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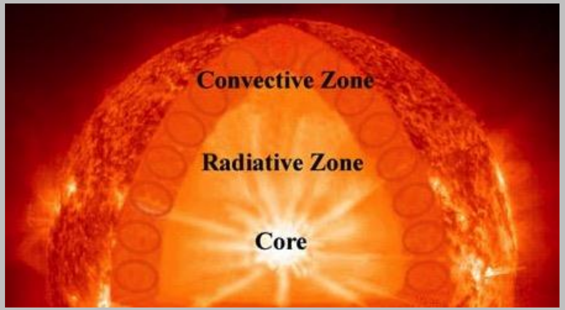

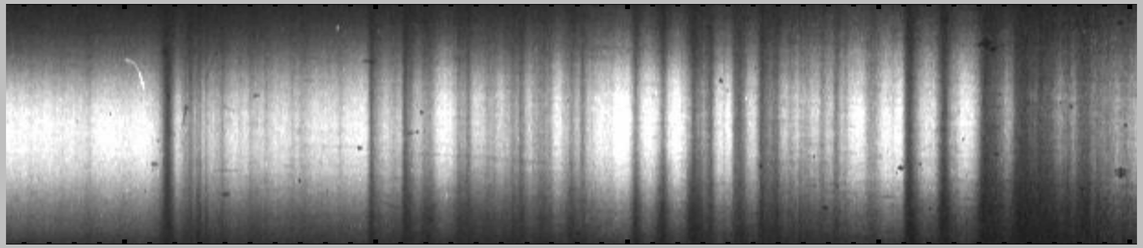

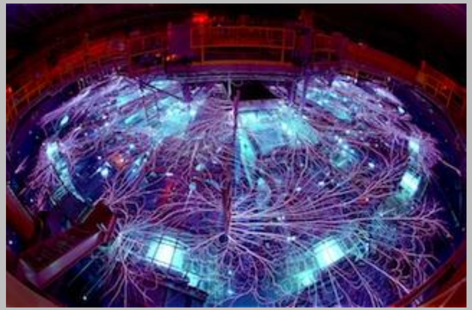

Opacity data for stellar models and its uncertainties

Jim Bailey

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, 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.

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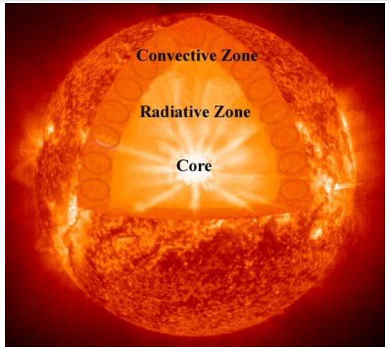
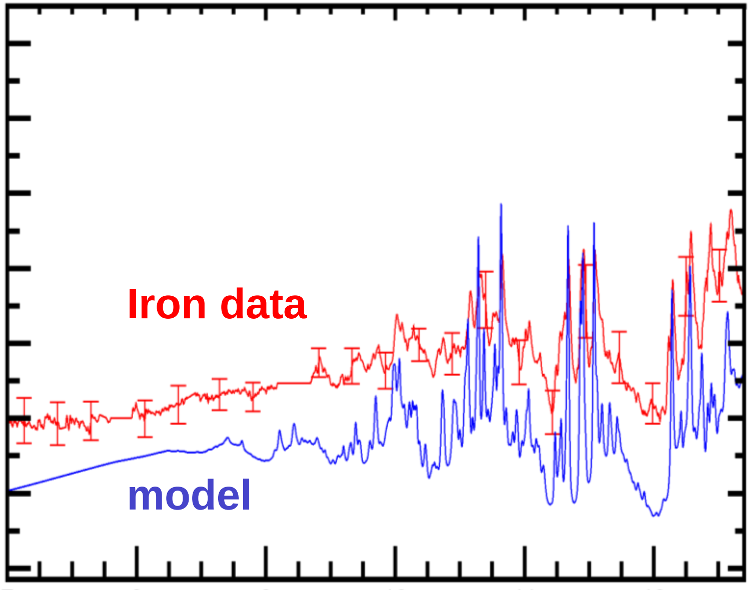


- Solar interior predictions don't match helioseismology
  → Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?
- Z experiments have measured iron plasma opacity at near-solar-interior conditions
- The measured high temperature/density iron opacity is higher than predictions
  → helps resolve the solar problem, but we need to understand what causes the discrepancy
- No systematic error has yet been found – experiment examination continues
- Experimental and theoretical research is aimed testing hypotheses to resolve the difference



Bailey *et al*., *Nature* 2015

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

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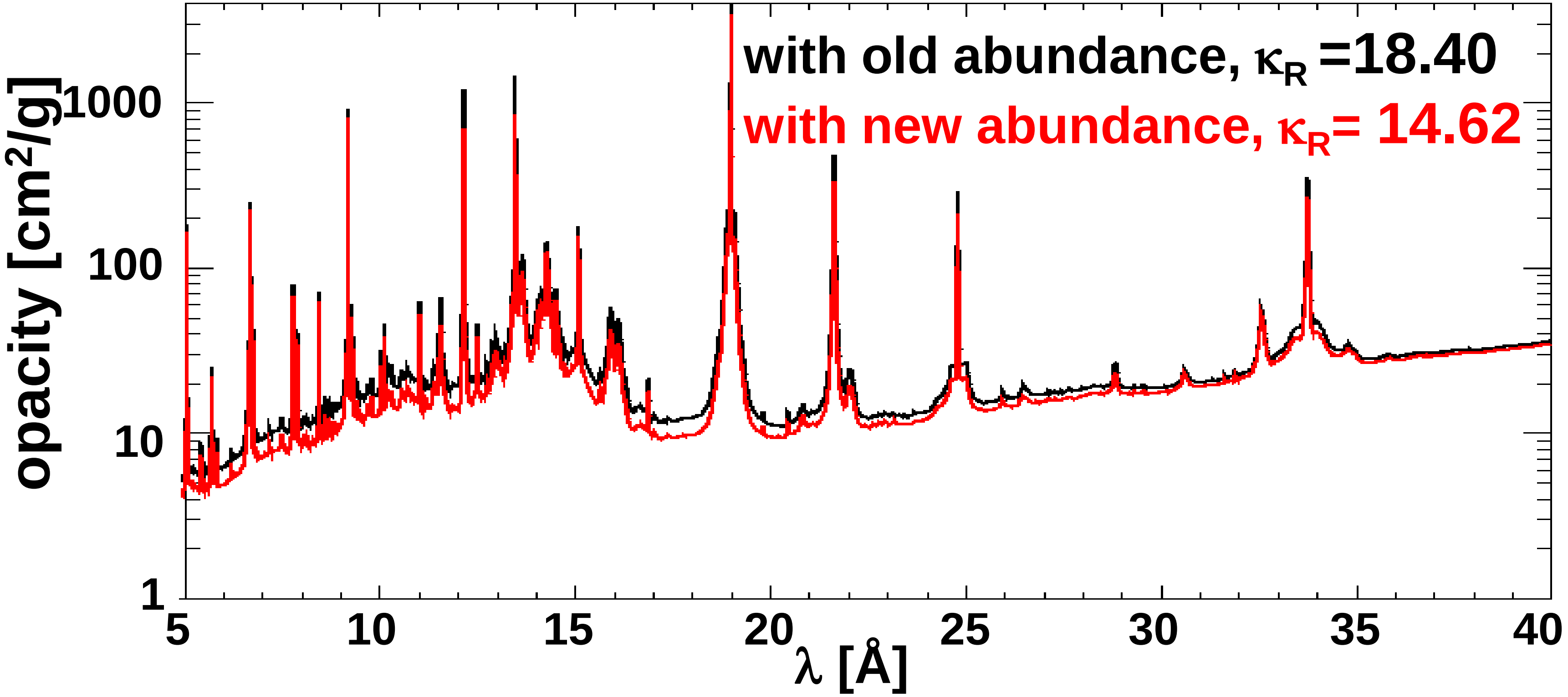
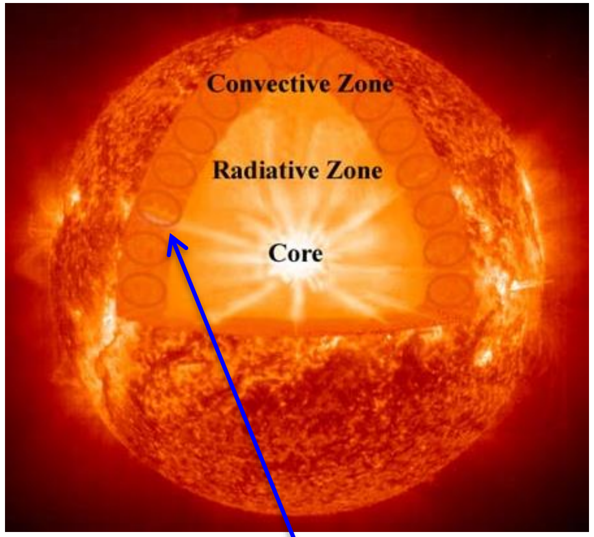
Solar mixture opacity at Convection Zone Base (CZB)





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

Rosseland mean opacity → energy transfer by radiation

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

Photons are transported in opacity windows

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

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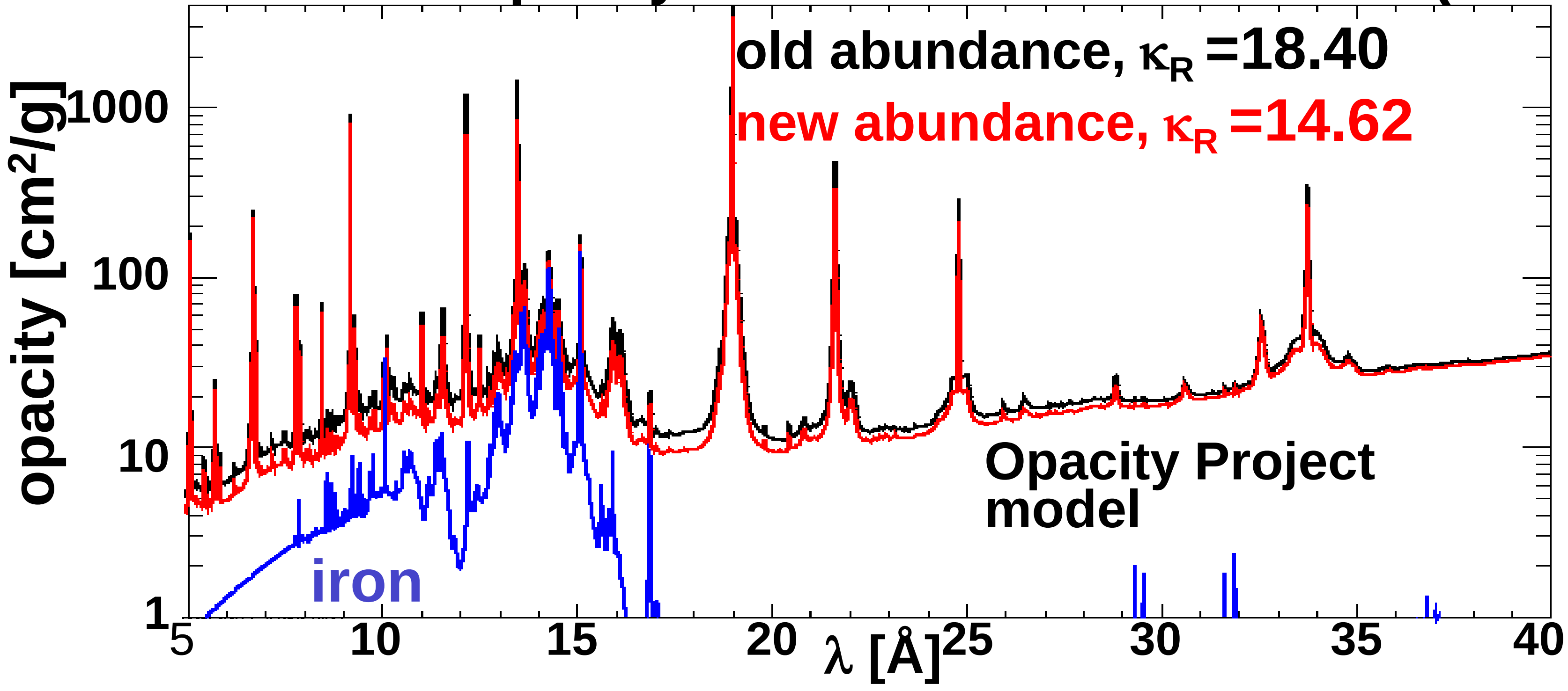
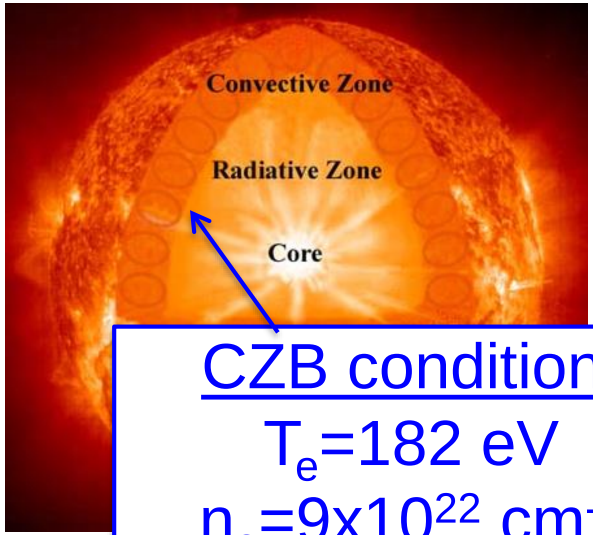
Solar mixture opacity at Convection Zone Base (CZB)





CZB condition:

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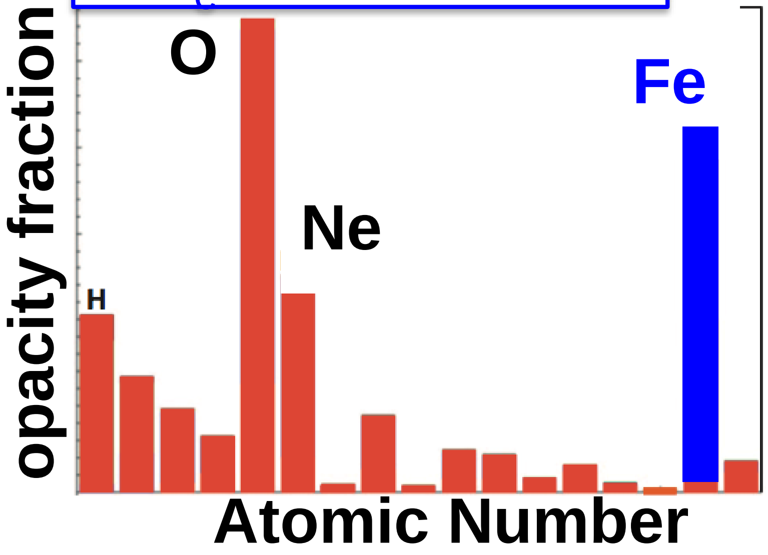

CEA OPAS calculation

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
Barkla

1925
Siegbahn
X-ray spectroscopy

1965

only bound-free and free-free absorption

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

What physics is a concern for opacities?

“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

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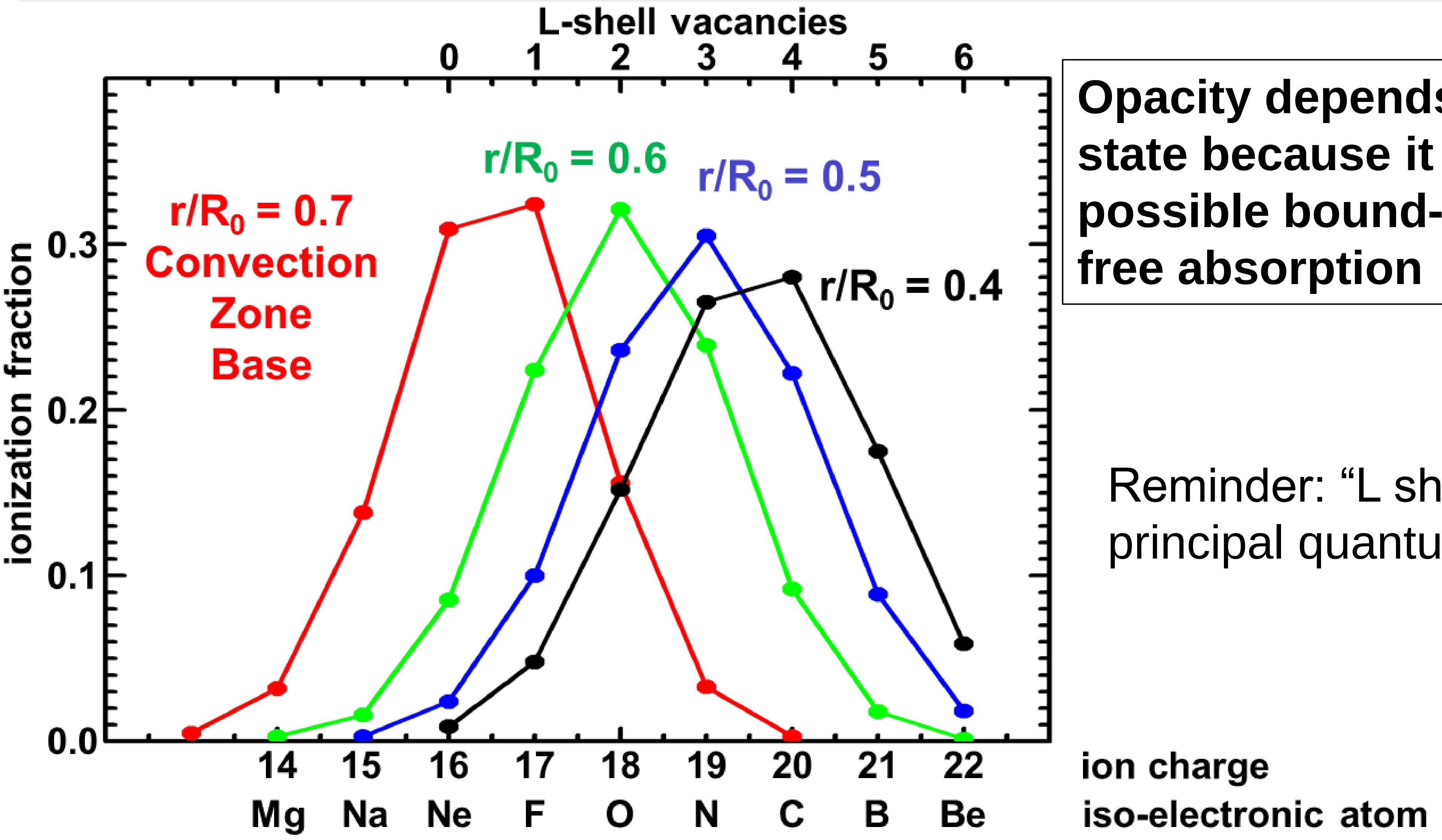
Attenuation is caused by photon interactions with bound and free electrons:

- 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

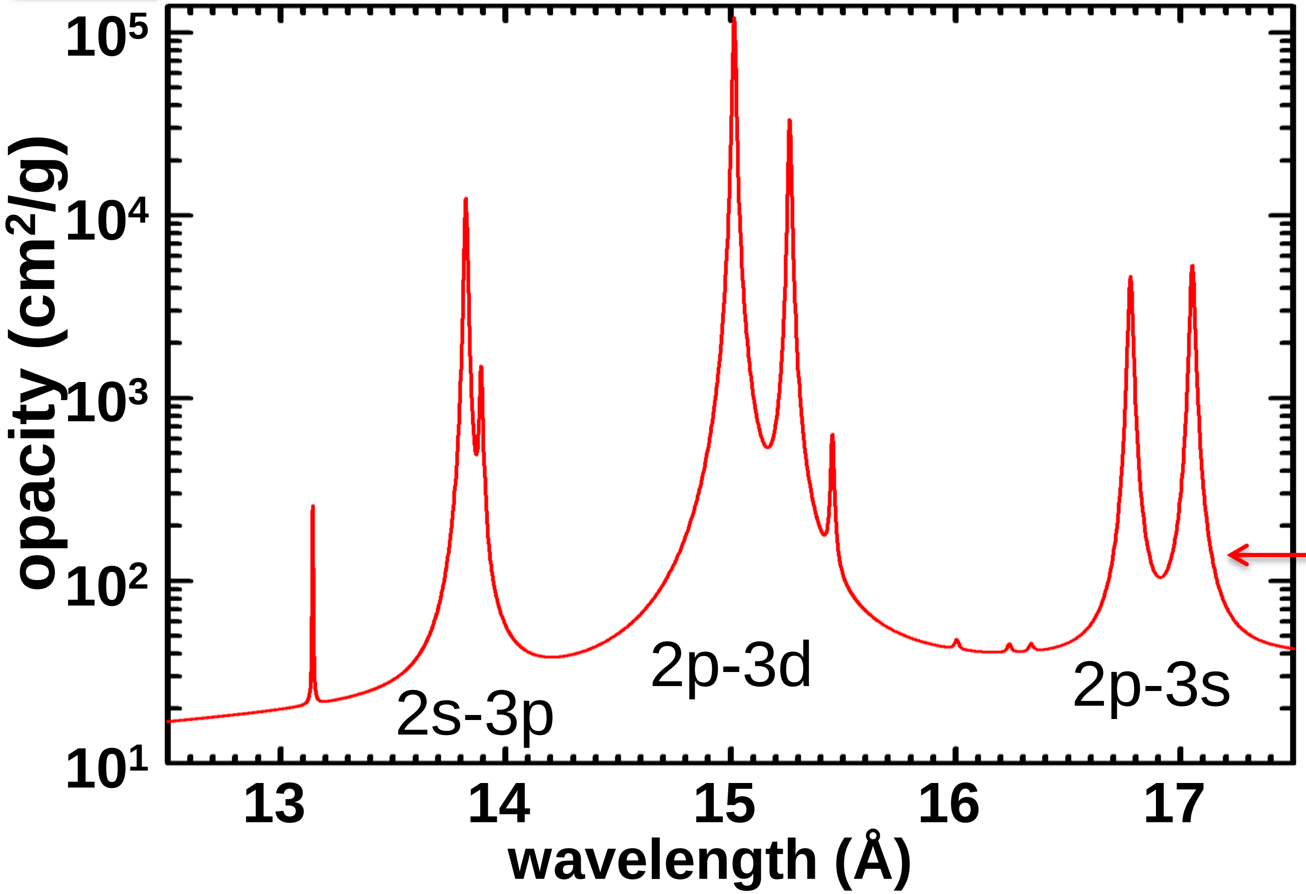
Iron charge states with L-shell vacancies exist throughout most of the solar radiation zone



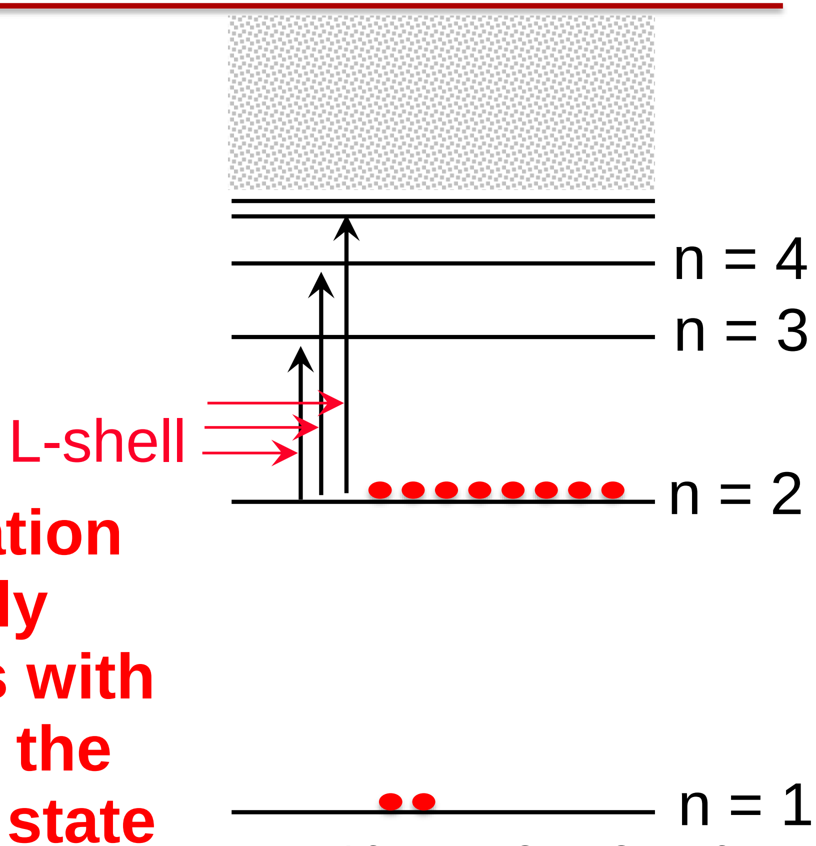
Opacity depends on the ionization state because it controls the possible bound-bound and bound-free absorption

