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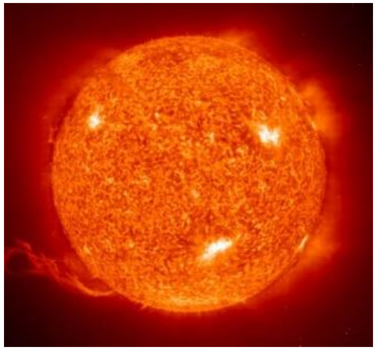

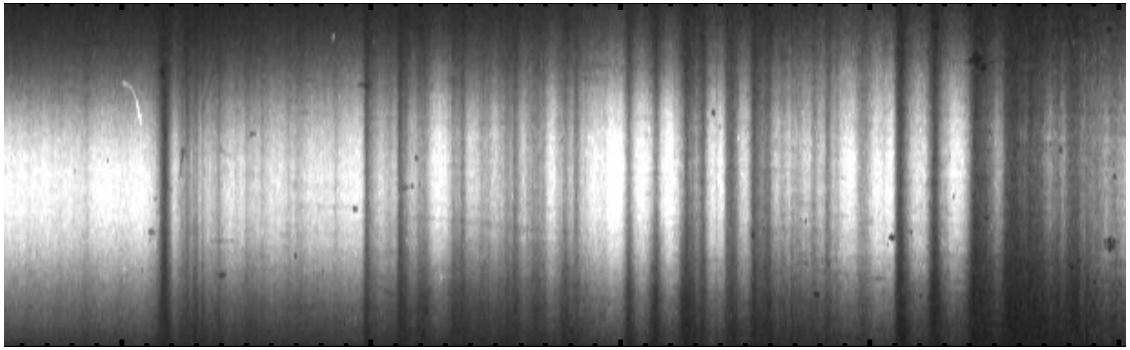

Stellar interior opacity measurements

Jim Bailey

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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

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Z iron opacity experiments refine our understanding of the sun.

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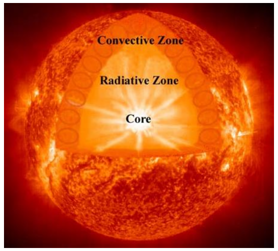
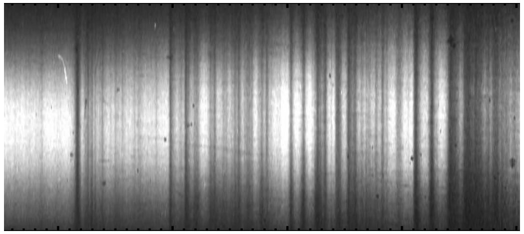
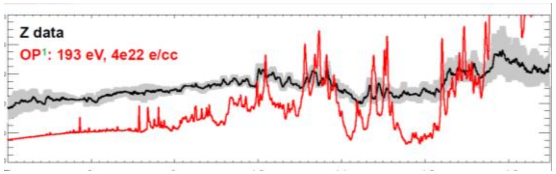
- **Solar interior predictions don't match helioseismology**
  - → **Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?**



- **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**



- **Opacity models disagree with measurements at near-solar-interior conditions**
  - → **The solar Rosseland mean opacity is ~ 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

Bailey et al., *Nature* 2015

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**

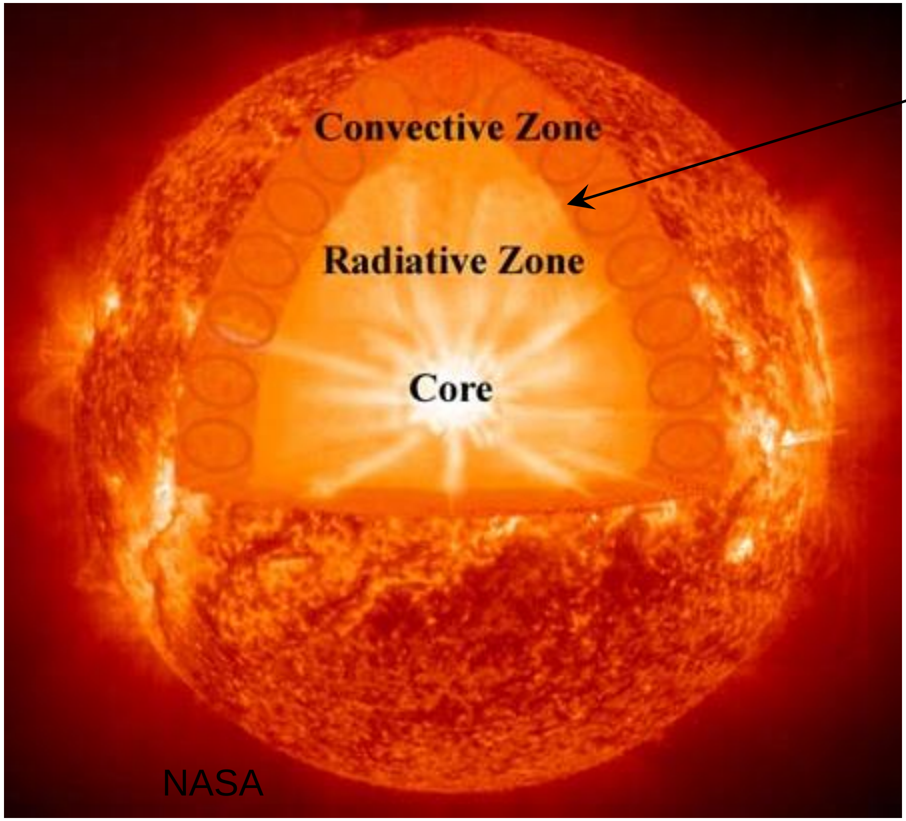
Applications include numerous HED plasmas:

- **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 3 years investigating possible errors and refining results**
- **The major conclusions survived this scrutiny**
- **New experiments are testing hypotheses for the model-data discrepancy, including ongoing investigation of the experiment accuracy**

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



Discrepancies in CZ boundary location, C_s (r), and ρ(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

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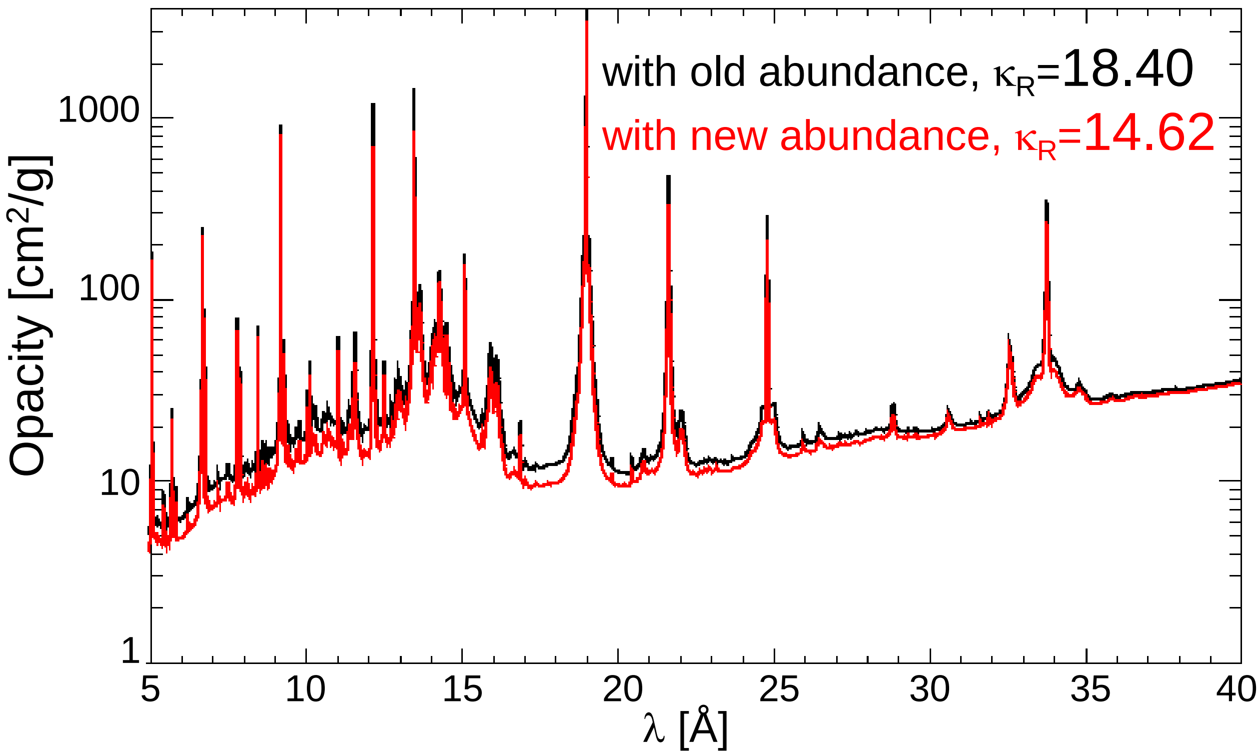
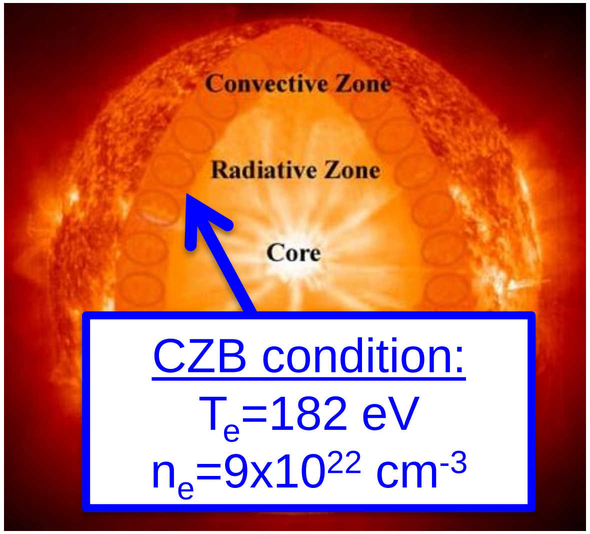
Solar mixture opacity at Convection Zone Base (CZB)

