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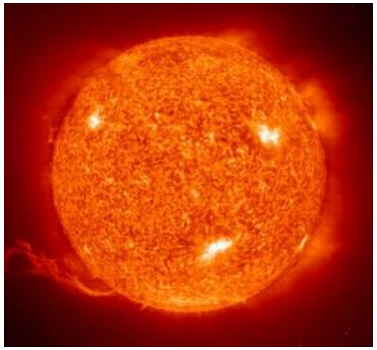

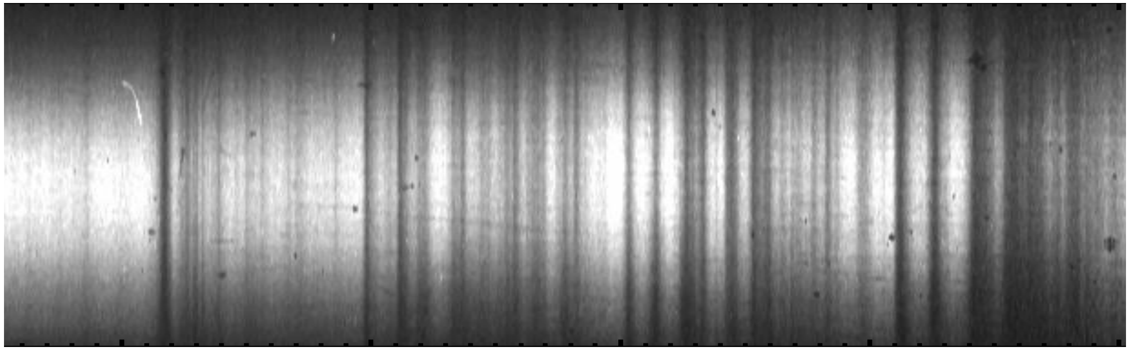

Measuring the opacity of stellar interior matter in terrestrial laboratories

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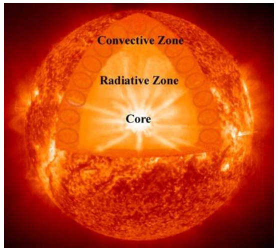
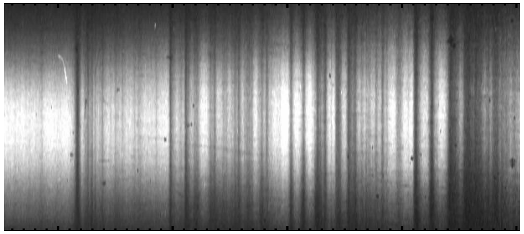
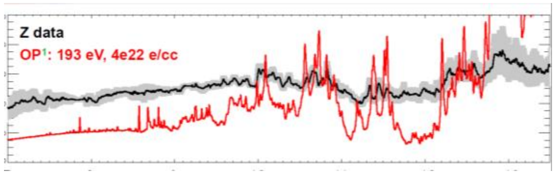
- **Solar interior predictions don't match helioseismology**
  - → **Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?**



- **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

Outline

Motivation – the solar interior problem

What physics is a concern for opacities?

How do we do opacity measurements?

Opacity results

How can we resolve the model-data discrepancy?

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Motivation – the solar interior problem

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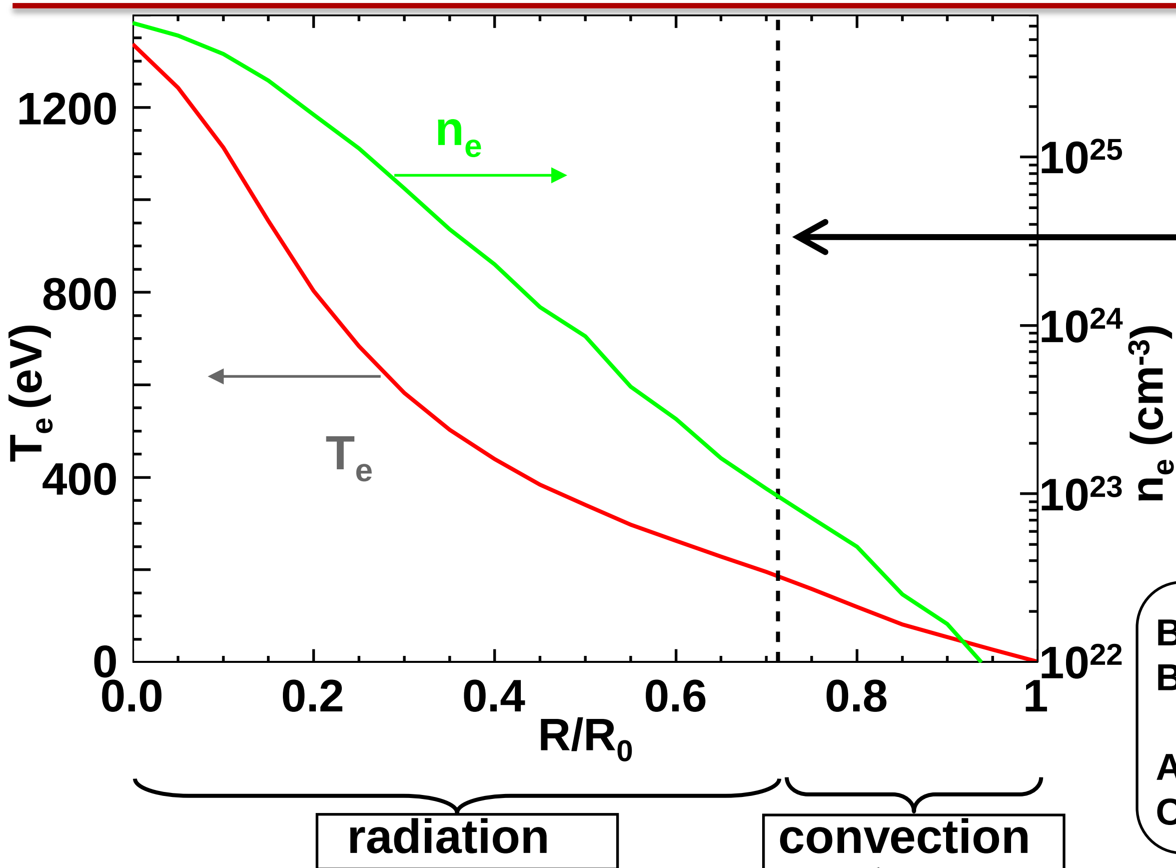
Standard solar model predictions of the solar structure disagree with helioseismology



- 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

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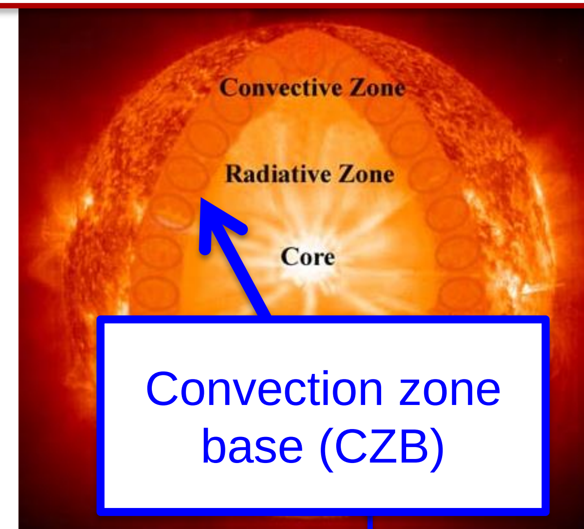
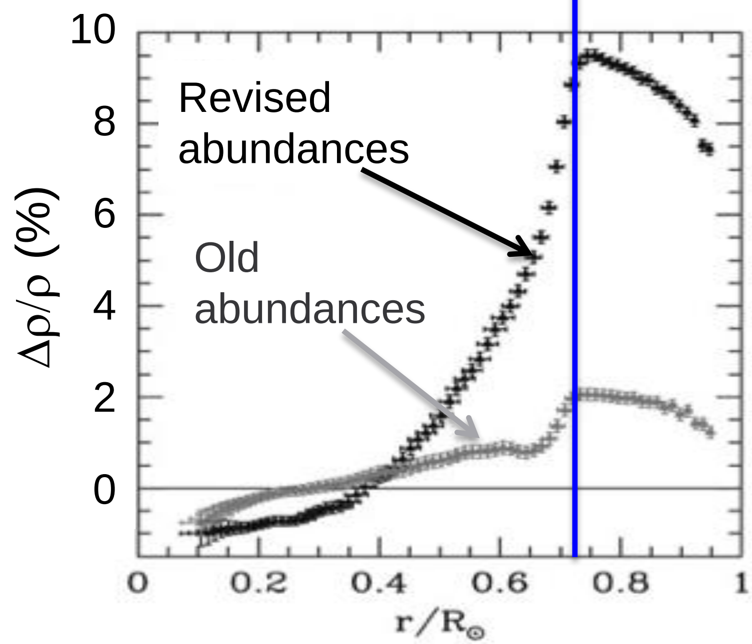
- Standard solar model (simulation)
  Inputs:
  - Abundance
  - EOS
  - Opacity
  - Etc.
- Helioseismology (measurements)



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

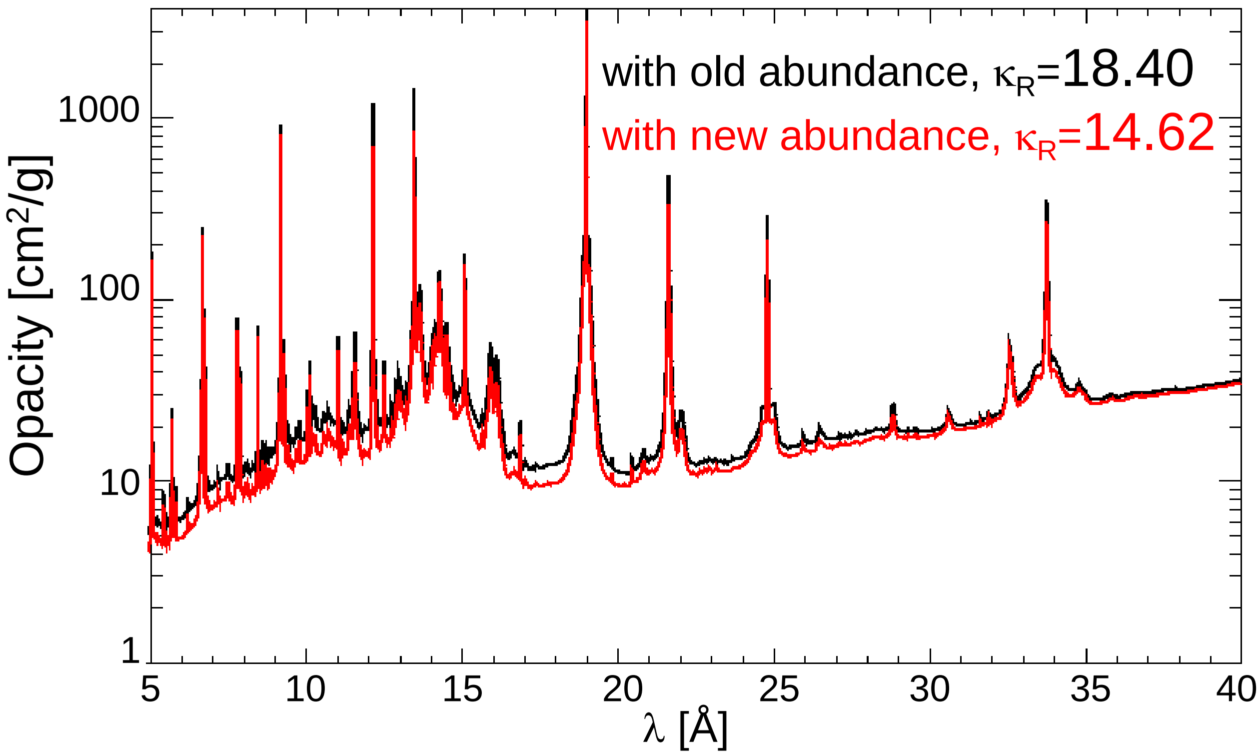
CZB location: 1σ → 13-30 σ

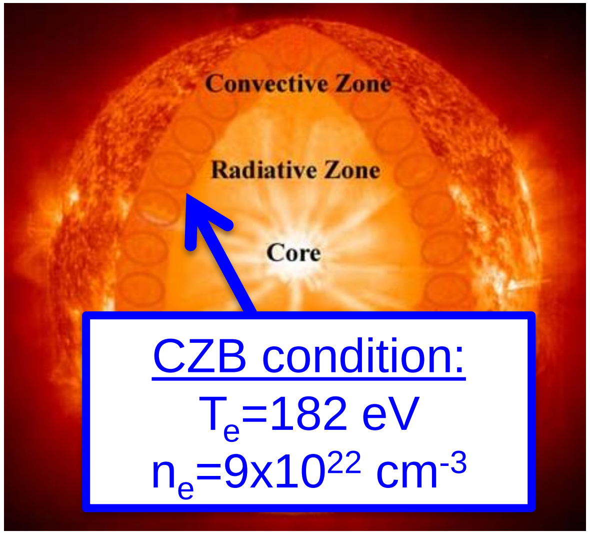


S. Basu *et al*, Physics Reports (2008). M. Asplund *et al*, Annu. Rev. Astro. Astrophys. (2005).

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

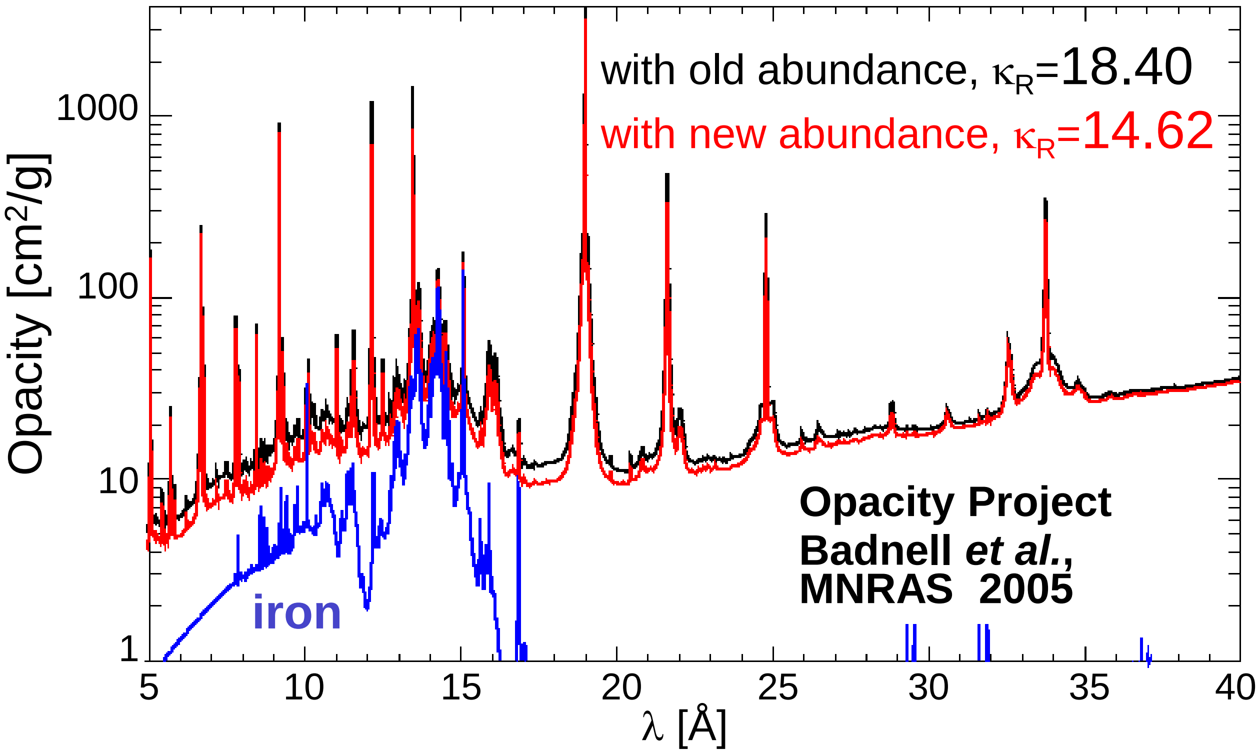
$$\frac{1}{\kappa_R} = \int \frac{1}{\kappa_\nu} \frac{\partial B_\nu}{\partial T} d\nu \Big/ \int \frac{\partial B_\nu}{\partial T} d\nu$$

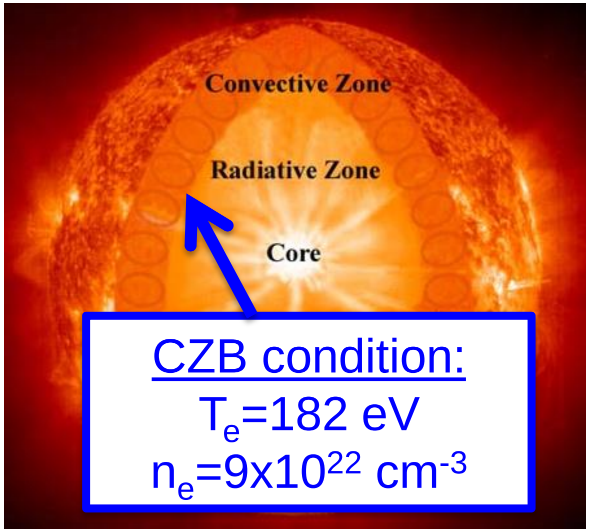
Photons are transported in opacity windows

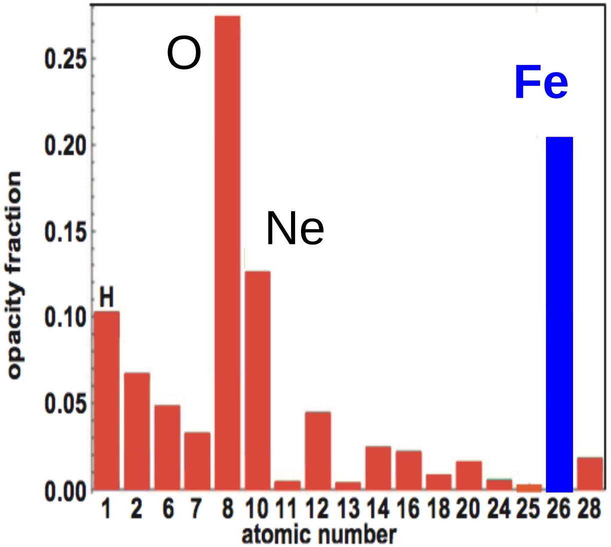
Rosseland, *MNRAS* 1924 Serenelli, *ApJ* 2009

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

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

Our stellar opacity research continues a century-old endeavor

Eddington
“The Internal Constitution of the Stars”

Cox
bound-bound
~1.5x opacity increase

Rogers & Iglesias
OPAL
2-3x opacity increase
resolves Cepheid problem

OP

1905 **1925** **1965** **1988** **1995** **2005** **2015**

Barkla

Siegbahn
X-ray spectroscopy

only bound-free and free-free absorption

Davidson *et al.*
Perry *et al.*
hot dense plasma opacity
20-70 eV

Bailey *et al.*
stellar interior opacity
156-195 eV

Stellar interior opacity measurements are now possible for the first time

Outline

Motivation – the solar interior problem

What physics is a concern for opacities?

How do we do opacity measurements?

Opacity results

How can we resolve the model-data discrepancy?

"In considering absorption and opacity the mutilation of the electron system of the atom is of vital importance, because it is just this system which contains the mechanism of absorption"

Eddington, *The Internal Constitution of the Stars* 1926

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

<u>Opacity depends on:</u>

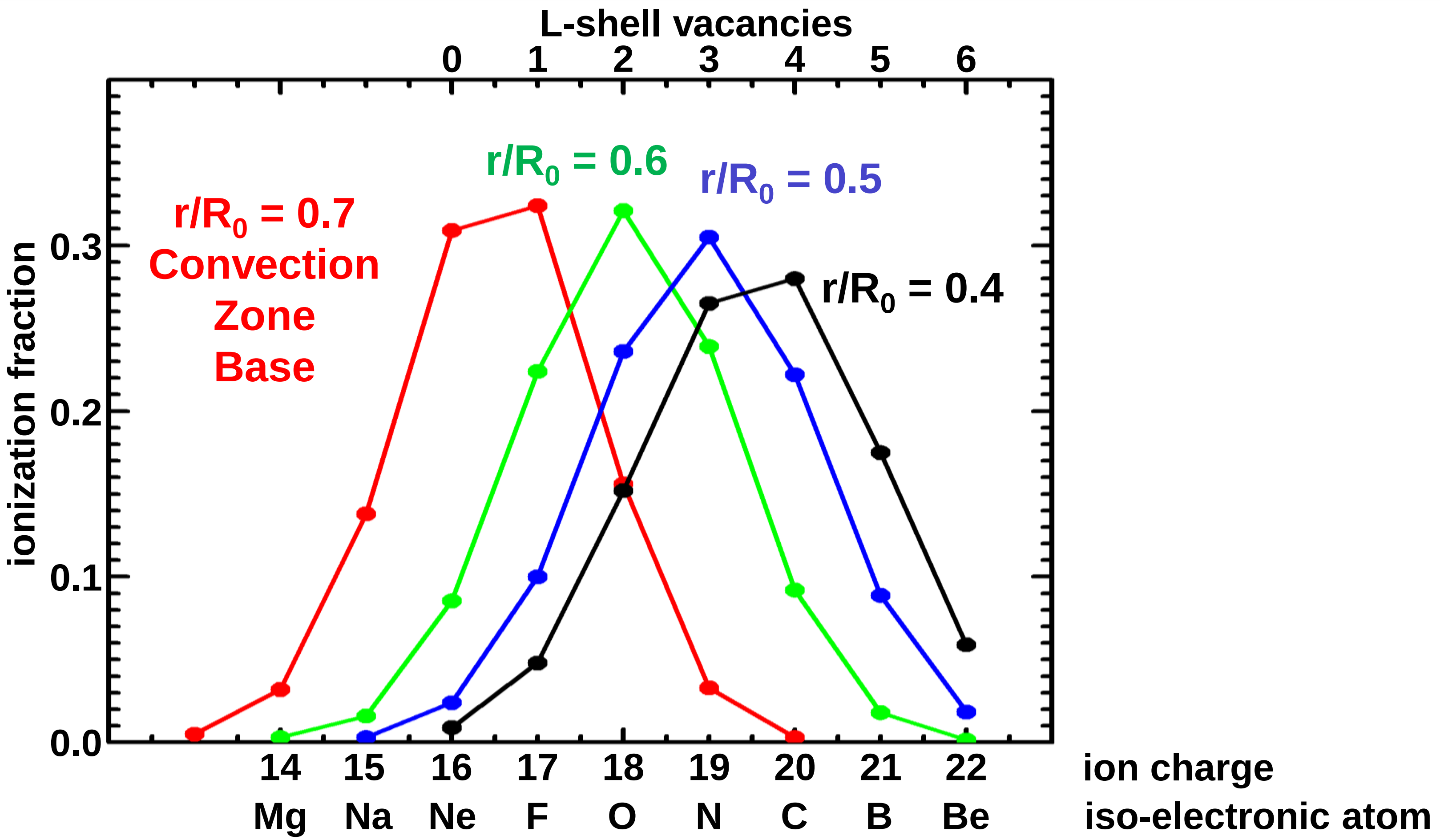
Charge state distribution

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:

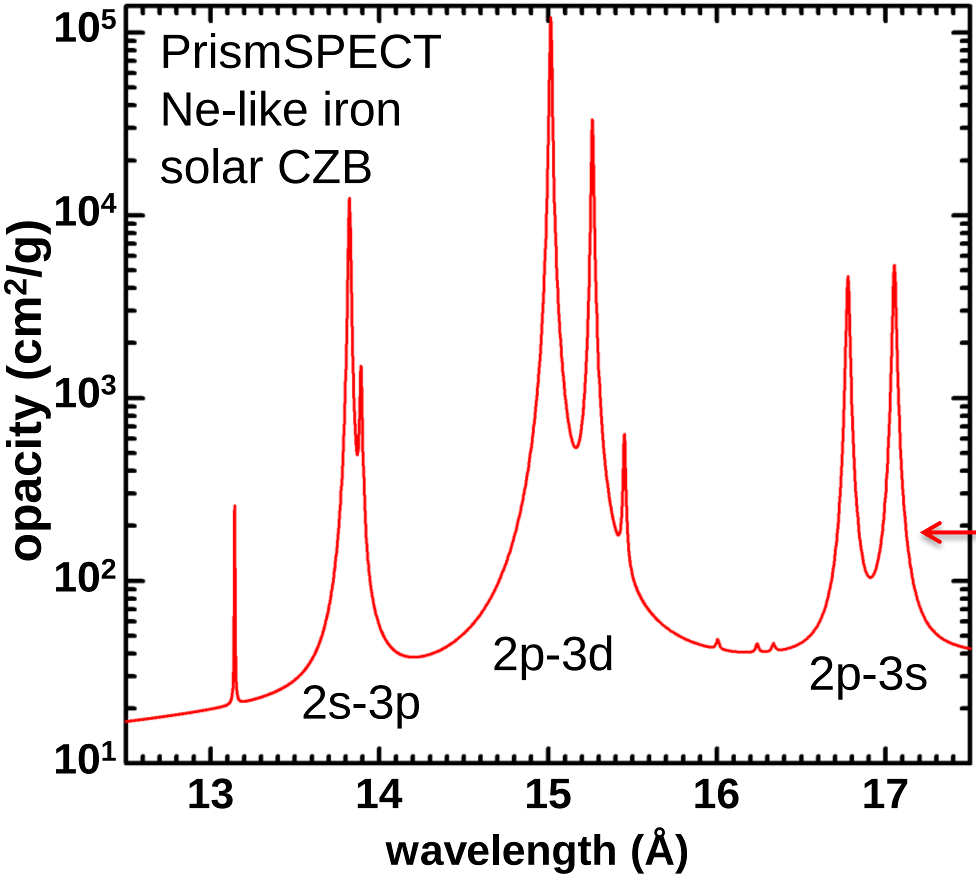
Charge state distribution

Energy level structure

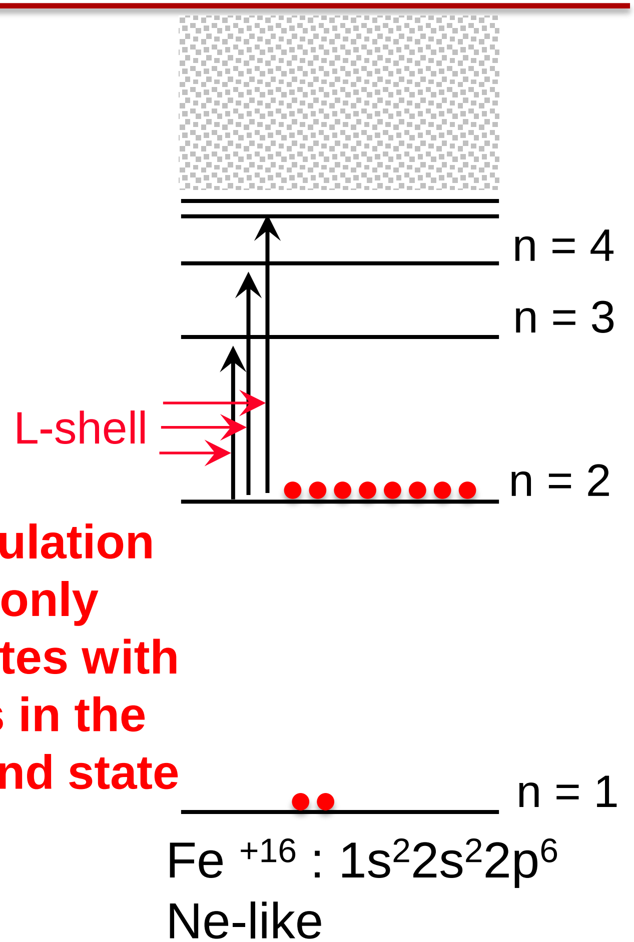
Energy level populations

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

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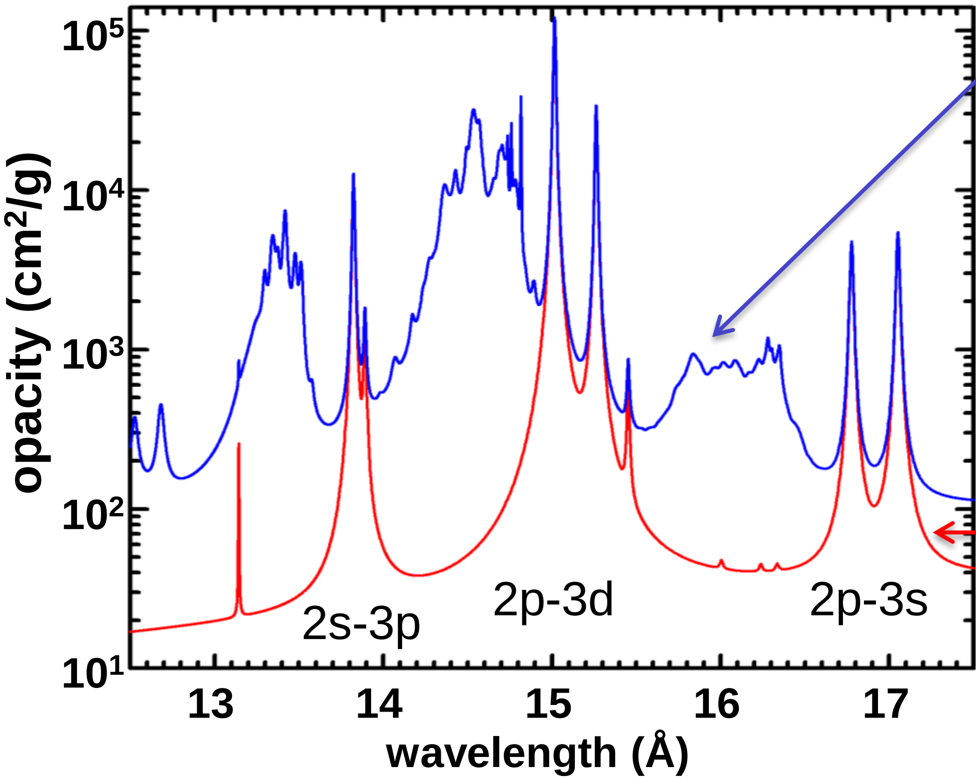
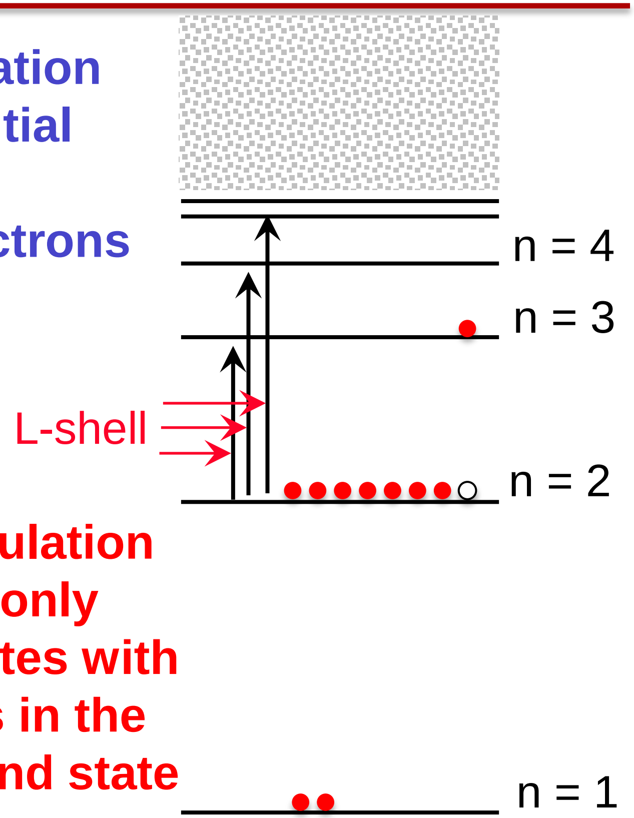


This calculation includes initial states with excited electrons

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

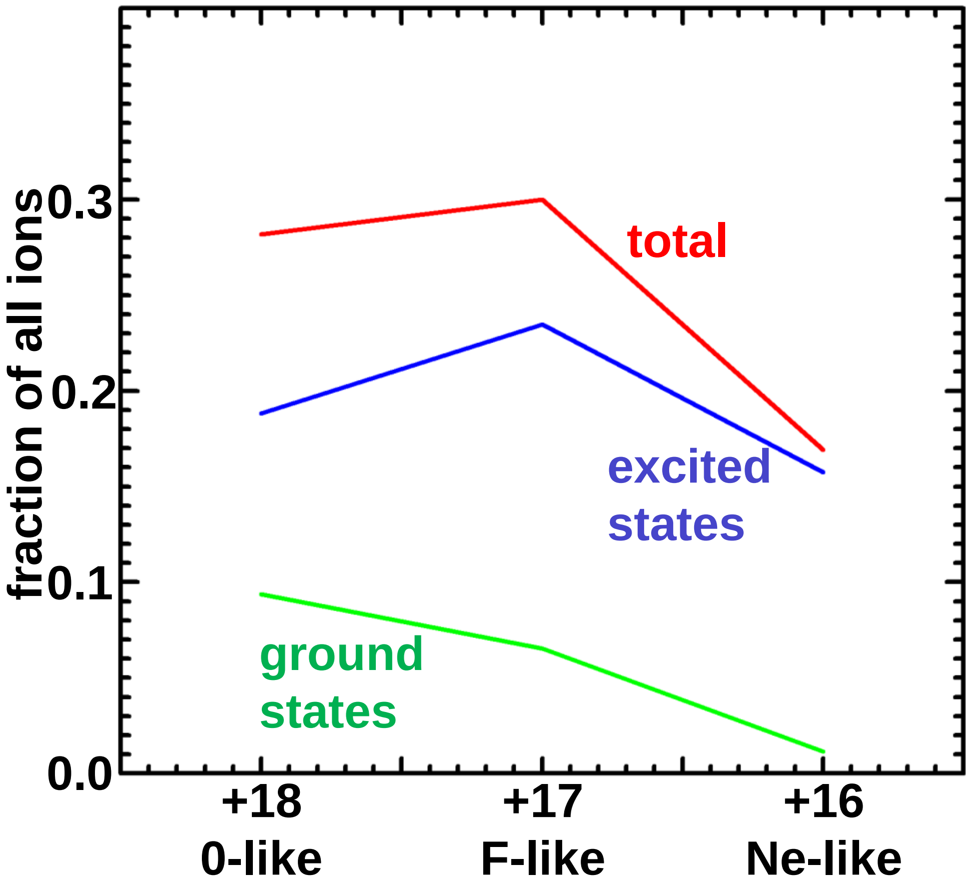


Fe $^{+16}$: $1s^2 2s^2 2p^6$
Ne-like

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

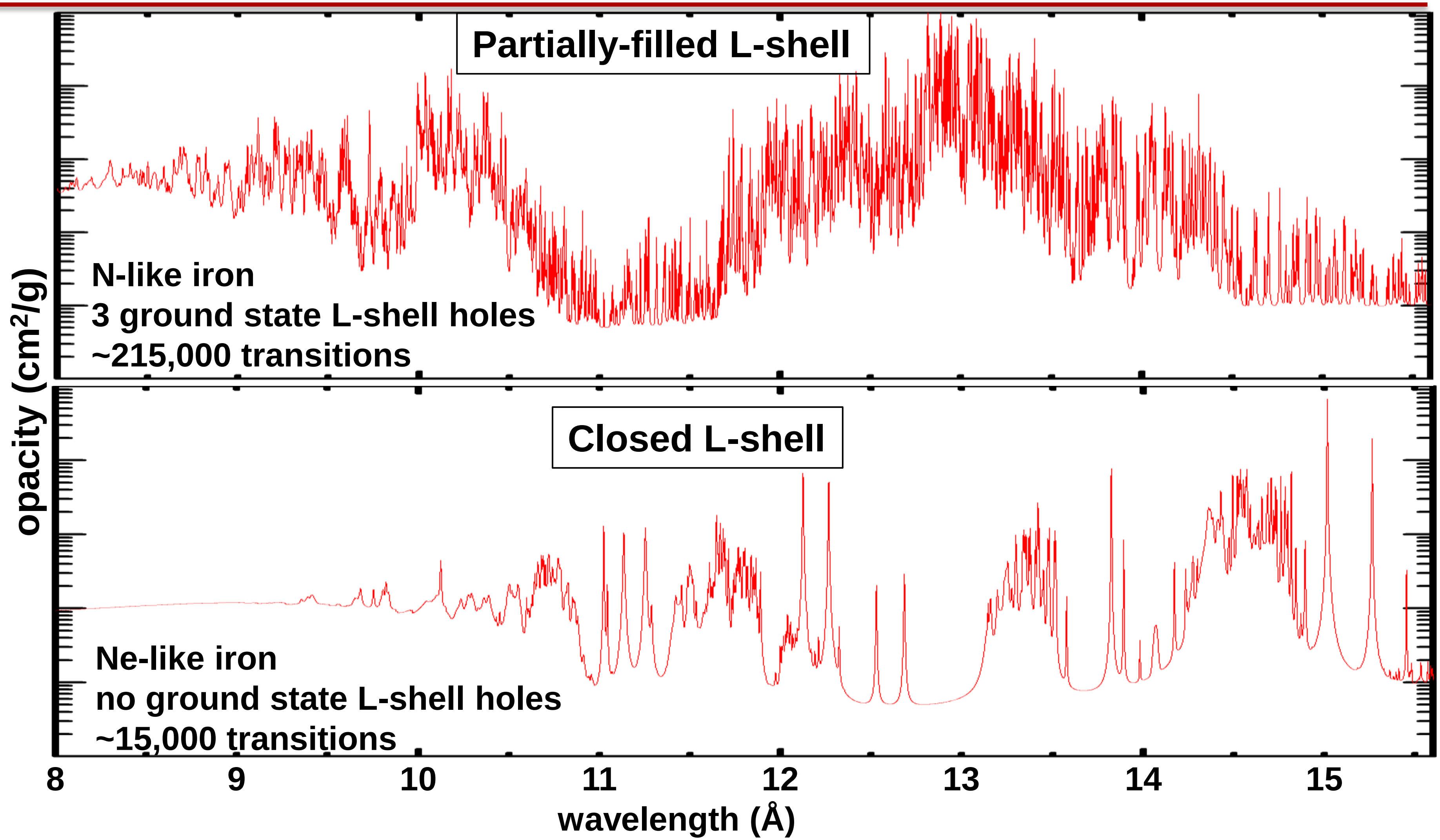


Iron at 195 eV, 4e22 electrons/cc
SCRAM calculation

<u>Challenge:</u>
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:

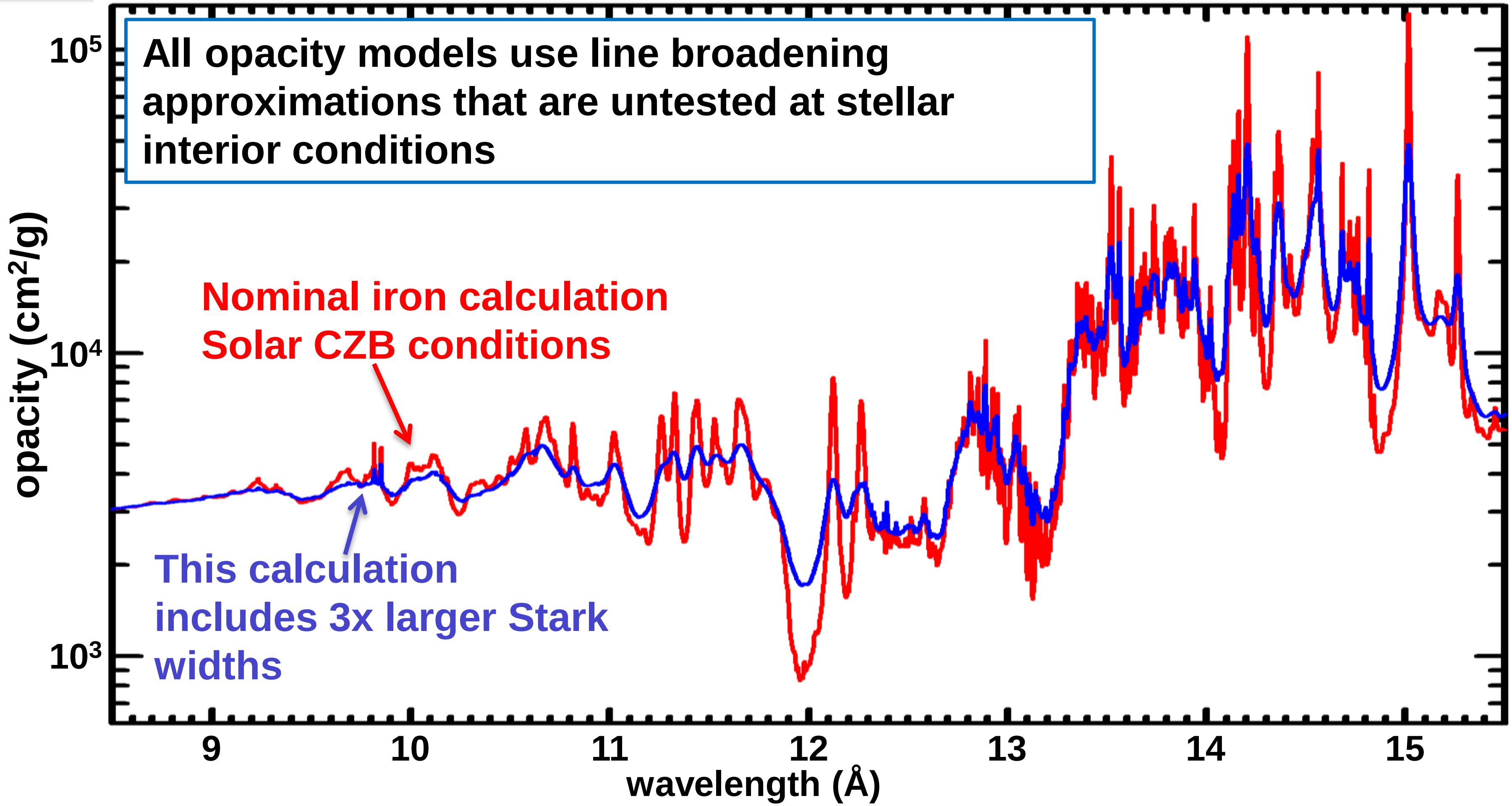
Charge state distribution

Energy level structure

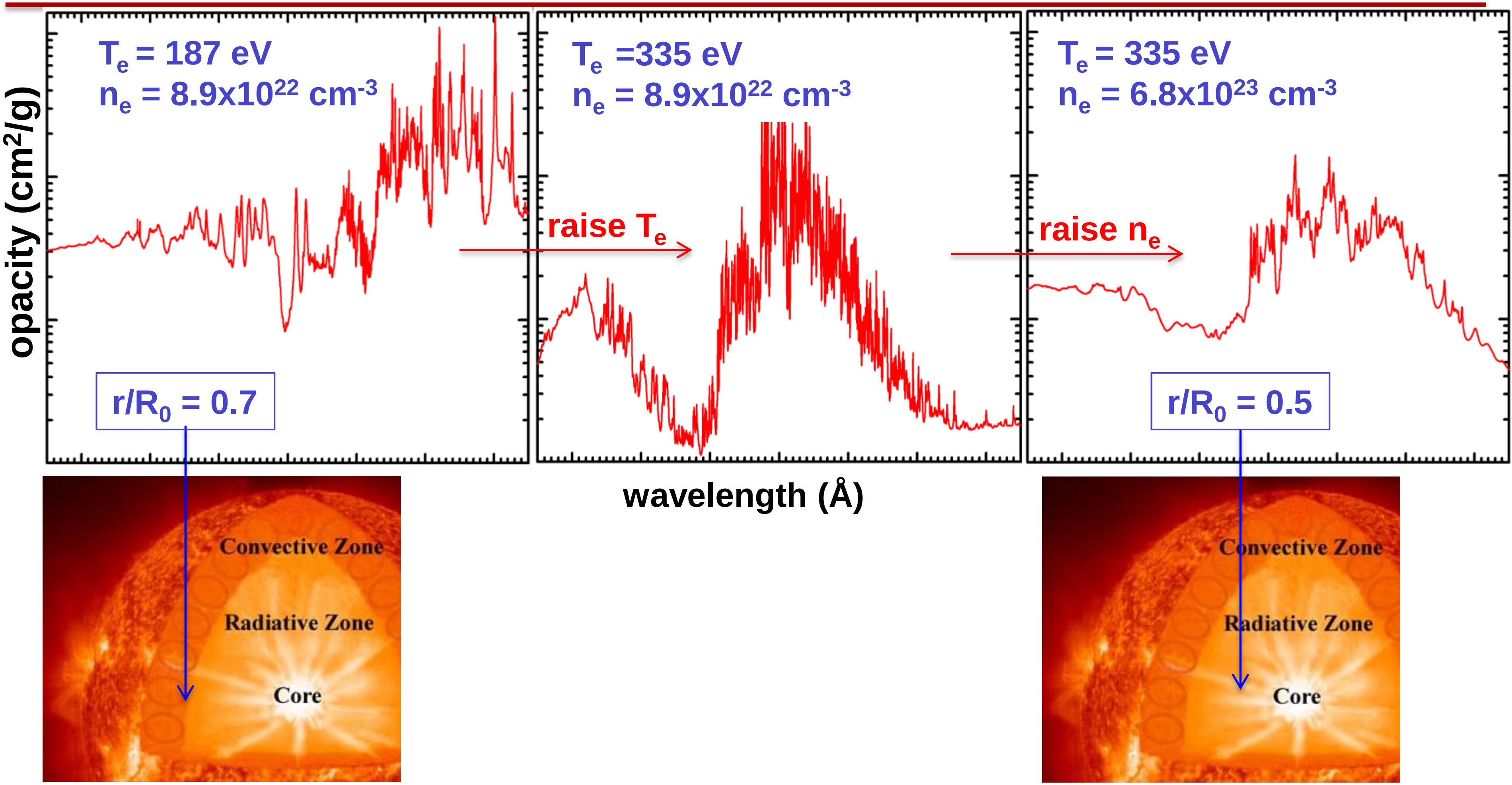
Energy level populations

Plasma effects (line broadening, continuum lowering)

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

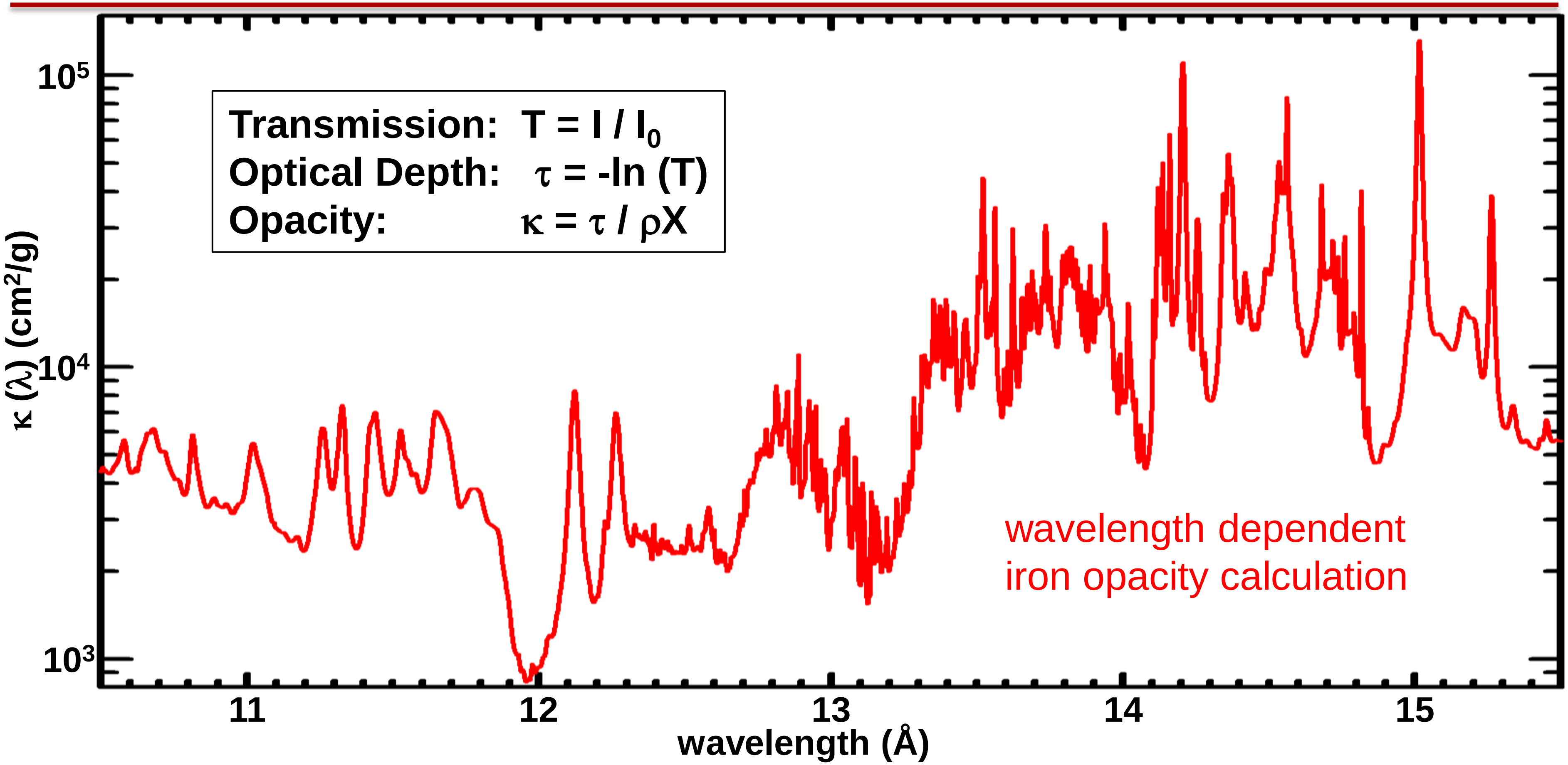


Complexity grows deeper in the sun as the solar interior temperature and density increase



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.

Outline

Motivation – the solar interior problem

What physics is a concern for opacities?

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No laboratory opacity measurements have been done at stellar interior conditions up to now. Why?

