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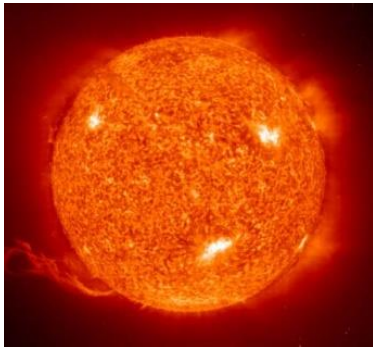

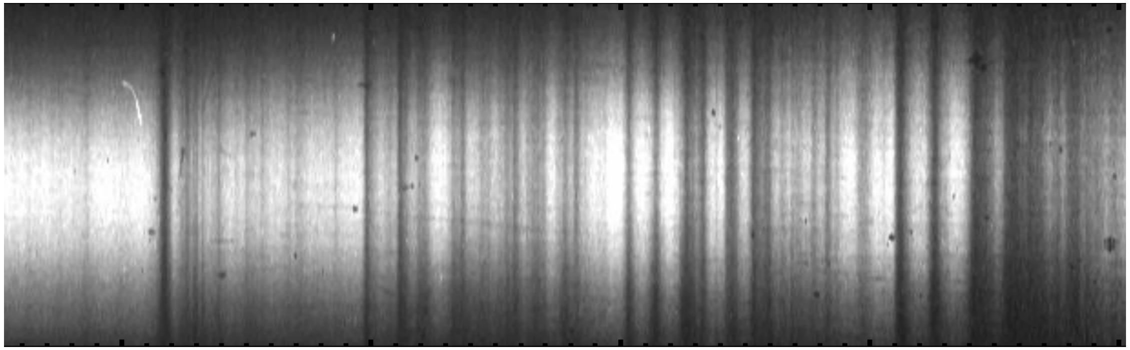

Stellar interior opacity measurements

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 and photon absorption in high energy density matter.

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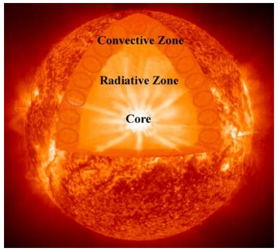
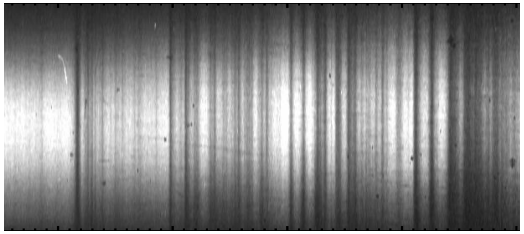
- **Solar interior predictions don't match helioseismology**

  → Arbitrary opacity increase of 10-20% would fix the problem, but is this the correct explanation?



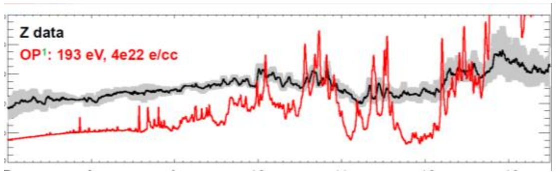
- **Z experiments have measured iron plasma opacity at nearly solar convection zone base conditions**

  → 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

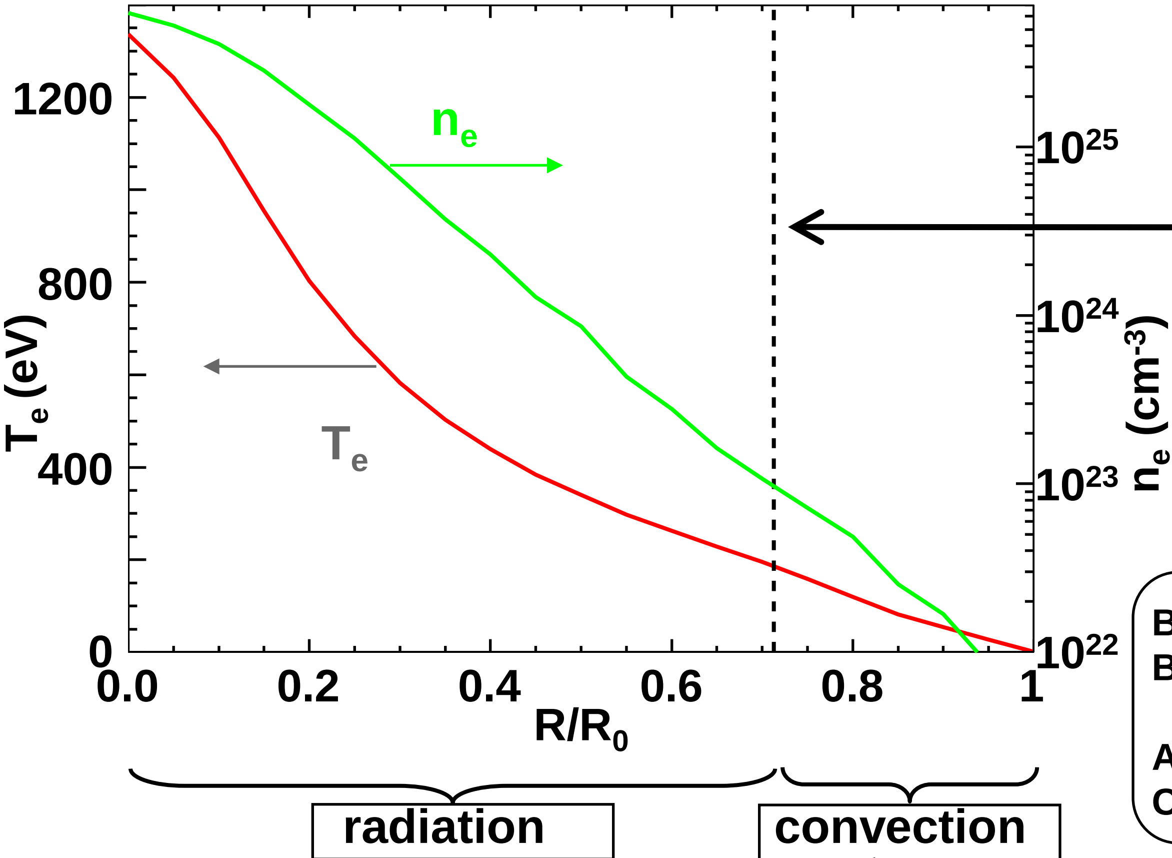
If our opacity measurements are correct, we must revise our understanding for atoms in HED plasmas

- **Measured opacities are generally higher than theory predicts – e.g., Rosseland mean is 30-60% higher**
- **The measurements alter our understanding of the sun**
- **Solar physics calibrates many other objects. Therefore the measurements alter our understanding of every main sequence star in the sky, including exoplanet host stars**
- **The measurements imply likely revisions for ICF capsule dopants**

These serious consequences mandate continued effort

- **We invested the last 2 years investigating possible errors and refining results**
- **The major conclusions survived this scrutiny**
- **Going forward, new experiments will further test hypotheses for possible theory deficiencies and possible experiment deficiencies**
- **Our job isn't finished until we resolve the model/data discrepancy**

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.
- This accuracy is a challenge – experiments are needed to know if the solar problem arises in the opacities or elsewhere.

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

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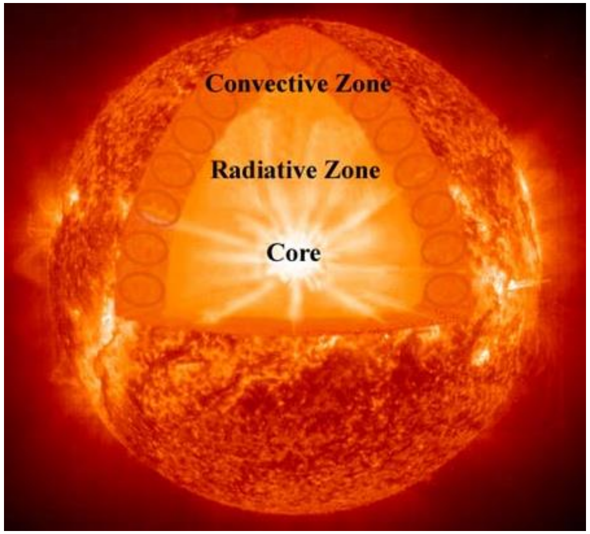
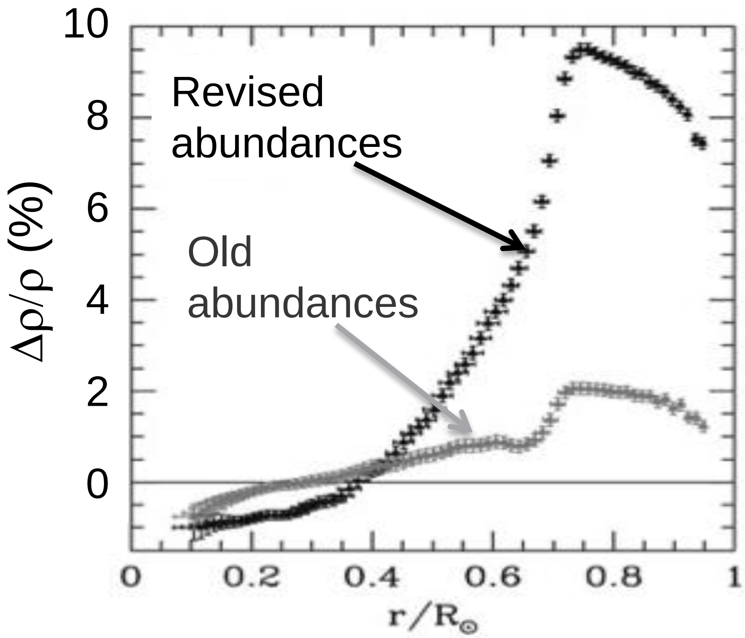
- Standard solar model (simulation)
  Inputs:
  - Abundance
  - EOS
  - Opacity
  - Etc.
- Helioseismology (measurements)



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

CZB location: 1σ → 13-30 σ



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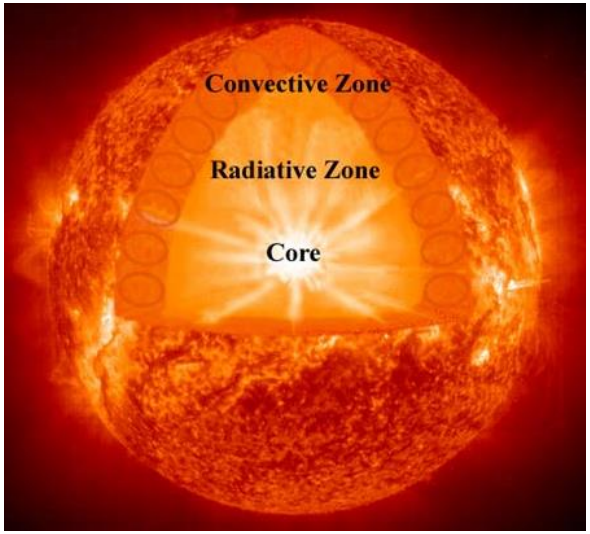

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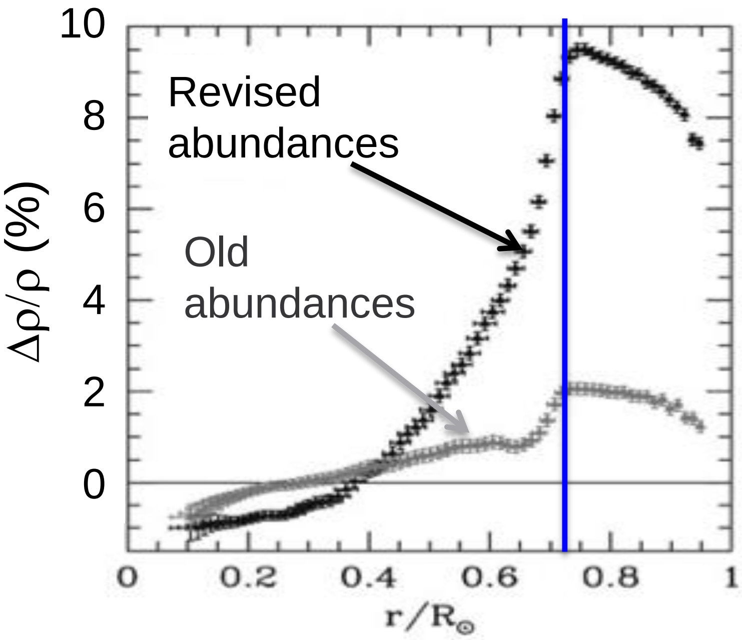

S. Basu *et al*, Physics Reports **457**, 217 (2008). M. Asplund *et al*, Annu. Rev. Astro. Astrophys. **43**, 481 (2005).

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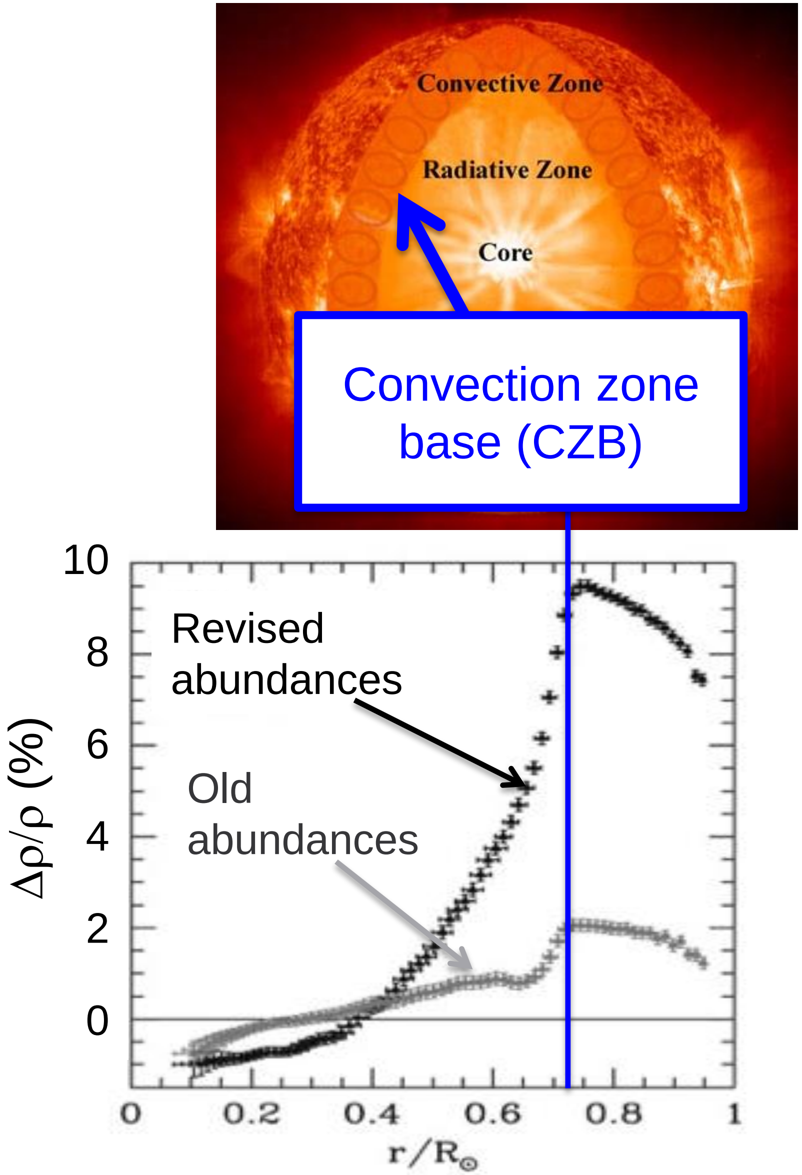
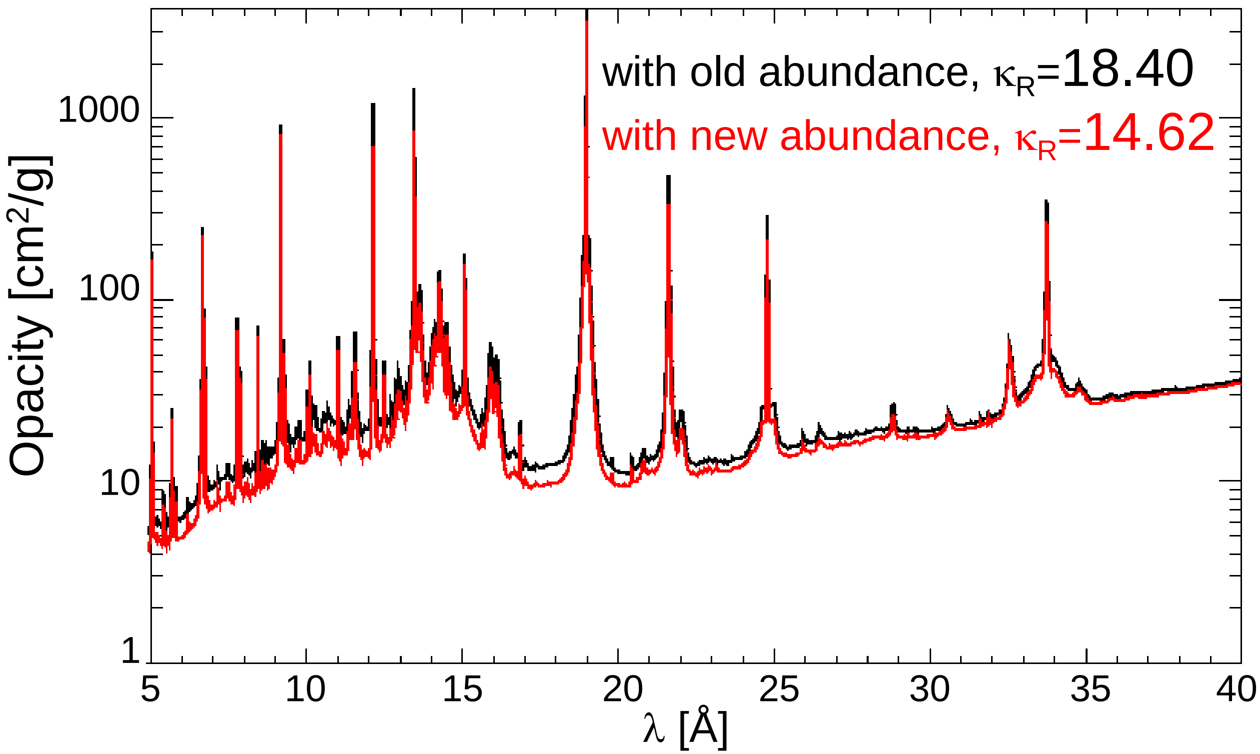
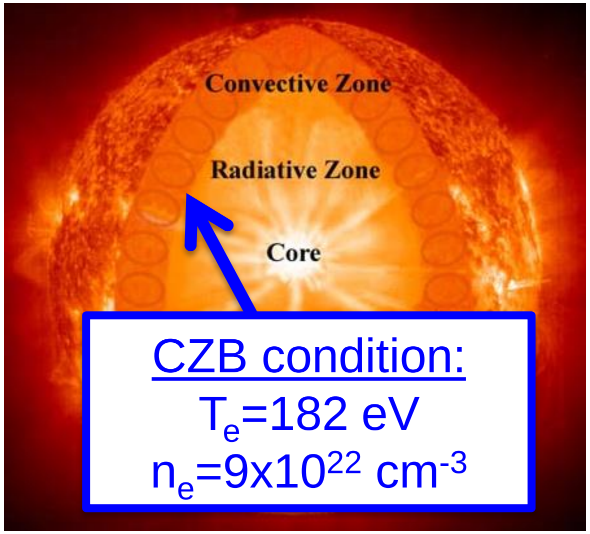


S. Basu *et al*, Physics Reports **457**, 217 (2008). M. Asplund *et al*, Annu. Rev. Astro. Astrophys. **43**, 481 (2005).

