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Sandia National Laboratories

Laboratory Tests of Stellar Interior Opacity Models

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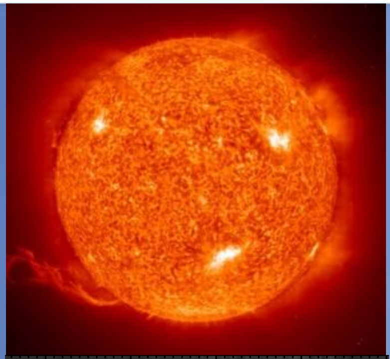
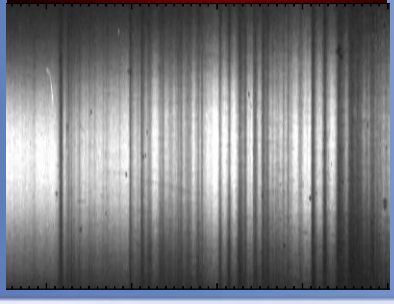
Fundamental Science using Pulsed Power and High-Power Lasers
July 28, 2011





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.

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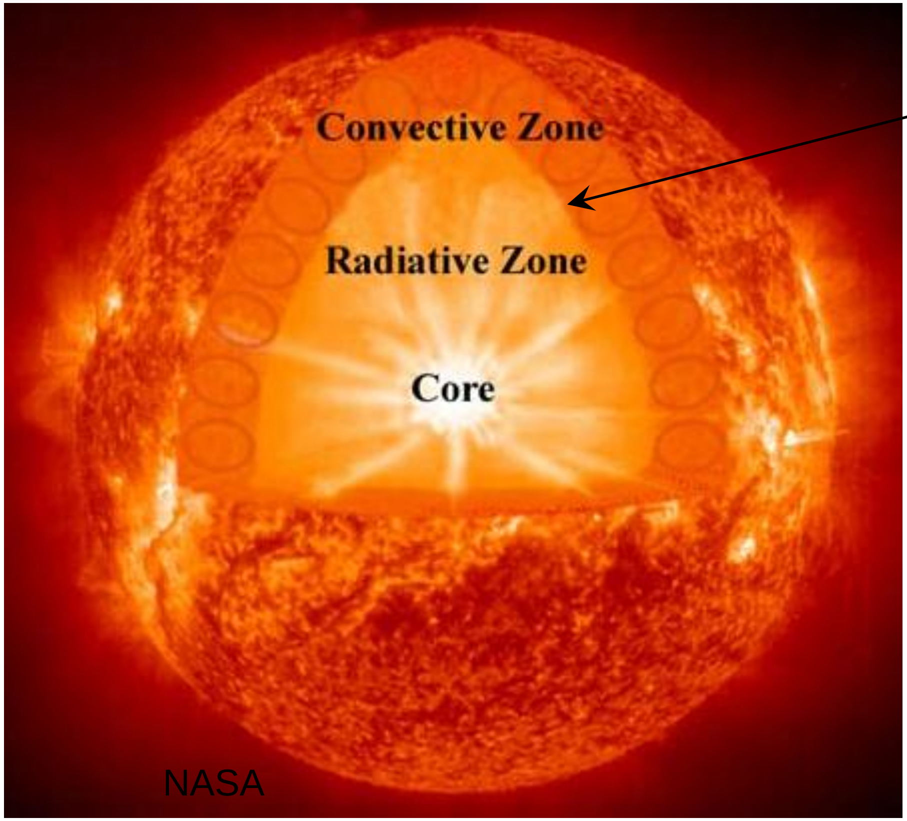
Models for solar interior structure disagree with helioseismology observations



Boundary location differs at 10-30 σ

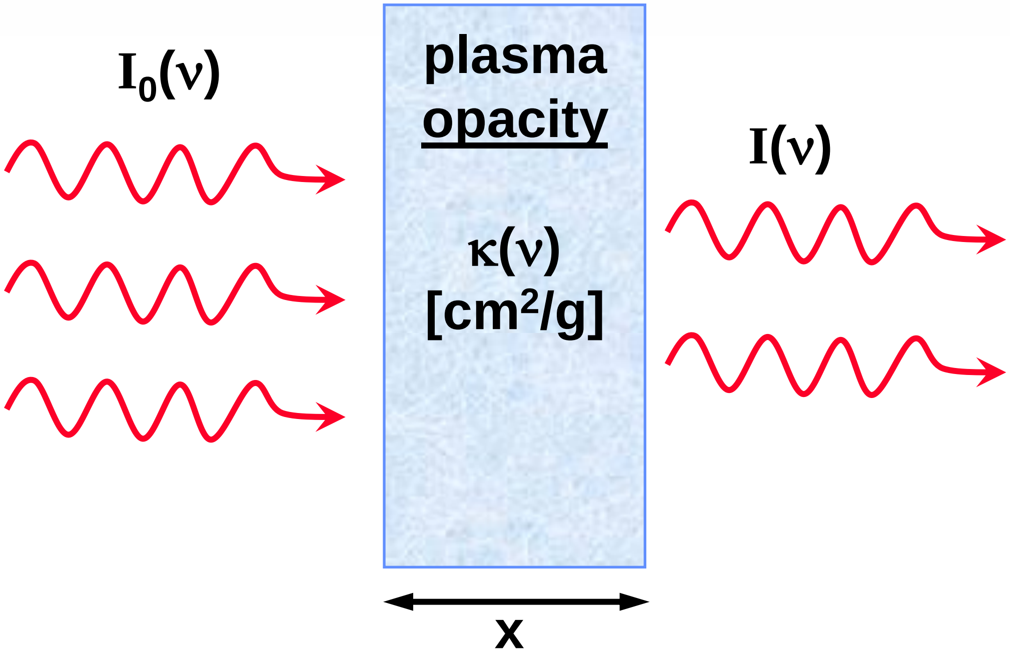
C_s (r) and ρ(r) differ (by ~ 10%)

<u>Models depend on:</u>

- **What the sun is made of (photospheric spectra, meteorites)**
- **EOS as a function of radius**
- **The solar matter opacity at the local T, ρ**
- **Nuclear cross sections**

Is opacity uncertainty the cause of the disagreement?

