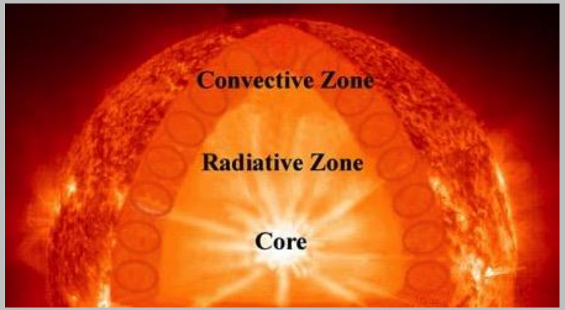
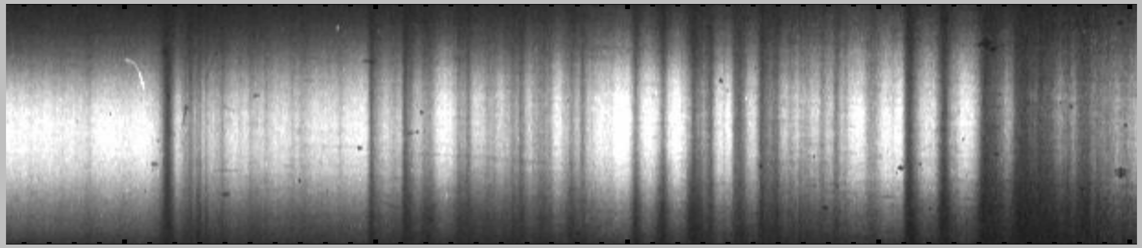
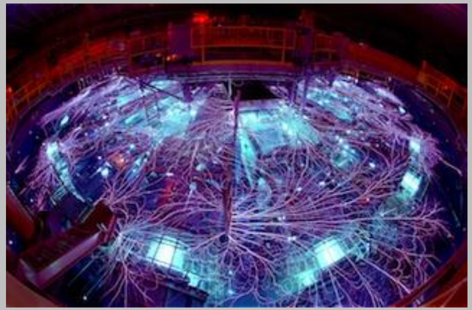
SAND2017-11322C

Exceptional service in the national interest

Sandia National Laboratories







Opacity data for stellar models and its uncertainties

Jim Bailey

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

APS Division of Plasma Physics, October 23, 2017, Milwaukee, Wisconsin

The stellar opacity collaboration involves universities, U.S. national labs, a private company, the French CEA, and the Israeli NRCN laboratories

J.E. Bailey, T. Nagayama, G.P. Loisel, G.A. Rochau, S.B. Hansen, G.S. Dunham, R. More
Sandia National Laboratories, Albuquerque, NM, 87185-1196

C. Blancard, Ph. Cosse, G. Faussurier, F. Gilleron, J.-C. Pain
CEA, France

A.K. Pradhan, C. Orban, and S.N. Nahar
Ohio State University, Columbus, Ohio, 43210

C.A. Iglesias and B. Wilson
Lawrence Livermore National Laboratory, Livermore, CA, 94550

J. Colgan, C. Fontes, D. Kilcrease, and M. Sherrill
Los Alamos National Laboratory, Los Alamos, NM 87545

J.J. MacFarlane and I. Golovkin
Prism Computational Sciences, Madison, WI

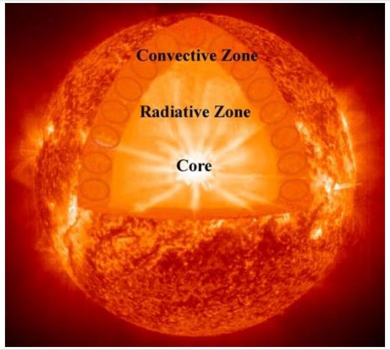
R.C. Mancini
University of Nevada, Reno, NV

Y. Kurzweil and G. Hazak
Nuclear Research Center Negev, Israel

Opacity experiments at the Z facility refine our understanding of photon absorption in high energy density stellar matter.

Sandia National Laboratories

- **Measured iron opacity at near-solar-interior conditions is higher than predictions**
  → helps resolve the solar problem, but we need to understand what causes the discrepancy

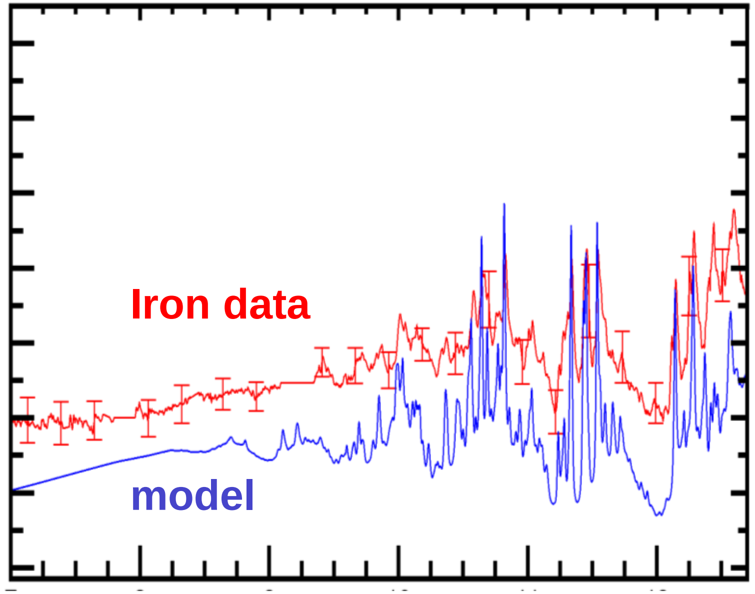


Opacity model questions:

- **Multi-photon absorption**
- **Density effects**
- **Atomic structure and populations**

Experiment questions:

- **Transmission accuracy**
- **Temporal evolution**
- **Plasma diagnostics**

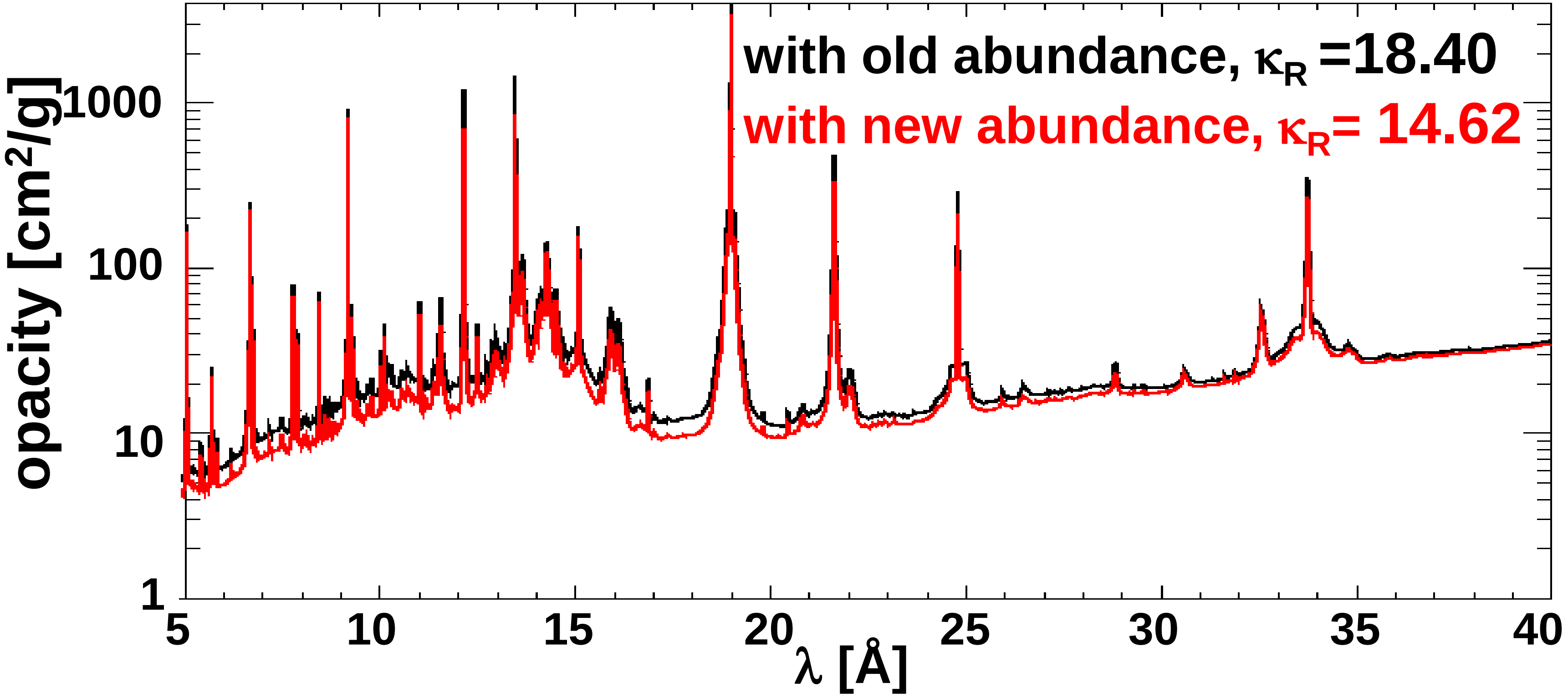


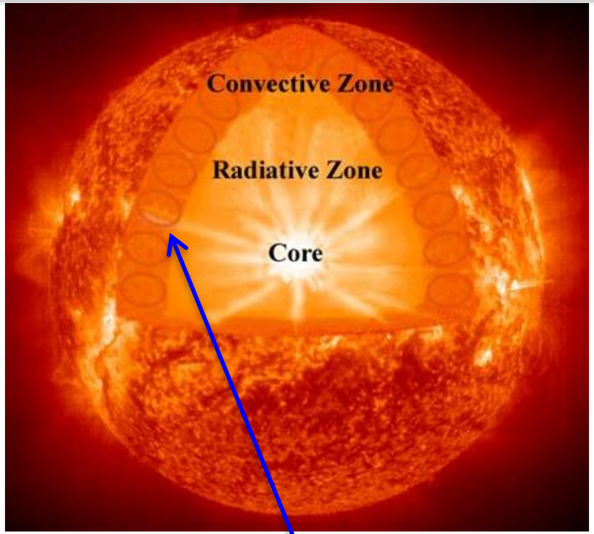
A systematic examination of Cr, Fe, and Ni opacity can help answer these questions

The solar problem could be resolved if the true mean opacity for solar matter is 10-30% higher than predicted

Sandia National Laboratories

Solar mixture opacity at Convection Zone Base (CZB)