Disagreement could be resolved if the true opacity is higher than predicted

Solar mixture opacity at Convection Zone Base (CZB)



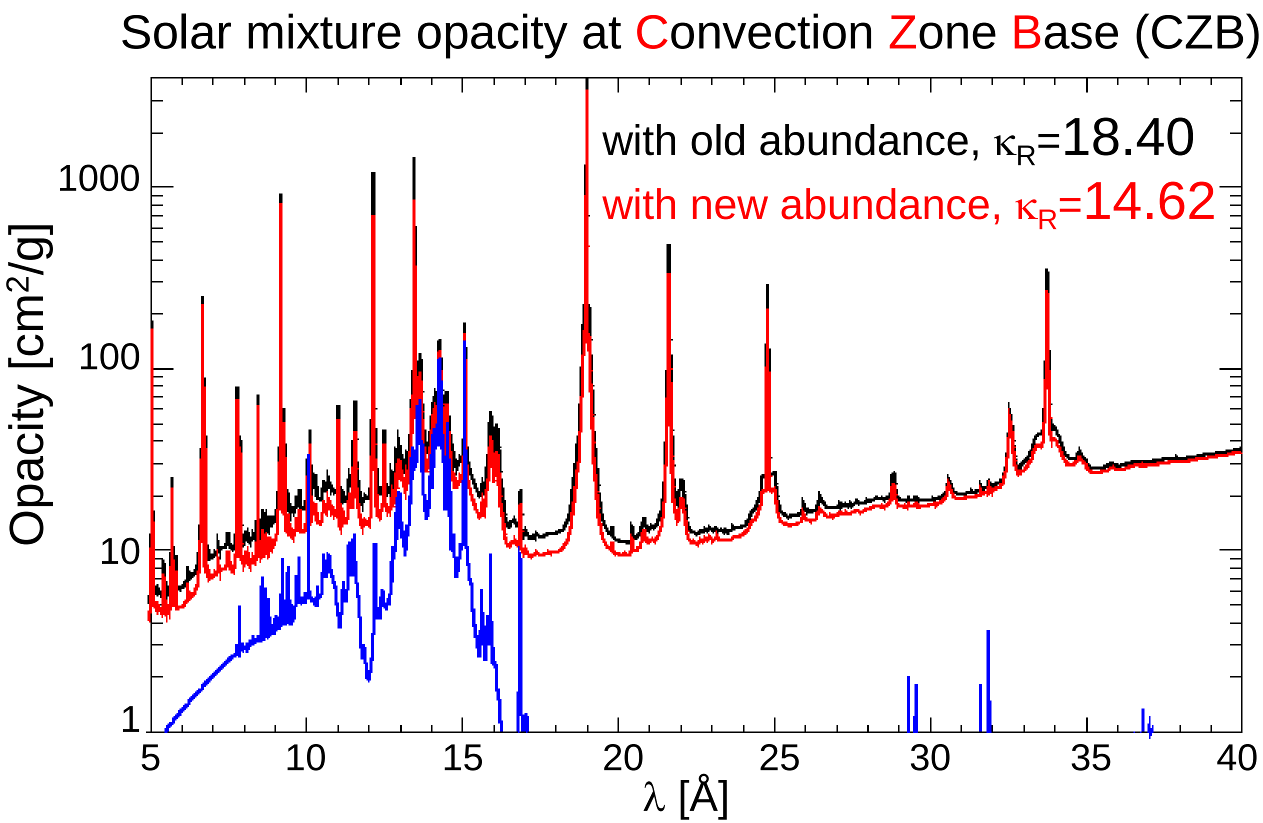


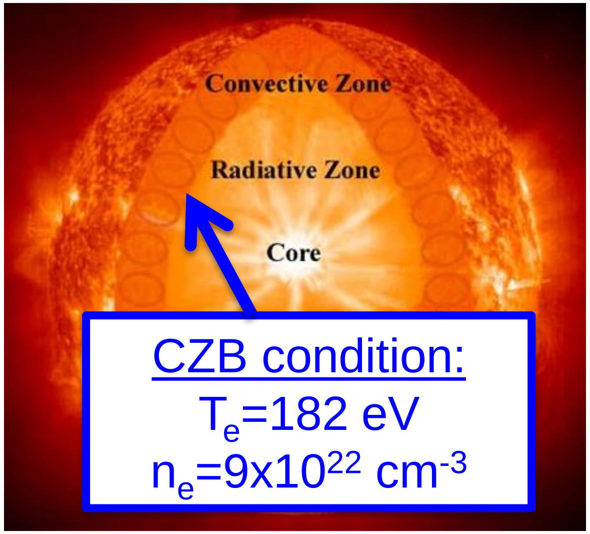
The disagreement is mostly resolved by ad-hoc opacity increases of 10-30%

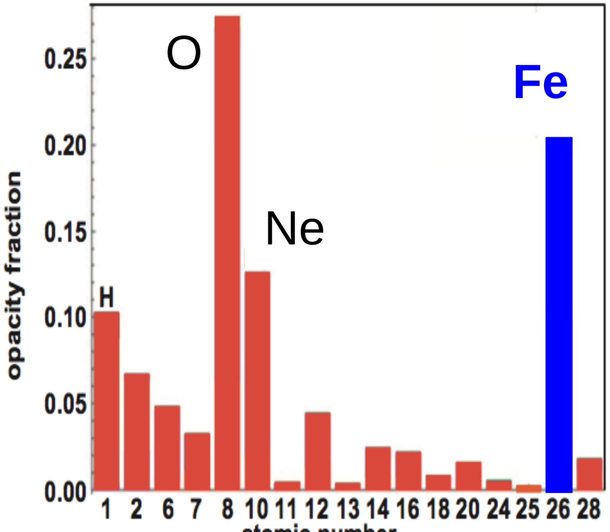
Rosseland mean opacity → heat transfer by radiation

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

Iron makes an important contribution to the solar opacity

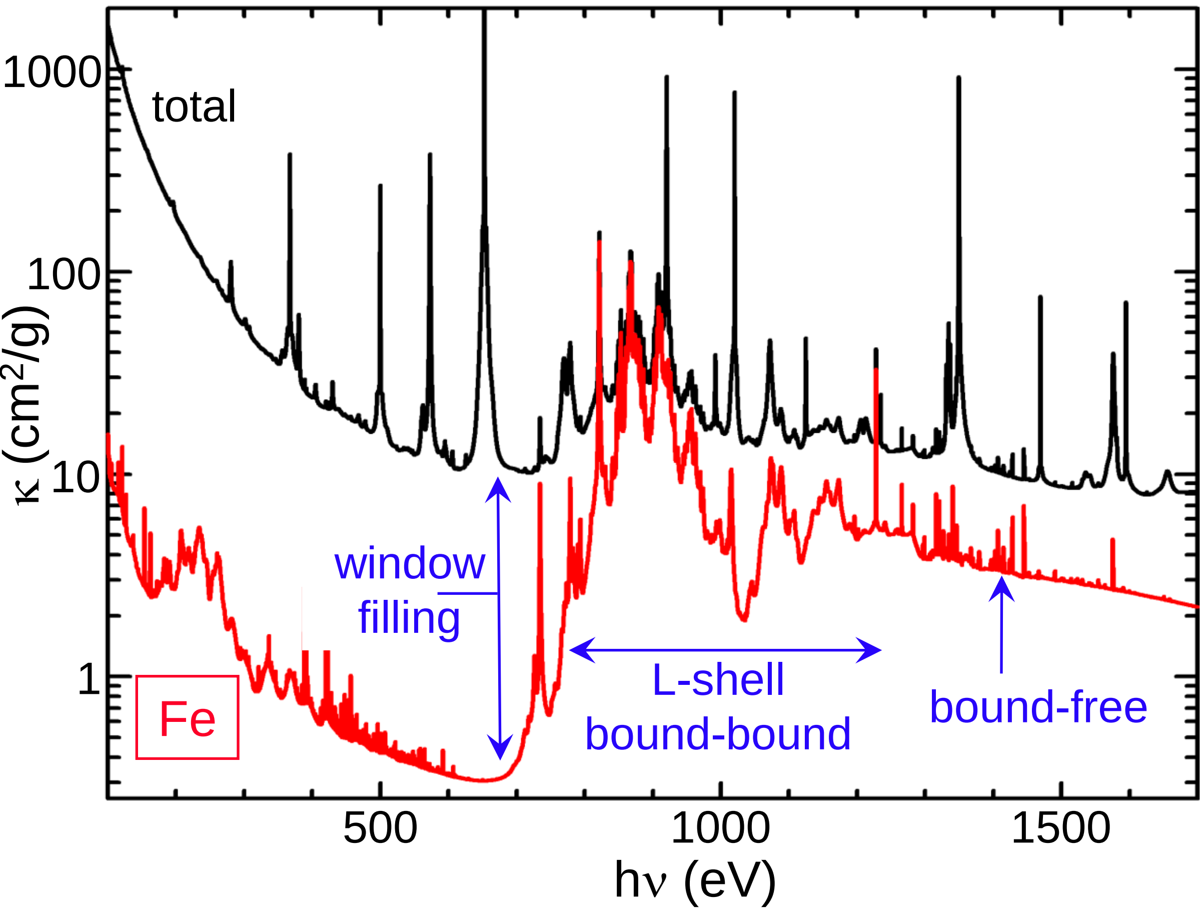






CEA OPAS calculation

At the convection zone base iron contributes opacity predominantly from L-shell transitions



Opacity Project
Badnell *et al.*,
MNRAS 2005

T_e, n_e determine ionization

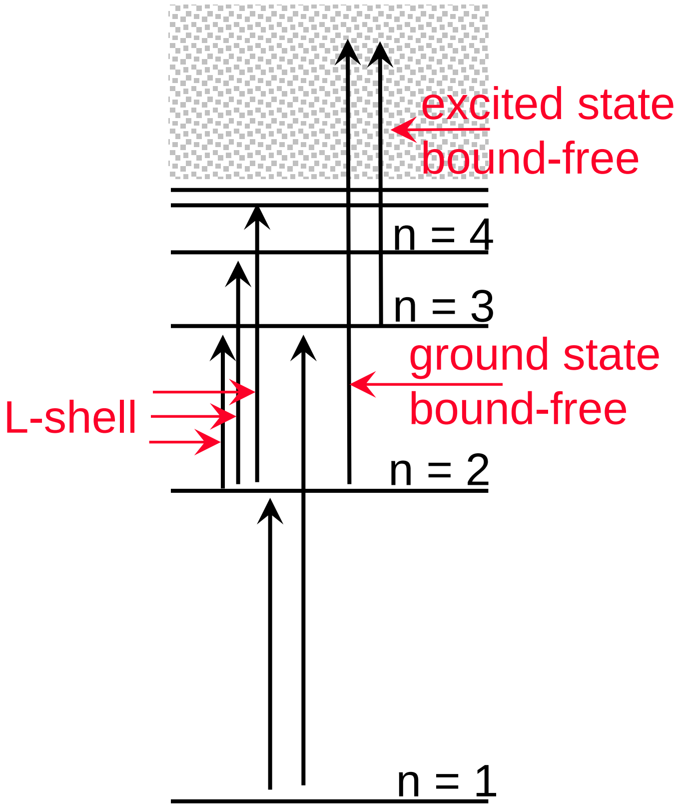
{190 eV, 9e22 e/cc}

Ionization determines which transitions are important

At CZB, dominant charge states are Fe^{+16}, Fe^{+17}, Fe^{+18}

Photons are transported in opacity windows, but windows are filled by other elements

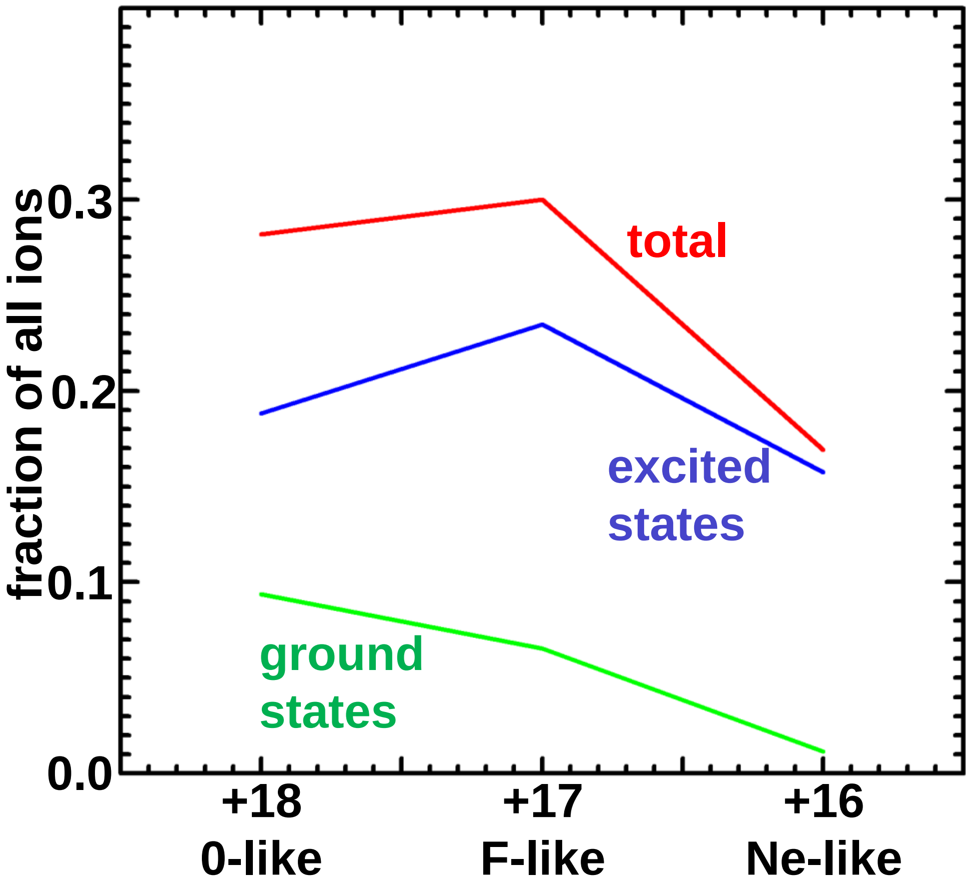
Multiple entangled physical processes are a concern for opacity models



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

One challenge for iron opacity models is that significant population resides in myriad excited states



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

Accurate energy level description required for *all* excited states

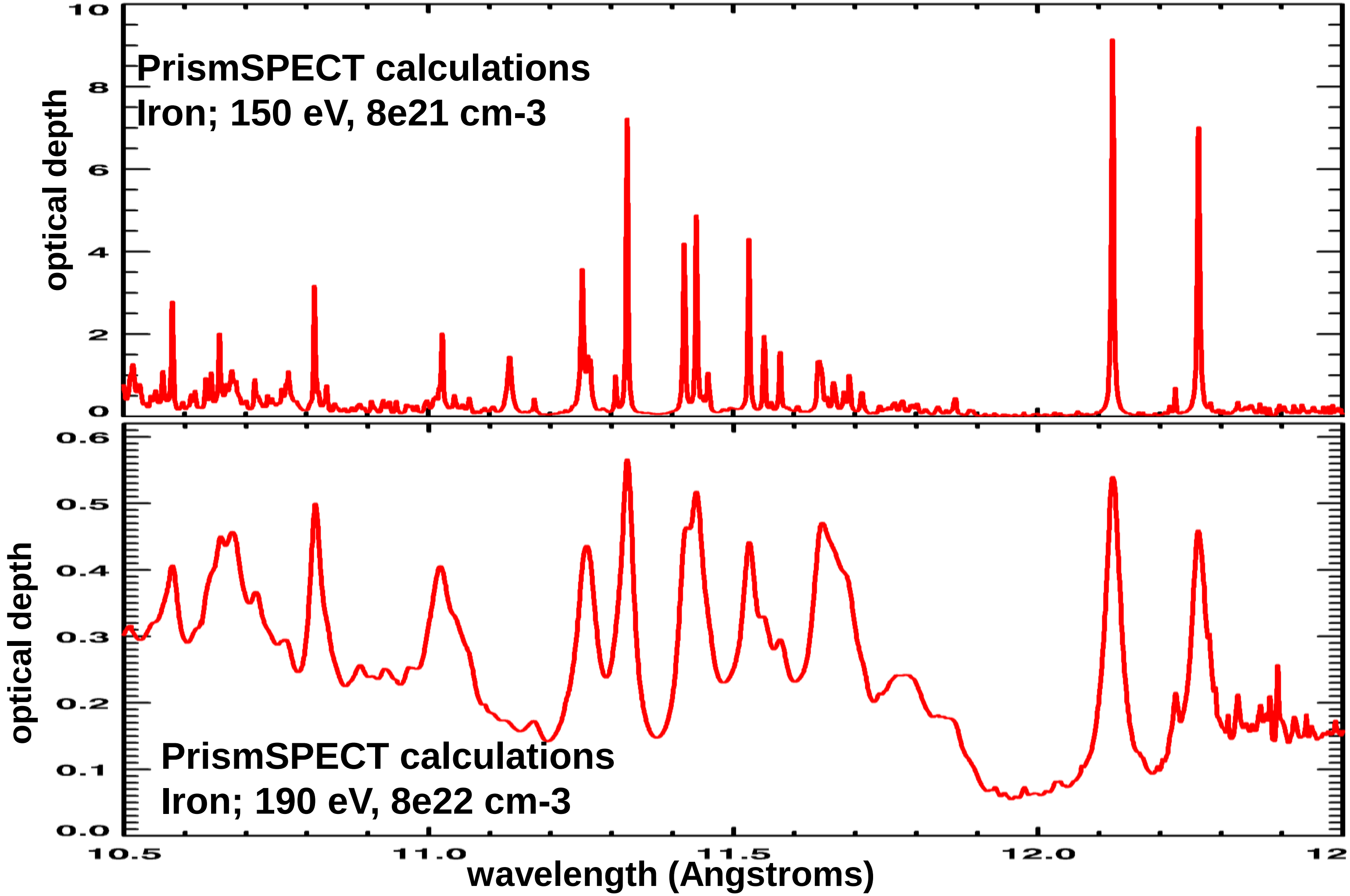
Plasma effects more easily modify excited states

<u>Example: </u>Ne-like iron
excited state fraction = 93%
ground state fraction = 7%

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

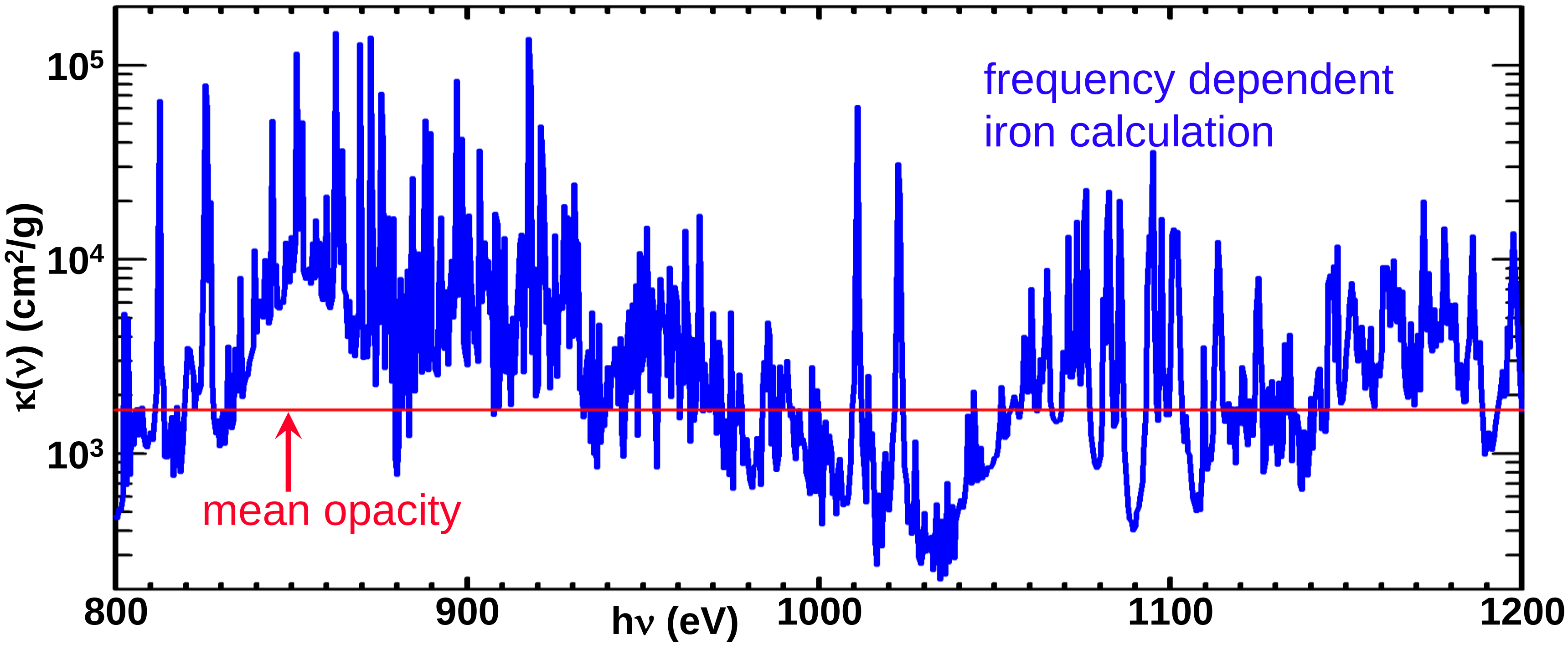
i.e., 40% decrease in lines originating from ground state

Another challenge: Line broadening influences opacities but models for many-electron ions are untested



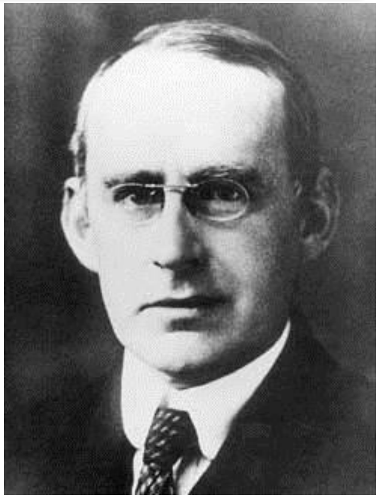
- **Broadening tends to close the opacity windows between lines**
- **Modeling high-n and multiply-excited states is difficult**

Strategy: frequency-dependent transmission measurements test opacity model physics



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

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 $\tau = -\ln(T)$

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

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

Benchmark quality opacity experiment requirements have been developed over 30 years

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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