Opacity quantifies how transparent or opaque a plasma is to radiation



Transmission

$T = I(\nu) / I_0(\nu) = \exp\{-\tau(\nu)\}$

Optical depth

$\tau(\nu) = \kappa(\nu)\rho x$

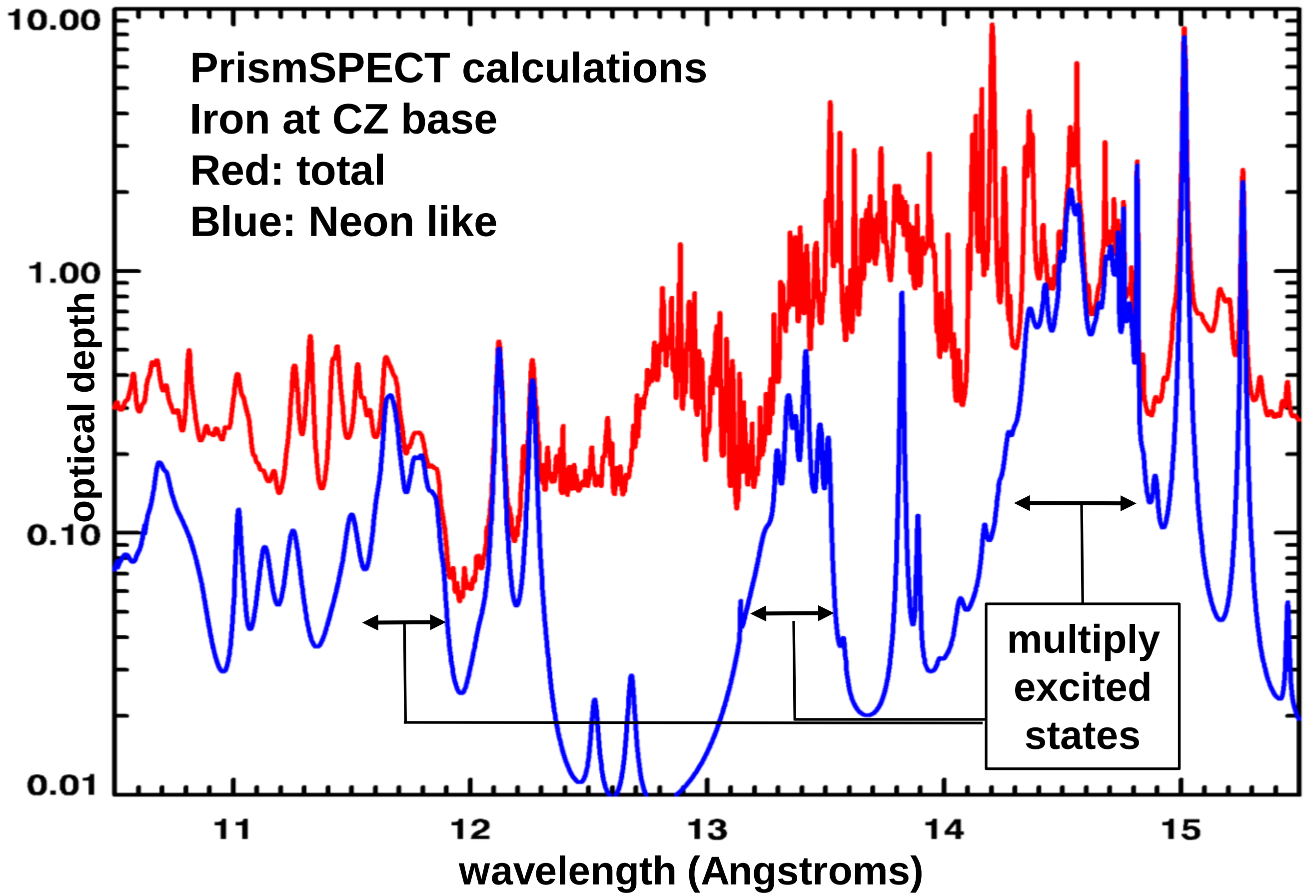
Stellar structure depends on opacities that have never been measured

Challenge: create and diagnose stellar interior conditions on earth

The solar problem defines a useful opacity experiment for stellar interior physics

- Base of solar convection zone: T_e ~ 193 eV, n_e ~ 10^{23} cm^{-3}
- Most important elements: O, Ne, Fe
- Fe is the most complex and therefore the most suspect
- Fe charge states: +16, +17, +18 (Ne-like, F-like, O-like)
- Photon energy range $h\nu$ ~ 700-1400 eV
- Atomic processes: L-shell bb transitions and bf transitions

