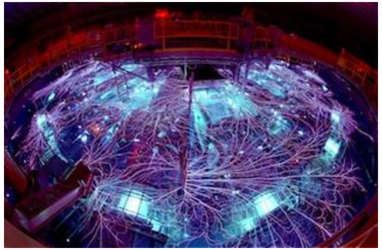

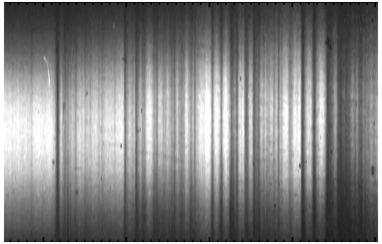

Experimental methods for stellar interior opacity measurements at the Z facility

Jim Bailey, T. Nagayama, G.P. Loisel, G.S. Dunham, S.B. Hansen, G.A. Rochau

Sandia National Laboratories

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An extensive collection of methods has been developed to measure monochromatic stellar interior opacity

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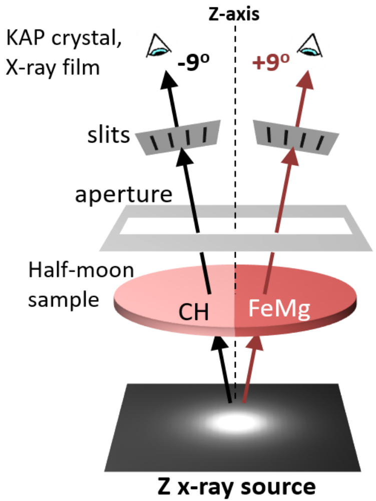
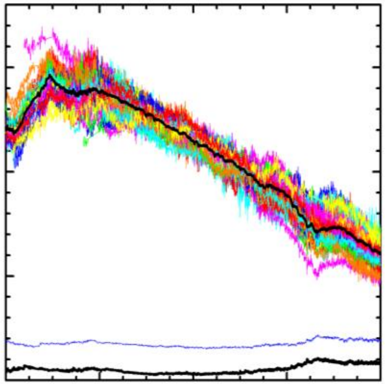
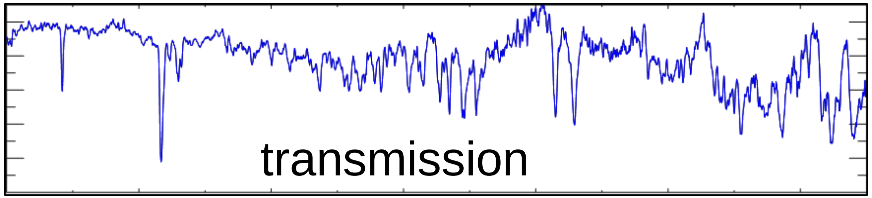
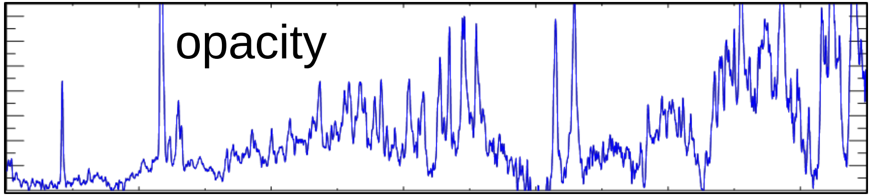
- Transmission is measured using an array of spectrometers that view an x-ray source through a sample
- The sample temperature and density are adjustable using low Z tampers
- The plasma conditions are measured with Mg spectroscopy
- The large accumulated data set enables reproducibility and accuracy tests

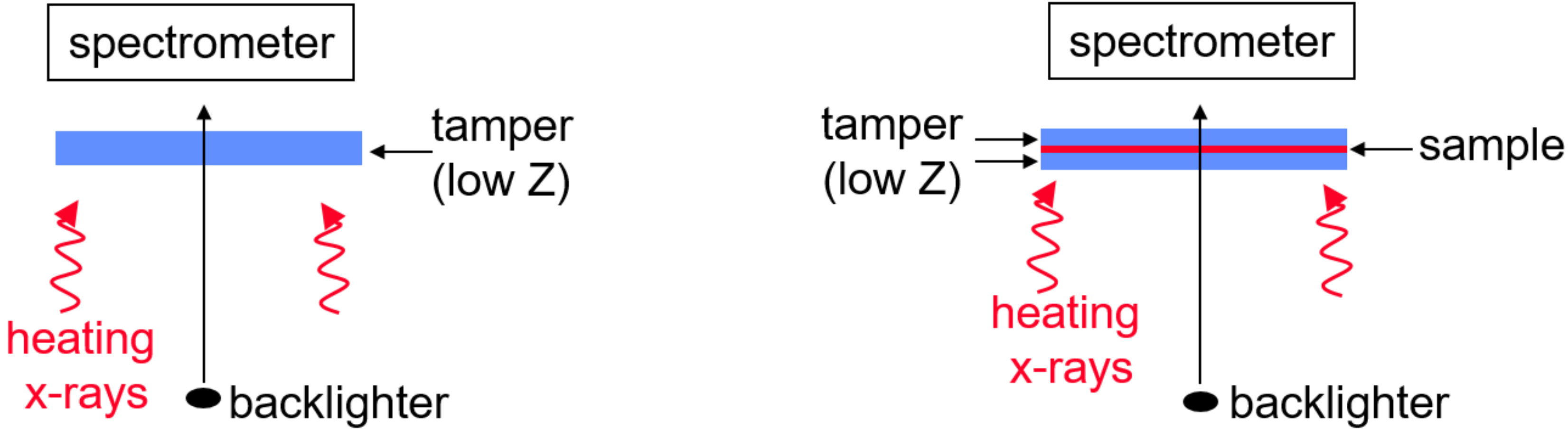








Opacity model tests rely on wavelength dependent (monochromatic) transmission measurements



T.S. Perry et. al. Phys. Rev. E 54, 5617 (1996); Bailey *et al*., Phys Plasmas 16 (2009)

Benchmark quality opacity experiment requirements are demanding

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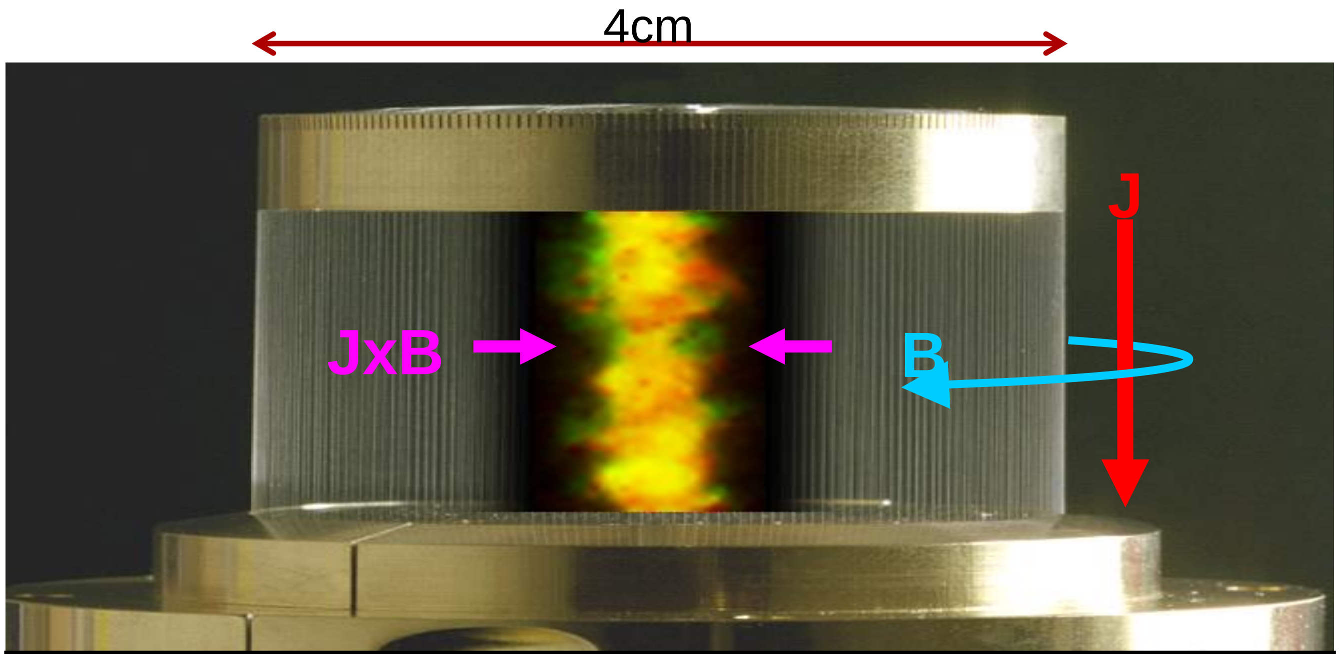
<u>Experiment requirements:</u>