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Overarching requirements:

1. Reproduce the temperature, density, and radiation field that exist inside a star, for uniform well-controlled and well-diagnosed macroscopic samples of stellar matter

2. Backlight bright enough to overcome emission at stellar interior temperatures

High accuracy at these conditions requires large facilities and disciplined technique

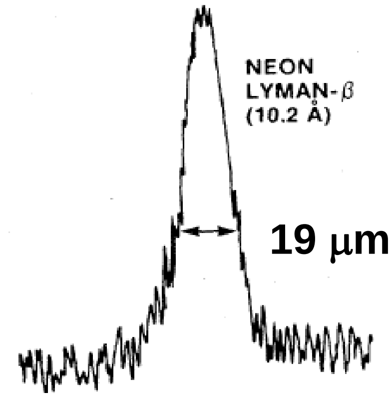
Stellar opacity measurements are possible for the first time:
MegaJoule class facilities like Z and NIF
3 decades of opacity research at smaller scale facilities to hone our approach
Advanced plasma diagnostic techniques

Future experiments at short pulse lasers (ORION) and x-ray lasers (LCLS, XFEL, SACLA) will advance opacity knowledge at extreme conditions

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

High Energy Density experiments have reached extreme conditions for many years

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



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

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

Benchmark quality opacity experiment requirements are demanding

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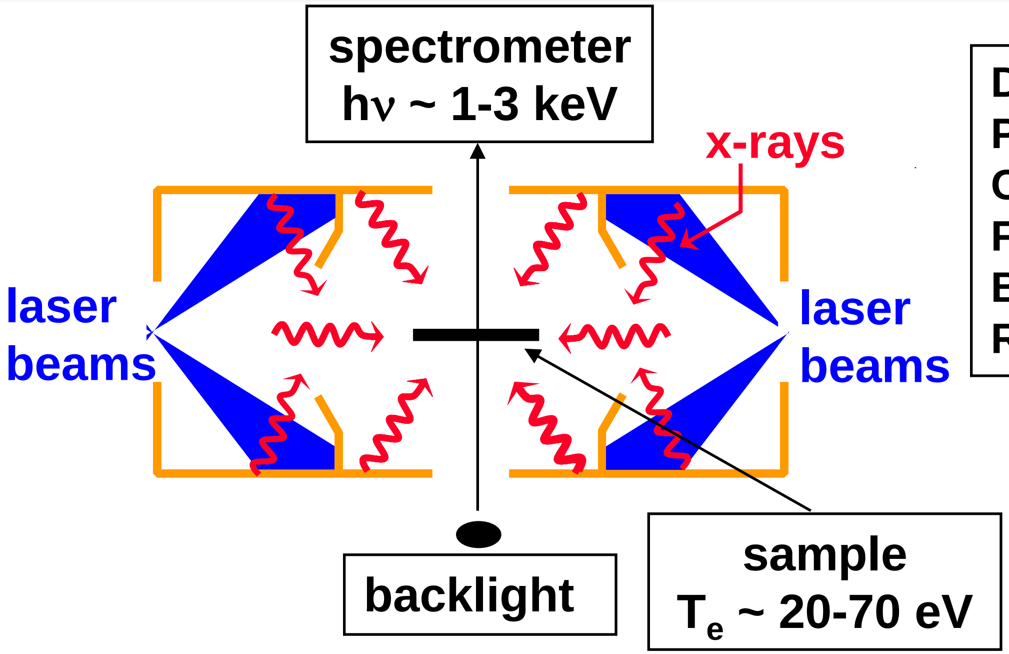
Experiment requirements:

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 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

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

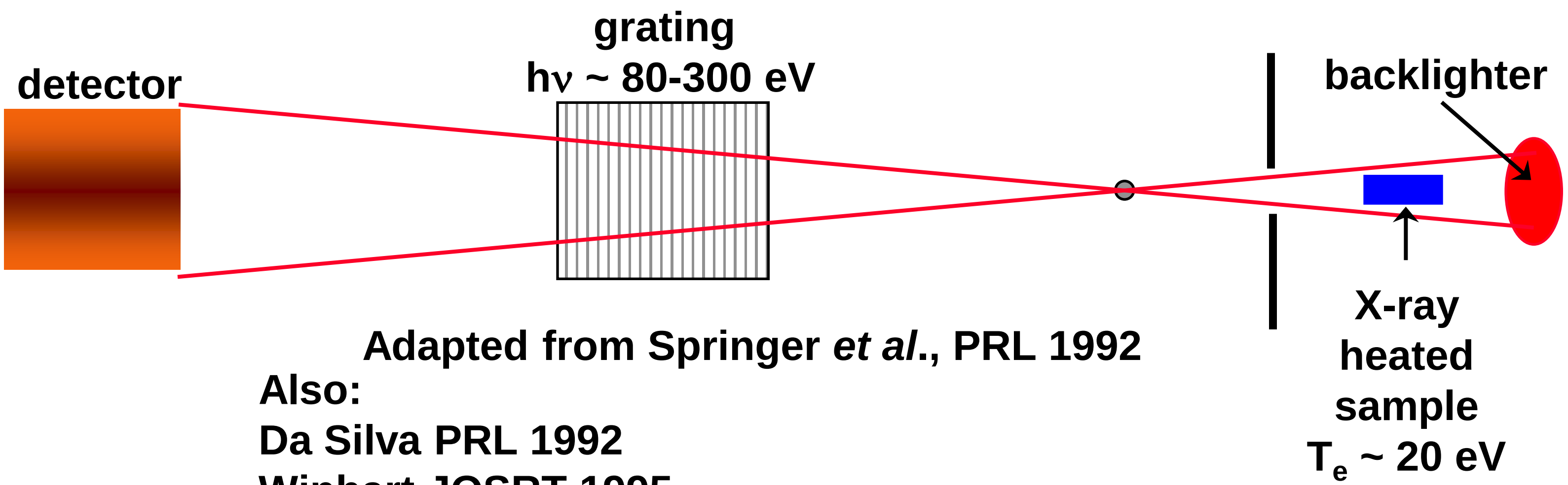
Opacity experiment requirements have been developed over 30 years



Davidson, Appl Phys Lett 1988
Perry, PRL 1991, Phys Rev E 1996
Chenais-Popovics, ApJ 2000
Foster, PRL 1991
Bruneau, J Phys B 1992
Renaudin, JQSRT 2006

- A few experiments have achieved benchmark status
- The temperatures and densities were too low for stellar interiors
- The photon energies were too high for stellar envelopes

Experiments measured opacities for outer stellar atmospheres beginning in the 1990s



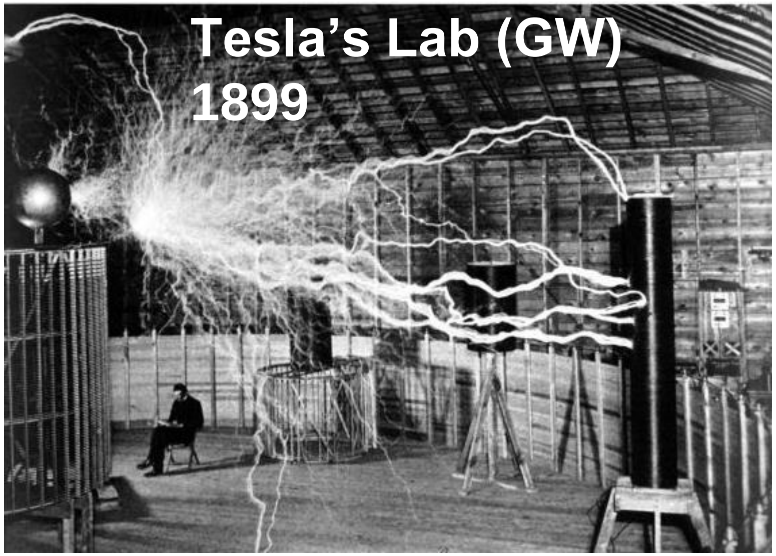
Adapted from Springer *et al*., PRL 1992

Also:
Da Silva PRL 1992
Winhart JQSRT 1995
Springer JQSRT 1997
Loisel 2009

This work supported the 2-3x opacity increase calculated by OPAL for stellar envelopes

These were proof-of-principle experiments and true experiment benchmarks have still not been performed for this important problem

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

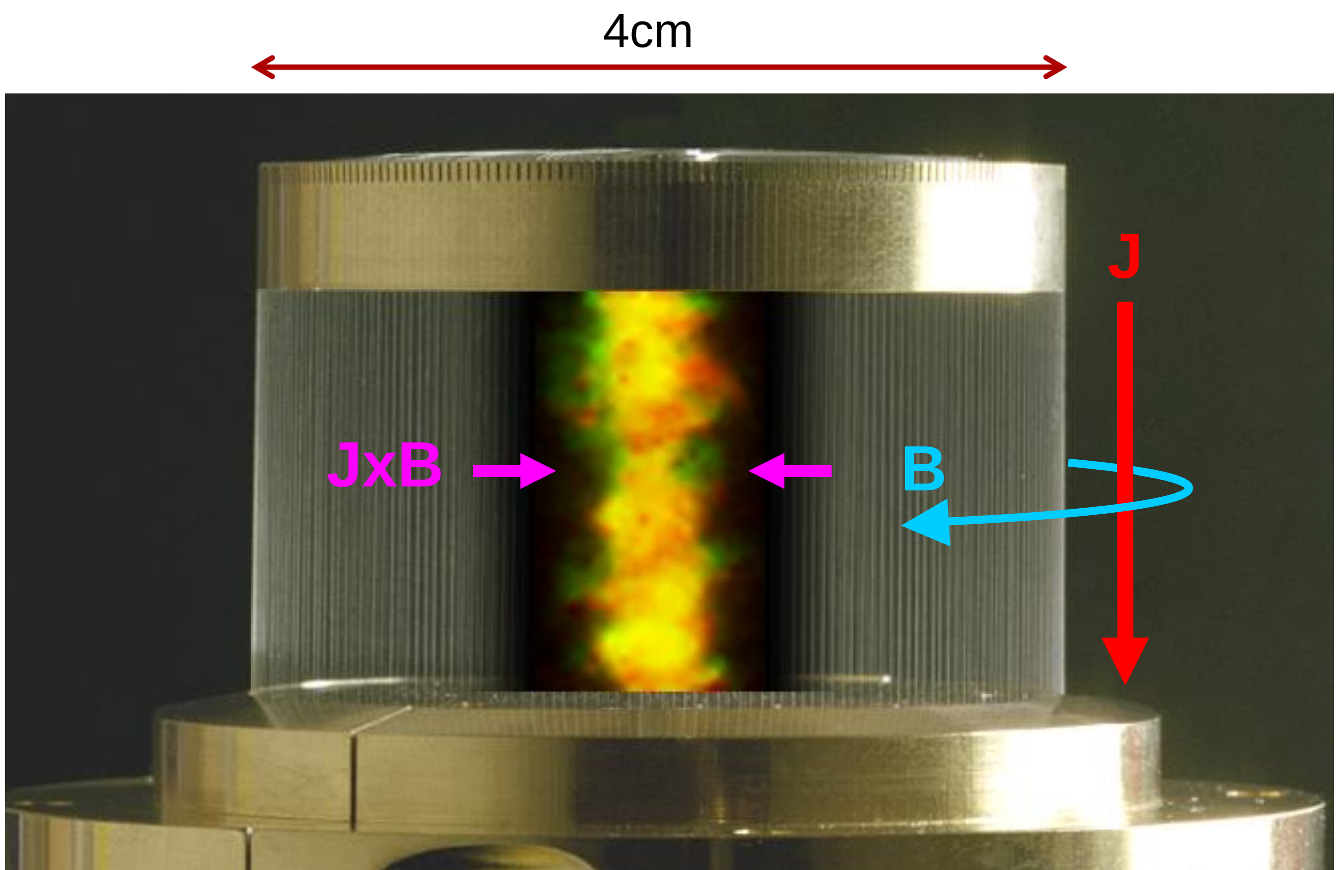


- **Pulsed power has been developed over the last century**

<u>Goal</u>: "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.

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



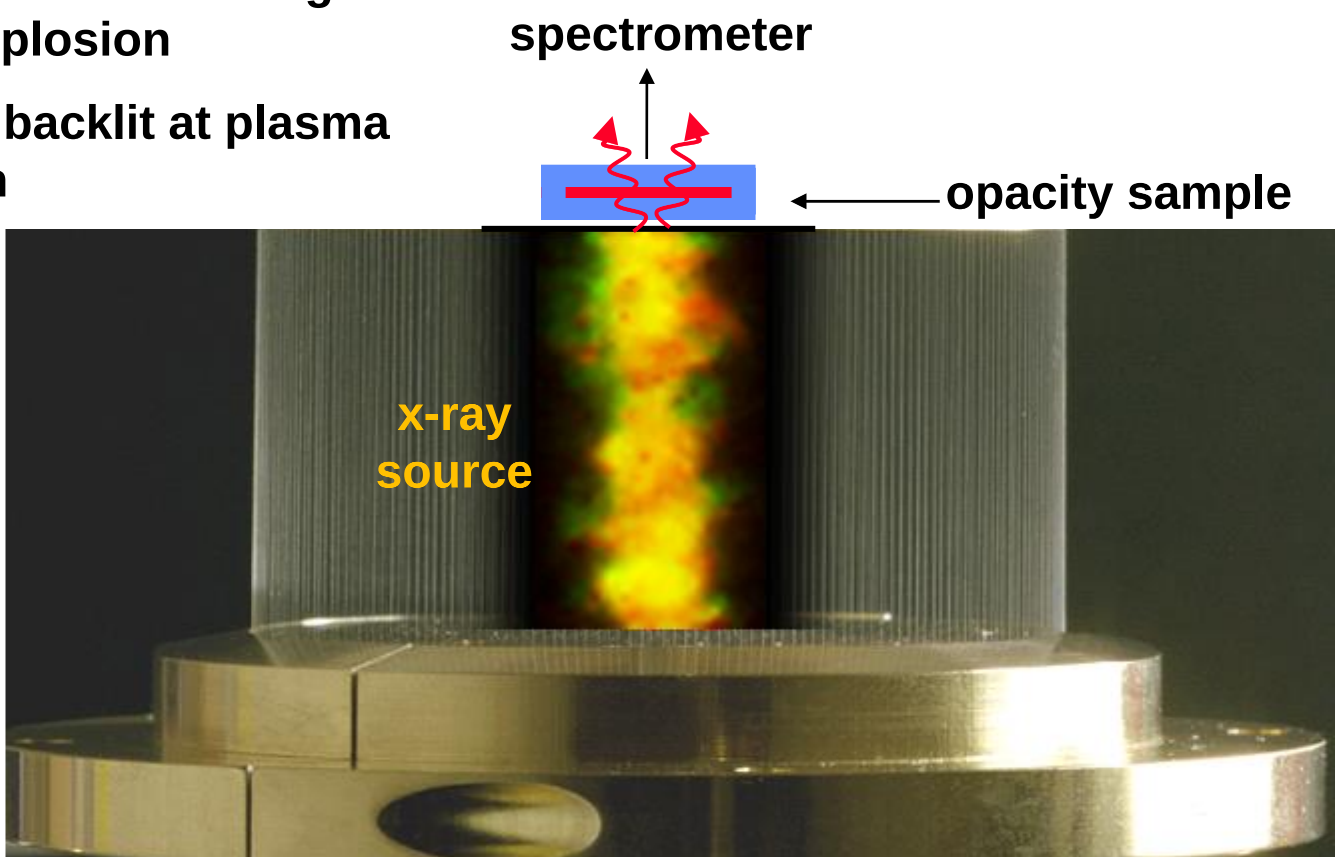
P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

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

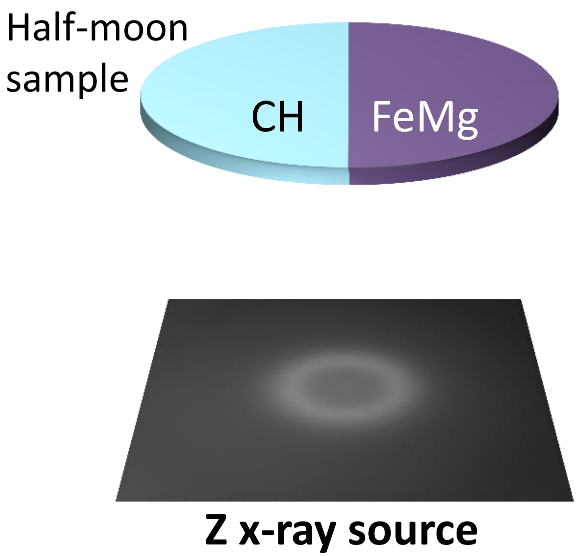
The Z x-ray source both heats and backlights samples to stellar interior conditions.

Sample is heated during plasma implosion

Sample is backlit at plasma stagnation



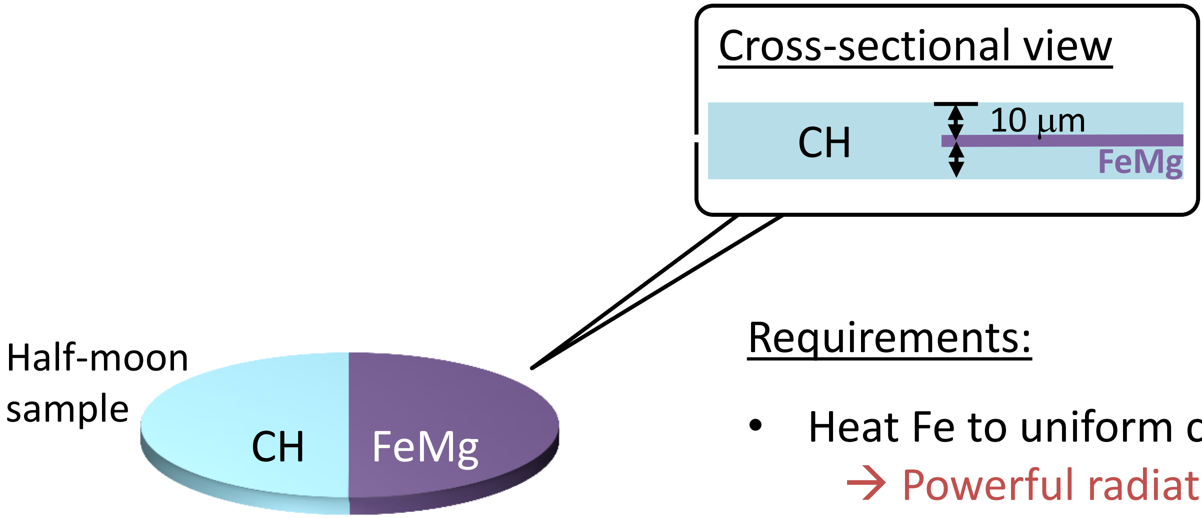
Z opacity science configuration satisfies challenging requirements for reliable opacity measurements

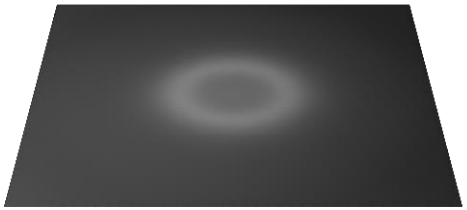


Requirements:

- Heat Fe to uniform conditions
  → Powerful radiation
- Measure Fe conditions independently
  → Mg spectroscopy
- Bright backlight
  → 350 eV Planckian at stagnation
- Measure transmission spectra accurately
  → multiple spectra

Z opacity science configuration satisfies challenging requirements for reliable opacity measurements





Z x-ray source

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- Heat Fe to uniform conditions
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Bailey et al PoP 2009

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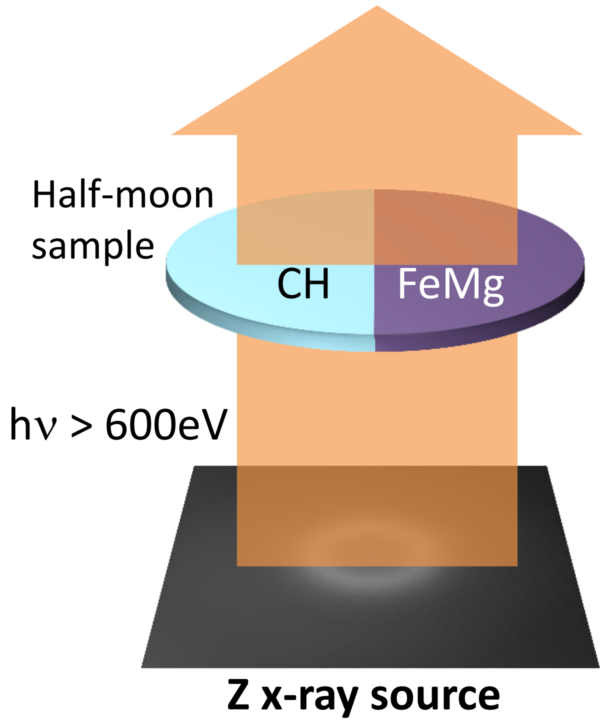

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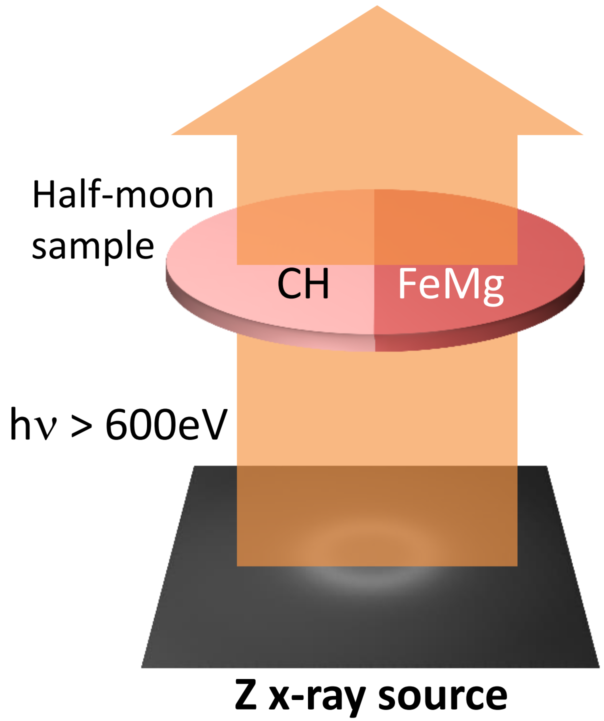

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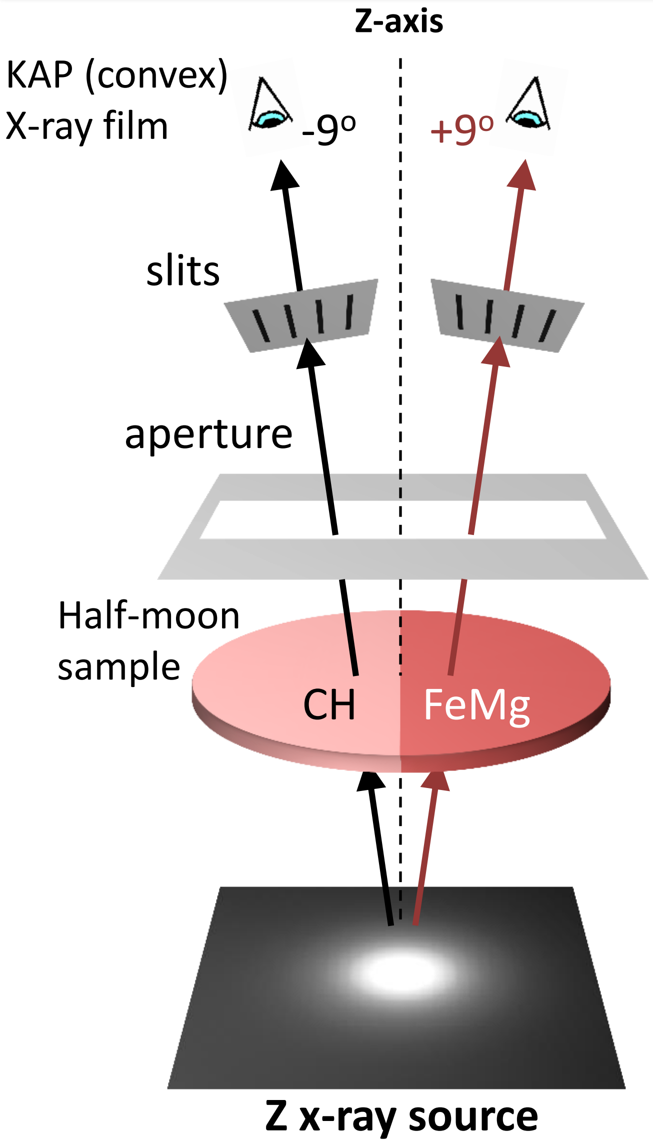

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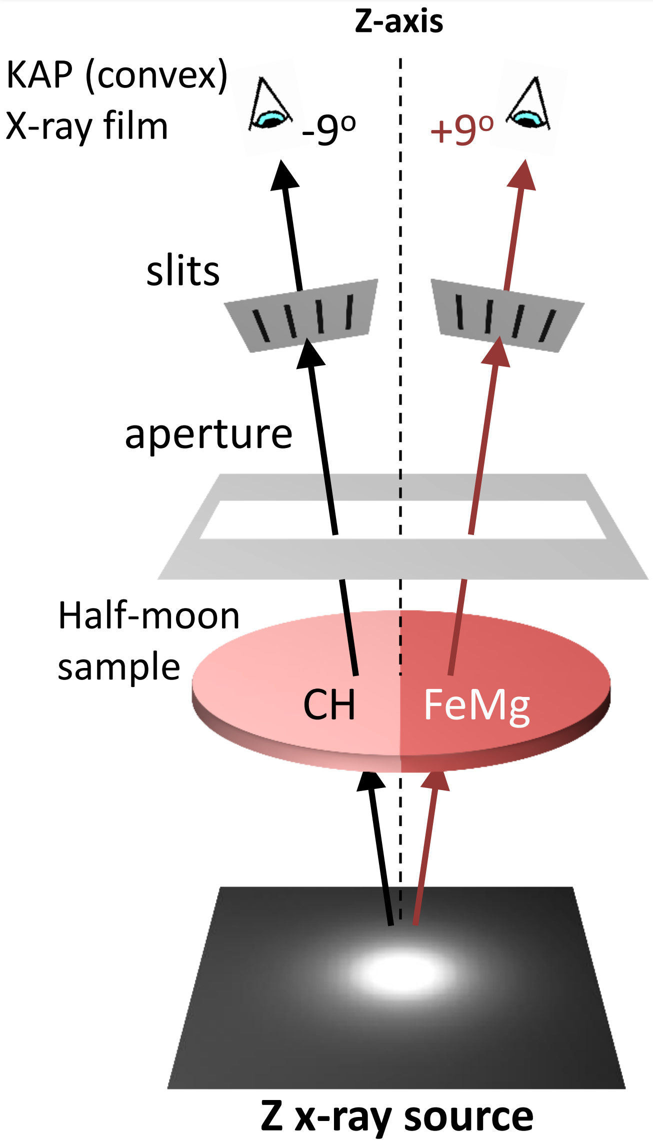