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



Fe^{+16} : $1s^2 2s^2 2p^6$

Ne-like

<u>Ground state</u>

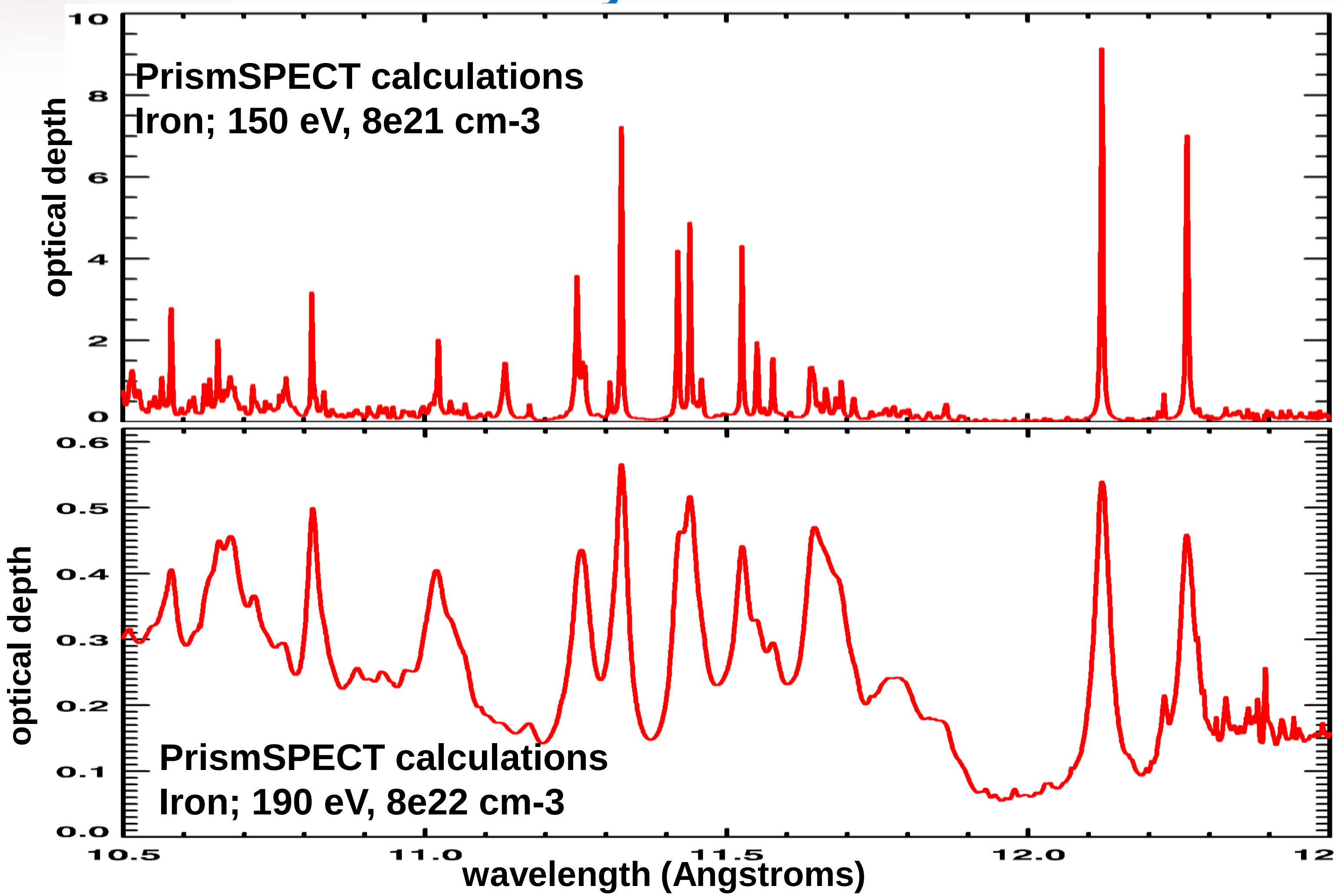
$1s^2 2s^2 2p^6$ - $1s^2 2s^2 2p^5 3d$

<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

