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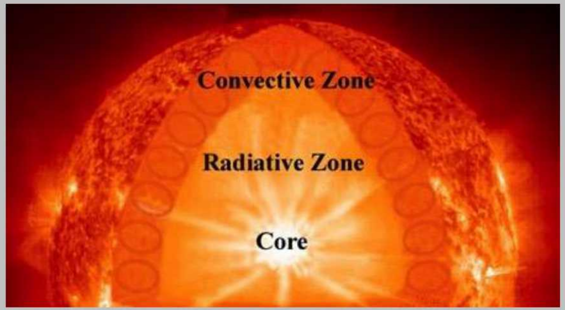

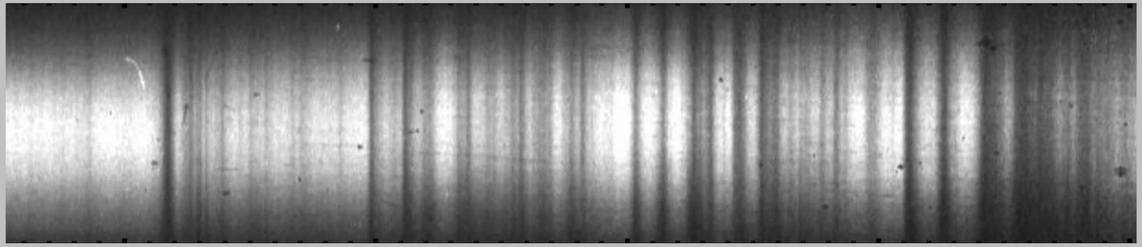

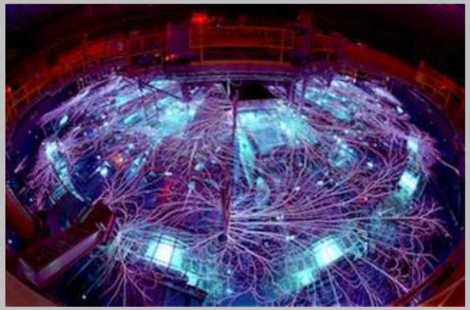

Opacity data for stellar models and its uncertainties

Jim Bailey

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

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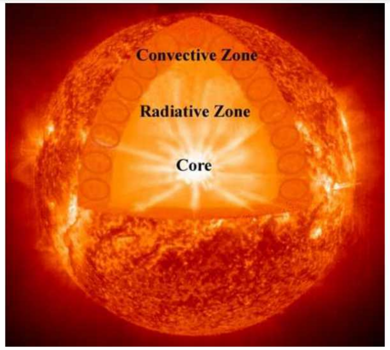
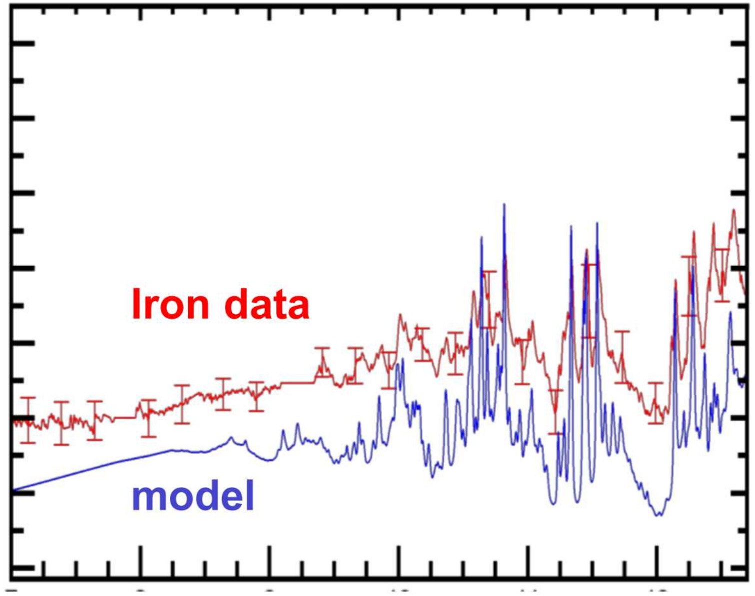
Opacity experiments at the Z facility refine our understanding of photon absorption in high energy density stellar matter.

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



- **Z experiments measure higher-than-predicted iron plasma opacity at near-solar-interior conditions**
  → helps resolve the solar problem, but what causes the discrepancy?
- **No systematic error has yet been found – but experiment examination continues**
- **If data are correct, we are forced to conclude that model refinements are needed for stellar opacity**



Standard solar model predictions of the solar structure disagree with helioseismology

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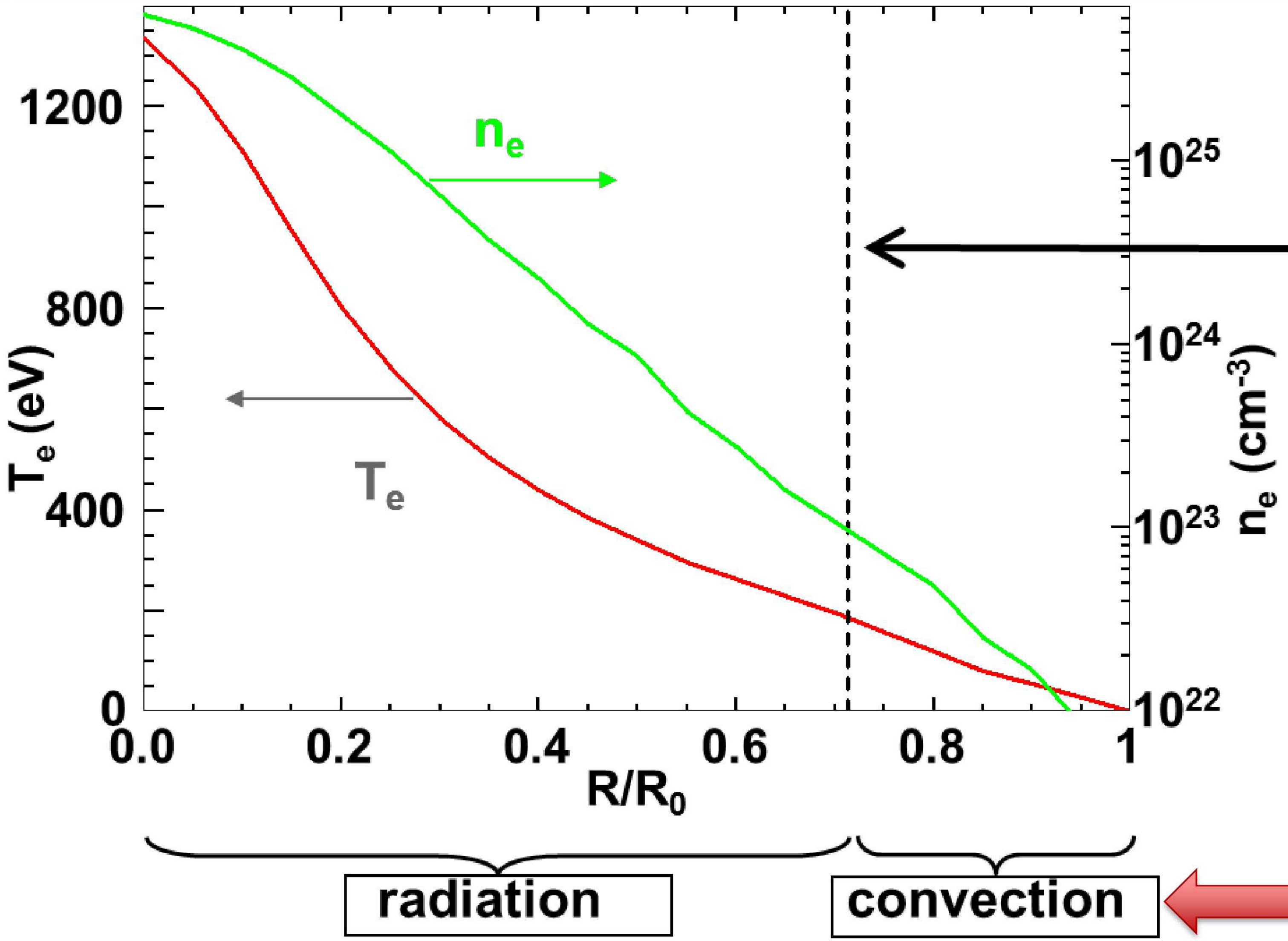


predicted boundary location different from measured {~ 10-20 σ difference}

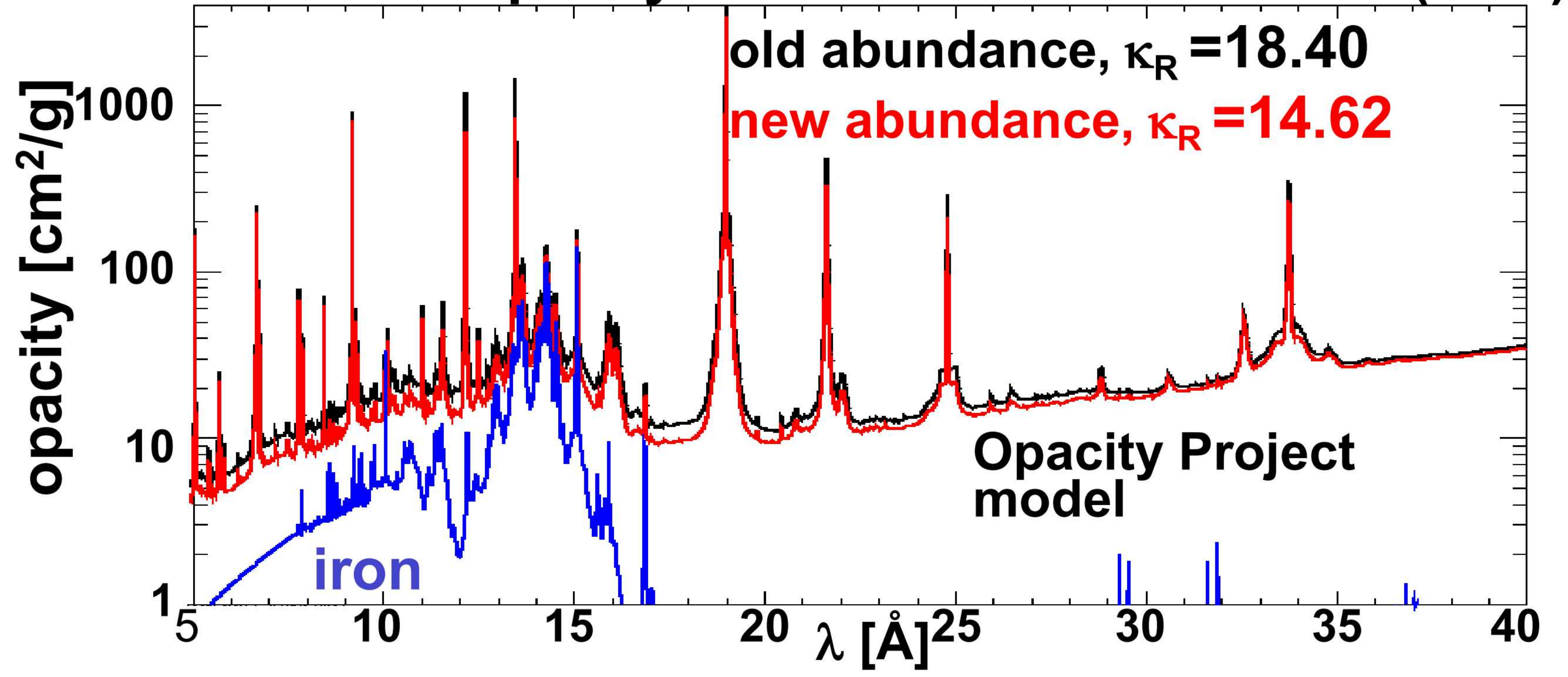
The disagreement arose after the solar abundance revision that began in 2000

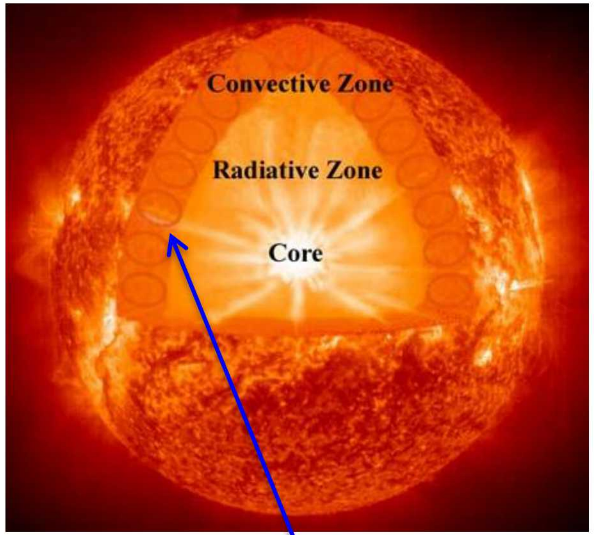
Boundary location depends on opacity.

Asplund *AnnRev AA* 2008; Bahcall *ApJ* 2004; Basu and Antia *Phys Rep* 2008

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)





CZB condition:
T_e=182 eV
n_e=9x10^{22} cm^{-3}

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

Serenelli, *ApJ* 2009 Badnell *et al.*, *MNRAS* 2005 Bailey et al, Phys. Plasmas (2009).

Photon absorption in plasma depends on multiple entangled physical processes

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

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

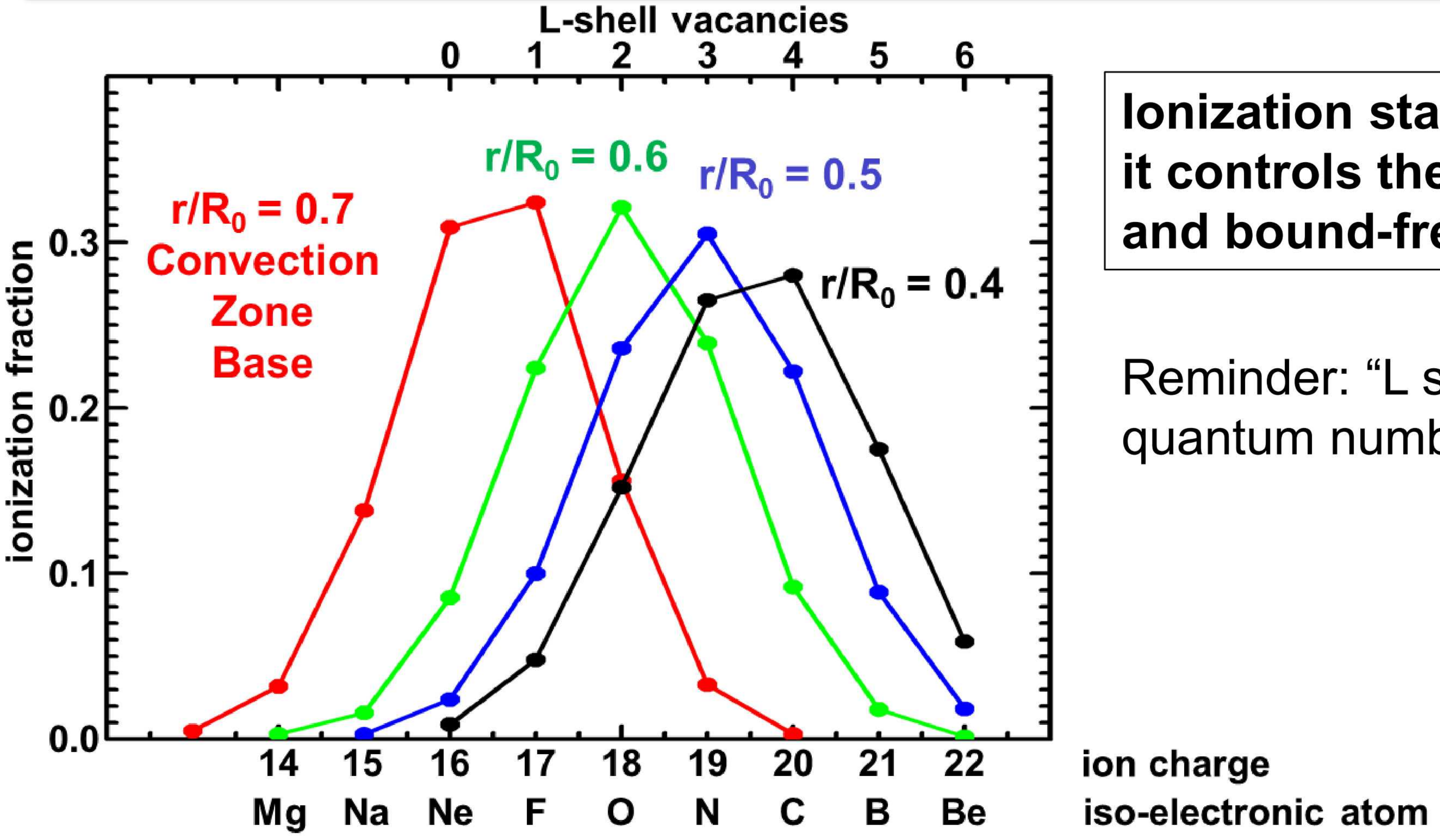
These interactions depend on :

