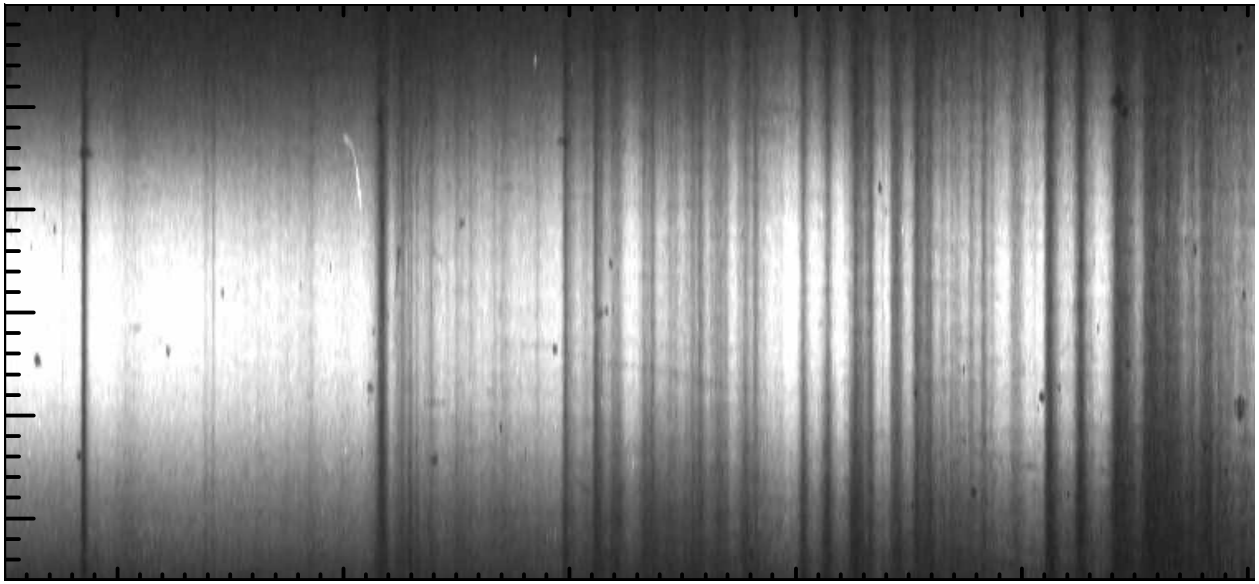
SAND2008-3122C

Diagnosing Opacity Experiments That Approach Stellar Interior Temperatures



Fe & Mg absorption spectrum

High Temperature Plasma Diagnostics

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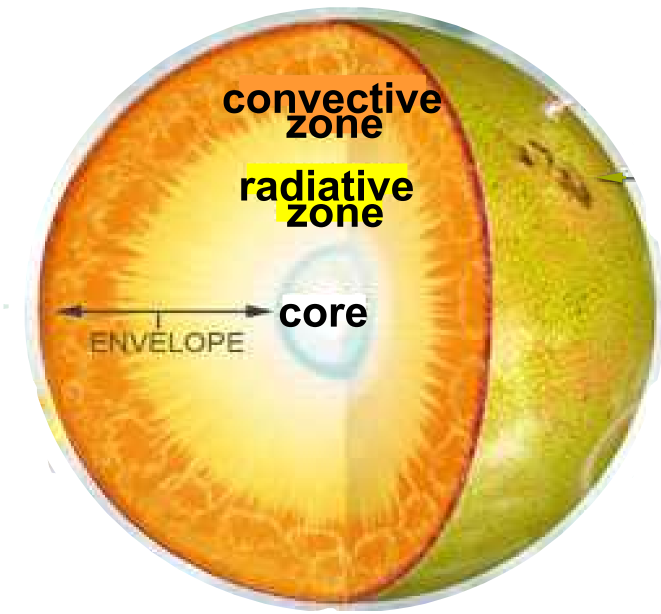
Z experiments test opacity models that are crucial for stellar interior physics



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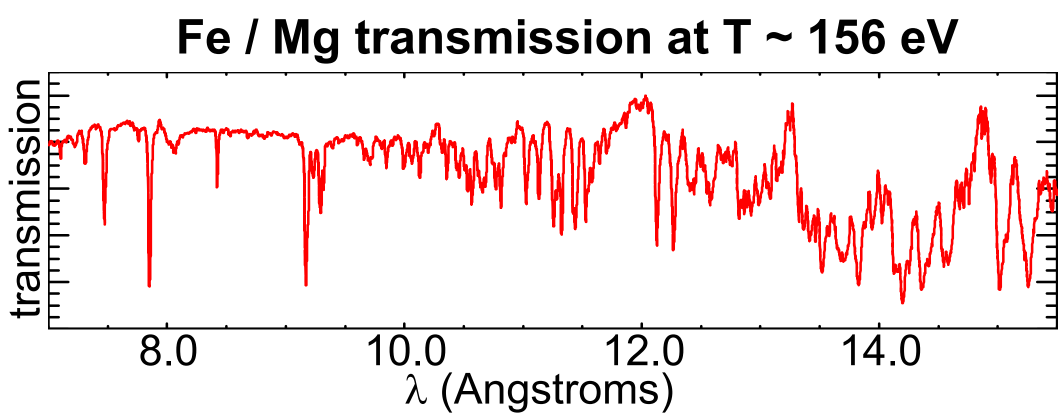
Solar predictions and observations do not agree

Solar structure depends on opacities that have never been measured

Challenge: create *and diagnose* stellar interior conditions on earth

Z opacity experiments reach T ~ 156 eV

High T enables first studies of transitions important in stellar interiors



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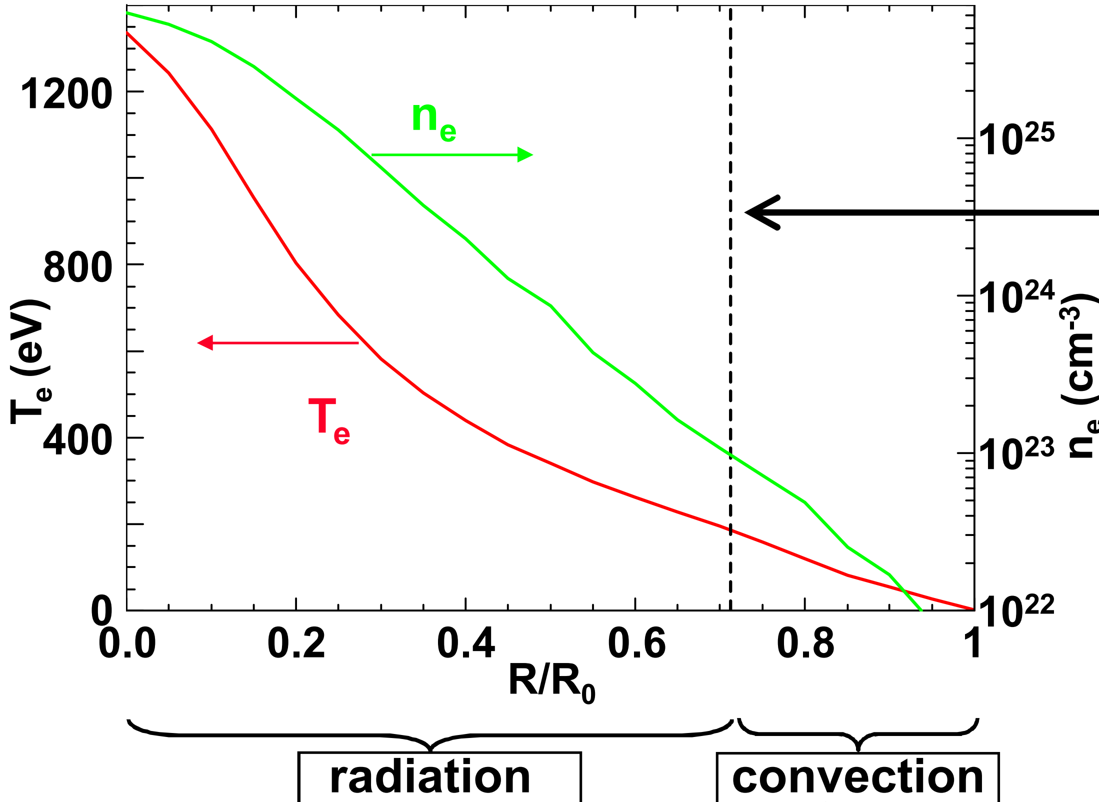
Modern solar models disagree with observations. Why?



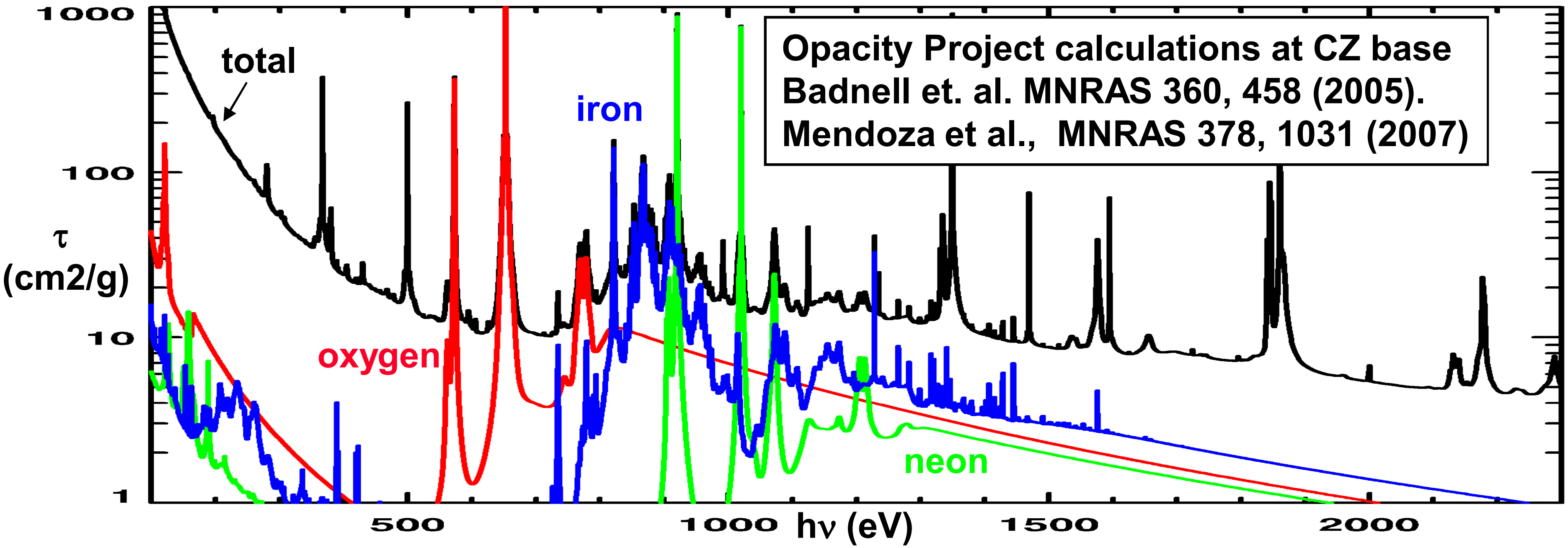
- measured boundary $R_{CZ} = 0.713 \pm 0.001$
- Predicted $R_{CZ} = 0.726$
- Thirteen σ difference

"The CZ problem"

Bahcall et al, ApJ 614, 464 (2004).
Basu & Antia
Physics Reports 457, 217 (2008).