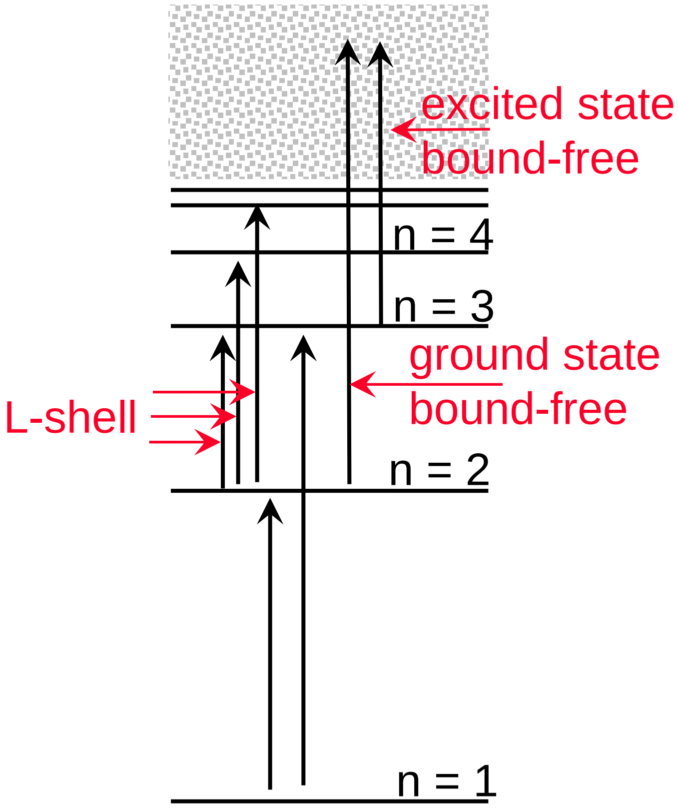




Rosseland mean opacity → heat transfer by radiation

$$\frac{1}{\kappa_R} = \int \frac{1}{\kappa_\nu}\frac{\partial B_\nu}{\partial T}\,d\nu \Big/ \int \frac{\partial B_\nu}{\partial T}\,d\nu$$

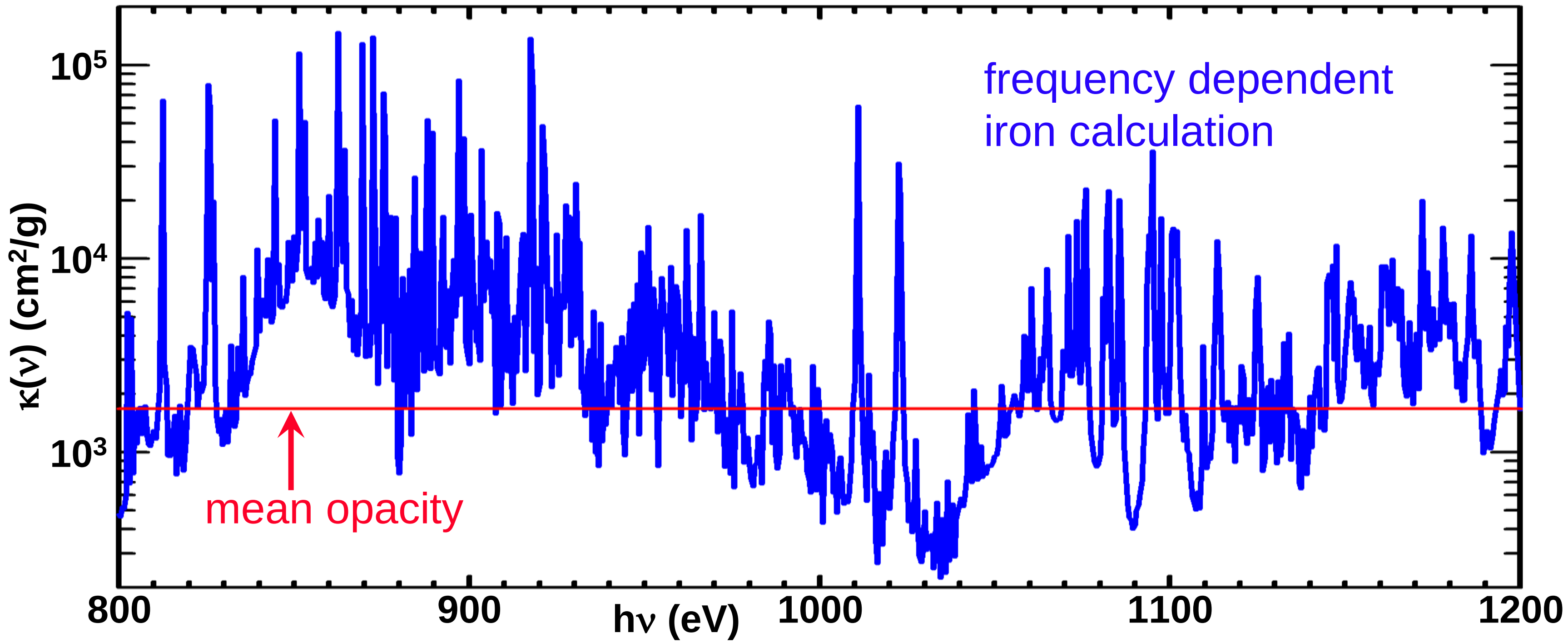
Multiple entangled physical processes are a concern for opacity models



Fe $^{+17}$: $1s^2 2s^2 2p^5$
F-like

- 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

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

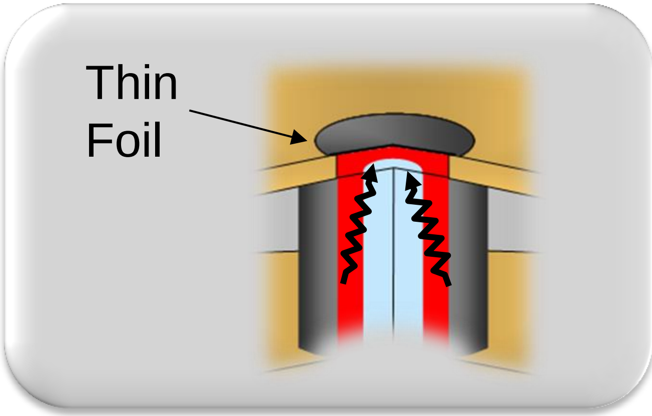
Experiment requirements:

1. Accurate transmission measurements (~ $\pm$ 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 disentagling physical effects and help verify robustness against systematic errors
11. Multiple experiments of each type, to confirm reproducibility
12. Peer review and documentation

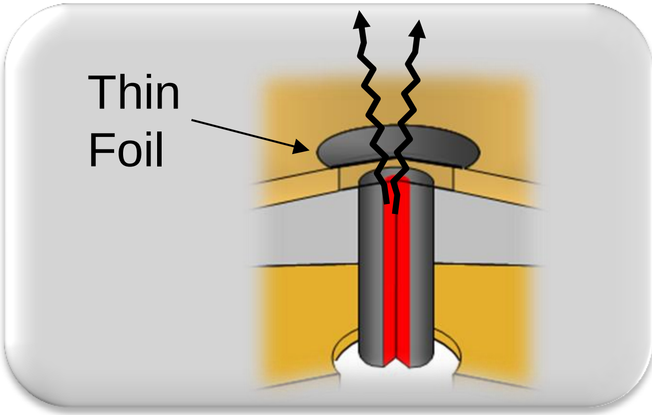
Bailey *et al*., Phys Plasmas 16 (2009)

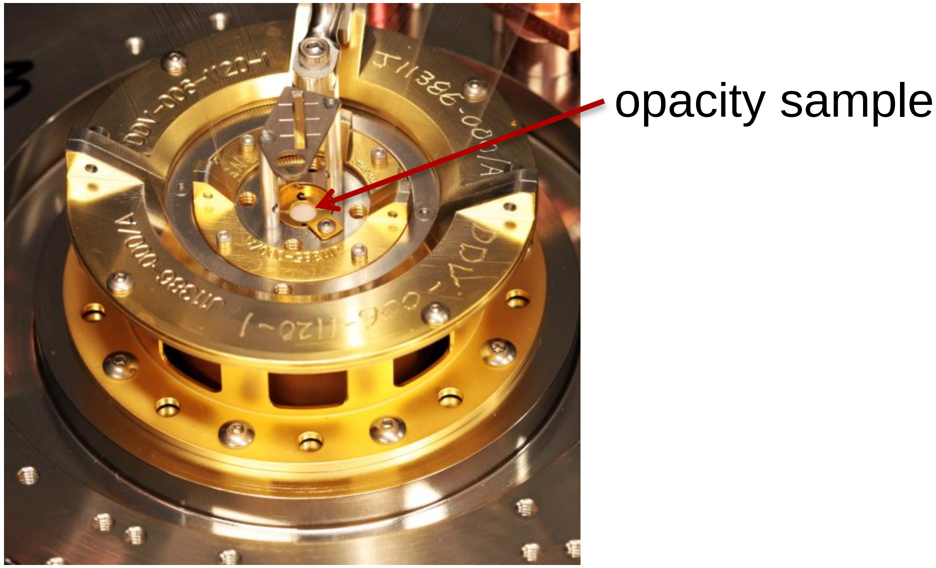
The ZPDH radiating shock is used to both heat and backlight samples to stellar interior conditions.