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

"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

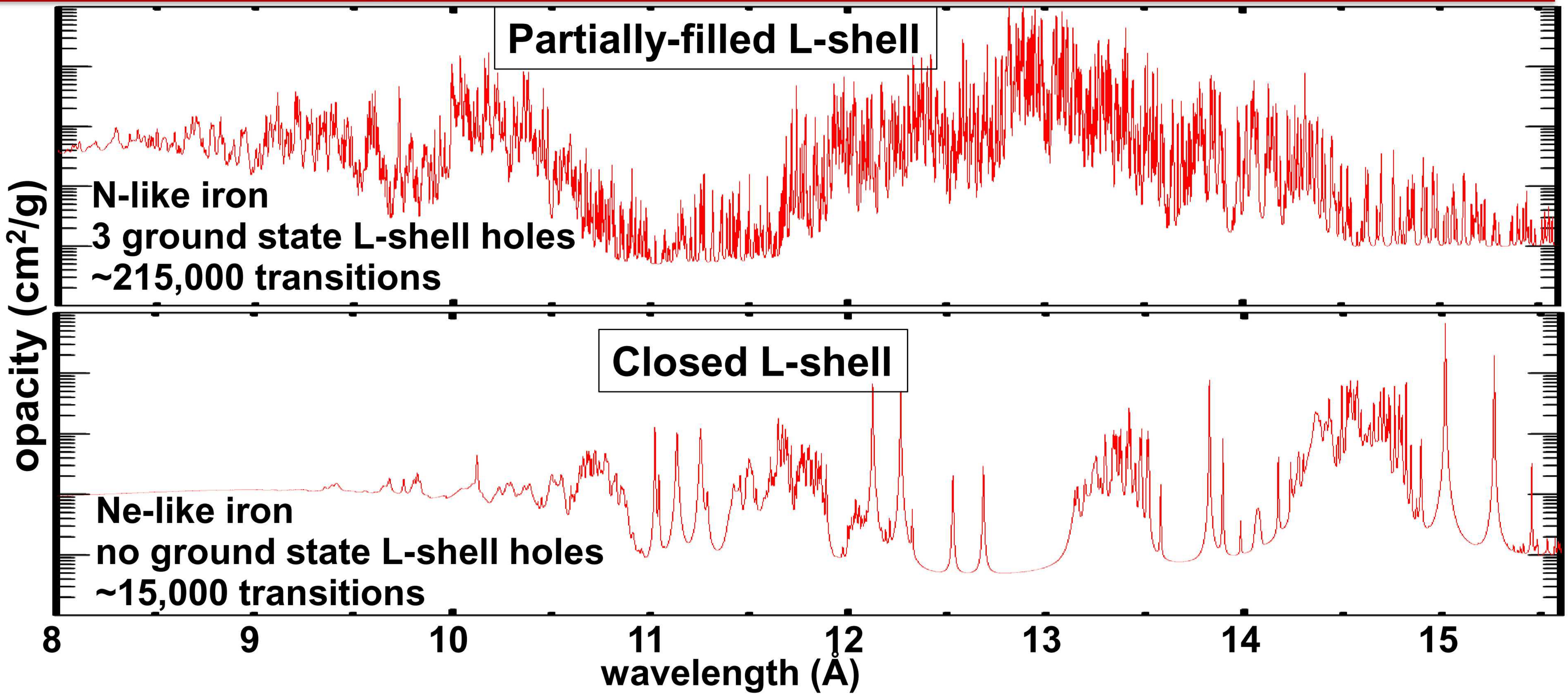
Iron charge states with L-shell vacancies exist throughout most of the solar radiation zone



Ionization state is important for opacity: it controls the possible bound-bound and bound-free absorption

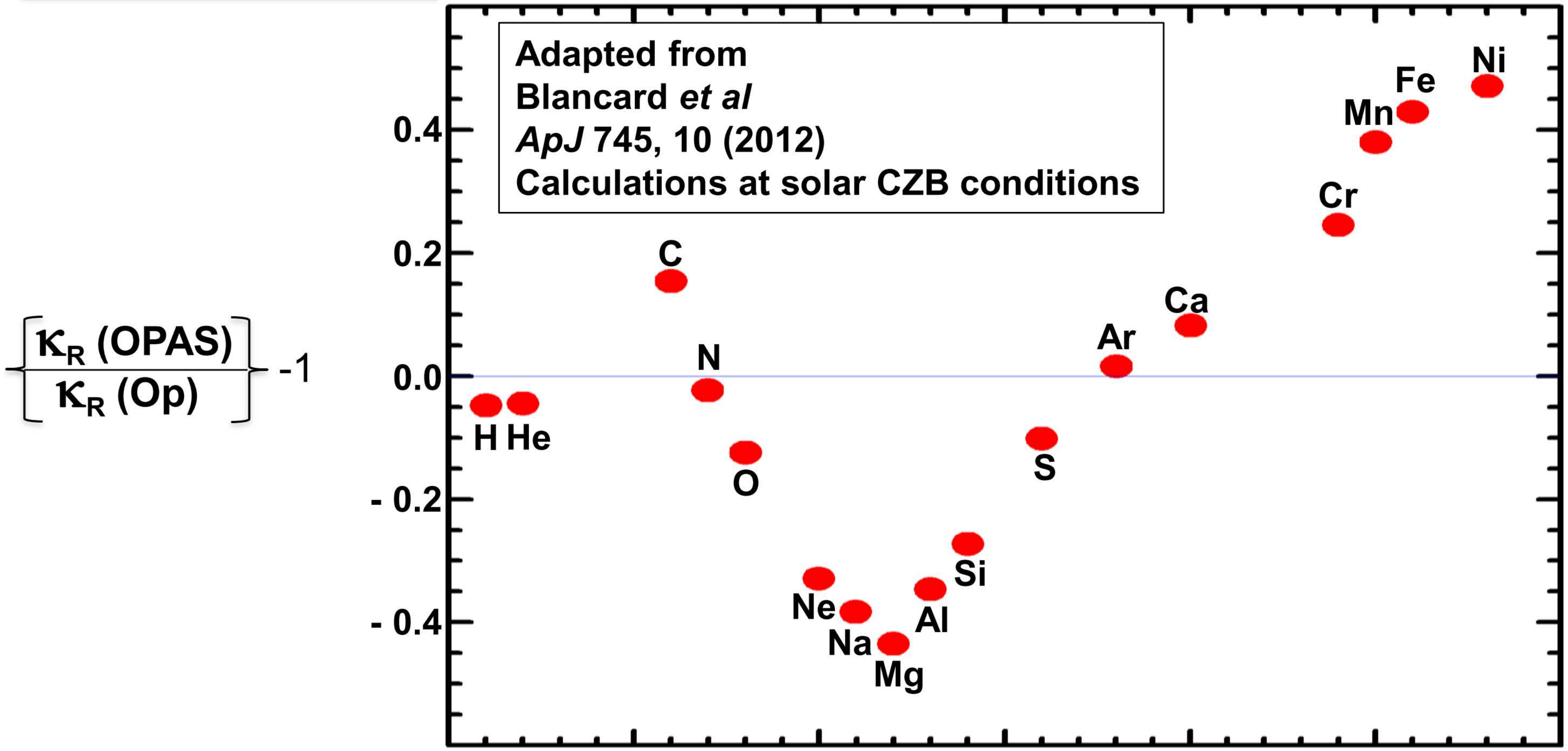
Reminder: “L shell” refers to principal quantum number = 2

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



PrismSPECT, iron in CZB

Opacity model differences exist even when the solar mixture mean opacity predictions are the same



Rosseland mean opacity (κ_R) predictions from OPAS and OP differ by up to ~45% for individual elements
Solar mixture κ_R predicted by these models agrees – but this might be partly coincidence

It has been clear for nearly a century that stellar opacities should be measured

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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
Barkla

1925
Siegbahn
X-ray spectroscopy

only bound-free and free-free absorption

1965

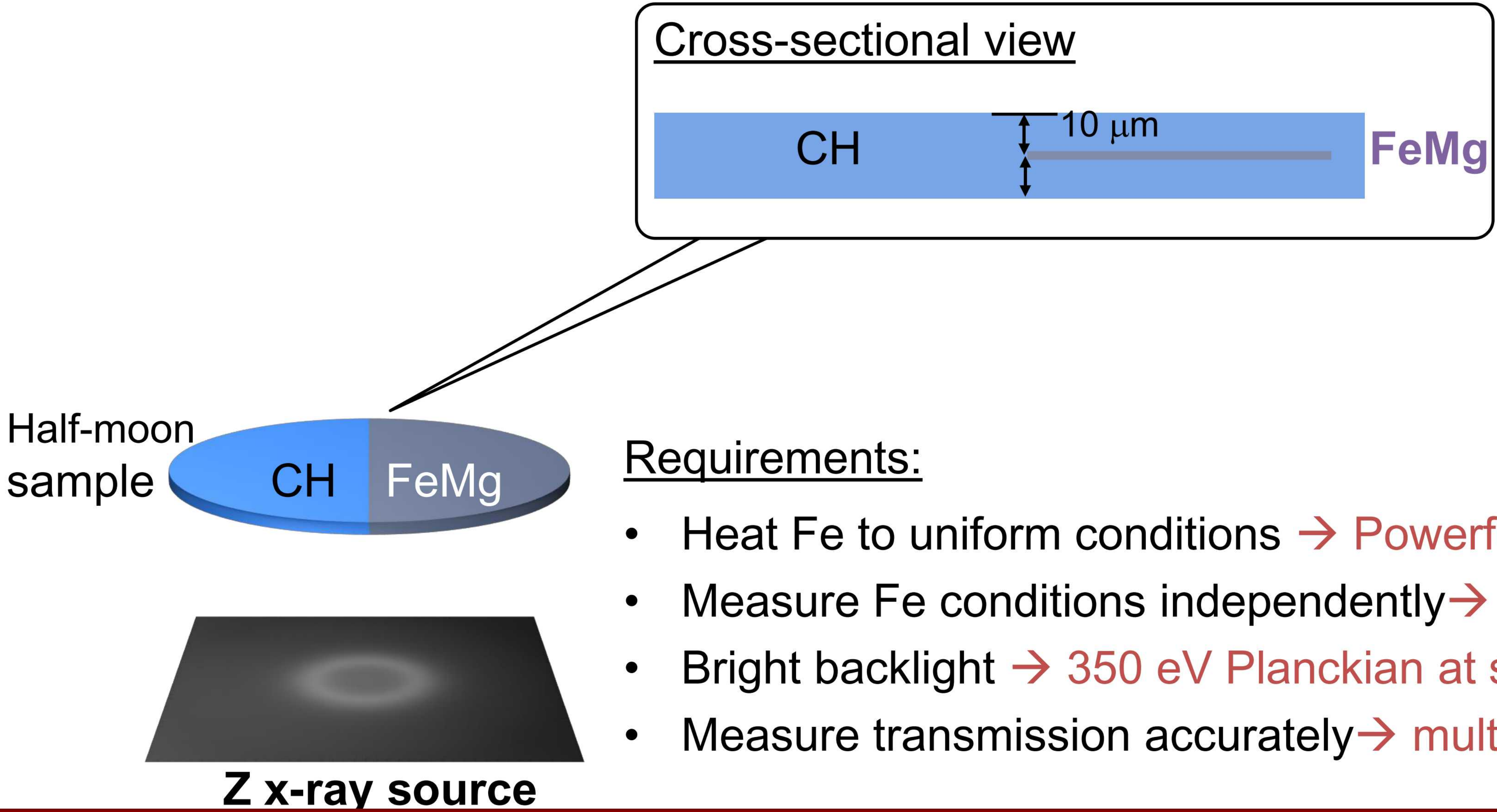
1988
Davidson *et al.*
Perry *et al.*
hot dense plasma opacity
20-70 eV

1995

2015
Bailey *et al.*
stellar interior opacity
156-195 eV

Stellar interior opacity measurements are now possible for the first time

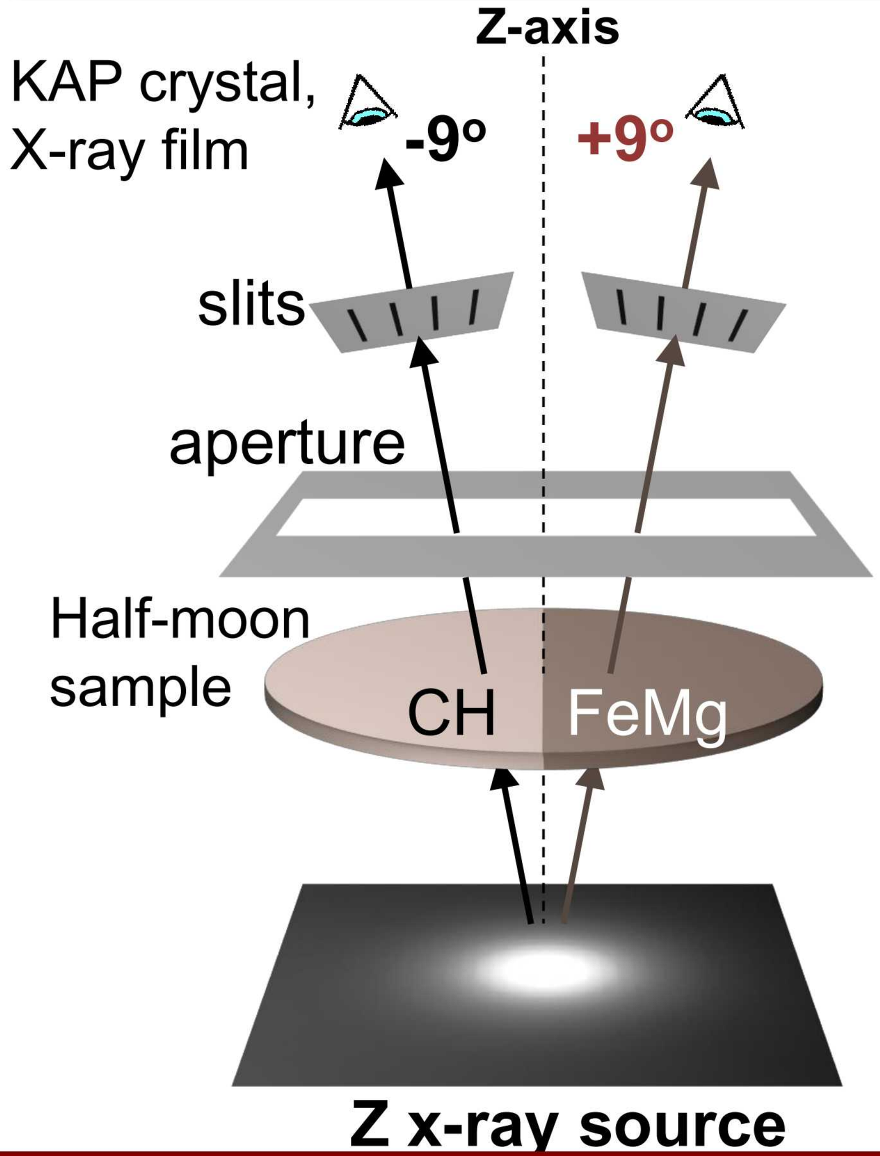
Z opacity science configuration satisfies challenging requirements for reliable opacity measurements