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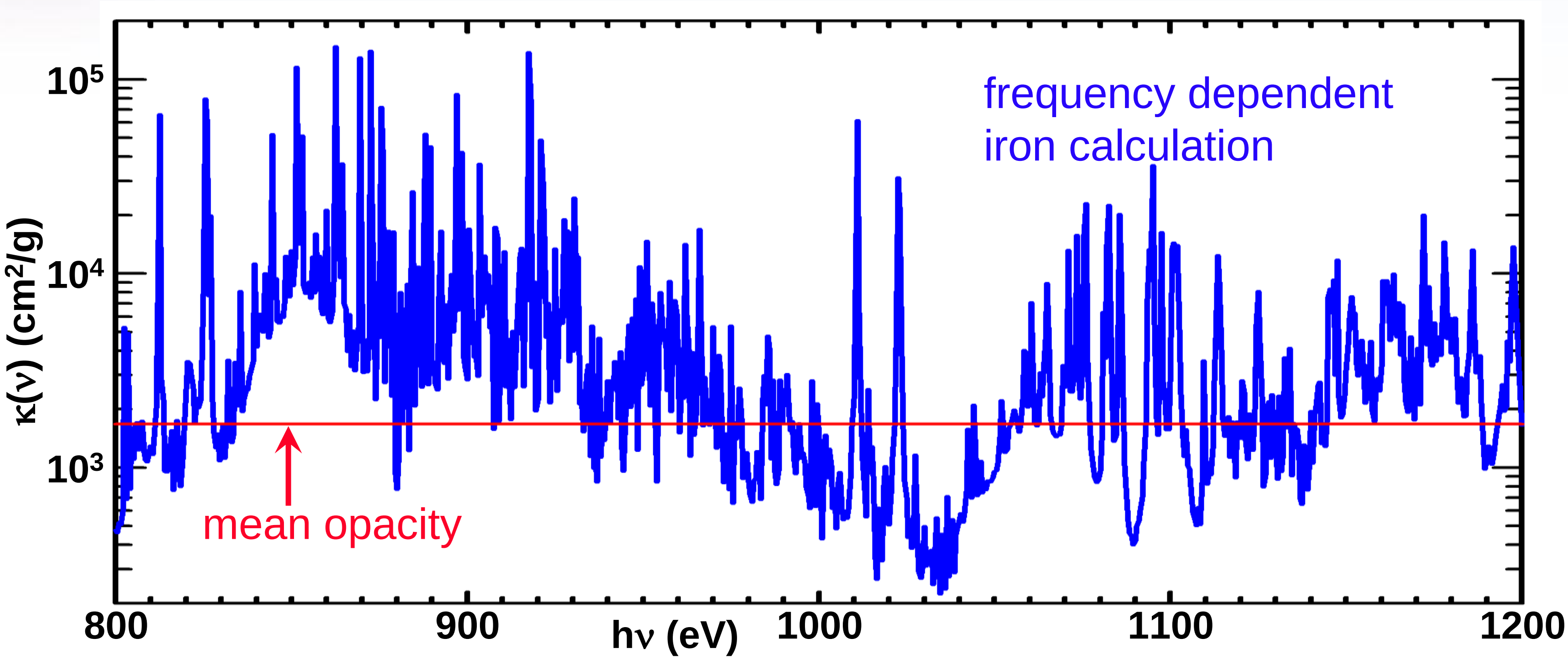
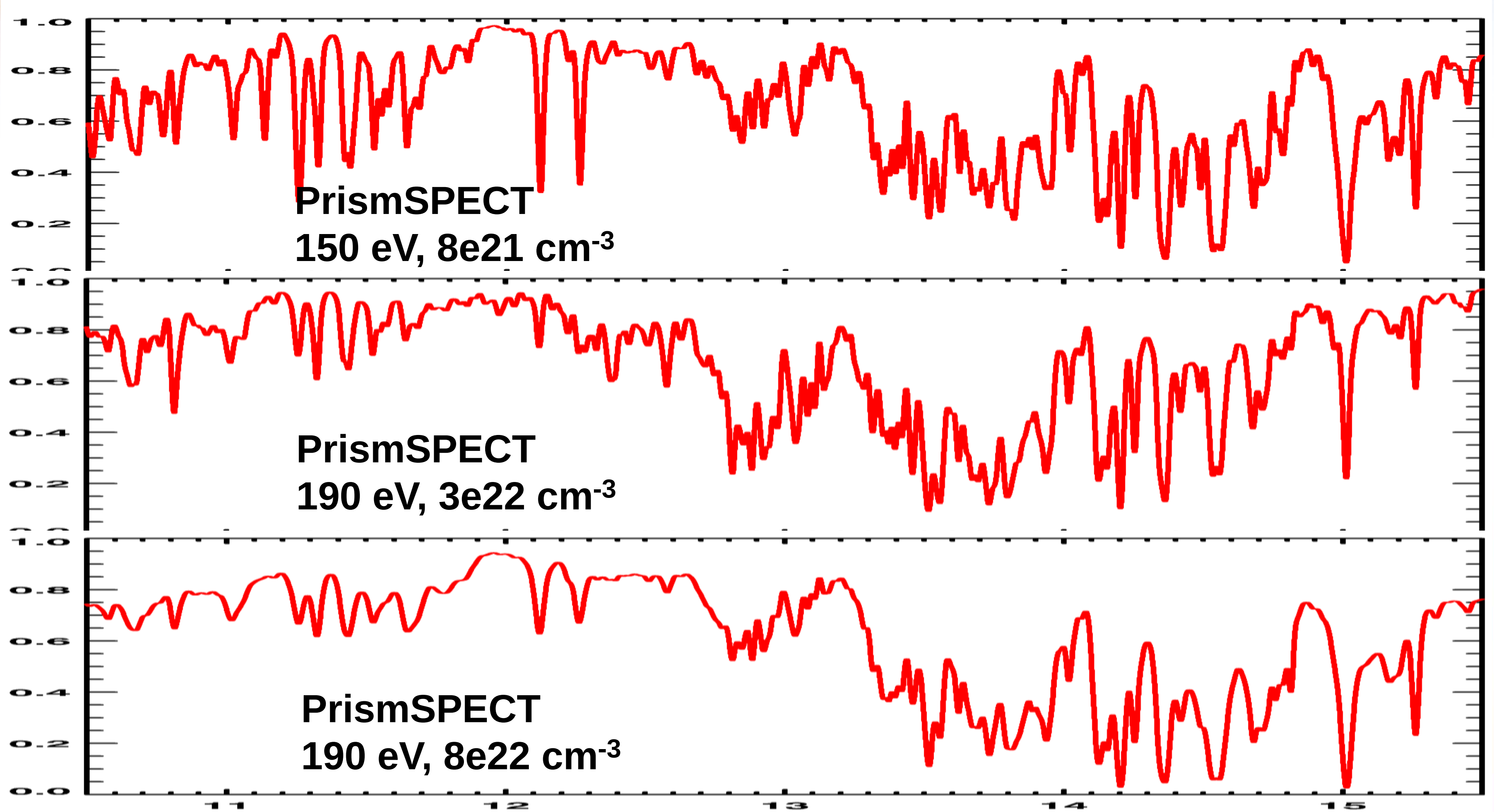
Strategy: frequency-dependent transmission measurements test opacity model physics



