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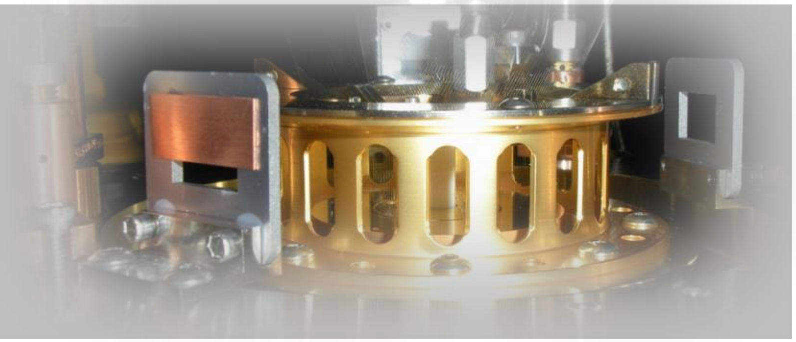

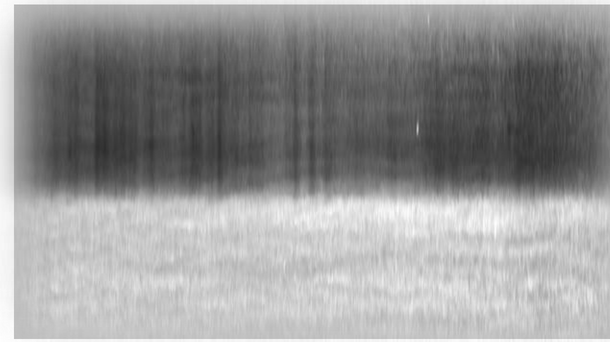

Opacity Measurements and Analysis at Stellar Interior Conditions

Gregory A. Rochau

19th International Conference on Atomic Processes in Plasmas

Paris, France

April 5, 2016

SAND No.

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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This work is a decadal collaboration between US National Labs, Universities, and the French CEA

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Summary: A first-ever systematic study of L-shell opacity is underway and will provide new understanding of atomic processes in hot, dense plasmas.

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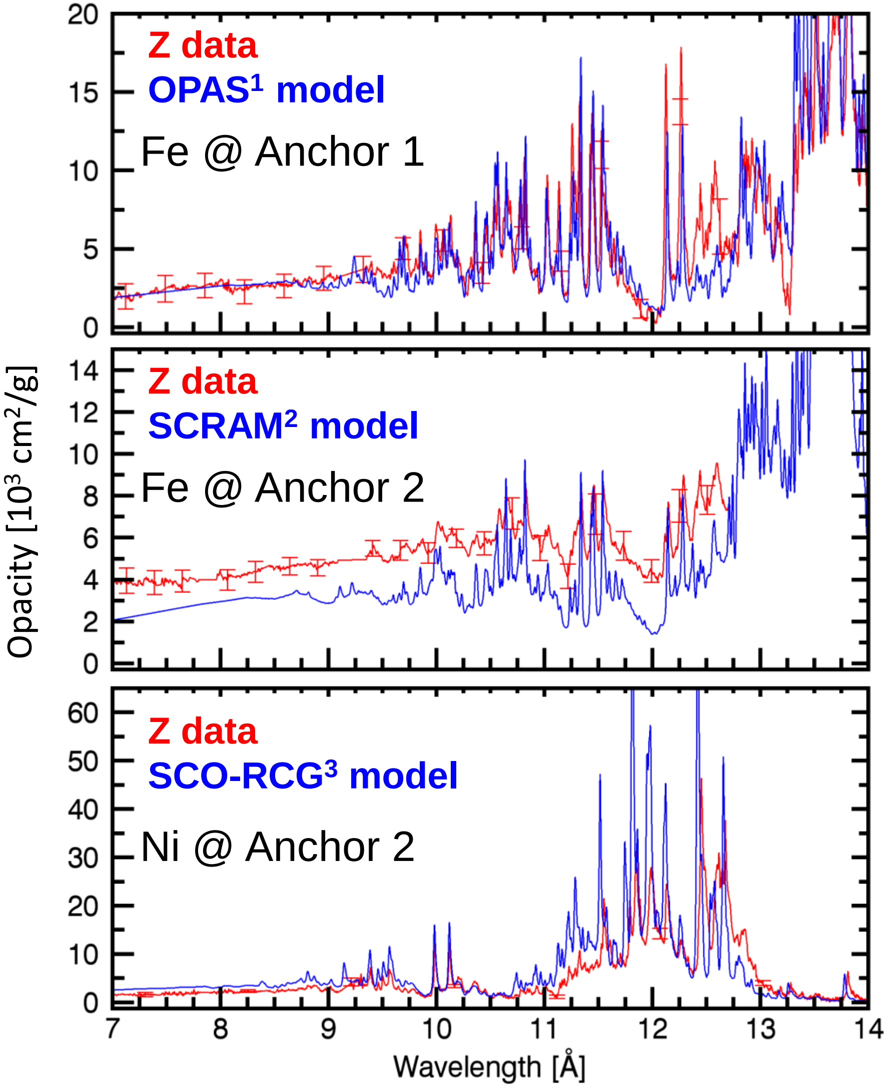
- Experiments on Z measure the opacity of materials at conditions similar to the base of the solar convection zone.
- Models of iron opacity agree with Z data at some conditions, but show disturbing disagreement at increased Te and ne.

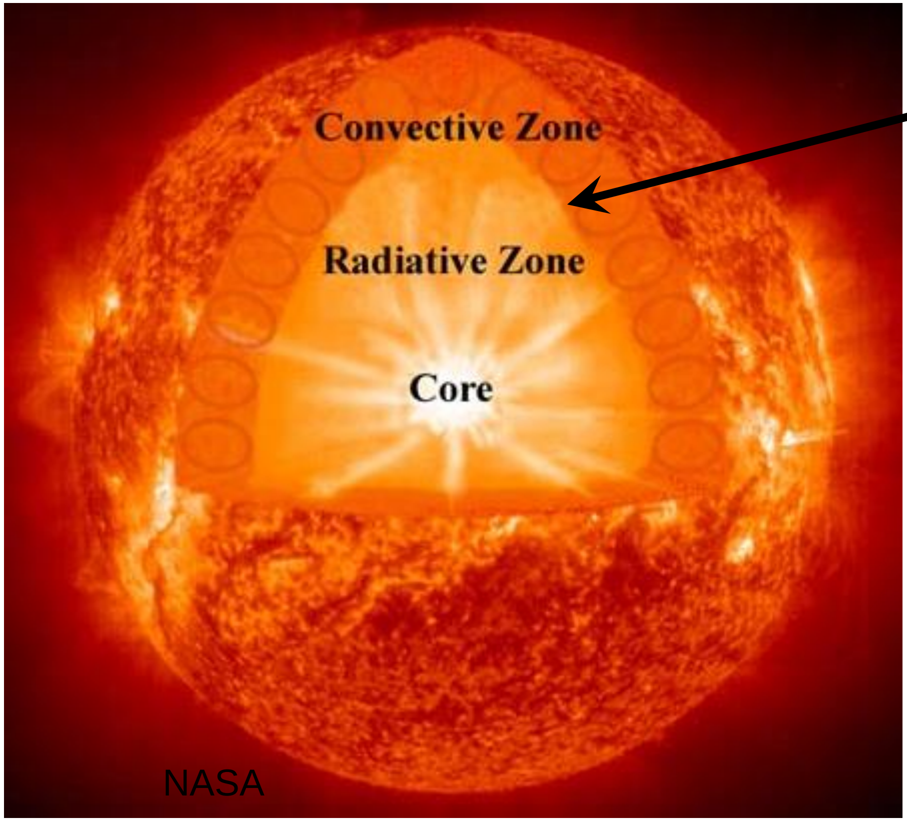
Anchor 1	Anchor 2
[160 eV, 7E21 e^-/cc]	[185 eV, 3e22 e^-/cc]

- New measurements of nickel and chromium opacity support the accuracy of previous iron data and provide important clues on data-model discrepancies.



[1]Blancard et al., Astrophys. J. (2012) [2]Hansen et al., HEDP (2007) [3]Porcherot et al., HEDP (2011)

Models for solar interior structure disagree with helioseismology observations.



<u>Convection-Zone (CZ) Boundary</u>
Models are off by 10-30 σ

<u>Models depend on:</u>

- **Composition (revised in 2005*)**
- **EOS as a function of radius**
- **The solar matter *opacity***
- **Nuclear cross sections**

<u>Question</u>: Is opacity uncertainty the cause of the disagreement?

*M. Asplund *et al*, Annu. Rev. Astro. Astrophys. **43**, 481 (2005).

Iron opacity measurements help determine if opacity model inaccuracies cause the solar problem

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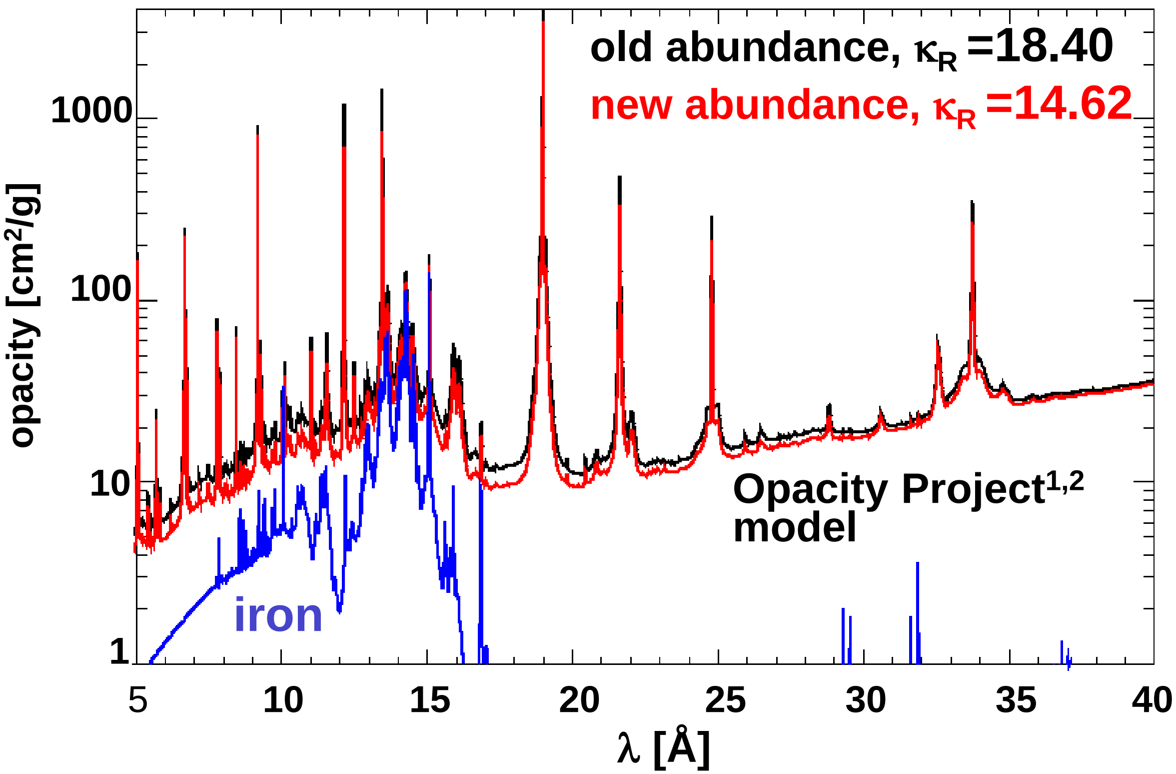
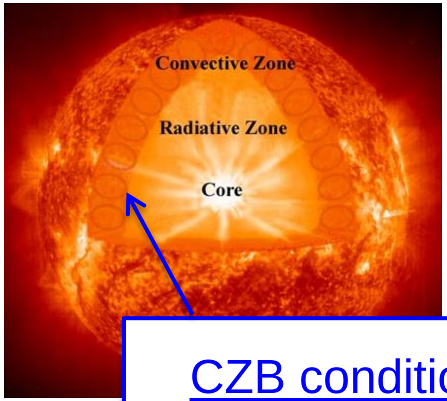
Solar mixture opacity at Convection Zone Base (CZB)



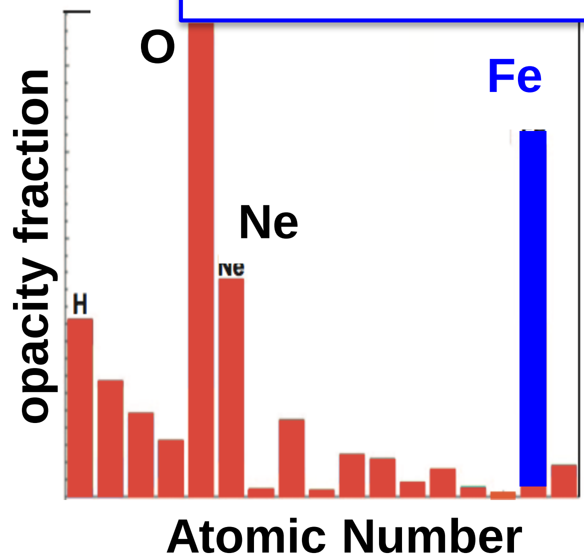
Iron contributes about 20% of the total solar opacity at the convection/radiation boundary



CZB condition:

T_e=182 eV

n_e=9x10^{22} cm^{-3}

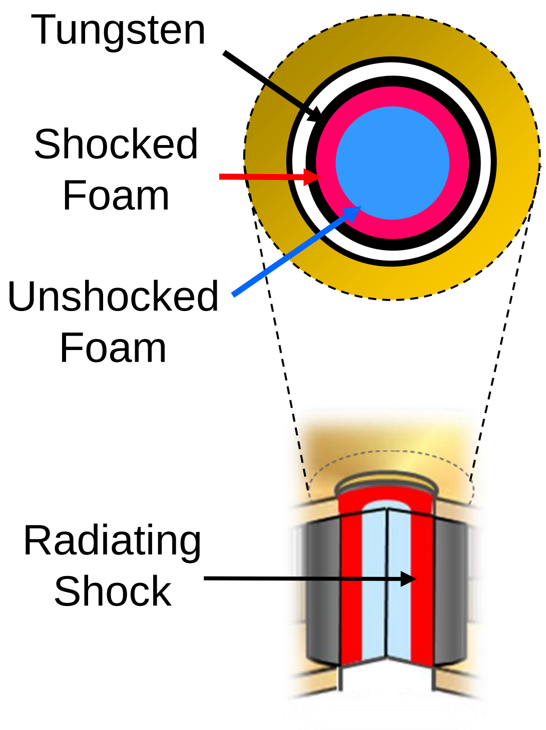


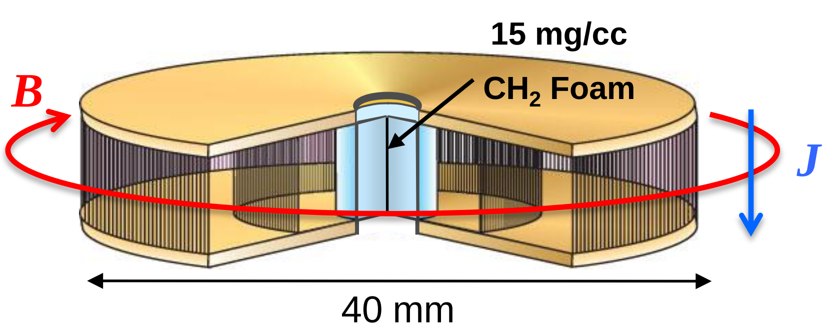
CEA OPAS calculation

[1]Badnell *et al.*, MNRAS (2005)

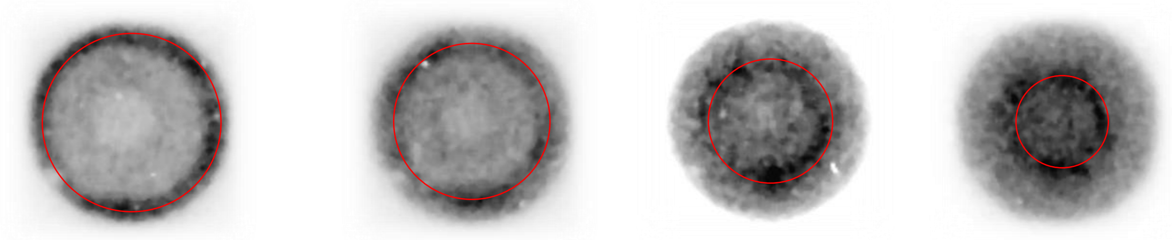
[2]Seaton et al., MNRAS (1994)

The Z-pinch Dynamic Hohlraum provides a bright x-ray source to heat and backlight opacity samples.



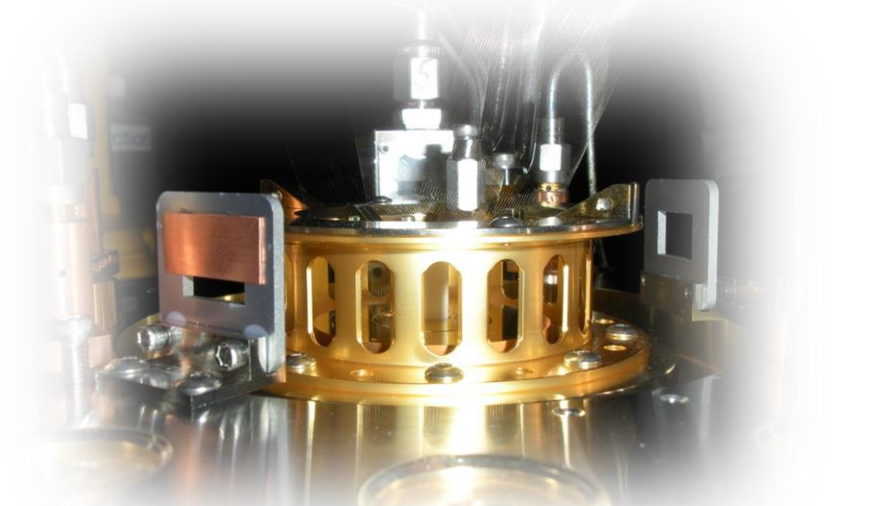


Framing Pinhole Camera Images



<u>Hohlraum characteristics</u>

- Peak current 26 MA
- Radiation Temp >250 eV during heating phase
- Pulse duration ~3.5 ns FWHM
- Radiation Temp ~350 eV during stagnation phase



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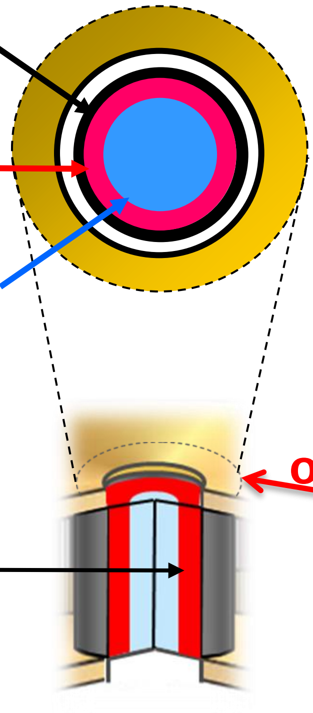

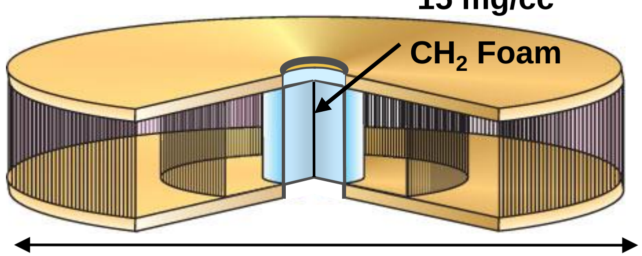

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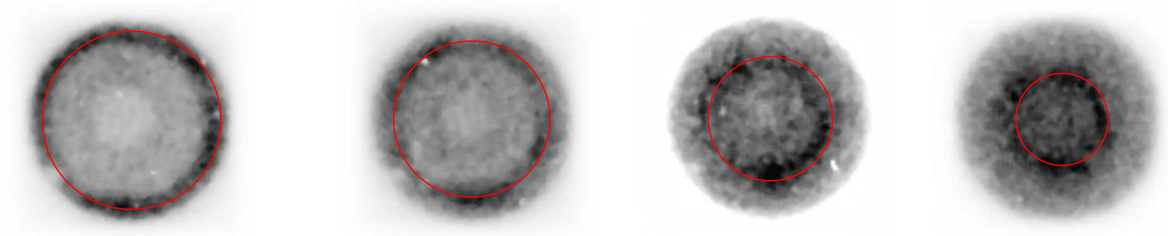
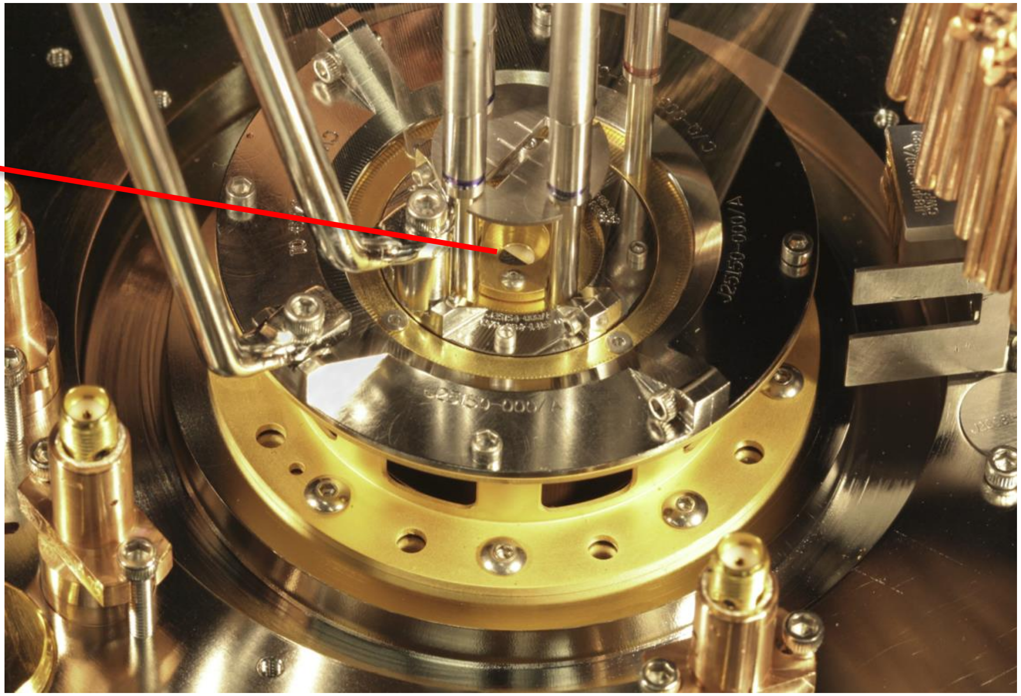
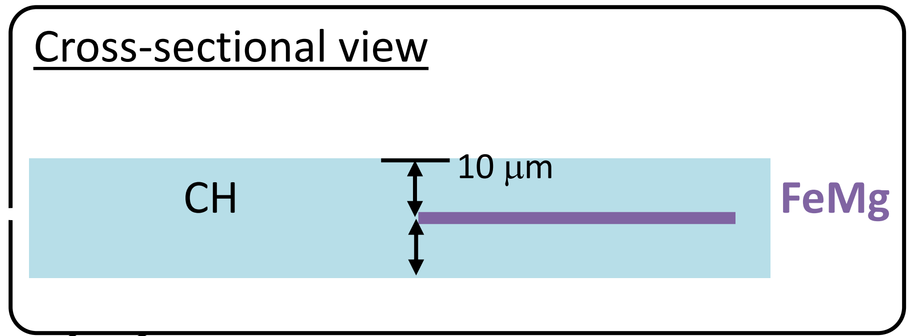
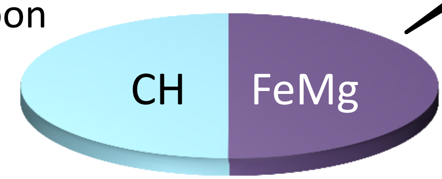


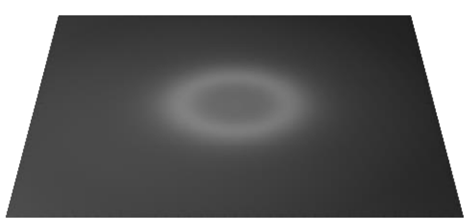


The Z opacity platform satisfies many challenging requirements for reliable opacity measurements.



Half-moon sample





Z x-ray source

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

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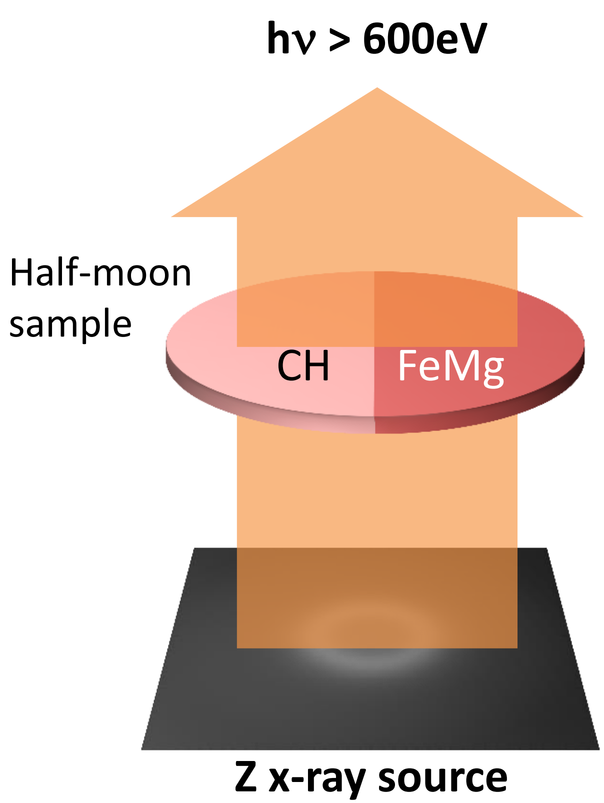

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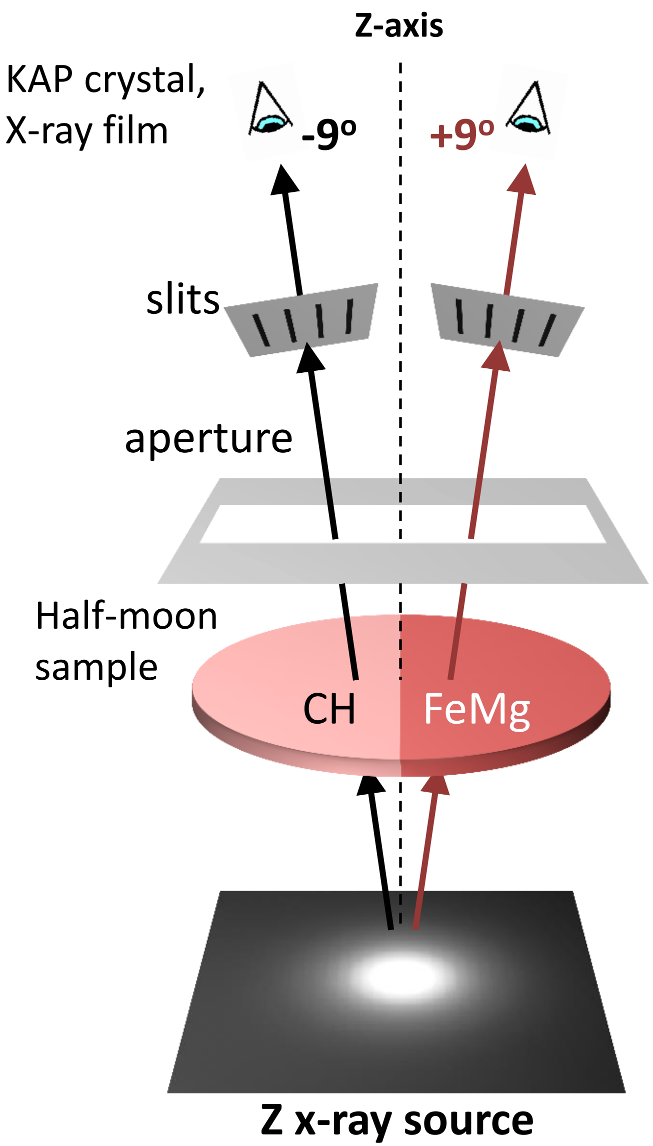