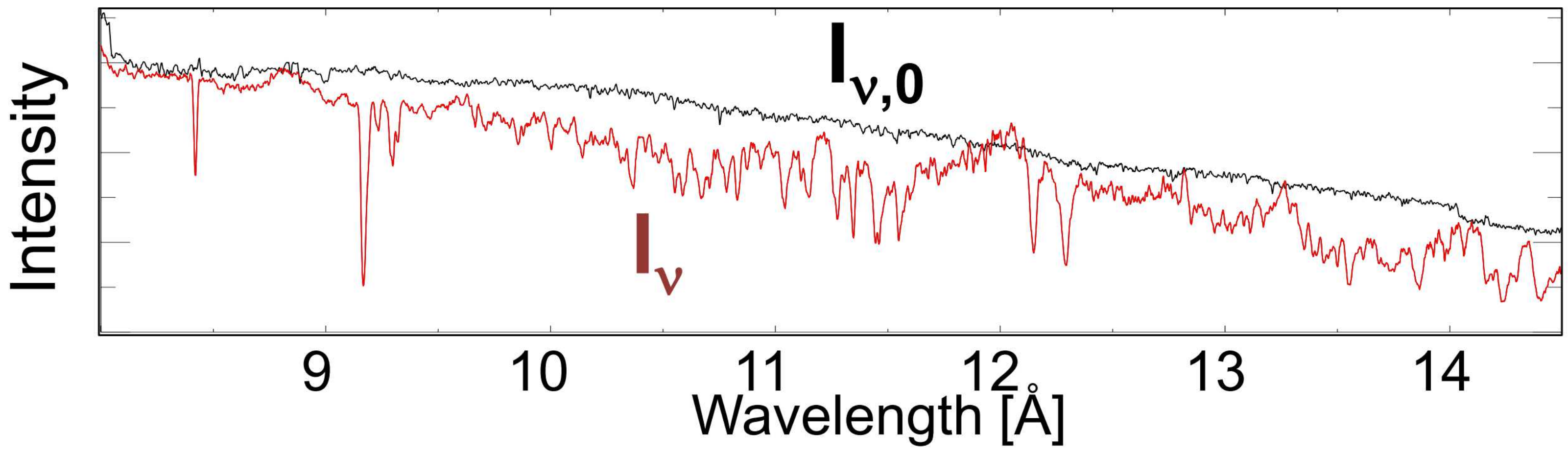


Requirements:

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

Z opacity science configuration satisfies challenging requirements for reliable opacity measurements





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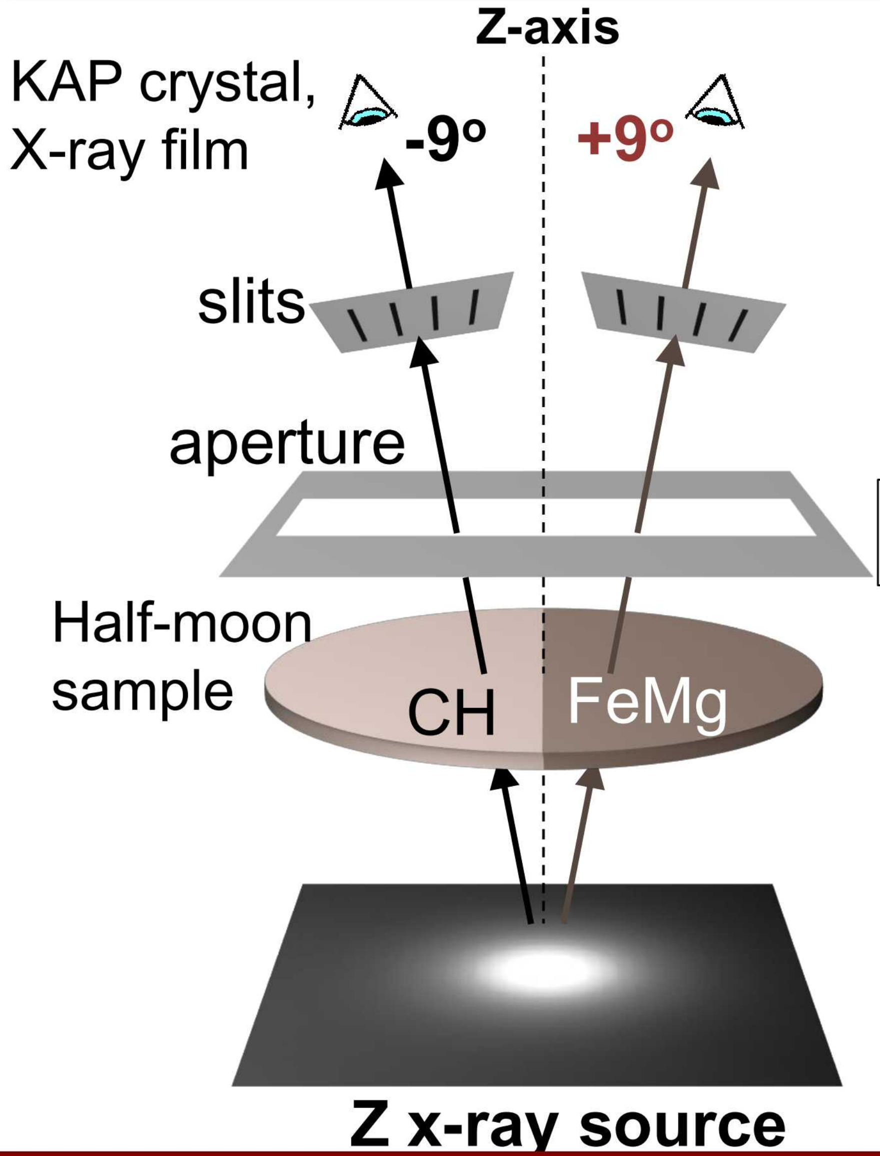

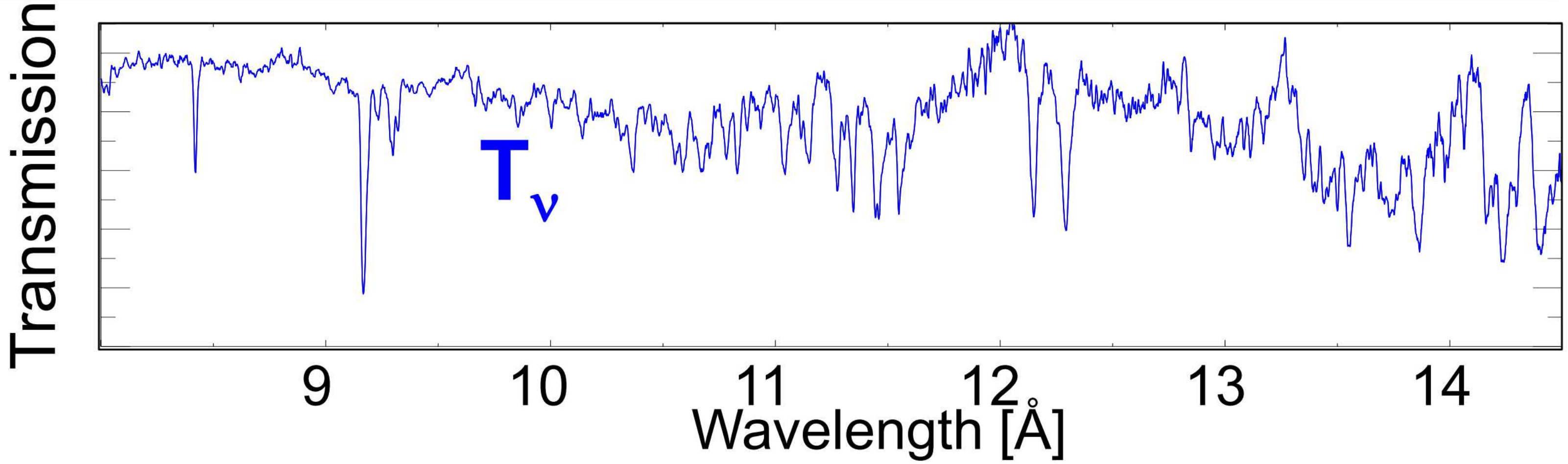

Transmission: $T_\nu = I_\nu / I_{\nu,0}$

Requirements:

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Z opacity science configuration satisfies challenging requirements for reliable opacity measurements

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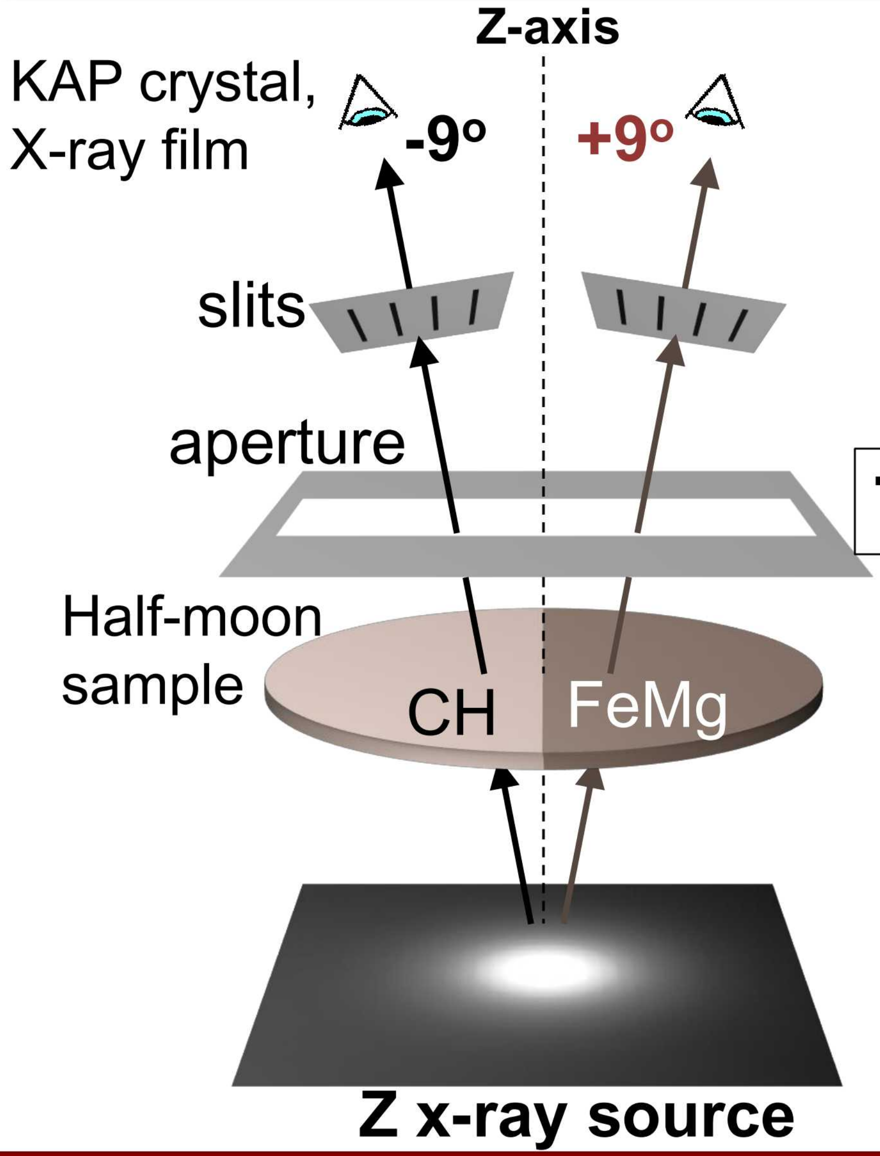
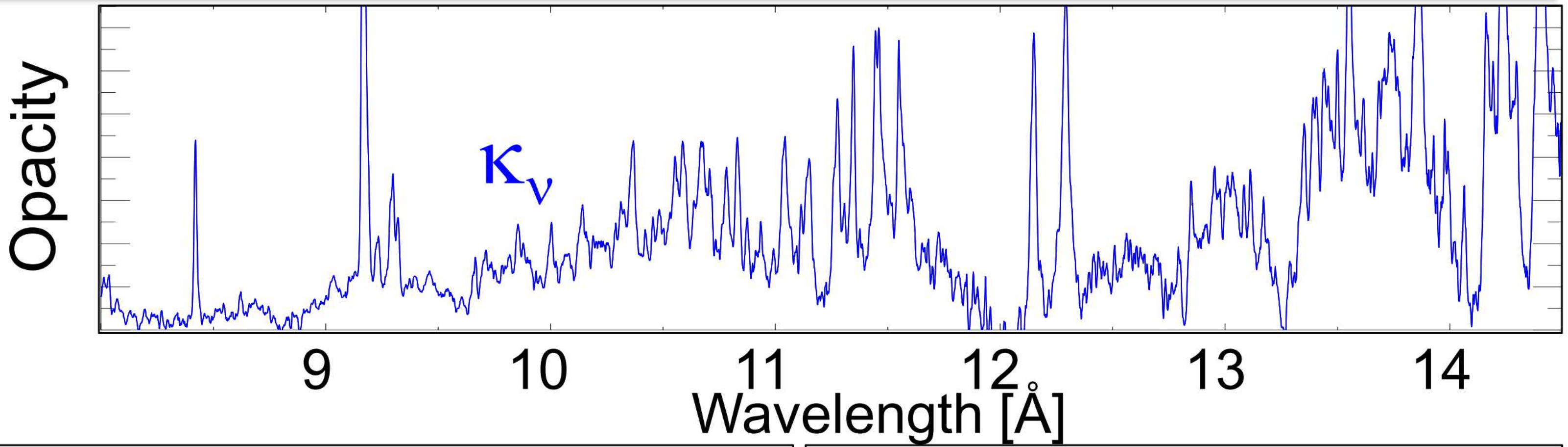




Transmission: $T_\nu = I_\nu / I_{\nu,0}$

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

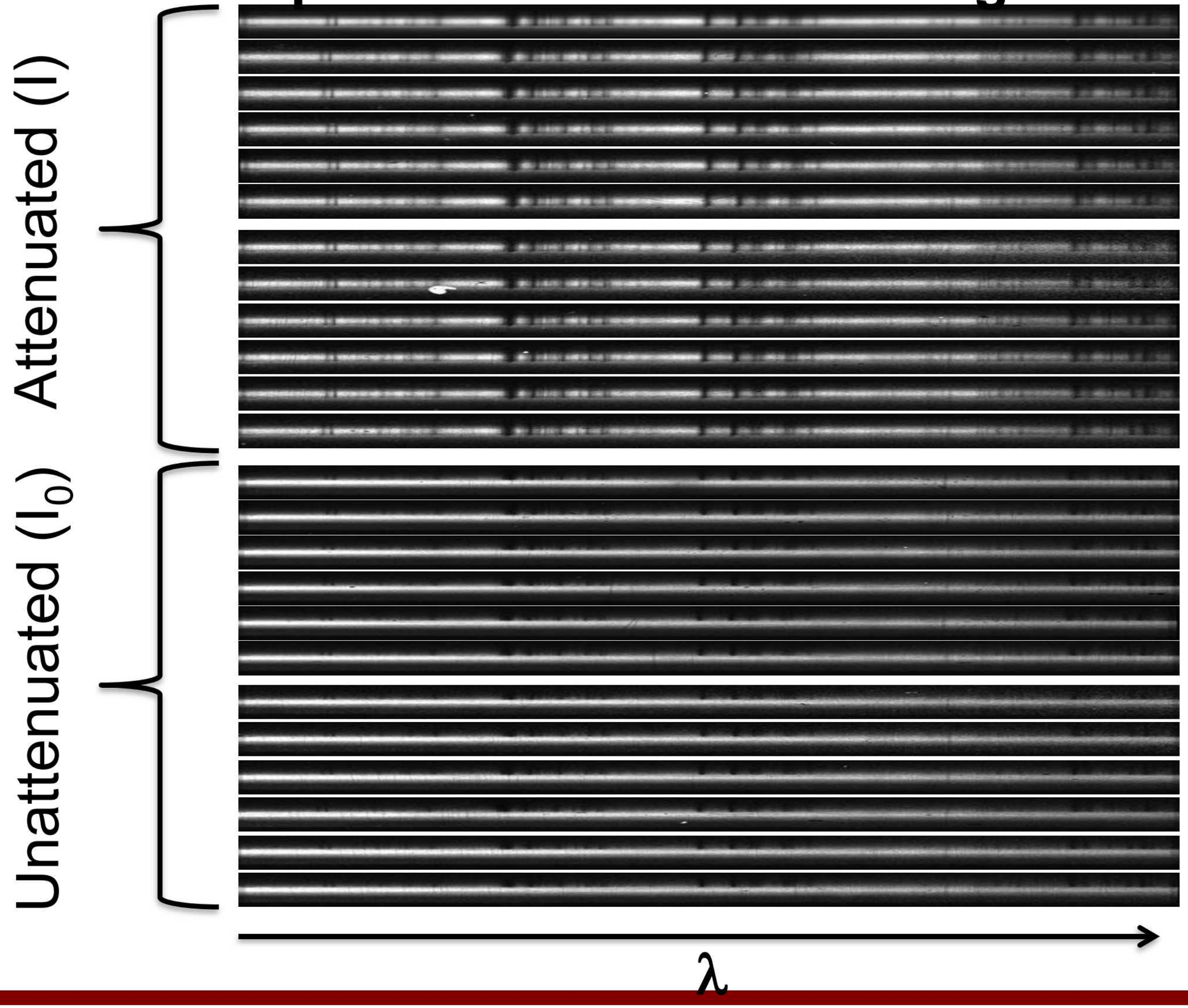
<u>Requirements:</u>

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

Hundreds of spectra over multiple shots are used to assess reproducibility and achieve high precision.

