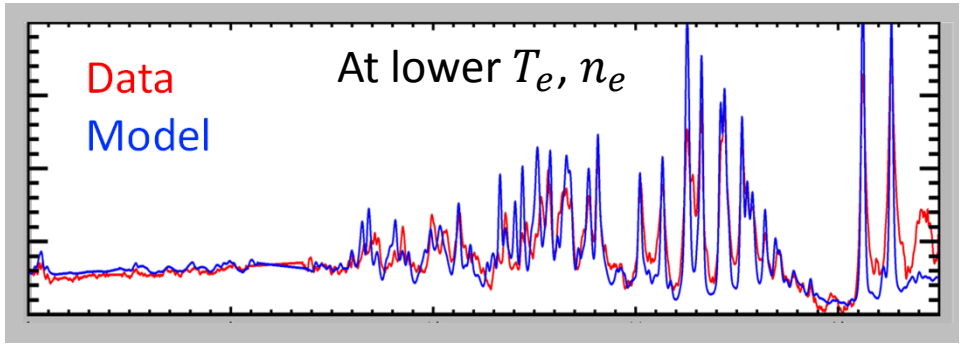
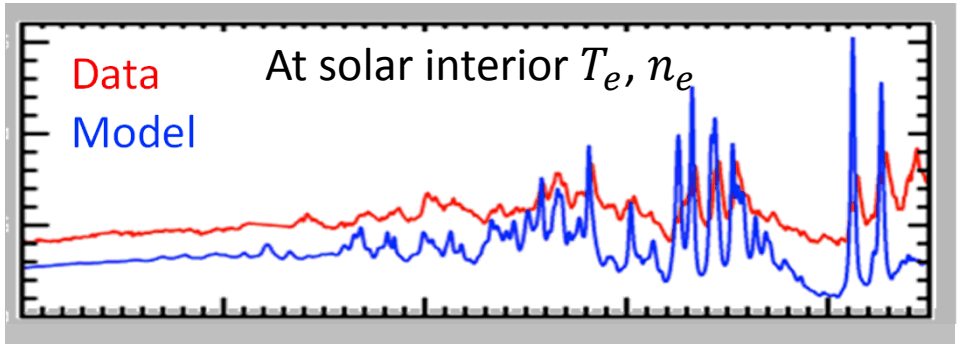
SAND2017-11422C





Systematic measurements of opacity dependence on temperature, density, and atomic number at stellar interior conditions

Taisuke Nagayama

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

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

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

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

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

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

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

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

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

Y. Kurzweil and G. Hazak
Nuclear Research Center Negev, Israel

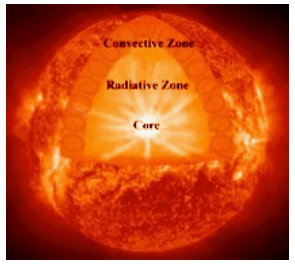
Calculated Fe opacity at solar interior condition disagrees with data; Various investigations provide clues for the discrepancy

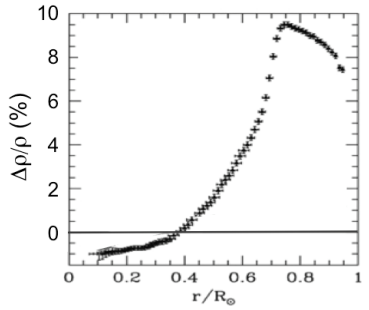
- **We found 30–400% disagreement between modeled and measured Fe opacity at solar interior conditions**

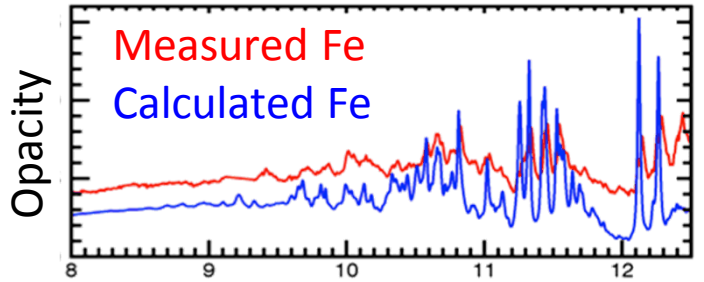
  → Partially resolves solar problem, but the source of discrepancy needs to be identified

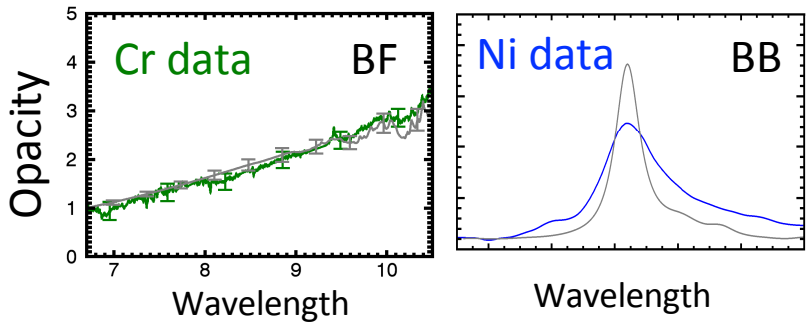
- **Cr, Fe, and Ni opacities measured at multiple electron temperatures (T_e) and electron densities (n_e)**
  - Opacity valley disagreement found on Cr and Fe, but not Ni
  - Calculated line-broadening is too narrow
  - Element dependence on bound-free (BF) agreement is puzzling

- **Missing physics in opacity theory:**
  - Two-photon opacity may be important



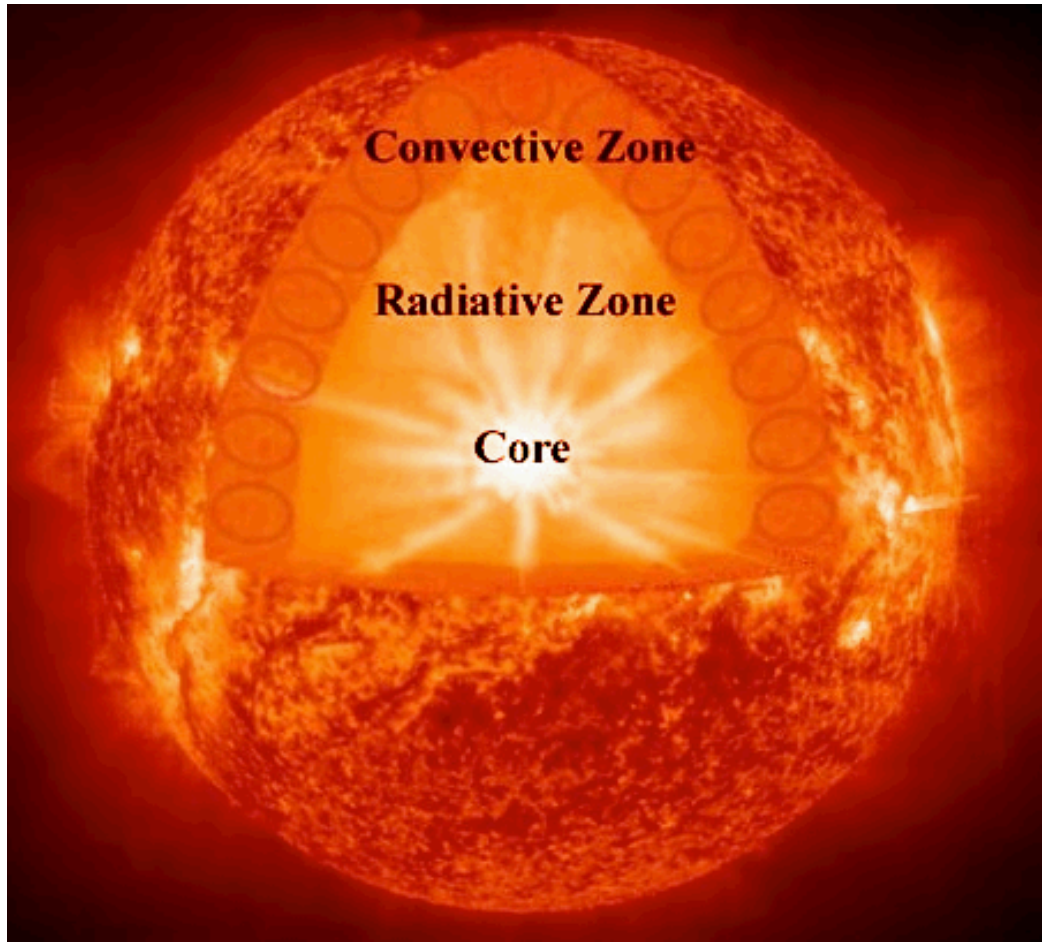




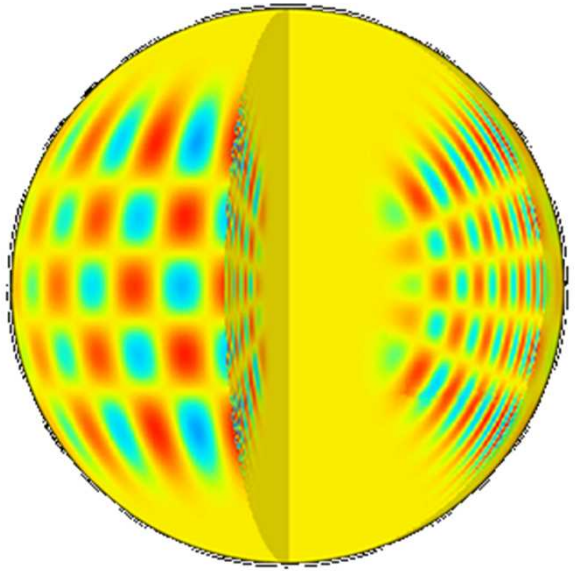


Working towards completing the systematic study to resolve the discrepancy

Modeled solar structure disagree with observations

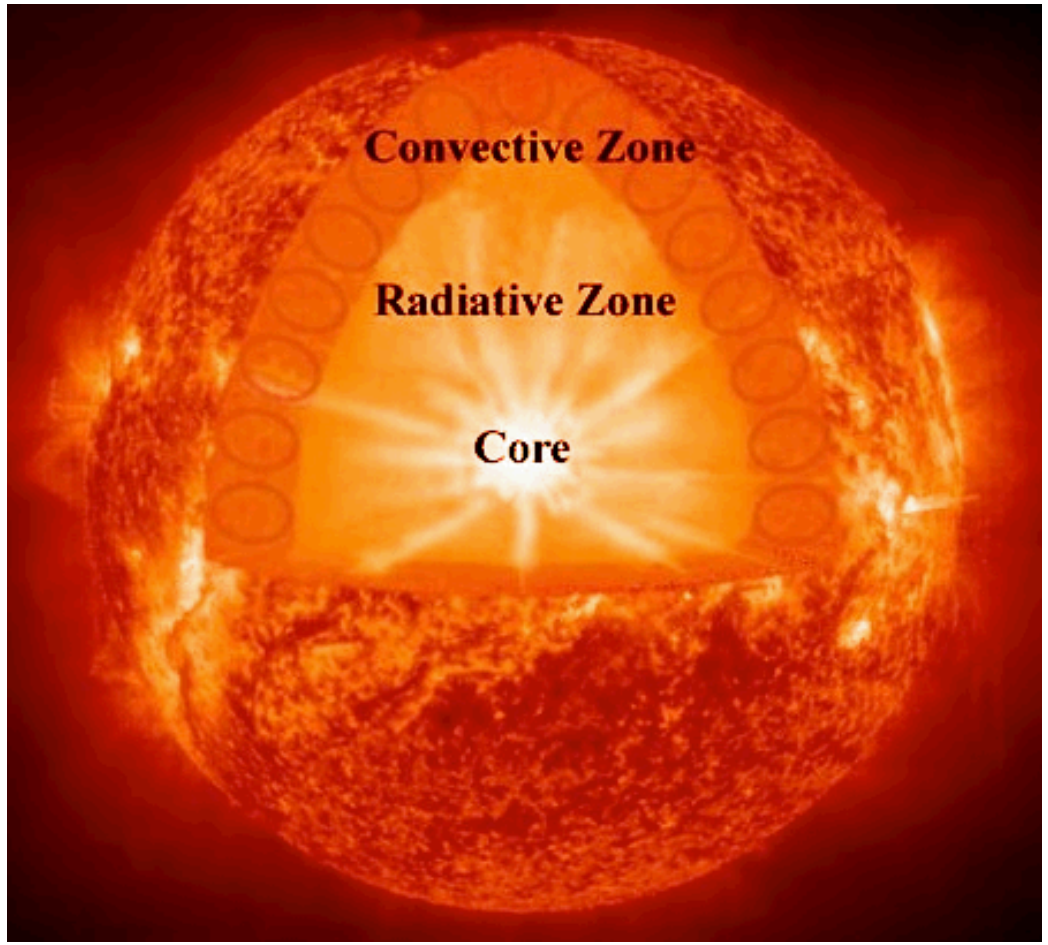


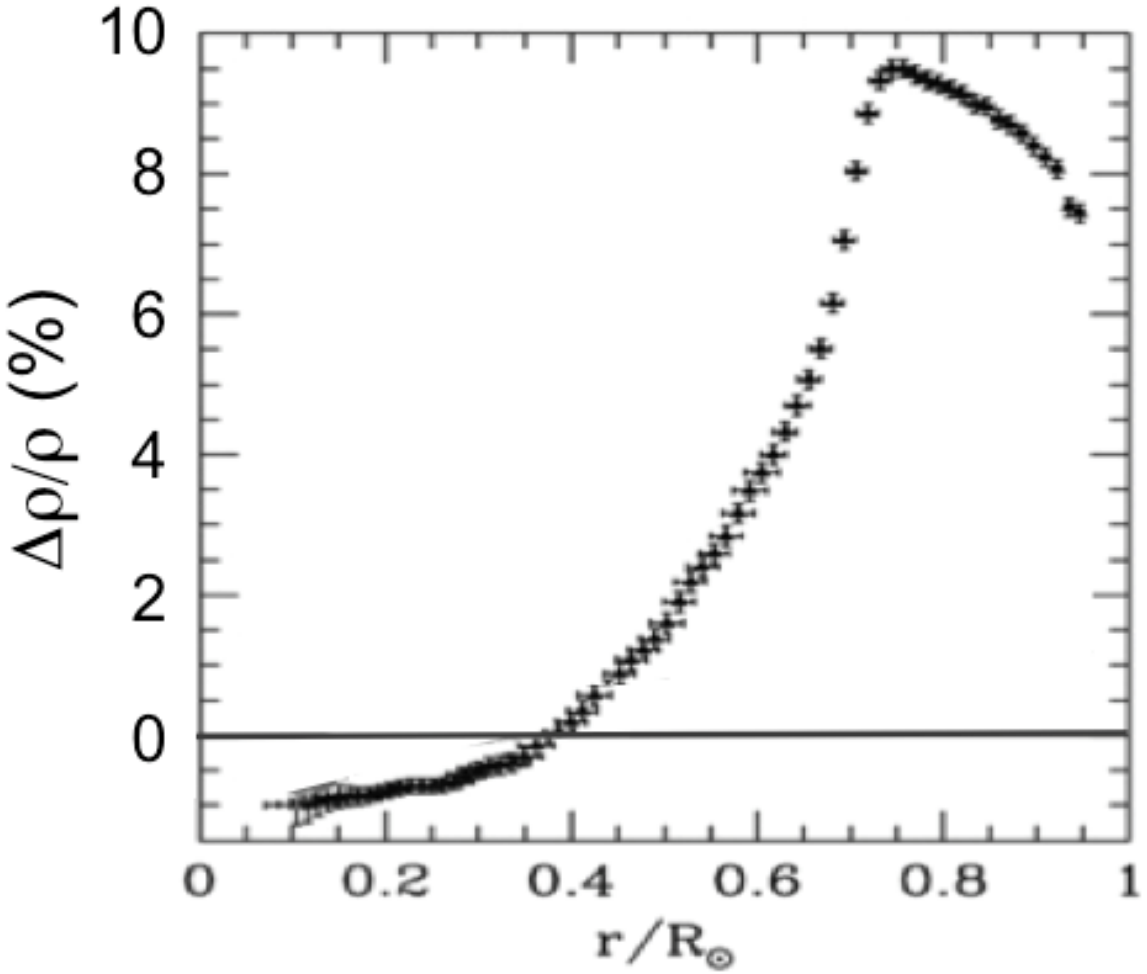
- Standard solar model (simulation)
  Inputs:
  - Abundance
  - EOS
  - Opacity
  - Etc.
- Helioseismology (measurements)



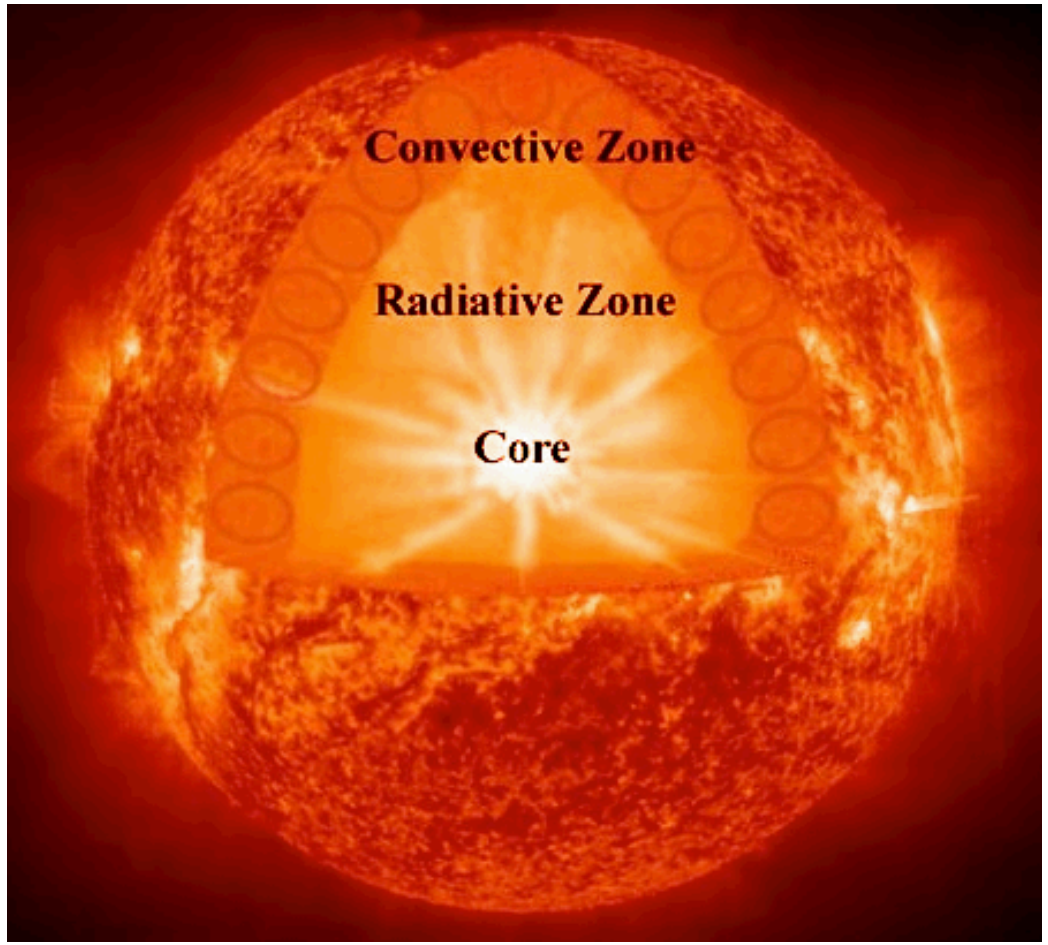
Analysis of 2D-resolved pulsation reveals the solar structure

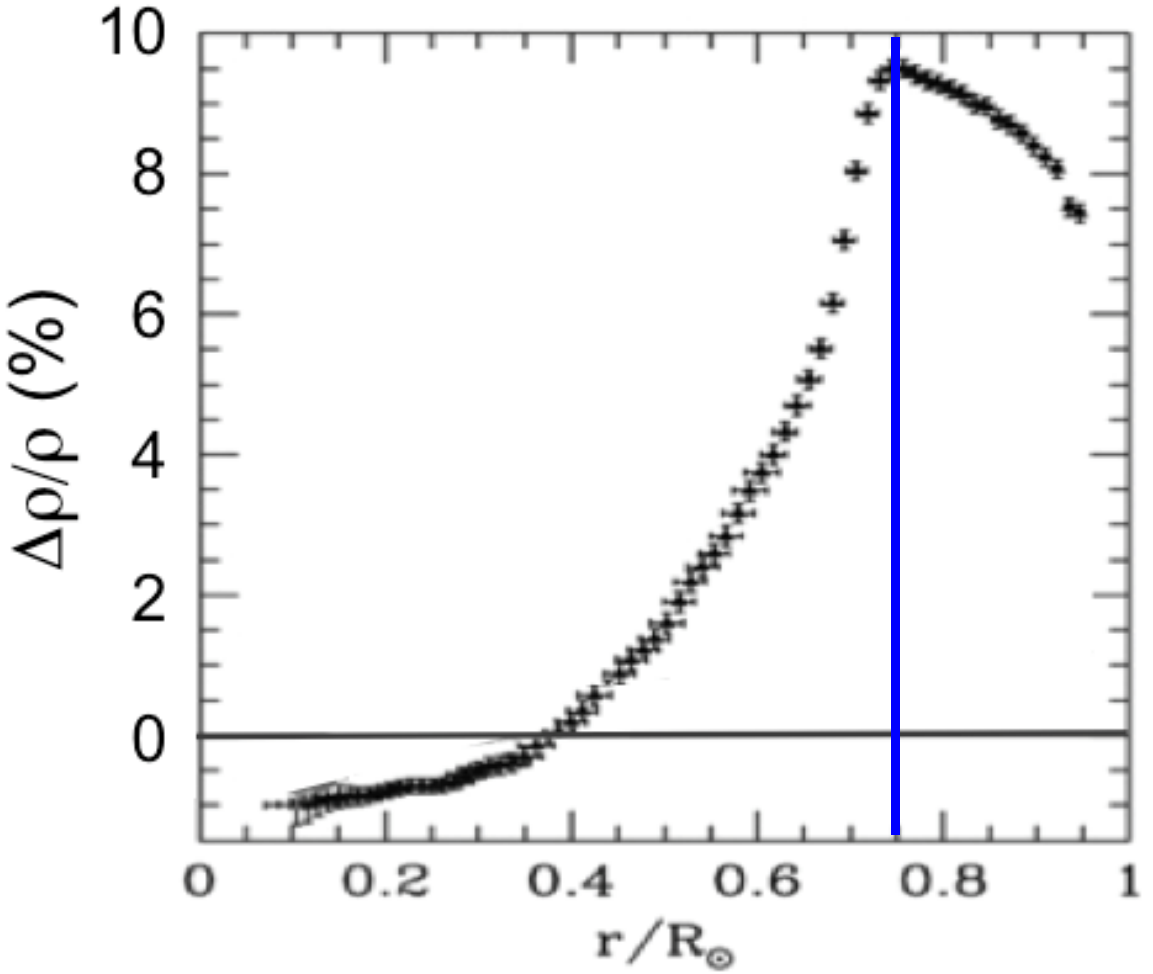
Modeled solar structure disagree with observations



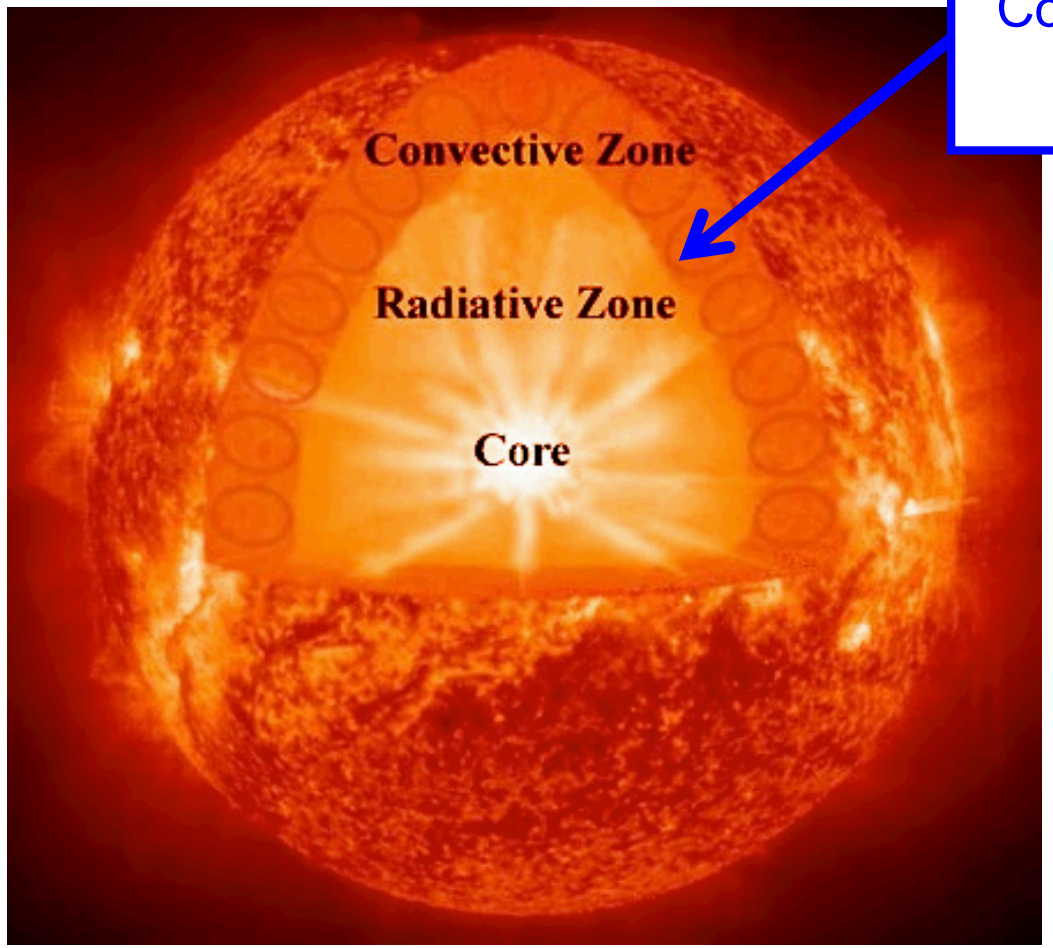


Modeled solar structure disagree with observations

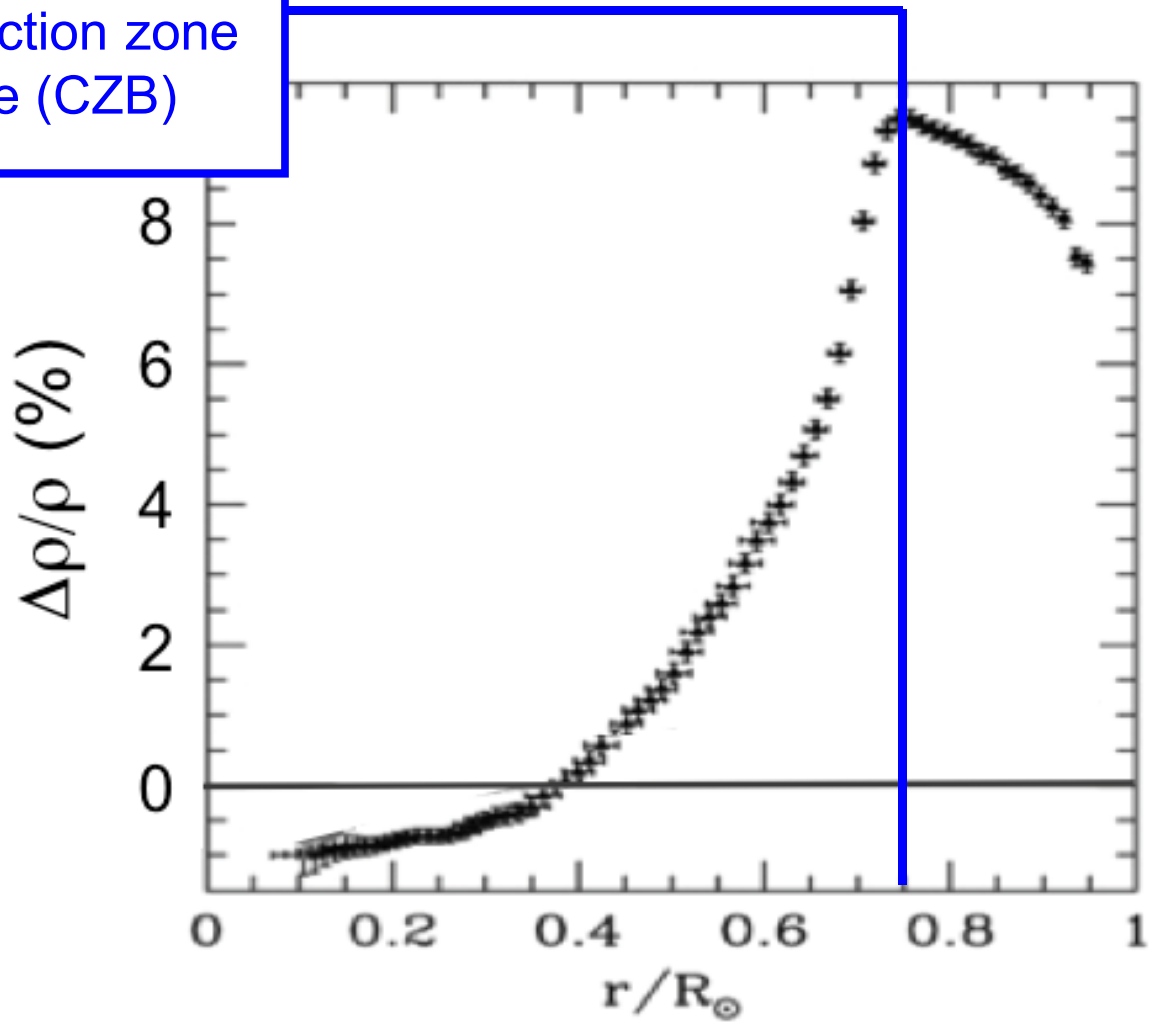




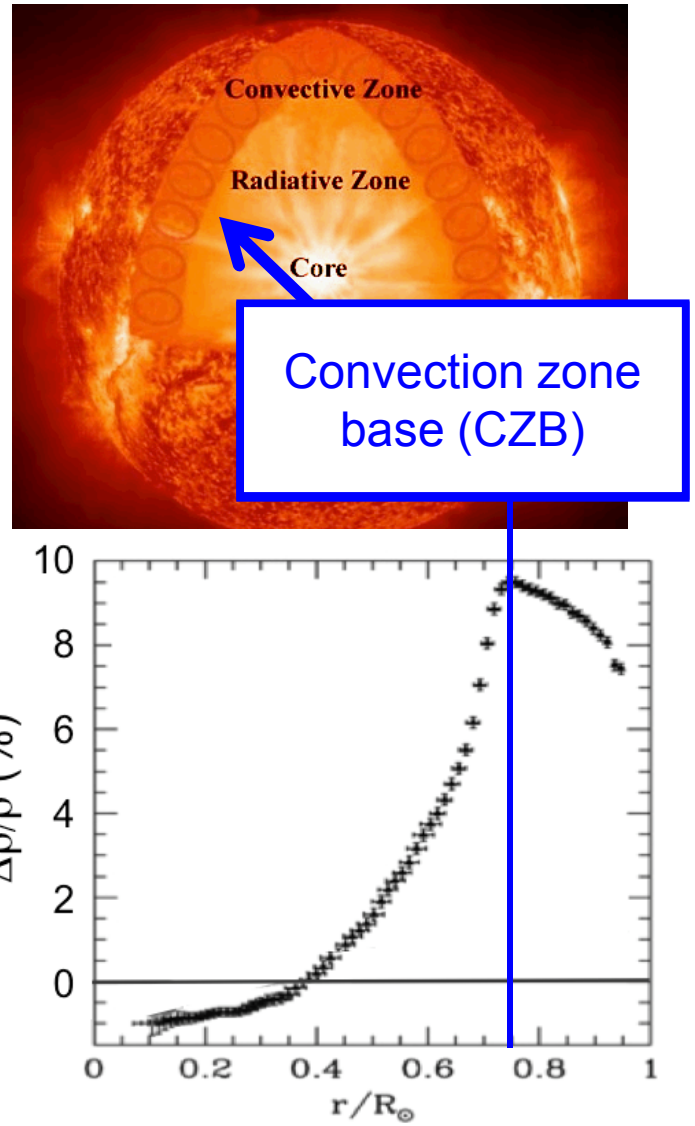
Modeled solar structure disagree with observations



Convection zone base (CZB)



17% mean-opacity increase in the solar model is needed to resolve this discrepancy

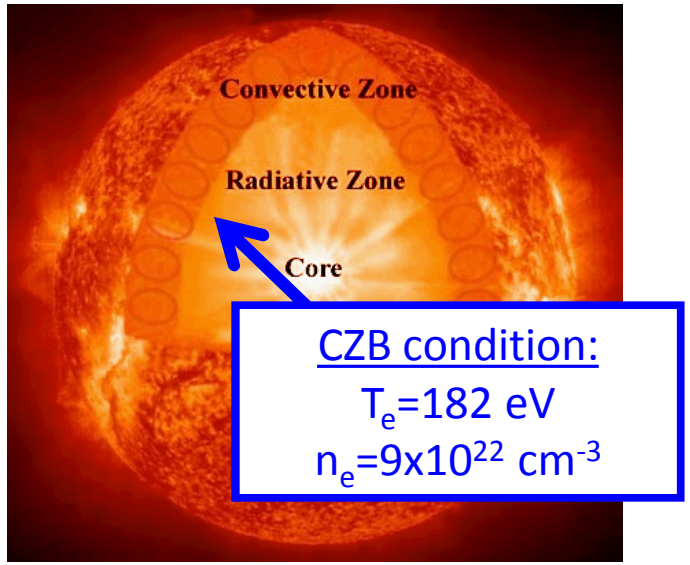


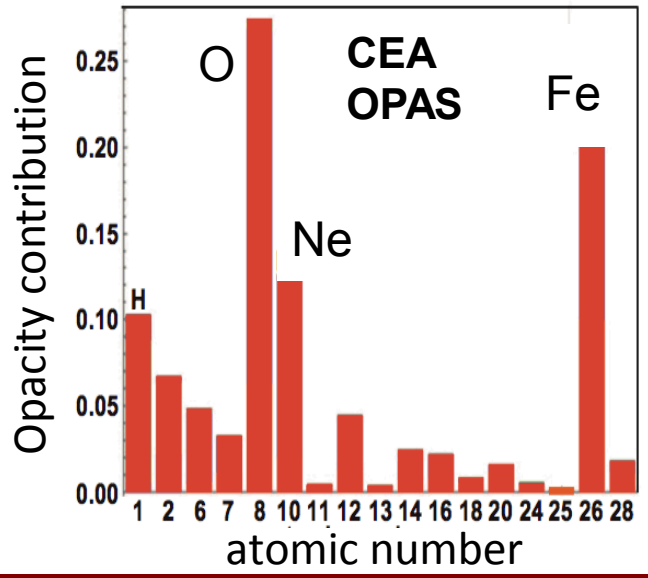
Opacity: κ_ν

- Quantifies radiation absorption
- $\kappa_\nu(T_e, n_e)$ … input for solar models
- Opacity models have never been tested

[1] Basu et al, J Phys: Conf Ser 440, 012017 (2013).
[2] M. Asplund et al Annu. Rev. Astro. Astrophys. 47, 481 (2009).