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

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

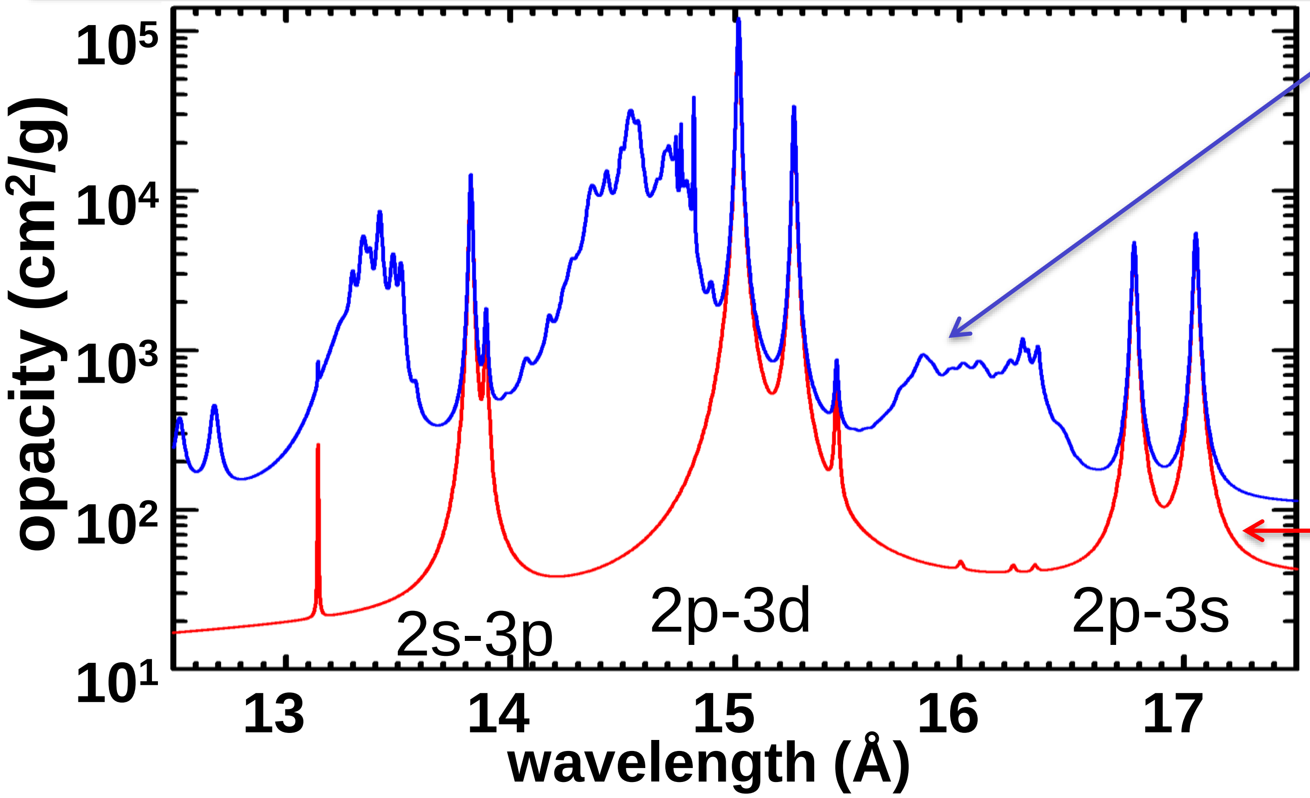


Fe $^{+16}$: $1s^2 2s^2 2p^6$

Ne-like

PrismSPECT
Ne-like iron
solar CZB

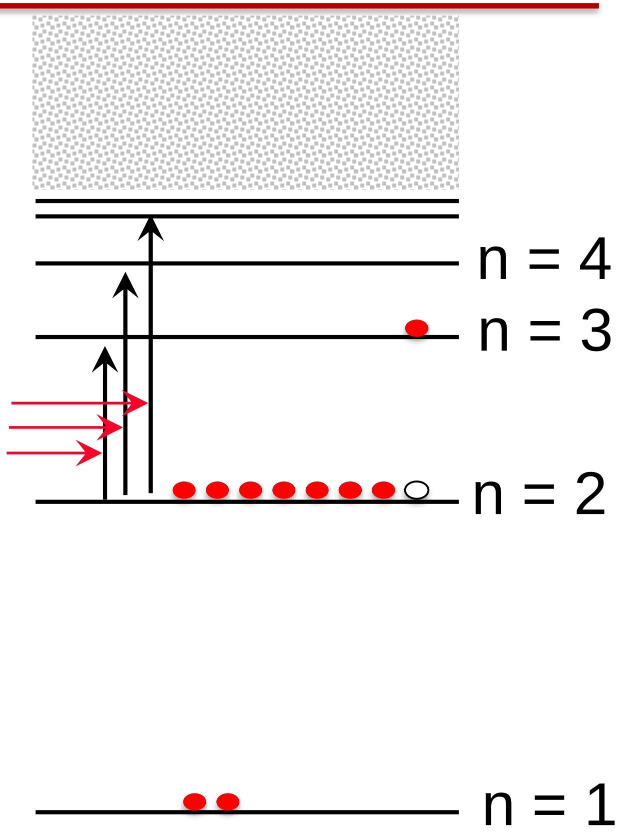
Excitations produce vacancies in the L-shell, adding complexity to Ne-like iron opacity



This calculation includes initial states with excited electrons

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

L-shell



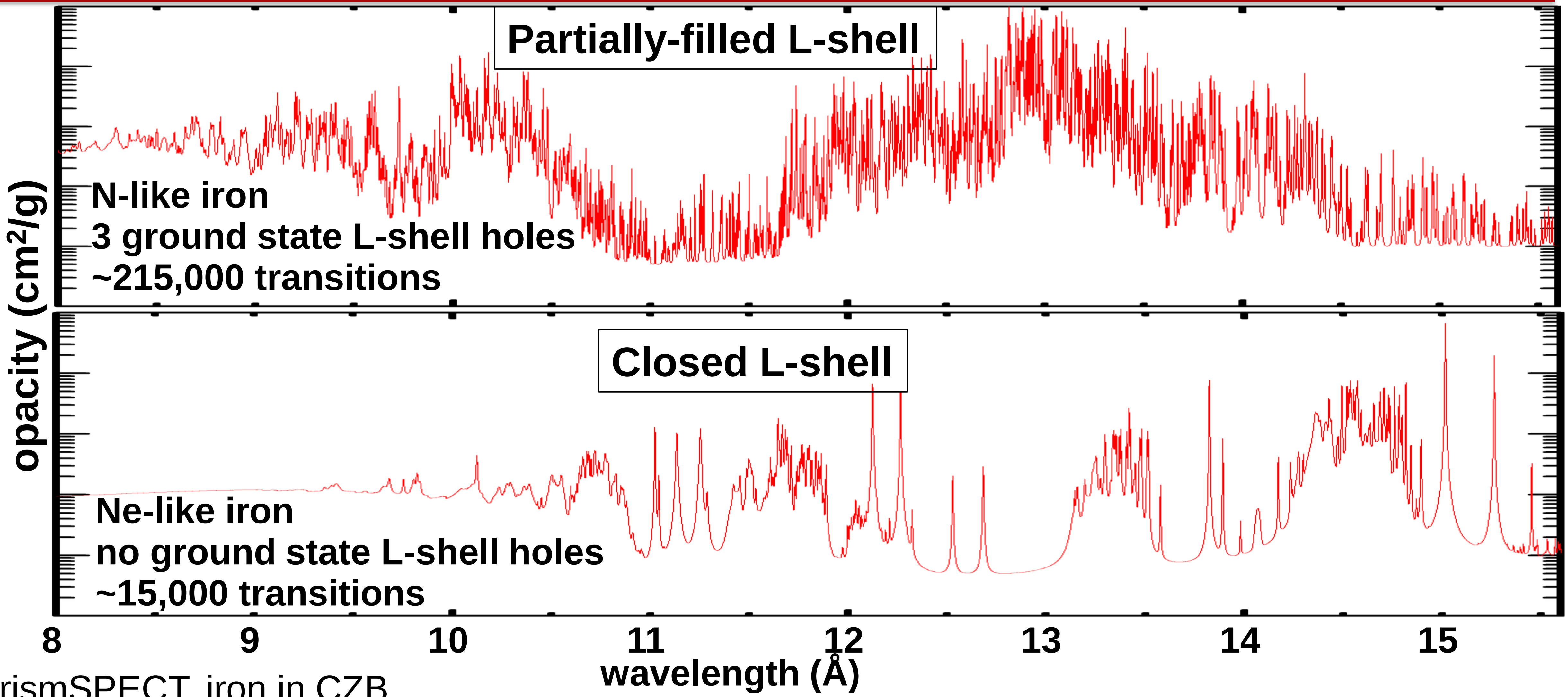
Fe^{+16} : $1s^2 2s^2 2p^6$

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

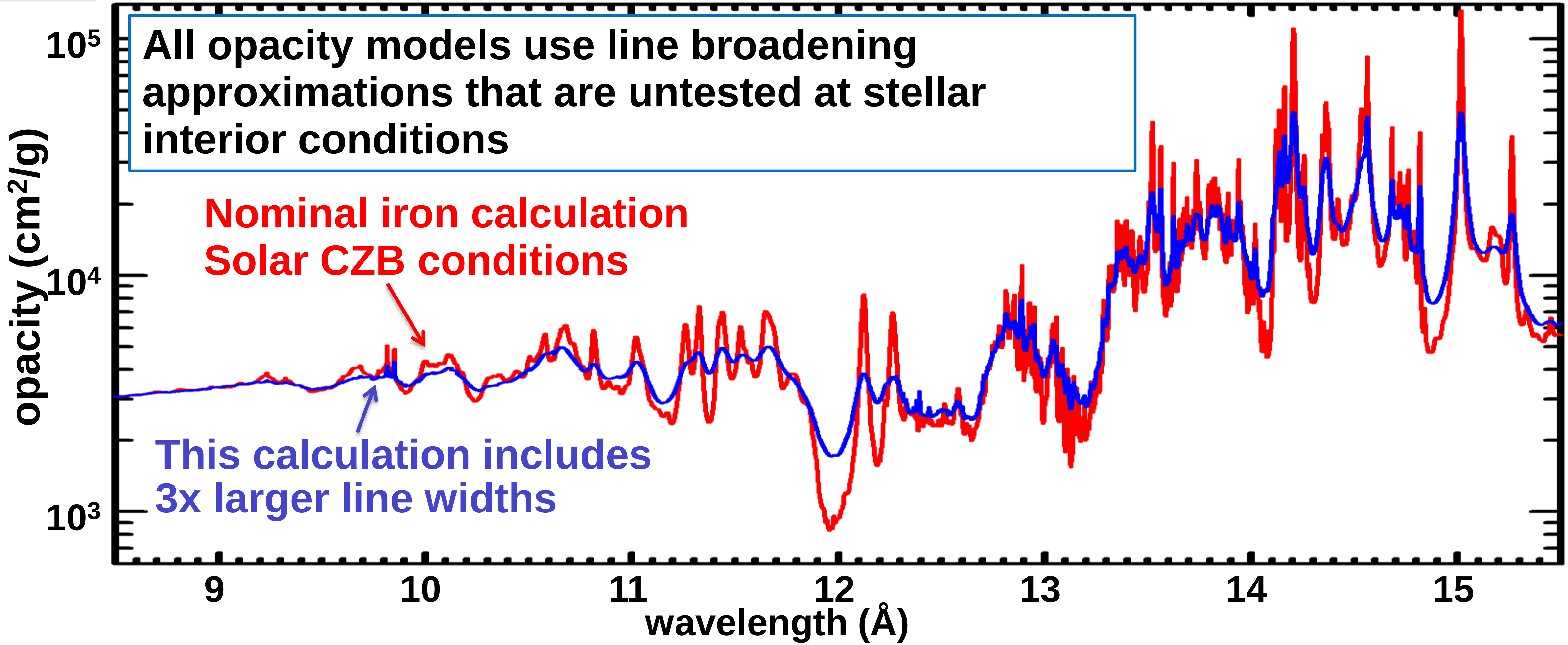
Partially-filled L-shell charge states are more complex because the number of angular momentum combinations increases



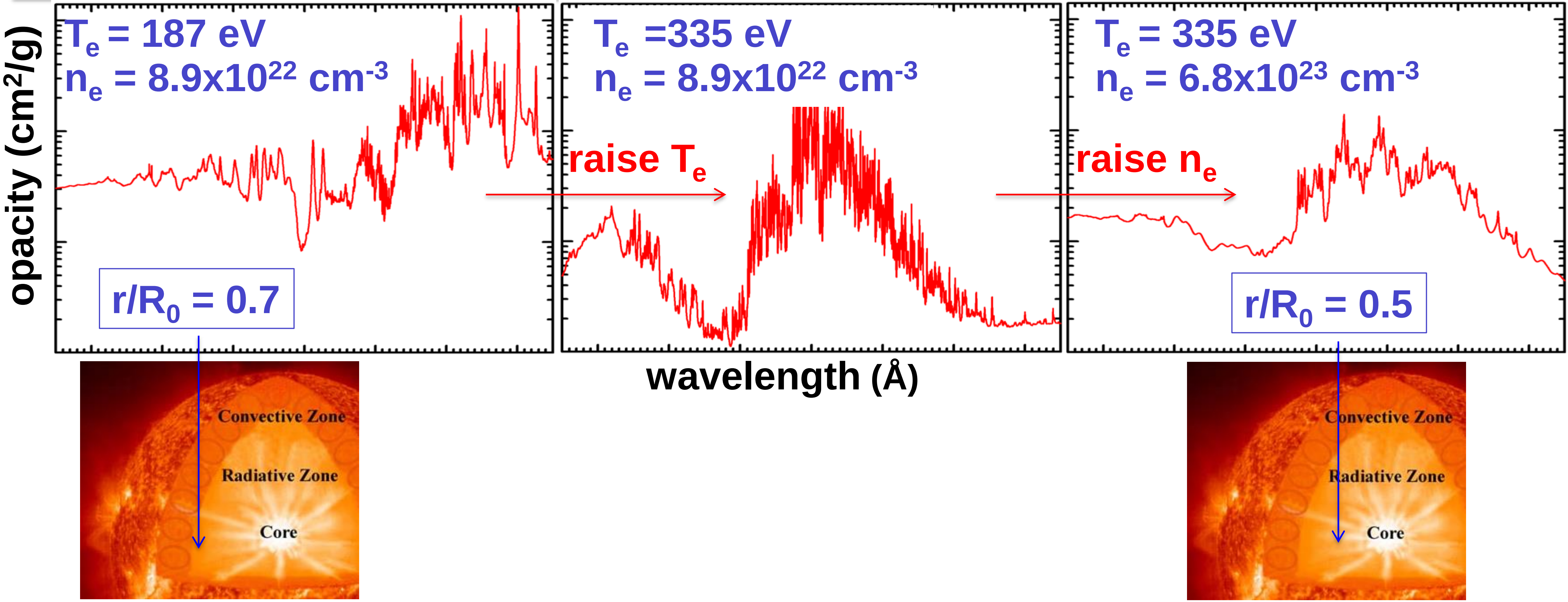
PrismSPECT, iron in CZB

These calculations used reduced line broadening to limit line blending

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

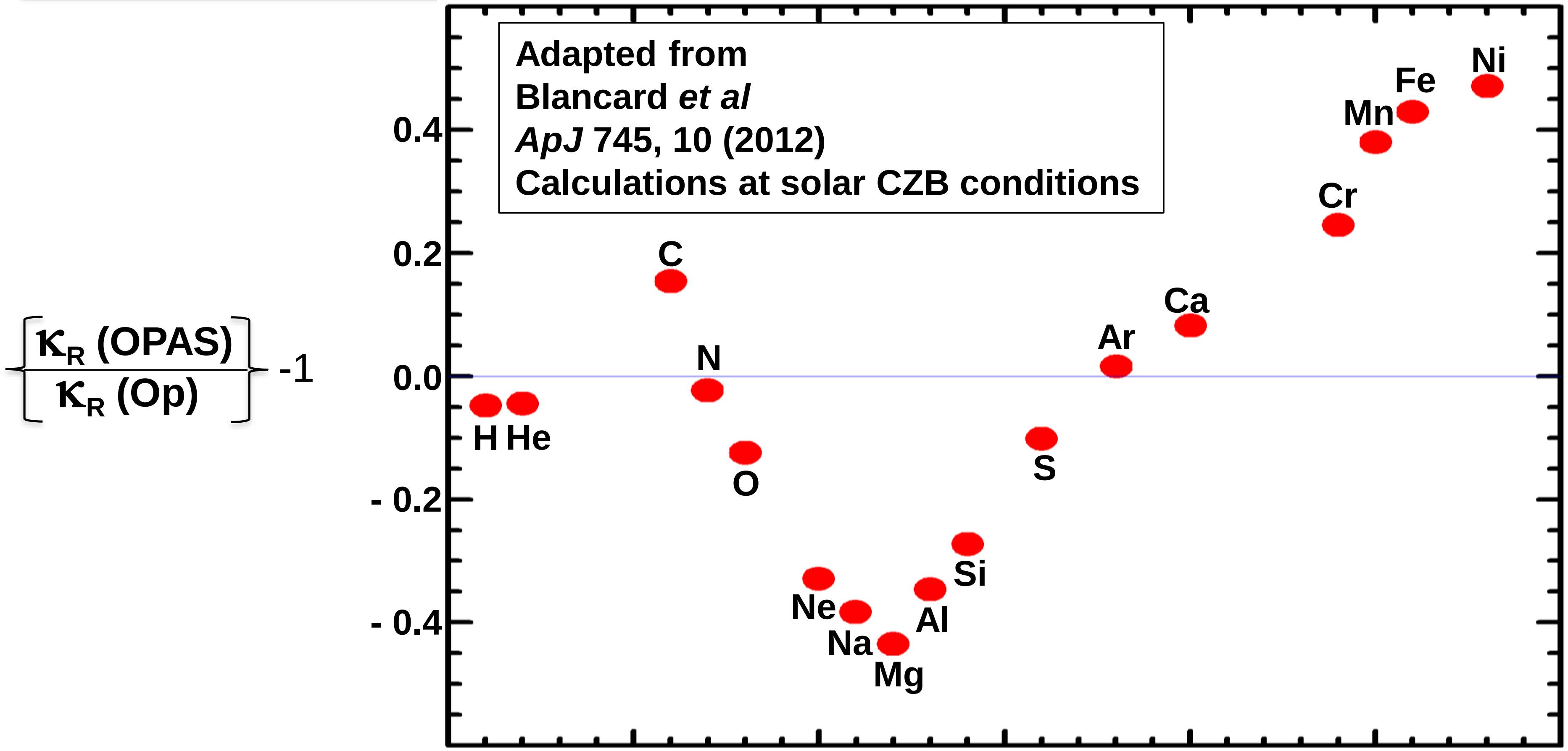


Complexity grows deeper in the sun as the solar interior temperature and density increase



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

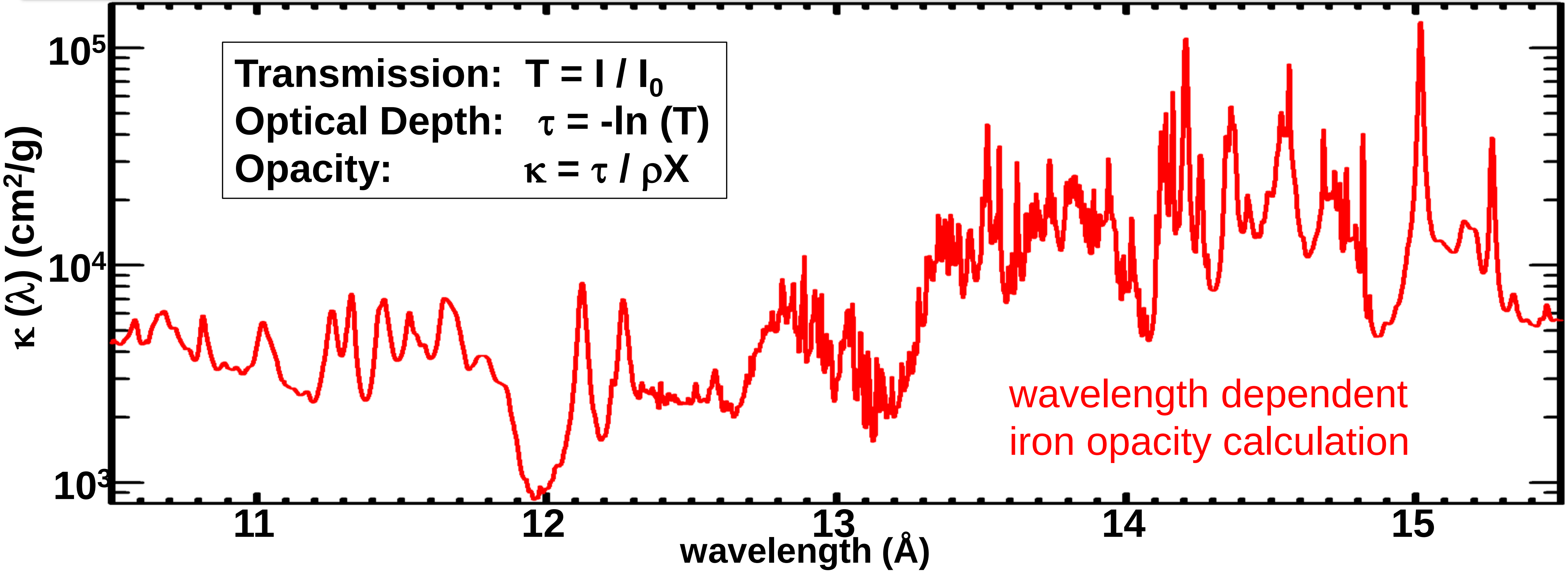
Complexities create uncertainties in opacity models that are best to address by comparison with experiments



Rosseland mean opacity predictions from OPAS and OP differ by up to ~45% for individual elements

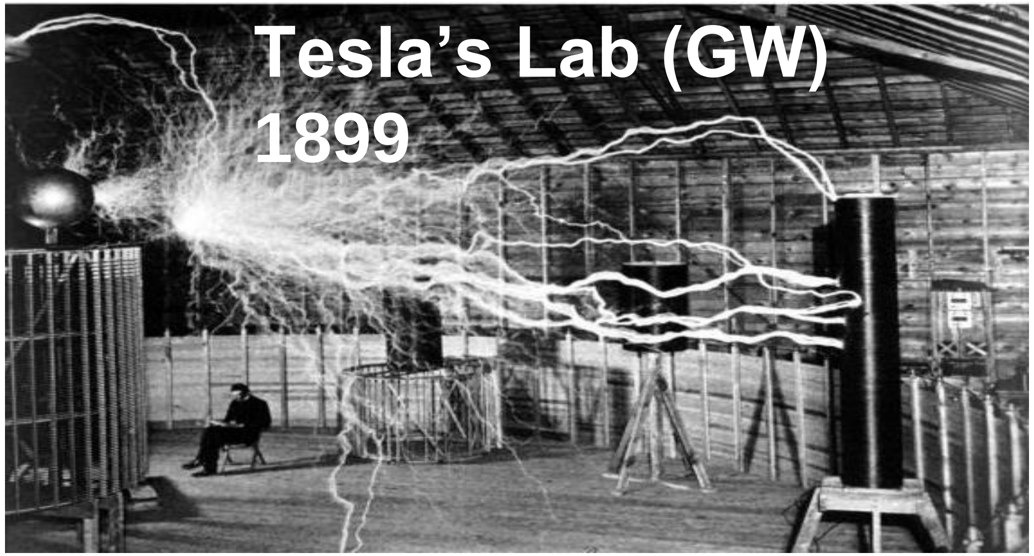
The agreement for the solar mixture κ_R may be partly coincidence

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.