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



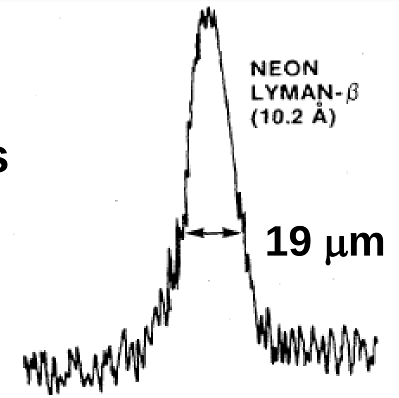
- **Measurements at multiple conditions promote our ability to isolate the relative importance of different effects**

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 grain of sand



Spatial profile of laser driven fusion capsule
Yaakobi, PRL (1977)
300eV, 0.26 g/cc

beach sand

1.0 mm

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

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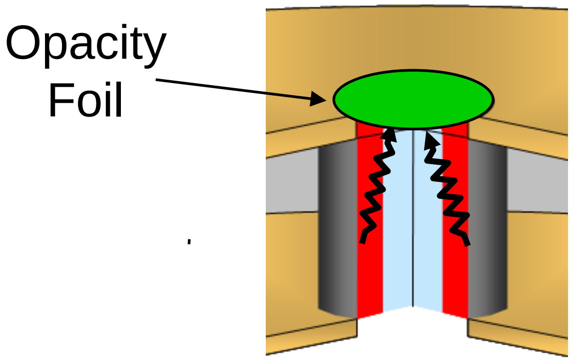
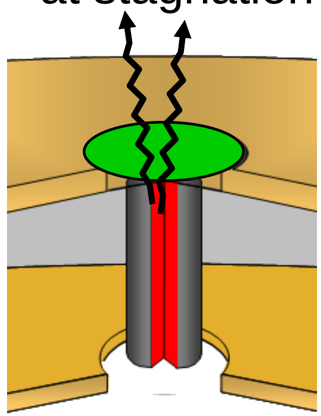
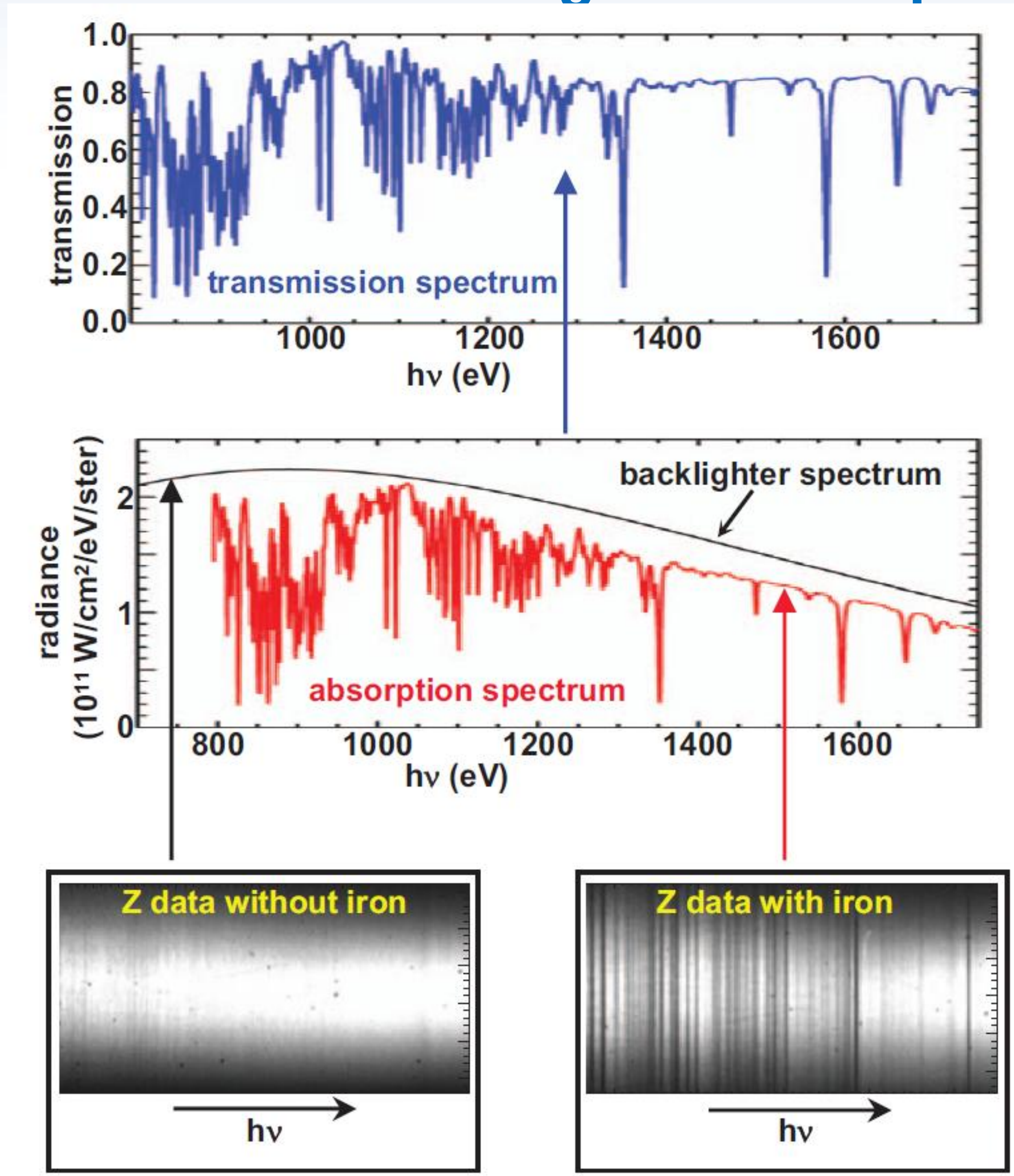
Opacity platform uses the Z dynamic hohlraum radiation source to heat and backlight the sample