17% mean-opacity increase in the solar model is needed to resolve this discrepancy

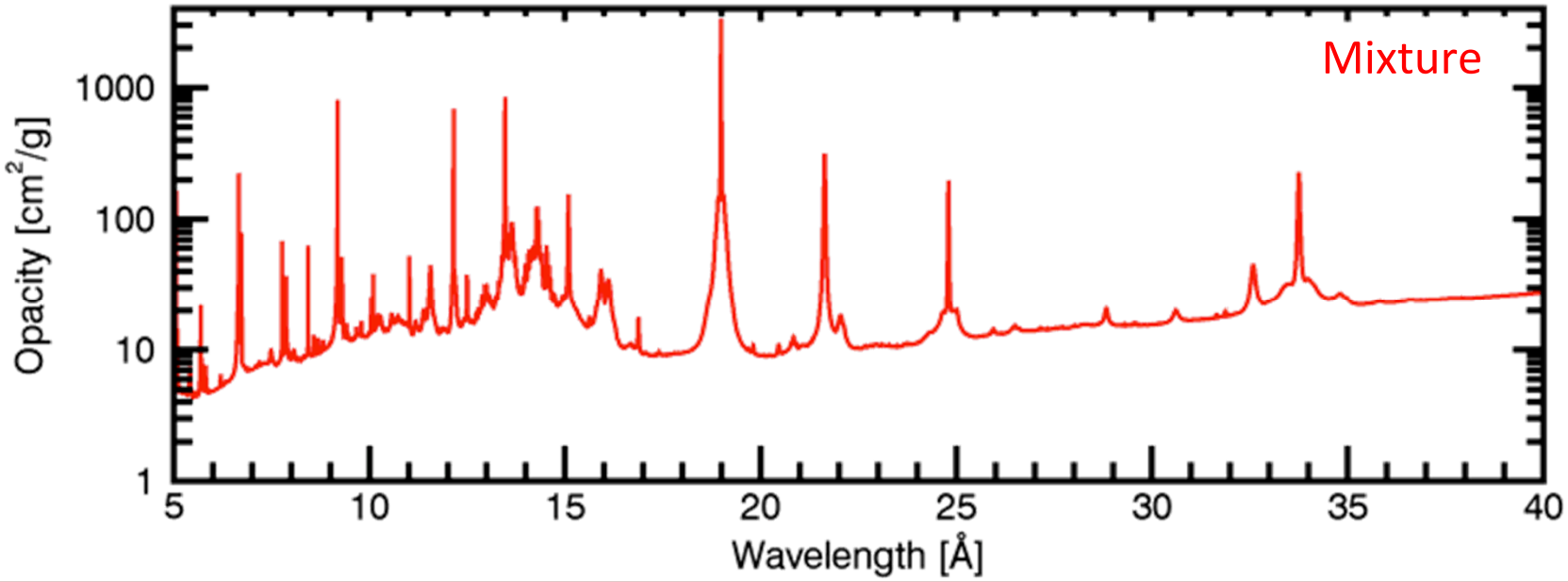




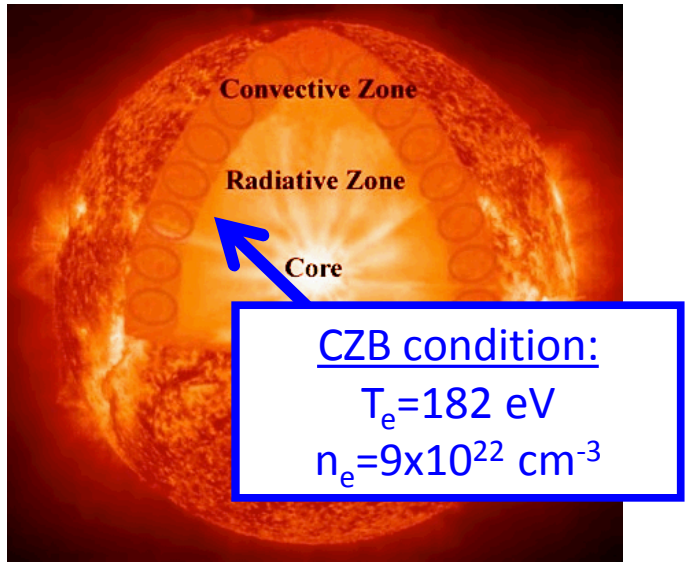
Opacity: κ_ν

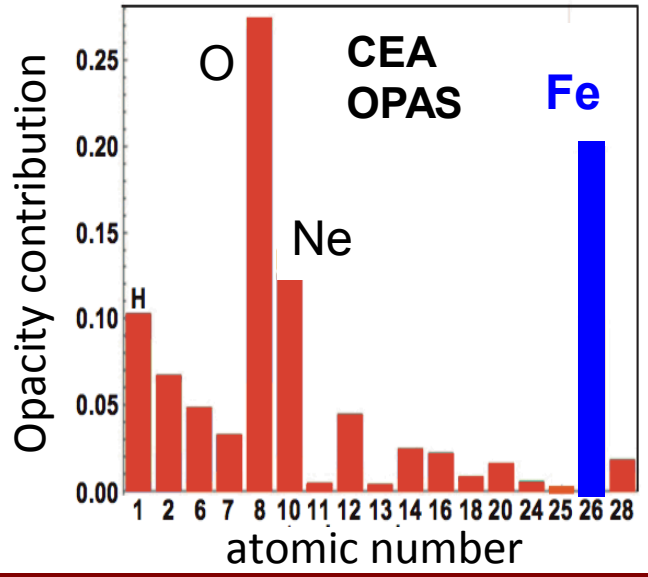
- Quantifies radiation absorption
- $\kappa_\nu(T_e, n_e)$ … input for solar models
- Opacity models have never been tested

Solar mixture opacity at Convection Zone Base (CZB)



17% mean-opacity increase in the solar model is needed to resolve this discrepancy





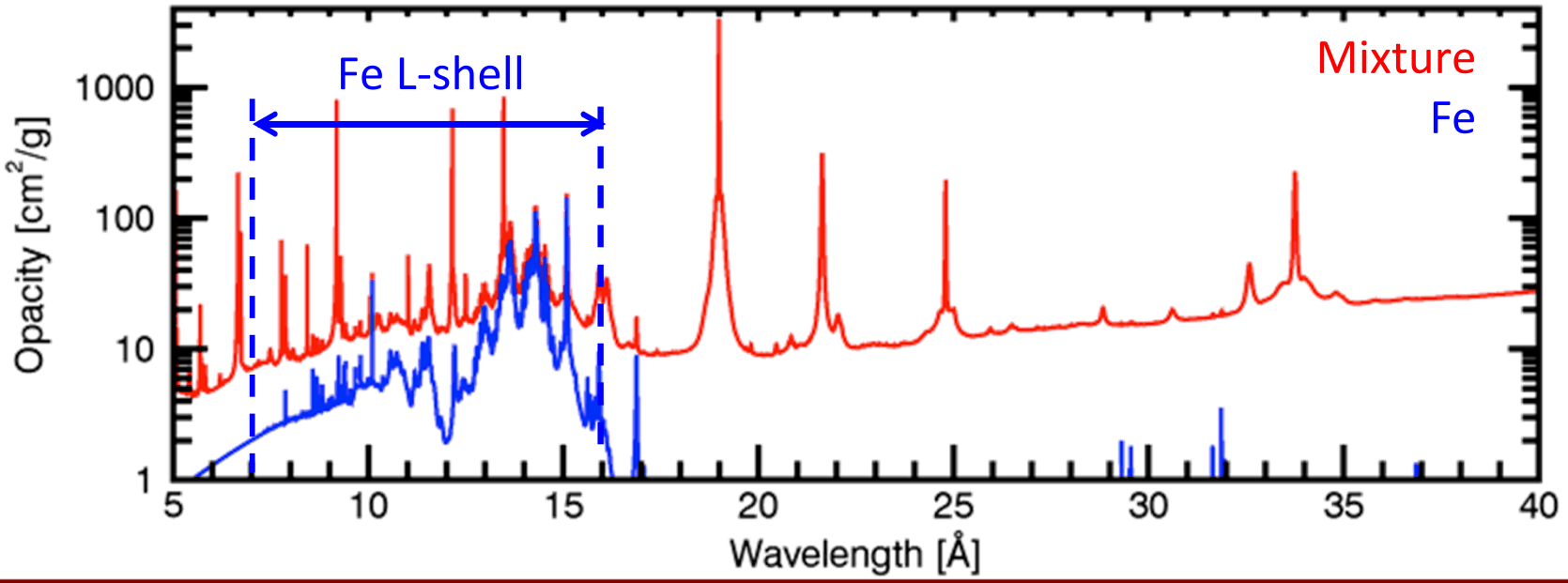
Opacity: κ_ν

- Quantifies radiation absorption
- $\kappa_\nu(T_e, n_e)$ … input for solar models
- Opacity models have never been tested

Fe is a likely suspect:

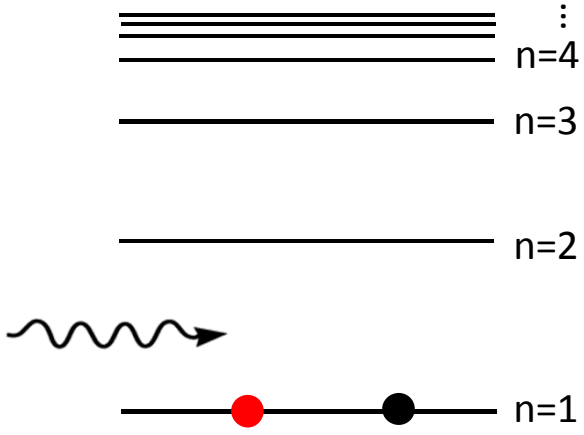
- 2nd largest contribution
- Most difficult to model

Solar mixture opacity at Convection Zone Base (CZB)

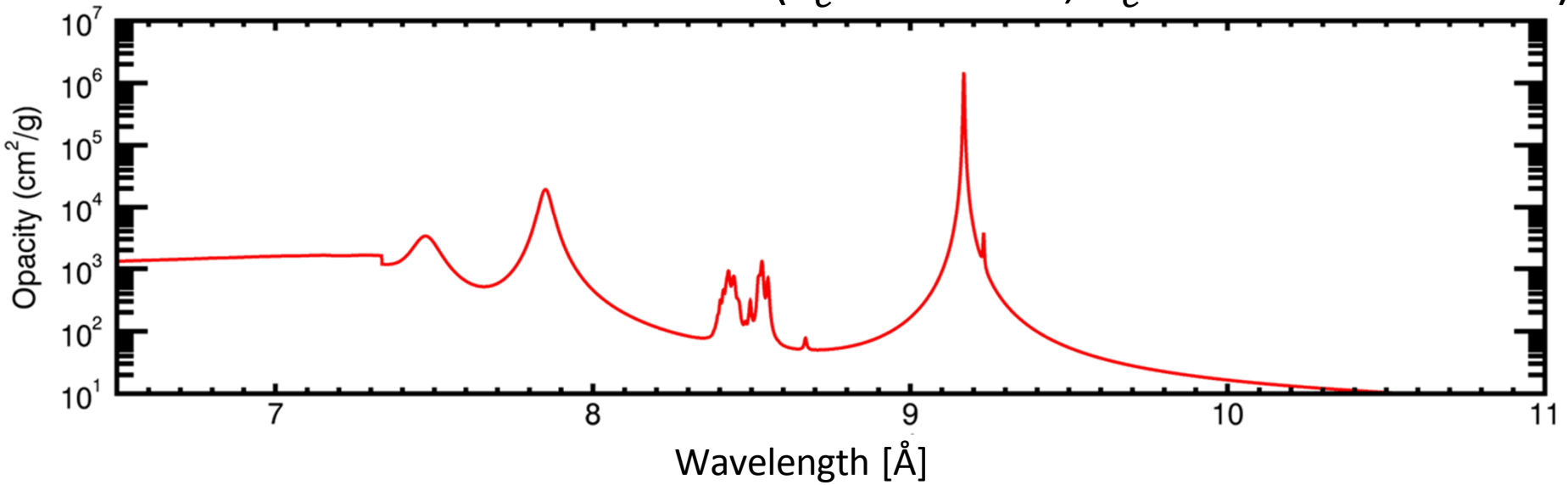


Opacity calculation at Convection-Zone Base is easier for lower atomic number elements

Mg at CZB (Z=12)



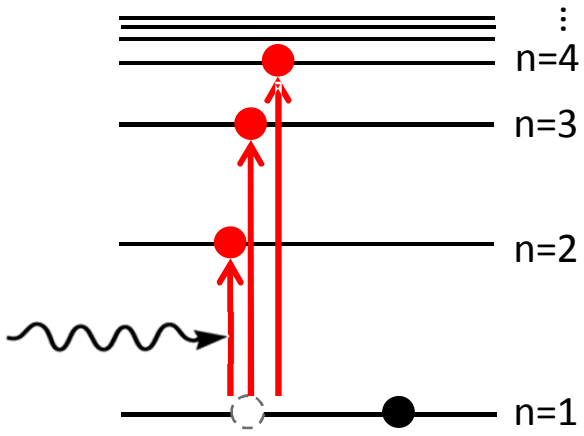
CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



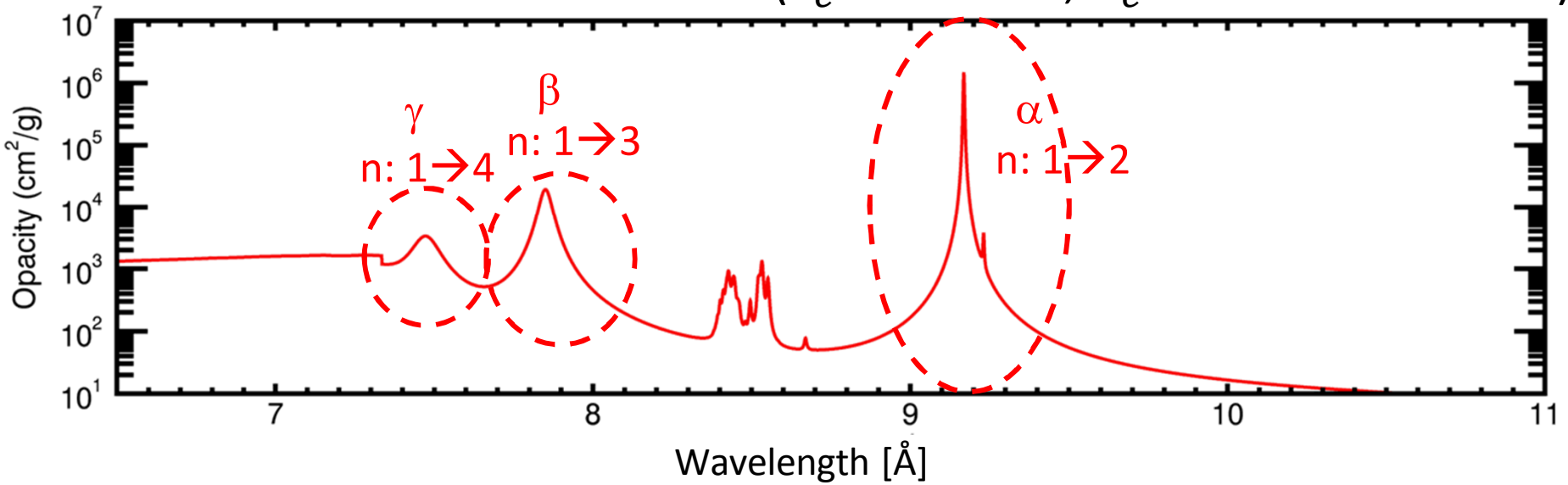
Opacity calculation at Convection-Zone Base is easier for lower atomic number elements

Sandia National Laboratories

Mg at CZB (Z=12)



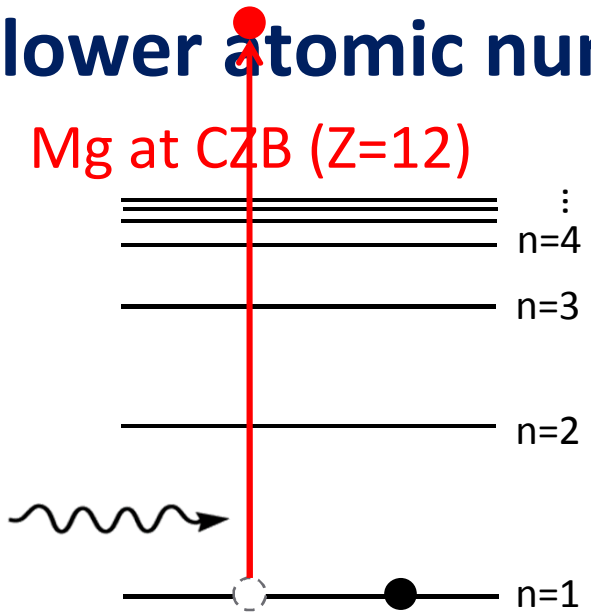
CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



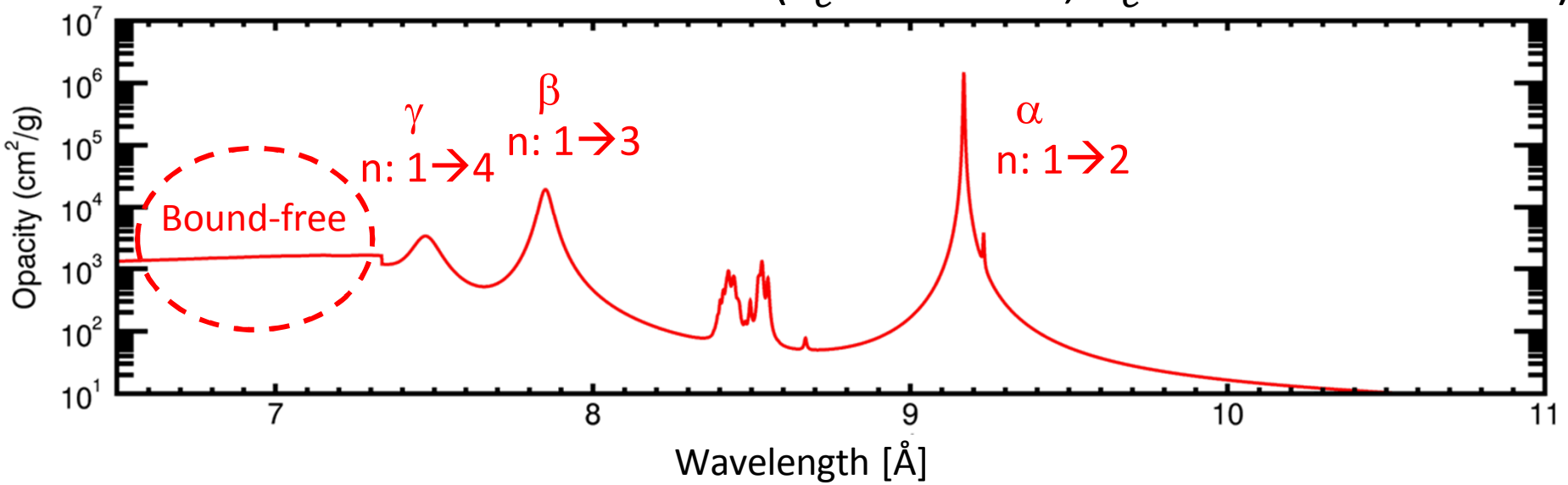
Opacity calculation at Convection-Zone Base is easier for lower atomic number elements

Sandia National Laboratories

Mg at CZB (Z=12)

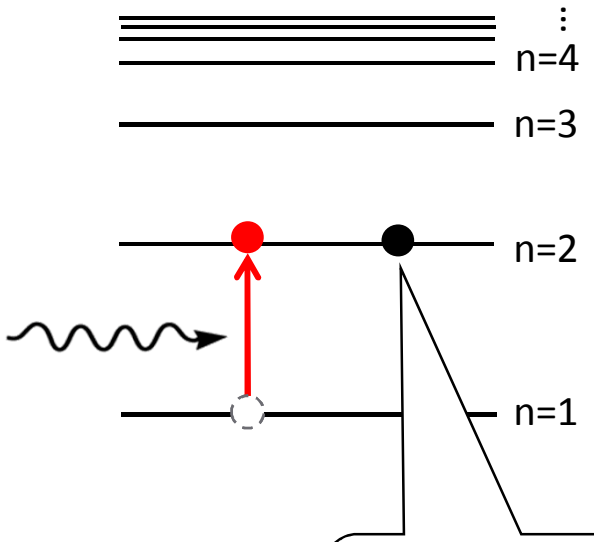


CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



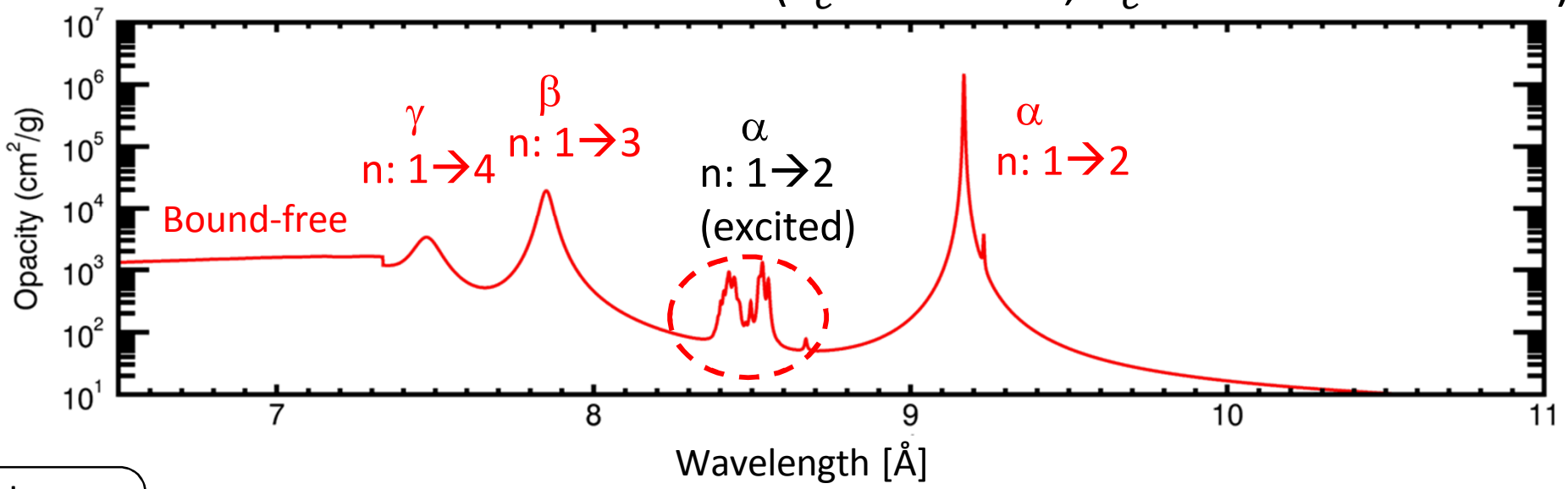
Opacity calculation at Convection-Zone Base is easier for lower atomic number elements

Mg at CZB (Z=12)



Spectator electron affects the transition energies

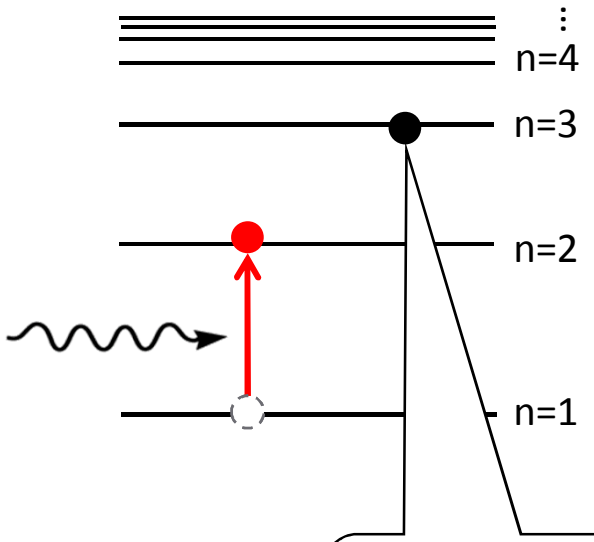
CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



Opacity calculation at Convection-Zone Base is easier for lower atomic number elements

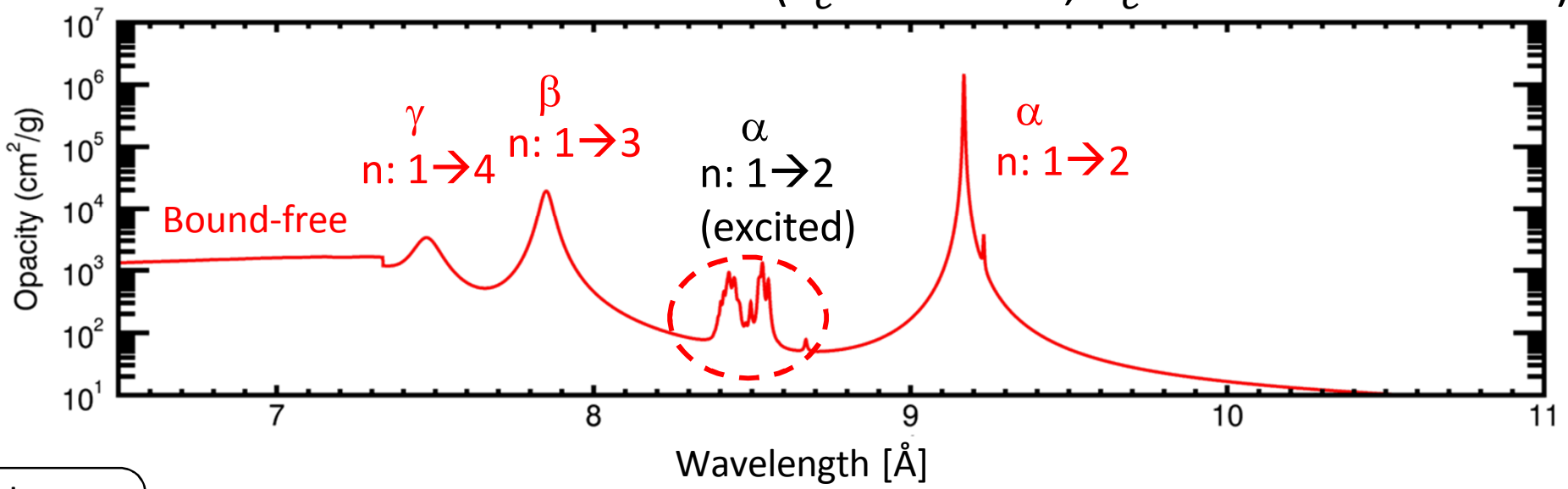
Sandia National Laboratories

Mg at CZB (Z=12)



Spectator electron affects the transition energies

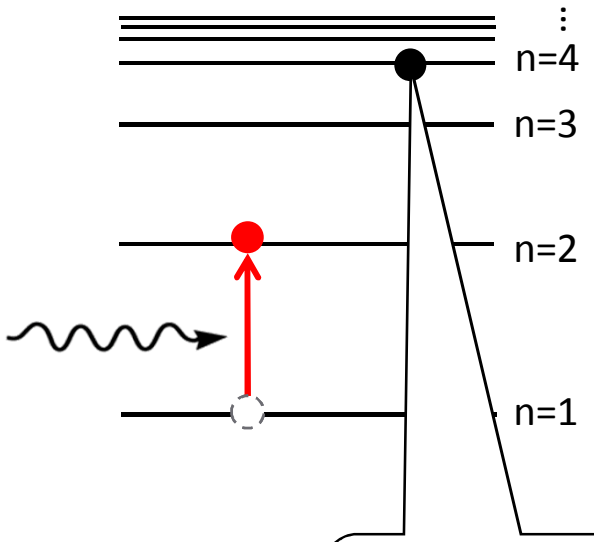
CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



Opacity calculation at Convection-Zone Base is easier for lower atomic number elements

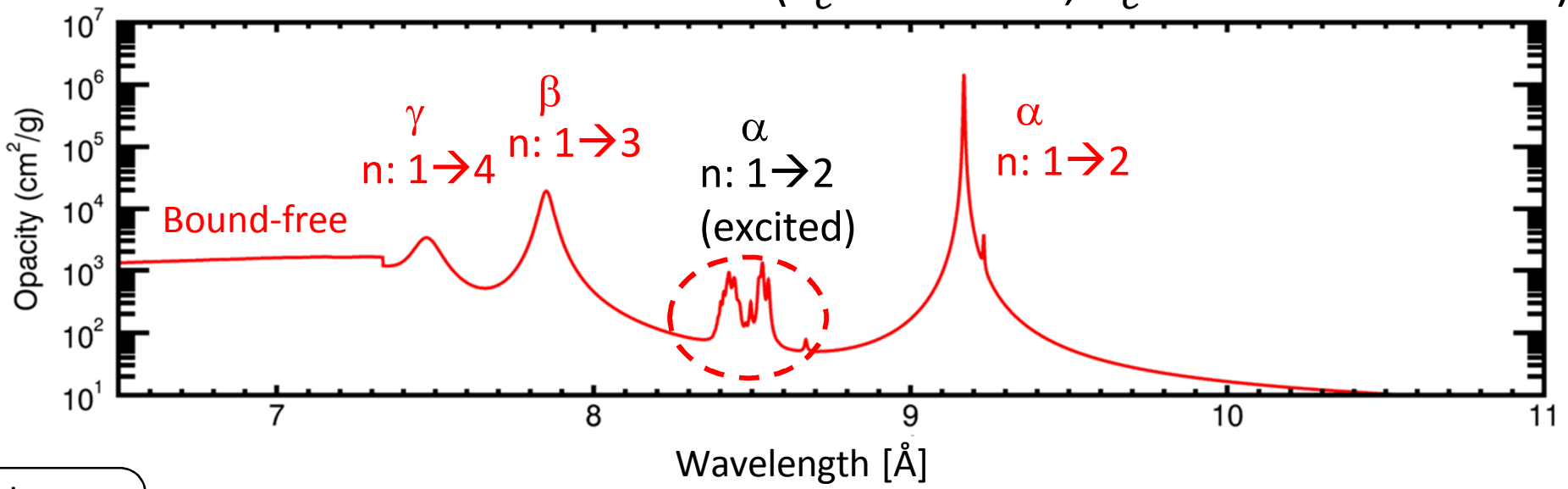
Sandia National Laboratories

Mg at CZB (Z=12)



Spectator electron affects the transition energies

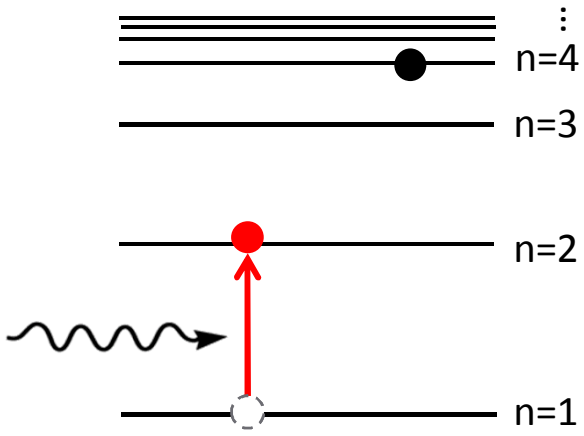
CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



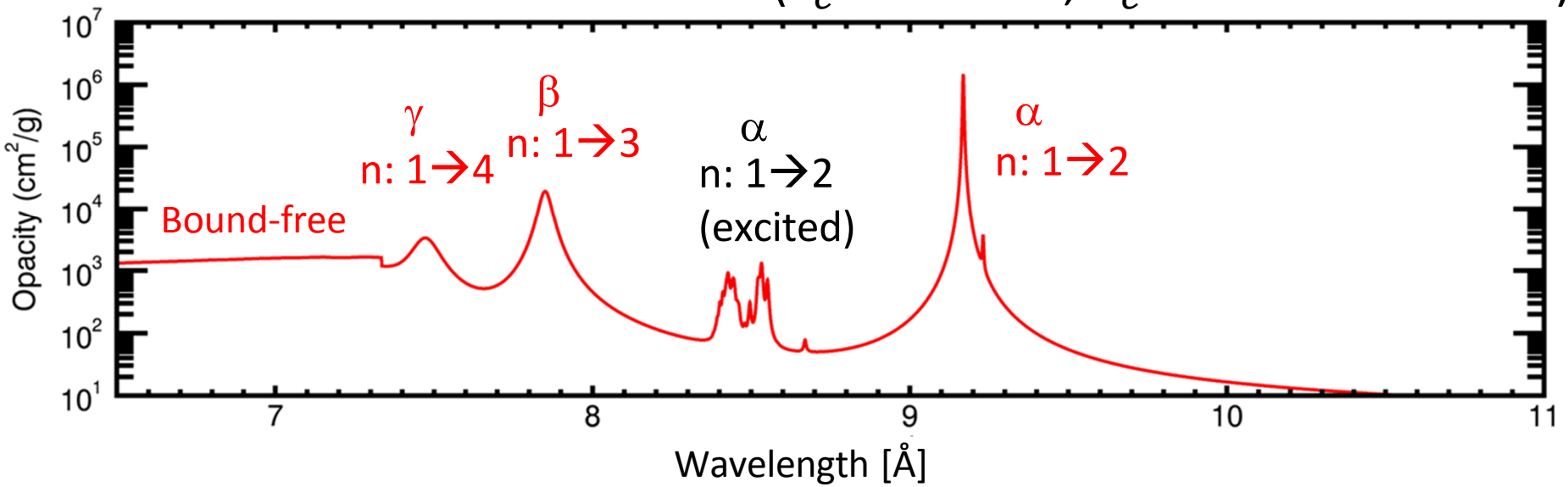
Opacity calculation at Convection-Zone Base is easier for lower atomic number elements

Sandia National Laboratories

Mg at CZB (Z=12)



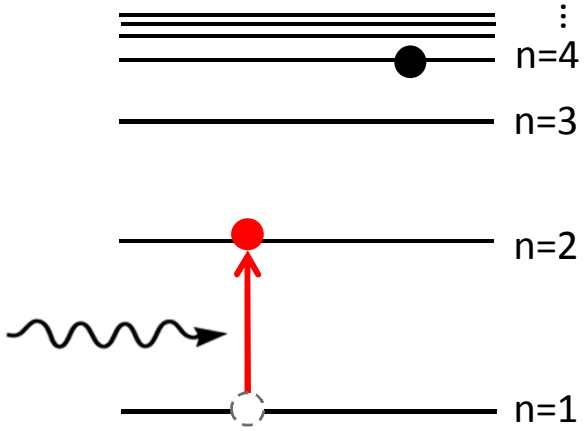
CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



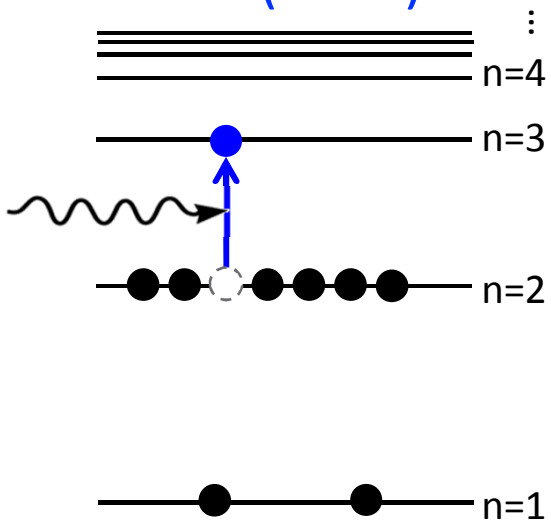
Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

Sandia National Laboratories

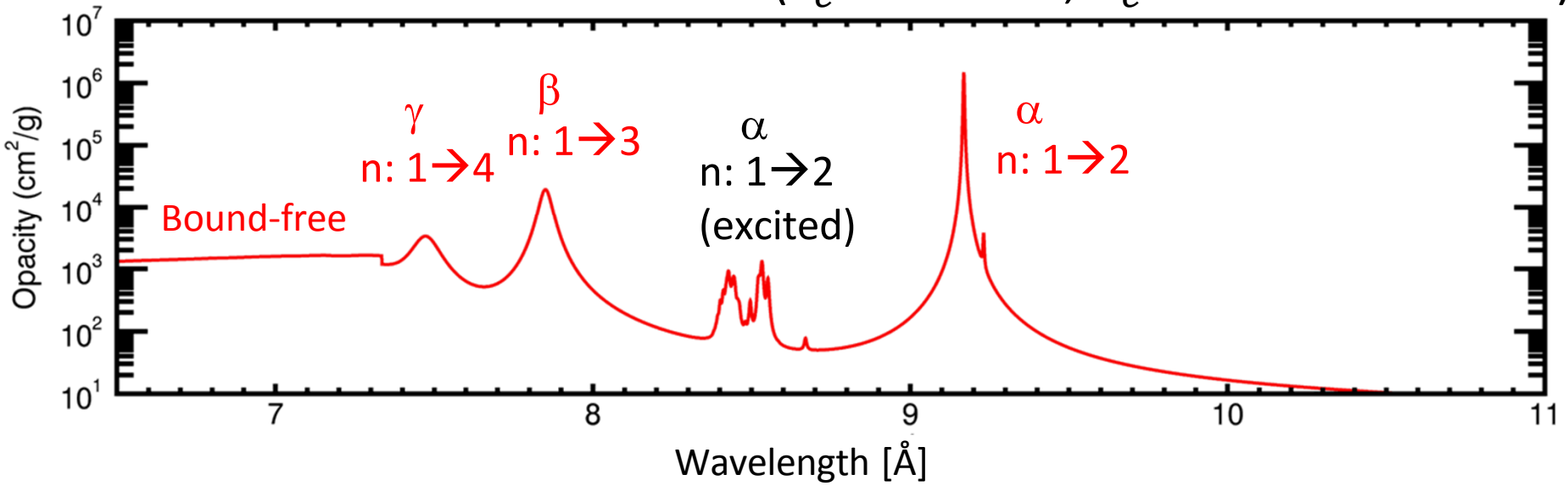
Mg at CZB (Z=12)



Fe at CZB (Z=26)



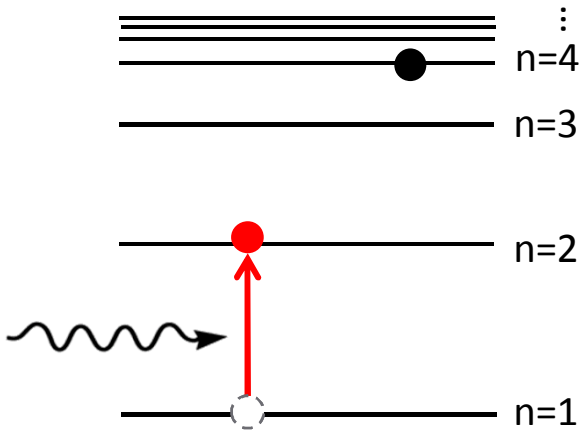
CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



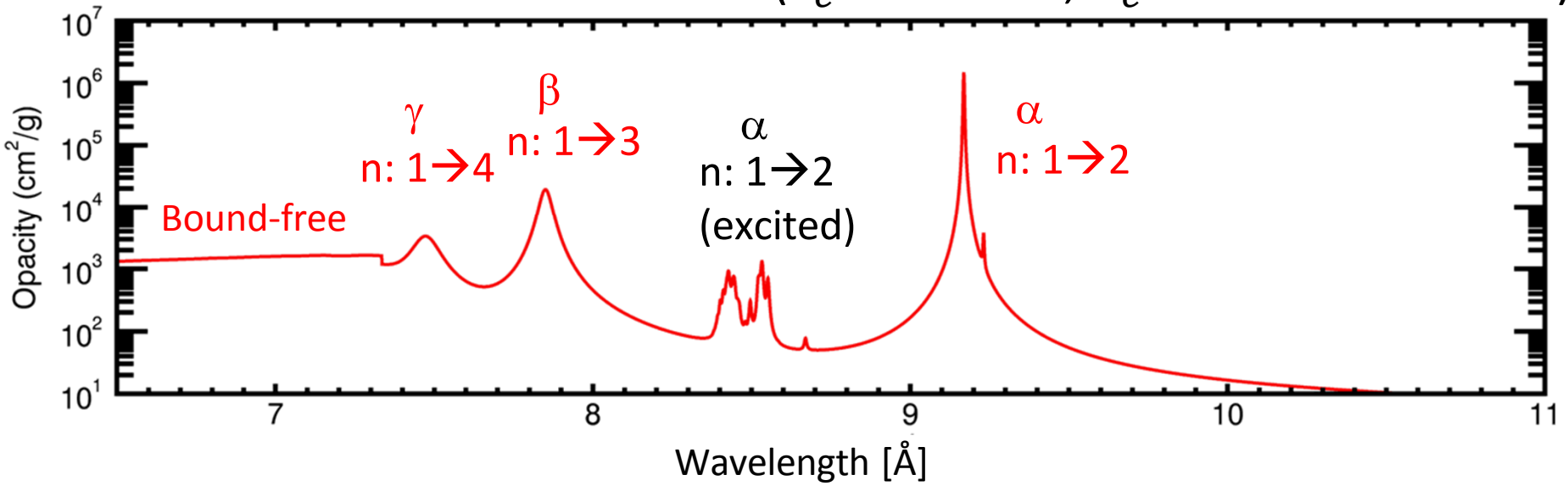
Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

Sandia National Laboratories

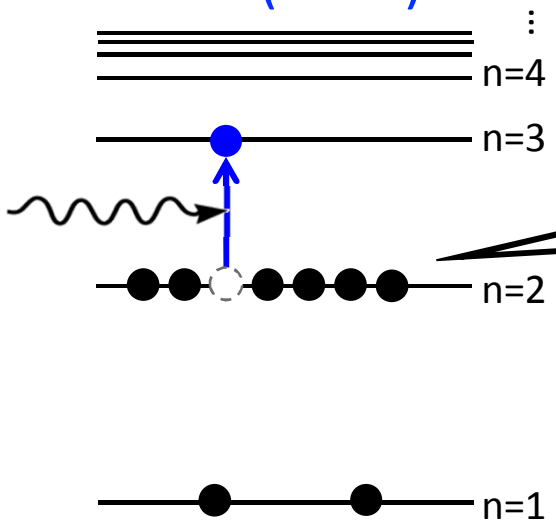
Mg at CZB (Z=12)



CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



Fe at CZB (Z=26)

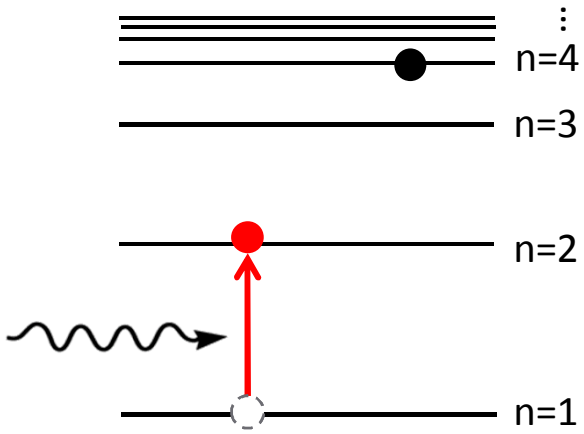


- So many spectator electrons!

