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Improving accuracy of stellar opacity experiments using calibration statistics and Monte-Carlo error propagation

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Sandia National Laboratories, New Mexico

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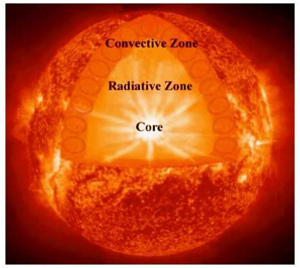
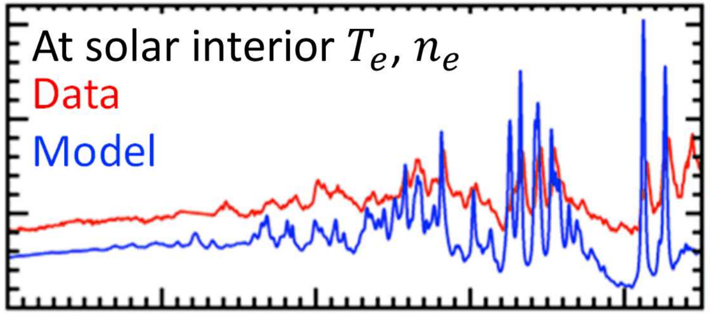
New analysis method confirmed experiment reproducibility and enabled accurate systematic study of Cr, Fe, and Ni opacity

Is iron opacity inaccurate?

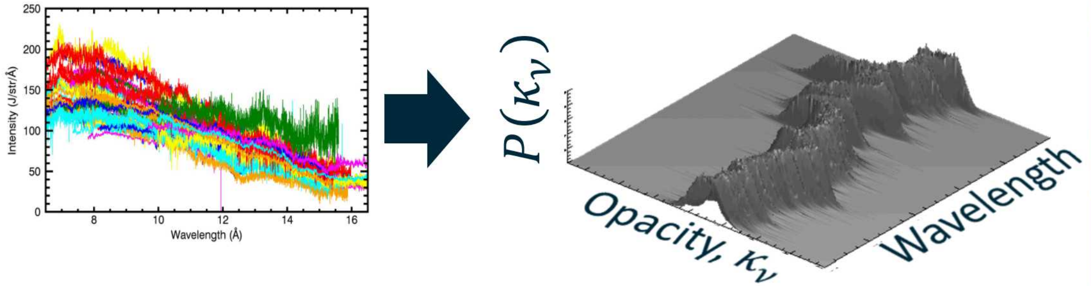
- Fe opacity is measured at solar interior condition
- **Severe disagreement with modeled opacity → Why?**





Data analysis method is refined

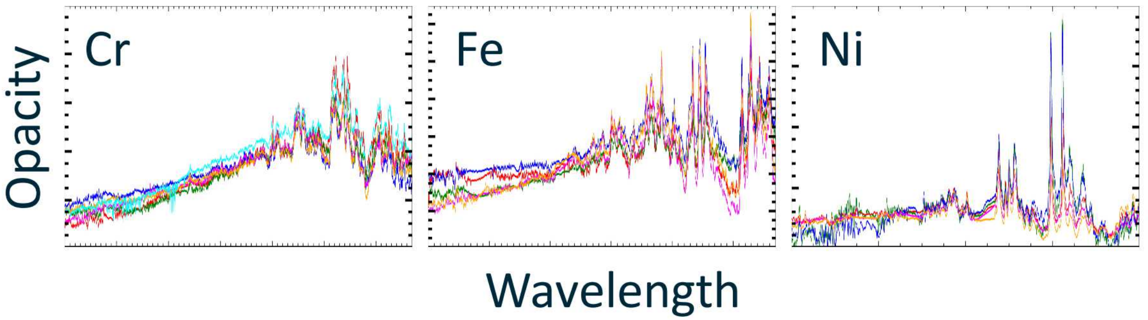
- Large volume of calibration-shot statistics
- Error propagation with Monte Carlo
- Method tested



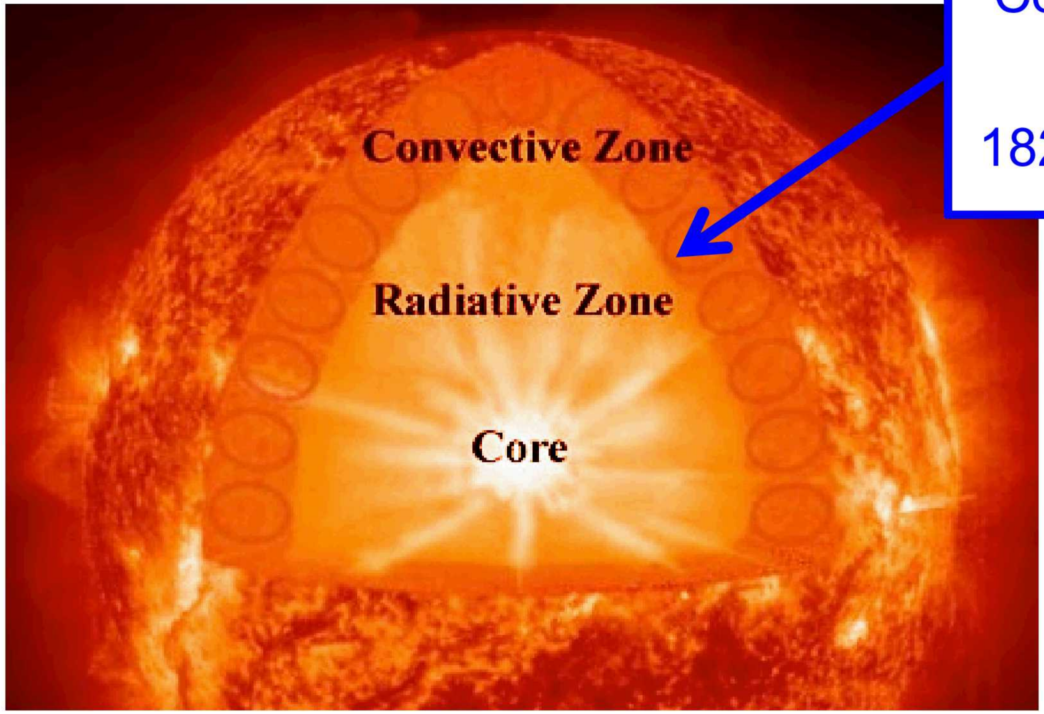
New analysis improved reproducibility, providing insight into the problem

- Improved reproducibility: 10-20%
- First systematic study published by PRL

T. Nagayama et al, PRL 122, 235001 (2019)

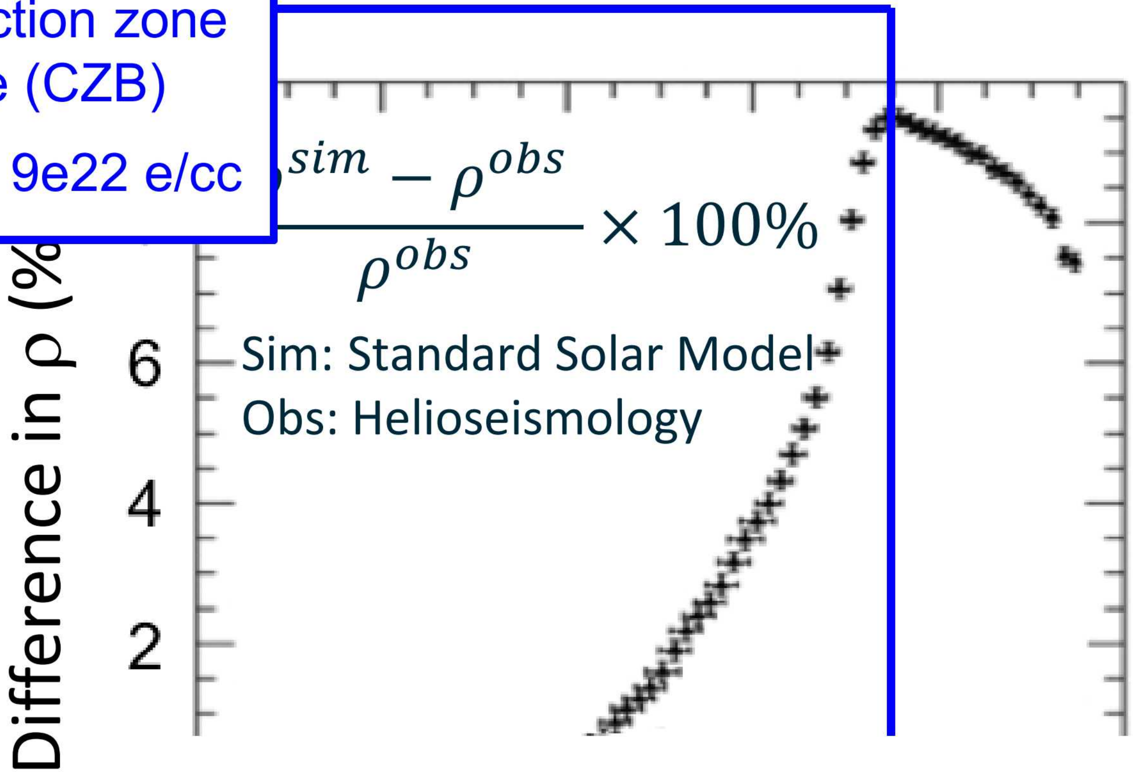


Is the decade-old solar problem caused by inaccuracy of opacity models?



