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Sandia National Laboratories

Updates on iron opacity measurements at solar interior temperature

Taisuke Nagayama, J. E. Bailey, G. P. Loisel, D. C. Mayes, G. S. Dunham

U.S. DEPARTMENT OF ENERGY NNSA

SAND2022-14431 C

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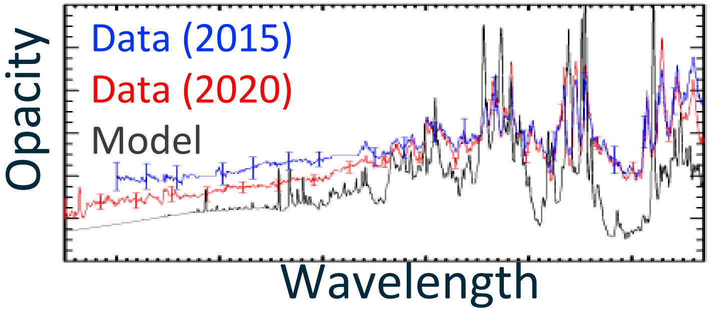

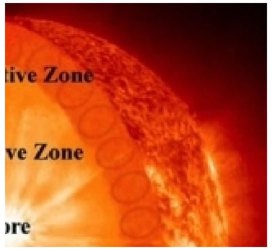

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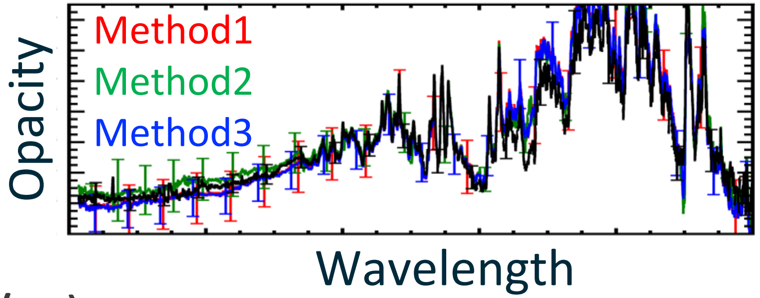

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- Performed more experiments for scrutiny
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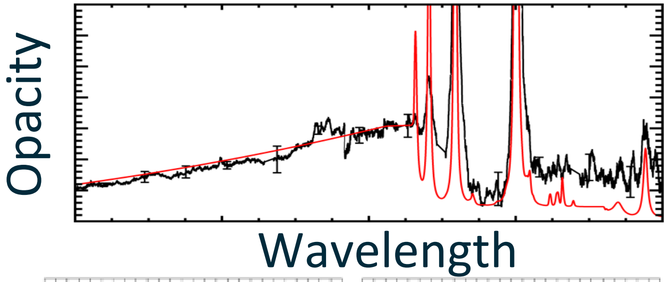

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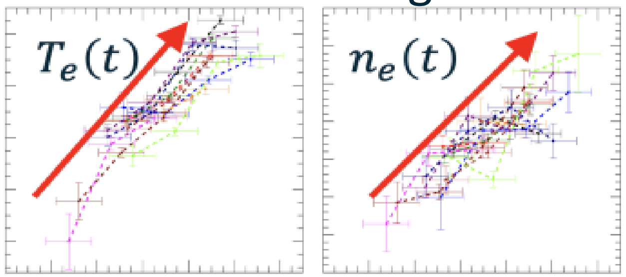

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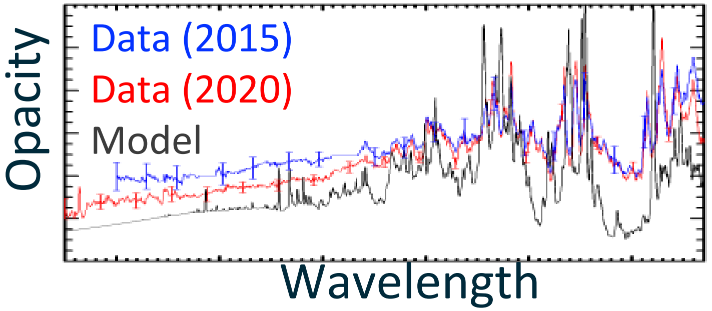

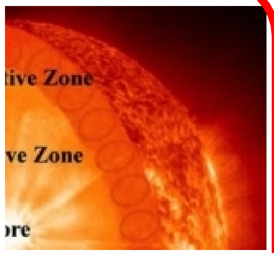

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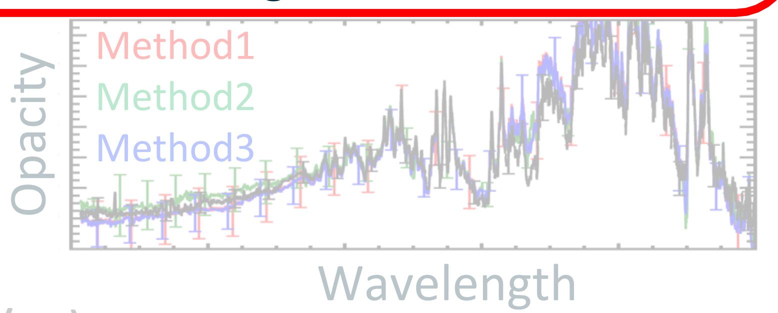

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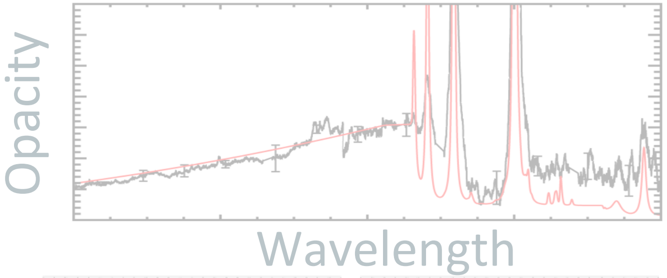

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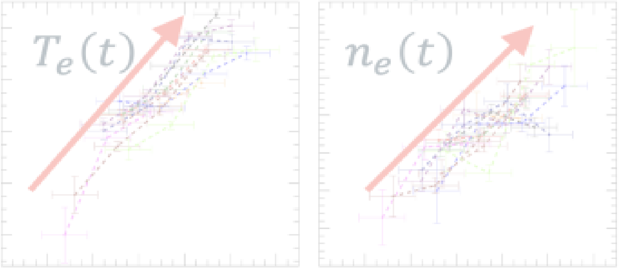

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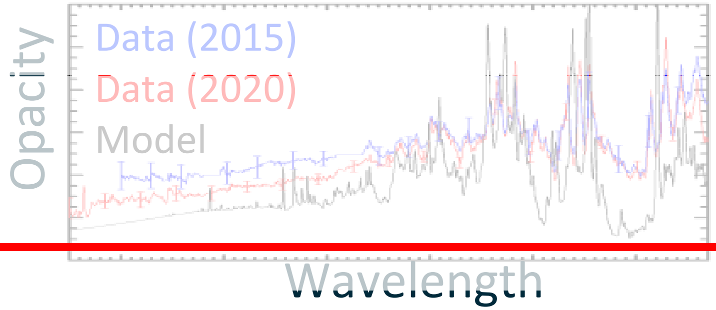

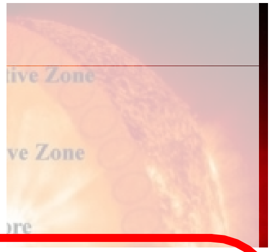

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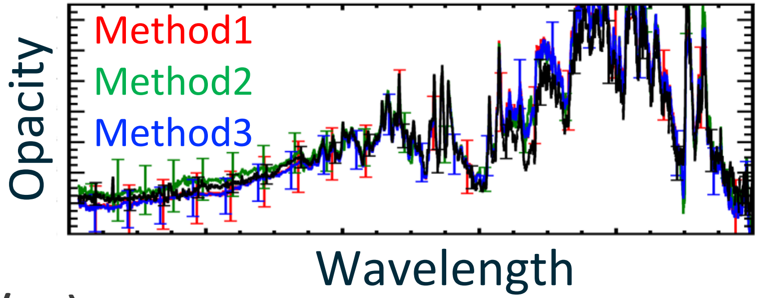

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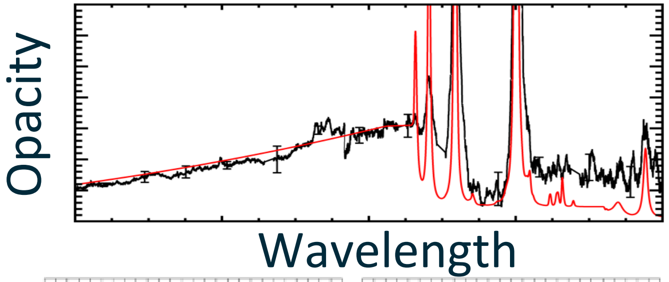

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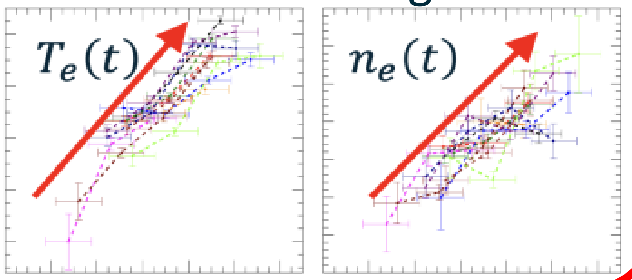

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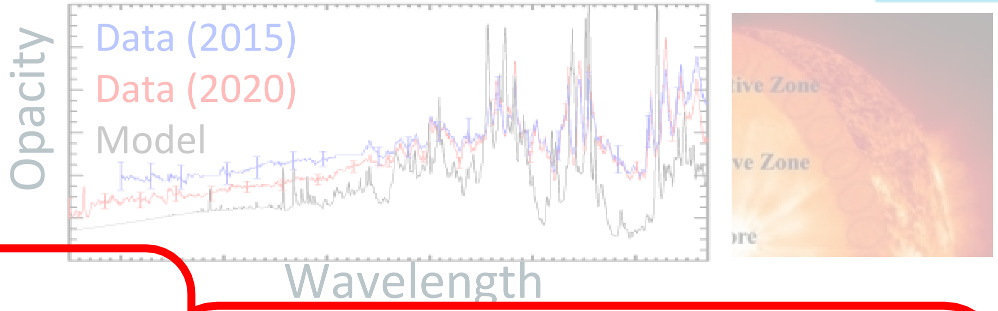

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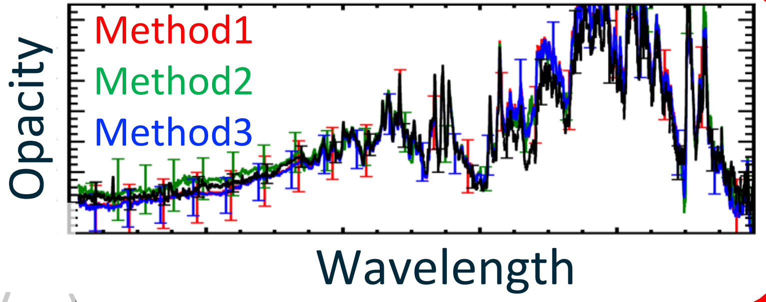

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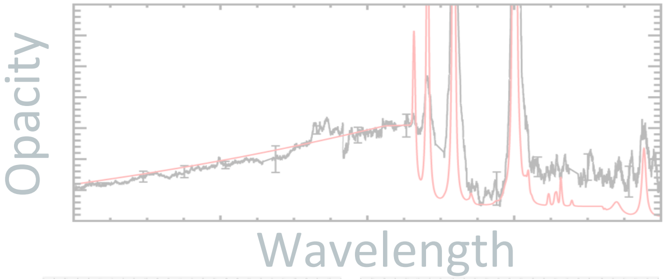

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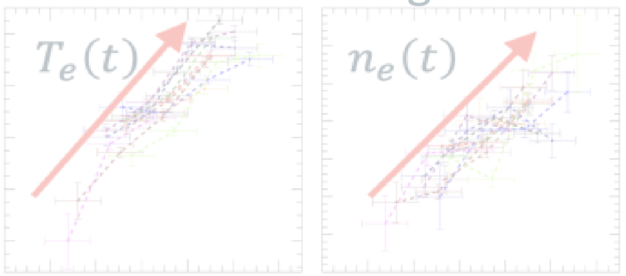

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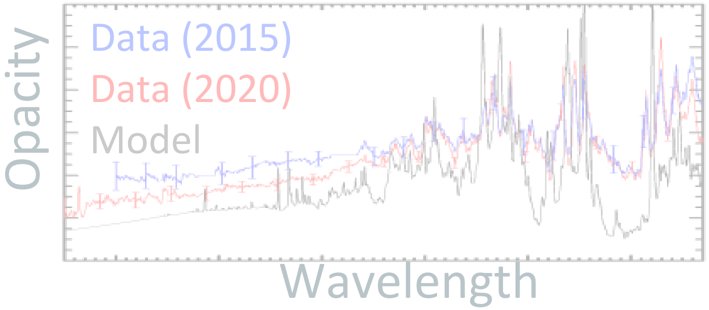

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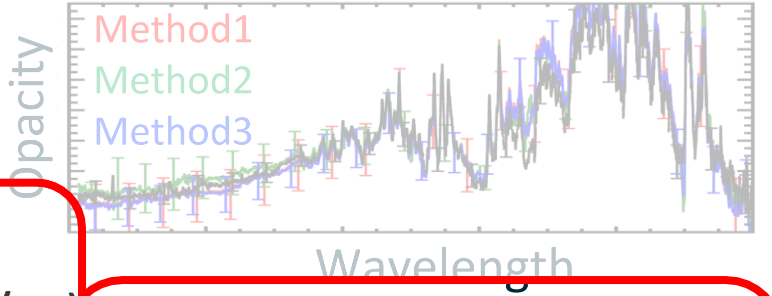

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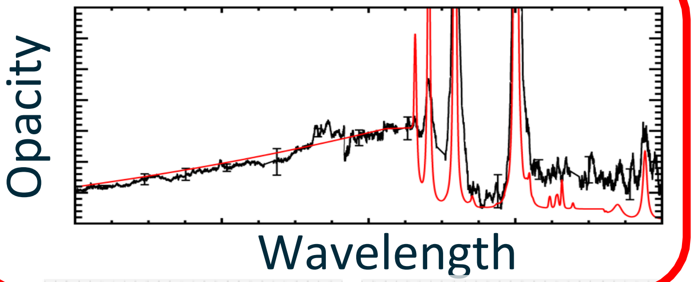

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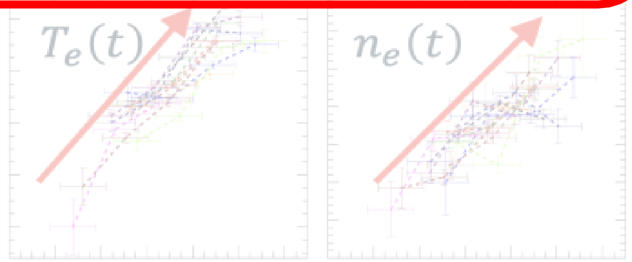

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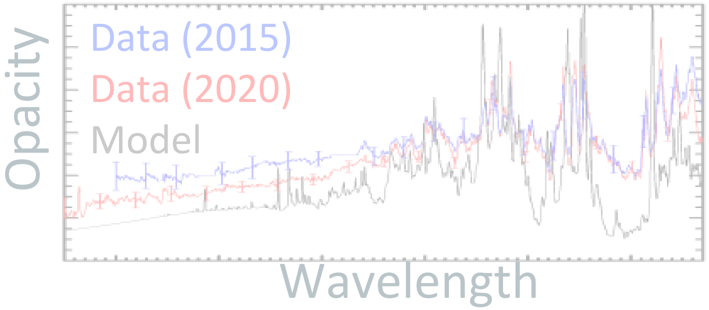

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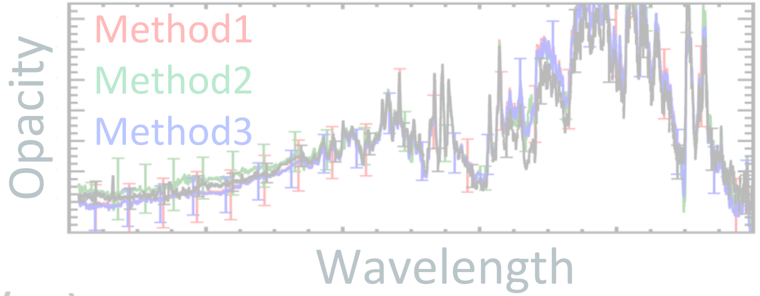

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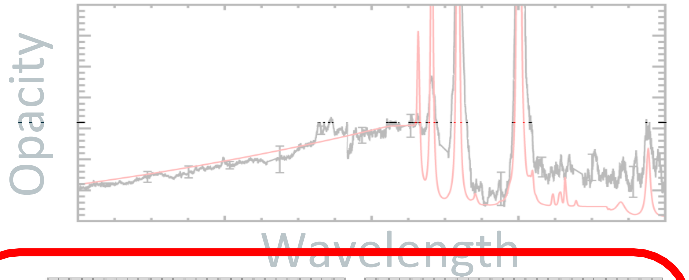

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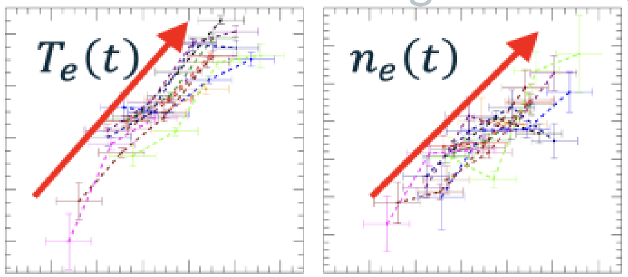

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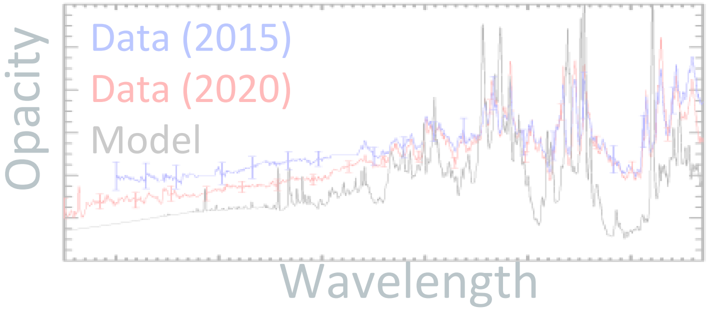

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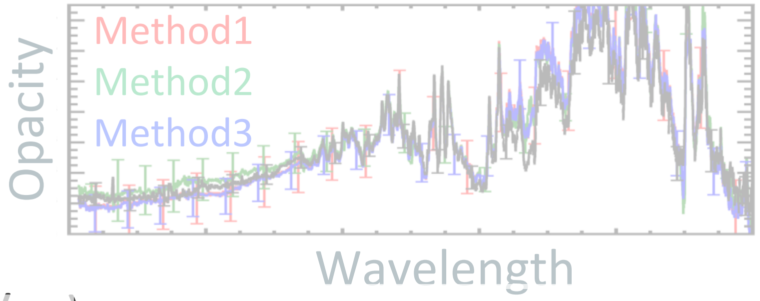

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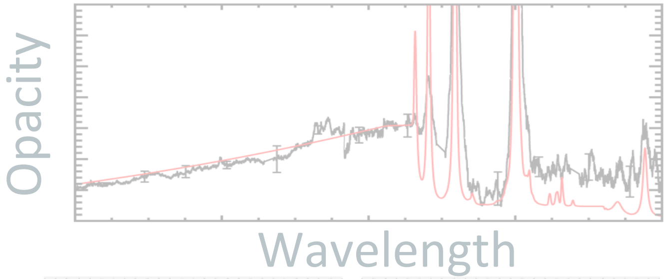

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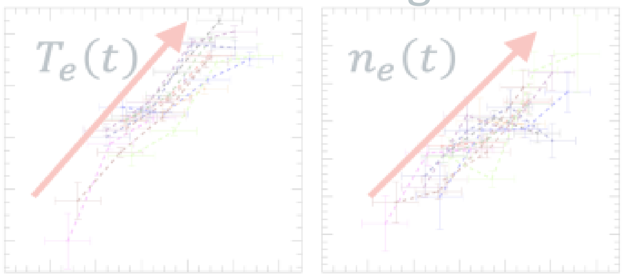

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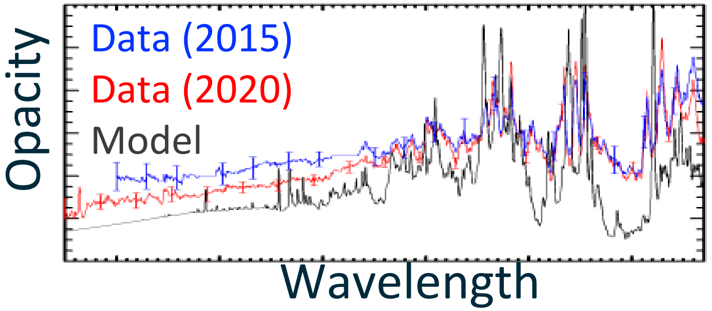

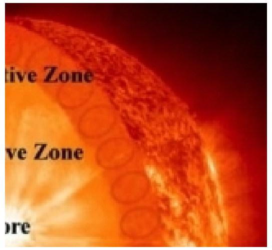

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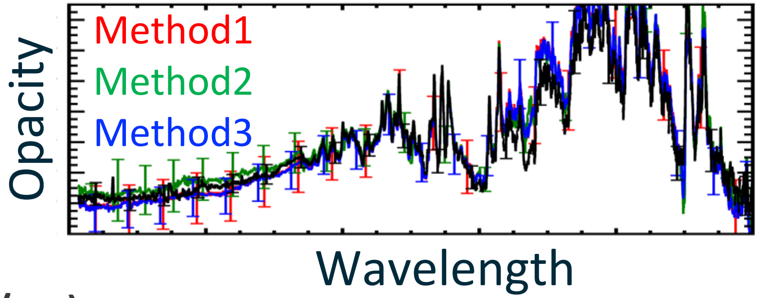

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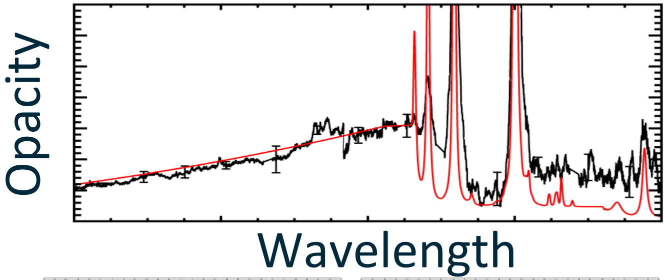

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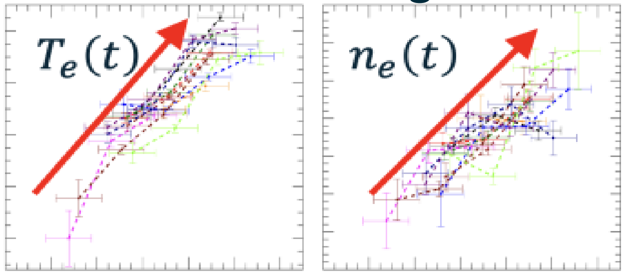

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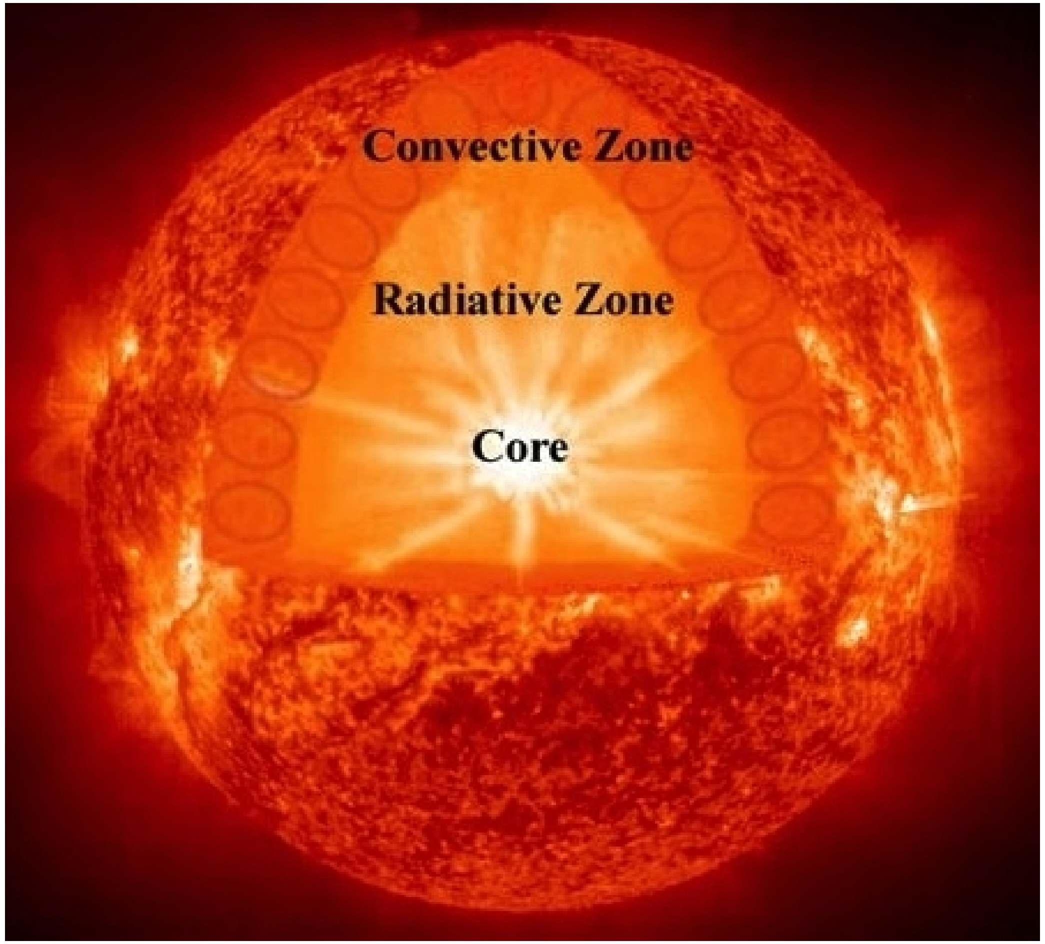
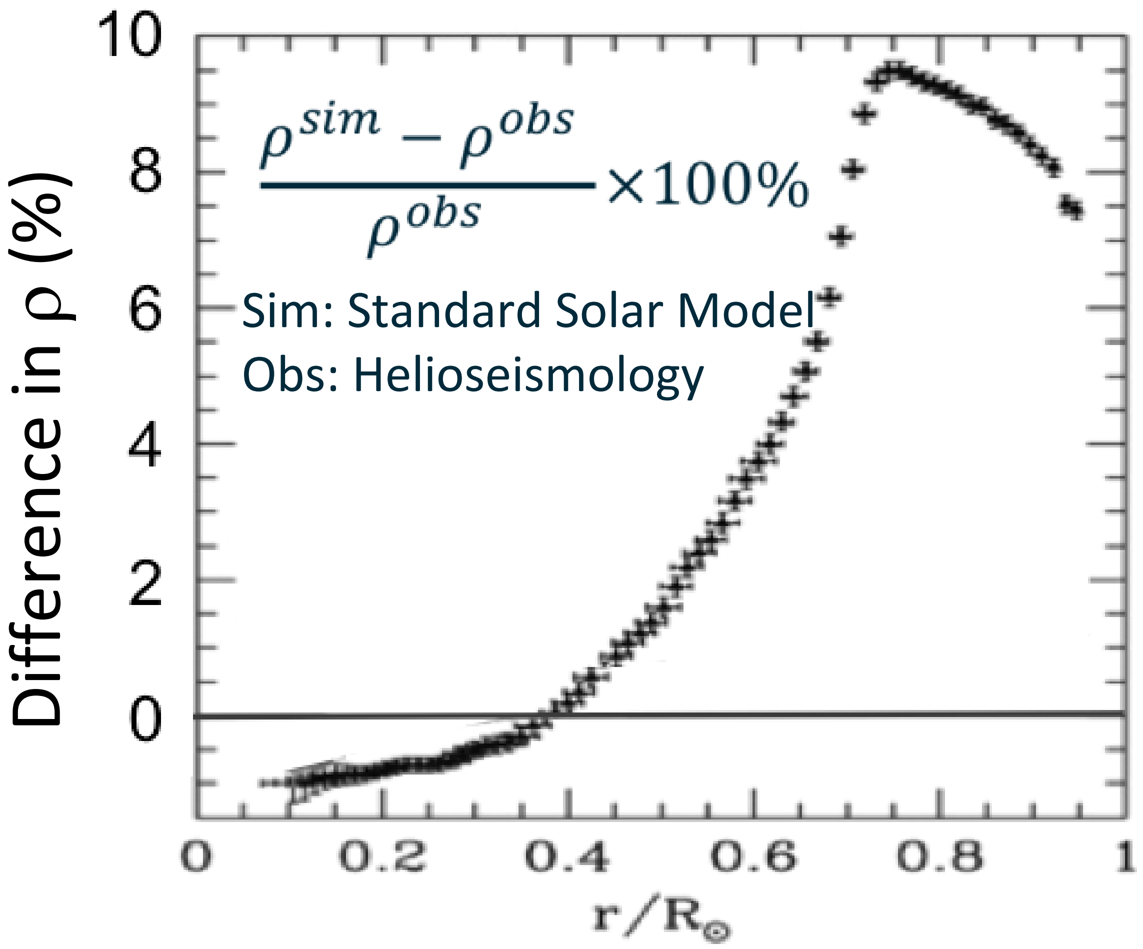
Solar structure simulated by Standard Solar Model disagrees with Helioseismology





10-30% opacity increase in the model can help resolve the discrepancy. Is opacity wrong?

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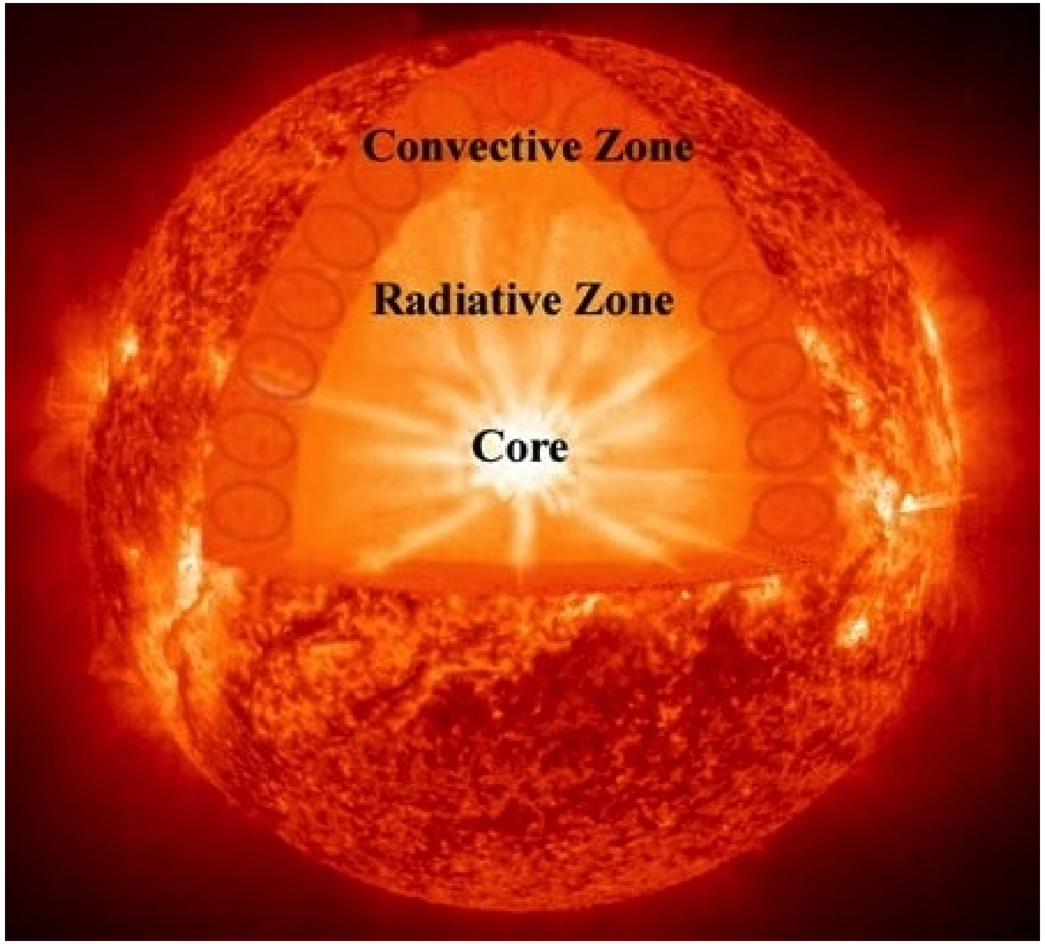

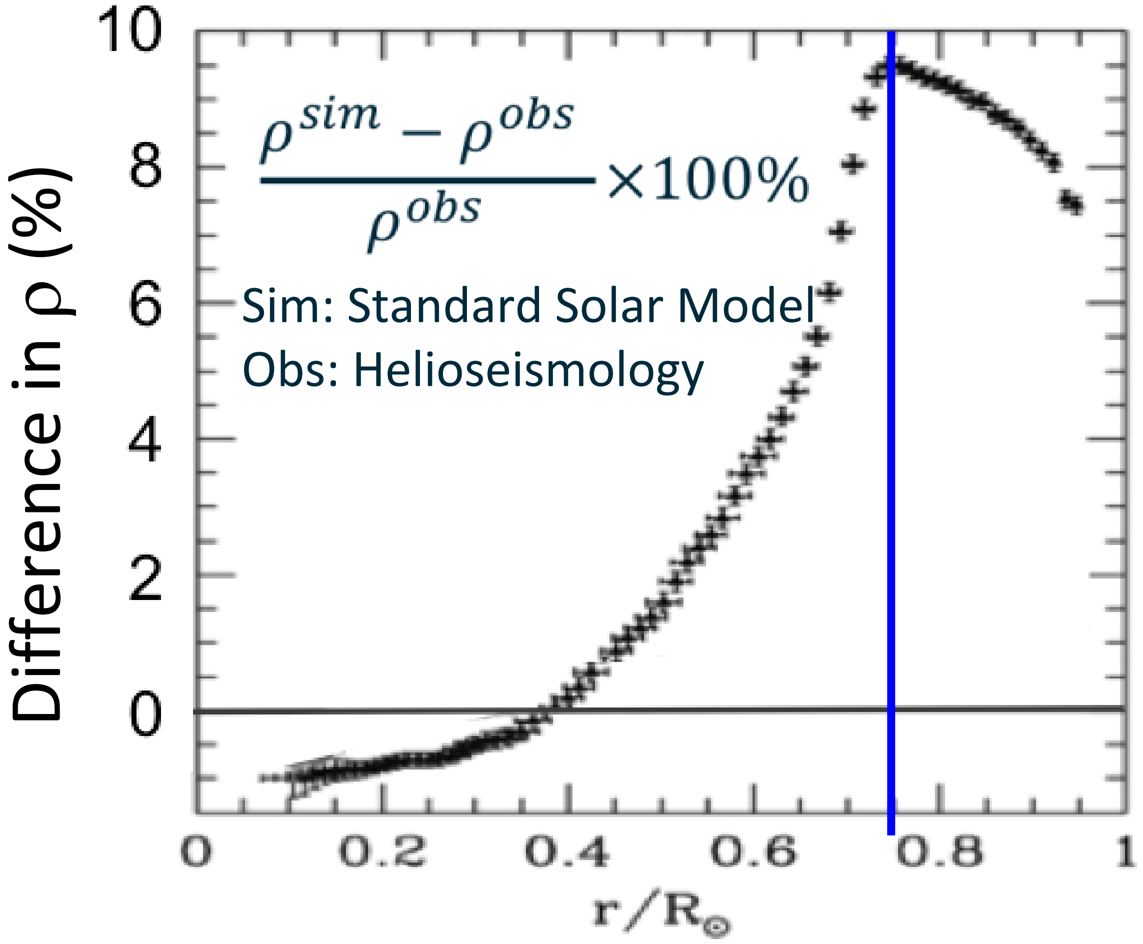

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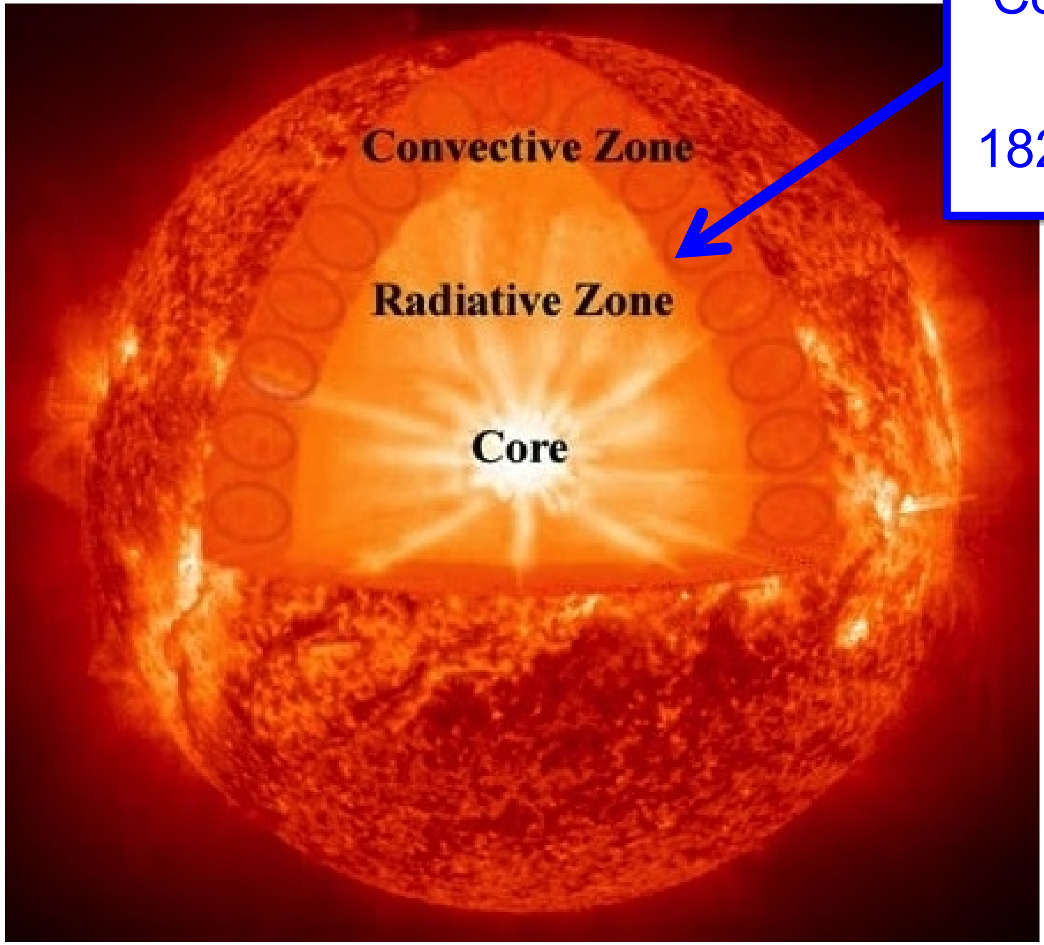
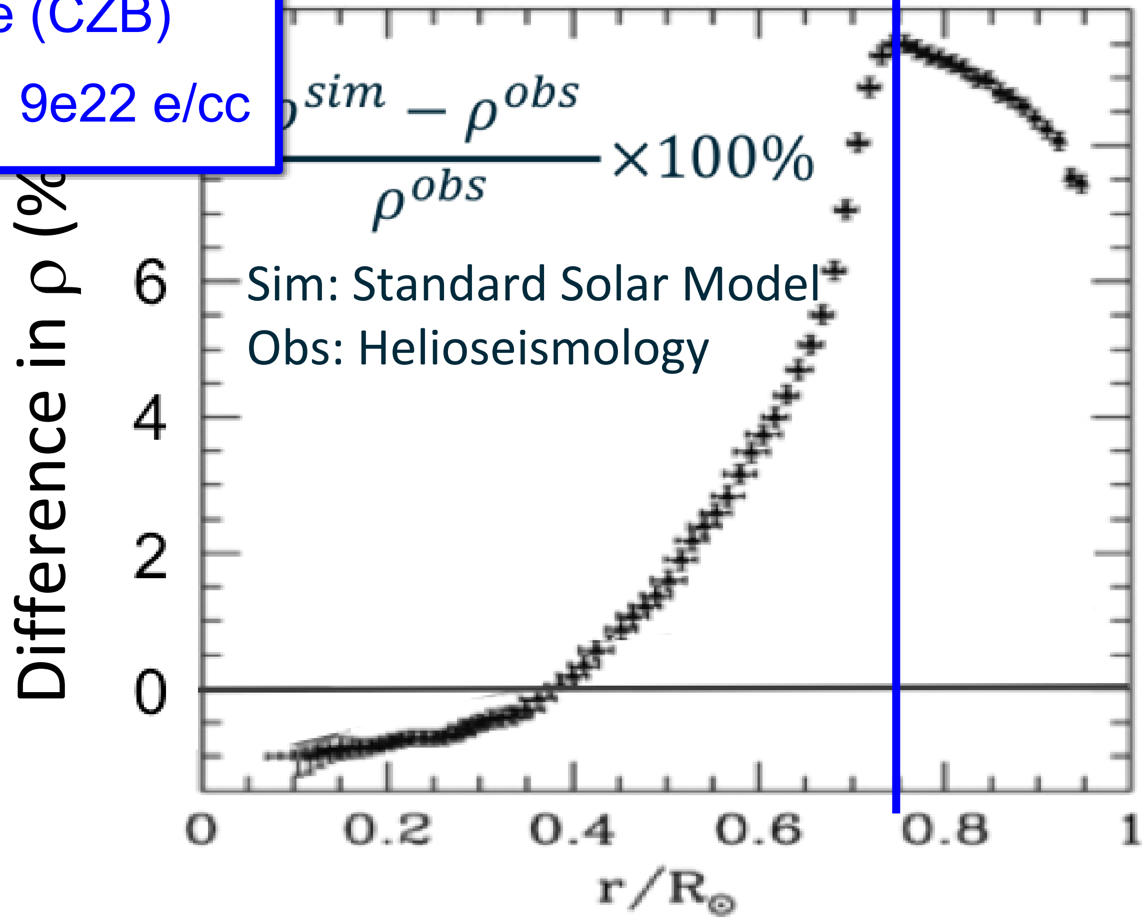


