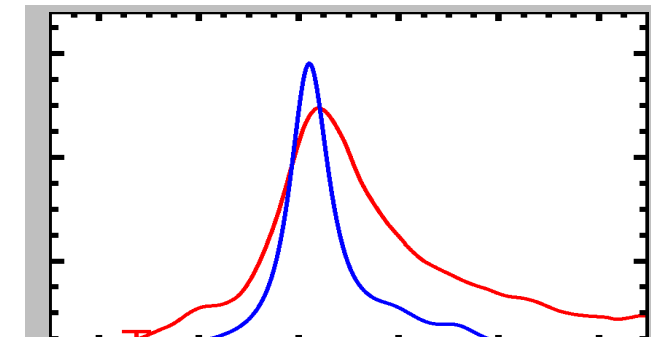
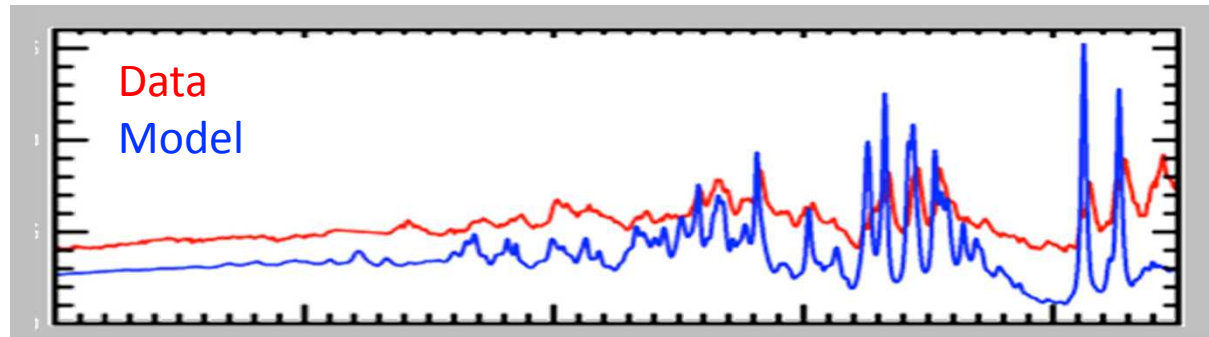
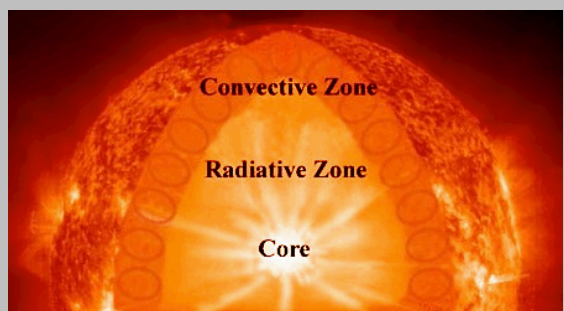


Systematic measurements of opacity dependence on temperature, density, and atomic number at stellar interior conditions

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



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

Taisuke Nagayama

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

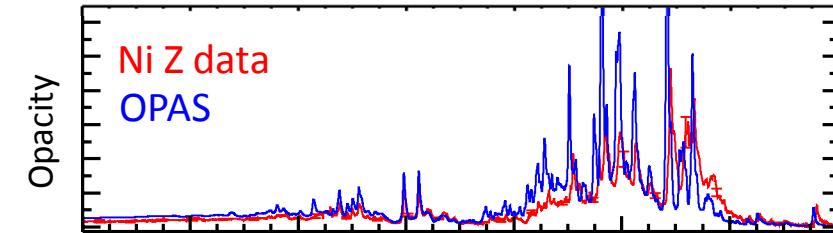
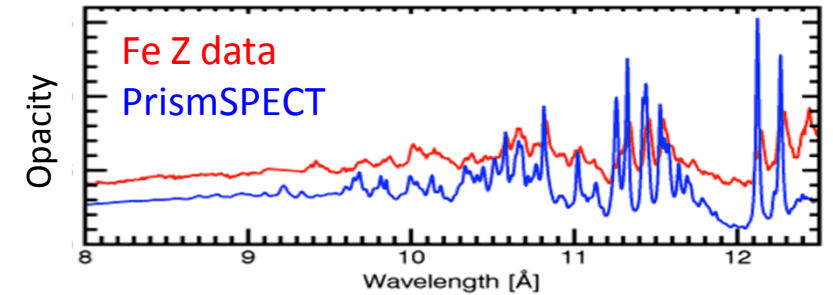
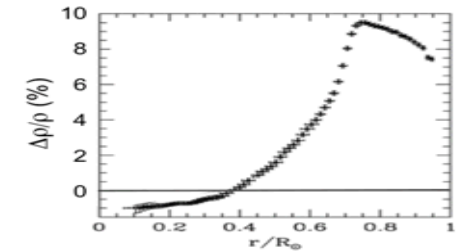
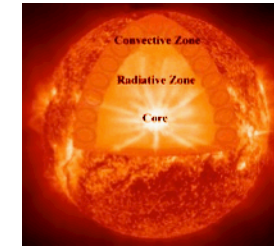


R.C. Mancini
University of Nevada, Reno, NV

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

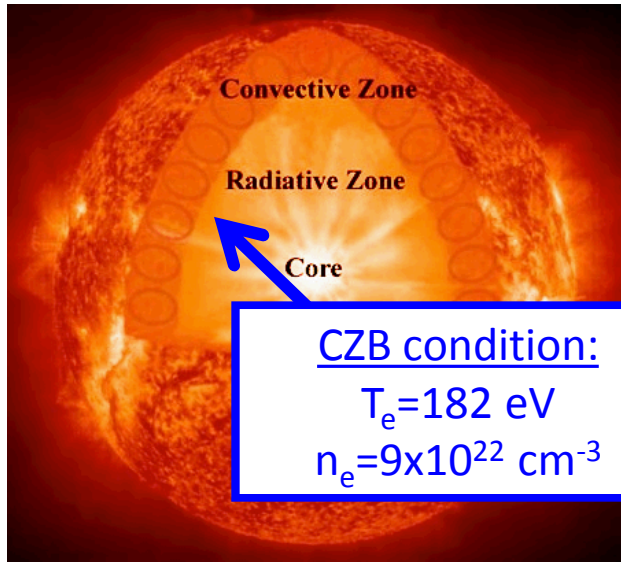
We are helping resolve the reported stellar opacity discrepancy with experiments, data interpretation, and theory

- Solar models disagree with observations
 - Solar mean opacity is underestimated by 17% [1]
 - Hypothesis: Fe opacity too low?
- SNL Fe opacity measurement revealed 30-400% disagreement with calculated opacity [2]
 - >7% increase in solar mean opacity
- Progress towards the resolution of the discrepancy:
 - Experiment scrutiny:
 - Density error partially explain peak-to-valley contrast
 - Fe, Ni, and Cr opacity measurements:
 - Platform is not always biased
 - Bound-free disagreement most prominent in Fe
 - Theory: Two-photon opacity may be important

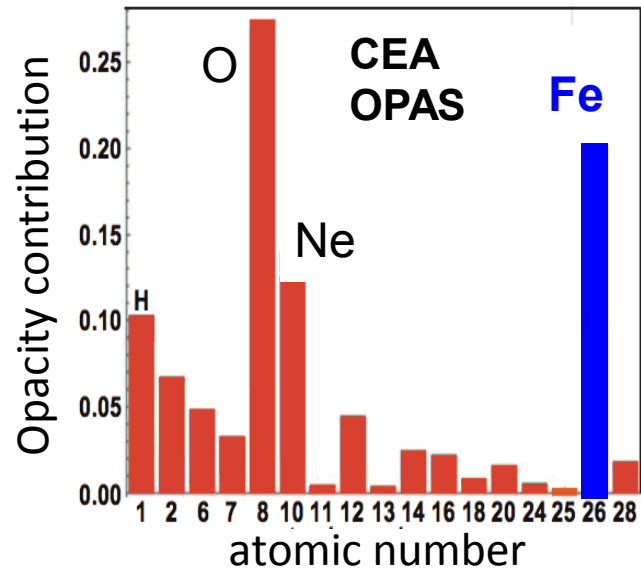


Working towards completing the systematic study

Simulated solar structure disagree with observations; 17% mean-opacity increase is needed



CZB condition:
 $T_e = 182 \text{ eV}$
 $n_e = 9 \times 10^{22} \text{ cm}^{-3}$



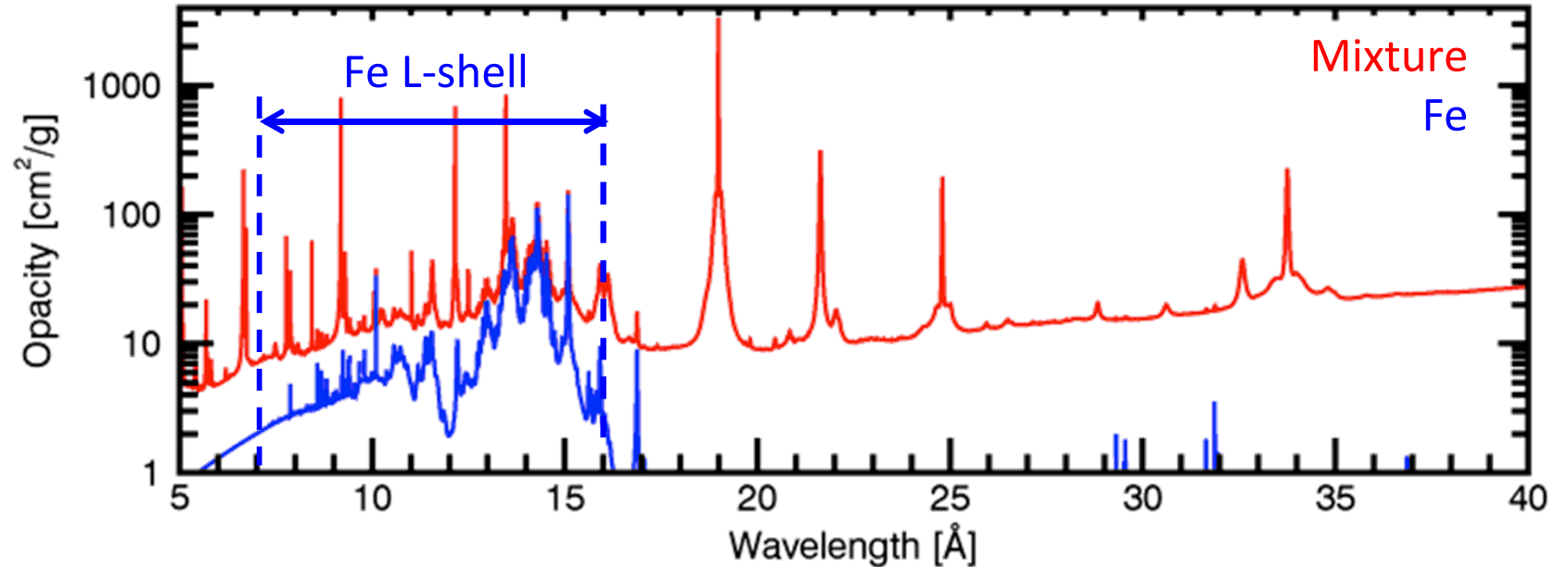
Opacity: κ_v

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

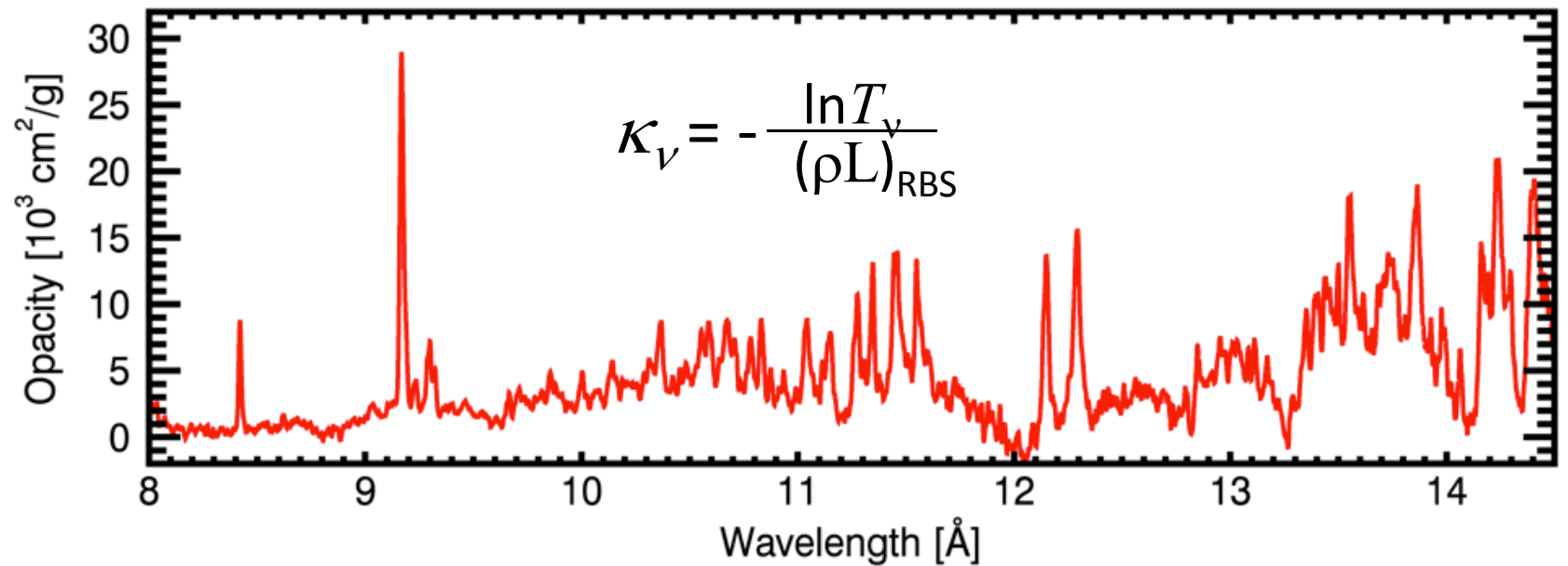
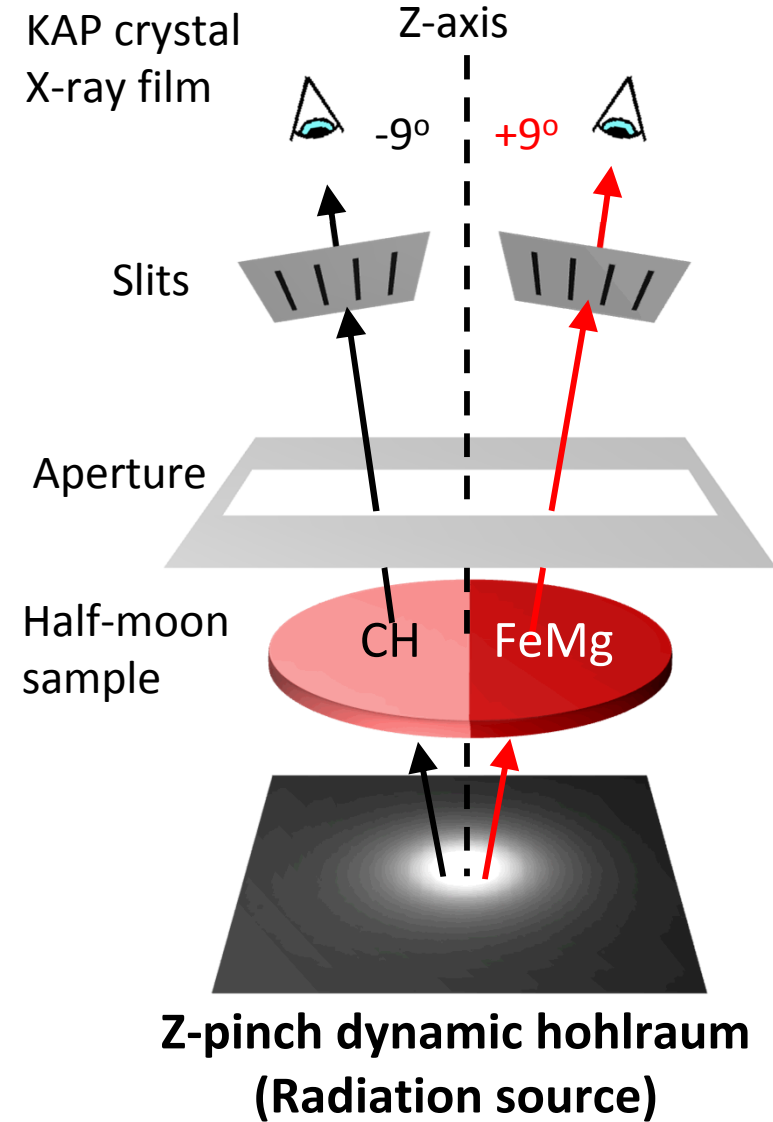
Fe is a likely suspect:

- 2nd largest contribution
- Most difficult to model

Solar mixture opacity at Convection Zone Base (CZB)



High temperature Fe opacities are measured using the Z-Pinch dynamic hohlraum (ZPDH) opacity science platform



Requirements

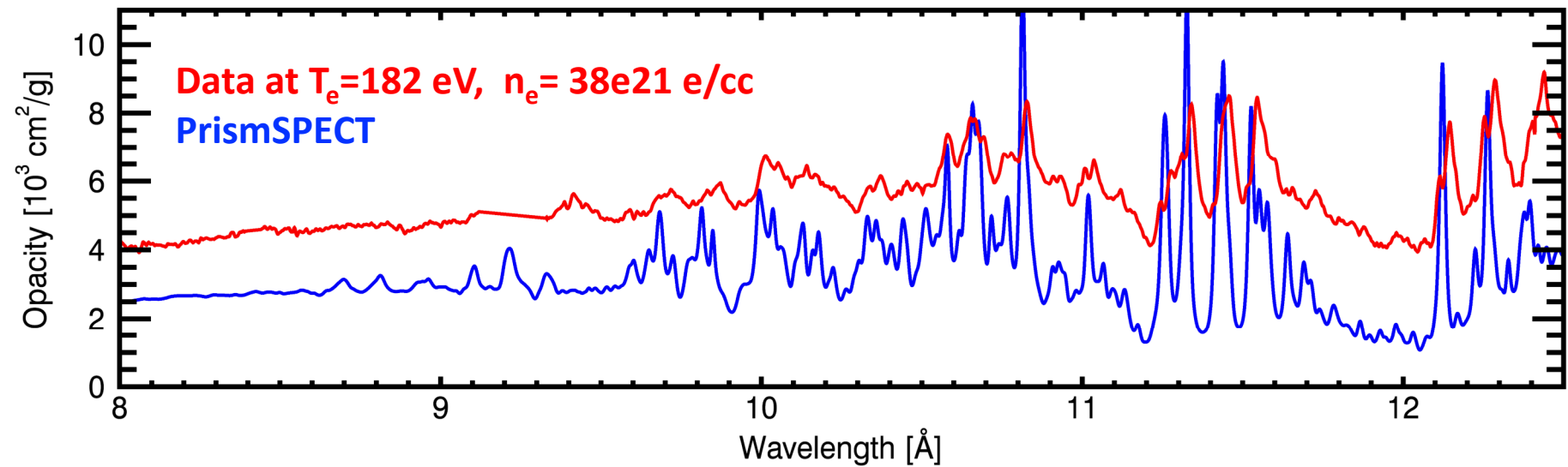
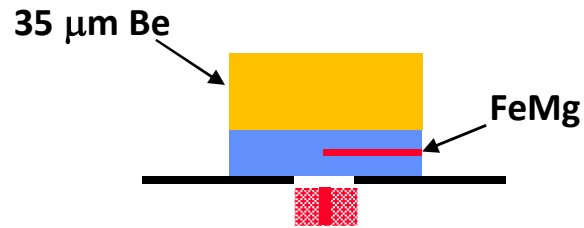
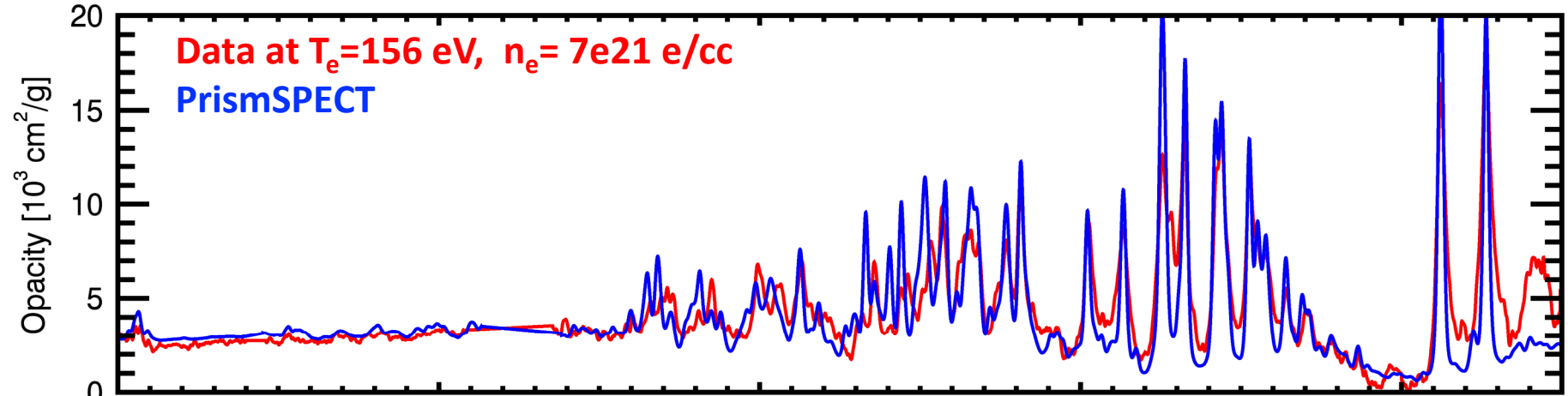
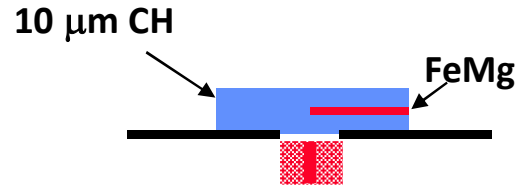
- Uniform heating
- Mitigating self emission
- Condition measurements

SNL Z satisfies:

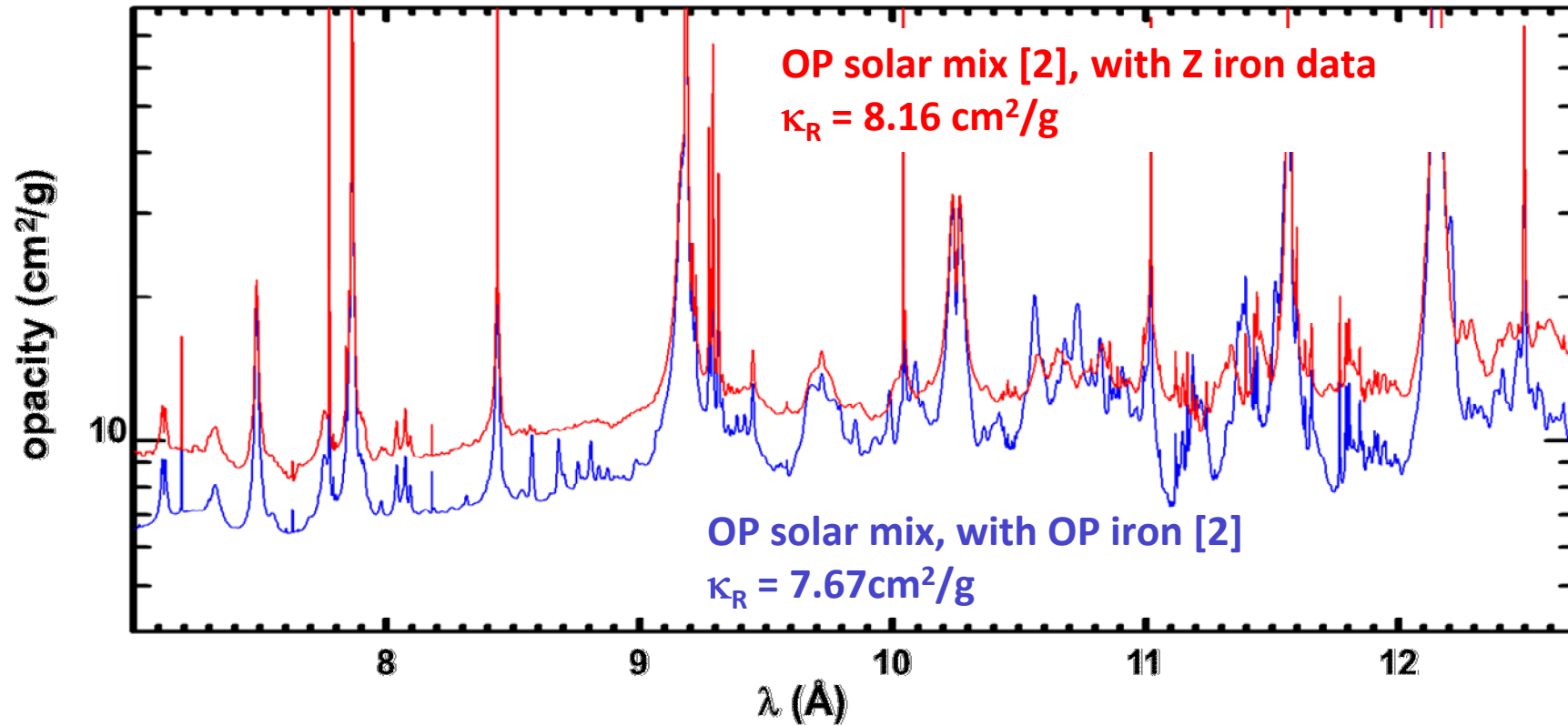
- Volumetric heating
- 350-eV Planckian backlight
- Mg K-shell spectroscopy

Modern best-effort models disagree with the Z iron data at stellar interior conditions

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



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

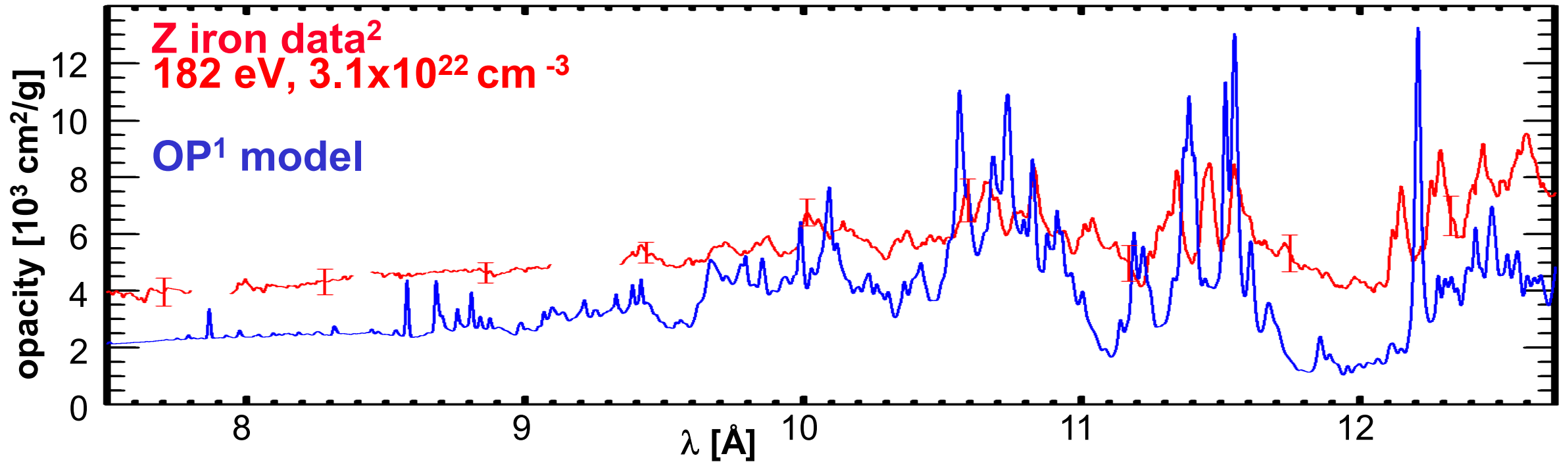


- A 7% Rosseland increase partially resolves the solar problem
- But the measured iron opacity by itself cannot account for the entire discrepancy
- We need to extend our measurement in spectral range, elements, and conditions

[1] Bailey et al, Nature (2015)

[2] Seaton et al, MNRAS (1994)

Reported opacity discrepancy is disturbing and deserves further scrutiny



Flaws in experiment?
Inaccuracy in theory?

Common hypotheses for experimental flaws

Sample characterization error

- Any contamination?
- Is Fe thickness accurately know?