- Boundary location depends on radiation transport
- A 10-20% opacity change solves the CZ problem.
- This accuracy is a challenge – experiments are needed to know if the solar problem arises in the opacities or elsewhere.

The solar mixture opacity has contributions from many elements

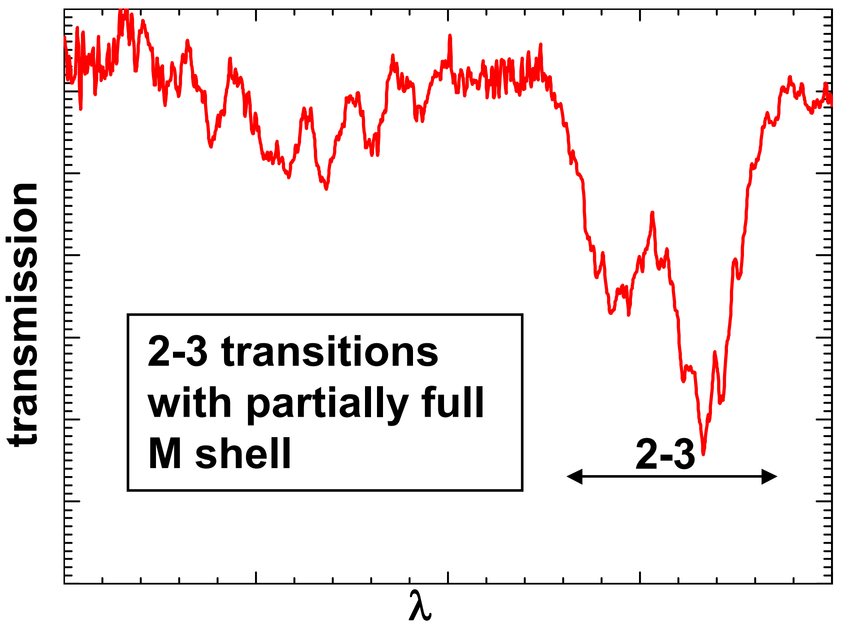


- K-shell oxygen, K-shell neon, and L-shell iron are important at the CZ base
- The complexity of L-shell iron demands special scrutiny
- The importance of any single element is diluted by the mixture

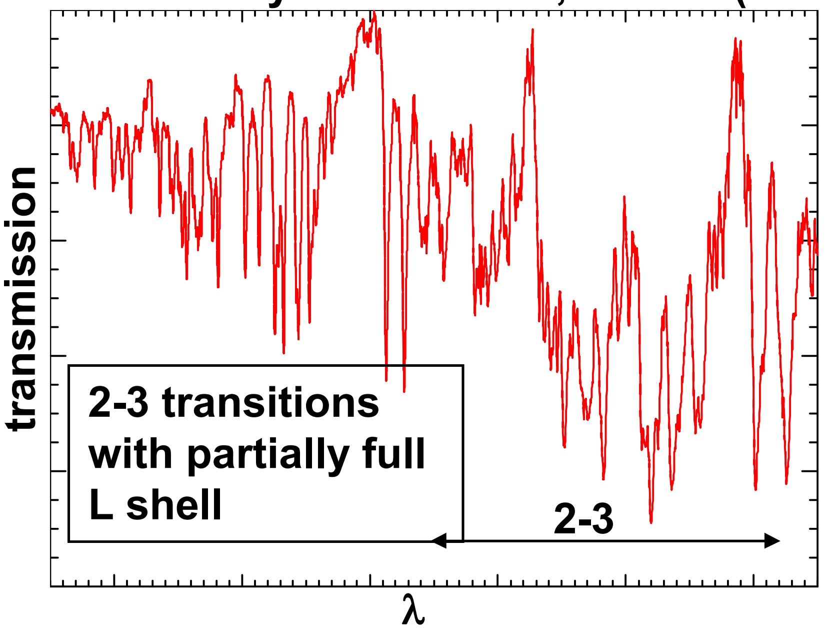
Example:
Changing Fe L-shell by 1.5x causes ~11% change in total mean opacity

The charge state distribution depends on Te/ne and it strongly affects both BB and BF transitions

Br at 50 eV, $3x10^{21}$ cm^{-3}
Ti-like to Fe-like
J.E. Bailey et al., JQSRT 81, 31 (2003).



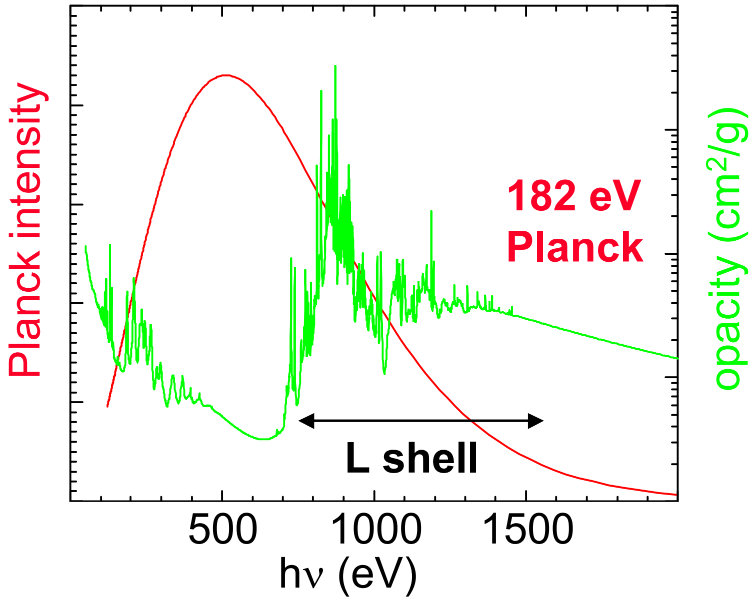
Fe at 156 eV, 6.9 x 10^{21} cm^{-3}
N-like to Na-like
J.E. Bailey et al. PRL 99, 265002 (2007).



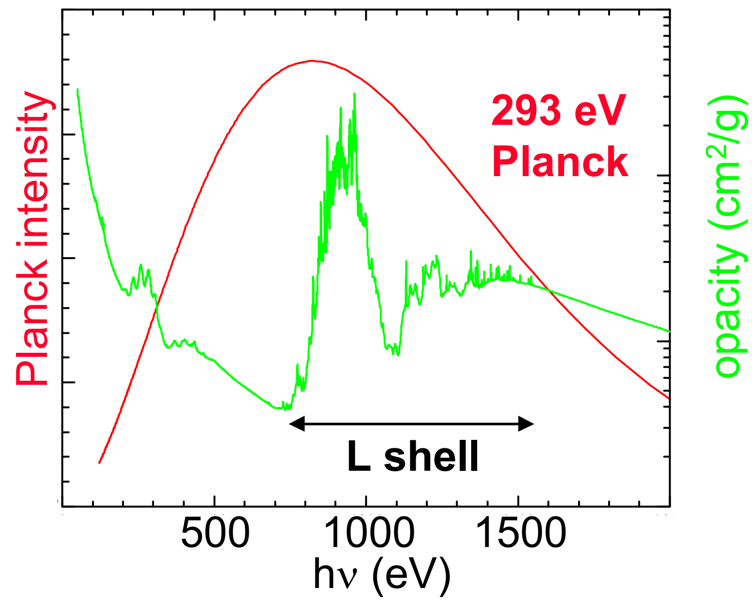
- There is a qualitative change in transitions as vacancies in L-shell appear

Opacity experiment priority: produce the charge states found in stellar interiors

Fe at 182 eV, 9 x 10 ^{22} cm^{-3}
Radiation/convection boundary
O-like to Ne-like Fe predominate

