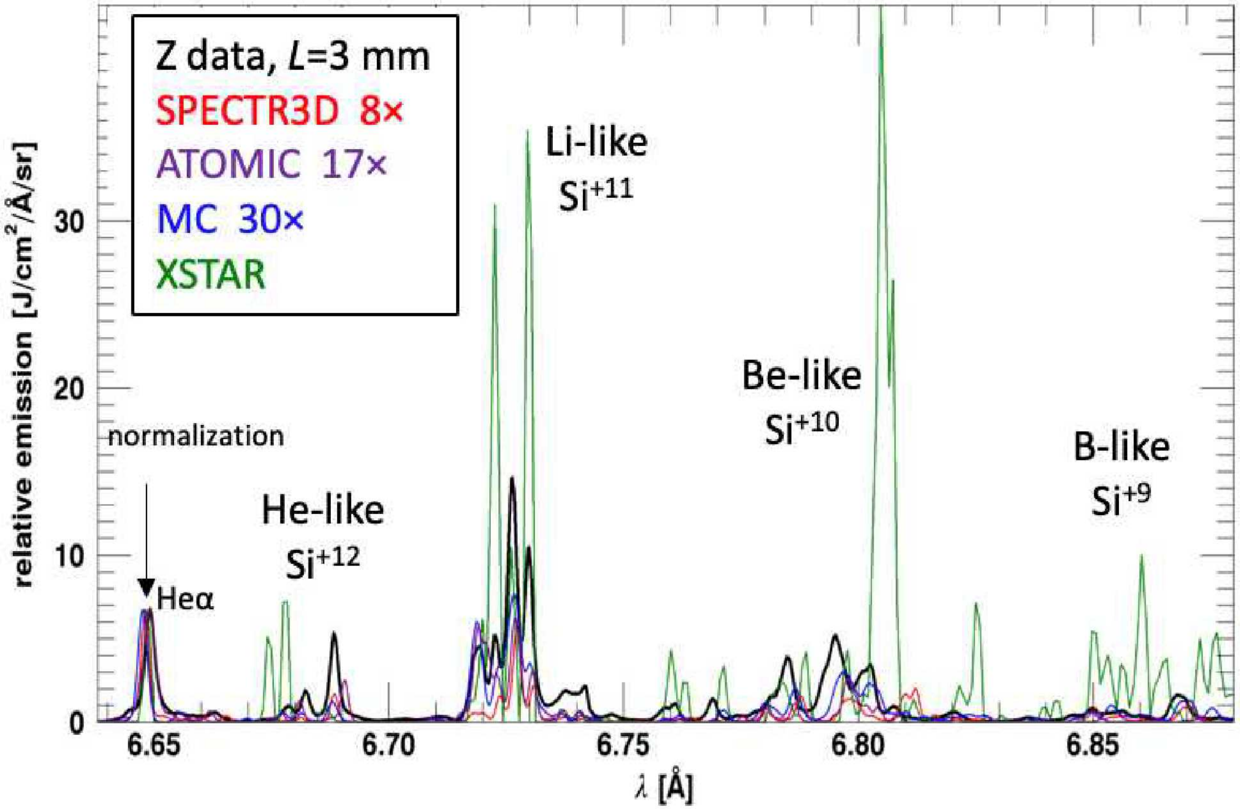
Comparison with a Monte Carlo radiation transport code exhibits improved agreement

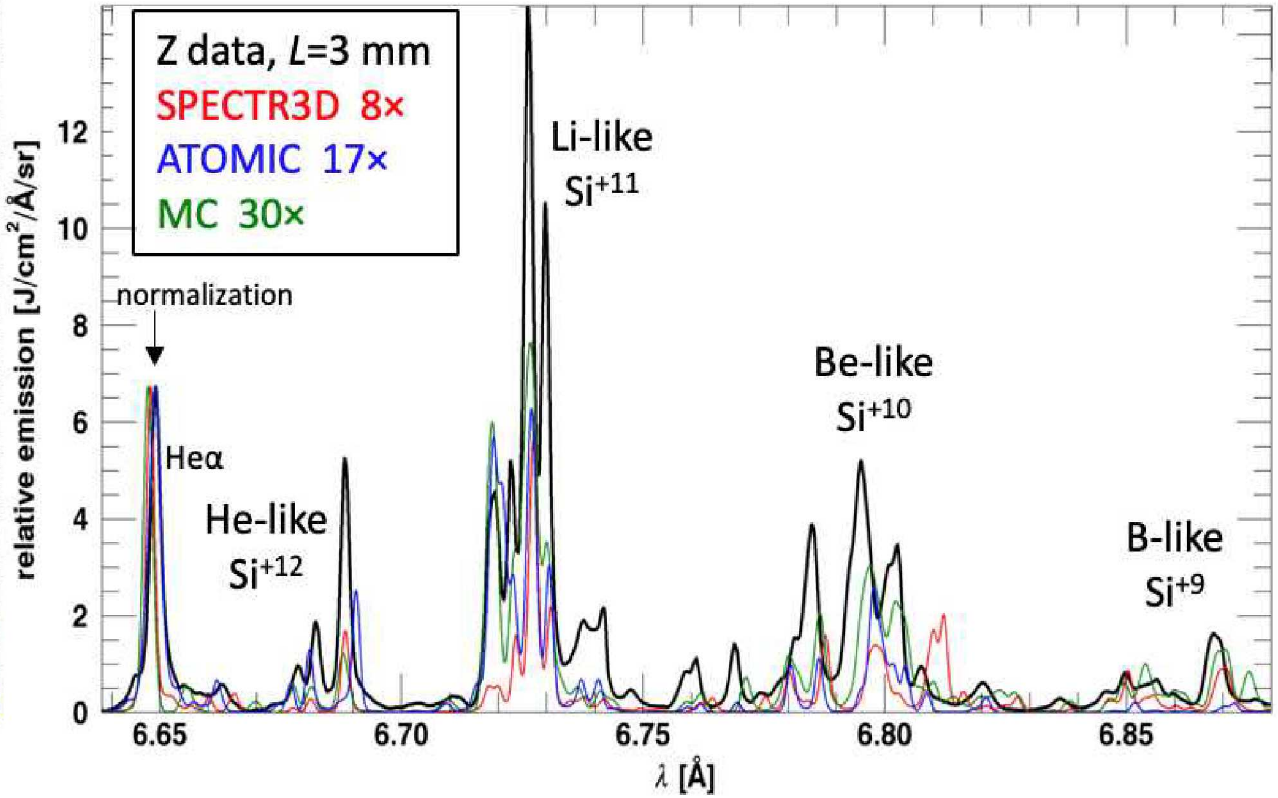


The effect of the different atomic physics data must also be evaluated

MC: Monte Carlo radiation transport code, D. Liedahl

Models also disagree with each other





First improvements to XSTAR to match Z data:

- **fine structure oscillator strengths were added for He-like Silicon (update atomic database)**
- **more accurate description of driving radiation**
- **identify that radiation transport model can be improved**

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 ±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.