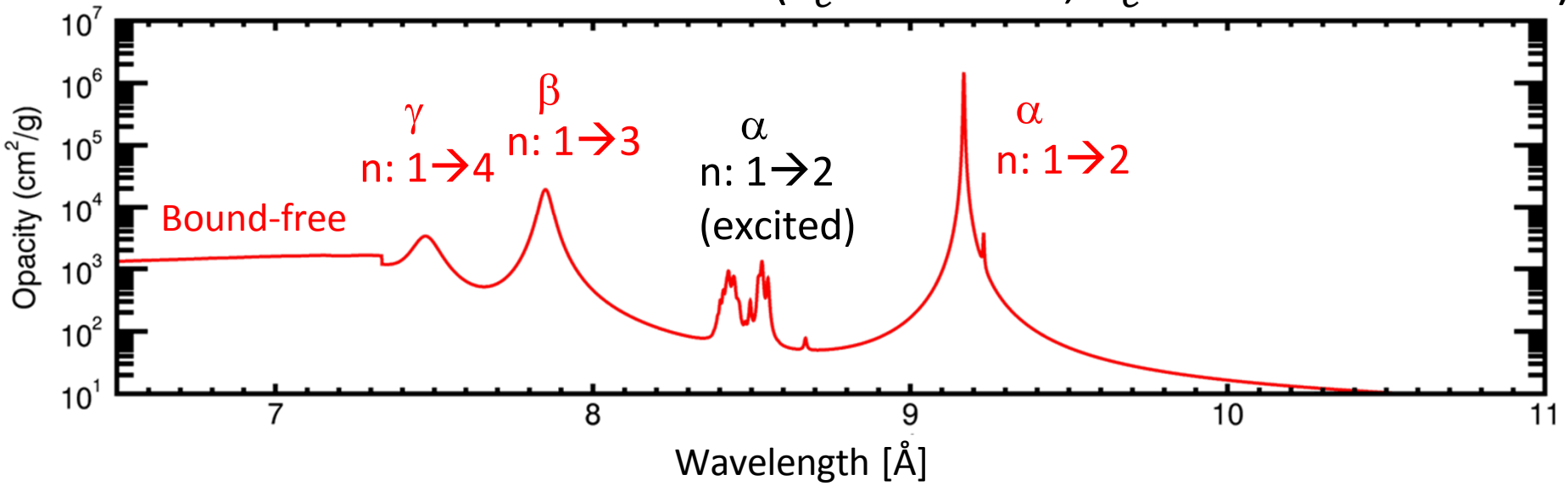
Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

Sandia National Laboratories

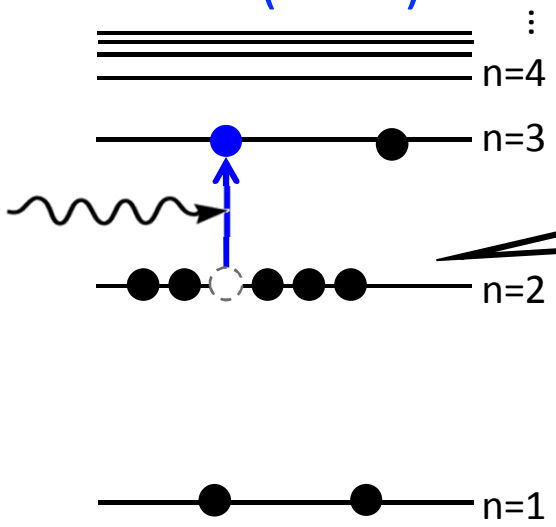
Mg at CZB (Z=12)



CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



Fe at CZB (Z=26)

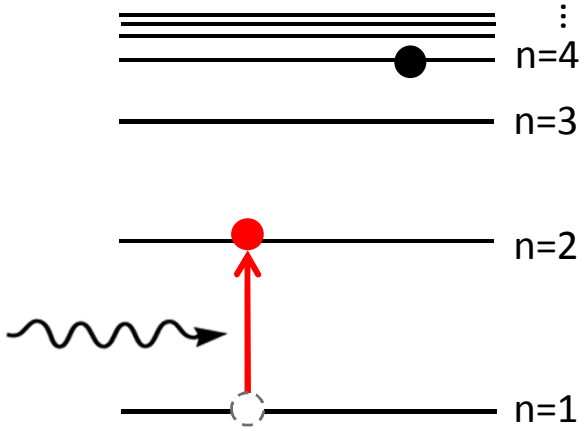


- So many spectator electrons!

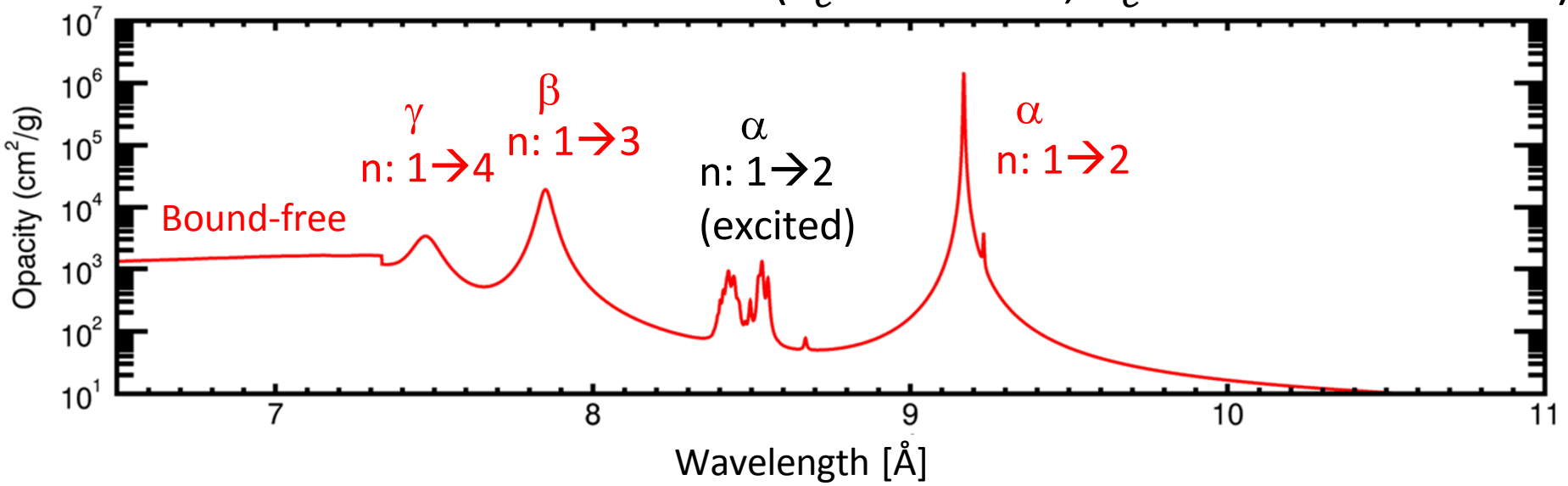
Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

Sandia National Laboratories

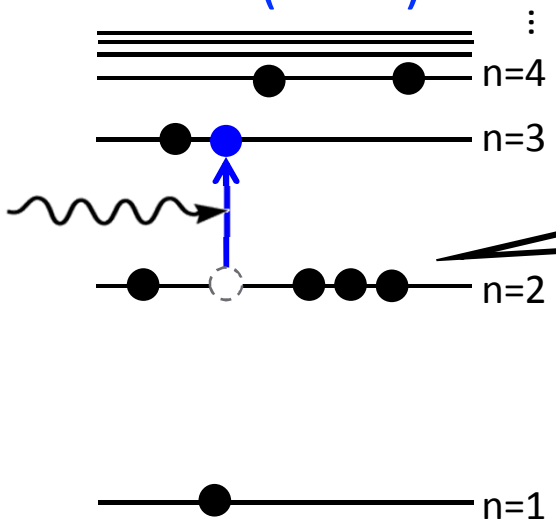
Mg at CZB (Z=12)



CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



Fe at CZB (Z=26)

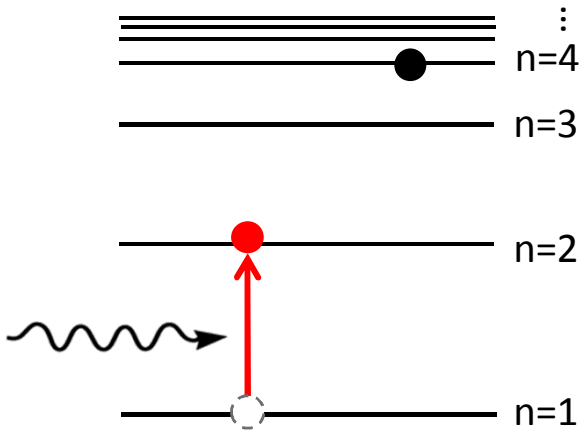


- So many spectator electrons!

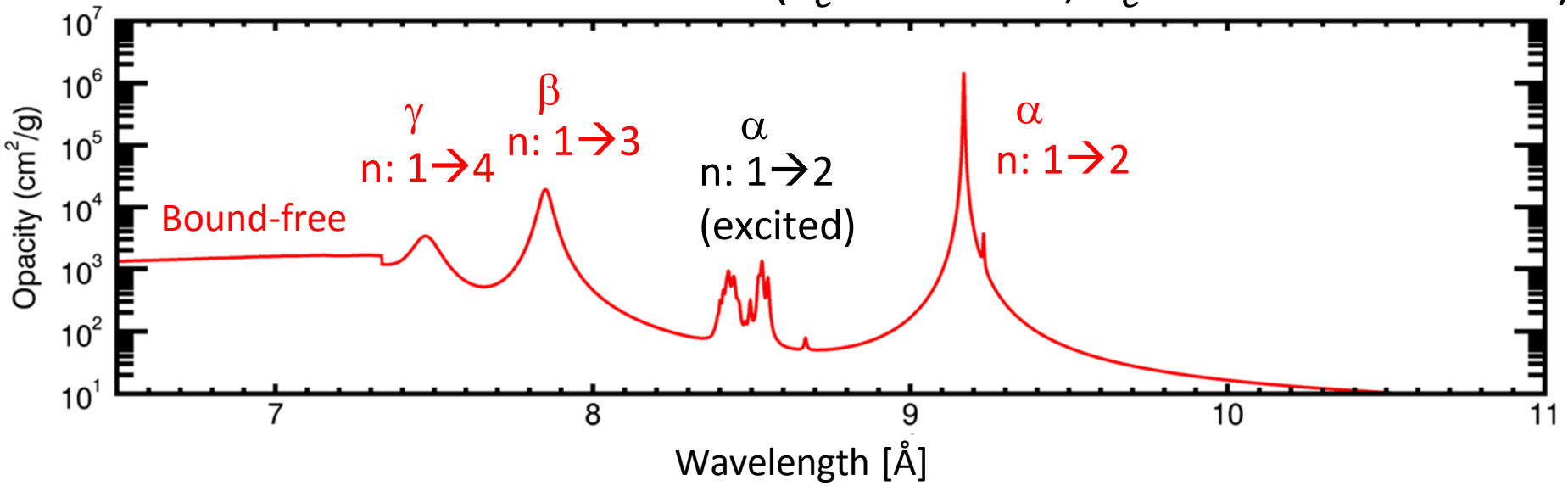
Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

Sandia National Laboratories

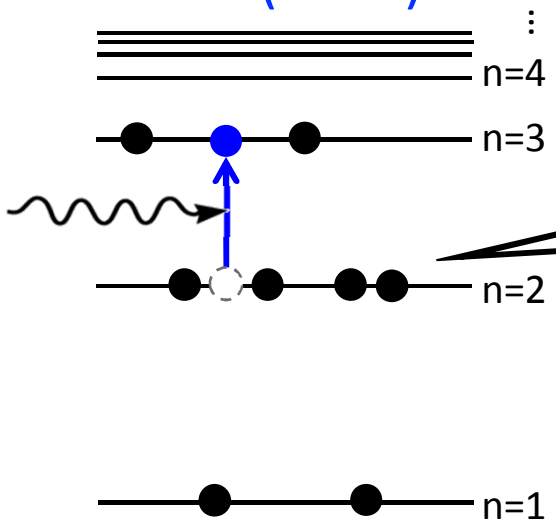
Mg at CZB (Z=12)



CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



Fe at CZB (Z=26)

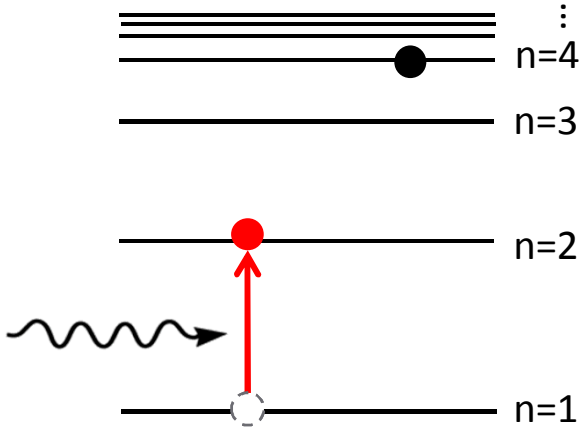


- So many spectator electrons!

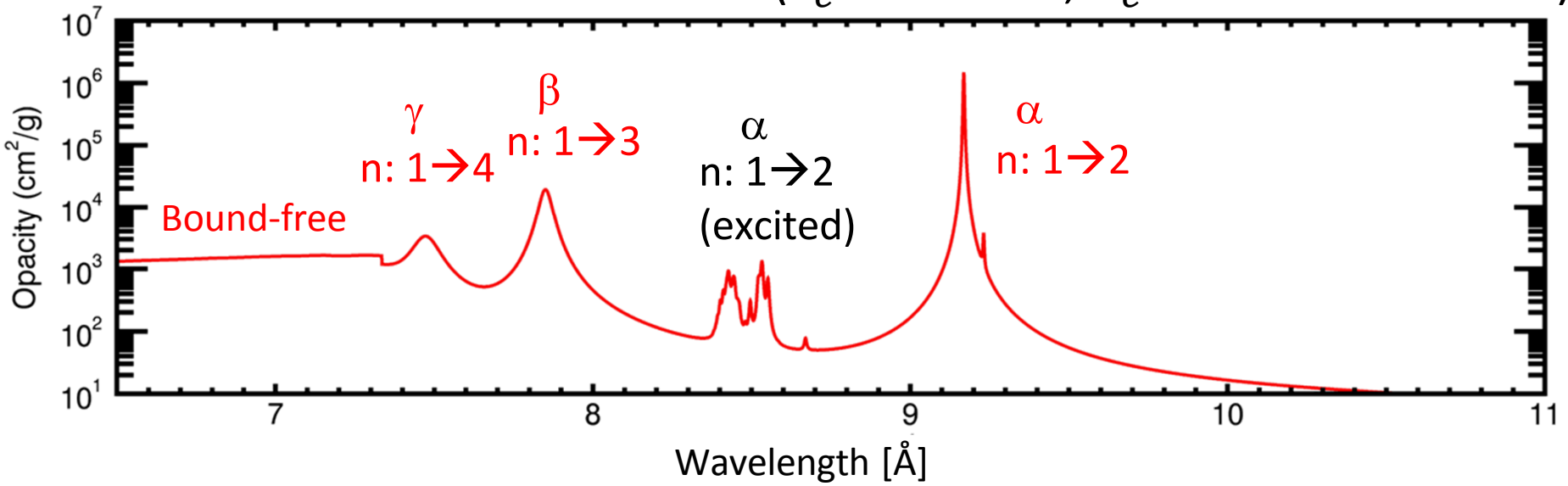
Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

Sandia National Laboratories

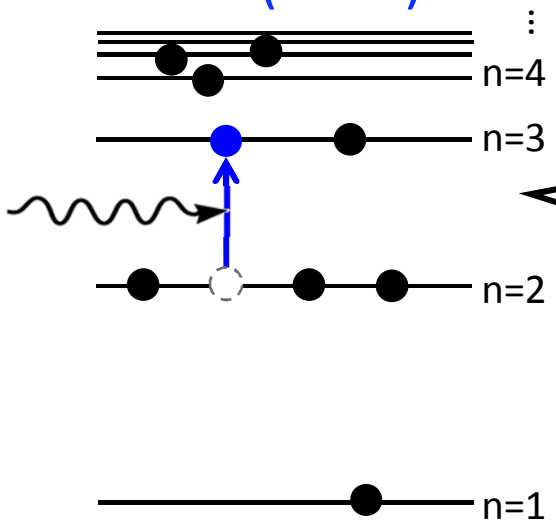
Mg at CZB (Z=12)



CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



Fe at CZB (Z=26)

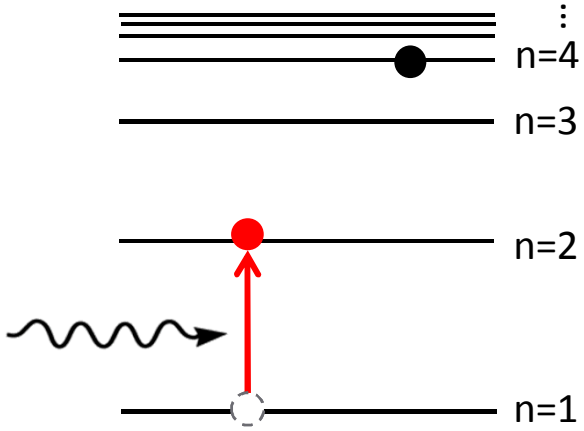


- So many spectator electrons!
- Tremendous contributions from excited states!

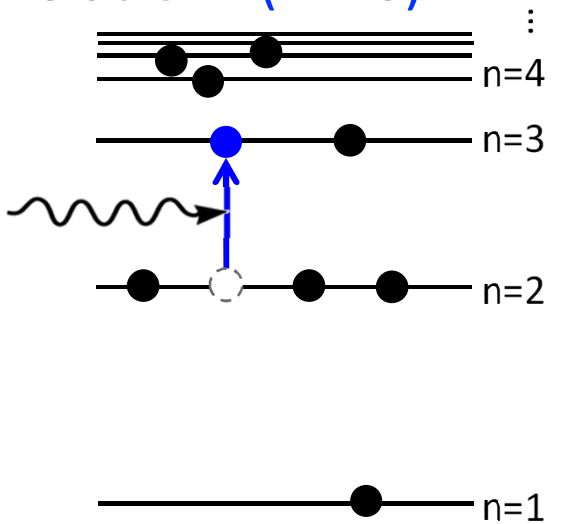
Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

Sandia National Laboratories

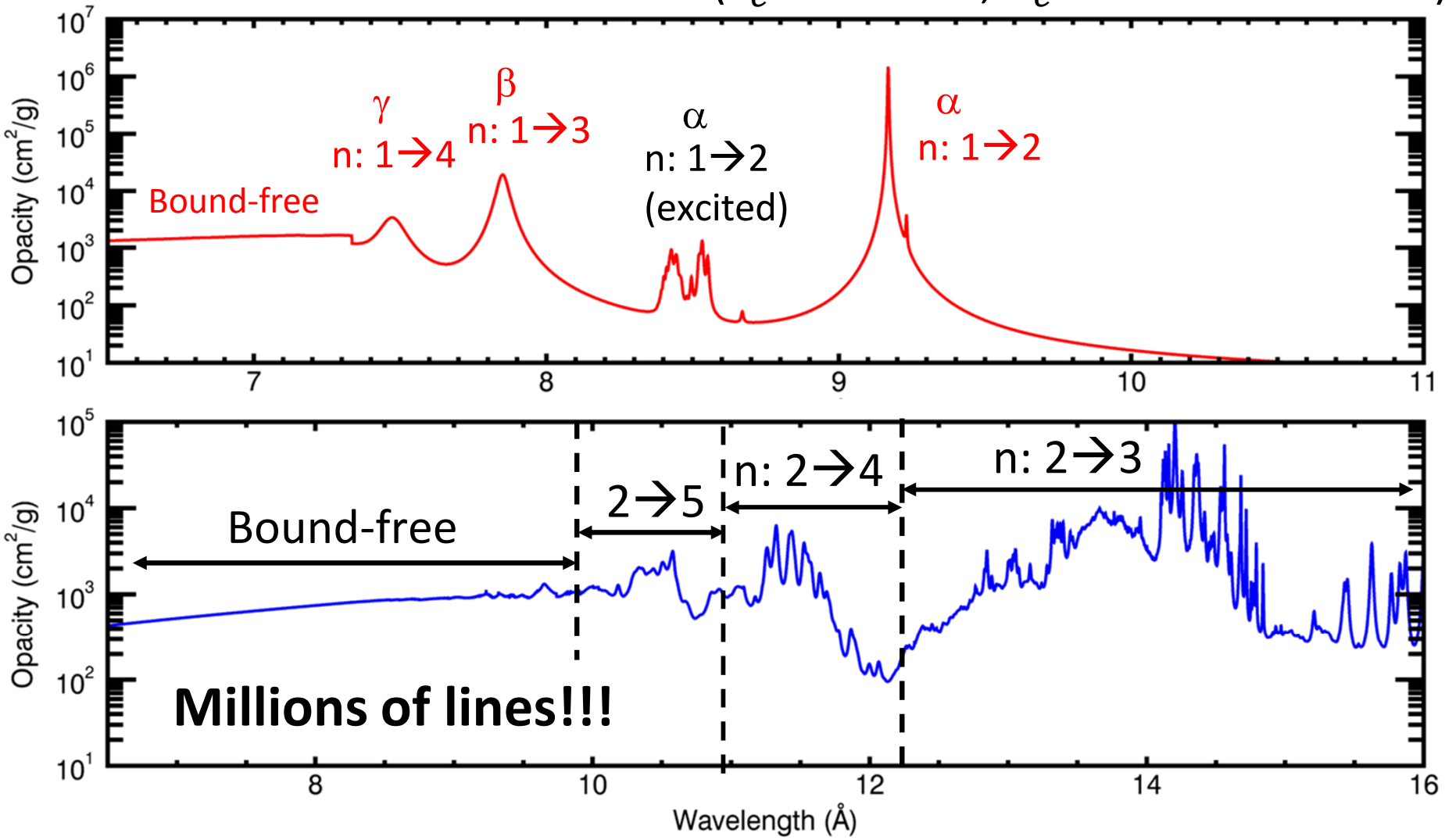
Mg at CZB (Z=12)



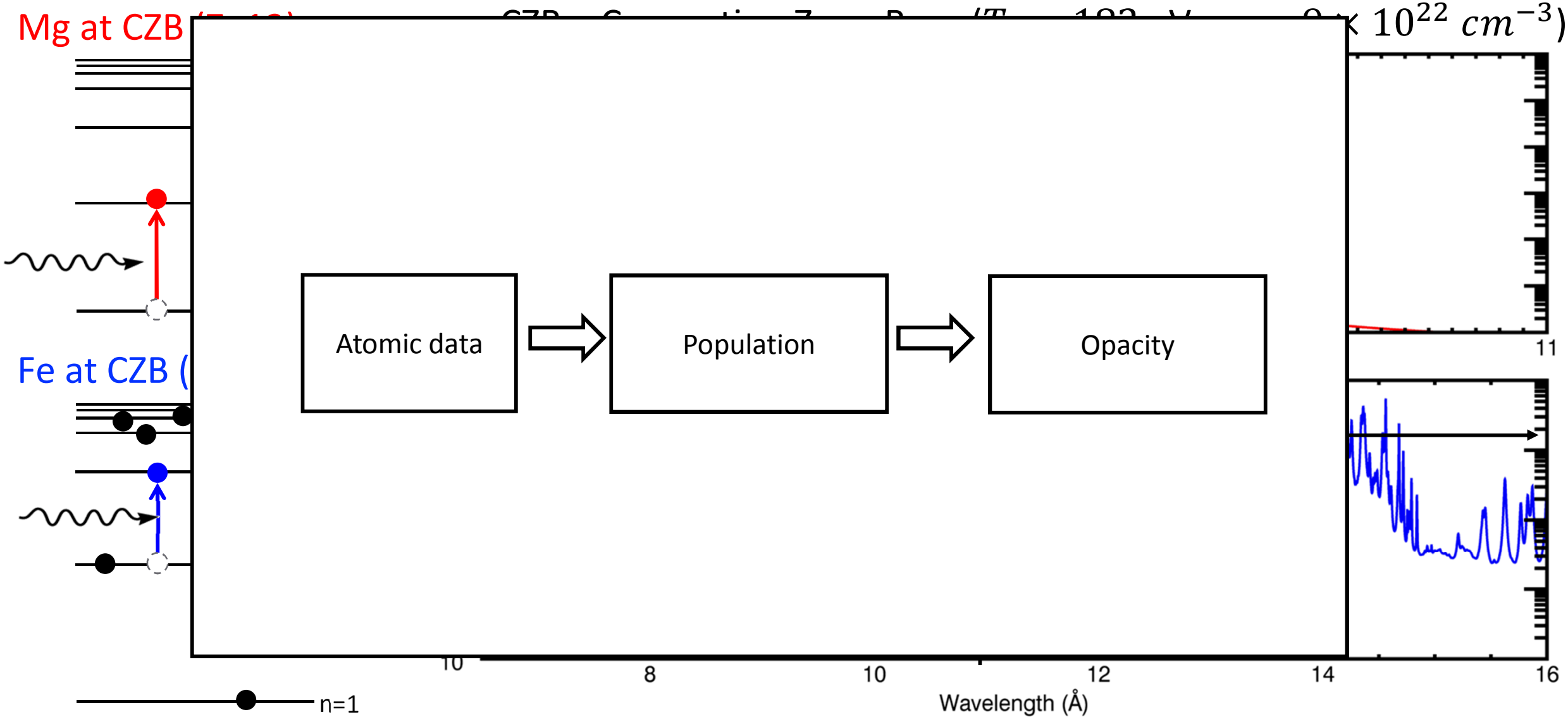
Fe at CZB (Z=26)



CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)

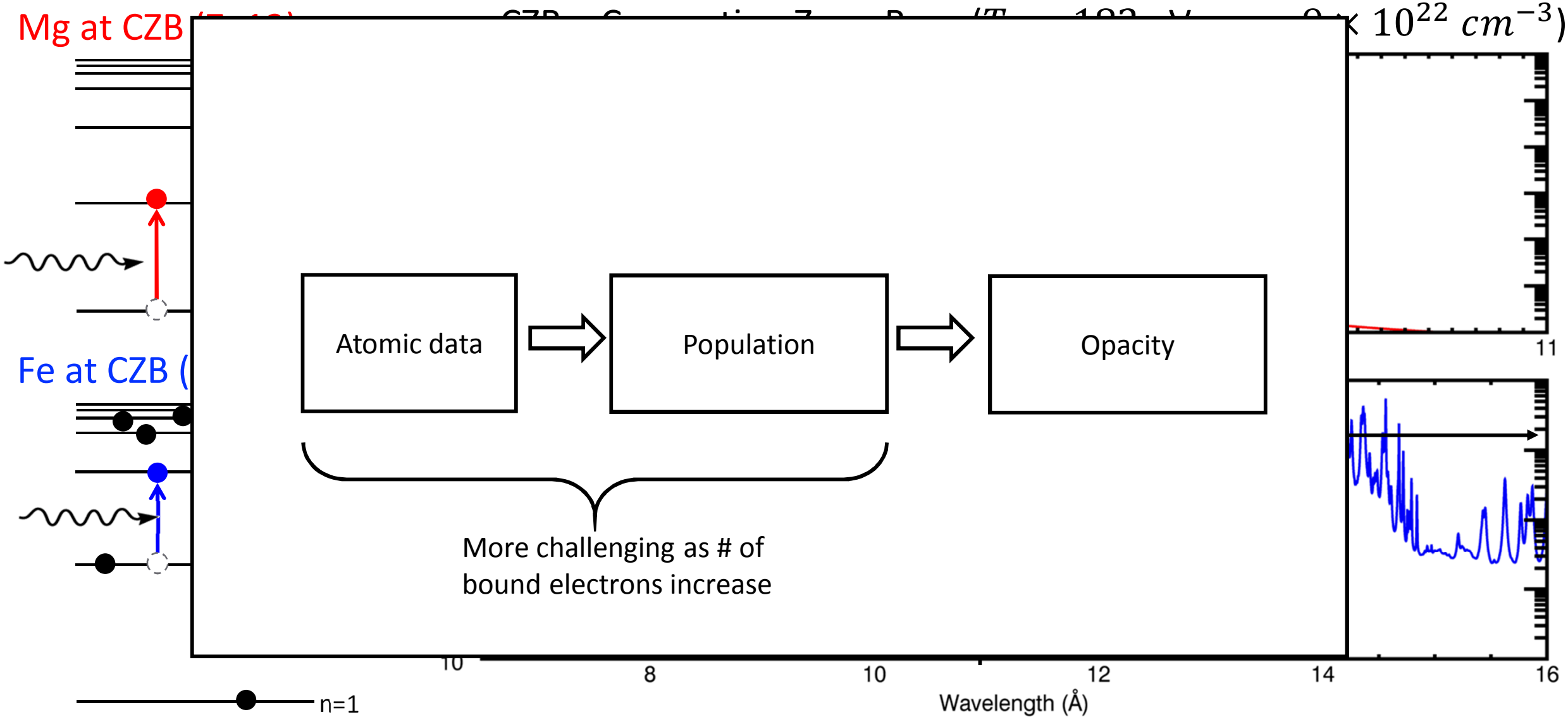


Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states



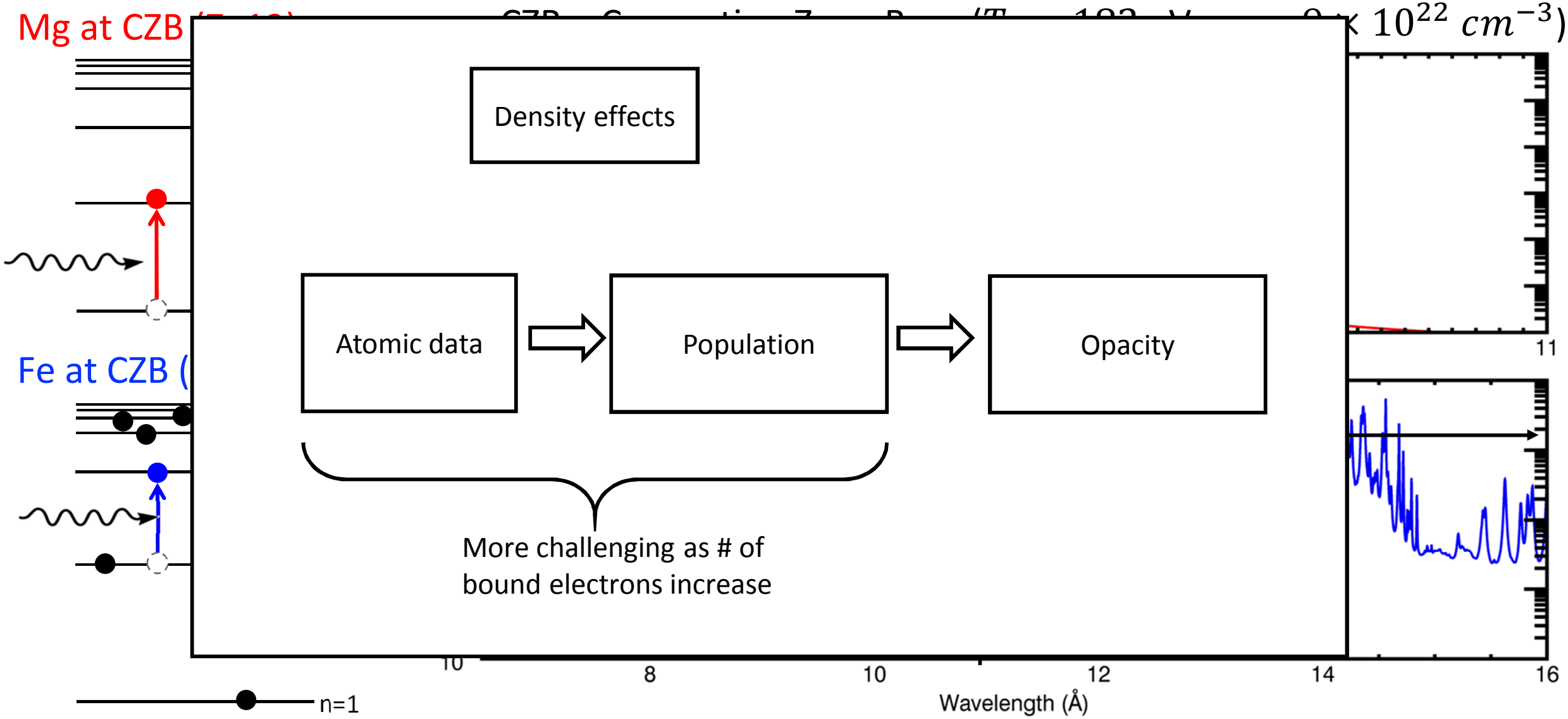
Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

Sandia National Laboratories



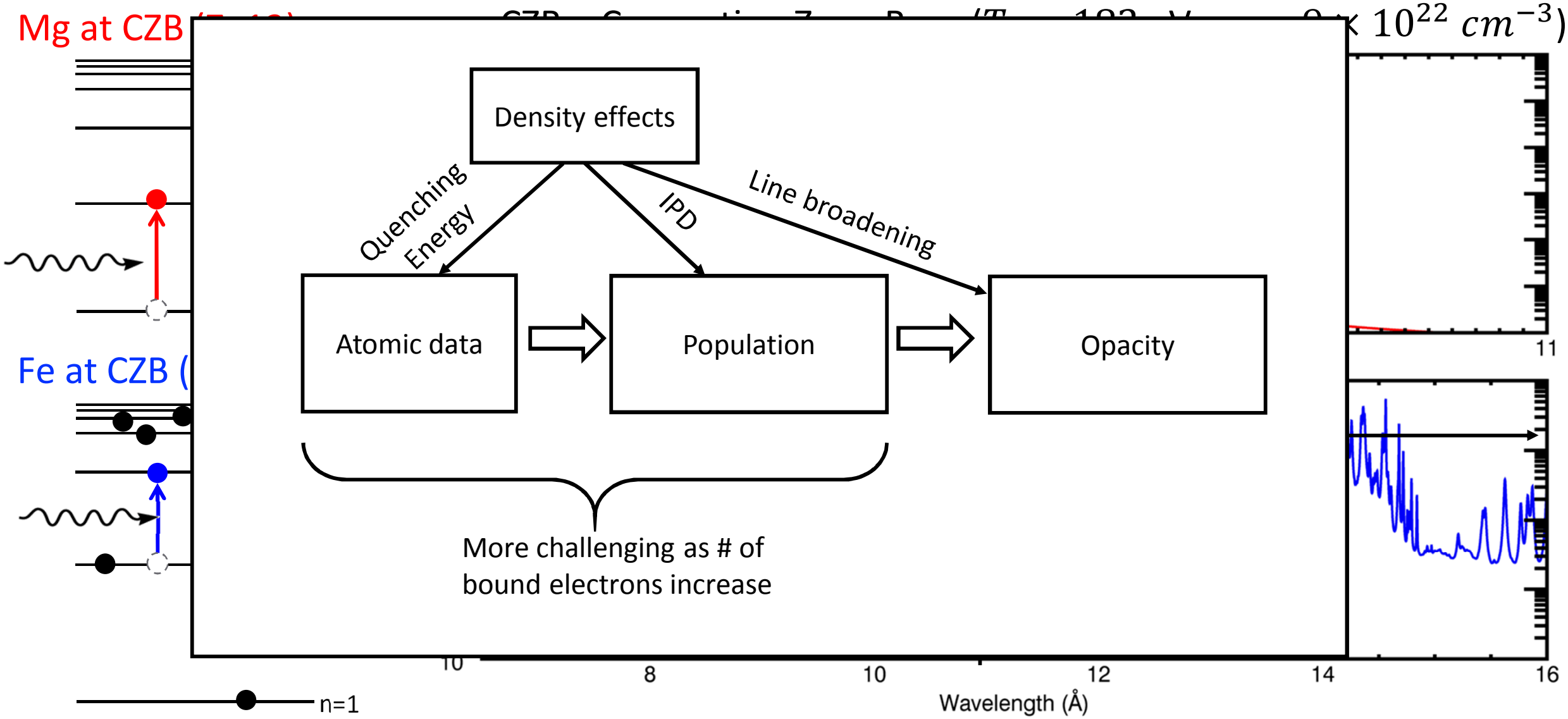
Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

Sandia National Laboratories



Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

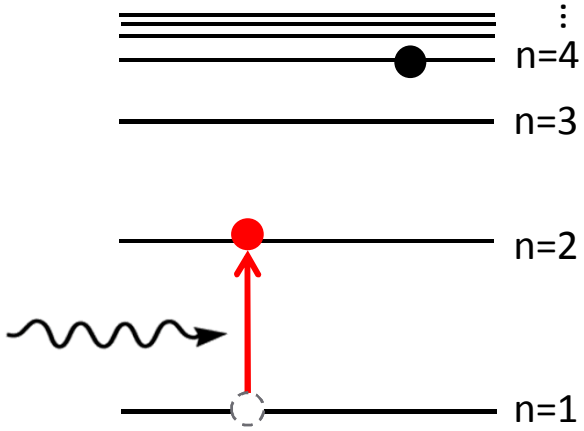
Sandia National Laboratories



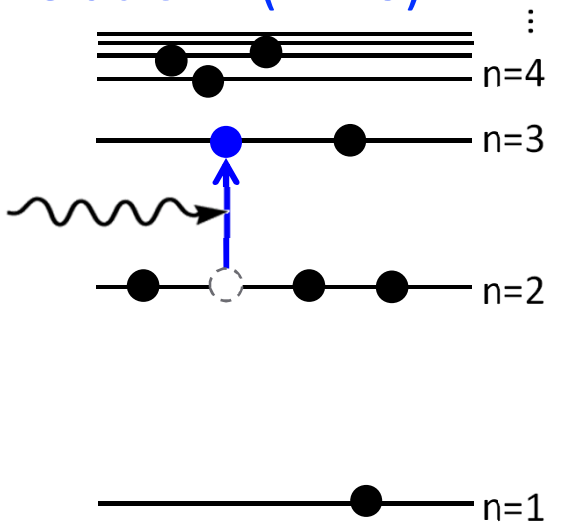
Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

