SAND2010-7088P

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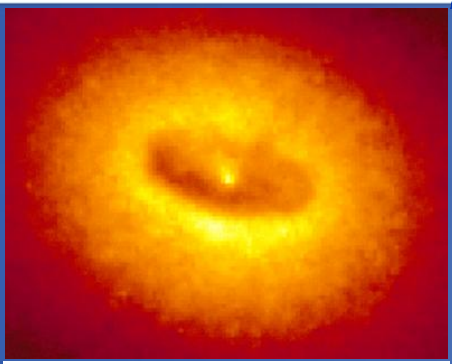
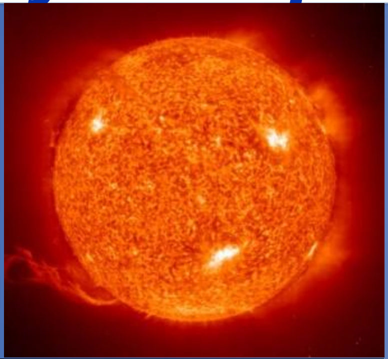
Measurements of radiative material properties for astrophysical plasmas

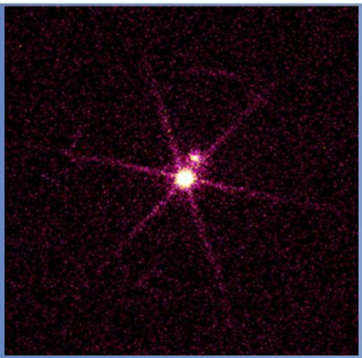
Jim Bailey

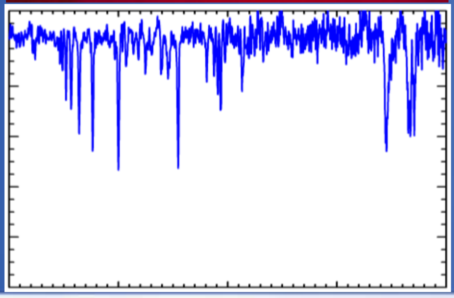
CEA seminar

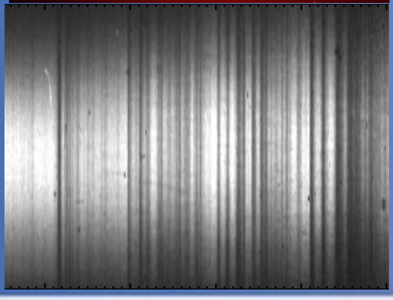
September 29, 2010

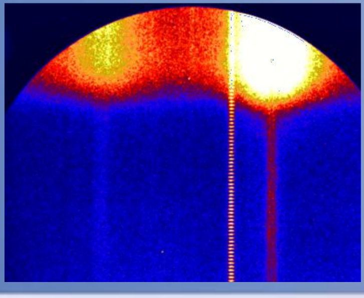












Many people and institutions contribute to this work

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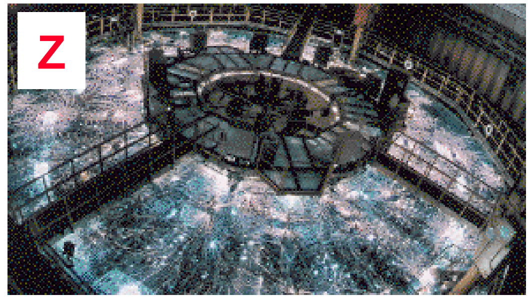
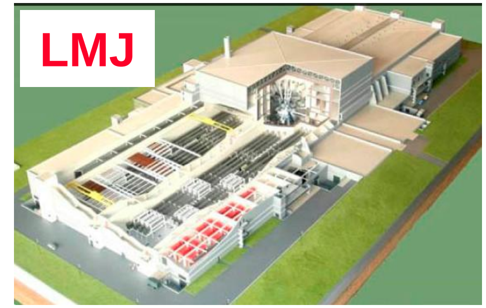
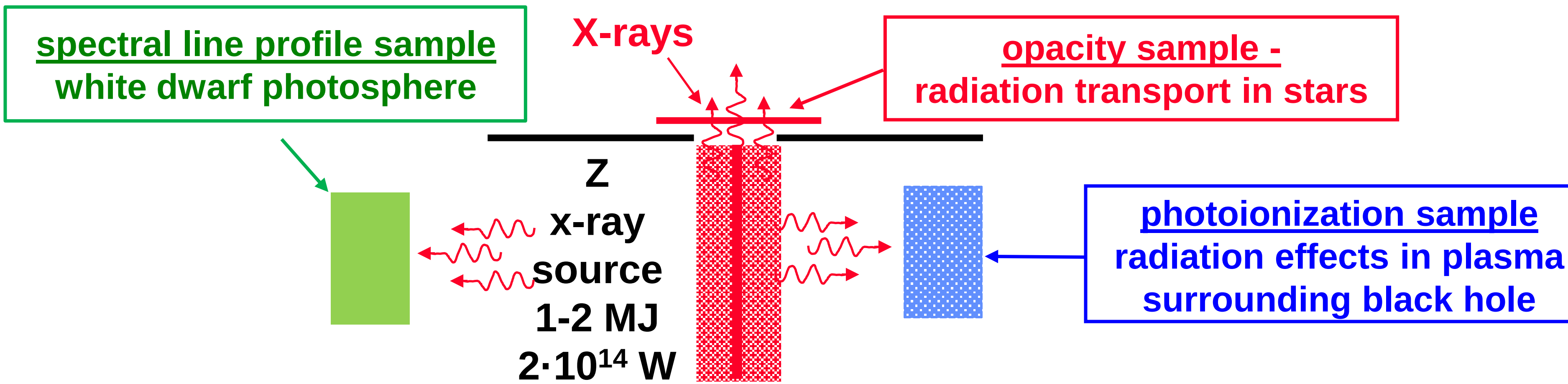
The new generation of High Energy Density facilities can *create* and *diagnose* astrophysical matter on earth

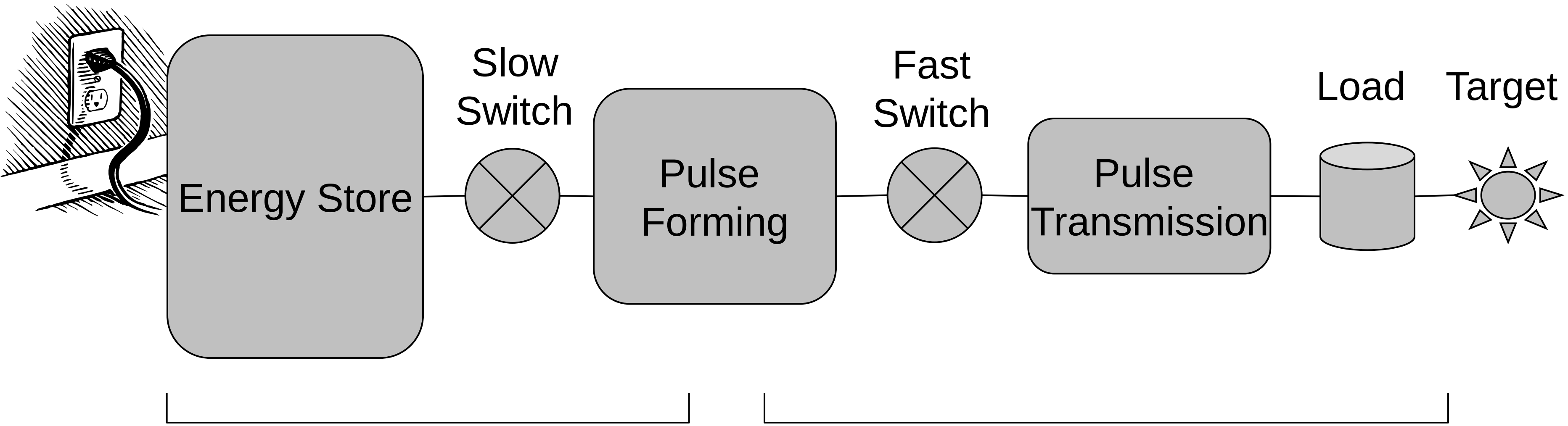






Mega-Joule class facilities create *macroscopic enough* quantities of astrophysical matter for detailed measurements

Z compresses electrical energy to produce short bursts of high power.



Low Electrical Power
Up to 10^7 J – 10^6 W

High Electrical Power
Up to 10^7 J – 10^{14} W

Goal: "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)"

…S T Pai & Qi Zhang, "Introduction to High Power Pulse Technology," World Scientific Publishing Co., Singapore, 1995.

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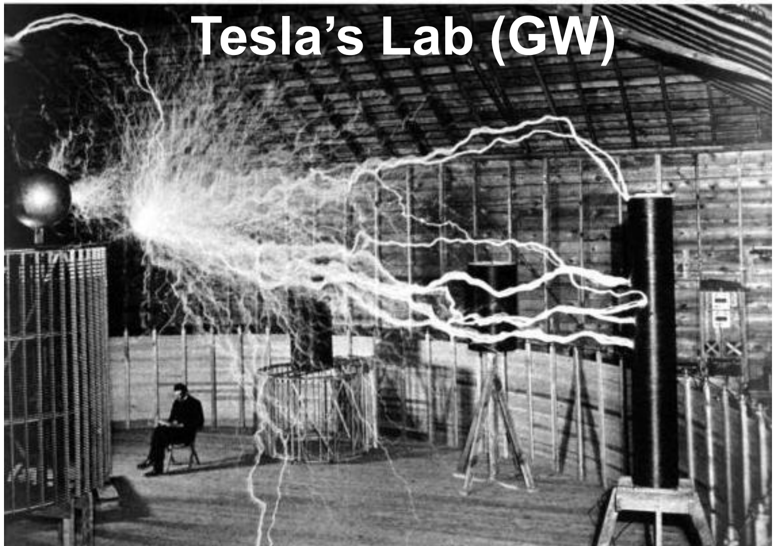
Pulsed power has been investigated for over a century.



Hermes - II {SNL}
e-beam (TW)

PBFA - II {SNL}
Ion Beams (20 TW)

WWII

1900 | 1920 | 1940 | 1960 | 1980 | 2000

Radar (MW)
- Germany
- US
- Russia
- Great Britain

Angara - II {Russia}
Simulator (TW)

DARHT {LANL}
Radiography (10 GW)

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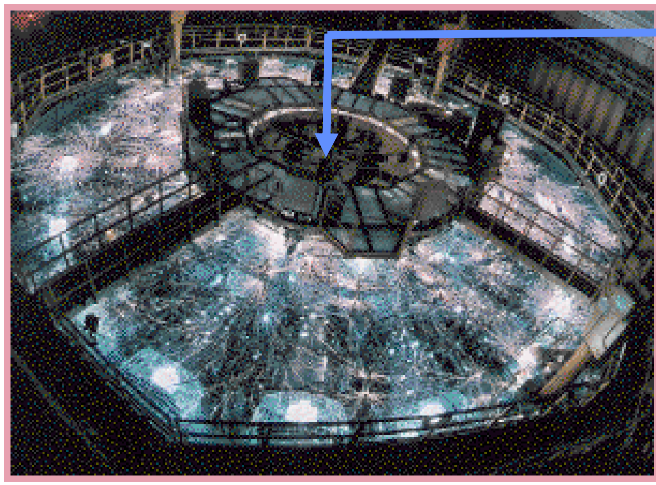
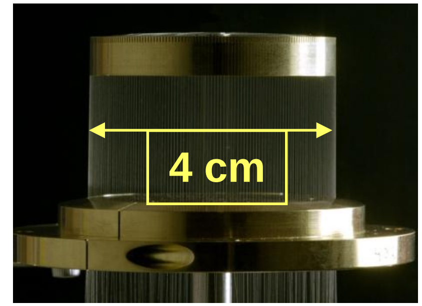
The 24 million Ampere current on Z provides access to new laboratory astrophysics regimes

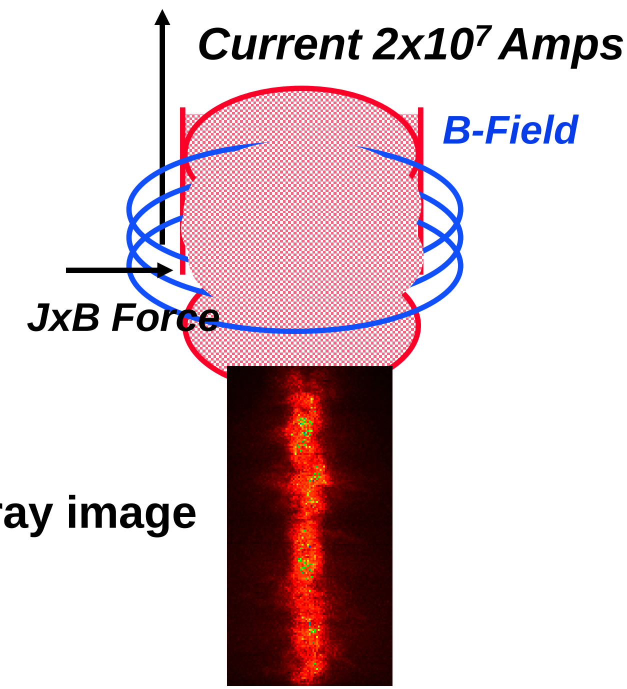
Z accelerator



40 m



tungsten
wire array



X-ray image

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

Z-pinch experiments advance understanding for multiple astrophysics topics

Discussed here:

Why do modern solar models disagree with helioseismology?

What is the structure of an active galactic nucleus?

What causes the white dwarf mass run away problem?

Other topics:

Why did models for Cepheid variable pulsation disagree with observations? {Springer *etal* JQSRT 1997; Rogers & Iglesias Science 1994}

Did the giant planets form by accretion onto a solid massive core? {Saumon & Guillot ApJ 2004; Bailey *etal* PhysRevB 2008}

How do astrophysical jets form and evolve? {Lebedev *etal* ApJ 2004}

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"… the deep interior of the sun and stars is less accessible to scientific investigation than any other region of the universe….What appliance can pierce through the outer layers of a star and test the conditions within? "

A.S. Eddington ***The internal constitution of the stars Cambridge, 1926***

exterior observations

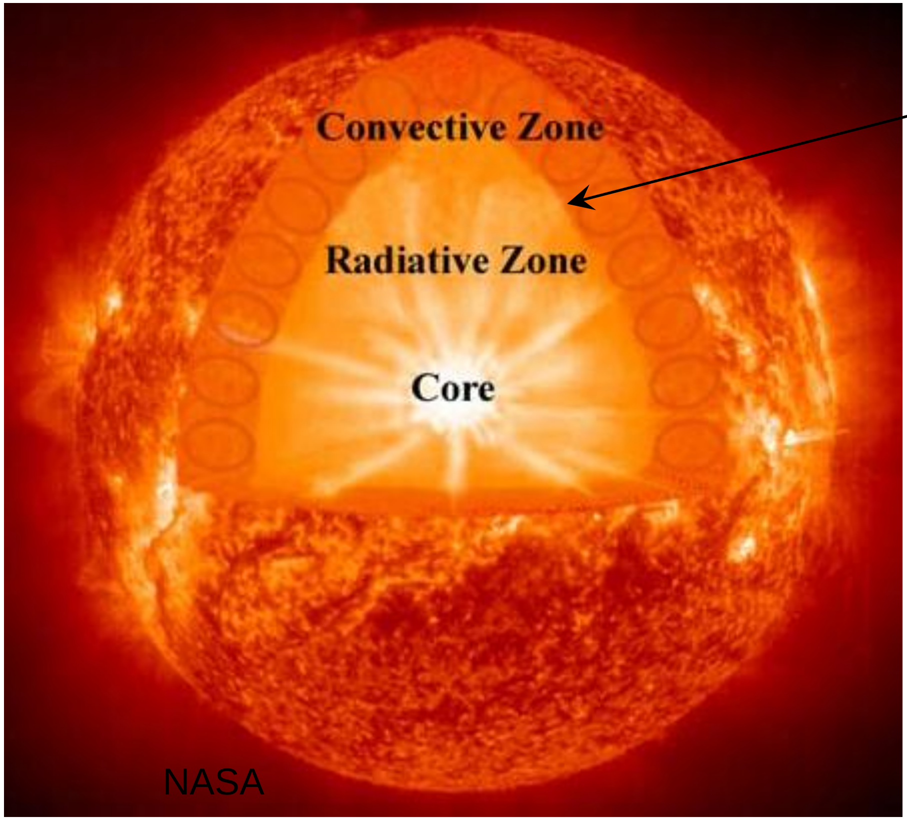
+

interior plasma property models

= understanding

model reliability requires laboratory experiments

Stellar interior structure depends on radiation transport



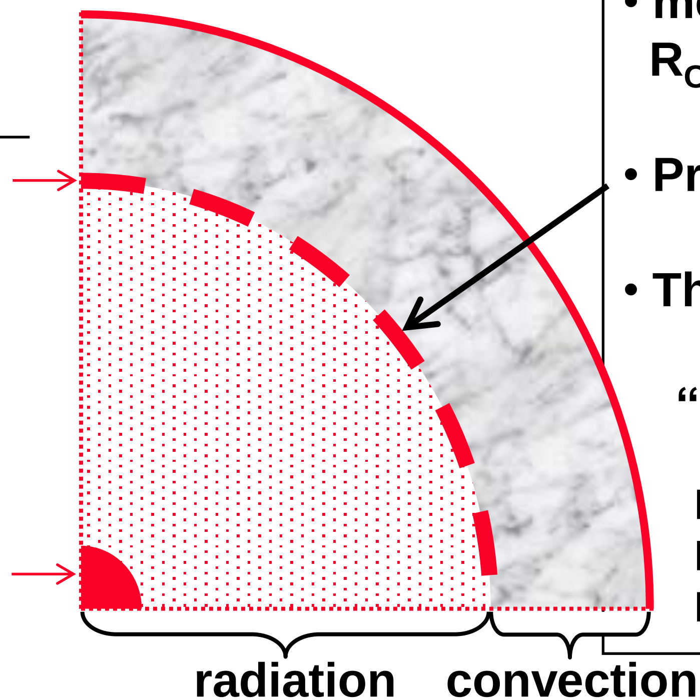
Boundary location depends on radiation transport

Radiation transport depends on:

- What the star is made of (photospheric spectra, meteorites)
- T & ρ as a function of radius (stellar models)
- The stellar matter opacity at the local T, ρ
(theory of atoms in plasmas)

Solar structure predictions disagree with helioseismic data. Why?

T(eV)	$n_e(cm^{-3})$	r/R_0
193	$1x10^{23}$	0.7133
1360	$6x10^{25}$	0



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

"The CZ problem"

Bahcall et al, ApJ 2004
Basu & Antia
Physics Reports 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.

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But isn't the sun a solved problem?

SCIENCE VOL 322 3 OCTOBER 2008

ASTRONOMY

The Shining Make-Up of Our Star

Martin Asplund

A revision to the chemical composition of the Sun based on models of its outer atmosphere is at odds with our understanding of its inner workings.

THE ASTROPHYSICAL JOURNAL, 614:464–471, 2004 October 10

HOW ACCURATELY CAN WE CALCULATE THE DEPTH OF THE SOLAR CONVECTIVE ZONE?

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VOLUME 93, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2004

Surprising Sun: A New Step Towards a Complete Picture?

S. Turck-Chièze,[1] S. Couvidat,[2,1] L. Piau,[3] J. Ferguson,[4] P. Lambert,[1] J. Ballot,[1] R. A. García,[1] and P. Nghiem[1]

We know much about the sun, more than any other star, but models do not match observations

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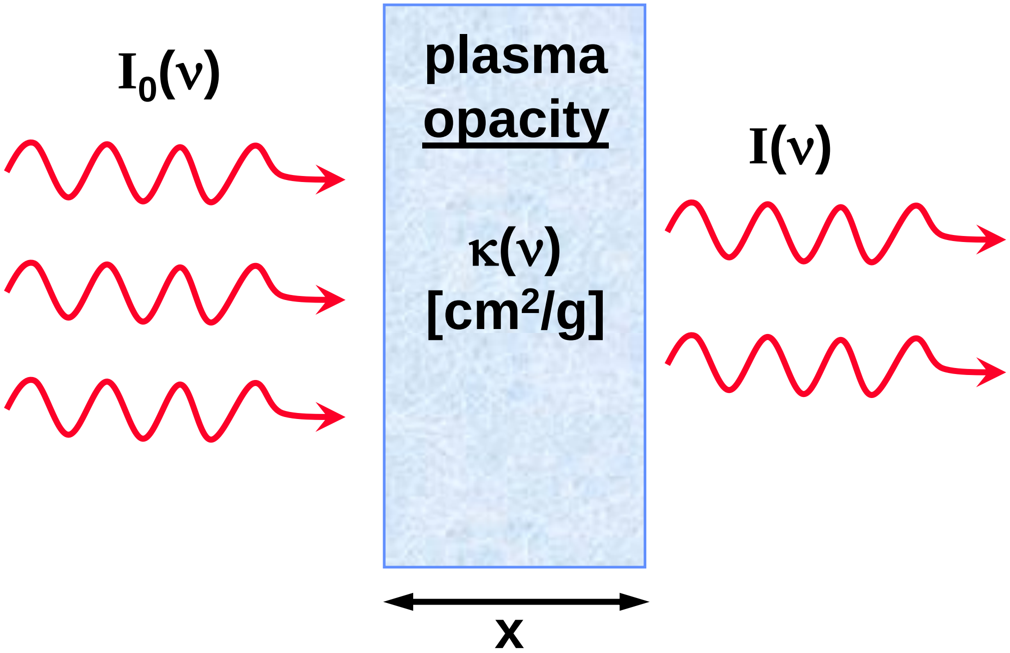
Opacity quantifies how transparent or opaque a plasma is to radiation