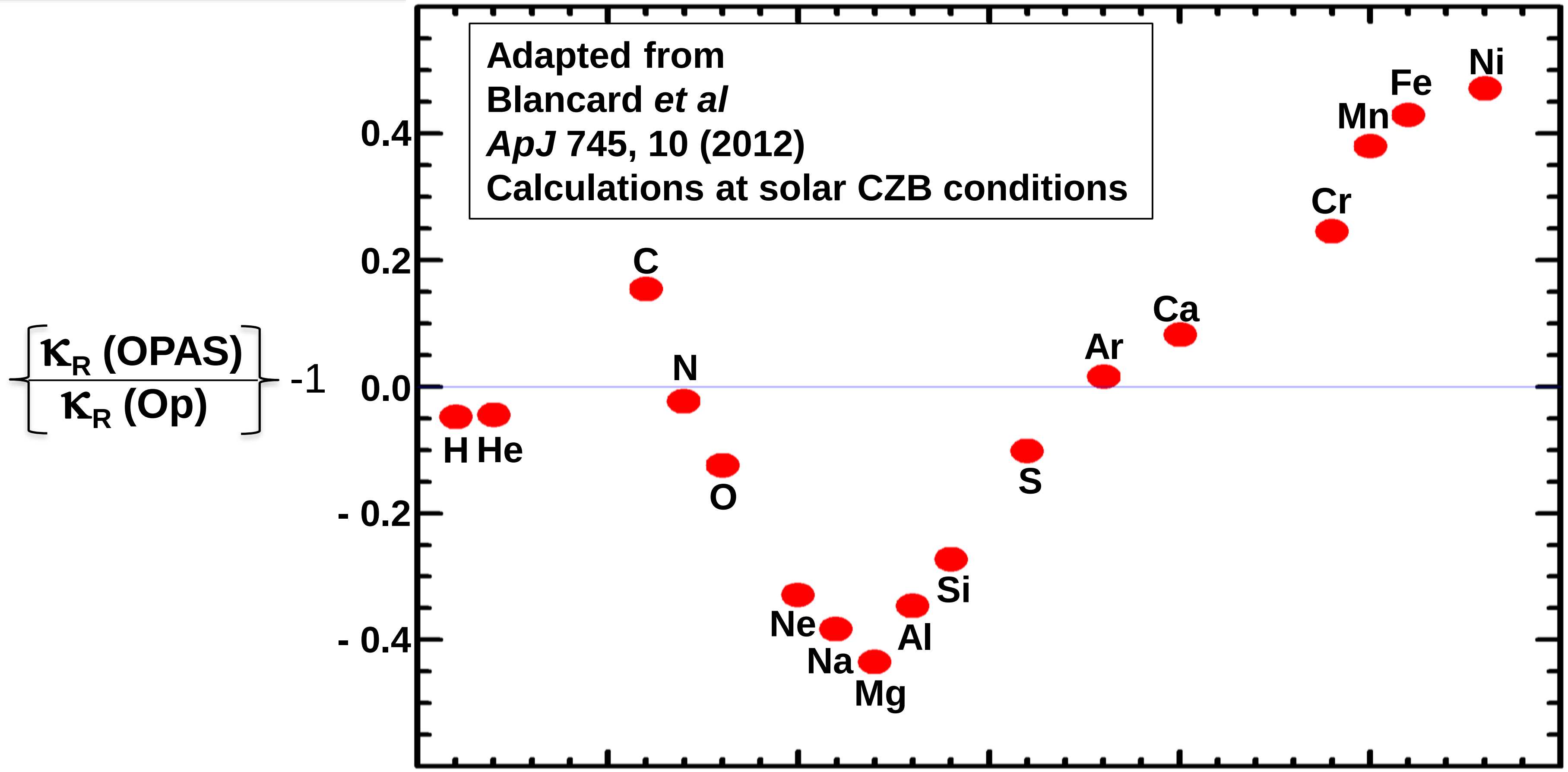




CZB condition:
T_e=182 eV
n_e=9x10^{22} cm^{-3}

Revised abundances reduce amounts of some elements, lead to lower total opacity
This causes disagreements between helioseismology and solar models
Agreement is restored if we assume opacity is higher than predicted – but is this correct?

Complexities create uncertainties in opacity models that are best to address by comparison with experiments



Rosseland mean opacity (κ_R) predictions from OPAS and OP differ by up to ~45% for individual elements

Solar mixture κ_R predicted by these models agrees – but this appears to be partly coincidence

Multiple entangled physical processes create uncertainty in opacity model predictions

Sandia National Laboratories

Multi-Photon Absorption

- Scales with (principal quantum number)^8
- spectral irradiance critical
- More *HEDP* 2017

Line Broadening

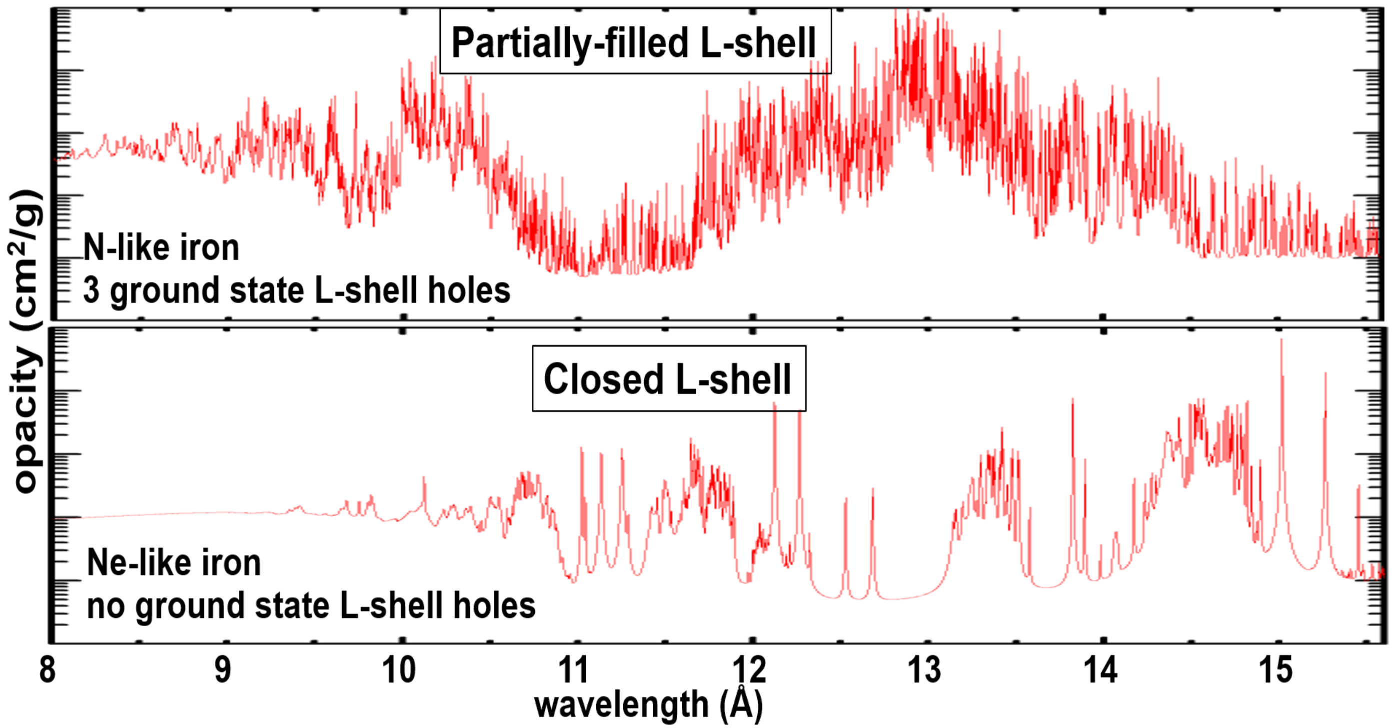
- L shell models un-tested at stellar interior conditions
- Mancini *J Phys* 2016; Krief *ApJ* 2016

Continuum Lowering

- Affects ionization, populations
- Ciricosta *PRL* 2012, Hoarty *PRL* 2013, Crowley *HEDP* 2014, Hansen *HEDP* 2017