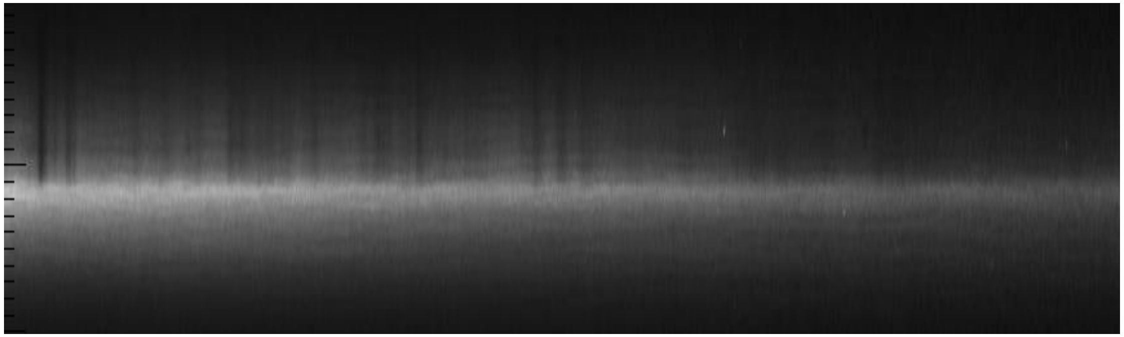

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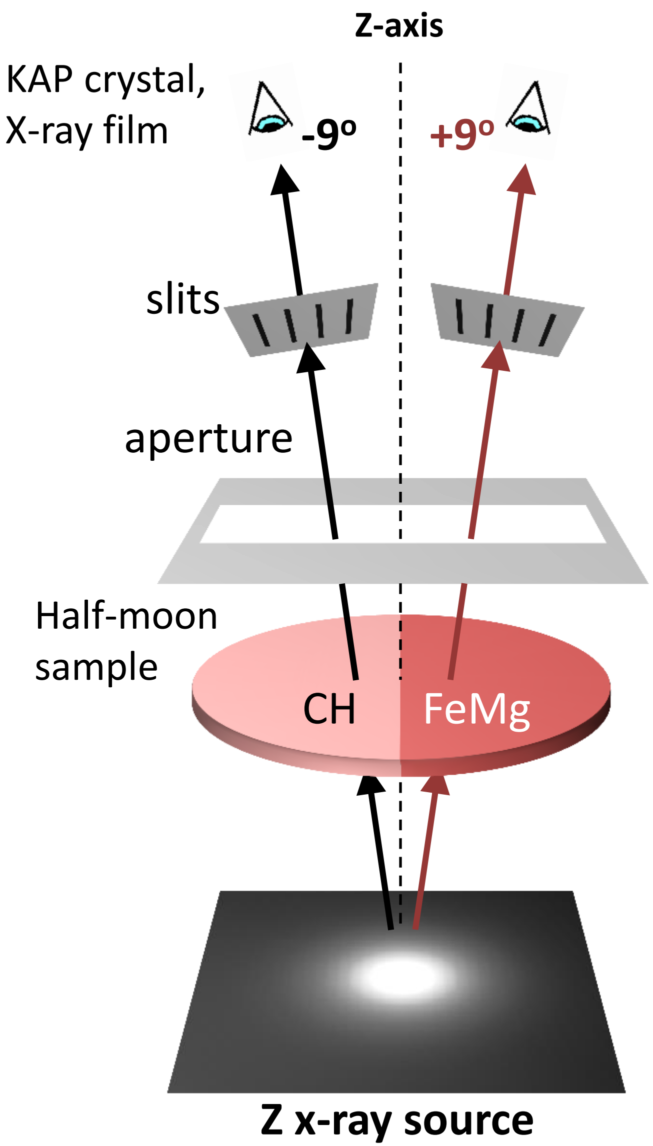

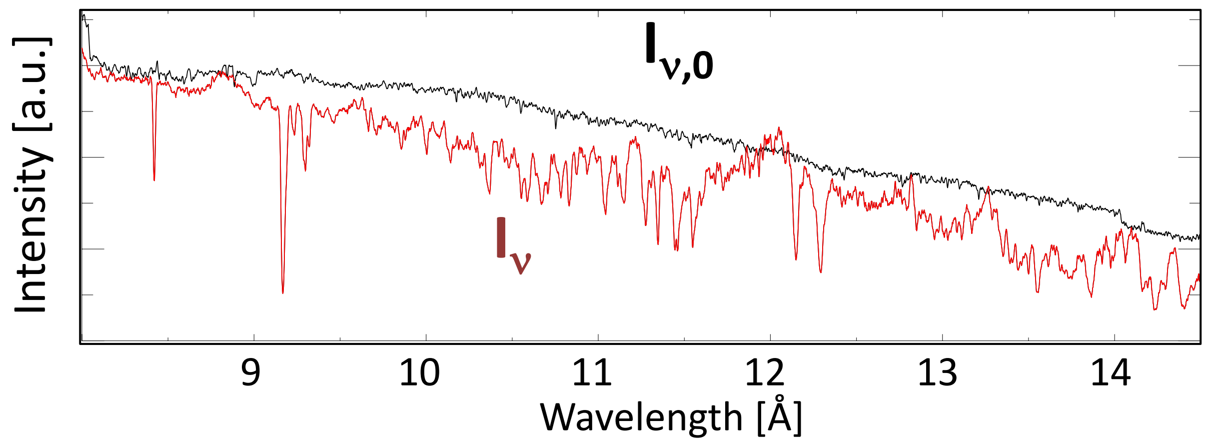

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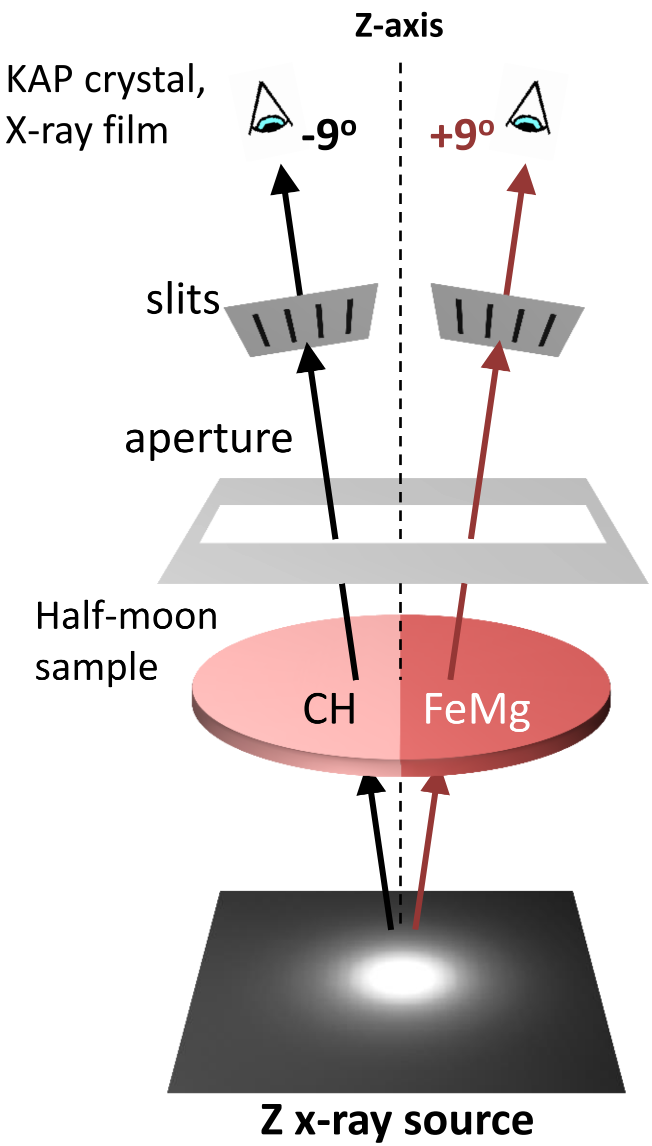

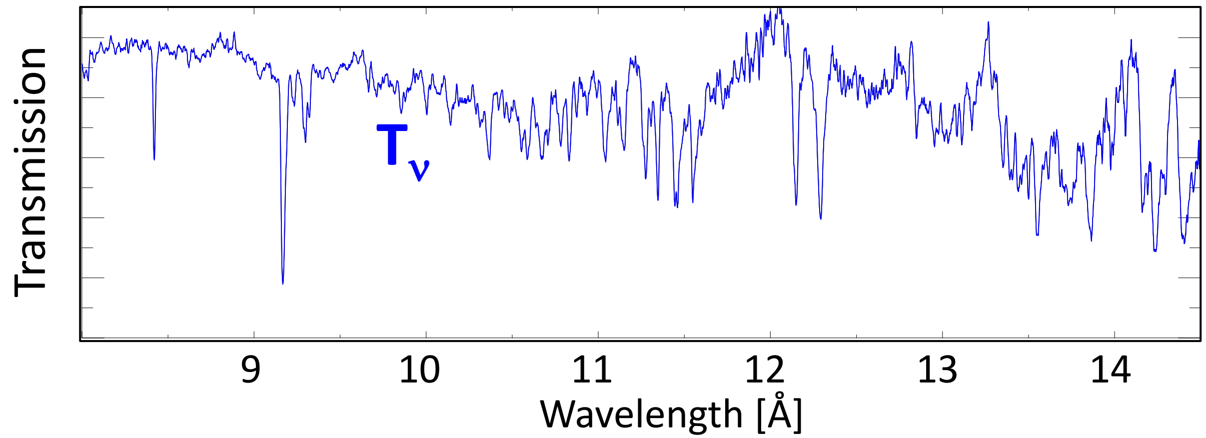

Transmission: $T_\nu = I_\nu / I_{\nu,0}$

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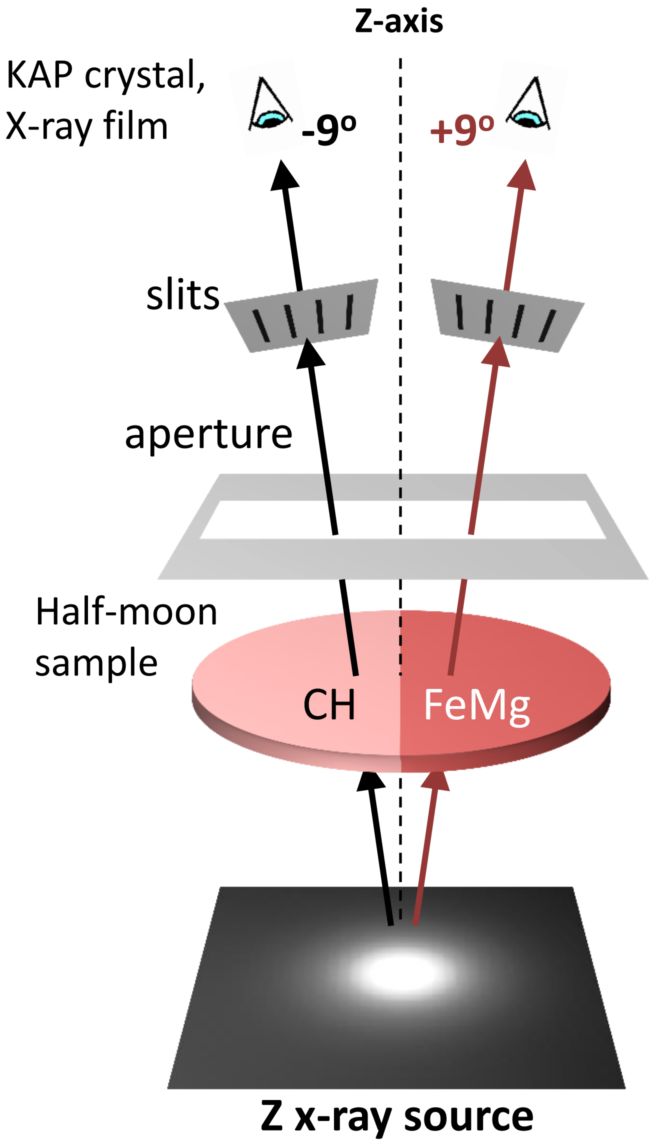
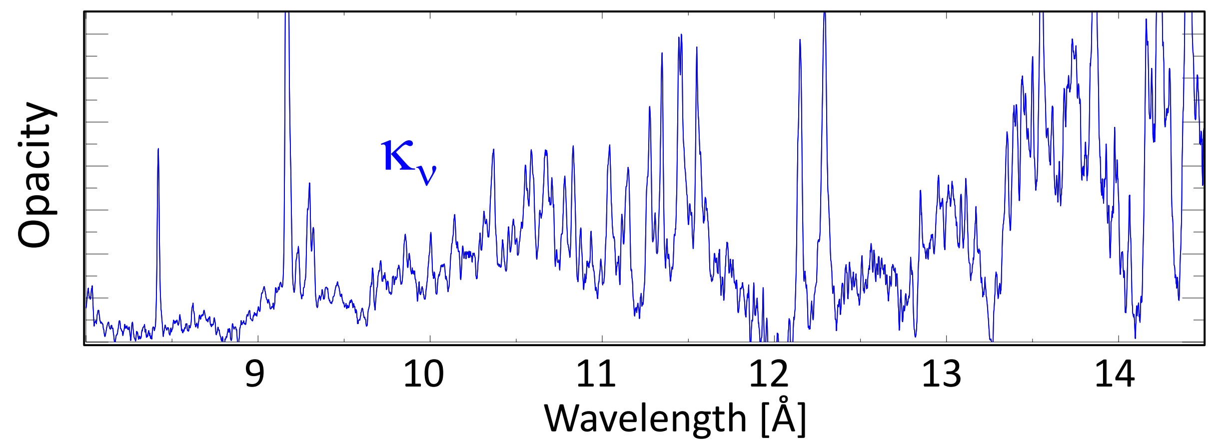