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

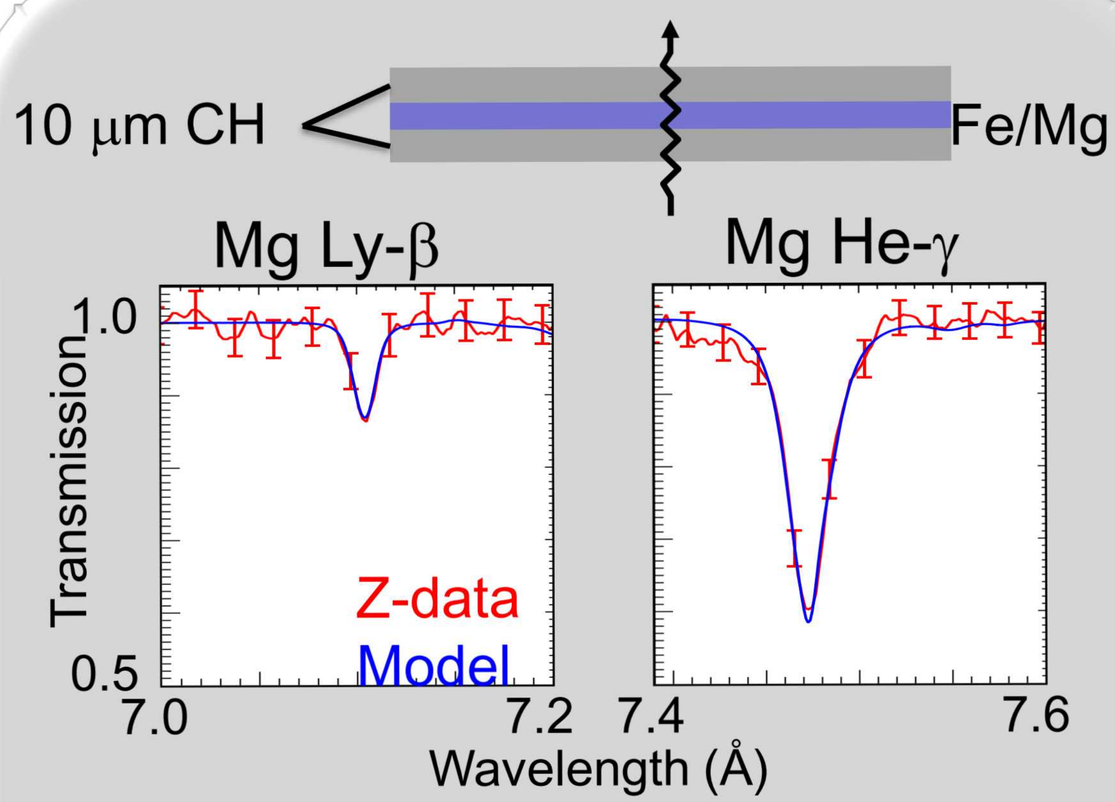
24 spectra recorded on a single shot



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

Increasing the back-side tamper mass increases the sample temperature and density

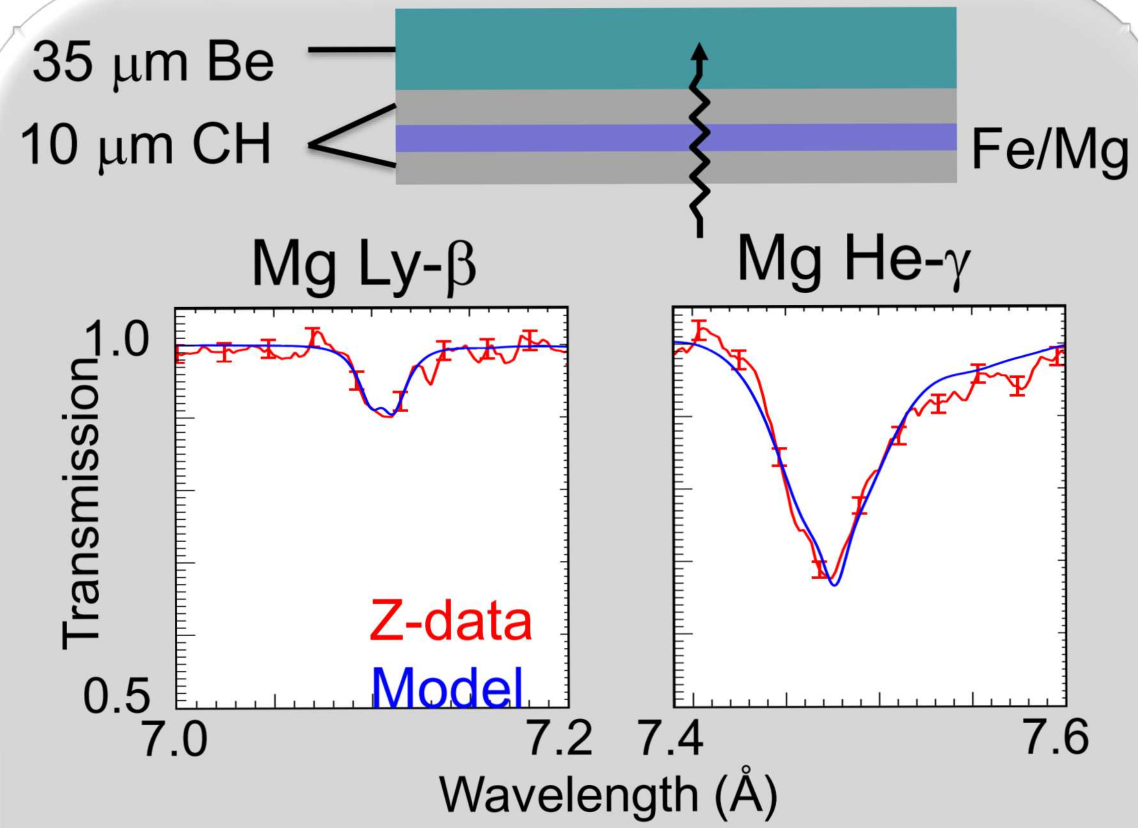
Anchor 1



T_e = 156 ± 6 eV

n_e = 6.9 ± 1.7 x10^{21} cm $^{-3}$

Anchor 2

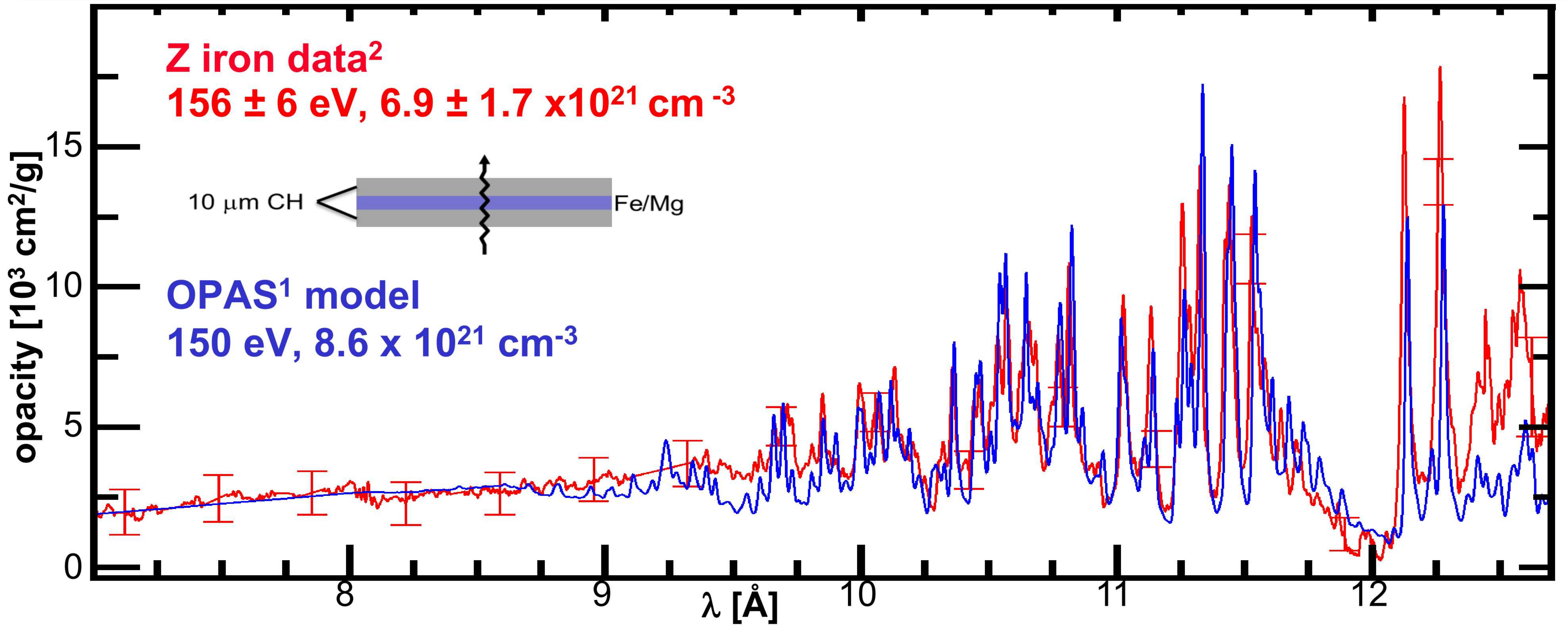


T_e = 182 ± 3 eV

n_e = 31. ± 3. x10^{21} cm $^{-3}$

Nash *et al. Rev. Si. Instrum.* 2010; Nagayama *et al. Phys.Plasmas* 2014

Some opacity models agree with Z iron data at Anchor 1 conditions, supporting experiment method accuracy

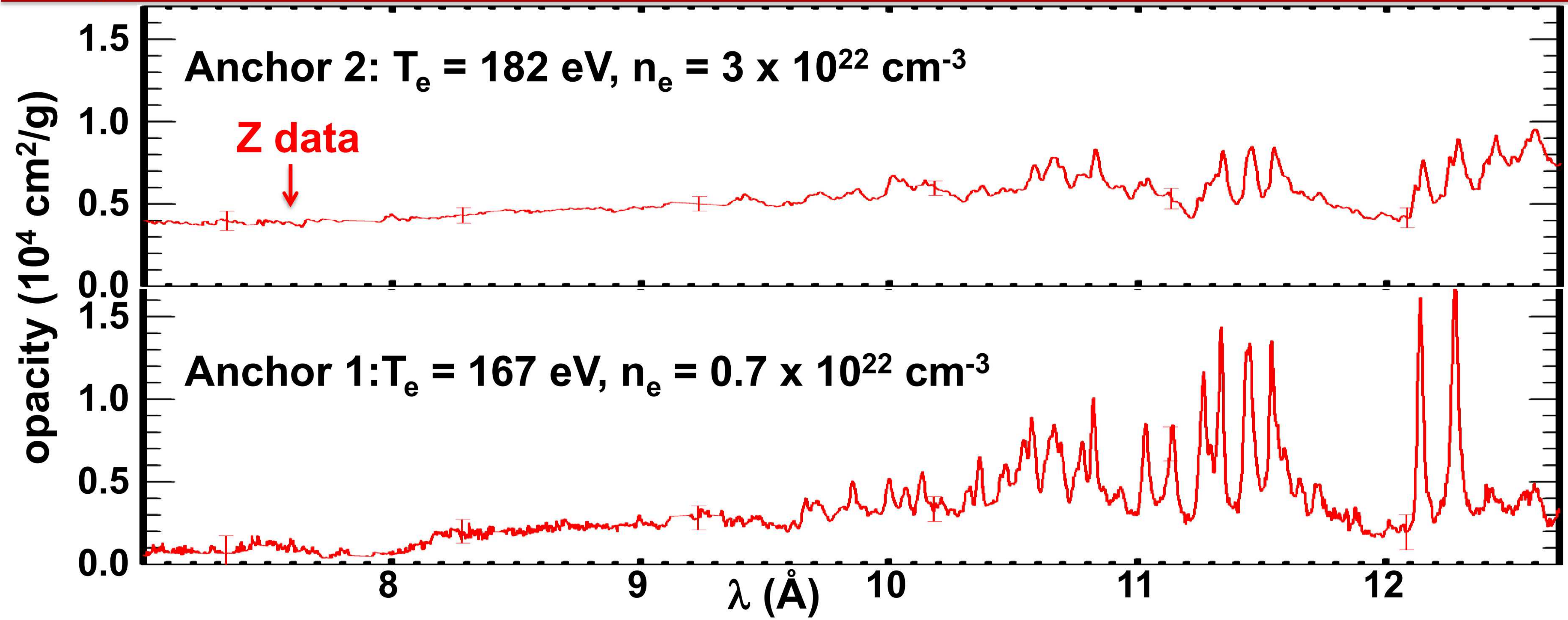


The 1.8 million Kelvin temperatures here were too low to fully test models for the sun

[1]Blancard *et al.*, *ApJ* (2012)

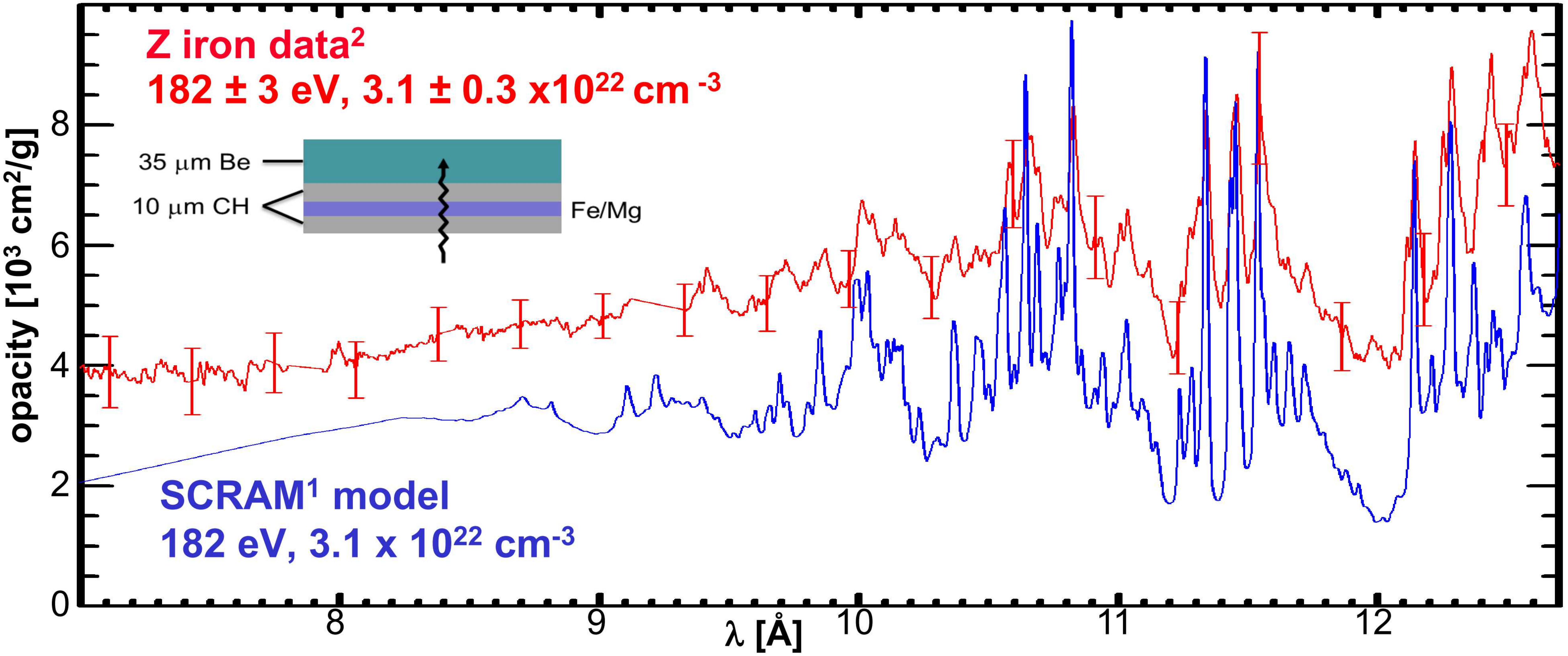
[2]Bailey *et al.*, *PhysRevLett* (2007)