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

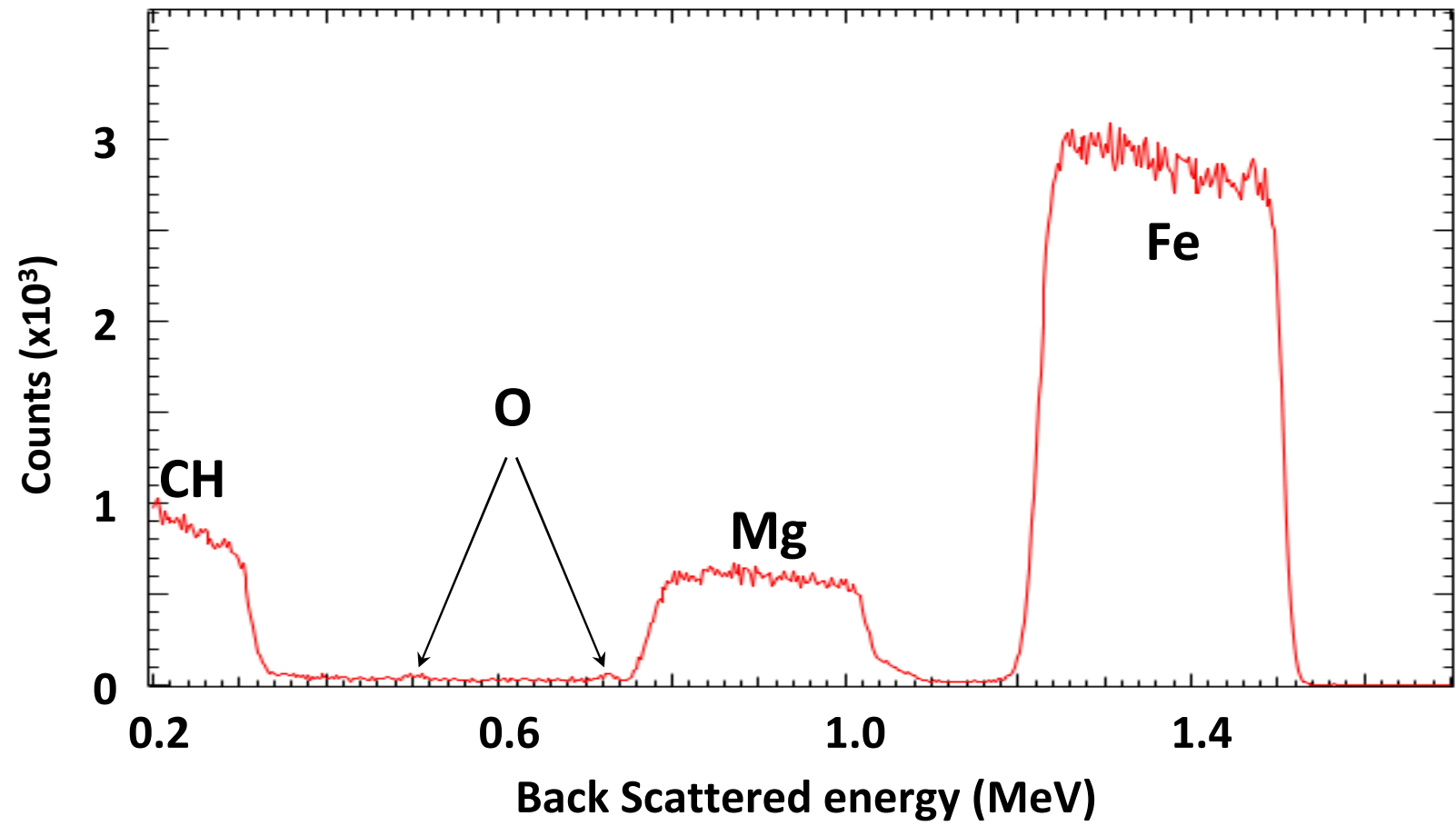
Common hypotheses for experimental flaws

Sample characterization error

- Any contamination?
- Is Fe thickness accurately know?

RBS measurements confirm there is no unexpected contamination

Pre-shot Rutherford backscattered spectrum (RBS)

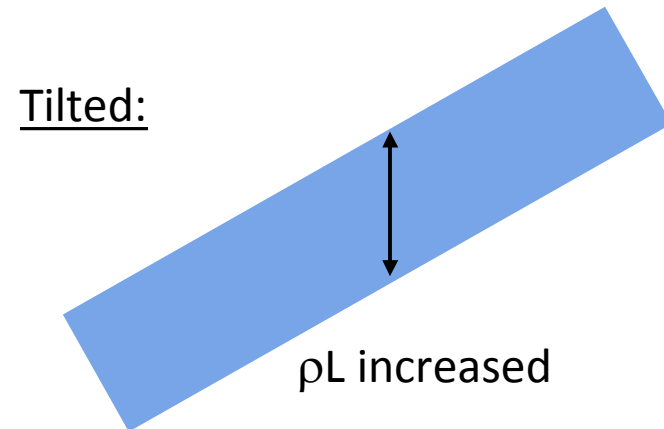
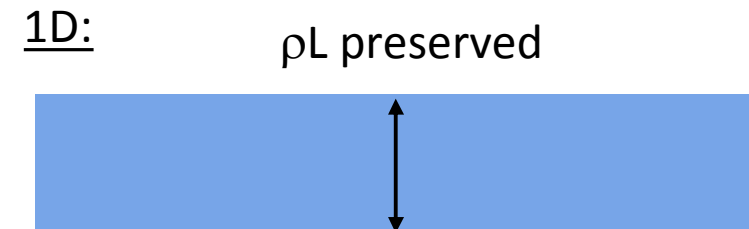
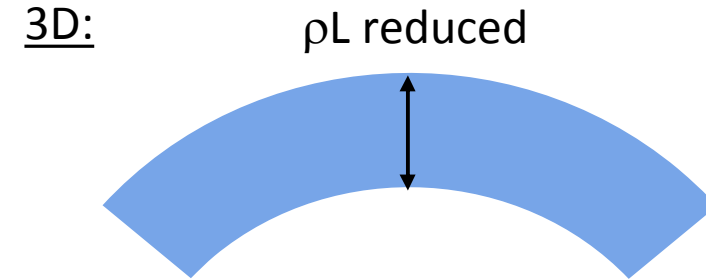
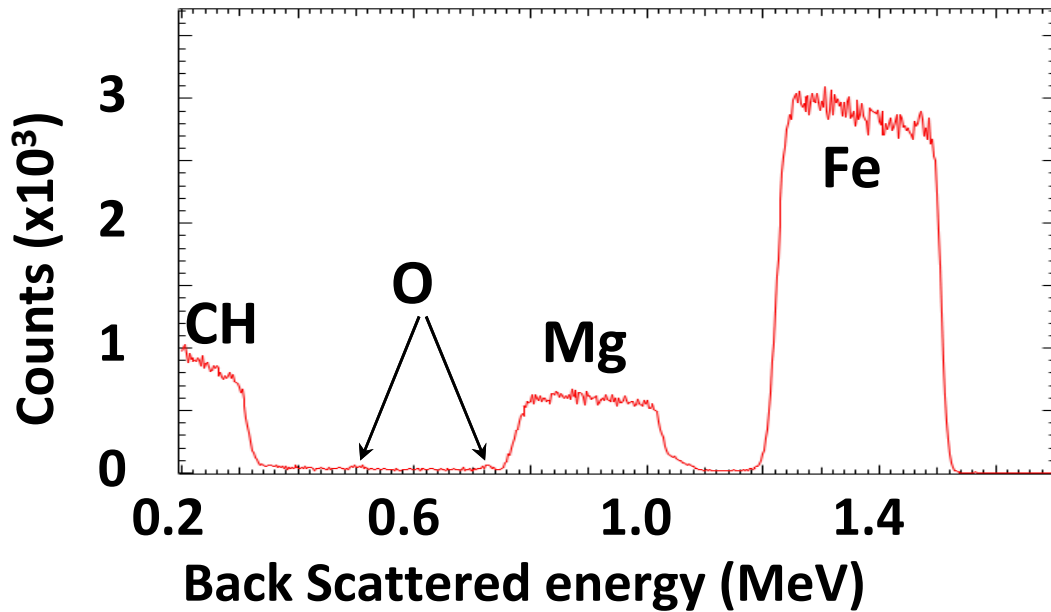


The measured areal density is used to infer Fe opacity from the measured FeMg transmission

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

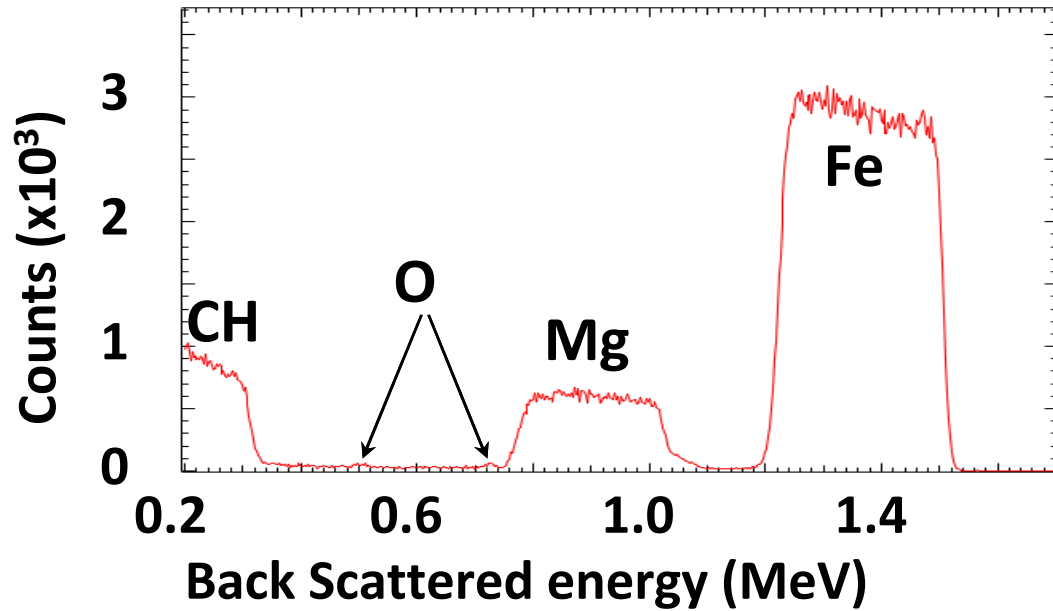
$$\kappa_{\nu} = -\frac{\ln T_{\nu}}{\rho L}$$

Pre-shot Rutherford backscattered spectrum (RBS)

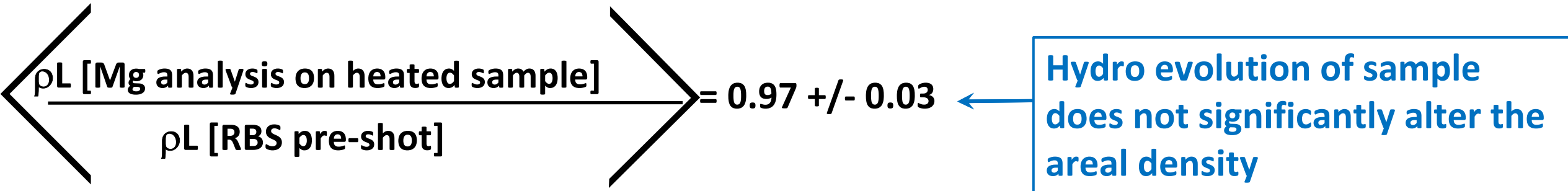
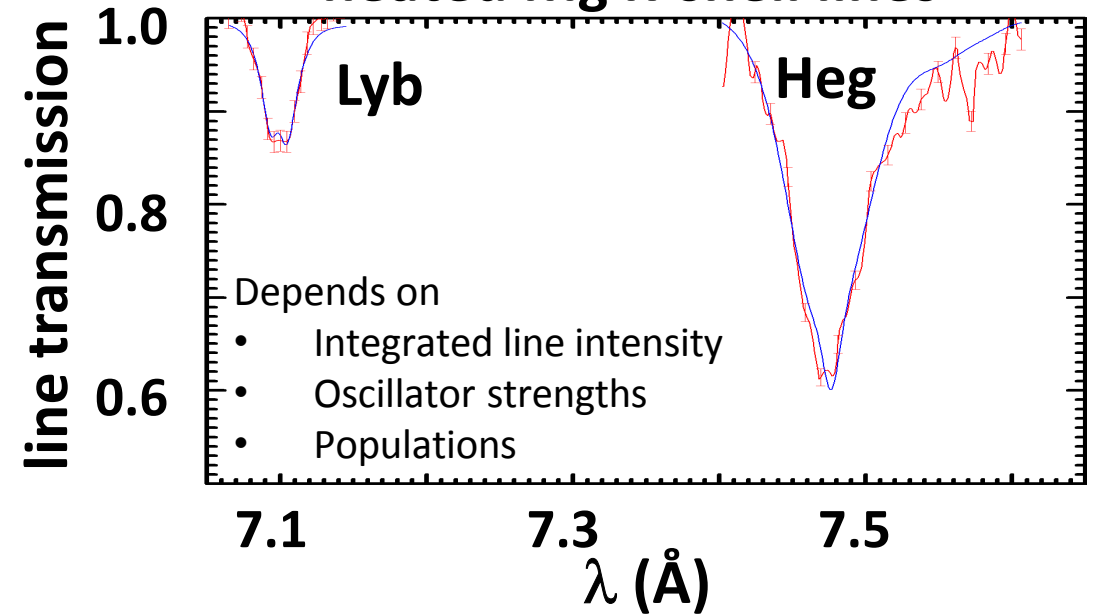


In-situ Mg areal density measurement confirms hydro evolution does not significantly alter the areal density

Pre-shot Rutherford backscattered spectrum (RBS)



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



Common hypotheses for experimental flaws

Sample characterization error

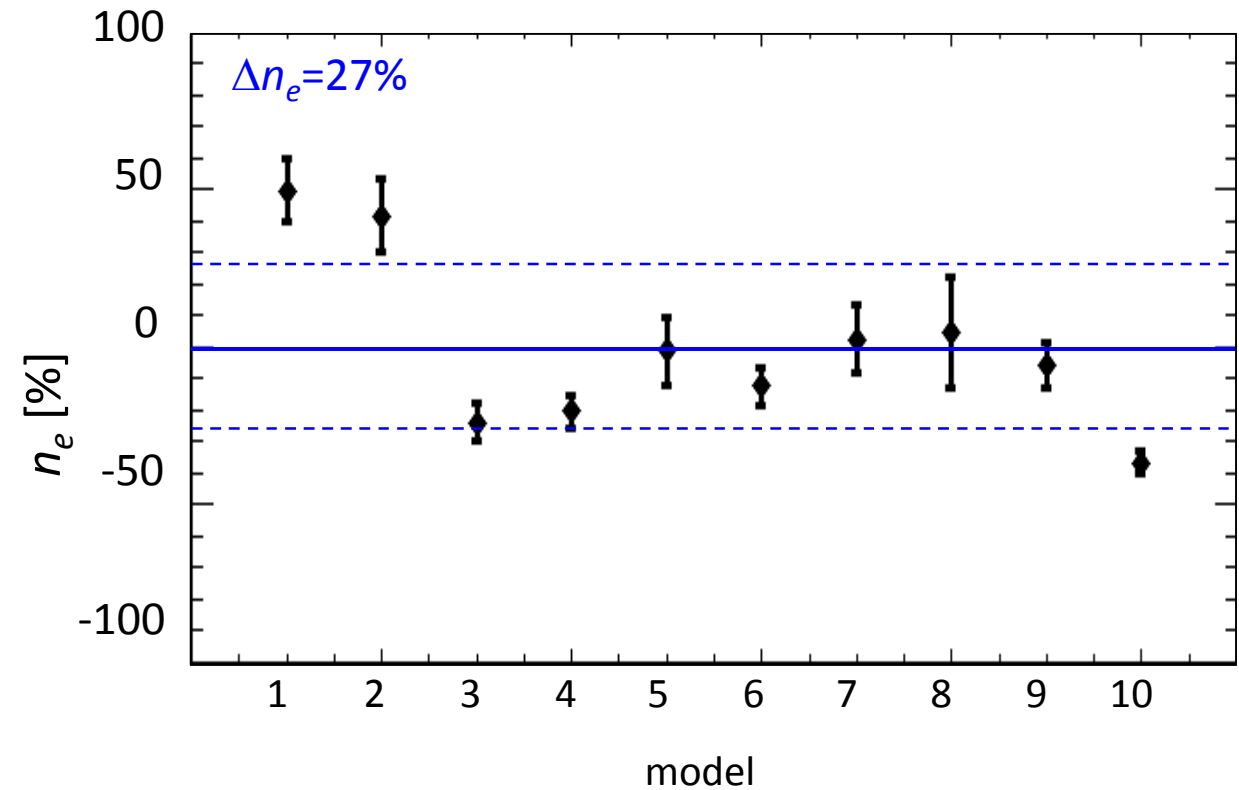
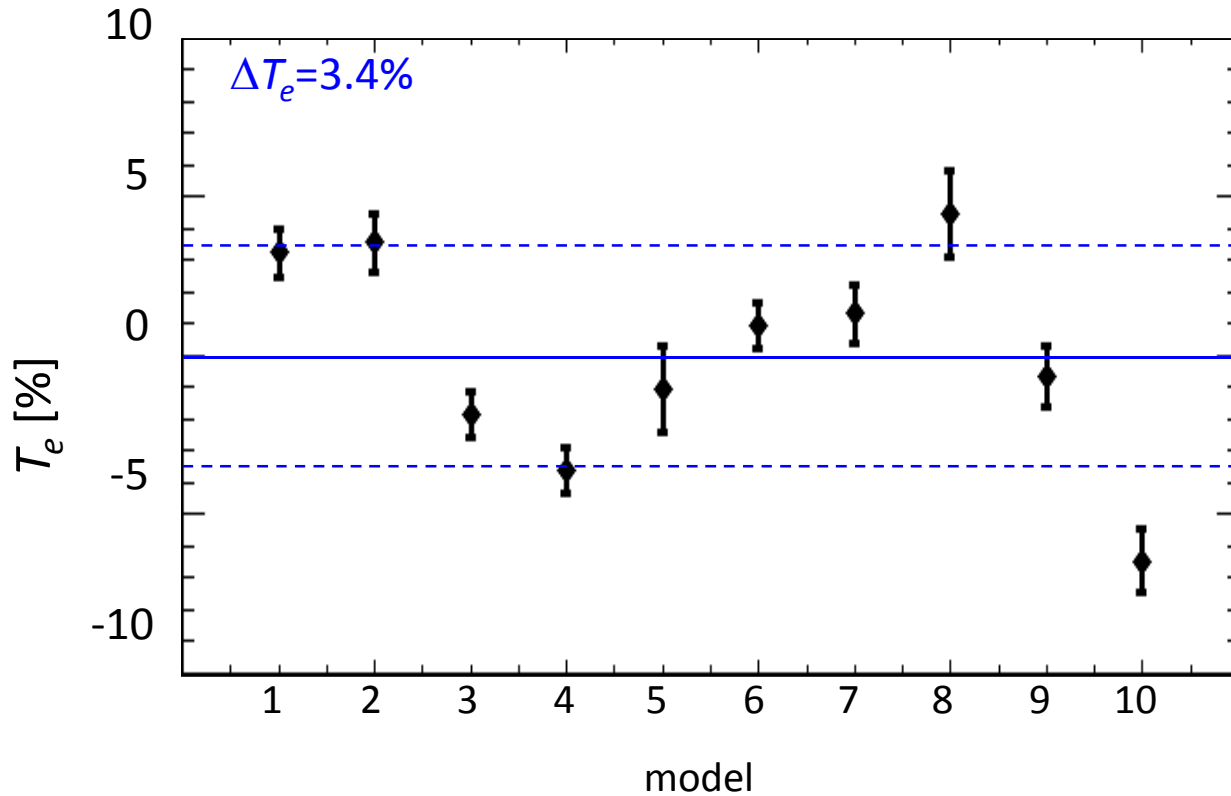
- Any contamination?
 - RBS confirmed no contamination
- Is Fe thickness accurately know?
 - In-situ measurements agree with RBS

Common hypotheses for experimental flaws

T_e and n_e diagnostics error

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

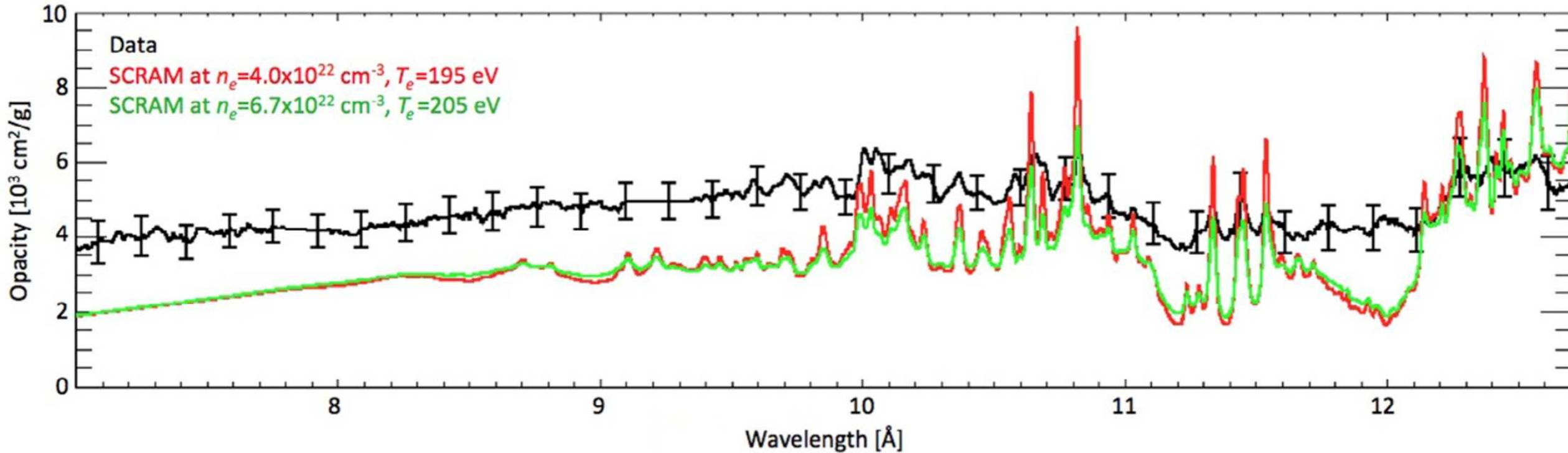
T_e and n_e diagnostic results vary $\pm 4\%$ and $\pm 30\%$, depending on choice of spectral models [1]



- Main source of discrepancy comes from difference line-broadening models

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

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 needs to be quantified

Common hypotheses for experimental flaws

T_e and n_e diagnostics error

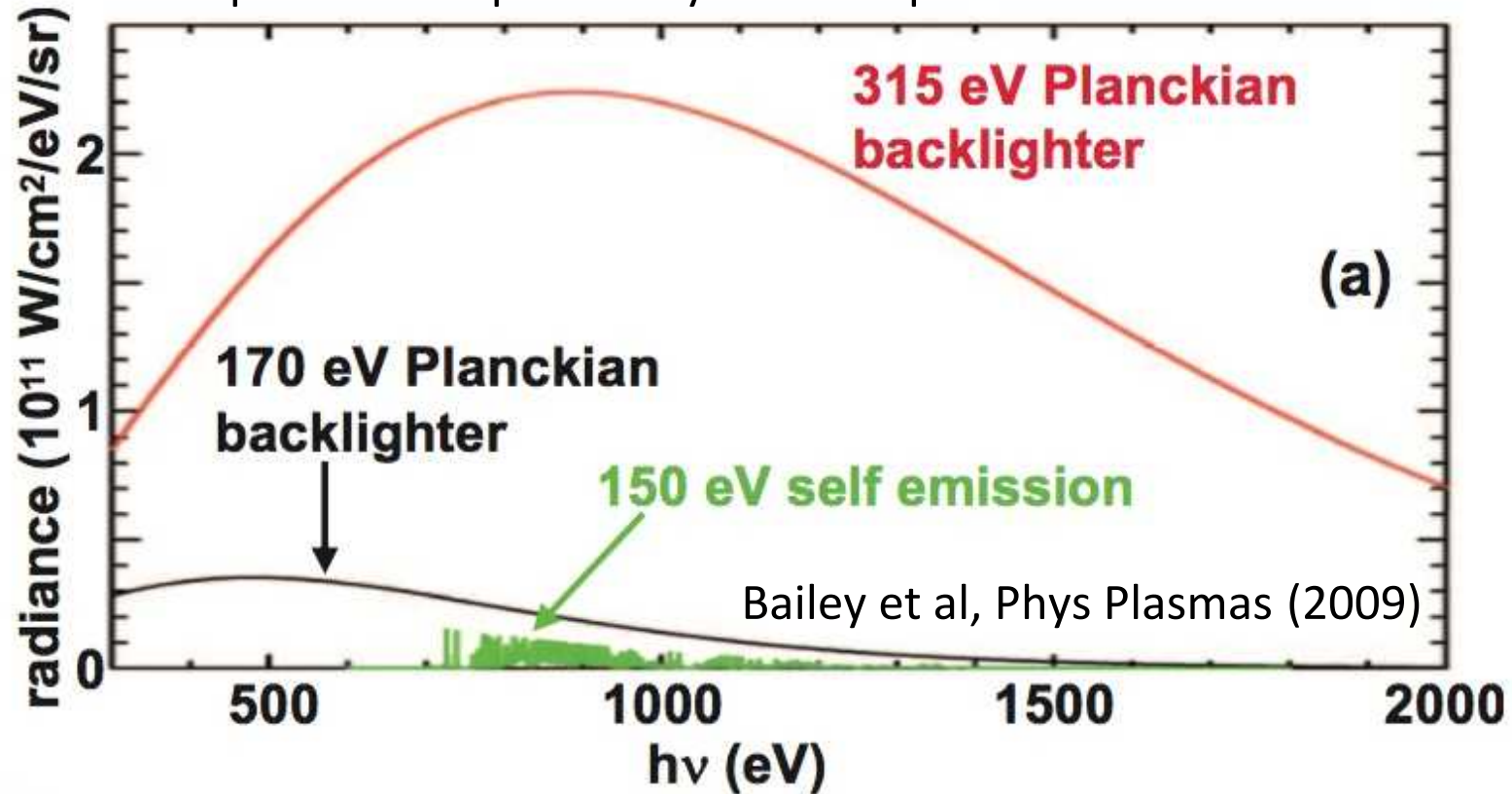
- How large is the diagnostic error?
 - True n_e maybe higher by 50%
- How much does it affect?
 - Partially explain peak-to-valley contrast

Data interpretation error

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

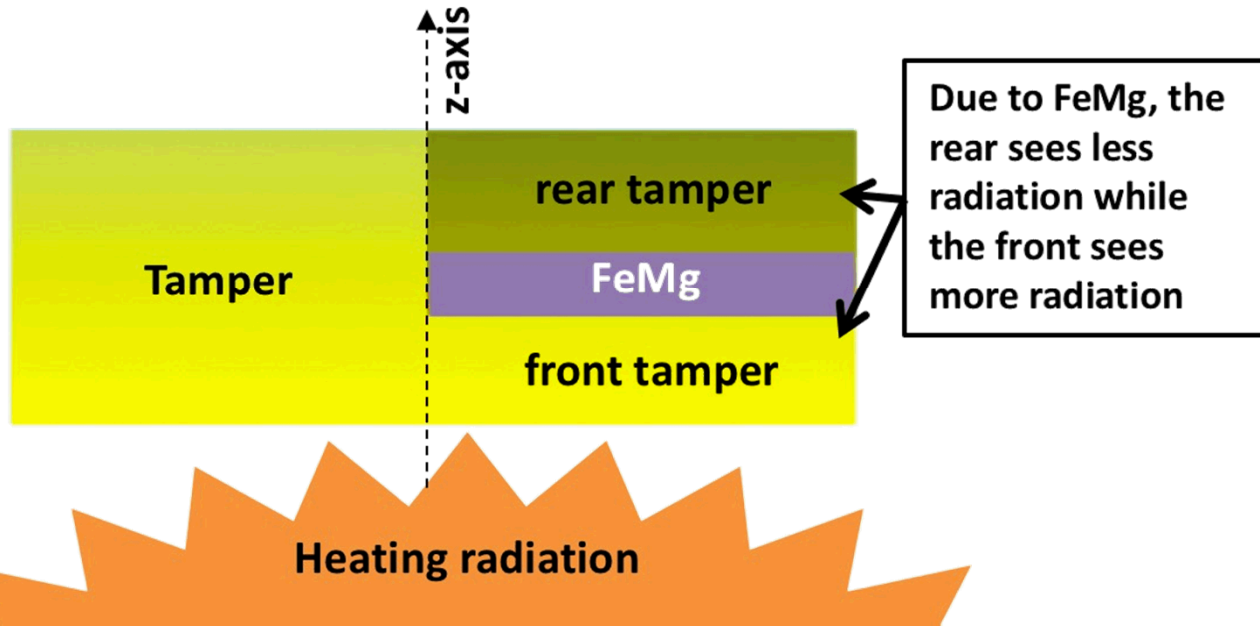
Concern 1: Is self-emission negligible?

Comparison was previously done in spectral radiance



- Comparison is done in $\text{erg/s/cm}^2/\text{sr/eV}$, but
 - Duration (time history)
 - Emission area } can be different!

Concern 2: Do we have the same tamper transmission on both side?



$$T^{measured} = \frac{I^{+9^\circ}}{I^{-9^\circ}} = \frac{BT_{FeMg}T_{CH}^{+9^\circ}}{BT_{CH}^{-9^\circ}} \approx T_{FeMg}$$

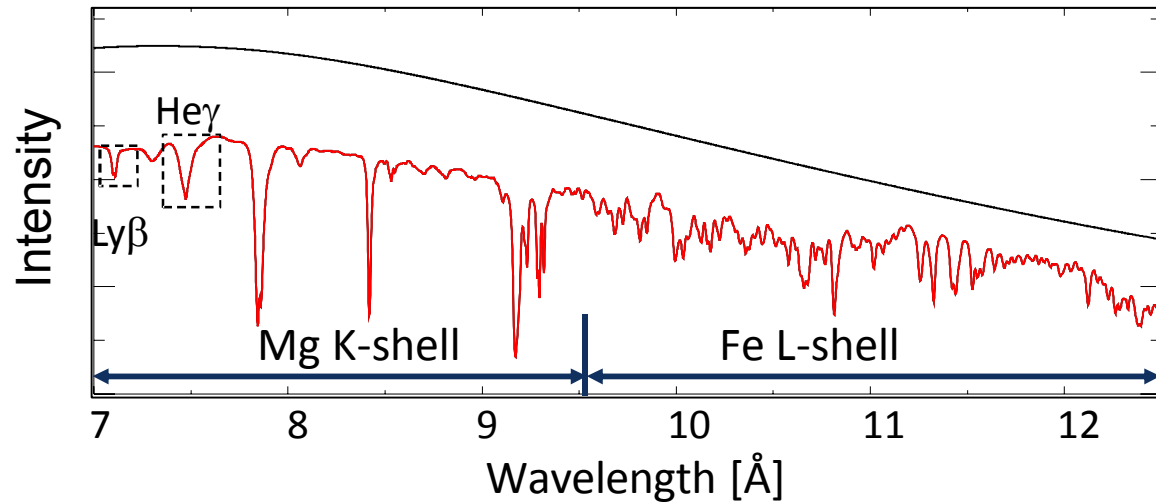
only when $T^{+9^\circ} \approx T^{-9^\circ}$

- If tamper-only side is heated more, $T^{-9^\circ} > T^{+9^\circ}$
 - $T^{measured} < T_{FeMg}$
 - $\kappa^{measured} > \kappa_{FeMg}$

Is this source of higher b-f and window?