Transmission: $T_\nu = I_\nu / I_{\nu,0}$

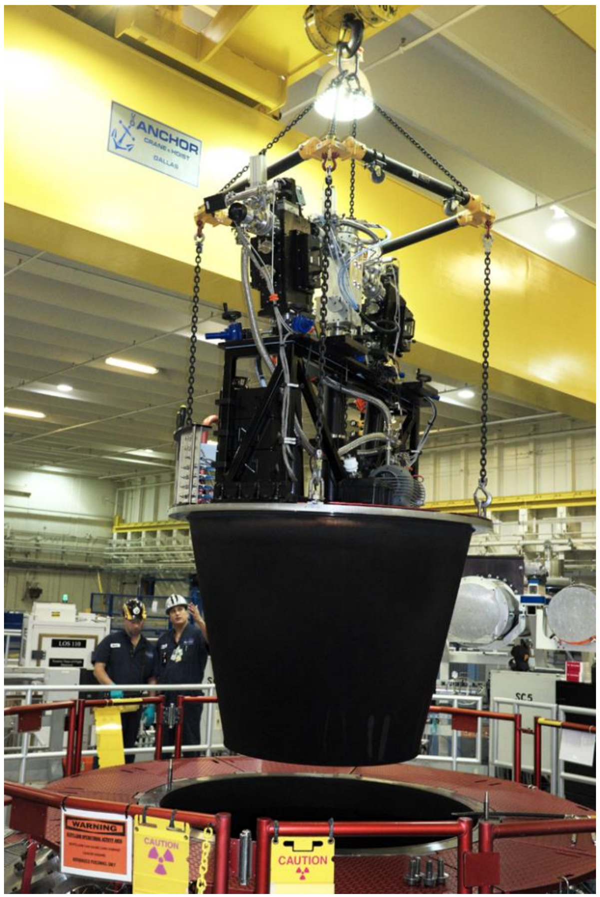
Opacity: $\kappa_\nu = -\ln(T_\nu)/\rho L$

Requirements:

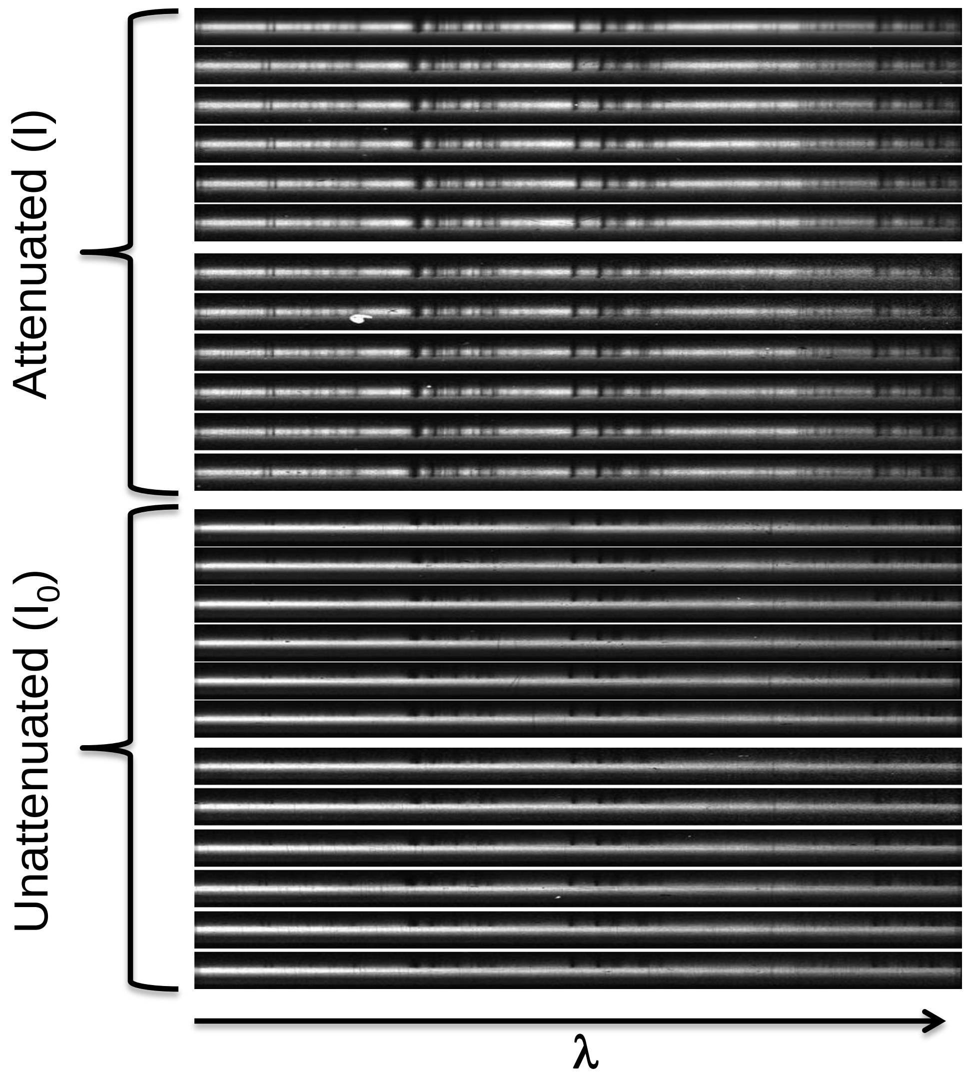
- Heat Fe to uniform conditions → Powerful radiation
- Measure Fe conditions independently → Mg spectra
- Bright backlight → 350 eV Planckian at stagnation
- Measure transmission accurately → multiple spectra

Hundreds of spectra over multiple shots are used to assess reproducibility and achieve high precision.

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

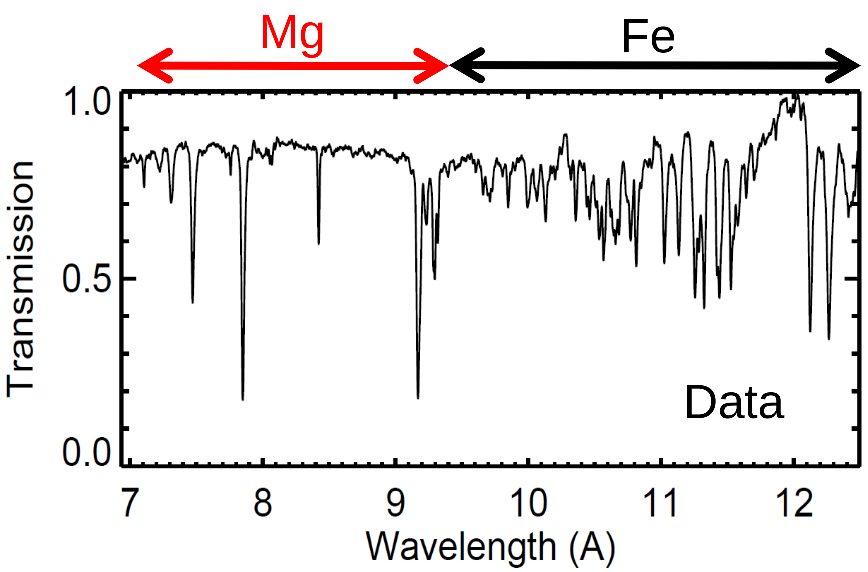


24 spectra recorded on a single shot

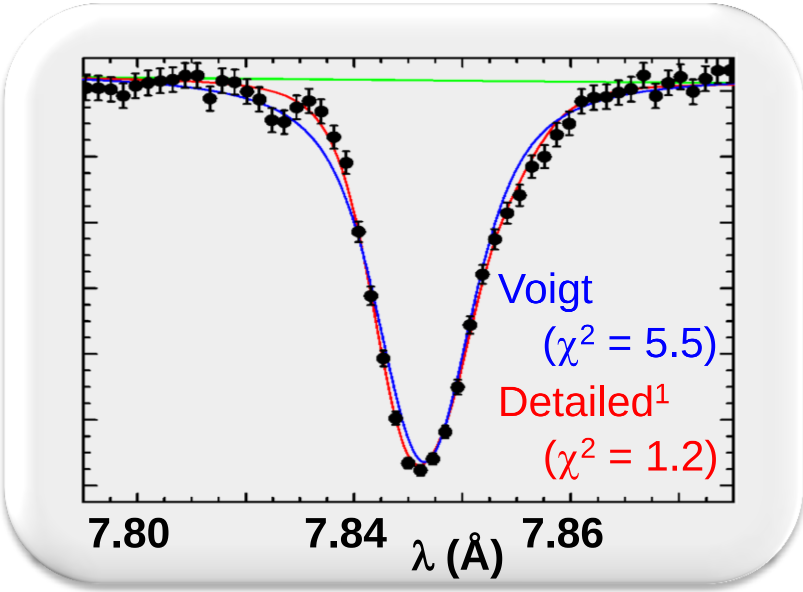


Loisel et al., Rev. Sci. Instrum. (2012)

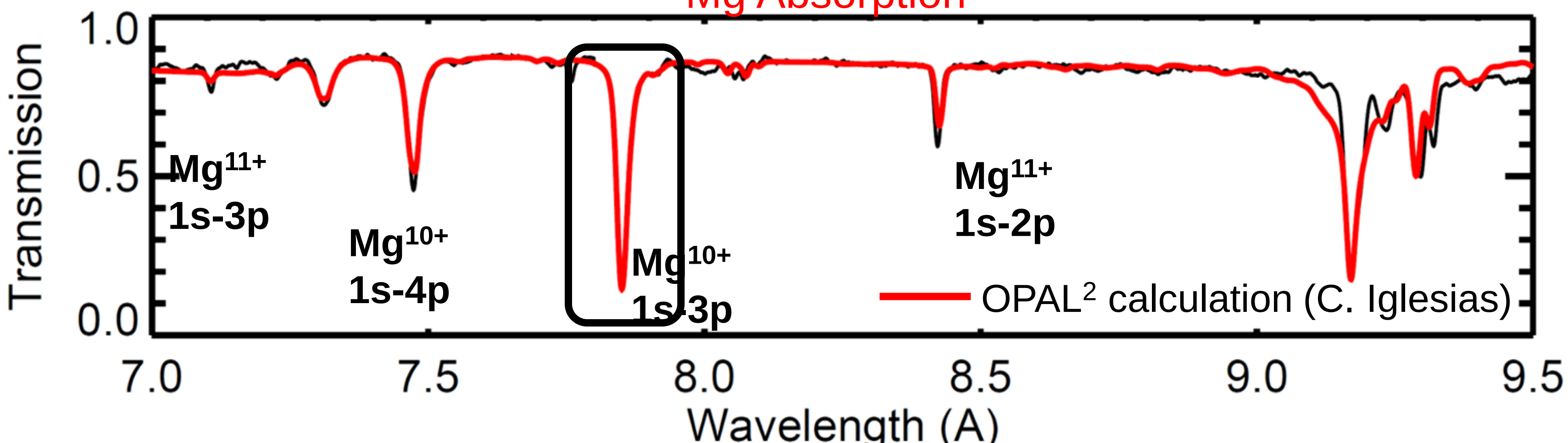
Mg K-shell spectra are mixed in with the iron to determine the plasma conditions.



Mg^{10+} 1s-3p Line Profile

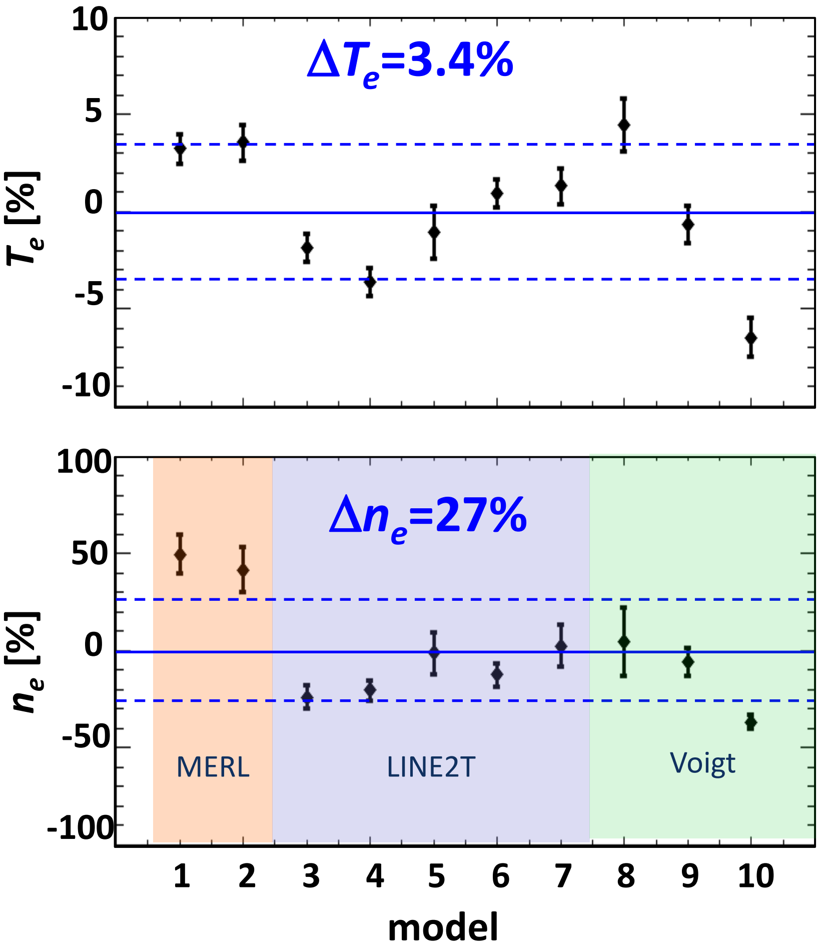


Mg Absorption

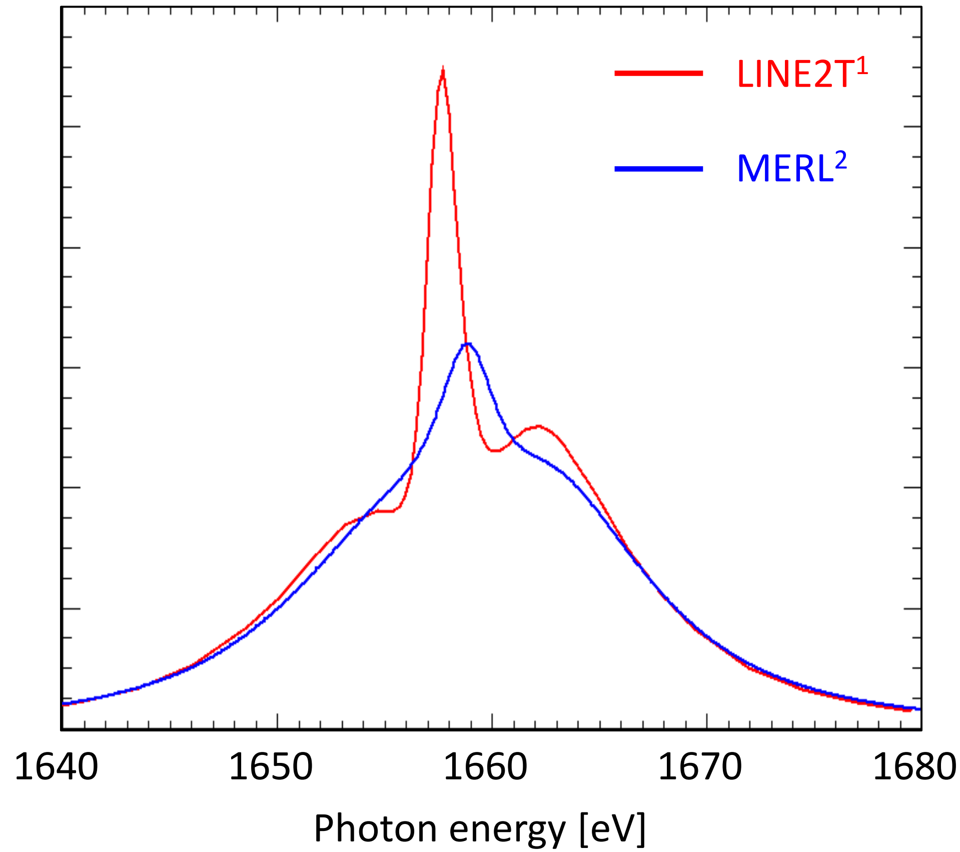


Inferred plasma conditions systematically depend on the model used to fit the Mg K-shell spectra