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



As T_e, n_e increase:
shorter, fatter lines; windows fill in; continuum κ increases

At the higher T_e, n_e Anchor 2 conditions corresponding to the solar CZB, models no longer agree with the Z iron data



[1]Hansen *et al.*, *HEDP* (2007)

[2]Bailey *et al.*, *Nature* (2015)

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

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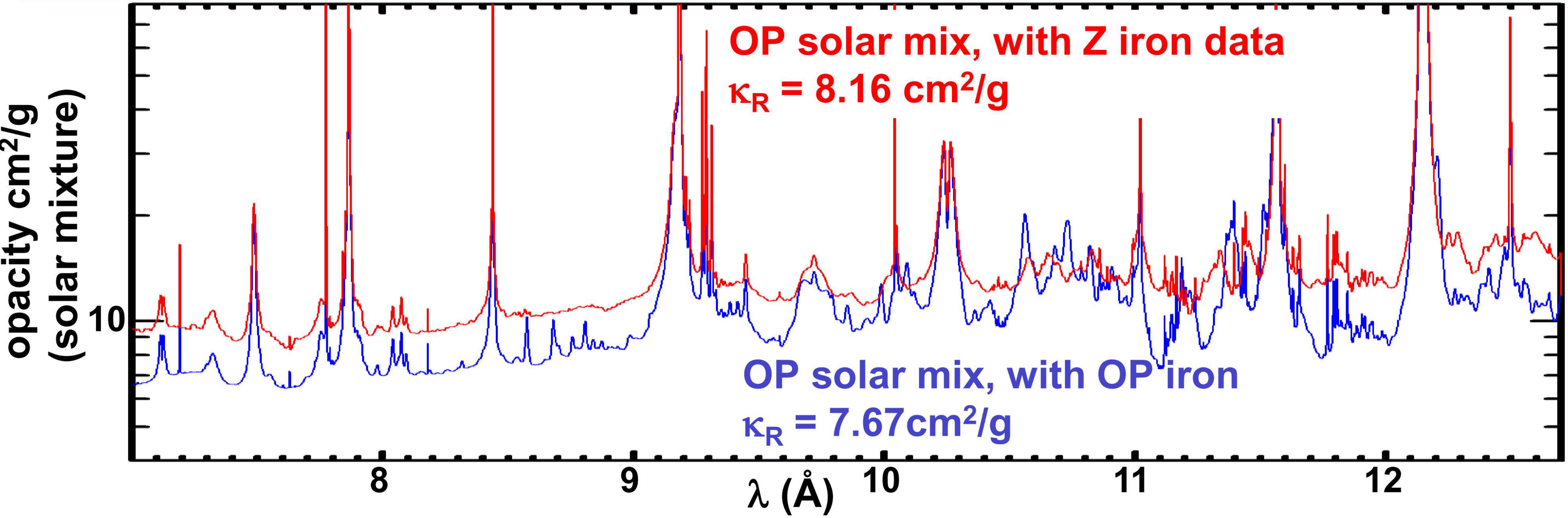


- **A 7% Rosseland increase partially resolves the solar problem, but the measured iron opacity by itself cannot account for the entire discrepancy**
- **Other elements and regions deeper in the sun could contribute**

193 eV, 3.3 e22 e/cc Asplund09 solar abundances **Badnell *et al.*, *MNRAS* 2005**

We must determine the origin of the discrepancy between iron opacity models and the Z data

If the Z iron data are correct, then solar models and helioseismology could be (mostly) reconciled

- This supports accuracy of revised solar abundances
- In turn this alters composition assumed for many astrophysical objects

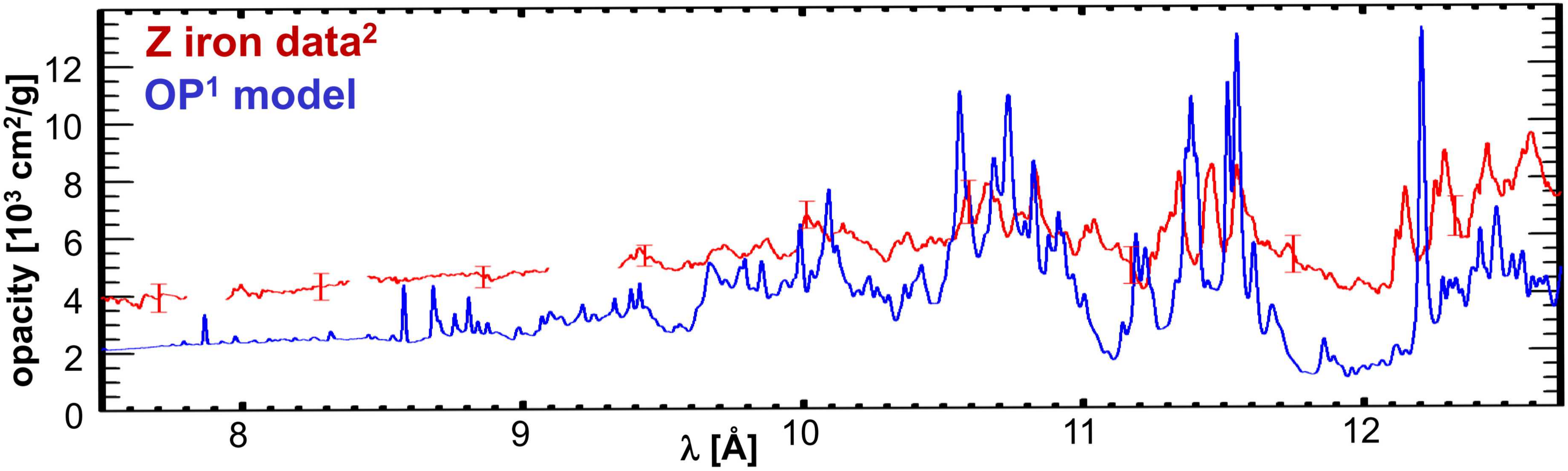
Opacity revisions will also:

- Modify inferred stellar ages
- Change inferred properties of exoplanet host stars

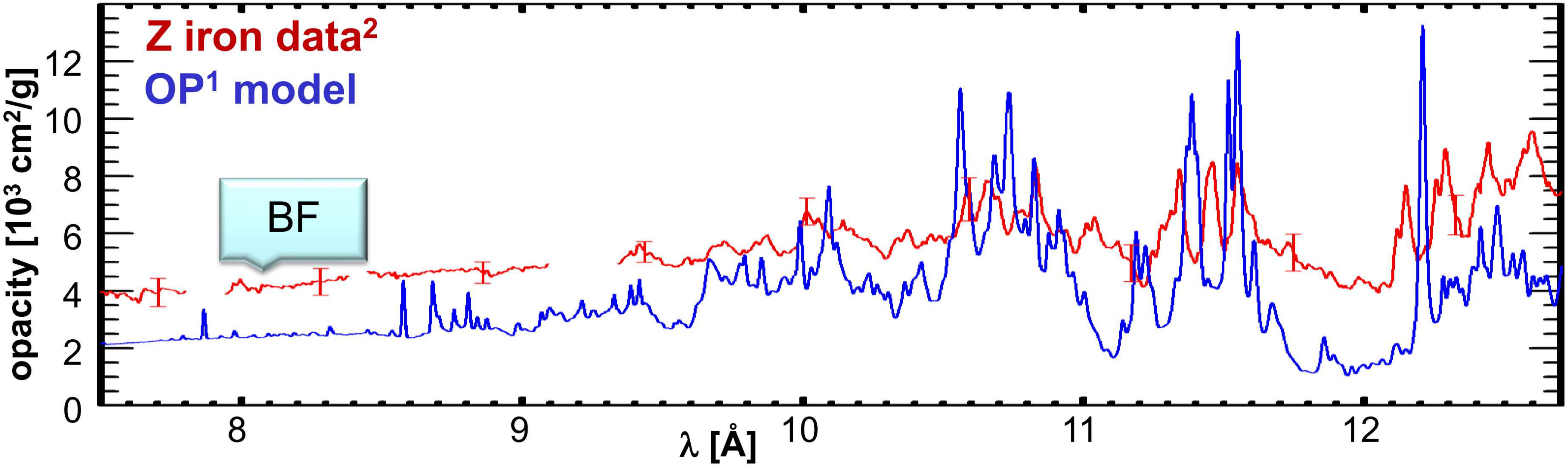
The high impact mandates that we do our utmost to ensure data reliability

Ultimately, astrophysics must rely on opacity models – if the Z data are correct we need to learn how to revise the models

Identifying the opacity model-data differences helps formulate possible hypotheses



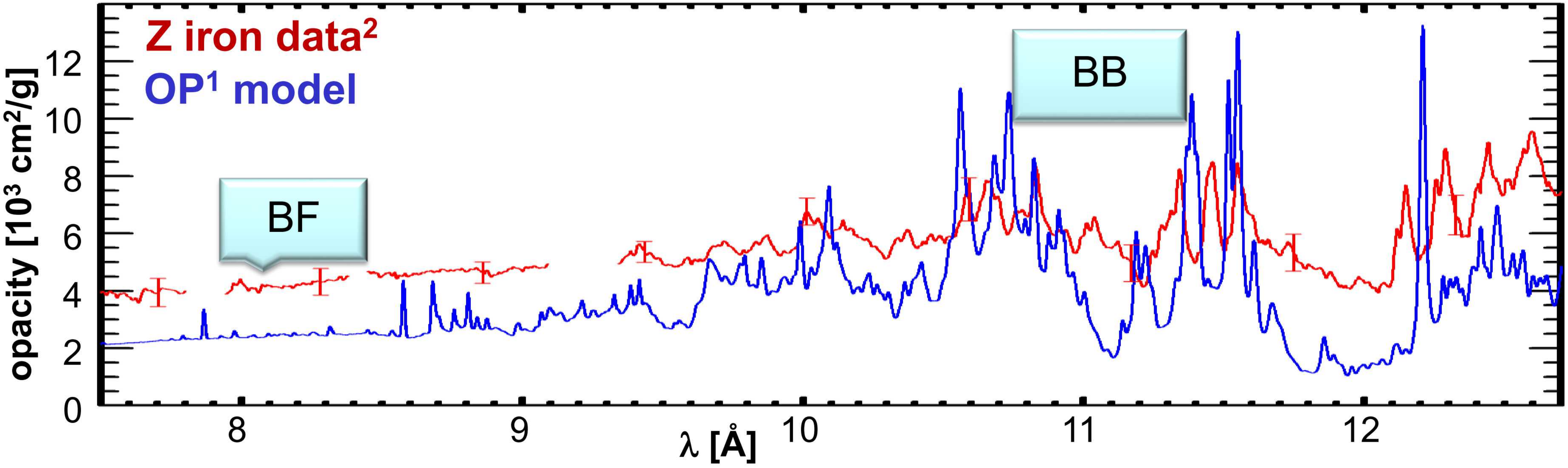
Identifying the opacity model-data differences helps formulate possible hypotheses



BF: bound-free/quasi-continuum:

- Bound-free (b-f) cross-section?
- Missing lines from multi-excited states?
- Multi-photon processes?

Identifying the opacity model-data differences helps formulate possible hypotheses



BF: bound-free/quasi-continuum:

- Bound-free (b-f) cross-section?
- Missing lines from multi-excited states?
- Multi-photon processes?

BB: bound-bound line features*

- Line location → Atomic structure
- Strength → Oscillator strength?
  Population?
- Line width → Line shape?
  Missing lines?

*ATOMIC, OPAS, SCO-RCG, SCRAM, and TOPAZ show much better agreement in line locations

Identifying the opacity model-data differences helps formulate possible hypotheses

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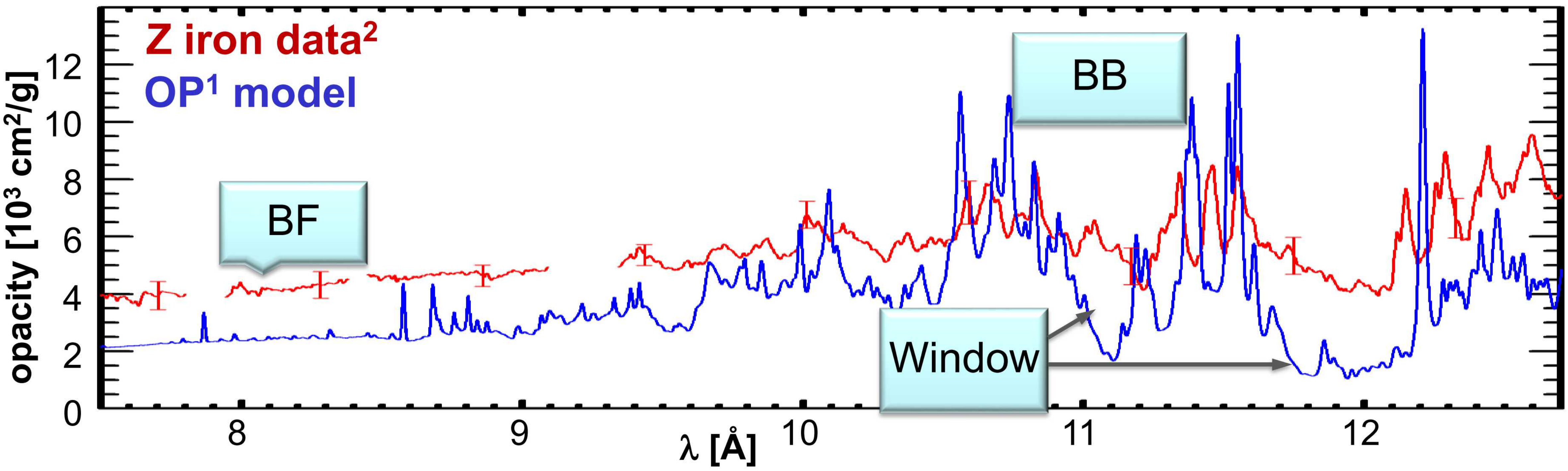


BF: bound-free/quasi-continuum:

- Bound-free (b-f) cross-section?
- Missing lines from multi-excited states?
- Multi-photon processes?

BB: bound-bound line features*

- Line location → Atomic structure
- Strength → Oscillator strength? Population?
- Line width → Line shape? Missing lines?

Window filling:

- Broader line shape filling the window?
- Missing lines from multi-excited states?
- Multi-photon processes?