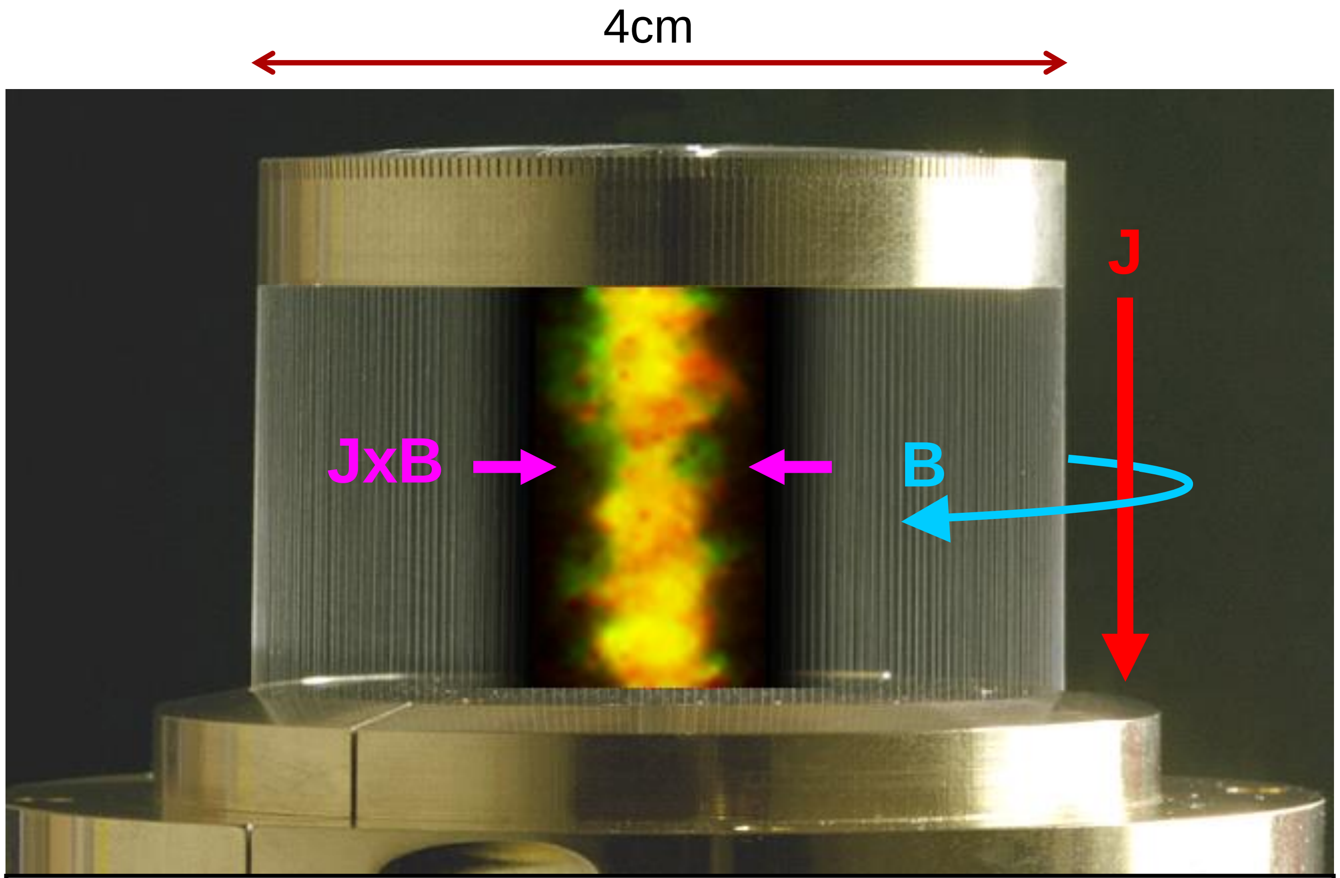
Springer *et al.* JQSRT 1997

Experiment requirements:

1. Accurate transmission measurements (~ ± 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 appoximation 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)

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



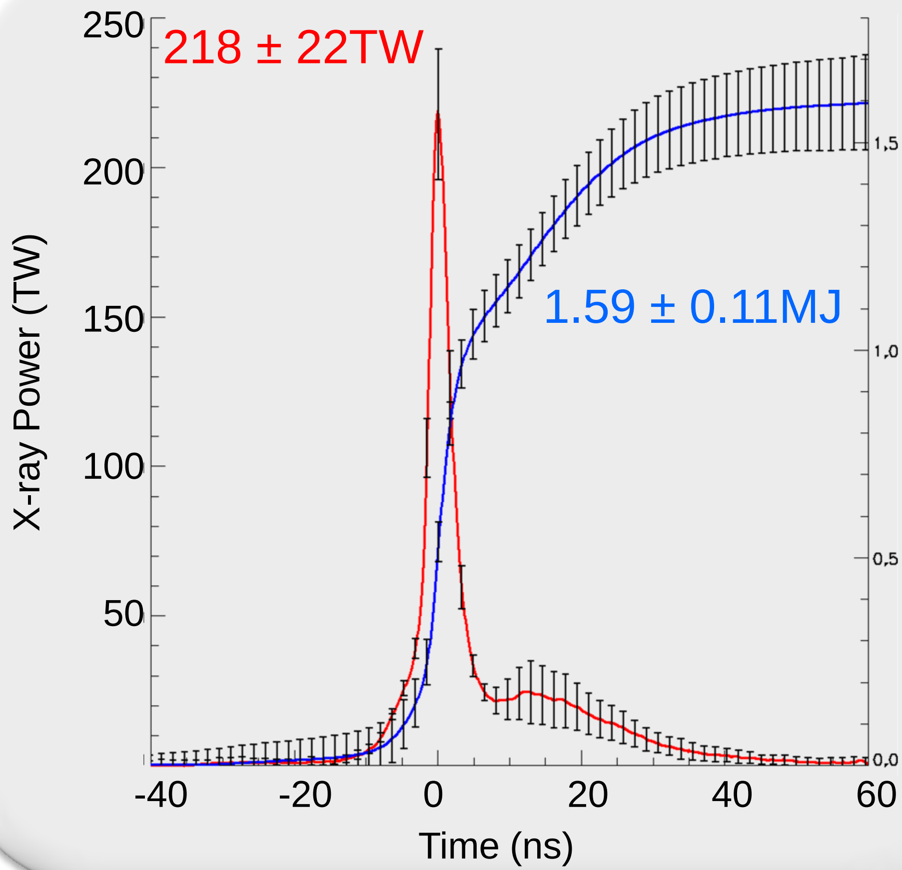
P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

~ 8% wall plug efficiency

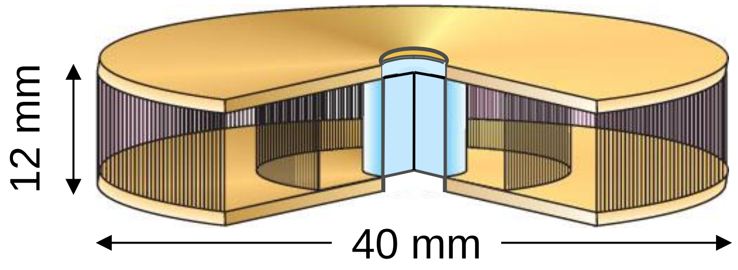
**Stanford, PoP 9 (2002); Bailey et al,PoP 13 (2006); Slutz et al., PoP 13 (2006); Rochau et al., PPCF 49 (2007)*

The ZPDH x-ray emission is reproducible to ± 10% in peak power and ± 7% in energy

Radial X-ray Power and Energy (20 shot average)



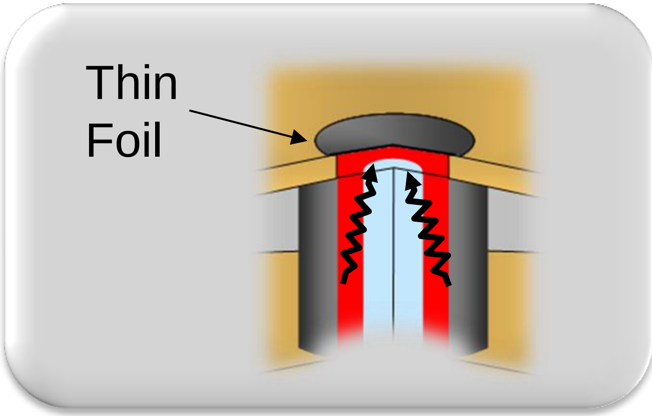
Z-pinch Dynamic Hohlraum



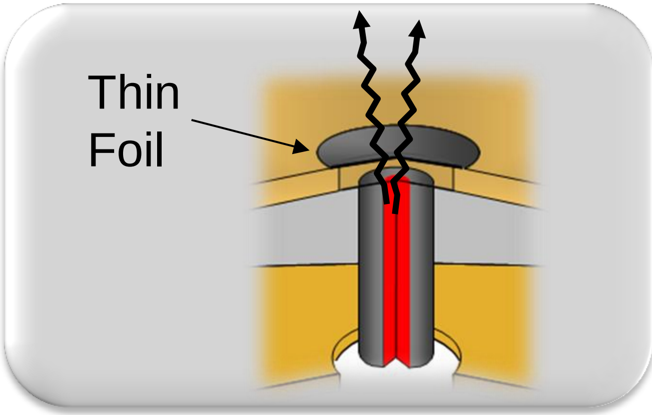
	ZR	Z
Marx Energy	21 MJ	12 MJ
Ipeak	25.8 MA	21.8 MA
Mass	8.5 mg	3.8 mg
Peak Power	220 TW (10%)	120 TW (14%)
Radiated Energy	1.6 MJ (7%)	0.82 MJ (17%)

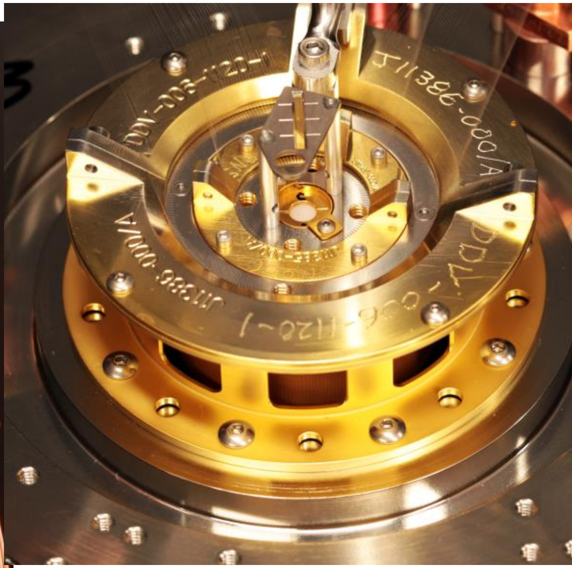
The ZPDH radiating shock is used to both heat and backlight samples to stellar interior conditions.

Foil is heated during the ZPDH implosion

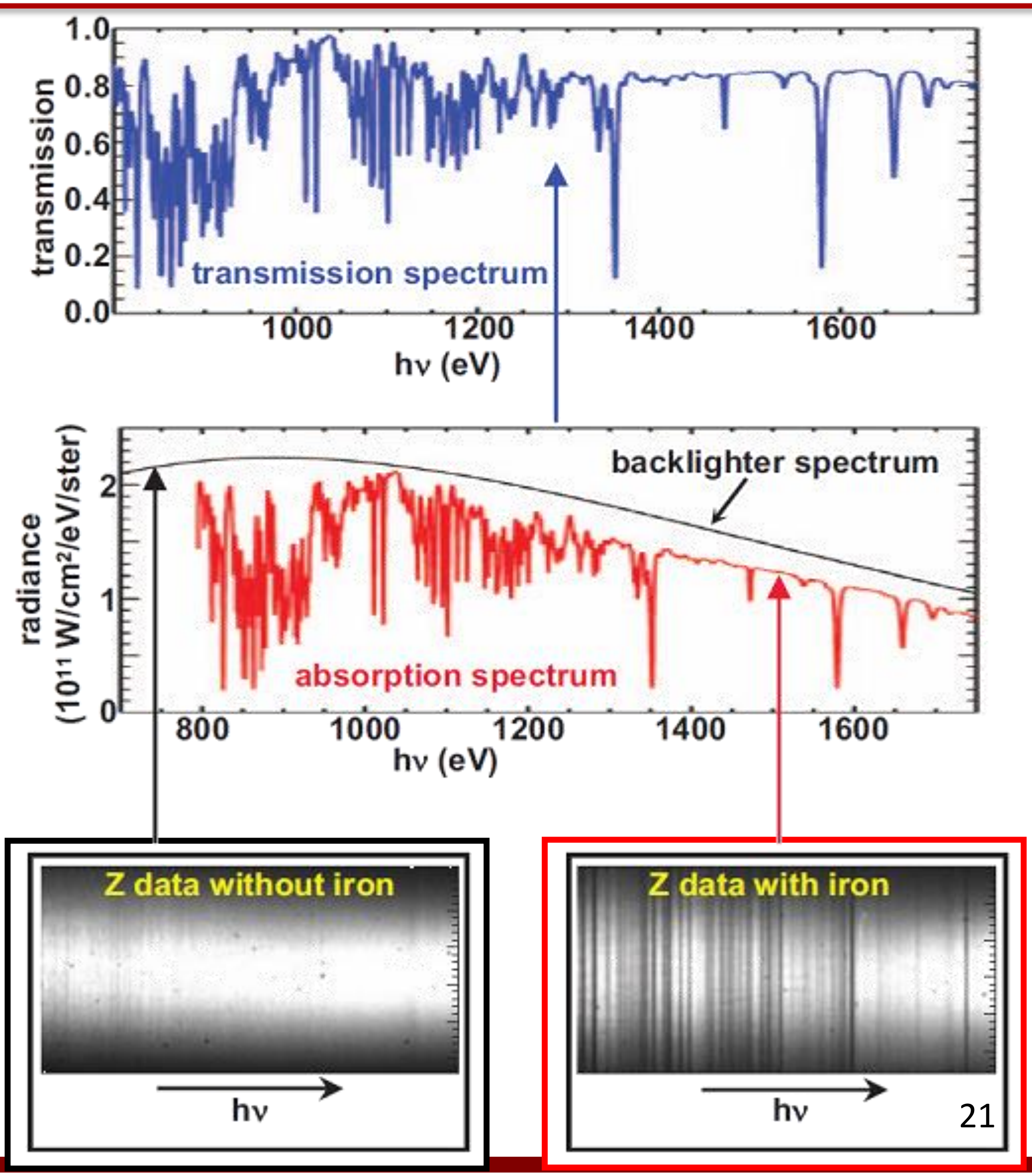


Foil is backlit at shock stagnation

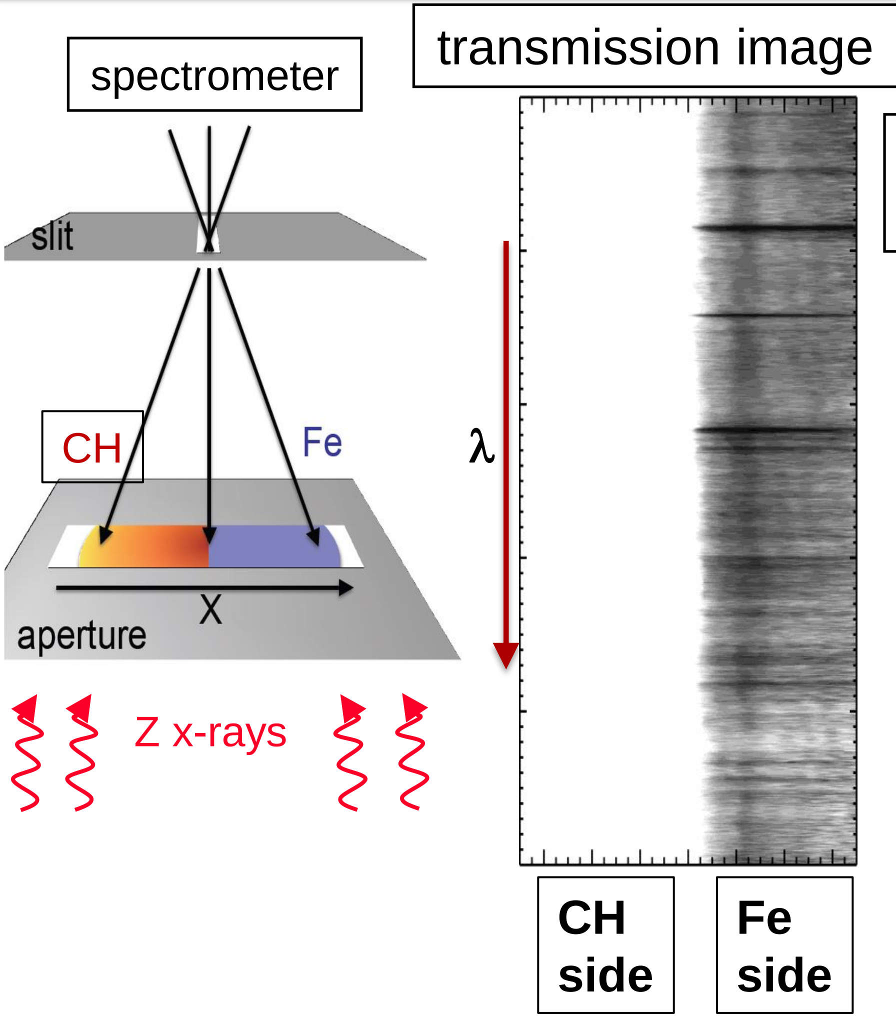




Transmission is inferred by dividing the attenuated spectrum by the unattenuated spectrum.



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

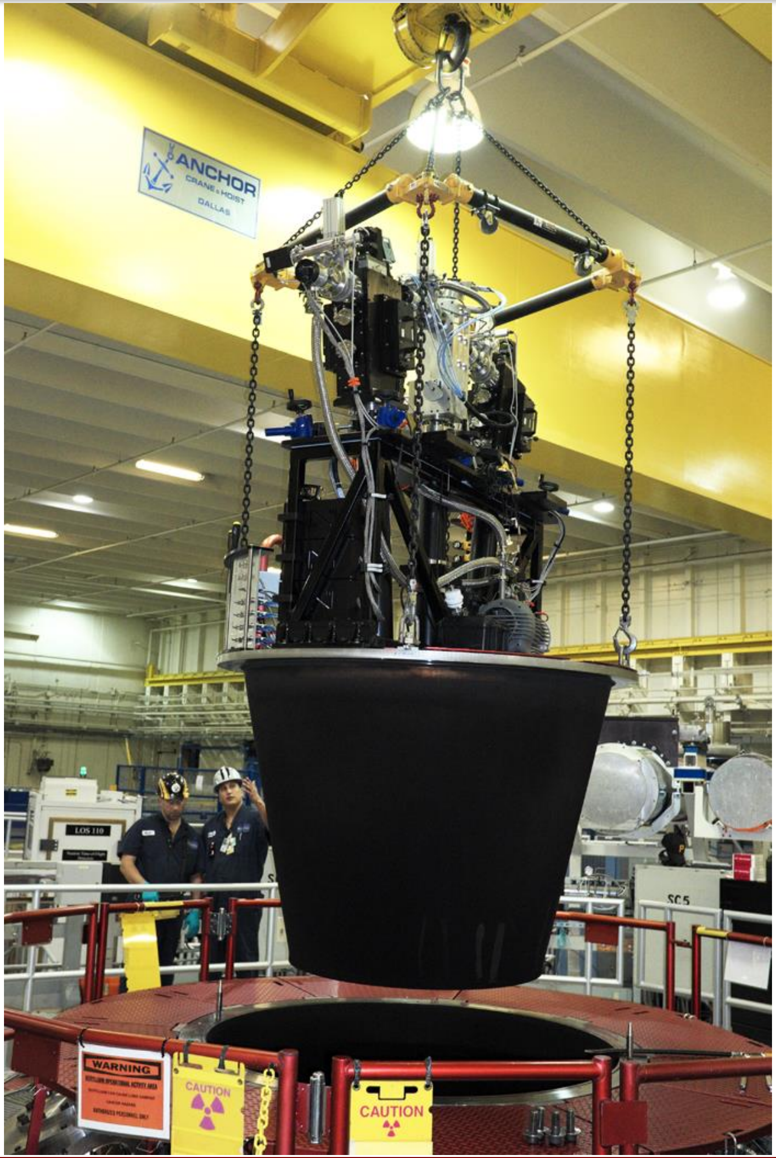


Backlit spectra with and without sample determine transmission

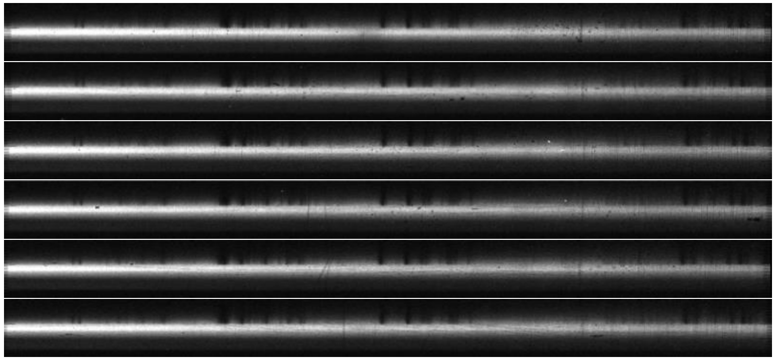
T.S. Perry *et.al.* Phys. Rev. E (1996)
J.E. Bailey *et.al.* Phys. Plasmas (2009)

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

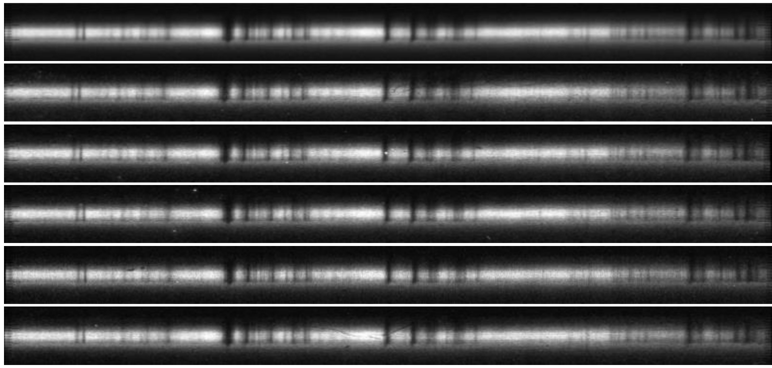
Opacity data are recorded with an array of crystal spectrometers



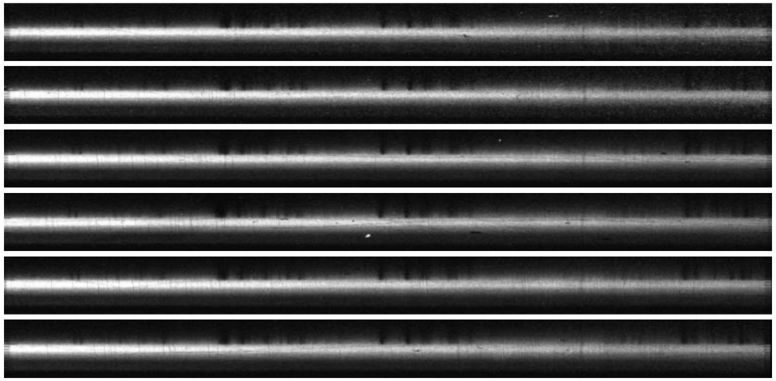
Hundreds of spectra were measured and analyzed to support the experiment reliability and reproduciblity