T_e = 195 eV, n_e = 4.0e22 e^-/cc



Mg Heγ line shape at n_e = 4e22 e/cc

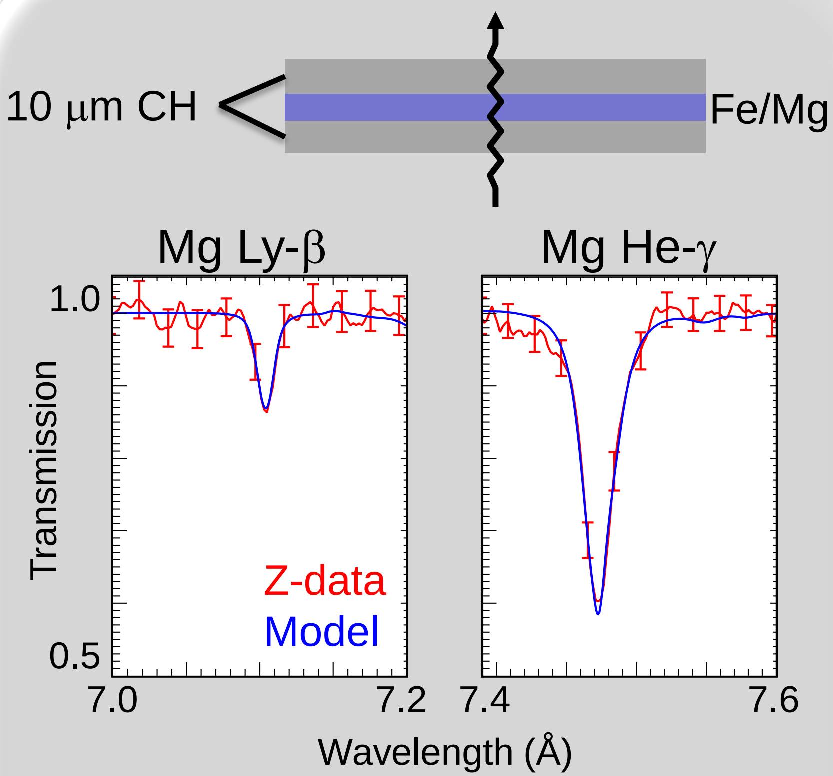


[1]Lee et al., JQSRT (1988)

[2]Mancini et al., Comput. Phys. Commun. (1991)

Increasing the back-side tamper mass increases the sample temperature and density

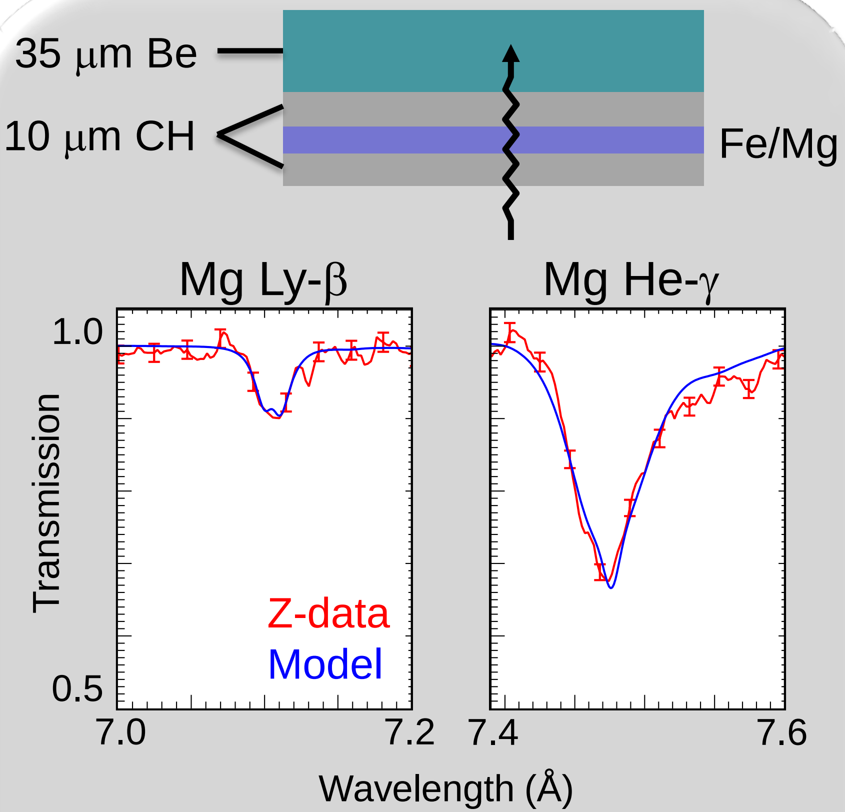
Anchor 1



$T_e = 156 \pm 6$ eV

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

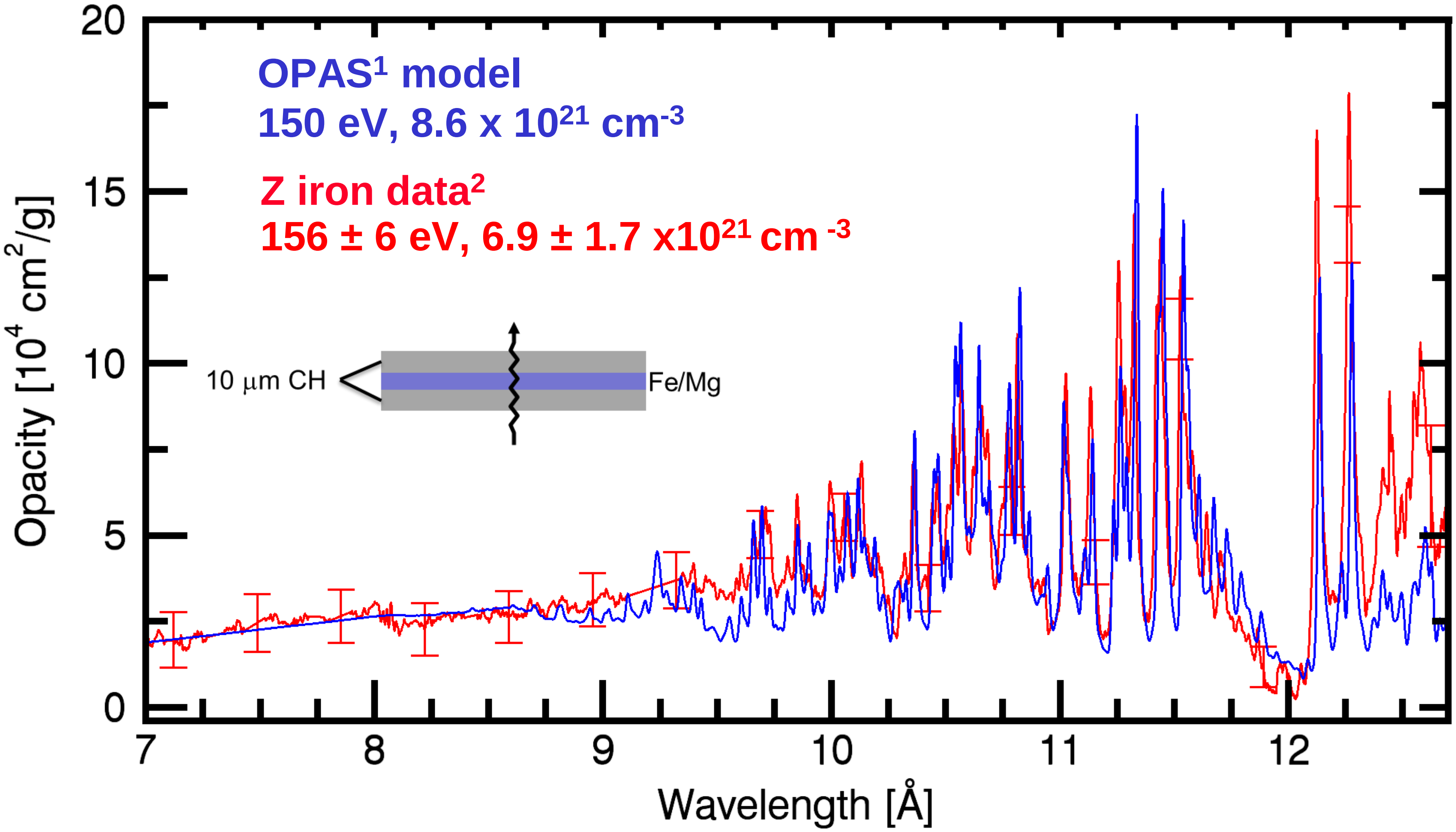
Anchor 2



$T_e = 182 \pm 3$ eV

$n_e = 31. \pm 3. \times 10^{21}$ cm $^{-3}$

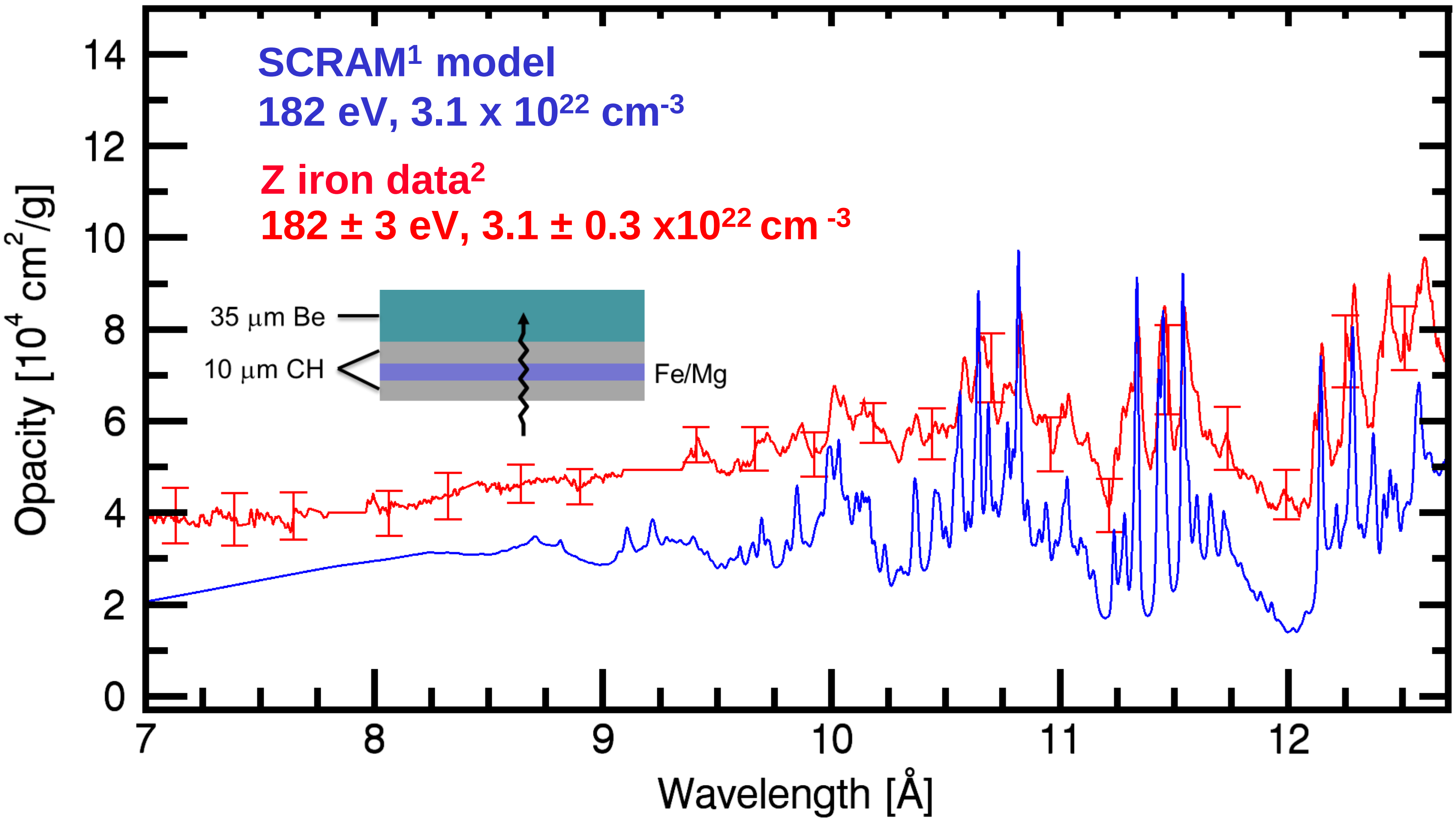
Modern best-effort models agree very well with the Z iron data at Anchor 1 conditions



[1]Blancard et al., Astrophys. J. (2012)

[2]Bailey *et al.*, PRL (2007)