Convection zone base (CZB)

182 eV, 9e22 e/cc



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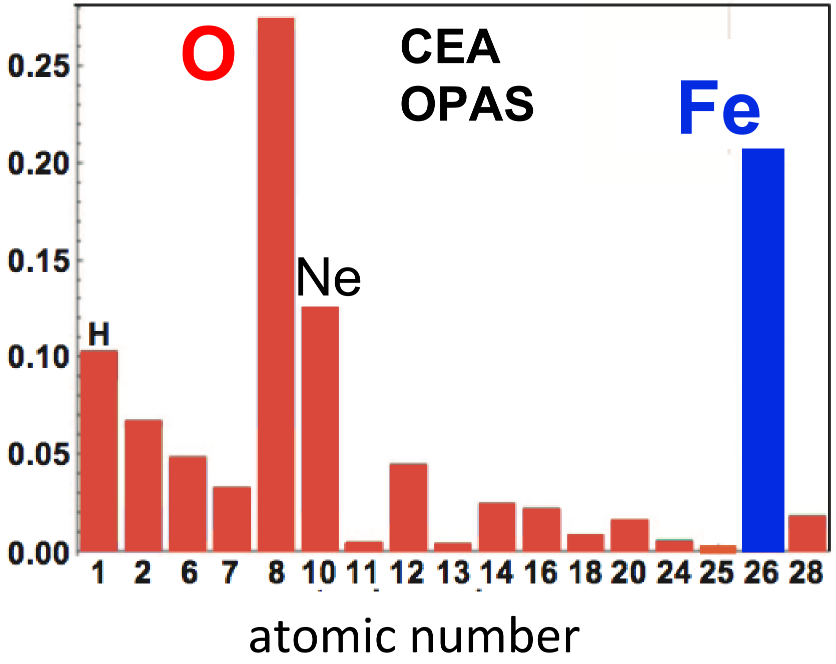
  → Is calculated solar opacity accurate?

Element contribution to solar opacity



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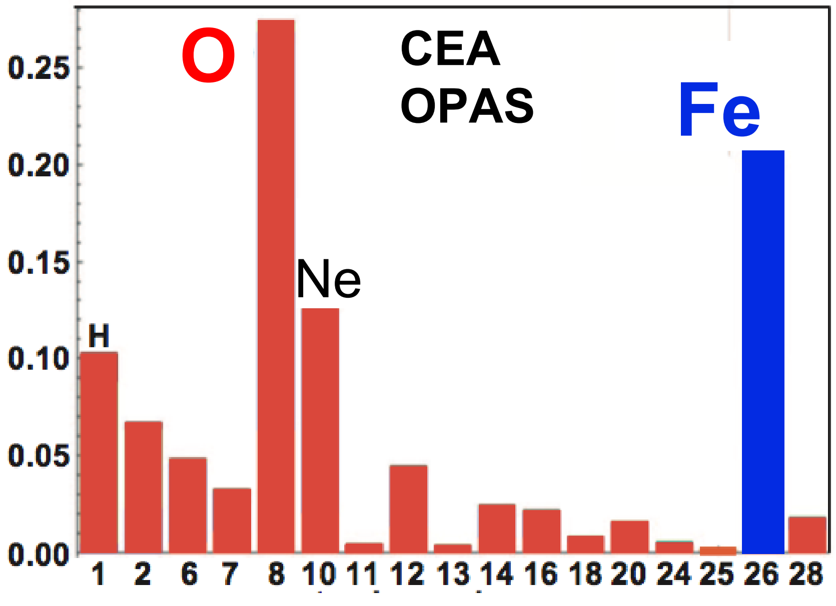

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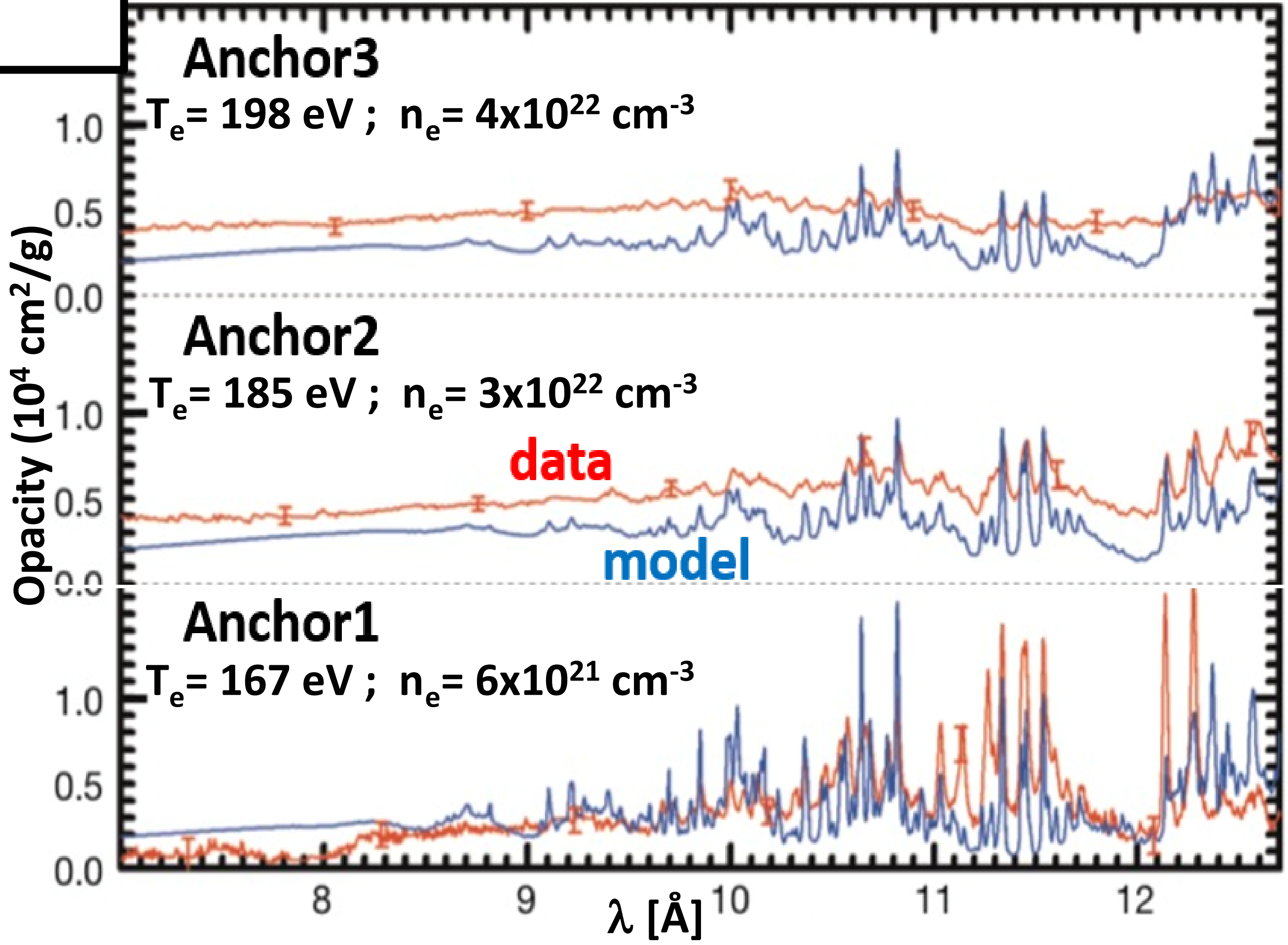

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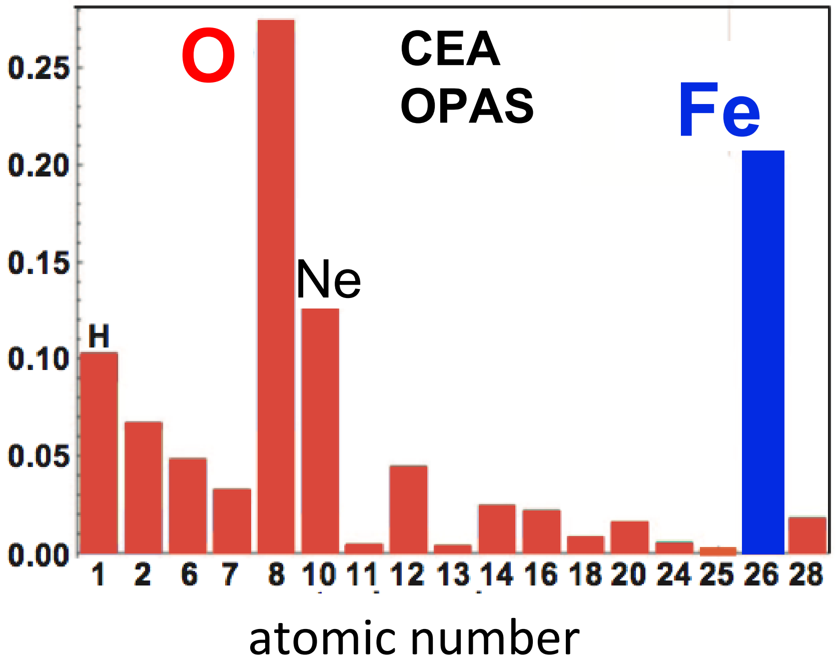

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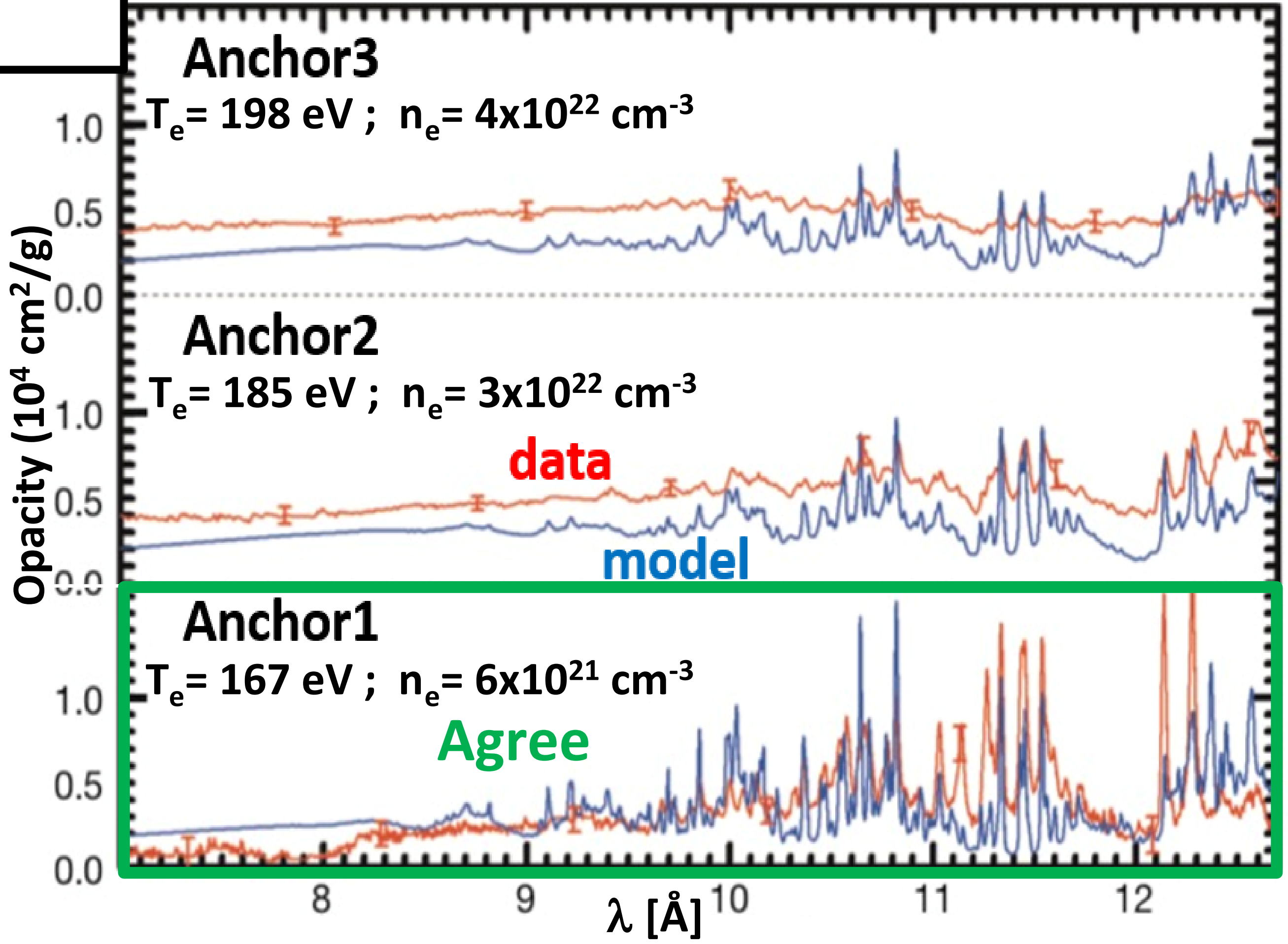

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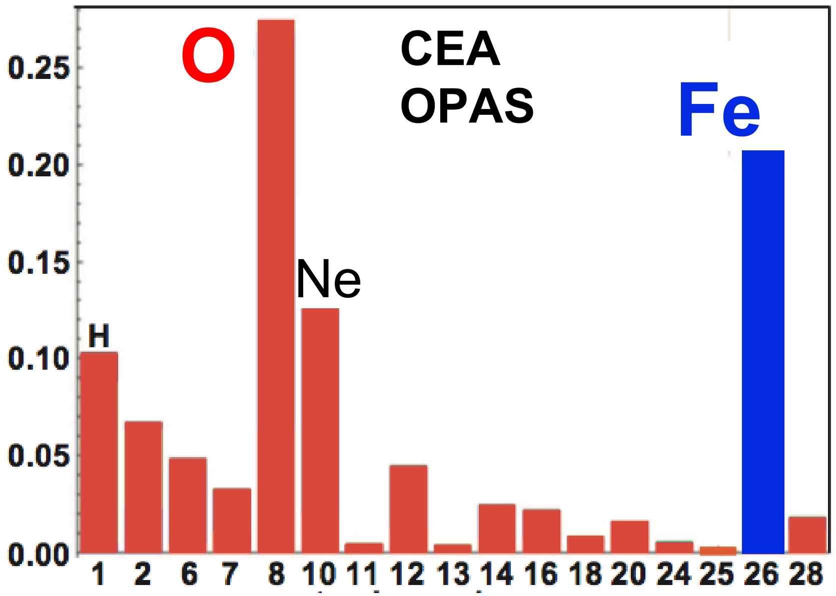

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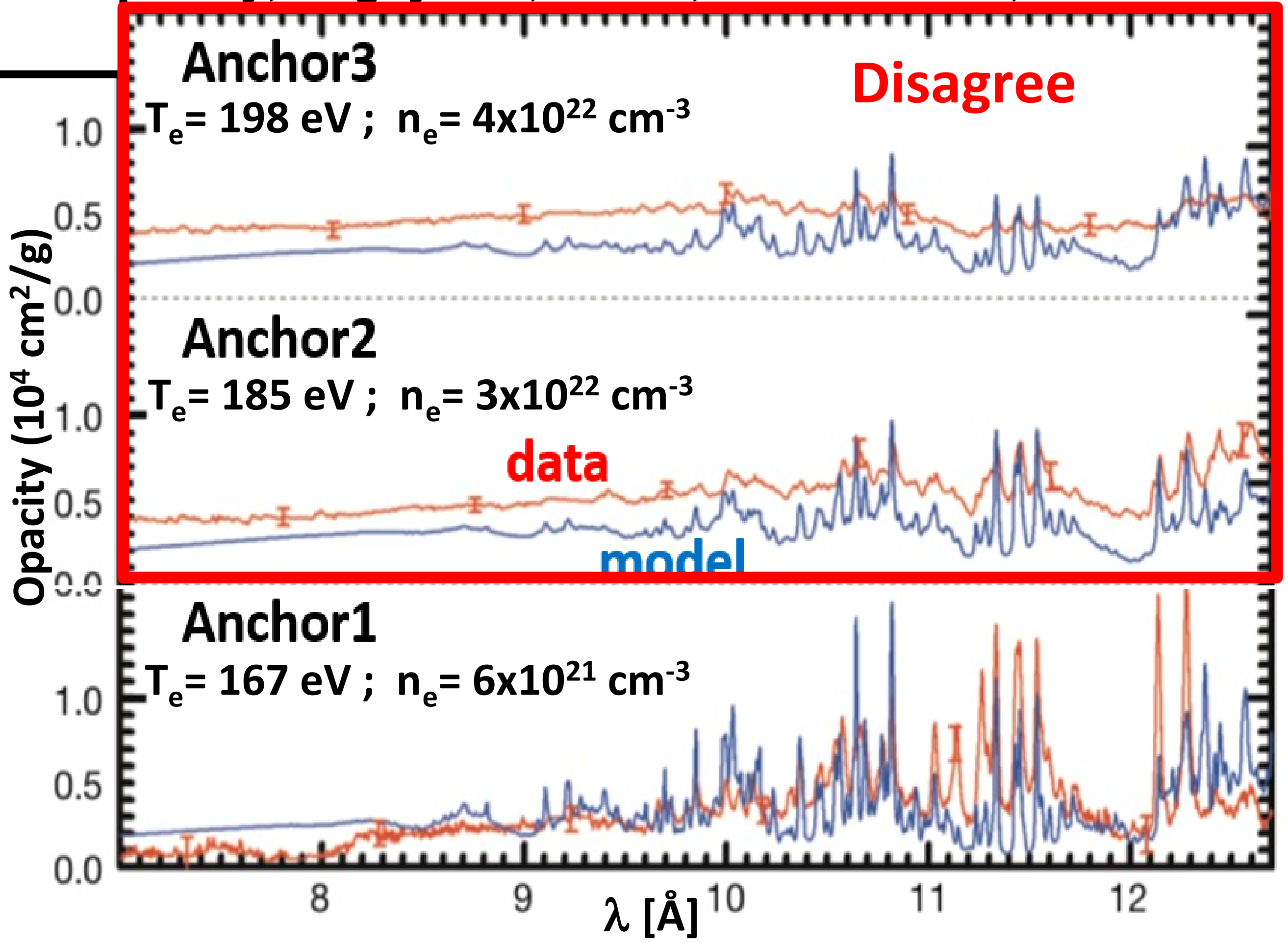

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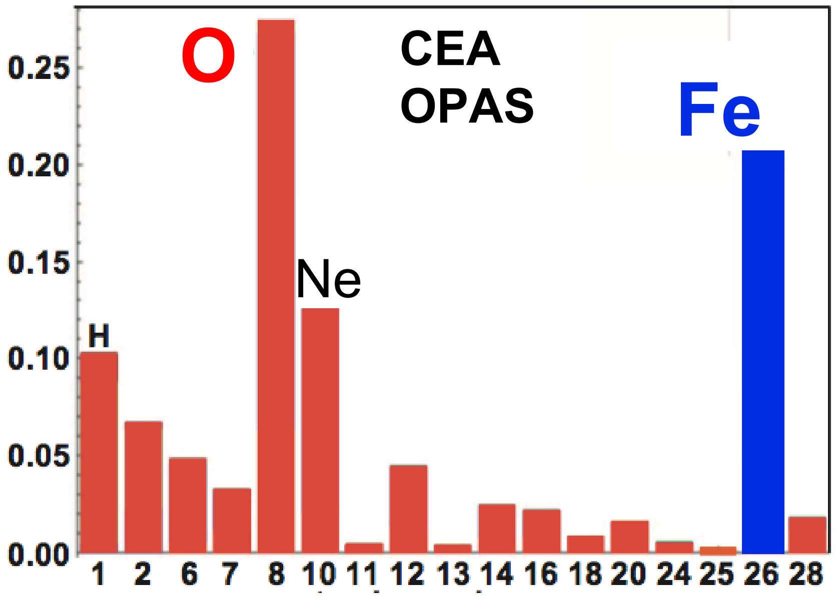

atomic number

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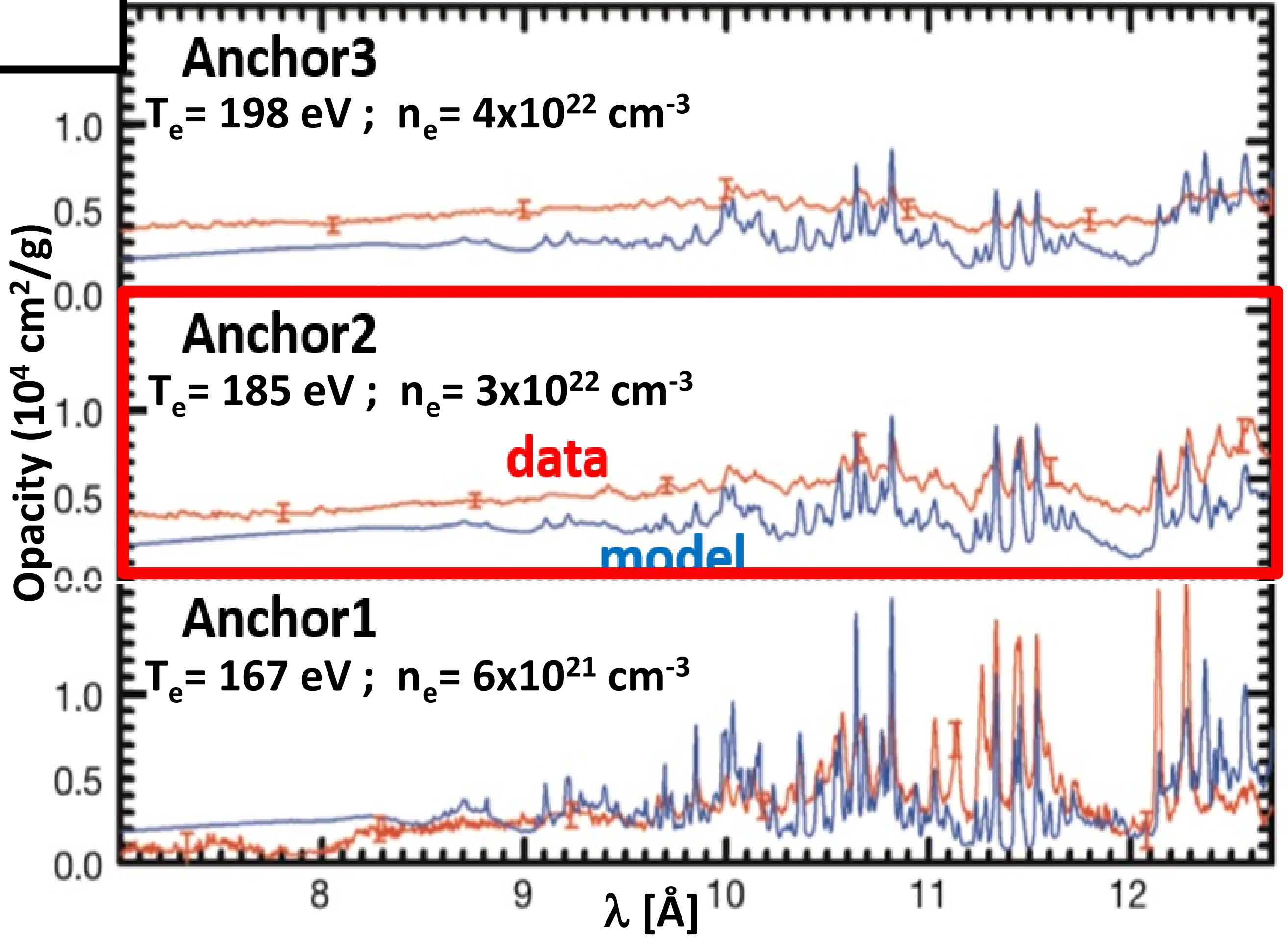

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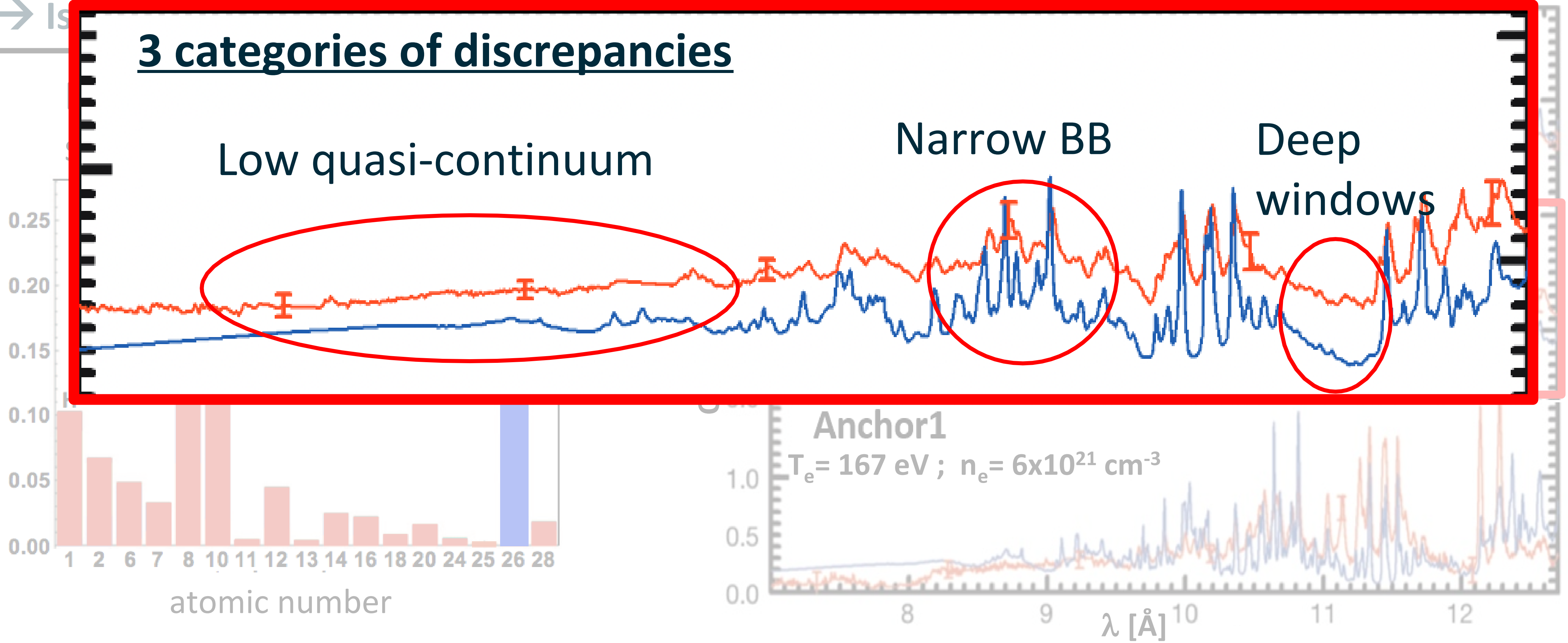
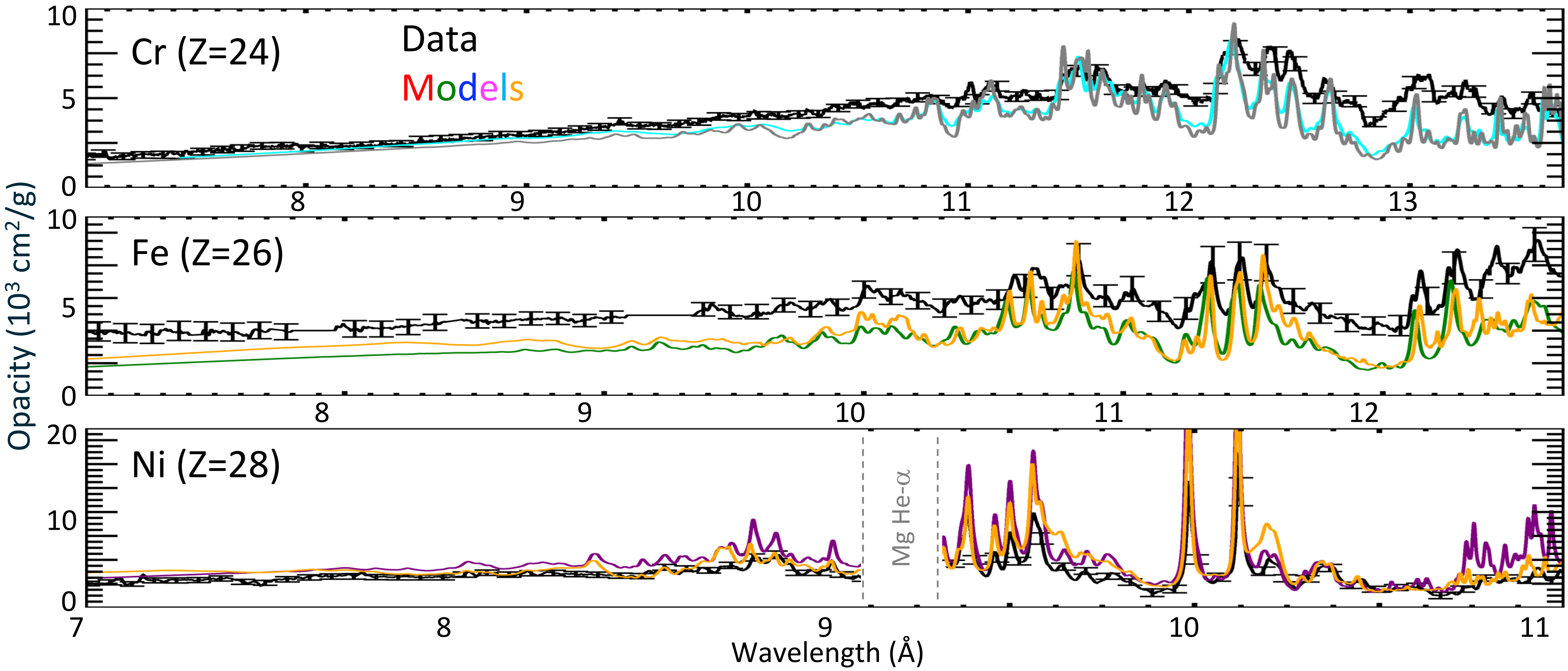


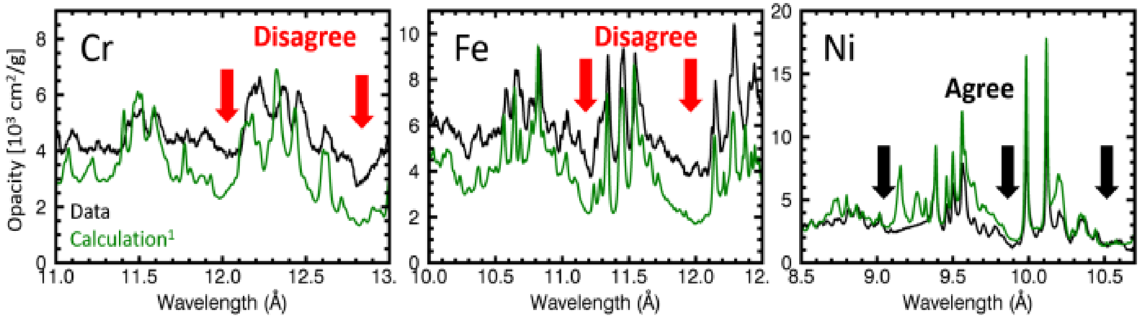
We measured opacity of Cr, Fe, and Ni at anchor2
Systematic study helped refine hypotheses for discrepancy



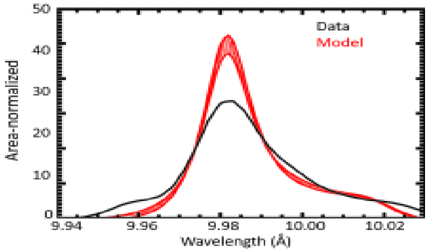
Nagayama et al, *Phys. Rev. Lett.* **122**, 235001 (2019)

A systematic study suggested a few theoretical refinements and deepened one puzzle

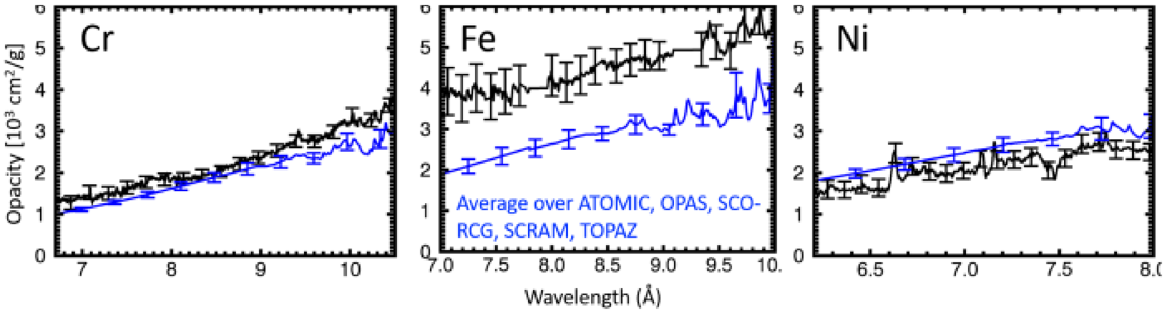
Window: discrepancy appears at open L-shell configuration



Spectral lines: broader than calculated



Quasi-continuum : broader than calculated



Hypotheses

Equation of state calculation?

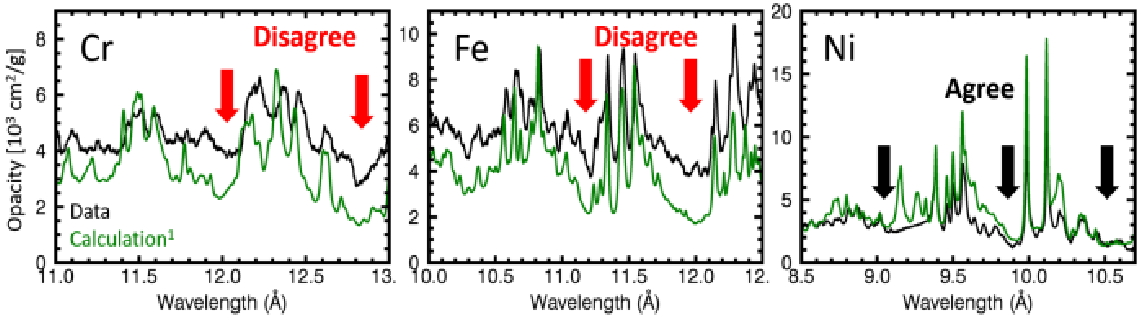
Line-shape calculations?