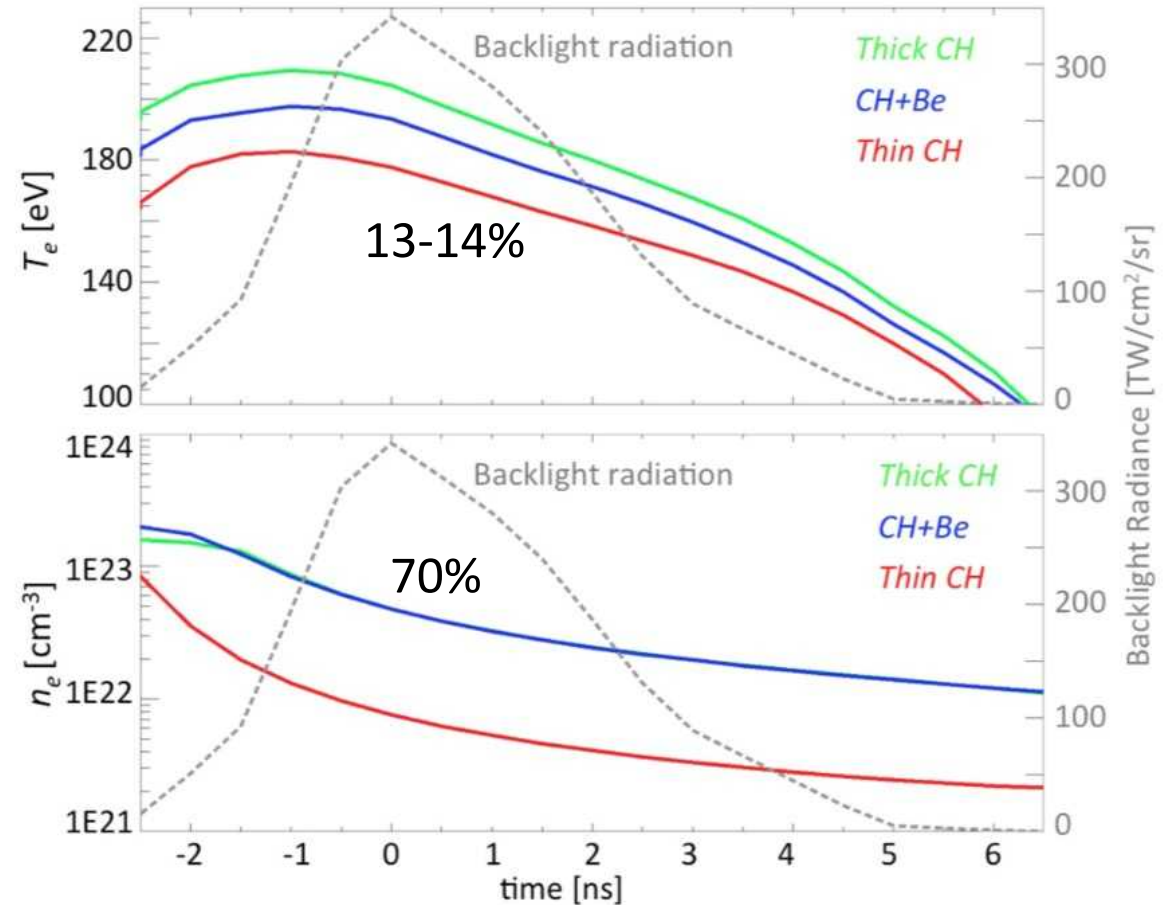
Concern 3: Are temporal and spatial gradients important?

1) Data are interpreted in static-uniform picture

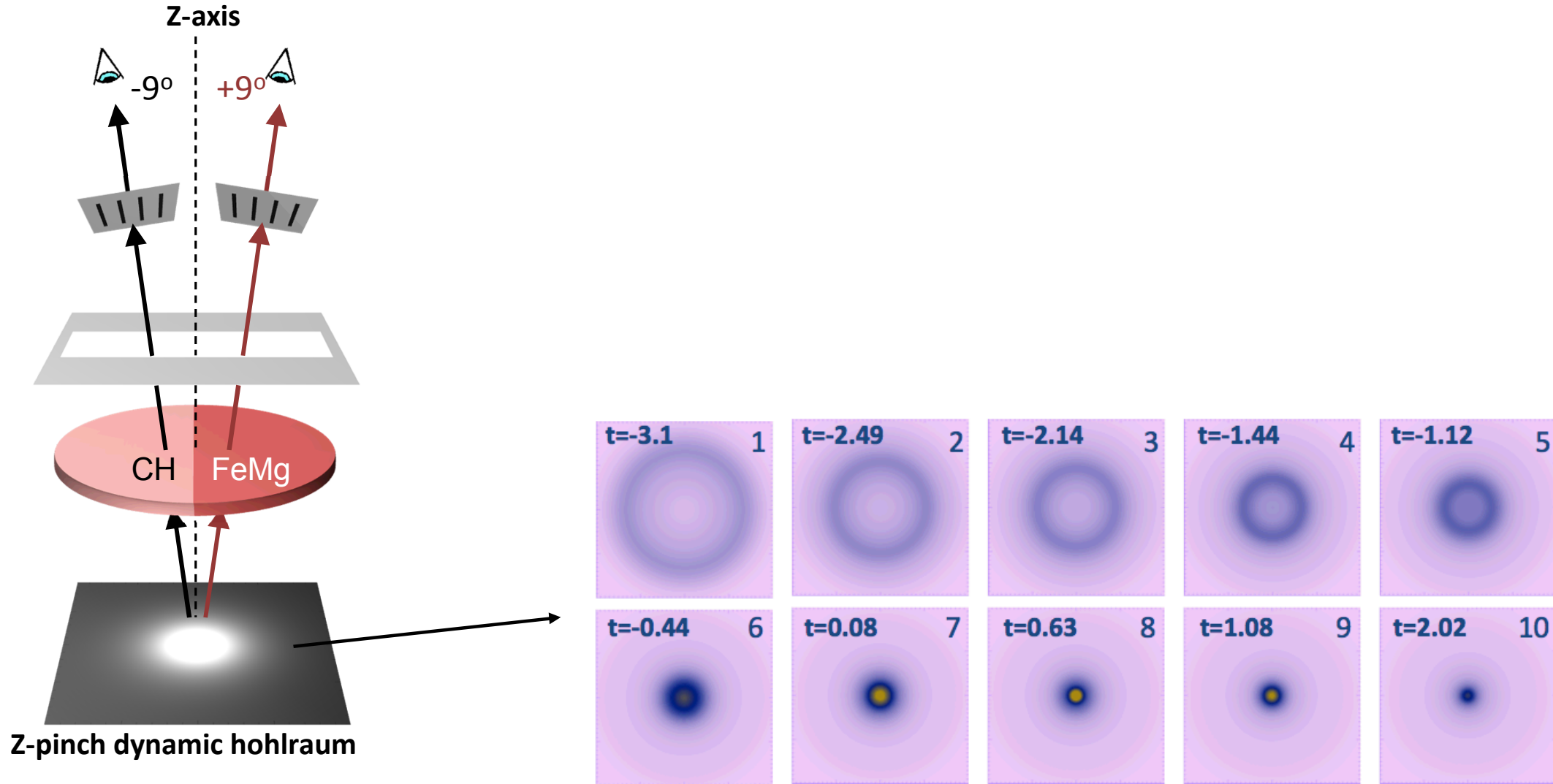


- Is discrepancy caused by the gradients?
 - Axial: <10%
 - Temporal: 13-14% (T_e), 70% (n_e)
- How much error does the static-uniform picture introduce?

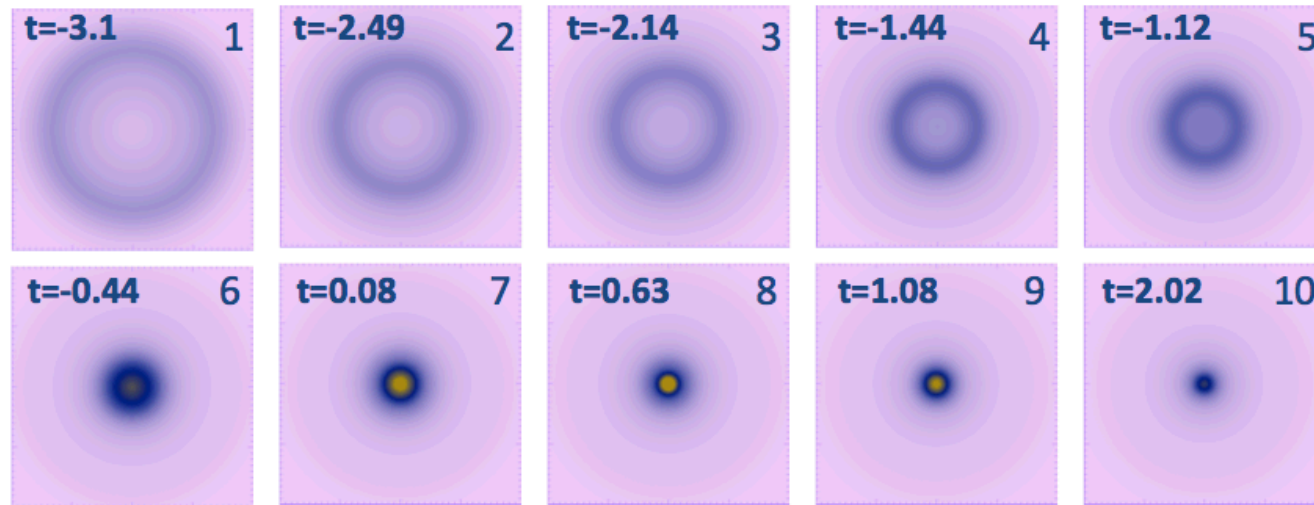
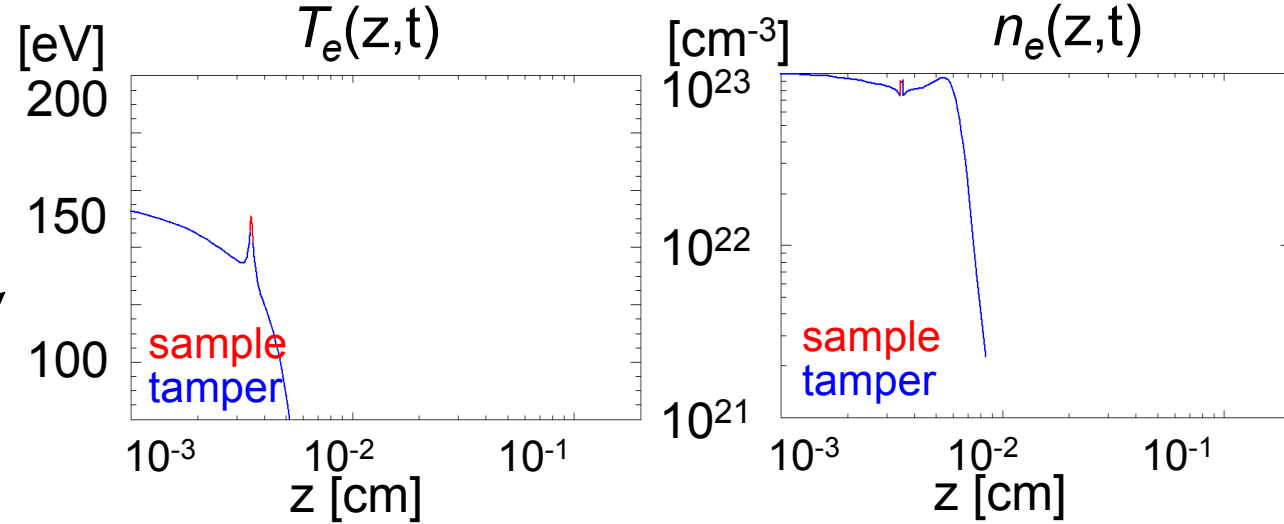
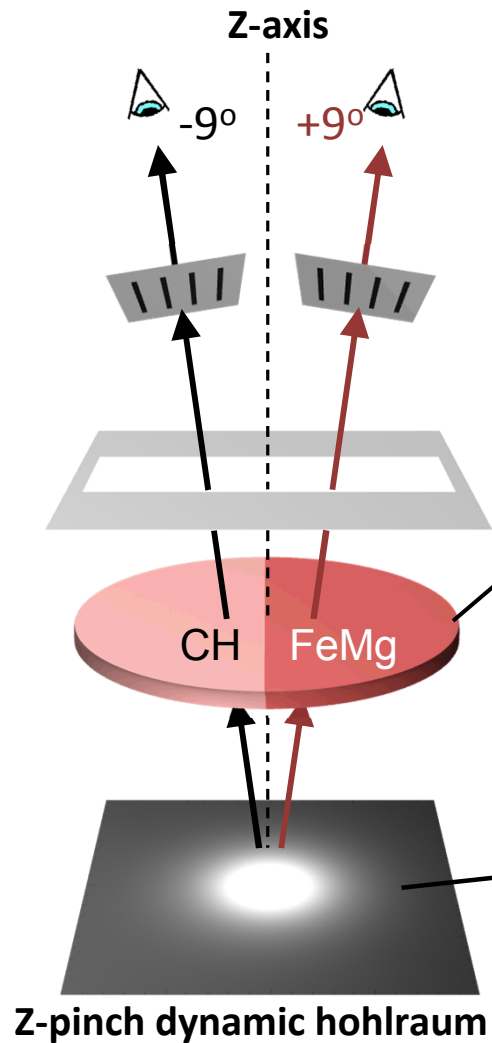
2) Simulation suggests notable gradient



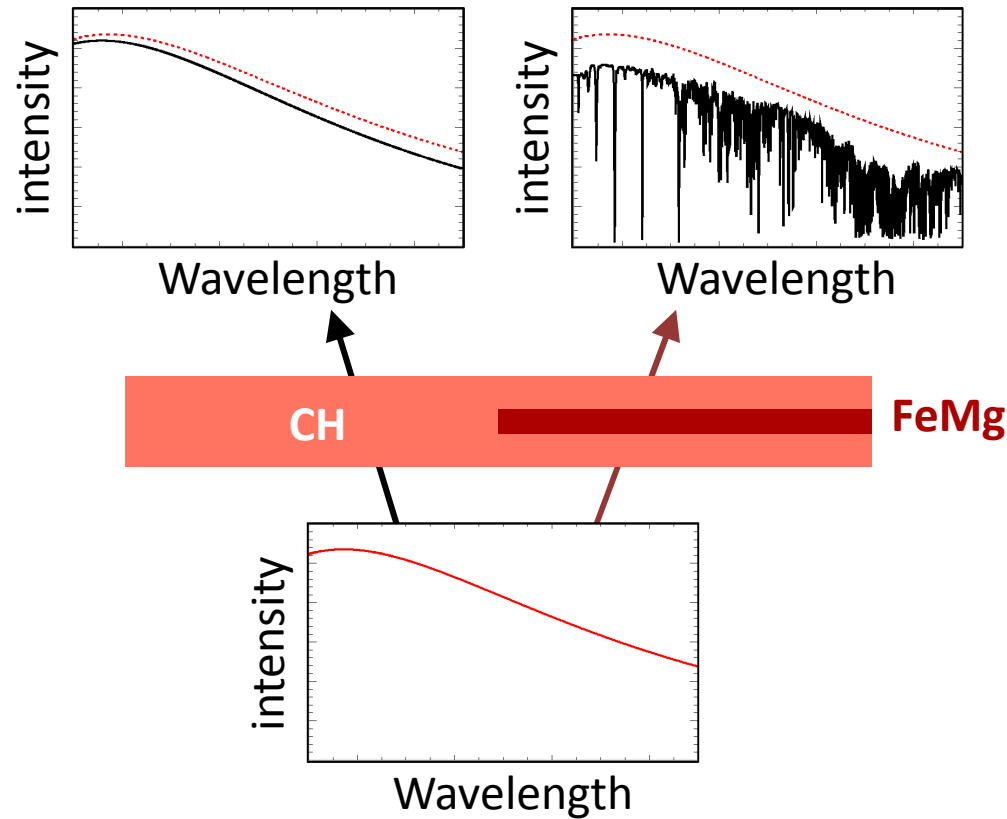
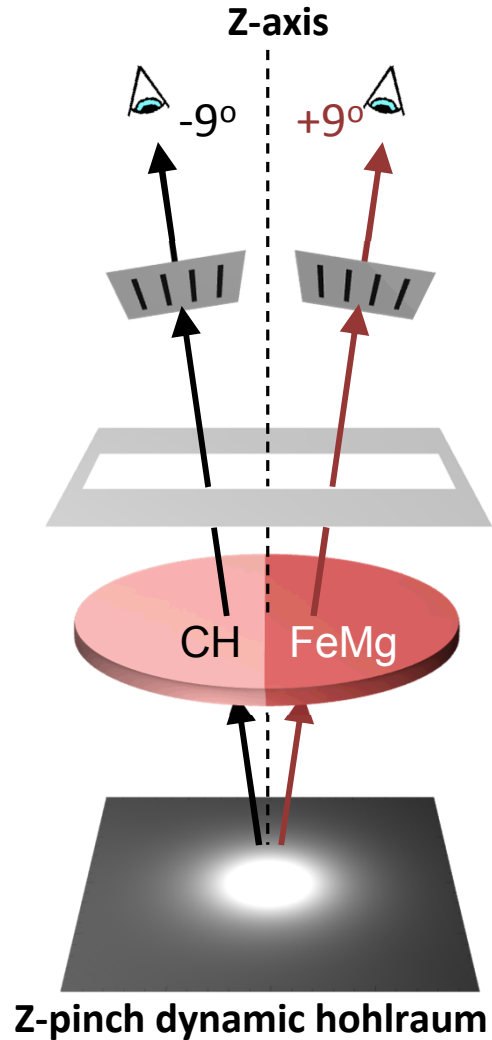
Simulation investigates the differences between the static picture used in data analysis and the actual dynamic plasma



Simulation investigates the differences between the static picture used in data analysis and the actual dynamic plasma



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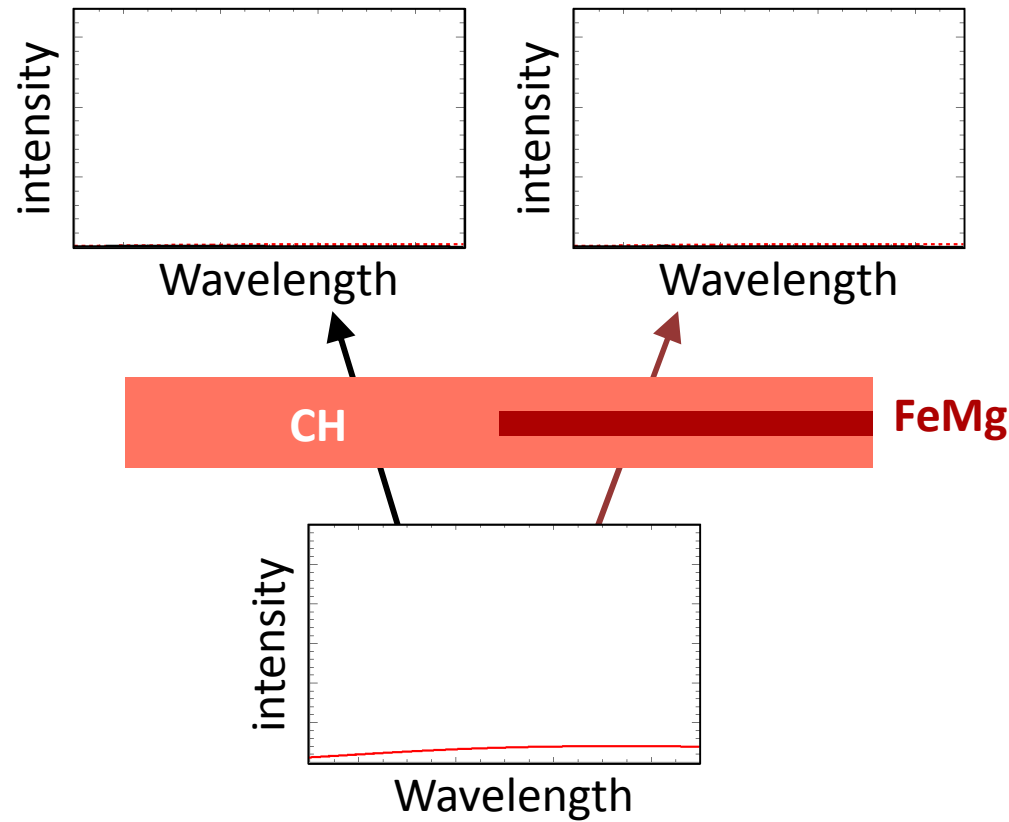
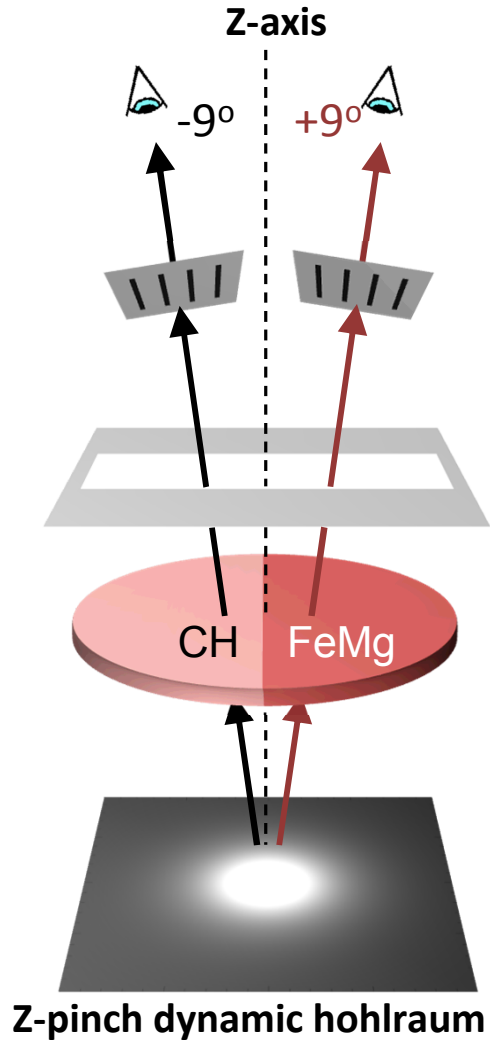
Concerns:

1. Plasma self-emission
2. Tamper transmission difference
3. Time- and space-integration

Simulations:

1. Radiation (VISRAD) :
 - 3-D view factor code
 - Measured ZPDH radiation
2. Hydrodynamics (HELIOS) :
 - 1-D Lagrangian
3. Radiation transport*

Simulation investigates the differences between the static picture used in data analysis and the actual dynamic plasma