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

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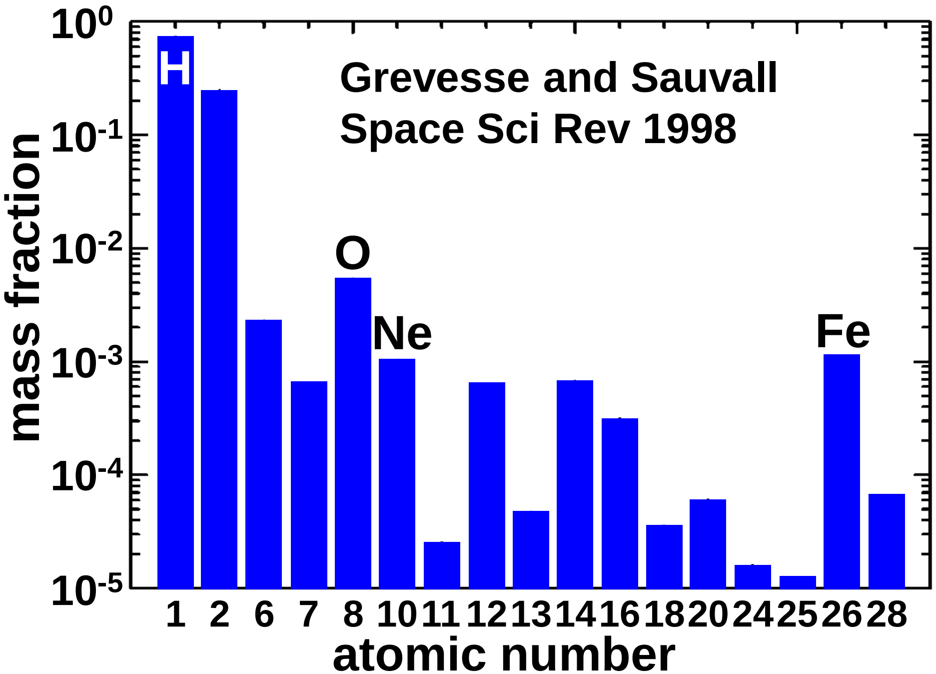
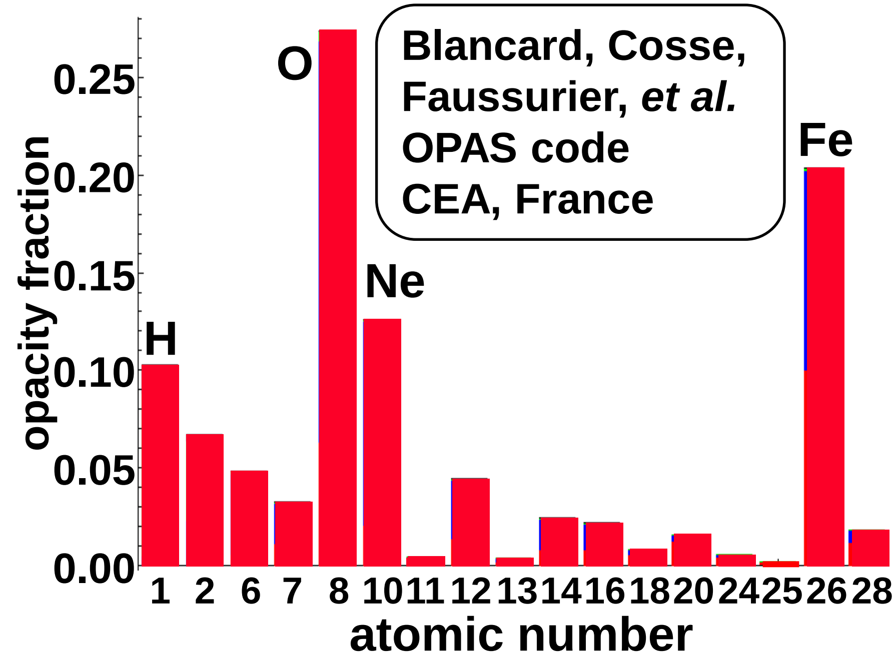
The solar mixture opacity has contributions from many elements



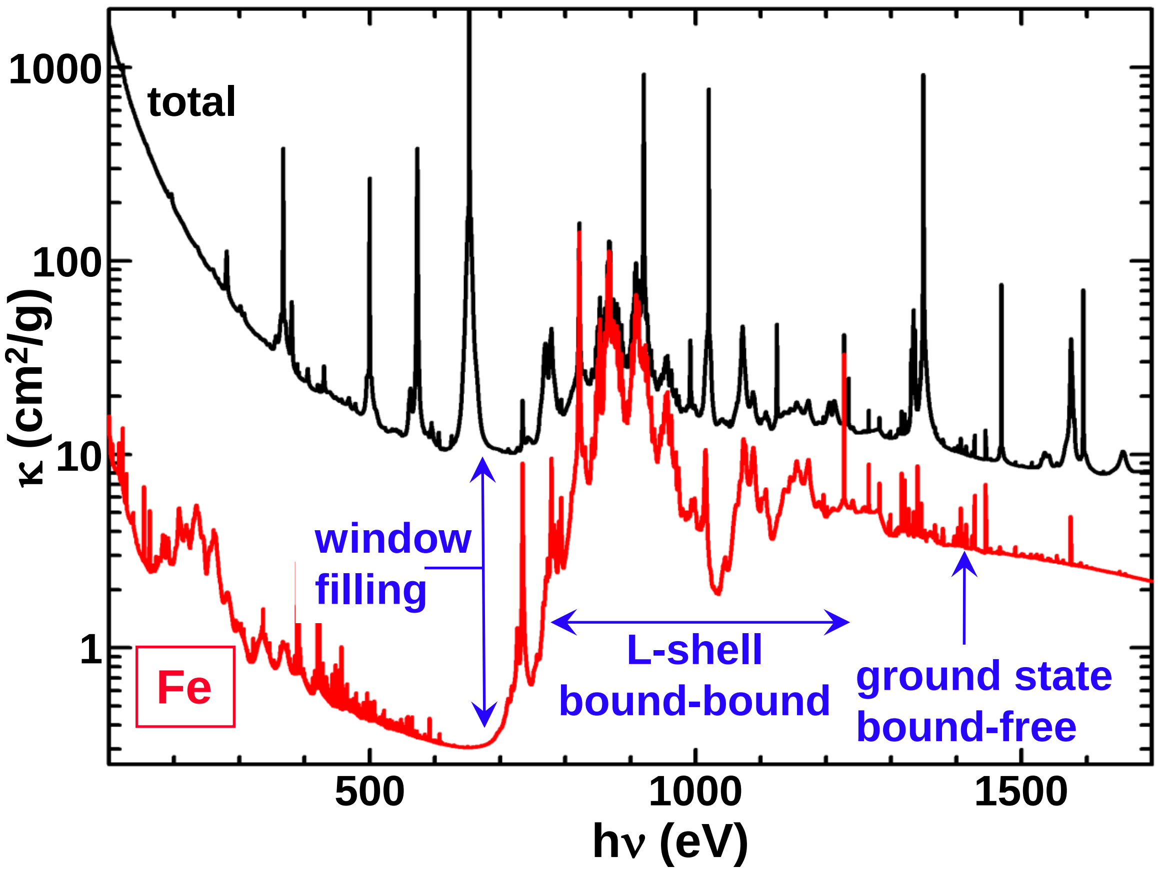


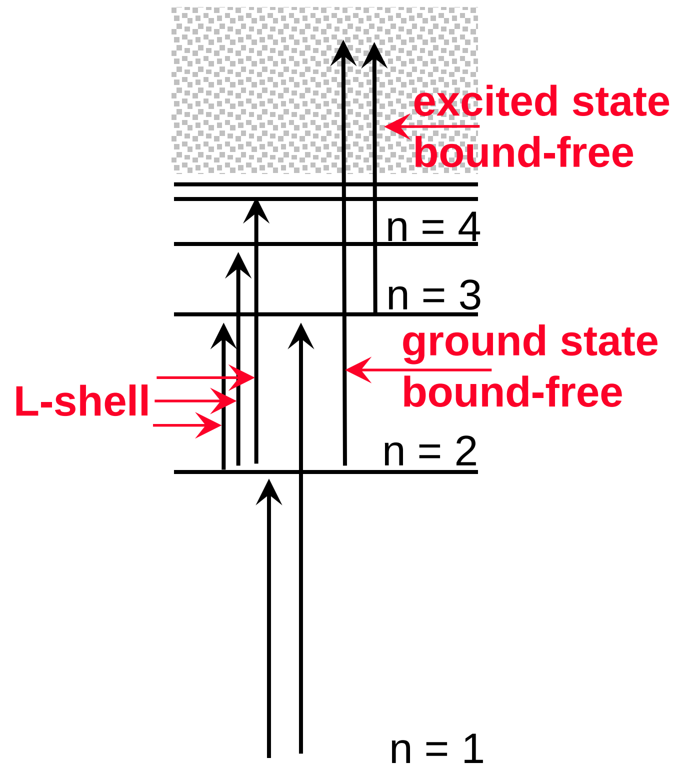
- oxygen, neon, and iron are most important at the CZ base
- The importance of any single element is diluted by the mixture

<u>Example:</u>

Changing Fe opacity by 1.5x causes ~11% change in total mean opacity

Ionization determines how each species contributes. Example: iron at the CZ base



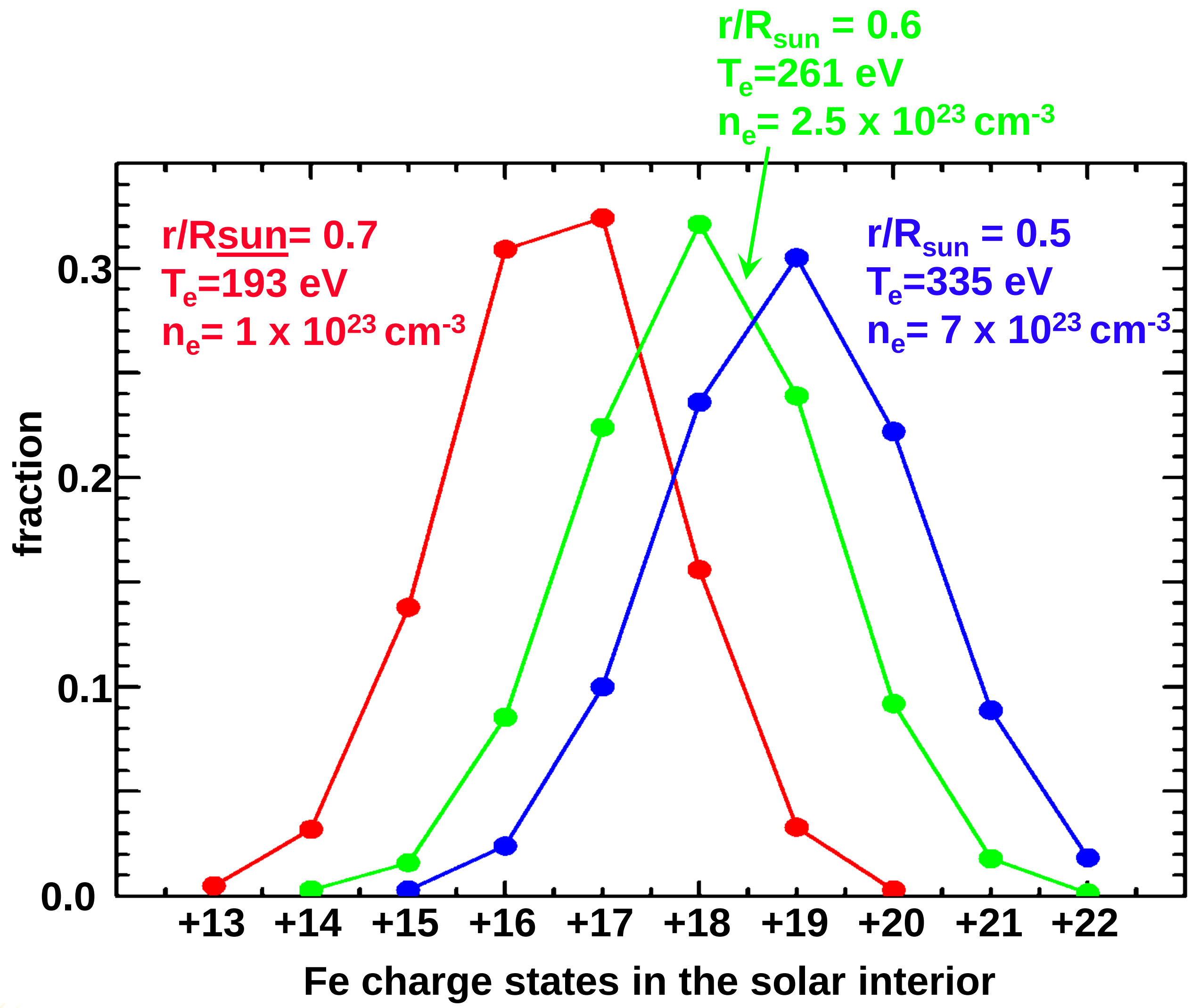


Fe^{+17} : $1s^2 2s^2 2p^5$
F-like

In a pure-iron plasma, bound-free transitions out of excited states are more important

In the solar mixture, the L-shell is much more important

The plasma electron temperature and density determine the ionization



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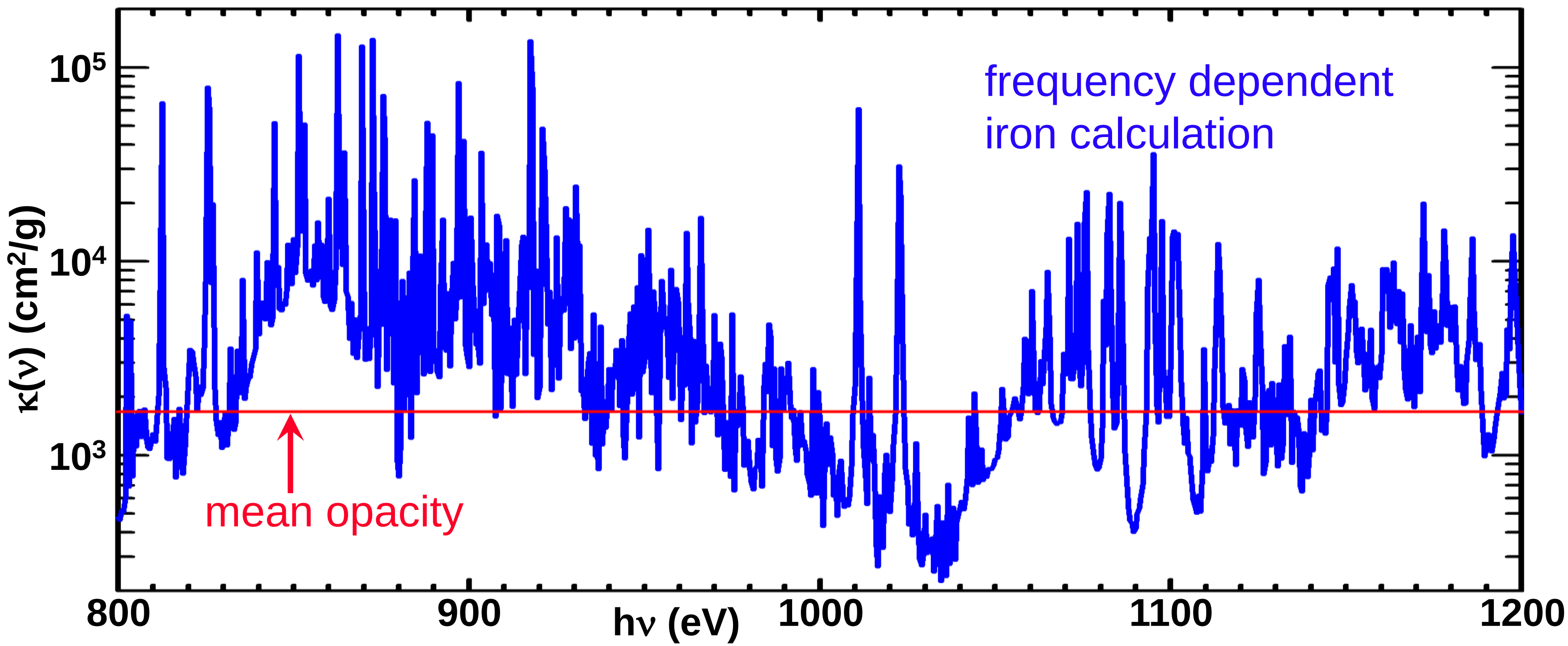
Now we can define a useful opacity experiment for stellar interior physics

- 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

Strategy: frequency-dependent transmission measurements test opacity model physics



Some applications require $\kappa(\nu)$; e.g., levitation in stars

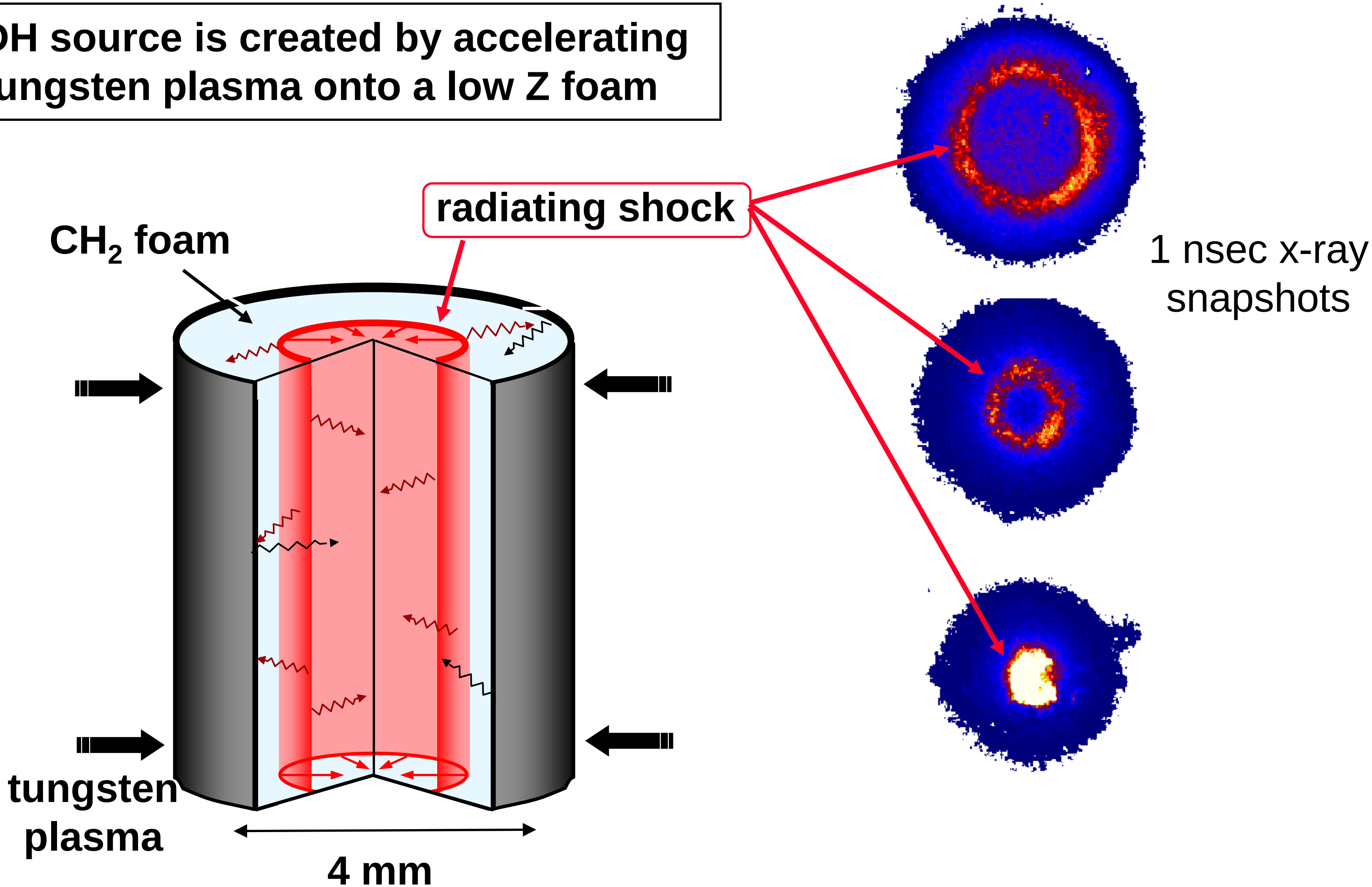
Other applications only use the mean opacity κ_R

In both cases, experiments are scarce. Models must be extrapolated.

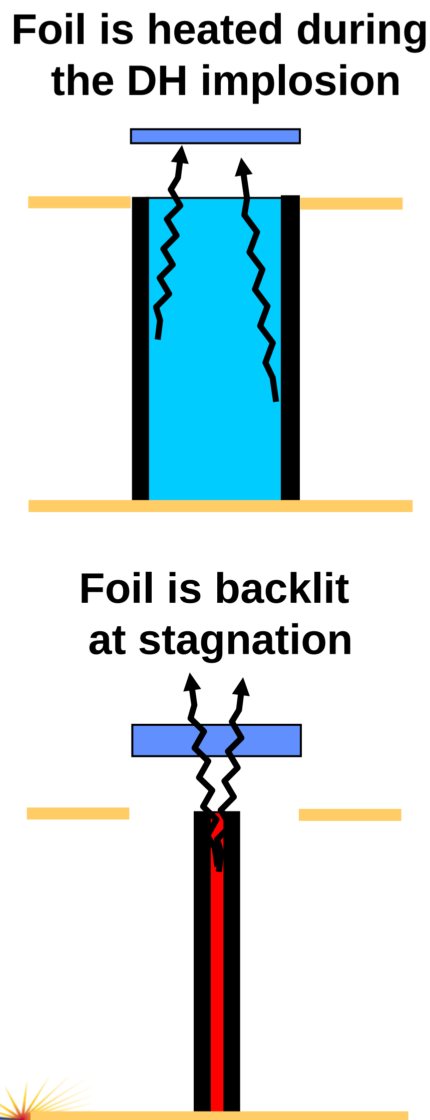
Therefore, we need a reliable physical basis for opacity models.