No trend found

Puzzling

A systematic study suggested a few theoretical refinements and deepened one puzzle

Window: discrepancy appears at open L-shell configuration



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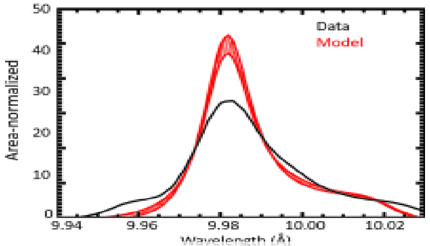

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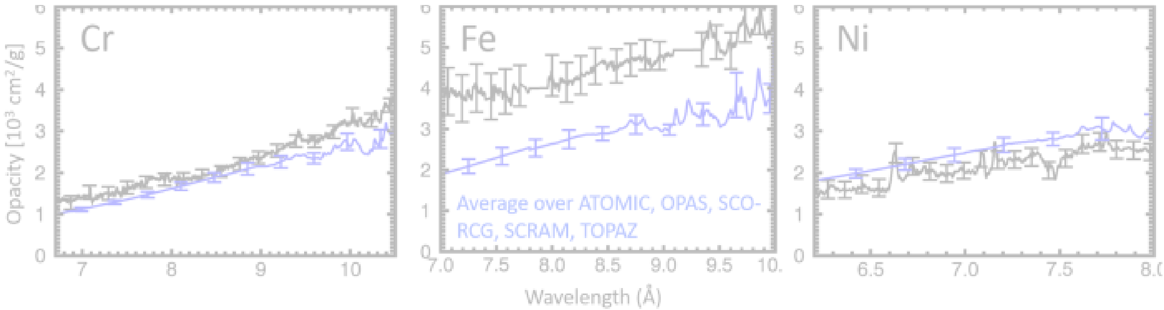

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Nagayama et al, *Phys. Rev. Lett.* **122**, 235001 (2019)

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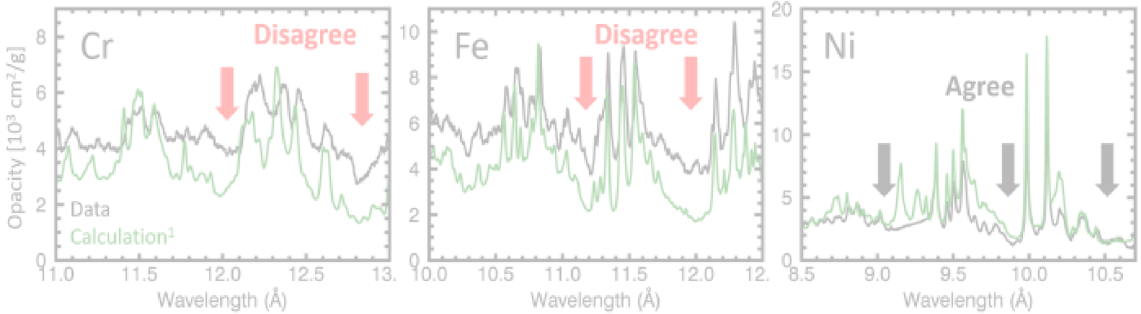

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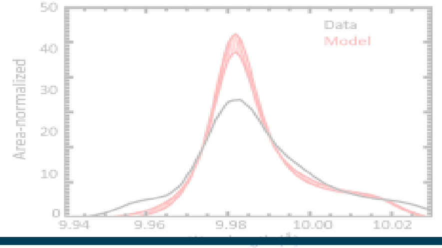

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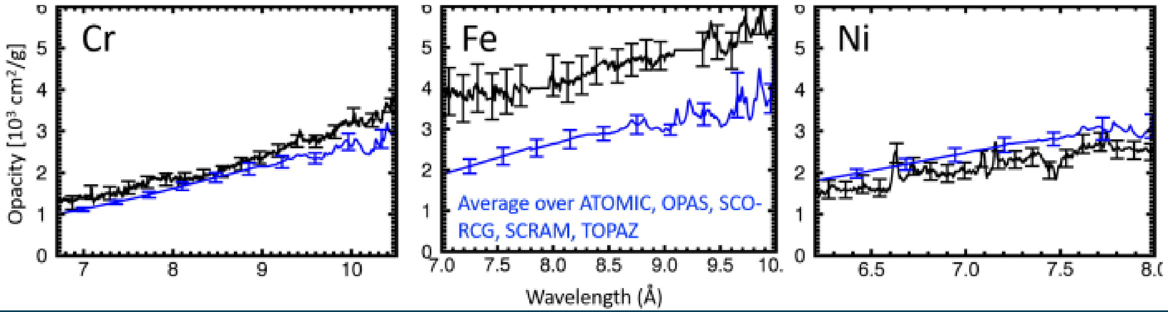

→ No trend found

Puzzling

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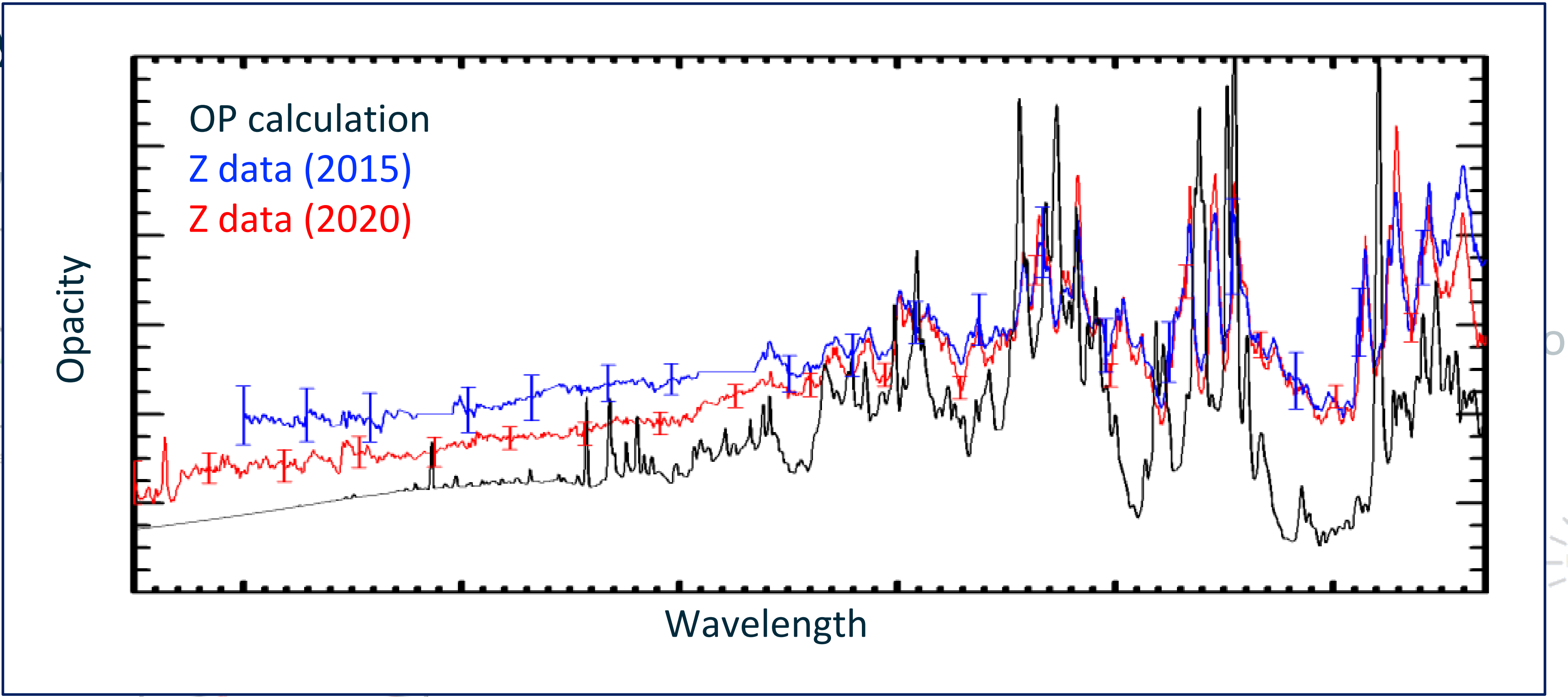

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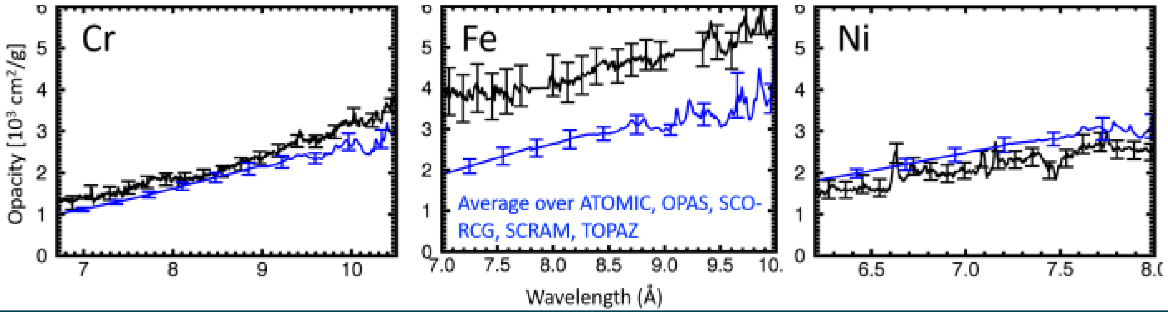


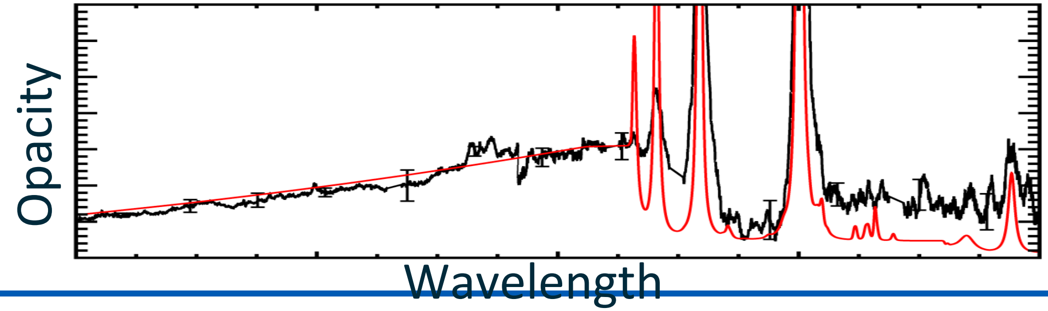
→ No trend found
Puzzling

We have been working on four investigations for resolving the opacity puzzle and the solar problem

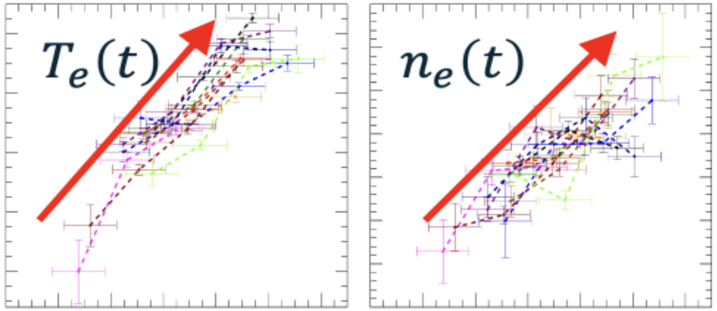
Revisit Z iron opacity results
(this talk by T. Nagayama from SNL)

- Temperature and density re-analysis
- More experiments
- Re-analysis

Z oxygen opacity measurements
(2nd talk by D. Mayes from UT)



Z time-resolved experiments
(poster by G. Loisel from SNL)



Helping NIF opacity measurements
(3rd talk by T. Perry from LANL)

- Define high-fidelity opacity data
- Pros and cons of NIF and Z
- Scrutinize each experiments and analyses

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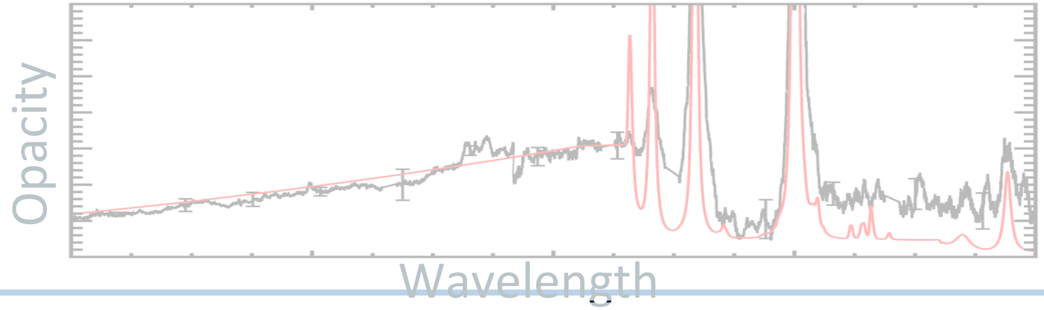

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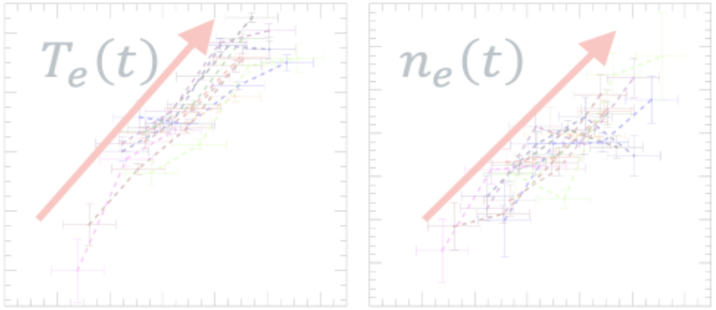

Helping NIF opacity measurements
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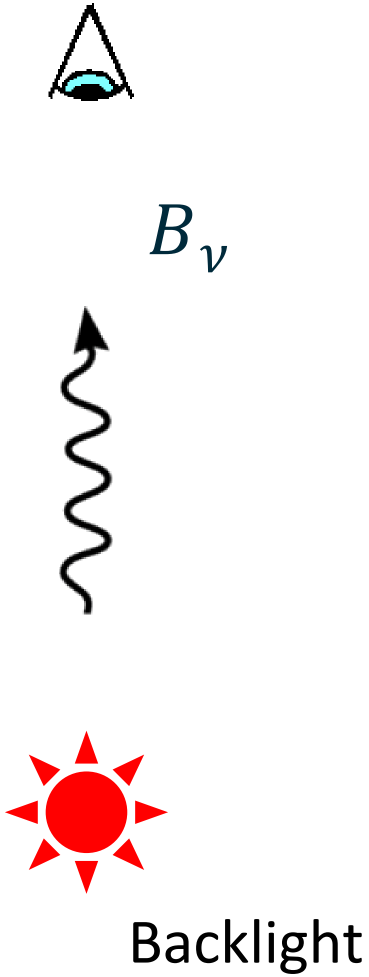
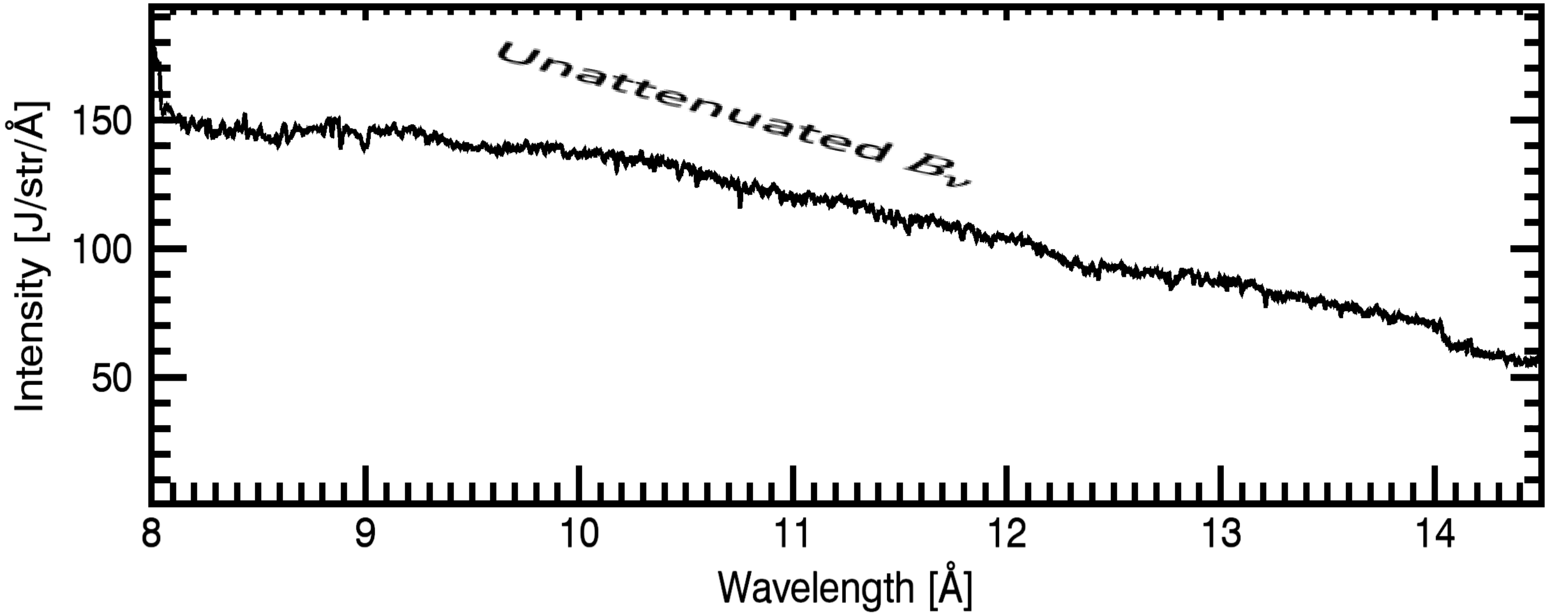
- **Define high-fidelity opacity data**
- **Pros and cons of NIF and Z**
- **Scrutinize each experiments and analyses**

Revisiting Z iron opacity results

How is opacity measured?
Why are experiments challenging?

Sample opacity is inferred by measuring backlight with and without the sample





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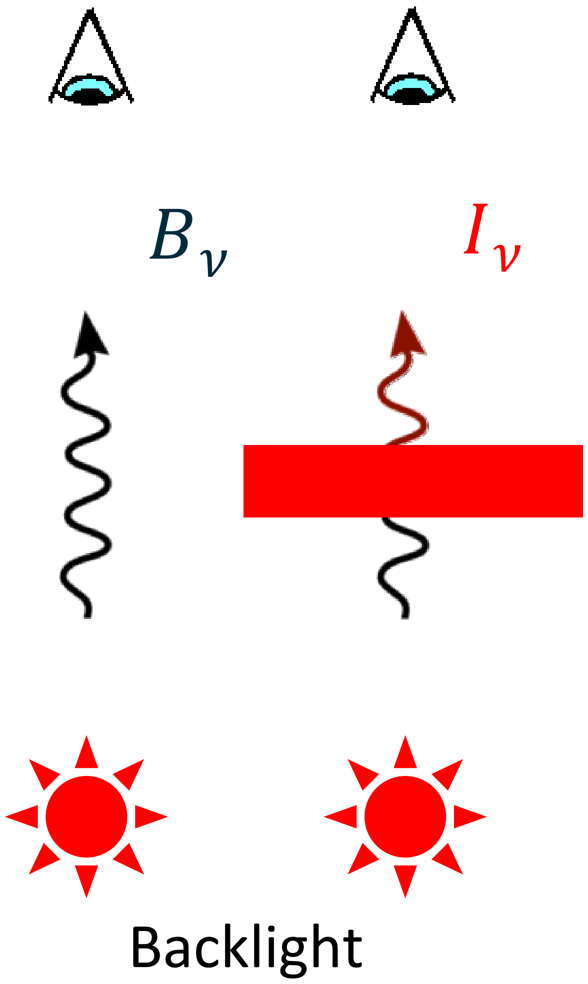

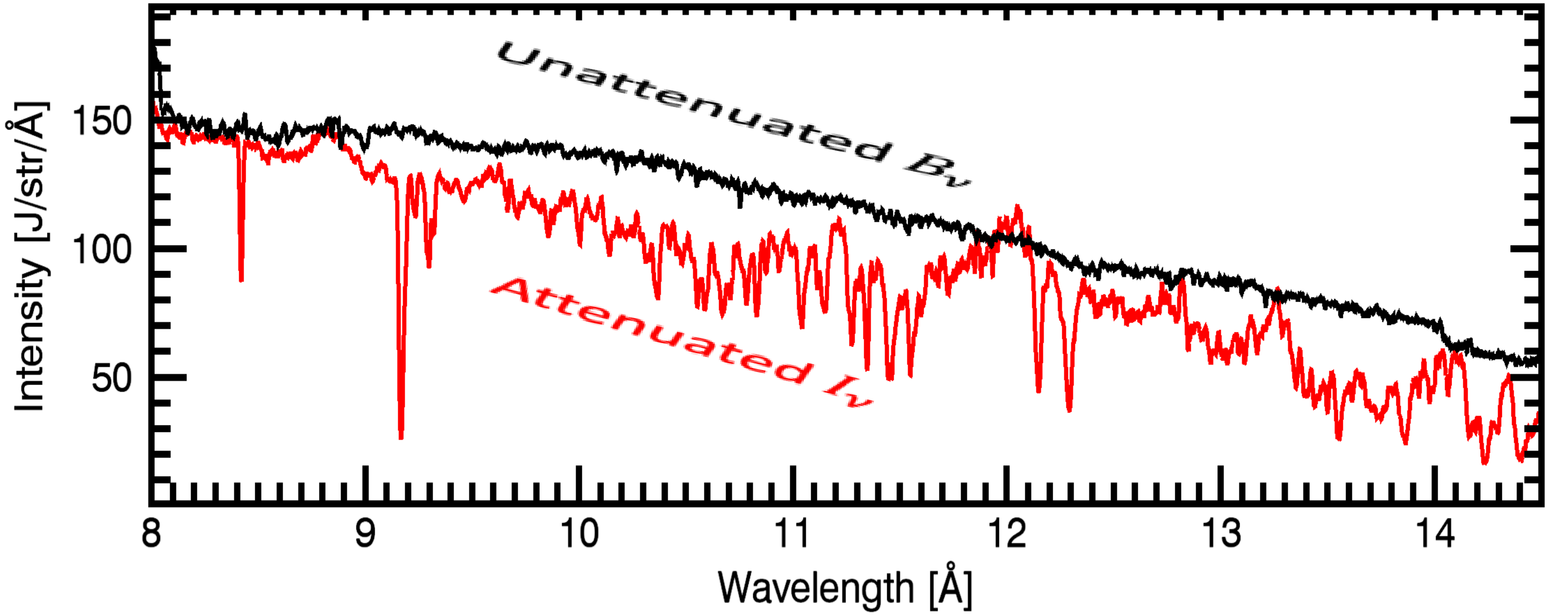

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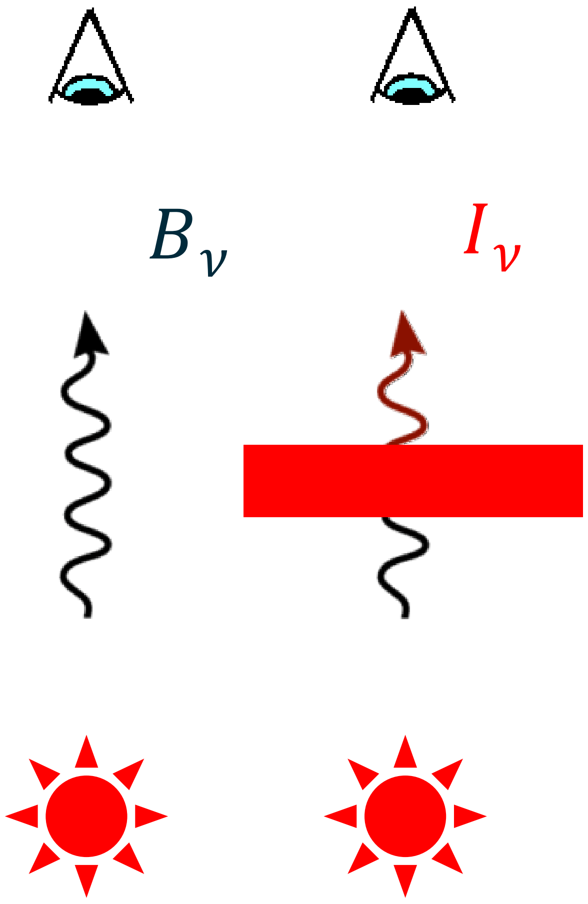
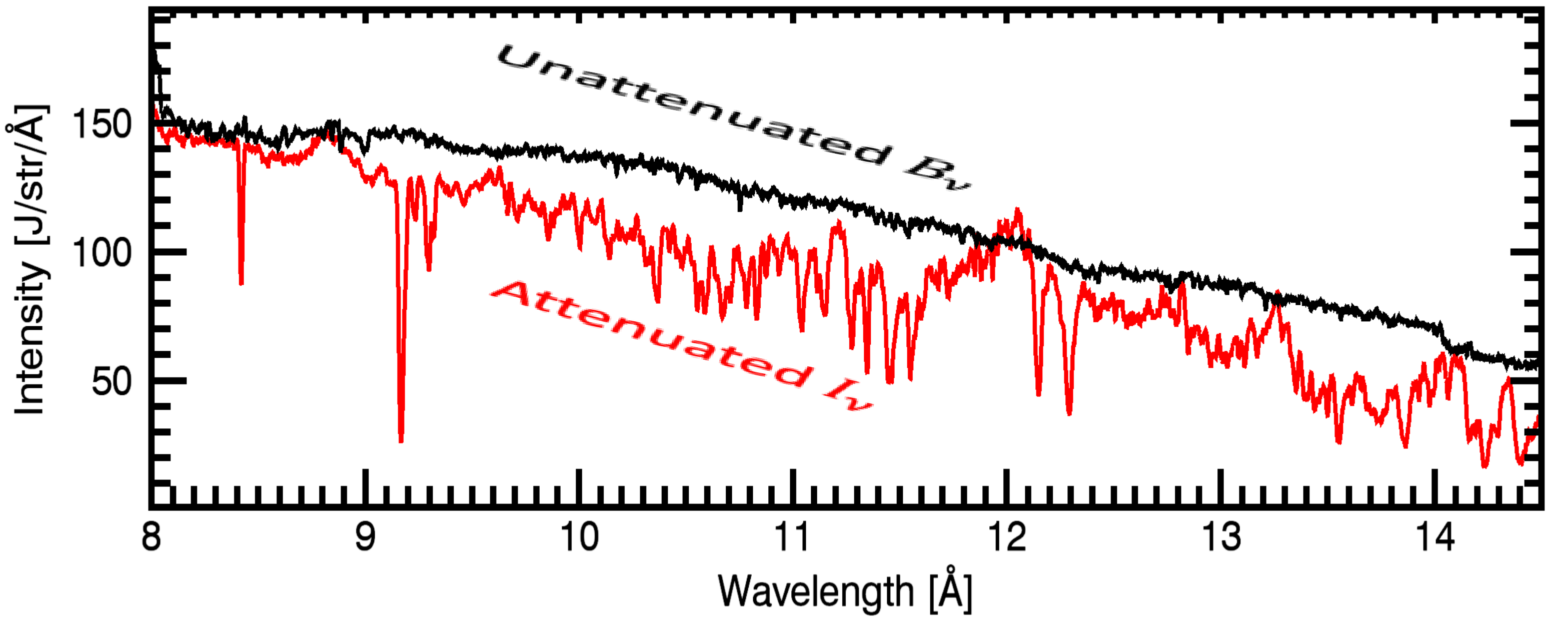
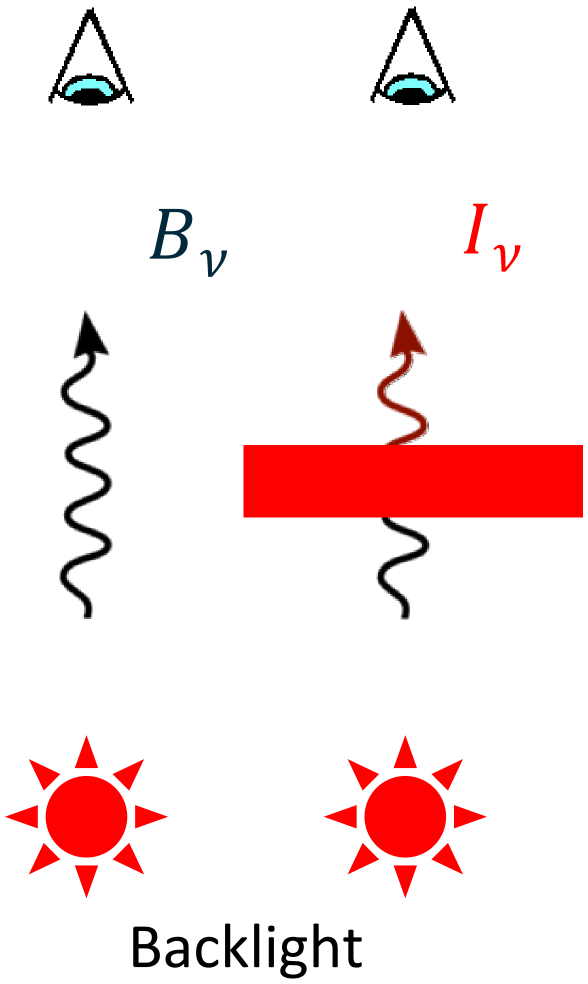


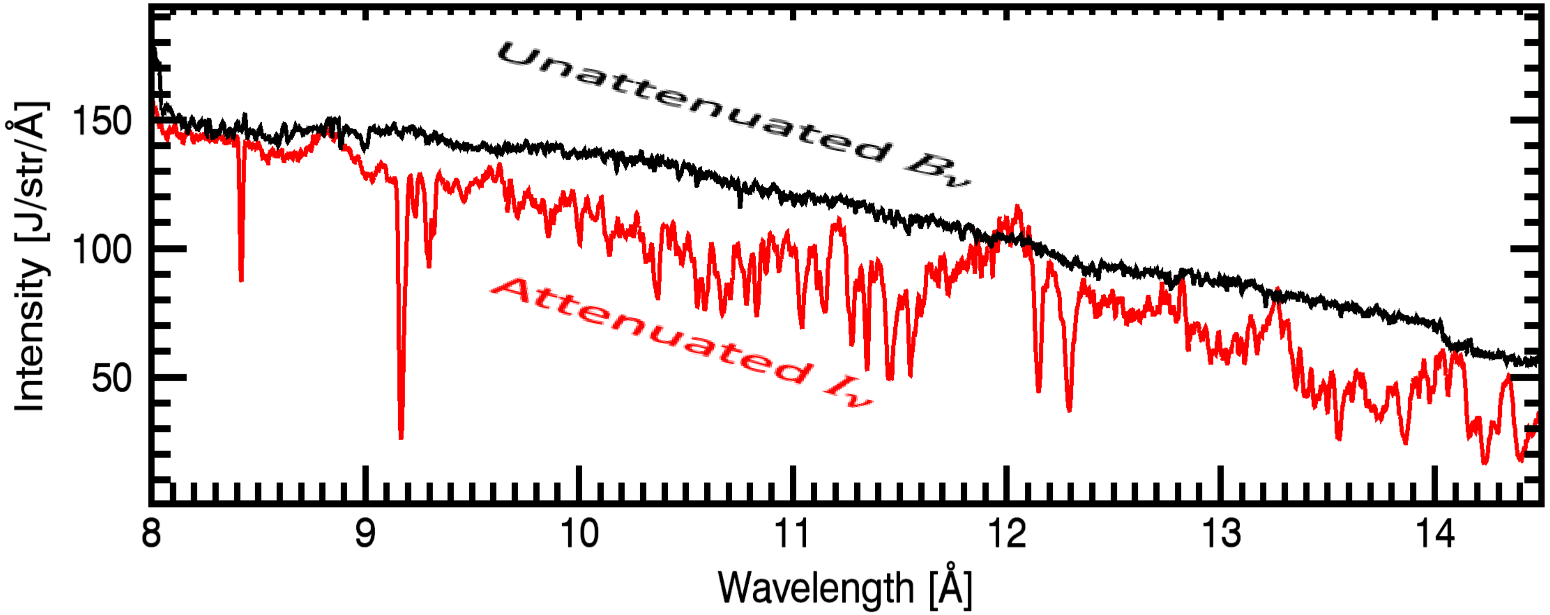


1. Determine transmission T_ν

$$T_\nu = \frac{I_\nu}{B_\nu}$$

Sample opacity is inferred by measuring backlight with and without the sample





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2. Convert T_ν to opacity κ_ν

$$\kappa_\nu = -\ln T_\nu / \rho L$$

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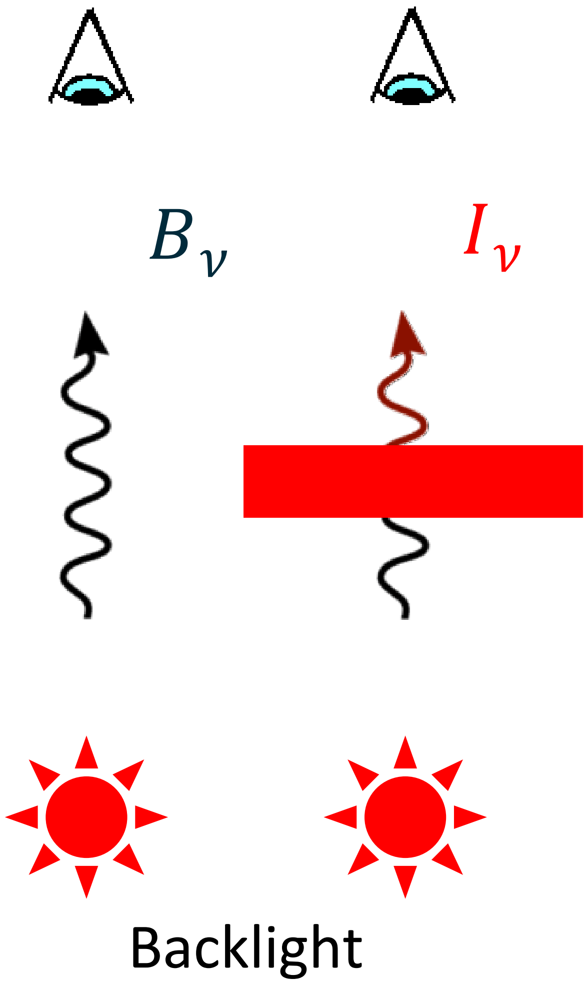

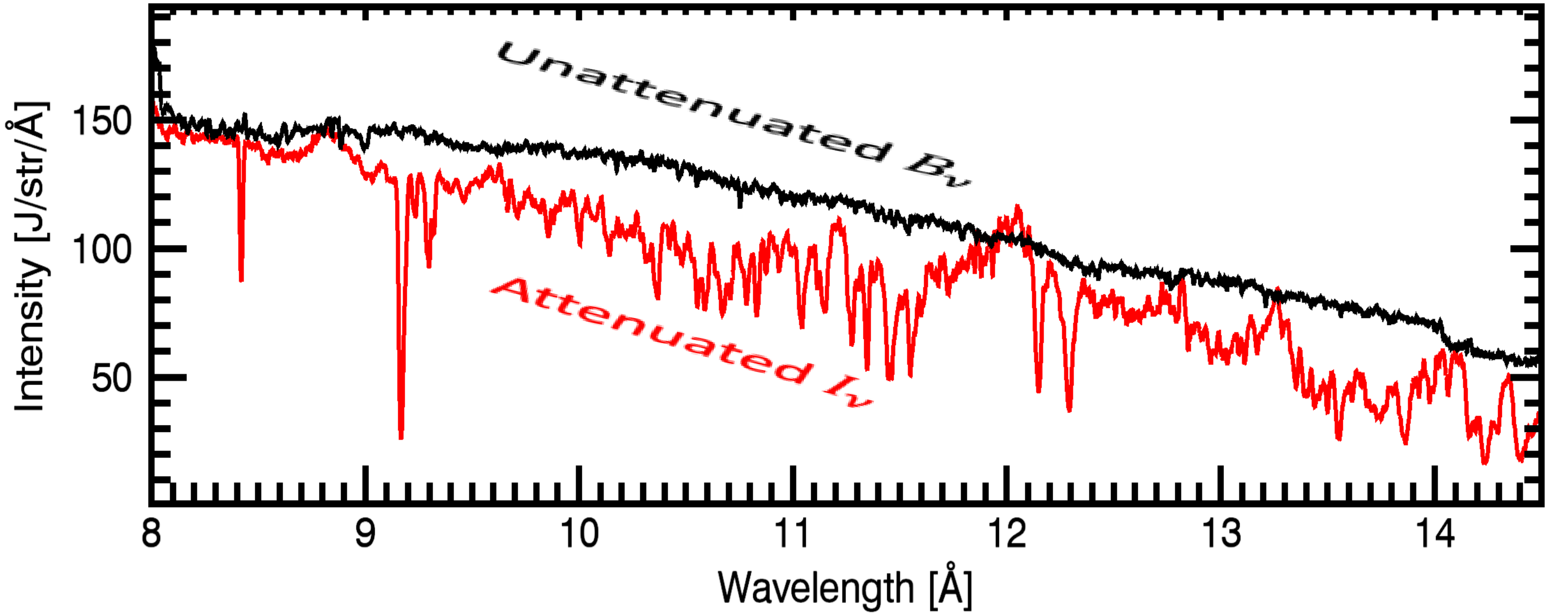

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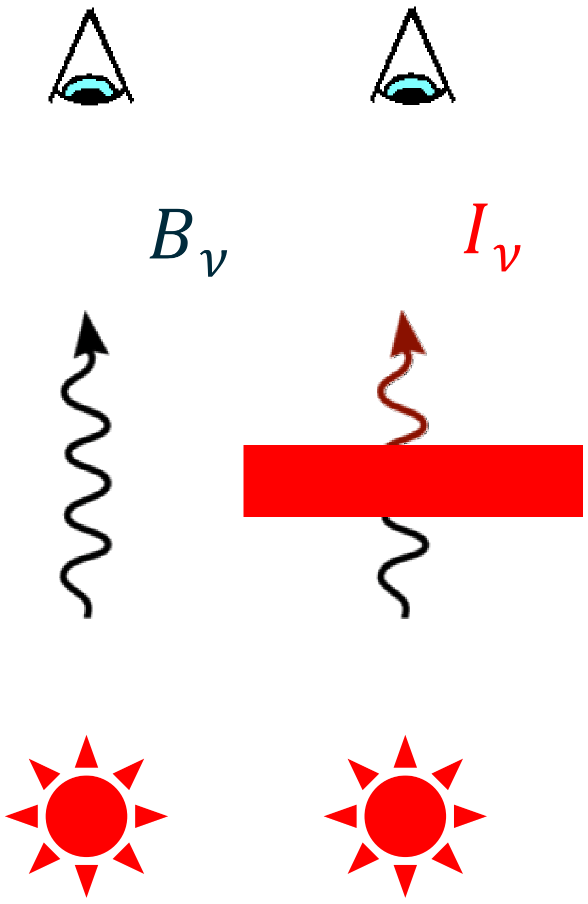

