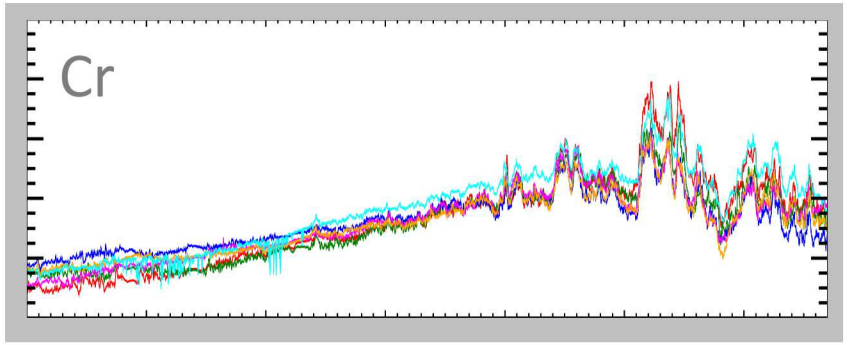
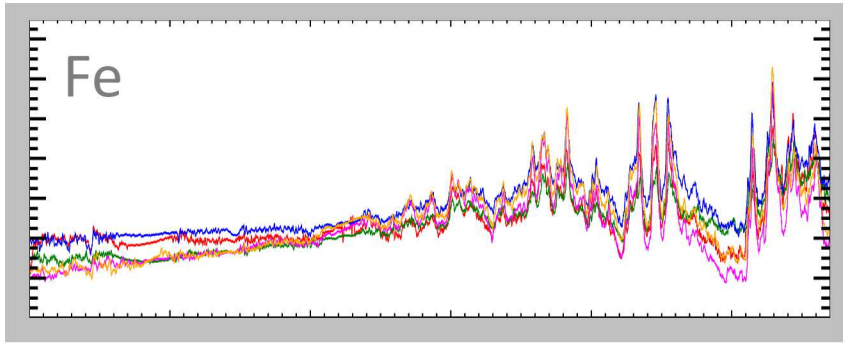
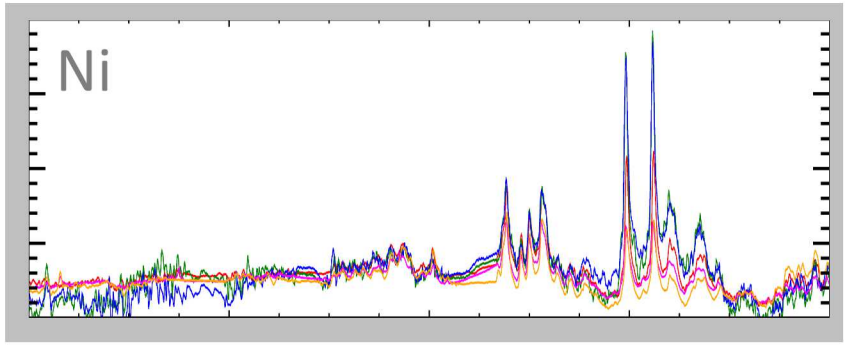
SAND2019-1912D







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, a private company, U.S. national labs, 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, T. Gomez
Sandia National Laboratories, Albuquerque, NM, 87185-1196

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

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

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

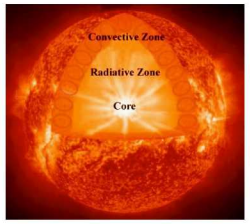
J.J. MacFarlane and I. Golovkin
Prism Computational Sciences, Madison, WI

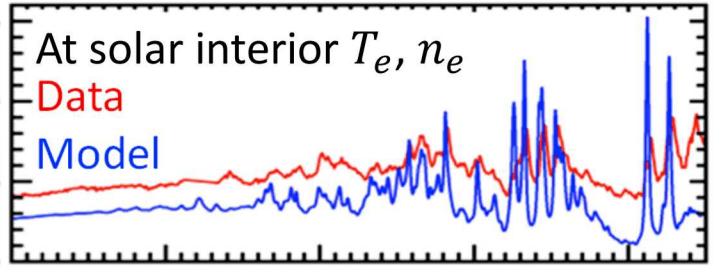
R.C. Mancini
University of Nevada, Reno, NV

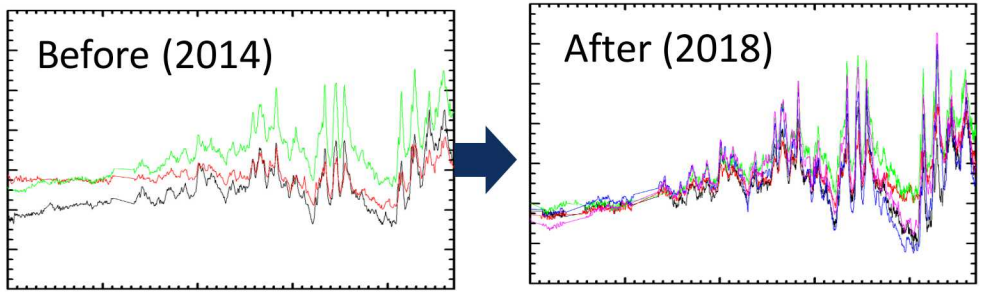
Y. Kurzweil and G. Hazak
Nuclear Research Center Negev, Israel

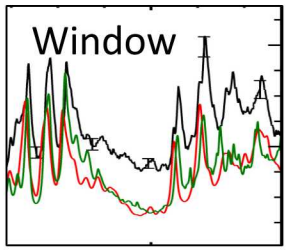
Systematic study of L-shell opacities with refined analysis validates experiment reliability and suggest necessary model refinements

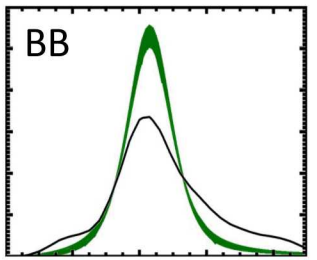
- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**
  - → Is opacity theory wrong? Is experiment flawed?
- **Refined analysis improved shot-to-shot reproducibility, demonstrating opacity experiment reliability**
- **Systematic measurement of Cr, 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

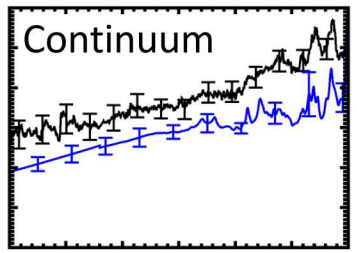








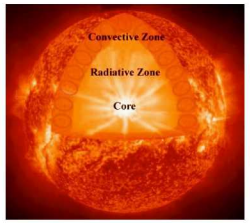


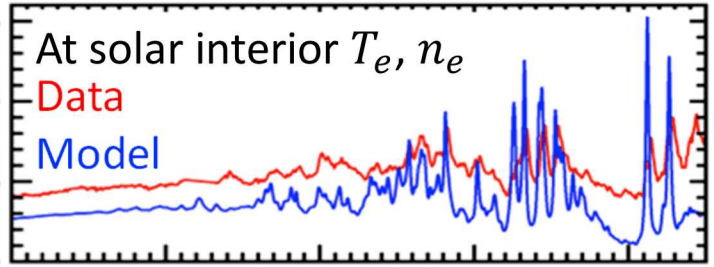


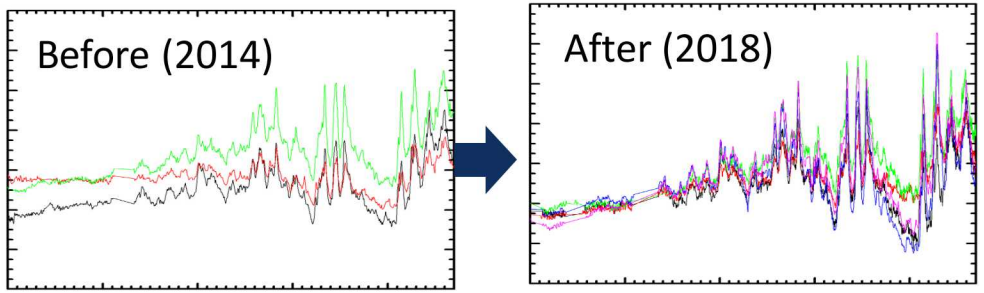
Systematic study of L-shell opacities with refined analysis validates experiment reliability and suggest necessary model refinements

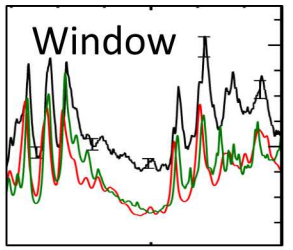
Sandia National Laboratories

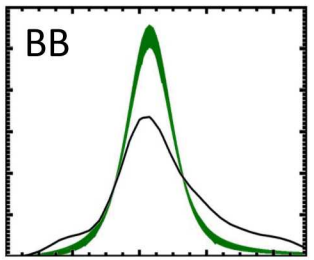
- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**
  - → Is opacity theory wrong? Is experiment flawed?
- **Refined analysis improved shot-to-shot reproducibility, demonstrating opacity experiment reliability**
- **Systematic measurement of Cr, 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

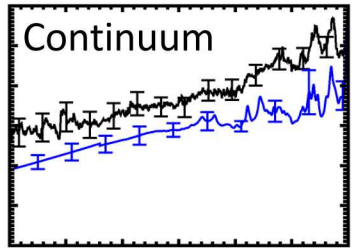






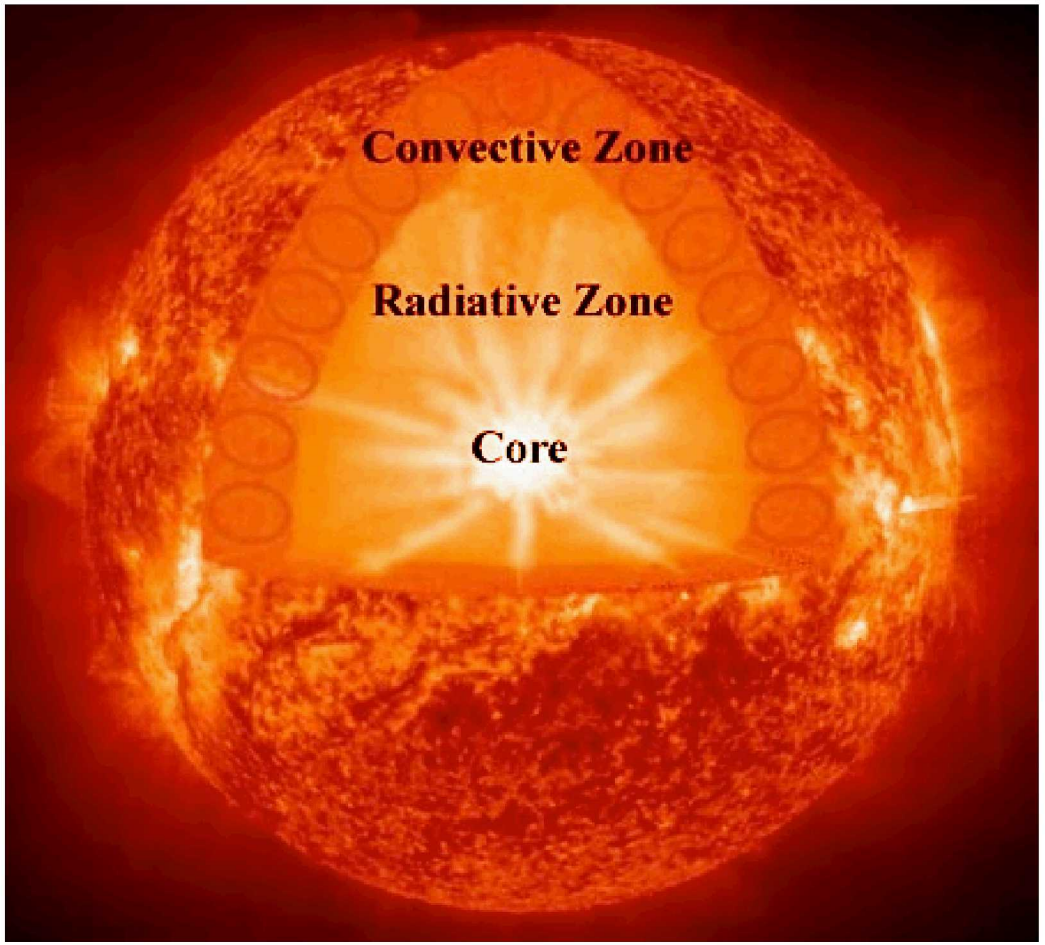


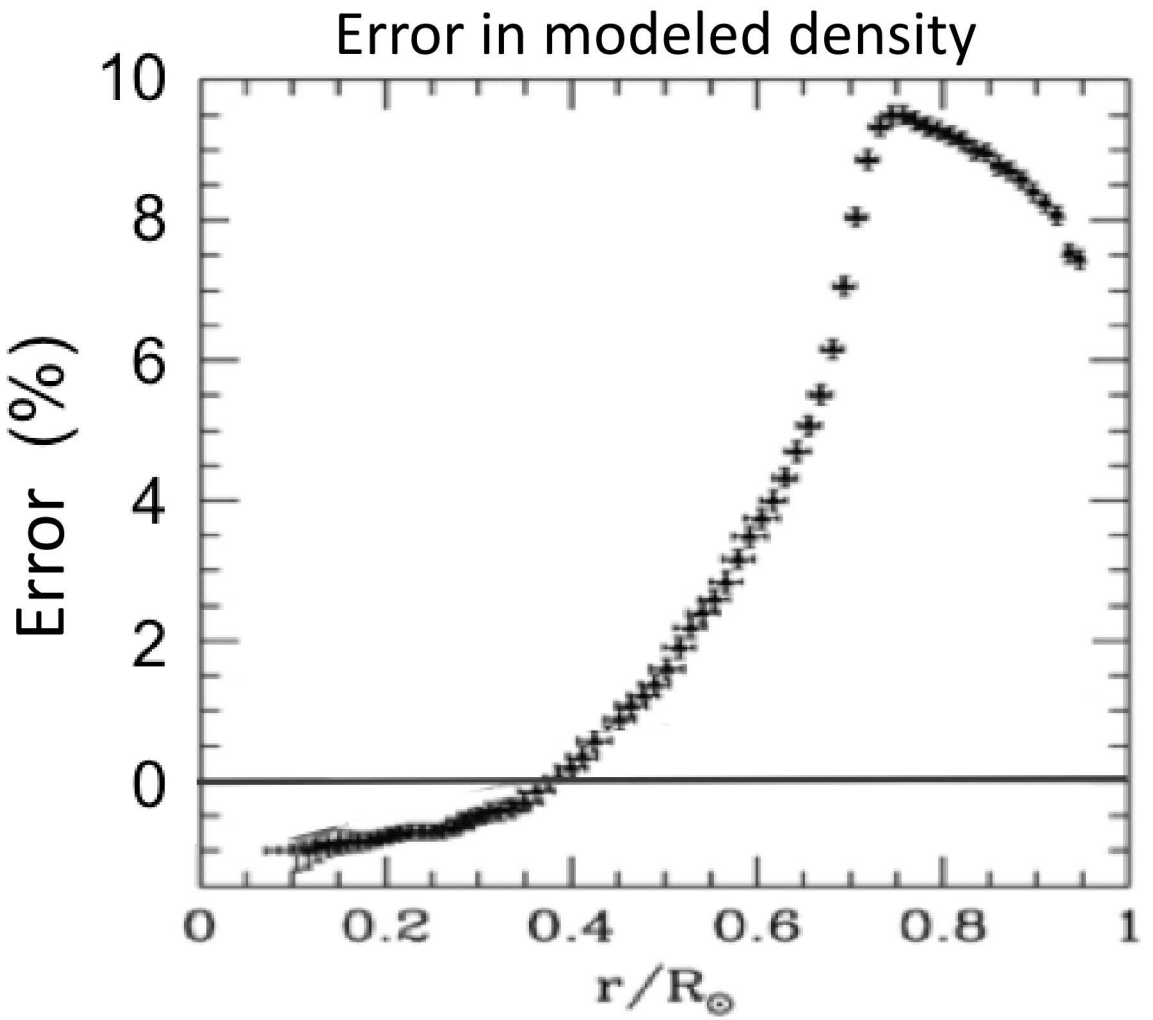




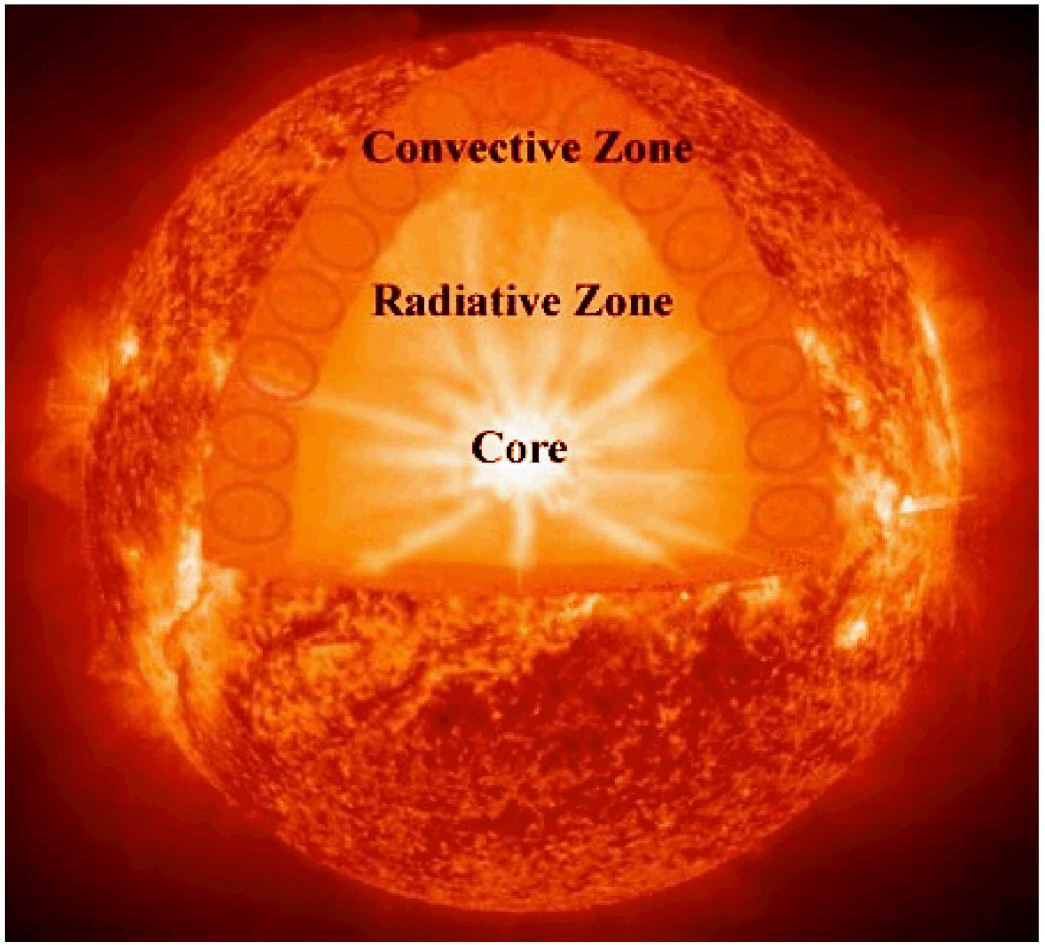
Results are improved over two years by collecting more data and refining analysis methods

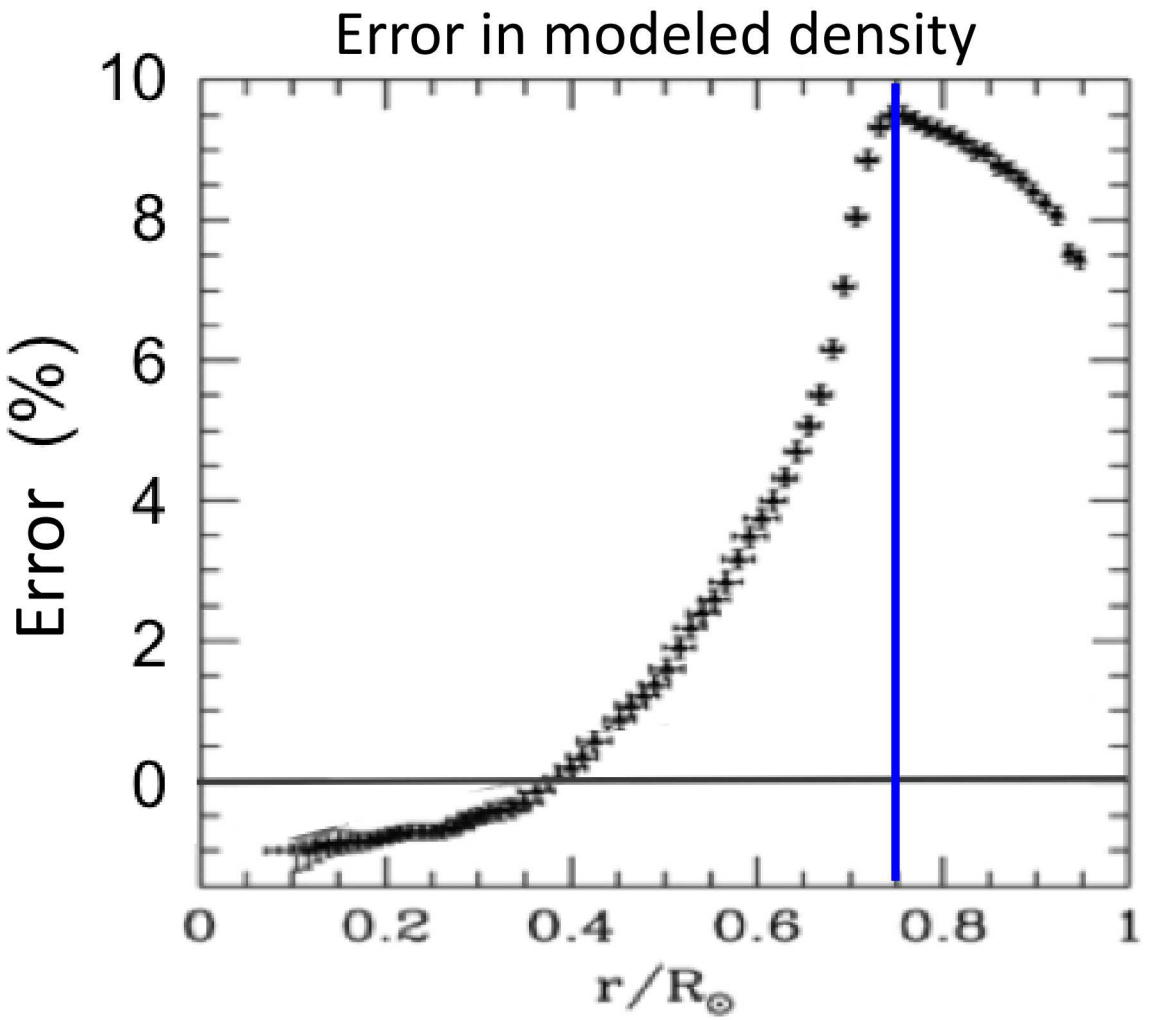
Modeled solar structure disagrees with observations



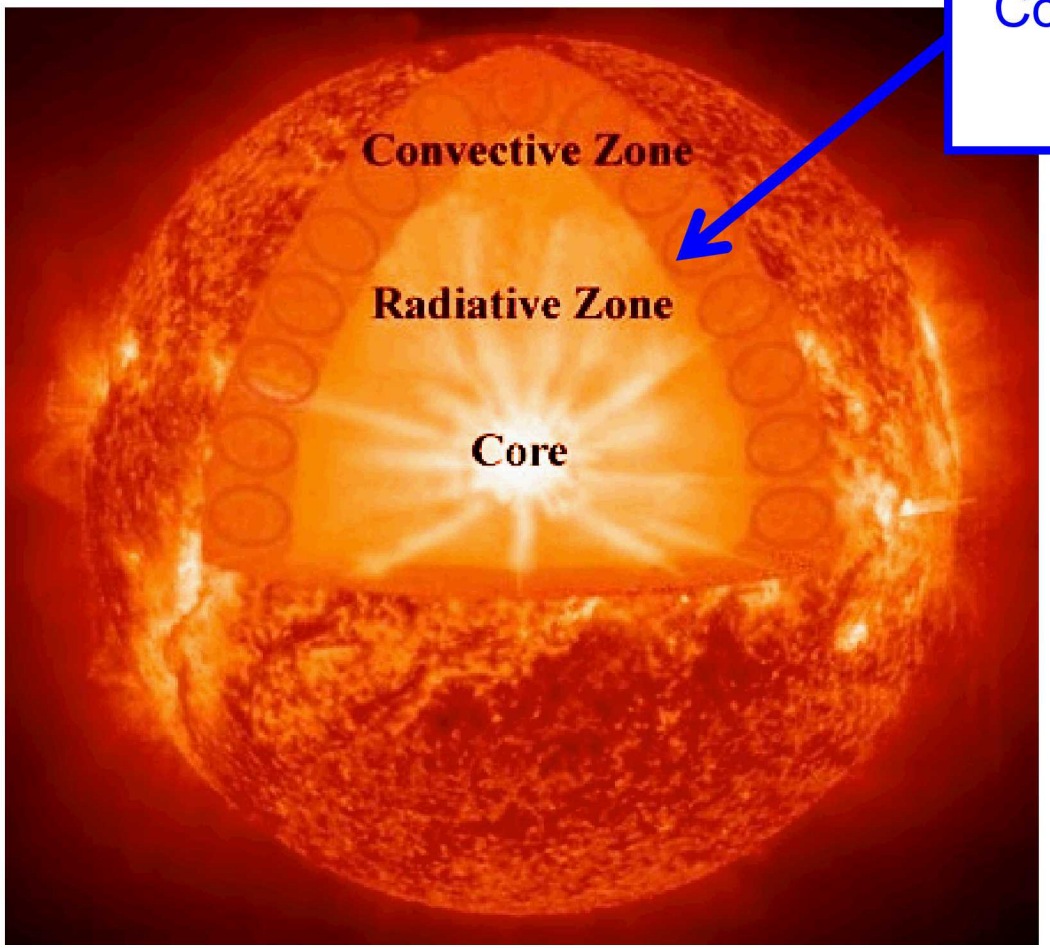


Modeled solar structure disagrees with observations

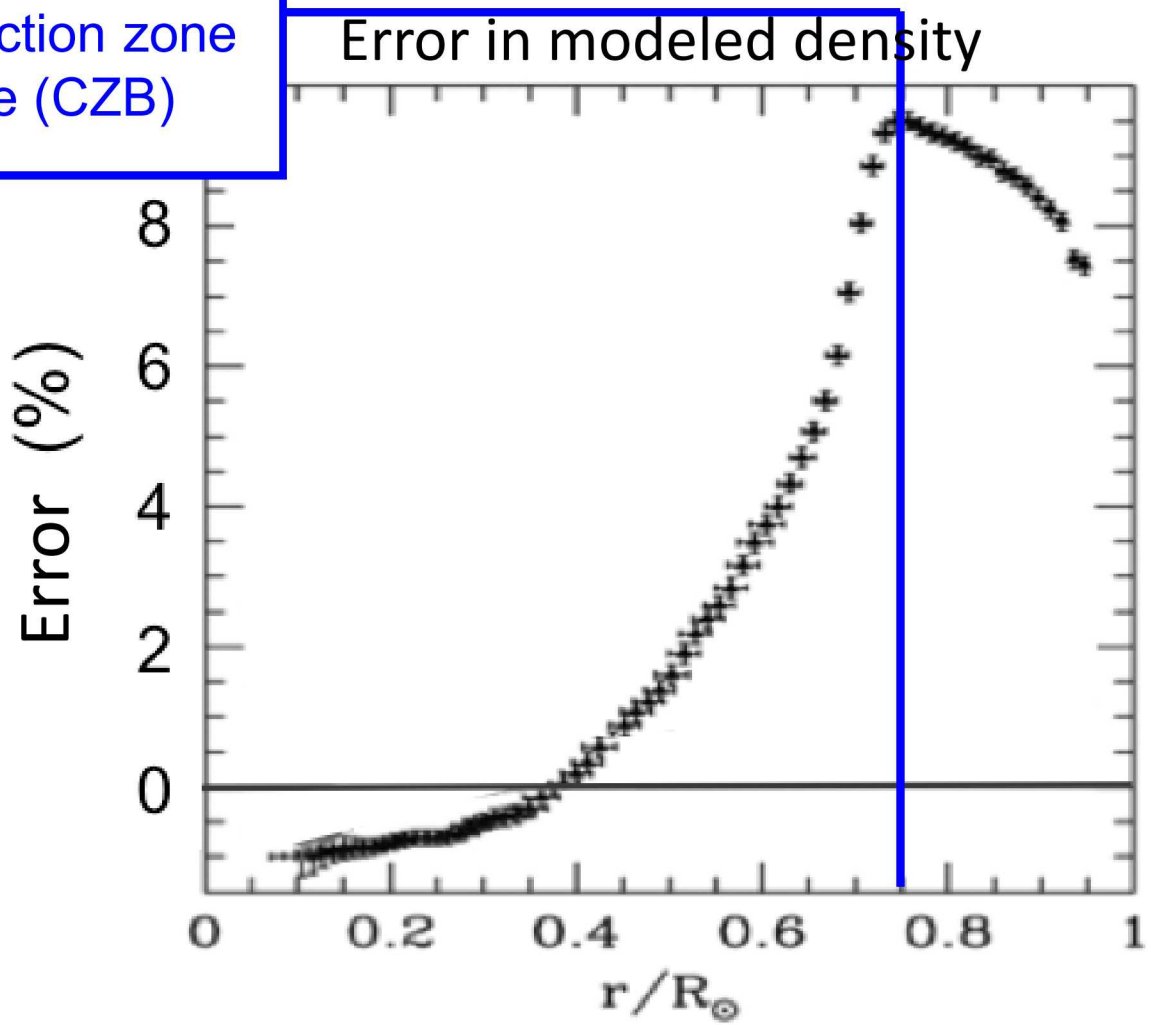




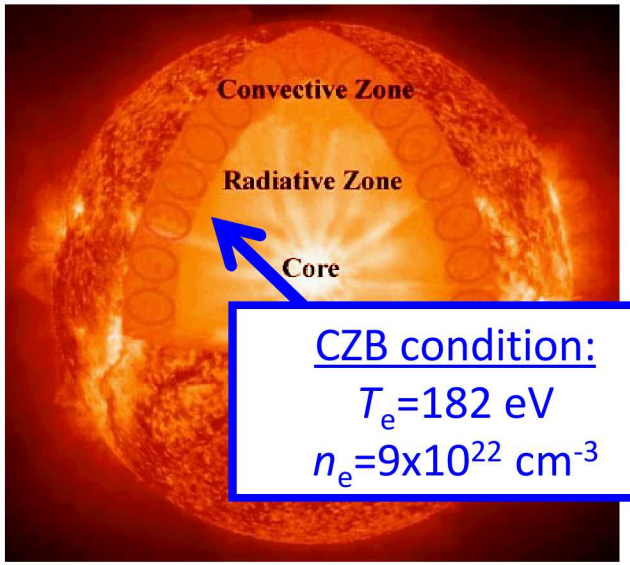
Modeled solar structure disagrees with observations



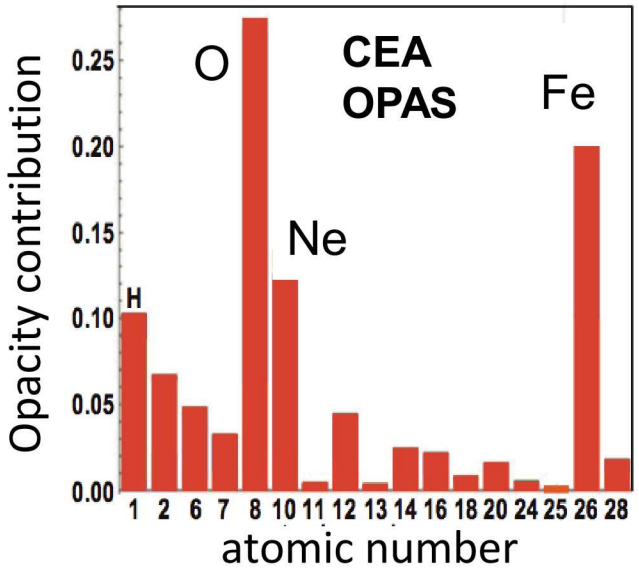
Convection zone base (CZB)



10-30% mean-opacity increase in the solar model is needed to resolve this discrepancy



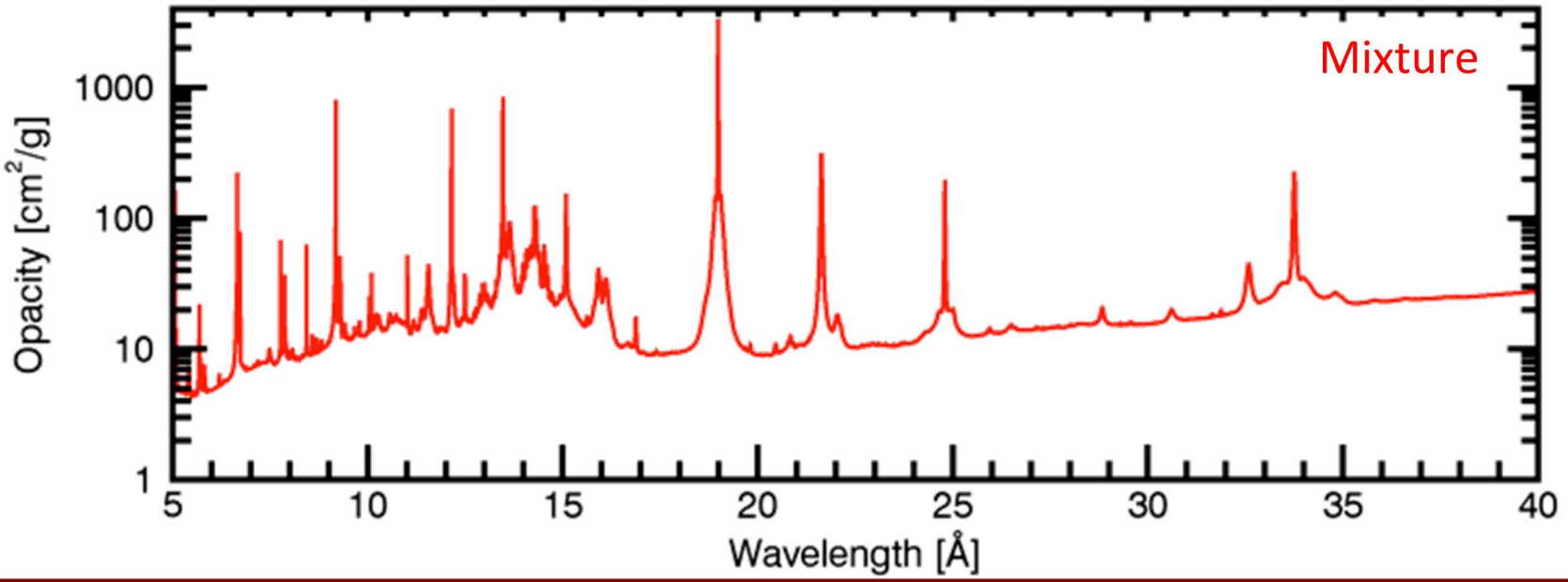
CZB condition:
T_e=182 eV
n_e=9x10^{22} cm^{-3}



Opacity: κ_ν

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

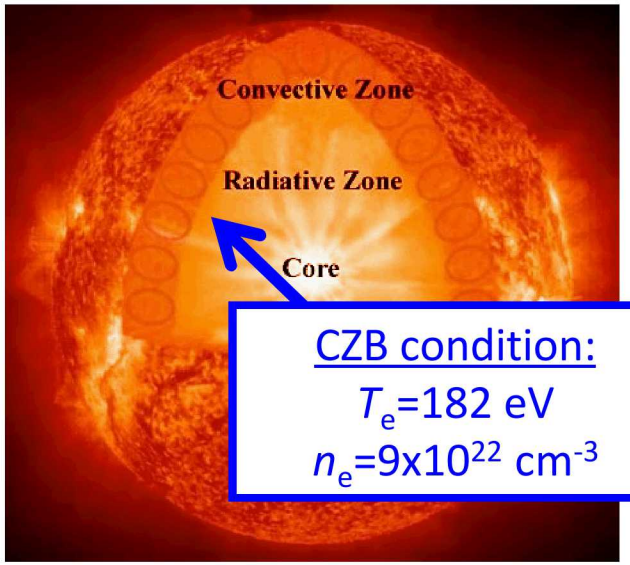
Solar mixture opacity at Convection Zone Base (CZB)



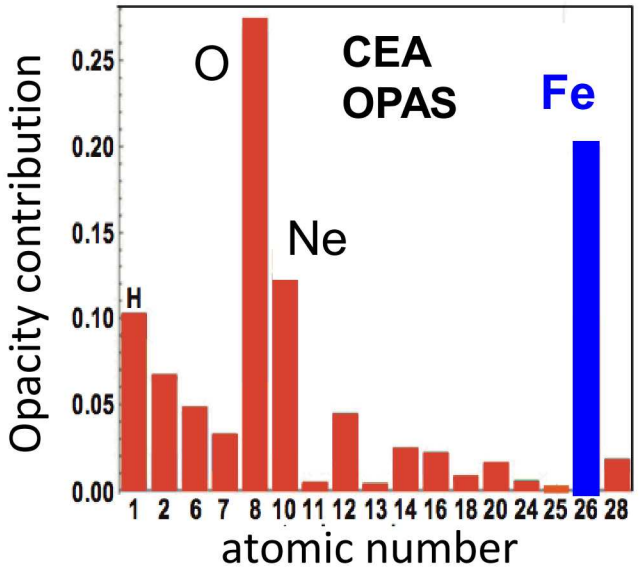
C. Blancard et al., *The Astrophysical Journal* 745, 10 (2012)

10-30% mean-opacity increase in the solar model is needed to resolve this discrepancy

Sandia National Laboratories



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



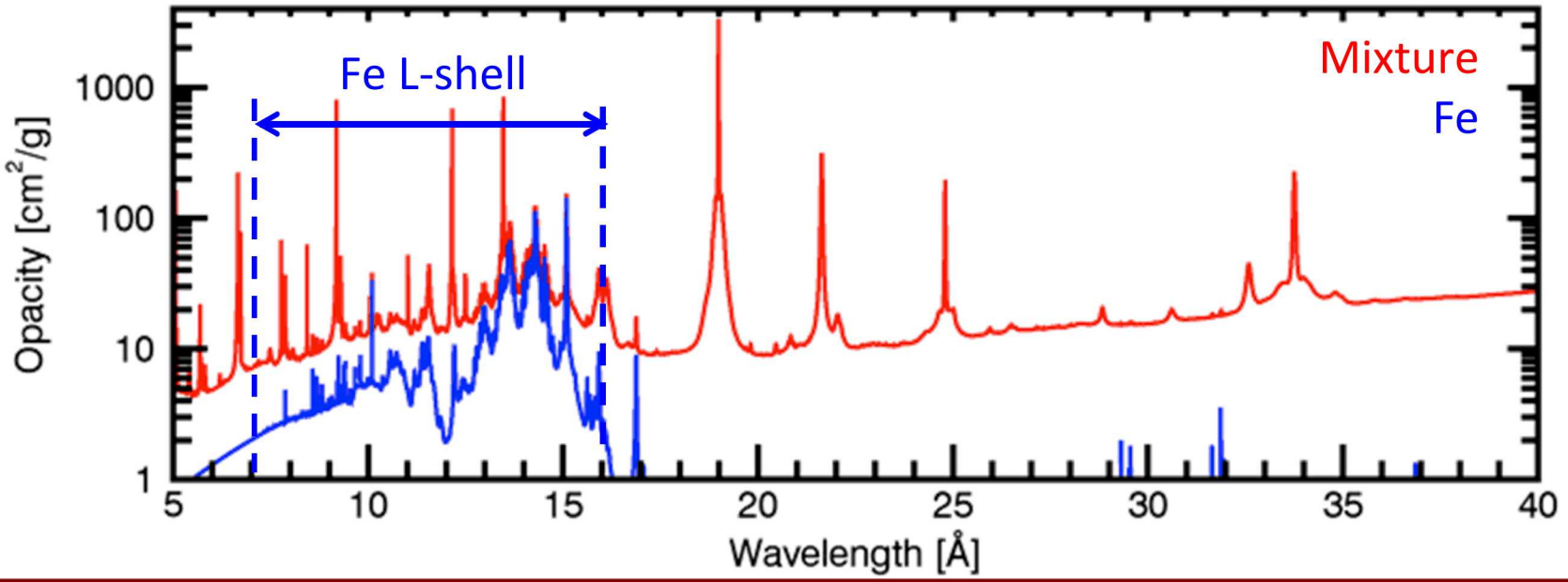
Opacity: κ_ν

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

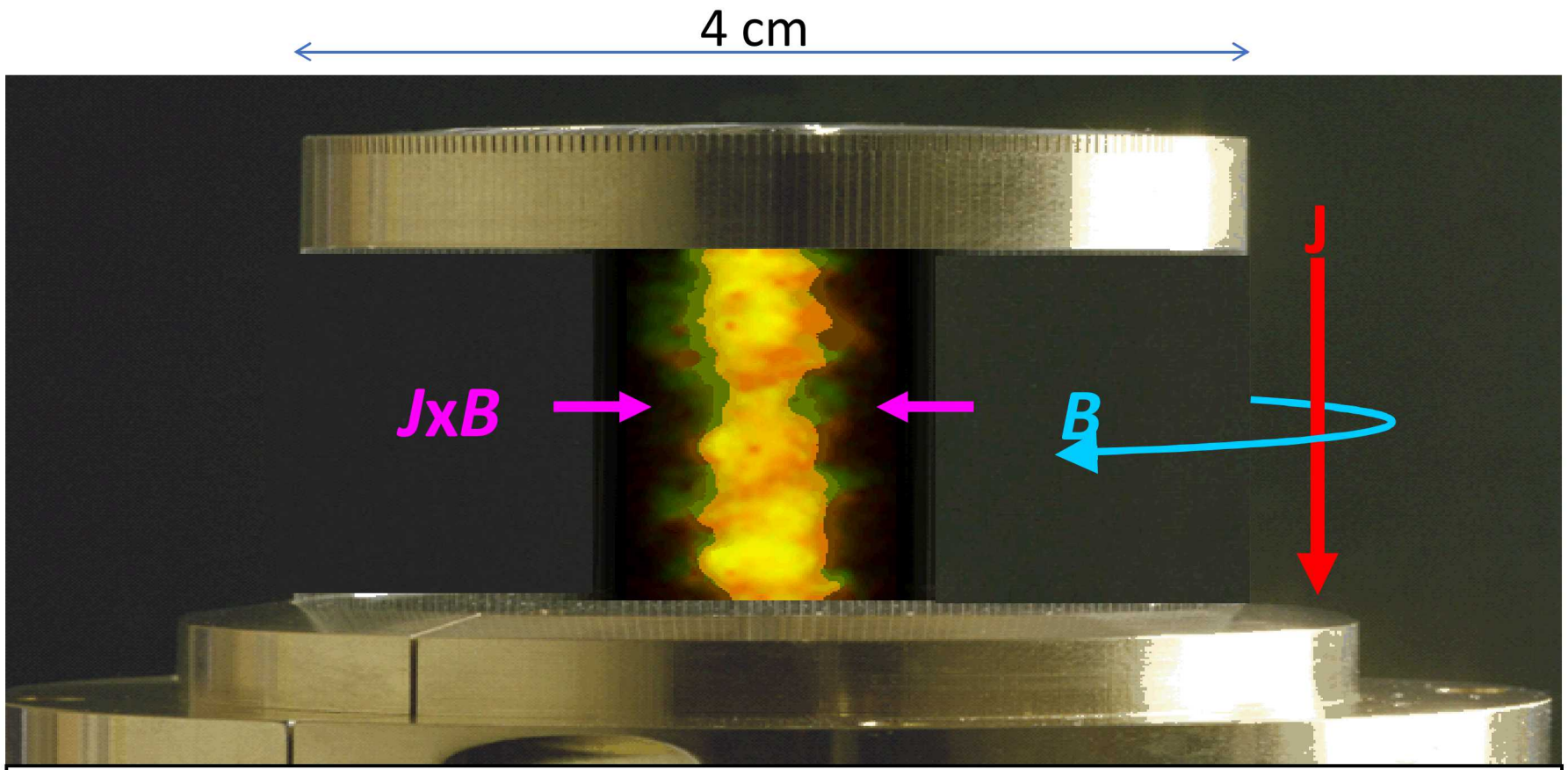
Fe is a likely suspect:

- 2nd largest contribution
- Most difficult to model

Solar mixture opacity at Convection Zone Base (CZB)



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



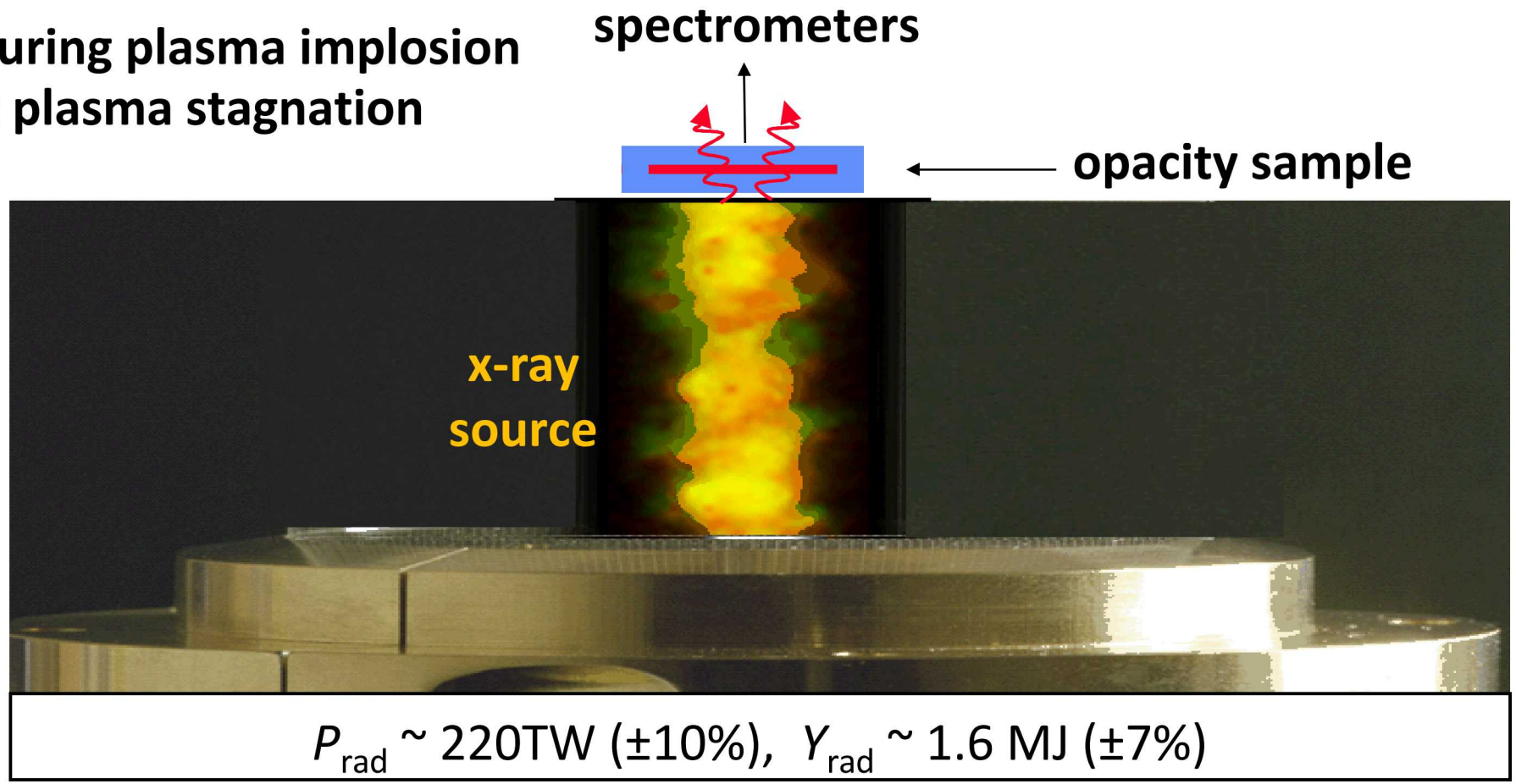
P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

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

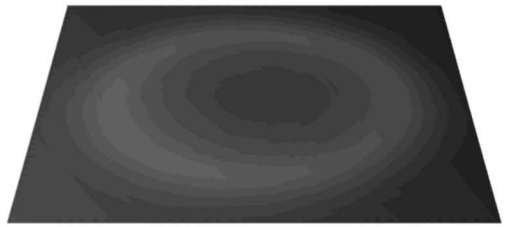


P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

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



Z-pinch radiation source

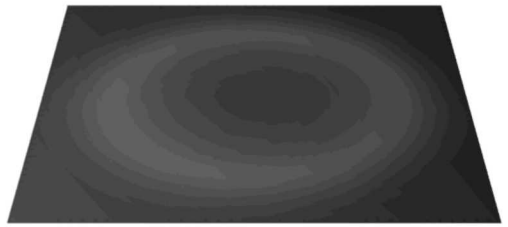
Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements
- Checking reproducibility

[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
- Checking reproducibility

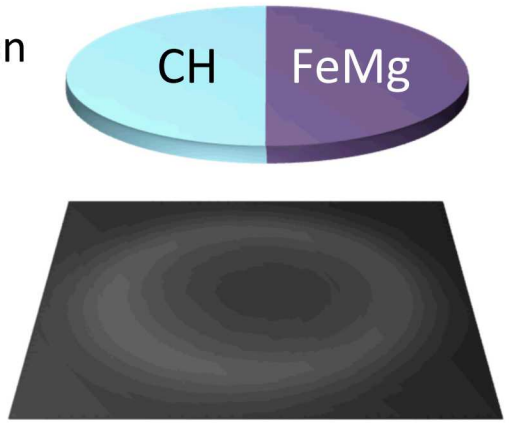
[1] Bailey et al., *Phys Plasmas* 16, 058101 (2009)

[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

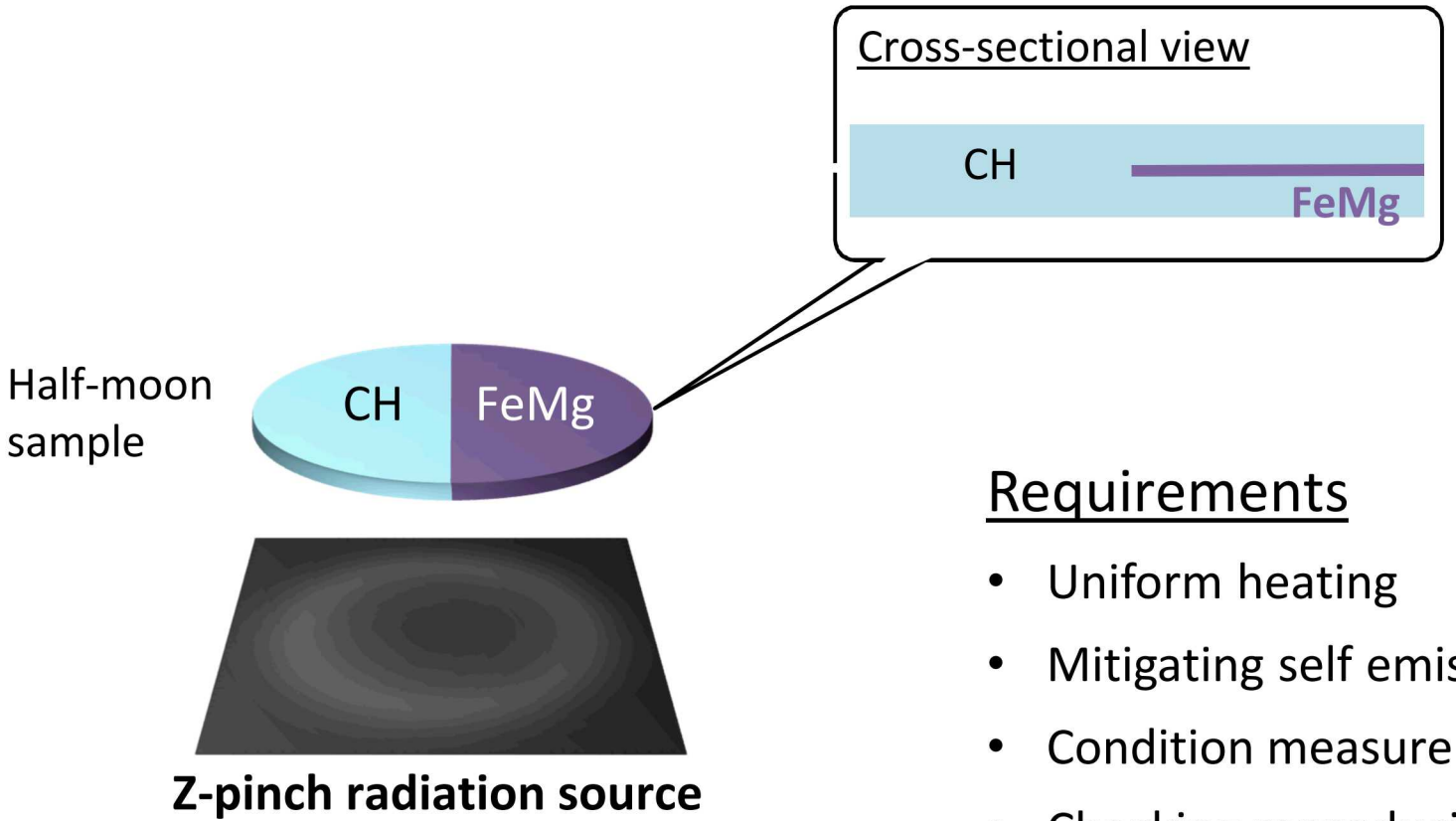
Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements
- Checking reproducibility

[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

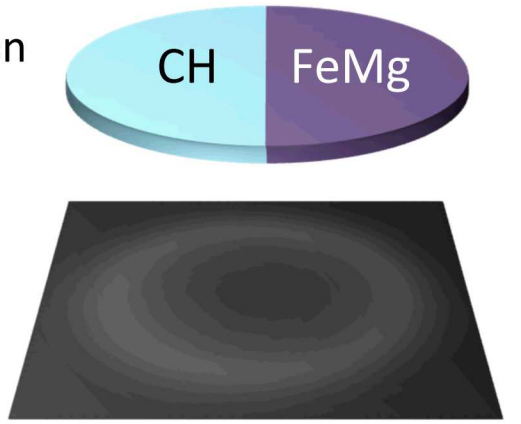
- Uniform heating
- Mitigating self emission
- Condition measurements
- Checking reproducibility

[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

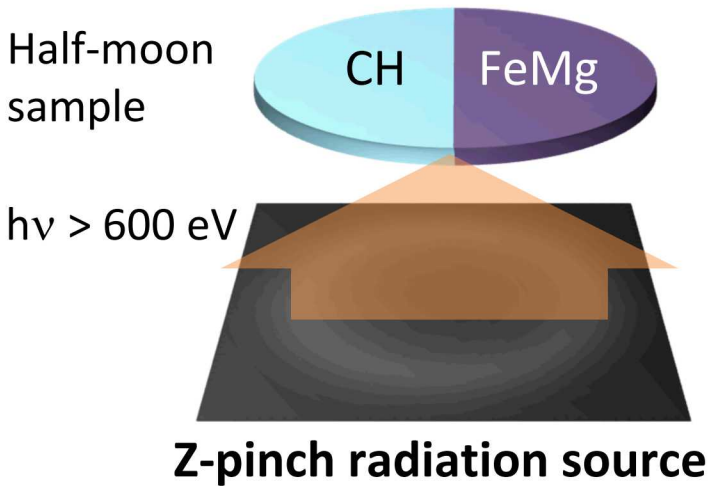
Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements
- Checking reproducibility

[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

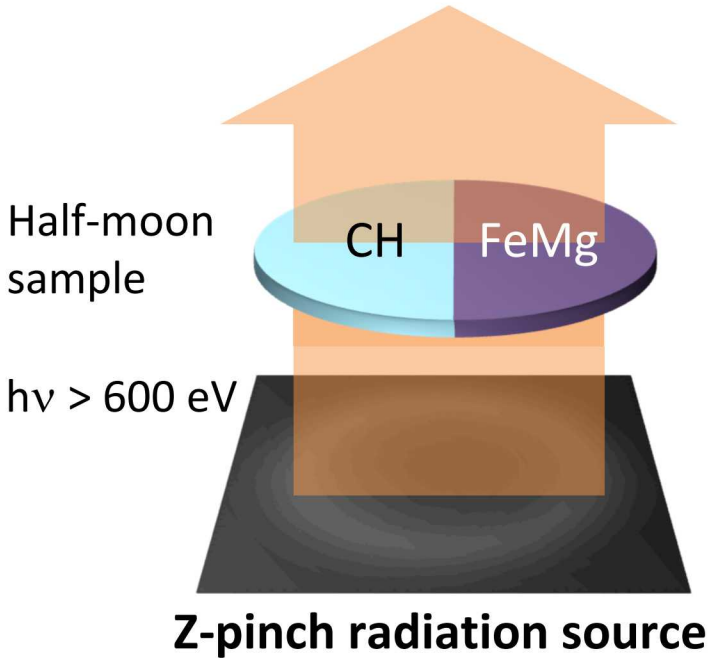


Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements
- Checking reproducibility