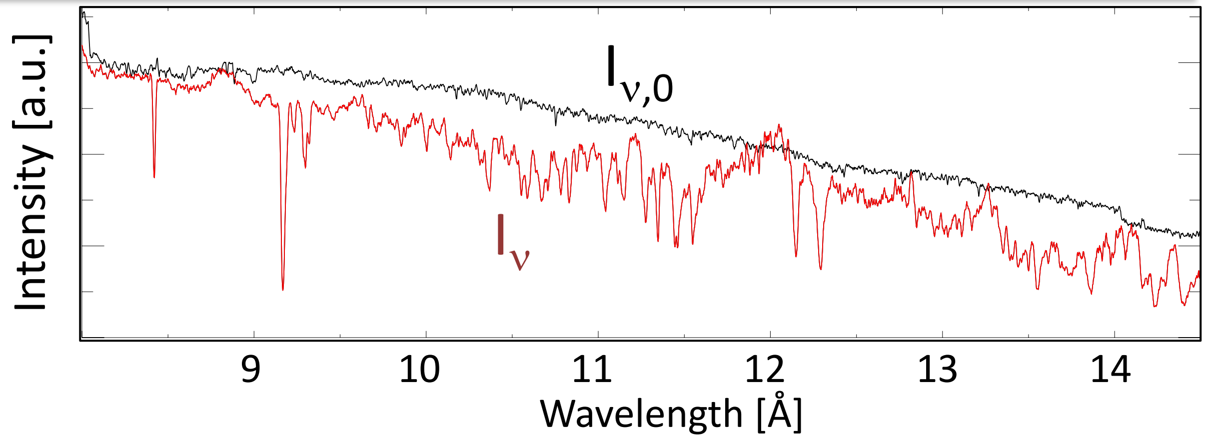

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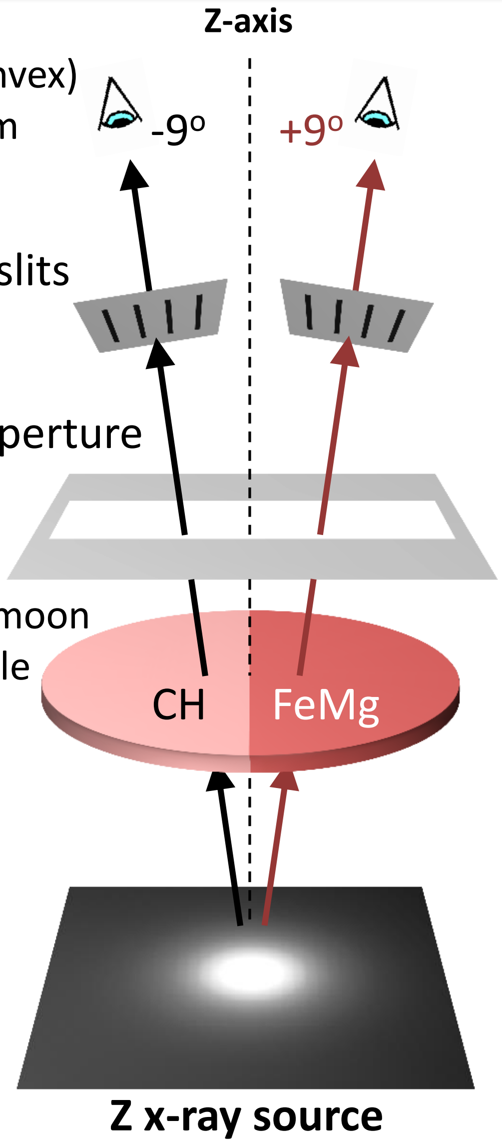

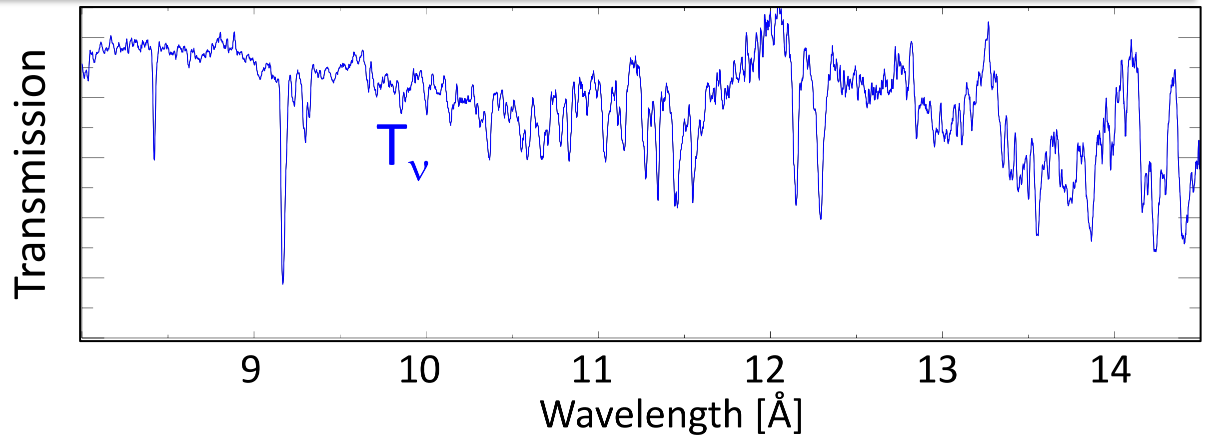

Transmission: $T_\nu = I_\nu / I_{\nu,0}$

Requirements:

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  - → Powerful radiation
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  - → multiple spectra

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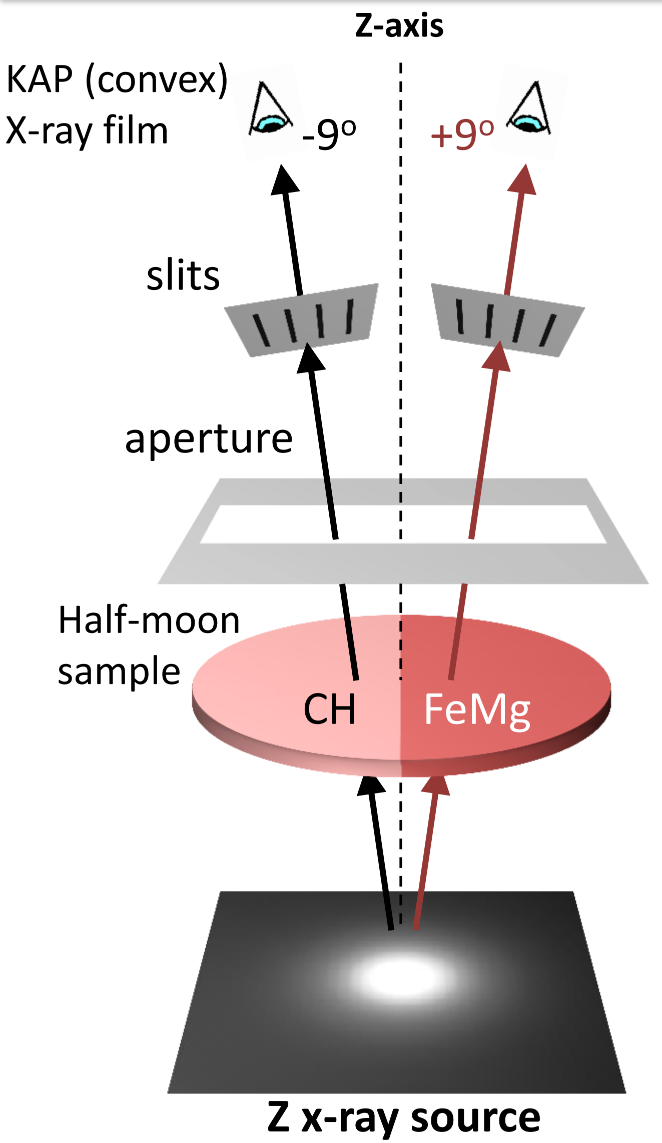
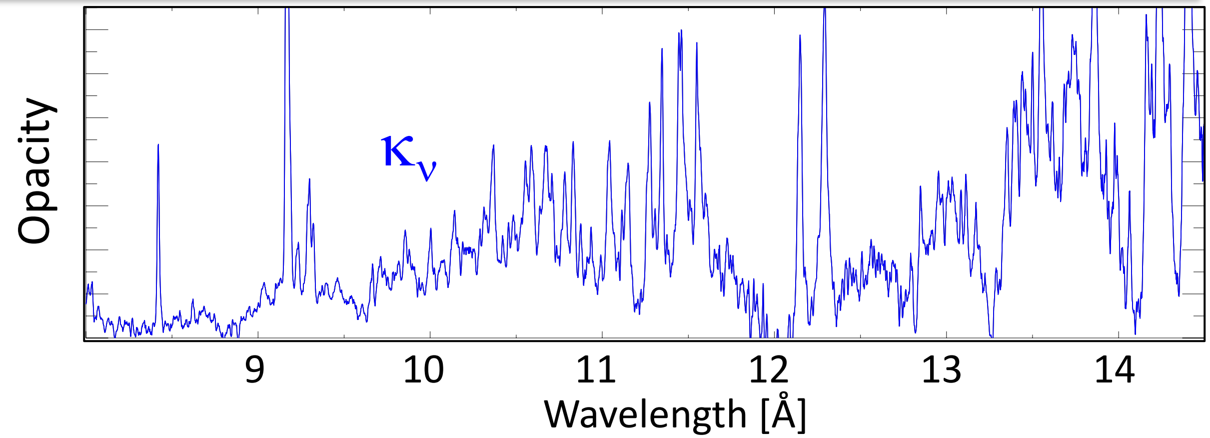




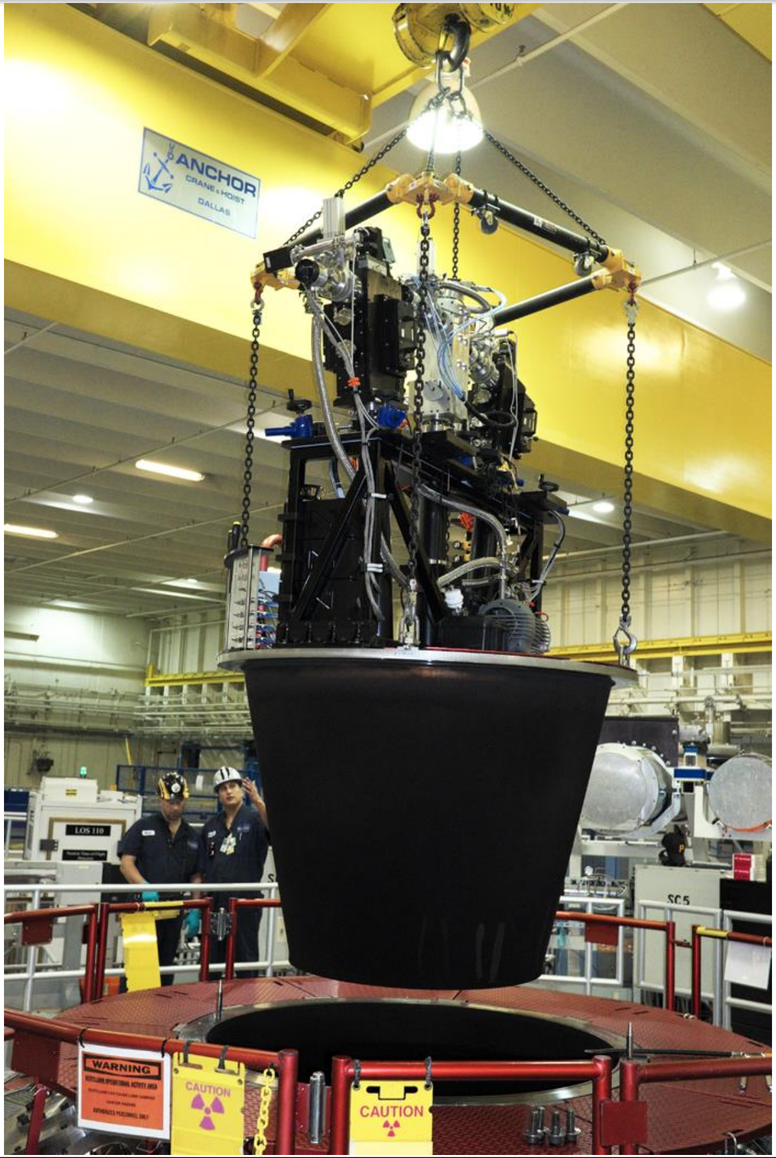
Transmission: $T_\nu = I_\nu / I_{\nu,0}$

Opacity: $\kappa_\nu = -\ln(T_\nu)/\rho L$

Requirements:

- Heat Fe to uniform conditions
  - → Powerful radiation
- Measure Fe conditions independently
  - → Mg spectroscopy
- Bright backlight
  - → 350 eV Planckian at stagnation
- Measure transmission spectra accurately
  - → multiple spectra

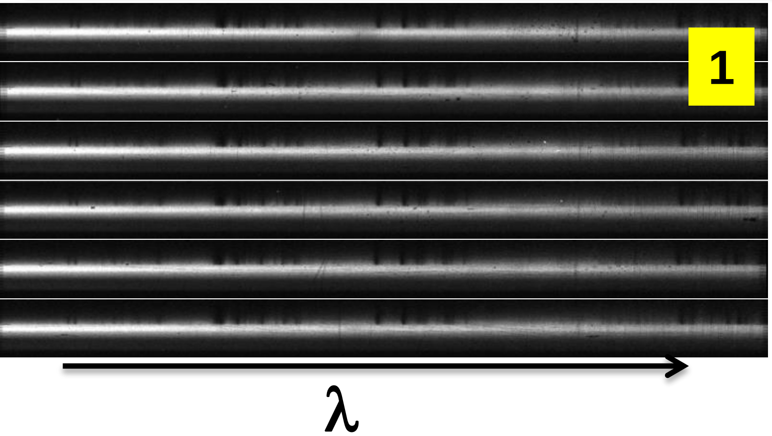
Opacity data are recorded with an array of crystal spectrometers

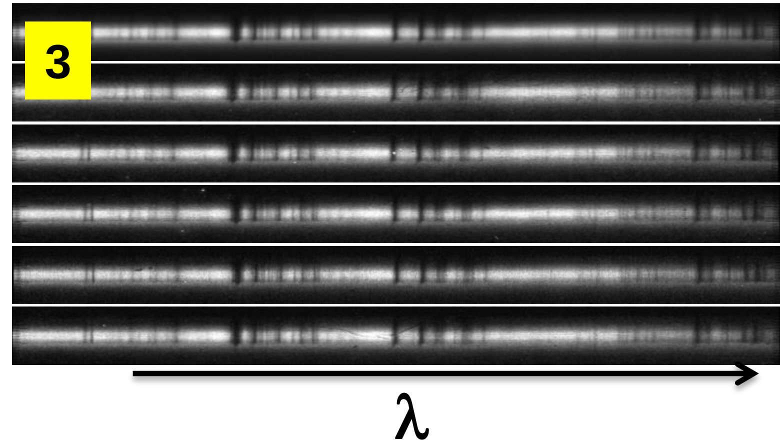


The array of opacity spectrometers is lowered into place with a 20 ton crane

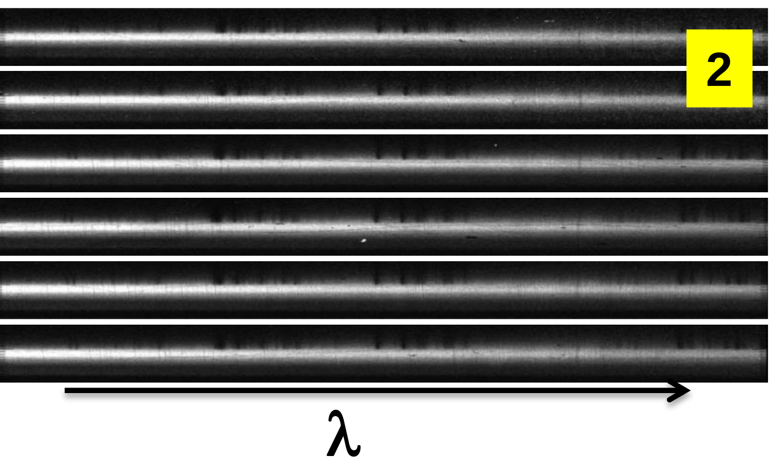
Loisel et al., Rev. Sci. Instrum. (2012)

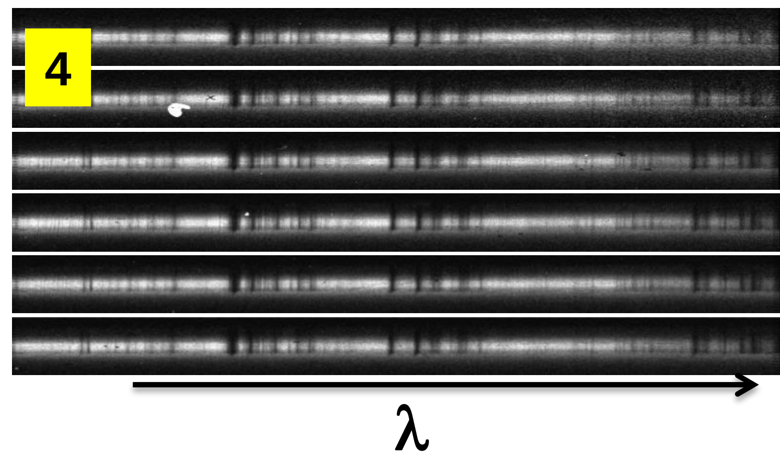
Hundreds of spectra were measured and analyzed to support the experiment reliability and reproducibility





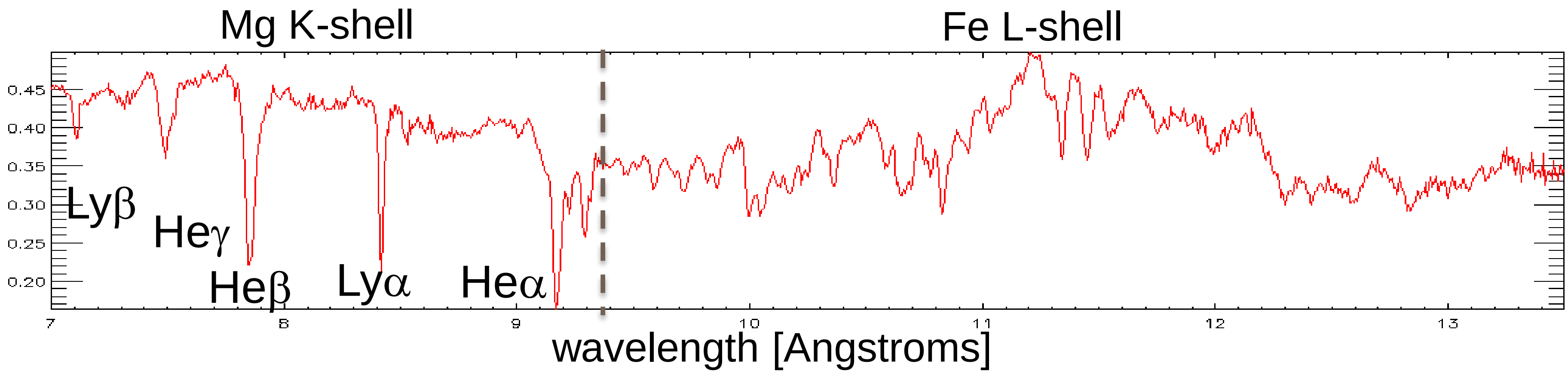
1 experiment
4 spectrometers
24 spectra



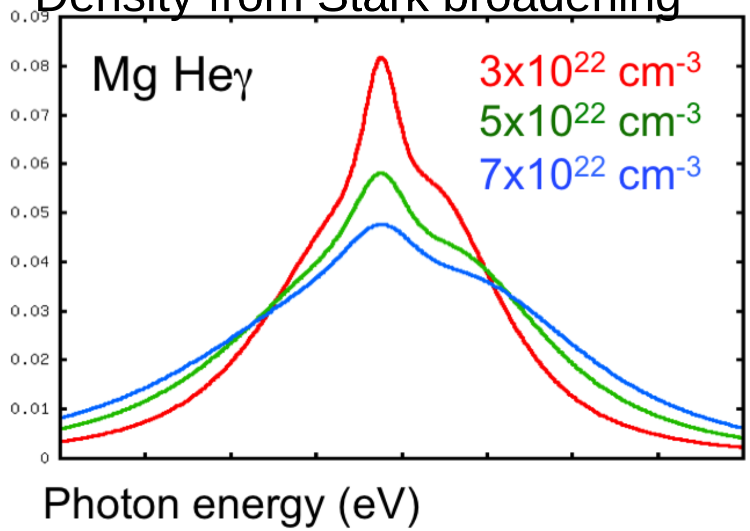


Averaging results from many measurements provides ~ 15% opacity accuracy

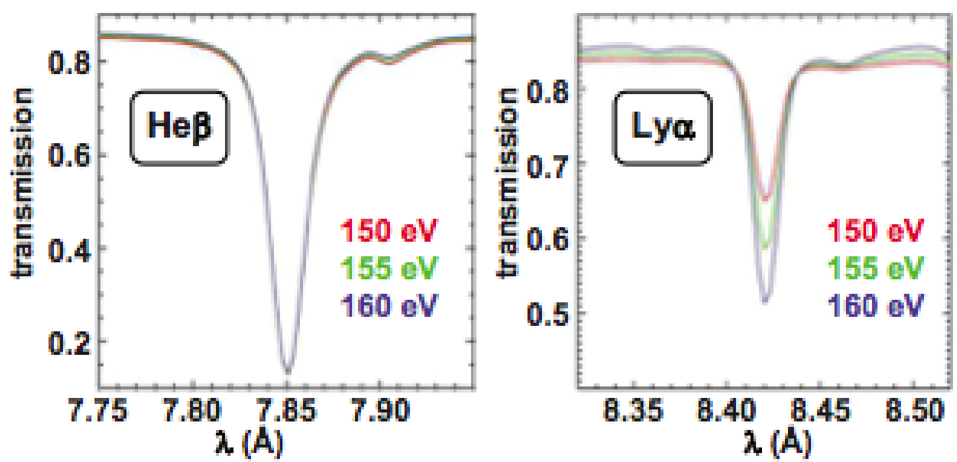
Plasma conditions are inferred by mixing Mg with Fe and using K-shell line transmission spectroscopy



Density from Stark broadening[1]

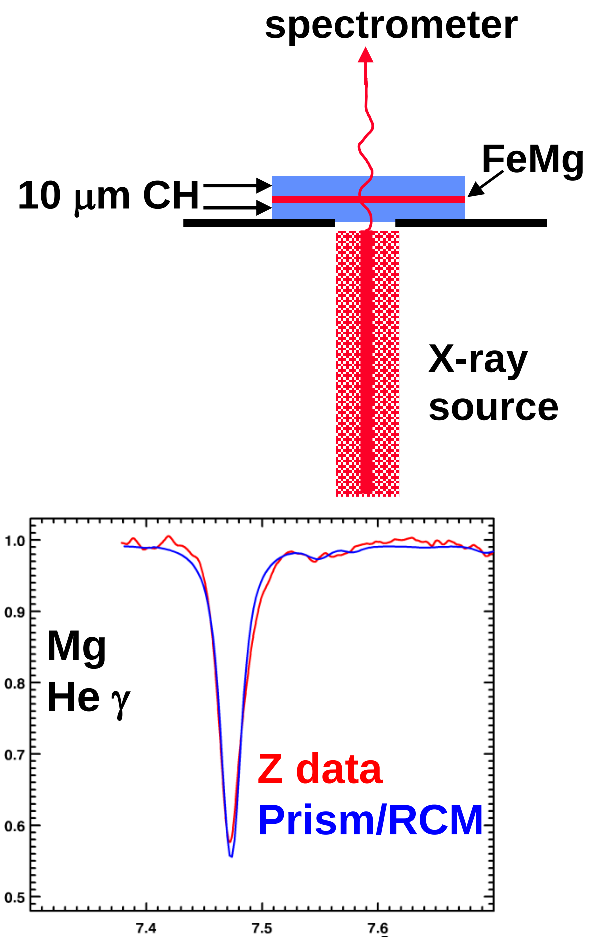


Temperature from line ratios



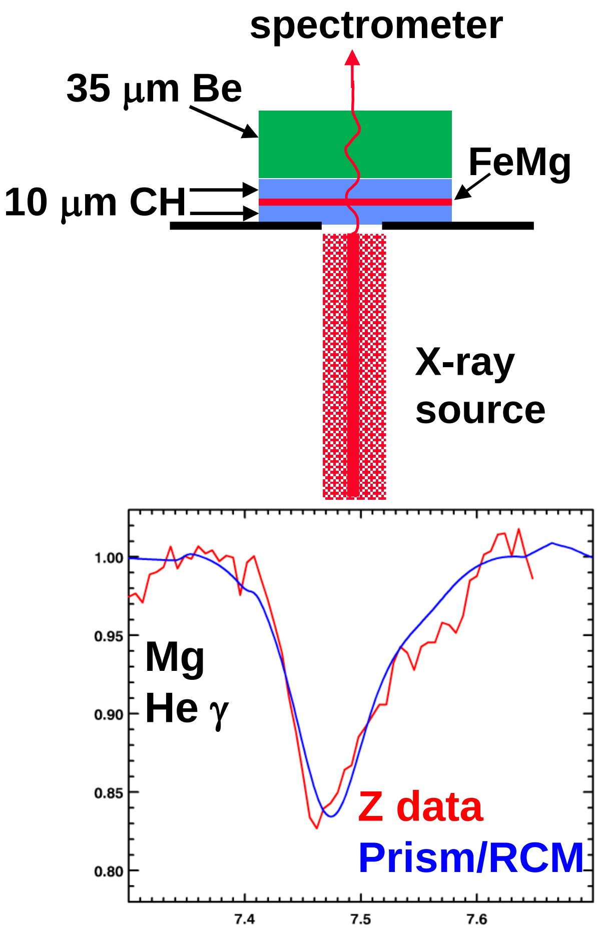
R. C. Mancini, comp. phys. commun. (1991)
T.N. Nagayama et. al. RSI (2013)
T.N. Nagayama et. al. POP (2014)

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



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

$T_e \sim 167$ eV



$n_e \sim 3e22\ cm^{-3}$

$T_e \sim 184$ eV

Nash et al RSI (2010)

Outline

Motivation – the solar interior problem

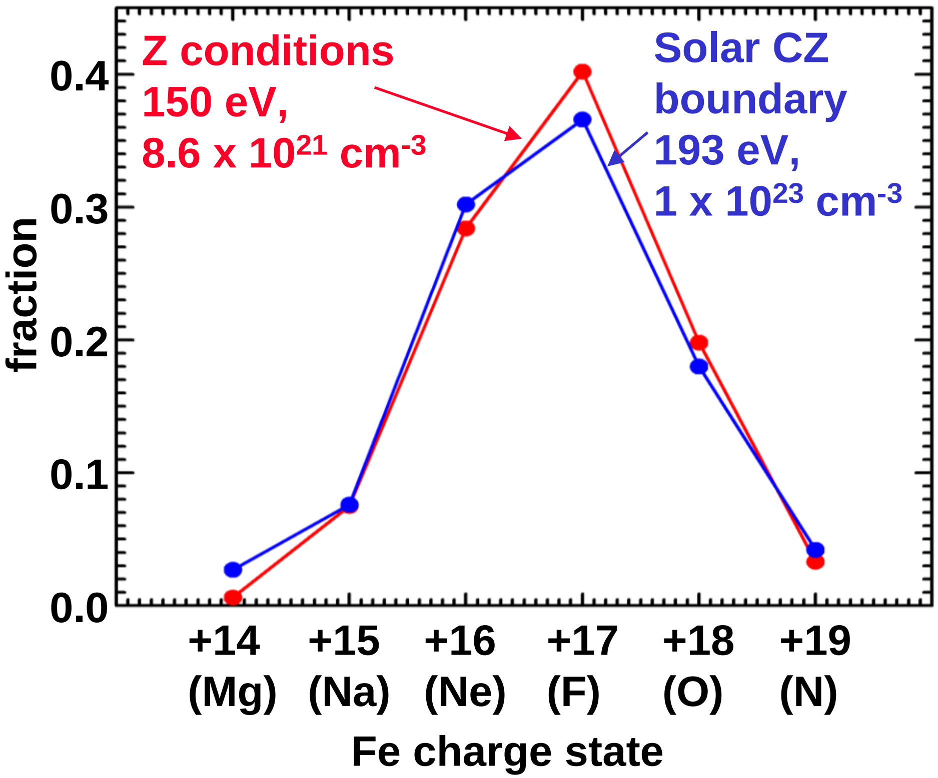
What physics is a concern for opacities?

