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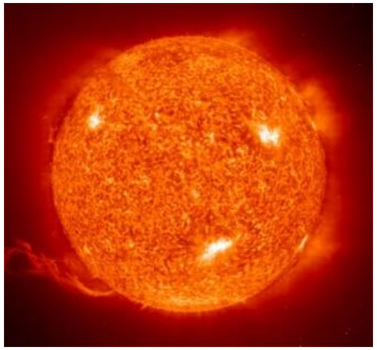

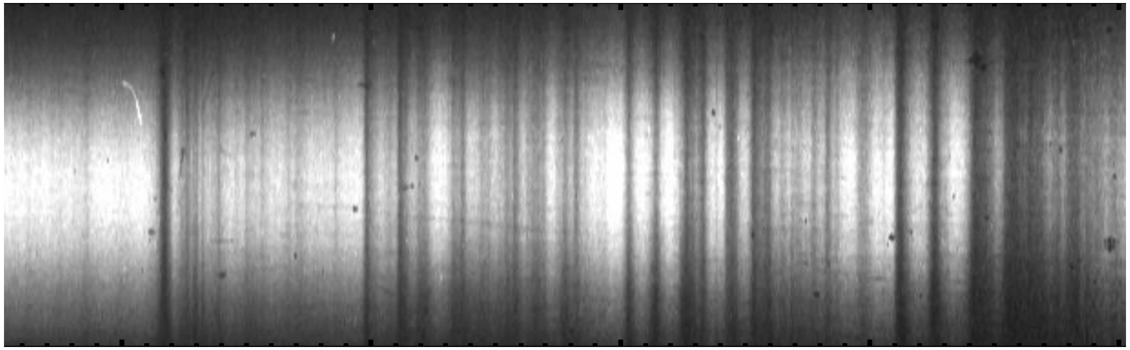

IRON OPACITY MEASUREMENTS AT SOLAR INTERIOR TEMPERATURES

Jim Bailey

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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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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Z iron opacity experiments refine our understanding of the sun.

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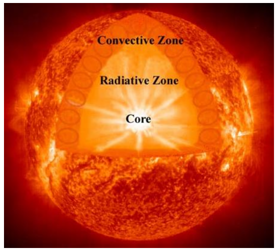
- **Solar interior predictions don't match helioseismology**
  - **→ Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?**



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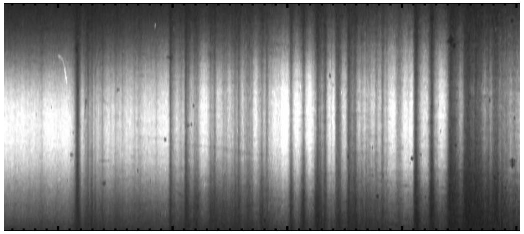

- **Opacity models disagree with measurements at near-solar-interior conditions**
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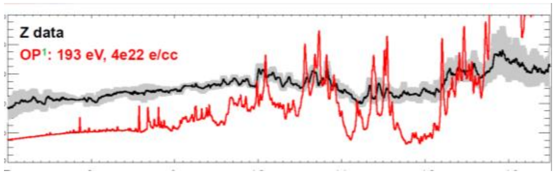


The measurements imply photon absorption in high energy density matter is different than previously believed

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**

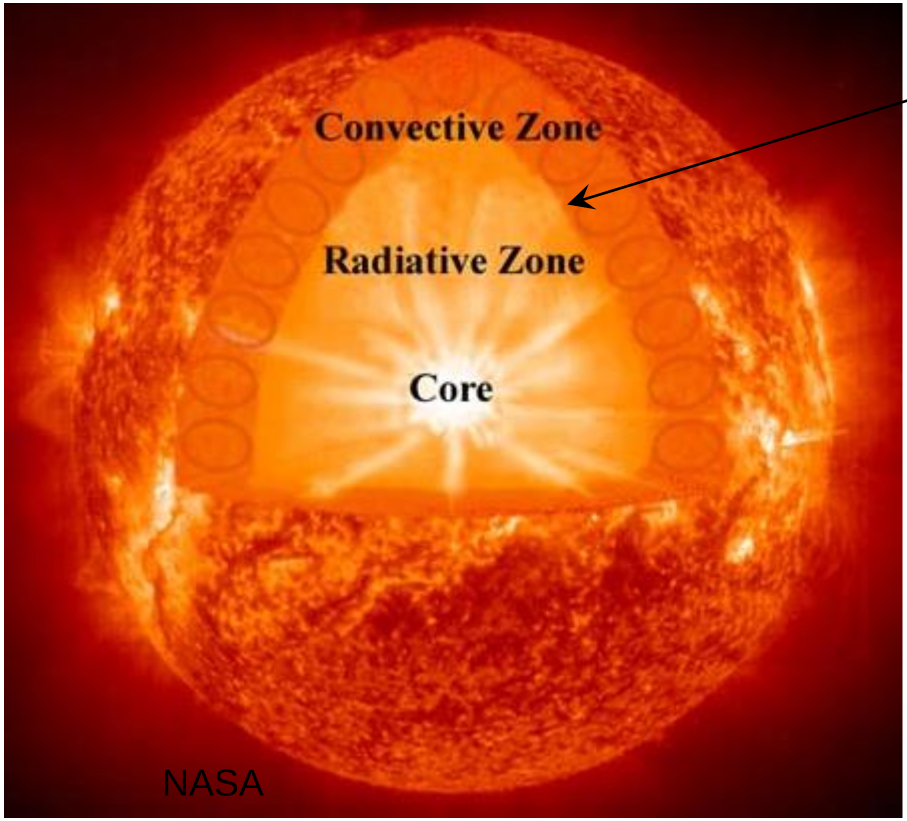
Applications include numerous HED plasmas:

- **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)

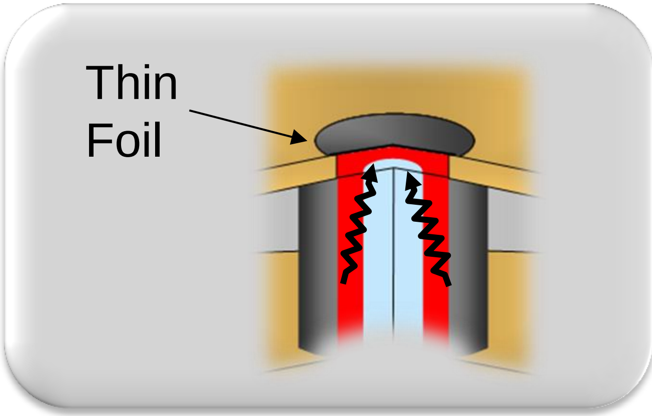
<u>Models depend on:</u>
- **element abundances**
- **EOS**
- **opacity**

focus: iron at convection zone base {187 eV, 9e22 e/cc}

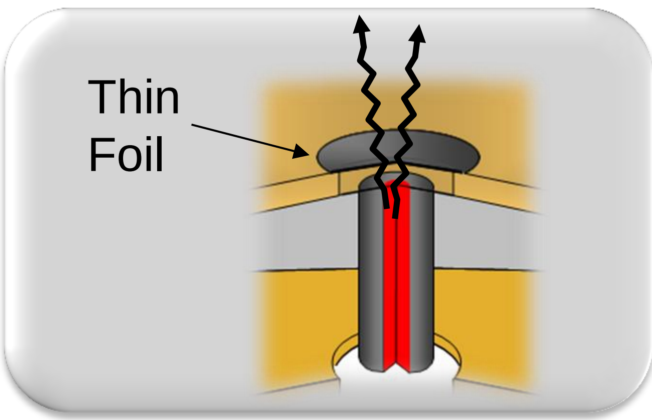
Disagreement could be resolved if the true mean opacity for solar matter is 10-30% higher than predicted

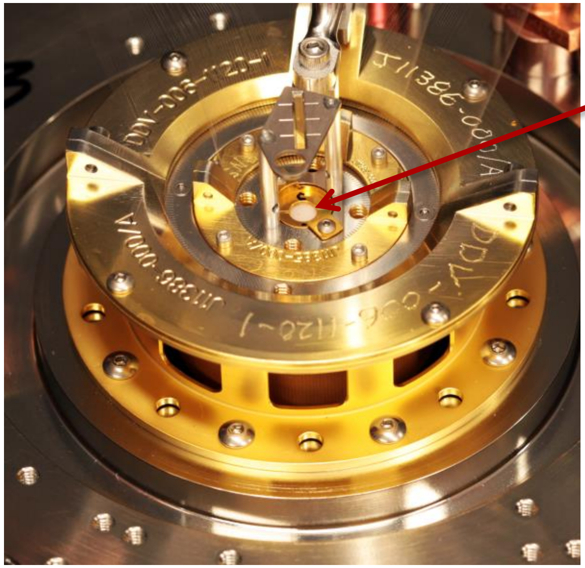
The ZPDH radiating shock is used to both heat and backlight samples to stellar interior conditions.