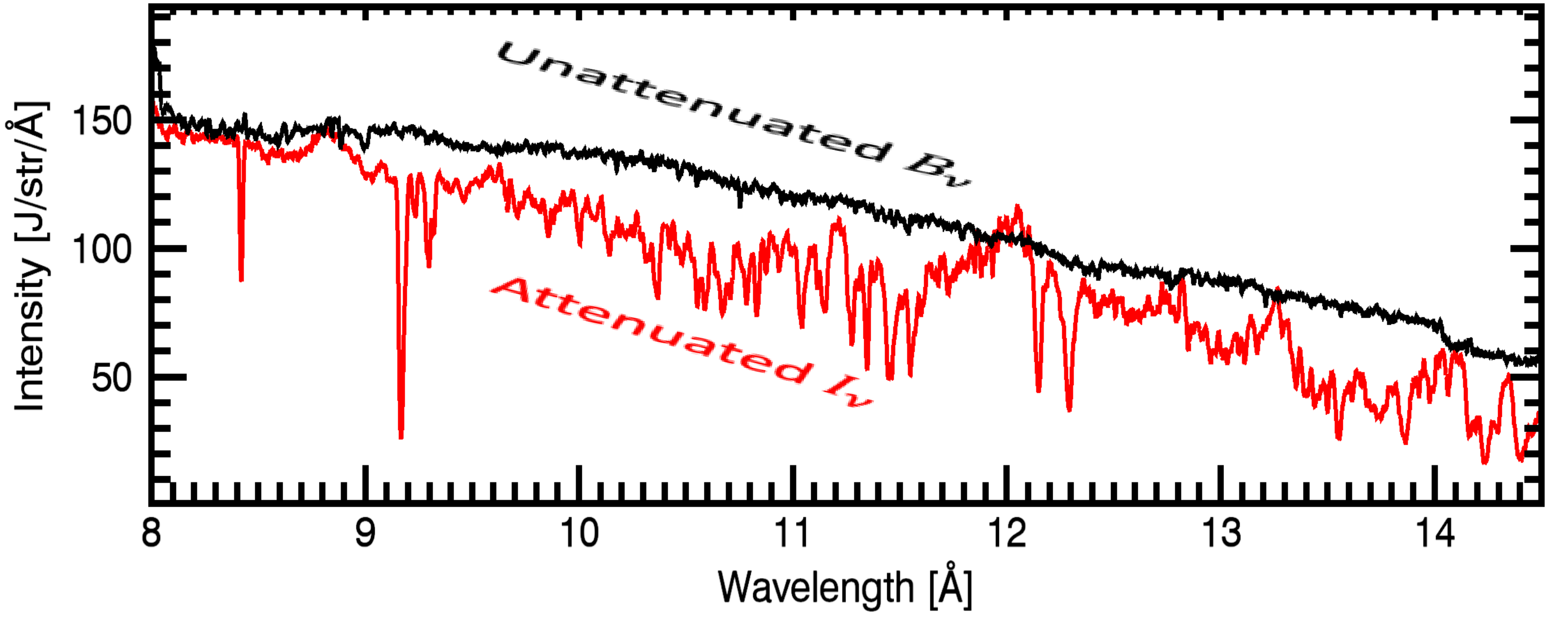

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Sources of uncertainty

- **Unattenuated B_ν**
- **Background ϵ_ν**
- **Sample thickness ρL**

Challenging requirements for HED opacity measurements

Opacity measurements

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Challenging requirements

- Bright backlight
- No gradients (spatial, temporal)
- Local Thermodynamic Equilibrium (LTE)
- Accurate plasma diagnostics

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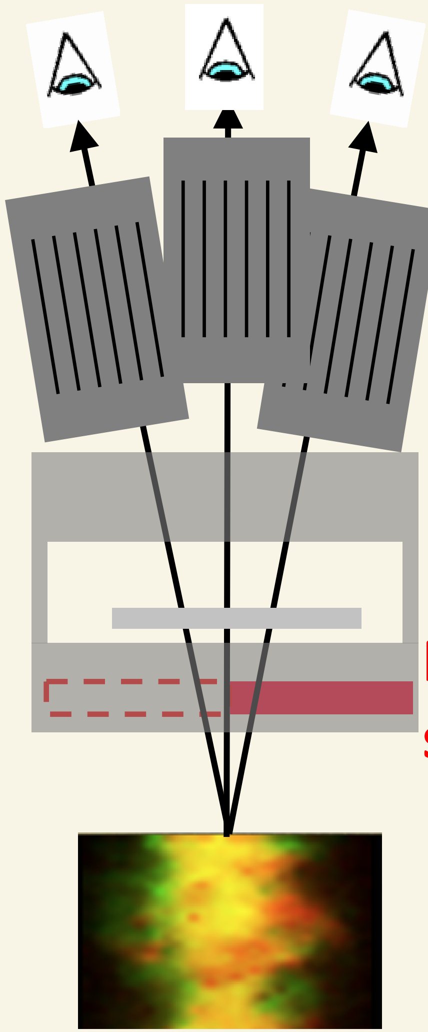
Focus of this talk

Experimental challenges are platform dependent

Approach1: Area backlight (e.g., Z)



Fe opacity sample

Pro: Negligible ϵ_ν

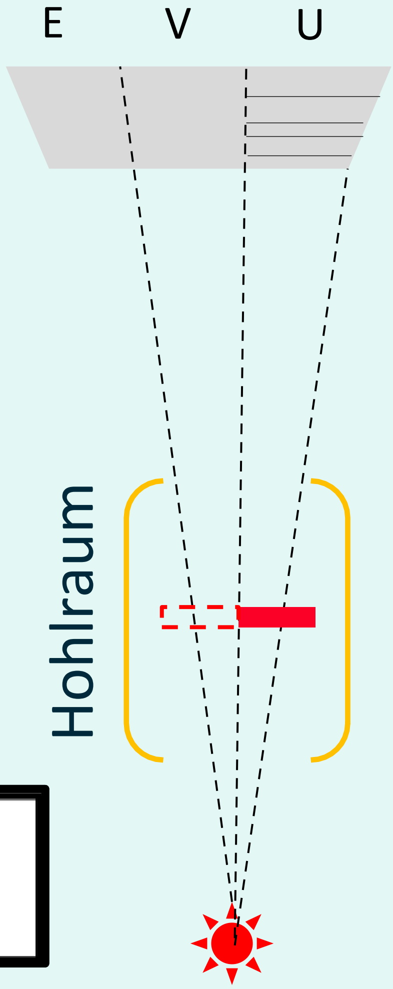
Con: Quantify B_ν

$$T_\nu = \frac{I_\nu - \epsilon_\nu}{B_\nu - \epsilon_\nu}$$

Approach2: Point projection (e.g., NIF)

Pro: Quantify B_ν

Con: Significant ϵ_ν



We use an areal backlight. Our main challenge is determining the unattenuated backlight intensity B_ν

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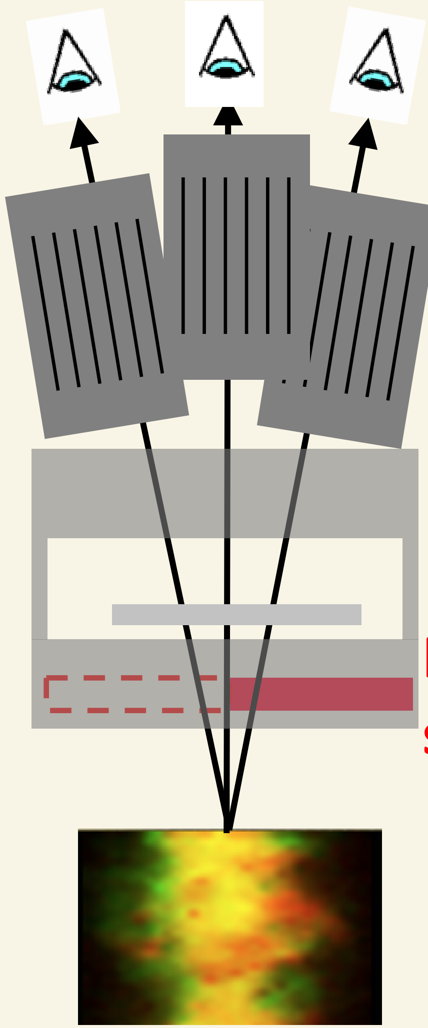

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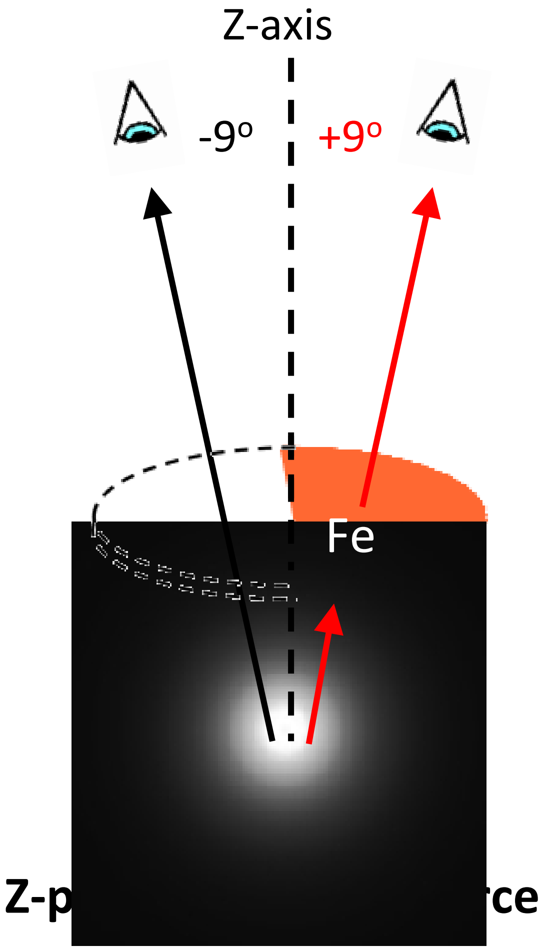
How to constrain B_ν at Z

- Use half-moon sample
- Field 6 spectrometers per experiment
- Perform many backlight-only experiments

➔ Key question is how to use this information

We use an areal backlight. Our main challenge is determining the unattenuated backlight intensity B_ν

Transmission spectra is determined by dividing attenuated by unattenuated spectra → ±20% uncertain



We use spatial shape to improve our accuracy of our transmission analysis

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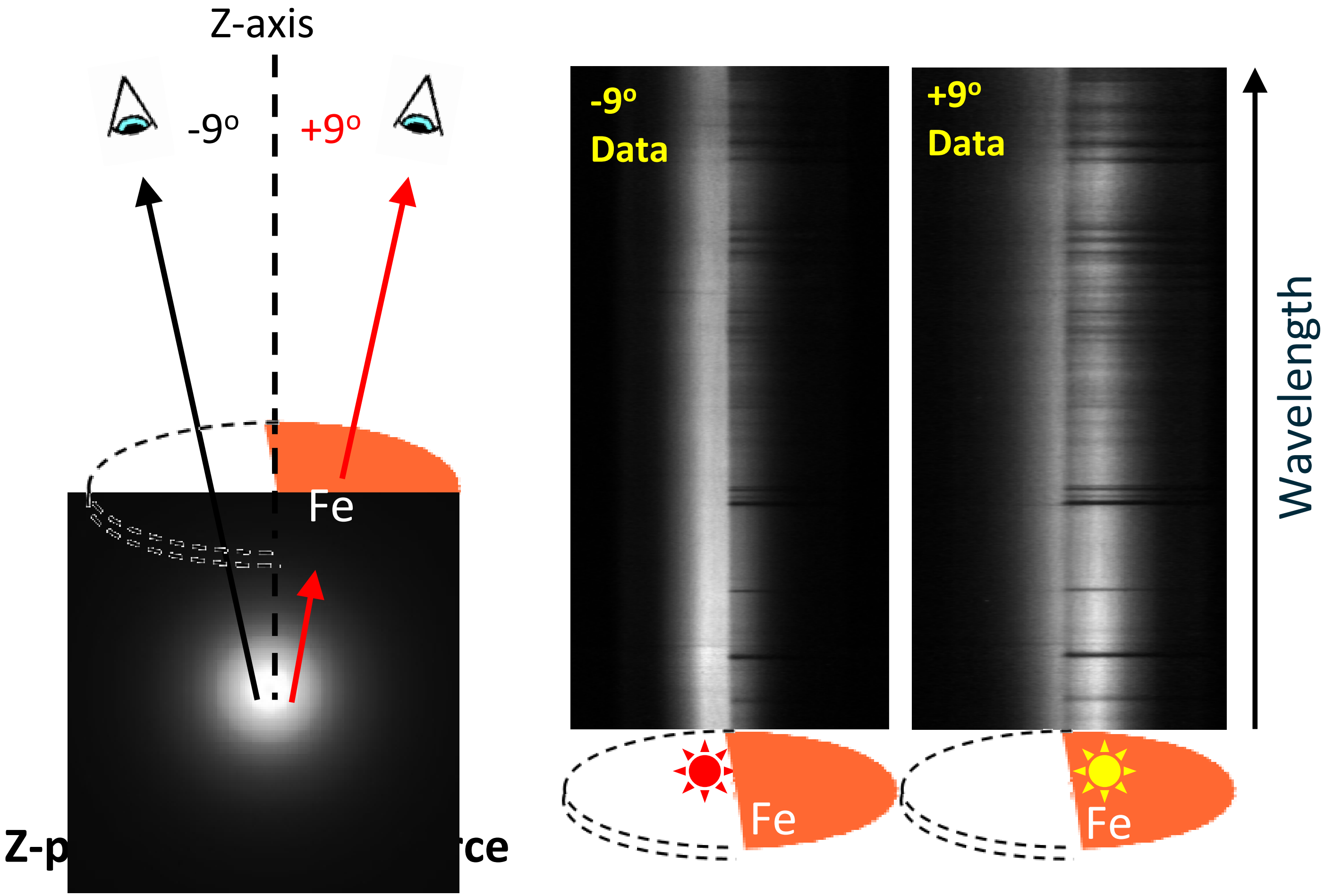

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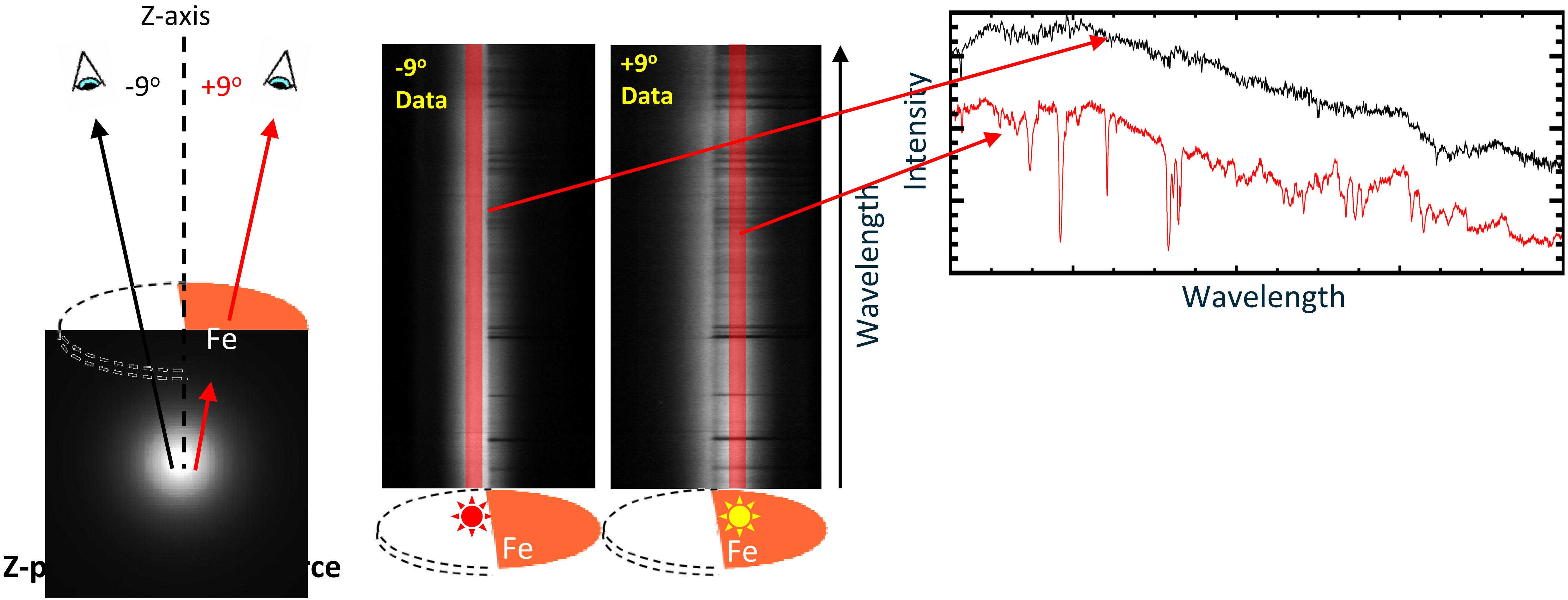

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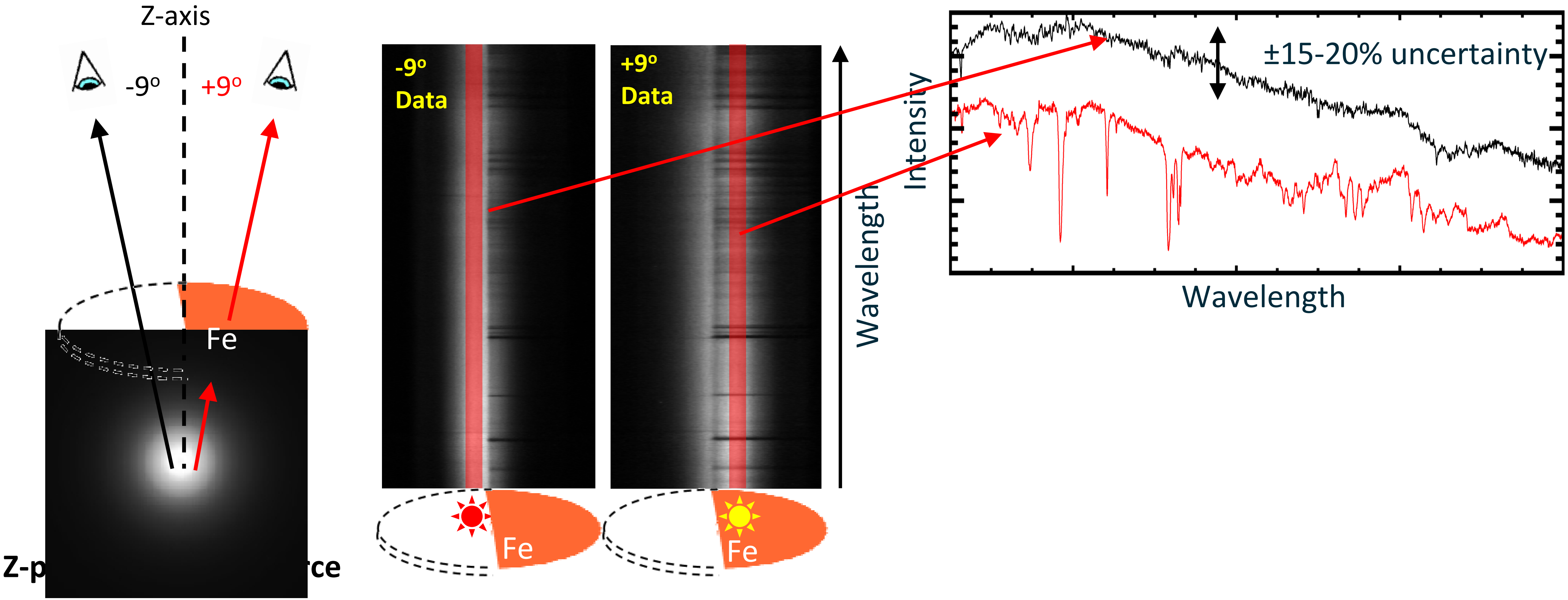

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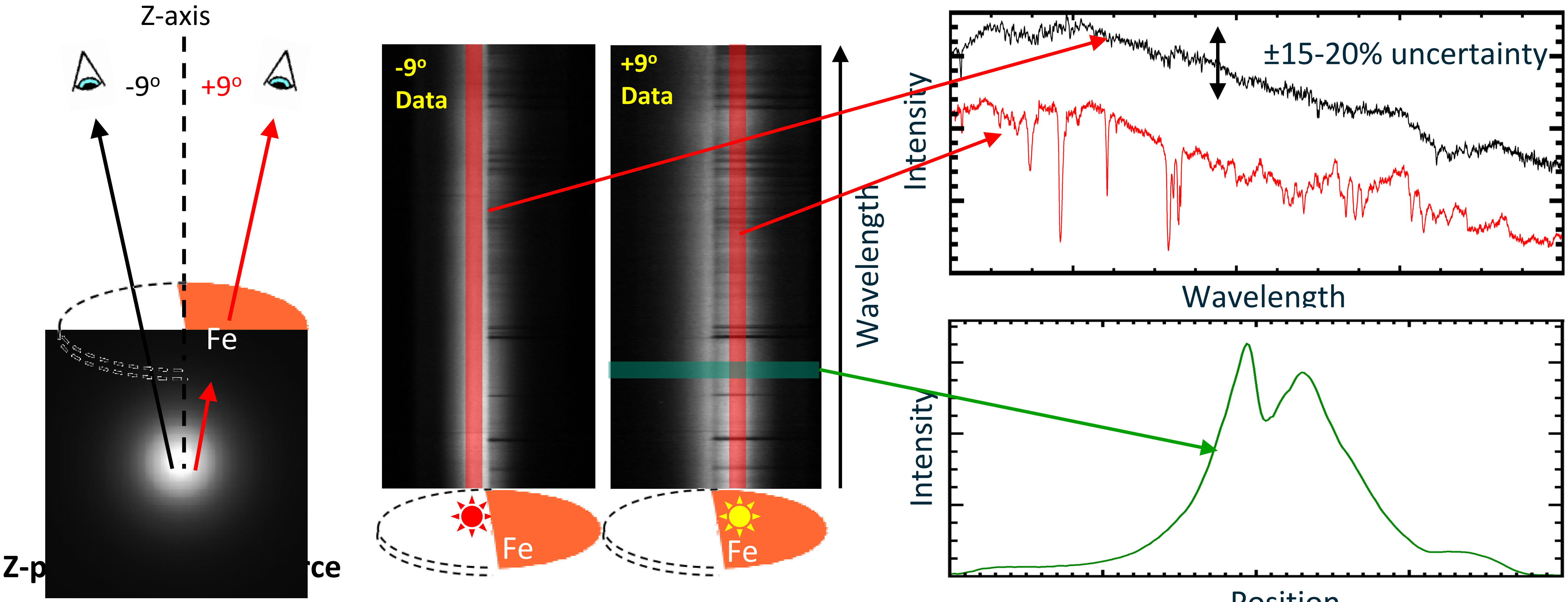

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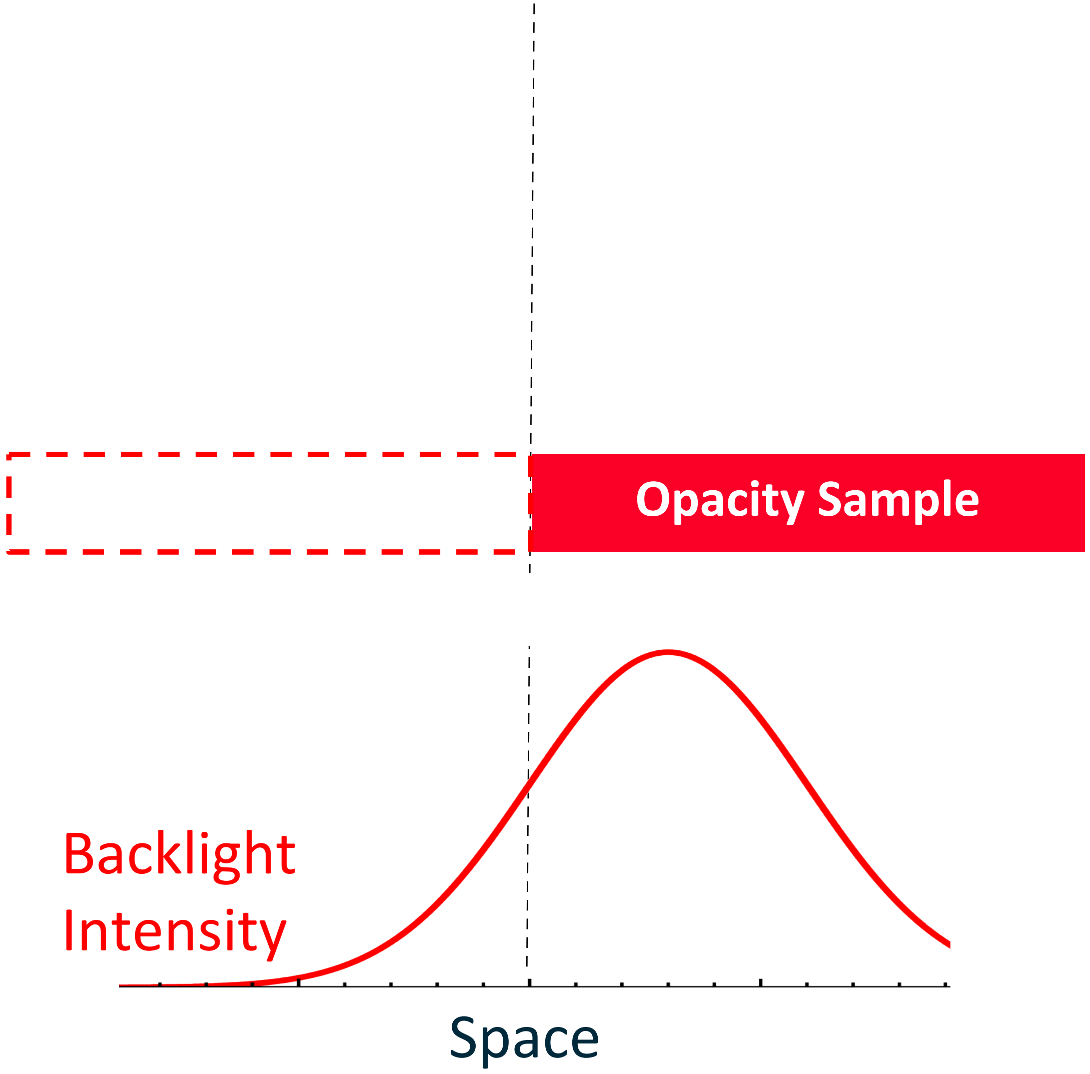
Spatial shape has unattenuated and attenuated side and provide essential clue on transmission



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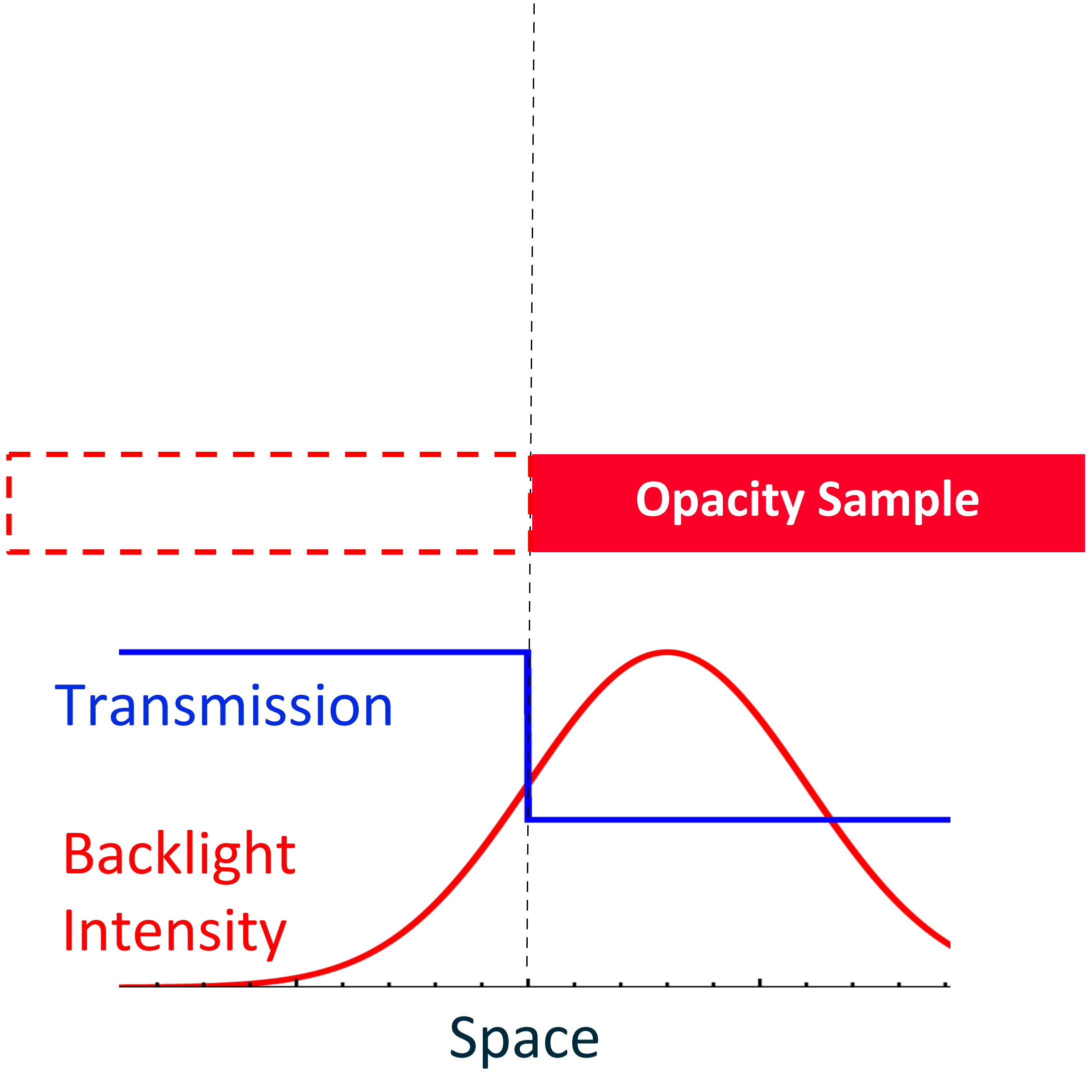

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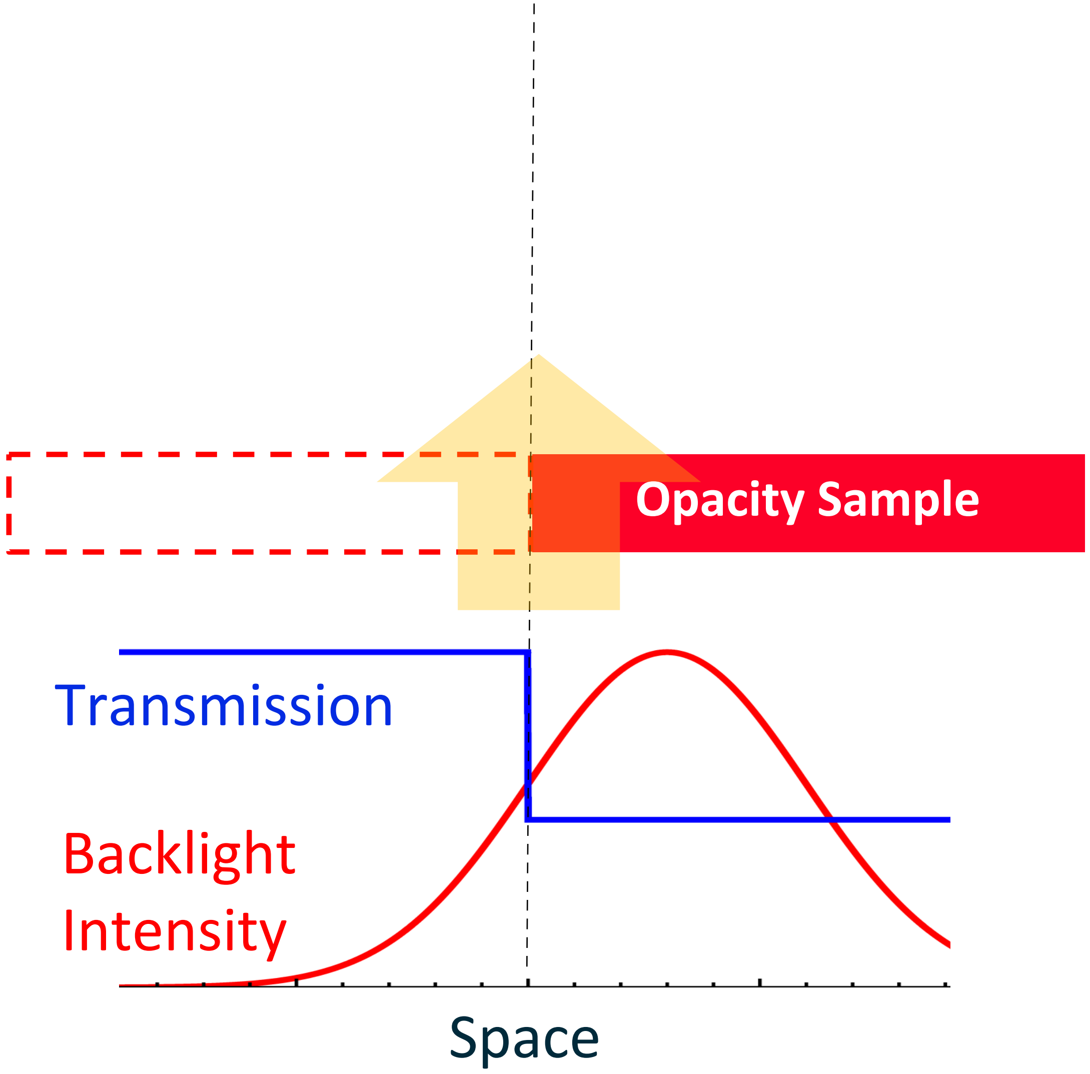

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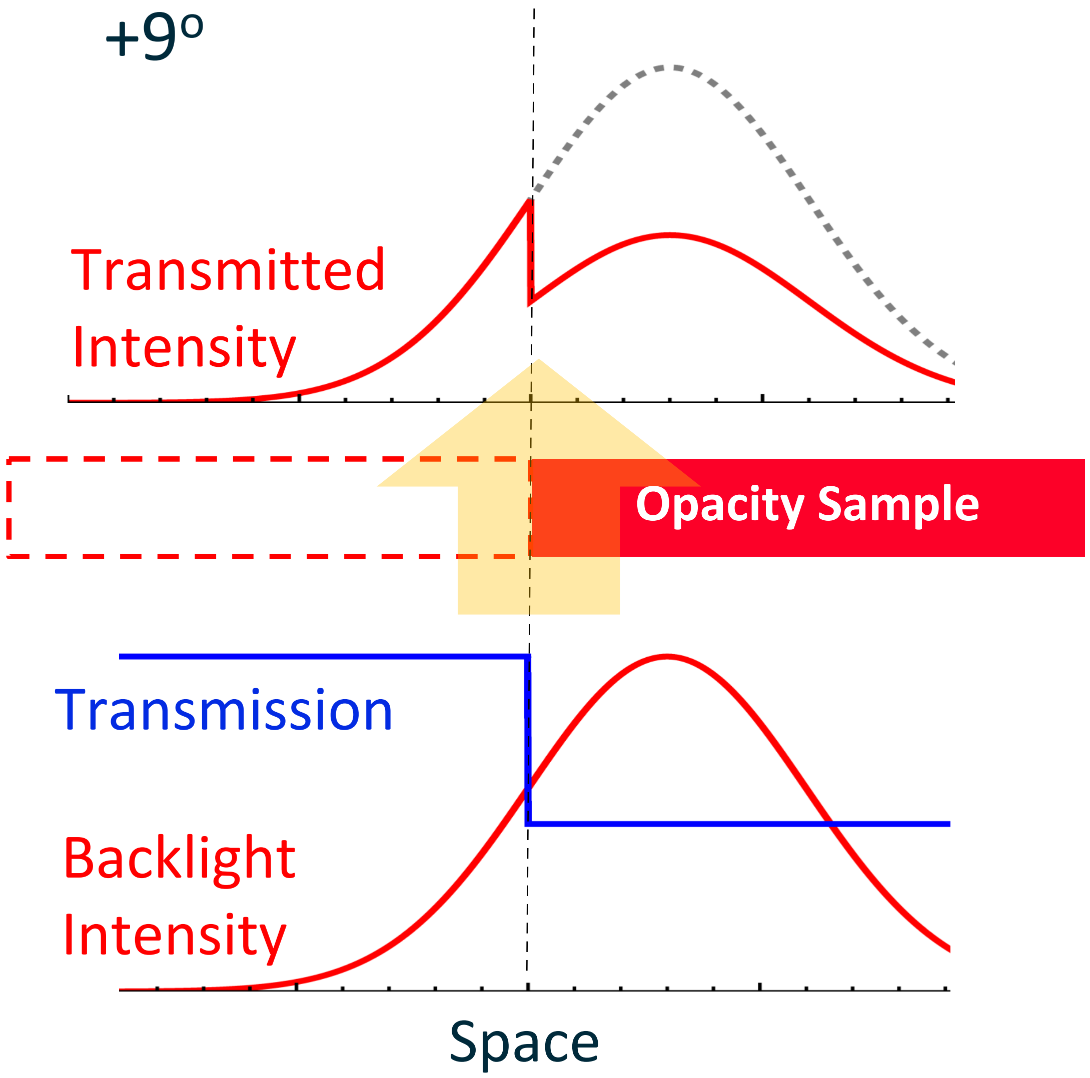