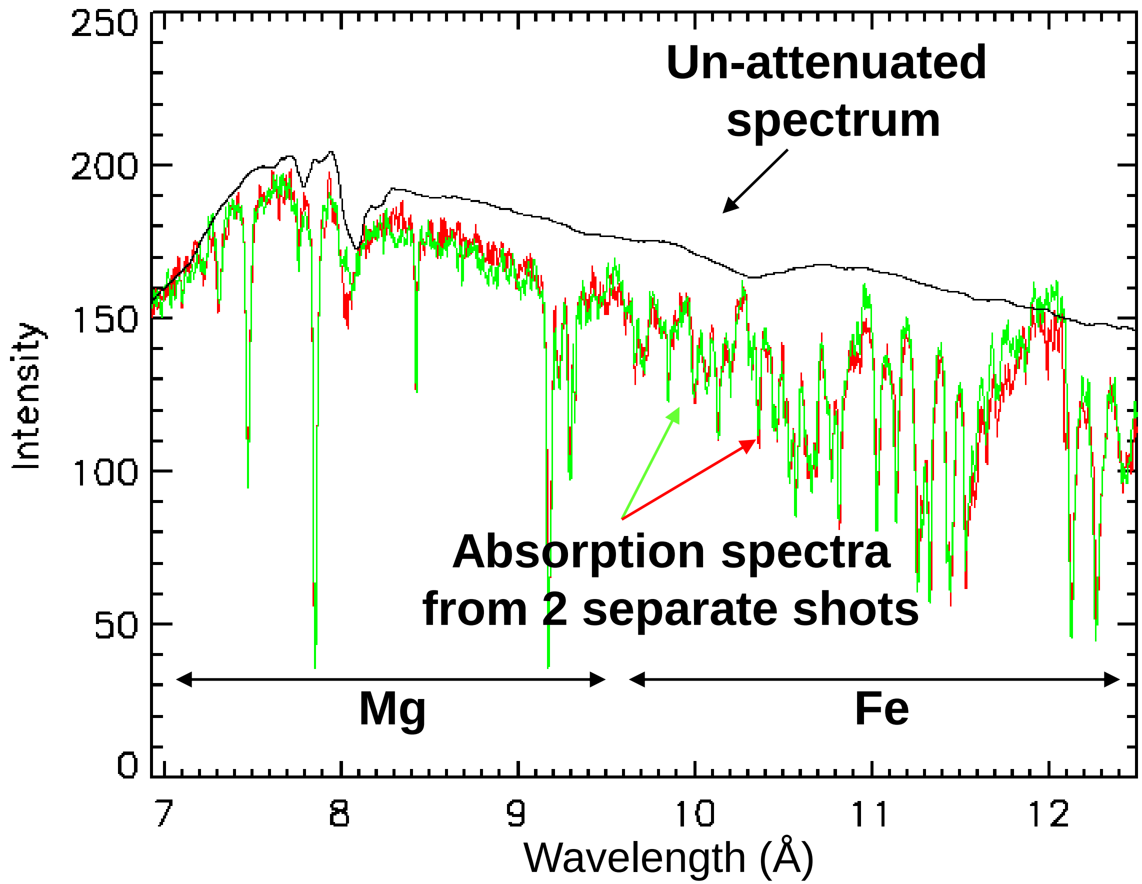
Opacity science experiments use a dynamic hohlraum radiation source

DH source is created by accelerating tungsten plasma onto a low Z foam



Transmission is determined from backlight spectra recorded with and without the sample





- Fe is the test element; Mg provides diagnostics

Opacity experiment requirements

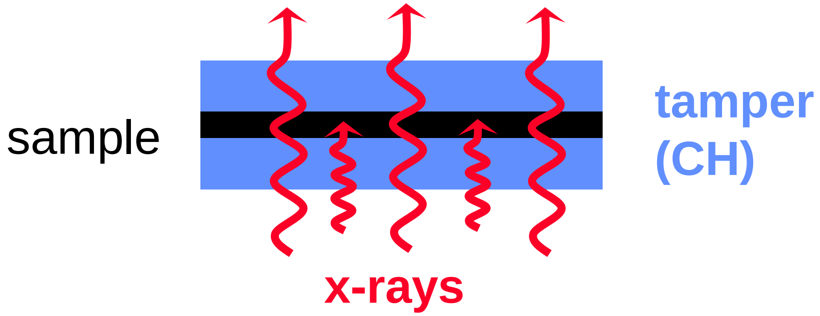
1) Uniform sample heating

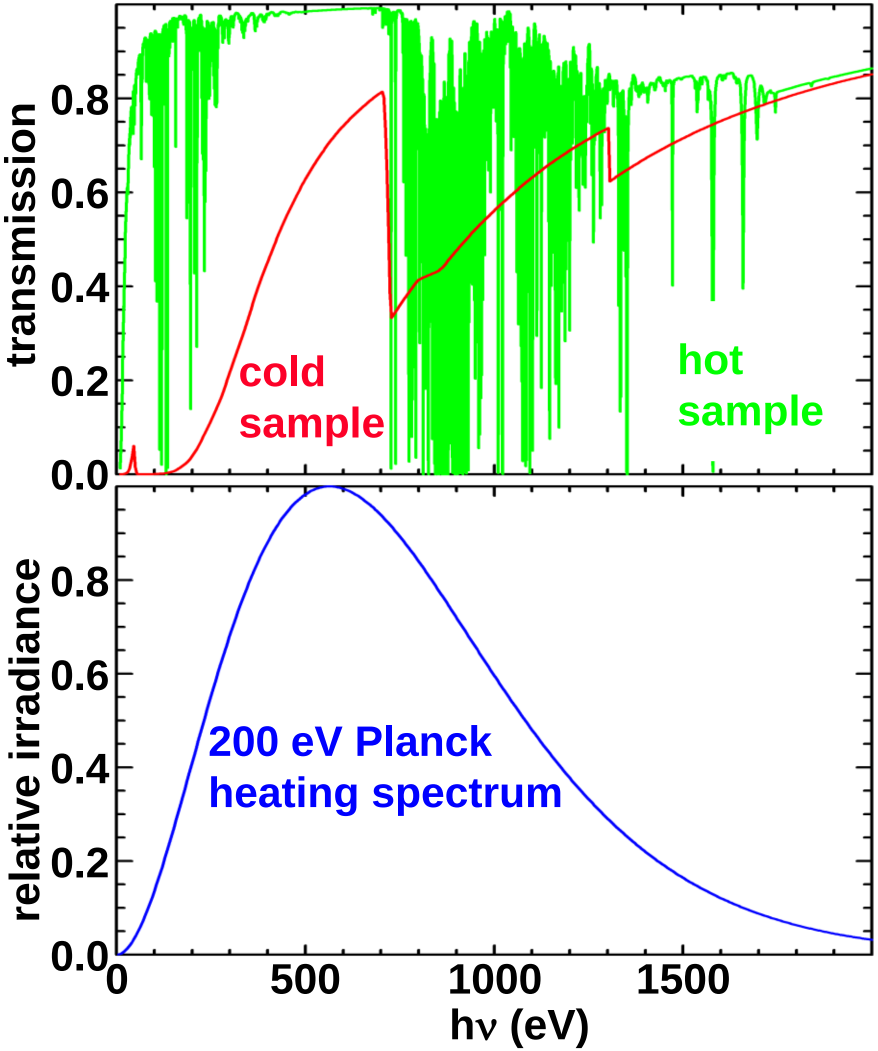
2) Accurate transmission measurements

3) Plasma diagnostics

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

X-rays stream through tamped samples and heat volumetrically





- Transparency implies inefficient heating
- Intense heat sources are required for uniform ***hot*** samples

This is a major reason why large facilities are needed for stellar opacity research

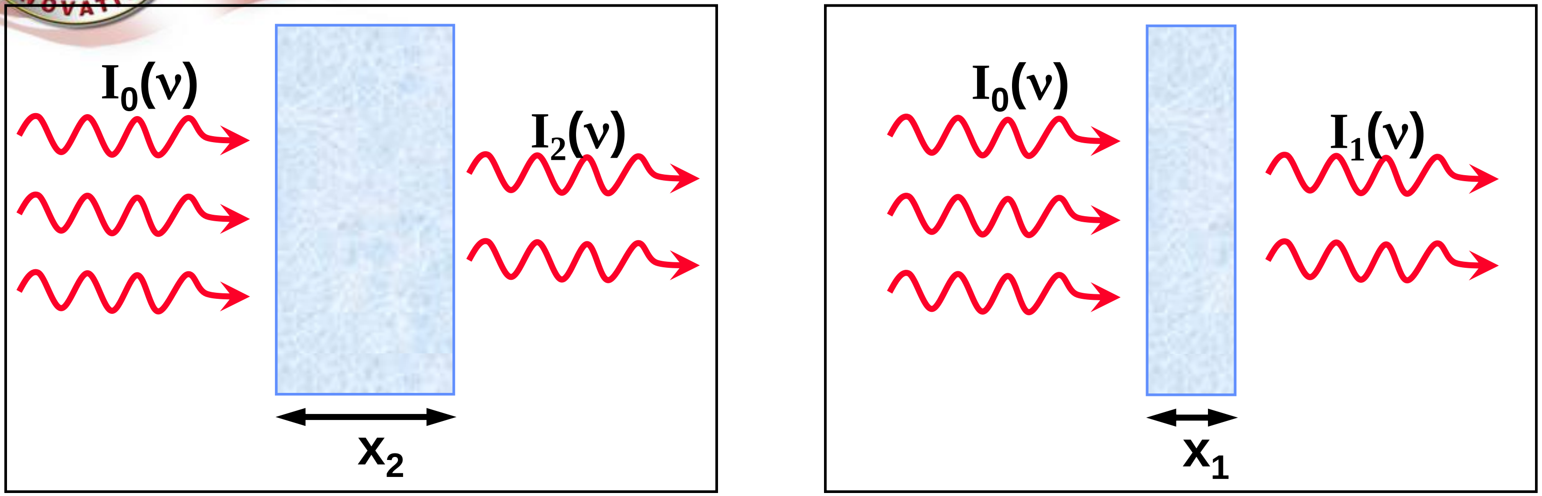
Opacity experiment requirements

1) Uniform sample heating

2) Accurate transmission measurements

3) Plasma diagnostics

Transmission scaling with sample thickness tests for possible experiment flaws



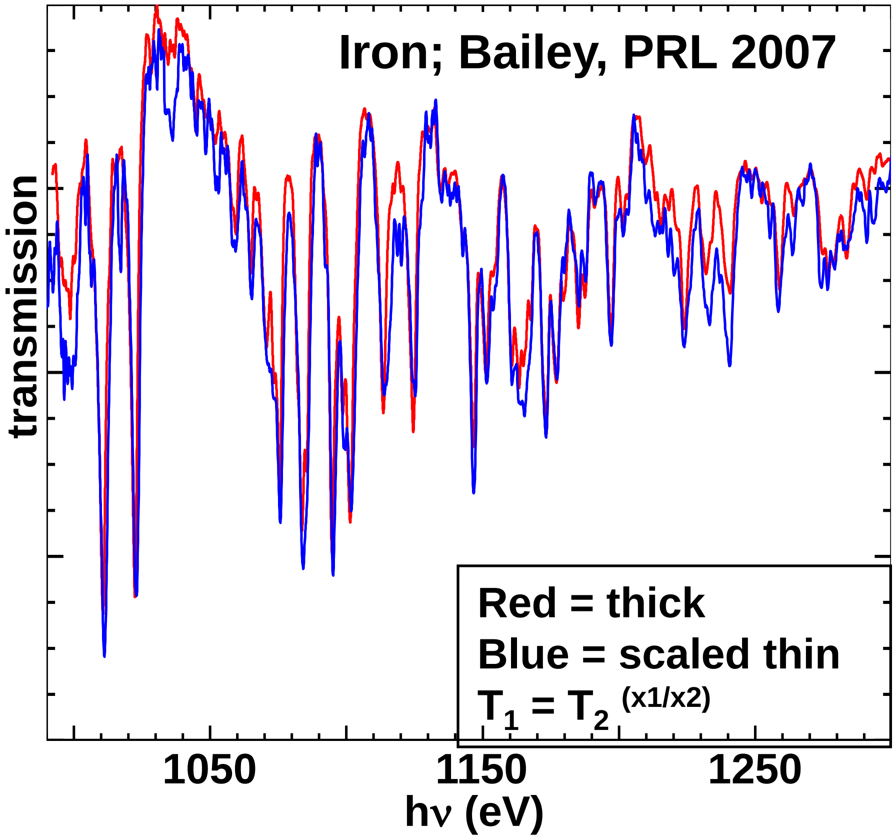
Beer/Lambert/Bouguer Law: $T = \exp\{-\kappa\rho x\}$

Expected scaling with thickness : $T_1 = T_2^{(x1/x2)}$
e.g., if $X_2 = 2 * X_1$, then $T_2 = T_1 * T_1$

<u>experiment problems cause transmission scaling to deviate:</u>

- **Sample emission**
- **Background subtraction**
- **Crystal defects**
- **Gradients**

Transmission scaling with thickness confirms experiment reliability



Agreement rules out un-desired effects such as:

self emission

gradients

transmission errors

Opacity experiment requirements

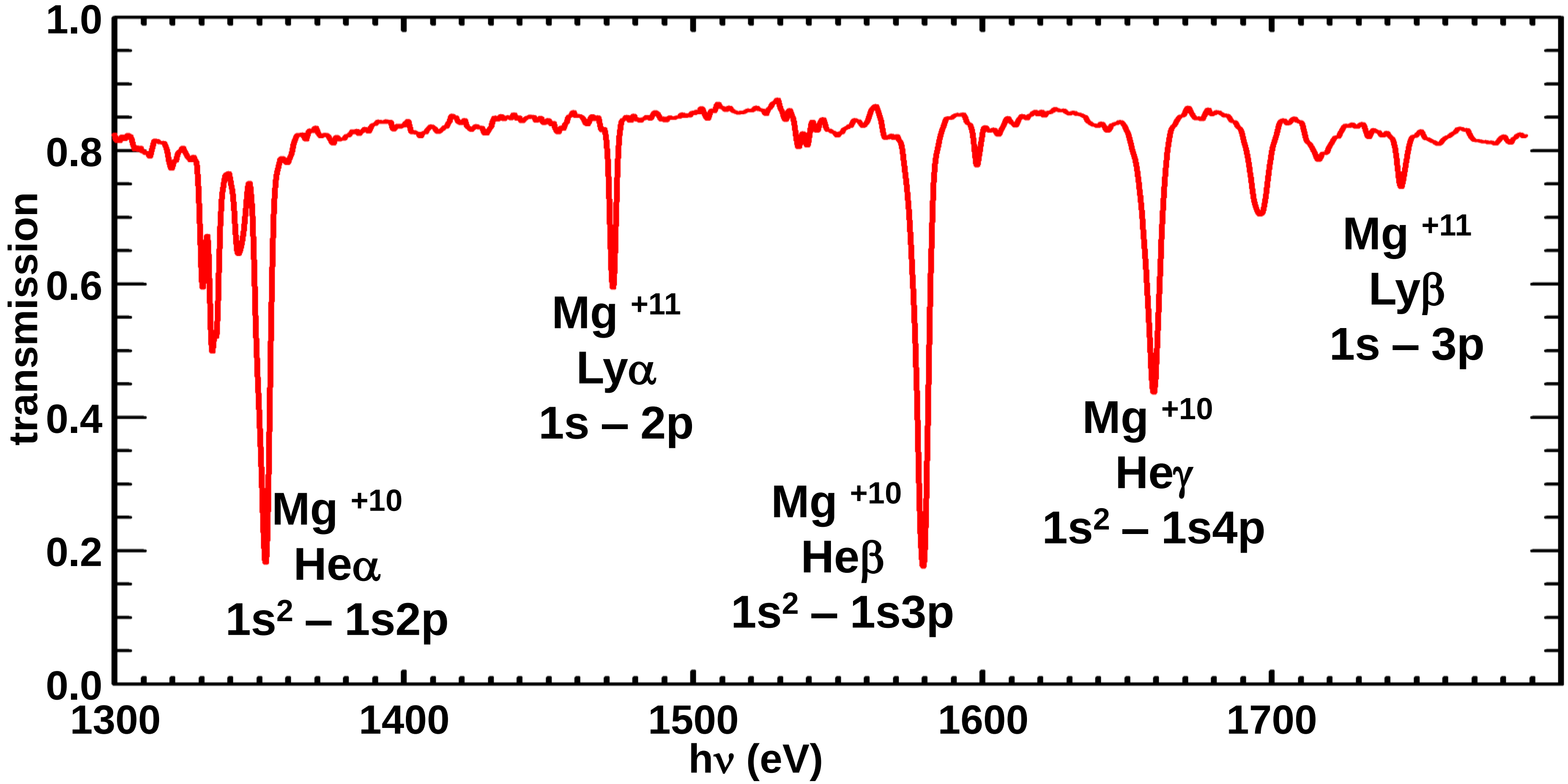
1) Uniform sample heating

2) Accurate transmission measurements

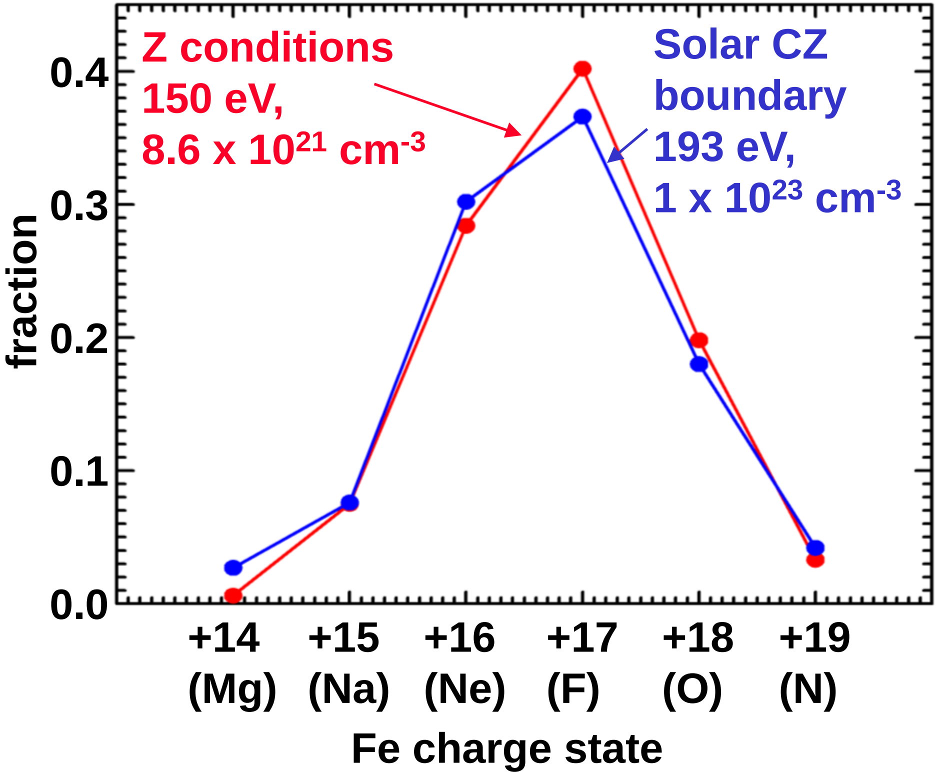
3) Plasma diagnostics

K-shell absorption spectra provide density diagnostics and a sample "thermometer".

Line absorption strength ratios provide temperature
Line profiles provide density



Z experiments produce the iron charge states that exist in the solar interior



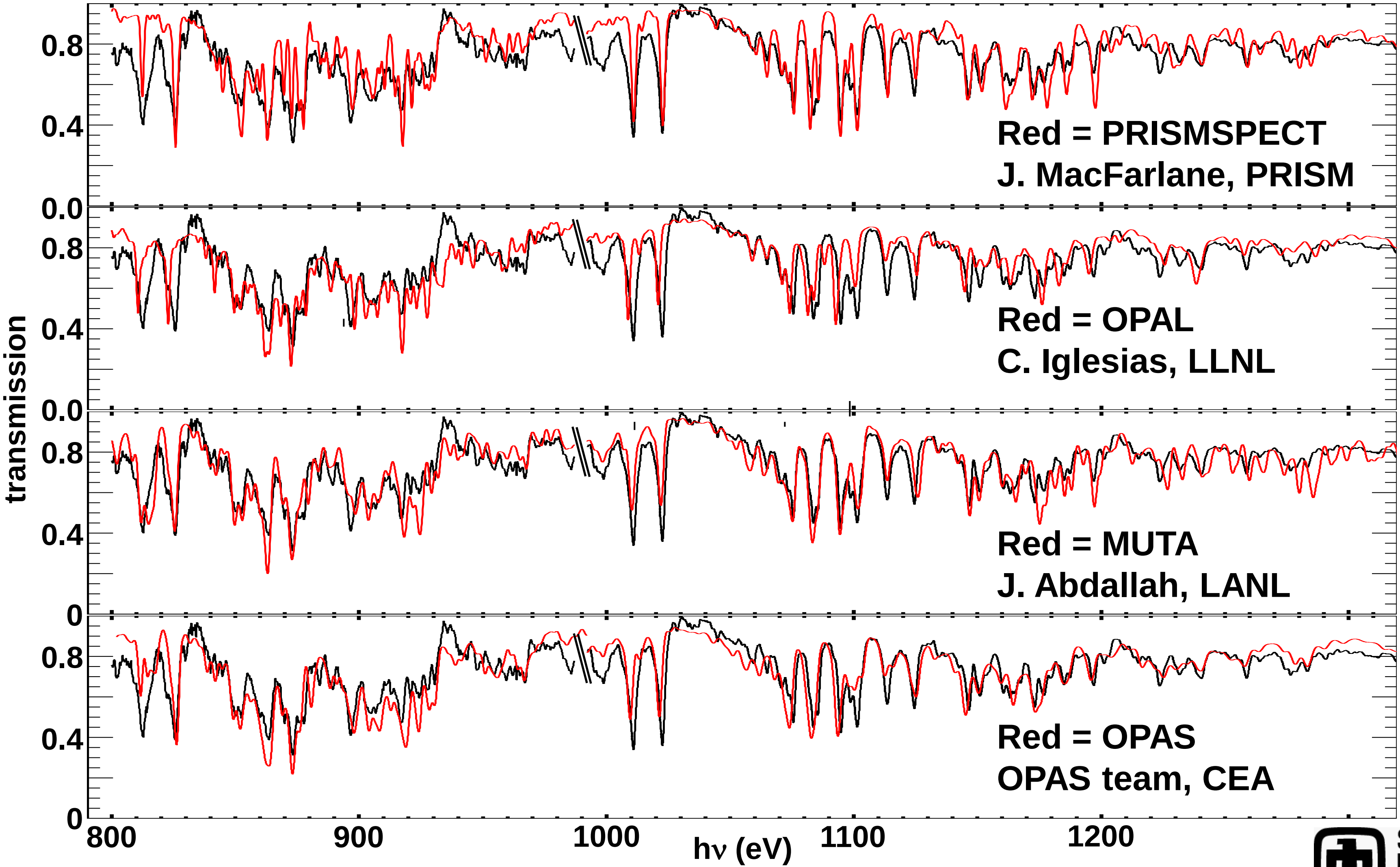
Producing the correct charge states enables opacity model tests:

1) Charge state distribution

2) Energy level description

High density studies require further progress

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



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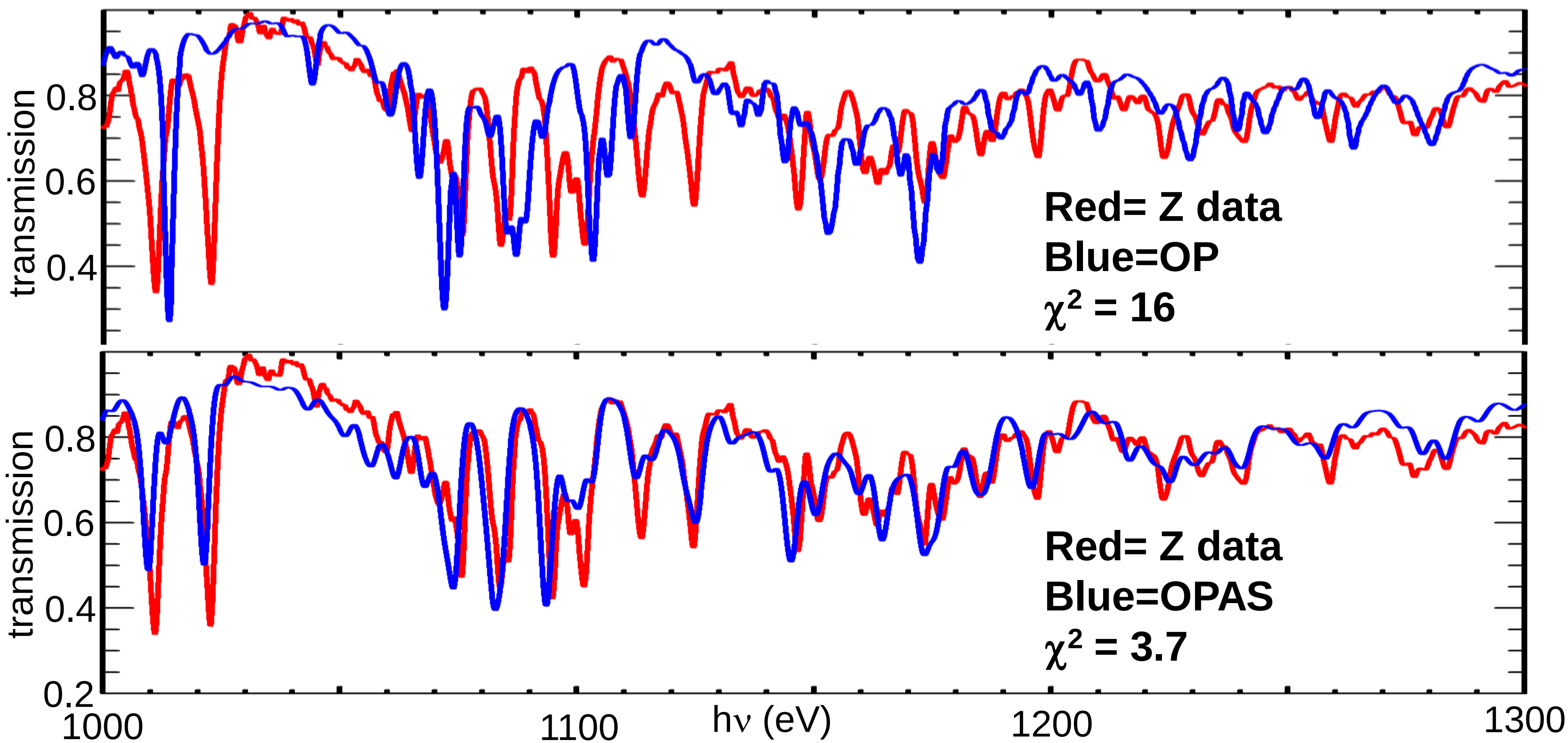
The OP model used in solar research predicts Fe L-shell opacity that is too low at Z conditions



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

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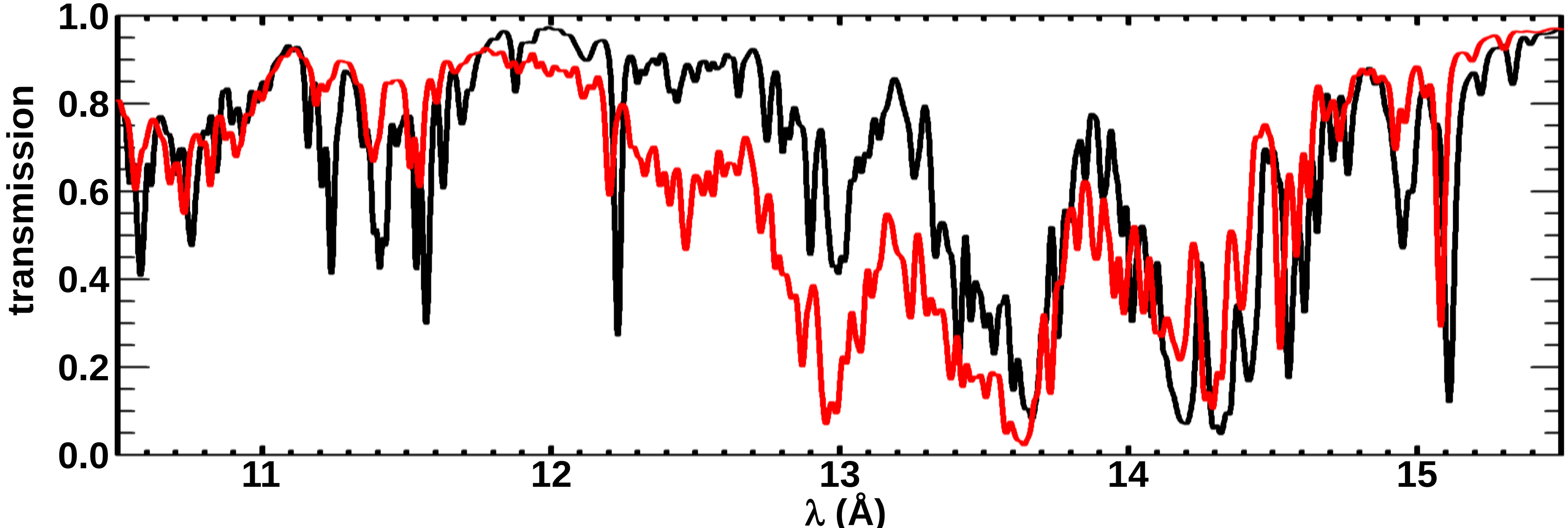
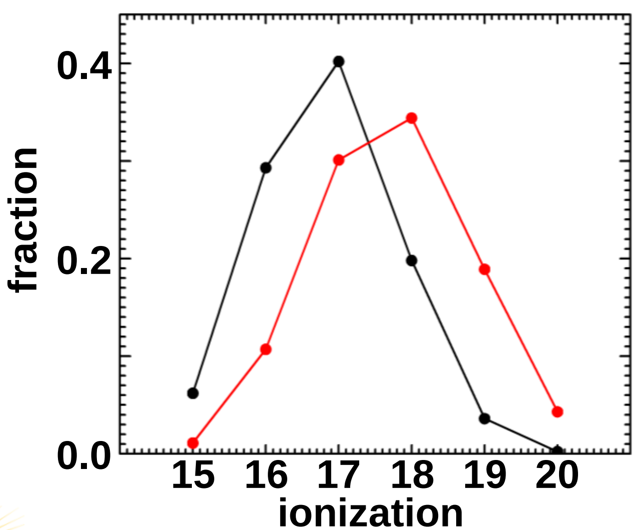
Experiments at higher n_e and T_e are a logical next step in stellar opacity research





<u>OP calculations</u>

Black: 153 eV, 1x10^{22} cm^{-3}.

Red: 193 eV, 3.2x10^{22} cm^{-3}.

Differences due to ionization shift, continuum lowering, line broadening, inner shell excitation

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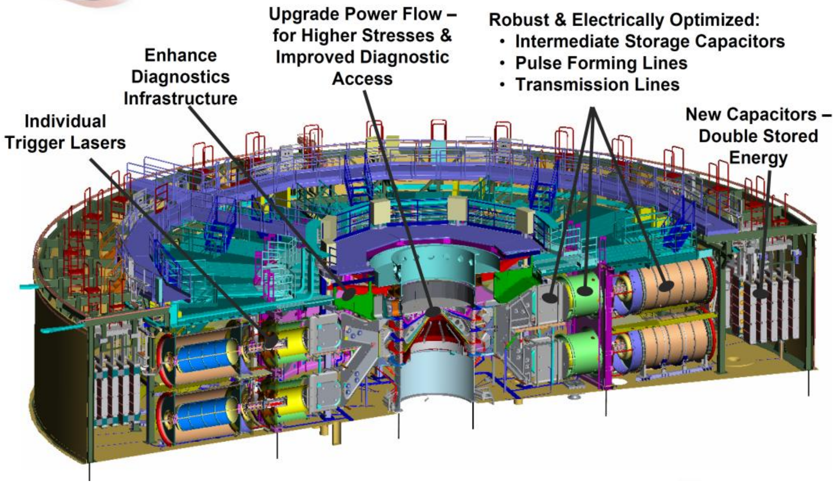
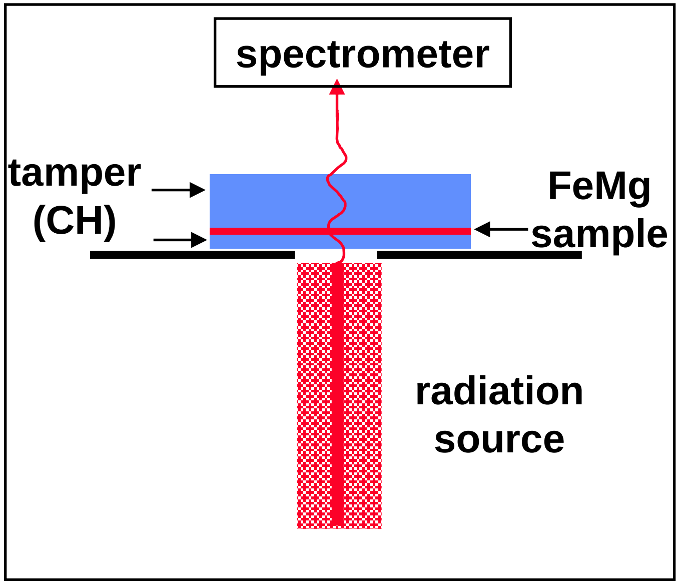
The refurbished Z significantly increased the energy available for opacity experiments





<u>New Z</u>

The refurbished Z delivers 24 million Amps to the load

50% electrical energy increase in present day experiments

100% increase possible, full capacity

<u>New sample design</u>

Increasing the rear tamper thickness increase pressure

This increases ne, Te in the Fe/Mg

<u>New challenges</u>

Diagnostics re-engineering

Opacity platform recertification

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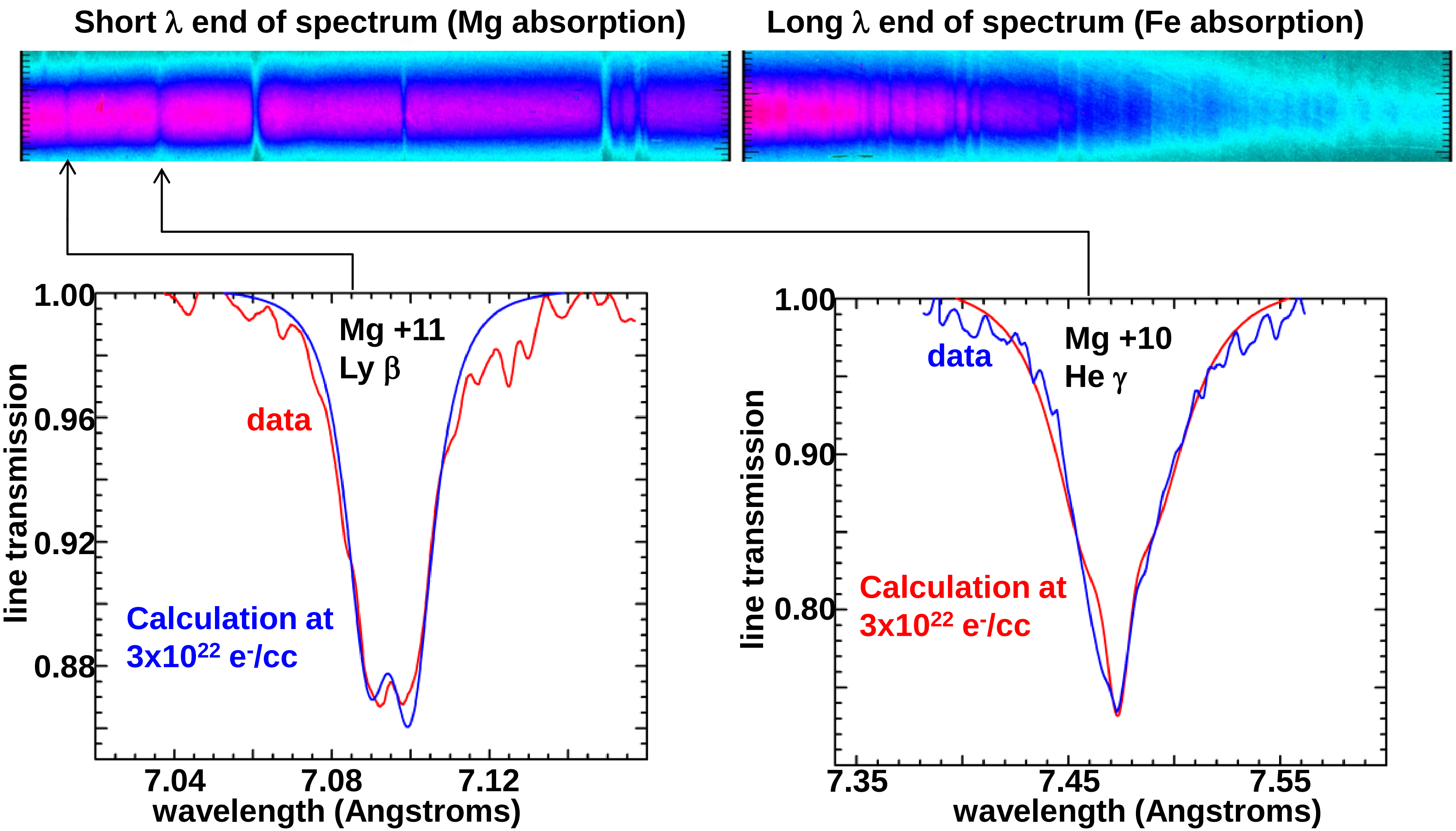
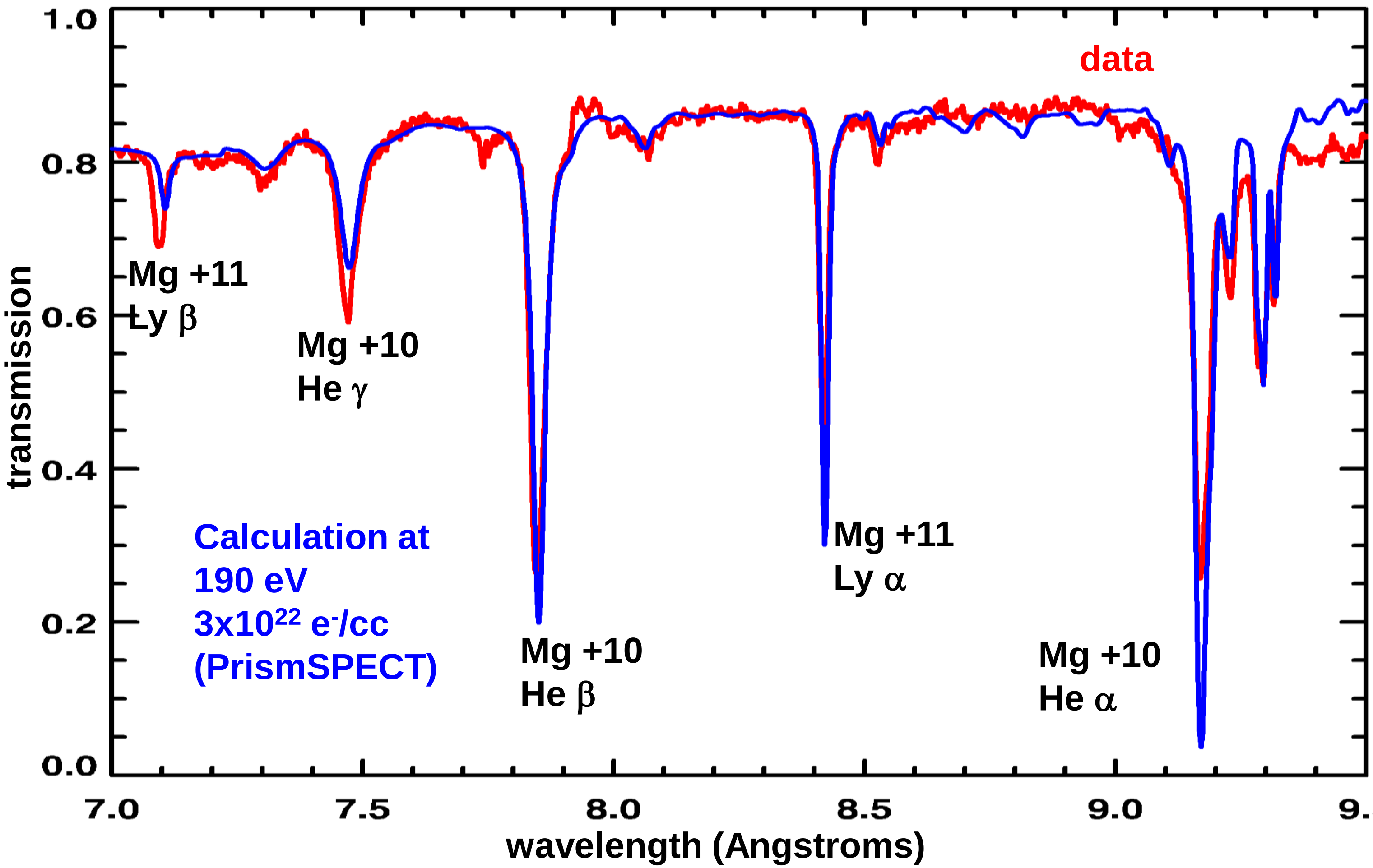
The density in new Z experiments is within a factor of three of the CZ boundary value