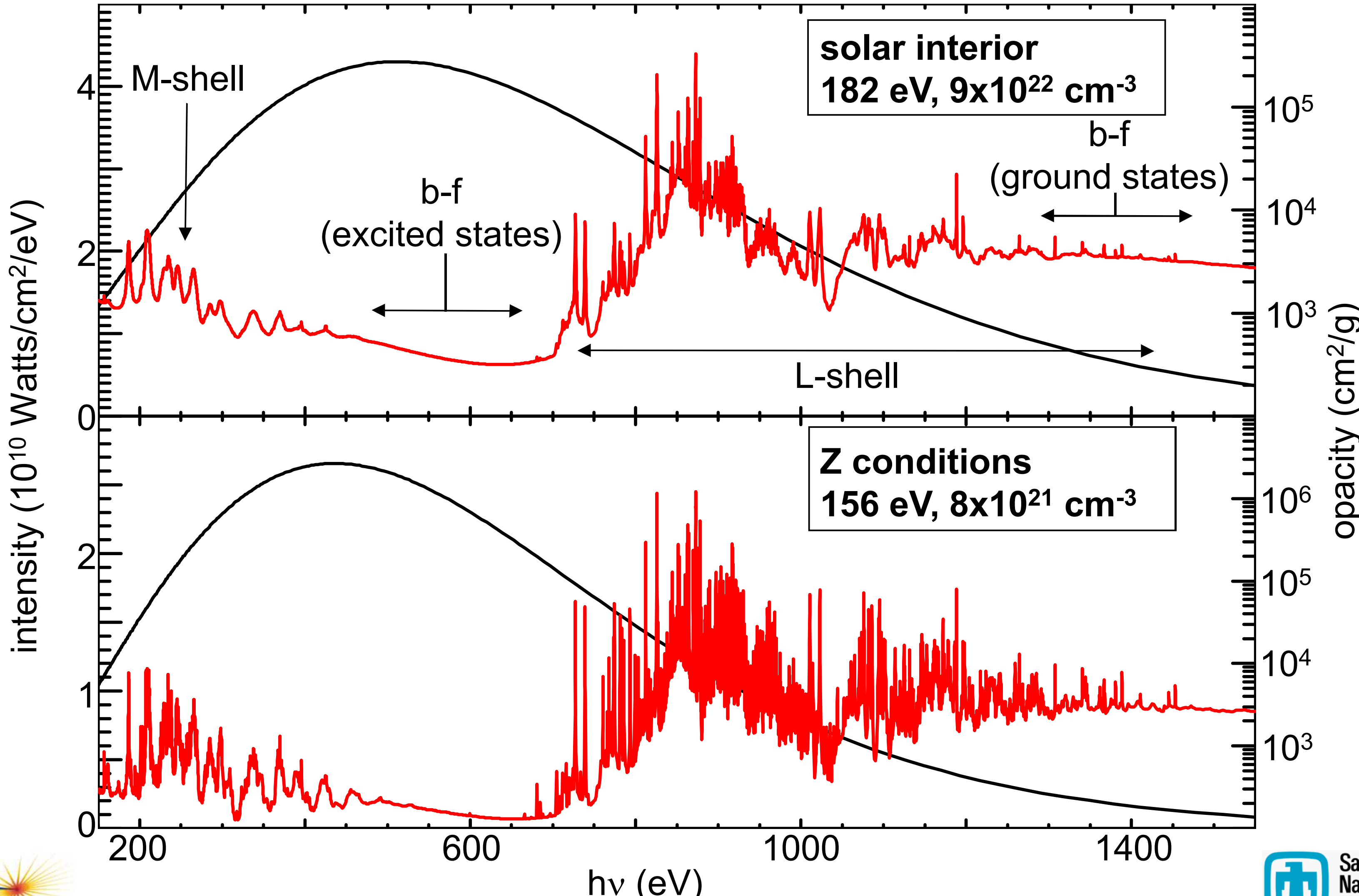


Fe at 293 eV, 4 x 10 ^{23} cm^{-3}
Radius = 0.5 R_0
O-like to Ne-like Fe predominate

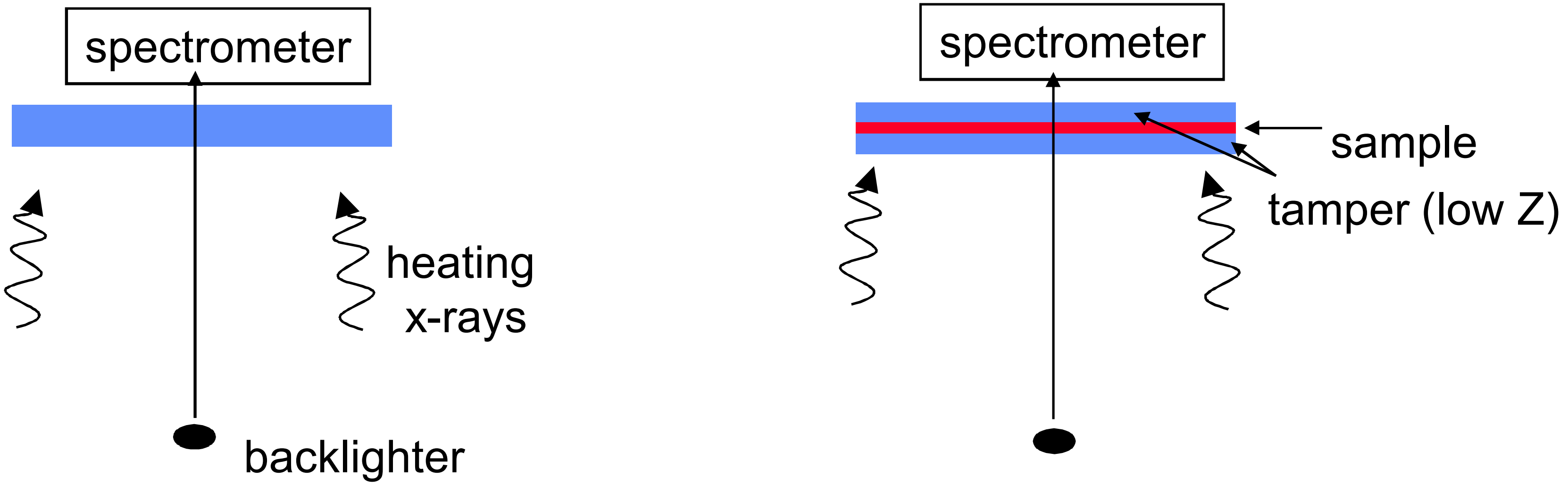


- **Transitions in Fe with L-shell vacancies are important in the sun**
- **Laboratory experiments must produce high enough temperatures to ionize Fe into the L shell**

Z experiments investigate Fe L-shell configurations that are important in the sun



Anatomy of an opacity experiment



Comparison of unattenuated and attenuated spectra determines transmission
T = exp –{μρx}

Model calculations of transmission are typically compared with experiments, rather than opacity. This simplifies error analysis.

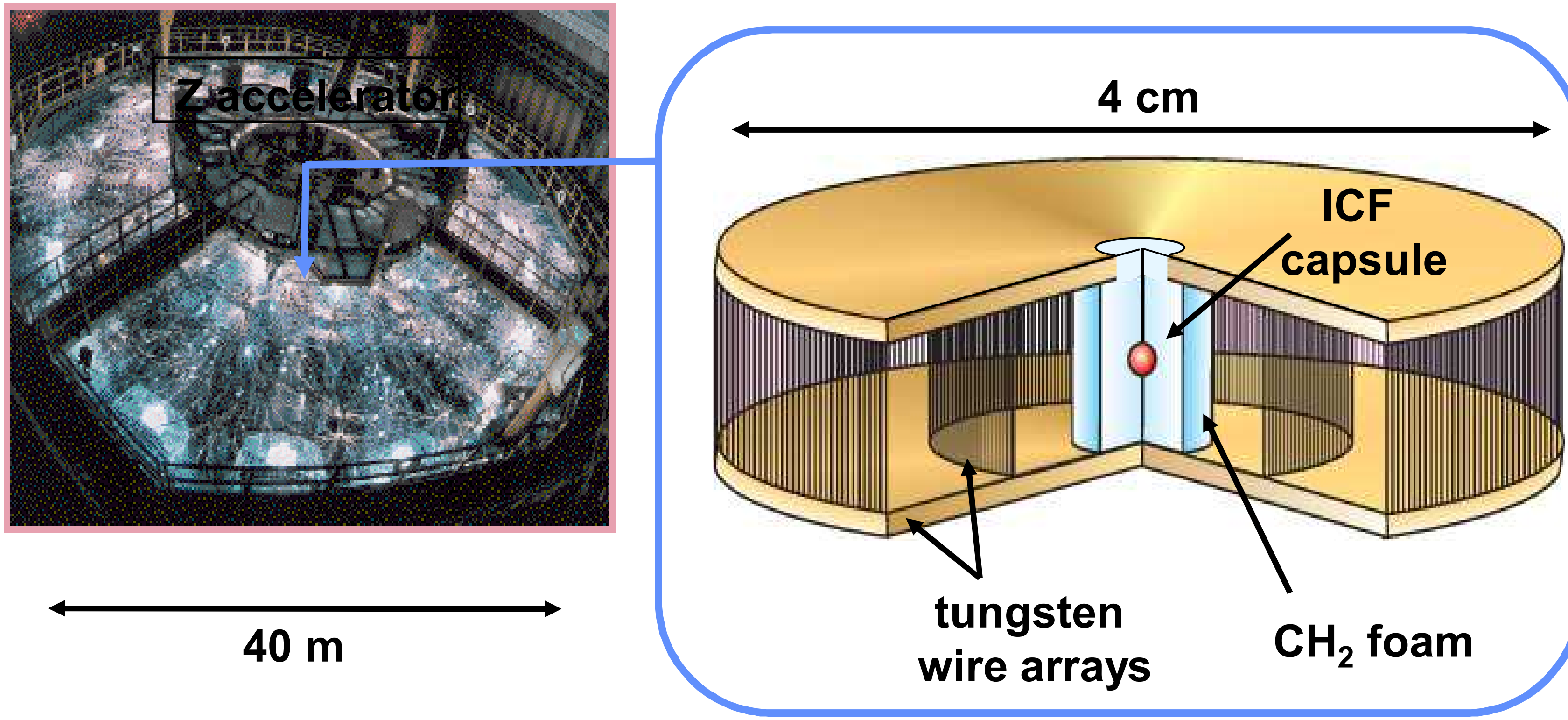
Desirable features of an opacity experiment

- Sample spatial uniformity (thin, large lateral size, thick tamper)
- Minimal temporal variations during probe time (backlight short compared to heating x-ray variation)
- Steady state (long duration heating x-rays)
- Temperature and density measurements (large wavelength range to enable simultaneous low Z and high Z measurements)
- Sample areal density knowledge
- Accounting of sample self emission and experiment background

Characteristics of Z x-ray source can promote quality measurements

T.S. Perry et. al. Phys. Rev. E 54, 5617 (1996)

