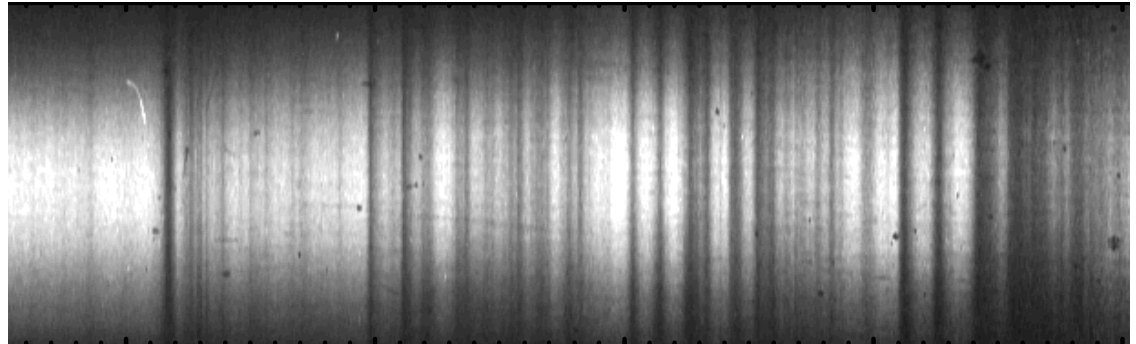
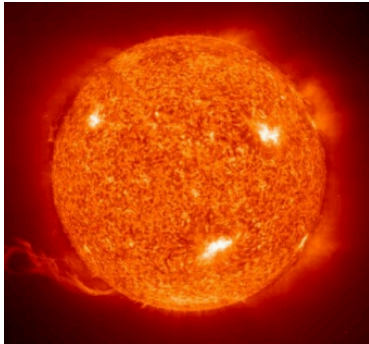
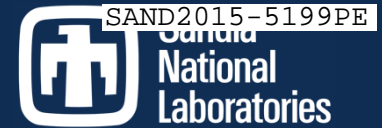


Exceptional service in the national interest



Stellar interior opacity measurements

Jim Bailey

Sandia National Laboratories



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The stellar opacity collaboration involves universities, U.S. national labs, a private company, and the French CEA laboratory



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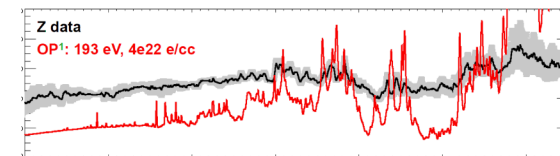
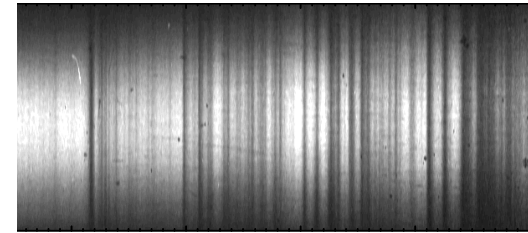
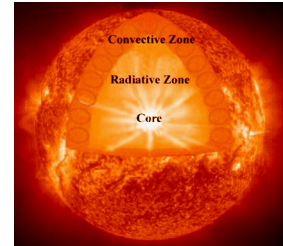


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- Solar interior predictions don't match helioseismology
 - Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?
- Z experiments have measured iron plasma opacity at nearly solar convection zone base conditions
 - Experiment temperature is the same as in sun, density within a factor of 2
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 - The solar Rosseland mean opacity is $\sim 7\%$ higher using Z iron data instead of OP calculations



The measurements imply photon absorption in high energy density matter is different than previously believed

If our opacity measurements are correct, we must revise our understanding for atoms in HED plasmas

- Measured iron opacities are 30-400% higher than theory predicts
- Opacity model accuracy reflects how well we understand atoms in plasma

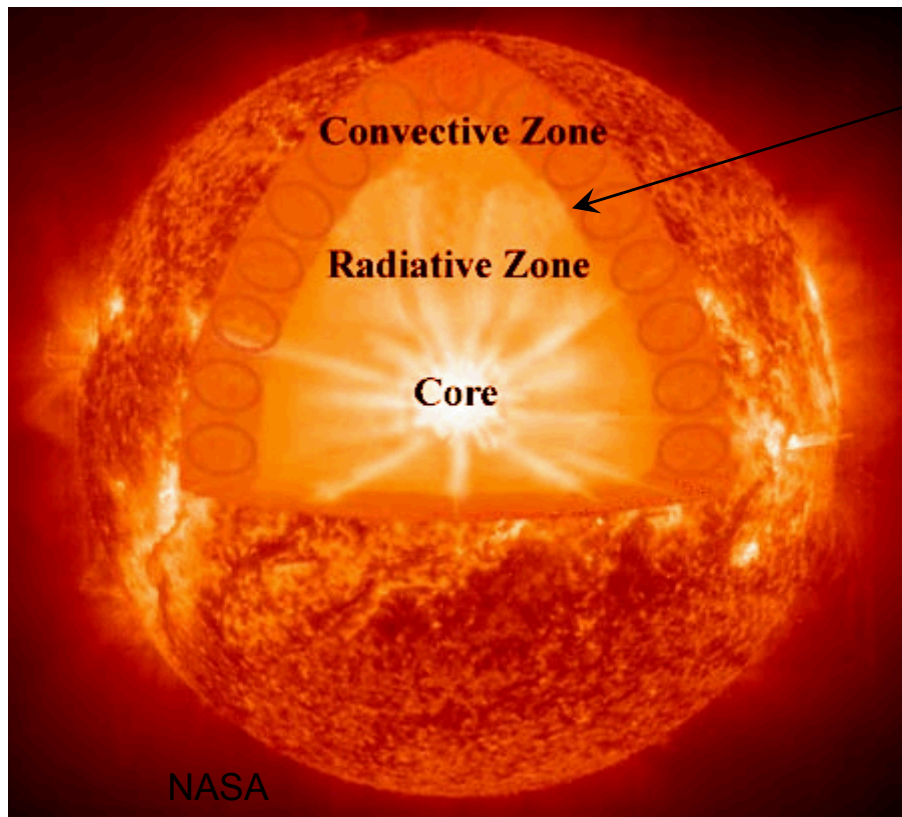
Applications include numerous HED plasmas:

- Solar opacity, composition, structure, and evolution are inter-connected
- Solar physics calibrates many other objects. Therefore the measurements alter our understanding of every main sequence star in the sky, including exoplanet host stars
- The measurements imply likely revisions for ICF capsule dopants

These serious consequences mandate continued effort

- We invested the last 2 years investigating possible errors and refining results
- The major conclusions survived this scrutiny
- New experiments are testing hypotheses for the model-data discrepancy

Does opacity uncertainty cause the disagreement between solar interior models and helioseismology?



Discrepancies in CZ boundary location, $C_s(r)$, and $\rho(r)$

Models depend on:

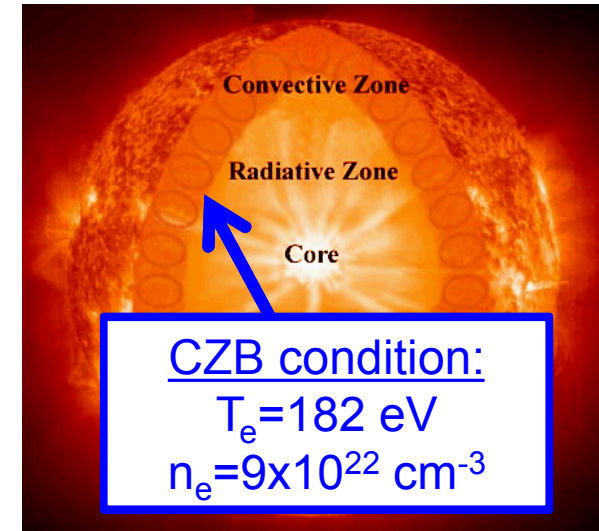
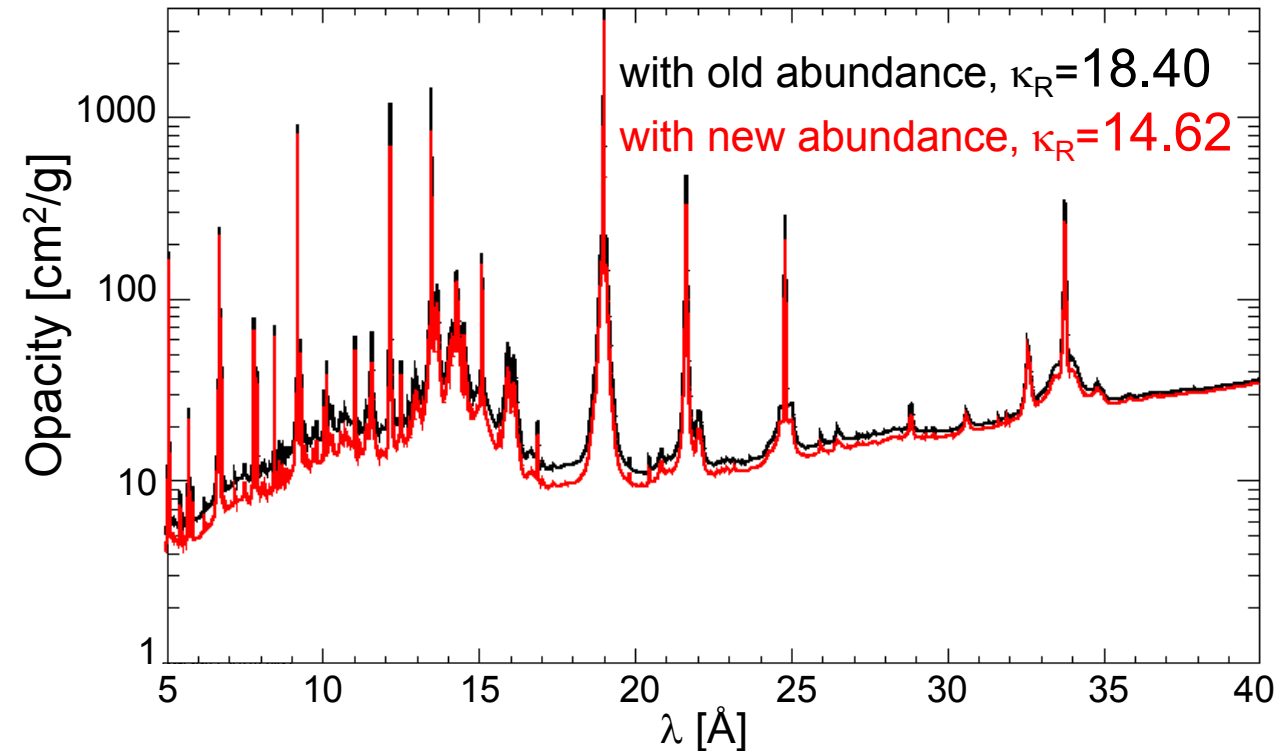
- element abundances
- EOS
- opacity

Discrepancies for other stars are appearing as asteroseismology matures

**focus: iron at convection zone base
{190 eV, $9e22$ e/cc}**

Disagreement could be resolved if the true mean opacity for solar matter is 10-30% higher than predicted

