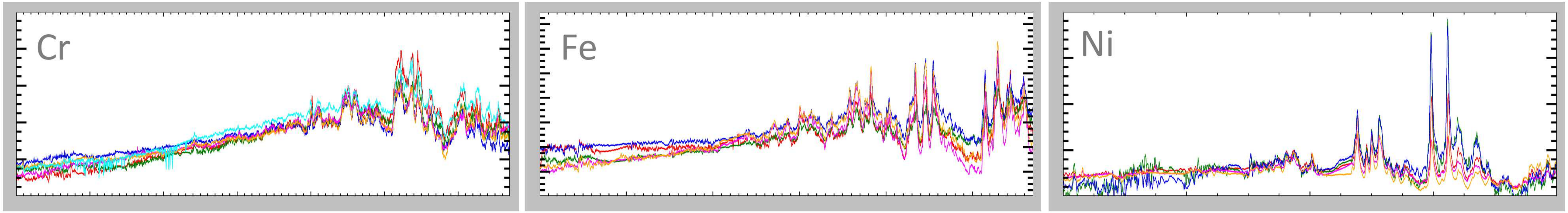
SAND2018-11855C



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

Taisuke Nagayama

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59th Annual Meeting of the APS Division of Plasma Physics, October 23, 2017, Milwaukee, Wisconsin

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
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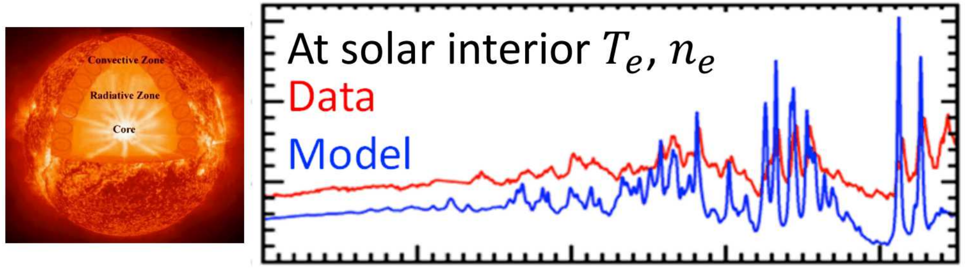
Nuclear Research Center Negev, Israel

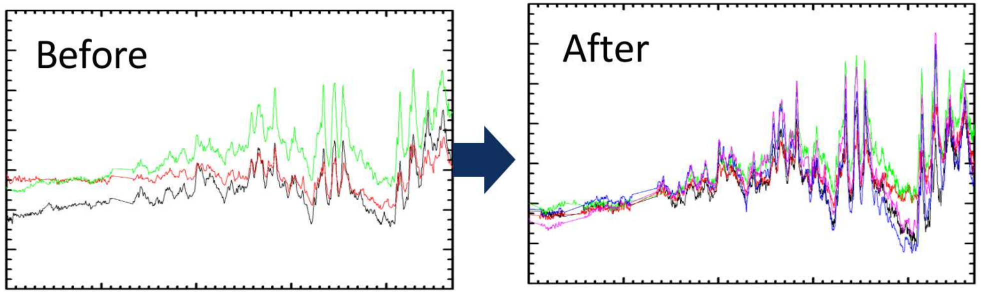
Systematic study of L-shell opacities with refined analysis validates experiment reliability and suggest necessary model refinements

- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**

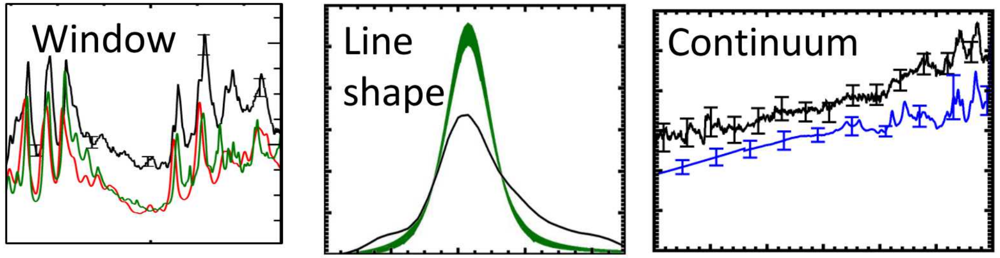
  → Is opacity theory wrong? Is experiment flawed?



- **Refined analysis improved shot-to-shot reproducibility, demonstrating opacity experiment reliability**

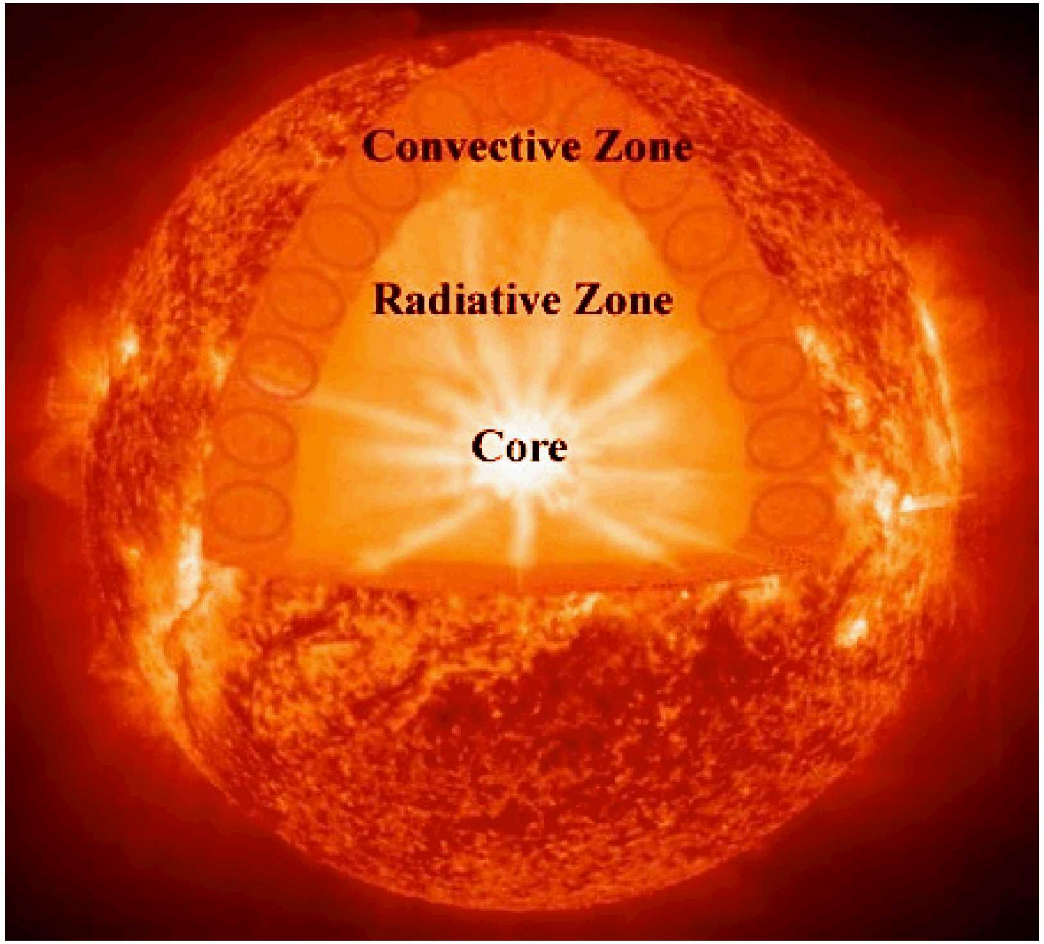


- **Systematic measurement of Cr, Fe, and Ni opacities suggests model refinements in three areas**
  - Window: Challenge associated with open L-shell config.
  - BB: Inaccurate treatment of density effects
  - Continuum: Peculiar dependence on atomic number

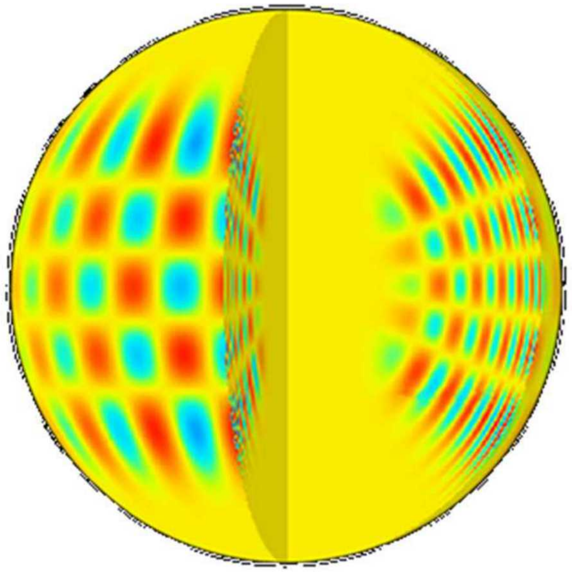


High reproducibility qualifies SNL to be a unique HED-opacity-benchmark facility

Modeled solar structure disagrees with observations

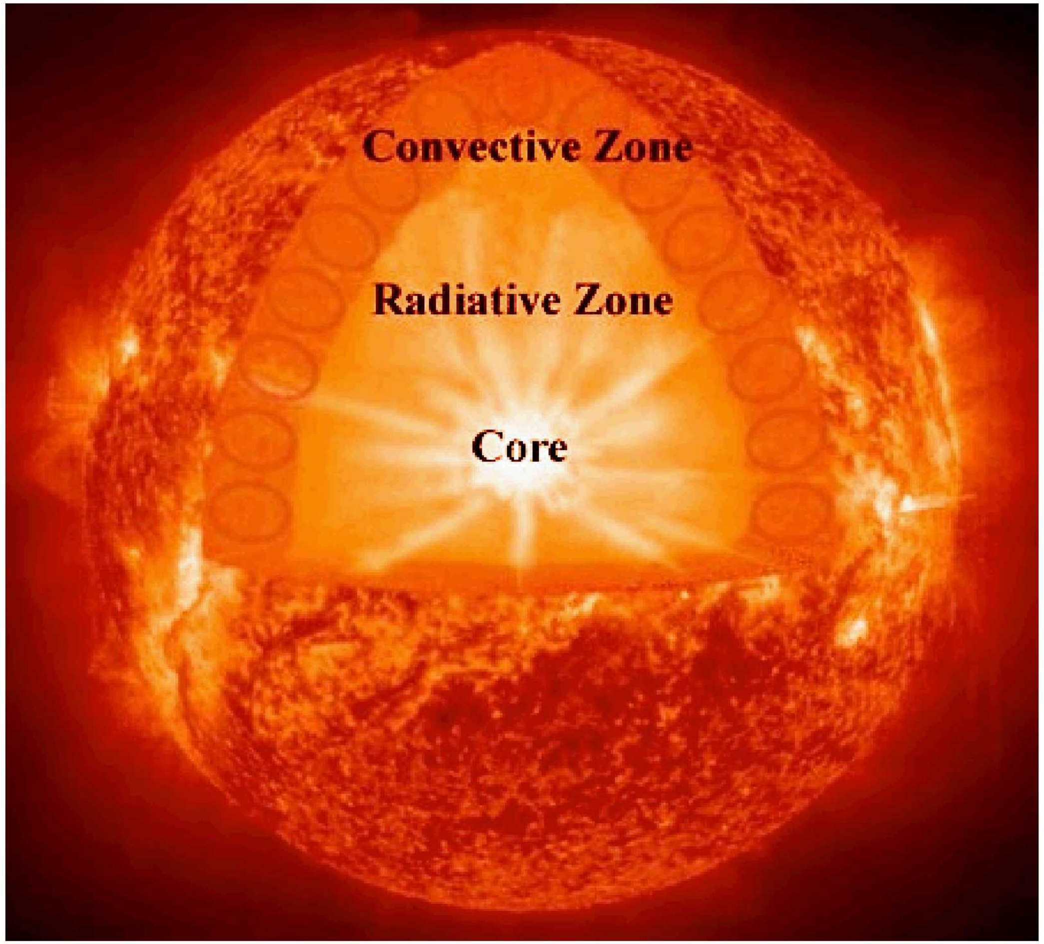


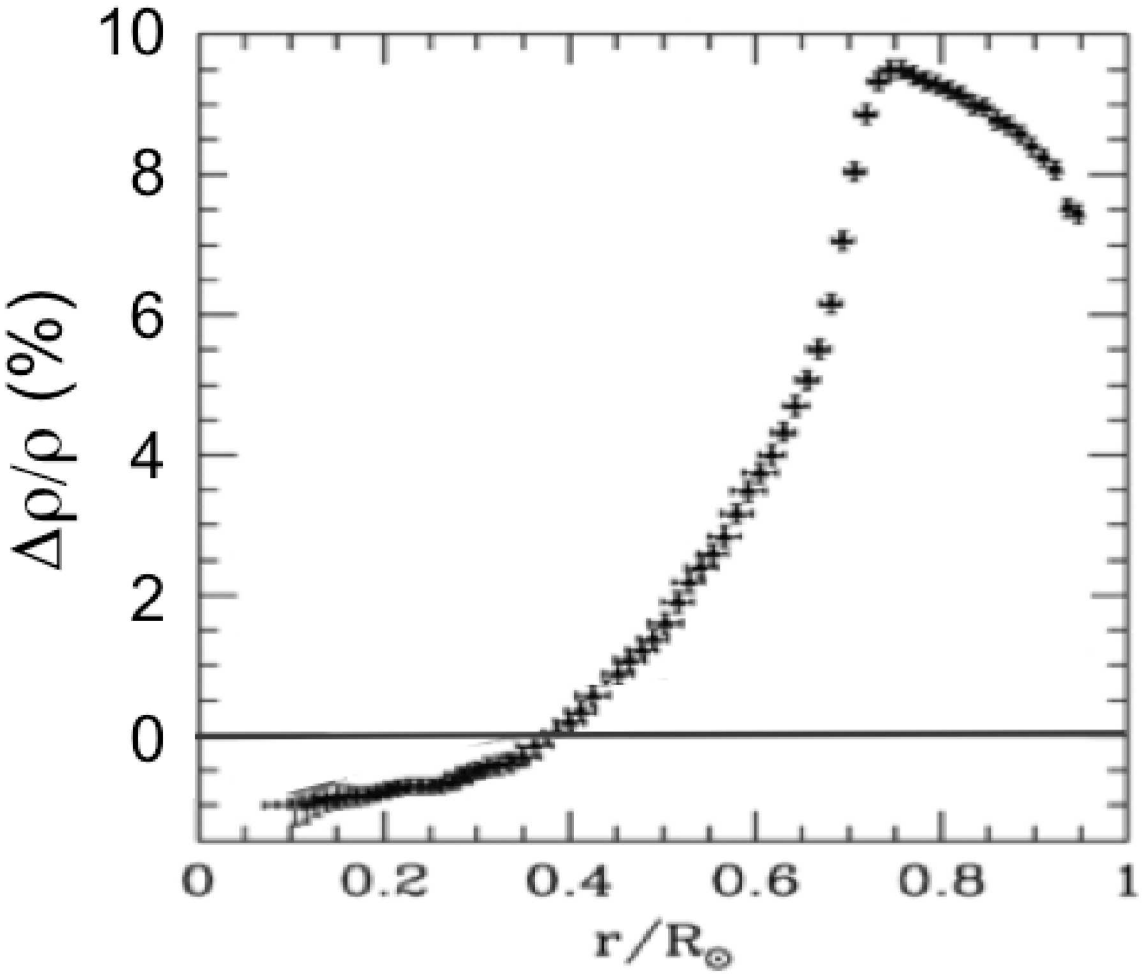
- Simulation: Standard solar model
  <u>Inputs:</u>
  - Abundance
  - EOS
  - Opacity
  - Etc.
- Measurements: Helioseismology



Analysis of 2D-resolved pulsation reveals the solar structure

Modeled solar structure disagrees with observations





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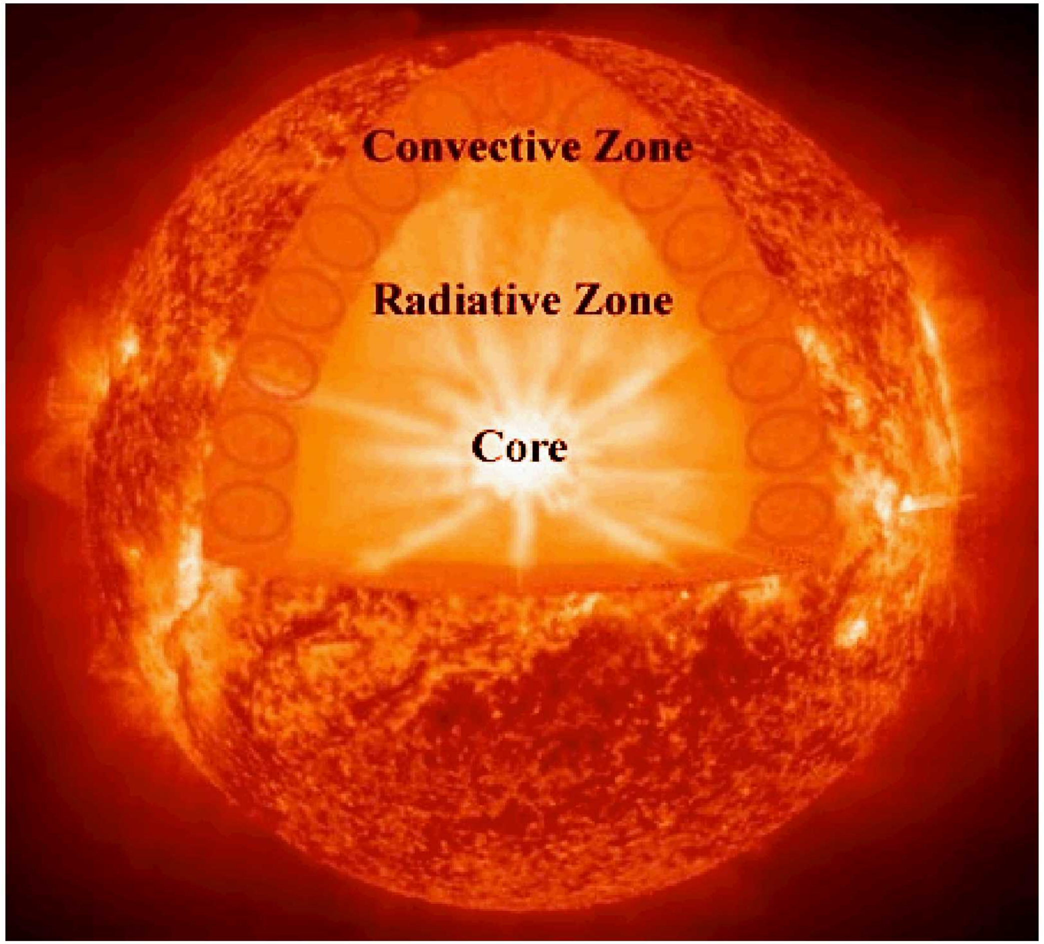
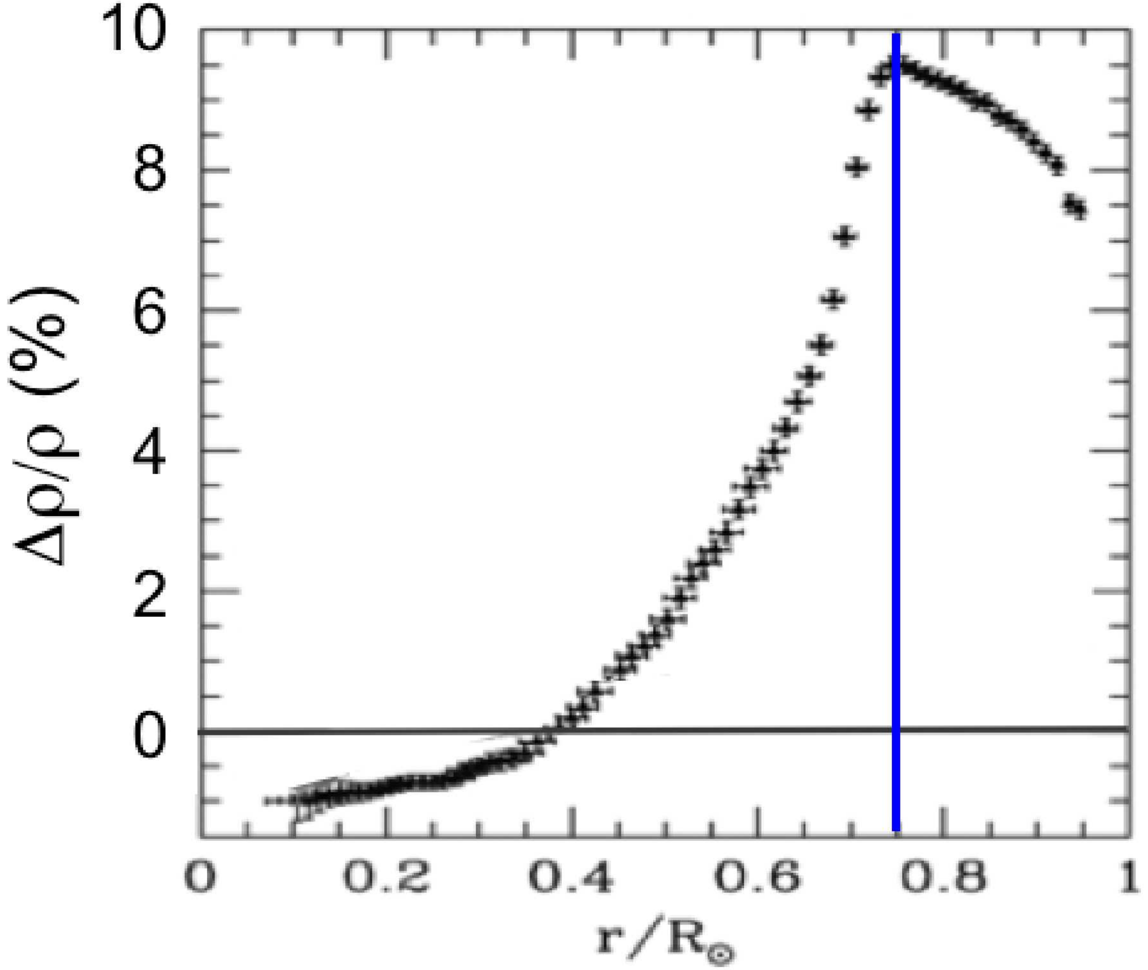
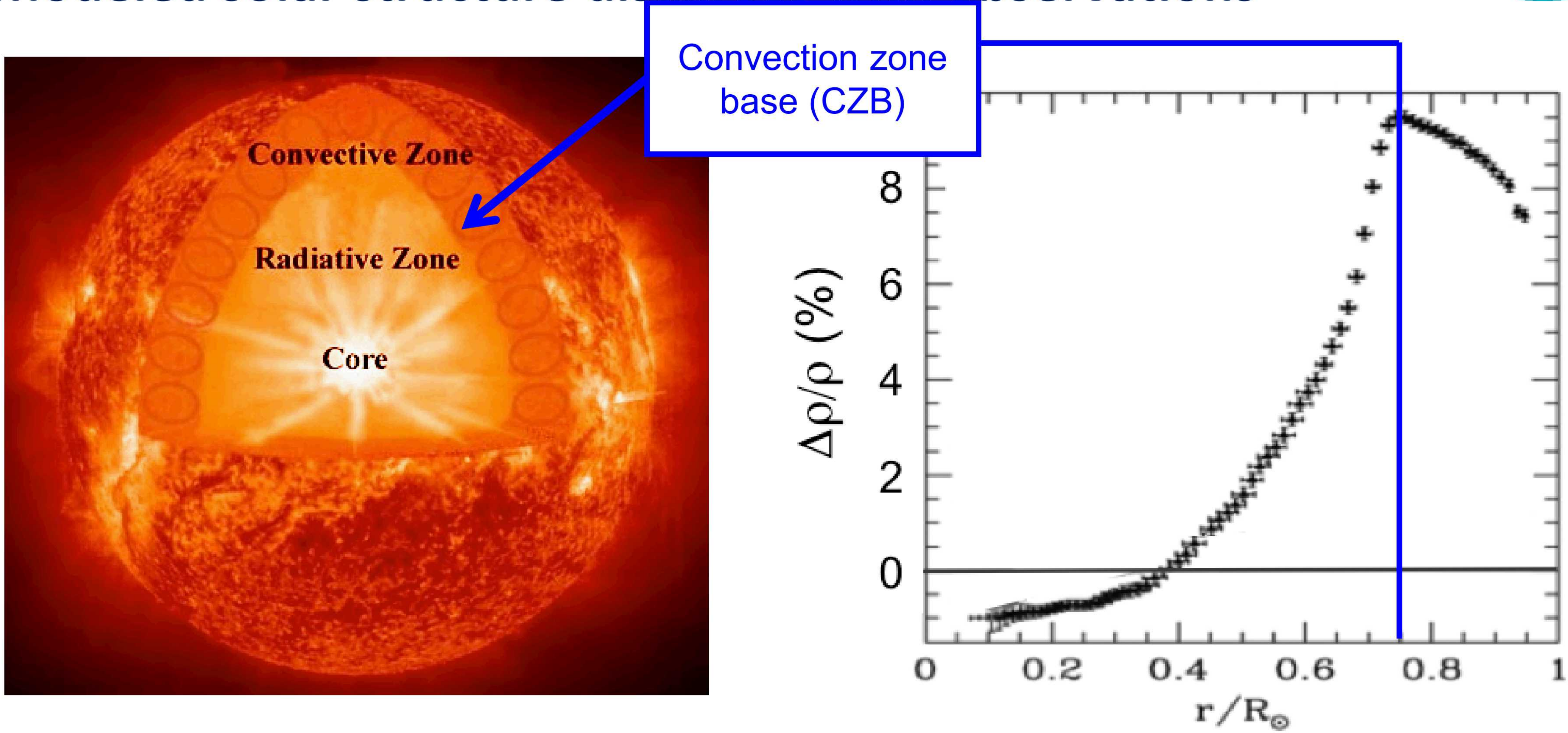
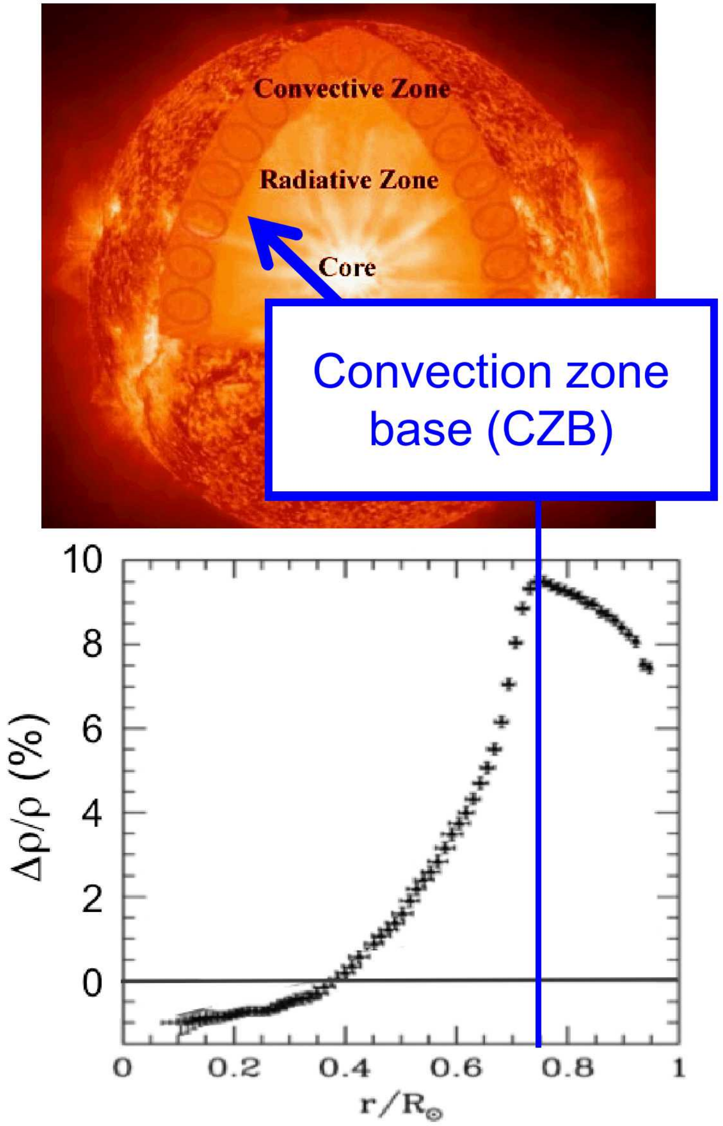




Modeled solar structure disagrees with observations



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



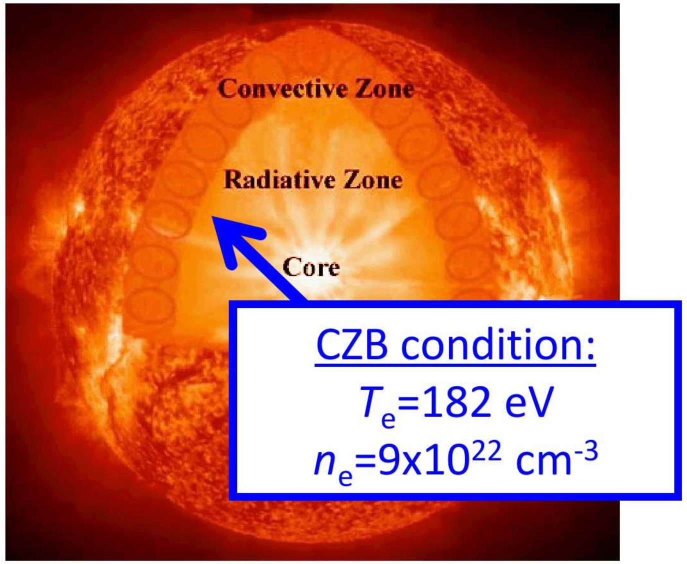
Opacity: κ_ν

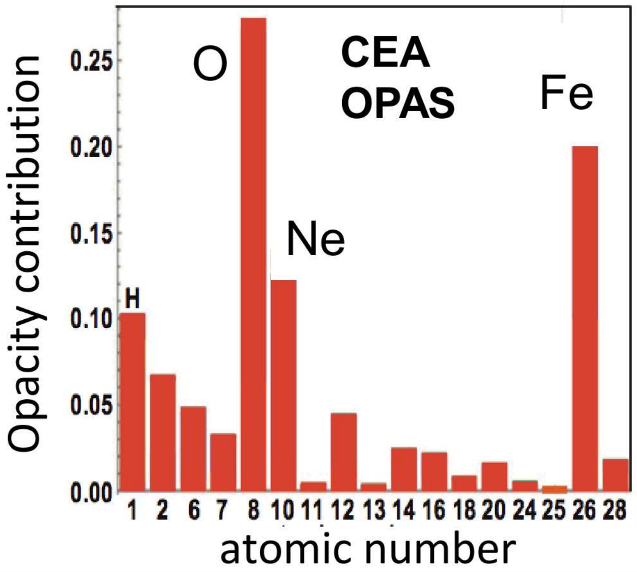
- Quantifies radiation absorption
- $\kappa_\nu(T_e, n_e)$ … input for solar models
- Opacity models have never been tested

[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





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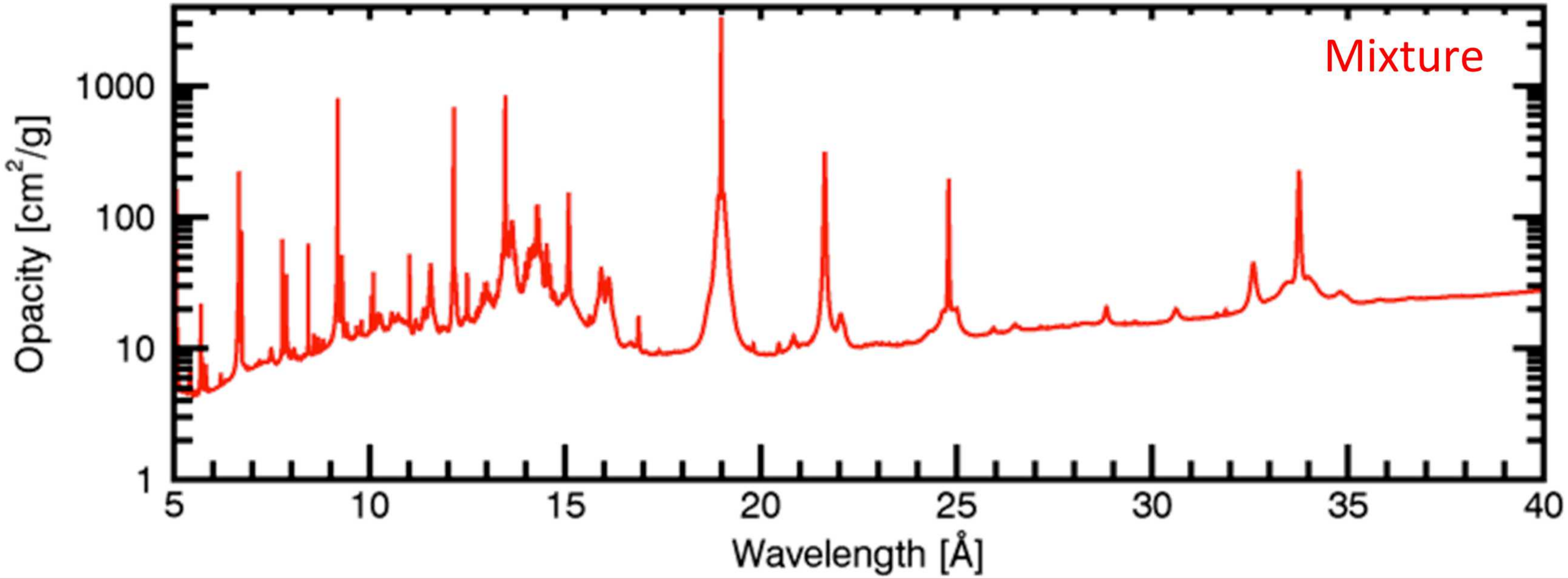
Solar mixture opacity at Convection Zone Base (CZB)



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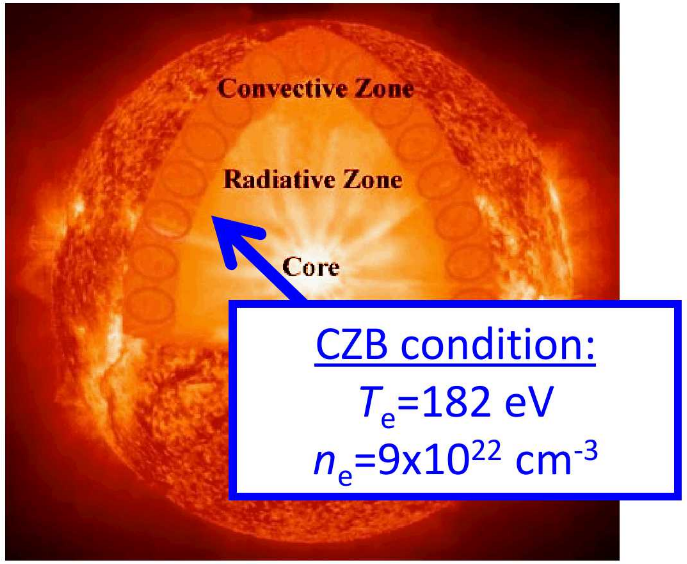

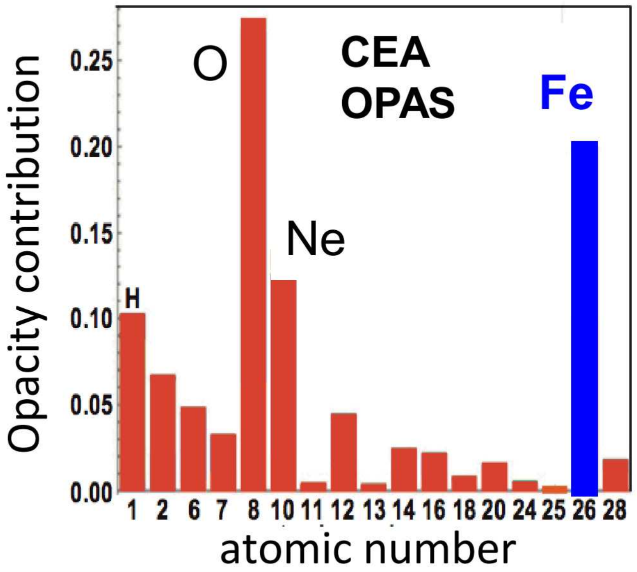

Opacity: κ_ν

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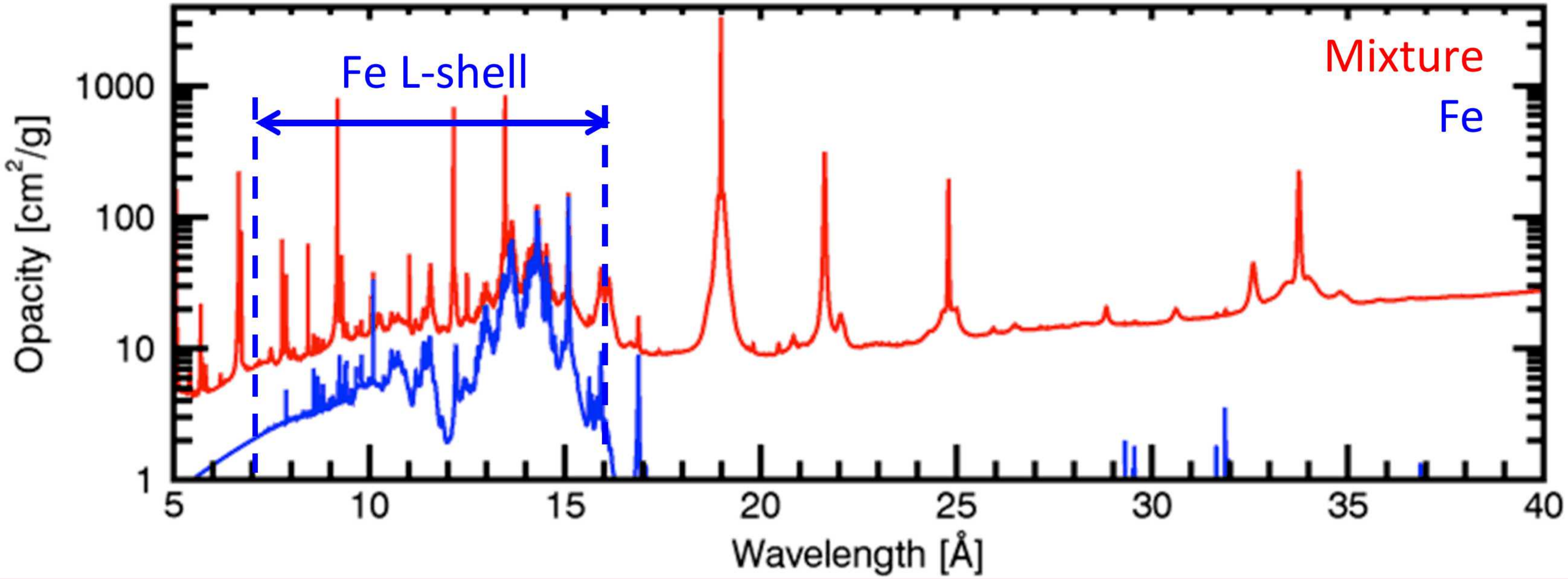
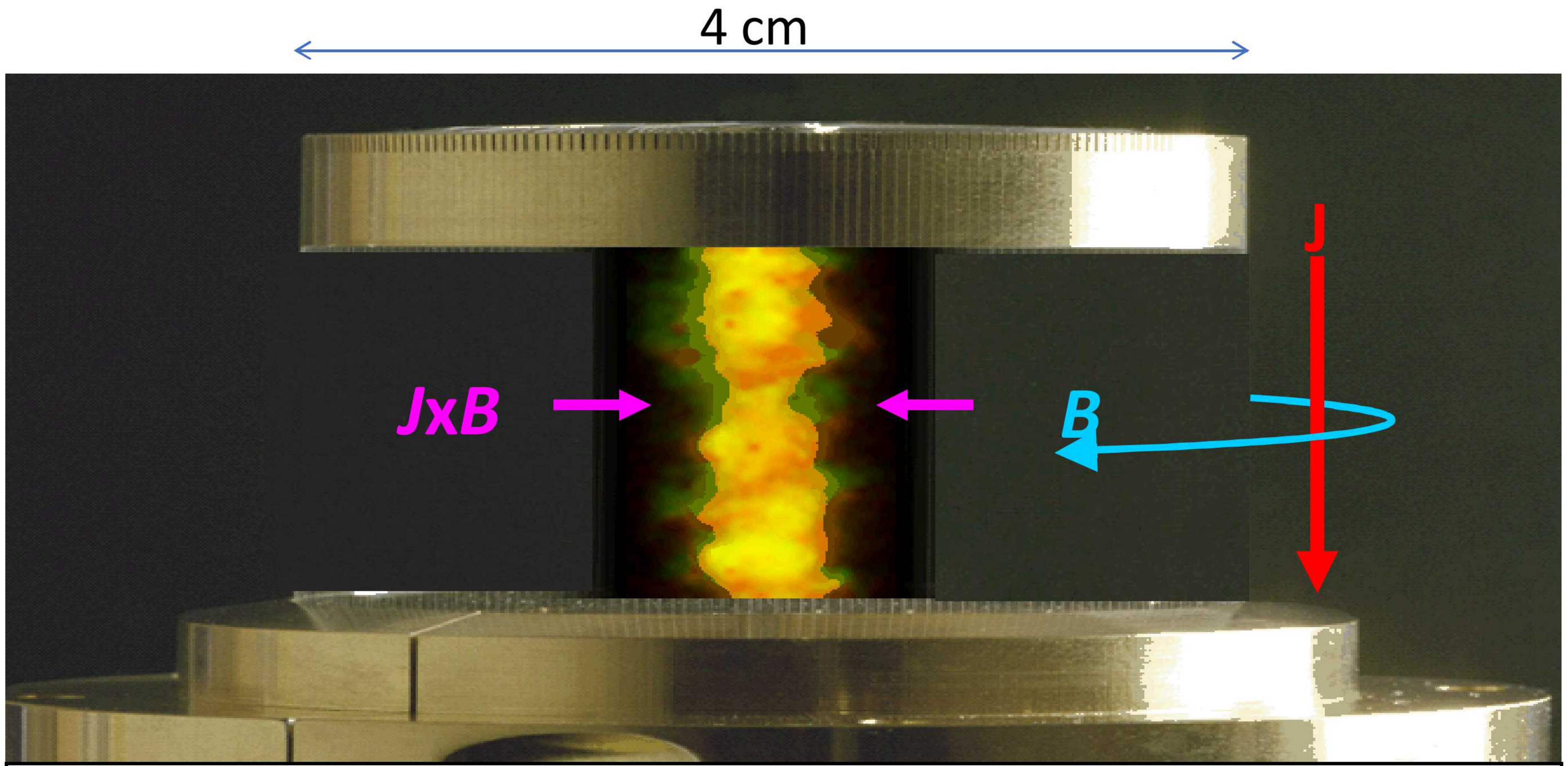
Fe is a likely suspect:

- 2nd largest contribution
- Most difficult to model

Solar mixture opacity at Convection Zone Base (CZB)



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

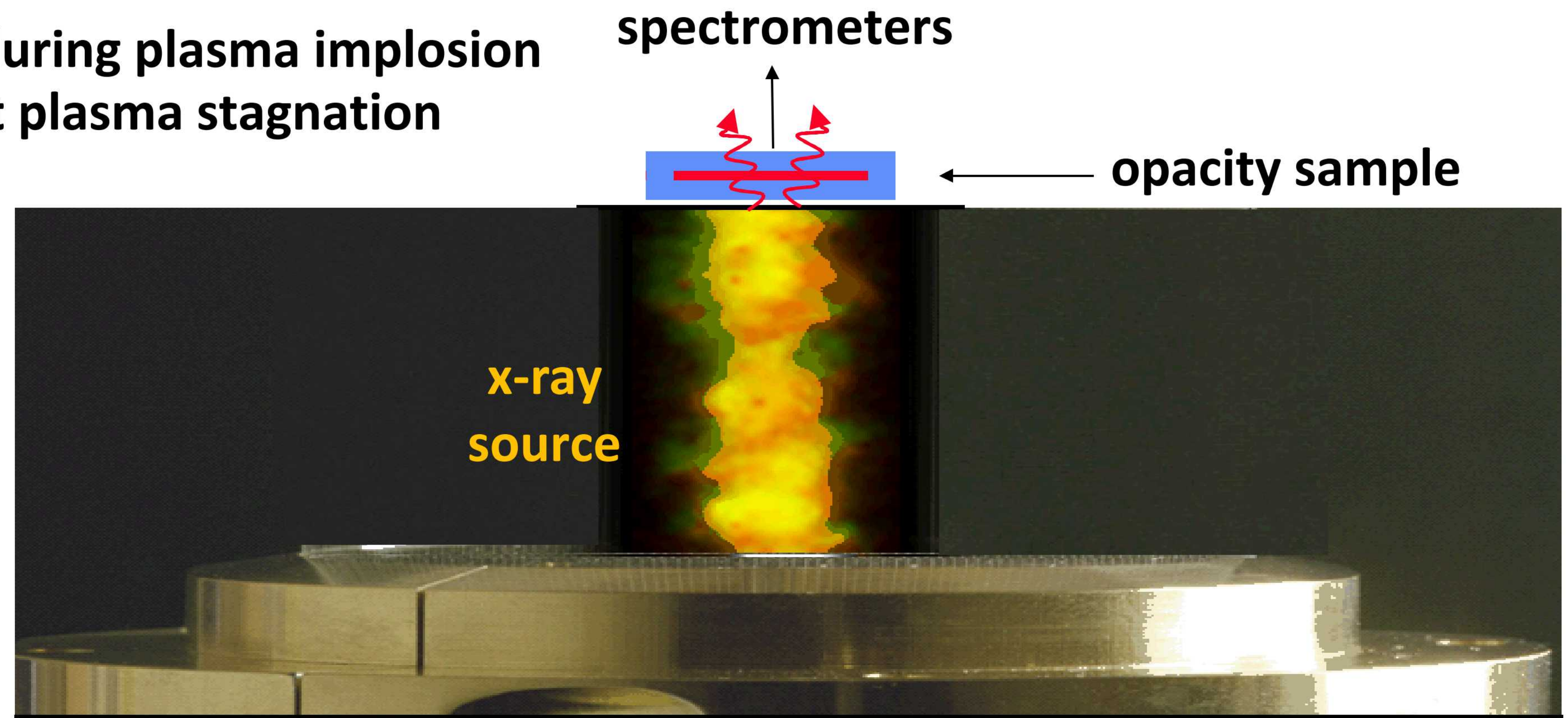


P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

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

Sample is:

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



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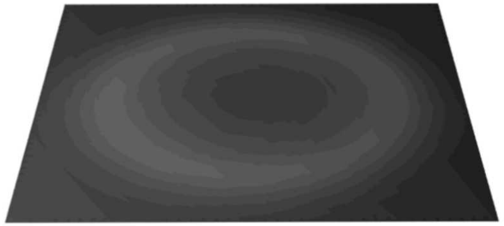
Sanford, *PoP* (2002); Bailey et al., *PoP* (2006); Slutz et al., *PoP* (2006); Rochau et al., *PPCF* (2007)

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



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)

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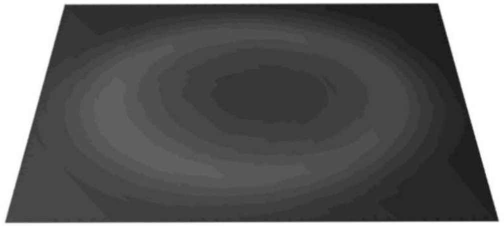

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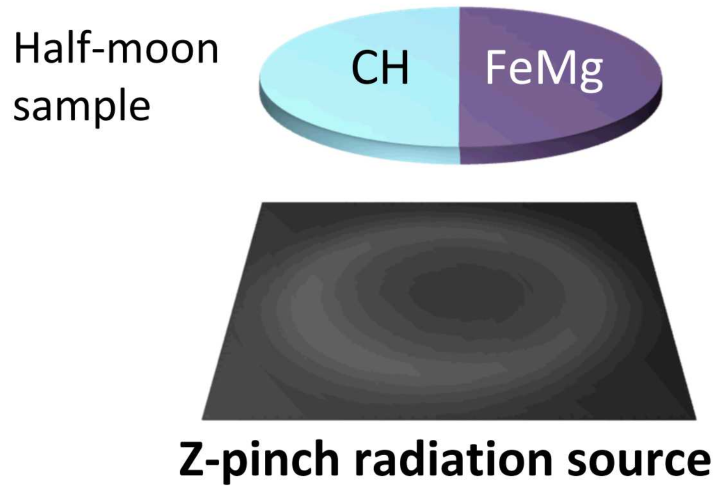