1. Accurate transmission measurements (~ ± 5%)
2. Demonstrated uniformity
3. Reliable plasma diagnostics
4. Freedom from self emission
5. Freedom from background contamination
6. Multiple areal densities (for dynamic range and systematic error tests)
7. Thorough sample characterization
8. An evaluation of how suitable the LTE approximation is
9. Multiple T_e, n_e conditions, to aid disentangling physical effects
10. Multiple atomic number elements, to aid disentangling physical effects and help verify robustness against systematic errors
11. Multiple experiments of each type, to confirm reproducibility
12. Peer review and documentation

Bailey *et al*., Phys Plasmas 16 (2009)

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



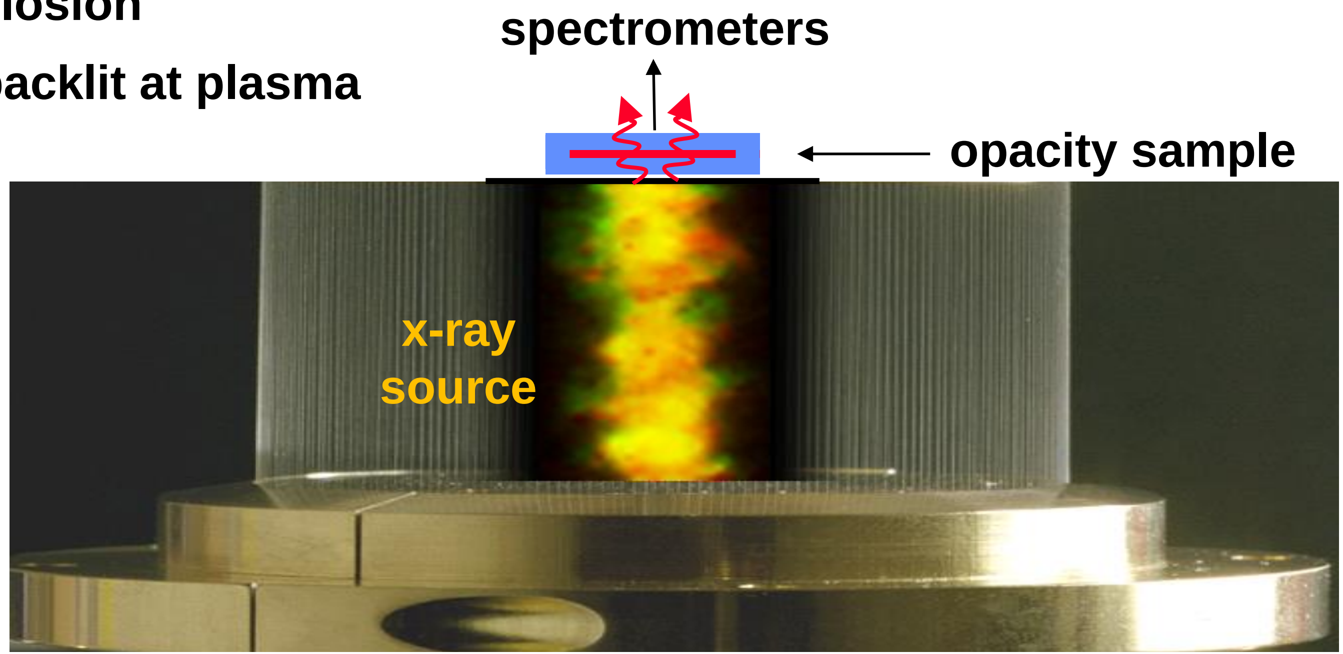
P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

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

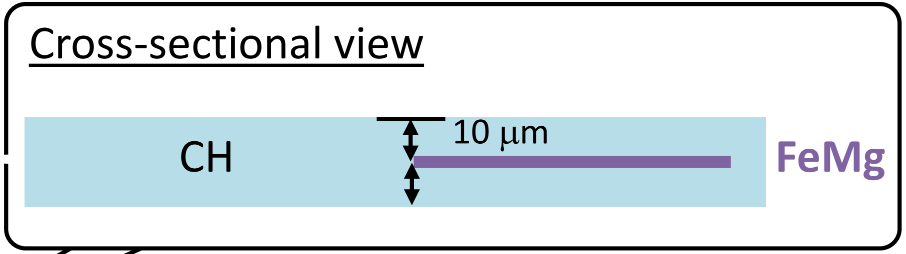
The Z x-ray source both heats and backlights samples to stellar interior conditions.

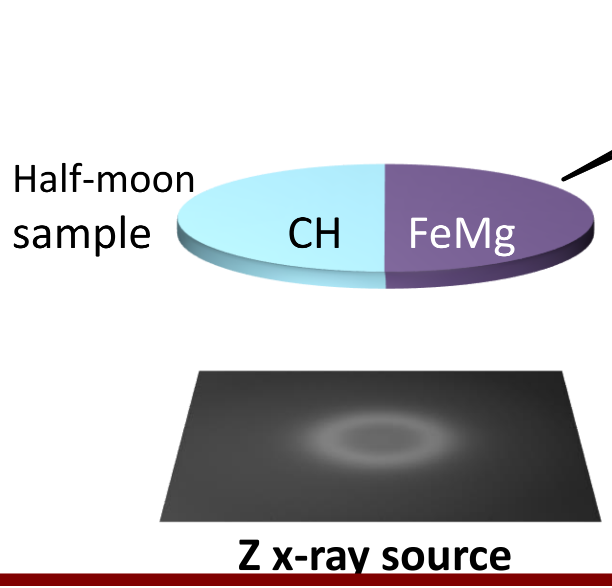
Sample is heated during plasma implosion

Sample is backlit at plasma stagnation



Z opacity science configuration satisfies challenging requirements for reliable opacity measurements





Requirements:

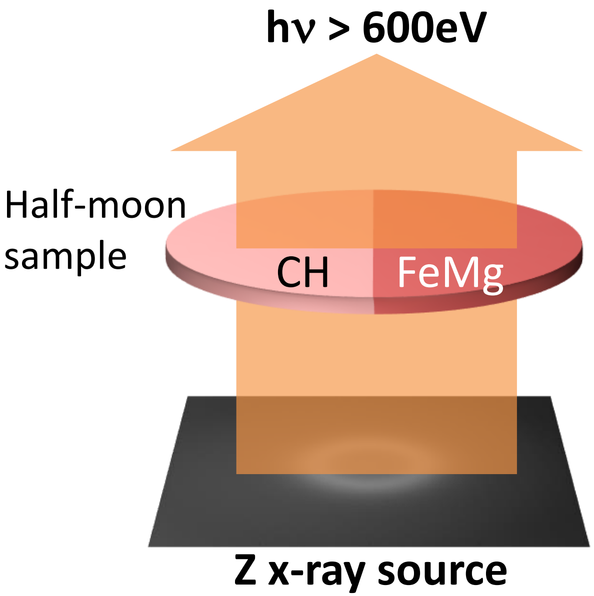
- Heat Fe to uniform conditions → Powerful radiation
- Measure Fe conditions independently→ Mg spectra
- Bright backlight → 350 eV Planckian at stagnation
- Measure transmission accurately→ multiple spectra

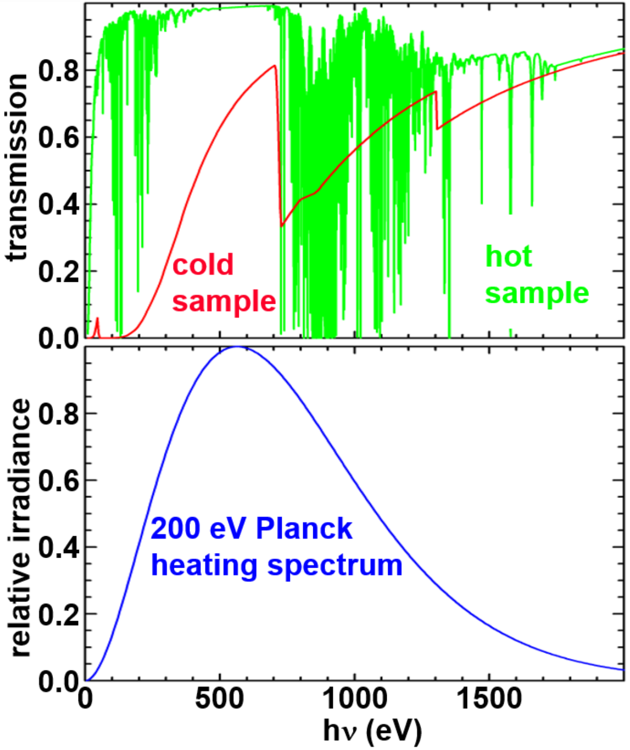
Bailey et al PoP 2009

Z opacity science configuration satisfies challenging requirements for reliable opacity measurements

<u>**Transmission**</u> $T(\nu) = \exp\{-\int \kappa[\nu, T_e(x), n_e(x)]\rho(x)dx\}$