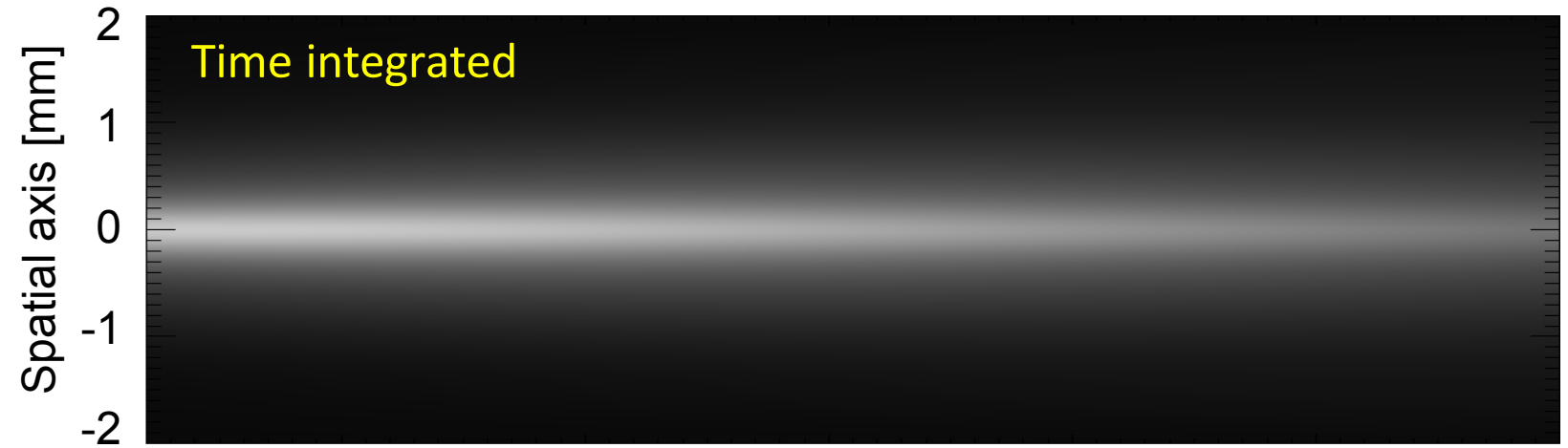
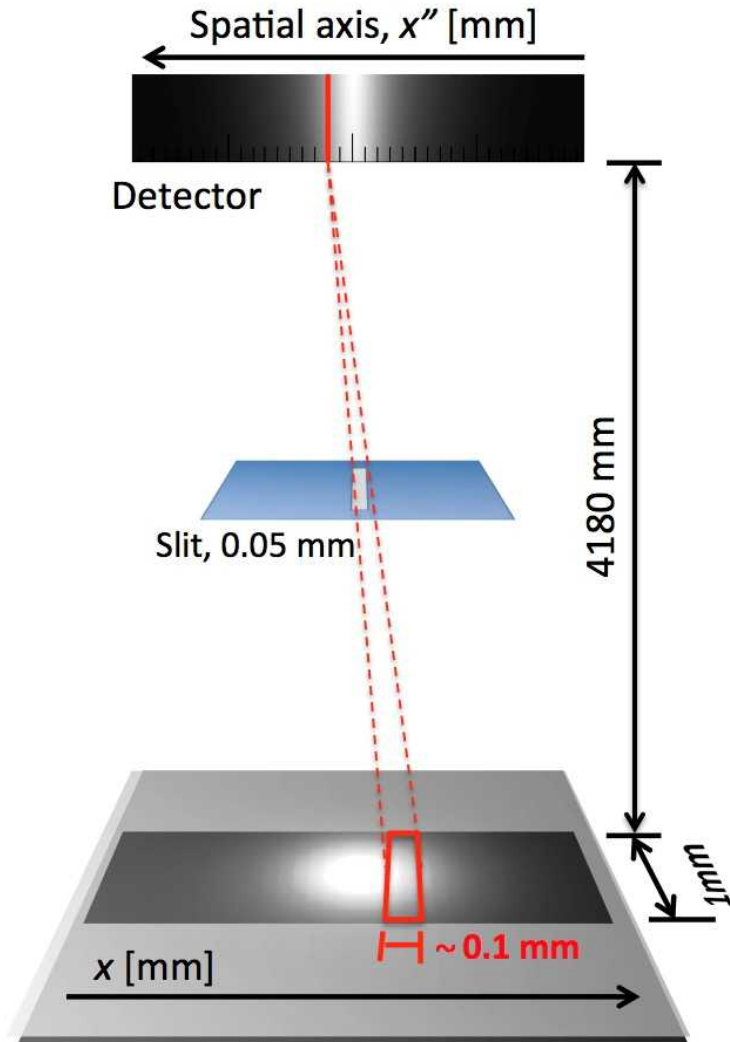
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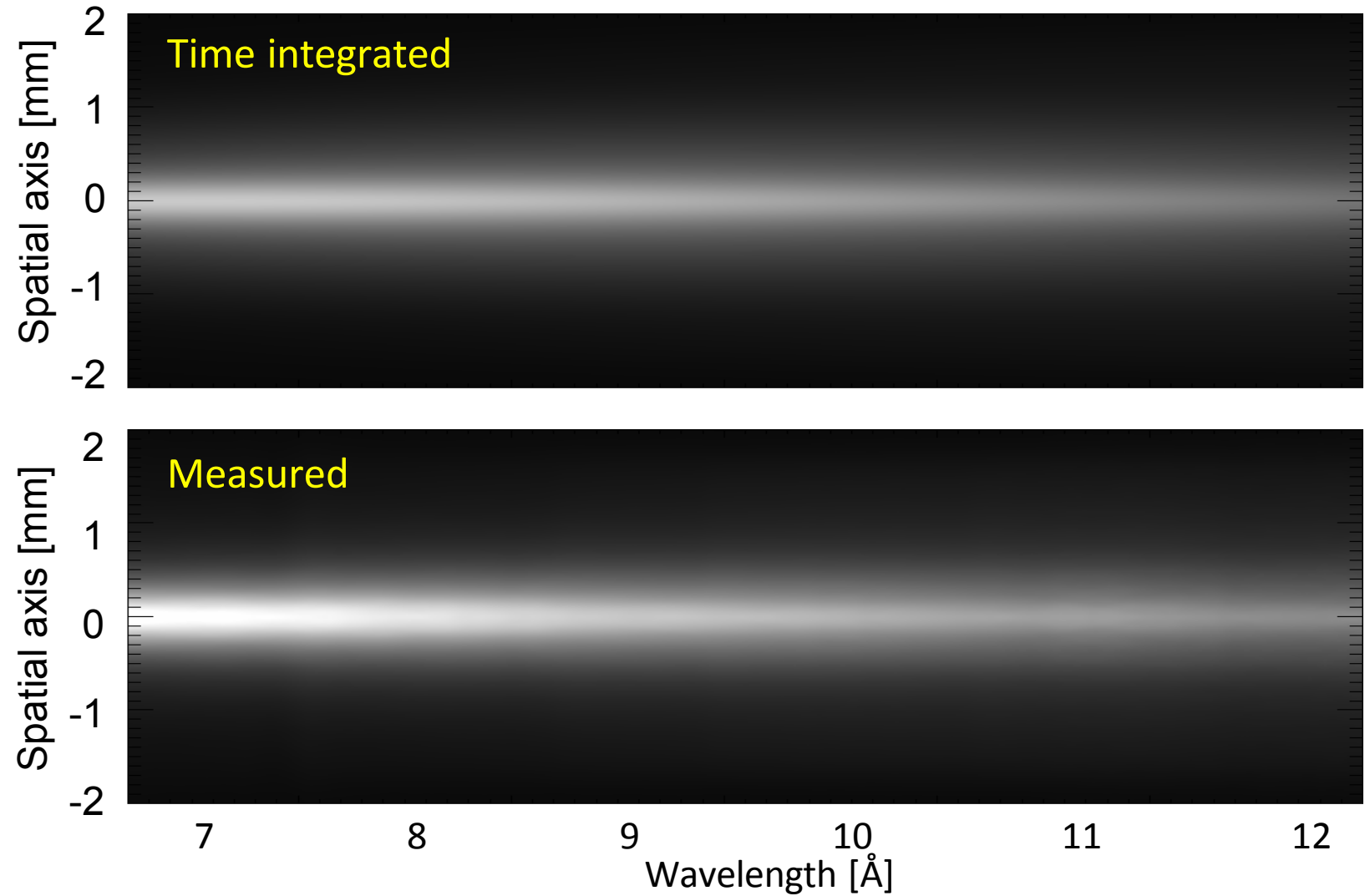
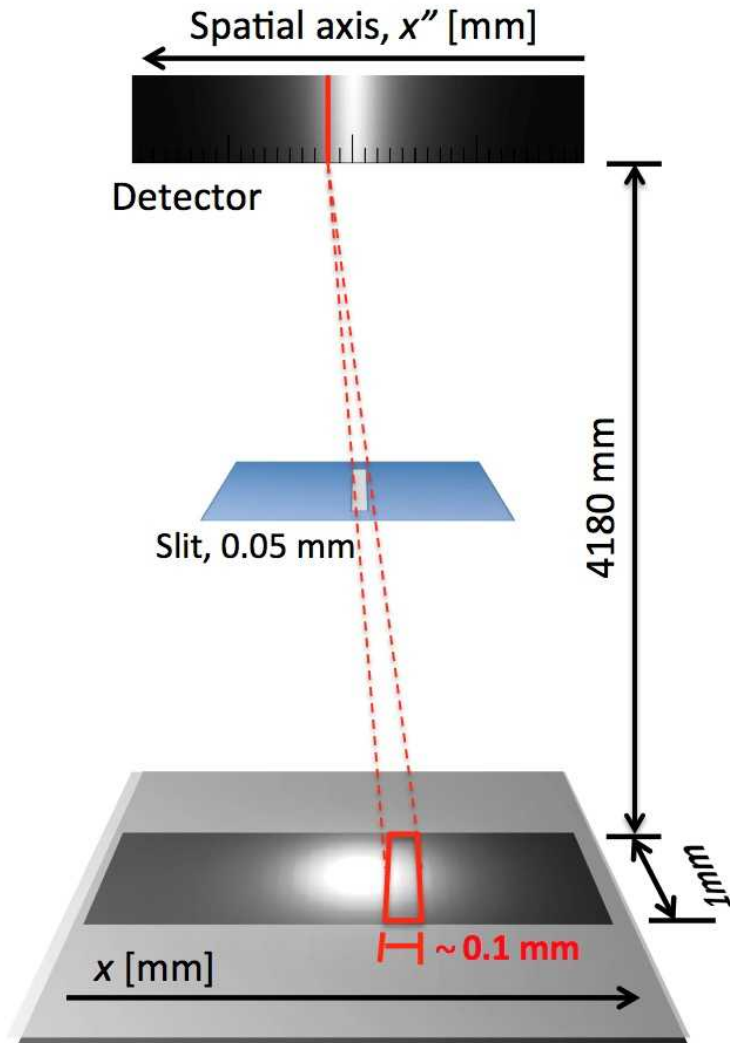
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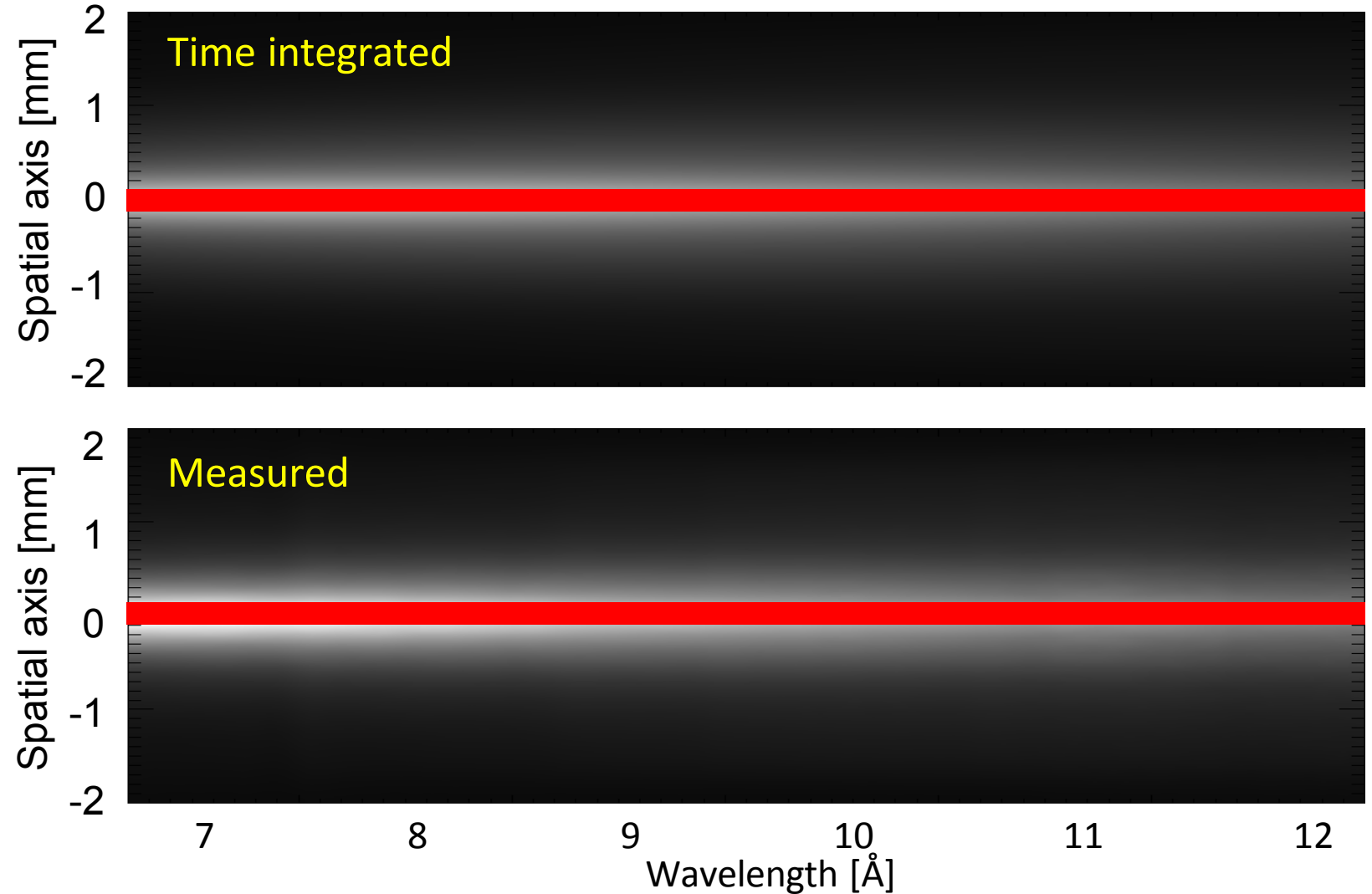
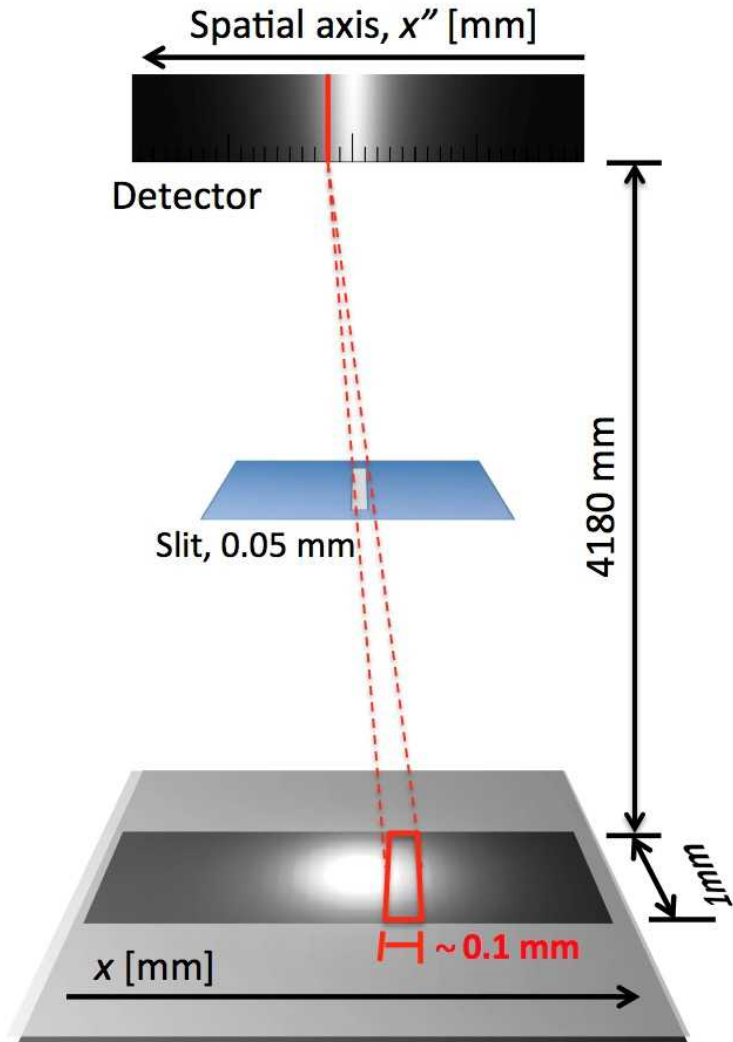
Simulation reproduced the measured backlight spectral image



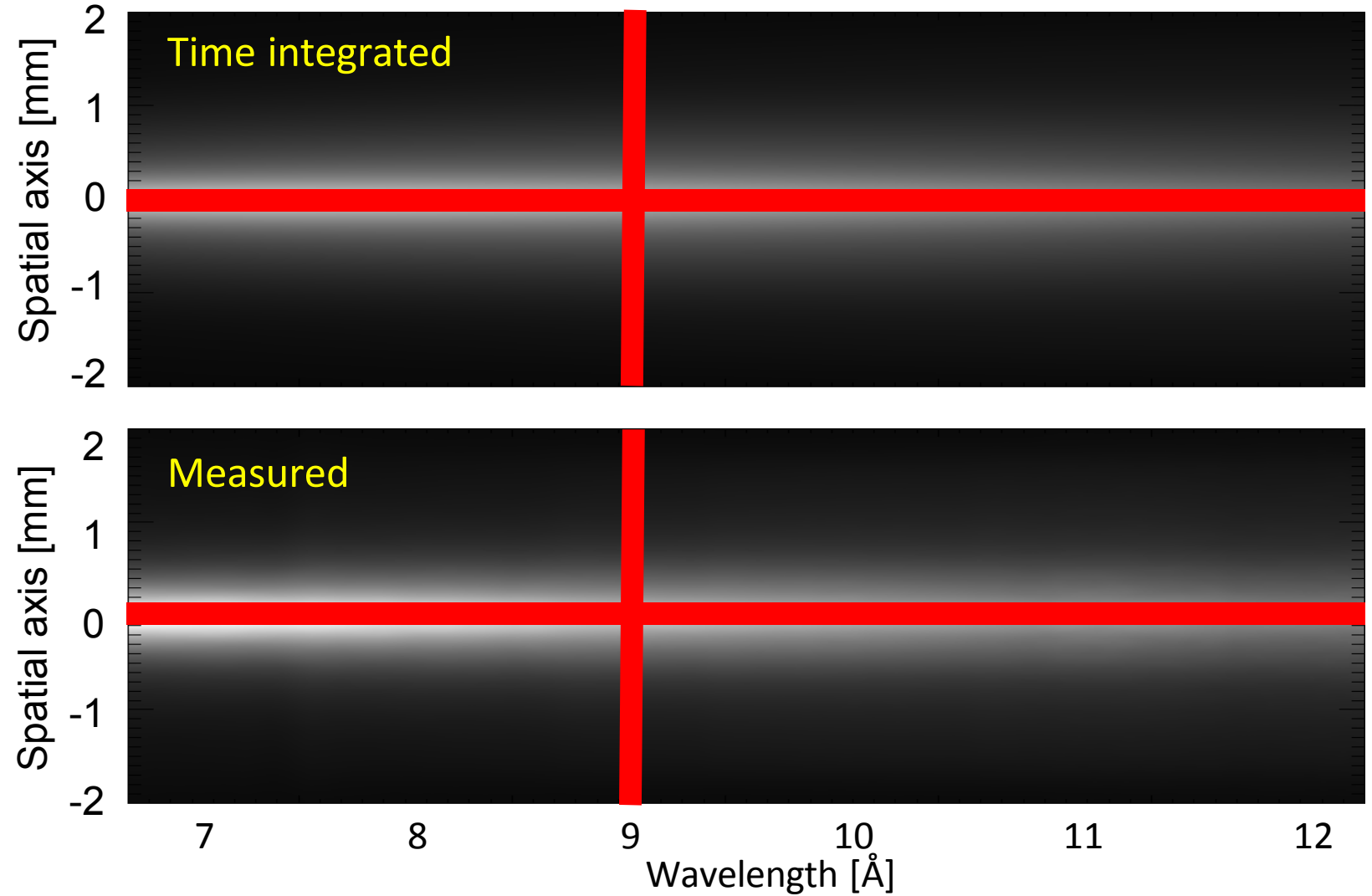
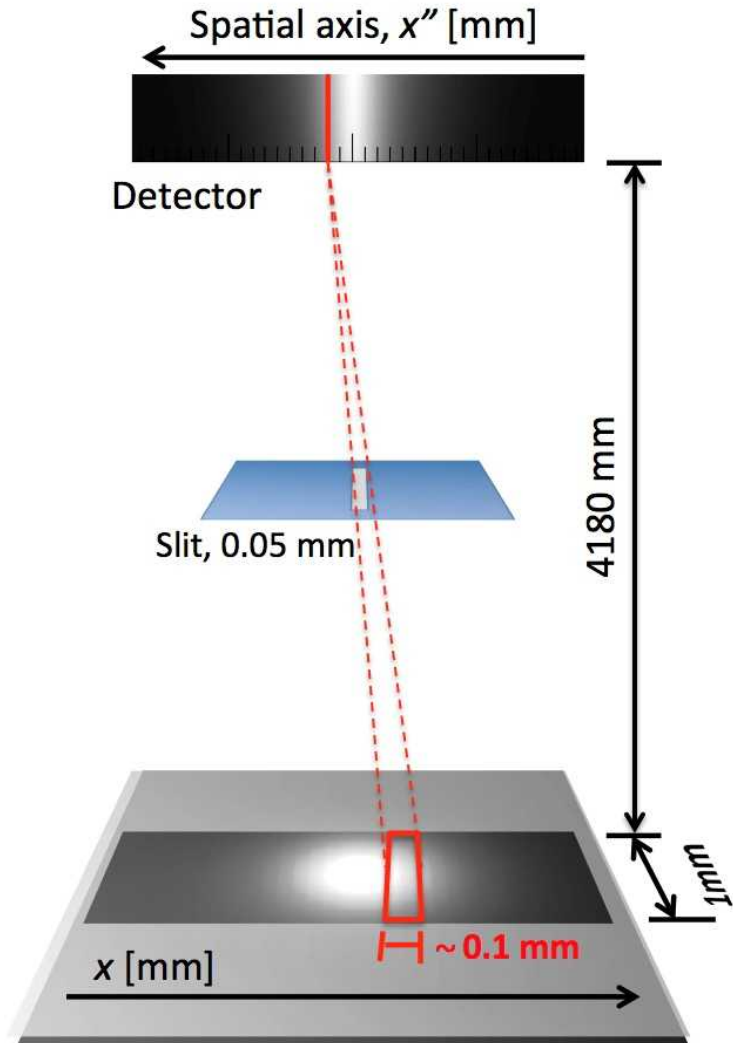
Simulation reproduced the measured backlight spectral image



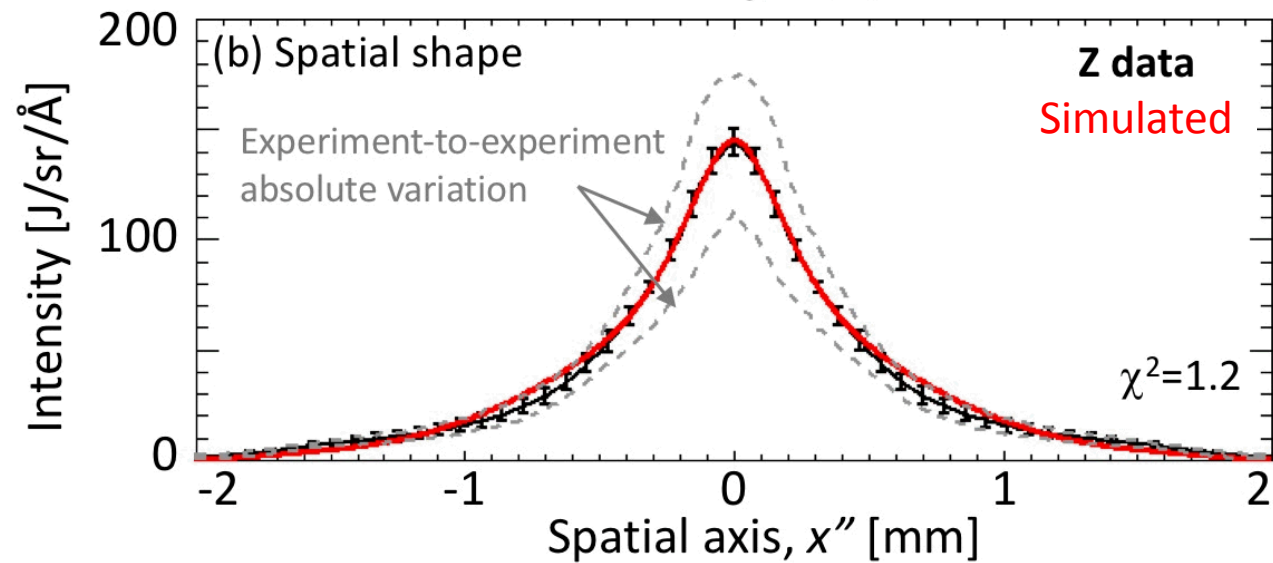
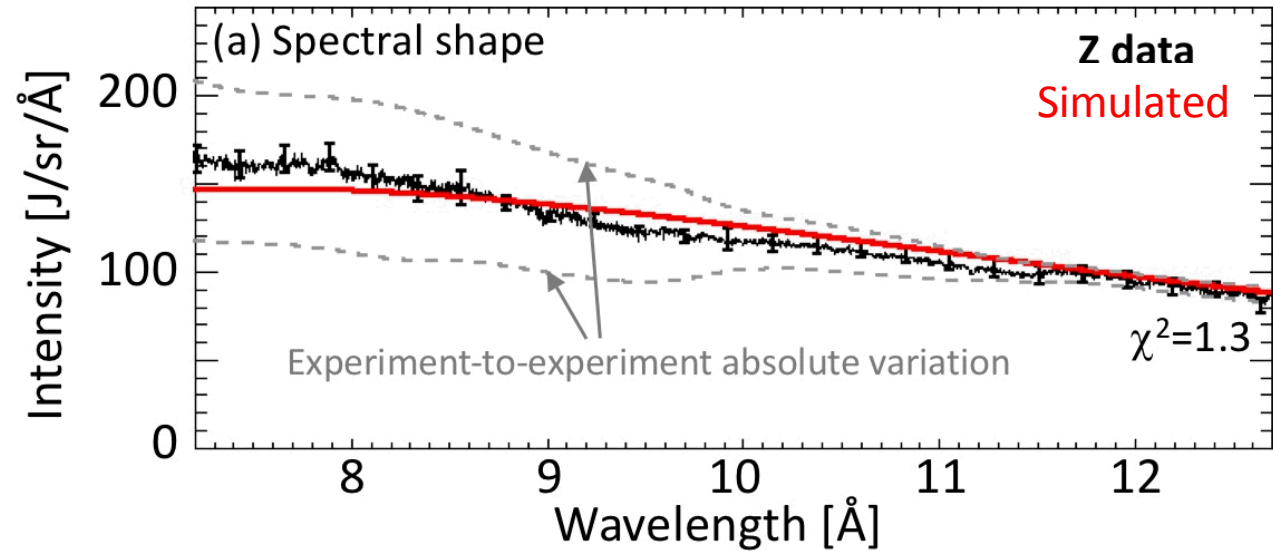
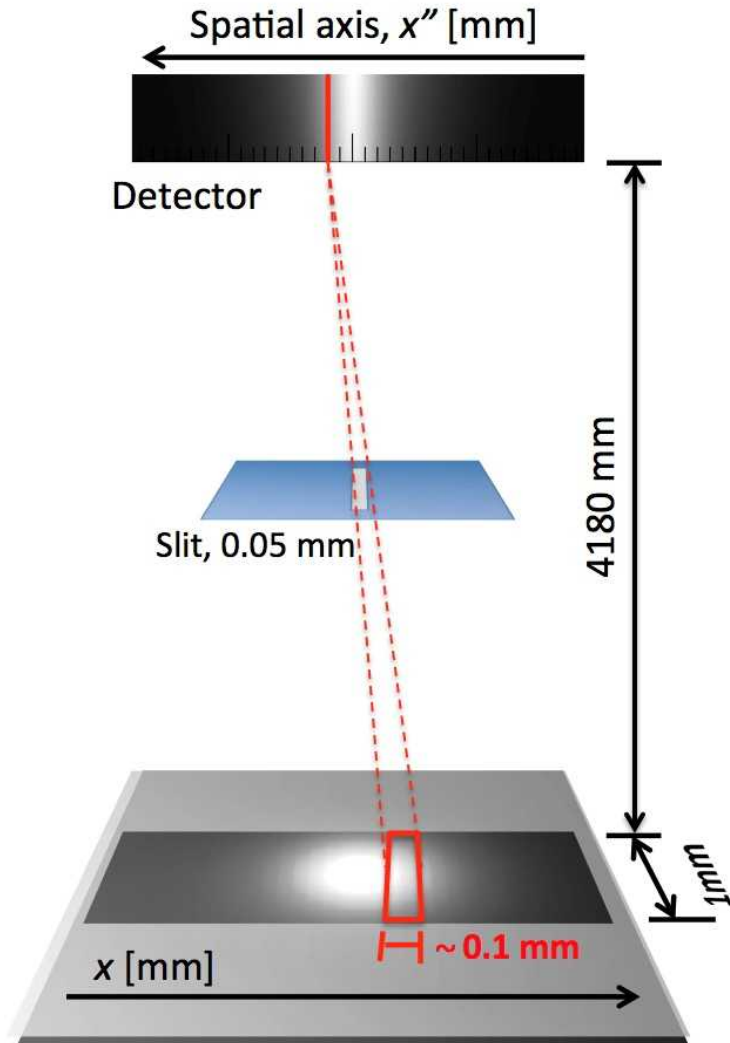
Simulation reproduced the measured backlight spectral image



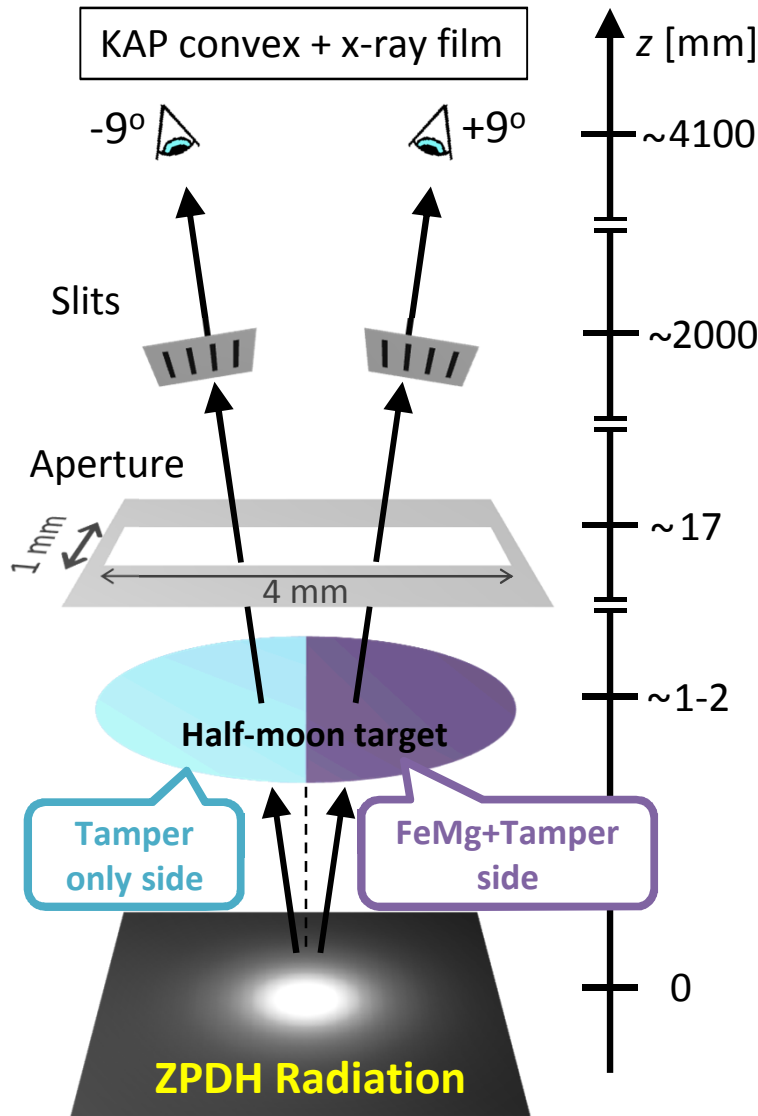
Simulation reproduced the measured backlight spectral image



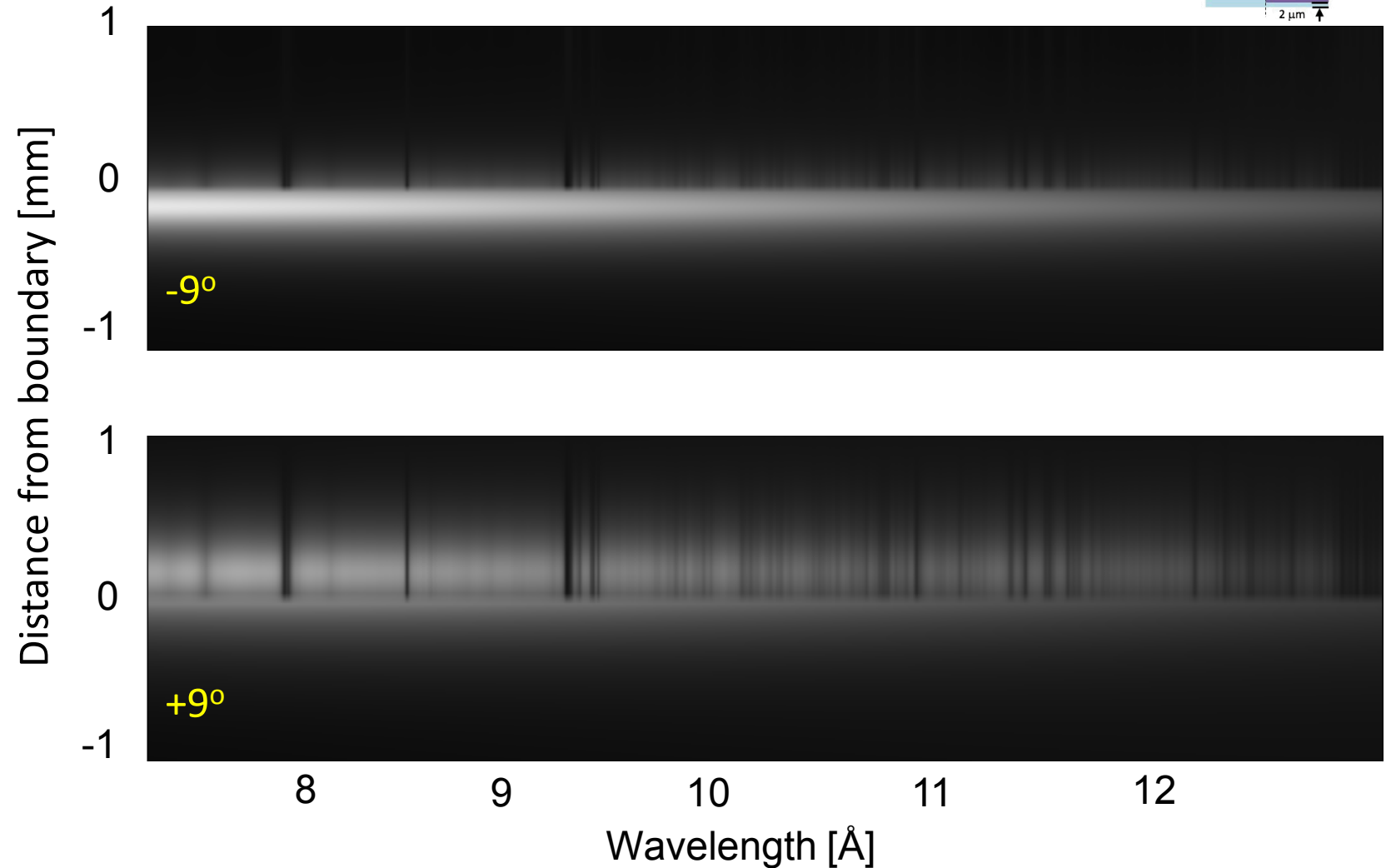
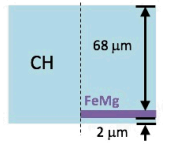
Simulation reproduced the measured backlight spectral image, demonstrating our understanding of backlight formation



Simulated half-moon spectral image confirmed that the simulation reproduces the measured sample conditions