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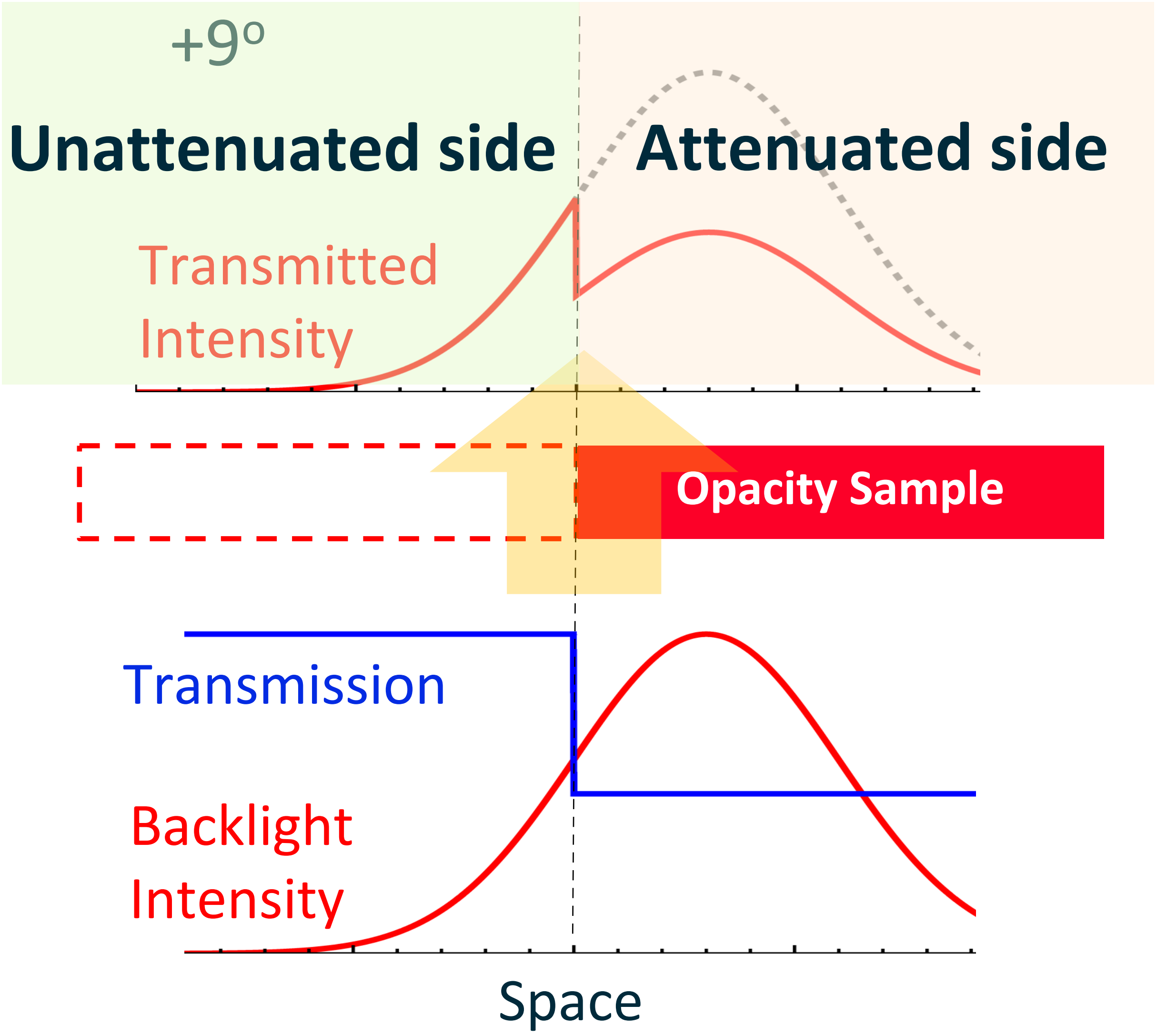
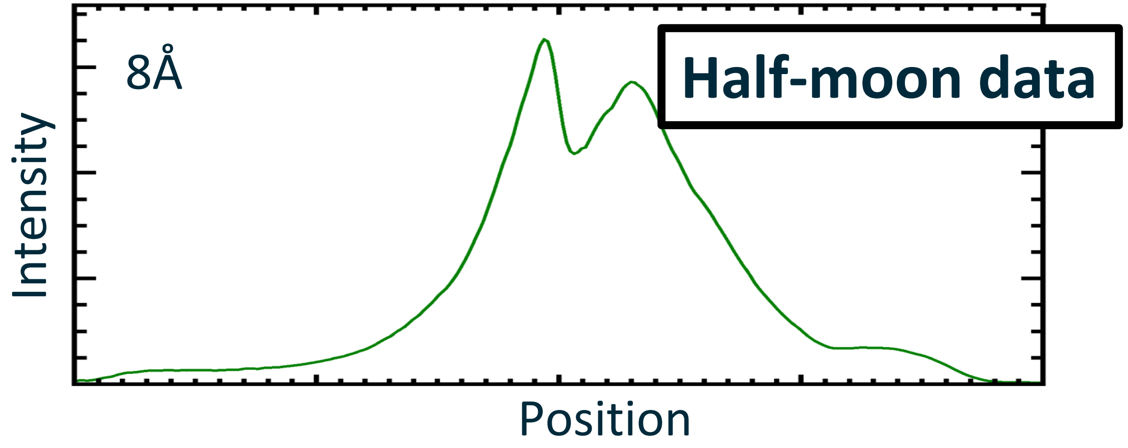
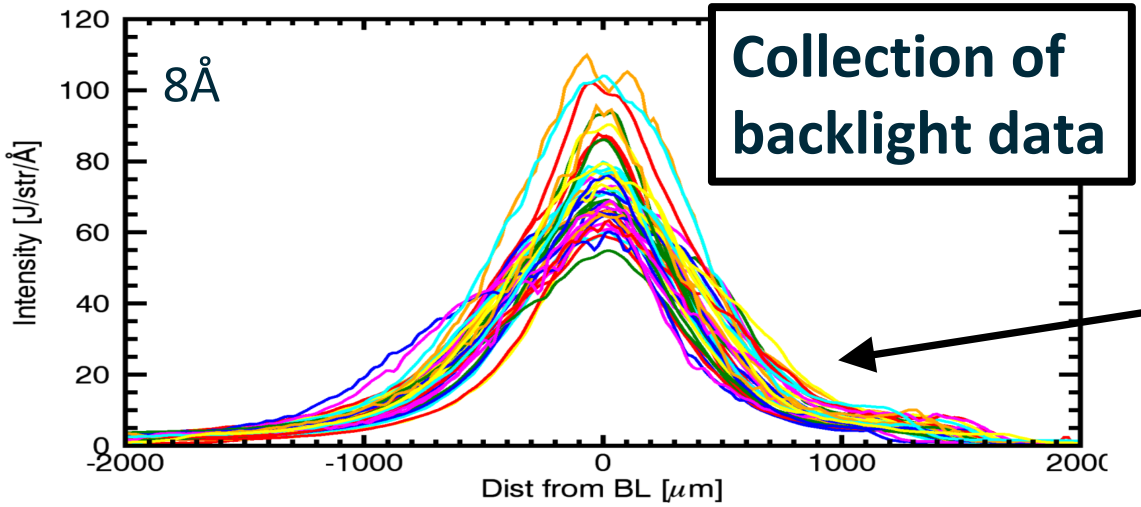


We analyze measured half-moon sample aided by backlight statistics to improve transmission accuracy

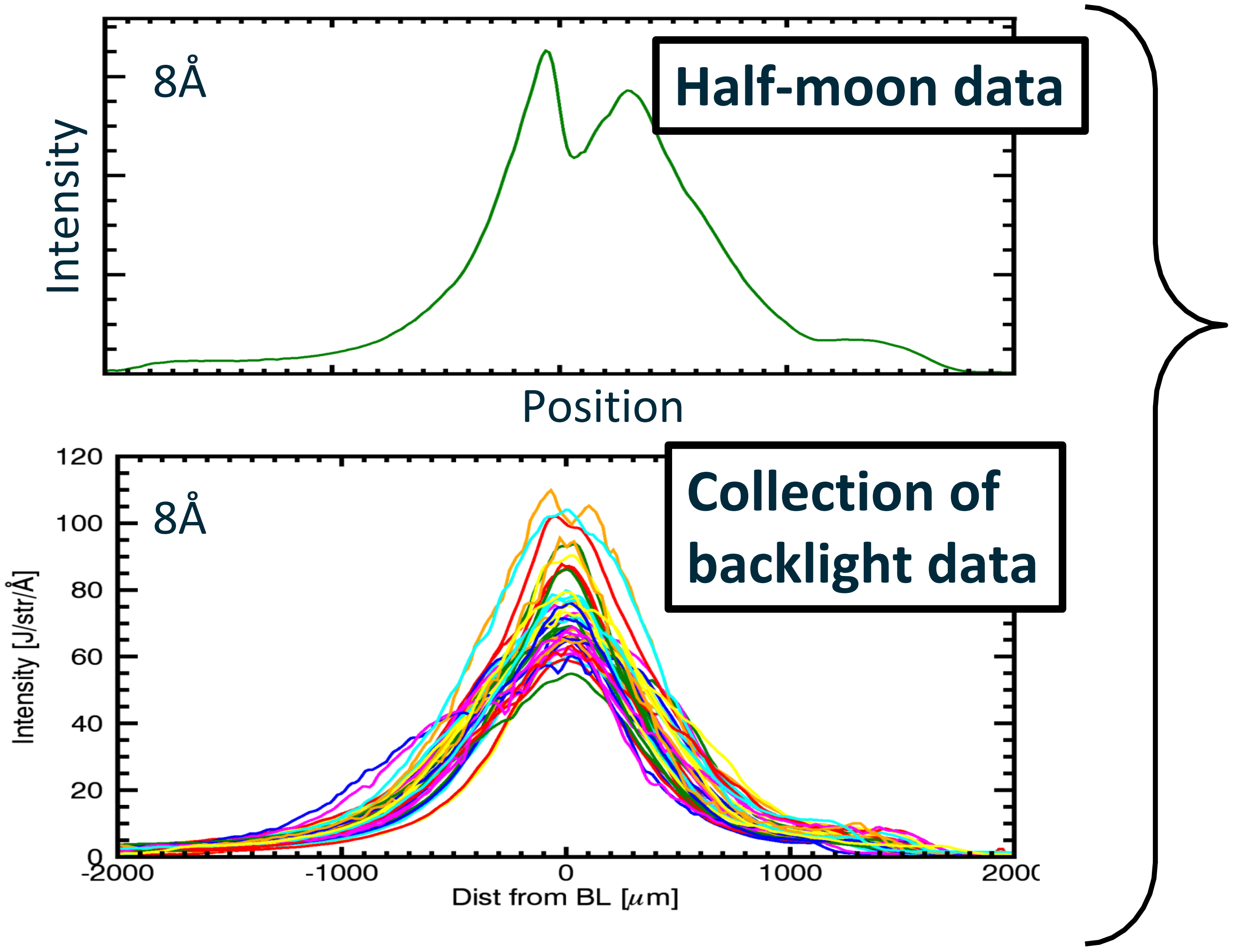


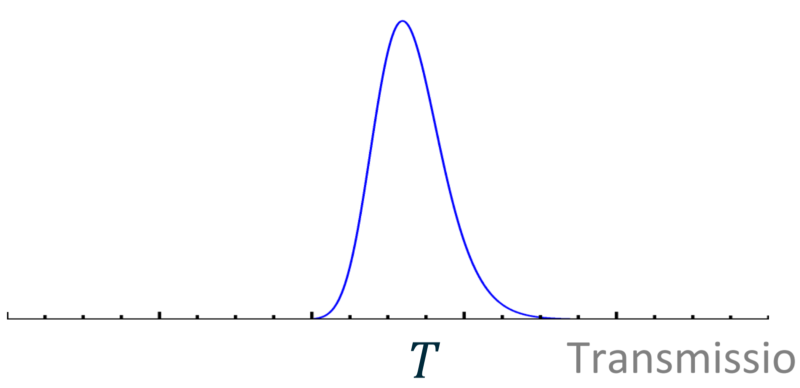


This provides calibration to the actual backlight radiation

≡ Calibration data

We analyze measured half-moon sample aided by backlight statistics to improve transmission accuracy





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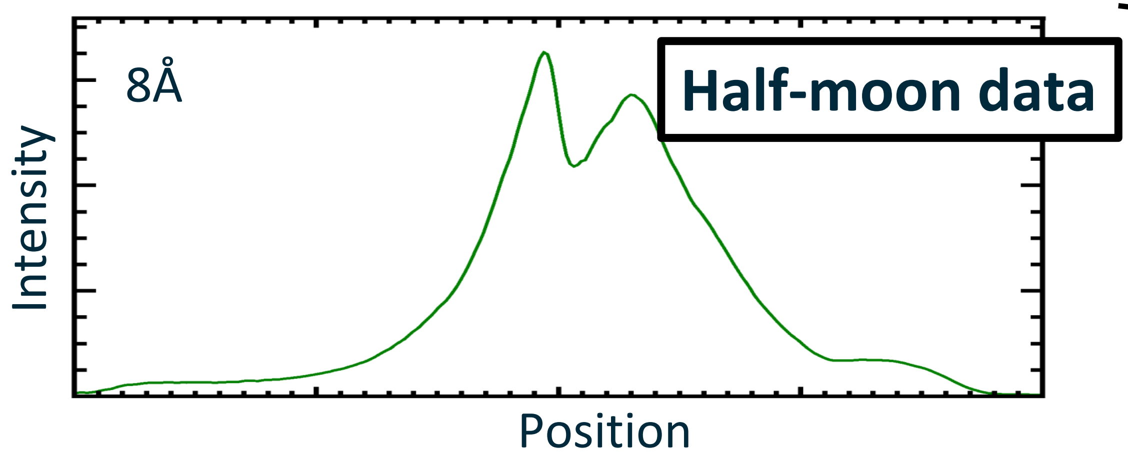

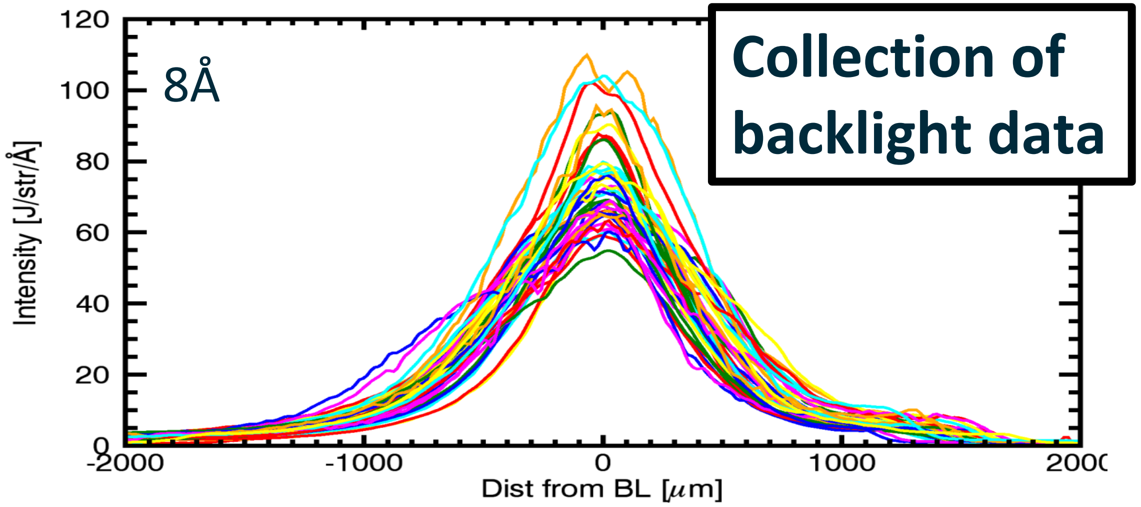

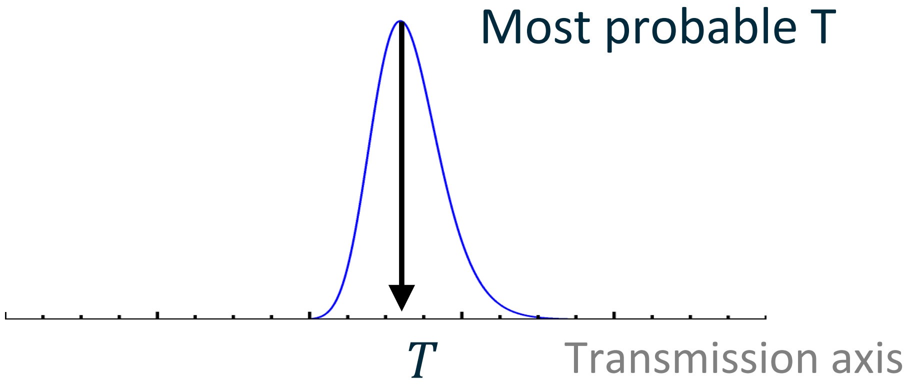

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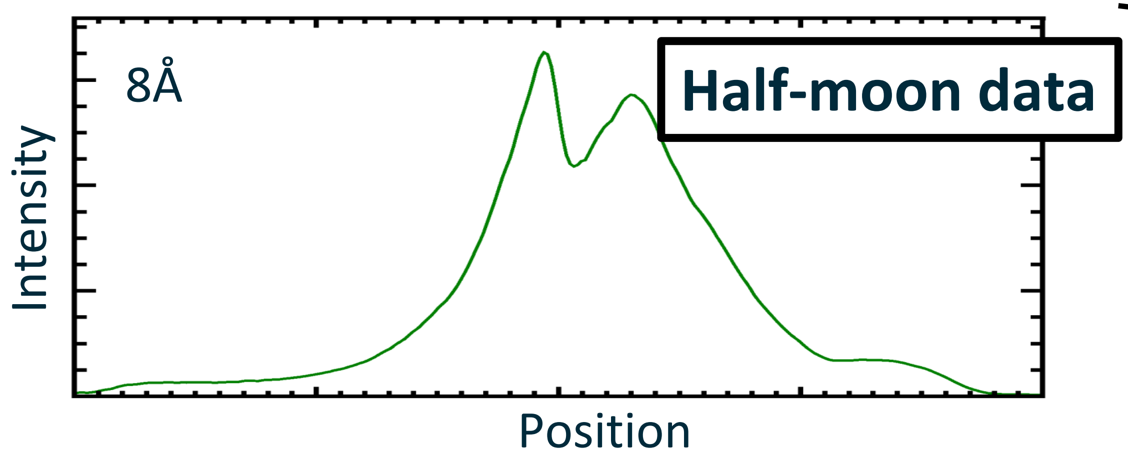
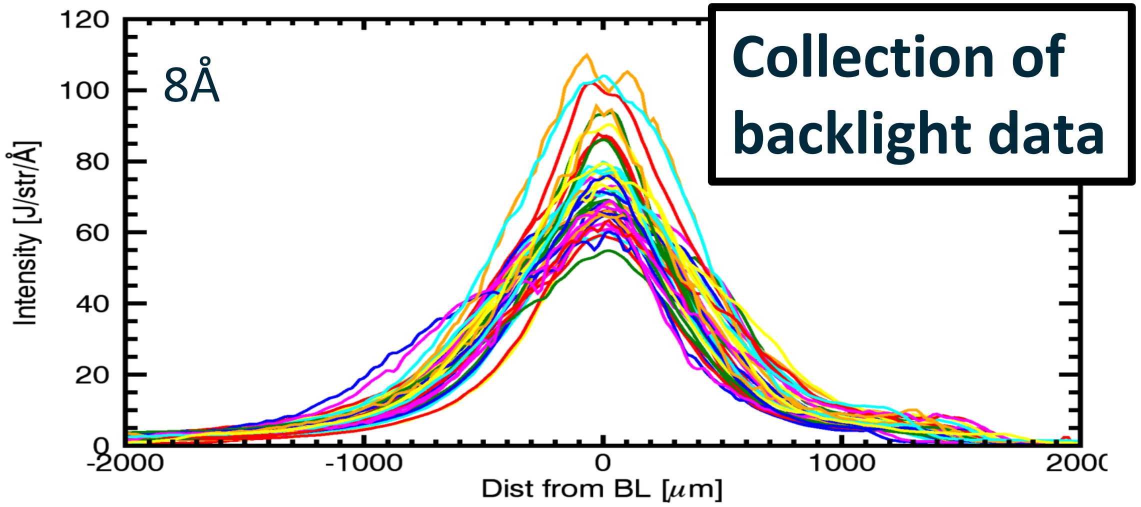
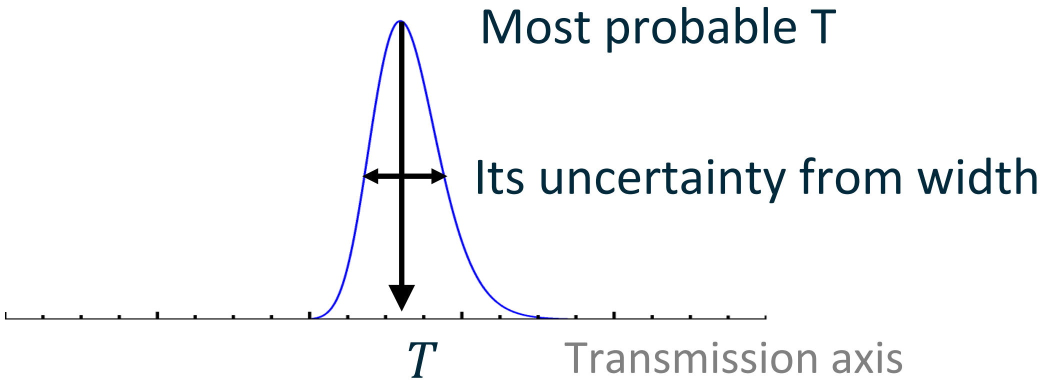


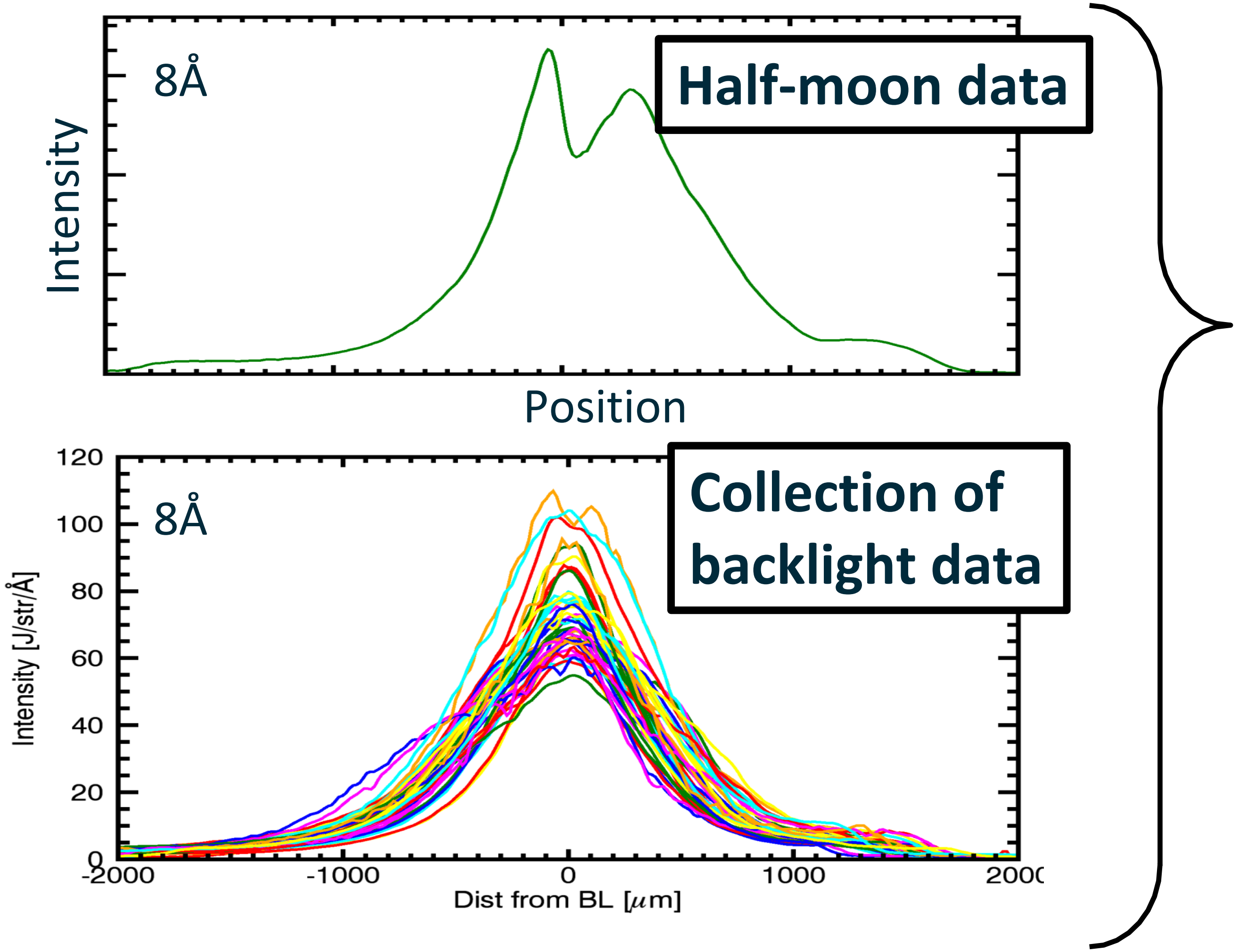


Transmission Probability Distribution (TPD)



[1] Nagayama et al PRL (2019)

We analyze measured half-moon sample aided by backlight statistics to improve transmission accuracy



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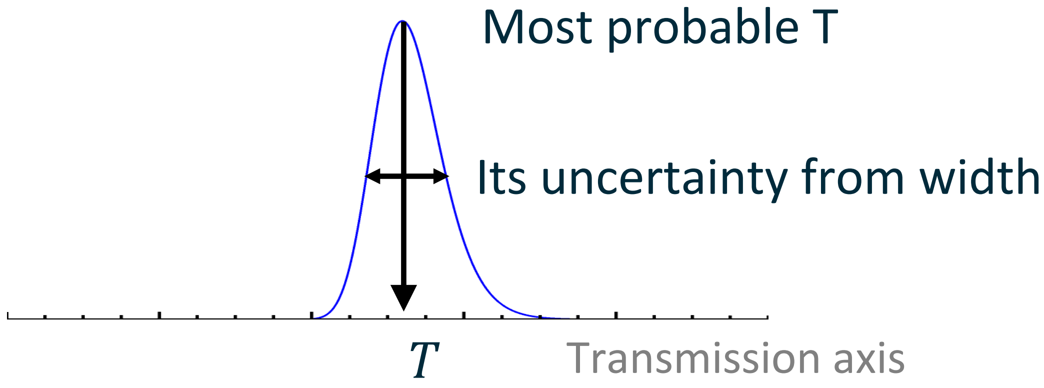
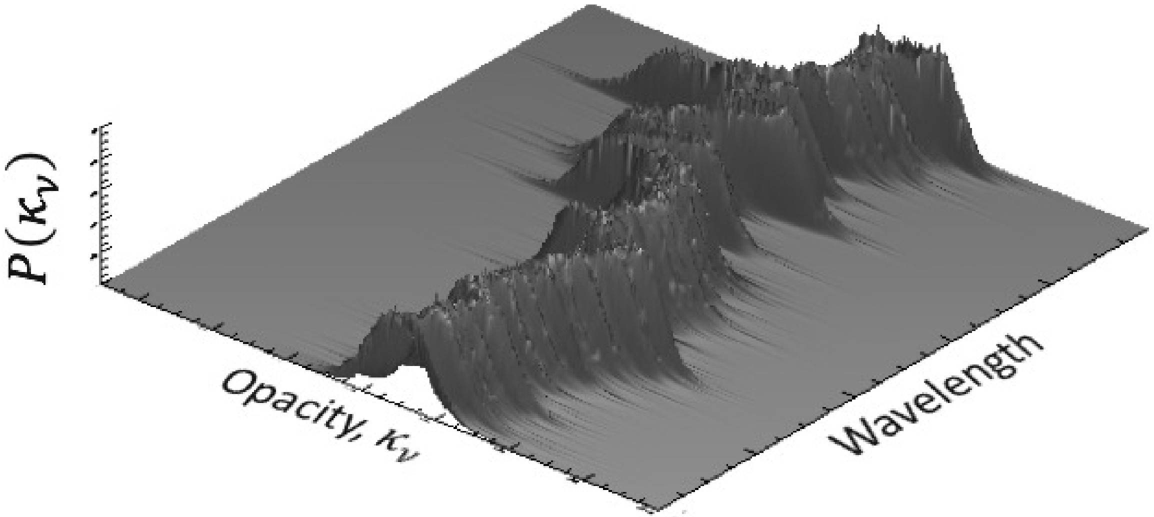


We developed multiple TPD methods that rely on different backlight statistics.

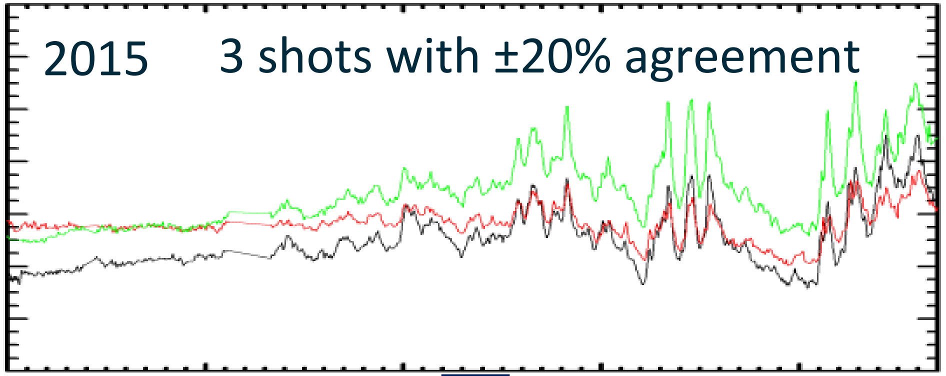
TPD1 … Peak Brightness
TPD2 … Slope over boundary
⋮

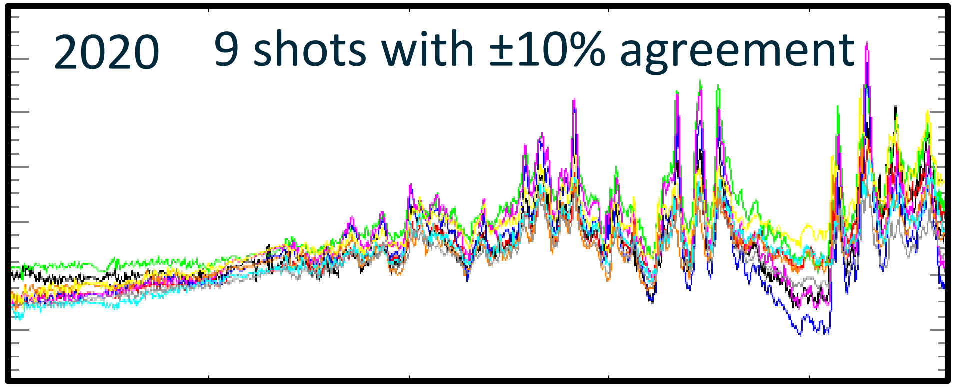
TPDs* are converted to opacity probability distribution by propagating all three sources of uncertainties

Asymmetric non-Gaussian opacity PDF*



- Large volume of backlight-only data statistics
- Monte Carlo for robust errors propagations
  - Backlight intensity, B_ν
  - Background, ϵ_ν
  - Sample areal density, ρL





Limitation: Old TPD methods rely on brightness reproducibility in some ways

TPD = Transmission Probability Distributions

Backlight brightness changed over the decade due to experiment and diagnostic changes

We have been performing opacity experiments ***more than a decade***

Changes we made

- Spectrometer improvements
- Crystal
  - Material (KAP, RAP, PET)
  - Removal of 013 plane
  - Crystal edge cover
- Aperture height
- Reflectivity models (XRV, XOP)

} Could affect apparent brightness reproducibility

- **Keep collecting backlight-only data for accurate use of old TPD methods**
- **Develop new TPD methods that do not rely on brightness reproducibility**

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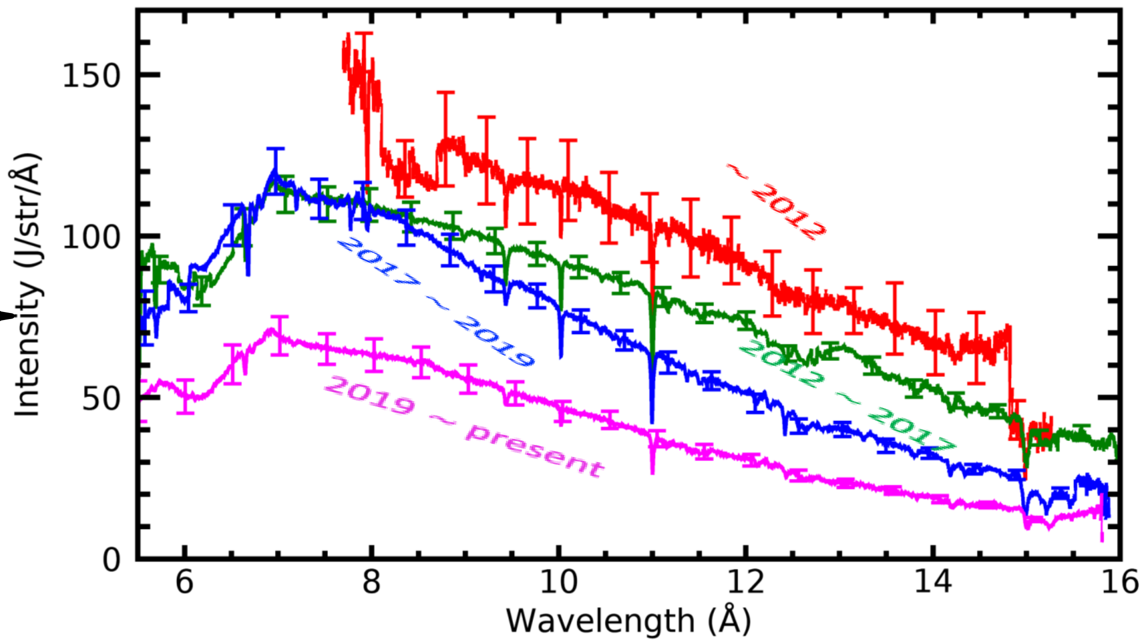
Backlight changes over the decade

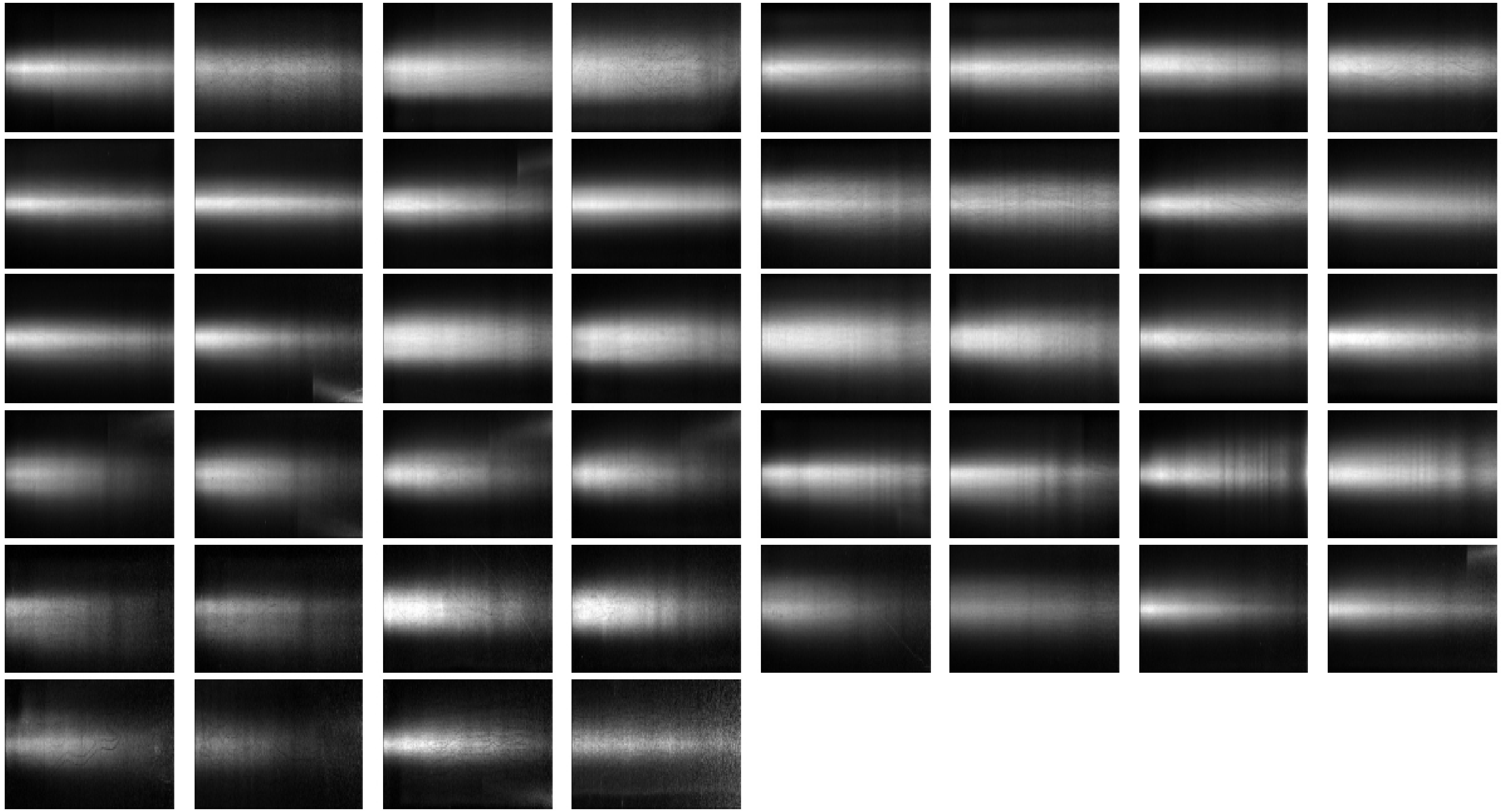


- **Keep collecting backlight-only data for accurate use of old TPD methods**
- **Develop new TPD methods that do not rely on brightness reproducibility**

Over the past three years, we continued to perform BL-only data to improve backlight statistics

With KAP crystal (44→62)

Before 2019 (44)



We have also increased the number of RAP backlight data (8 → 19)

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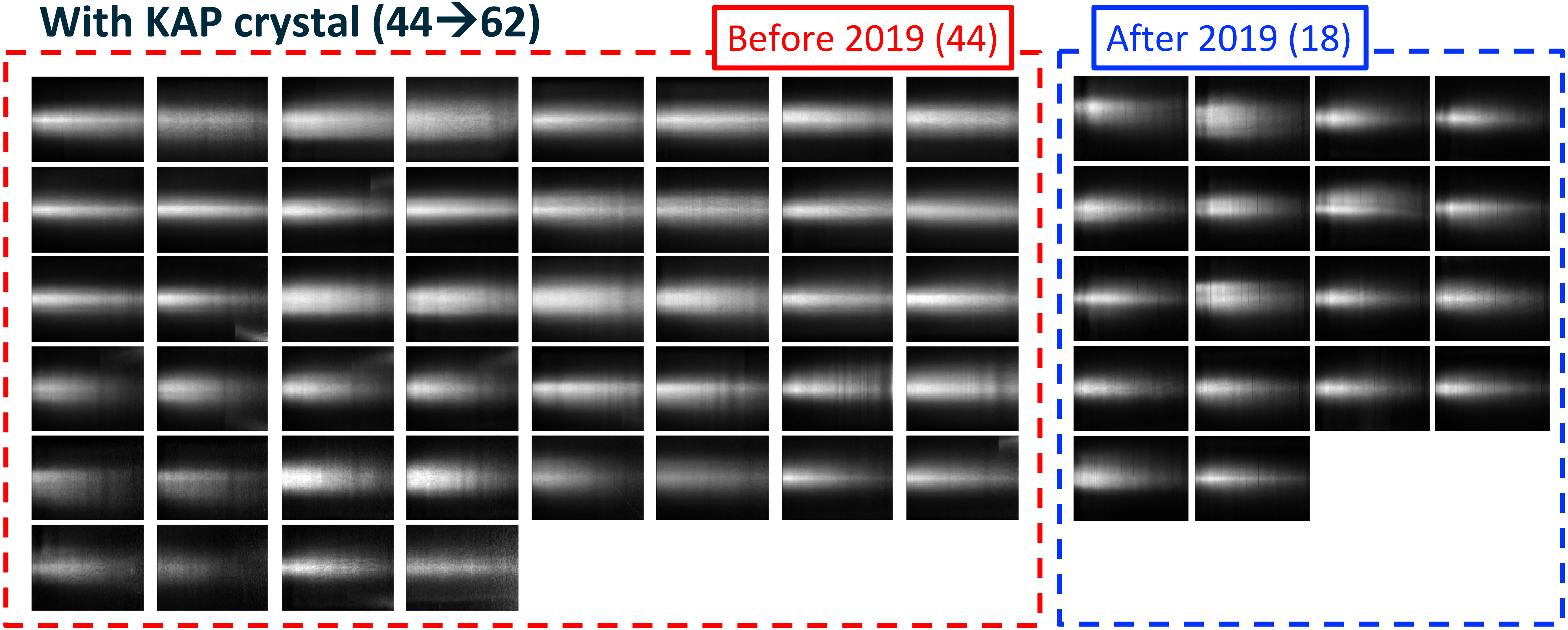

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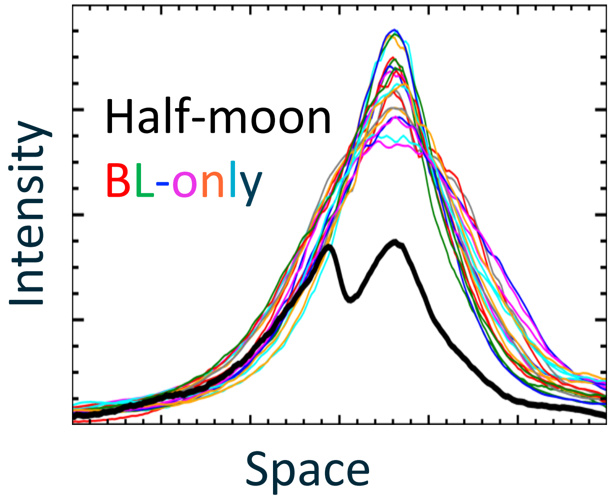
Spatial shape

Reproduce spatial shape after correcting transmission

Need collection of spatial prof.