Foil is heated during the ZPDH implosion

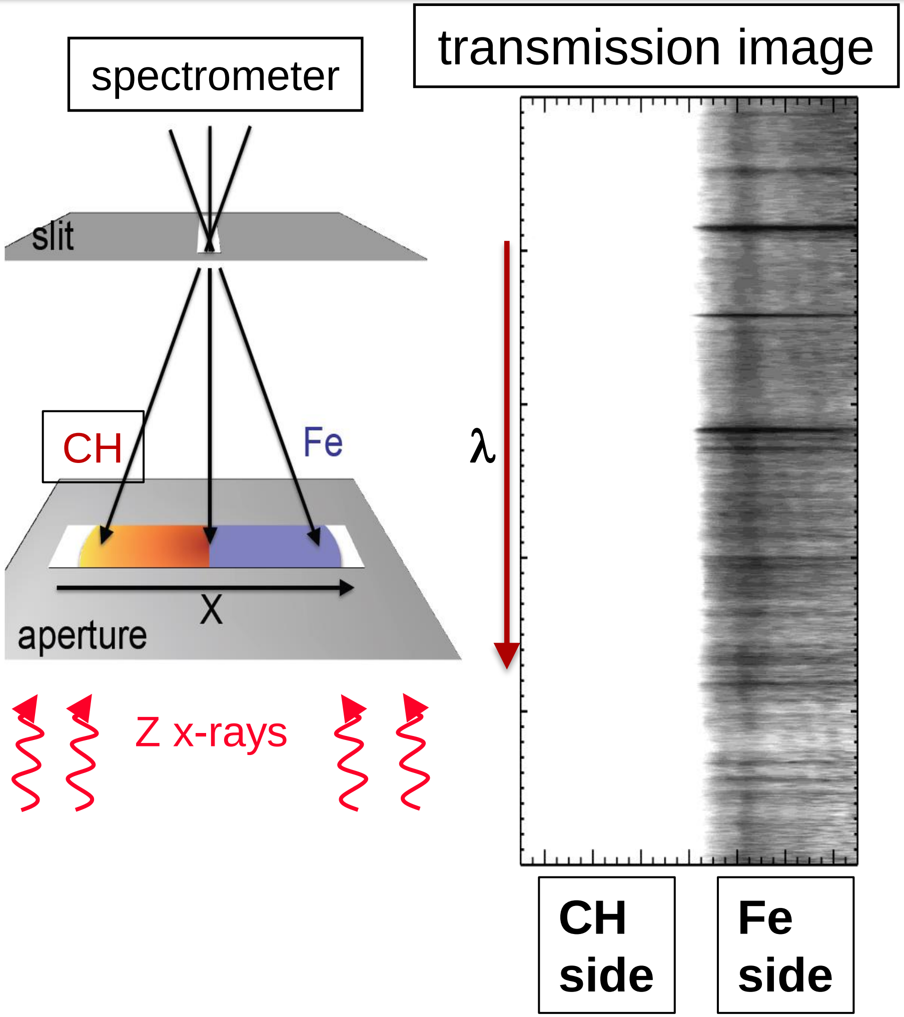


Foil is backlit at shock stagnation





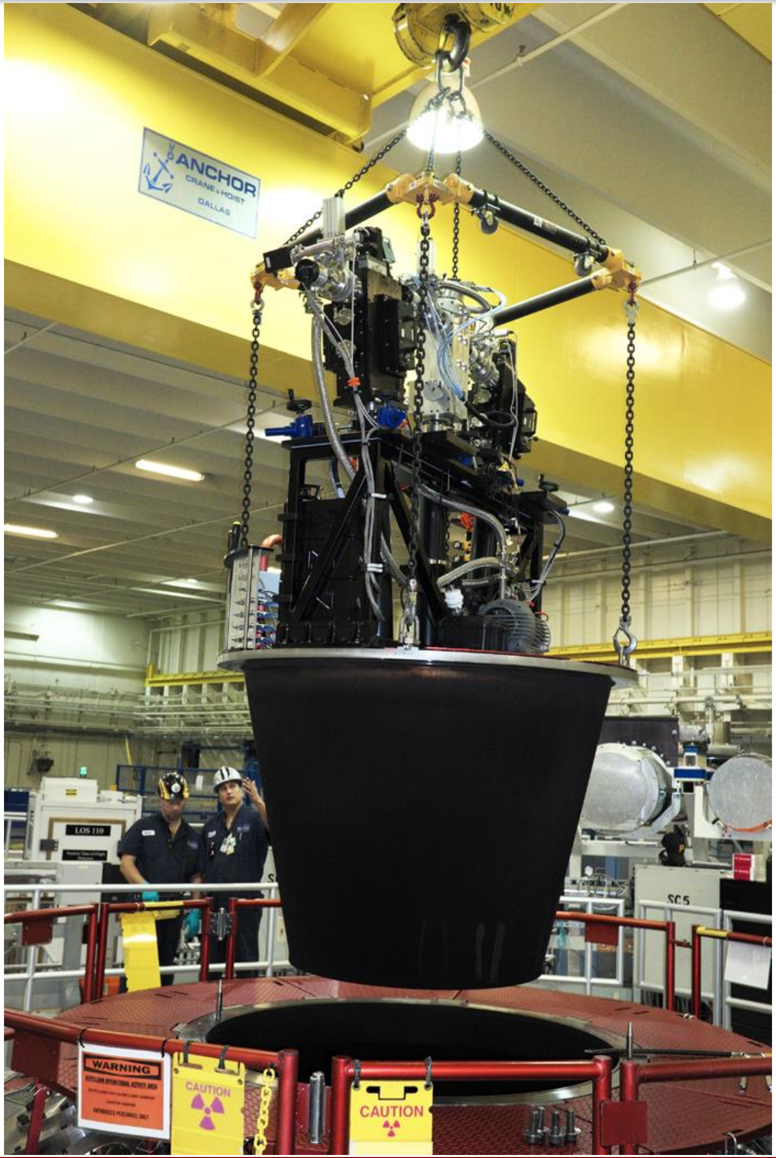
Transmission is inferred by dividing the attenuated spectrum by the unattenuated spectrum.



half-moon samples enable transmission determination from single experiments

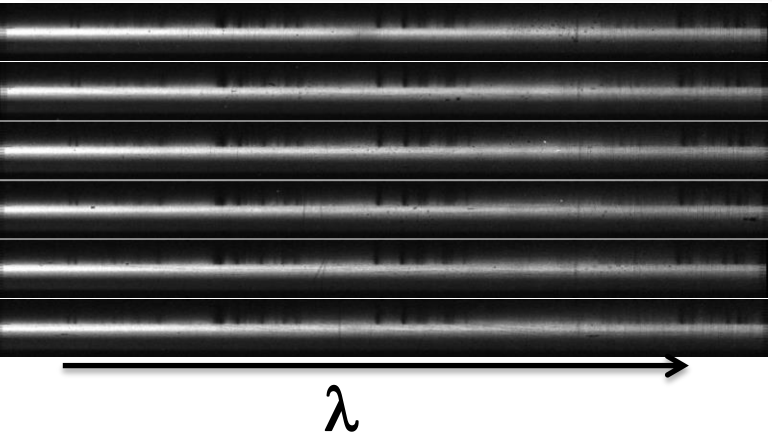
Bailey et al., POP 16 (2009)   Bailey *et al*, RSI (2008).