[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

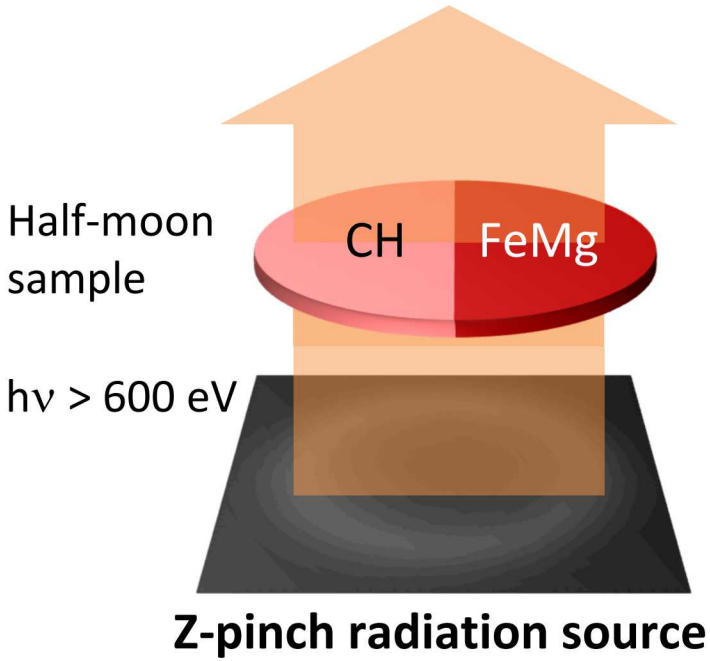


Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements
- Checking reproducibility

[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
- Checking reproducibility

<u>SNL Z satisfies:</u>

Volumetric heating

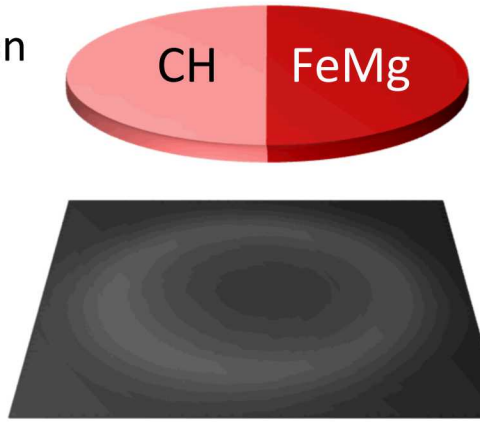
[1] Bailey et al., *Phys Plasmas* 16, 058101 (2009)

[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
- Checking reproducibility

<u>SNL Z satisfies:</u>

Volumetric heating

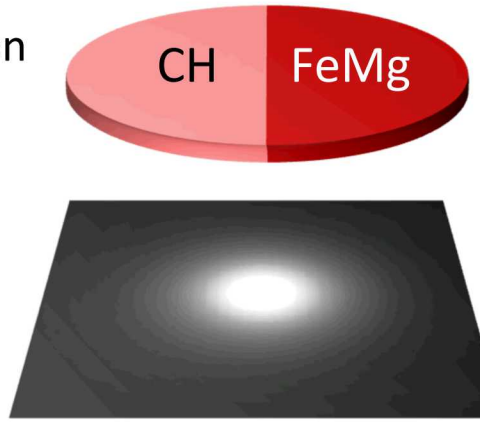
[1] Bailey et al., *Phys Plasmas* 16, 058101 (2009)

[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
- Checking reproducibility

<u>SNL Z satisfies:</u>

Volumetric heating

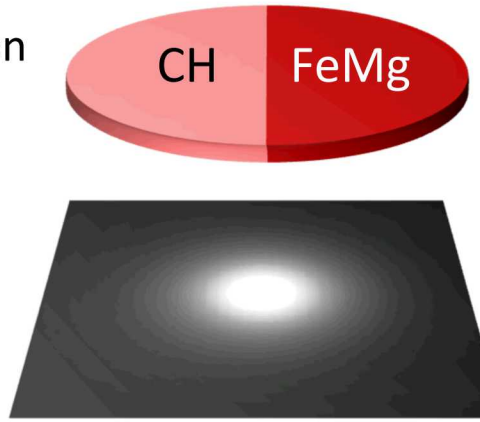
[1] Bailey et al., *Phys Plasmas* 16, 058101 (2009)

[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



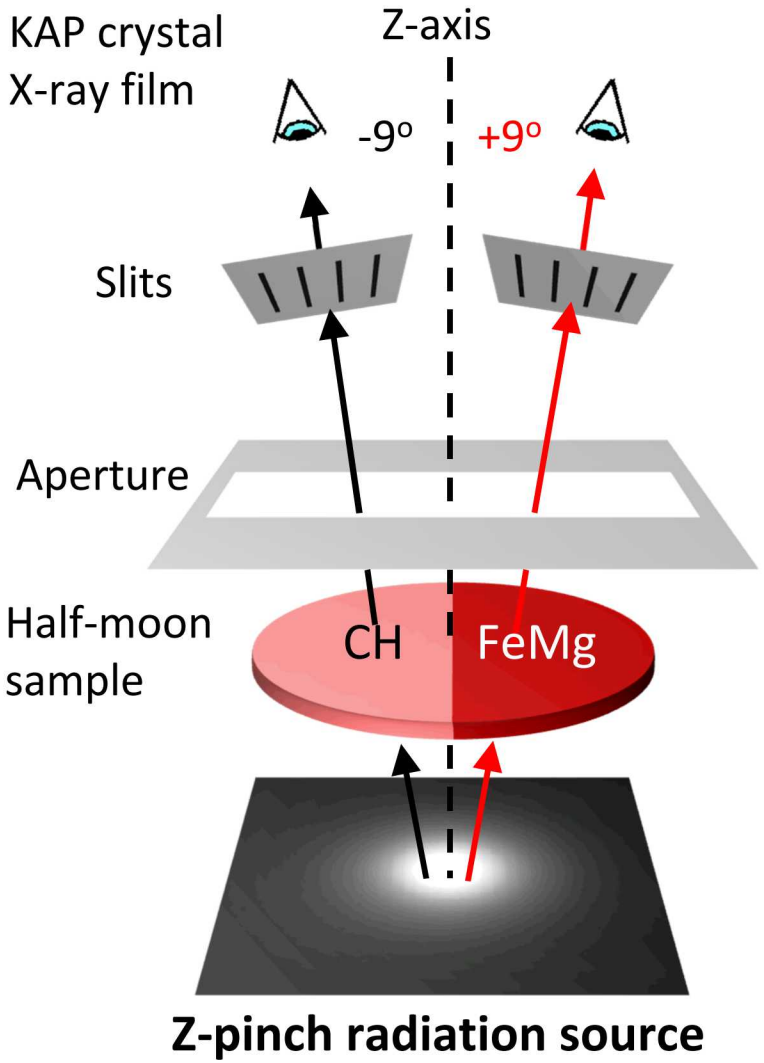
Z-pinch radiation source

Requirements		SNL Z satisfies:
• Uniform heating	→	Volumetric heating
• Mitigating self emission	→	350 eV Planckian backlight (>> 200eV sample self-emission)
• Condition measurements		
• Checking reproducibility		

[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

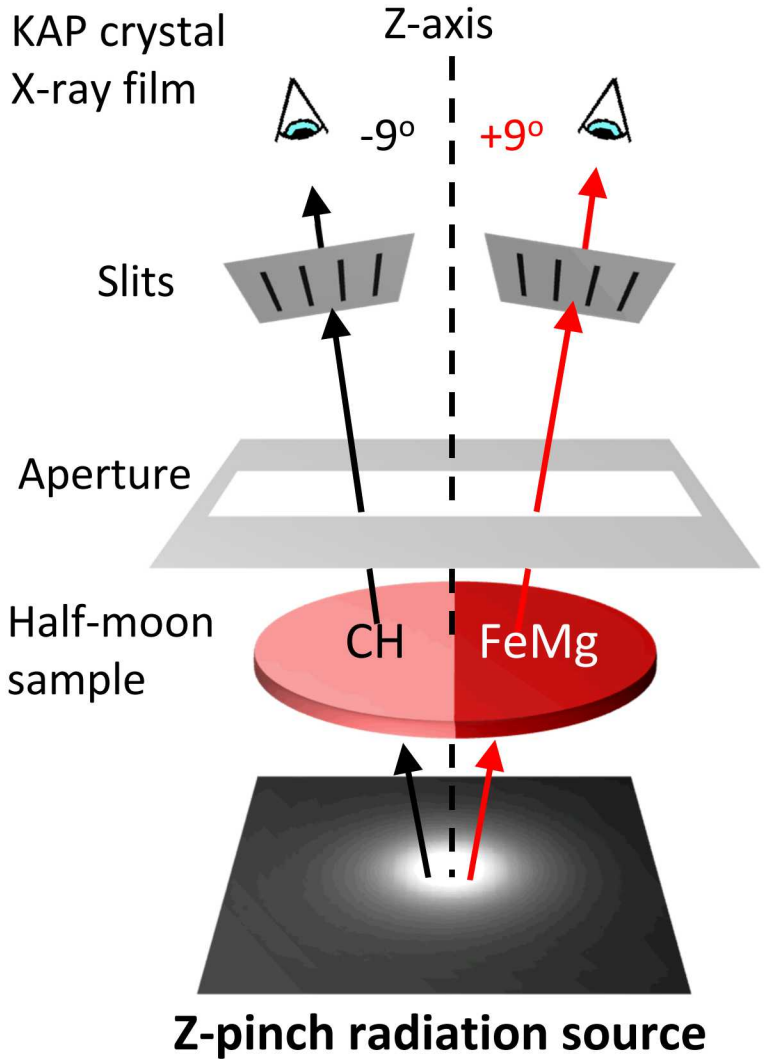
- Uniform heating → Volumetric heating
- Mitigating self emission → 350 eV Planckian backlight (>> 200eV sample self-emission)
- Condition measurements
- Checking reproducibility

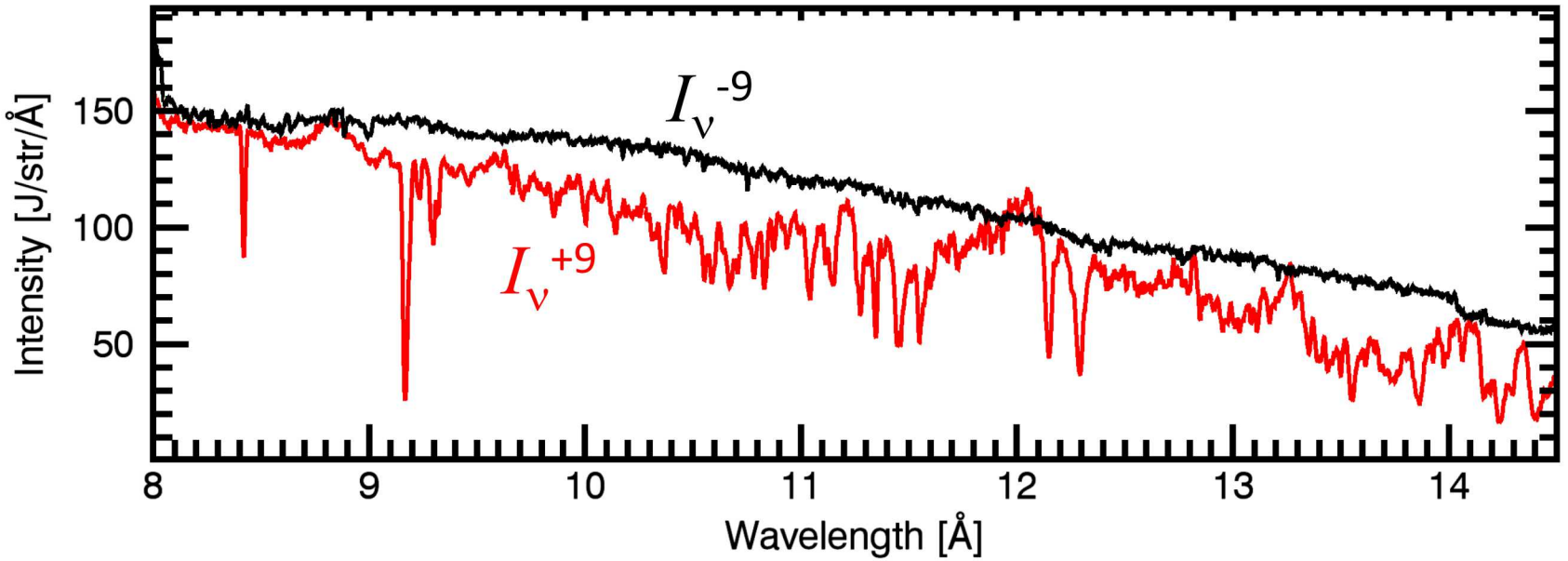
SNL Z satisfies:

[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

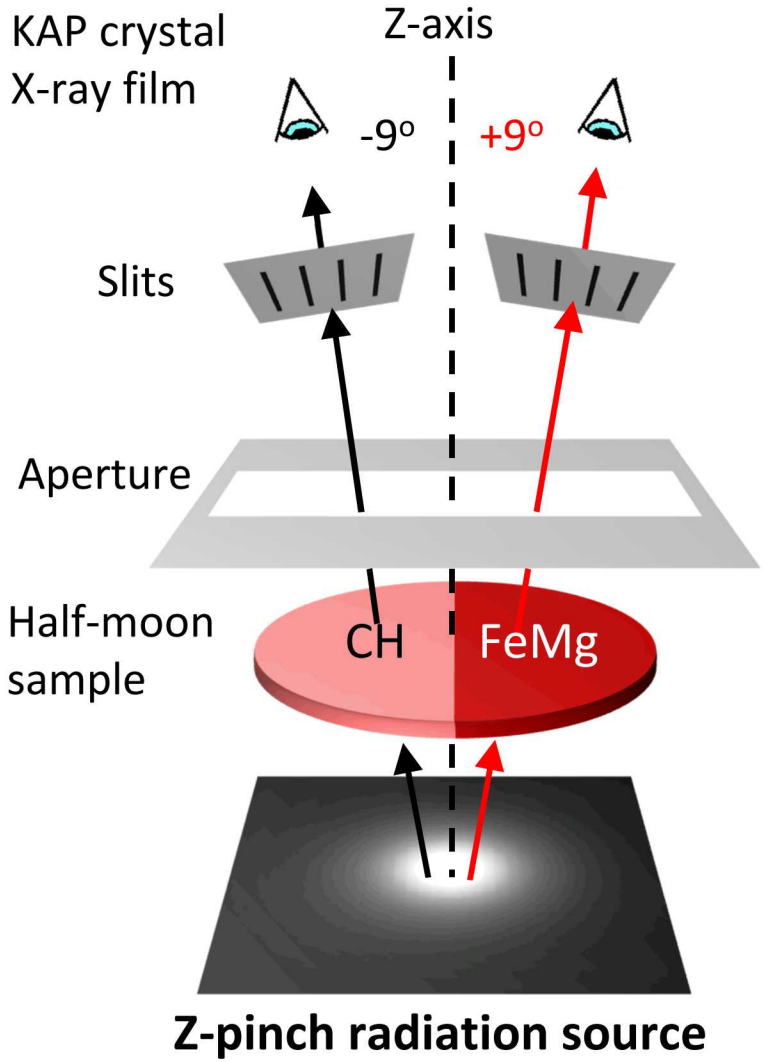
- Uniform heating → Volumetric heating
- Mitigating self emission → 350 eV Planckian backlight (>> 200eV sample self-emission)
- Condition measurements
- Checking reproducibility

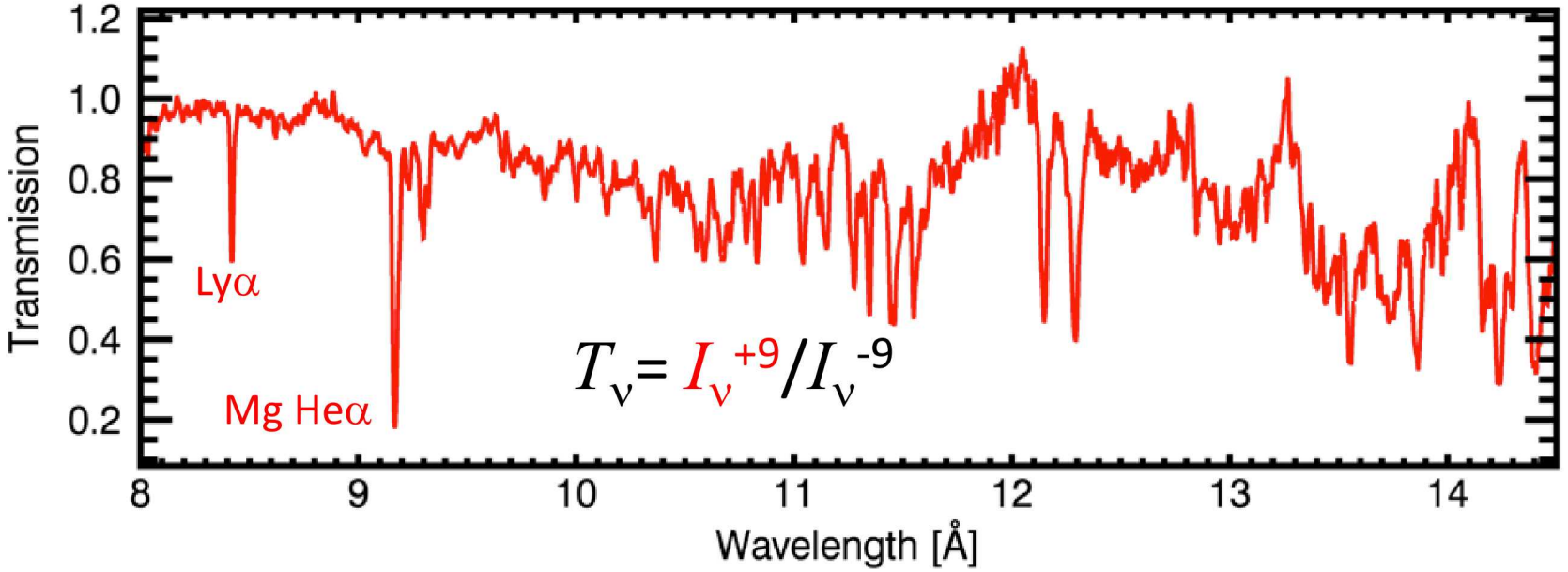
SNL Z satisfies:

[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

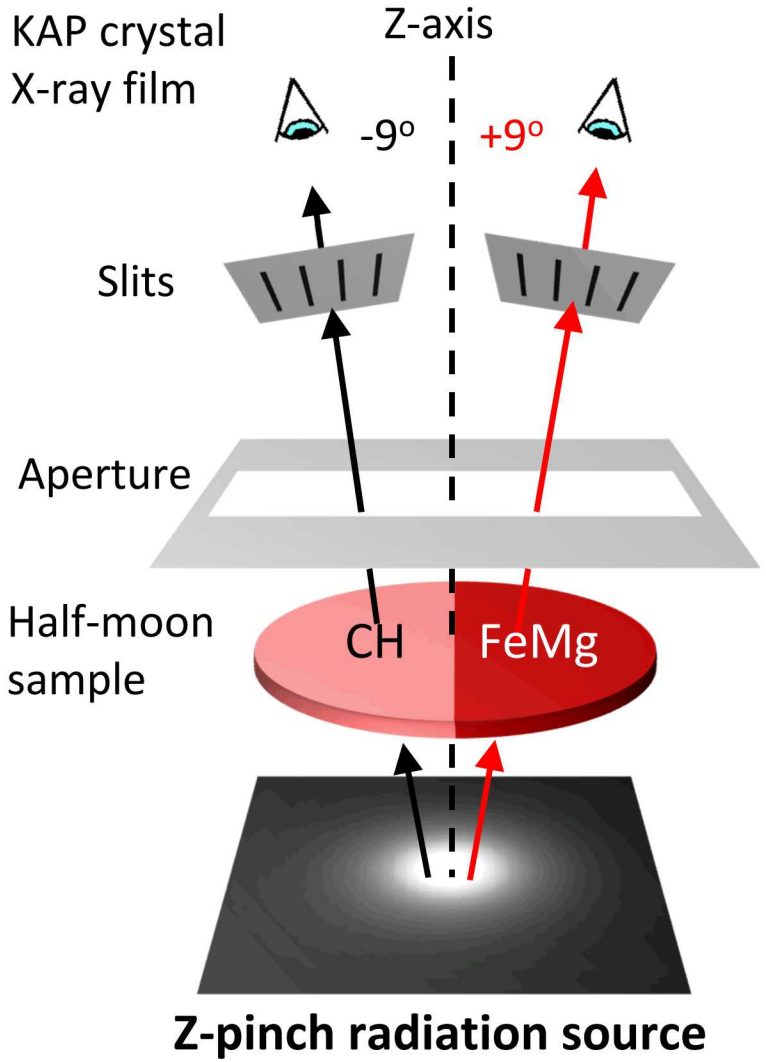
- Uniform heating → Volumetric heating
- Mitigating self emission → 350 eV Planckian backlight (>> 200eV sample self-emission)
- Condition measurements
- Checking reproducibility

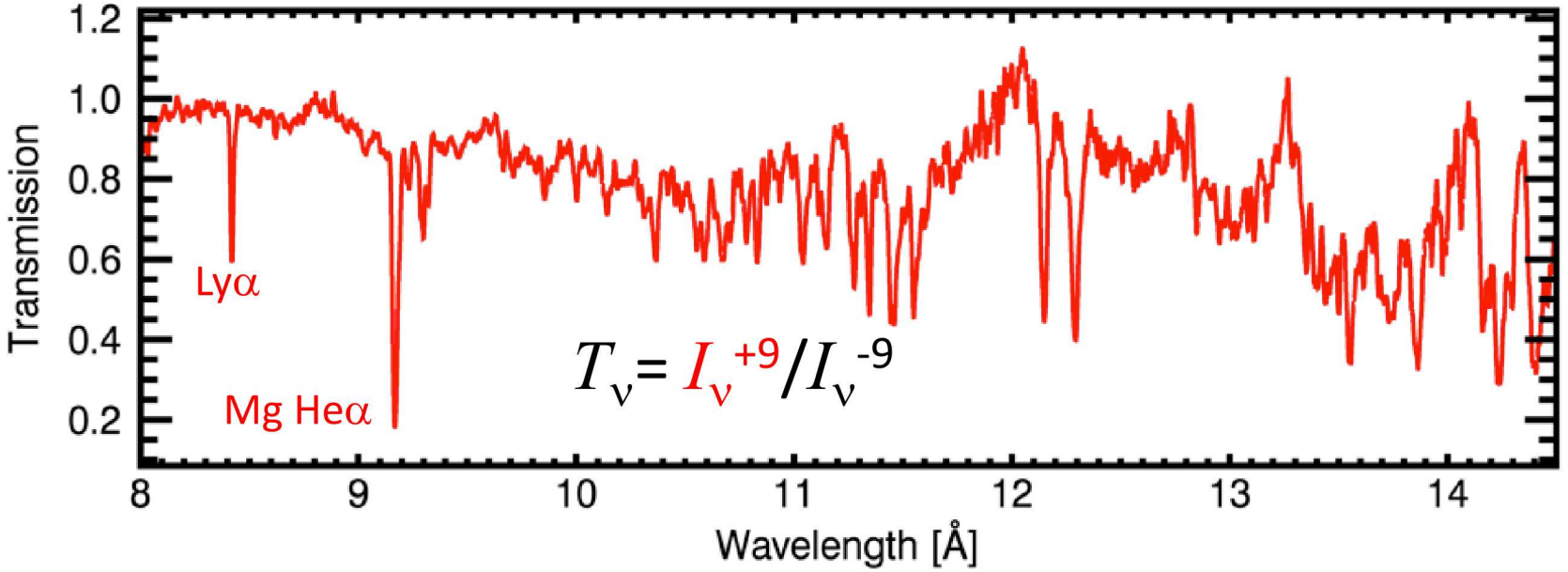
SNL Z satisfies:

[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

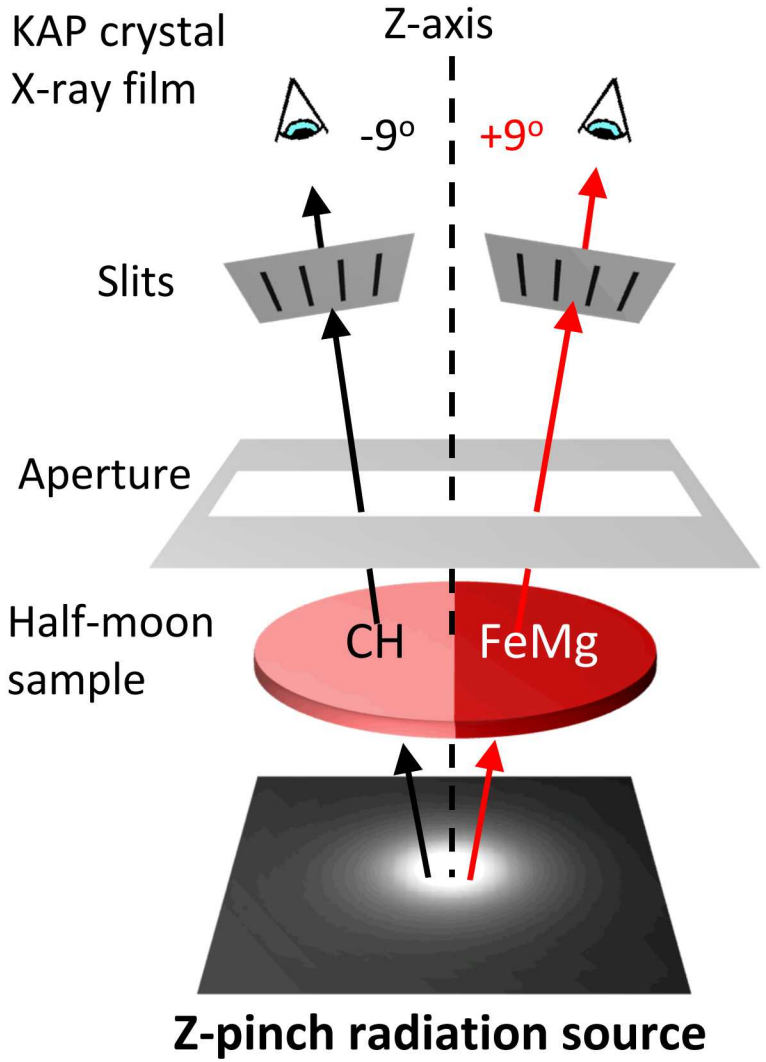
- Uniform heating → Volumetric heating
- Mitigating self emission → 350 eV Planckian backlight
- Condition measurements → Mg K-shell spectroscopy
- Checking reproducibility

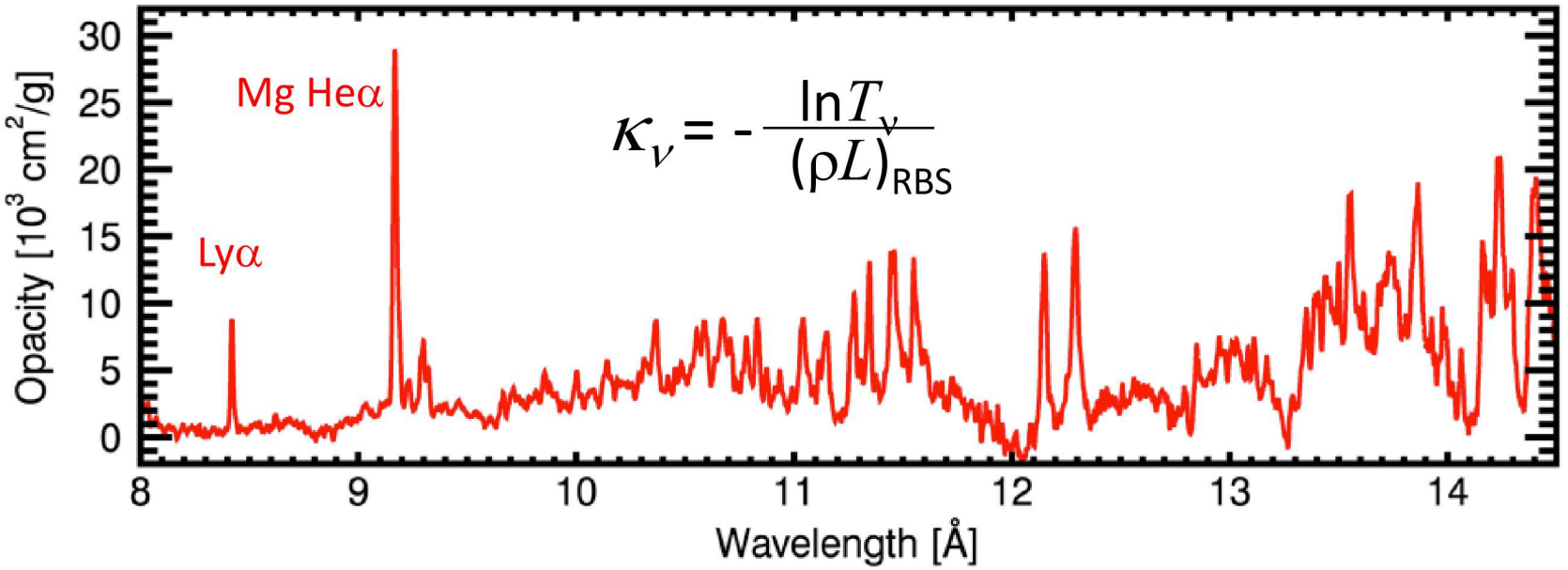
SNL Z satisfies:

[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

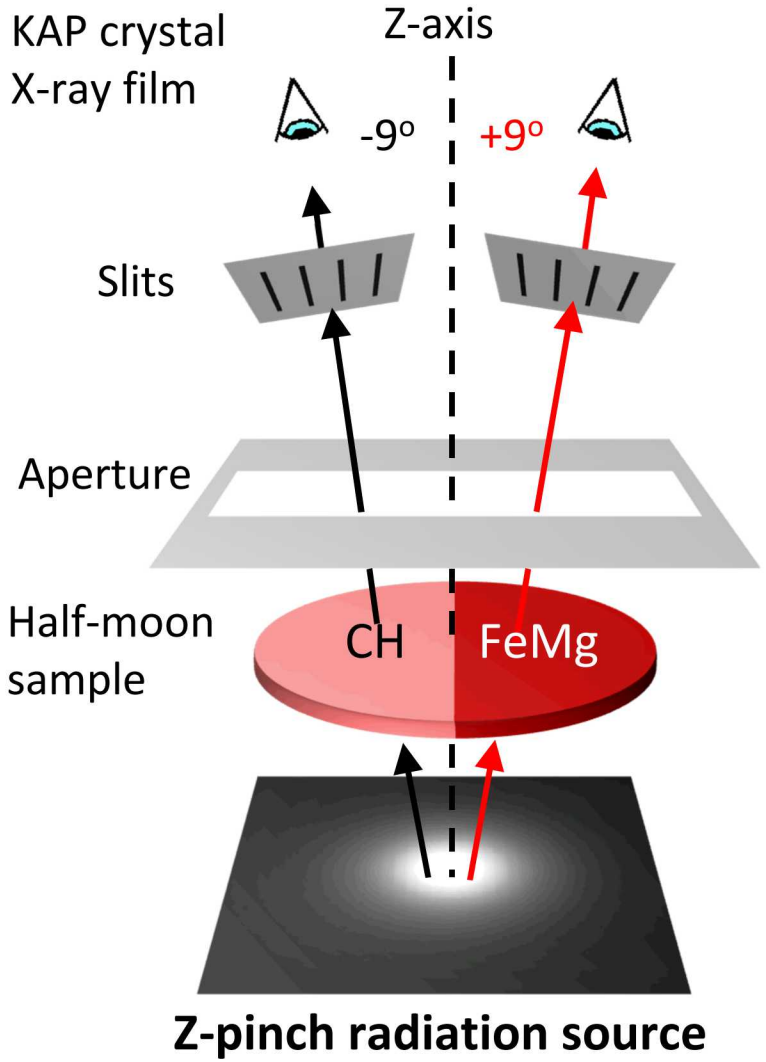
- Uniform heating → Volumetric heating
- Mitigating self emission → 350 eV Planckian backlight
- Condition measurements → Mg K-shell spectroscopy
- Checking reproducibility

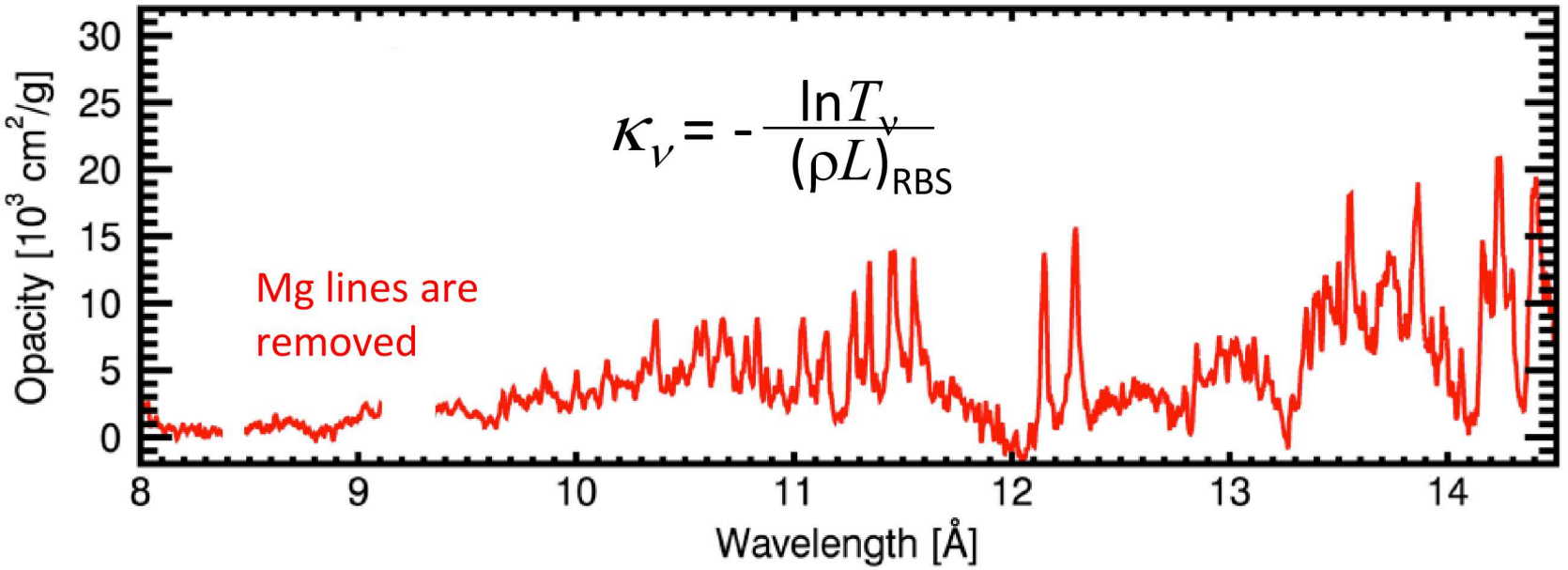
SNL Z satisfies:

[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

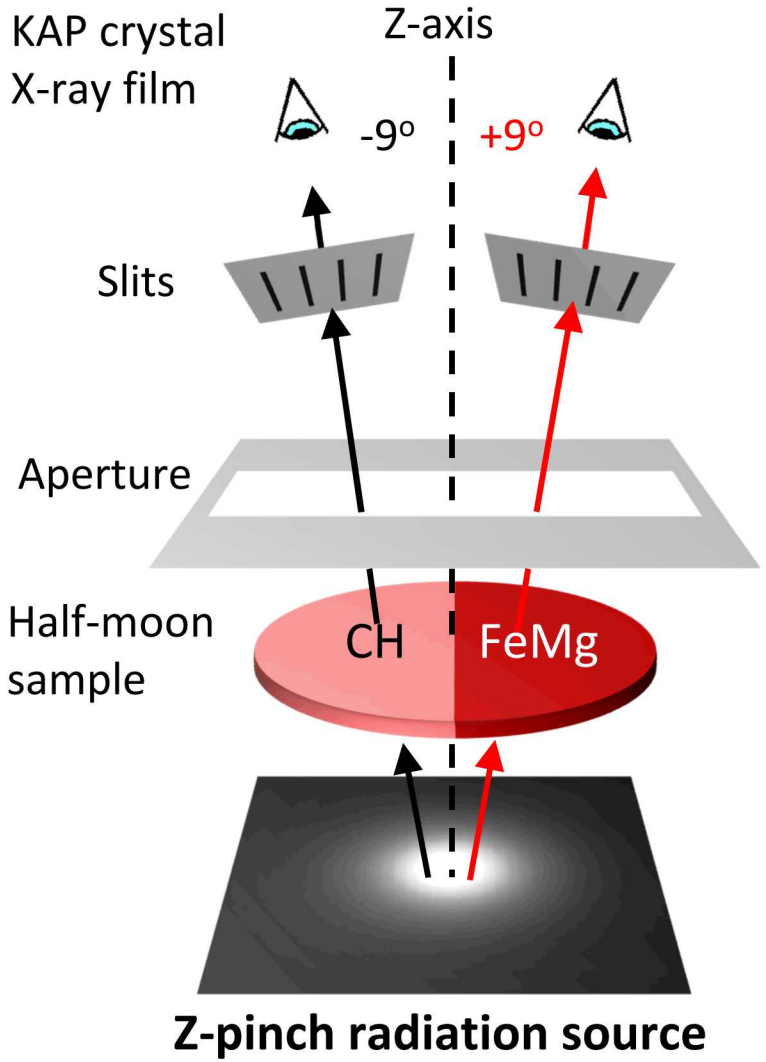
- Uniform heating → Volumetric heating
- Mitigating self emission → 350 eV Planckian backlight
- Condition measurements → Mg K-shell spectroscopy
- Checking reproducibility

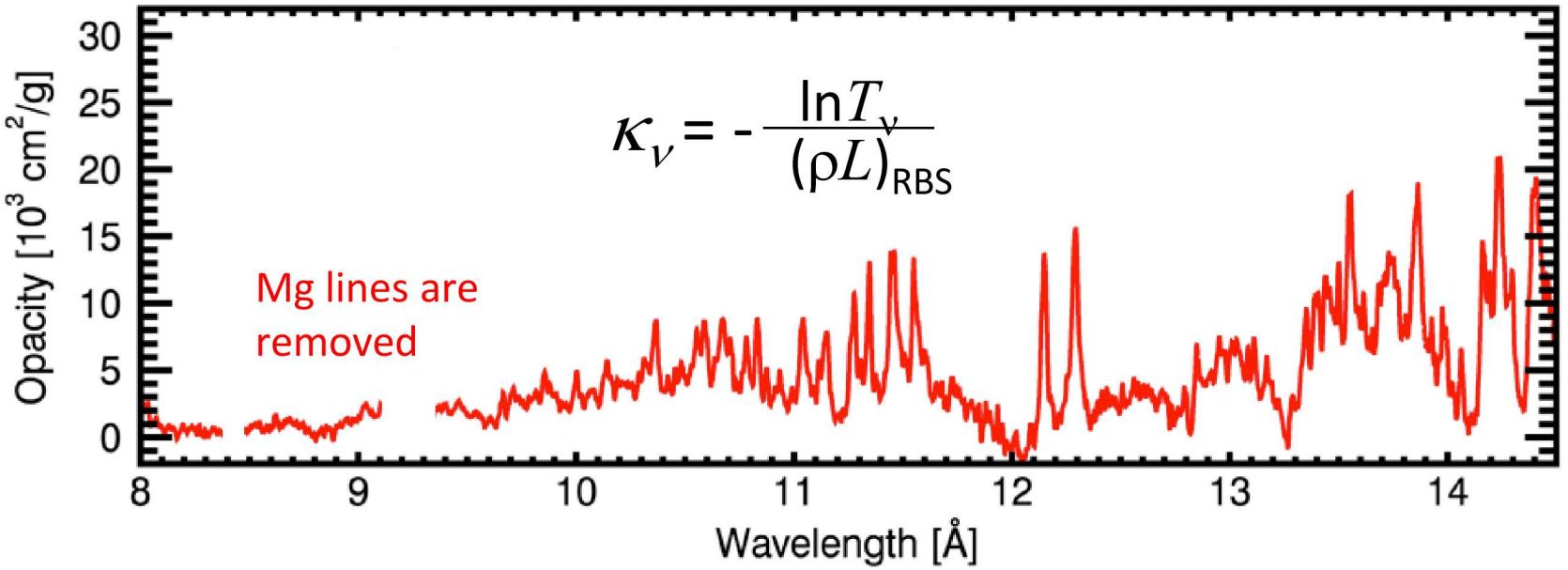
SNL Z satisfies:

[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
- Checking reproducibility → ≥ 5 shots

SNL Z satisfies:

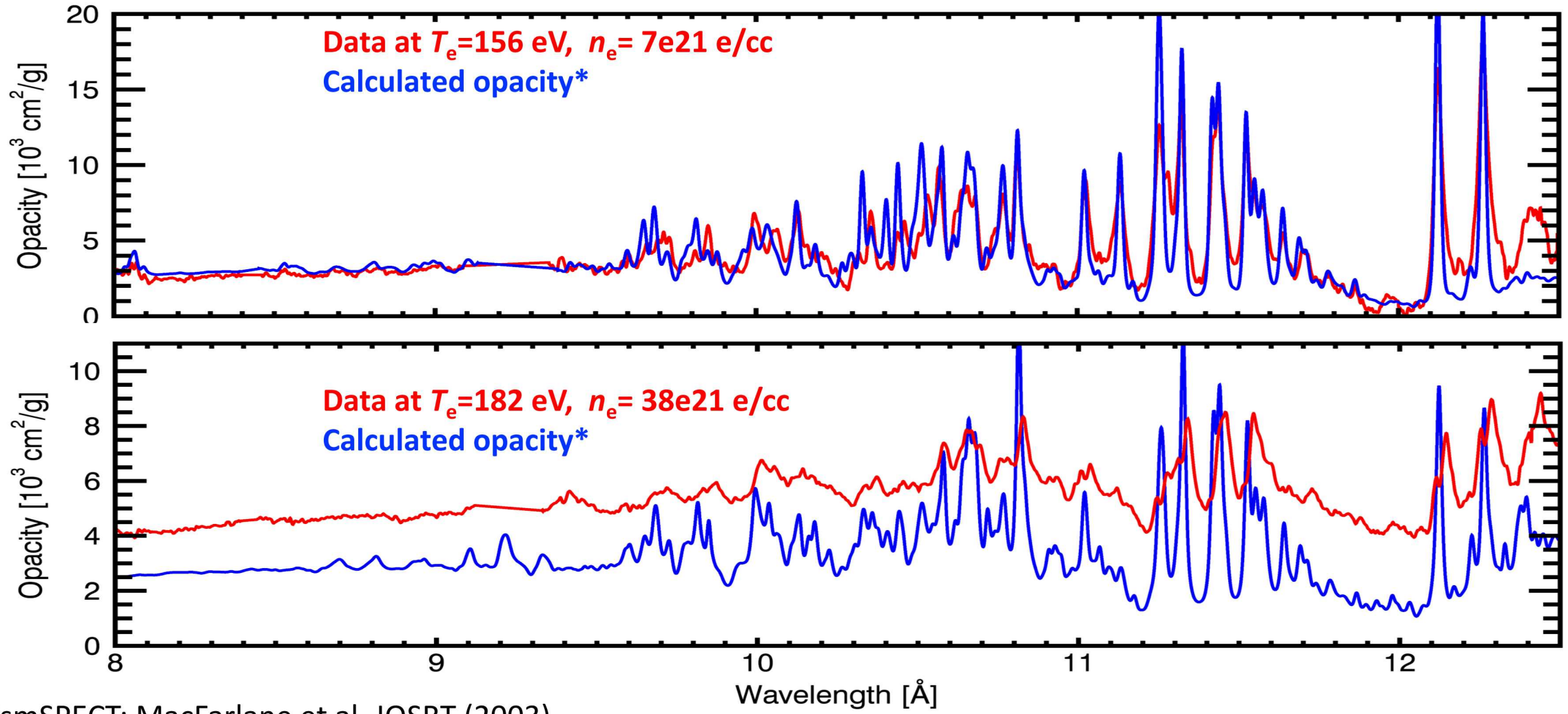
[1] Bailey et al., *Phys Plasmas* 16, 058101 (2009)

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

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

Sandia National Laboratories

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

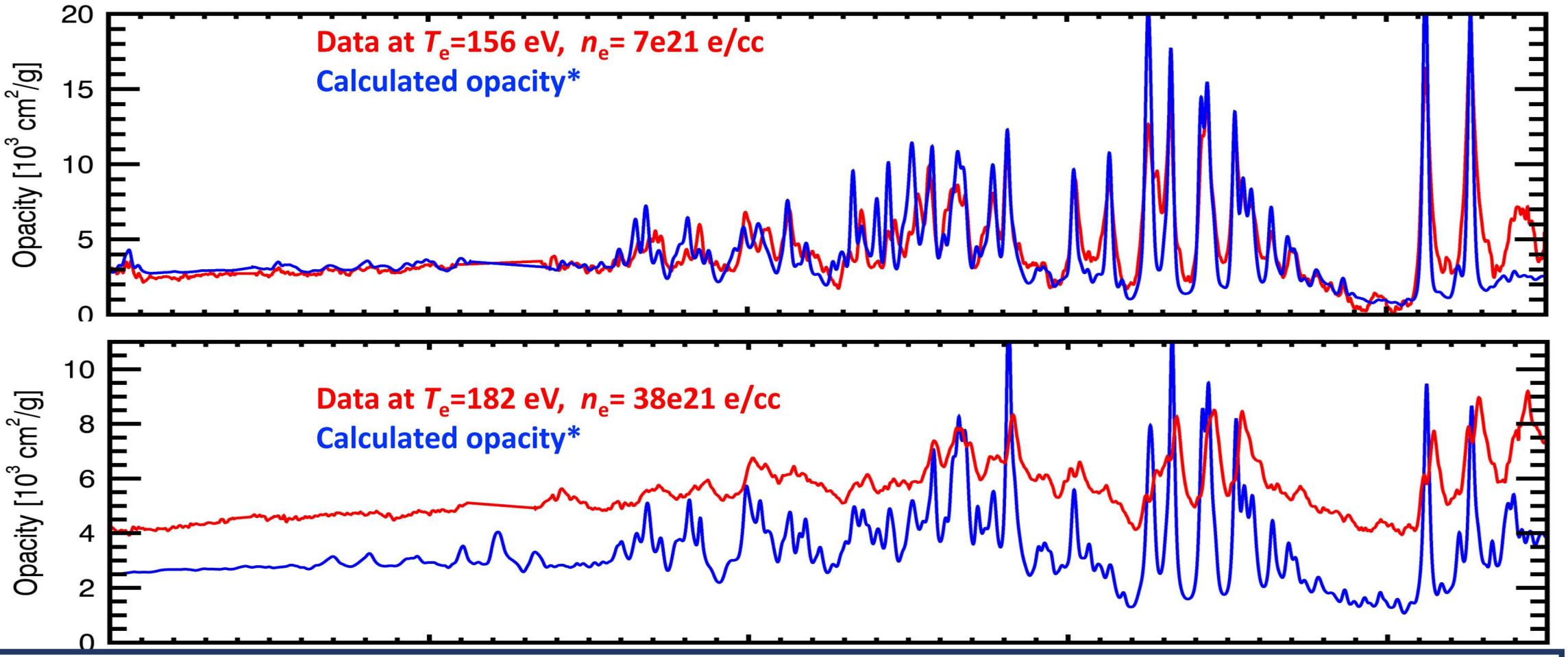


* PrismSPECT: MacFarlane et al, JQSRT (2003)

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

Sandia National Laboratories

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



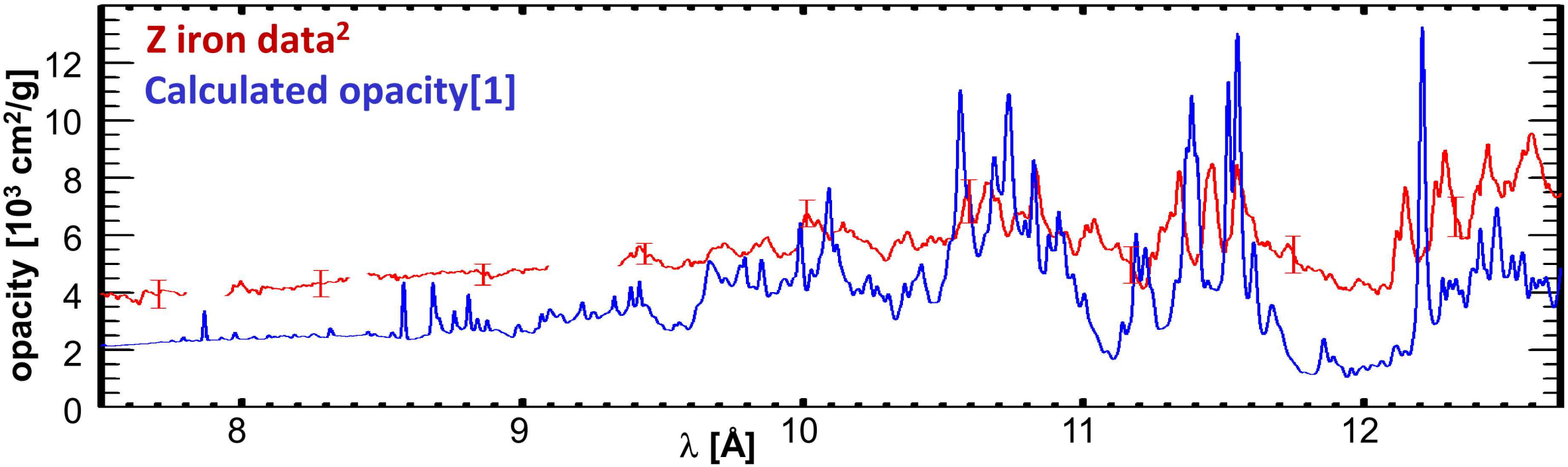
If measured Fe opacity is correct, it would increase the solar mean opacity by ~7%.

* P

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

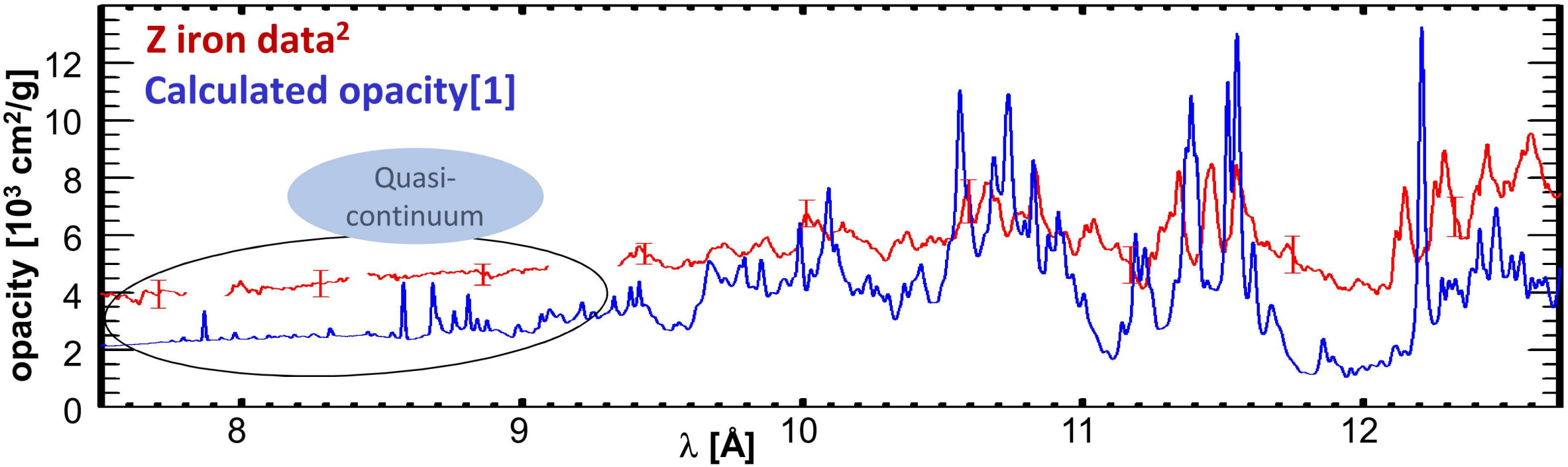
[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

Reported opacity discrepancy is complex and deserves further scrutiny

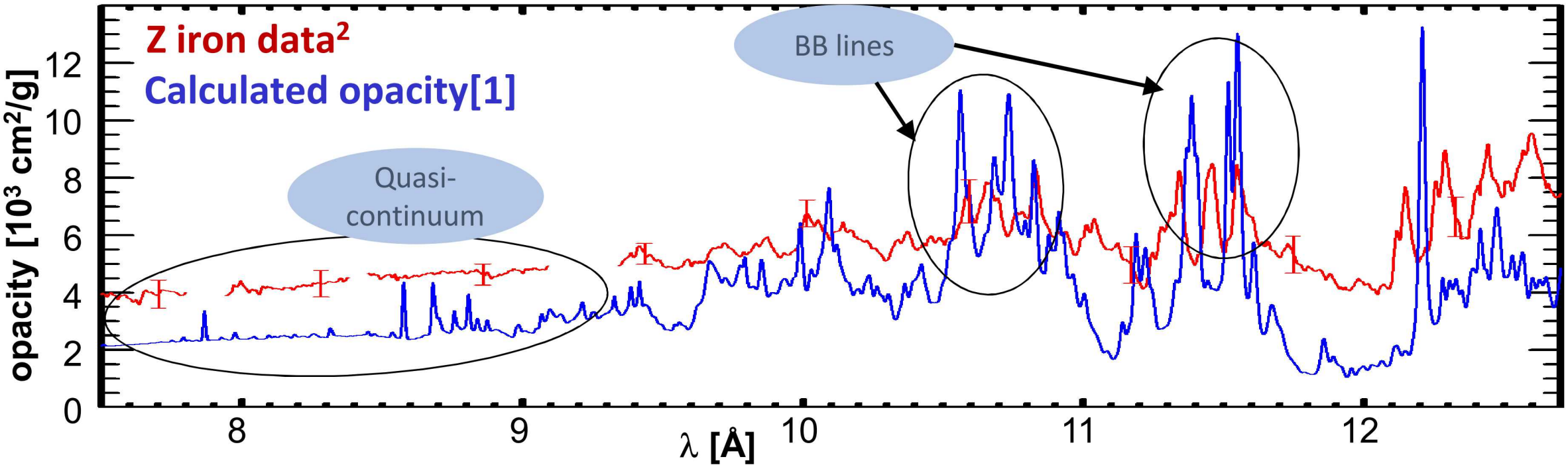


[1] Seaton et al., *MNRAS* (1994)

Reported opacity discrepancy is complex and deserves further scrutiny

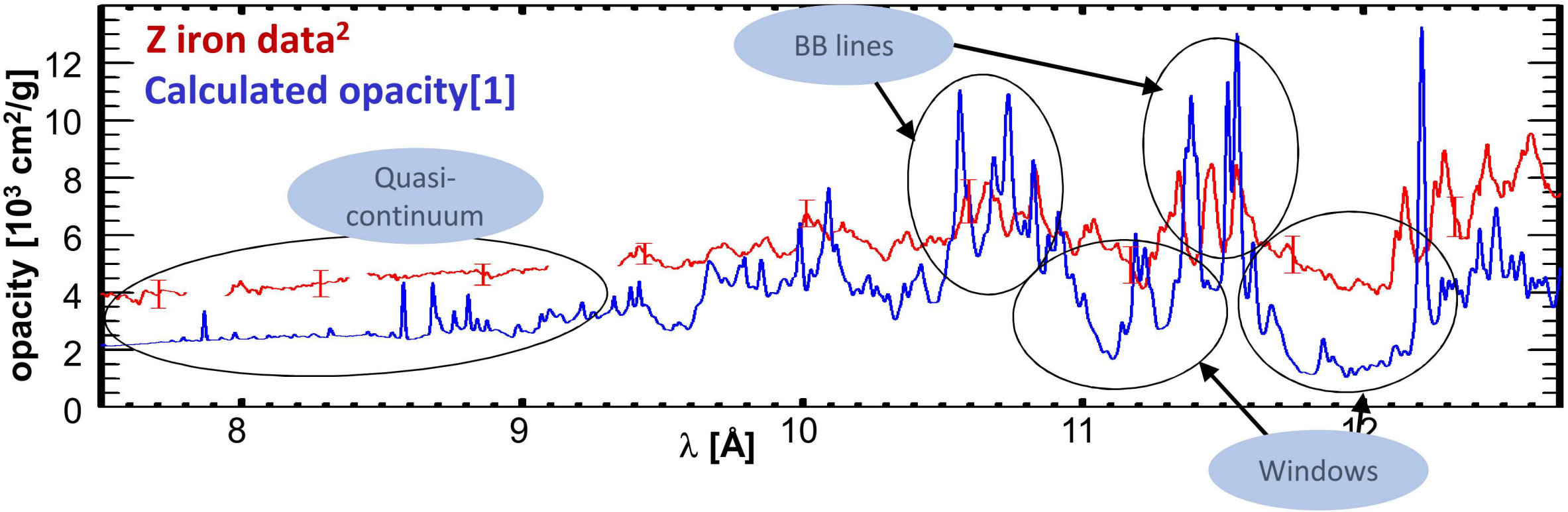


Reported opacity discrepancy is complex and deserves further scrutiny



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

Reported opacity discrepancy is complex and deserves further scrutiny



Is opacity theory inaccurate?

