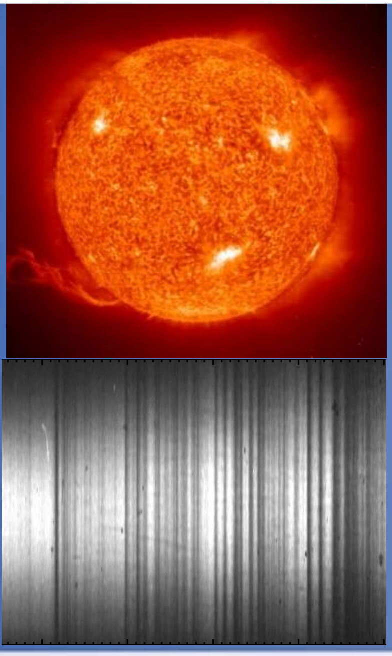
Experimental Astrophysics: Stellar Interior Opacity Measurements



Jim Bailey

Impact of Asteroseismology Across Astrophysics

Santa Barbara, California

October 24, 2011

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.

Many people and institutions contribute to this work

J.E. Bailey, G.A. Rochau, P.W. Lake, S.B. Hansen, T.J. Nash, D.S. Nielsen
Sandia National Laboratories, Albuquerque, N.M., 87185-1196

A.K. Pradhan, M. Pinsonneault, and S.N. Nahar
Ohio State University, Columbus, Ohio, 43210

C.A. Iglesias
Lawrence Livermore National Laboratory, Livermore, CA, 94550

M. Sherrill
Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

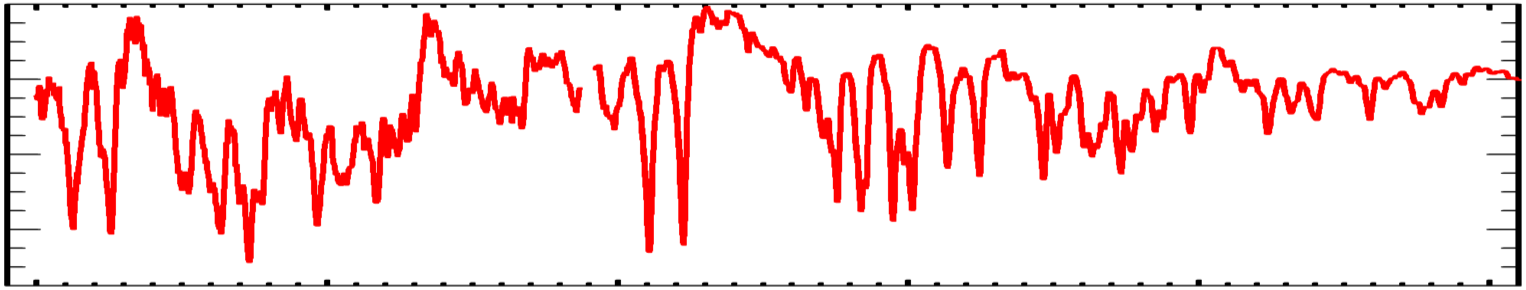
J.J. MacFarlane, I. Golovkin, P. Wang
Prism Computational Sciences, Madison, WI

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

C. Blancard, Ph. Cosse, G. Faussurier, F. Gilleron, J.C. Pain
CEA, DAM, DIF, F-91297 Arpajon, France

Opacity research is on the verge of *creating* and *diagnosing* stellar interior matter on earth

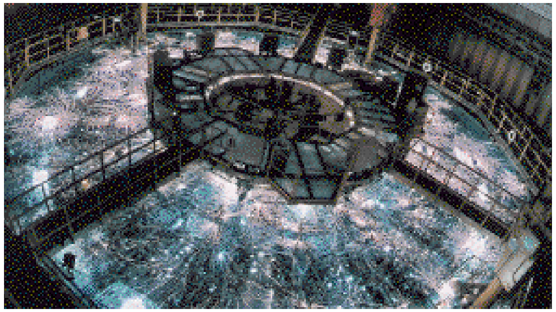
Z experiments study iron charge states and electron configurations found inside stars for the first time.



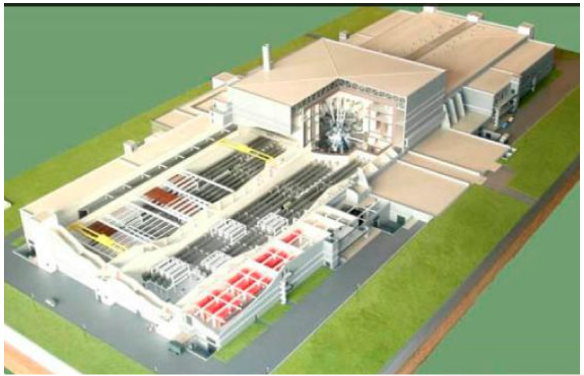
The new generation of HED facilities will allow us to replicate and study a ~ microgram of stellar interior matter

NIF

Z



LMJ

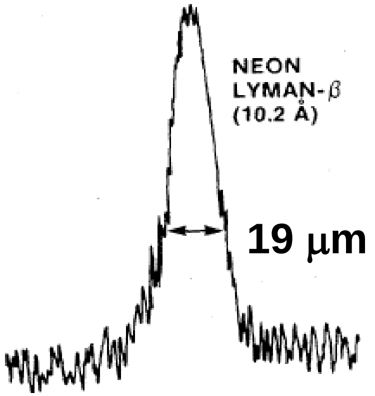


What is new:
Mega-Joule class facilities create *macroscopic enough* quantities of astrophysical matter for detailed studies

High Energy Density experiments have reached extreme conditions for many years

But small size, spatial structure, and short duration hampered material property measurements

In contrast, Z opacity samples are similar in size to a sand grain



laser fusion capsule
(Yaakobi, PRL, 1977)
300 eV, 0.26 g/cc

Creating mm-scale replicas of cosmic matter will strengthen the laboratory foundation of astrophysics

Six fundamental science experiments were awarded time on Z in CY12

Z Astrophysical Plasma Properties (ZAPP) (2 weeks allocated):

1. Stellar interior opacities

(project lead) [SNL/Ohio State/LLNL/CEA]

2. Spectral line formation in White Dwarf Photospheres

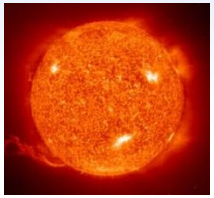
[U. Texas/SNL]

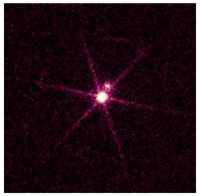
3. Atomic kinetics in warm absorber photoionized plasmas

[U. Nevada Reno/Swarthmore/SNL]

4. Resonant Auger Destruction in Accretion powered objects

[LLNL/UNR/SNL]





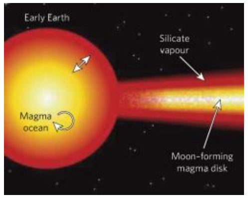
Magnetic field driven experiments:

1. Earth/super earth

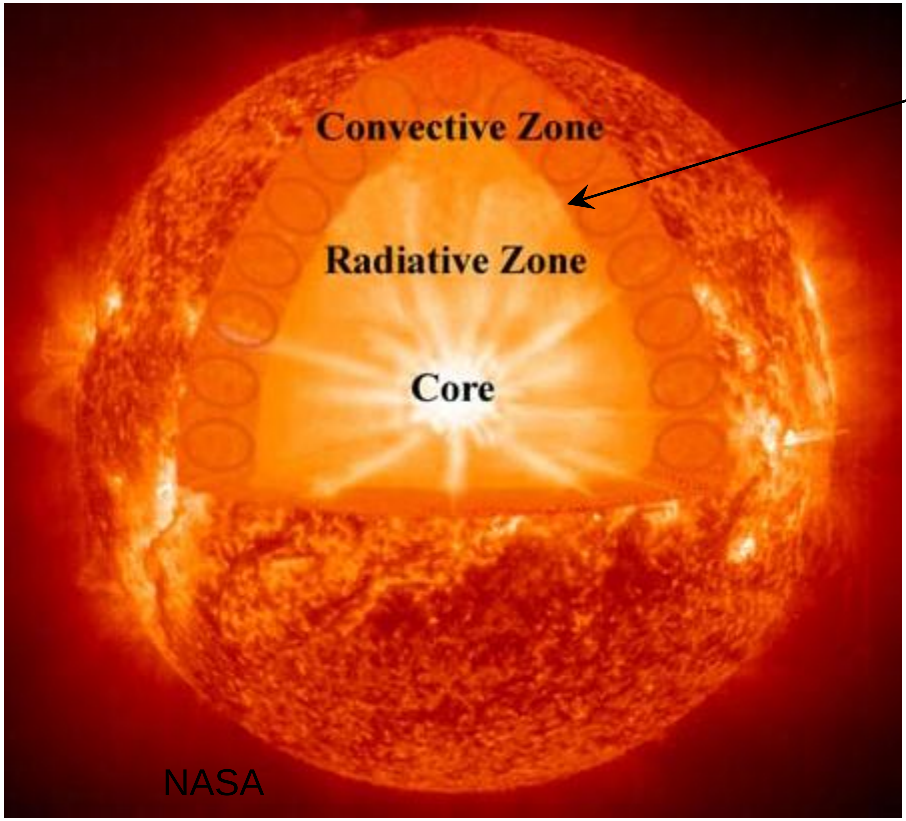
[Harvard/SNL] (1 week)

2. Jovian planet interiors

[U. Rostock/SNL] (1 week)



Models for solar interior structure disagree with helioseismology observations



NASA

Discrepancies in CZ boundary location, C_s (r), and ρ(r)

<u>**Models depend on:**</u>

- **element abundances**
- **EOS**
- **opacity**

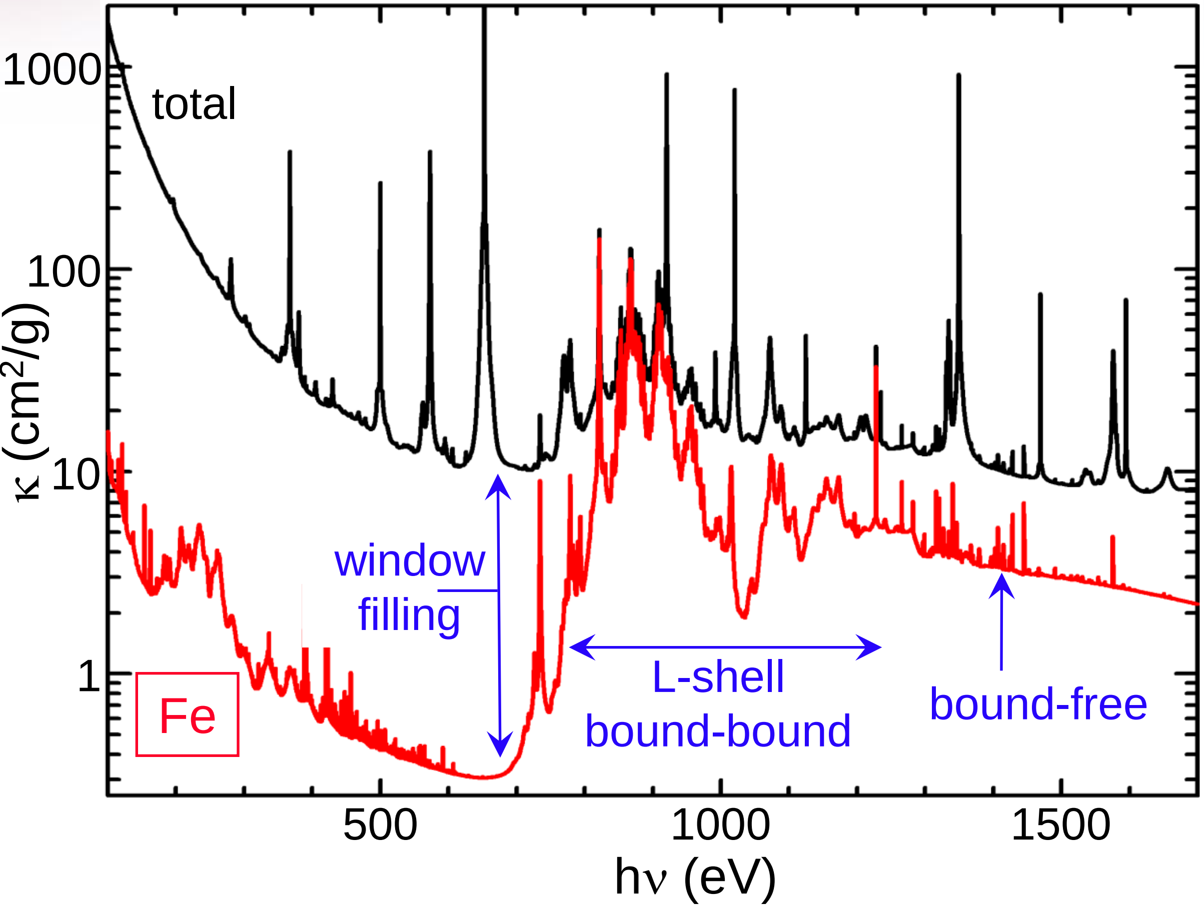
Discrepancies for other stars are appearing as asteroseismology matures

Is opacity uncertainty the cause of the disagreement?

focus: iron at convection zone base

What physics might be a concern for opacity models?

The iron contribution to the CZ base opacity depends on T_e, n_e, and the solar mixture



Opacity Project
Badnell *et al.*,
MNRAS 2005

T_e, n_e determine ionization

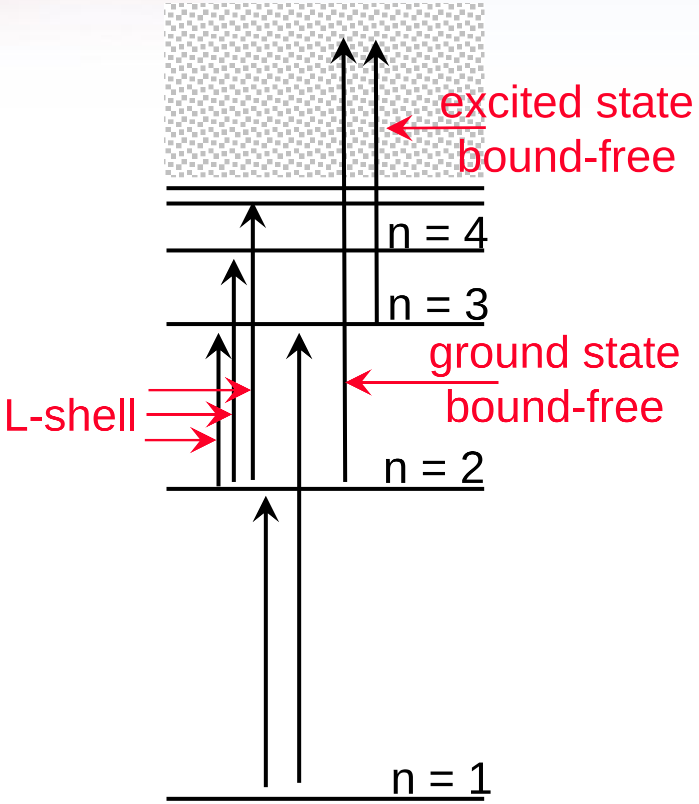
{190 eV, 9e22 e/cc}

Ionization determines which transitions are important

At CZB, dominant charge states are Fe^{+16}, Fe^{+17}, Fe^{+18}

Photons are transported in opacity windows, but windows are filled by other elements