Opacity data are recorded with an array of crystal spectrometers

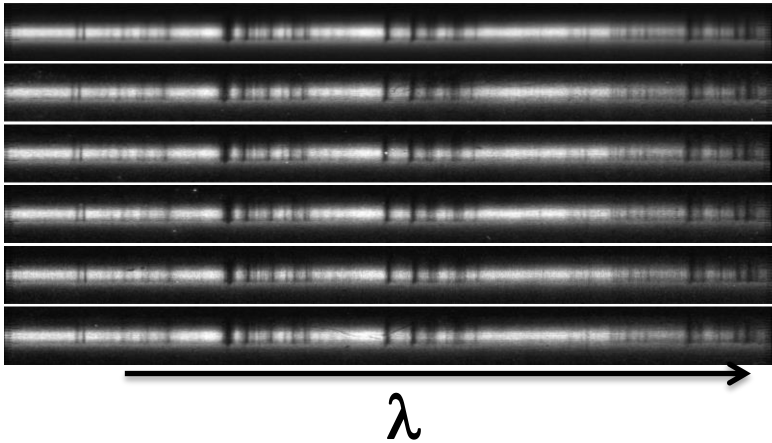


The array of opacity spectrometers is lowered into place with a 20 ton crane

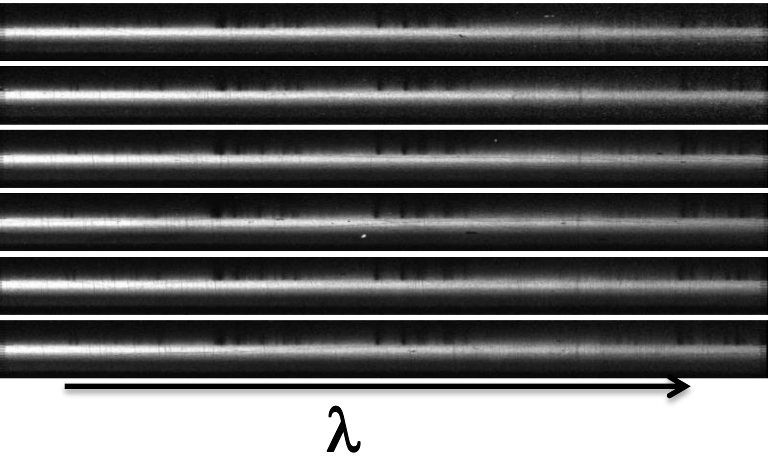
Hundreds of spectra were measured and analyzed to support the experiment reliability and reproduciblity