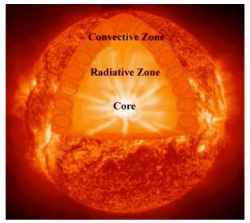
Is opacity experiment flawed?

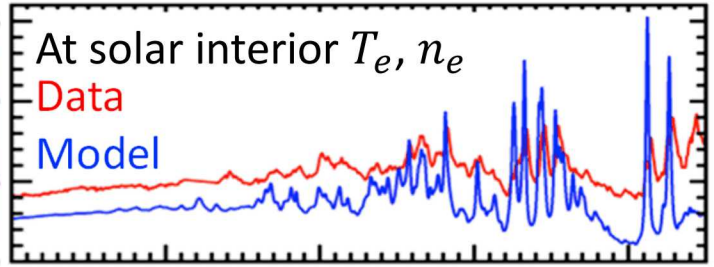
[1] Seaton et al., *MNRAS* (1994)

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

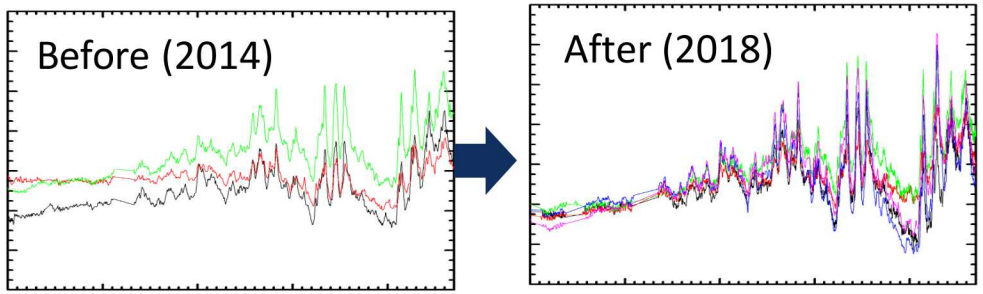
Sandia National Laboratories

- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**
  - → Is opacity theory wrong? Is experiment flawed?

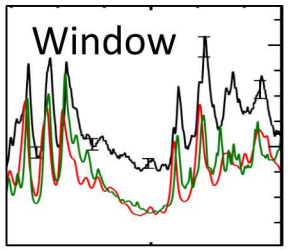


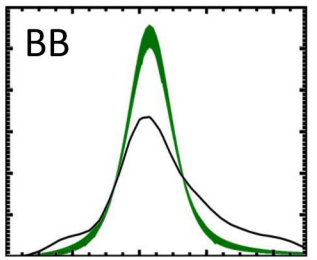


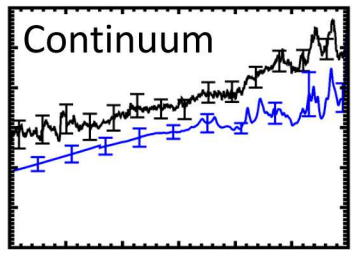
- **Refined analysis improved shot-to-shot reproducibility, demonstrating opacity experiment reliability**



- **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





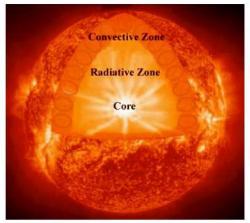


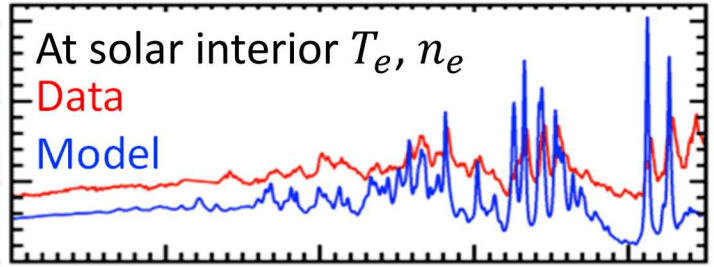
High reproducibility demonstrates unprecedented benchmark capability of SNL opacity platform

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

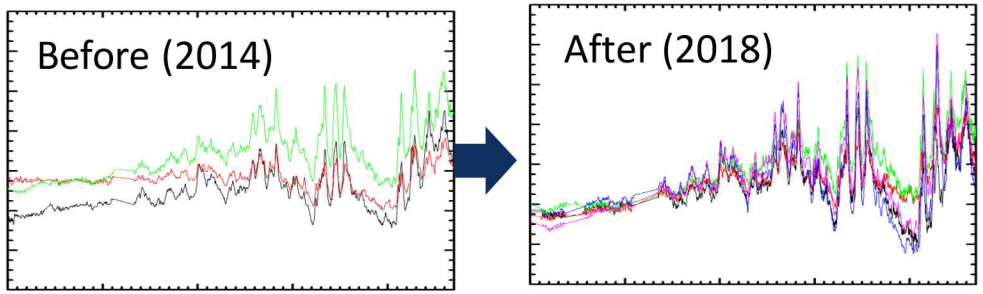
Sandia National Laboratories

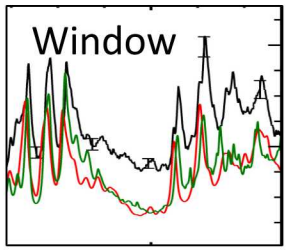
- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**
  - → Is opacity theory wrong? Is experiment flawed?

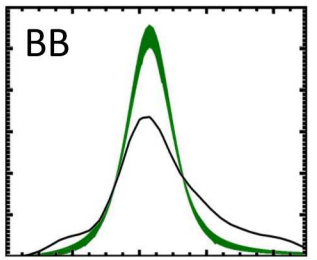


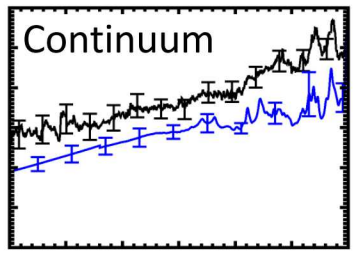


- **Refined analysis improved shot-to-shot reproducibility, demonstrating opacity experiment reliability**
- **Systematic measurement of Cr, Fe, and Ni opacities suggests model refinements in three areas**
  - Window: Challenge associated with open L-shell config.
  - BB: Inaccurate treatment of density effects
  - Continuum: Peculiar dependence on atomic number



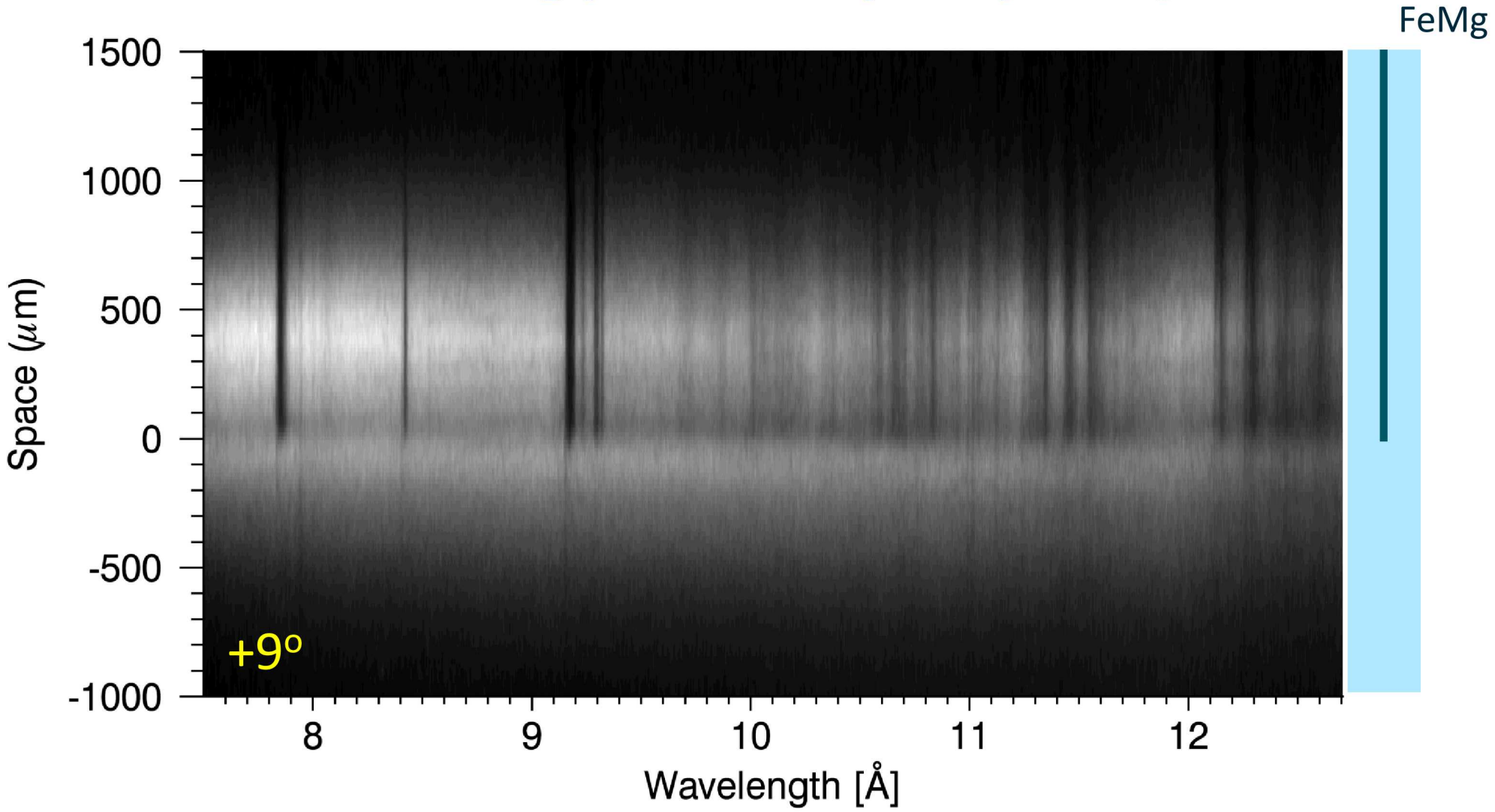




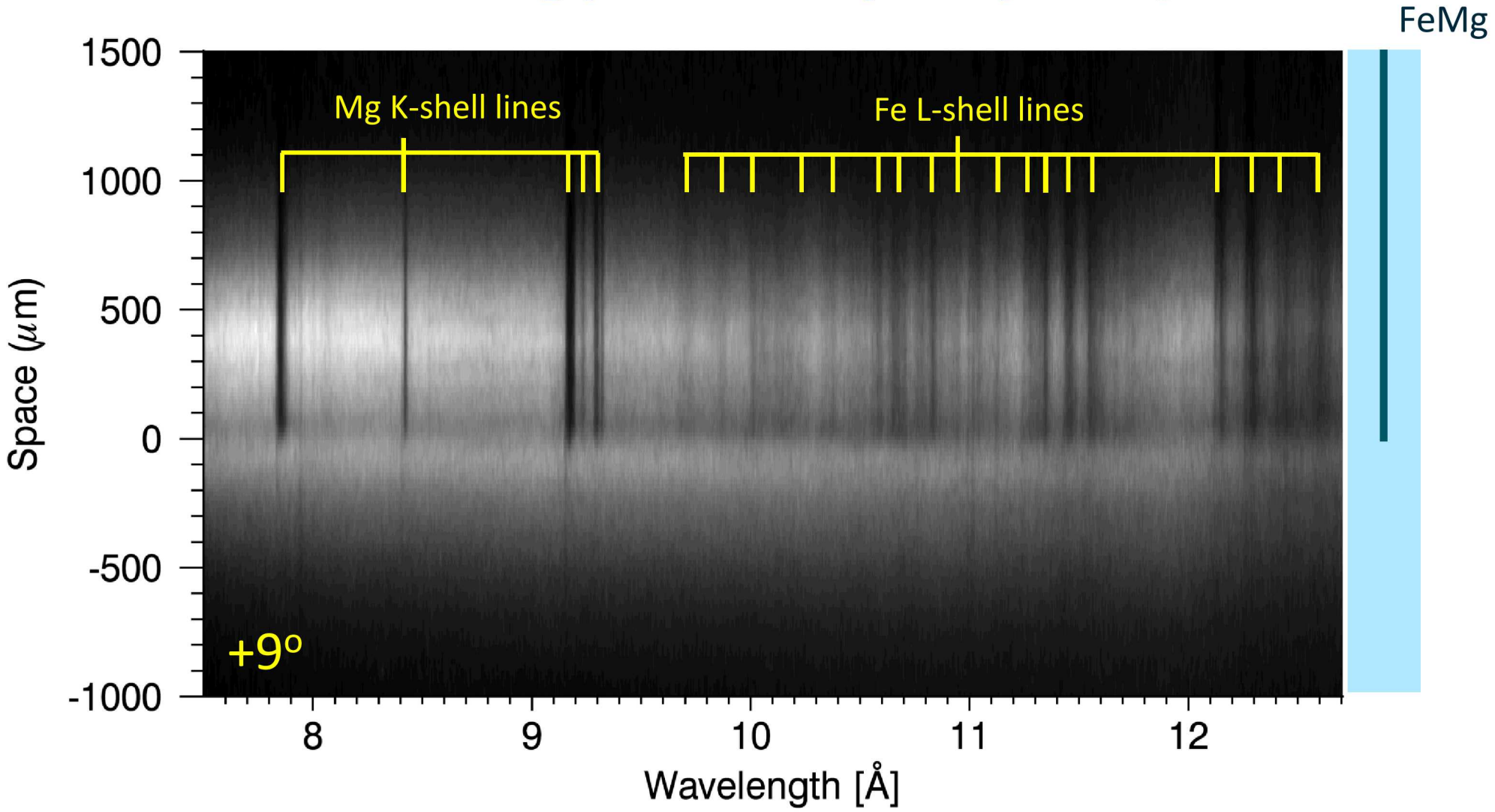


High reproducibility demonstrates unprecedented benchmark capability of SNL opacity platform

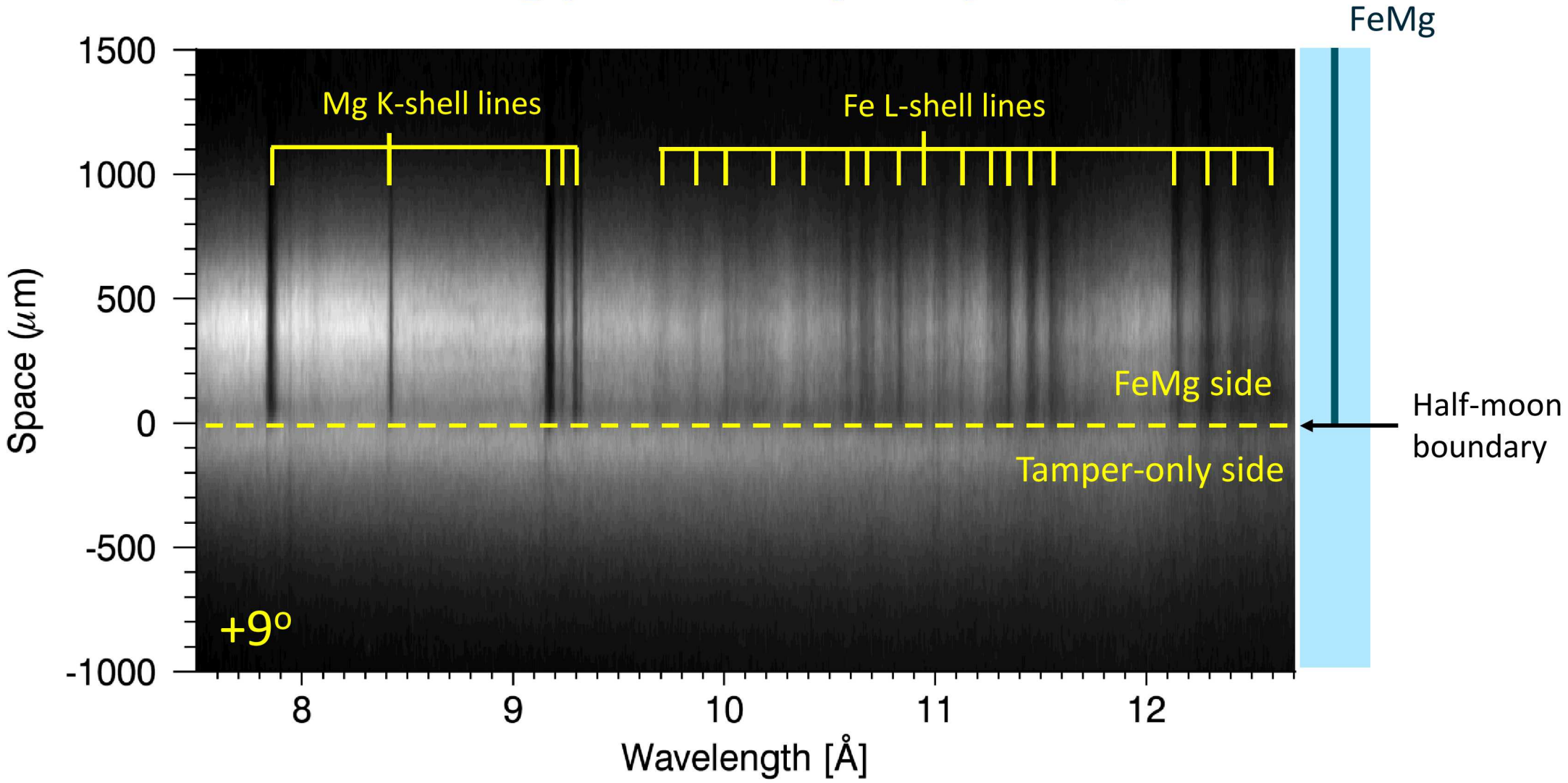
Spectral image is resolved in space and wavelengths and provides essential starting point for opacity analysis



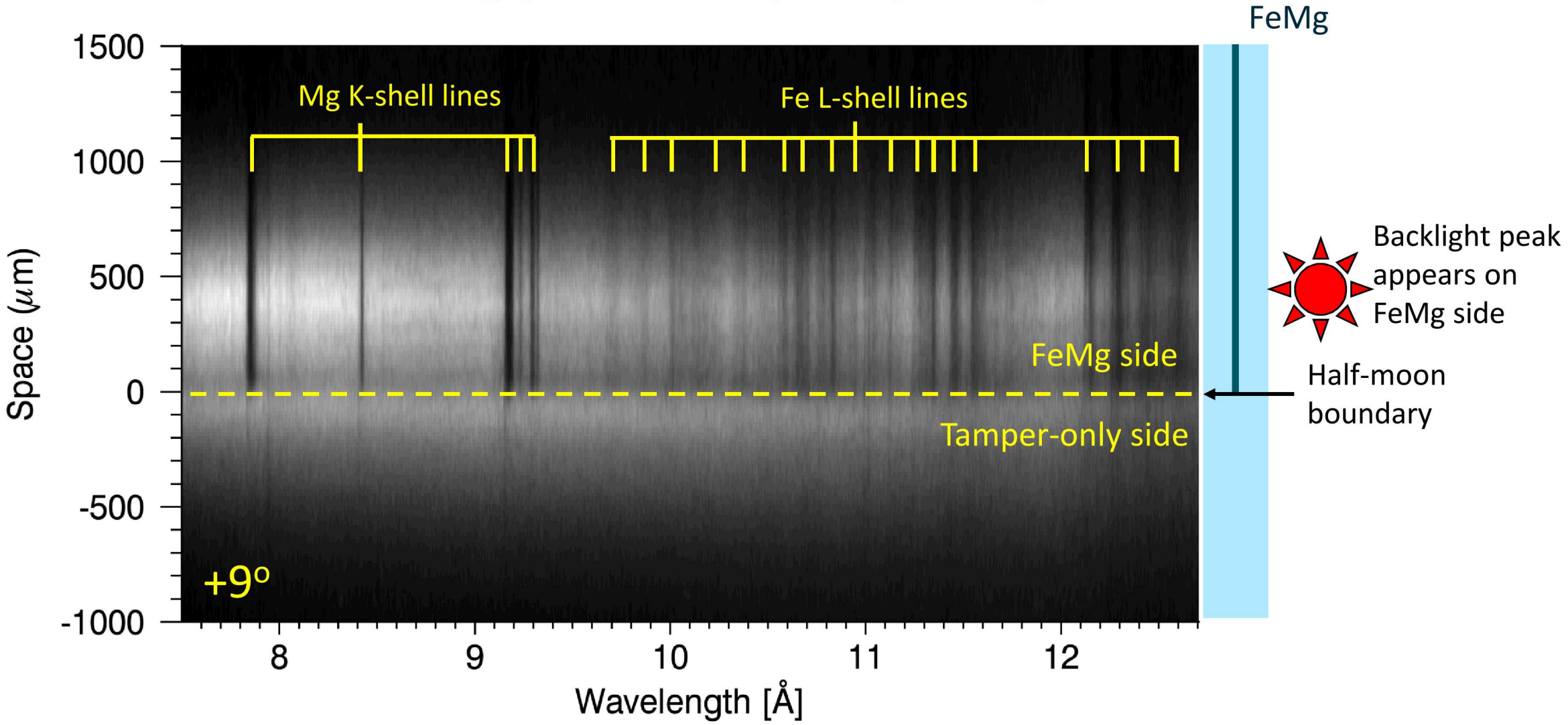
Spectral image is resolved in space and wavelengths and provides essential starting point for opacity analysis



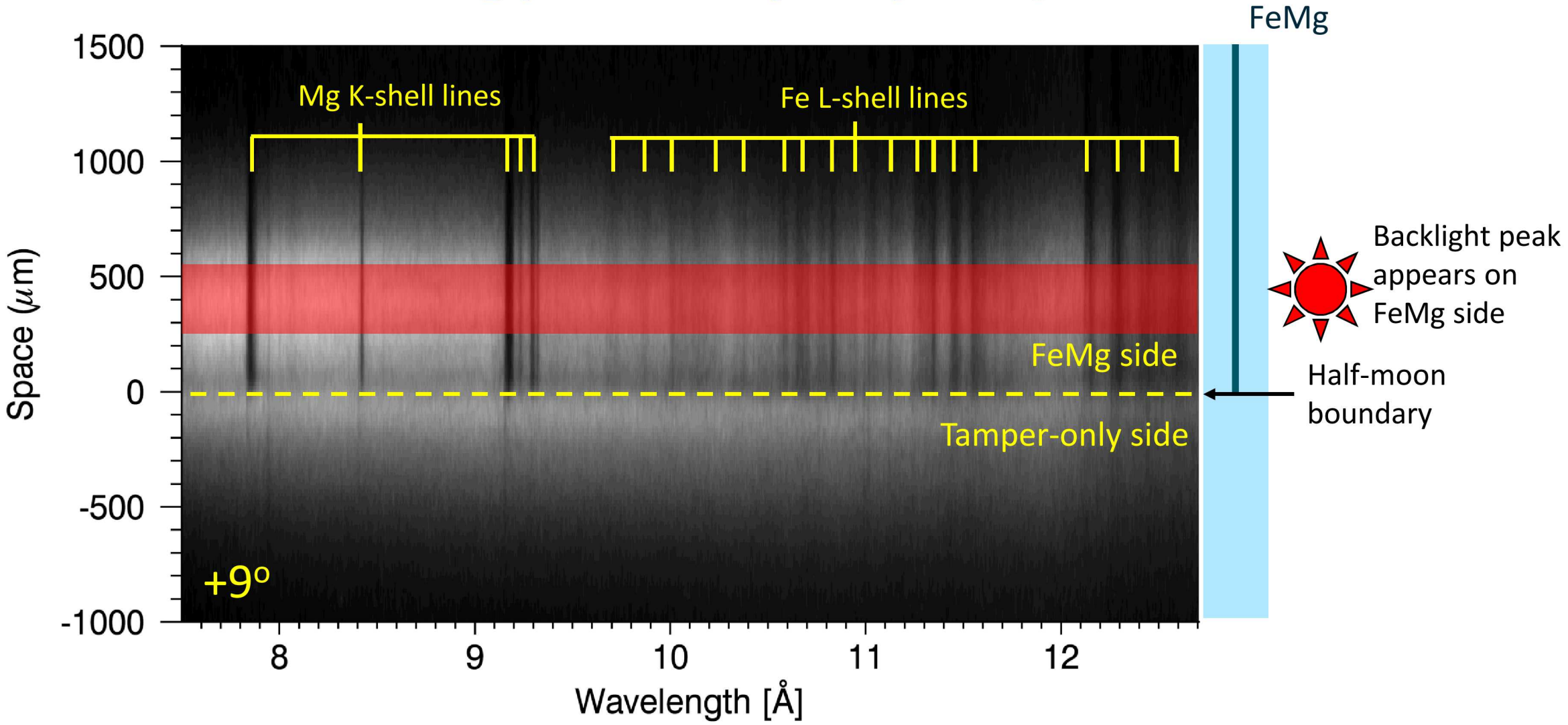
Spectral image is resolved in space and wavelengths and provides essential starting point for opacity analysis



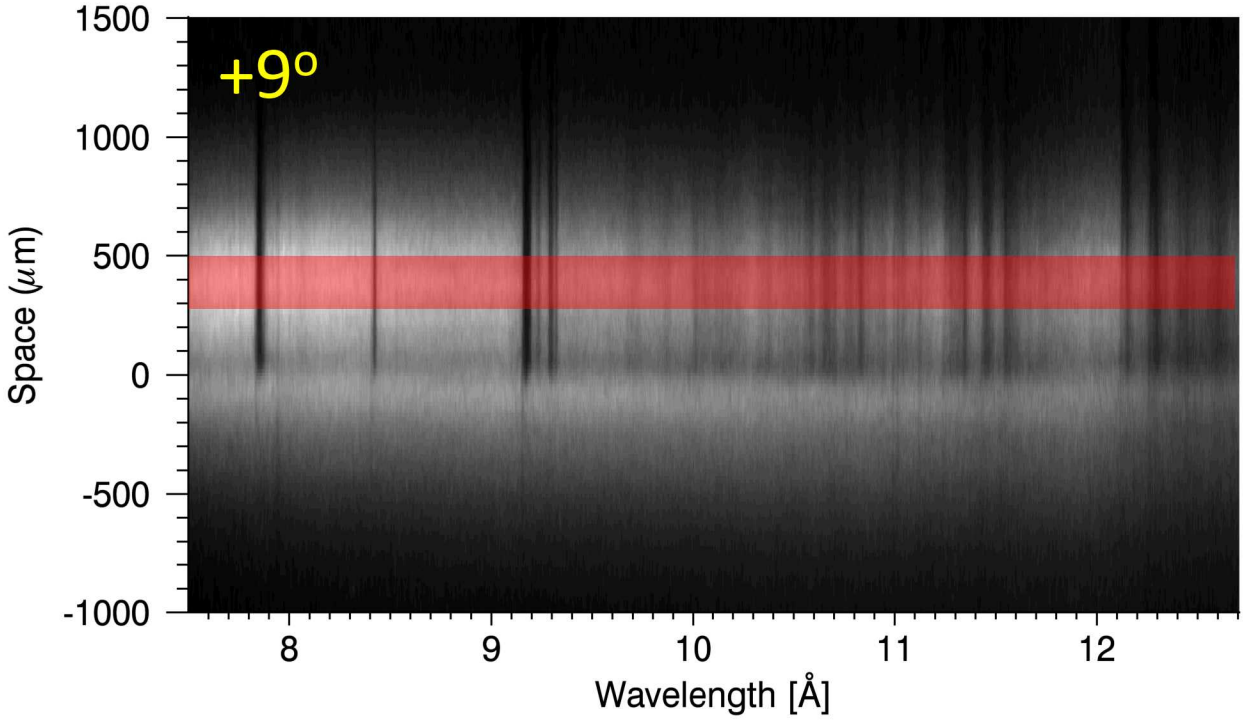
Spectral image is resolved in space and wavelengths and provides essential starting point for opacity analysis

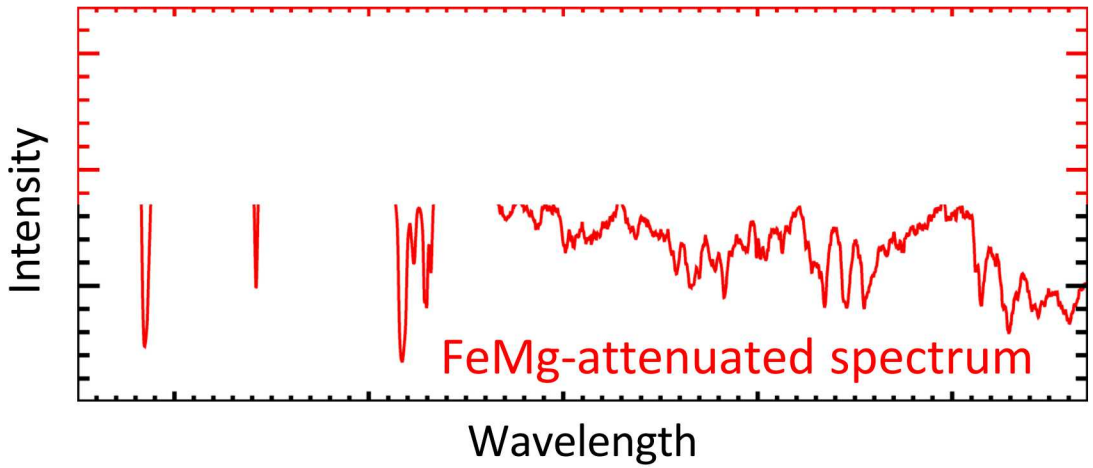


Spectral image is resolved in space and wavelengths and provides essential starting point for opacity analysis

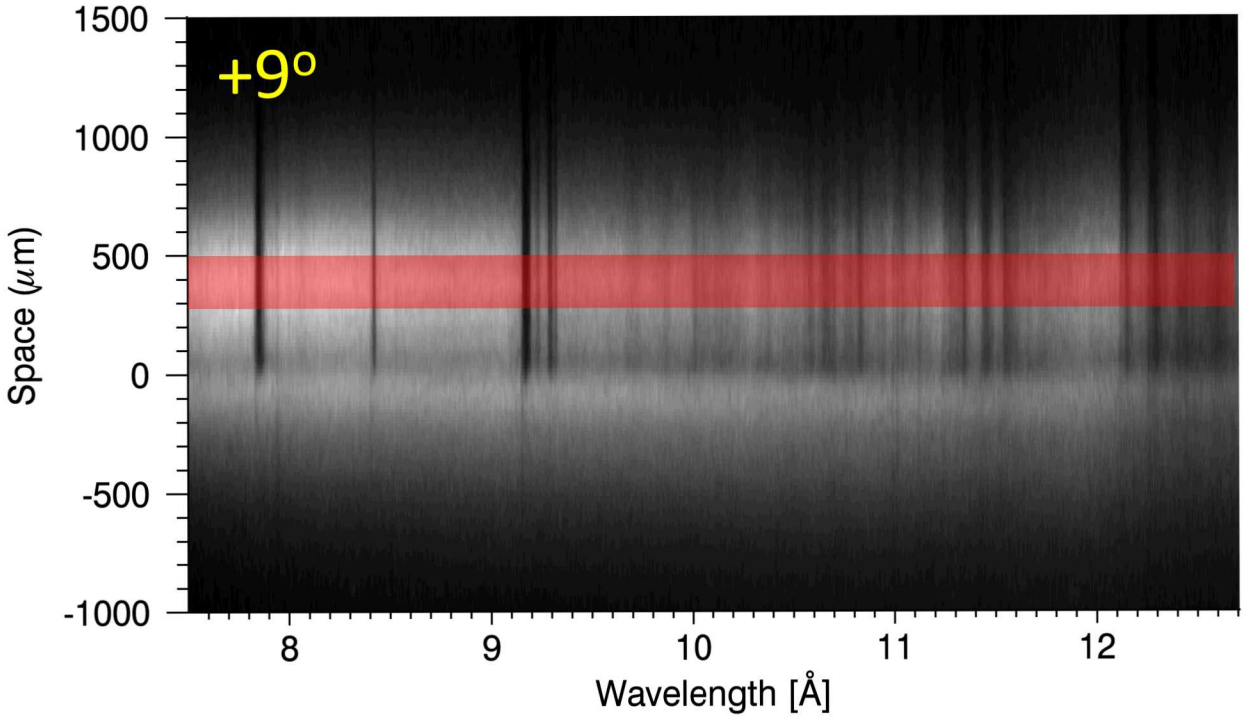


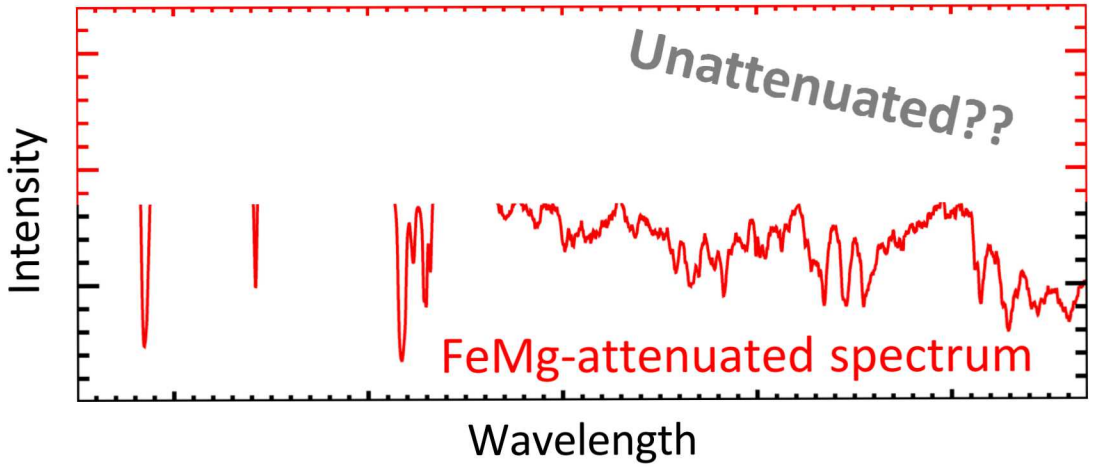
Old method: we take the spectral lineout and determine unattenuated spectrum from multiple statistics



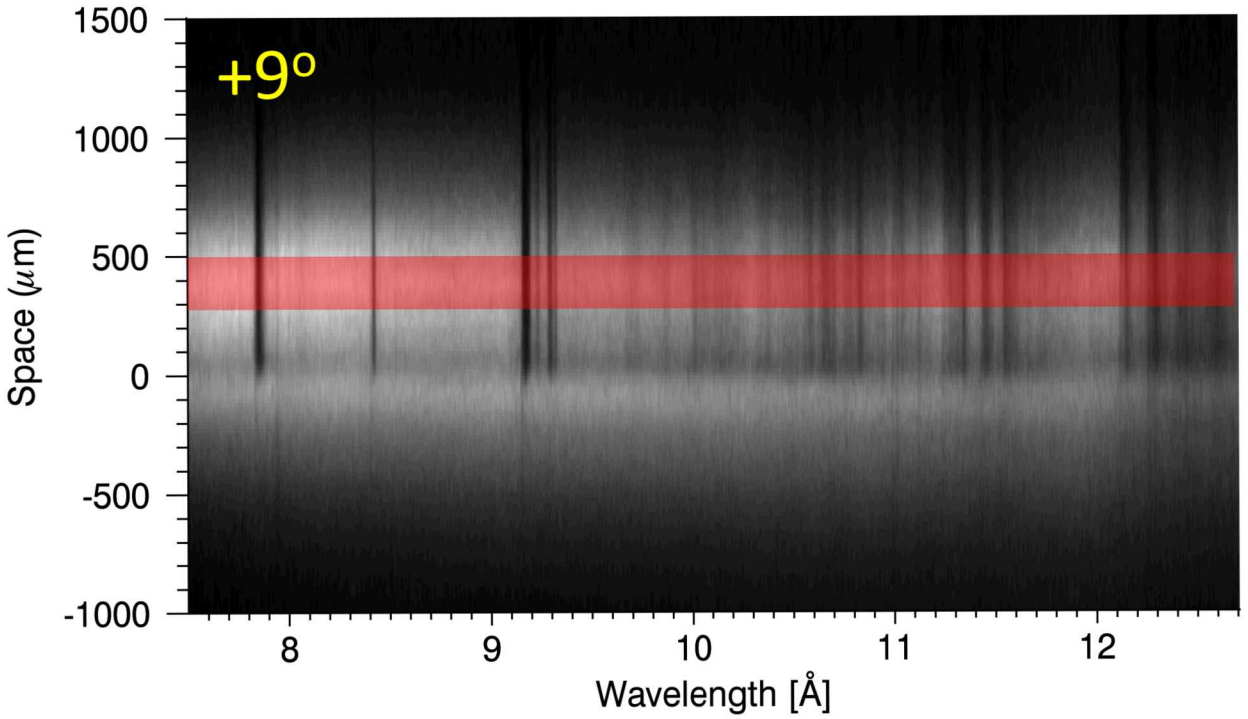


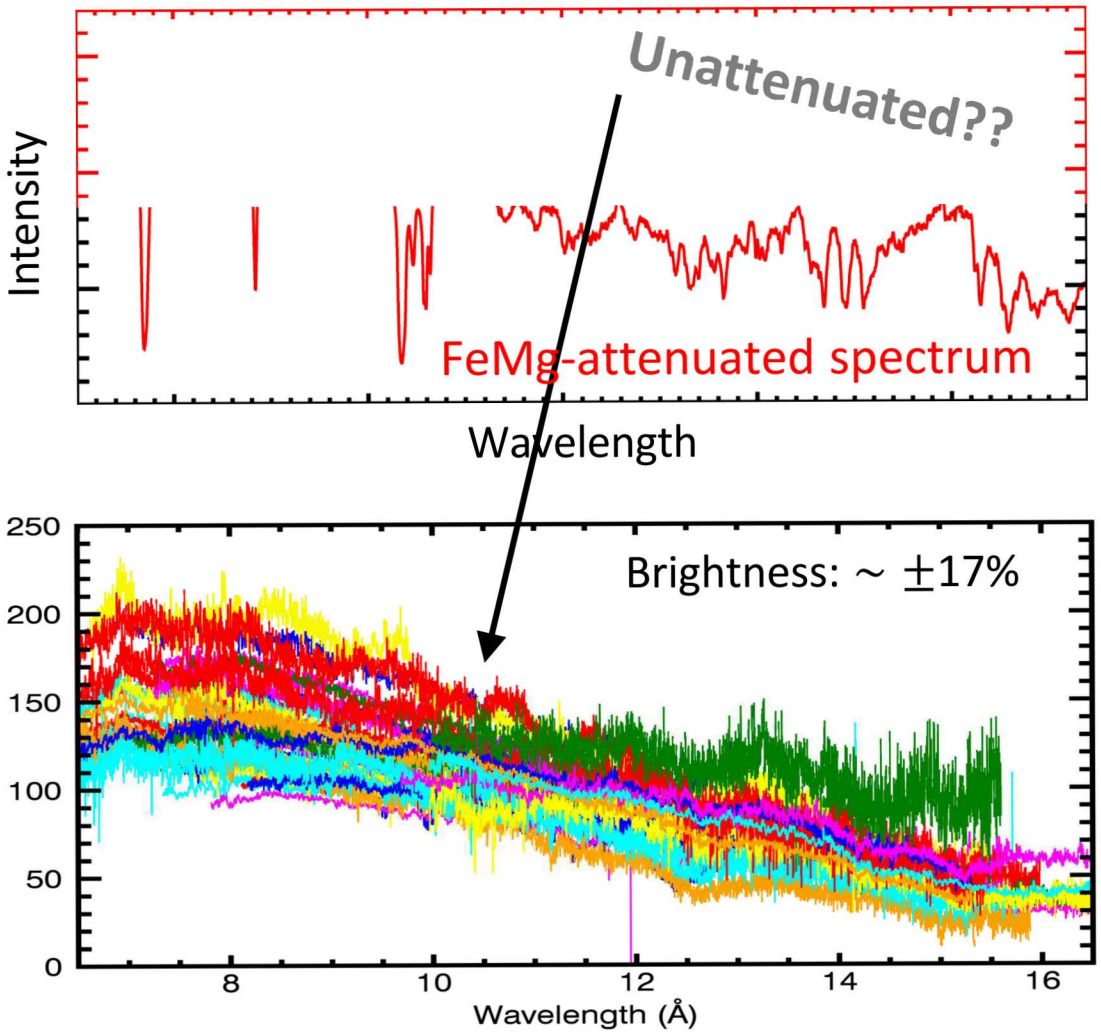
Old method: we take the spectral lineout and determine unattenuated spectrum from multiple statistics



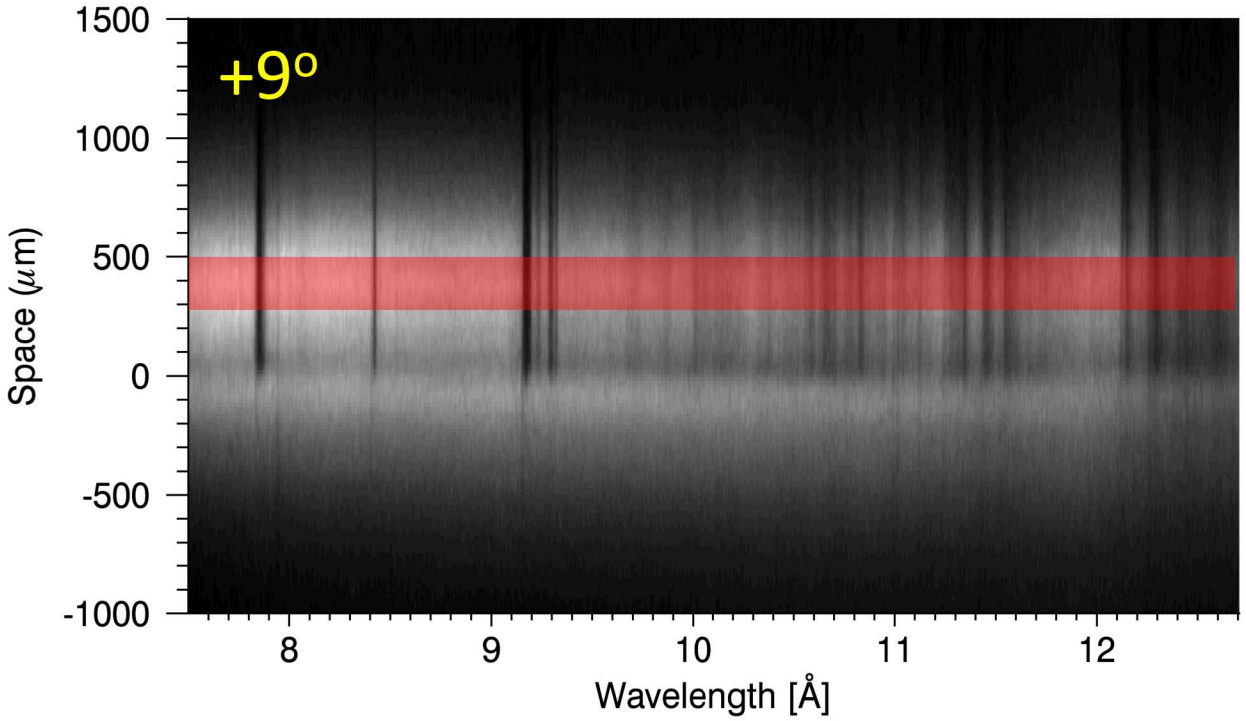


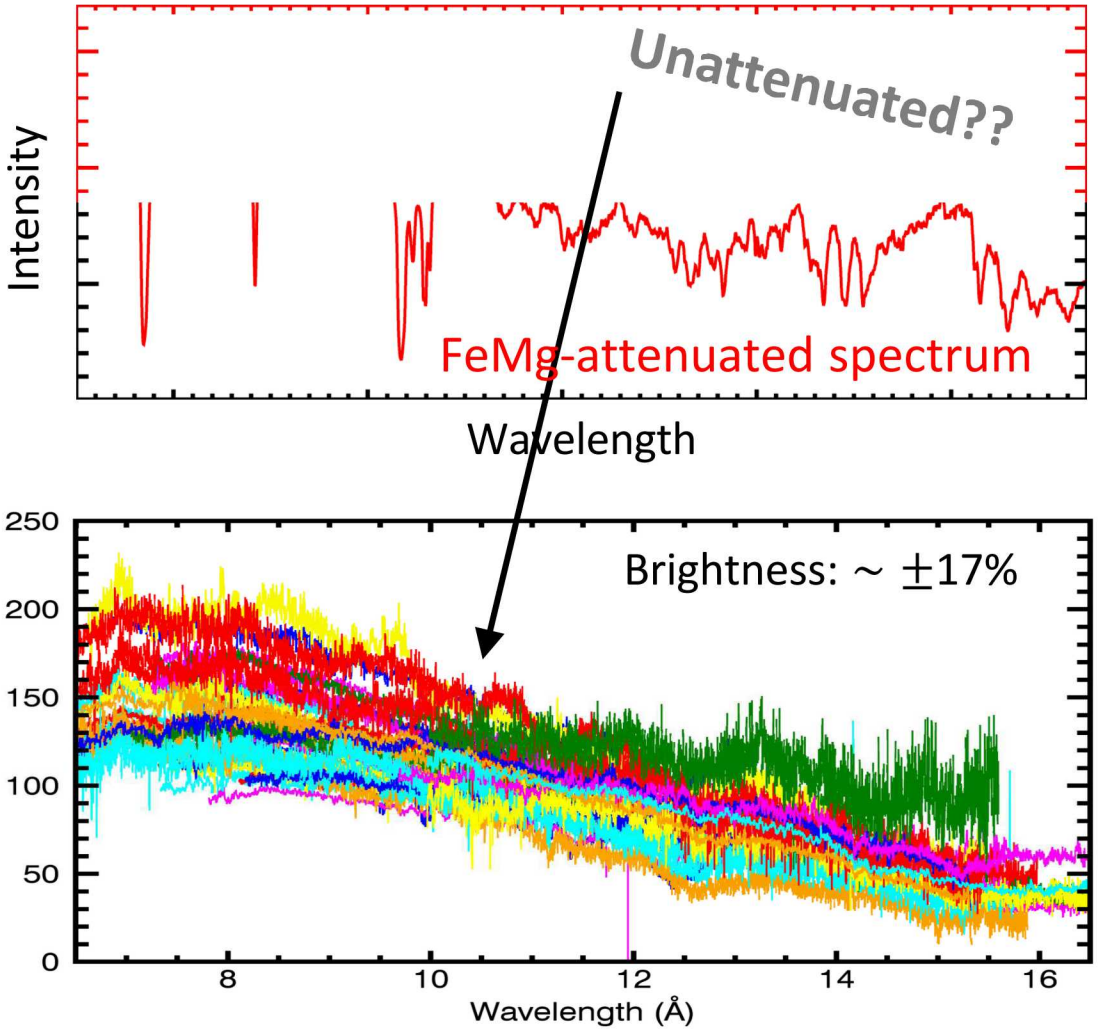
Old method: we take the spectral lineout and determine unattenuated spectrum from multiple statistics





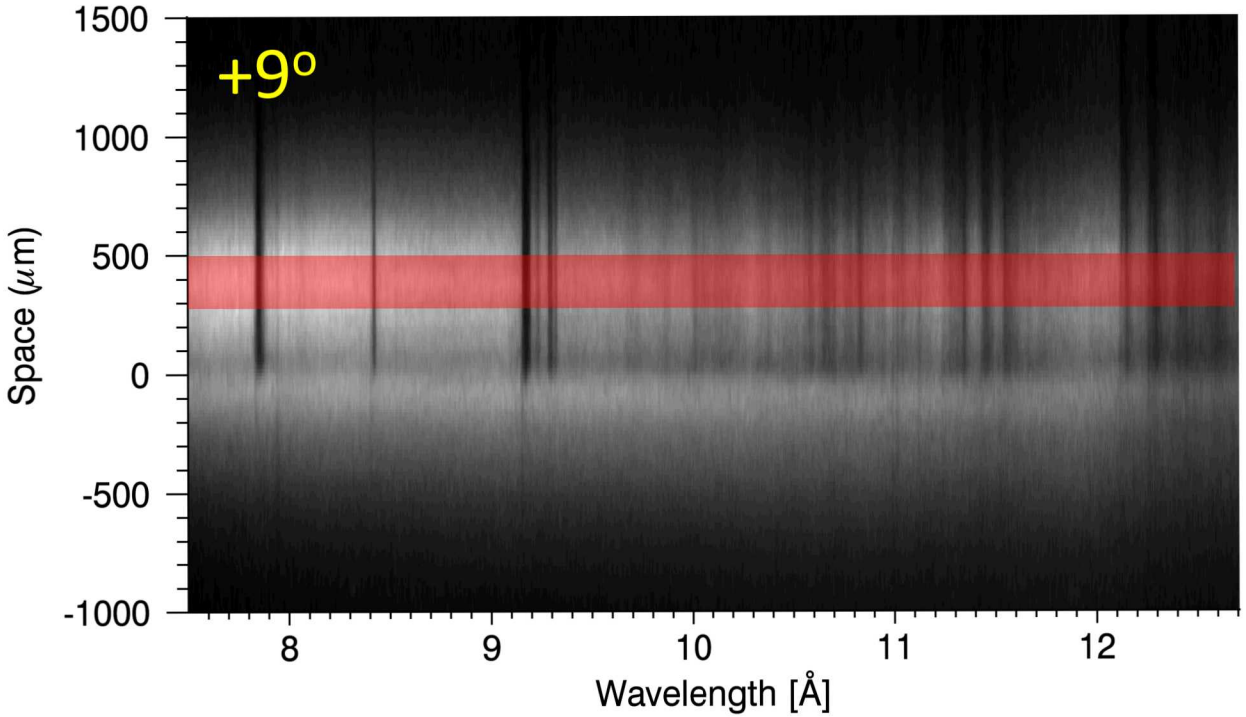
Old method: we take the spectral lineout and determine unattenuated spectrum from multiple statistics

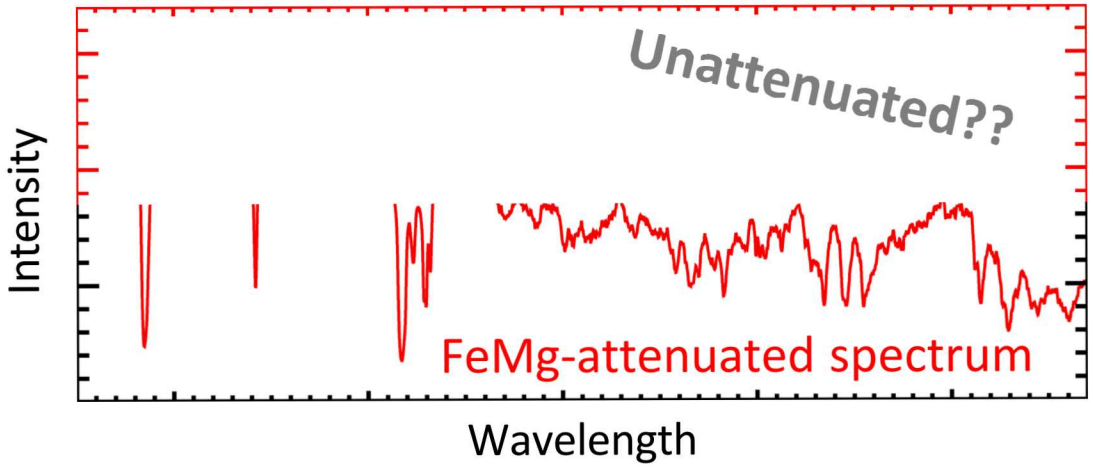




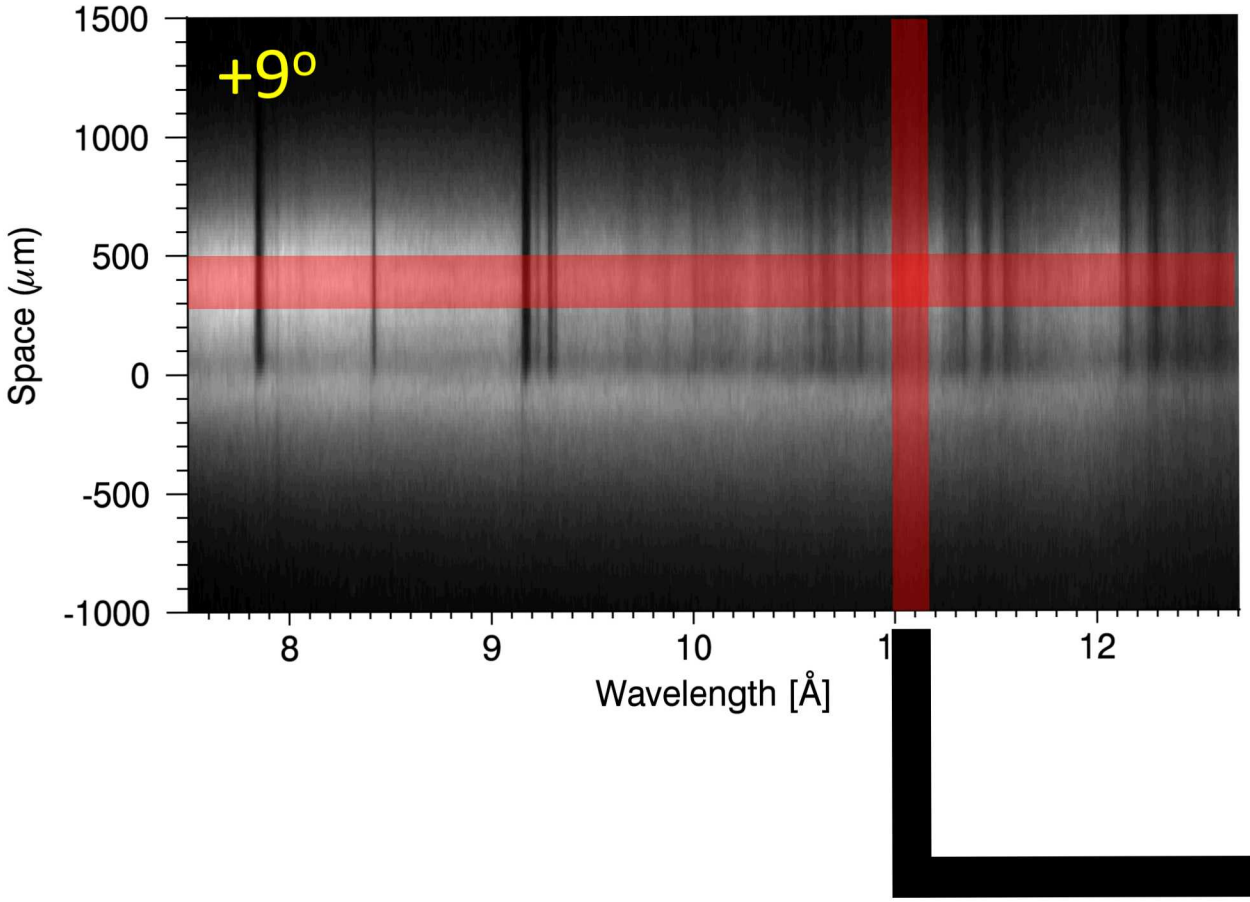
Single experiment unattenuated error is reduced to ~ 10% by combining multiple uncorrelated statistics

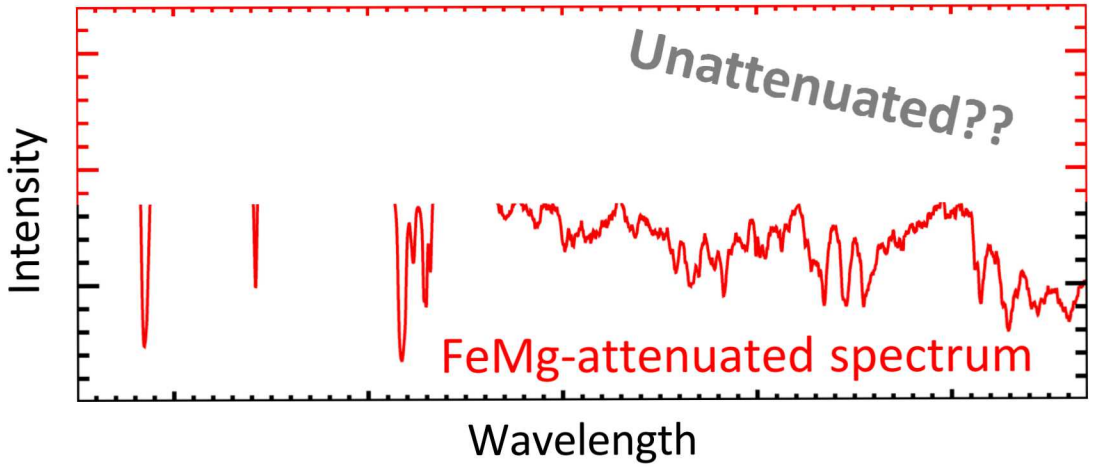
Paradigm shift: Spectral lineout → Spatial lineout