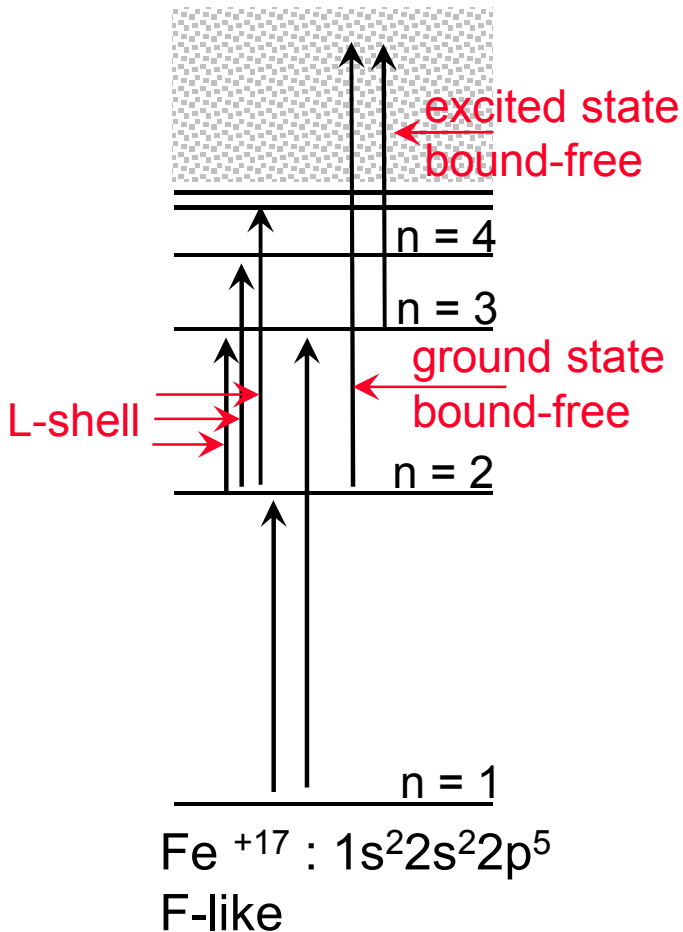
Solar mixture opacity at **C**onvection **Z**one **B**ase (CZB)



Rosseland mean opacity \rightarrow heat transfer by radiation

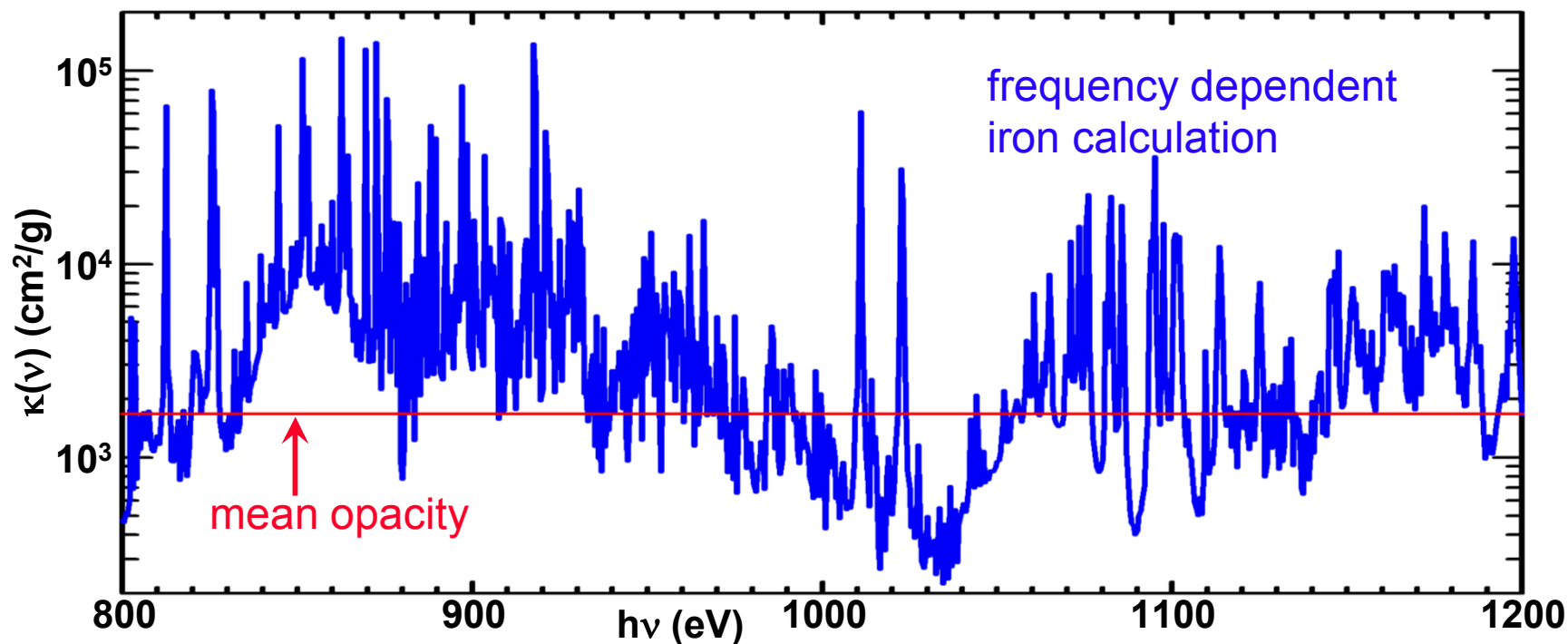
$$\frac{1}{\kappa_R} = \int \frac{1}{\kappa_v} \frac{\partial B_v}{\partial T} dv \bigg/ \int \frac{\partial B_v}{\partial T} dv$$

Multiple entangled physical processes are a concern for opacity models



- Energy level structure and detail
- Multiply excited states
- Autoionizing levels
- Photoionization
- Line broadening
- Continuum lowering

Strategy: frequency-dependent transmission measurements test opacity model physics



Detailed information about the physical basis for opacity models is encoded in the frequency dependent opacity spectra.

How do we perform opacity measurements?

Benchmark quality opacity experiment requirements have been developed over 30 years

Overarching requirements for each application:

Ideally: Reproduce the temperature, density, and radiation

Minimum: Reproduce the same charge states and measure the same transitions

Experiment requirements:

1. Accurate transmission measurements ($\sim \pm 5\%$)
2. Demonstrated uniformity
3. Reliable plasma diagnostics
4. Freedom from self emission
5. Freedom from background contamination
6. Multiple areal densities (for dynamic range and systematic error tests)
7. Thorough sample characterization
8. An evaluation of suitable the LTE approximation is
9. Multiple Te, ne conditions, to aid disentangling physical effects
10. Multiple atomic number elements, to aid disentangling physical effects and help verify robustness against systematic errors
11. Multiple experiments of each type, to confirm reproducibility
12. Peer review and documentation

Example references:

Davidson *et al.* Appl. Phys. Lett. 1988

Perry *et al.* Phys. Rev. Lett 1991

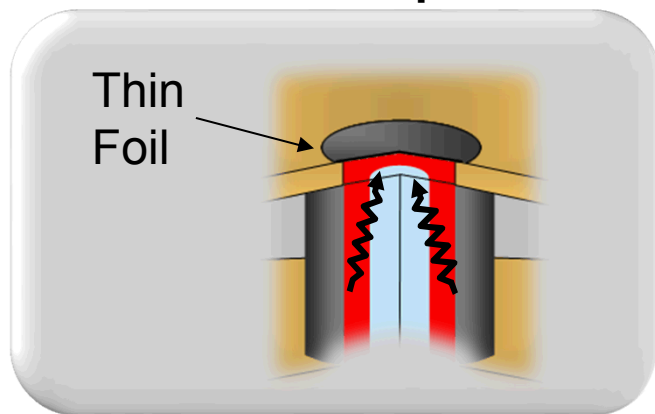
Foster *et al.* Phys. Rev. Lett. 1991

Perry *et al.* Phys. Rev. E 1996

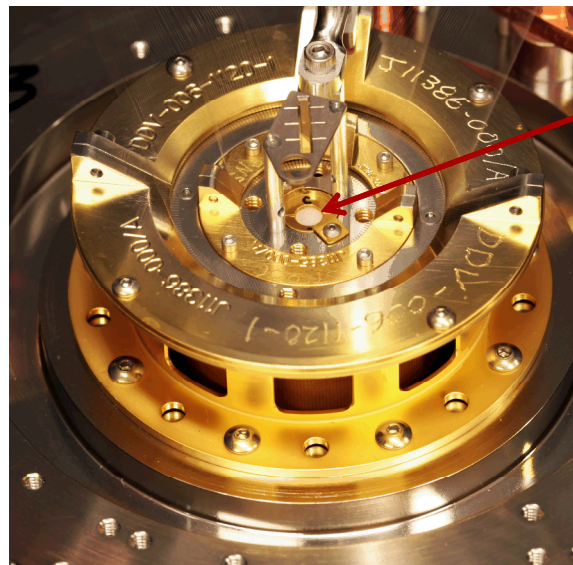
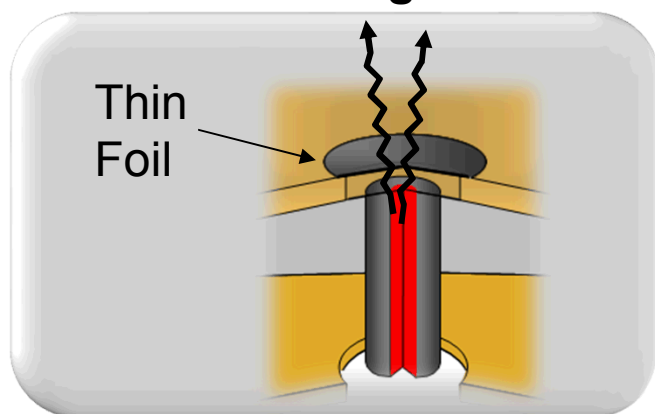
Springer *et al.* JQSRT 1997

The ZPDH radiating shock is used to both heat and backlight samples to stellar interior conditions.