Convection zone base (CZB)

182 eV, 9e22 e/cc

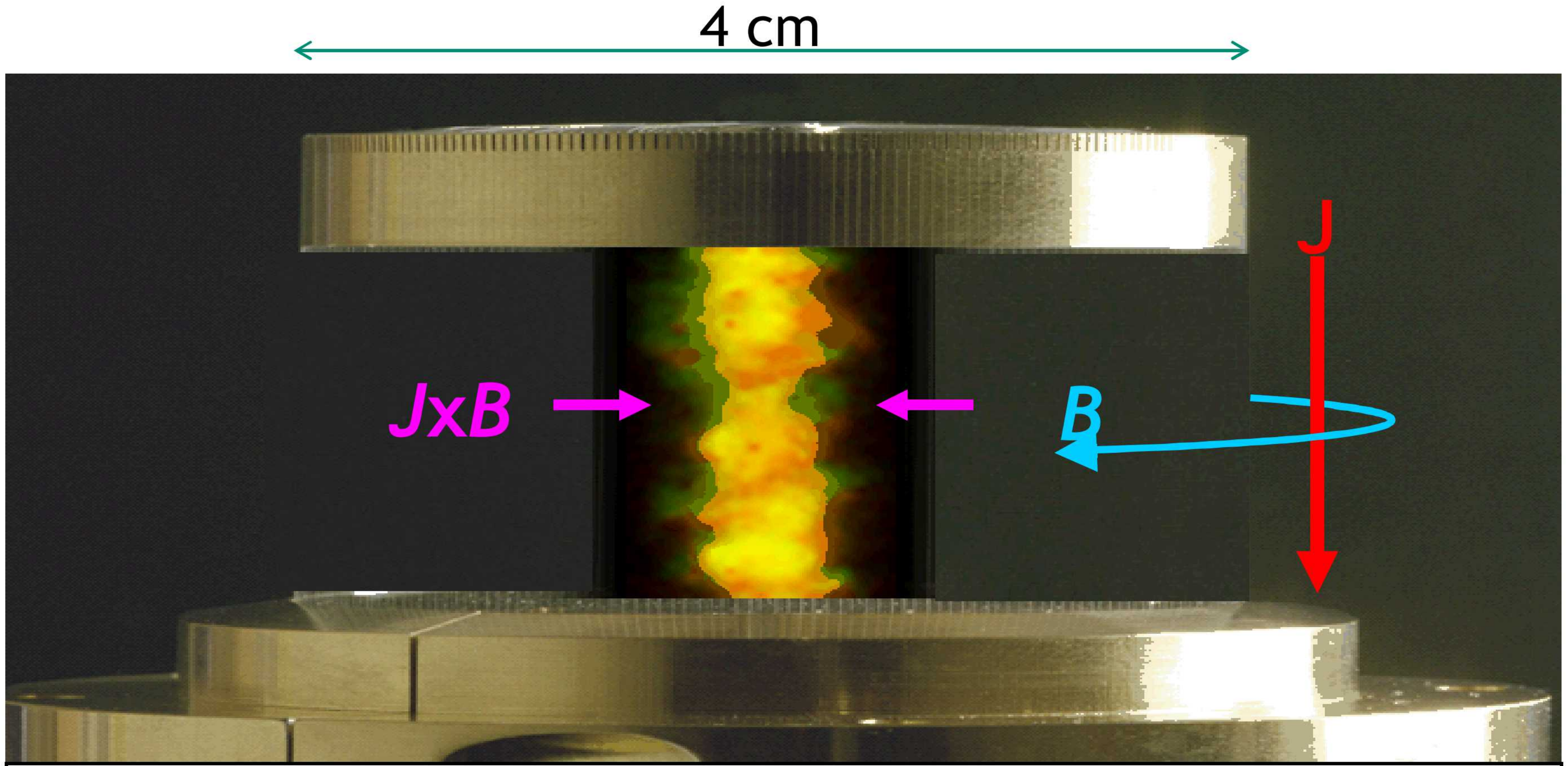


- <u>Solar physicists:</u> solar models need 10-30% higher mean opacity at CZB [1]
- <u>Hypothesis:</u> Iron opacity calculated at CZB is underestimated

Let's measure and check Fe opacity at CZB conditions

[1]. Basu, S. & Antia, H. M. *Physics Reports* 457, 217–283 (2008).

Iron opacity at solar interior conditions is measured using bright radiation generated by Z-pinch



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)

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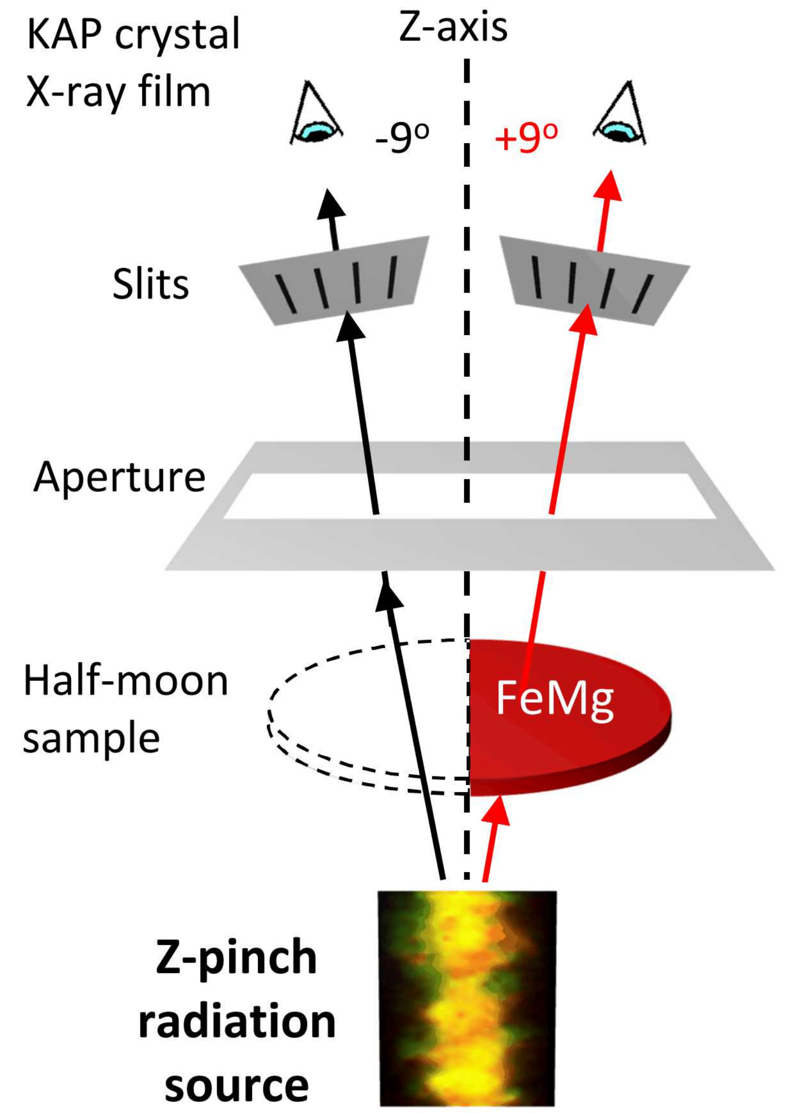
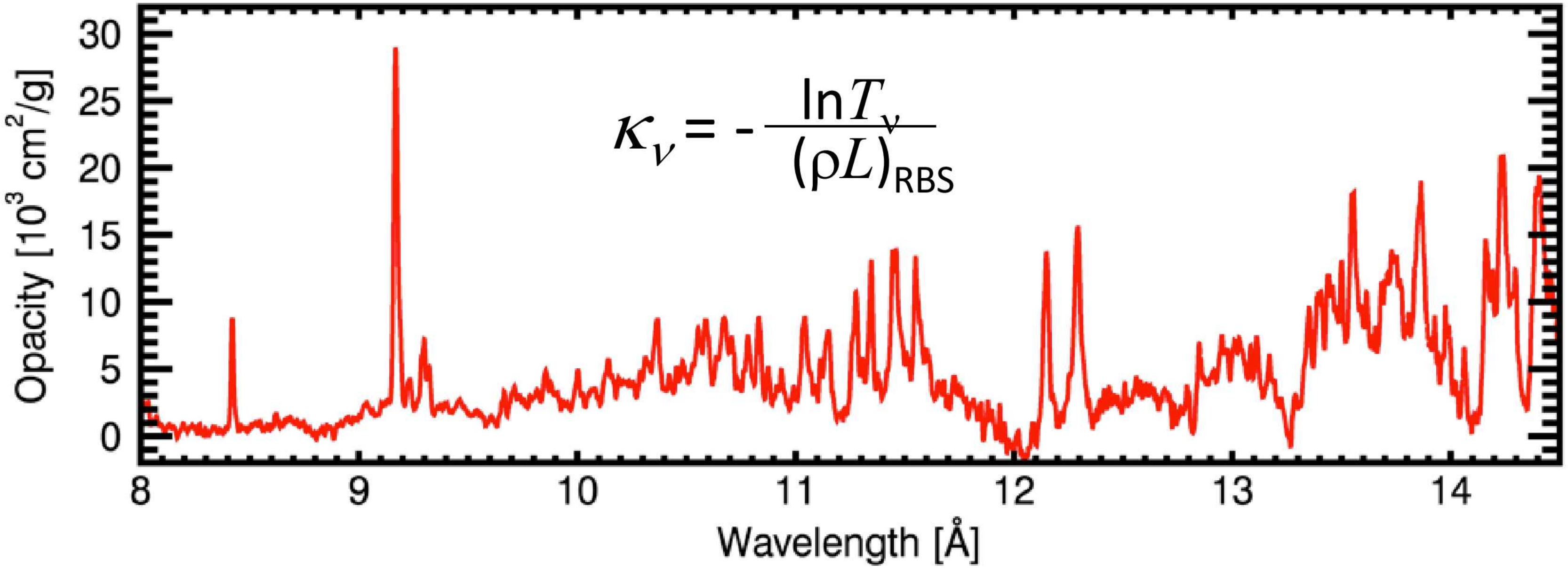