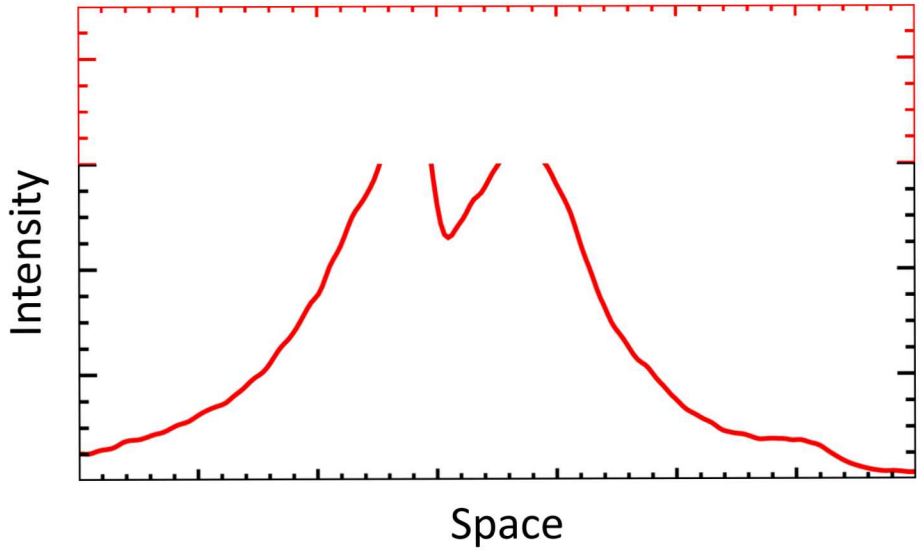




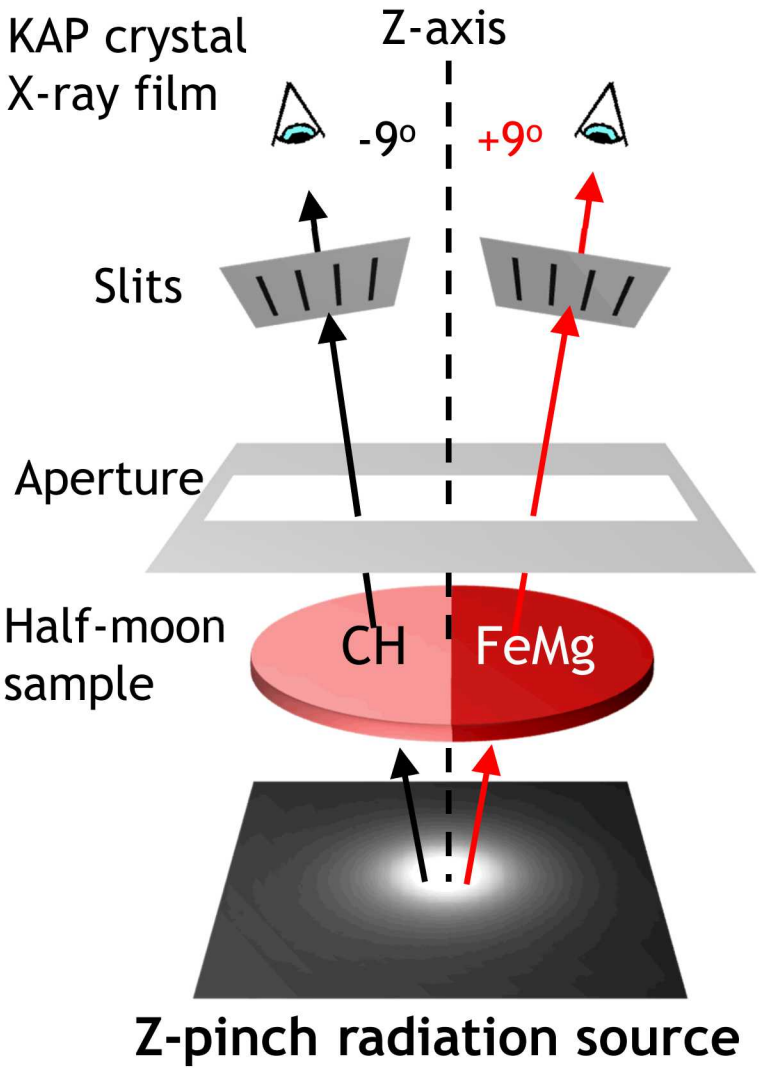
Paradigm shift: Spectral lineout → Spatial lineout



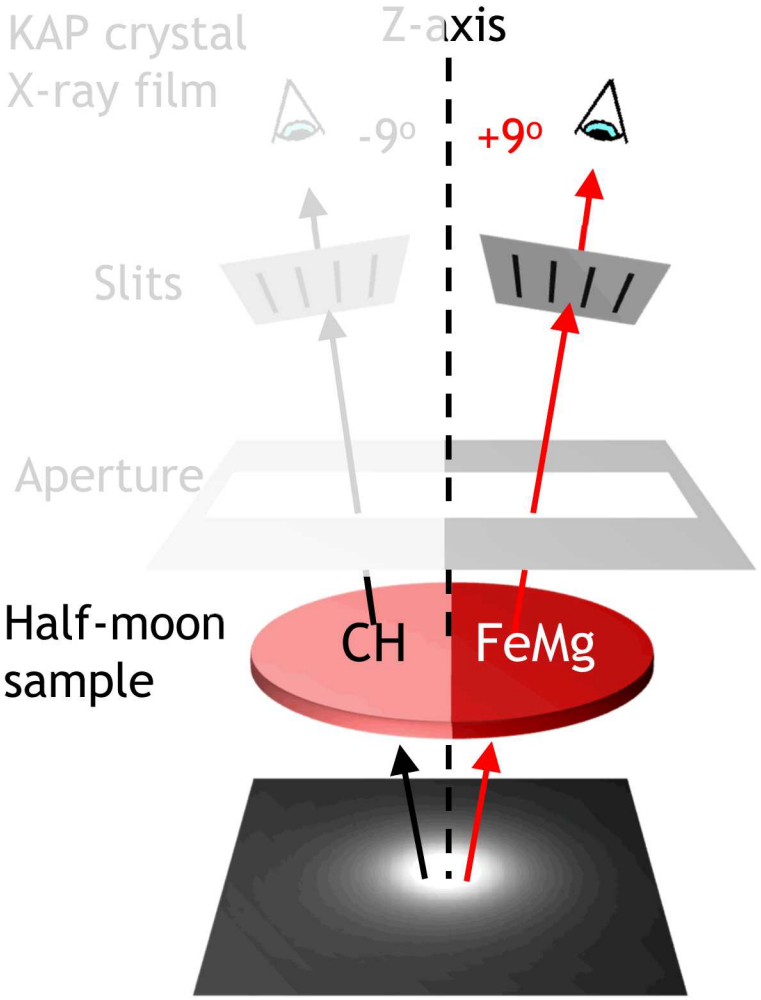




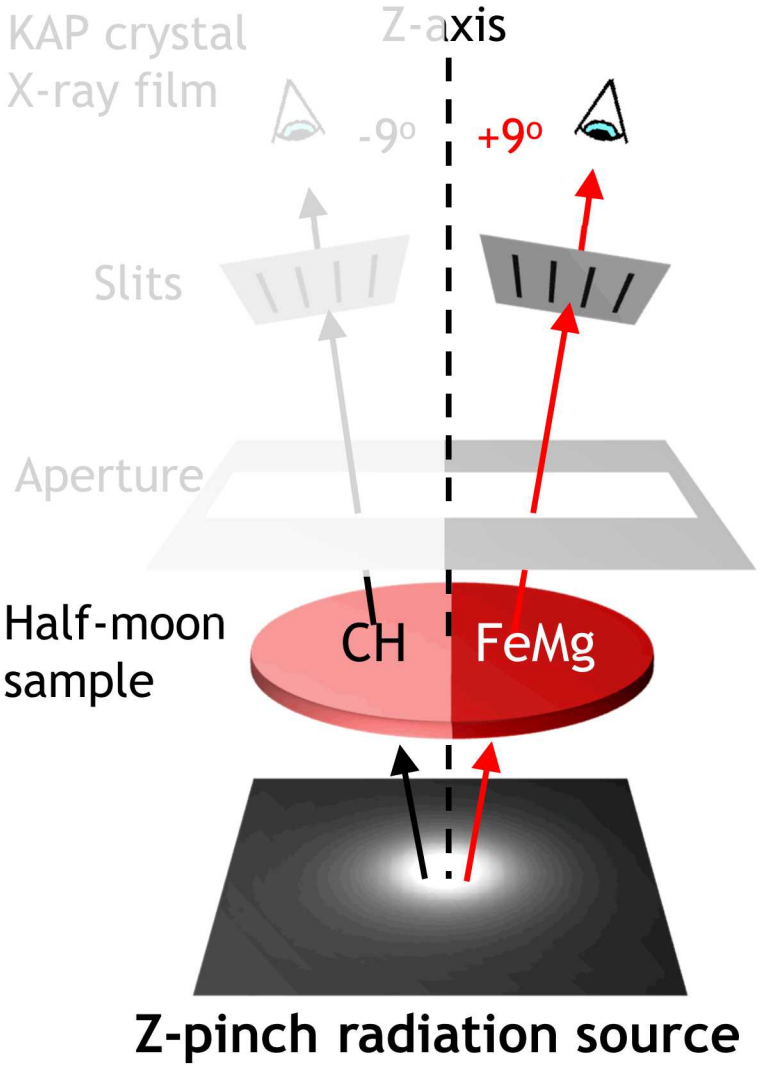
Observing finite-area backlighter through half-moon sample produces complicated spatial shape

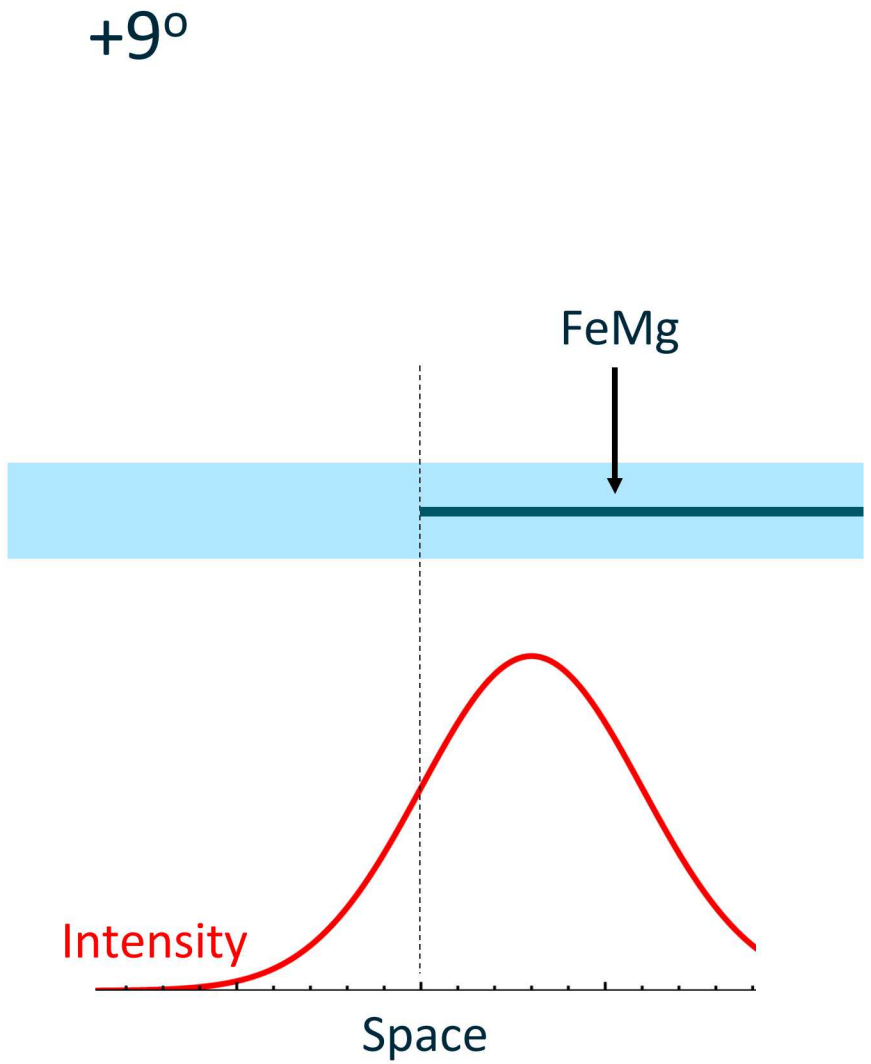


Observing finite-area backlighter through half-moon sample produces complicated spatial shape

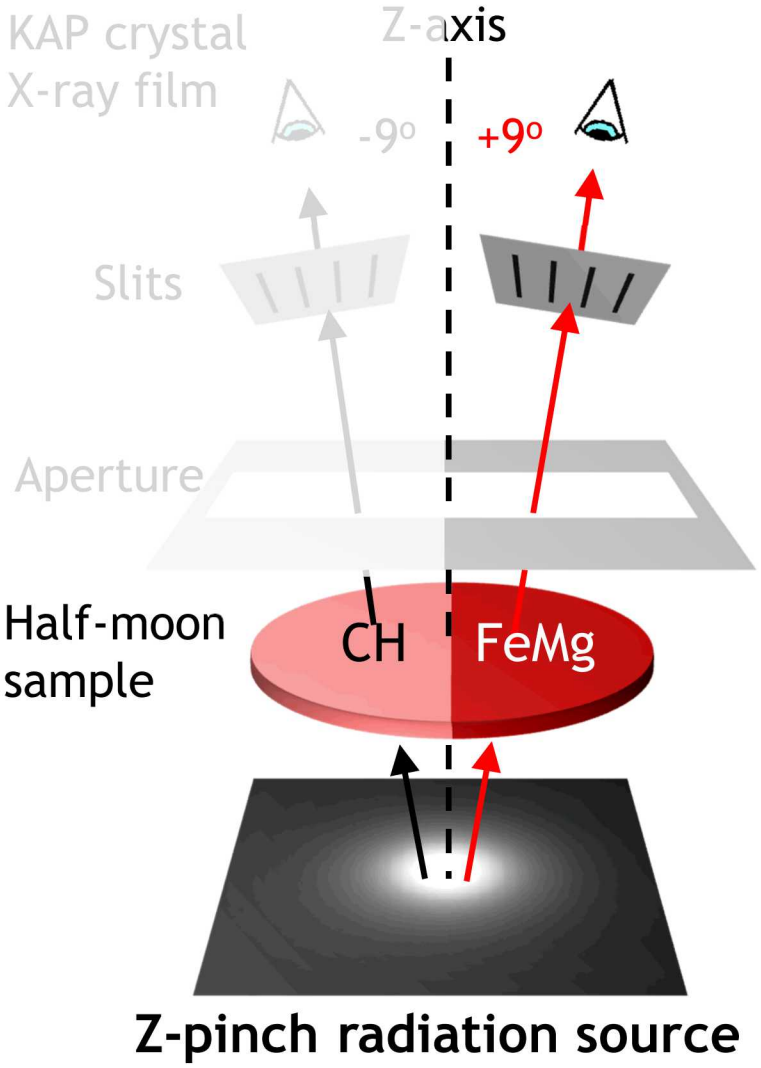


Observing finite-area backlighter through half-moon sample produces complicated spatial shape

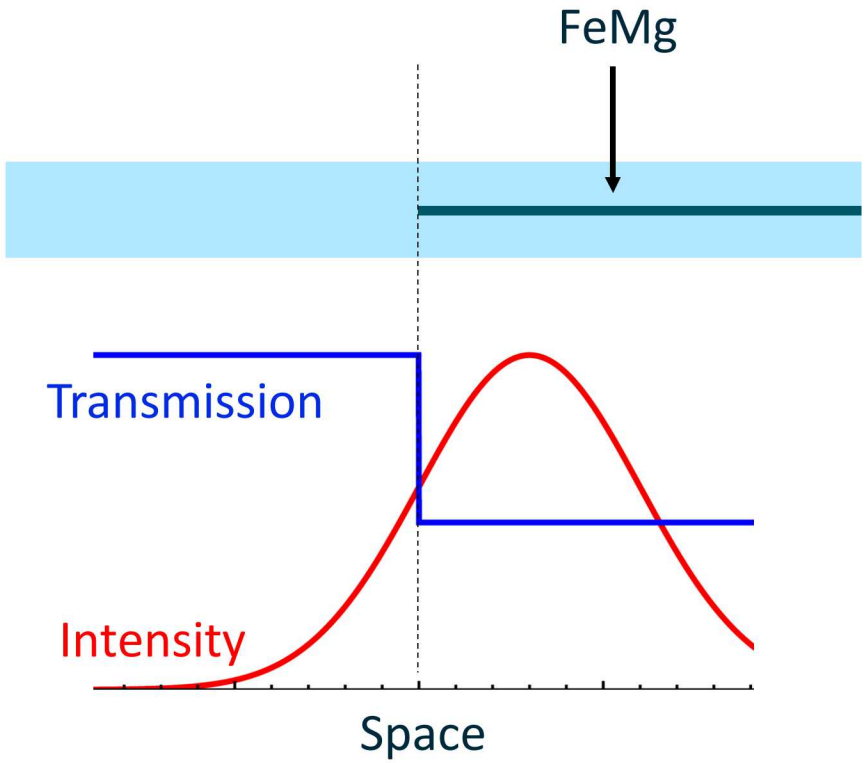




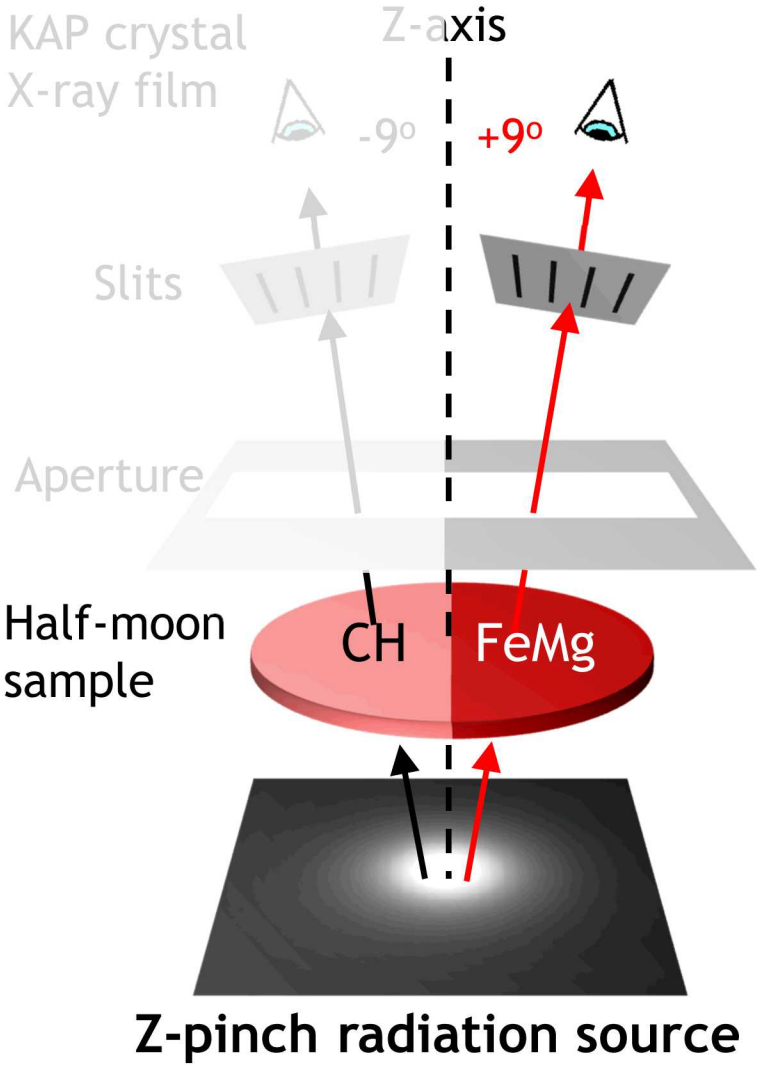
Observing finite-area backlighter through half-moon sample produces complicated spatial shape



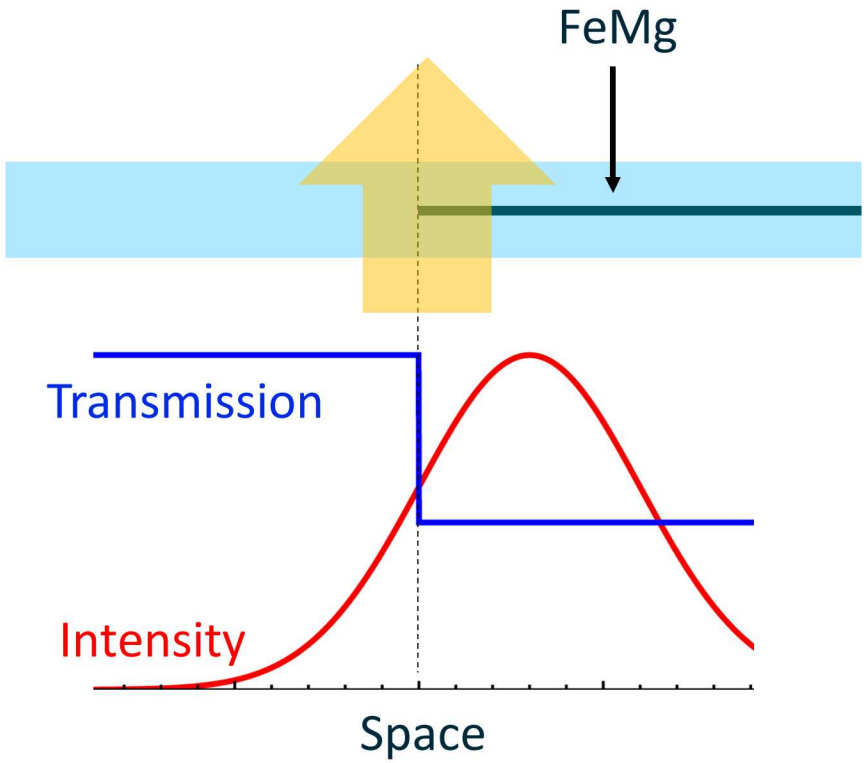
+9°



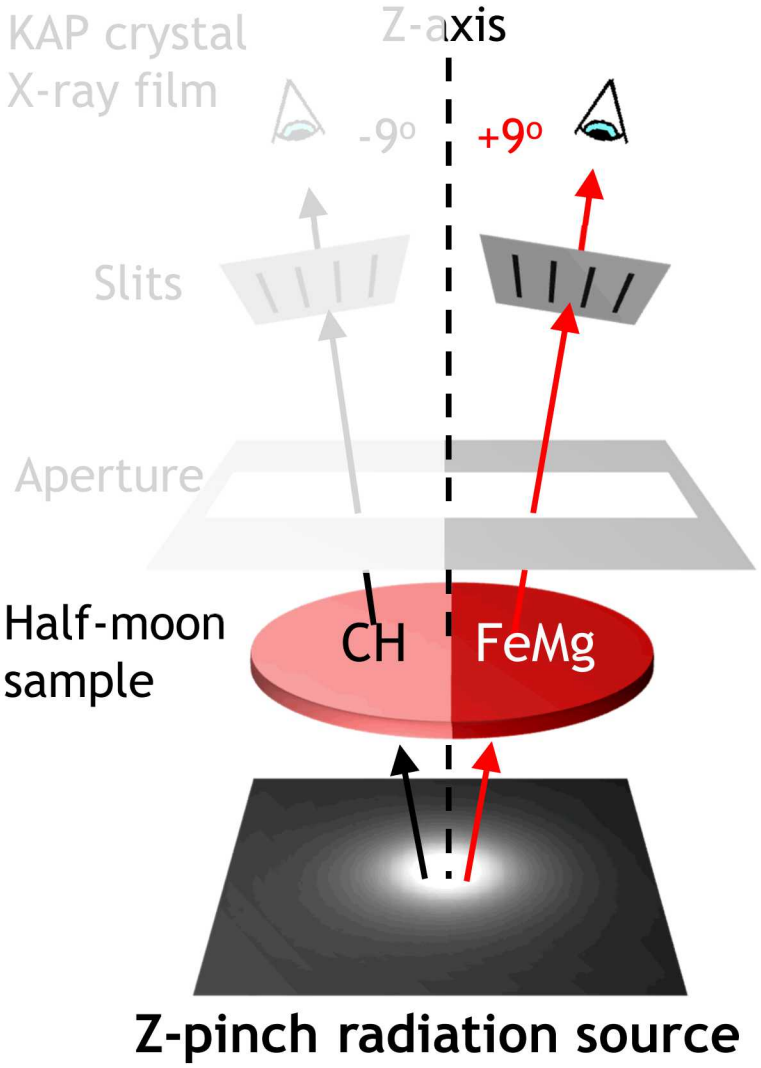
Observing finite-area backlighter through half-moon sample produces complicated spatial shape

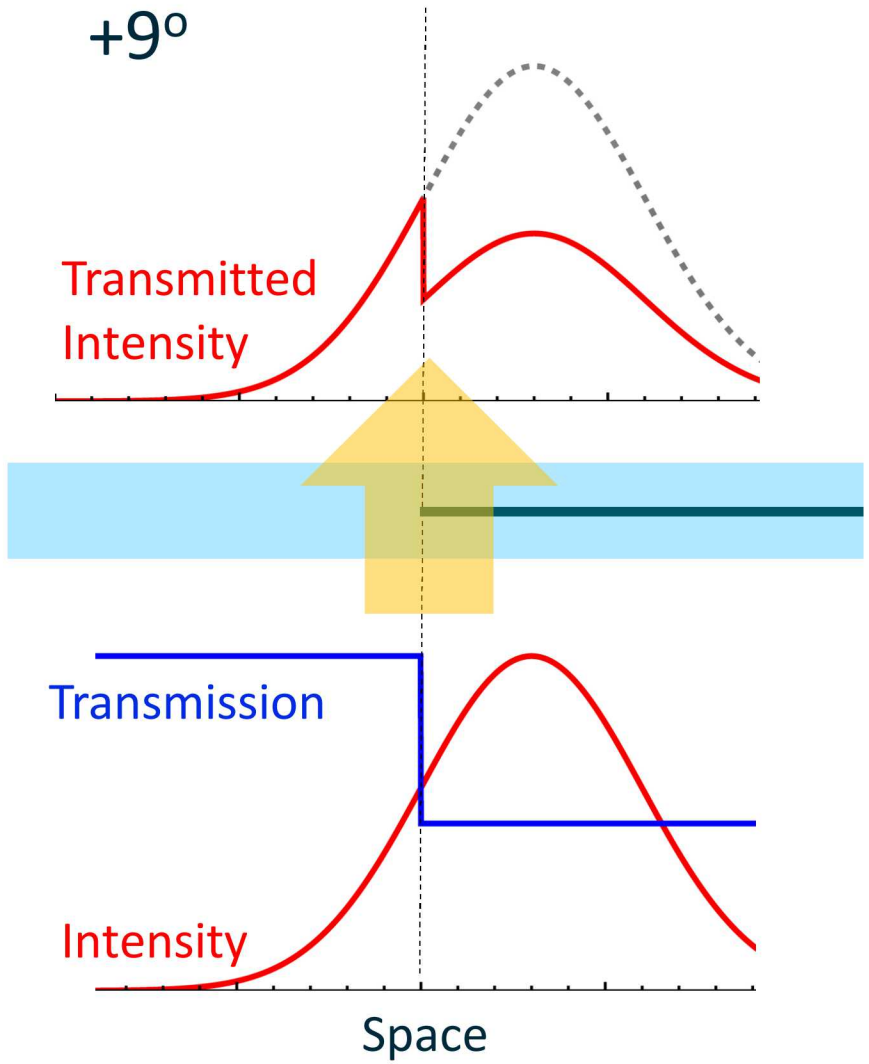


+9°

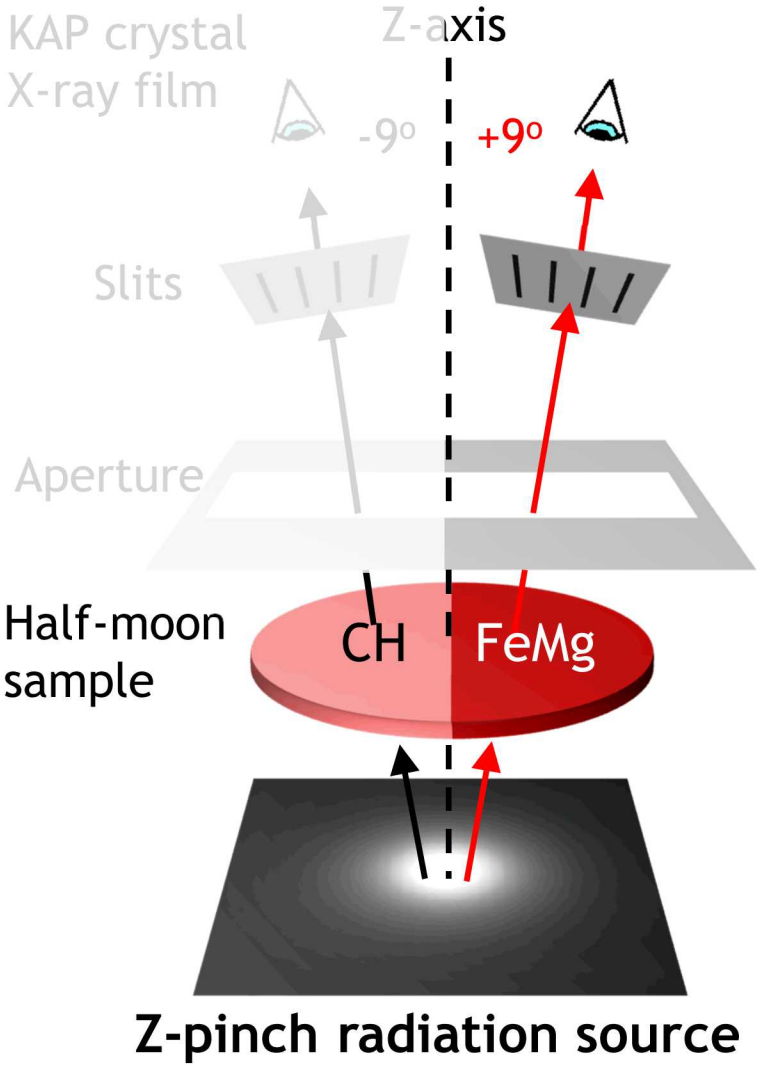


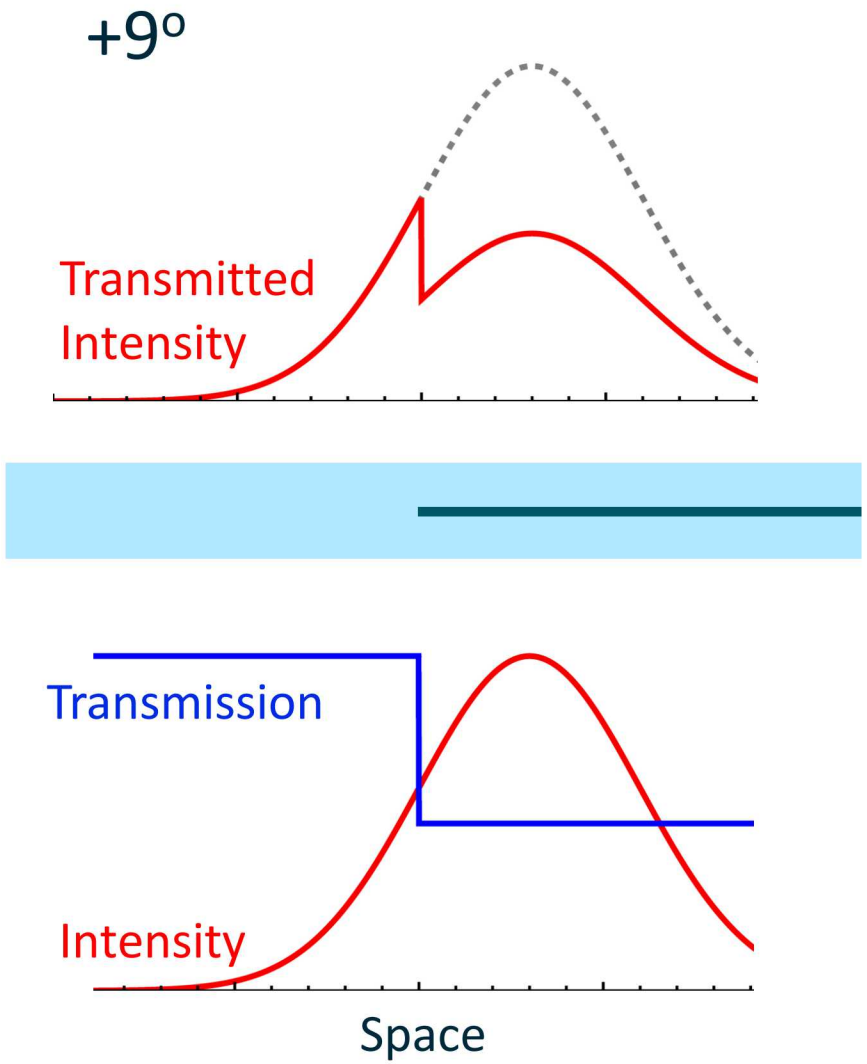
Observing finite-area backlighter through half-moon sample produces complicated spatial shape



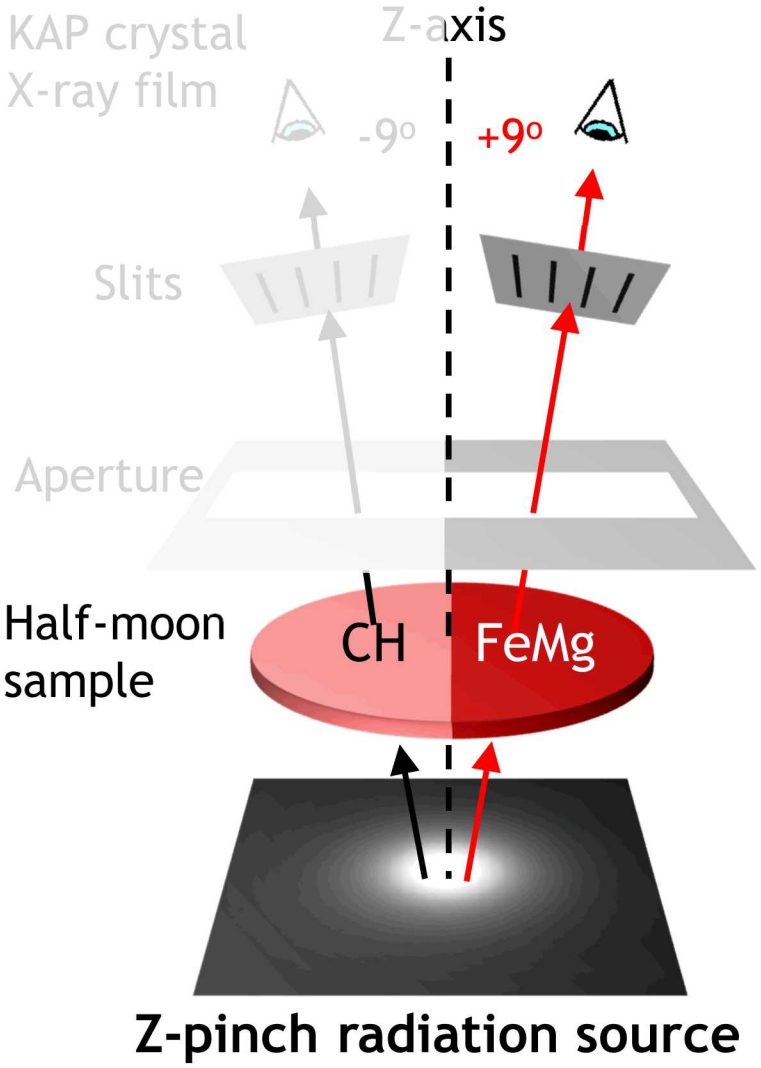


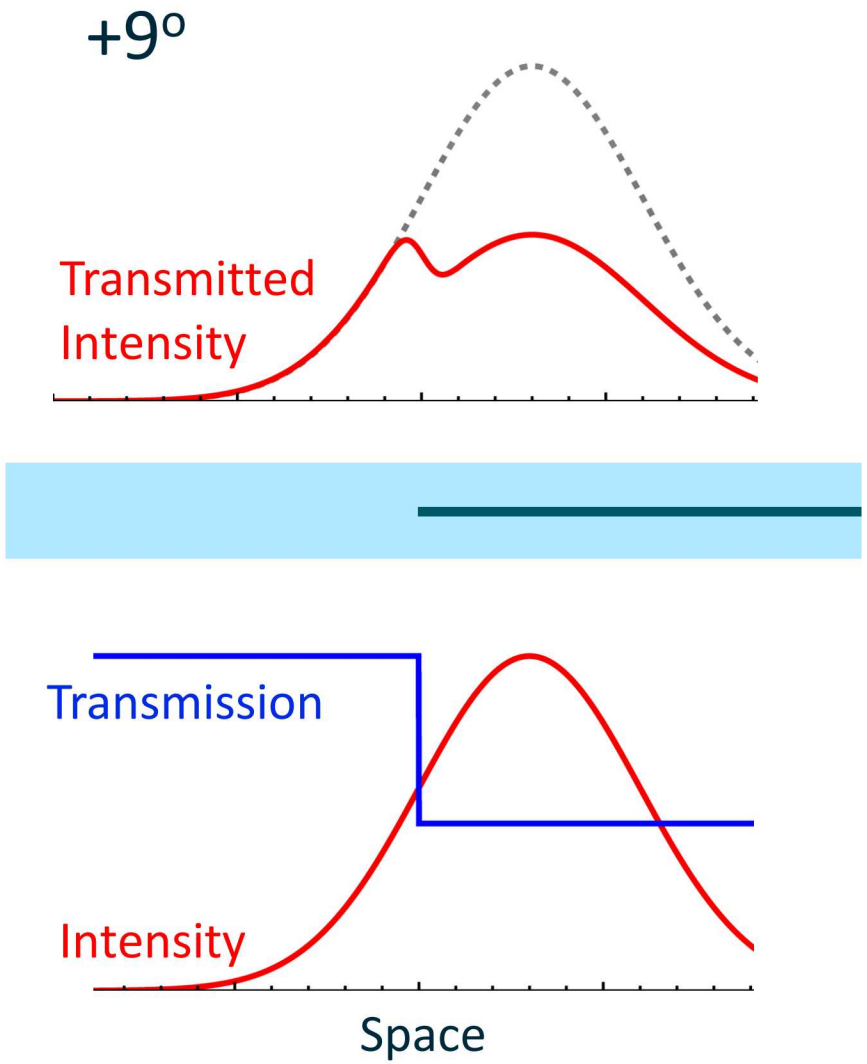
Observing finite-area backlighter through half-moon sample produces complicated spatial shape





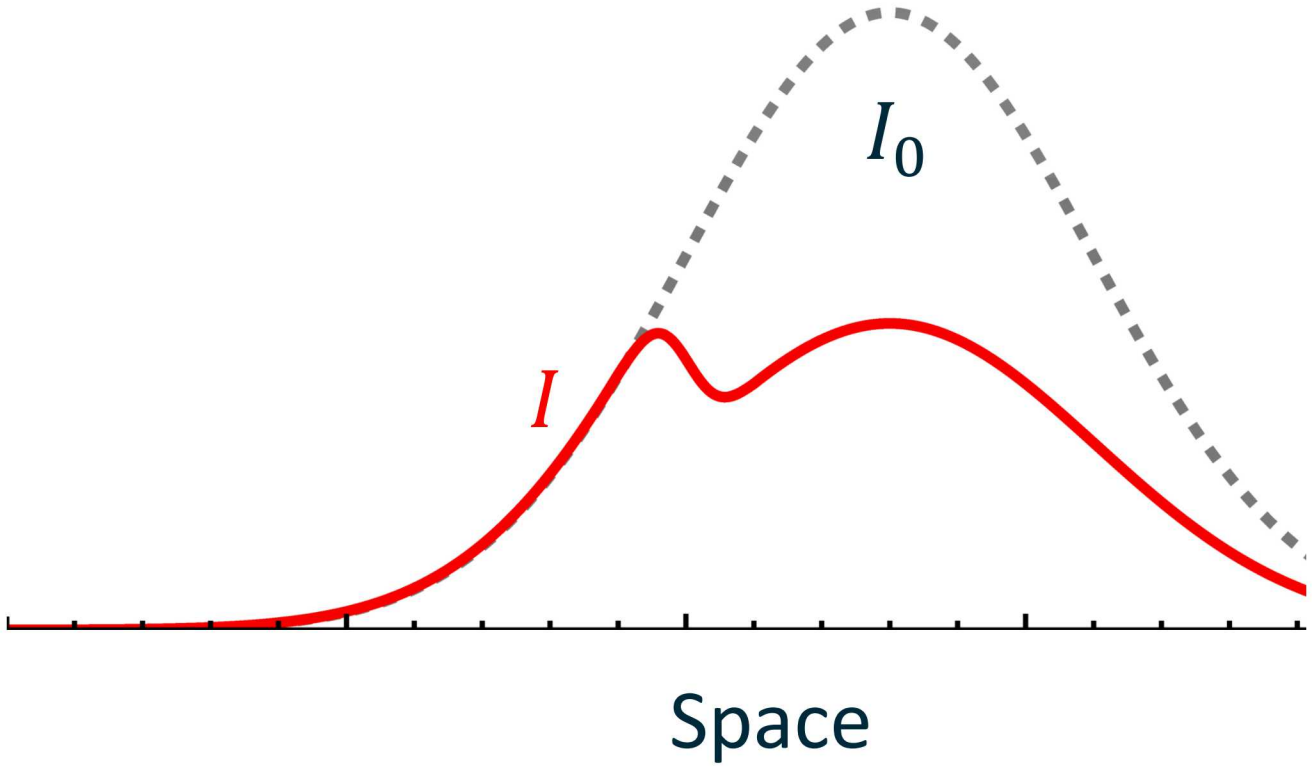
Observing finite-area backlighter through half-moon sample produces complicated spatial shape



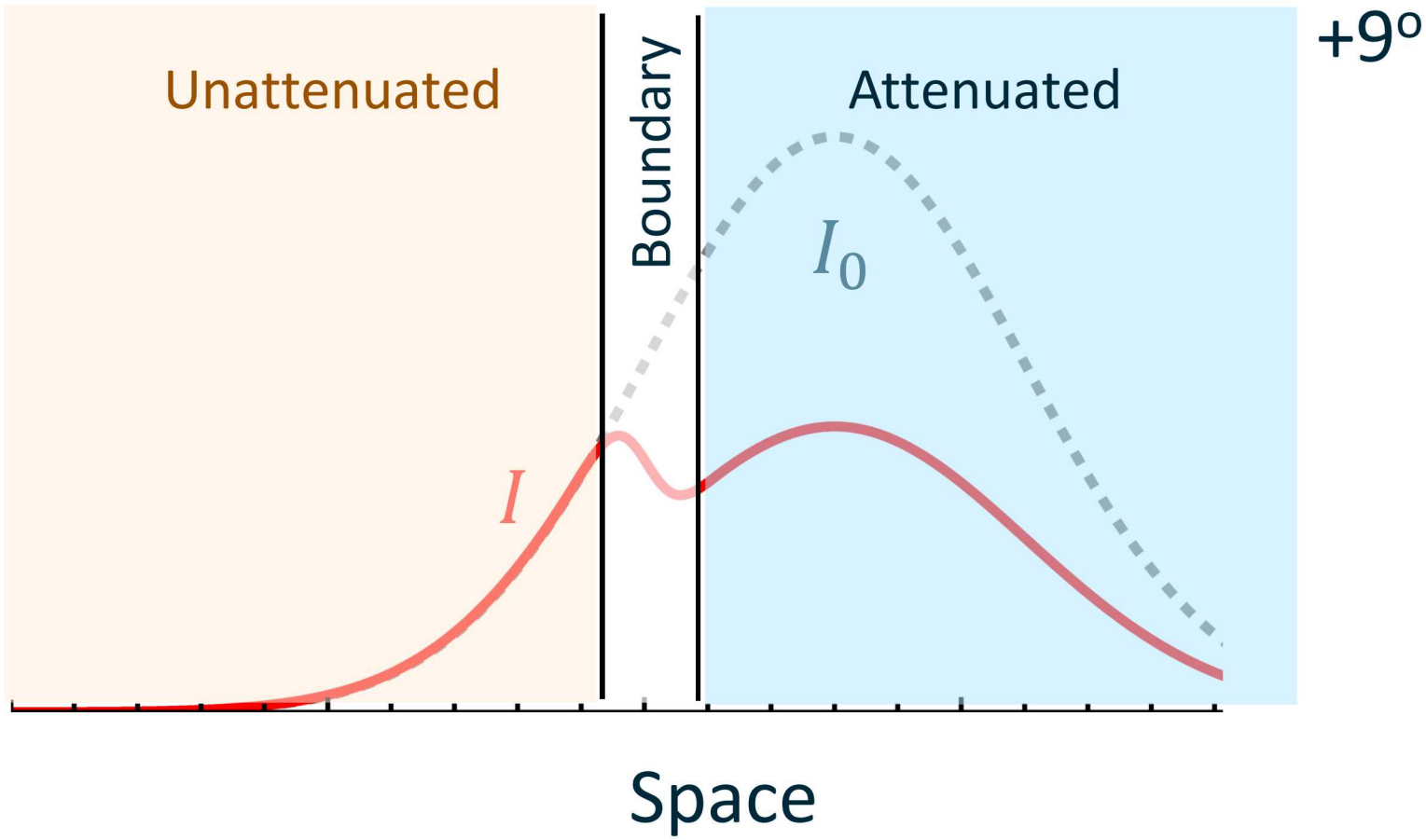


Half-moon spatial profile has both attenuated and unattenuated intensities, enabling accurate analysis

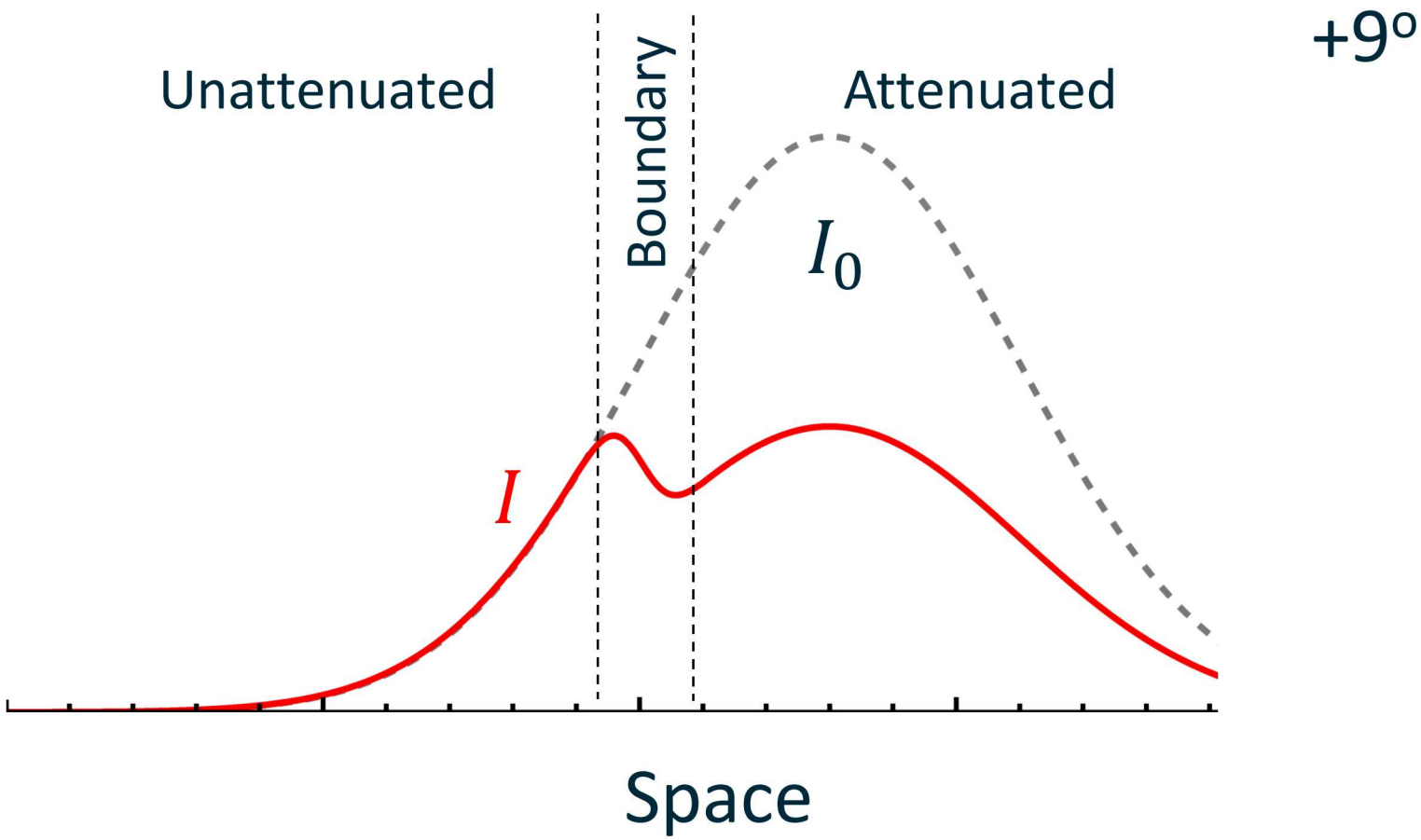
+9°



Half-moon spatial profile has both attenuated and unattenuated intensities, enabling accurate analysis

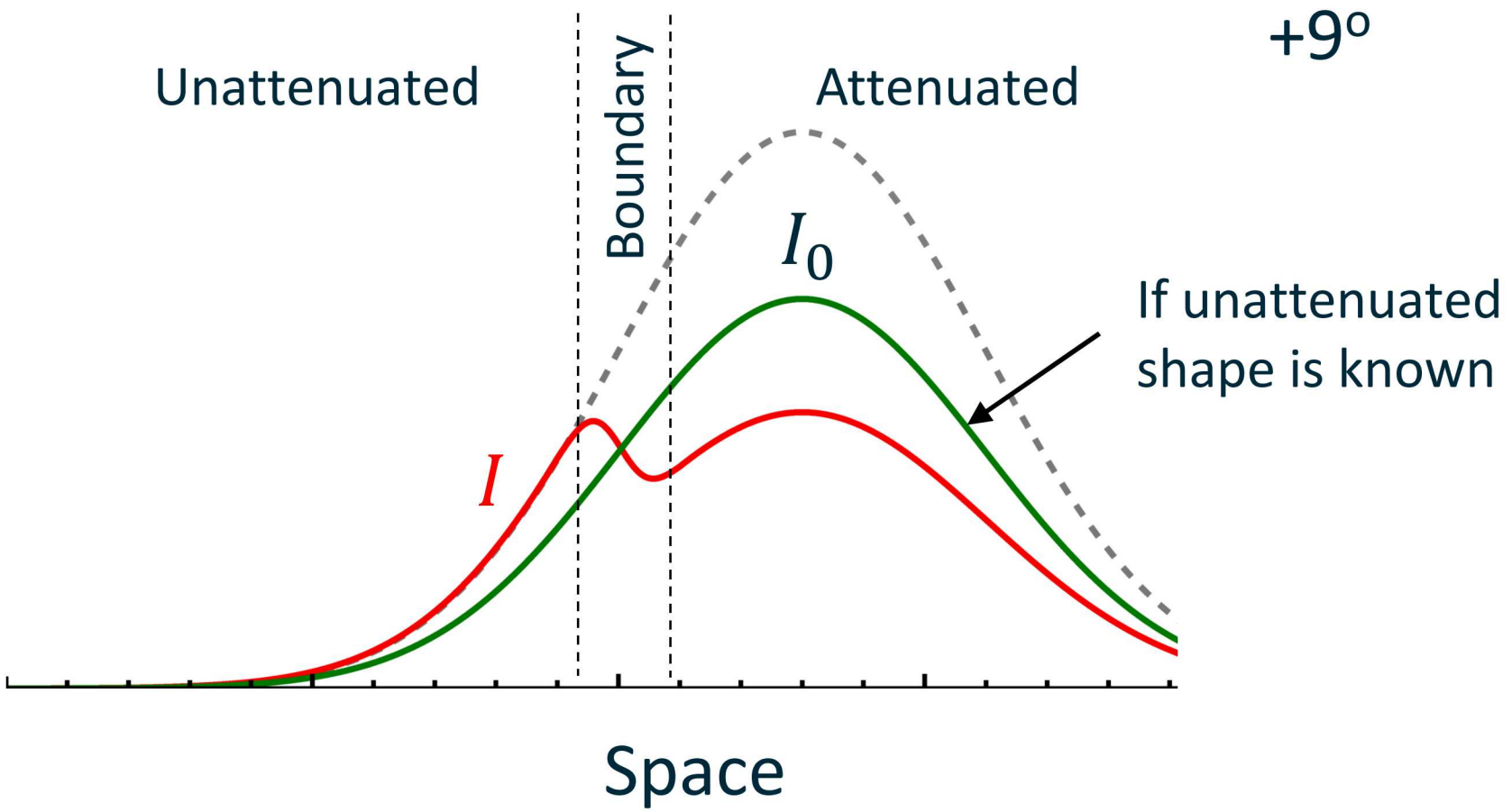


Half-moon spatial profile has both attenuated and unattenuated intensities, enabling accurate analysis



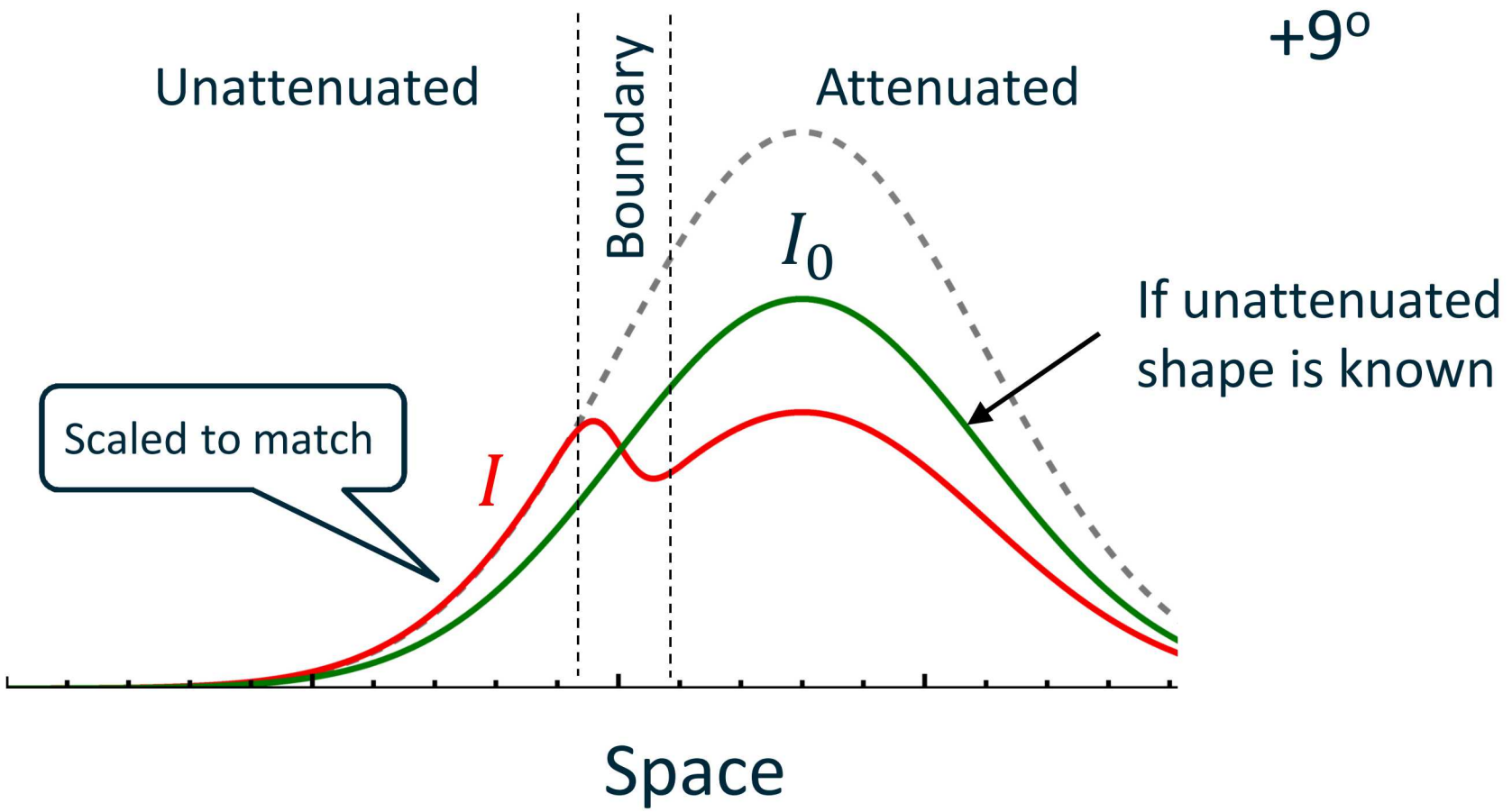
If the unattenuated shape is known, we can determine FeMg transmission accurately

Half-moon spatial profile has both attenuated and unattenuated intensities, enabling accurate analysis