Benchmark emission data and conclusion on RAD were first published

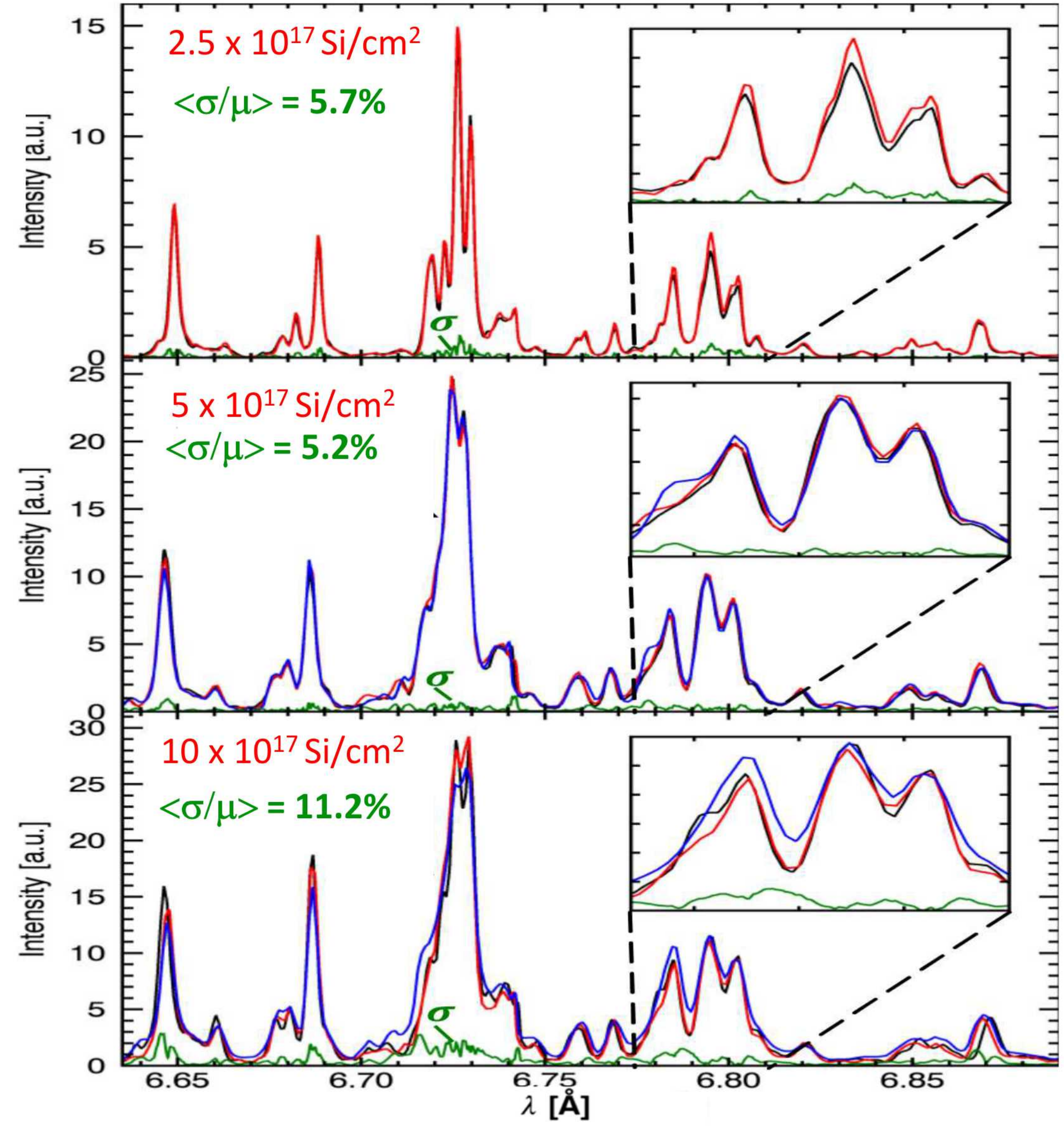
PRL 119, 075001 (2017) PHYSICAL REVIEW LETTERS week ending 18 AUGUST 2017

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.

Reproducible emission at 3 column densities

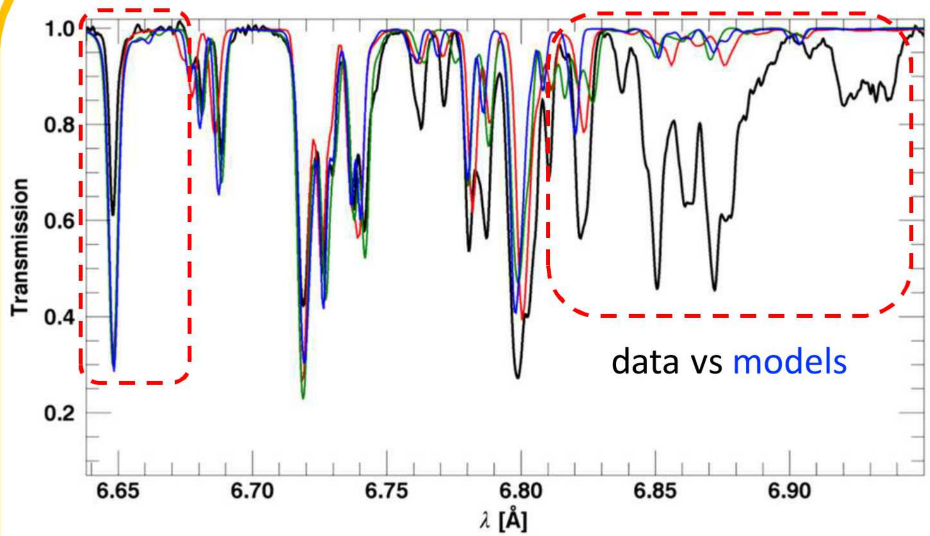


- Transmission was measured with 4.7% reproducibility enabling test of ionization predictions
- Emission is measured down to 5.2% reproducibility and at three column densities thus enabling test of radiation transport
- Resonant Auger Destruction is not 100% effective at quenching L-shell ion K emission

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

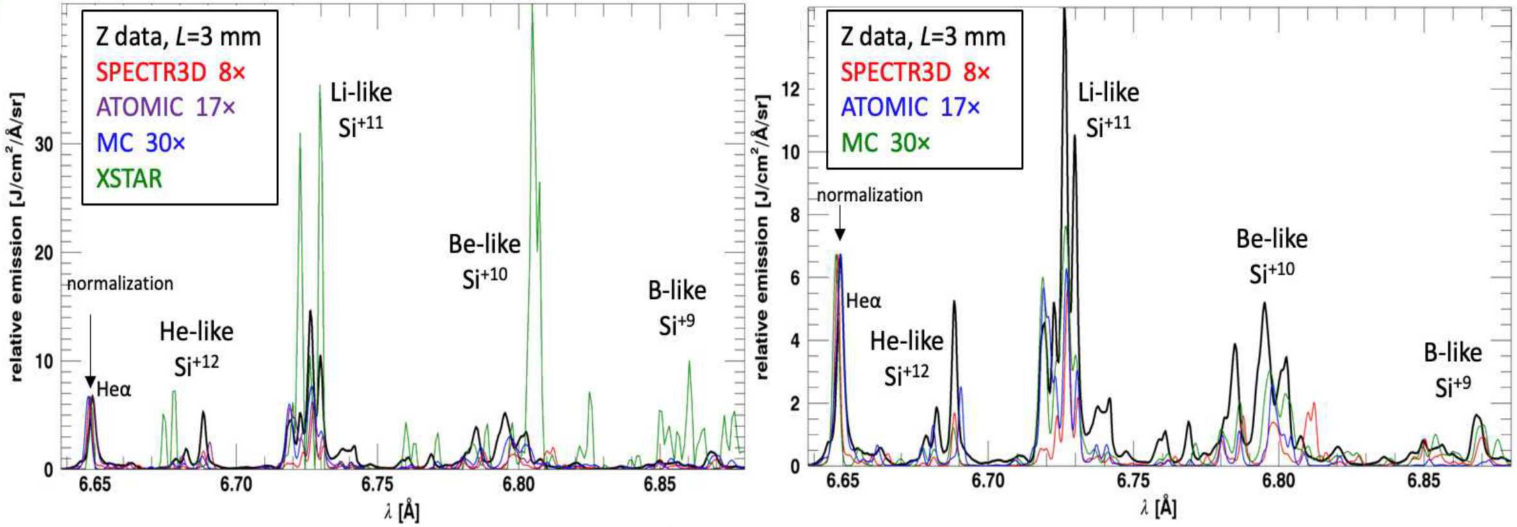
Puzzles drive current and future developments