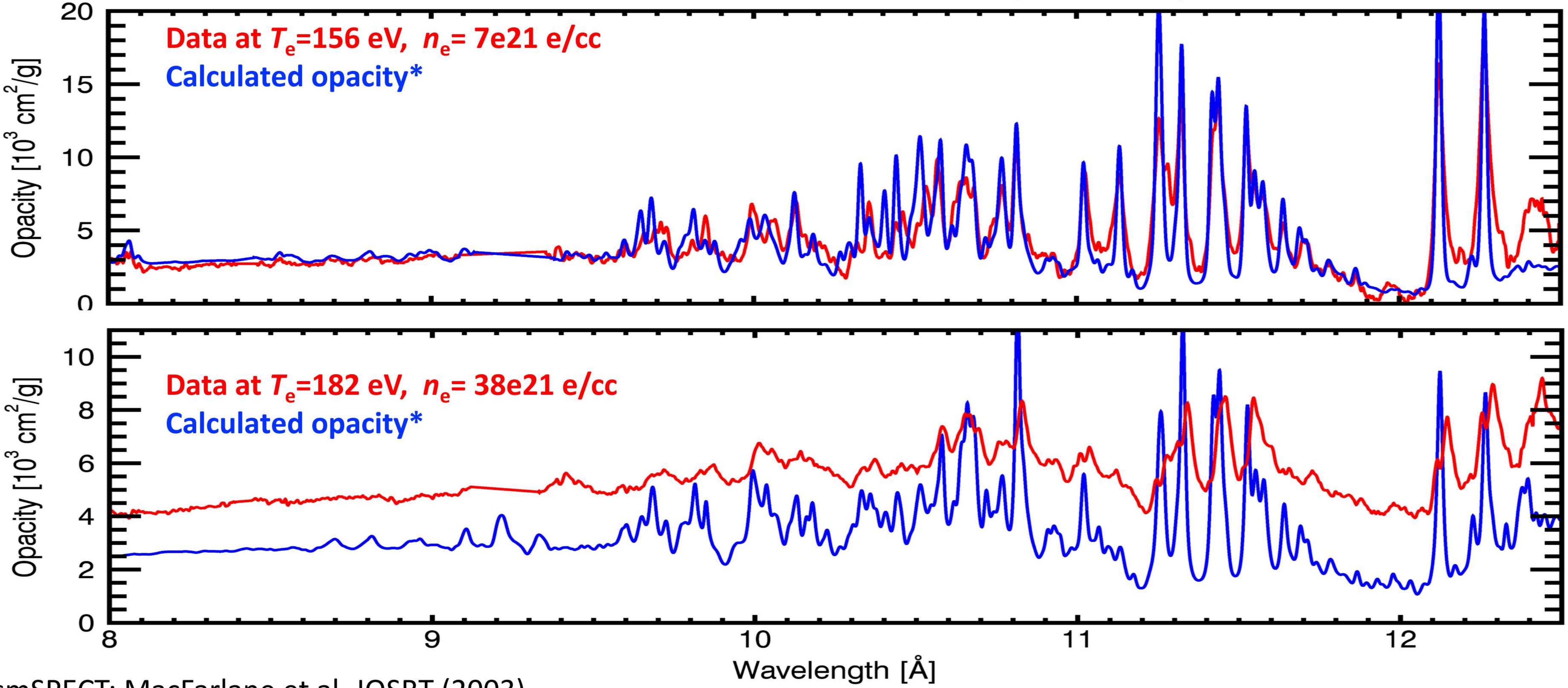
<u>Z experiment satisfies challenging requirements:</u>

- 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)

Severe opacity model-data disagreement was found as condition approaches solar interior conditions

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



* PrismSPECT: MacFarlane et al, JQSRT (2003)

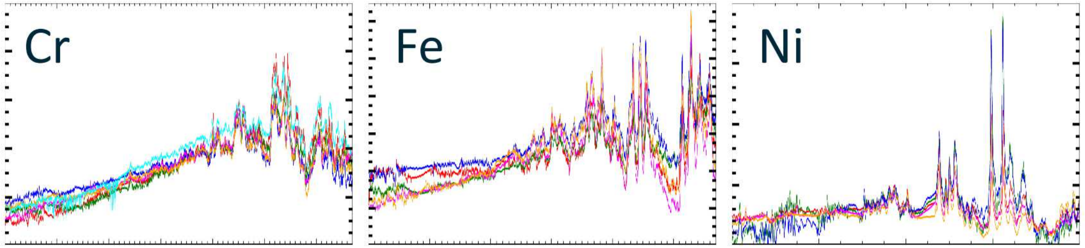
[1] Bailey et al., *Nature* 517, 56 (2015)

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

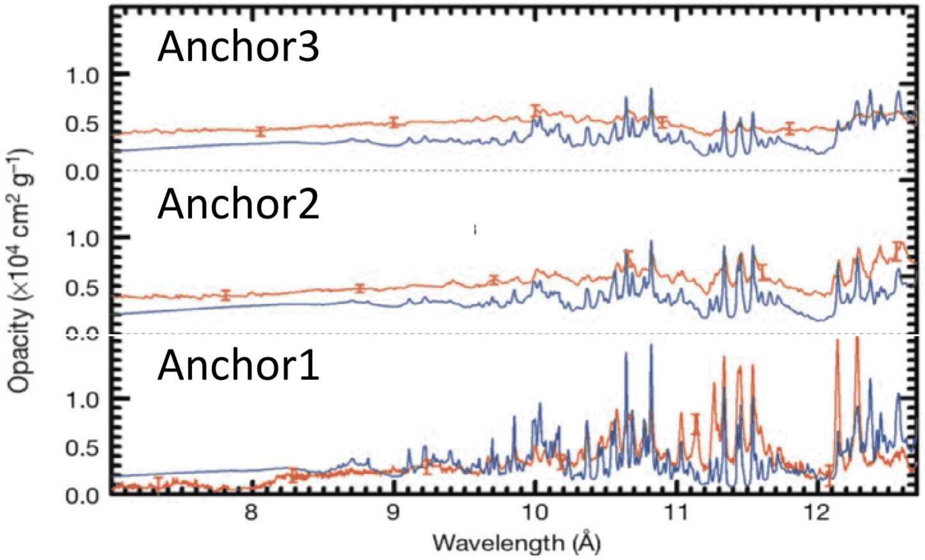
Next three talks will provide our updates in three areas