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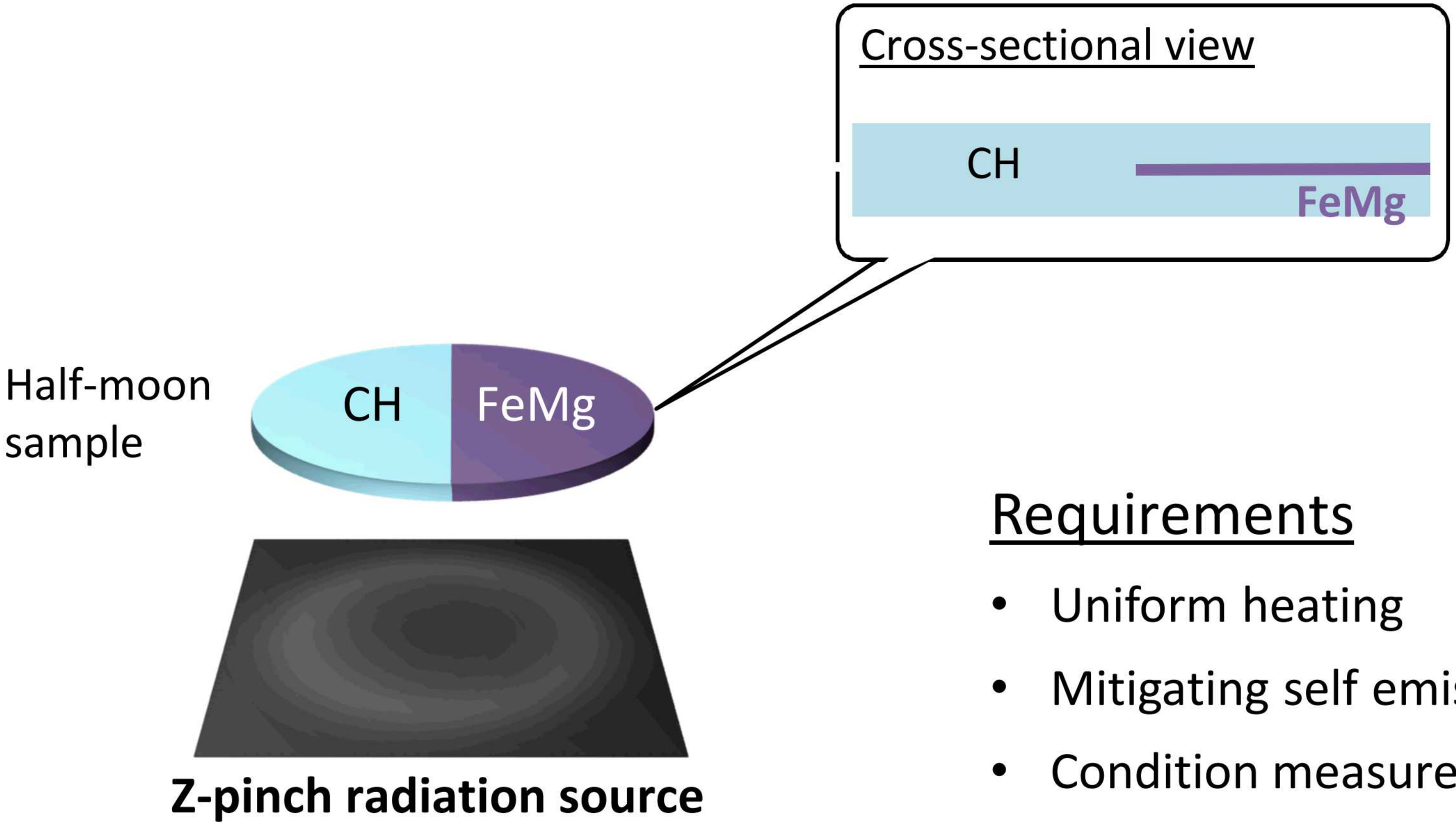

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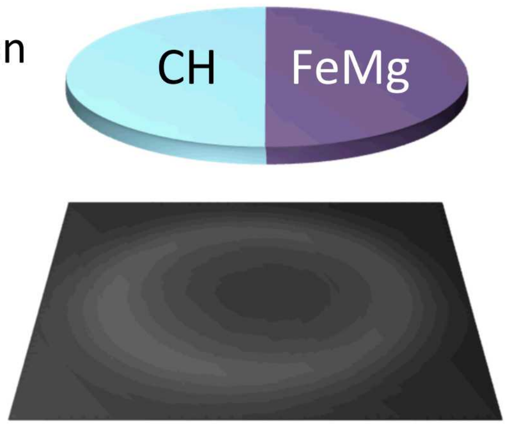
Half-moon sample



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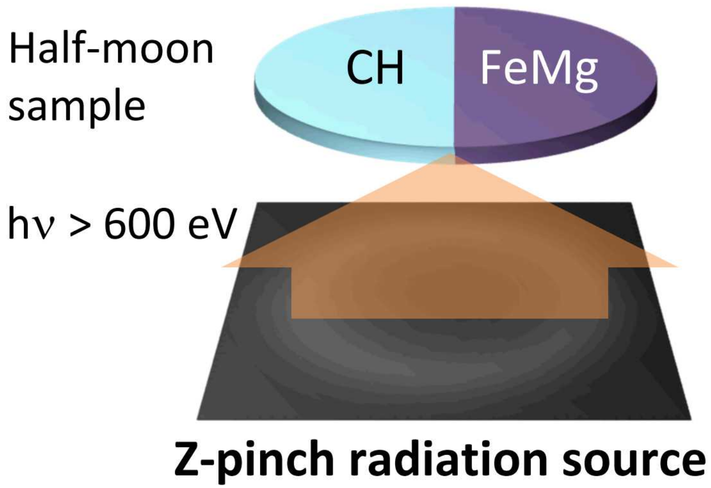

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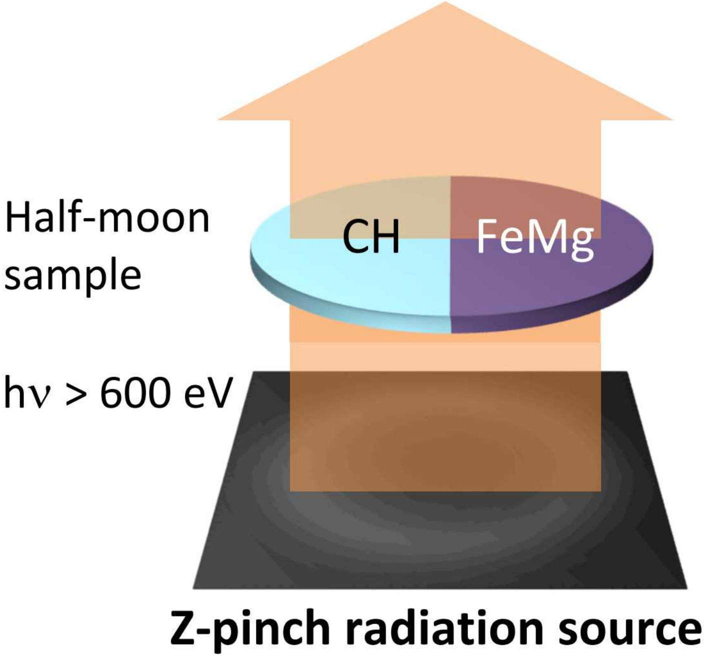

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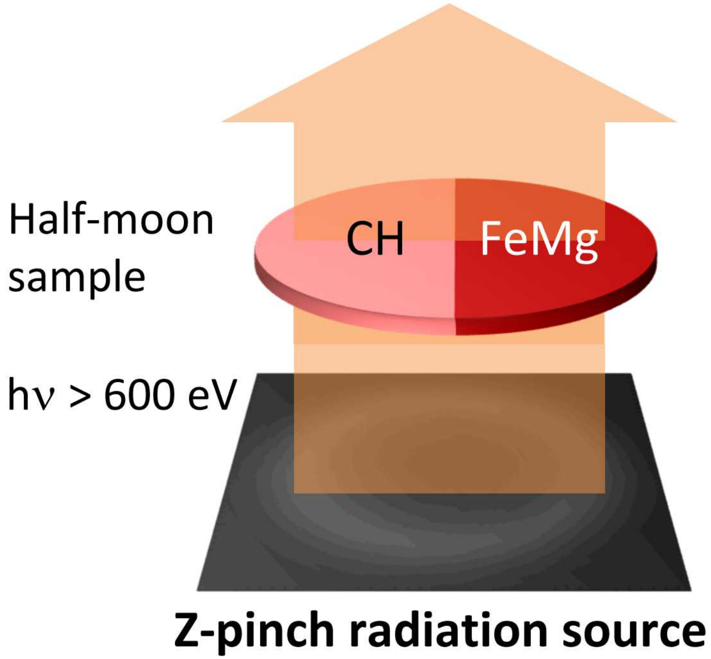

Requirements

- Uniform heating → Volumetric heating
- Mitigating self emission
- Condition measurements

SNL Z satisfies:

Volumetric heating

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

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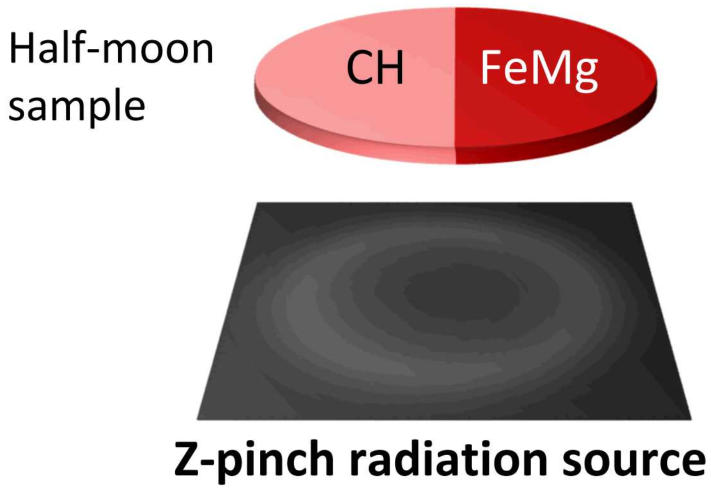

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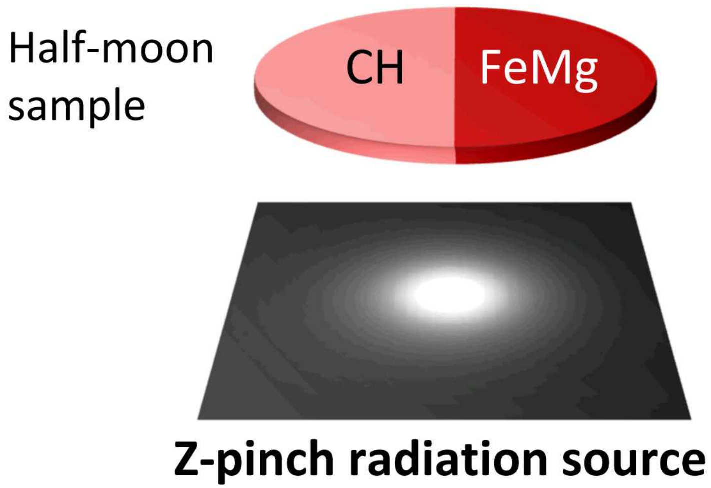

Requirements		SNL Z satisfies:
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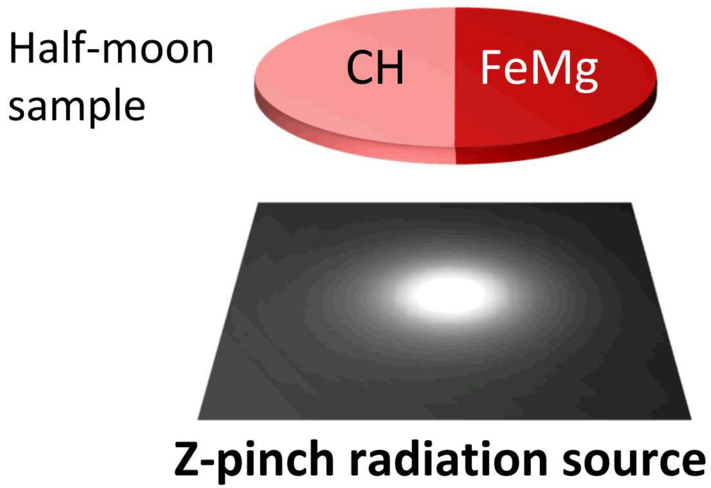

Requirements	SNL Z satisfies:
• Uniform heating →	Volumetric heating
• Mitigating self emission →	350 eV Planckian backlight
• Condition measurements	

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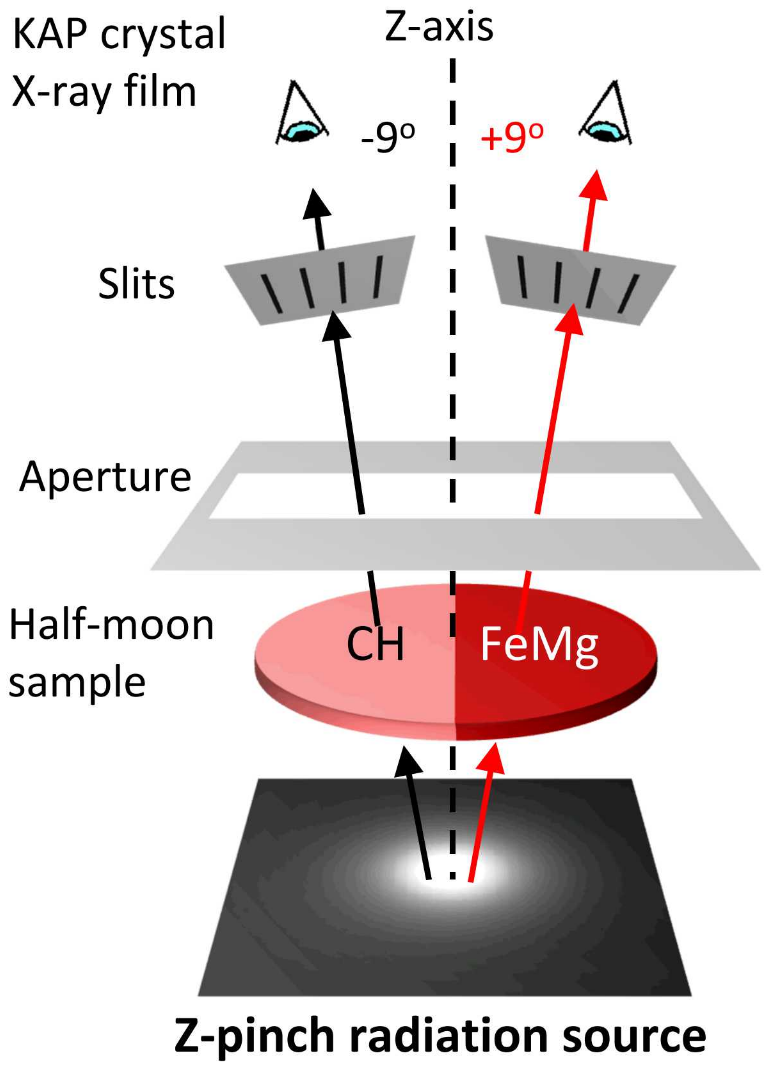

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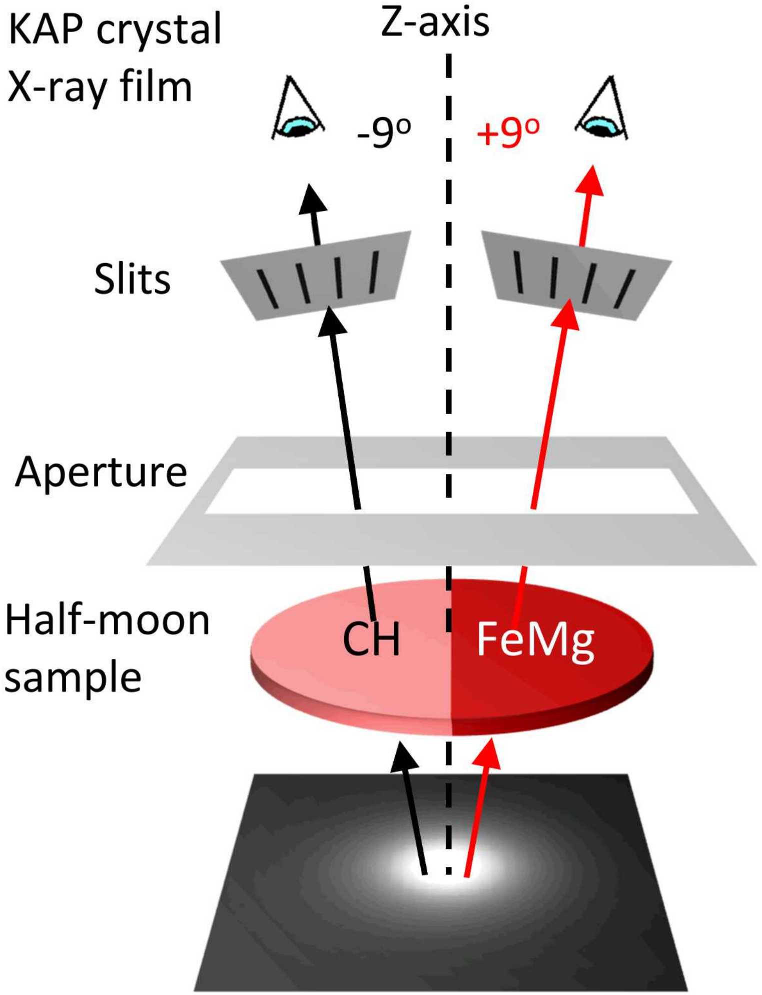
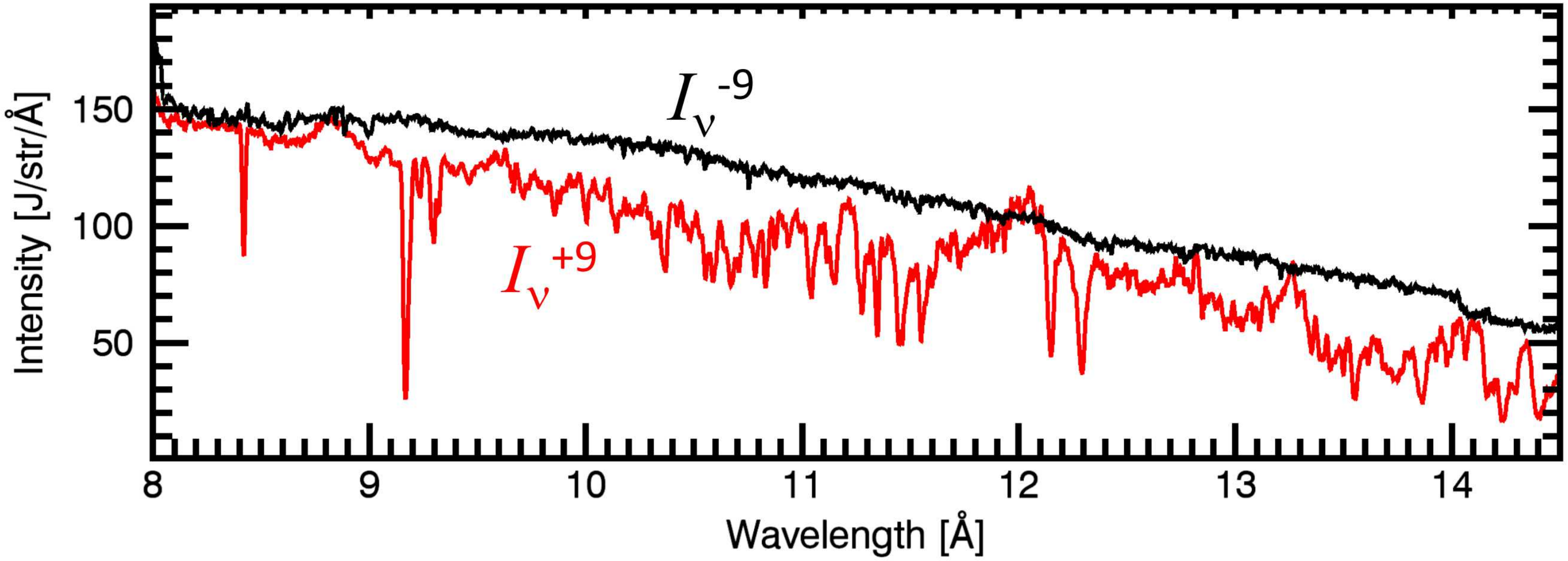


Z-pinch radiation source



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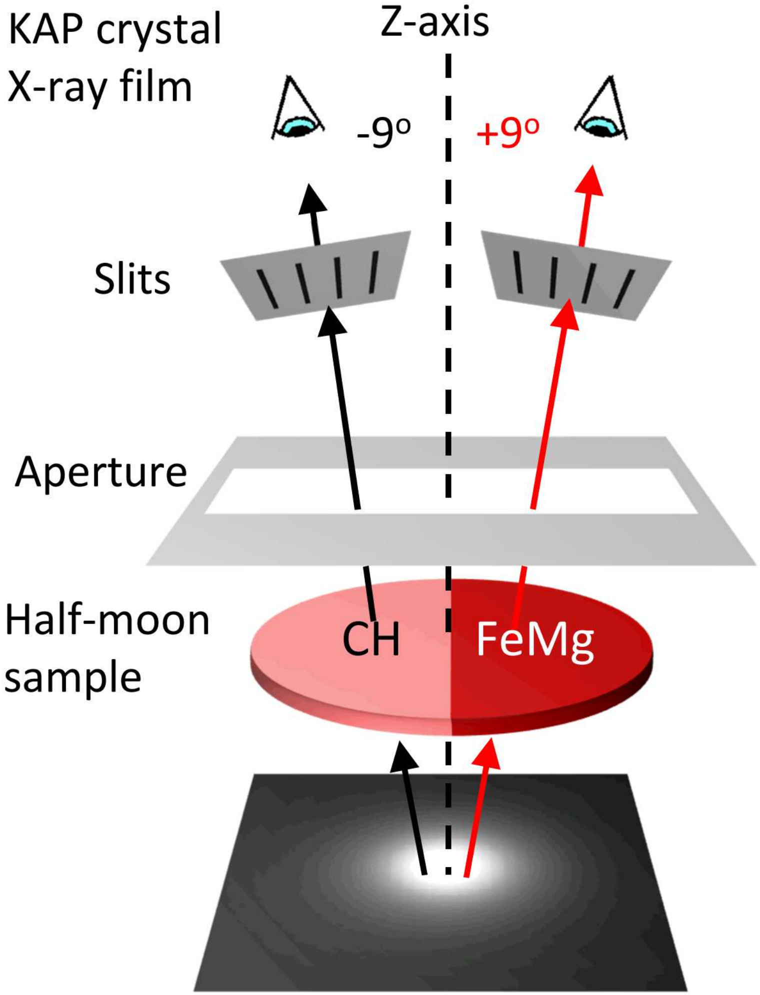

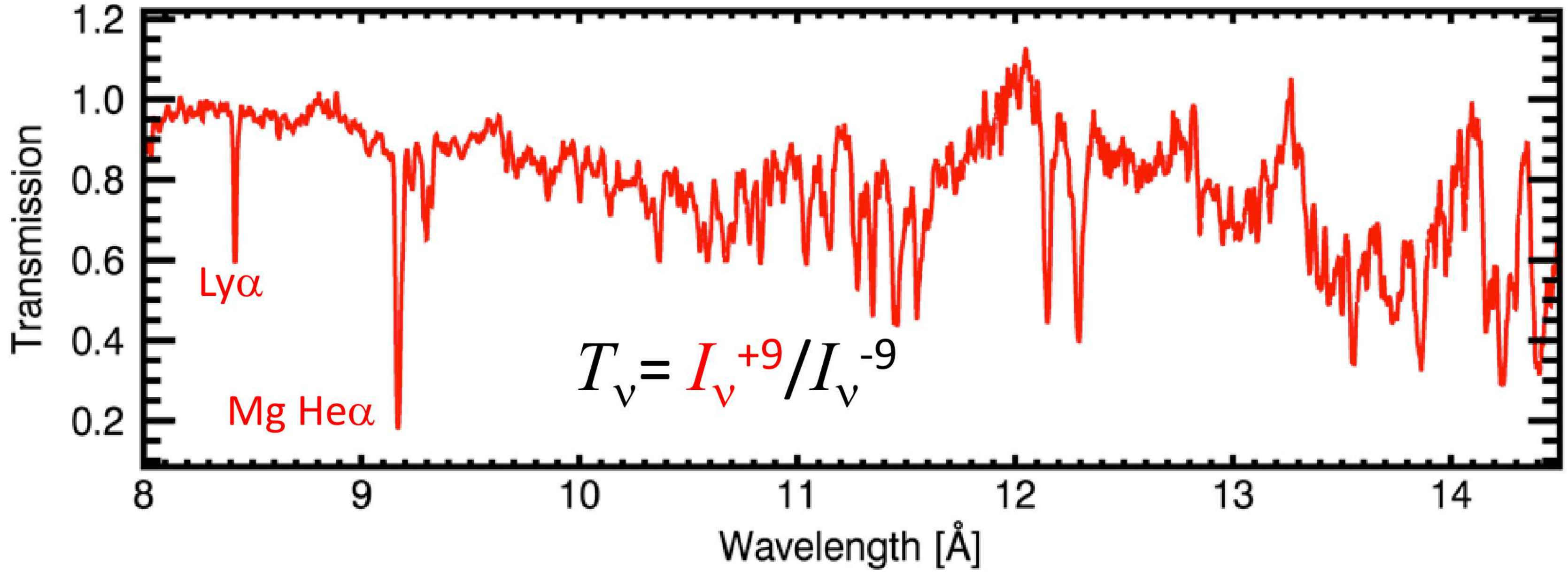

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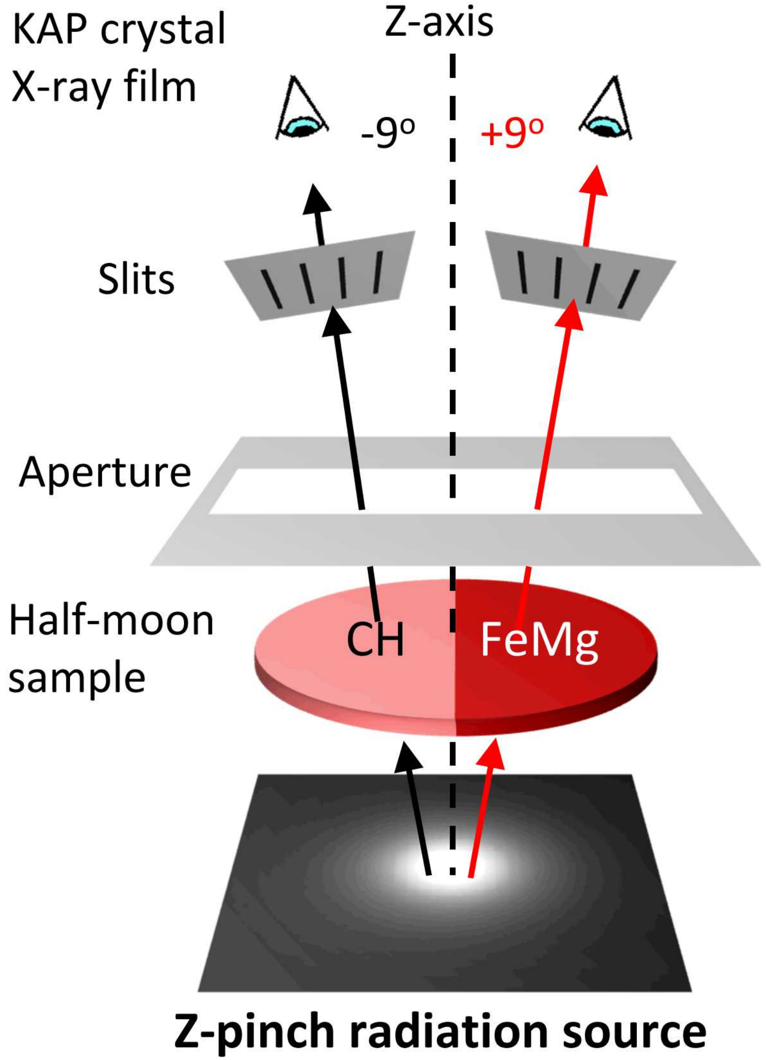

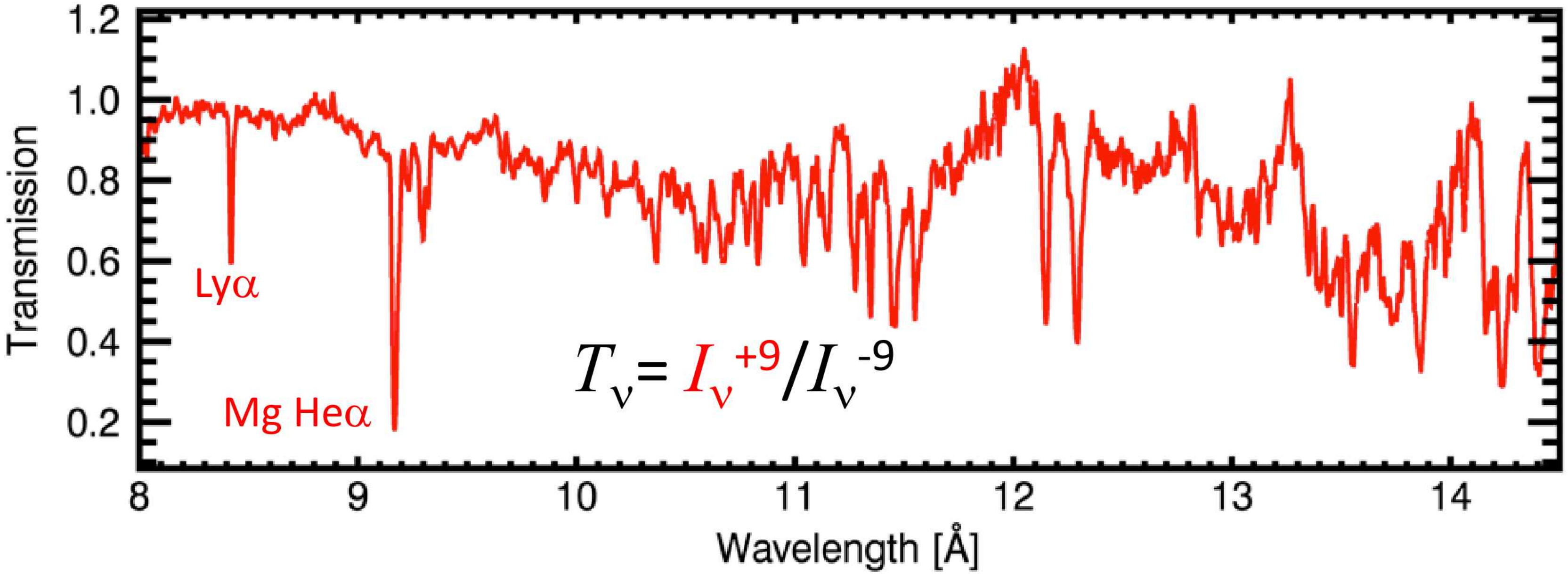

Requirements	SNL Z satisfies:
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• Condition measurements →	Mg K-shell spectroscopy

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

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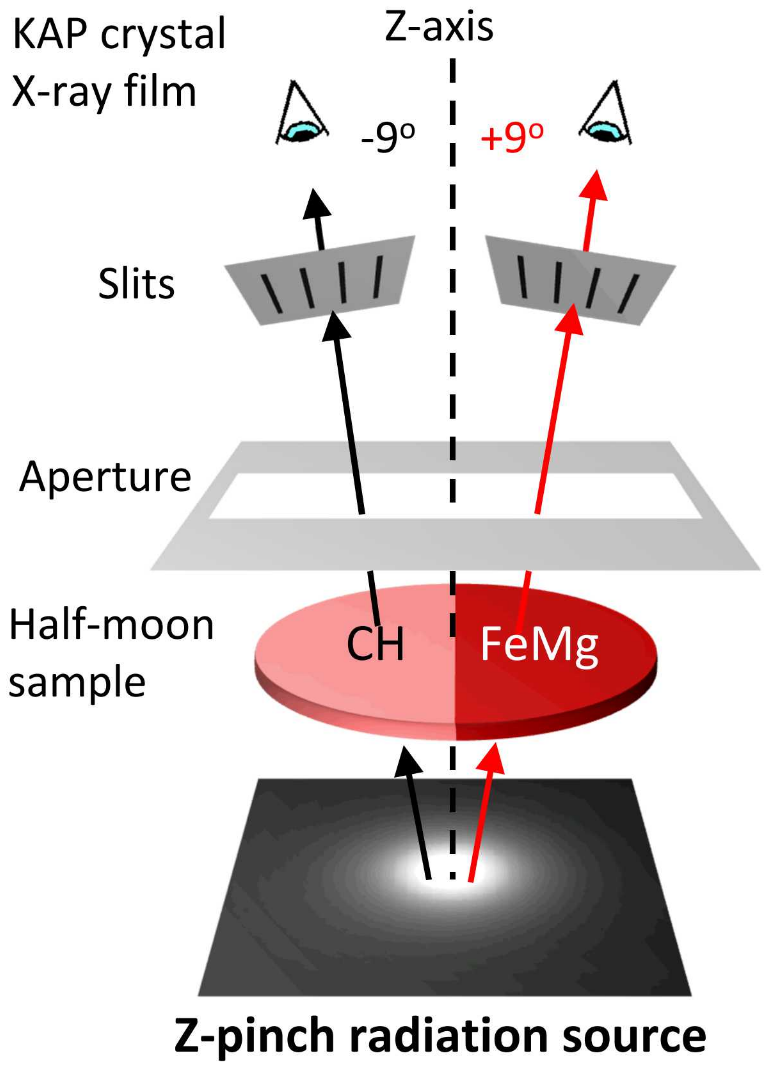

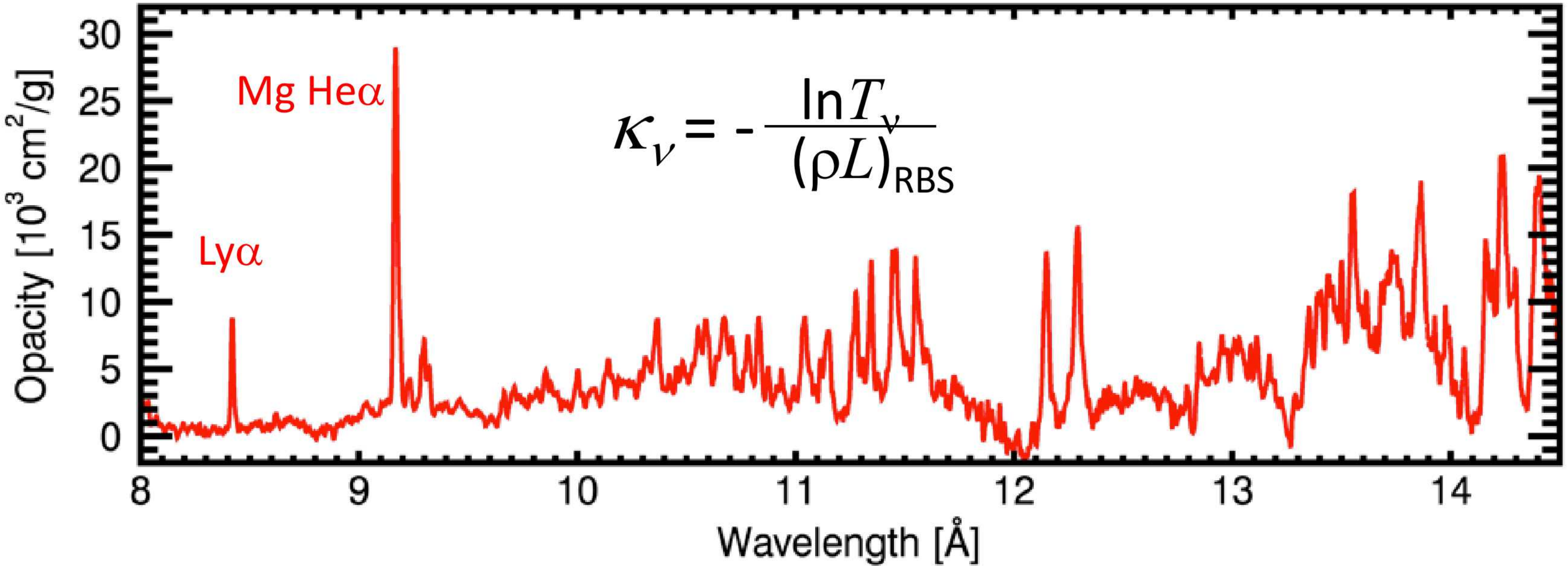

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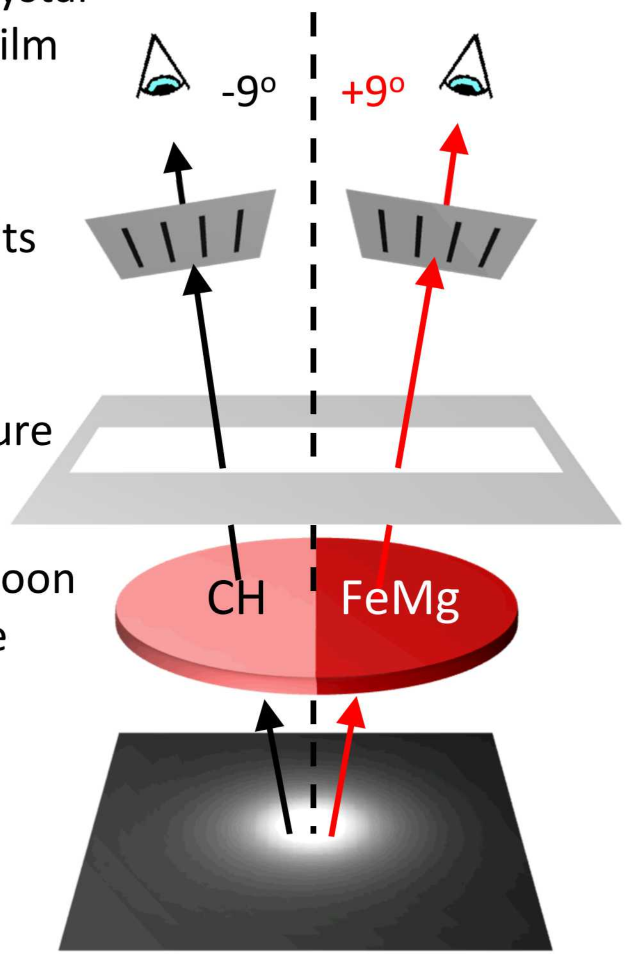

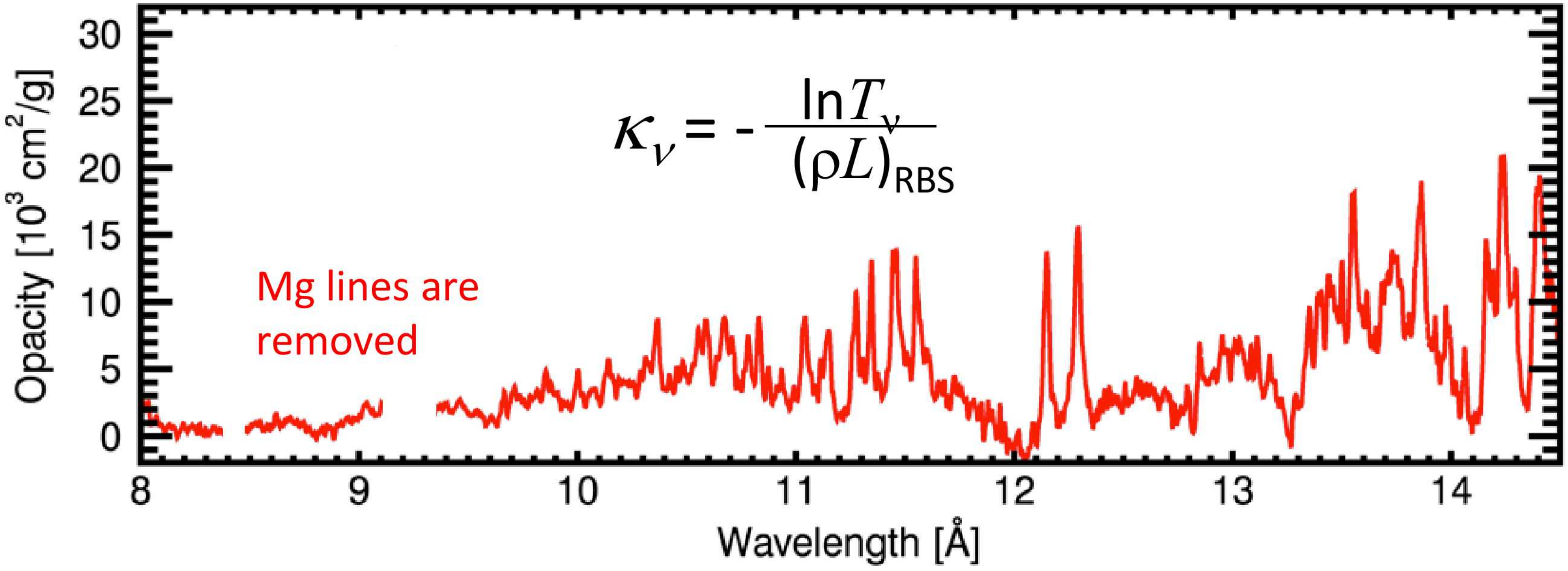

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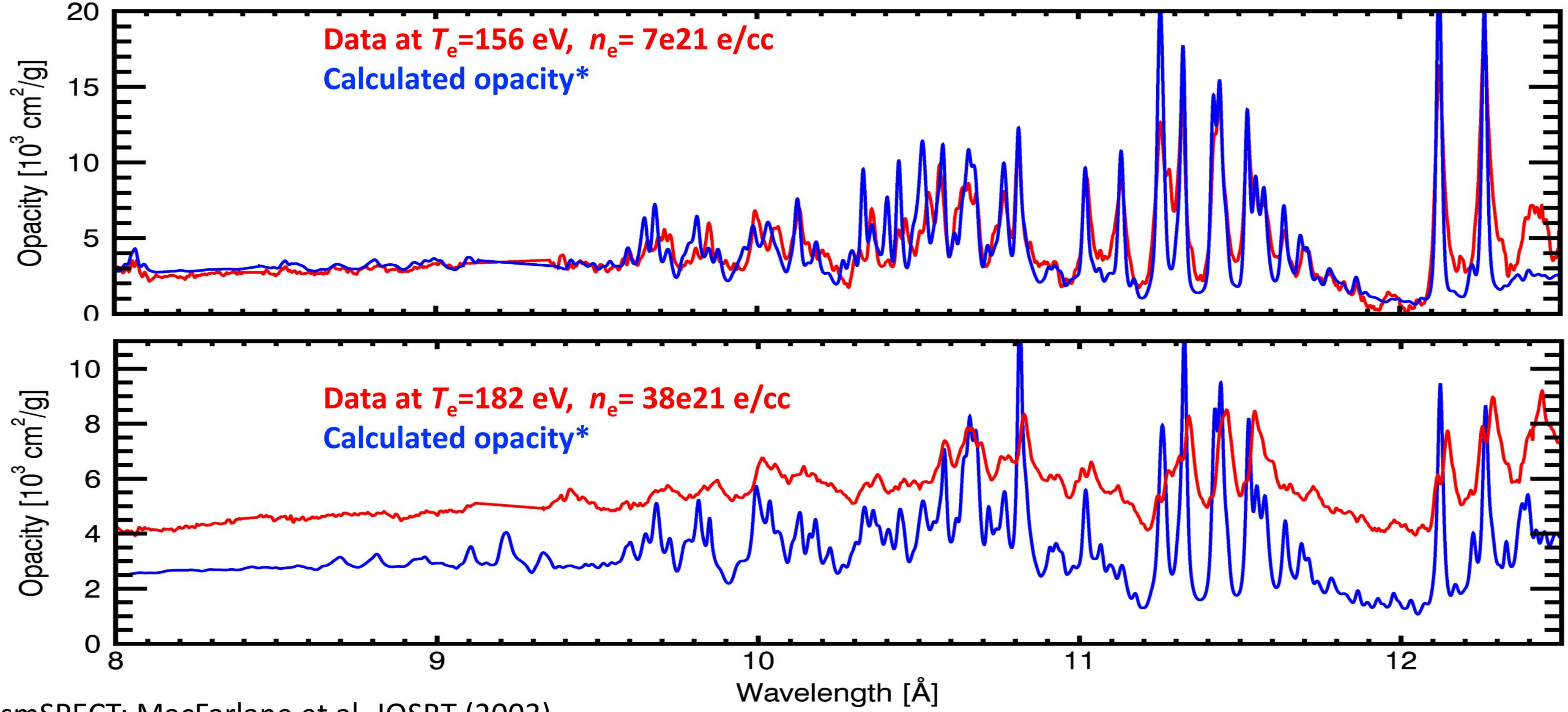
[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

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

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



* PrismSPECT: MacFarlane et al, JQSRT (2003)

[1] Bailey et al., *Nature* 517, 56 (2015)
[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

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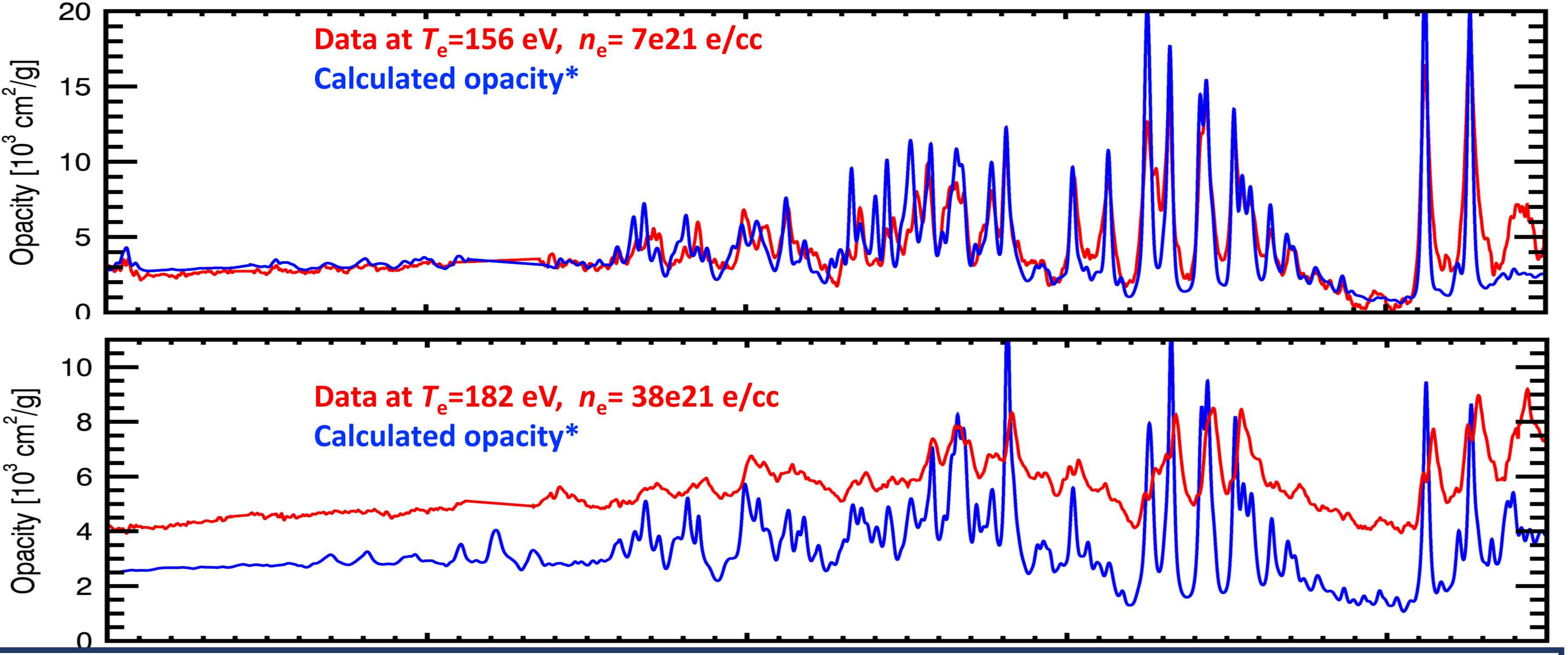
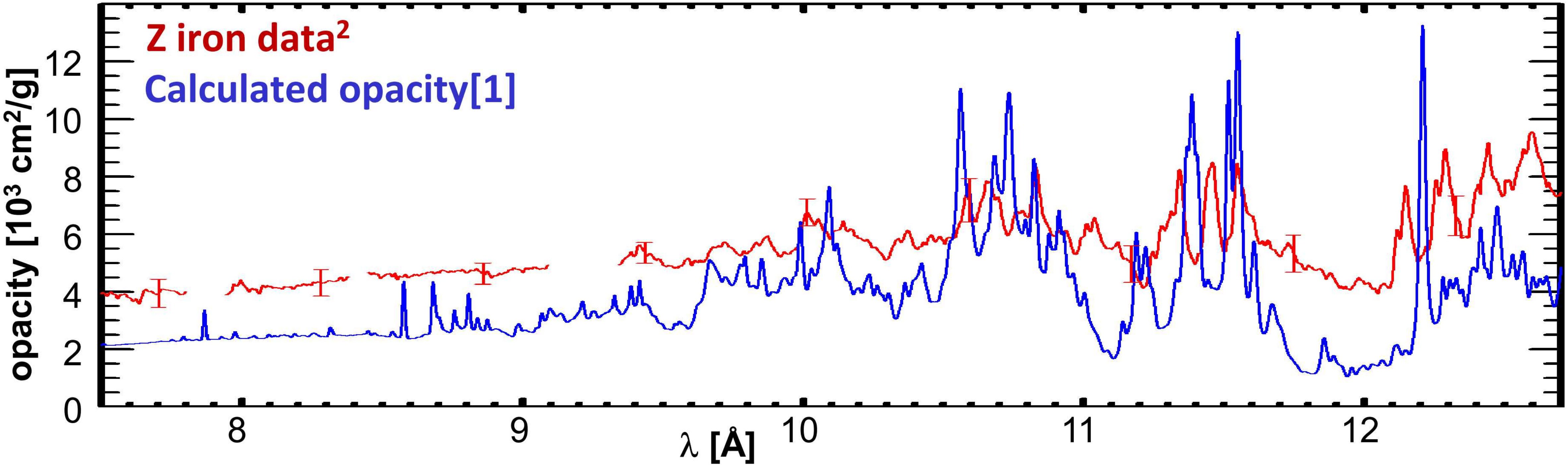


If measured Fe opacity is correct, it would increase the solar mean opacity by ~7%.