1 Foil is heated by dynamic hohlraum



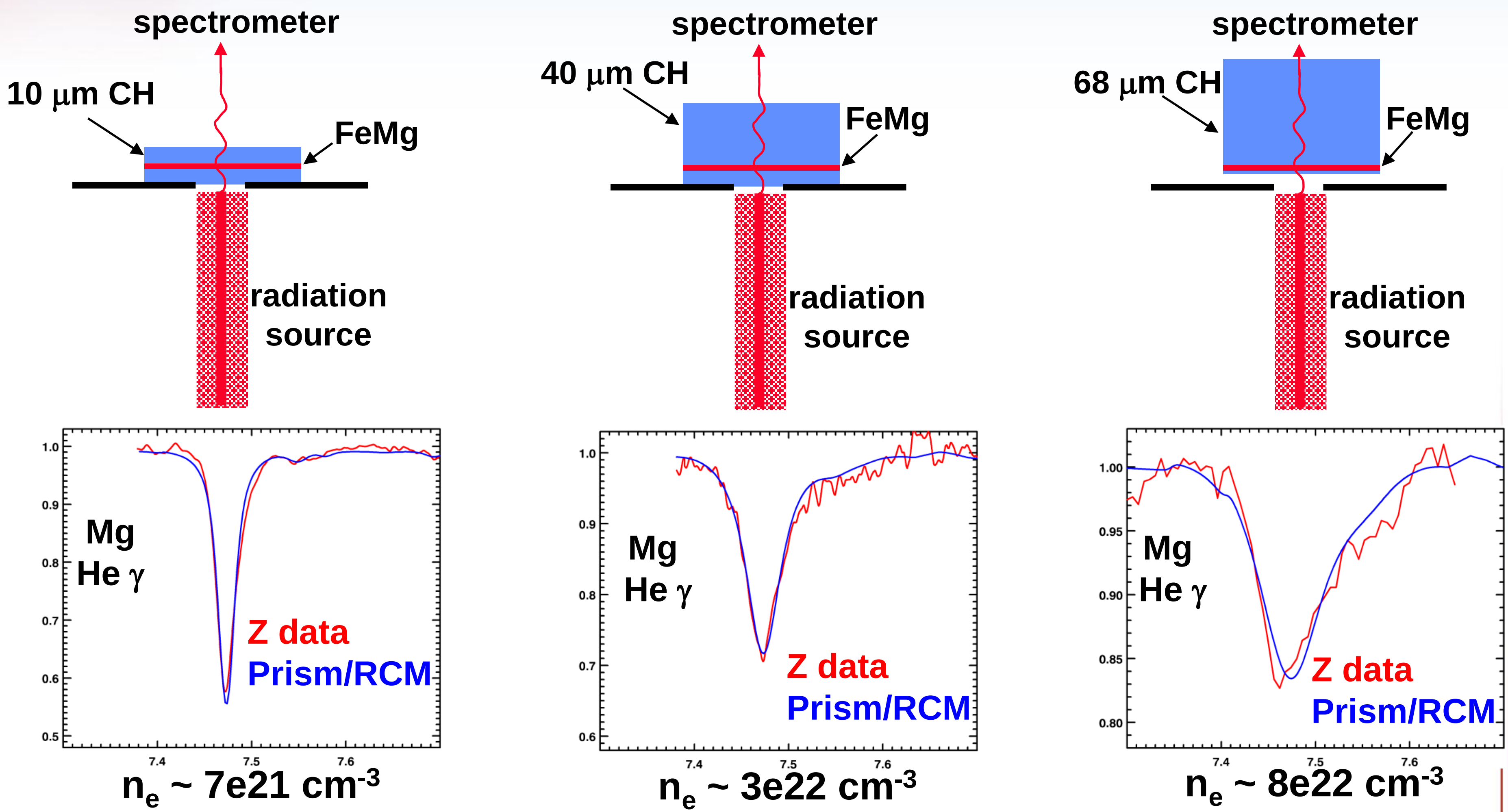
2 Foil is backlit at stagnation





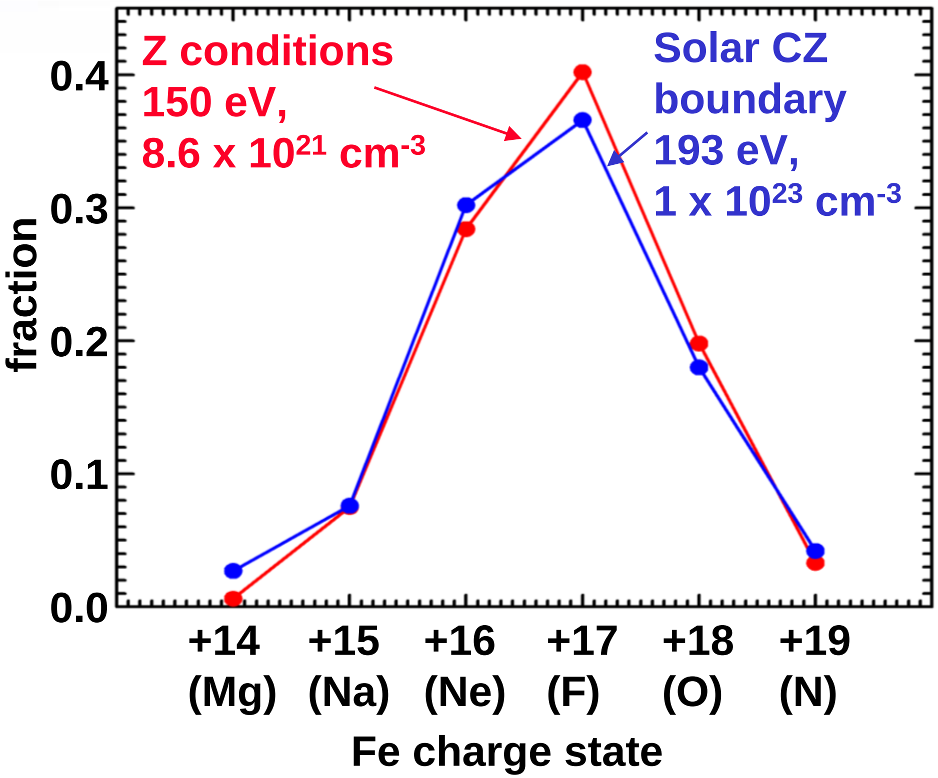
Bailey et al., POP (2009)

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



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

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



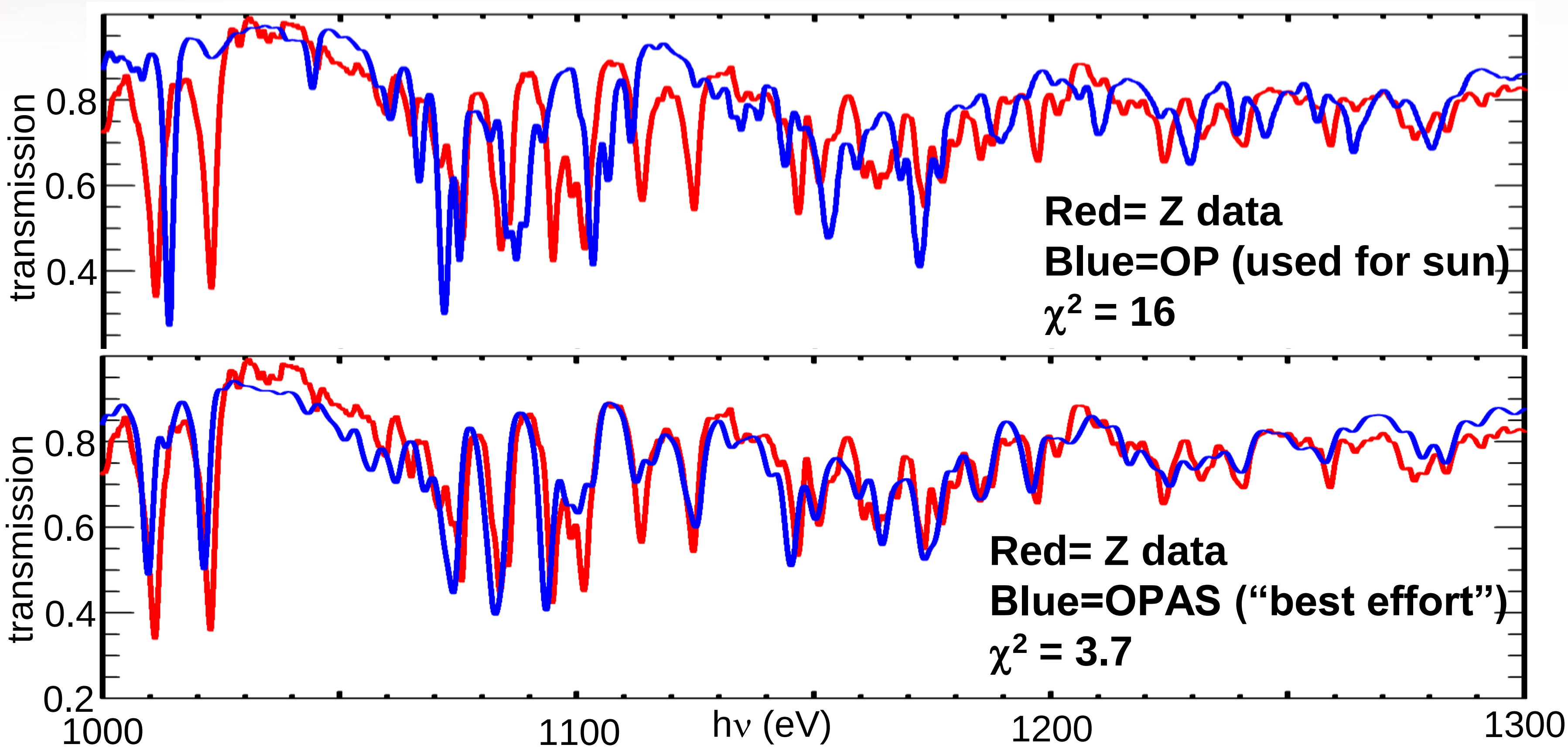
Producing the correct charge states enables opacity model tests:

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

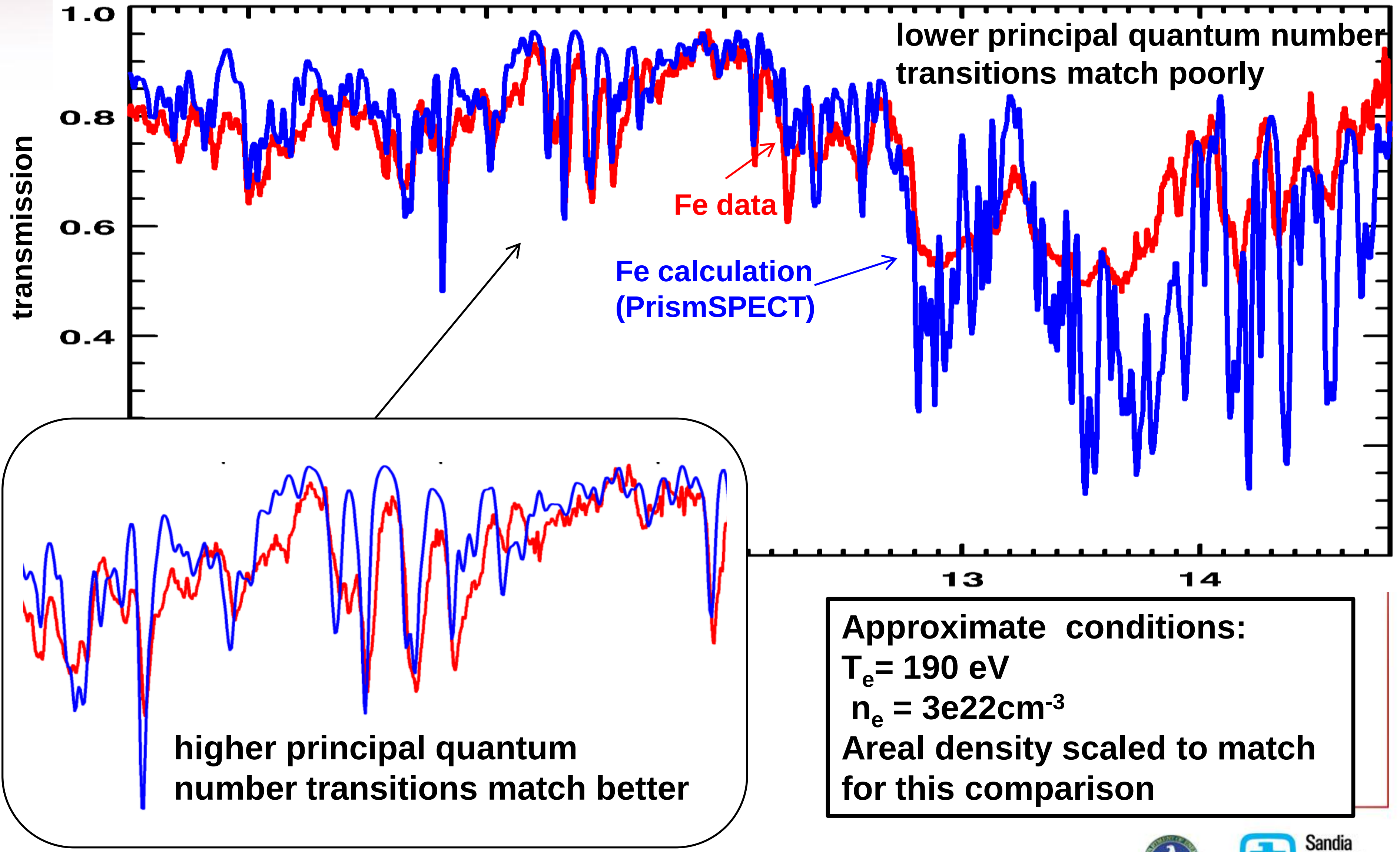


OP Rosseland mean is ~ 1.5x lower than OPAS at Z conditions.