1. Refining analysis method (T. Nagayama)

- Robust method improved reproducibility
- Systematic study narrow down hypotheses [1]

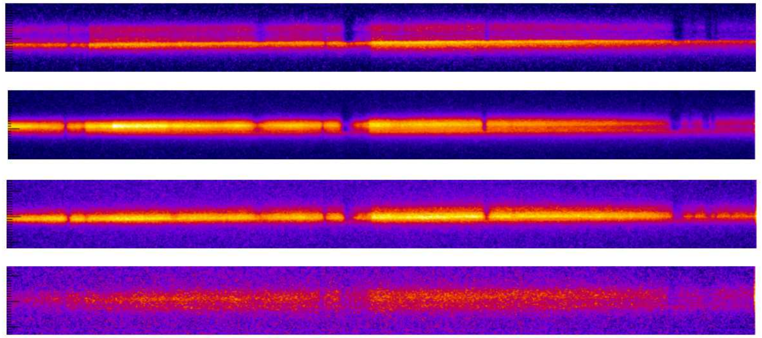


2. Revisiting iron results (J. Bailey)

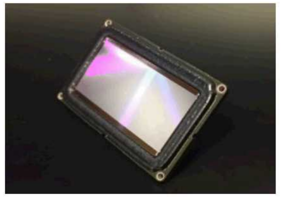


3. Time-resolved measurements (G. Loisel)

- Check our experiment
- Quantify impact of gradient



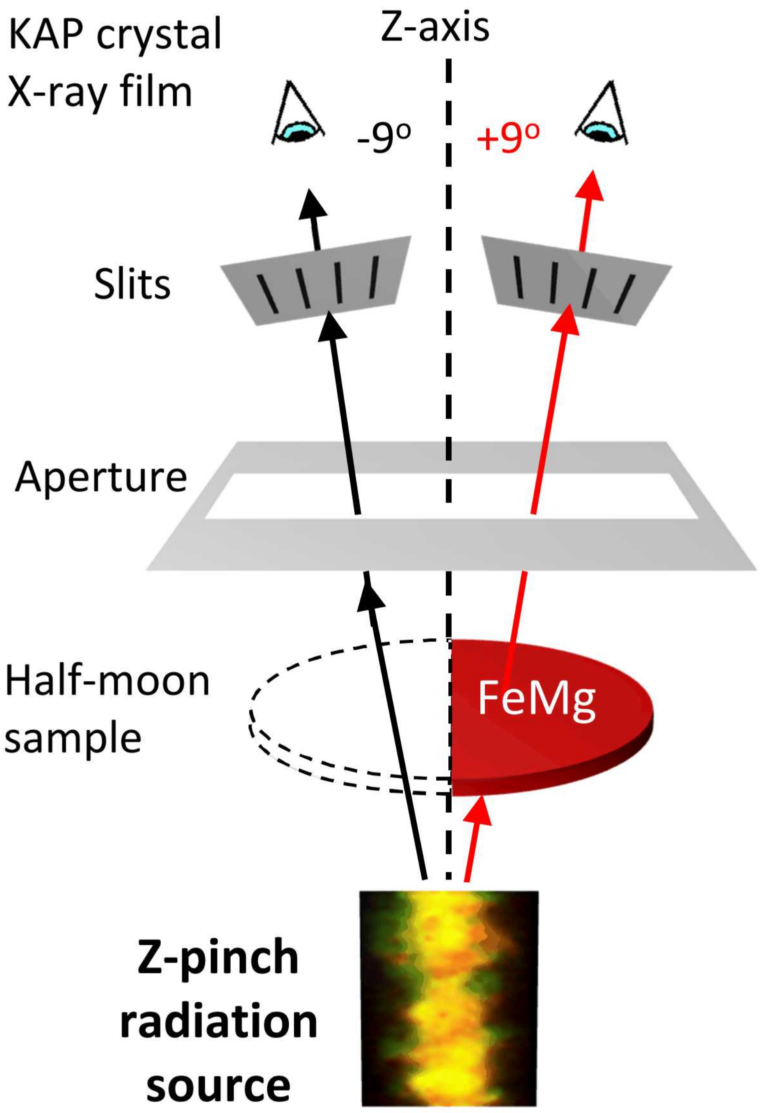
CMOS

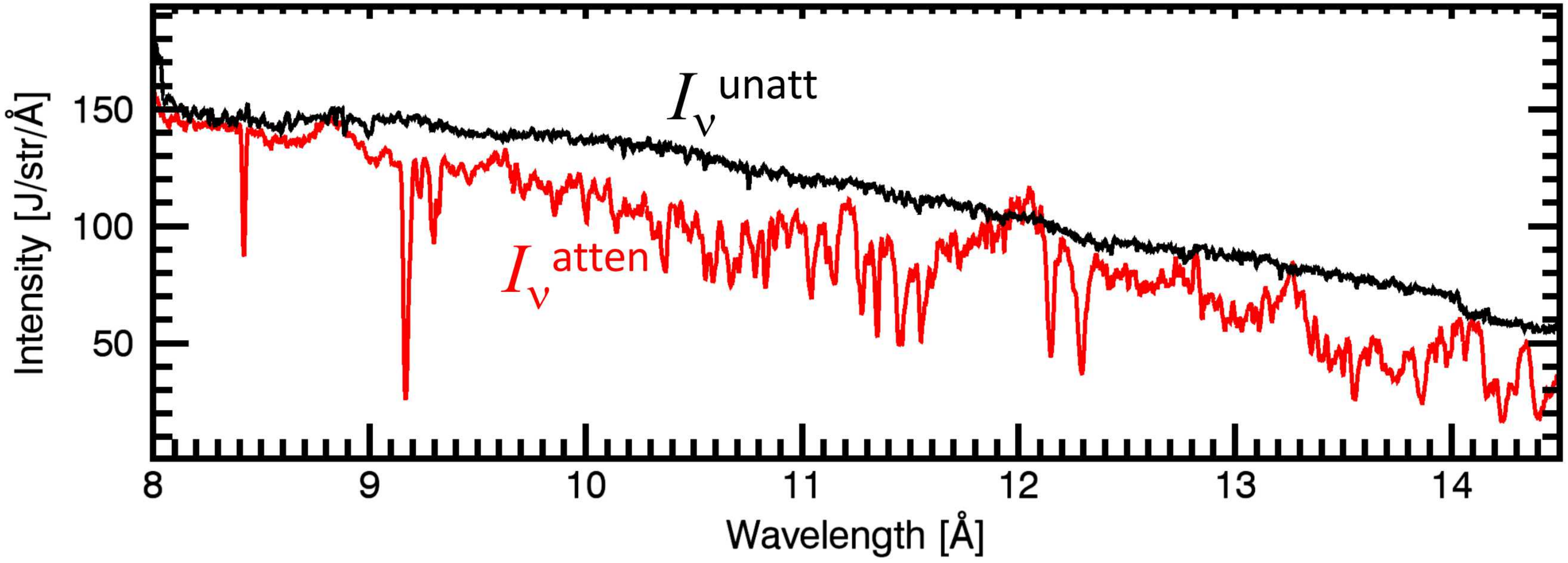


Our strategic approaches help us understand sources of iron model-data discrepancy

[1] T. Nagayama et al, PRL 122, 235001 (2019)

Backlight measured by $\pm 9°$ spectrometers are different by 10-20% based on calibration shots