Energy Level Structure and Completeness

Multiply-Excited States

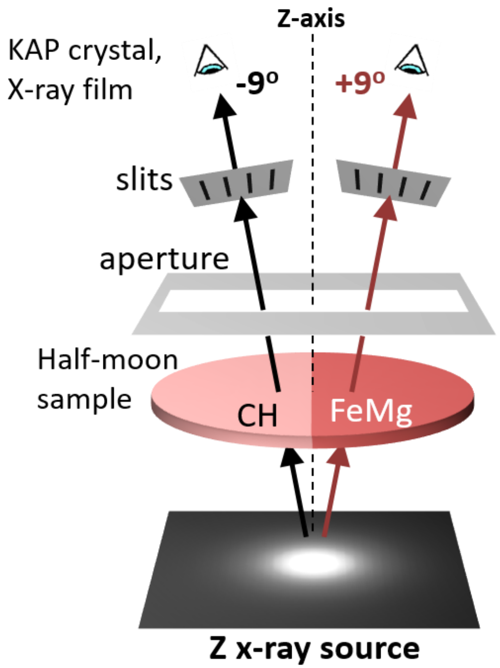


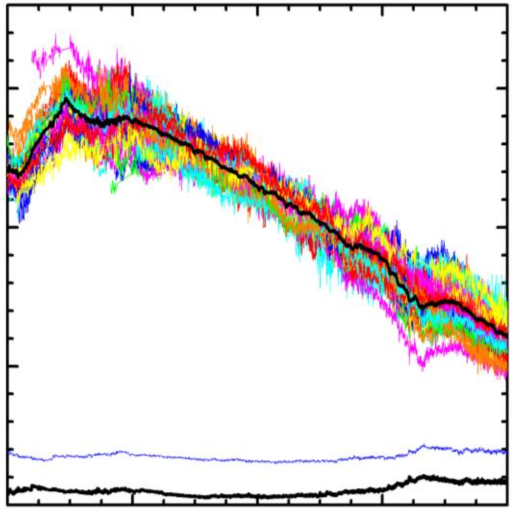
PrismSPECT, iron in CZB

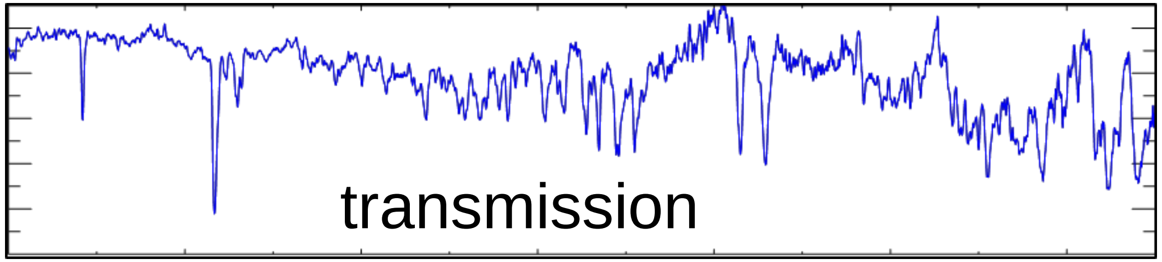
Complexity of L shell ions makes solar interior opacity calculations challenging

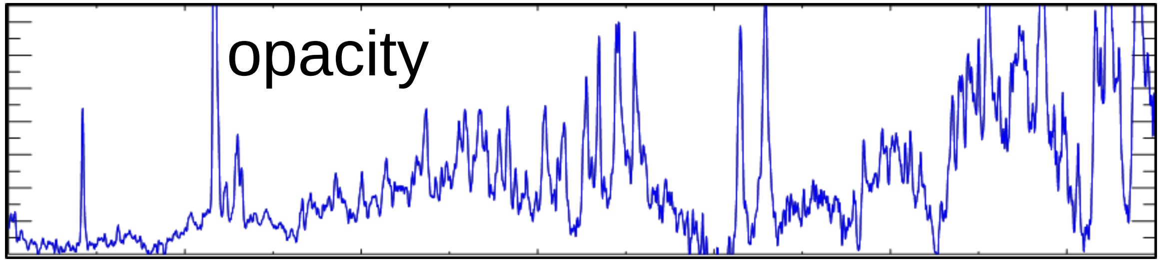
An extensive collection of methods has been developed to measure monochromatic stellar interior opacity

- 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









Benchmark quality opacity experiment requirements are demanding

Sandia National Laboratories

<u>Experiment requirements:</u>

1. Accurate transmission measurements (~ ± 5%)
2. Demonstrated uniformity – spatial and temporal
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

Z experiments meet these requirements, but the degree to which they do so can always be improved

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

Benchmark quality opacity experiment requirements are demanding

Sandia National Laboratories

Experiment requirements:

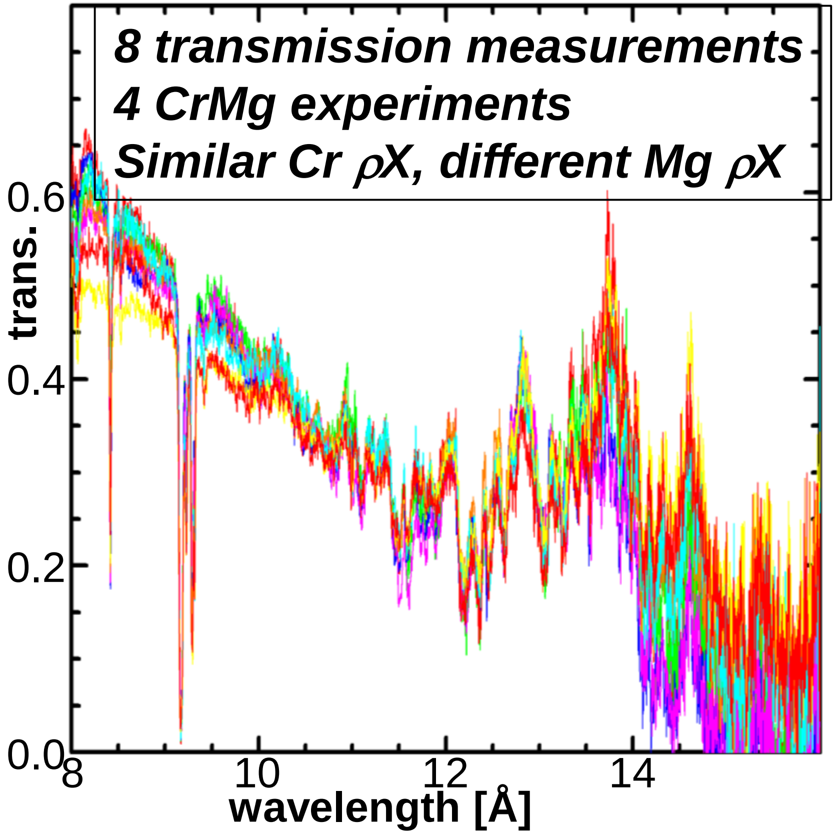
1. **Accurate transmission measurements (~ ± 5%)**
2. **Demonstrated uniformity – spatial and temporal**
3. **Reliable plasma diagnostics**
4. **Freedom from self emission**
5. **Freedom from background contamination**
6. **Multiple areal densities (for dynamic range and systematic error tests)**
7. **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**