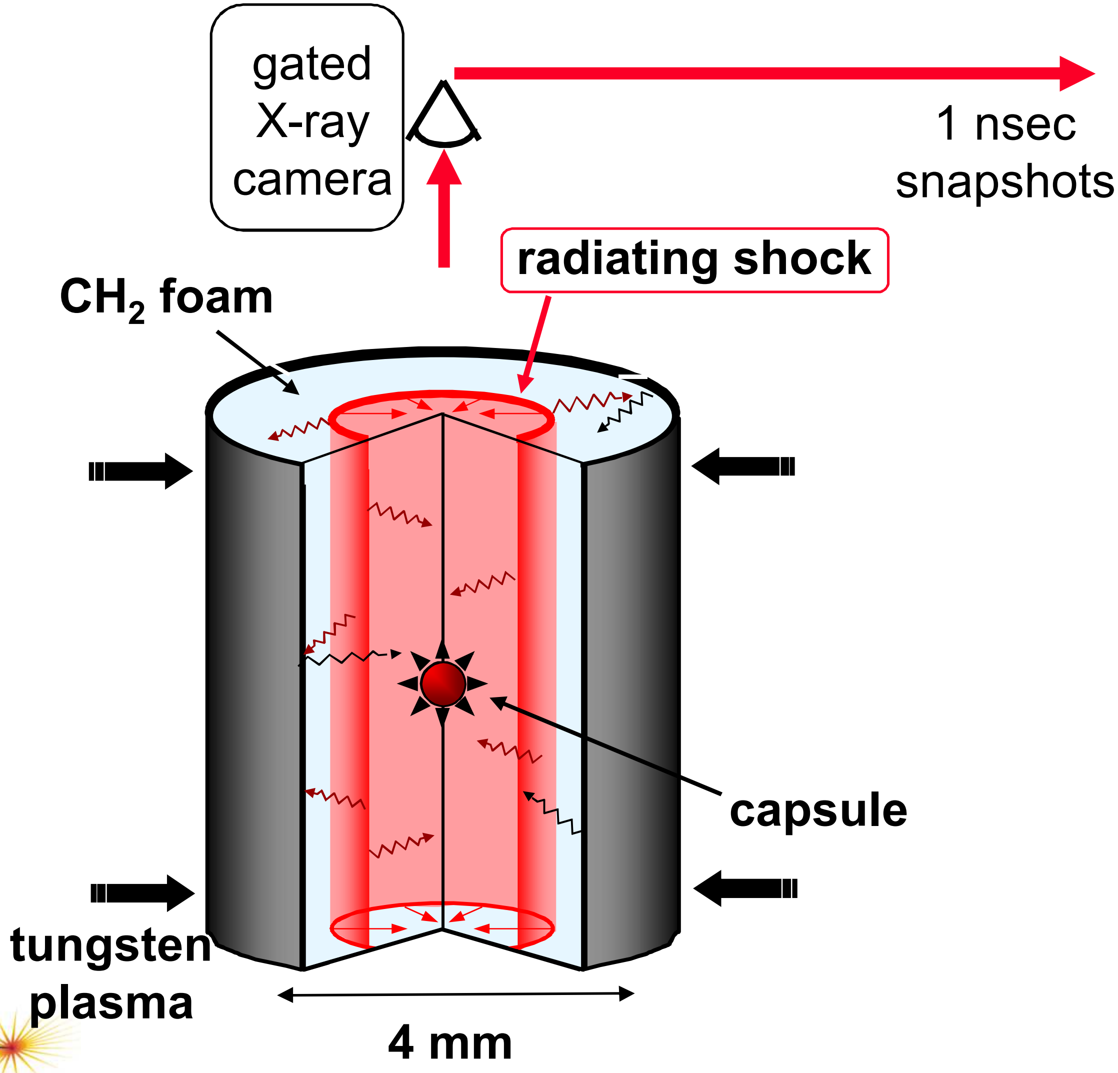
Opacity experiments exploit the intense radiation provided by the Z accelerator

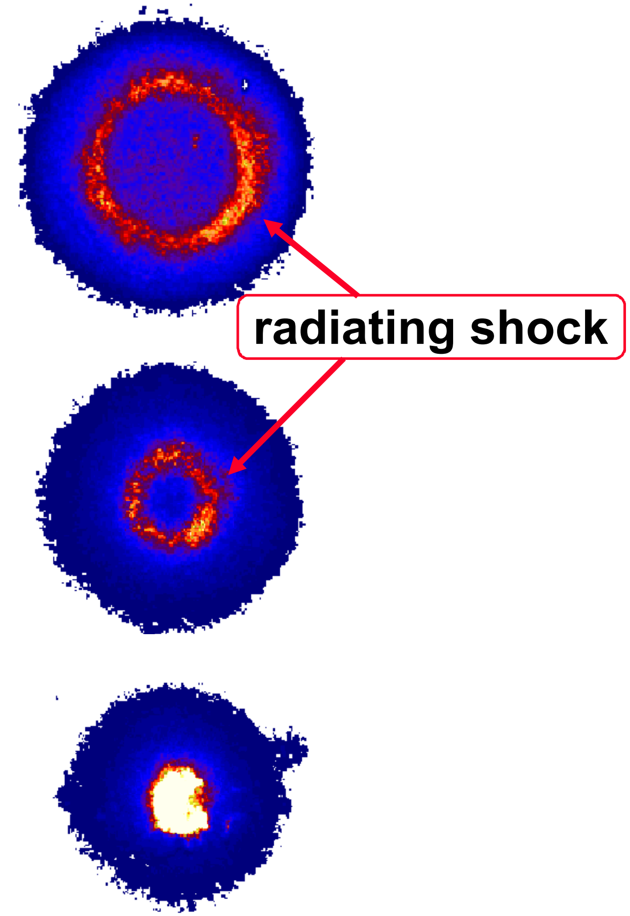


Previous work used samples ~5 cm from side of pinch to probe Te ~ 50 eV:
Phys. Plasmas 9, 2186 (2002).
JQSRT 81, 31 (2003)
Phys Rev E 72, 066405 (2005)

Present work places sample ~0.1 cm above pinch to probe higher Te

Dynamic hohlraum radiation source is created by accelerating a tungsten plasma onto a low Z foam





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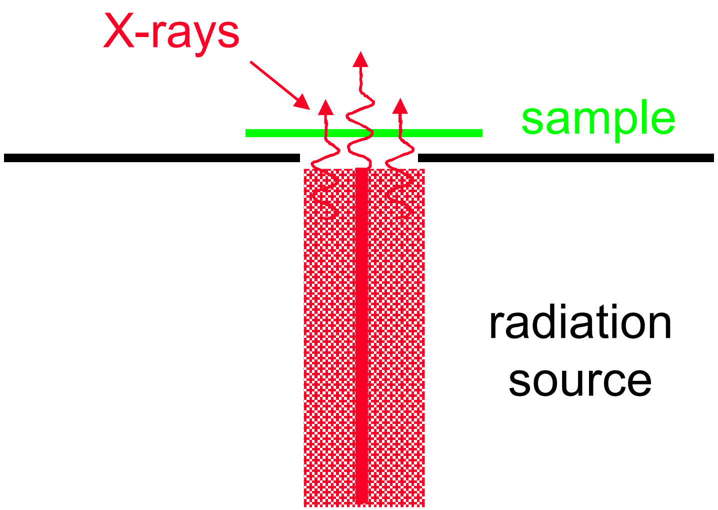
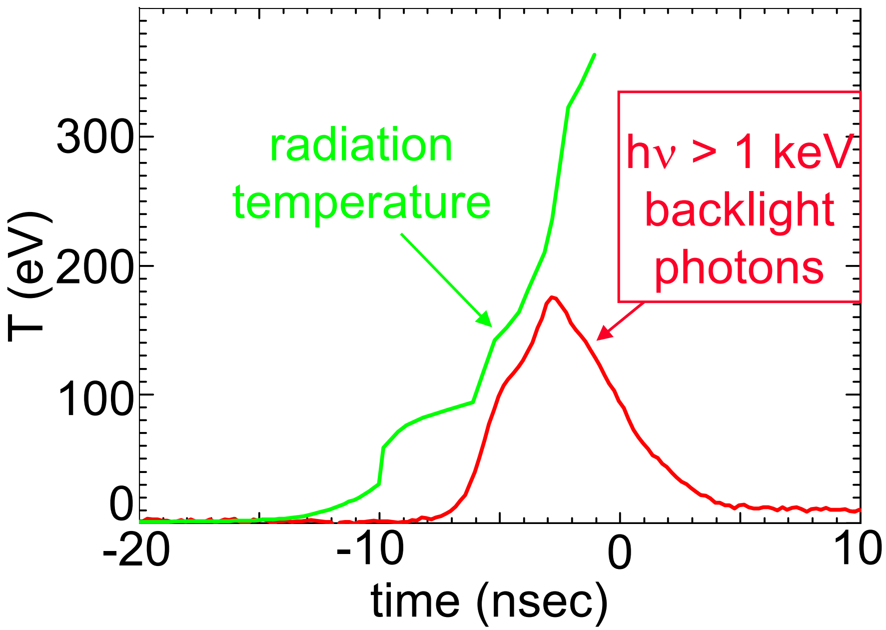
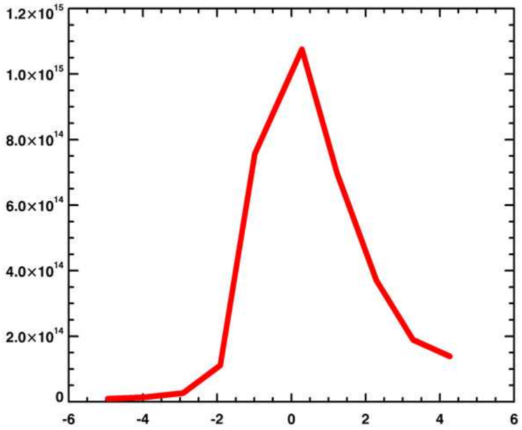
The radiation source heats and backlights the sample

