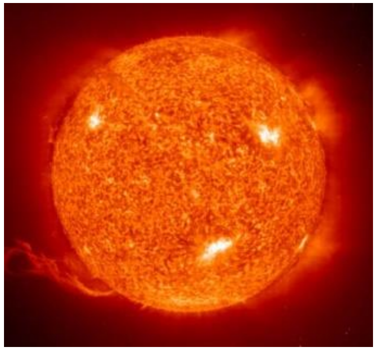
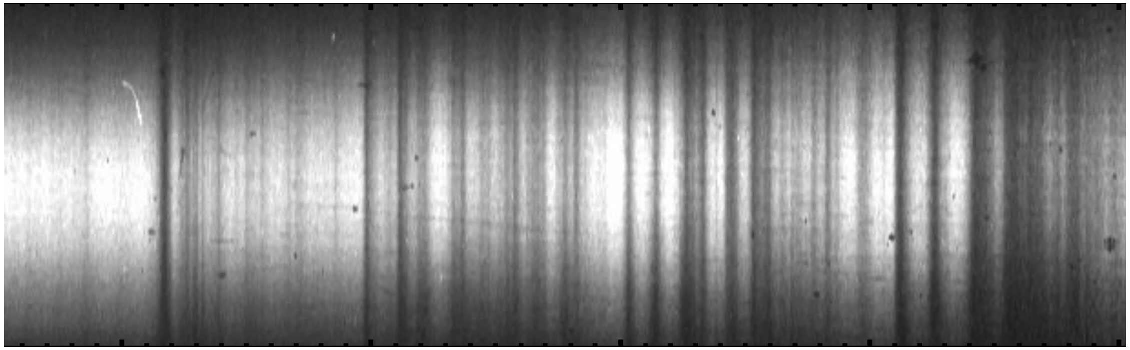
Exceptional service in the national interest

SAND2015-9353PE

Sandia National Laboratories





Measuring the opacity of stellar interior matter in terrestrial laboratories

Jim Bailey

Sandia National Laboratories

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

Sandia National Laboratories

J.E. Bailey, T. Nagayama, G.P. Loisel, G.A. Rochau, S.B. Hansen
Sandia National Laboratories, Albuquerque, NM, 87185-1196

C. Blancard, Ph. Cosse, G. Faussurier, F. Gilleron, J.-C. Pain
CEA, France

A.K. Pradhan, C. Orban, and S.N. Nahar
Ohio State University, Columbus, Ohio, 43210

C.A. Iglesias and B. Wilson
Lawrence Livermore National Laboratory, Livermore, CA, 94550

J. Colgan, C. Fontes, D. Kilcrease, and M. Sherrill
Los Alamos National Laboratory, Los Alamos, NM 87545

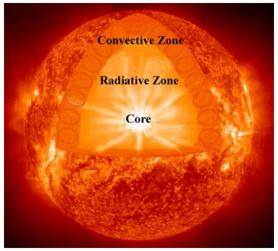
J.J. MacFarlane, I. Golovkin
Prism Computational Sciences, Madison, WI

R.C. Mancini
University of Nevada, Reno, NV

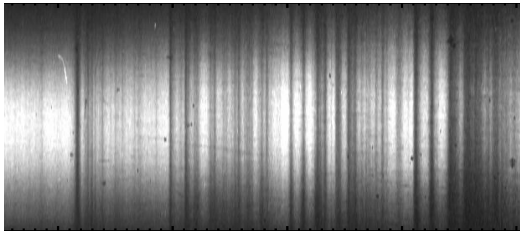
Z iron opacity experiments refine our understanding of the sun.

Sandia National Laboratories

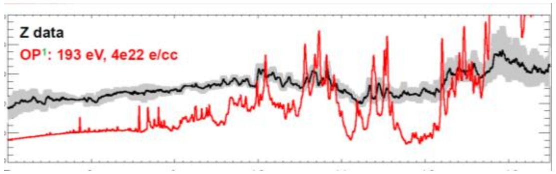
- **Solar interior predictions don't match helioseismology**
  - → **Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?**



- **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**



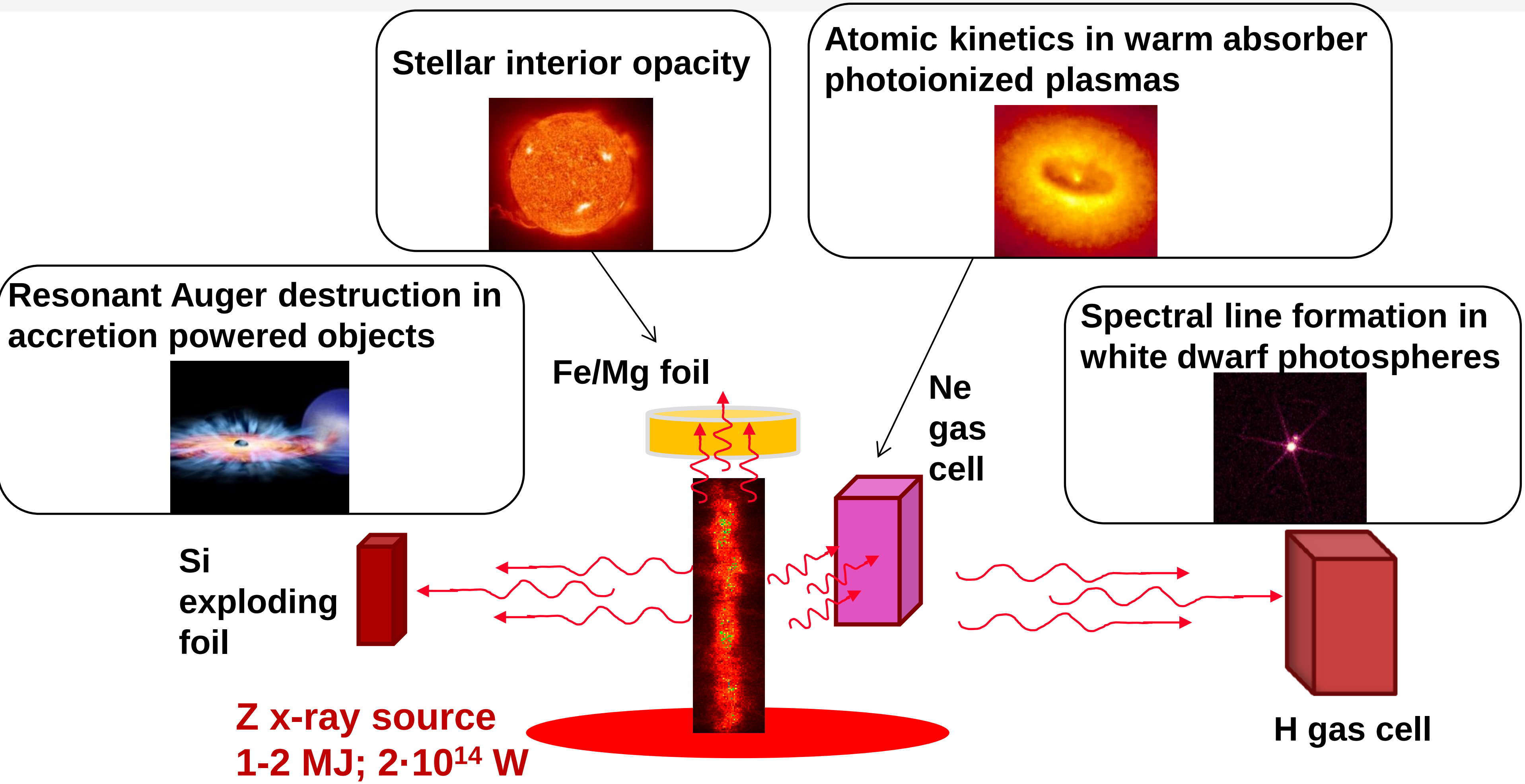
- **Opacity models disagree with measurements at near-solar-interior conditions**
  - → **The solar Rosseland mean opacity is ~ 7% higher using Z iron data instead of OP calculations**



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

Bailey et al., *Nature* 2015

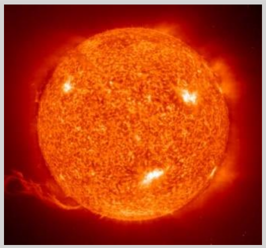
Stellar opacity experiments are one of four topics investigated within the Z Astrophysical Plasma Properties (ZAPP) collaboration



- Multiple physics experiments on each shot
- Crucial for progress on oversubscribed MJ-class facility

ZAPP campaigns simultaneously study multiple issues spanning 200x in temperature and 10^6x in density

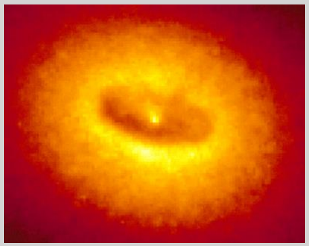
Solar Opacity



Question:
Why can't we predict the location of the convection zone boundary in the Sun?

Achieved Conditions:
T_e ~ 200 eV, n_e ~ 10^{23} cm^{-3}

Photoionized Plasmas



Question:
How does ionization and line formation occur in accreting objects?

Achieved Conditions:
T_e ~ 20 eV, n_e ~ 10^{18} cm^{-3}

White Dwarf Line-Shapes

Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

Acheived Conditions:
T_e ~ 1 eV, n_e ~ 10^{17} cm^{-3}

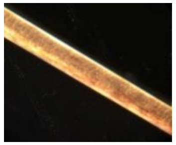
What is new:
Mega-Joule class facilities create *macroscopic enough* quantities of astrophysical matter for detailed studies

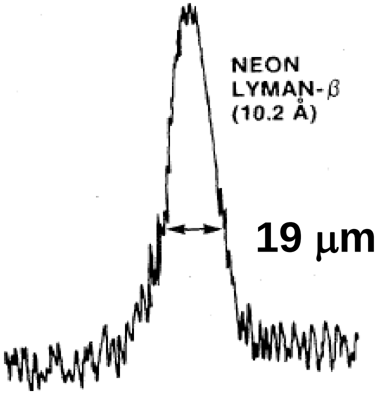
Sandia National Laboratories

High Energy Density experiments have reached extreme conditions for many years

But small size, spatial structure, and short duration hampered material property measurements

Typical size scale ~ human hair





laser fusion capsule
(Yaakobi, PRL, 1977)
300 eV, 0.26 g/cc

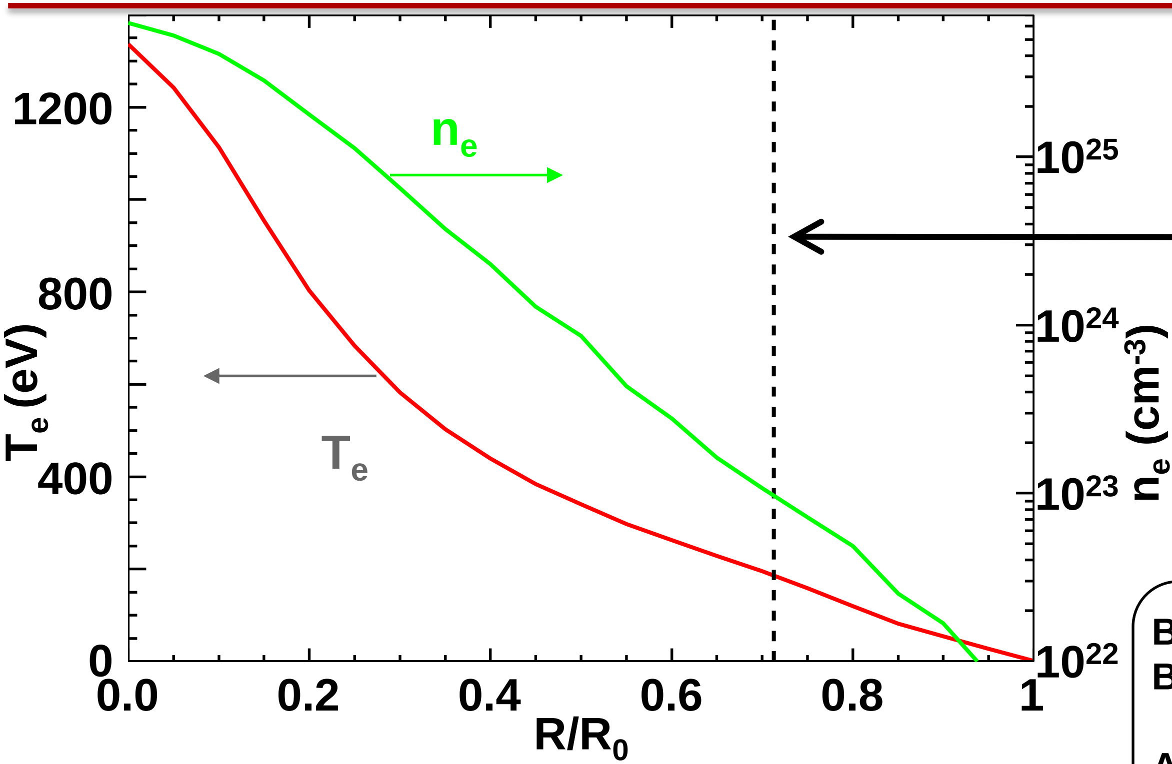
Z opacity samples are similar in size to a ~ 1 mm sand grain

Z White Dwarf samples are similar in size to a phone (~ 100 cm^3)

Creating mm-scale replicas of cosmic matter will strengthen the laboratory foundation of astrophysics

Motivation

Standard solar model predictions of the solar structure disagree with helioseismology



radiation | convection

- predicted boundary location different from measured {~ 10-20 σ difference}

Density and sound speed structure are also very different

Bahcall et al, ApJ (2004)
Basu & Antia Physics Reports 2008

Asplund et al Ann Rev AA (2009)
Christensen-Dalsgaard et al A&A (2009)

- Boundary location depends on radiation transport
- A 1% opacity change leads to observable changes.

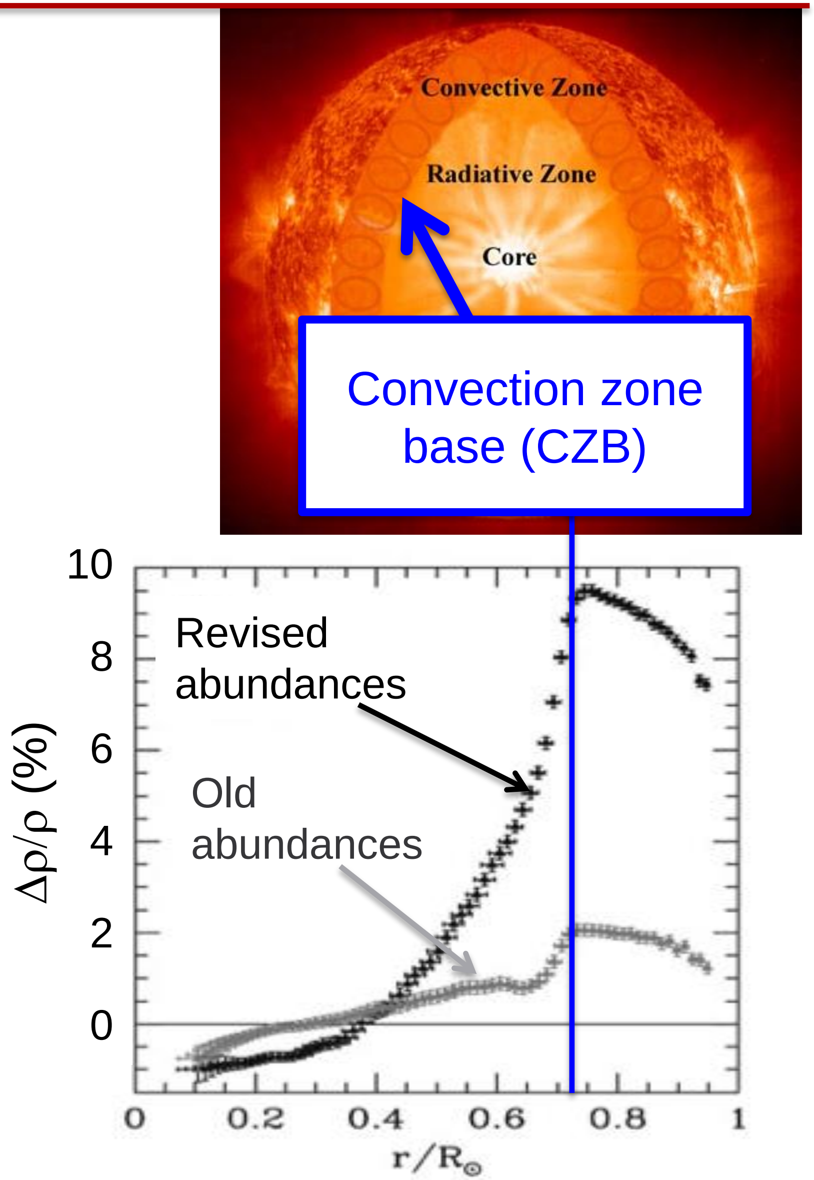
The disagreement arose after the solar abundance revision that began in 2000

Sandia National Laboratories

- Standard solar model (simulation)
  Inputs:
  - Abundance
  - EOS
  - Opacity
  - Etc.
- Helioseismology (measurements)

- Solar abundance revision [Asplund 2005]
  C, N, O, Ar, Ne → lowered by 35-45%
- Now, standard solar model disagrees with helioseismic measurements