**Foil is heated during
the ZPDH implosion**

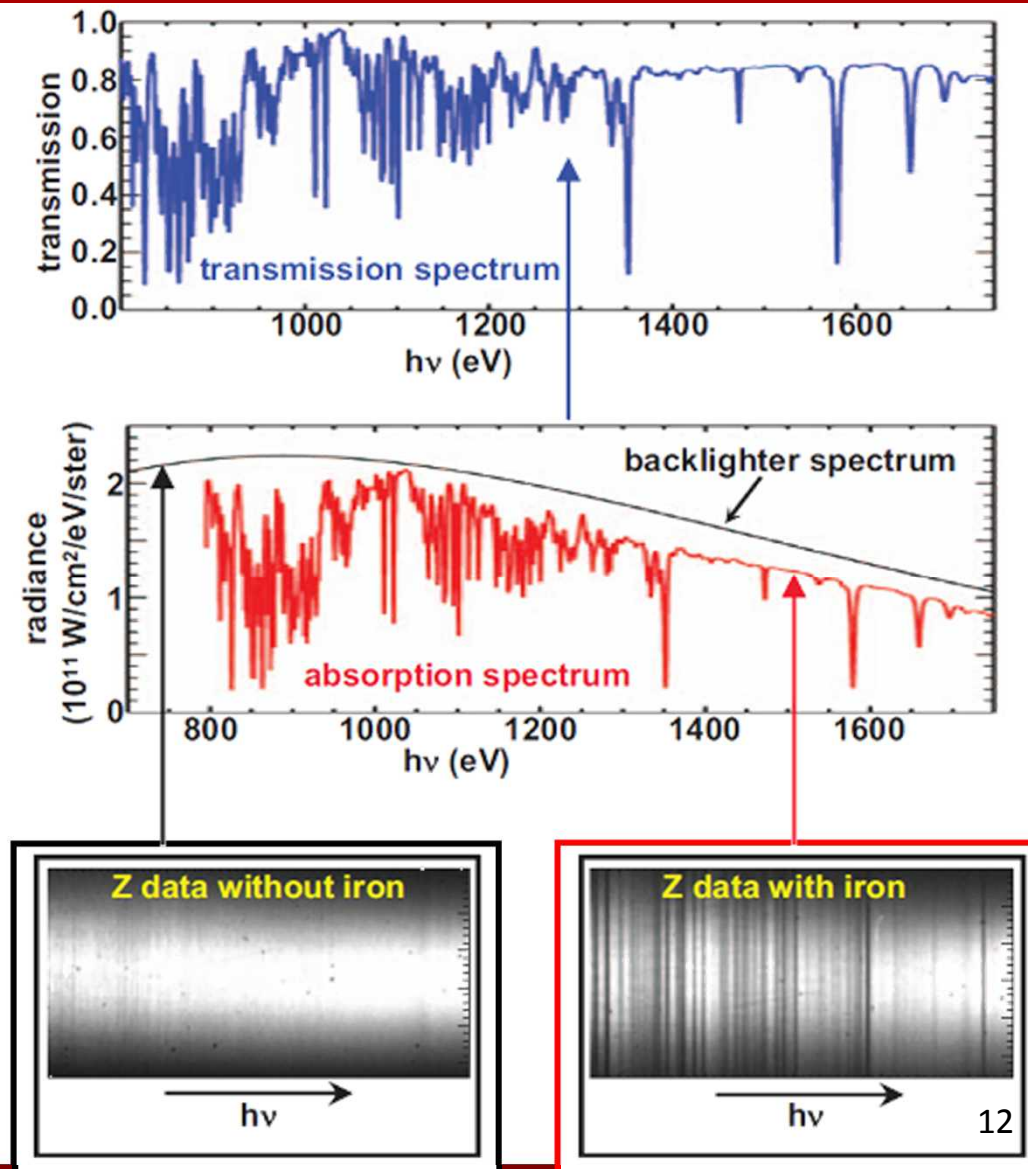


**Foil is backlit
at shock stagnation**

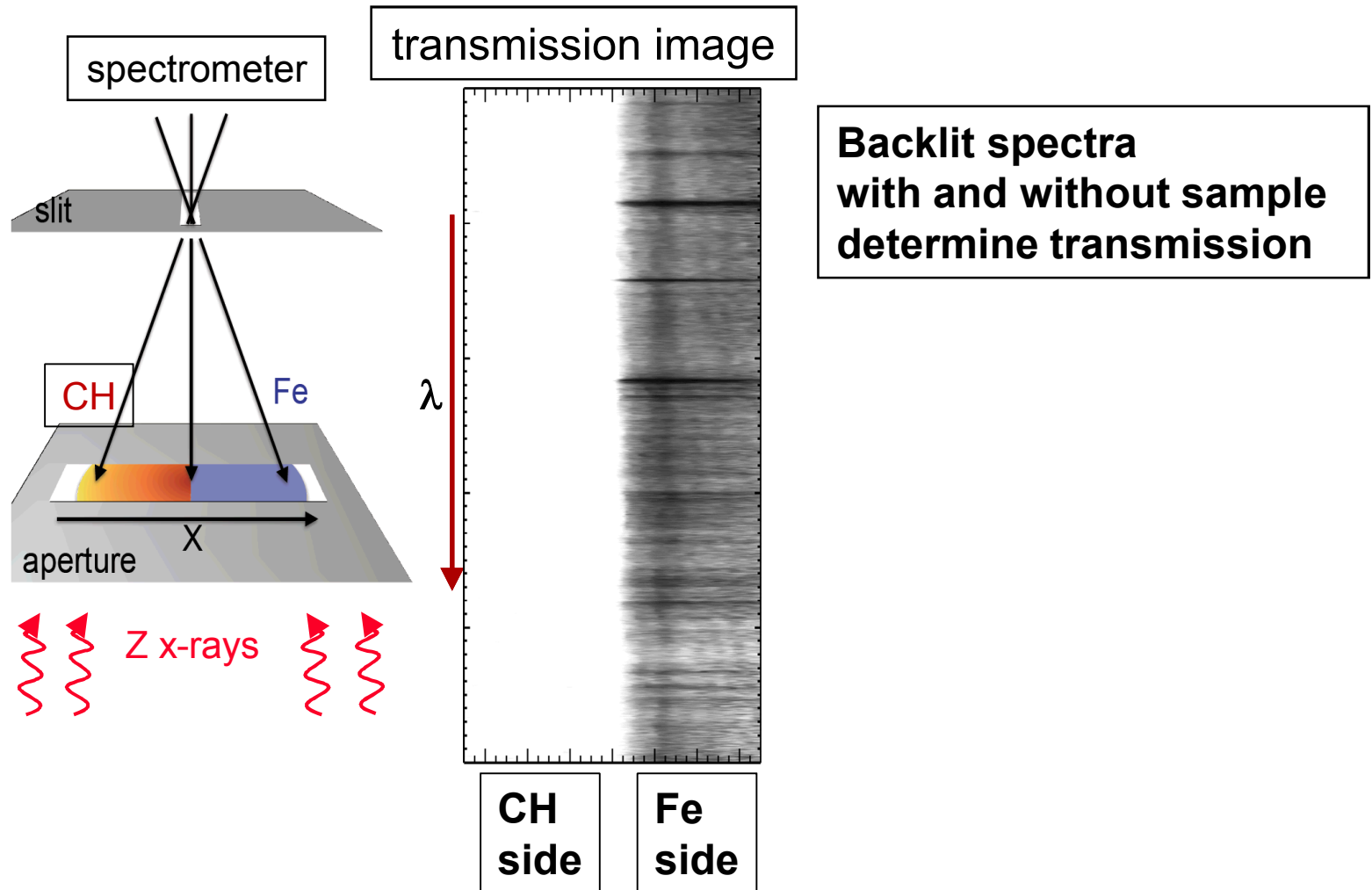


opacity sample

Transmission is inferred by dividing the attenuated spectrum by the unattenuated spectrum.



Measurements with half-moon shaped samples enable transmission determination from single experiments

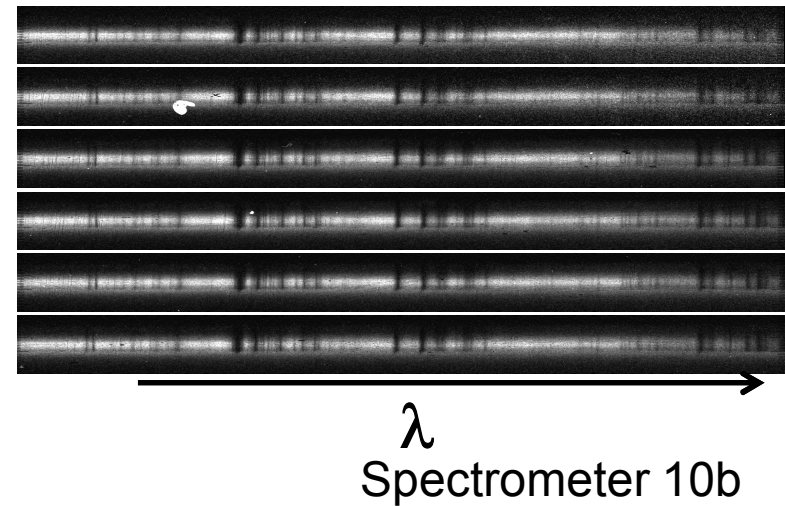
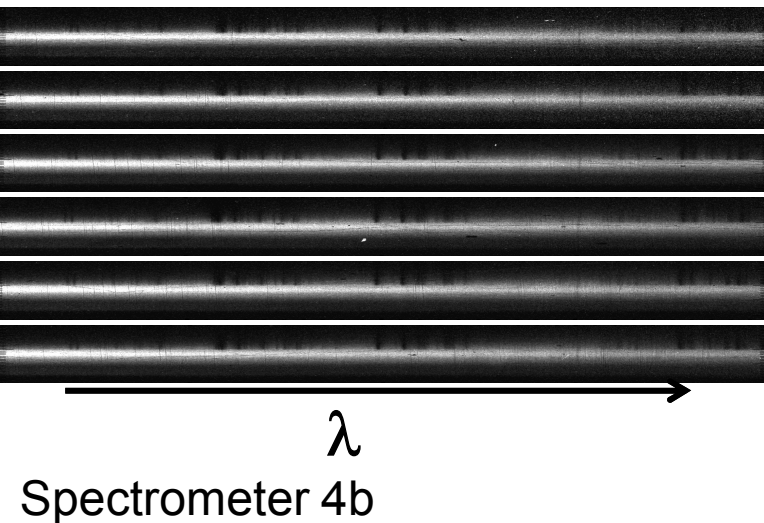
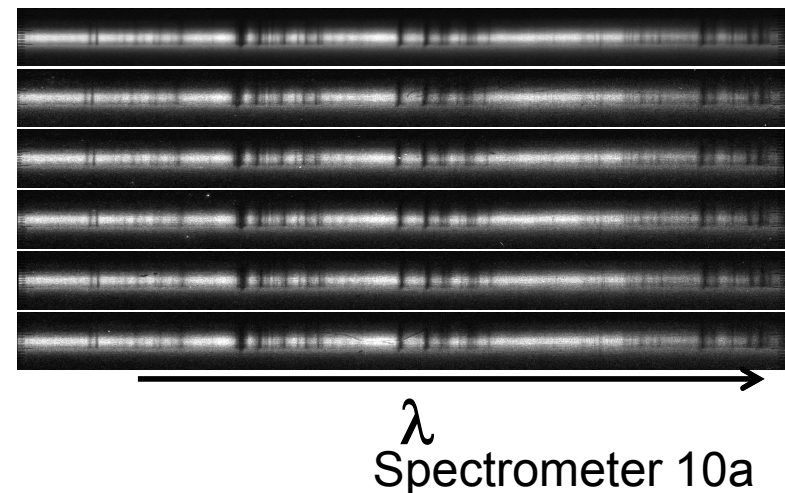
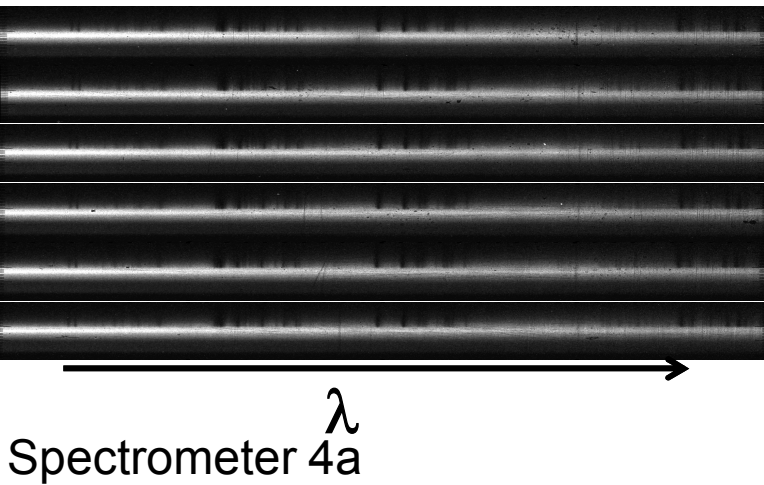