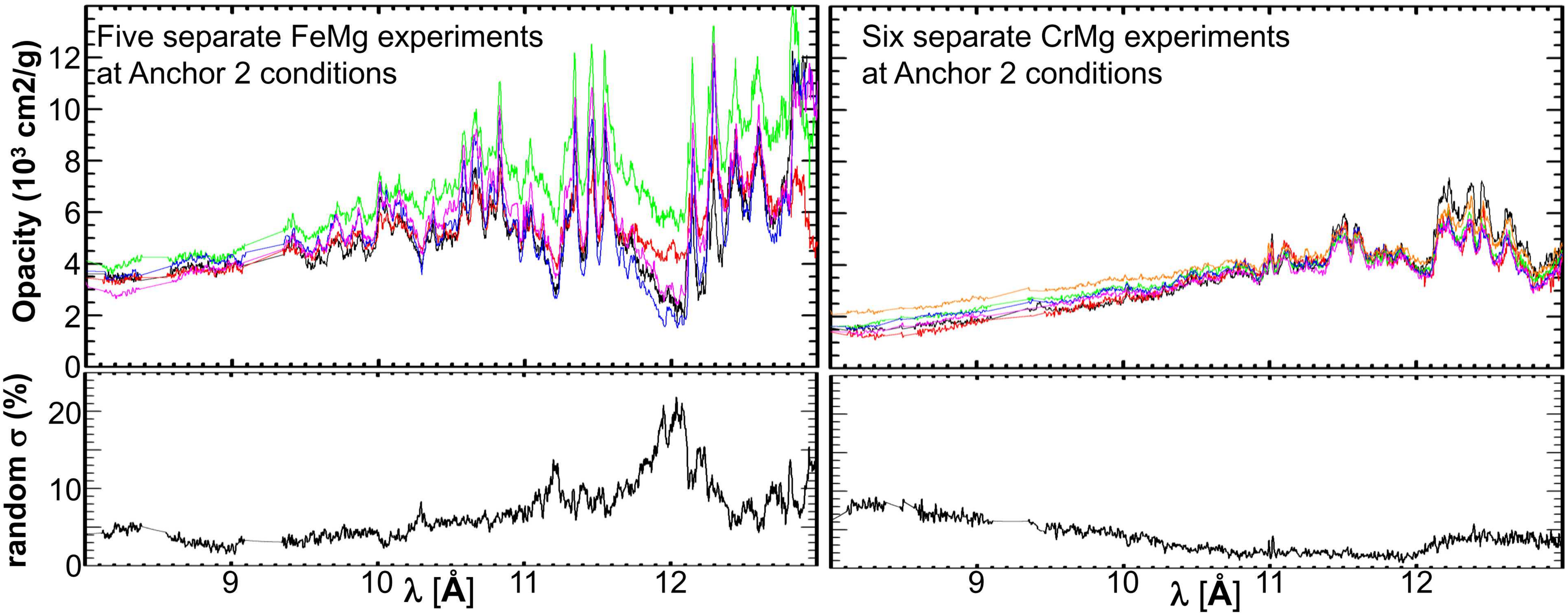
*ATOMIC, OPAS, SCO-RCG, SCRAM, and TOPAZ show much better agreement in line locations

There are two broad hypothesis categories for the opacity model-data discrepancy

A. The iron experiment is flawed for some reason

B. Photon absorption in HED matter is different than we previously believed

Random errors - and some possible systematic errors -are evaluated using experiment reproducibility and the Beer-Lambert-Bouguer Law



Measurements use different sample thicknesses, providing systematic error tests according to the Beer-Lambert-Bouguer Law $T_1 = T_2^{(x1/x2)}$ e.g., if $X_2 = 2 * X_1$, then $T_2 = T_1 * T_1$

σ estimated here using standard deviation / sqrt (N)

Comparisons between experiments at different T_e, n_e provide powerful hypothesis tests

Simply changing the tamper - without changing anything else - alters the temperature and density at the backlight probe time

- Example: If we propose that unquantified sample contaminants bias the opacity measurement, this should be true for all temperatures and densities

Many systematic errors are ruled out by agreement between experiments and models at lower T_e, n_e conditions

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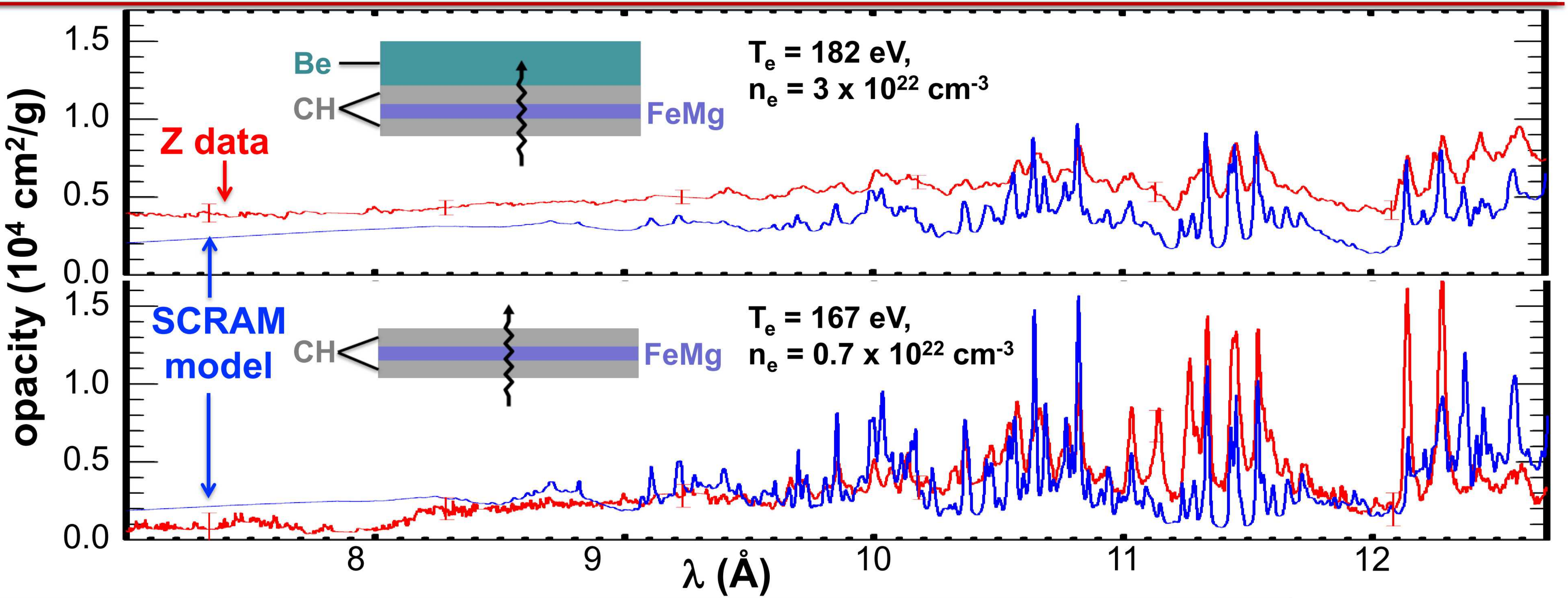

The only change between these experiments is the tamper
The simplicity of this change precludes many experiment flaw hypotheses (e.g., contamination, non-LTE, transmission analysis, spectrometer problems…)

Bailey *et al.*, Nature (2015)

Comparisons between experiments at different T_e, n_e or different elements provides powerful hypothesis tests

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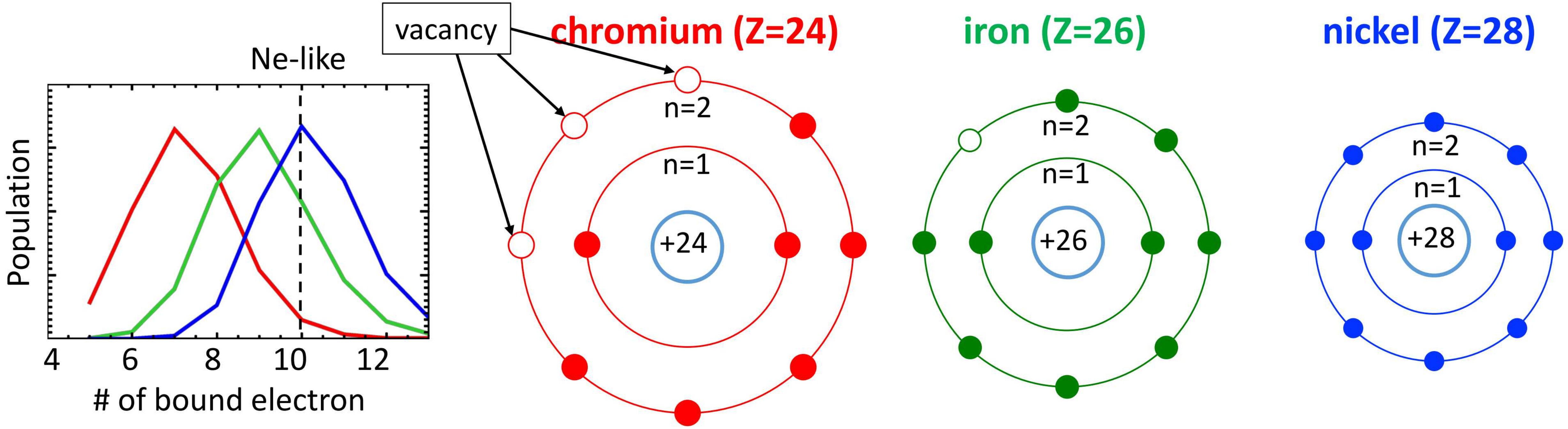
Simply changing the tamper alters the temperature and density at the backlight probe time

- **Example: If we propose that unquantified sample contaminants bias the opacity measurement, this should be true for all temperatures and densities**

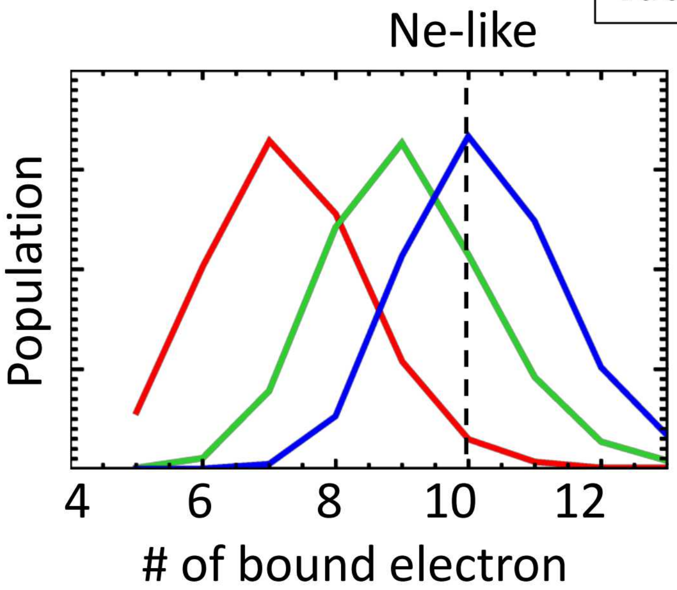
Simply changing the sample element without changing the x-ray heating source, backlight source, diagnostics, or analysis helps test the experiment methods

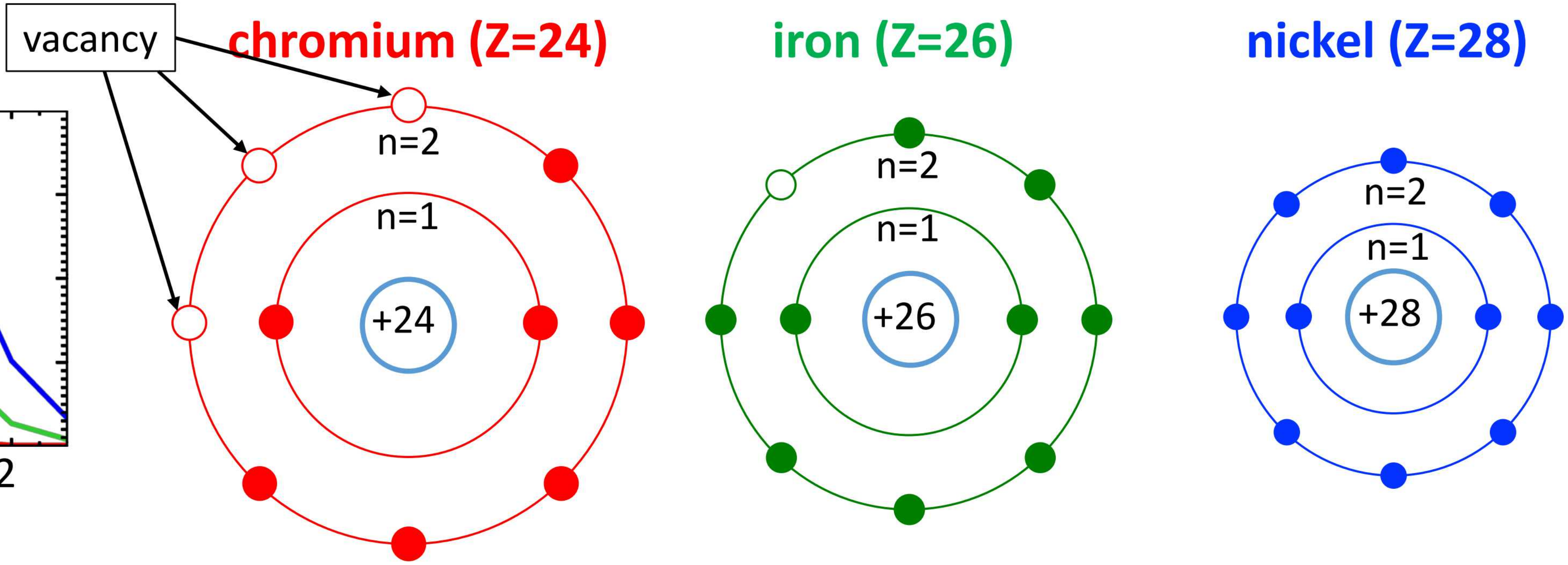
- **Example: If we propose that an unquantified gradient biases the opacity measurement, then all elements should be biased**

The same platform drives different elements to similar conditions, leading to different charge state distributions



Experiments with different elements are a rich source of opacity model tests as well as experiment-platform tests