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

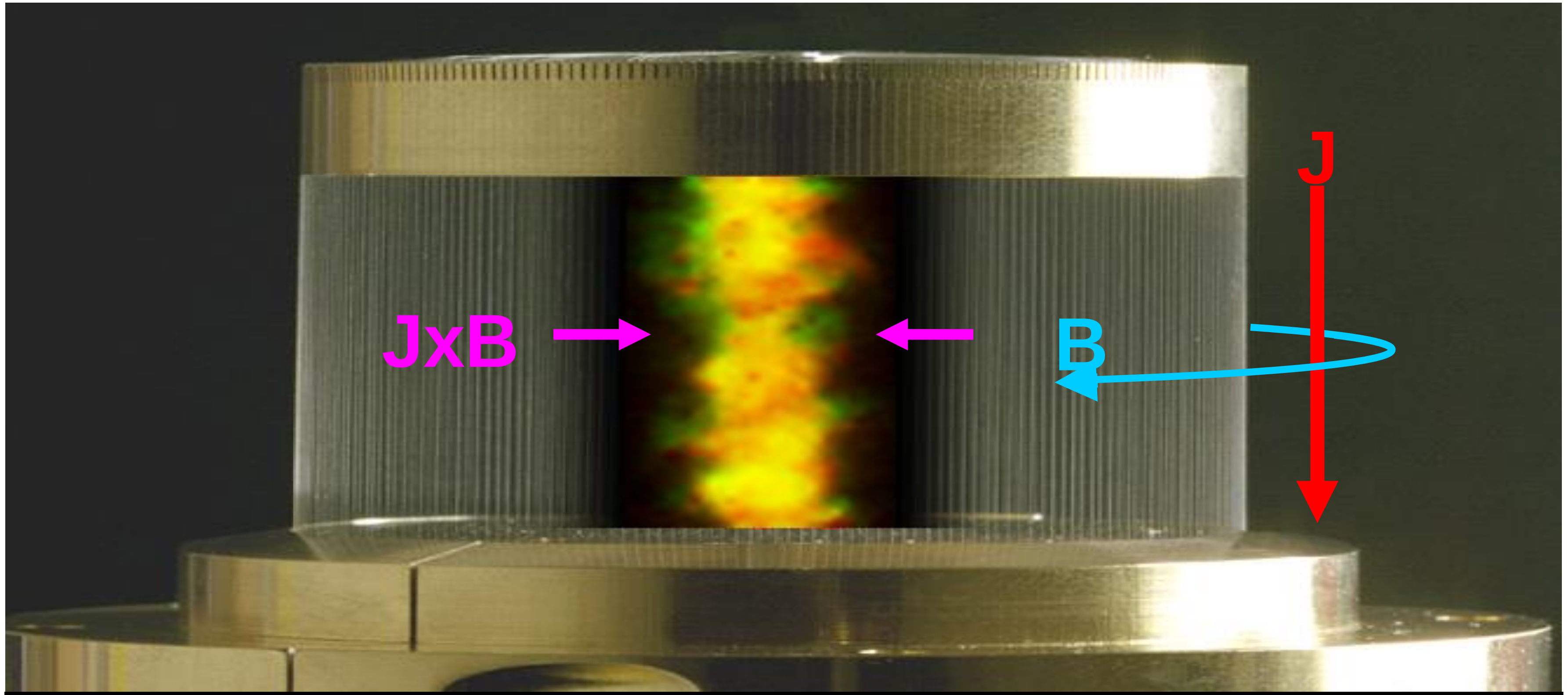


Pulsed power has been developed over the last century

<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)"

The Z machine uses 27 million Amperes to create x-rays

4cm



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

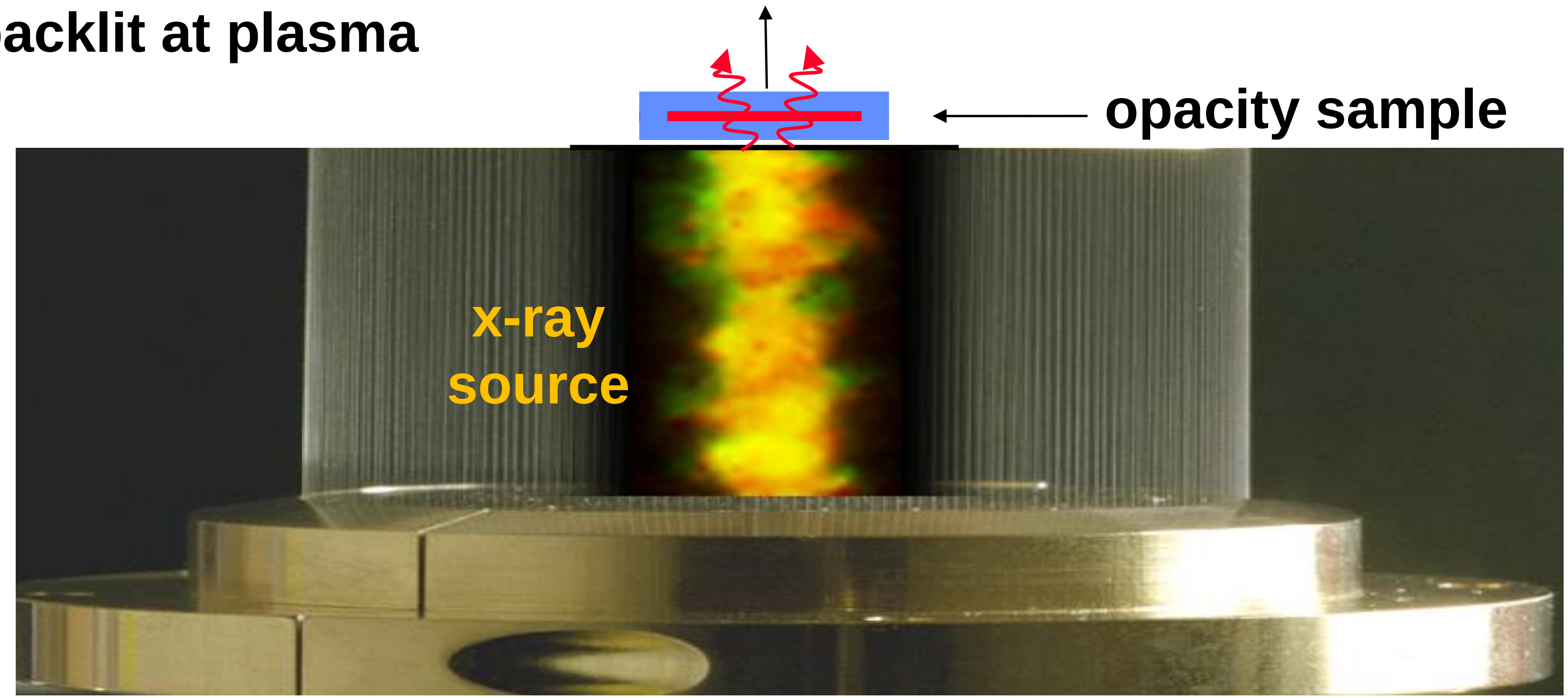
Sanford, PoP (2002); Bailey et al,PoP (2006); Slutz et al., PoP (2006); Rochau et al., PPCF(2007)

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

Sample is heated during plasma implosion

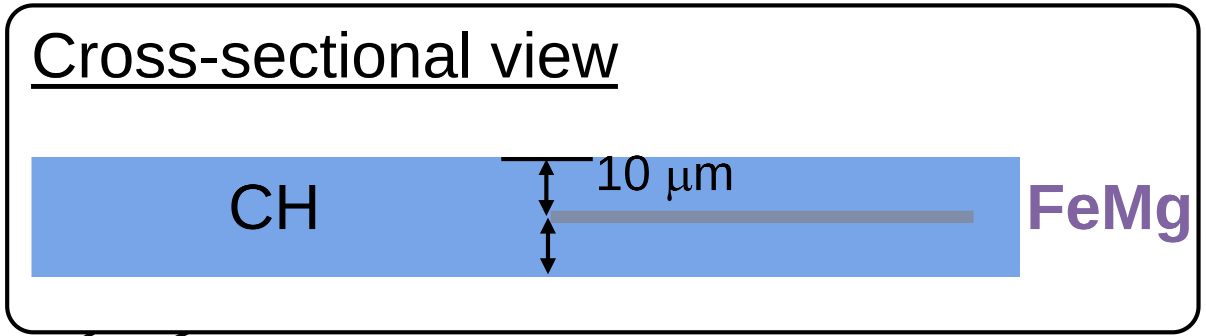
Sample is backlit at plasma stagnation

spectrometers

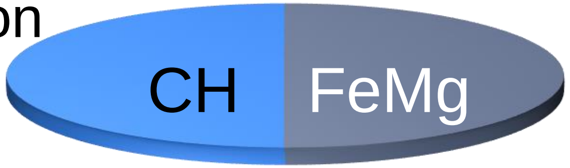


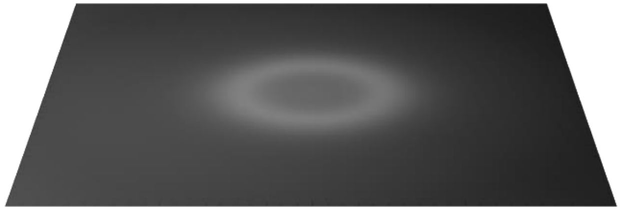
opacity sample

Z opacity science configuration satisfies challenging requirements for reliable opacity measurements



Half-moon sample



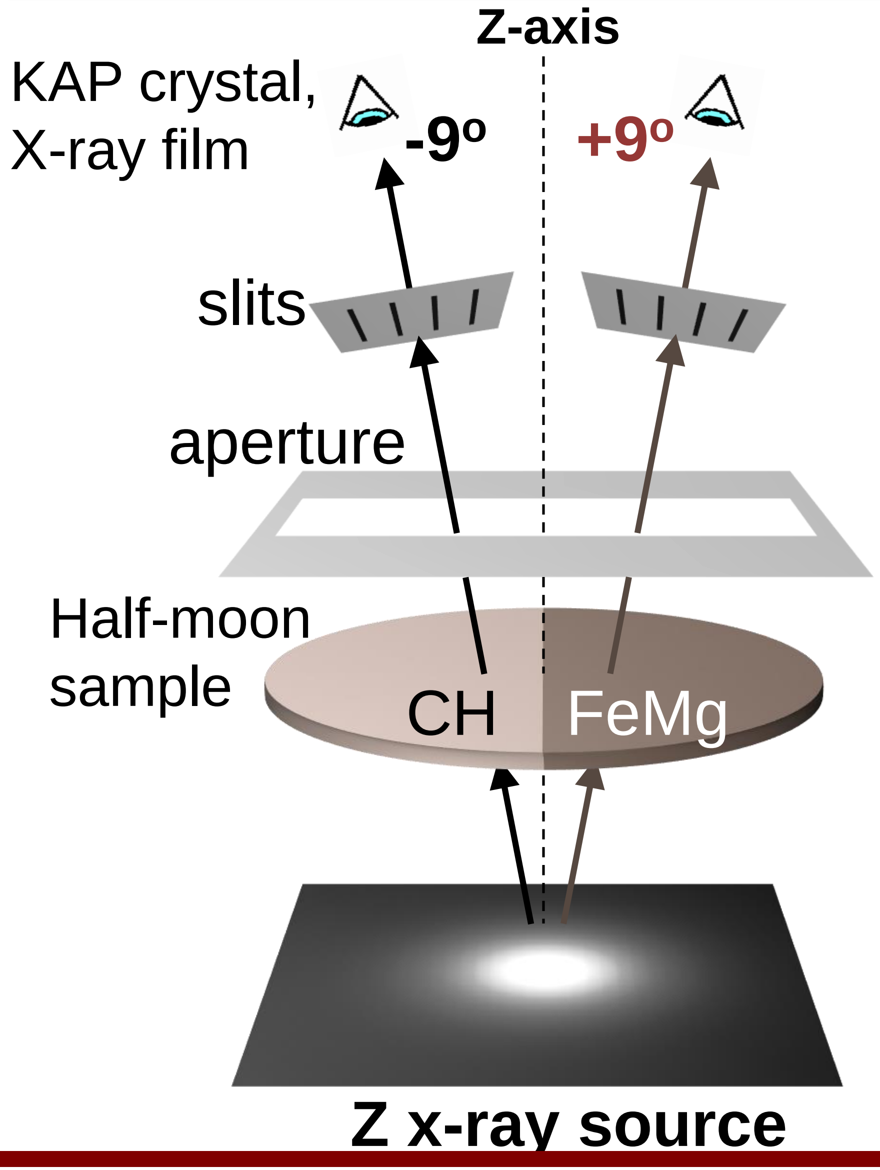


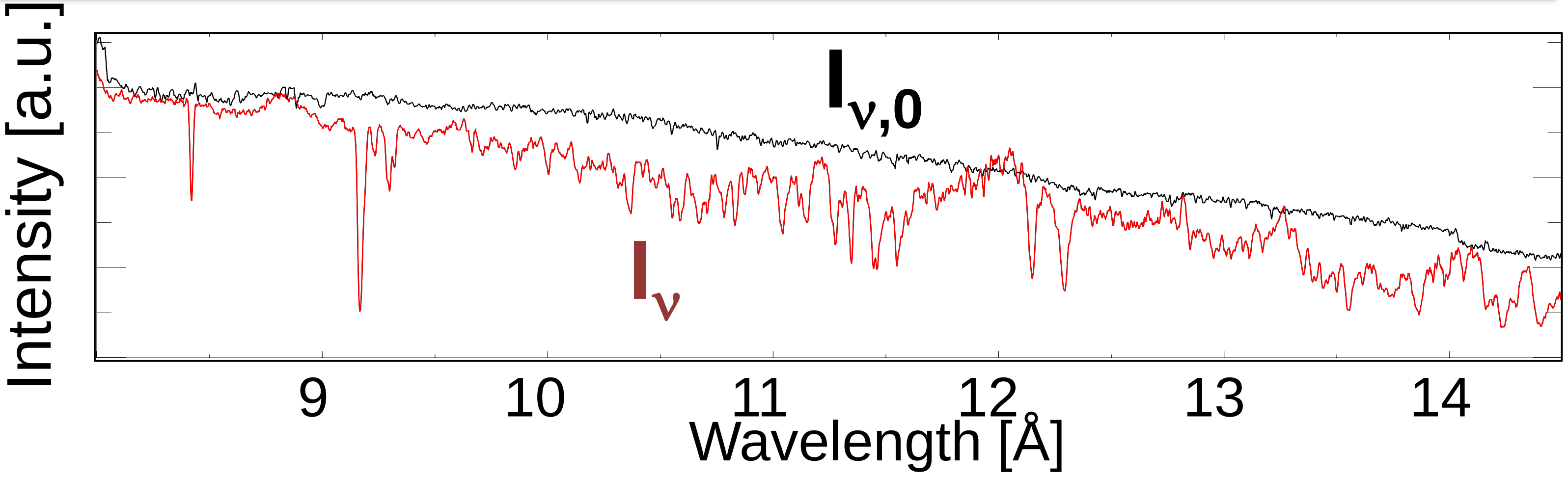
Z x-ray source

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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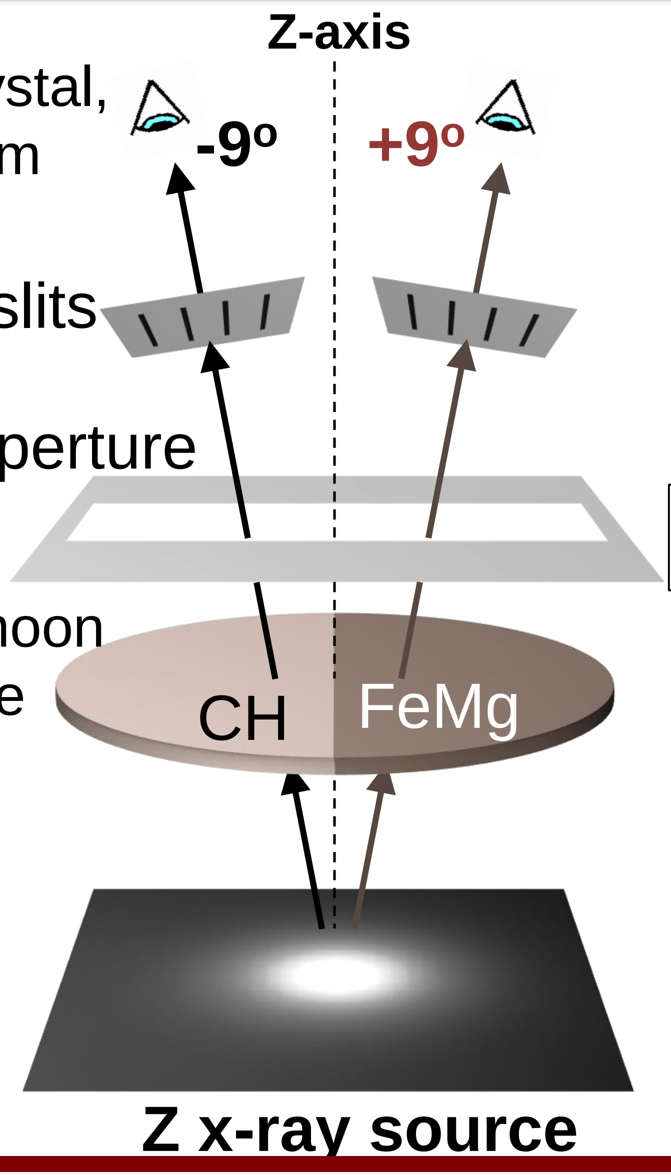

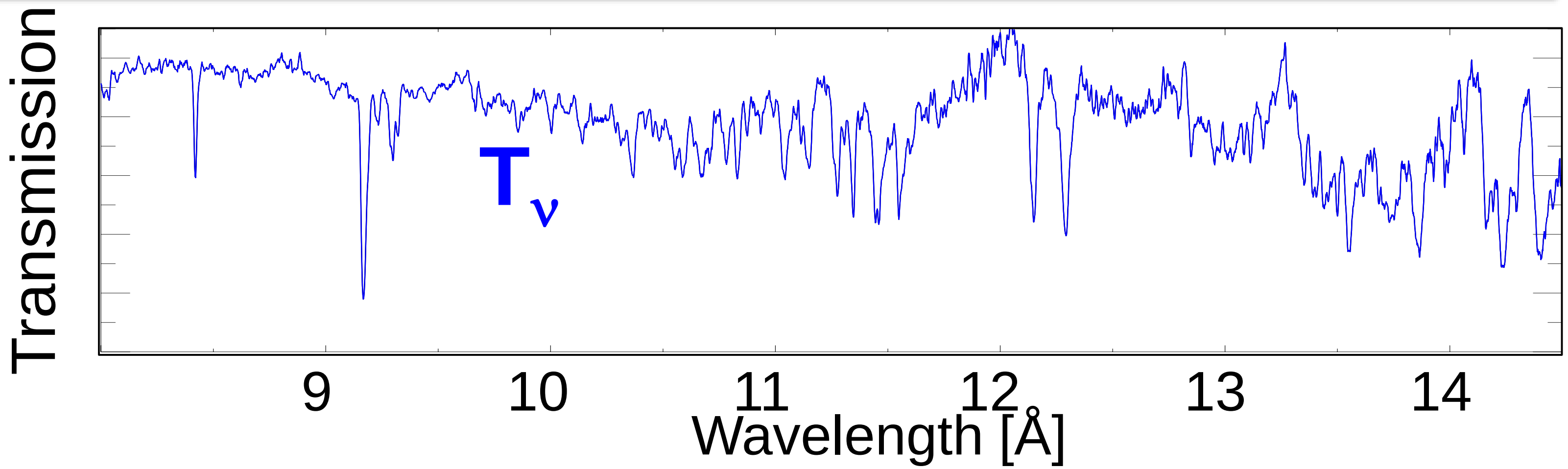

Transmission: $T_\nu = I_\nu / I_{\nu,0}$

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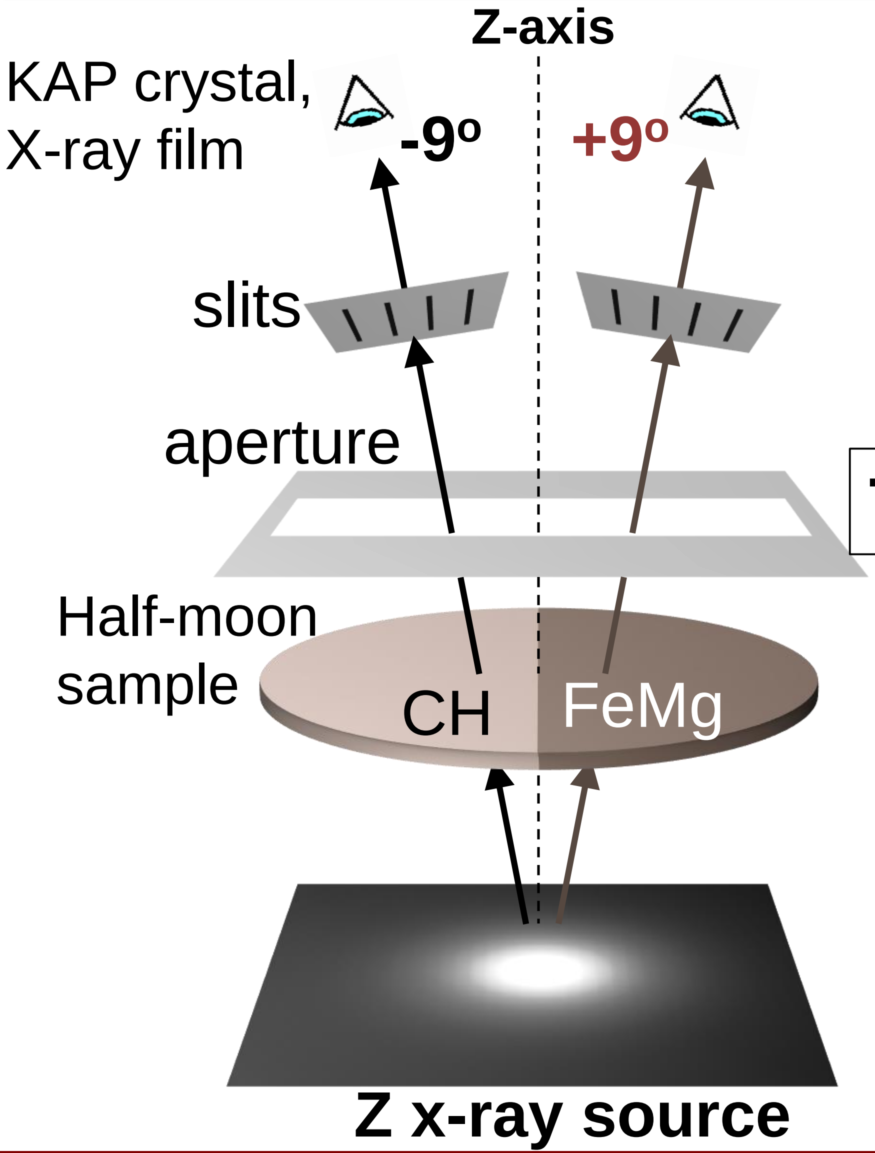

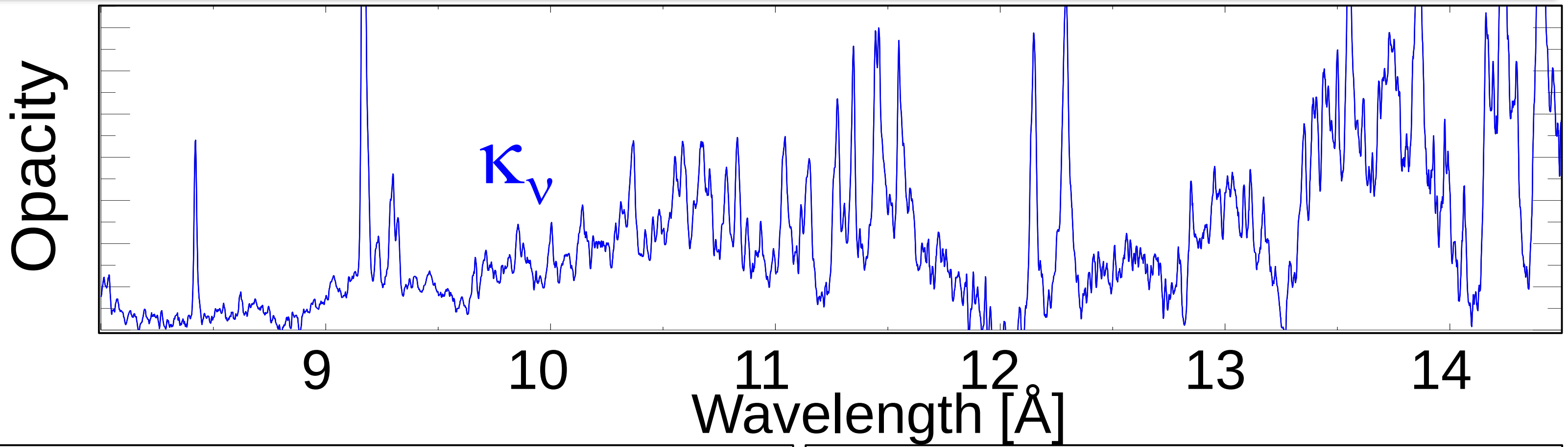

Transmission: $T_\nu = I_\nu / I_{\nu,0}$

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

Requirements:

- Heat Fe to uniform conditions → Powerful radiation
- Measure Fe conditions independently → Mg 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.