<u>***If* plasma is uniform:**</u> $T(\nu) \approx \exp\{-\kappa(\nu)\rho L\}$





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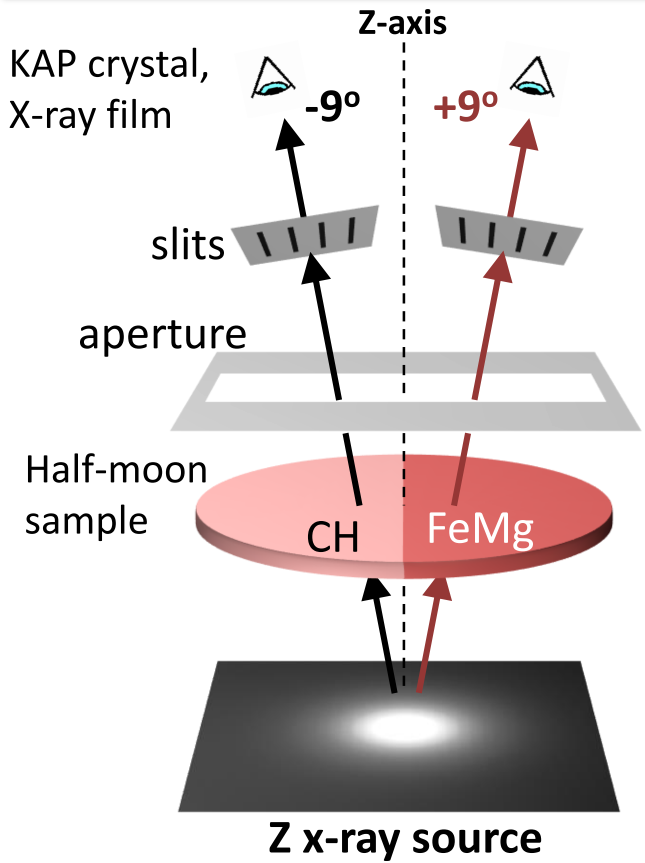

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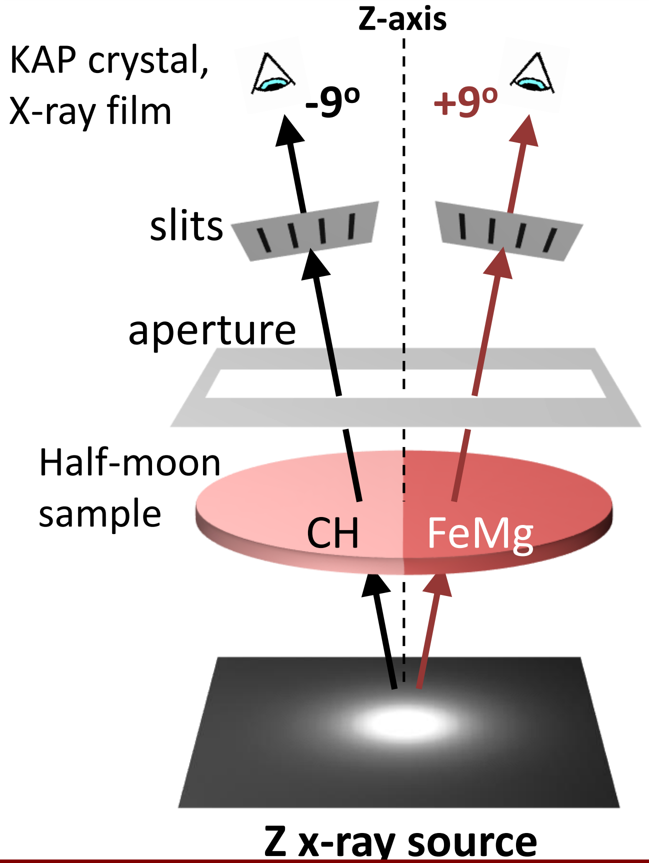

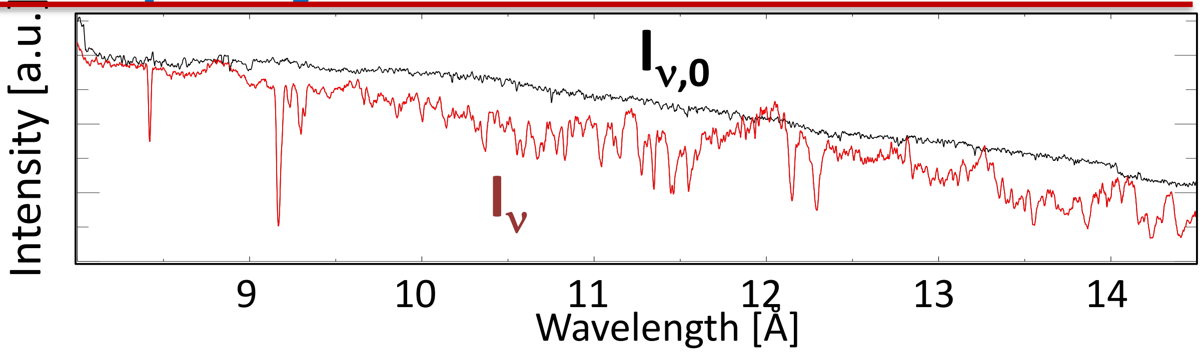

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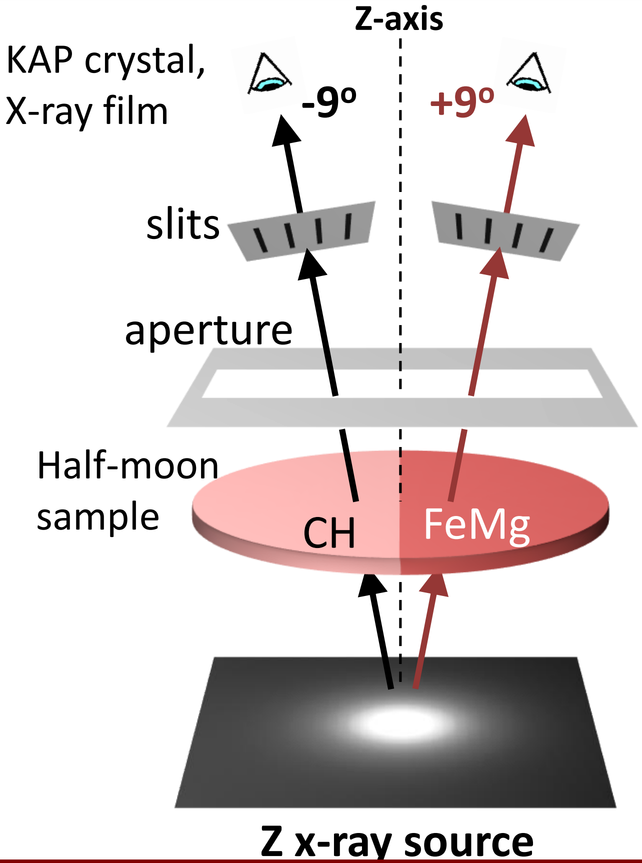