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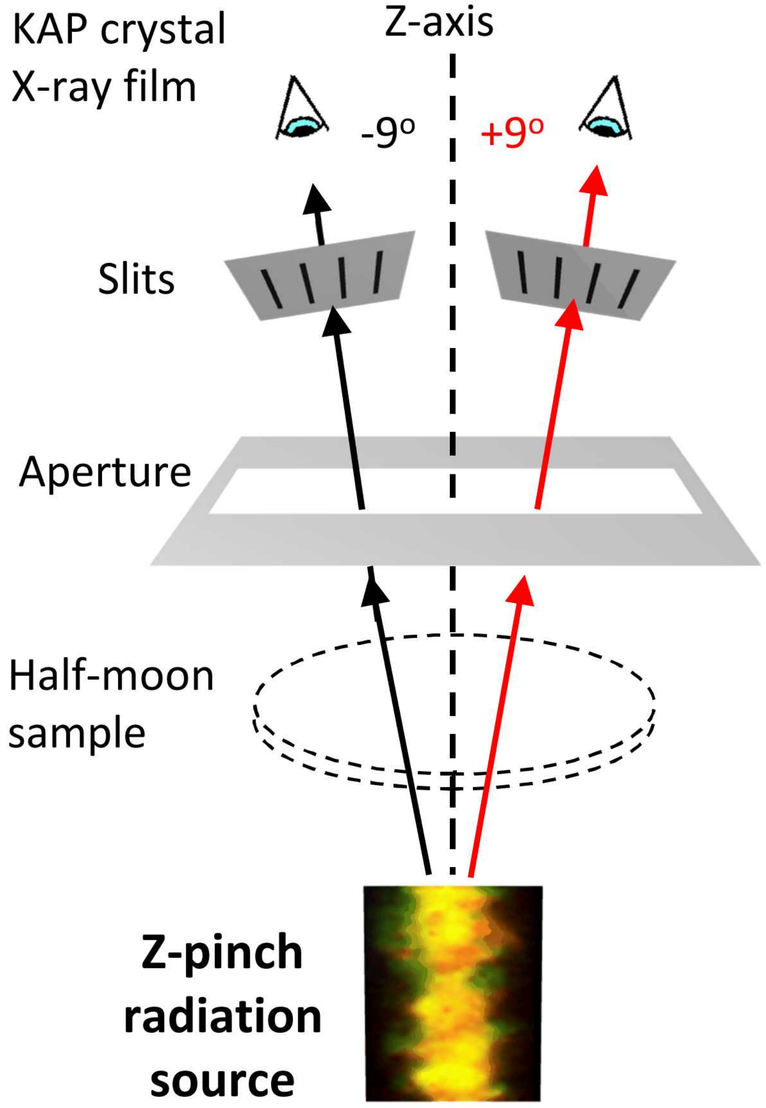

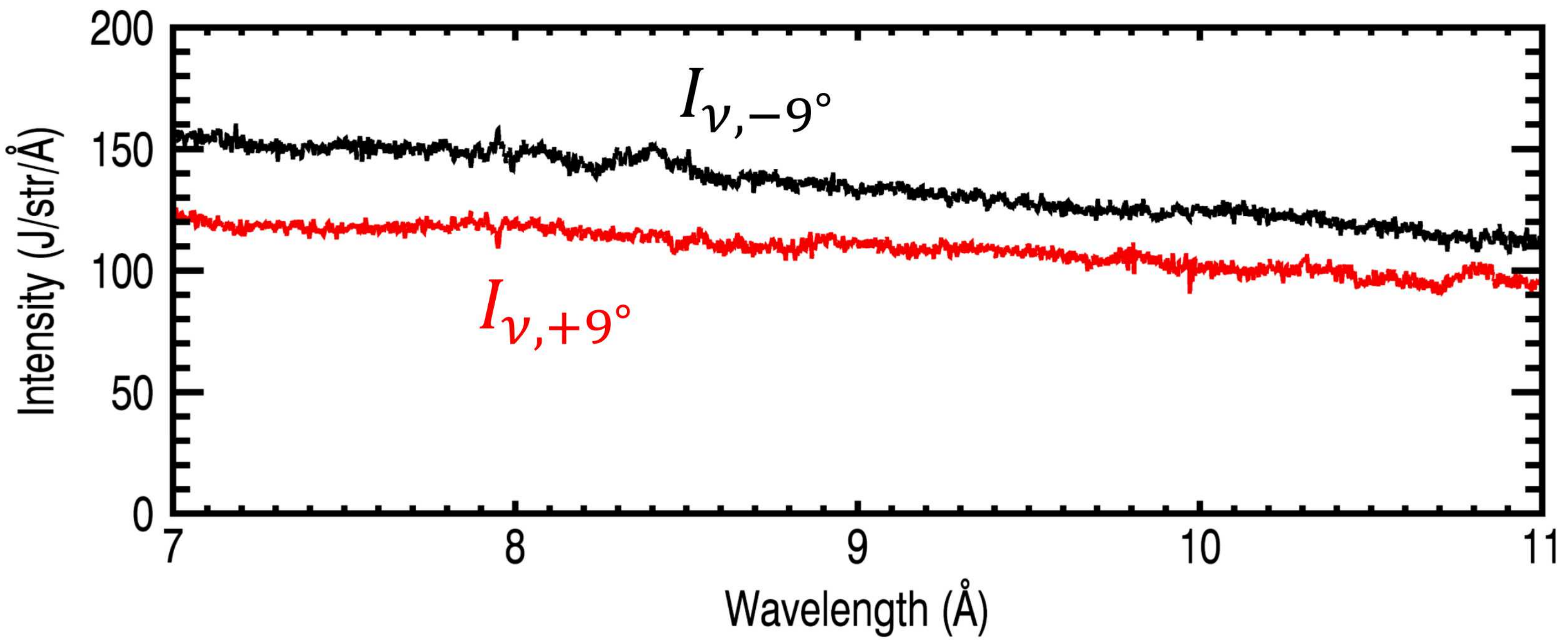

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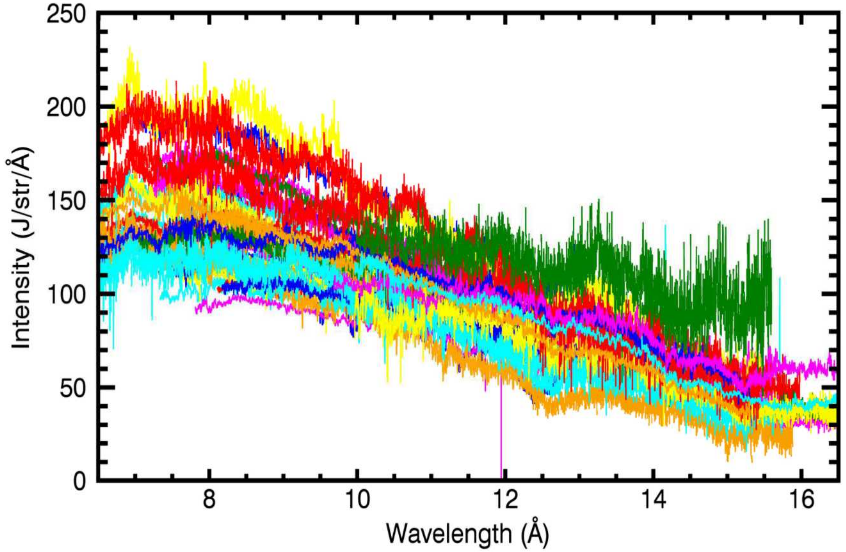
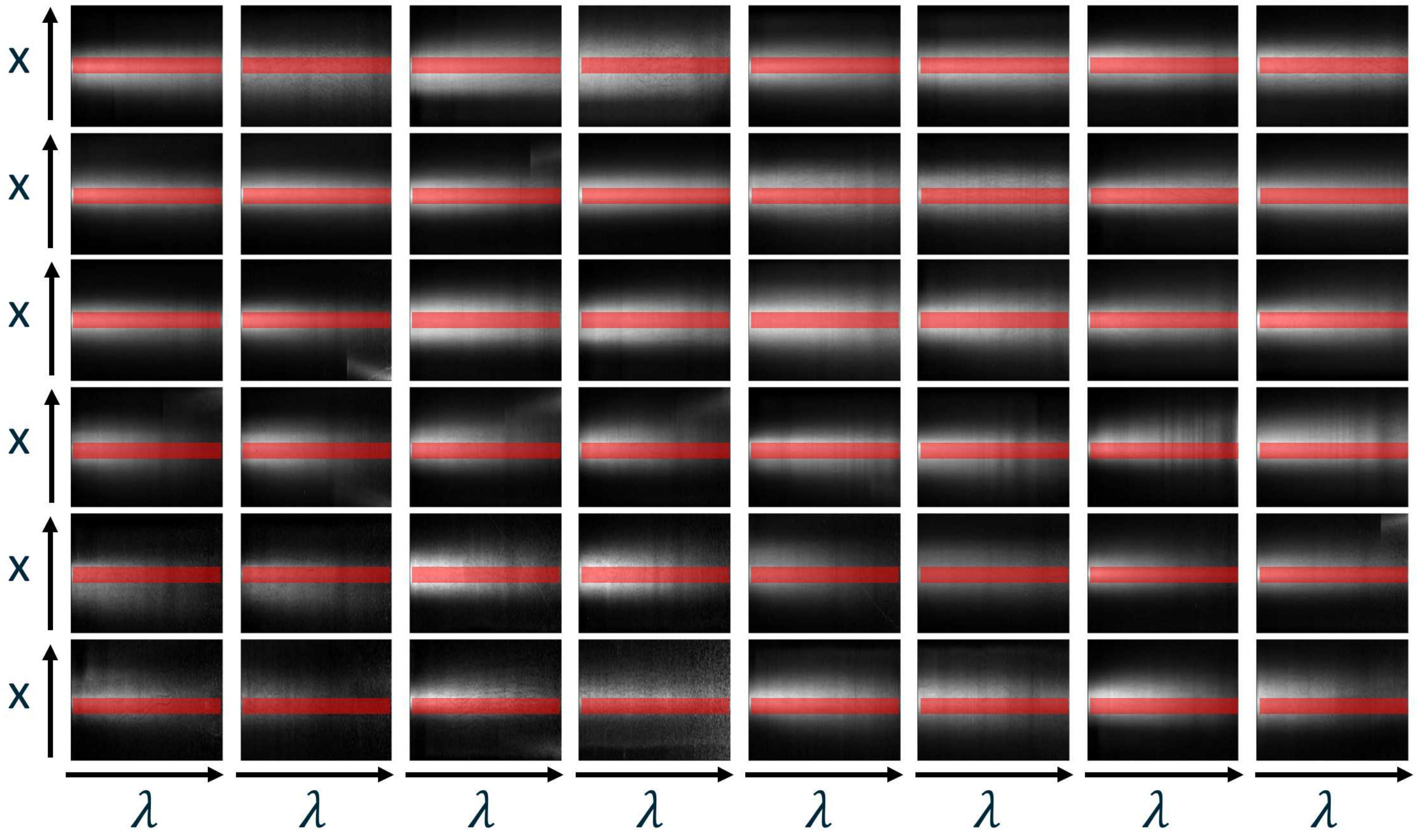
Large volume of calibration shots revealed that backlight radiation are reproduced within ±20%