Spectral shape

Assume transmission at one wavelength is known
➔ High-transmission method

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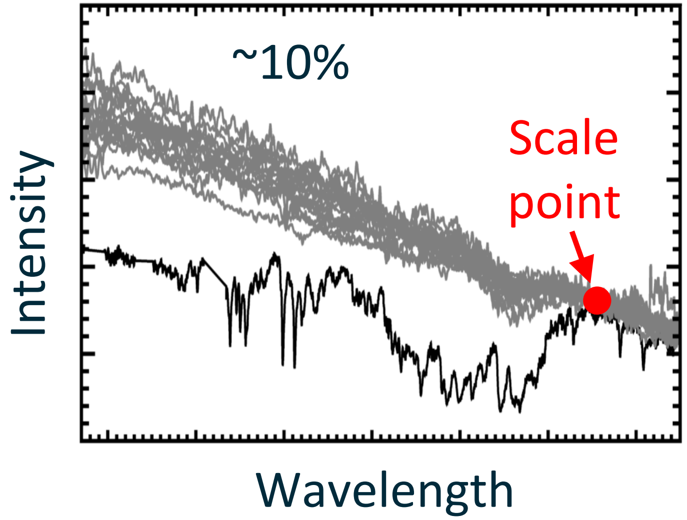
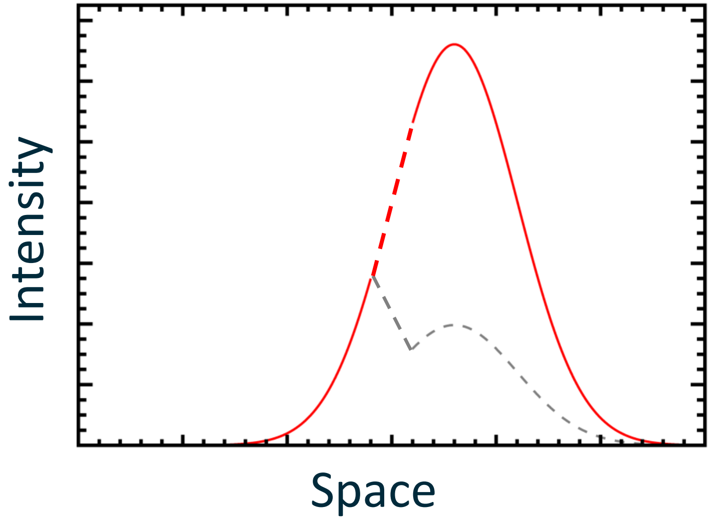


Polynomial fit

Search for transmission such that its correction produce a smooth spatial profile

No BL statistics needed



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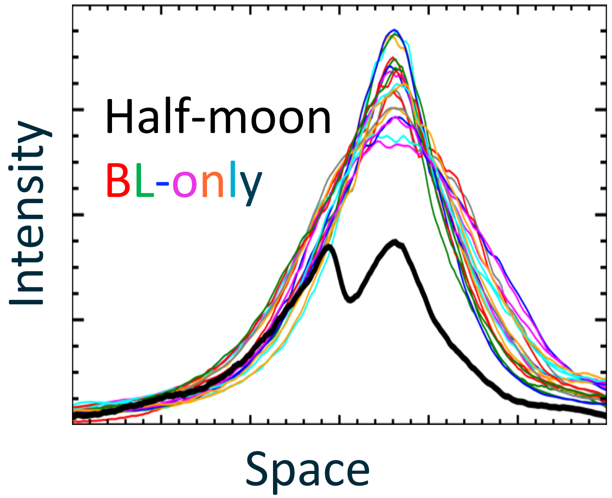

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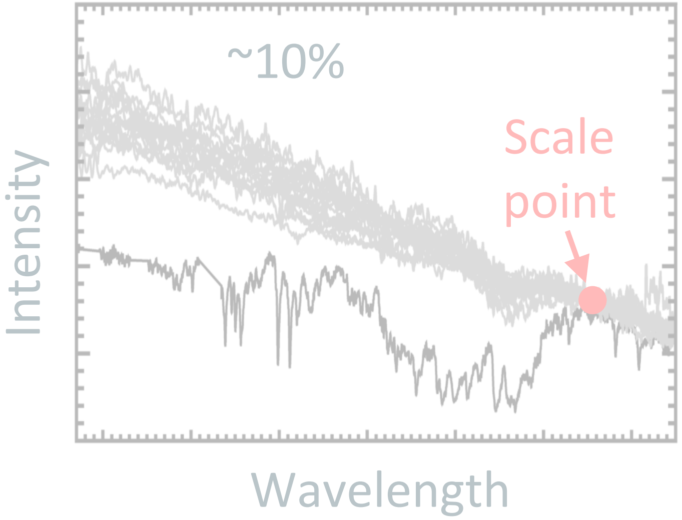

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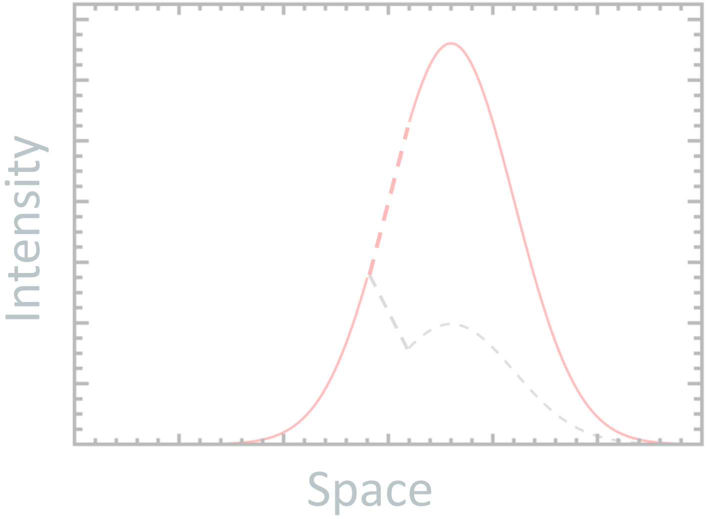

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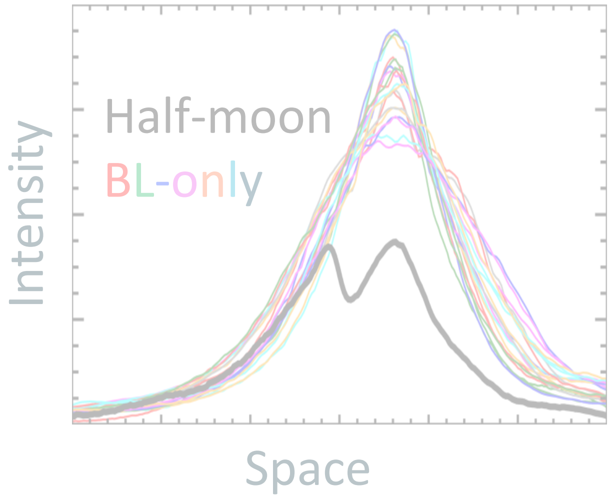

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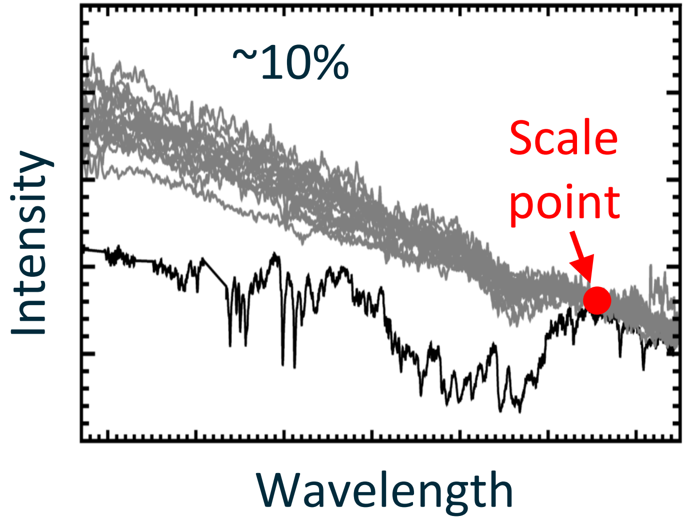

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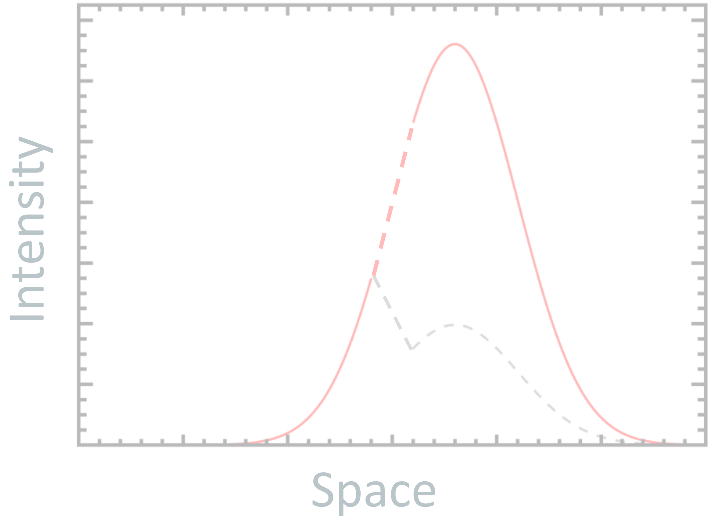

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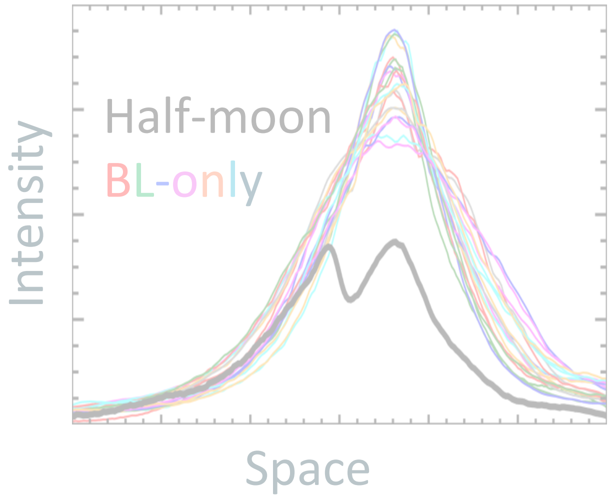

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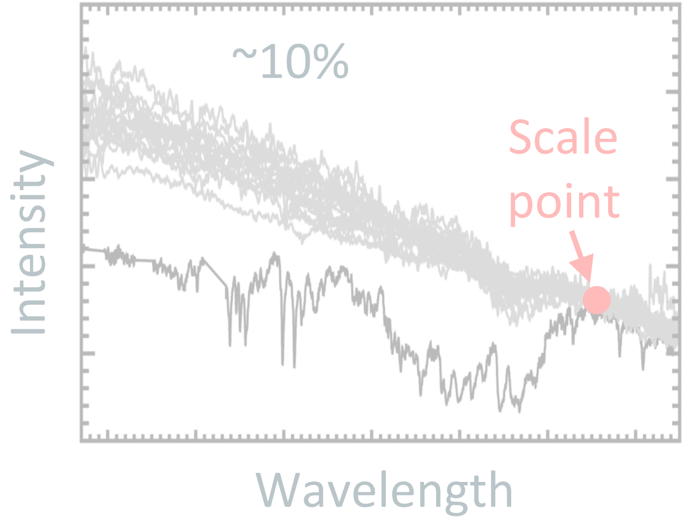

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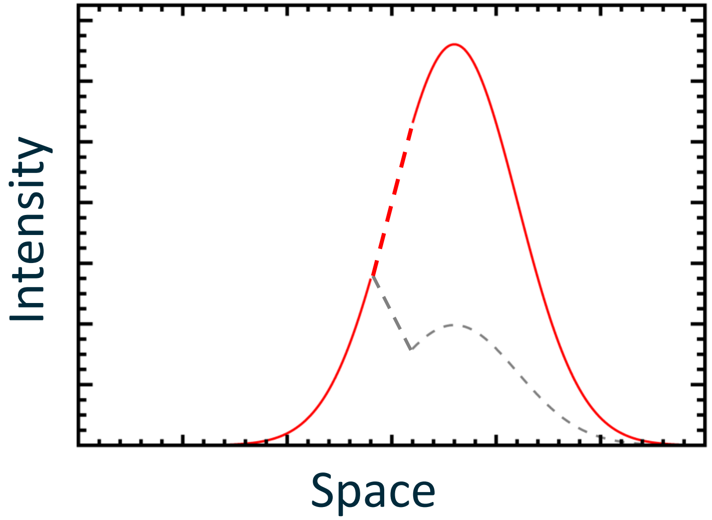
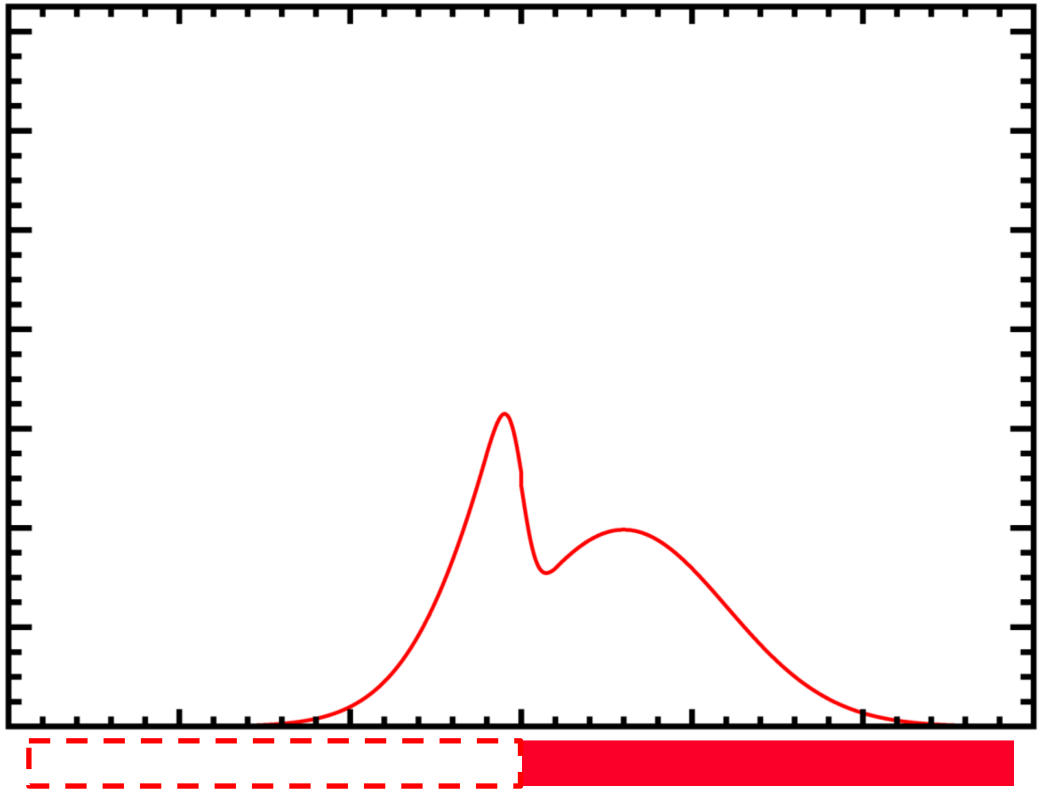


Search for the transmission that makes the T-corrected profile as smooth as measured unattenuated profiles



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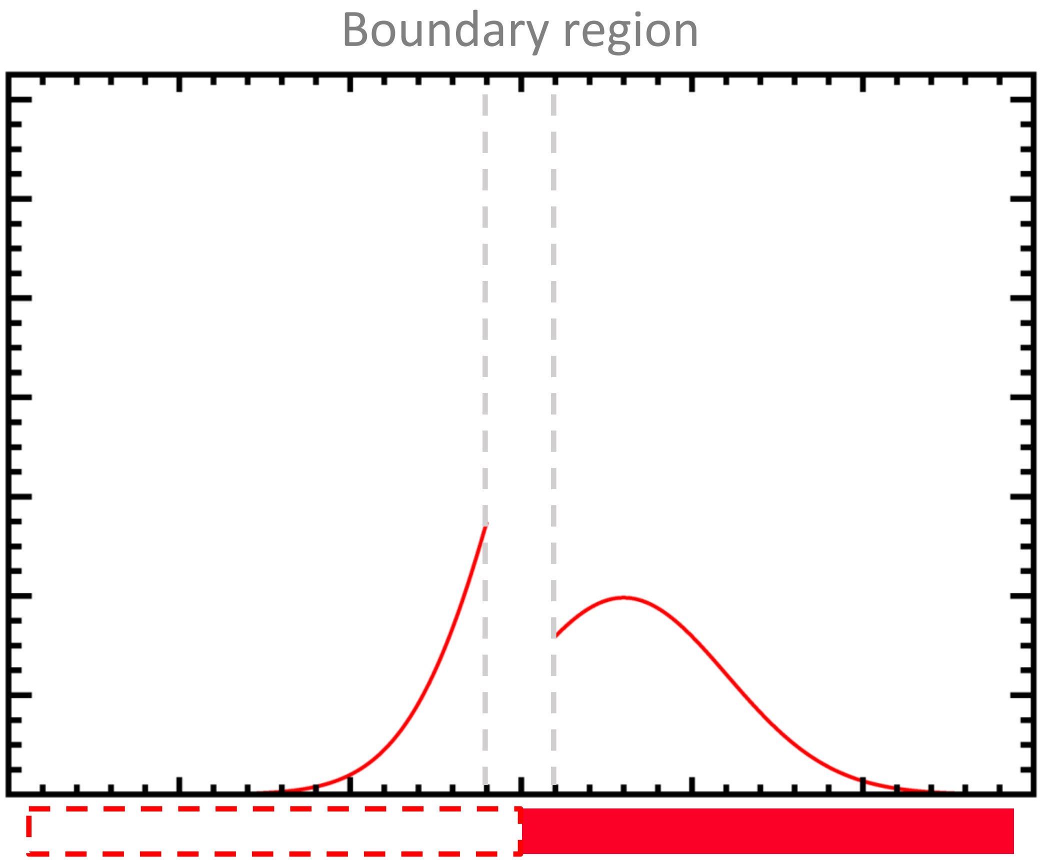

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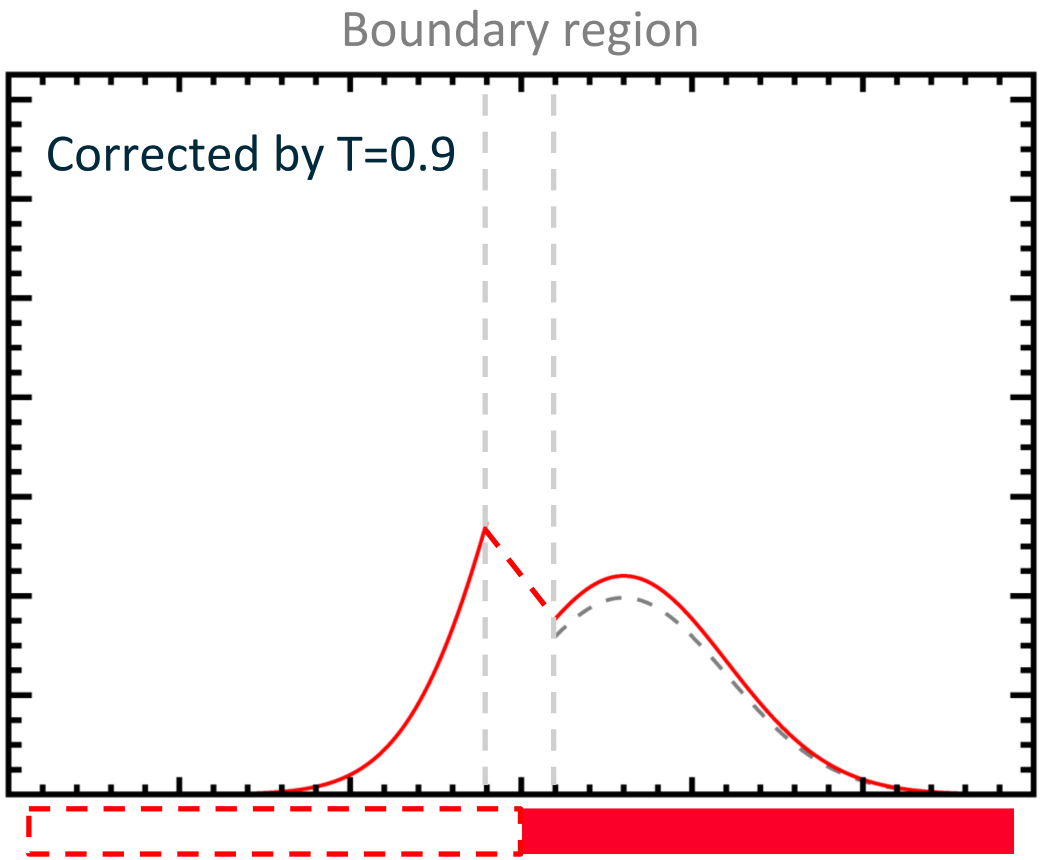

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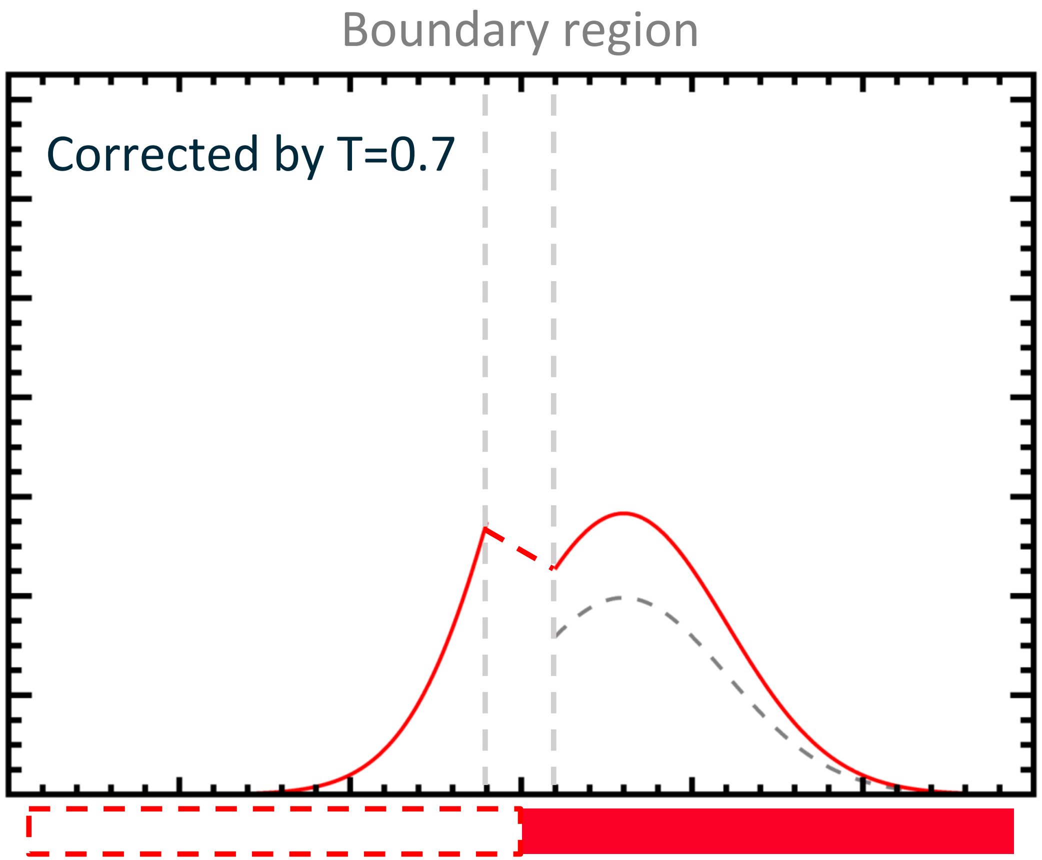

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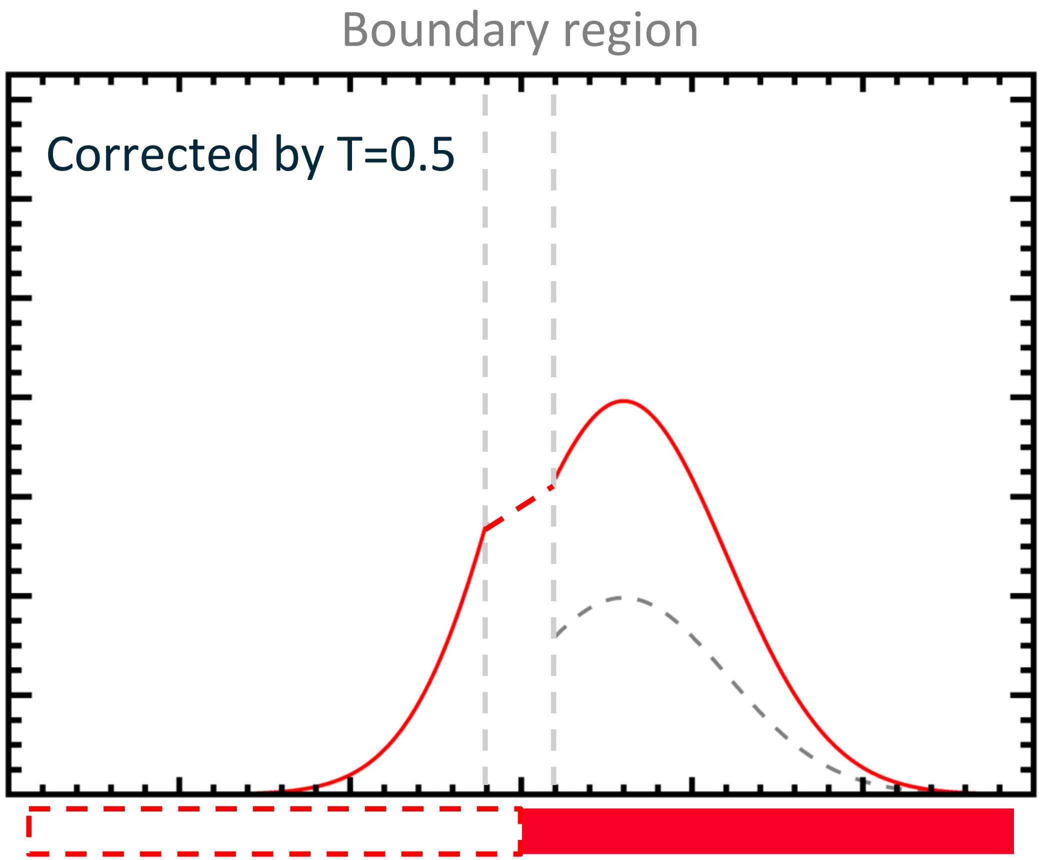

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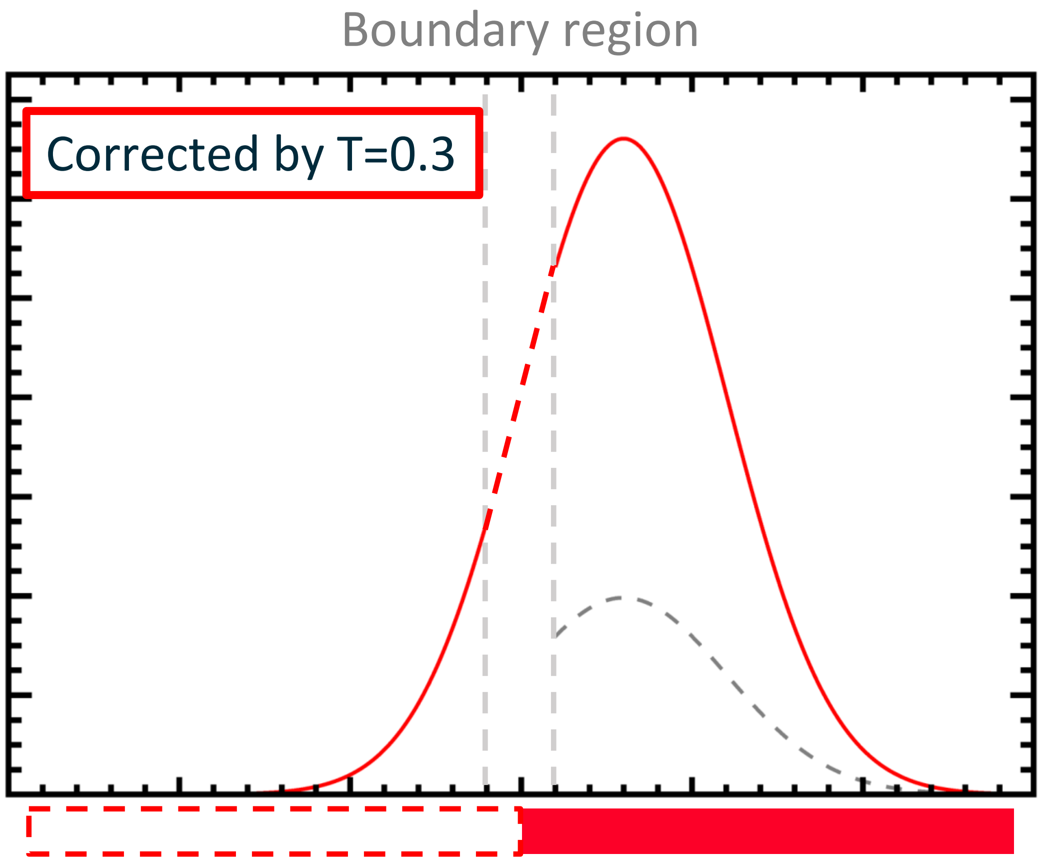

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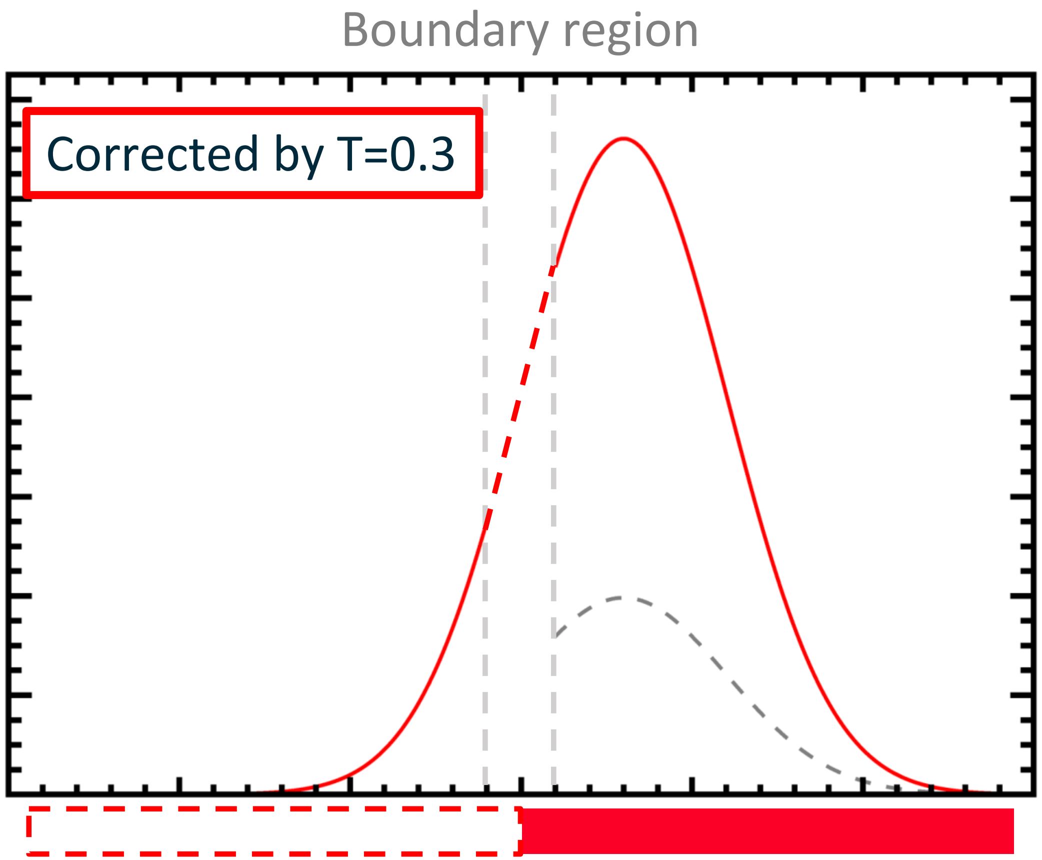