Z experiments meet these requirements, but the degree to which they do so can always be improved

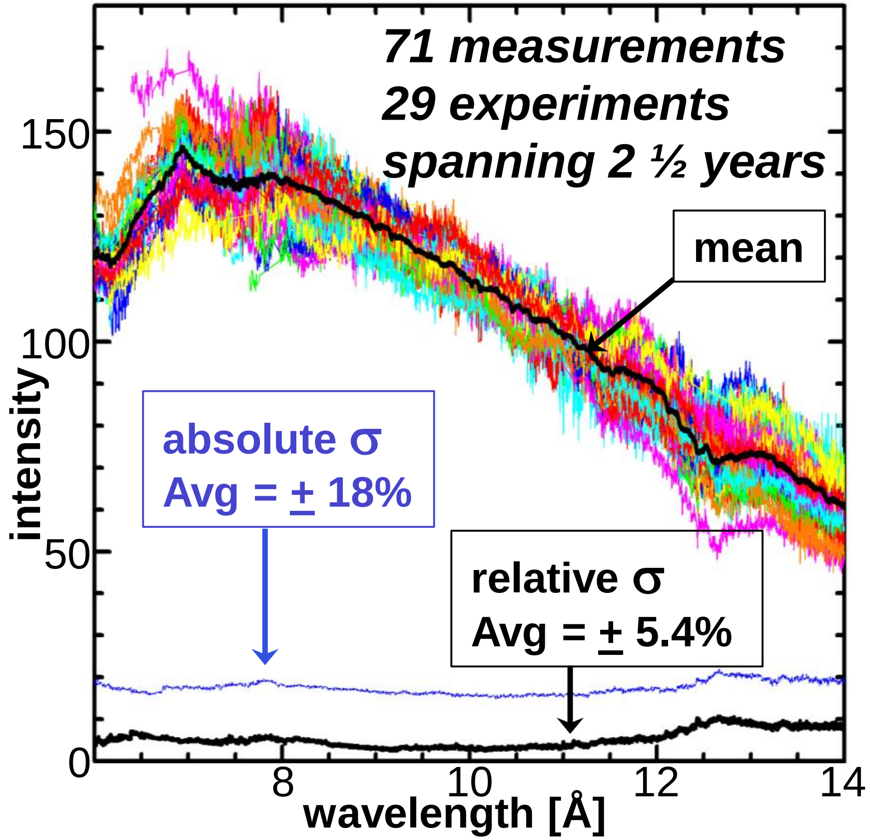
Bailey *et al*., Phys Plasmas 16 (2009)

A growing data set accumulated over years of experiments enables refined transmission accuracy tests