1) Absorption



Models over-predict ionization at measured conditions

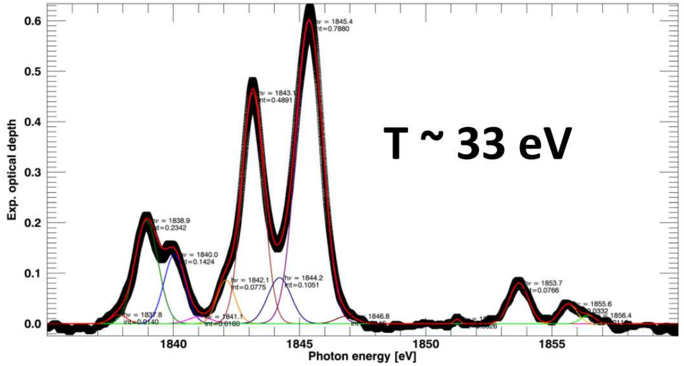
2) Emission



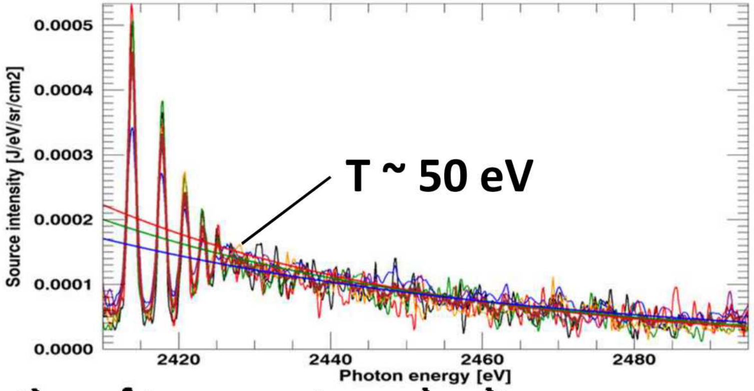
Models don't reproduce the *absolute* nor the *relative* measured emission

3) Temperature diagnostics

optical depth

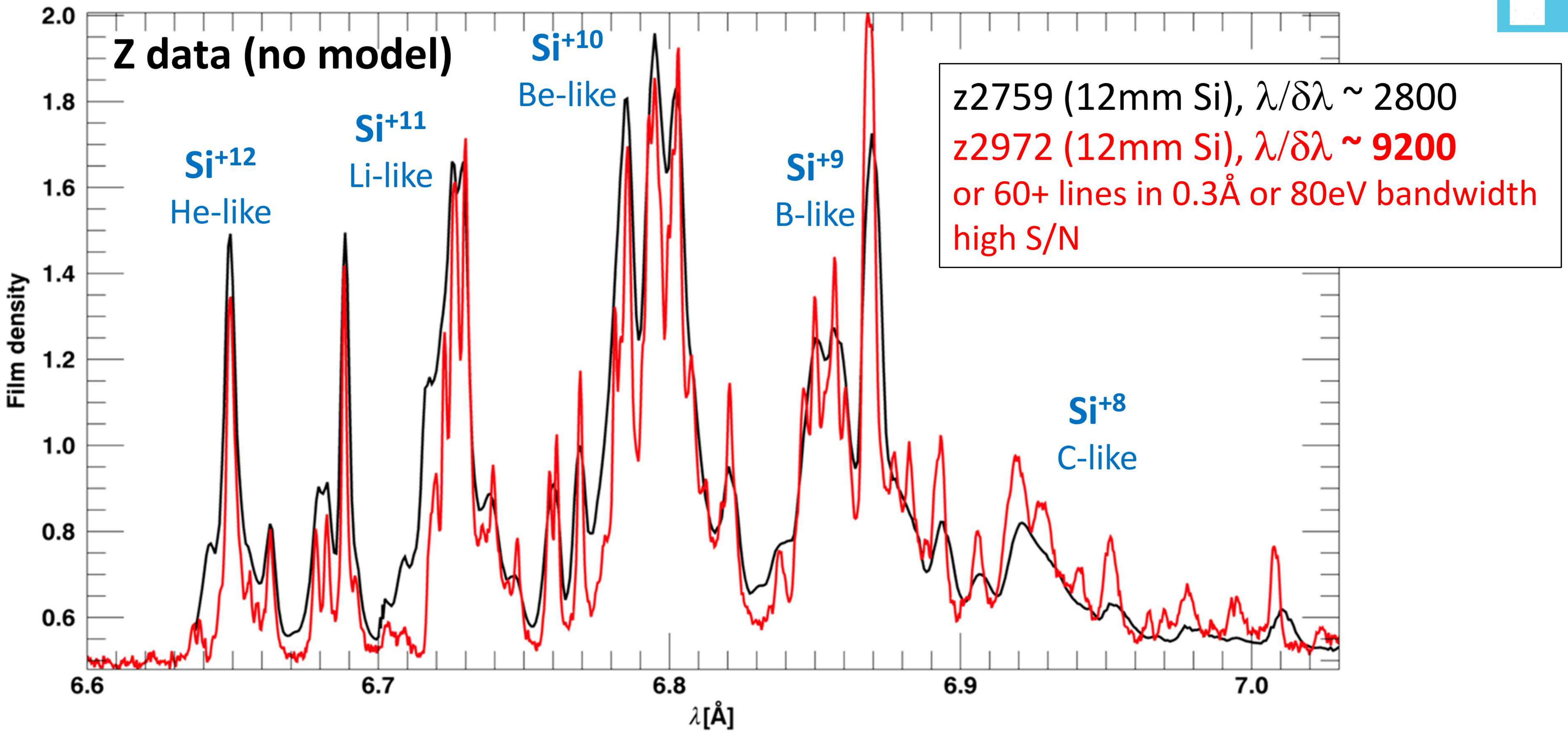


Radiative recombination continuum



Independent diagnostics of temperature don't agree

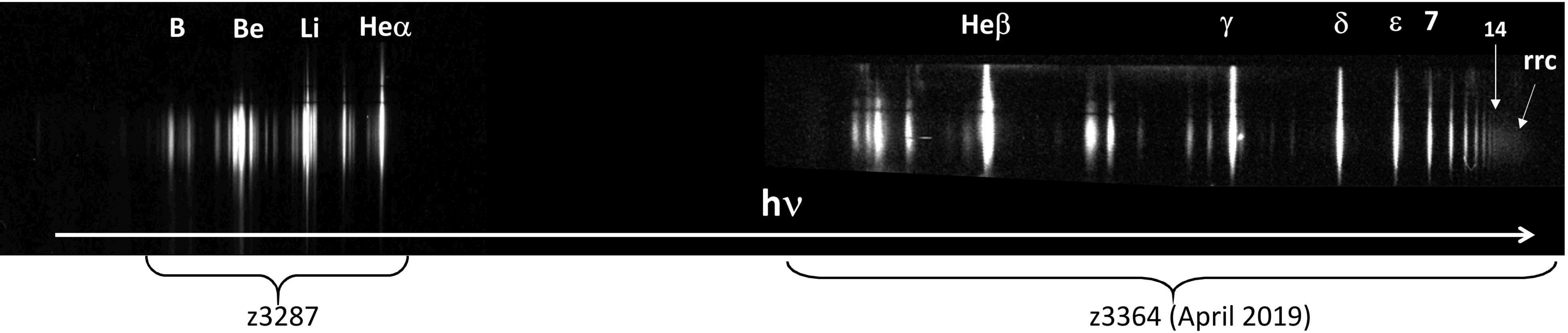
<u>Recent work</u>: Emission spectrum can be measured at ultra high spectral resolution