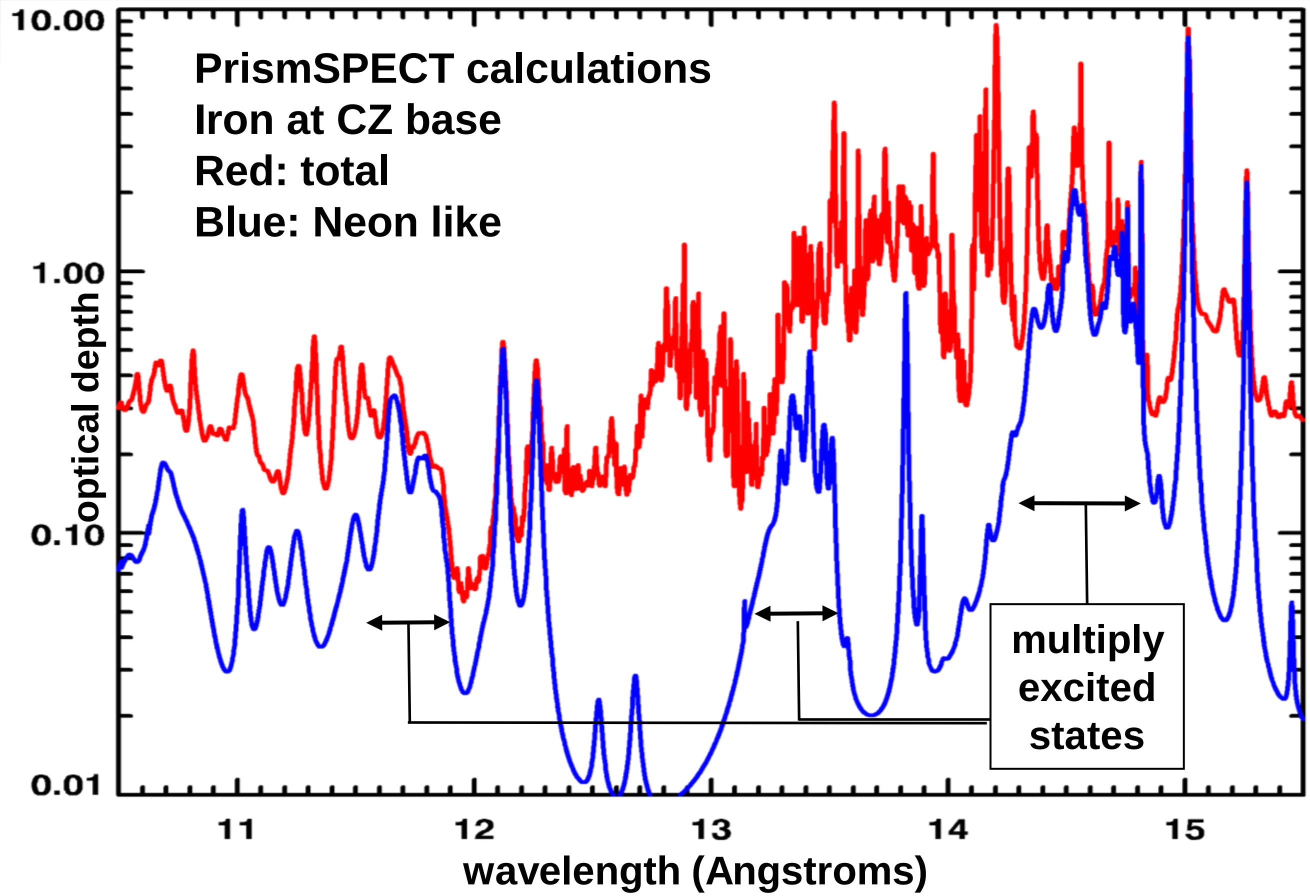
Multiple entangled physical processes are a concern for opacity models



Fe $^{+17}$: $1s^2 2s^2 2p^5$
F-like

- Energy level structure and detail
- Multiply excited states
- Autoionizing levels
- Photoionization
- Line broadening
- Continuum lowering

Accurate and complete descriptions of multiply excited states is an opacity model challenge



PrismSPECT calculations
Iron at CZ base
Red: total
Blue: Neon like

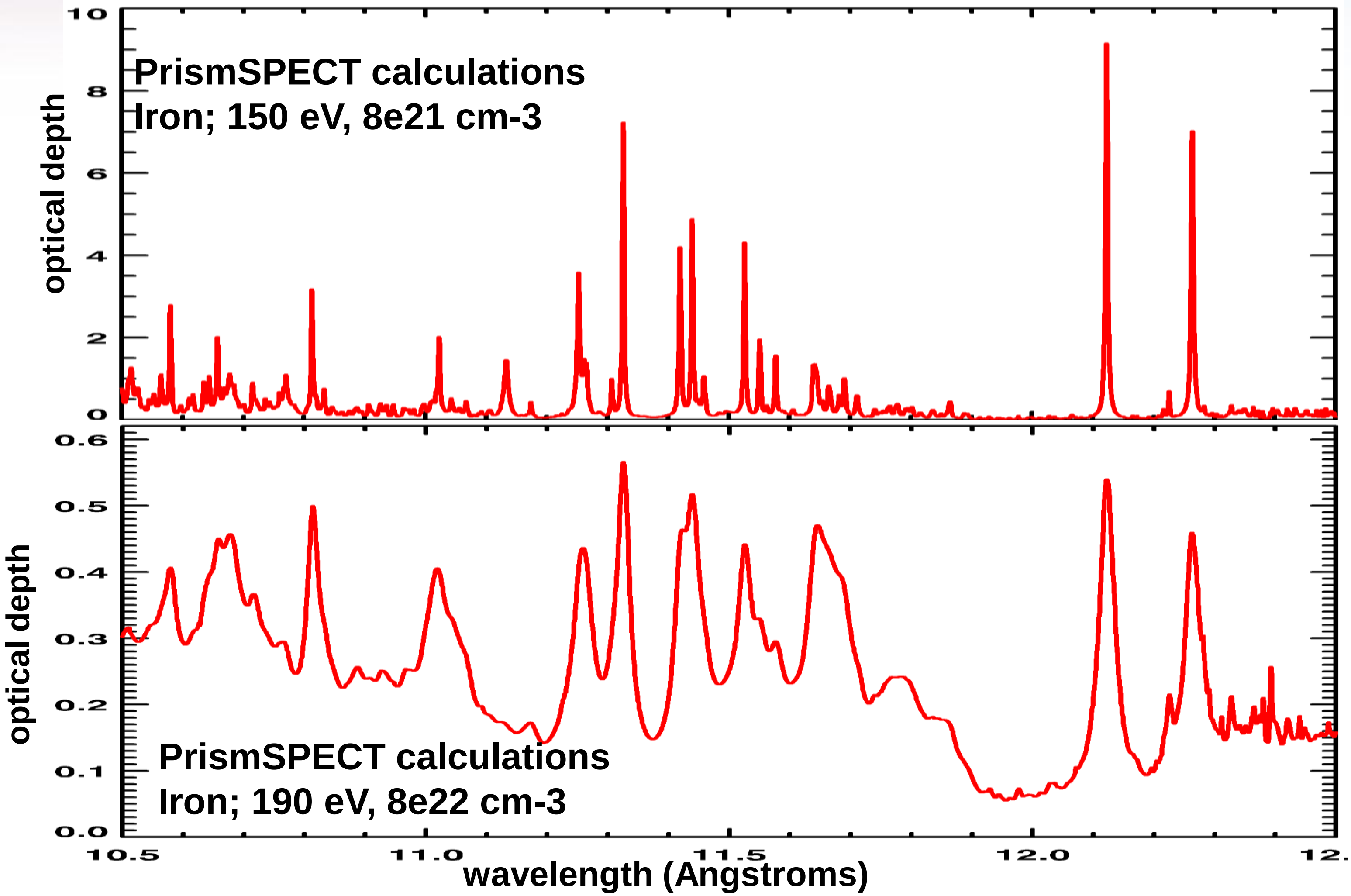
multiply excited states

Fe $^{+16}$: $1s^2 2s^2 2p^6$
Ne-like
<u>Ground state</u>
$1s^2 2s^2 2p^6$ - $1s^2 2s^2 2p^5 3d$