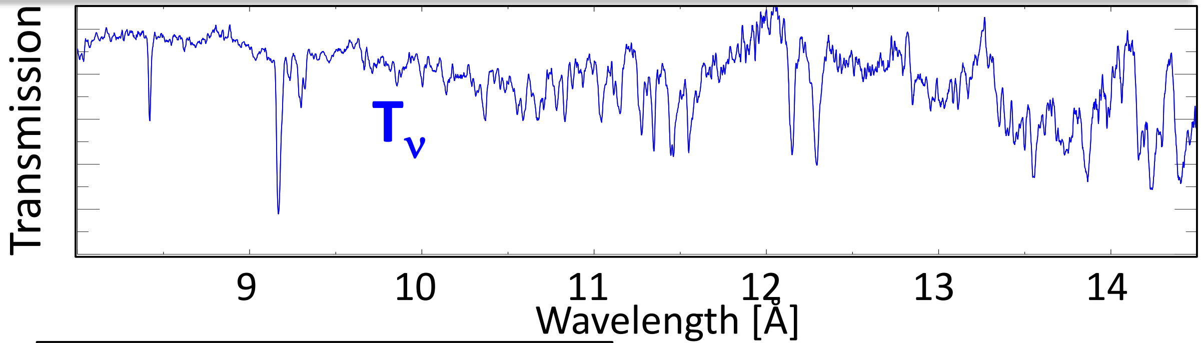

Transmission: $T_\nu = I_\nu / I_{\nu,0}$

<u>Requirements:</u>

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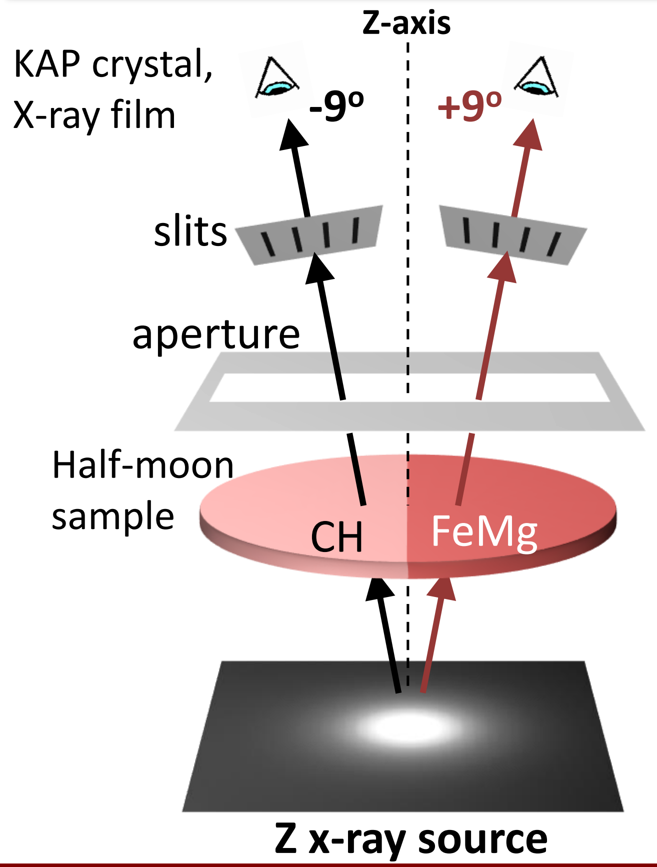
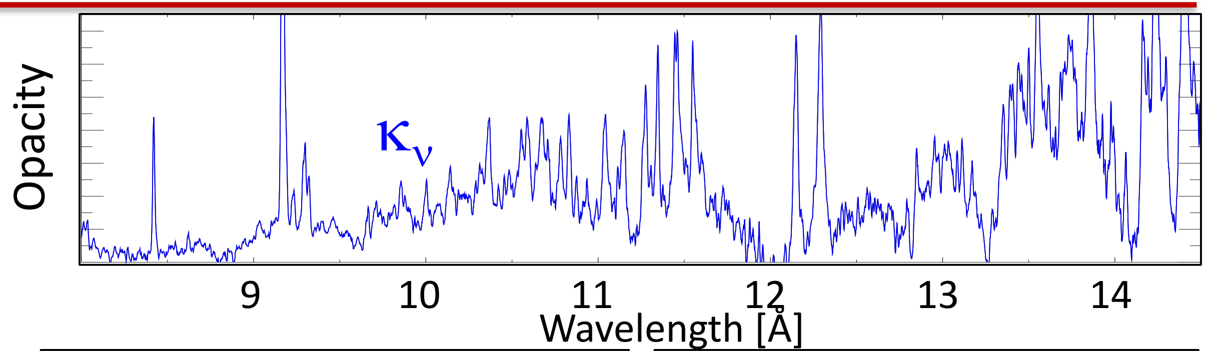




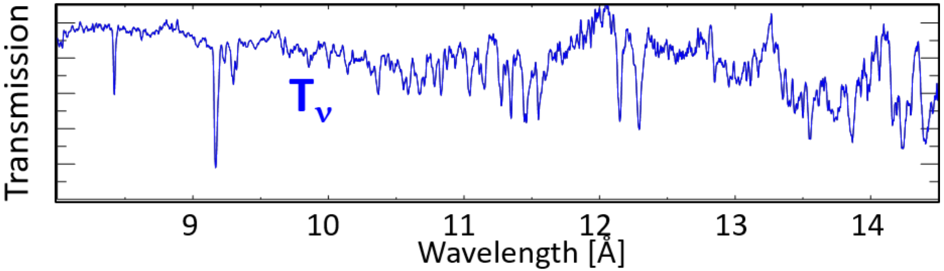
Transmission: $T_\nu = I_\nu / I_{\nu,0}$

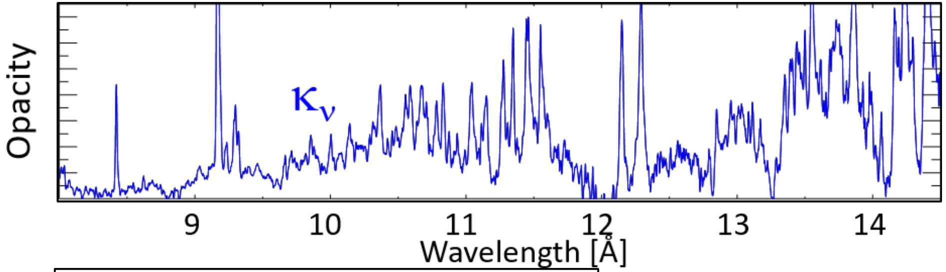
Opacity: $\kappa_\nu = -\ln(T_\nu)/\rho L$

<u>Requirements:</u>

- Heat Fe to uniform conditions → Powerful radiation
- Measure Fe conditions independently → Mg spectra
- Bright backlight → 350 eV Planckian at stagnation
- Measure transmission accurately → multiple spectra

We primarily use transmission data for experiment accuracy evaluation and opacity for model tests





Transmission: $T_\nu = I_\nu / I_{\nu,0}$

Advantages:

- More direct measurement units
- Best for evaluating data limitations
- Data with T < 0.1 and T>0.9 suspect

Disadvantages:

- Non-linear relation with opacity
- Model constraints difficult to evaluate

Opacity: $\kappa_\nu = -\ln(T_\nu)/\rho L$

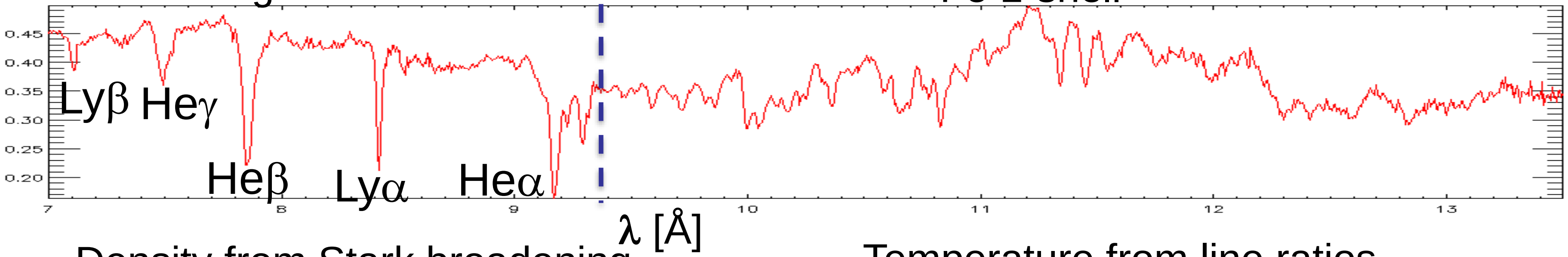
Advantages:

- Linear relation atomic and plasma physics
- Straightforward to average experiments
- Easier to compare different elements

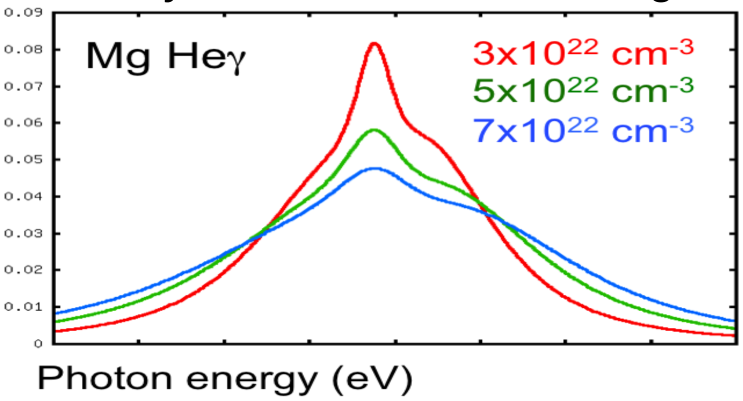
Disadvantages:

- Less direct experiment problem evaluation
- Asymmetric uncertainties can be challenging to evaluate

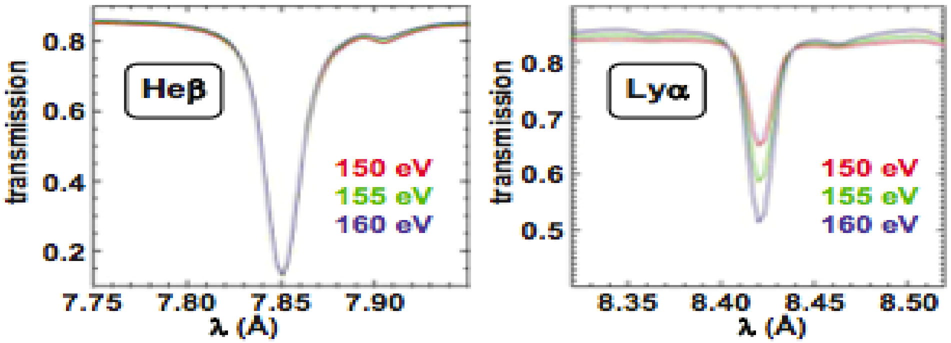
Plasma conditions are inferred by mixing Mg with Fe and using K-shell line transmission spectroscopy