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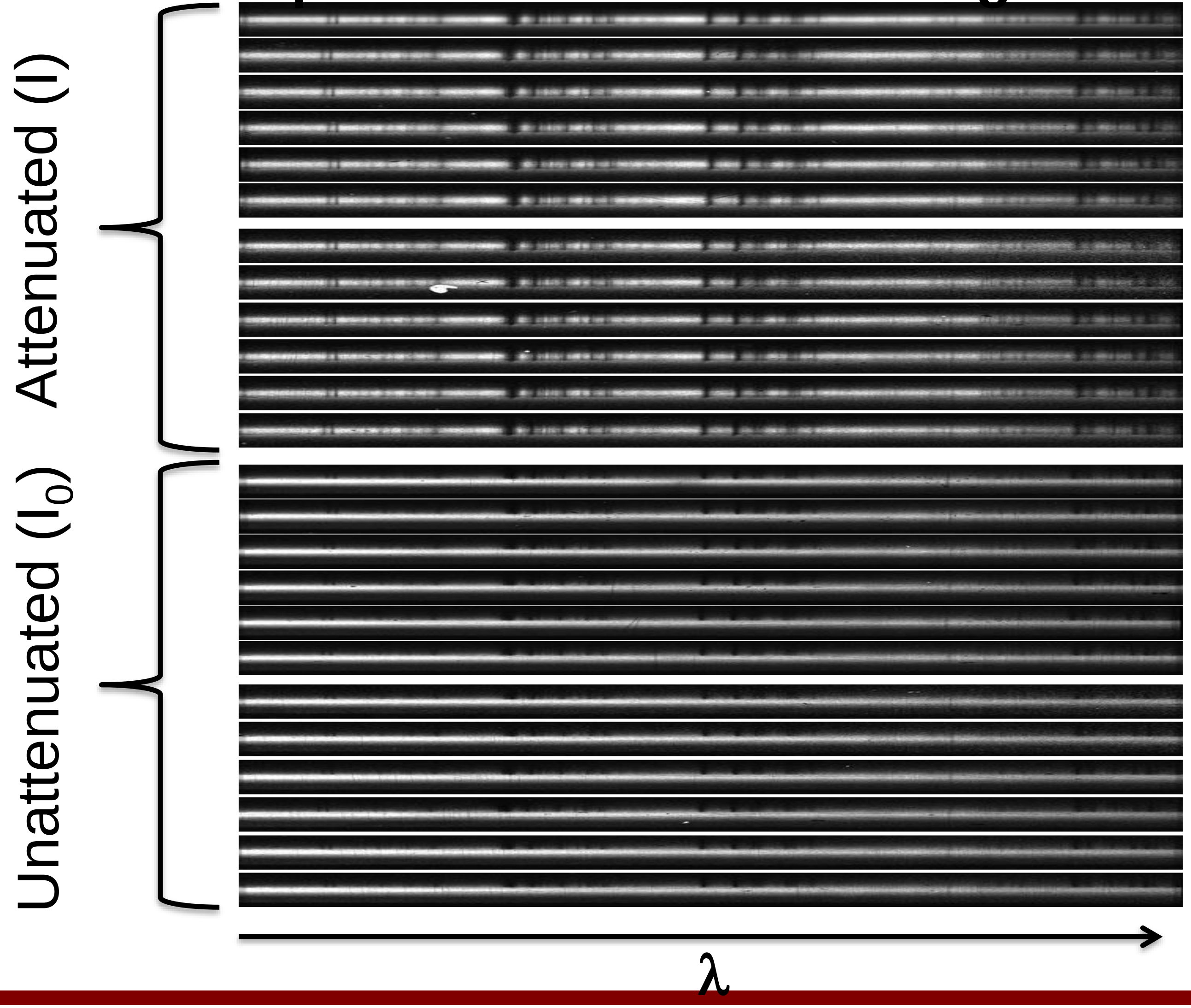
The array of opacity spectrometers is lowered into place with a 20 ton crane

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

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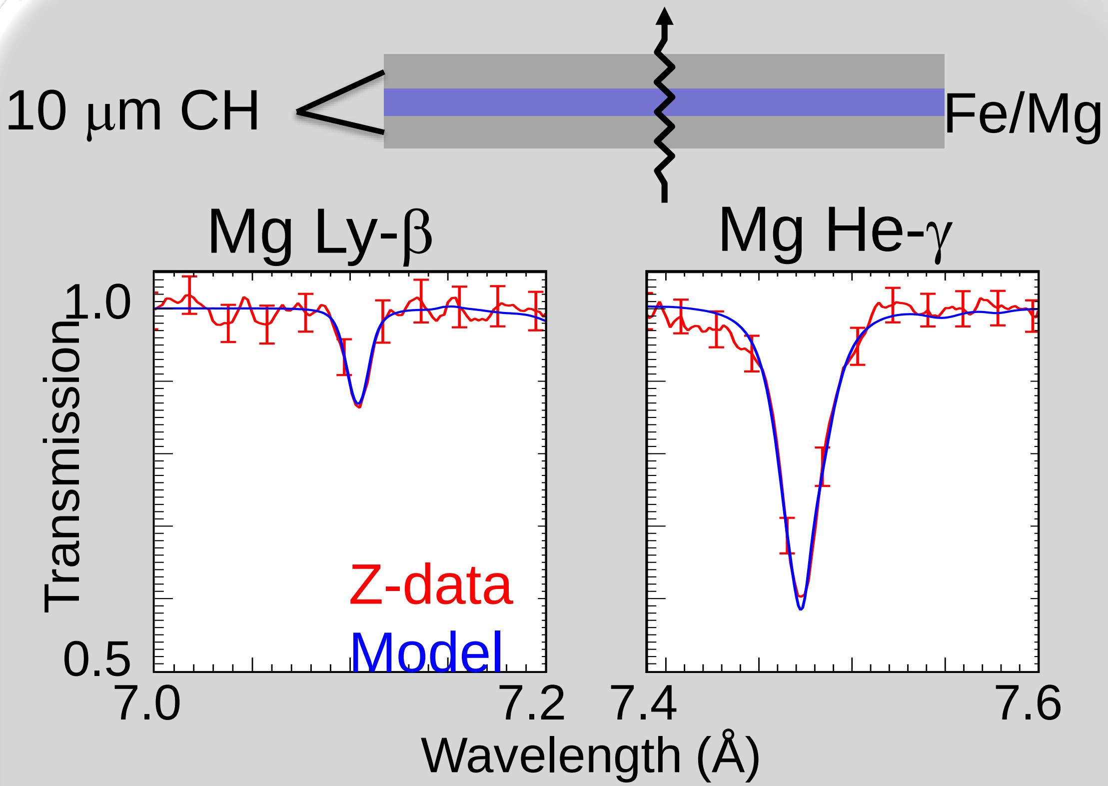
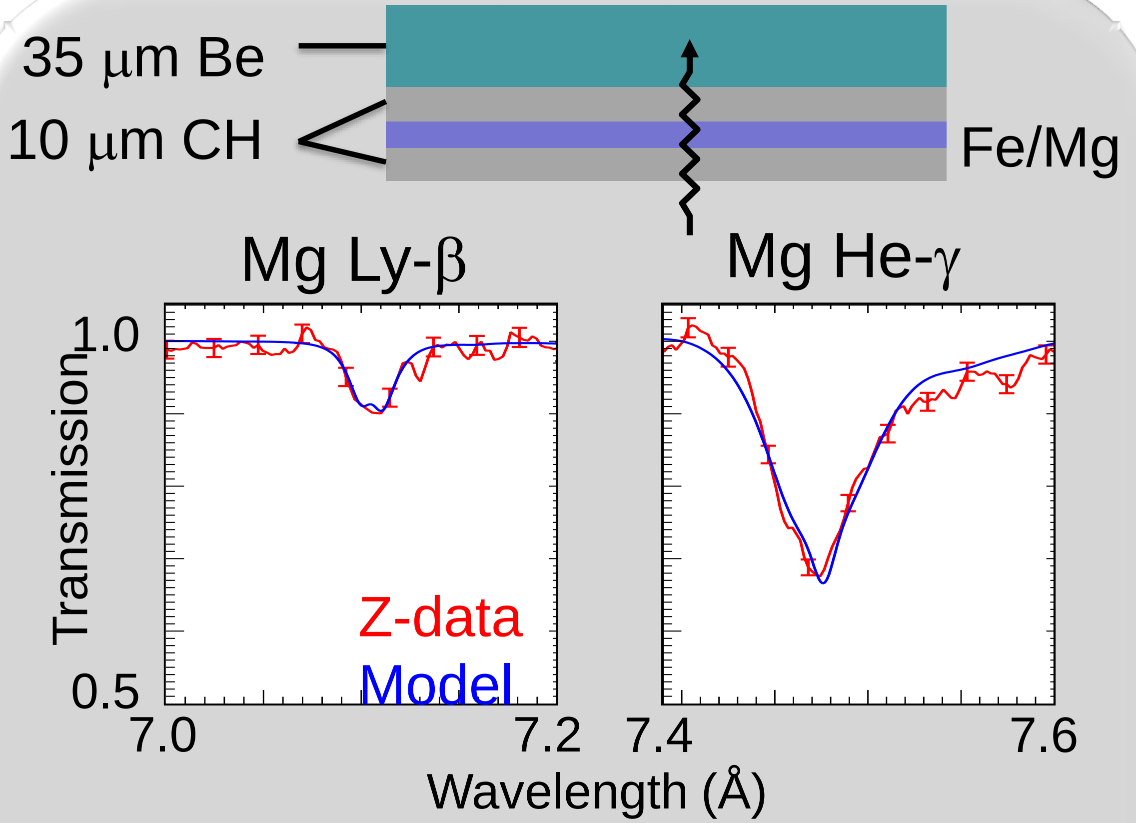
Anchor 1



$T_e = 156 \pm 6$ eV

$n_e = 6.9 \pm 1.7 \times 10^{21}$ cm^{-3}

Anchor 2

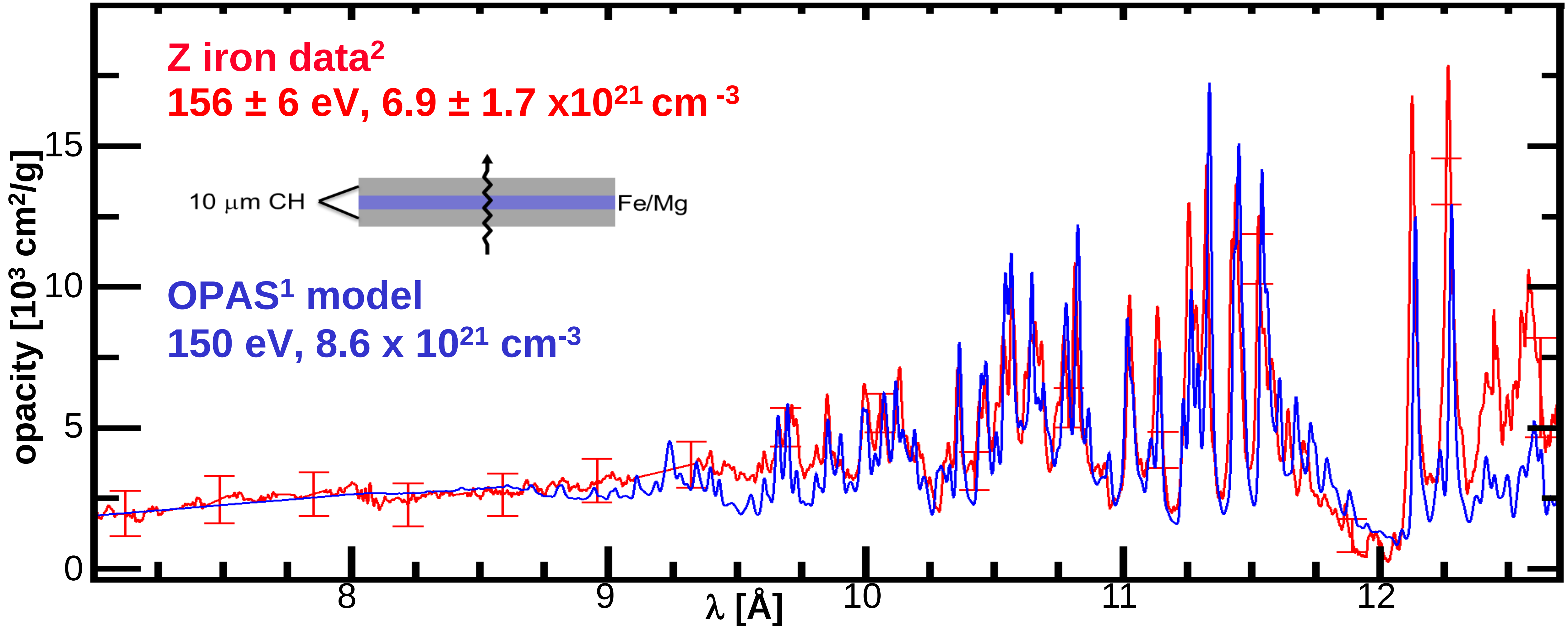


$T_e = 182 \pm 3$ eV

$n_e = 31. \pm 3. \times 10^{21}$ cm^{-3}

Nagayama *et al.* Phys.Plasmas 2014

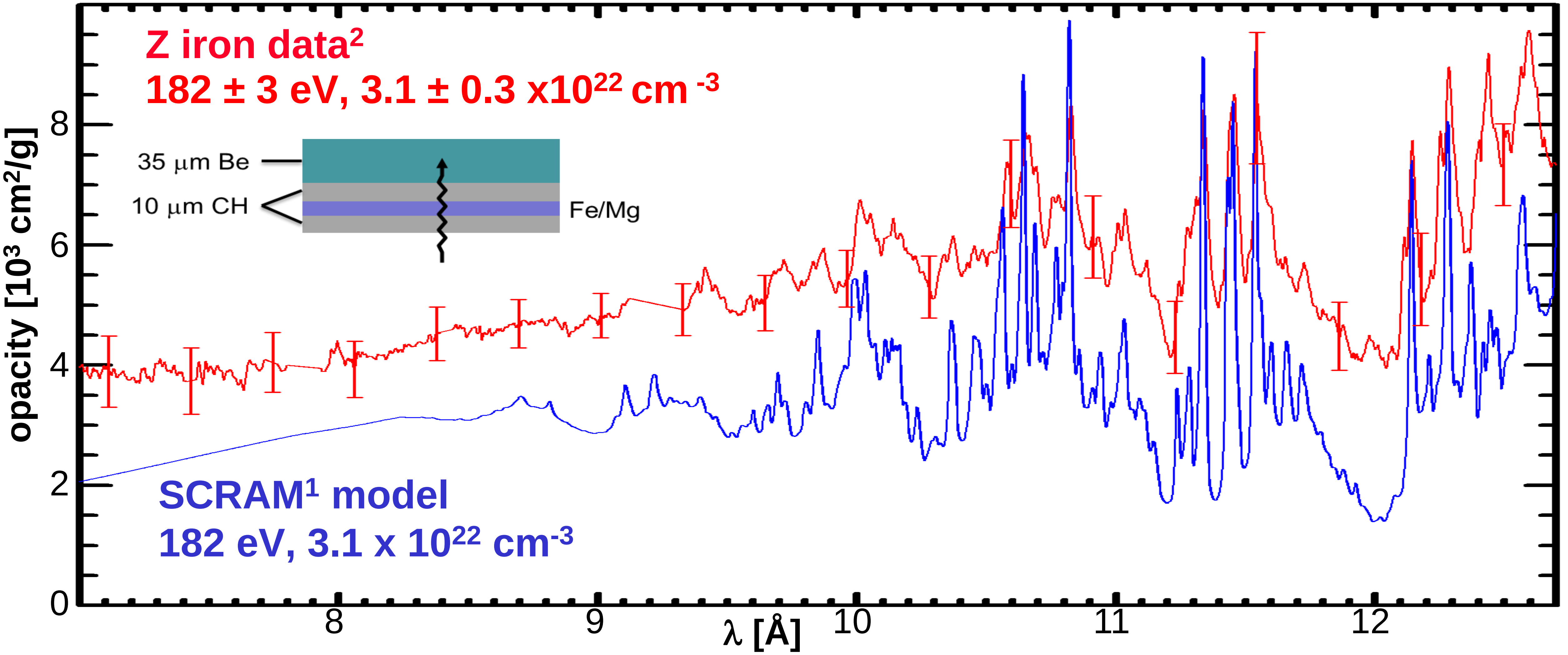
Modern best-effort models agree very well with the Z iron data at Anchor 1 conditions



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

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

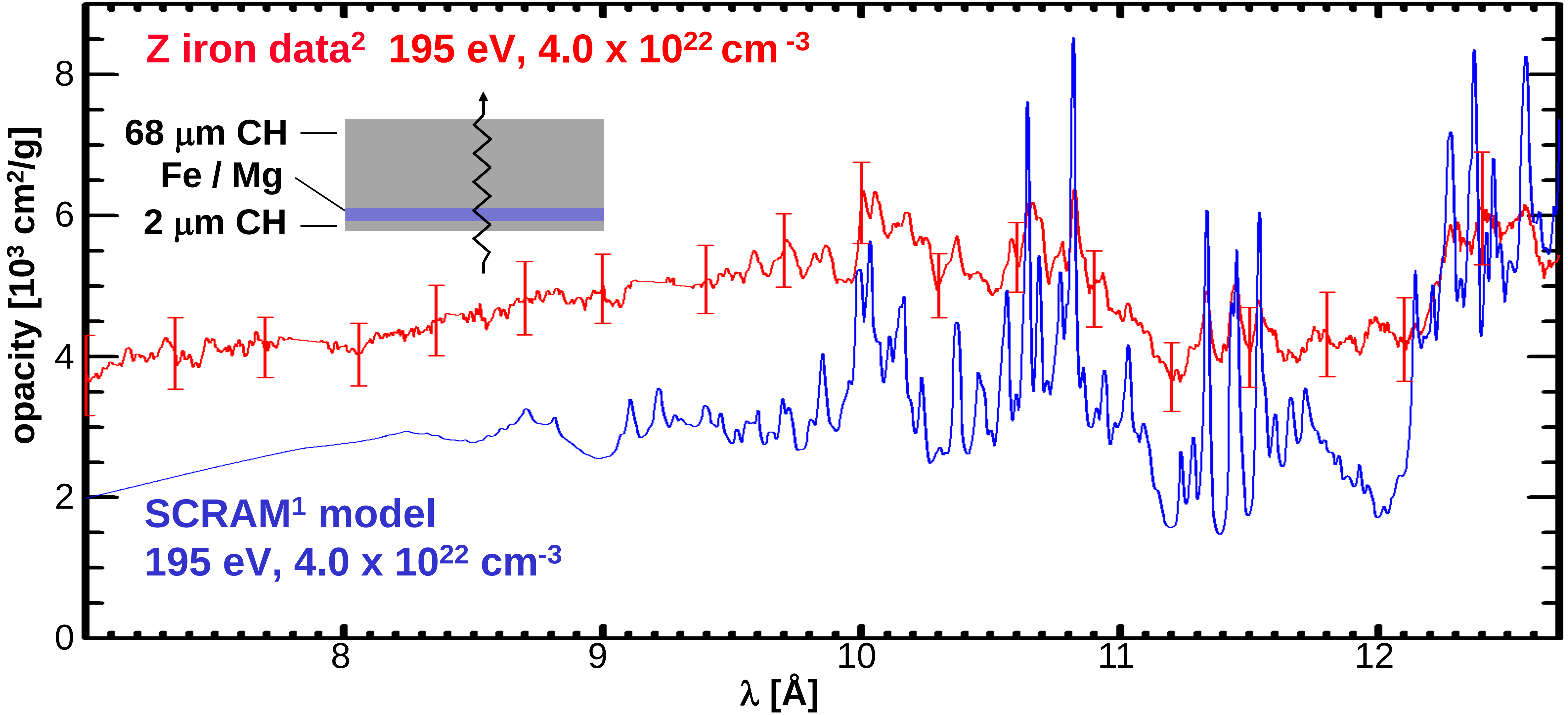
Modern best-effort models disagree with the Z iron data at Anchor 2 conditions



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

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

Modern best-effort models also disagree with the Z iron data at the highest temperature/density conditions



[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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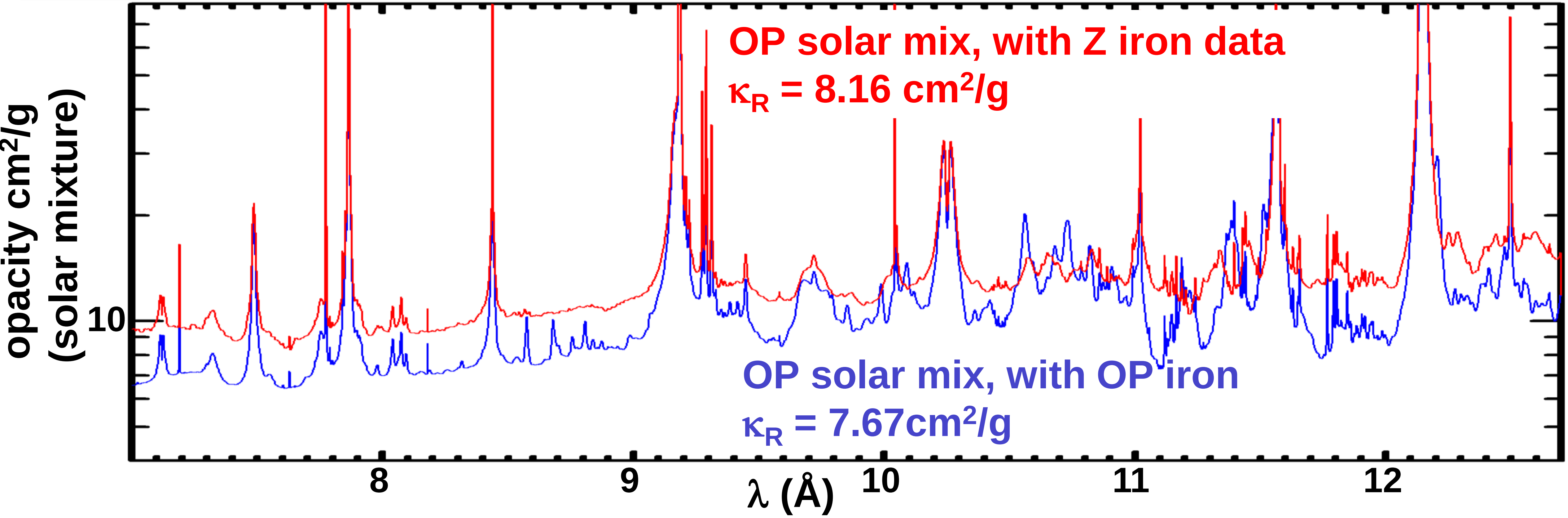


- **A 7% Rosseland increase partially resolves the solar problem, but the measured iron opacity by itself cannot account for the entire discrepancy**
- **Other elements and regions deeper in the sun could contribute**

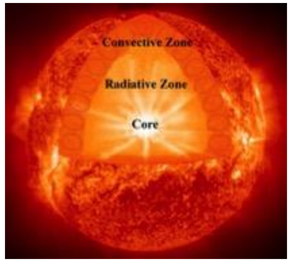
193 eV, 3.3 e22 e/cc Asplund09 solar abundances **Badnell *et al.*, MNRAS 2005**

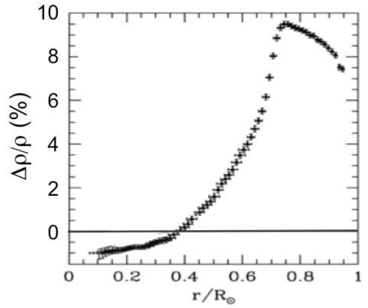
Calculated Fe opacity at solar interior condition disagrees with data; Various investigations provide clues for the discrepancy

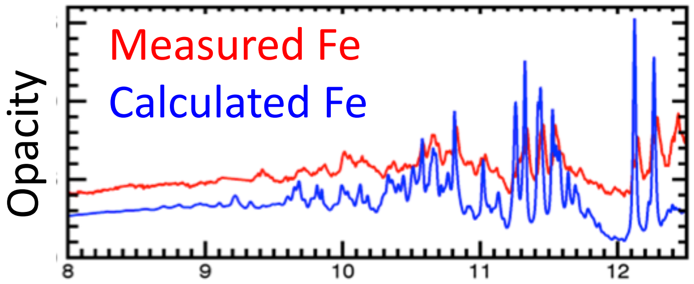
- **We found 30–400% disagreement between modeled and measured Fe opacity at solar interior conditions**