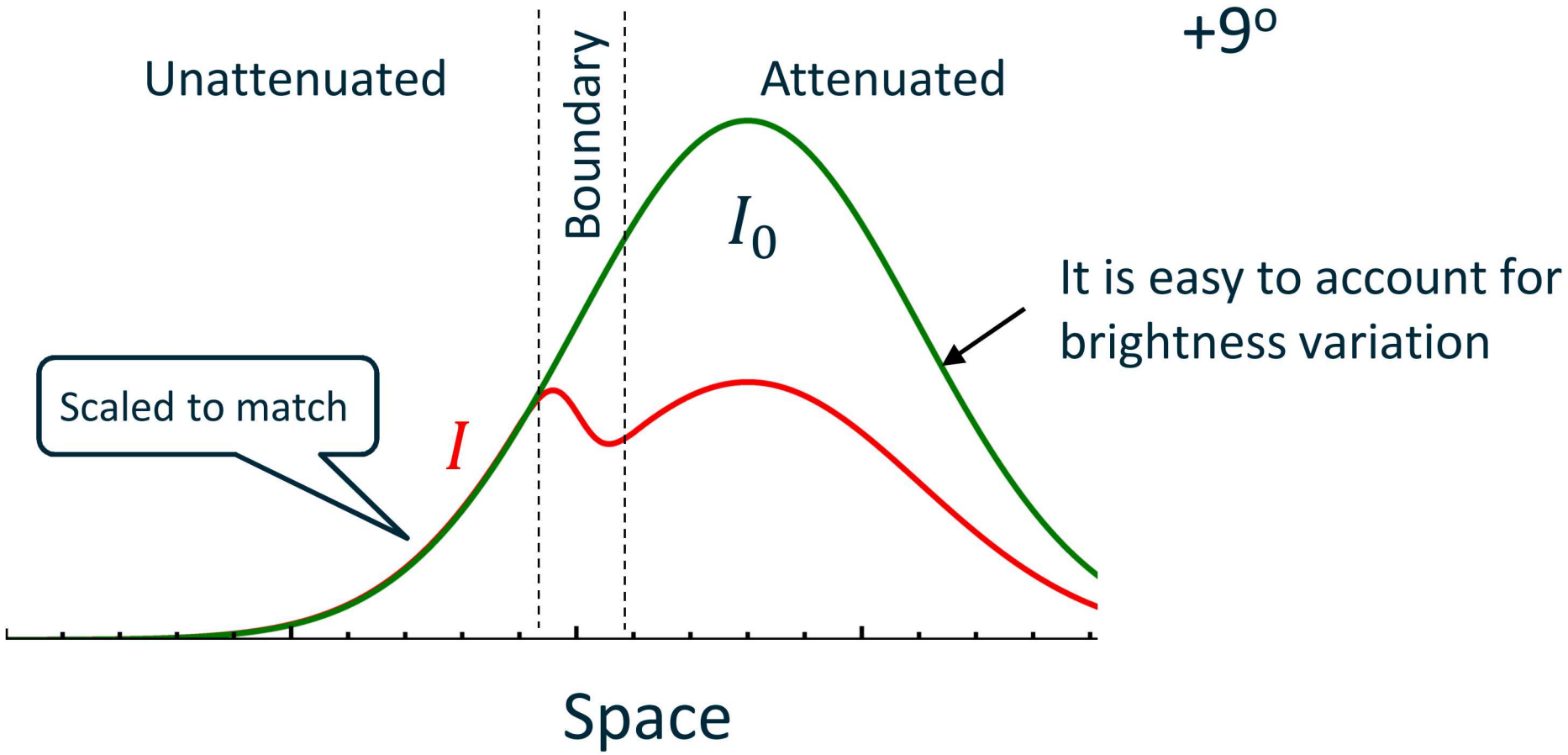
If the unattenuated shape is known, we can determine FeMg transmission accurately

Half-moon spatial profile has both attenuated and unattenuated intensities, enabling accurate analysis



If the unattenuated shape is known, we can determine FeMg transmission accurately

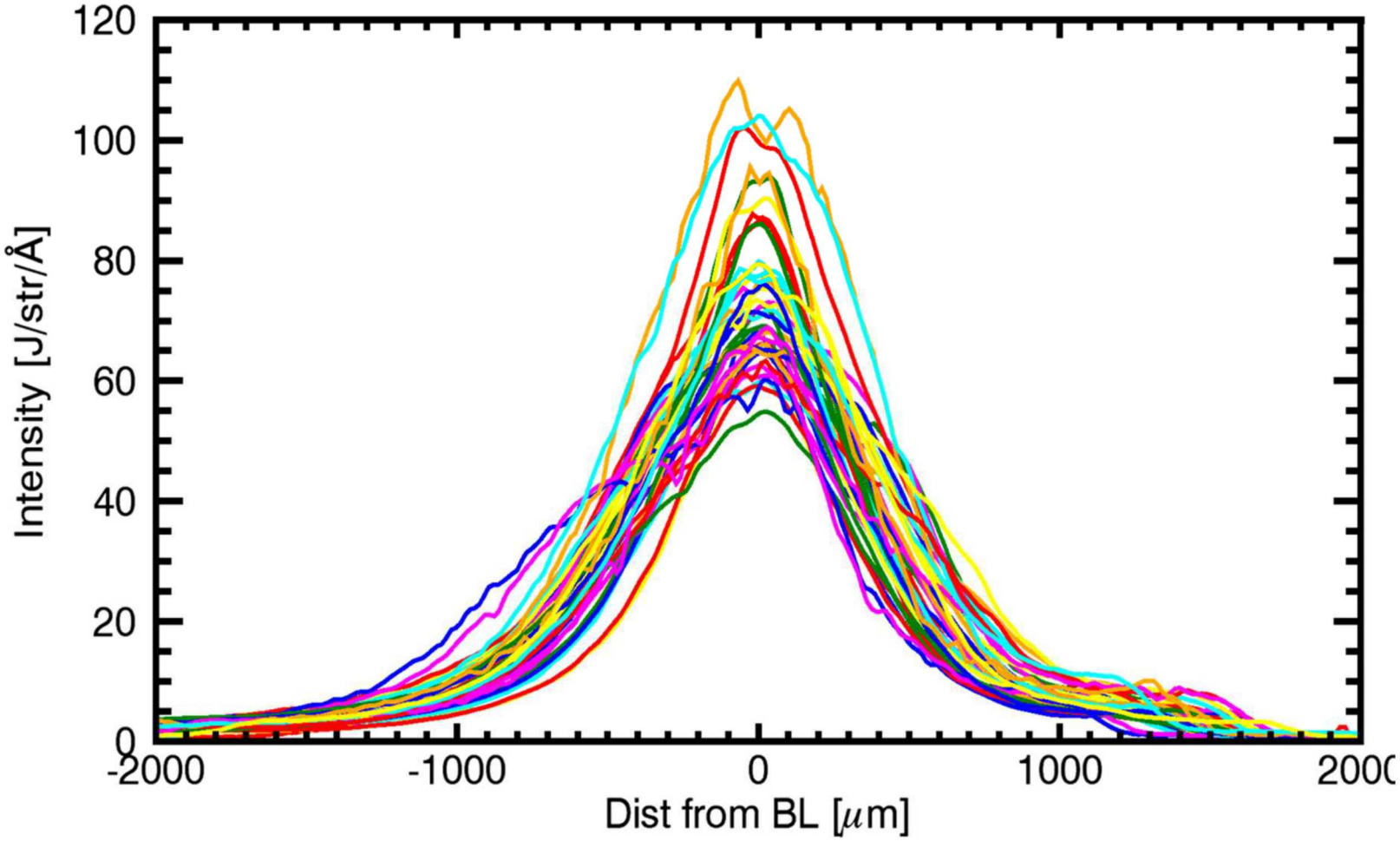
Half-moon spatial profile has both attenuated and unattenuated intensities, enabling accurate analysis



If the unattenuated shape is known, we can determine FeMg transmission accurately

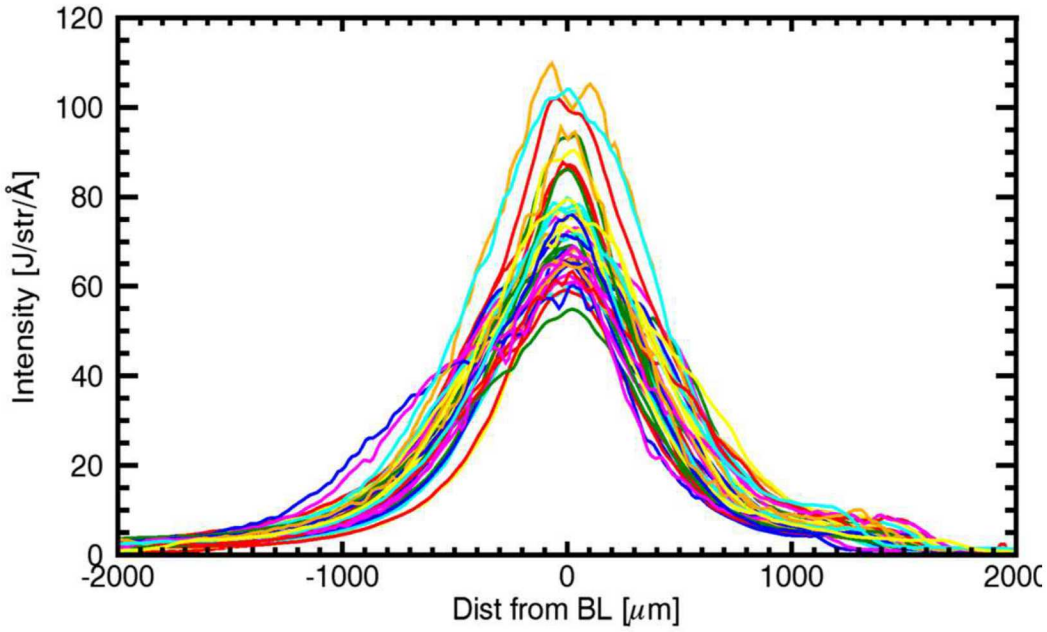
Challenge comes from the fact that both shape and brightness are known to limited accuracy

Reproducibility in unattenuated spatial shape and brightness

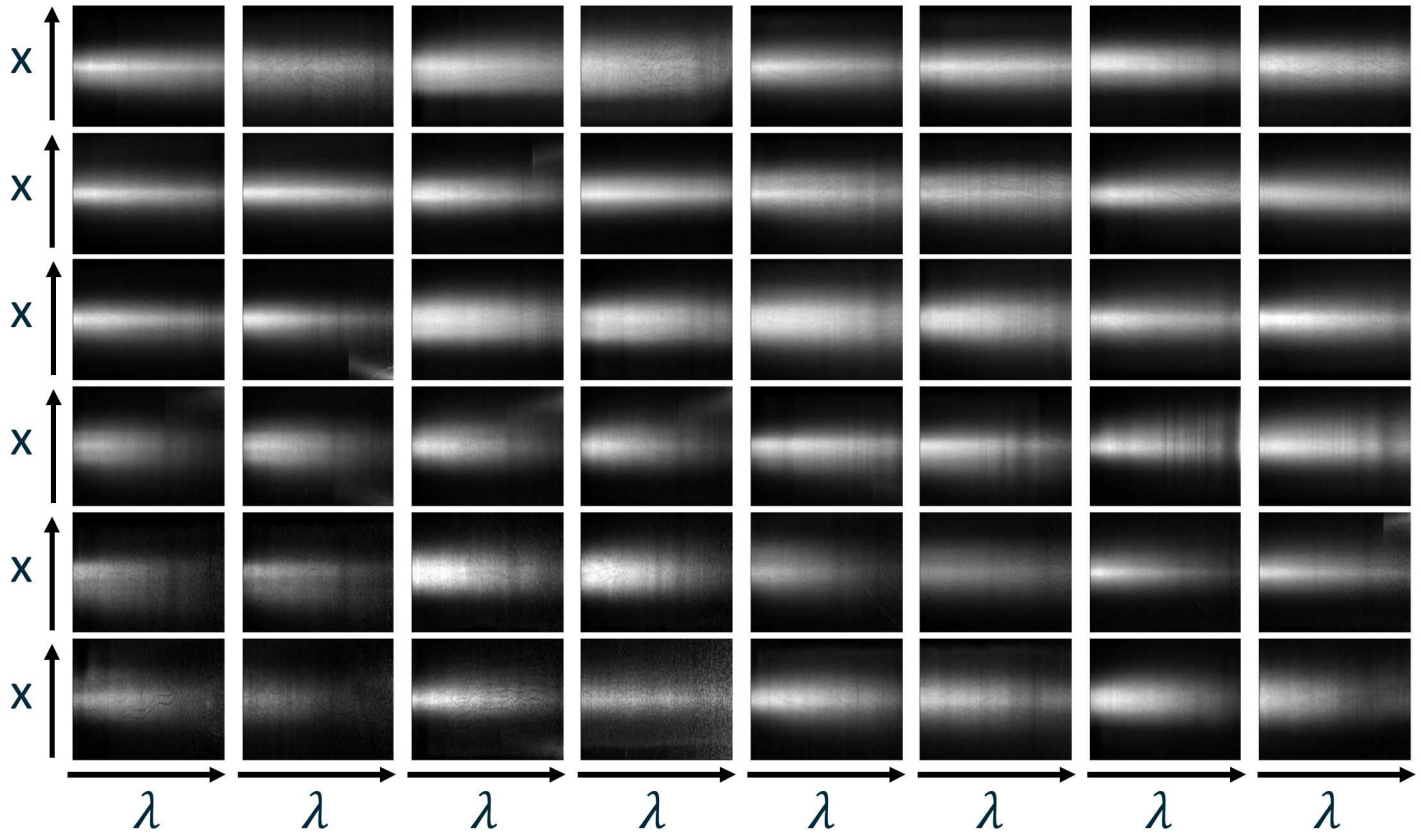


Challenge comes from the fact that both shape and brightness are known to limited accuracy

Reproducibility in unattenuated spatial shape and brightness

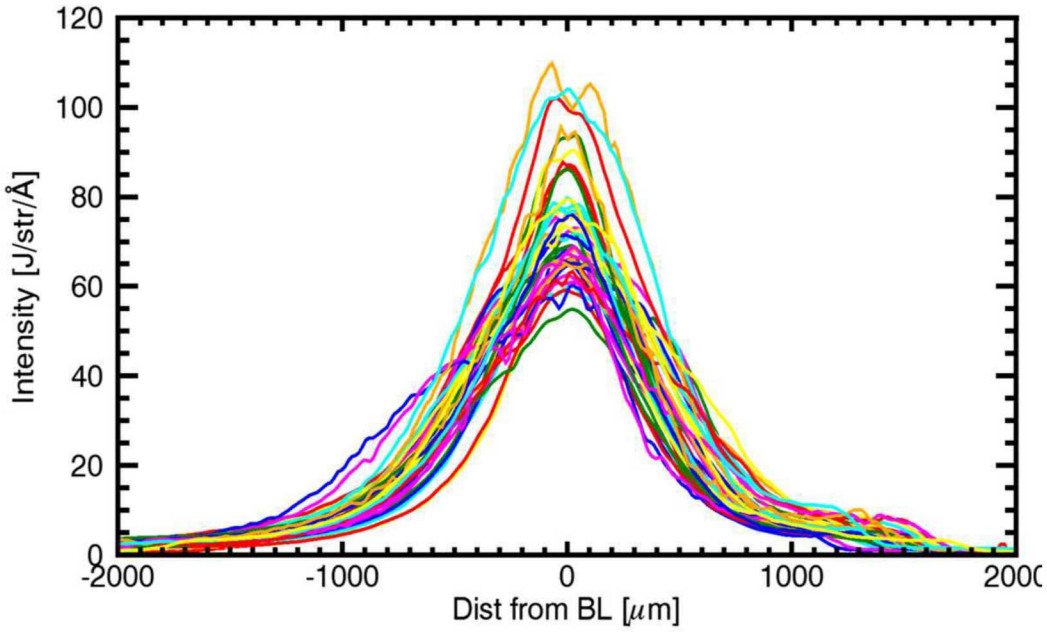


48 spectral images from 12 calibration shots collected over a decade

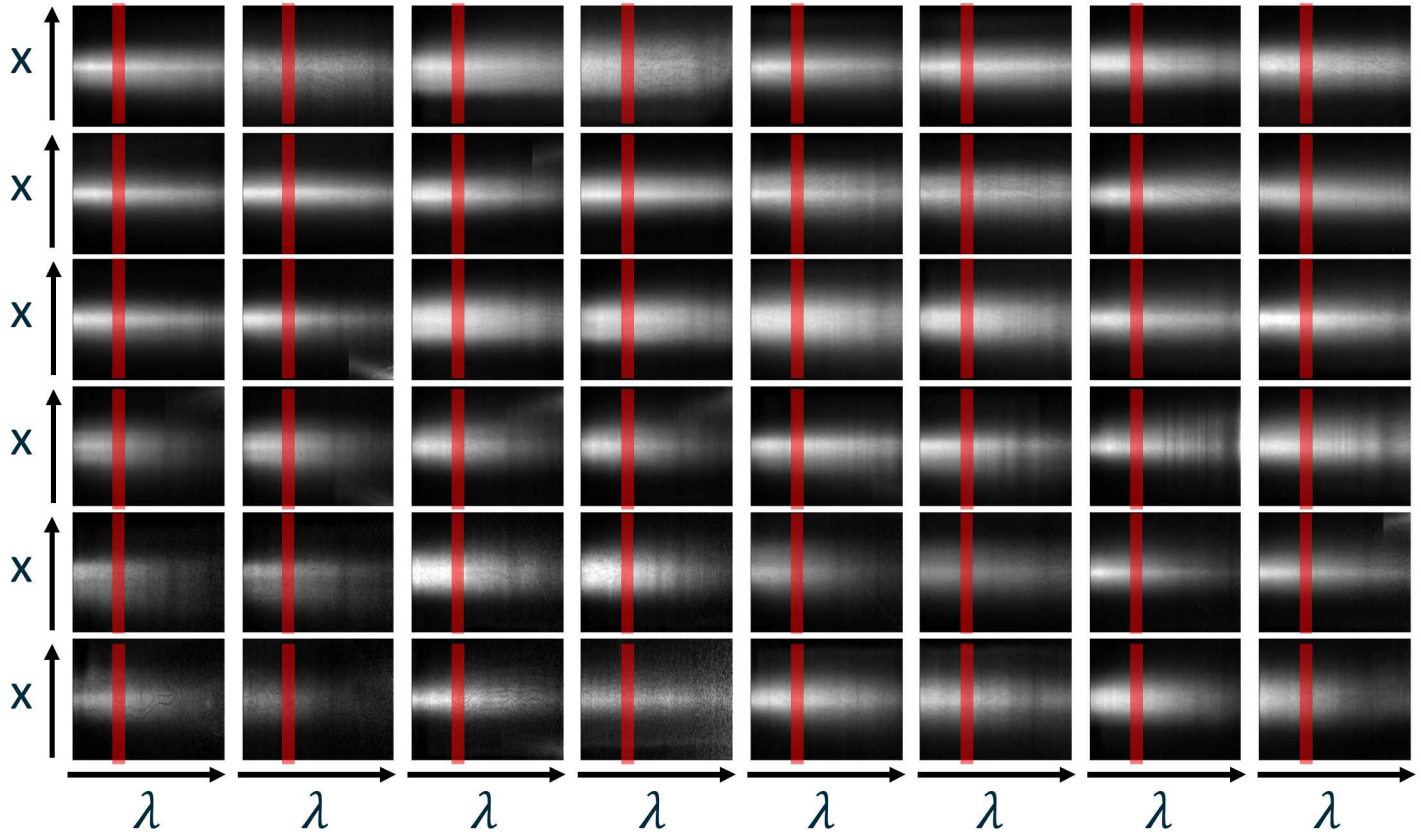


Challenge comes from the fact that both shape and brightness are known to limited accuracy

Reproducibility in unattenuated spatial shape and brightness

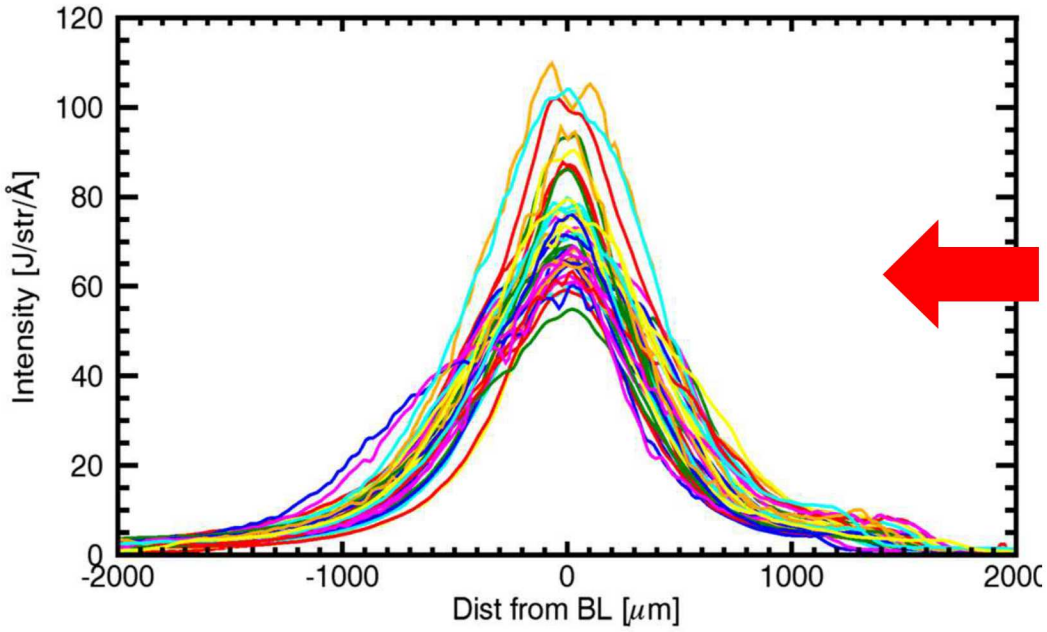


48 spectral images from 12 calibration shots collected over a decade

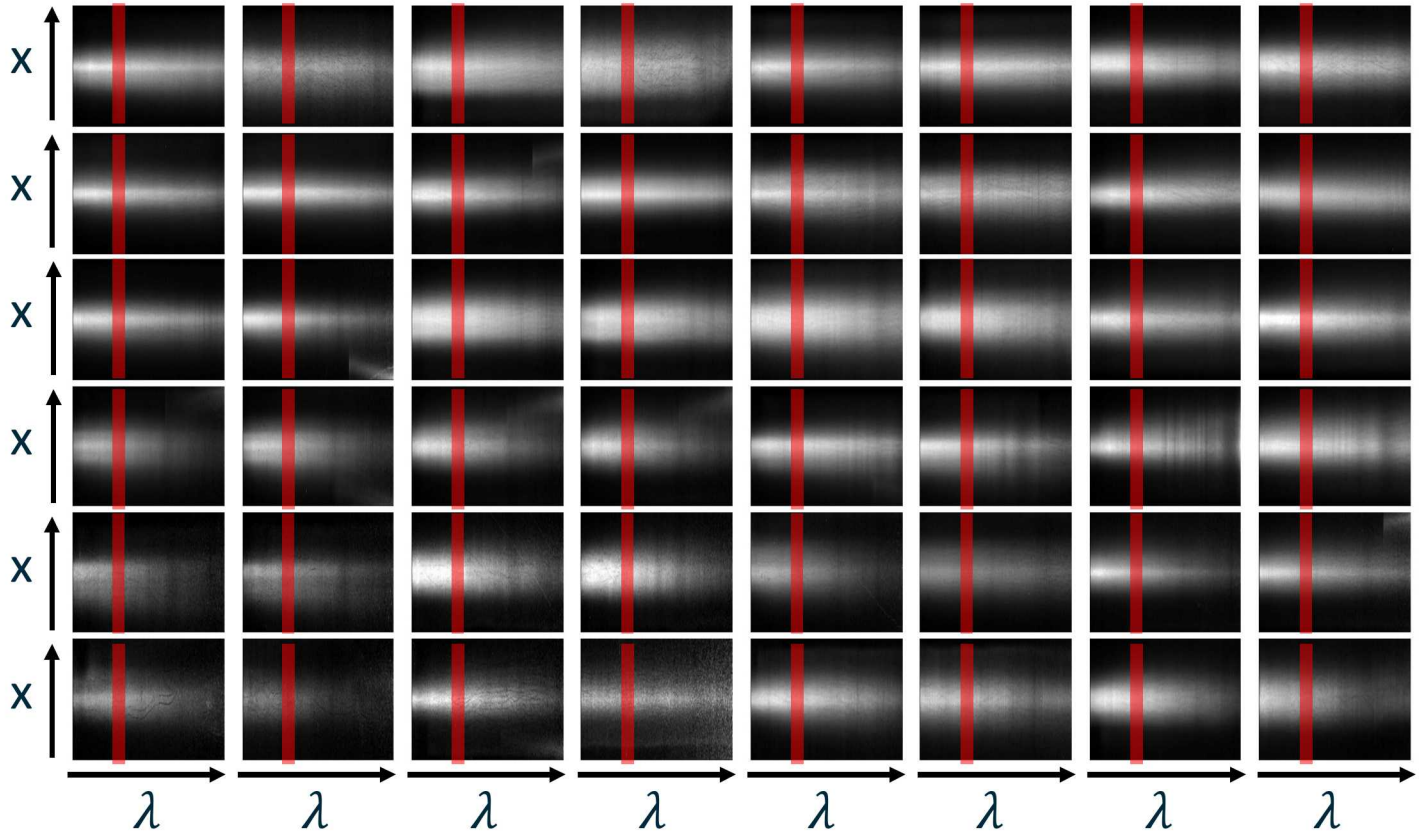


Challenge comes from the fact that both shape and brightness are known to limited accuracy

Reproducibility in unattenuated spatial shape and brightness

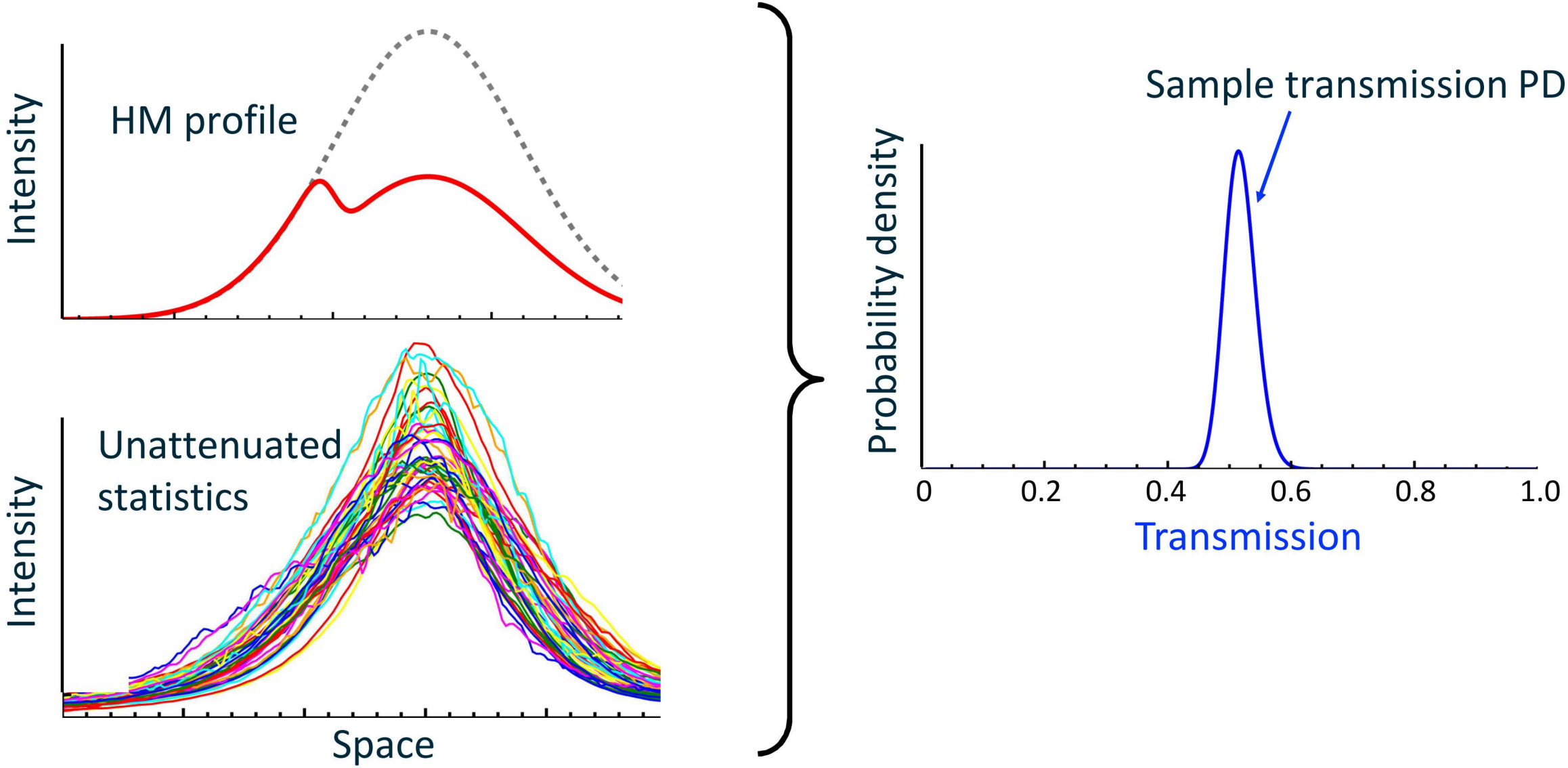


48 spectral images from 12 calibration shots collected over a decade

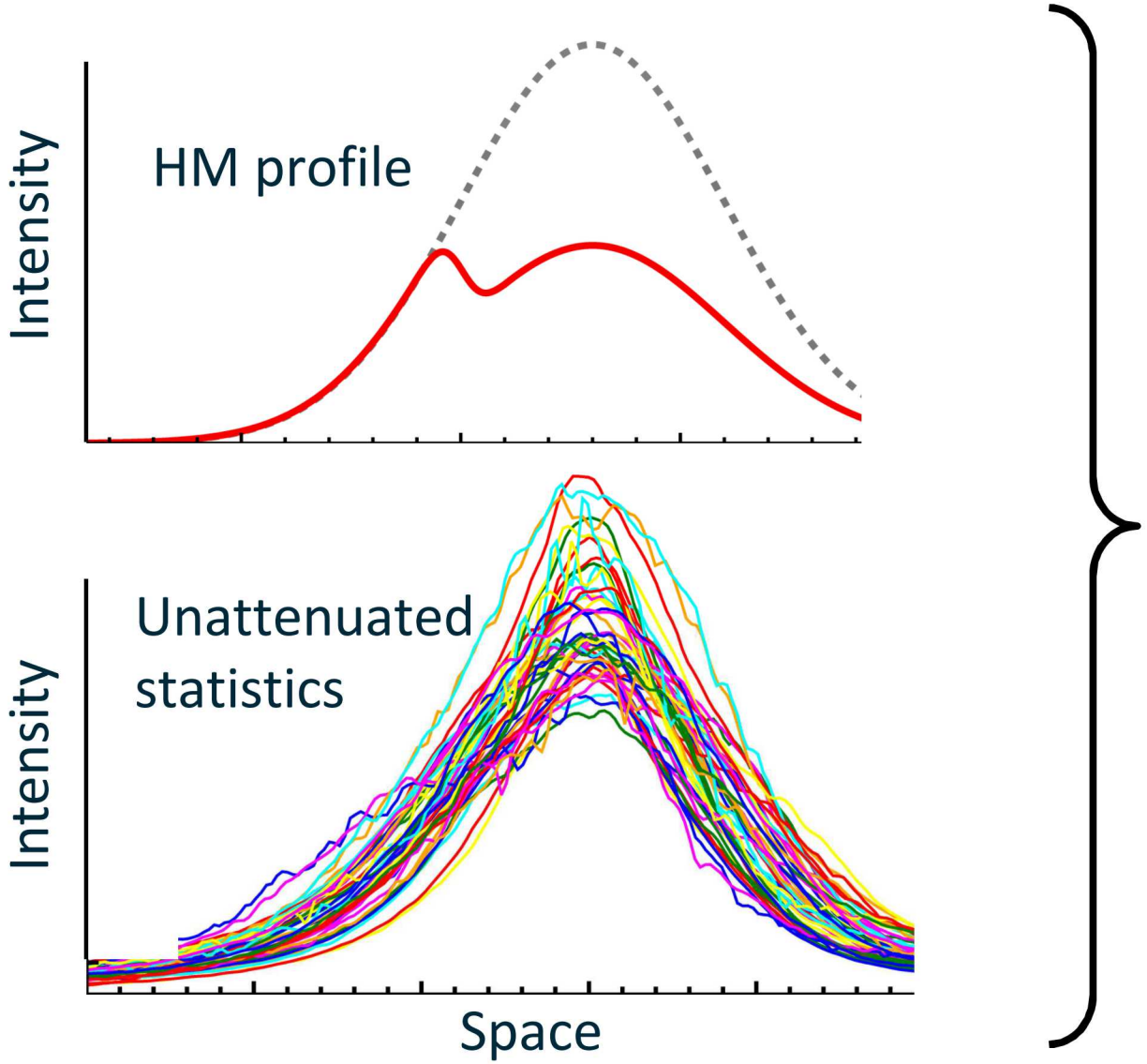


We can use this statistics to determine FeMg transmission

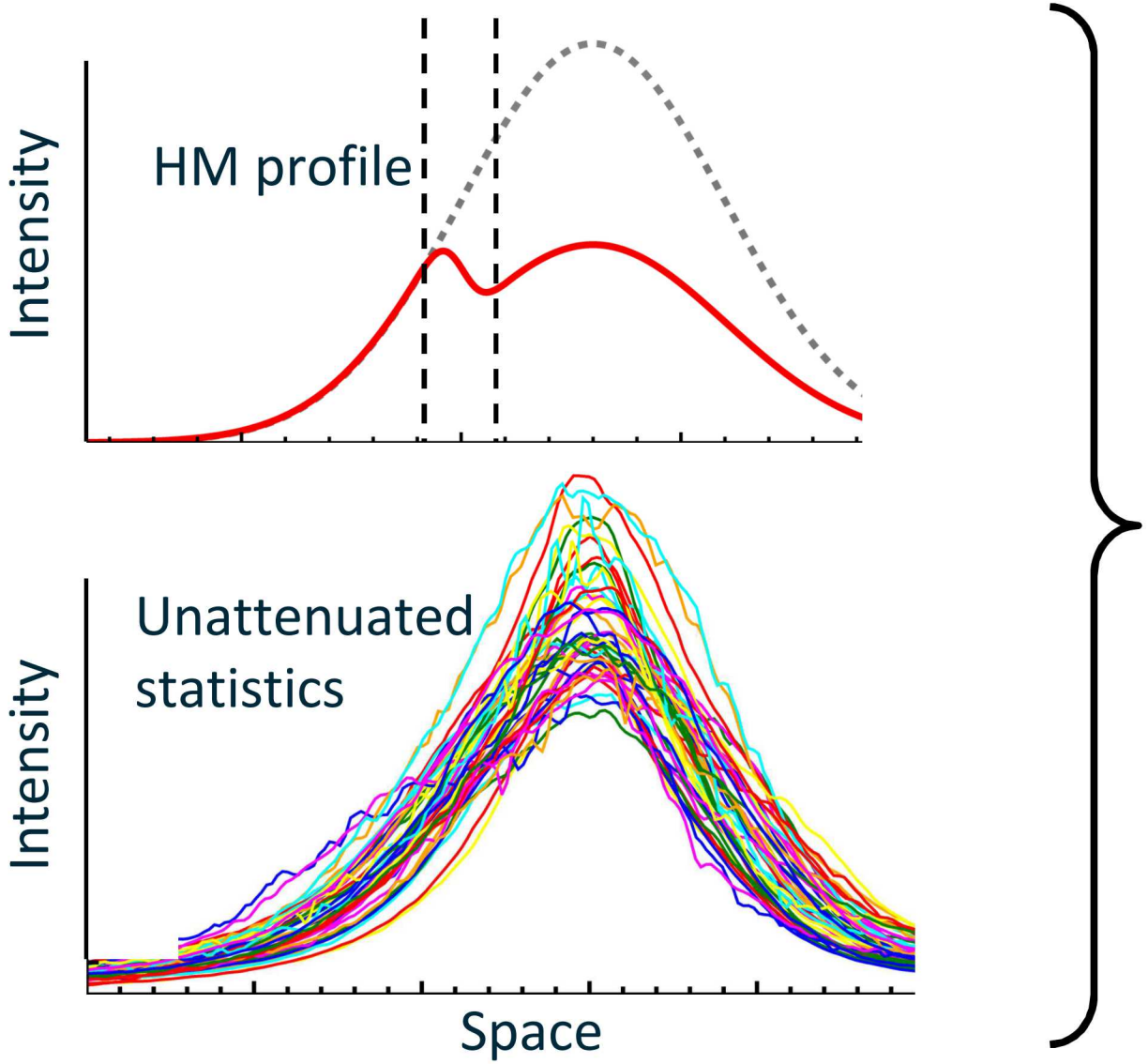
New method: sample transmission probability distribution is analytically derived spatial lineout



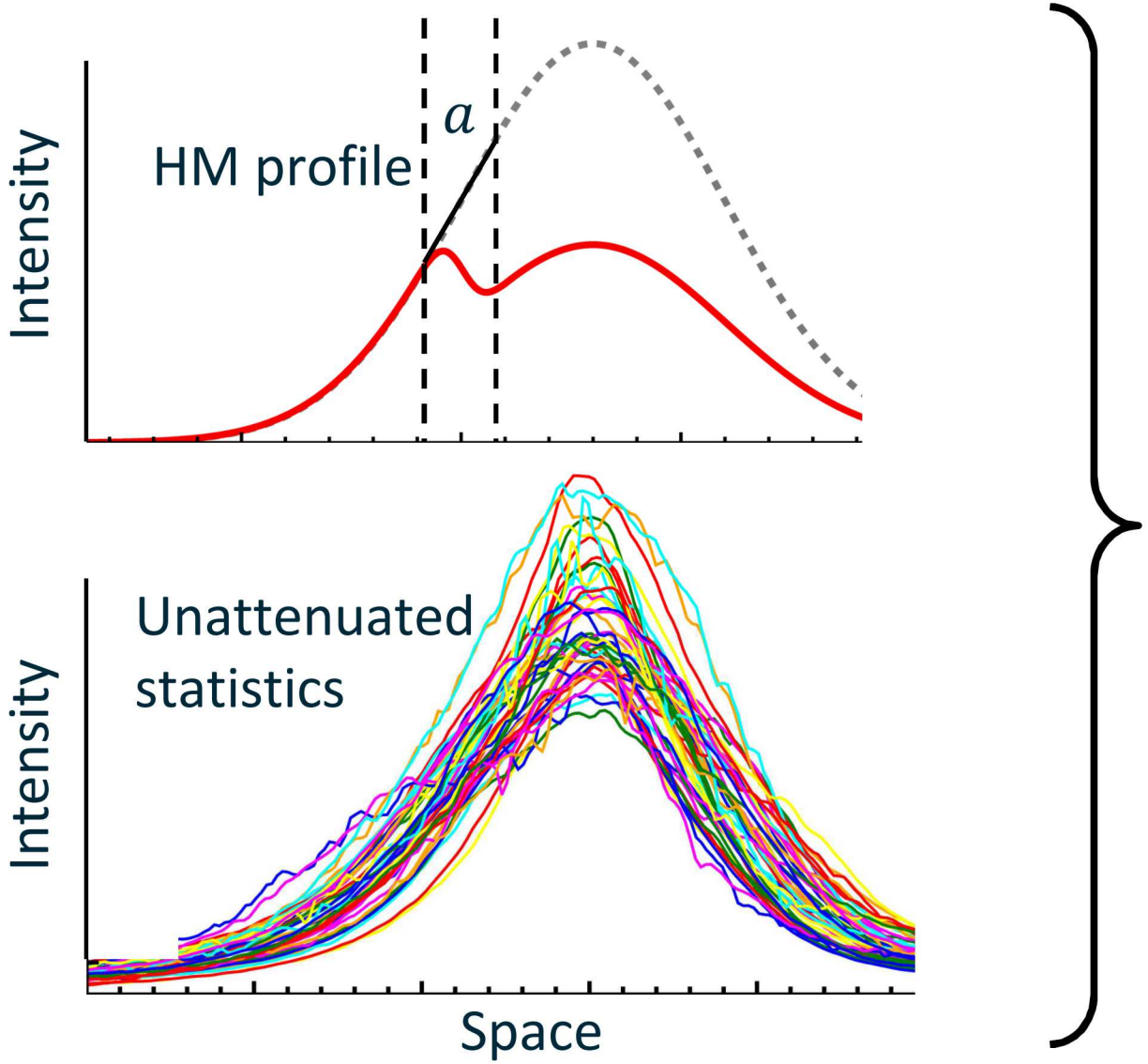
Example: transmission from boundary-slope statistics



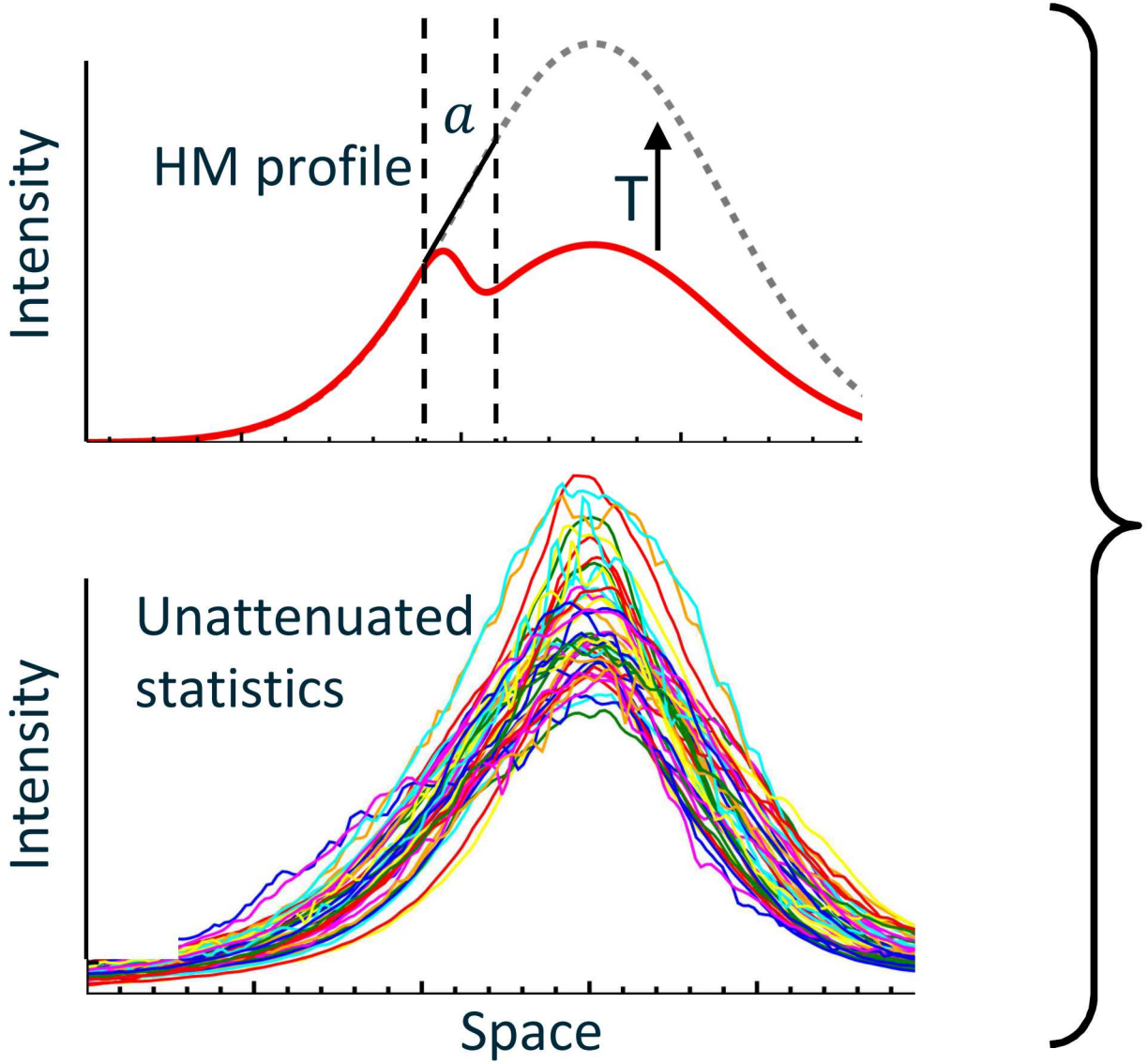
Example: transmission from boundary-slope statistics



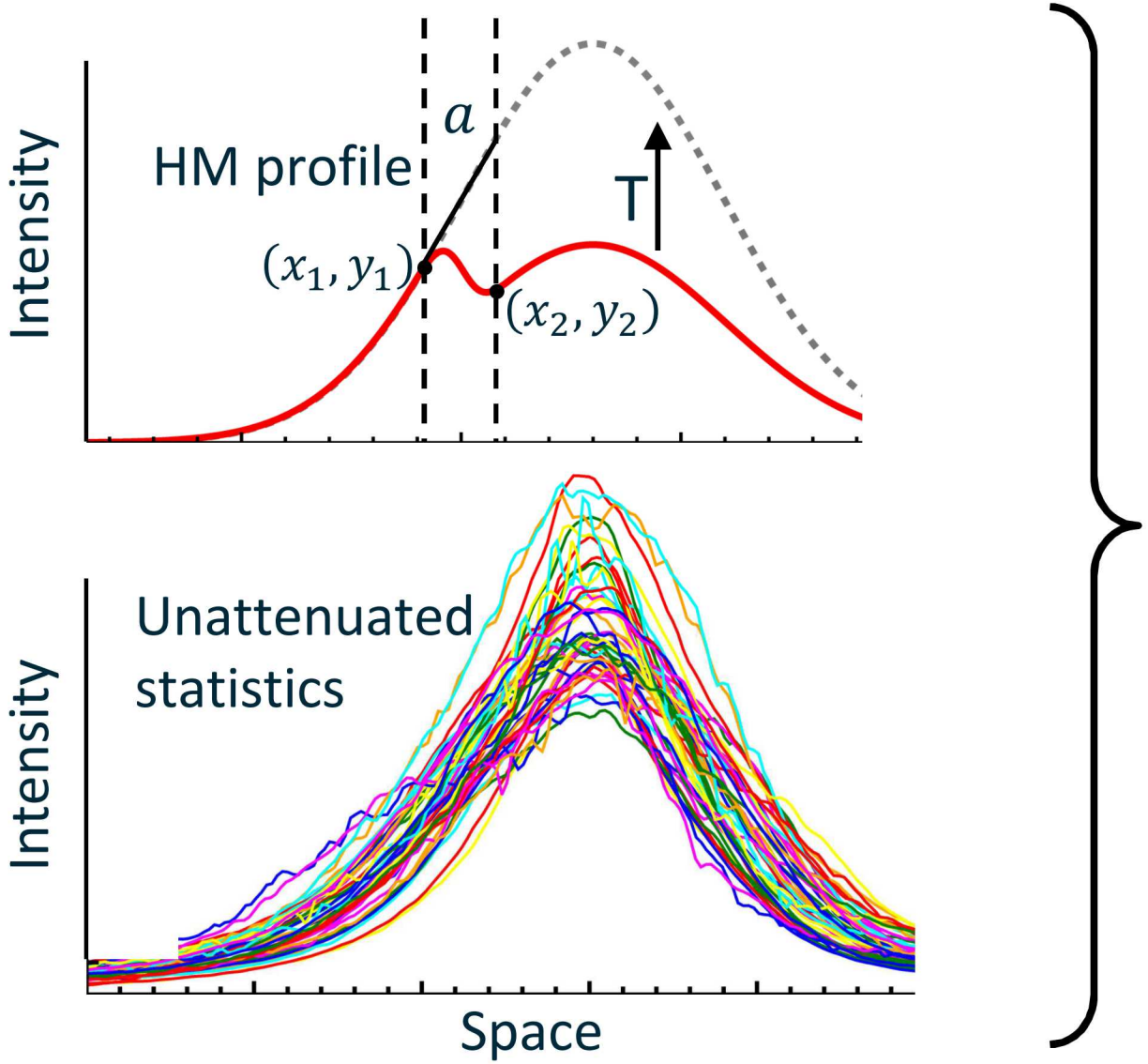
Example: transmission from boundary-slope statistics