Opacity data are recorded with an array of crystal spectrometers



The array of opacity spectrometers is lowered into place with a 20 ton crane

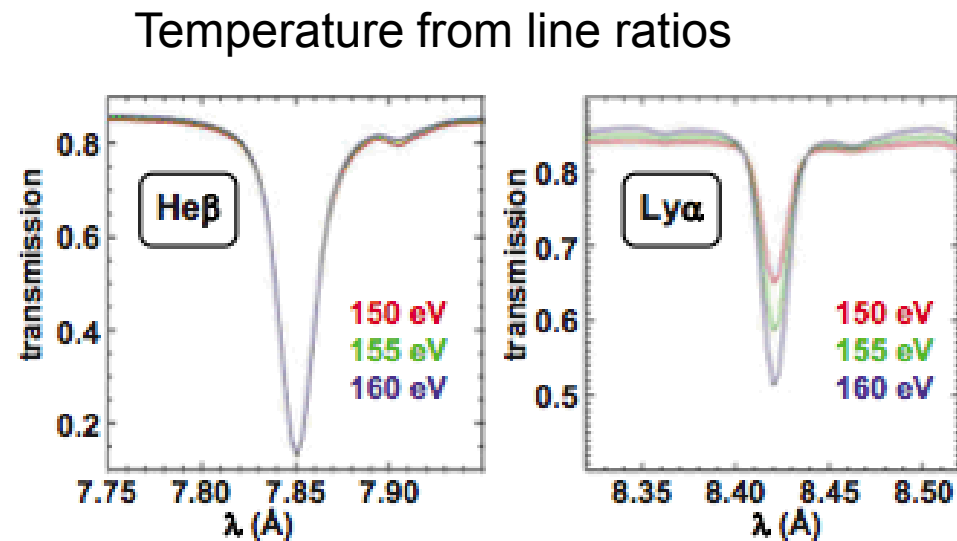
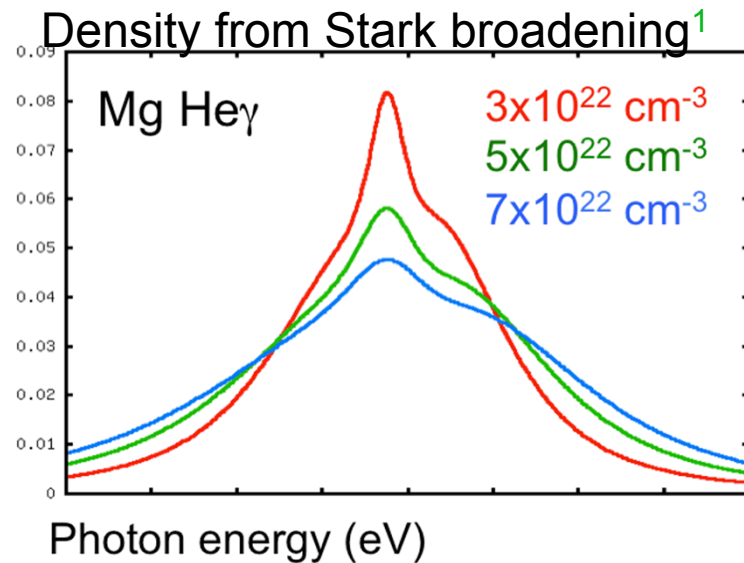
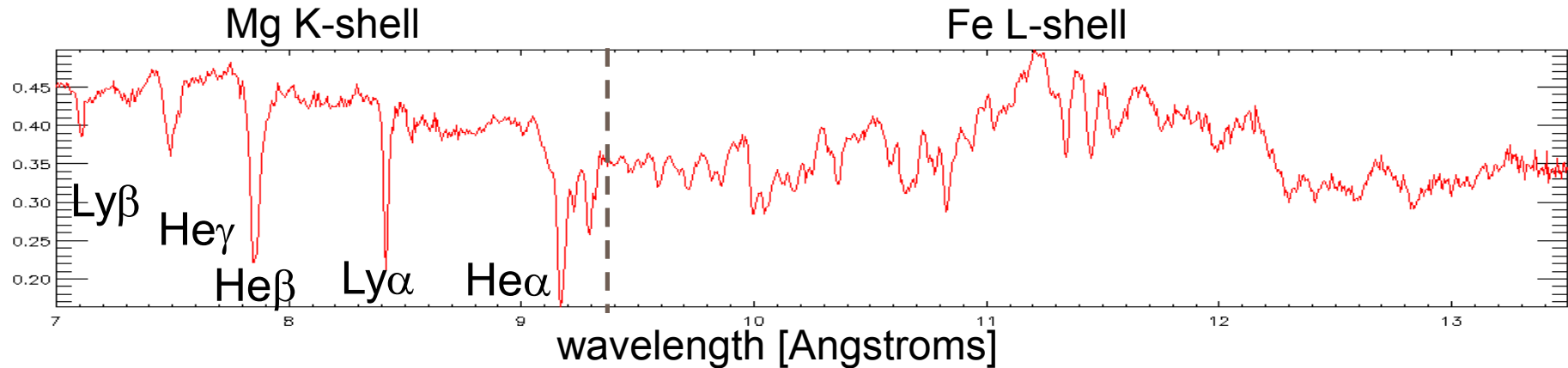
Hundreds of spectra were measured and analyzed to support the experiment reliability and reproducibility



Data from z2762

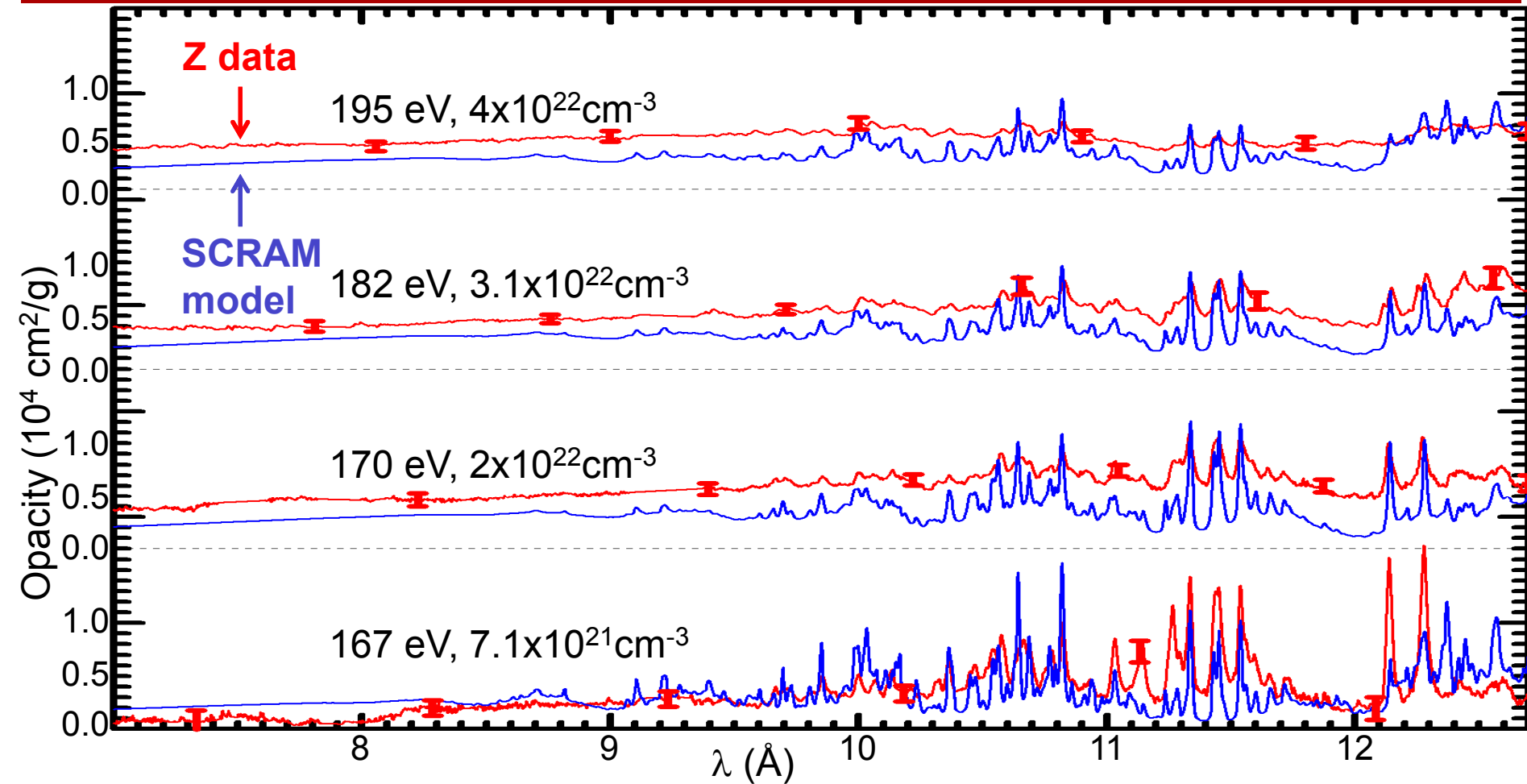
This experiment used four spectrometers to record 24 spectra

Plasma conditions are inferred by mixing Mg with Fe and using K-shell line transmission spectroscopy



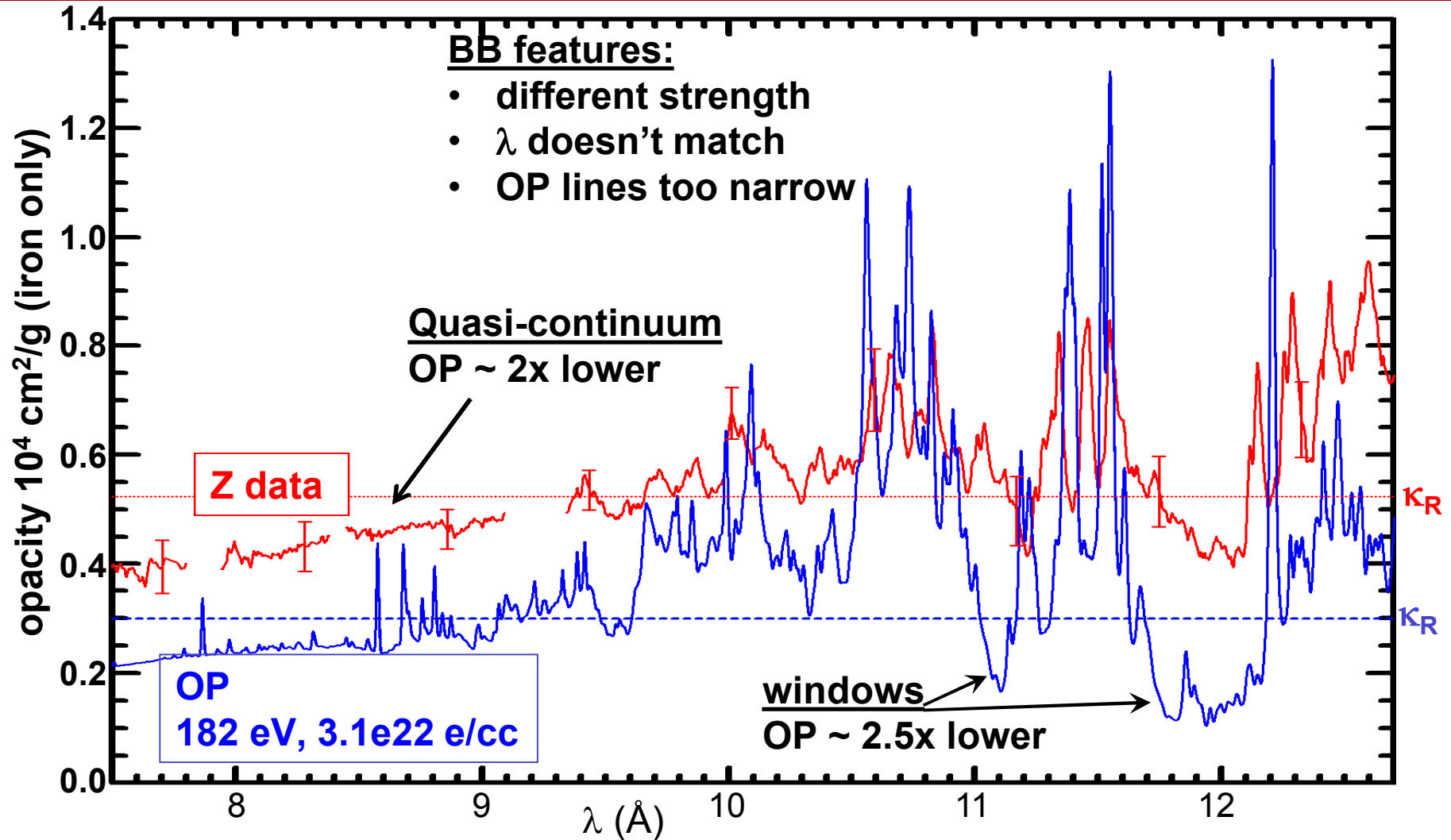
R. C. Mancini, comp. phys. commun. (1991)
T.N. Nagayama et. al. RSI (2013)
T.N. Nagayama et. al. POP (2014)