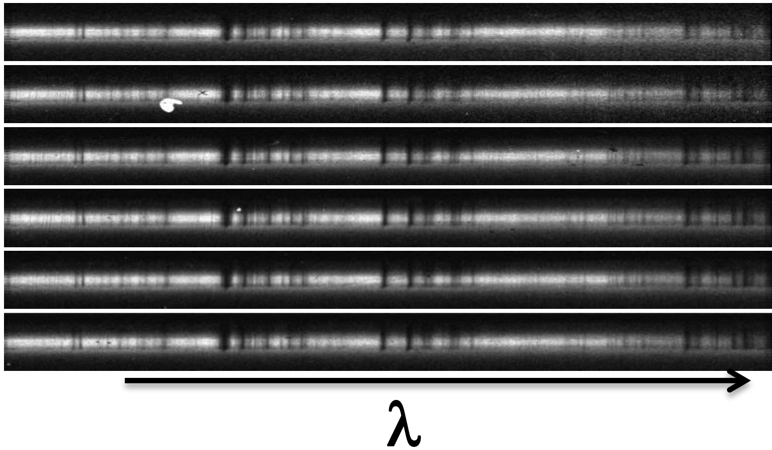
Spectrometer 4a



Spectrometer 10a



Spectrometer 4b

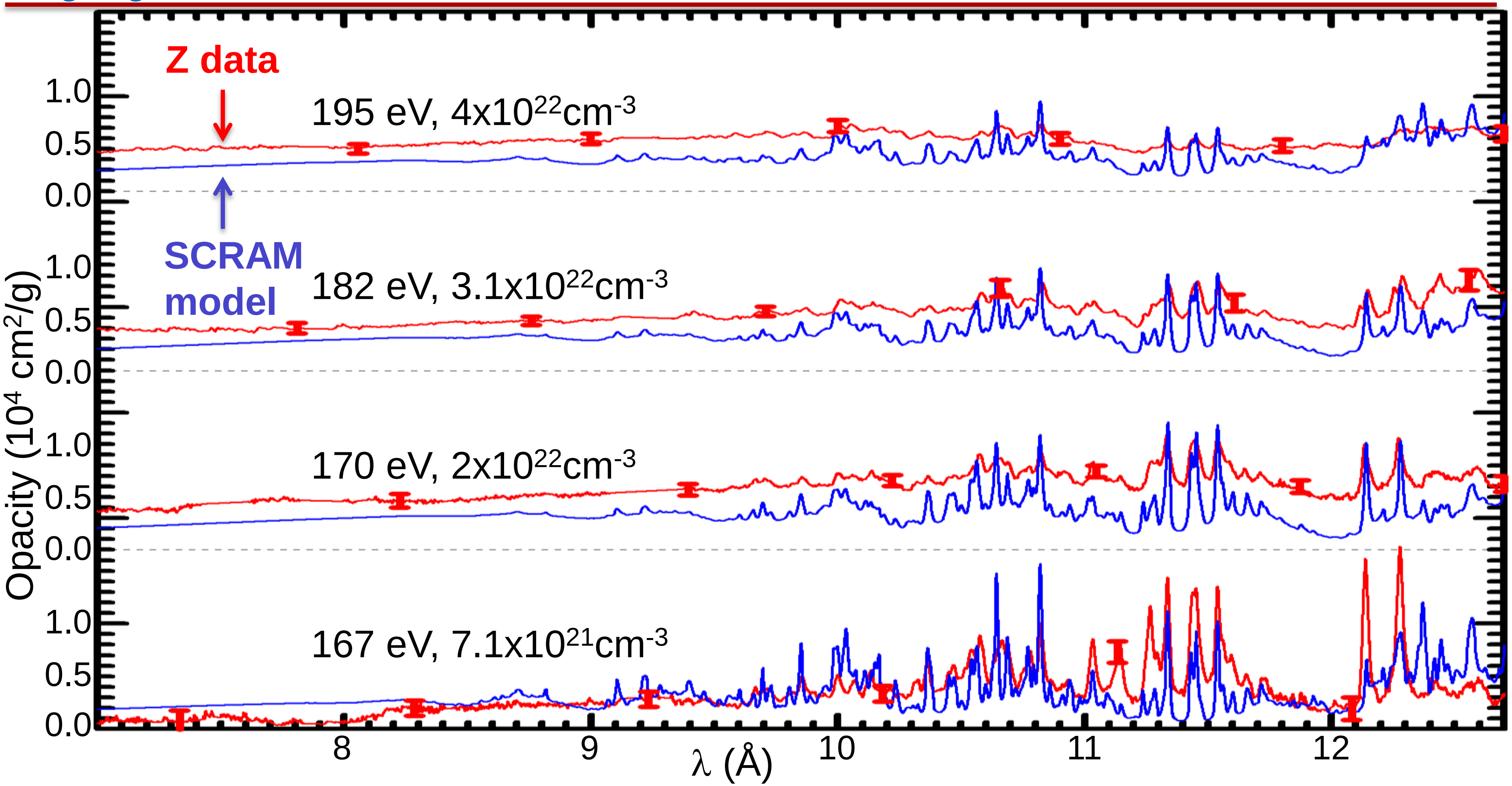


Spectrometer 10b

Data from z2762

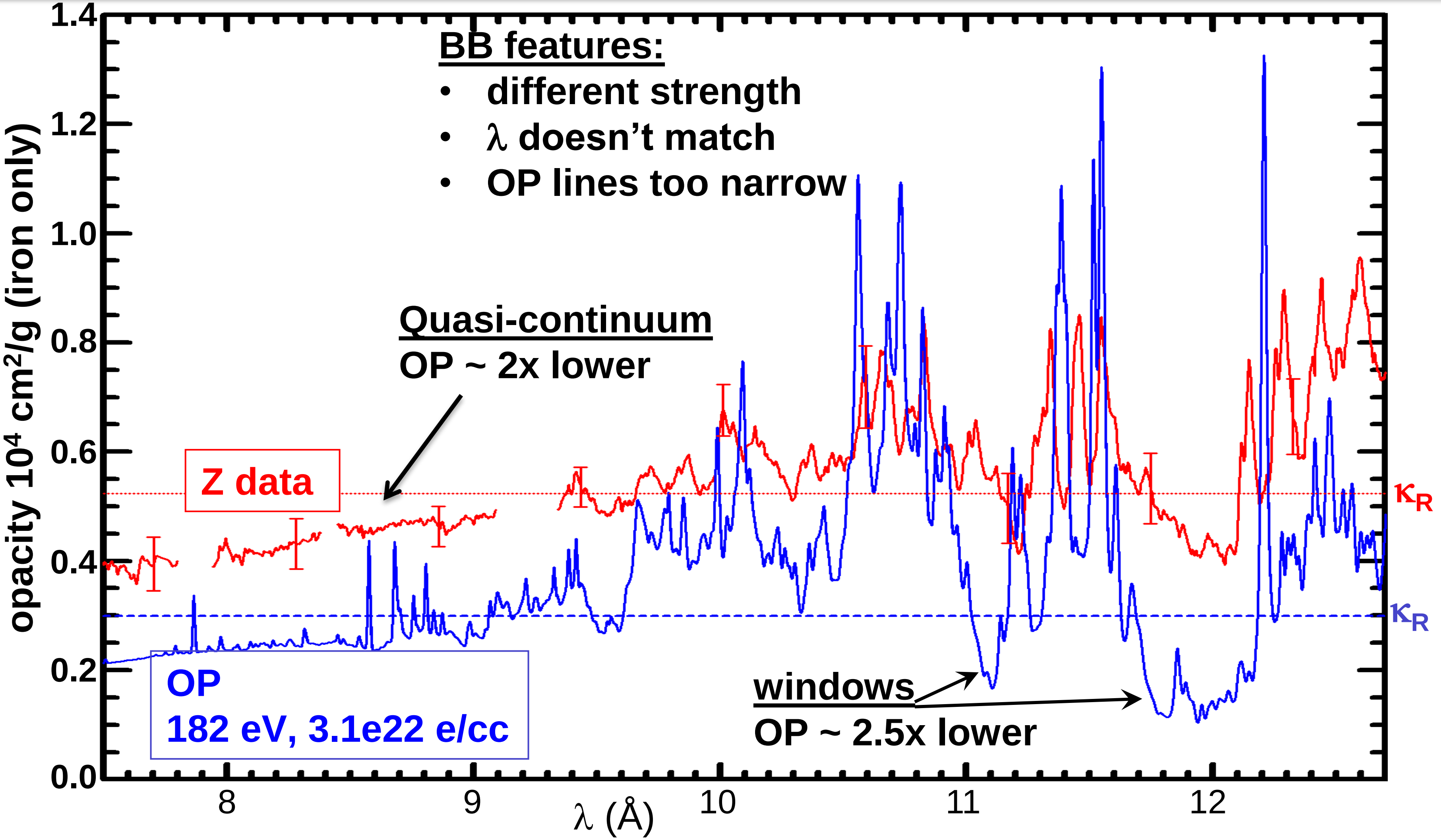
This experiment used four spectrometers to record 24 spectra

“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

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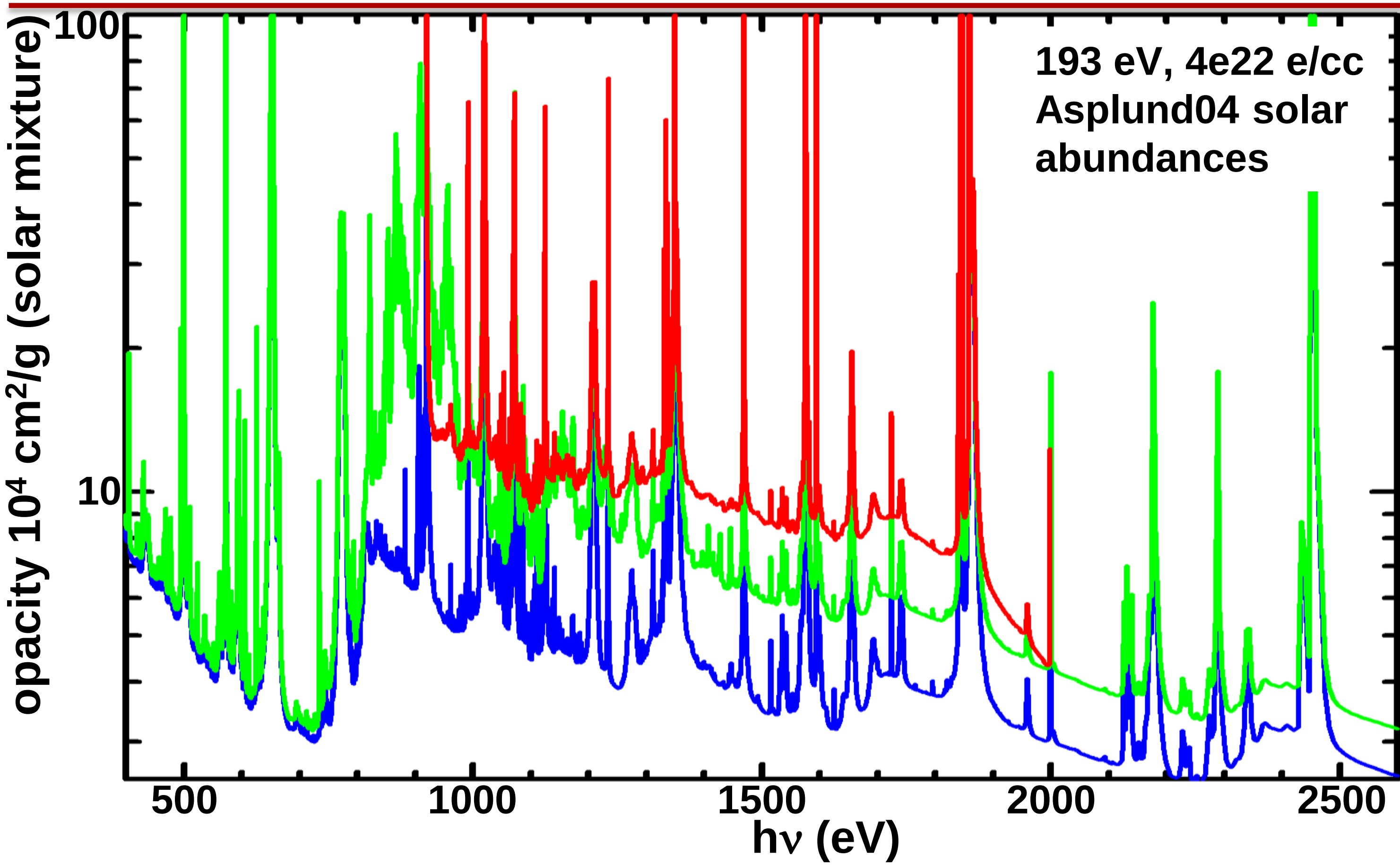

OP solar mix, with Z iron data
κ_R = 8.16 cm^2/g

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**

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

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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

C) Experiments on a different platform (NIF)

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

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Random error determination: average many spectra from multiple experiments

Systematic error evaluation:
Experiment tests
Postprocess benchmarked simulations