<u>Singly-excited</u>
$1s^2 2s^2 2p^5 3s$ –
$1s^2 2s^2 2p^4 3s 3d$

- **Opacity contributions from multiply excited states are significant**
- **The multitude of possible transitions makes accurate descriptions challenging**

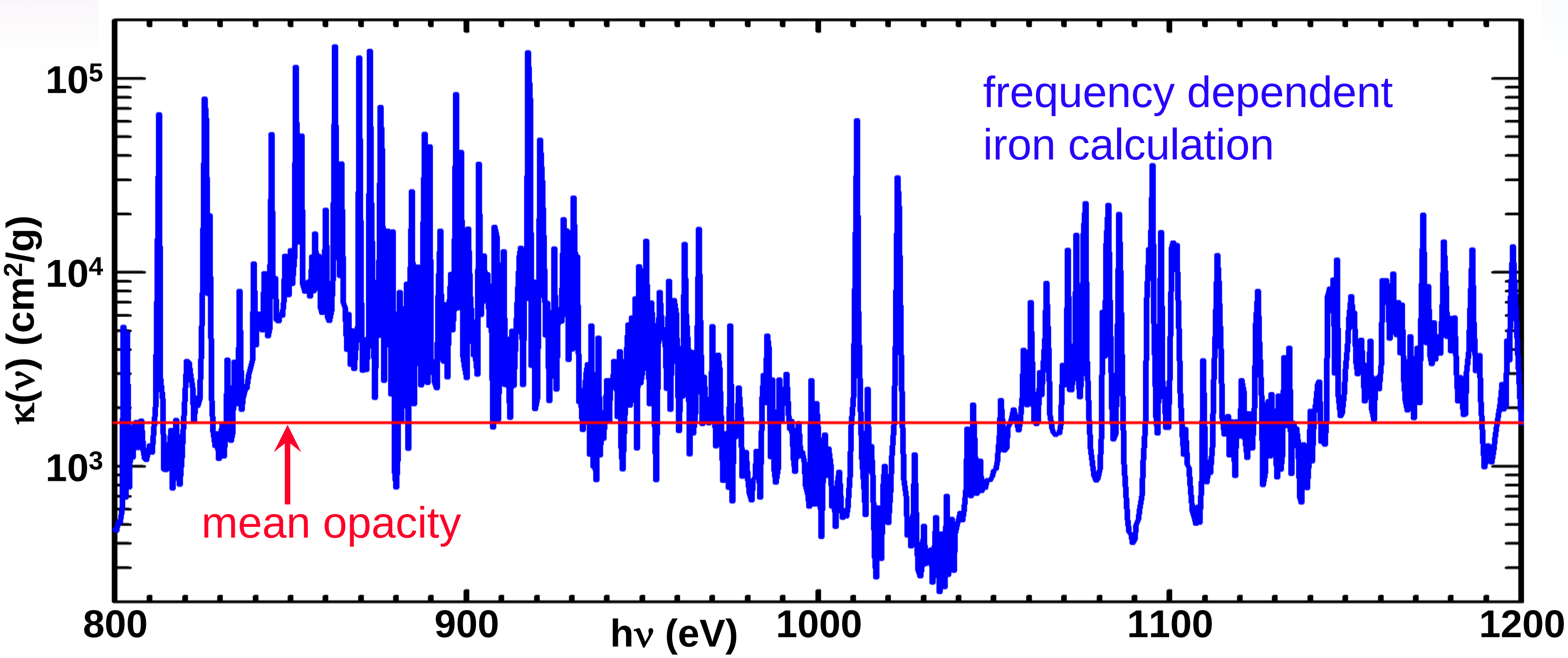
Line broadening strongly influences opacities but models for many-electron ions are untested



- Broadening tends to close the opacity windows between lines
- Modeling high-n and multiply-excited states is a challenge

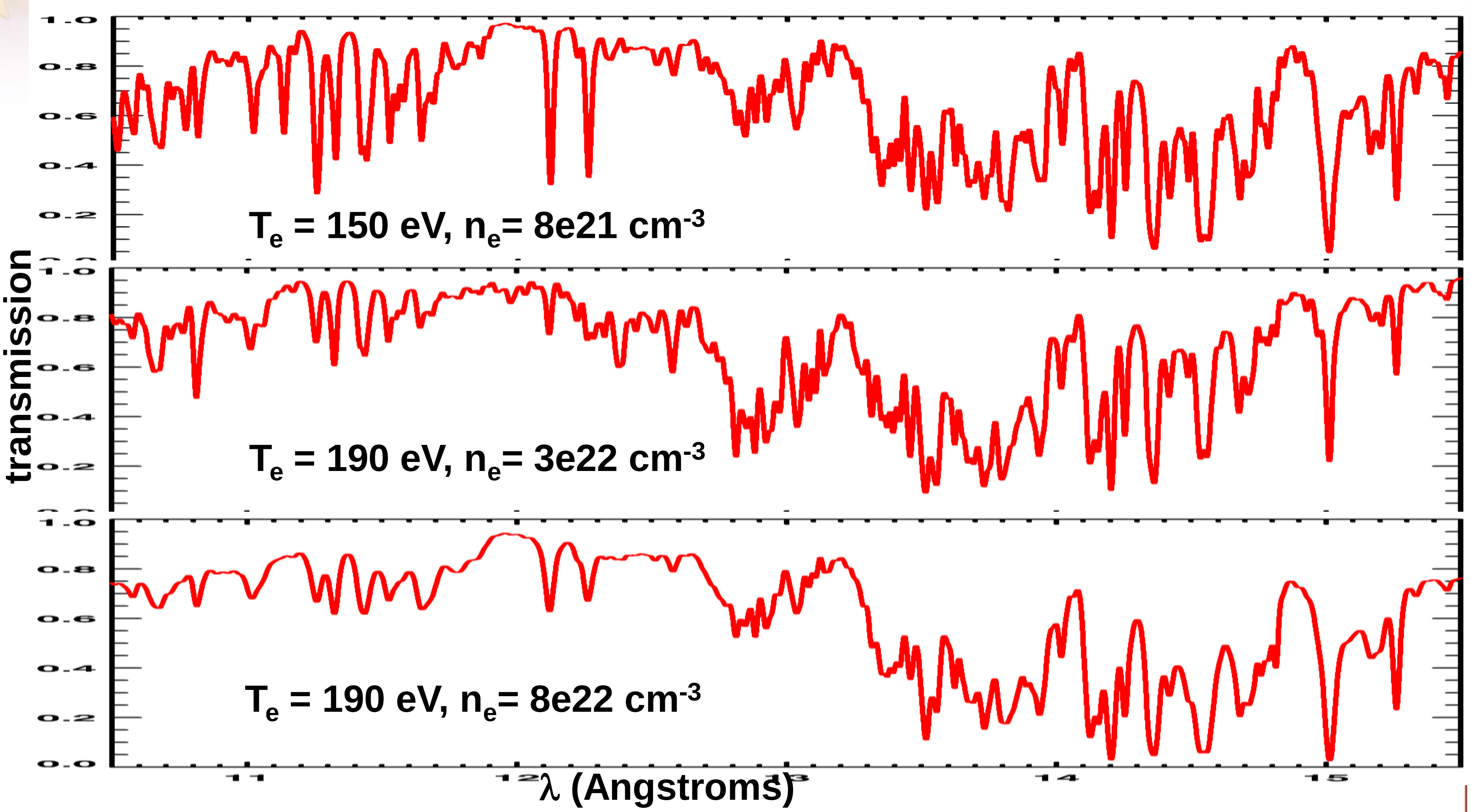
How do we measure opacity?

Strategy: frequency-dependent transmission measurements test opacity model physics



Detailed information about the physical basis for opacity models is encoded in the frequency dependent transmission spectra.