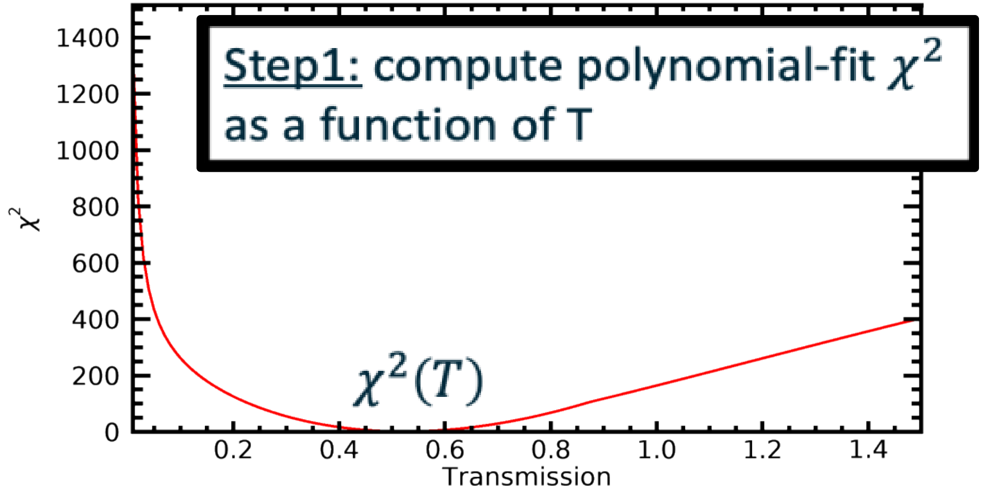

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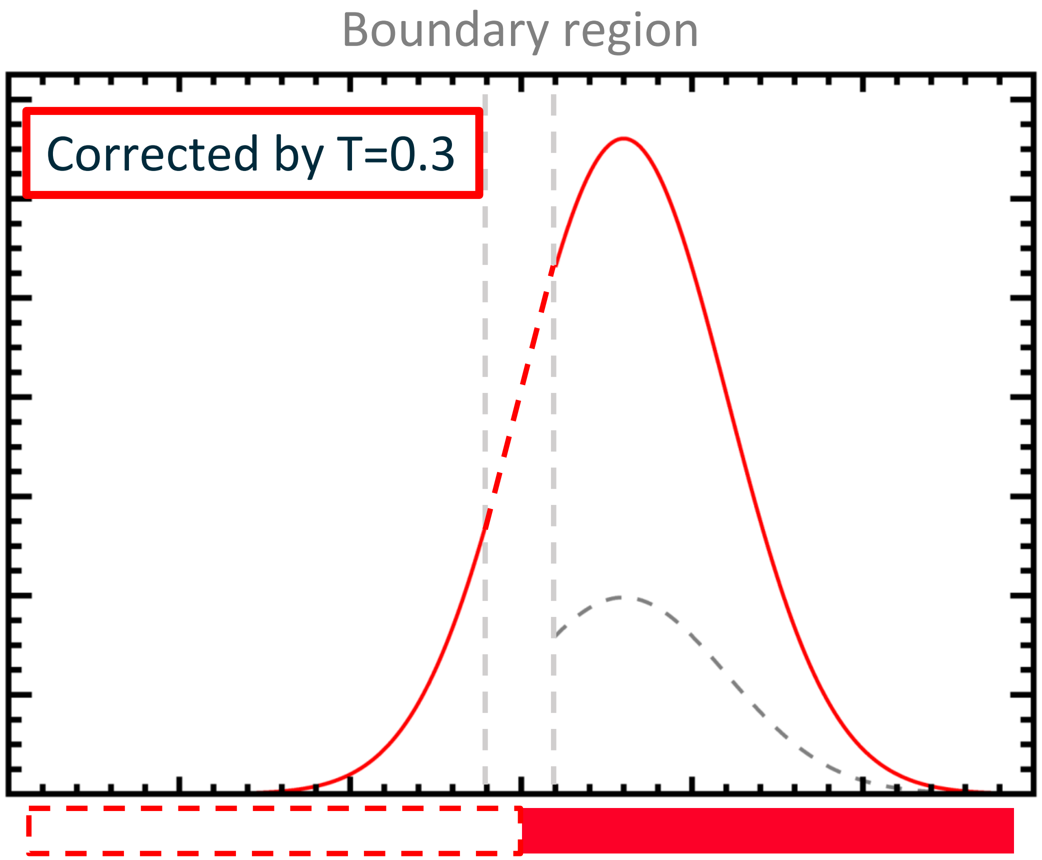

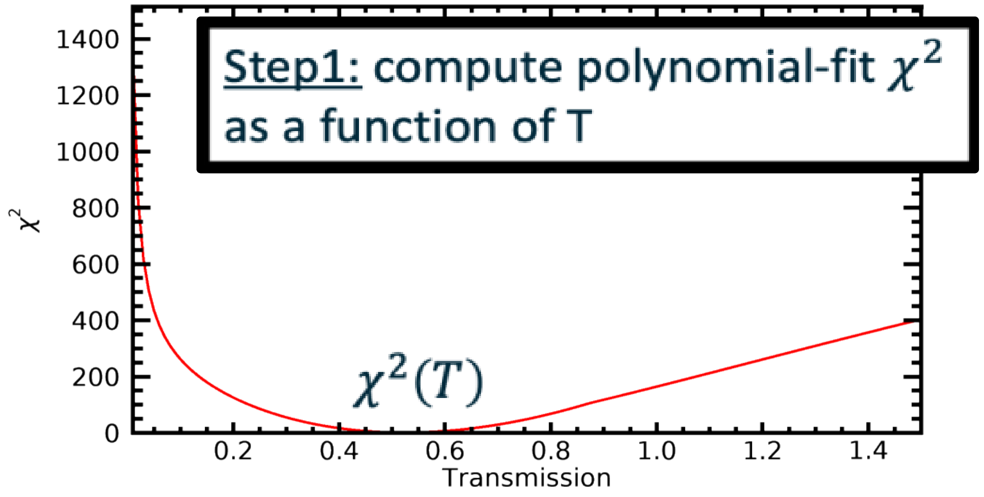

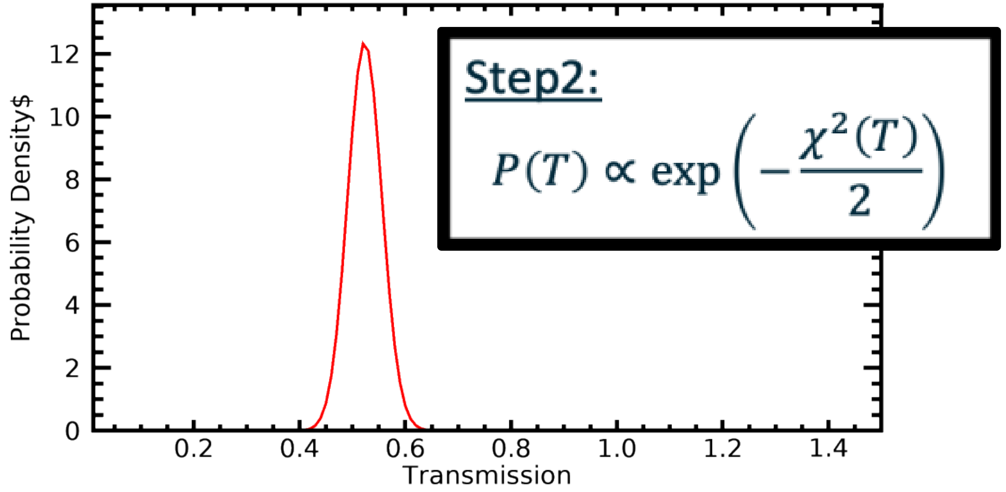

How can we validate the accuracy of these TPD methods?
➔ Synthetic-data tests

Spatial shape

Reproduce spatial shape after correcting transmission

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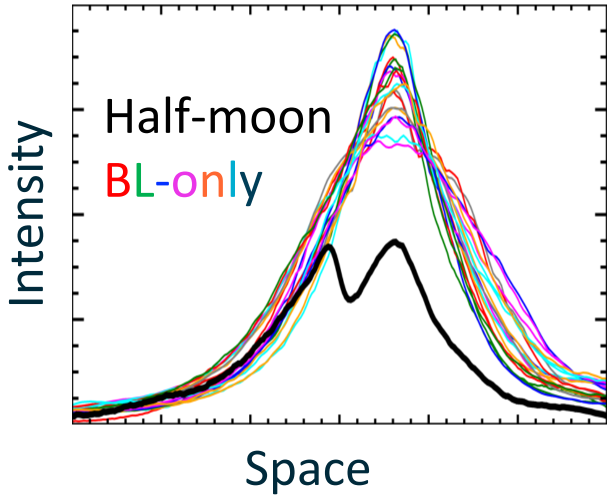

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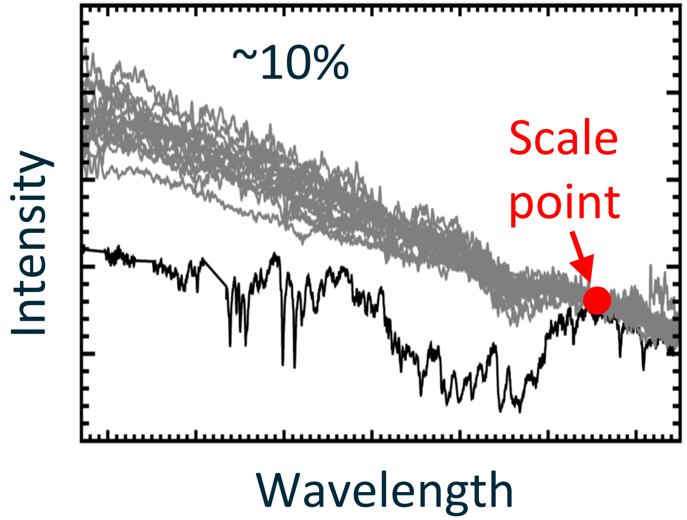

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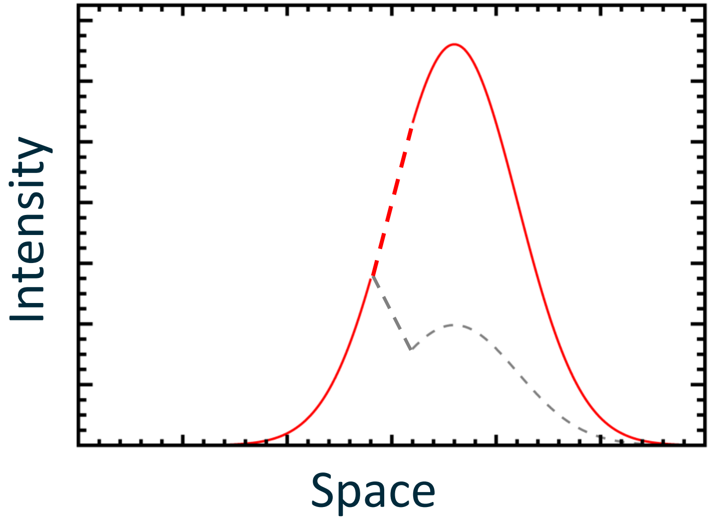
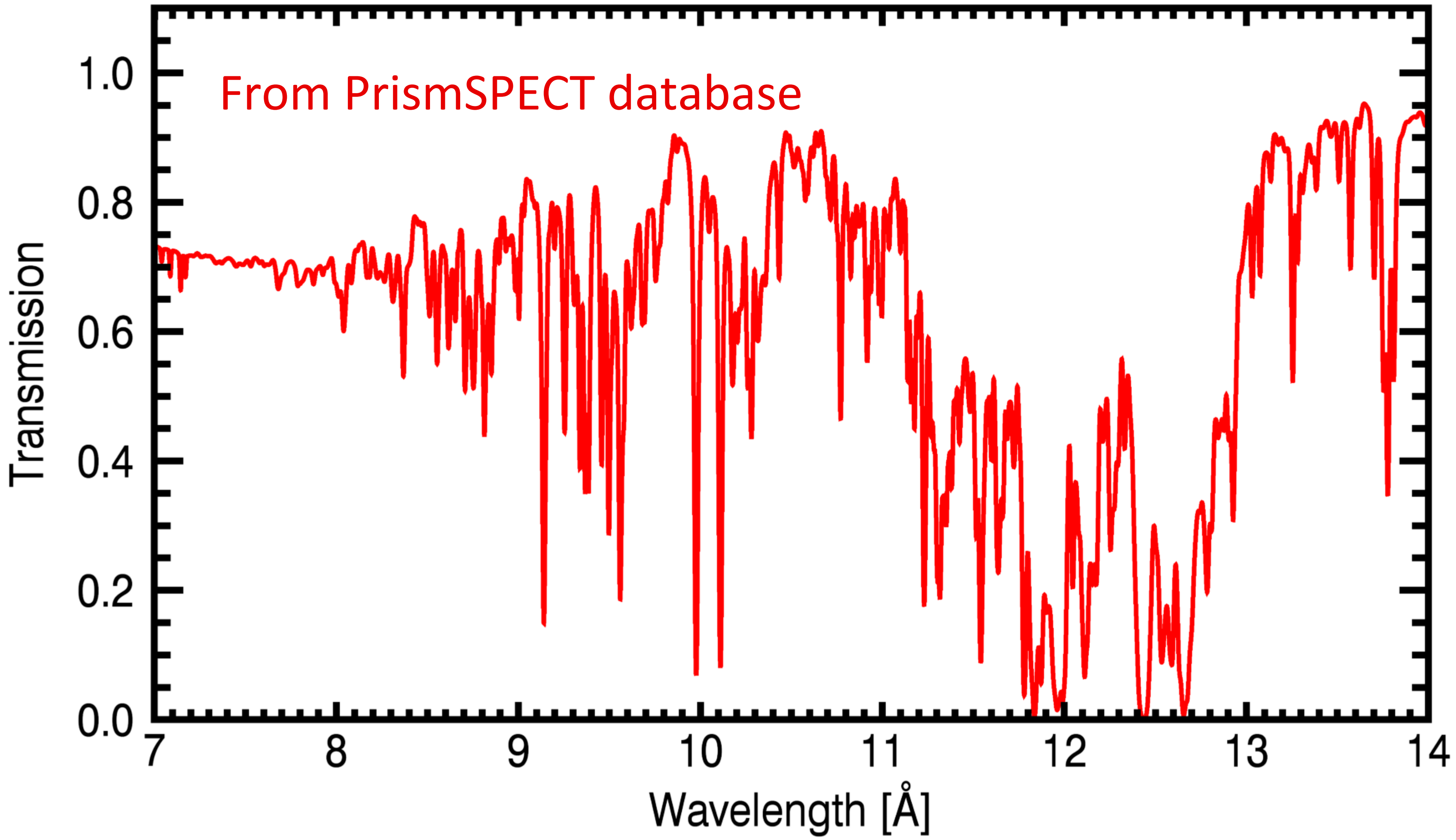


Method accuracy can be tested with synthetic-data tests
Step1: compute synthetic transmission



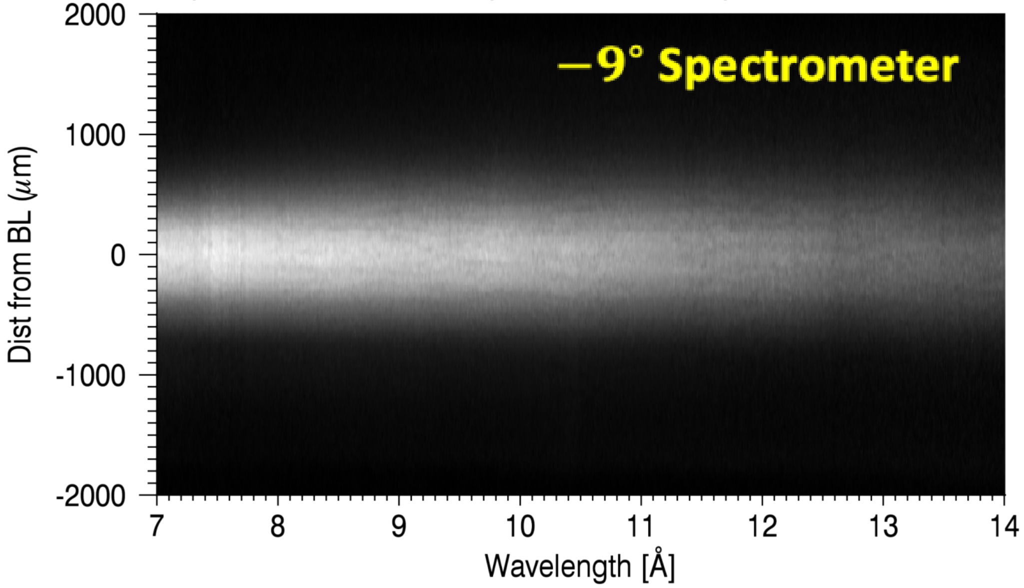
Element=Ni

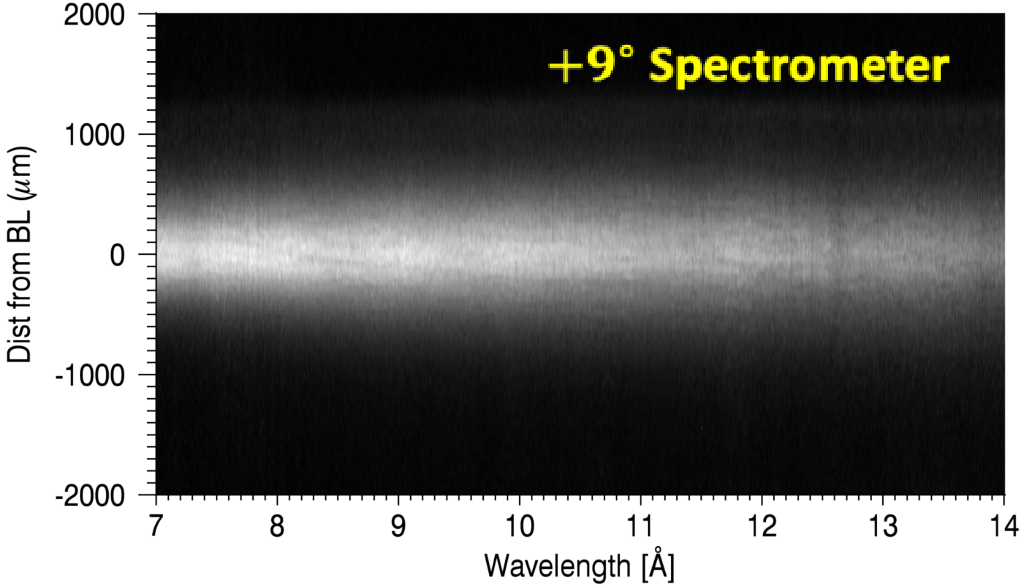
Te=182 eV

ne=3e22 cm^{-3}

niL=1.41e18 Ni/cm^2

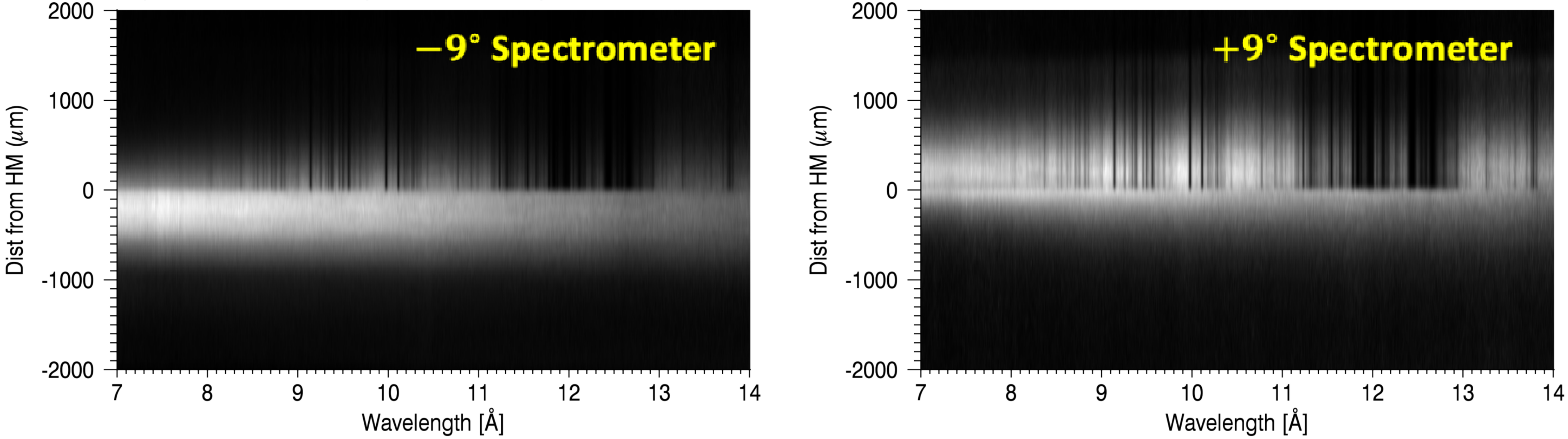
Method accuracy can be tested with synthetic-data tests
Step2: compute synthetic half-moon data





***Backlight-only data from z2972**

Method accuracy can be tested with synthetic-data tests
Step2: compute synthetic half-moon data



Q. Why using experimental BL-only data?

Method accuracy can be tested with synthetic-data tests
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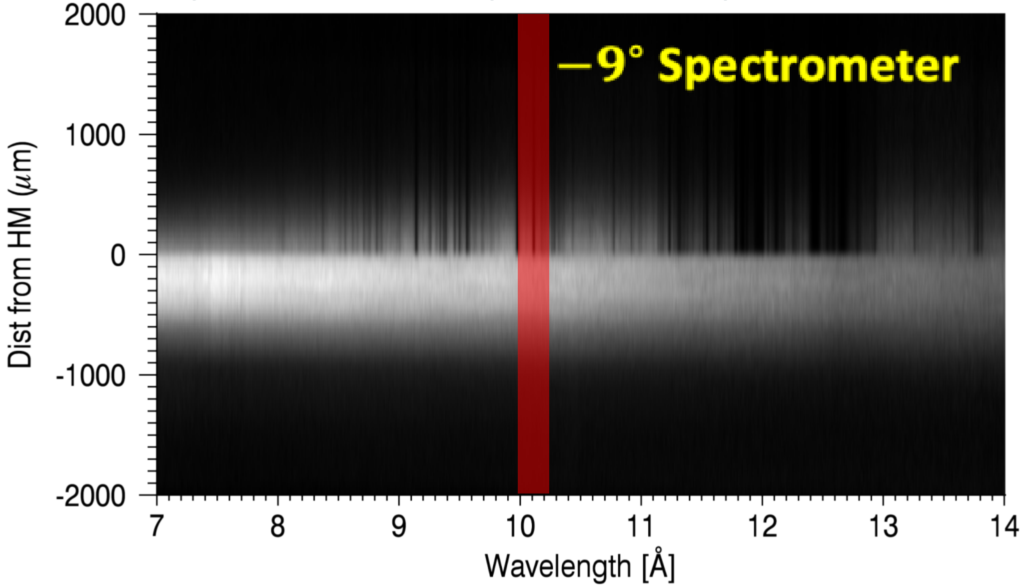

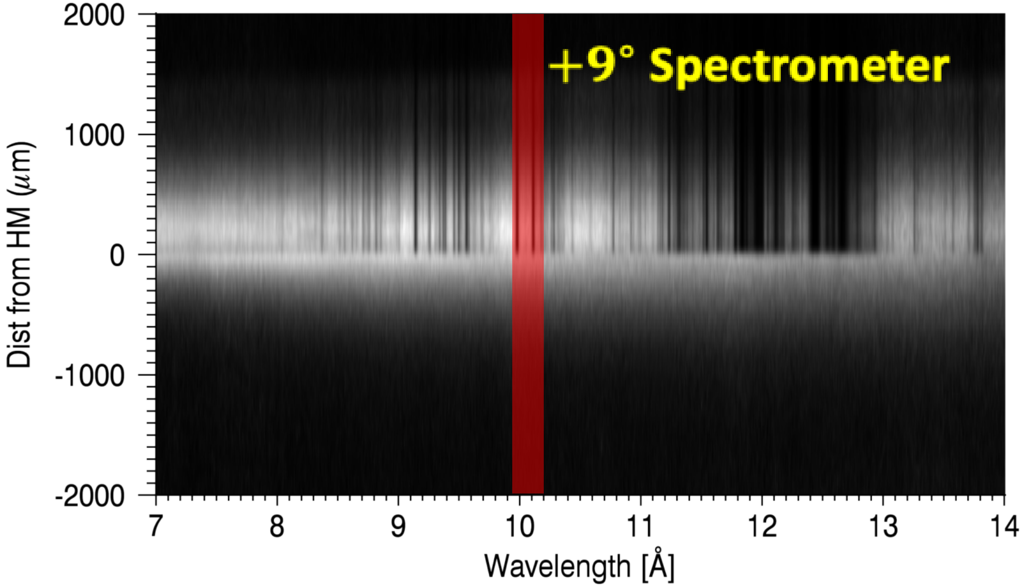

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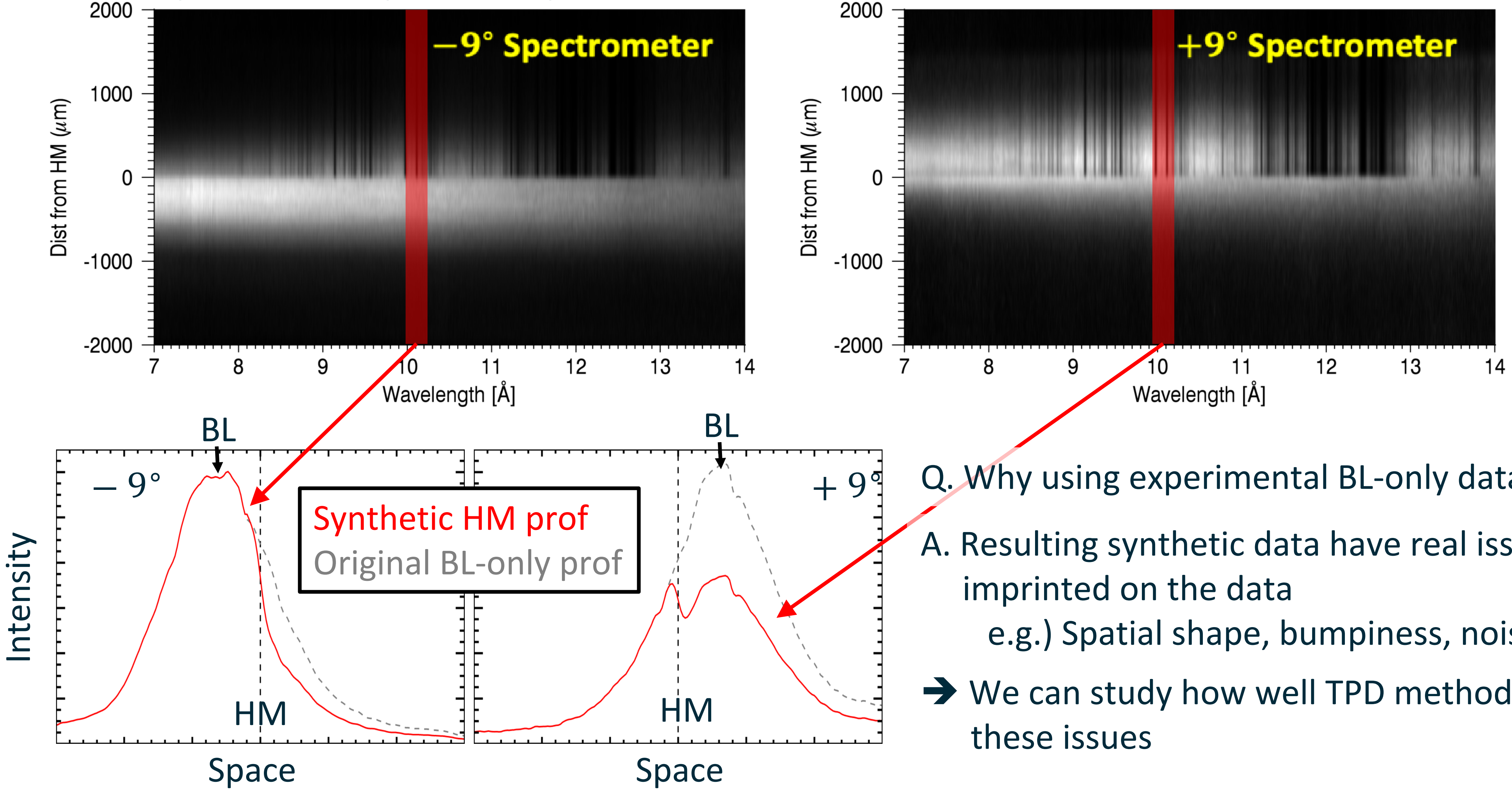


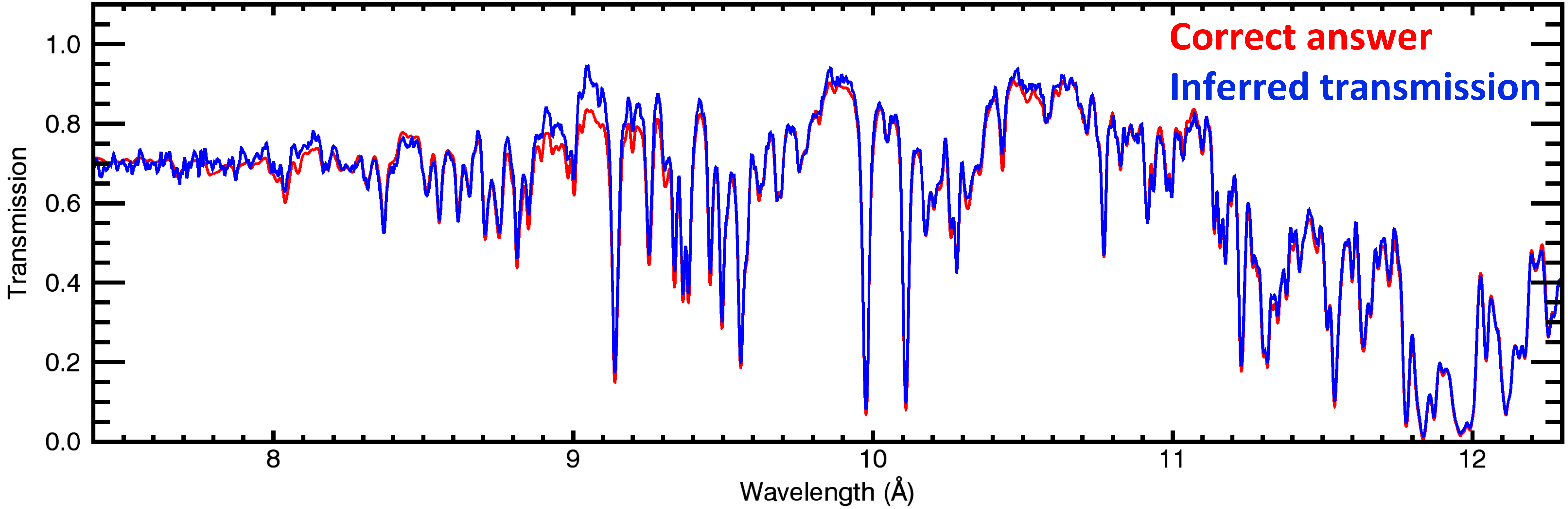
Q. Why using experimental BL-only data?

A. Resulting synthetic data have real issues imprinted on the data

e.g.) Spatial shape, bumpiness, noise, etc

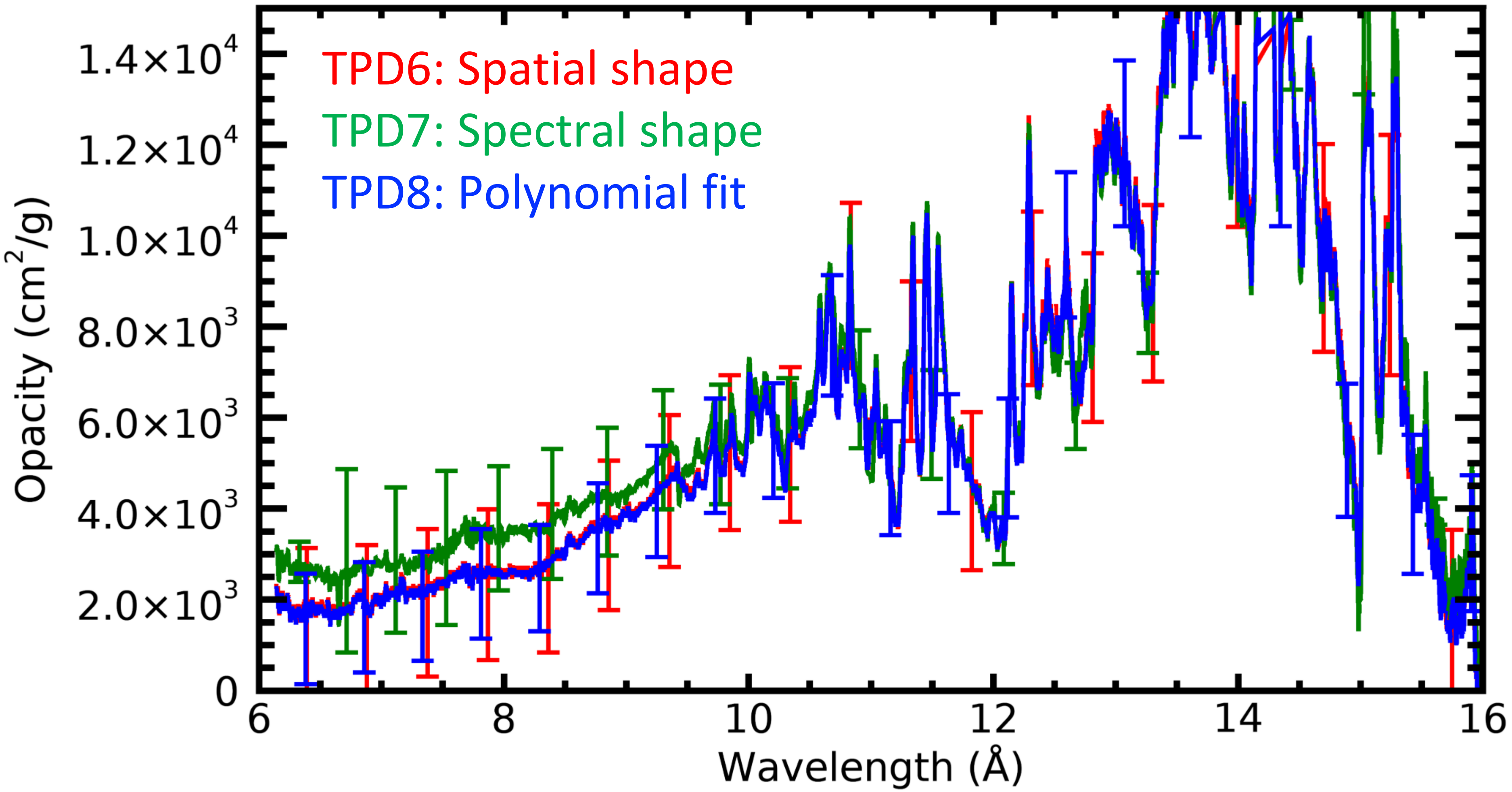
➔ We can study how well TPD methods work under these issues

Method accuracy can be tested with synthetic-data tests
Step3: Analyze the synthetic data and compare with true transmission spectra



Step4: Repeat it for 20-50 times using independent calibration measurements and check the accuracy of inferred uncertainty

Preliminary analysis of z2784 (anchor2 Fe) showed excellent agreement between three new methods and old results



TPD methods could fail when their underlying assumptions fail.
Thus, applying various TPD methods will help understand characteristic of each data set.