Foil is heated during the ZPDH implosion

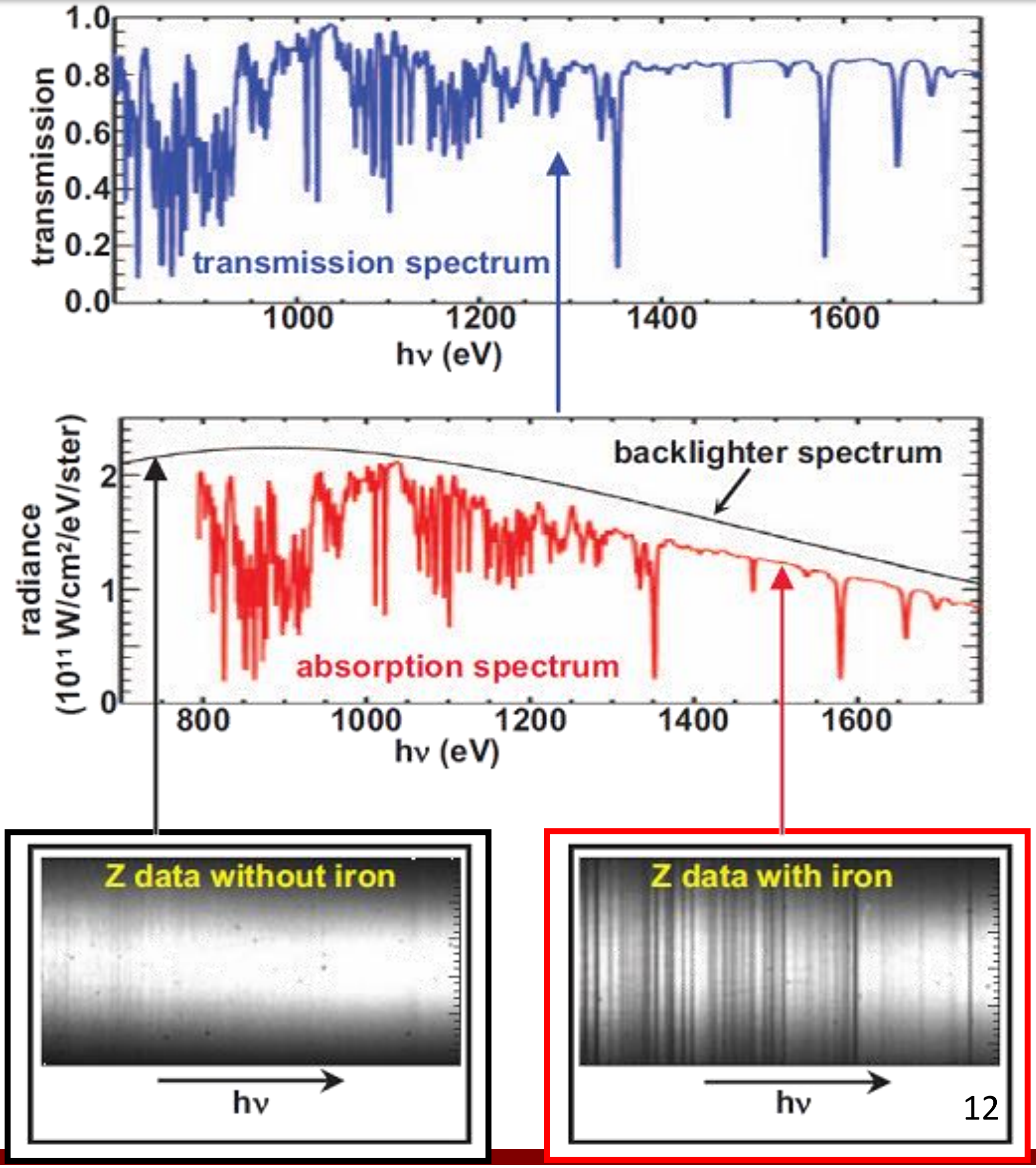


Foil is backlit at shock stagnation



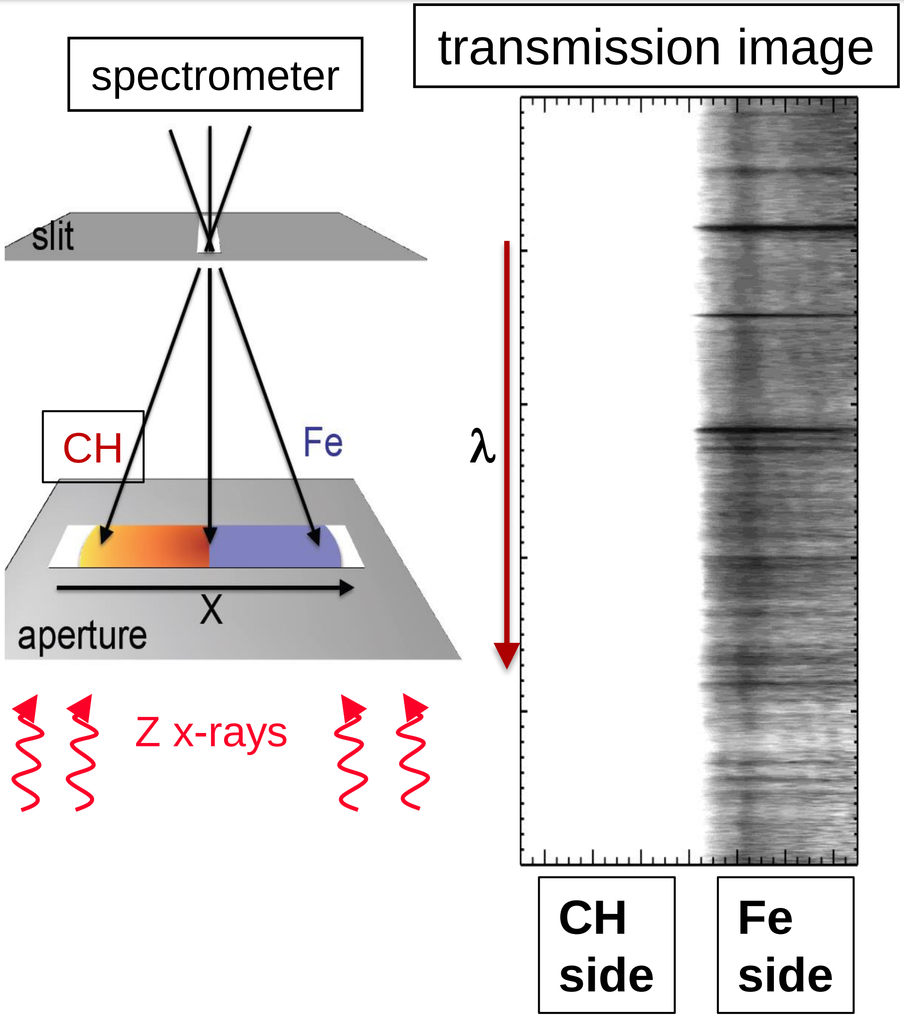


Transmission is inferred by dividing the attenuated spectrum by the unattenuated spectrum.



Bailey et al., POP 16 (2009)

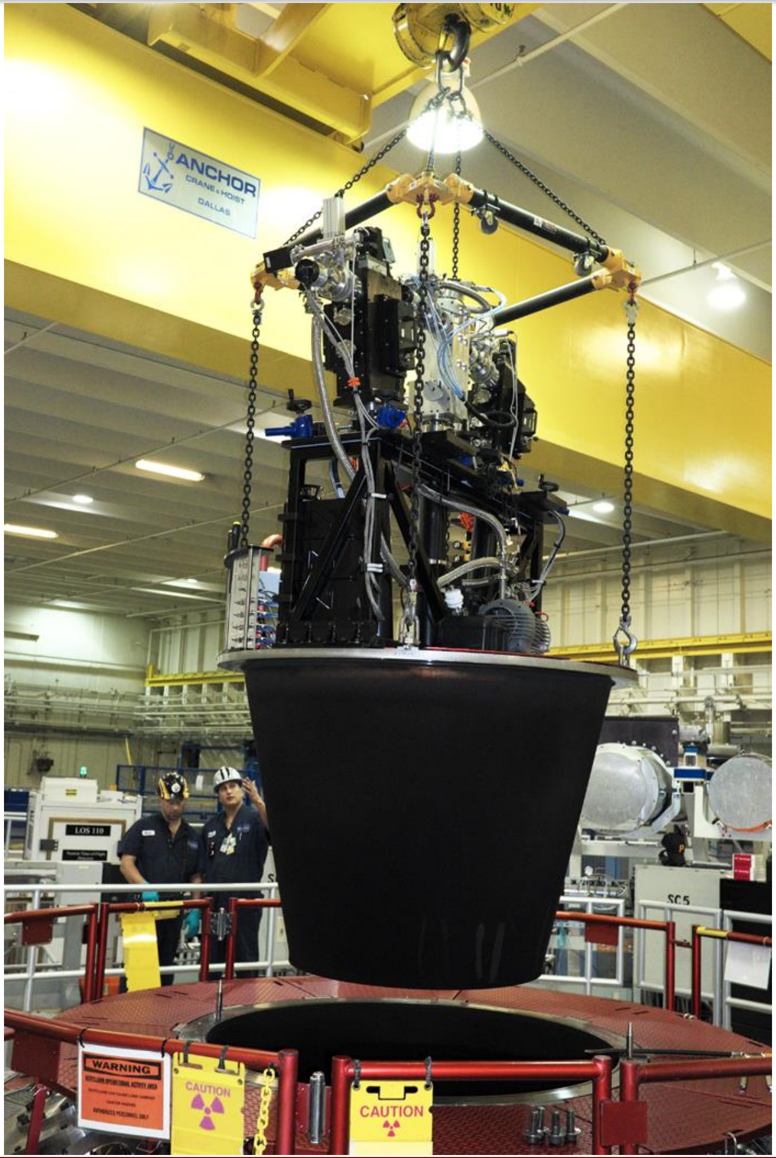
Measurements with half-moon shaped samples enable transmission determination from single experiments



Backlit spectra with and without sample determine transmission

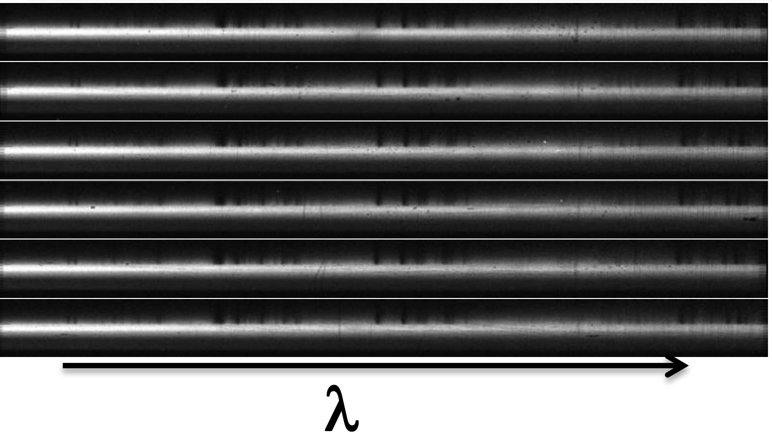
J.E. Bailey *et al*, RSI (2008).