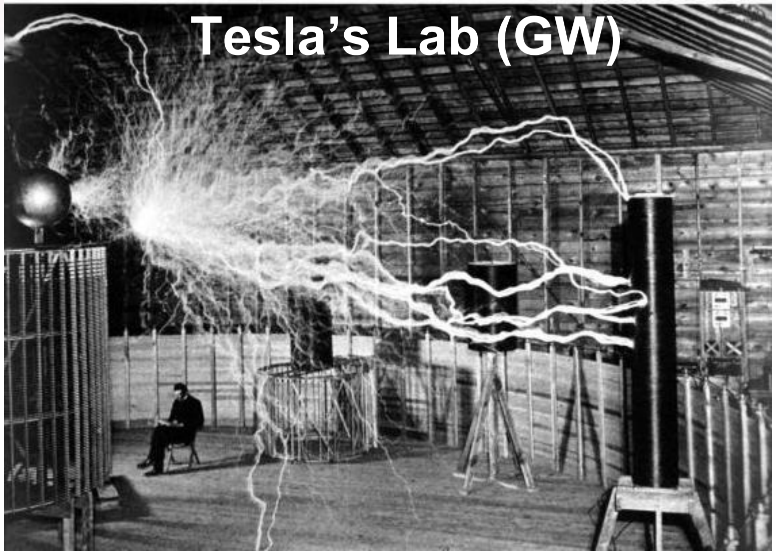
Goal: Test the physical underpinnings of opacity models using data at three T_e/n_e values

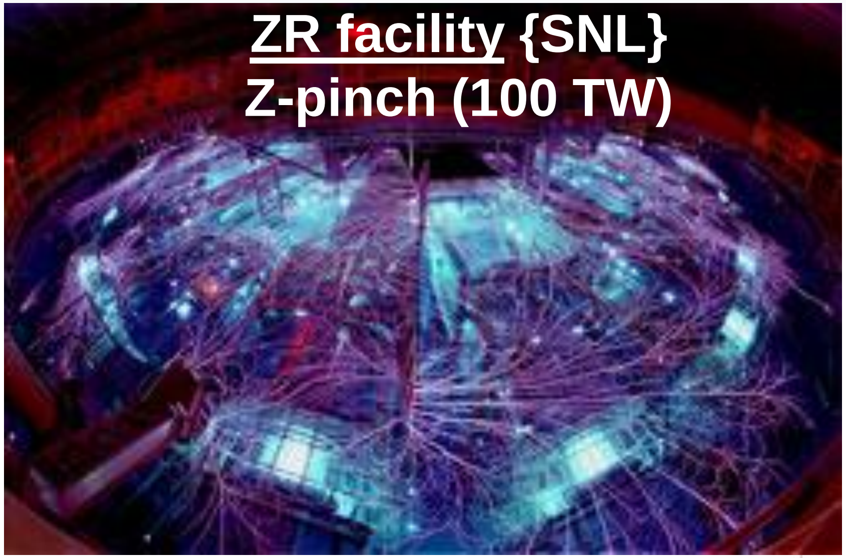


- This promotes our ability to isolate different effects
- The iron calculations shown here were done with PrismSPECT

Sandia
National
Laboratories

The 26 million Ampere current on Z provides access to new laboratory astrophysics regimes



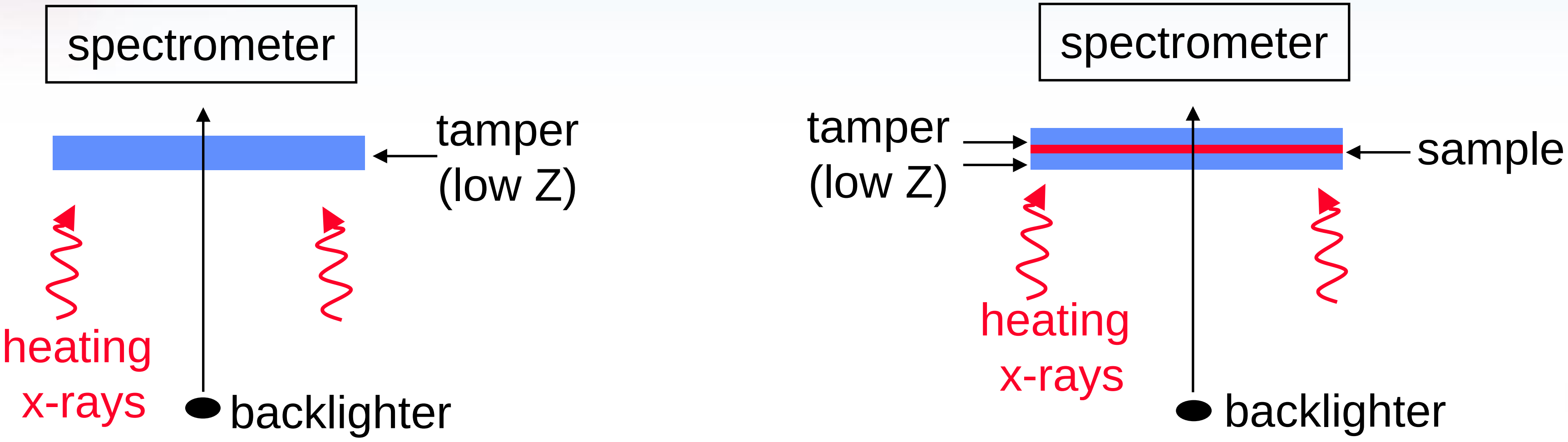


Pulsed Power:

"Take the equivalent energy required to operate a TV for a few hours (1-2 MJ) and compress it into more electrical power than provided by all the power plants in the world combined (~15 TW)" Pai & Zhang 1995.

Z experiments use large magnetic fields or large x-ray flux to create extreme environments

Transmission measurements exploit volumetric x-ray heating and a bright x-ray backlight



spectrometer

tamper
(low Z)

heating
x-rays

backlighter

spectrometer

tamper
(low Z)

sample

heating
x-rays

backlighter

Backlit spectra with and without sample determine transmission

<u>Opacity experiment requirements:</u>

1) Uniform sample plasma

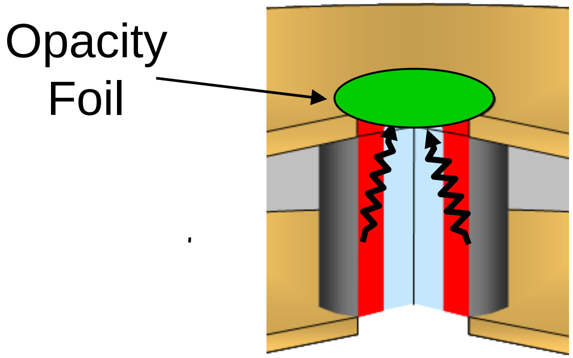
2) Accurate transmission measurements

3) Plasma diagnostics – mix Mg & Fe

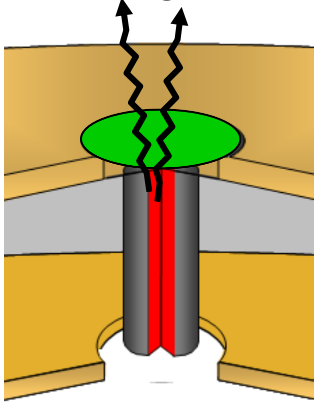
T.S. Perry *et.al.* Phys. Rev. E 54, 5617 (1996)
J.E. Bailey *et.al.* Phys. Plasmas (2009)