- ➢ **We can study very detailed level structure and more precise radiation transport effects on lines that have variable optical depth.**
- ➢ **Detailed line identification is allowed (P. Cho project).**

Recent work: the *complete* He-like series up to n=14 can be obtained for a single target

Silicon closer to the x-ray source

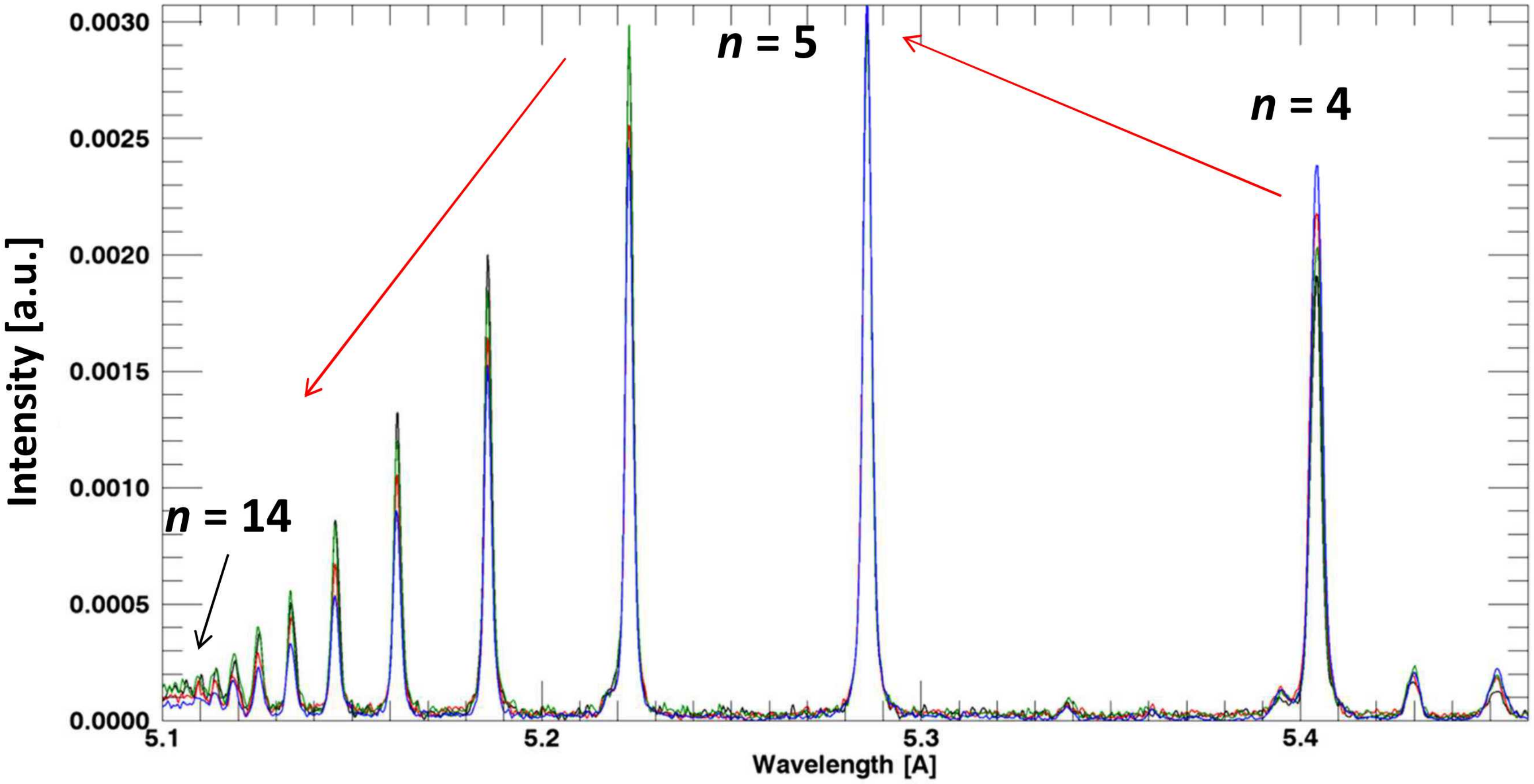


Extended range XRS3 spectrometer data

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

Recent work: 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:

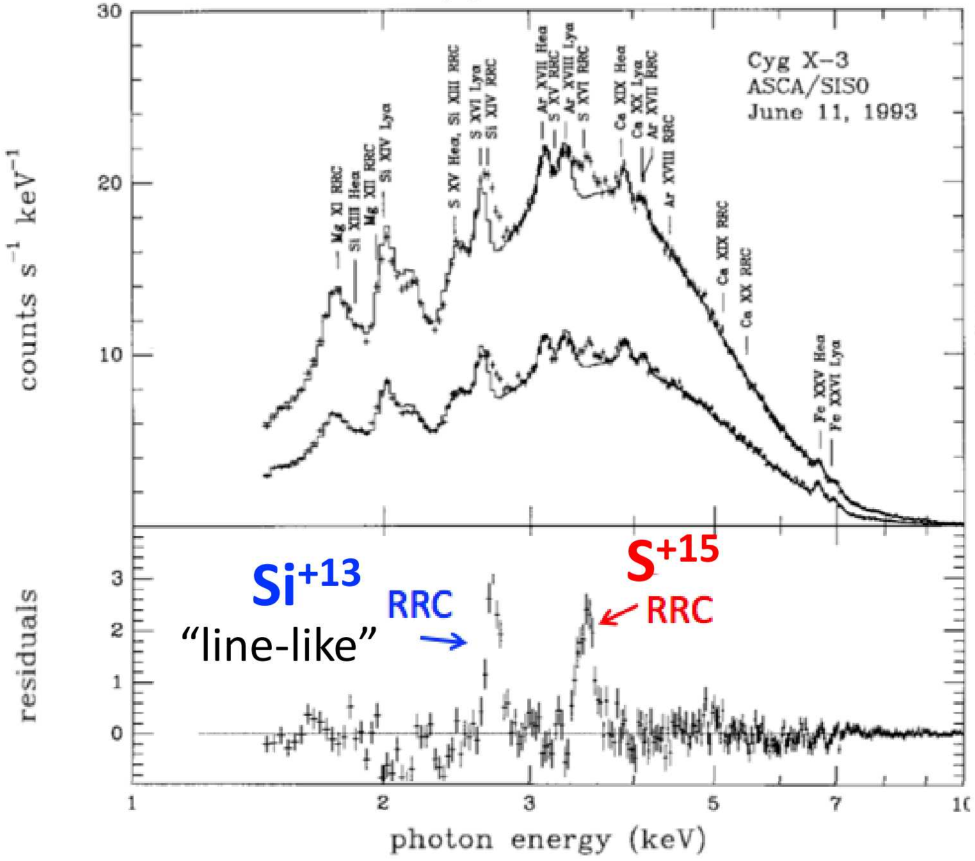
- **recombination following photoionization**
- **or photoexcitation**

Also line intensity is affected by radiation transport.