“Best Effort” opacity models “match” the iron data at lower T_e/n_e conditions but not at conditions near the solar CZB

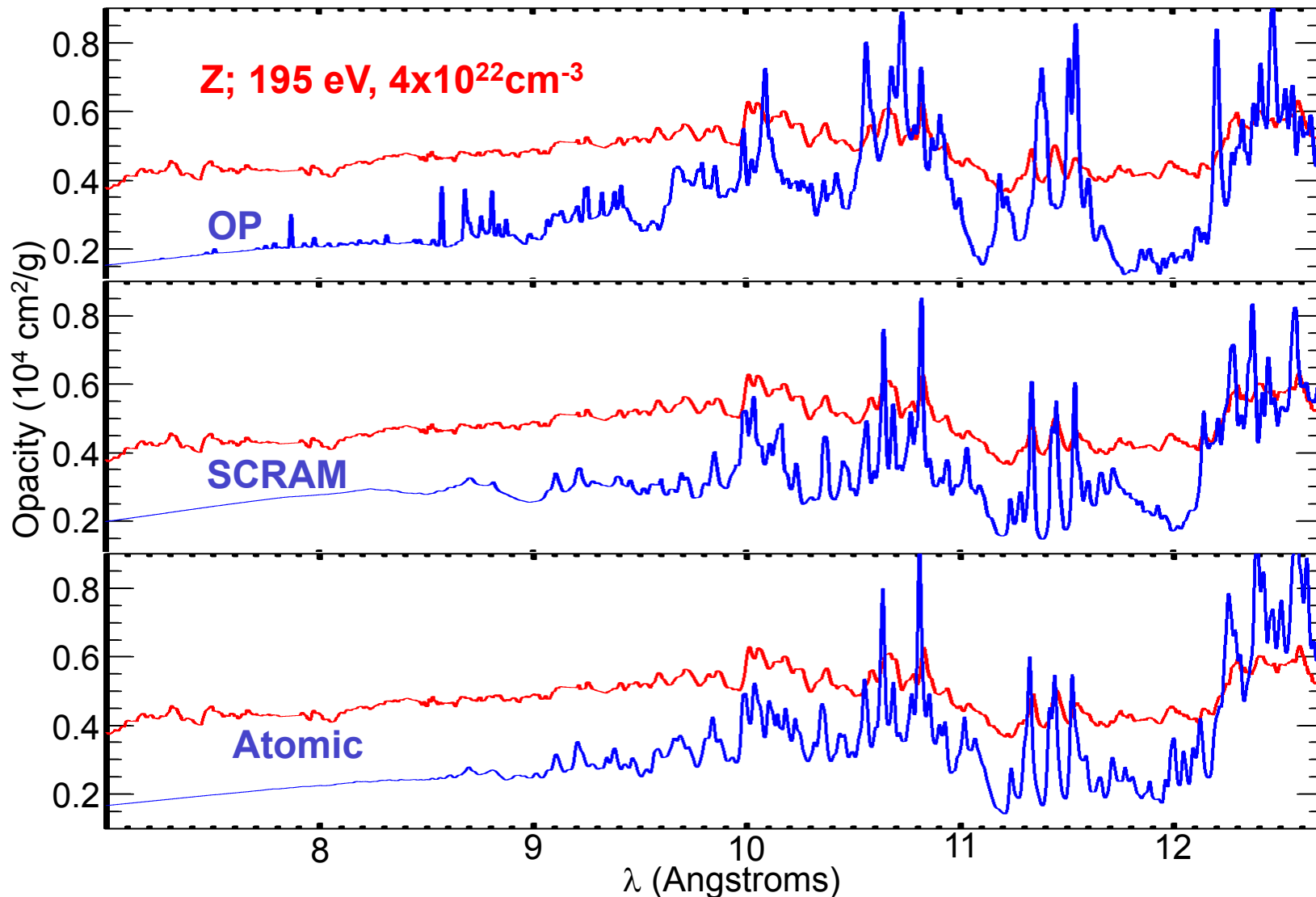


At high temperature , density, calculations are generally lower than the data

The OP opacity model is used in solar models but it disagrees with Z measurements at solar CZB conditions



No model examined up to now has satisfactory agreement with iron opacity measured at near-CZB conditions



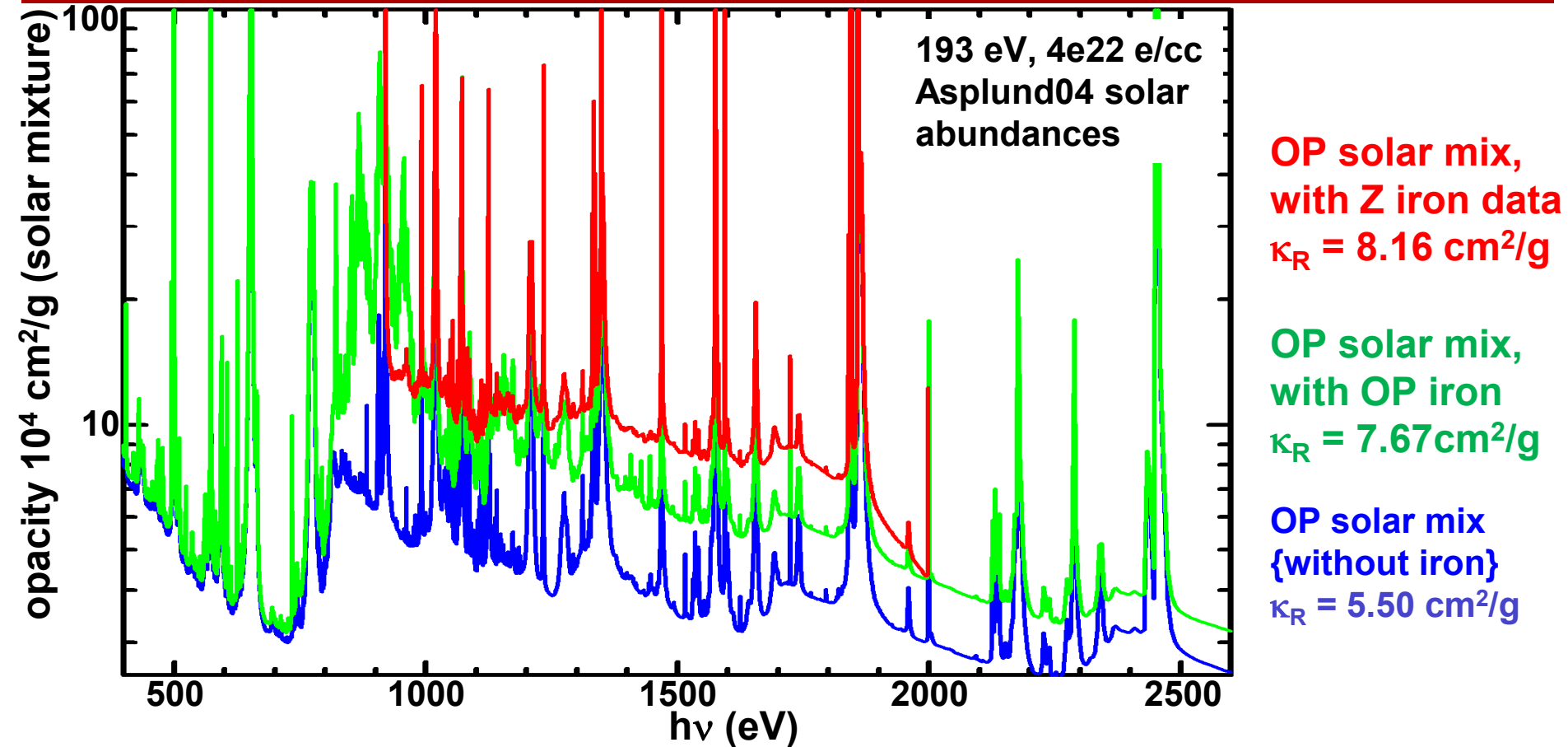
The measured pure iron Rosseland mean opacity is higher than calculated

Model	experiment/model ratio Rosseland Mean
OP	1.75
OPAS	1.53
ATOMIC	1.75
SCO-RCG	1.57
SCRAM	1.67

This comparison:

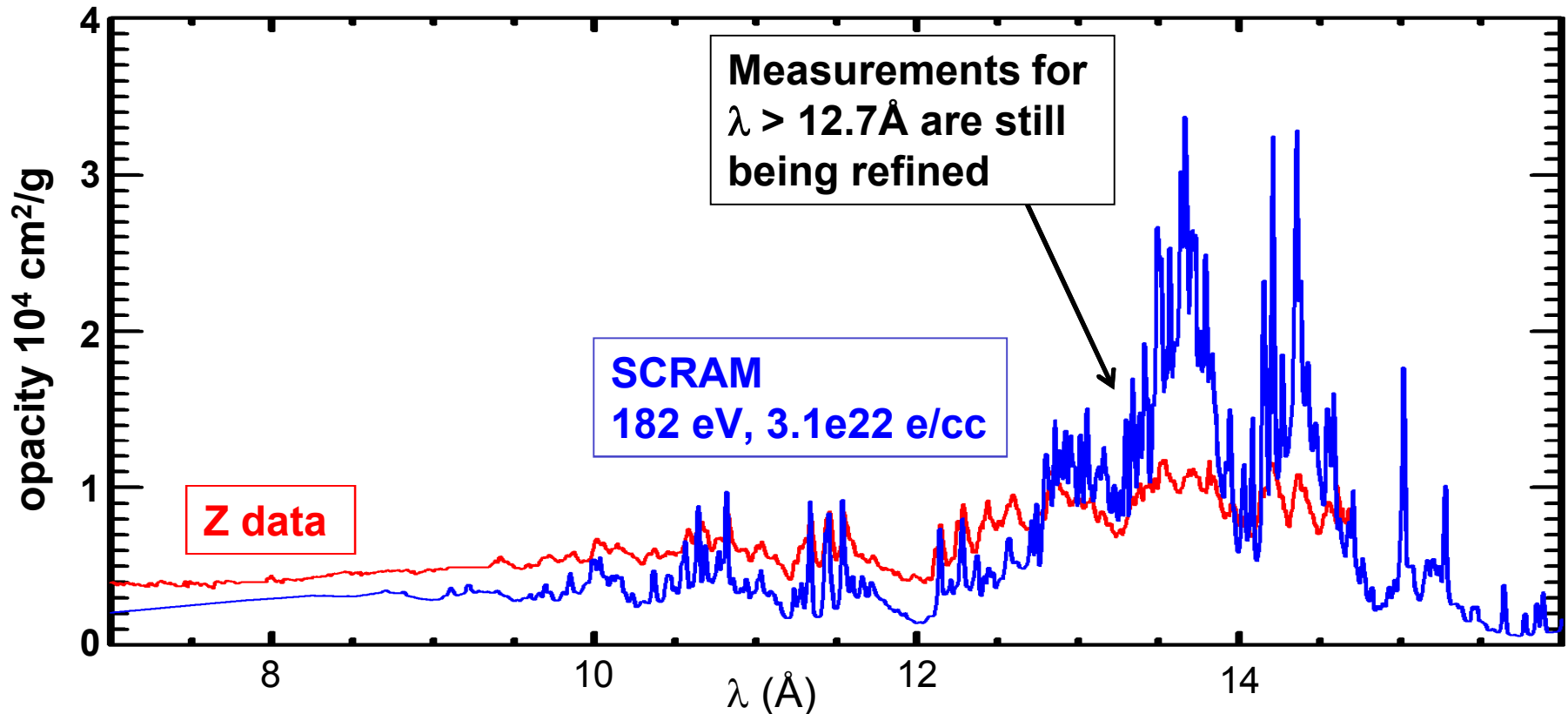
- 1) Is for the Be-tamped conditions (182 eV, 3.1×10^{22} electrons/cc)
- 2) uses only the measured wavelength range
- 3) accounts for the measured instrument resolution

A solar mixture plasma using Z iron data has ~ 7% higher Rosseland mean opacity than using OP iron



- A 7% Rosseland increase partially resolves the solar problem, but the measured iron opacity by itself cannot account for the entire discrepancy
- Other elements and regions deeper in the sun could contribute

The f sum rule might guide our understanding, but it requires measurements of all relevant transitions



Is sum rule valid?