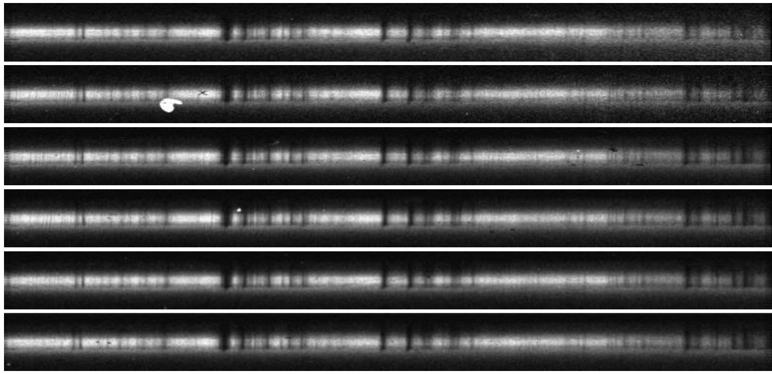
ccp4a



ccp10a



ccp4b



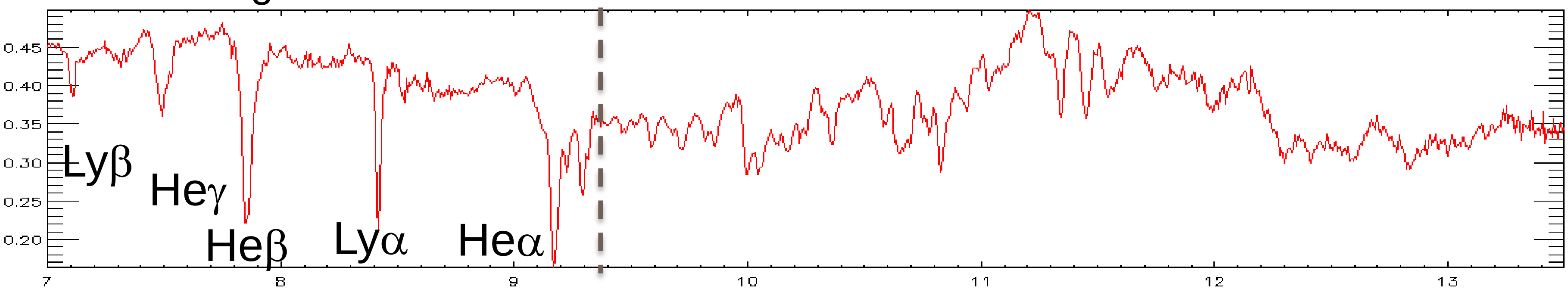
ccp10b

Data from z2762

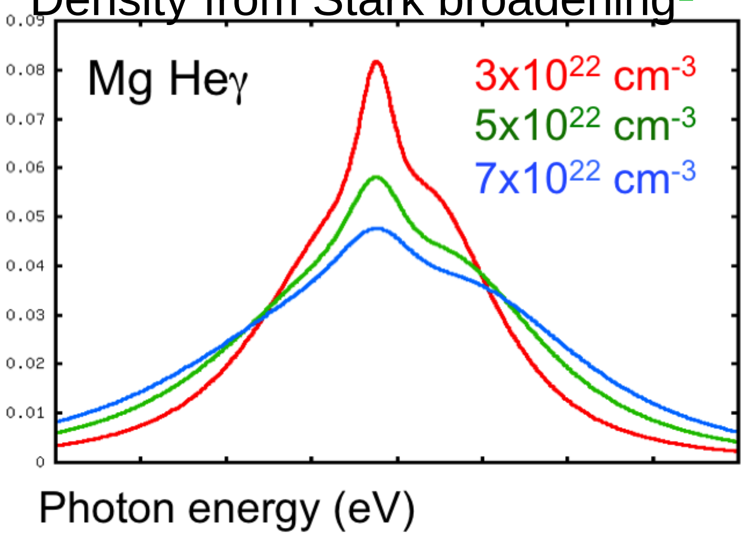
Plasma conditions are inferred by mixing Mg with Fe and using K-shell line transmission spectroscopy

Mg K-shell

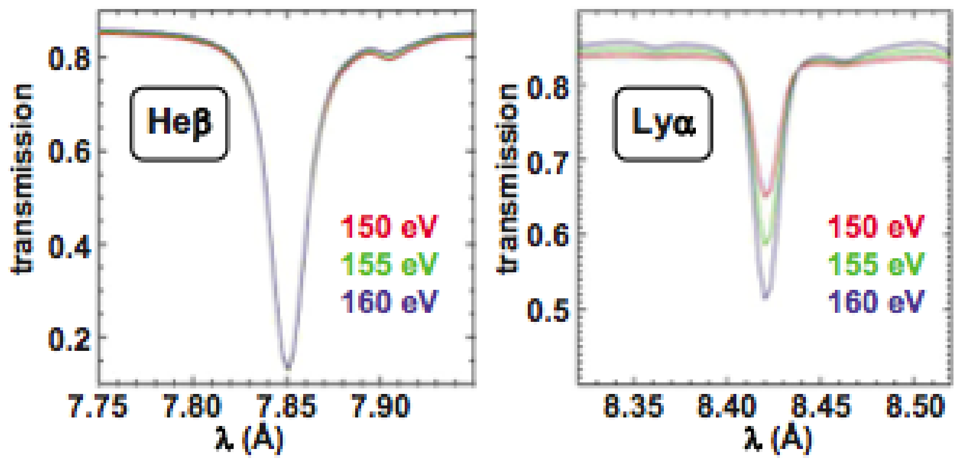
Fe L-shell



Density from Stark broadening[1]

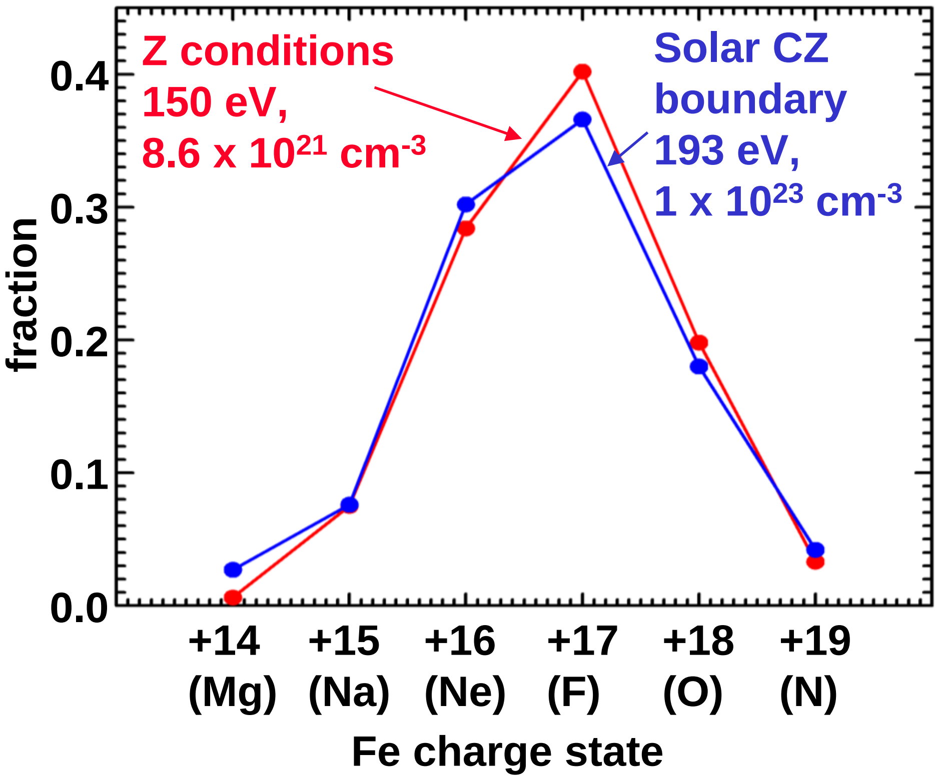


Temperature from line ratios



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

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



<u>Producing the correct charge states enables opacity model tests:</u>

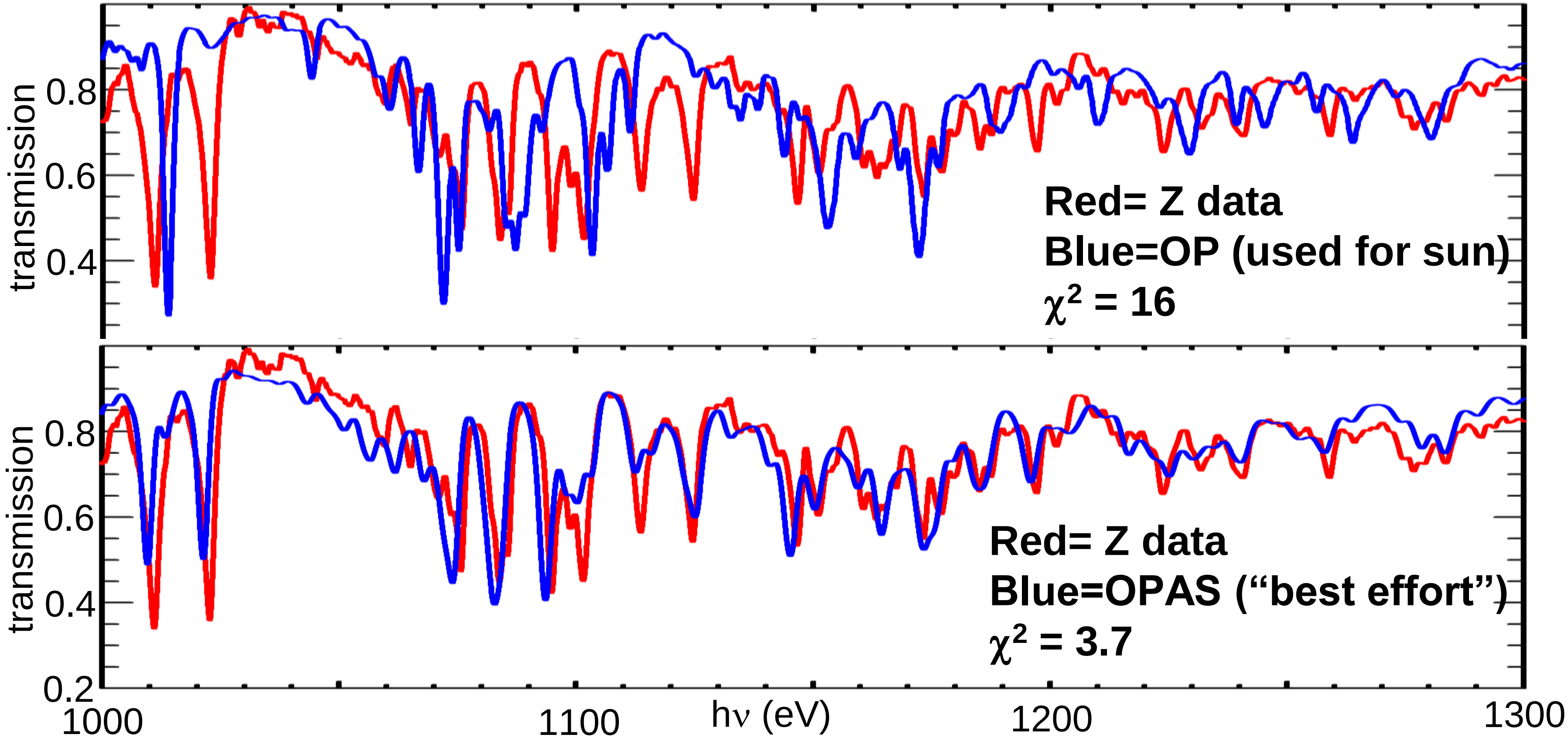
1) Charge state distribution

2) Energy level description

High density and high temperature studies required further progress

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

The 2007 Z data was matched well by “best-effort” models, but not by a model used in solar research



OP Rosseland mean is ~ 1.5x lower than OPAS at Z conditions.
If this difference persisted at solar conditions, it would solve the CZ problem
Experiments at higher density needed

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

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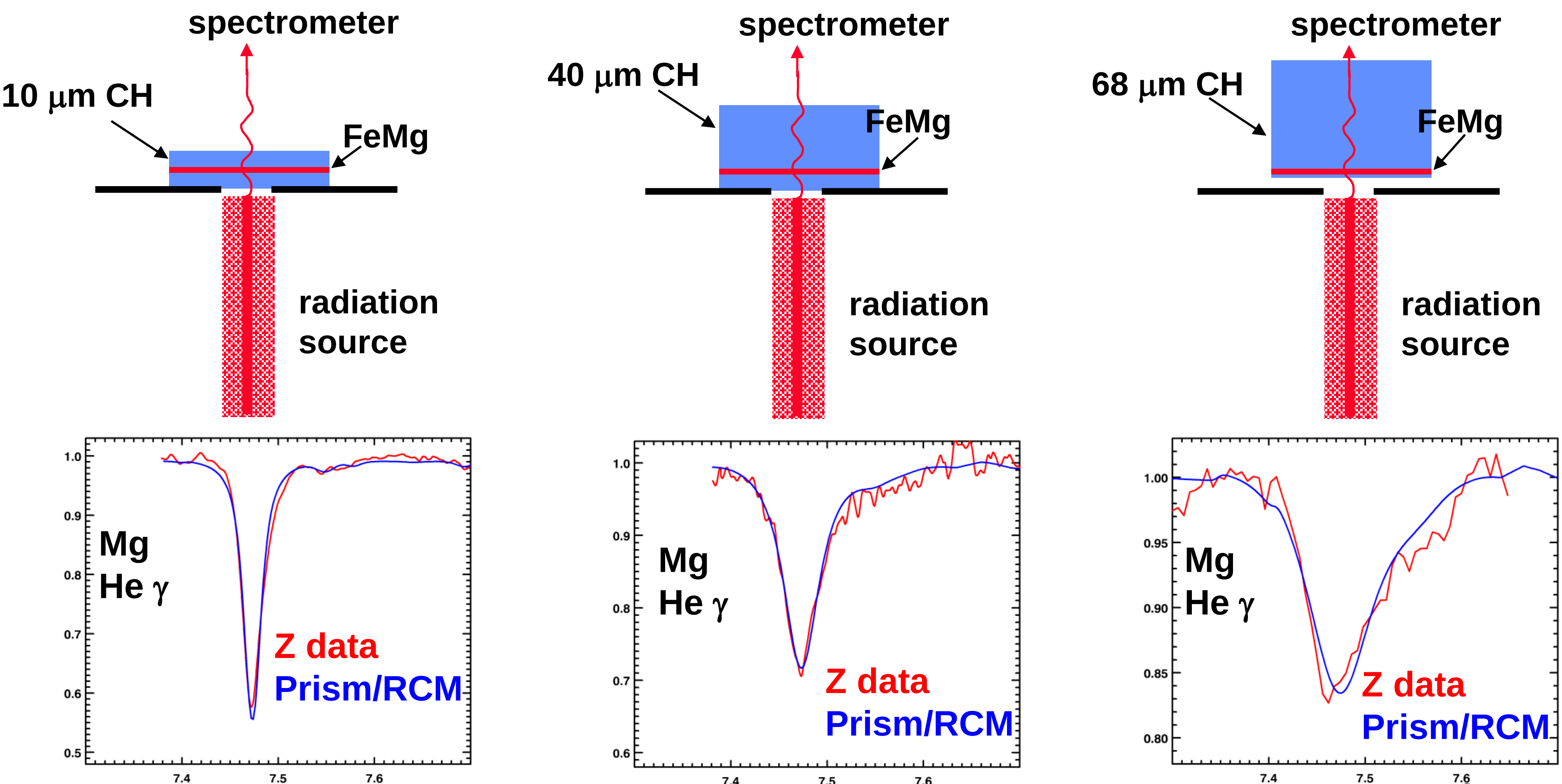


$n_e \sim 7e21\ cm^{-3}$ $T_e \sim 167$ eV

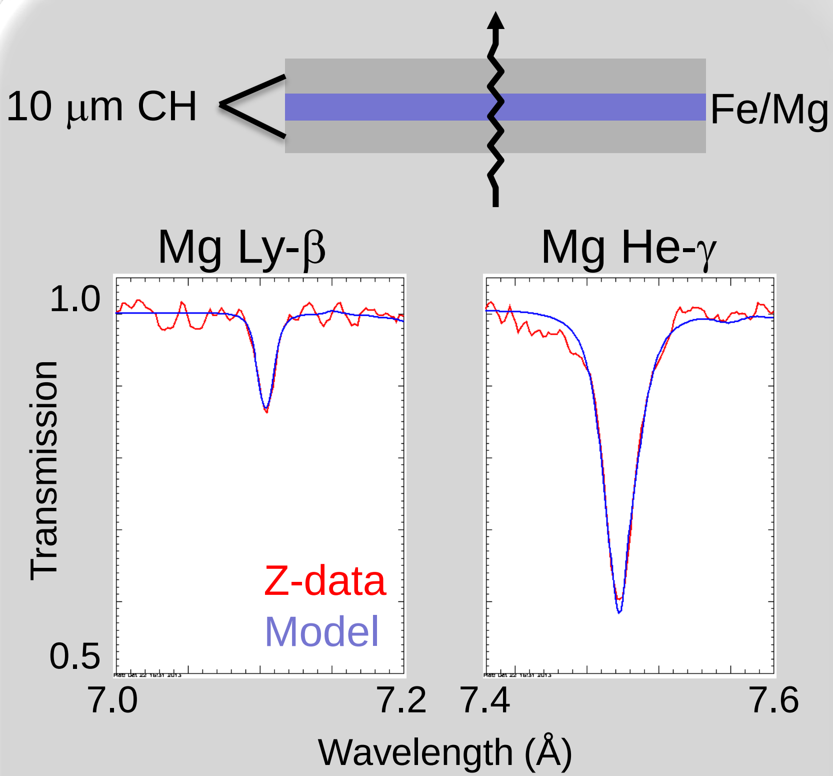
$n_e \sim 2e22\ cm^{-3}$ $T_e \sim 170$ eV

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

Nash et al RSI (2010)

The achieved temperature and density depend on the target design.