How do we do opacity measurements?

Opacity results

How can we resolve the model-data discrepancy?

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



Producing the correct charge states enables opacity model tests:

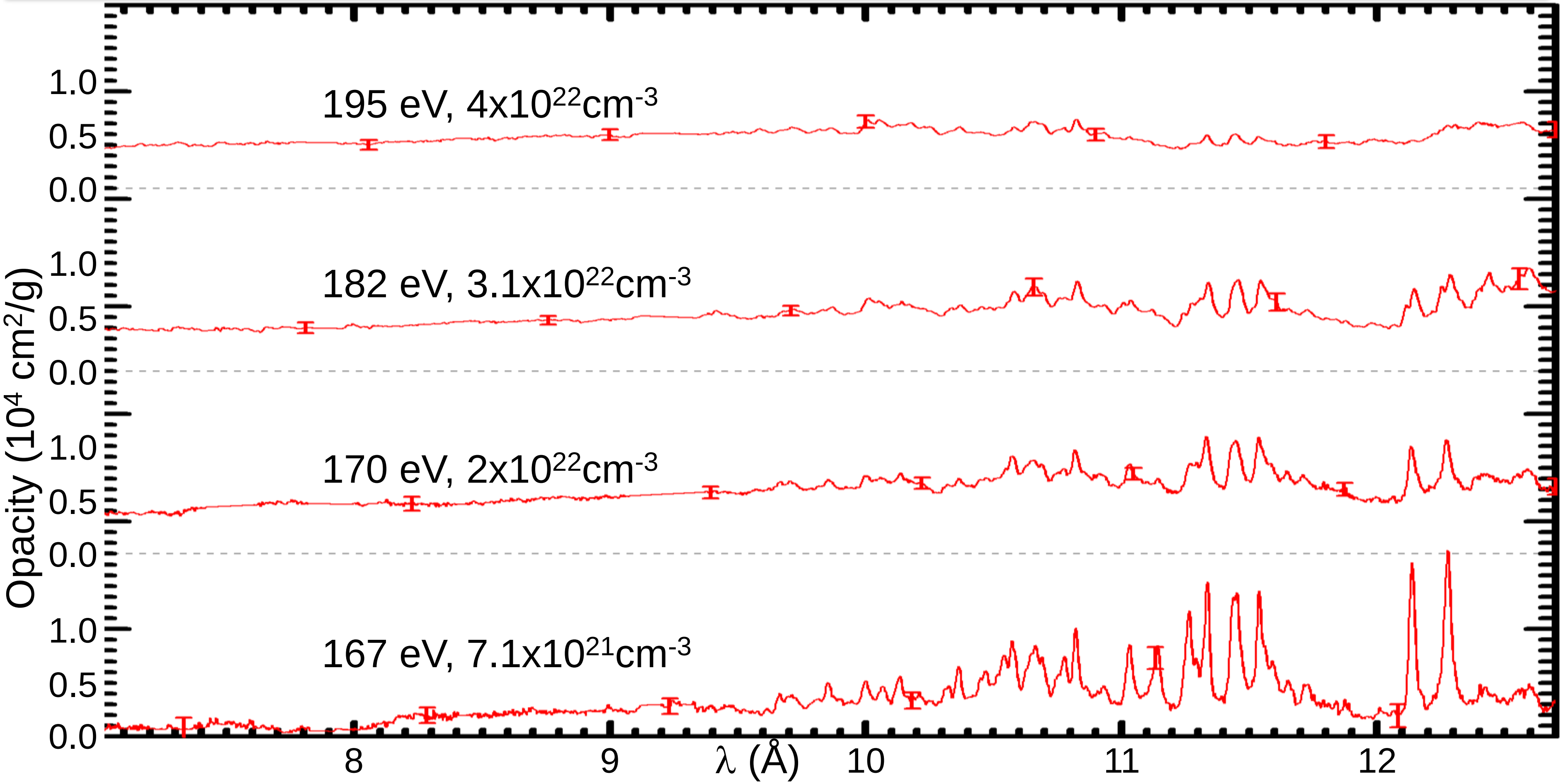
1) Charge state distribution

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

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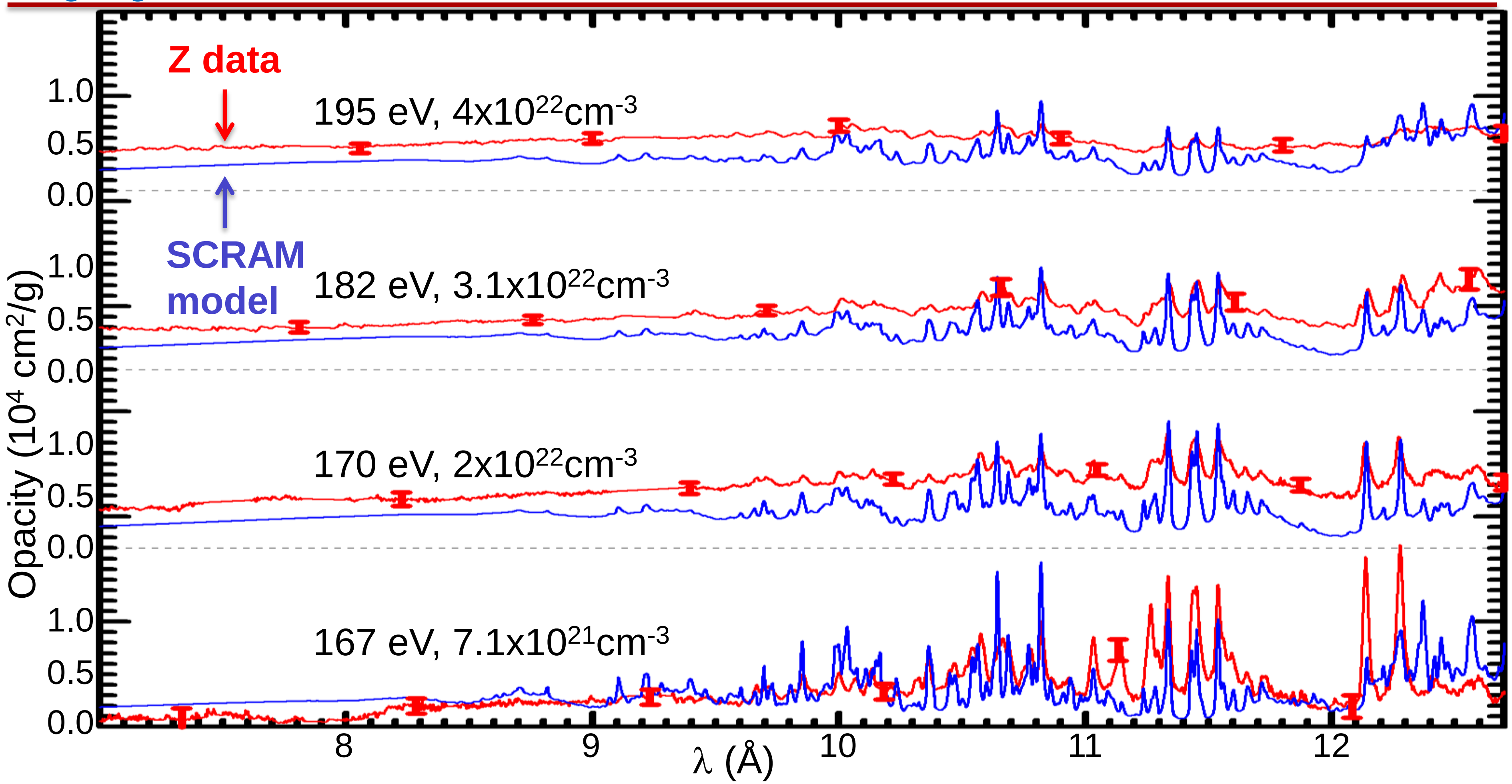

At high temperature , density, calculations are generally lower than the data

Bailey *et al.*, PRL (2007)

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

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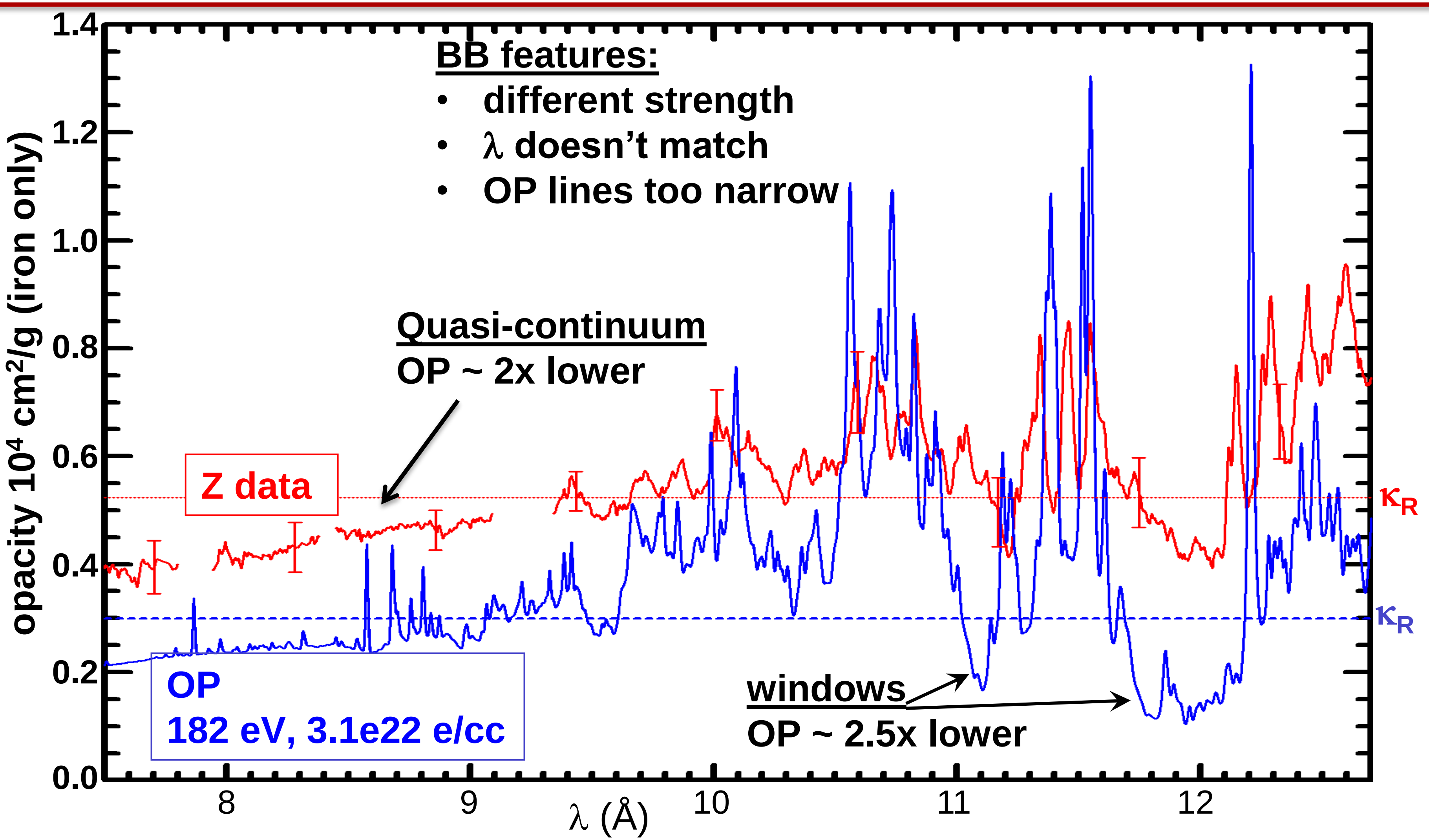
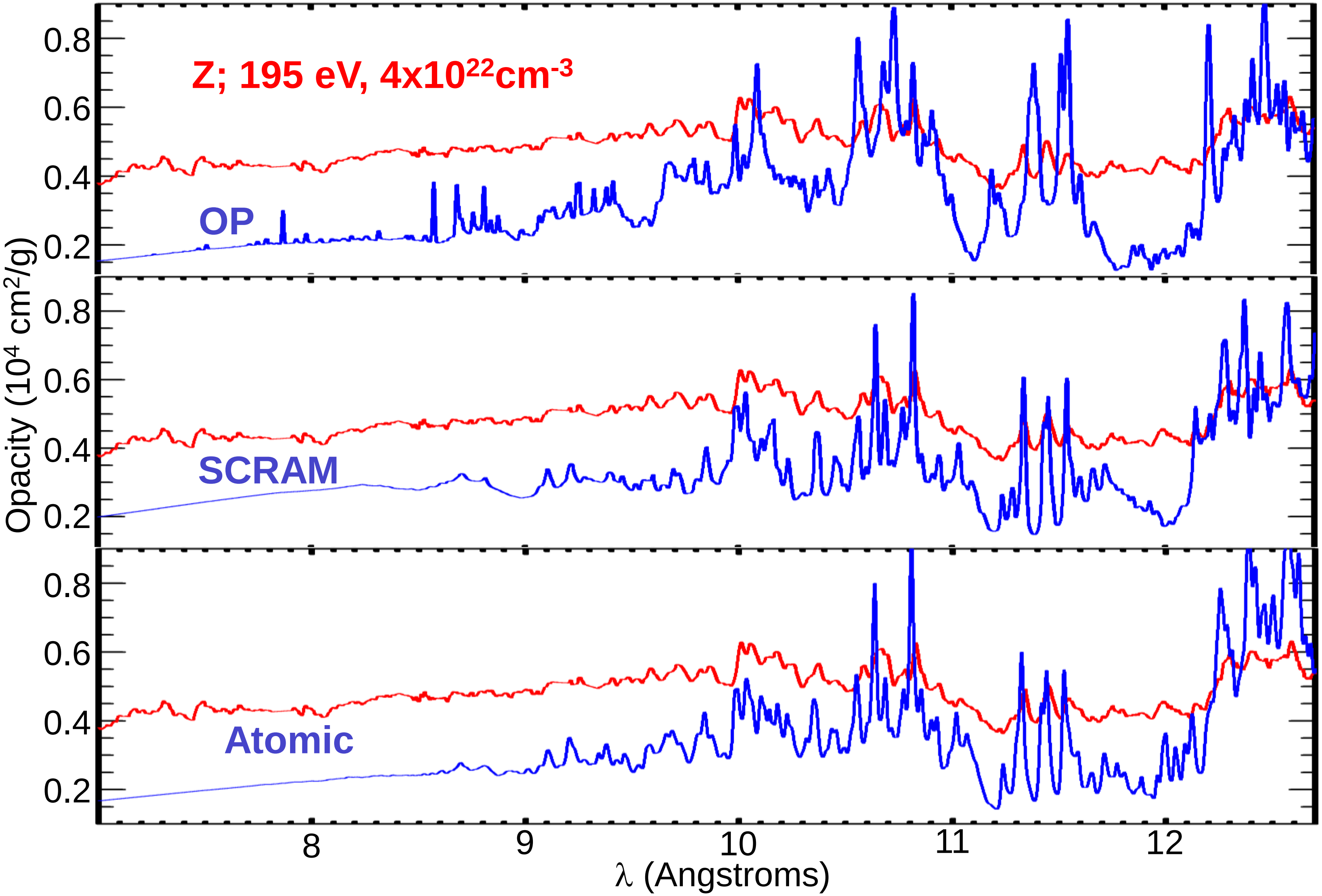


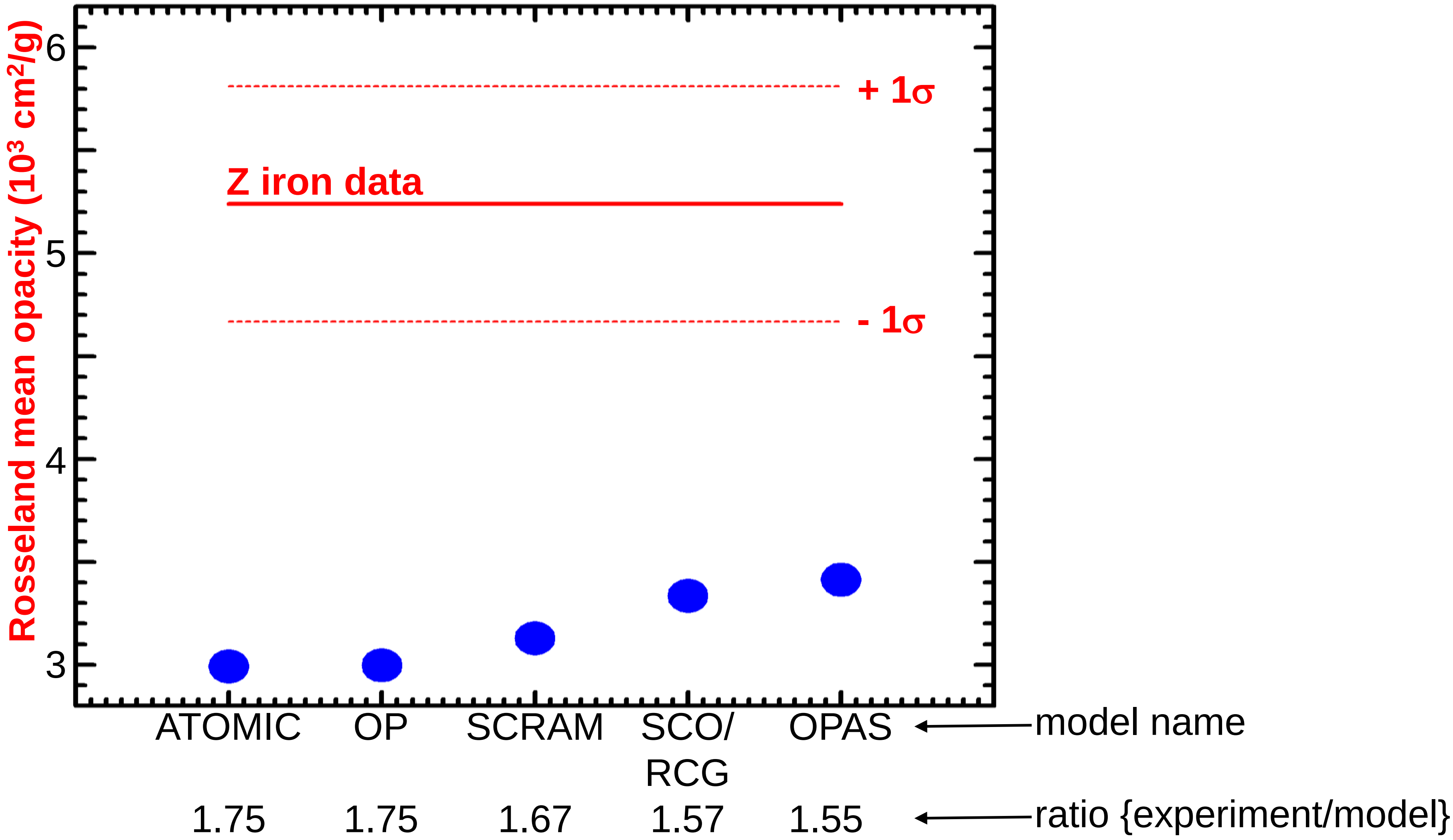
No model examined up to now has satisfactory agreement with iron opacity measured at near-CZB conditions

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

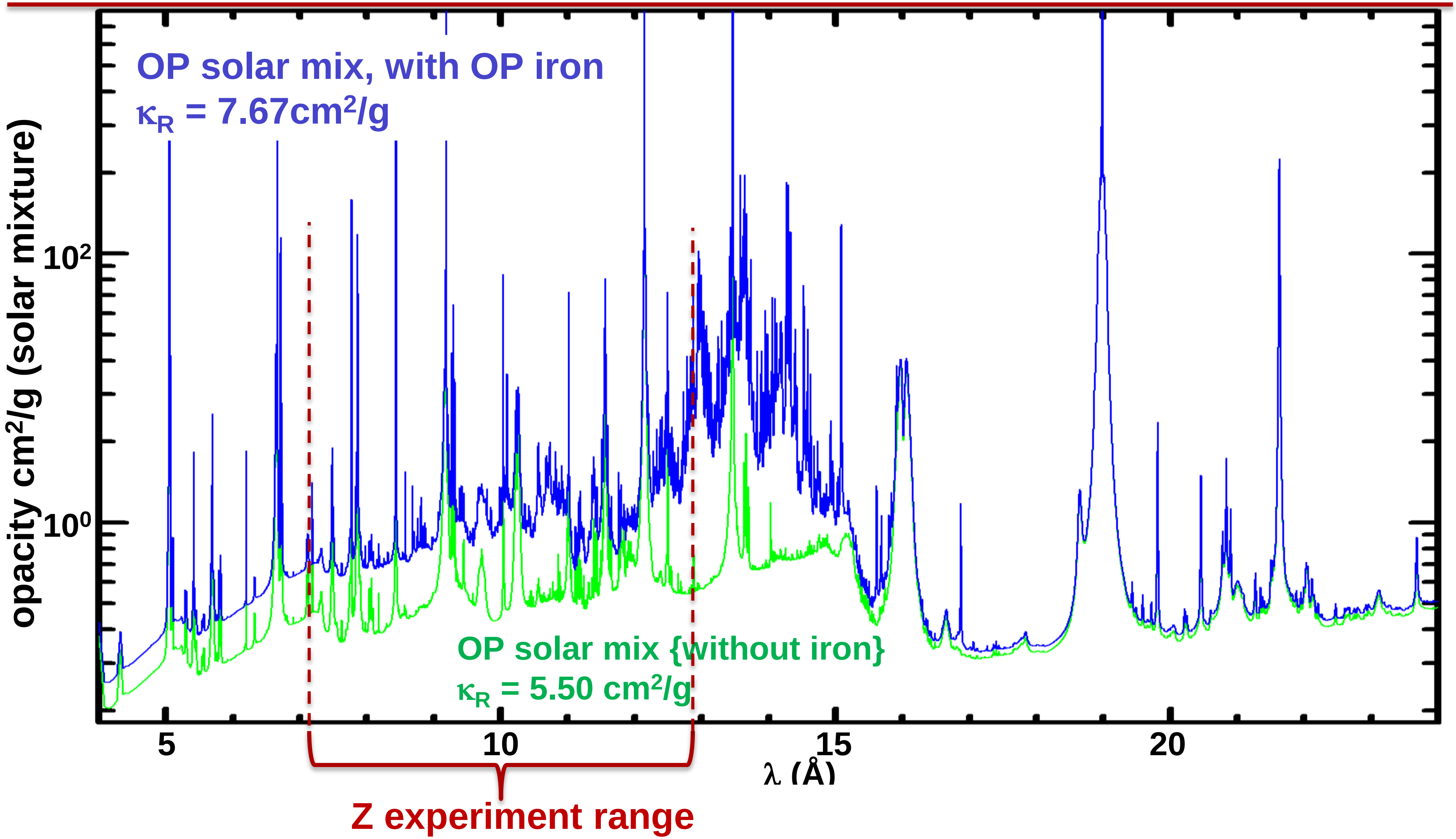
No model examined up to now has satisfactory agreement with iron opacity measured at near-CZB conditions



The measured pure iron Rosseland mean opacity is higher than calculated

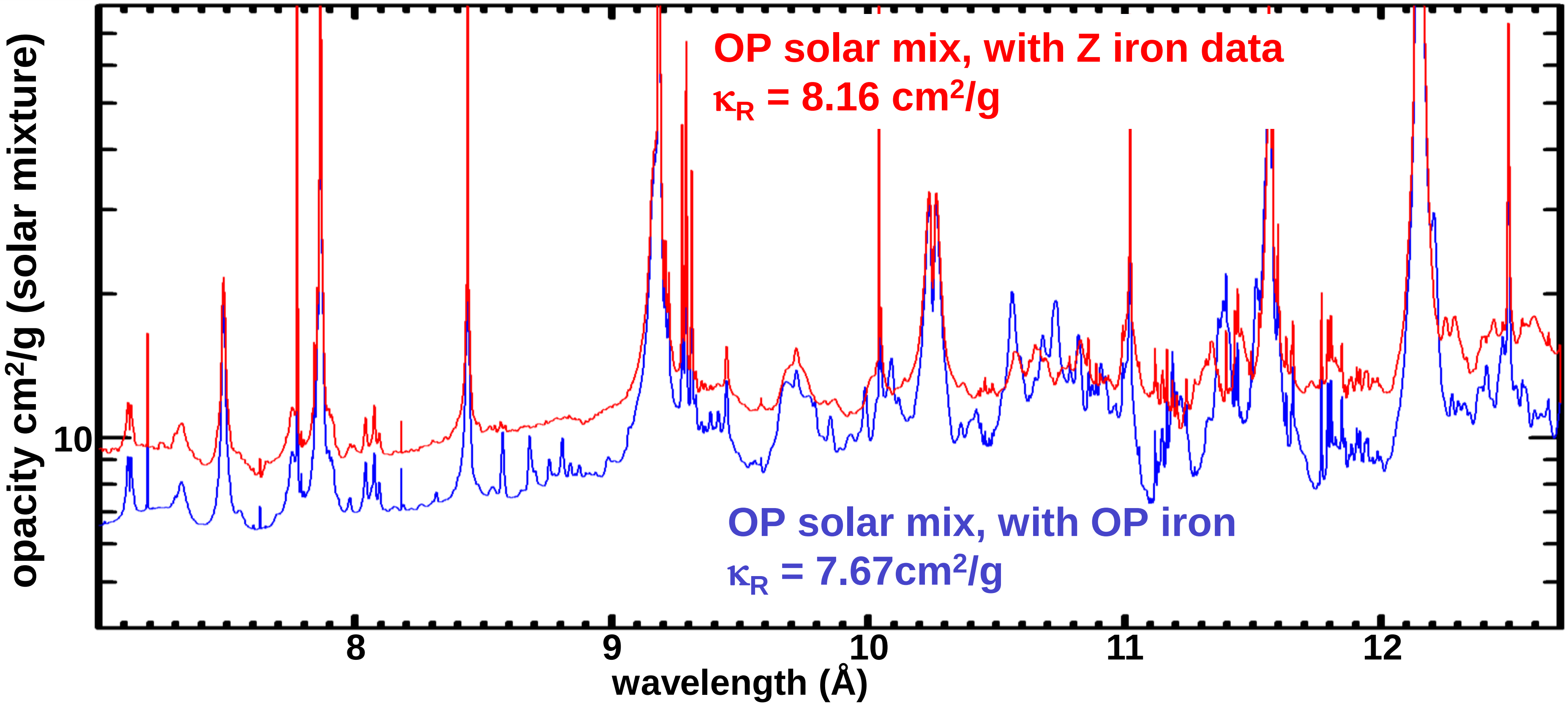


The sun contains many elements and the impact of changing iron opacity is diluted



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



- **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

Outline

Motivation – the solar interior problem

What physics is a concern for opacities?