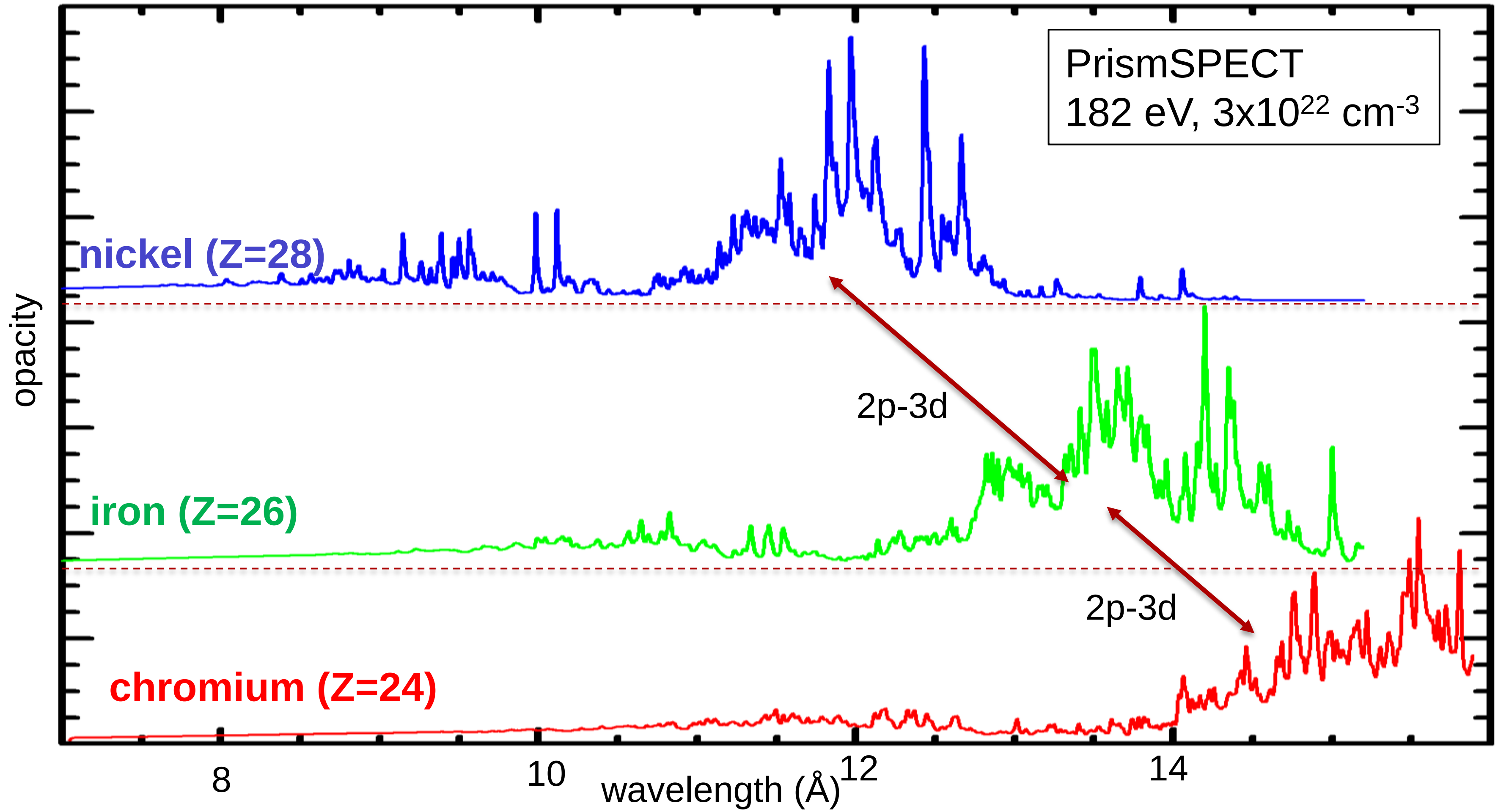
Eleven different potential systematic errors were investigated:

Sample contamination
Tamper shadowing
} potential increase for inferred opacity

Fe self emission
Tamper self emission
Extraneous background
} potential decrease for inferred opacity

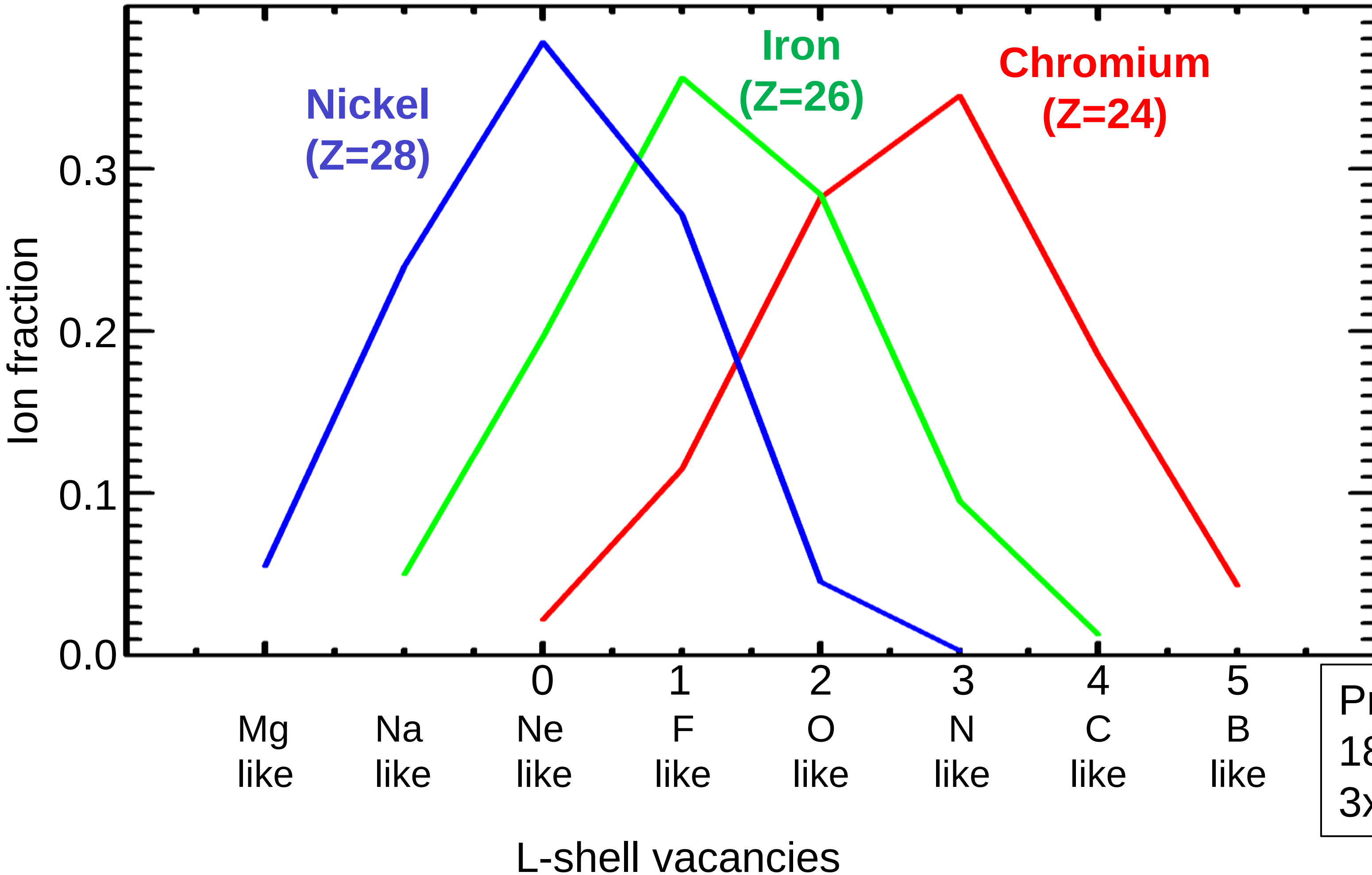
Sample areal density errors
Transmission errors
Spatial non-uniformities
Temporal non-uniformities
Departures from LTE
Plasma diagnostic errors
} potential increase or decrease for inferred opacity

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)