Opacity data are recorded with an array of crystal spectrometers

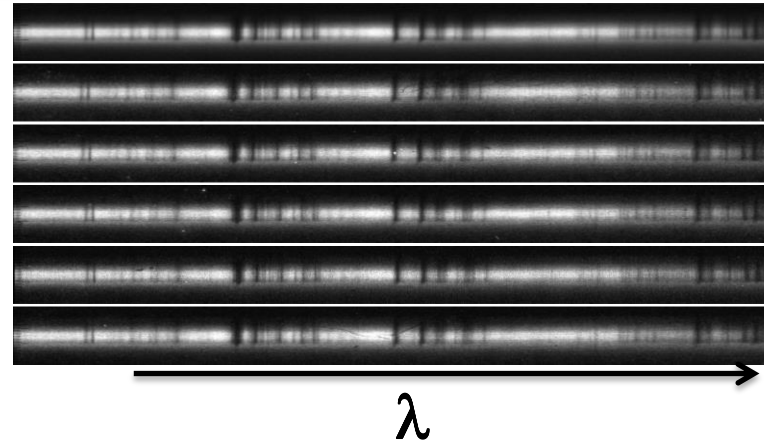


The array of opacity spectrometers is lowered into place with a 20 ton crane

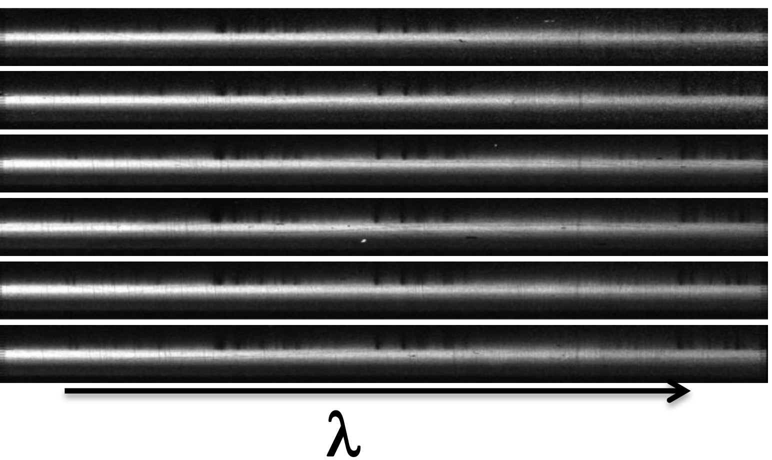
Hundreds of spectra were measured and analyzed to support the experiment reliability and reproduciblity



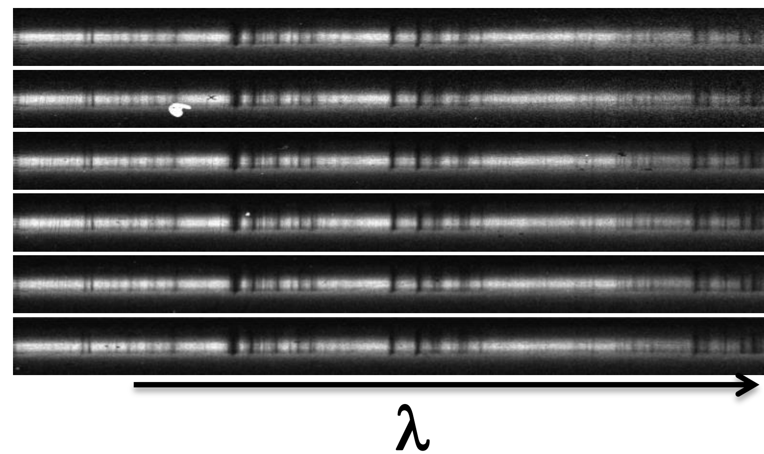
Spectrometer 4a



Spectrometer 10a



Spectrometer 4b

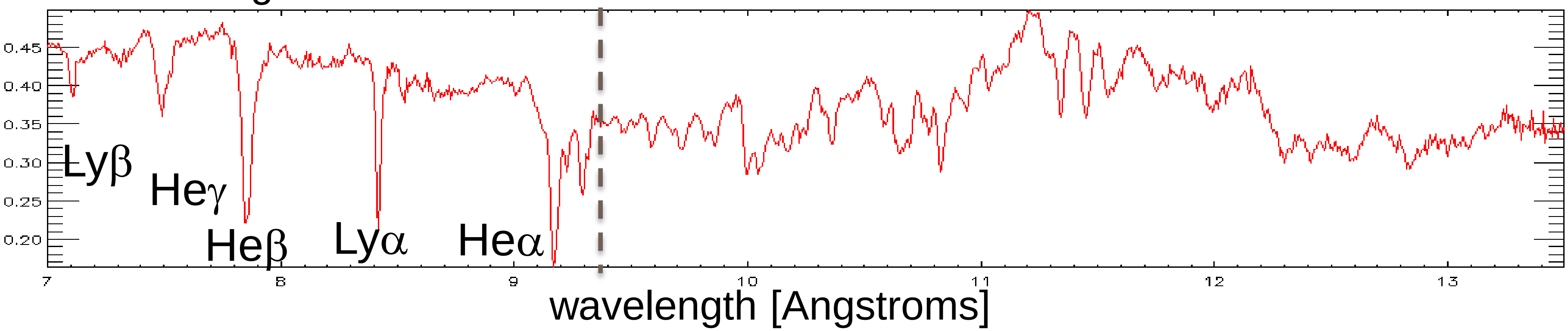


Spectrometer 10b

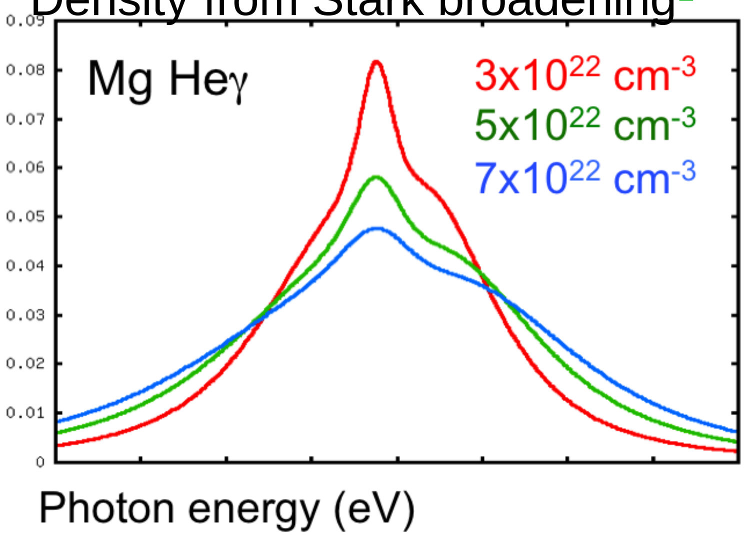
Data from z2762

This experiment used four spectrometers to record 24 spectra

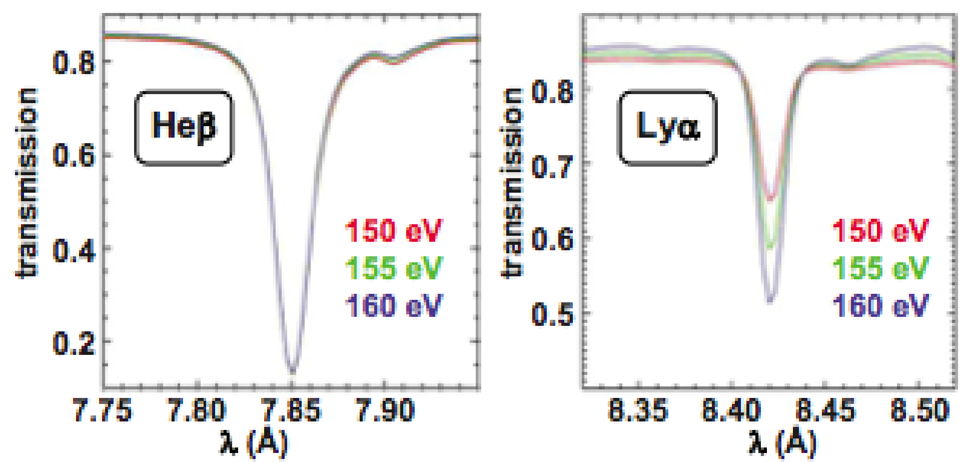
Plasma conditions are inferred by mixing Mg with Fe and using K-shell line transmission spectroscopy



Density from Stark broadening[1]