Density from Stark broadening

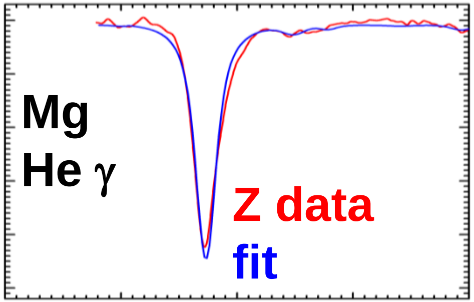


Temperature from line ratios



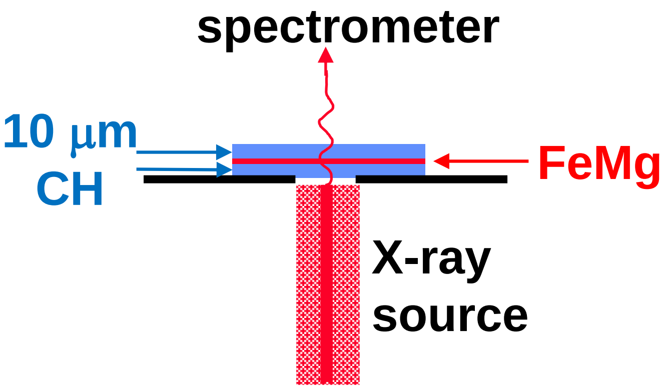
Mancini, Comp. Phys. Commun. (1991); Nagayama RSI (2013); Nagayama POP (2014)

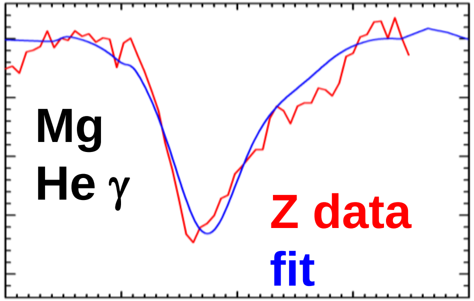
The tamper thickness and composition control the opacity sample density and temperature



$n_e \sim 0.7\text{x}10^{22}\ cm^{-3}$

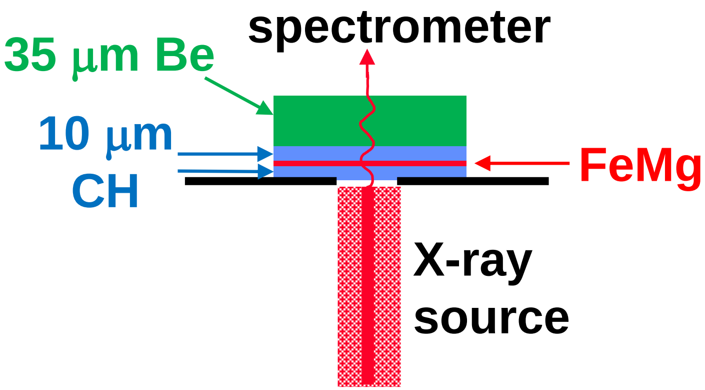
$T_e \sim 167$ eV





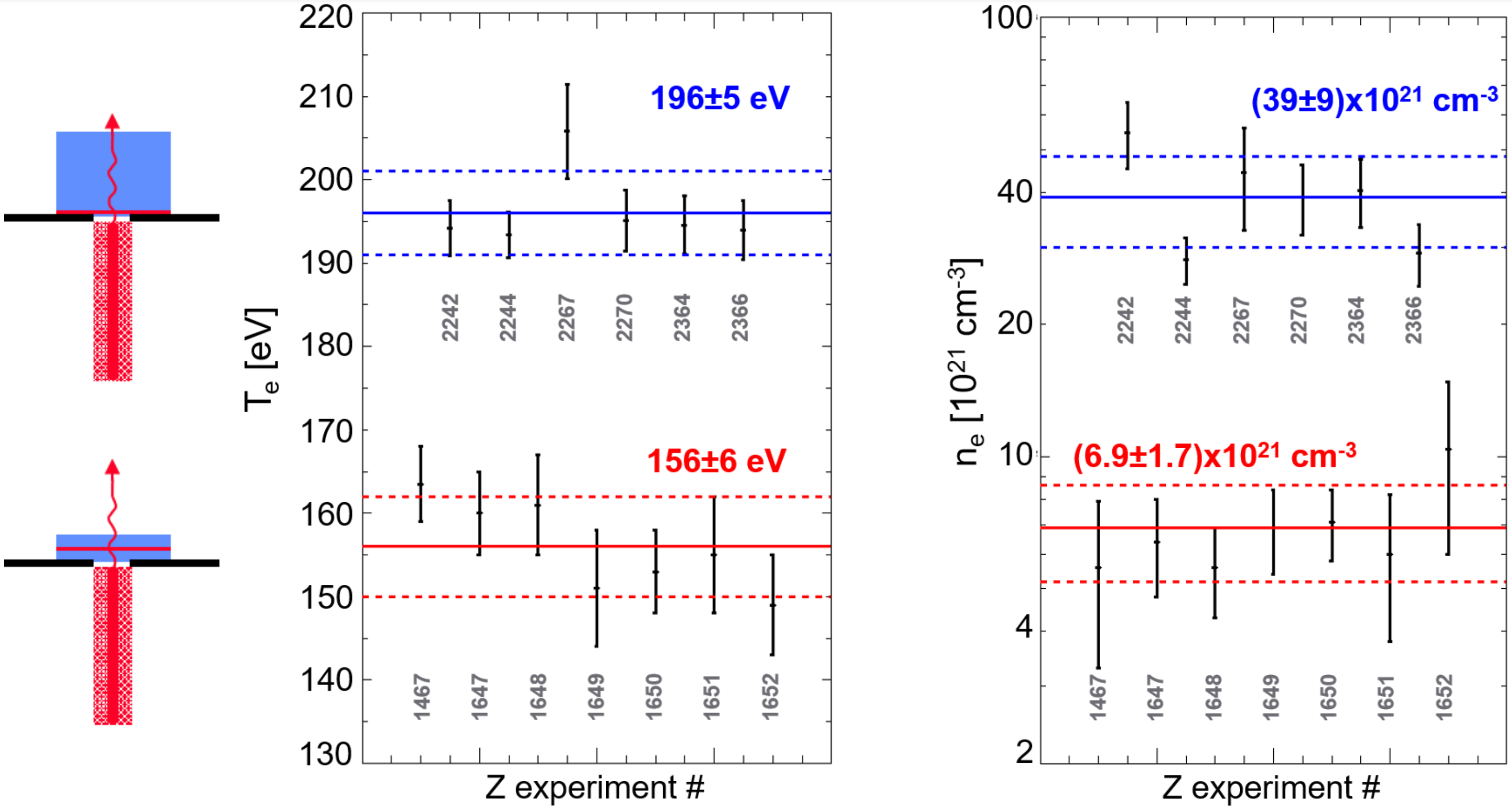
$n_e \sim 3\text{x}10^{22}\ cm^{-3}$

$T_e \sim 184$ eV



Nash Rev.Sci.Instrum. (2011)

The measured plasma temperature and density are reproducible to within ± 4% and ±25%, respectively



Nagayama PhysPlasmas (2014)

Opacity data are recorded with an array of crystal spectrometers

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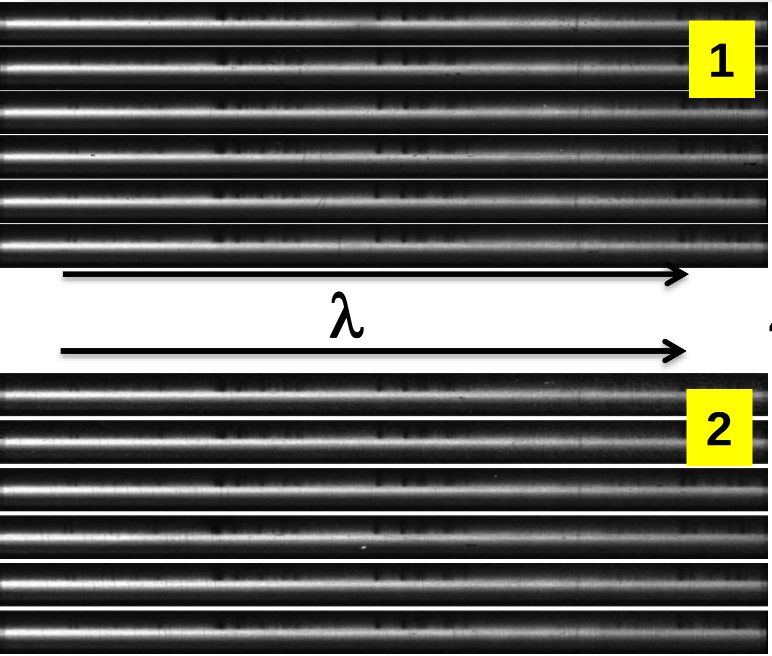
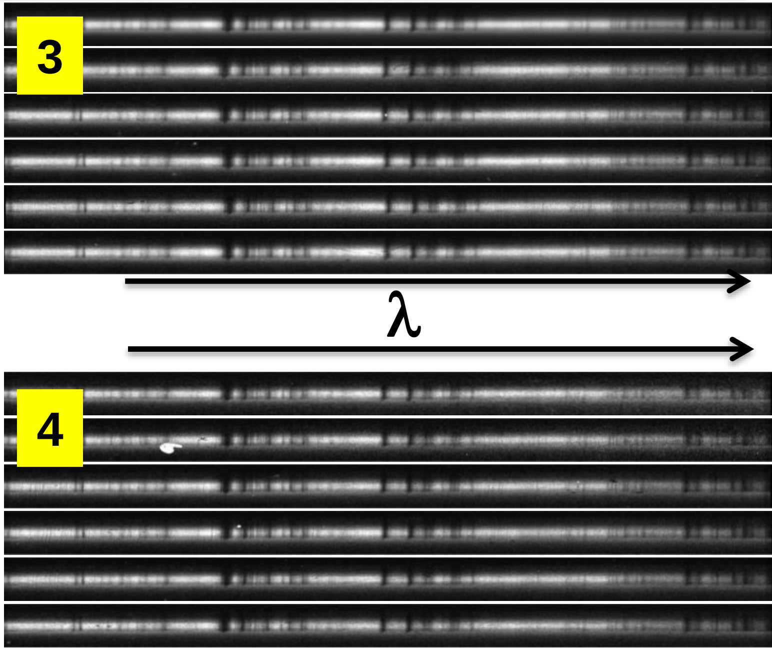
The array of opacity spectrometers is lowered into place with a 20 ton crane