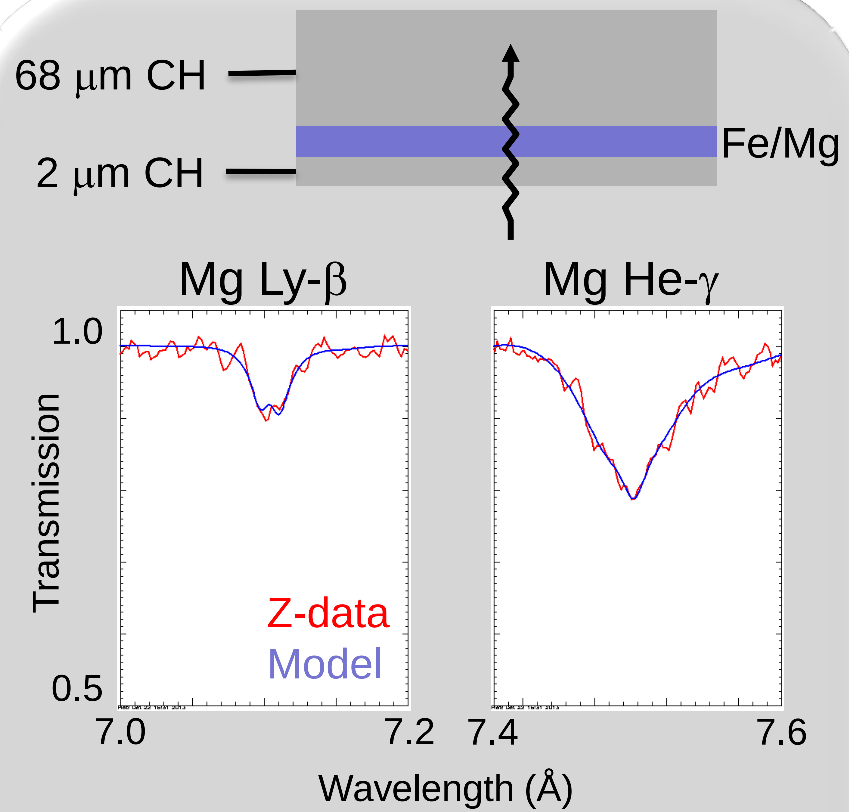
Thin Tamper



T_e = 156 ± 6 eV

n_e = 6.9 ± 1.7 x10^{21} cm $^{-3}$

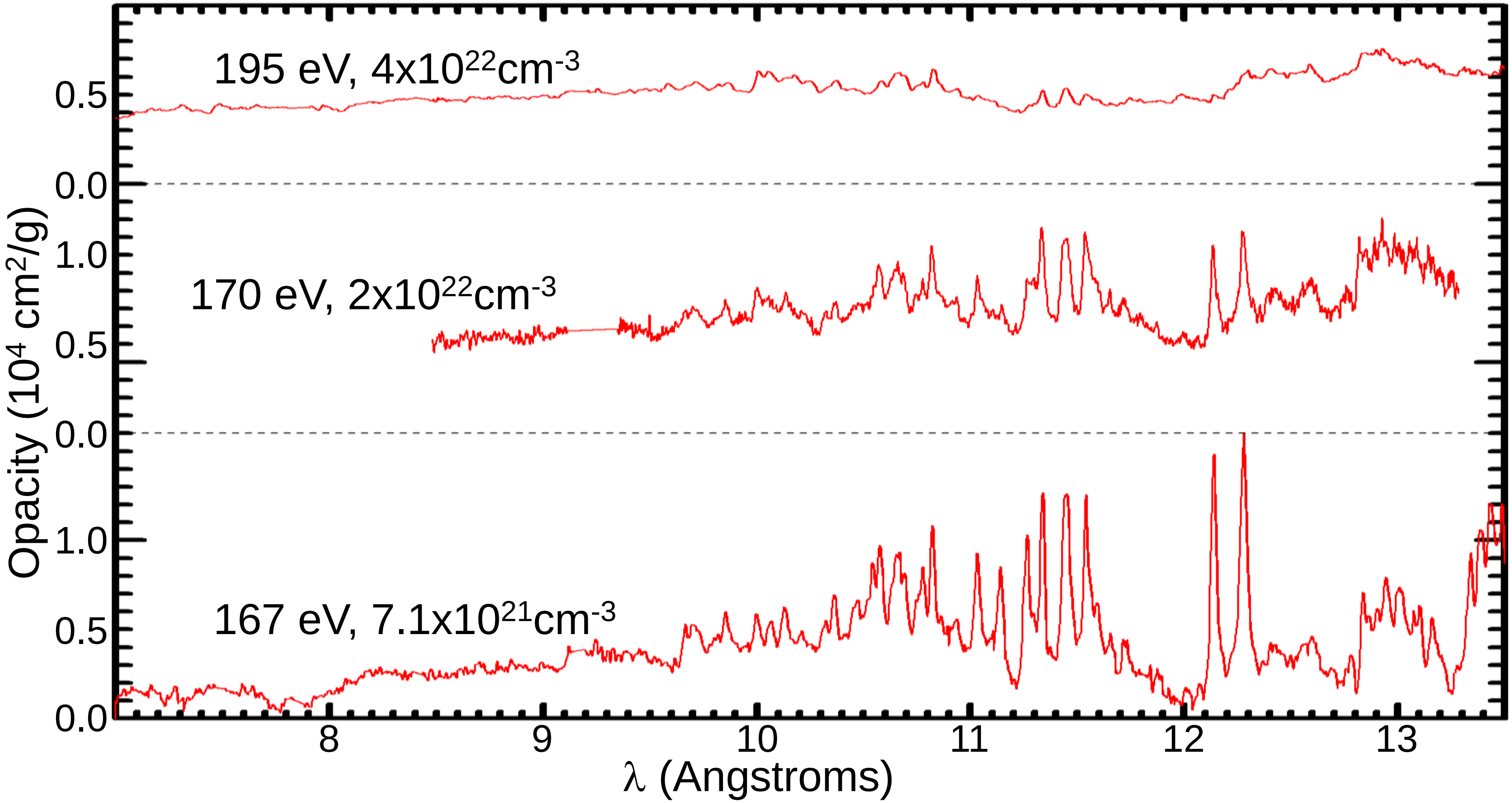
Thick Tamper



T_e = 196 ± 5 eV

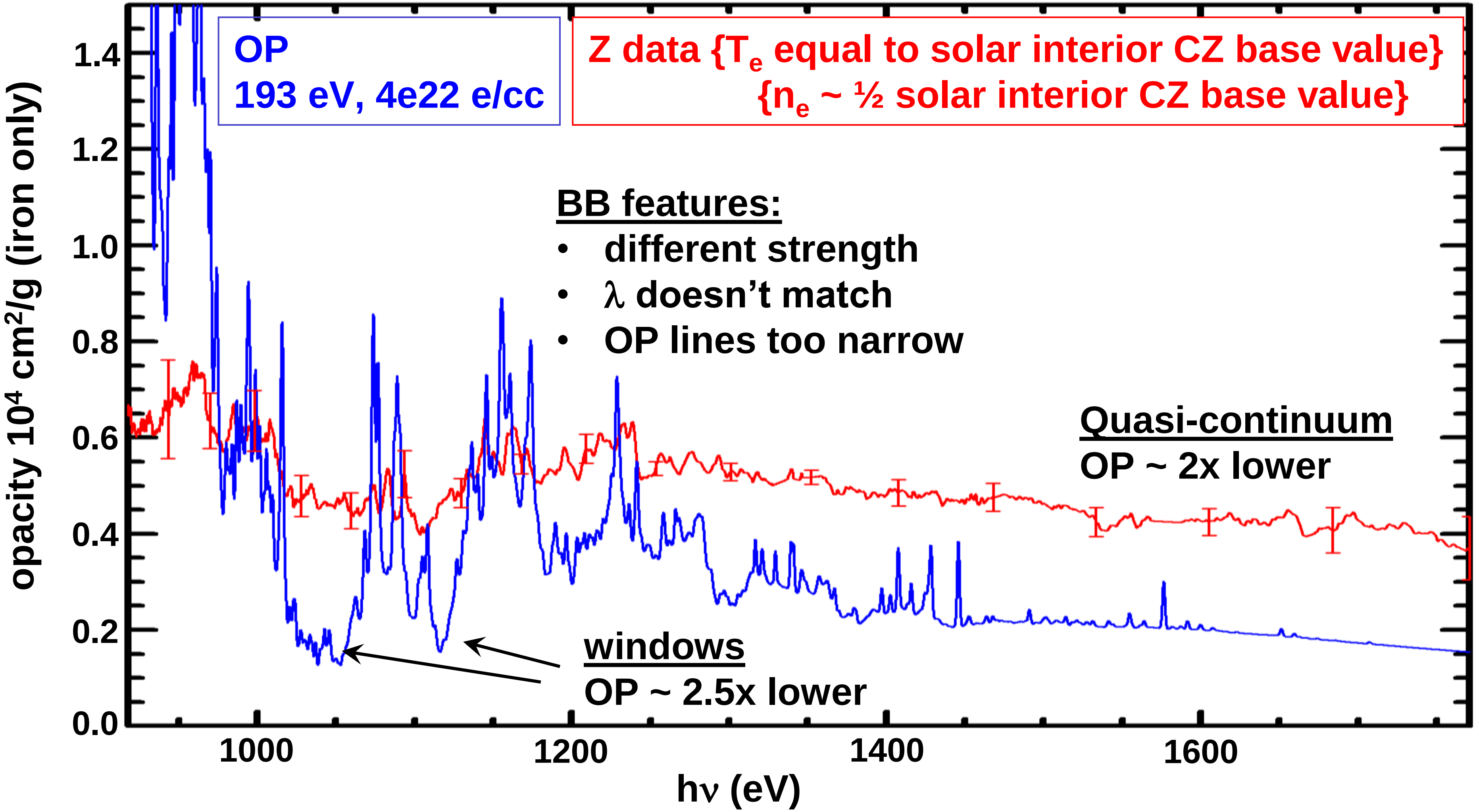
n_e = 39. ± 9. x10^{21} cm $^{-3}$

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



- Multiple conditions helps 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

The OP opacity model is used in solar models but it disagrees with Z iron plasma opacity measurements



"Best Effort" opacity models "match" the data at lower Te/ne conditions but not at conditions near the CZB

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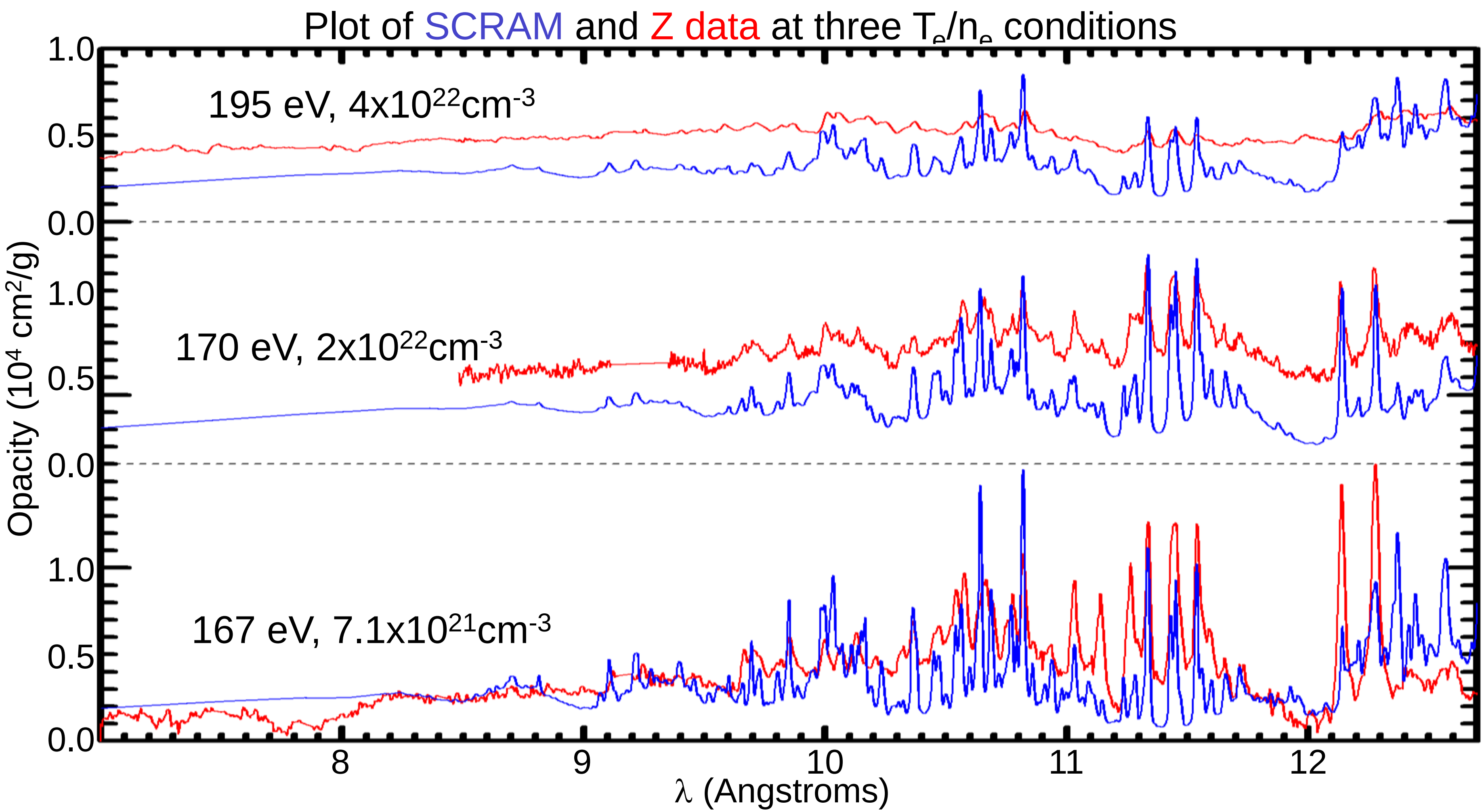

At high temperature , density, calculations are generally lower than the data

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

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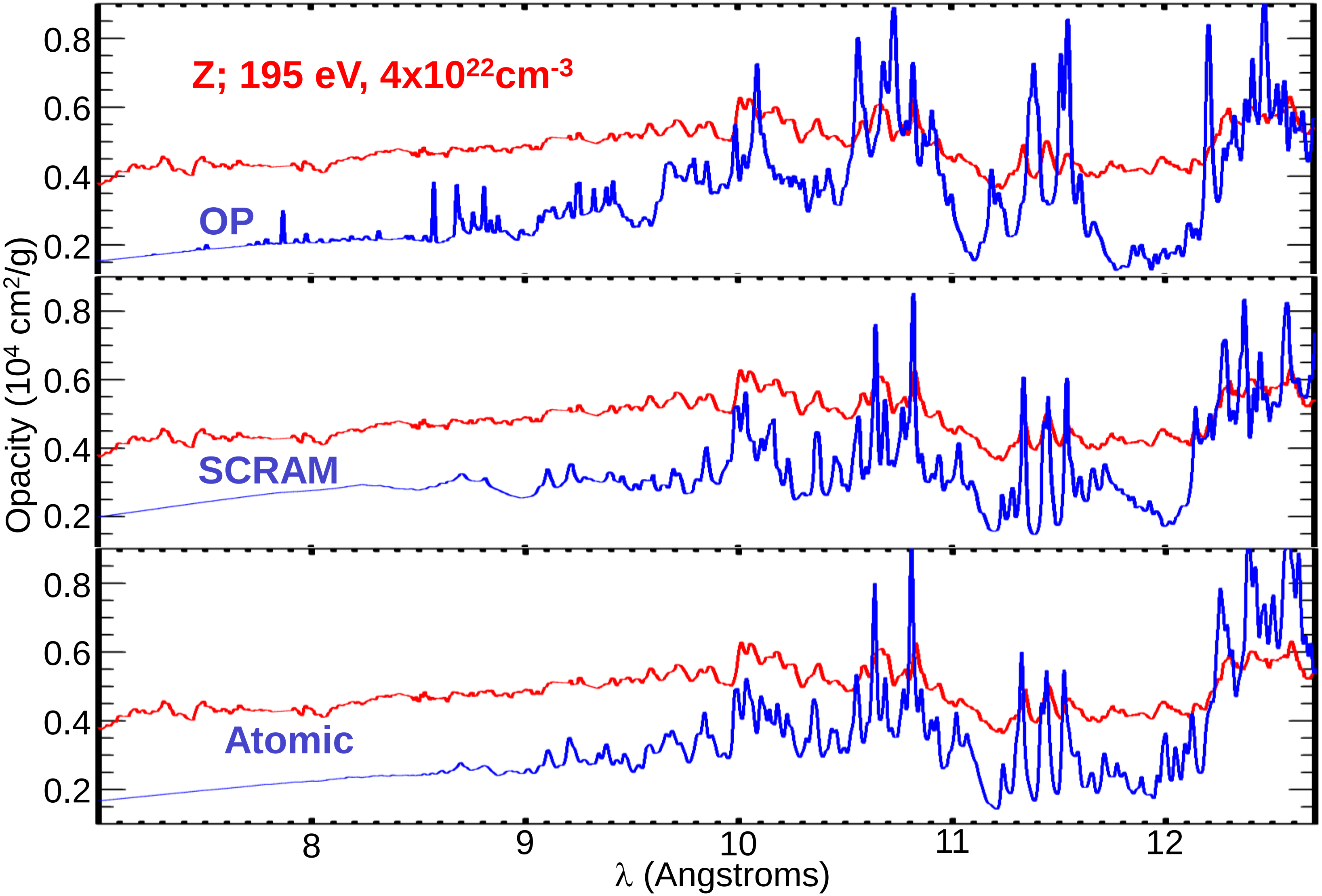
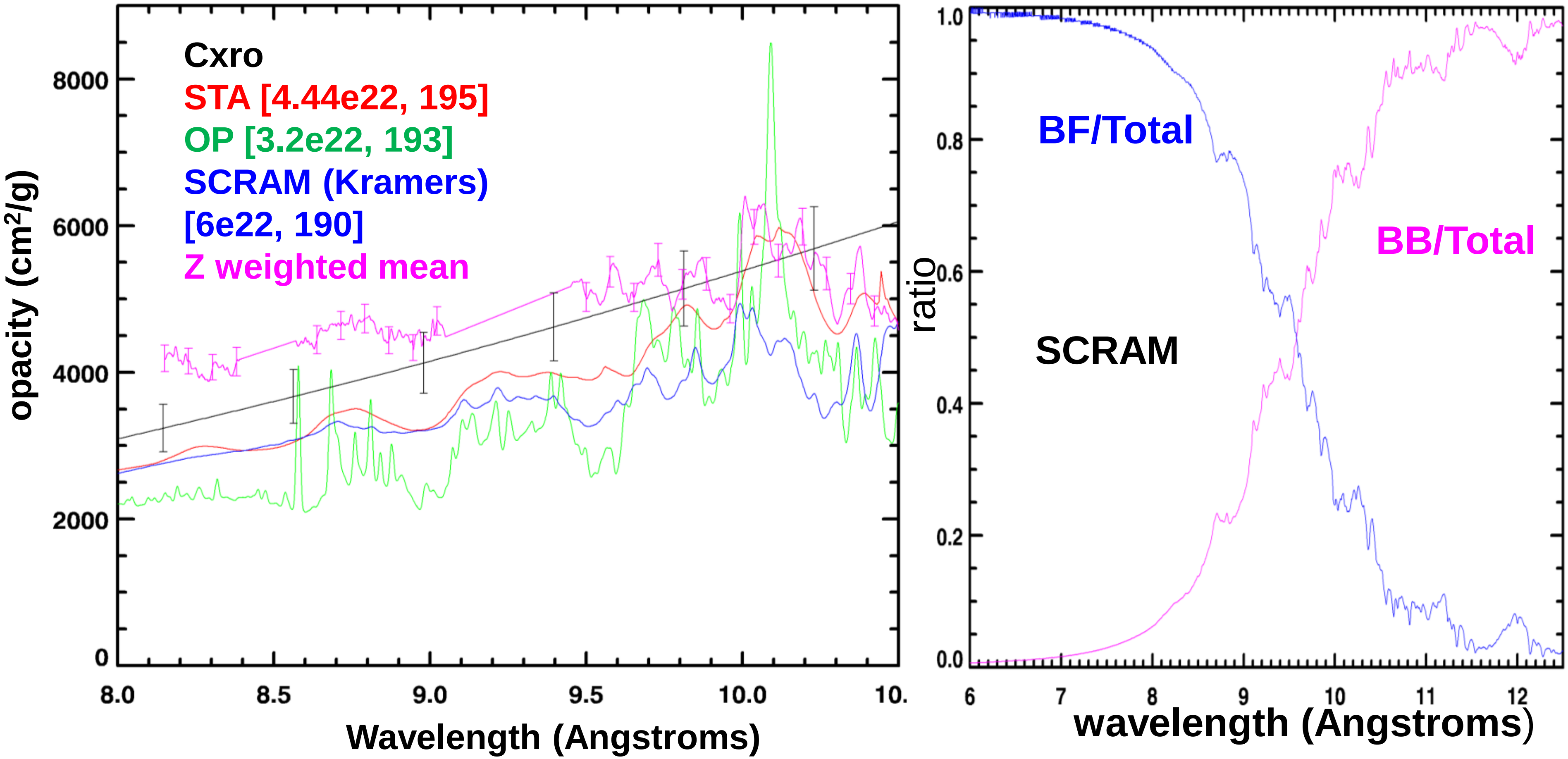


The measured hot iron plasma opacity exceeds past measurements of the cold iron opacity



This could imply errors in either our hot opacity measurement, the cold opacity measurement, photoionization calculations, or BB opacity calculations

The serious implications of this research mandate scrutiny of random and systematic uncertainties

Random error determination: average many spectra from multiple experiments

Systematic error determination:
Experiment tests of hypotheses
Simulations of sample conditions, postprocessed

Specific potential errors investigated include:

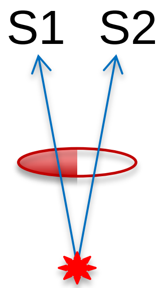
Transmission accuracy – tamper-only experiments, reproducibility, Beer's Law scaling

Sample uniformity – direct measurements, simulations

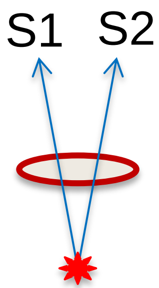
Self emission – direct observations, Beer's Law tests, post-processed simulations

Tamper attenuation – change tamper material, Beer's Law, post-process simulations

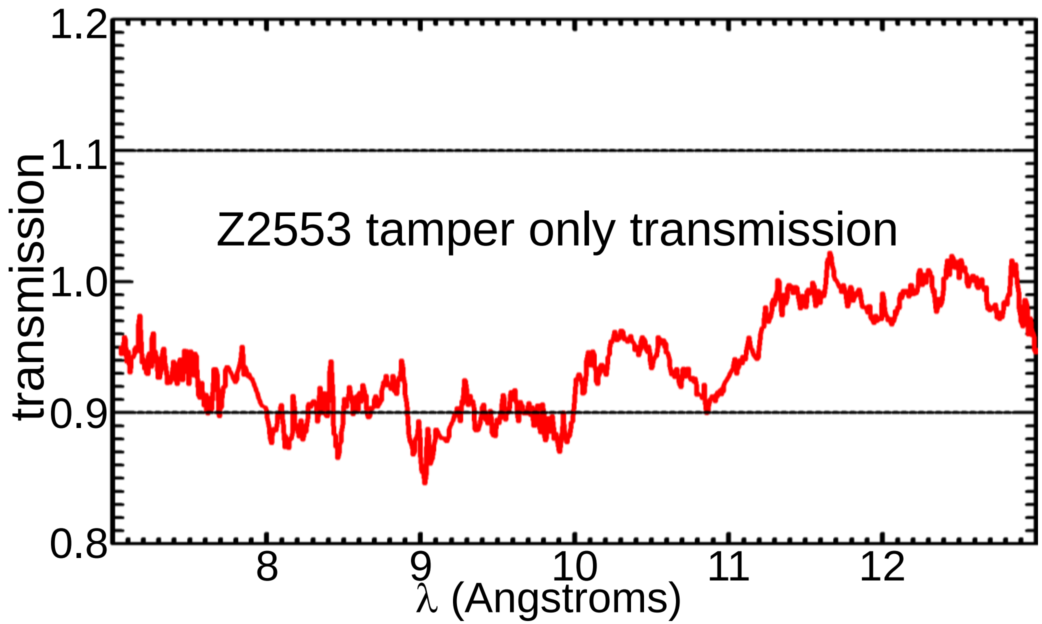
Tamper-only experiments confirm transmission accuracy