Sandia National Laboratories

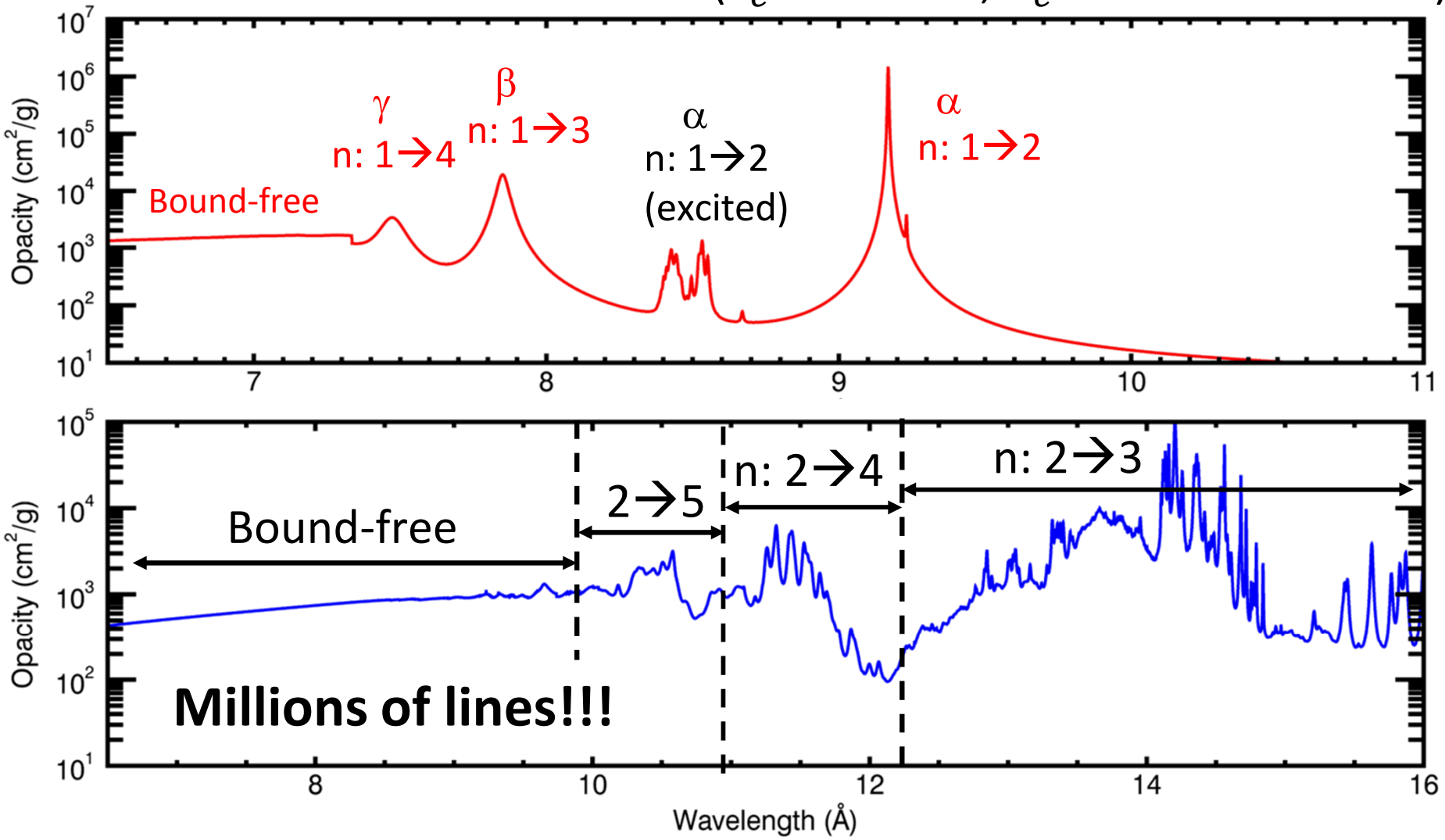
Mg at CZB (Z=12)



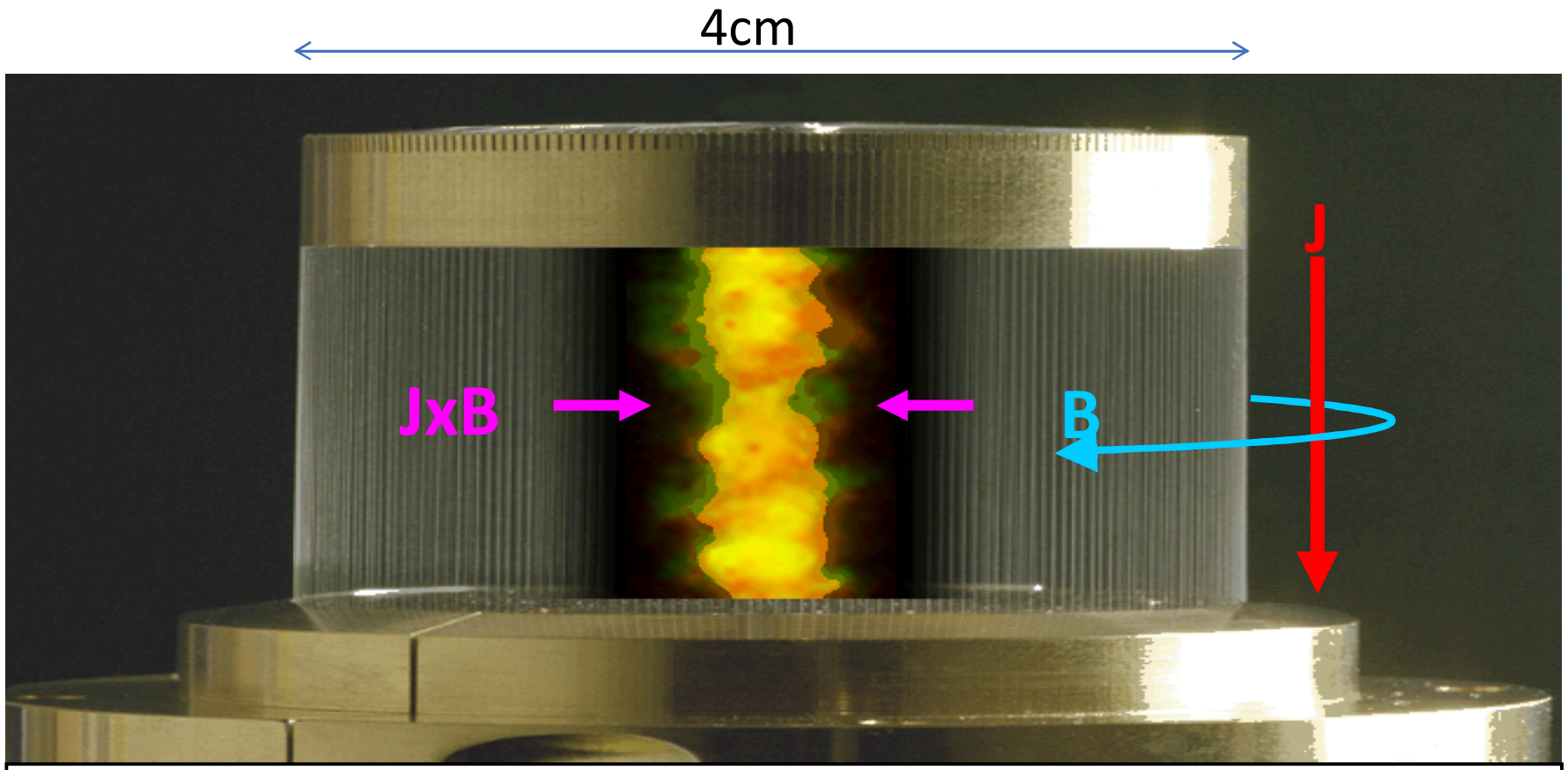
Fe at CZB (Z=26)



CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



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



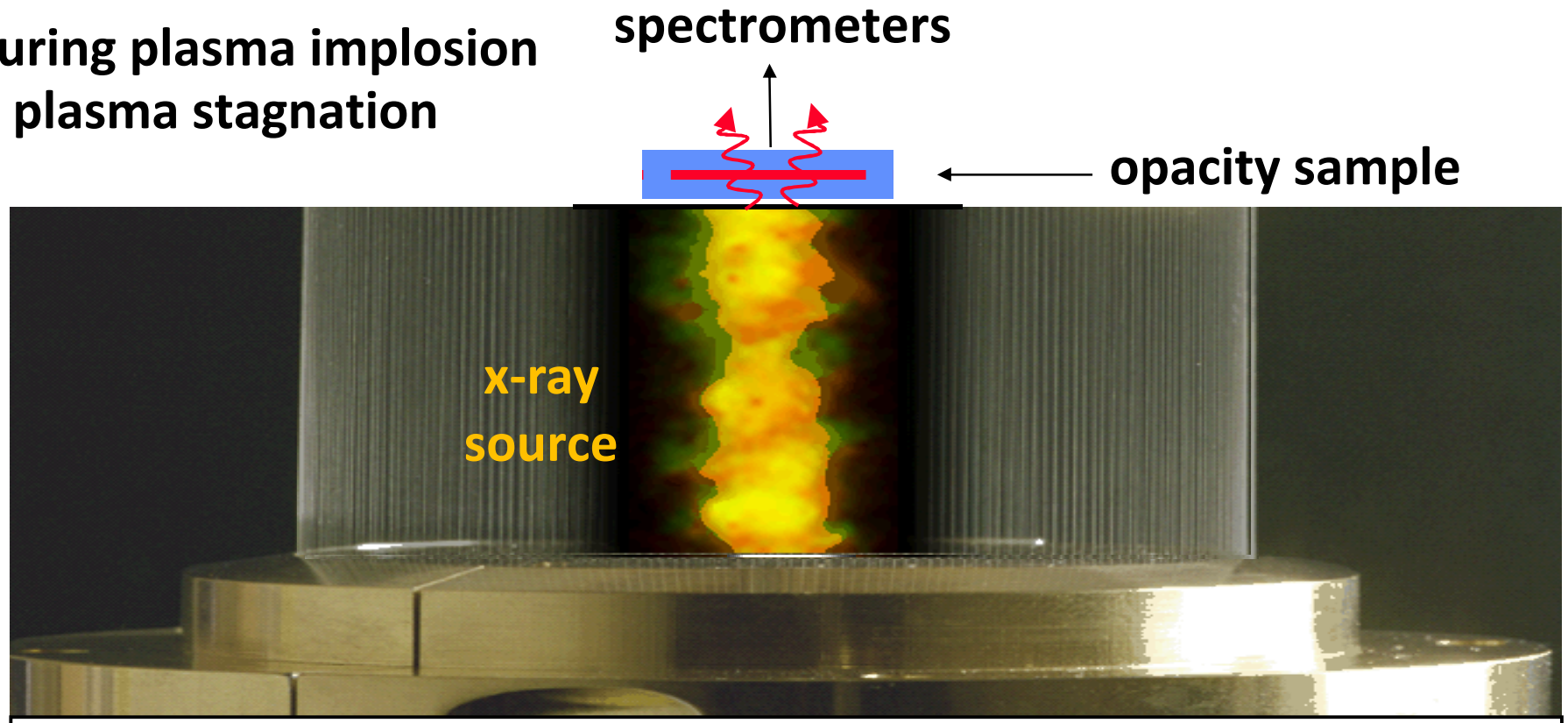
P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

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

Sandia National Laboratories

Sample is:

- **Heated during plasma implosion**
- **Backlit at plasma stagnation**



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

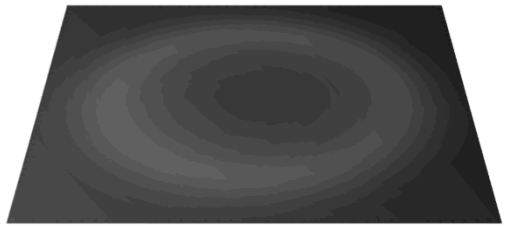
Sanford, PoP (2002); Bailey et al,PoP (2006); Slutz et al., PoP (2006); Rochau et al., PPCF(2007)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform

Sandia National Laboratories

Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements

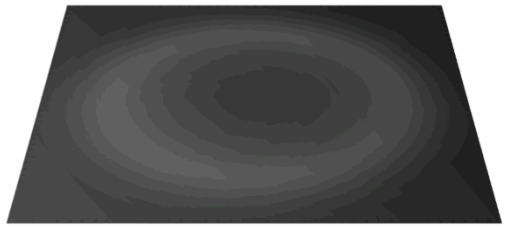


Z-pinch radiation source

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform



Z-pinch radiation source

Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements

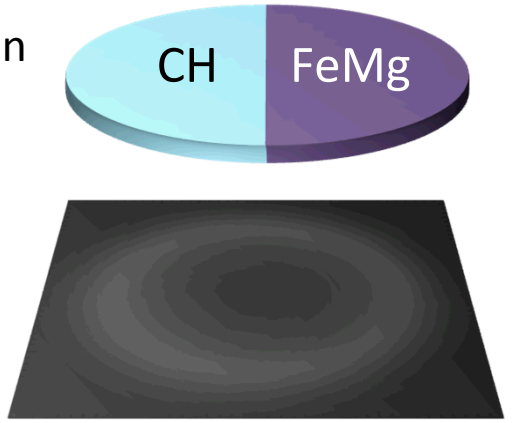
[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform

Sandia National Laboratories

Half-moon sample



Z-pinch radiation source

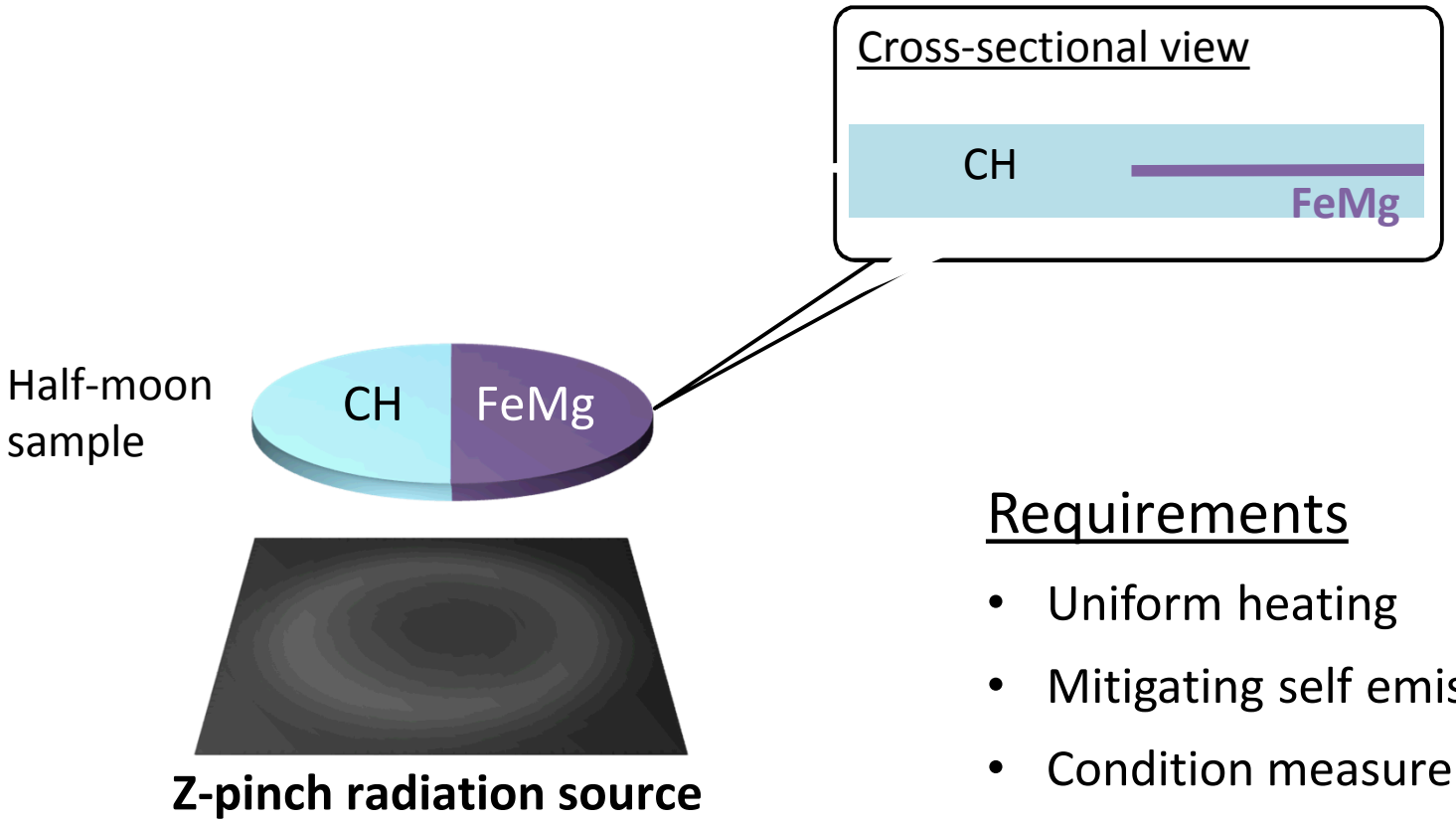
Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform



Requirements

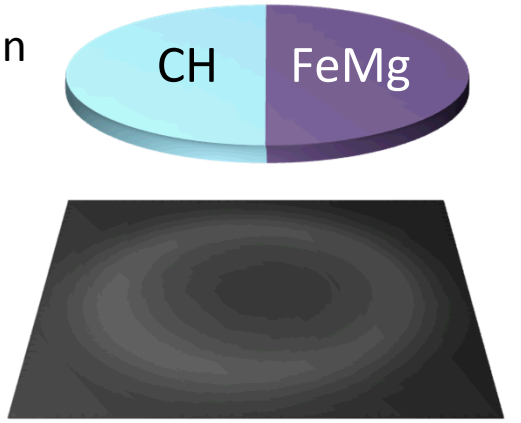
- Uniform heating
- Mitigating self emission
- Condition measurements

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)
[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform

Sandia National Laboratories

Half-moon sample



Z-pinch radiation source

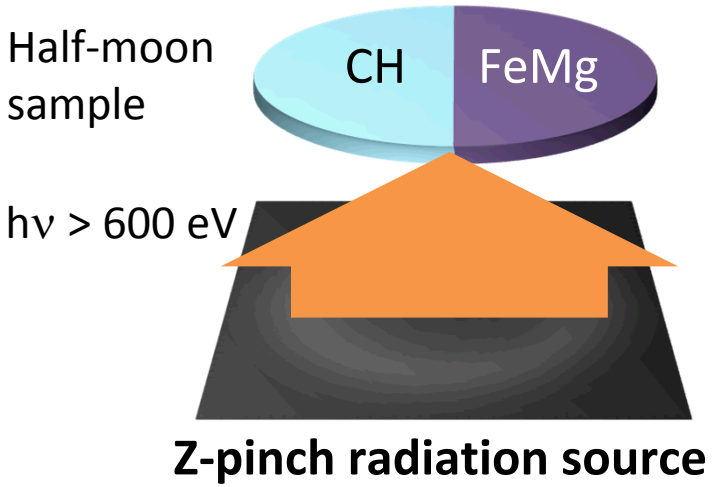
Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform

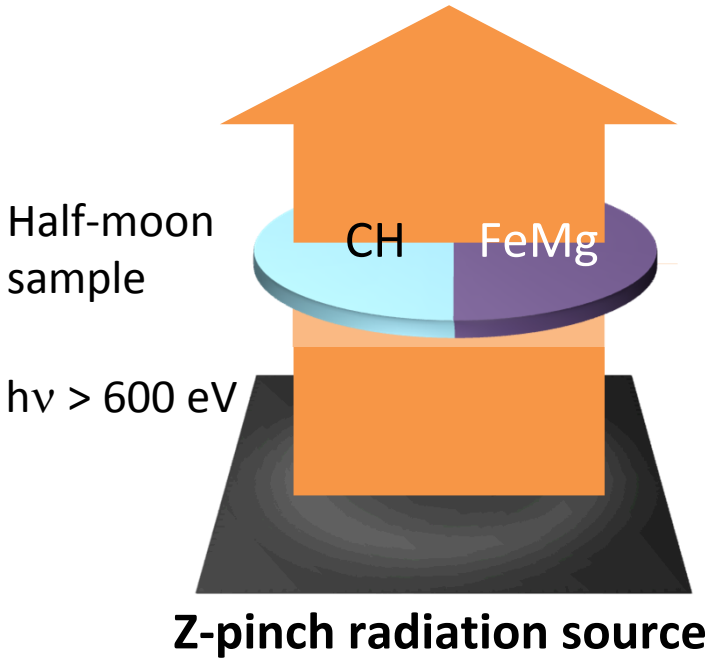


Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)
[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform

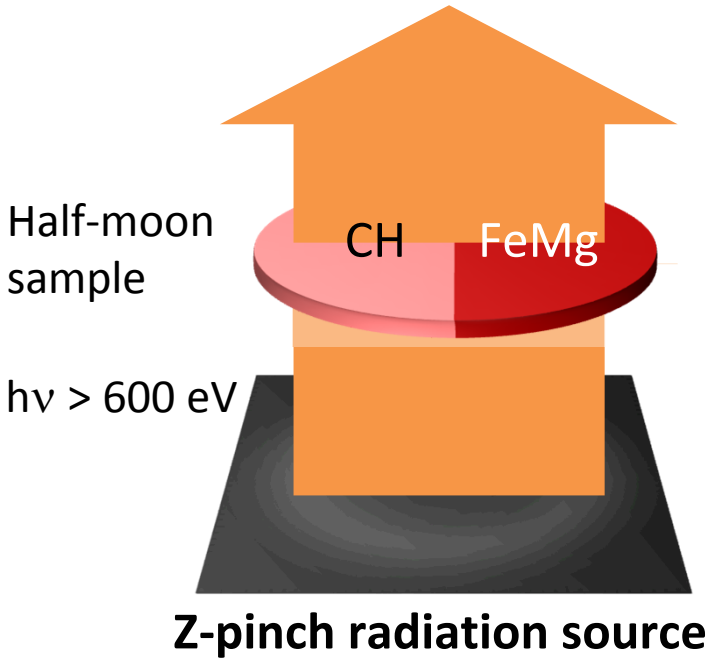


Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)
[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform



<u>Requirements</u>

- Uniform heating
- Mitigating self emission
- Condition measurements

<u>SNL Z satisfies:</u>

Volumetric heating

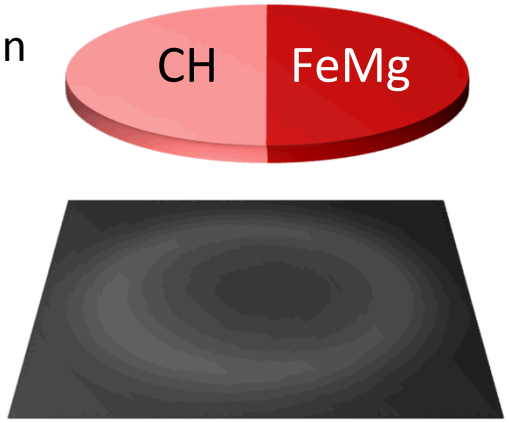
[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform

Sandia National Laboratories

Half-moon sample



Z-pinch radiation source

<u>Requirements</u>

- Uniform heating
- Mitigating self emission
- Condition measurements

<u>SNL Z satisfies:</u>

Volumetric heating

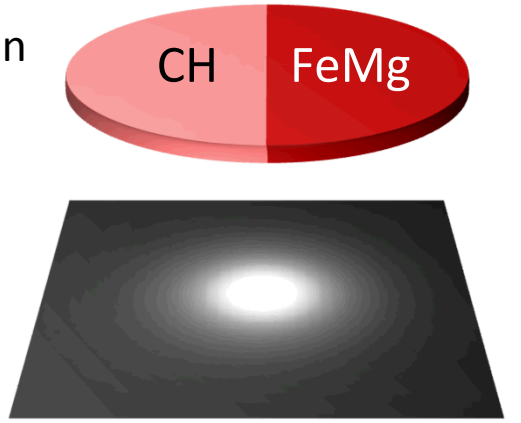
[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform

Sandia National Laboratories

Half-moon sample



Z-pinch radiation source

<u>Requirements</u>

- Uniform heating
- Mitigating self emission
- Condition measurements

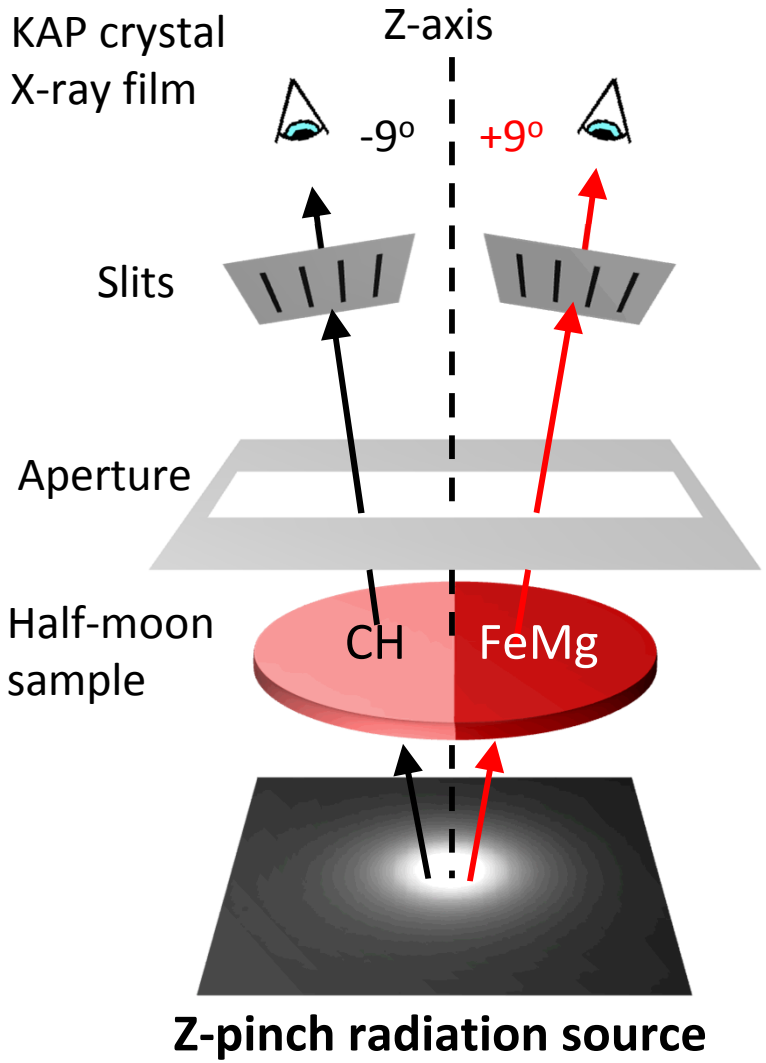
<u>SNL Z satisfies:</u>

Volumetric heating

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform



Requirements

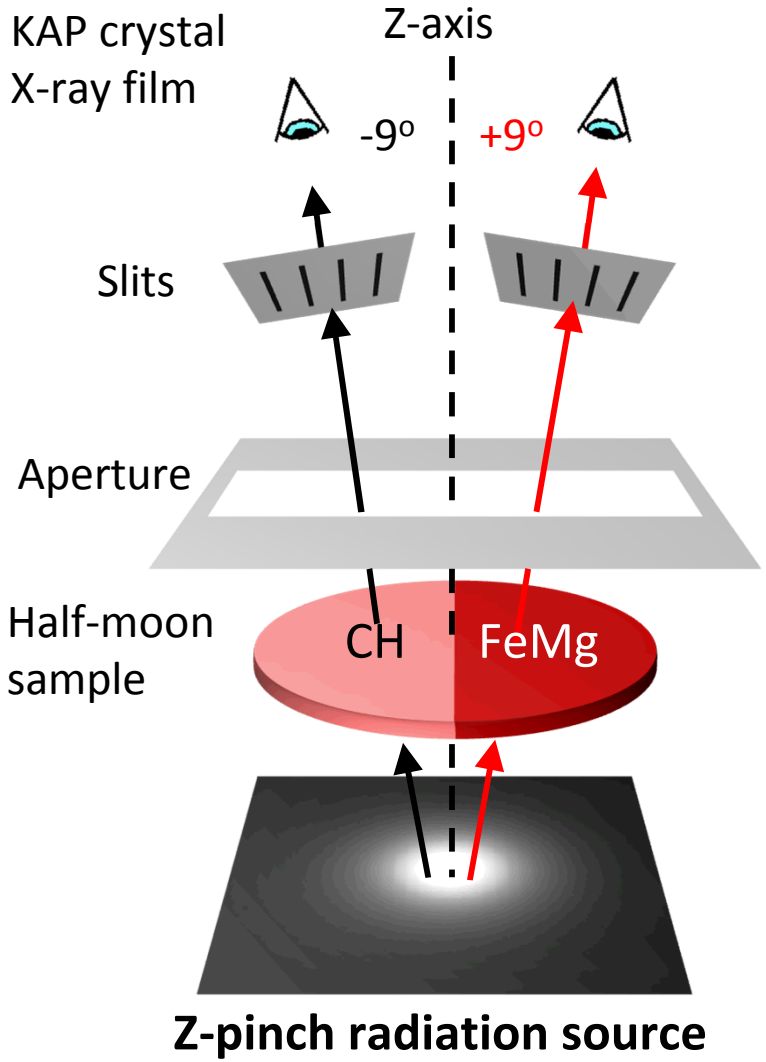
- Uniform heating → Volumetric heating
- Mitigating self emission → 350-eV Planckian backlight
- Condition measurements

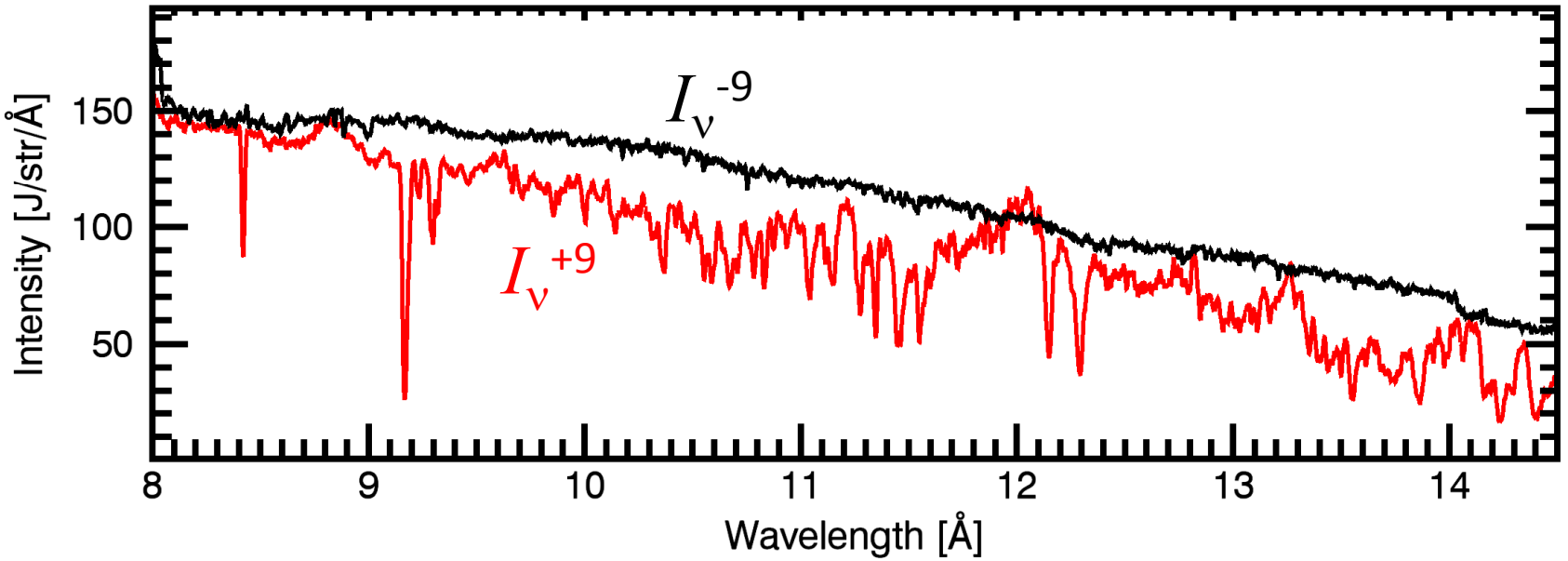
SNL Z satisfies:

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform





Requirements

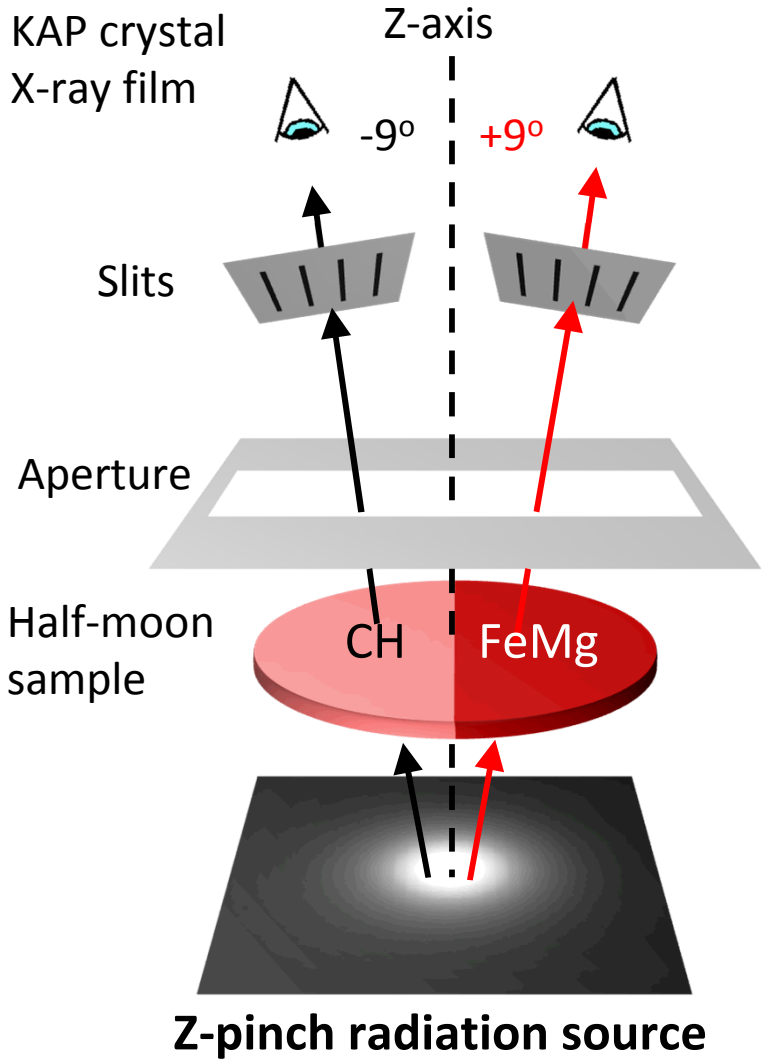
- Uniform heating → Volumetric heating
- Mitigating self emission → 350-eV Planckian backlight
- Condition measurements

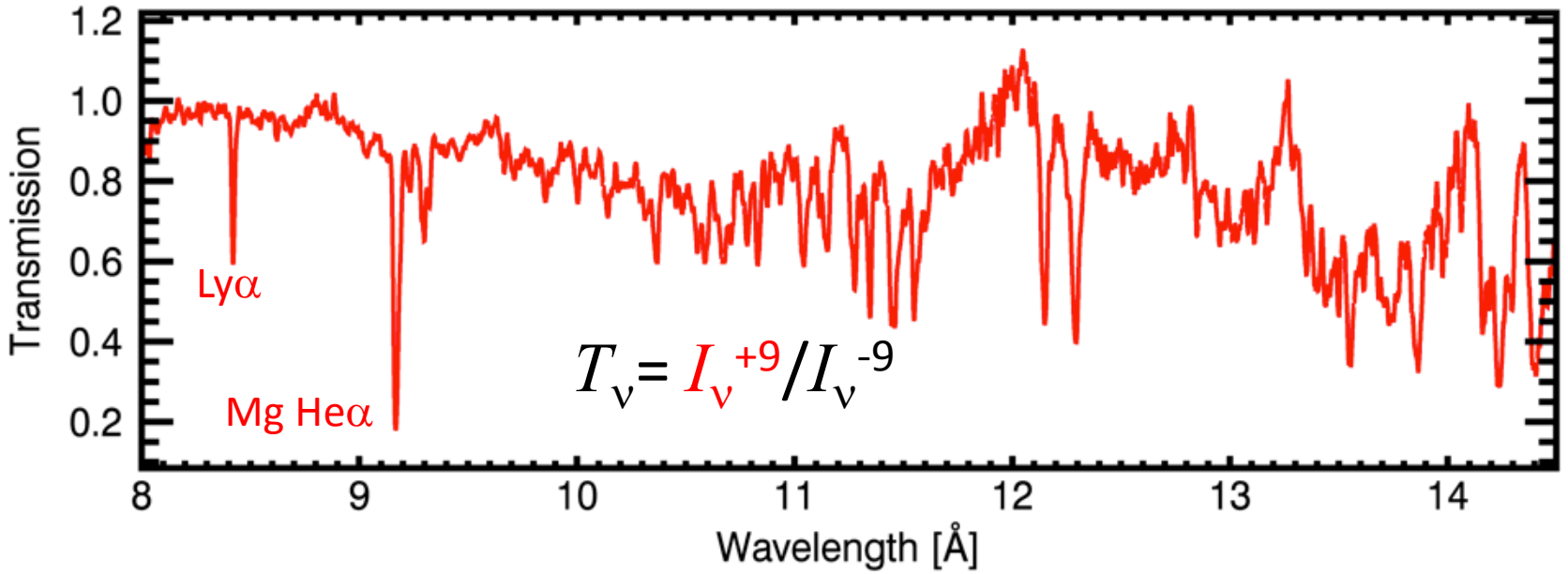
SNL Z satisfies:

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform





Requirements

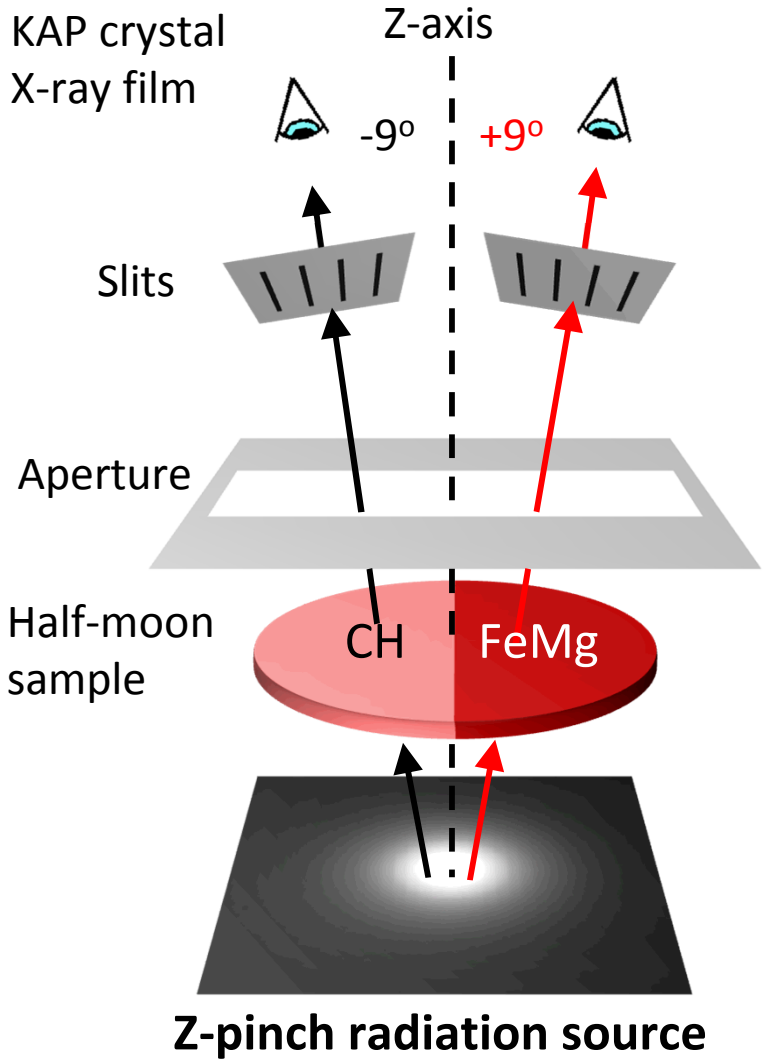
- Uniform heating → Volumetric heating
- Mitigating self emission → 350-eV Planckian backlight
- Condition measurements