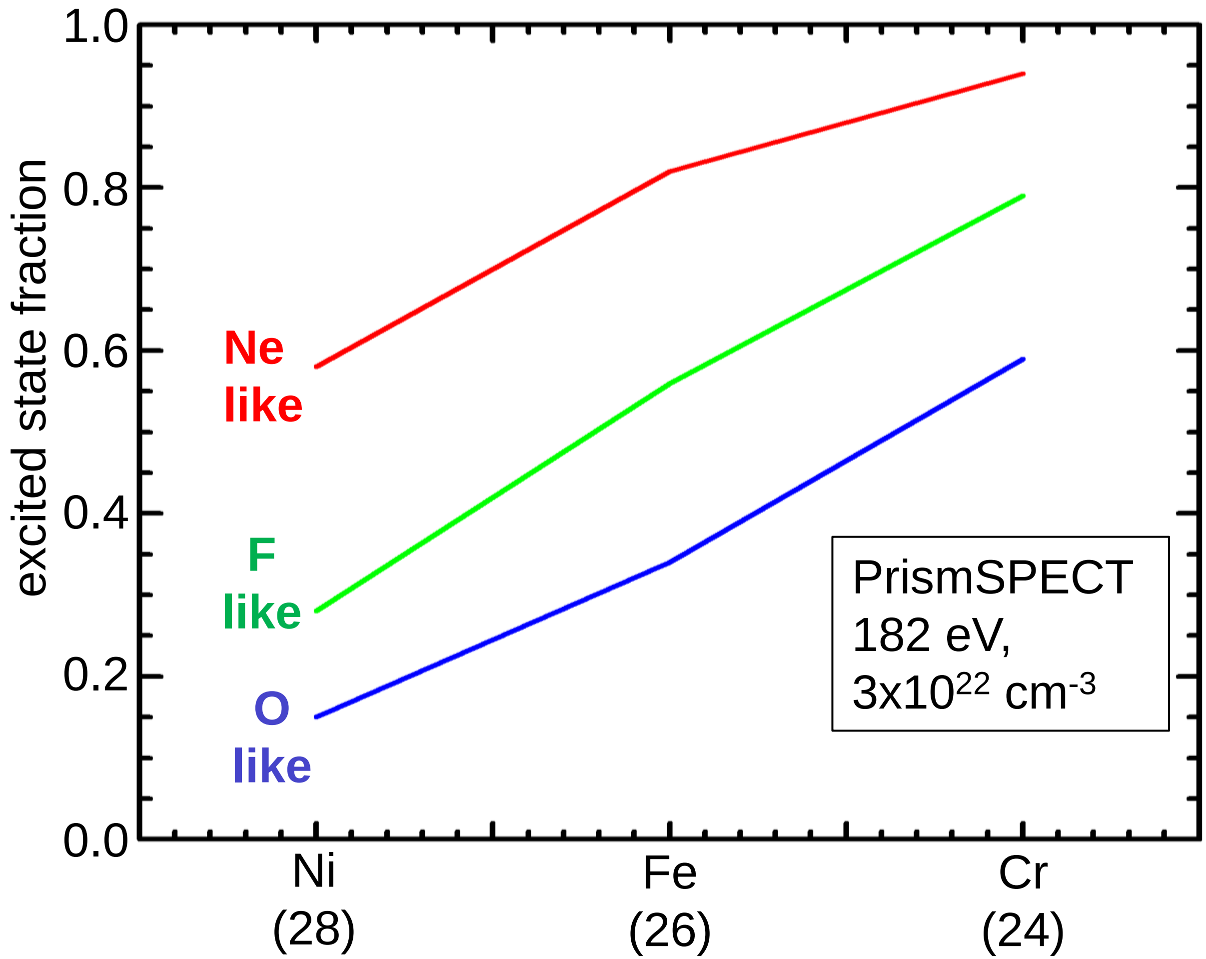
The number of L shell vacancies changes with the sample element



PrismSPECT
182 eV,
3×10^{22} cm^{-3}

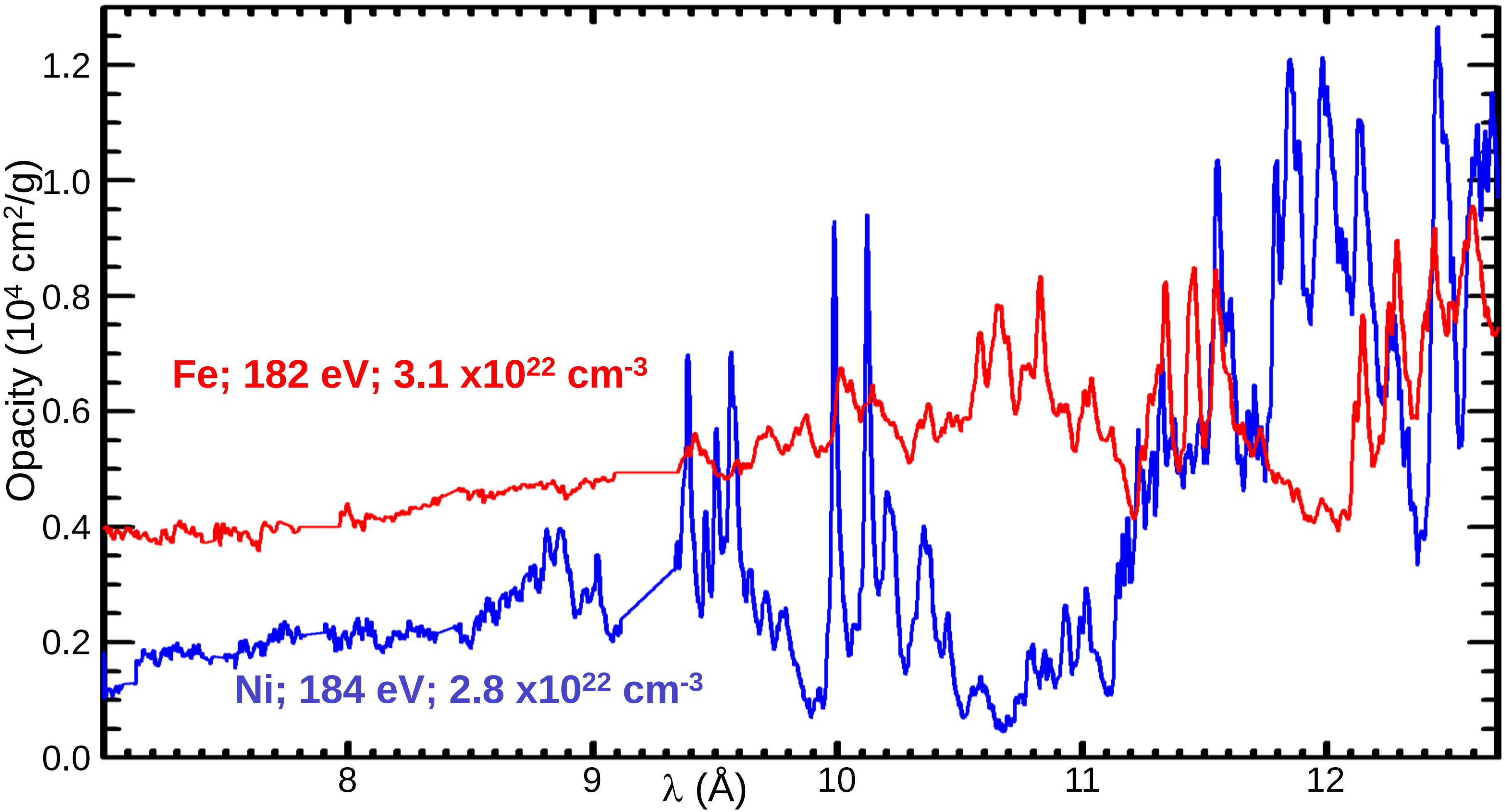
Opacity from transitions with an open L-shell may be more complex to model