Is photon absorption shifted from long λ to short λ ?

Or is experiment flawed somehow?

No systematic error has been found that can explain the model-data discrepancy

Random error determination: average many spectra from multiple experiments

Systematic error evaluation:

Experiment tests

Postprocess benchmarked simulations

Eleven different potential systematic errors were investigated:

Sample contamination

Tamper shadowing

} potential increase for inferred opacity

Fe self emission

Tamper self emission

Extraneous background

} potential decrease for inferred opacity

Sample areal density errors

Transmission errors

Spatial non-uniformities

Temporal non-uniformities

Departures from LTE

Plasma diagnostic errors

} potential increase or decrease for inferred opacity

What are the hypotheses for the discrepancy and how can we test them?

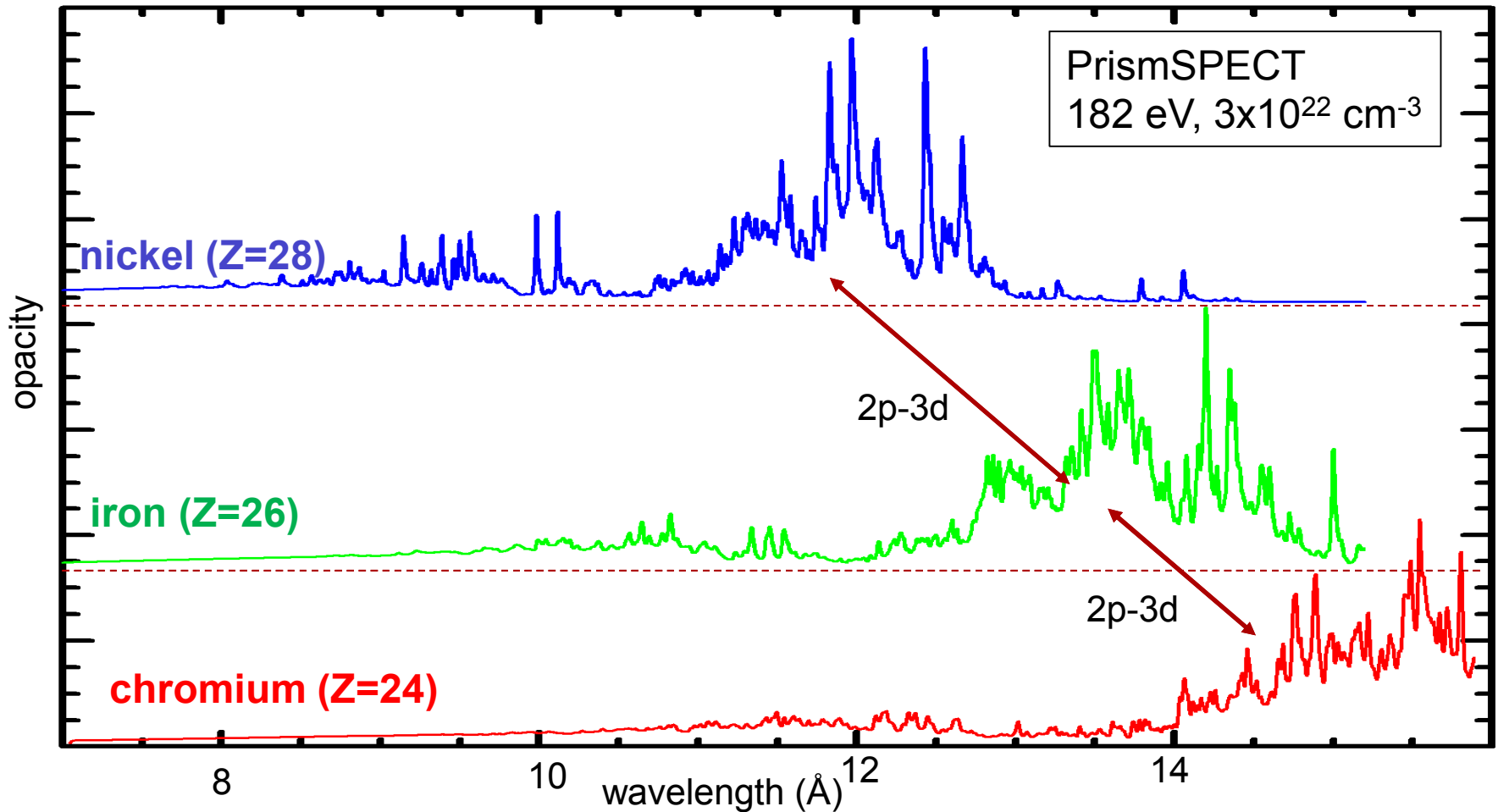
Hypotheses:

- 1) Despite all our effort, iron measurement is flawed somehow
- 2) Photon absorption is shifted from long λ to short λ by a process that is as yet undetermined
- 3) Models have difficulty predicting opacity for open L-shell configurations
- 4) Models have difficulty predicting highly excited configurations

Tests:

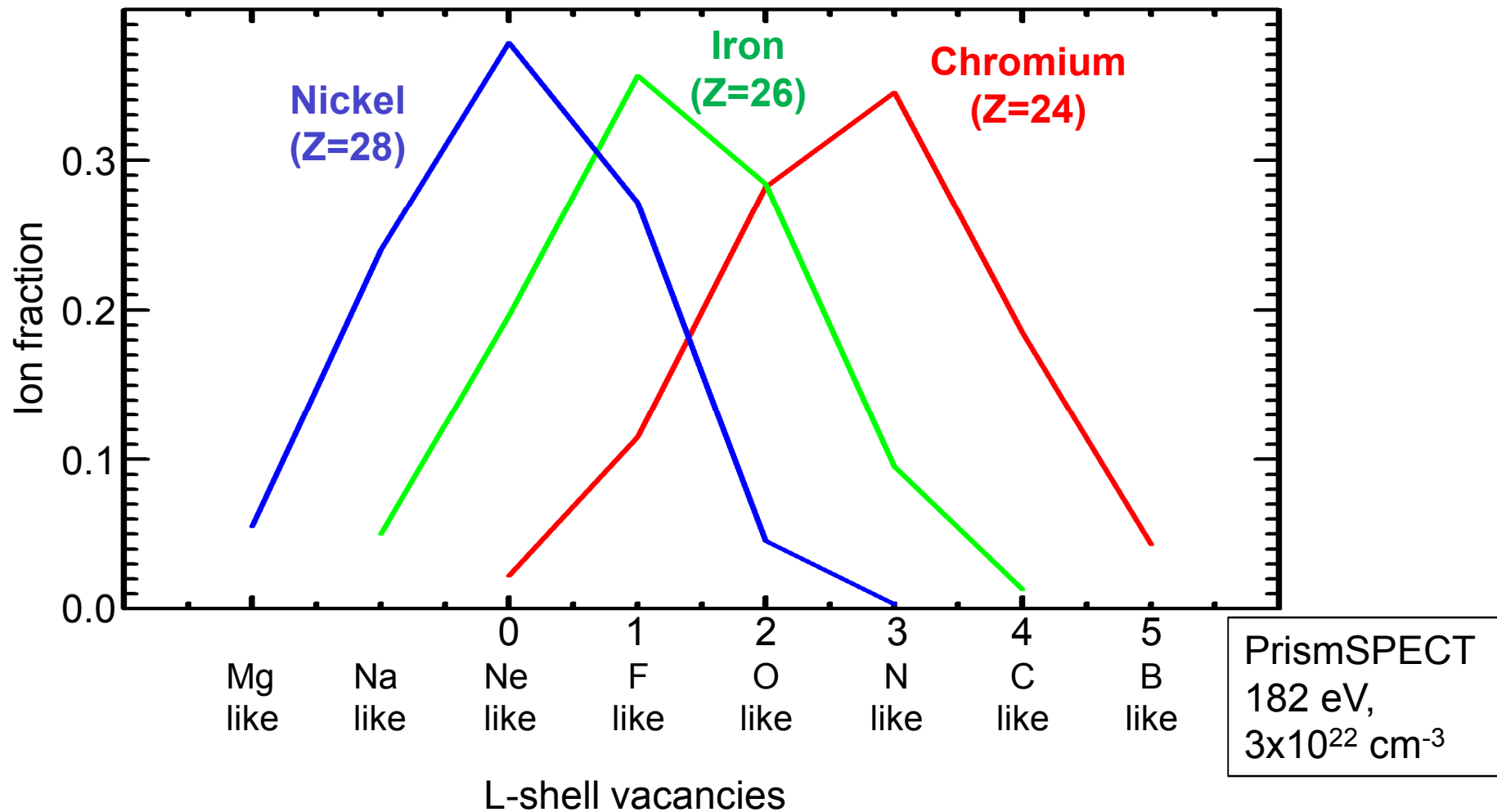
- A) Z experiments with lower and higher atomic number elements
- B) Z experiments with lower and higher temperature and density
- B) Experiments on a different platform (NIF)

Experiments with different elements shift different spectral regions into the highest accuracy experiment range