* F

[1] Bailey et al., *Nature* 517, 56 (2015)
[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

Reported opacity discrepancy is complex and deserves further scrutiny



[1] Seaton et al., *MNRAS* (1994)

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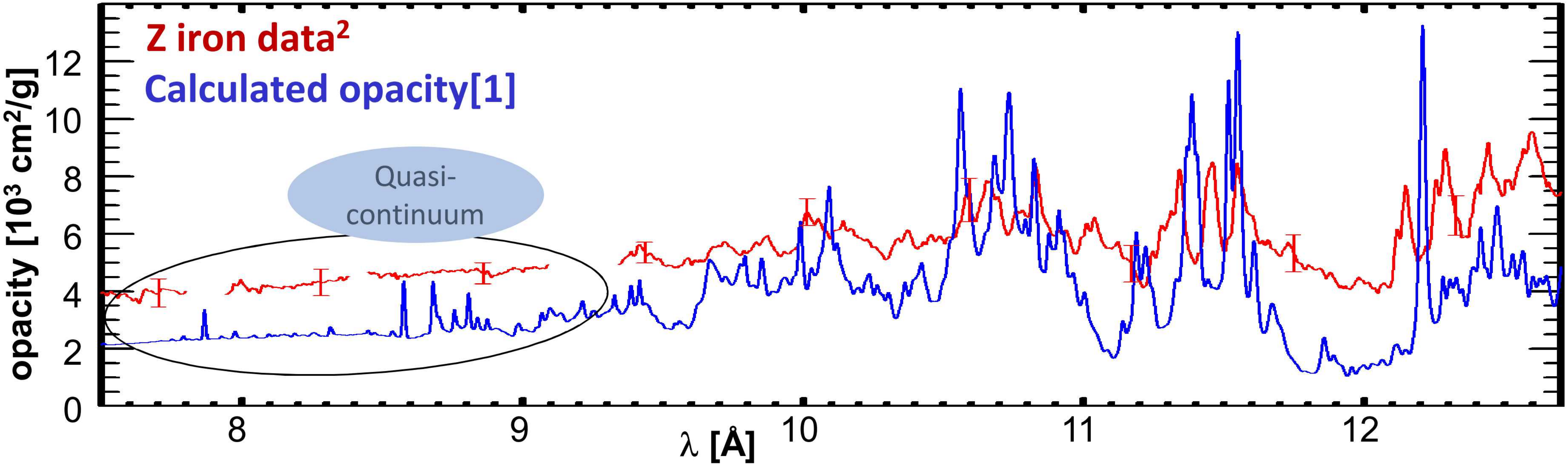

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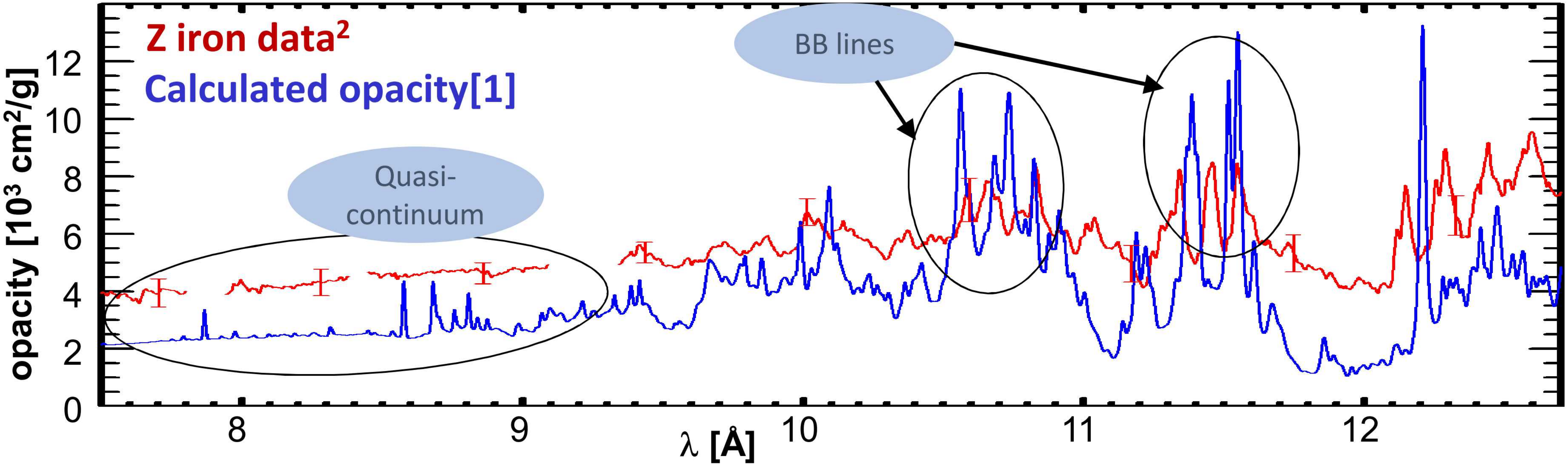

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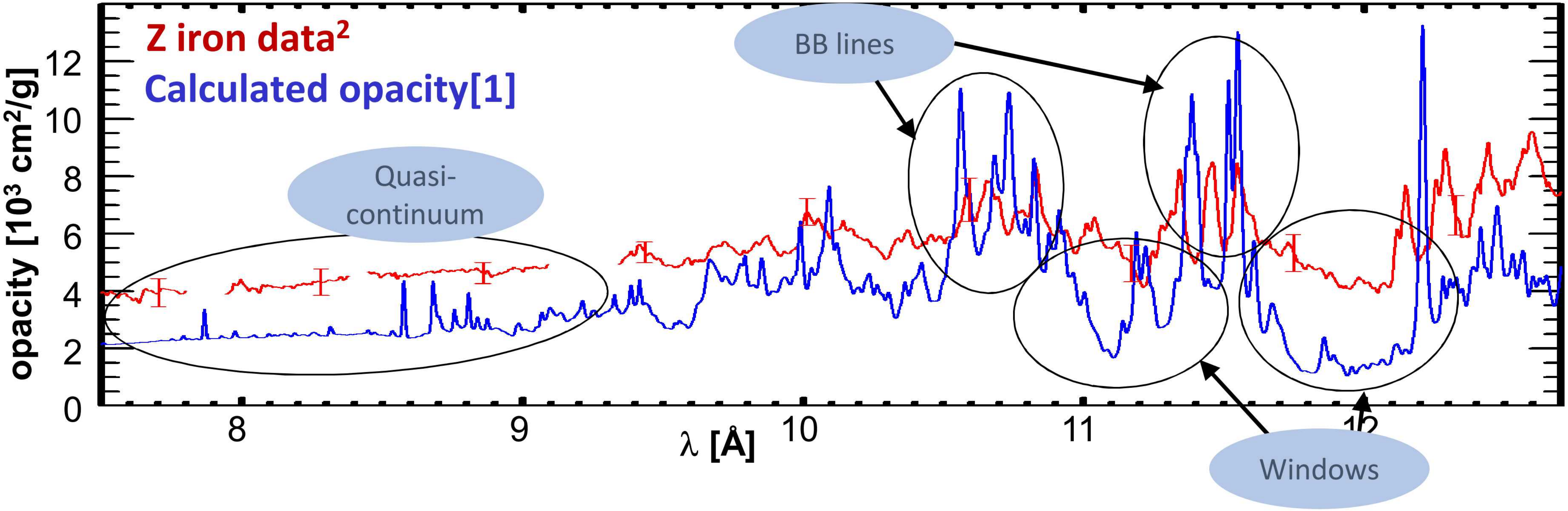


Is opacity theory inaccurate?

Is opacity experiment flawed?

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

Random error:

→ Average over many spectra from multiple experiments

Systematic error evaluation:

→ Evaluated with experiments and simulations

- Plasma T_e and n_e 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

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

Random error:

→ Average over many spectra from multiple experiments

Systematic error evaluation:

→ Evaluated with experiments and simulations

Experimental evidence

- Plasma T_e and n_e errors → $\pm 4\%$ and $\pm 25\%$, respectively [1]
- Sample areal density errors → RBS measurements agree with Mg spectroscopy
- Transmission errors → Transmission analysis on null shot shows $\pm 5\%$
- Spatial non-uniformities → Al and Mg spectroscopy
- Temporal non-uniformities → Backlight radiation lasts 3ns
- Departures from LTE

- Fe self emission → Measurement do not show Fe self-emission
- Tamper self emission
- Extraneous background → (Tamper self emission and Extraneous background) Quantified amount do not explain the discrepancy

- Sample contamination → RBS measurements show no contamination
- Tamper transmission difference

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

Random error:

→ Average over many spectra from multiple experiments

Systematic error evaluation:

→ Evaluated with experiments and simulations

Numerical evidence

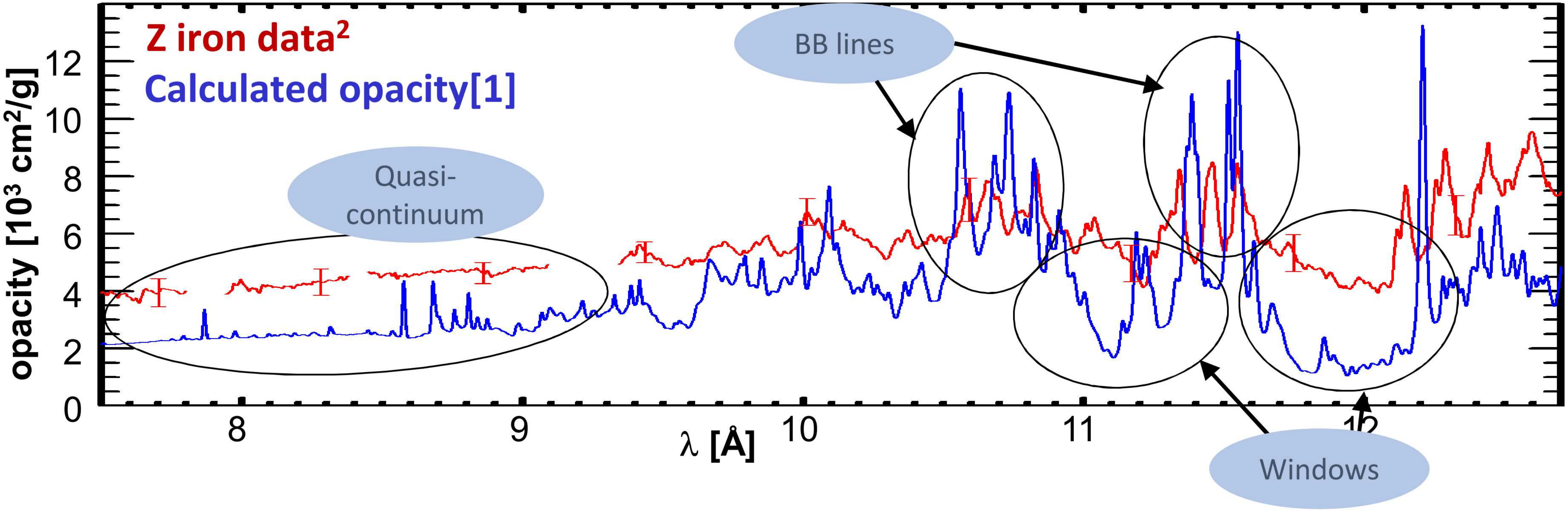
- Plasma T_e and n_e errors → Suggested n_e error did not explain the discrepancy
- Sample areal density errors
- Transmission errors
- Spatial non-uniformities
- Temporal non-uniformities
- Departures from LTE
- Fe self emission
- Tamper self emission
- Extraneous background
- Sample contamination
- Tamper transmission difference

Spatial non-uniformities, temporal non-uniformities, departures from LTE, Fe self emission, tamper self emission, tamper transmission difference → Simulation found they were negligible

Nagayama et al, *High Energ Dens Phys* (2016)
Iglesias et al, *High Energ Dens Phys* (2016)

Nagayama et al, *Phys Rev E* **93**, 023202 (2016)
Nagayama et al, *Phys Rev E* **95**, 063206 (2017)

Reported opacity discrepancy is complex and deserves further scrutiny



Is opacity theory inaccurate?

Is opacity experiment flawed?

[1] Seaton et al., *MNRAS* (1994)

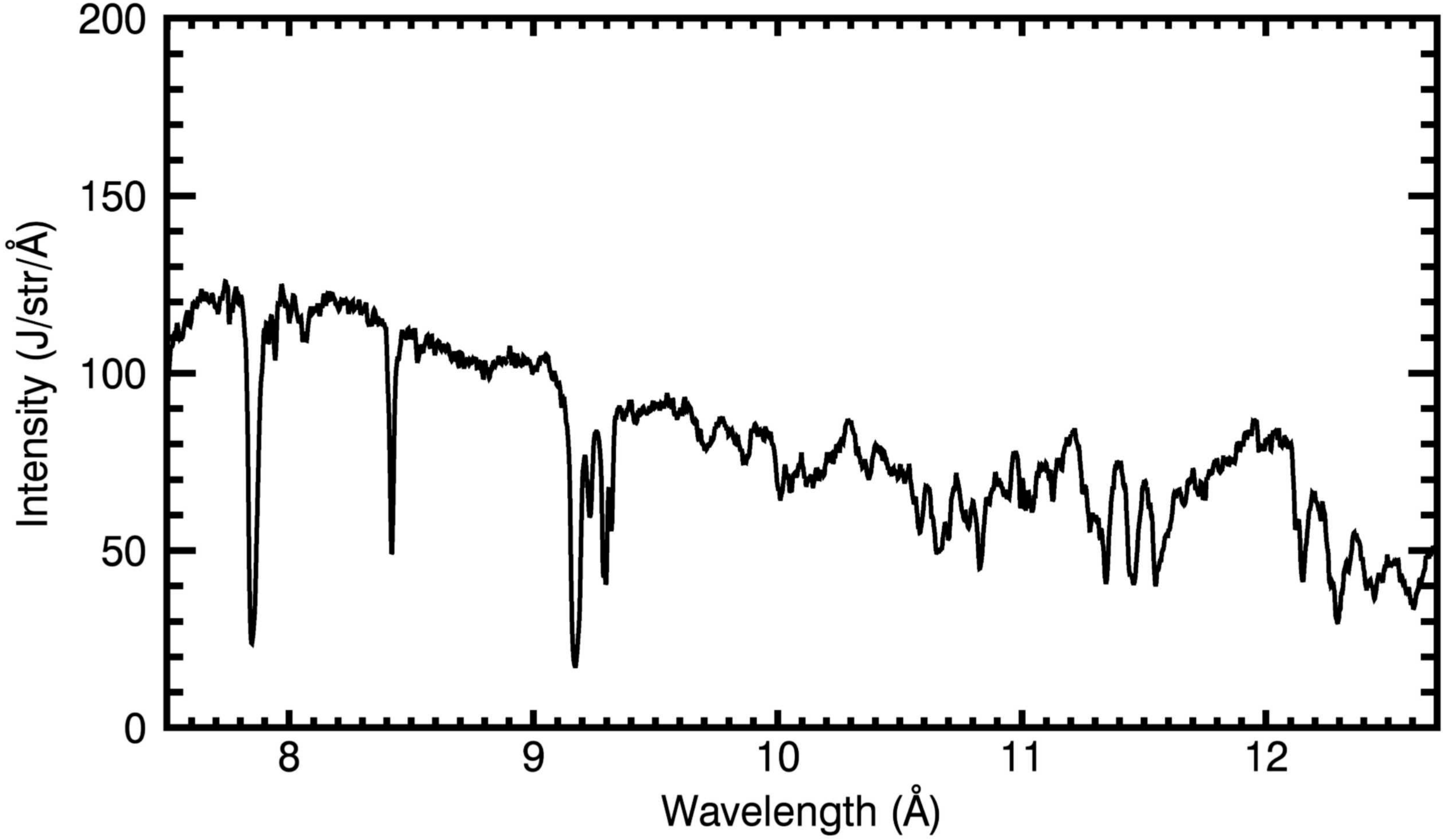
Discrepancy is further scrutinized by i) refining analysis method and ii) systematically measuring opacity of Cr, Fe, and Ni

Transmission error is dominated by error in *unattenuated* spectrum

$$\kappa \propto \ln T$$

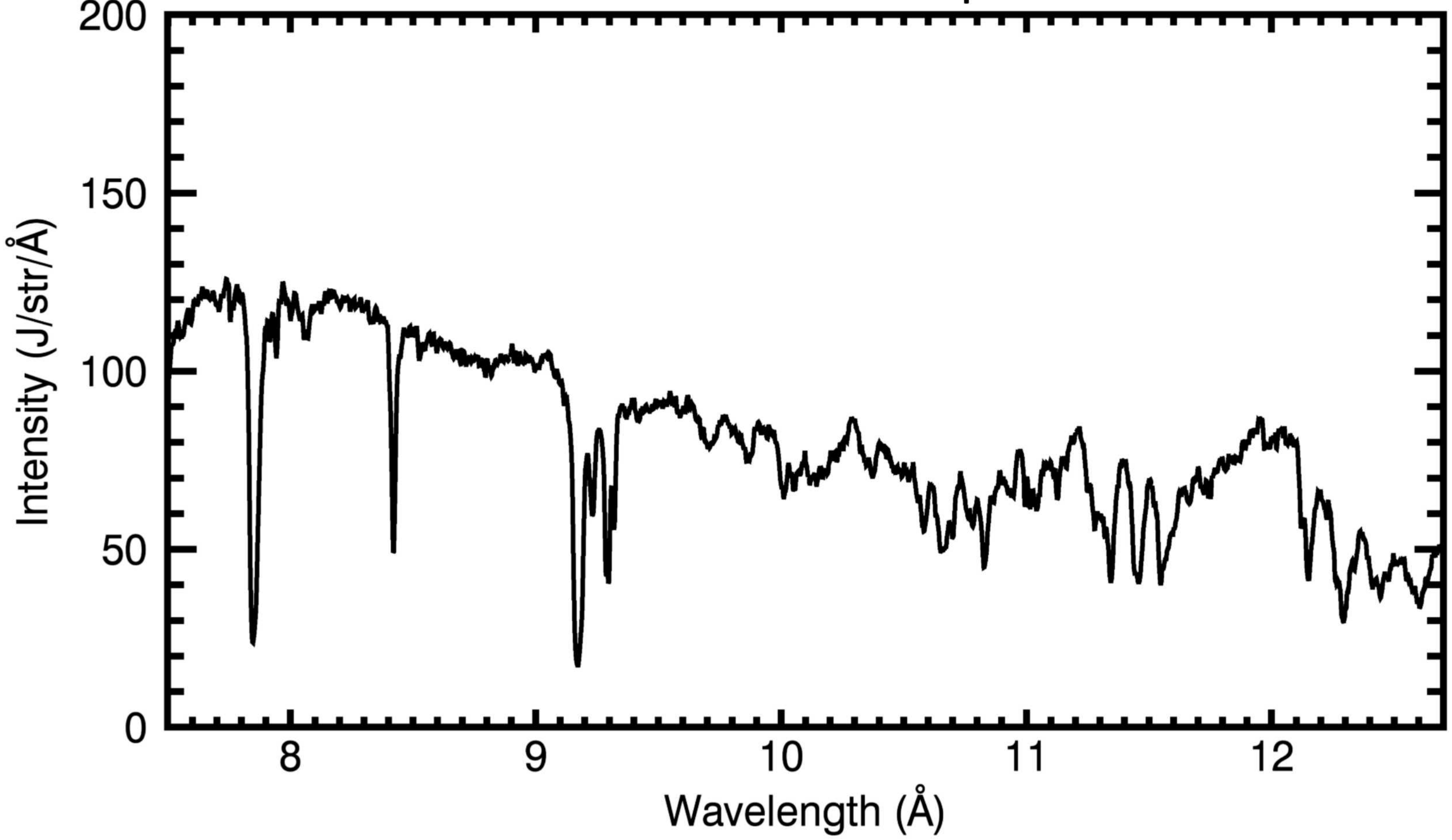
10% opacity accuracy requires 2% transmission accuracy
→ Opacity error is dominated by transmission error

Transmission error is dominated by error in *unattenuated* spectrum



Transmission error is dominated by error in *unattenuated* spectrum

What is its unatteuated spectrum?



Unattenuated spectrum ≡ If you did not have FeMg, what would you have measured?

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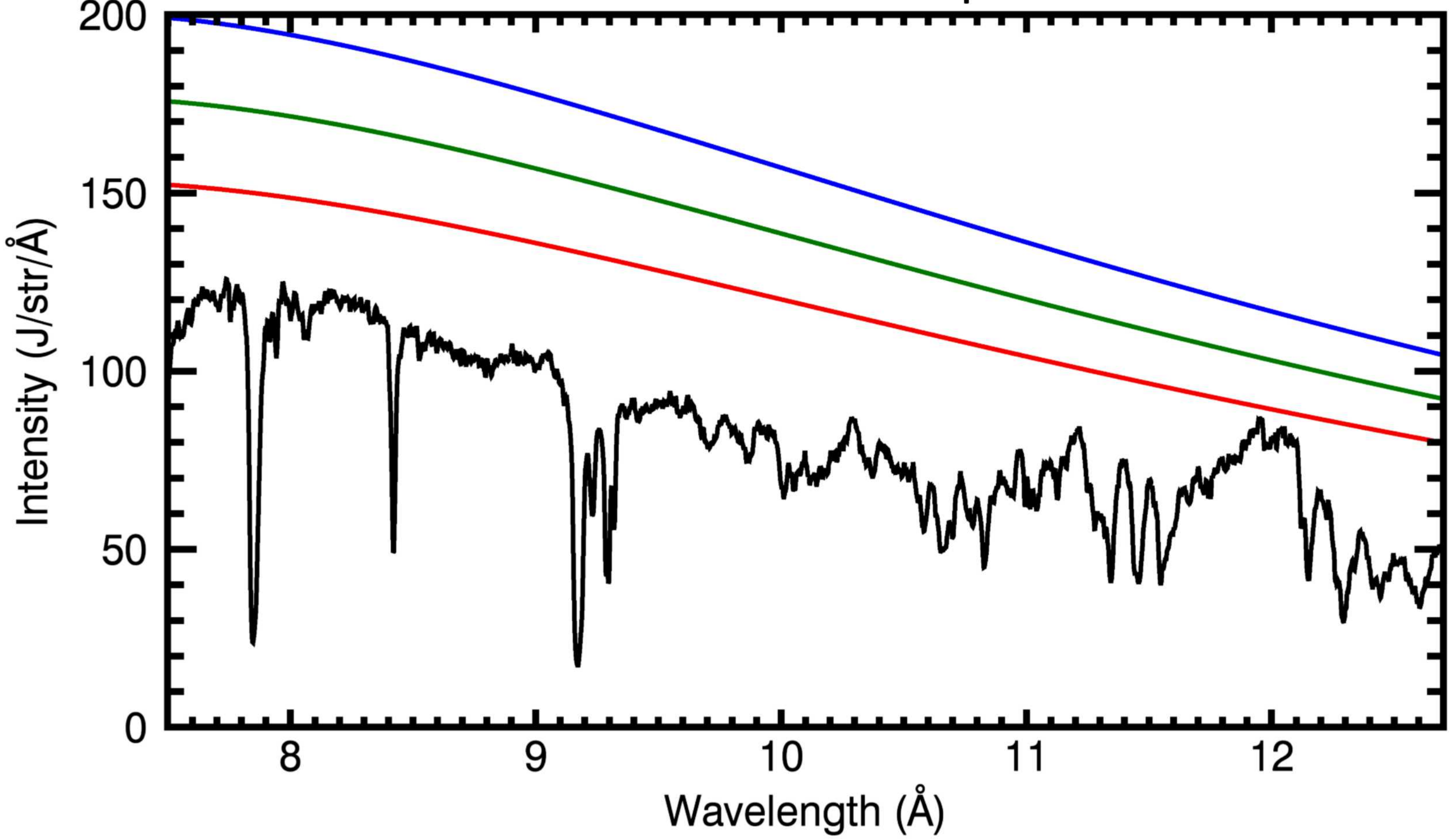

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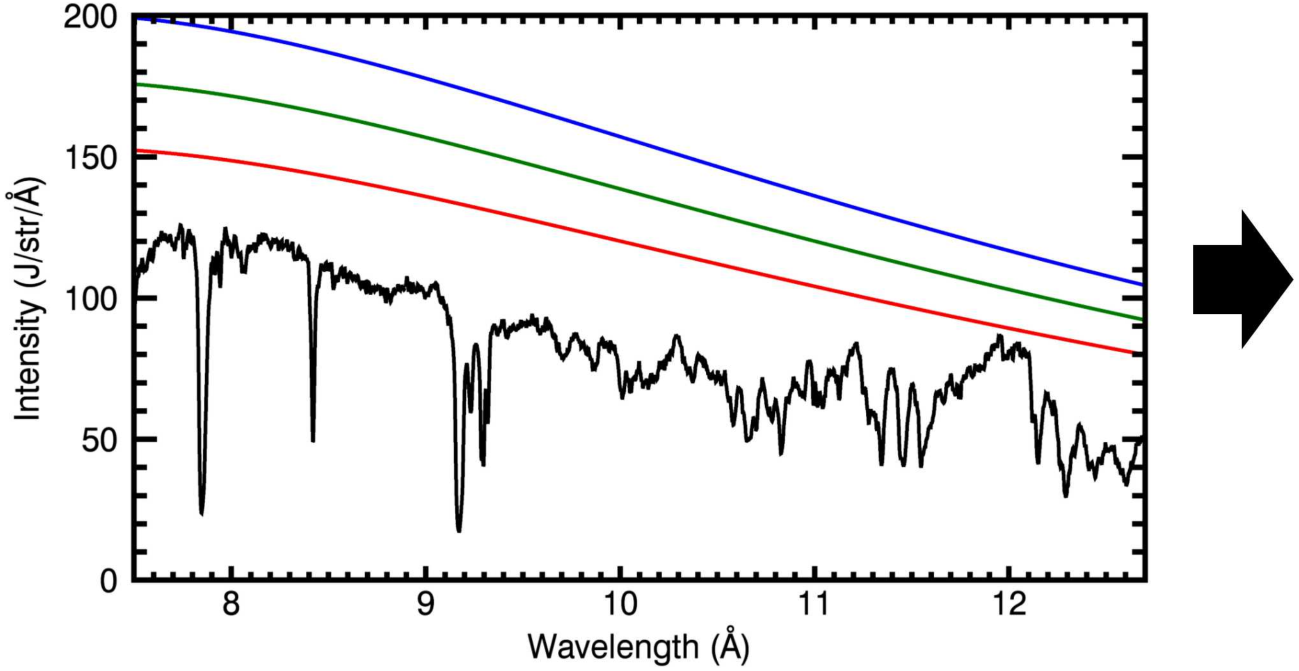

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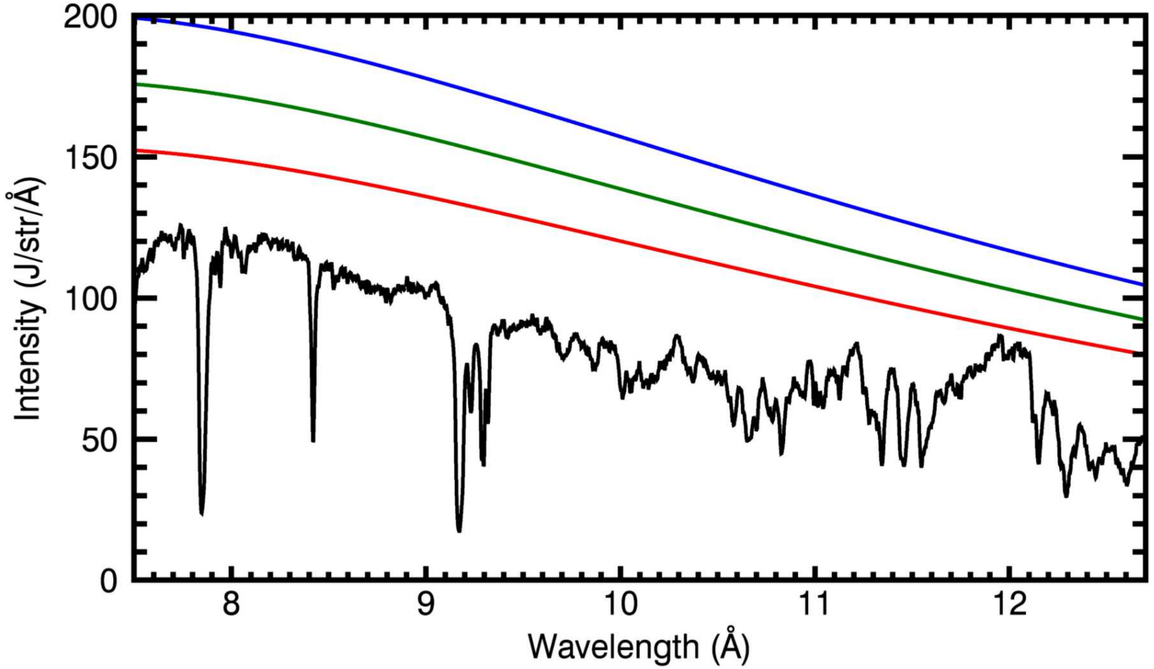

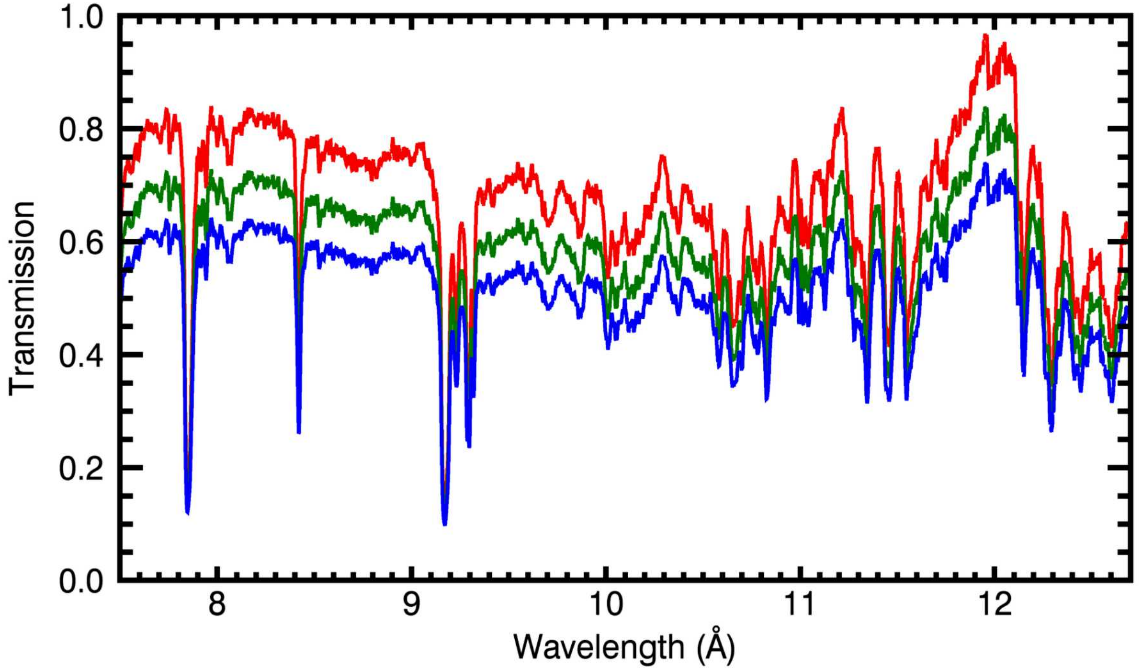

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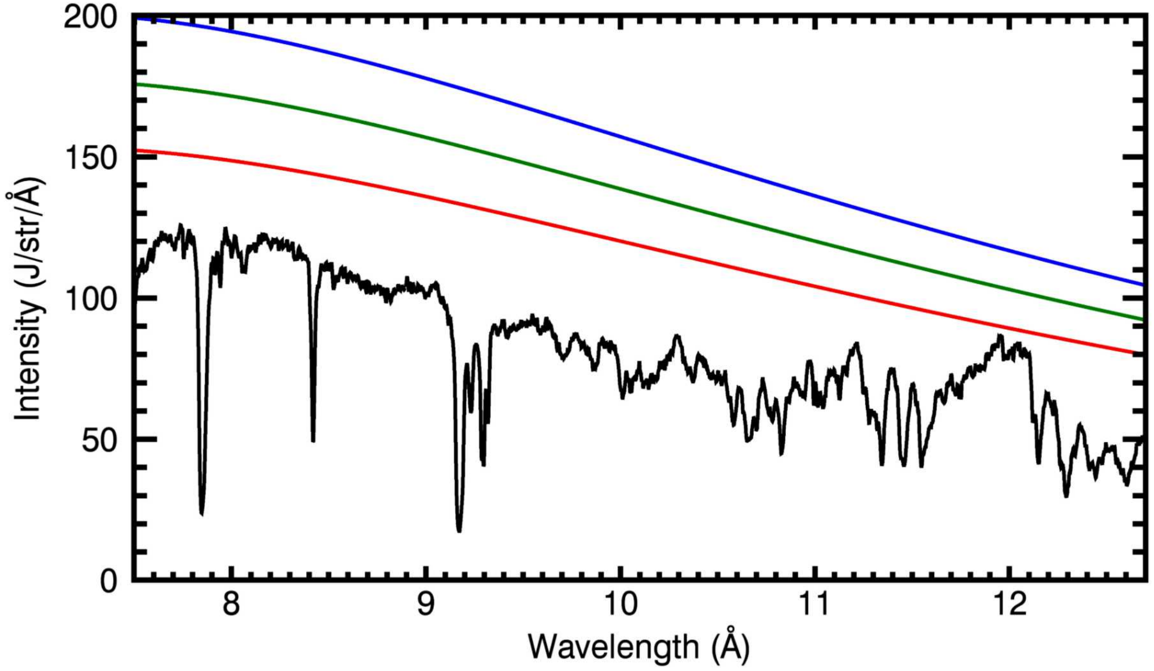
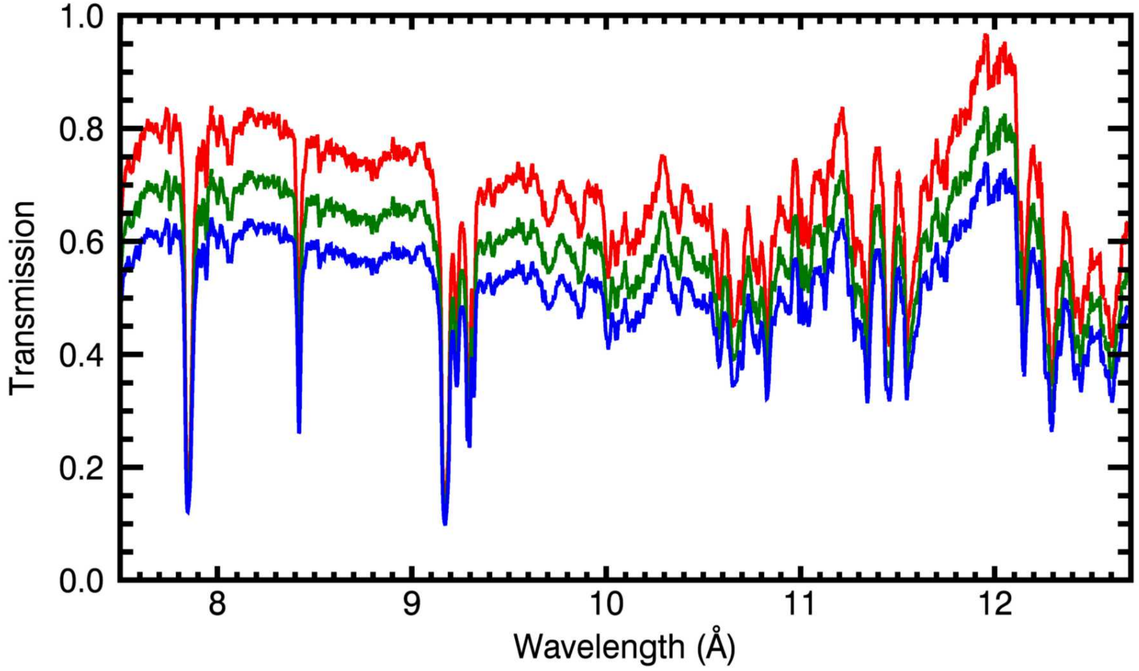


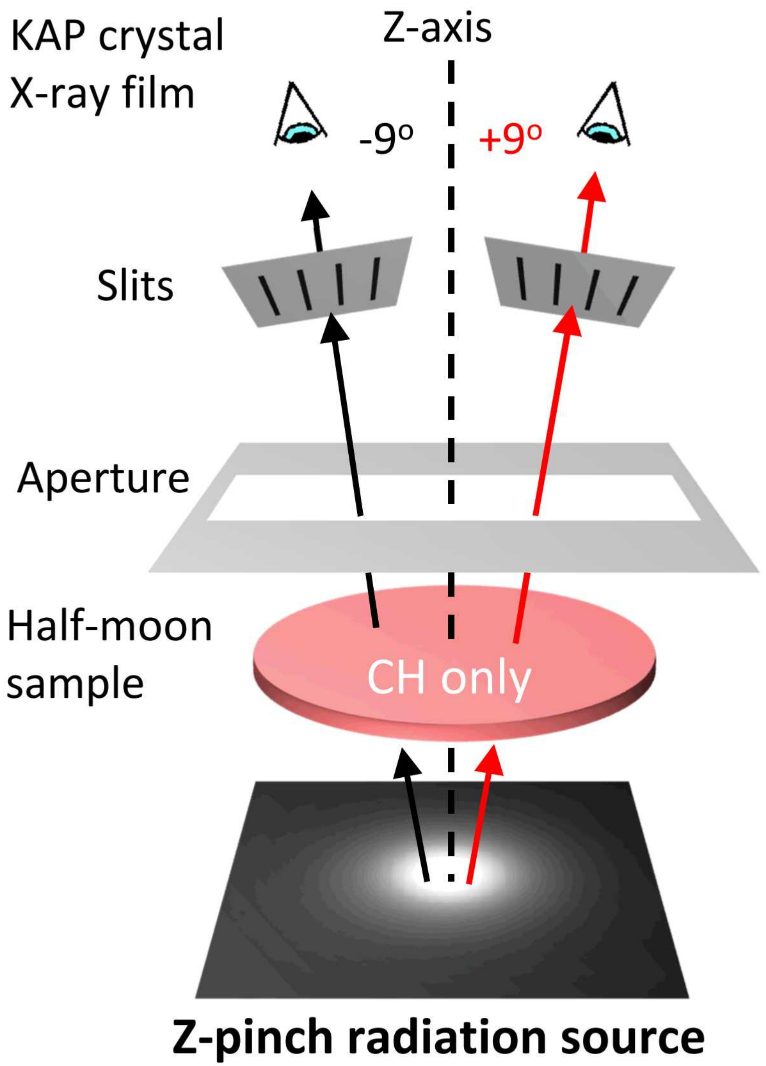


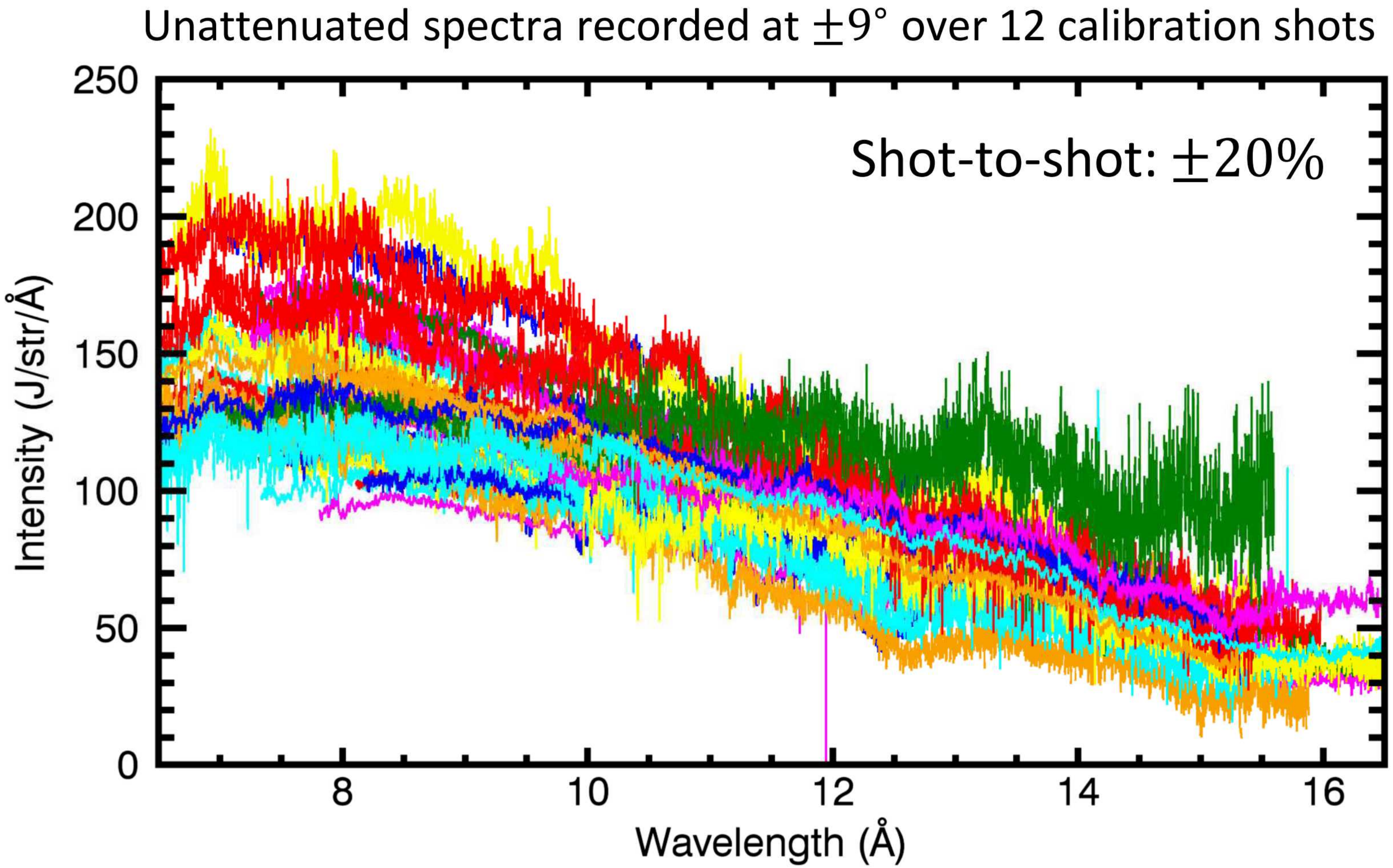
Unattenuated spectrum ≡ If you did not have FeMg, what would you have measured?