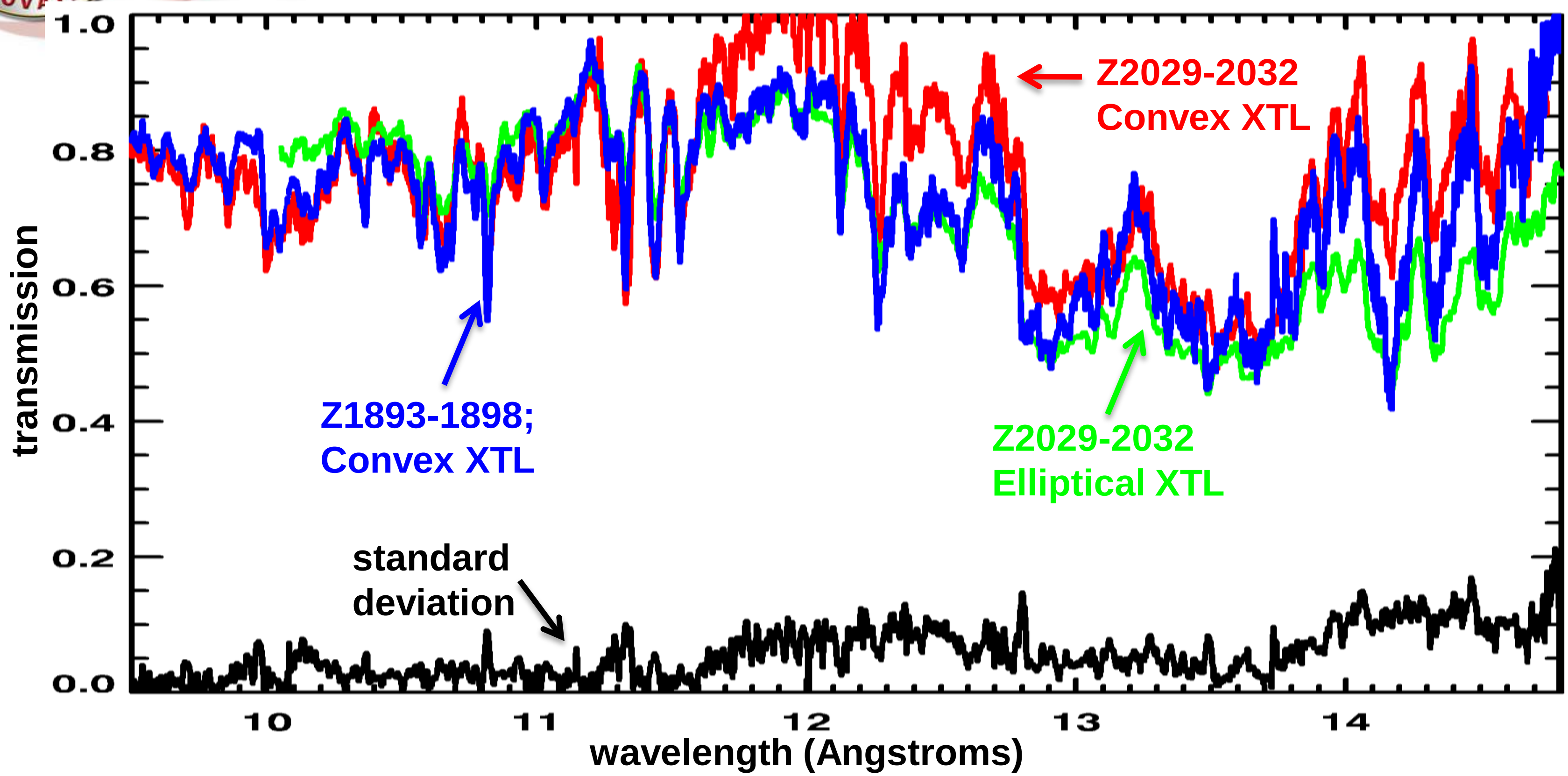


Most recent experiments reached even higher densities

New Z experiments reach the temperature at the solar convection zone boundary

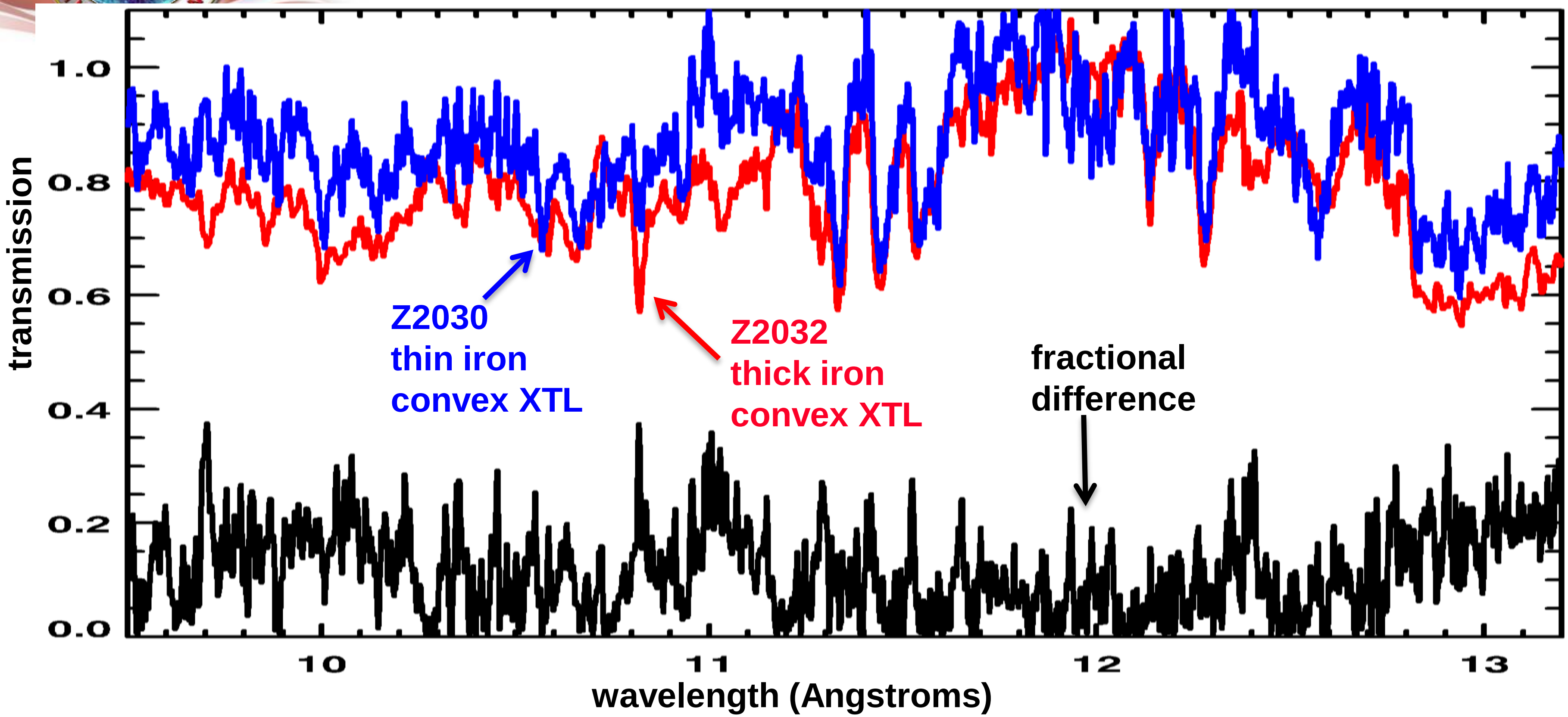


New Z experiments are reproducible to better than ± 10%



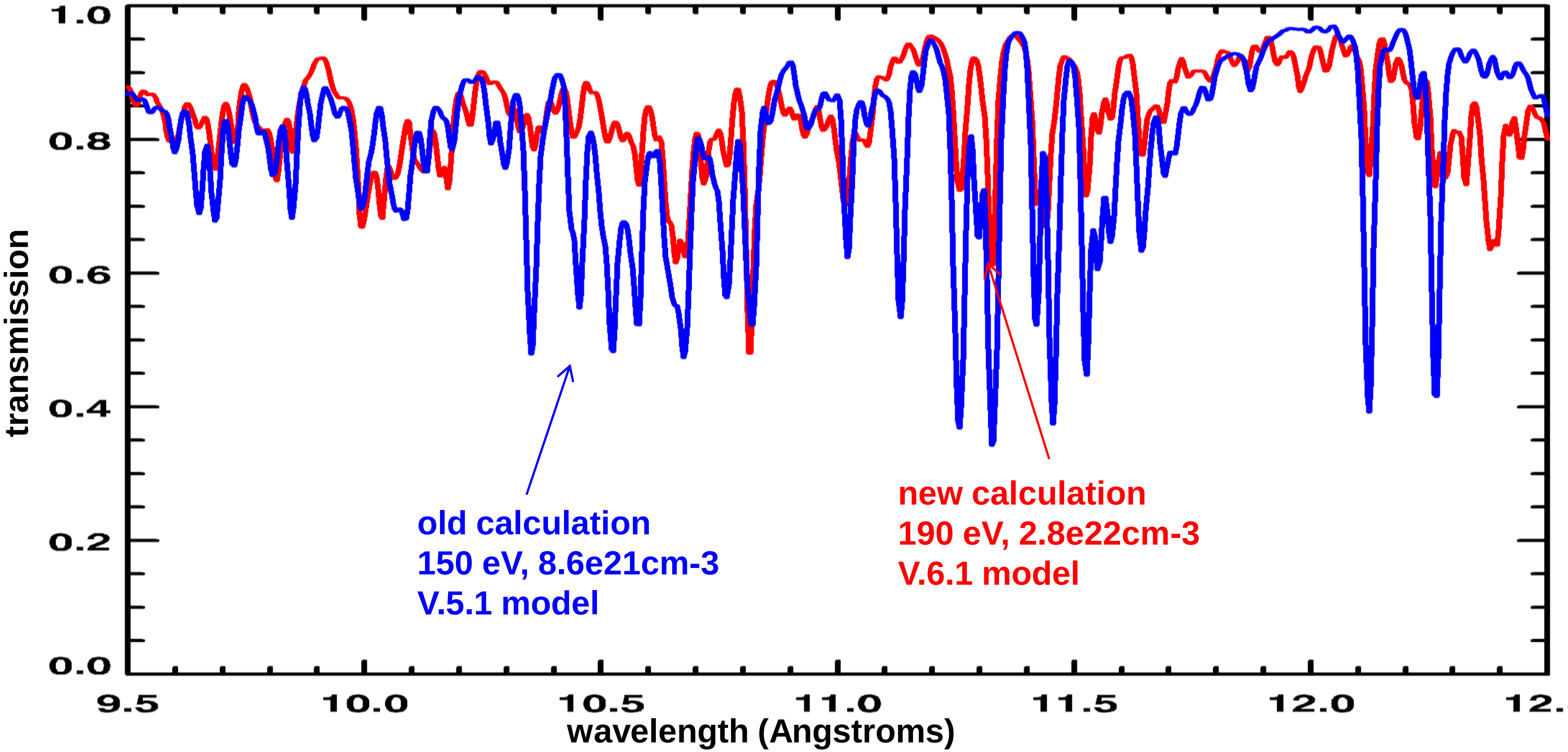
Each measurement is itself an average over 3-6 measurements
One estimate for the uncertainty in the mean is just [sdev/sqrt(3)]
<σ> ~ ± 4.8% over the 10-15 Angstrom region

New Z experiments scale according to Beer's Law to within ± 11%

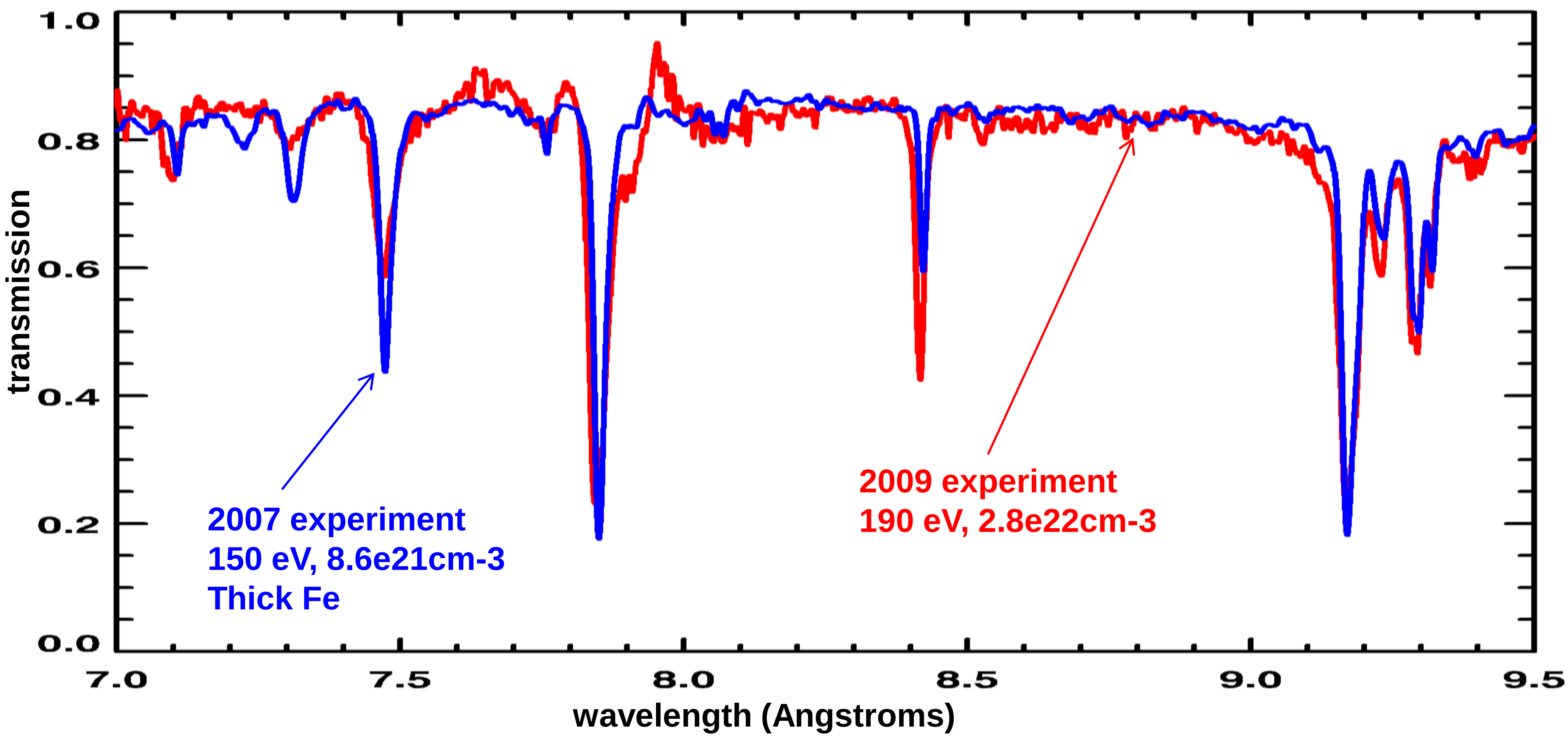


- Average difference between the two measurements is 11%
- Note that possible problems such as self emission would render the thin iron case lower than the thick iron – we observe no such problems
- This result is confirmed by elliptical spectrometer measurements

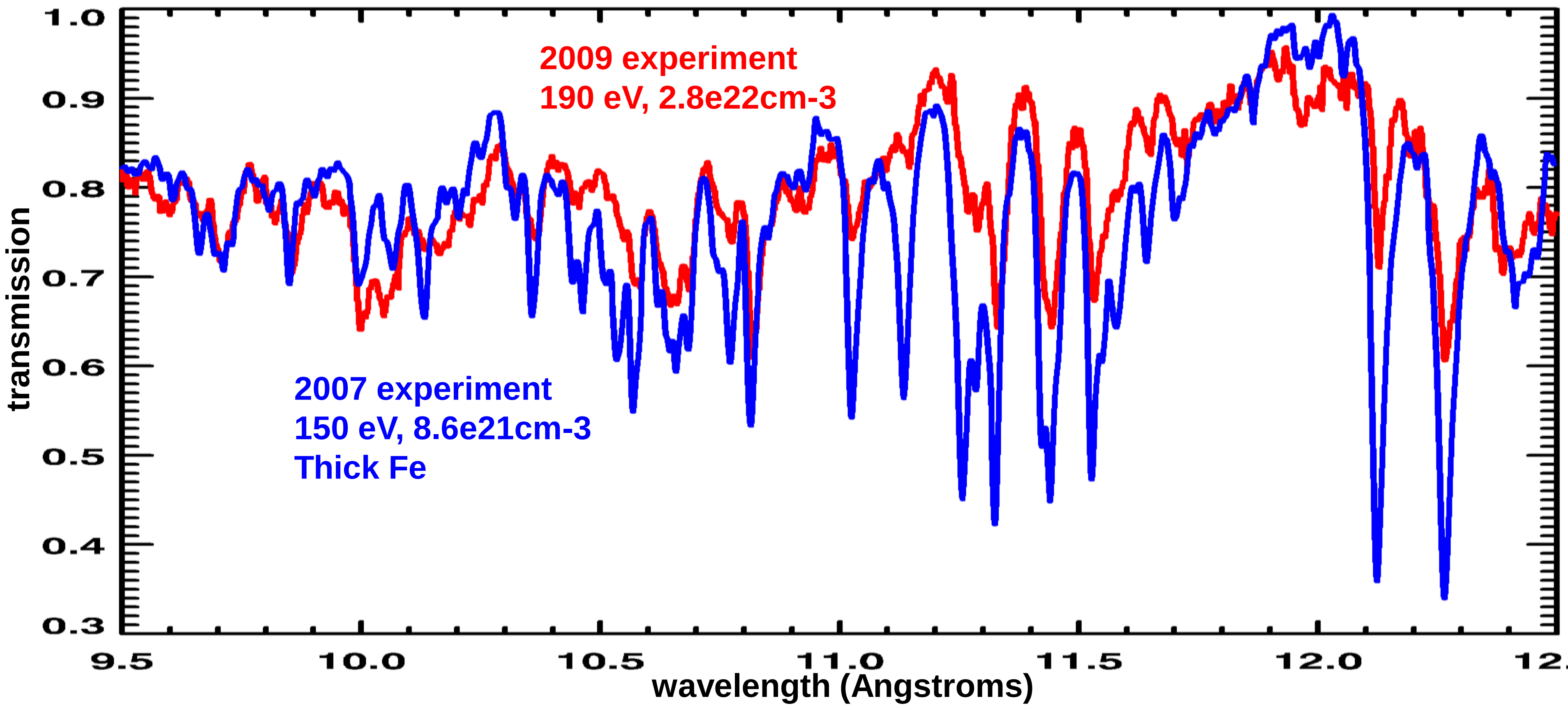
PrismSPECT calculations predict significant changes as the conditions change



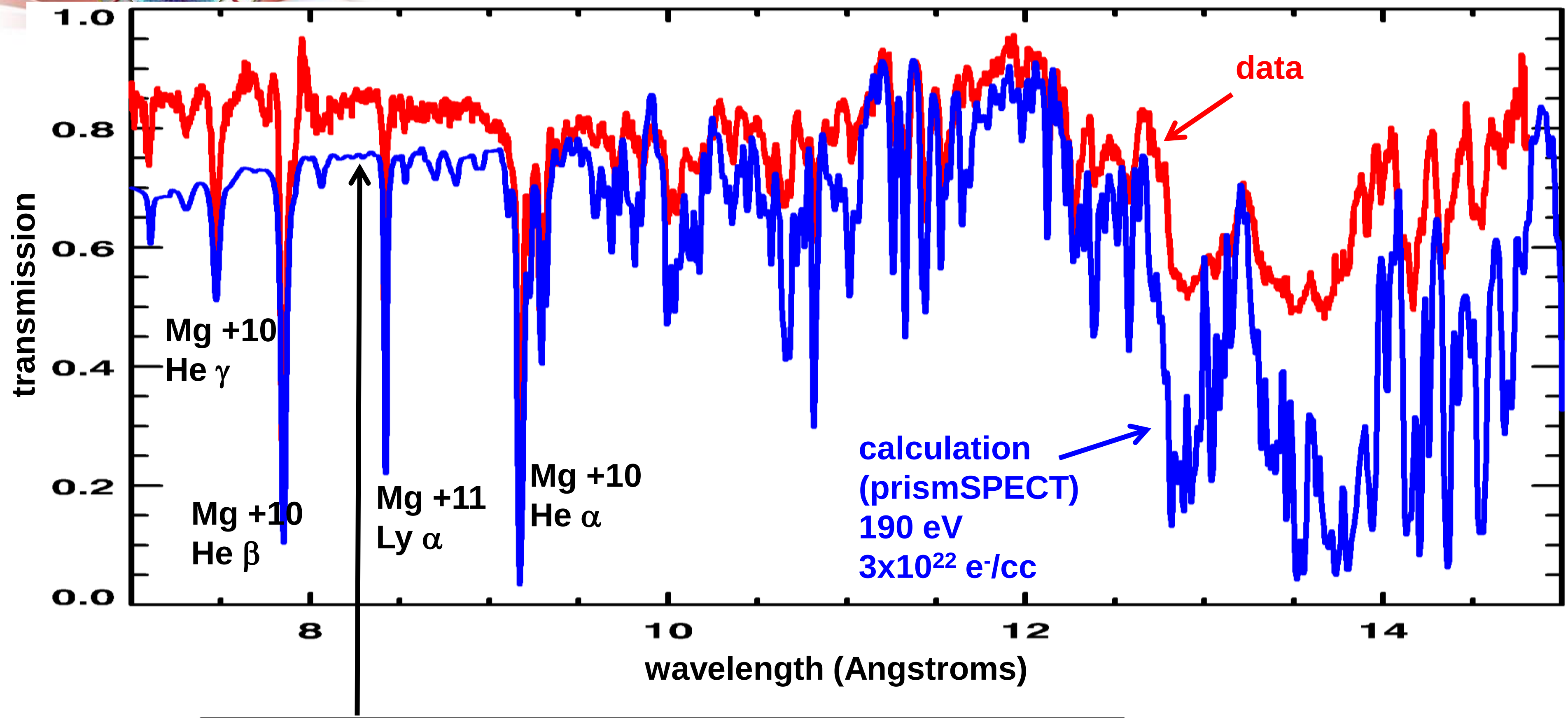
The change in plasma conditions causes significant changes in transmission



The change in plasma conditions causes significant changes in transmission



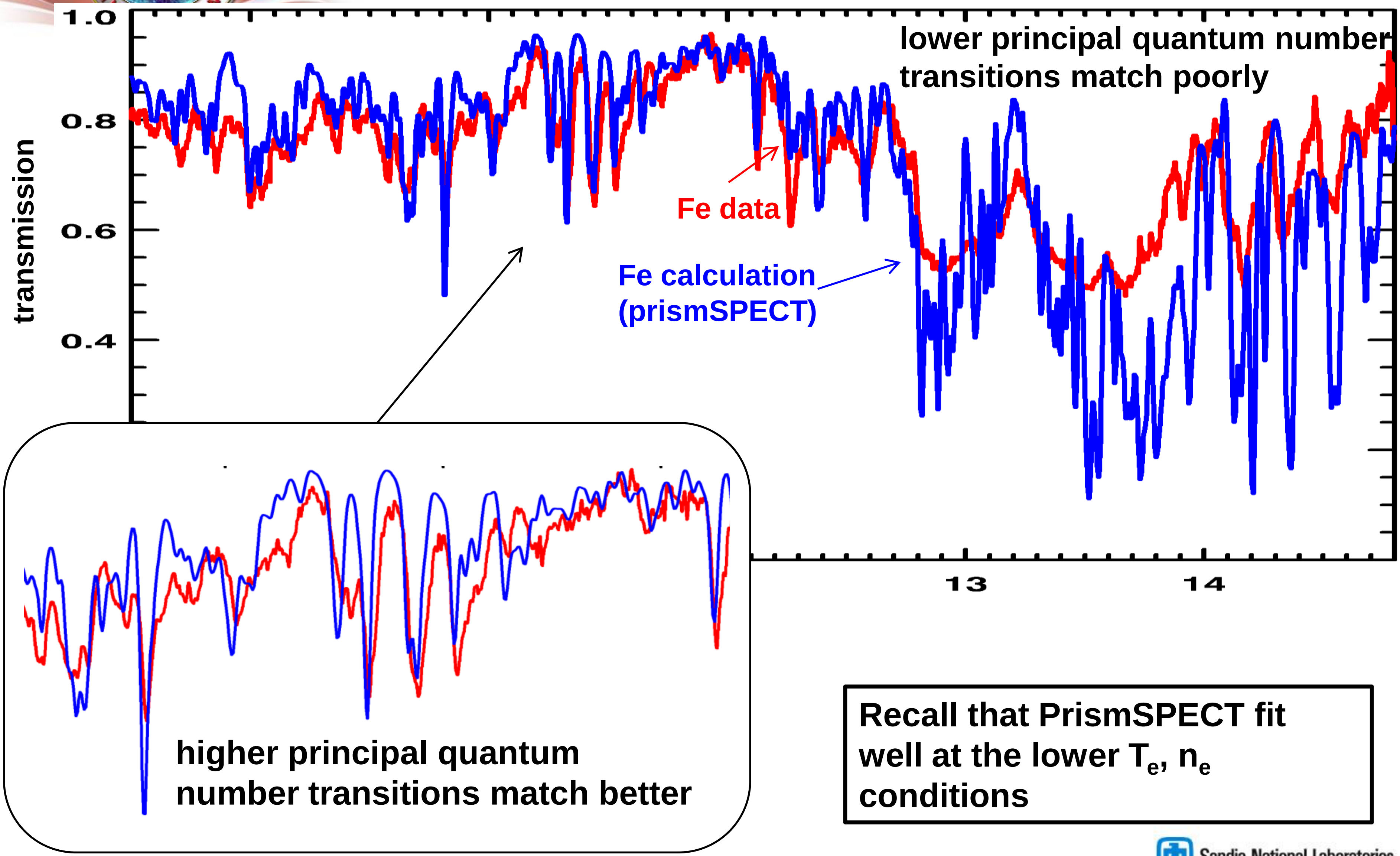
Discrepancies exist in opacity model tests, even for models that agreed in prior work



This difference in continuum absorption implies a ~ 1.6x difference in optical depth