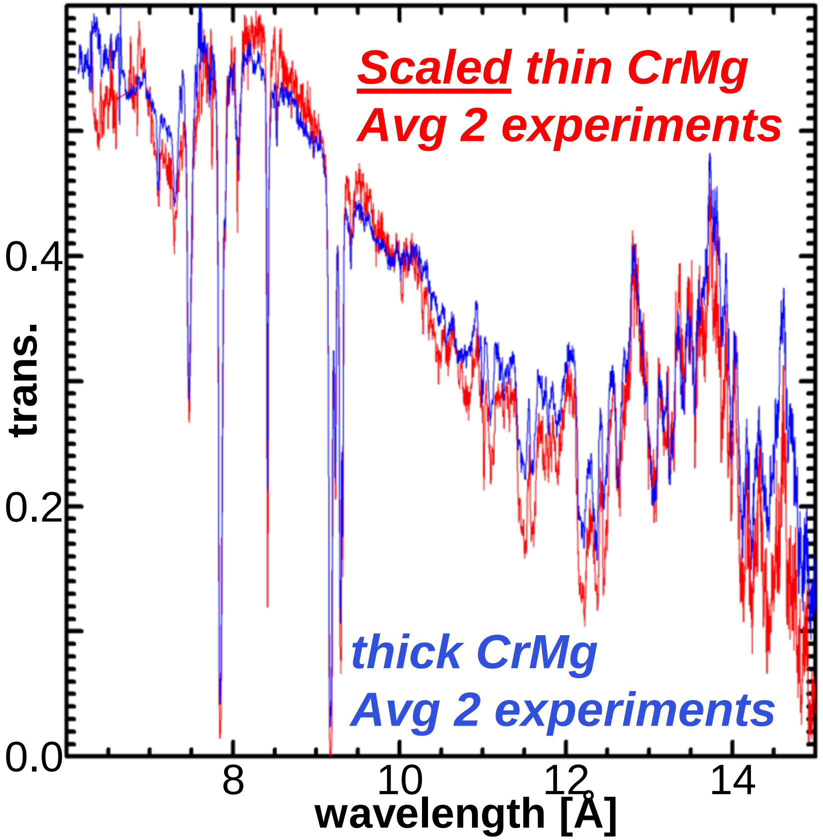
transmission reproducibility



tamper only calibrations



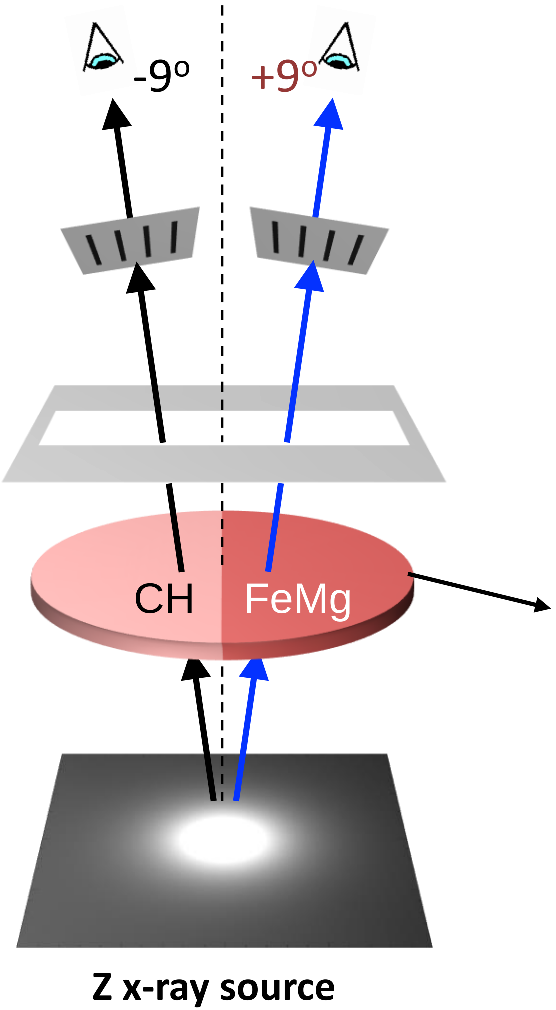
Beer's Law scaling

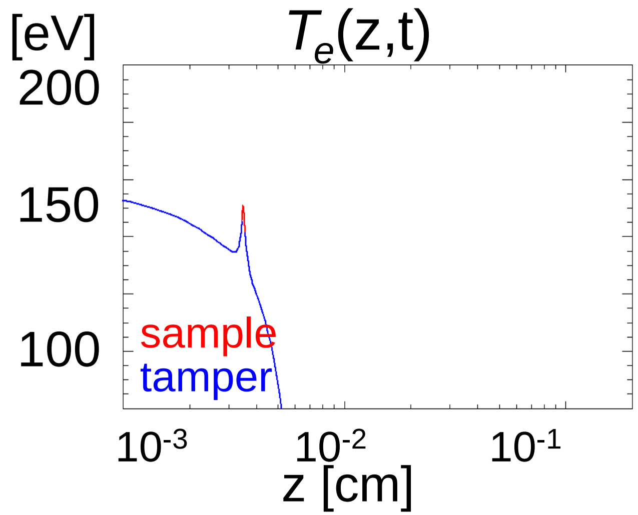


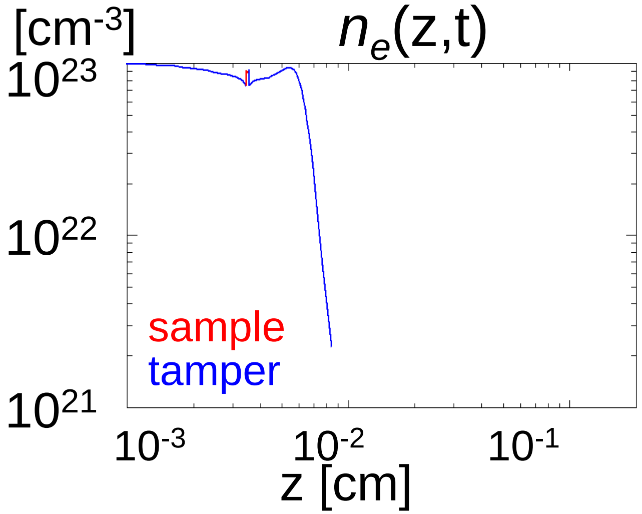
- **The non linear opacity-transmission relation makes transmission accuracy an ongoing concern**

Opacity: $\kappa_\nu = -\ln T_\nu / \rho L$; so $d\kappa_\nu / \kappa_\nu \propto [1/\ln T_\nu]\,[\delta T_\nu / T_\nu]$

Simulations that match temperature and density measurements predict temporal gradients are negligible