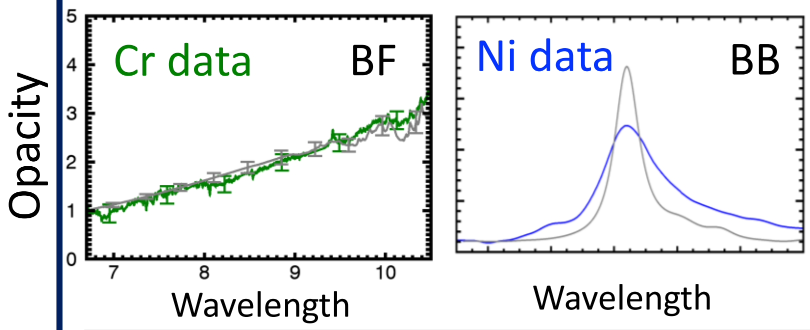
  → Partially resolves solar problem, but the source of discrepancy needs to be identified

- **Various scrutiny narrows down the sources of discrepancy**
  - Scrutiny on Experiments: Experiment accuracy is verified
    - Diagnostic error partially explains peak-to-valley contrast difference
  - More measurements:
    - **Cr, Fe, and Ni opacities measured at multiple electron temperatures (T_e) and electron densities (n_e)**
    - Calculated line-broadening is too narrow
    - Element dependence on bound-free (BF) agreement is puzzling
  - Scrutiny on opacity theory: two-photon opacity may be important









Working towards completing systematic study

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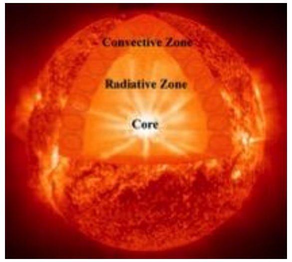

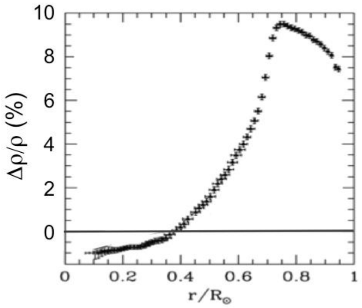

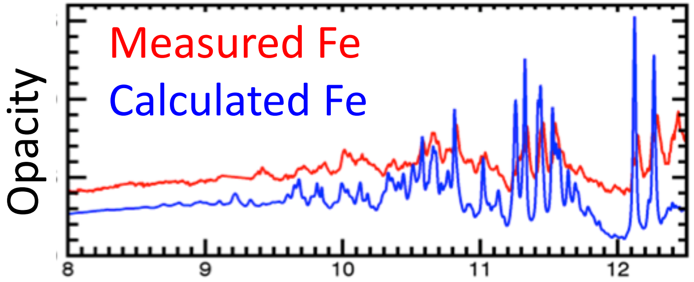

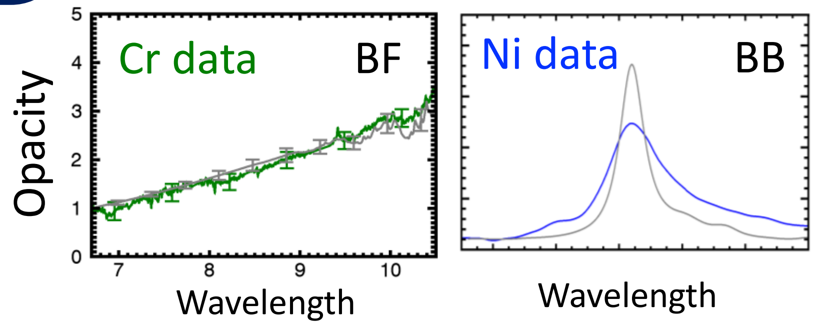

Working towards completing systematic study

Common hypotheses for experimental flaws

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Sample characterization error

- Is Fe areal density accurately known?
- Any contamination?

T_e and n_e diagnostics error

- How large is the diagnostic error?
- How much does it affect?

Data interpretation error

- Followings are considered negligible:
  1. Sample self-emission
  2. Tamper transmission difference
  3. Time- and space-gradient effects
  4. Non-LTE effects
- How important are they?

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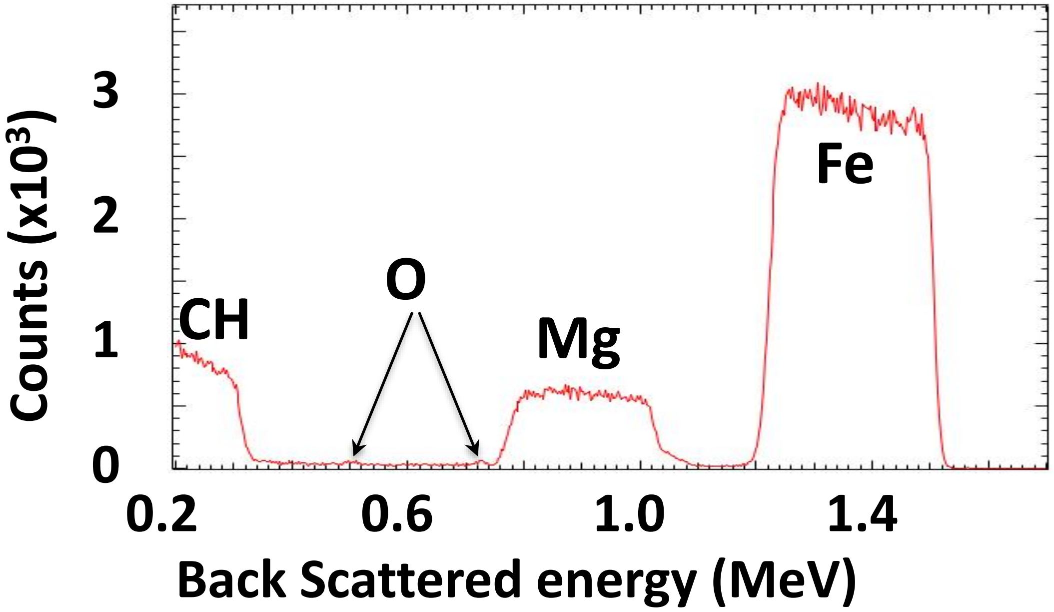
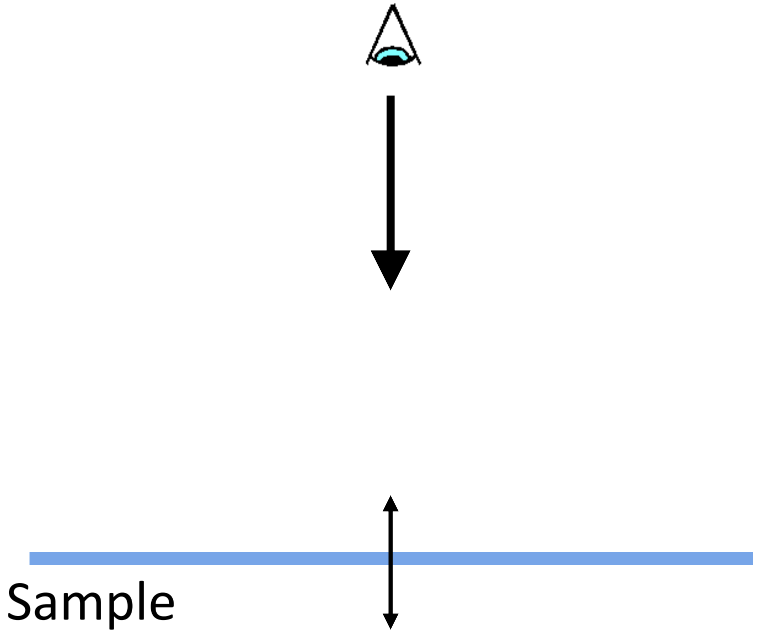
We measure transmission, and accurate areal density is critical to get accurate opacity

$$\kappa_\nu = -\frac{\ln T_\nu}{\rho L}$$

Pre-shot Rutherford backscattered spectrum (RBS)





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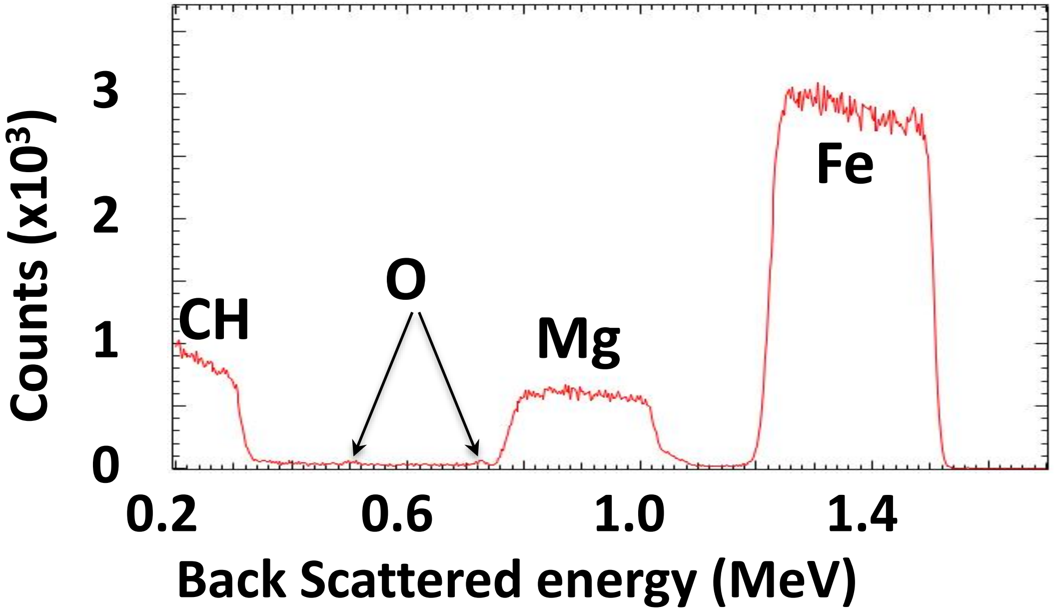

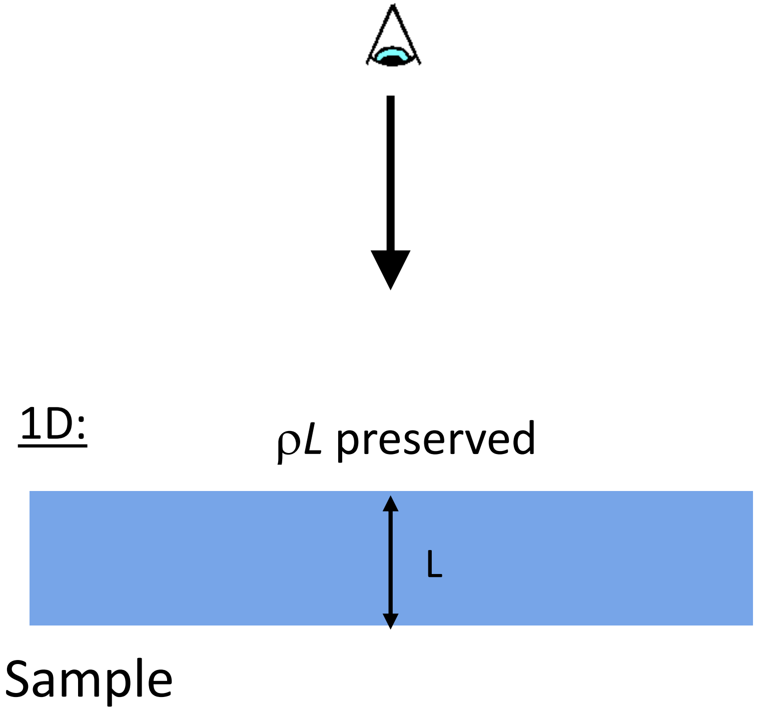

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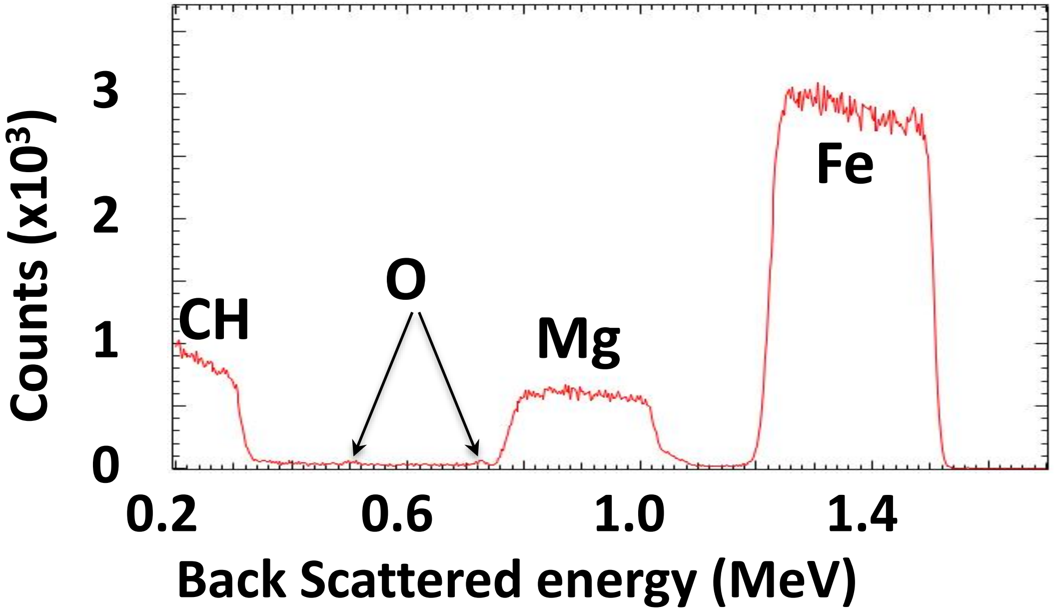

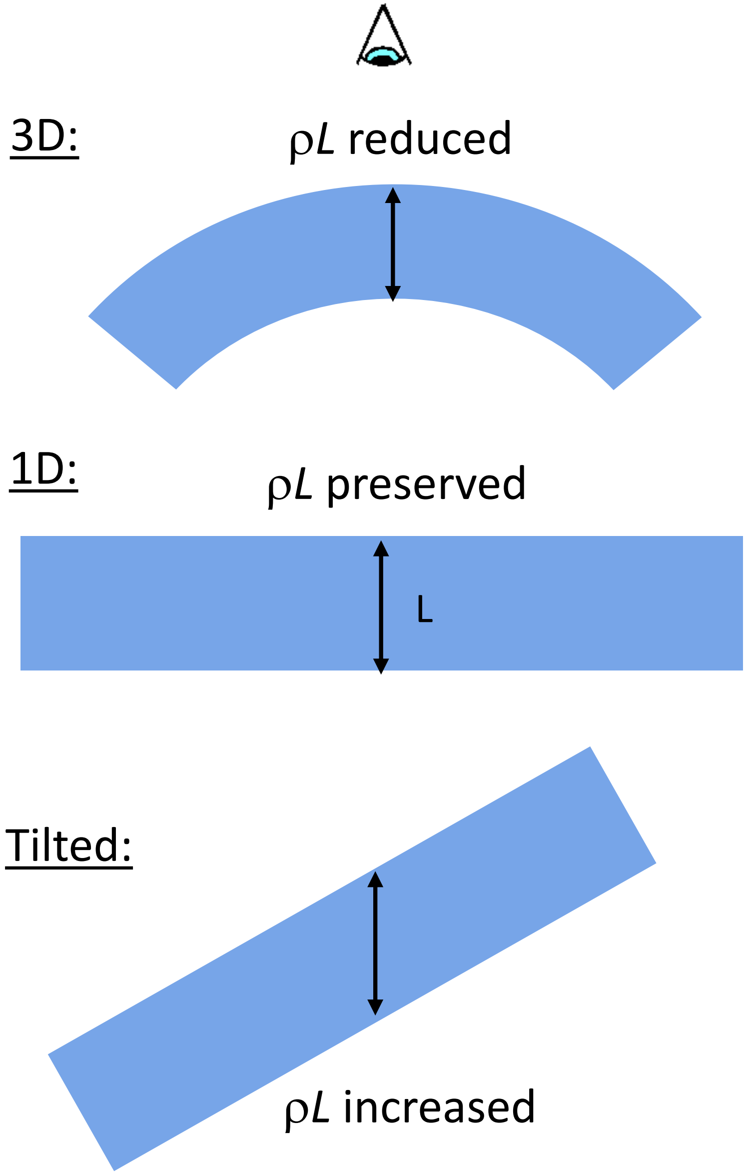

In-situ Mg areal density measurement confirms hydro evolution does not significantly alter the areal density

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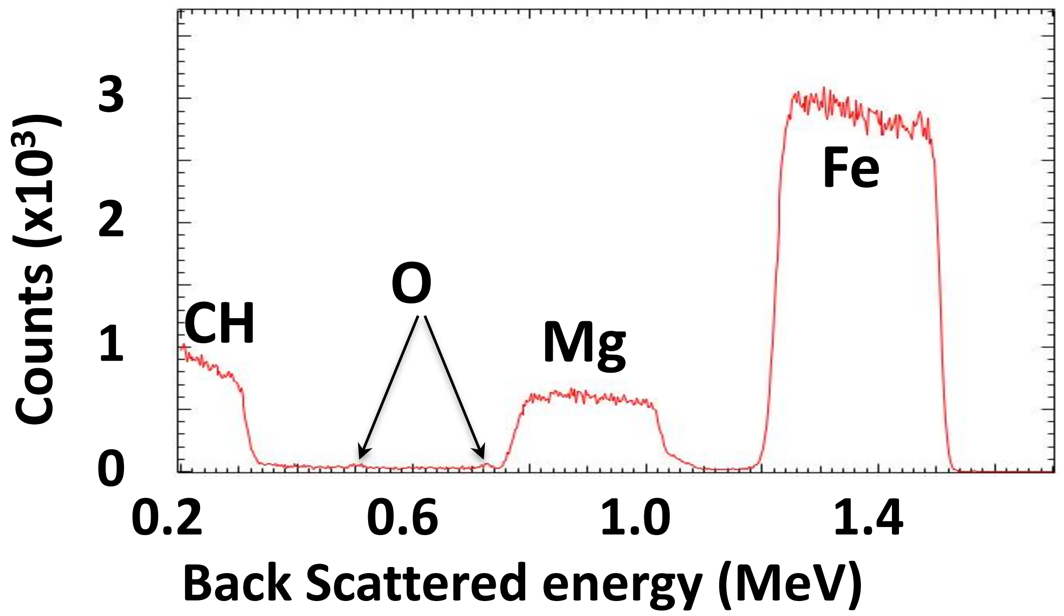
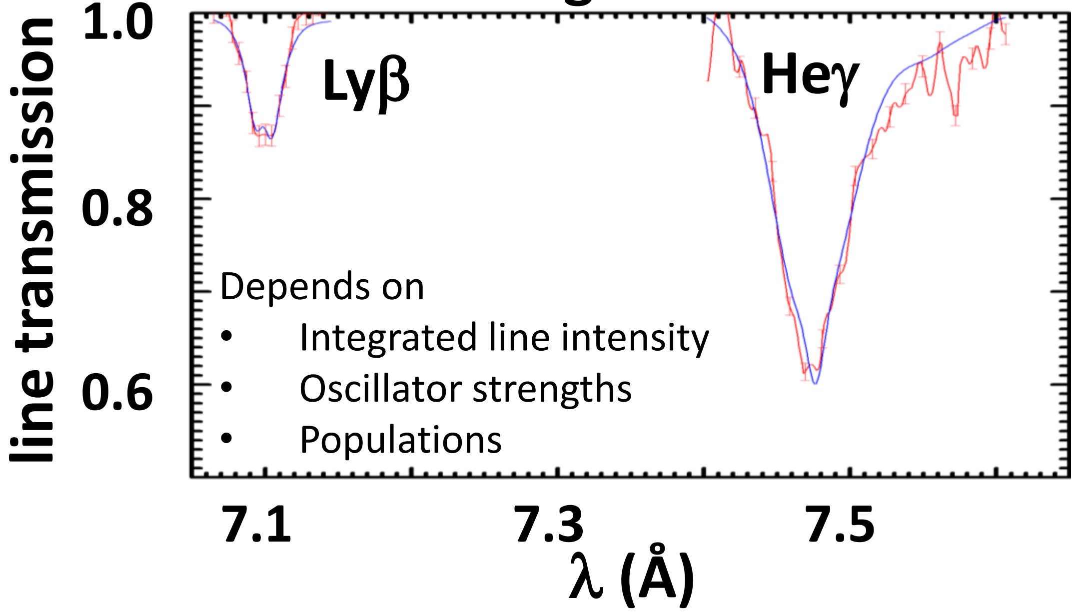


In-situ areal density from strength of heated Mg K-shell lines



Mg spectra sensitivity:

- Line broadening → n_e
- Line ratios → T_e
- Line depth → ρL

In-situ Mg areal density measurement confirms hydro evolution does not significantly alter the areal density

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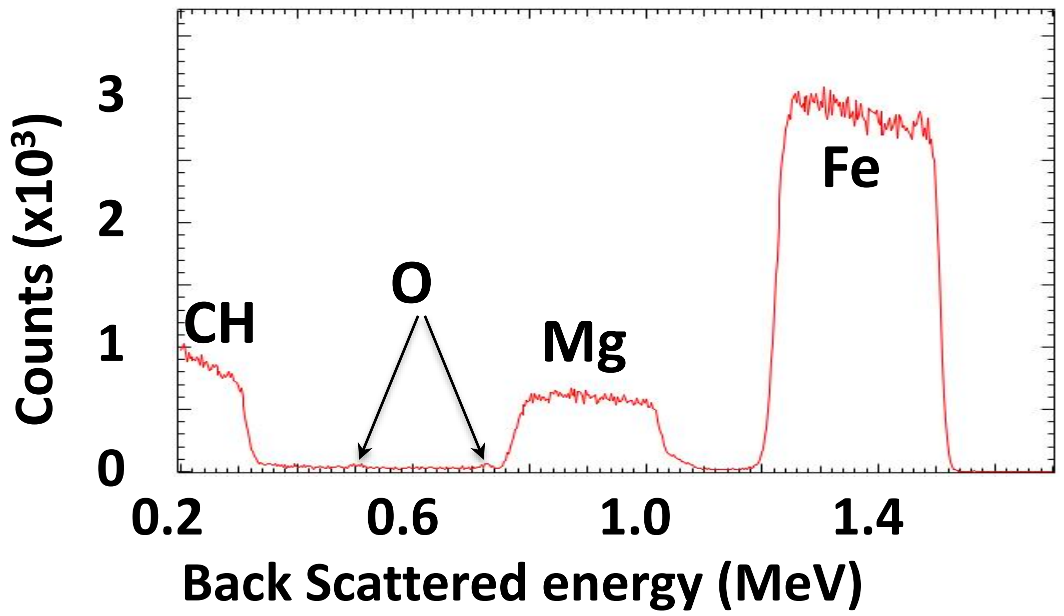

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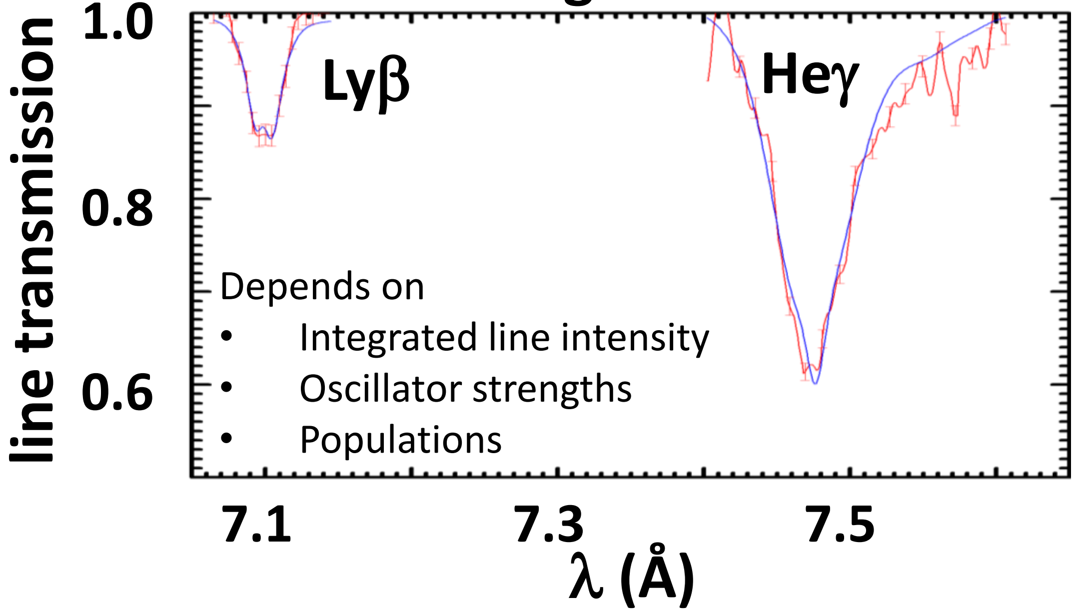

$$\left\langle \frac{\rho L \text{ [Mg analysis on heated sample]}}{\rho L \text{ [RBS pre-shot]}} \right\rangle = 0.97 \pm 0.03$$