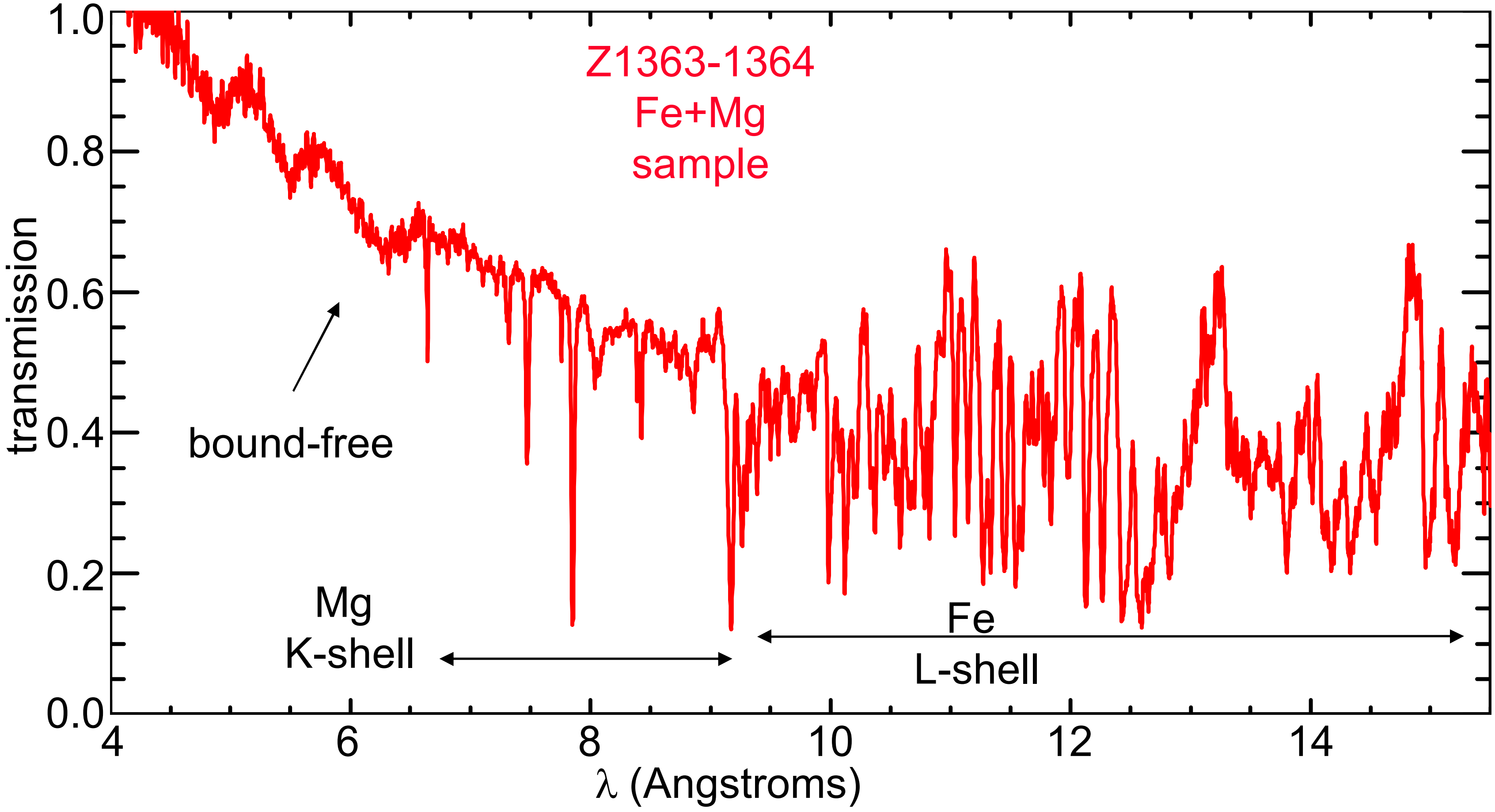




The dynamic hohlraum backlighter effective brightness temperature exceeds Tr ~ 300 eV



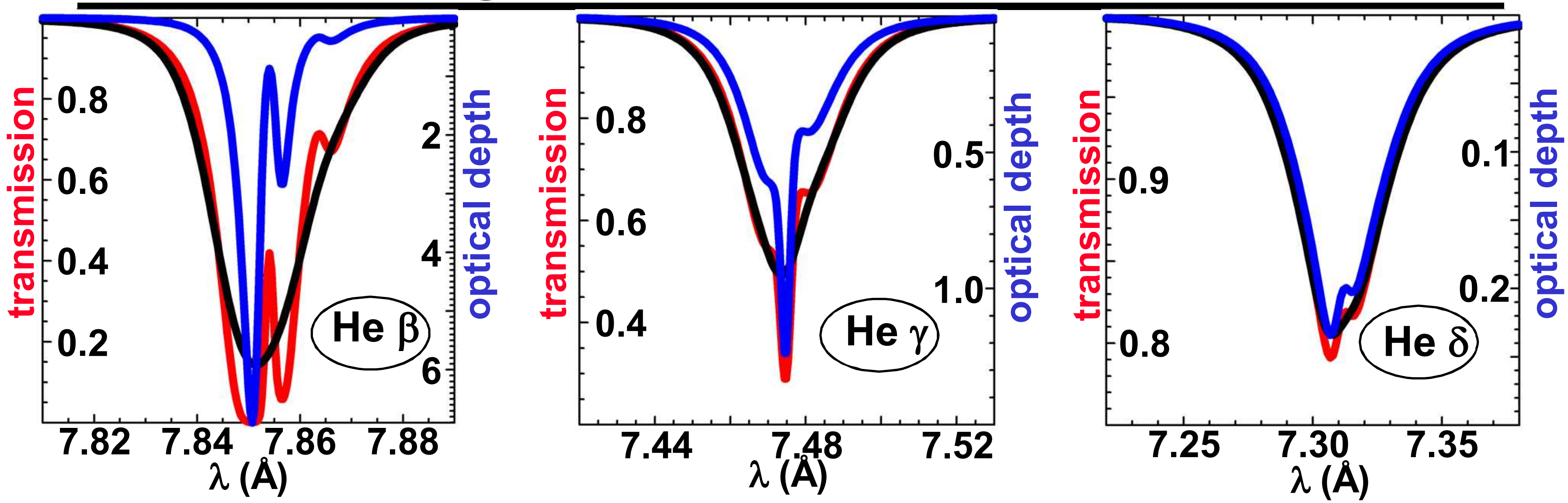
The dynamic hohlraum backlighter measures transmission over a very broad λ range



Absorption spectra are obtained using large working distance convex crystal spectrometers

The spectral resolution exceeds $\lambda/\delta\lambda$ = 700

Absorption line profiles depend on Stark broadening and saturation



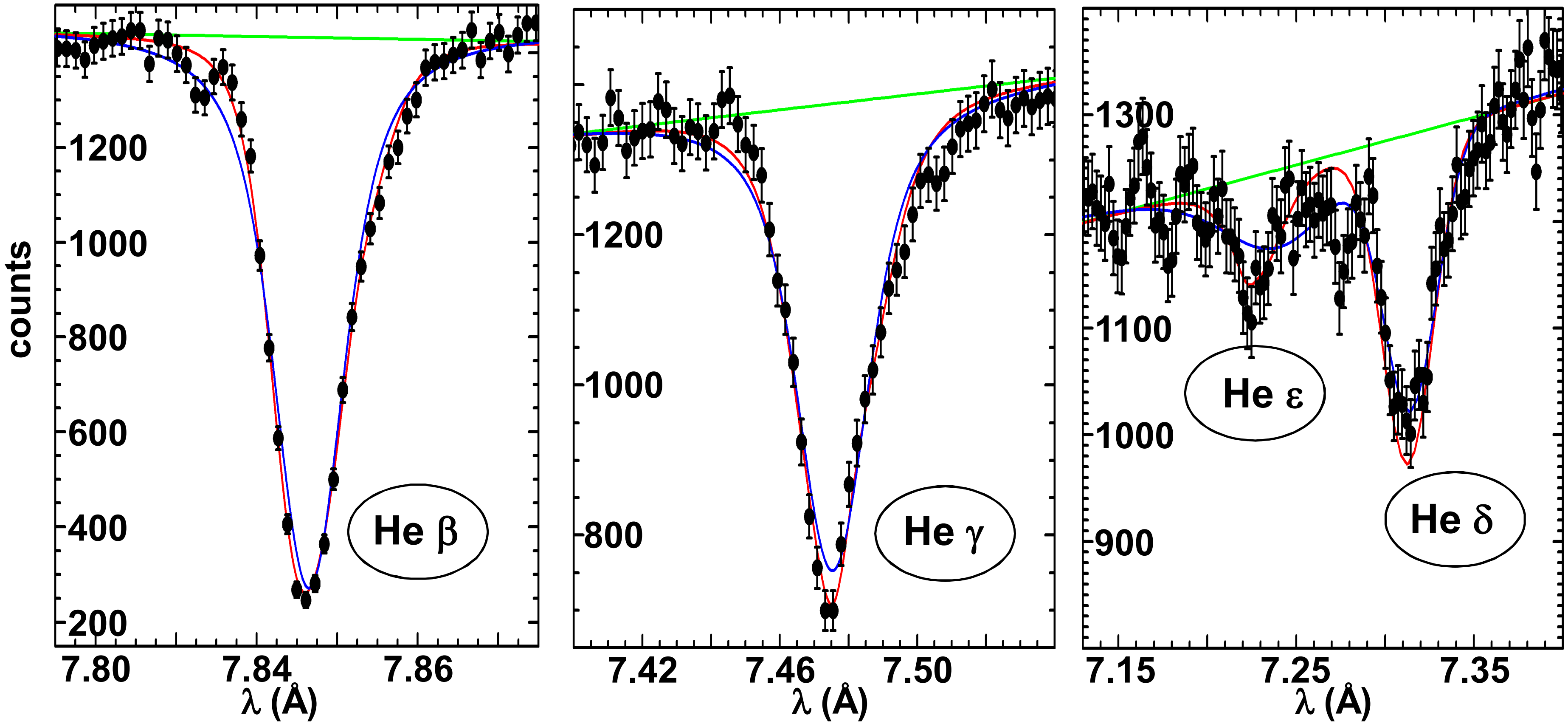
Stark broadening increases and saturation decreases with principle quantum number

This favors using high n lines

However, The high n lines are weaker and are measured less accurately

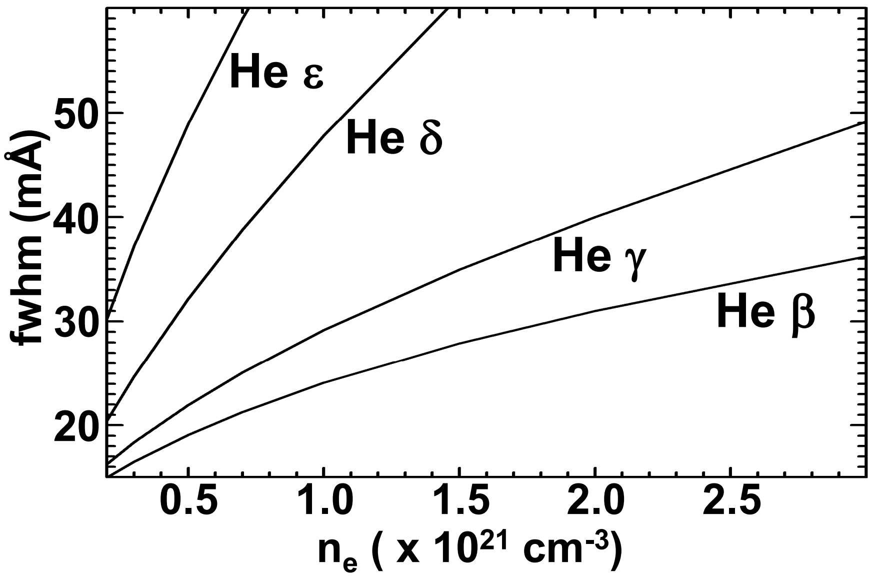
Strategy: use a range of lines, but account for measurement accuracy in determining the overall uncertainty

High quality absorption line fits are obtained using detailed line broadening calculations