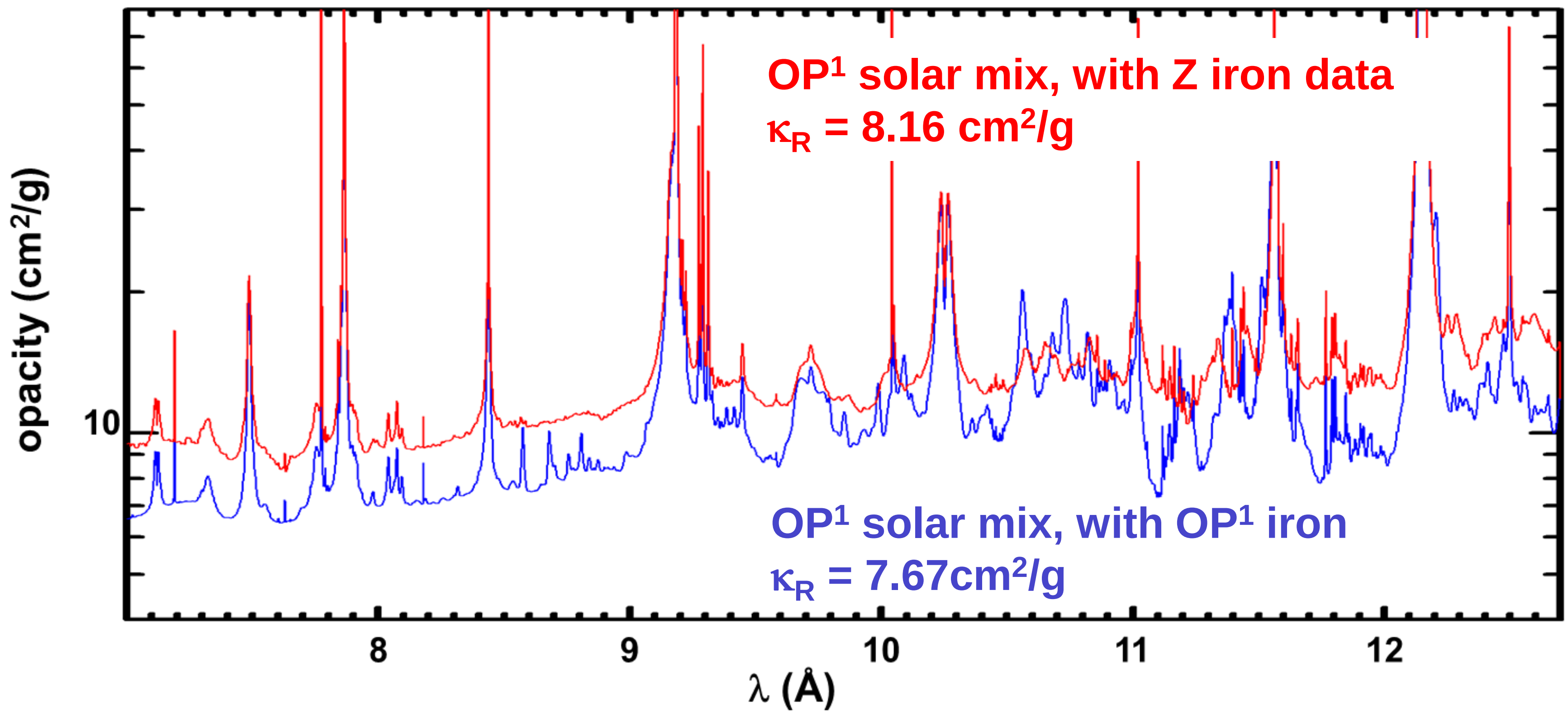
Modern best-effort models disagree with the Z iron data at Anchor 2 conditions



[1]Hansen et al., HEDP (2007)

[2]Bailey *et al.*, Nature (2015)

A solar mixture plasma using Z iron data has ~ 7% higher Rosseland mean opacity than using OP iron



- A 7% Rosseland increase partially resolves the solar problem, but the measured iron opacity by itself cannot account for the entire discrepancy
- Other elements and regions deeper in the sun could contribute

193 eV, 3.3 e22 e/cc Asplund09 solar abundances

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

No systematic error has been found that explains the model-data discrepancy of Fe at Anchor 2

Random error determination: average many spectra from multiple experiments

Systematic error evaluation: Experiment tests; Post-processed simulations

More than eleven different potential systematic errors were investigated:

Potential systematic errors	Effect
Sample contamination Tamper shadowing	True opacity potentially lower than inferred opacity
Fe self emission Tamper self emission Extraneous background	True opacity potentially higher than inferred opacity
Sample areal density errors Transmission errors Spatial non-uniformities Temporal non-uniformities Departures from LTE Plasma diagnostic errors	True opacity potentially either lower or higher than inferred opacity

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1D simulations reproduce the measured conditions and rule out some systematic errors

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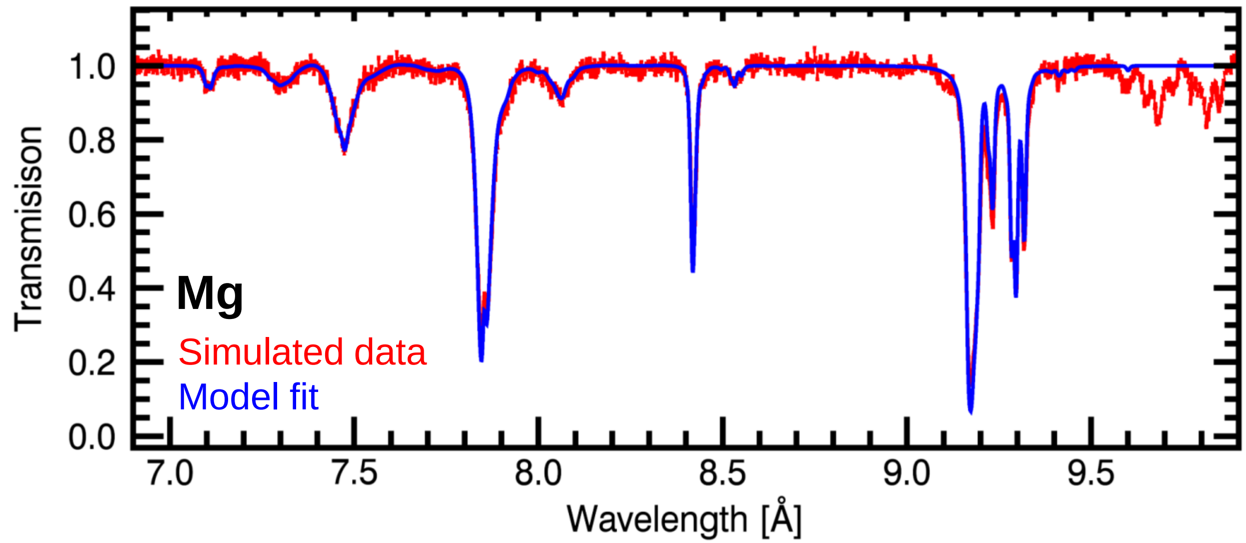
	T_e [eV]	N_e [10^{21}cm^{-3}]
Data	182±3	31±3
Simulated Data	183±2	35±3



Simulated data:

1. Model drive radiation
   - 3D view factor code
   - Measured radiation
2. 1-D Helios simulation
3. Radiation transport
   - Simulated T_e(t,z), n_e(t,z)
   - Backlighter: B_ν(t,x,y)
4. Add noise

Systematic error investigations:

Following effects are found to be negligible

- Sample/tamper self-emission
- Tamper attenuation
- Time- and space-integration

1D simulations reproduce the measured conditions and rule out some systematic errors

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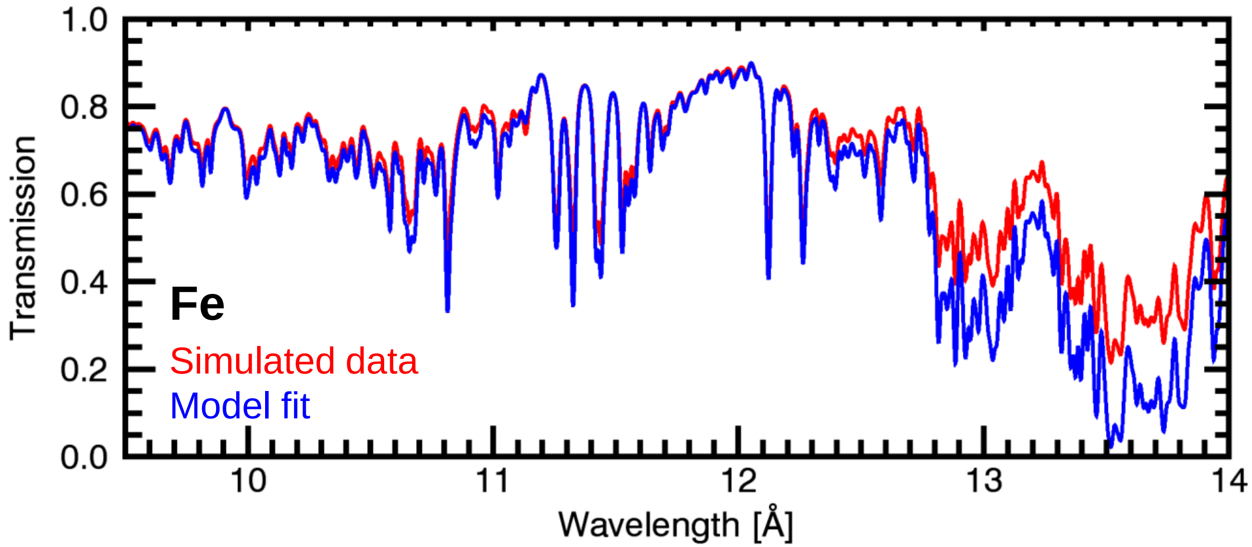

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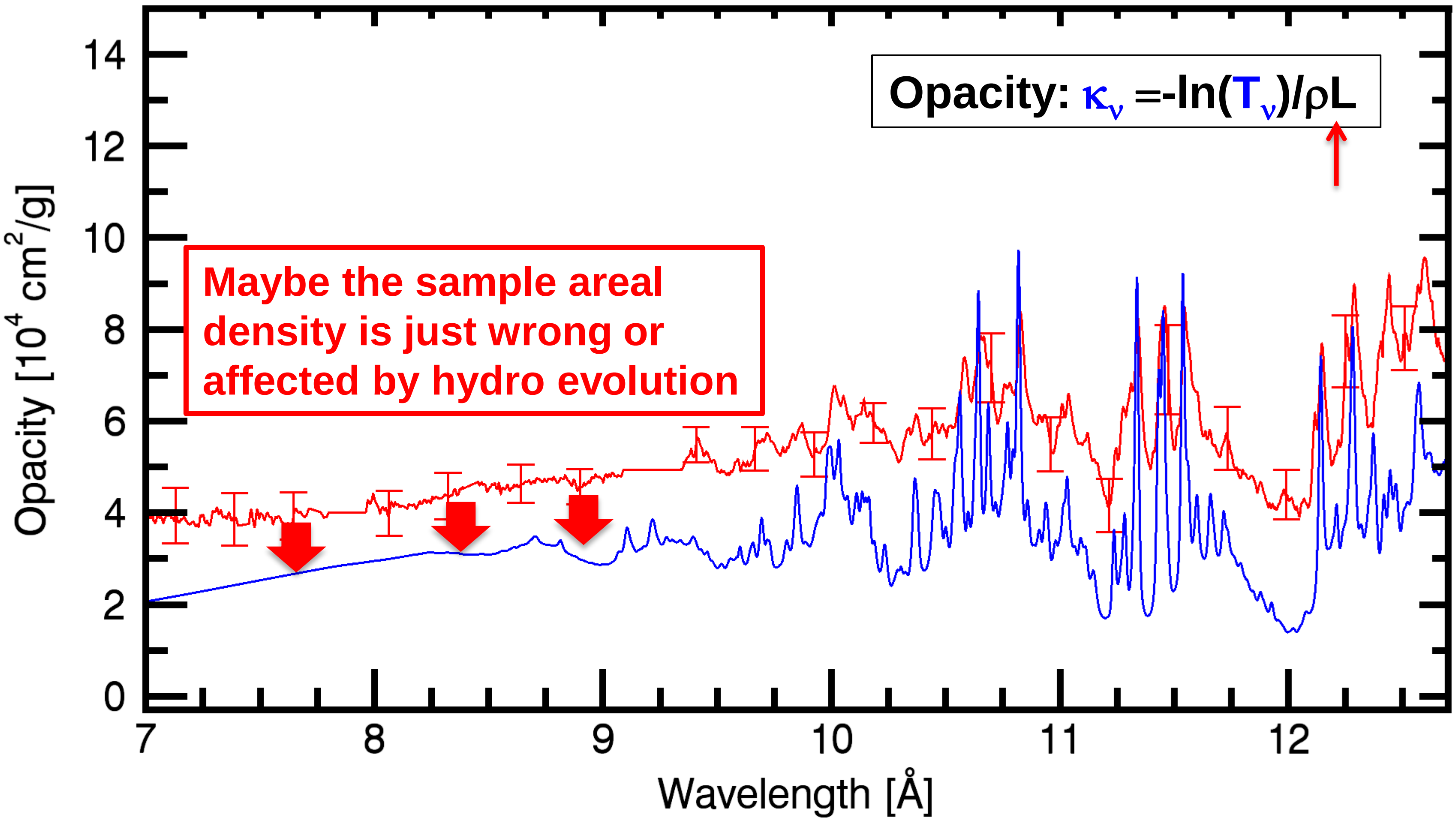
4. Add noise

Systematic error investigations:

Following effects are found to be negligible up to 12.5 Å

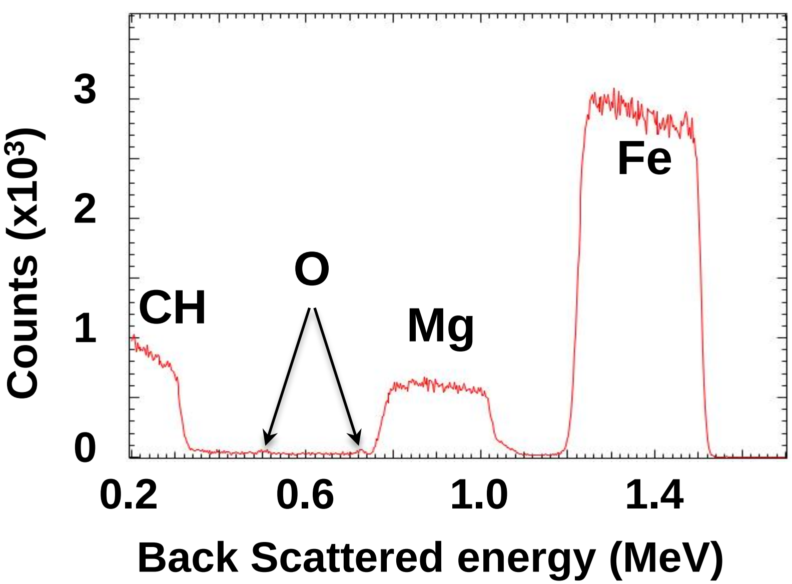
- Sample/tamper self-emission
- Tamper attenuation
- Time- and space-integration