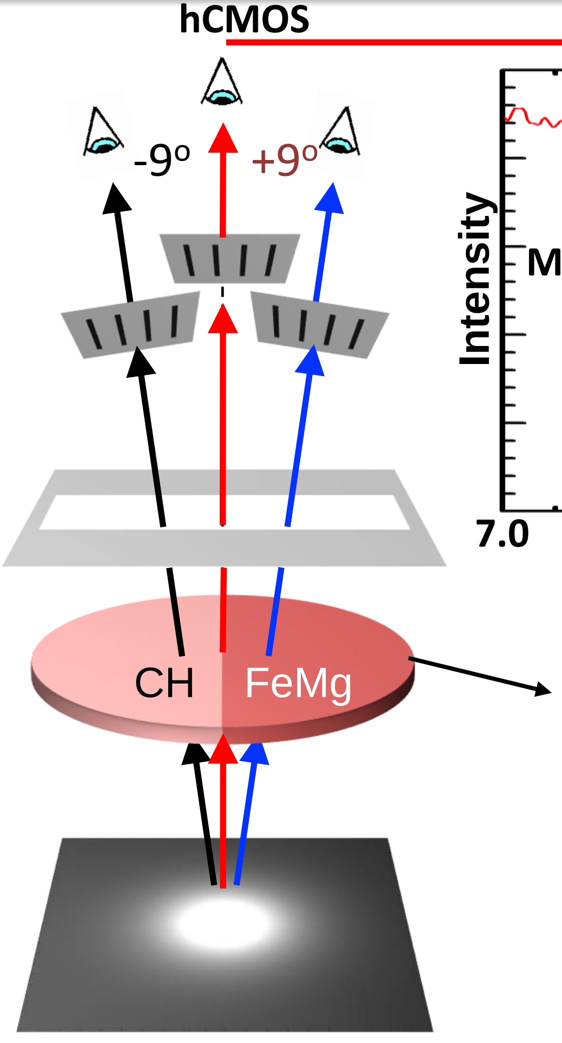


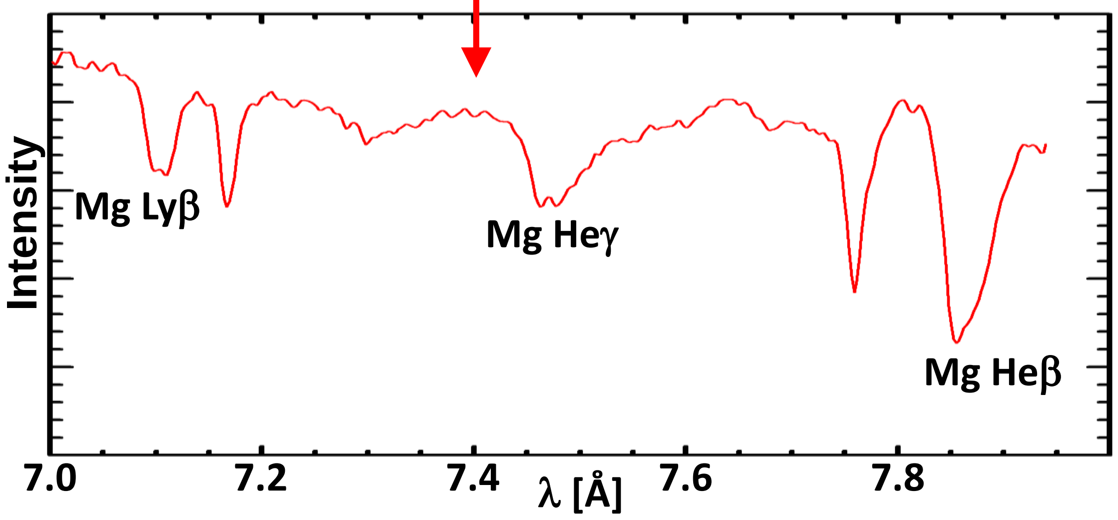




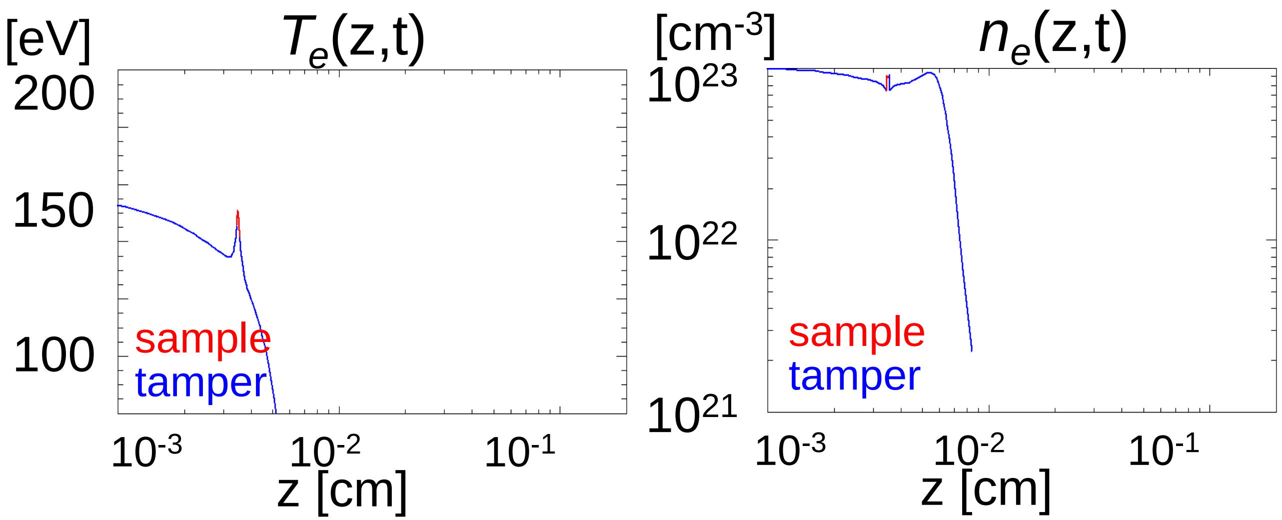
Simulation predictions Nagayama *Phys Rev E* 2016, 2017

Time dependent spectral measurements can test whether temporal effects are as small as simulations predict





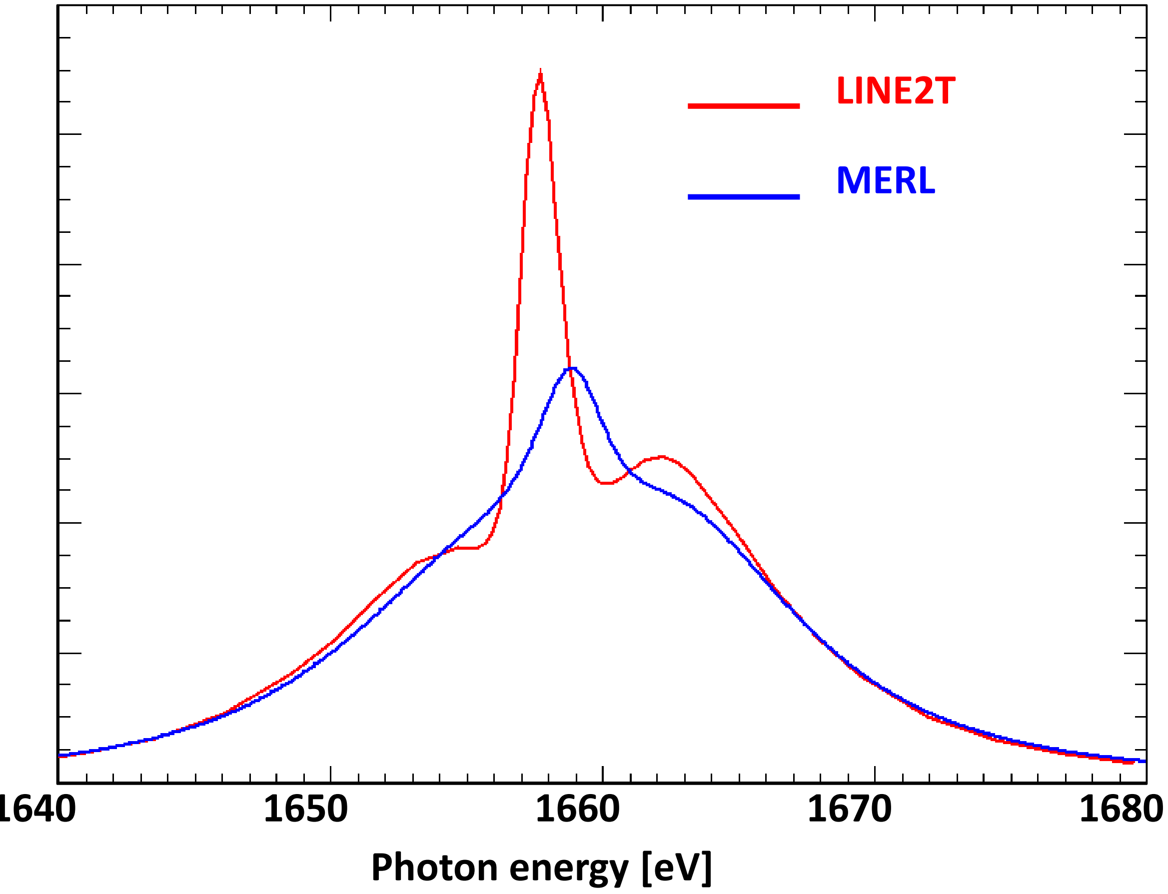
- First time resolved absorption spectra from Z opacity sample
- Recorded with h-CMOS detector
- Demonstrates possibility to measure temporal evolution of T_e and n_e



Simulation predictions Nagayama *Phys Rev E* 2016, 2017

Line broadening model examination is needed to reduce plasma diagnostic uncertainty

Mg Heγ line shape at n_e=4e22 e/cc



- **Different widely-used line broadening models cause inferred density to change by ~1.5x**
- **Experiments are needed to resolve this question**
- **Heeter & Perry et al, NIF; Lane et al, WVU**