Temperature from line ratios



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

Opacity measurements

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

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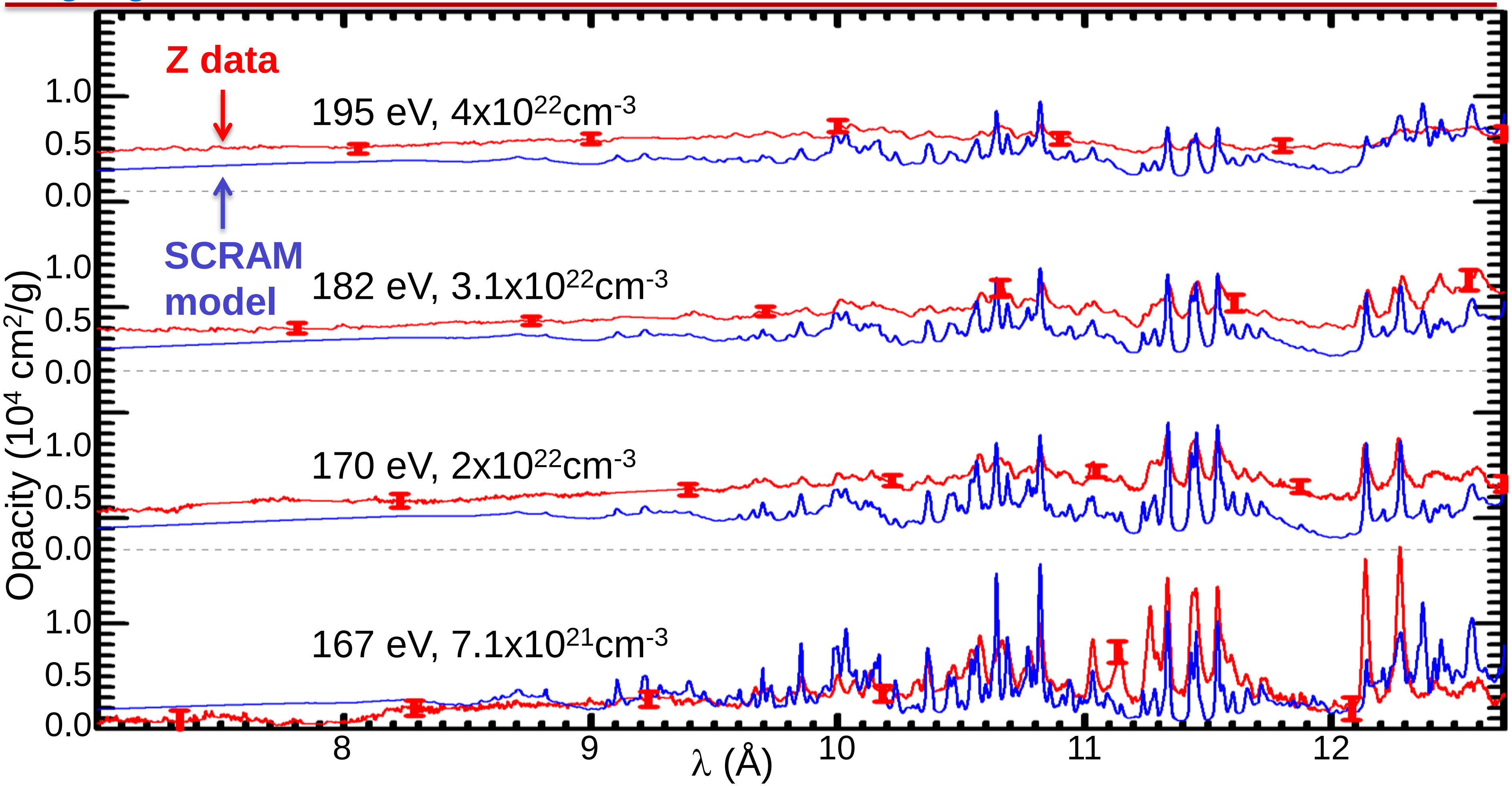
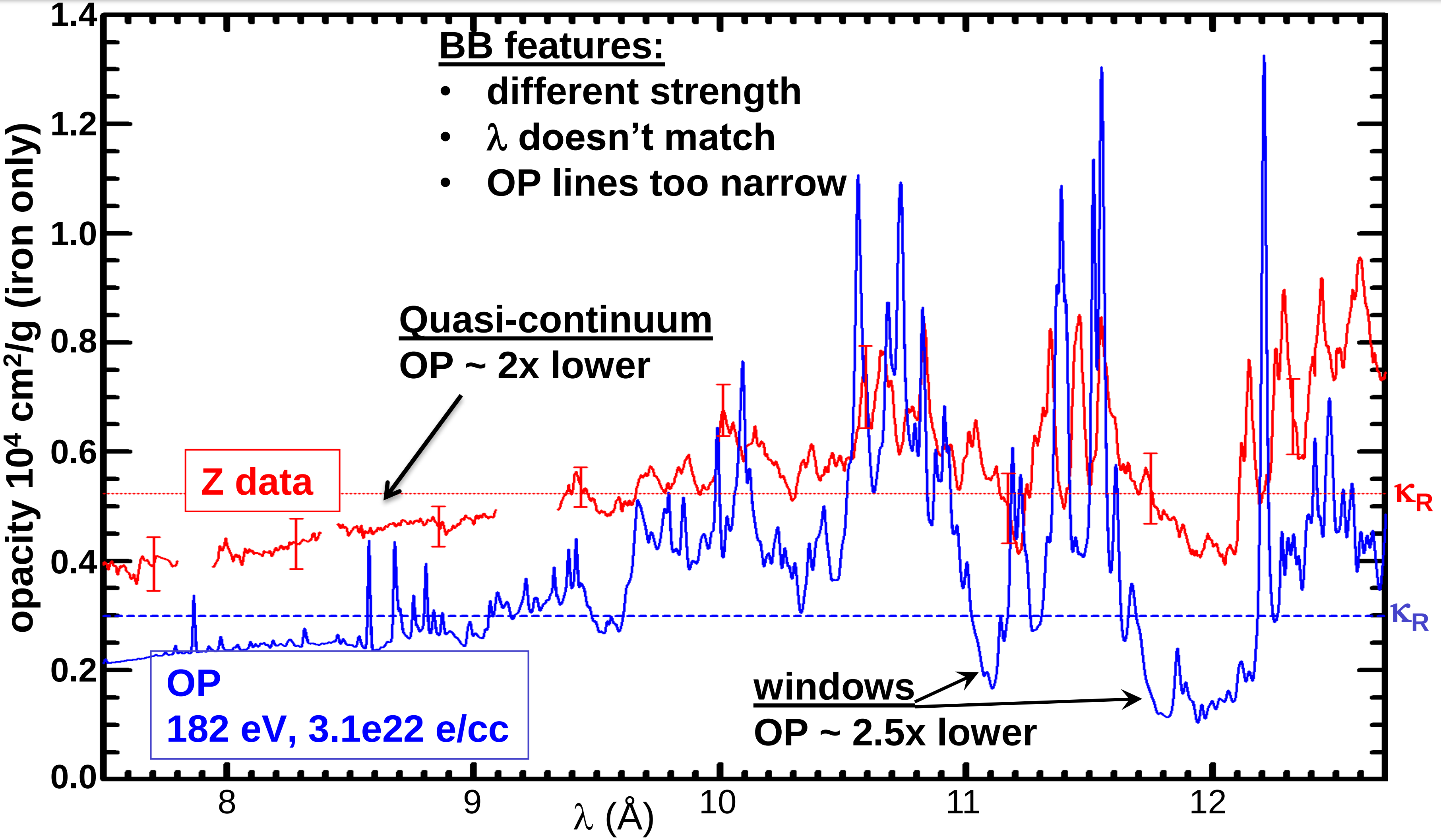


At high temperature , density, calculations are generally lower than the data

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

Implications for the sun

The measured pure iron Rosseland mean opacity is higher than calculated

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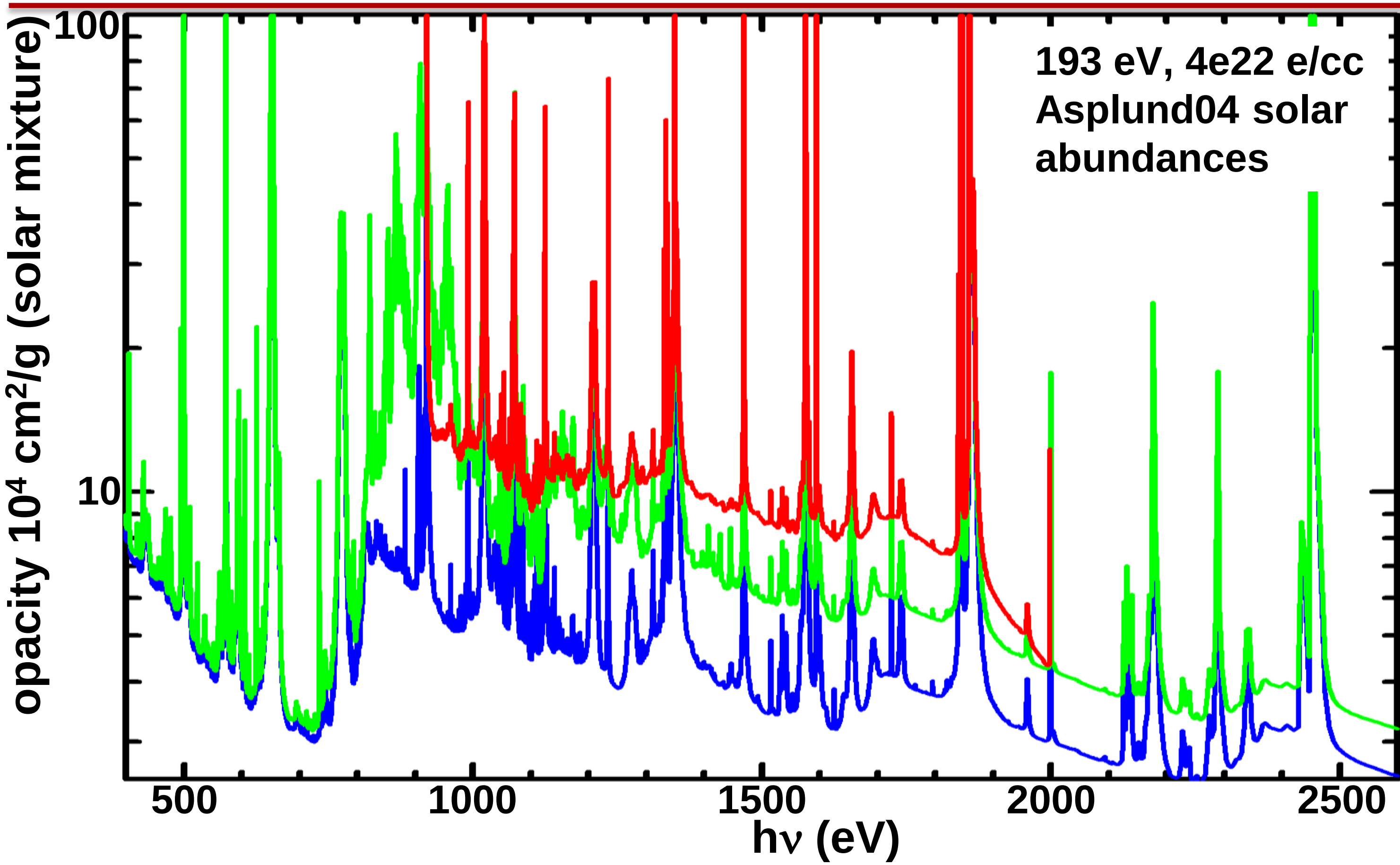
Model	experiment/model ratio Rosseland Mean
OP	1.75
OPAS	1.53
ATOMIC	1.75
SCO-RCG	1.57
SCRAM	1.67

<u>This comparison:</u>

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



OP solar mix, with Z iron data κ_R = 8.16 cm^2/g

OP solar mix, with OP iron κ_R = 7.67cm^2/g

OP solar mix {without iron} κ_R = 5.50 cm^2/g

- 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

Path forward

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?