- Advantage: what we care is relative accuracy
- Challenge: it's impossible to answer this perfectly

→ We have to rely on reproducibility

We have various ways to approximate the unattenuated spectrum within 20%





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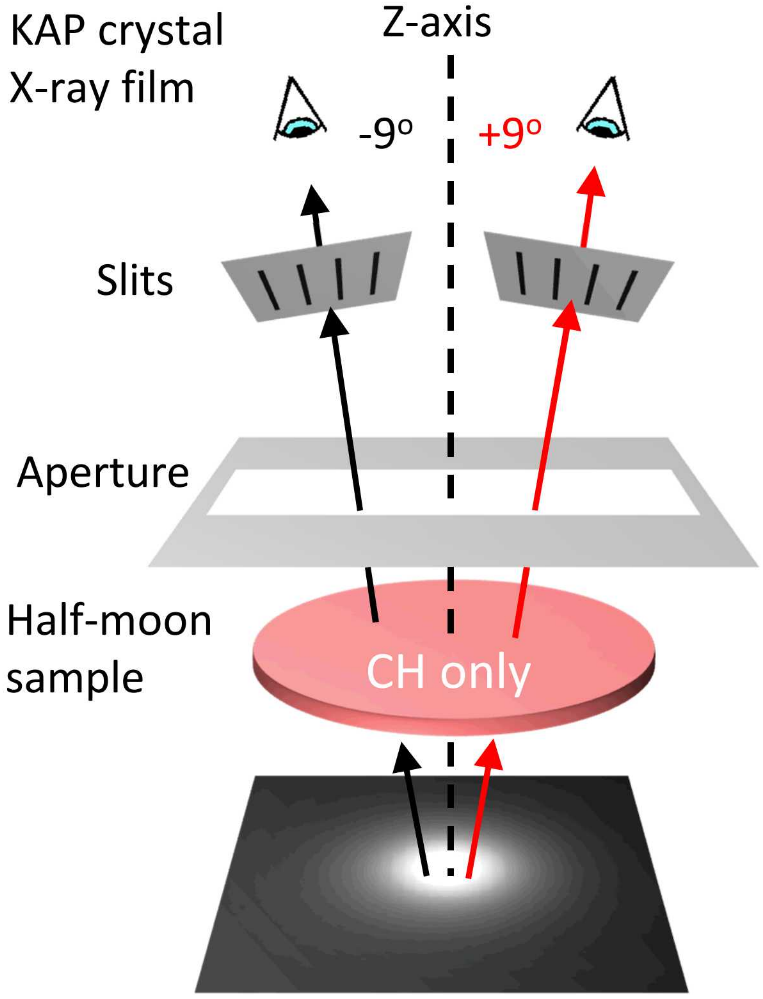
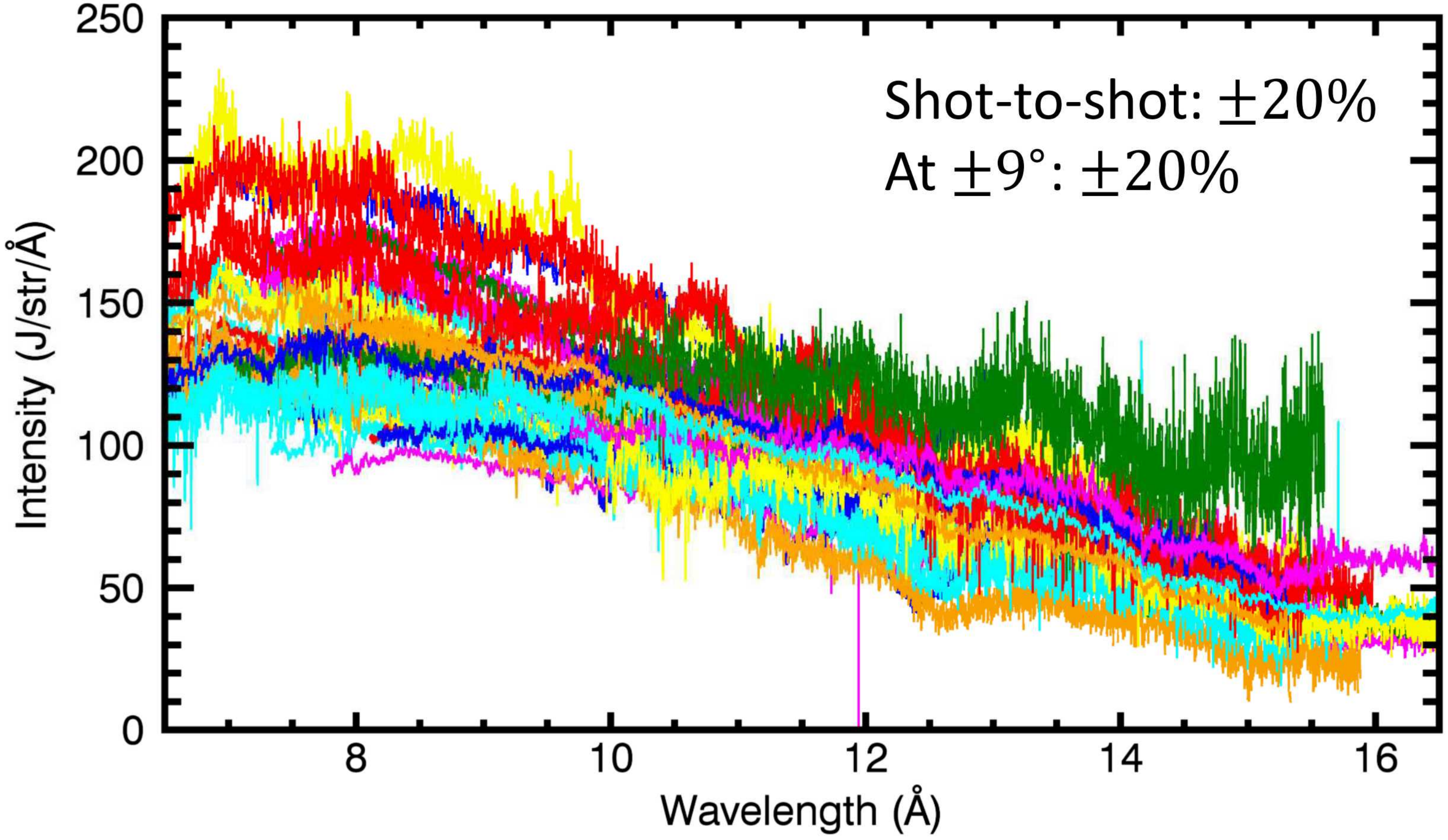


Z-pinch radiation source

Unattenuated spectra recorded at ±9° over 12 calibration shots



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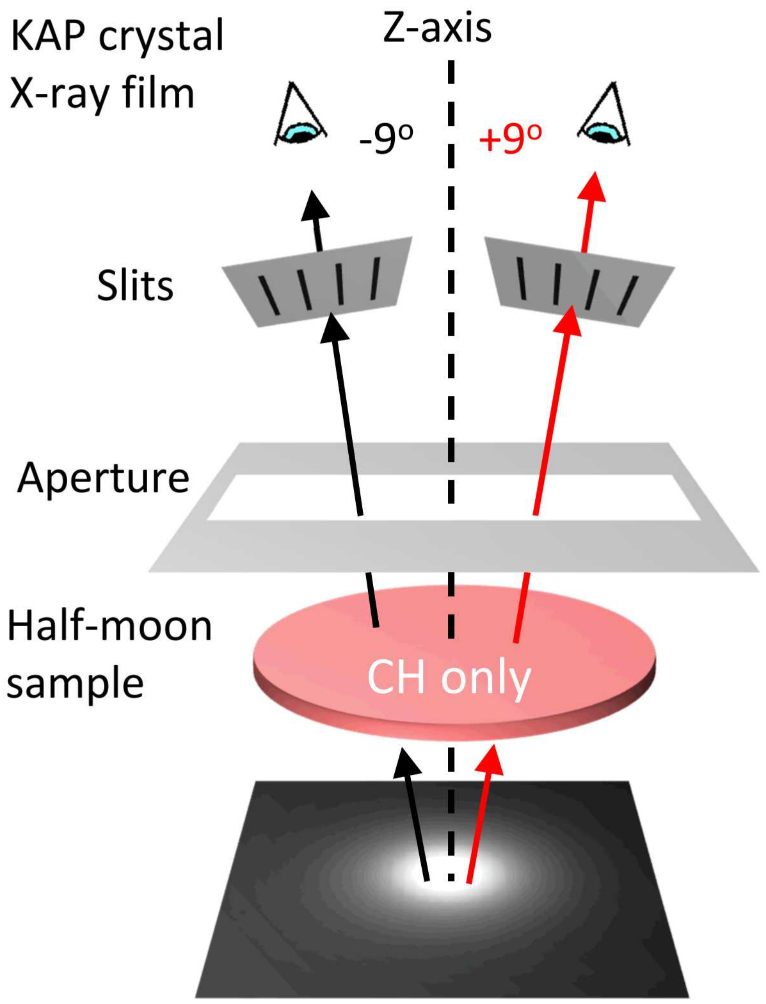

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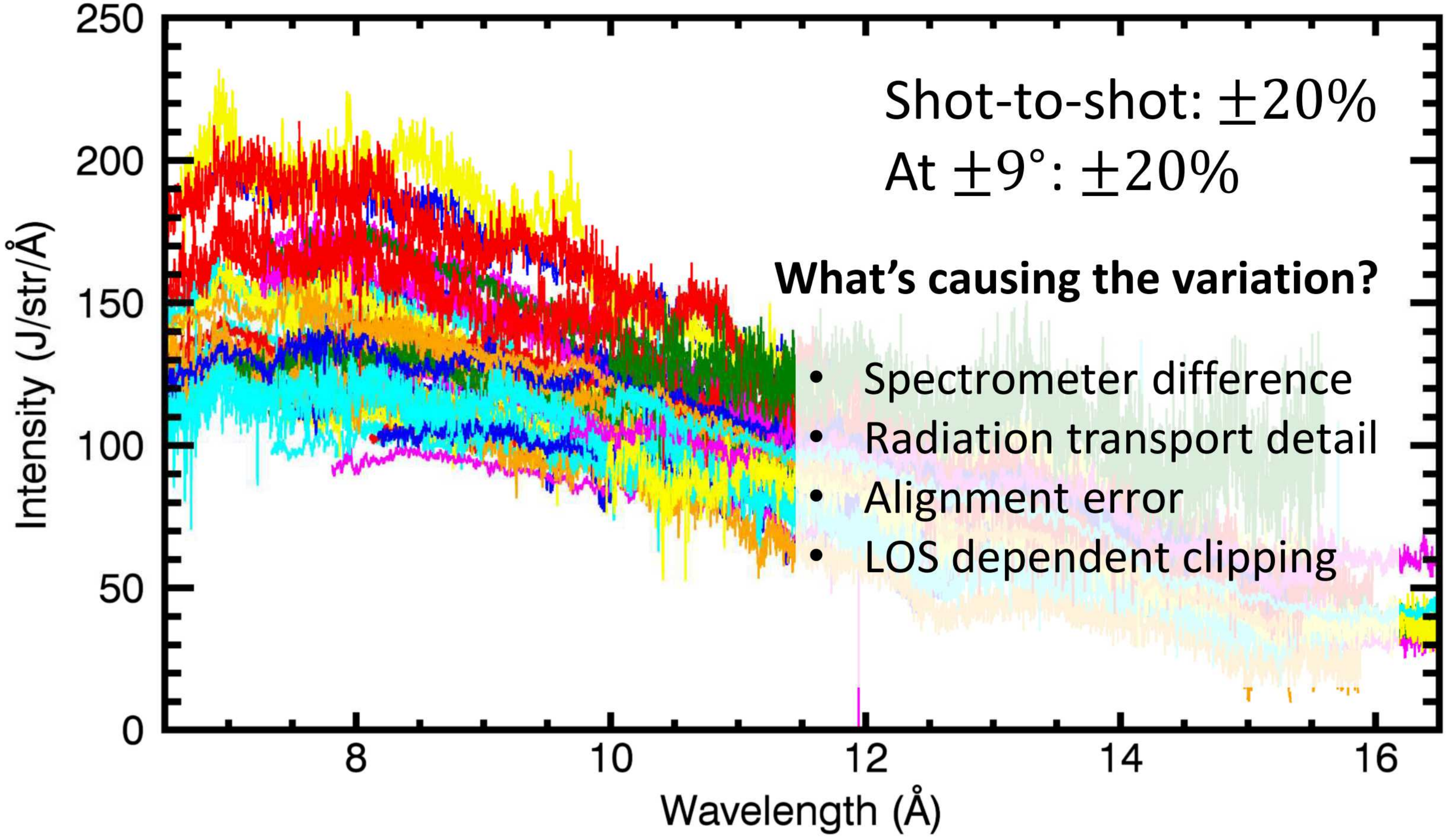
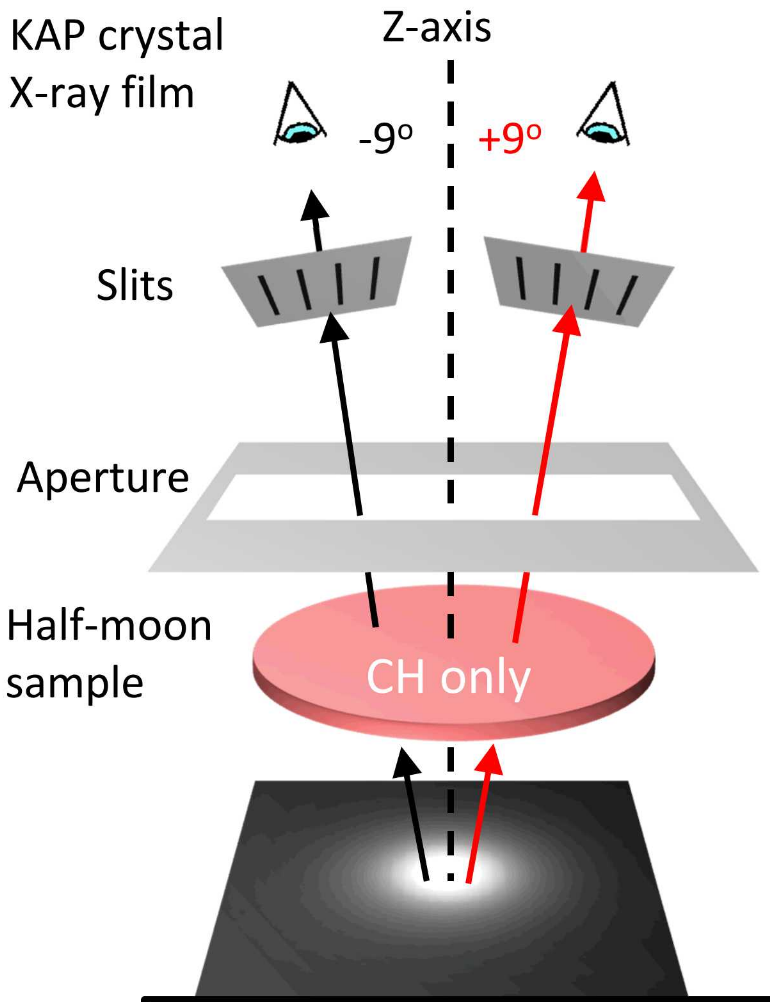


Shot-to-shot: ±20%
At ±9°: ±20%

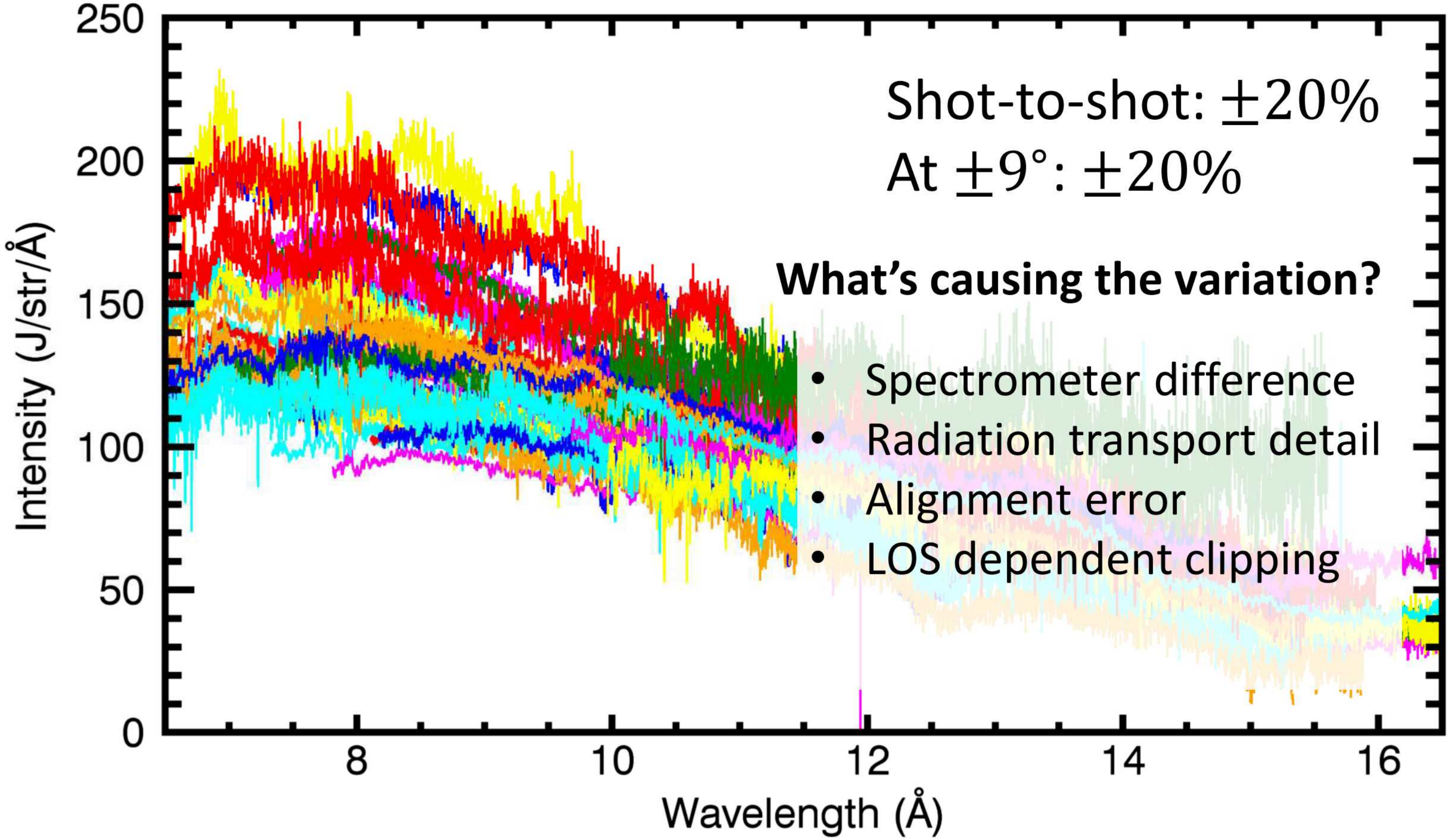
What's causing the variation?

- Spectrometer difference
- Radiation transport detail
- Alignment error
- LOS dependent clipping

We have various ways to approximate the unattenuated spectrum within 20%



Unattenuated spectra recorded at $\pm 9°$ over 12 calibration shots

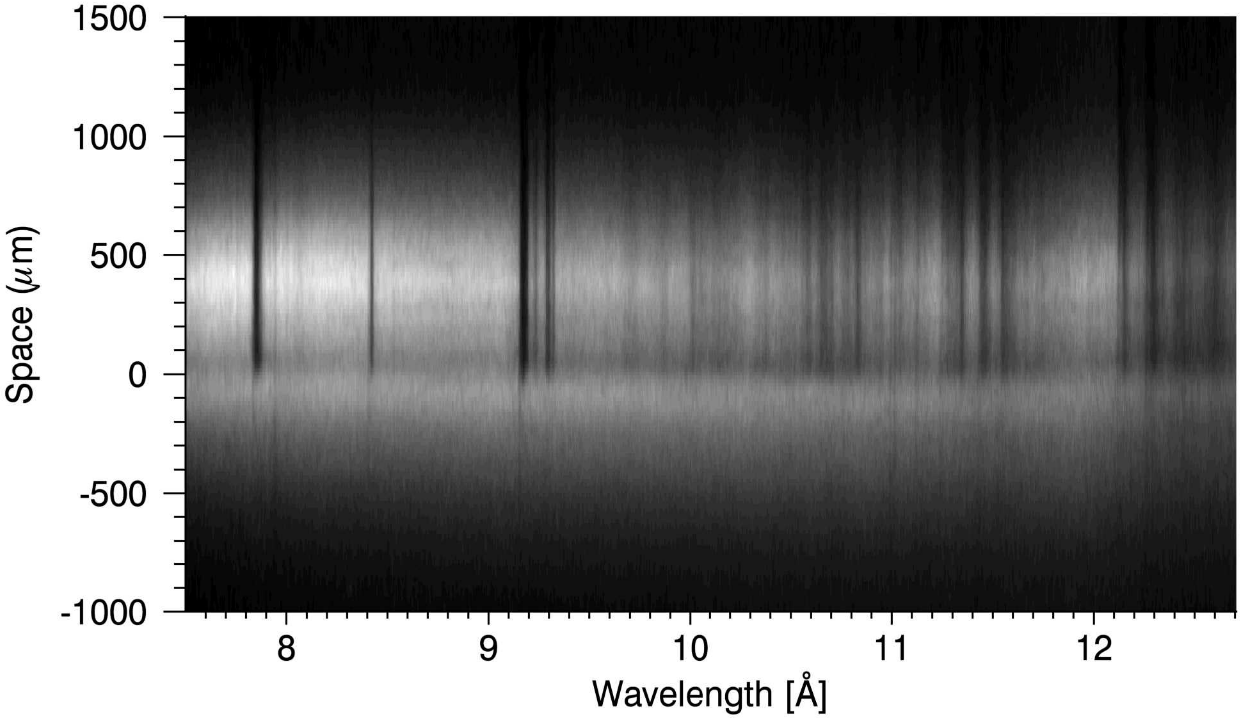


Single shot transmission error is reduced to $\sim 10\%$ by averaging multiple methods

Paradigm shift:

Spatial shape is more constraining

The data is resolved not only spectrally but also spatially; spatial profile provides more constraints



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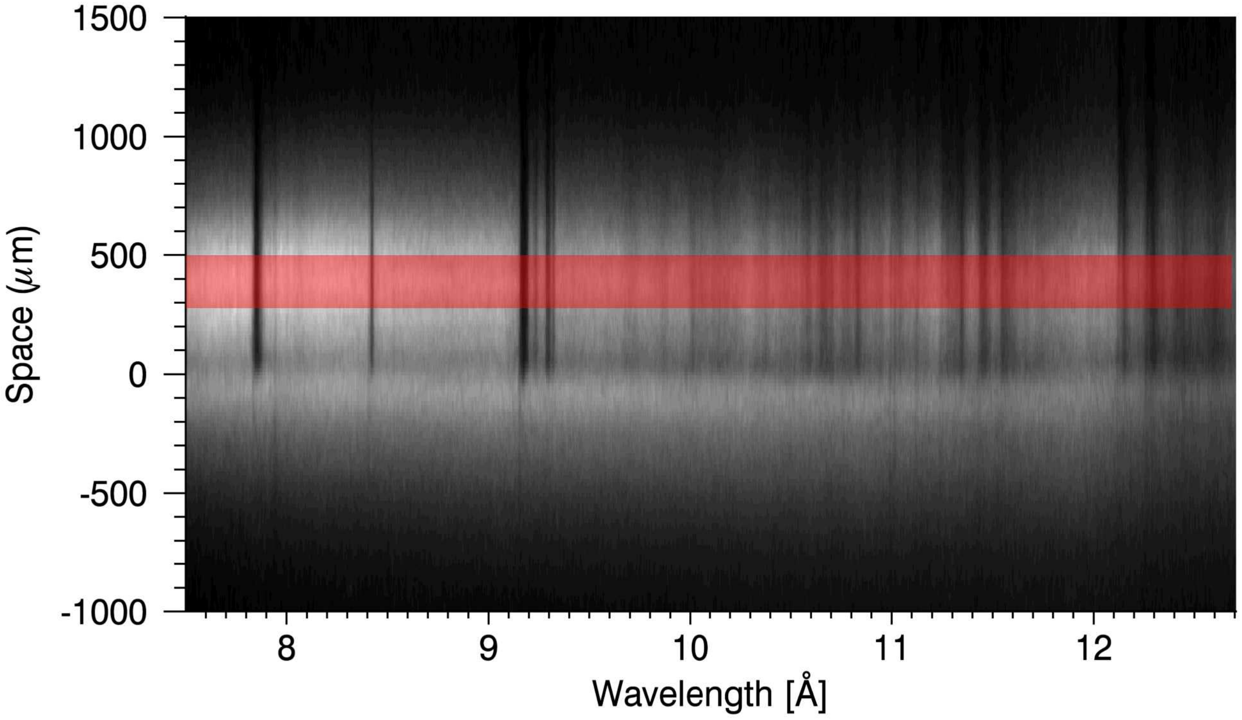

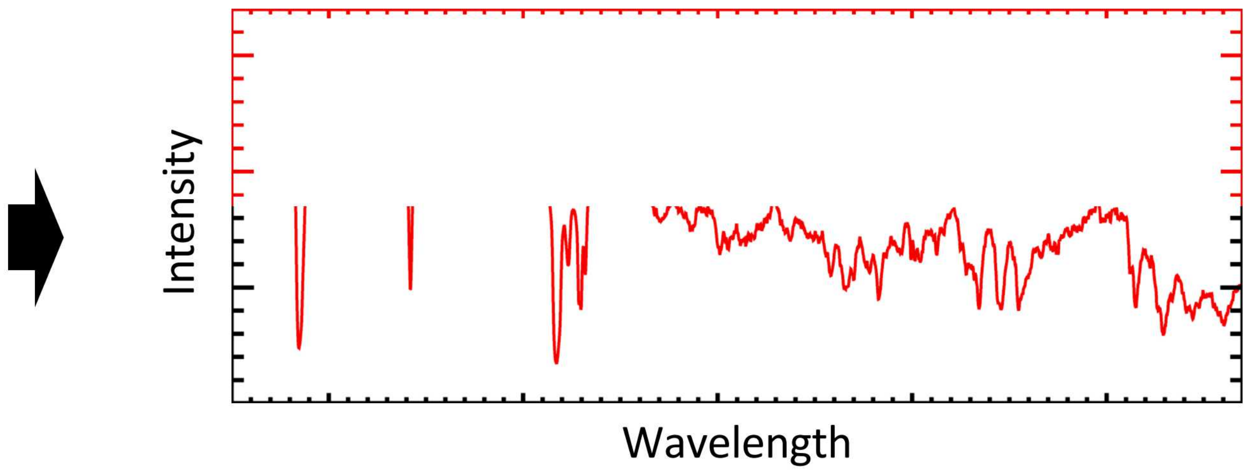

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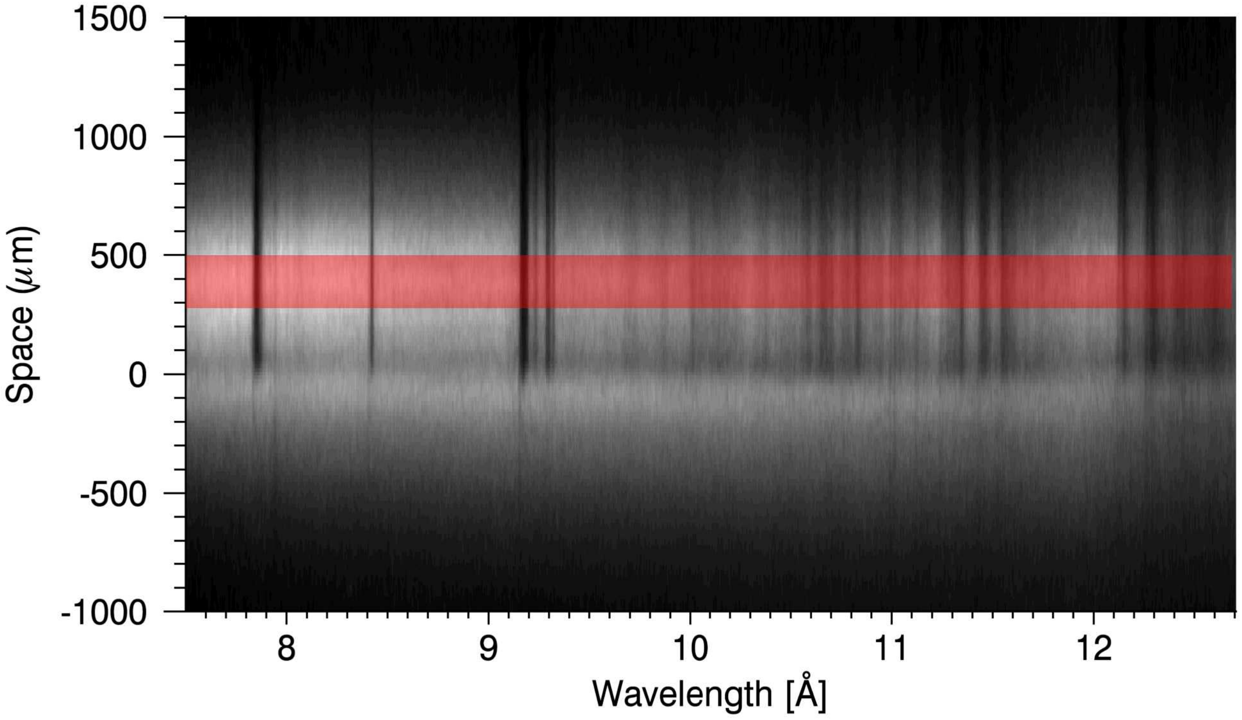

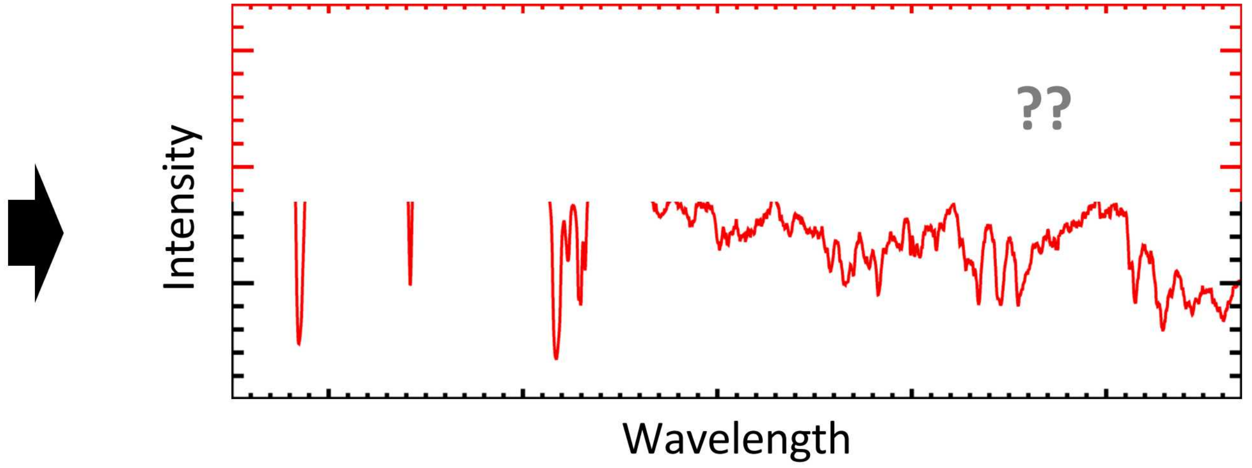

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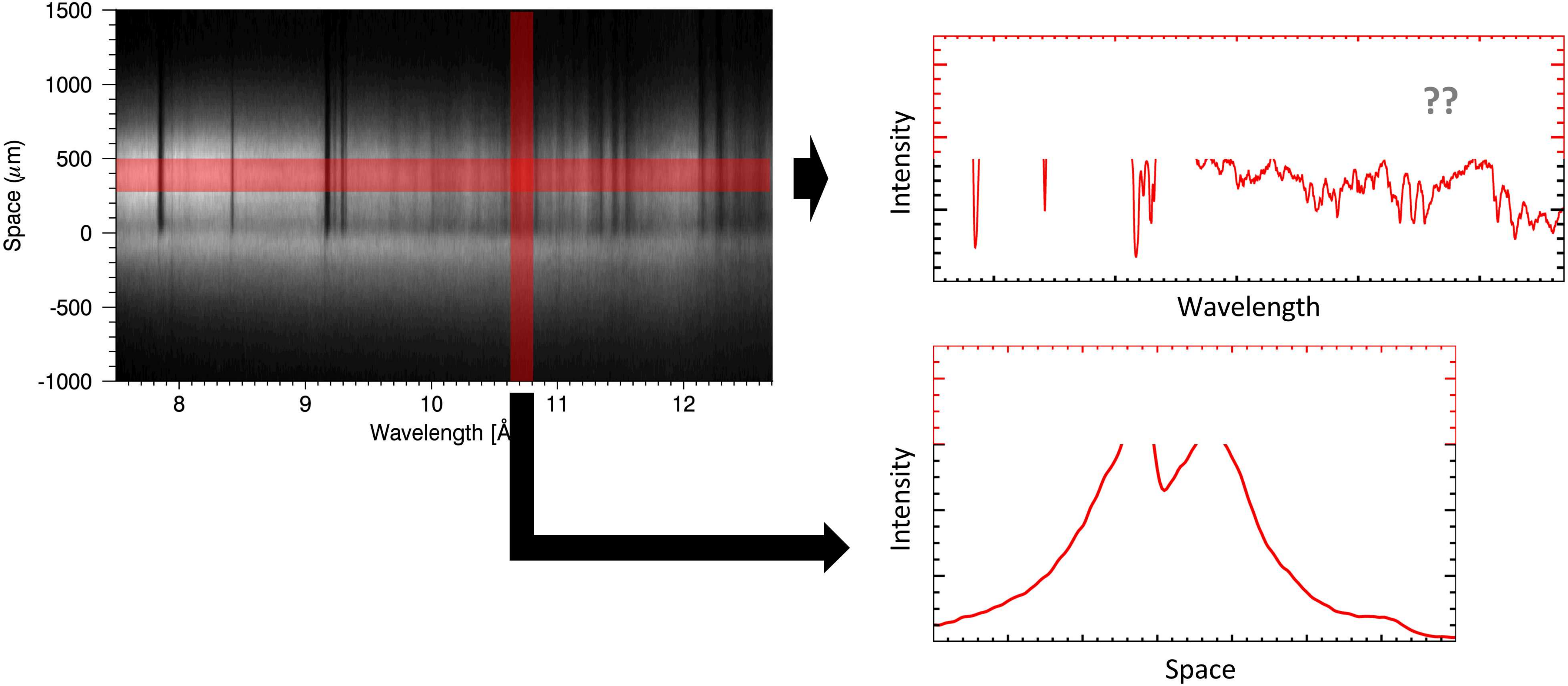
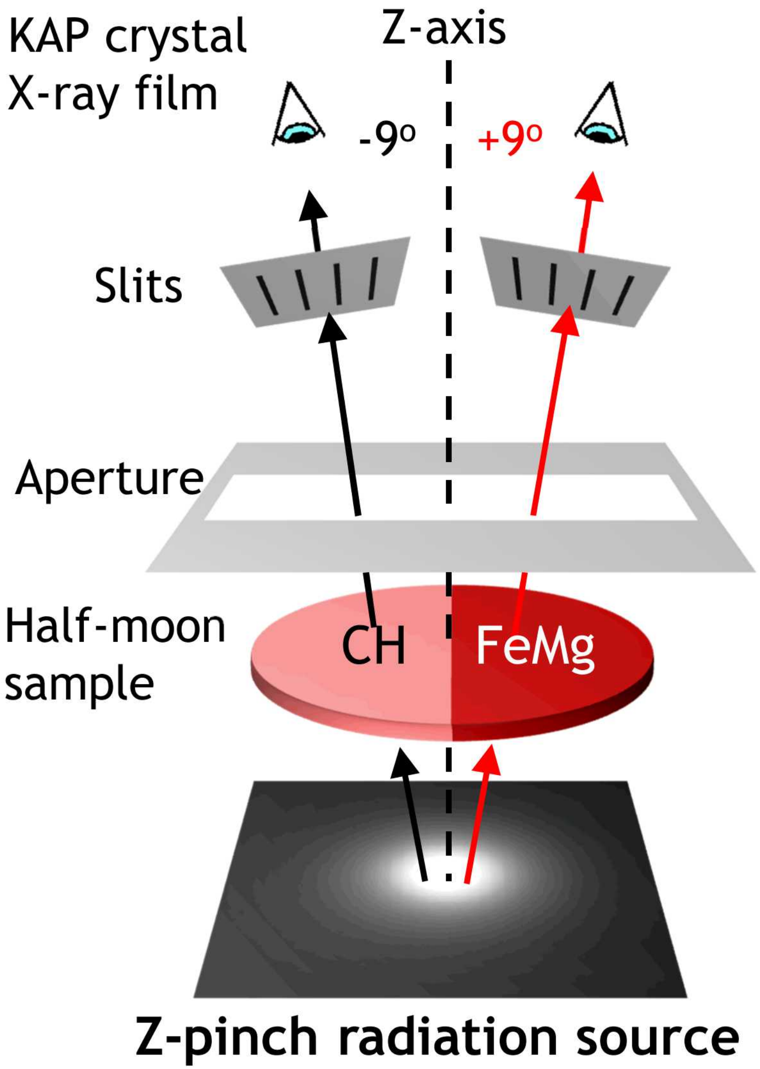


Observing finite-area backlighter through half-moon sample at $\pm 9°$ produces complicated spatial shape



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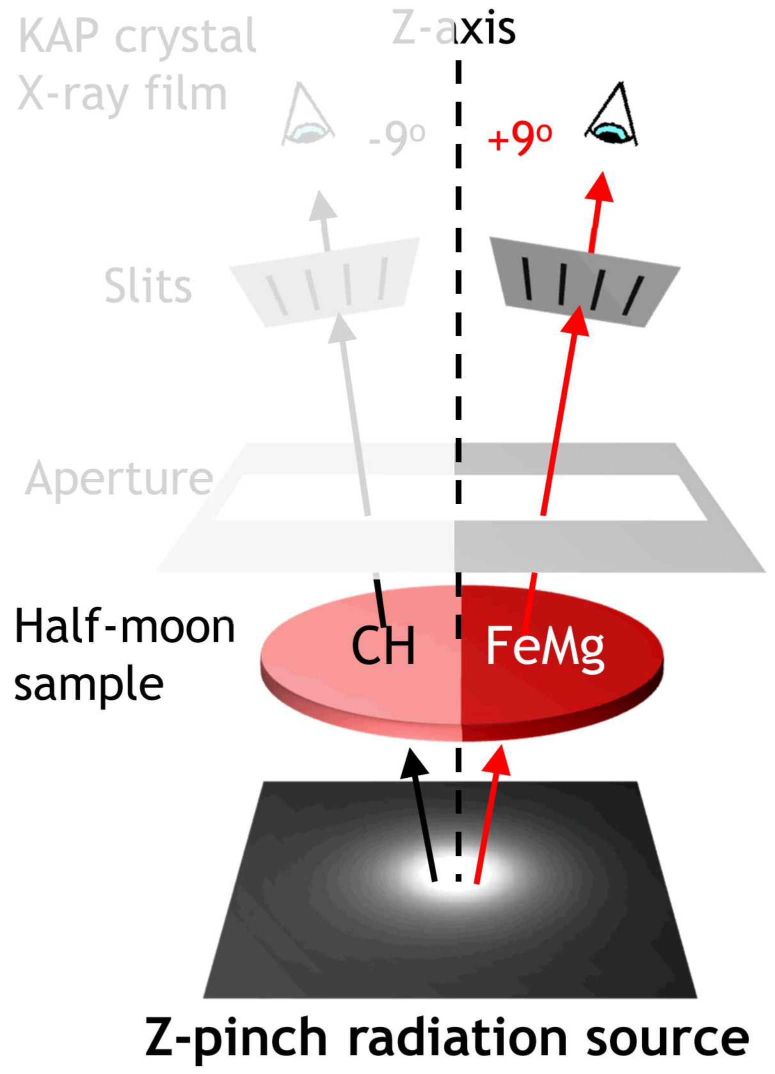

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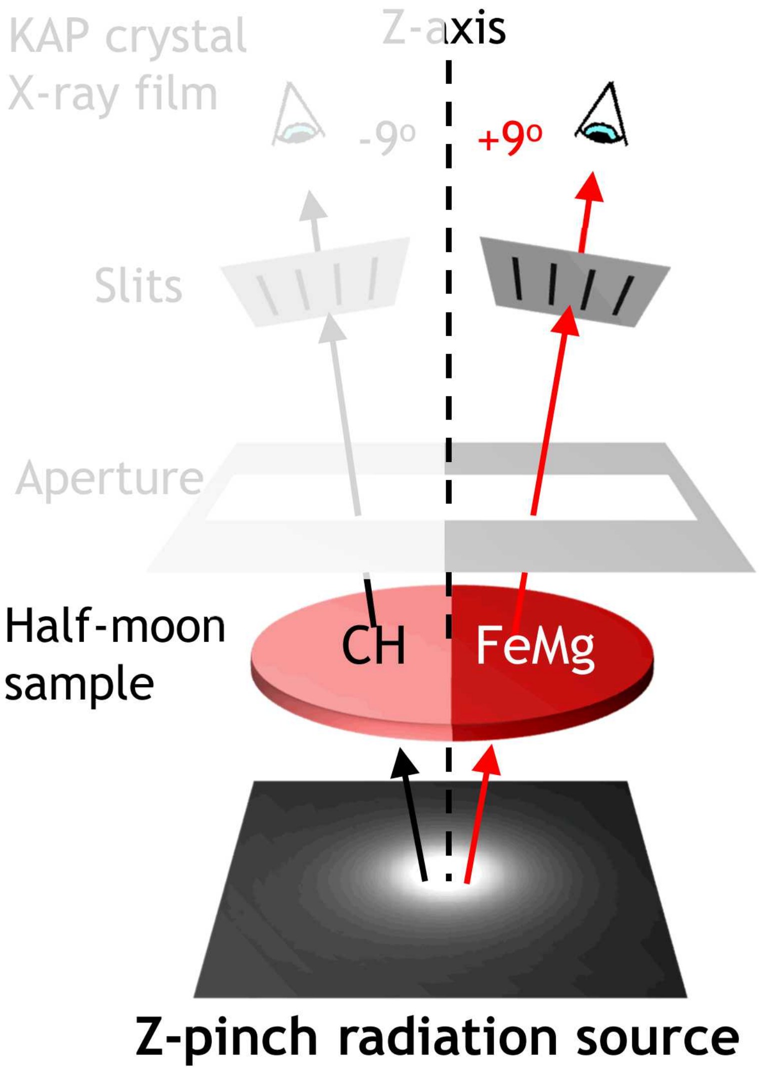

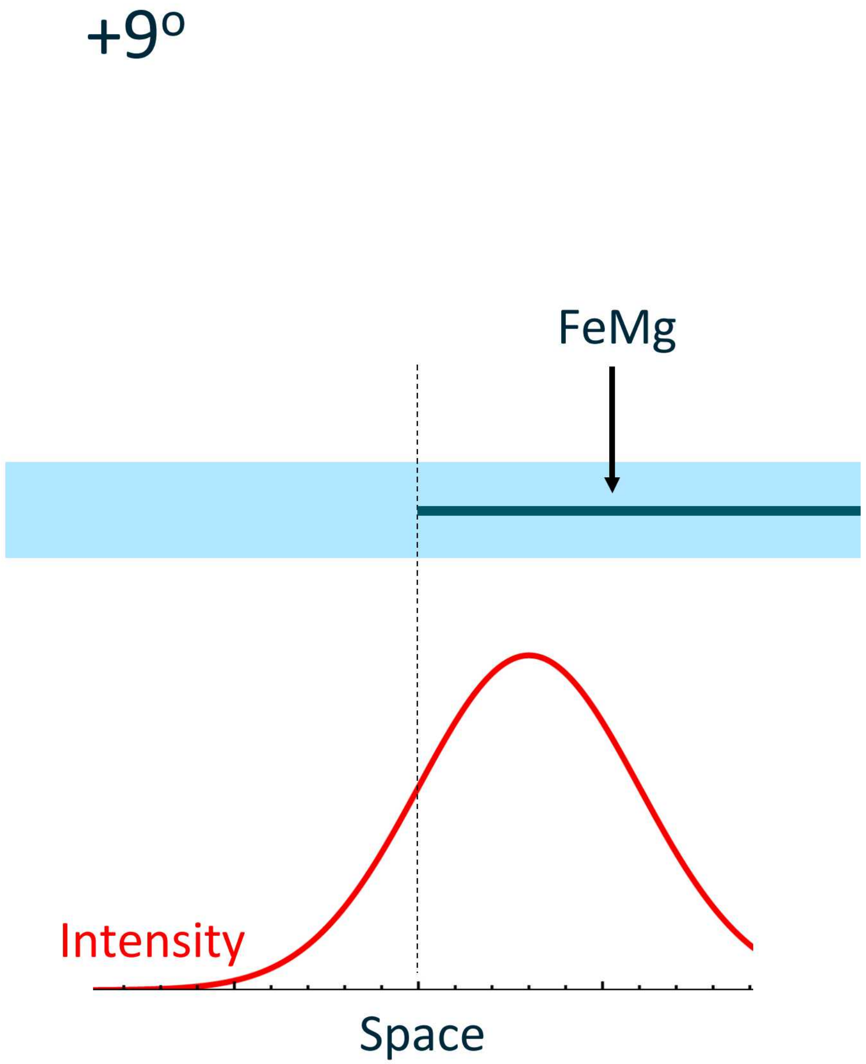

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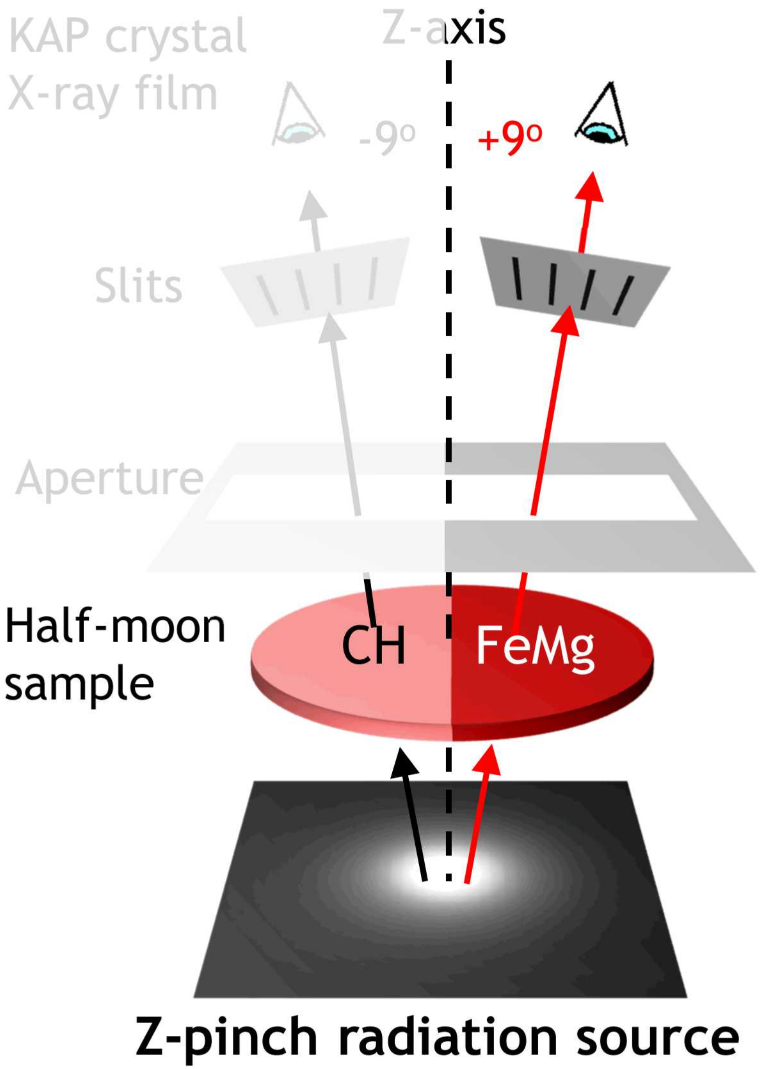

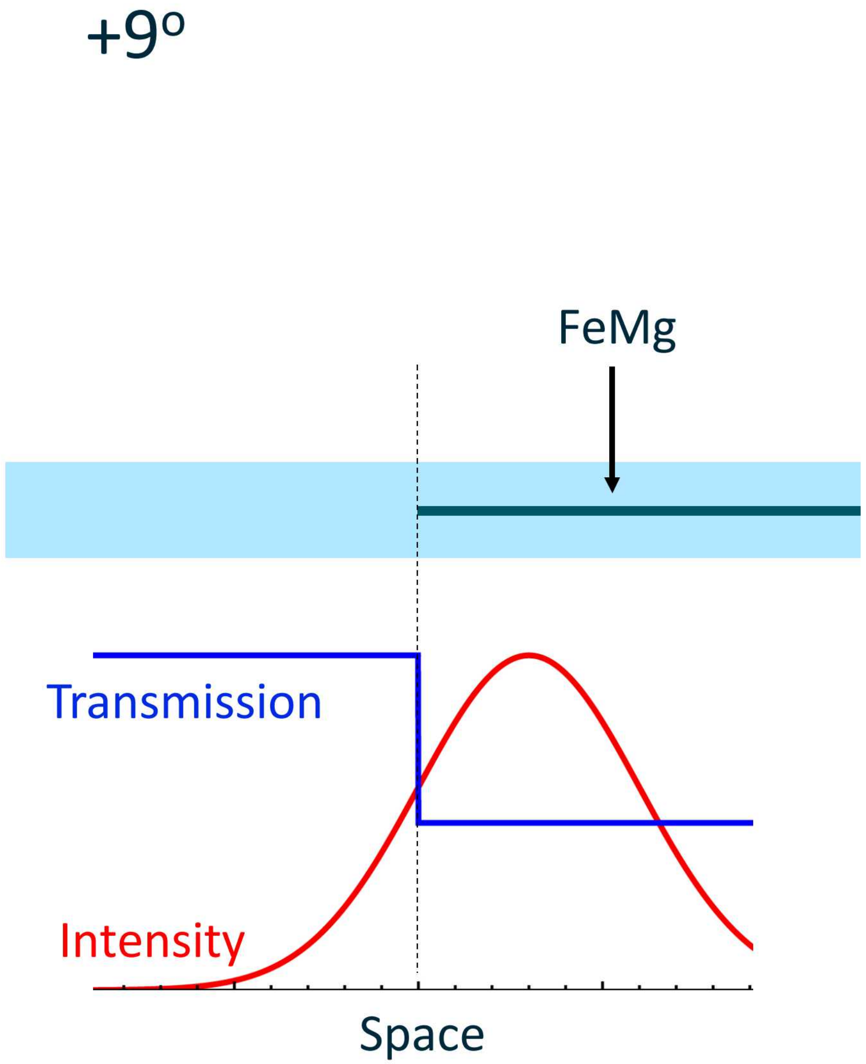

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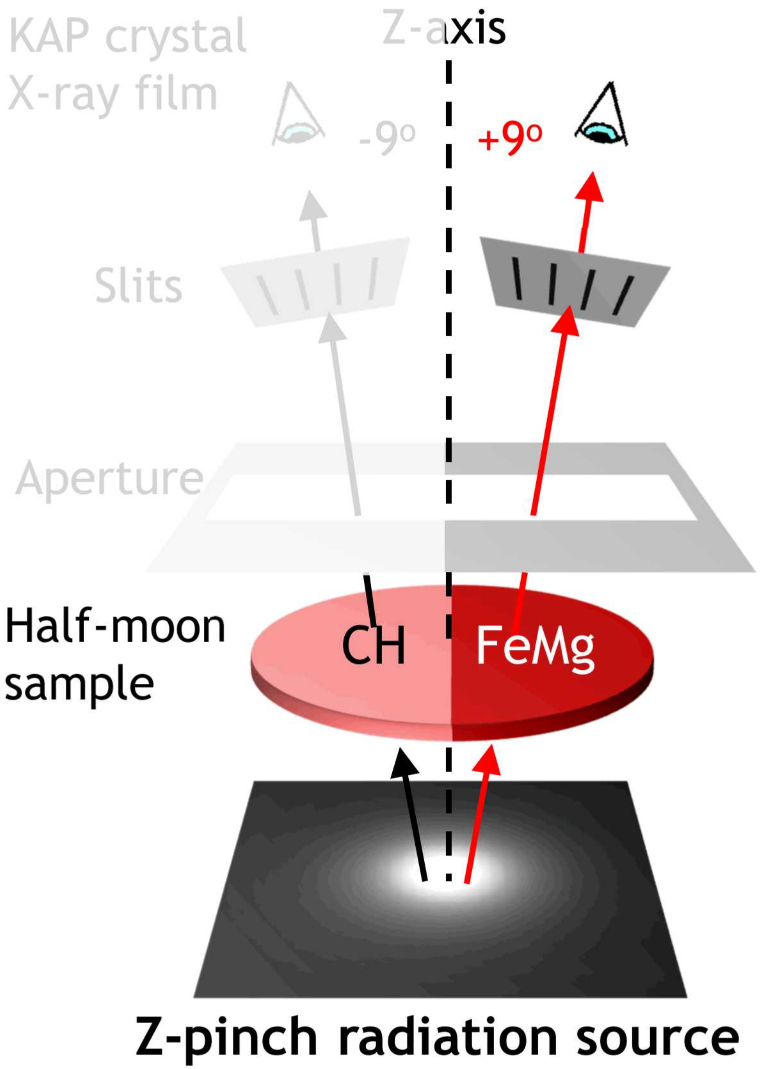

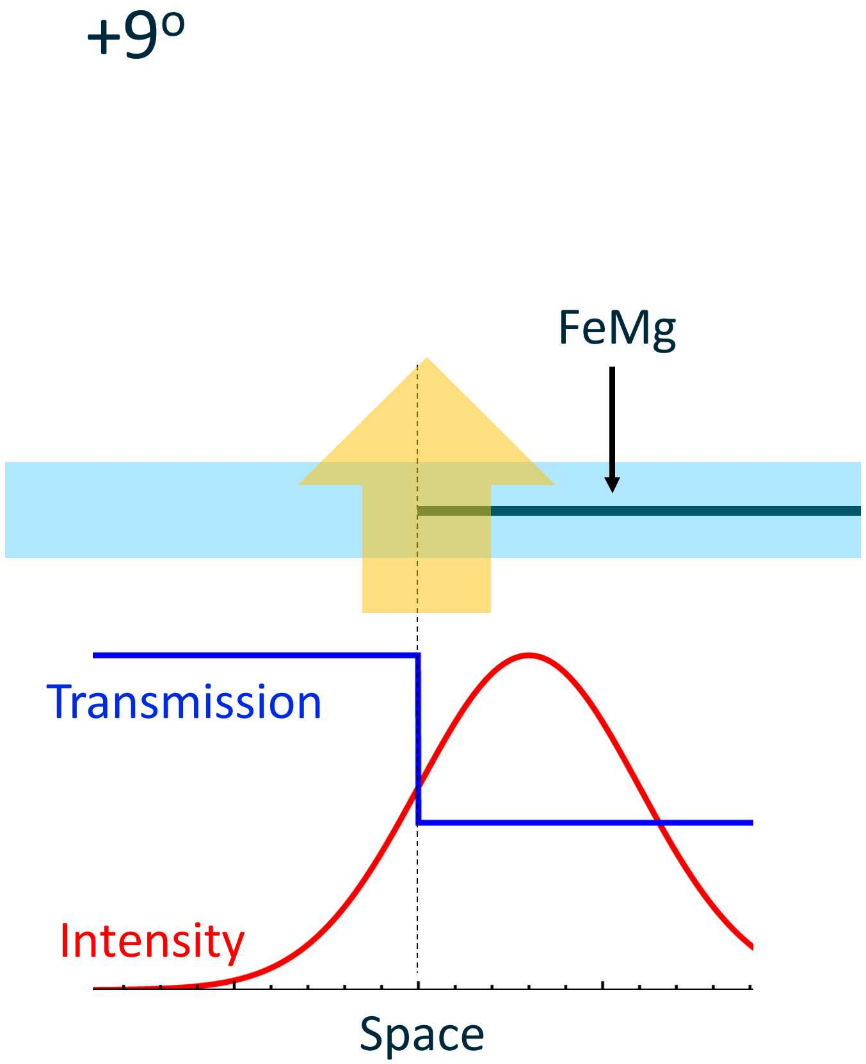

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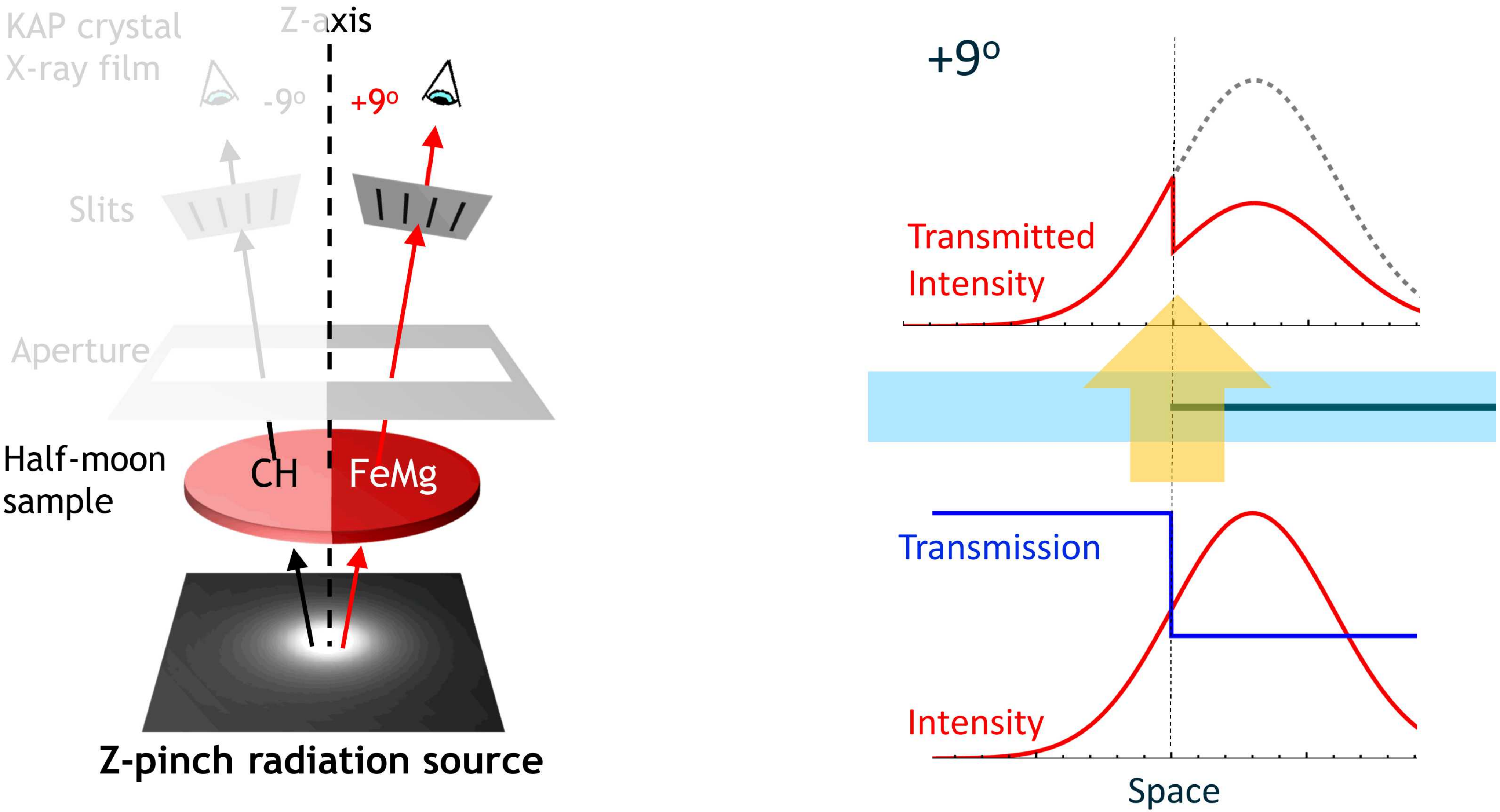