How do we do opacity measurements?

Opacity results

How can we resolve the model-data discrepancy?

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 measuring longer wavelengths

B) Z experiments with lower and higher atomic number elements

C) Z experiments with lower and higher temperature and density

D) Experiments on a different platform (NIF laser)

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

More than eleven different potential systematic errors were investigated:

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

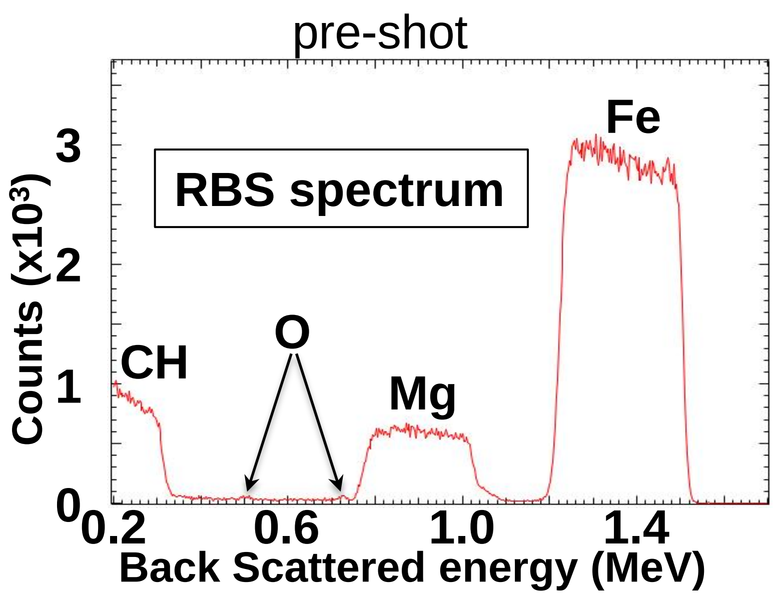
Sample areal density errors
Transmission errors
Spatial non-uniformities
Temporal non-uniformities
Departures from LTE
Plasma diagnostic errors
} True opacity potentially either lower or higher than inferred opacity

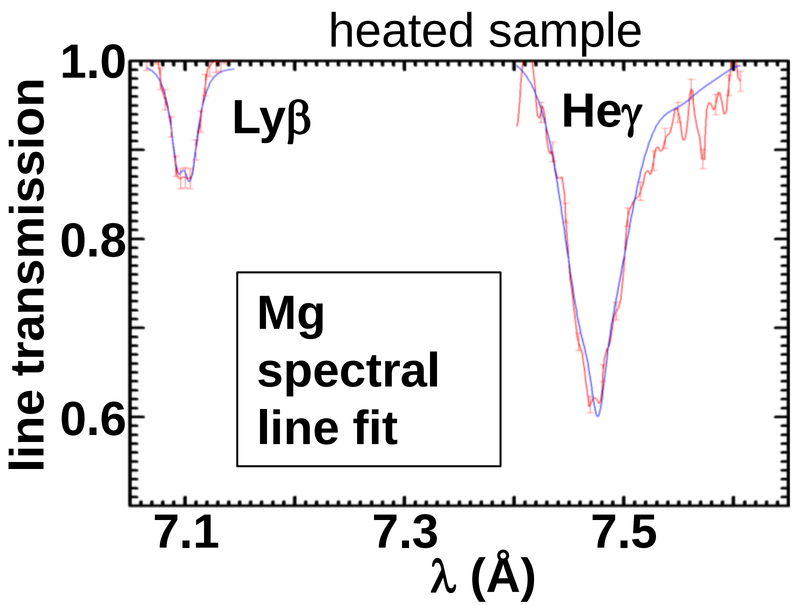
In-situ areal density measurements confirm sample hydro does not cause the opacity model-data discrepancy

Pre-shot areal density measured using Rutherford Back Scattering on witness

Question: Could the sample evolve in some way that increases the areal density?

Solution: Measure sample areal density directly on the heated sample





$$\frac{\rho X\ [\text{Mg analysis on heated sample}]}{\rho X\ [\text{RBS pre-shot}]} = 0.97 \pm 0.03$$

Hydro evolution of sample does not significantly alter the areal density

RBS spectrum provided by K. Hubbard and I. Usov, LANL

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

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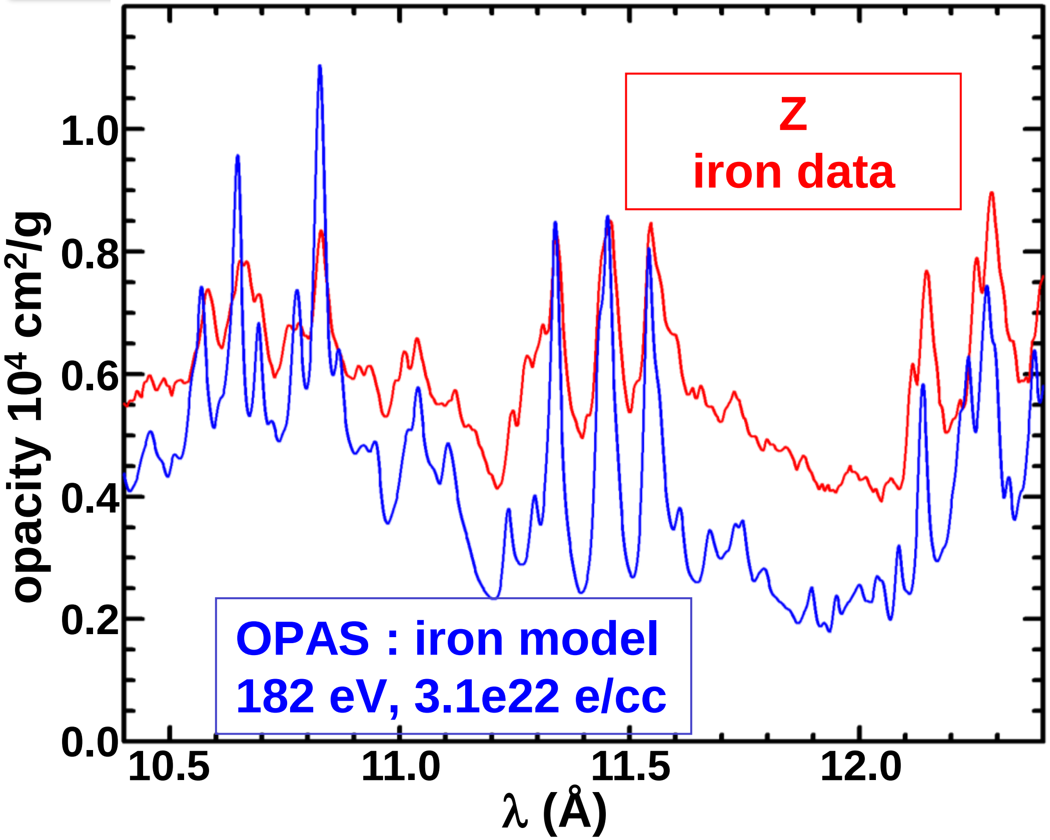

<u>Discrepancy:</u>
The experiment has wider spectral features and windows between features that are more filled in: these strongly effect photon transport

<u>Hypotheses:</u>

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?

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

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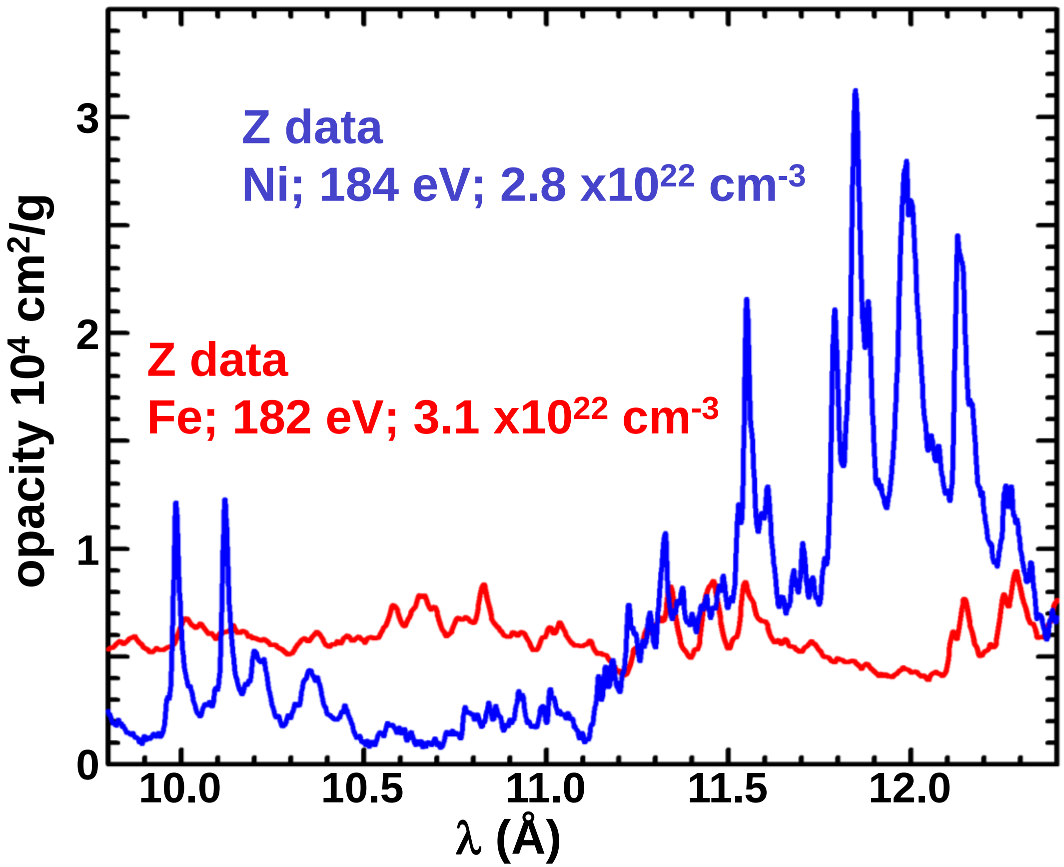

Discrepancy:

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

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?

New question: How do we understand the difference between Fe and Ni?

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

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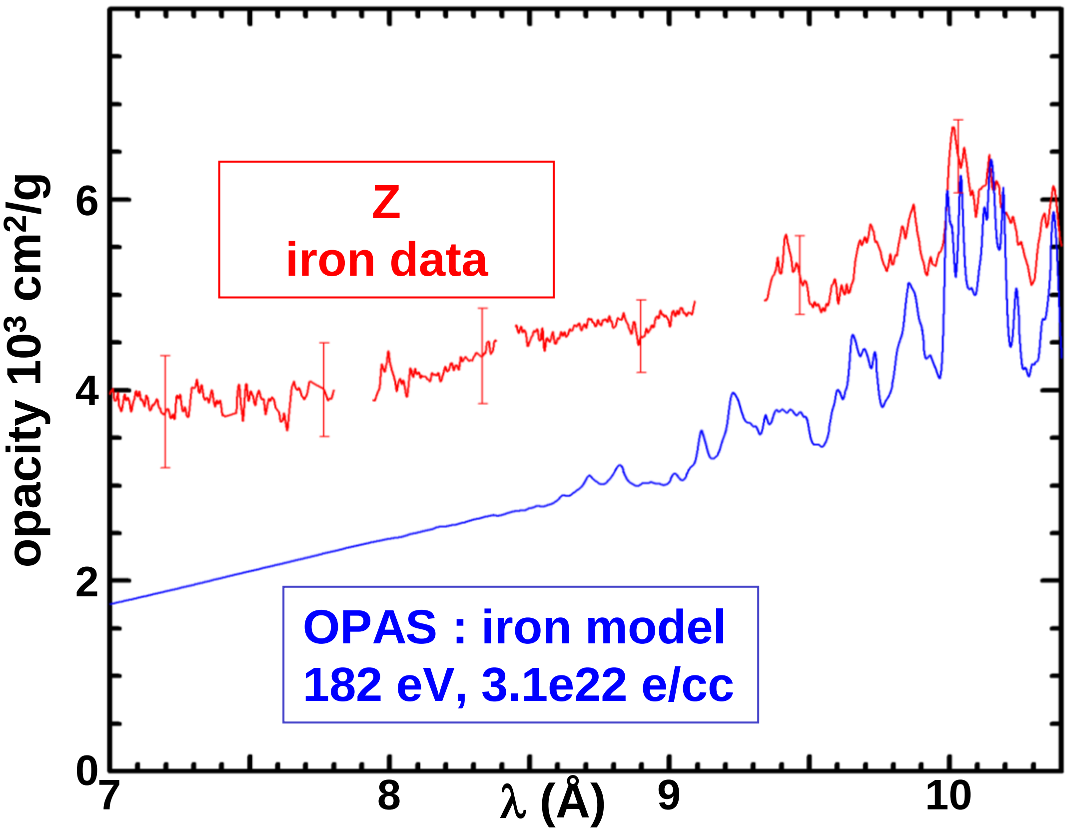


Discrepancy:

The quasi-continuum opacity at short wavelengths is predicted to be lower than measurements

Hypotheses:

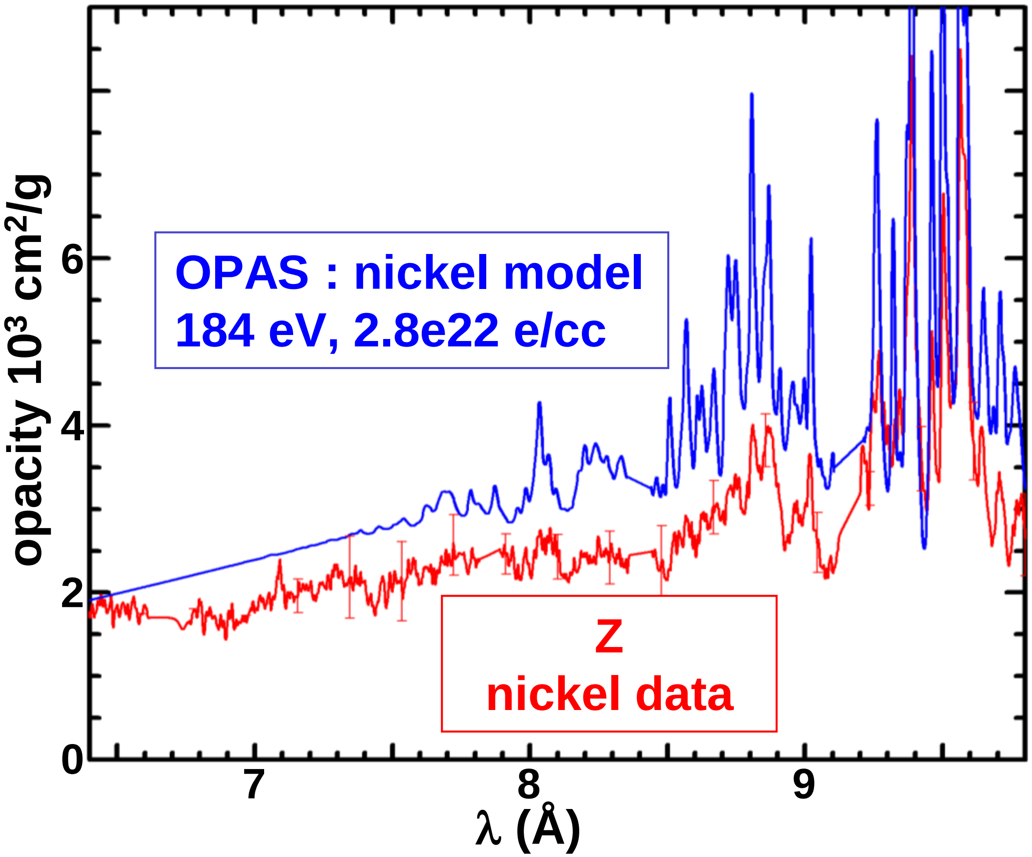
1) Could the experiment be biased to measure an opacity that is higher than the true value?

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

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

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

Preliminary Ni data shows the high T_e/n_e experiments are not biased to measure higher than predicted opacity



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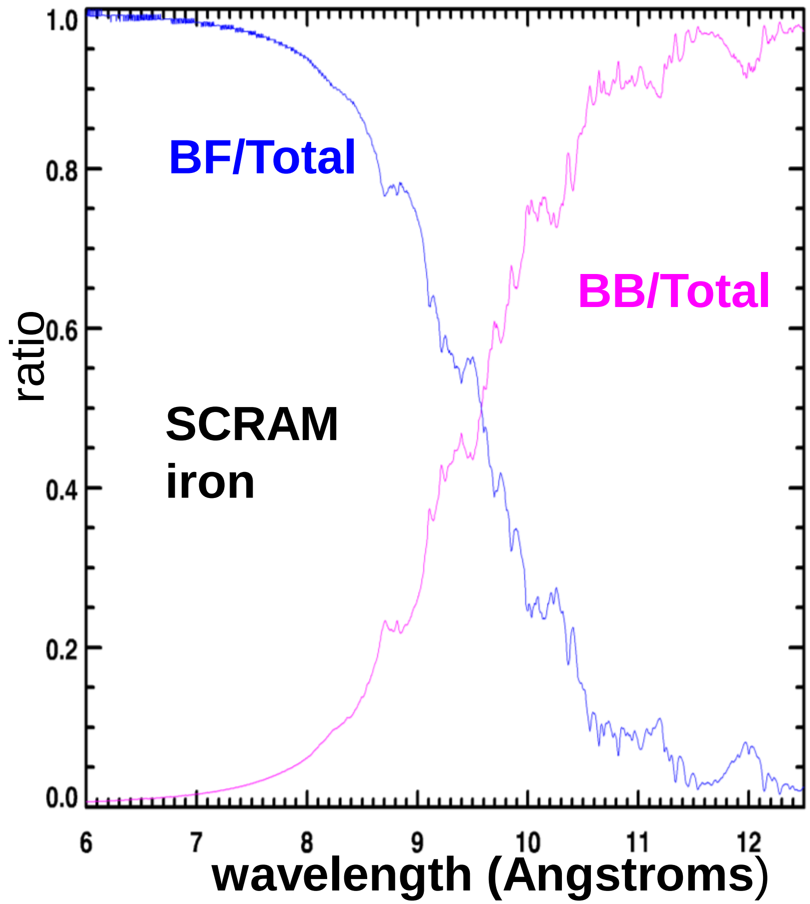
OPAS: C. Blancard *et al*, ApJ 745, 10 (2011)

Models predict the opacity is dominated by bound-free transitions for wavelengths below ~ 9 Å



Discrepancy:

The quasi-continuum opacity at short wavelengths is predicted to be lower than measurements

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~~1) Could the experiment be biased to measure an opacity that is higher than the true value?~~

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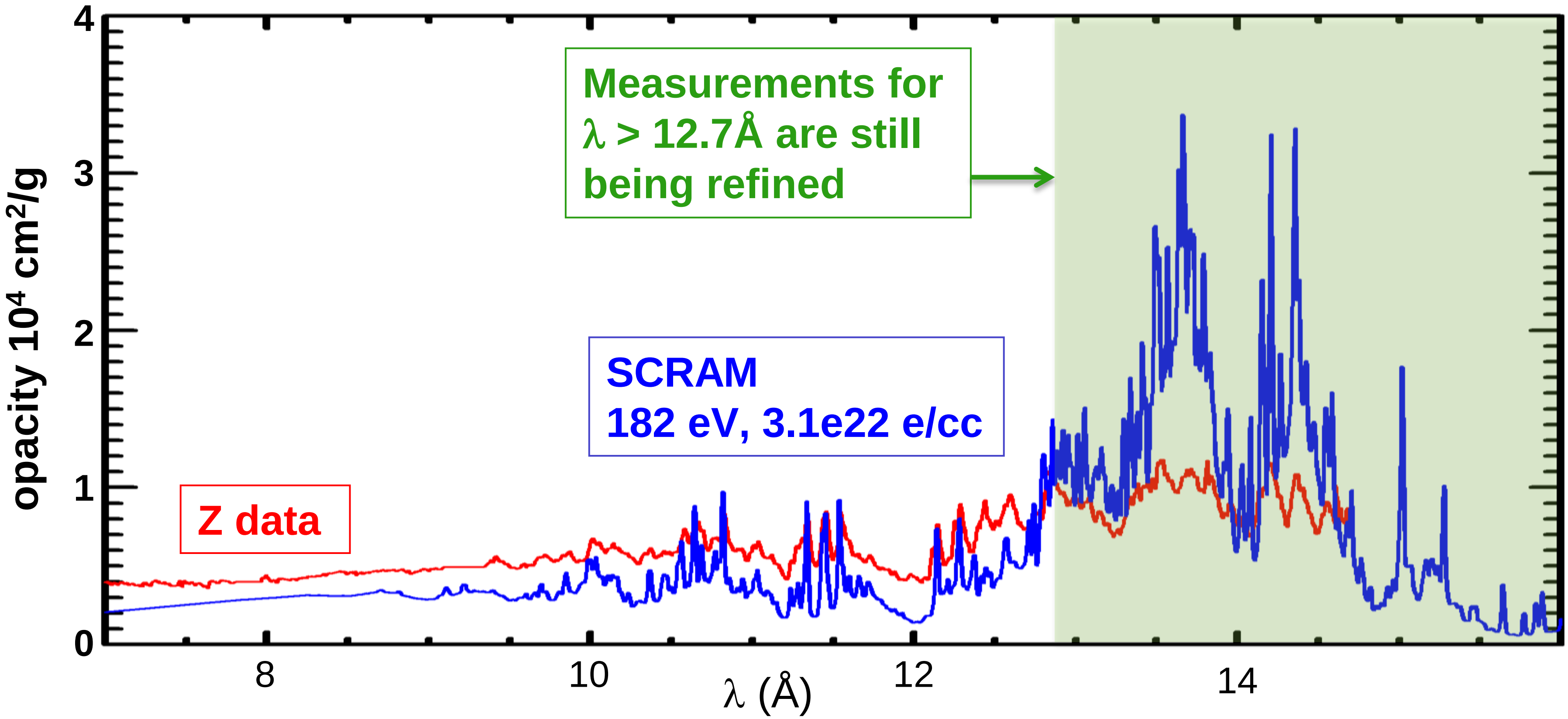
3) Is the photoionization for atoms in HED matter accurately modeled?

If models under-predict absorption over some λ range, then it must be over-predicted elsewhere (f sum rule)

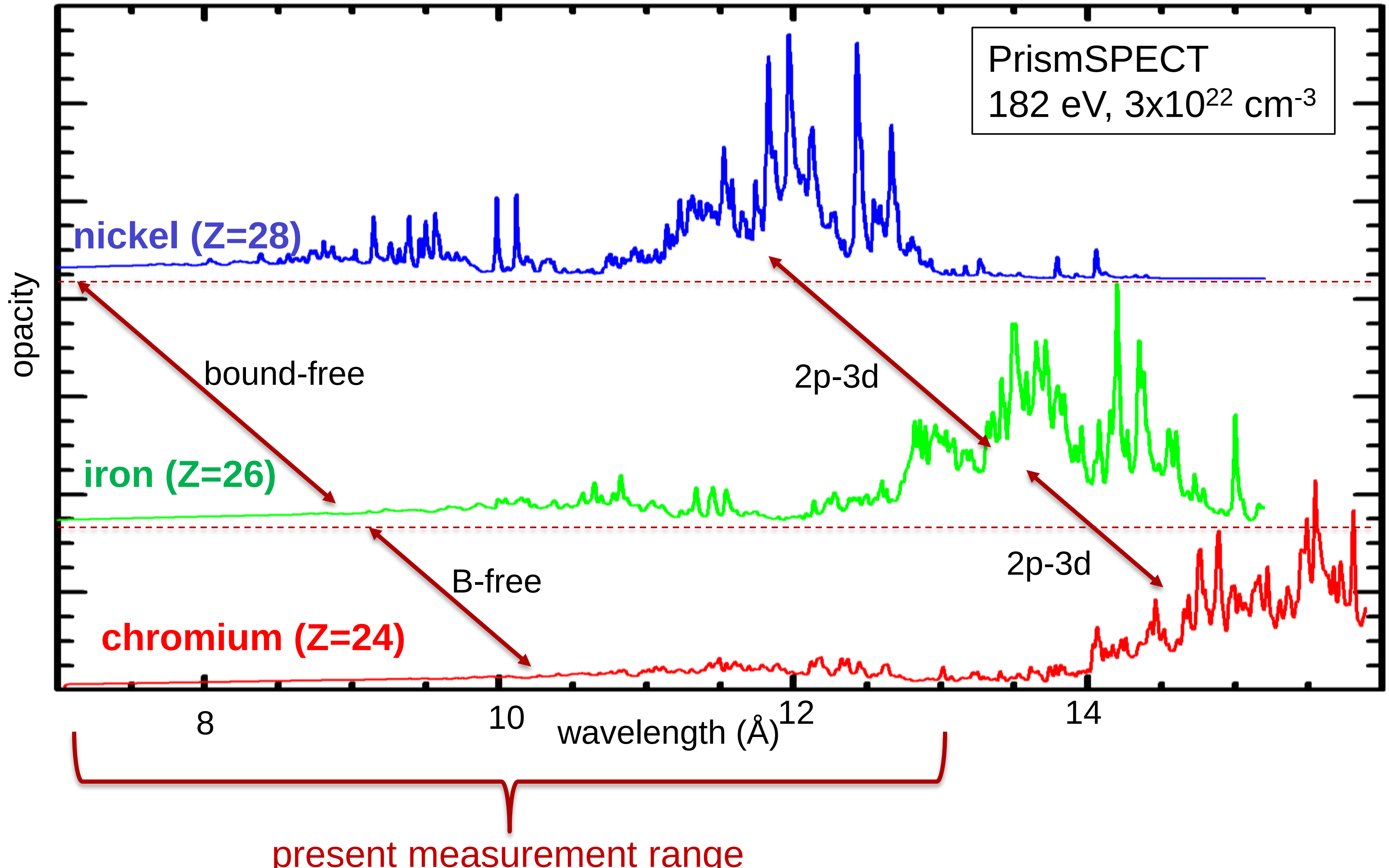


The sum rule requires integration over all wavelengths.
The sum rule is widely accepted, but not experimentally tested for HED plasmas.
Is it valid?
Is photon absorption shifted from long λ to short λ?