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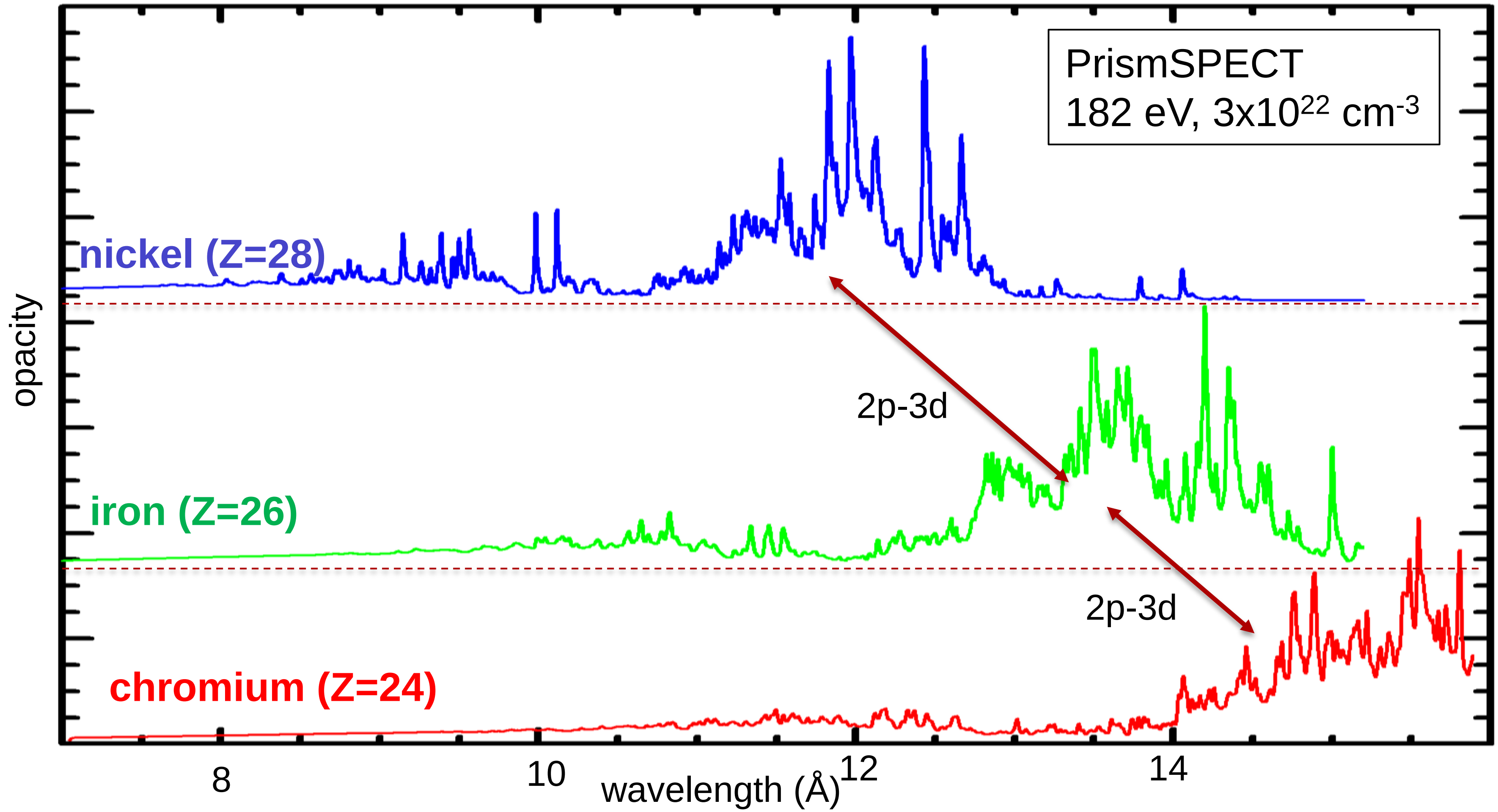
<u>**Hypotheses:**</u>

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

<u>**Tests:**</u>

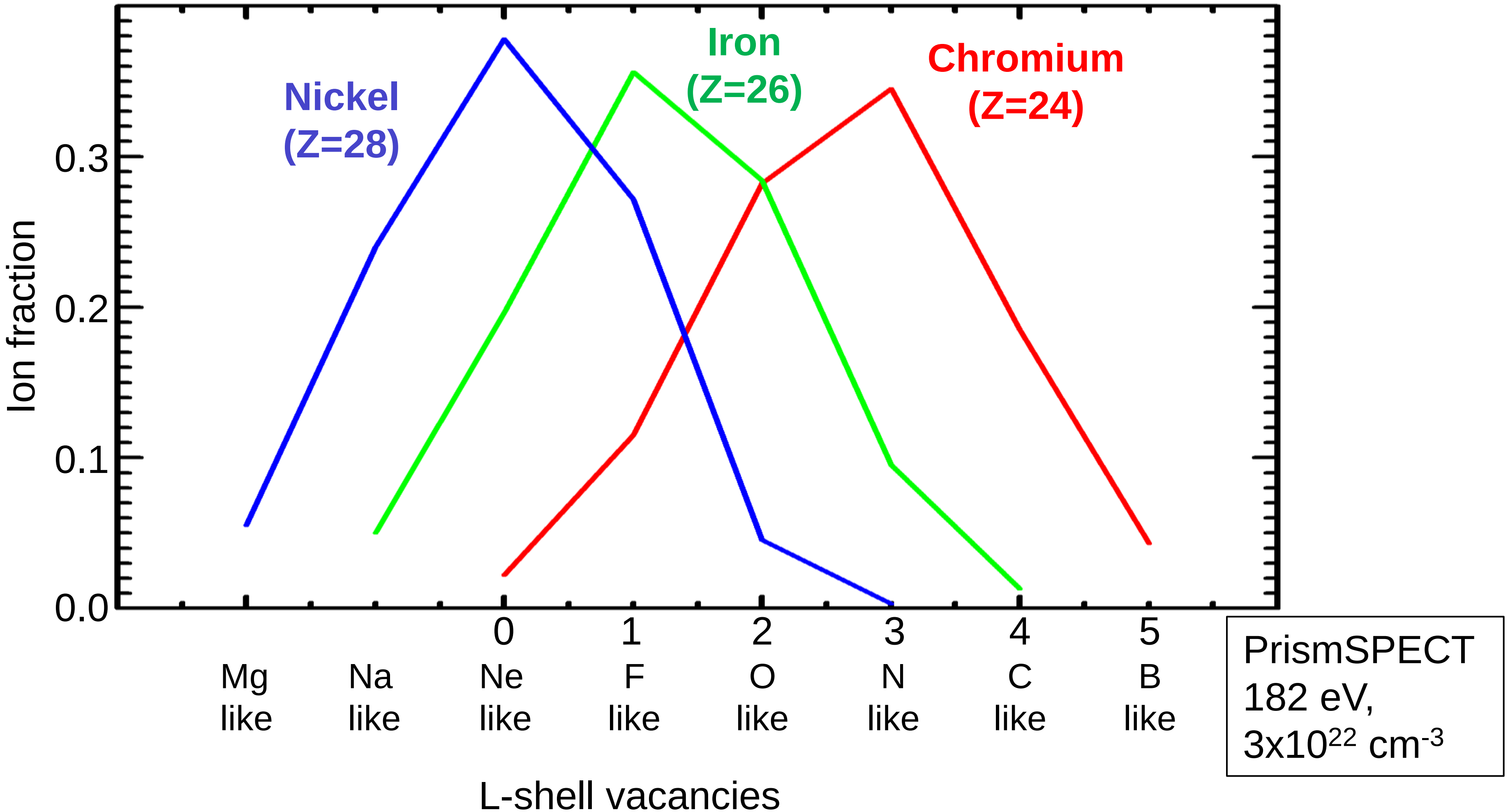
A) Z experiments with lower and higher atomic number elements
B) Z experiments with lower and higher temperature and density
B) Experiments on a different platform (NIF)

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



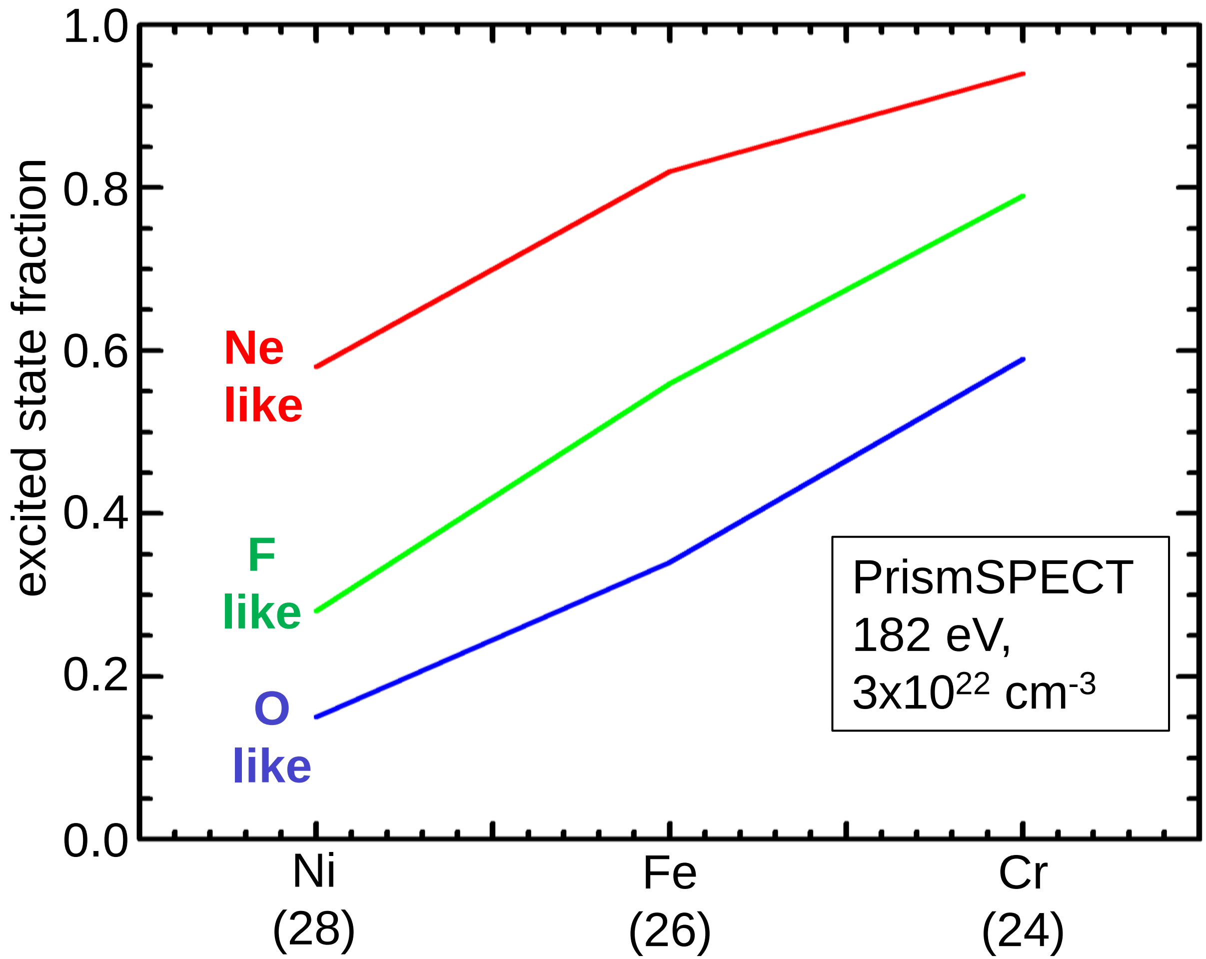
Experiments with different elements also can help identify possible experiment peculiarities with the iron measurements (e.g., unknown contaminants)