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

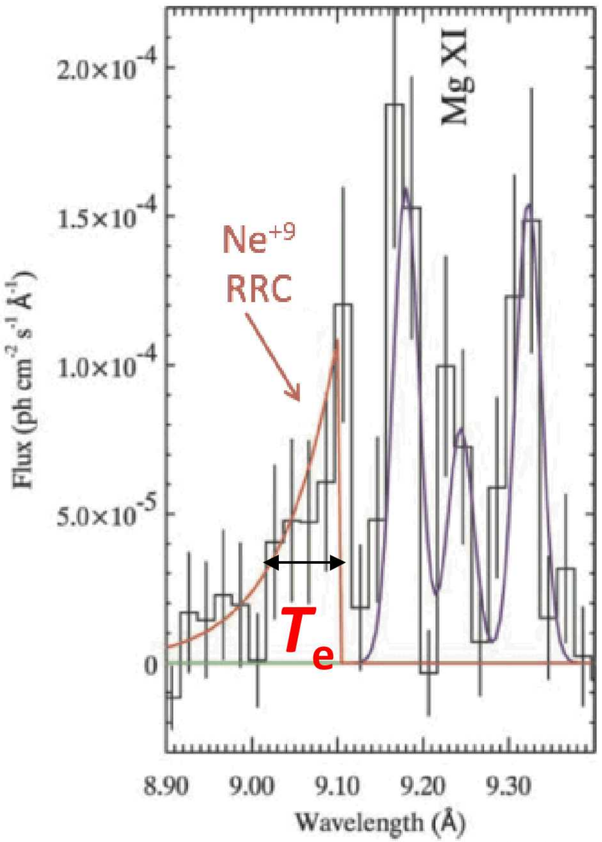
Recent work: First RRC (~10^{-8} Z-pinch energy) in a photoionized plasma in a terrestrial laboratory was recorded

Cygnus X-3



T_e = 5-50 eV [1]

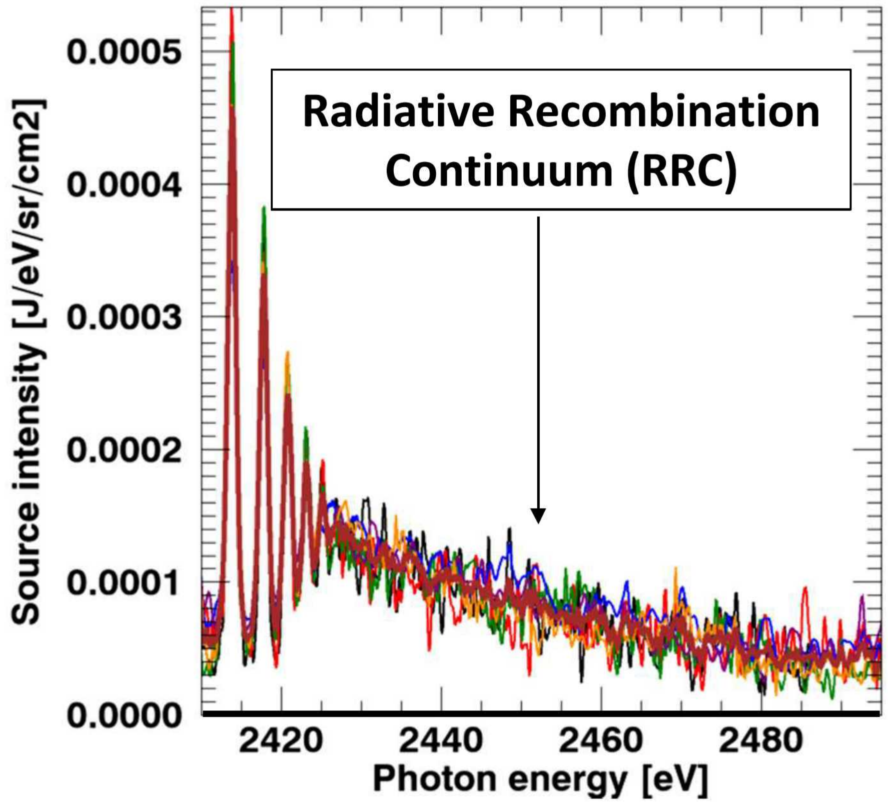
Vela X-1



T_e = 10 ± 2eV [2]

T_e = 6.6 ± 2eV [3]

Earth: Z plasma



exp. slope => T_e

→ ~Maxwellian e^- distribution

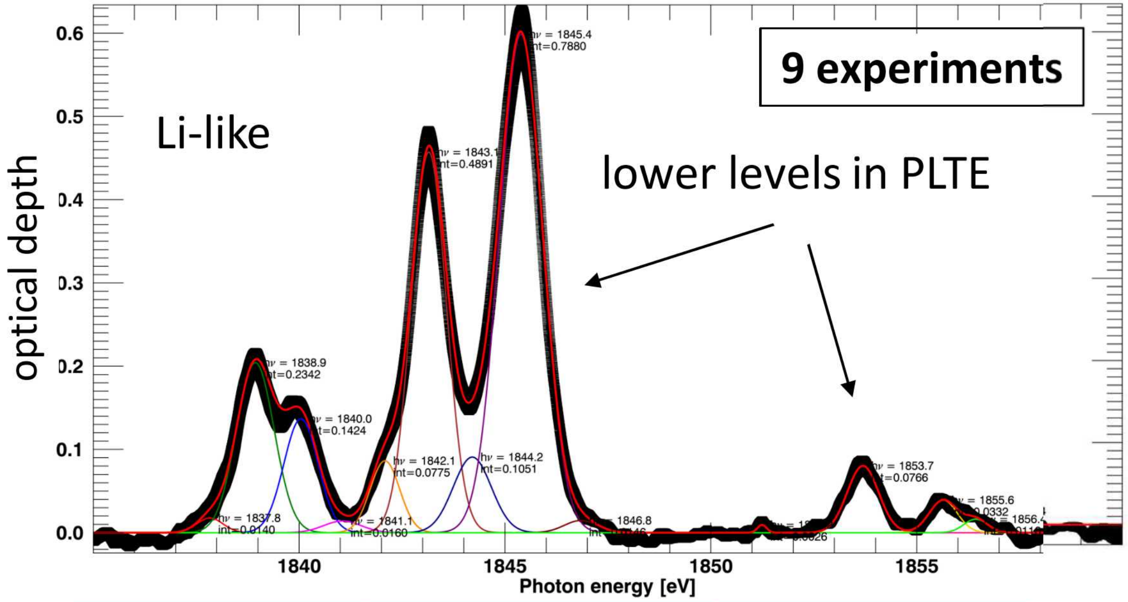
- → **RRC visibility with highly charged ions supports the photoionized nature of the accreted matter**
- → **Untested in the laboratory in a well-characterized photoionized plasma.**

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

Recent work: temperature inferred from the absorption spectra disagree with the RRC-inferred temperature