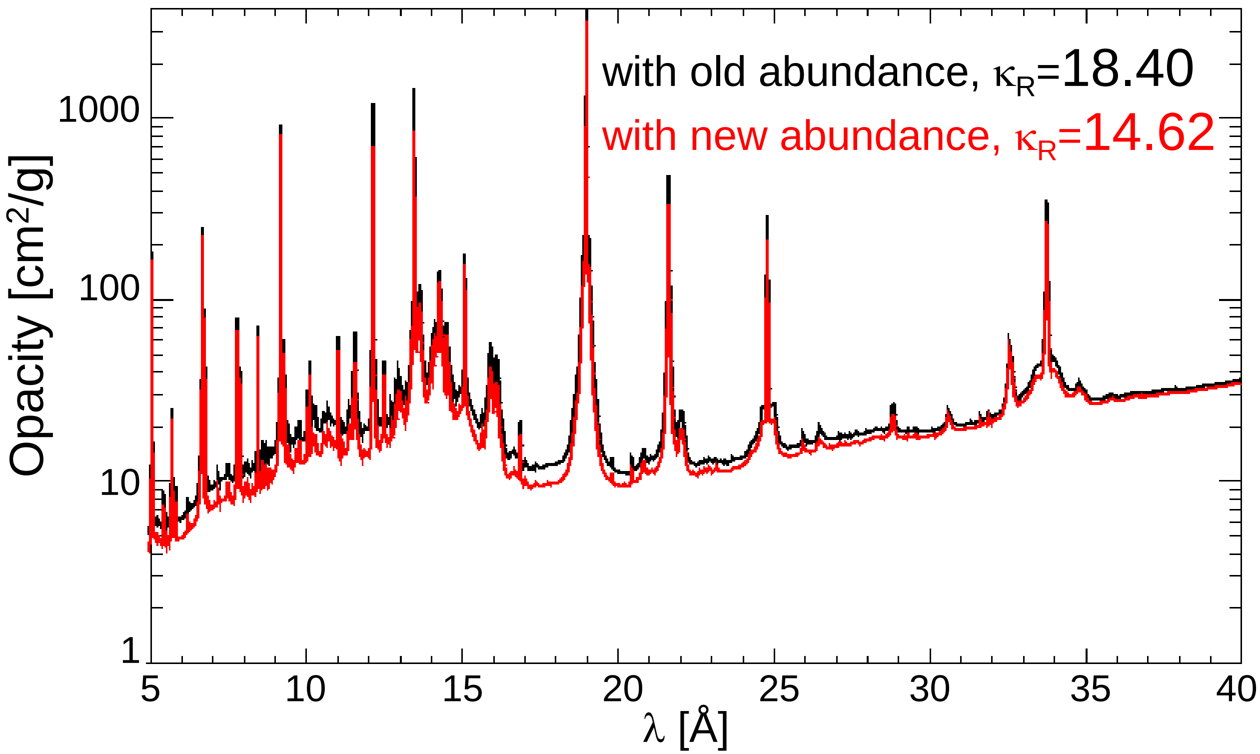
  CZB location: 1σ → 13-30 σ

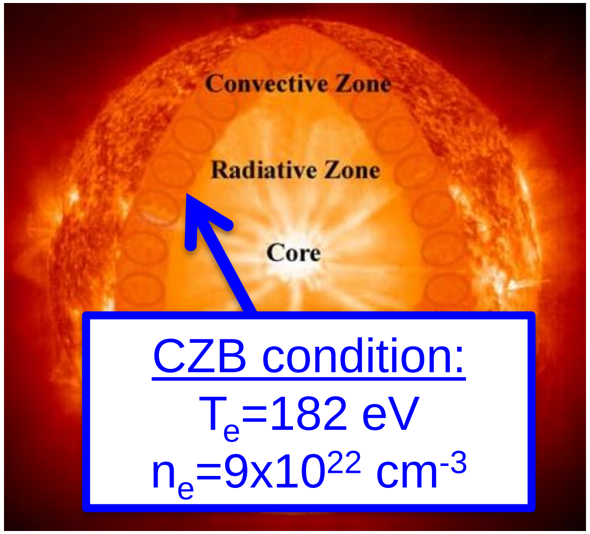


S. Basu *et al*, Physics Reports (2008). M. Asplund *et al*, Annu. Rev. Astro. Astrophys. (2005).

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

Solar mixture opacity at Convection Zone Base (CZB)





Rosseland mean opacity → heat transfer by radiation

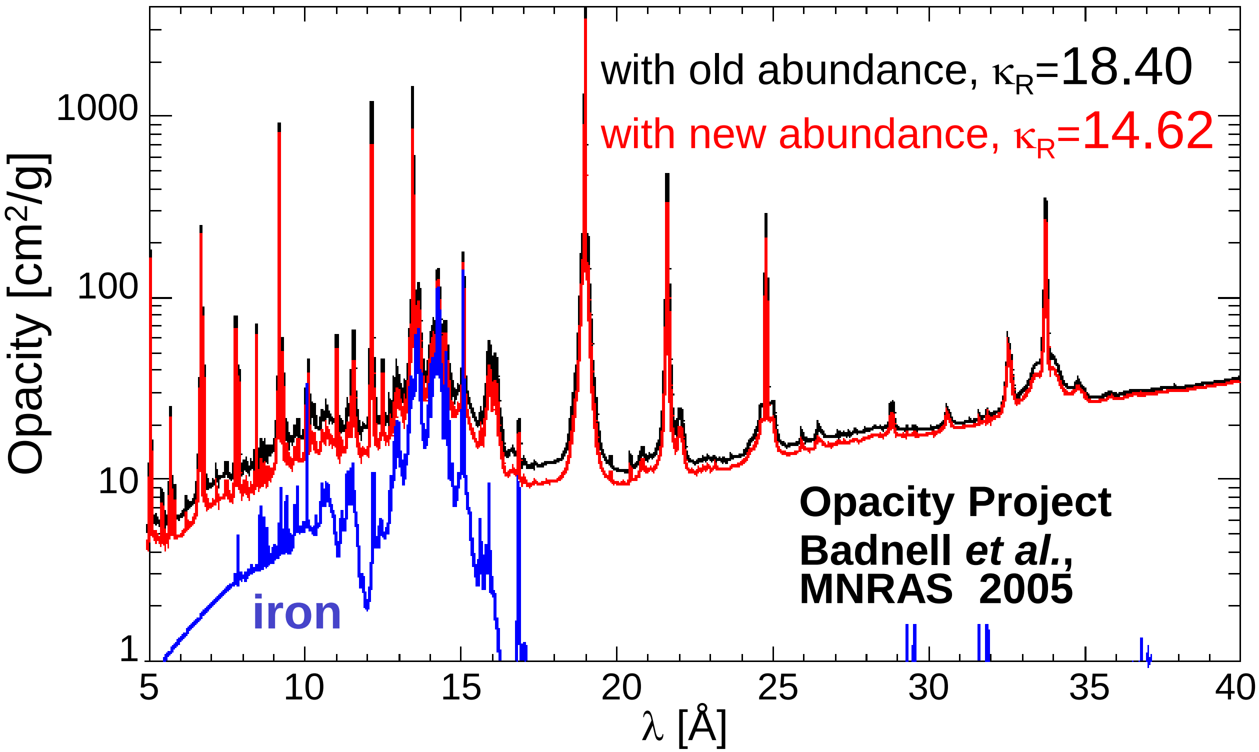
$$\frac{1}{\kappa_R} = \int \frac{1}{\kappa_\nu} \frac{\partial B_\nu}{\partial T} d\nu \Big/ \int \frac{\partial B_\nu}{\partial T} d\nu$$

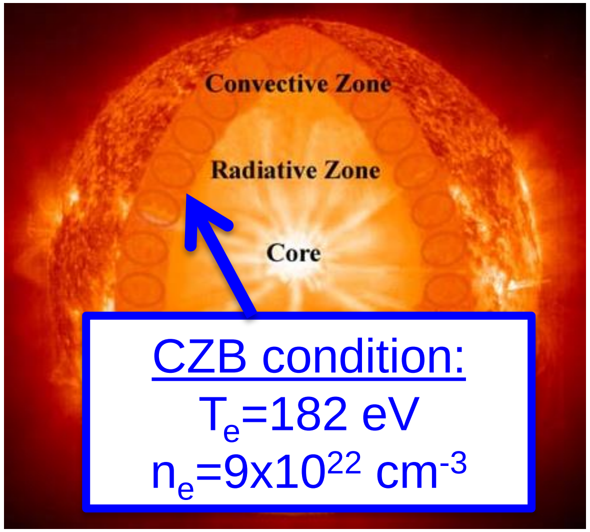
Photons are transported in opacity windows

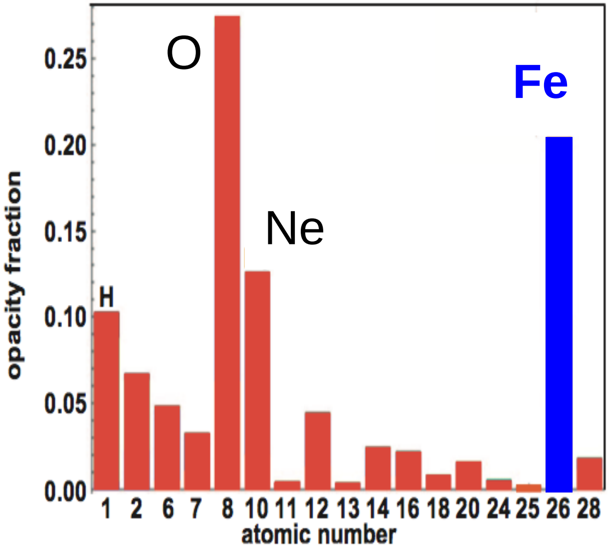
Iron opacity measurements can help determine if opacity model inaacuracies cause the solar problem

Sandia National Laboratories

Solar mixture opacity at Convection Zone Base (CZB)







CEA OPAS calculation

Iron contributes about 20% of the total solar opacity at the convection/radiation boundary

J.E. Bailey *et al*, Phys. Plasmas (2009).

What physics is a concern for opacities?

Photon absorption in plasma depends on multiple entangled physical processes

Attenuation is caused by photon interactions with bound and free electrons:

- bound-bound
- bound-free
- free-free
- scattering

These interactions depend on :

- Charge state distribution
- Energy level structure and completeness
- Multiply-excited states
- Autoionizing levels
- Photoionization
- Line broadening
- Continuum lowering

Opacity depends on:

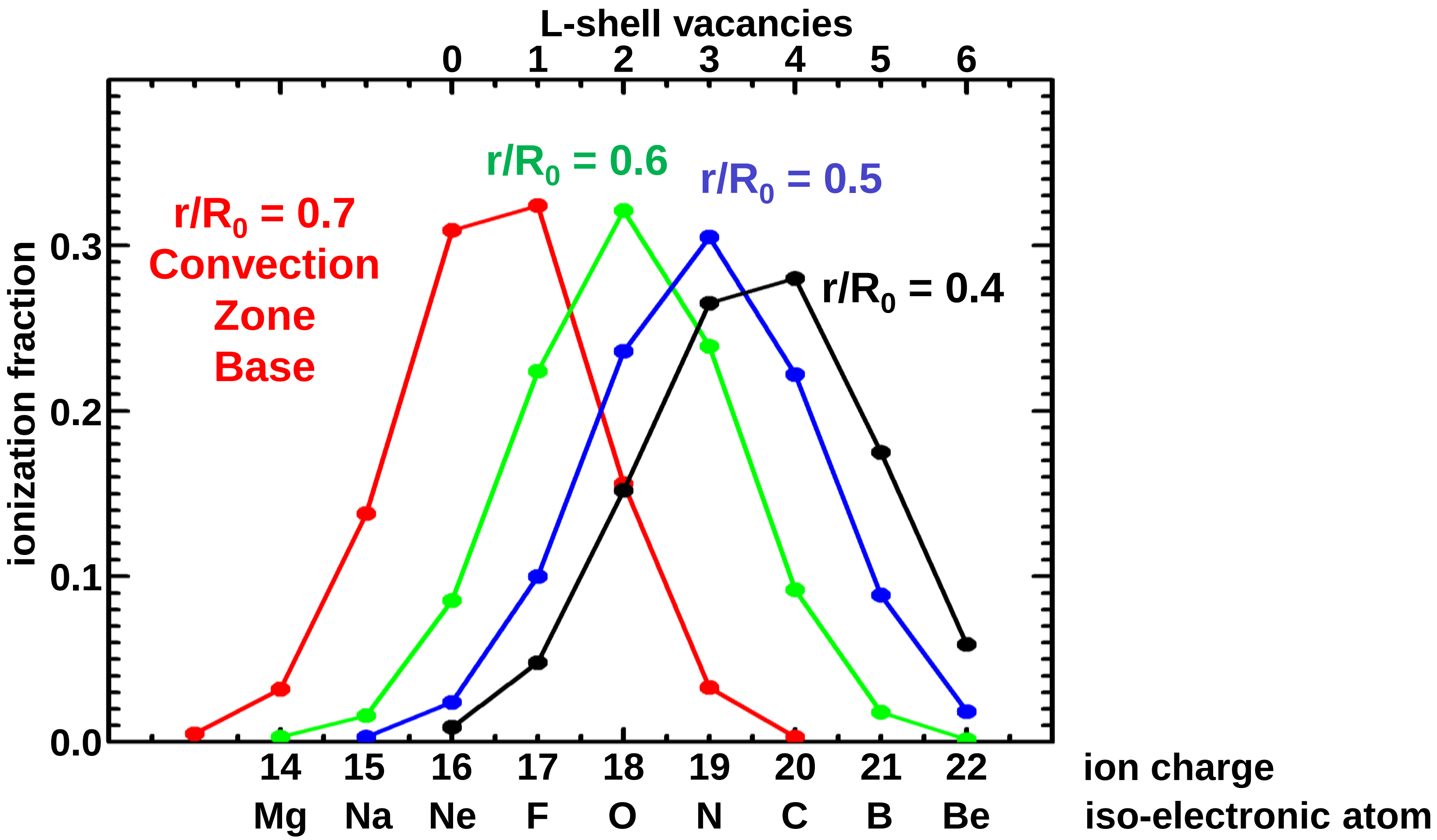
Charge state distribution

Energy level structure

Energy level populations

Plasma effects (line broadening, continuum lowering)

Iron charge states with L-shell vacancies exist throughout most of the solar radiation zone



Opacity depends on the ionization state because it controls the possible bound-bound and bound-free absorption

Opacity depends on:

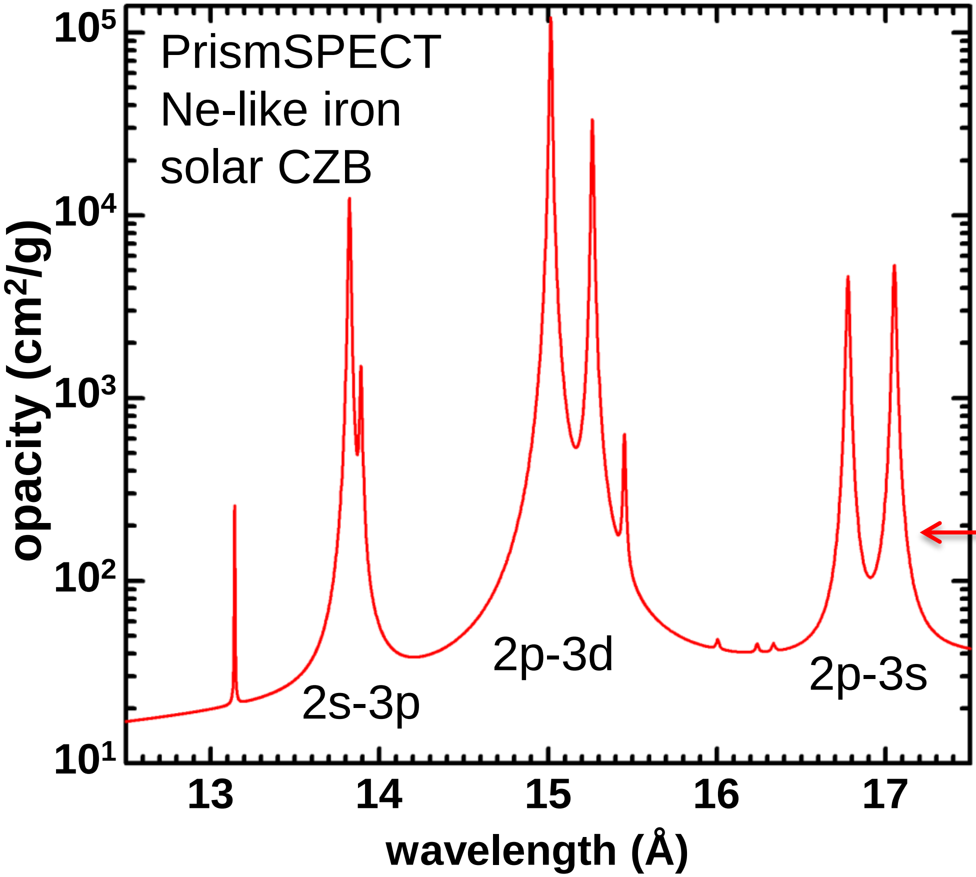
Charge state distribution

Energy level structure

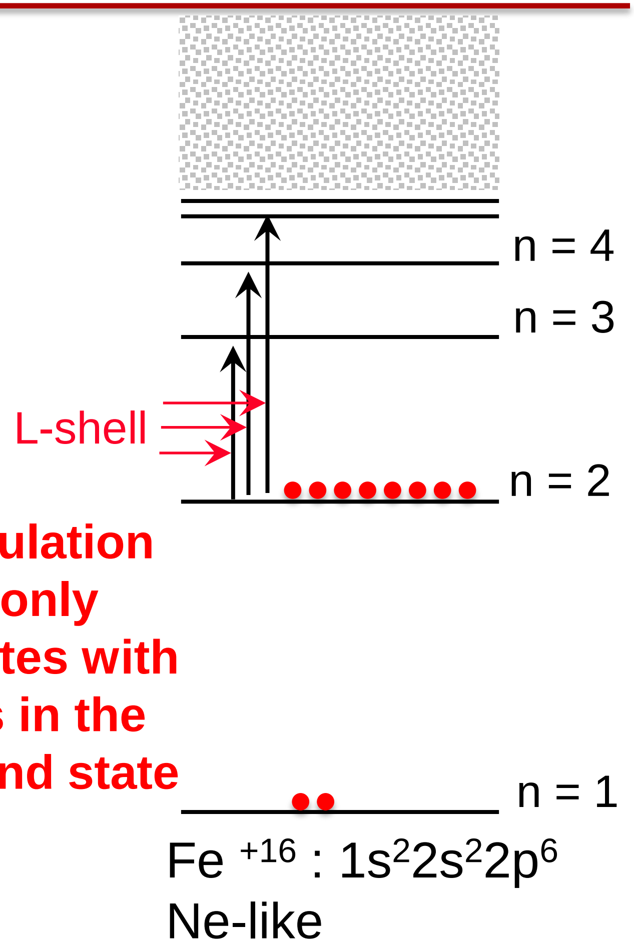
Energy level populations

Plasma effects (line broadening, continuum lowering)

The neon-like iron closed-shell ground state contributes a relatively simple opacity spectrum



This calculation includes only initial states with electrons in the n=2 ground state



Opacity depends on:

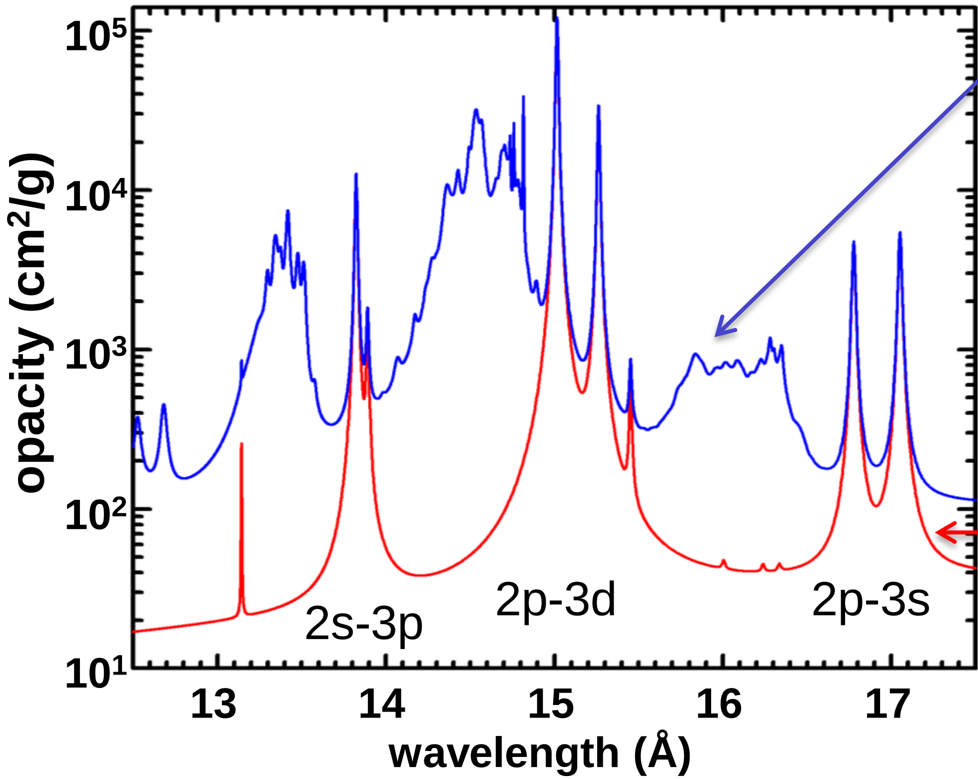
Charge state distribution

Energy level structure

Energy level populations

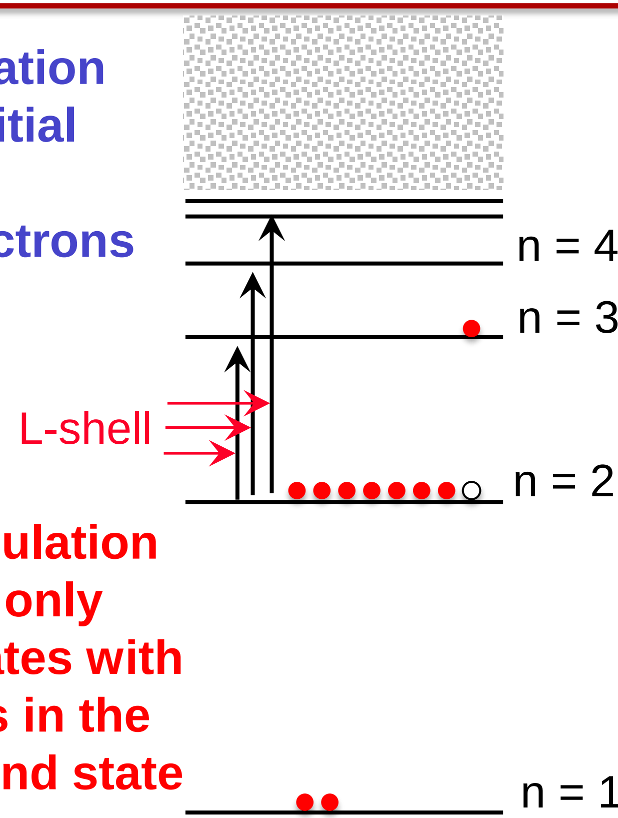
Plasma effects (line broadening, continuum lowering)

Excitations produce vacancies in the L-shell, adding complexity to Ne-like iron opacity



This calculation includes initial states with excited electrons

This calculation includes only initial states with electrons in the n=2 ground state

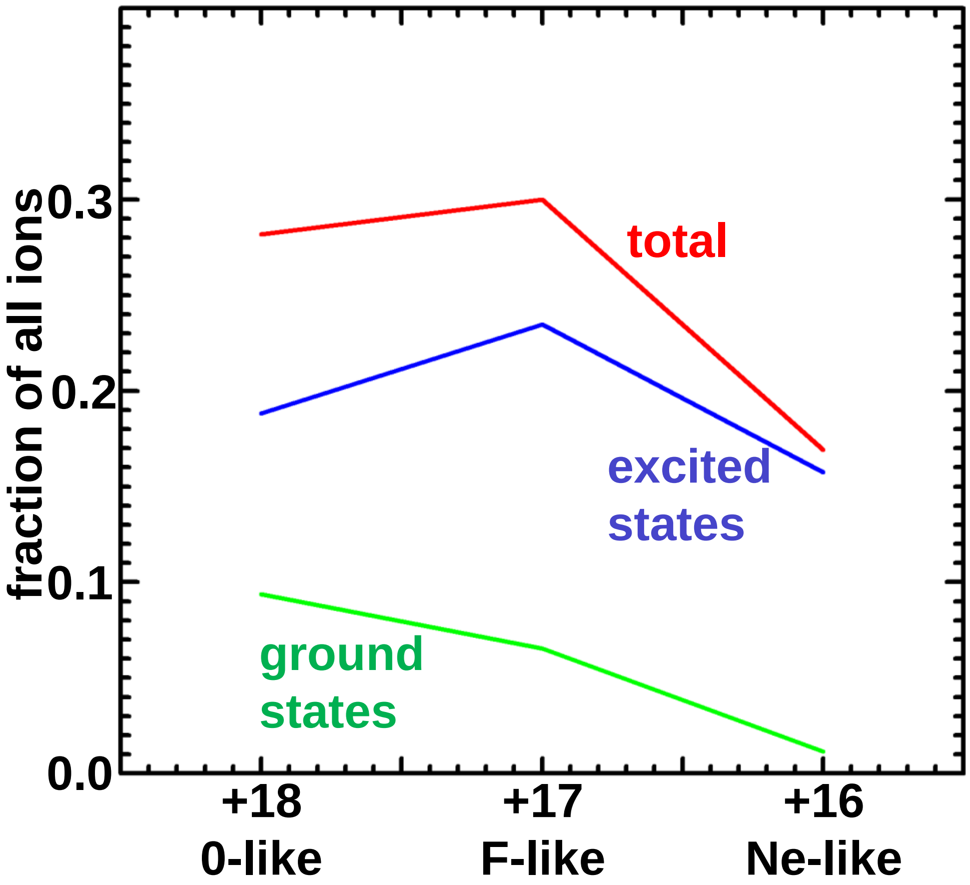


Fe $^{+16}$: $1s^2 2s^2 2p^6$
Ne-like

Complexity increases because the number of angular momentum combinations increases

Excited state transitions fill in the windows between the lines, inhibiting photon transport

Excited states prevail in iron at solar interior conditions



Iron at 195 eV, 4e22 electrons/cc
SCRAM calculation

Example: Ne-like iron at CZB
excited state fraction = 93%
ground state fraction = 7%

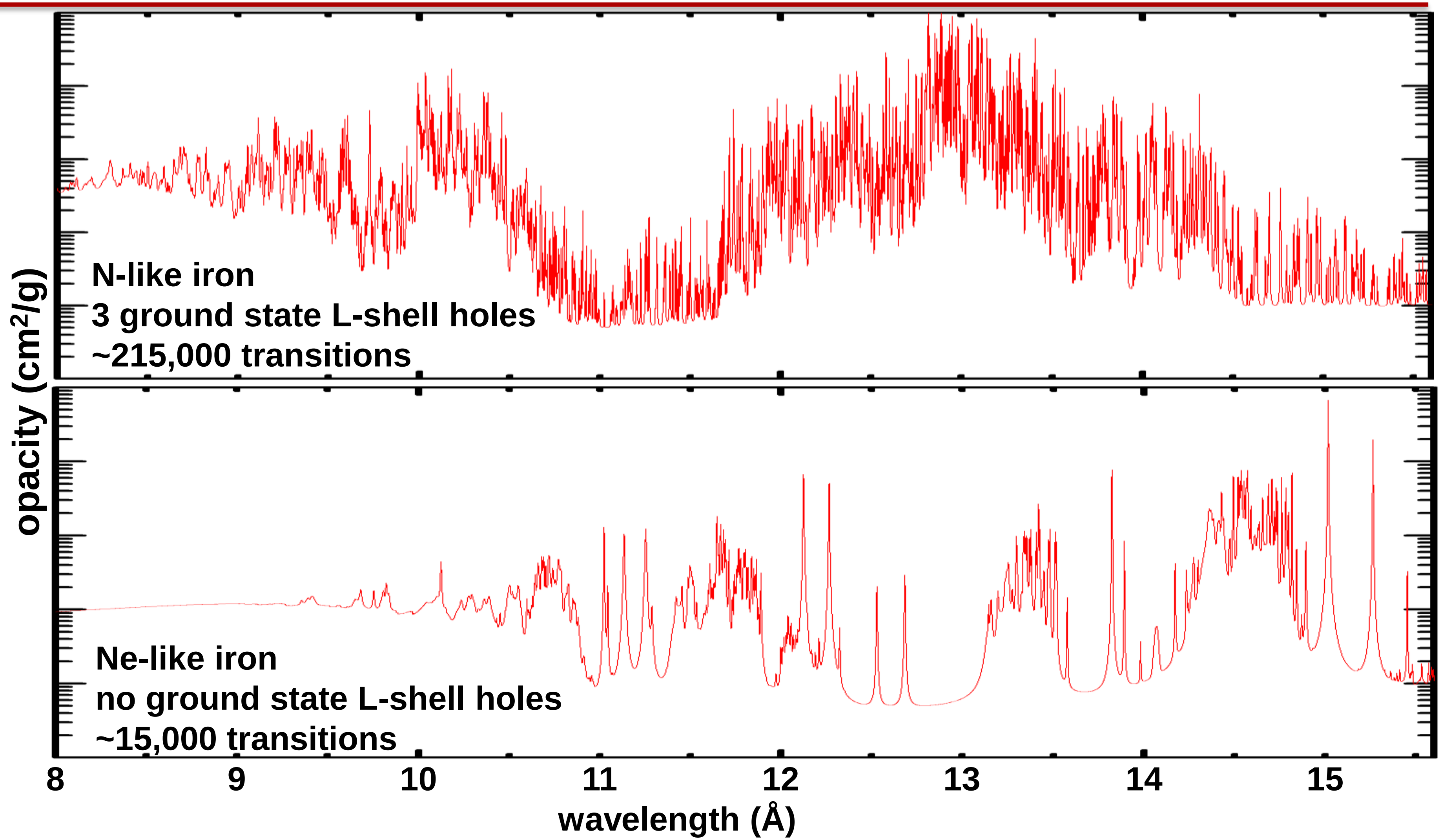
Implies a ~3% increase in excited state population causes ~40% decrease in ground state population

i.e., 40% decrease in lines originating from ground state

Challenge:
Accurate energy level description required for *all* excited states

Plasma effects more easily modify excited states

Partially-filled L-shell charge states are more complex because the number of angular momentum combinations increases



PrismSPECT, iron at CZB conditions

These calculations used reduced line broadening to limit line blending

Opacity depends on:

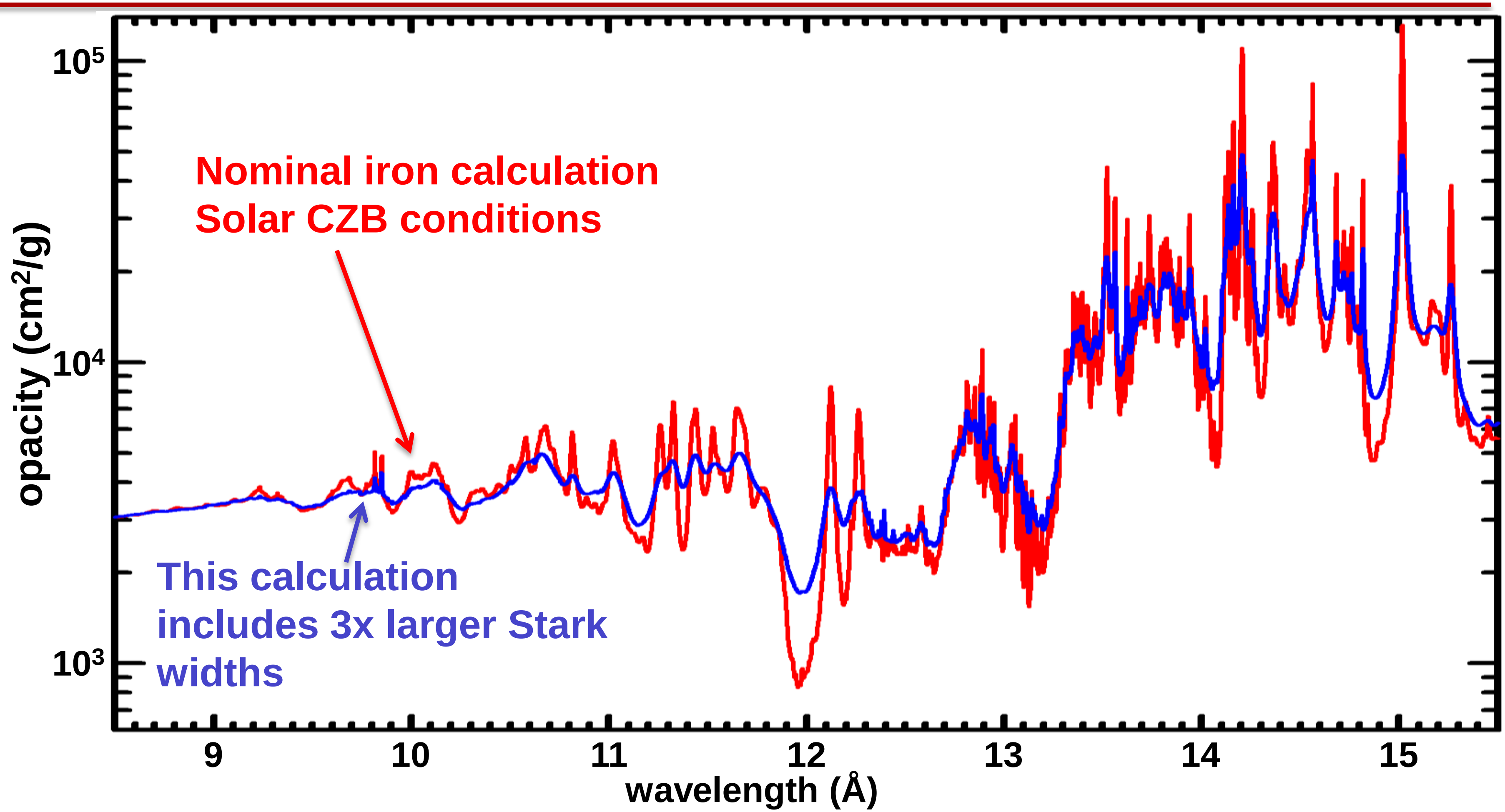
Charge state distribution

Energy level structure

Energy level populations

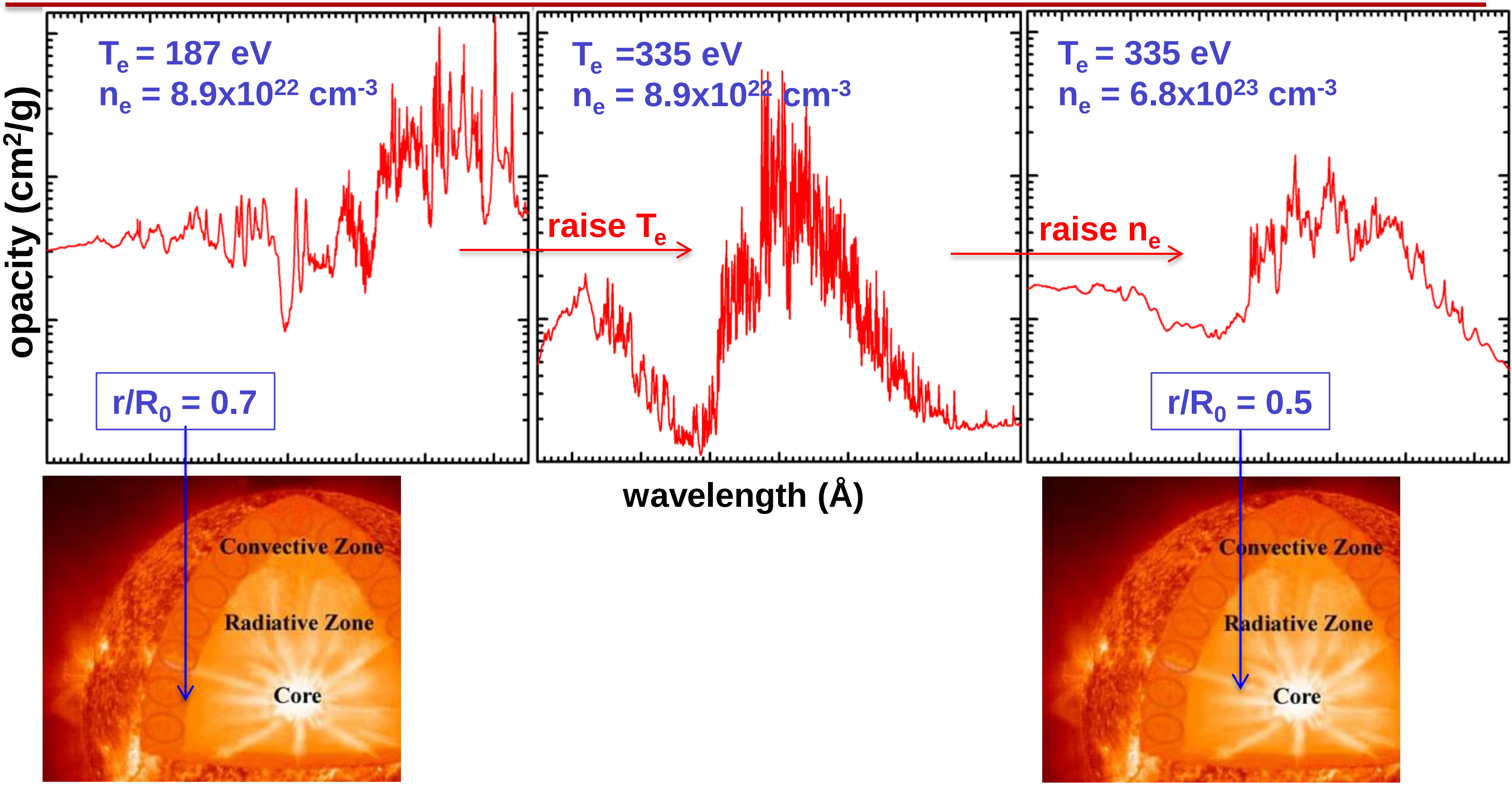
Plasma effects (line broadening, continuum lowering)