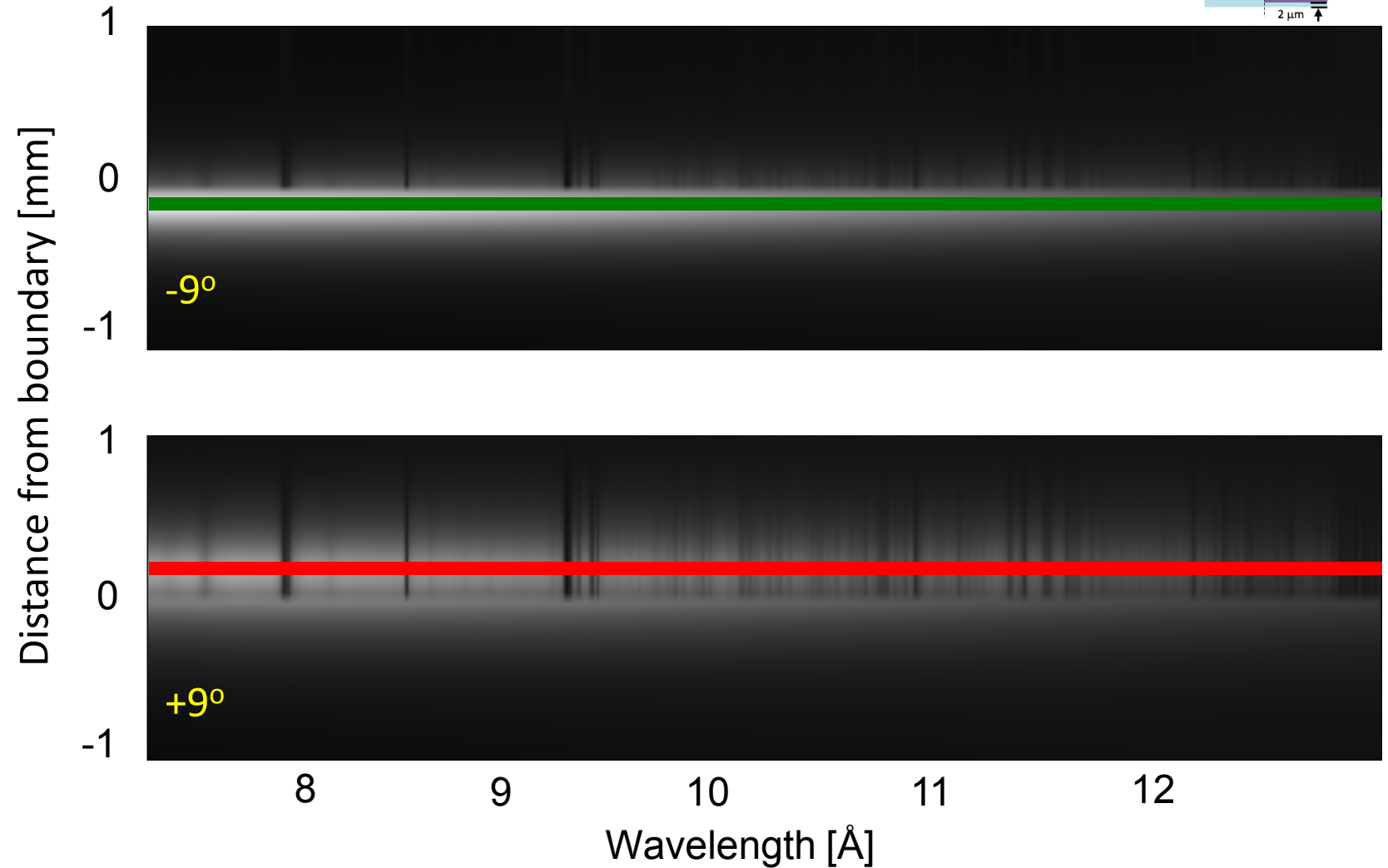
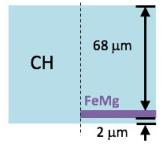
Thick CH case



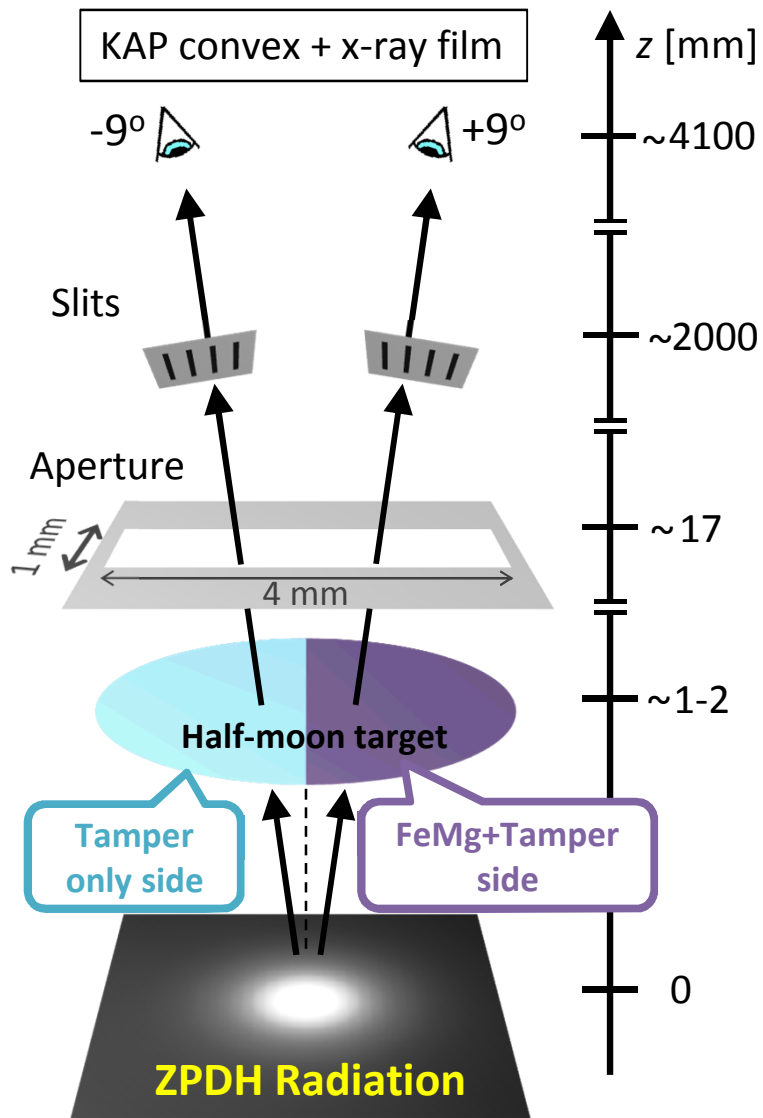
Simulated half-moon spectral image confirmed that the simulation reproduces the measured sample conditions



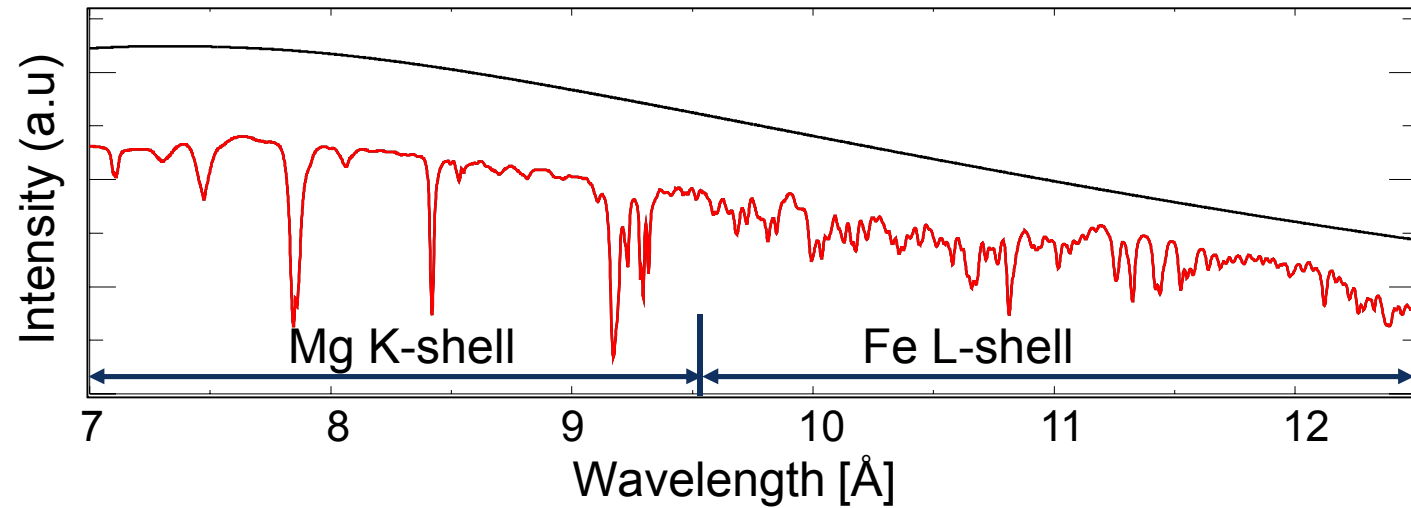
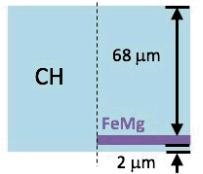
Thick CH case



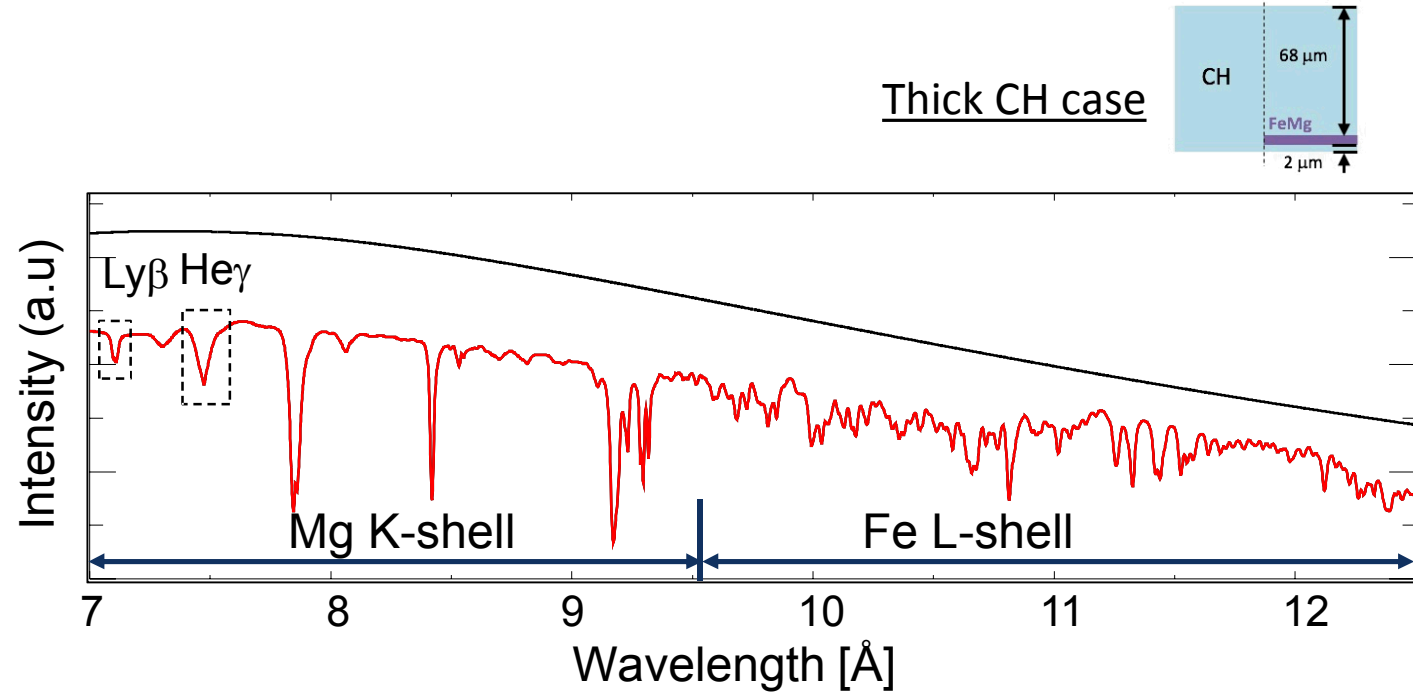
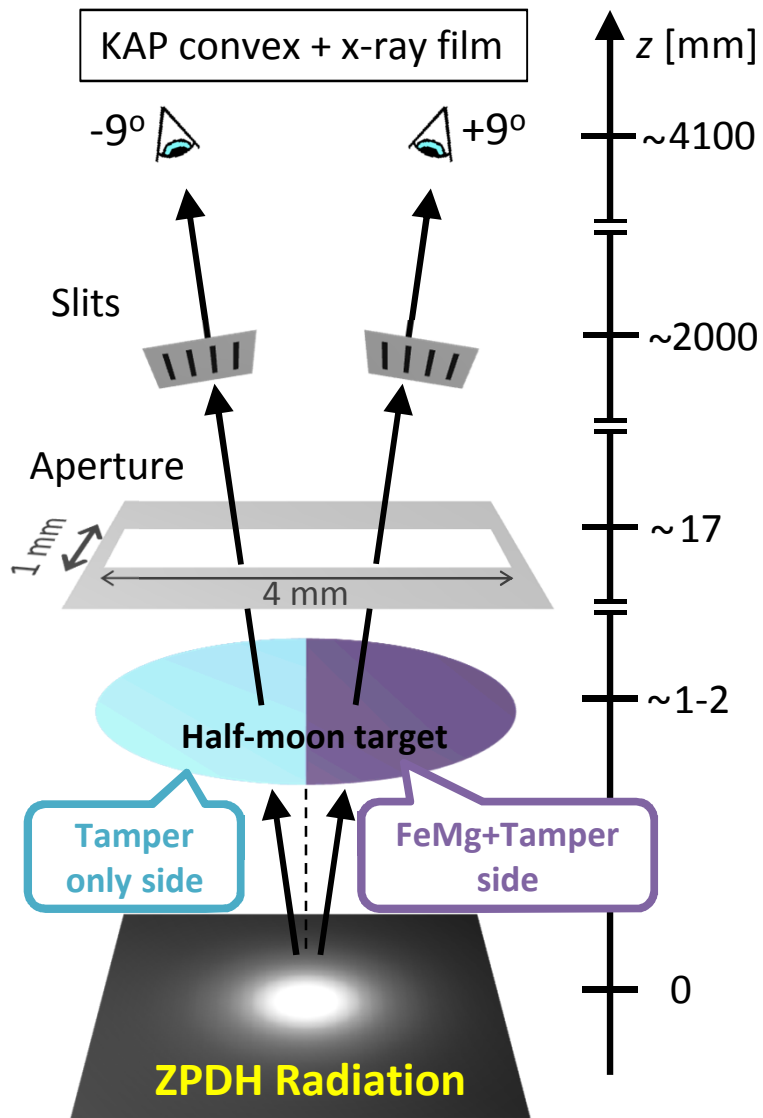
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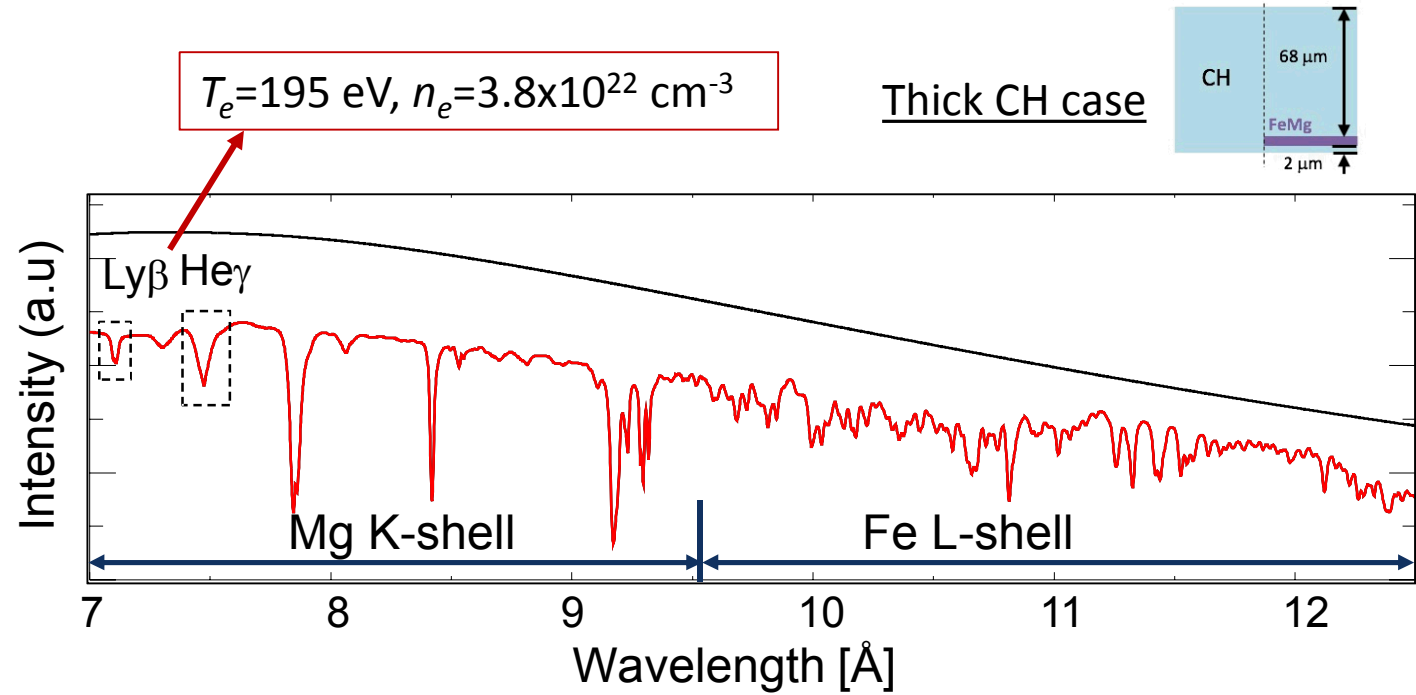
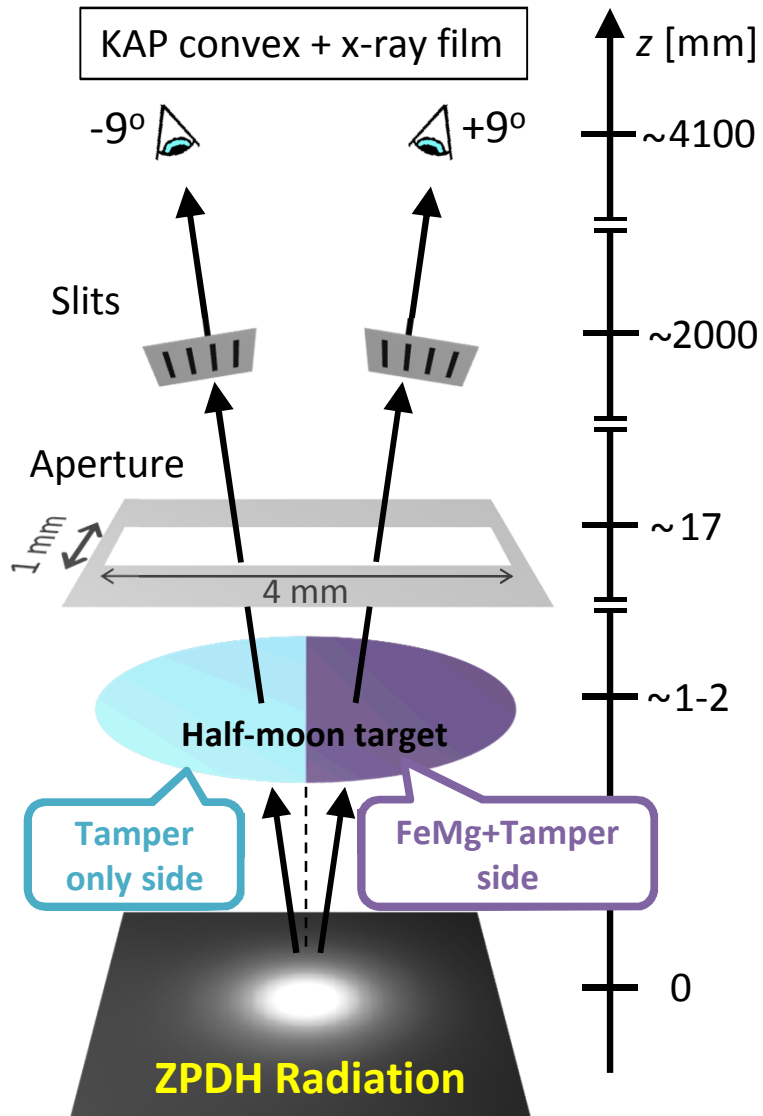
Thick CH case



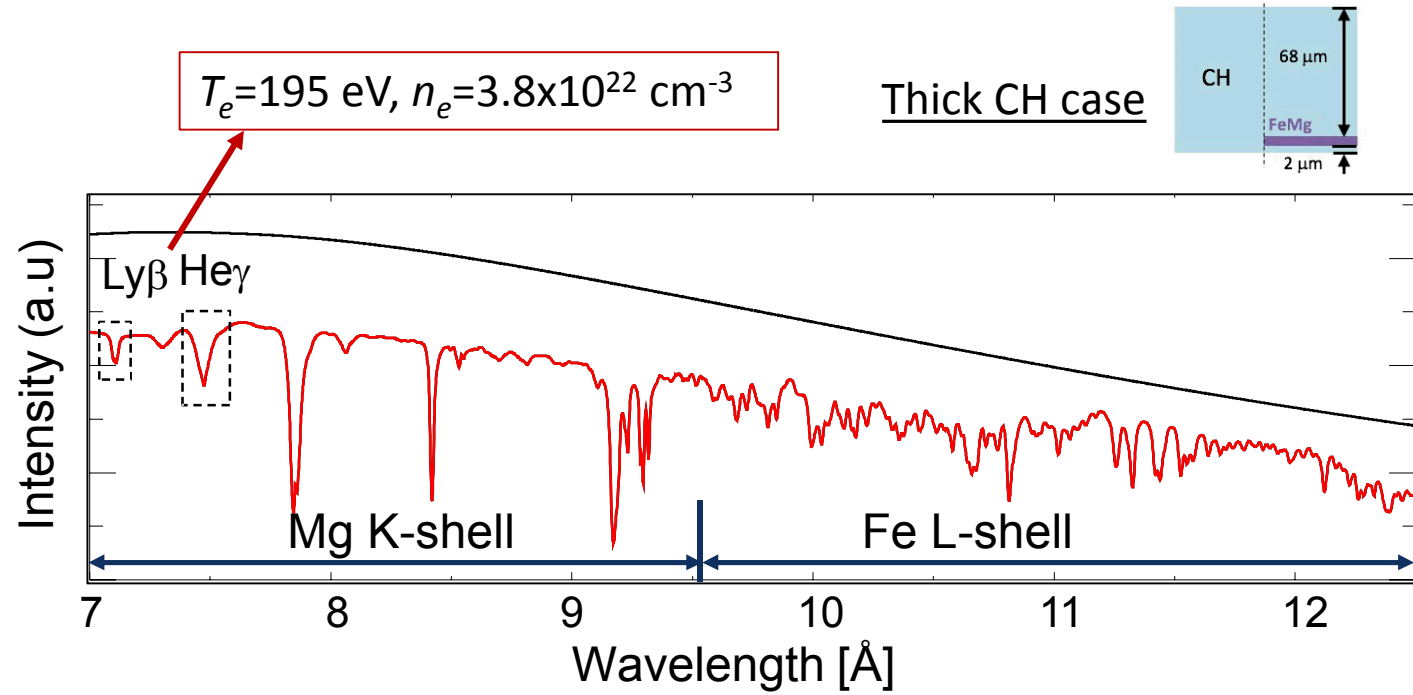
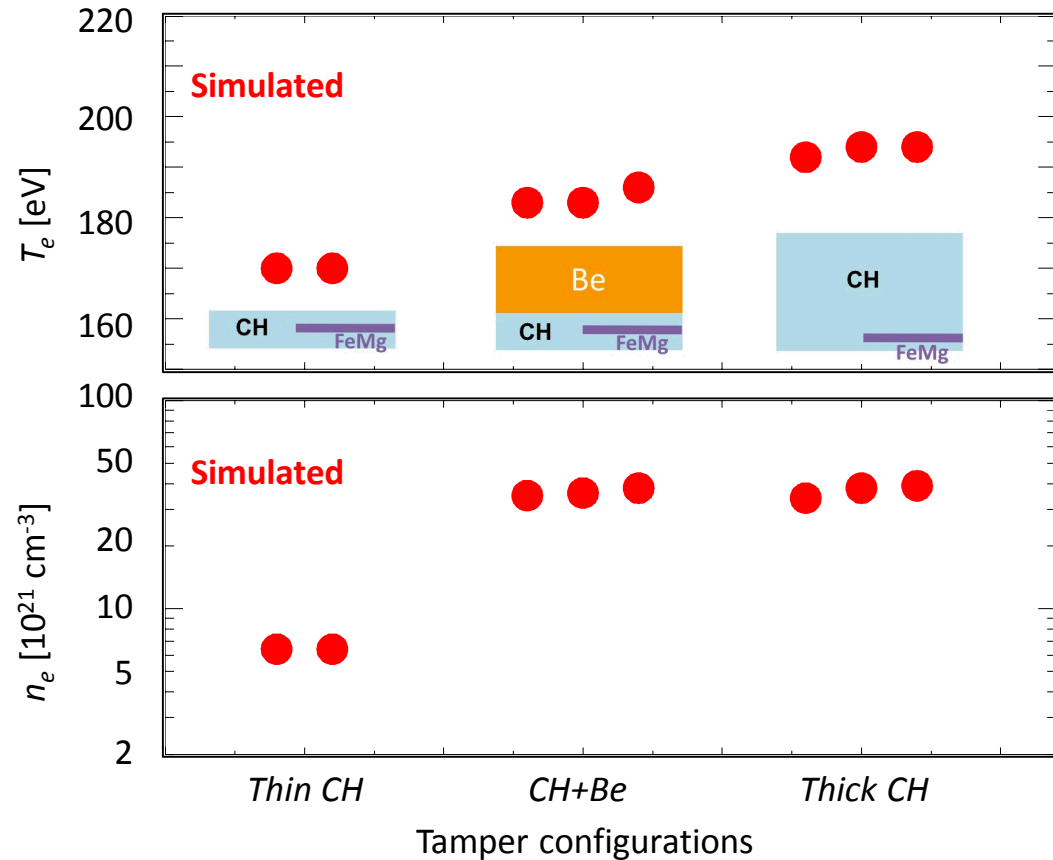
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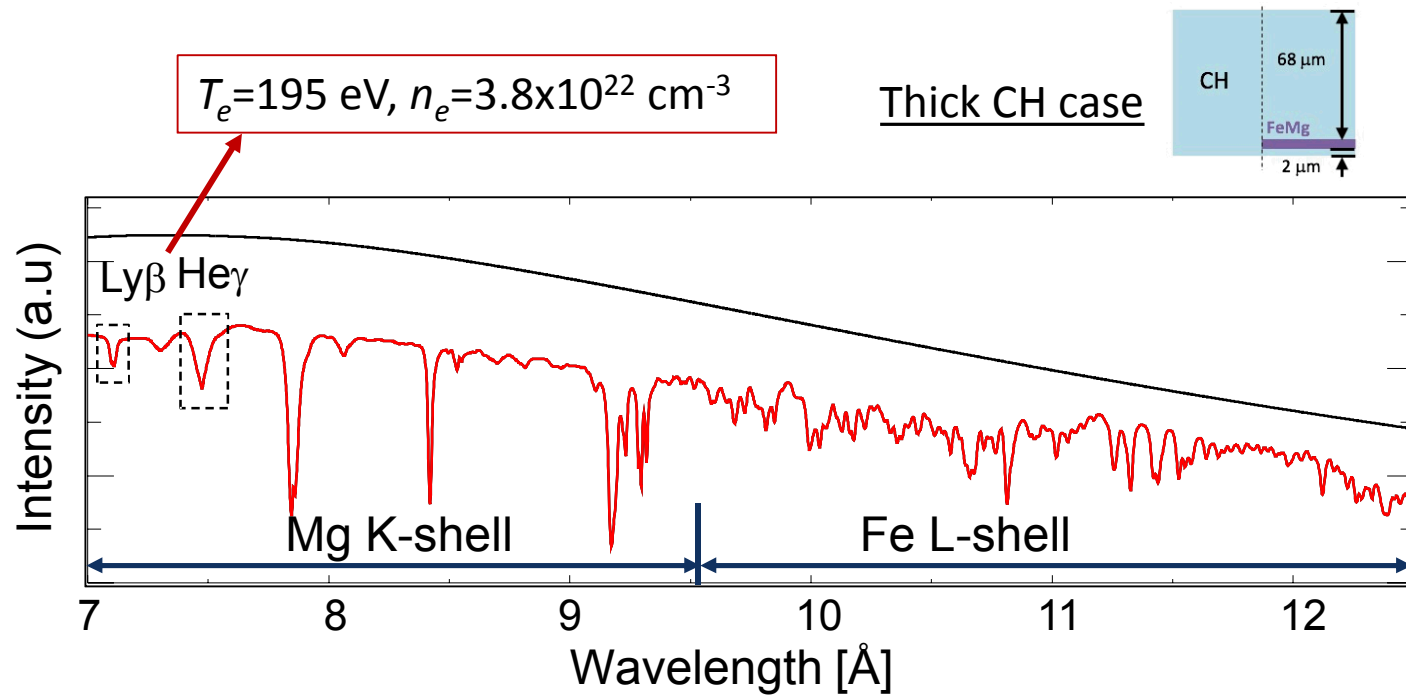
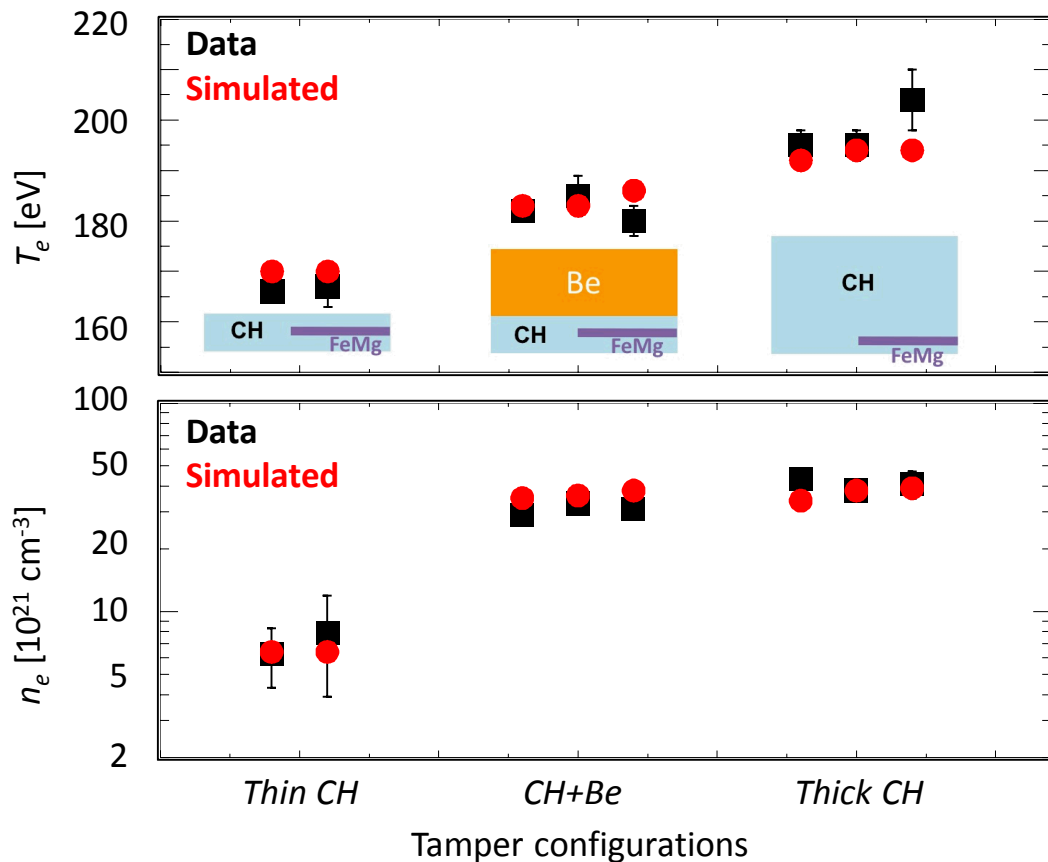
Simulated half-moon spectral image confirmed that the simulation reproduces the measured sample conditions