Incorrect sample areal density or multi-dimensional hydrodynamic evolution would impact the opacity

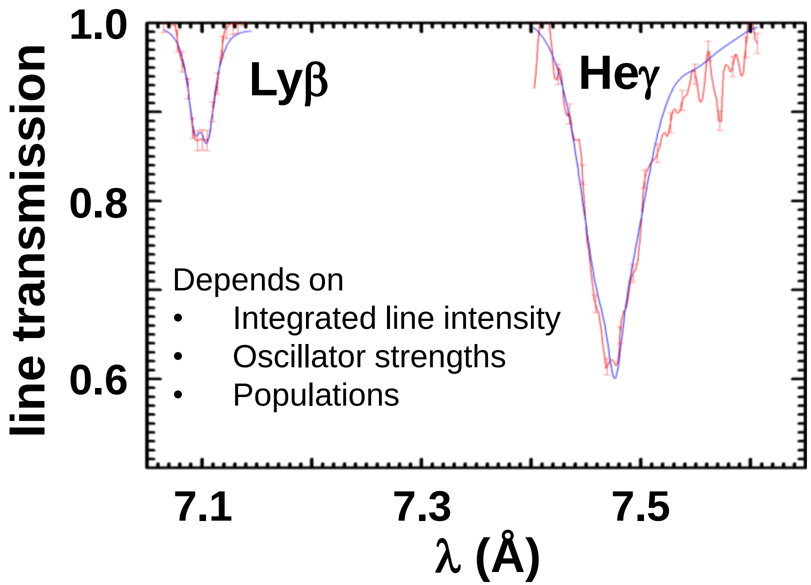


In-situ areal density inference agrees with pre-shot RBS measurements

Pre-shot Rutherford backscattered spectrum



In-situ areal density from strength of heated Mg K-shell lines



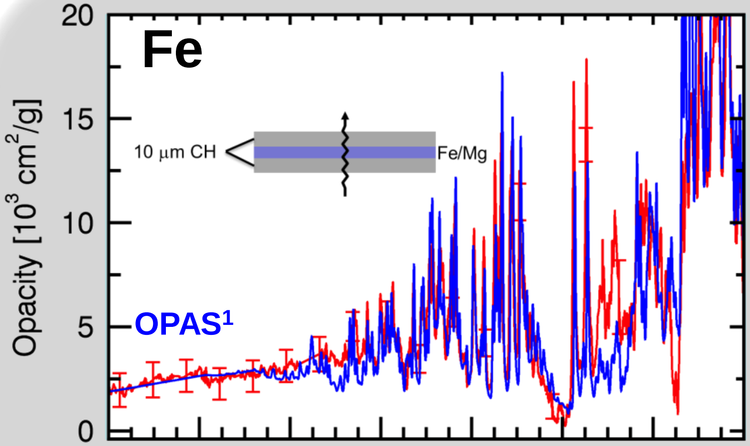
$$\frac{\rho X \text{ [Mg analysis on heated sample]}}{\rho X \text{ [RBS pre-shot]}} = 0.97 \pm 0.03$$

Hydro evolution of sample does not significantly alter the areal density

RBS spectrum provided by K. Hubbard and I. Usov, LANL

Measurements of nickel and chromium rule-out many systematic uncertainty hypothesis.

Anchor 1 (160 eV, 7e21 e/cc)



Anchor 2 (185 eV, 3e22 e/cc)

[1]Blancard et al., Astrophys. J. (2012) [2]Hansen et al., HEDP (2007) [3]Porcherot et al., HEDP (2011)

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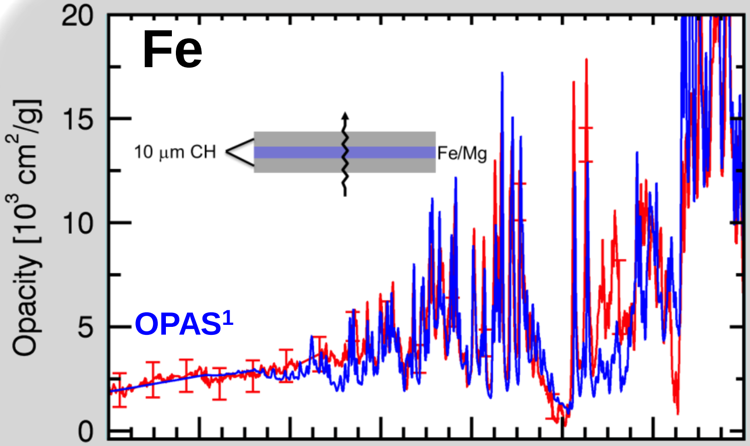

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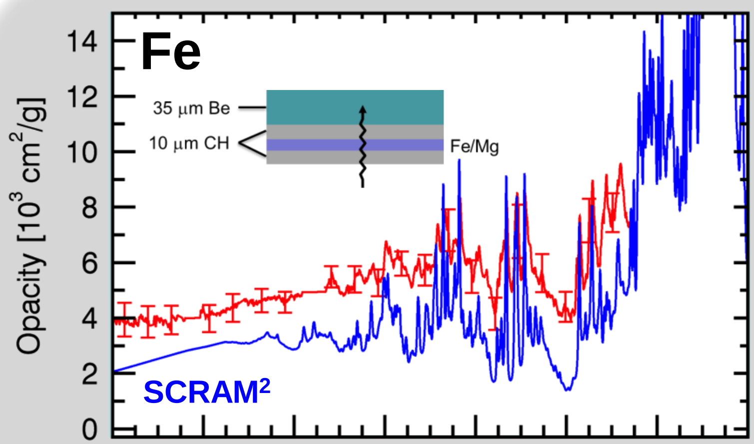

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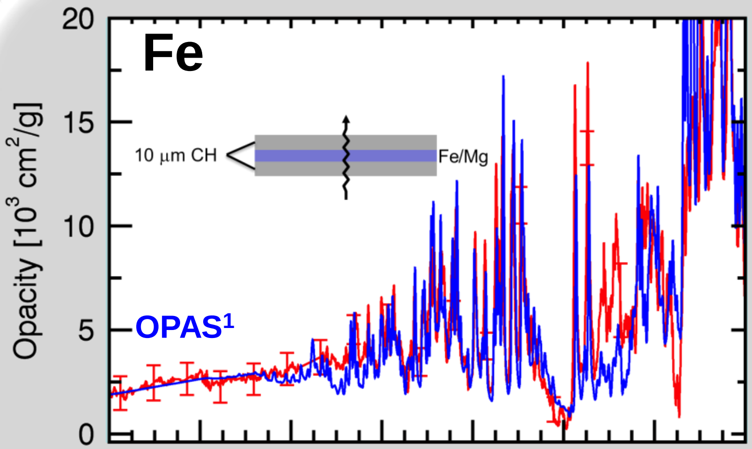

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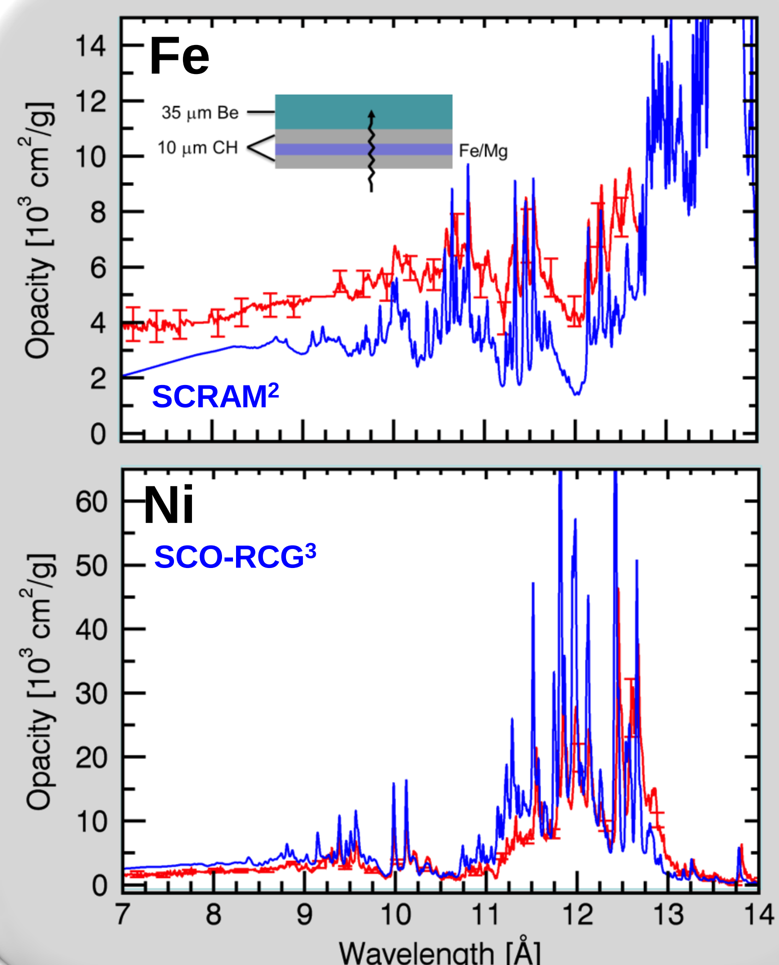
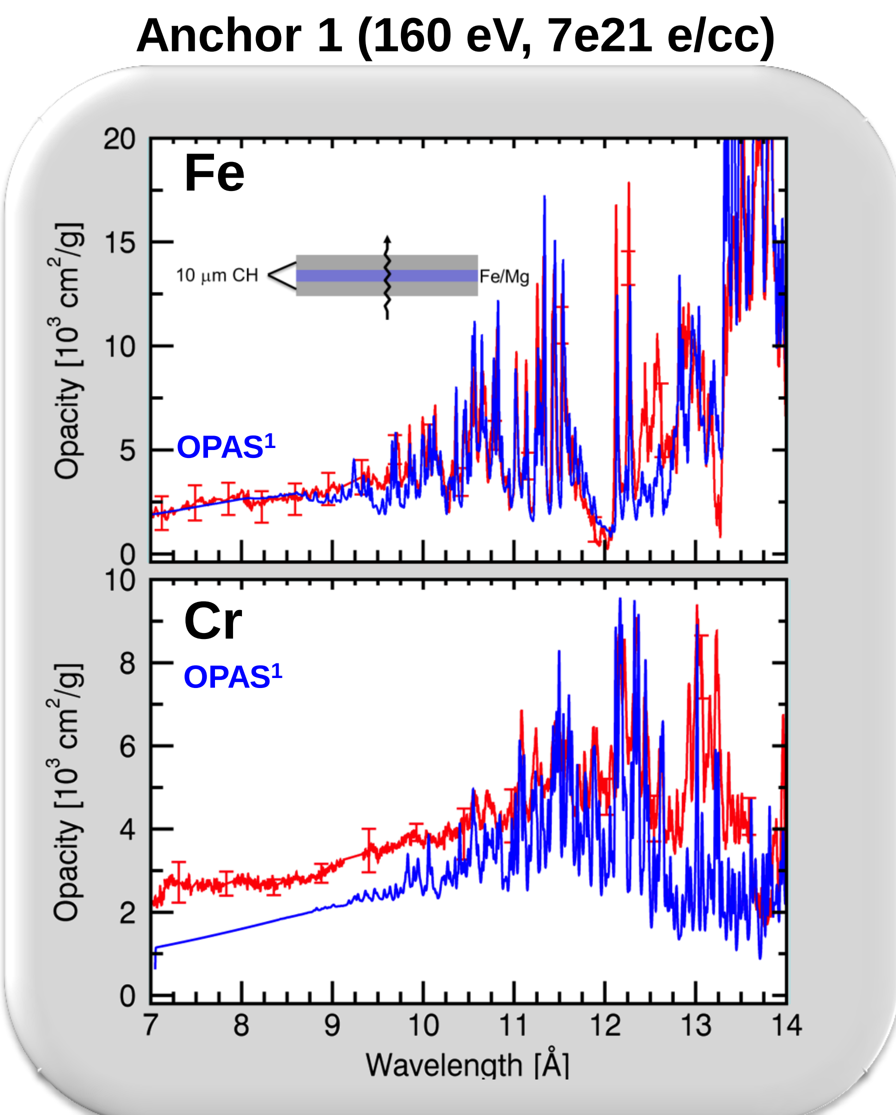
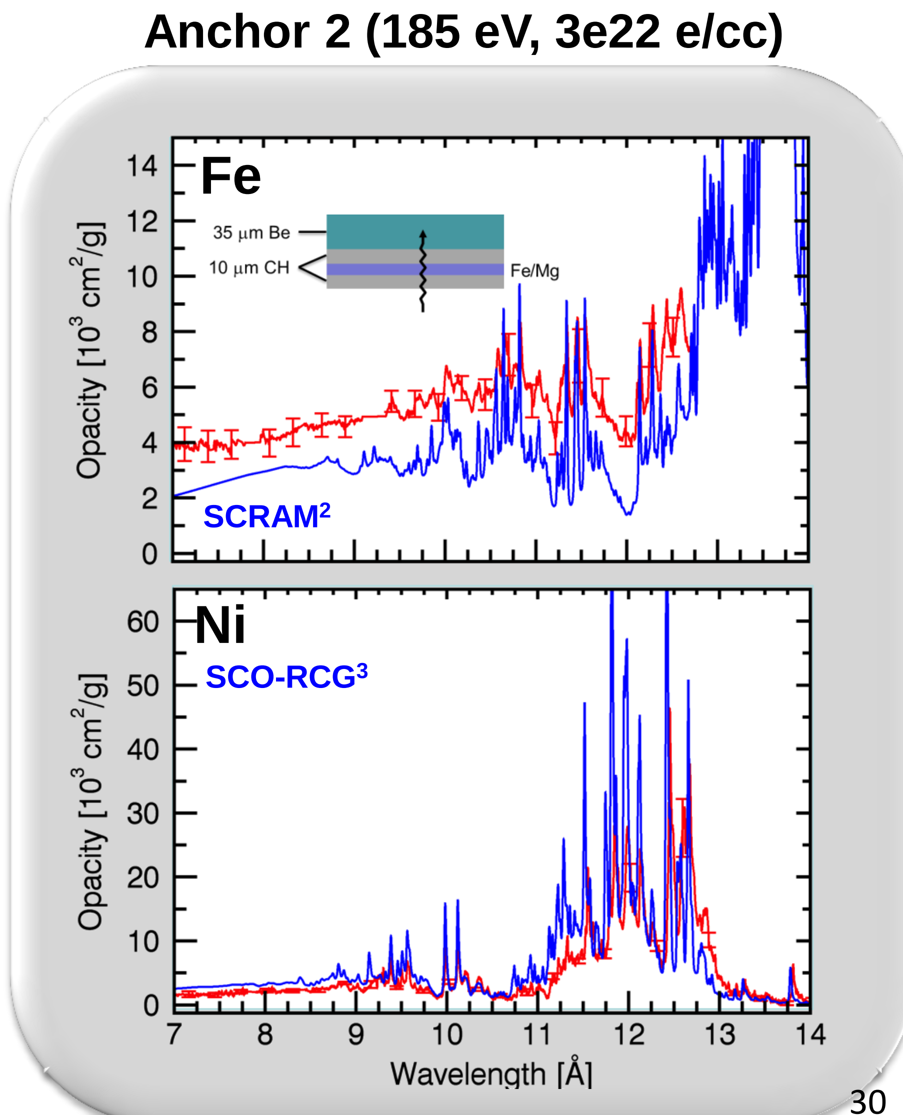


[1]Blancard et al., Astrophys. J. (2012) [2]Hansen et al., HEDP (2007) [3]Porcherot et al., HEDP (2011)

Measurements of nickel and chromium rule-out many systematic uncertainty hypothesis.