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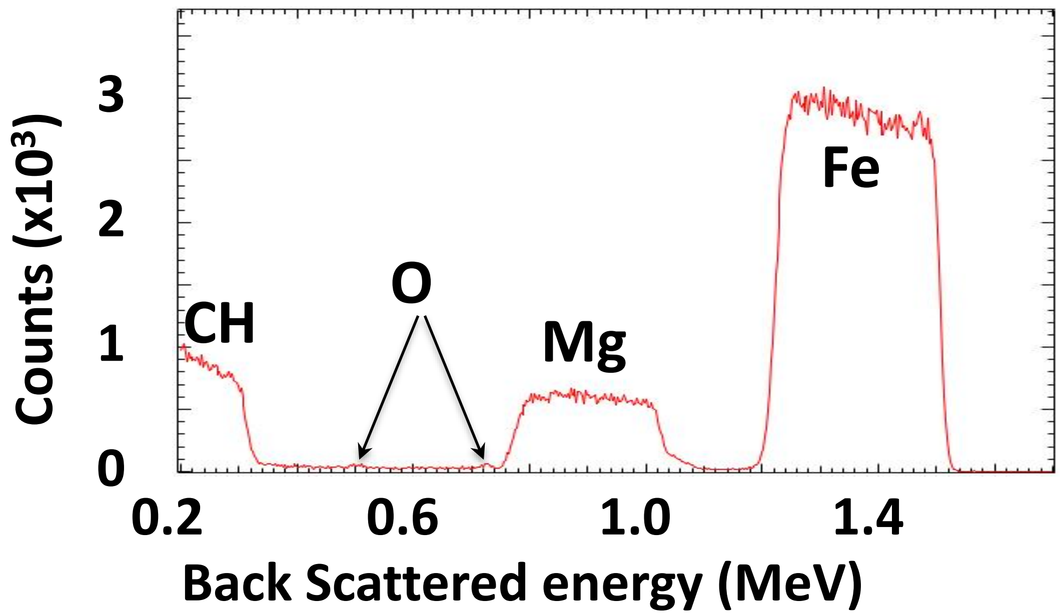

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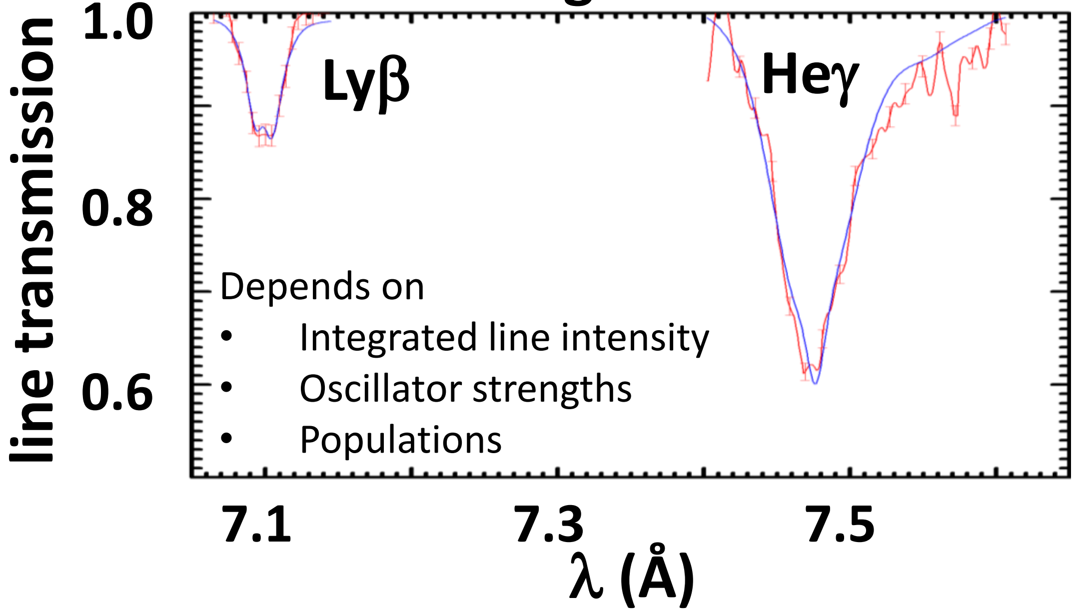

$$\left\langle \frac{\rho L \text{ [Mg analysis on heated sample]}}{\rho L \text{ [RBS pre-shot]}} \right\rangle = 0.97 \pm 0.03$$

Hydro evolution of sample does not significantly alter the areal density

Common hypotheses for experimental flaws

Sample characterization error

- Is Fe areal density accurately known?
  → In-situ measurements agree with RBS
- Any contamination?
  → RBS confirmed no contamination

Data interpretation error

- Followings are considered negligible:
  - Sample self-emission
  - Tamper transmission difference
  - Time- and space-gradient effects
  - Non-LTE effects
- How important are they?

T_e and n_e diagnostics error

- How large is the diagnostic error?
- How much does it affect?

T_e and n_e diagnostic results vary $\pm 4\%$ and $\pm 30\%$, depending on choice of spectral model [1]

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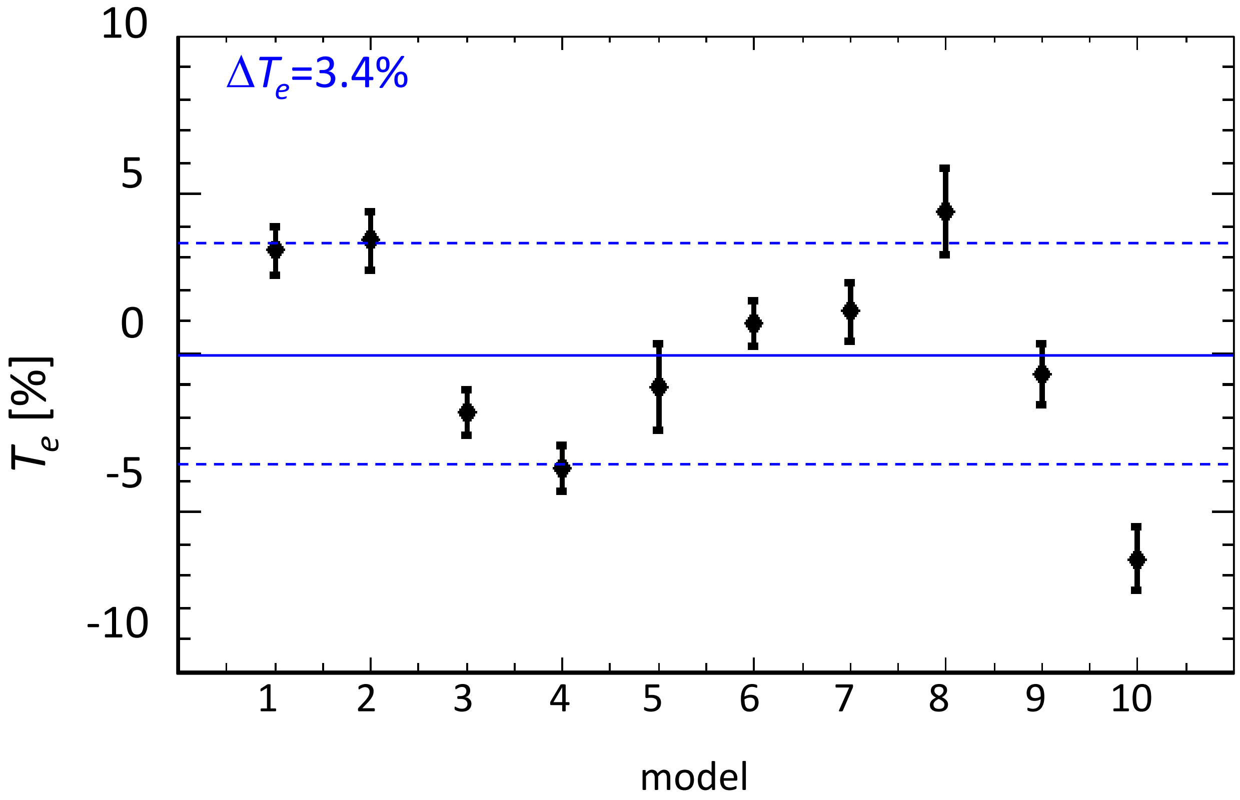
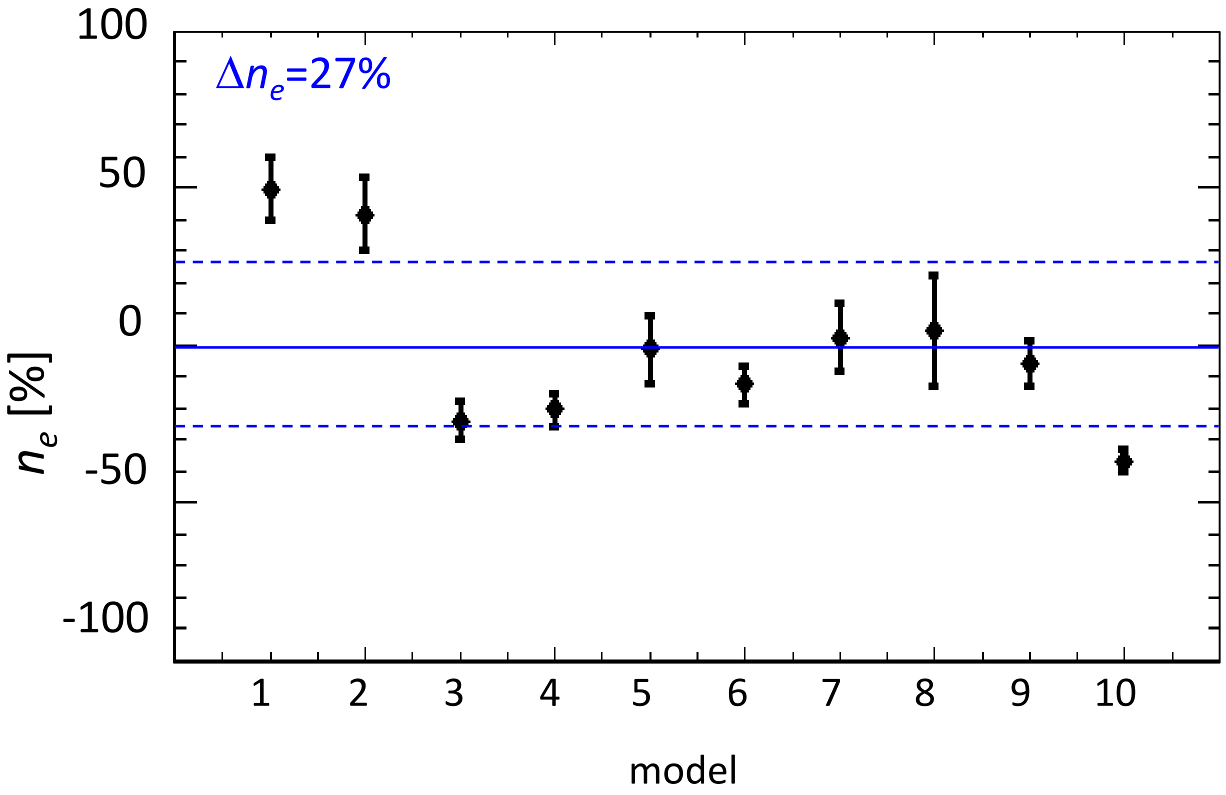


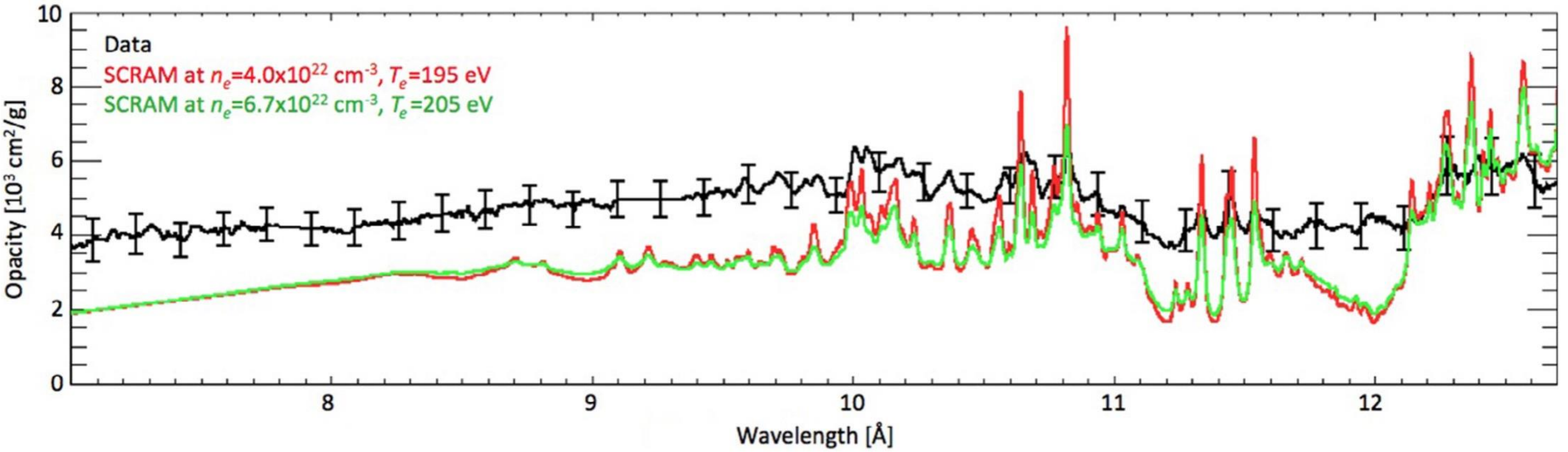


- Main source of discrepancy comes from difference in line-broadening model

C. Iglesias suggests that true n_e would be 50% higher [2]

[1] Nagayama et al., High Energy Density Physics **20**, 17-22 (2016)
[2] Iglesias, High Energy Density Physics **18**, 14-19 (2016)

50% higher n_e would partially resolve peak-to-valley contrast difference



- Discrepancy in b-f and window did not improve
- Absolute uncertainty in n_e still needs to be quantified

Common hypotheses for experimental flaws

Sample characterization error

- Is Fe areal density accurately know?
  → In-situ measurements agree with RBS
- Any contamination?
  → RBS confirmed no contamination

T_e and n_e diagnostics error

- How large is the diagnostic error?
  → True n_e maybe higher by 50%
- How much does it affect?
  → Partially explain peak-to-valley contrast

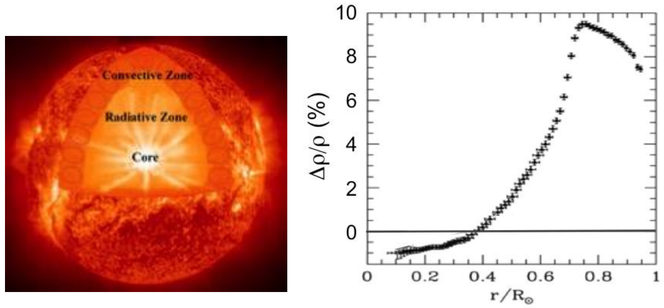
Data interpretation error

- Followings are considered negligible:
  - Sample self-emission
  - Tamper transmission difference
  - Time- and space-gradient effects
  - Non-LTE effects
- How important are they?
  → These are negligible

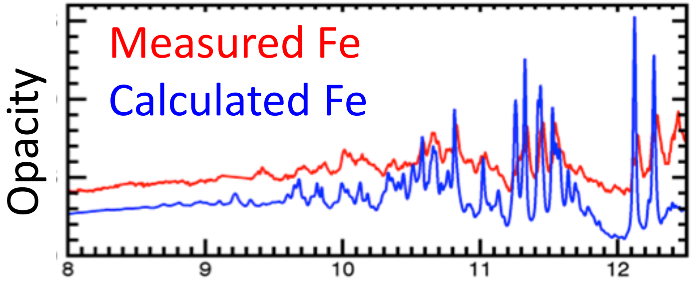
Calculated Fe opacity at solar interior condition disagrees with data; Various investigations provide clues for the discrepancy

- **We found 30–400% disagreement between modeled and measured Fe opacity at solar interior conditions**

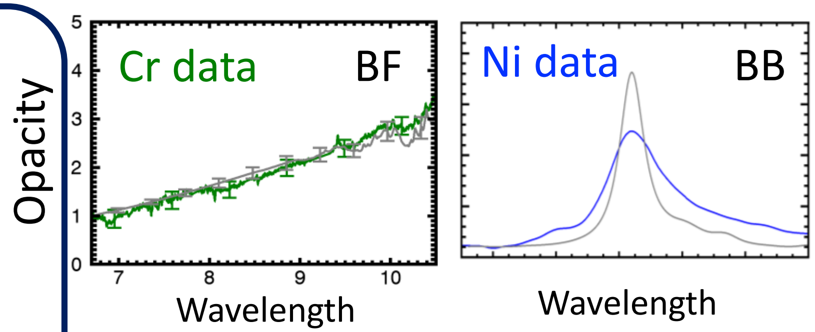
  → Partially resolves solar problem, but the source of discrepancy needs to be identified



- **Various scrutiny narrows down the sources of discrepancy**
  - Scrutiny on Experiments: Experiment accuracy is verified
    - Diagnostic error partially explains peak-to-valley contrast difference



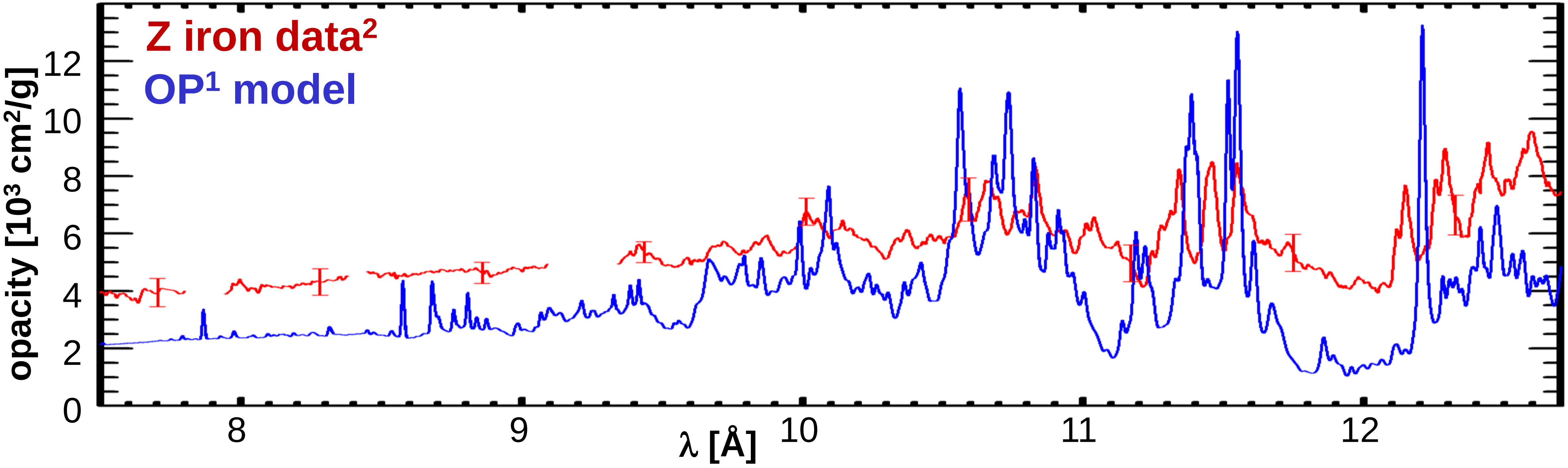
  - More measurements:
    - **Cr, Fe, and Ni opacities measured at multiple electron temperatures (T_e) and electron densities (n_e)**
    - Calculated line-broadening is too narrow
    - Element dependence on bound-free (BF) agreement is puzzling



  - Scrutiny on opacity theory: two-photon opacity may be important

Working towards completing systematic study

Opacity disagreement is disturbing and most likely caused by multiple sources



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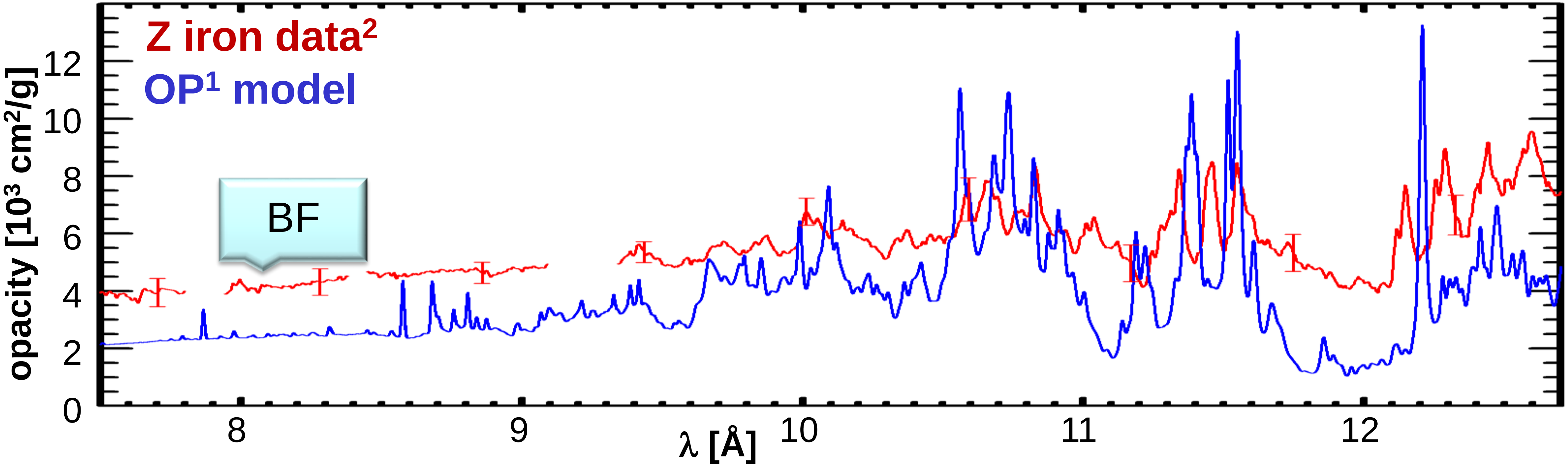

BF: bound-free/quasi-continuum:

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

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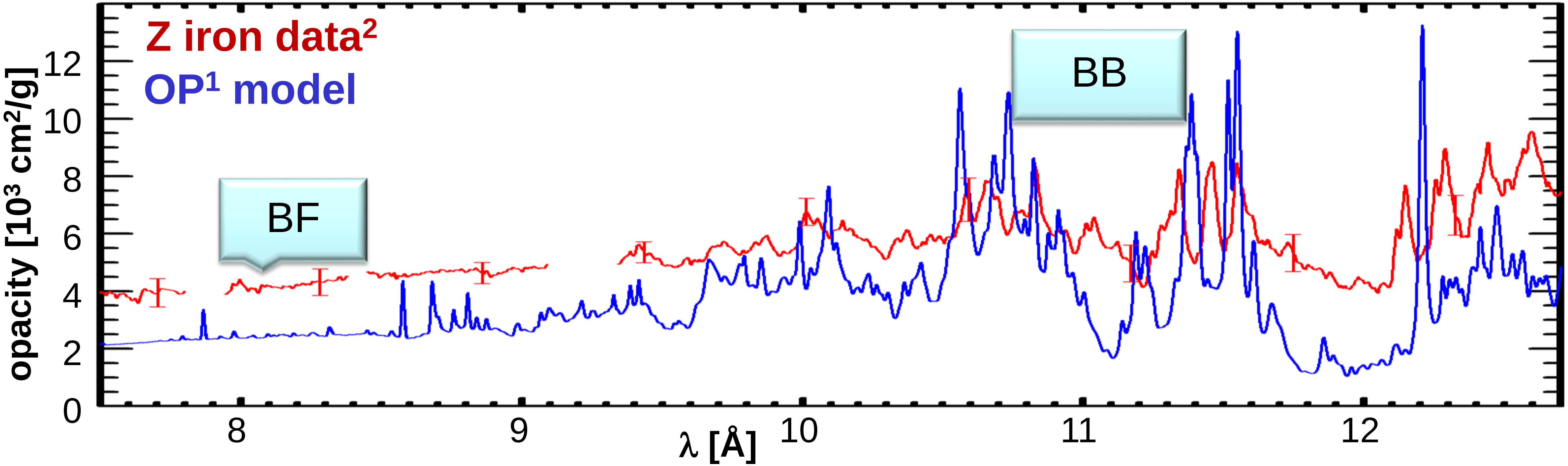