Half-moon sample:
Transmission = S1/S2

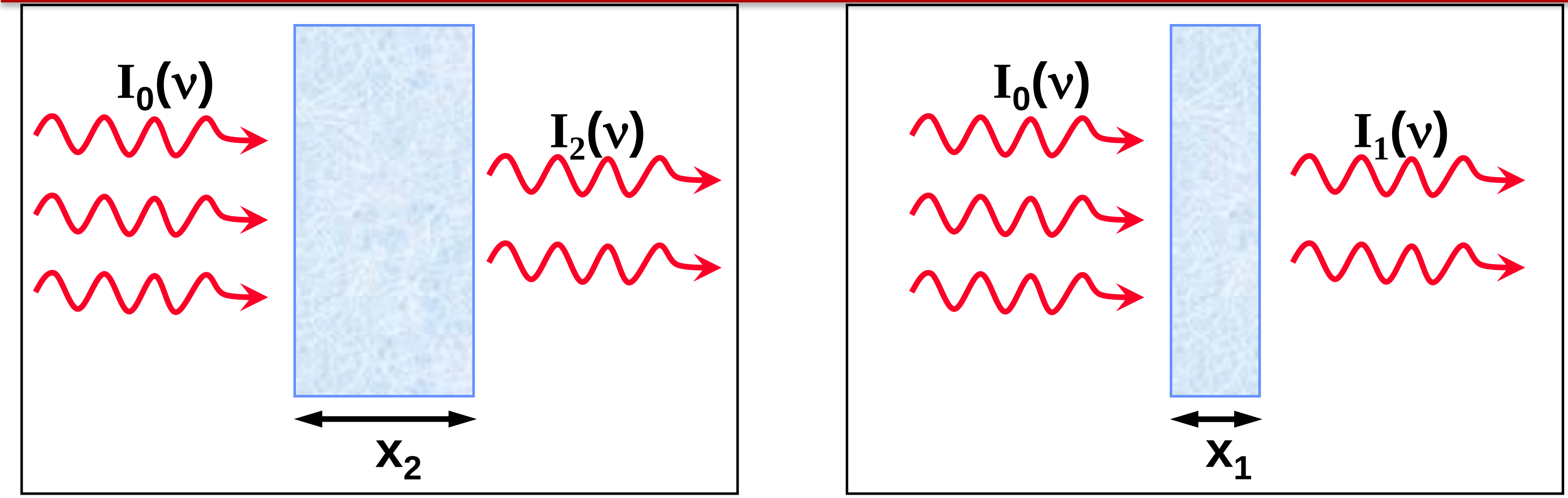


Tamper-only sample:
Transmission = S1/S2 **= 1.0**



- **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)



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

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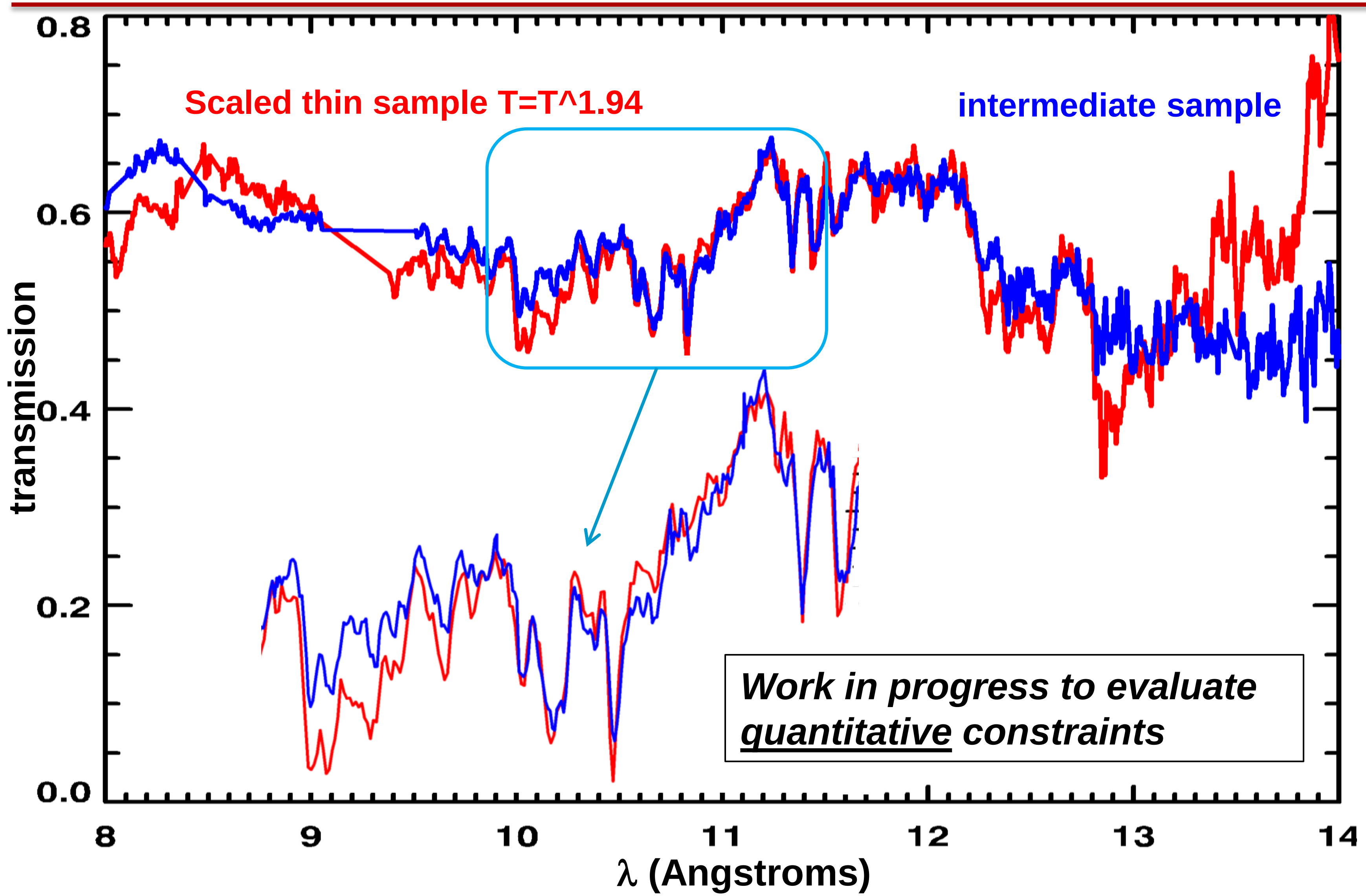
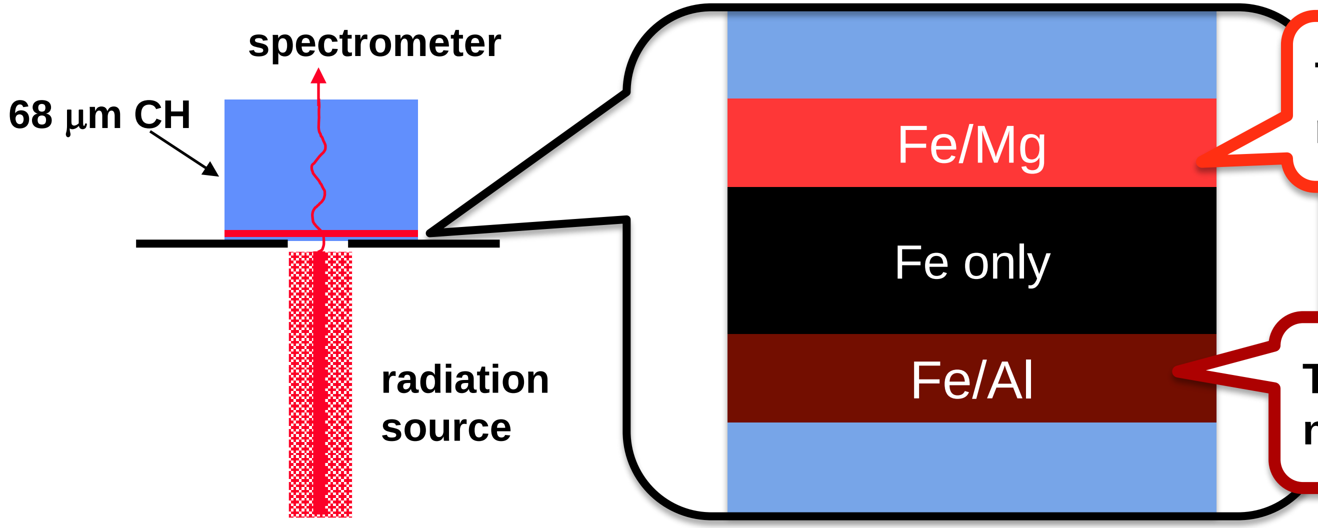


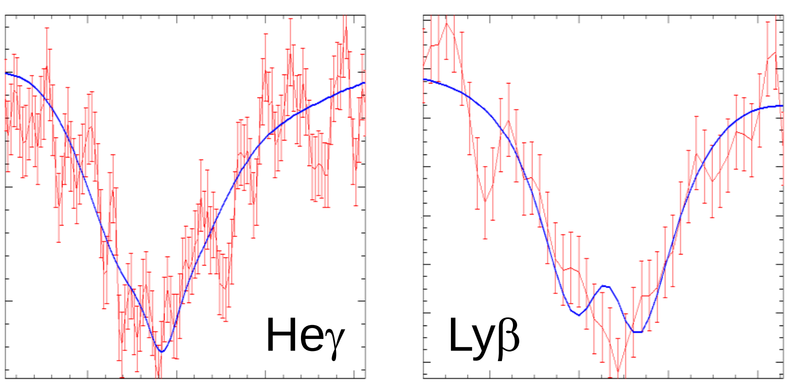
Direct uniformity measurement confirmed that there is no significant spatial gradient in the sample



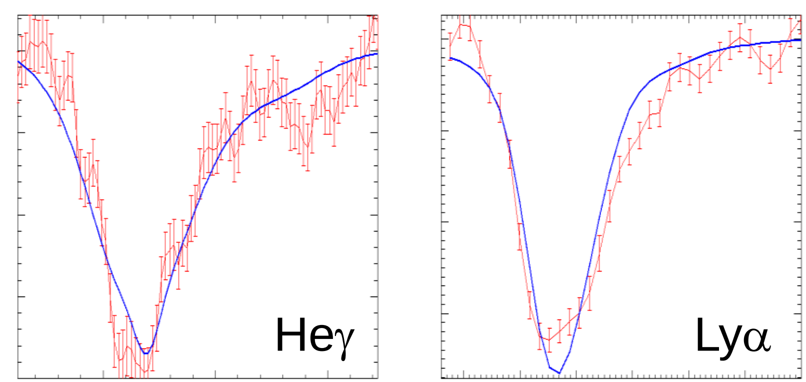
T_e=213±4 eV
n_e=(4.5±0.9)x10^{22} cm^{-2}

T_e=212±2 eV
n_e=(5.1±0.9)x10^{22} cm^{-2}

Mg lines



Al lines



Simulations can provide significant insight and quantitative estimates for systematic error hypotheses

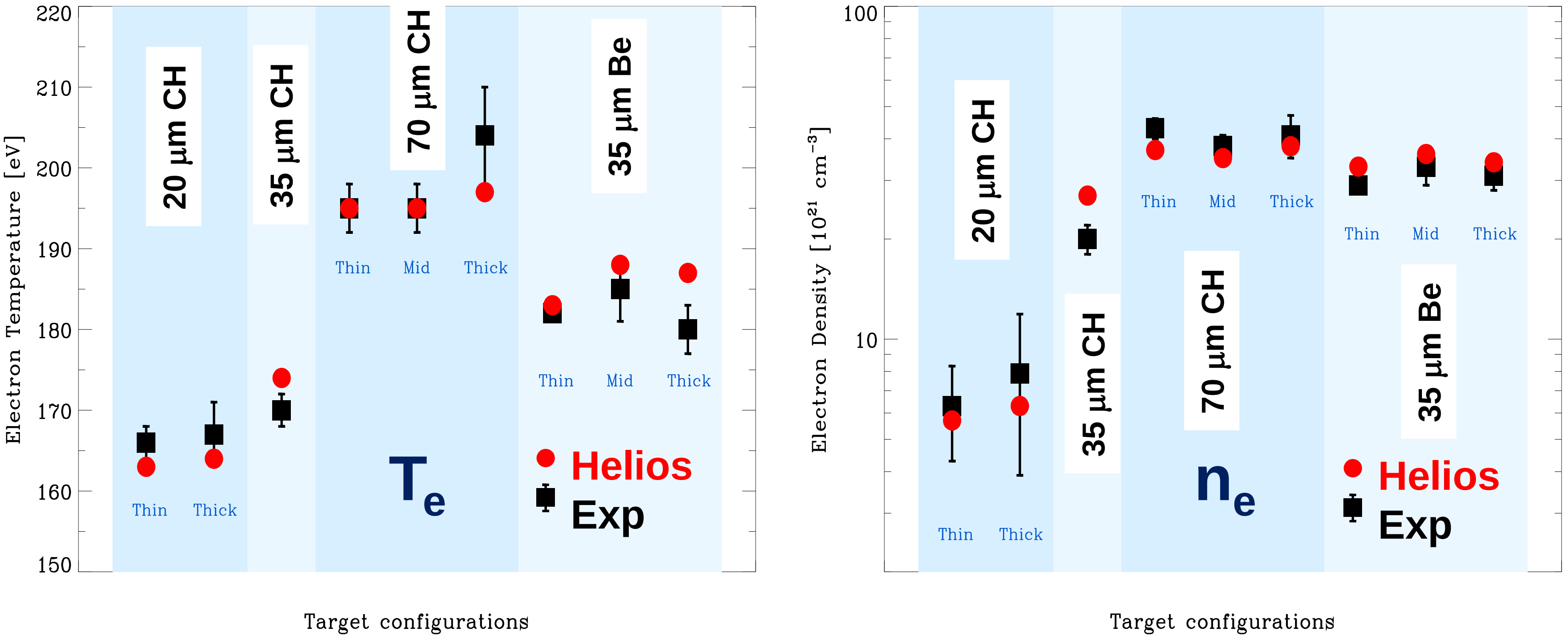
1. Why do T_e and n_e increase with tamper thickness?
2. Is sample shadowing predicted to be important? [Yes]
3. Are spatial gradients predicted to be important? [No]
4. Are temporal gradients predicted to be important? [No]
5. Is the time-integrated Fe/Mg self-emission negligible compared to the time-integrated backlighter? [No]
6. Is the time-integrated CH self-emission negligible compared to the time integrated CH attenuated backlighter? [Yes]

We use 1D HELIOS simulations to help answer these questions

We use our best experimental knowledge of the radiation drive, but this knowledge is imperfect

Therefore a key question is simulation credibility

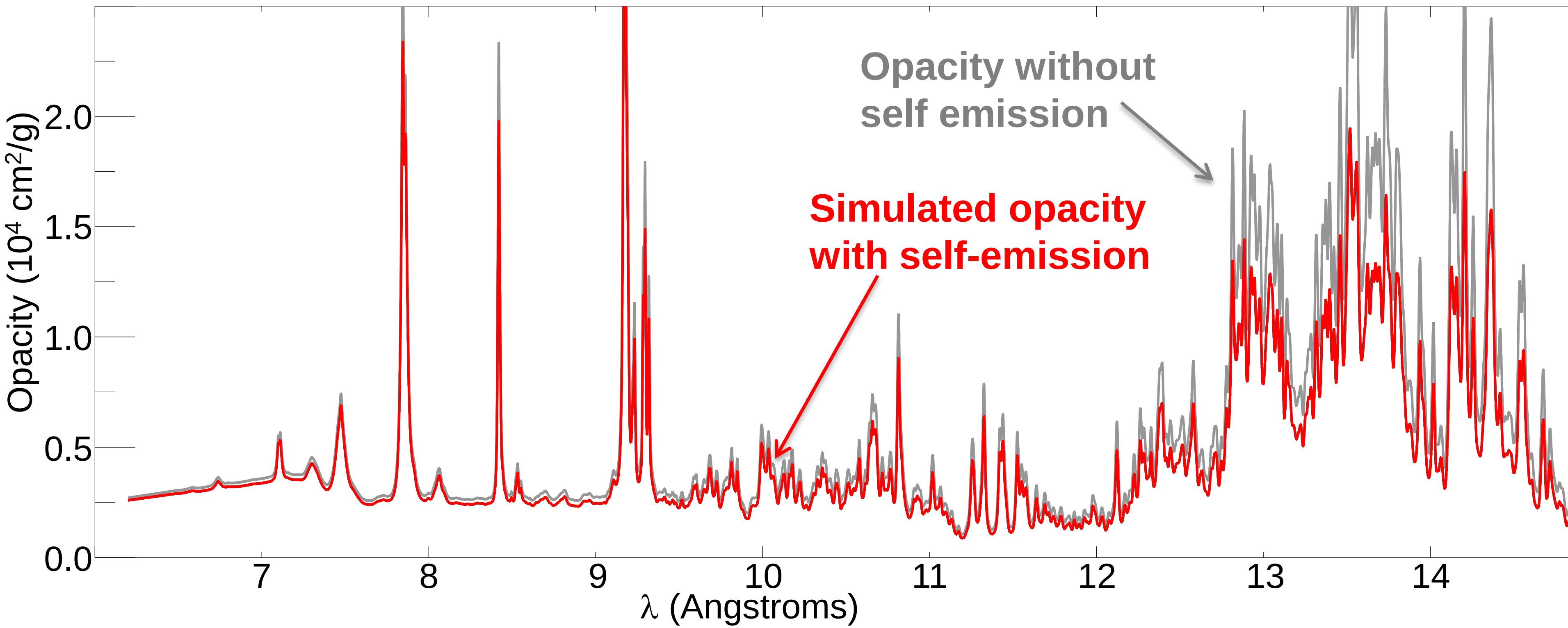
Simulations reproduce sample temperature and density for a wide range of experiments



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

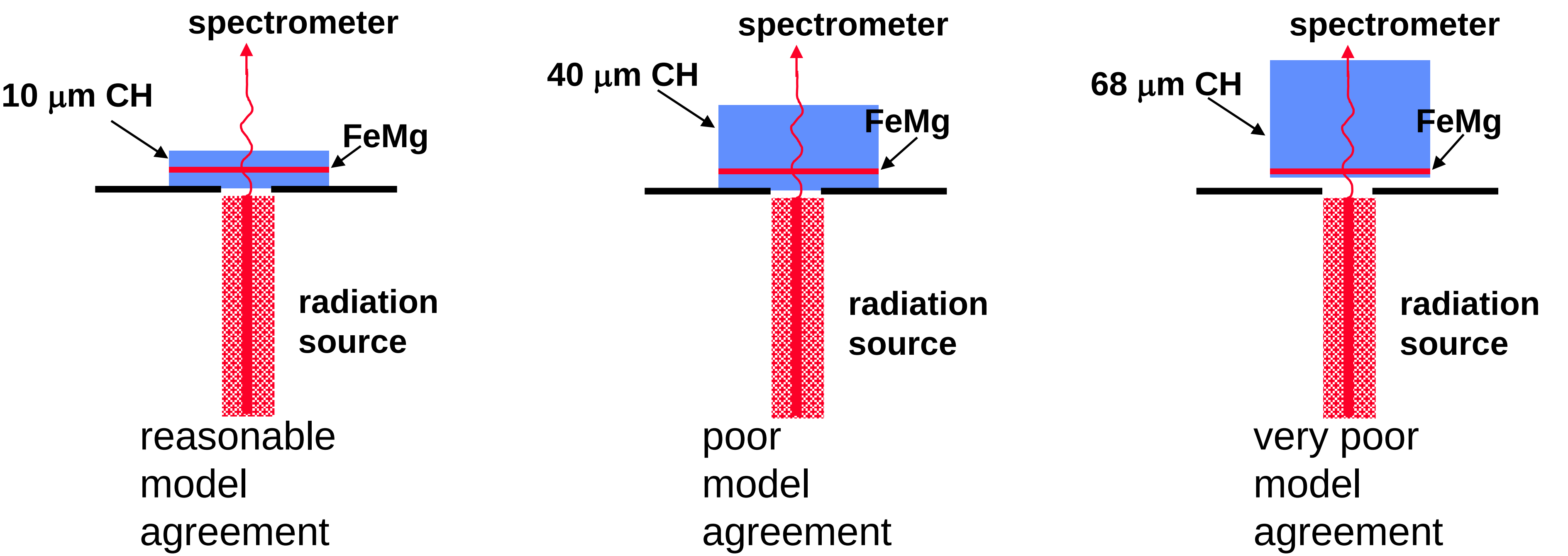
Tamper thickness changes
Sample thickness changes
Tamper material changes

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



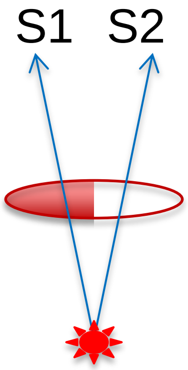
- **If present, self emission always reduces the inferred opacity**
- **Any self emission correction will increase model discrepancies for λ < 13 A**
- **We observe no self emission, but the quantitative constraint this provides is still under evaluation**

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



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

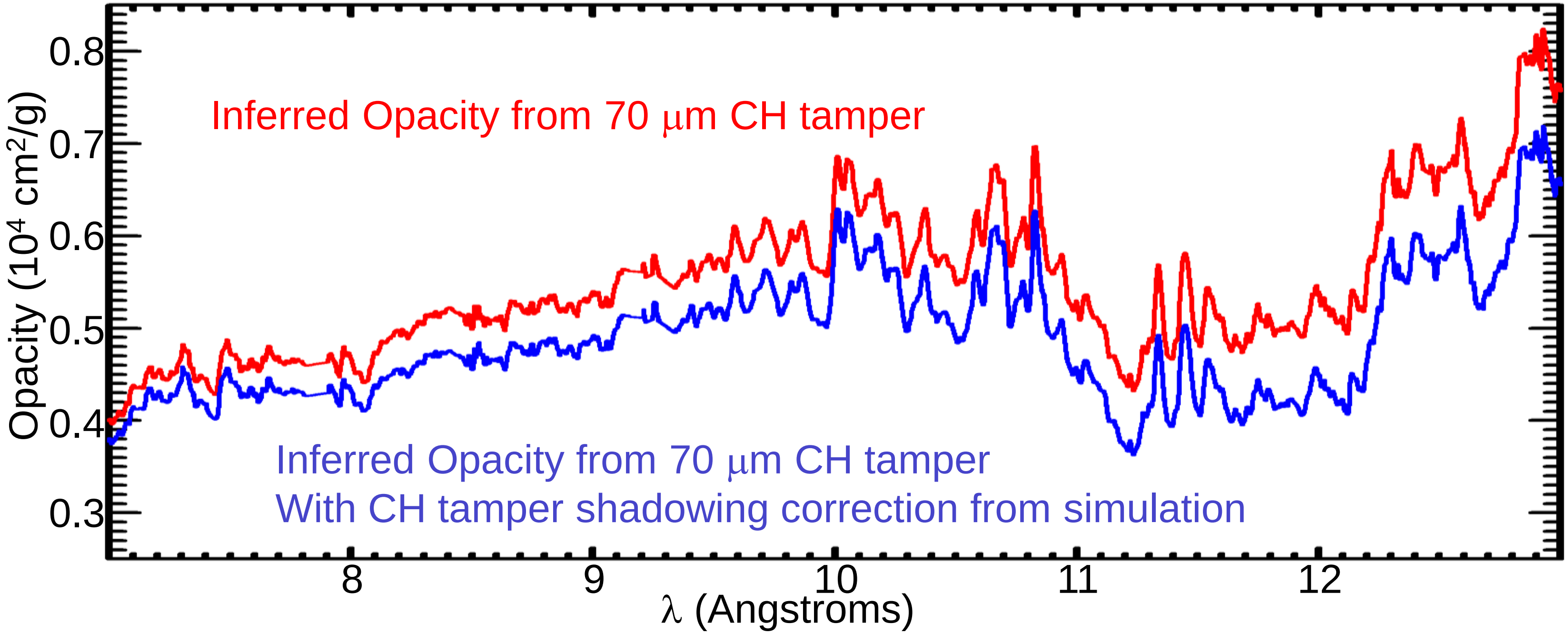
Hypothesis: Does the FeMg sample "shadow" the CH tamper behind it enough to enhance inferred attenuation?