Example: transmission from boundary-slope statistics

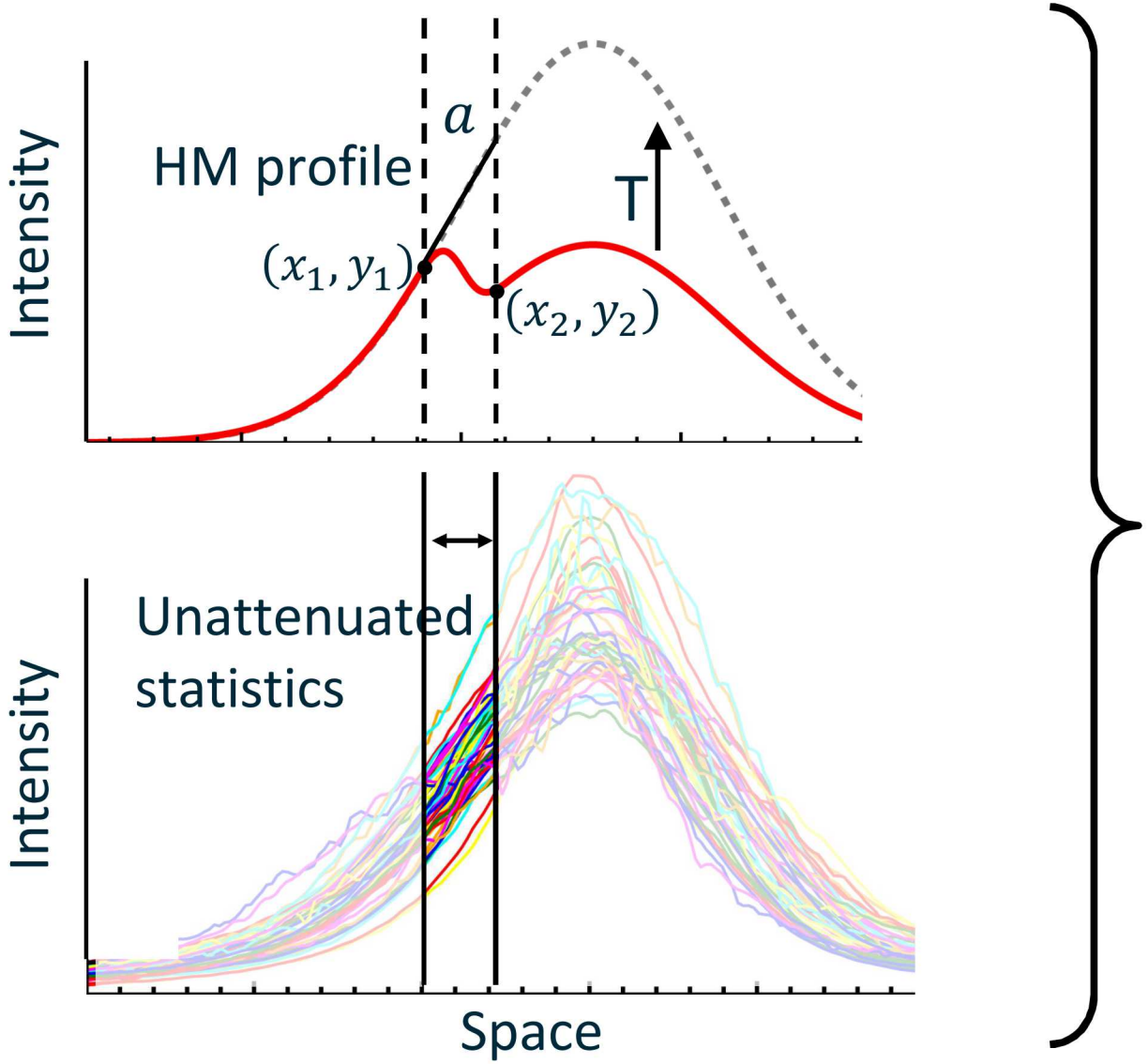


Example: transmission from boundary-slope statistics



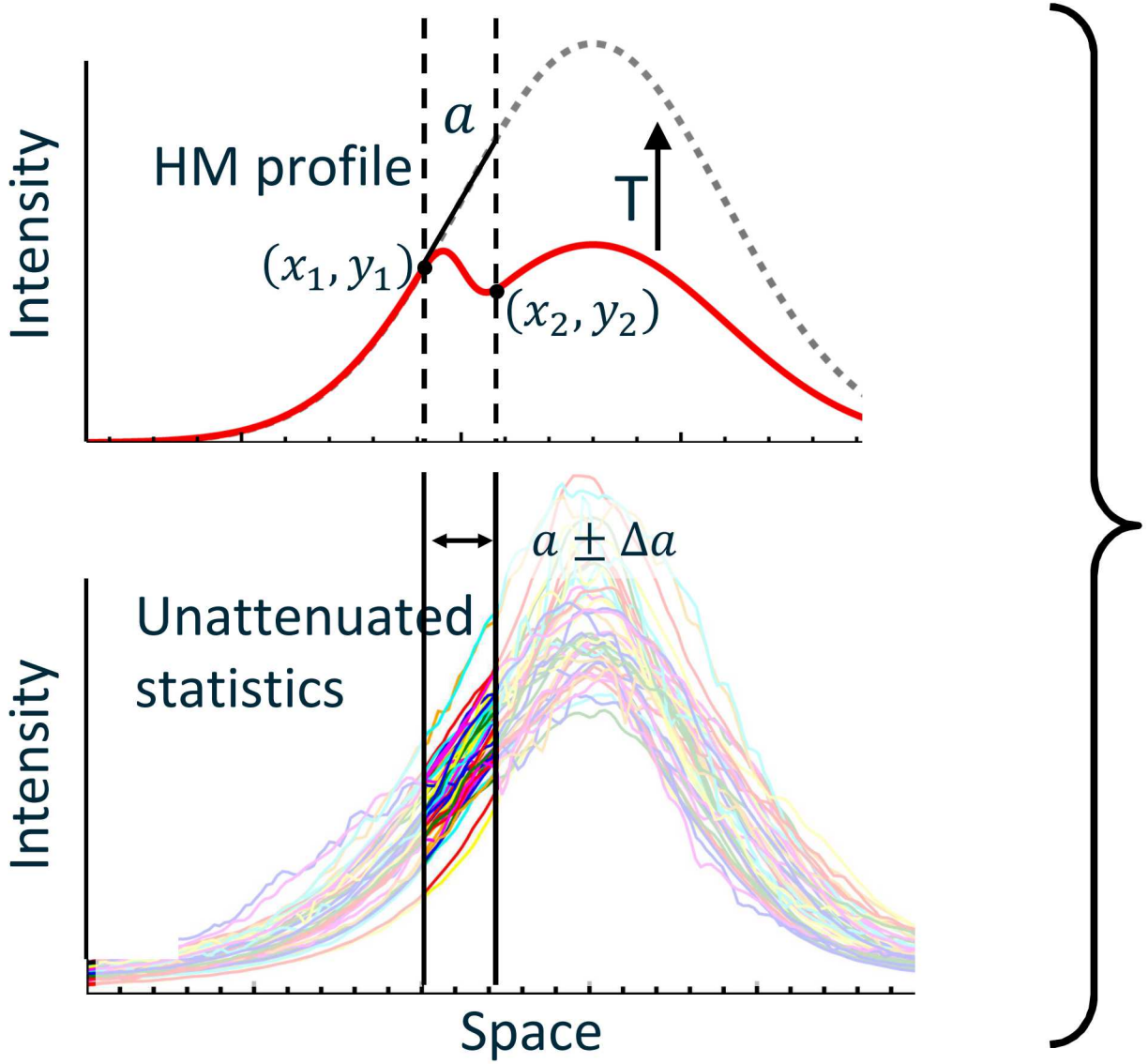
$$T = \frac{y_2}{y_1 + a(x_2 - x_1)}$$

Example: transmission from boundary-slope statistics



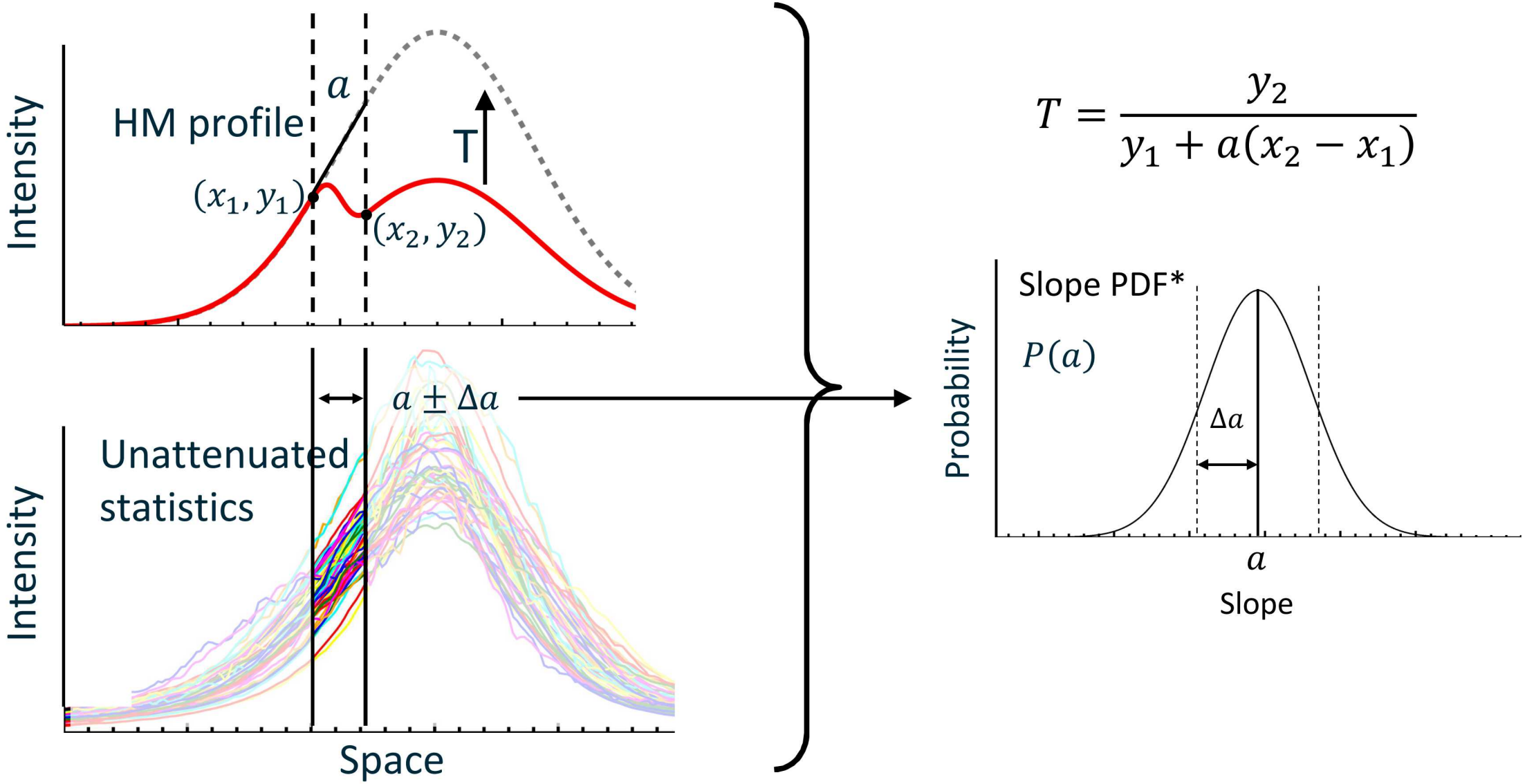
$$T = \frac{y_2}{y_1 + a(x_2 - x_1)}$$

Example: transmission from boundary-slope statistics



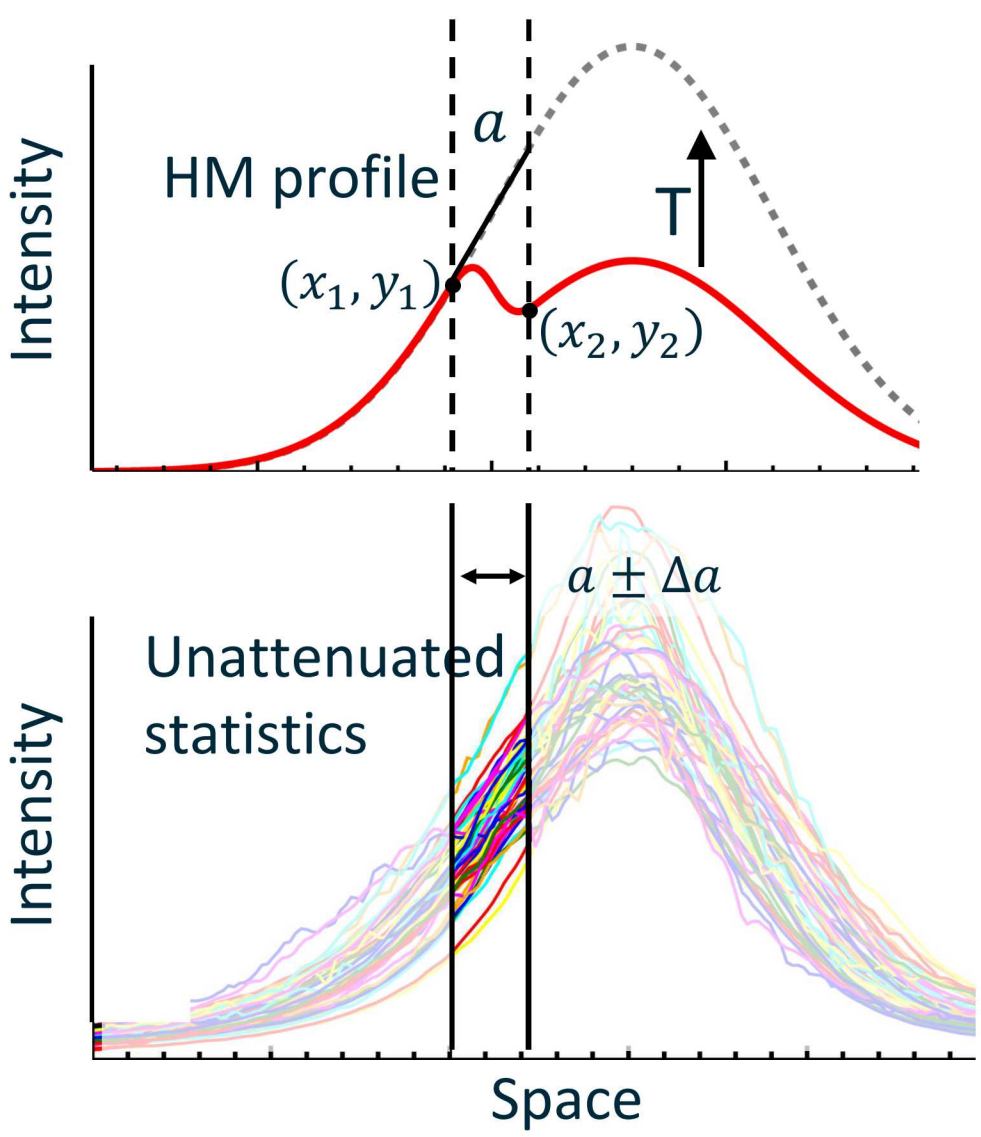
$$T = \frac{y_2}{y_1 + a(x_2 - x_1)}$$

Example: transmission from boundary-slope statistics

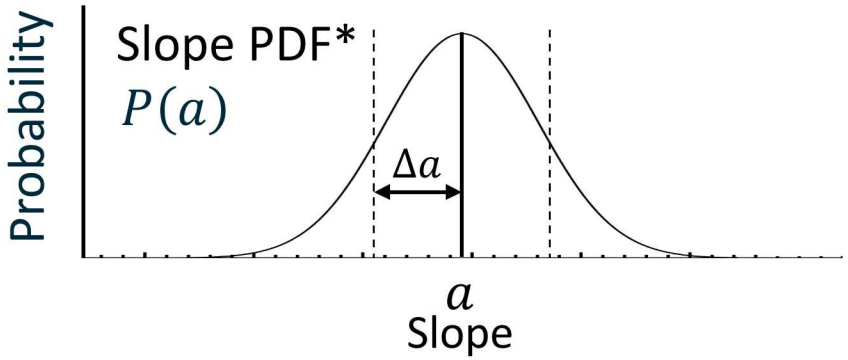


*PDF = Probability distribution function

Example: transmission from boundary-slope statistics



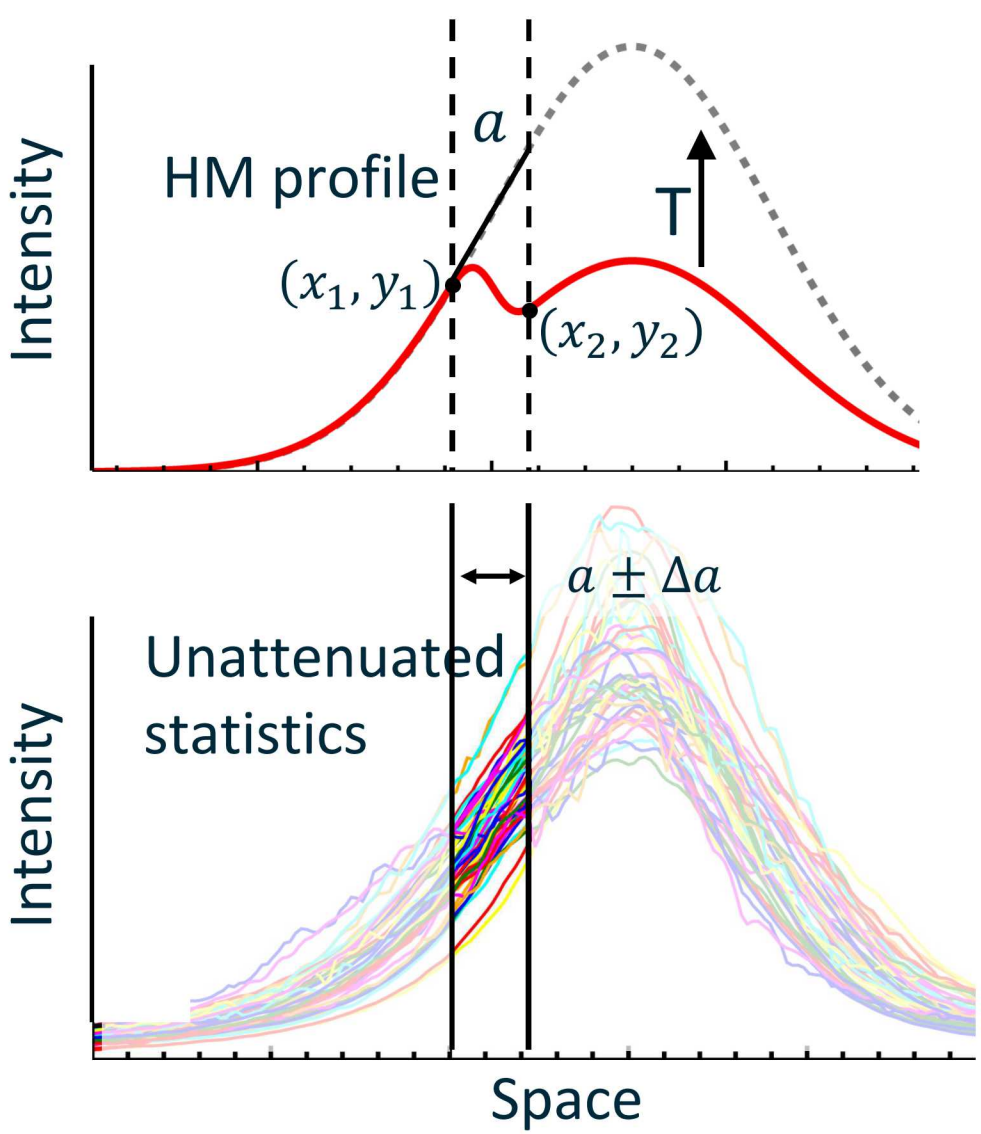
$$T = \frac{y_2}{y_1 + a(x_2 - x_1)}$$



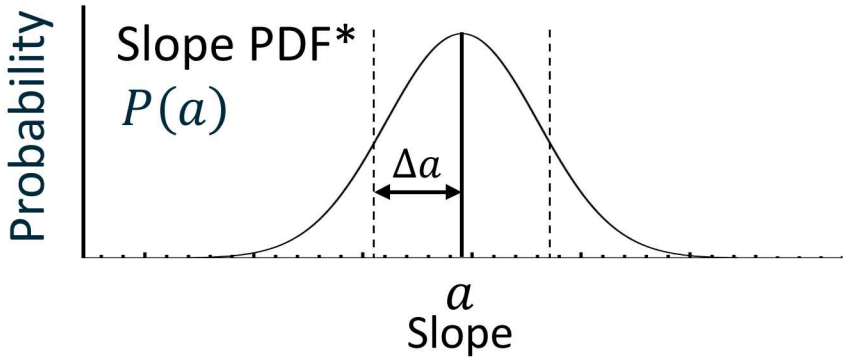
$$P(T) = P(a)\frac{da}{dT}$$

*PDF = Probability distribution function

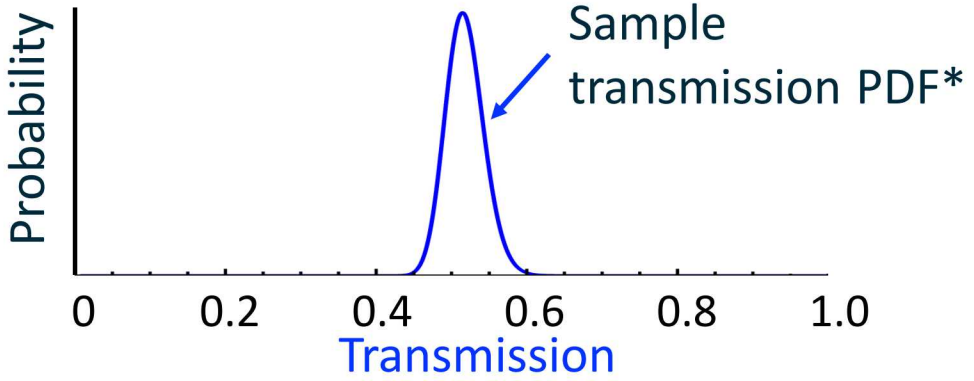
Example: transmission from boundary-slope statistics



$$T = \frac{y_2}{y_1 + a(x_2 - x_1)}$$

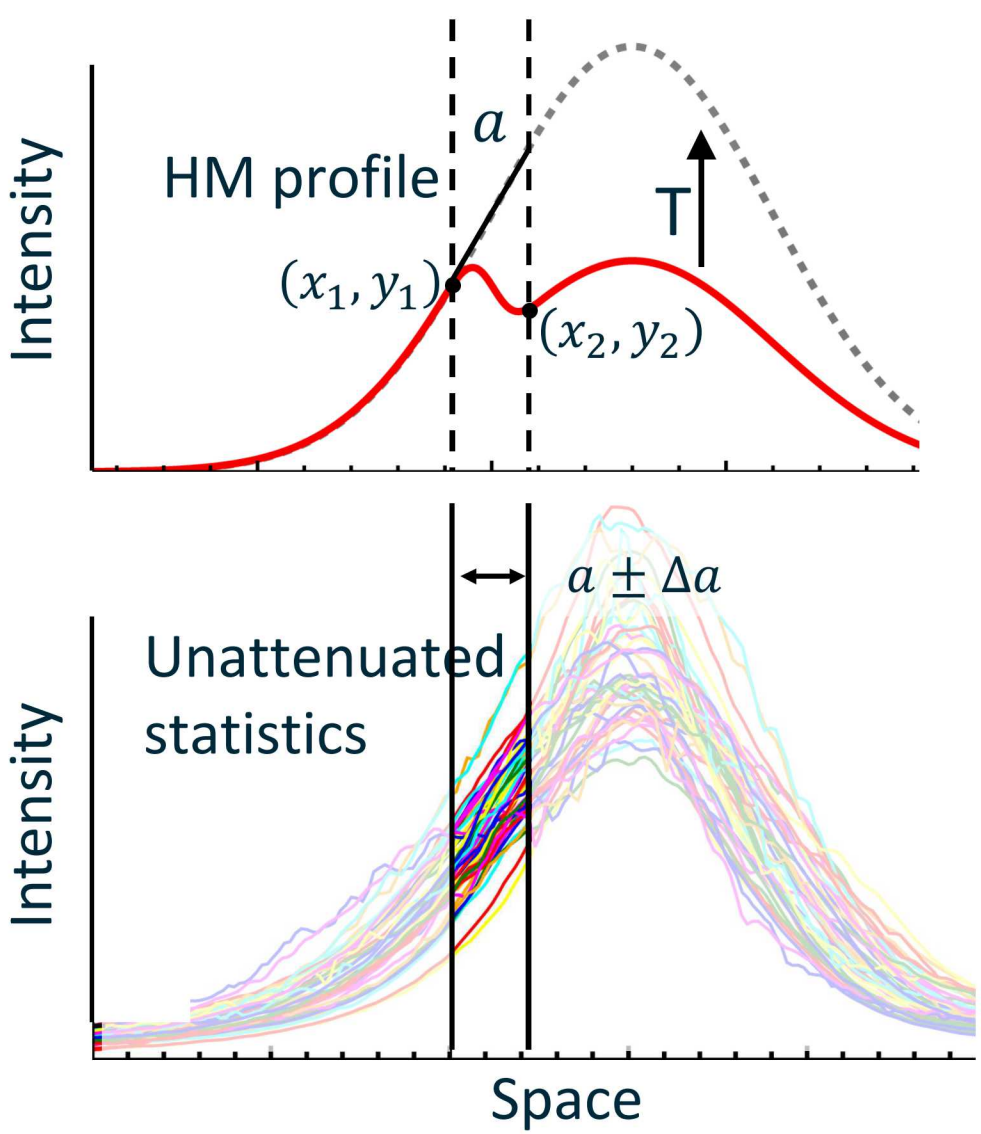


$$P(T) = P(a)\frac{da}{dT}$$

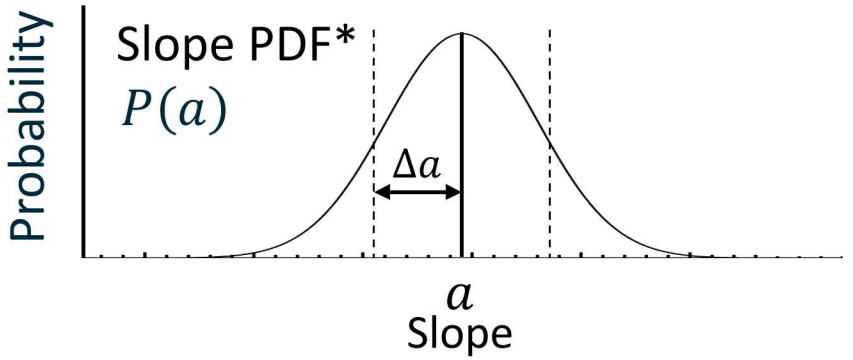


*PDF = Probability distribution function

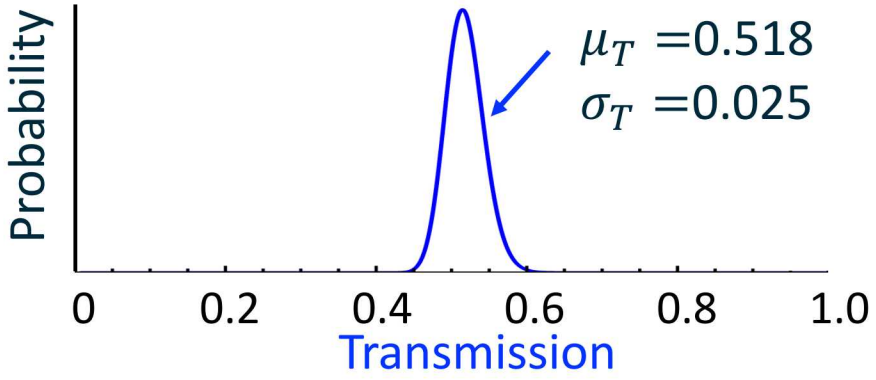
Example: transmission from boundary-slope statistics



$$T = \frac{y_2}{y_1 + a(x_2 - x_1)}$$

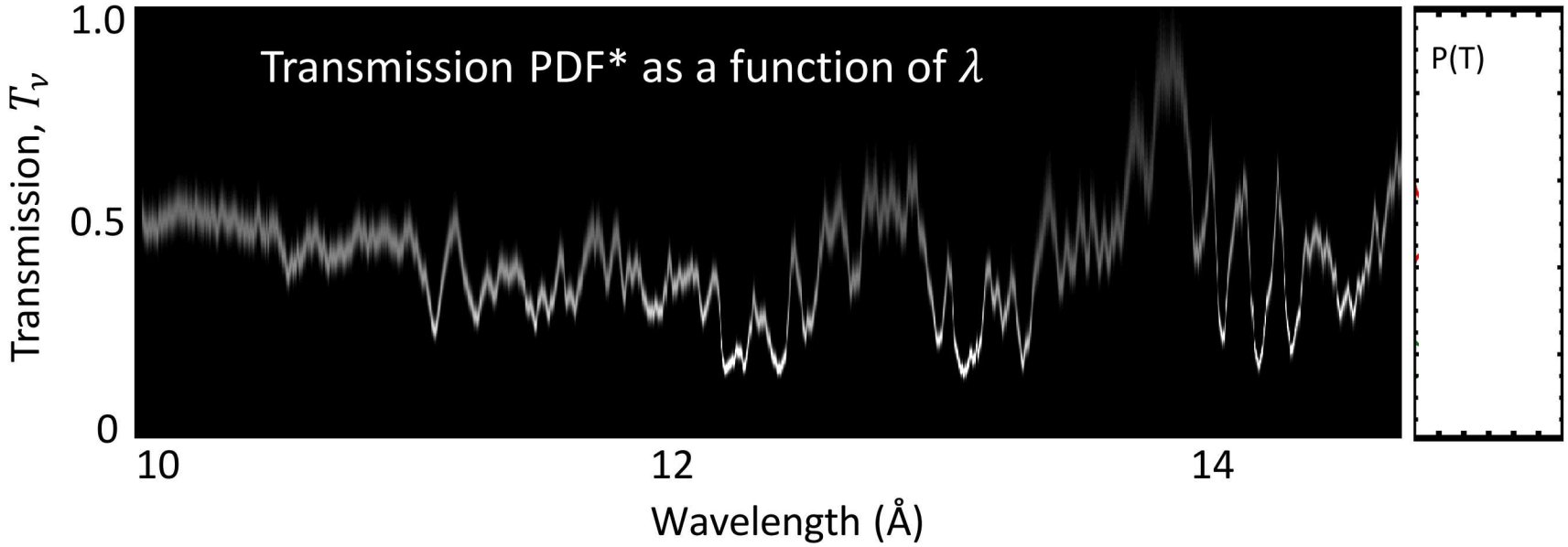


$$P(T) = P(a)\frac{da}{dT}$$



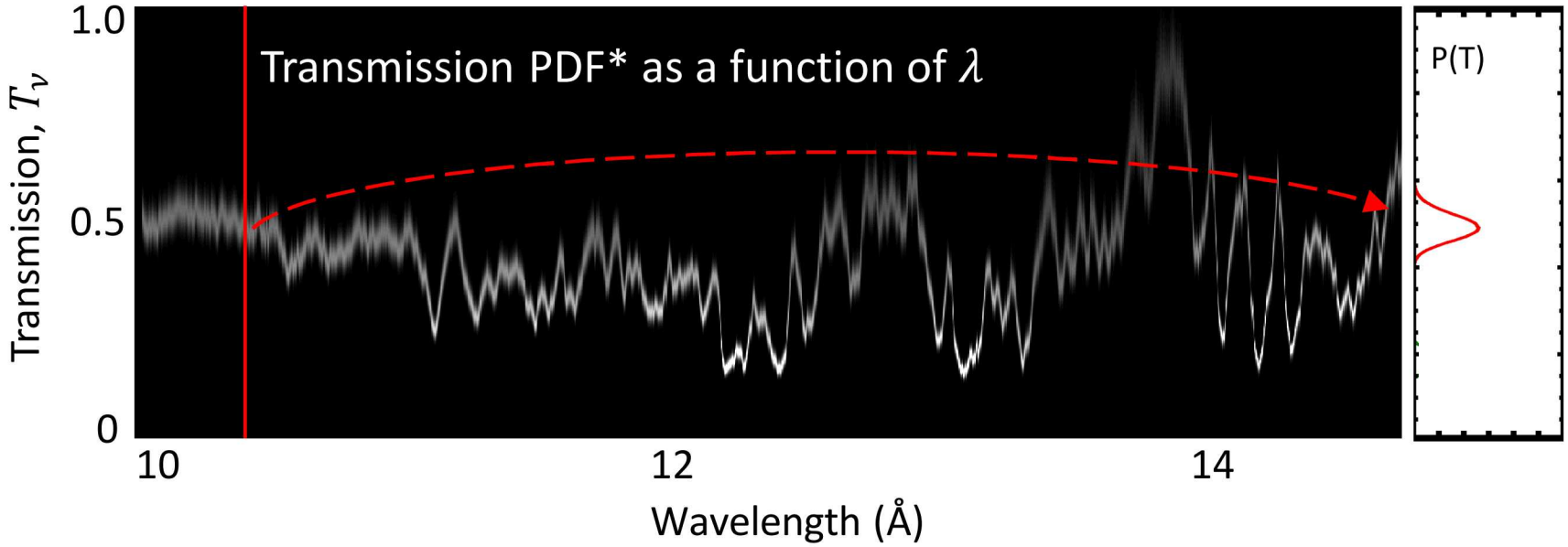
*PDF = Probability distribution function

Transmission PDF as a function of λ is determined by repeating HM-spatial-profile analysis at multiple wavelengths



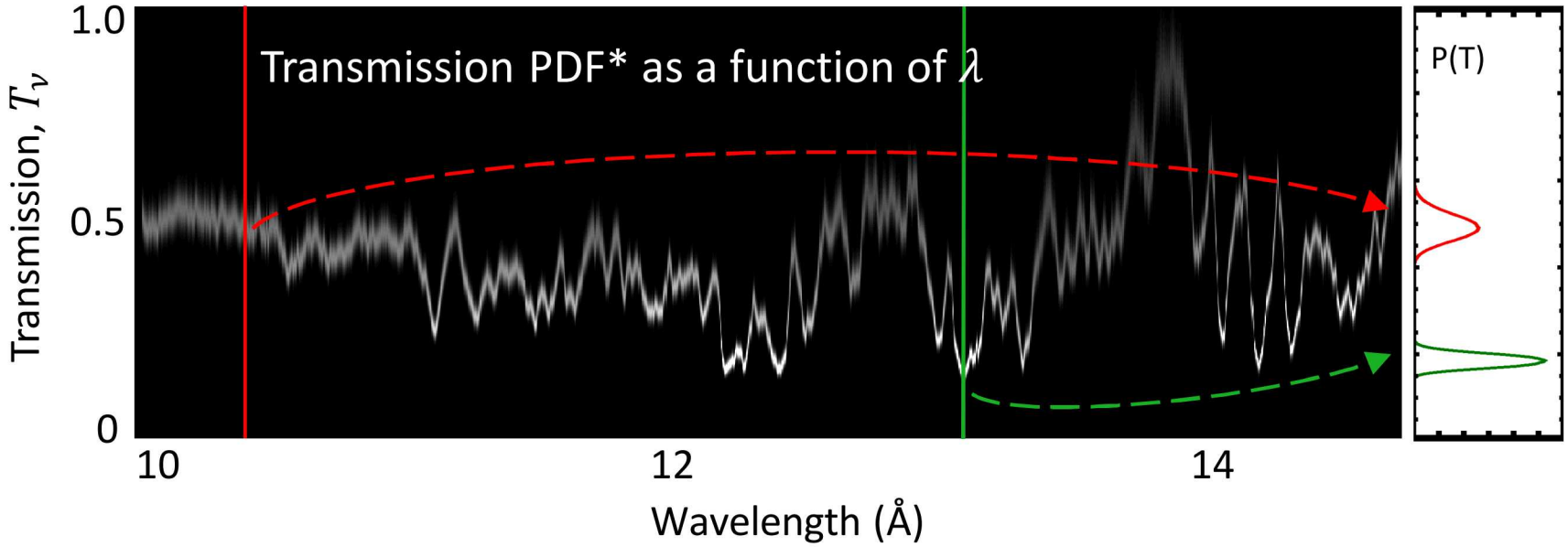
*PDF = Probability distribution function

Transmission PDF as a function of λ is determined by repeating HM-spatial-profile analysis at multiple wavelengths



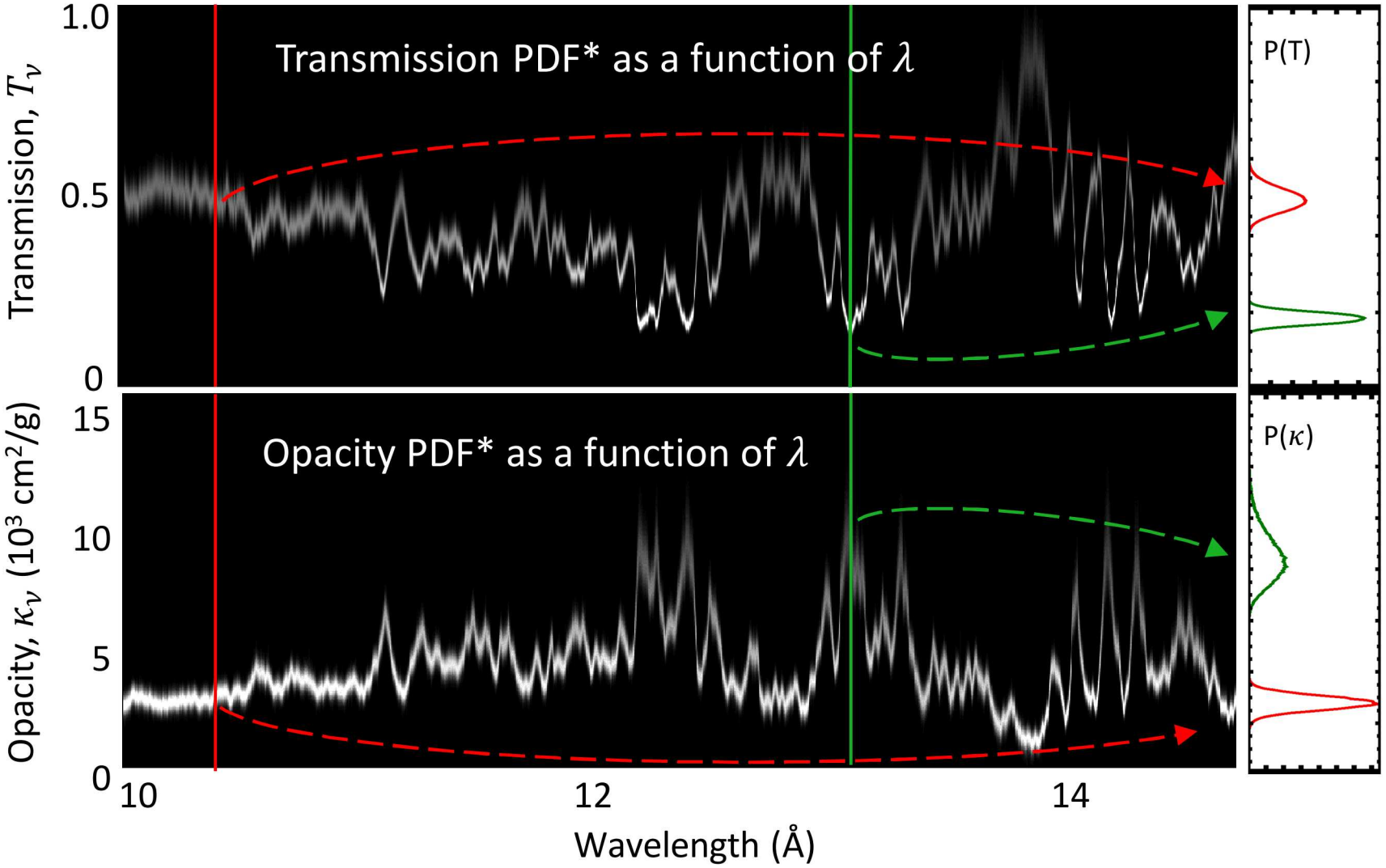
*PDF = Probability distribution function

Transmission PDF as a function of λ is determined by repeating HM-spatial-profile analysis at multiple wavelengths



*PDF = Probability distribution function

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

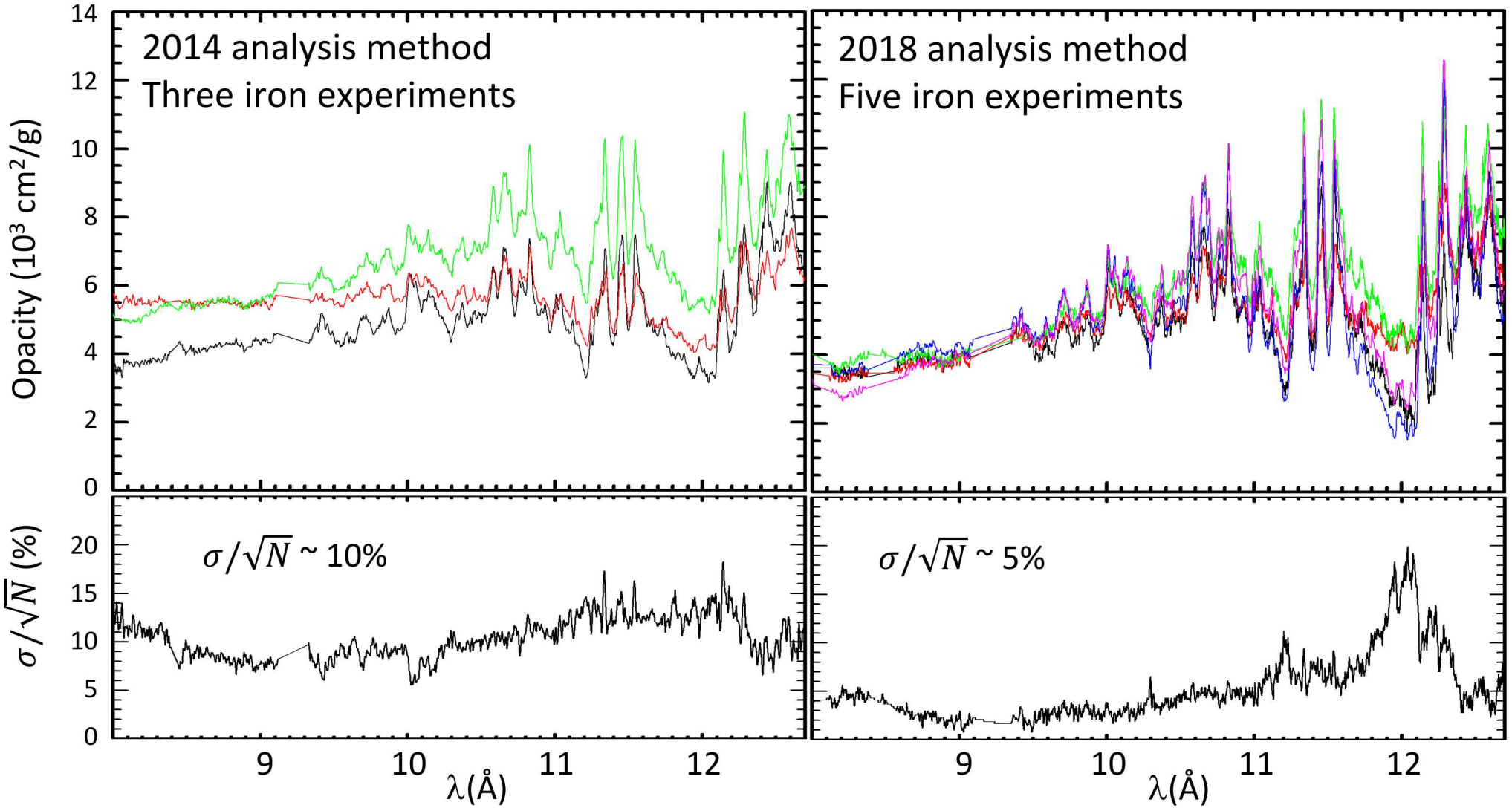


Monte-Carlo to propagate errors:

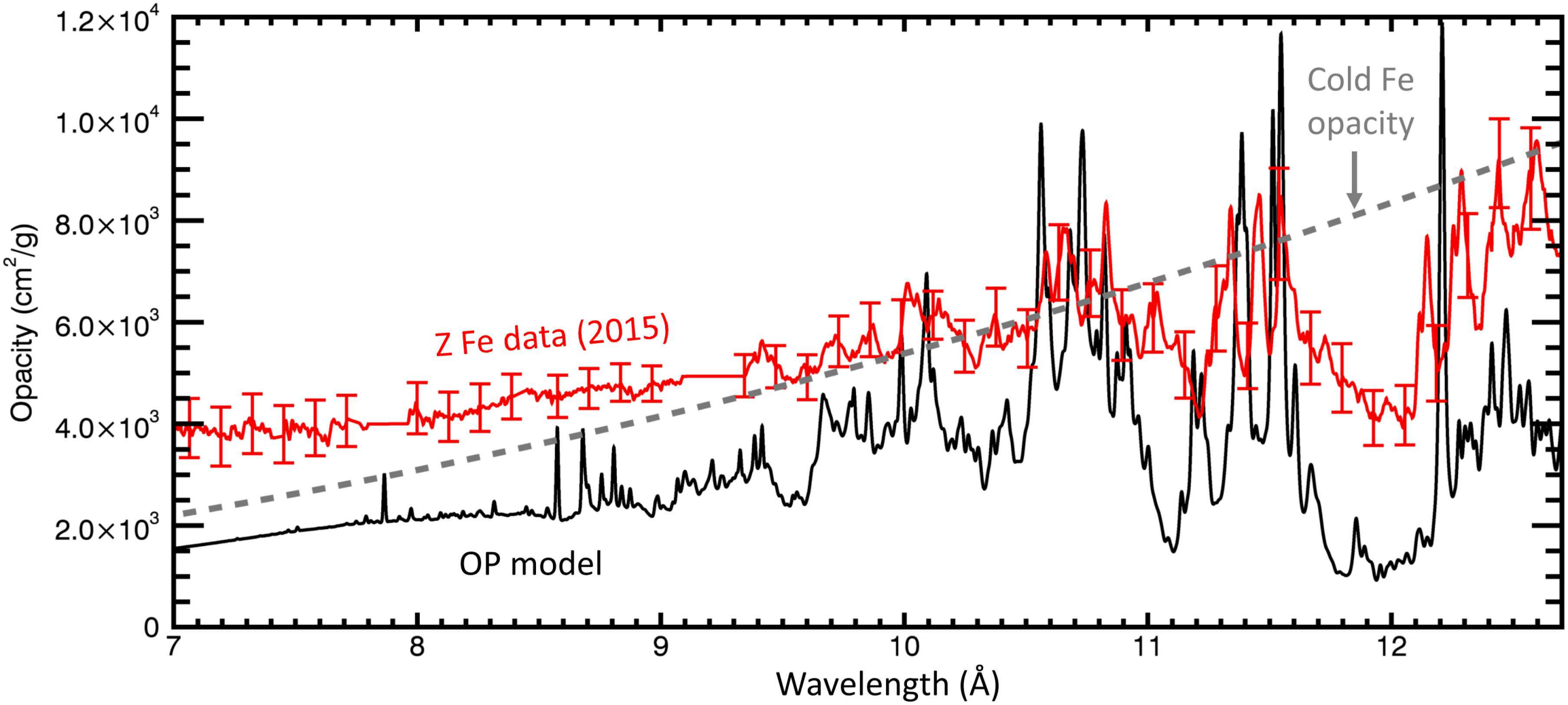
- Transmission error
- Background subtraction error
- Areal density error

*PDF = Probability distribution function

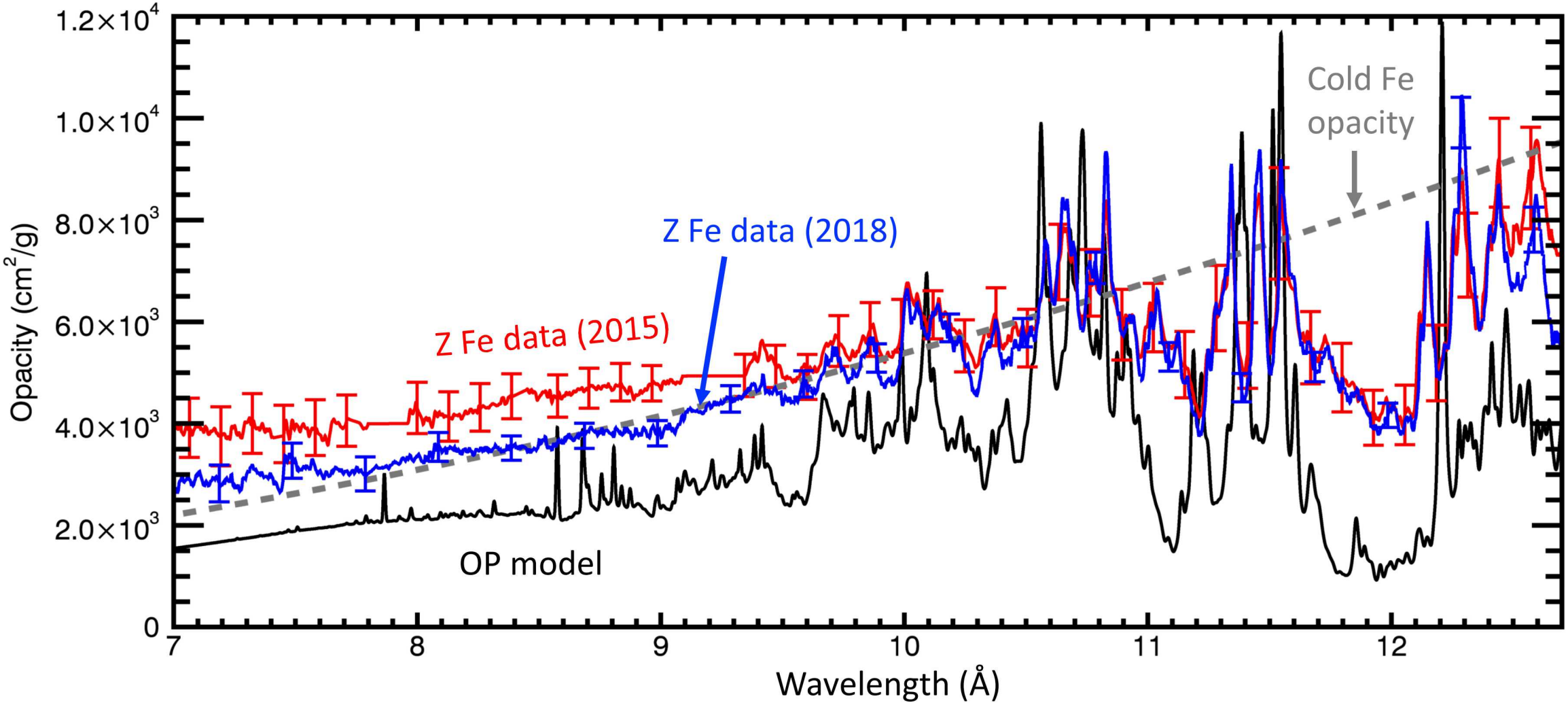
Both refined analysis and more experiments helped to improve shot-to-shot agreement on Anchor2 Fe



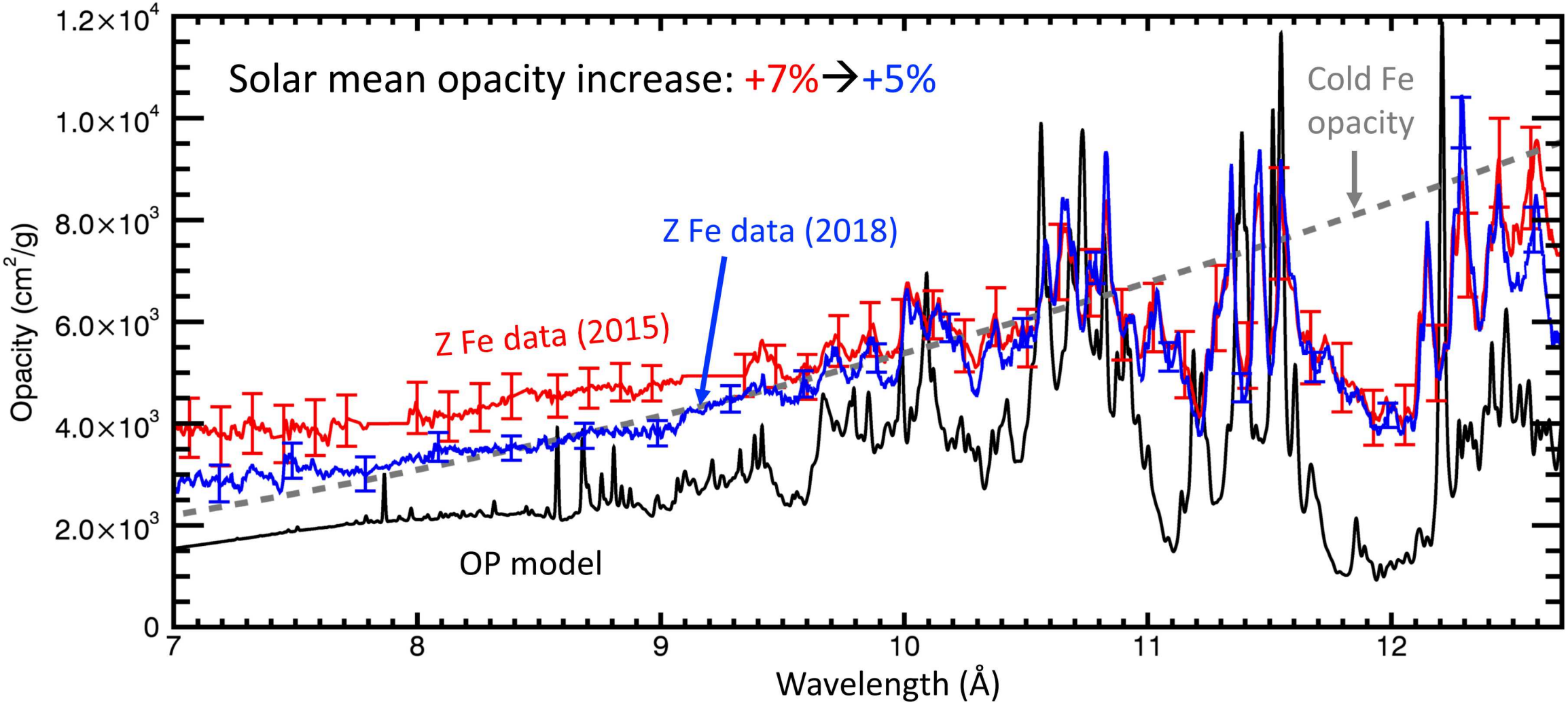
Analysis from 2015 showed 2x higher quasi-continuum opacity than astrophysical opacity-model prediction



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



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

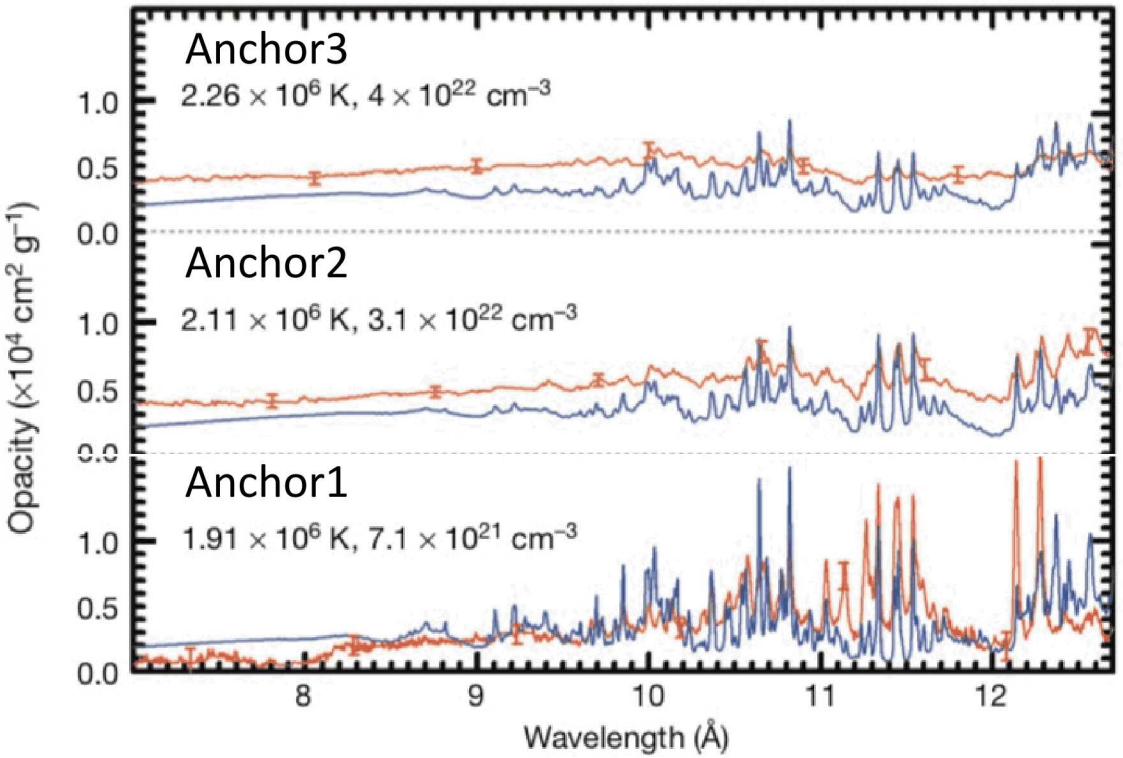


Revised Fe results still show statistically significant disagreement; More work needed to update Fe results

- Anchor2:
  - Mode-data disagreement is statistically significant

    $4\,\sigma \rightarrow 4\,\sigma$ (for OP*)
  - Very little change in BB and Windows
  - Impact on solar mean is still important
  - More data to be included
- Anchor3:
  - Biggest model-data discrepancy

    → Need to be reanalyzed.
  - We acquire more data
- Anchor1:
  - It helps to rule out various hypothesis for experiment flaws (e.g., LTE, temporal gradient, areal density errors, etc)



Bailey, Nagayama, et al, Nature (2015)

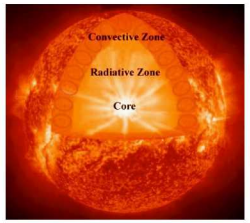
The systematic study of Cr, Fe, and Ni provides a holistic view on the complicated model-data discrepancy

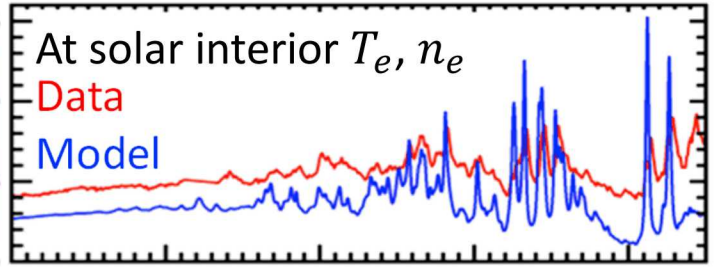
* OP: Astrophysics opacity code by Seaton et al., *MNRAS* (1994)

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

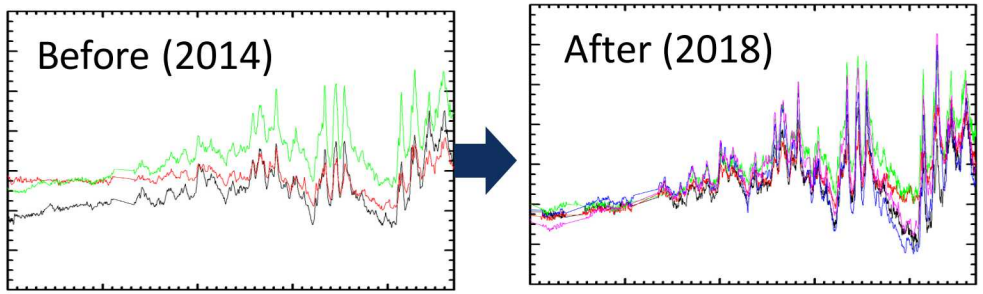
Sandia National Laboratories

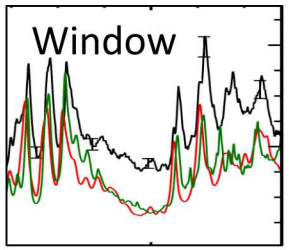
- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**
  - → Is opacity theory wrong? Is experiment flawed?

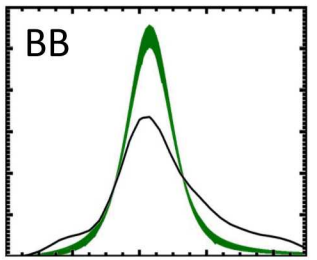


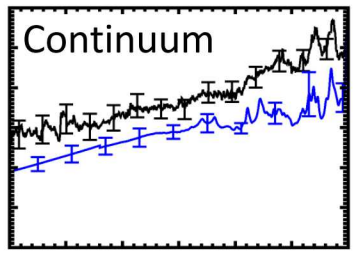


- **Refined analysis improved shot-to-shot reproducibility, demonstrating opacity experiment reliability**
- **Systematic measurement of Cr, Fe, and Ni opacities suggests model refinements in three areas**
  - Window: Challenge associated with open L-shell config.
  - BB: Inaccurate treatment of density effects
  - Continuum: Peculiar dependence on atomic number







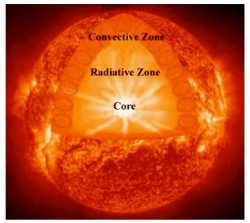


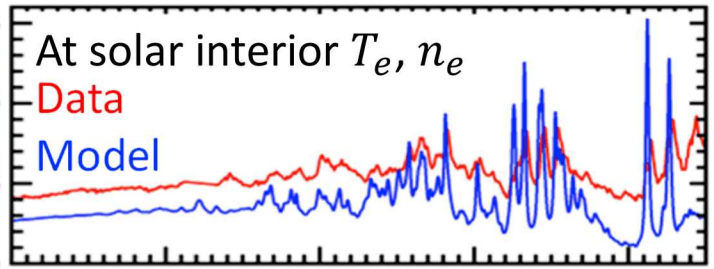
High reproducibility demonstrates unprecedented benchmark capability of SNL opacity platform

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

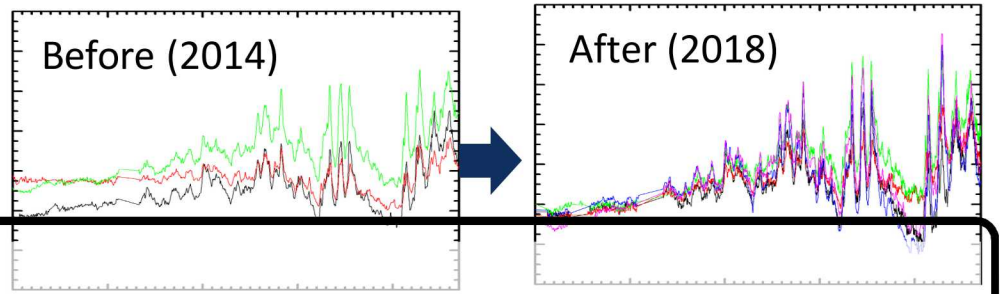
Sandia National Laboratories

- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**
  - → Is opacity theory wrong? Is experiment flawed?