Simply changing elements provides strong hypothesis constraints

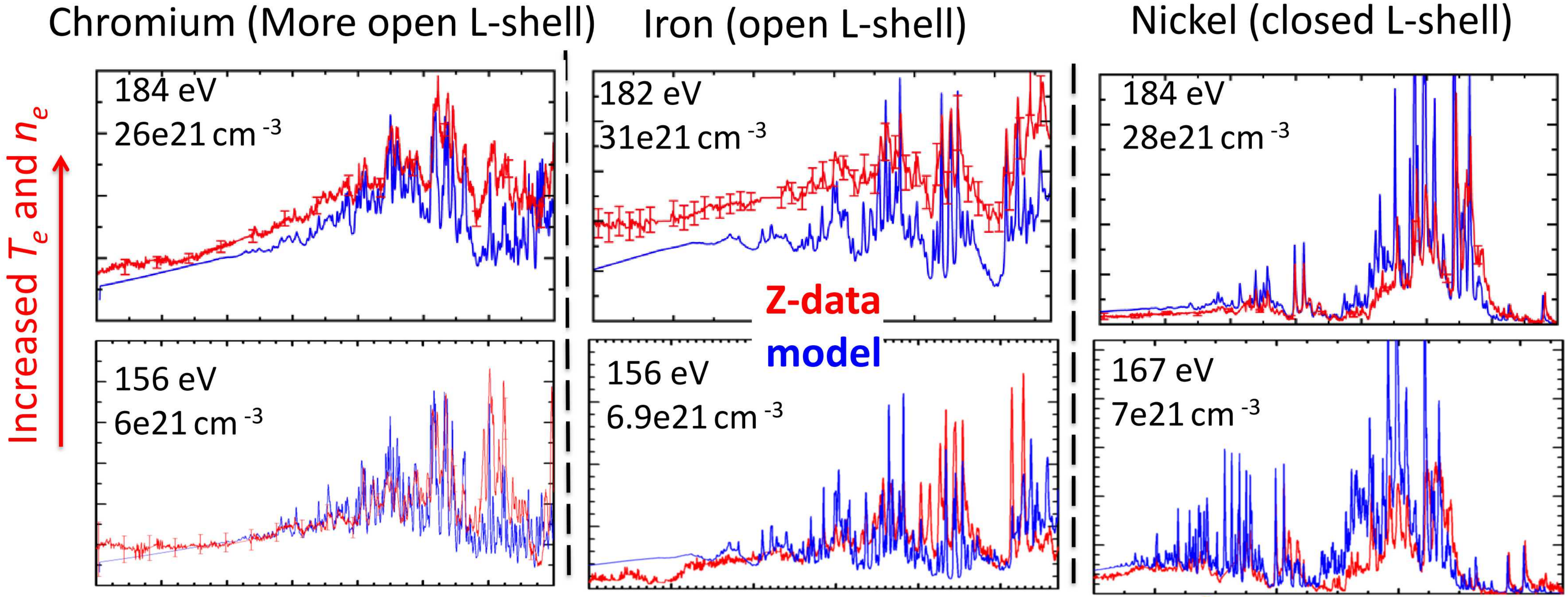
More ← L-shell vacancies — Less

More ← # of excited states — Less

More ← Density effects — Less

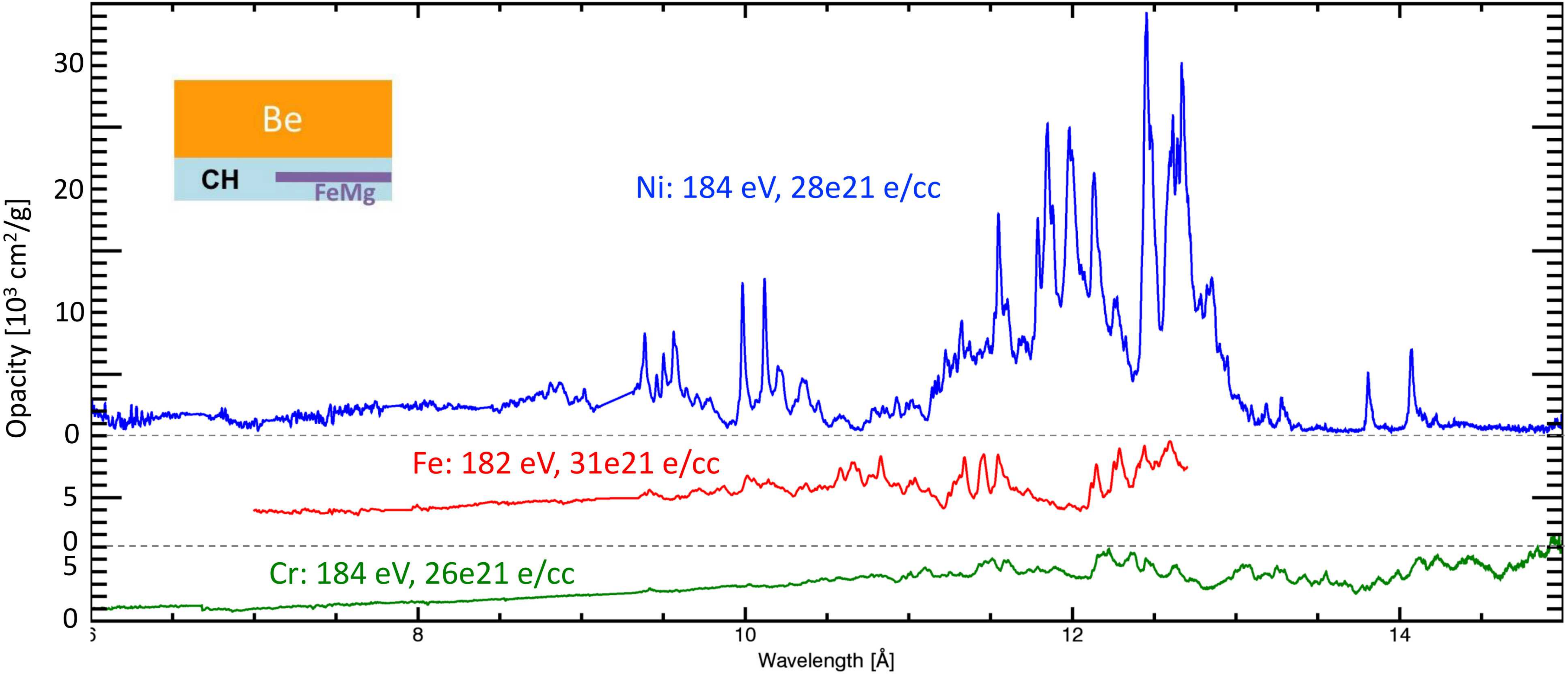
We will untangle the complex opacity issues through precise measurements across a range of T_e, n_e, and atomic number

fewer L-shell vacancies, smaller # of excited states, less Stark broadening

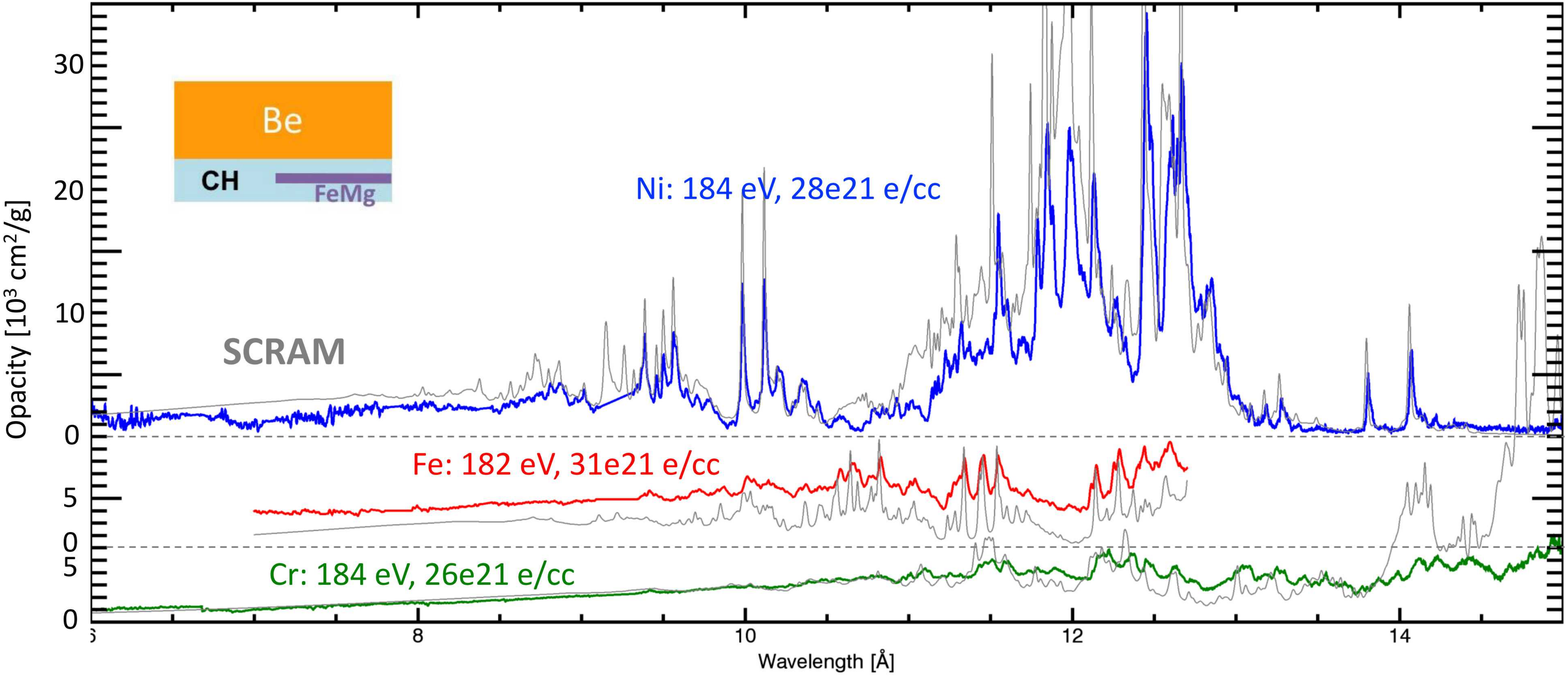


Increased Atomic Number

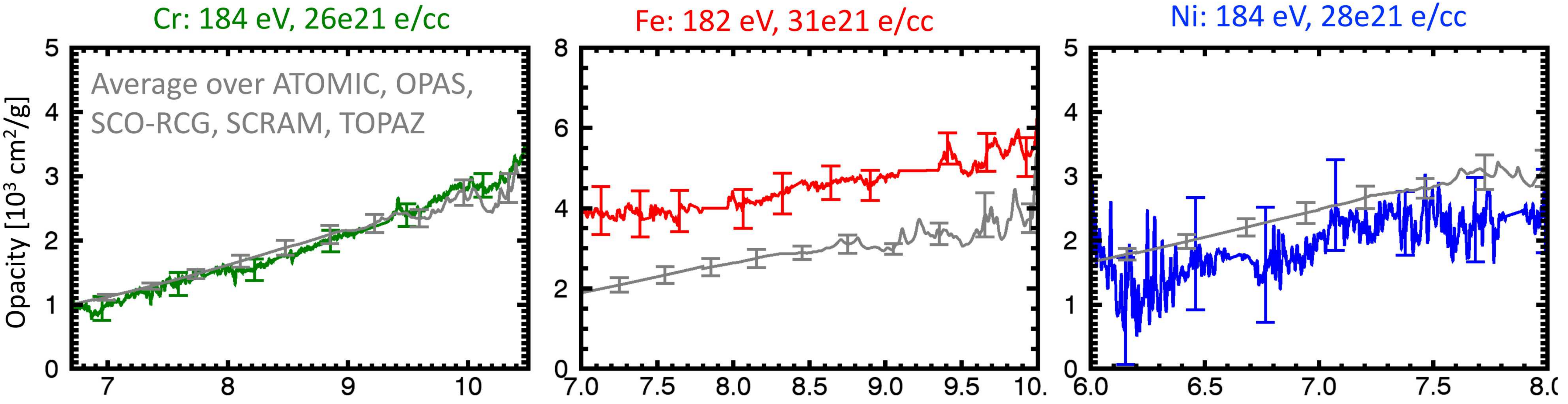
Measured Cr, Fe, and Ni opacities enable many tests for proposed experiment errors and opacity model inaccuracies



Measured Cr, Fe, and Ni opacities enable many tests for proposed experiment errors and opacity model inaccuracies

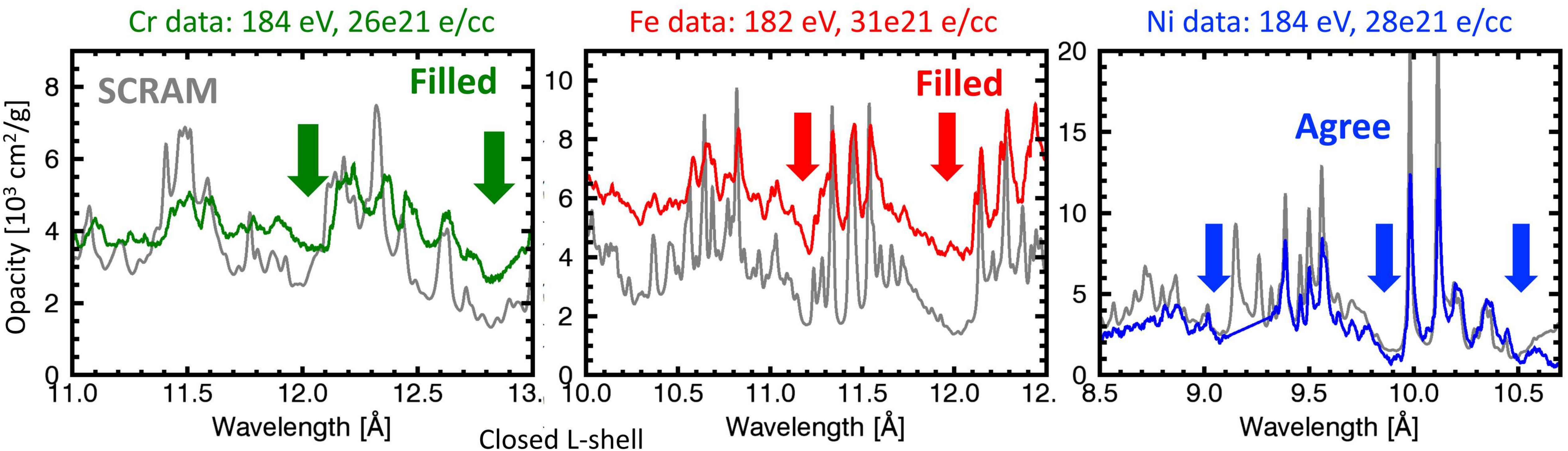


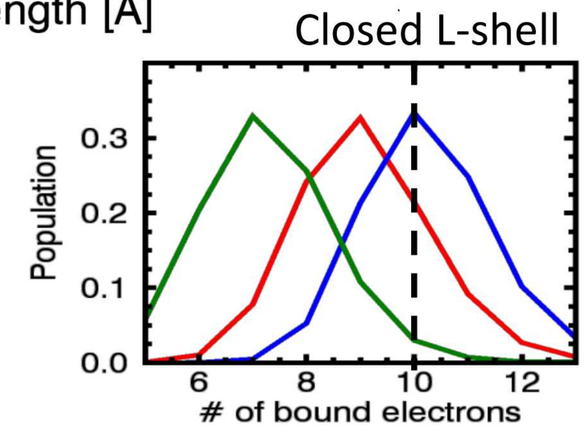
Cr and Ni data prove the experiment is not always biased to measure higher-than-predicted continuum opacity



Fe at 195 eV and 40e21 e/cc also shows higher continuum opacity. What's so special about Fe?
Is Fe experiment flawed after all? If so, how?
If Fe is correct, what physics could be missing or inaccurate in present models?

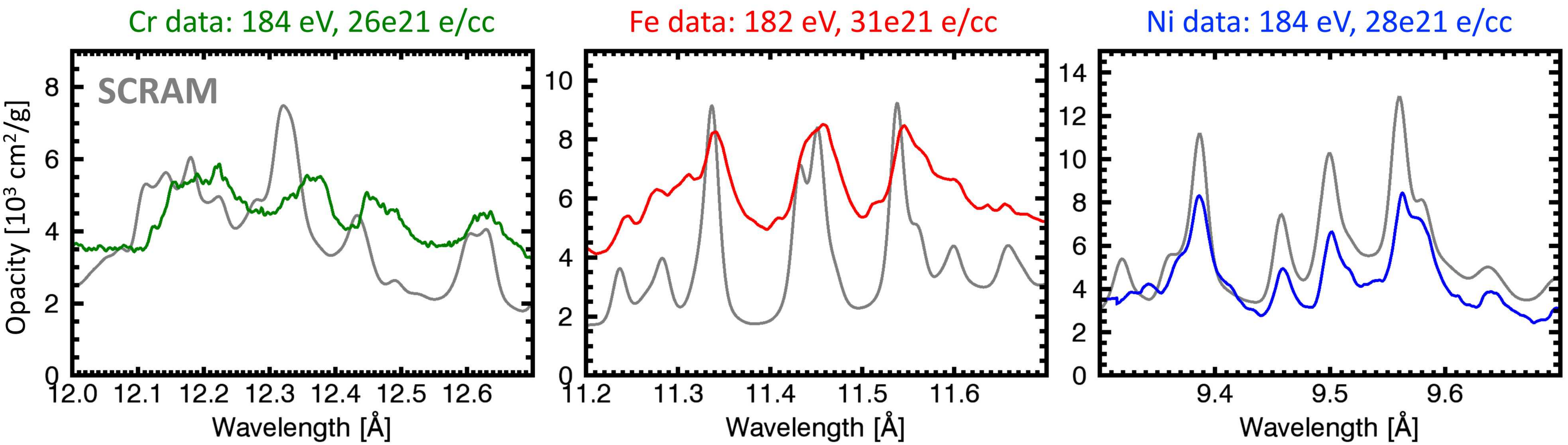
Higher than predicted opacity windows are observed in Cr and Fe data, but not Ni





Matching opacity window is challenging in open L-shell?