	LINE2T	MERL
Extended basis set	NO	YES
Electron broadening*	Dielectric constant	Gaunt factor

Nagayama et al., *High Energy Density Physics* (2016)
Iglesias, *High Energy Density Physics* (2016)
Springer, Perry *et al*
Rad. Prop. Hot Dense Matter 1991 proceedings

This model-dependence does not eliminate the iron opacity model-data discrepancy, but it might help reduce it

LINE2T: R. W. Lee, JQSRT (1988). **MERL: R. C. Mancini et al, Comput. Phys. Commun. (1991).**

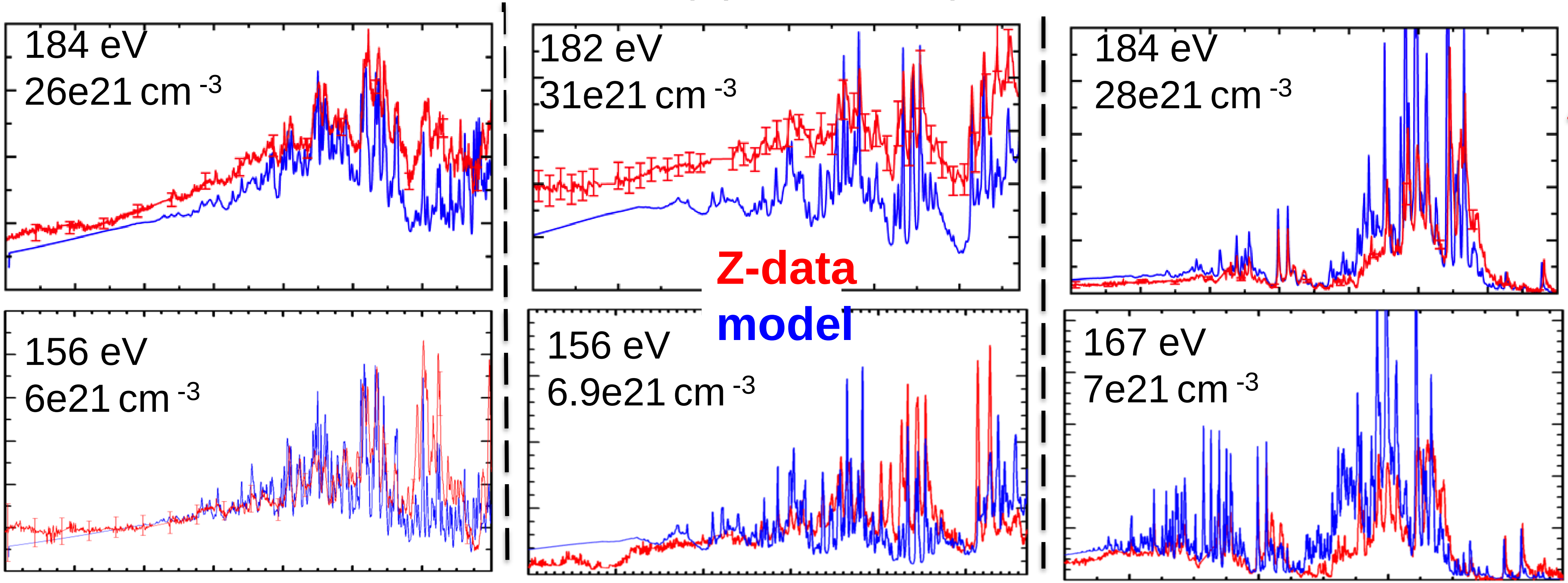
Systematic opacity experiments can test hypotheses for model data discrepancies

Sandia National Laboratories

fewer L-shell vacancies, smaller # of excited states, less Stark broadening →

Chromium (More open L-shell) | Iron (open L-shell) | Nickel (closed L-shell)

Increased T_e and n_e ↑



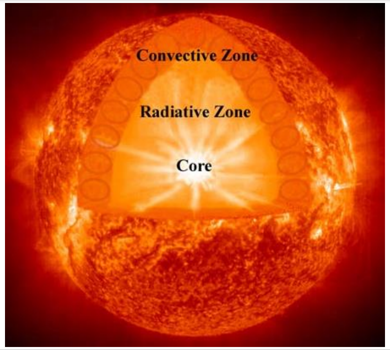
Increased broadening, excited populations ↑

Increased Atomic Number →

Opacity experiments at the Z facility refine our understanding of photon absorption in high energy density stellar matter.

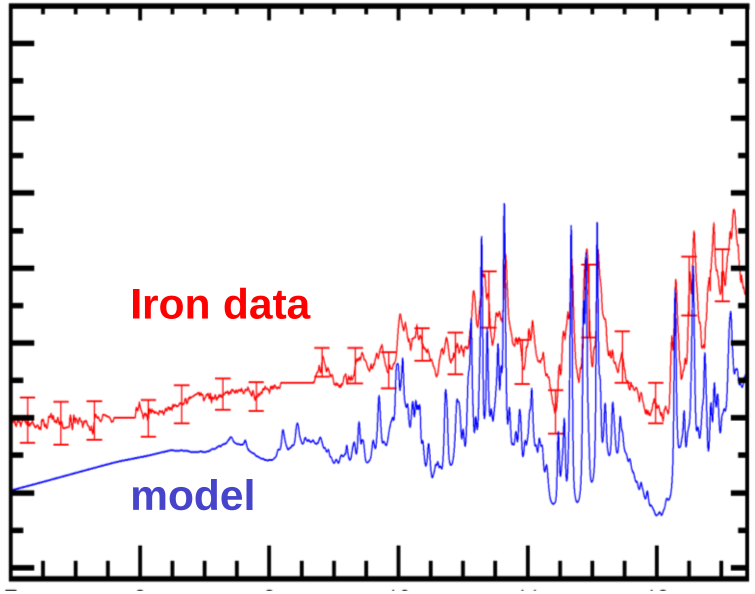
Sandia National Laboratories

- **Measured iron opacity at near-solar-interior conditions is higher than predictions**
  → helps resolve the solar problem, but we need to understand what causes the discrepancy



<u>Opacity model questions:</u>

- **Multi-photon absorption**
- **Density effects**
- **Atomic structure and populations**



<u>Experiment questions:</u>

- **Transmission accuracy**
- **Temporal evolution**
- **Plasma diagnostics**

A systematic examination of Cr, Fe, and Ni opacity can help answer these questions