Line broadening affects the photon transport because it closes the windows between the lines



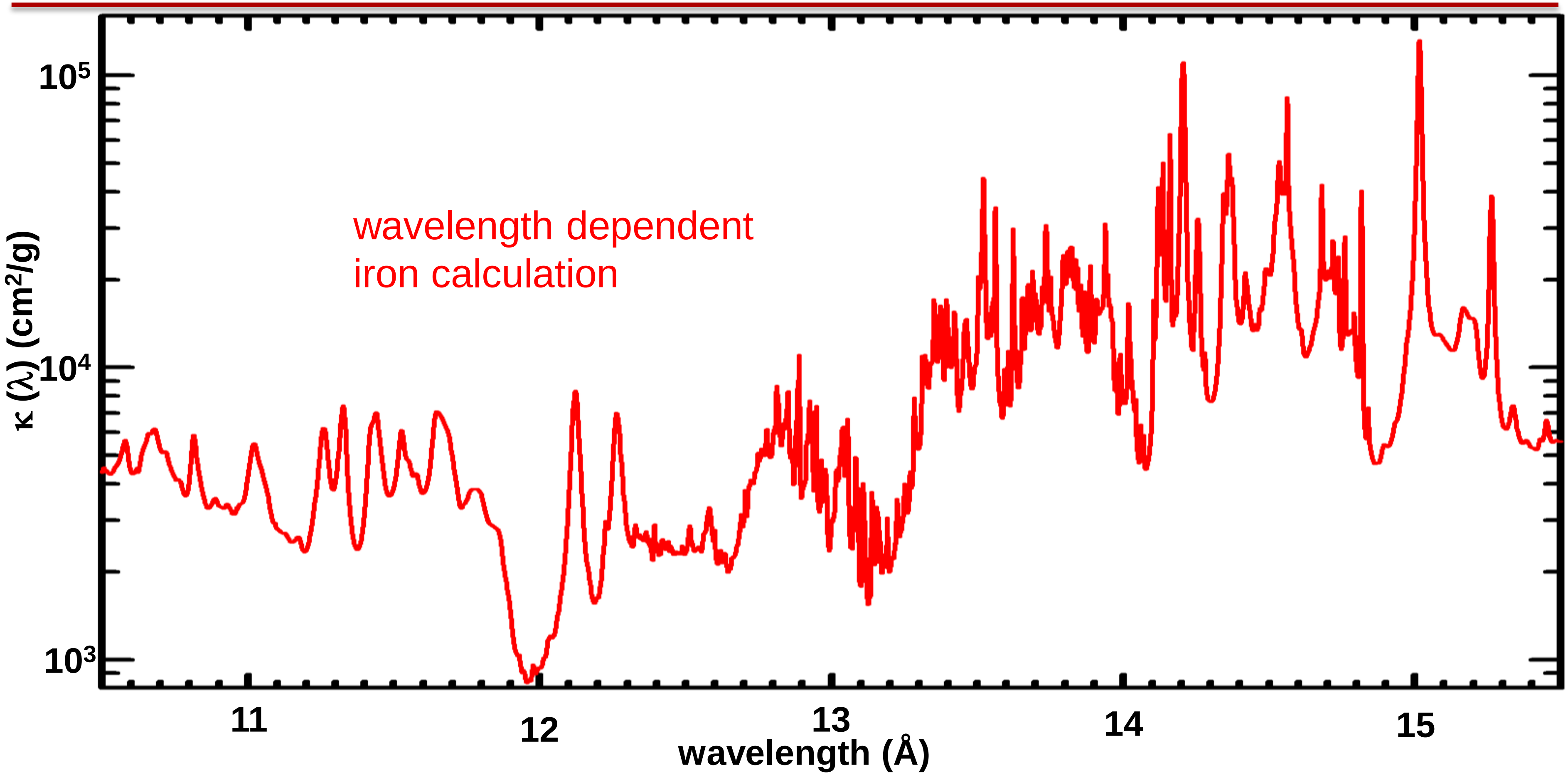
All opacity models for stars use approximations for line broadening that are untested at stellar interior conditions

Complexity grows as the solar radius shrinks and solar interior temperature and density increase



Complexity increases because the number of angular momentum combinations and plasma effects both increase

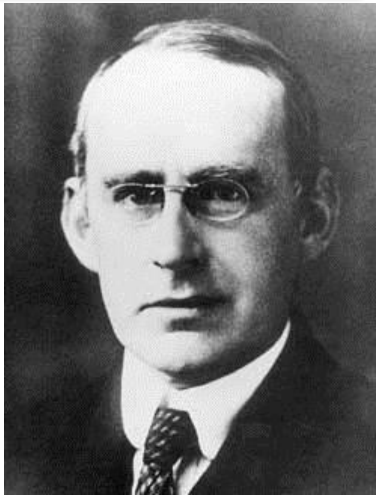
Strategy: wavelength-dependent transmission measurements test opacity model physics



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

How do we perform opacity measurements?

The importance of stellar opacity was recognized nearly a century ago, but no laboratory measurements have been done up to now. Why?



Eddington, “The Internal Constitution of the Stars”, 1926

High transmission accuracy is needed since
$\tau = -\ln(T)$ and $\delta\tau/\tau = (1 / \ln\{T\})\, \delta T/T$
e.g., if $\delta T/T \sim 5\%$ and $T \sim 0.7$, then $\delta\tau/\tau \sim 15\%$

<u>High accuracy requires:</u>
Macroscopic samples uniformly heated to stellar interior conditions
Backlight bright enough to overcome emission at stellar interior temperatures

<u>Stellar opacity measurements are possible for the first time:</u>
MegaJoule class facilities like Z and NIF
3 decades of opacity research at smaller scale facilities to hone our approach
Advanced plasma diagnostic techniques

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 (~ ± 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 how suitable the LTE approximation is
9. Multiple T_e, n_e 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

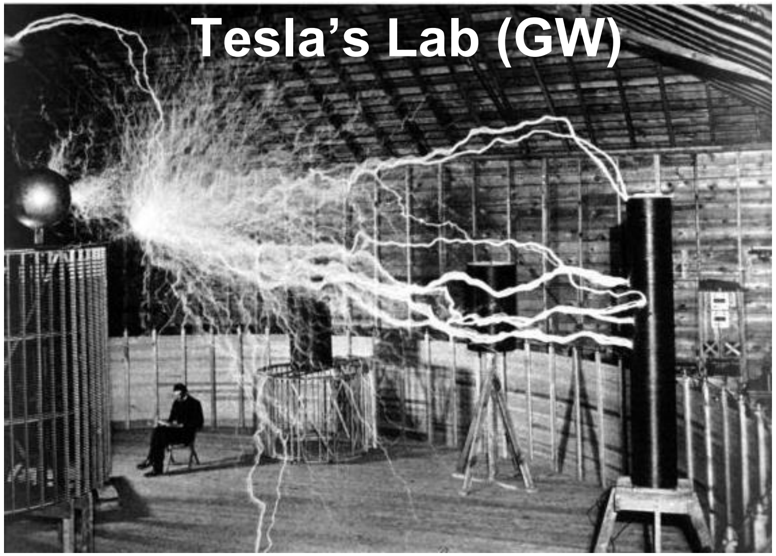
Foster *et al.* Phys. Rev. Lett. 1991

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

Springer *et al.* JQSRT 1997

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

ZAPP experiments use the Z machine to create energetic and powerful x-ray sources


Tesla's Lab (GW)


Z facility (100 TW)

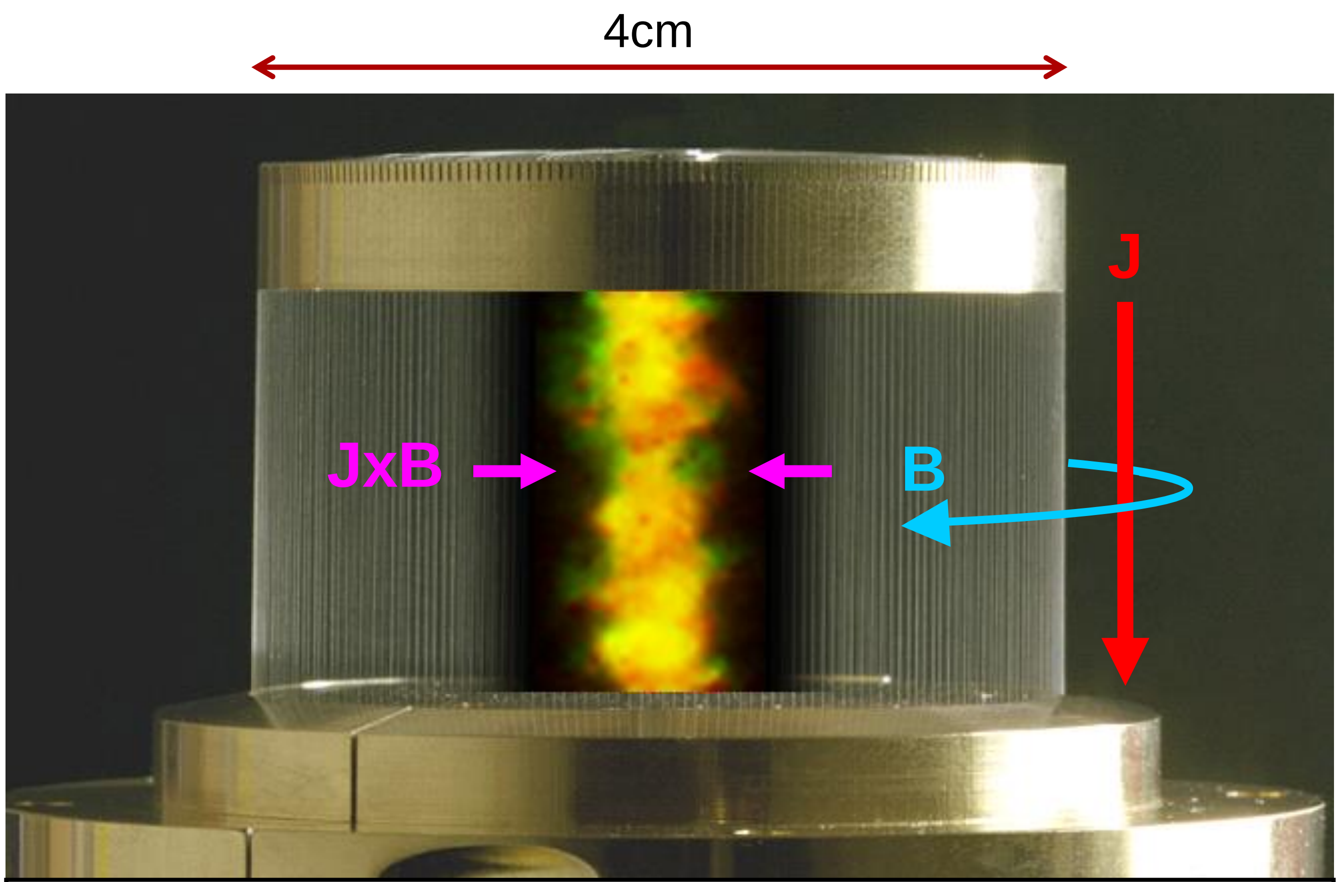
- **Pulsed power has been developed over the last century**
- **Large magnetic fields or large x-ray fluxes create extreme environments**

Goal: "Take the equivalent energy required to operate a TV for a few hours (1-2 MJ) and compress it into more electrical power than provided by all the power plants in the world combined (~15 TW)"

…S T Pai & Qi Zhang, "Introduction to High Power Pulse Technology," World Scientific Publishing Co., Singapore, 1995.

**Sanford, PoP 9 (2002); Bailey et al,PoP 13 (2006); Slutz et al., PoP 13 (2006); Rochau et al., PPCF 49 (2007)*

We use the Z machine to create energetic and powerful x-ray sources

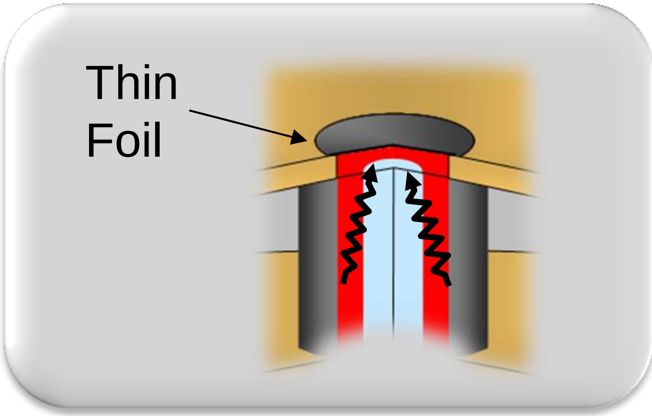


P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)
~ 8% wall plug efficiency

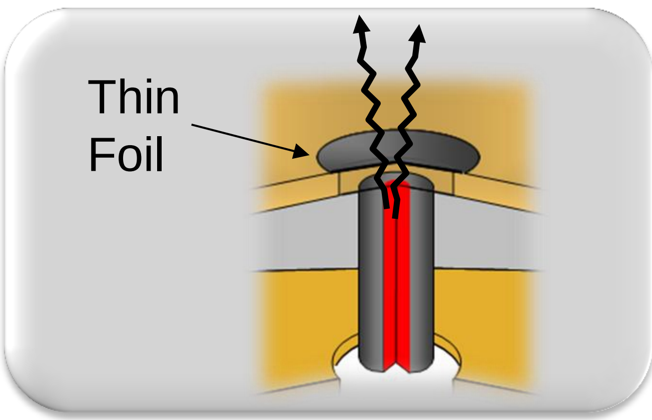
**Sanford, PoP 9 (2002); Bailey et al,PoP 13 (2006); Slutz et al., PoP 13 (2006); Rochau et al., PPCF 49 (2007)*

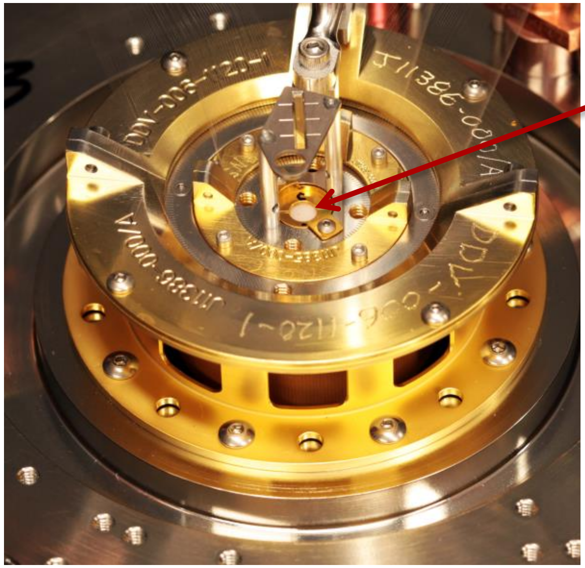
The Z-Pinch dynamic hohlraum is used to both heat and backlight samples to stellar interior conditions.

Foil is heated during the ZPDH implosion



Foil is backlit at shock stagnation

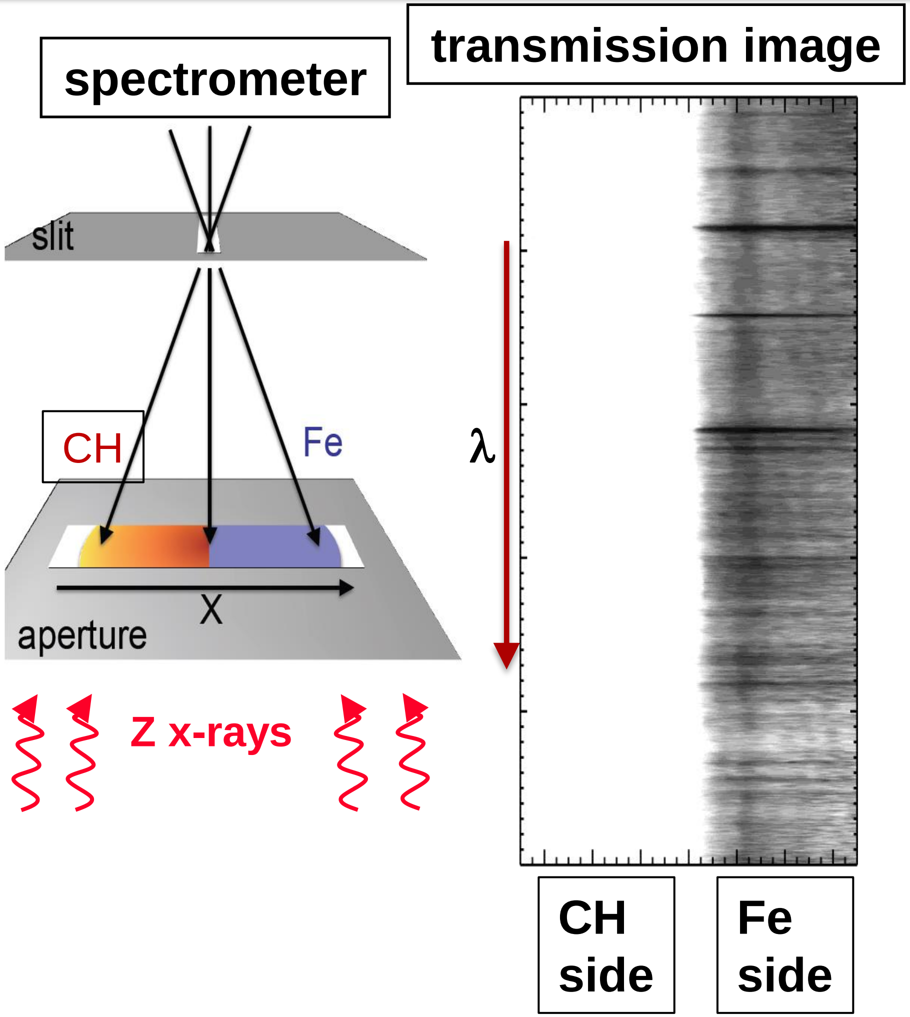




P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)
~ 8% wall plug efficiency