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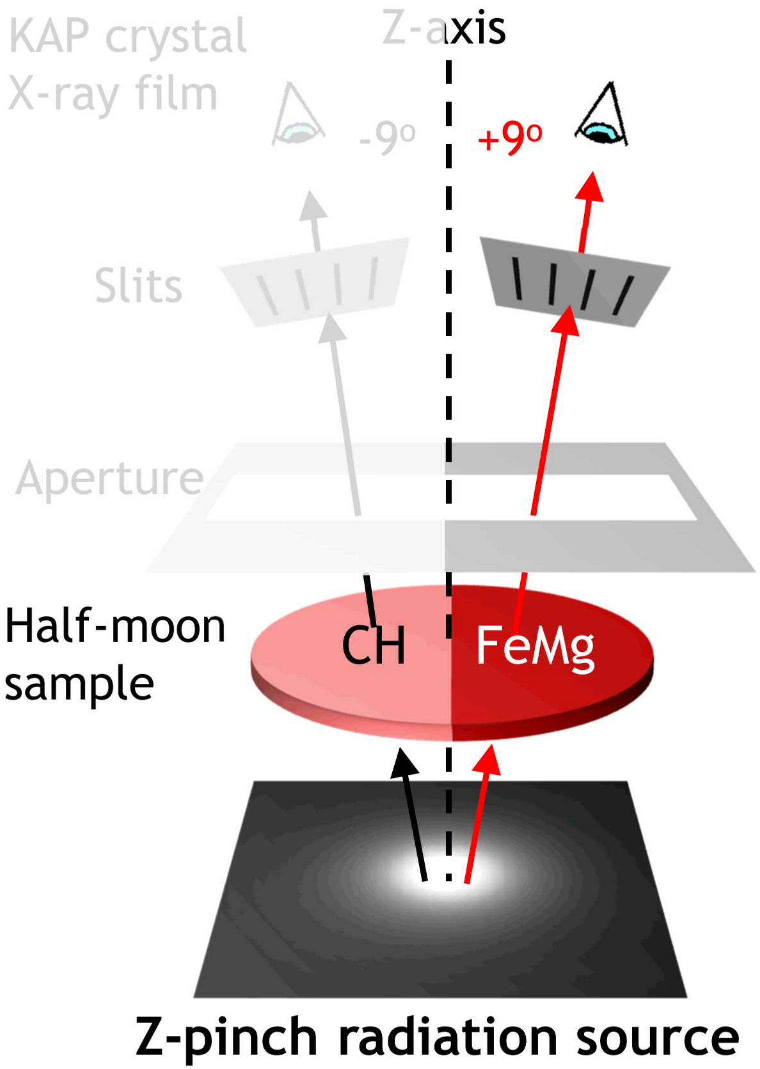

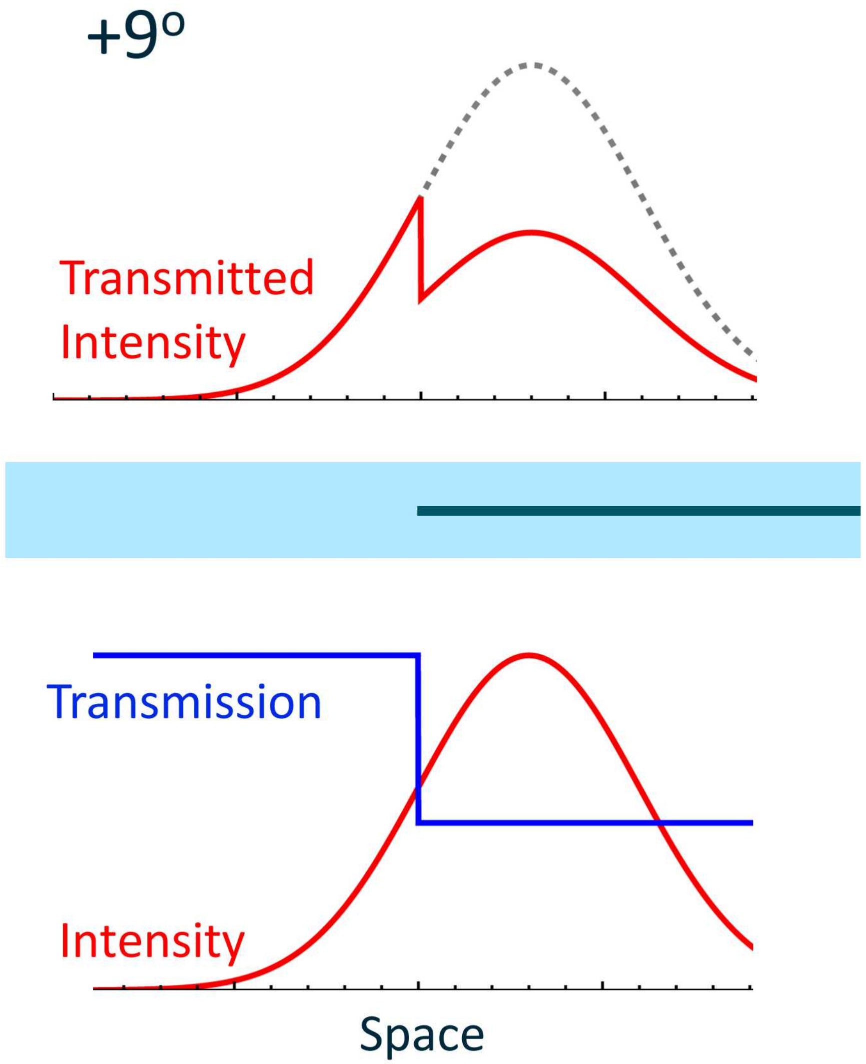

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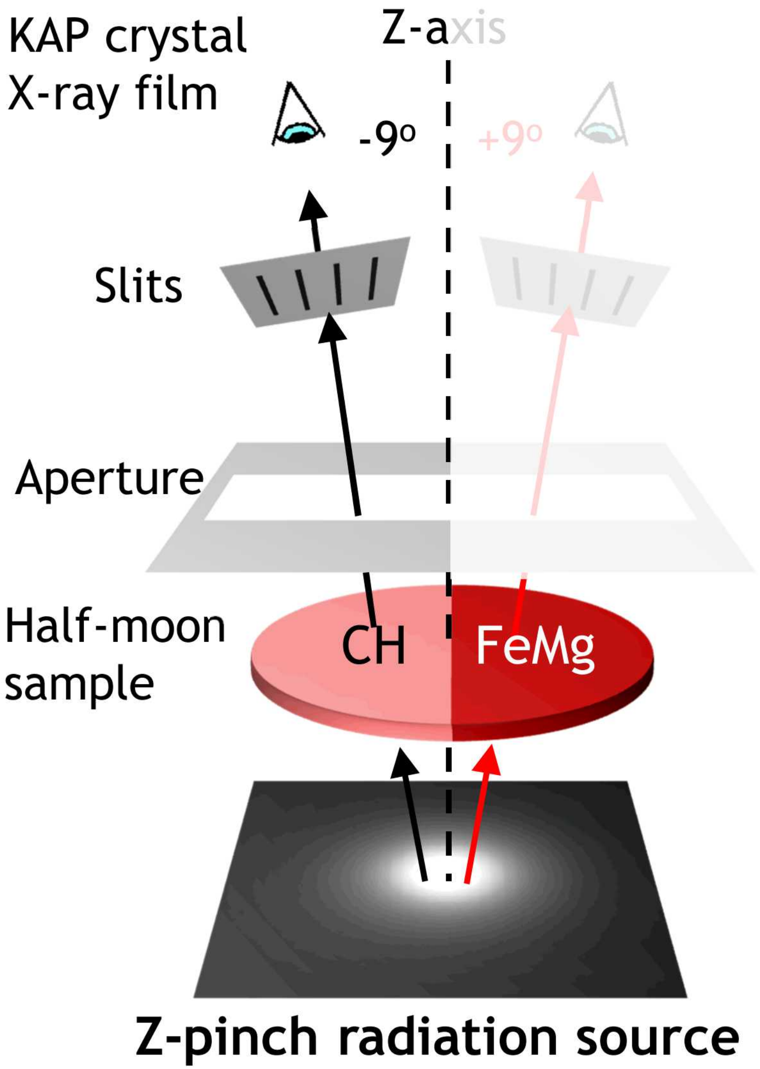

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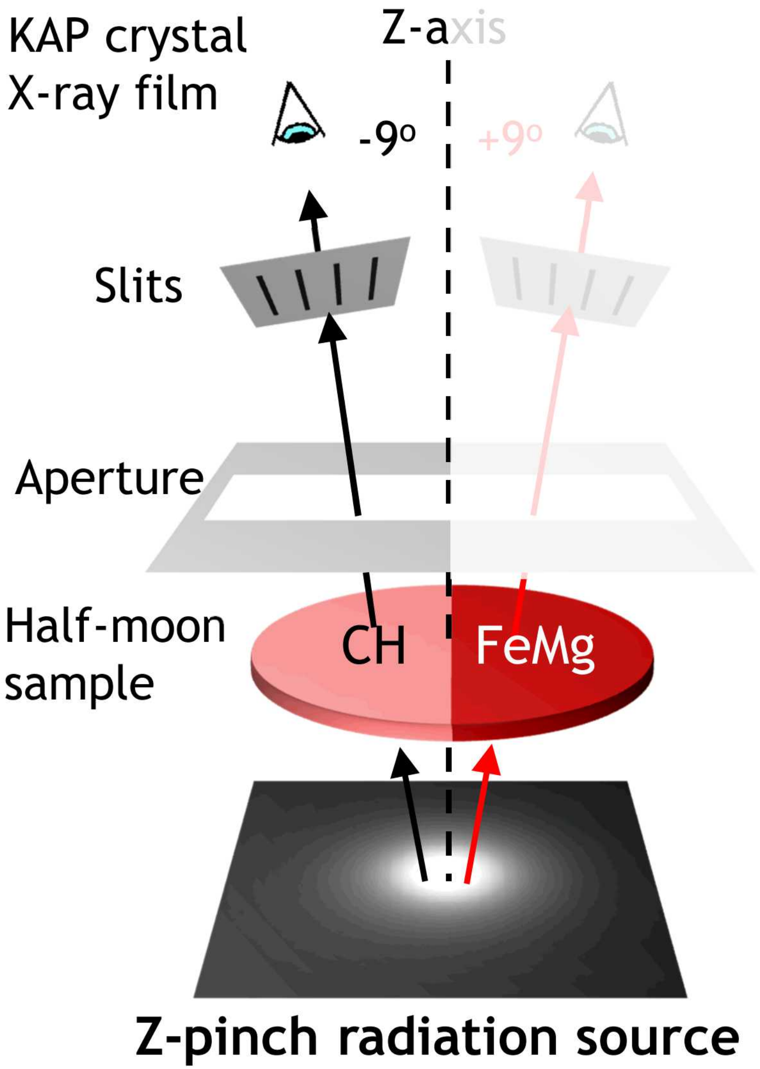

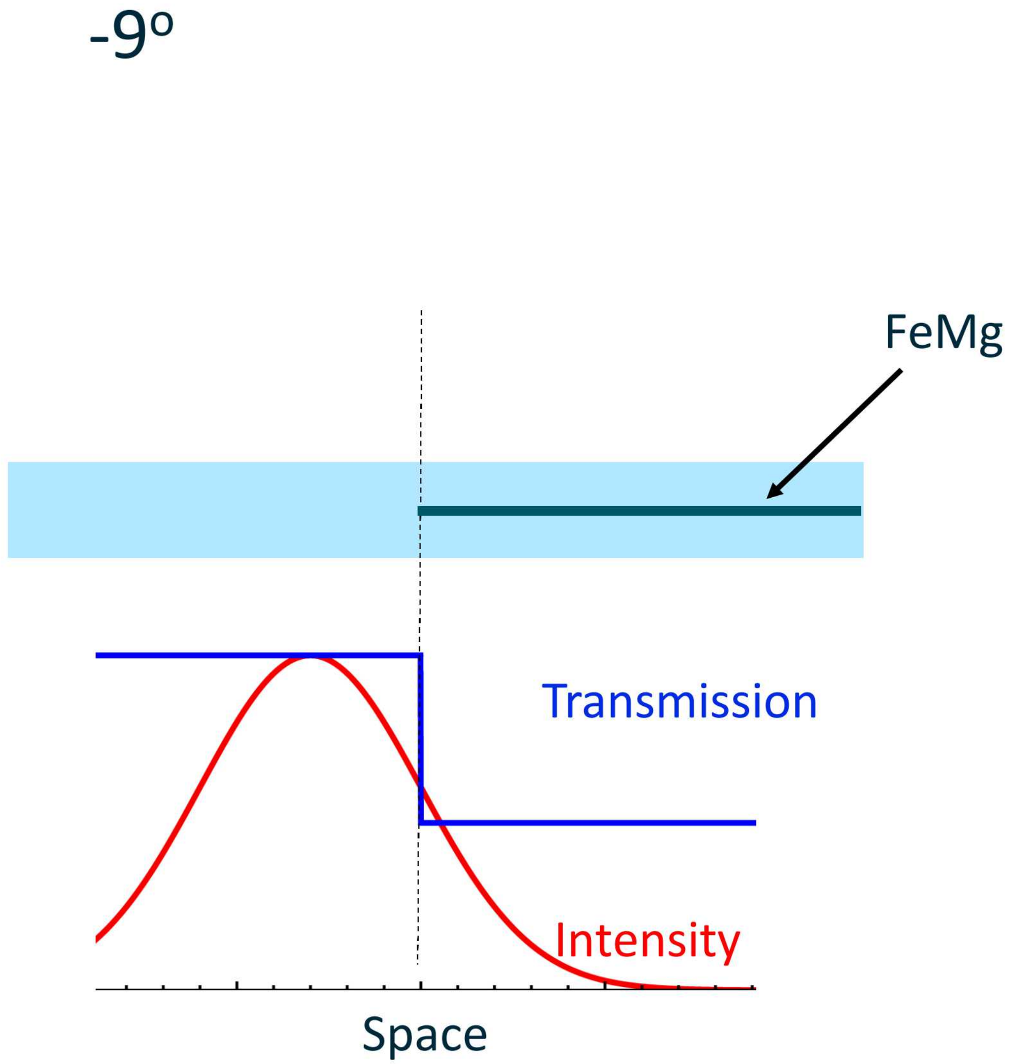

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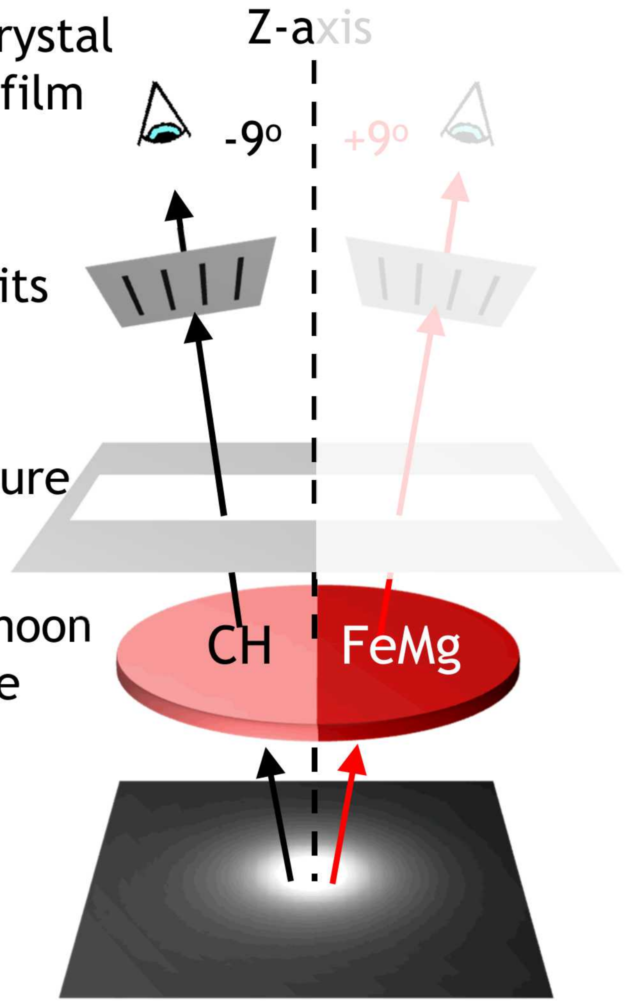

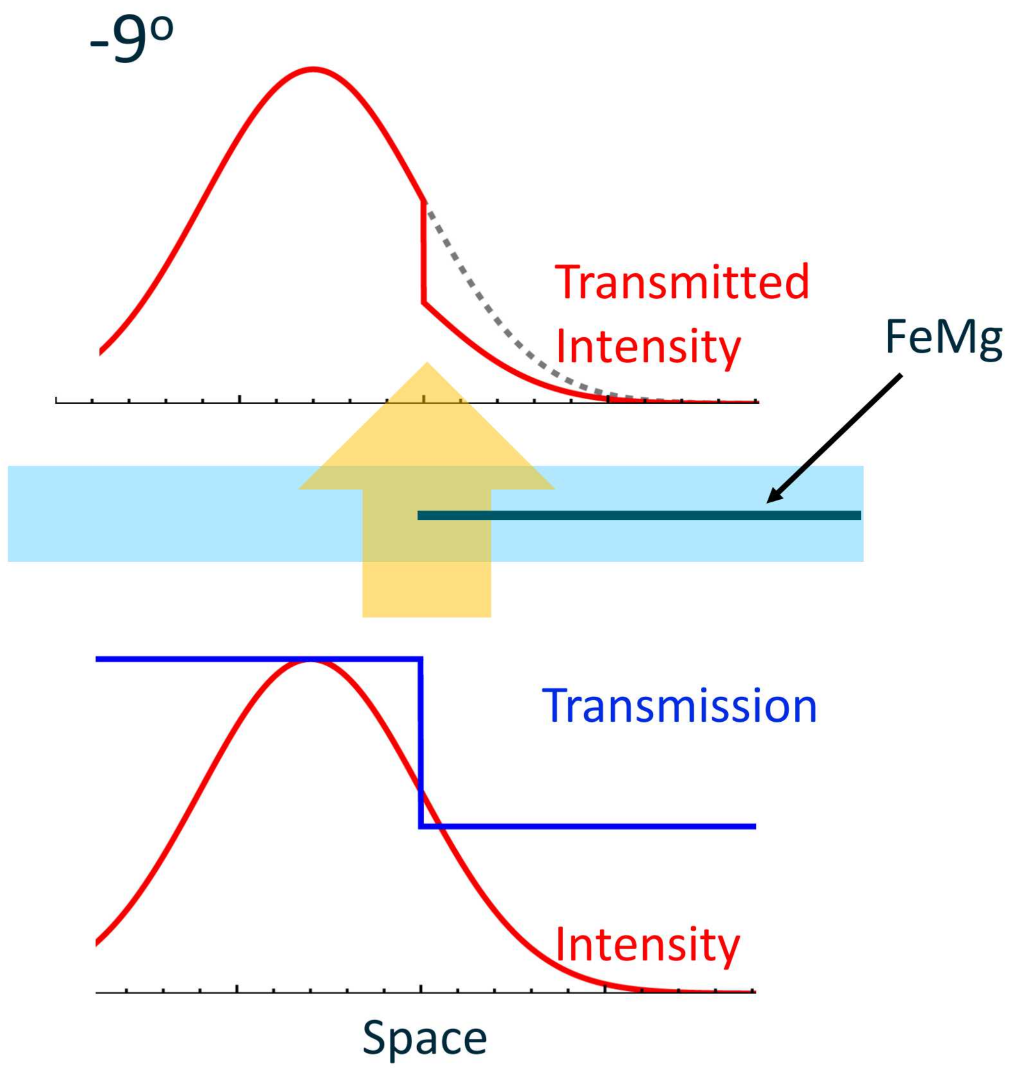

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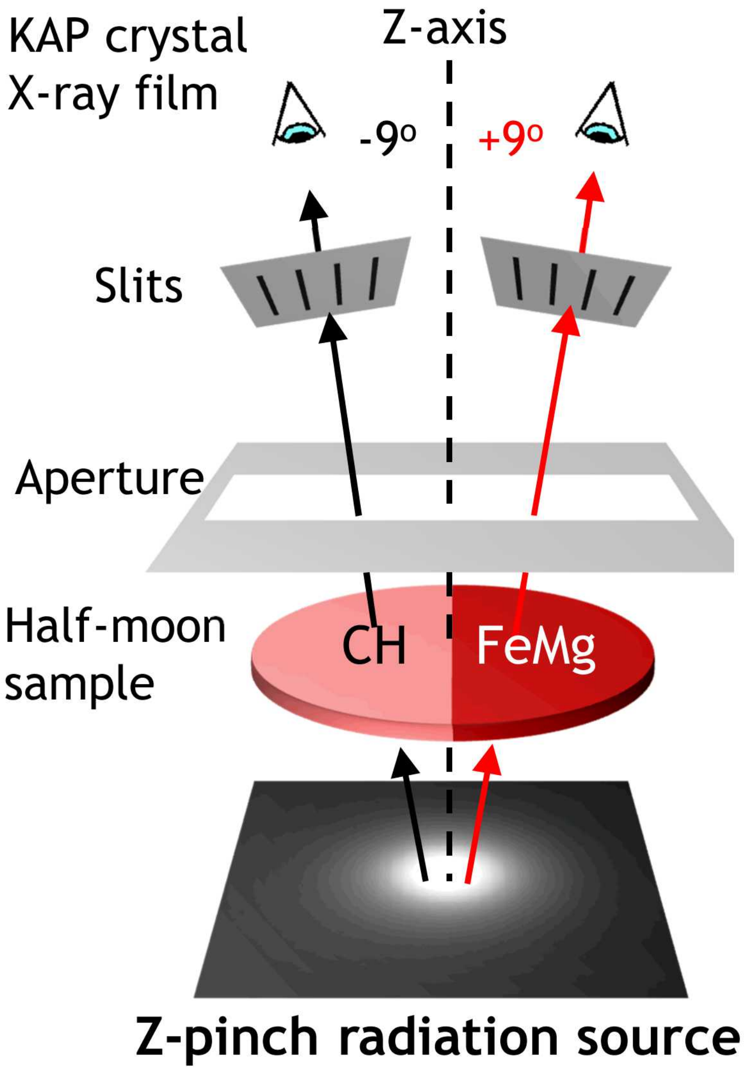
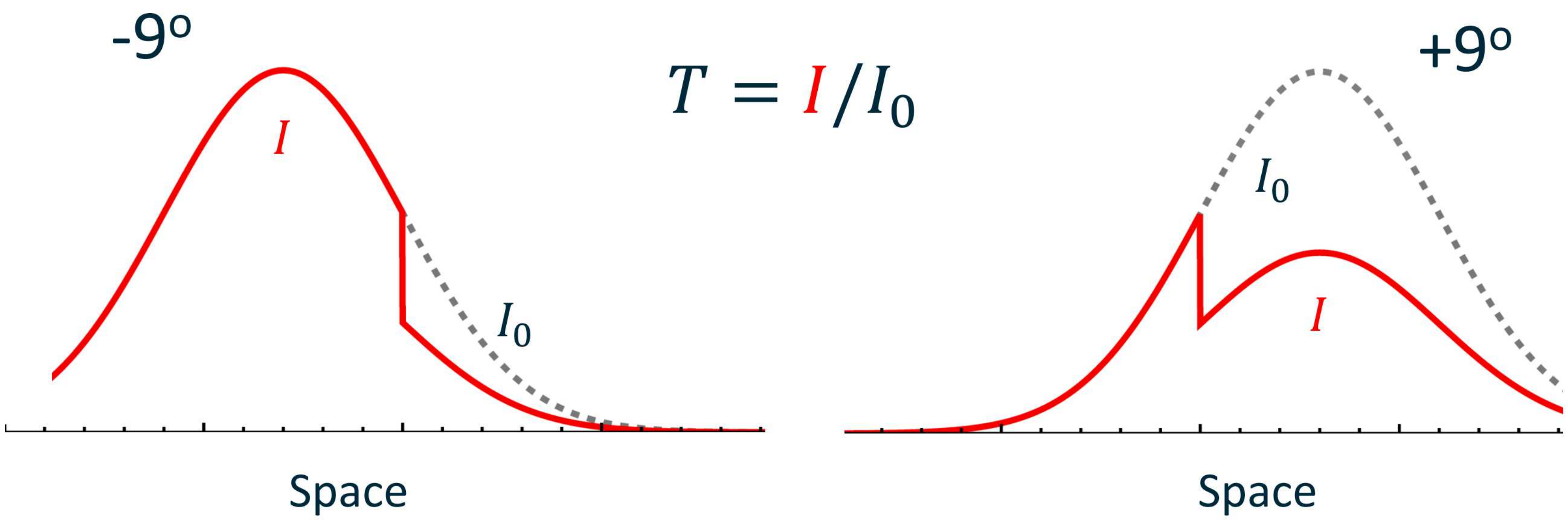
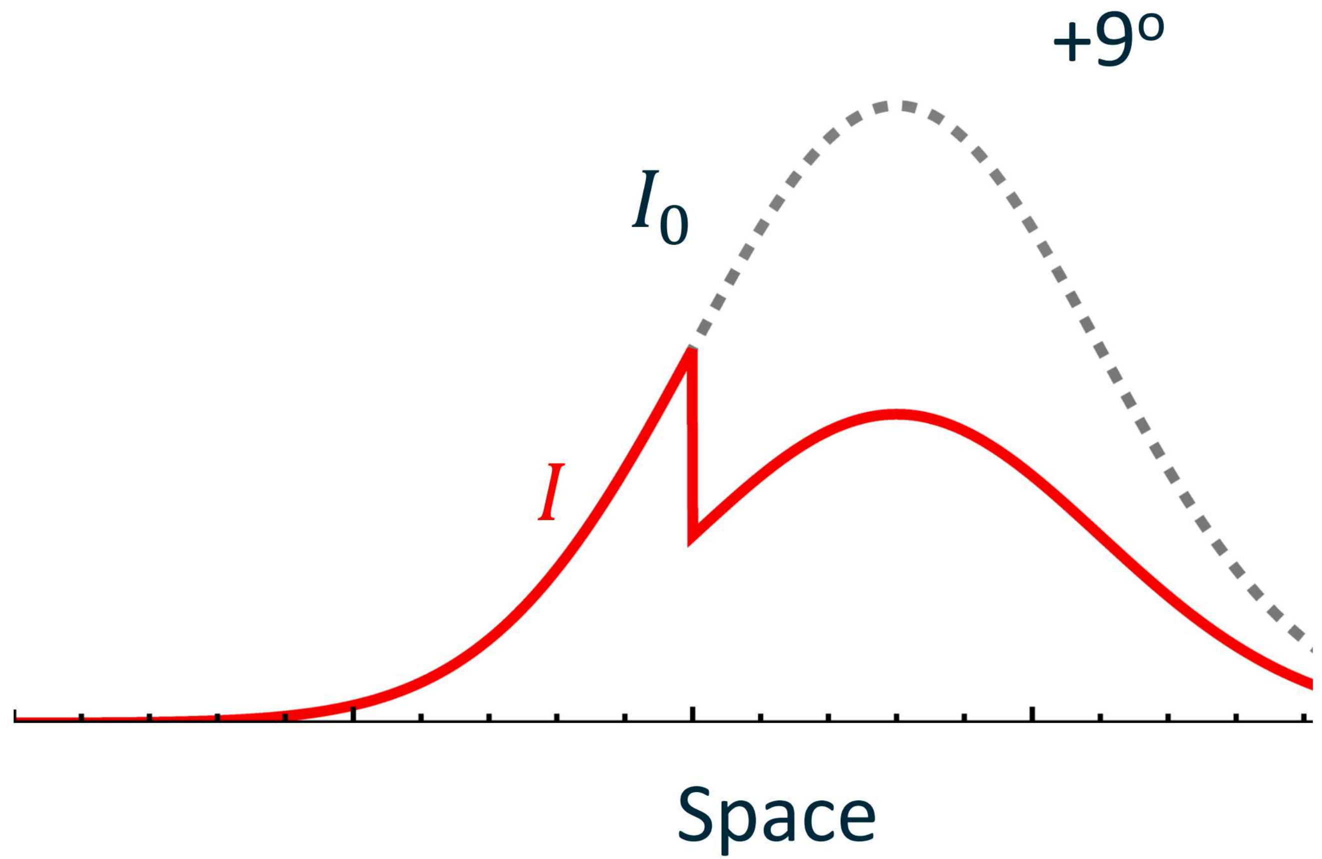




Advantage 1: Level of transmission is imprinted on spatial profile itself



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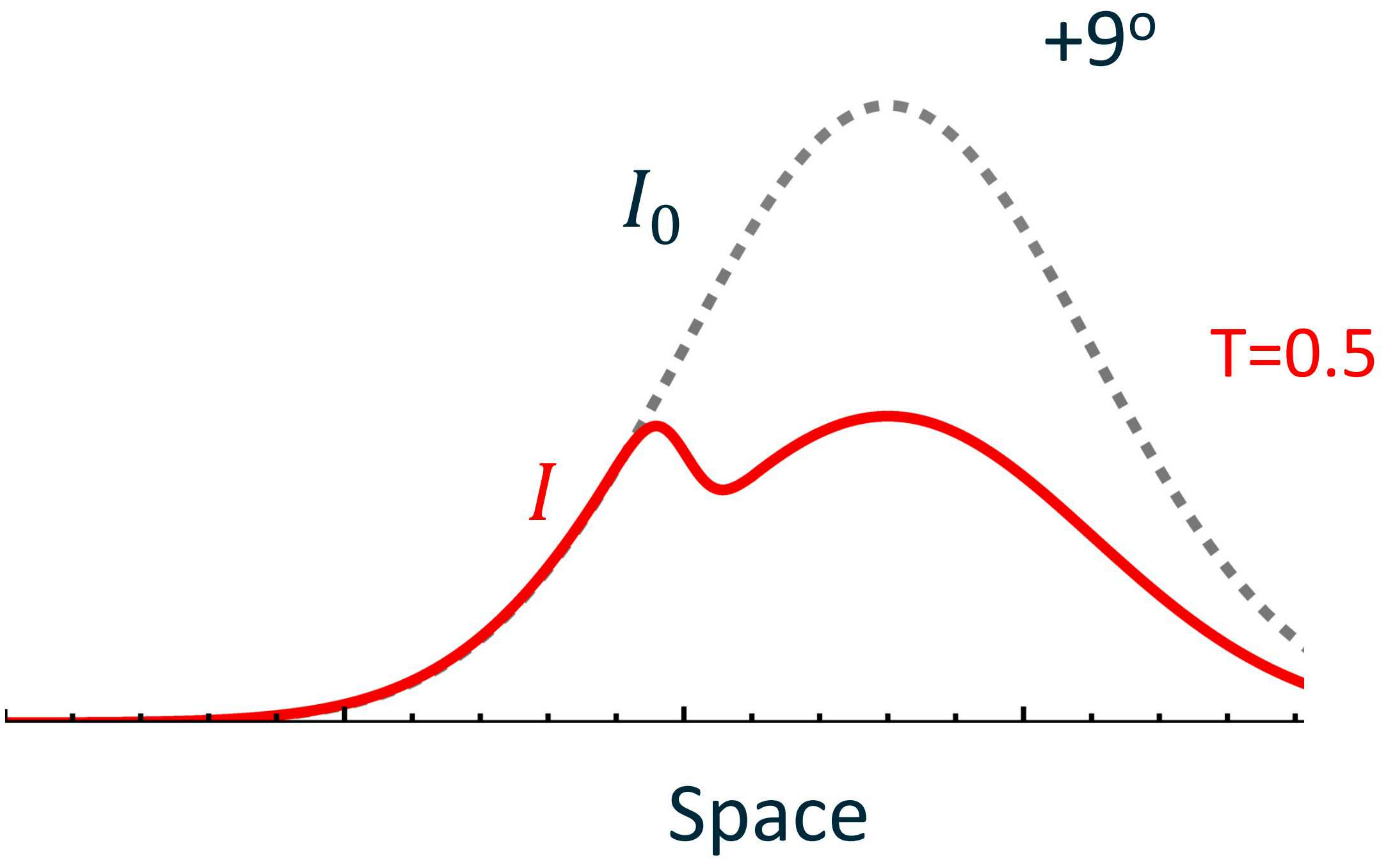

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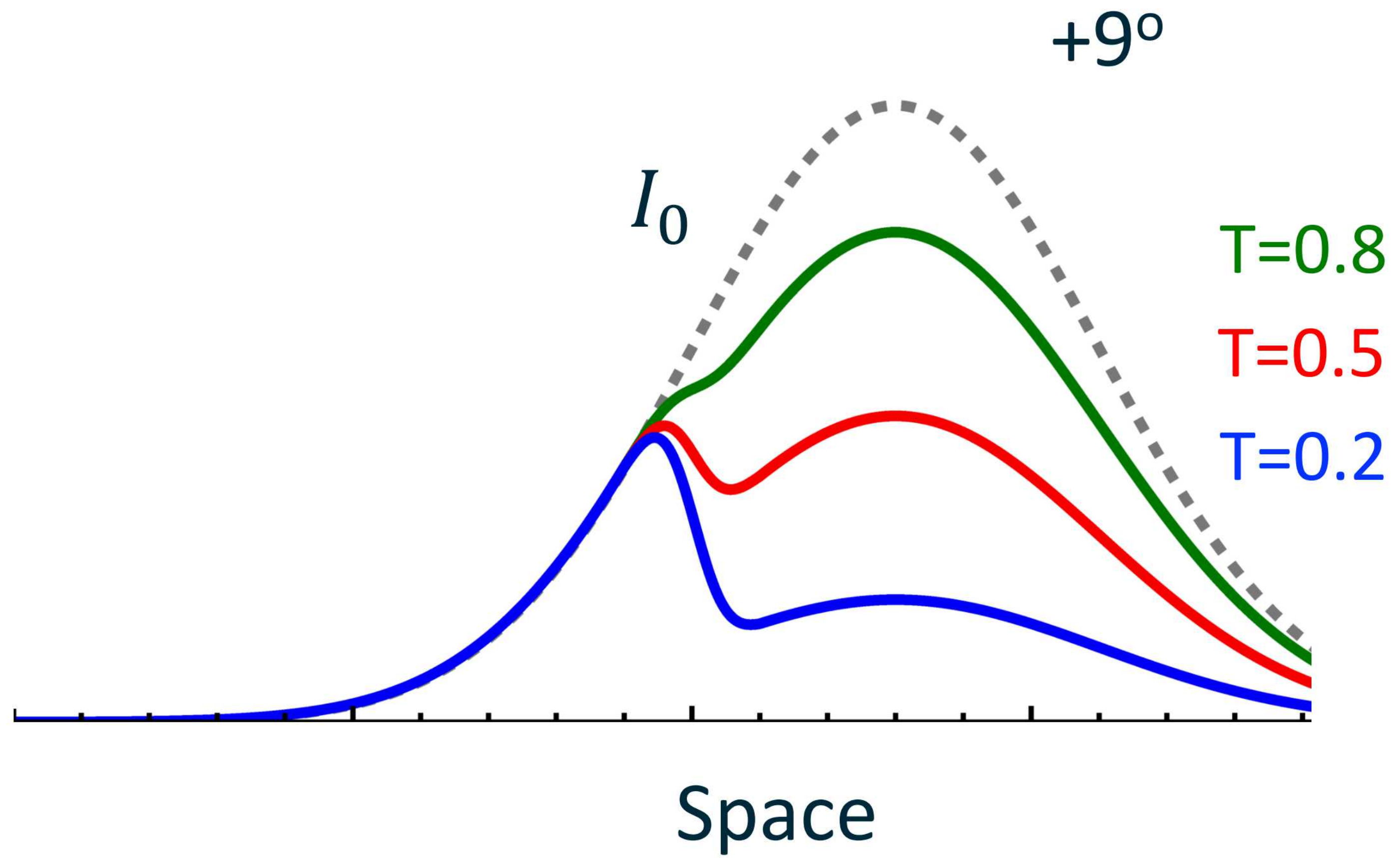

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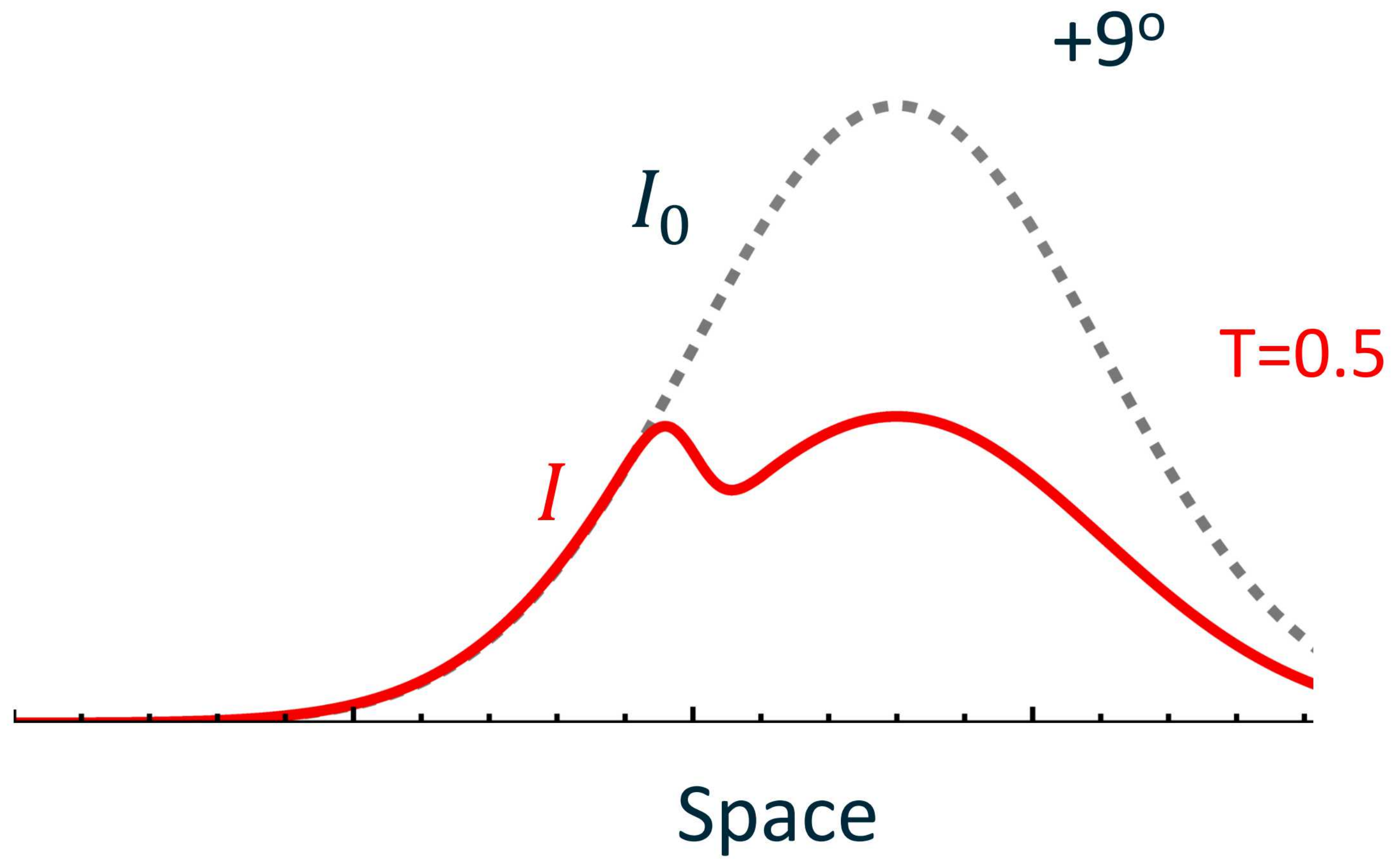

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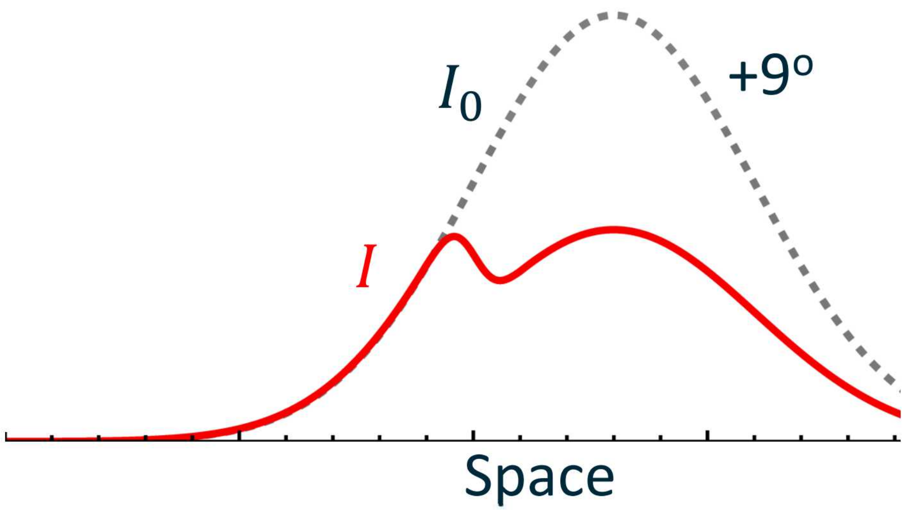
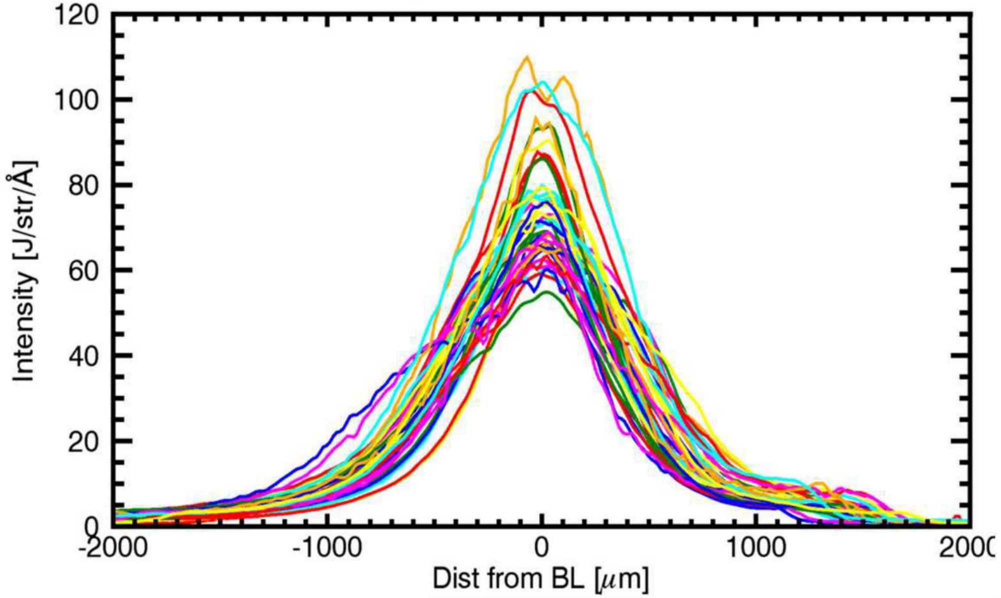
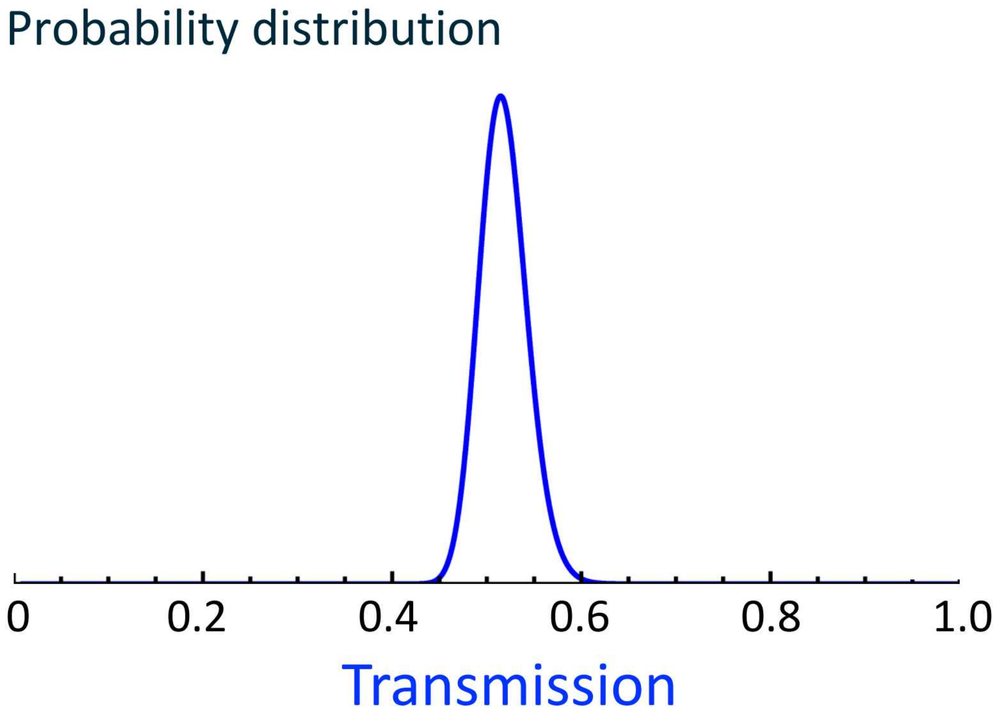
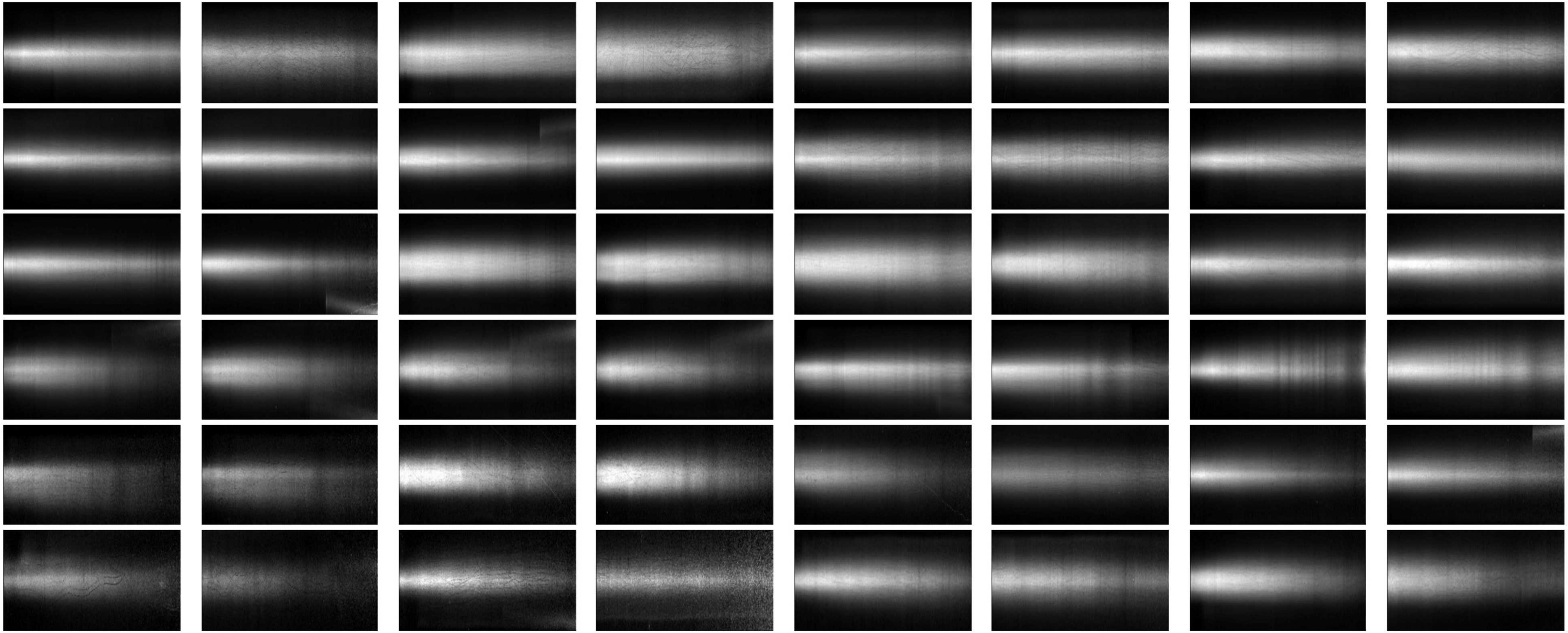