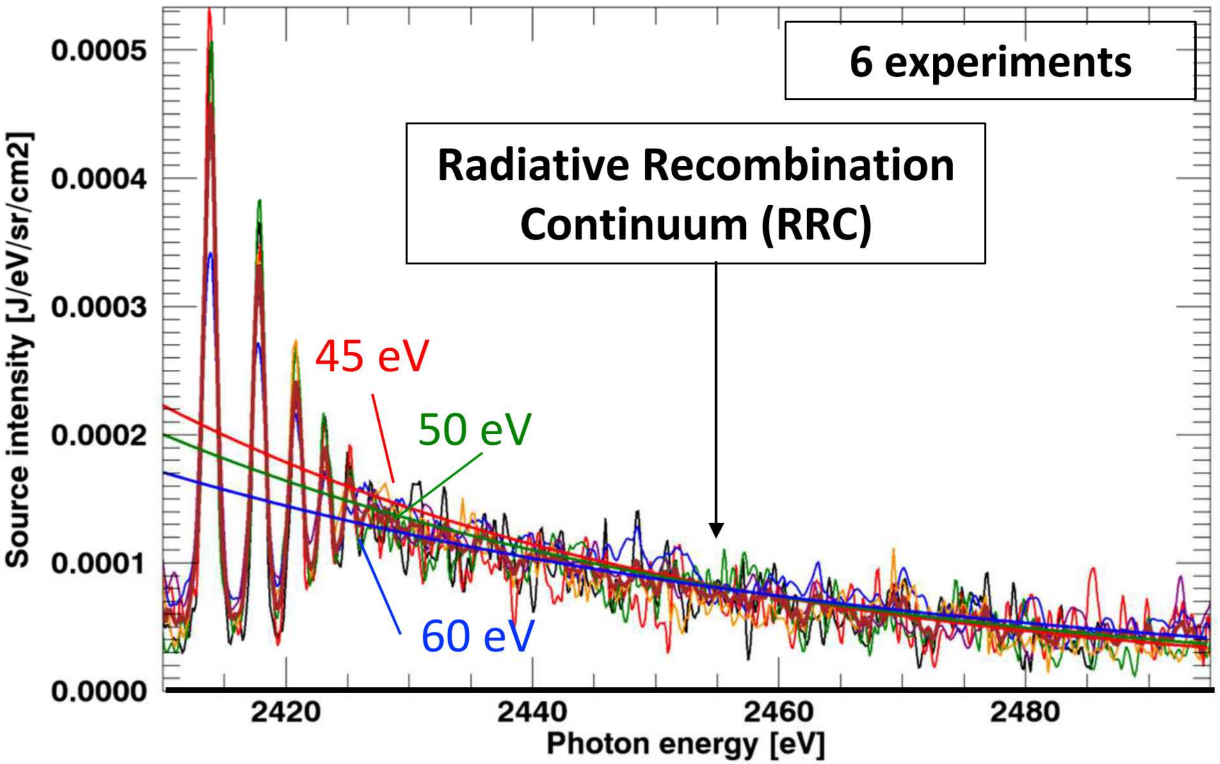
Silicon closer to the x-ray source

Absorption



Absorption initial level	Oscillator strength code	Temperature T_e [eV]
$1s^2\,2p_{1/2}$	PRISM	33.3 ± 1.46
$1s^2\,2p_{3/2}$	PRISM	33.4 ± 1.30
$1s^2\,2p_{1/2}$	CATS	33.2 ± 1.83
$1s^2\,2p_{3/2}$	CATS	32.6 ± 1.55

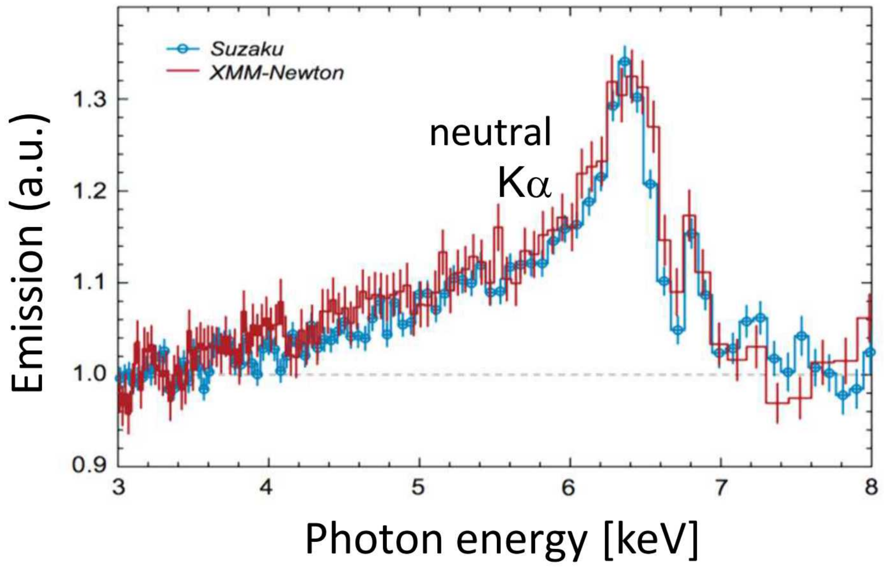
Emission



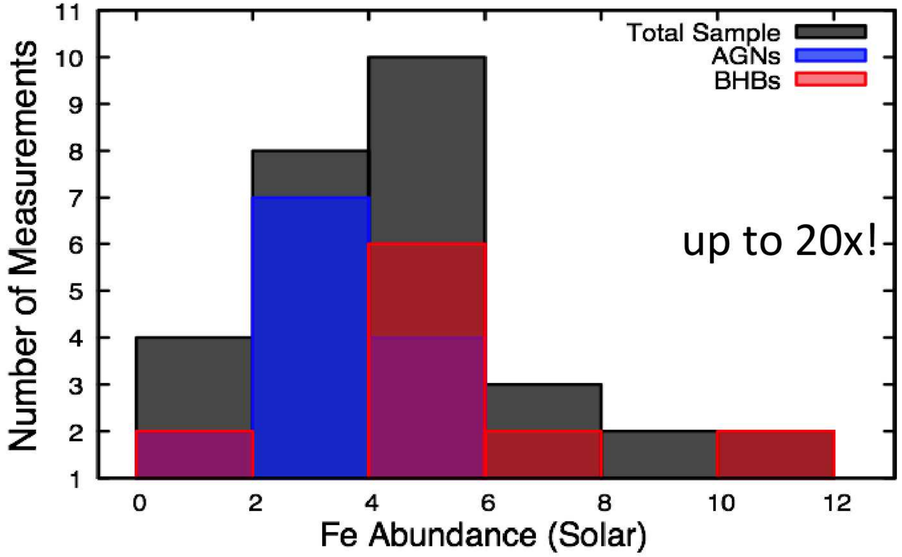
RRC slope → T_e = 52 ± 7 eV
Li-like sat. ratio → T_e ~ 33 ± 2 eV
Data need more scrutiny

Future work: the Z platform might address the black hole accretion *supersolar* abundance problem