	He β	Heγ	Heδ,ε
Detailed line profile	$\chi^2 = 1.2$	$\chi^2 = 1.13$	$\chi^2 = 0.6$
Voigt profile	$\chi^2 = 5.5$	$\chi^2 = 2.28$	$\chi^2 = 1.0$

The electron density is determined from the He-like Mg line widths



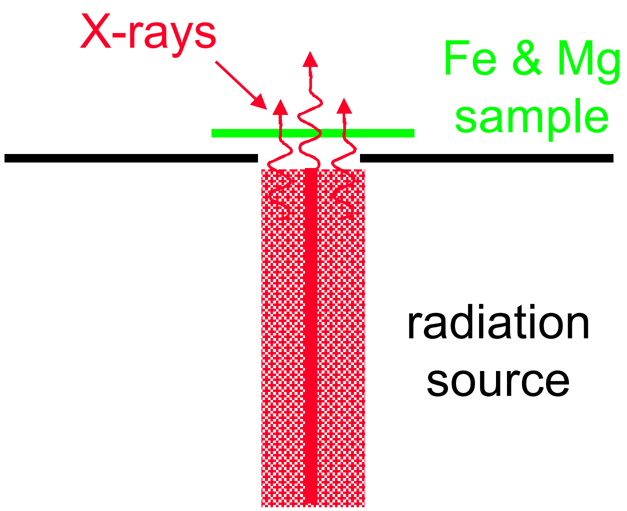
Detailed line profiles calculated by Roberto Mancini (U. Nevada Reno) using MERL:

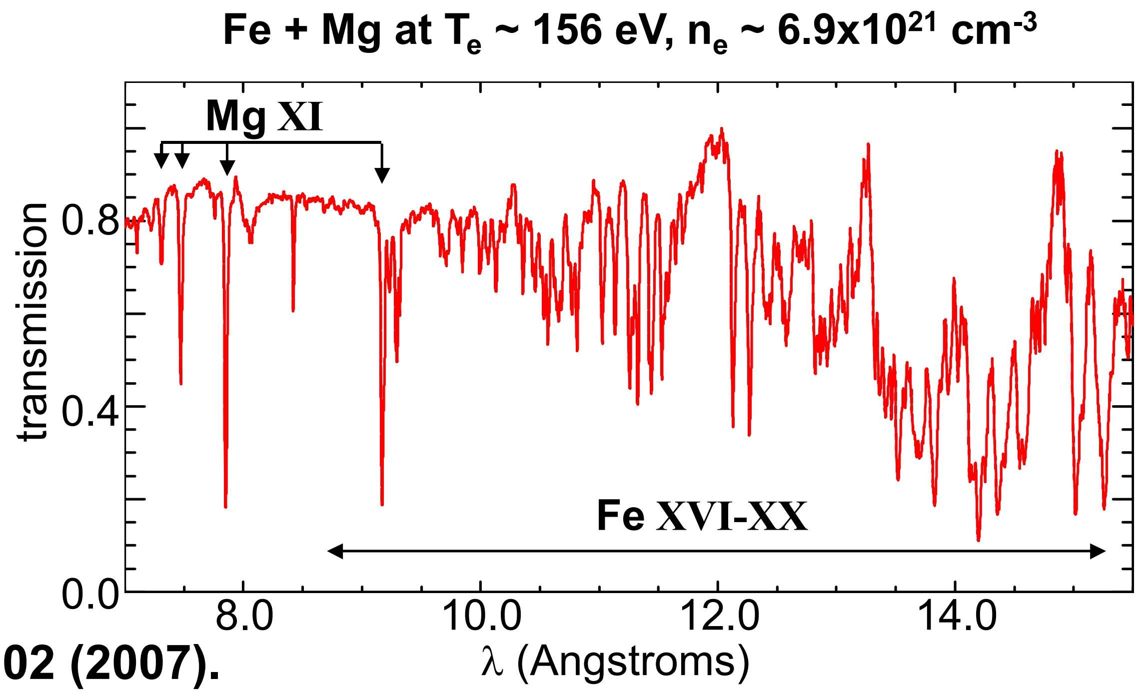
$n_e = 6.9 \pm 1.7 \times 10^{21}\ cm^{-3}$

Completely independent analysis by F. Gilleron and J.C. Pain using PimPamPoom:

$n_e = 6.5 \times 10^{21}\ cm^{-3}$

Z opacity experiments reach T ~ 156 eV, two times higher than in prior Fe research

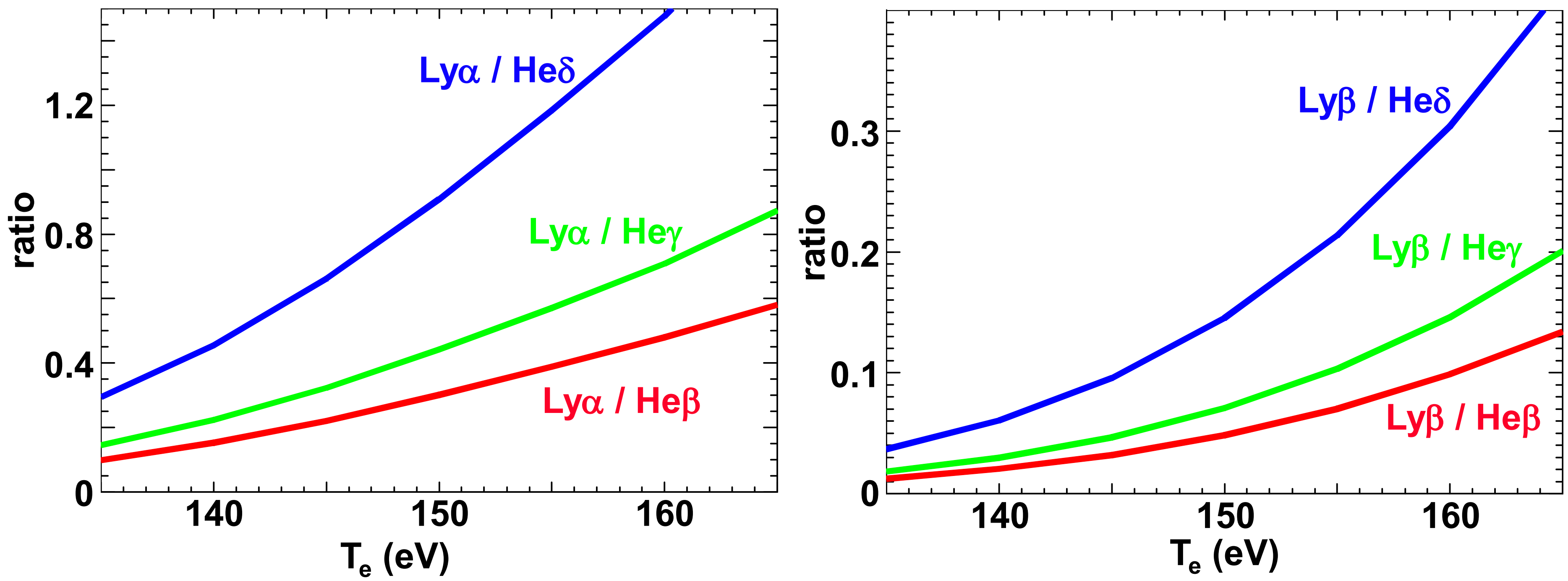




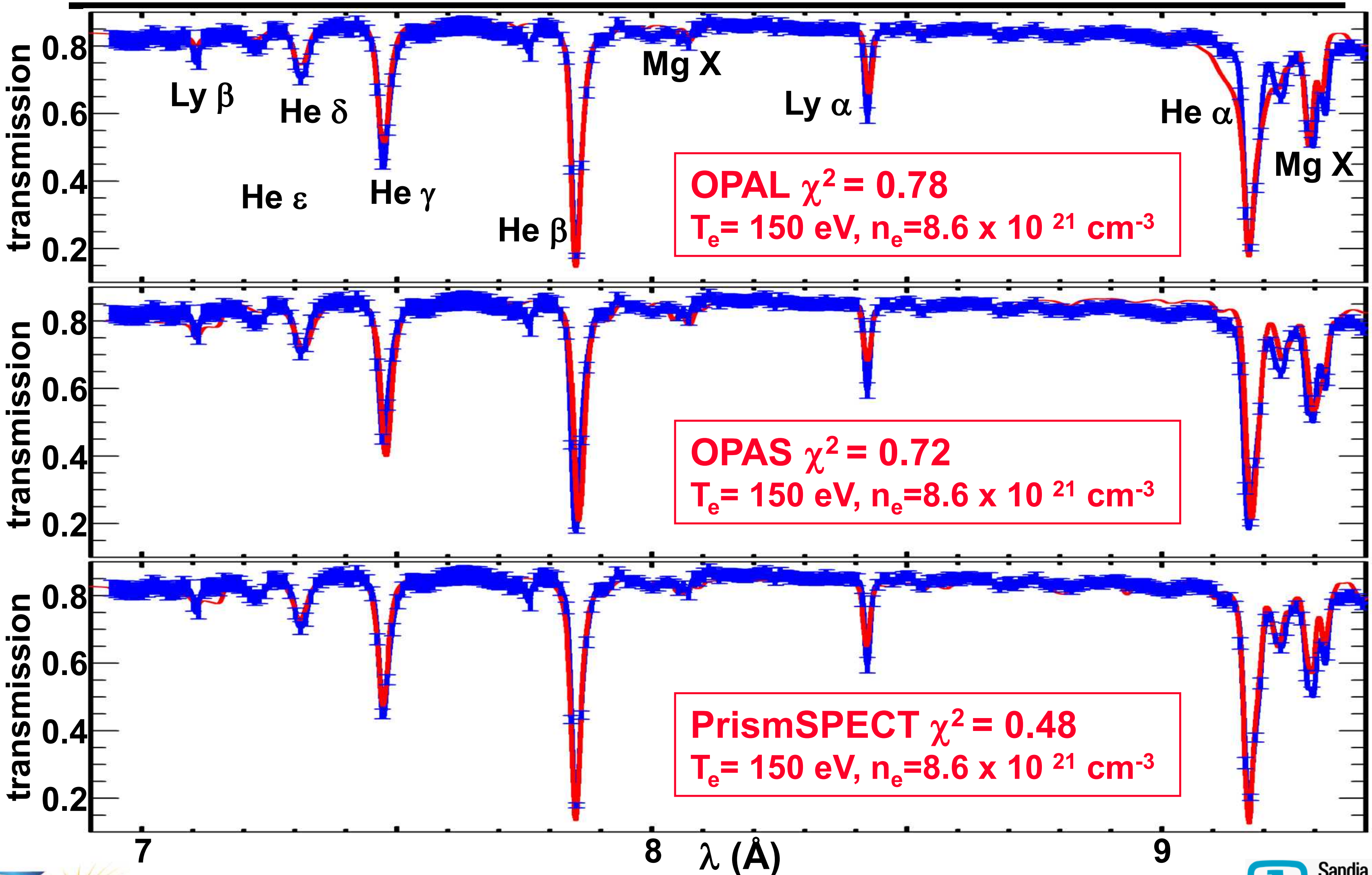
J.E. Bailey et al., PRL 99, 265002 (2007).