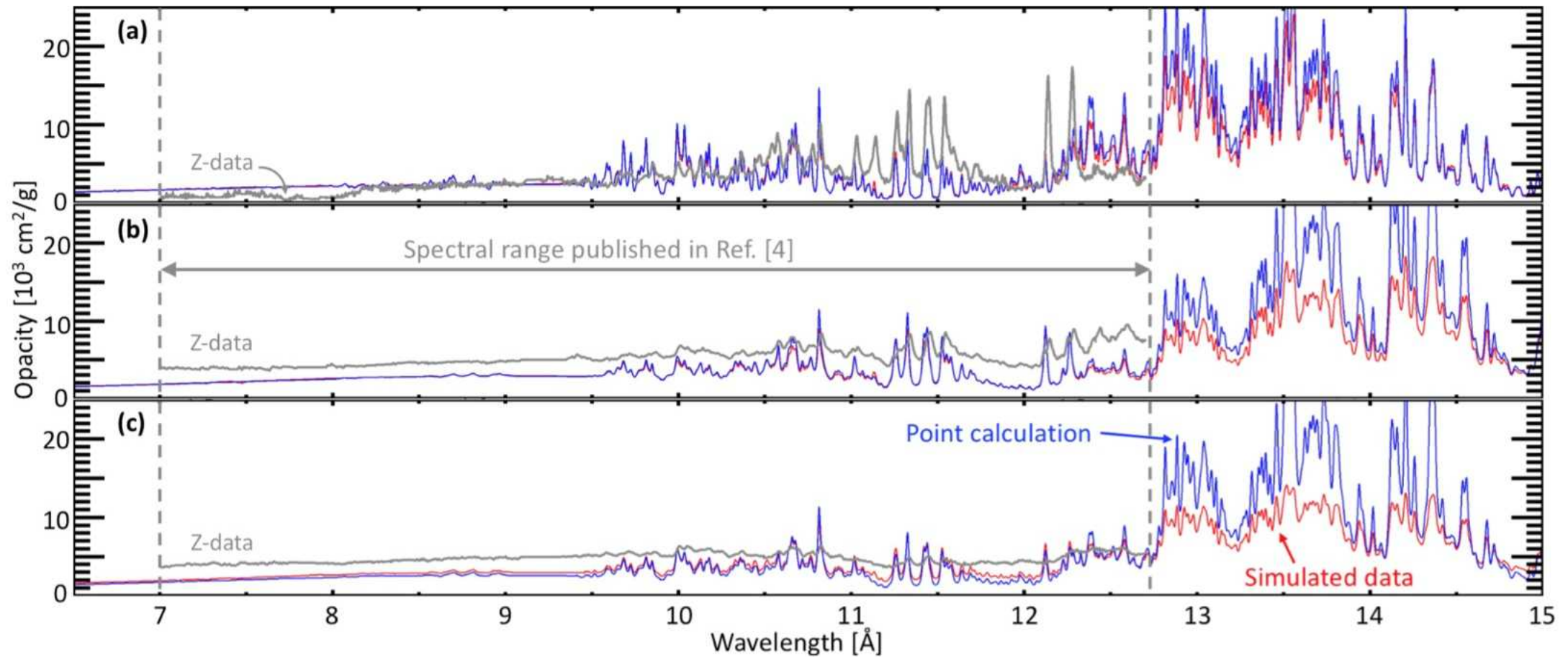
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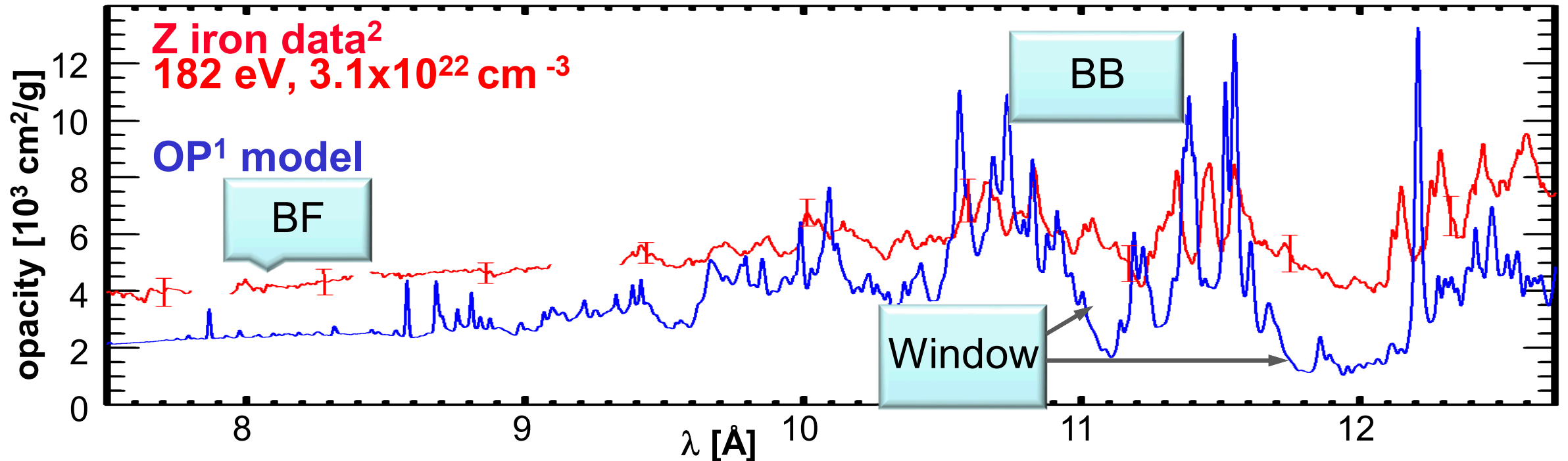


Numerical investigation suggests negligible impact of self-emission, tamper attenuation, and gradients



- [1] 1-D hydro-simulation and its post-processing reproduced measured Te, ne, and backlight spectral image
- [2] Simulated self-emission, tamper-transmission difference, and temporal and spatial gradient do not explain the observed data-model discrepancy

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 \rightarrow Atomic structure
- Strength \rightarrow Oscillator strength?
Population?
- Line width \rightarrow Line shape?
Missing lines?

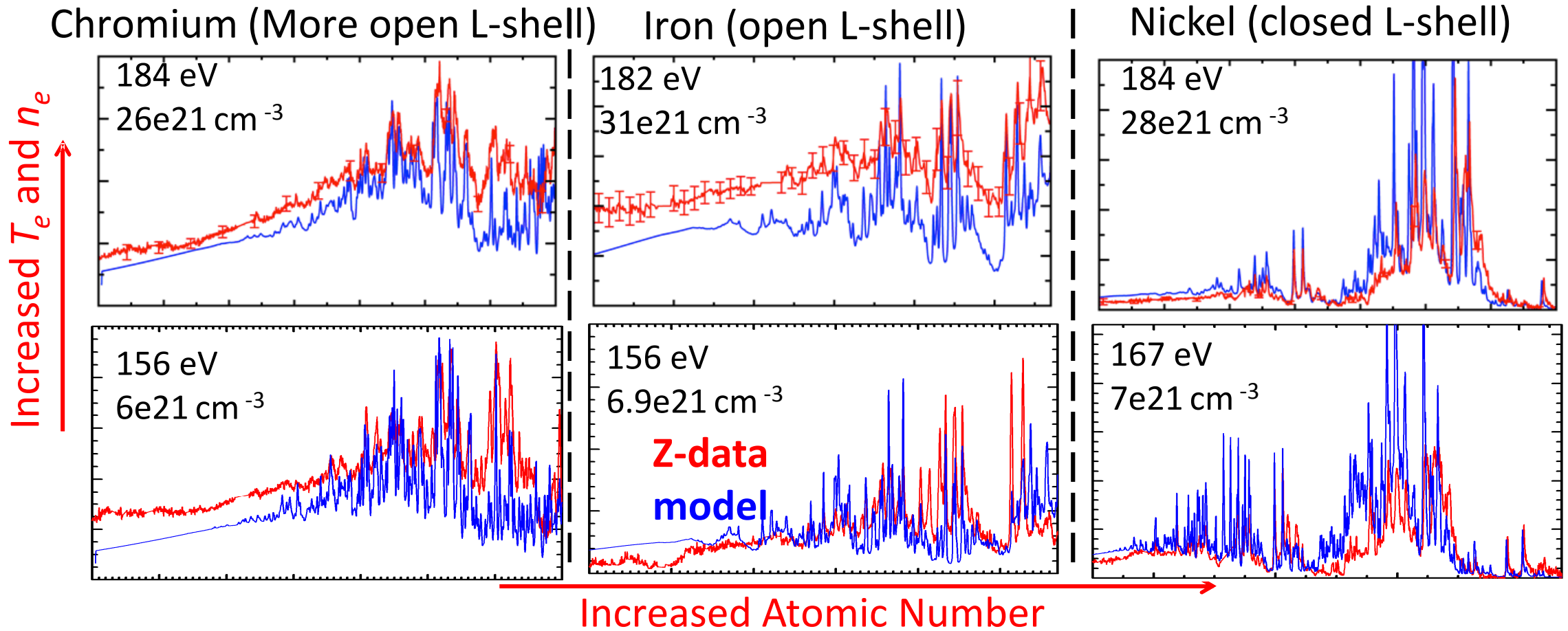
Window filling:

- 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

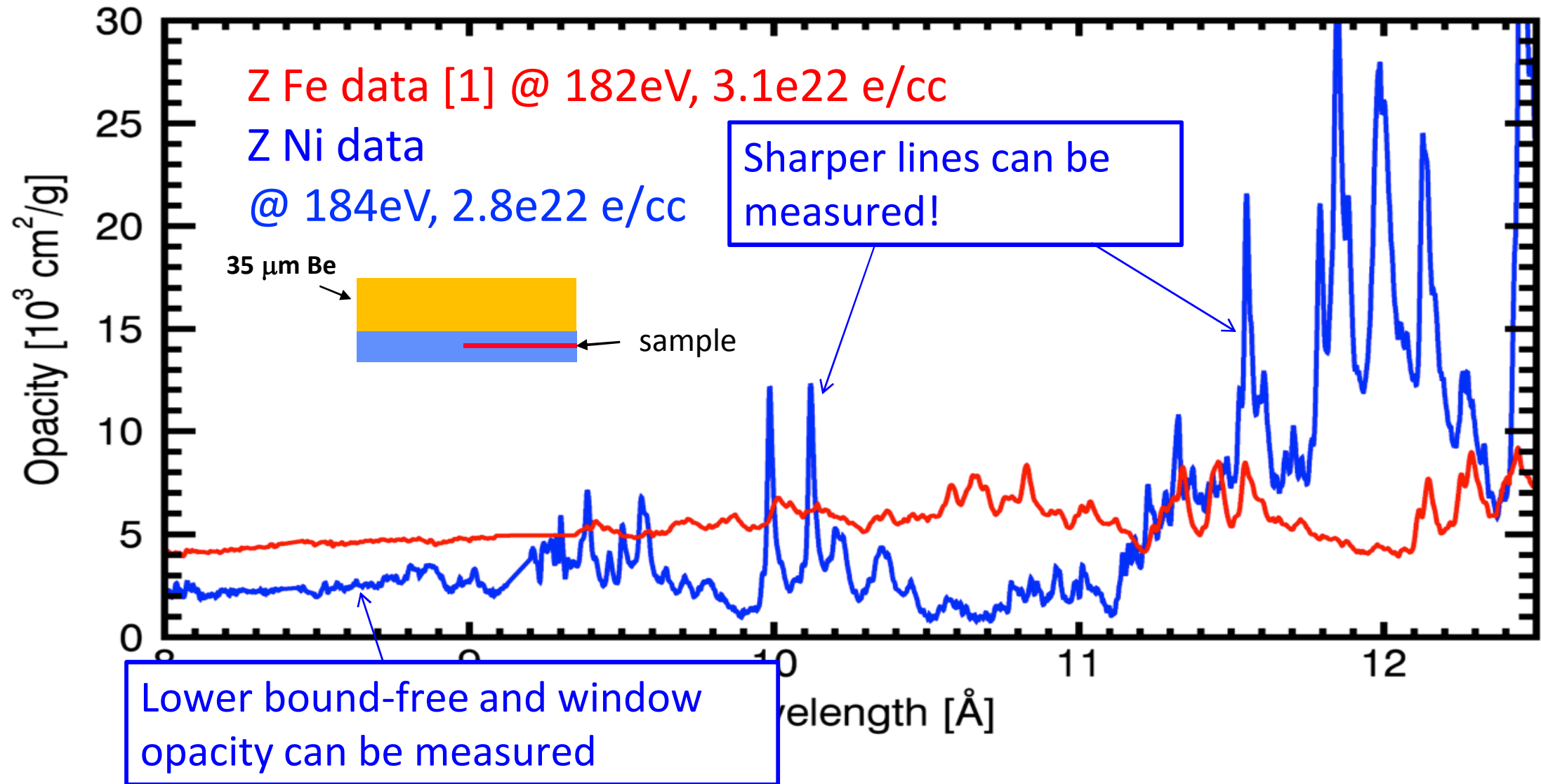
We will untangle the complex opacity issues through precise measurements across a range of T_e , n_e , and Z

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

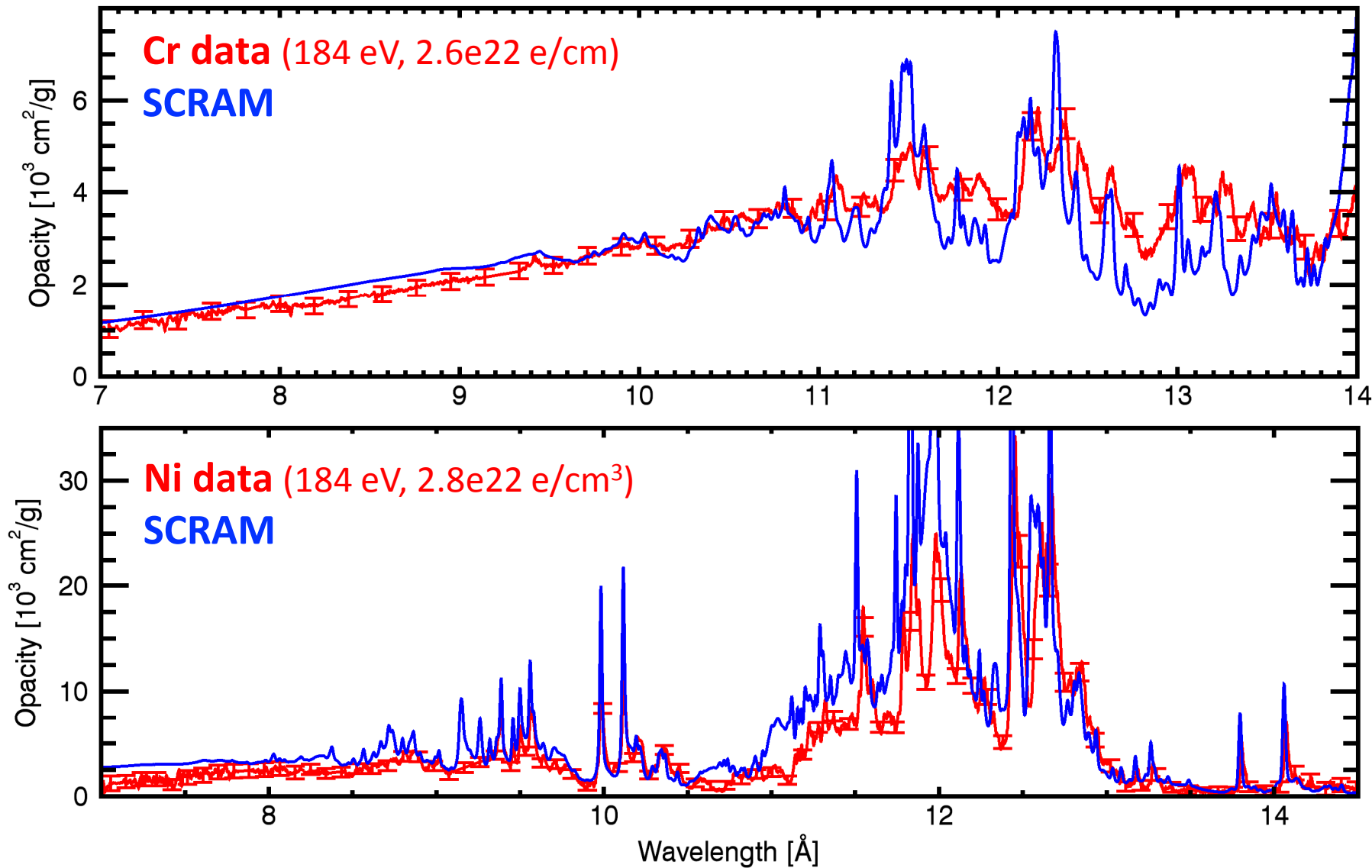


We performed 5 Cr, 1 Ni, and 4 Fe more opacity measurements to consolidate our conclusions.

Ni data confirm that the platform is not biased to measure high b-f, broad b-b lines, and filled window



Cr and Ni opacities were measured and data-model comparisons show interesting agreement/disagreement



Potential source of disagreement:

Window:

- Line location?
- Missing lines from multi-excited states?

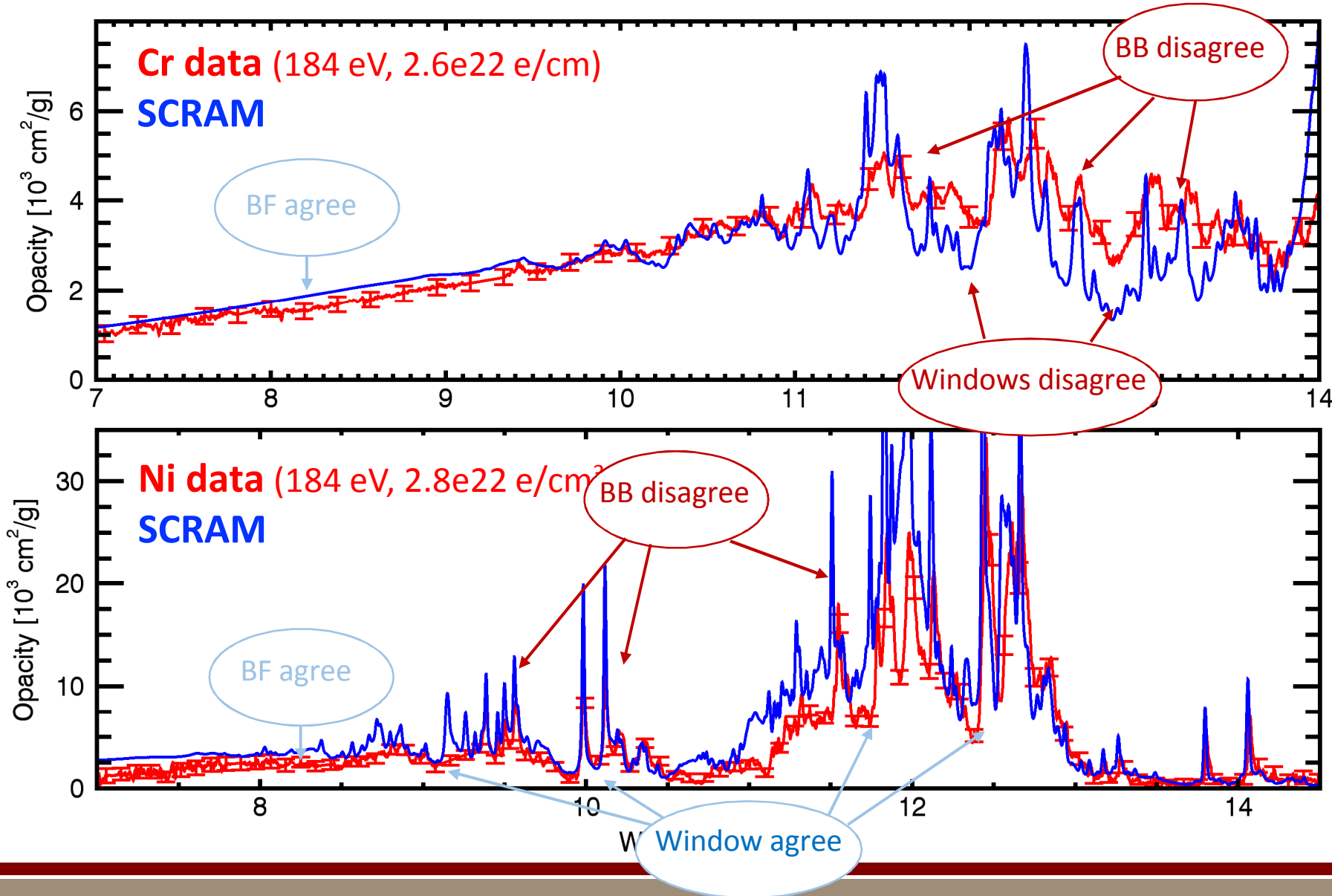
BB:

- Oscillator strengths?
- Initial state population?
- Line shape?

BF:

- Photoionization cross-section?
- Two photon processes?
- Quasi-continuum from multi-excited states?

Cr and Ni opacities were measured and data-model comparisons show interesting agreement/disagreement



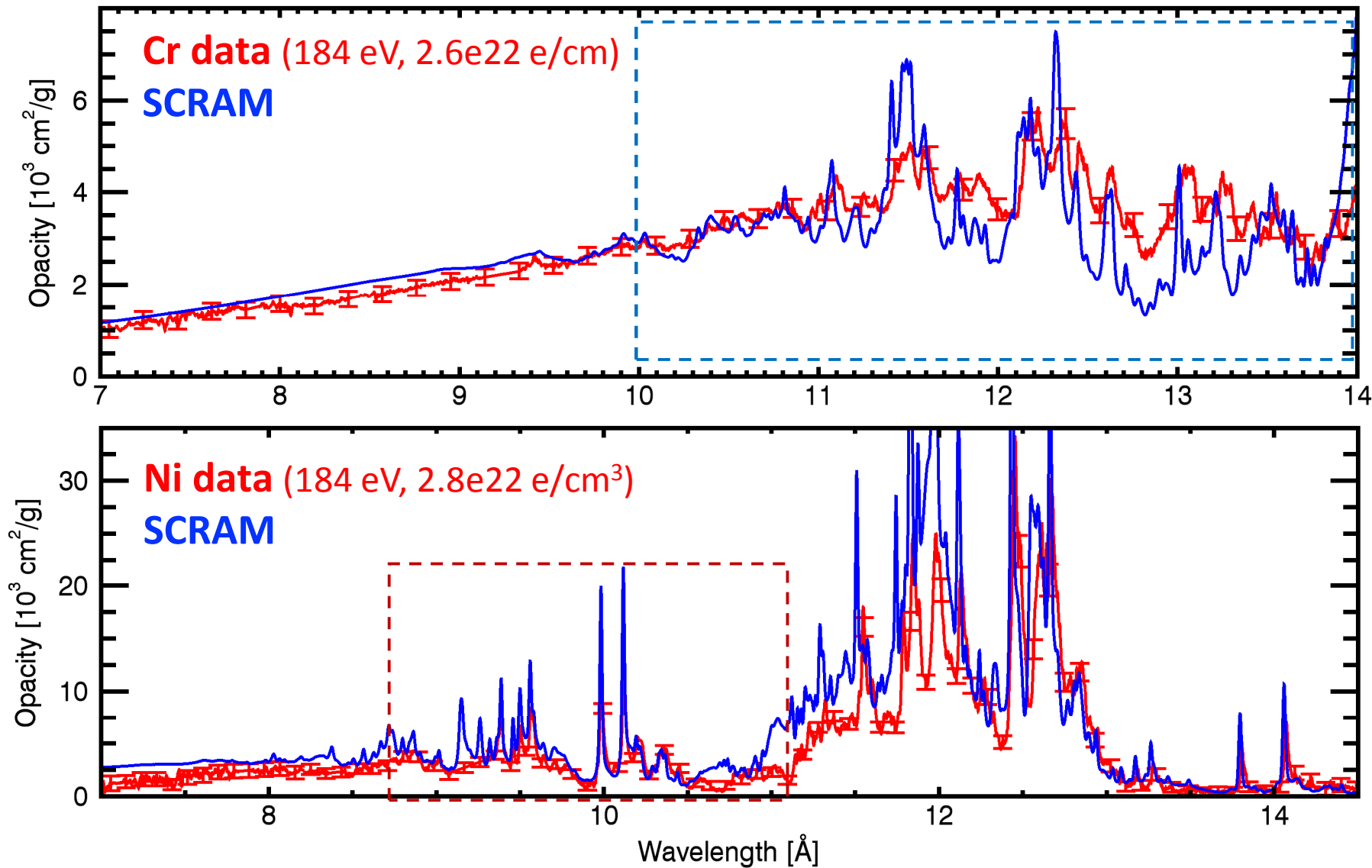
Potential source of disagreement:

- Window:
- Line location?
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- Line location?
- Missing lines from multi-excited states?

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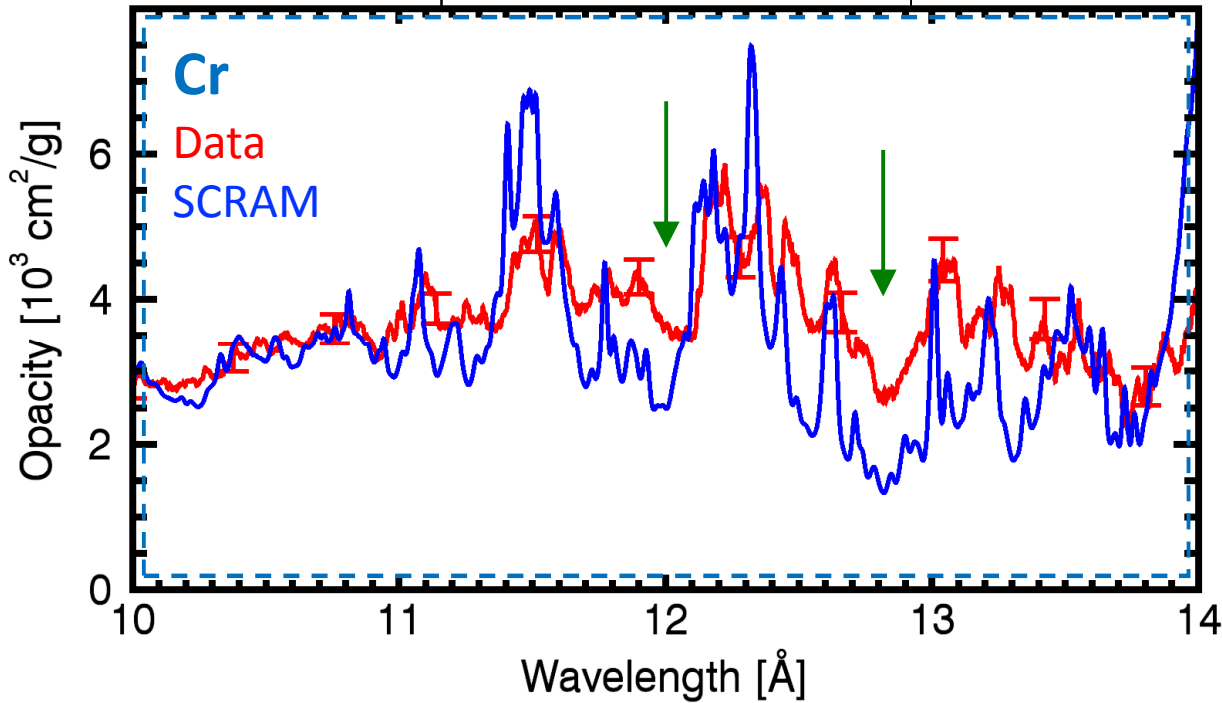
- Oscillator strengths?
- Initial state population?
- Line shape?