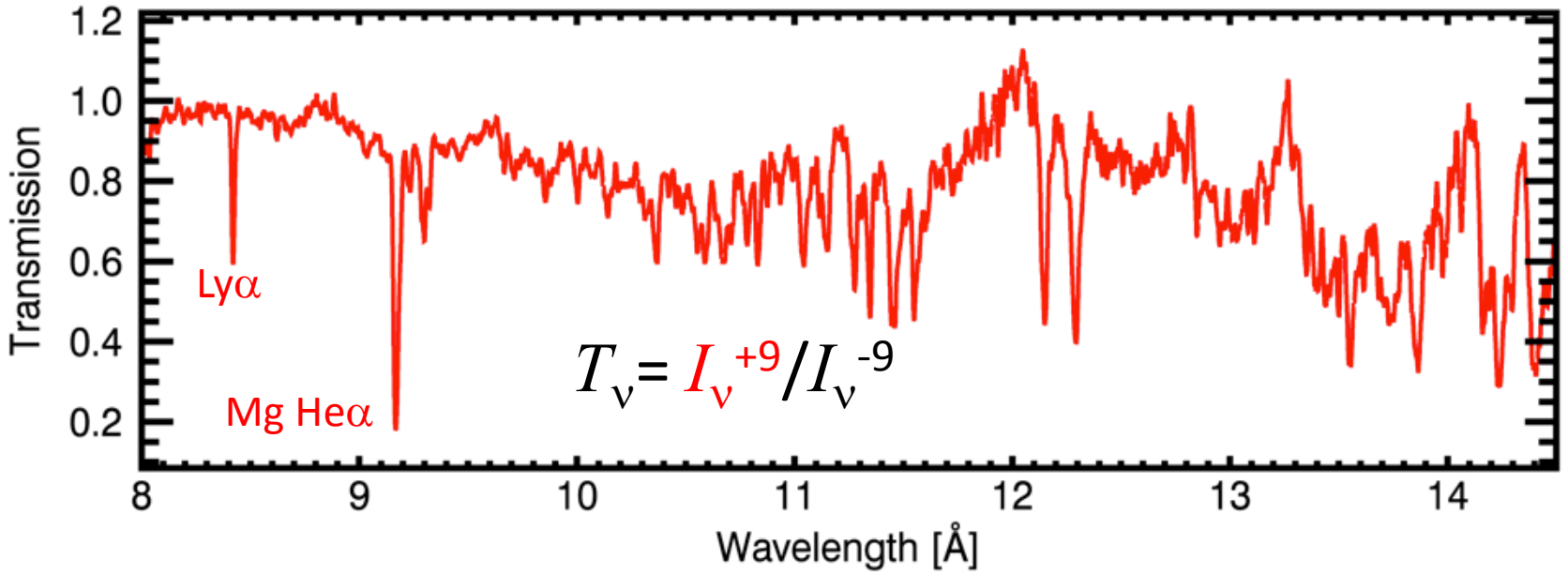
SNL Z satisfies:

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform





Requirements

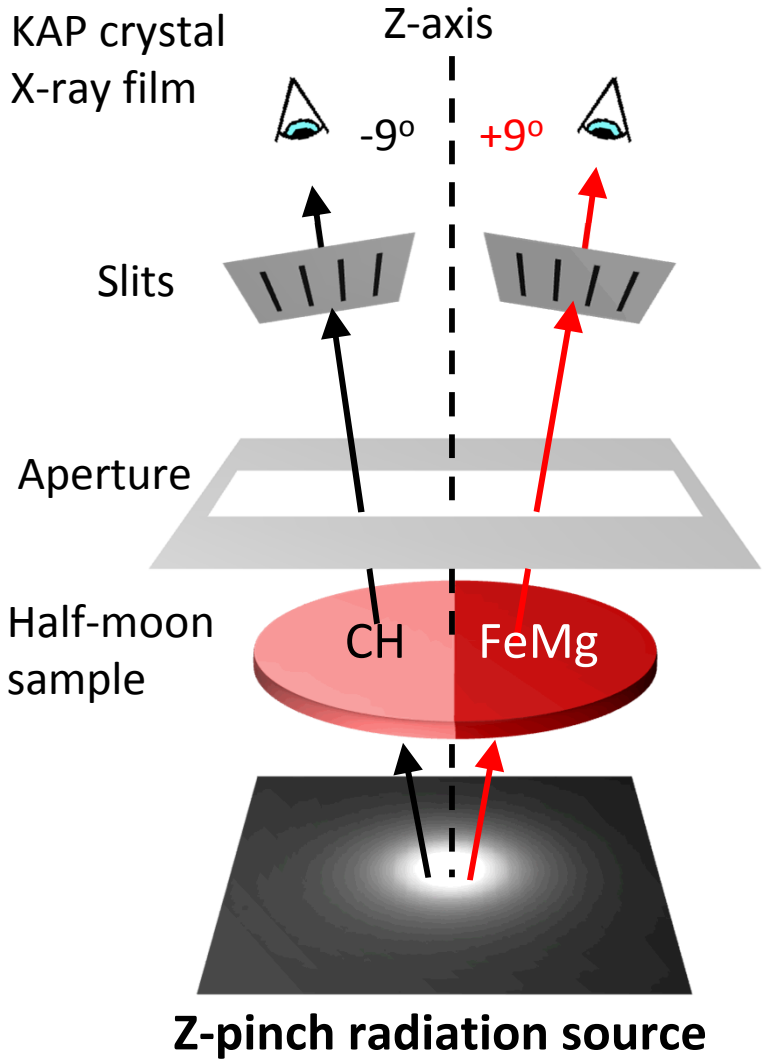
- Uniform heating → Volumetric heating
- Mitigating self emission → 350-eV Planckian backlight
- Condition measurements → Mg K-shell spectroscopy

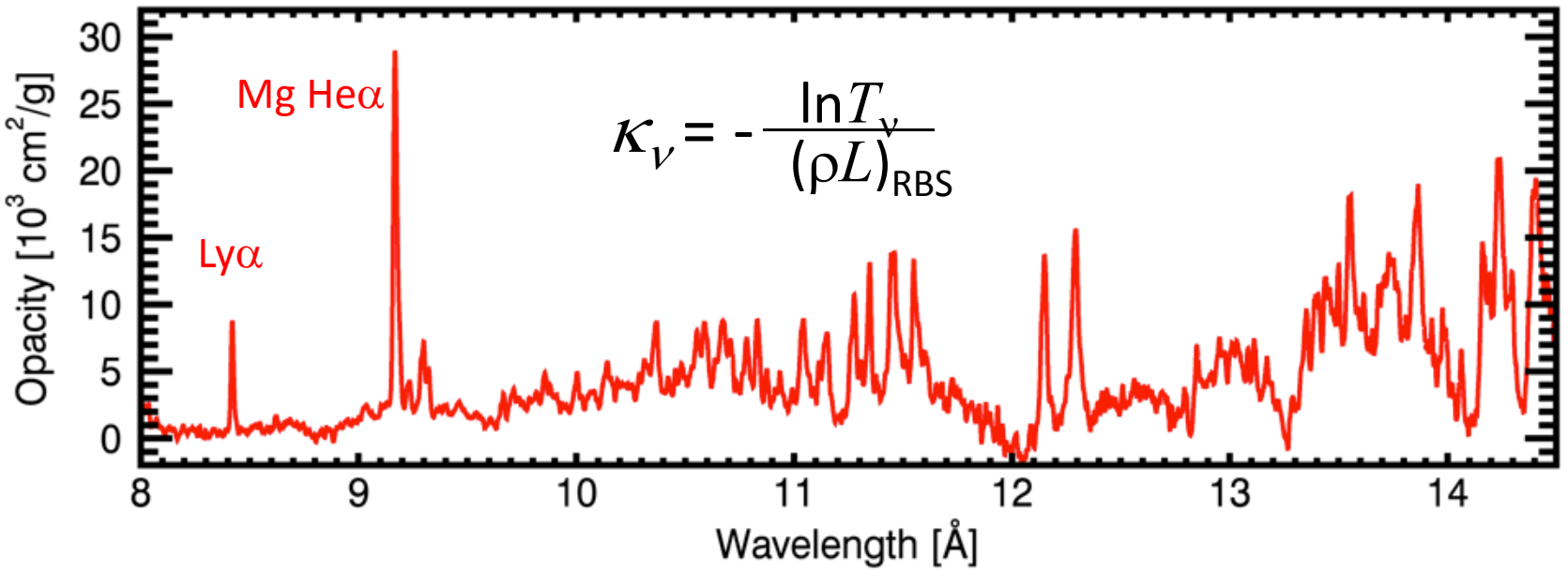
SNL Z satisfies:

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform





Requirements

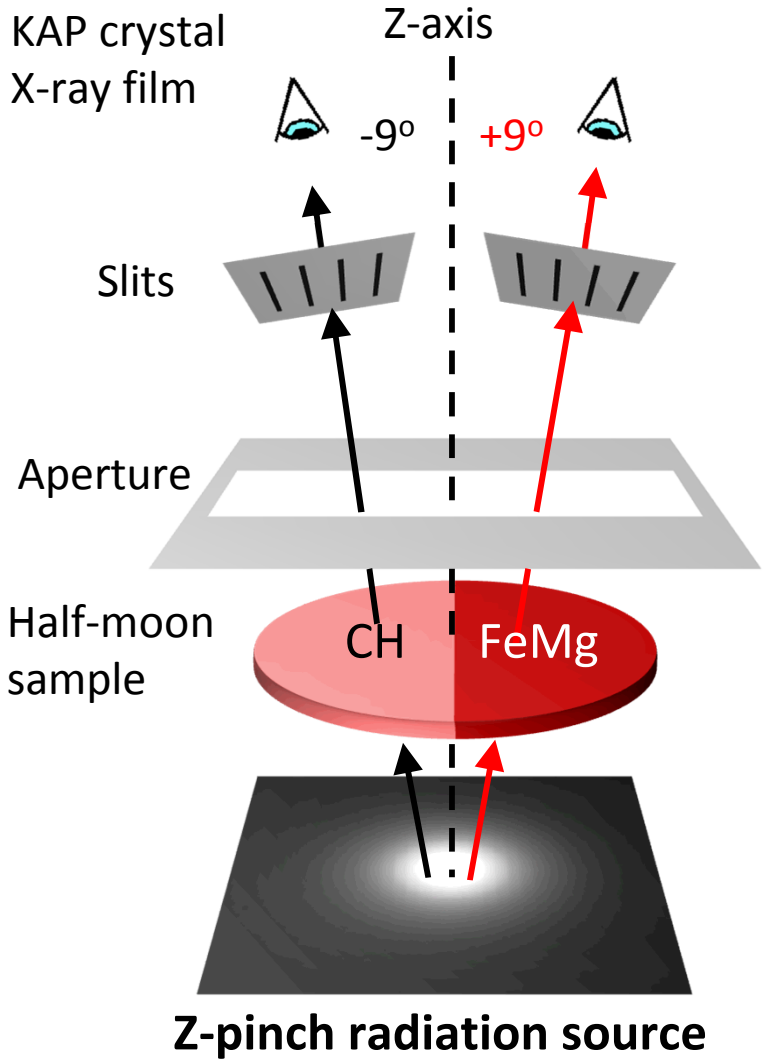
- Uniform heating → Volumetric heating
- Mitigating self emission → 350-eV Planckian backlight
- Condition measurements → Mg K-shell spectroscopy

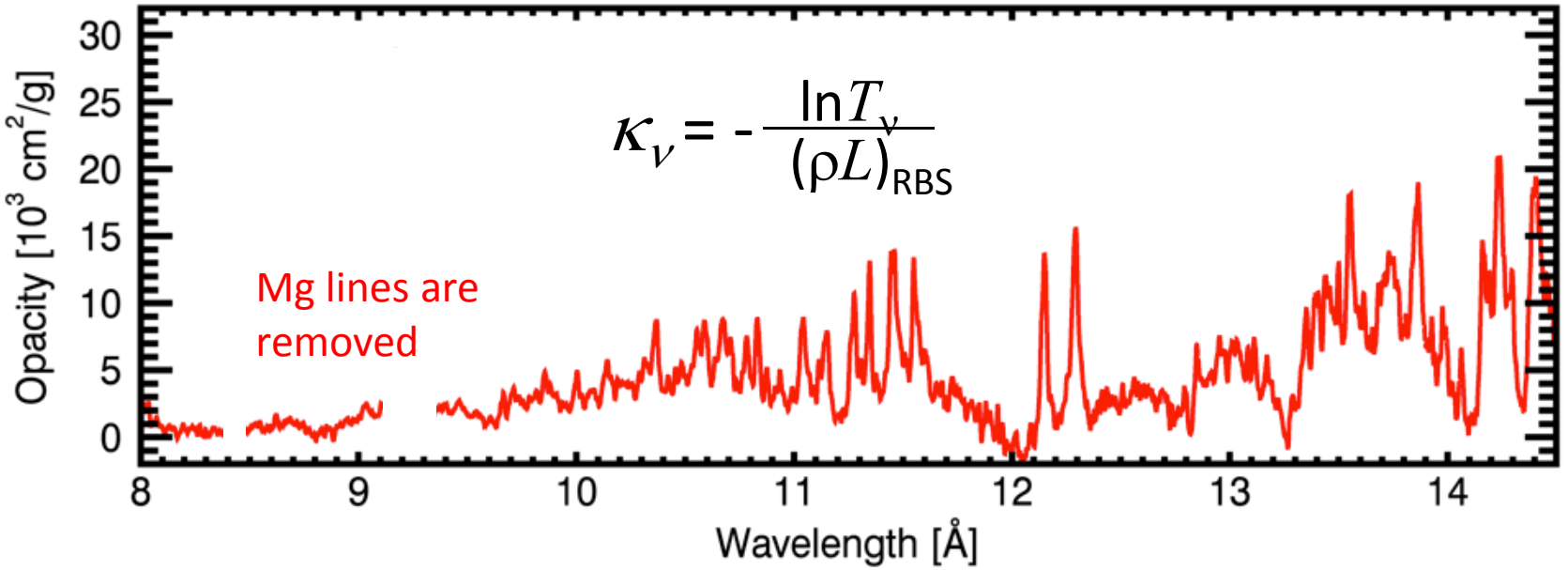
SNL Z satisfies:

[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform





Requirements

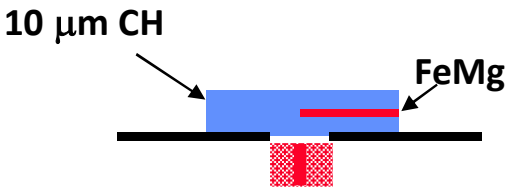
- Uniform heating → Volumetric heating
- Mitigating self emission → 350-eV Planckian backlight
- Condition measurements → Mg K-shell spectroscopy

SNL Z satisfies:

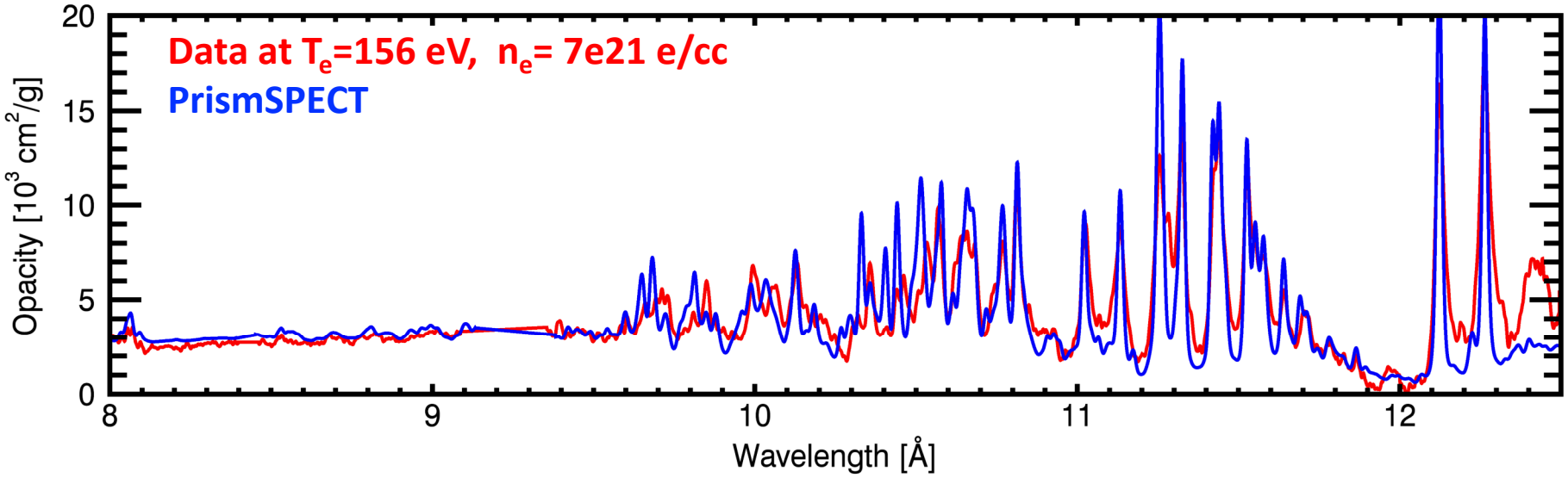
[1] Bailey et al, Phys Plasmas 16, 058101 (2009)

[2] Nagayama et al, Phys Plasmas 21, 056502 (2014)

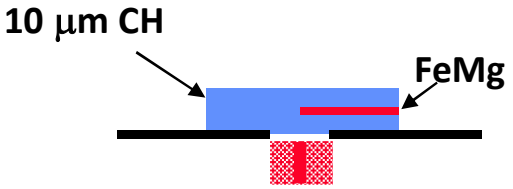
Modeled opacity agrees well with the Z iron data at lower temperature T_e and density n_e than solar interior

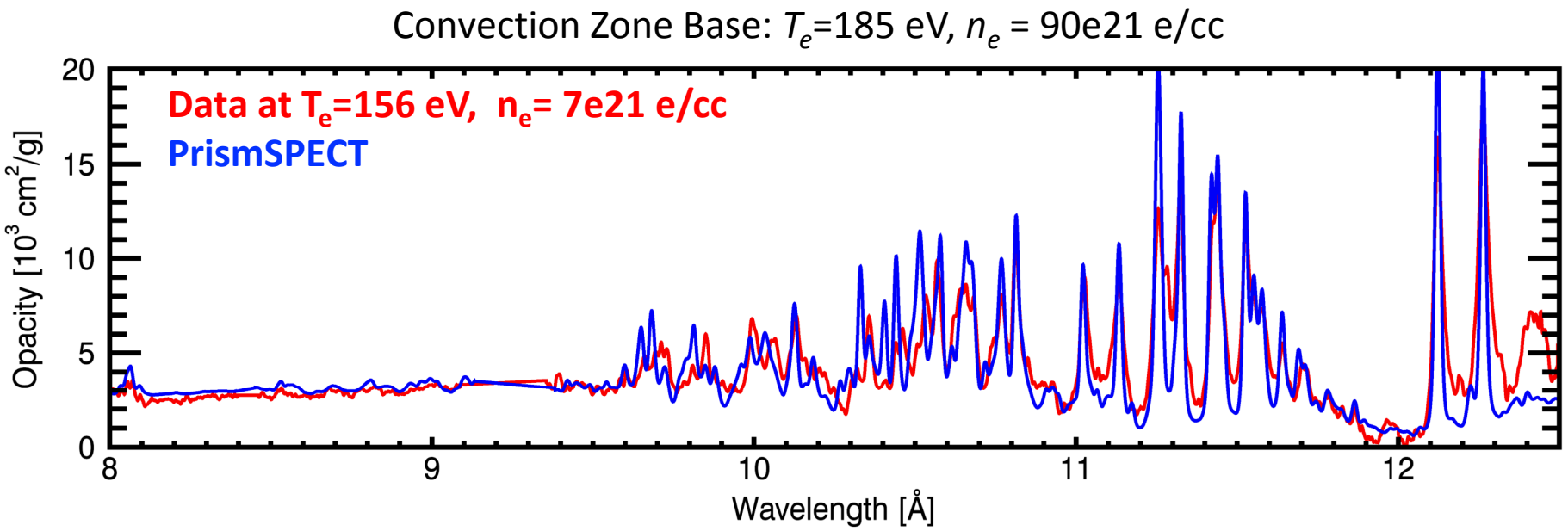


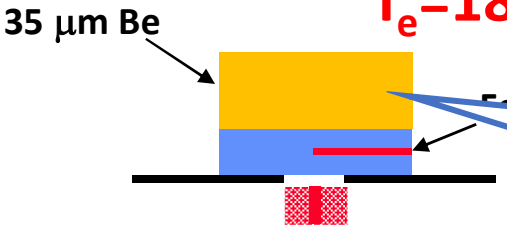
Convection Zone Base: T_e=185 eV, n_e = 90e21 e/cc



Extra mass on the top helps to increase both T_e and n_e







T_e=182 eV, n_e= 38e21 e/cc

Slows down sample expansion → Higher n_e

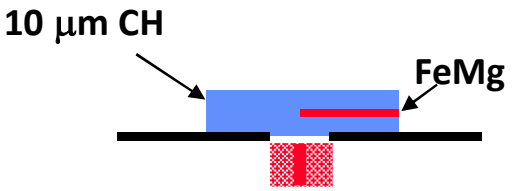
Slows down upward sample motion → Higher T_e

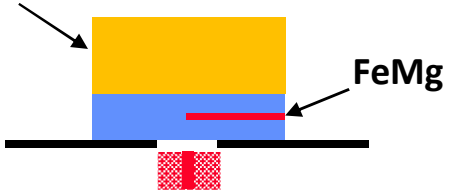
[1] Bailey et al., Nature 517, 56 (2015)

[2] Nagayama et al., Phys Plasmas 21, 056502 (2014)

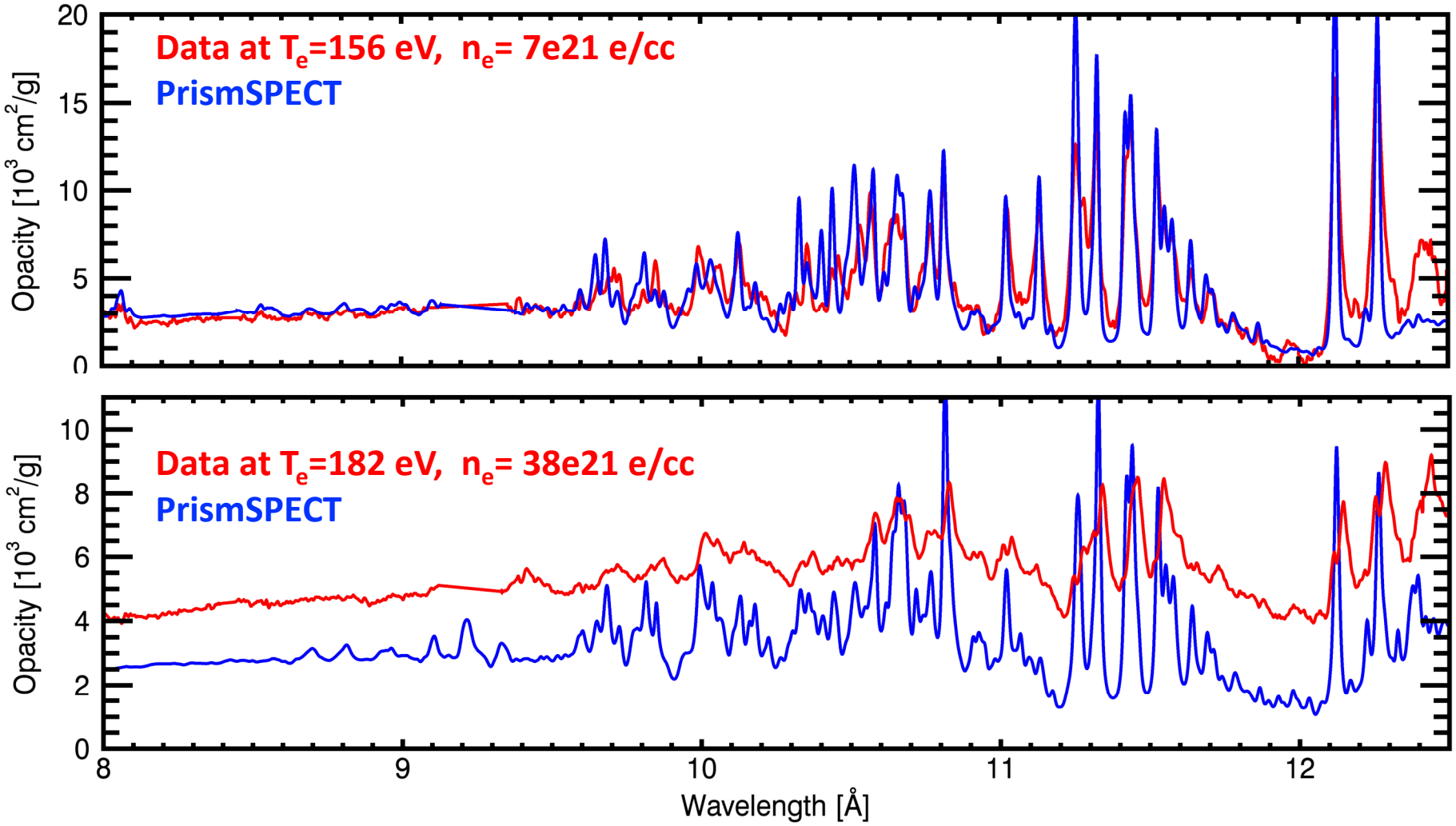
Modeled opacity shows disturbing disagreement as T_e and n_e approach to solar interior conditions

Sandia National Laboratories





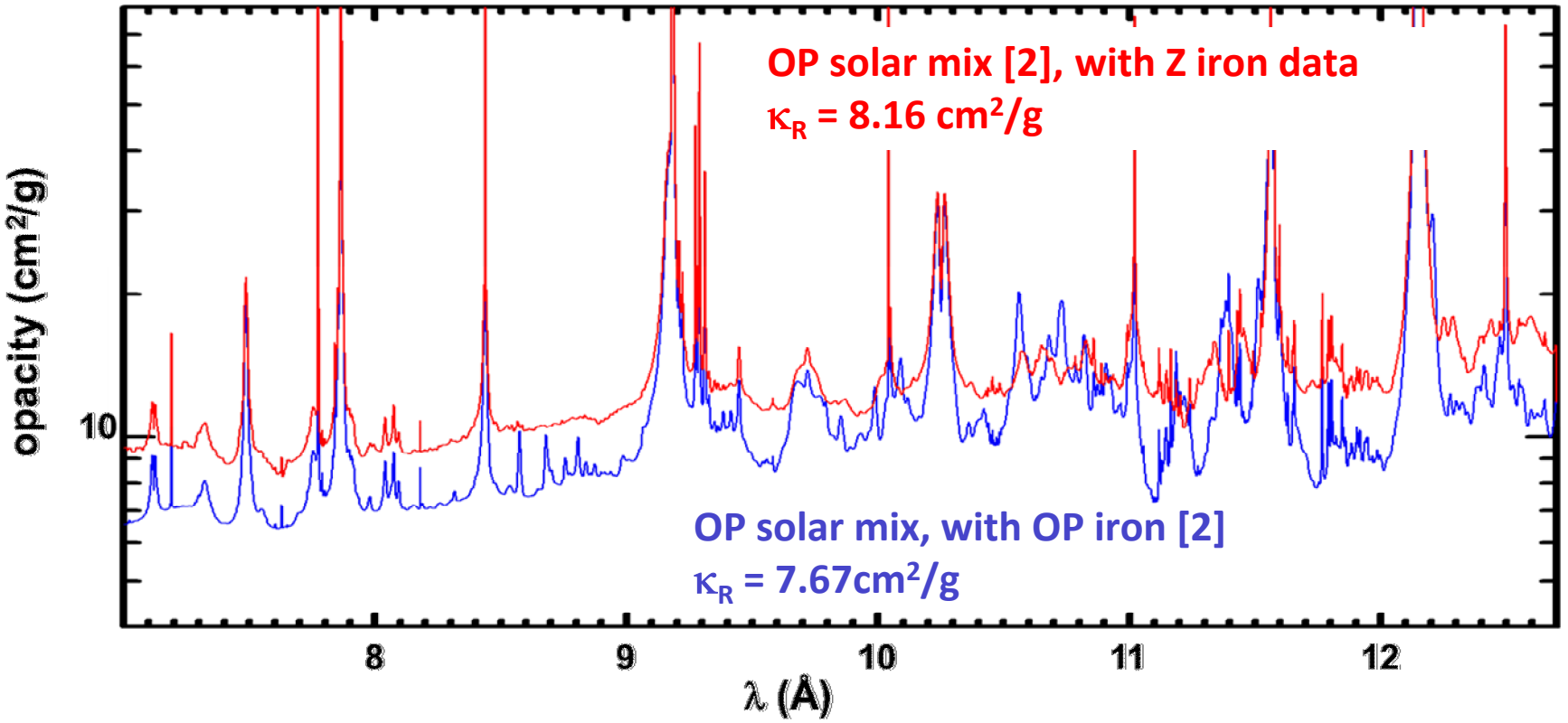
Convection Zone Base: T_e=185 eV, n_e = 90e21 e/cc



[1] Bailey et al., Nature 517, 56 (2015)

[2] Nagayama et al., Phys Plasmas 21, 056502 (2014)

A solar mixture plasma using Z iron data has ~ 7% higher Rosseland mean opacity than using OP iron[1]

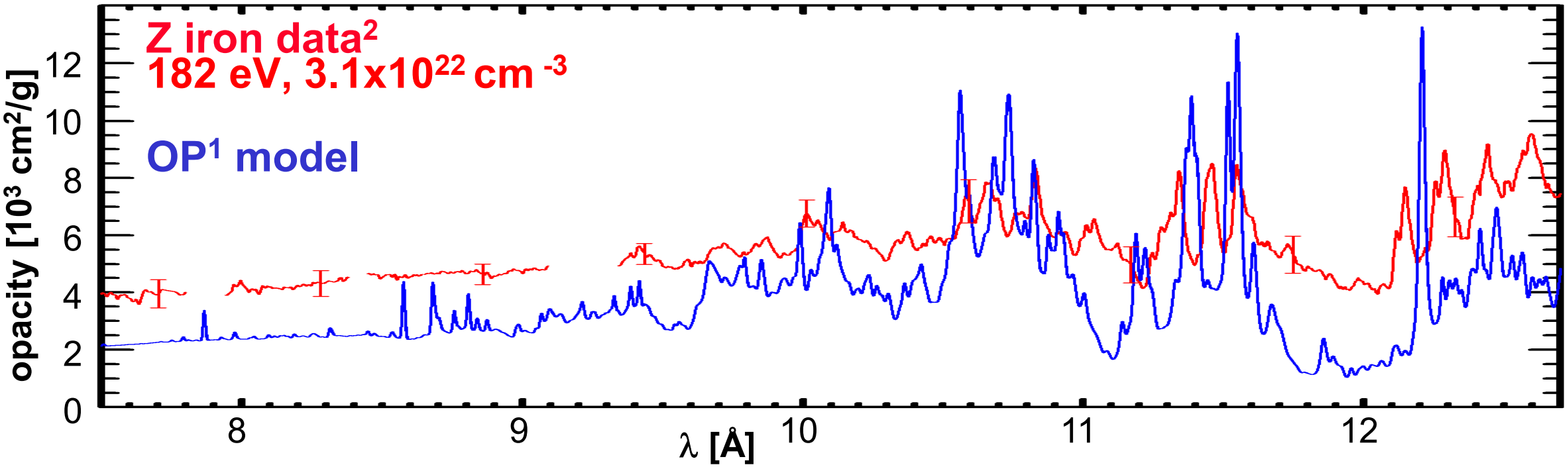


- A 7% Rosseland increase partially resolves the solar problem
- But the measured iron opacity by itself cannot account for the entire discrepancy
- We need to extend our measurement in spectral range, elements, and conditions

[1] Bailey et al, Nature (2015)

[2] Seaton et al, MNRAS (1994)

Reported opacity discrepancy is disturbing and deserves further scrutiny



Inaccuracy in theory?

Flaws in experiment?

No systematic error has been found that explains the model-data discrepancies

Sandia National Laboratories

Random error:

→ Average over many spectra from multiple experiments

Systematic error evaluation:

→ Evaluated with experiments and simulations

- Plasma condition diagnostic errors
- Sample areal density errors
- Transmission errors
- Spatial non-uniformities
- Temporal non-uniformities
- Departures from LTE

} Either increase or decrease

- Fe self emission
- Tamper self emission
- Extraneous background

} Artificially decrease measured opacity

- Sample contamination
- Tamper transmission difference

} Artificially increase measured opacity

No systematic error has been found that explains the model-data discrepancies

Sandia National Laboratories

Random error:

→ Average over many spectra from multiple experiments

Systematic error evaluation:

→ Evaluated with experiments and simulations

- Plasma condition diagnostic errors
- Sample areal density errors
- Transmission errors
- Spatial non-uniformities
- Temporal non-uniformities
- Departures from LTE

- Fe self emission
- Tamper self emission
- Extraneous background

- Sample contamination
- Tamper transmission difference

Condition diagnostics uncertainty:

- Nagayama et al, Phys Plasma (2014)
- Nagayama et al, HEDP (2016)
- Iglesias, HEDP (2016)

No systematic error has been found that explains the model-data discrepancies

Sandia National Laboratories

Random error:

→ Average over many spectra from multiple experiments

Systematic error evaluation:

→ Evaluated with experiments and simulations

- Plasma condition diagnostic errors
- Sample areal density errors
- Transmission errors
- Spatial non-uniformities
- Temporal non-uniformities
- Departures from LTE

- Fe self emission
- Tamper self emission
- Extraneous background

- Sample contamination
- Tamper transmission difference

Condition diagnostics uncertainty:

- Nagayama et al, Phys Plasma (2014)
- Nagayama et al, HEDP (2016)
- Iglesias, HEDP (2016)

Systematic uncertainty:

- Nagayama et al, Phys Rev E (2016)
- Nagayama et al, Phys Rev E (2017)

No systematic error has been found that explains the model-data discrepancies

Sandia National Laboratories

Random error:

→ Average over many spectra from multiple experiments

Systematic error evaluation:

→ Evaluated with experiments and simulations

- Plasma condition diagnostic errors
- Sample areal density errors
- Transmission errors
- Spatial non-uniformities
- Temporal non-uniformities
- Departures from LTE

- Fe self emission
- Tamper self emission
- Extraneous background

- Sample contamination
- Tamper transmission difference

Condition diagnostics uncertainty:

- Nagayama et al, Phys Plasma (2014)
- Nagayama et al, HEDP (2016)
- Iglesias, HEDP (2016)

Systematic uncertainty:

- Nagayama et al, Phys Rev E (2016)
- Nagayama et al, Phys Rev E (2017)

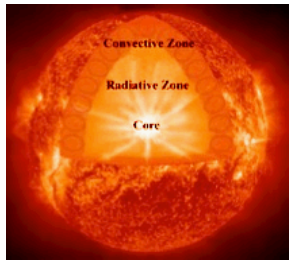
Rest supported by various measurements

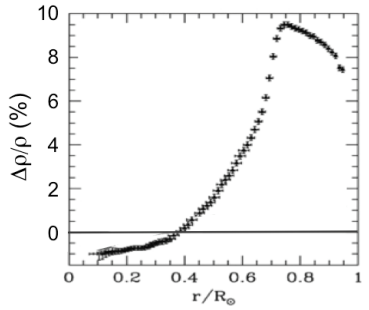
Calculated Fe opacity at solar interior condition disagrees with data; Various investigations provide clues for the discrepancy

Sandia National Laboratories

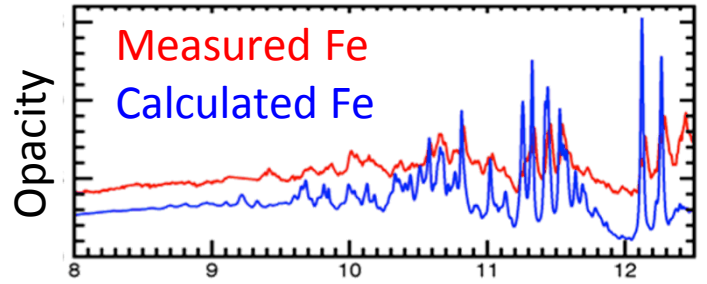
- **We found 30–400% disagreement between modeled and measured Fe opacity at solar interior conditions**

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

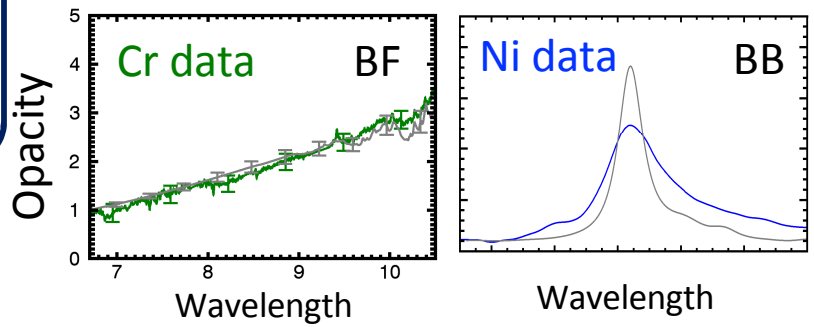




- **Cr, Fe, and Ni opacities measured at multiple electron temperatures (T_e) and electron densities (n_e)**
  - Opacity valley disagreement found on Cr and Fe, but not Ni
  - Calculated line-broadening is too narrow
  - Element dependence on bound-free (BF) agreement is puzzling