- Mg is the "thermometer", Fe is the test element
- Mg features analyzed with PrismSPECT, Opal, RCM, PPP, Opas

The plasma electron temperature is determined from the (H-like)/(He-like) Mg line ratios.



The inferred conditions are quantitatively consistent with multiple independent models



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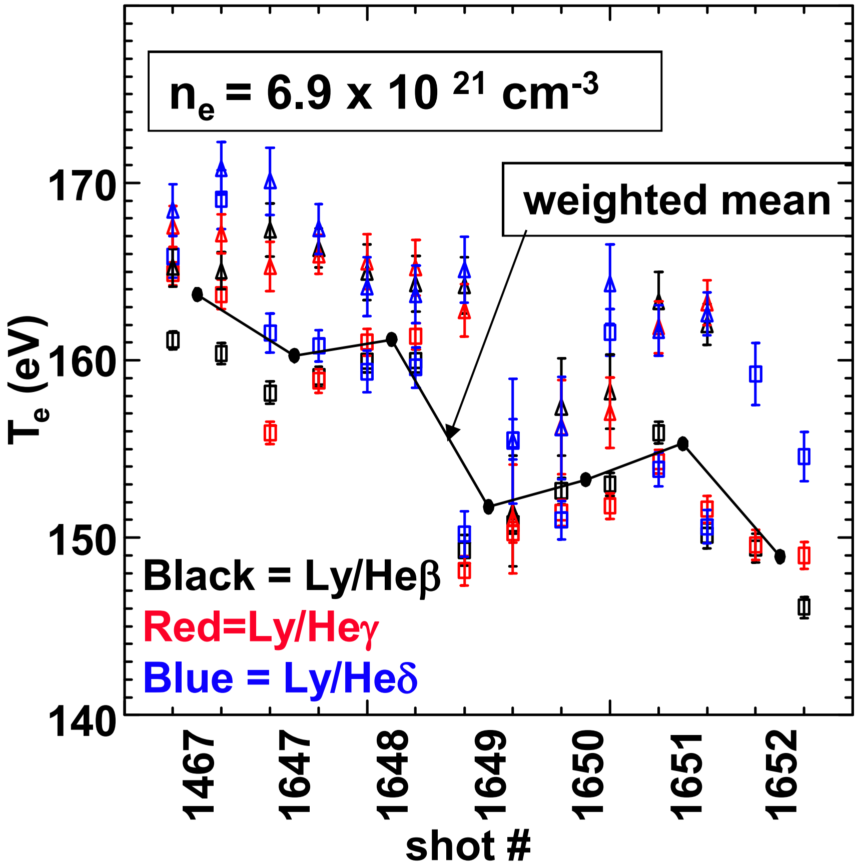
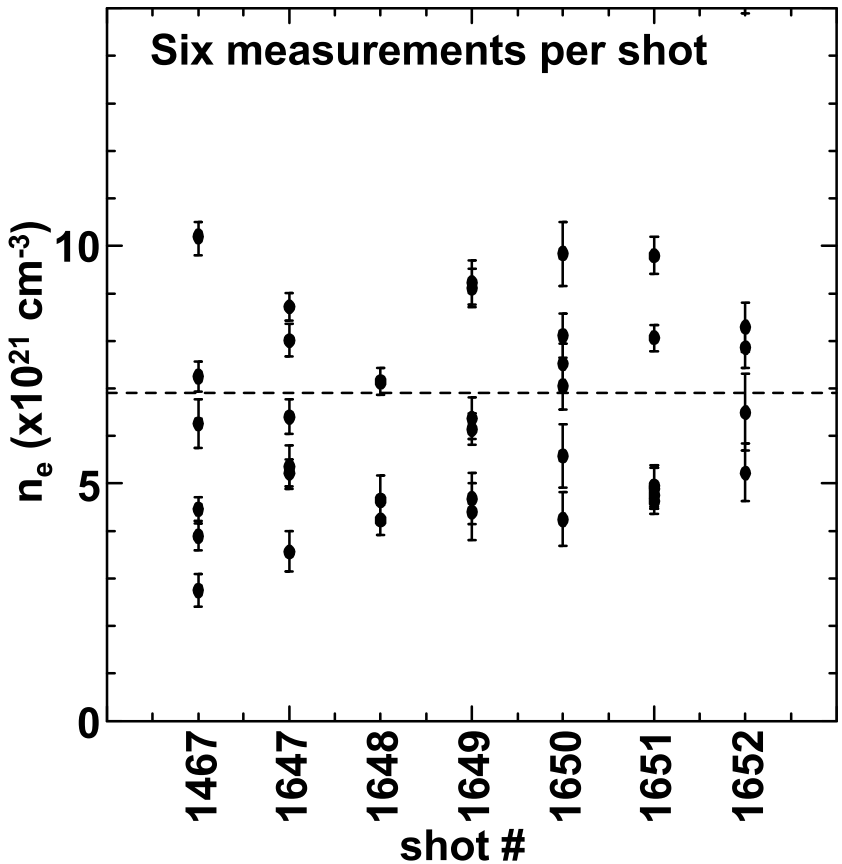
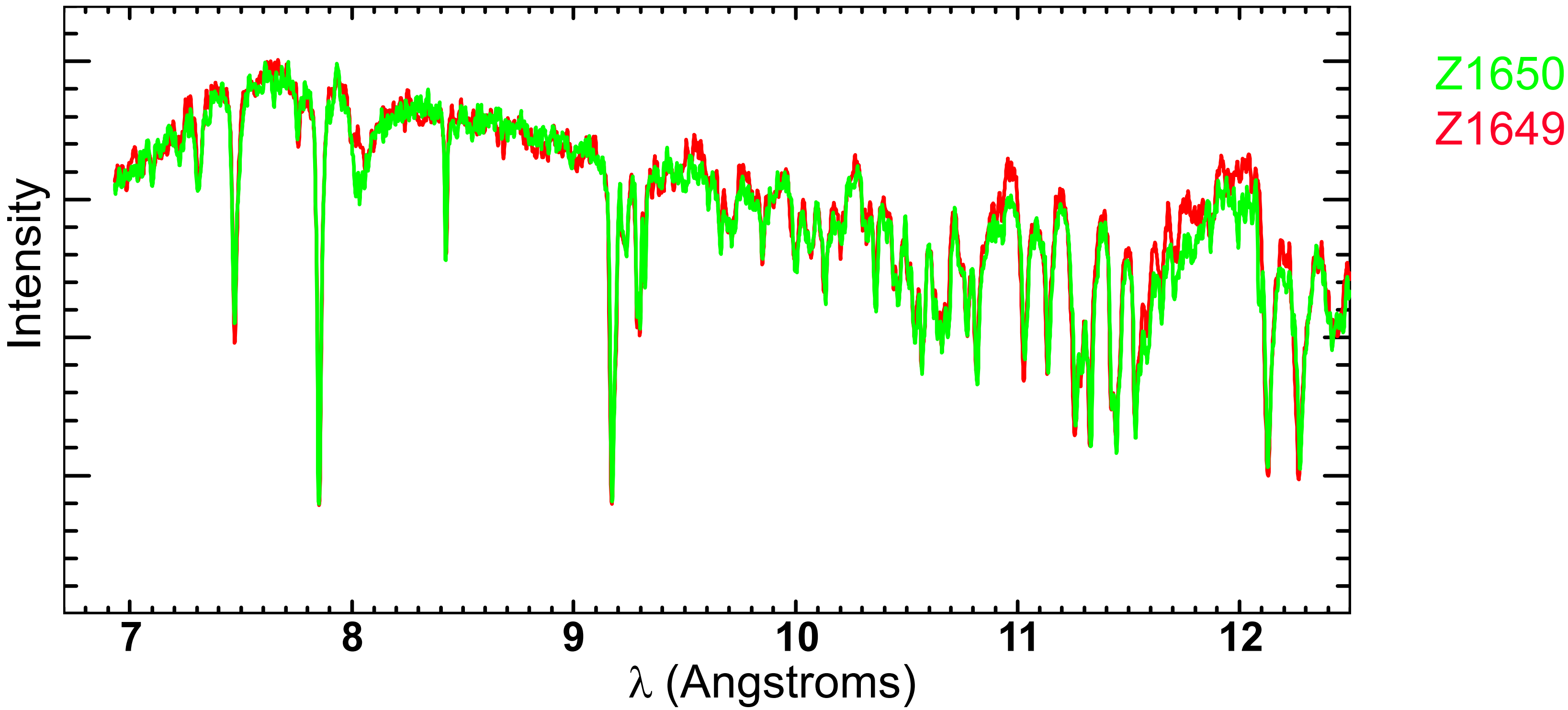
Plasma T_e and n_e are reproducible to better than ± 4% and ± 25%, respectively.