We can study reproducibility of spatial shape and brightness from our calibration shots



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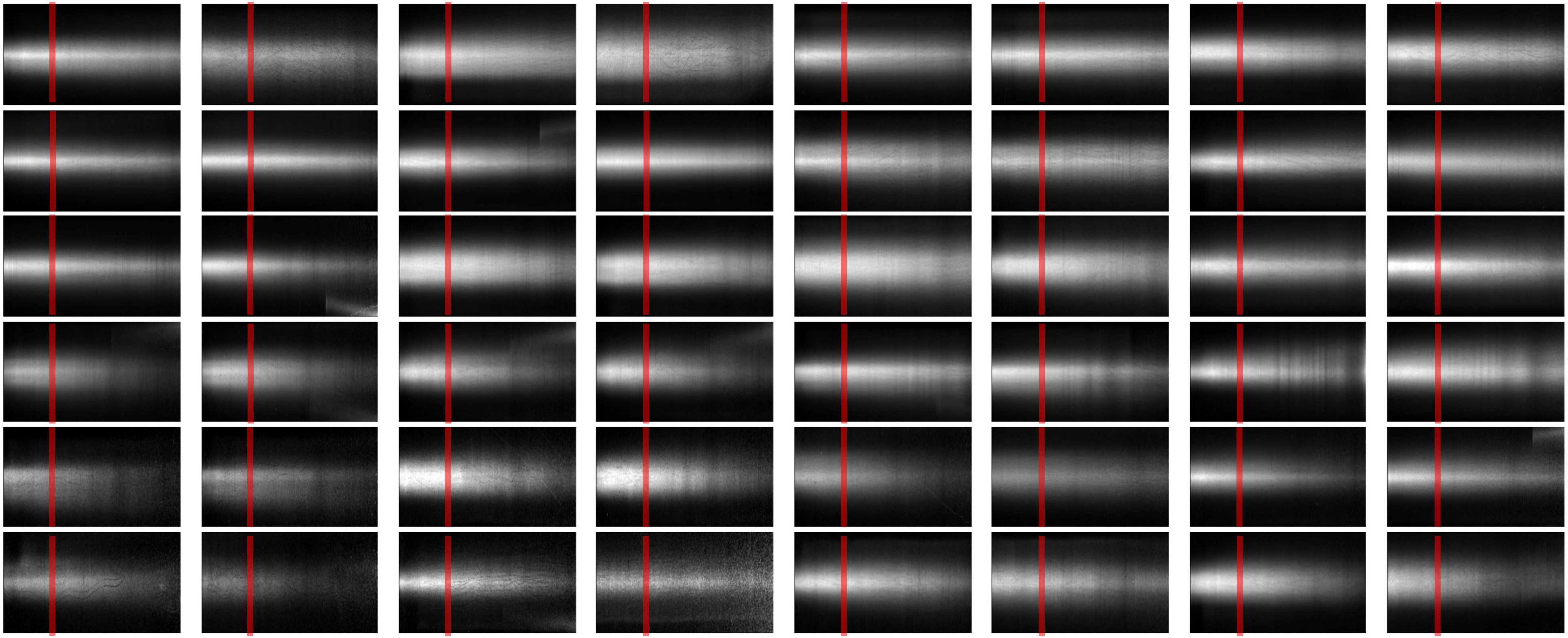

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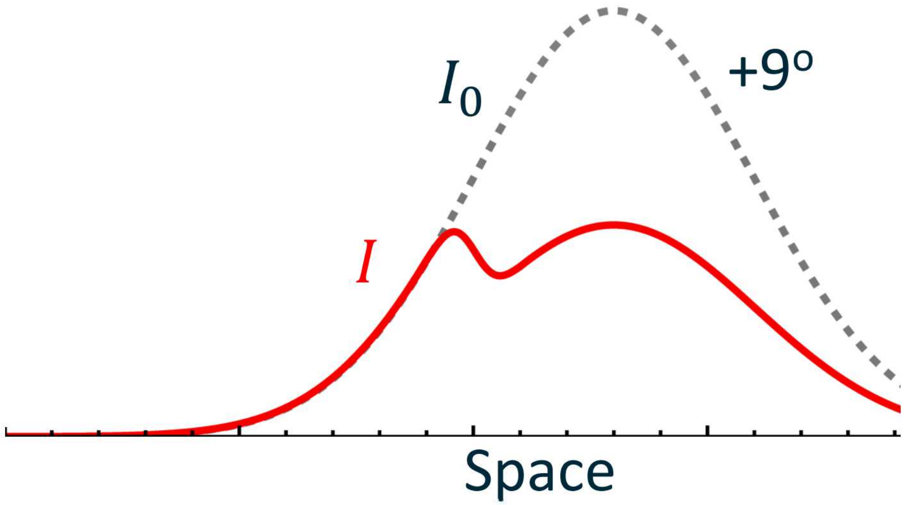

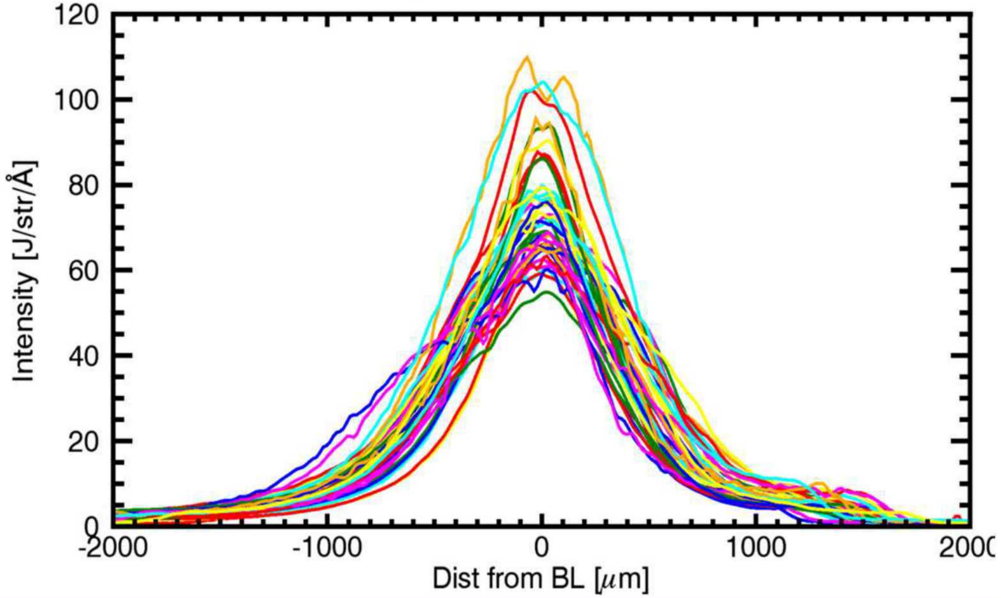

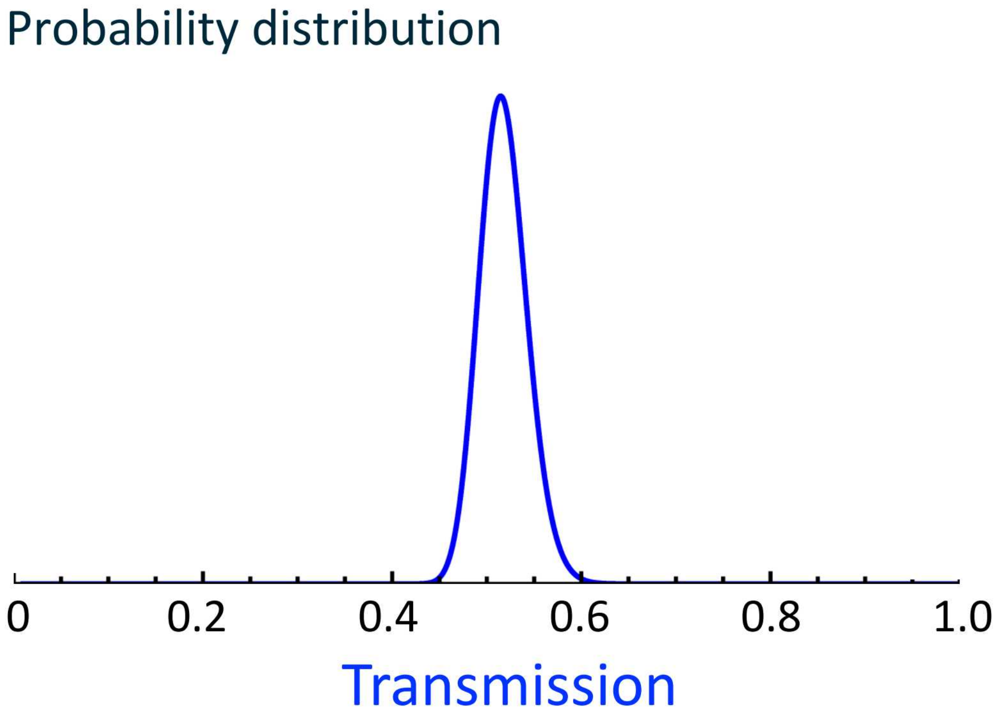

Transmission PDF* is analytically derived from attenuated profile and calibration shot statistics

*PDF = Probability distribution function

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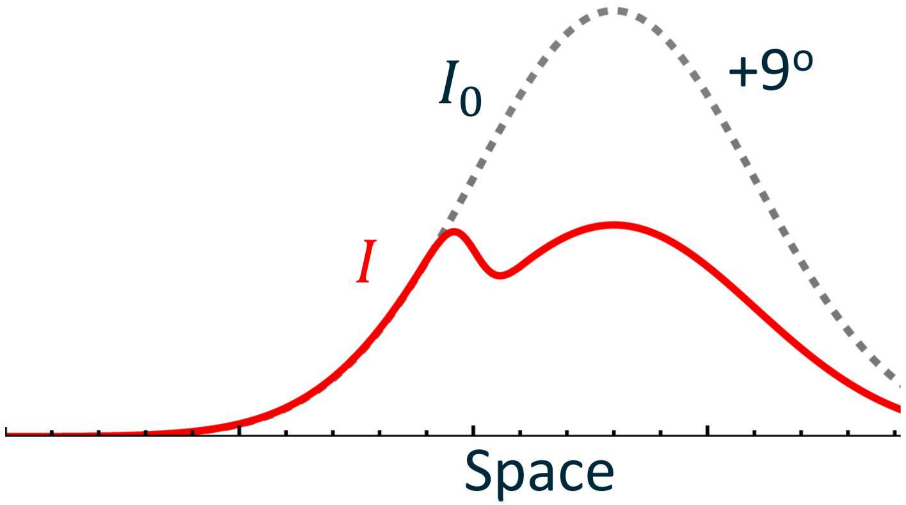

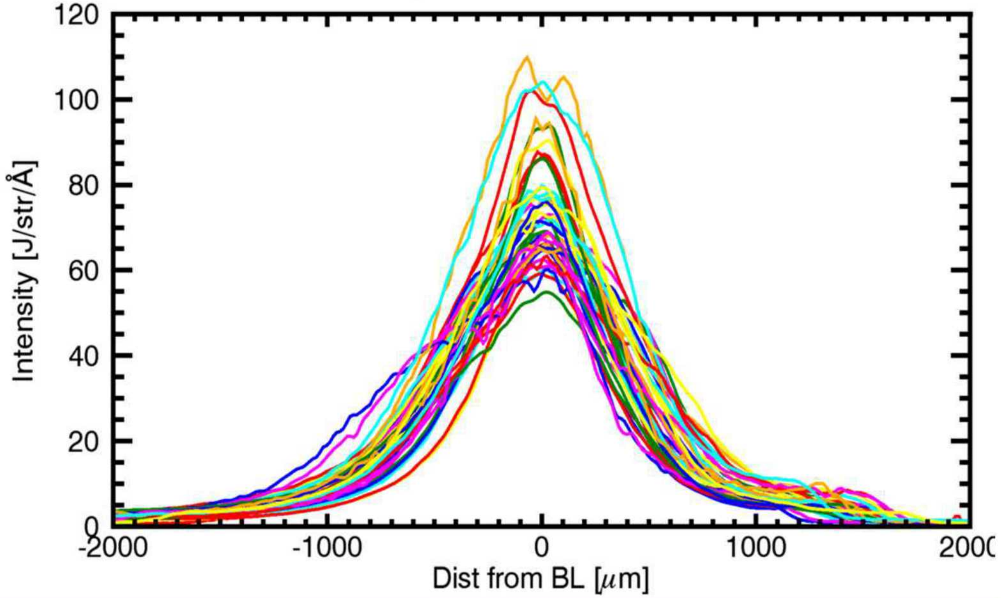

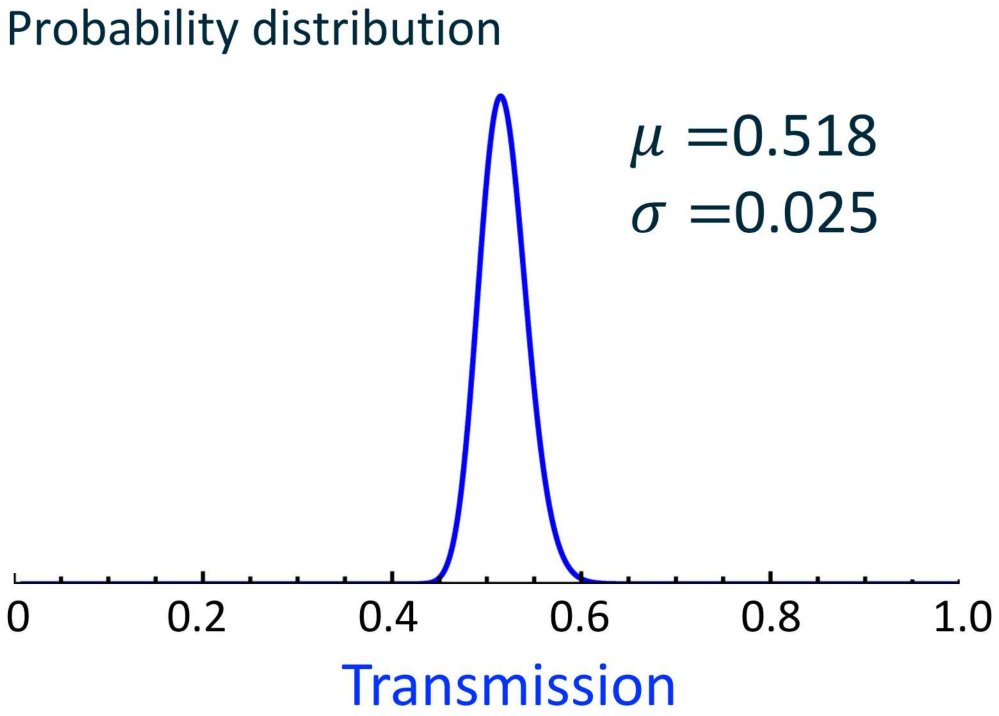

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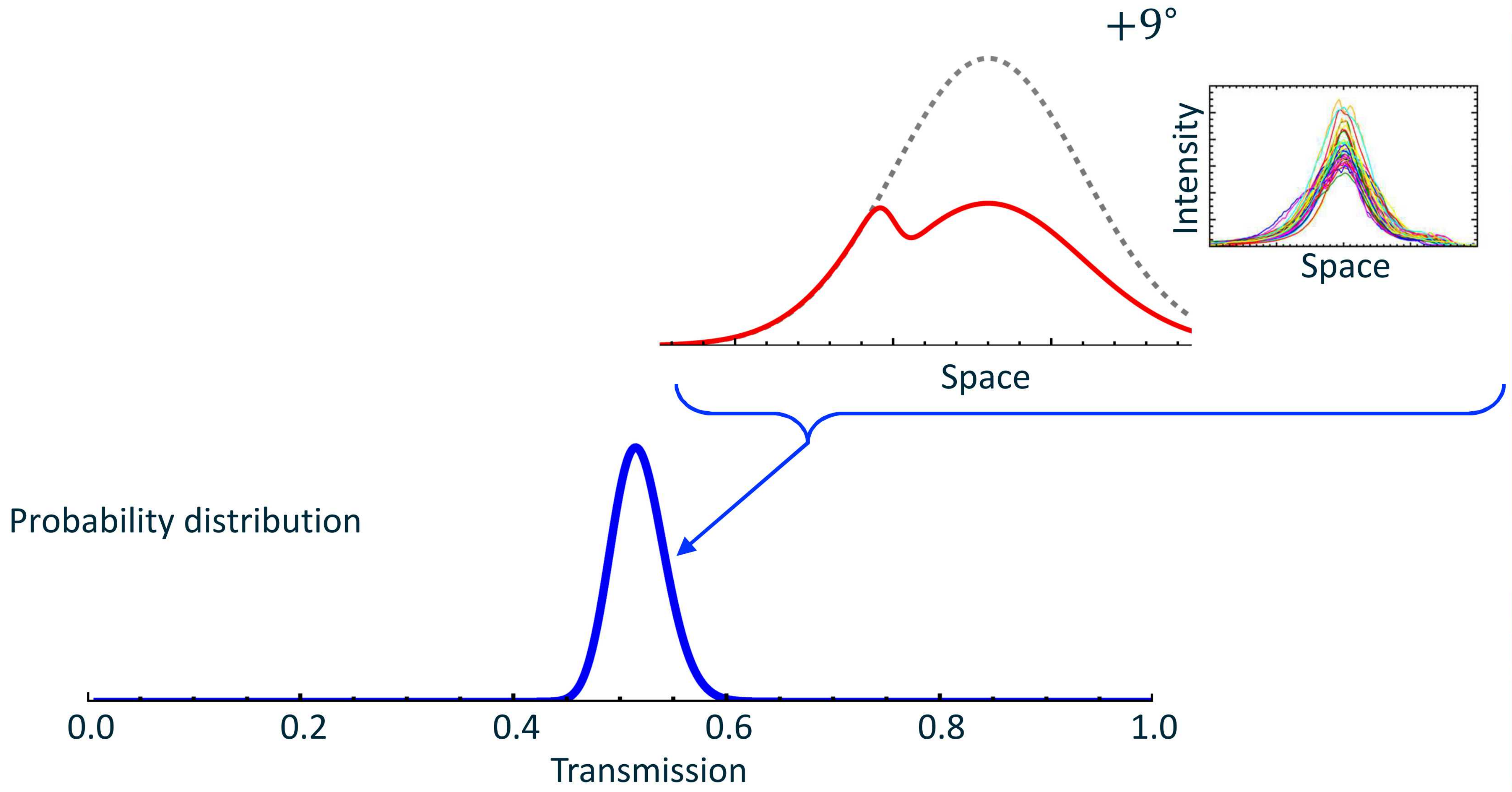
Advantage 2: Transmission is analyzed for $\pm 9°$ data independently on a equal footing



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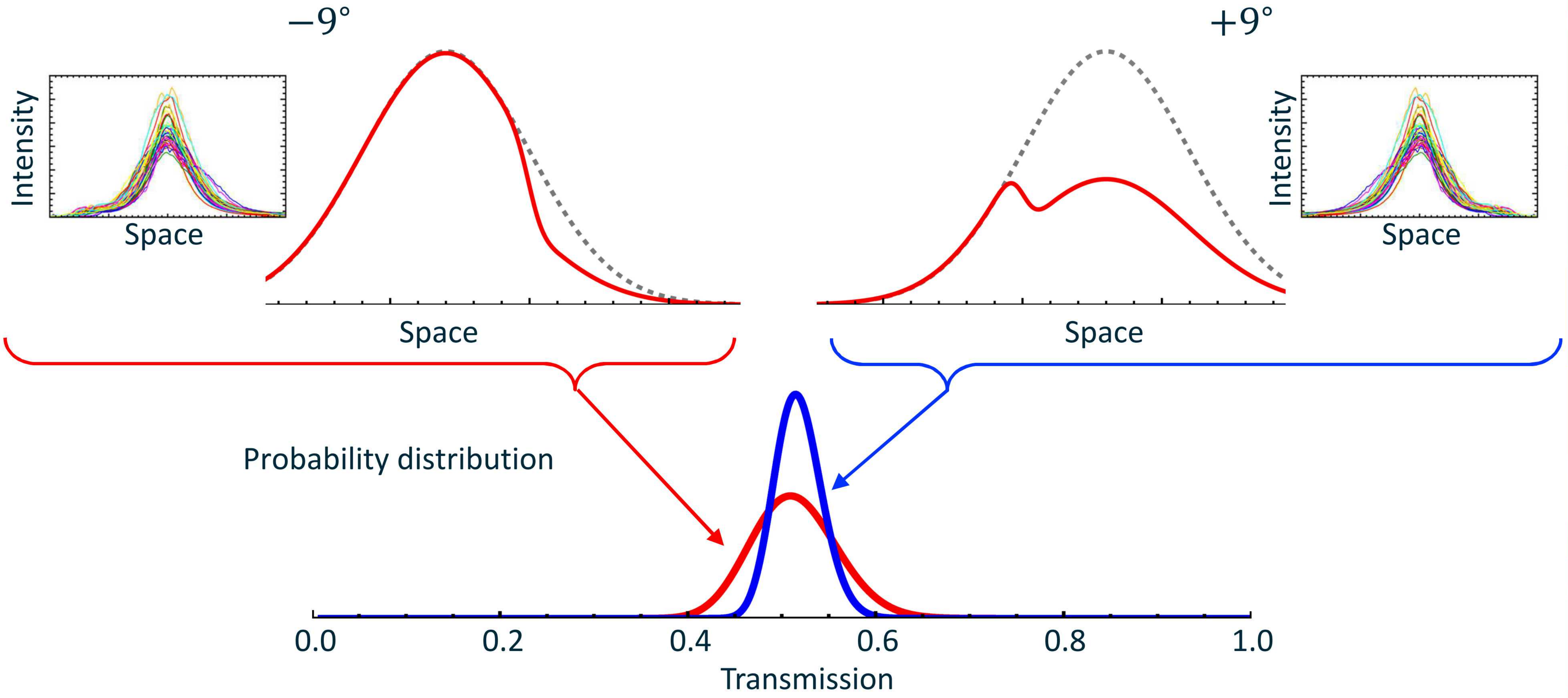

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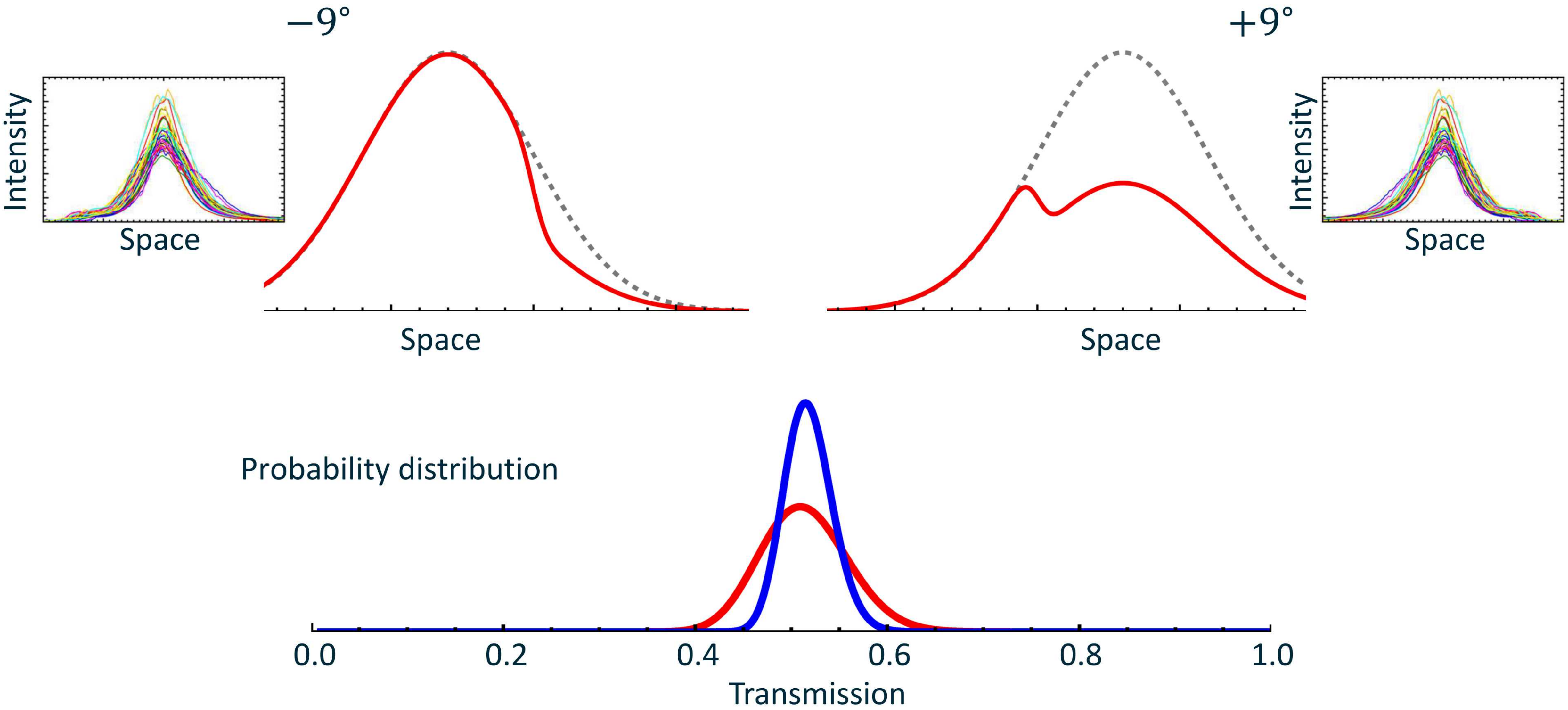

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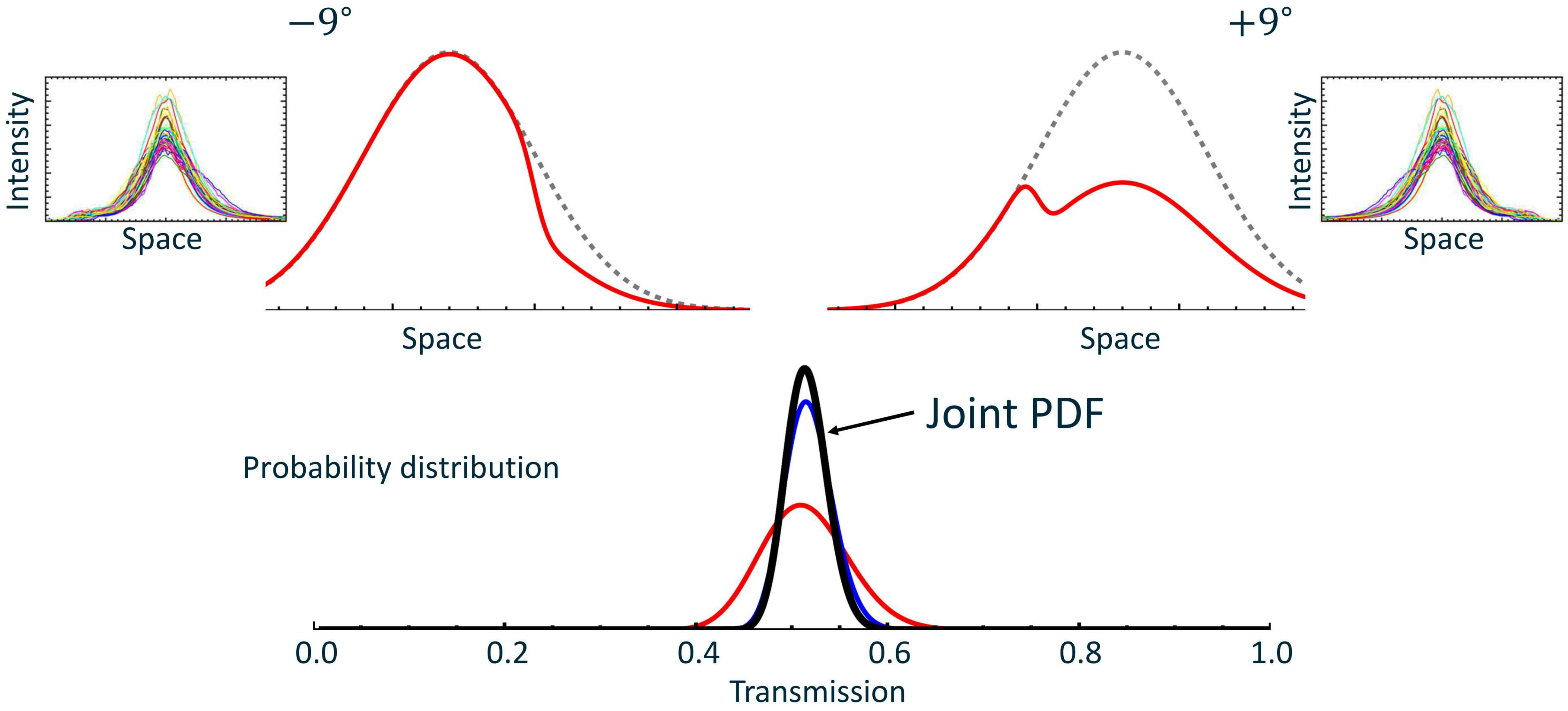
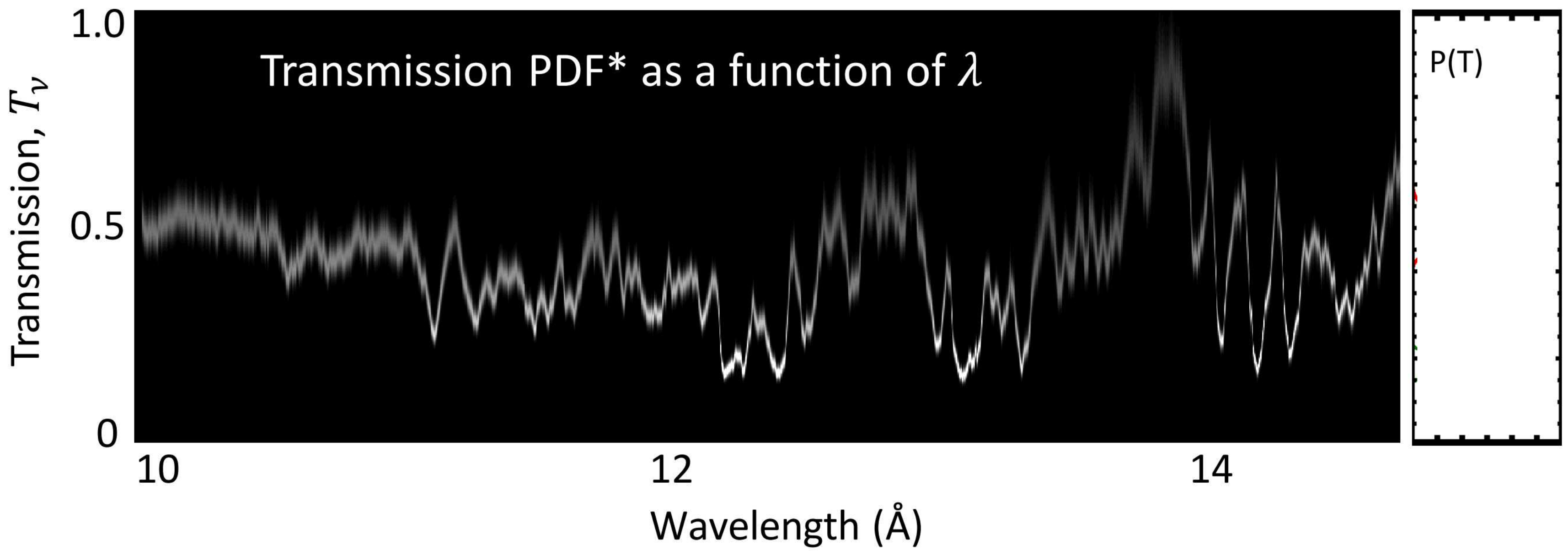


Advantage 3: Transmission of each wavelength is analyzed independently



*PDF = Probability distribution function

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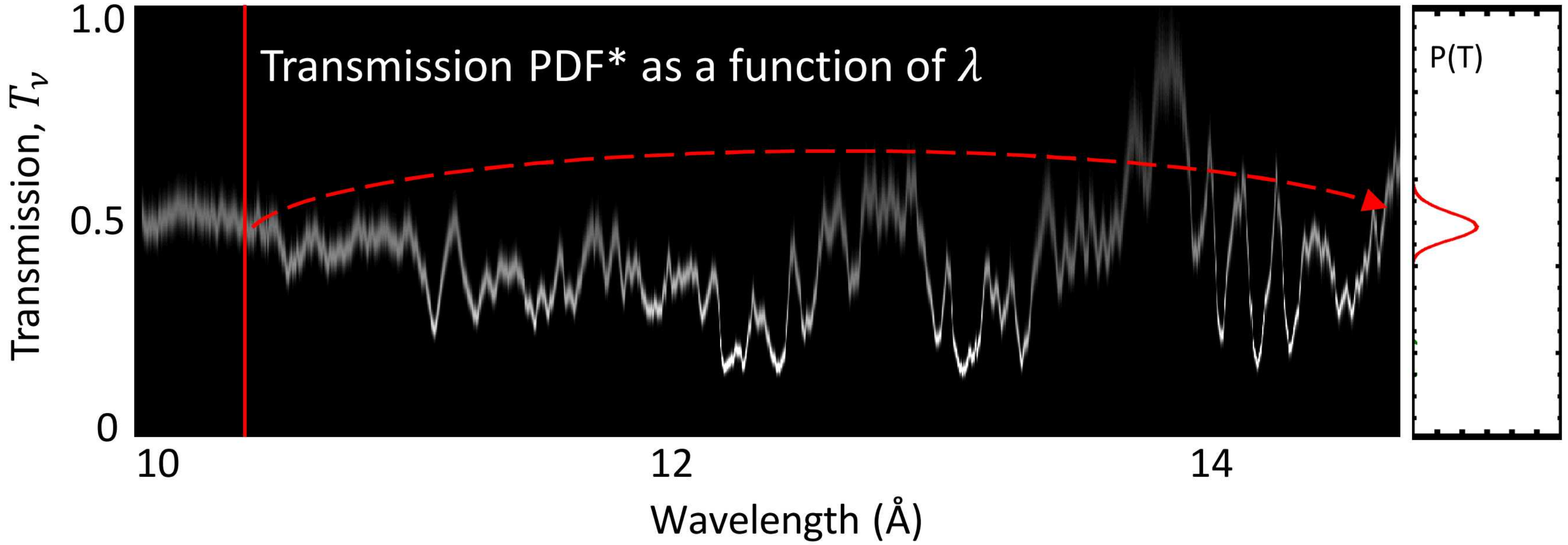

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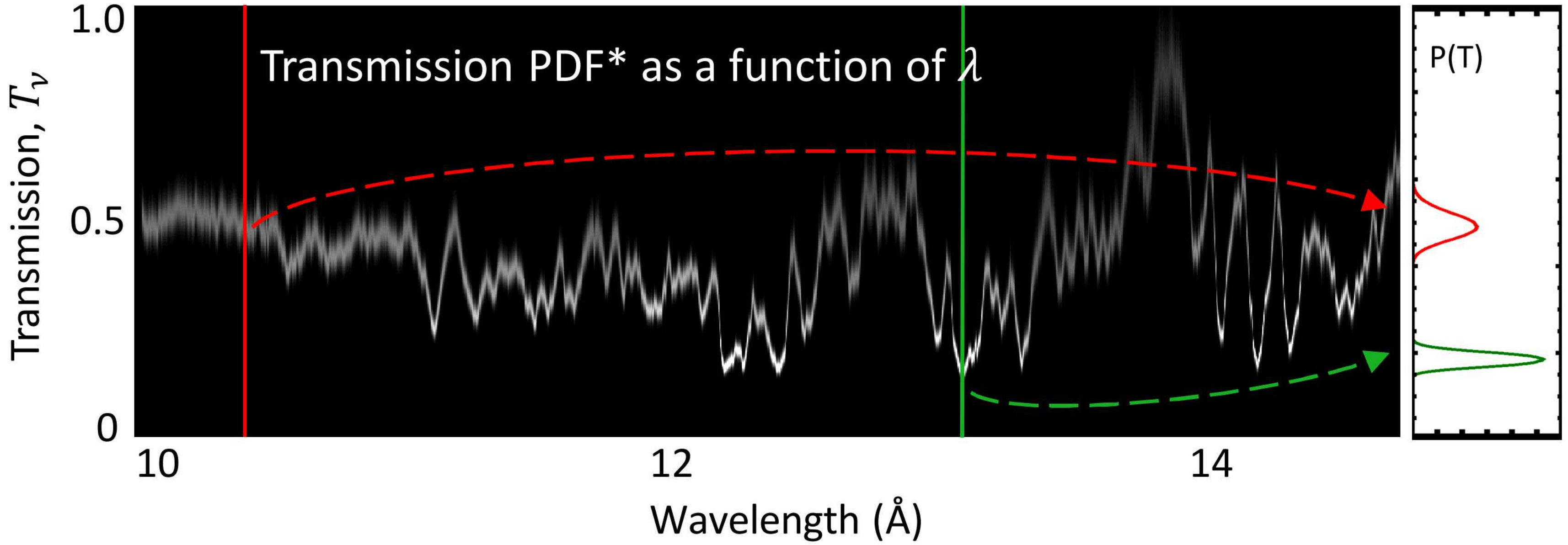
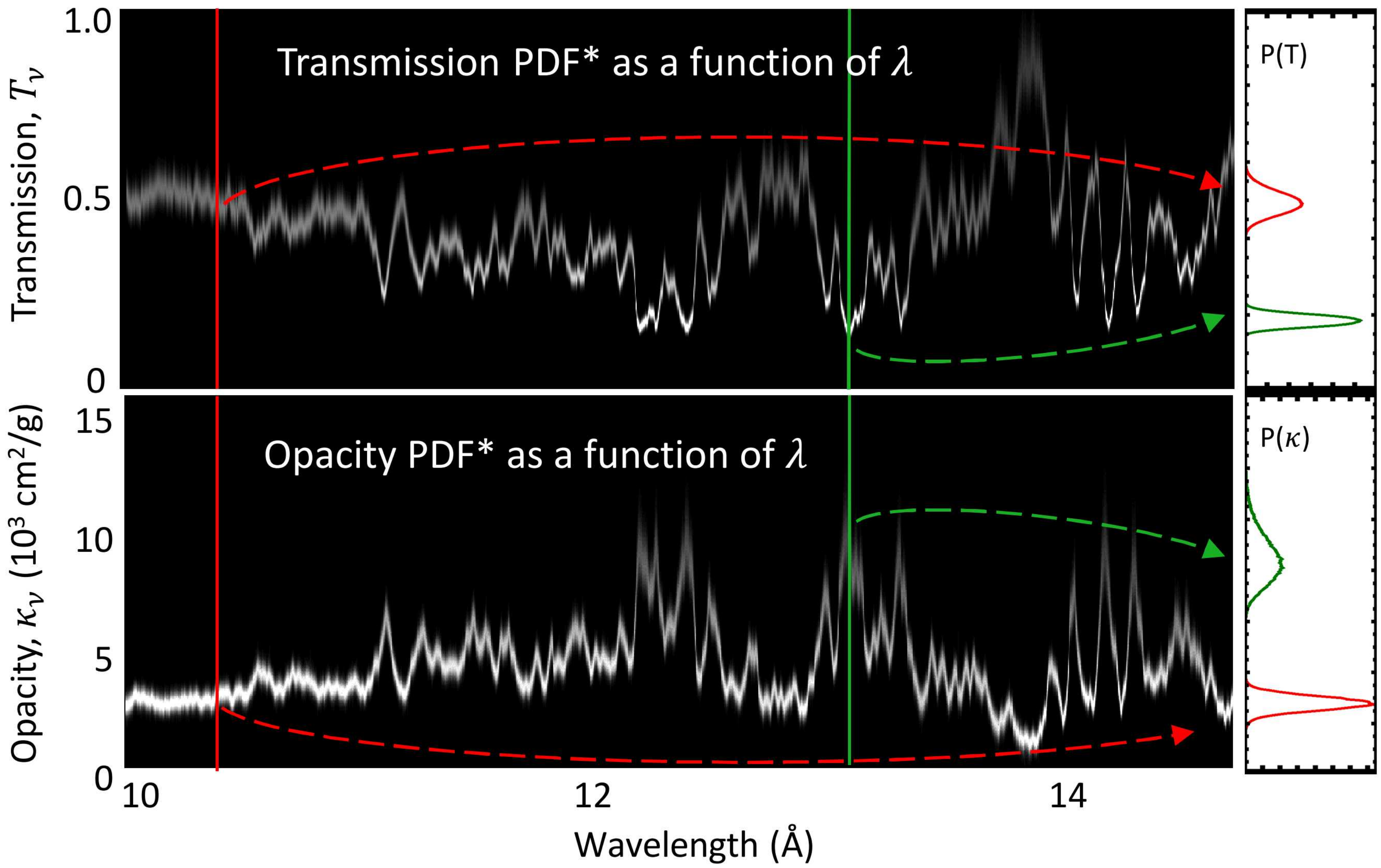


*PDF = Probability distribution function

Transmission PDF is converted to opacity PDF using Monte-Carlo technique, propagating various uncertainties



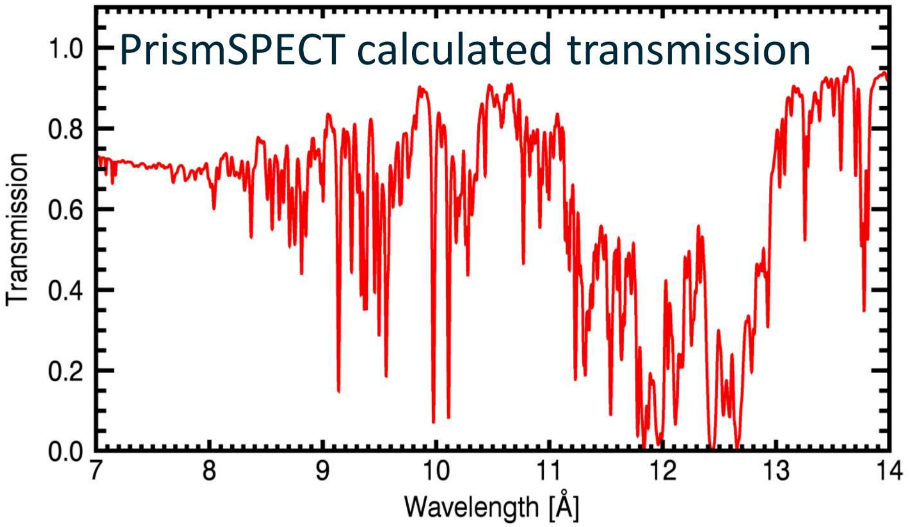
Monte-Carlo to propagate errors:

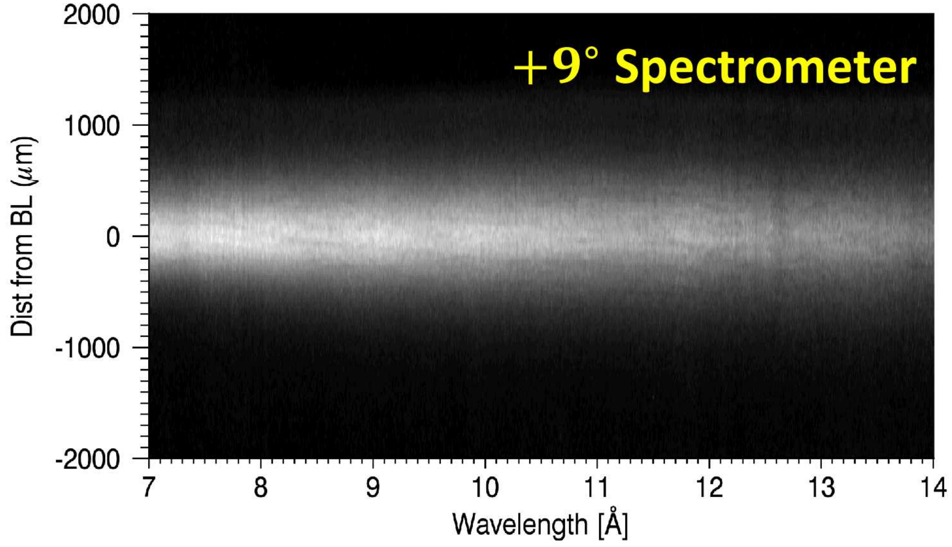
- Transmission error
- Background subtraction error
- Areal density error

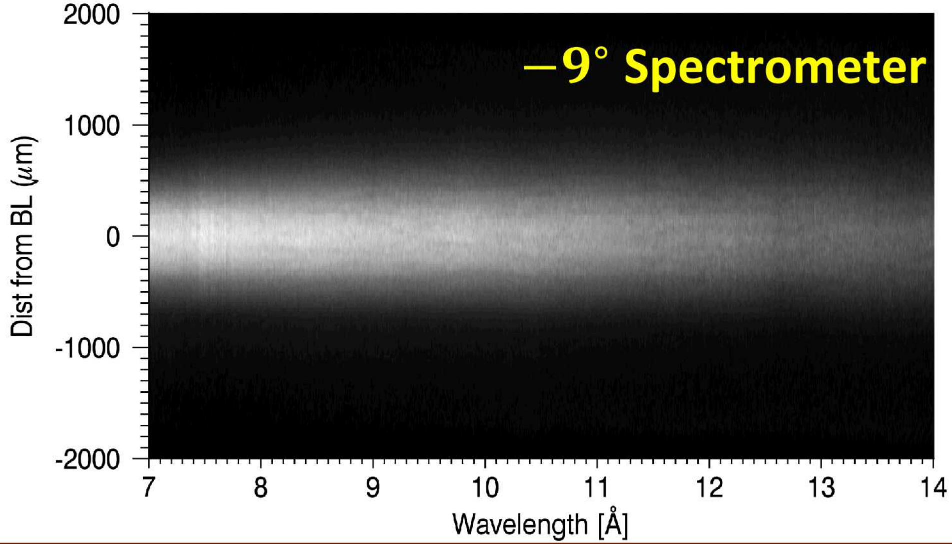
*PDF = Probability distribution function

How do we know if the method is accurate?