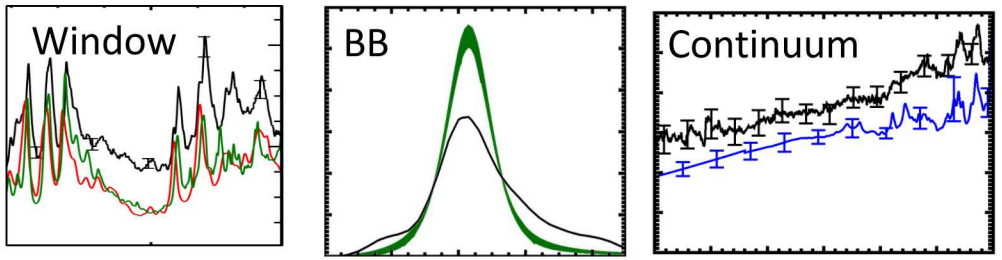




- **Refined analysis improved shot-to-shot reproducibility, demonstrating opacity experiment reliability**



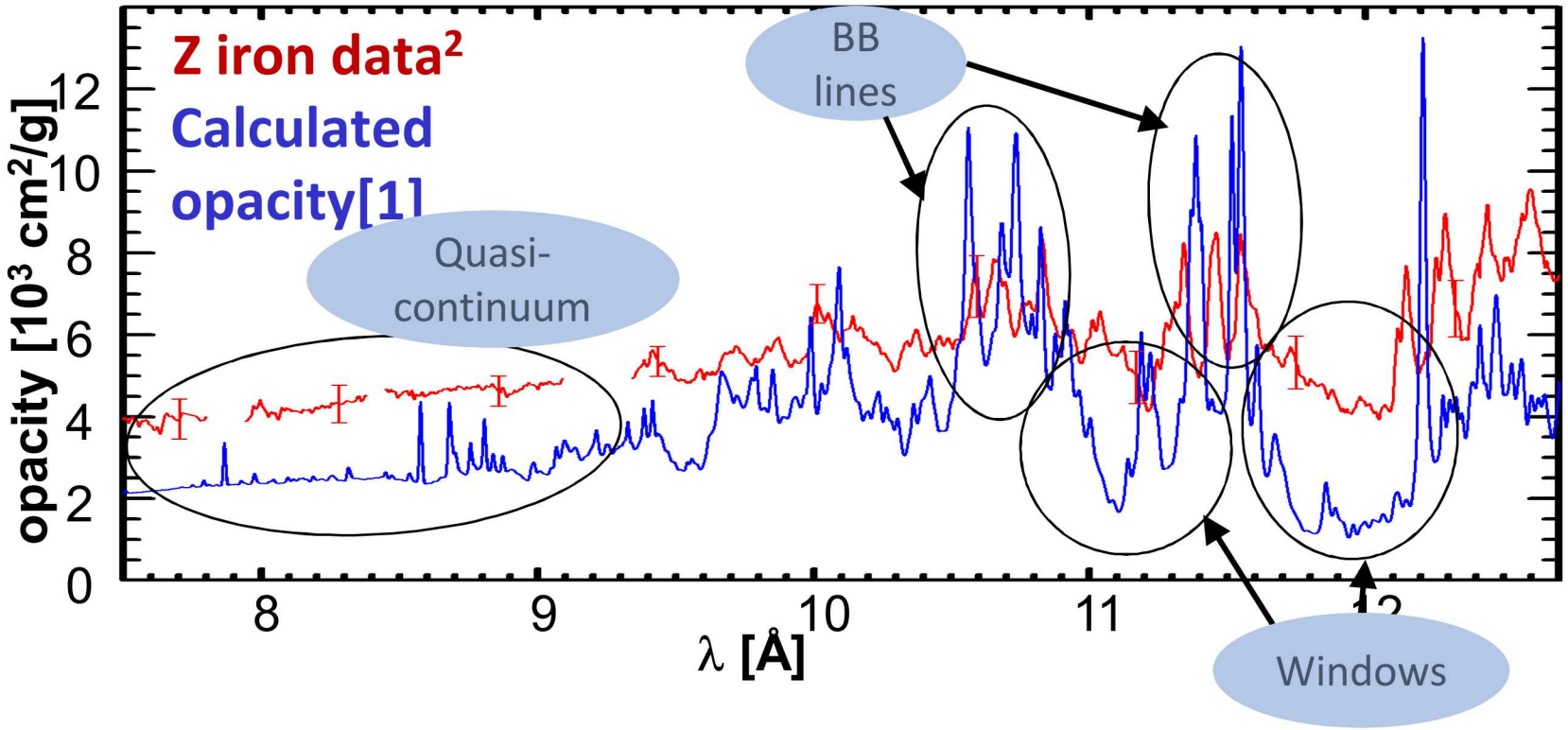
- **Systematic measurement of Cr, Fe, and Ni opacities suggests model refinements in three areas**
  - Window: Challenge associated with open L-shell config.
  - BB: Inaccurate treatment of density effects
  - Continuum: Peculiar dependence on atomic number



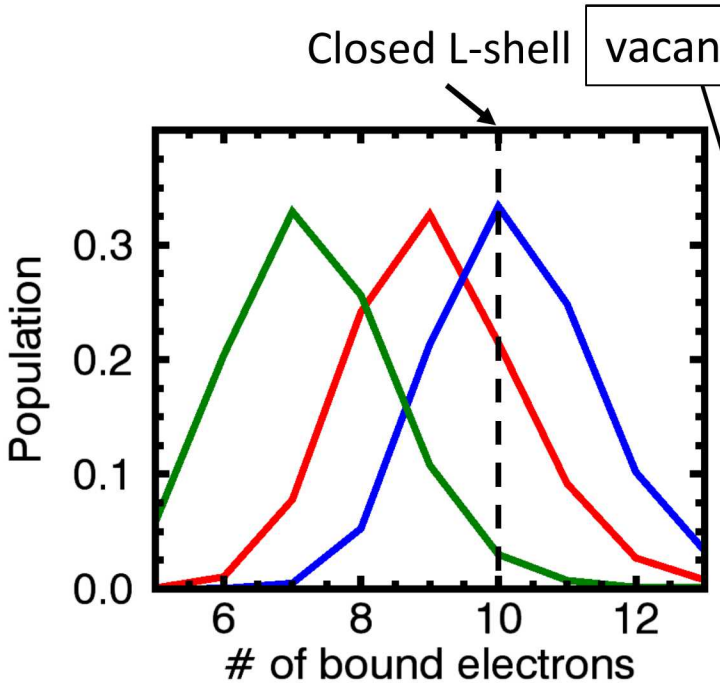
High reproducibility demonstrates unprecedented benchmark capability of SNL opacity platform

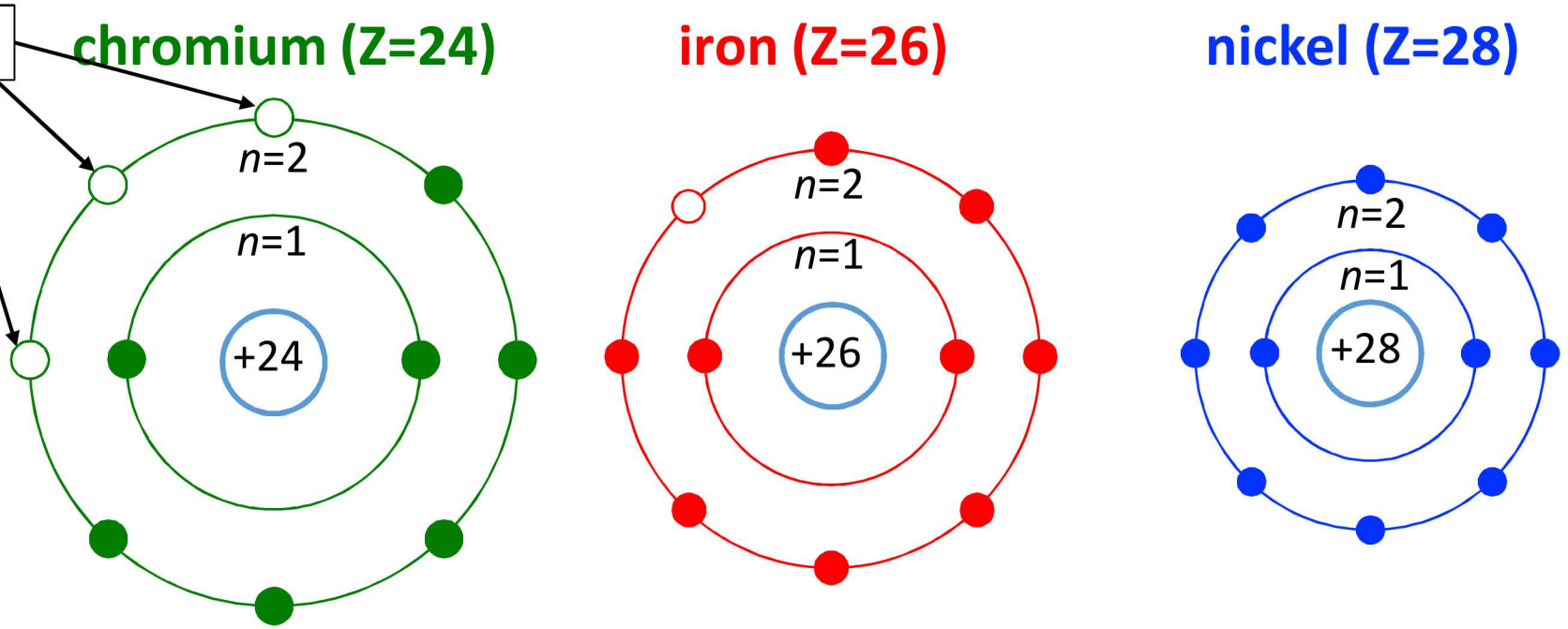
If opacity theory is wrong, which part of calculations is wrong?

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



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





Questioning Theory:

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

More

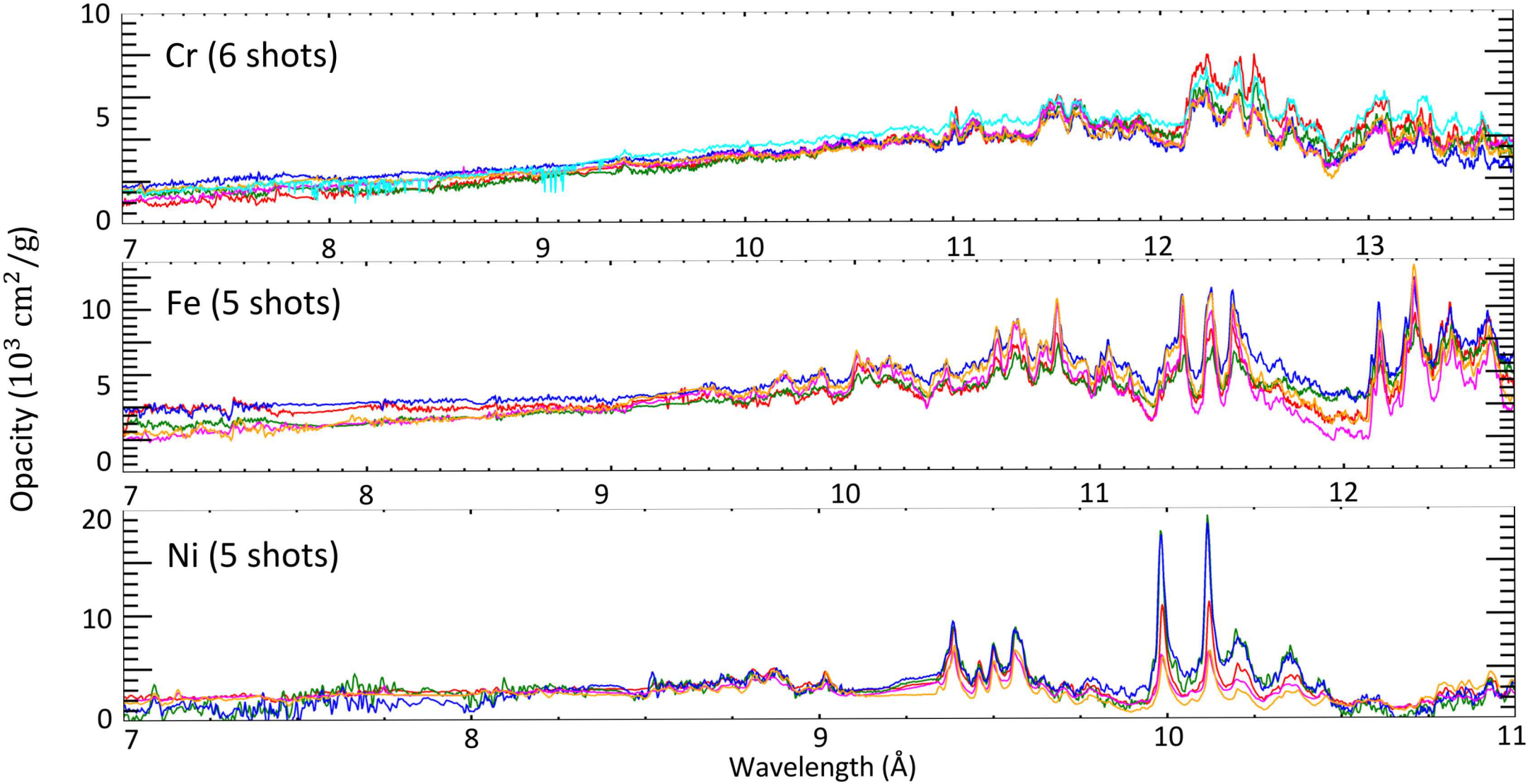
L-shell vacancies

# of excited states

Density effects

Less

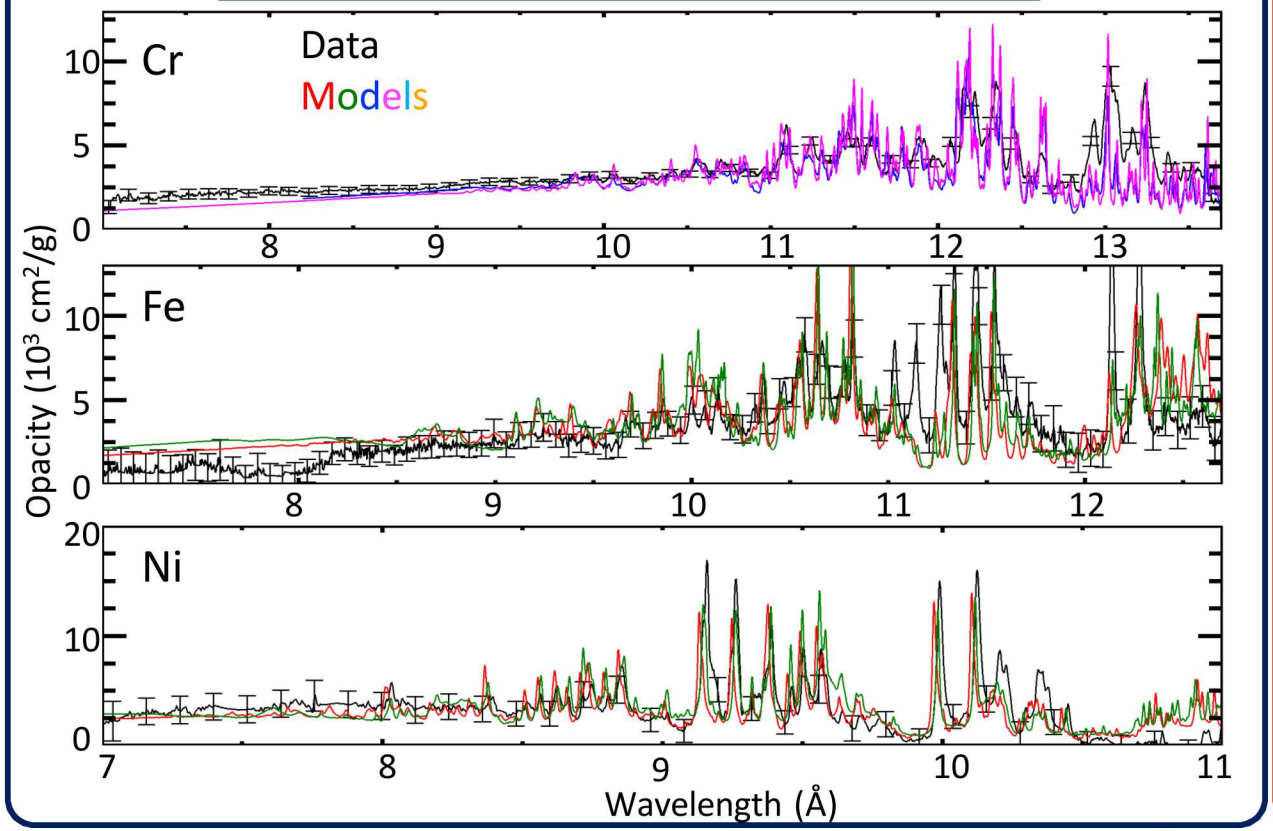
Excellent reproducibility is confirmed from all three elements, demonstrating experiment/analysis reliability



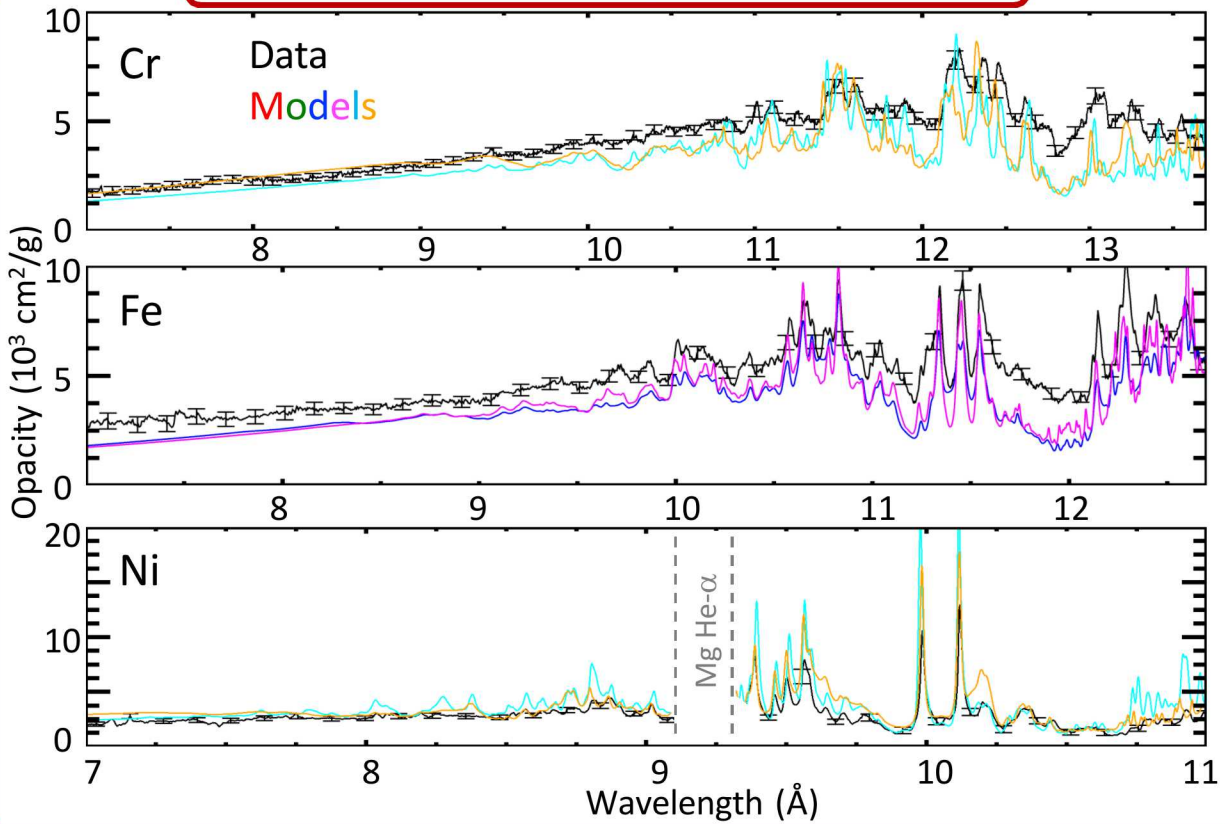
First systematic study of high-temperature L-shell opacities were performed for Cr, Fe, and Ni at two conditions

Sandia National Laboratories

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}



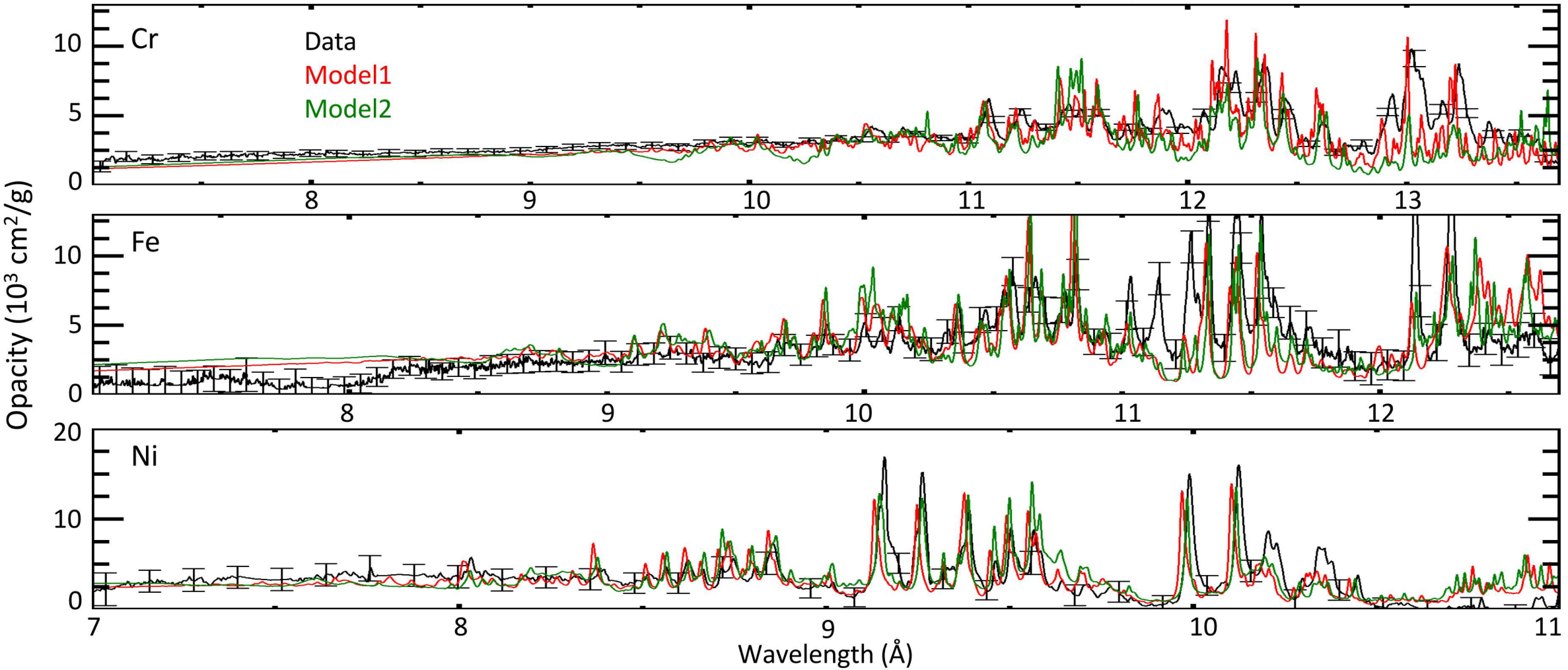
- **Opacities are measured at $T_e > 150$ eV**
- **T_e and n_e are diagnosed independently**
- **Reproducibility is confirmed**

Systematically performed for Cr, Fe, Ni at two conditions

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

Sandia National Laboratories

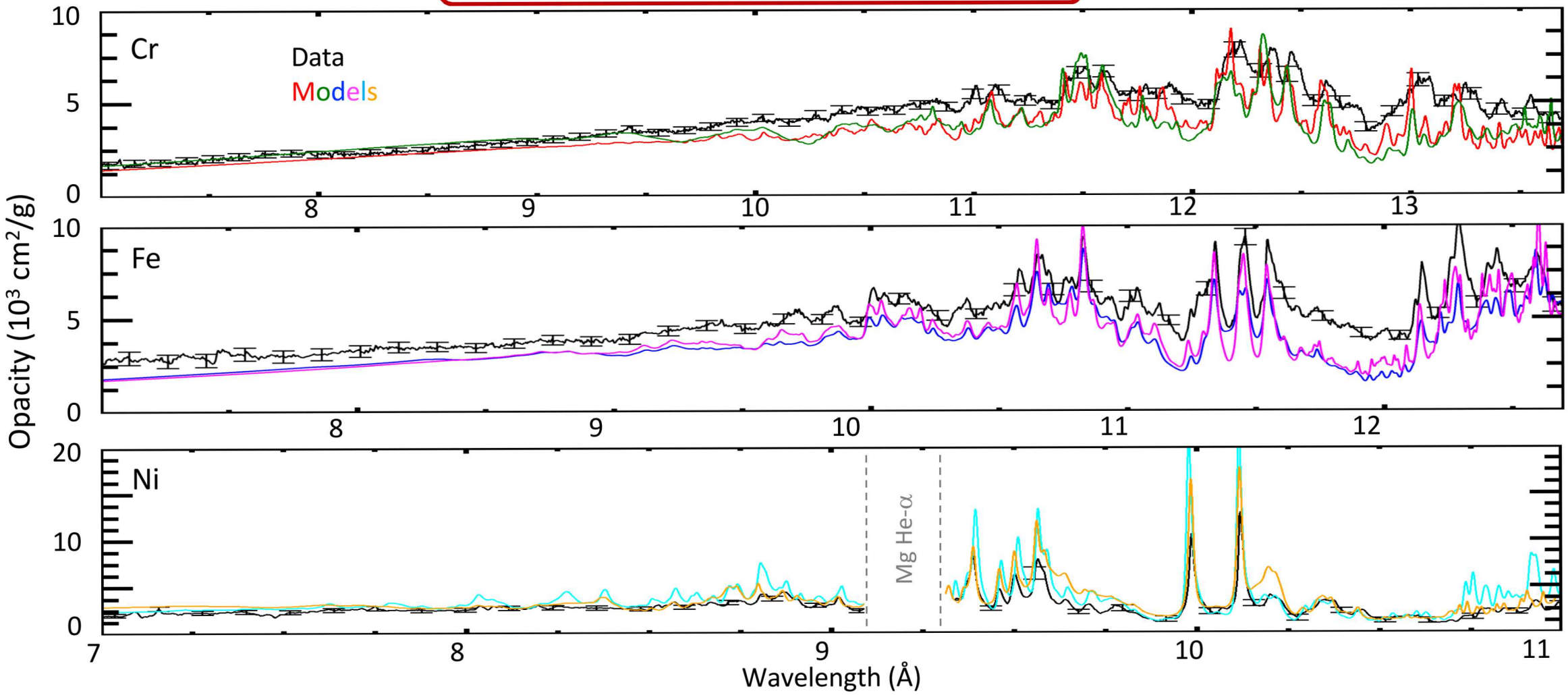
$T_e \sim 165$ eV, $n_e \sim 7 \times 10^{21}$ cm^{-3}



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

Sandia National Laboratories

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

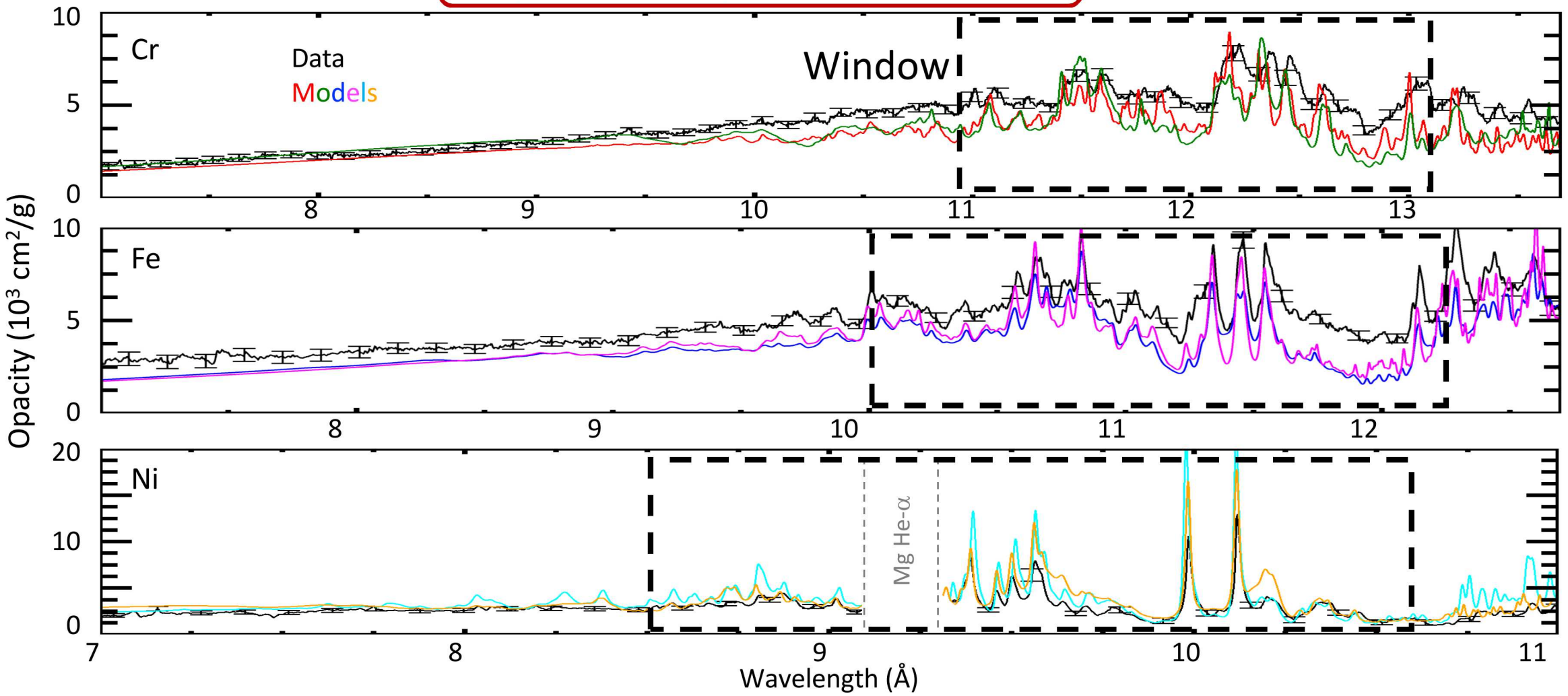


MODELS: ATOMIC, NOMAD, OPAS, SCO-RCG, SCRAM, TOPAZ

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

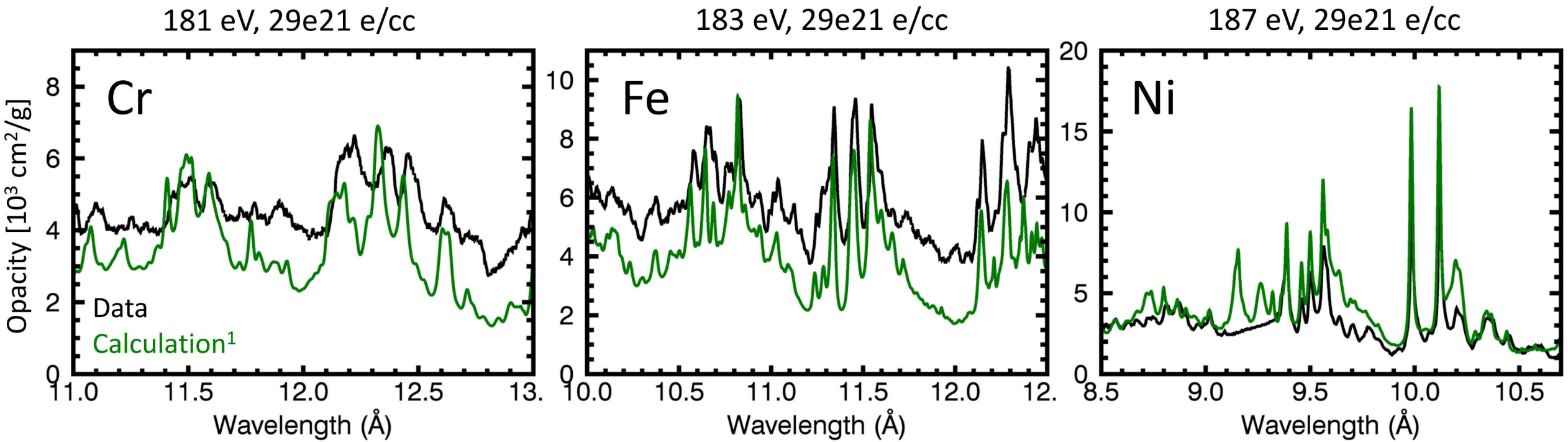
Sandia National Laboratories

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



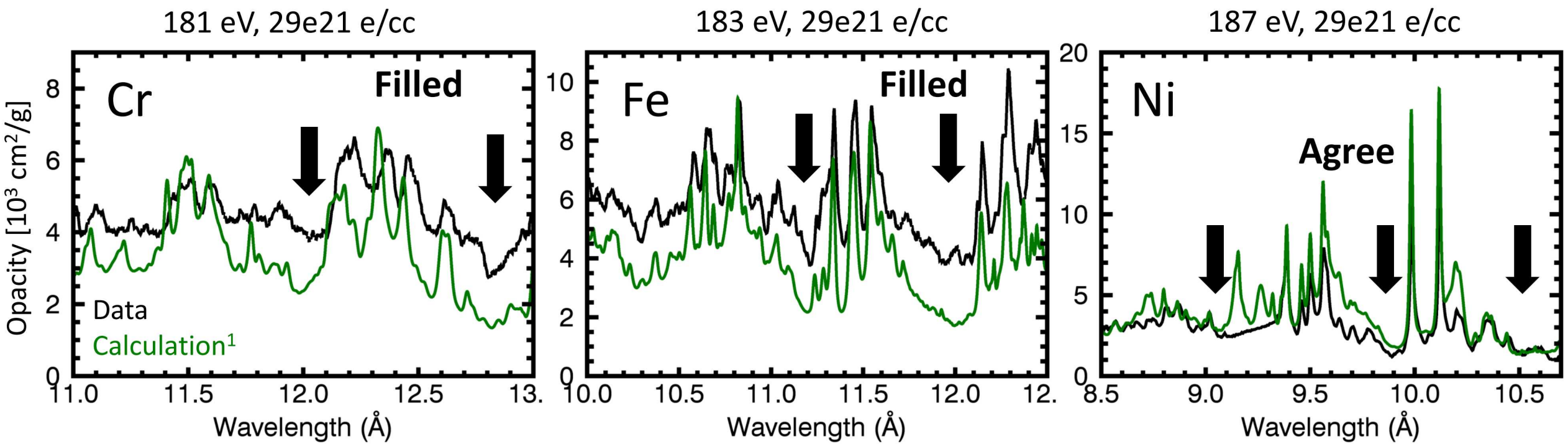
MODELS: ATOMIC, NOMAD, OPAS, SCO-RCG, SCRAM, TOPAZ

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



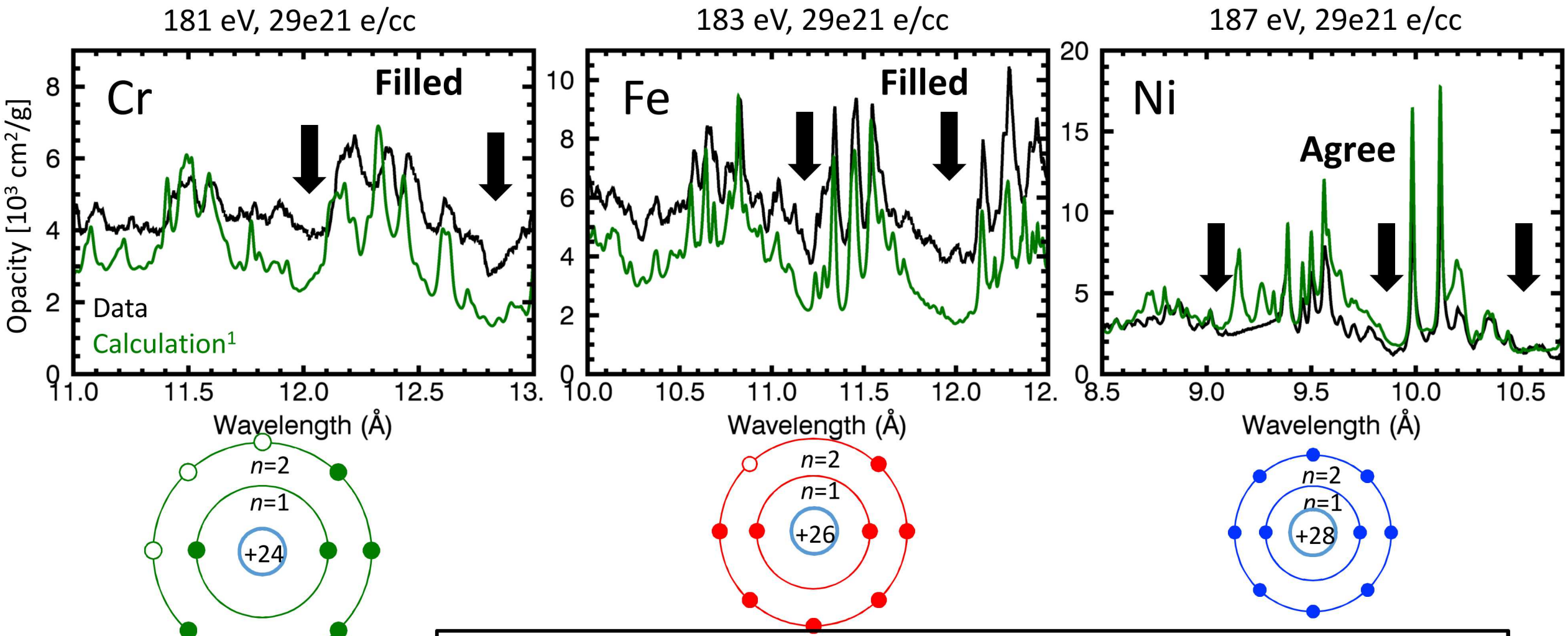
[1] SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

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



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

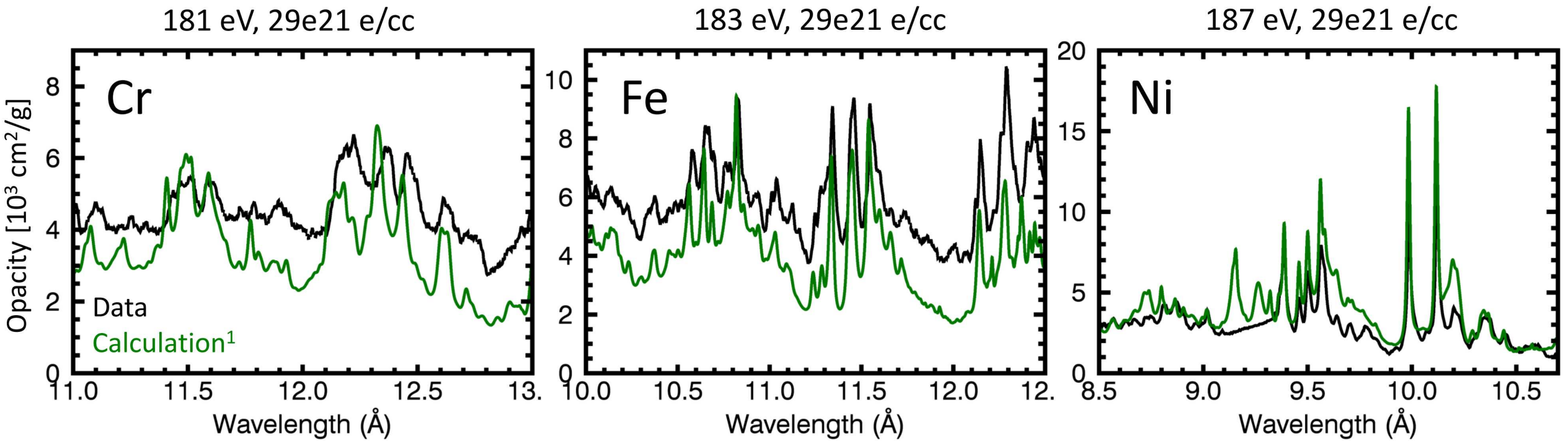
Window: Filled window observed from Cr and Fe, but not Ni



Hypothesis: Challenge associated with open L-shell configuration

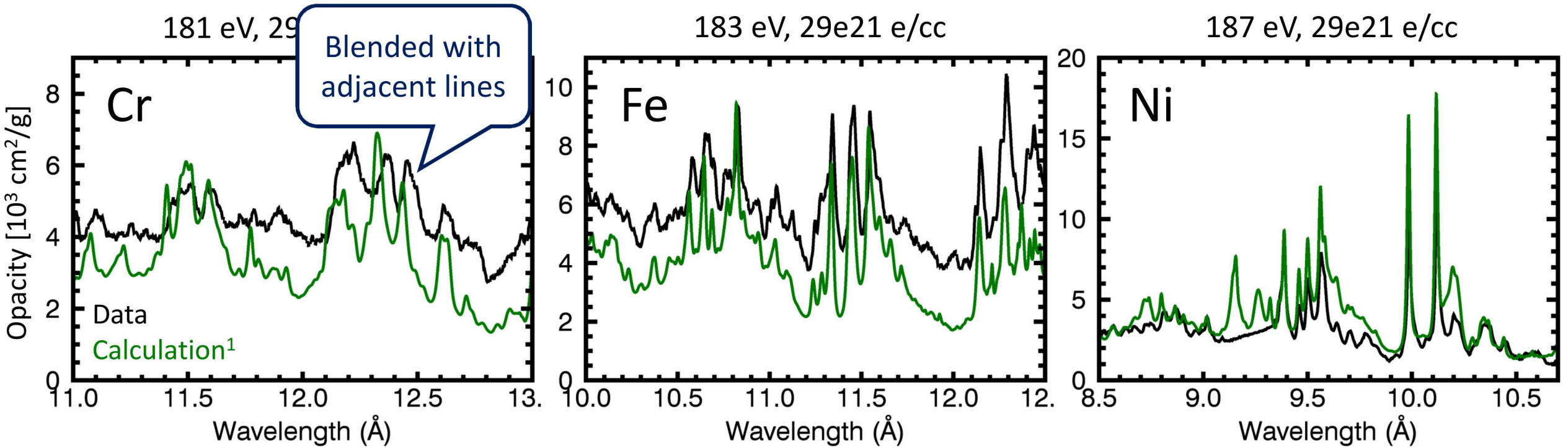
[1] SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

Can we check accuracy of modeled line shapes?



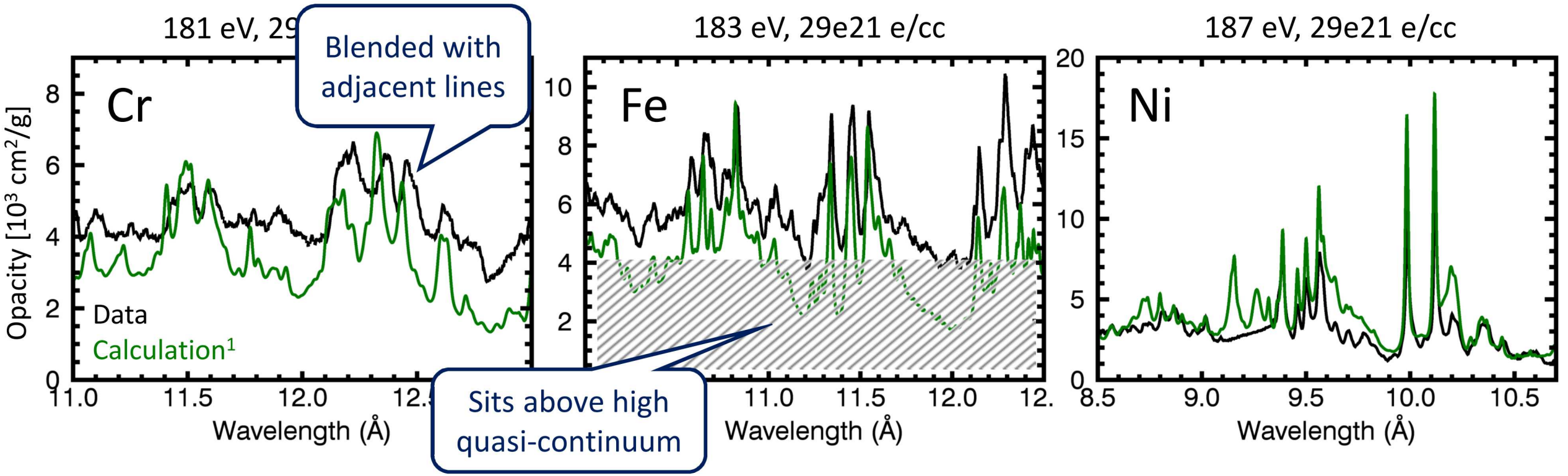
[1] SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

Can we check accuracy of modeled line shapes?



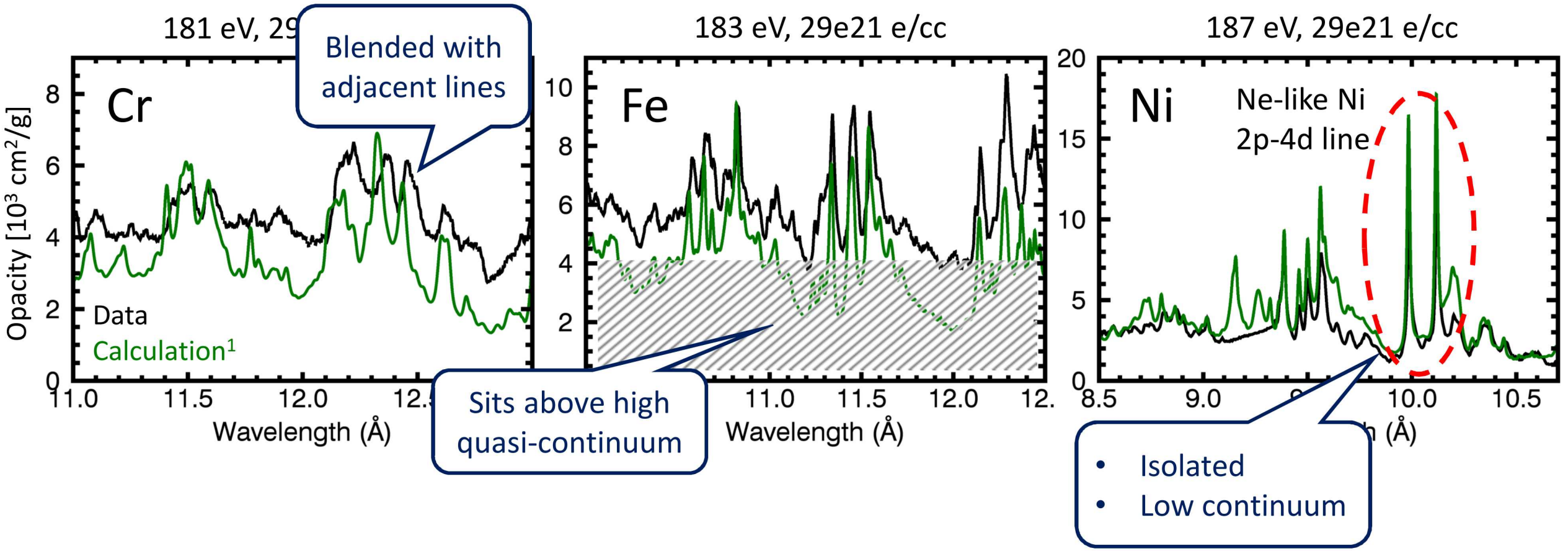
[1] SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

Can we check accuracy of modeled line shapes?



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

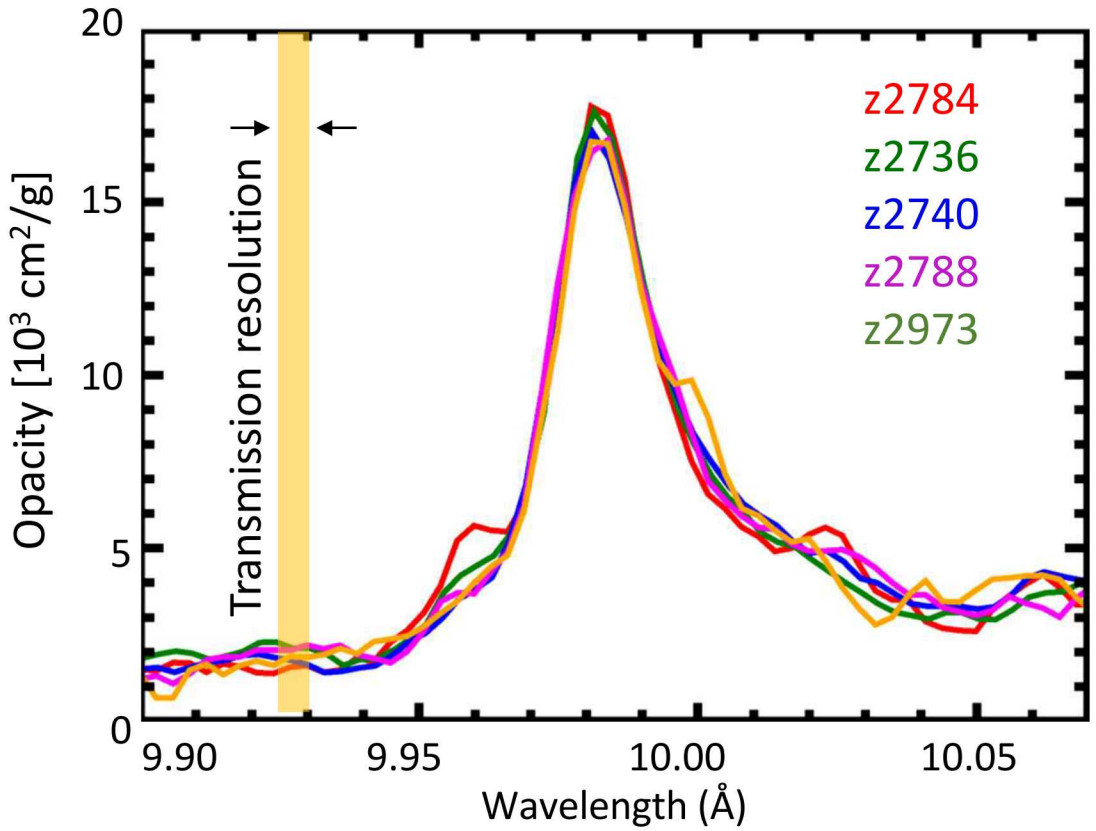
Can we check accuracy of modeled line shapes?



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

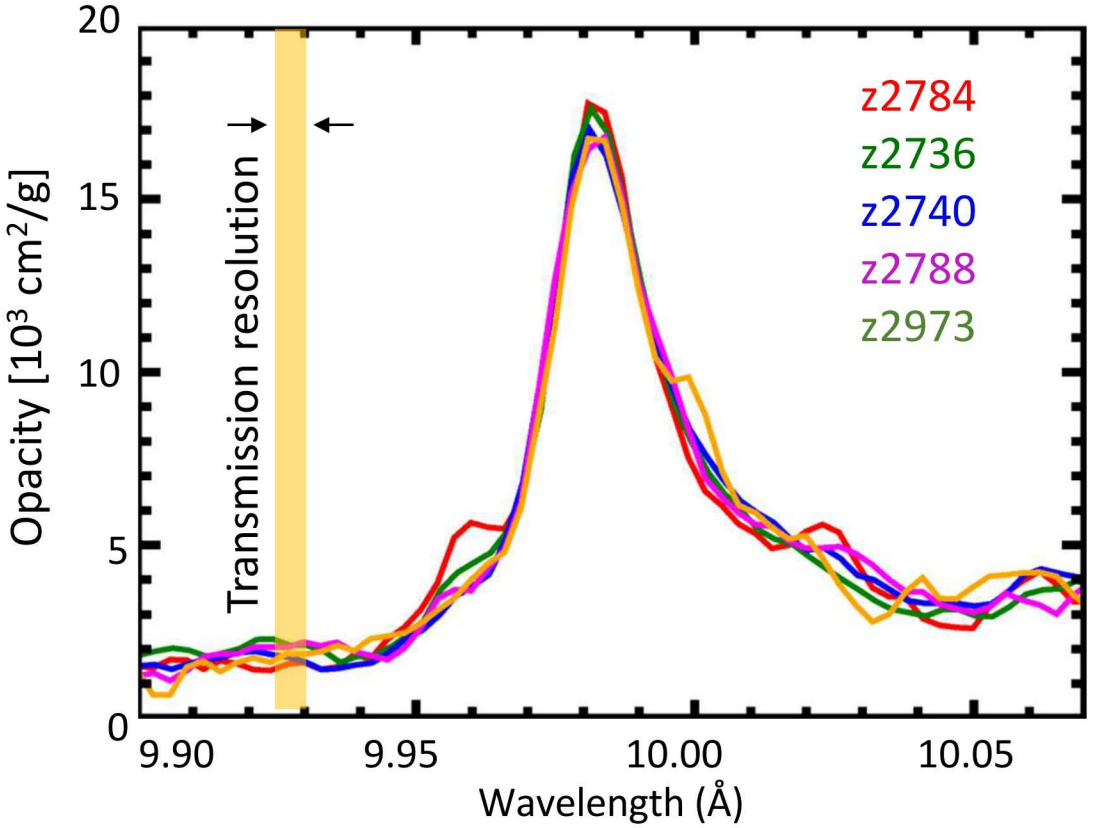
[1] SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

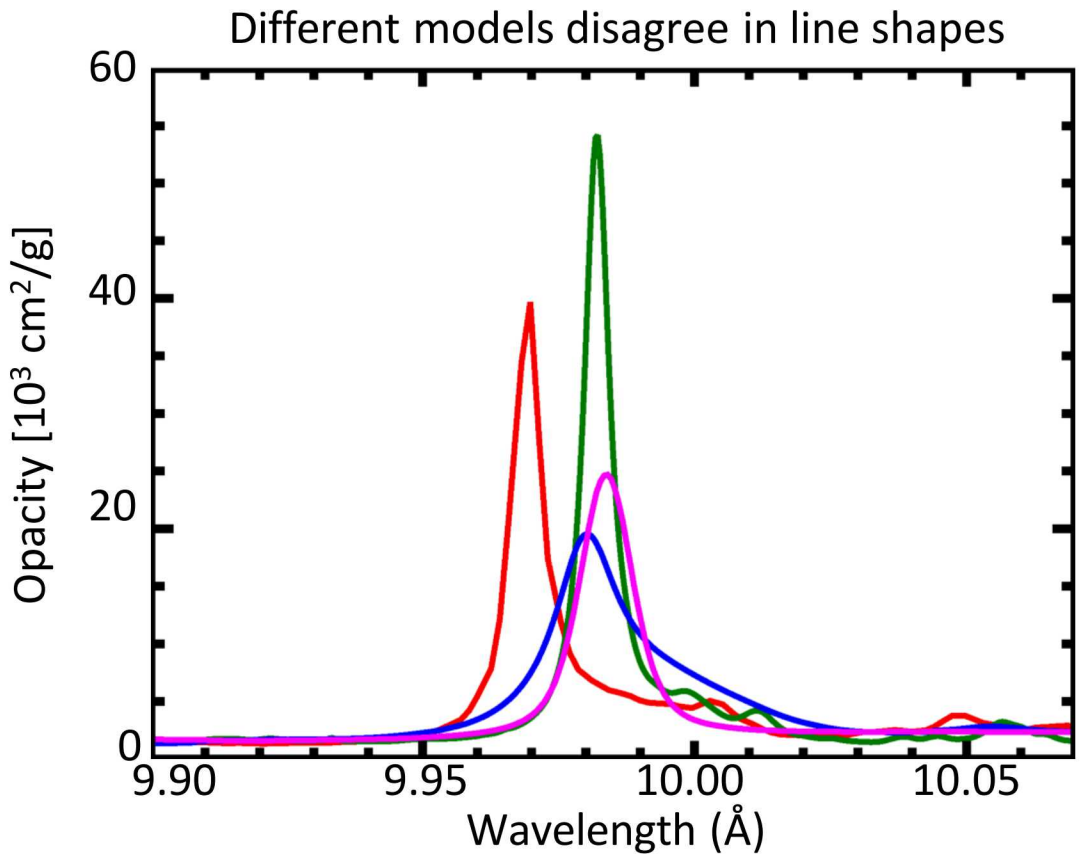
Line-shape of Ne-like Ni 2p-4d is accurately measured and appropriate to test approximations used in models



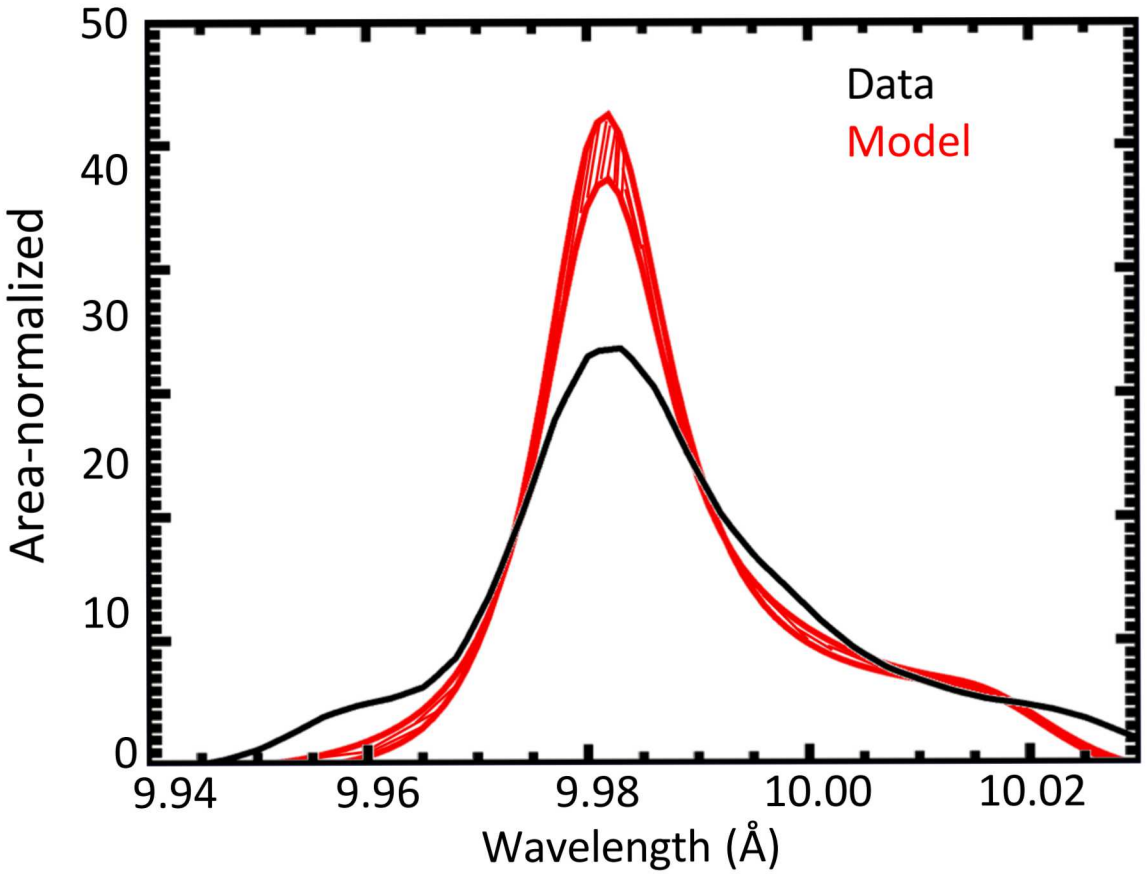
- This line-shape is reproduced by five experiments
- Models employ simple approximations for L-shell line shapes, which are not tested.
  - Electron broadening
  - Static ion broadening
  - Satellite contributions

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



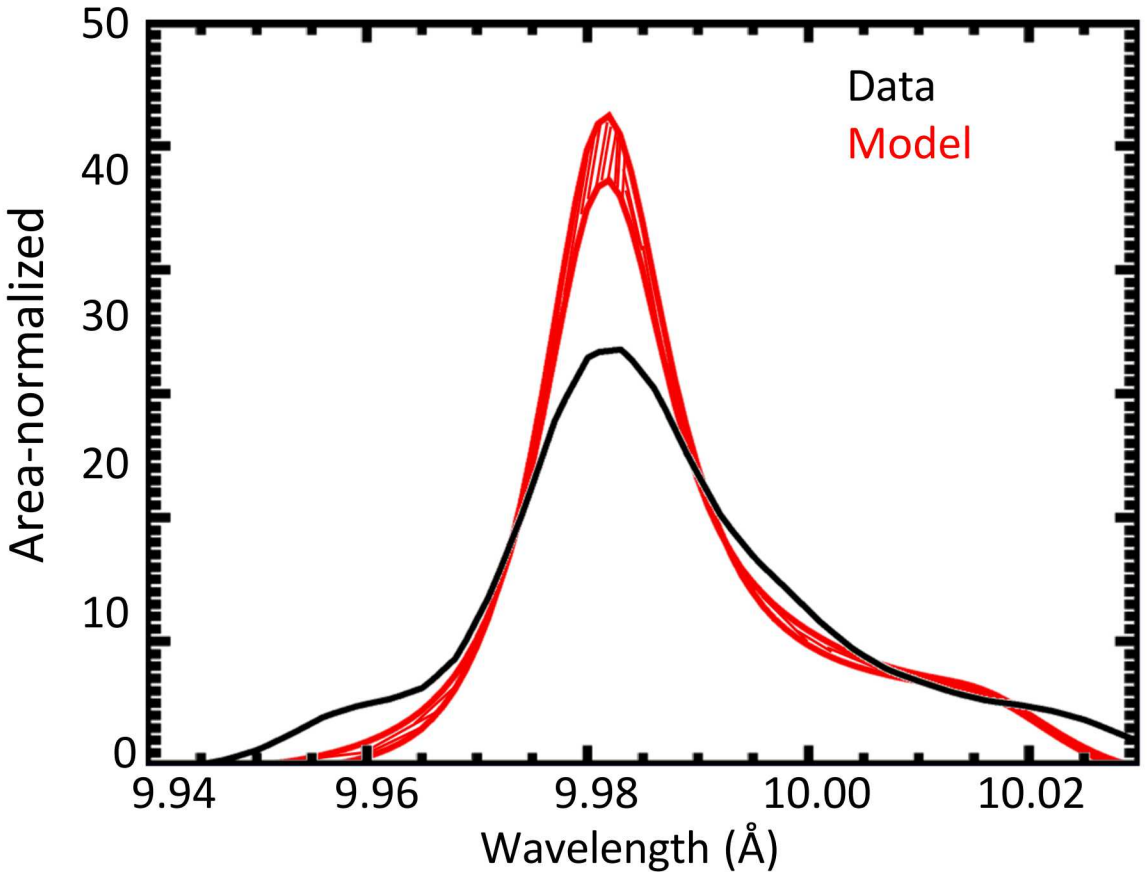


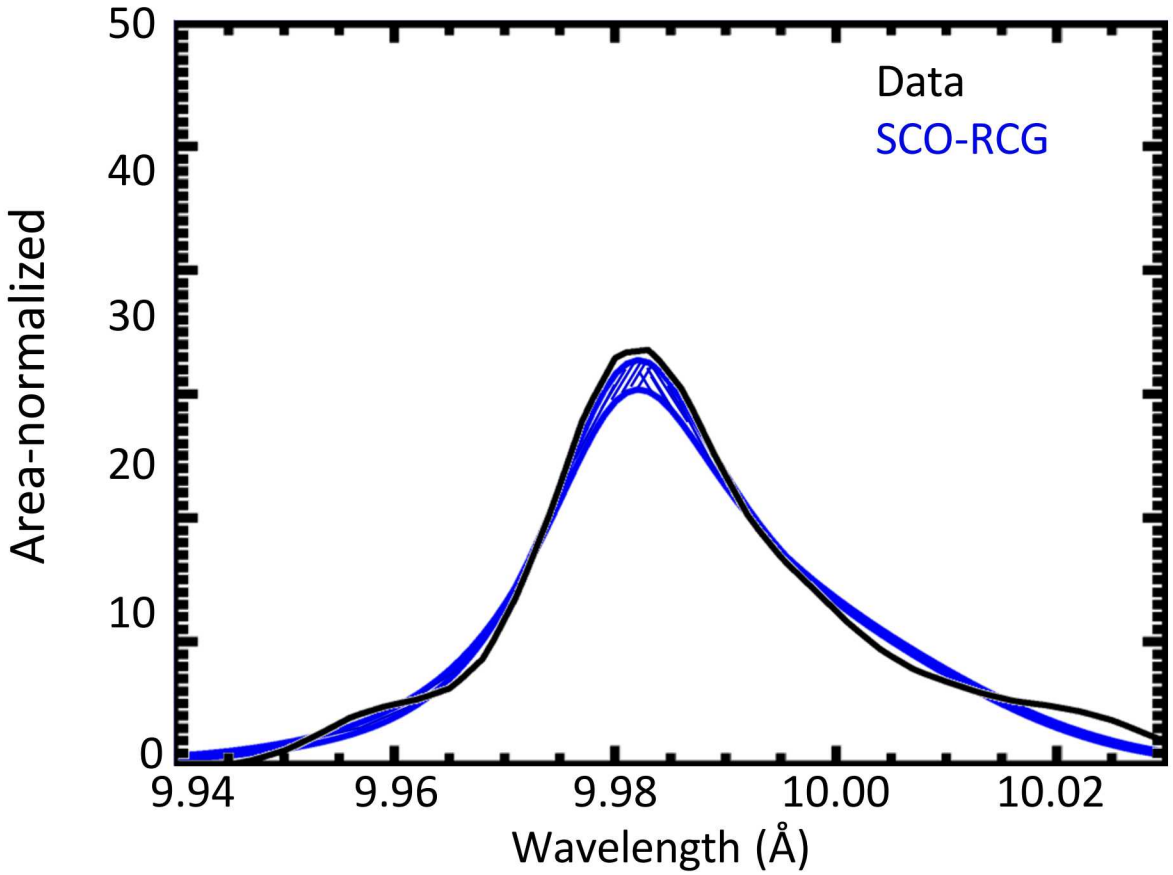
Most models underestimate the L-shell line widths



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

SCO-RCG model predicted the measured L-shell line width reasonably well



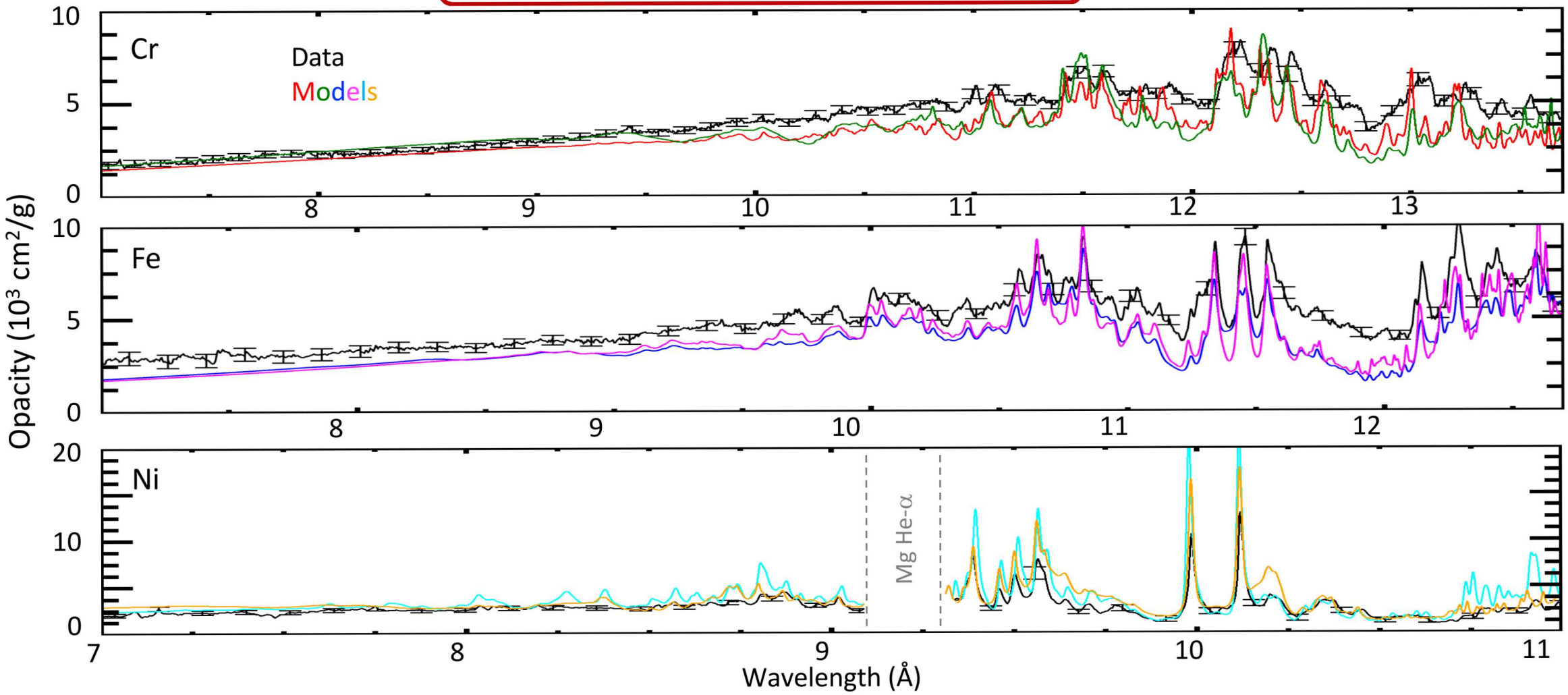


Models need to refine treatment of atomic interaction with plasma and excited states.