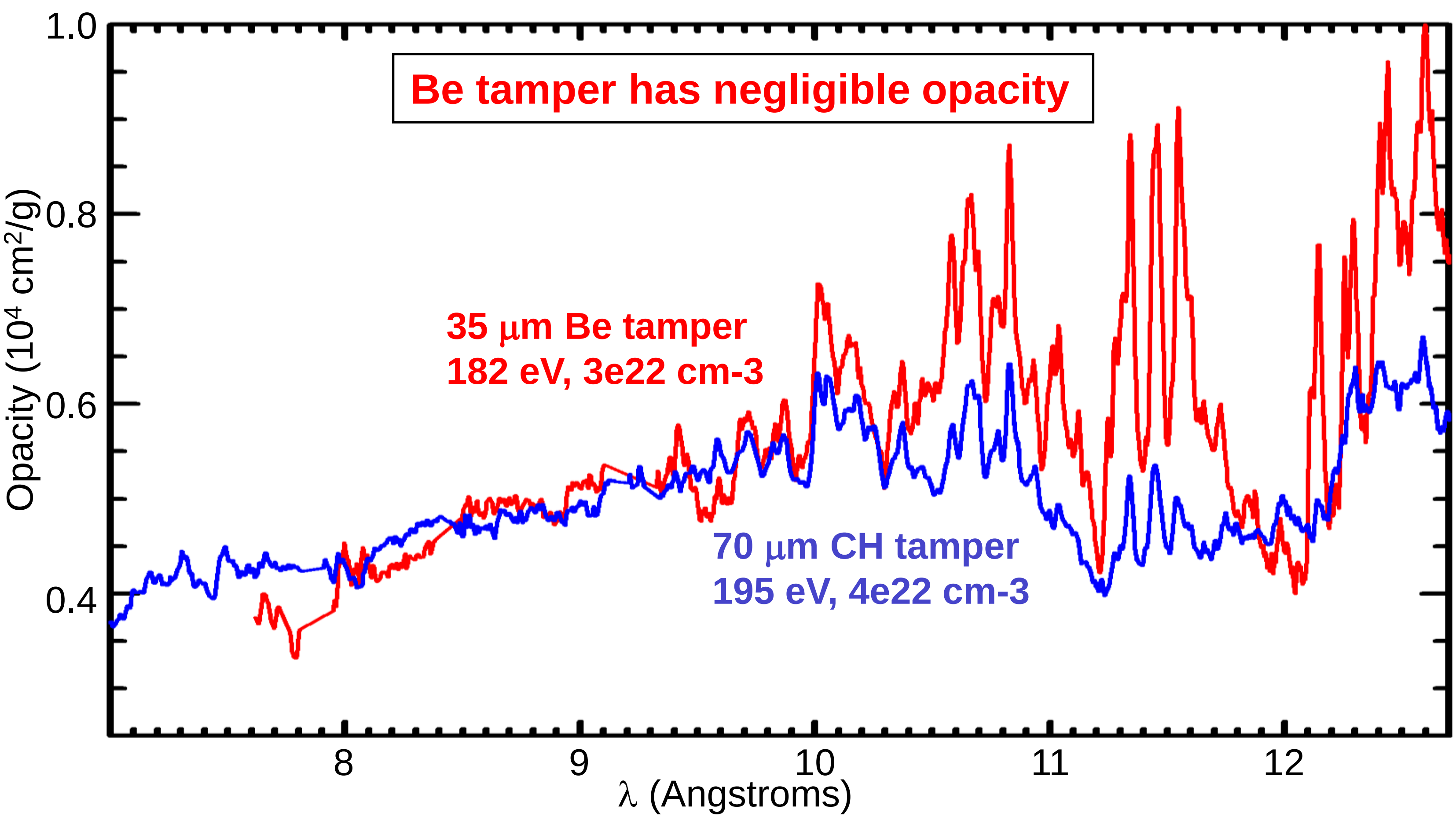
Half-moon sample: Transmission = S1/S2

This assumes the CH tamper on the side with the FeMg is heated the same as the side without the FeMg

Simulations suggest the cooler CH behind the FeMg may alter the inferred opacity by up to 20% ; the correction increased with λ

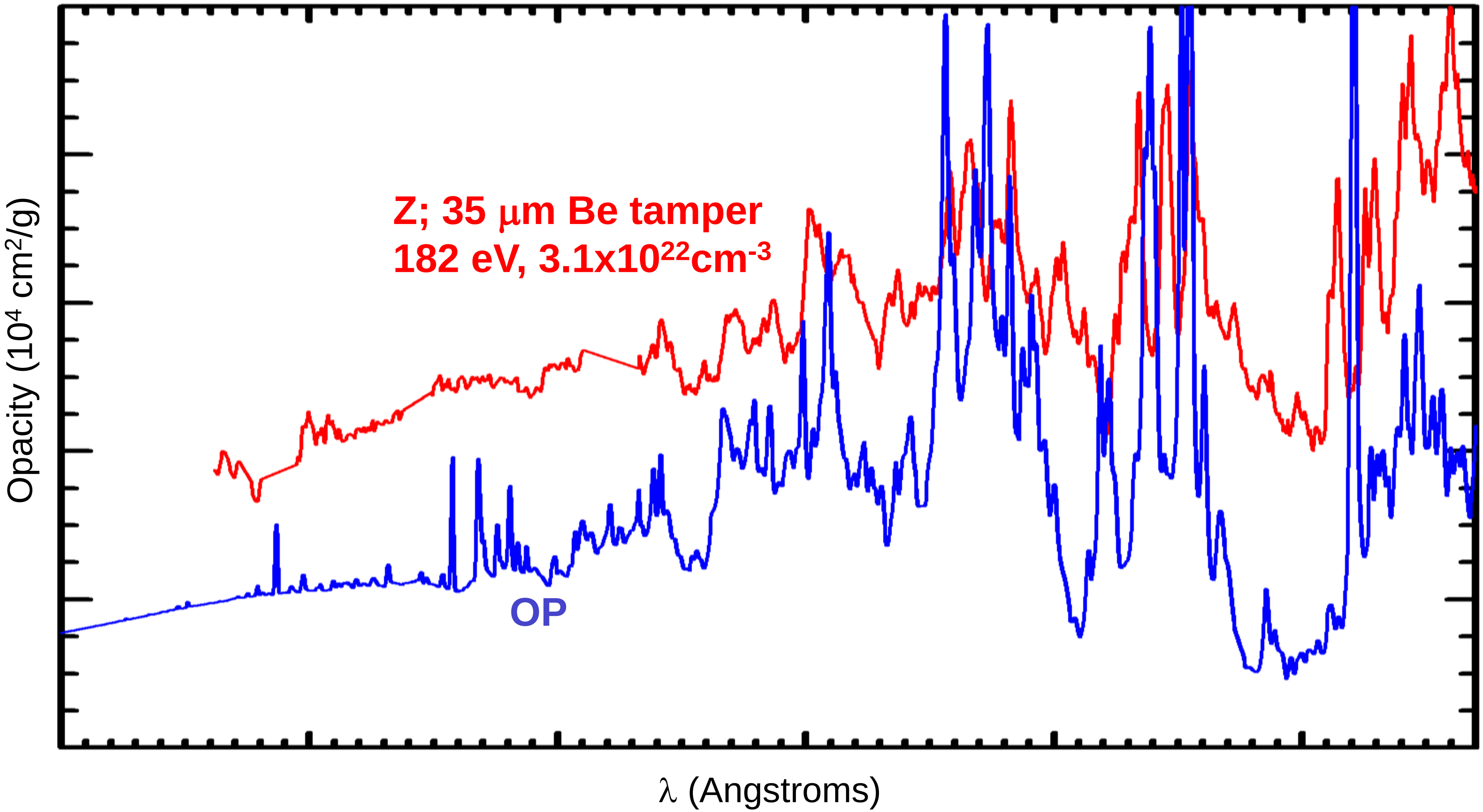


Be tamper experiments eliminate possible tamper effects on inferred iron transmission / opacity



The Be tamper experiments confirm CH-tamped data accuracy at λ <10.5 Angstroms AND the need for a CH tamper correction at longer wavelengths

The Be-tamped iron opacity measurement re-affirm the need for significant opacity model revisions



The Be-tamped iron opacity measurement re-affirm the need for significant opacity model revisions

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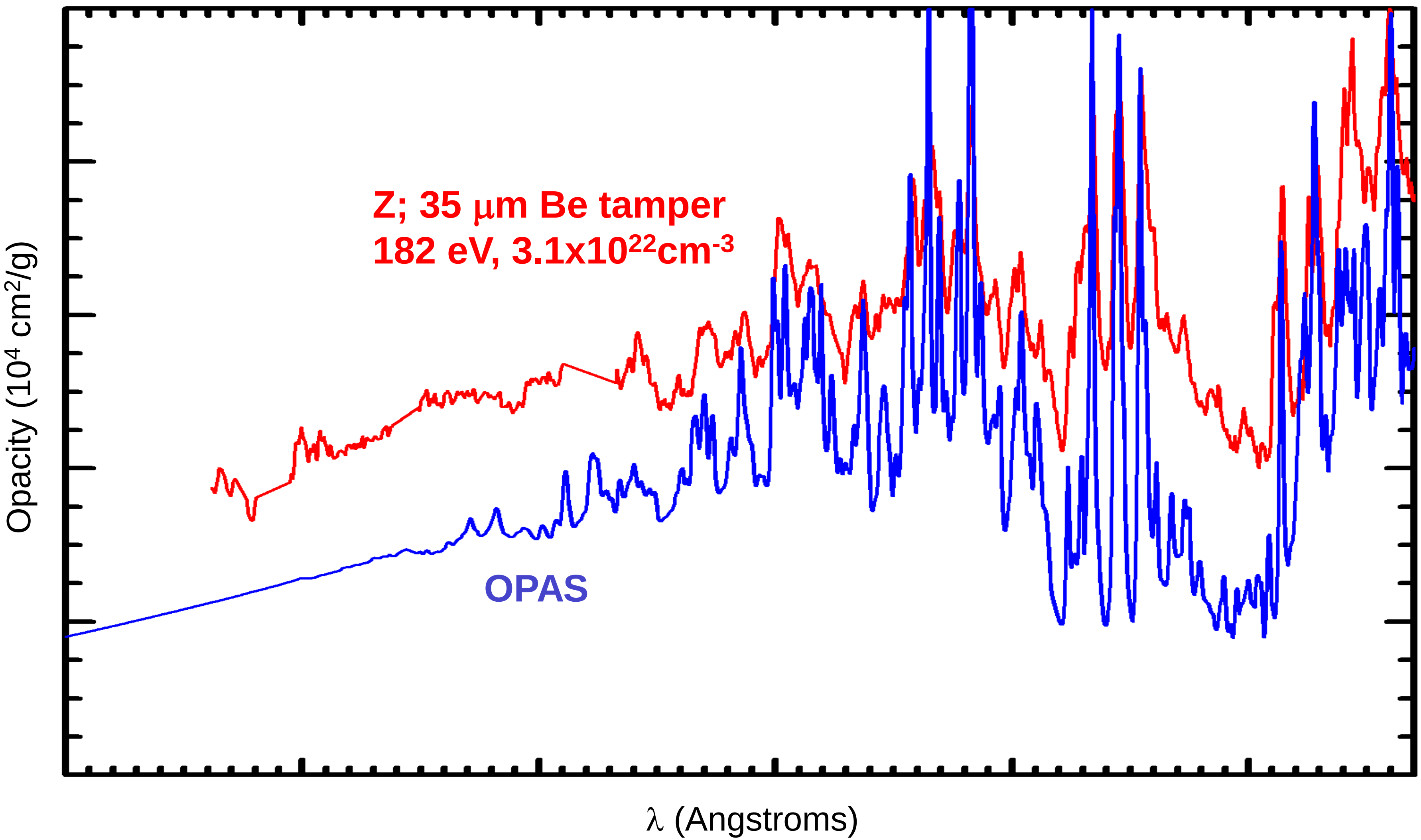

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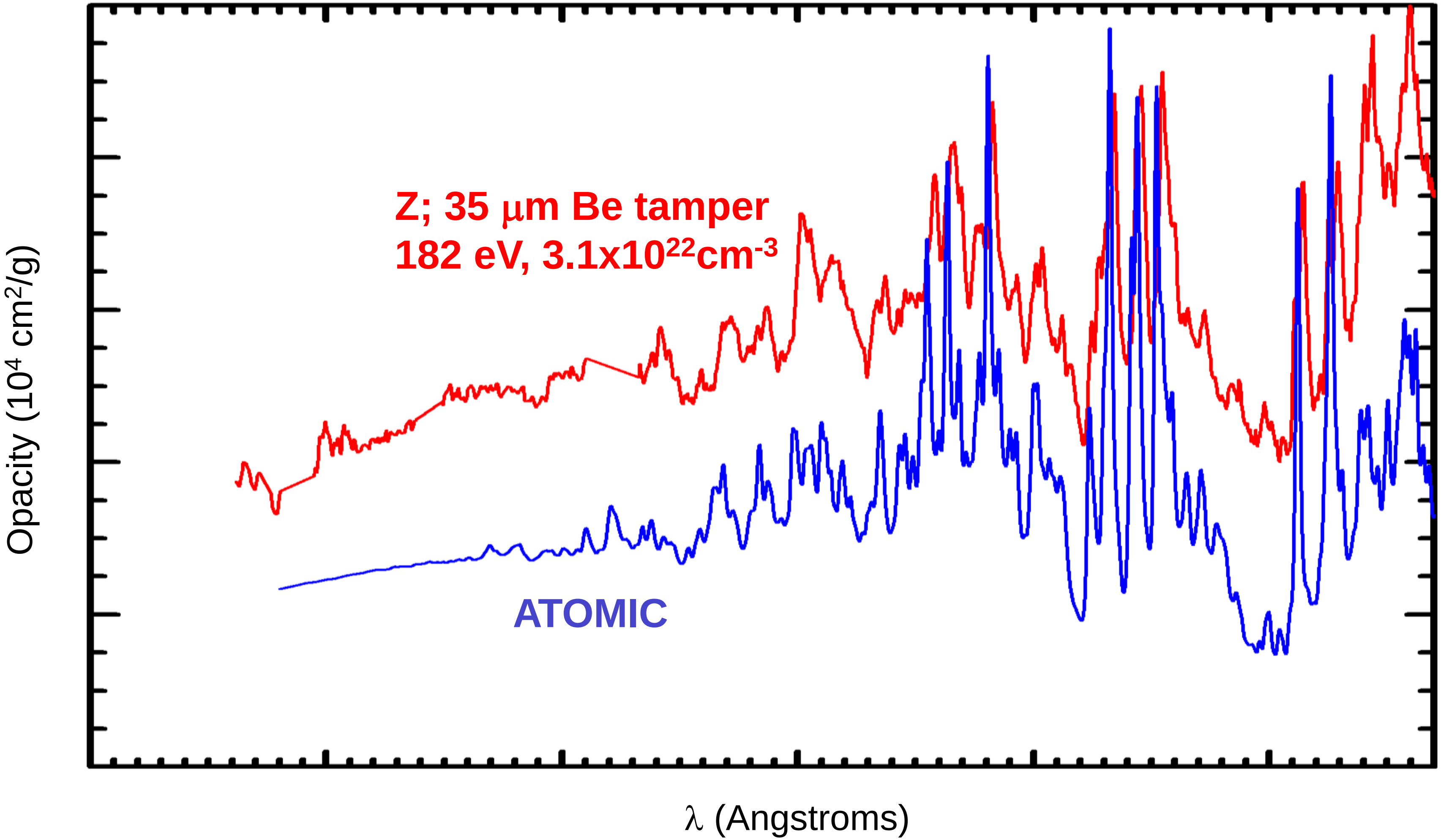

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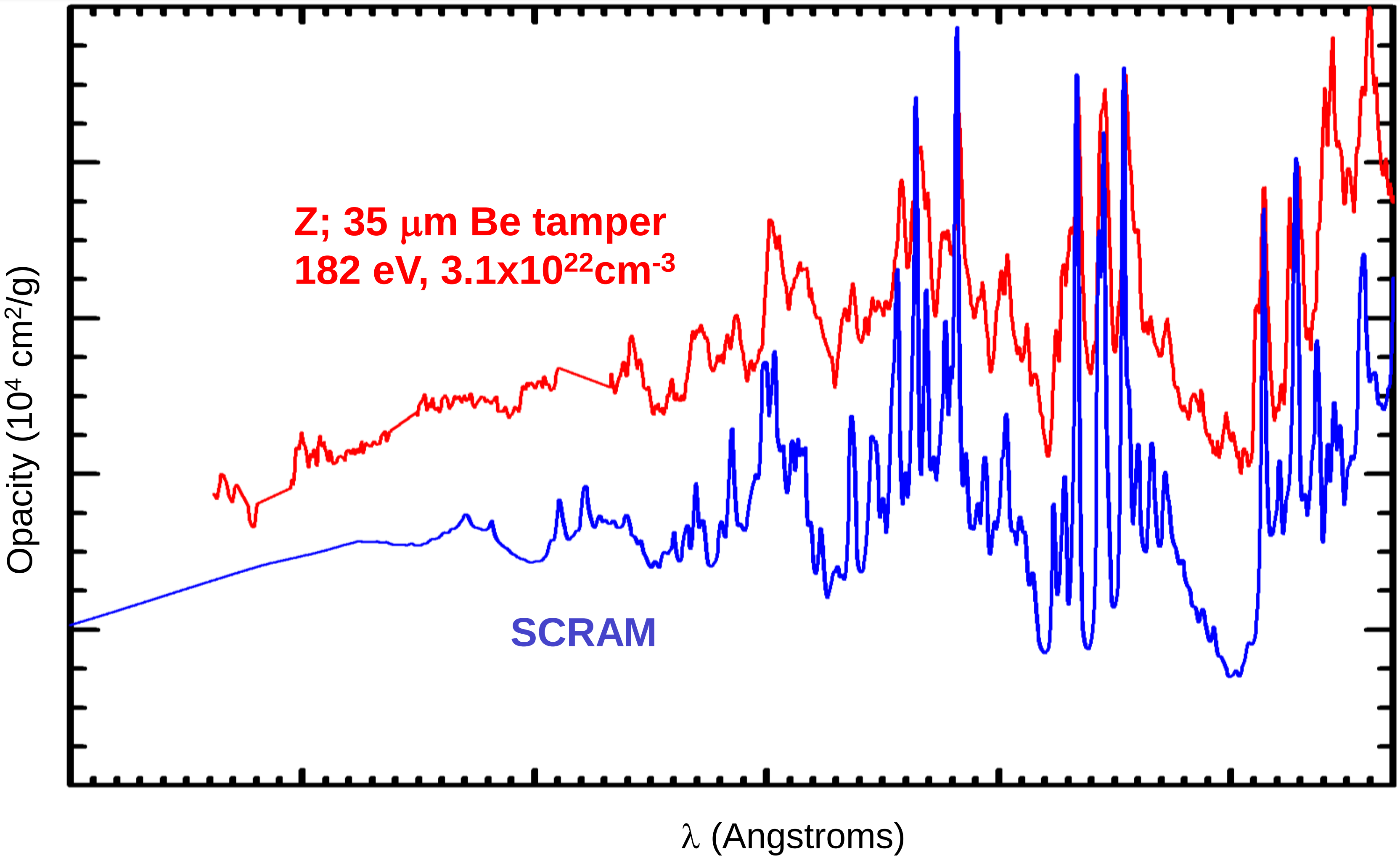

The measured pure iron Rosseland mean opacity is ~1.6x higher than calculated with OP