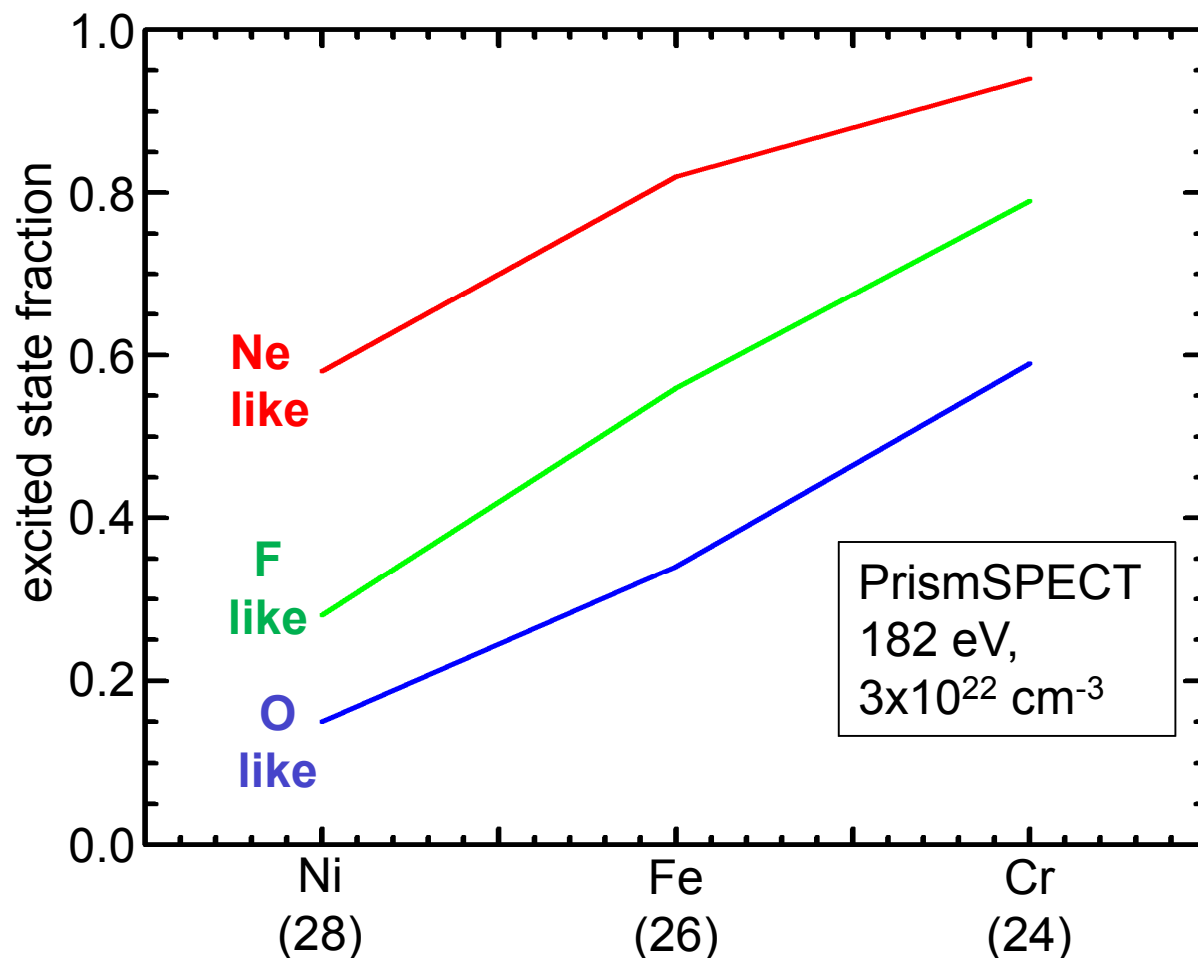
Experiments with different elements also can help identify possible experiment peculiarities with the iron measurements (e.g., unknown contaminants)

The number of L shell vacancies changes with the sample element



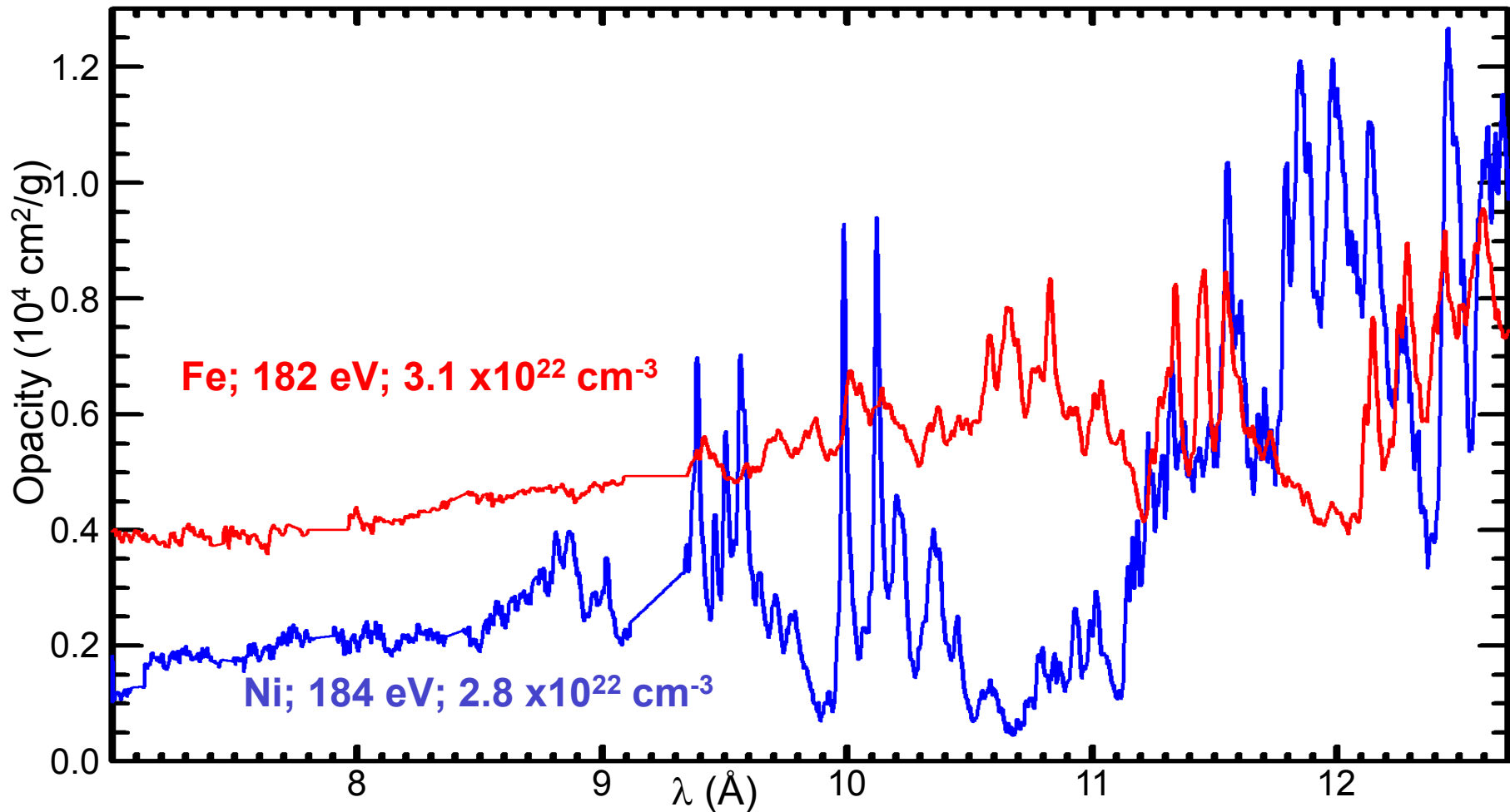
Opacity from transitions with an open L-shell may be more complex to model

The fractional excited state population increases as the atomic number decreases

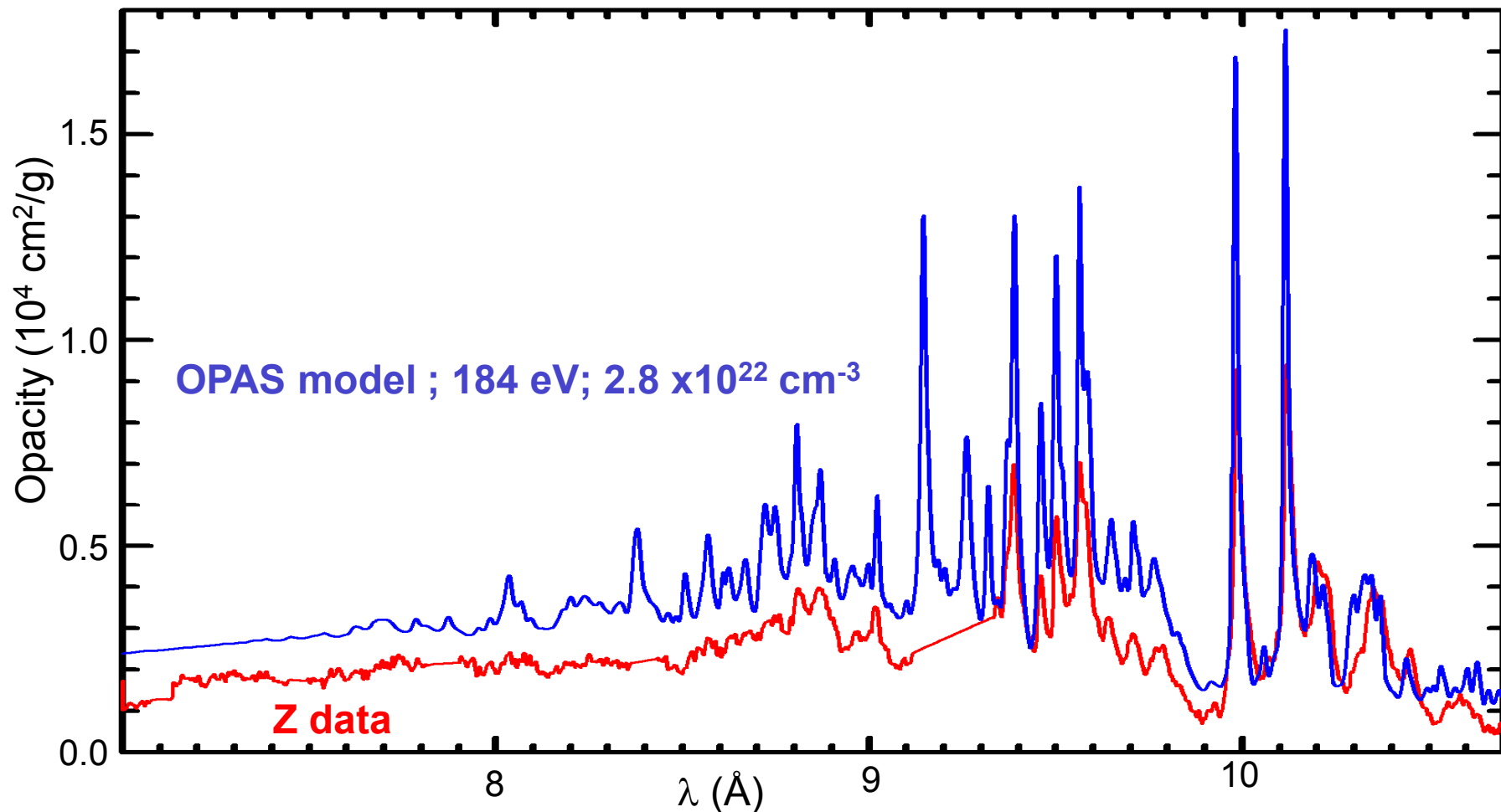


Opacity from ions with high excited state populations may be more complex to model
These difficulties increase as atomic number decreases