- ➢ **Benchmark measurements of the long λ transitions are needed**

Thomas; Reiche; Kuhn (1925); C. Blancard (2014); Iglesias, HEDP (2015)

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



Experiments with different elements are a rich source of opacity model tests

chromium (Z=24) **iron (Z=26)** **nickel (Z=28)**

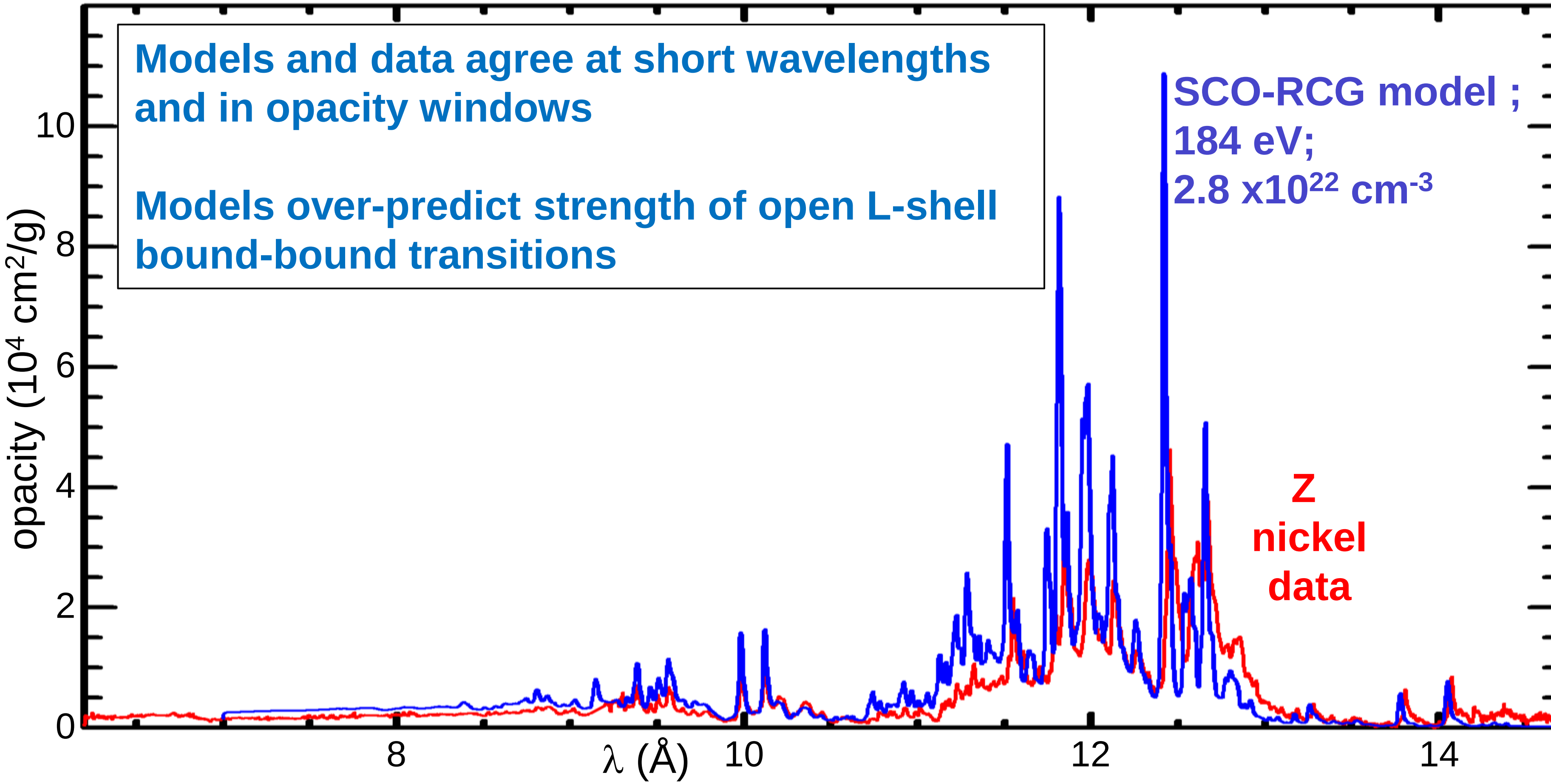
increased Atomic Number →

decreased wavelengths →

fewer L-shell vacancies →

lower excited state populations →

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 *et al.*, 2013

Preliminary Cr model-data discrepancy is similar to iron

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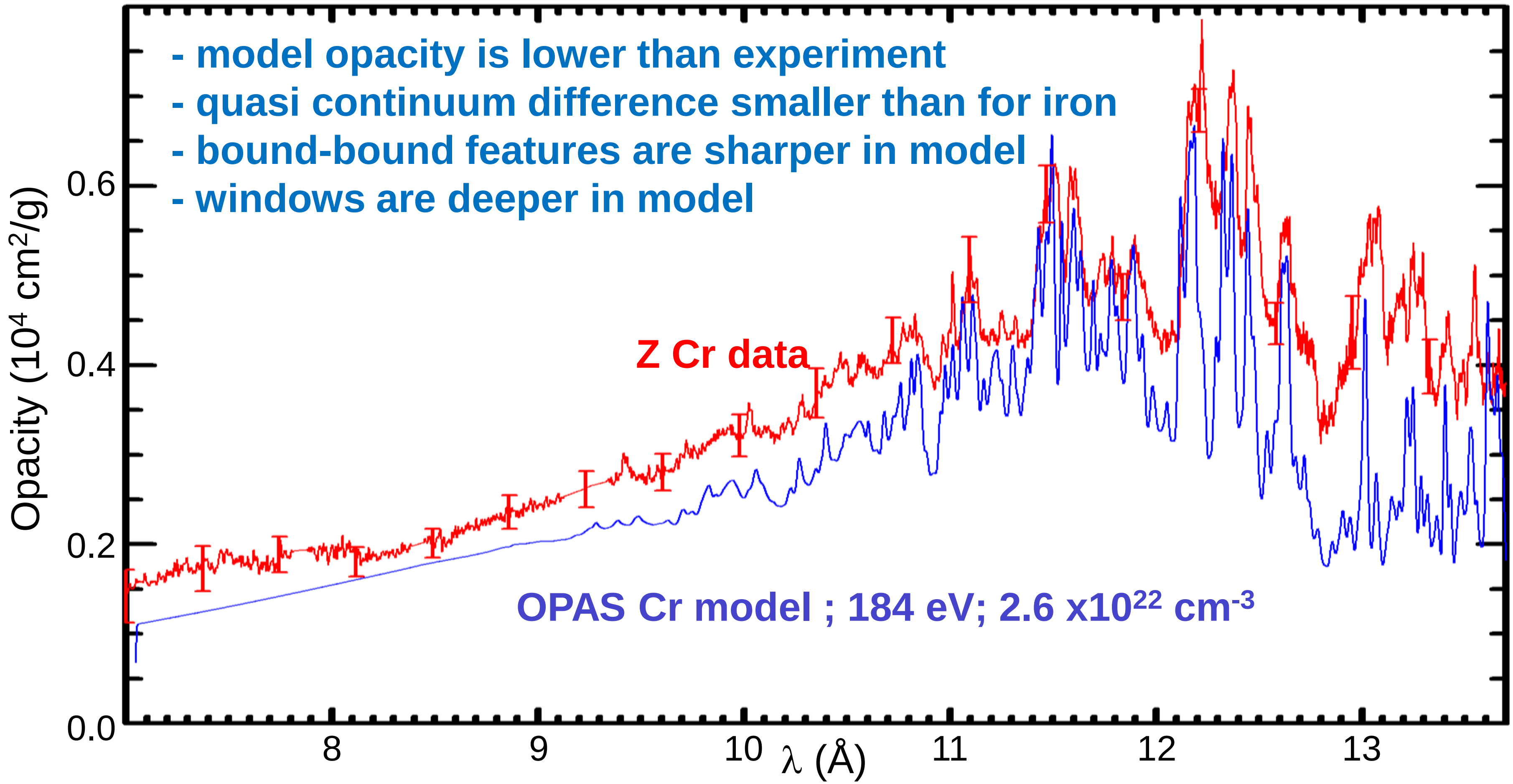

This generally supports the iron data validity
New questions, insights, and model constraints will certainly arise as we finalize the measurements

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

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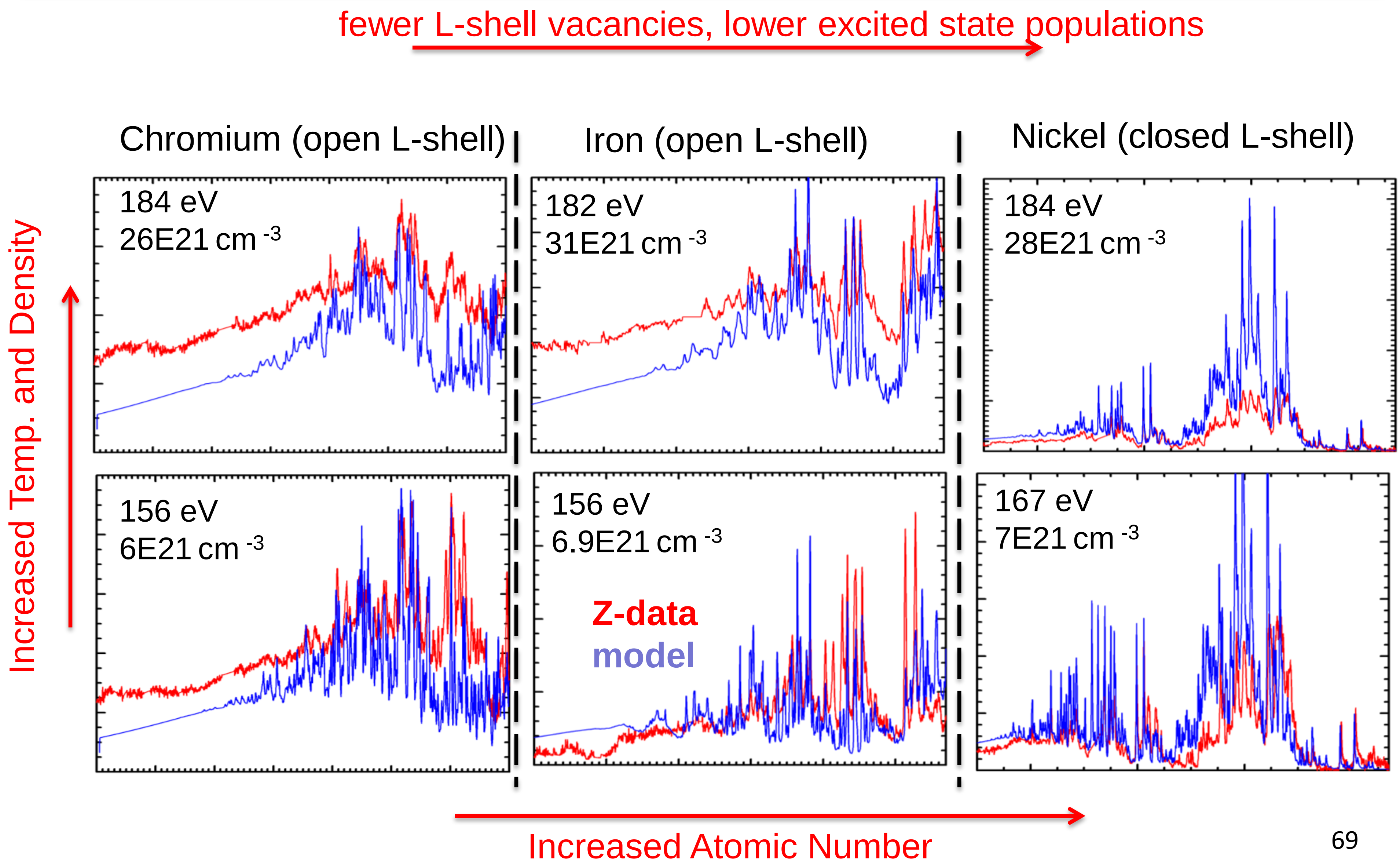

Z iron opacity experiments refine our understanding of the sun.

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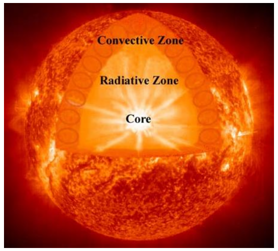
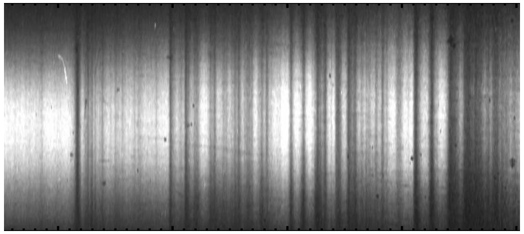
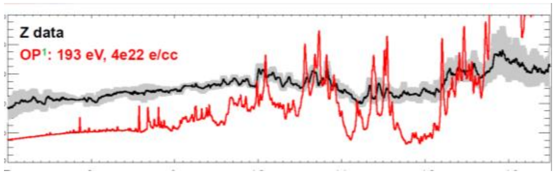
- **Solar interior predictions don't match helioseismology**
  - → **Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?**



- **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

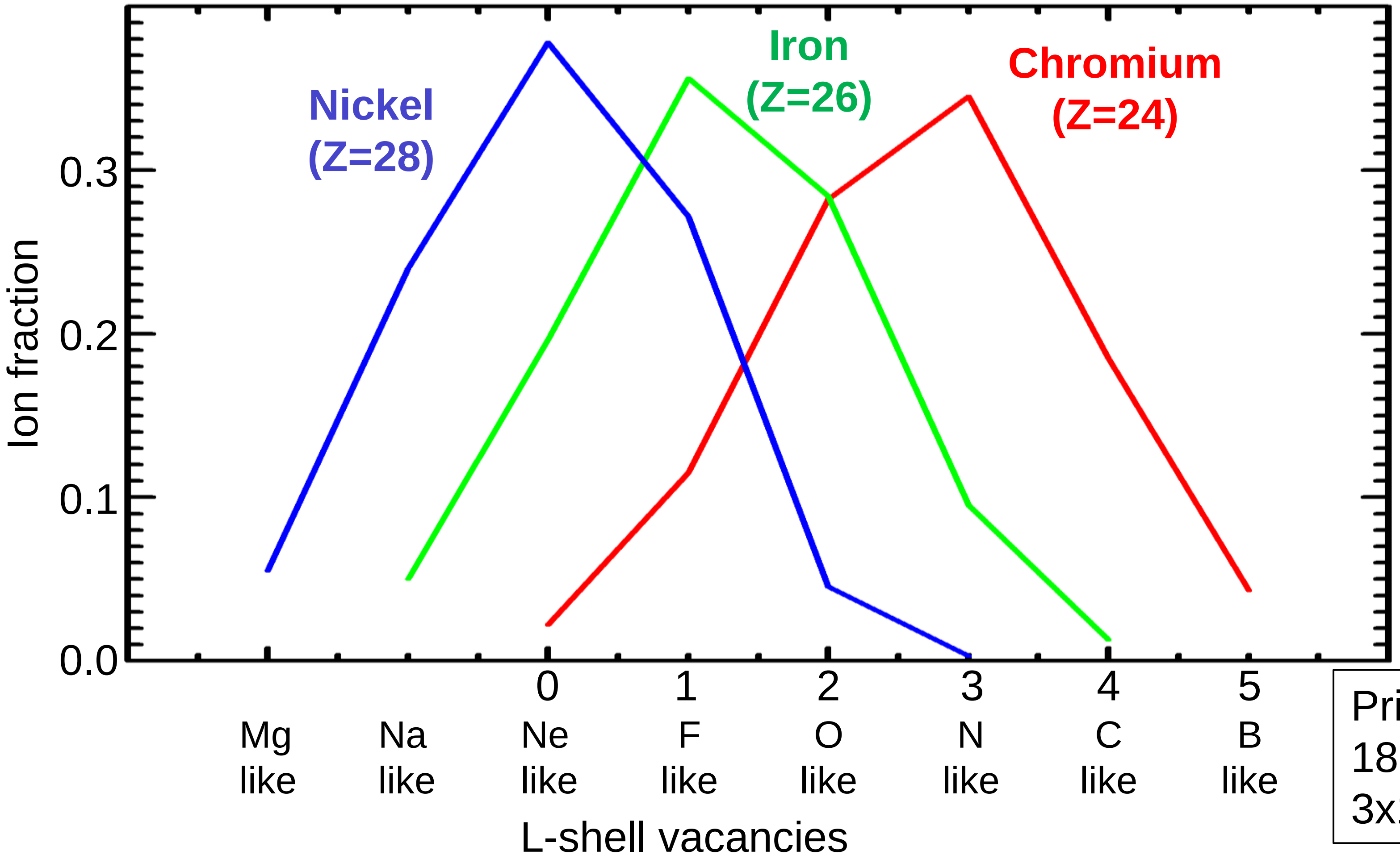
Siegbahn, Nobel Lecture, 1924:

"…x-rays give us a glimpse of the phenomenological world which lies inside the outer border lines of the atom. All these messages which leave this part of physical reality are so to speak written in the language of x-rays.

In order to understand and interpret these messages we must understand this language."

Extra slides: error evaluation

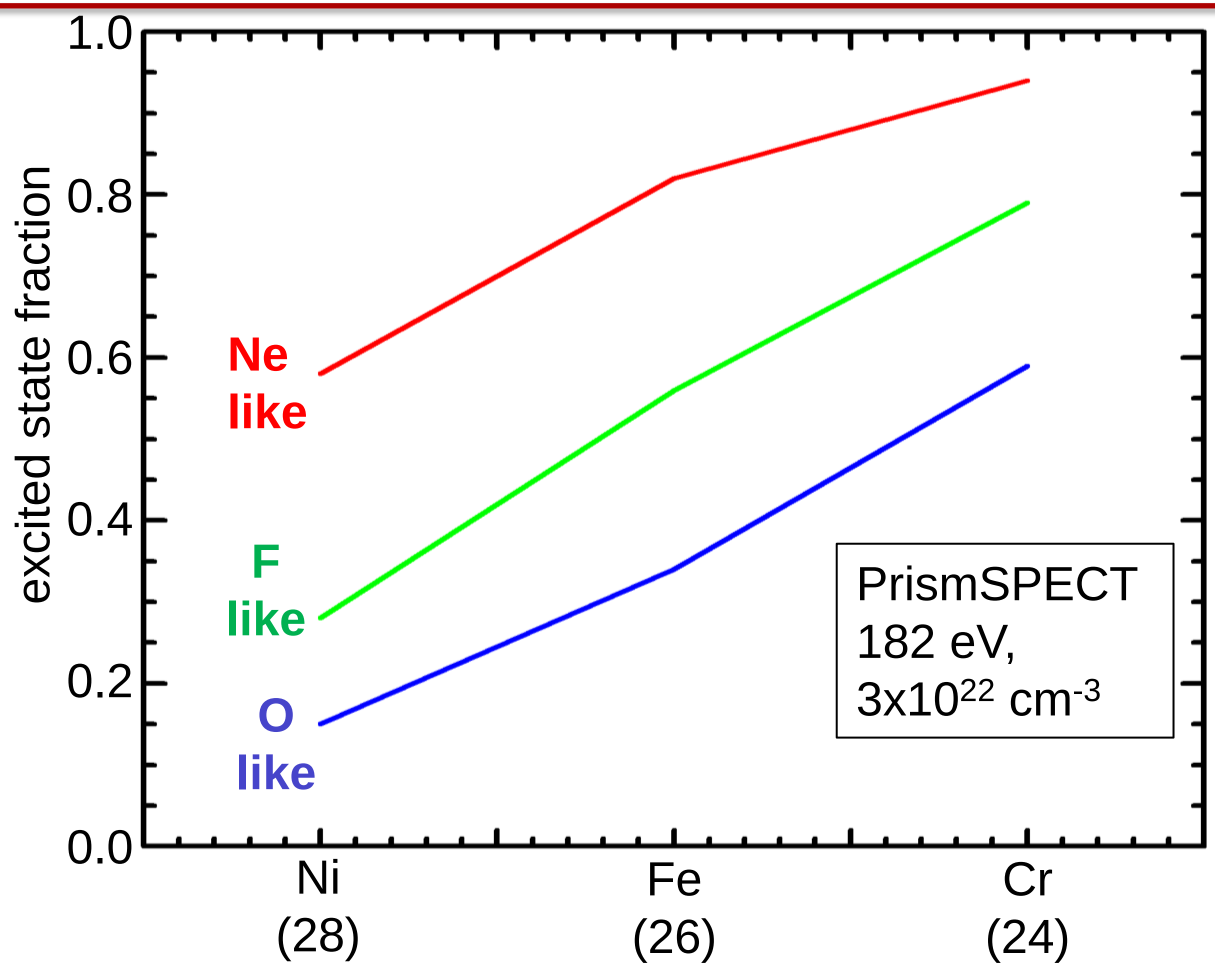
Partially-filled L-shell opacity is complex to model and can be studied by changing the element



PrismSPECT
182 eV,
3×10^{22} cm^{-3}

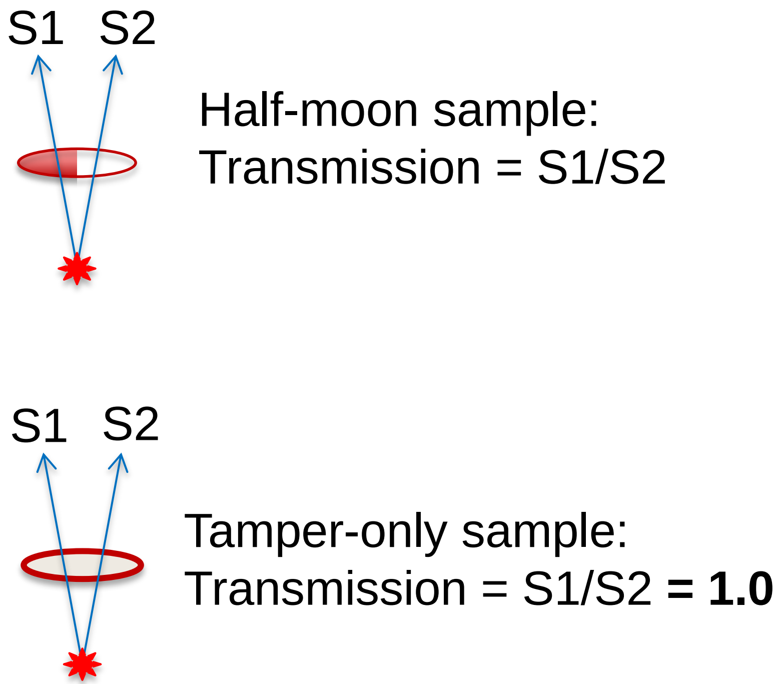
The number of L shell vacancies changes with the sample element

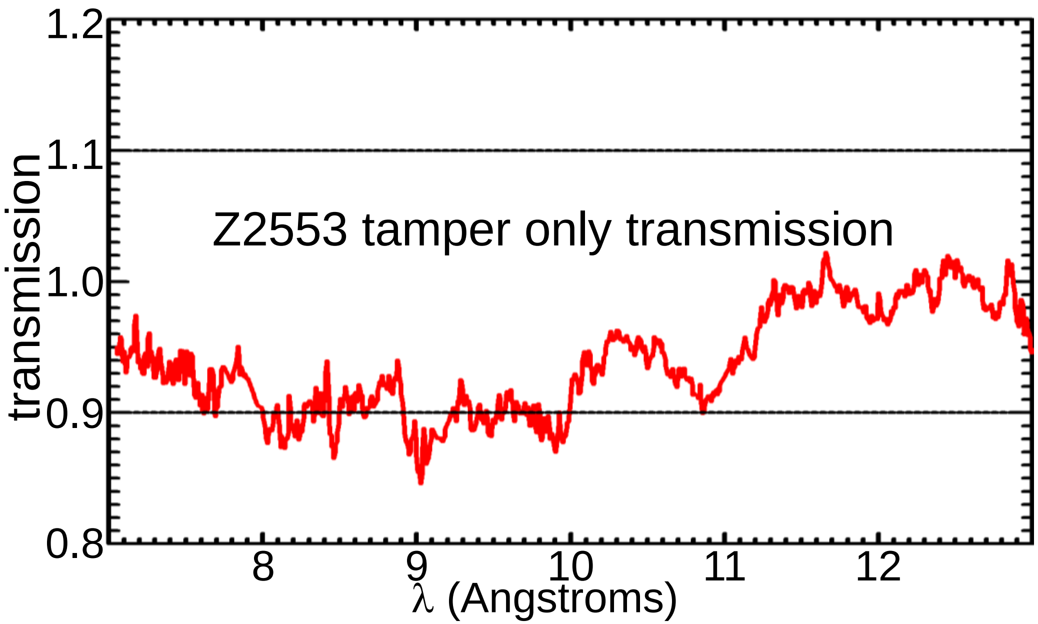
The fractional excited state population increases as the atomic number decreases



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

Tamper-only experiments confirm transmission accuracy





- **For this example the average absolute error is ~7%**
- **Errors are further reduced by averaging repeated experiments**
- **We repeat this test in every experiment series to avoid the possibility of anomalously large errors**

Possible experiment flaws can be evaluated from transmission scaling with sample thickness (Beer's Law)