Loisel et al., Rev. Sci. Instrum. (2012)

Hundreds of spectra were measured and analyzed to support the experiment reliability and reproducibility



1 experiment
4 spectrometers
24 spectra



Averaging many measurements provides ~ 15% opacity accuracy

Averaging multiple lineouts from each spectrometer boosts signal-to-noise and promotes freedom from artifacts

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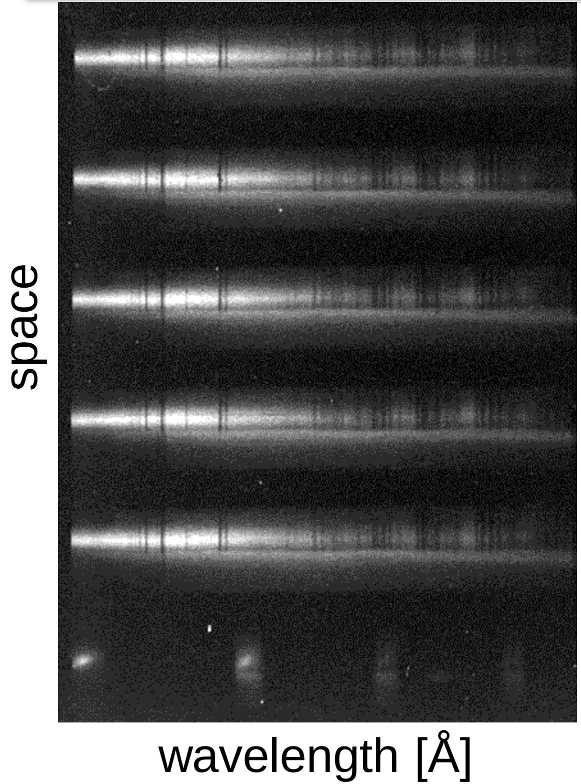
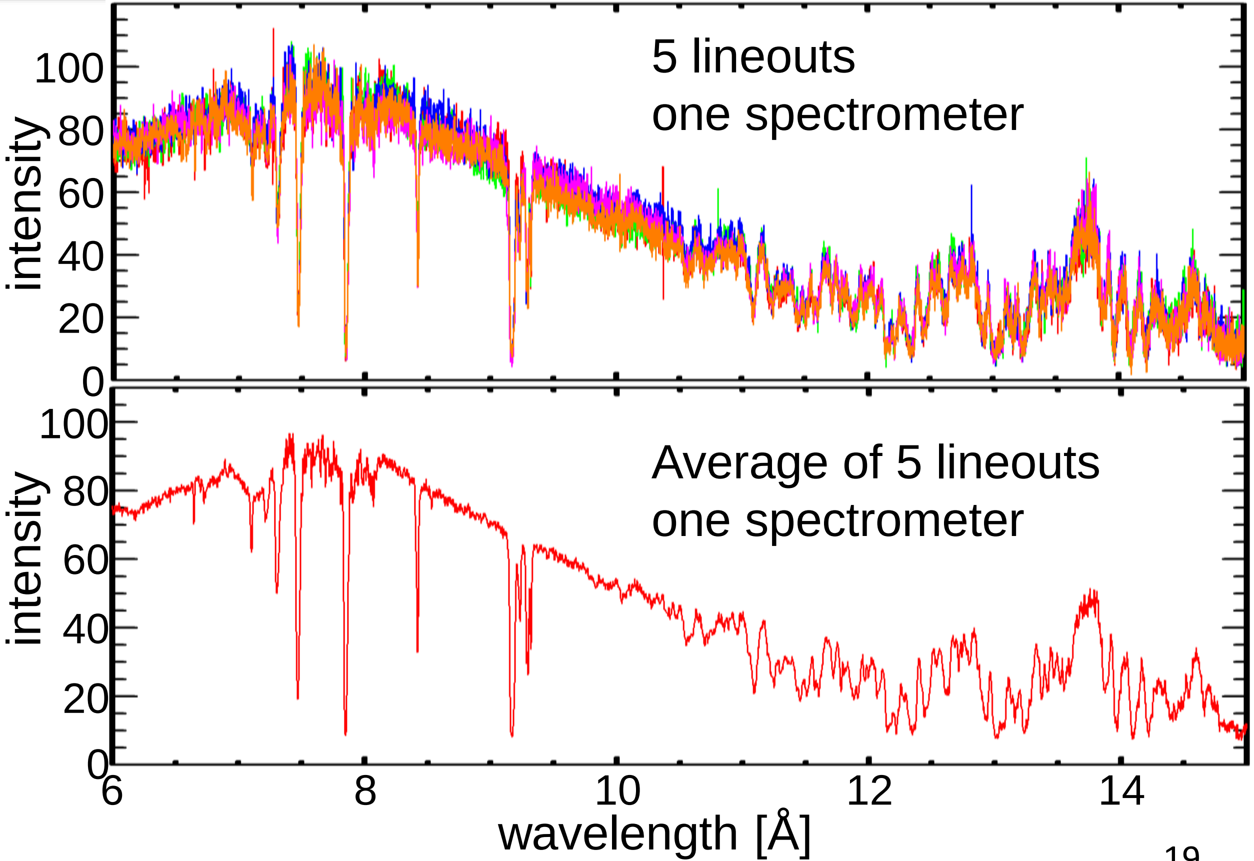
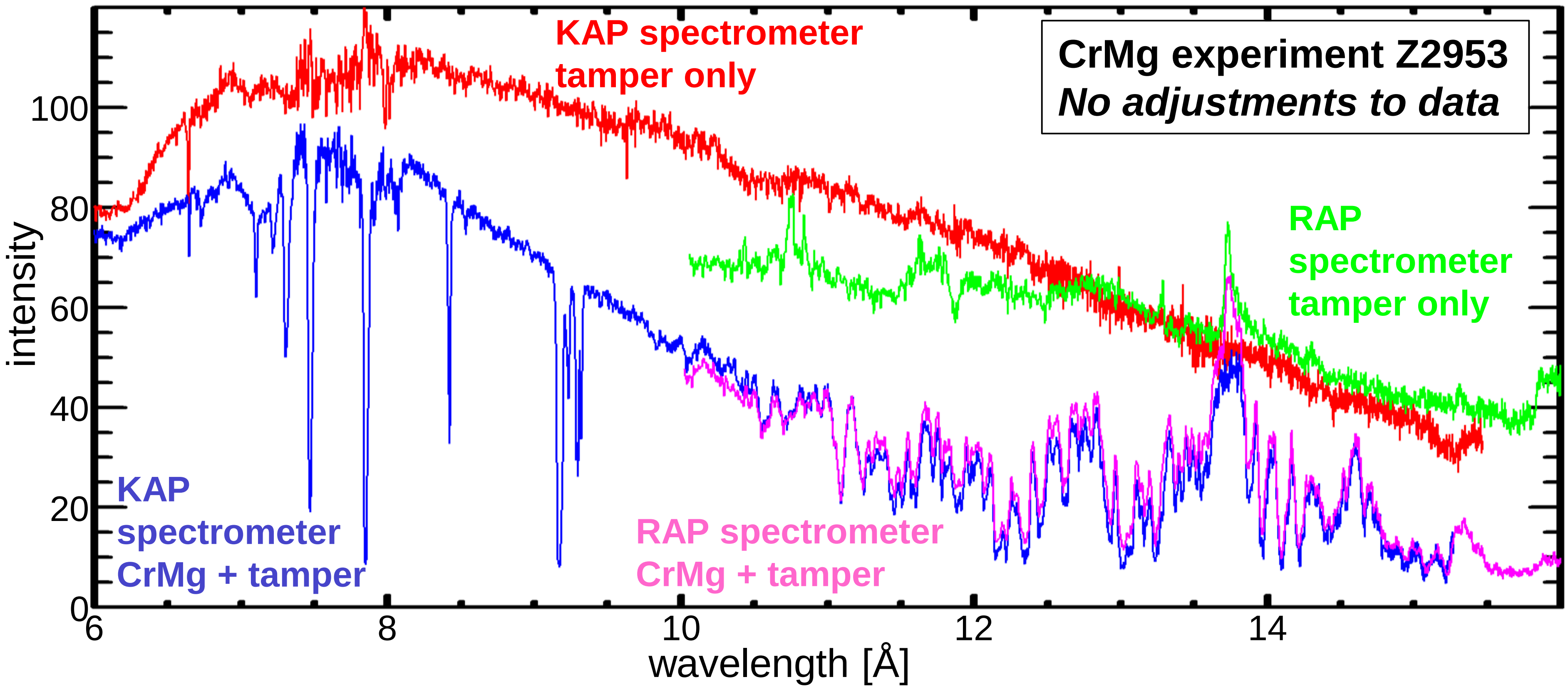