If this difference persisted at solar conditions, it would solve the CZ problem

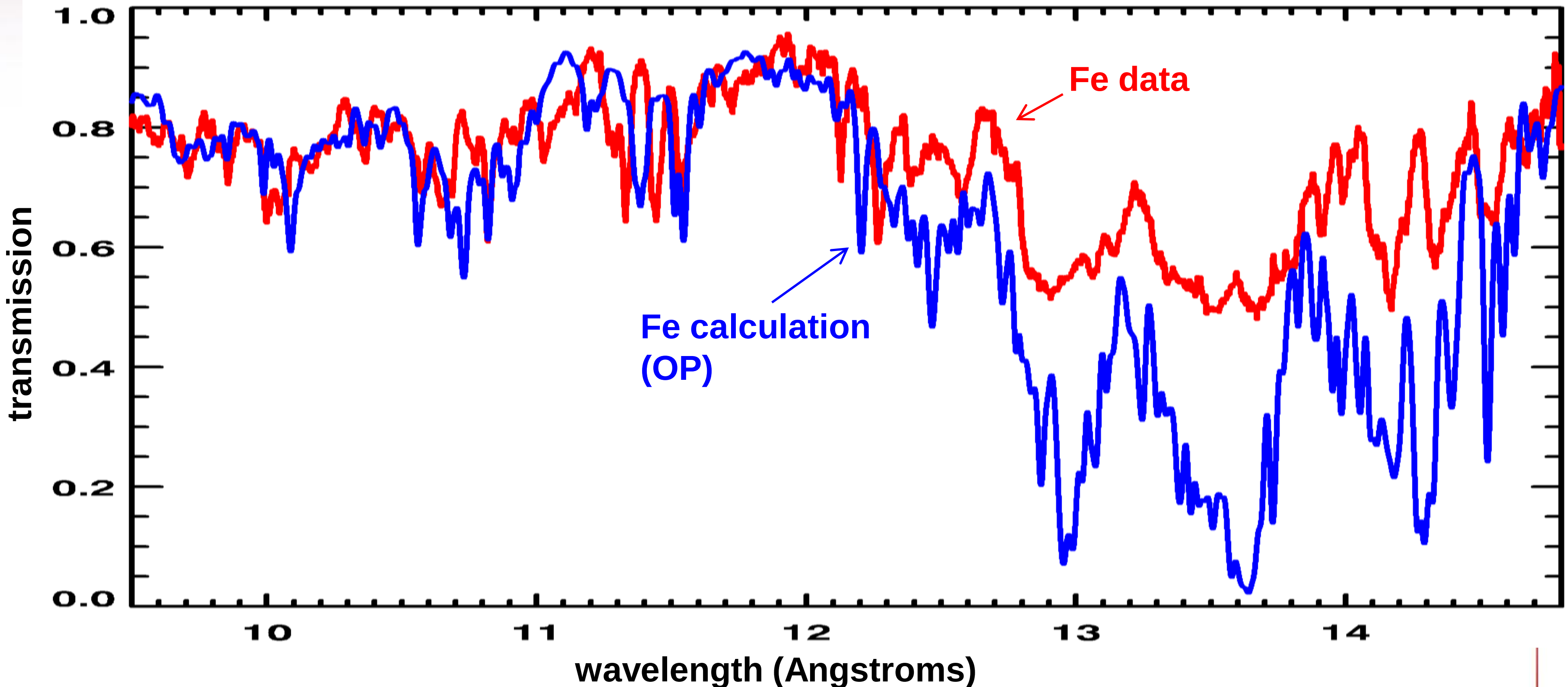
<u>Experiments at higher density needed</u>

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



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

Discrepancies with preliminary data exist in comparisons with other models

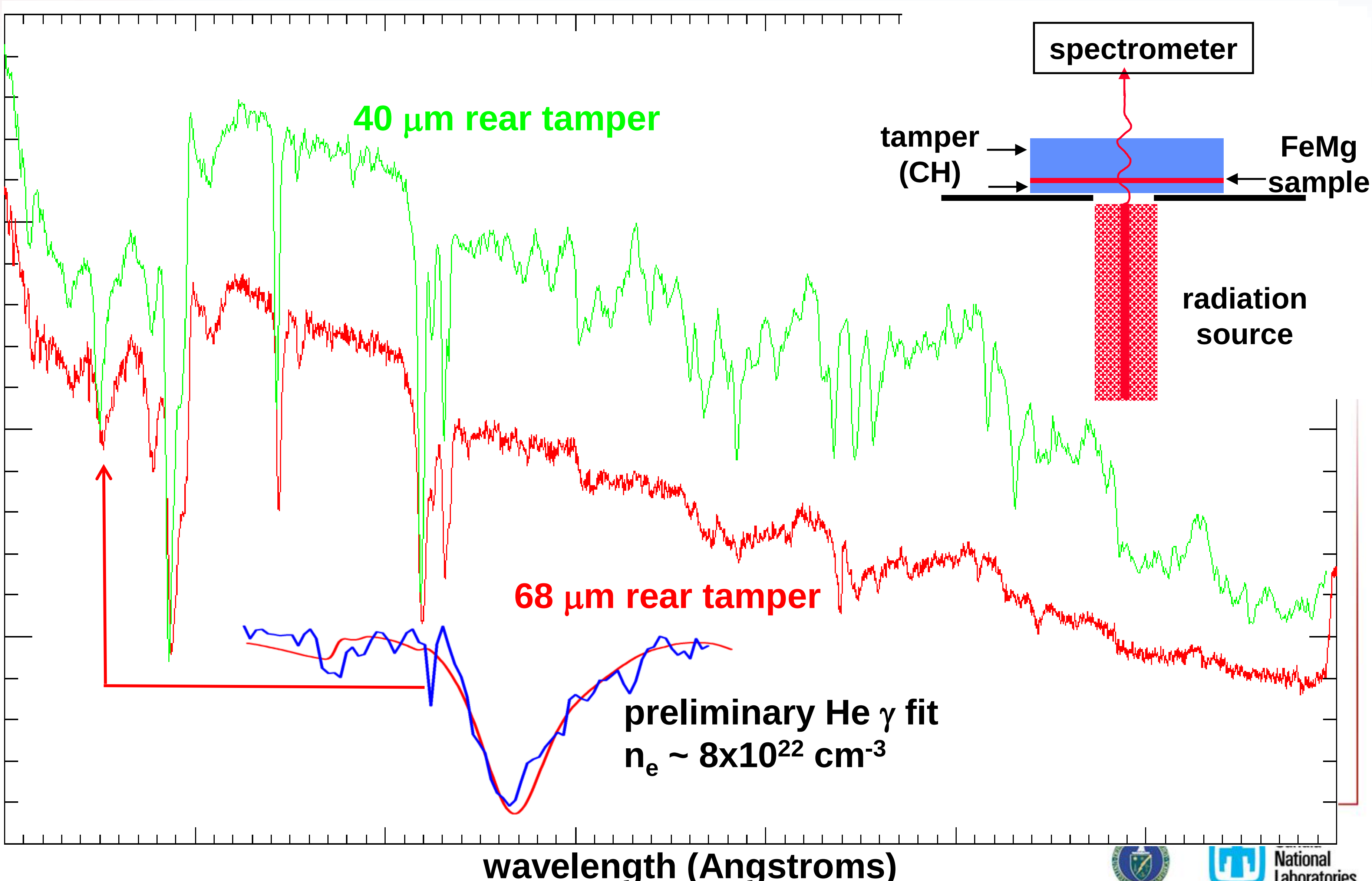


Could be experiment problems – this analysis was preliminary

Could be model problems – they have never been tested in the lab before

Probably it is both

Recent experiments extended density to within 10-30% of CZ boundary value



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 (starting in less than 3 weeks…)

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