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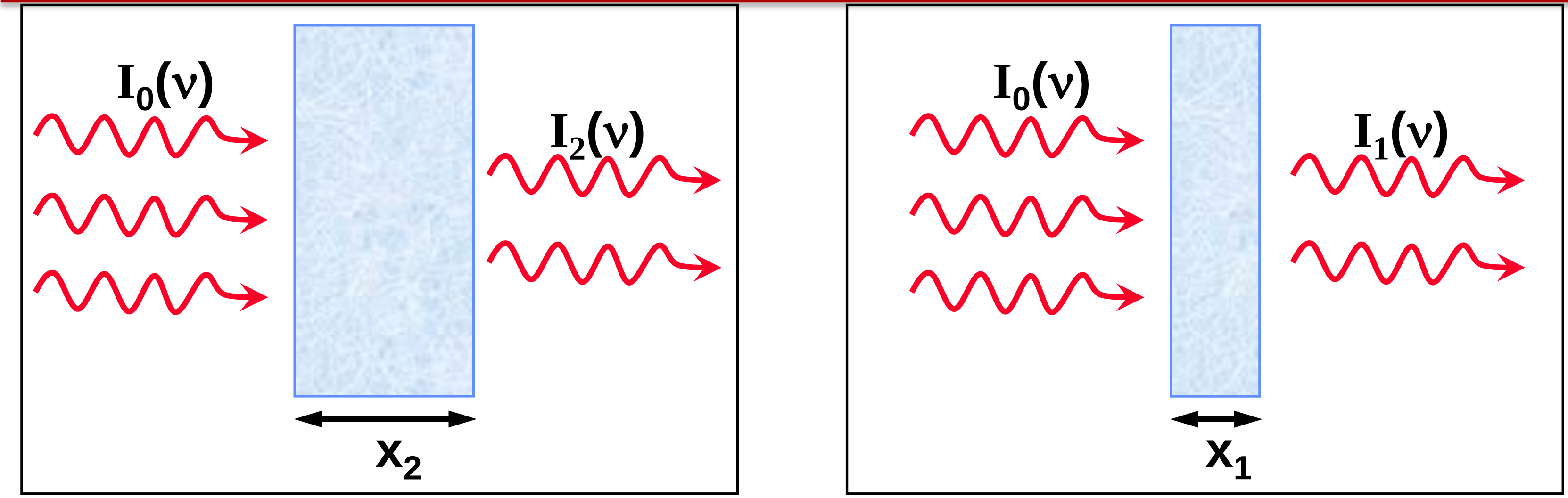


Expected scaling with thickness : $T_1 = T_2^{(x1/x2)}$

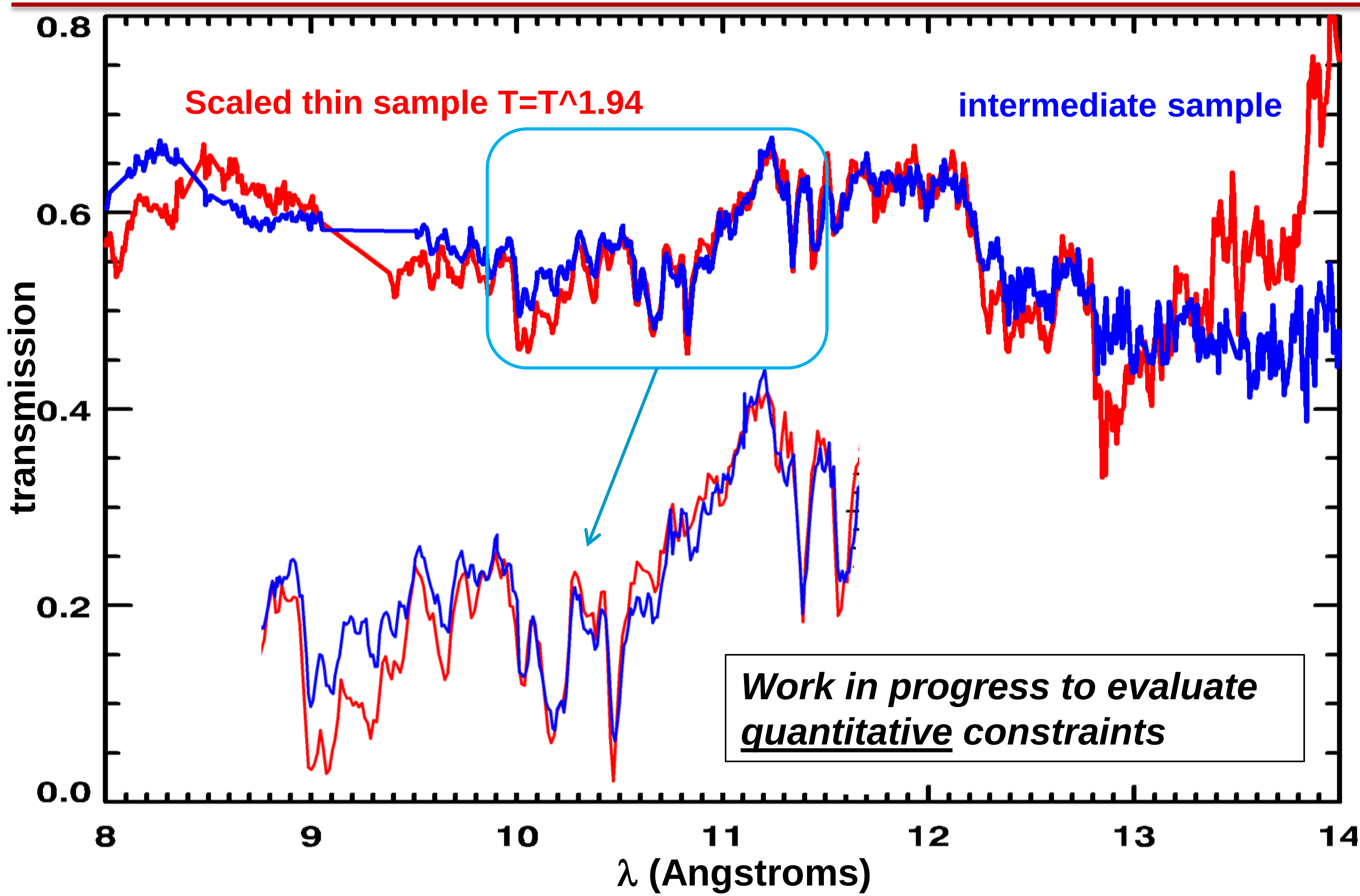
e.g., if $X_2 = 2 * X_1$, then $T_2 = T_1 * T_1$

<u>experiment problems cause transmission scaling to deviate:</u>

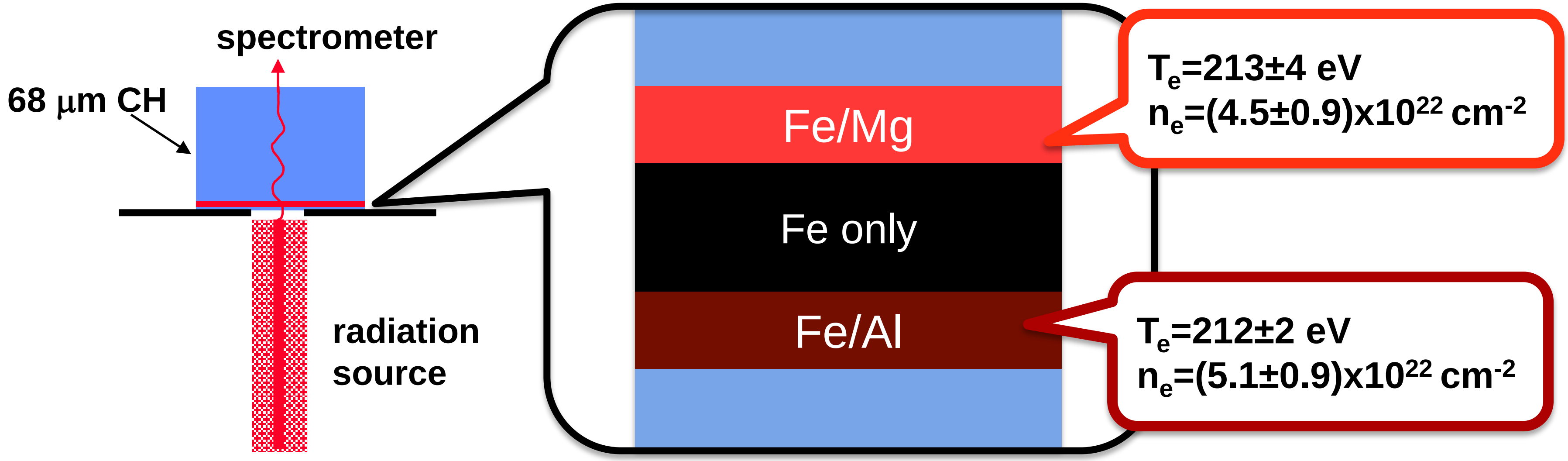
- **Sample emission**
- **Background subtraction**
- **Crystal defects**
- **Gradients**

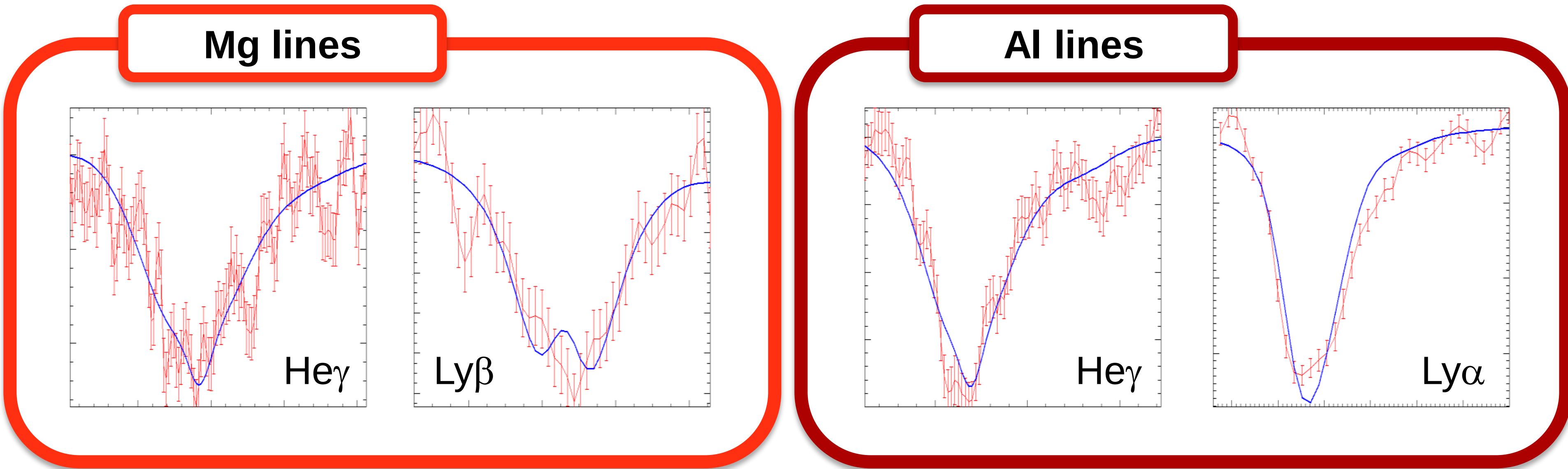
Most potential experiment problems cause the scaled thin sample transmission <u>to be lower</u> than the thick sample transmission

Beers Law test confirms reliability of high Te/ne iron data in the 8-13 Angstrom range

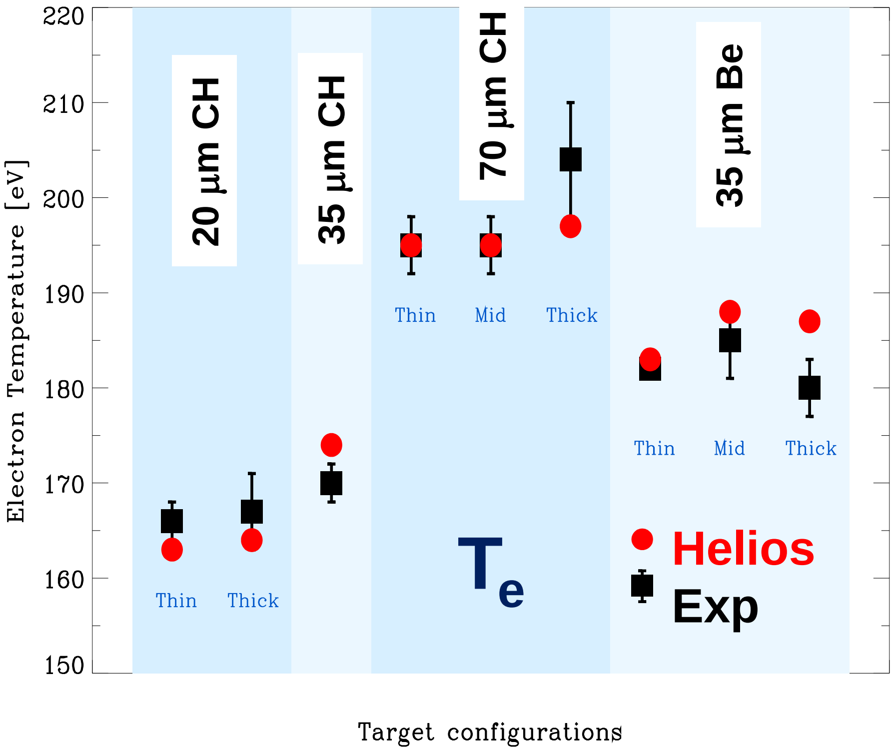


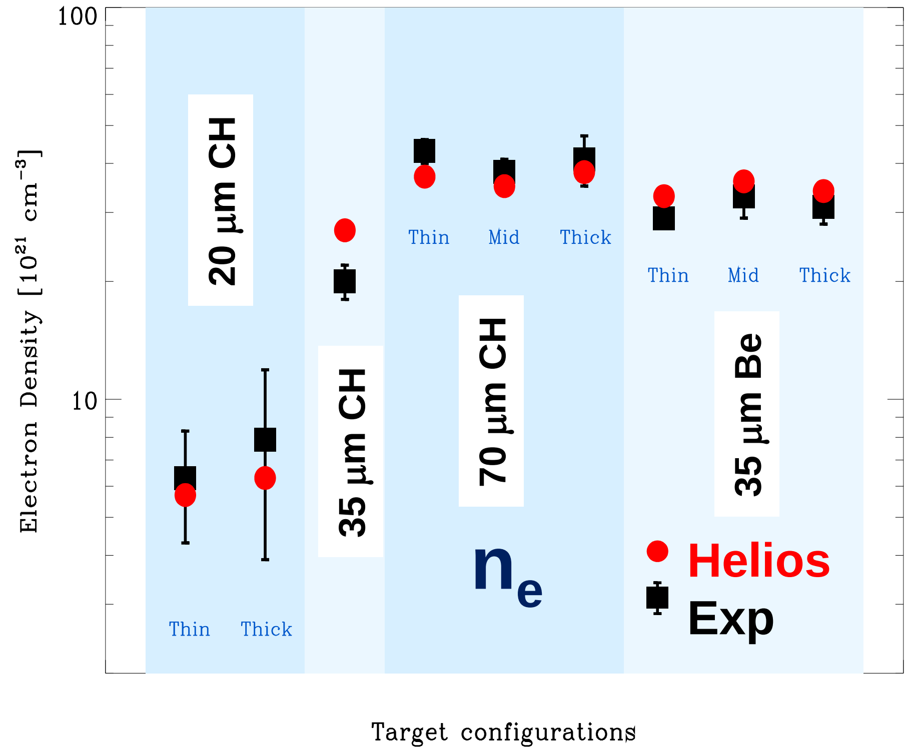
Direct uniformity measurement confirmed that there is no significant spatial gradient in the sample





Simulations can quantify systematic errors, if the simulation fidelity is benchmarked

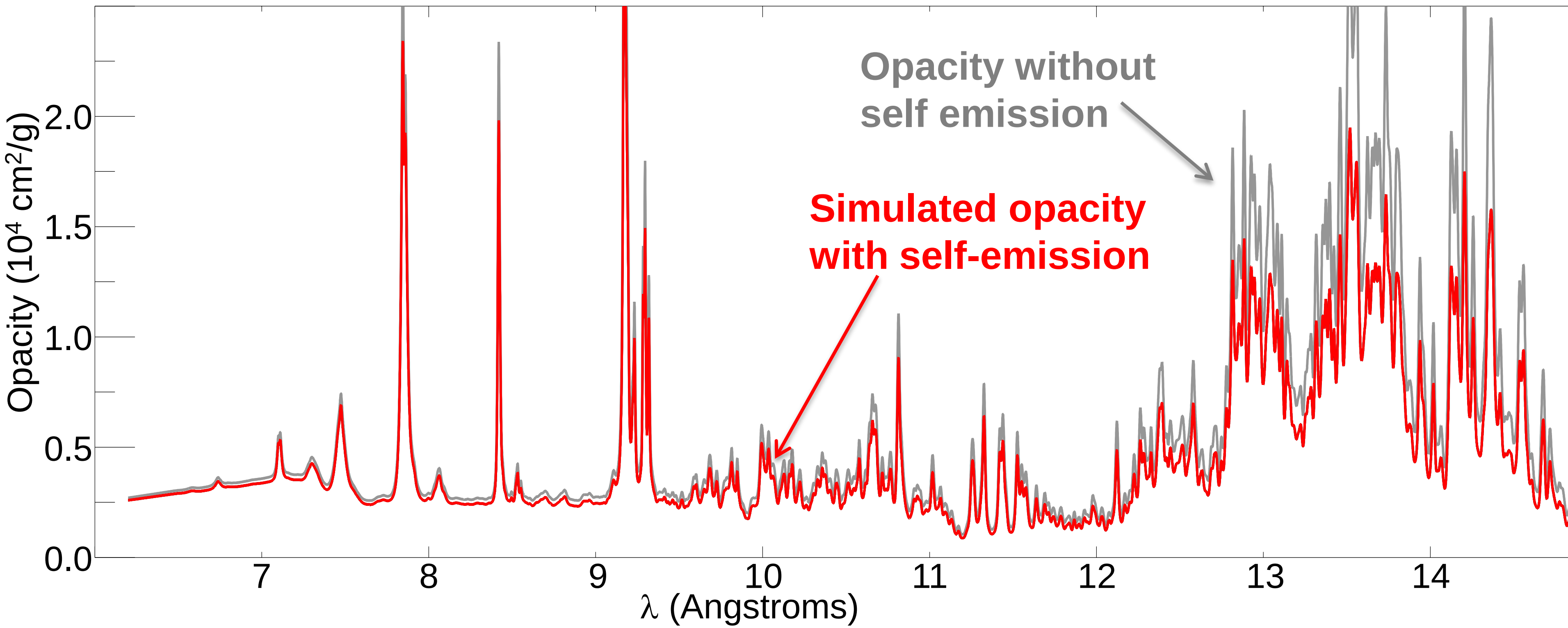




Credibility is supported by the fact that simulations reproduce multiple experiments using the same drive and backlight for all:

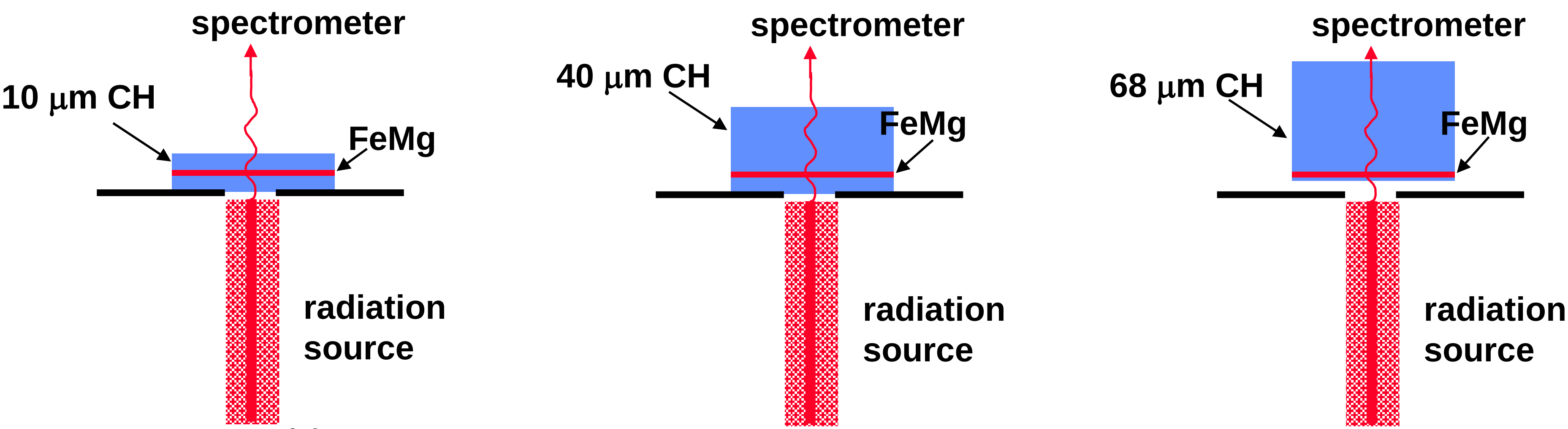
Tamper thickness changes
Sample thickness changes
Tamper material changes

Self emission influence on opacity is modest for wavelengths below ~12.5 Angstroms



- If present, self emission always reduces the inferred opacity
- Any self emission correction will increase model discrepancies for $\lambda < 13$ A
- We observe no self emission, but the quantitative constraint this provides is still under evaluation

A valid question is whether the rear tamper thickness alters the inferred opacity



reasonable model agreement

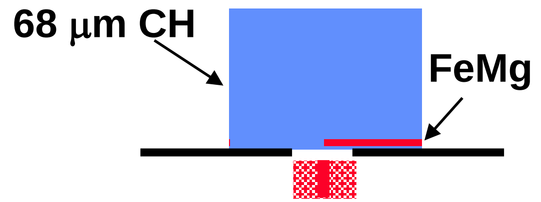
poor model agreement

very poor model agreement

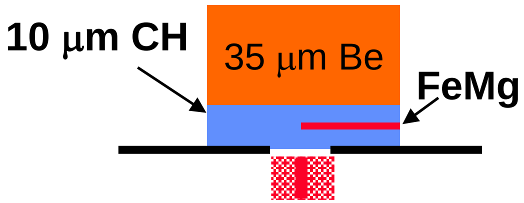
We use the same heating radiation, backlight, diagnostics, sample fabrication for all
The only difference is the tamper thickness

We test the potential tamper effect by changing most of the tamper material to beryllium

<u>Hypothesis:</u>
- The agreement deteriorates as top CH becomes thicker
- Could increased CH emission/absorption affects the measurements?



<u>Test:</u>
- Use Be tamper (lower Z element)
  - Negligible emission
  - Negligible absorption



Are the discrepancies caused by thick CH?

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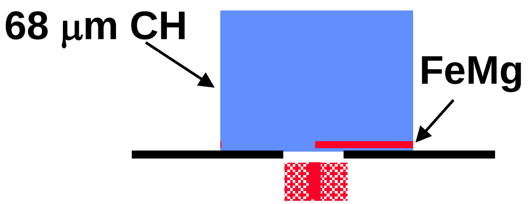
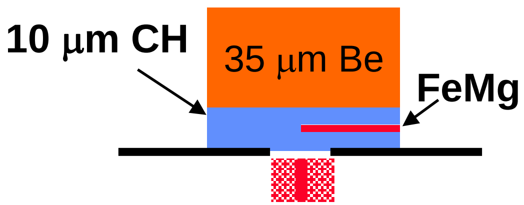
Hypothesis:

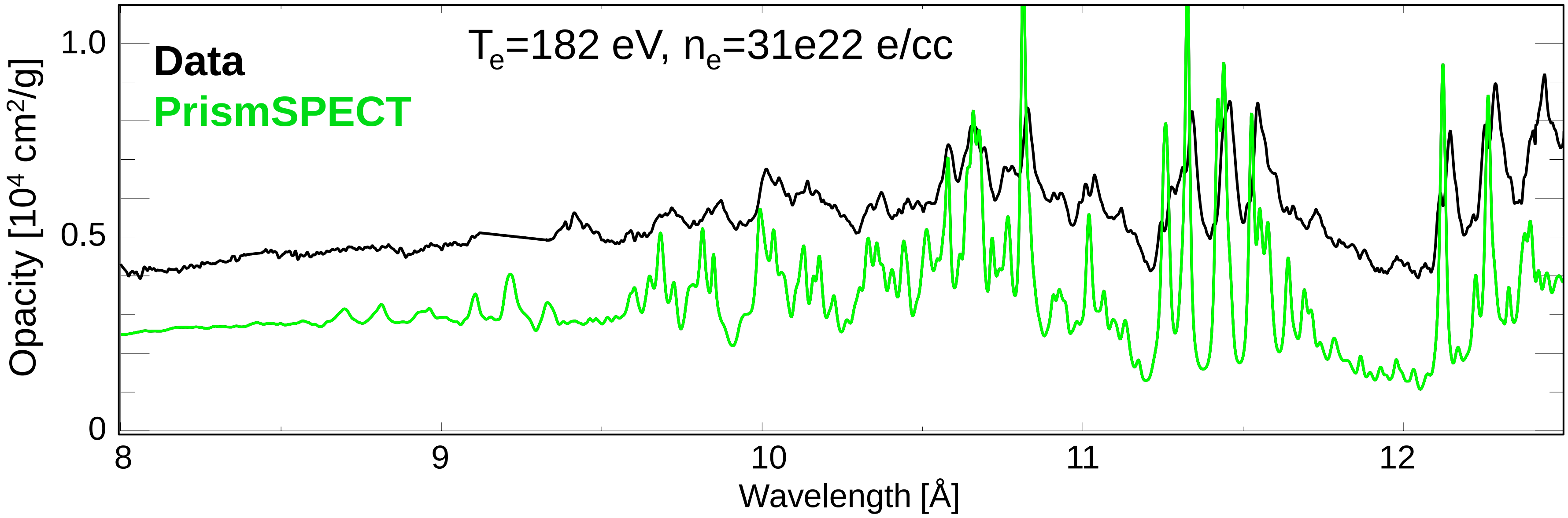
- The agreement deteriorates as top CH becomes thicker
- Could increased CH emission/absorption affect the measurements?



Test:

- Use Be tamper (lower Z element)
  - Negligible emission
  - Negligible absorption

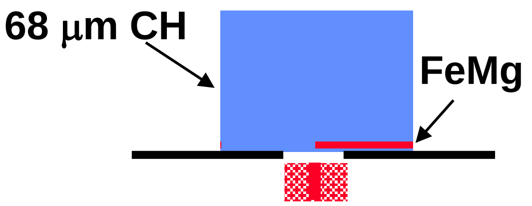




Are the discrepancies caused by thick CH?

<u>Hypothesis:</u>

- The agreement deteriorates as top CH becomes thicker
- Could increased CH emission/absorption affect the measurements?



<u>Test:</u>

- Use Be tamper (lower Z element)
  - Negligible emission
  - Negligible absorption