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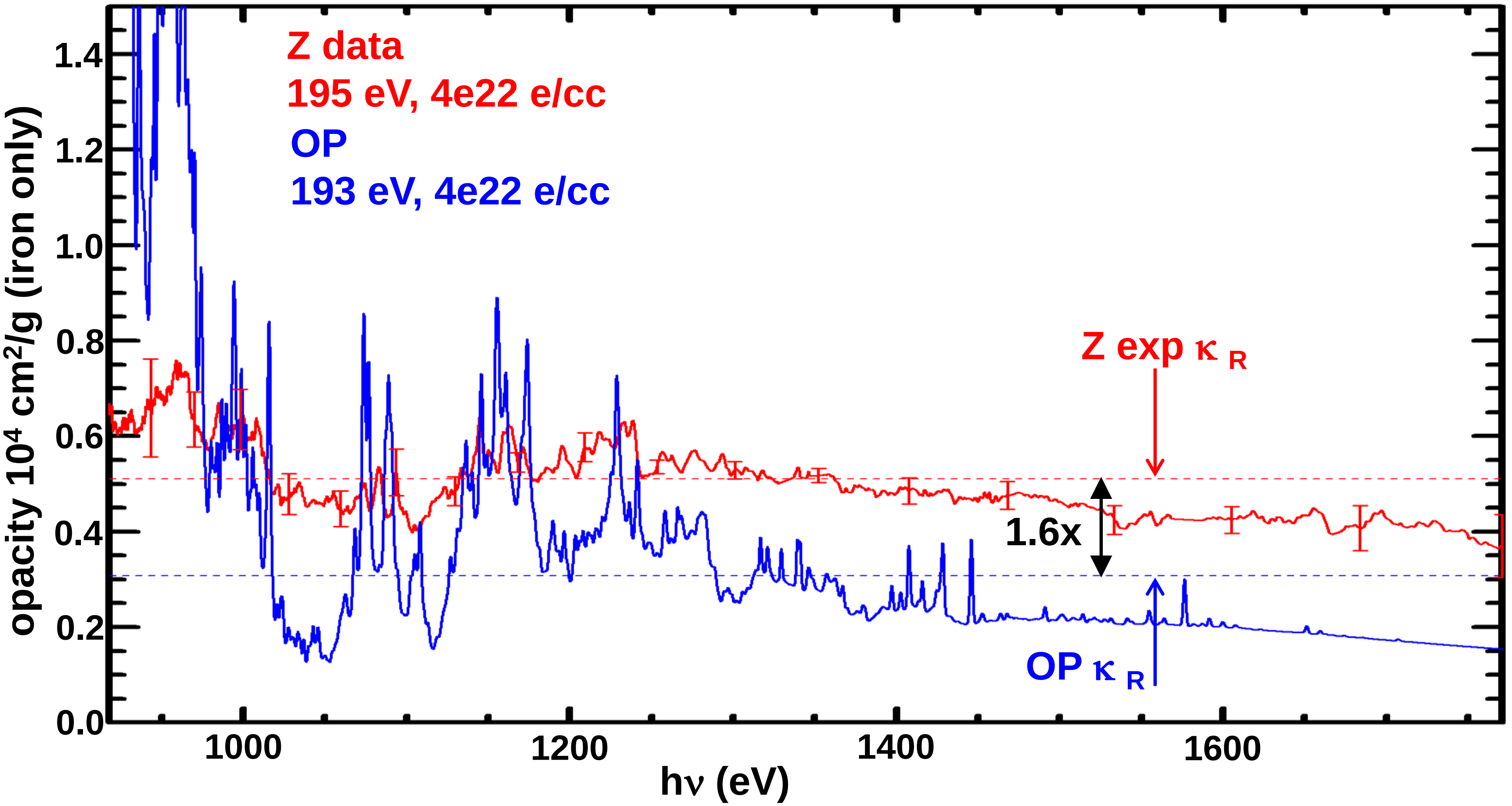
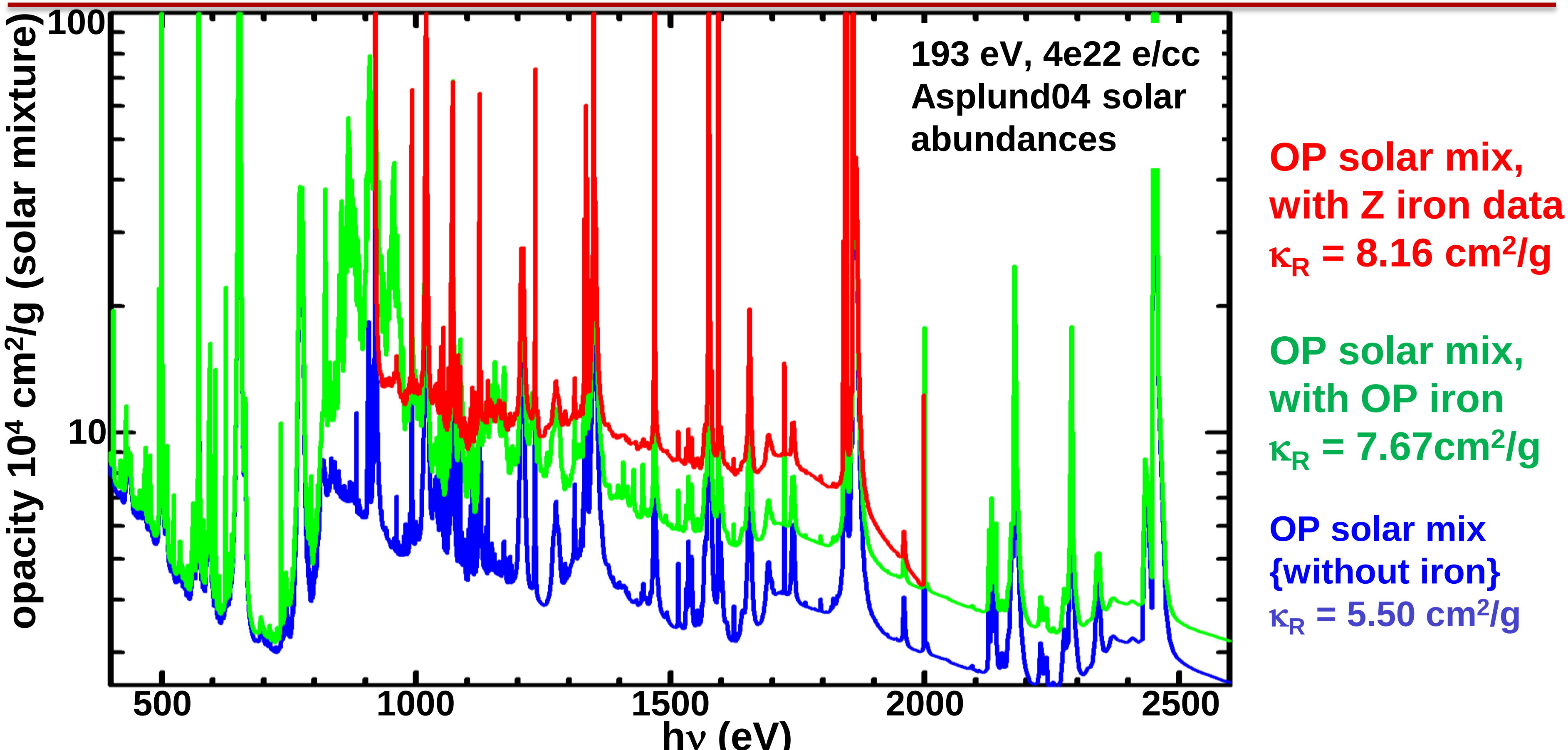


A solar mixture plasma using Z iron data has ~ 6% higher Rosseland mean opacity than using OP iron



- A 6% 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
- As we refine the analysis the conclusion could still change

Future opacity experiments will examine opacity model physics issues

2-3 transition arrays - Ni

Bound free quasi continuum – Cr

Line broadening

Higher densities – thicker Be tamper

Plasma composition – Fe mixed with low Z

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

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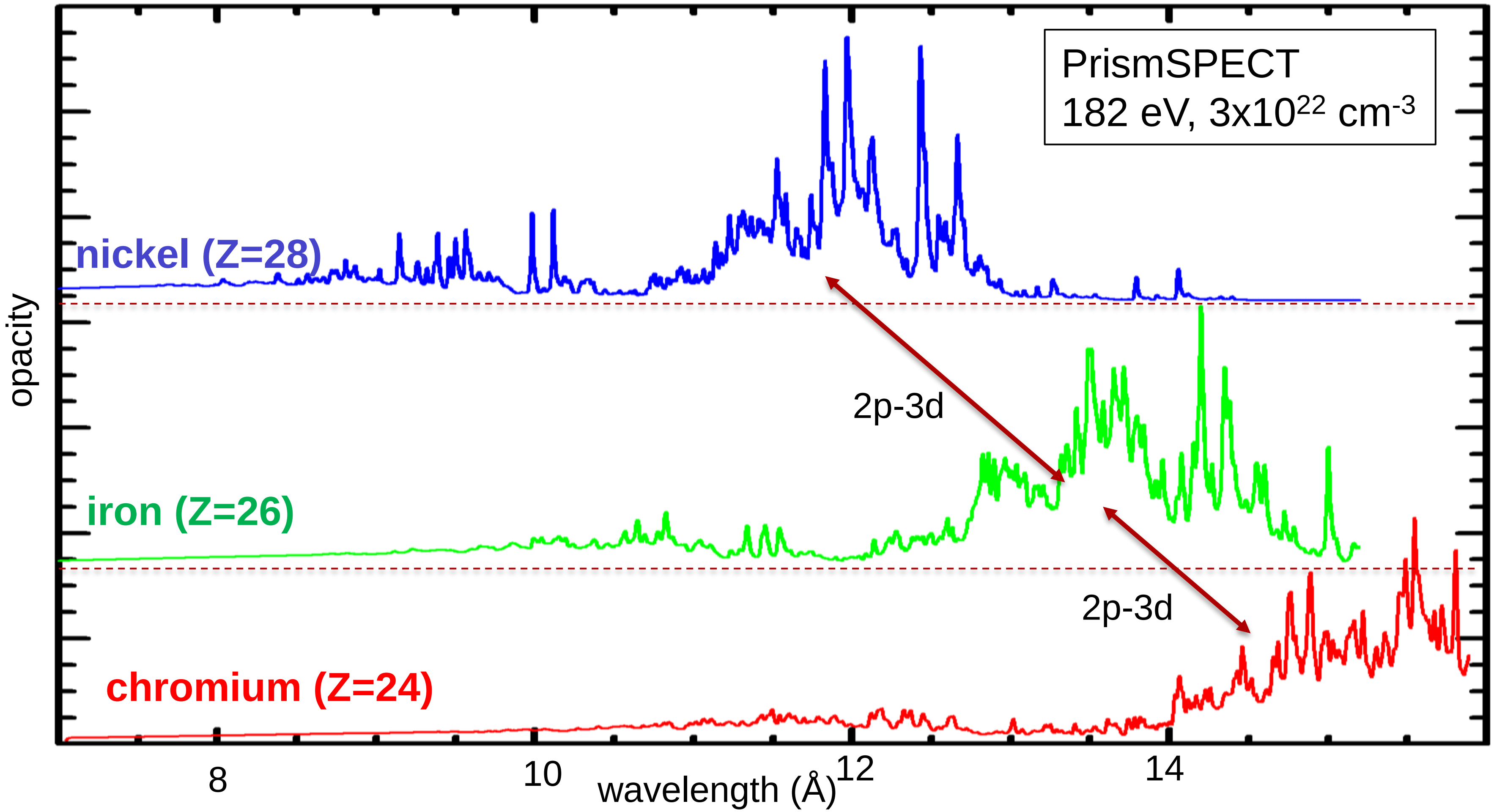
Hypotheses:

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:

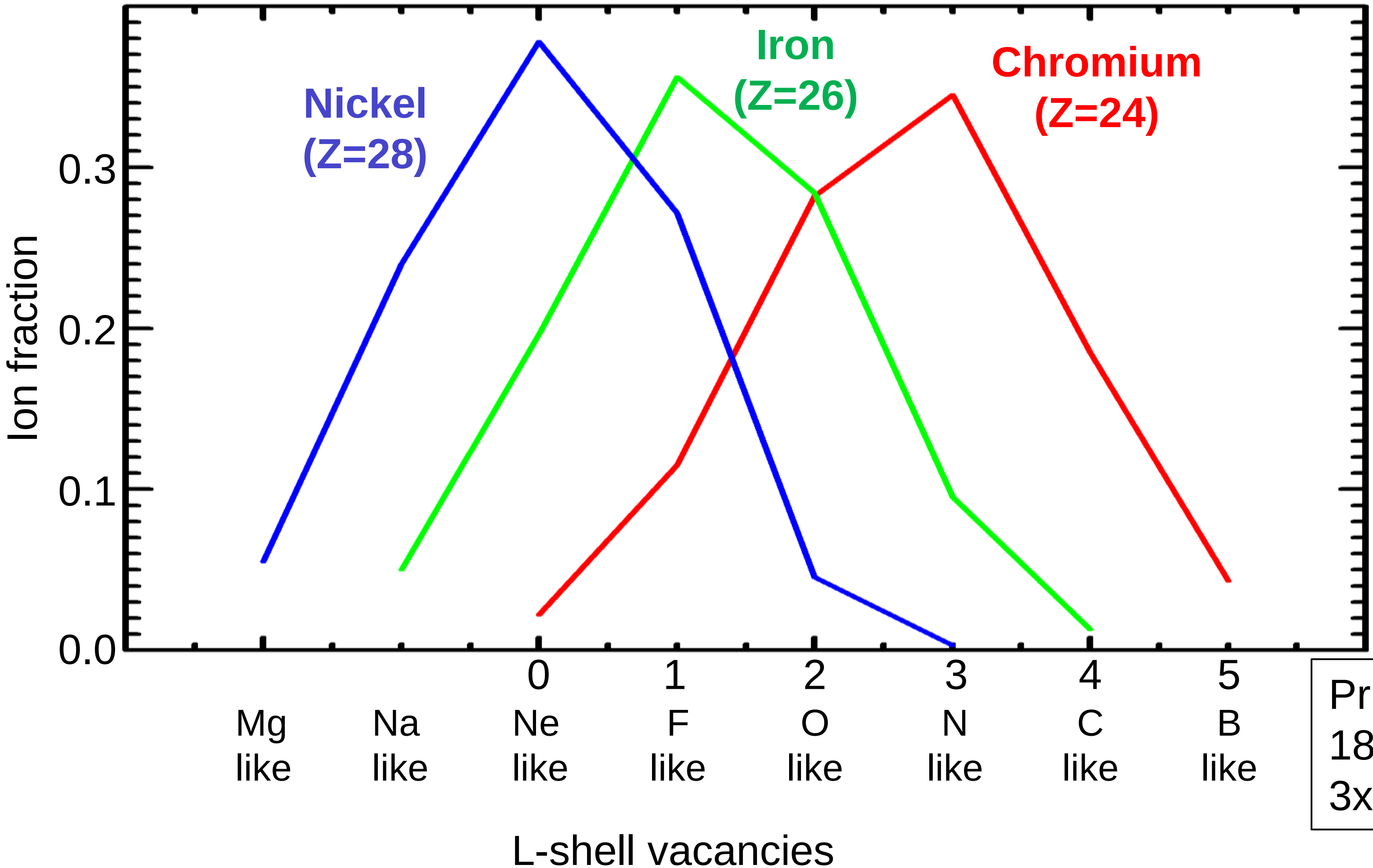
A) Z experiments with lower and higher atomic number elements
B) Experiments on a different platform (NIF)

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)

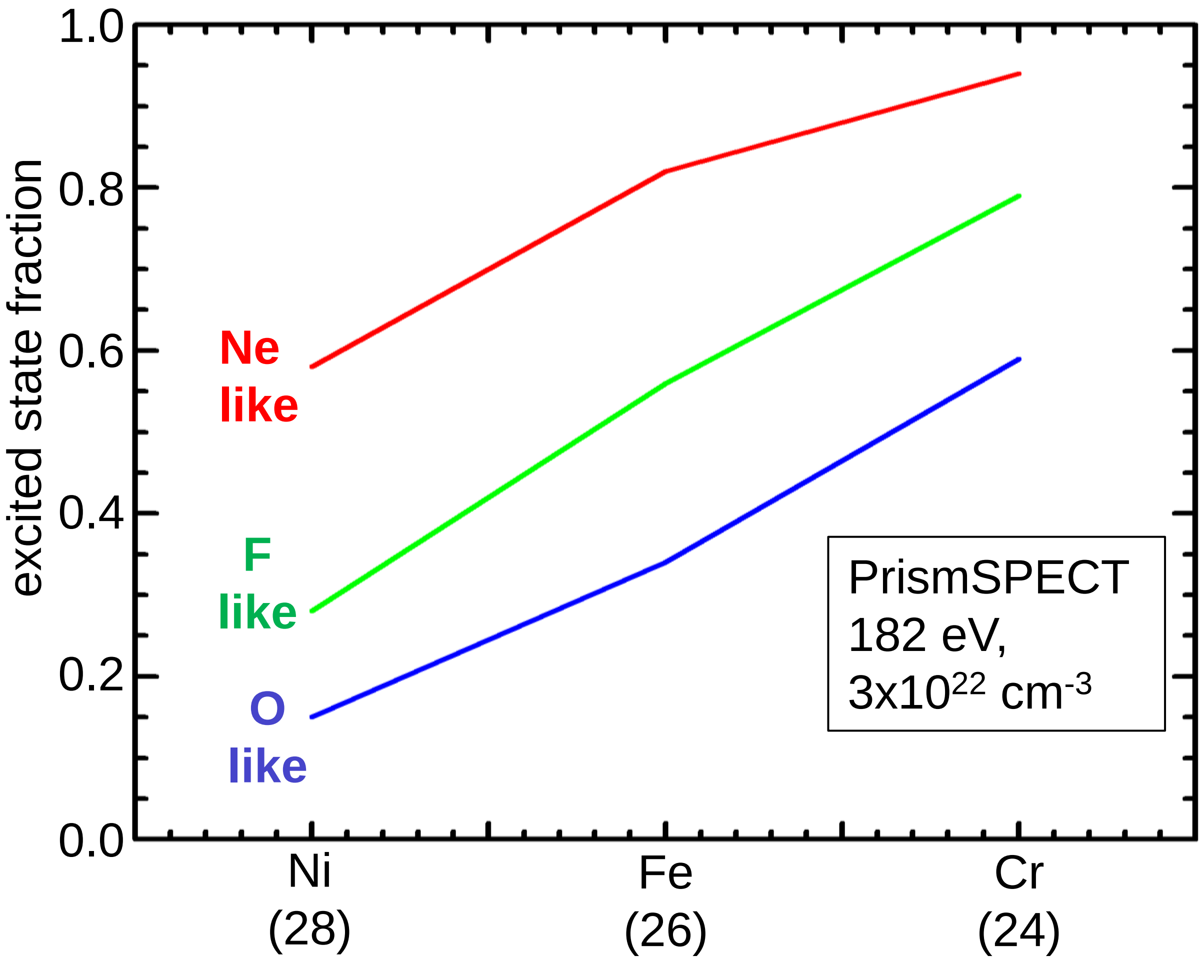
The number of L shell vacancies changes with the sample element



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

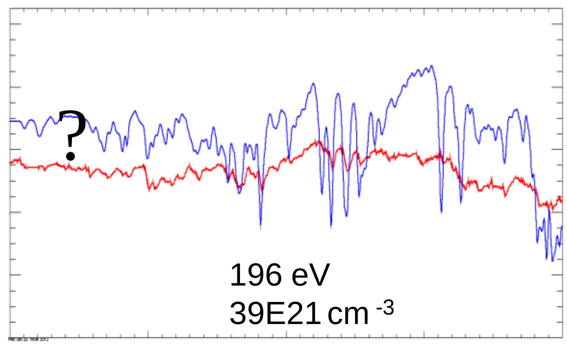
We will untangle the complex opacity issues through precise measurements across a range of T_e, n_e, and Z.

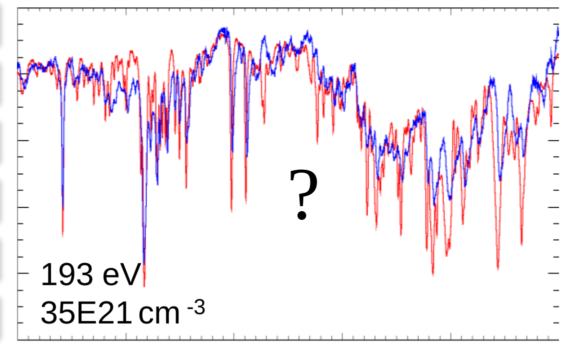
fewer L-shell vacancies, lower excited state populations

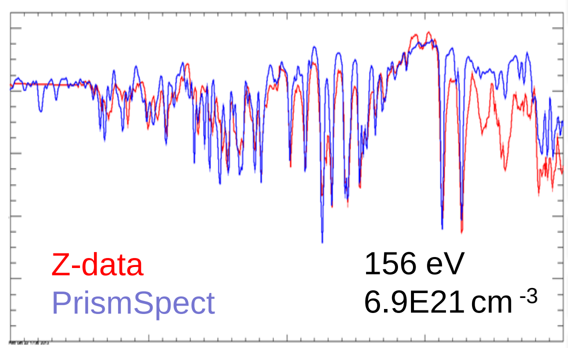
Chromium (open L-shell)

Iron (open L-shell)

Nickel (closed L-shell)







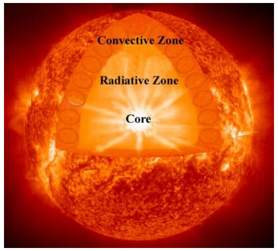
Increased Temp. and Density

Increased Atomic Number

Z iron plasma opacity experiments refine our understanding of solar interior structure

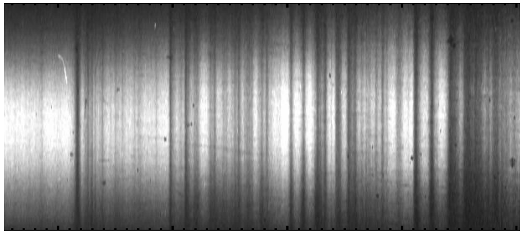
- **Solar interior predictions don't match helioseismology**

  → Arbitrary opacity increase of 10-30% would fix the problem, but is this the correct explanation?

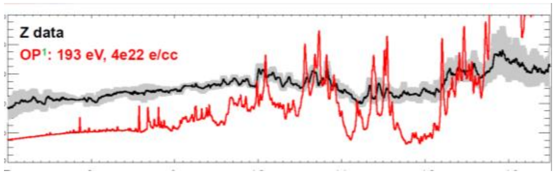


- **Z experiments have measured iron plasma opacity at nearly solar convection zone base conditions**

  → 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 Rosseland mean opacity for solar matter is ~ 6 % higher using Z iron data instead of OP model calculations