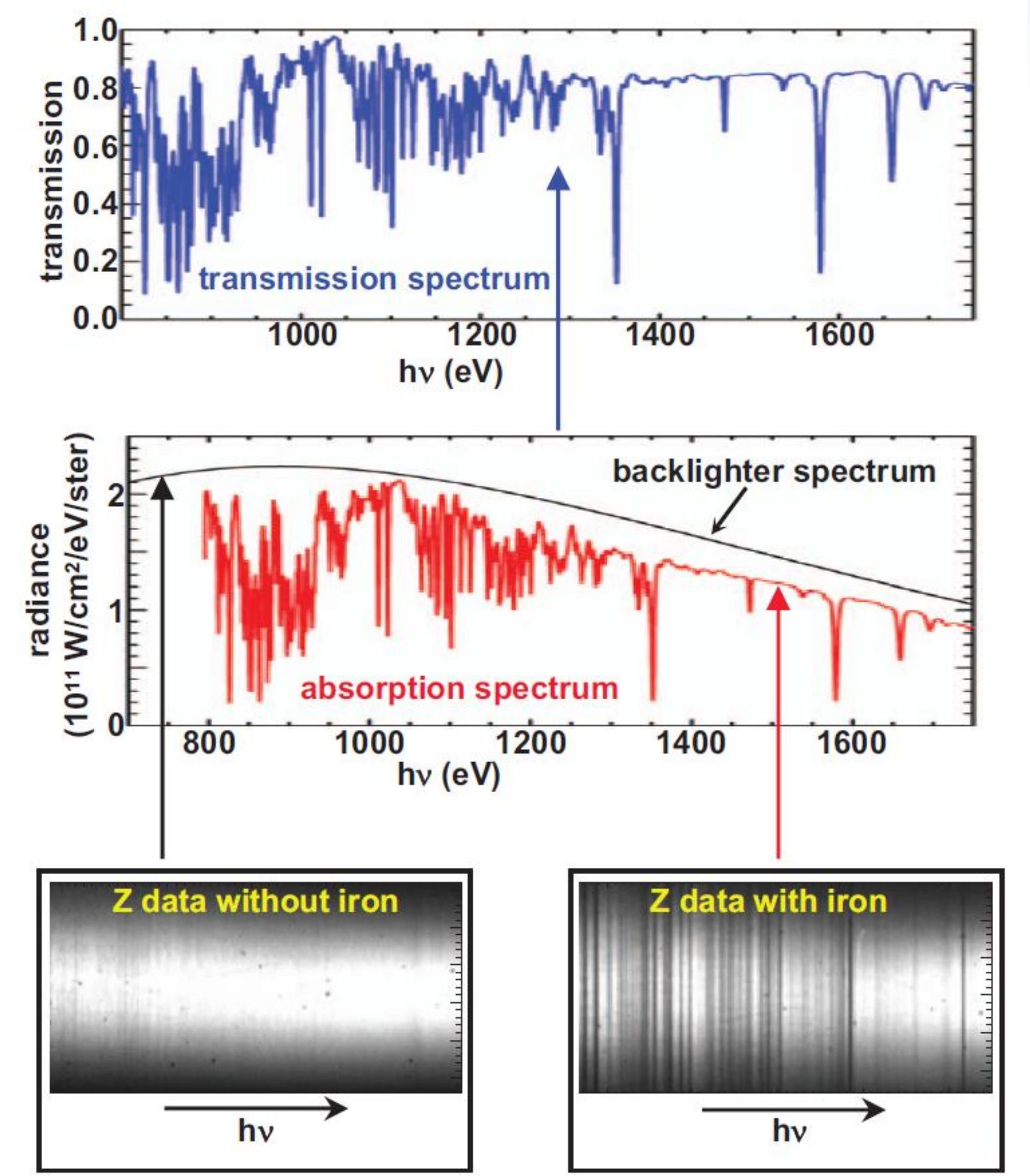
Opacity platform uses the Z dynamic hohlraum radiation source to heat and backlight the sample

1 Foil is heated by dynamic hohlraum



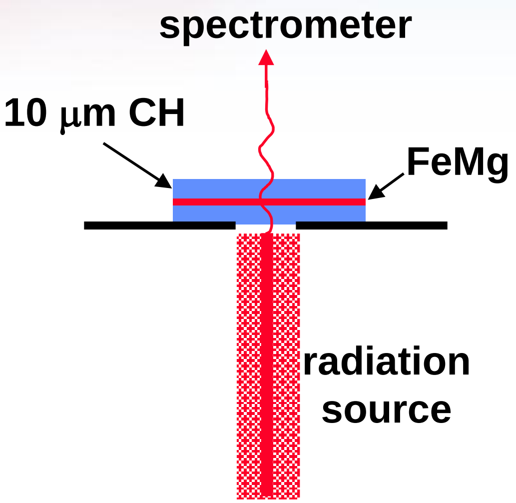
2 Foil is backlit at stagnation

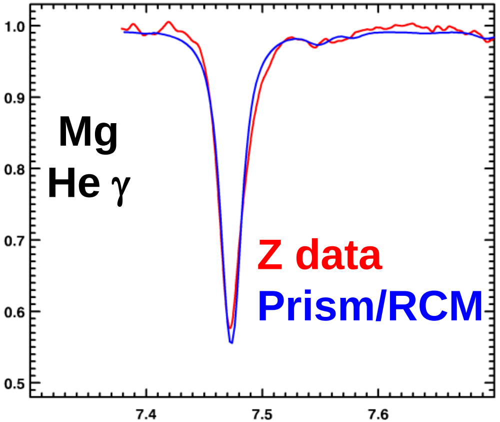




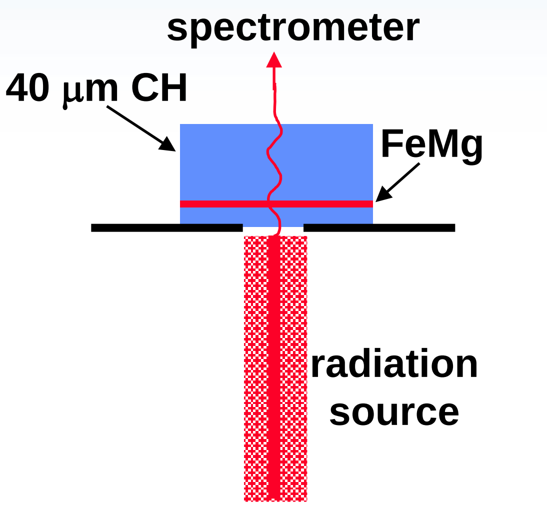
Bailey et al., POP (2009)

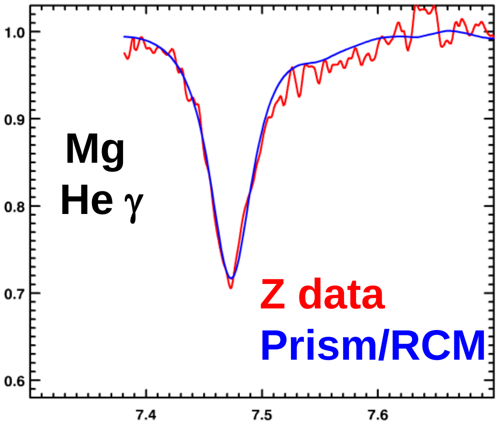
Adjusting the CH tamper thickness controls the opacity sample density and temperature