BF:

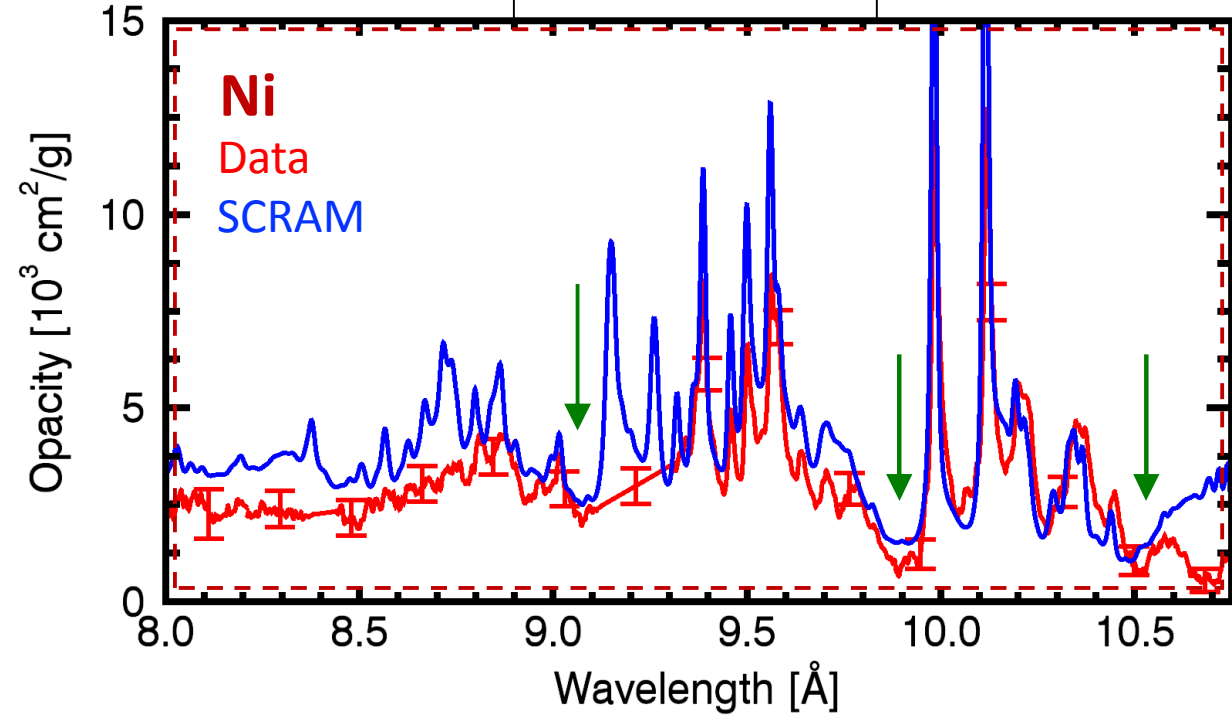
- Photoionization cross-section?
- Two photon processes?
- Quasi-continuum from multi-excited states?

Window disagreement in Fe and Cr may imply that missing physics becomes more important in open L-shell or lower atomic number

More open L-shell



Closed L-shell

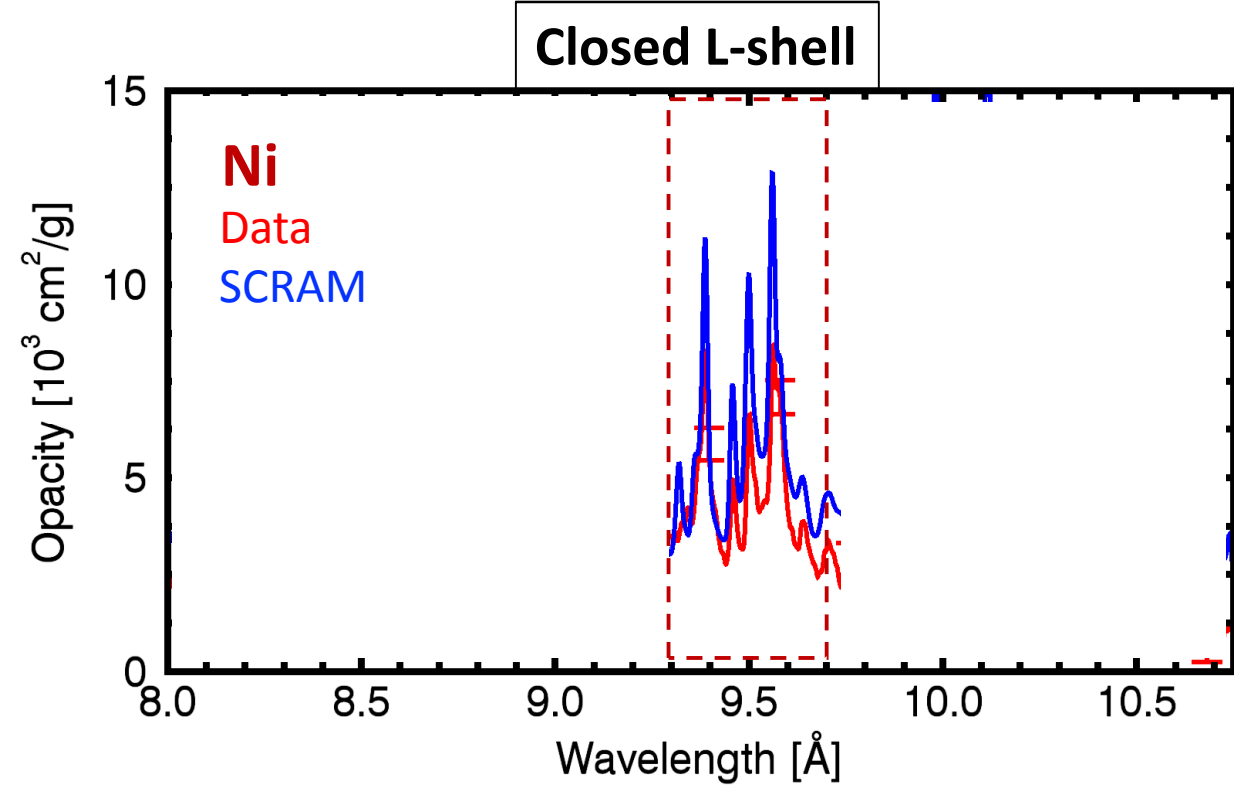
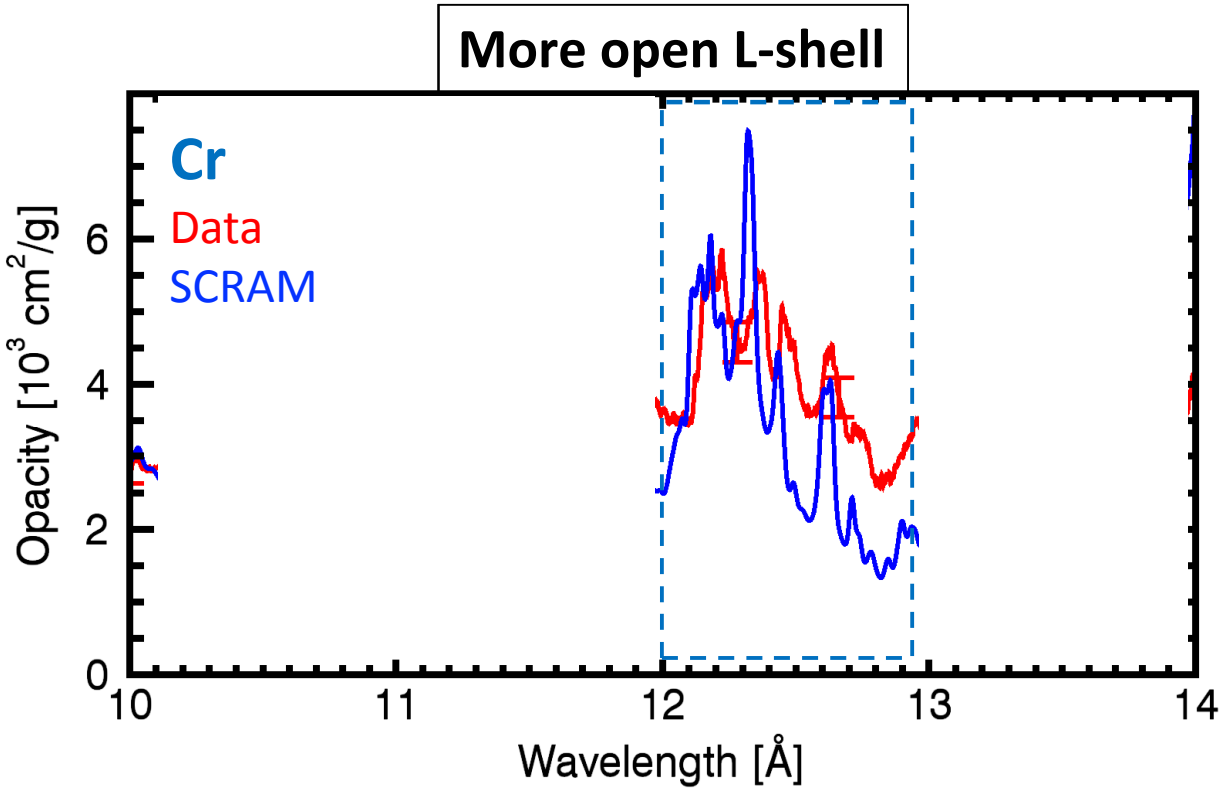


Potential source of window discrepancy:

- Underestimate in line broadening?
- Missing lines from multi-excited states?
- Multi-photon absorption?

Likely explanation

Window disagreement in Fe and Cr may imply that missing physics becomes more important in open L-shell or lower atomic number



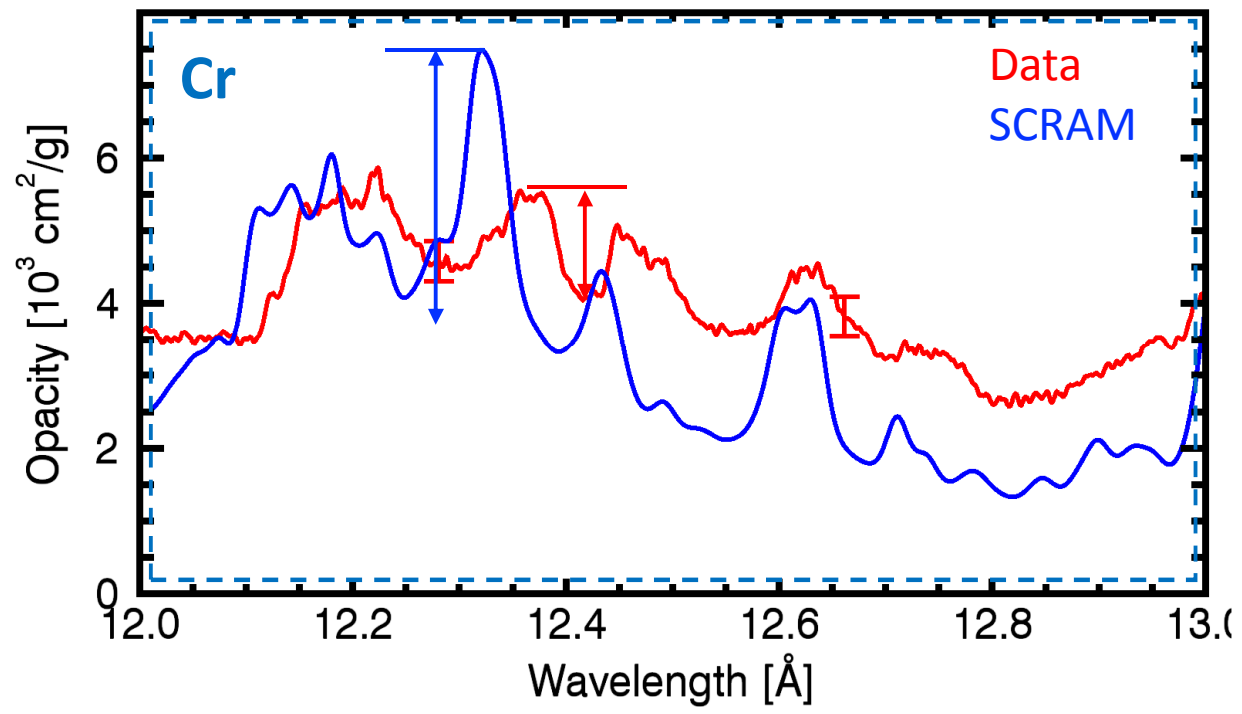
Potential source of window discrepancy:

- Underestimate in line broadening?
- Missing lines from multi-excited states?
- Multi-photon absorption?

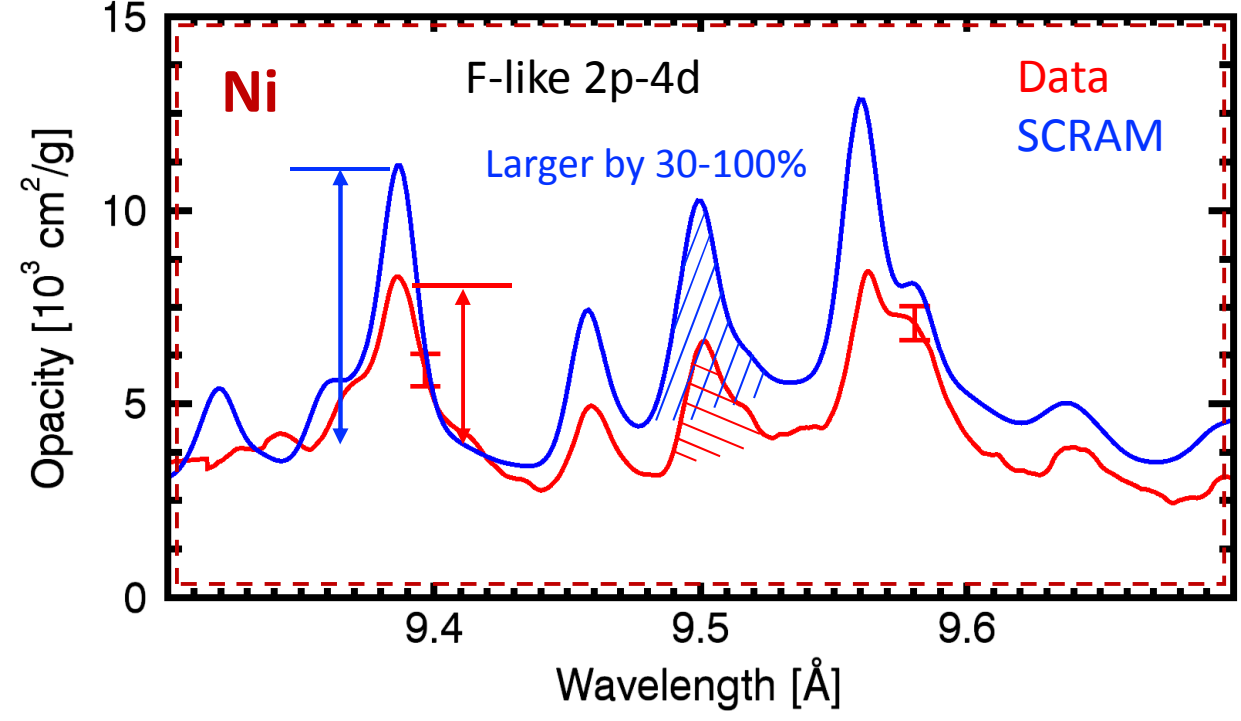
Likely explanation

Models predict similar b-b feature, wavelength, and relative strength, but peak-to-valley contrast is overestimated

More broadening



Less broadening



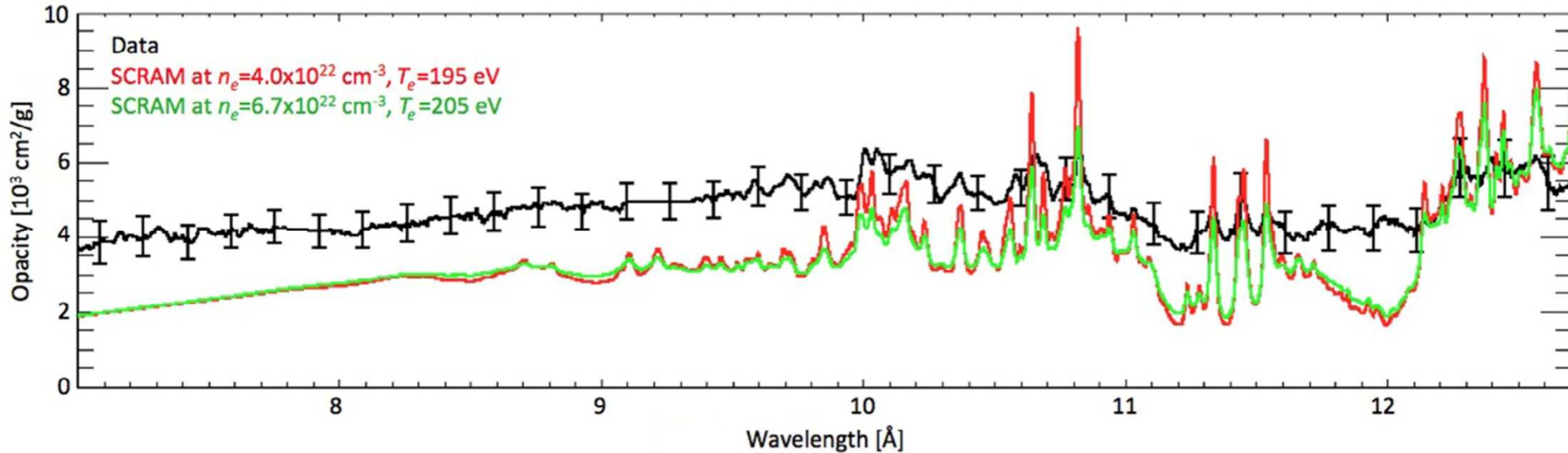
BB:

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

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

} Opacity integrated under line shape

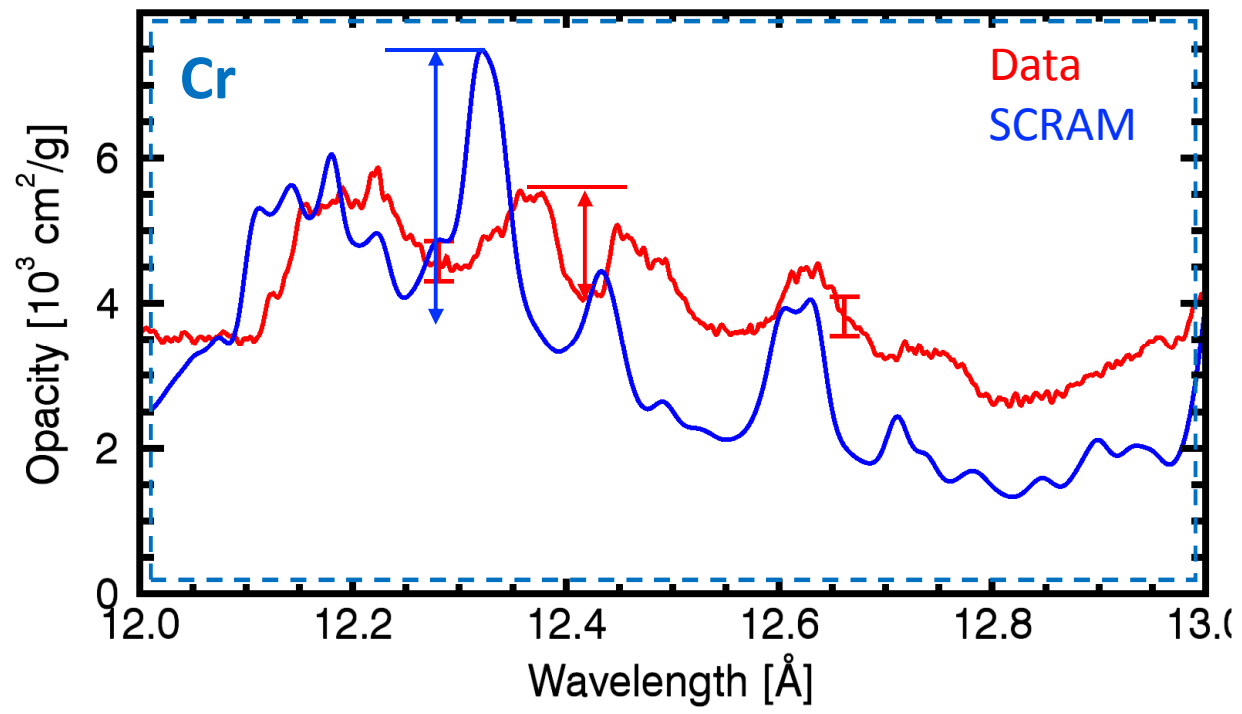
If the true density is higher by 50%, this peak-to-valley contrast and strength discrepancy will be smaller



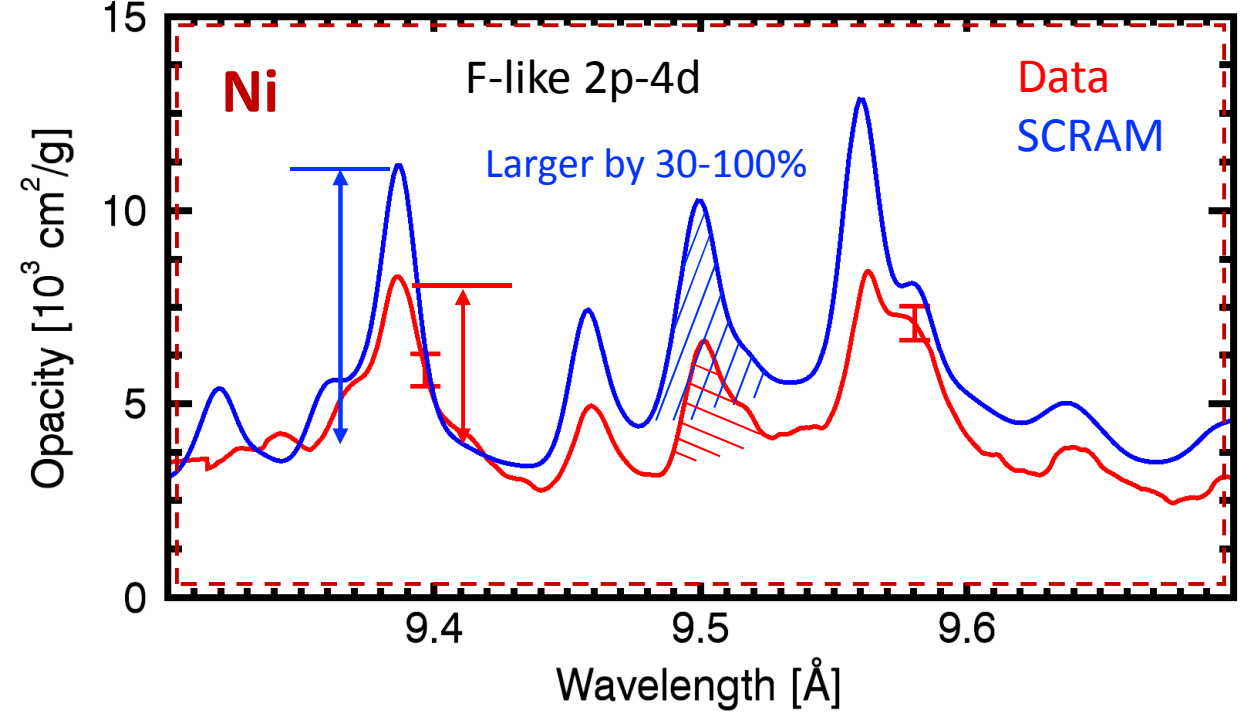
Further experimental or theoretical confirmation is needed.

Models predict similar b-b feature, wavelength, and relative strength, but peak-to-valley contrast is overestimated

More broadening



Less broadening



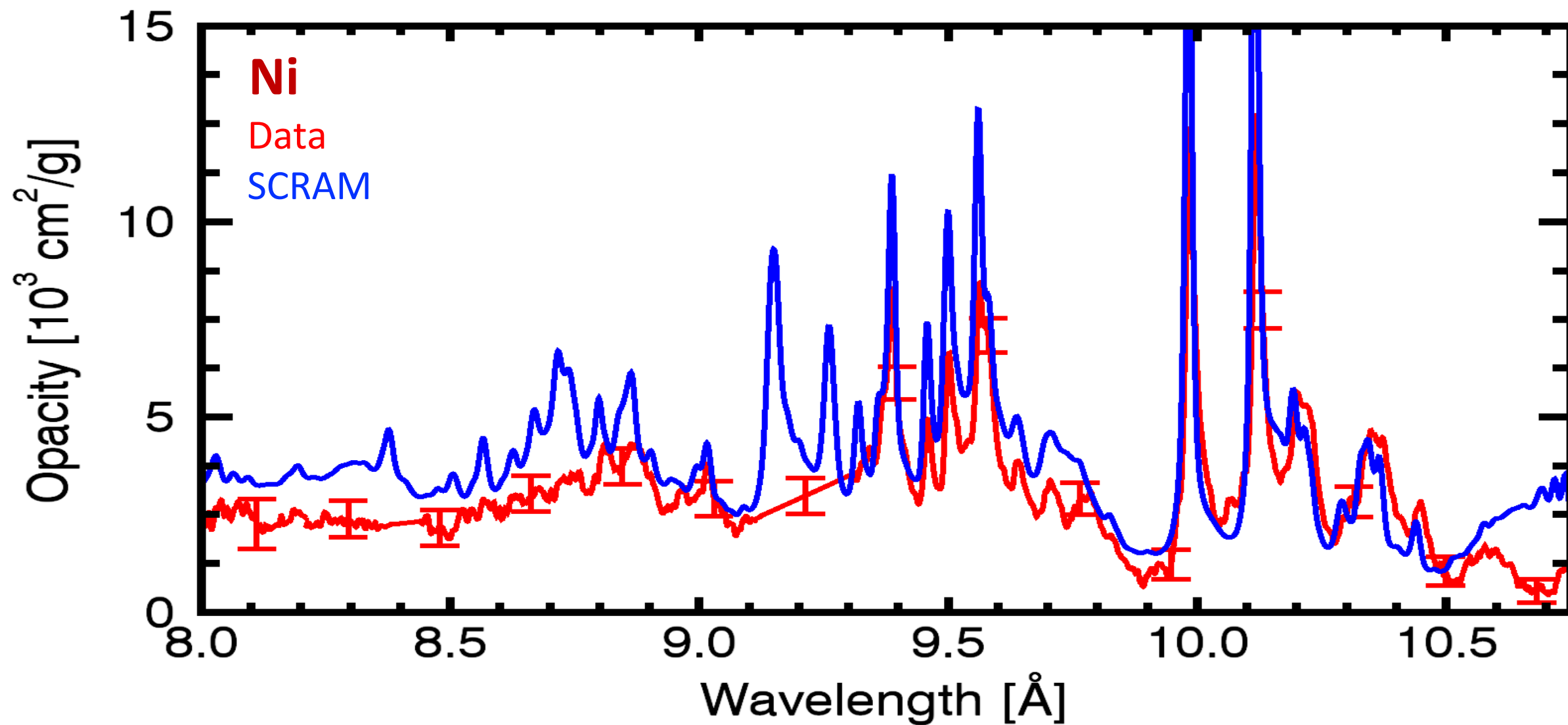
BB:

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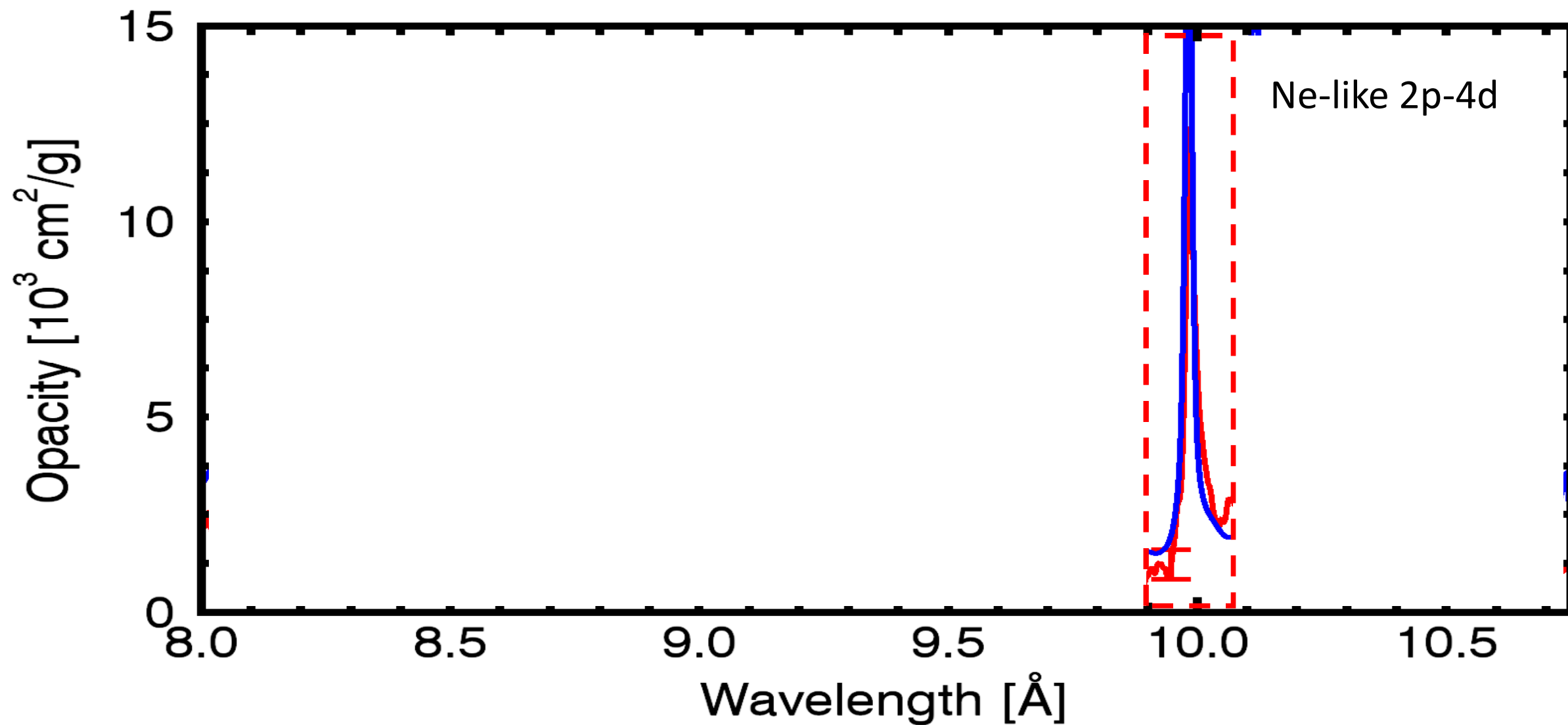
n_l ... lower state population
 f_{lu} ... oscillator strength
 $\phi(\nu)$... line shape