Broad Fe line MCG 6-30-15



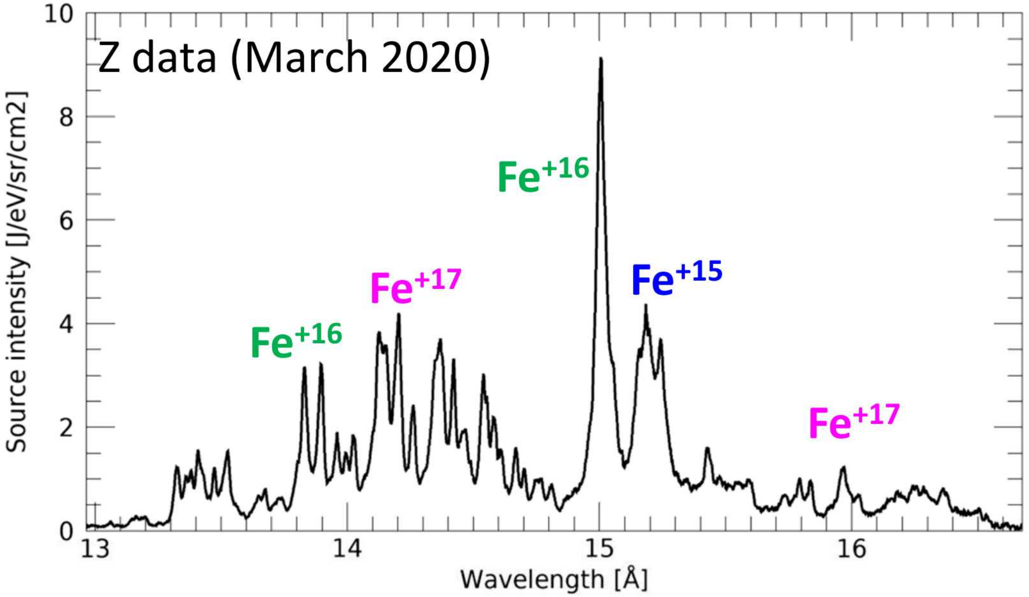
Histogram of AGN and BHB Fe abundances*

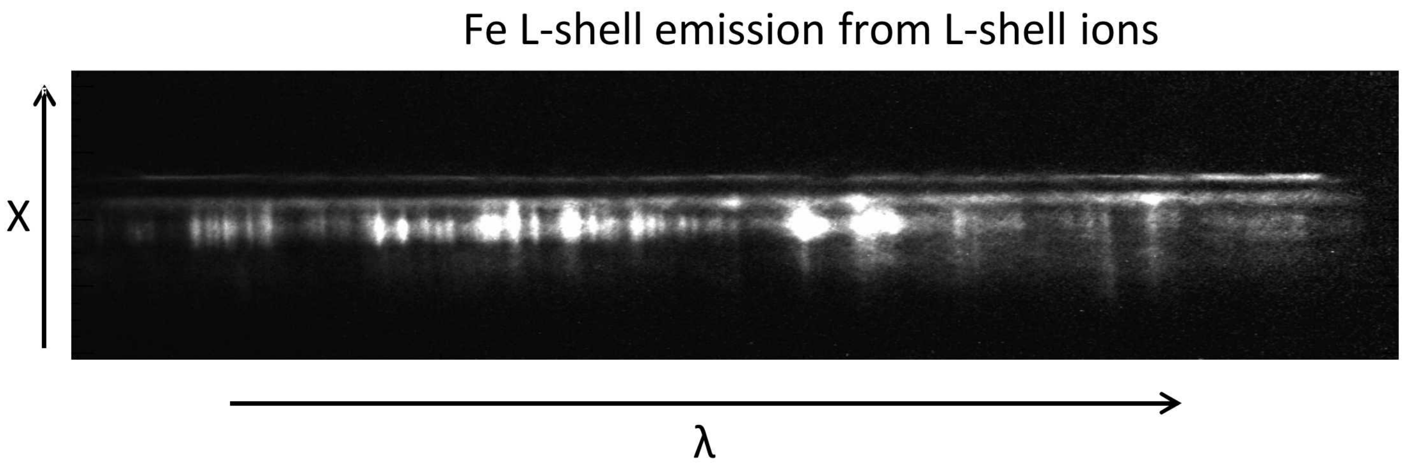


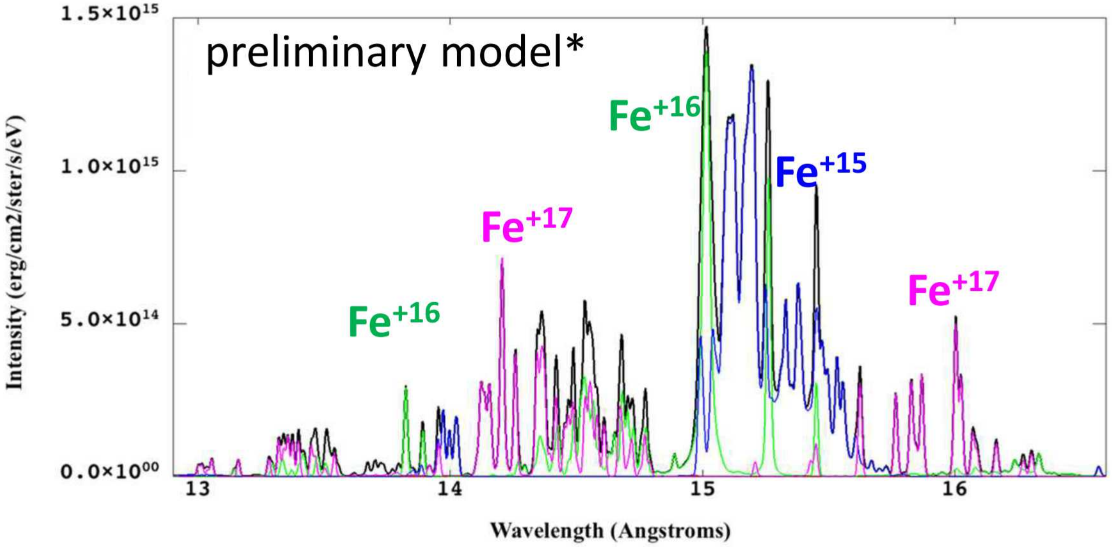
Could atomic data and kinetics be flawed at higher density?

**García, Kallman, Bautista et al. ASP Conf. Ser. 515 (2018)*

Future work: the Z platform might address the black hole accretion *supersolar* abundance problem





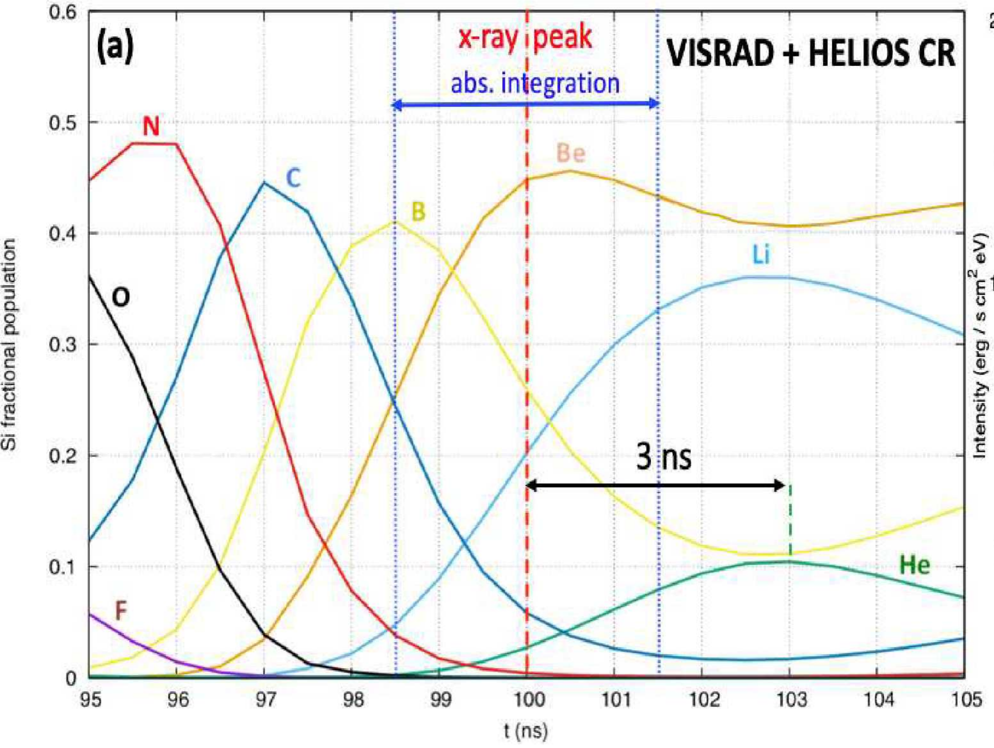


Preliminary observation: L-shell Fe ions are created when sample is located closer to the z-pinch (~3cm).
Paves the way to test Fe emission atomic and kinetics physics that might be linked to the supersolar abundance problem.