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BB: bound-bound line features*

- 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

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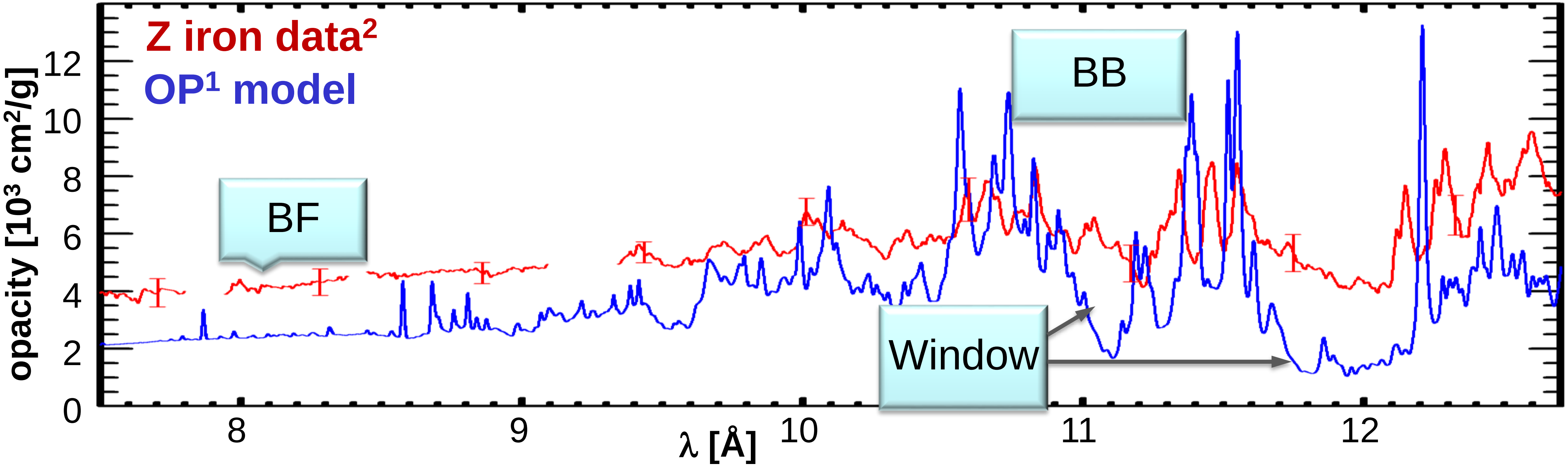

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Window filling:

- Broader line shape filling the window?
- Missing lines from multi-excited states?
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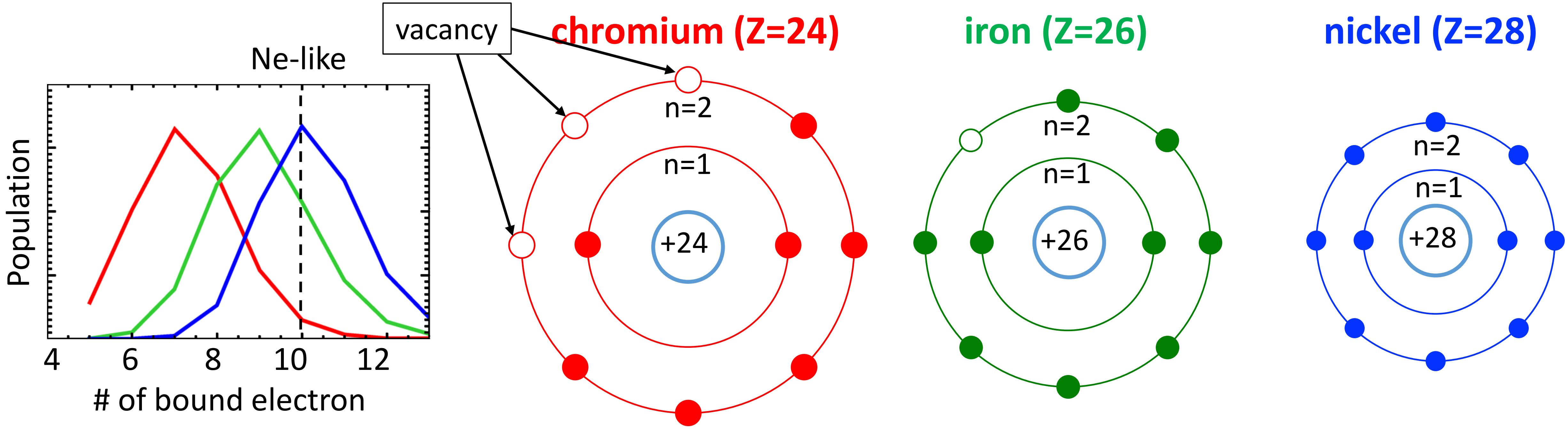
*ATOMIC, OPAS, SCO-RCG, SCRAM, and TOPAZ show much better agreement in line locations

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



Questioning Theory:

- Atomic data?
- Population kinetics?
- Density effects?
- Missing physics?

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

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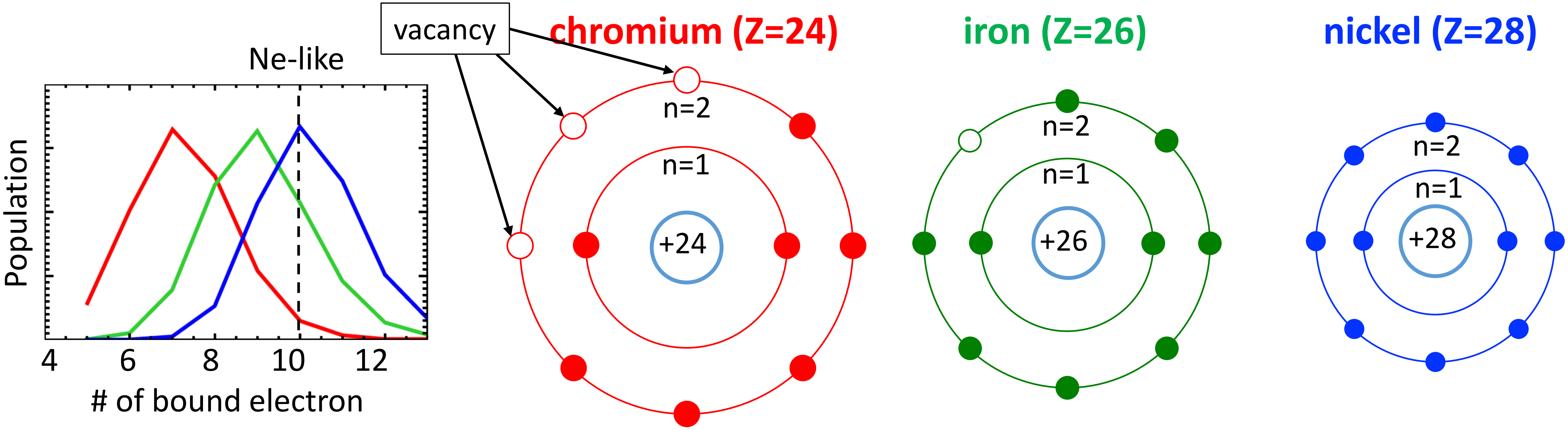

Questioning Theory:

- Atomic data?
- Population kinetics?
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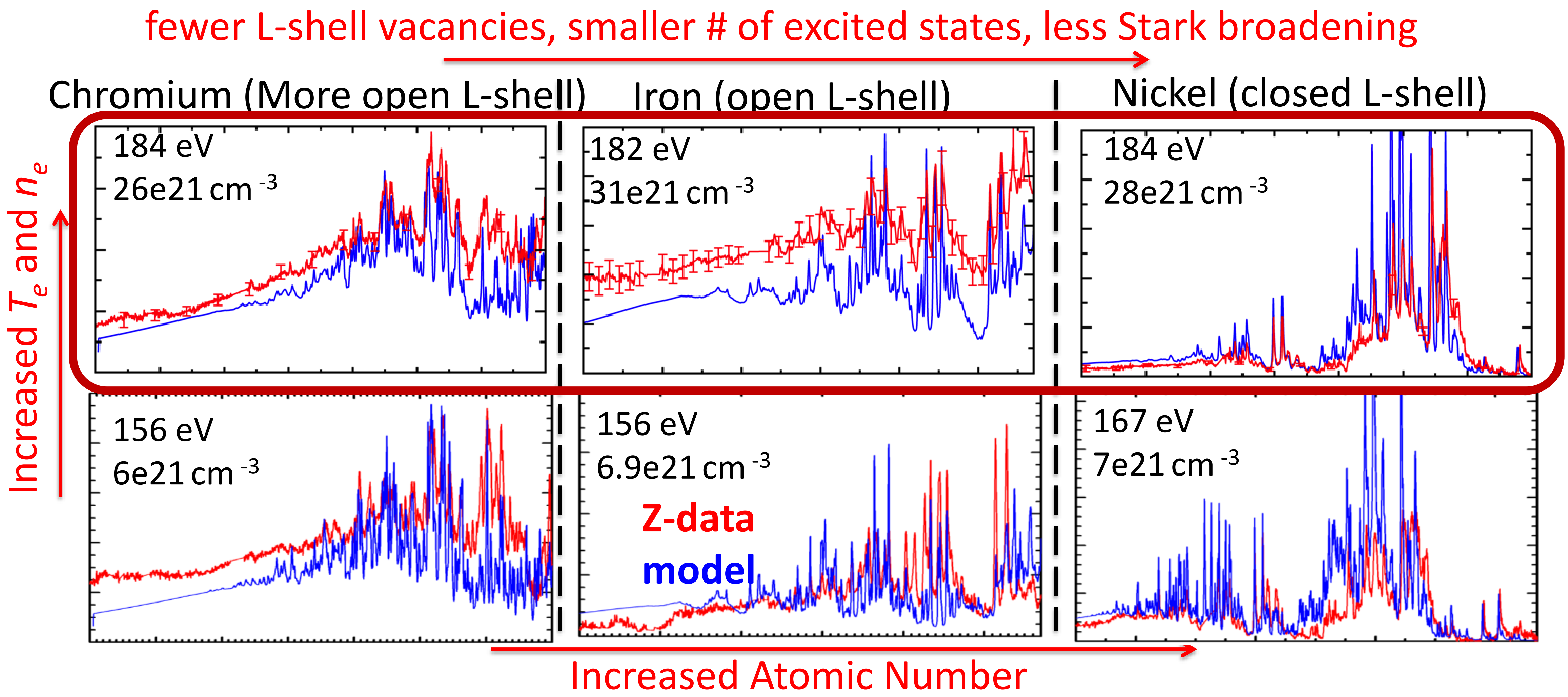
- Missing physics?

More ← L-shell vacancies ← Less

More ← # of excited states ← Less

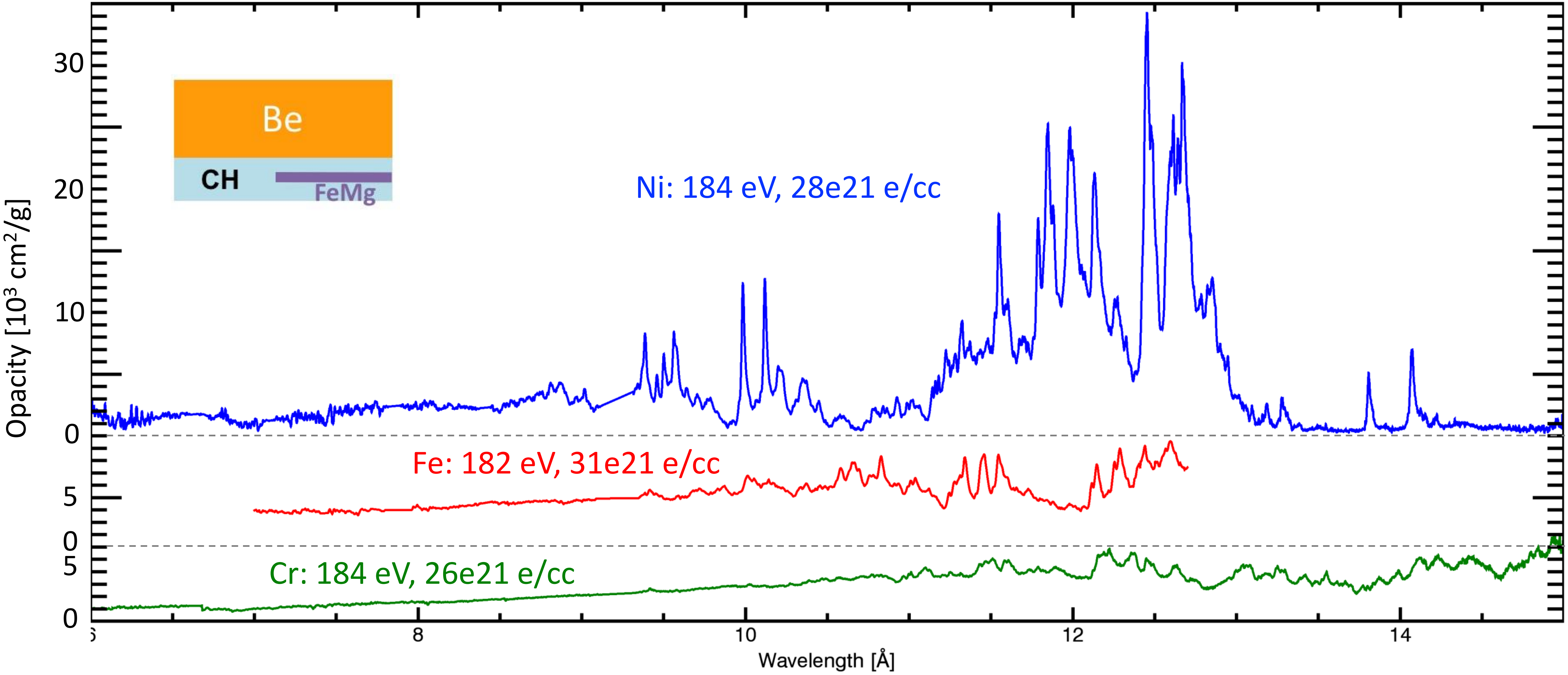
More ← Density effects ← Less

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

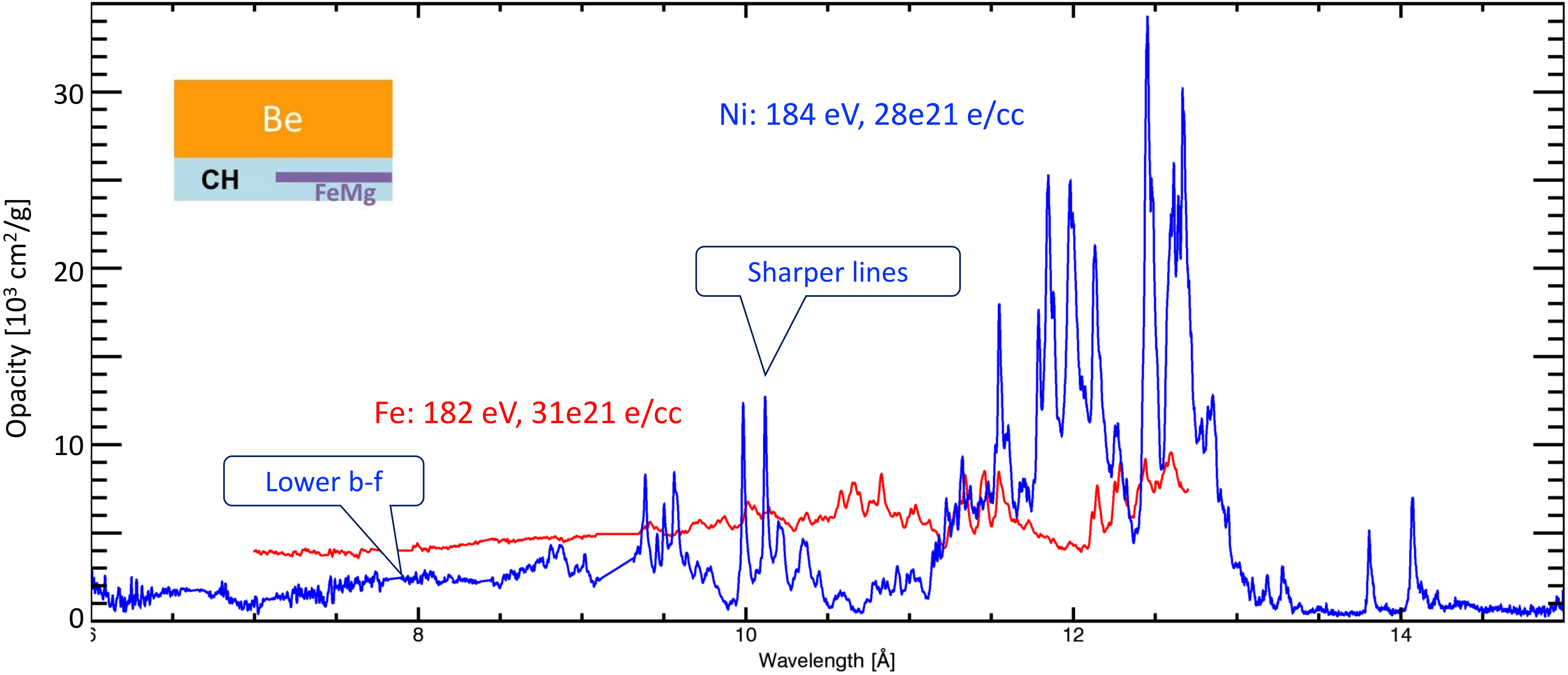


We performed 5 Cr, 1 Ni, and 4 Fe more opacity measurements to consolidate our conclusions.

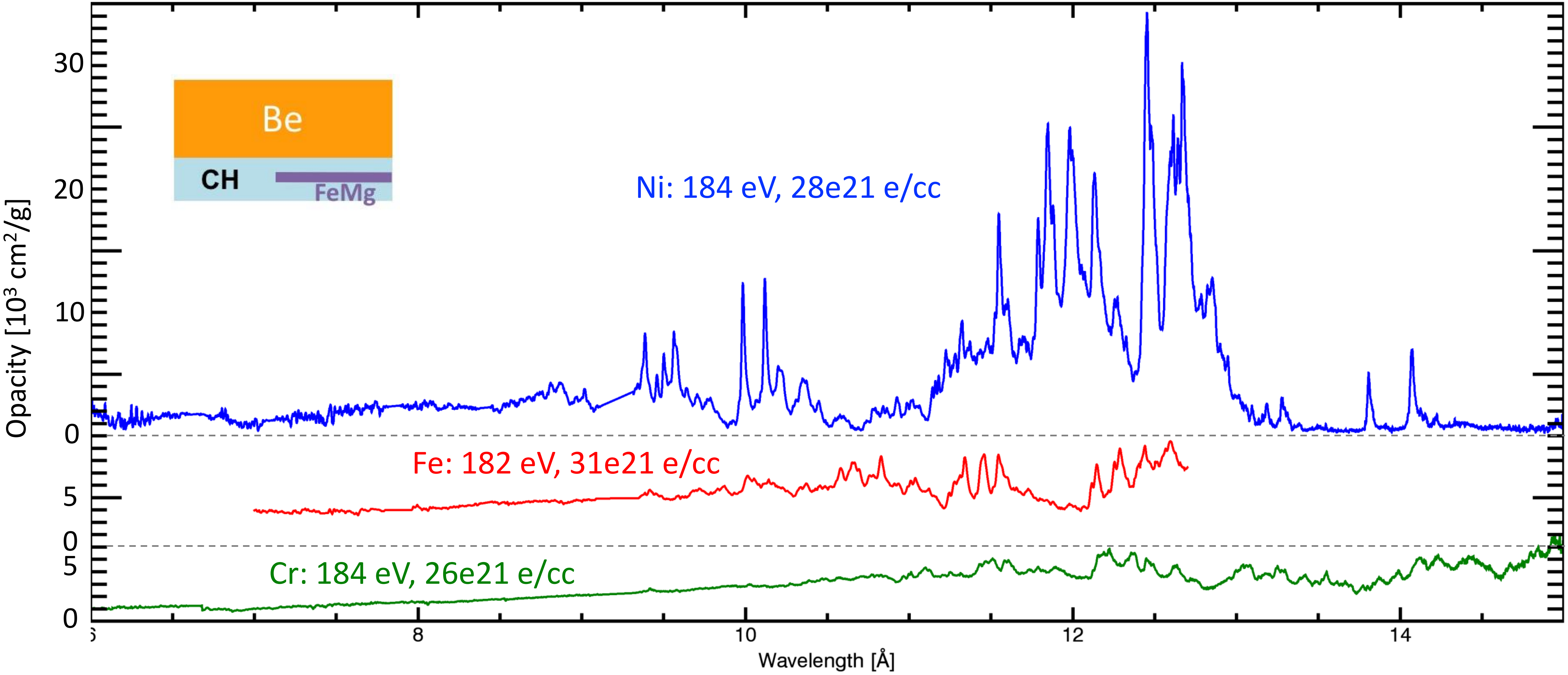
Fe, Cr, and Ni opacities are measured with the same platform
$T_e \approx$180 eV and $n_e \approx$30e21 e/cc



Ni data confirms that our platform can measure sharper lines and lower b-f and window



Observing model-data discrepancy trend would help narrow down hypothesis for discrepancy



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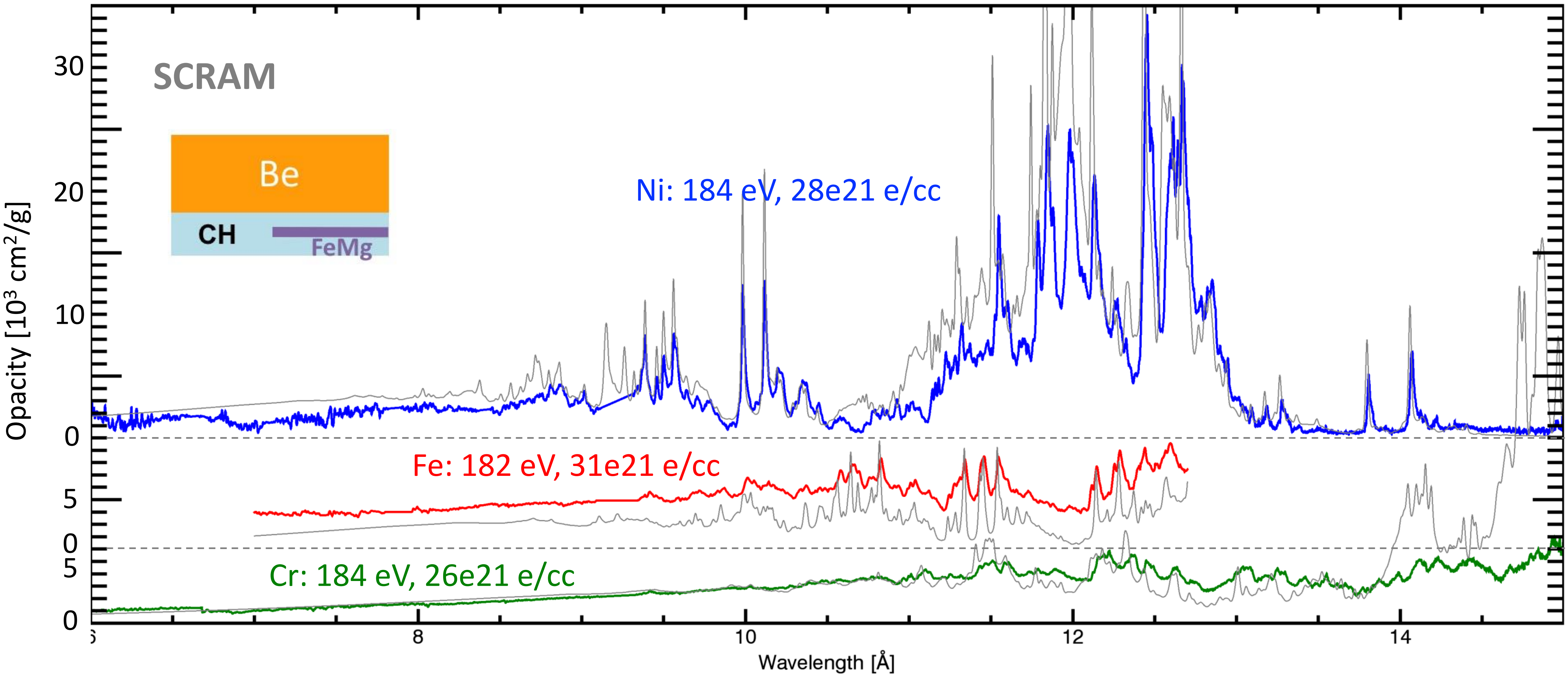

Preliminary model-data comparison in Cr, Fe, and Ni opacity suggests hypotheses for each discrepancy

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BB: Broader and shorter bound-bound lines

- Peak-to-valley contrasts are smaller on all data

  → Some explained by underestimate in n_e

- Modeled L-shell line shape was narrower

  → L-shell line shape needs to be improved

Window: Filled opacity window

- Filled windows are observed by Fe and Cr, but not Ni

  → Challenge due to open L-shell?