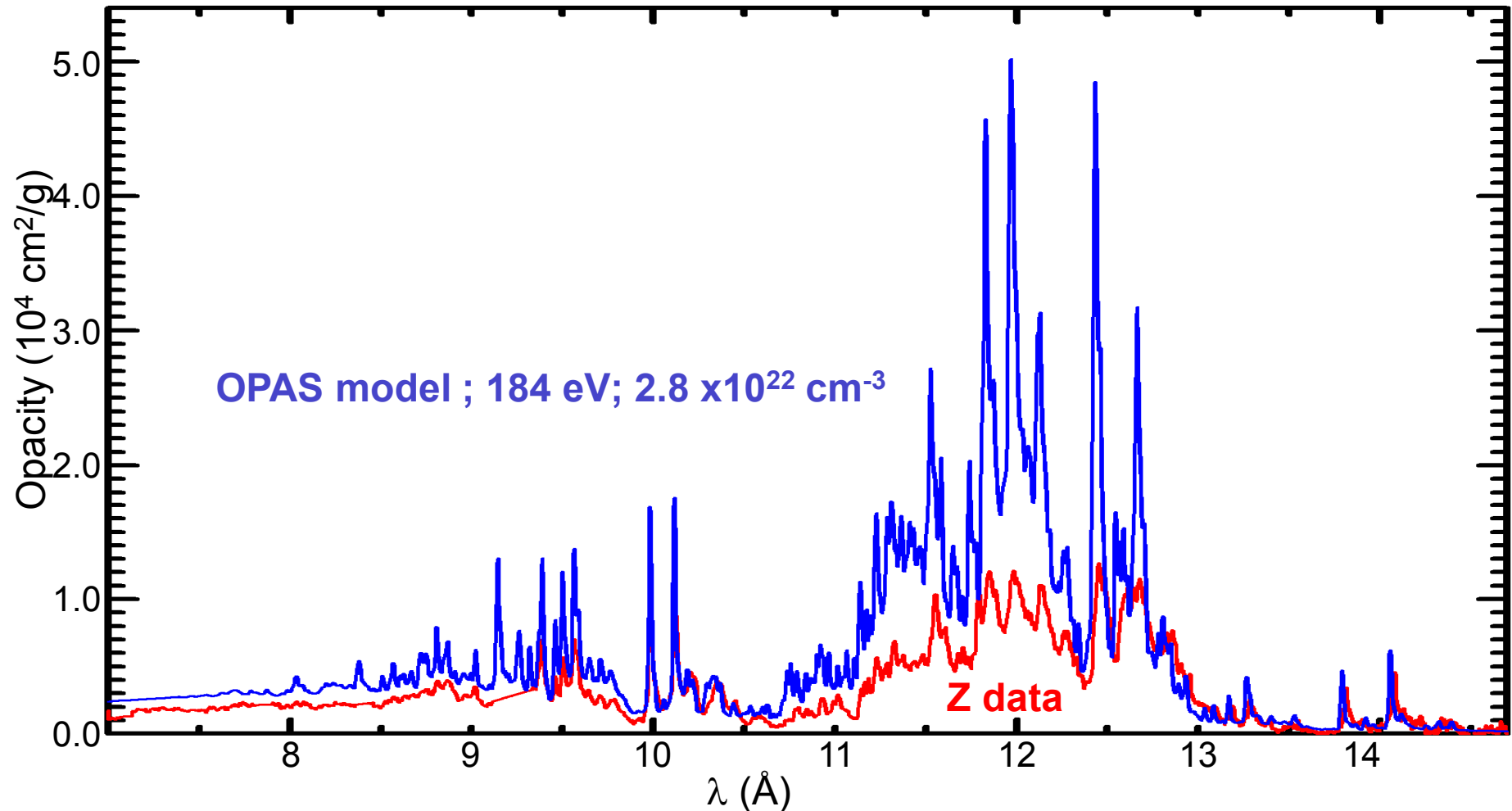
Preliminary Ni data shows the high Te/ne experiment platform is capable of measuring sharp spectral features



Predictions for Ni opacity windows and quasi-continuum agree reasonably well with preliminary data

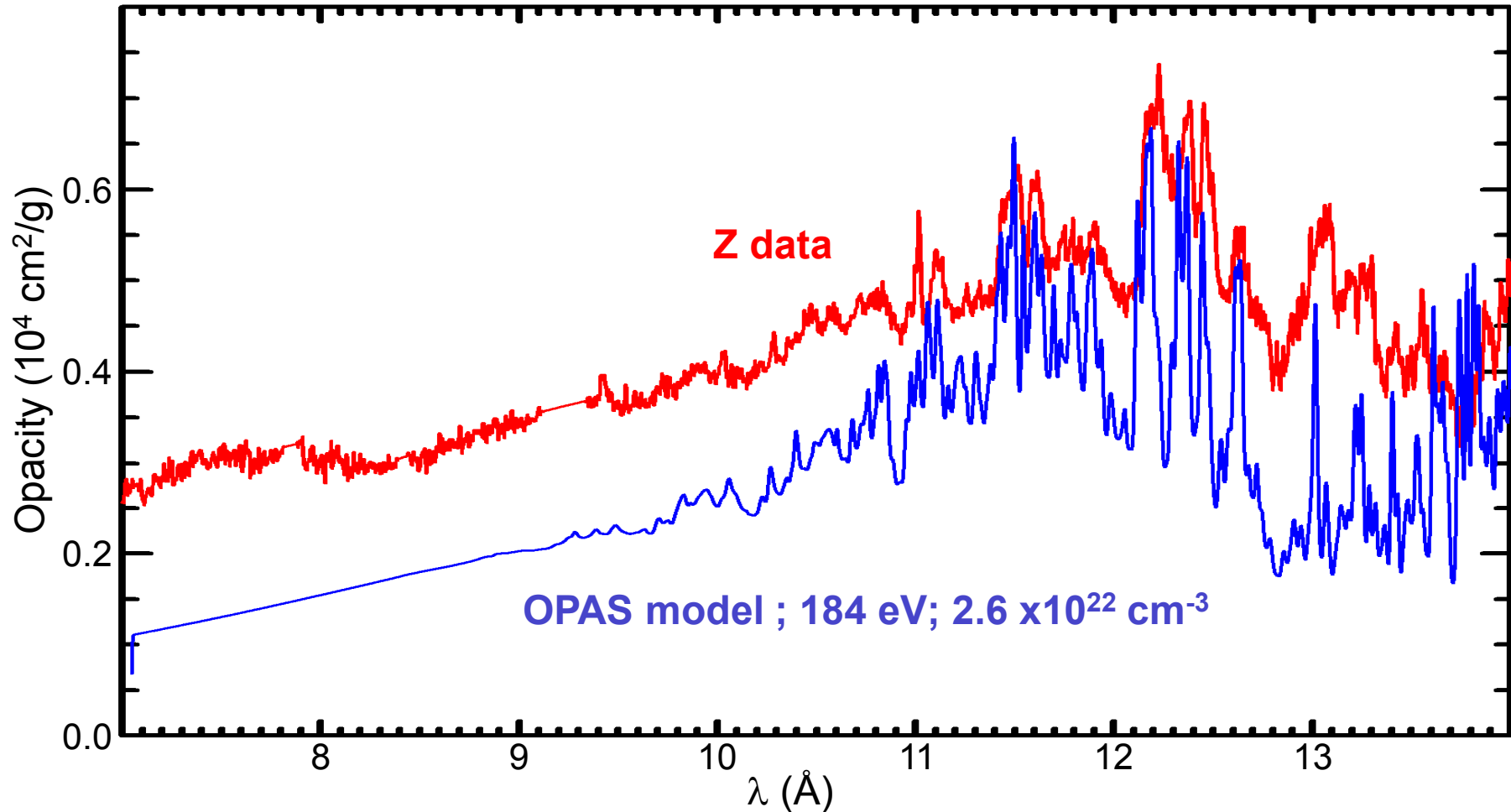


Predictions for Ni opacity in the 2p-3d spectral region are approximately 2x larger than measurements



Consistent with a hypothesis that photon absorption at long wavelengths is over-predicted while short wavelength absorption is under-predicted

Preliminary Cr model-data discrepancy is similar to iron

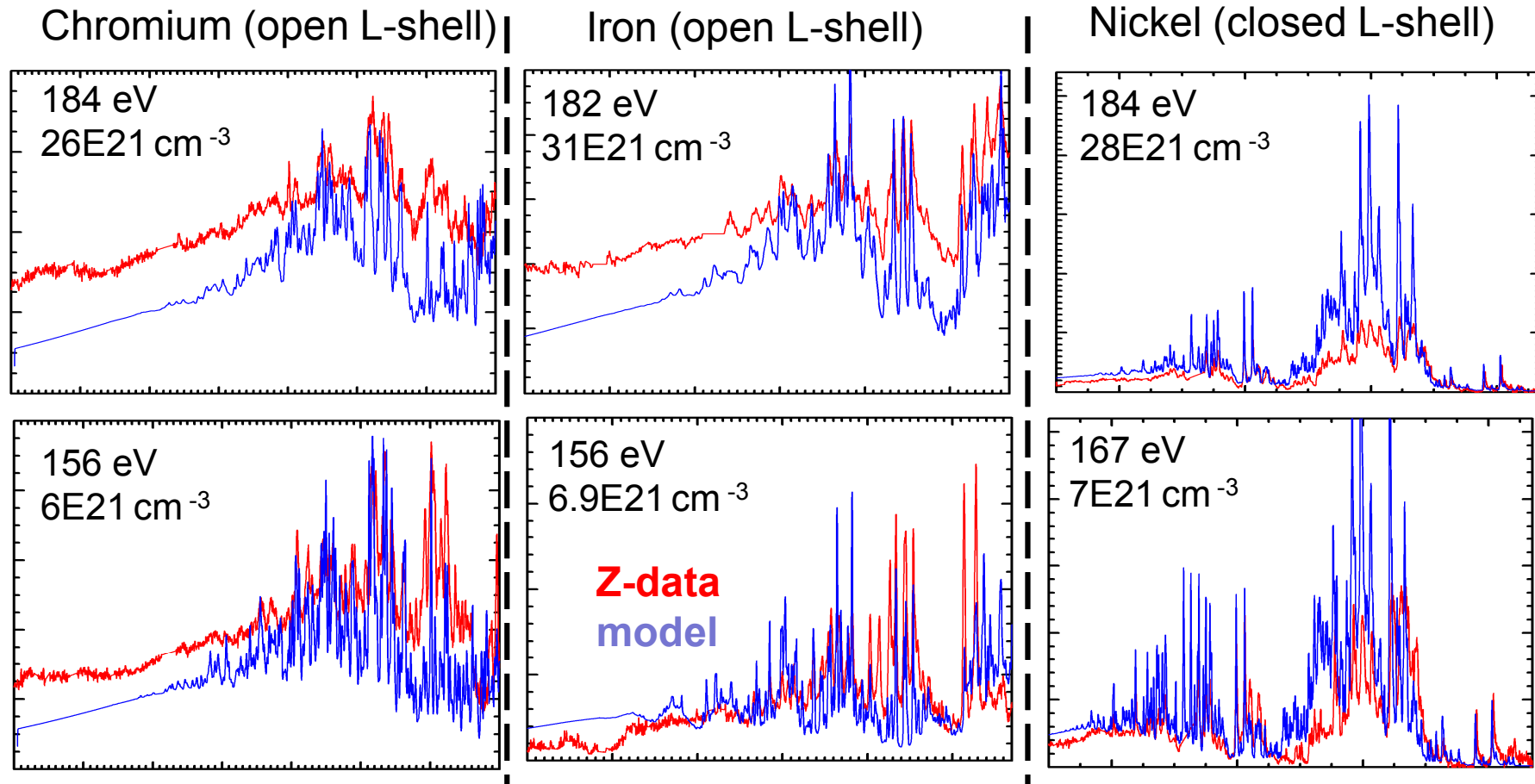


This supports the iron data validity

We will untangle the complex opacity issues through precise measurements across a range of T_e , n_e , and Z .

fewer L-shell vacancies, lower excited state populations

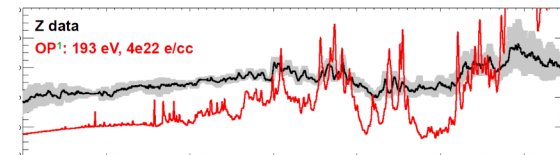
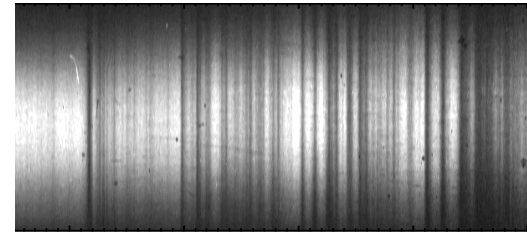
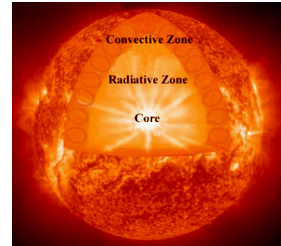
Increased Temp. and Density



Increased Atomic Number

Z iron opacity experiments refine our understanding of the sun.

- Solar interior predictions don't match helioseismology
 - Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?
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