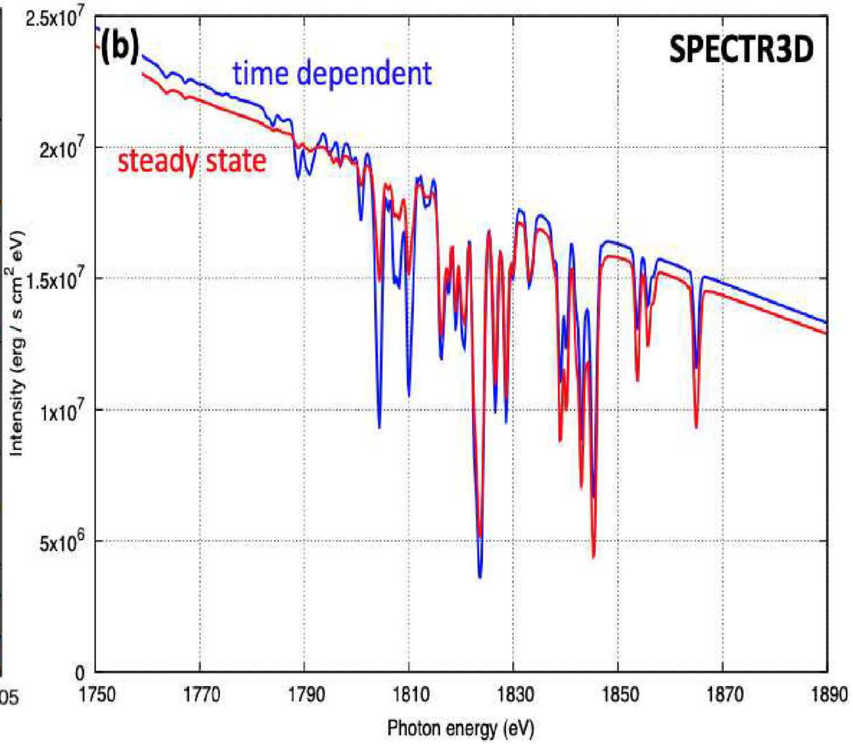
* Prismspect

Next work: Could time-dependent effects be part of the difficulty at predicting the measured emission?

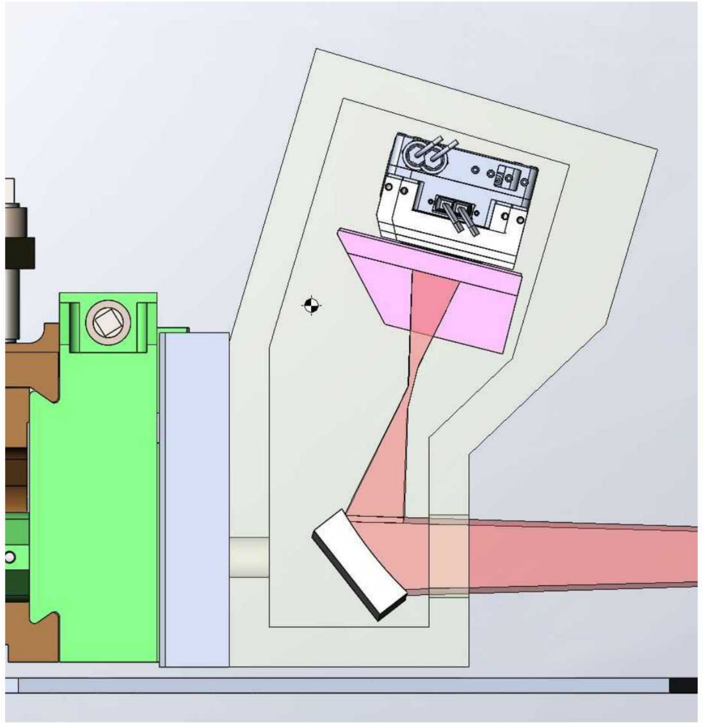
Time-evolution of ionization



Absorption spectrum



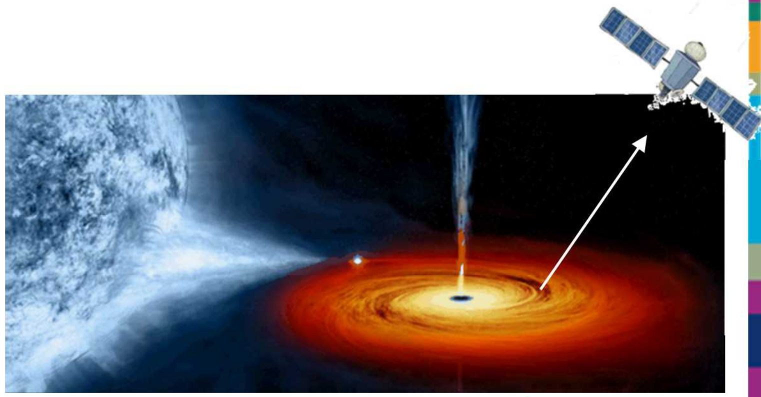
MONSSTR – time-gated spectrometer

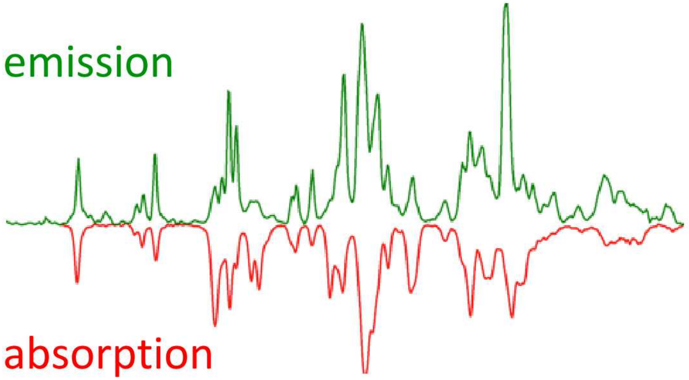


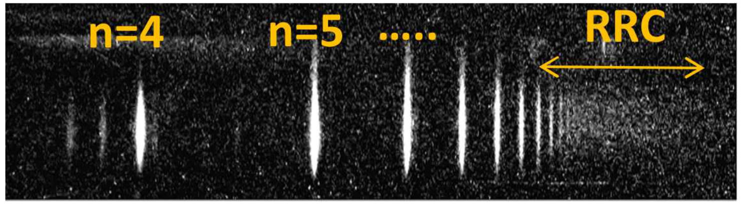
- → **Rad-hydro simulations predict lag of 3ns of steady-state ionization behind time-dependent ionization**
- → **Better agreement on the absorption spectrum**
- → **Also study transient kinetics relevant to astrophysics**

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







Si He-like emission

Experimental developments:

- First RRC from a photoionized plasma was obtained on Z
- First complete He-like line series
- Ultra high resolution emission spectra
- First Fe spectrum to address the super-solar abundance problem
- Time-resolved emission measurements design work

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