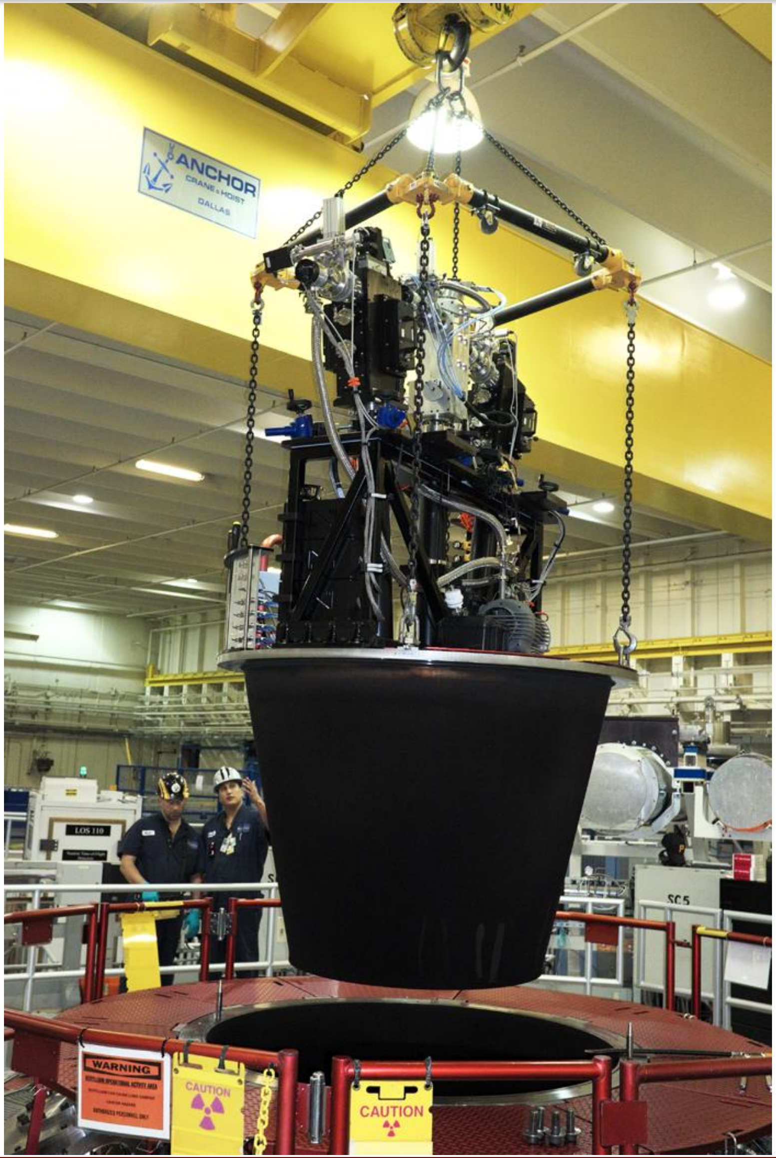
Bailey et al., Physics of Plasmas (2009)
Nash et al., Rev. Sci. Instrum (2014)
Nagayama et al., Physics of Plasmas (2014)
Nagayama et al., Rev. Sci. Instrum (2014)

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



half-moon samples enable transmission determination from single experiments

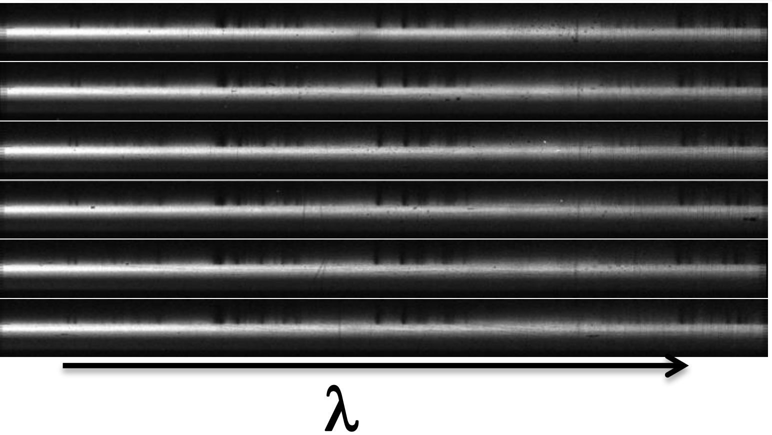
Opacity data are recorded with an array of crystal spectrometers



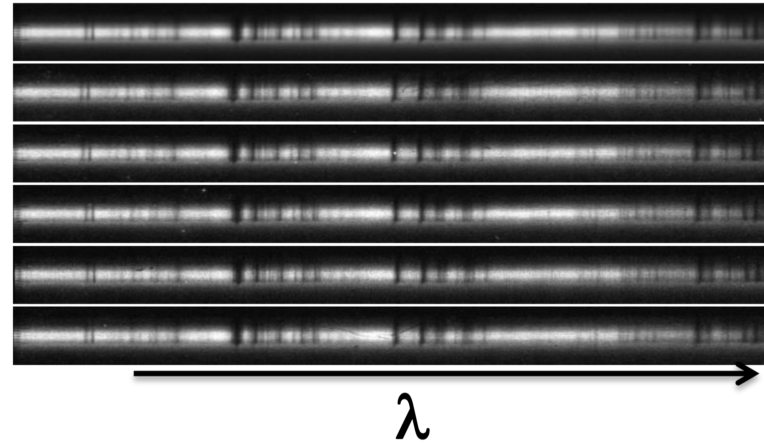
The array of opacity spectrometers is lowered into place with a 20 ton crane

Loisel et al., Rev. Sci. Instrum (2012)

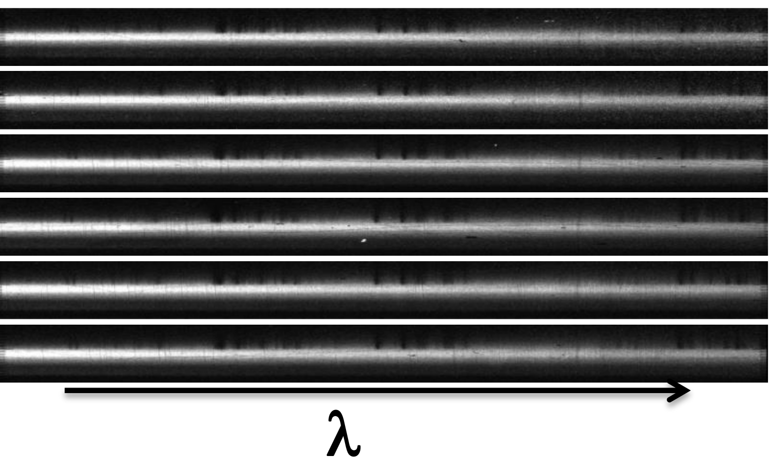
Hundreds of spectra were measured and analyzed to support the experiment reliability and reproducibility



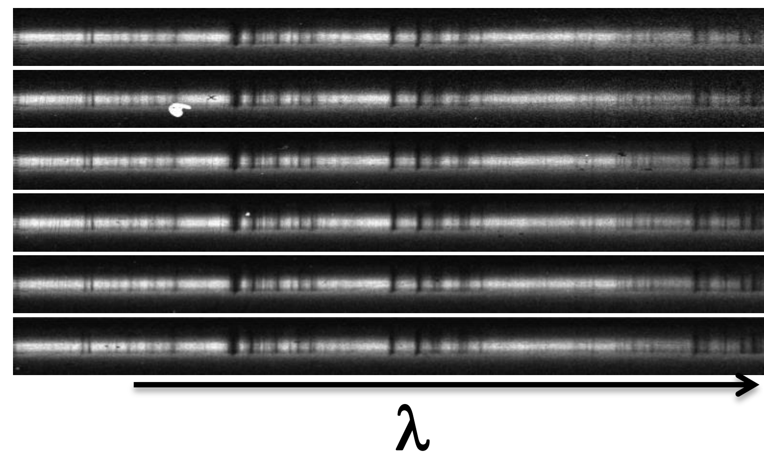
Spectrometer 4a



Spectrometer 10a



Spectrometer 4b



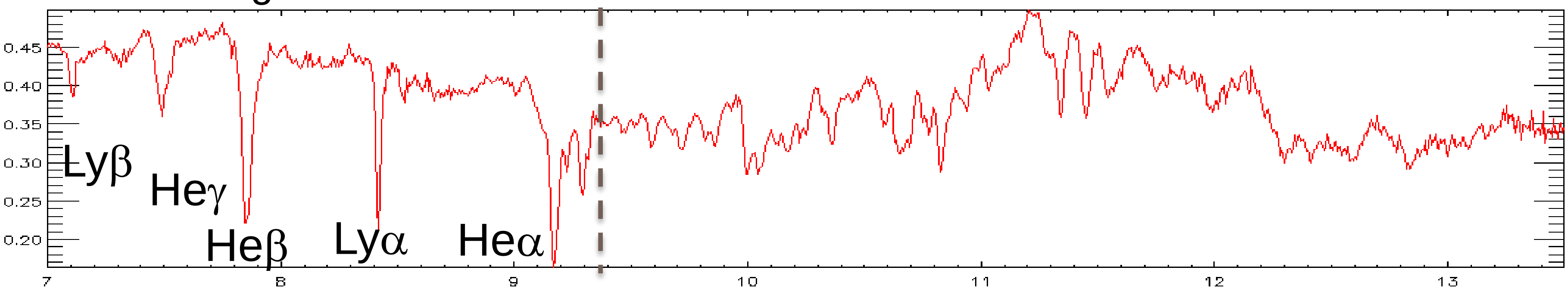
Spectrometer 10b

Data from z2762

This experiment used four spectrometers to record 24 spectra

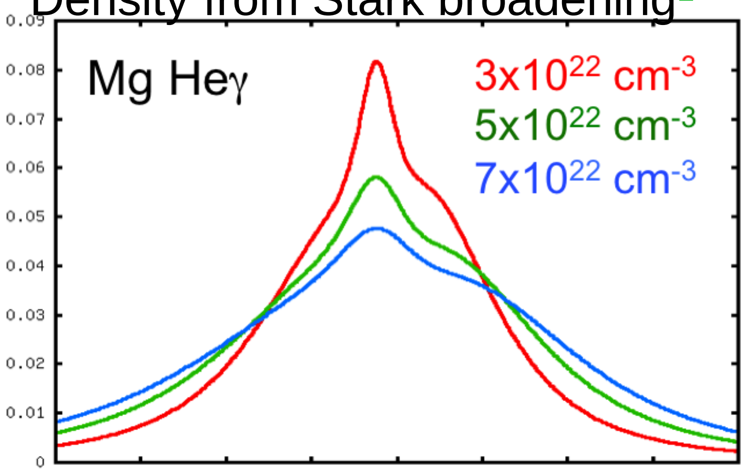
Plasma conditions are inferred by mixing Mg with Fe and using K-shell line transmission spectroscopy

Mg K-shell | Fe L-shell



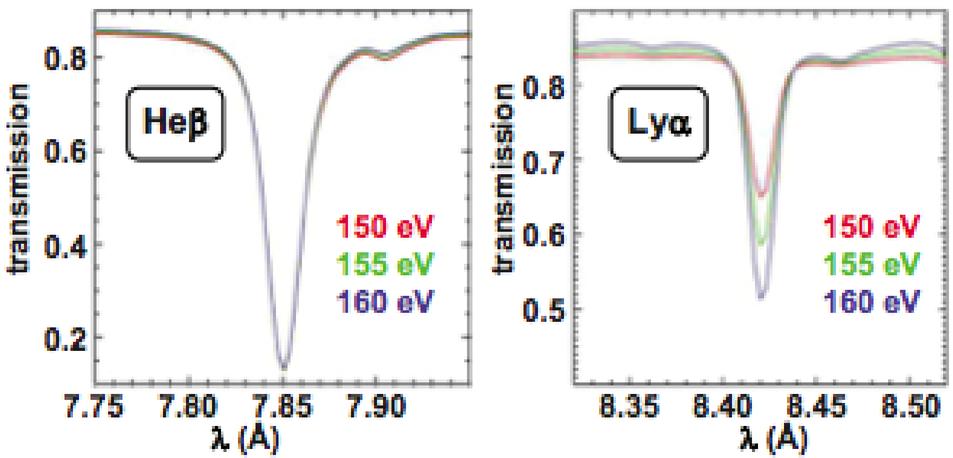
wavelength [Angstroms]

Density from Stark broadening[1]



Photon energy (eV)

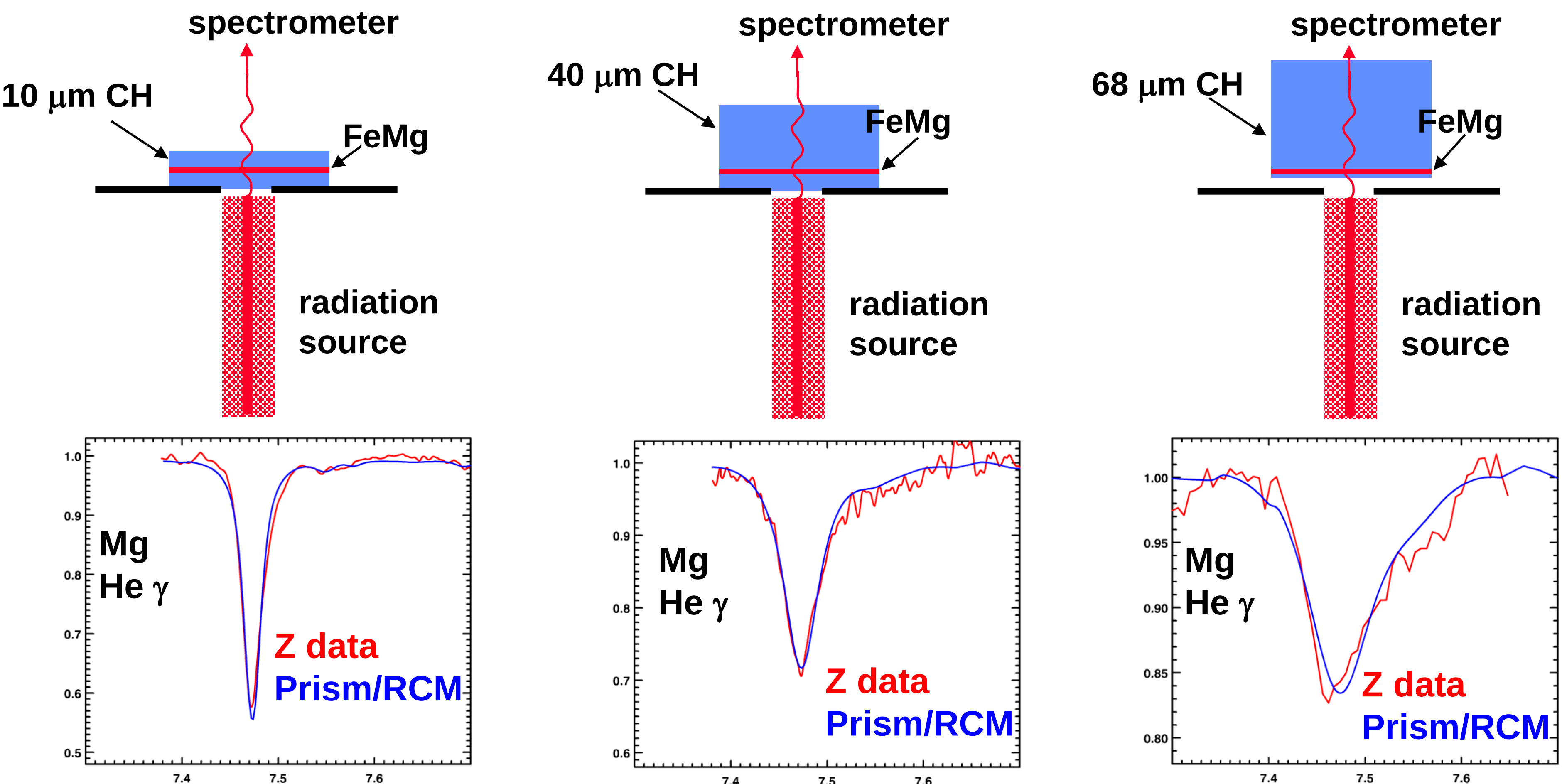
Temperature from line ratios



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

Adjusting the CH tamper thickness controls the opacity sample density and temperature

Sandia National Laboratories



$n_e \sim 7e21\ cm^{-3}$
$T_e \sim 167\ eV$

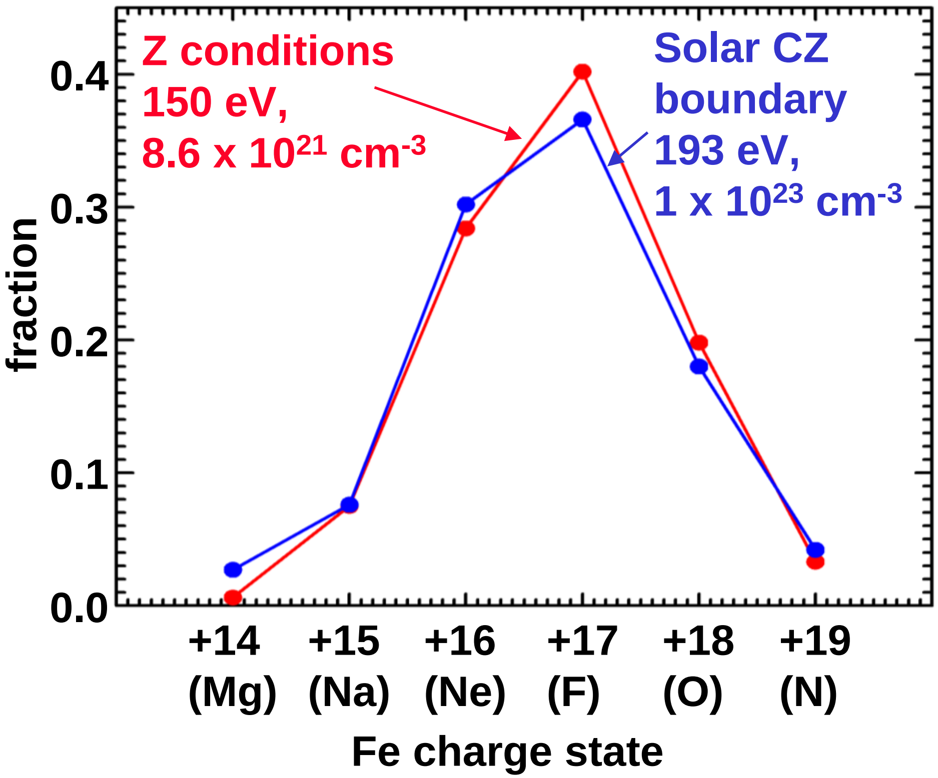
$n_e \sim 2e22\ cm^{-3}$
$T_e \sim 170\ eV$

$n_e \sim 4e22\ cm^{-3}$
$T_e \sim 195\ eV$

Nash et al RSI (2010)

Opacity measurements

In 2007, Z experiments produced the iron charge states that exist in the solar interior



Producing the correct charge states enables opacity model tests:

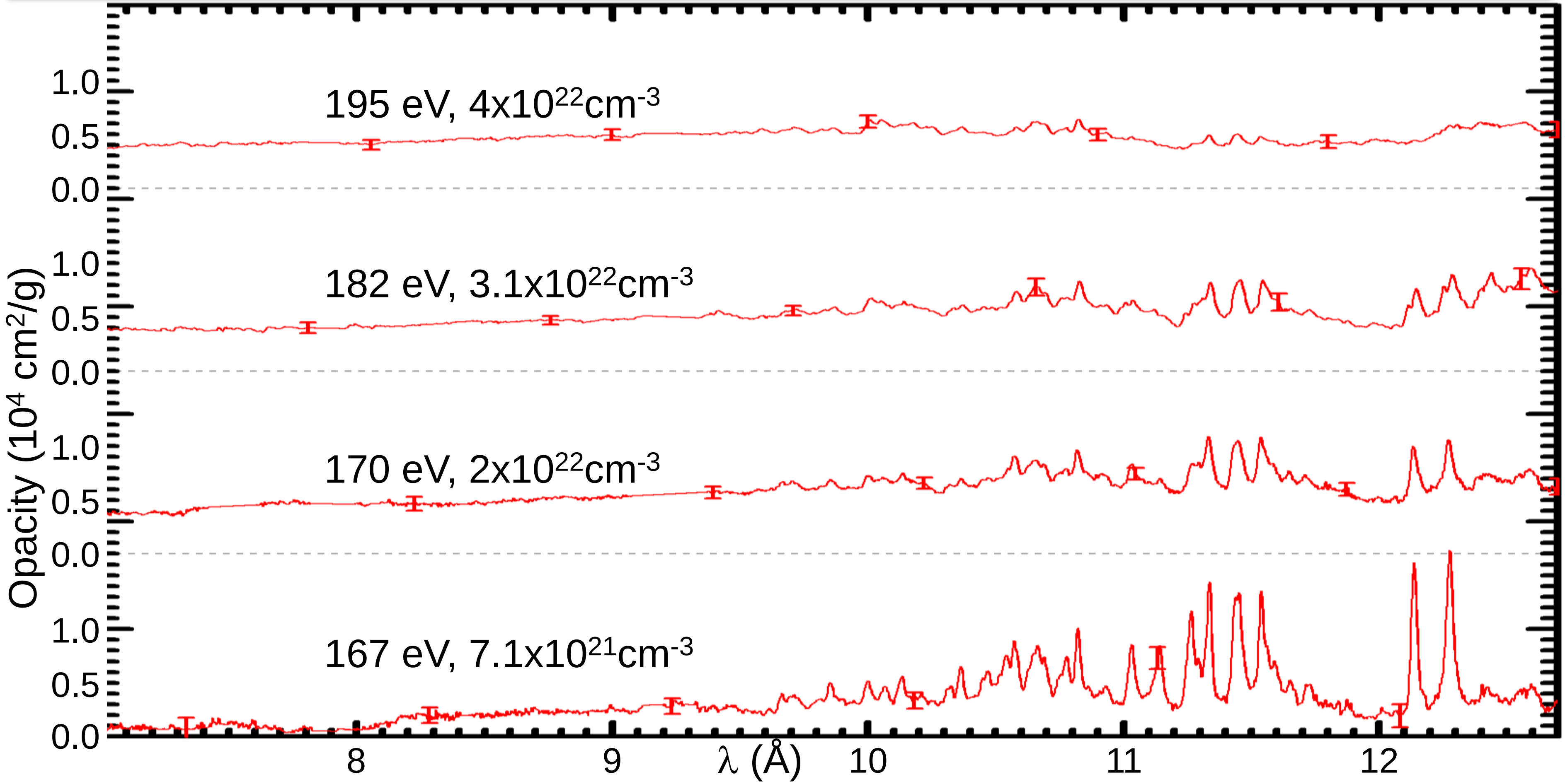
1) Charge state distribution

2) Energy level description

High density and high temperature studies required further progress

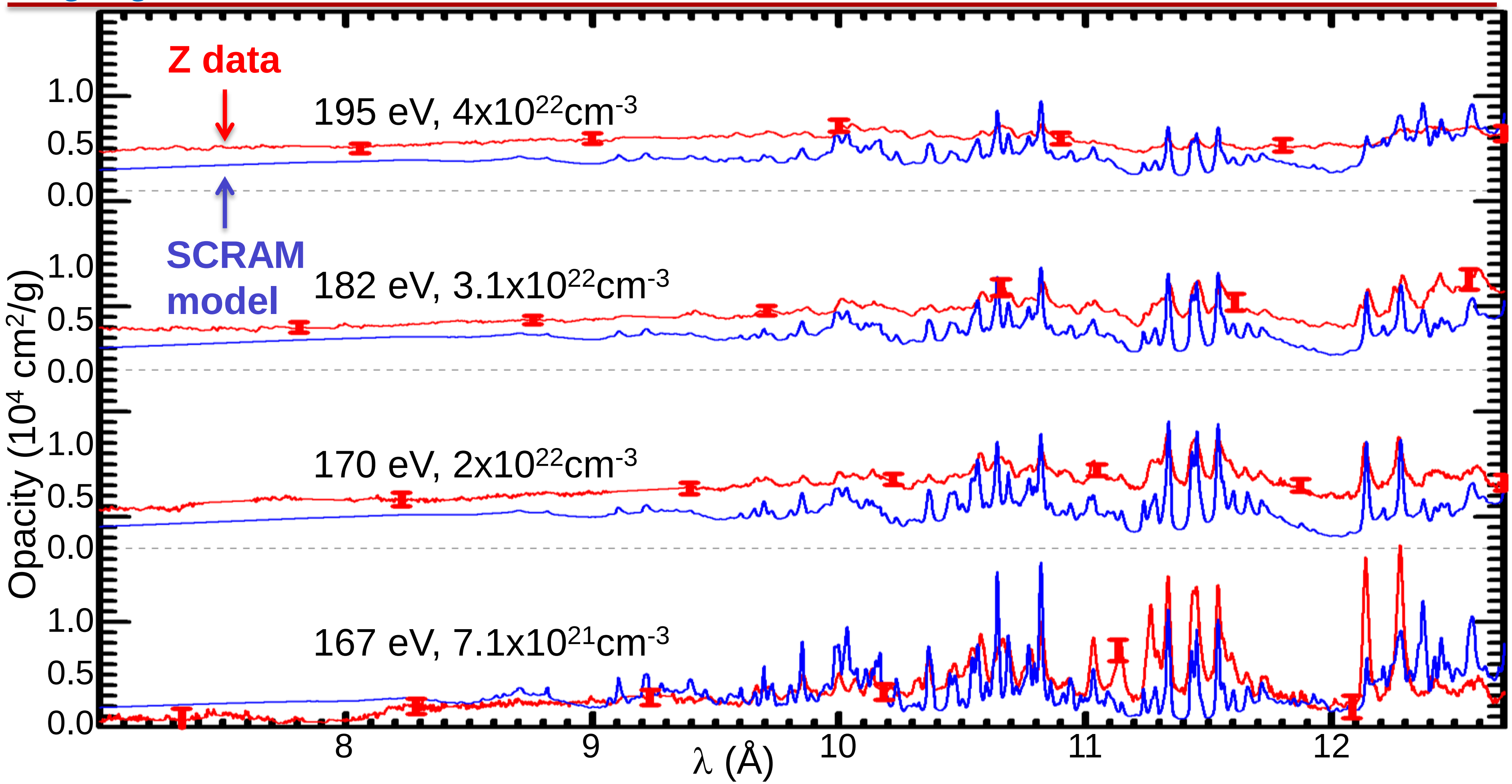
[Bailey *et al.*, PRL (2007)]

Iron opacity spectra have been acquired at conditions approaching the solar convection zone base



- Multiple conditions help dis-entangle the different physical processes
- Some clear trends are observed as T_e, n_e increase: shorter, fatter lines; windows fill in; quasi-continuum opacity increases

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

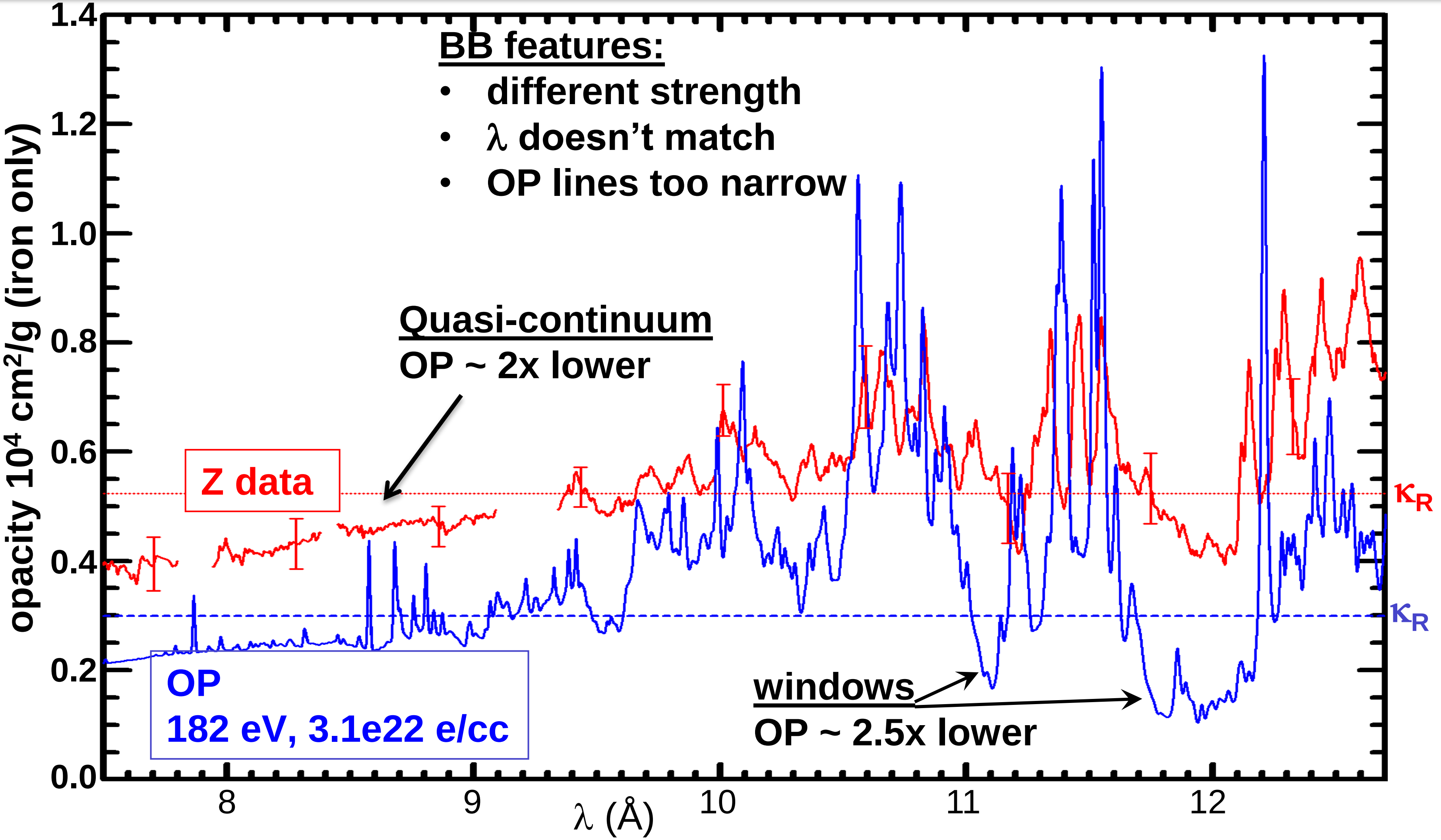


At high temperature , density, calculations are generally lower than the data

Bailey *et al.*, PRL (2007)

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

Sandia National Laboratories



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

Opacity Project: Seaton, MNRAS 1994; Badnell *et al.*, MNRAS 2005

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

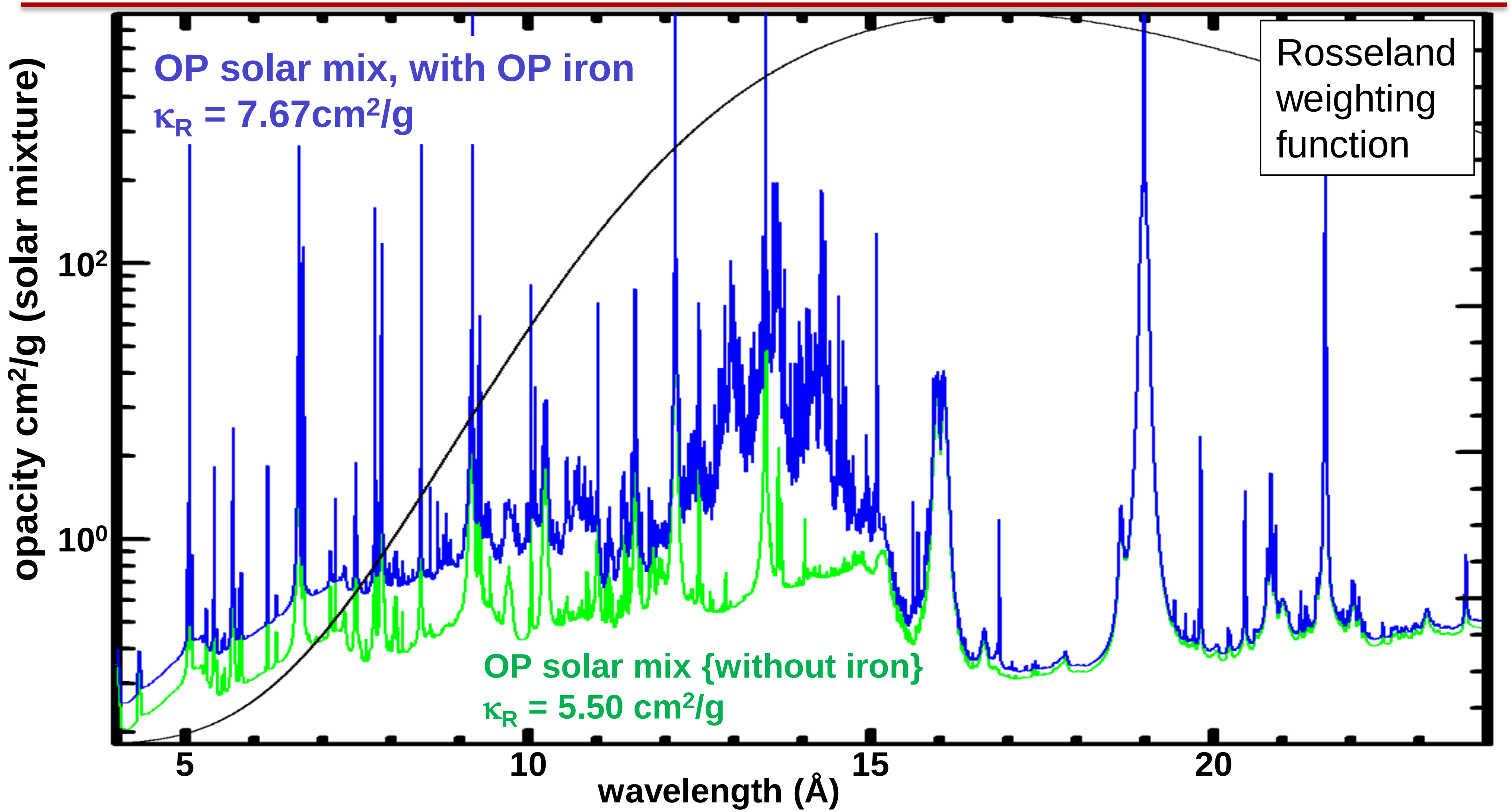
<u>This comparison:</u>

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

The sun contains many elements and the impact of iron is diluted

The consequences for ICF capsule dopants and radiative levitation in stars are probably larger than for the solar mixture

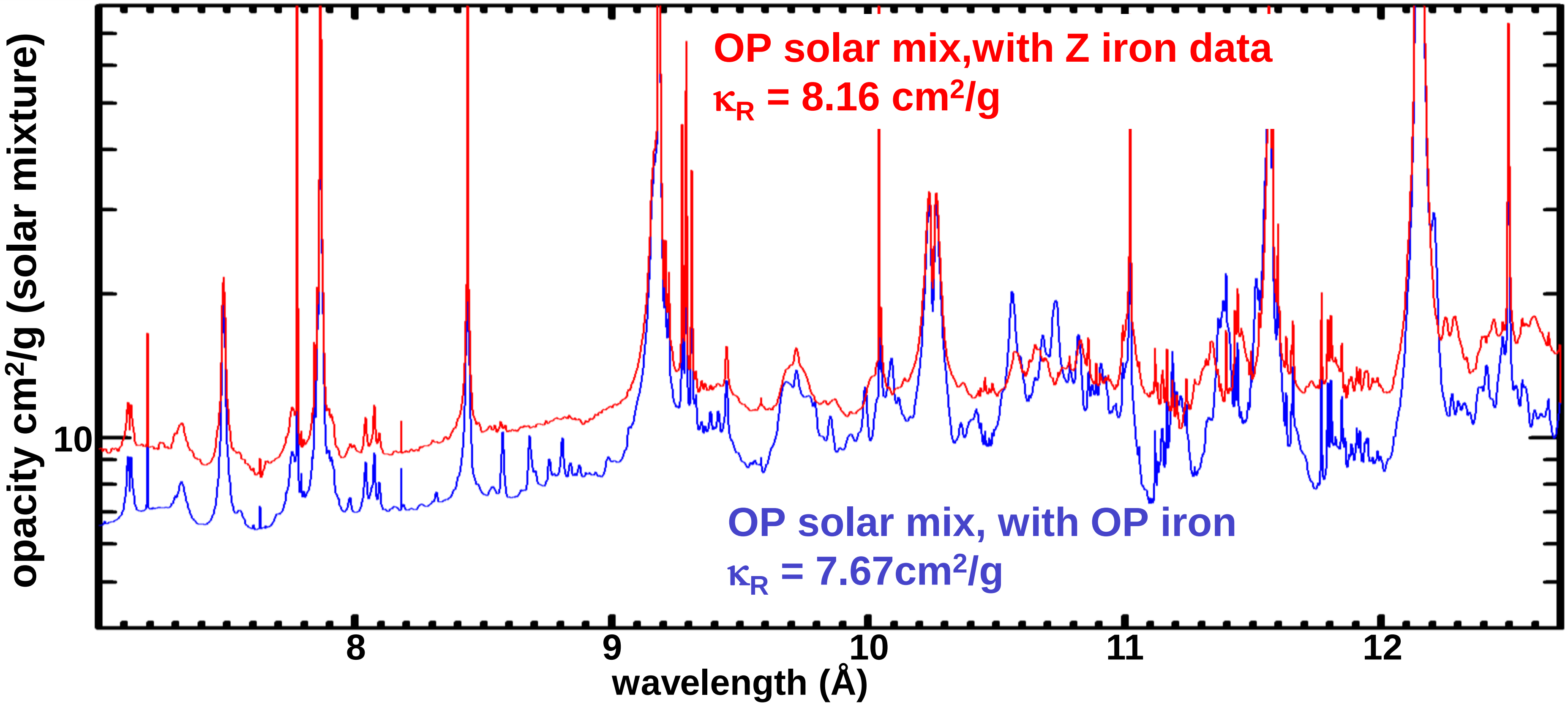
Z experiments measure the wavelength range where iron contributes the most to the solar CZB opacity