$T_e \sim 156 \pm 6$ eV
$n_e \sim 6.9 \pm 1.7 \times 10^{21}\ cm^{-3}$

The spectrum is reproducible from shot to shot



- No scaling was applied for this comparison
- Average standard deviation of transmission = ± 8%
- Transmission uncertainty = ± 2.3%

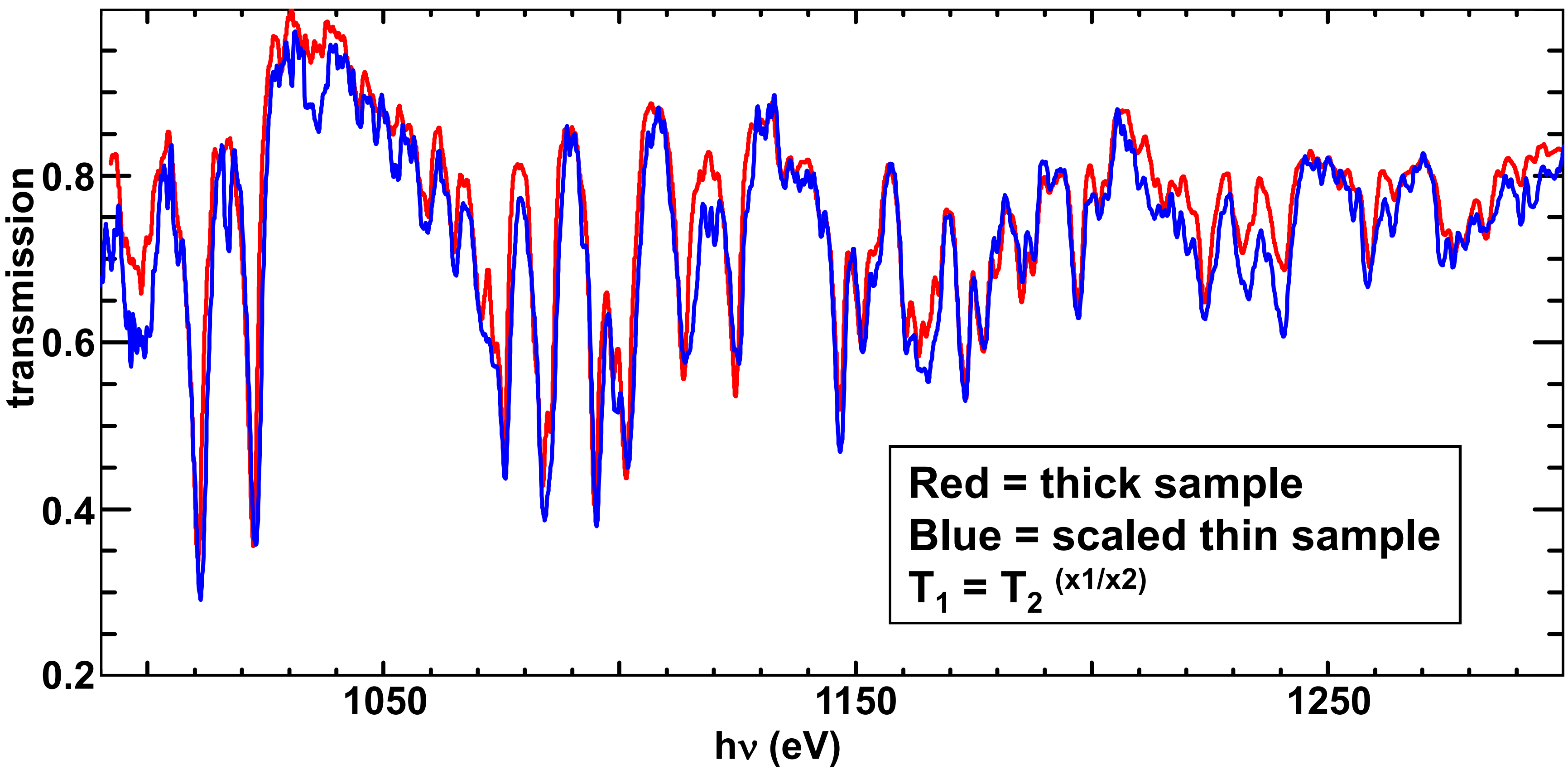
Possible experiment flaws can be evaluated from transmission scaling with sample thickness

Potential experiment problems:

- Sample may not be cartoon-like (pinholes, columnar structure)
- Sample composition or areal density may not match specifications (oxidation, contamination)
- Sample self emission may alter apparent transmission
- Conversion of film density to film exposure may be inaccurate
- Background subtraction incorrect
- Crystal defects may introduce artificial spectral features or mask actual features
- Gradients may alter transmission, becoming more important with thicker samples
- Lines may saturate

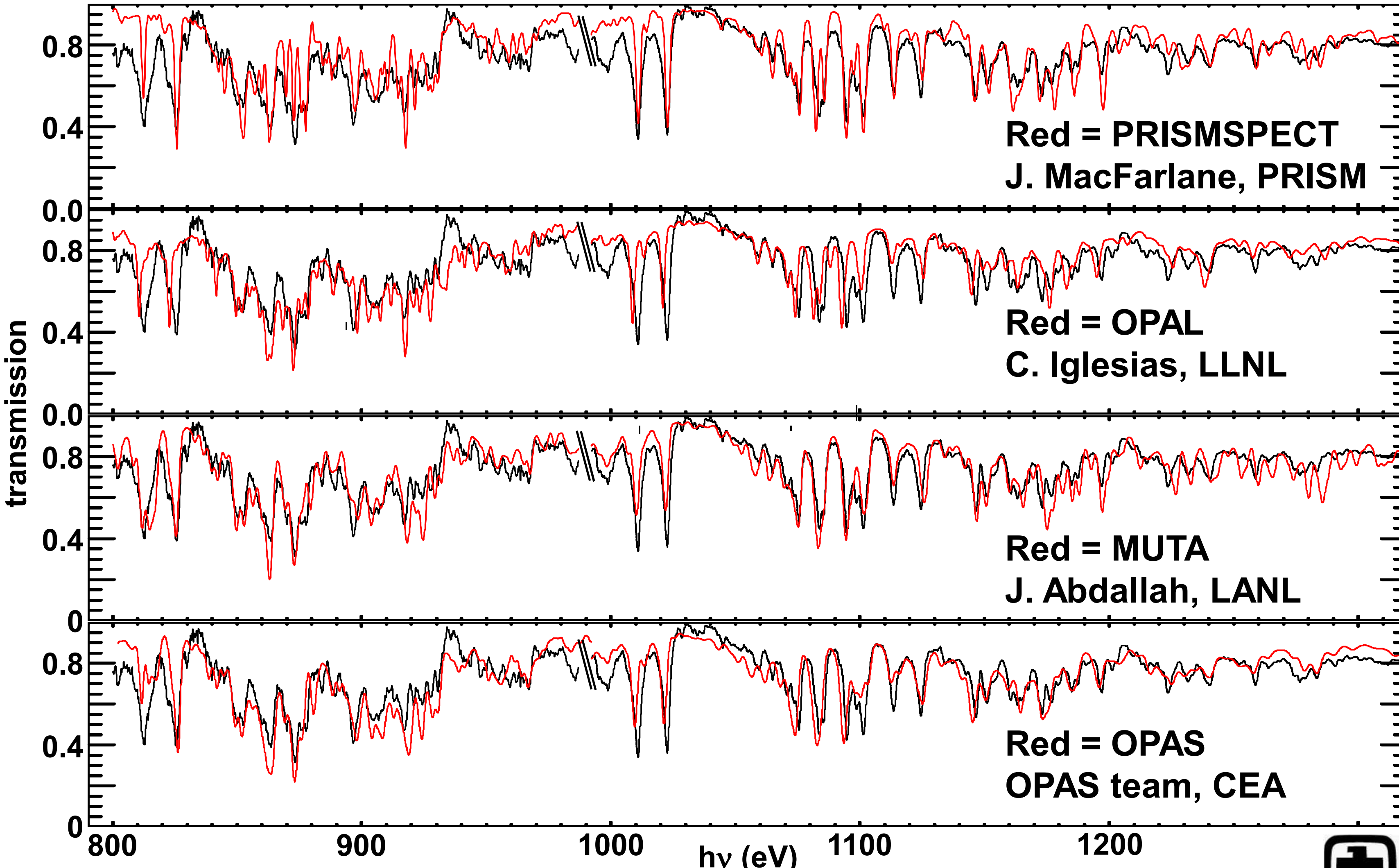
All of these problems cause transmission to deviate from expected scaling with thickness : $T_1 = T_2^{(x1/x2)}$

Transmission scaling with thickness confirms experiment reliability



Un-desired effects such as self emission, gradients, transmission errors all tend to change the transmission scaling with thickness

Modern detailed opacity models are in remarkable overall agreement with the Fe data



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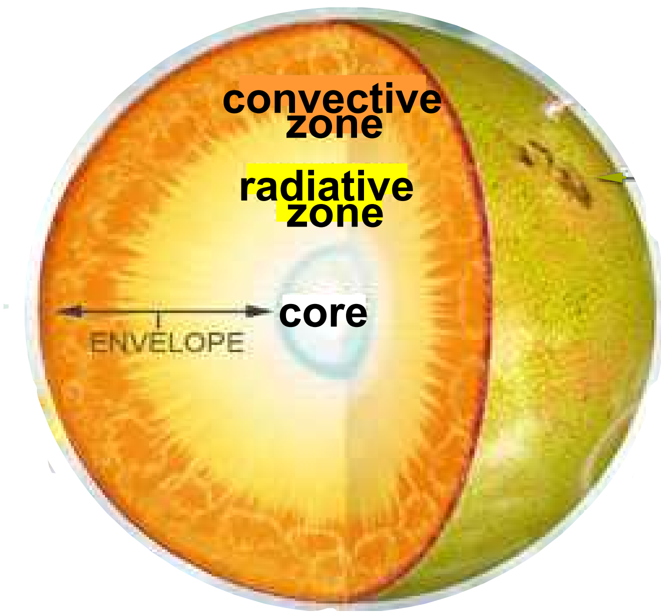
Z experiments test opacity models that are crucial for stellar interior physics



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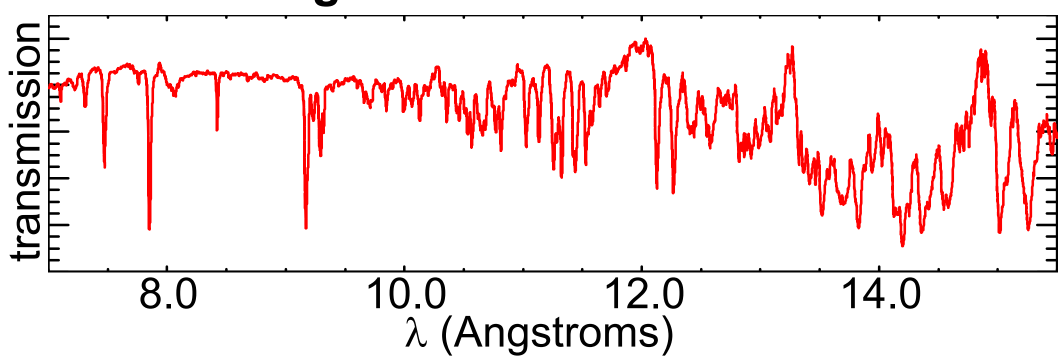
<u>Challenge: create *and diagnose* stellar interior conditions on earth</u>

Z opacity experiments reach T ~ 156 eV

High T enables first studies of transitions important in stellar interiors

Fe / Mg transmission at T ~ 156 eV



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