CrMg experiment Z2953

Comparing data from multiple spectrometers helps evaluate data reliability and accuracy



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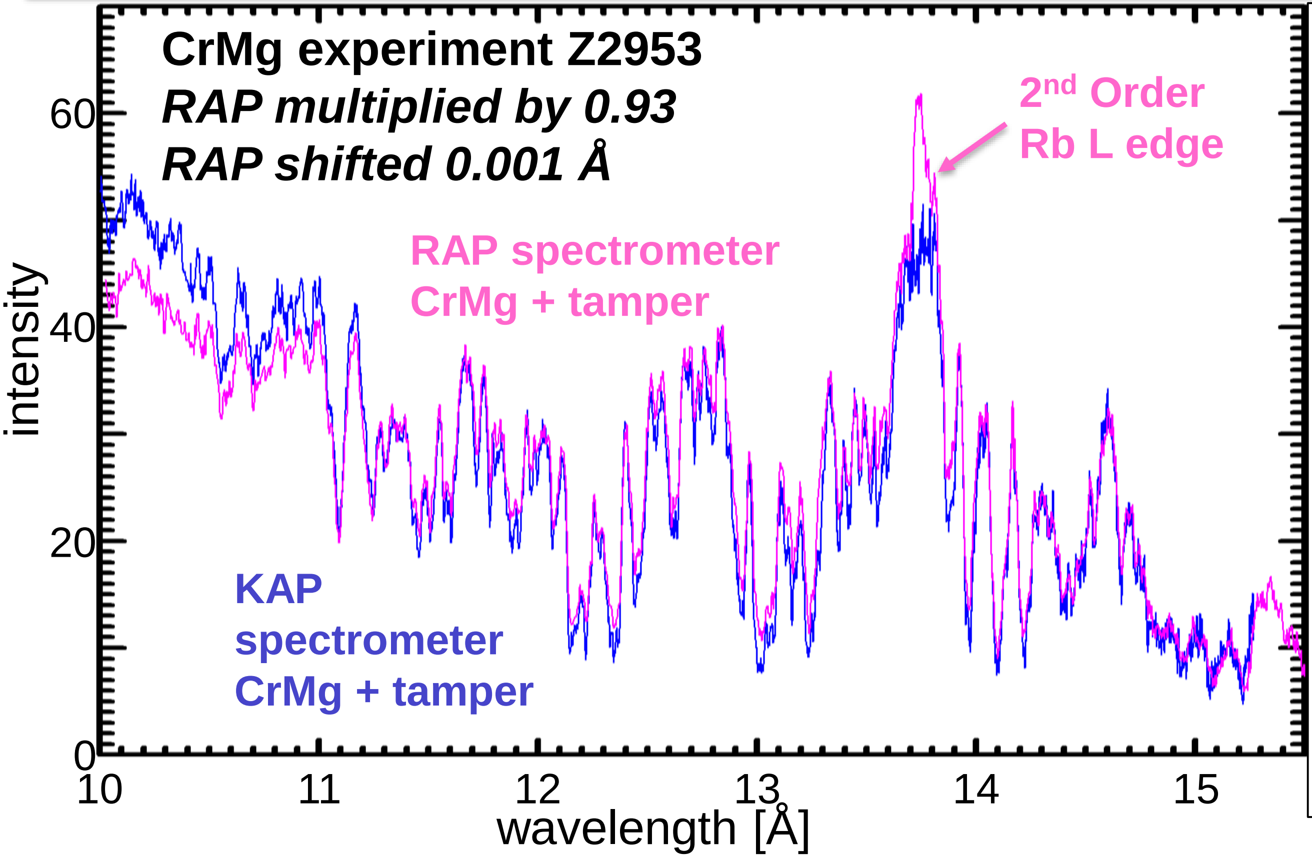


λ and line profiles agree, even for smaller features

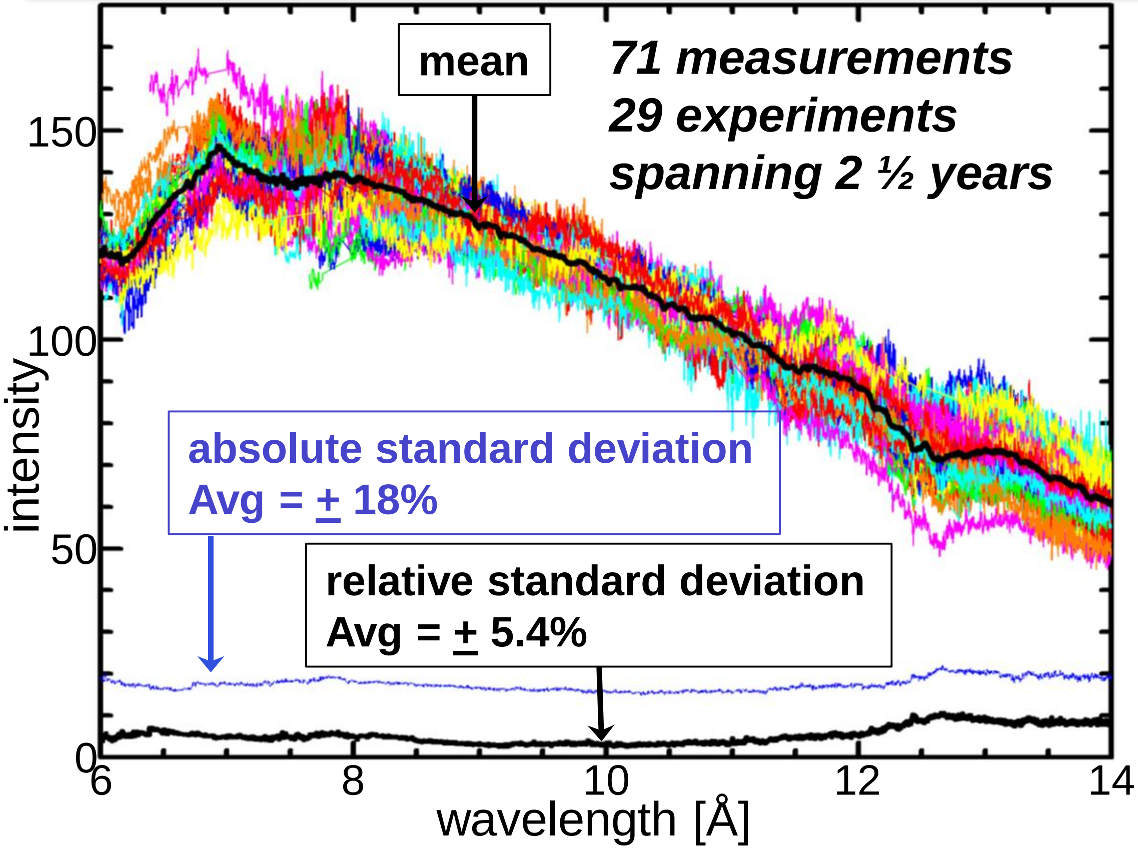
Intensities agree, with nominal reflectivities

KAP has been corrected for 2nd Order

RAP is ~ immune from 2nd Order above L edge

Agreement across edge is evidence for correct 2nd Order accounting

The backlight spectral radiance shape measured on tamper-only experiments is reproducible to within ± 5.4% over 6-14 Å



The unattenuated spectral shape is reproducible

Main challenge for transmission analysis is determining absolute unattenuated intensity for each spectrometer on each experiment

Combining transmission measurements from multiple experiments leads to improved opacity accuracy