The fractional excited state population increases as the atomic number decreases

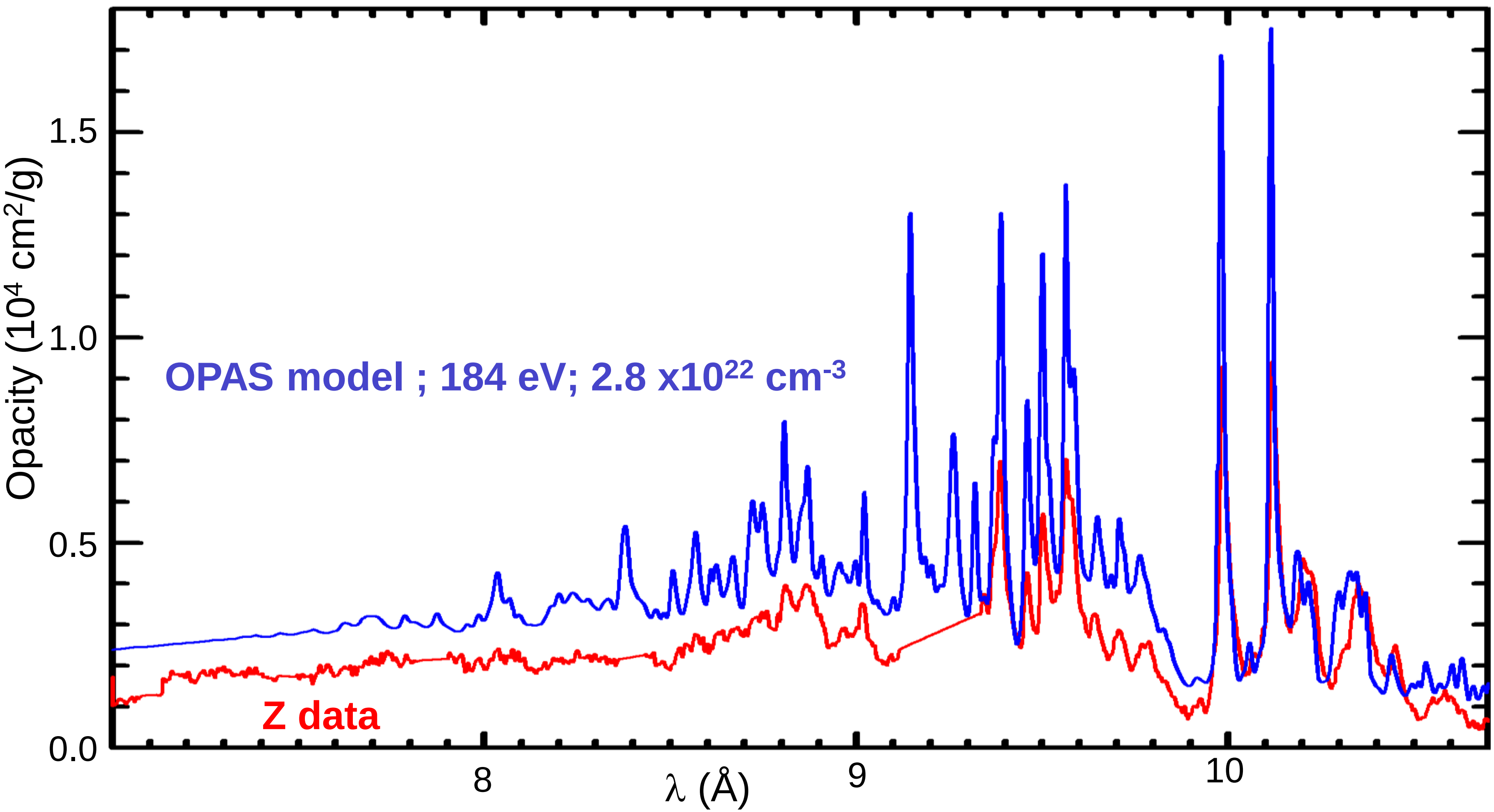


Opacity from ions with high excited state populations may be more complex to model
These difficulties increase as atomic number decreases

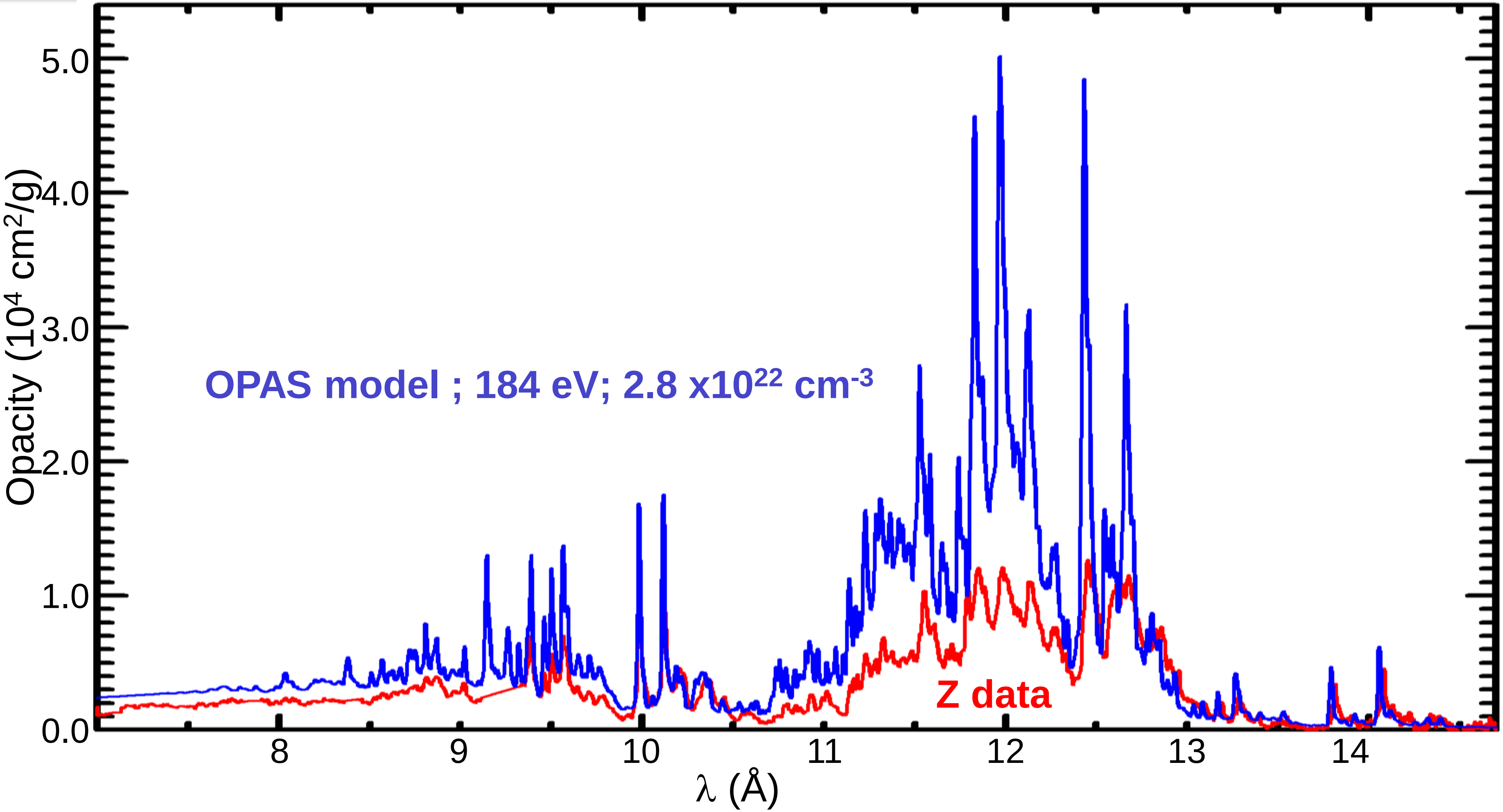
Preliminary Ni data shows the high T_e/n_e experiment platform is capable of measuring sharp spectral features