The number of L shell vacancies changes with the sample element



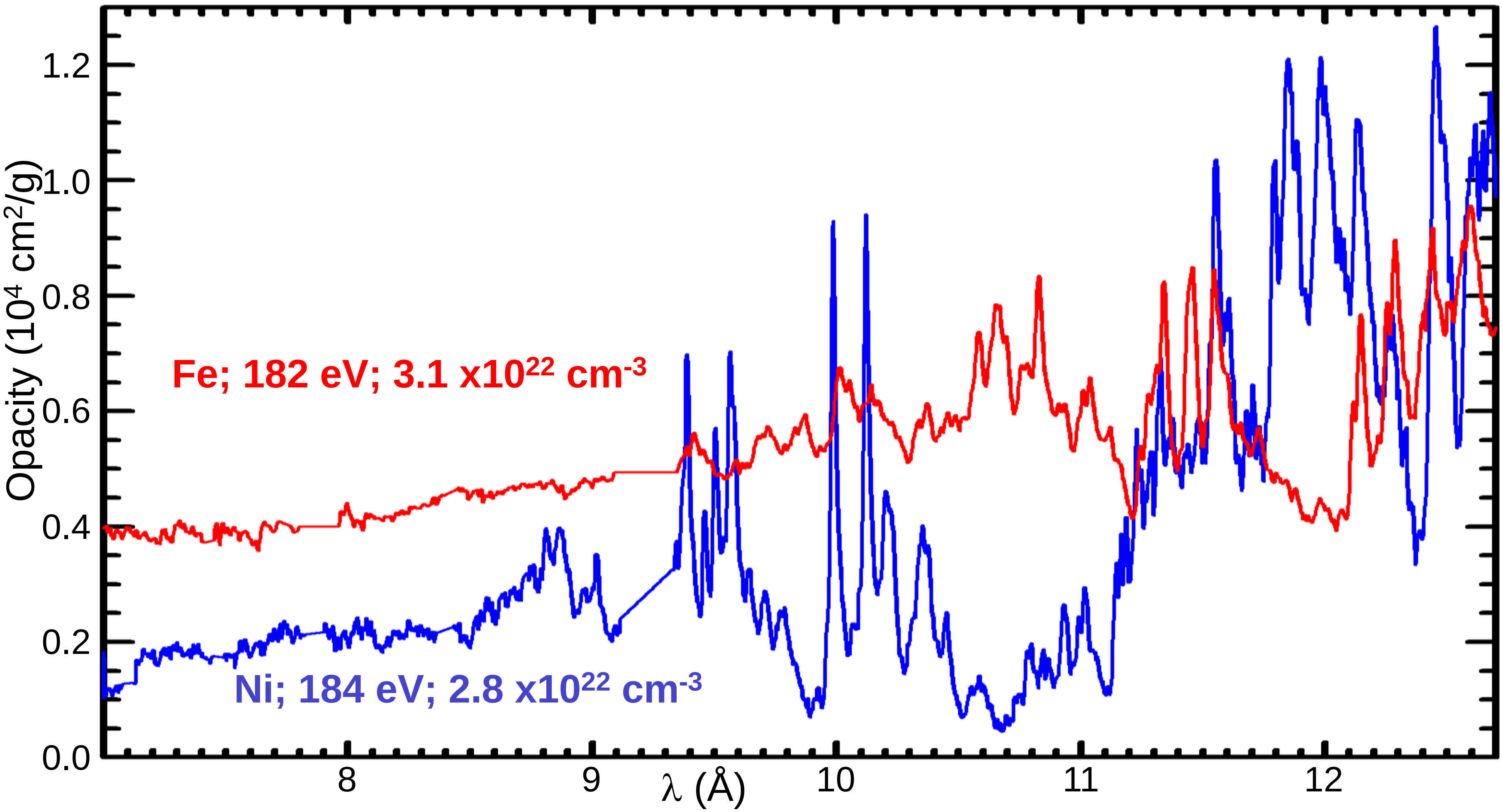
Opacity from transitions with an open L-shell may be more complex to model

The fractional excited state population increases as the atomic number decreases

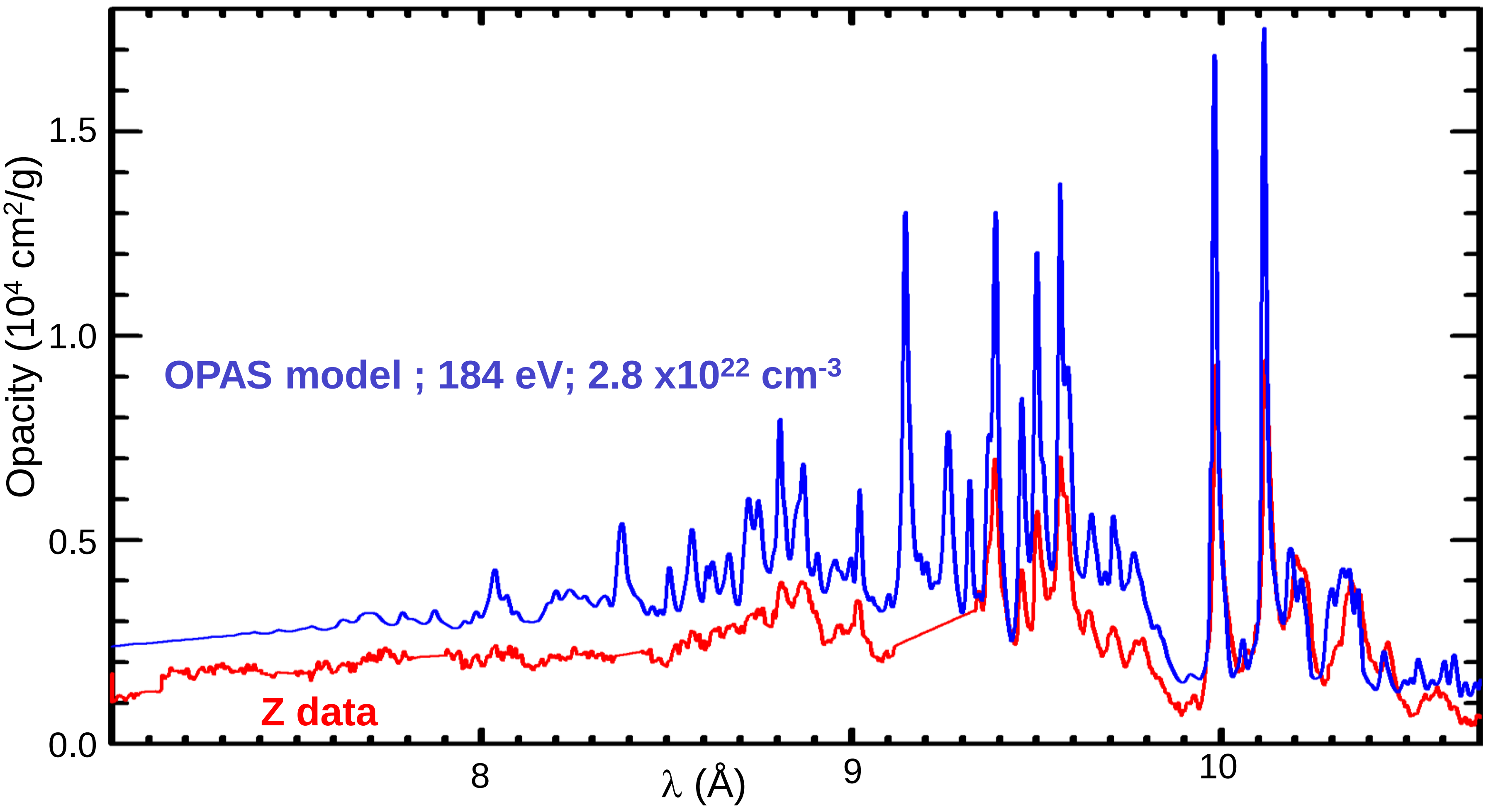


Opacity from ions with high excited state populations may be more complex to model
These difficulties increase as atomic number decreases

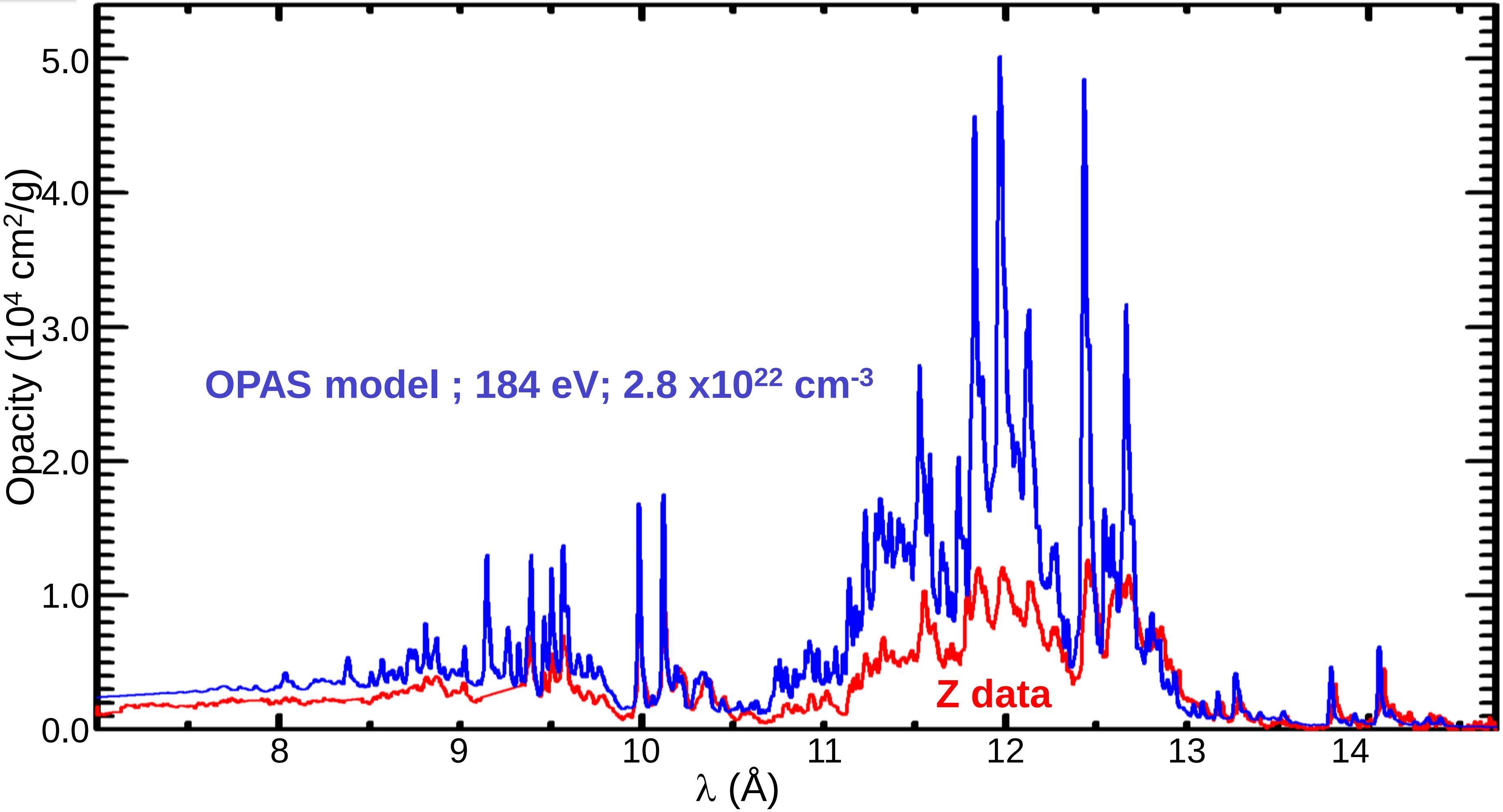
Preliminary Ni data shows the high Te/ne experiment platform is capable of measuring sharp spectral features