Synthetic data is created by multiplying calibration-shot data by calculated transmission







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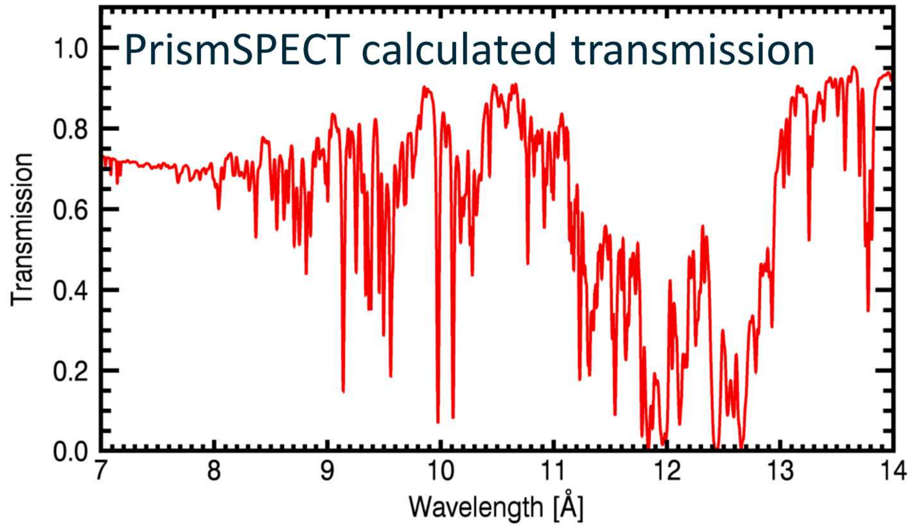
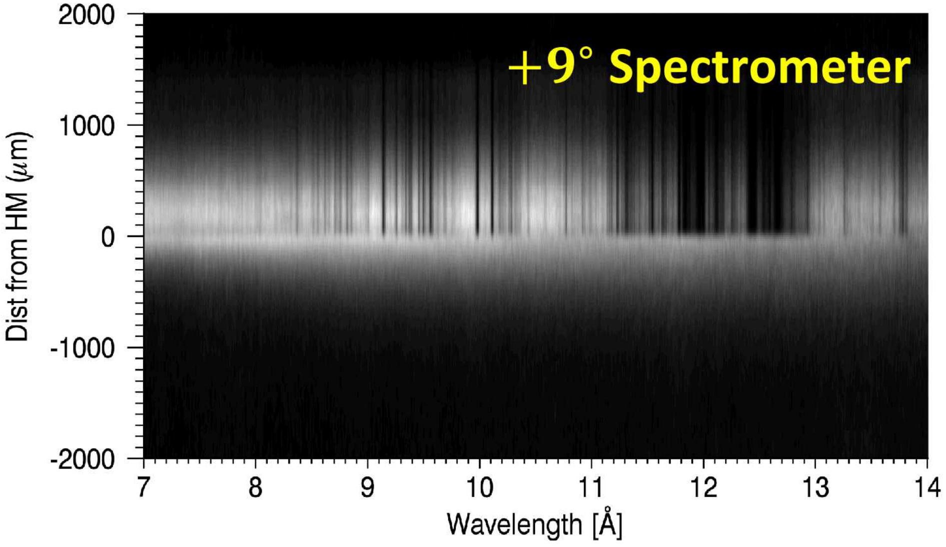
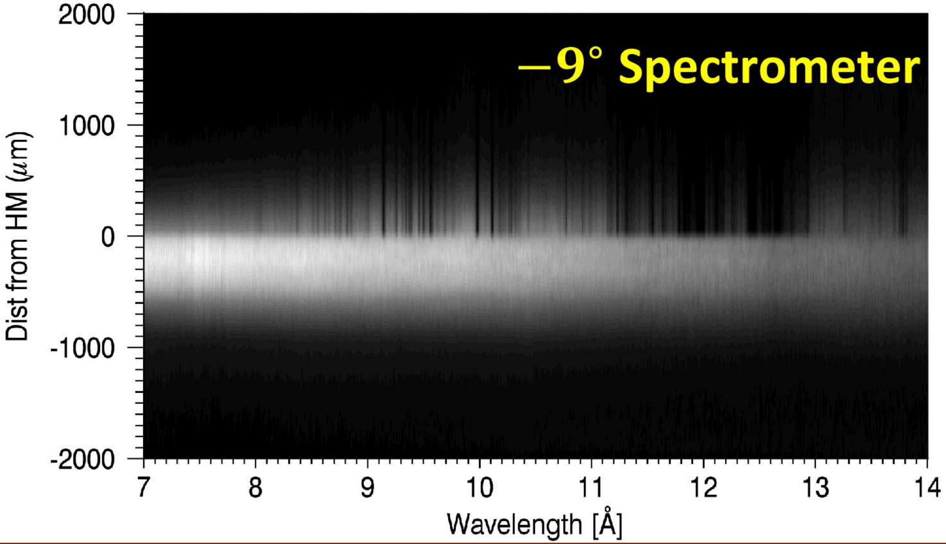
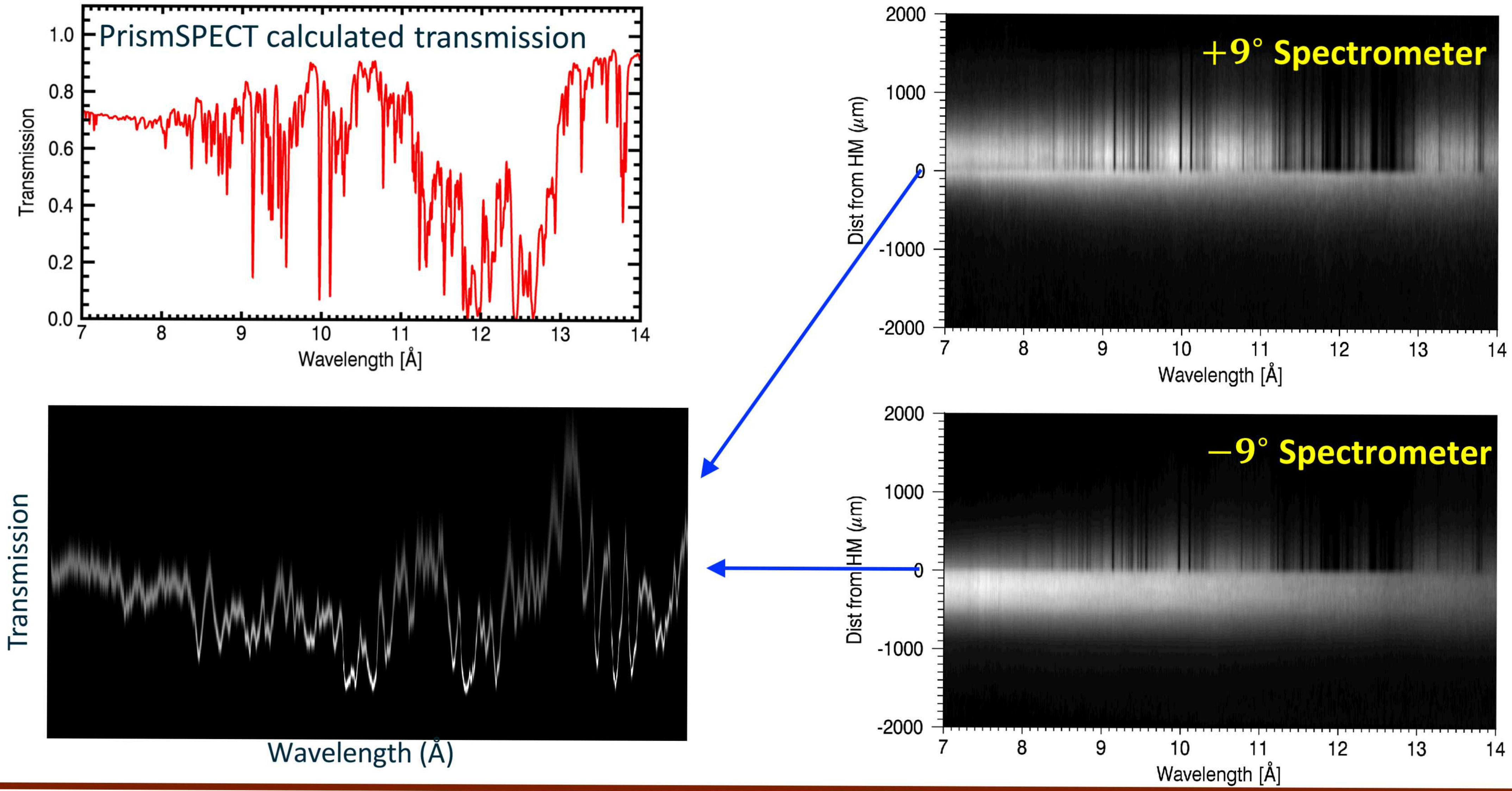






Attenuated spatial profiles are analyzed to produce transmission PDF as a function of λ



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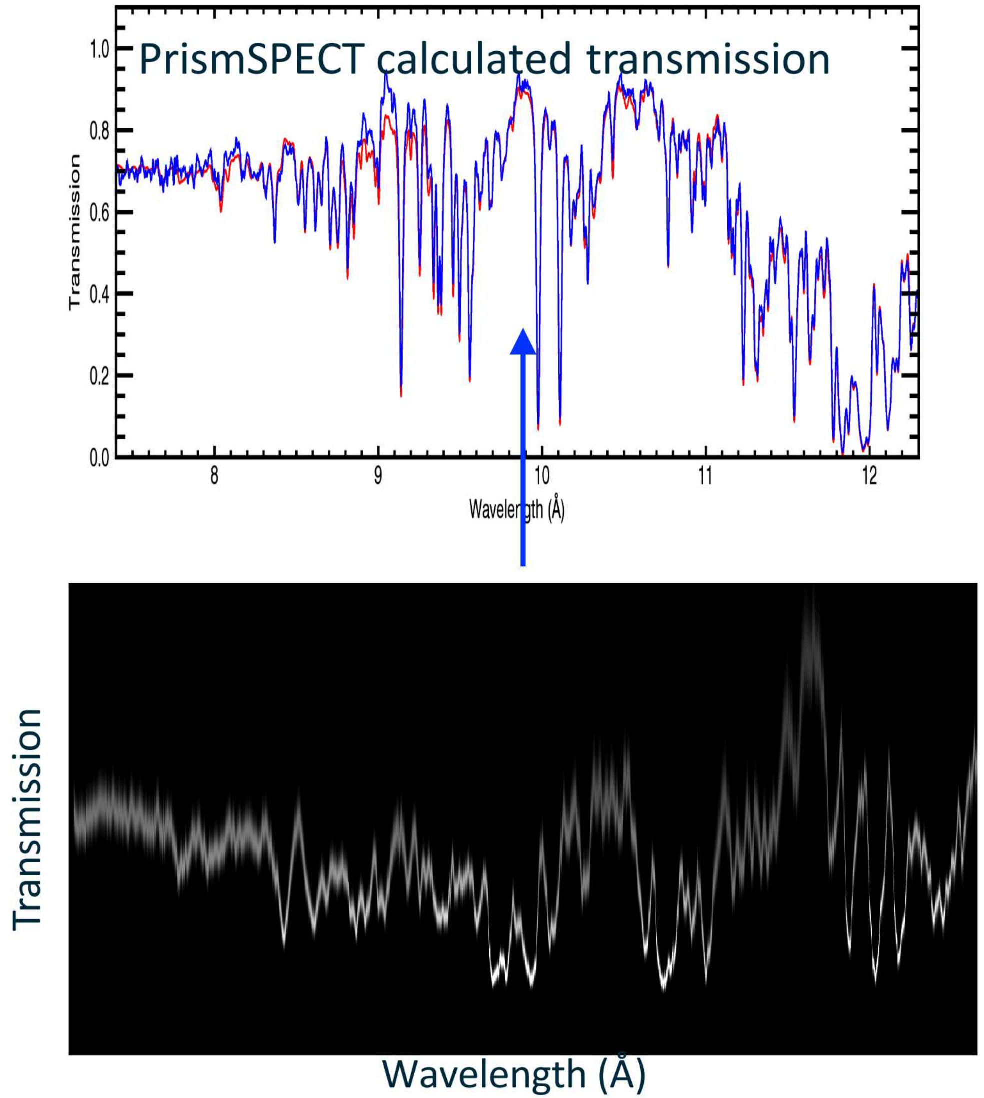
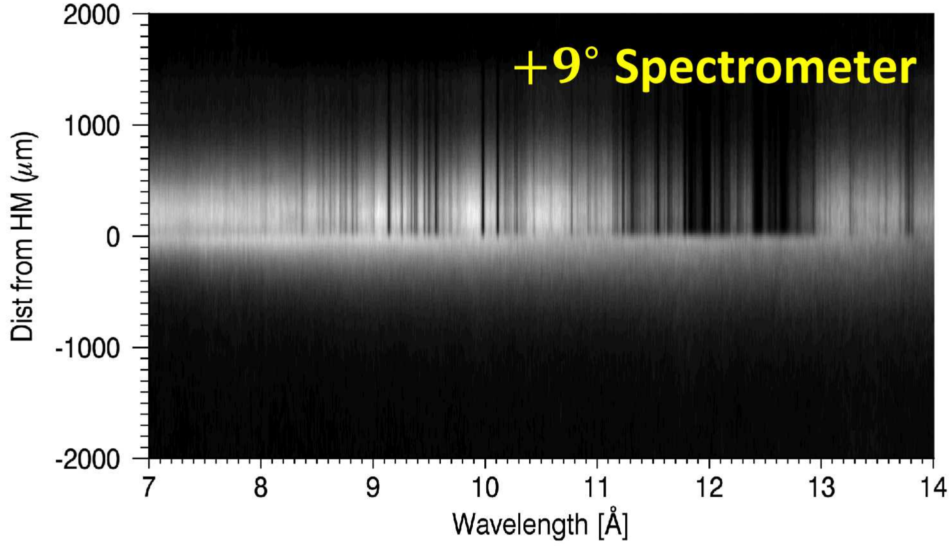
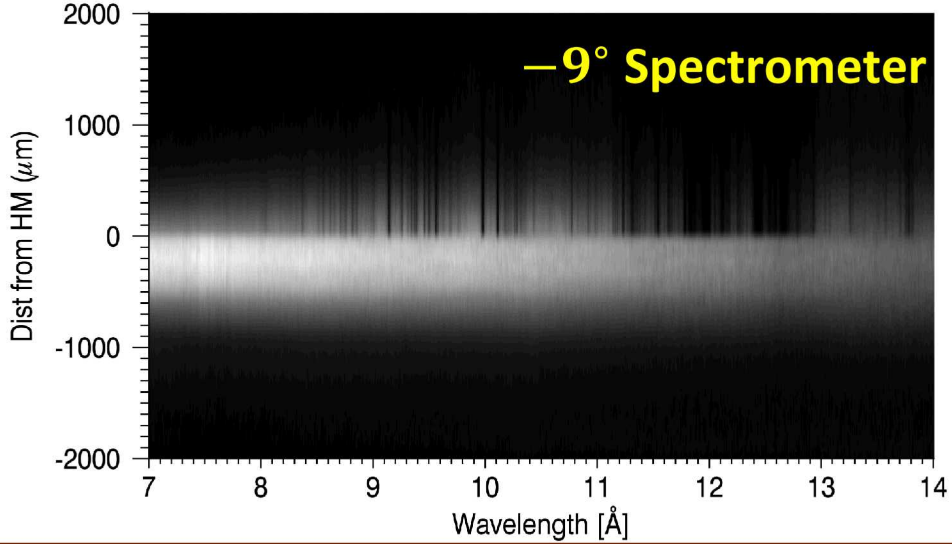
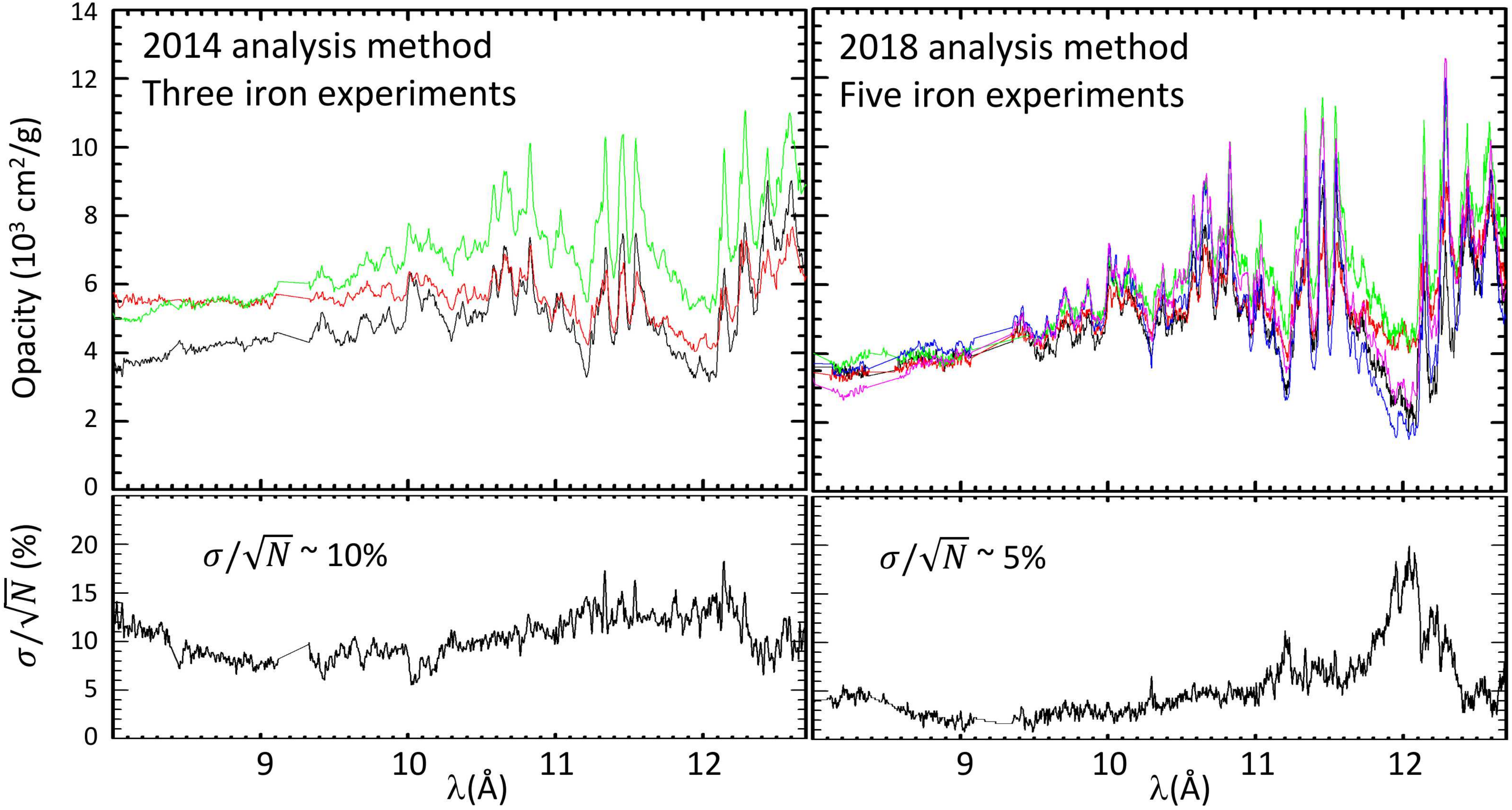


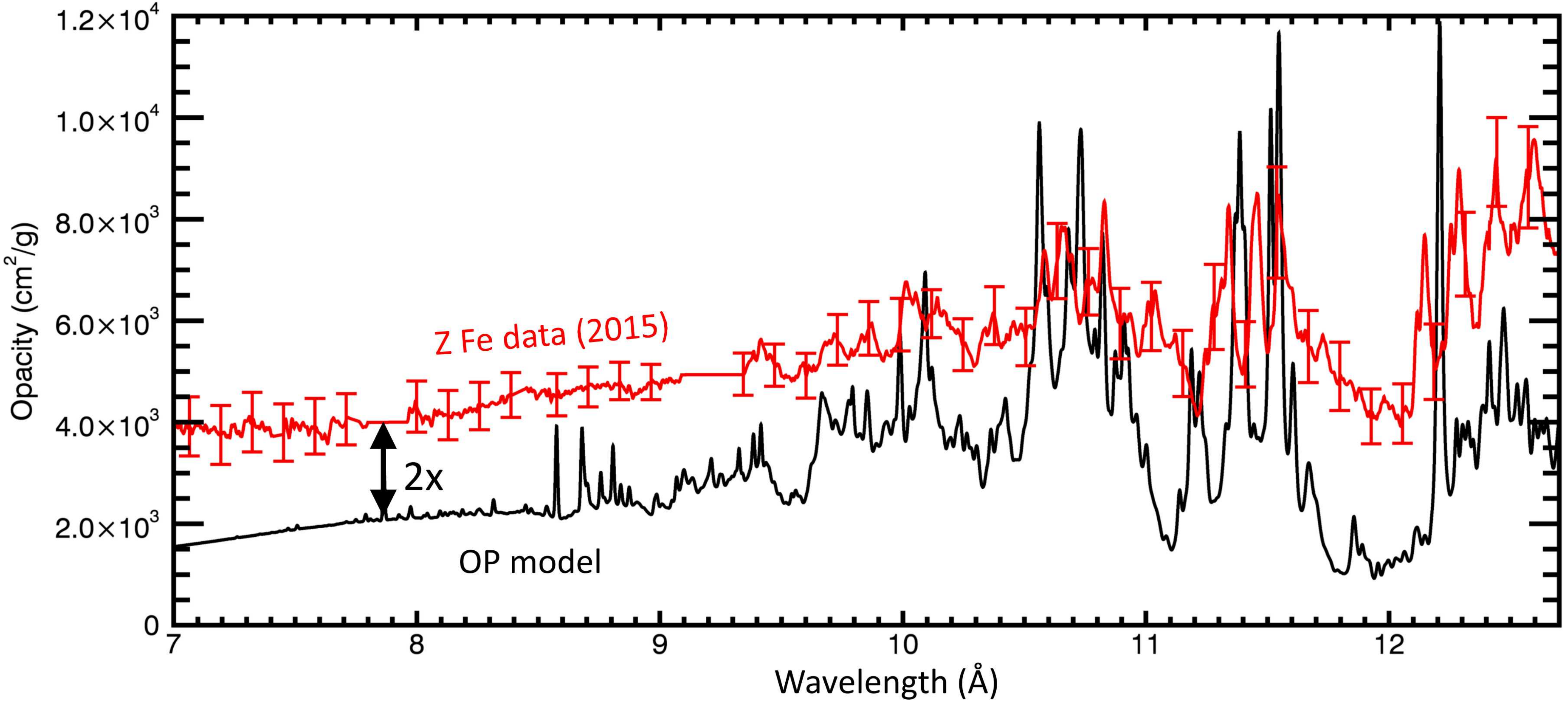




Both refined analysis and more experiments helped to improve shot-to-shot agreement on Anchor2 Fe



Analysis from 2015 showed 2x higher quasi-continuum opacity than astrophysical opacity-model prediction



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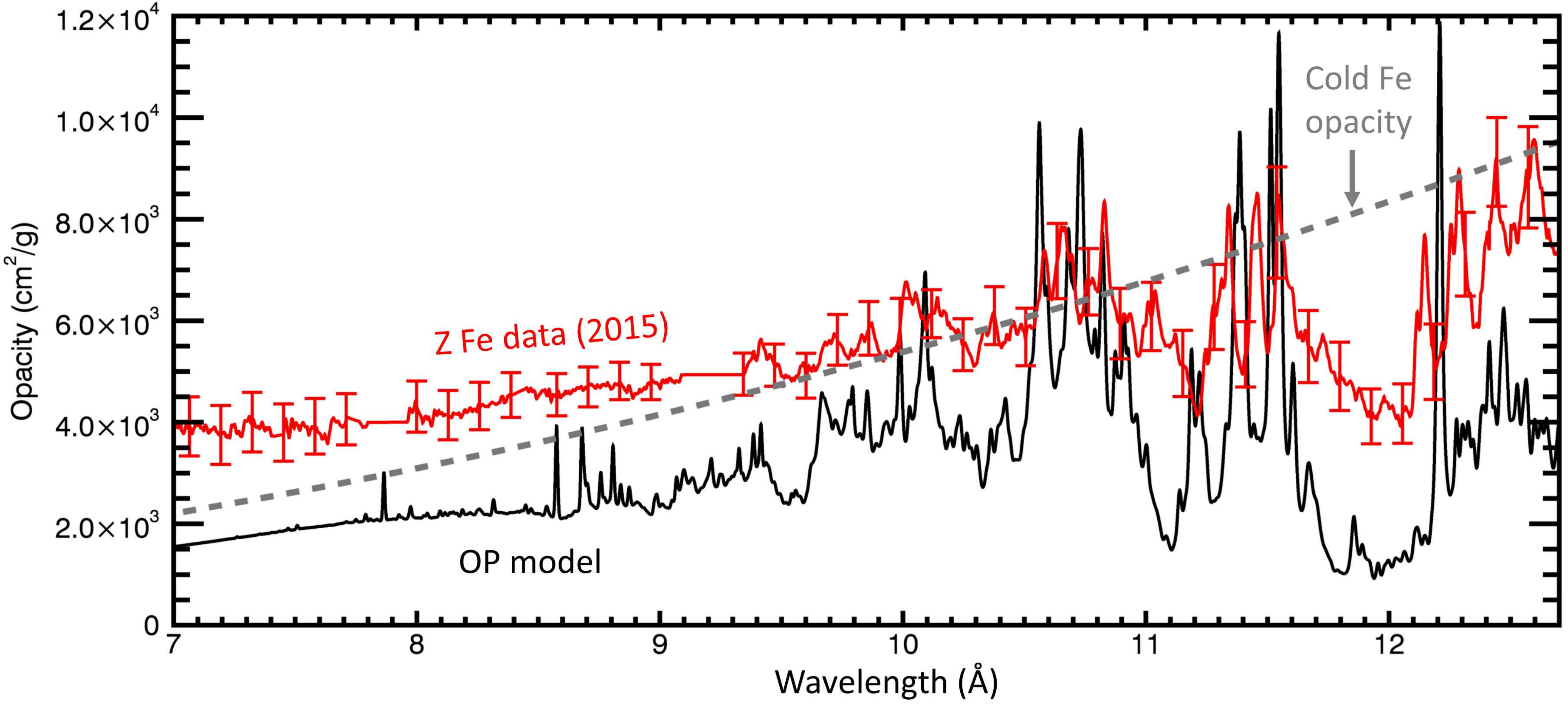

New analysis reduced the quasi-continuum disagreement from 2.0x to 1.6x, approaching to cold Fe opacity limit

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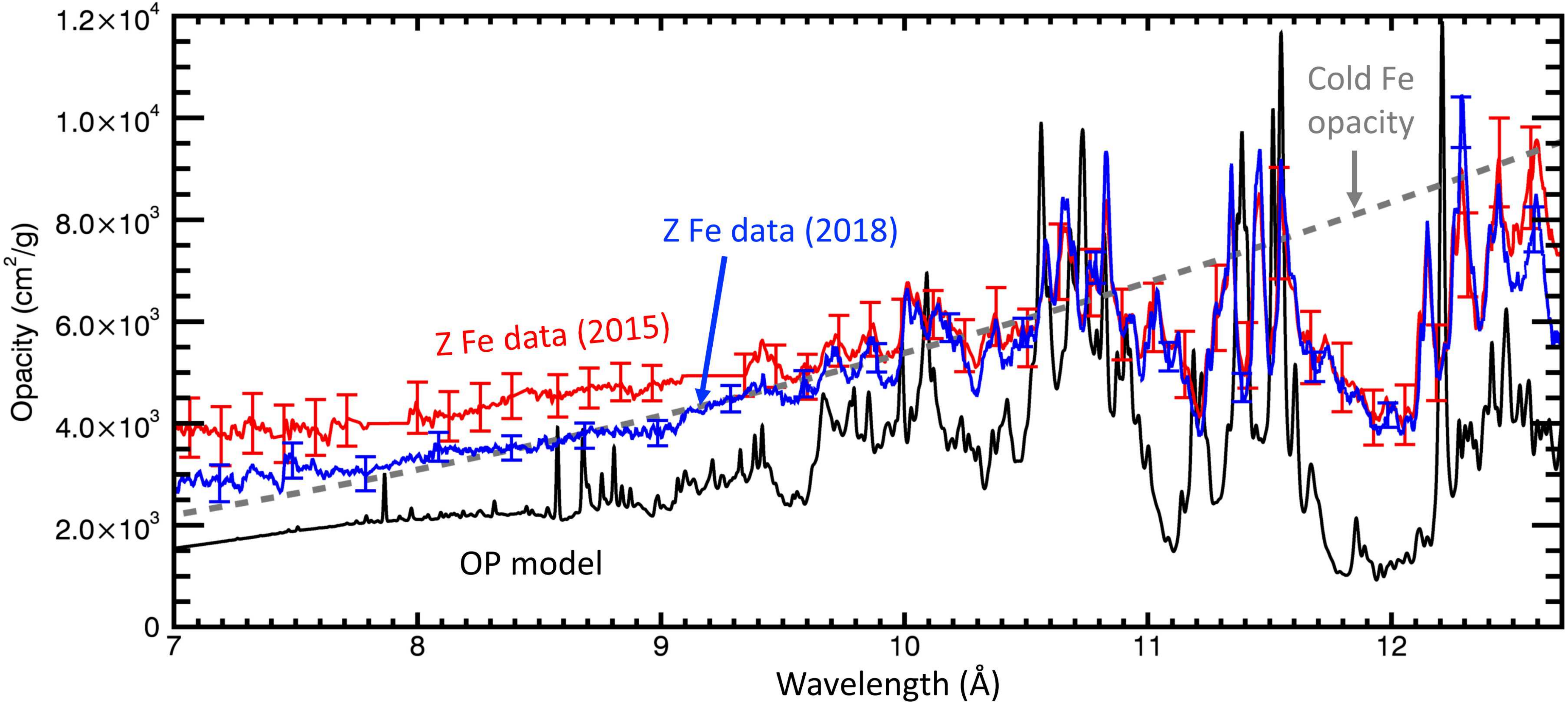

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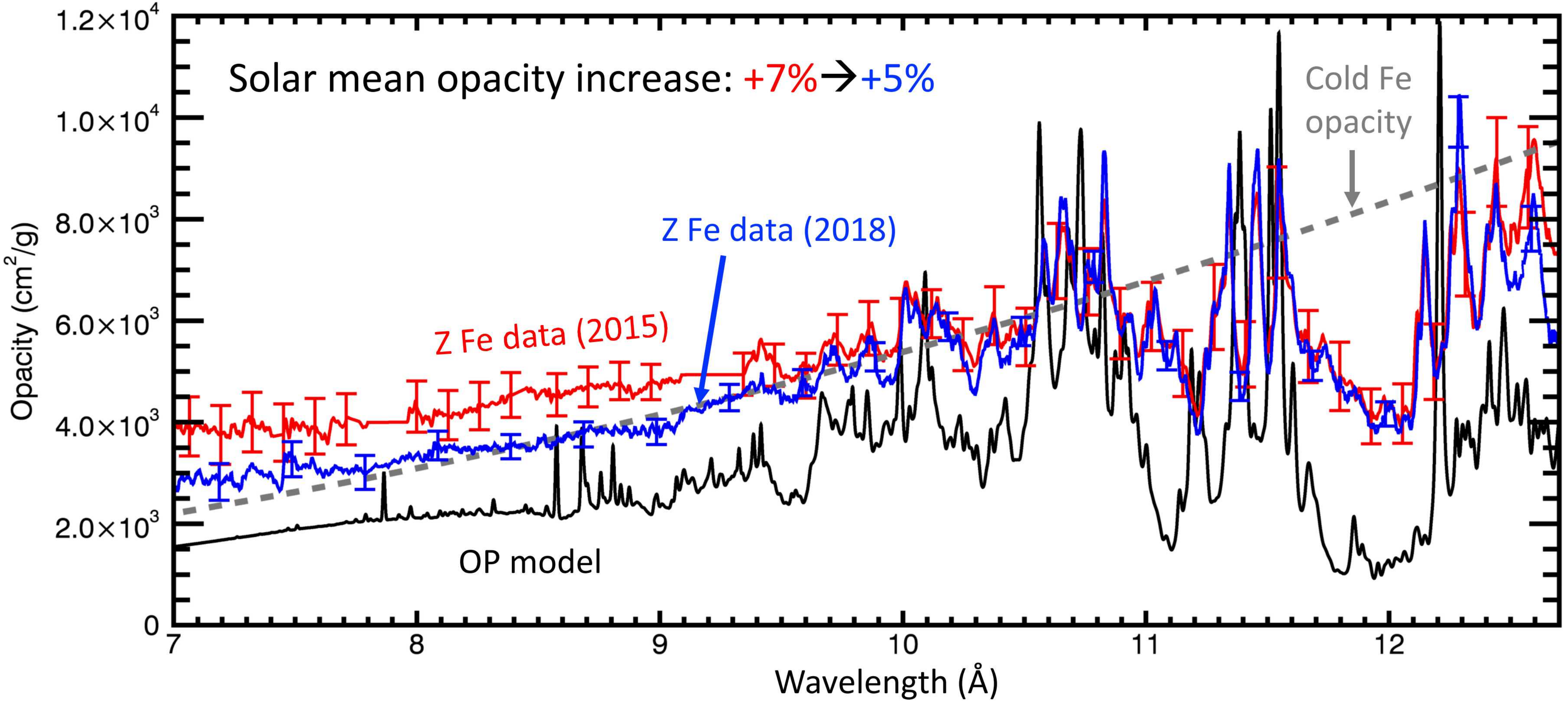
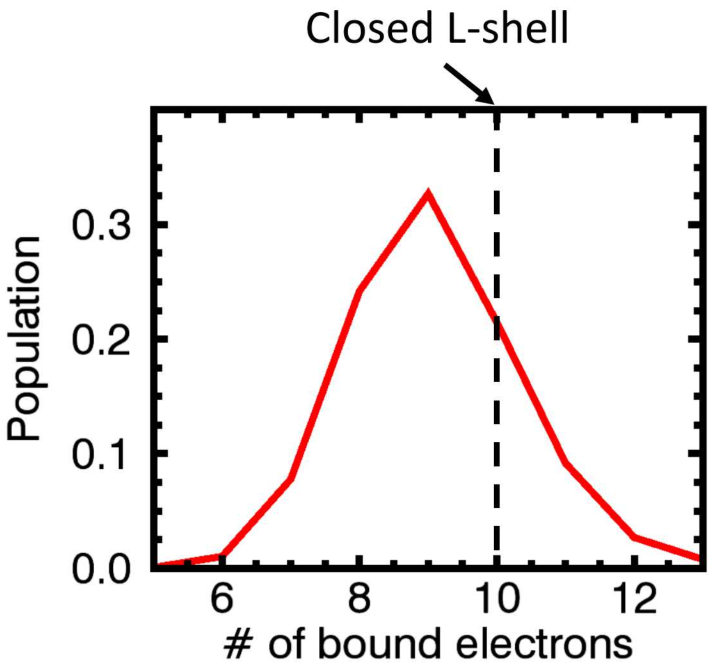
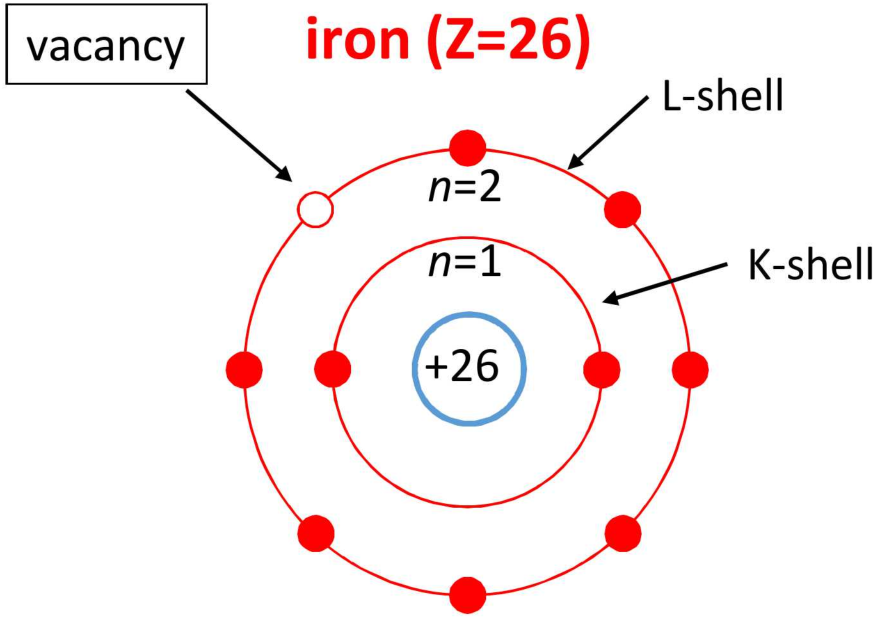


Different elements interact with plasma differently, providing unprecedented constraints for testing theory and experiments

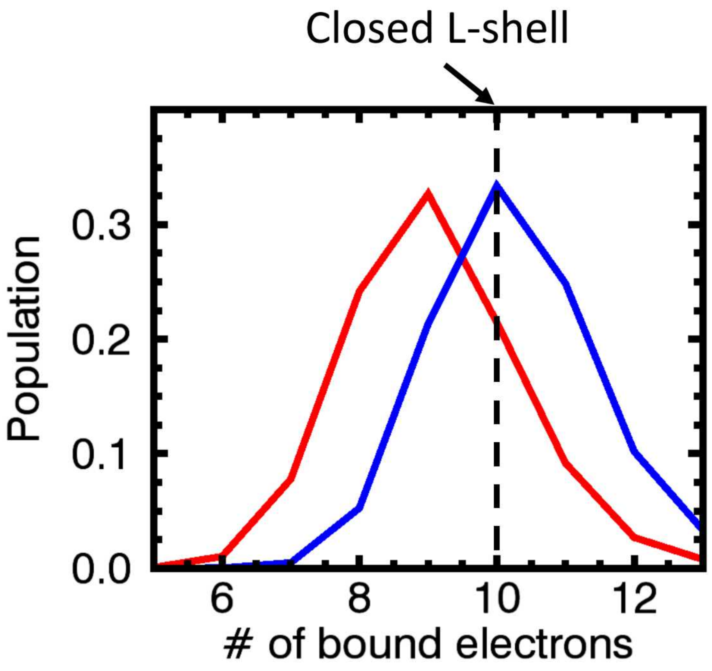


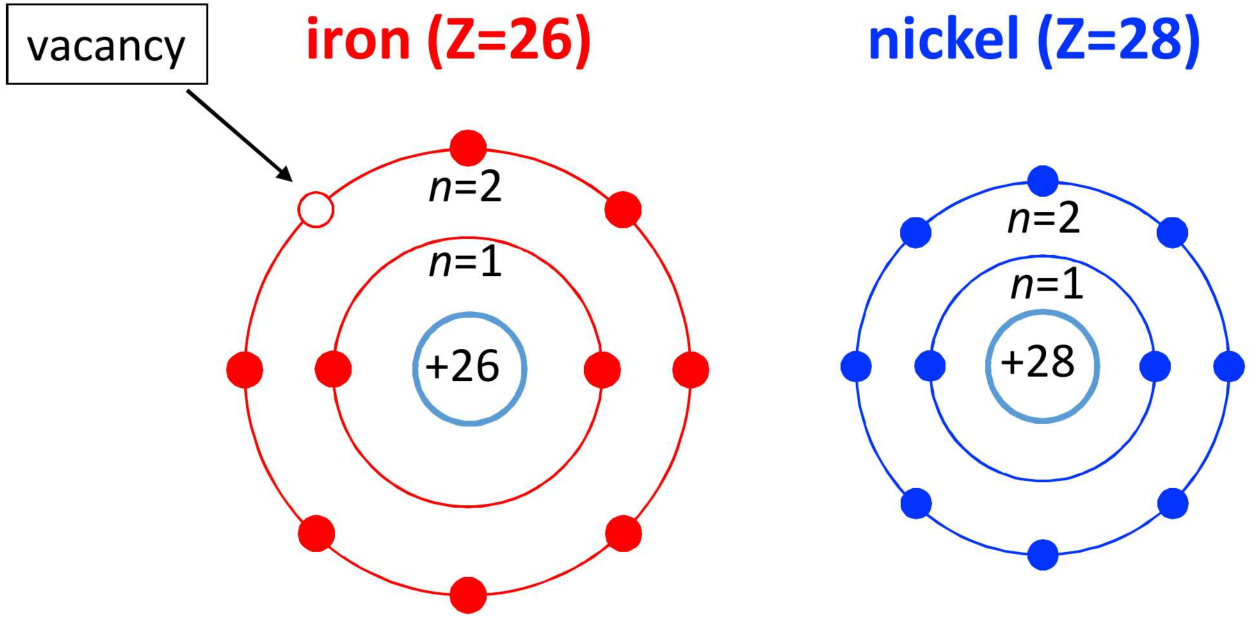


<u>Questioning Theory:</u>

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

Different elements interact with plasma differently, providing unprecedented constraints for testing theory and experiments





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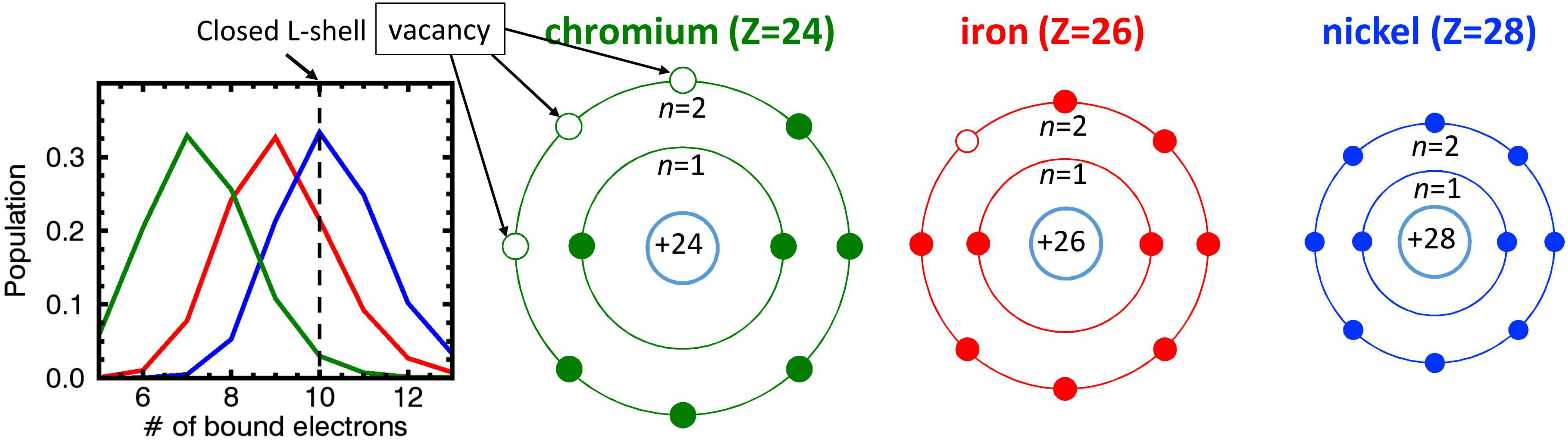

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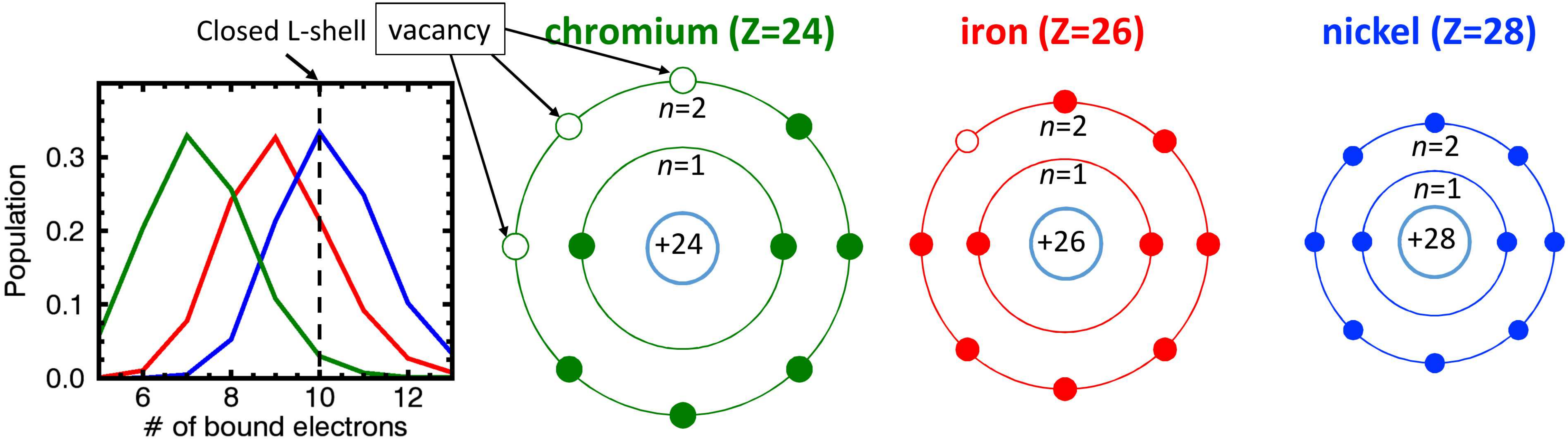


Questioning Theory:

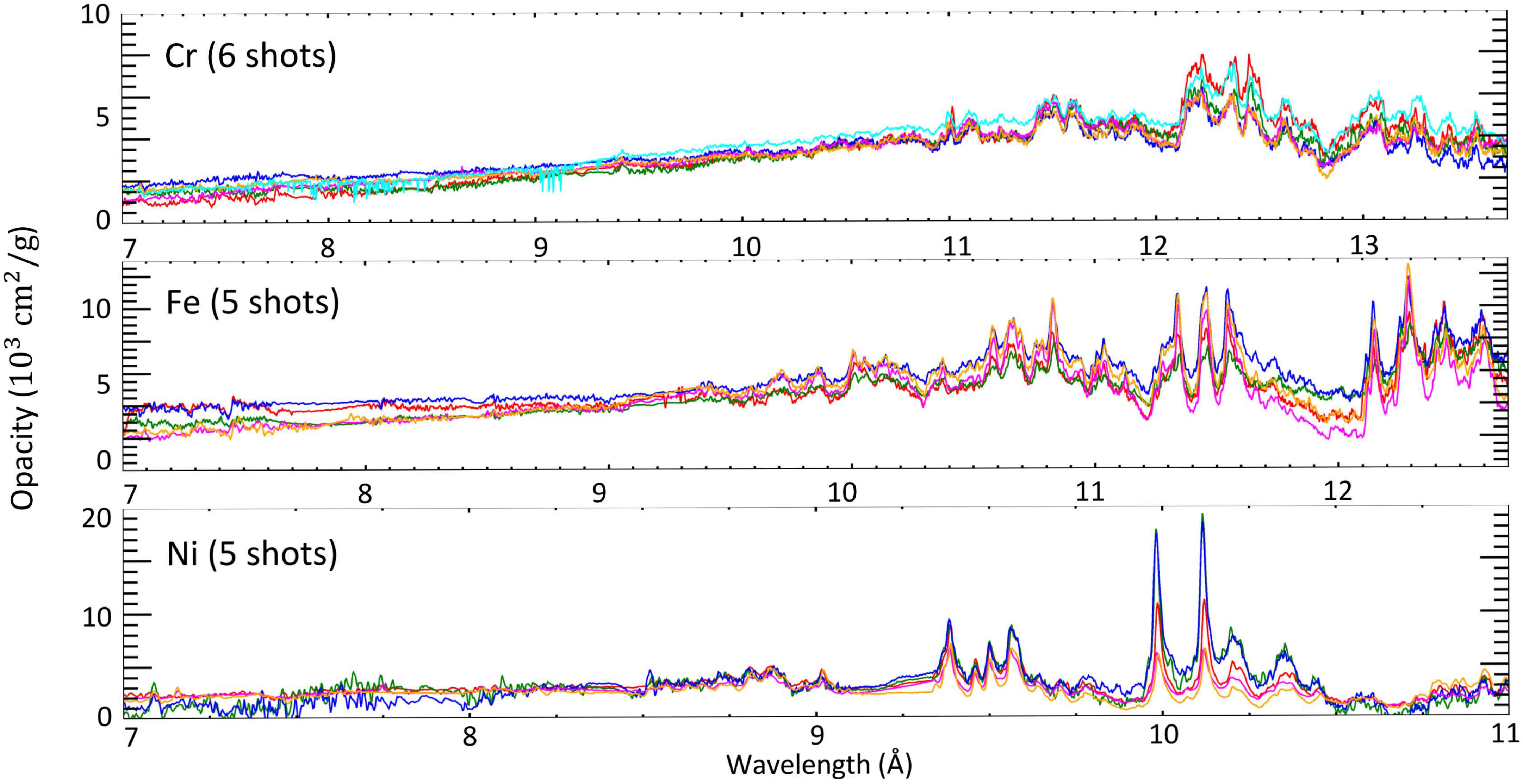
- Atomic data?
- Population?
- Density effects?
- Missing physics?