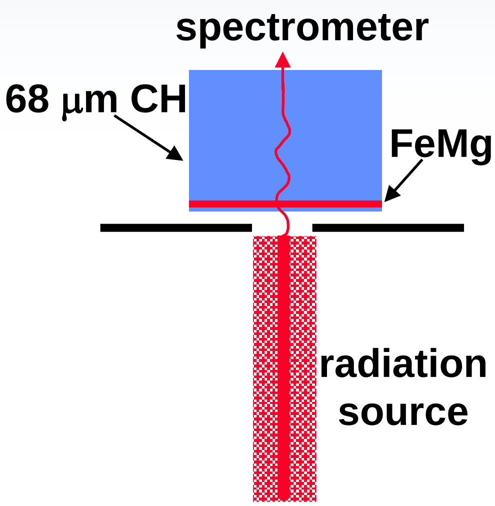


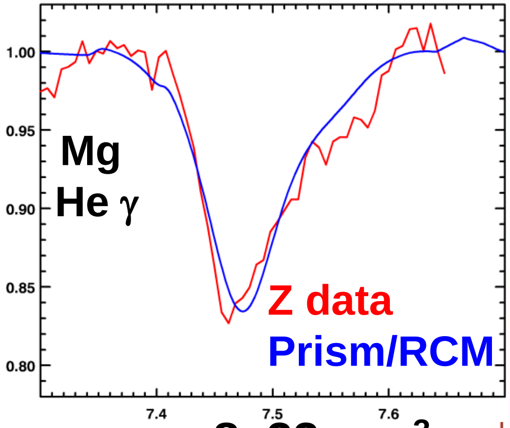
$n_e \sim 7e21\ cm^{-3}$





$n_e \sim 3e22\ cm^{-3}$



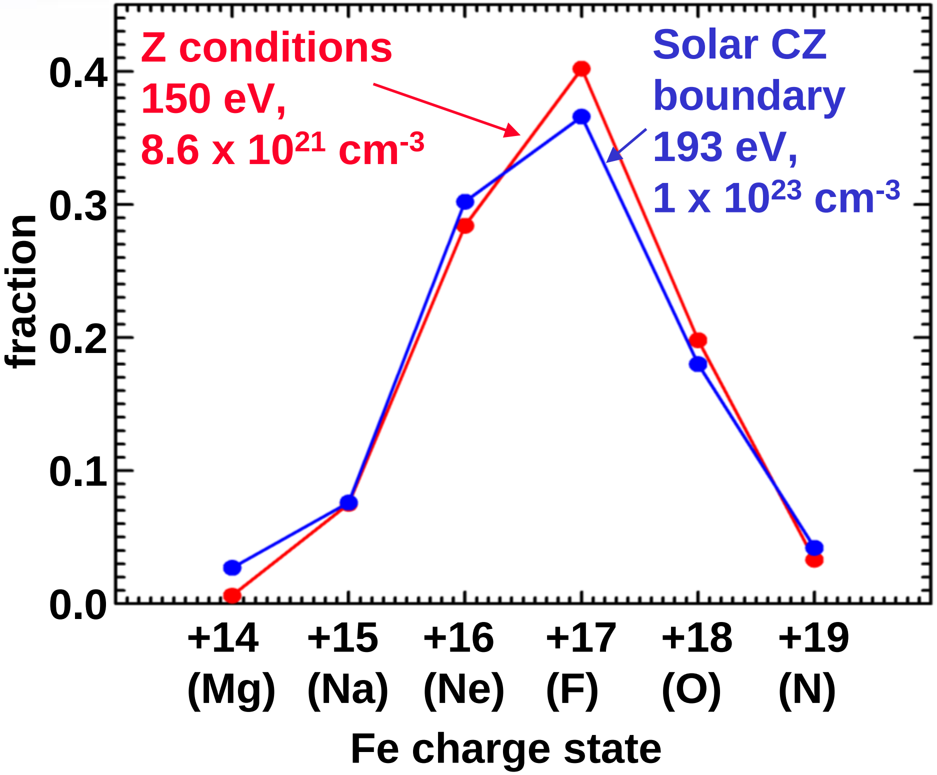


$n_e \sim 8e22\ cm^{-3}$

This trend was successfully predicted by simulations
Nash et al RSI (2010)

Opacity results: a progress report

In 2007, Z experiments produced the iron charge states that exist in the solar interior



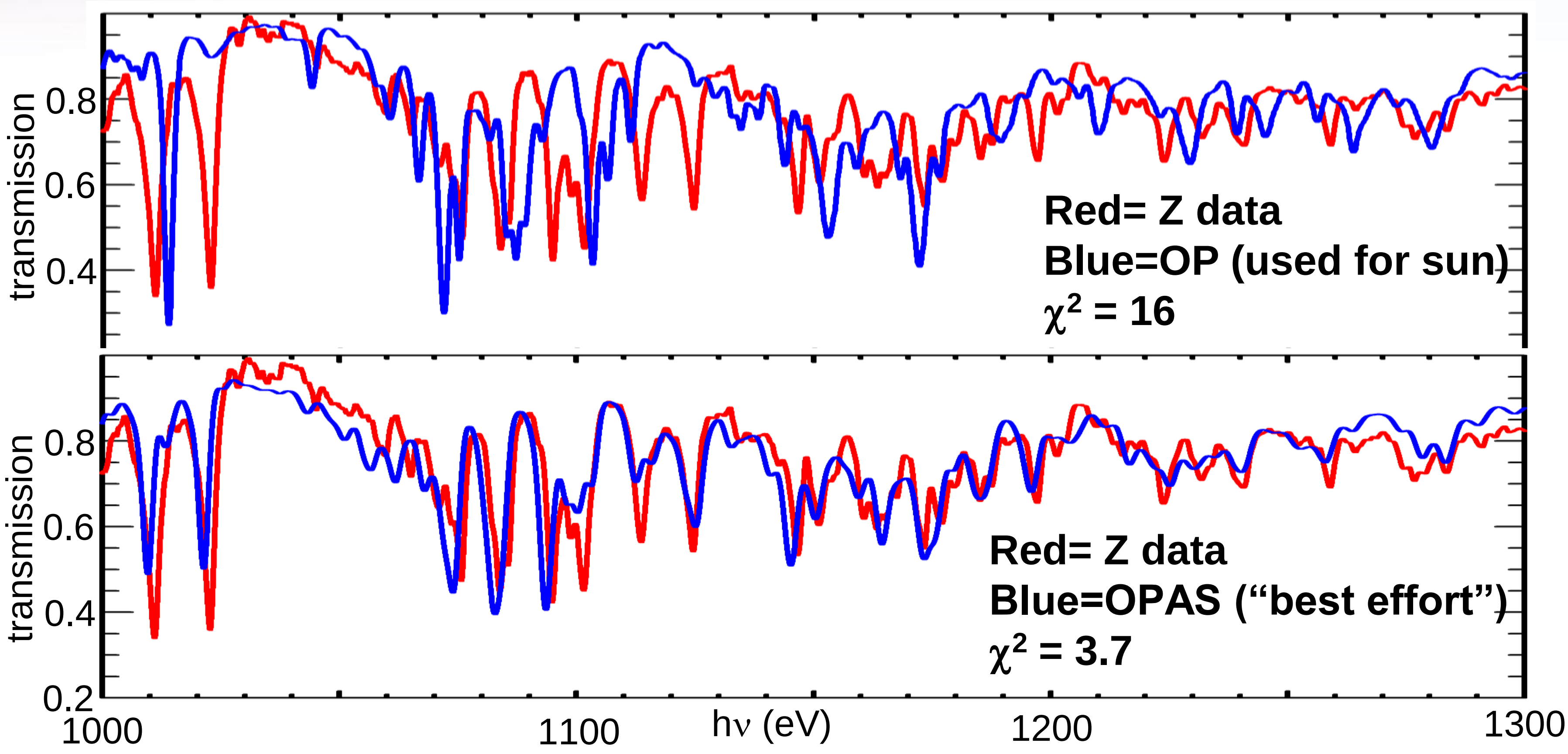
Producing the correct charge states enables opacity model tests:

1) Charge state distribution

2) Energy level description

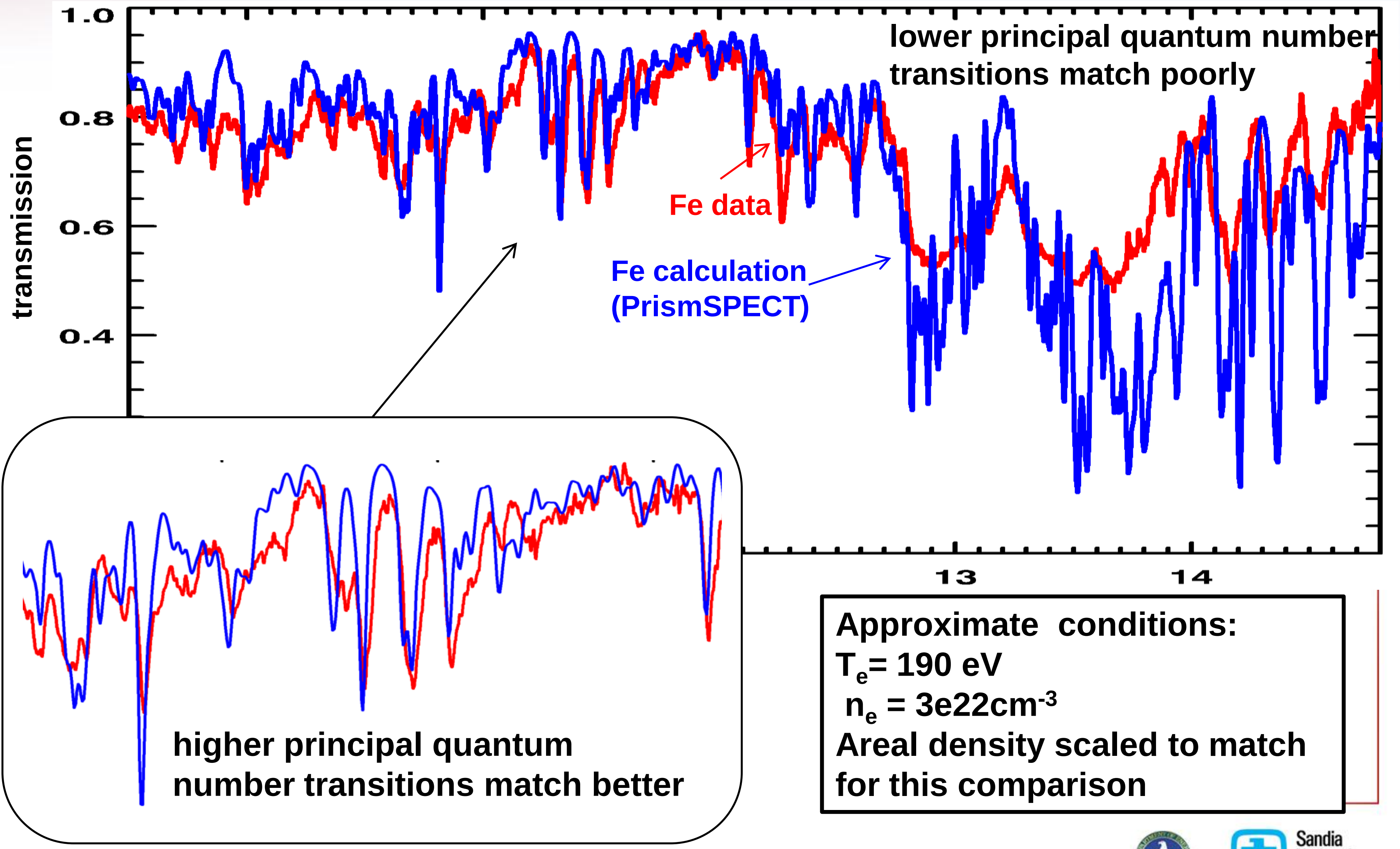
High density studies require further progress

The 2007 Z data was matched well by “best-effort” models, but not by a model used in solar research



OP Rosseland mean is ~ 1.5x lower than OPAS at Z conditions.
If this difference persisted at solar conditions, it would solve the CZ problem
Experiments at higher density needed

Discrepancies with preliminary intermediate density data exist, even for models that agreed in prior work



lower principal quantum number transitions match poorly

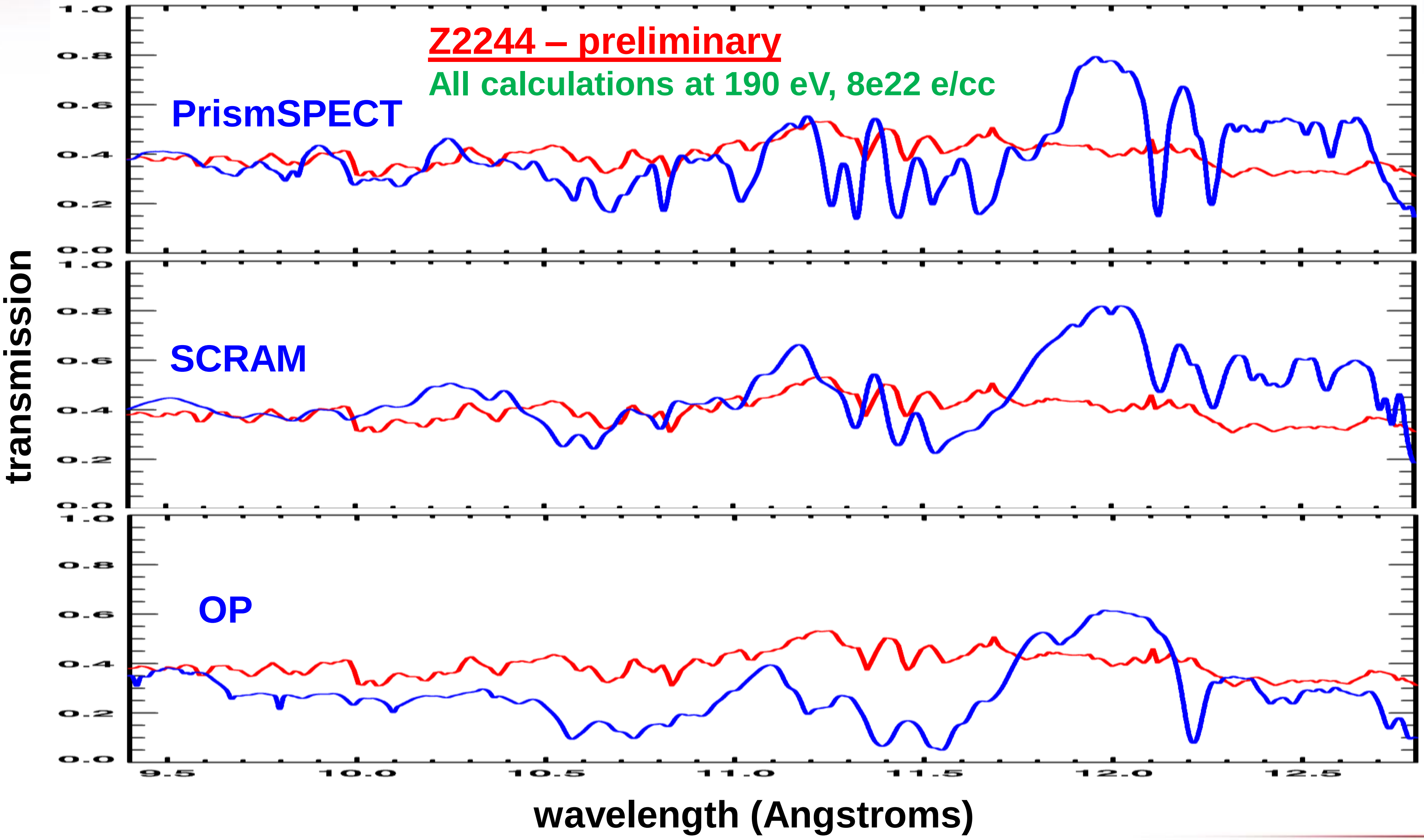
Fe data

Fe calculation (PrismSPECT)

higher principal quantum number transitions match better

Approximate conditions:
T_e= 190 eV
n_e = 3e22cm^{-3}
Areal density scaled to match for this comparison

Preliminary measurements at ~ CZB conditions indicate the next year should be exciting for stellar opacity research



Ongoing work will refine experiments, test the accuracy, and constrain solar opacity models

- The 2007 Z data reproduced iron charge states found at the base of the solar convection zone, but the density was an order of magnitude lower
- The 2007 comparisons should inspire concern for calculations, but higher density/temperature measurements are needed
- Recent experiments demonstrated the we can reach the conditions found at the base of the solar convection zone
- Transmission measurements at the higher density conditions are scheduled in the next six months

Evaluation of impact on the solar problem, refined experiments, refined calculations, and experiments that that approach the CZ boundary Te/ne are in progress

Sandia
National
Laboratories

Future directions for laboratory research advancing stellar interior understanding

Additional opacity questions

1) Oxygen opacity (photoionization, line broadening)
2) Is iron opacity different when it is embedded in a mainly hydrogen plasma?
3) What are the implications for radiation transport in other types of stars?
4) What are the implications for radiative levitation?

Broader questions for stellar interior physics

1) Can we test the non-LTE models used to infer the solar composition?
2) Scientists have proposed using helioseismology to infer compositions. But this effort relies on never-benchmarked EOS models in the convection zone. Can we test those EOS models?