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

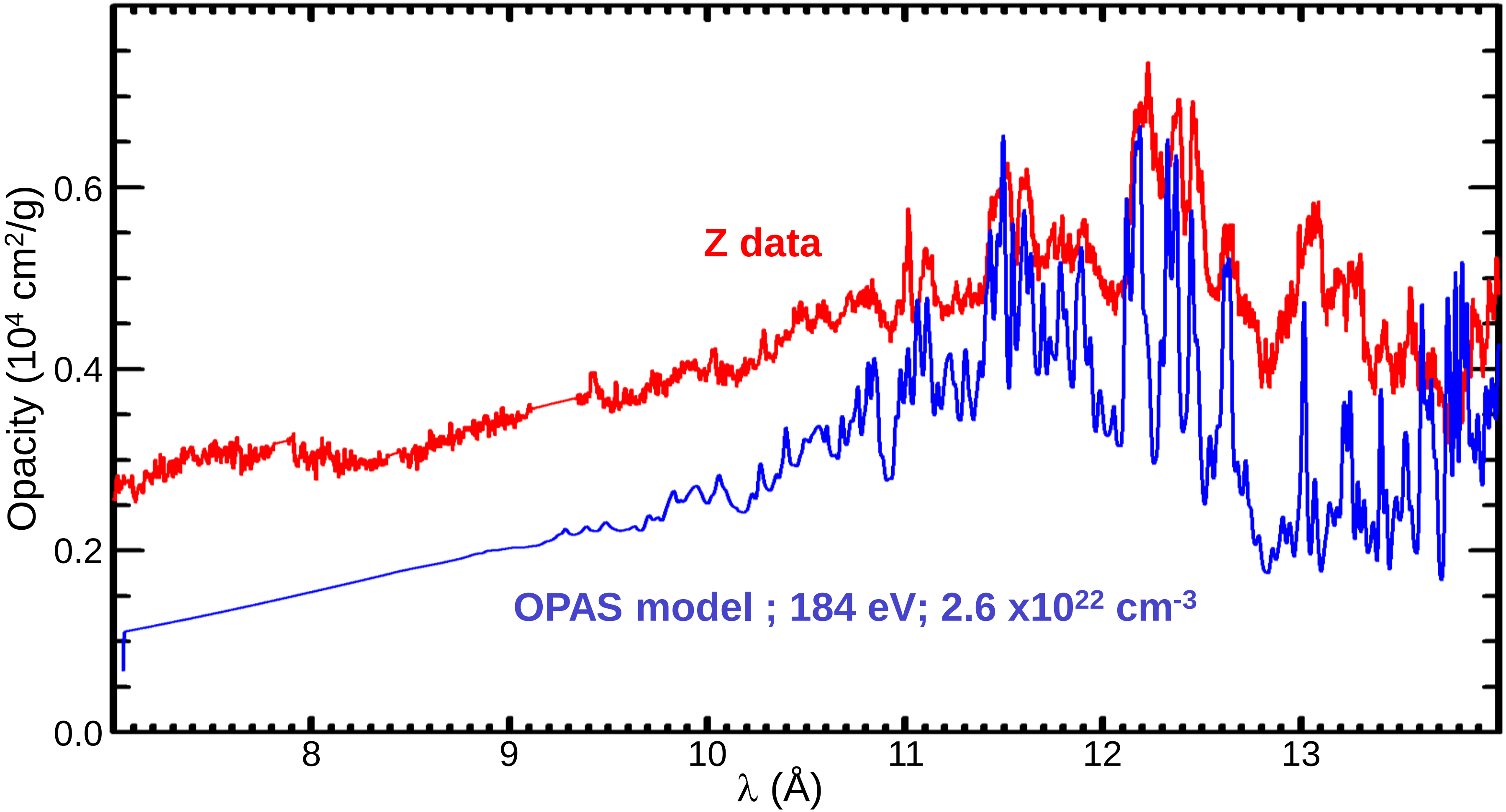


Predictions for Ni opacity in the 2p-3d spectral region are approximately 2x larger than measurements



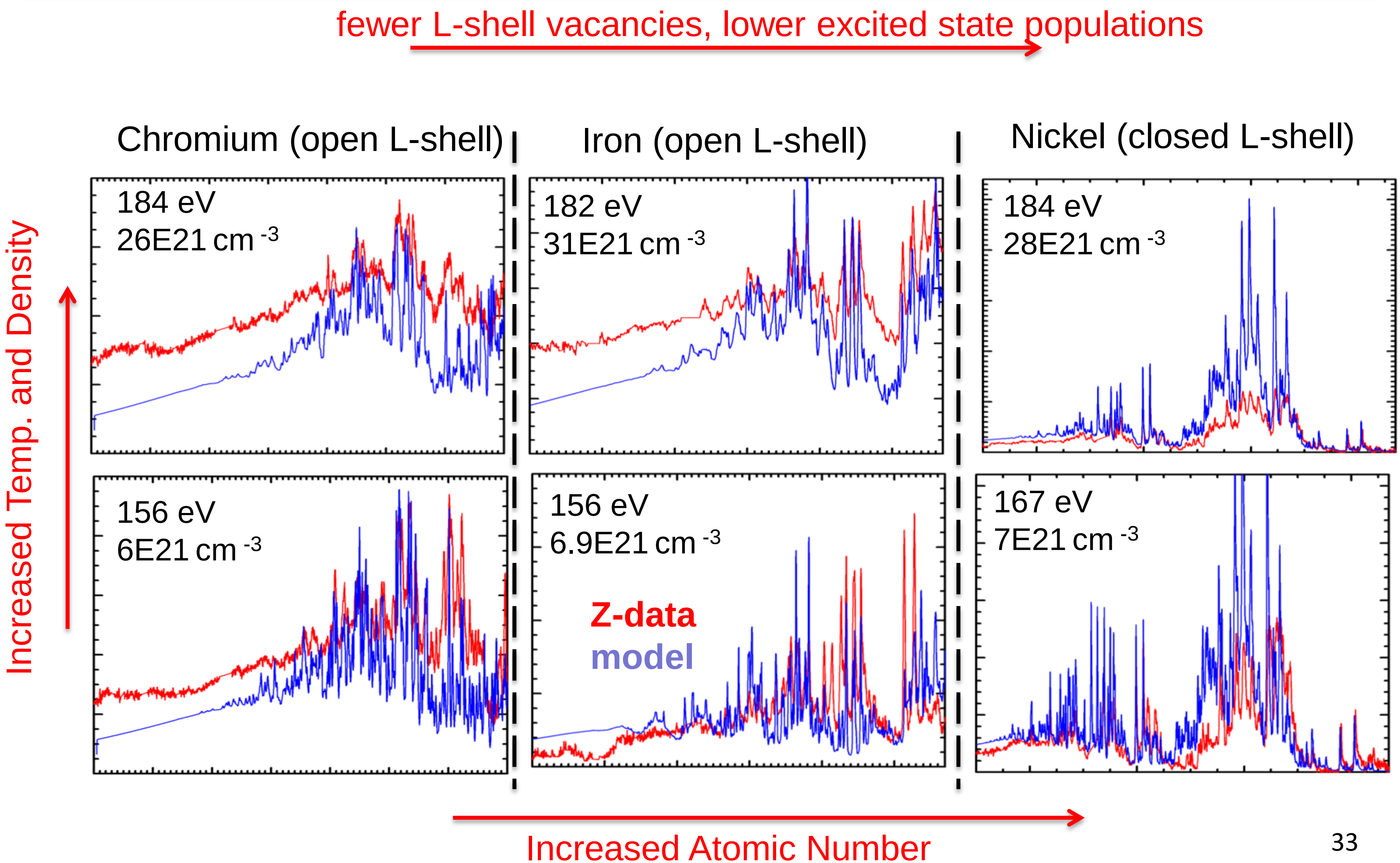
Consistent with a hypothesis that photon absorption at long wavelengths is over-predicted while short wavelength absorption is under-predicted

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.



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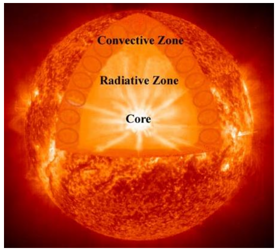

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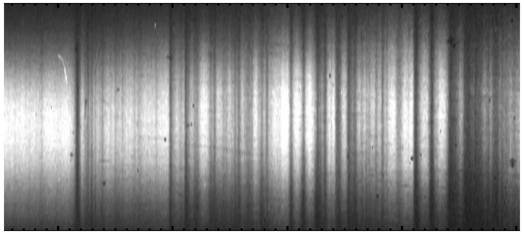

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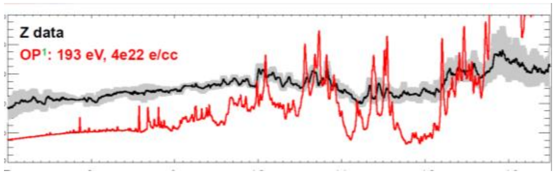

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Bailey et al., *Nature* 2015