More ← L-shell vacancies ← Less

More ← # of excited states ← Less

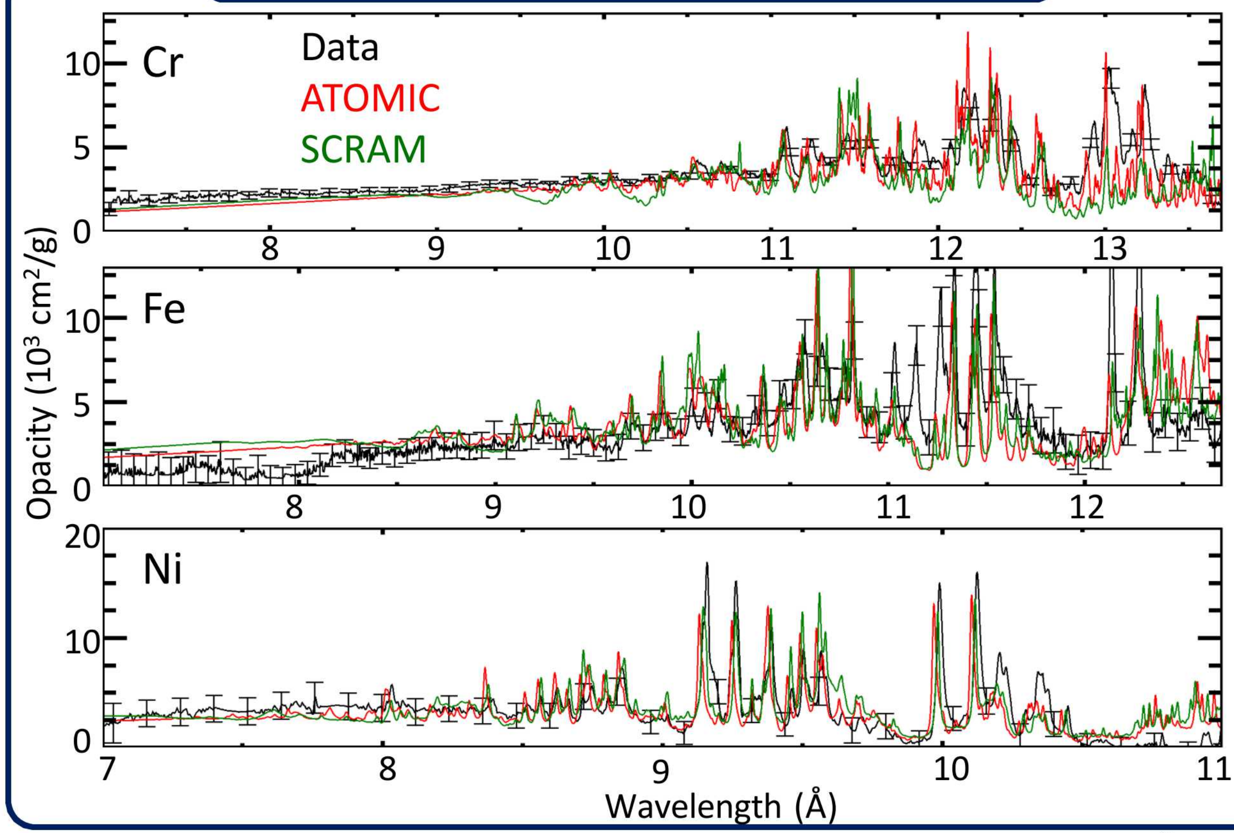
More ← Density effects ← Less

Excellent reproducibility is confirmed from all three elements, demonstrating experiment/analysis reliability

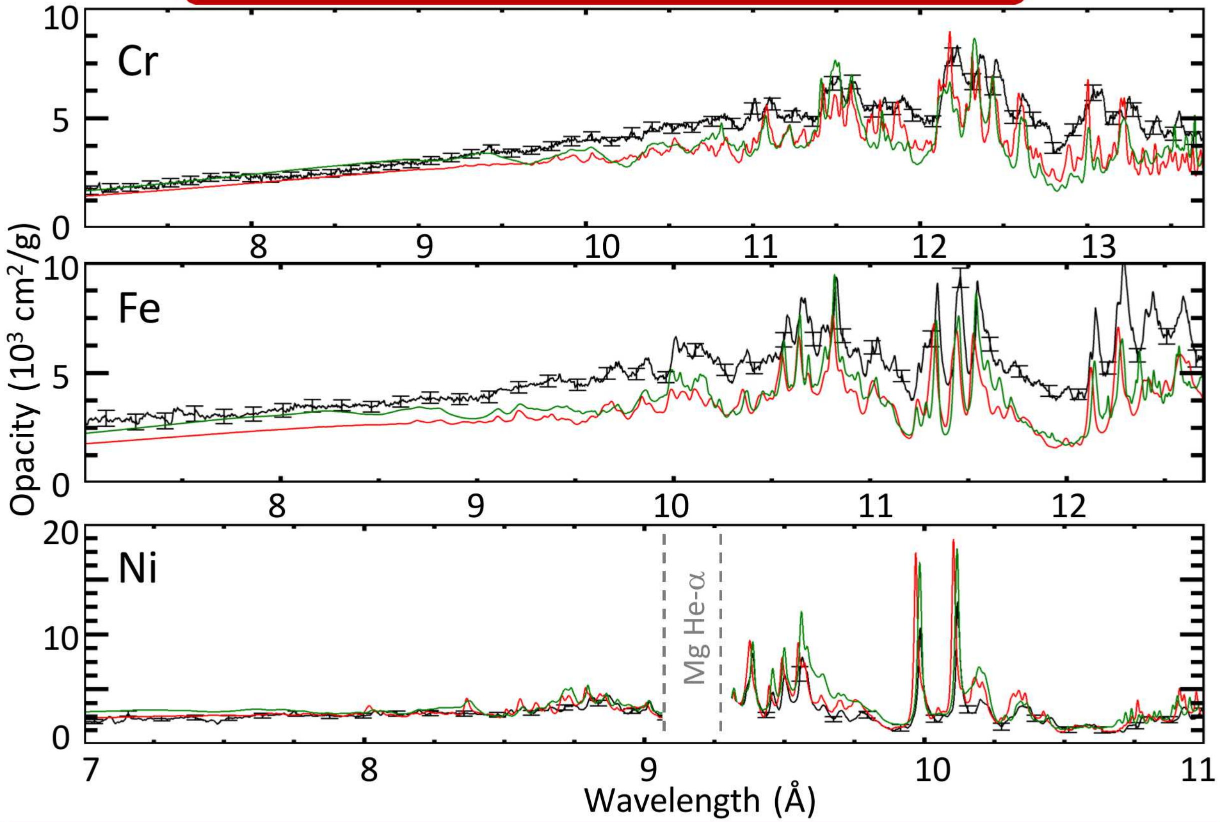


First systematic study of high-temperature L-shell opacities were performed for Cr, Fe, and Ni at two conditions

Anchor1: $T_e \sim 165$ eV, $n_e \sim 7 \times 10^{21}$ cm^{-3}



Anchor2: $T_e \sim 180$ eV, $n_e \sim 30 \times 10^{21}$ cm^{-3}

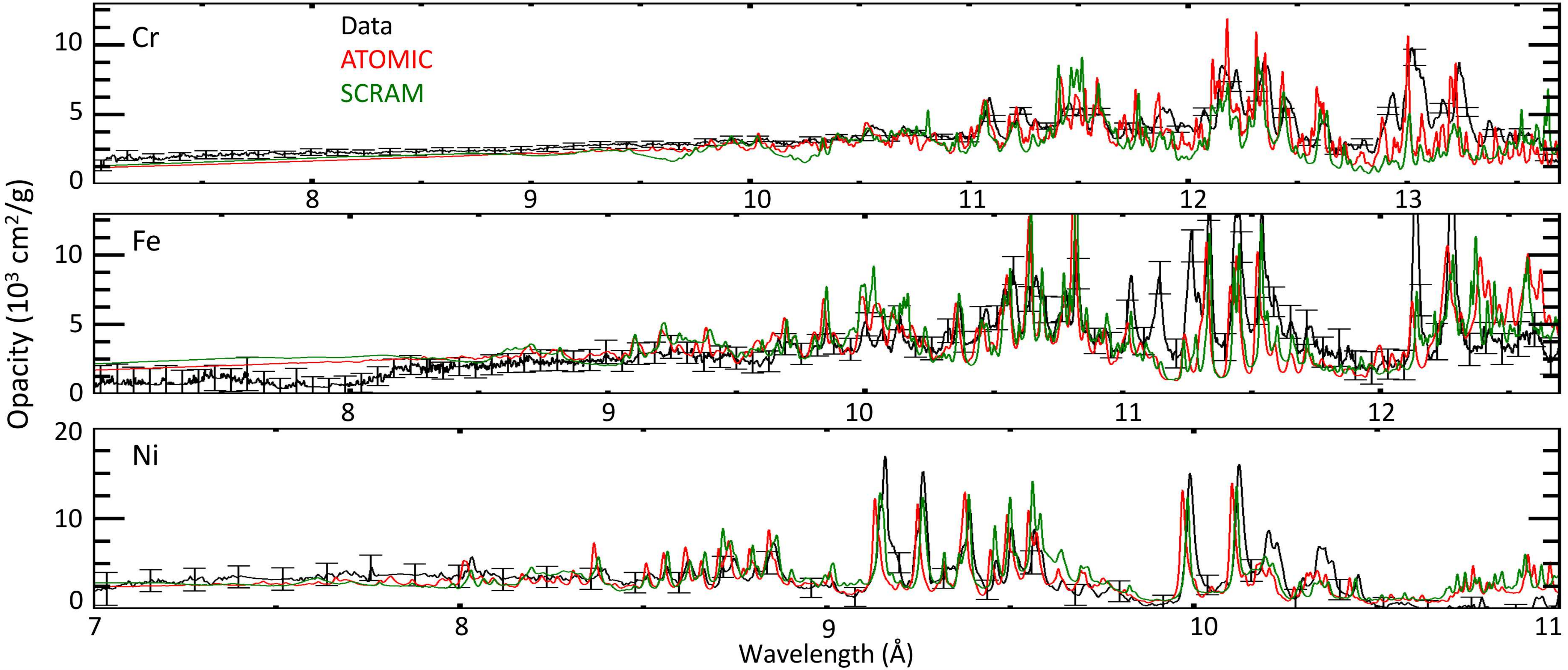


- Opacities are measured at $T_e > 150$ eV
- T_e and n_e are diagnosed independently
- Reproducibility is confirmed

Systematically performed for Cr, Fe, Ni at two conditions

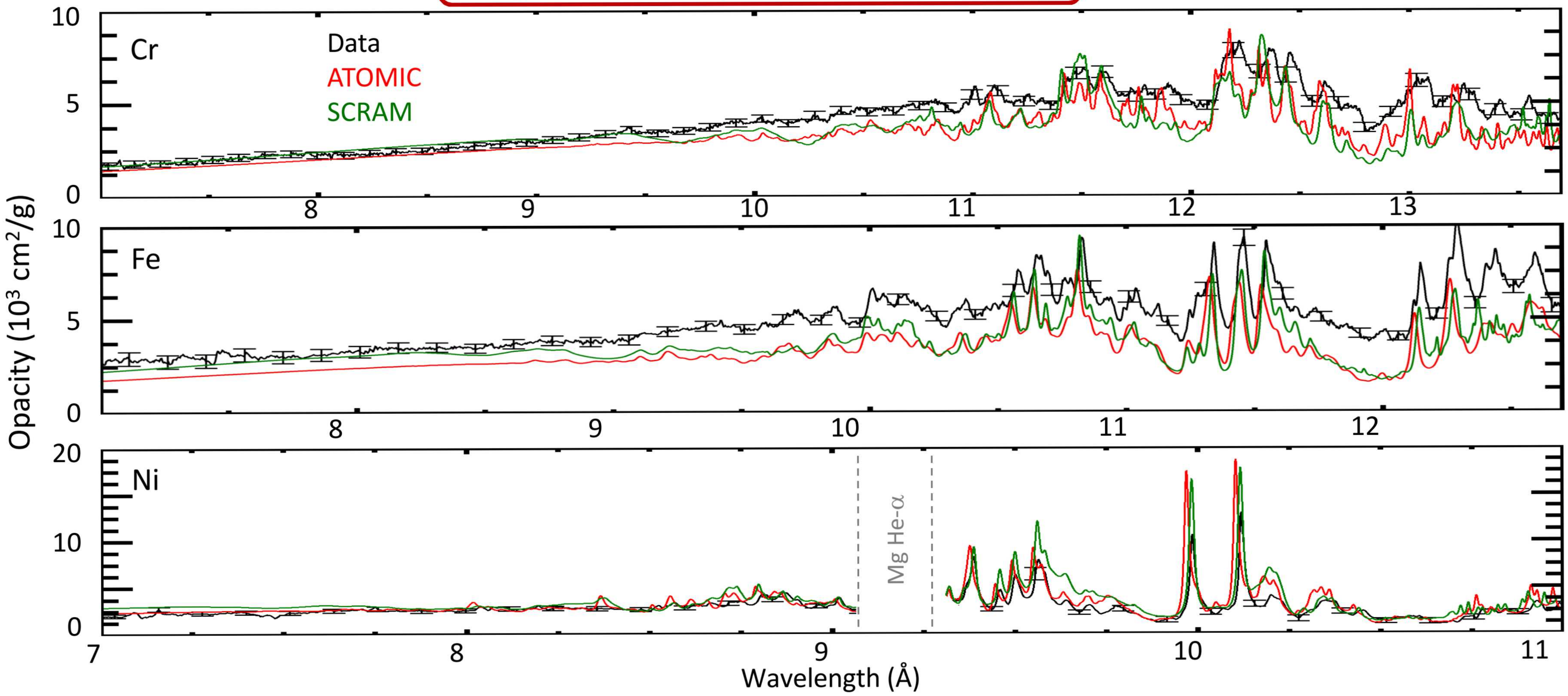
Anchor1: Modeled and measured opacities agree reasonably well at lower temperature and density

$T_e \sim 165$ eV, $n_e \sim 7 \times 10^{21}$ cm^{-3}

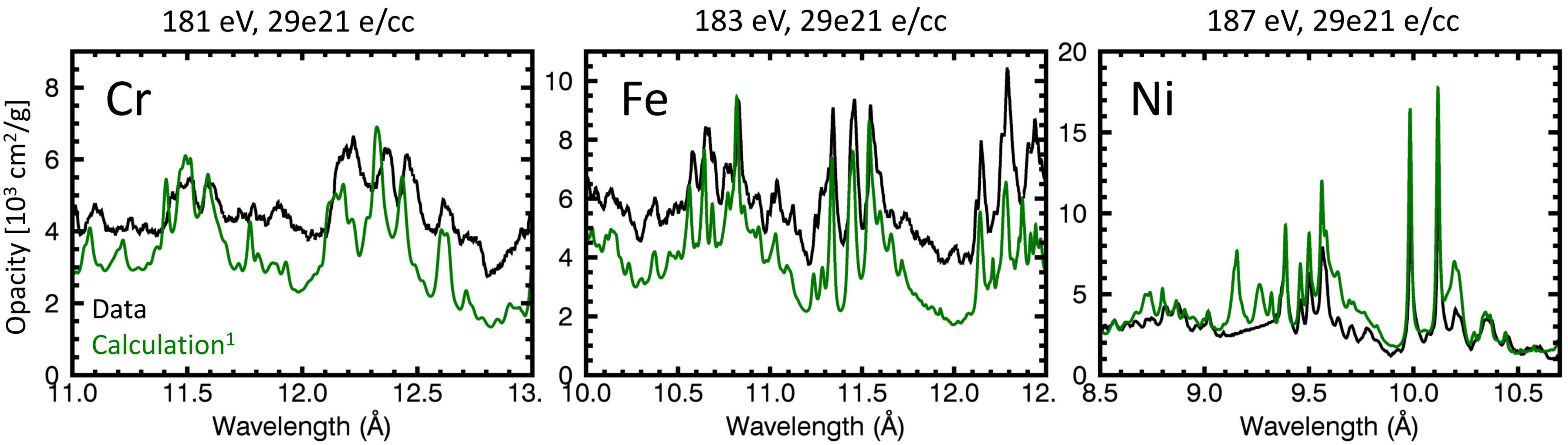


Anchor2: Interesting element-dependent disagreement appears as approaching to stellar interior conditions

$T_e \sim 180$ eV, $n_e \sim 30 \times 10^{21}$ cm^{-3}



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



[1] SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

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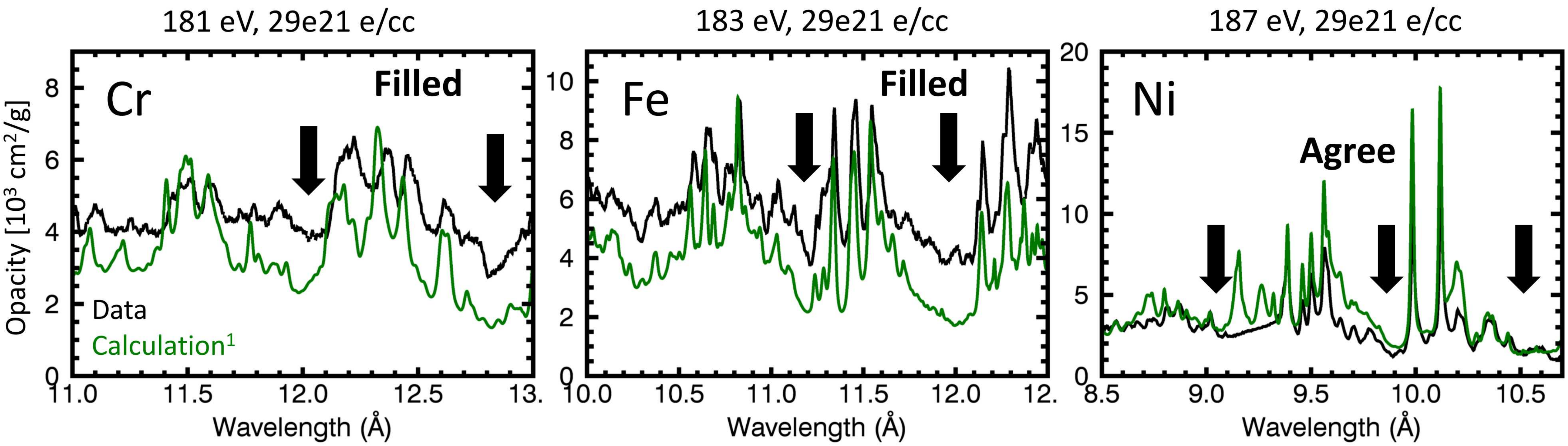

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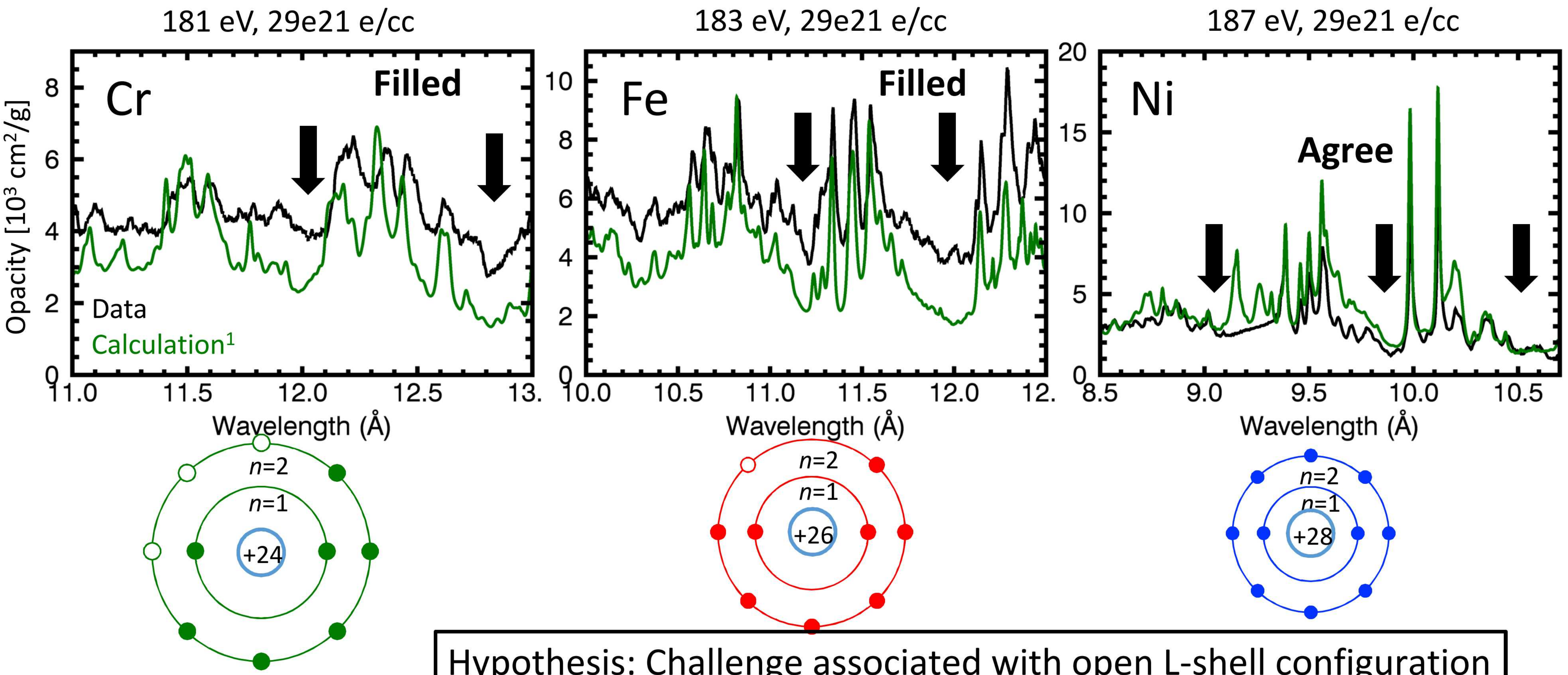
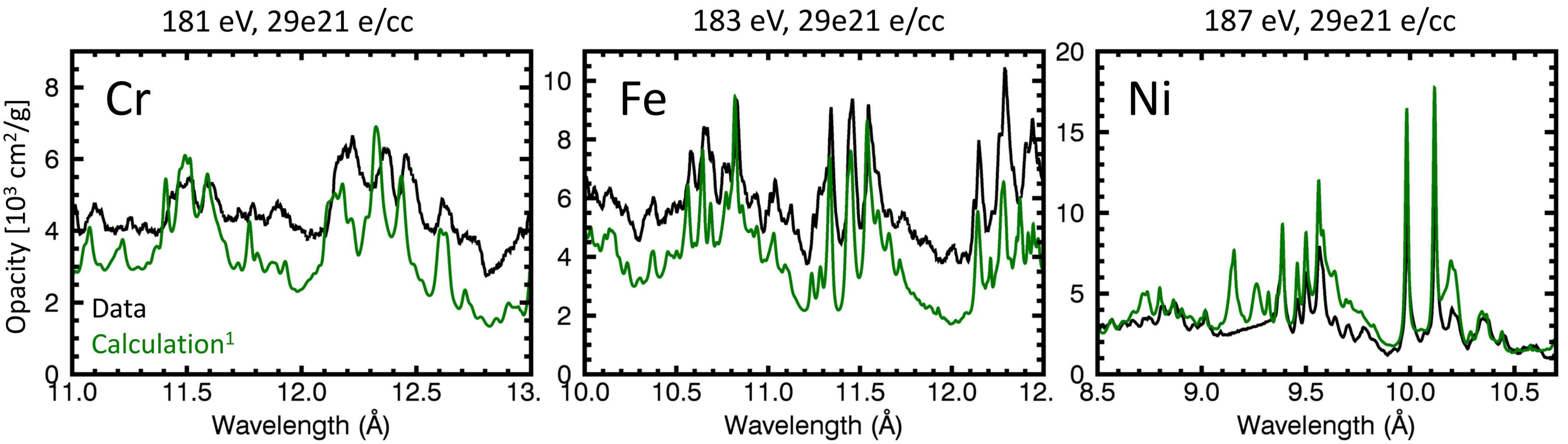


Hypothesis: Challenge associated with open L-shell configuration

[1] SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

Can we check accuracy of modeled line shapes?



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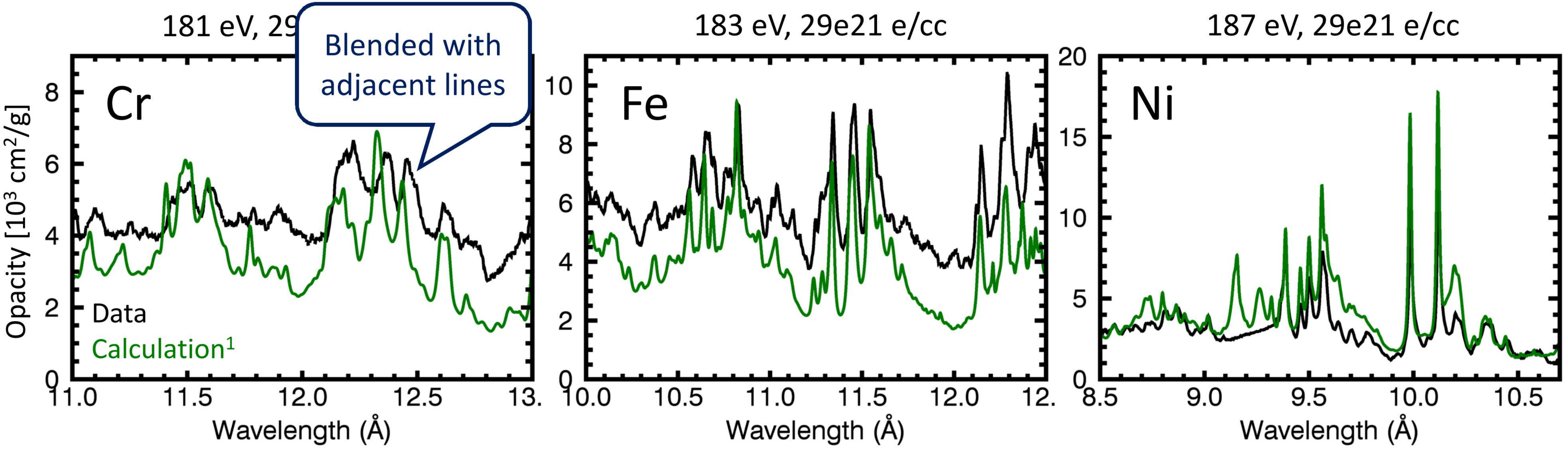

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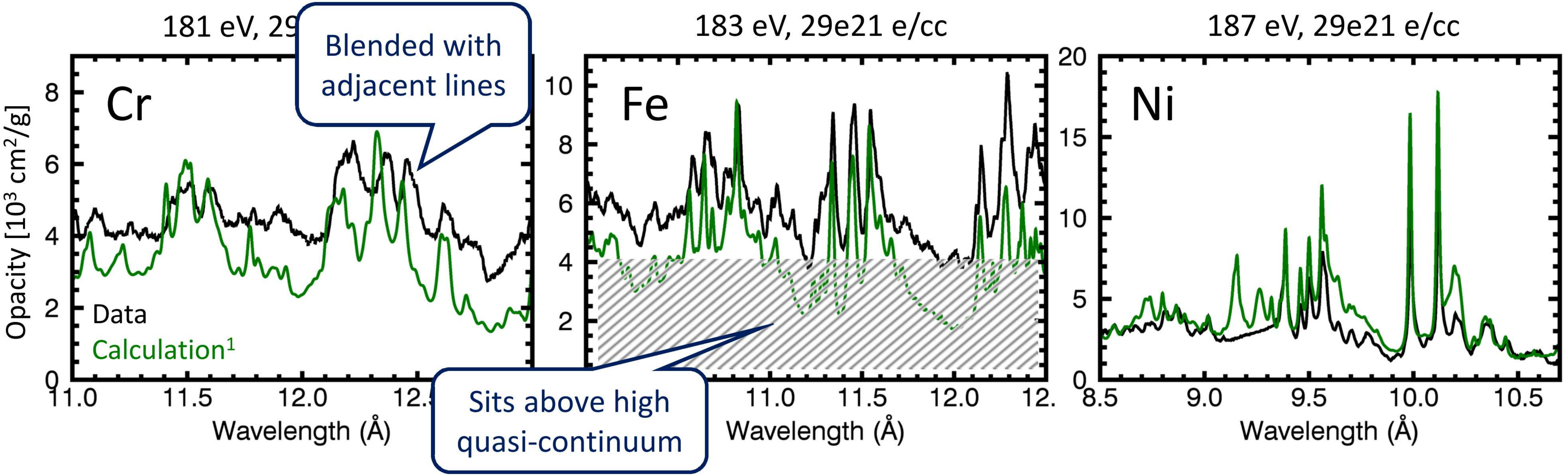

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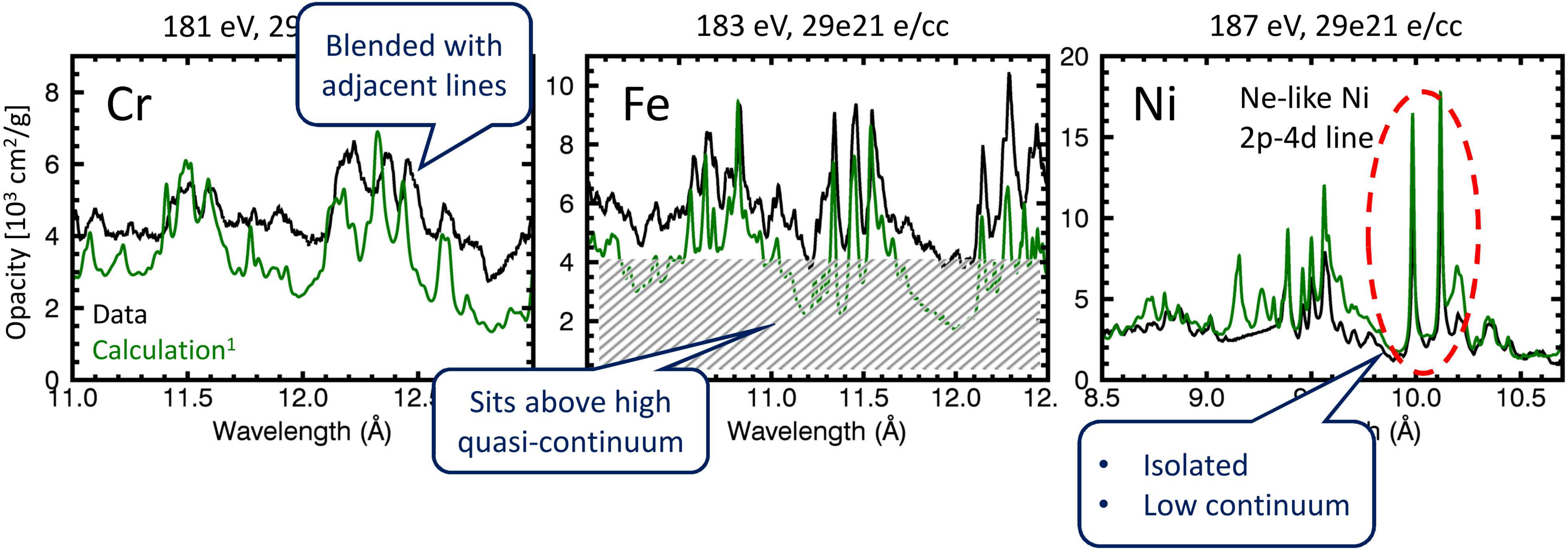

We use n=2 → 4 lines from Ne-like Ni to assess the accuracy of calculated line shape

[1] SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

Line-shape of Ne-like Ni 2p-4d is accurately measured and appropriate to test approximations used in models

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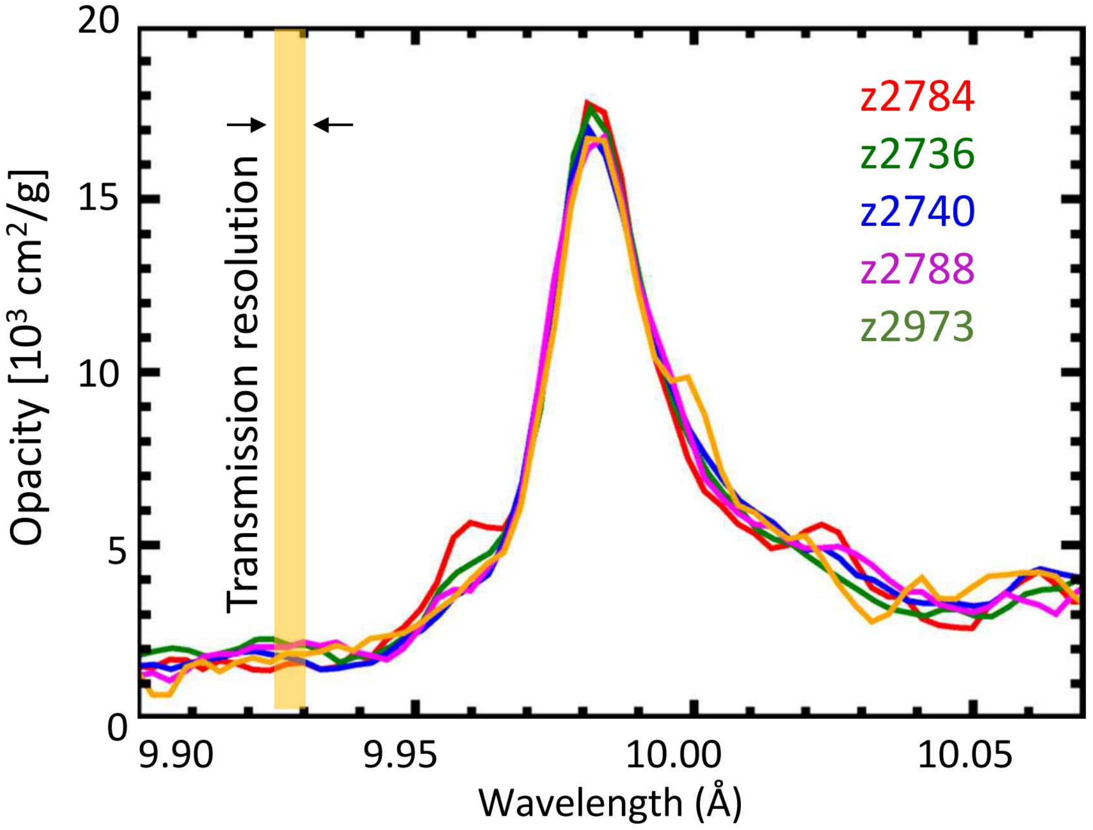
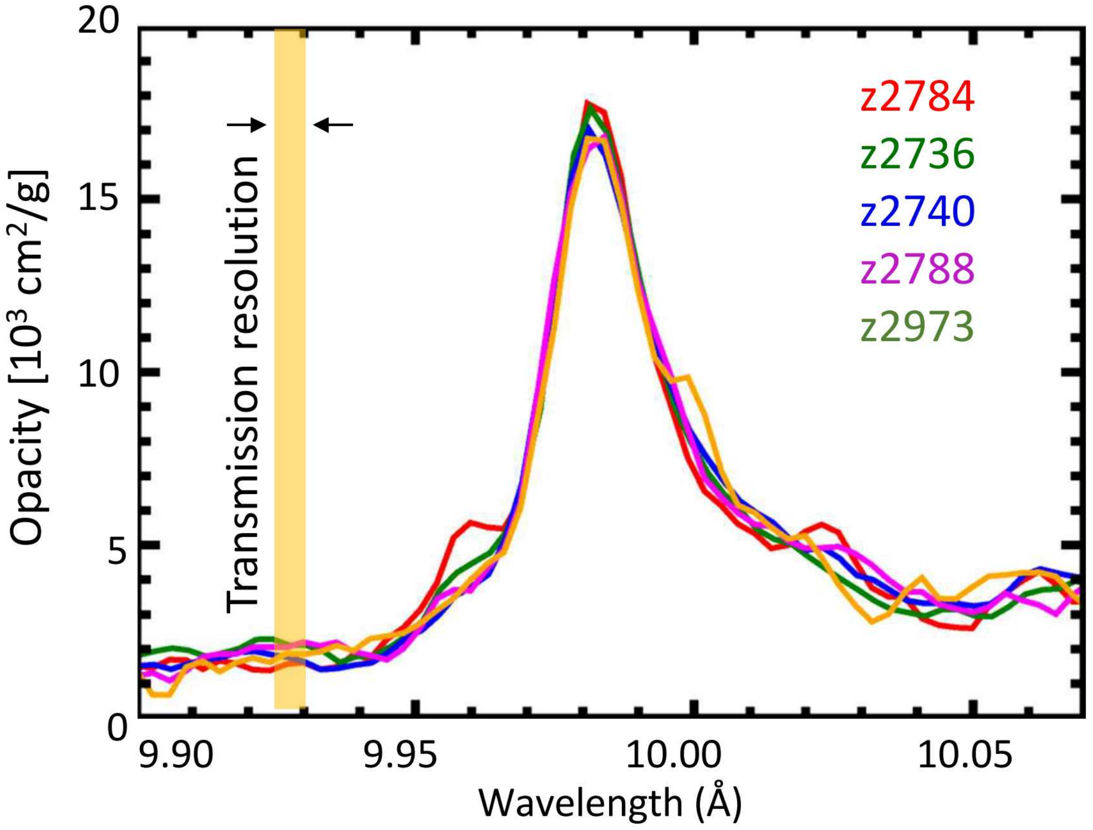
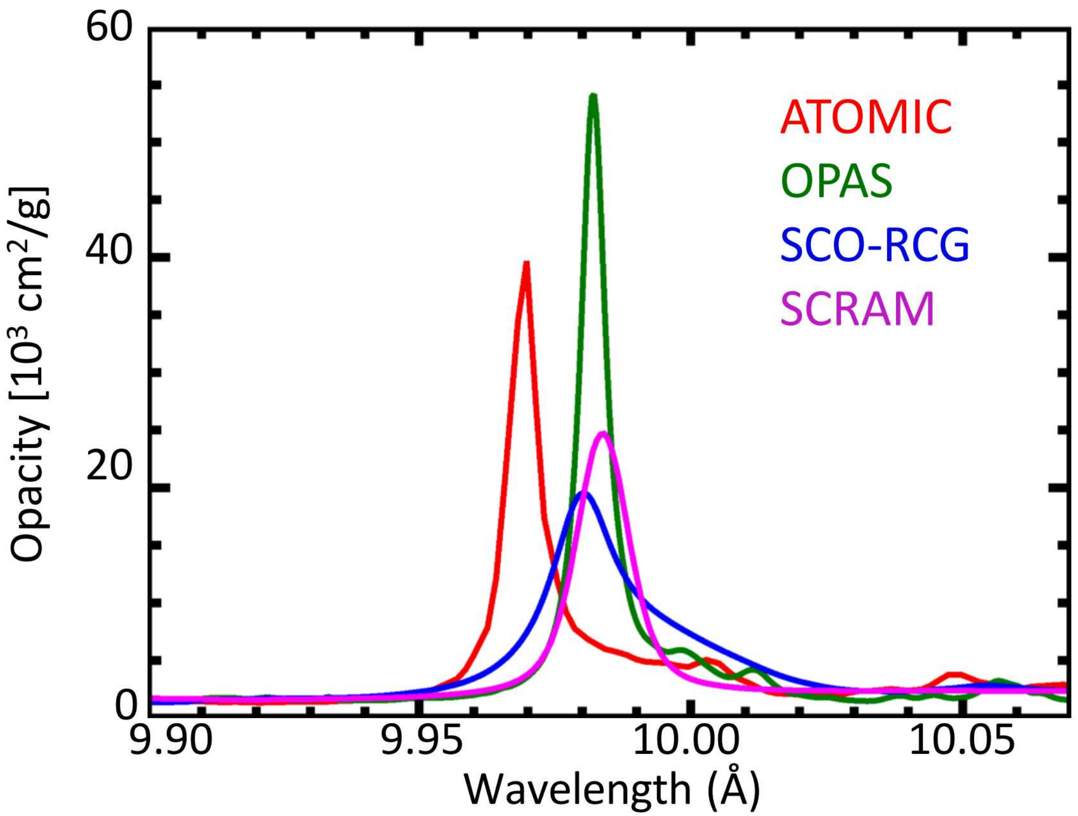


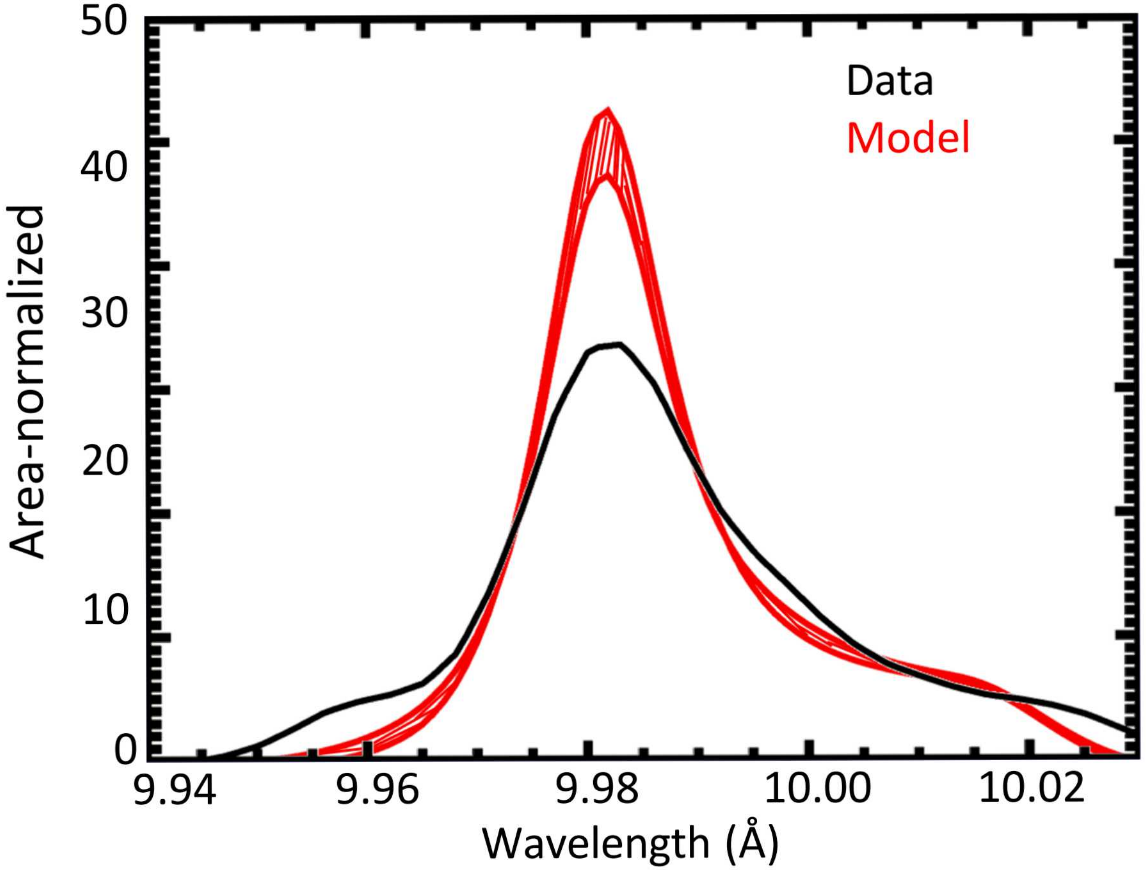
- This line-shape is reproduced by five experiments
- Model employs simple approximations for L-shell line shapes, which are not tested.

Line-shape of Ne-like Ni 2p-4d is accurately measured and appropriate to test approximations used in models



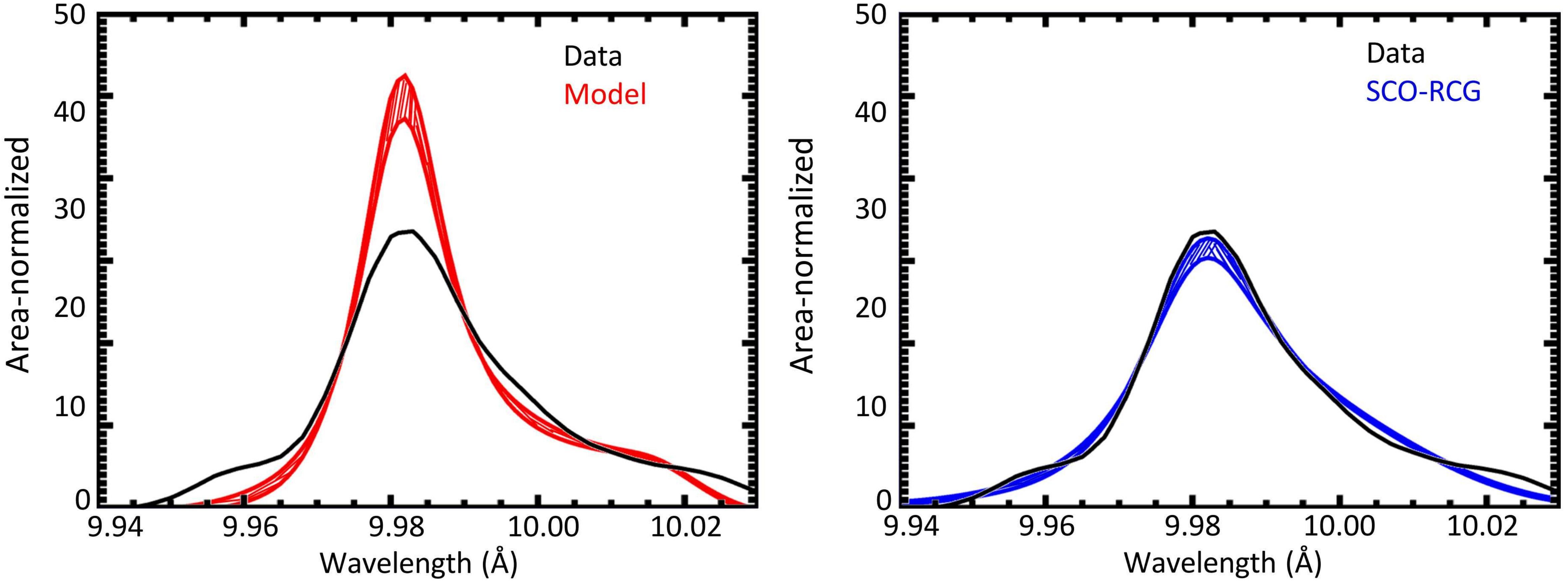


Most models underestimate the L-shell line widths



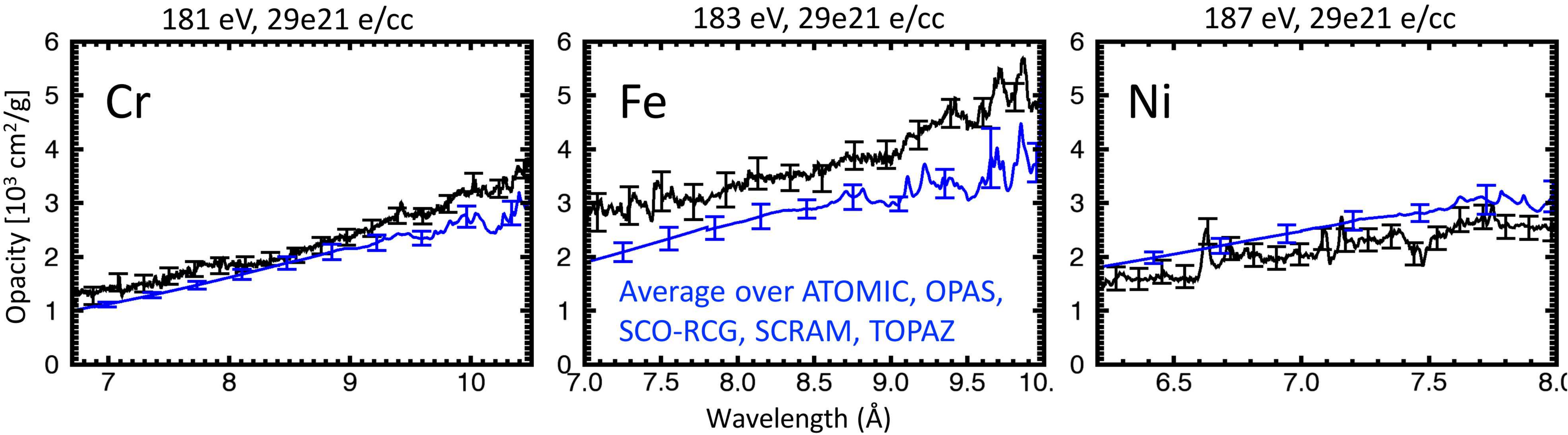
Models need to refine treatment of atomic interaction with plasma and excited states.

French CEA code, SCO-RCG, predicted the measured L-shell line width reasonably well



Models need to refine treatment of atomic interaction with plasma and excited states.

Refined analysis on Fe does not fully remove the reported quasi-continuum disagreement



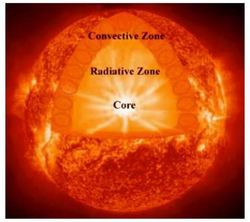
- Reanalysis on Fe reduced data/<model> from 1.6 to 1.3
- Excellent reproducibility in all three elements suggests the differences are real

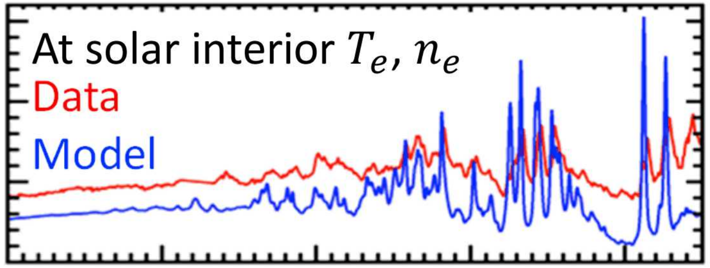
Any hypothesis has to explain not only why it enhances Fe opacity but also why it does not affect Cr and Ni opacities

Systematic study of L-shell opacities with refined analysis validates experiment reliability and suggest necessary model refinements

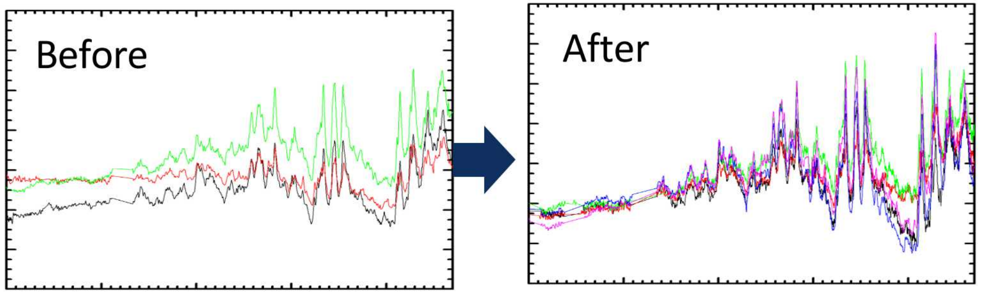
- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**

  → Is opacity theory wrong? Is experiment flawed?

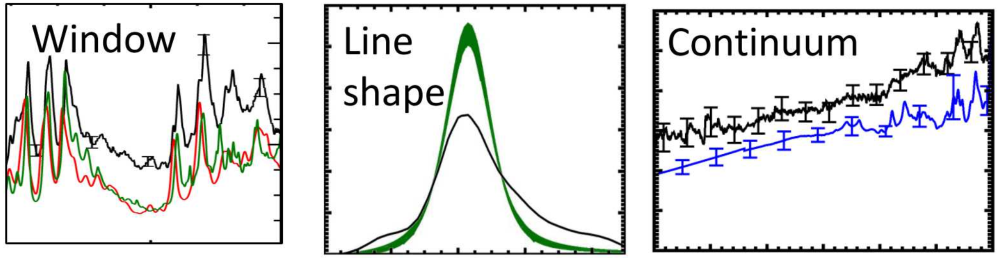




- **Refined analysis improved shot-to-shot reproducibility, demonstrating opacity experiment reliability**



- **Systematic measurement of Cr, Fe, and Ni opacities suggests model refinements in three areas**
  - <u>Window:</u> Challenge associated with open L-shell config.
  - <u>BB:</u> Inaccurate treatment of density effects
  - <u>Continuum:</u> Peculiar dependence on atomic number



High reproducibility qualifies SNL to be a unique HED-opacity-benchmark facility