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

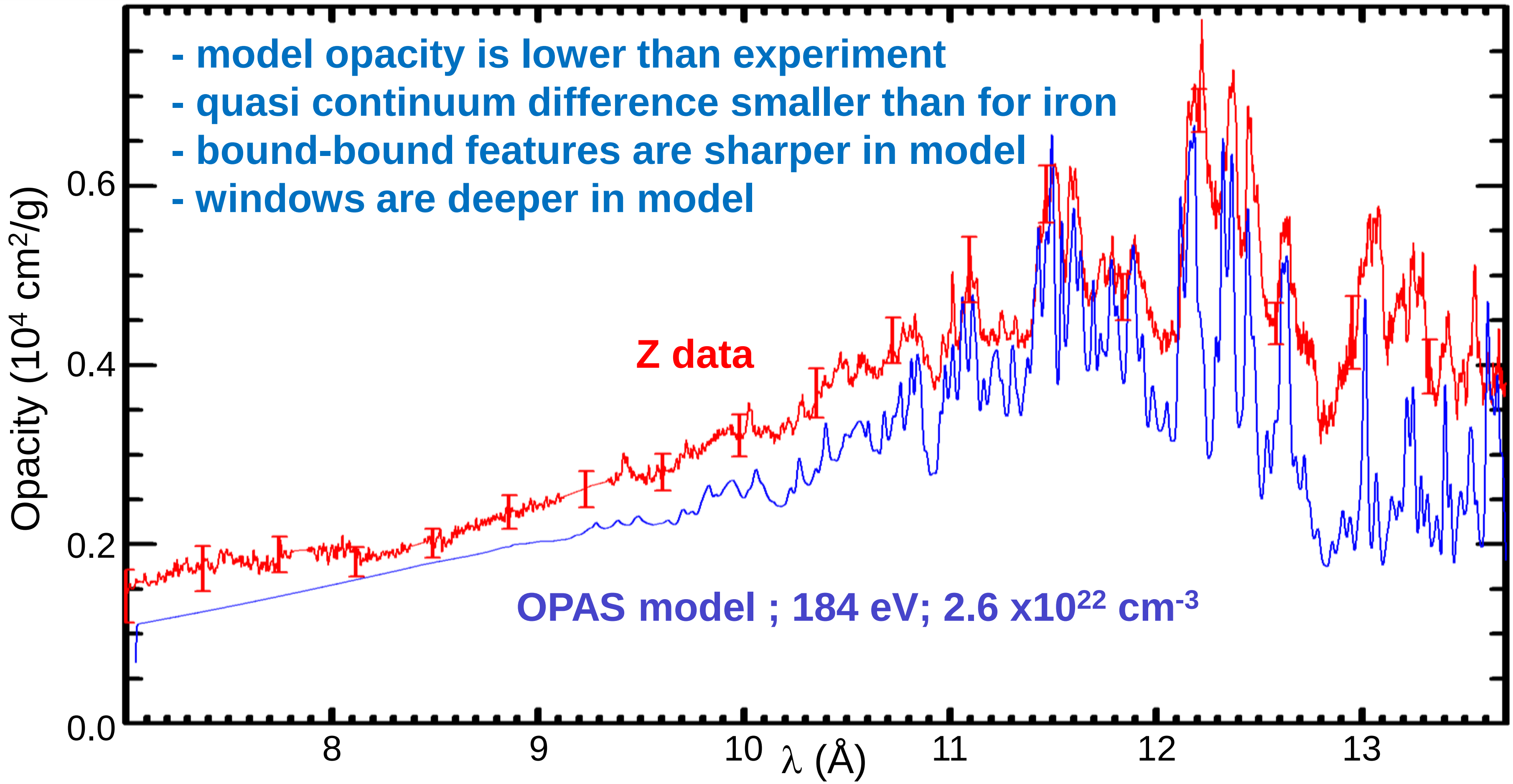


Predictions for Ni opacity in the 2p-3d spectral region are approximately 2x larger than preliminary measurements



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 generally supports the iron data validity
New questions, insights, and model constraints will certainly arise as we finalize the measurements

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

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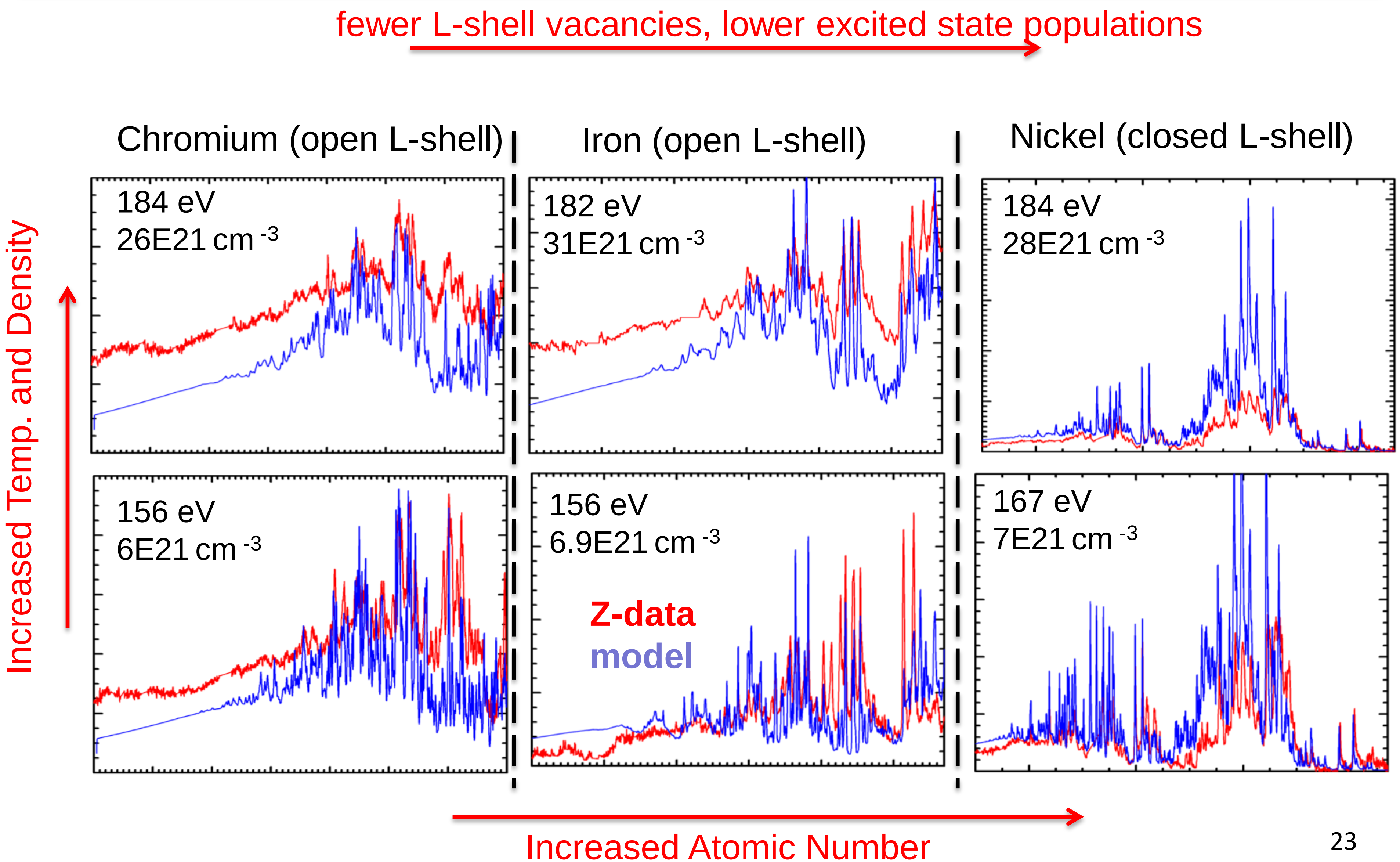

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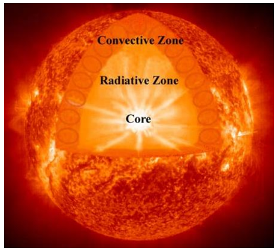

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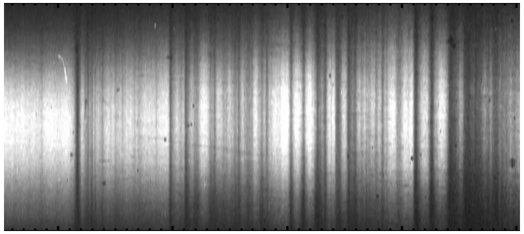

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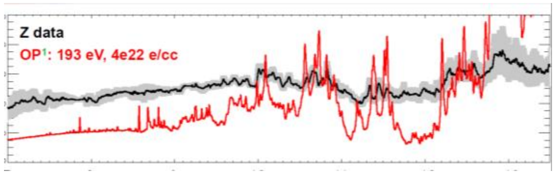

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