Backlight radiation is known within ±20%



Good news: **We have accumulated large volume of backlight radiation statistics**

48 spectral images from 12 calibration shots collected over a decade

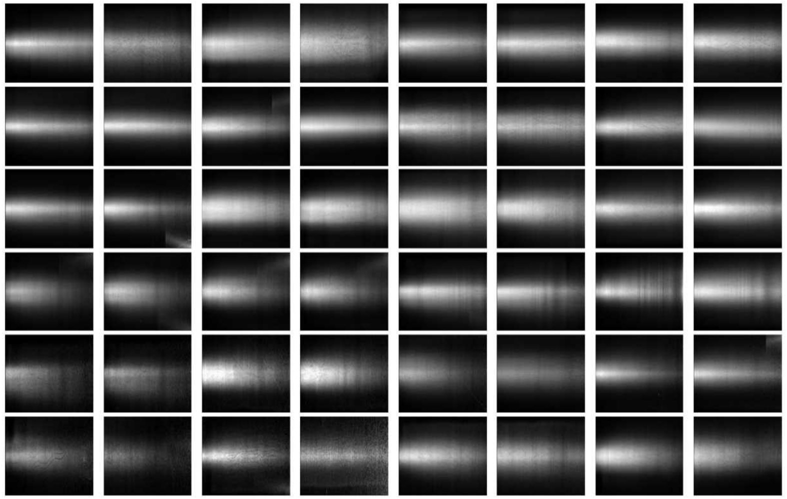


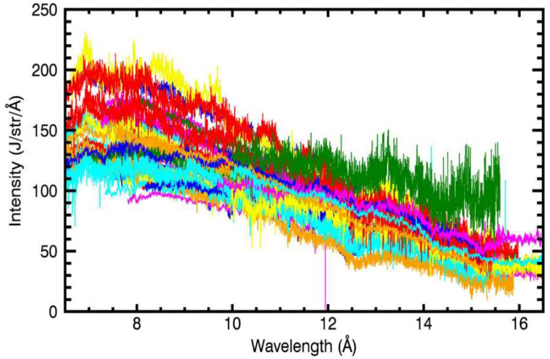
The analysis method can be improved by performing rigorous propagation of this statistics

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

New analysis perform rigorous error propagation in 3 steps

i) Calibration shot statistics





ii) Analytic statistics conversion

Calibration shot statistics

↓ Analytic conversion

Transmission PDF*

iii) Monte-Carlo error propagation

Transmission PDF*
Areal density PDF*
Background PDF*

↓ Monte Carlo

Opacity PDF*

*PDF = Probability Distribution Function

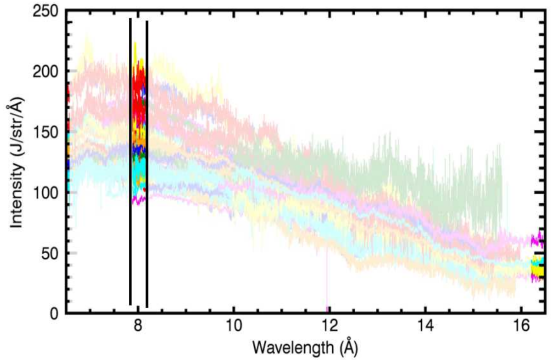
ii) Calibration-shot statistics can be analytically converted to transmission PDF (≡Probability Distribution Function)

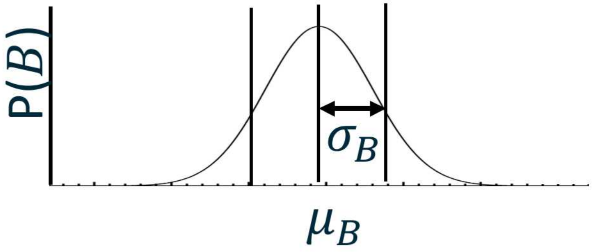
Example: Transmission at 8Å?

$$T_{8\text{Å}} = \frac{I_{8\text{Å}}}{B_{8\text{Å}}}$$

← We measure this

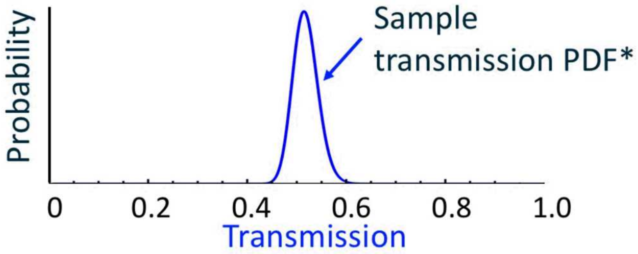
← We know this value statistically, μ_B and σ_B from





Key idea: If we know P(B), we can analytically derive P(T)

$$P(T) = P(B)\frac{dB_{8\text{Å}}}{dT_{8\text{Å}}}$$

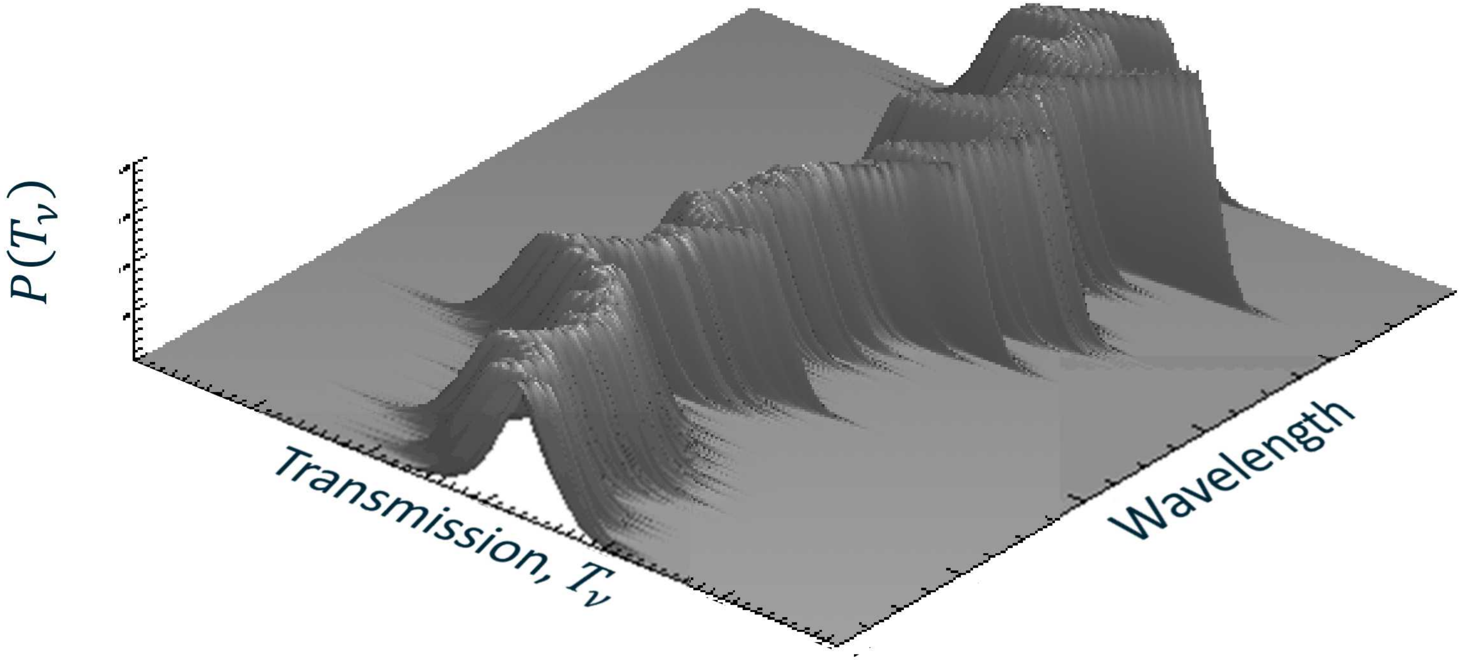


$\mu_T = 0.518$
$\sigma_T = 0.025$

Calibration shot gives statistics on absolute, spectra, and spatial shapes → Multiple ways to get PDF