193 eV, 3.3 e22 e/cc
Asplund09 solar abundances

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

Sandia National Laboratories



- **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**

193 eV, 3.3 e22 e/cc Asplund09 solar abundances

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

Sandia National Laboratories

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

Sandia National Laboratories

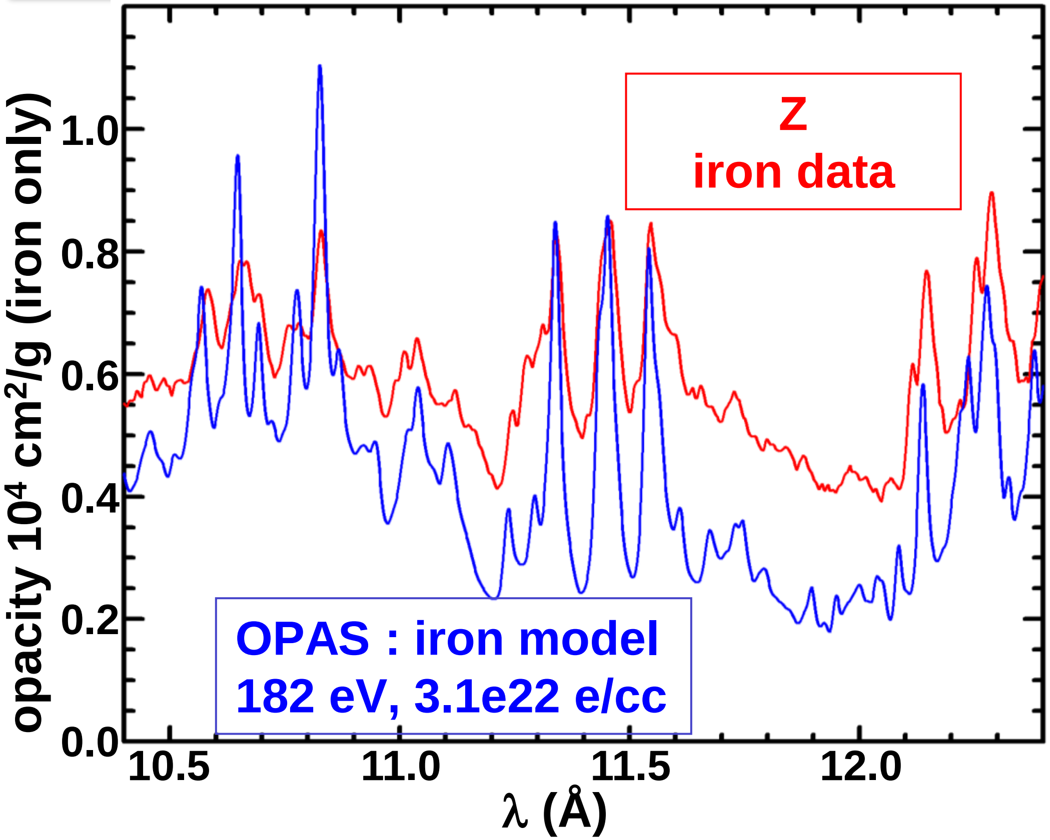
Random error determination: average many spectra from multiple experiments

Systematic error evaluation:
Experiment tests
Postprocess benchmarked simulations

Eleven different potential systematic errors were investigated:

Potential systematic error	Effect
Sample contamination Tamper shadowing	True opacity potentially lower than inferred opacity
Fe self emission Tamper self emission Extraneous background	True opacity potentially higher than inferred opacity
Sample areal density errors Transmission errors Spatial non-uniformities Temporal non-uniformities Departures from LTE Plasma diagnostic errors	True opacity potentially either lower or higher than inferred opacity

The detailed opacity measurements and calculations suggest testable hypotheses for the discrepancy



Hypotheses:

1) Could the experiment be incapable of measuring sharp lines?

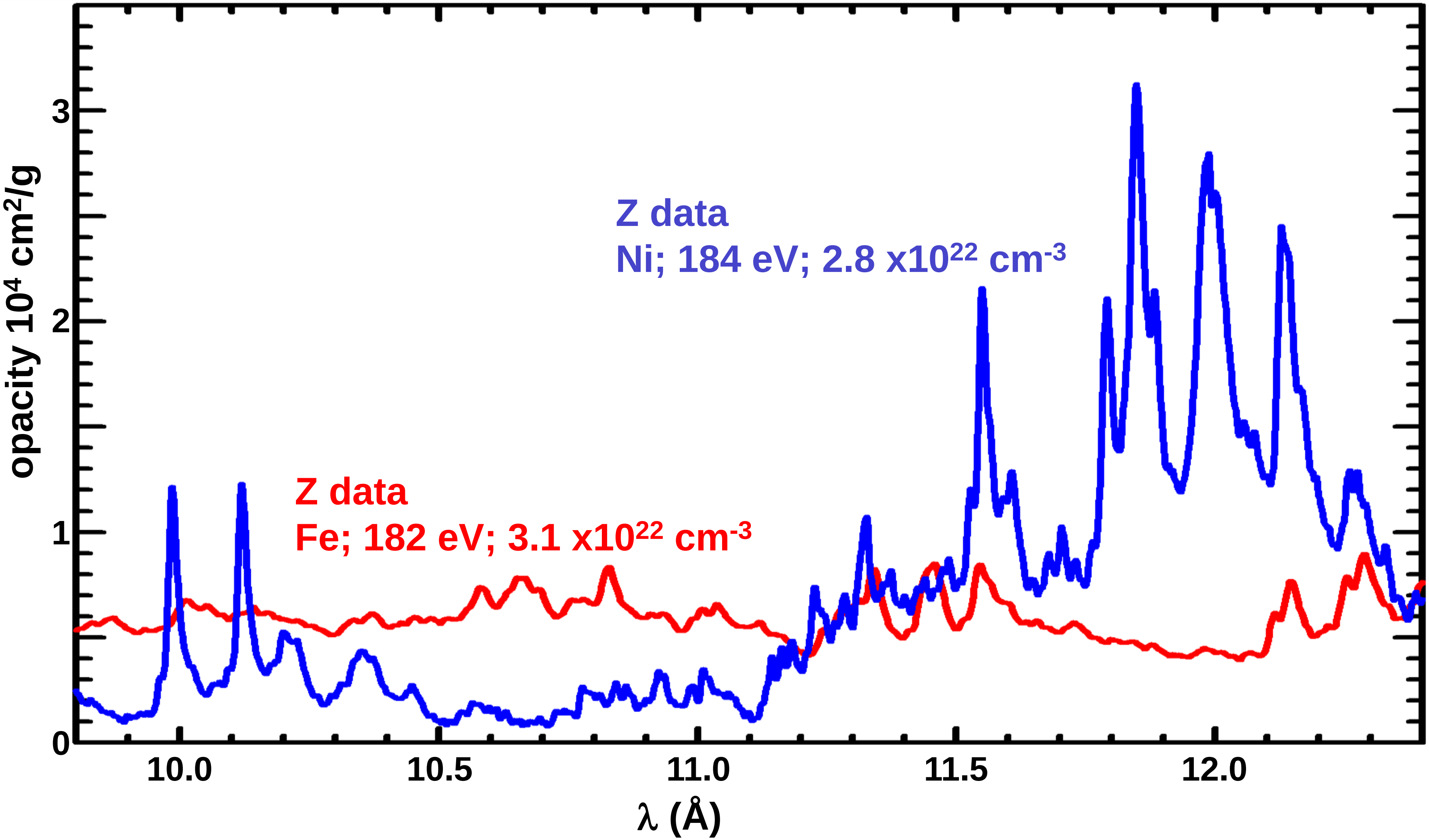
2) Are the windows filled in by excited state transitions not accurately modeled?

3) Is the actual Stark broadening larger than models predict? Or does line blending dominate the widths?

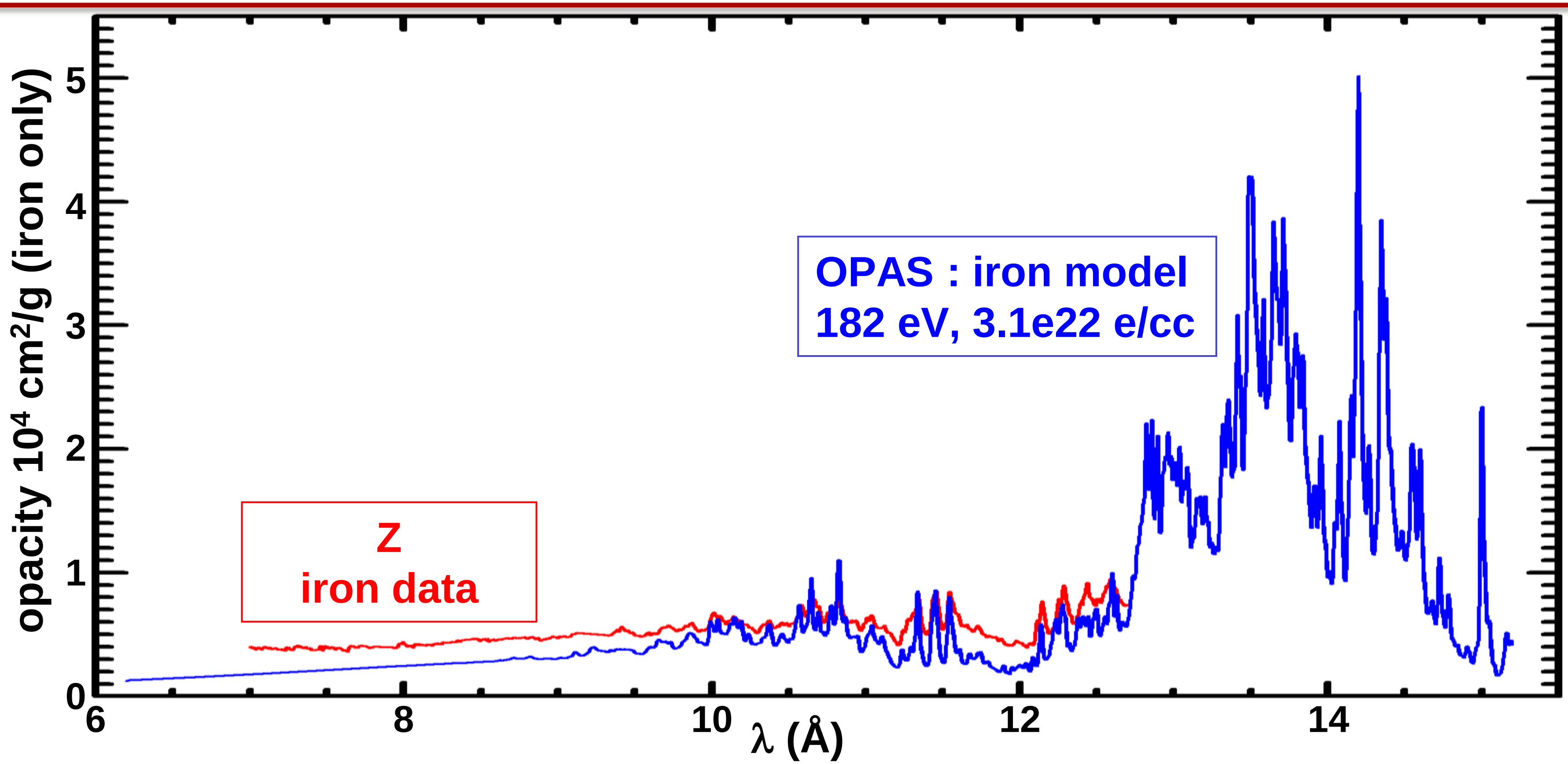
The experiment has wider spectral features and windows between features that are more filled in: these strongly effect photon transport

OPAS: C. Blancard *et al*, ApJ 745, 10 (2011)

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



The detailed opacity measurements and calculations suggest testable hypotheses for the discrepancy



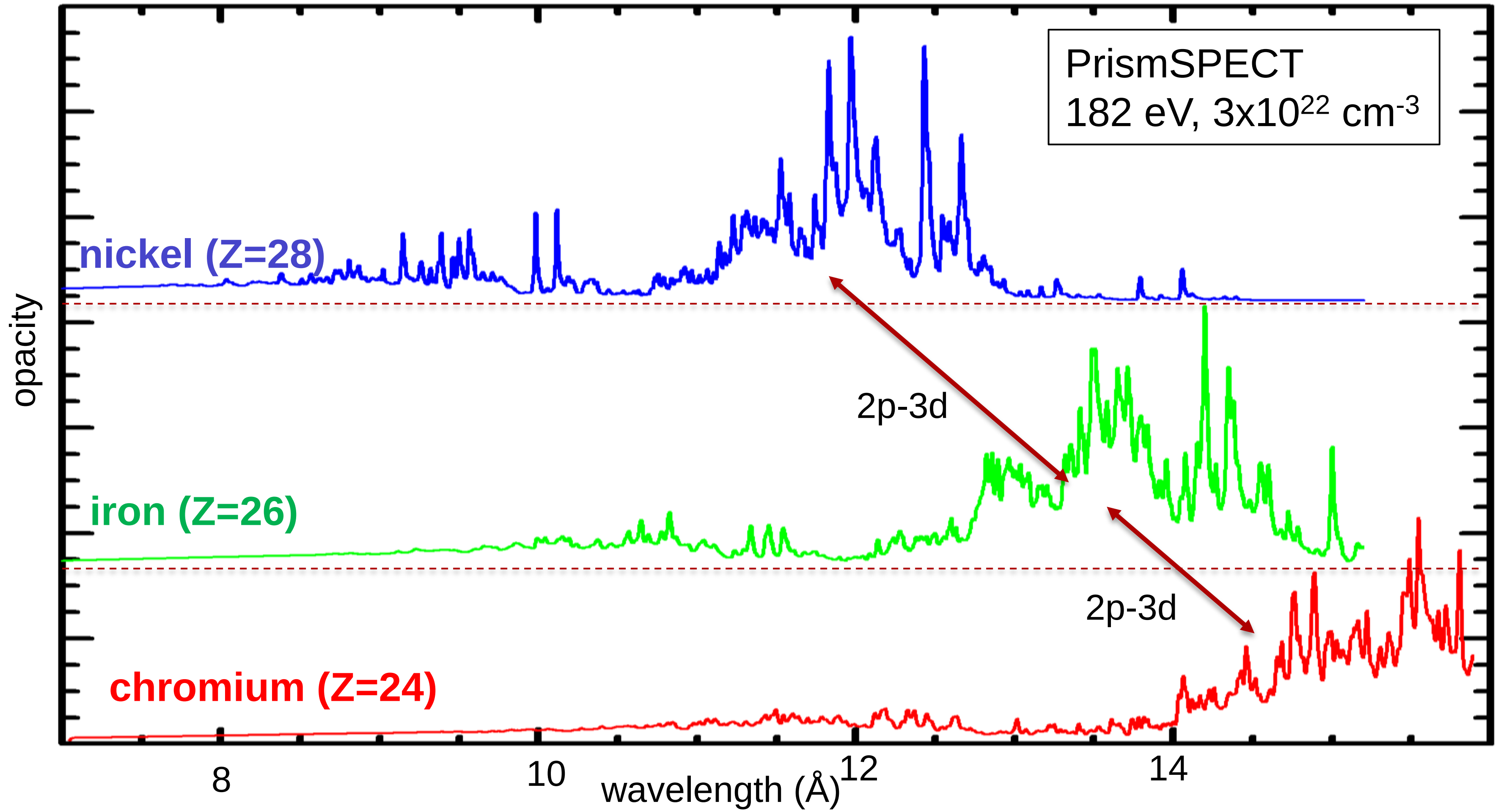
Hypotheses:

1) Is the higher-than-predicted opacity at short wavelengths because photon absorption is re-distributed?

2) Is the photoionization for atoms in HED matter accurately modeled?