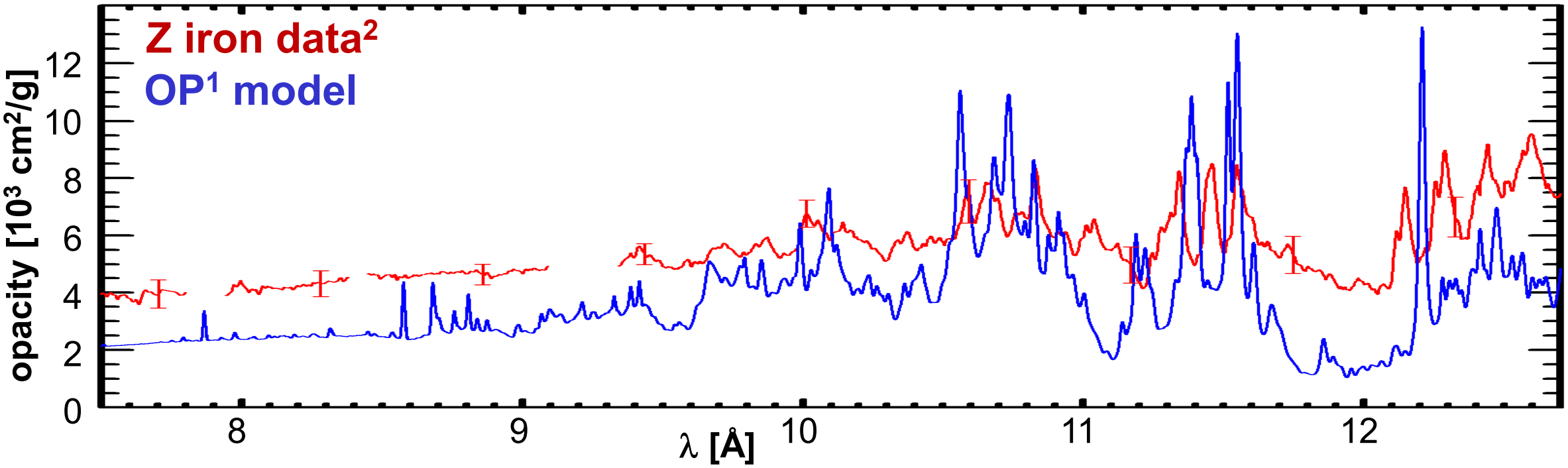


- **Missing physics in opacity theory:**
  - Two-photon opacity may be important



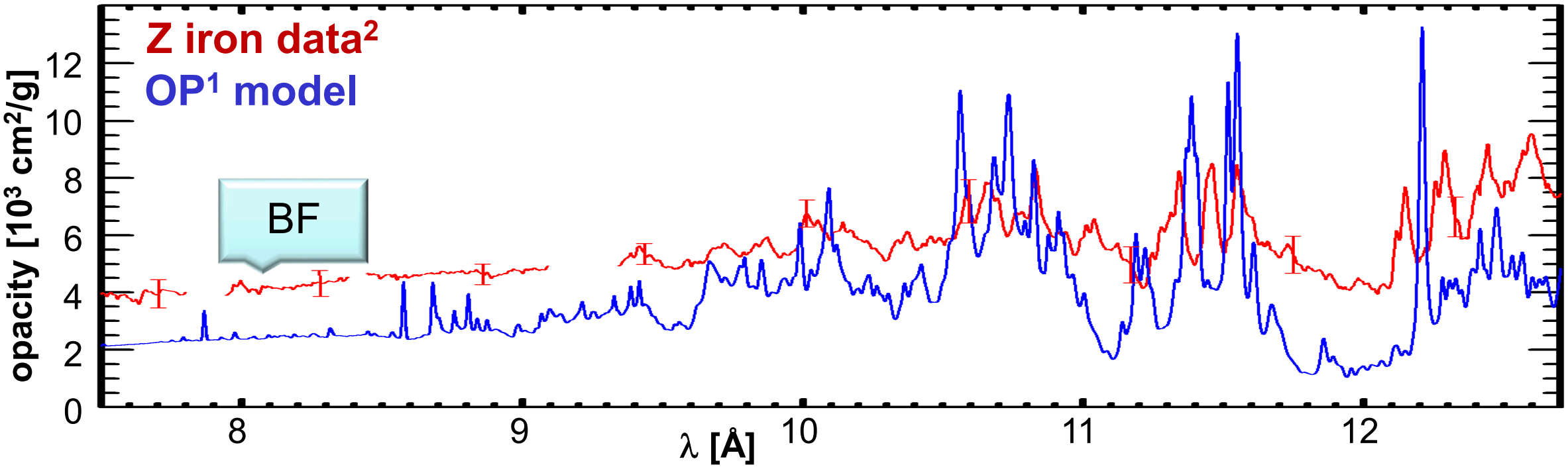
Working towards completing the systematic study to resolve the discrepancy

Opacity disagreement is disturbing and most likely caused by multiple sources



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

Opacity disagreement is disturbing and most likely caused by multiple sources

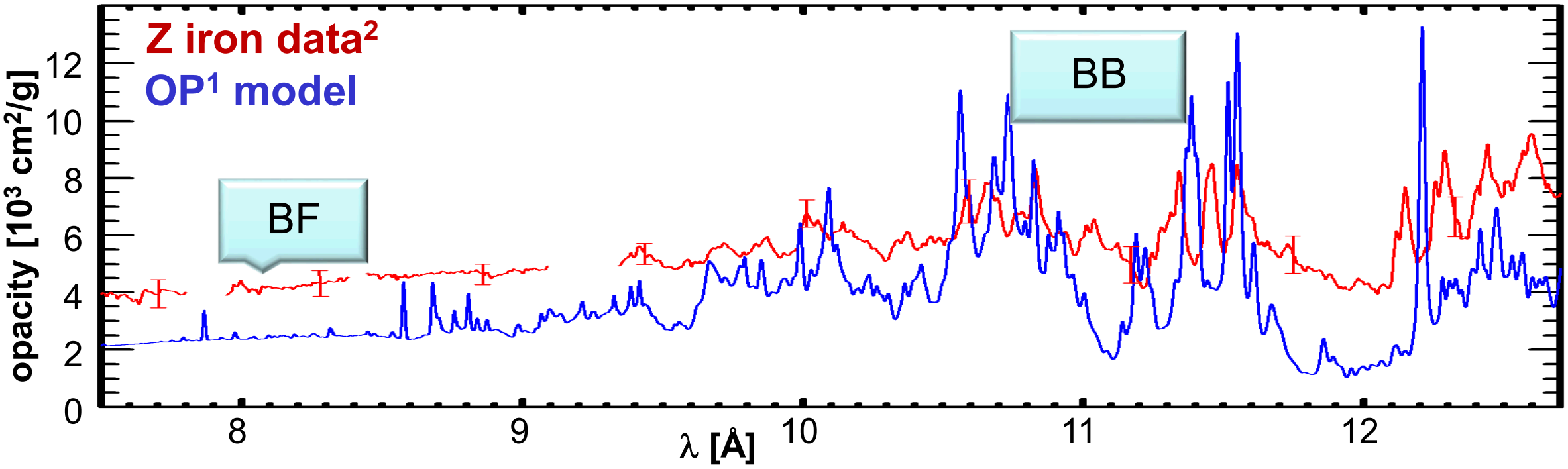


BF: bound-free/quasi-continuum:

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

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

Opacity disagreement is disturbing and most likely caused by multiple sources



BF: bound-free/quasi-continuum:

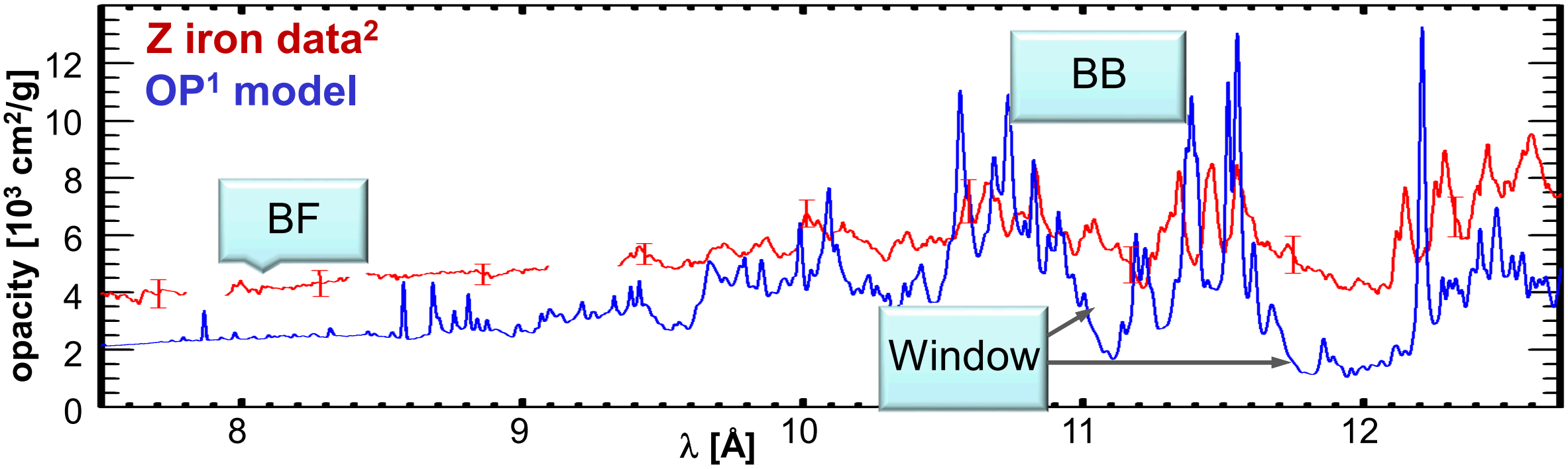
- Bound-free (b-f) cross-section?
- Missing lines from multi-excited states?
- Multi-photon processes?

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

Opacity disagreement is disturbing and most likely caused by multiple sources



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*

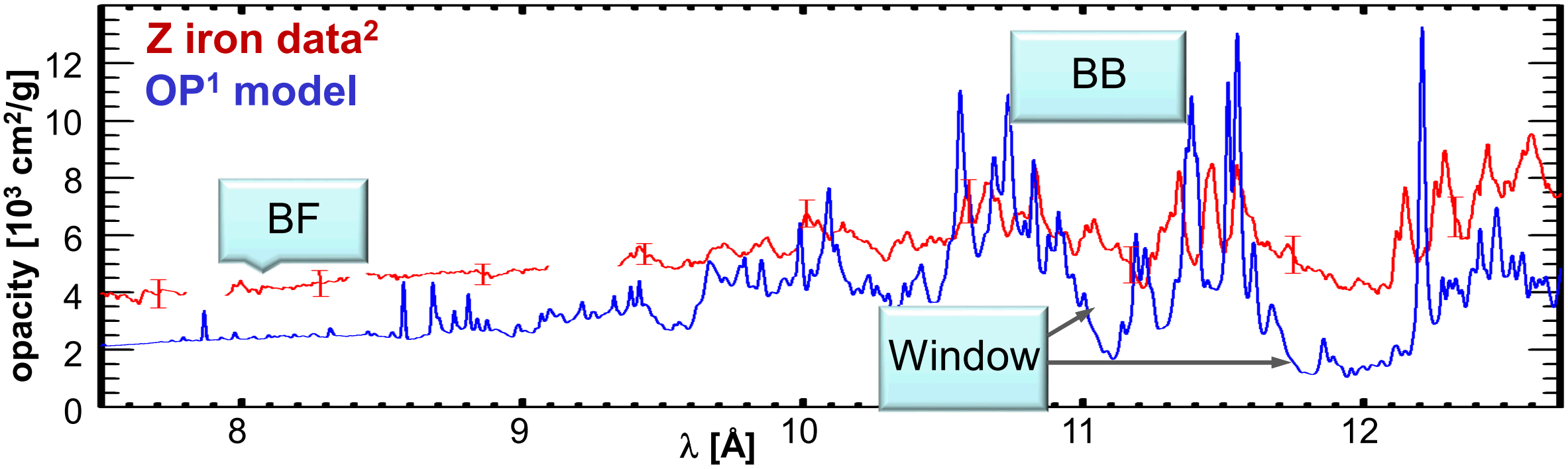
- Line location → Atomic structure
- Strength → Oscillator strength?
  Population?
- Line width → Line shape?
  Missing lines?

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

Questioning theory comes down to atomic data, population kinetics, density effects, or missing physics



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*

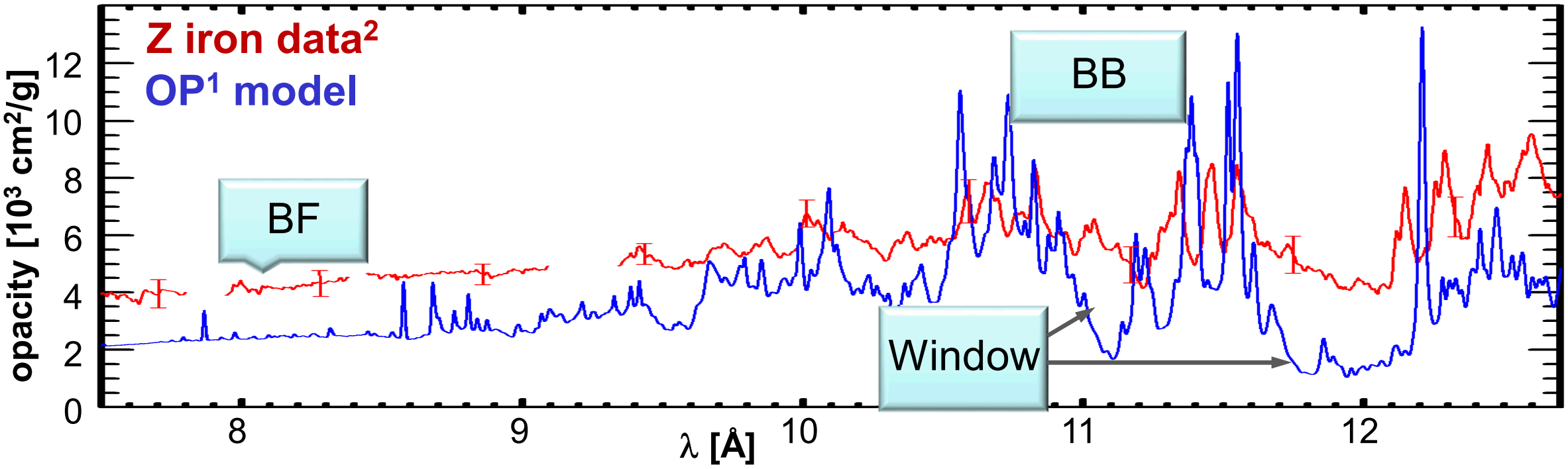
- Line location → Atomic structure
- Strength → Oscillator strength?
  Population?
- Line width → Line shape?
  Missing lines?

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

Questioning theory comes down to atomic data, population kinetics, density effects, or missing physics



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*

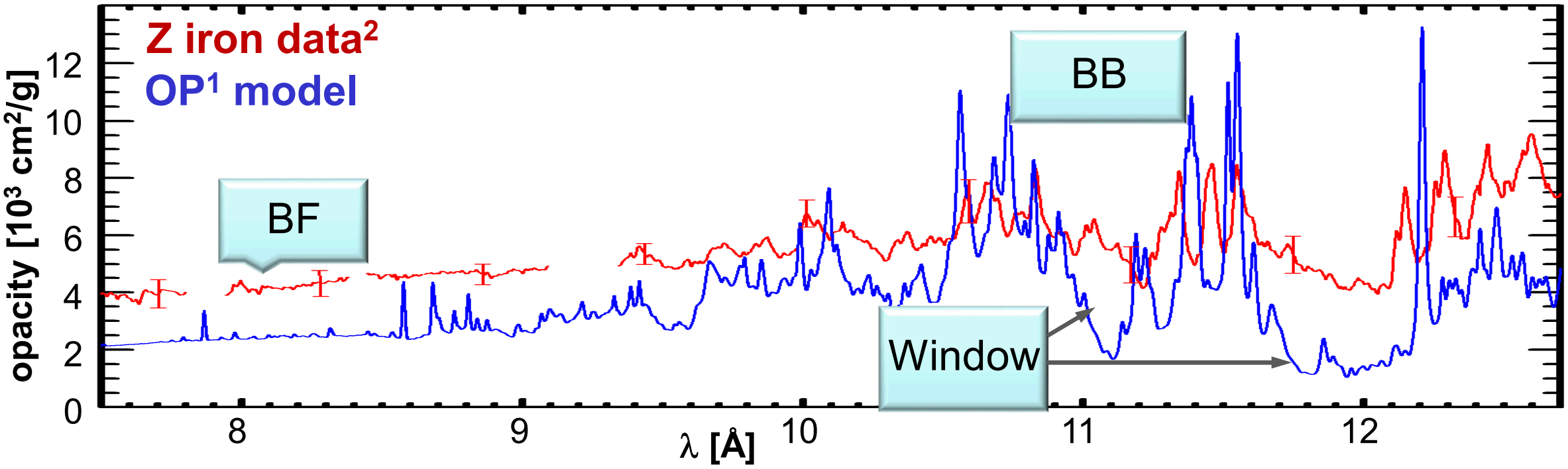
- Line location → Atomic structure
- Strength → Oscillator strength?
  Population?
- Line width → Line shape?
  Missing lines?

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

Questioning theory comes down to atomic data, population kinetics, density effects, or missing physics



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*

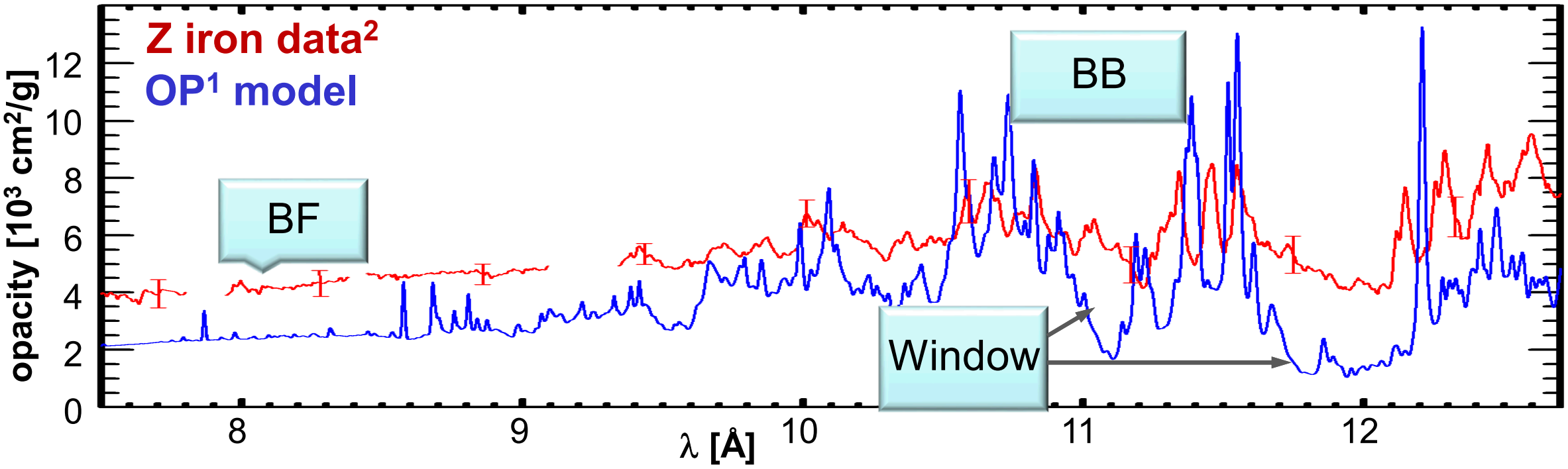
- Line location → Atomic structure
- Strength → Oscillator strength?
  Population?
- Line width → Line shape?
  Missing lines?

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

Questioning theory comes down to atomic data, population kinetics, density effects, or missing physics



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*

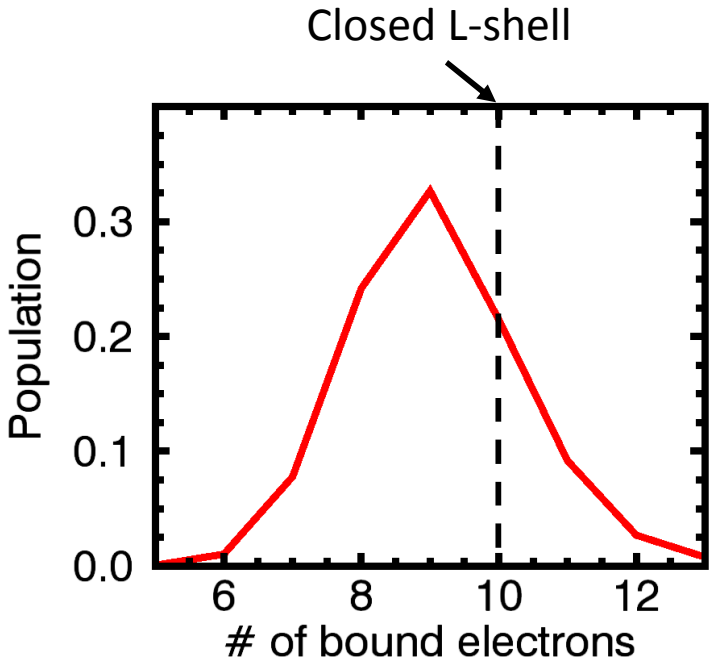
- Line location → Atomic structure
- Strength → Oscillator strength?
  Population?
- Line width → Line shape?
  Missing lines?

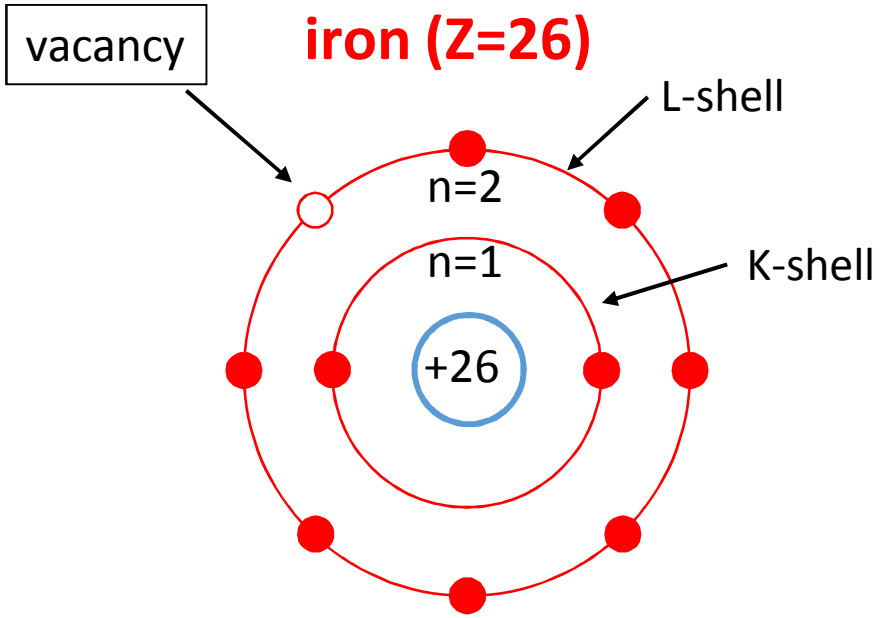
Window filling:

- 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

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

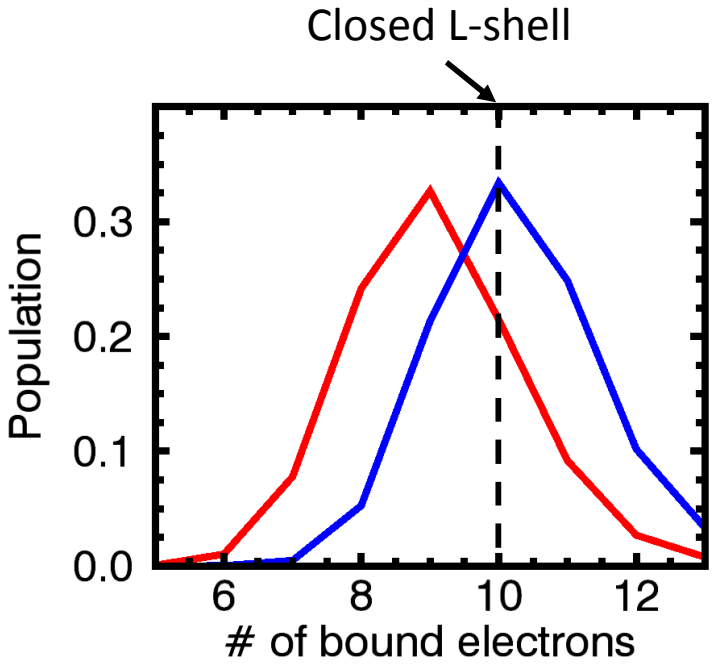


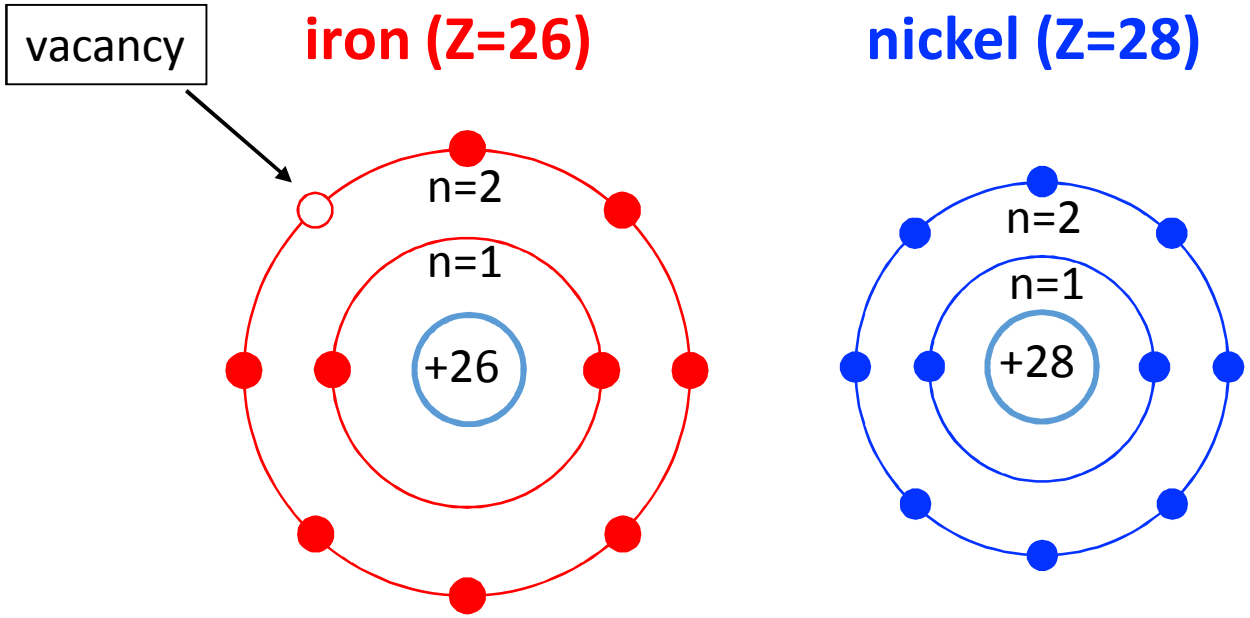


Questioning Theory:

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

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

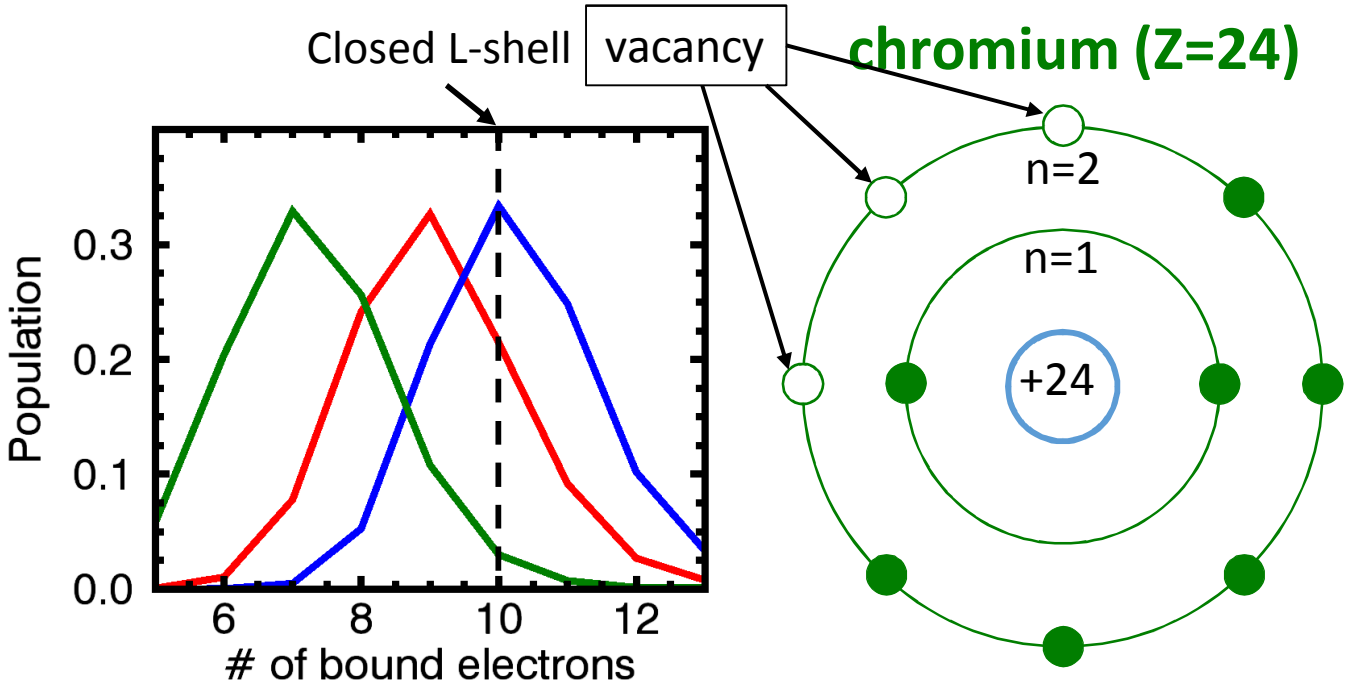


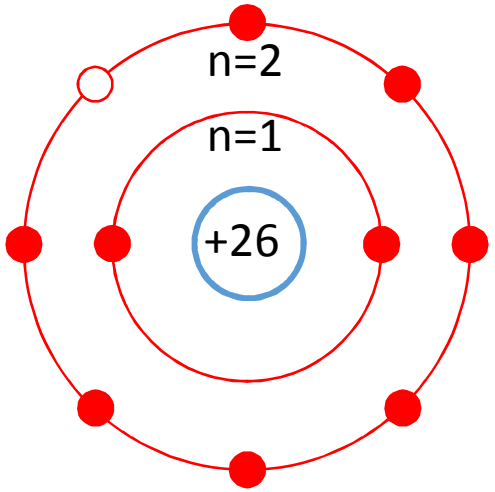


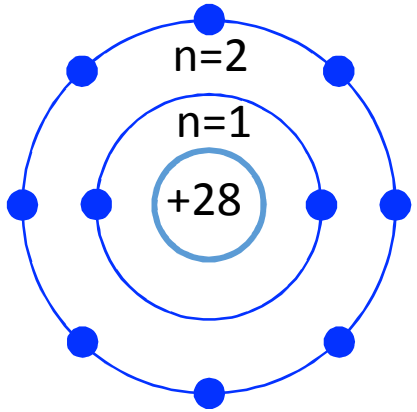
Questioning Theory:

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

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



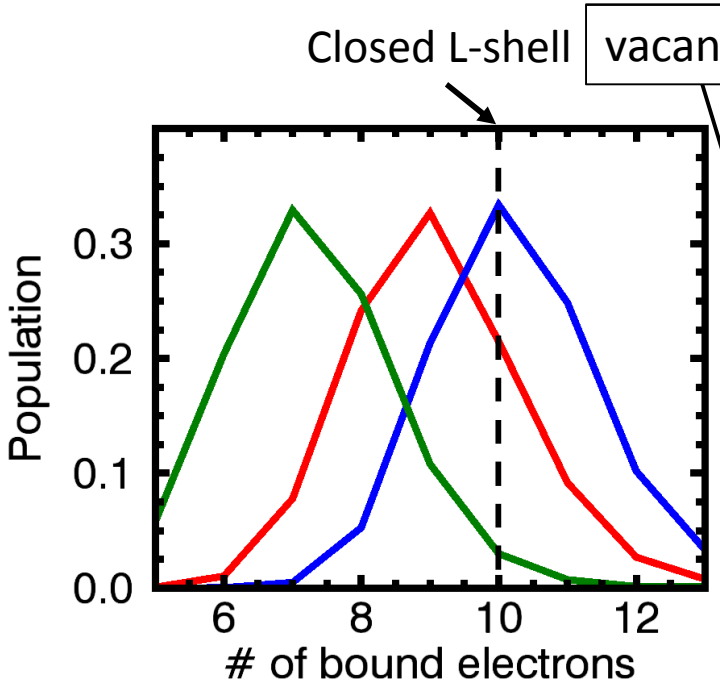


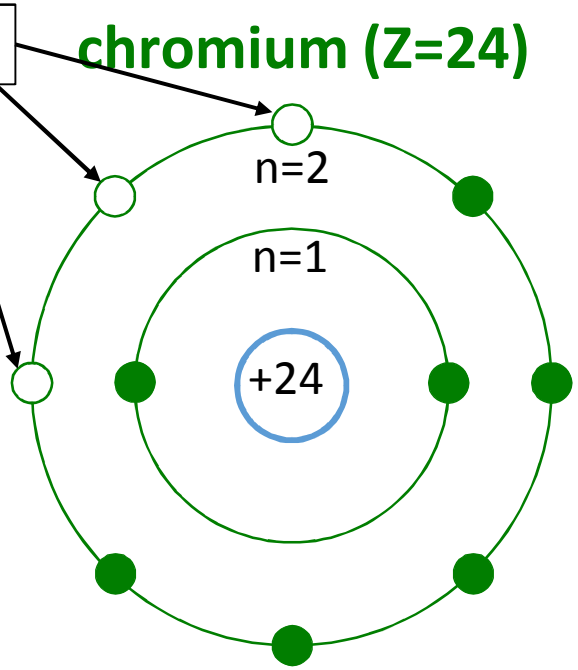


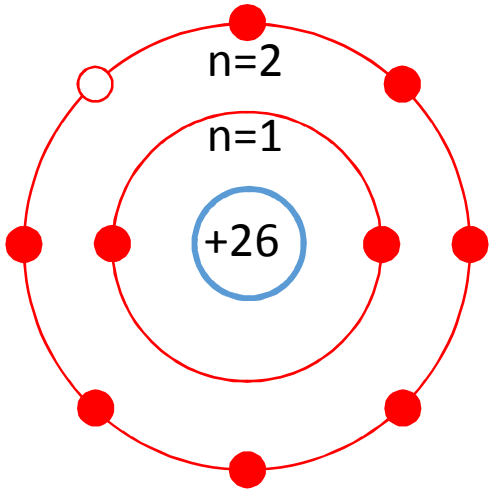
Questioning Theory:

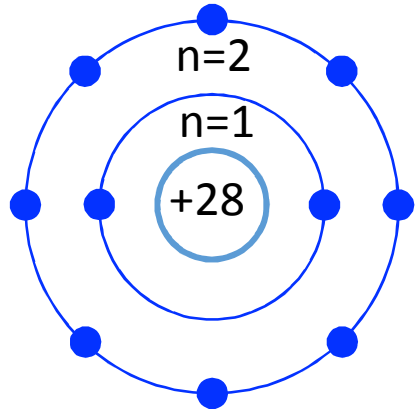
- Atomic data?
- Population kinetics?
- Density effects?
- Missing physics?