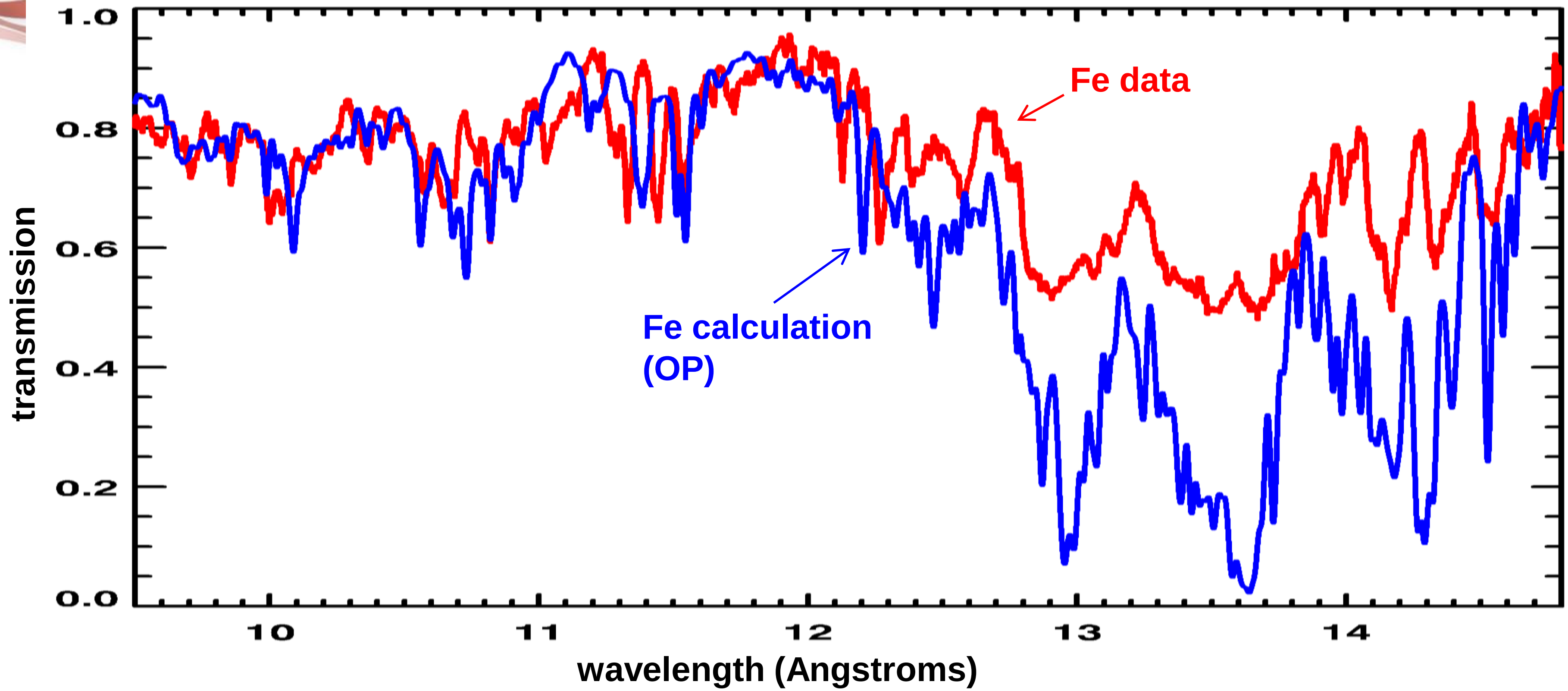
Either the experimental areal density is wrong or bound-free absorption is not accurate

Discrepancies with preliminary data persist even if we scale the areal density to match



Recall that PrismSPECT fit well at the lower T_e, n_e conditions

Discrepancies with preliminary data exist in comparisons with other models

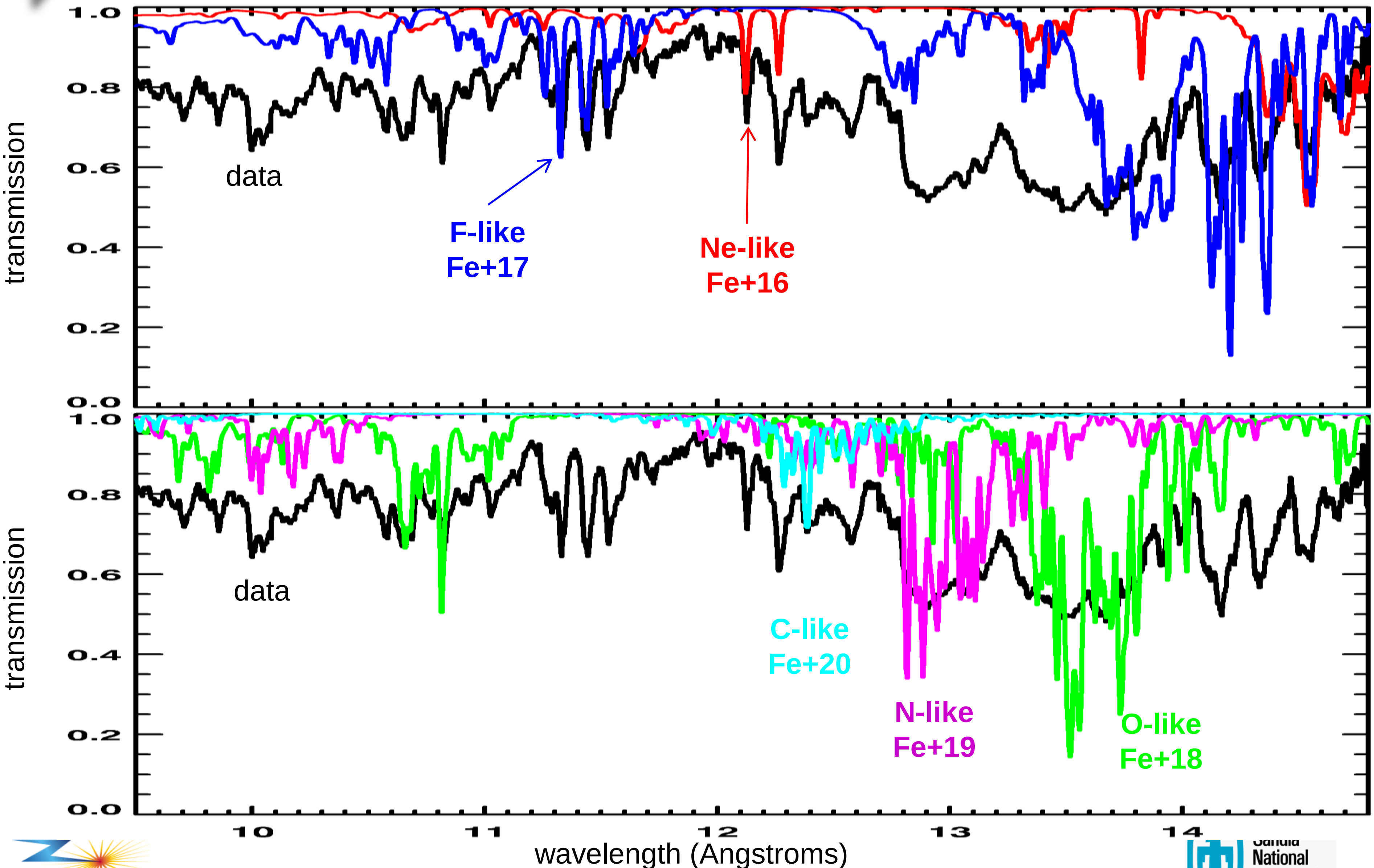


Could be experiment problems – this analysis was preliminary

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

Probably it is both

To investigate model discrepancies we must identify the spectral features



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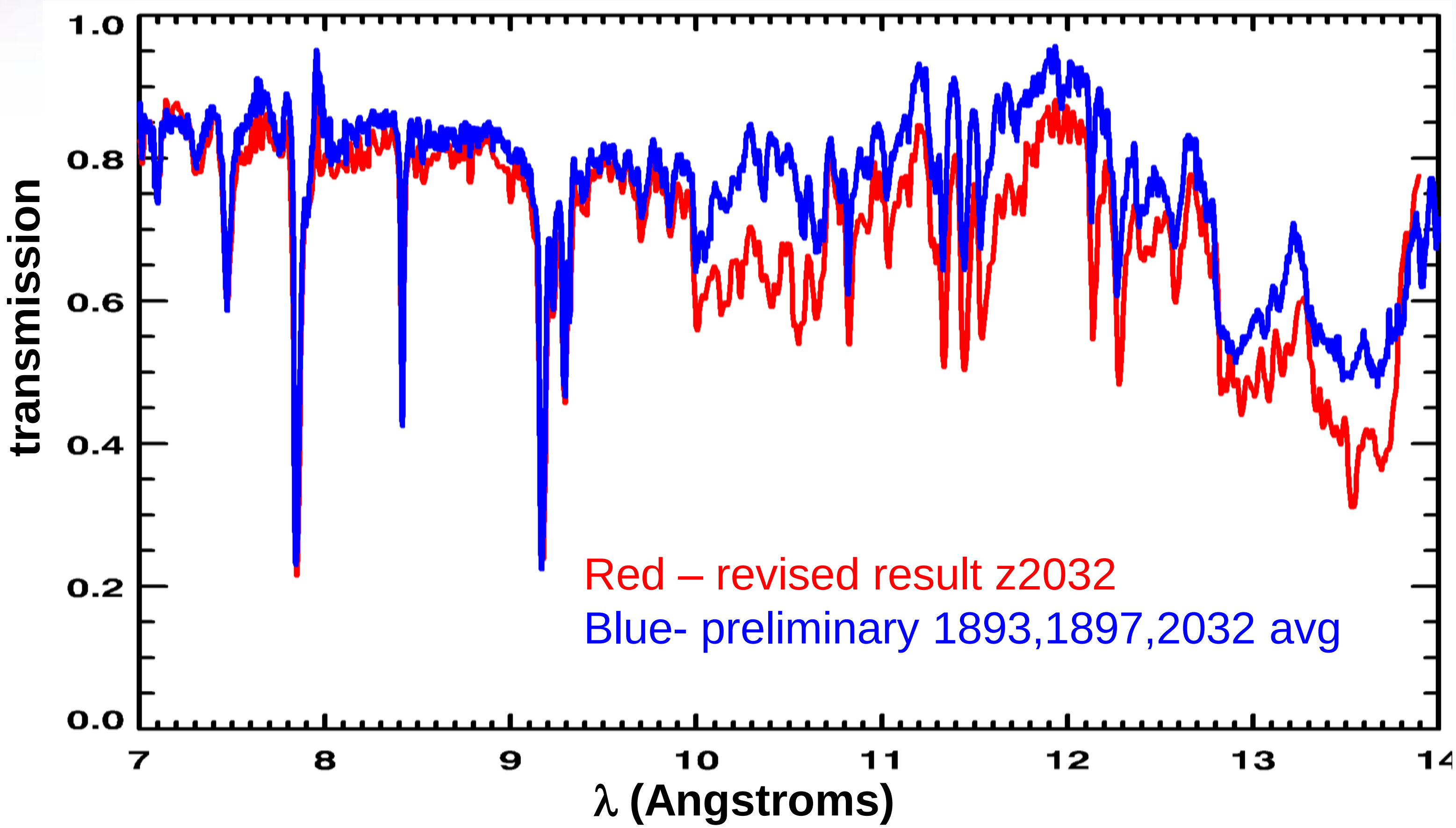
Continued scrutiny of experiments has led to several analysis refinements

1. Improved image orientation
2. Accurate lineout position relative to backlight spatial distribution
3. Accounting for 1D spatial integration
4. Subtraction of high order crystal reflections

Transmission revision is in progress; more experiments needed to reach benchmark quality



May improve agreement with models – deeper 2-3 features
This is one experiment, re-analysis of other experiments in progress
Revisions not yet complete - Correction for high order reflections remains

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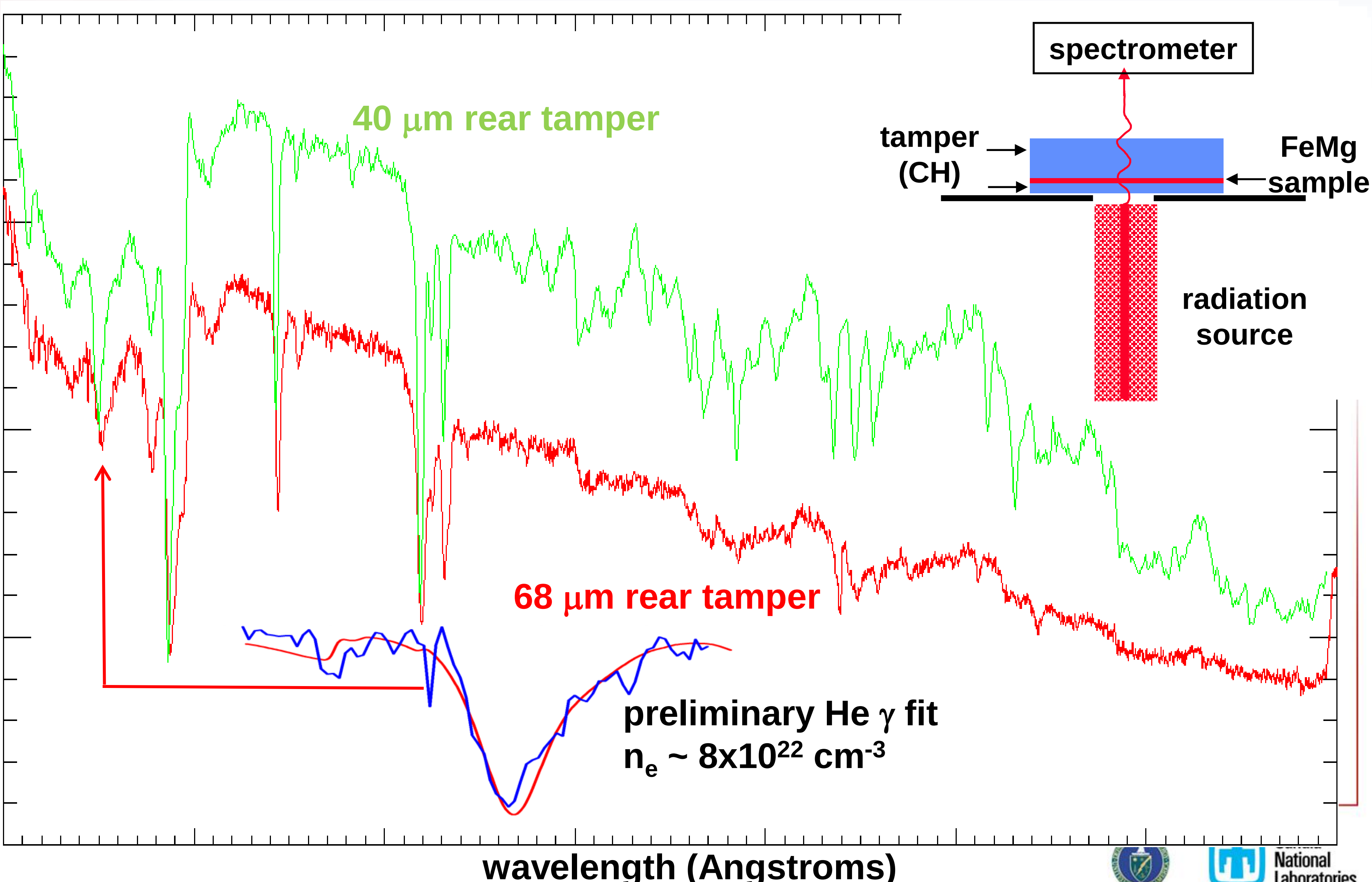
Very recent experiments have extended density to within 10-30% of CZ boundary value



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

- The present comparisons should inspire concern for stellar interior calculations using OP opacities. But note OP and OPAL1996 agree…
- Given the magnitude of the differences, we must continue to check the experiments. But …
- So far we can find no big problems with the data; Beer's Law scaling and reproducibility indicate the data are reliable.

Evaluation of impact on the solar problem, refined experiments, refined calculations, and experiments that further increase density are in progress

Future directions for laboratory research advancing stellar interior understanding

Iron opacity

Goal is benchmark quality data at 3 ne, Te conditions:

8×10^{21} cm^{-3} 156 eV

3×10^{22} cm^{-3} 190 eV

7×10^{22} cm^{-3} 190 eV

We believe such a data set would provide a powerful test of opacity model physics

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?

Z-pinch experiments advance understanding for multiple astrophysics topics

Discussed here:

Why do modern solar models disagree with helioseismology?

What is the structure of an active galactic nucleus?

What causes the white dwarf mass run away problem?

Other topics:

Why did models for Cepheid variable pulsation disagree with observations? {Springer *etal* JQSRT 1997; Rogers & Iglesias Science 1994}

Did the giant planets form by accretion onto a solid massive core? {Saumon & Guillot ApJ 2004; Bailey *etal* PhysRevB 2008}

How do astrophysical jets form and evolve? {Lebedev *etal* ApJ 2004}

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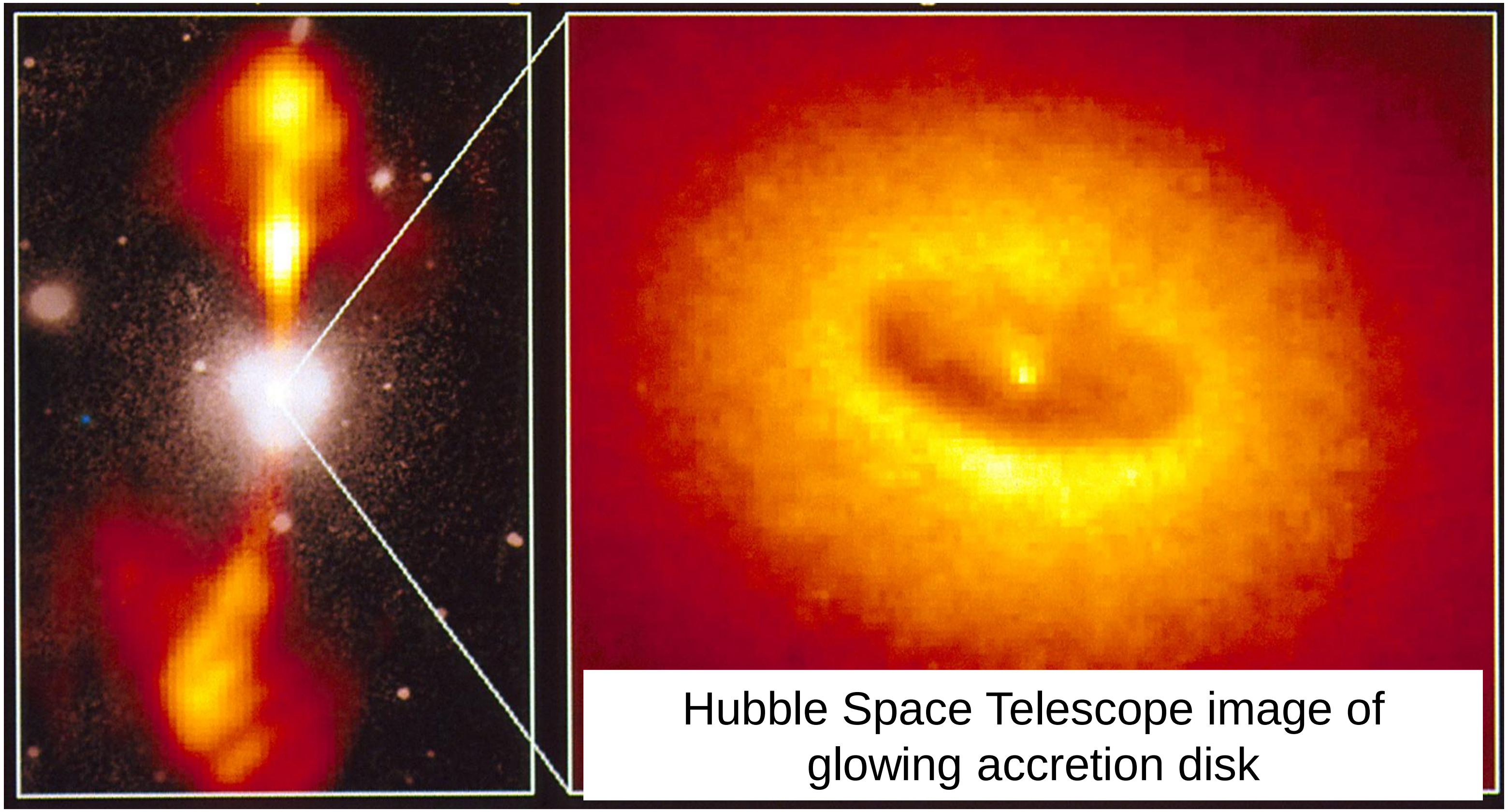
"we learn about neutron stars and black holes by watching matter fall onto (or into) them[1]."



Hubble Space Telescope image of glowing accretion disk

[1] D.A. Liedahl et al., ASP 247, 417 (2001).