Wider than predicted bound-bound features are observed in all tested elements: Cr, Fe, and Ni



Wider bound-bound features tend to raise the mean opacity
Wider features can be caused by inaccurate line broadening, or line blending, or both

No proposed hypothesis for experiment flaws has yet resolved the discrepancy

A. The experiment method is biased to infer higher opacity with filled opacity windows, for some as-yet undetermined reason
B. Transmission errors
C. Sample areal density errors
D. Sample contamination
E. Diagnostic errors
F. Sample self emission
G. Tamper transmission
H. Temporal gradients
I. Spatial gradients
J. Non-LTE effects

Several opacity model refinements are candidates to help resolve the discrepancy

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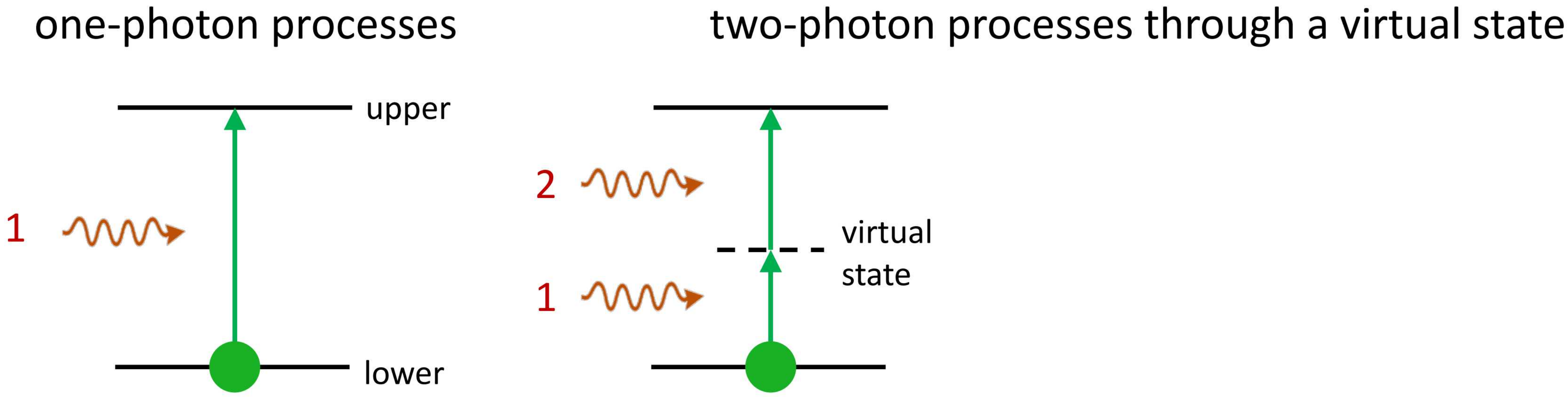
- **Line broadening**
- **Satellite line blending**
- **Multiphoton absorption**

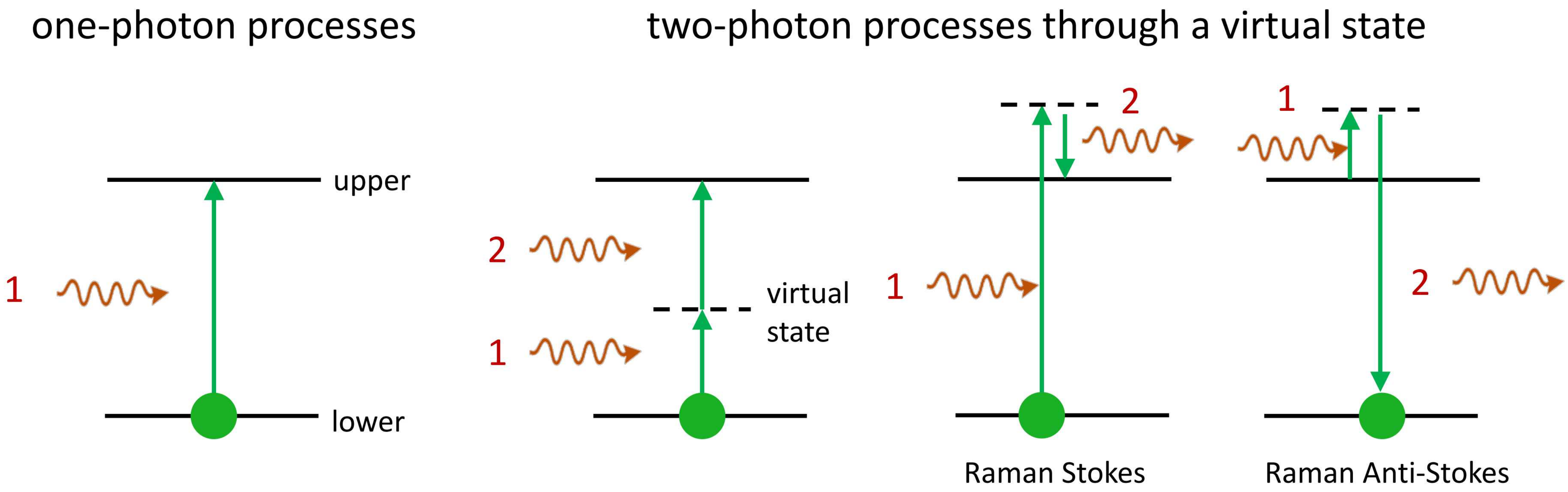
Opacity by two-photon processes are neglected from existing opacity models



Two-photon absorption was described by M. Goeppert-Mayer in 1931

The process is known, but the cross section is small

Opacity by two-photon processes are neglected from existing opacity models

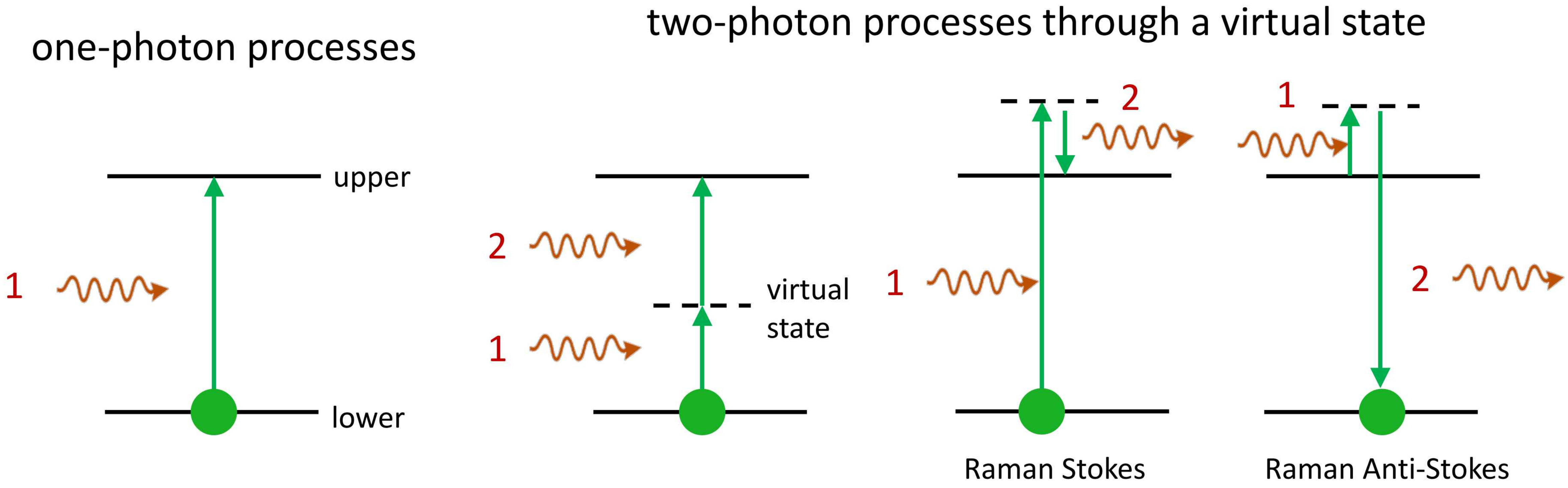


Neglecting 2-photon processes was deemed appropriate for the solar core where iron absorption is mainly from the K shell (principal quantum number n=1)

R. More and S. Rose, *Radiative Properties of Hot Dense Matter* (1991)

But in most of the sun, absorption from higher principal quantum numbers dominates….

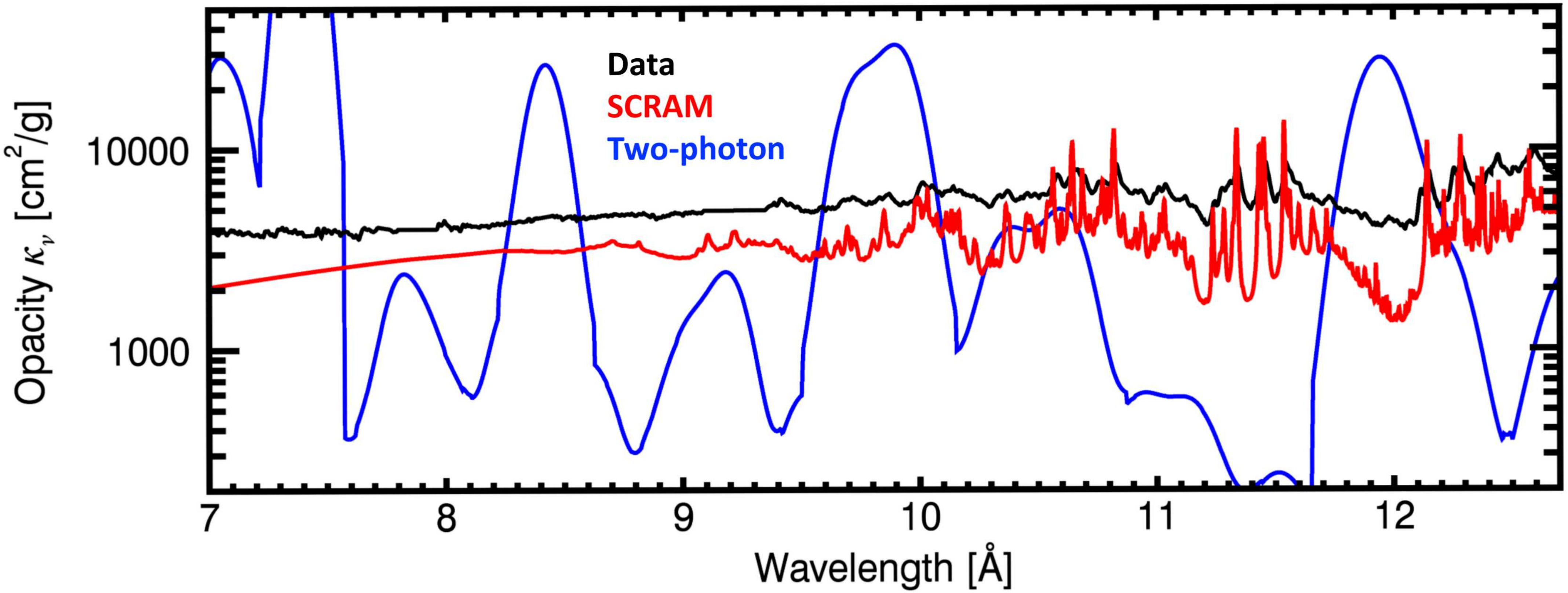
Opacity by two-photon processes are neglected from existing opacity models



- **Two-photon process cross-section** $\sim \boldsymbol{n^8}$
- Virtual state has short life-time → Bright radiation field

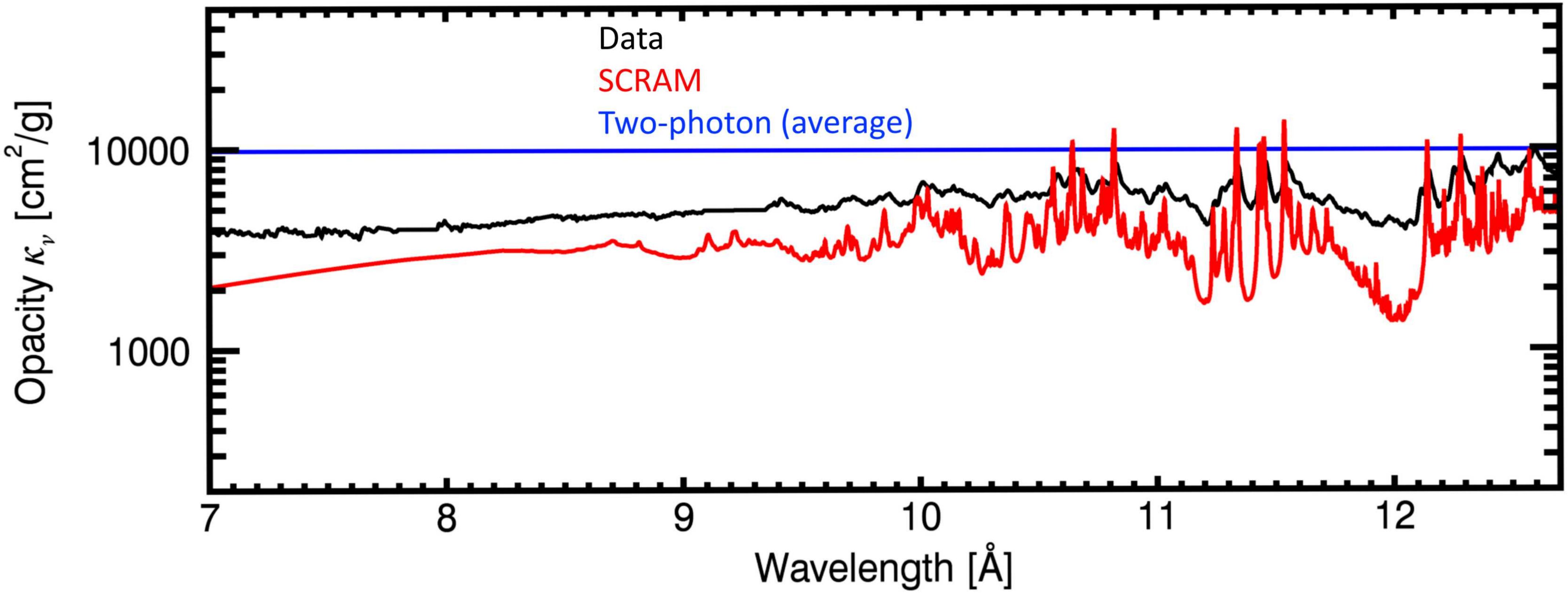
} Z opacity experiments have both

Two-photon absorption appears to have the correct order of magnitude, but the calculation needs to be refined



- First-principal method with simple atomic model
- Two-photon opacity more important than believed

Two-photon absorption appears to have the correct order of magnitude, but the calculation needs to be refined



- First-principal method with simple atomic model
- Two-photon opacity more important than believed

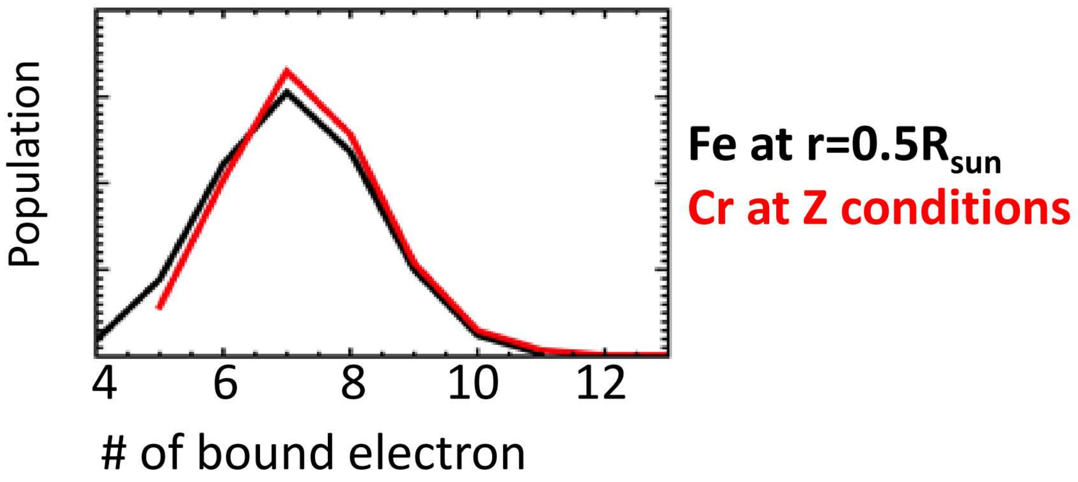
Ongoing experiments are in progress to further test the models and data

- **Repeat the Anchor 2 iron measurements**
- **Repeat Anchor 3 iron measurements with Be tamper**
- **Raise the temperature and density even further**
- **Repeat the experiment at the NIF (LMJ? LCLS? Orion?)**

Future work: Surrogate experiment for Fe opacity at deeper in the Sun

- **Measuring opacity of hotter plasma is challenging**
  - Increase sample temperature
  - Increase backlight brightness ($\propto T^4$)
- **Can a lower Z element using current platform act as a surrogate for iron opacity deeper in the Sun?**
  - Example: Cr reproduces charge state distribution at half-solar radius

Charge state distribution



Does Cr mimic challenges in atomic data, population kinetics, and density effects?

Collaboration: Y. Kurzweil and G. Hazak

Opacity experiments at the Z facility refine our understanding of photon absorption in high energy density stellar matter.

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

- **Z experiments measure higher-than-predicted iron plasma opacity at near-solar-interior conditions**
  → helps resolve the solar problem, but what causes the discrepancy?

- **No systematic error has yet been found – but experiment examination continues**

- **If data are correct, we are forced to conclude that model refinements are needed for stellar opacity**