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









Questioning Theory:

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

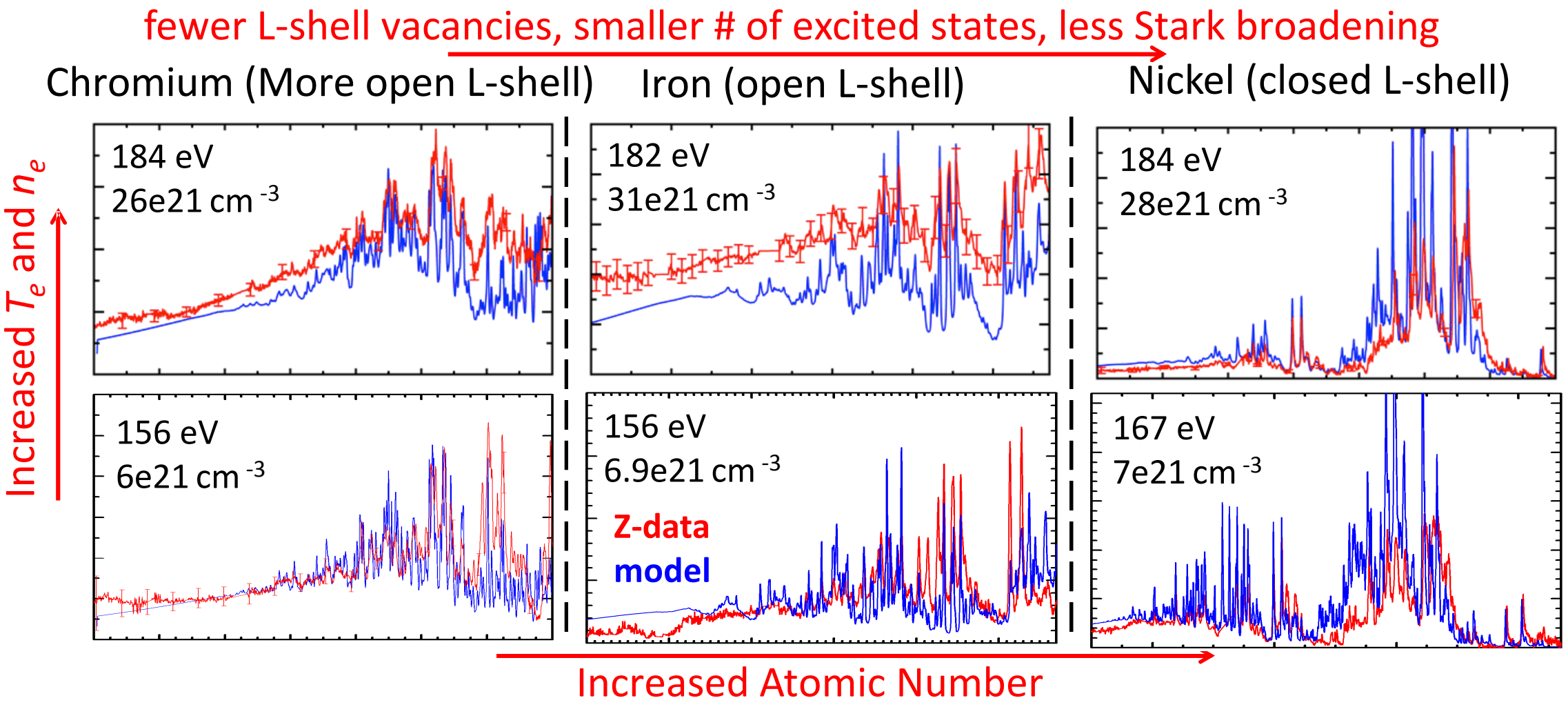
More ← L-shell vacancies

← # of excited states

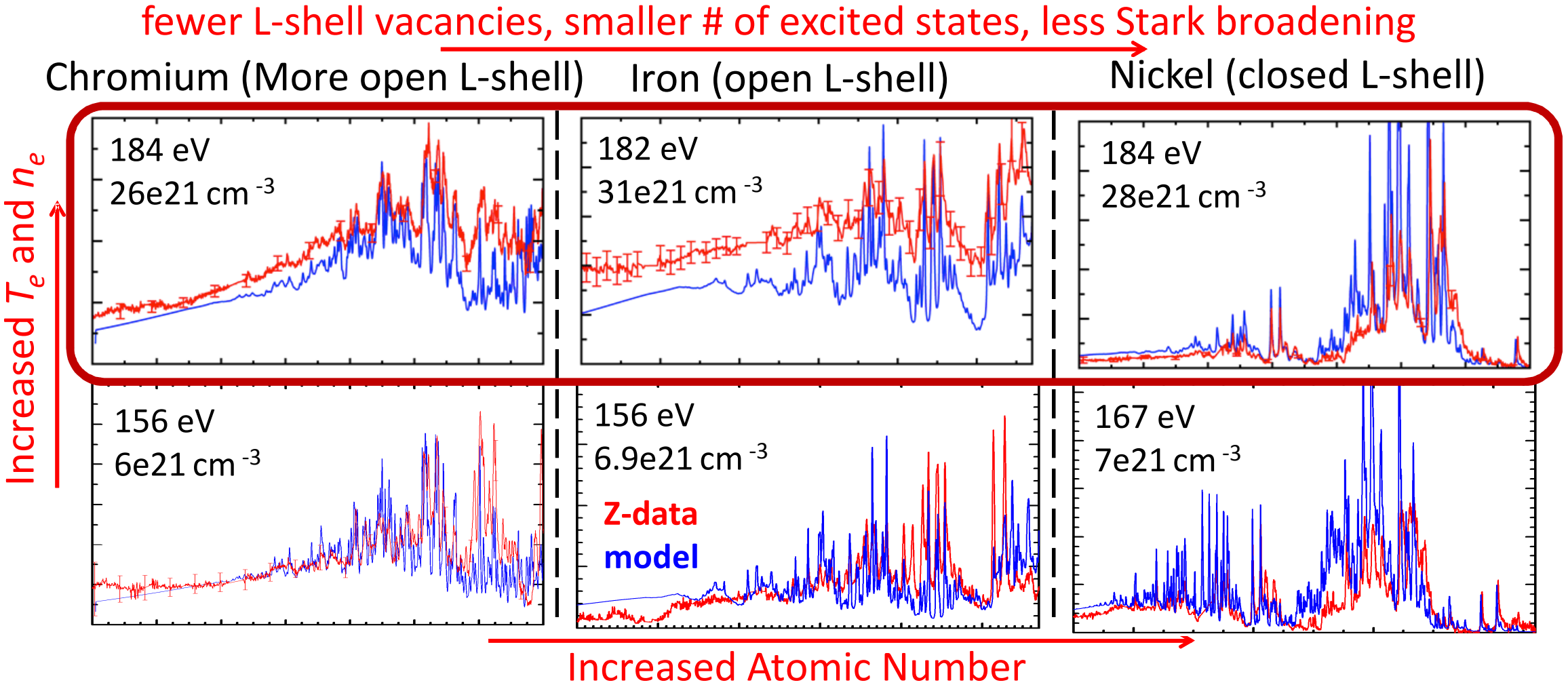
← Density effects

Less

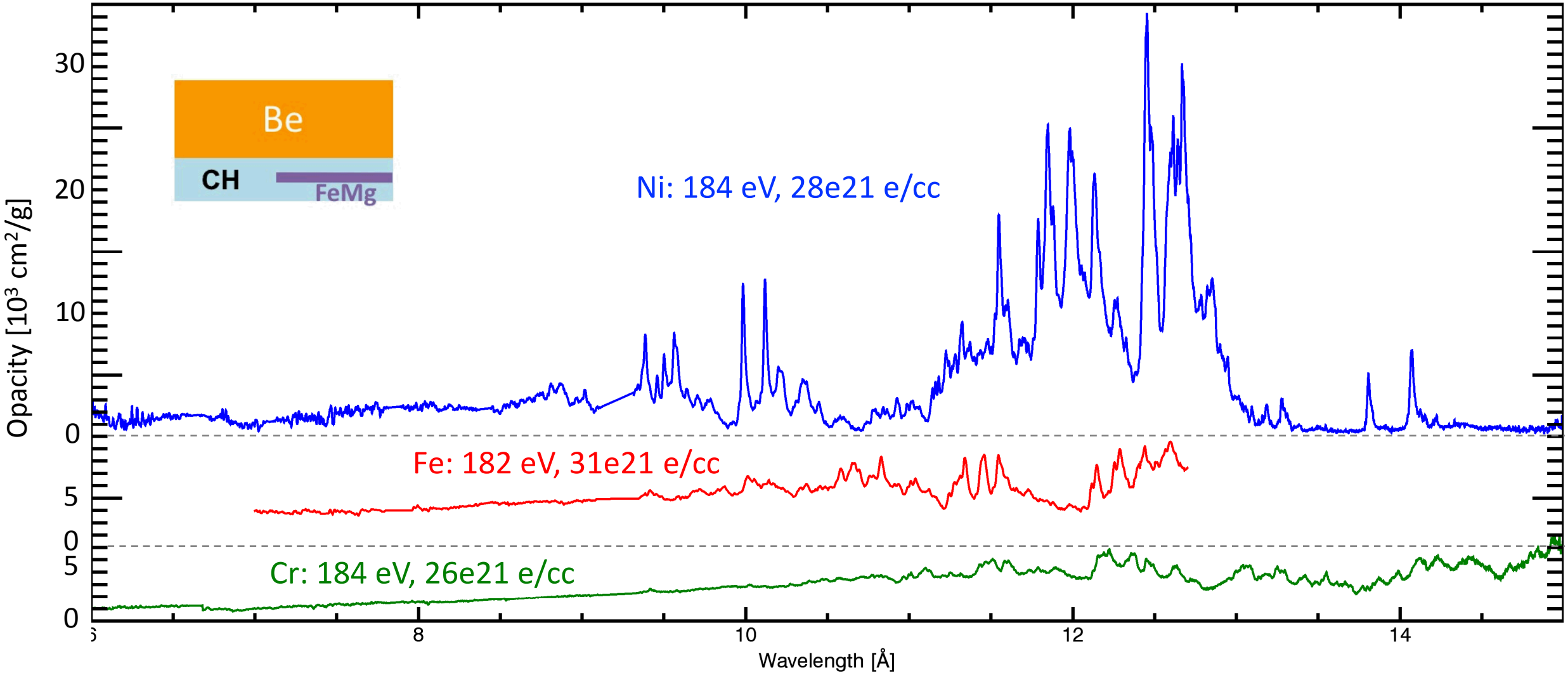
We will untangle the complex opacity issues through precise measurements across a range of T_e, n_e, and Z



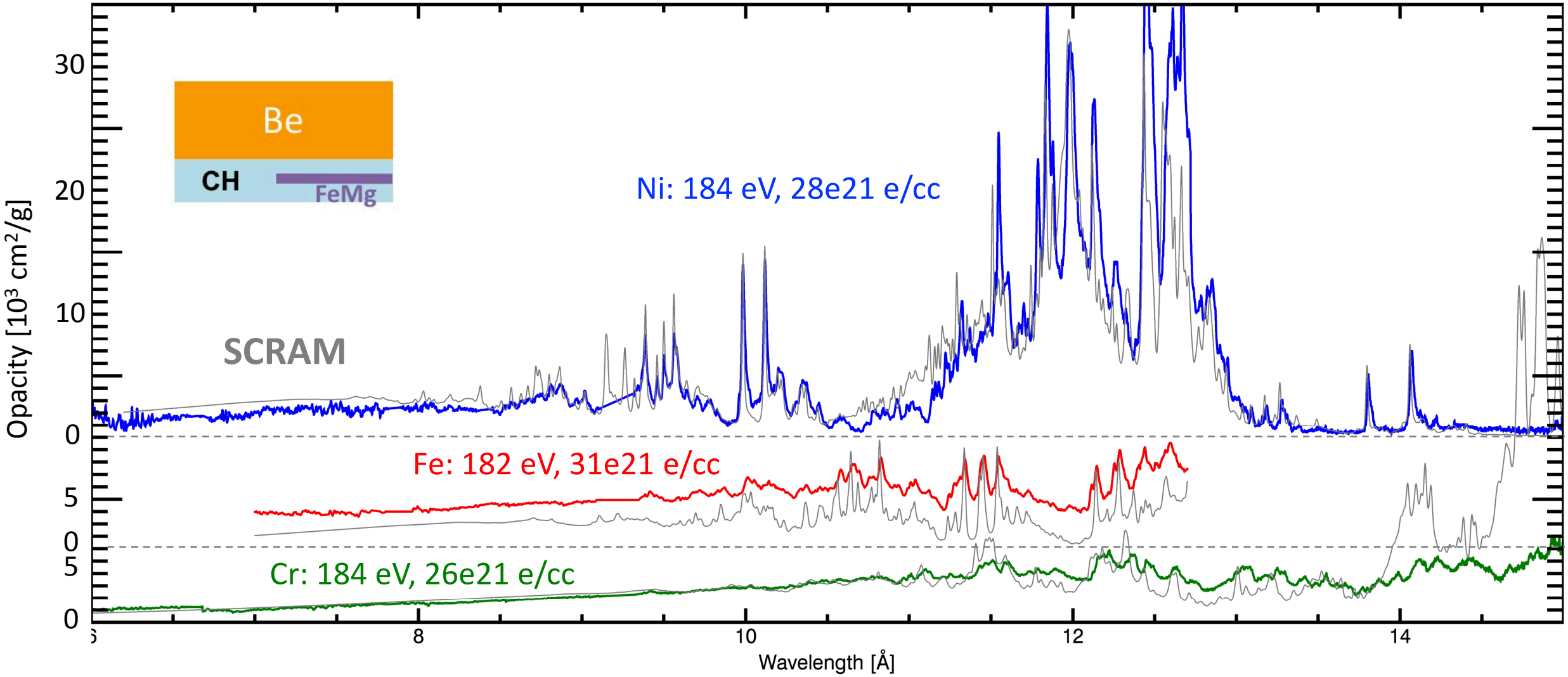
We will untangle the complex opacity issues through precise measurements across a range of T_e, n_e, and Z



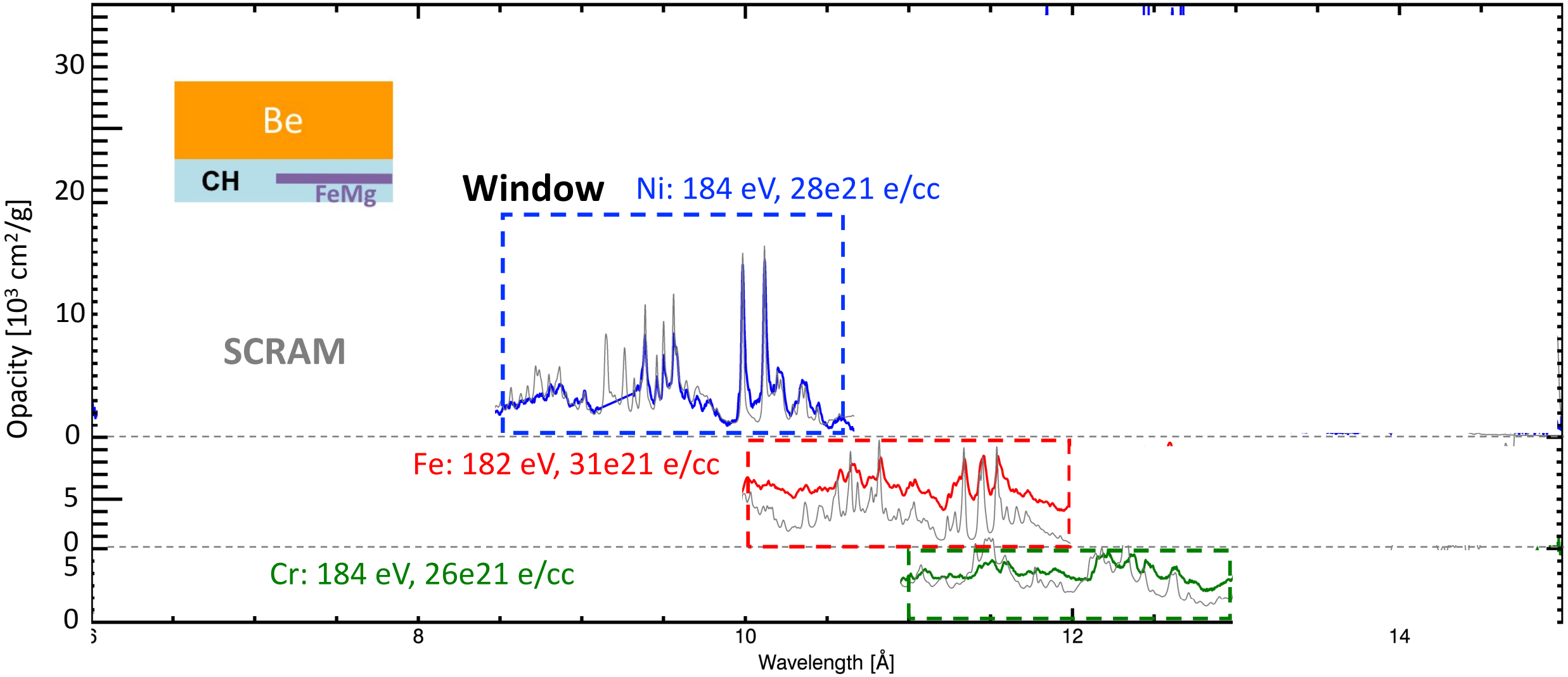
Fe, Cr, and Ni opacities are measured with the same platform: $T_e \approx$180 eV and $n_e \approx$30e21 e/cc



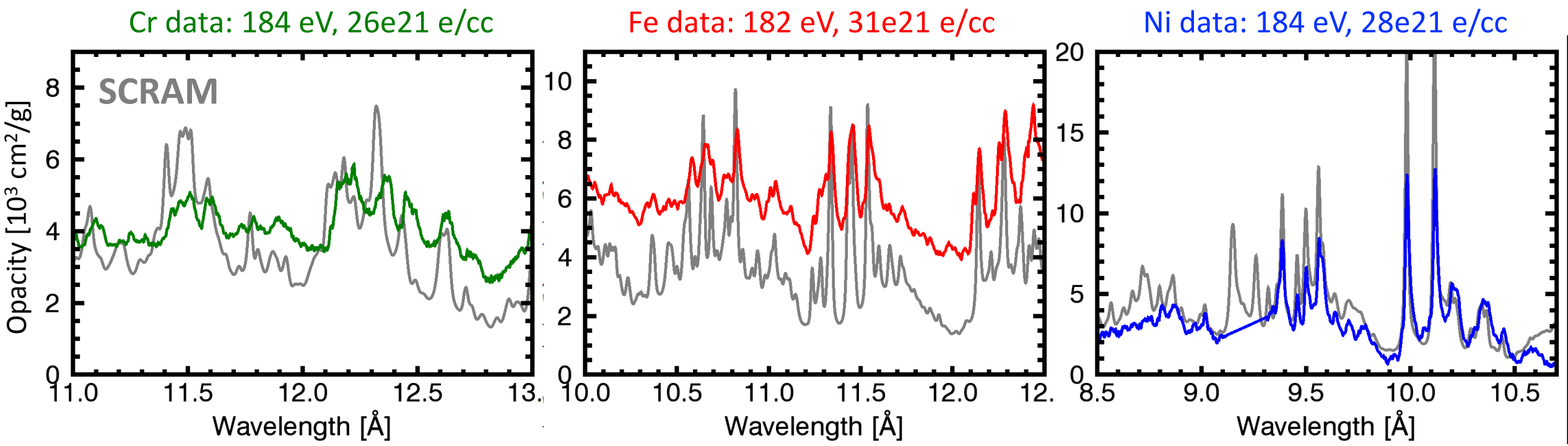
Observing model-data discrepancy trend would help narrow down hypothesis for discrepancy



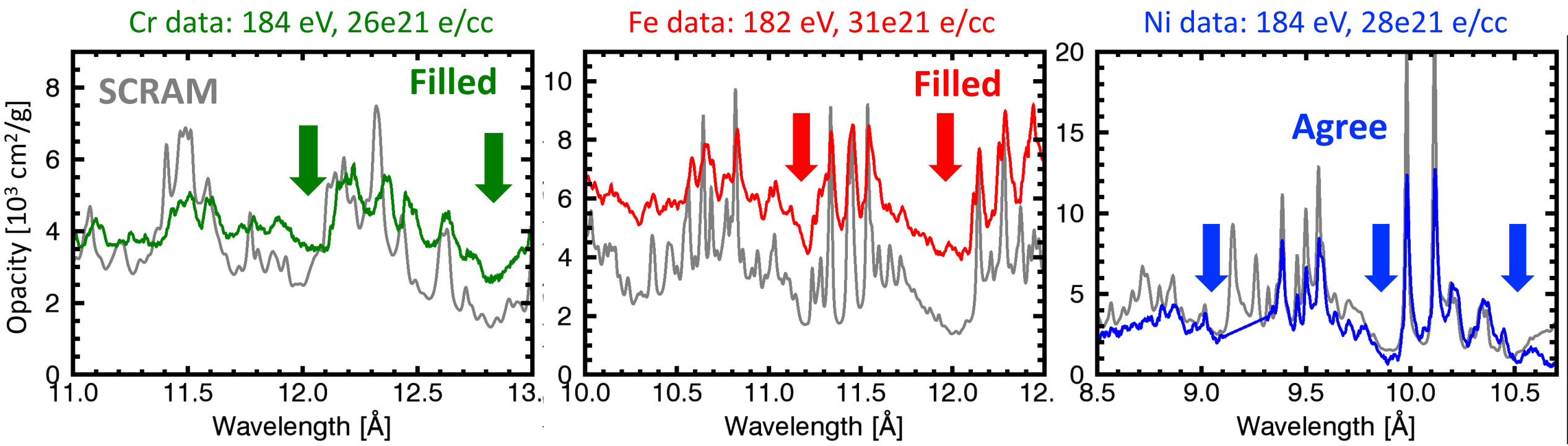
Observing model-data discrepancy trend would help narrow down hypothesis for discrepancy



Window: Filled window observed from Cr and Fe, but not Ni

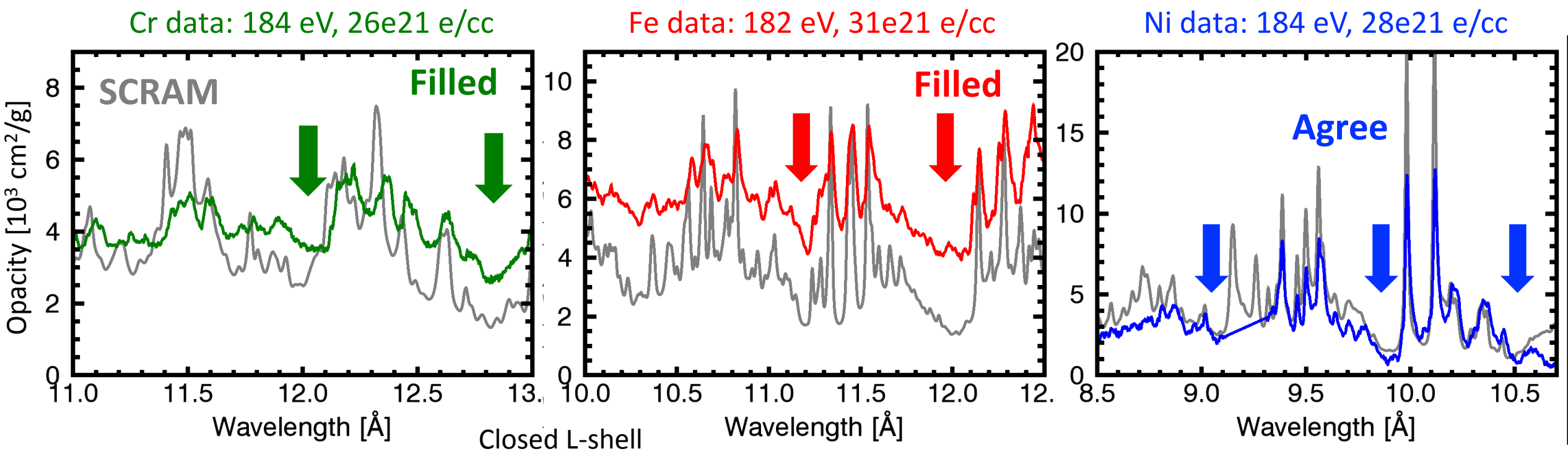


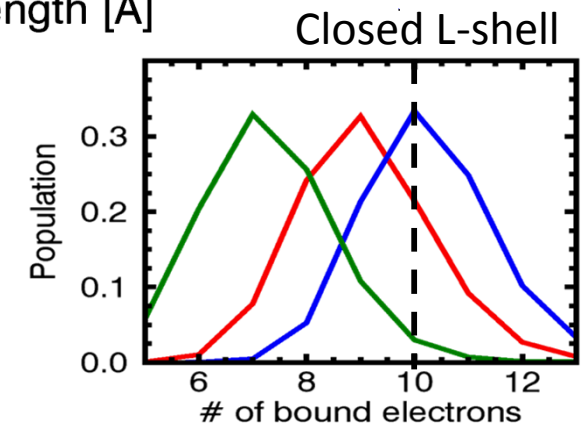
Window: Filled window observed from Cr and Fe, but not Ni



Window: Filled window observed from Cr and Fe, but not Ni

Sandia National Laboratories





Matching opacity window is challenging in open L-shell?

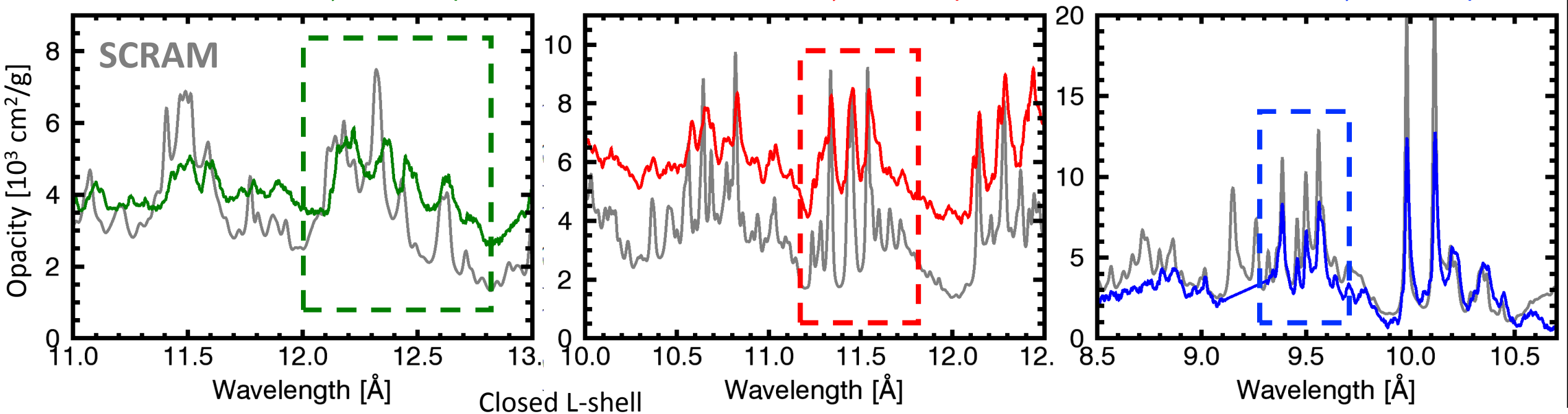
Window: Filled window observed from Cr and Fe, but not Ni

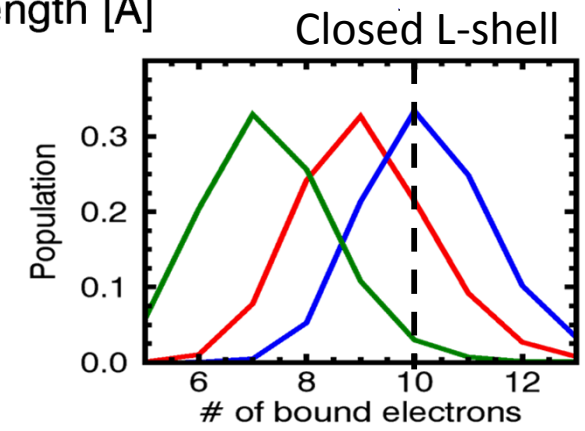
Sandia National Laboratories

Cr data: 184 eV, 26e21 e/cc

Fe data: 182 eV, 31e21 e/cc

Ni data: 184 eV, 28e21 e/cc





Matching opacity window is challenging in open L-shell?

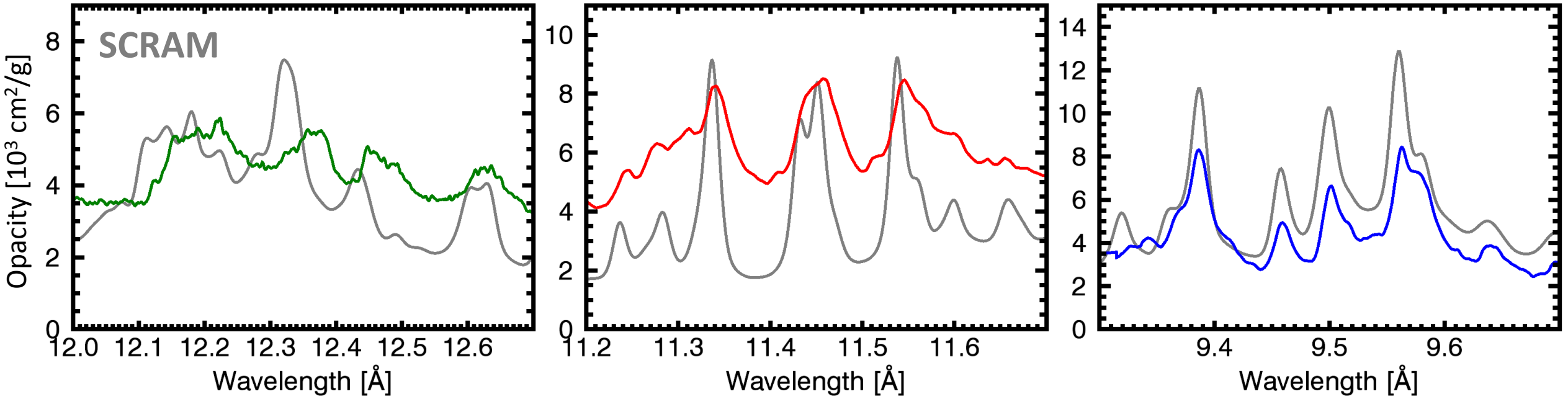
BB: Broader line and weak peak-to-valley contrast are confirmed from Cr, Fe, and Ni

Sandia National Laboratories

Cr data: 184 eV, 26e21 e/cc

Fe data: 182 eV, 31e21 e/cc

Ni data: 184 eV, 28e21 e/cc



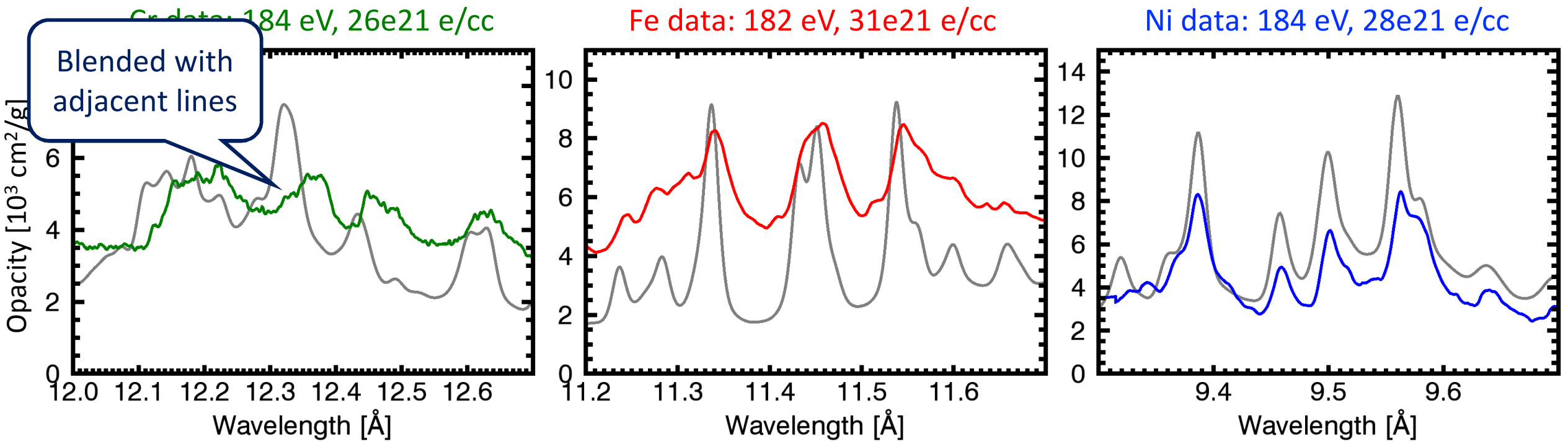
$$\kappa_\nu \propto n_l \, f_{lu} \, \phi(\nu)$$

n_l … lower state population
f_{lu}… oscillator strength
$\phi(\nu)$…line shape

} Opacity integrated under line shape

BB: Broader line and weak peak-to-valley contrast are confirmed from Cr, Fe, and Ni

Sandia National Laboratories

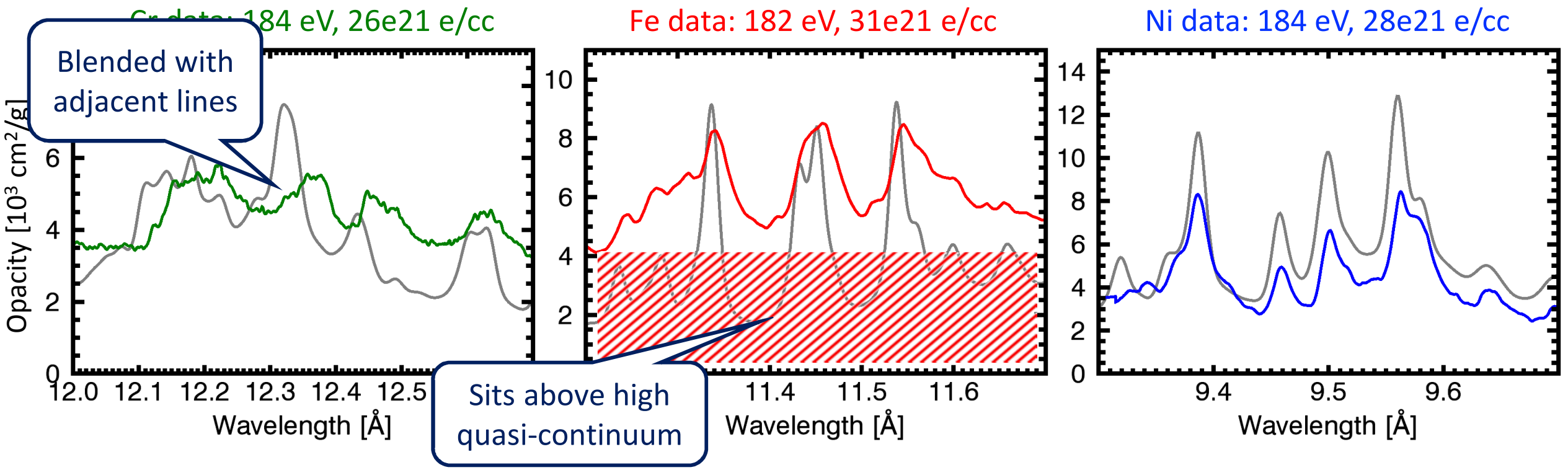


$$\kappa_\nu \propto n_l \, f_{lu} \, \phi(\nu)$$

n_l … lower state population
f_{lu}… oscillator strength
$\phi(\nu)$…line shape

} Opacity integrated under line shape

BB: Broader line and weak peak-to-valley contrast are confirmed from Cr, Fe, and Ni



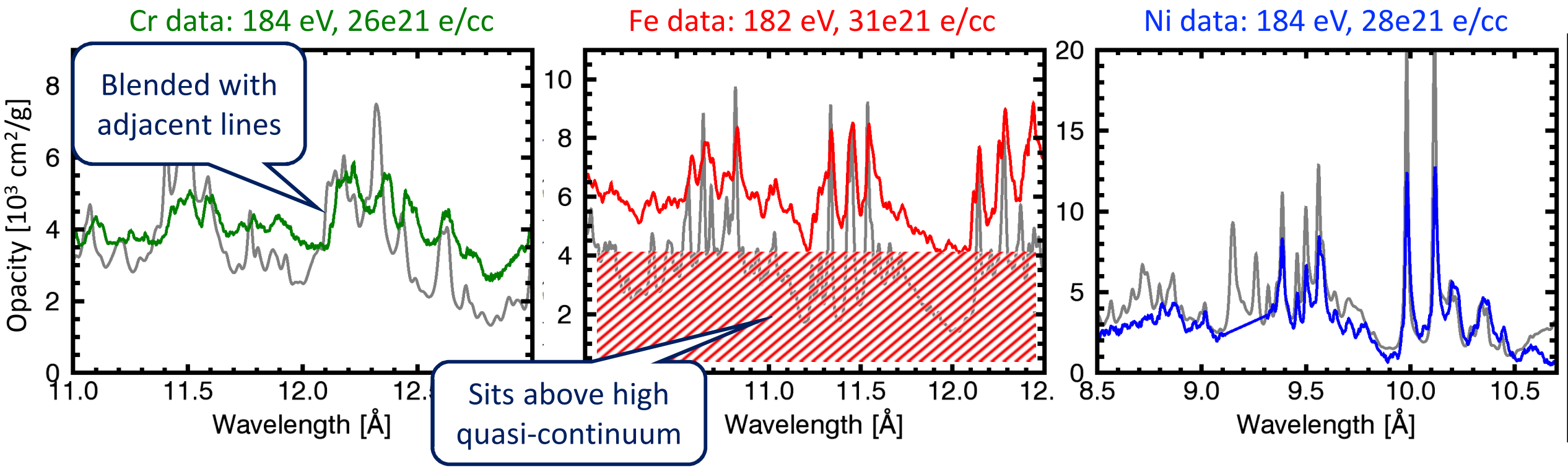
$$\kappa_\nu \propto n_l \, f_{lu} \, \phi(\nu)$$

n_l … lower state population
f_{lu}… oscillator strength
$\phi(\nu)$…line shape

} Opacity integrated under line shape

Checking line-broadening model accuracy is challenging due to line-blending and high continuum

Sandia National Laboratories



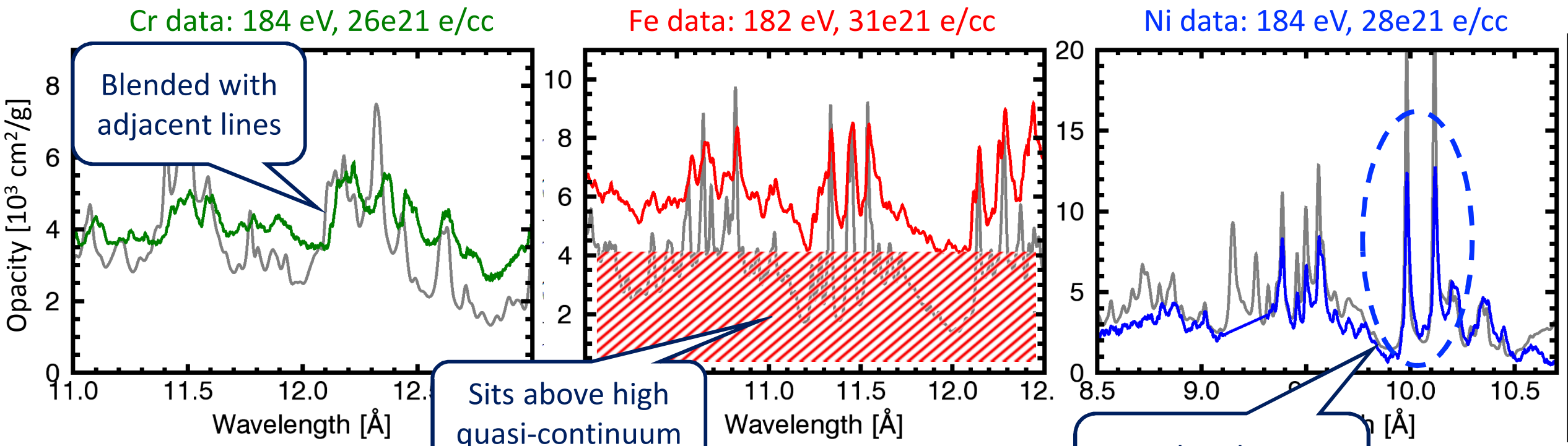
$$\kappa_\nu \propto n_l \, f_{lu} \, \phi(\nu)$$

n_l … lower state population
f_{lu}… oscillator strength
$\phi(\nu)$…line shape

} Opacity integrated under line shape

We use a n=2 → 4 lines from Ne-like Ni to assess the accuracy of calculated line shape

Sandia National Laboratories



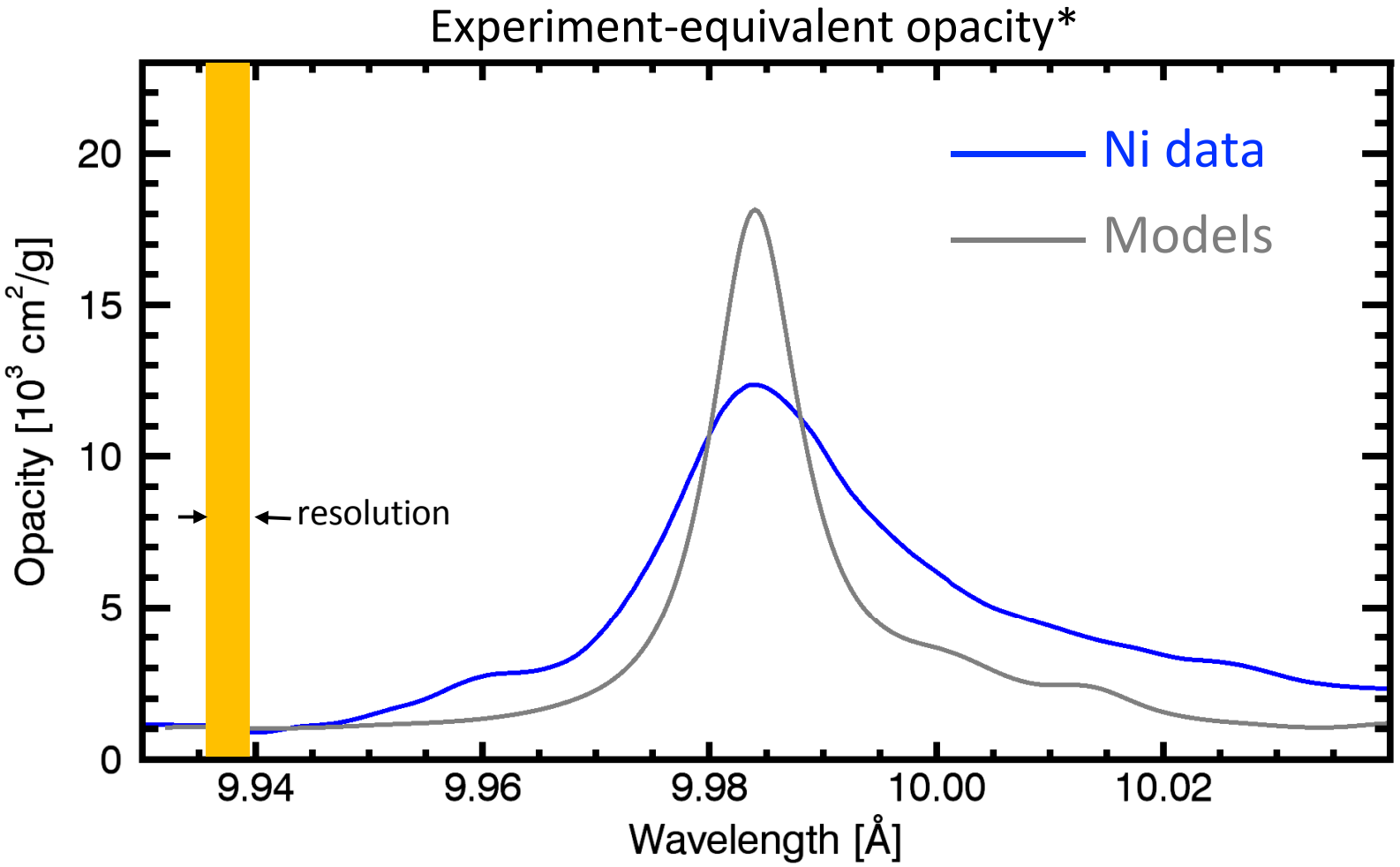
$$\kappa_\nu \propto n_l \, f_{lu} \, \phi(\nu)$$

n_l … lower state populati… integrated under line shape

f_{lu}… oscillator strength

$\phi(\nu)$…line shape

Most models predicted much narrower lines than measured

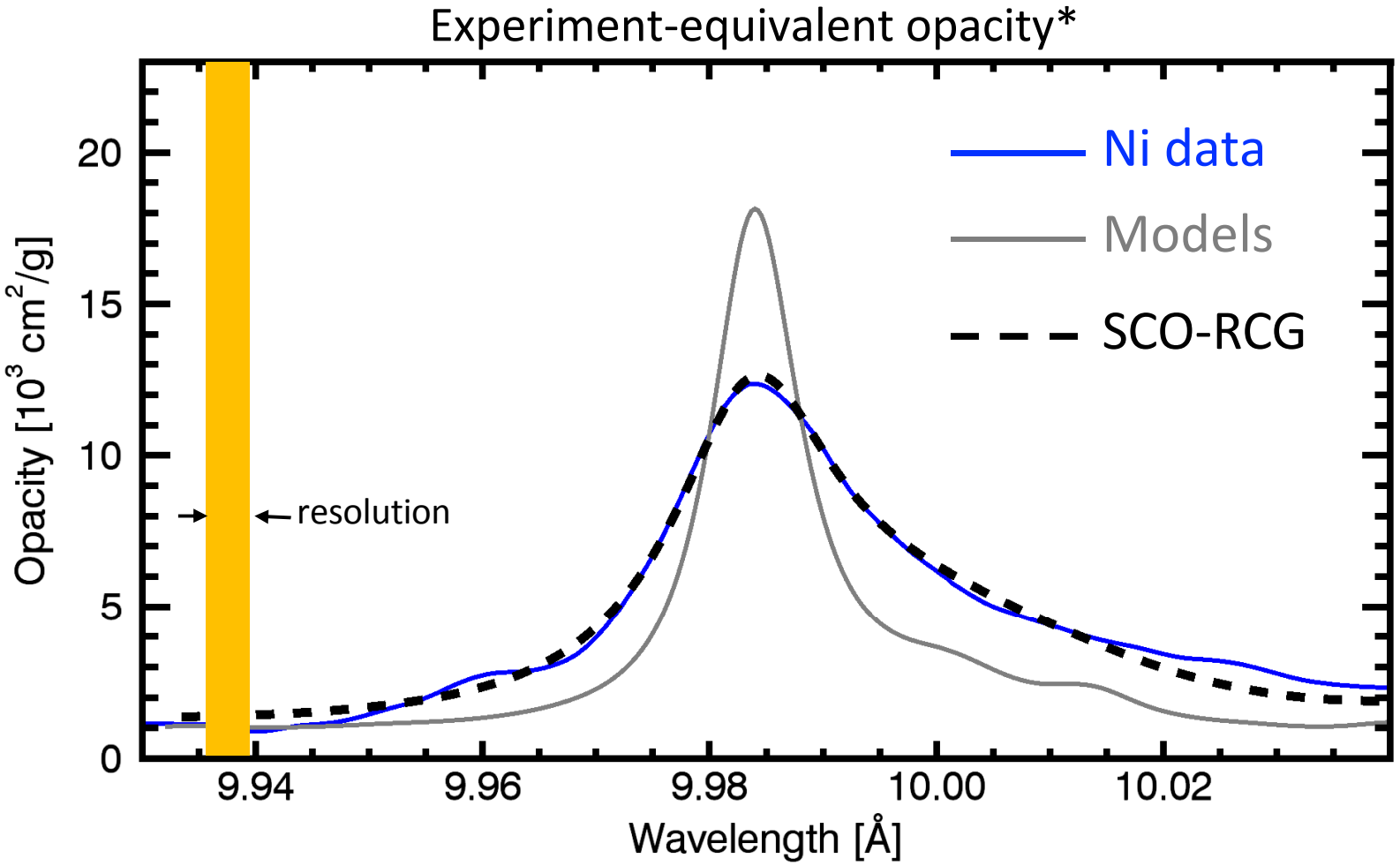


* Instrumental broadening applied on transmission

SCO-RCG: J.-C. Pain, HEDP (2015).