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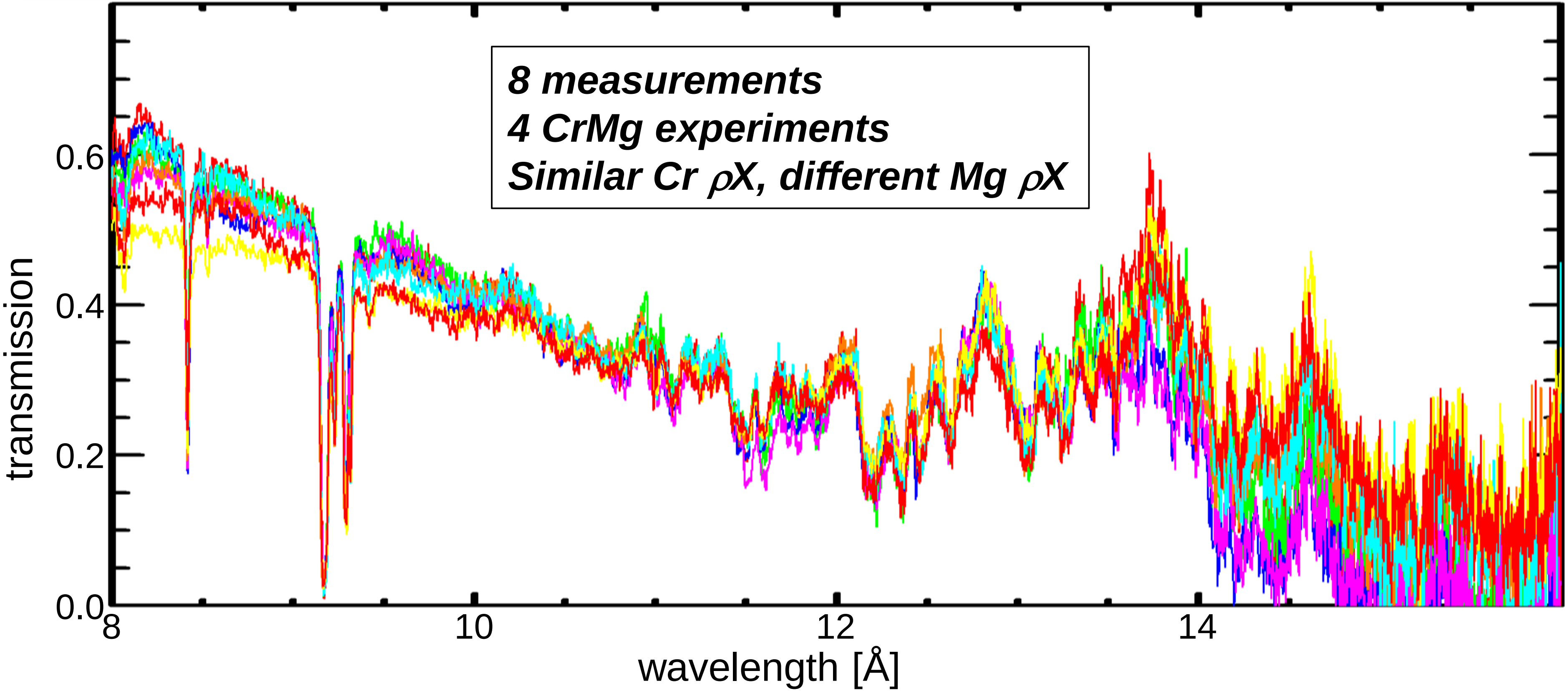
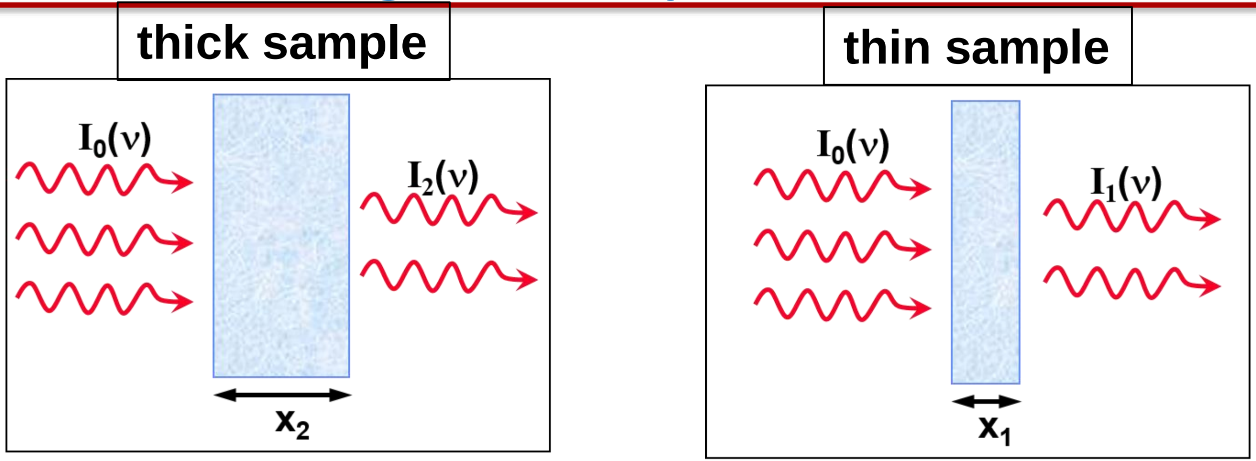


Possible experiment flaws can be evaluated from transmission scaling with sample thickness



Expected scaling with thickness : $T_1 = T_2^{(x1/x2)}$ e.g., if $X_2 = 2 * X_1$, then $T_2 = T_1 * T_1$

<u>experiment problems cause transmission scaling to deviate:</u>

- **Sample emission**
- **Background subtraction**
- **Crystal defects**
- **Gradients**

Combining transmission measurements from experiments with different areal density is an additional accuracy test

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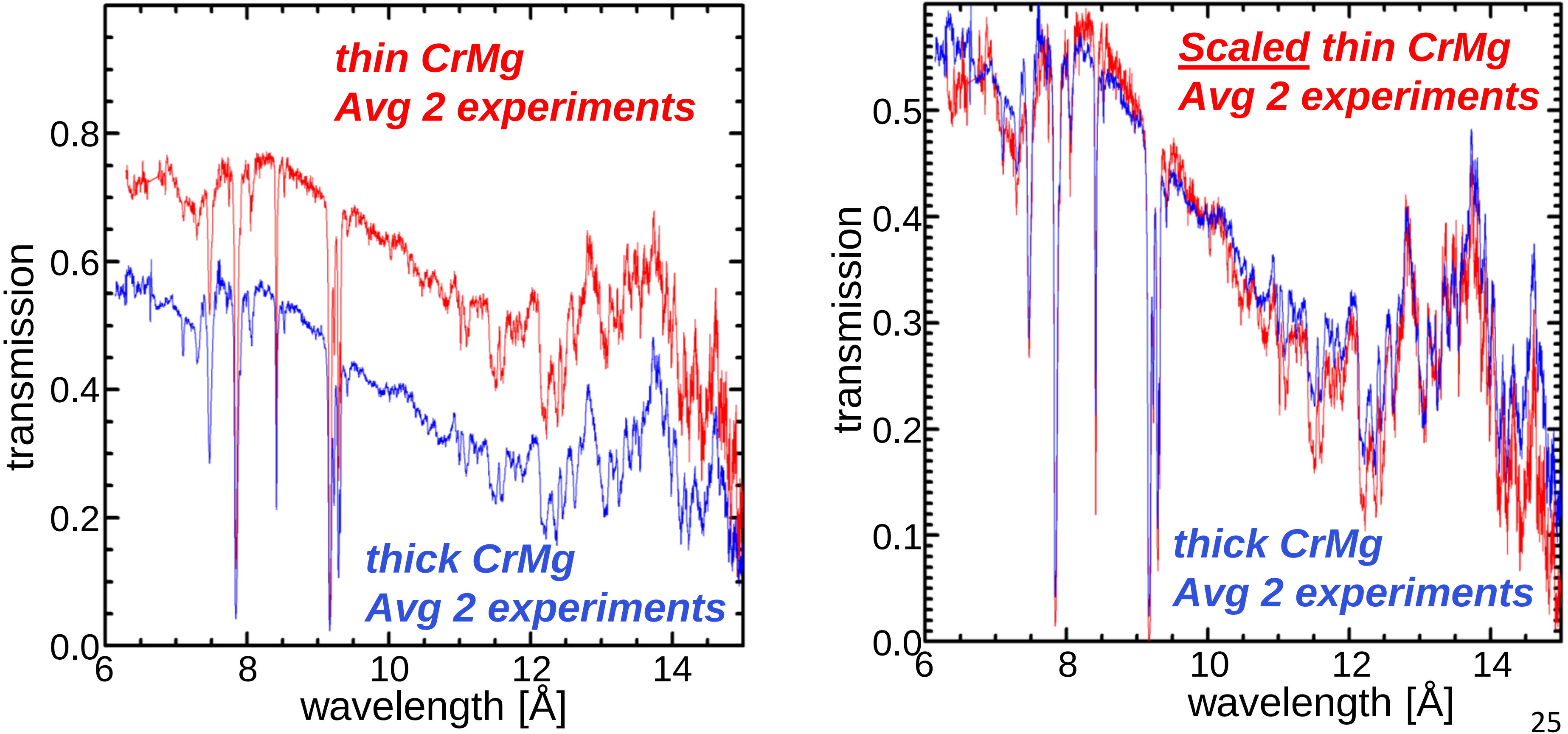

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