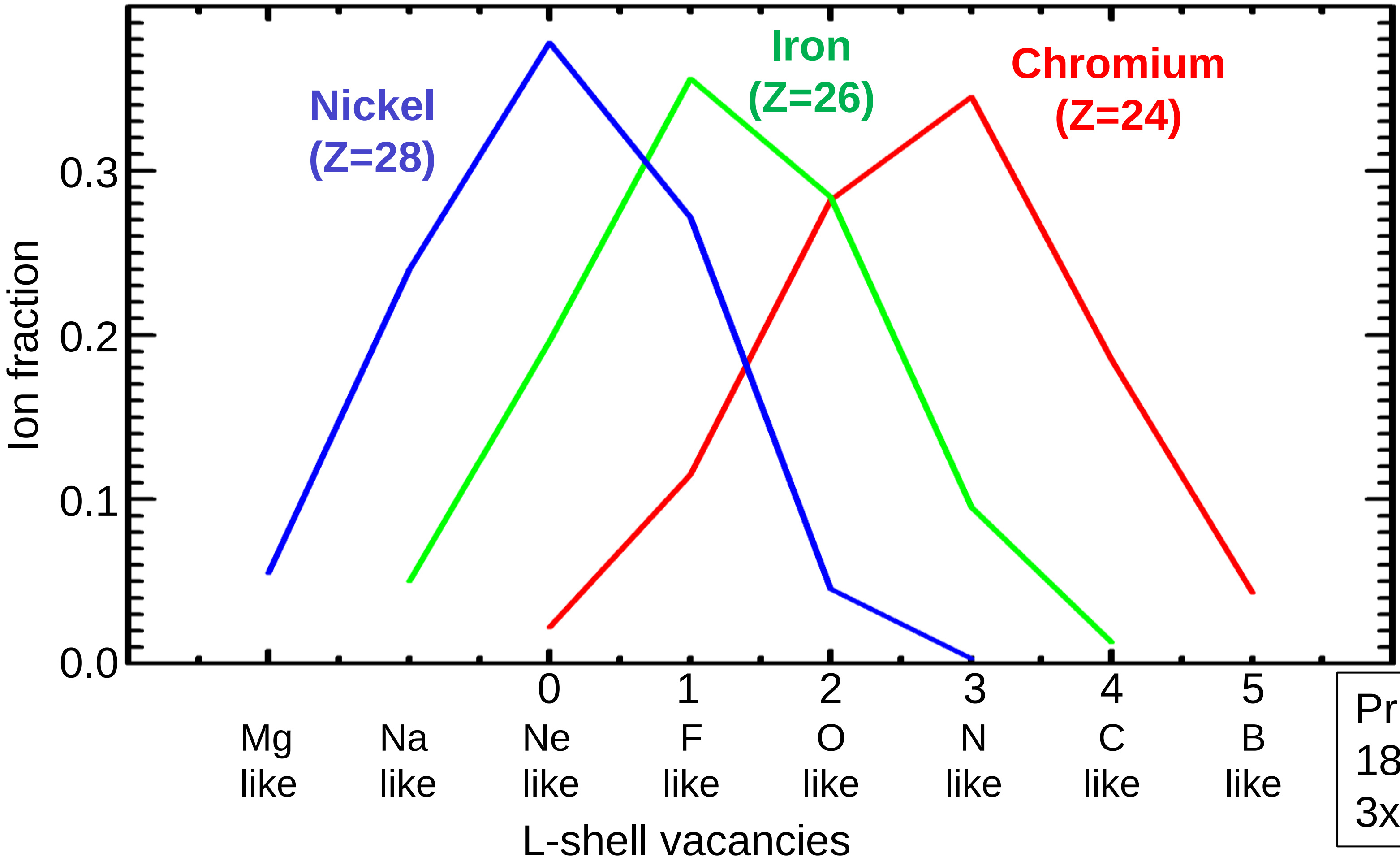
OPAS: C. Blancard *et al*, ApJ 745, 10 (2011)

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)

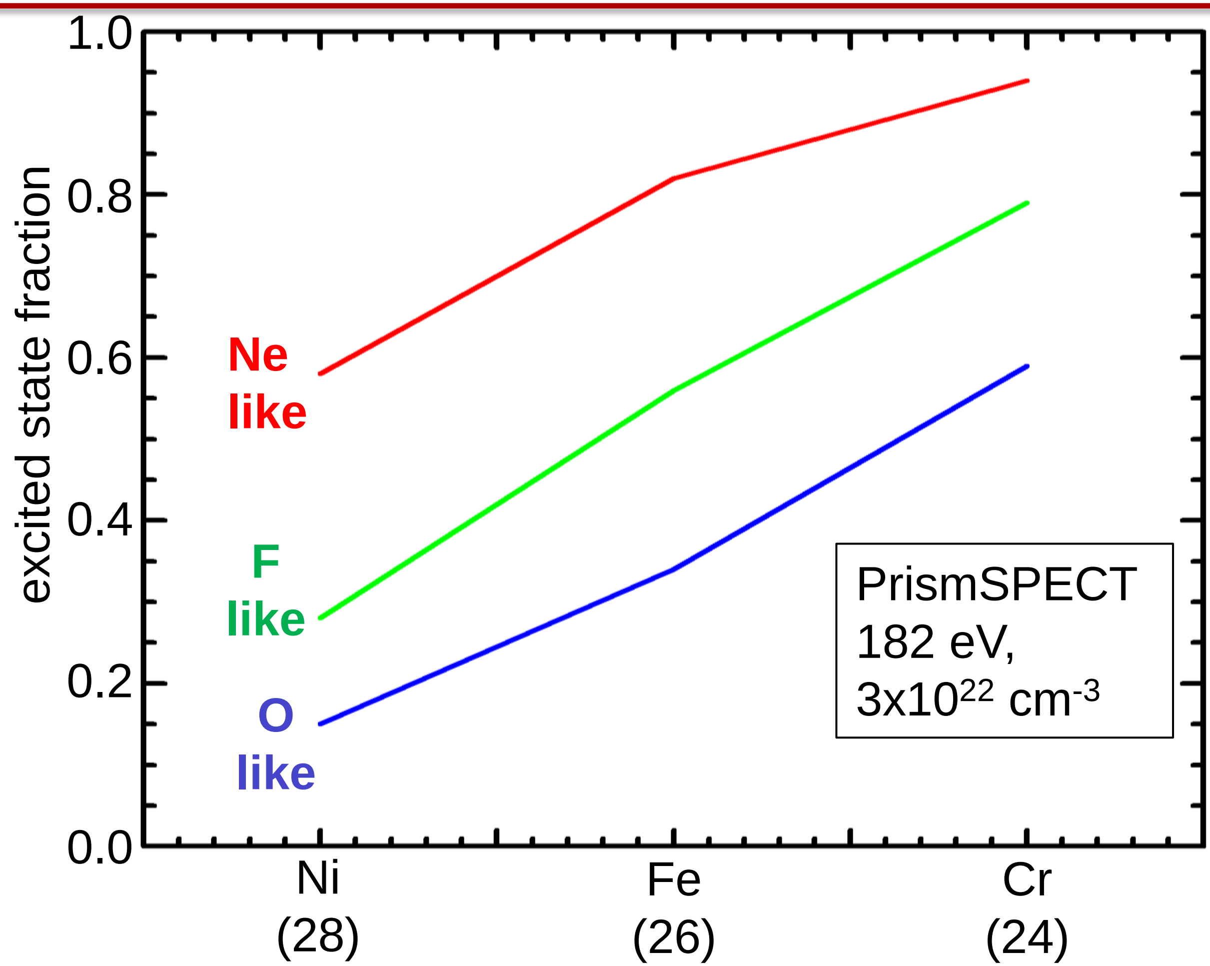
Partially-filled L-shell opacity is complex to model and can be studied by changing the element



PrismSPECT
182 eV,
3×10^{22} cm^{-3}

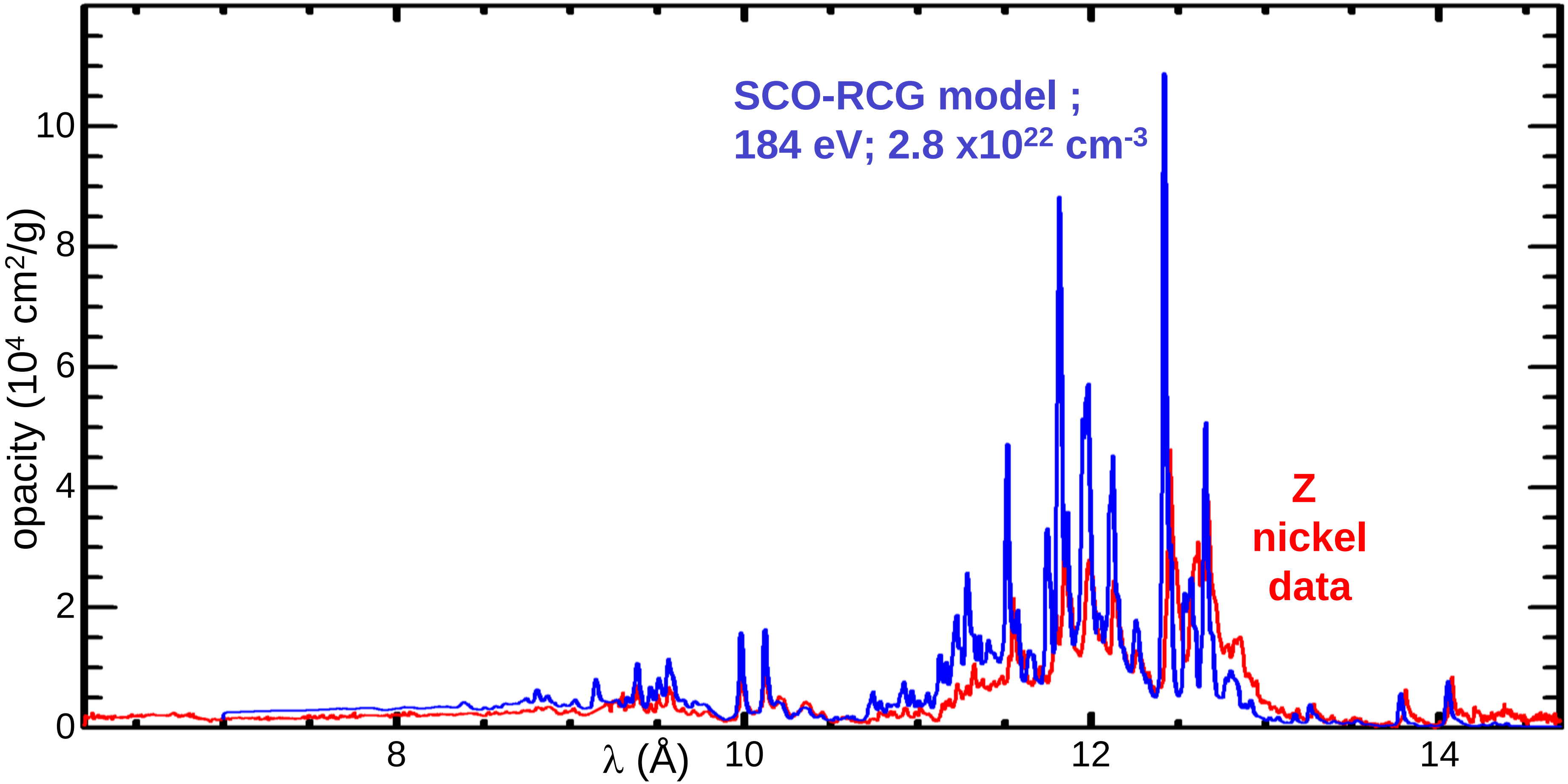
The number of L shell vacancies changes with the sample element

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

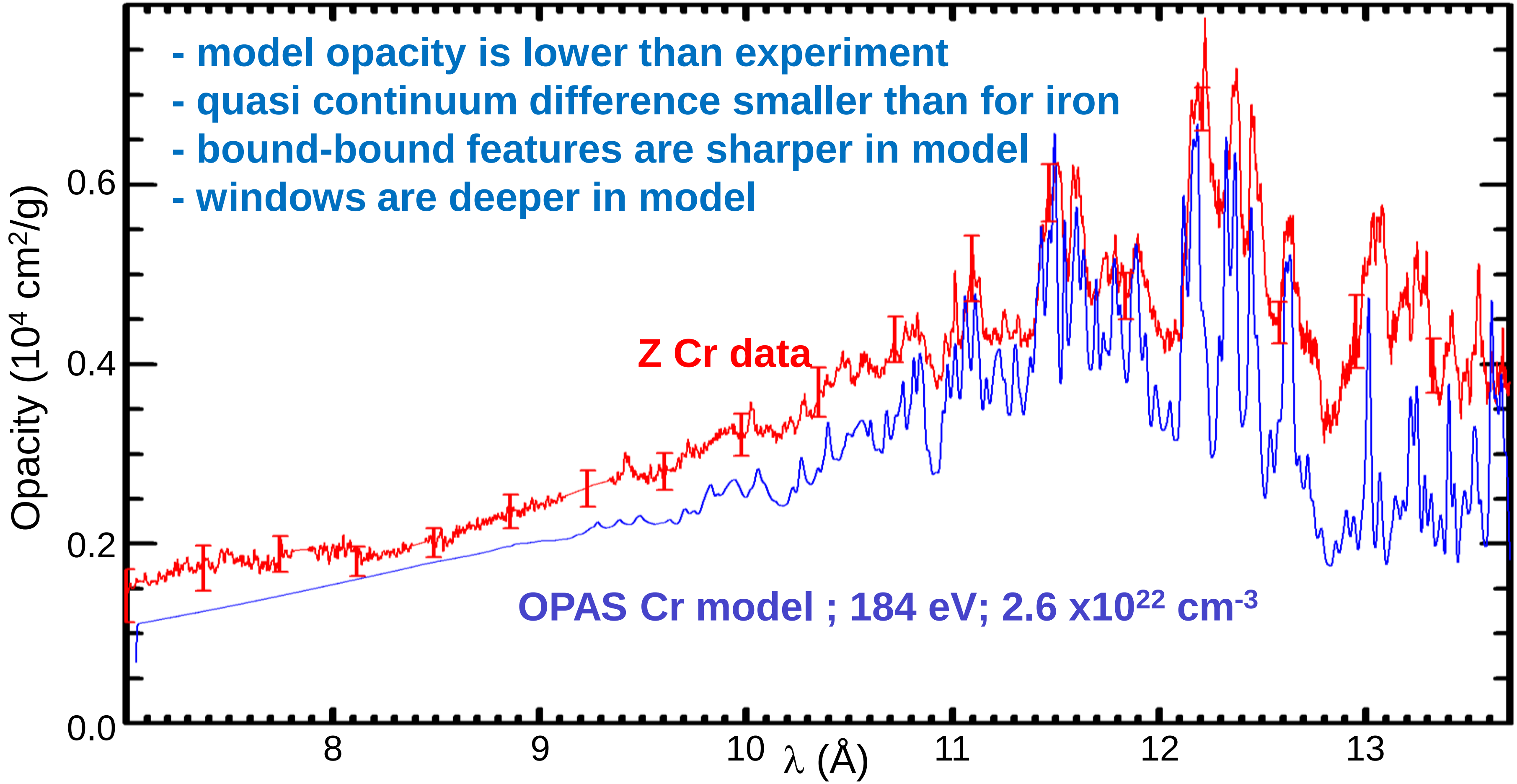
Predictions for Ni line opacities are larger than preliminary measurements, but windows between lines agree



Consistent with a hypothesis that photon absorption at long wavelengths is over-predicted while short wavelength absorption is under-predicted
However, errors are still being determined

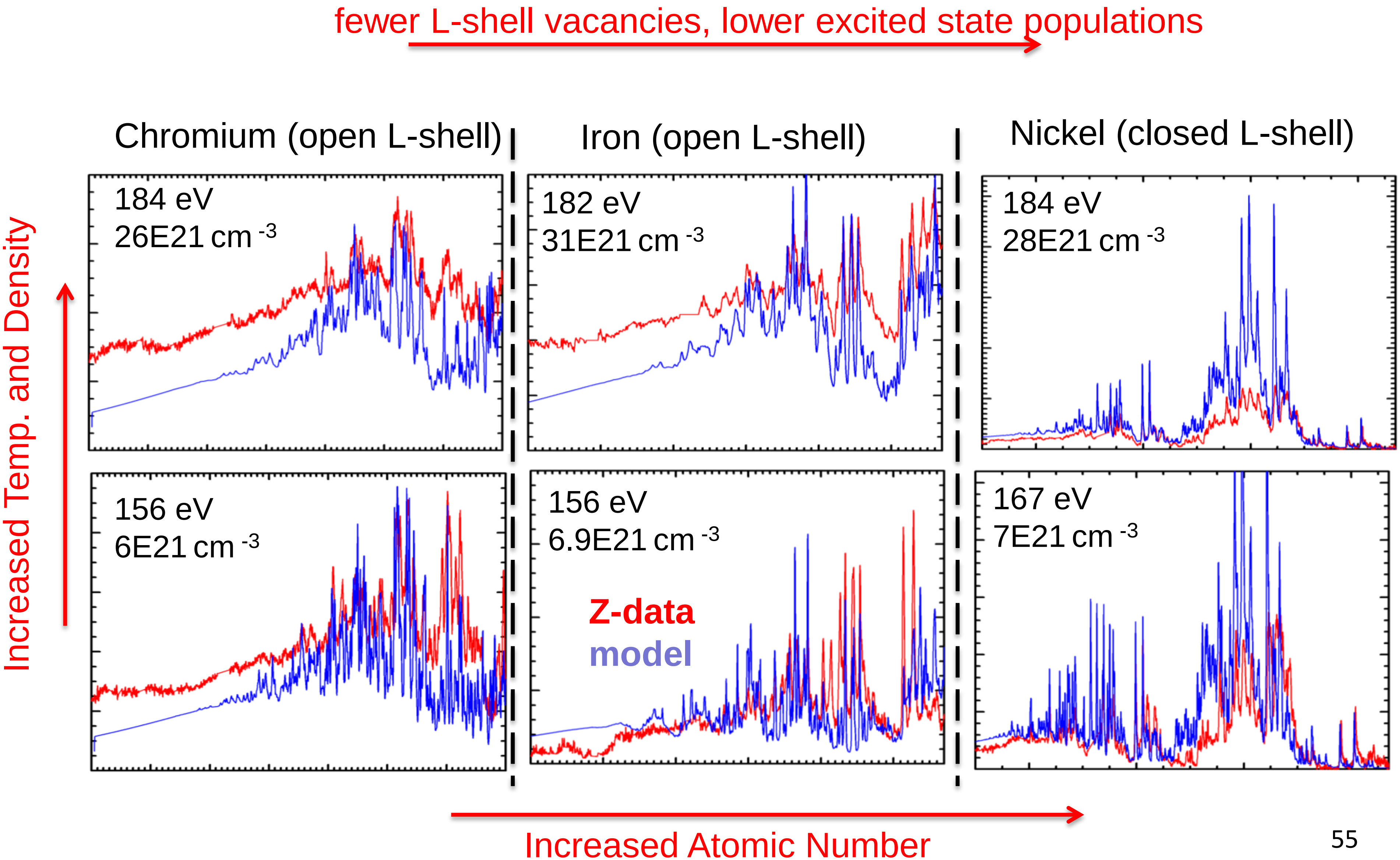
SCO-RCG: J.-C. Pain etal, 2013

Preliminary Cr model-data discrepancy is similar to iron



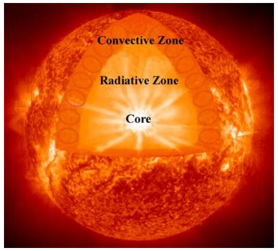
This generally supports the iron data validity
New questions, insights, and model constraints will certainly arise as we finalize the measurements

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

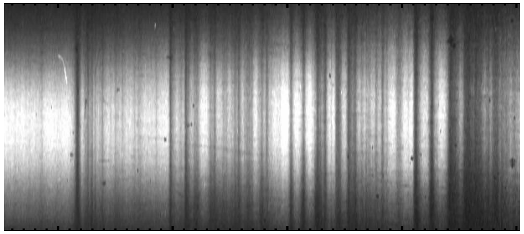


Z iron opacity experiments refine our understanding of the sun.

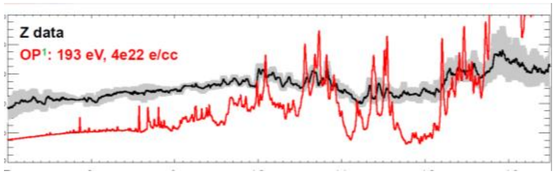
Sandia National Laboratories



- **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