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

Sandia National Laboratories

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

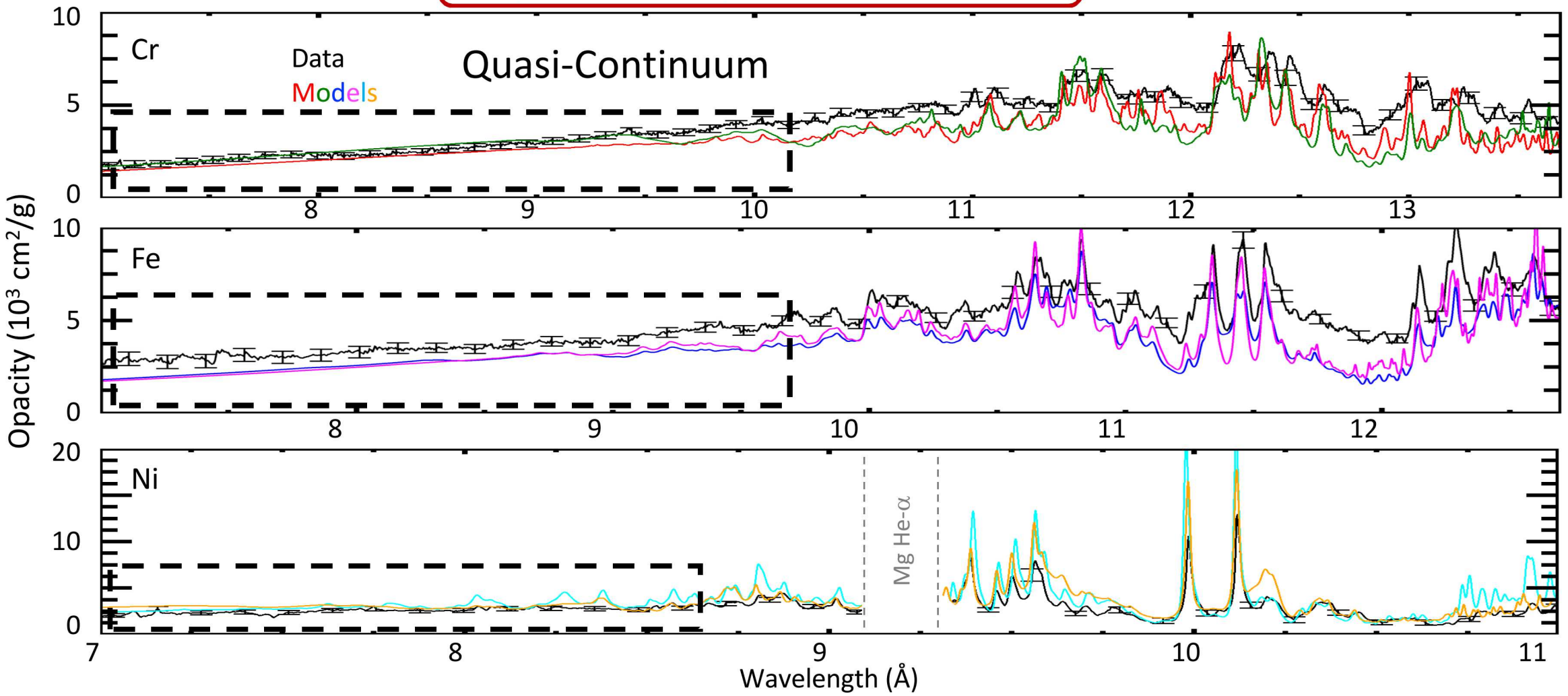


MODELS: ATOMIC, NOMAD, OPAS, SCO-RCG, SCRAM, TOPAZ

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

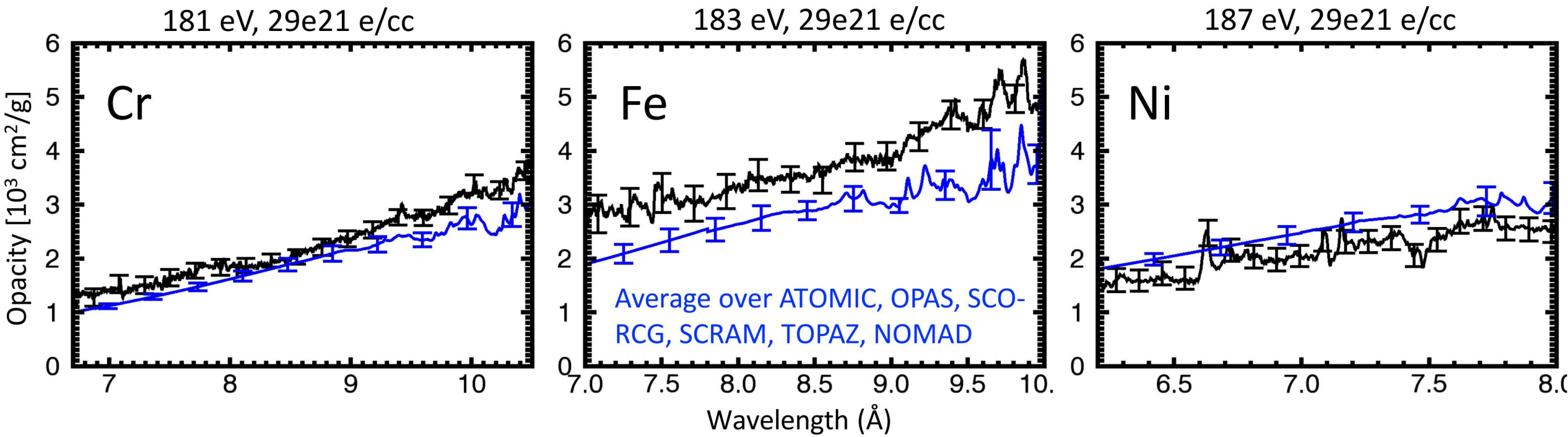
Sandia National Laboratories

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



MODELS: ATOMIC, NOMAD, OPAS, SCO-RCG, SCRAM, TOPAZ

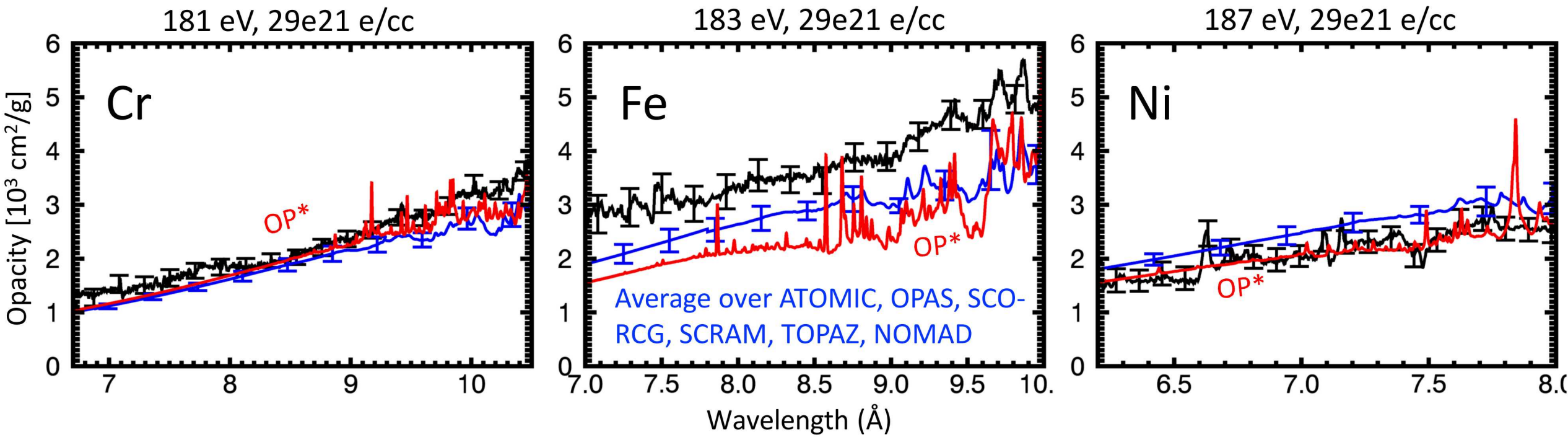
Refined analysis on Fe does not fully remove the reported quasi-continuum disagreement



- Reanalysis on Fe reduced data/<model> from +60% to +30%, still statistically significant
- Excellent reproducibility in all three elements suggests the Fe discrepancy is real

Any hypothesis has to explain not only Fe discrepancy but also better agreement in Cr and Ni

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



- Reanalysis on Fe reduced data/<model> from +60% to +30%, still statistically significant
- Excellent reproducibility in all three elements suggests the Fe discrepancy is real

Any hypothesis has to explain not only Fe discrepancy but also better agreement in Cr and Ni

* OP: Astrophysics opacity code by Seaton et al., *MNRAS* (1994)

Future work: exciting new investigations and further scrutiny are on the horizon

Sandia National Laboratories

New investigations:

- Opacity at higher T_e and n_e:
  - Higher T_e:
    - Window disagreement
  - Higher n_e
    - Line-shape disagreement
    - Closer to solar CZB conditions
- O opacity for solar problem
- Time-resolved measurement (UXI*)
  - Comparable S/N to x-ray film
  - Potentially, T_e and n_e points from single experiment

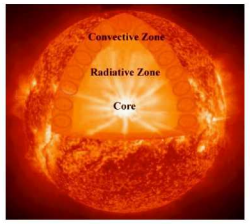
Further scrutiny:

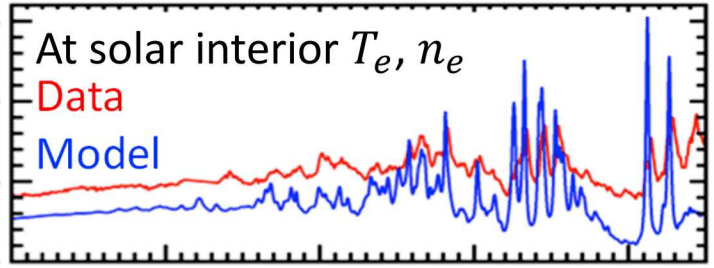
- Fe quasi-continuum puzzle
  - Anchor2
  - Anchor3
- Revisiting errors
  - Areal density
  - Background

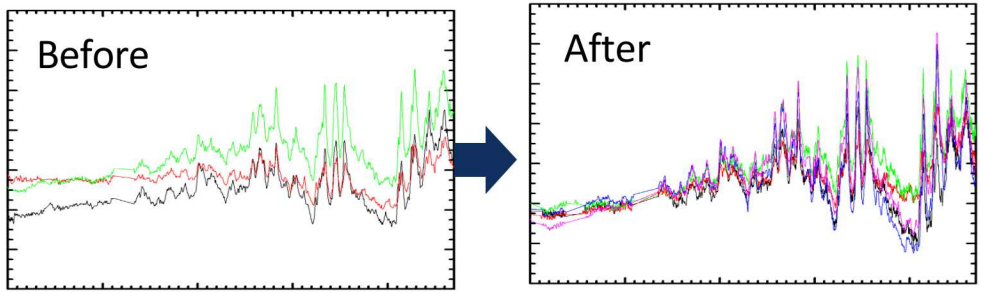
*UXI = Ultra-fast X-ray Imager

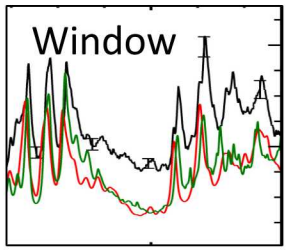
Systematic study of L-shell opacities with refined analysis validates experiment reliability and suggest necessary model refinements

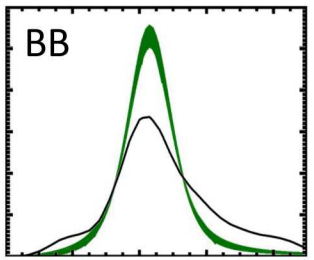
- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**
  - → Is opacity theory wrong? Is experiment flawed?
- **Refined analysis improved shot-to-shot reproducibility, demonstrating opacity experiment reliability**
- **Systematic measurement of Cr, 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

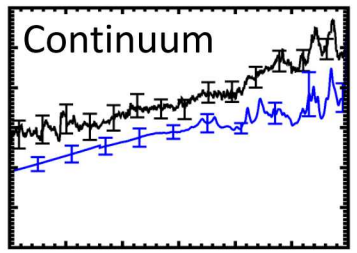






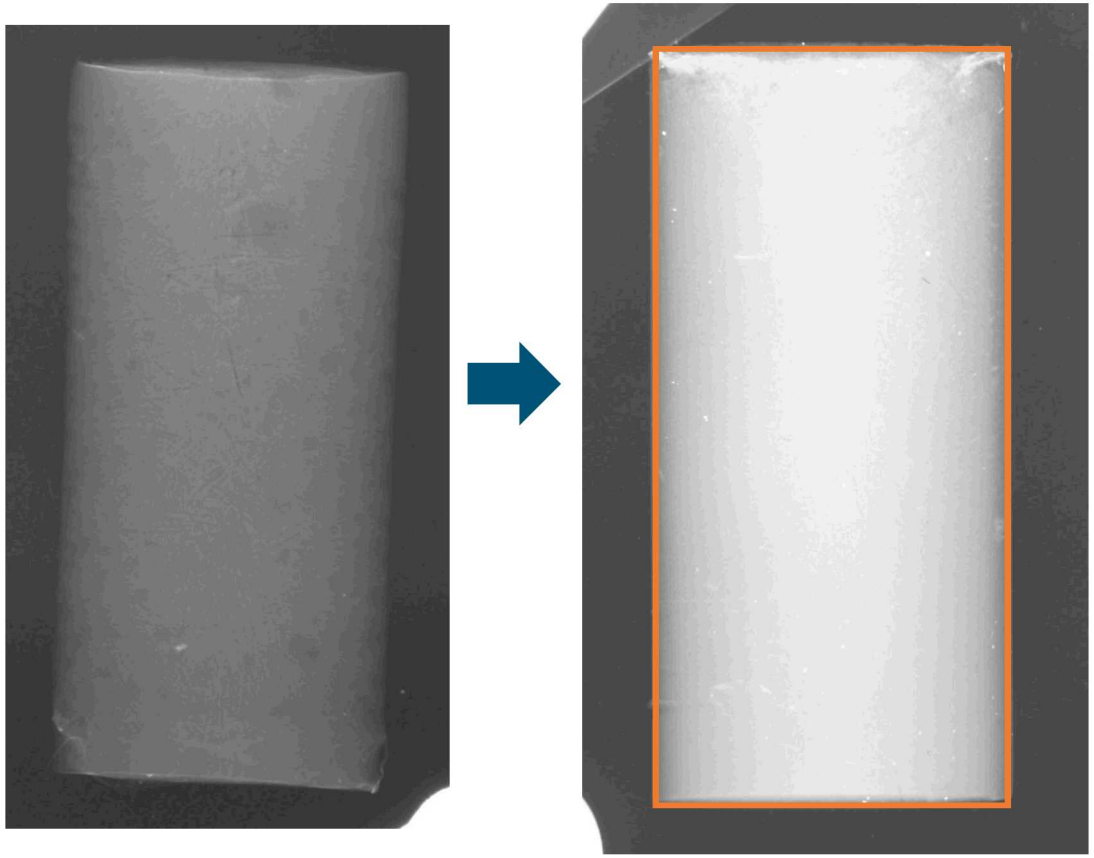




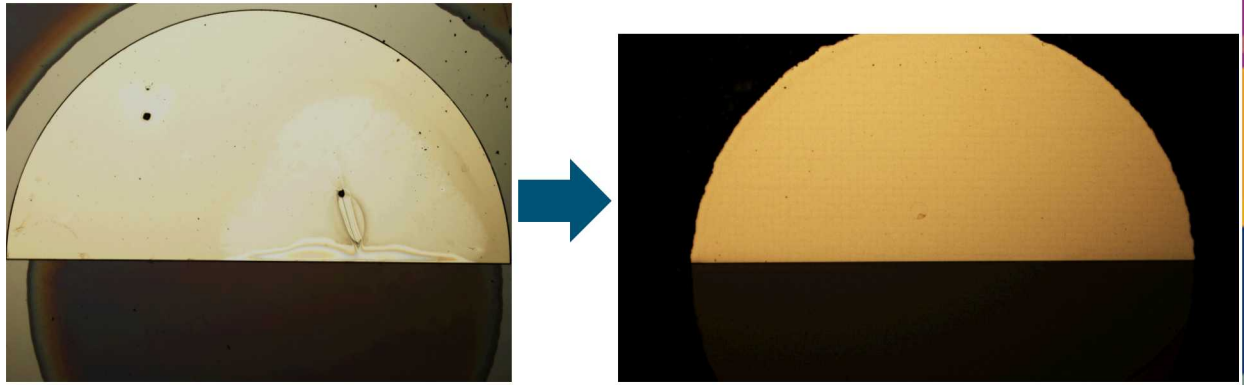


GA has developed and kept refining fabrication and metrology techniques to deliver us high-quality foam and opacity samples

CH foam

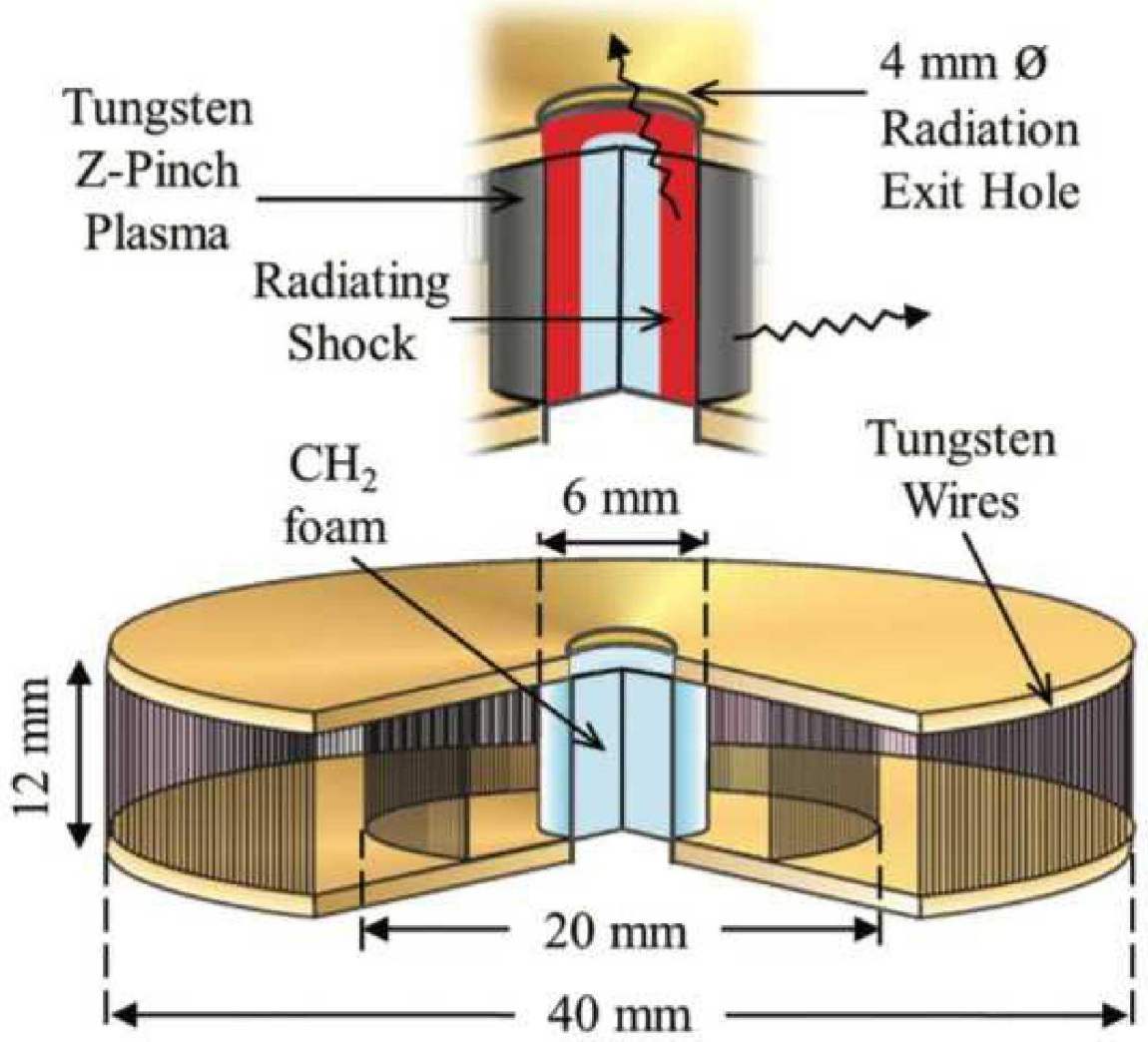


Opacity sample



The high-quality targets enabled us to perform high-quality HED opacity benchmark experiments

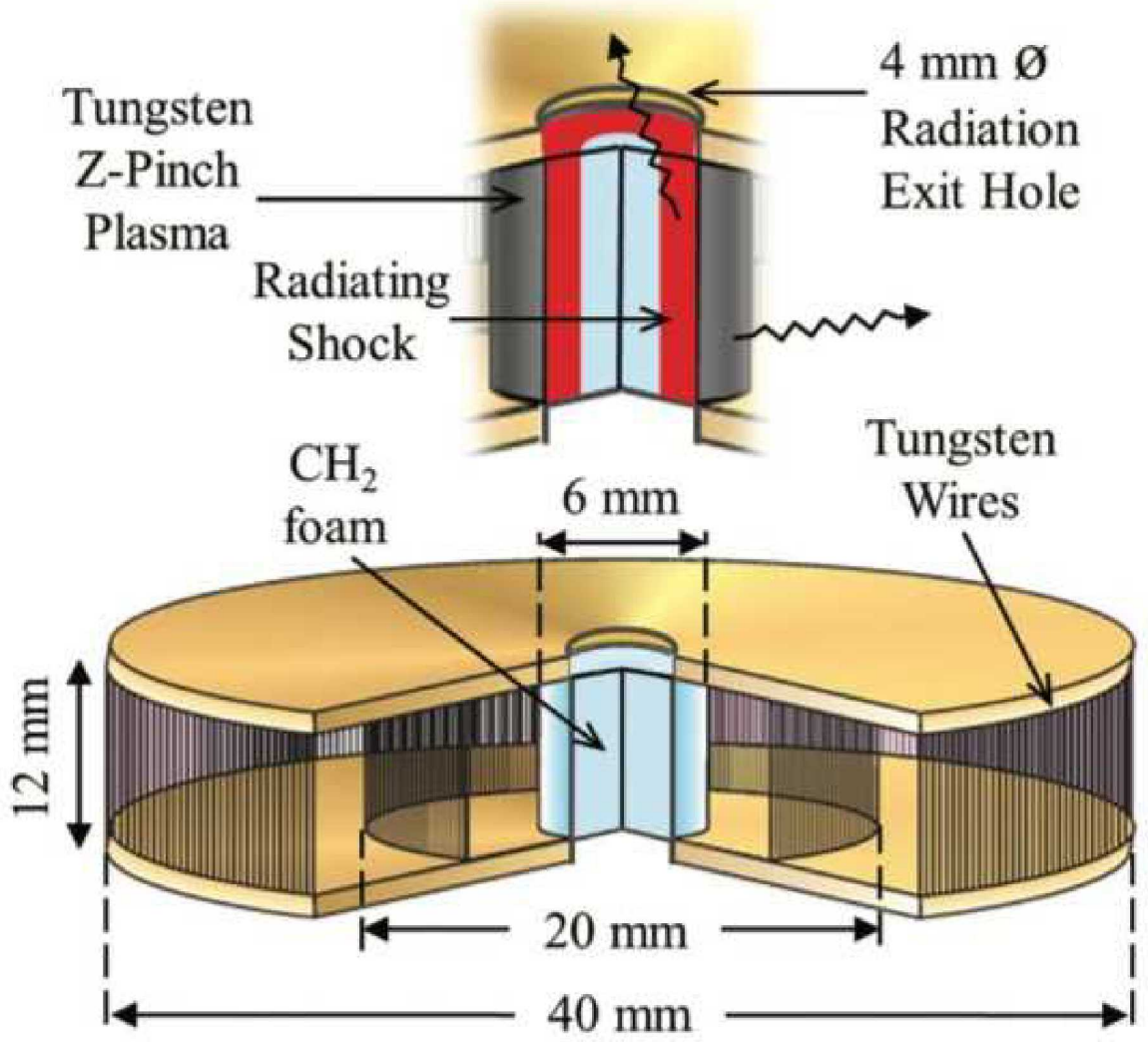
High quality CH foam is necessary for high radiation output and good reproducibility



- Z-pinch hohlraum radiation is produced by W wires imploding on to the CH foam and the generating radiative shock
- Criteria for CH foam
  - Density
  - Composition
  - Cosmetic defects/void/pore
  - Morphism

Schematic from G. A. Rochau et al, Phys. Plasmas **21**, 056308 (2014).

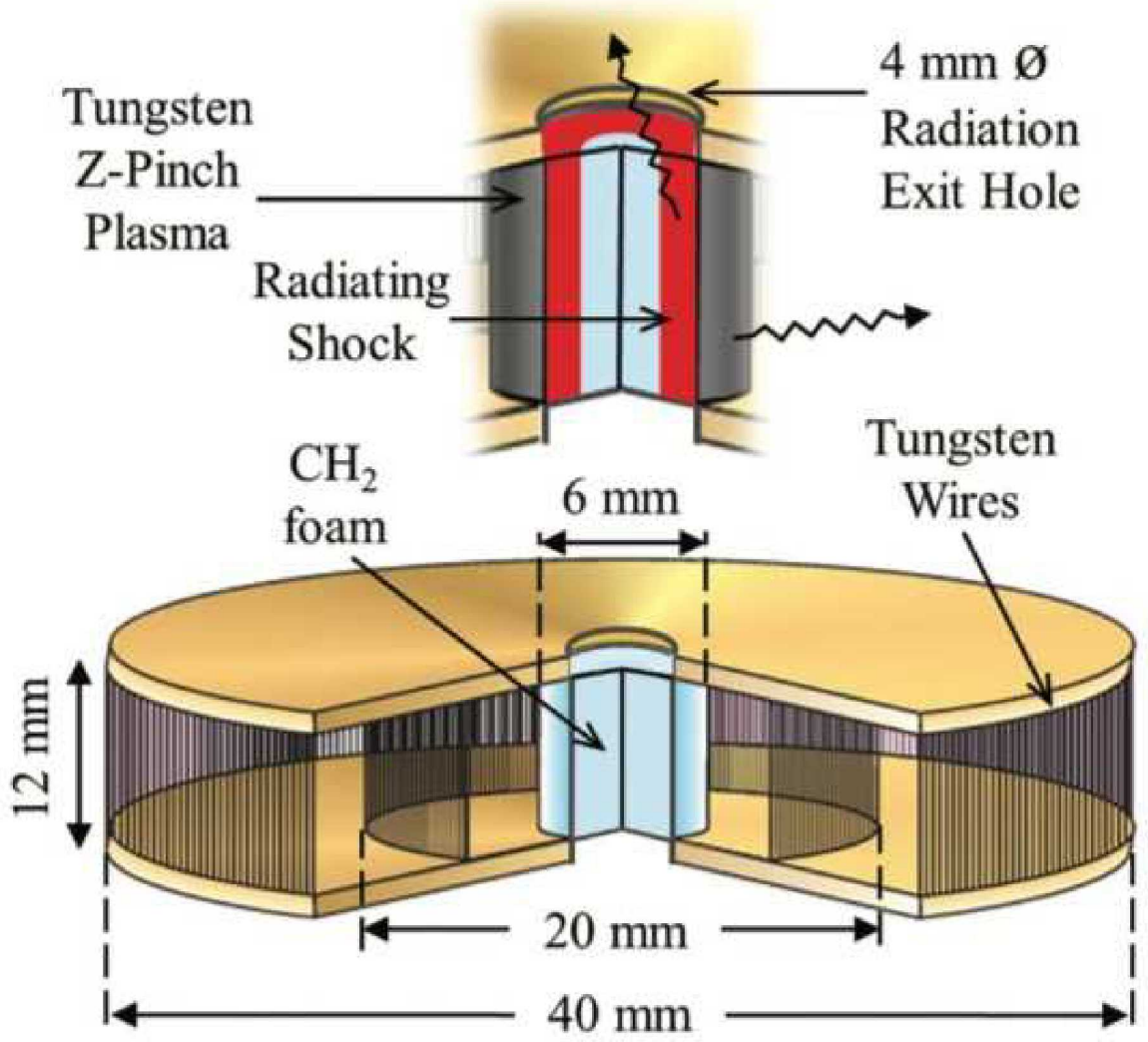
High quality CH foam is necessary for high radiation output and good reproducibility



- Z-pinch hohlraum radiation is produced by W wires imploding on to the CH foam and the generating radiative shock
- Criteria for CH foam
  - Density ← Affect radiation yield
  - Composition
  - Cosmetic defects/void/pore
  - Morphism

Schematic from G. A. Rochau et al, Phys. Plasmas **21**, 056308 (2014).

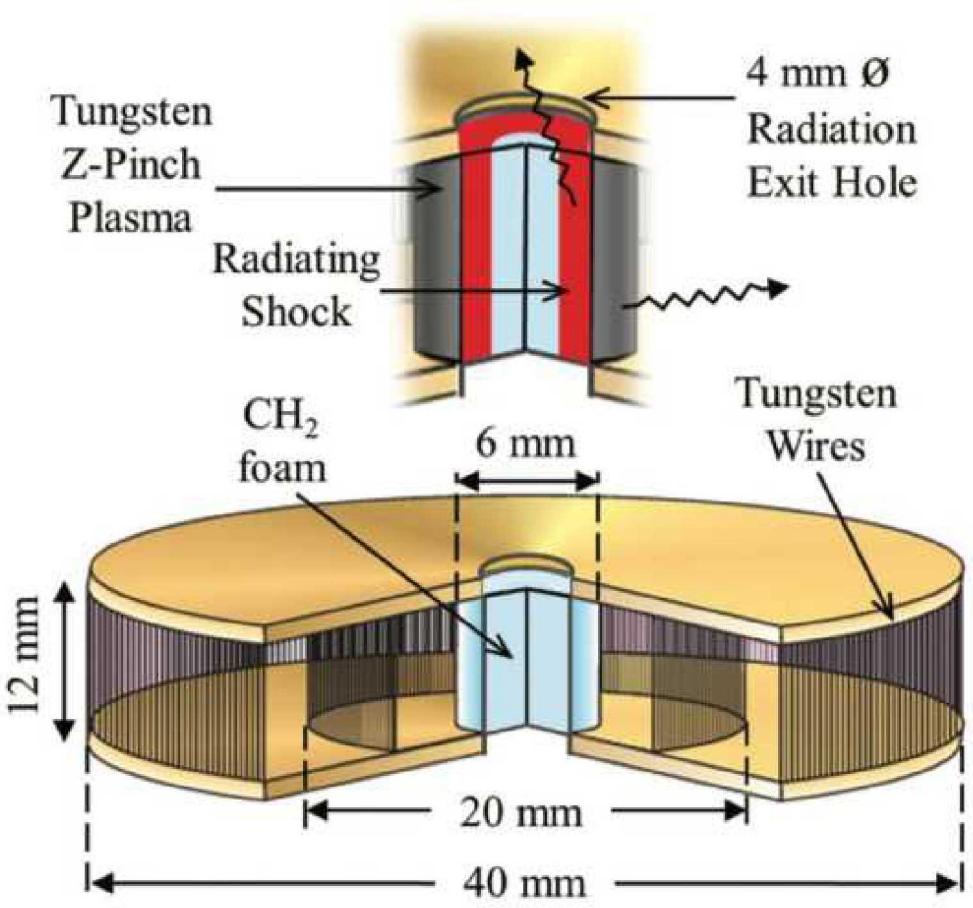
High quality CH foam is necessary for high radiation output and good reproducibility

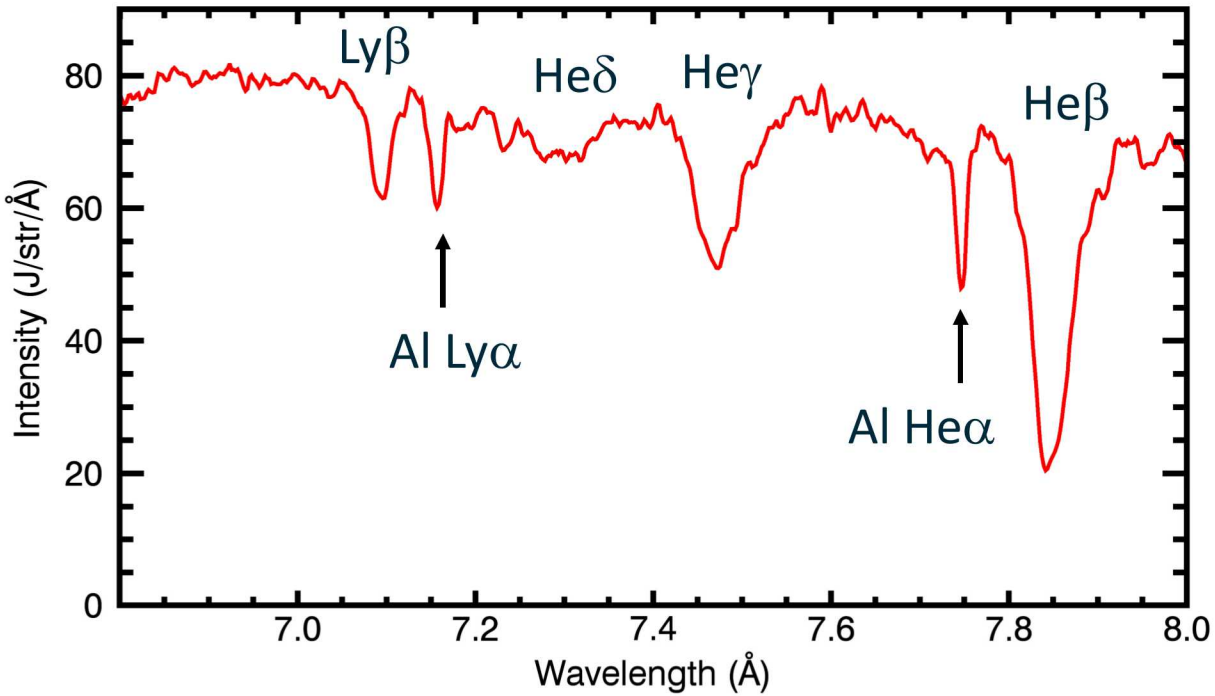


- Z-pinch hohlraum radiation is produced by W wires imploding on to the CH foam and the generating radiative shock
- Criteria for CH foam
  - Density
  - Composition
  - Cosmetic defects/void/pore
  - Morphism

Schematic from G. A. Rochau et al, Phys. Plasmas **21**, 056308 (2014).

Unexpected contamination can affect the source radiation yield





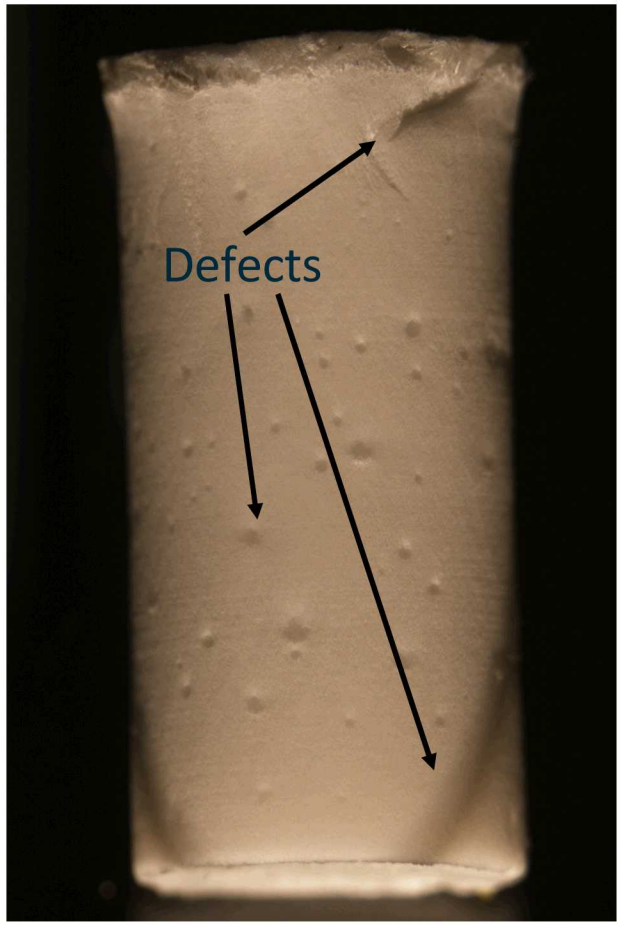
Where Al lines comes from? → CH foam contamination

Concern1: Change in radiation output

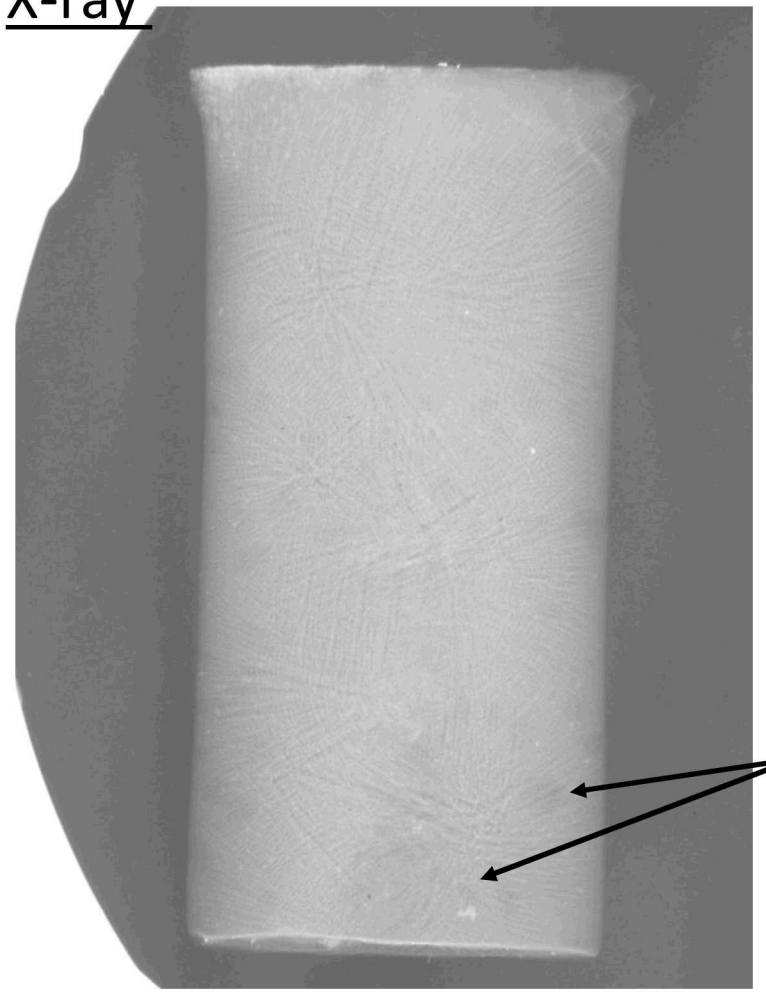
Concern2: Potential impact on Mg line analysis

Cosmetic defects/void/pore may affect implosion dynamics

Optical



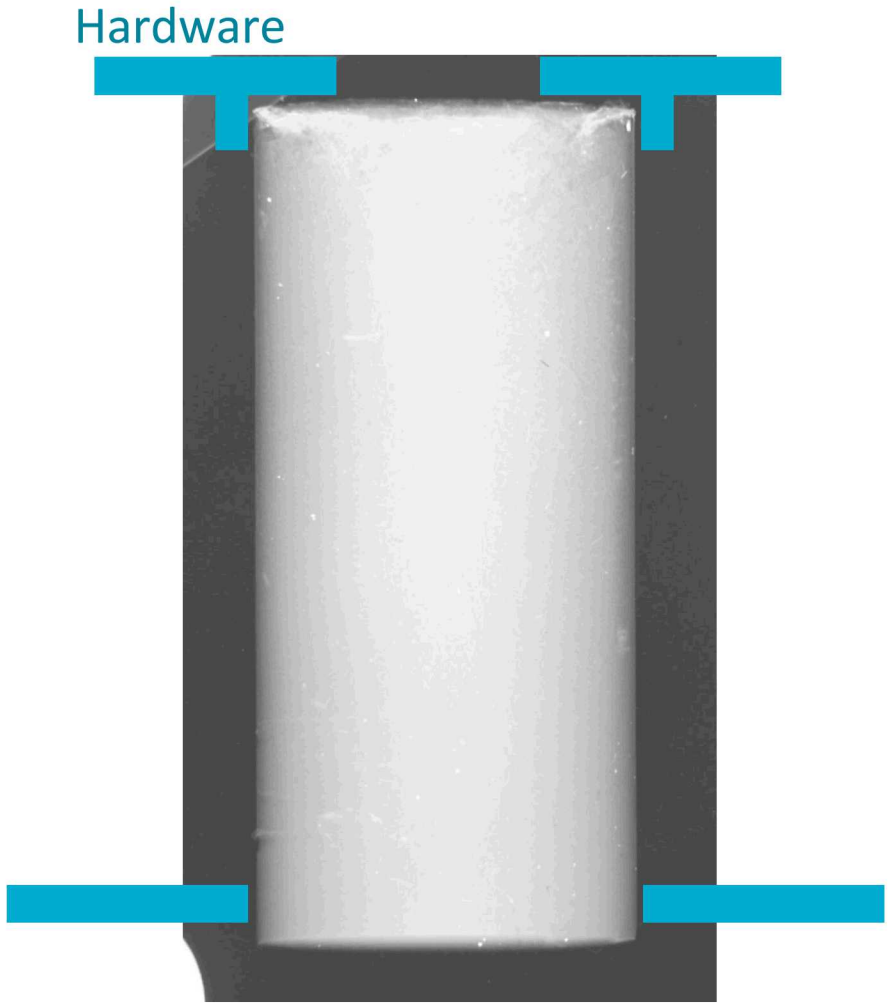
X-ray



Diameter and foam straightness are important to insert CH foam to the hardware and to perform symmetric implosion

- Diameter needs to be within the specified tolerance
  - If larger, it won't fit
  - If smaller, radiation could be lower
- The top surface and the body needs to be perpendicular
  - If not perpendicular, it can introduce asymmetry into the implosion

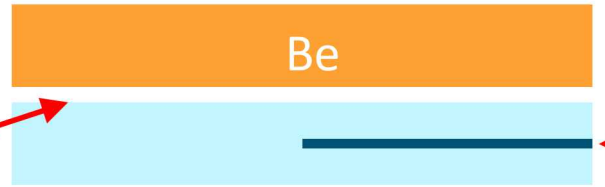
Diameter and foam straightness are important to insert CH foam to the hardware and to perform symmetric implosion



- Diameter needs to be within the specified tolerance
  - If larger, it won't fit
  - If smaller, radiation could be lower
- The top surface and the body needs to be perpendicular
  - If not perpendicular, it can introduce asymmetry into the implosion

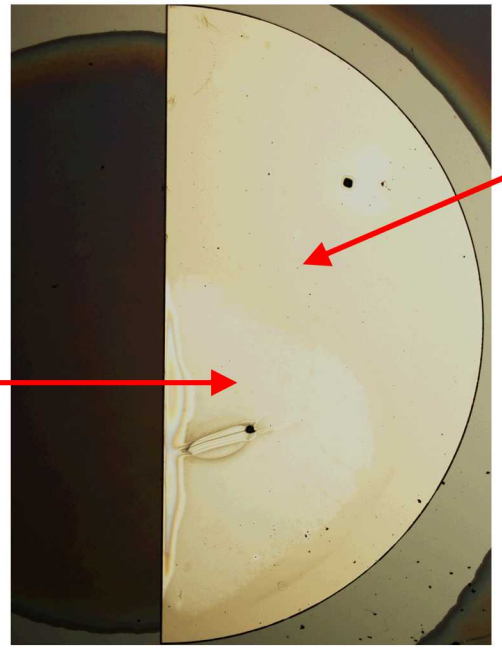
Well-characterized high-quality opacity sample are essential for accurate opacity measurements

Opacity sample



Criteria1: accurate and uniform ρL

Criteria4: Flat and smooth surface

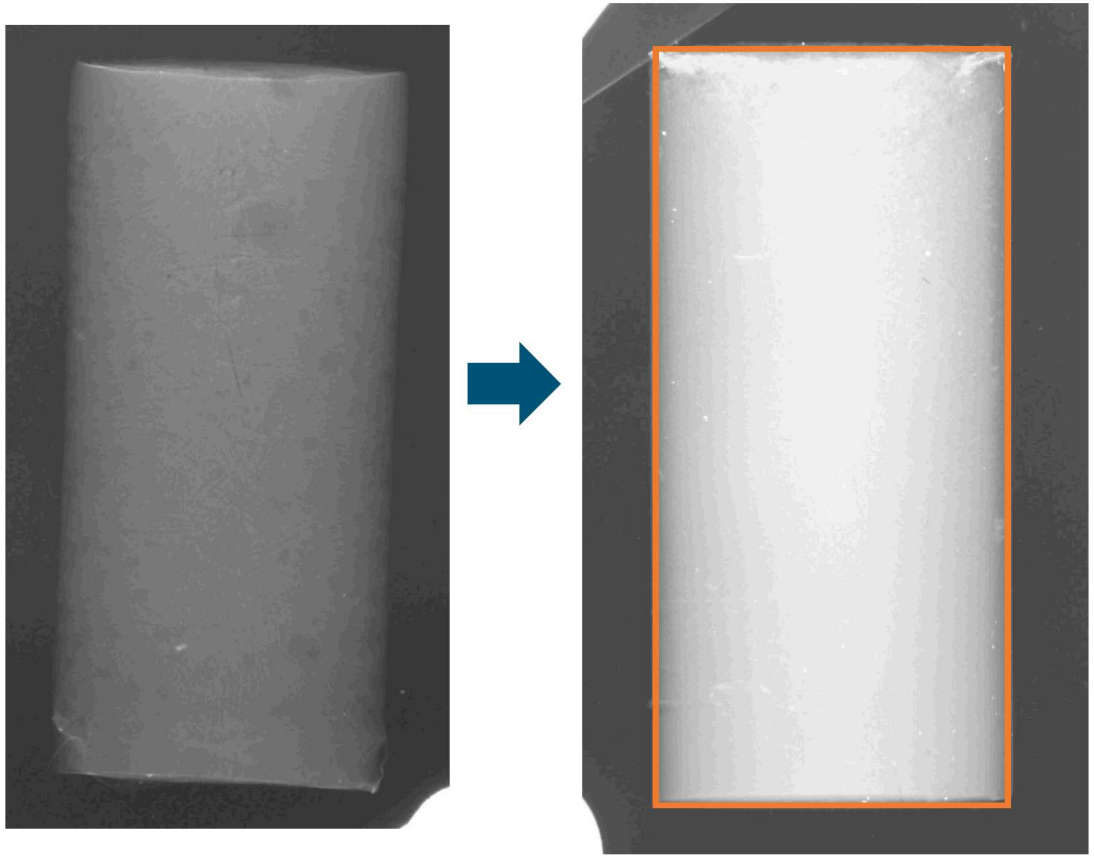


Criteria2: No contamination

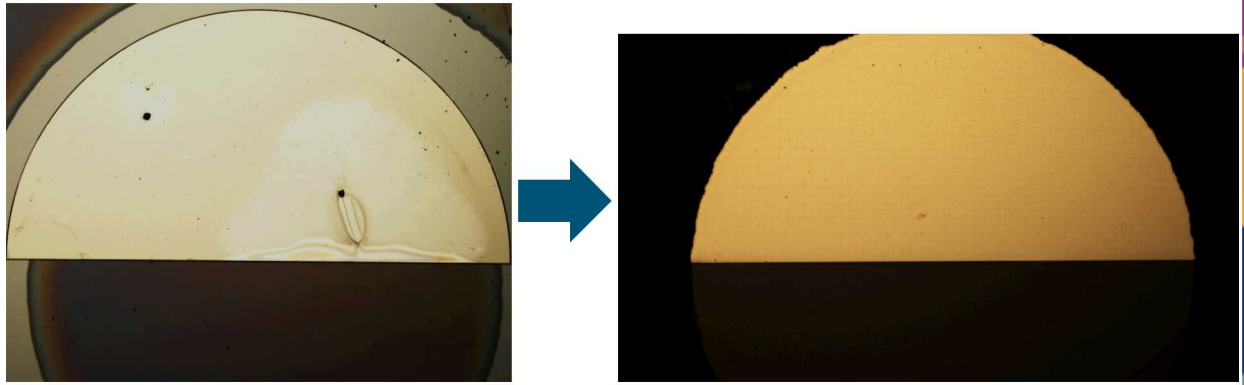
Criteria3: No artifacts such as pinholes or cracks

GA has developed and kept refining fabrication and metrology techniques to deliver us high-quality foam and opacity samples

CH foam



Opacity sample



The high-quality targets enabled us to perform high-quality HED opacity benchmark experiments