ii) Calibration-shot statistics can be analytically converted to transmission PDF (≡Probability Distribution Function)

Repeating this analysis at every wavelength gives you:

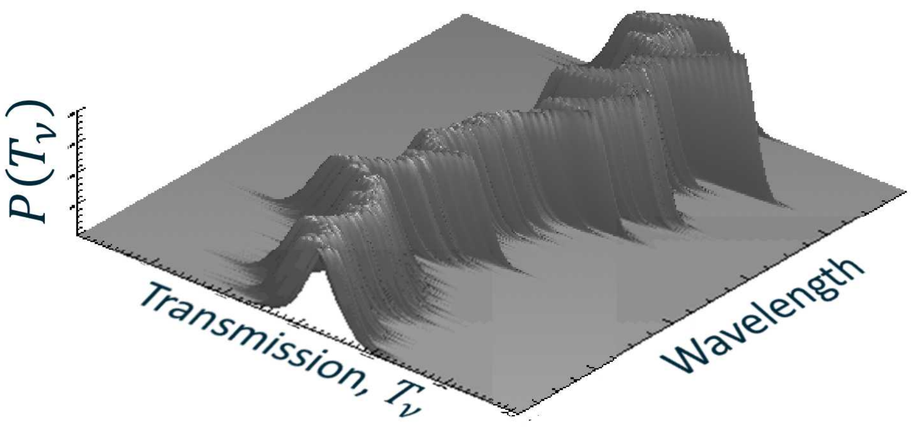


- We follow detailed transmission PDF
- Multiple methods and data are easily combined through joint probability

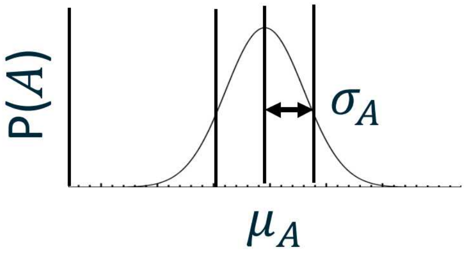
Analysis-method accuracy is confirmed through synthetic-data analysis