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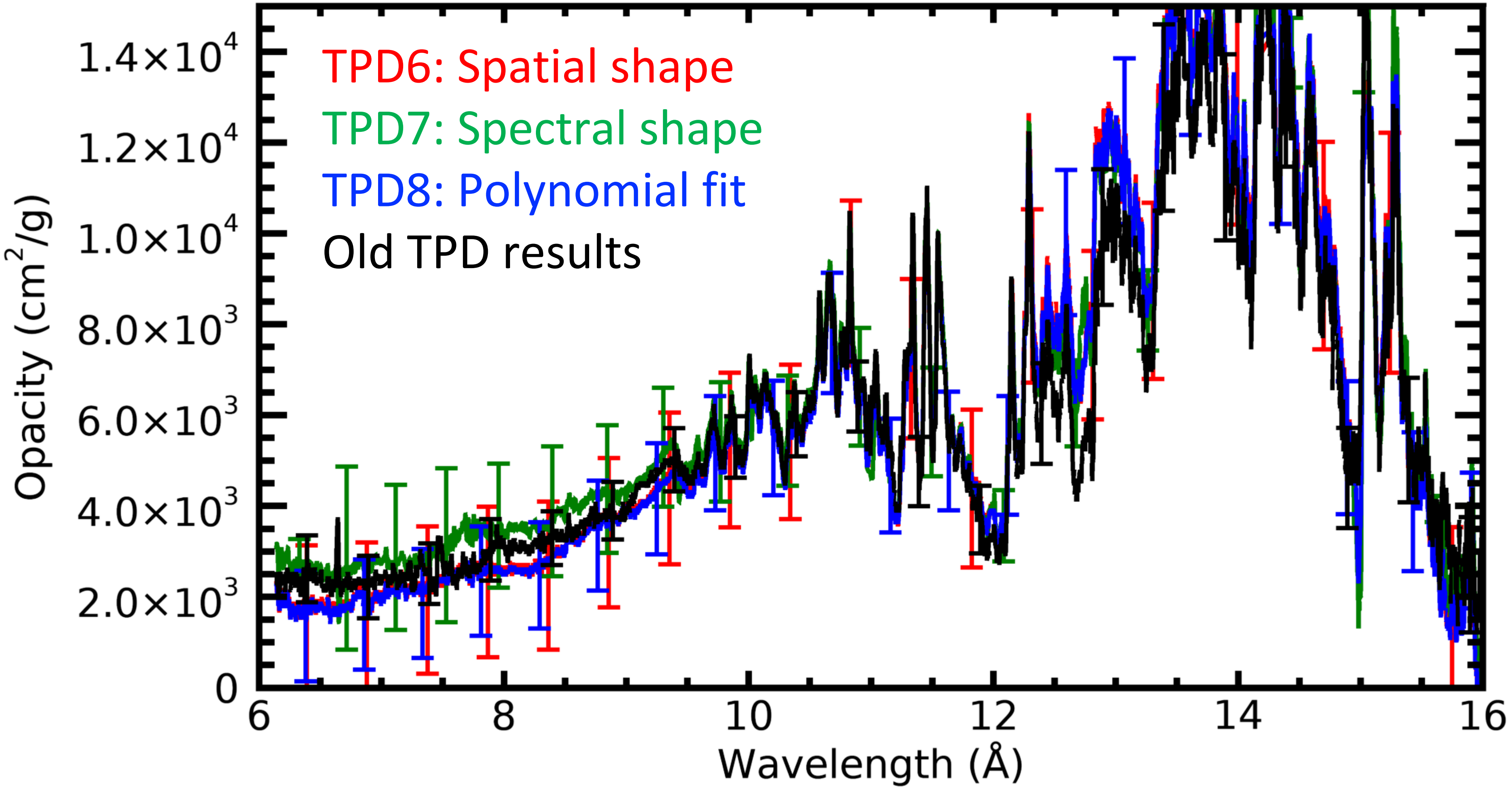

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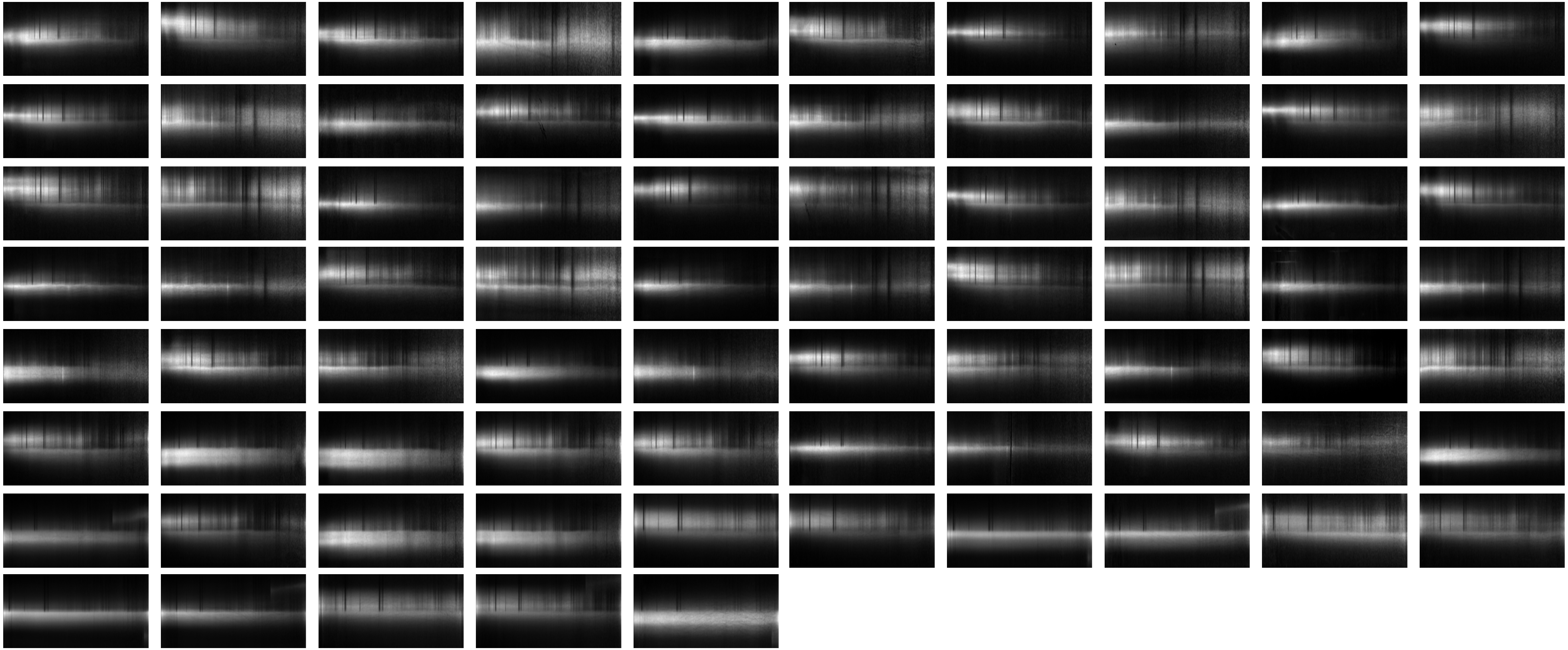
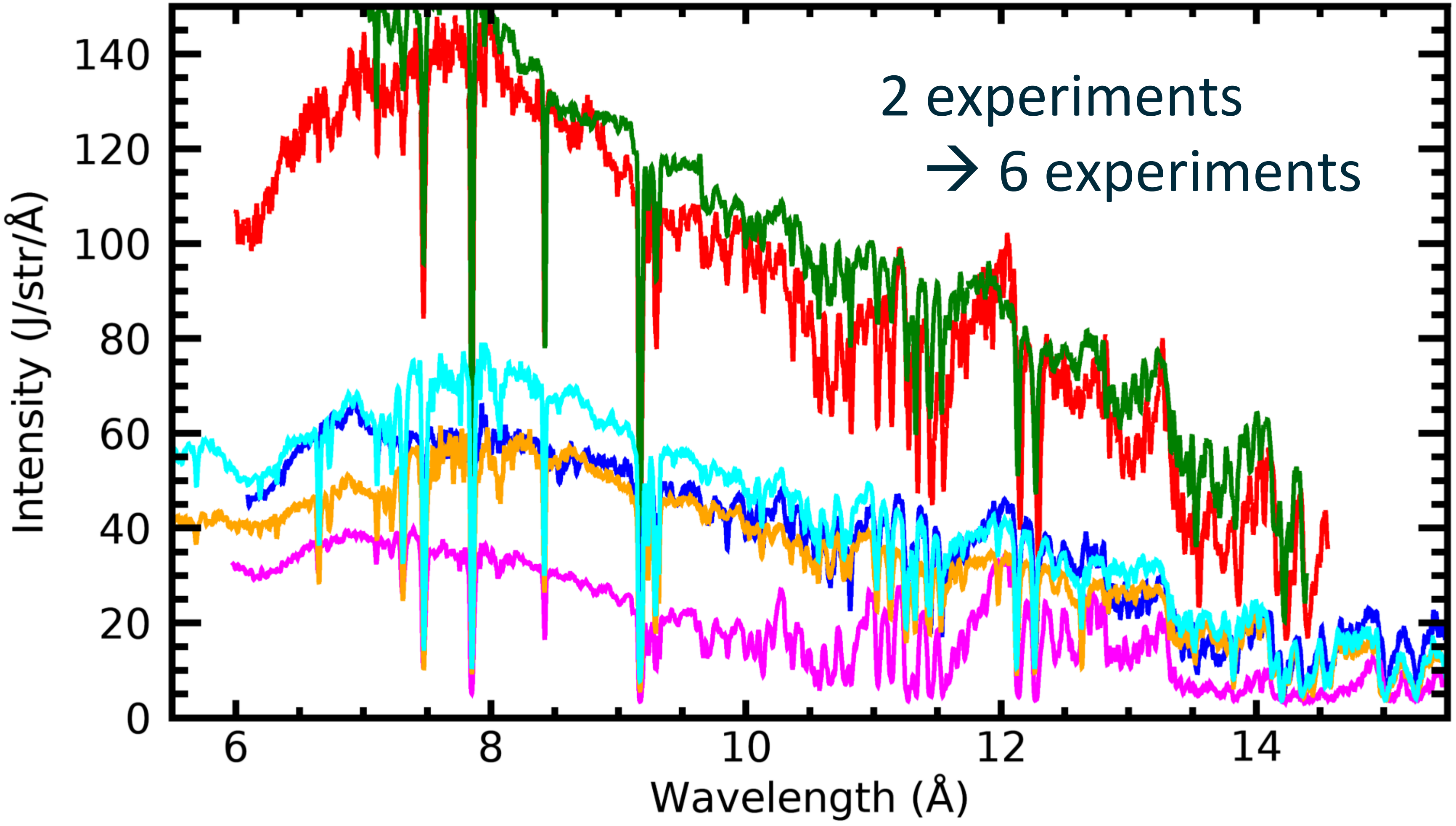
Thus, applying various TPD methods will help understand characteristic of each data set.

We are re-analyzing all anchor2 iron experiments
→ 19 experiments, 75 data sets, and 450 spectral images



Re-analysis of **all iron** experiments (anchor 1, 2, 3, etc) involve
42 experiments and roughly **1,000 spectral images**

Anchor1 data provide additional tests on the methods as well as potential Z-NIF data-to-data comparison

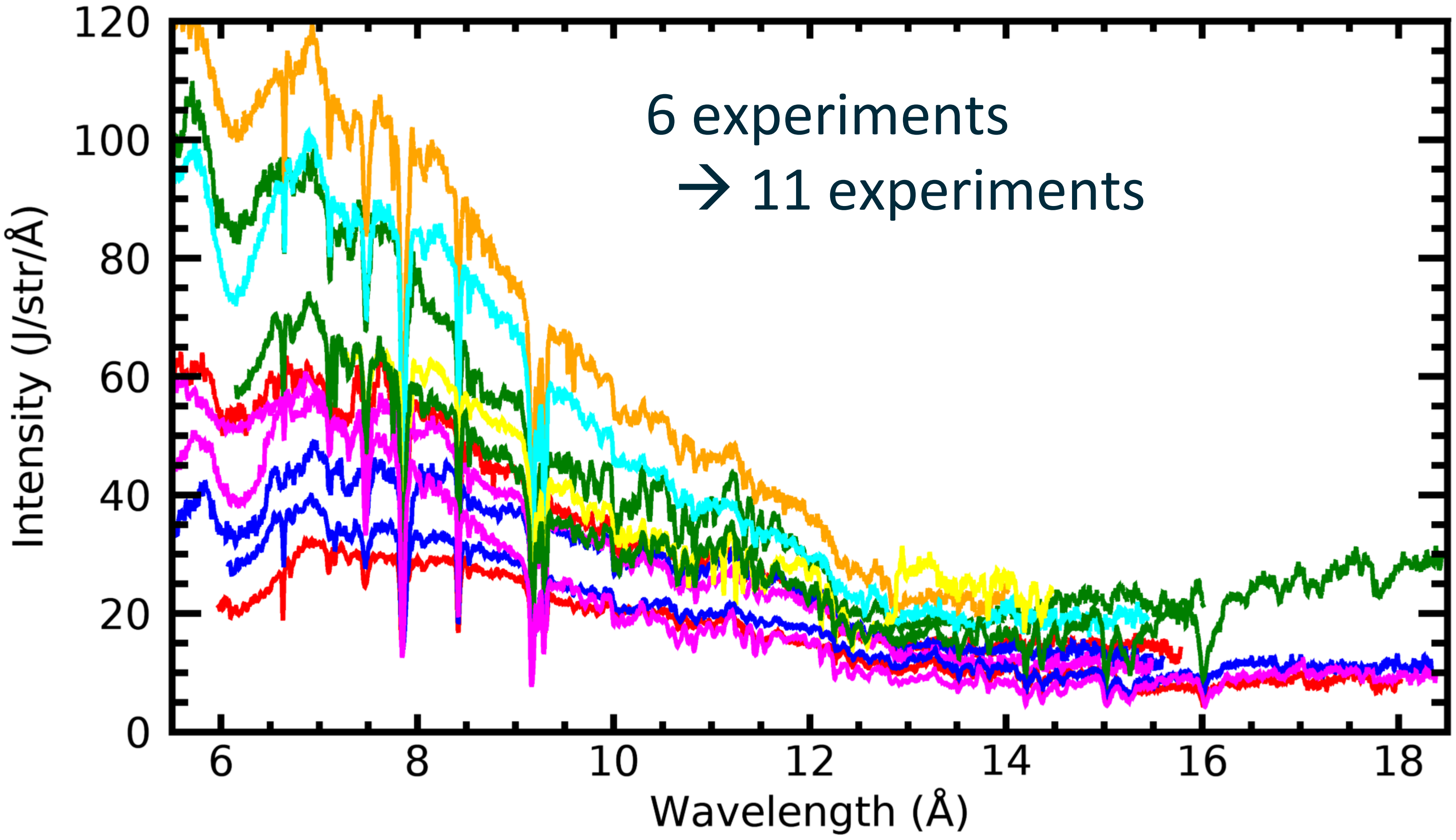


Why important?

- Consolidate anchor1 result
- Check experiment accuracy
- NIF-Z data comparison

[1] Bailey et al *PRL* 2007 [2] Bailey et al *Nature* 2015

Anchor3 data will test opacity models at most extreme conditions available



Most extreme conditions

T_e=195 eV

n_e=4e22 electrons/cm^3

Temperature and density re-analysis

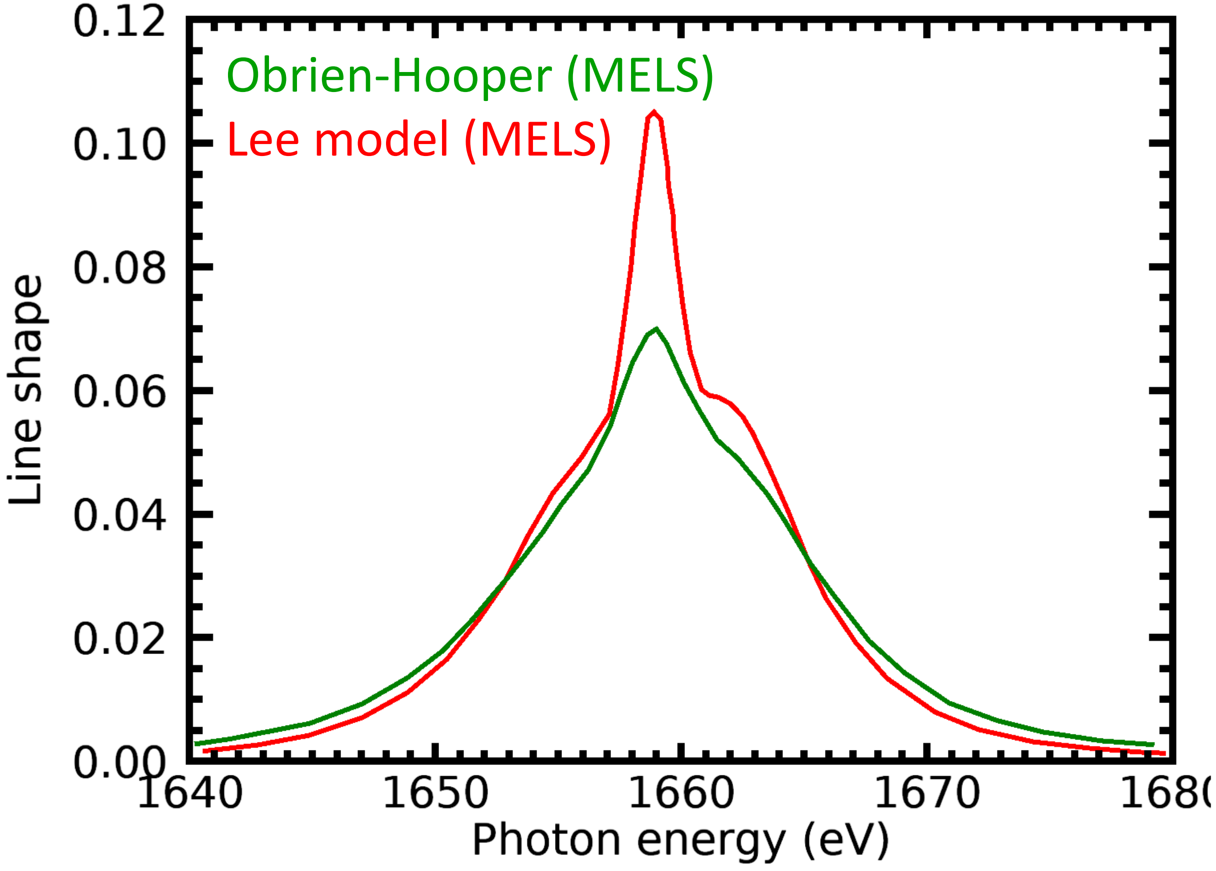
Temperature and density analysis were refined with refined line shapes and improved analysis method

1. Line shape improvements [1,2]

	OH	Lee
Quantum	Some	No
Strong-collision corr?	No	Yes
Screening?	No	Yes
All order?	No	No

2. Analysis method

- Multi-line fitting (χ^2, Bayesian) tends to underestimate parameter uncertainty
- New method incorporates inconsistencies into parameter uncertainties



[1] Nagayama et al HEDP (2016)
[2] Iglesias et al HEDP (2016)

Temperature and density analysis were refined with refined line shapes and improved analysis method

1. Line shape improvements [3,4]

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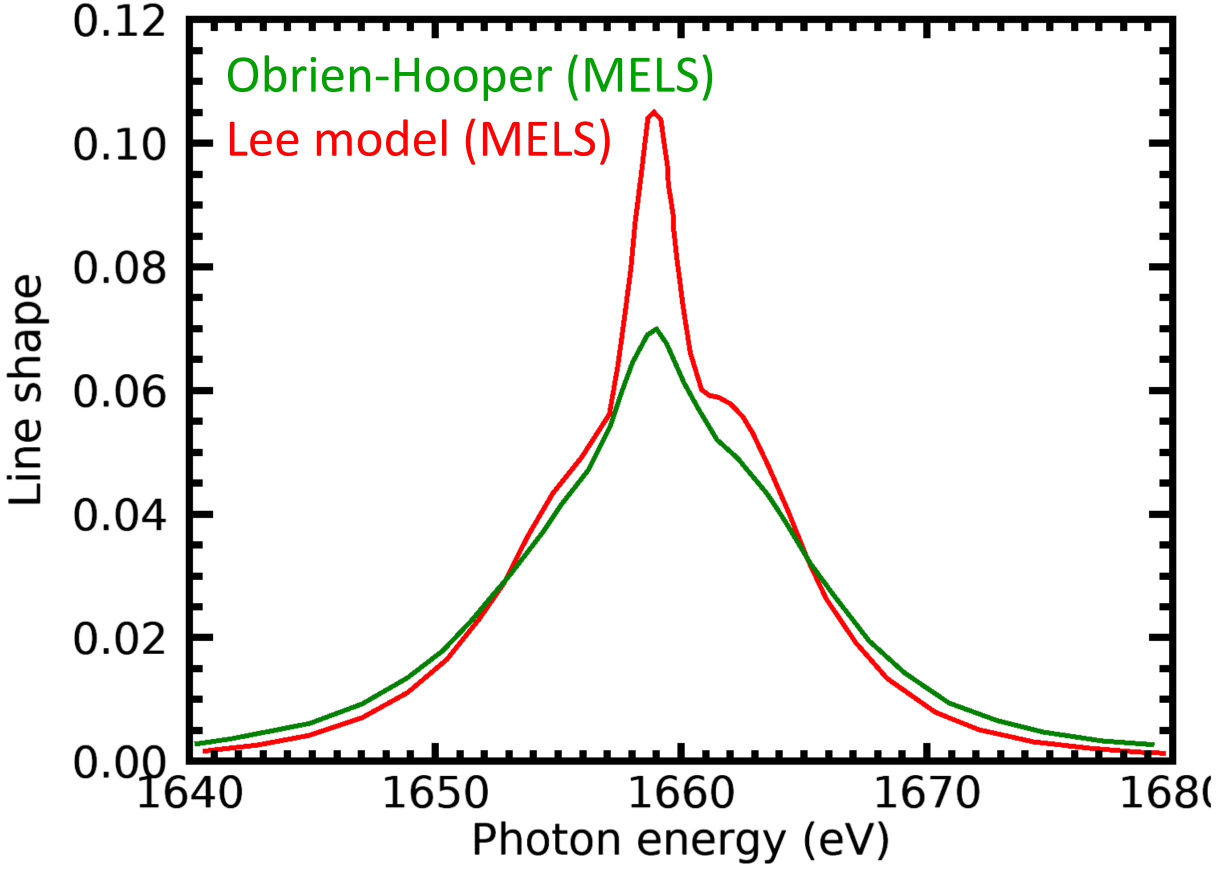

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[3] T. Gomez PRL (2020) [4] T. Gomez PRL (2021)

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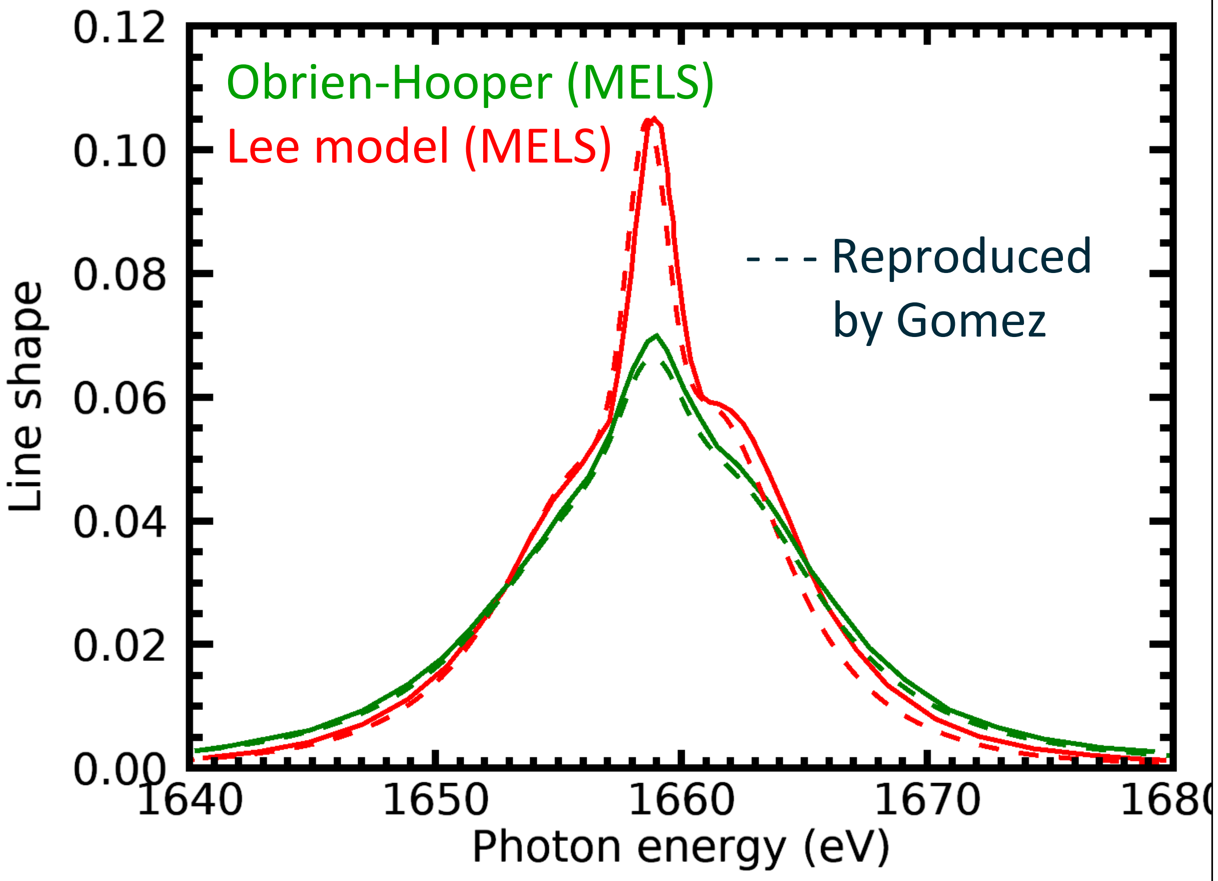

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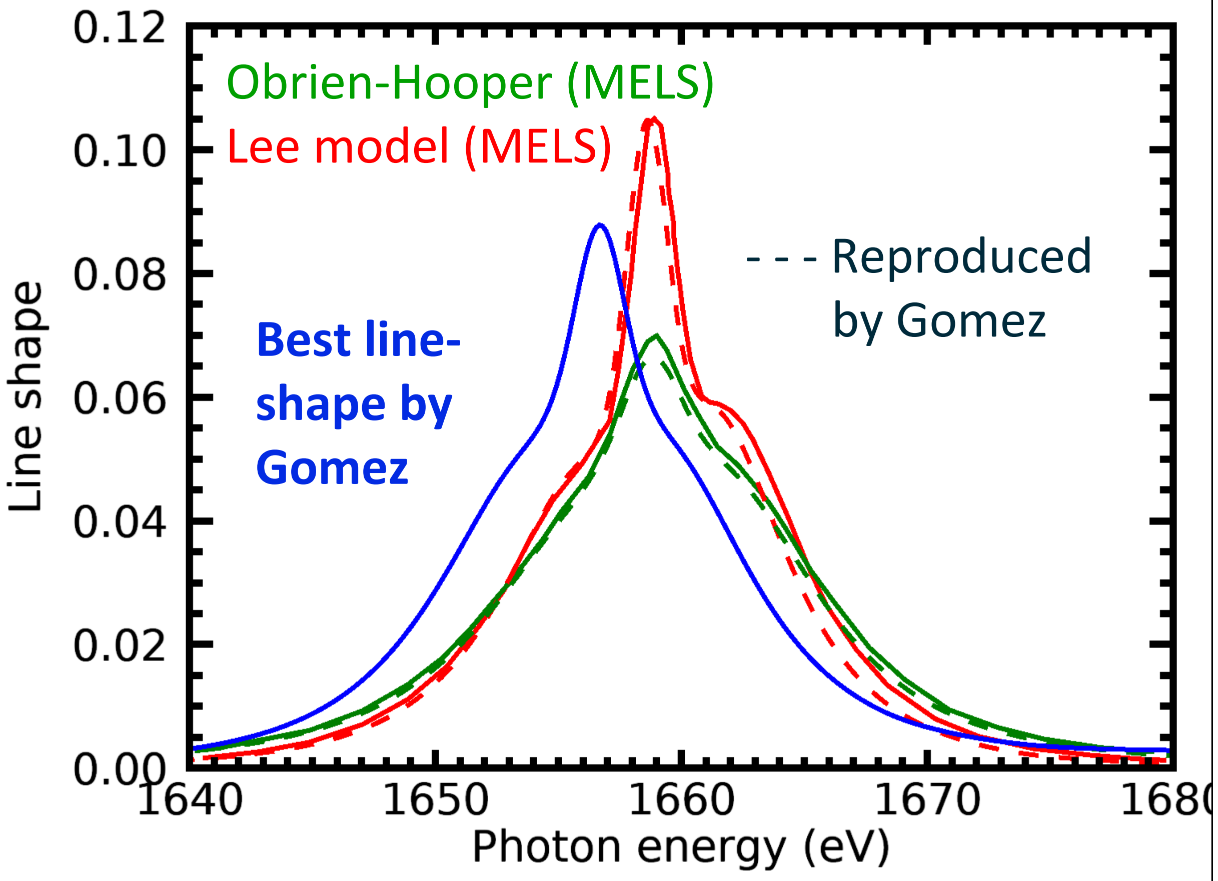

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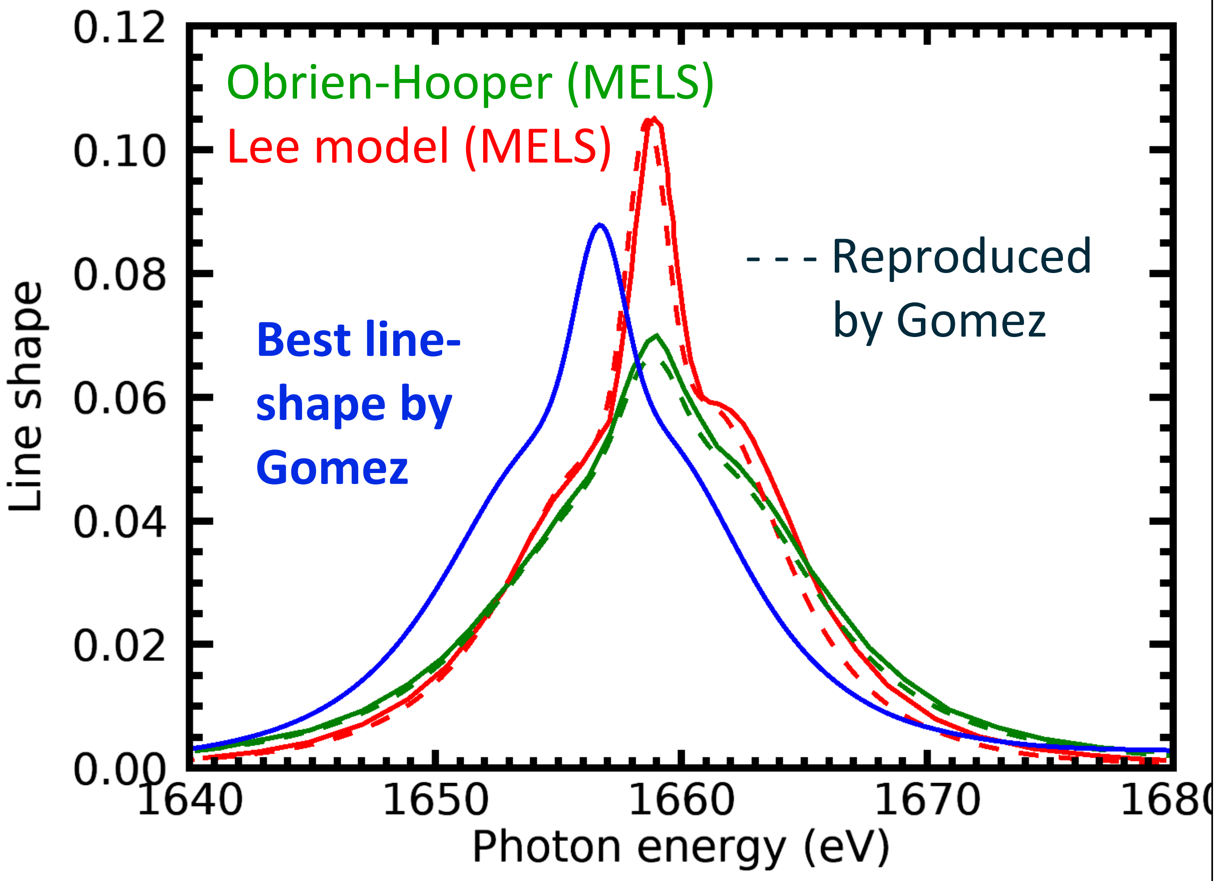

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Anchor 2*: n_e = 3.1e22 → 3.5e22 (+13%), T_e = 182 → 188 eV (+3%)

*** Reanalysis over the first three shots. All iron data need to be re-analyzed.**

In the next 2-3 months, temperature, density, and opacity of all iron data will be reanalyzed with the refined methods

Anchor1: 2 → 6 shots

Are experiments accurate?

Can Z data be directly compared with NIF data?

Anchor2: 3 → 19 shots

What is the true model-data discrepancy?

What's causing the discrepancy?

Anchor3: 6 → 11 shots

What is the model-data discrepancy at most extreme conditions?

Others: 1 → 6 shots

Can we control experiments with sample location, tamper, and preheat shields?

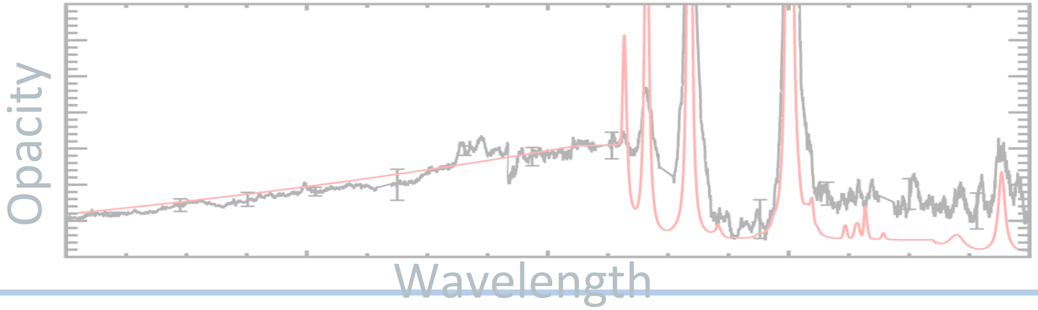
Increased number of calibration shots and analysis refinements were necessary.
Reanalysis on anchor 1 ~ 3 will answer many longstanding questions.

Our progress in opacity analysis and temperature and density analysis impact the other three opacity projects

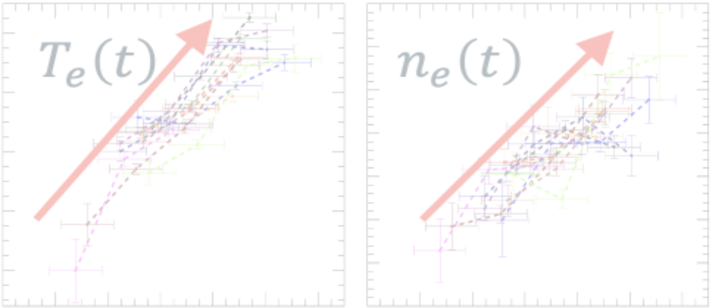
Revisit Z iron opacity results
(this talk by T. Nagayama from SNL)

- Temperature and density re-analysis
- More experiments
- Re-analysis

Z oxygen opacity measurements
(2nd talk by D. Mayes from UT)



Z time-resolved experiments
(poster by G. Loisel from SNL)



Helping NIF opacity measurements
(3rd talk by T. Perry from LANL)

- Define high-fidelity opacity data
- Pros and cons of NIF and Z
- Scrutinize each experiments and analyses

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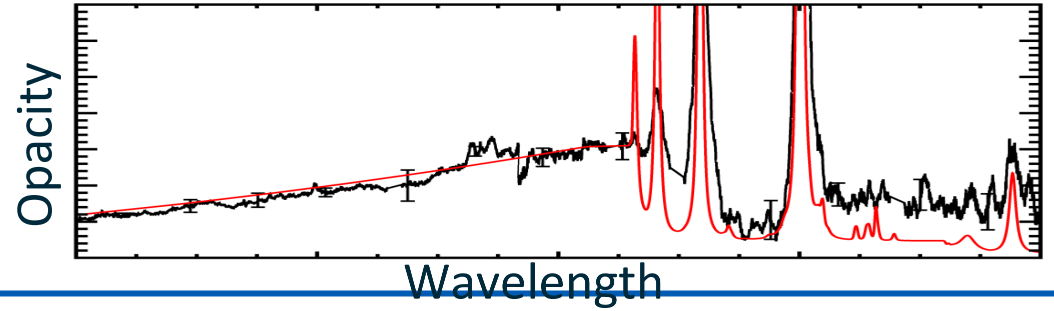

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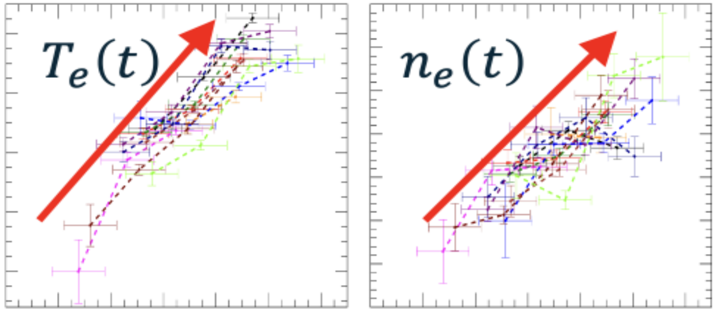

Helping NIF opacity measurements
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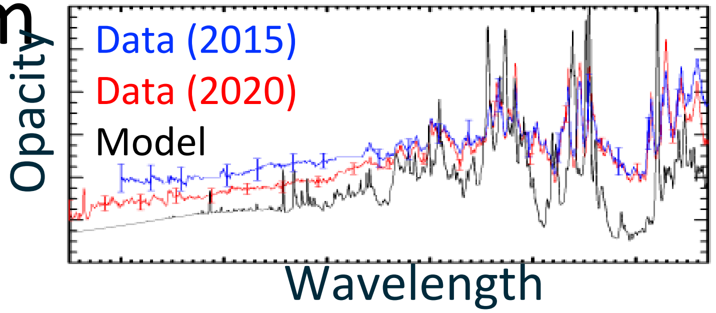
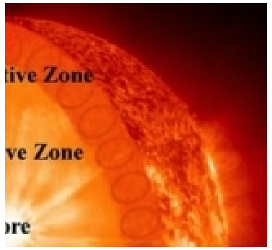
- Define high-fidelity opacity data
- Pros and cons of NIF and Z
- Scrutinize each experiments and analyses

Please see these talks to learn overall progresses in the stellar opacity projects

We made significant progress in four areas to resolve the opacity puzzles and the solar problem

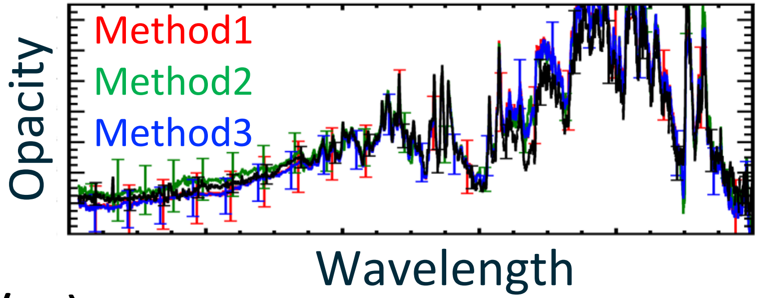
<u>Motivation:</u> There is significant disagreement between measured and modeled iron opacity





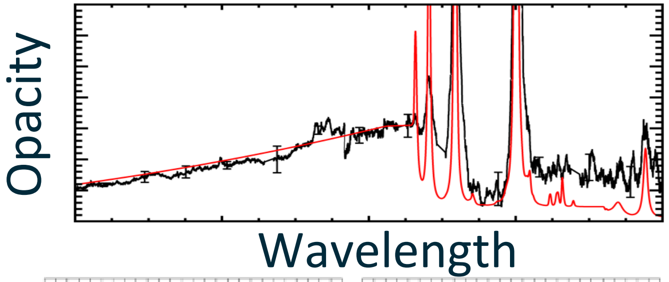
Effort1: Revisit iron opacity results

- Performed more experiments for scrutiny
- Refined analysis methods



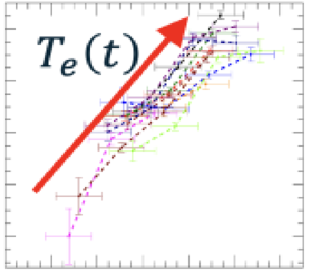
Effort2: Oxygen opacity measurements (D. Mayes)

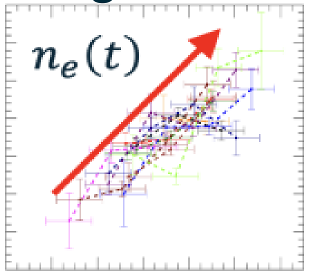
- Model and data agree on BF but not on BB (140 eV, 8e21e/cc)
- Performed a few experiments aiming at (180eV, 3e22 e/cc)



Effort3: Time resolved measurements (Poster: G. Loisel)

- Measured T_e(t) and n_e(t)
- Investigated the importance of temporal gradients





Effort4: Help independent experimental investigations

- Work closely with NIF opacity team **(T. Perry)**