BF: Higher bound-free (quasi-continuum) opacity

- Higher b-f opacity observed only from Fe
  - If higher b-f opacity measurement is flawed → Reinvestigate experimental flaws
  - If lower b-f opacity measurement is flawed → Look for missing physics for higher b-f
  - If both measurements are correct → Explanation must be complex

Calculated Fe opacity at solar interior condition disagrees with data; Various investigations provide clues for the discrepancy

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- **We found 30–400% disagreement between modeled and measured Fe opacity at solar interior conditions**

  → Partially resolves solar problem, but the source of discrepancy needs to be identified

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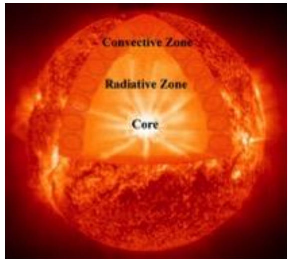
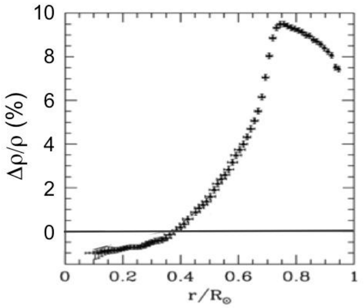
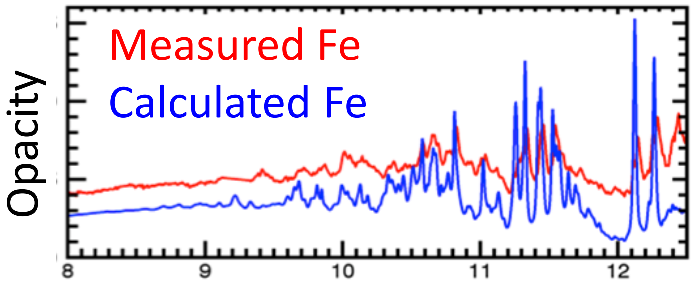
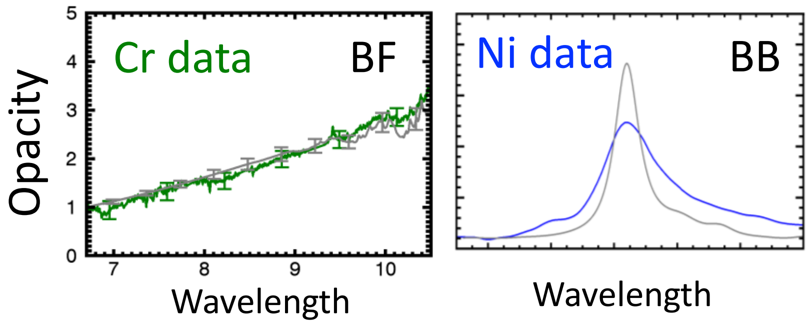




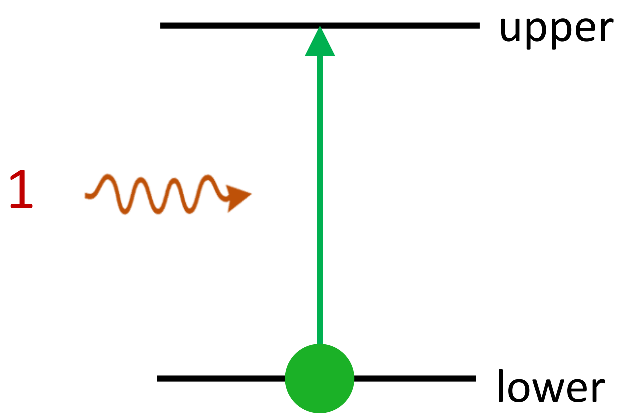




Working towards completing systematic study

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

one-photon processes



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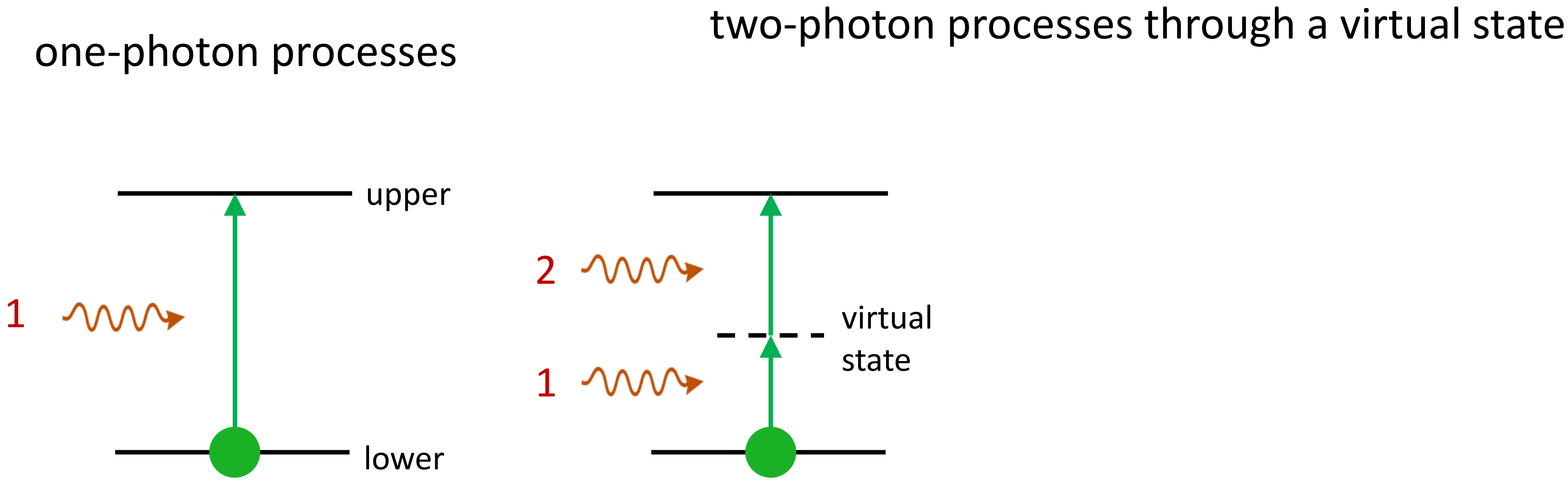

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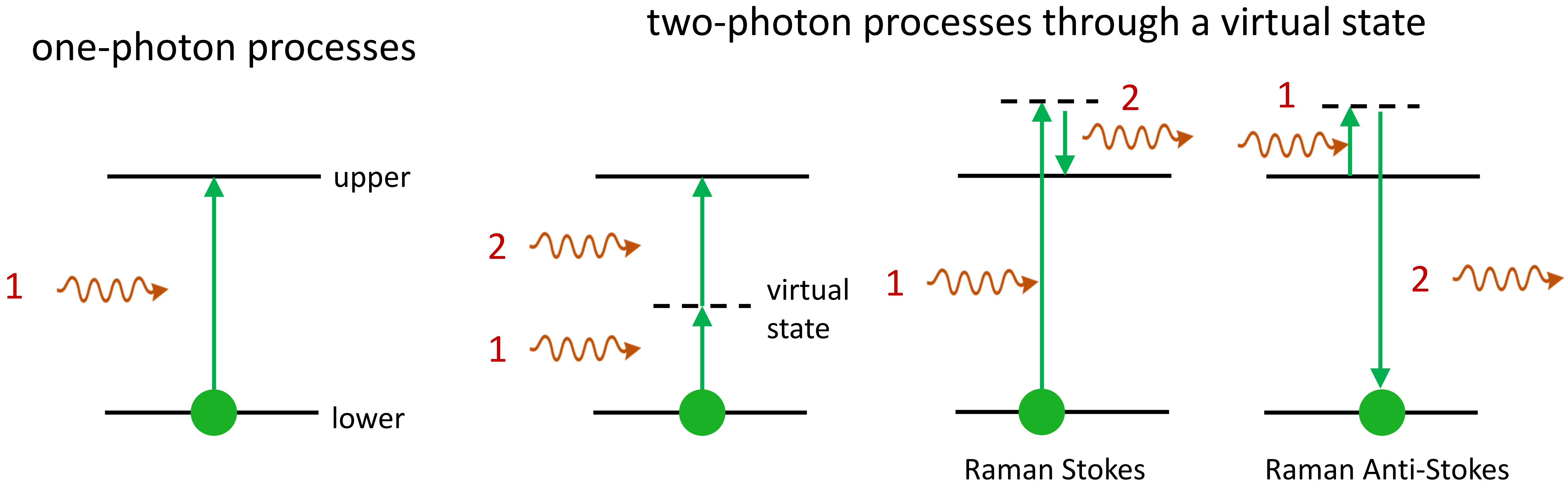

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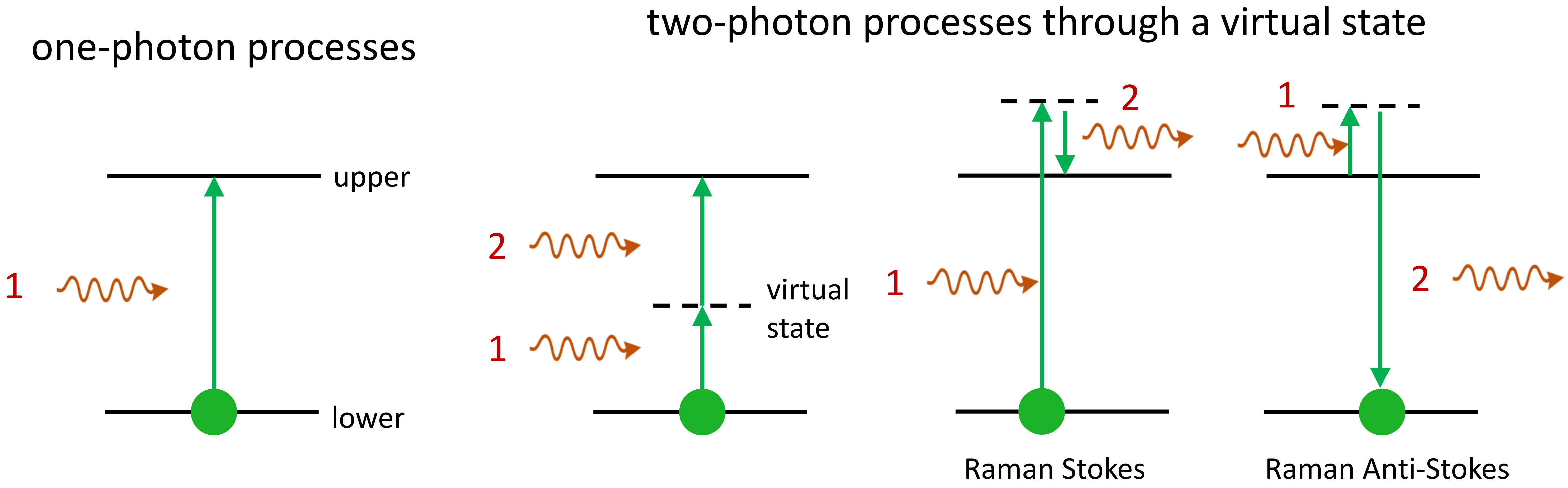
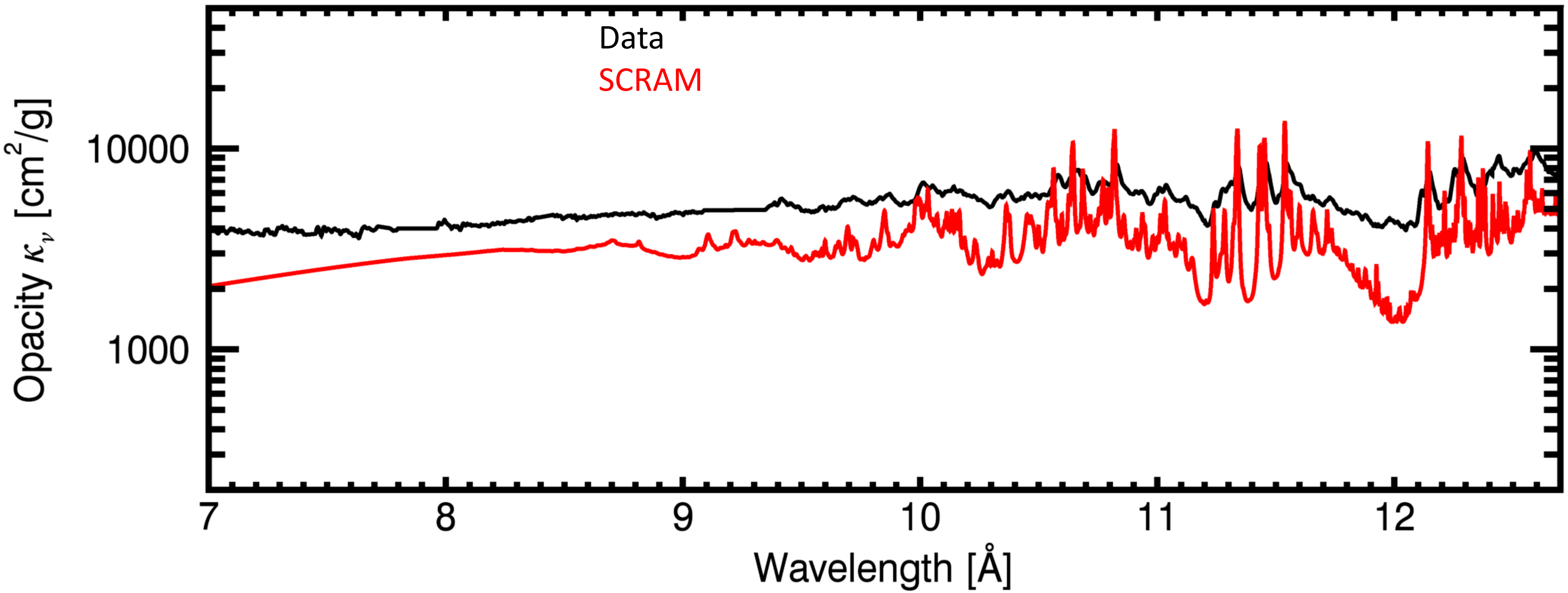


- Two-photon process cross-section $\sim n^8$
- Virtual state has short life-time → Bright radiation field

} Z opacity experiments have both

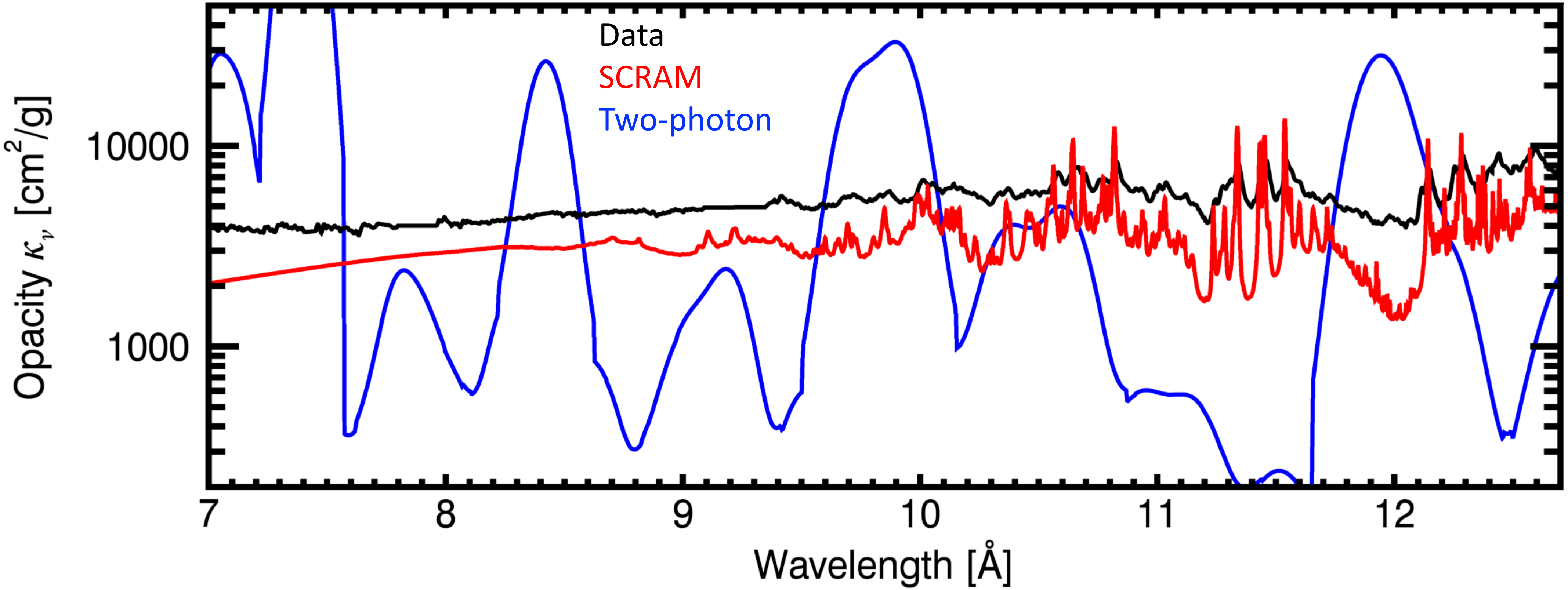
Two-photon opacity can be important for Fe L-shell opacity under strong radiation field

Two-photon processes may be important



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

Two-photon processes may be important, but the calculation needs to be refined with a more detailed atomic model



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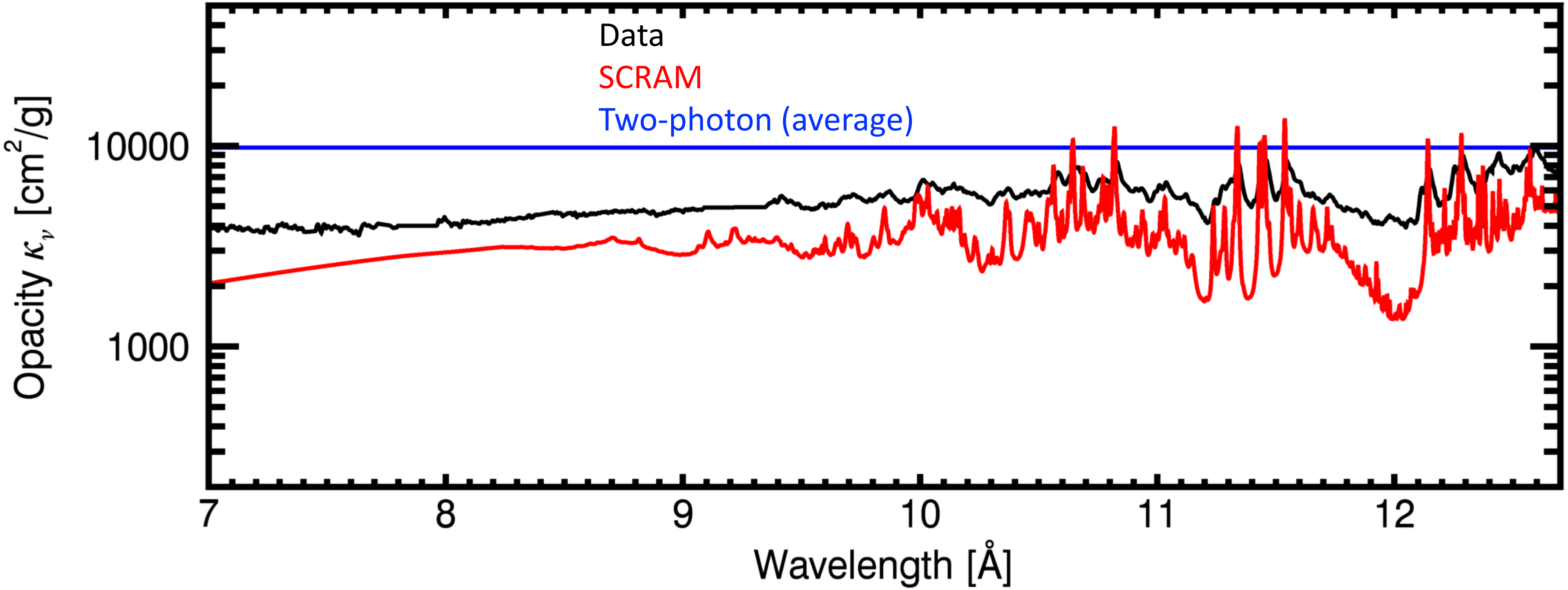
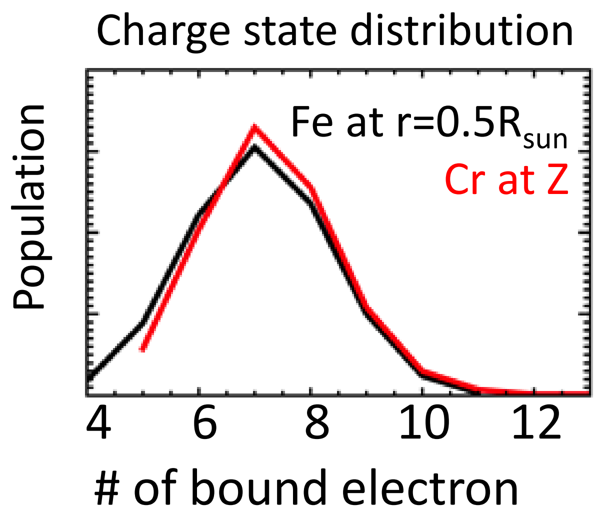


- First-principal method with simple atomic model
- Two-photon opacity more important than believed

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 ($\propto T^4$)
- Lower Z element at current platform can surrogate Fe opacity at deeper in the Sun
  - Example: Cr reproduces charge state distribution at half-solar radius



Does it reproduce 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.

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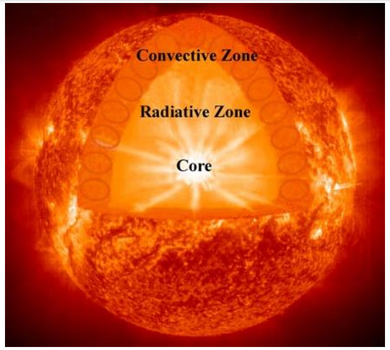
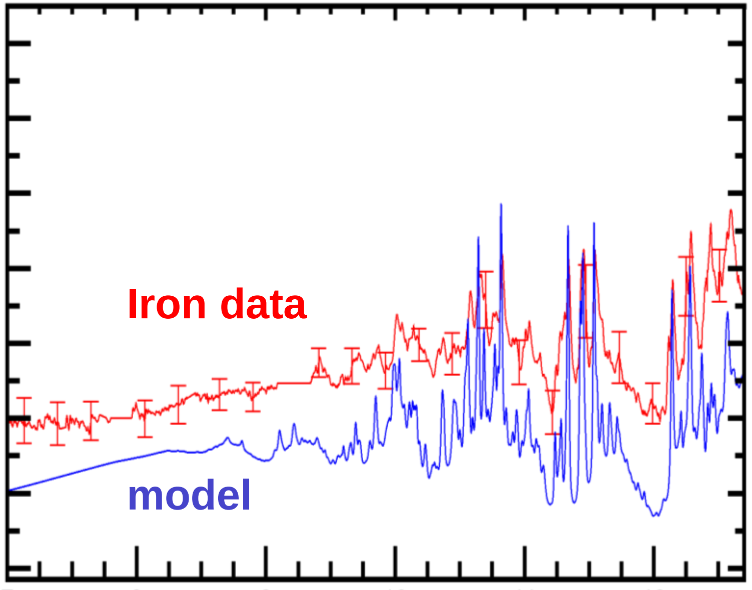
- **Solar interior predictions don't match helioseismology**

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



- **Z experiments have measured iron plasma opacity at near-solar-interior conditions**



- **The measured high temperature/density iron opacity is higher than predictions**

  → helps resolve the solar problem, but we need to understand what causes the discrepancy

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

- **Experimental and theoretical research is aimed testing hypotheses to resolve the difference**

Bailey *et al.*, *Nature* 2015