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

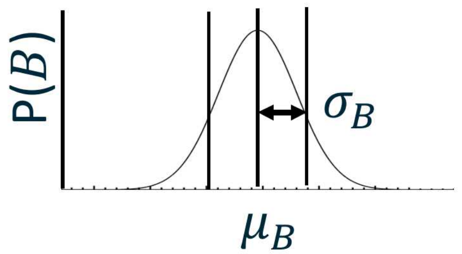
Transmission PDF, $P_\lambda(T)$



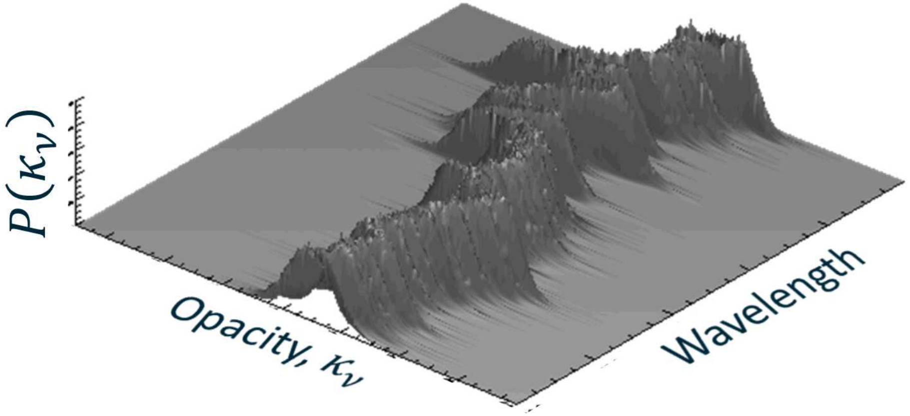
Areal-density PDF

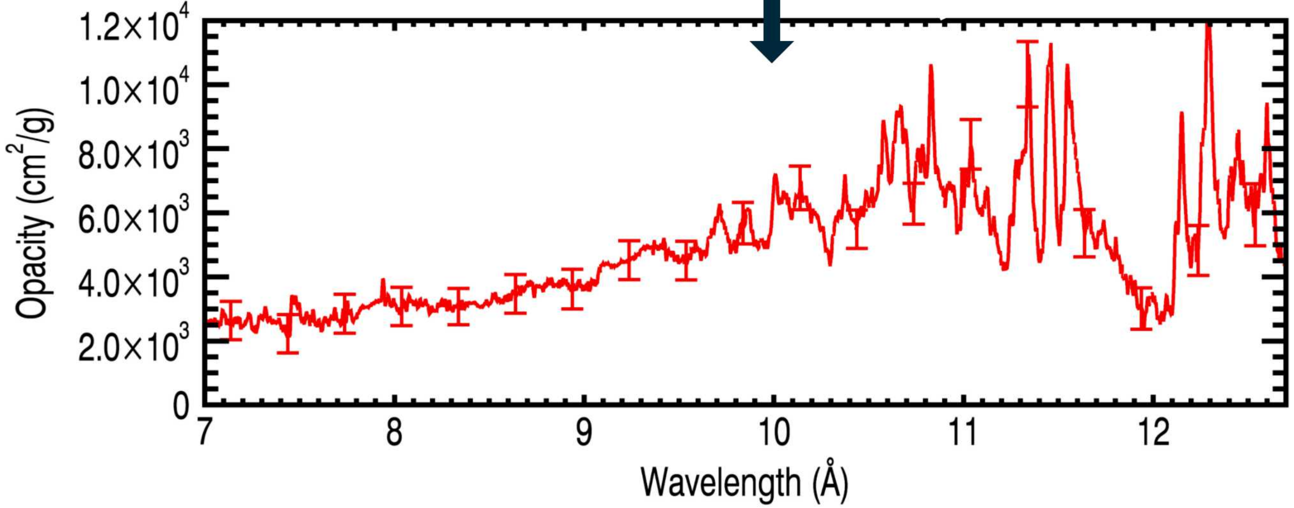


Background PDF



Monte Carlo

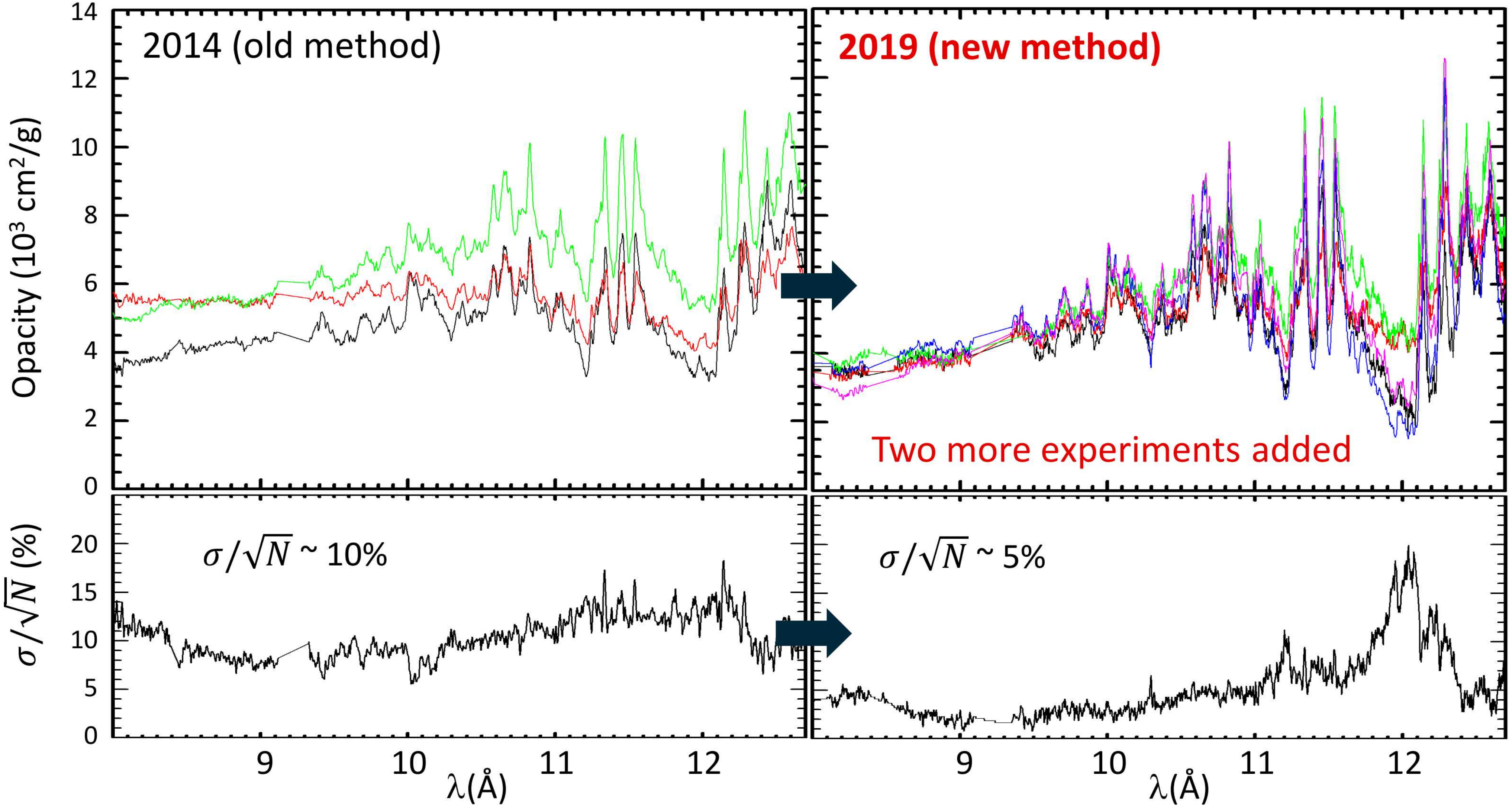




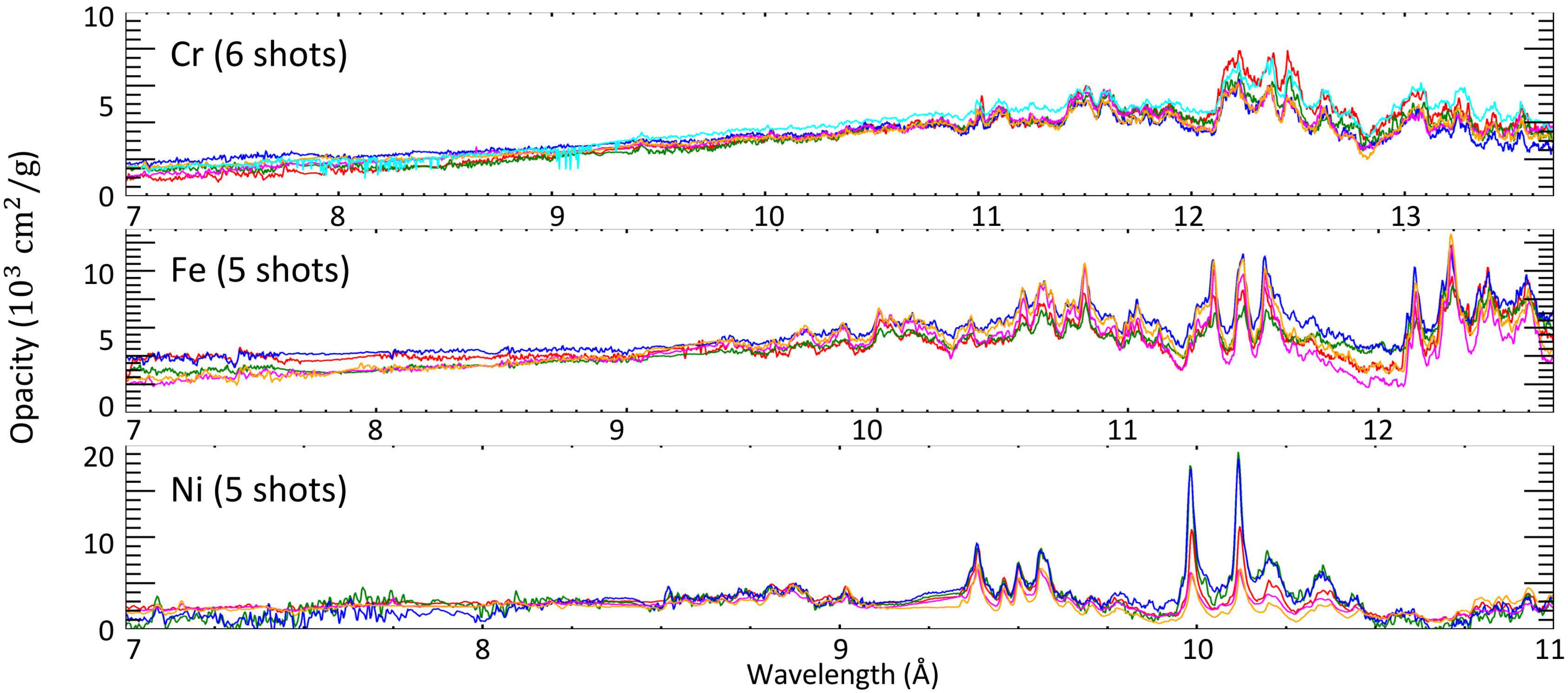
Analysis returns asymmetric non-Gaussian opacity PDF as a function of wavelengths

*PDF = Probability distribution function

New analysis was applied to old data; Experiment reproducibility is better than we believed



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



Model-data discrepancy as a function of atomic number helped narrow down sources of discrepancies [1]

[1] T. Nagayama et al, Phys. Rev. Lett. 122, 235001 (2019)

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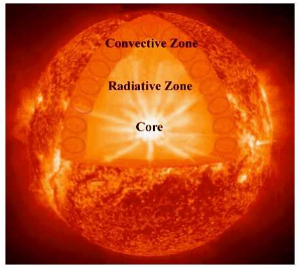

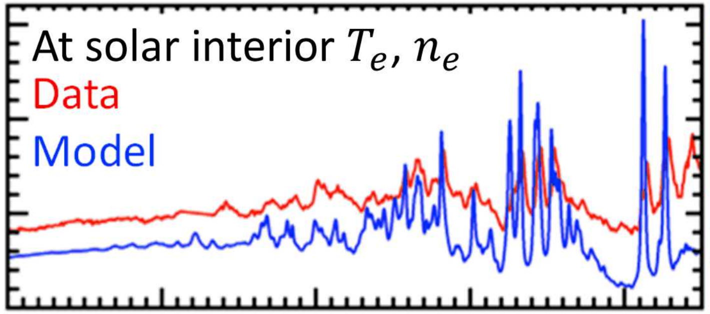

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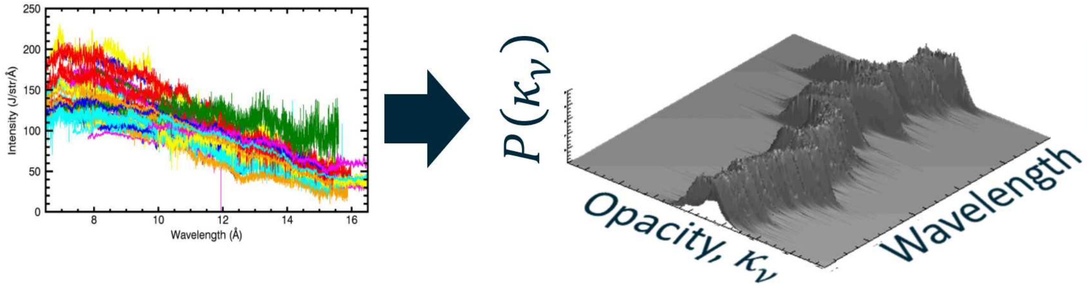

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