} Opacity integrated under line shape

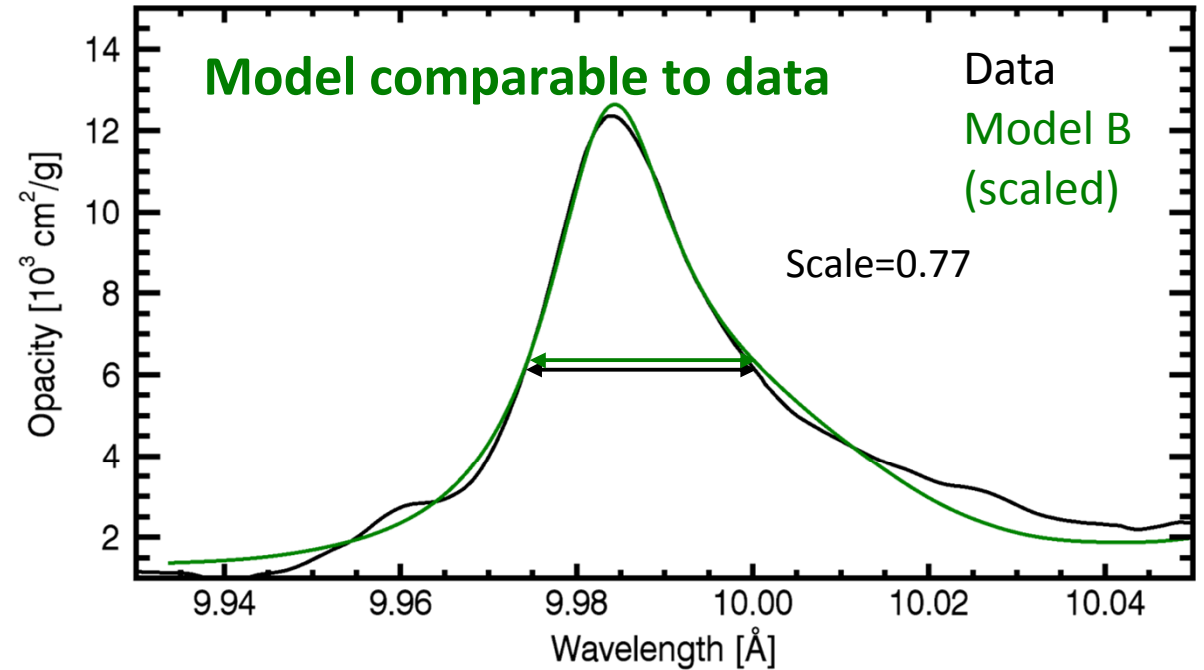
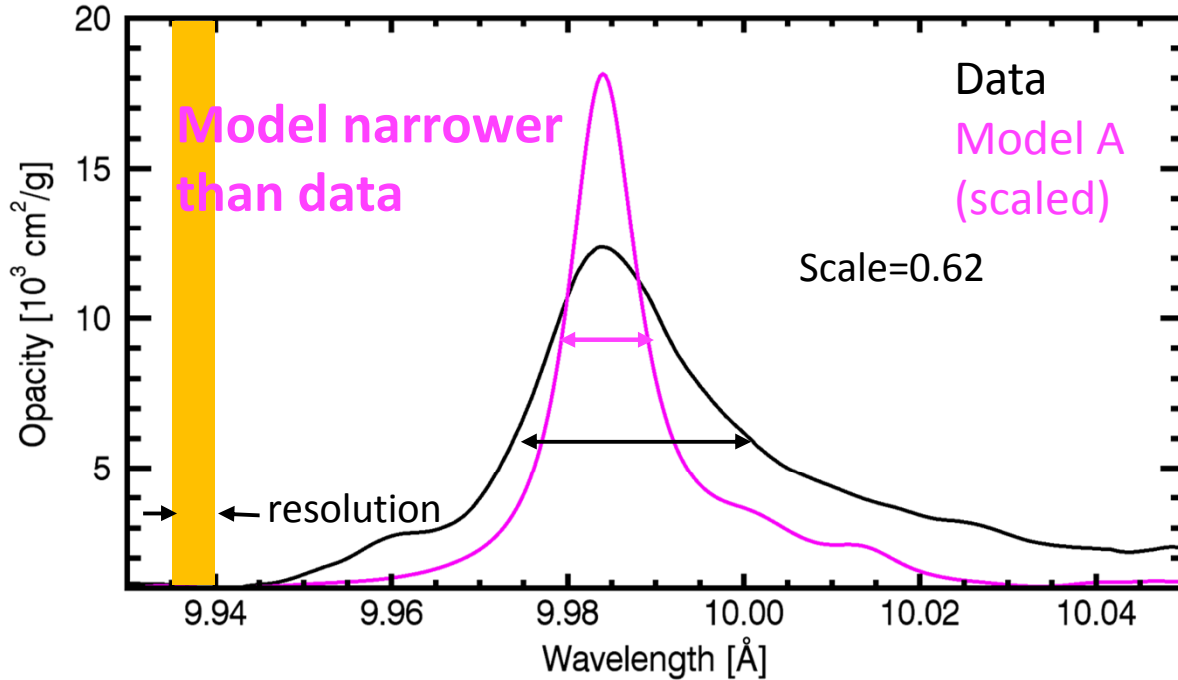
Strong isolated lines are more suitable to get better insight on line shape accuracy



Strong isolated lines are more suitable to get better insight on line shape accuracy

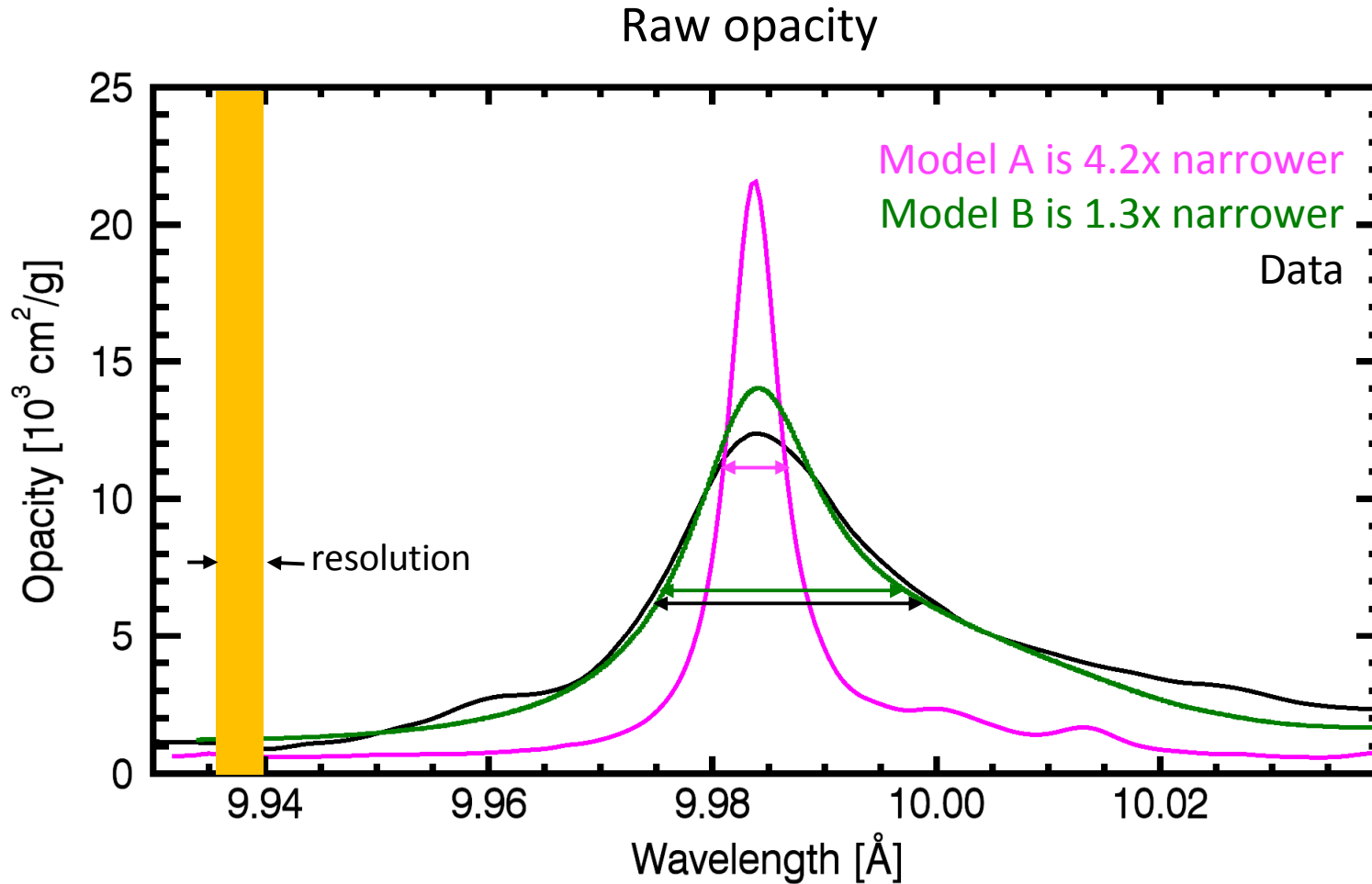


Ne-like Ni $n=2 \rightarrow 4$ b-b lines: Most models under-predict the line broadening



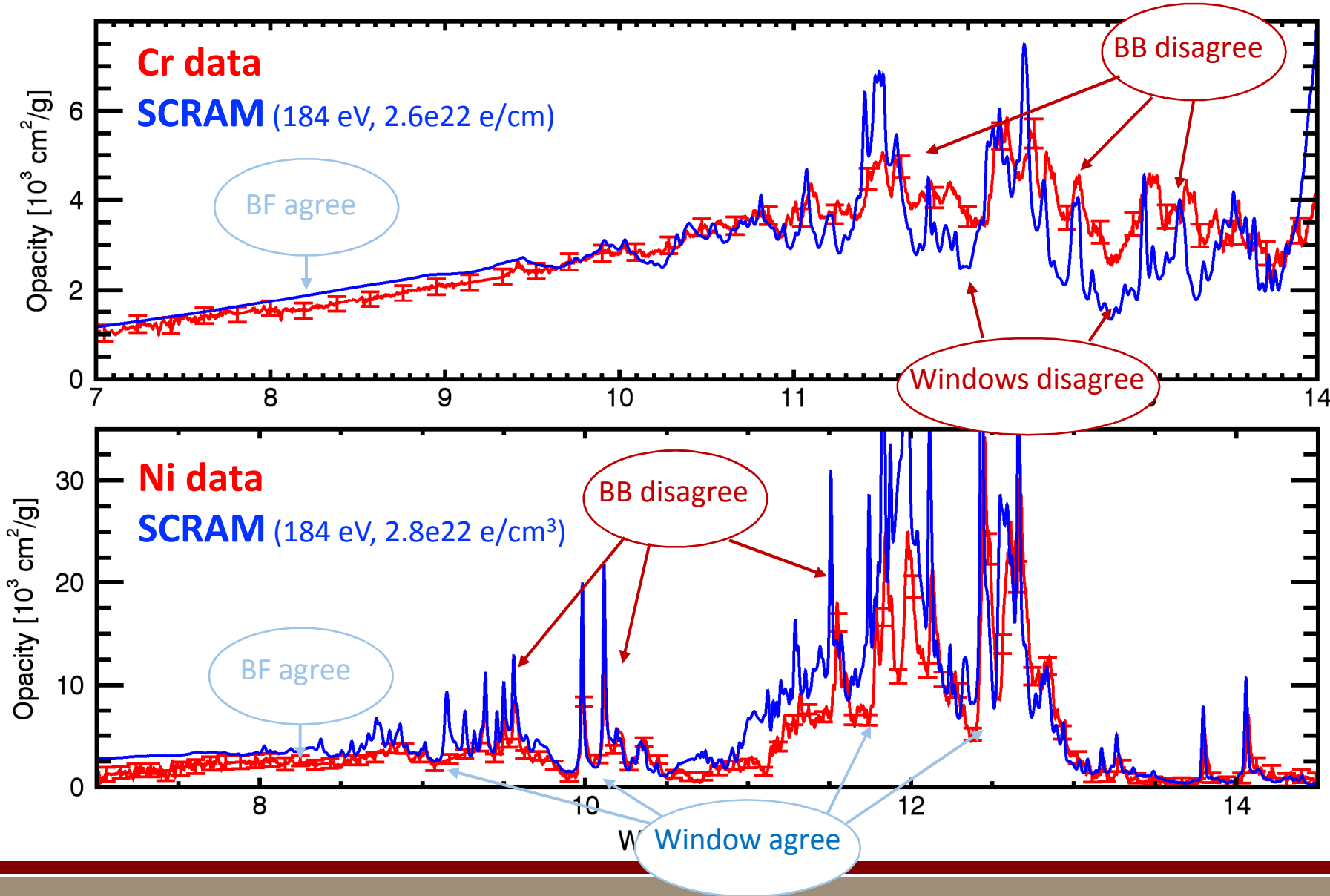
- Many models produced narrower lines like **Model A**
- One model shows excellent agreement in the line shape (**Model B**)
- Broad line shape can fill the opacity window and important for accurate opacity modeling

Without convolution, line shape is 4x narrower in Model A. 50% n_e increase is unlikely to explain the disagreement.



Many models may underestimate L-shell line broadening either due to inaccurate line shape or missing lines

Cr and Ni opacities were measured and data-model comparisons show interesting agreement/disagreement



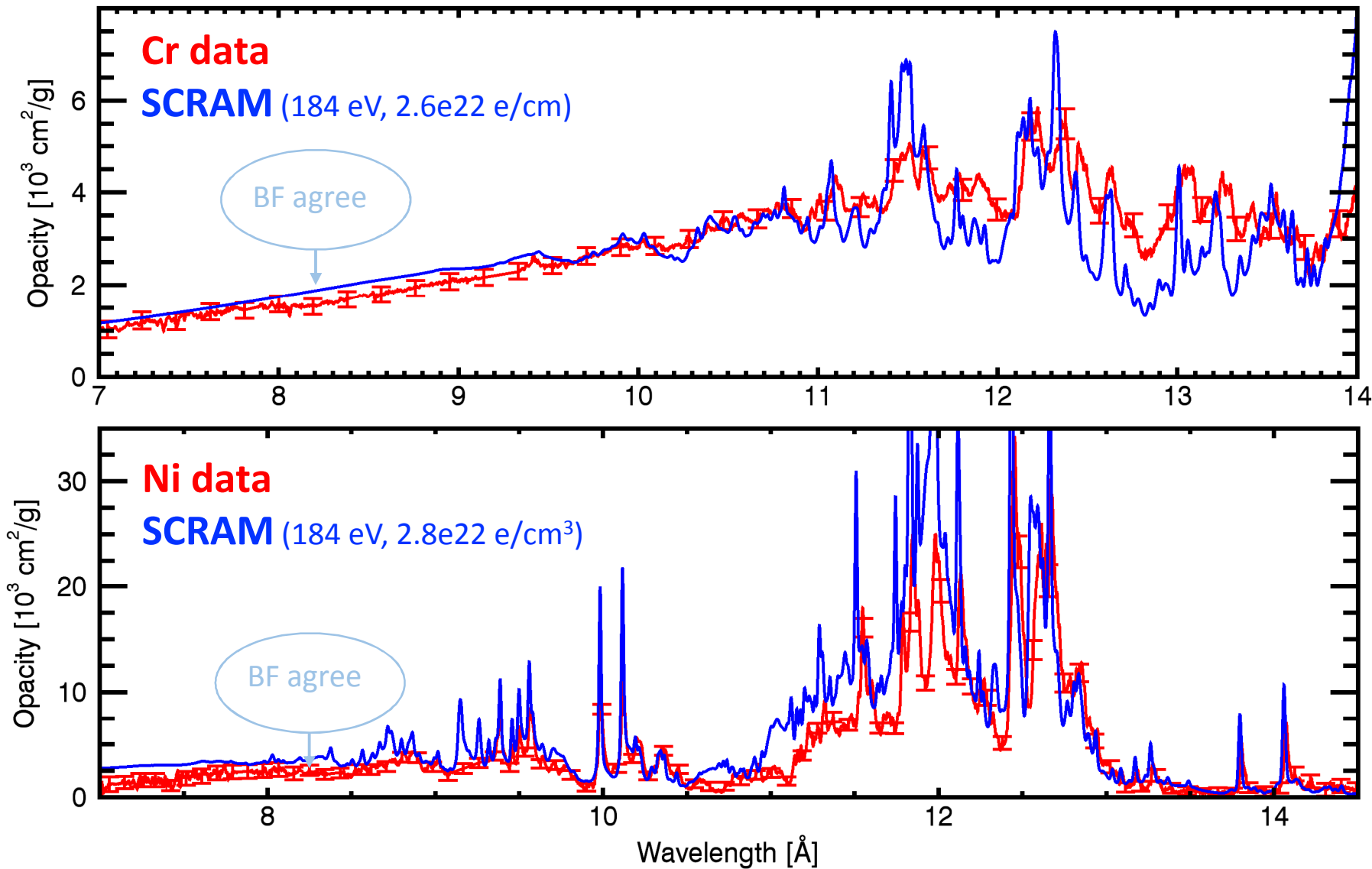
Potential source of disagreement:

- Window:
- Line location?
 - Missing lines from multi-excited states?

- BB:
- Oscillator strengths?
 - Initial state population?
 - Line shape?

- BF:
- Photoionization cross-section?
 - Two photon processes?
 - Quasi-continuum from multi-excited states?

Cr and Ni opacities were measured and data-model comparisons show interesting agreement/disagreement



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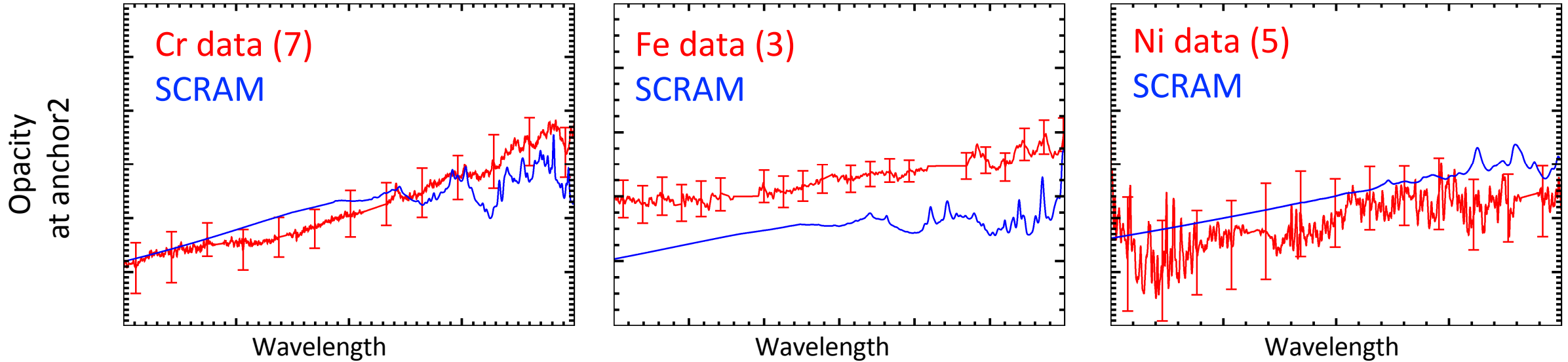
BB:

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- Photoionization cross-section?
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Short-wavelength continuum predictions agree with preliminary Cr and Ni measurements, but not Fe



If preliminary Cr and Ni are substantiated, why is Fe different?

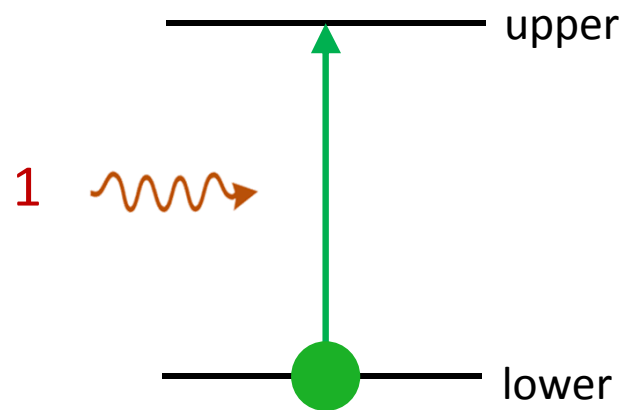
- Theory: Cr, Fe, and Ni opacities are systematically computed.
- Experiment: Methods identical for all elements and reproducibility is confirmed

Hypothesis development:

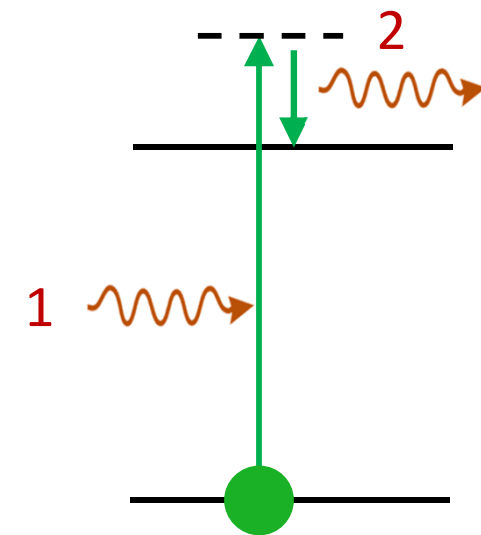
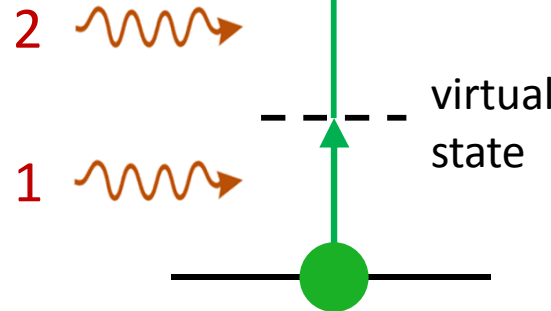
- If Fe b-f is different because of systematic error, a specific hypothesis is needed
- We must also search for systematic error for Ni and Cr results
- Is there any missing physics that selectively raises opacity of certain element at certain condition?

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

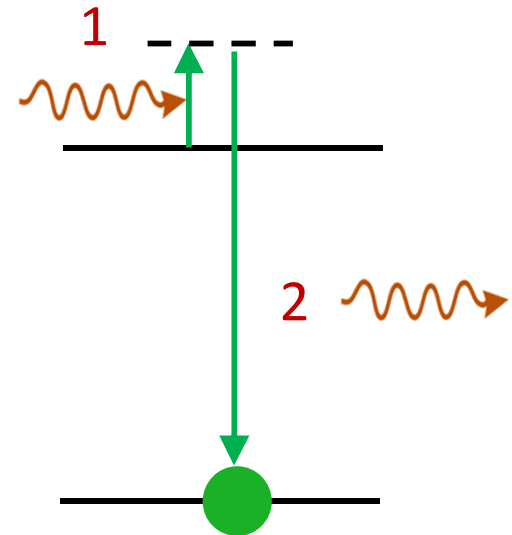
one-photon processes



two-photon processes through a virtual state



Raman Stokes



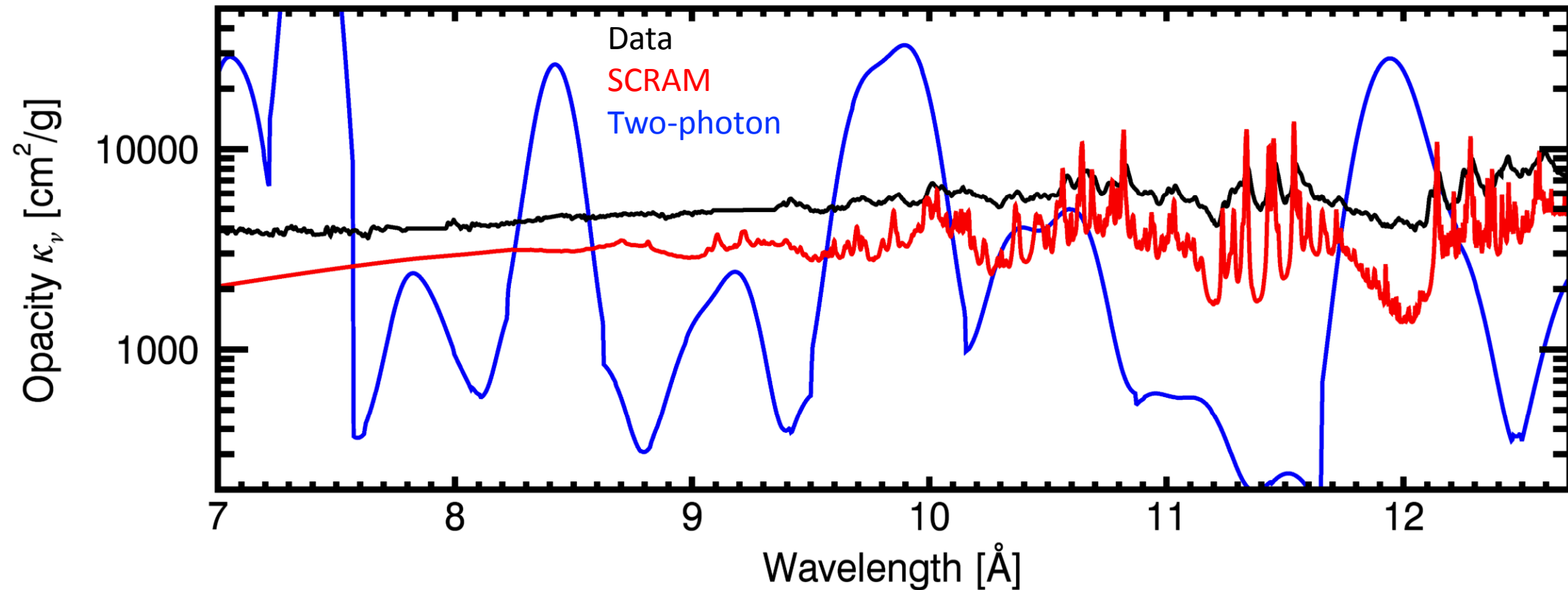
Raman Anti-Stokes

- Two-photon process cross-section $\sim n^8$
- Virtual state has short life-time \rightarrow 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; this would partially resolve the discrepancies in window and bound-free



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

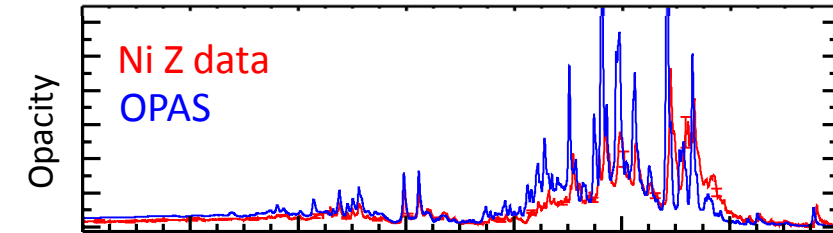
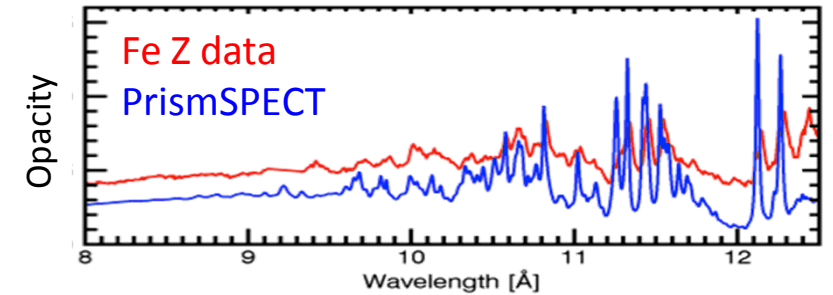
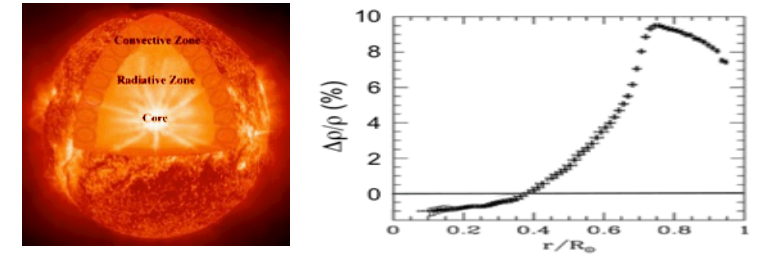
Two-photon opacity needs to be recomputed with more accurate atomic model.

Future work:

- Consolidate Cr and Ni
- Cr opacity surrogate Fe opacity at half solar radius
- Revisit Fe

We are helping resolve the reported stellar opacity discrepancy with experiments, data interpretation, and theory

- Solar models disagree with observations
 - Solar mean opacity is underestimated by 17% [1]
 - Hypothesis: Fe opacity too low?
- SNL Fe opacity measurement revealed 30-400% disagreement with calculated opacity [2]
 - >7% increase in solar mean opacity
- Progress towards the resolution of the discrepancy:
 - Experiment scrutiny:
 - Density error partially explain peak-to-valley contrast
 - Fe, Ni, and Cr opacity measurements:
 - Platform is not always biased
 - Bound-free disagreement most prominent in Fe
 - Theory: Two-photon opacity may be important



Working towards completing the systematic study