[1]Blancard et al., Astrophys. J. (2012) [2]Hansen et al., HEDP (2007) [3]Porcherot et al., HEDP (2011)

Measurements of iron, nickel, and chromium provide important clues on the underlying physics.

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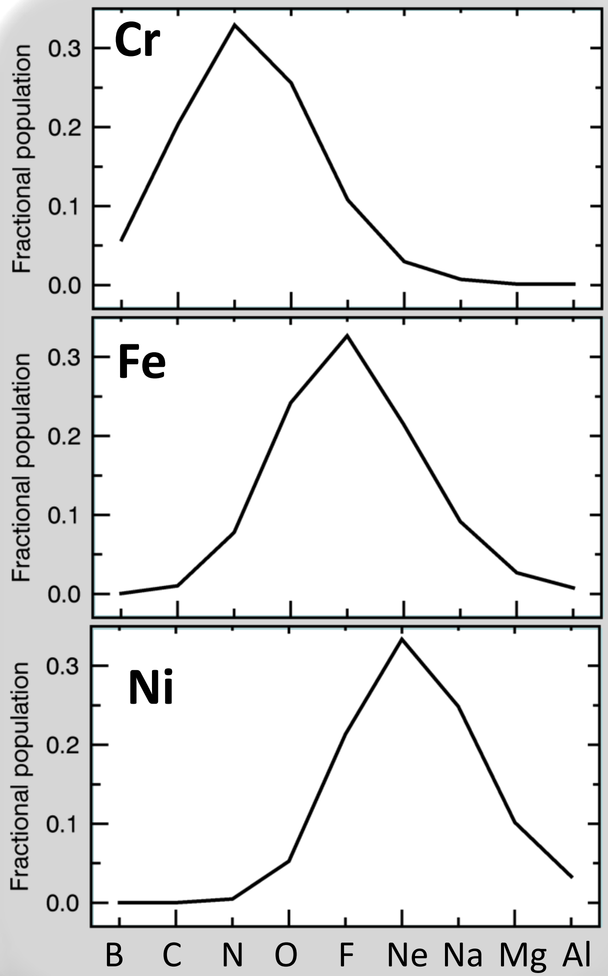
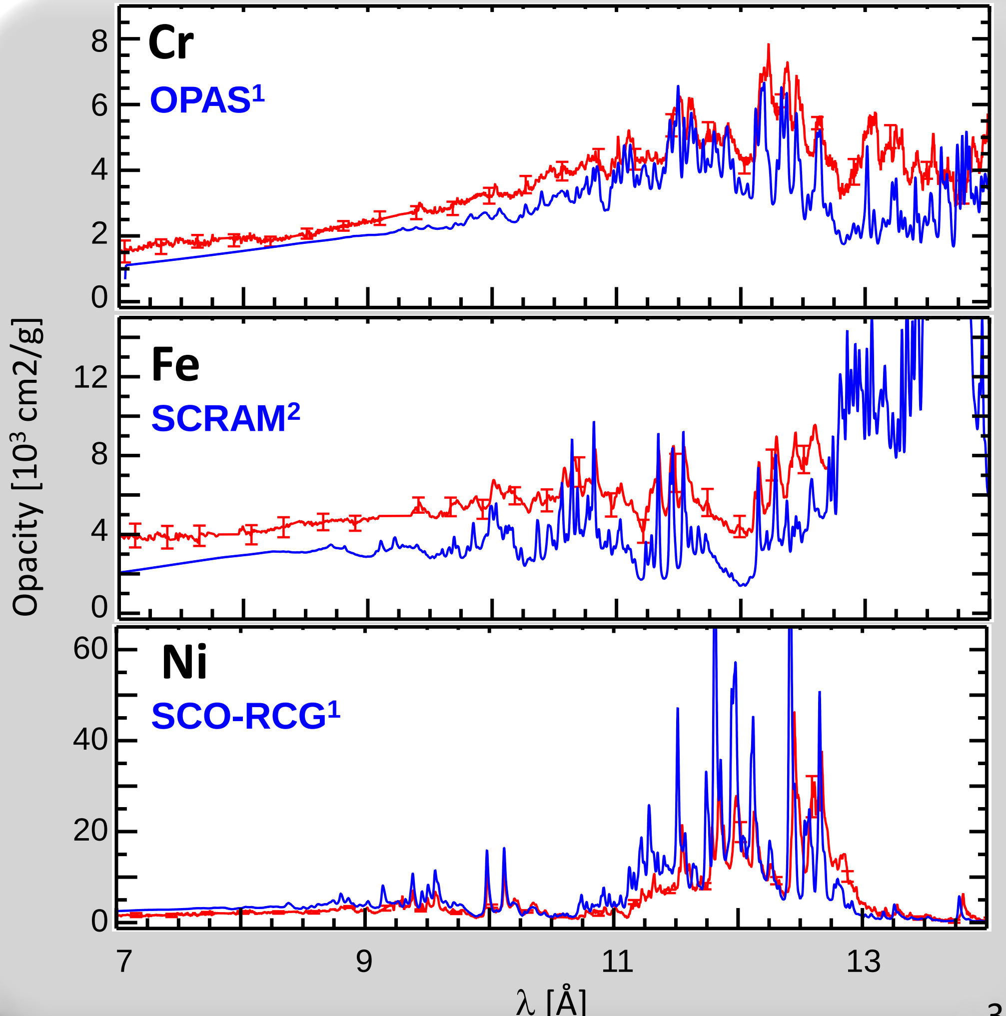
Calculated relative populations



Anchor 2 (185 eV, 3e22 e/cc)



[1]Blancard et al., Astrophys. J. (2012) [2]Hansen et al., HEDP (2007) [3]Porcherot et al., HEDP (2011)

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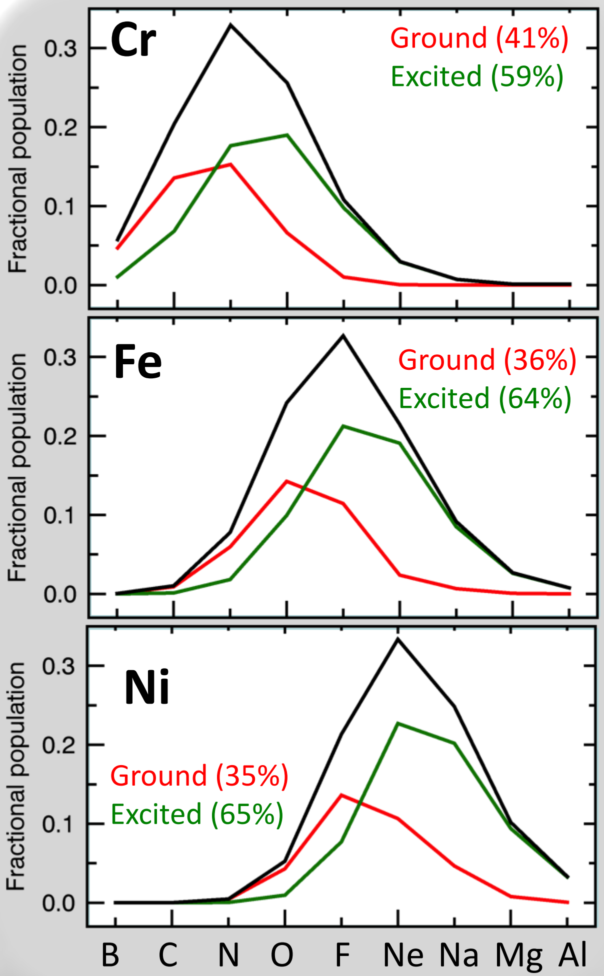
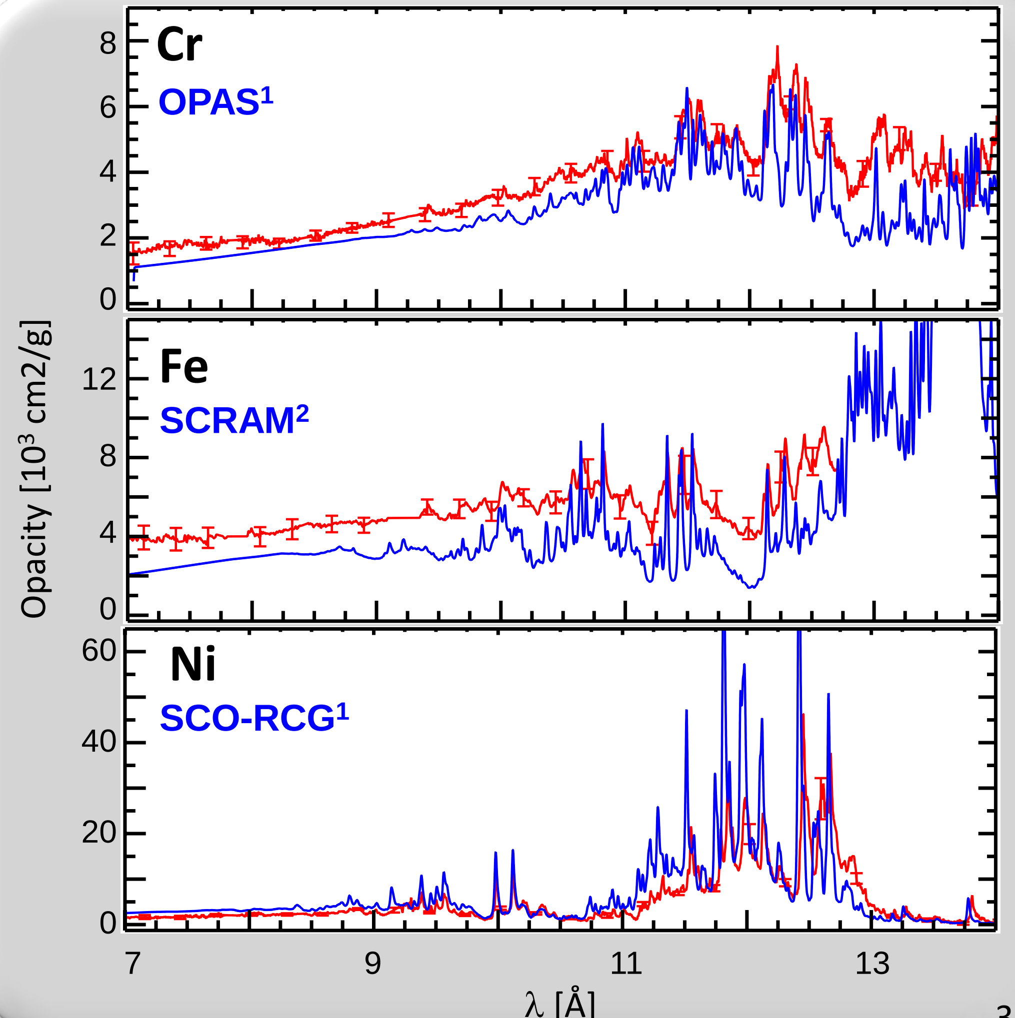


Anchor 2 (185 eV, 3e22 e/cc)



[1]Blancard et al., Astrophys. J. (2012) [2]Hansen et al., HEDP (2007) [3]Porcherot et al., HEDP (2011)

We will continue to scrutinize these results and extend the measurements. Future work will include:

- Additional Ni and Cr measurements for improved confidence and precision.
  - Additional material thicknesses to complete Beers-law scaling and validate reproducibility of the results
- Time-gated opacity measurements to rule-out any late-time effects such as long-lived sample self-emission or other plasma emission that contributes to the background.
  - Each of these effects results in an increase of the measured transmission (decrease in inferred opacity)
  - Also validate time-dependent simulations of sample evolution
- Multi-dimensional radiation-hydrodynamics simulations including the integrated z-pinch source formation, sample heating, and backlighting.
  - Search for effects we aren't presently considering
- Complementary experiments on the NIF.
  - First measurements of Fe at Anchor 1 scheduled for FY17, Anchor 2 in FY18.

Summary: A first-ever systematic study of L-shell opacity is underway and will provide new understanding of atomic processes in hot, dense plasmas.

- Experiments on Z measure the opacity of materials at conditions similar to the base of the solar convection zone.

- Models of iron opacity agree with Z data at some conditions, but show disturbing disagreement at increased Te and ne.

Anchor 1	Anchor 2
[160 eV, 7E21 e^-/cc]	[185 eV, 3e22 e^-/cc]

- New measurements of nickel and chromium opacity support the accuracy of previous iron data and provide important clues on data-model discrepancies.