Most models predicted much narrower lines than measured; Only one model reproduced measured line shape

Sandia National Laboratories

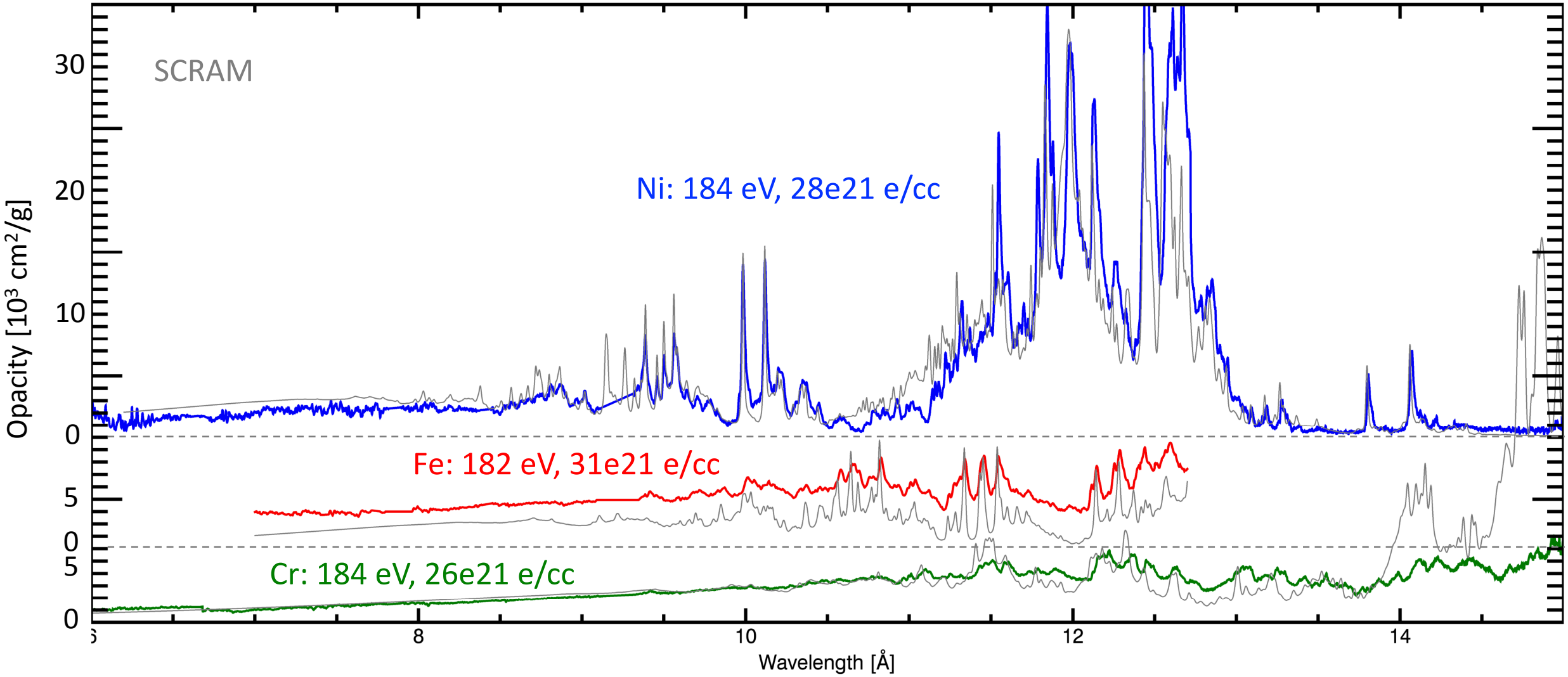


Accuracy of L-shell line-shape calculation needs to be improved

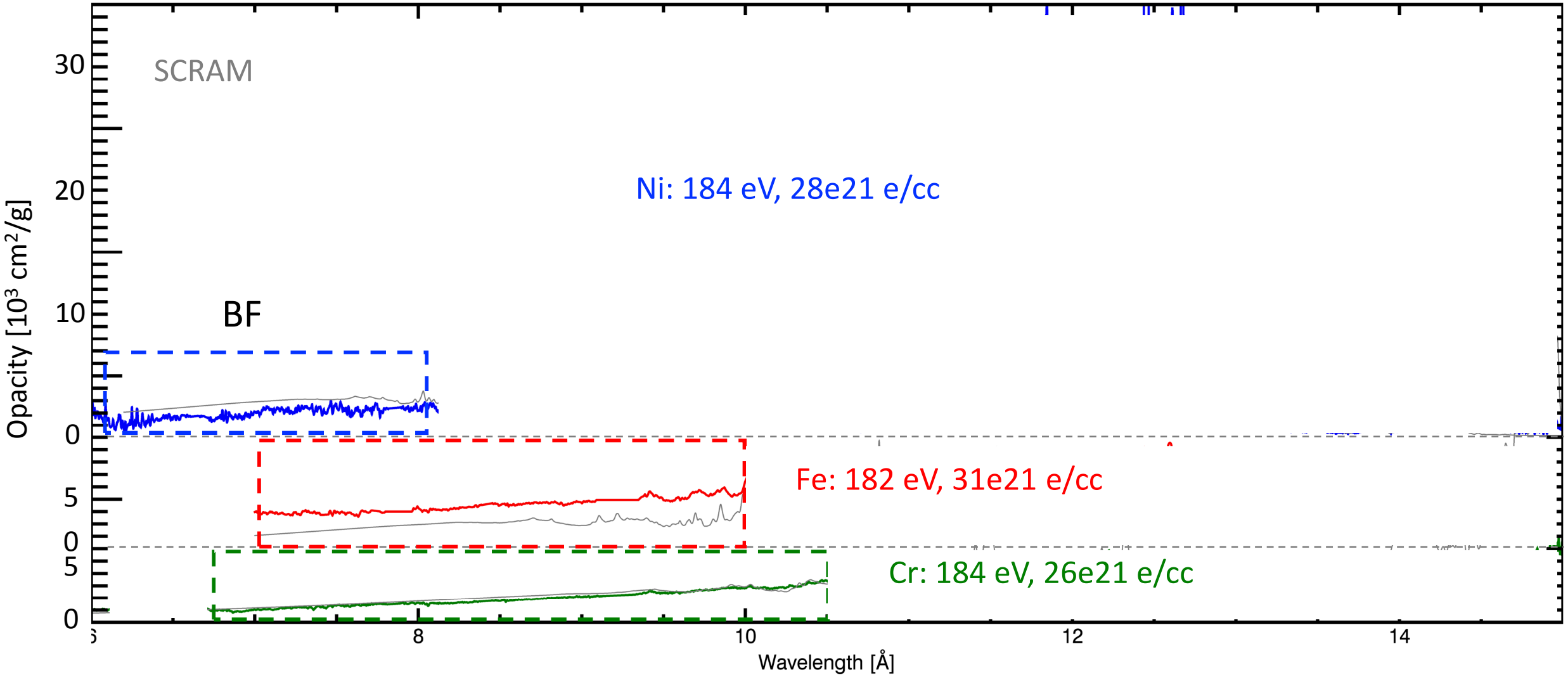
* Instrumental broadening applied on transmission

SCO-RCG: J.-C. Pain, HEDP (2015).

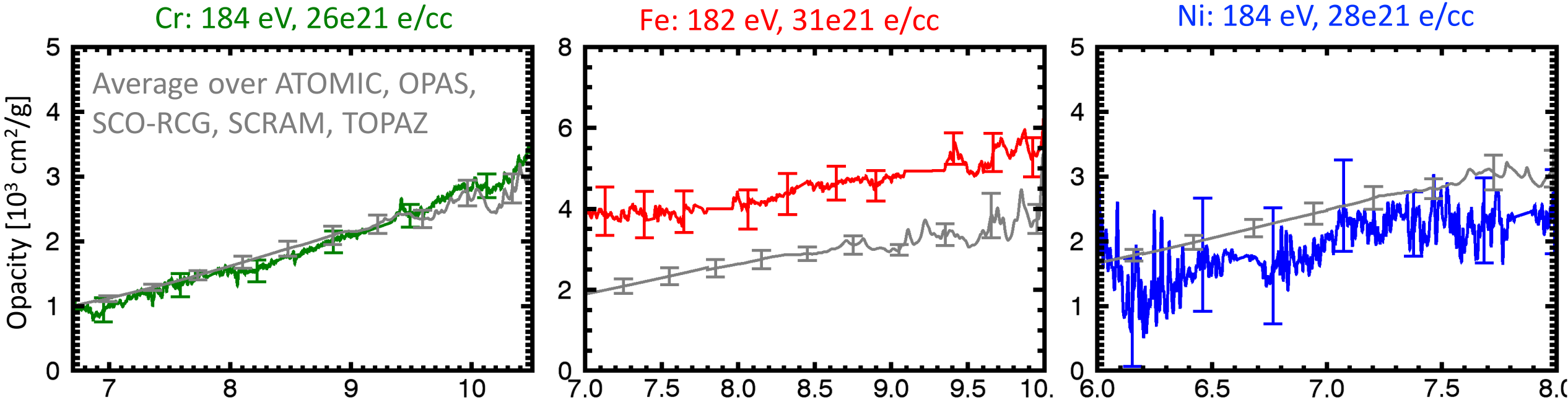
Observing model-data discrepancy trend would help narrow down hypothesis for discrepancy



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



BF: Significantly higher BF is observed only from Fe (preliminary)



- Results shown here are averages over multiple experiments
- Fe at 195 eV and 40e21 e/cc also shows higher bf → What's so special about Fe?

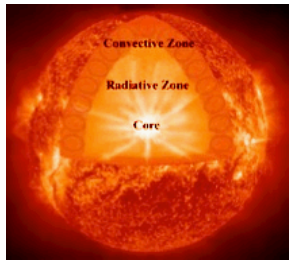
- **Hypothesis 1: Fe measurement was flawed after all the checks we did**
- **Hypothesis 2: Missing physics explains this complex BF issue**

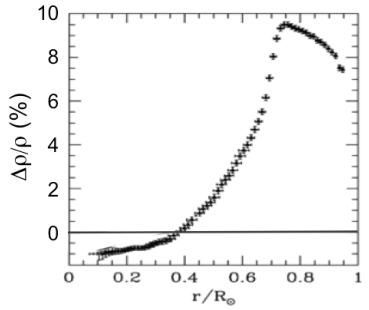
Calculated Fe opacity at solar interior condition disagrees with data; Various investigations provide clues for the discrepancy

Sandia National Laboratories

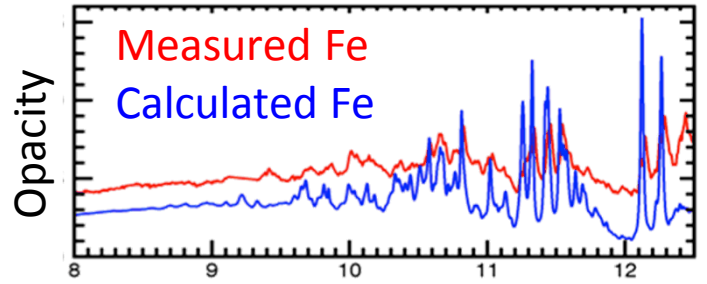
- **We found 30–400% disagreement between modeled and measured Fe opacity at solar interior conditions**

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

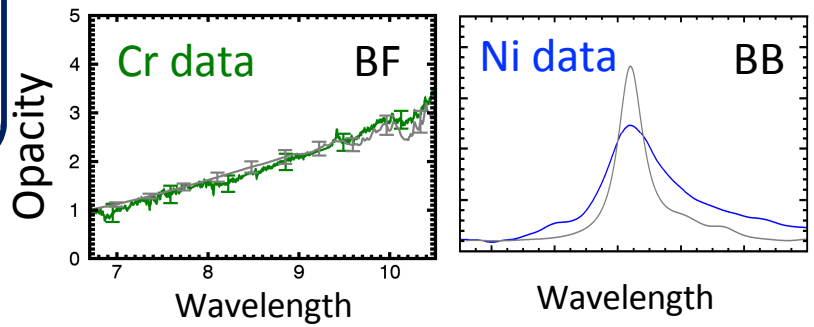




- **Cr, Fe, and Ni opacities measured at multiple electron temperatures (T_e) and electron densities (n_e)**
  - Opacity valley disagreement found on Cr and Fe, but not Ni
  - Calculated line-broadening is too narrow
  - Element dependence on bound-free (BF) agreement is puzzling



- **Missing physics in opacity theory:**
  - Two-photon opacity may be important



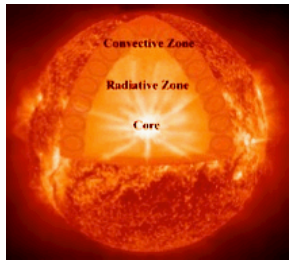
Working towards completing the systematic study to resolve the discrepancy

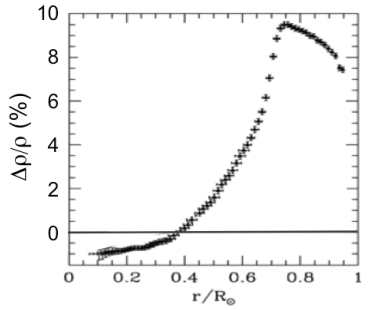
Calculated Fe opacity at solar interior condition disagrees with data; Various investigations provide clues for the discrepancy

Sandia National Laboratories

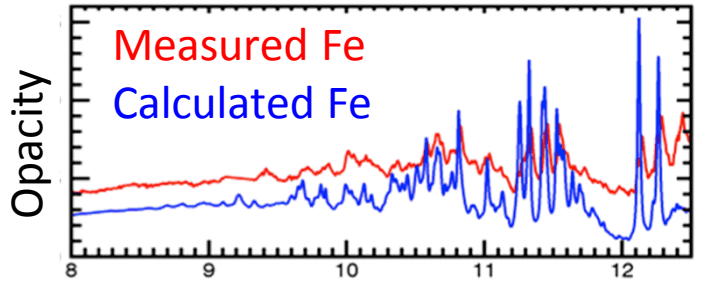
- **We found 30–400% disagreement between modeled and measured Fe opacity at solar interior conditions**

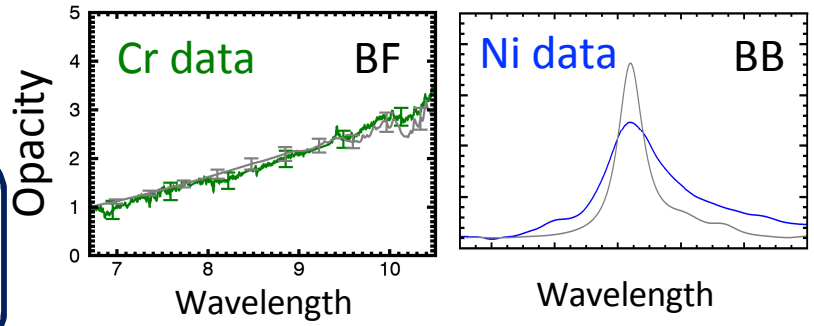
  → Partially resolves solar problem, but the source of discrepancy needs to be identified





- **Cr, Fe, and Ni opacities measured at multiple electron temperatures (T_e) and electron densities (n_e)**
  - Opacity valley disagreement found on Cr and Fe, but not Ni
  - Calculated line-broadening is too narrow
  - Element dependence on bound-free (BF) agreement is puzzling



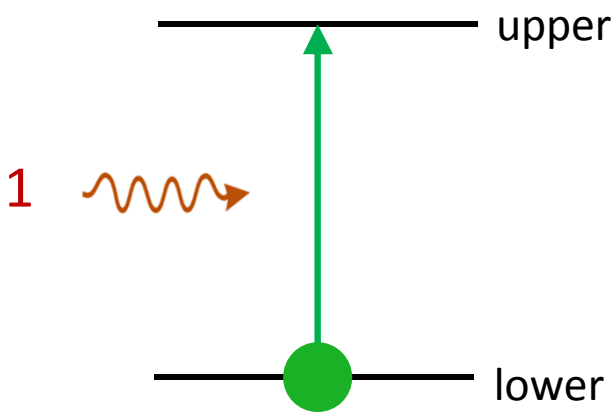


- **Missing physics in opacity theory:**
  - Two-photon opacity may be important

Working towards completing the systematic study to resolve the discrepancy

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

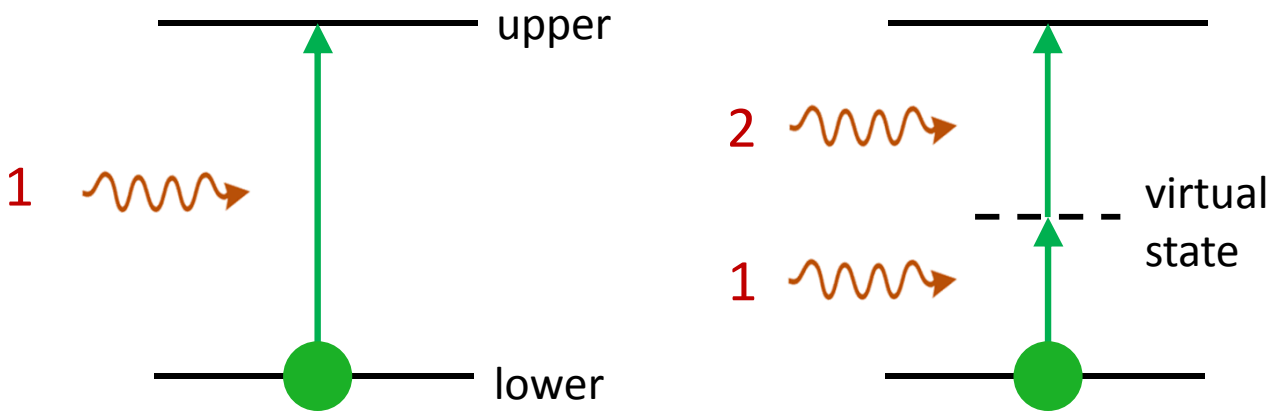
one-photon processes



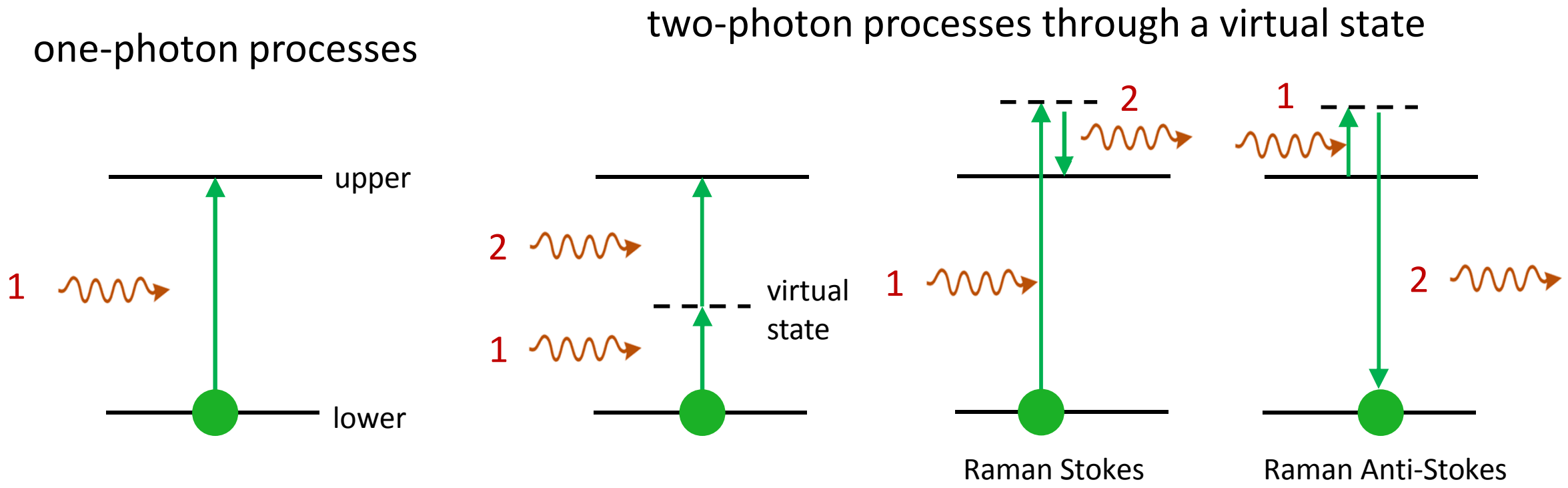
Opacity by two-photon processes are neglected from existing opacity models

one-photon processes

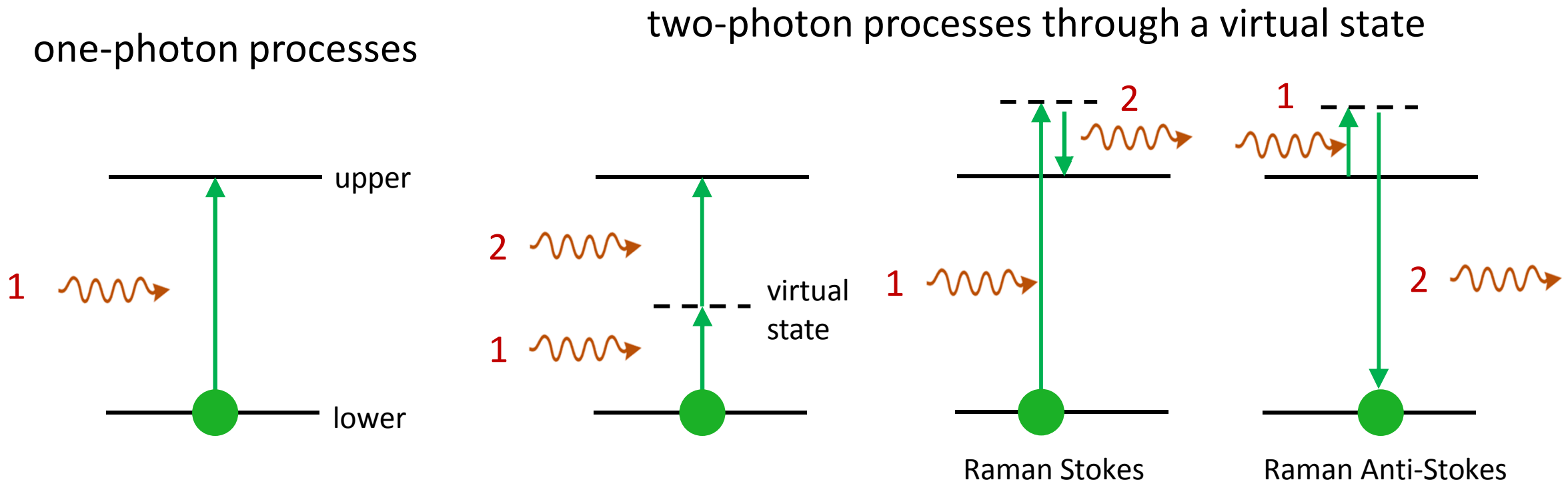
two-photon processes through a virtual state



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



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

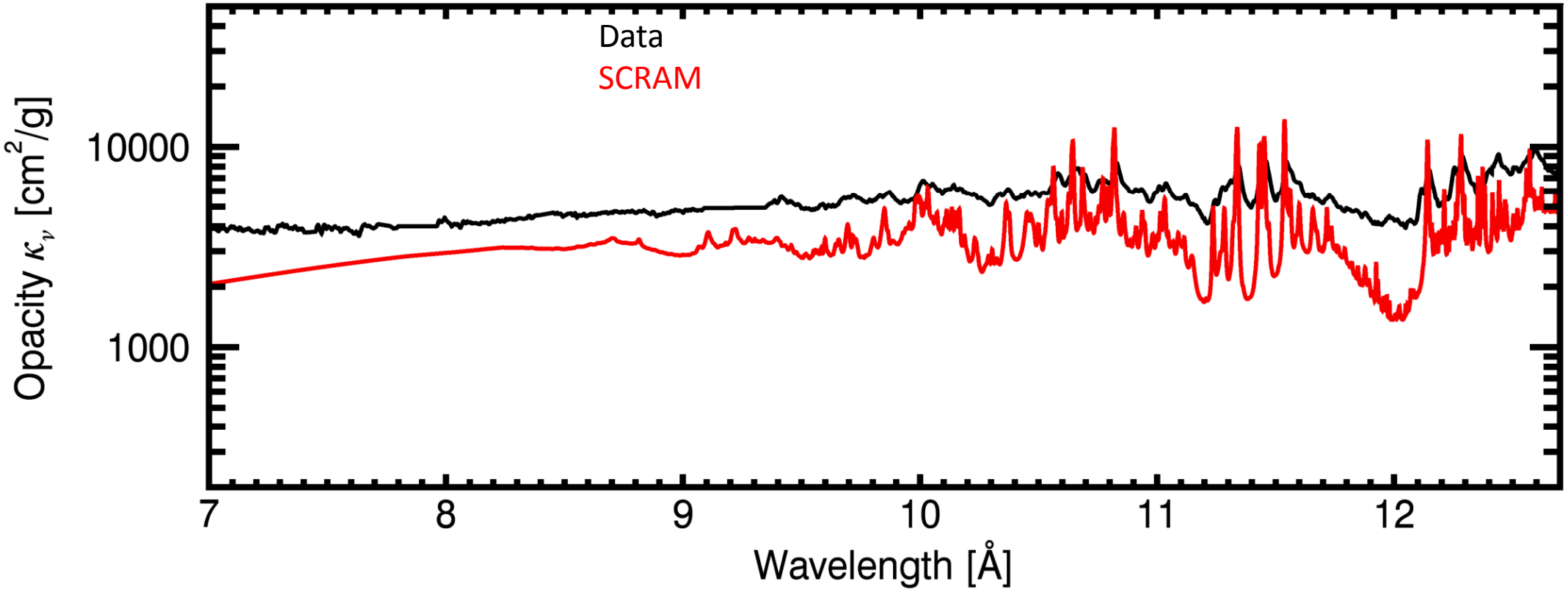


- Two-photon process cross-section $\sim n^8$
- Virtual state has short life-time → Bright radiation field

} Z opacity experiments have both

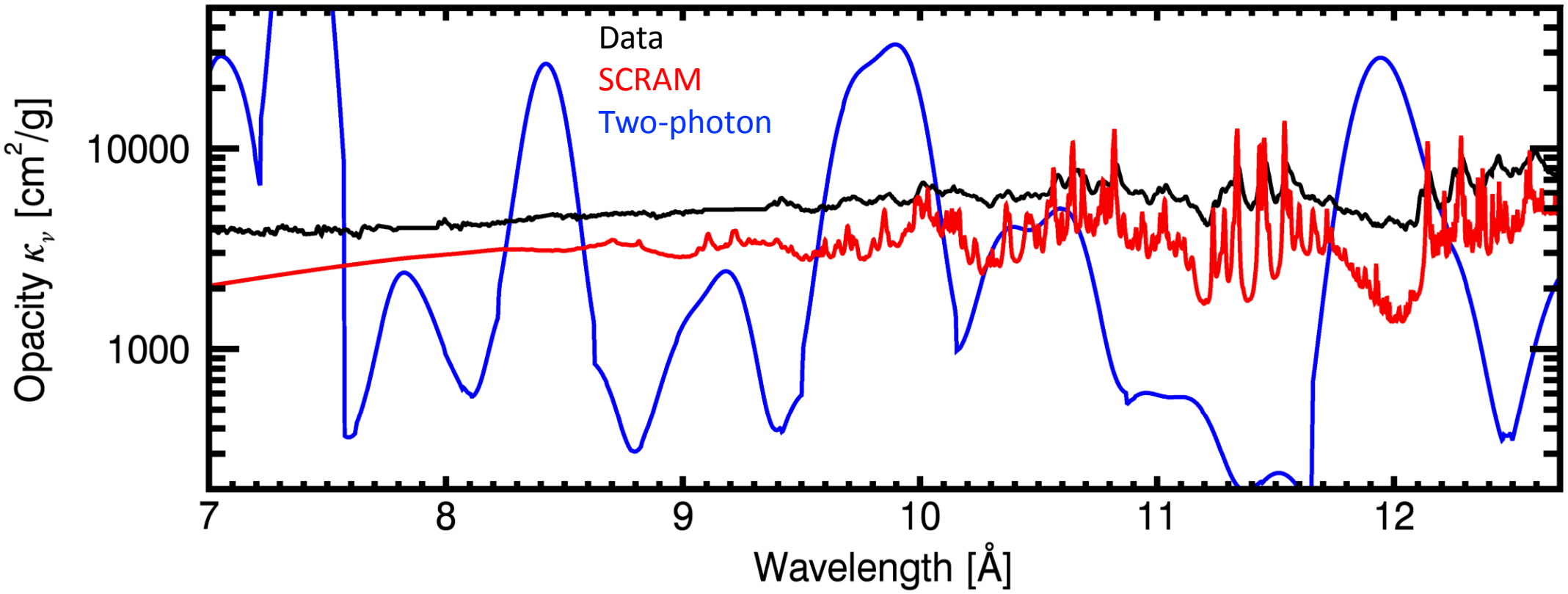
Two-photon opacity can be important for Fe L-shell opacity under strong radiation field

Two-photon processes may be important



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

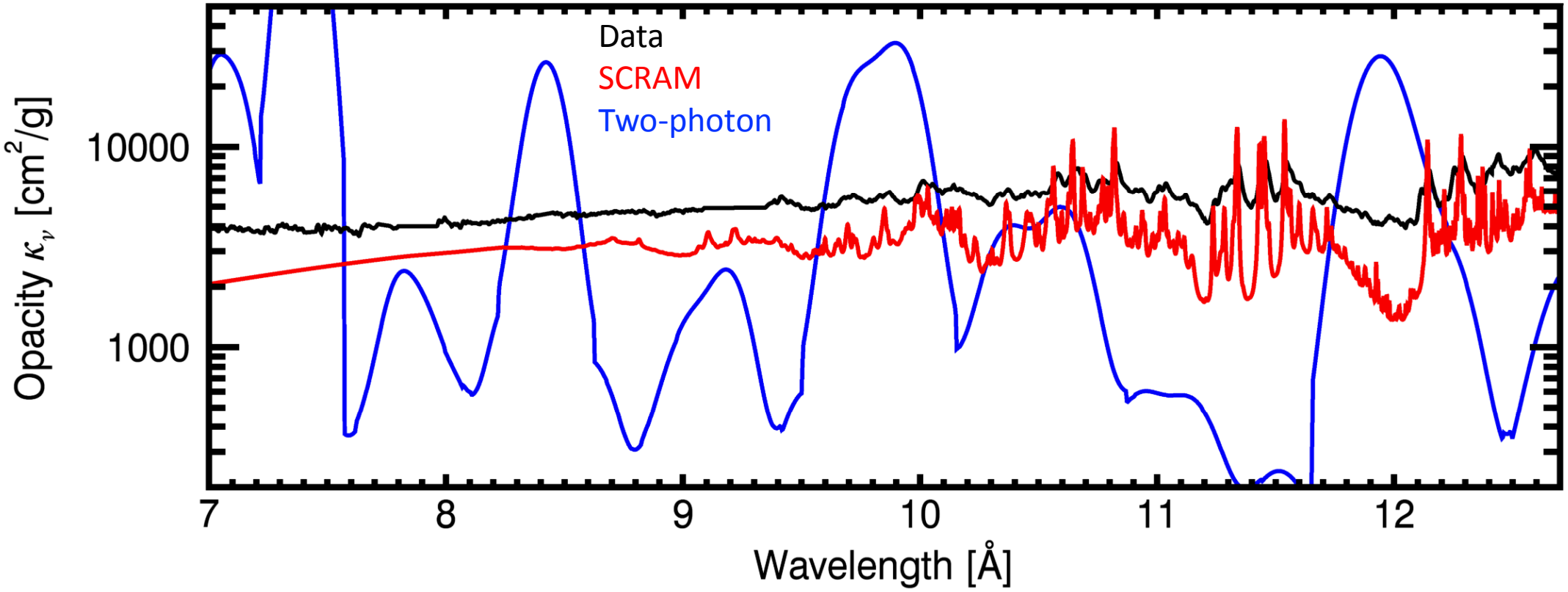
Two-photon processes may be important



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

R. More, S. Hansen, and T. Nagayama, High Energy Density Physics 24, 44 (2017)

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



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

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

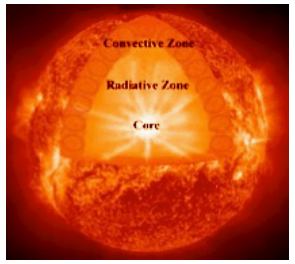
Sandia National Laboratories

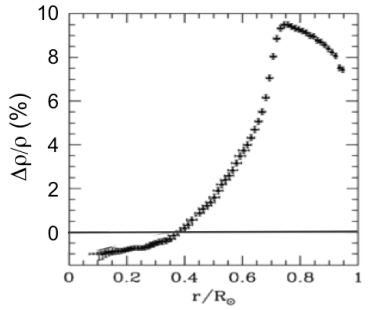
- **We found 30–400% disagreement between modeled and measured Fe opacity at solar interior conditions**

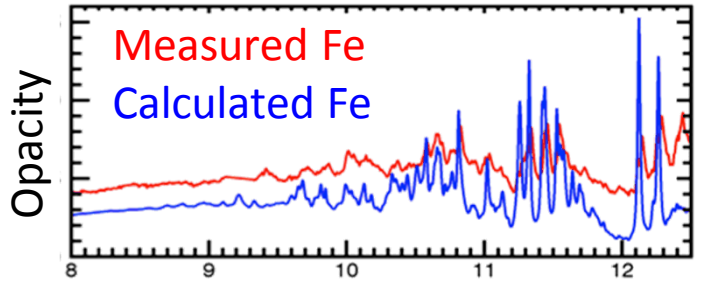
  → Partially resolves solar problem, but the source of discrepancy needs to be identified

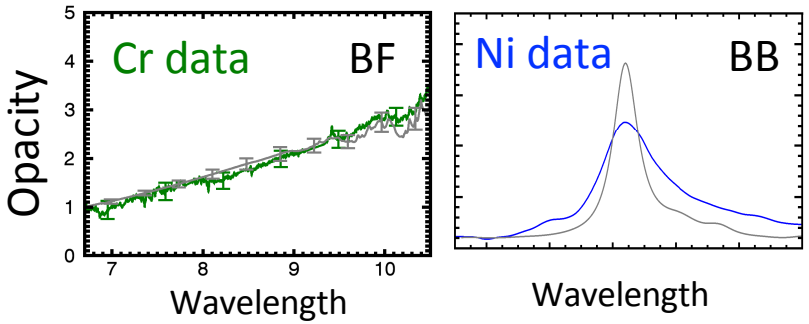
- **Cr, Fe, and Ni opacities measured at multiple electron temperatures (T_e) and electron densities (n_e)**
  - Opacity valley disagreement found on Cr and Fe, but not Ni
  - Calculated line-broadening is too narrow
  - Element dependence on bound-free (BF) agreement is puzzling

- **Missing physics in opacity theory:**
  - Two-photon opacity may be important









Working towards completing the systematic study to resolve the discrepancy