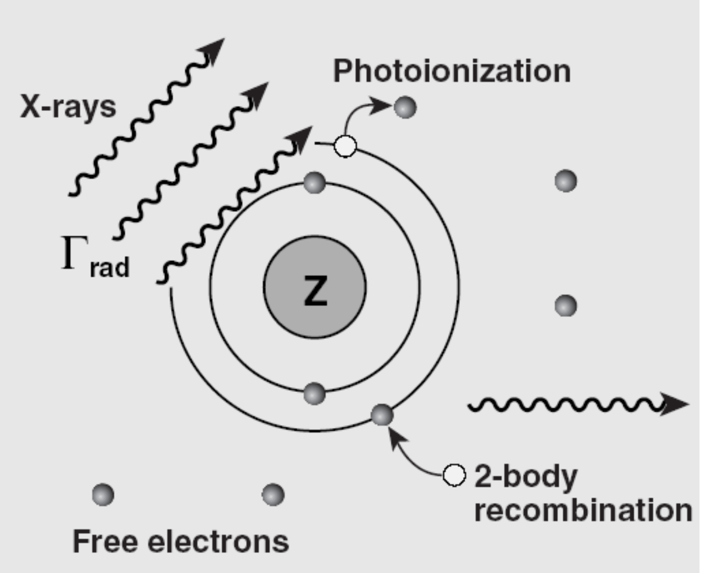
Spectra from accretion powered objects arise from photoionized plasmas

Collisional ionization equilibrium (CIE):
- Excitation/ionization dominated by electron-ion collisions
- <Z> determined by T, ne
- Examples: hot stars, supernova shocks;

Extensive laboratory data

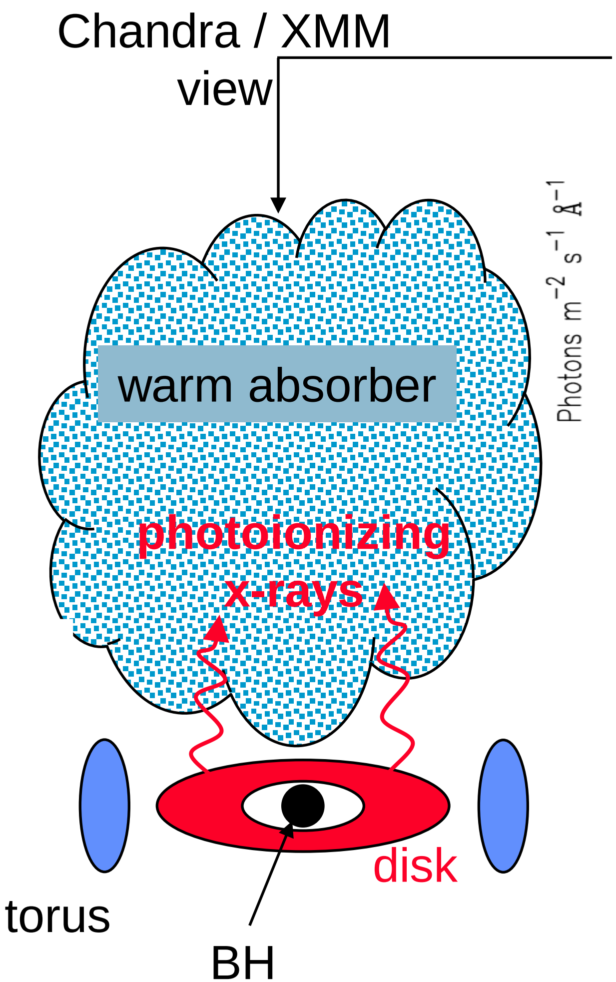
Photoionization equilibrium (PIE):
- Excitation/ionization dominated by radiation
- <Z> determined by $\xi = L/nr^2$
- where L= source luminosity, n=density, r=distance
- Examples: X-ray binaries, Active Galactic Nuclei,

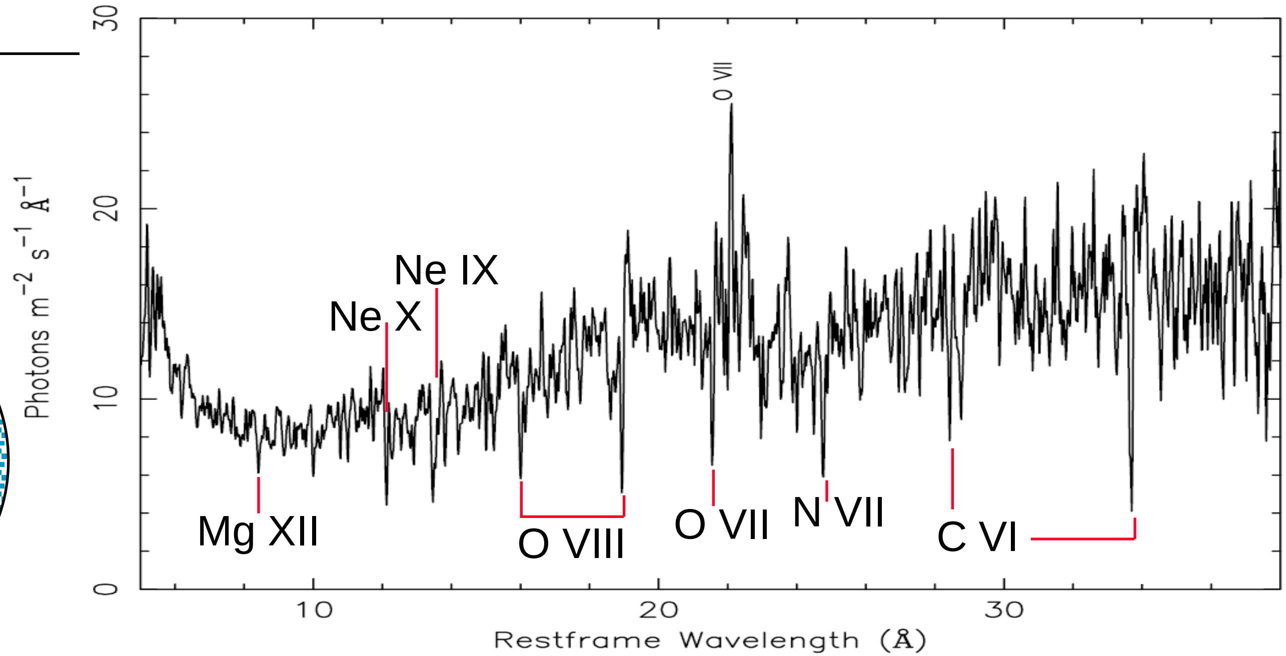
Almost no laboratory data



- The dearth of laboratory photoionized plasma data is due to inadequate radiation source energy
- Z can help fill this gap

Strategy: use astrophysics research to define laboratory astrophysics experiments





Example: warm absorber observations
Active Galactic Nucleus NGC 5548
J.S. Kaastra et al. , A&A 354 L84 (2000).

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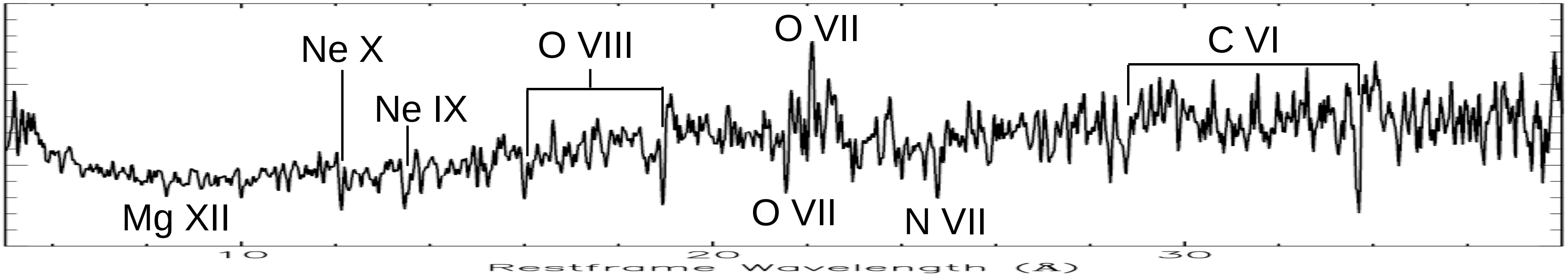
How to build a picture for AGN physics?
Example : Warm absorber in NGC 5548



1. **Identify the lines: C, N, O, Ne, Mg, Si, Fe**
2. **Plasma velocities – line shifts and widths**
3. **Measure column densities (~ 10^{18} atoms/cm^2) by fitting absorption spectra with opacity model**
4. **Infer ξ ~ 100 erg cm/s using measured column densities and photoionization model**
5. **Infer $n_e \sim 10^{12}$ cm^{-3} from emission line ratios**
6. **Infer photoionizing luminosity (L) from continuum measured at other wavelengths**
7. **Estimate distance to source using L, n, ionization parameter $\xi = L/nr^2$, (r ~ 10^{15} cm)**

How can laboratory astrophysics help?

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Laboratory experiments can help by measuring properties of photoionized matter

1. Line wavelengths; lab plasma composition known
2. Opacities; test methods to infer column density
3. Spectrum formation in presence of photoionizing radiation;
   Infer photoionization parameter from column densities and compare with independent diagnostics

Challenge:
Astrophysical densities (10^{12} cm^{-3}) are not practical in lab (10^{17}-10^{19} cm^{-3})
We need enough atoms to see a signal

Experiments at different densities can verify models for relative importance of collisions and radiation
Time-resolved experiments can verify that the short experiment duration does not bias the result

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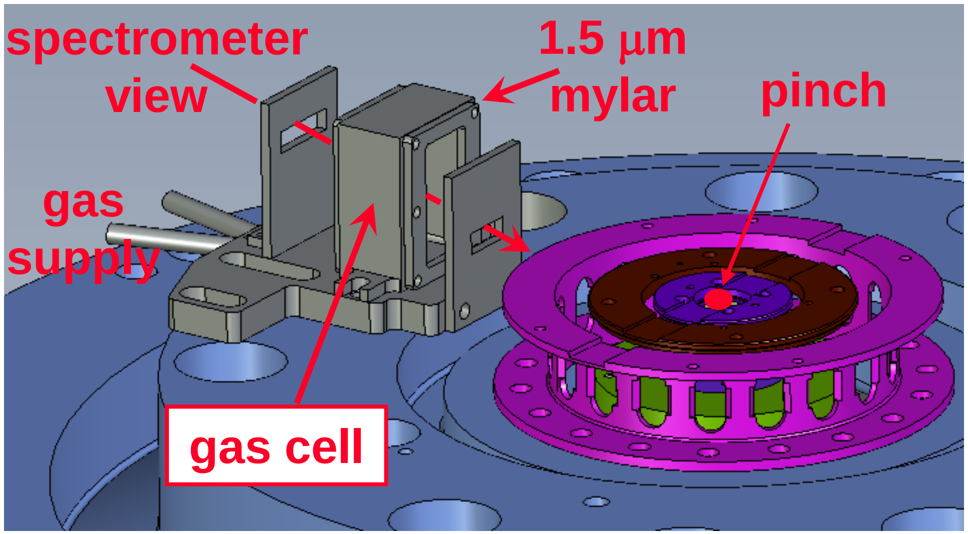
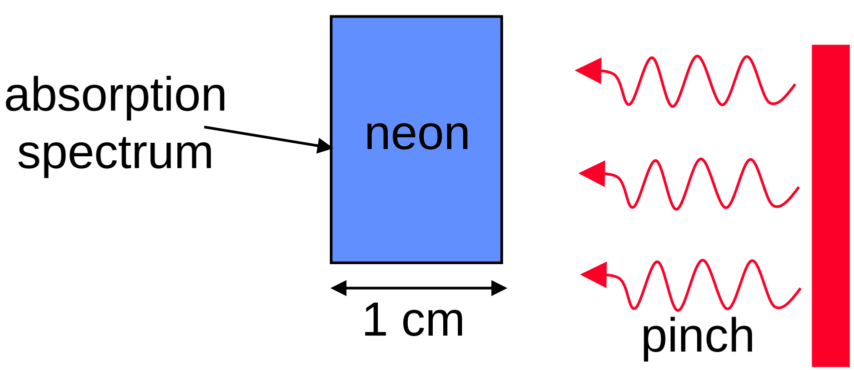
Strategy: Expose a cm-scale low density sample to photoionizing radiation



- Characterize the radiation
- Measure the absorption spectrum
- Apply the analysis as in astrophysics

Knowing the radiation conditions, density, and composition enables us to test the models



Proof of principle research:

R.F. Heeter et al., RSI 72, 1224 (2001).

M.E. Foord et al., PRL 93, 055002 (2004).

P.A.M. Van Hoof et al., Astrophysics and Space Science 298, 147 (2005)

J.E. Bailey *et al*., JQSRT 71 157 (2001).

D.H. Cohen *et al*., RSI 74, 1962 (2003).

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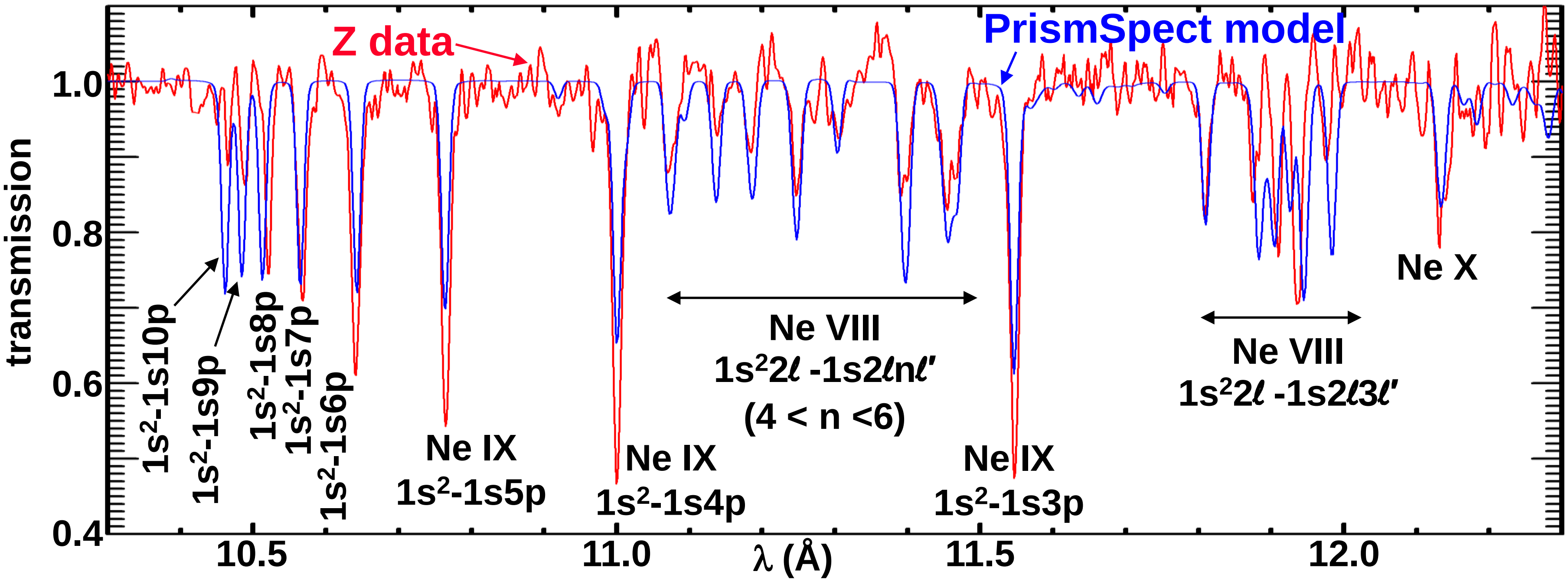
Initial Z gas cell experiments photoionized neon with $\xi \sim$ 5-7 erg-cm/s



Z experiment column densities are similar to astrophysical objects (10^{18} cm^{-2})
Therefore, these data can help resolve line identification puzzles:
"There is a problem with the NeIX 1s^2 -1snp resonance lines"
J.S. Kaastra et al , A&A 386, 427 (2002) (regarding NGC5548)

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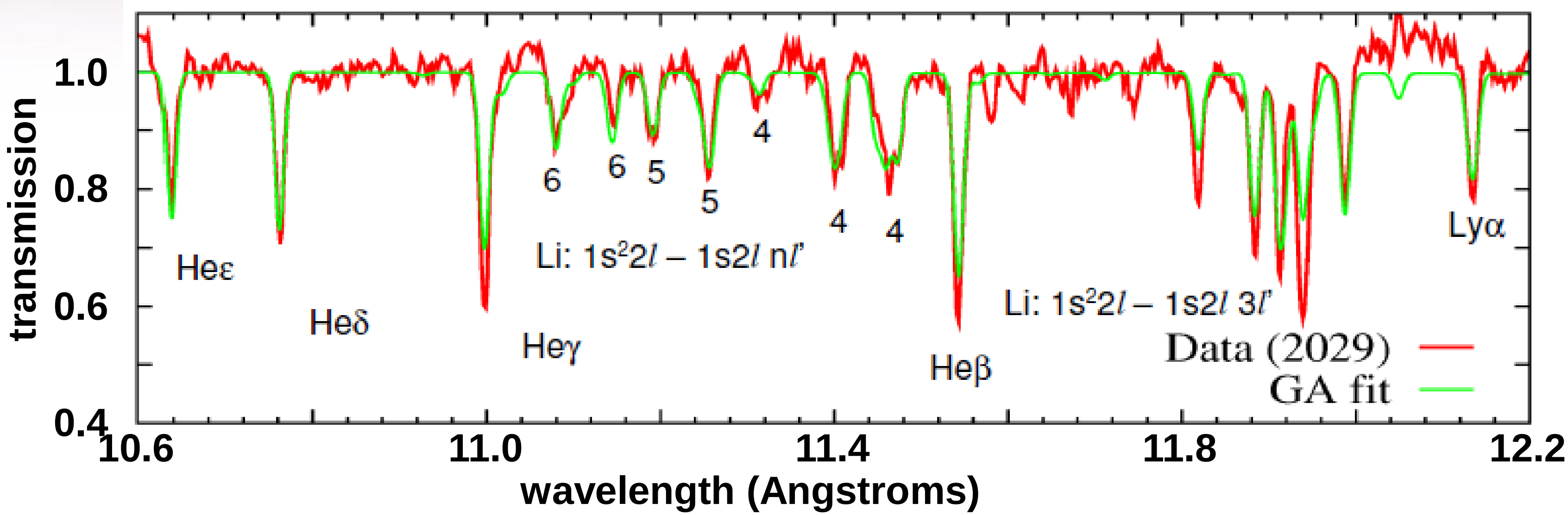
Transmission analysis with a genetic search algorithm determines the charge state distribution



1. For each ion stage, compute *total cross section* σ_ν for fine structure transitions from the low lying energy level(s) :

$$\sigma_\upsilon^i = \frac{\pi e^2}{m c} \sum_{j>i} f_{ij} \phi_{ij}$$

2. For each ion compute the absorption coefficent κ_ν :

$$\kappa_\nu^{ion} = \sum_i N_i^{ion} \sigma_\nu^i$$

3. Sum together contributions due to all ions :

$$\kappa_\nu^{total} = \sum_{ion} \kappa_\nu^{ion}$$

4. Compute the total optical depth τ_ν and transmission T_ν :

$$\tau_\nu^{total} = L \kappa_\nu^{total}$$

$$T_\nu = \exp(-\tau_\nu^{total})$$

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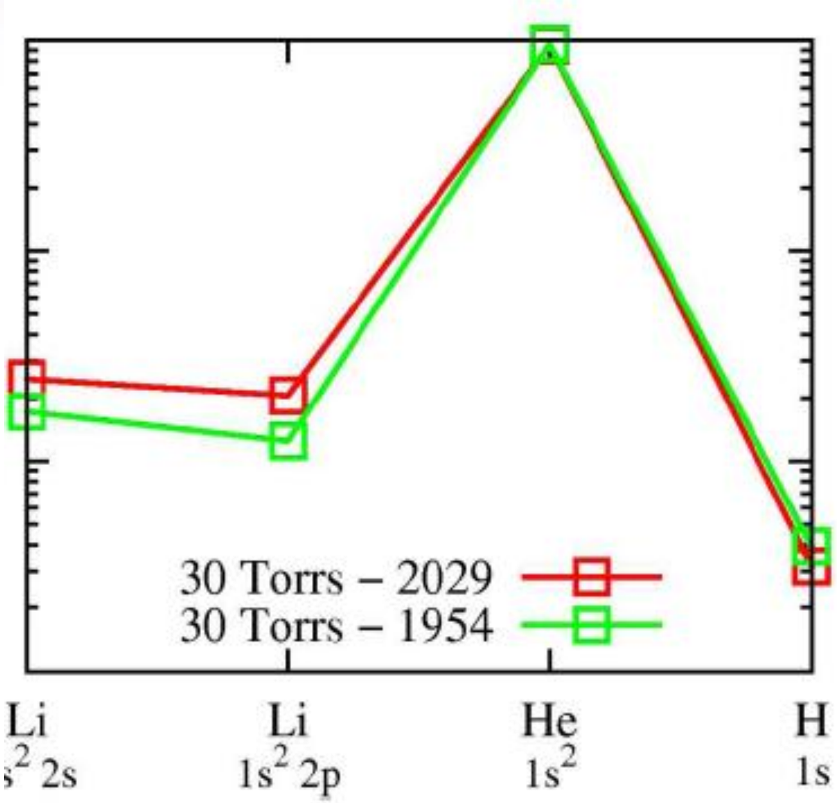
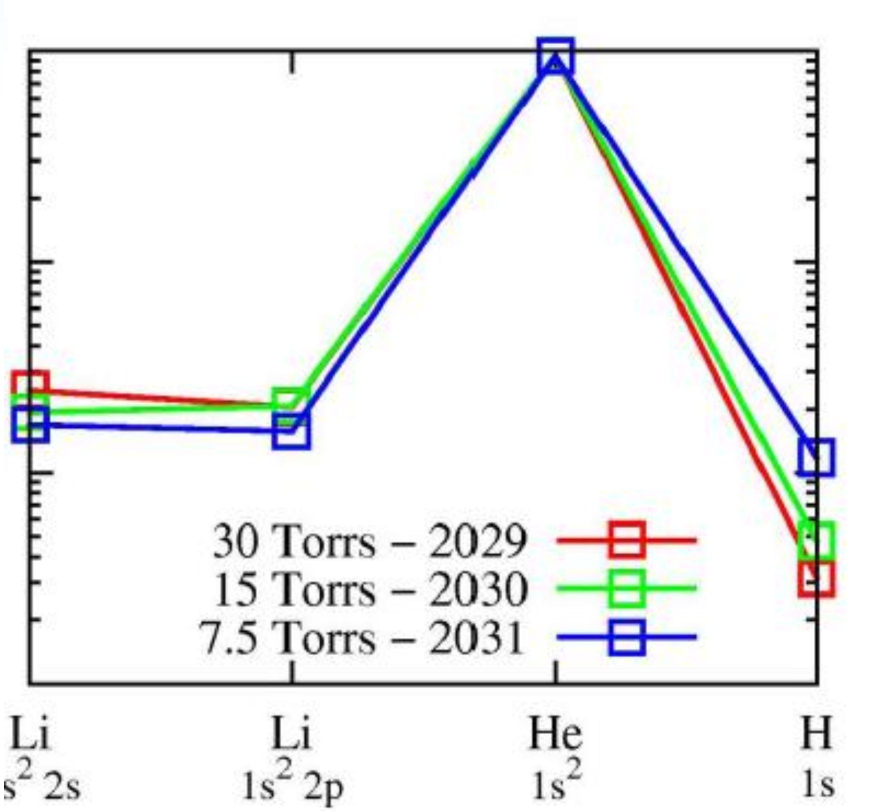
Comparing ionization predictions to observations at various ξ values will be a severe test for models



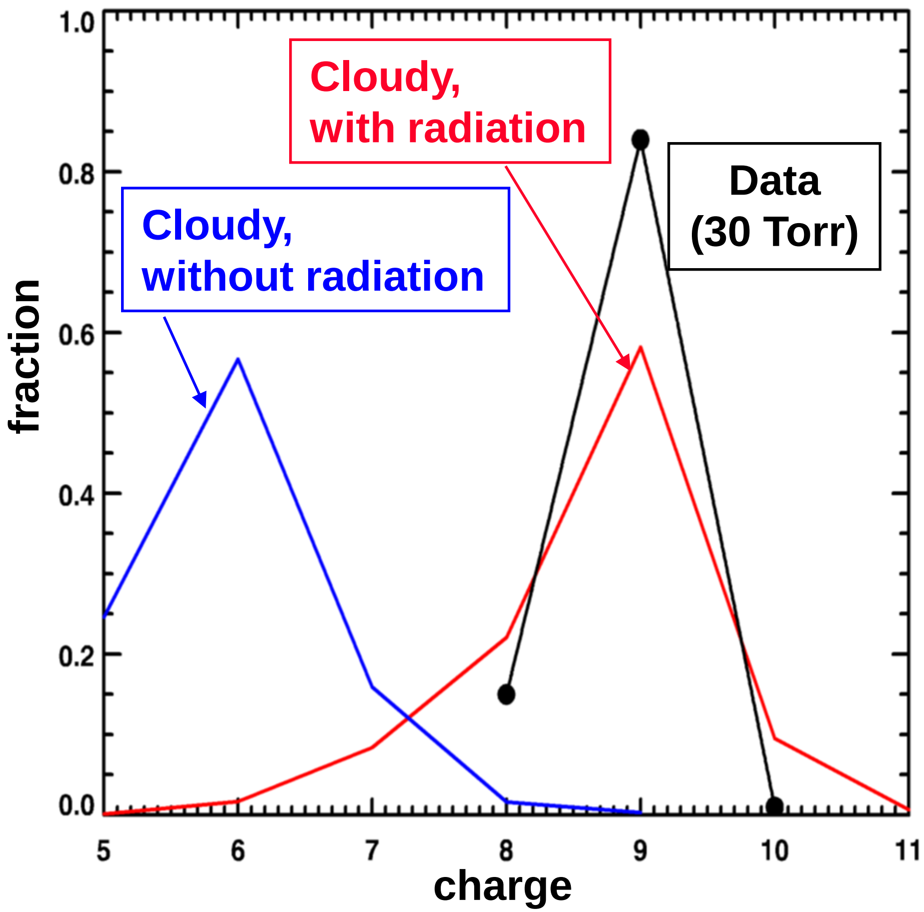


The charge state distribution measurements are reproducible

Decreasing the gas density increase the photoionization parameter

The amount of highly ionized neon increases in response

The neon charge state distribution can be used to test photoionization models



Preliminary results:

•Cloudy* predictions clearly demonstrate influence of radiation

• Predicted average charge with radiation is similar to the data

• H-like prediction is too high

*** Ferland et al.,PASP, 110, 761 (1998)**

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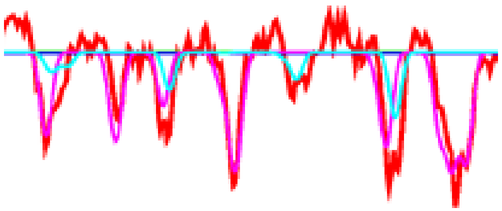
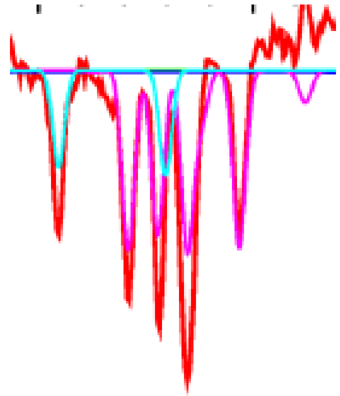
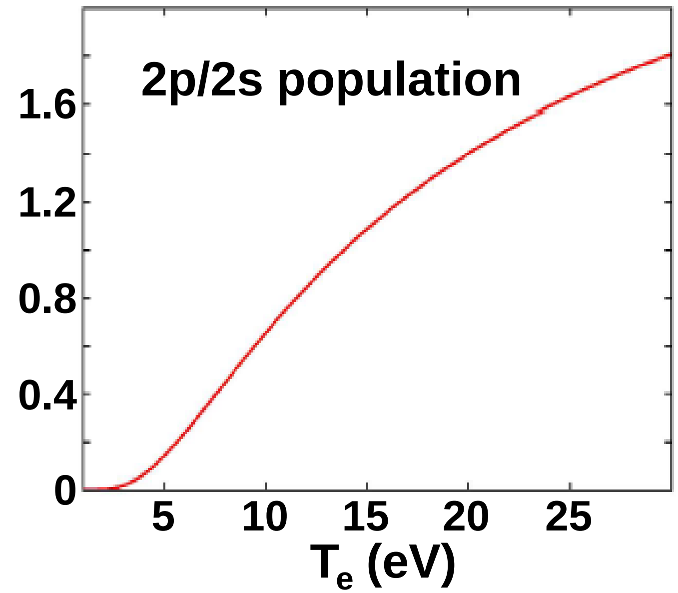
Population measurements of Li-like 2s ground state and 2p excited state may provide a new T_e diagnostic







Red = Li-like neon data
Cyan= $1s^2 2p$ lower level
Magenta = $1s^2 2s$ lower level

For the conditions in our experiment the relative populations are in LTE
The ratio leads to Te ~ 11-16 eV

Importance:
The low temperature confirms this is truly a photoionized plasma
The temperature is lower than predicted by simulations – reasons for this discrepancy are under investigation

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Status and near term goals for photoionized plasma experiments on Z

Status:

1. The platform to do photoionized gas experiments at Z is re-established
2. Measured neon absorption spectrum as a function of density and inferred charge state distribution
3. Measured absorption spectrum as a function of time – time resolved population measurements in progress

Next:

1. Use the results to test models employed in active galactic nuclei studies
2. Solidify the new T_e diagnostic and determine reason for simulation discrepancy

Future:

1. Develop emission techniques and test spectral synthesis models important for physics near the accretion disk and black hole itself
2. Explore higher photoionization parameters

Z-pinch experiments advance understanding for multiple astrophysics topics

Discussed here:

Why do modern solar models disagree with helioseismology?

What is the structure of an active galactic nucleus?

What causes the white dwarf mass run away problem?

Other topics:

Why did models for Cepheid variable pulsation disagree with observations? {Springer *etal* JQSRT 1997; Rogers & Iglesias Science 1994}

Did the giant planets form by accretion onto a solid massive core? {Saumon & Guillot ApJ 2004; Bailey *etal* PhysRevB 2008}

How do astrophysical jets form and evolve? {Lebedev *etal* ApJ 2004}

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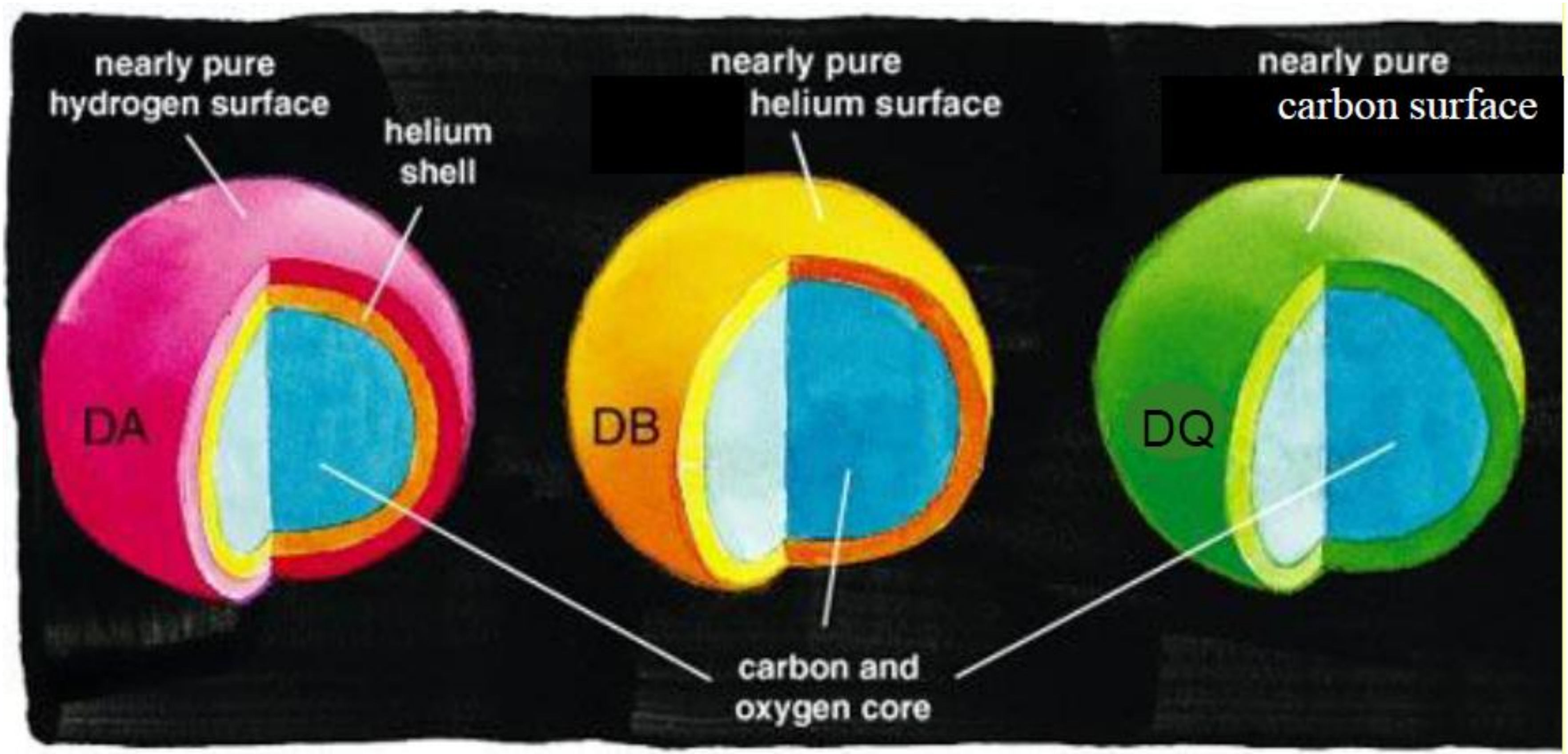
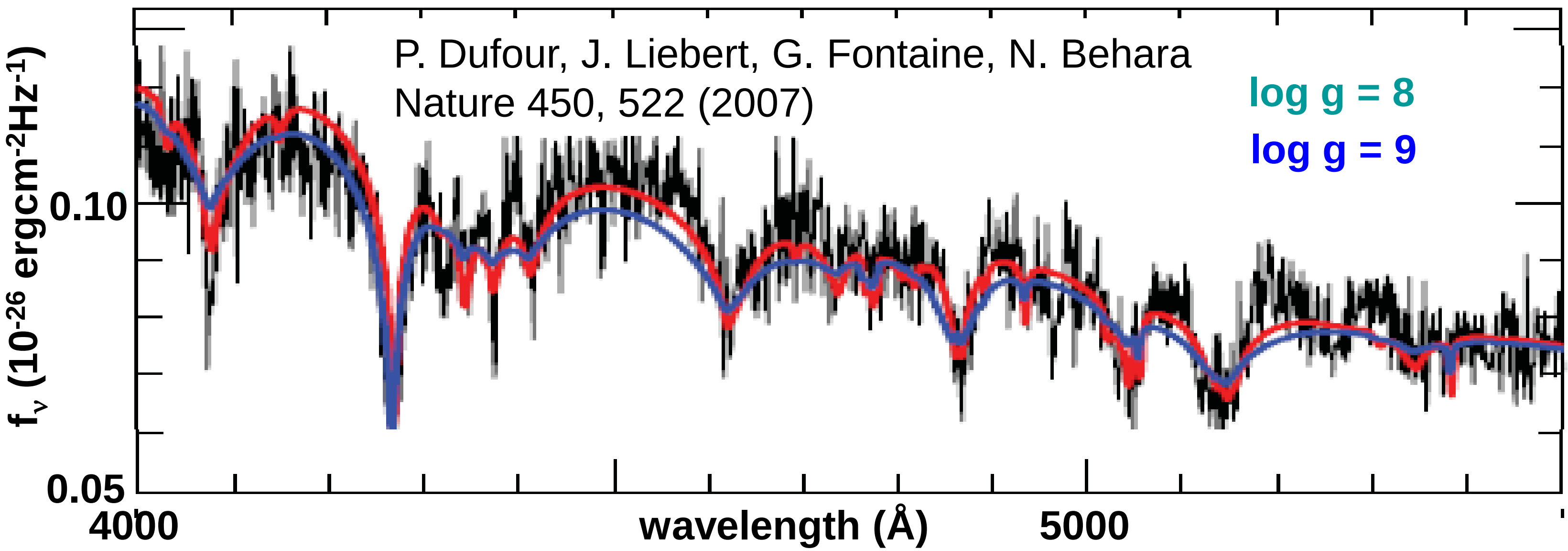
White Dwarf stars can serve as cosmic clocks

- Endpoint for 98% of all stars, including our sun
- Homogeneous single-element surface
- Uncomplicated structure and composition; evolution is just cooling

WD ages can be inferred from their temperature and mass
The age of the universe is at least as big as the oldest stars in it
This principle can map the ages of galactic components

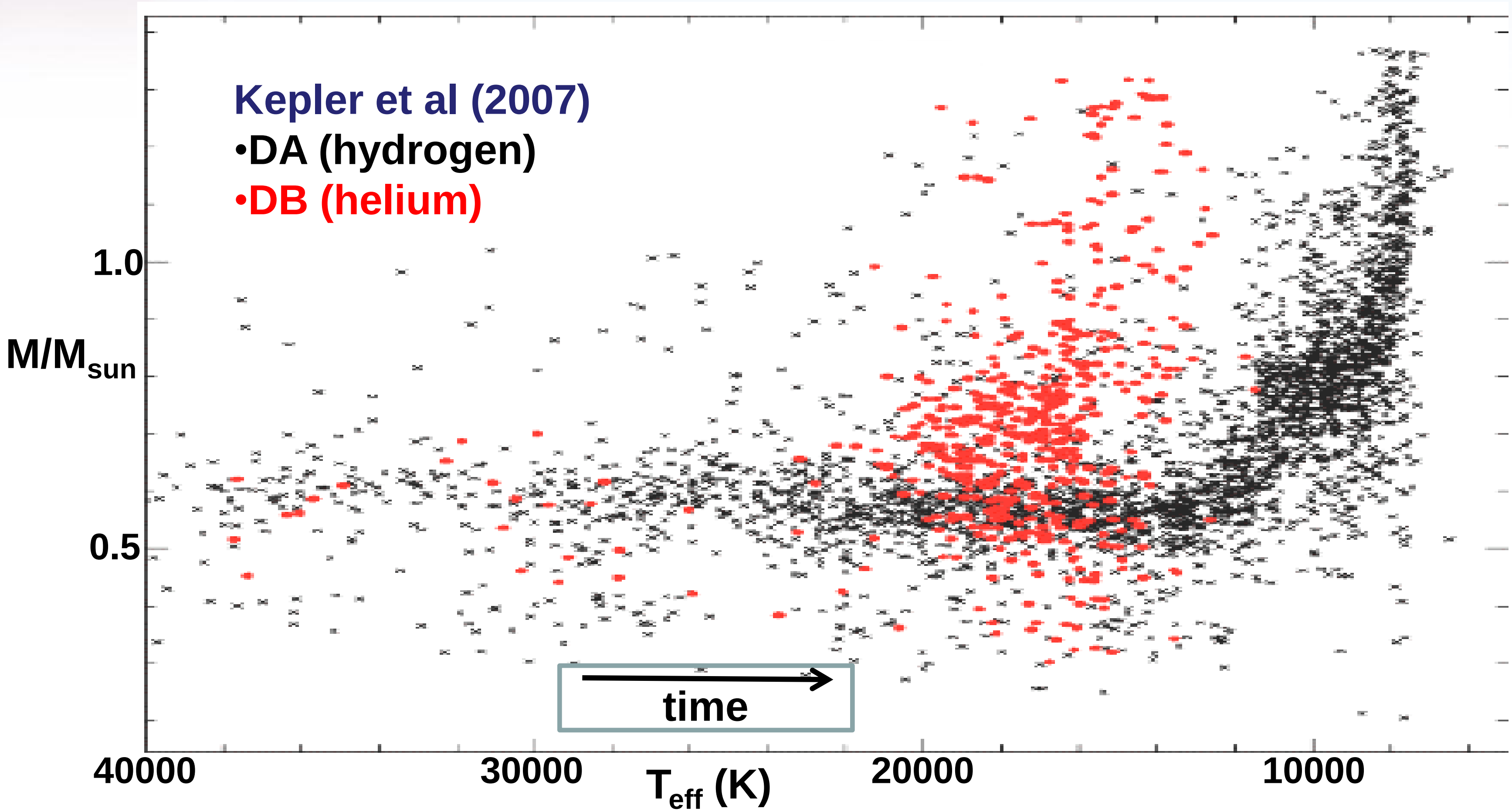


White dwarf surface gravity and composition are determined from spectral line formation



- The inferred characteristics depend on the spectral line profiles
- The plasma conditions are $n_e \sim 10^{17} - 10^{19}$ cm^{-3} and T ~ 1 - 4 eV
- For these conditions spectral line profiles are a challenge and experimental benchmarks are scarce

Spectral analysis of a large WD collection leads to mass run-away that is believed unphysical



Recent publication: the mass run away is un-physical (Falcon et al 2010)

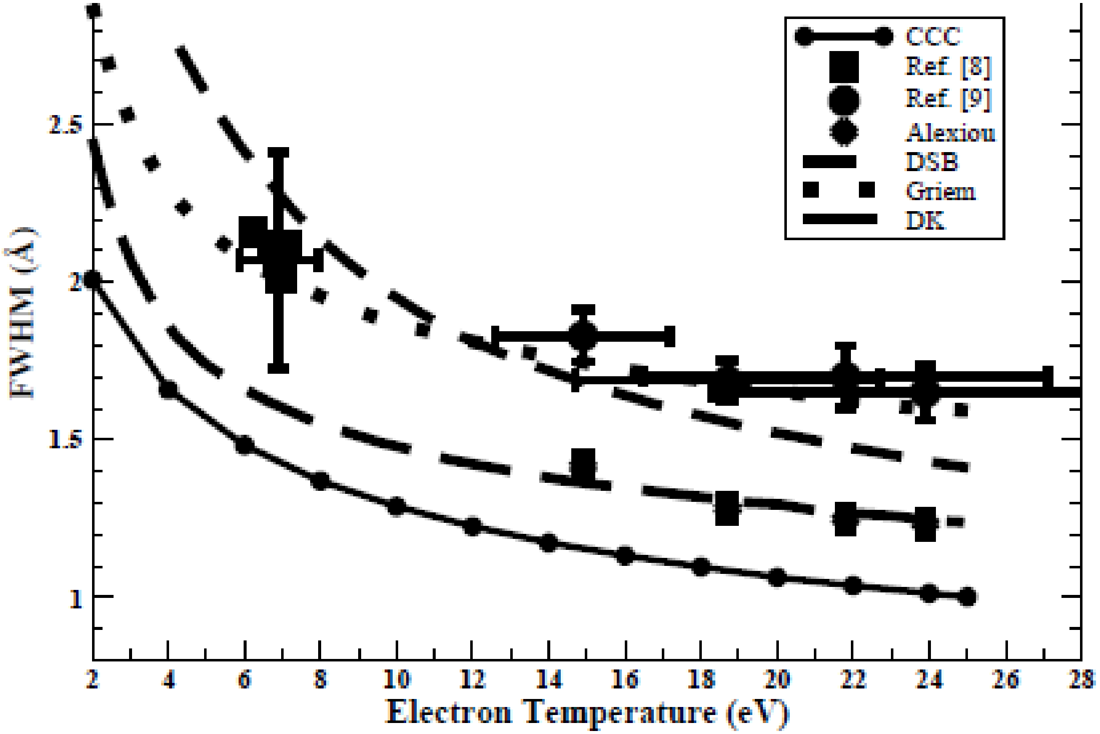
Leading hypothesis: Line profiles are not accurate enough

A flexible experimental platform using radiation-heated gas is being developed to benchmark line profiles on Z

White Dwarf photosphere problem defines a set of interesting conditions:
H, He, C lines at $n_e \sim 10^{17} - 10^{19}$ cm^{-3}, $T_e \sim$1-4 eV

A more general question:
What happens to atoms in plasmas as ion-ion coupling, Van der Waals forces, and quasi-molecule formation grow in importance?

A specific question:
Why do the quantum mechanical models disagree with measurements?



3s-3p broadening in NV

Ralchenko, Griem, and Bray, JQSRT 2003

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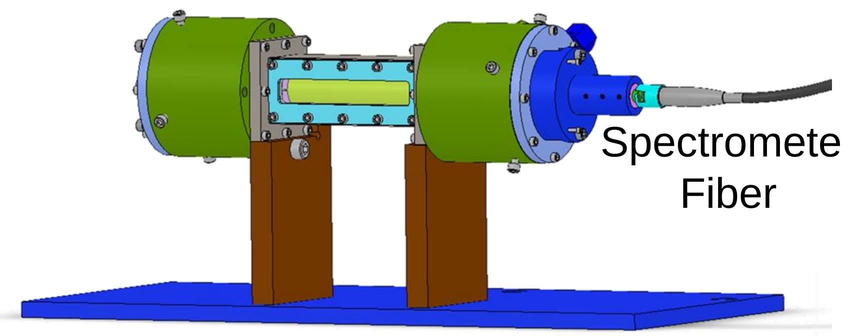
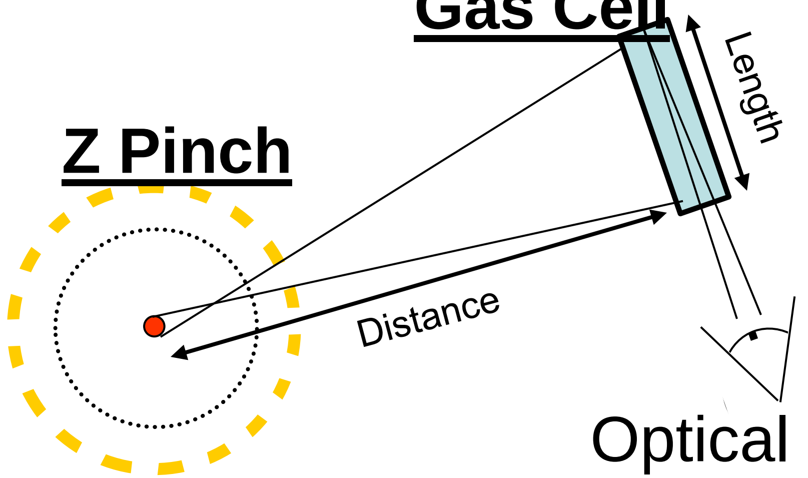
Radiatively heated gas cells are an attractive option for optical lineshape benchmark experiments

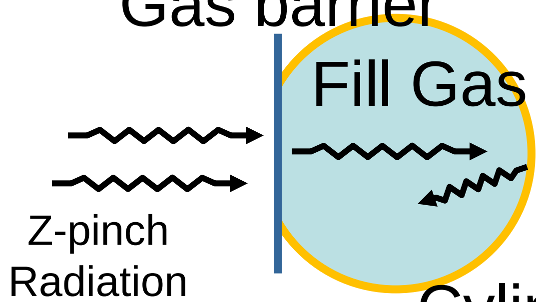
- Precisely known atom density (fill pressure)
- Heating control through distance and window composition/thickness
- Density control through variable fill pressure
- X-ray heating is volumetric
  - small gradients
  - low probability of turbulence

Gas Cell Model





Gas Cell Cross-Section



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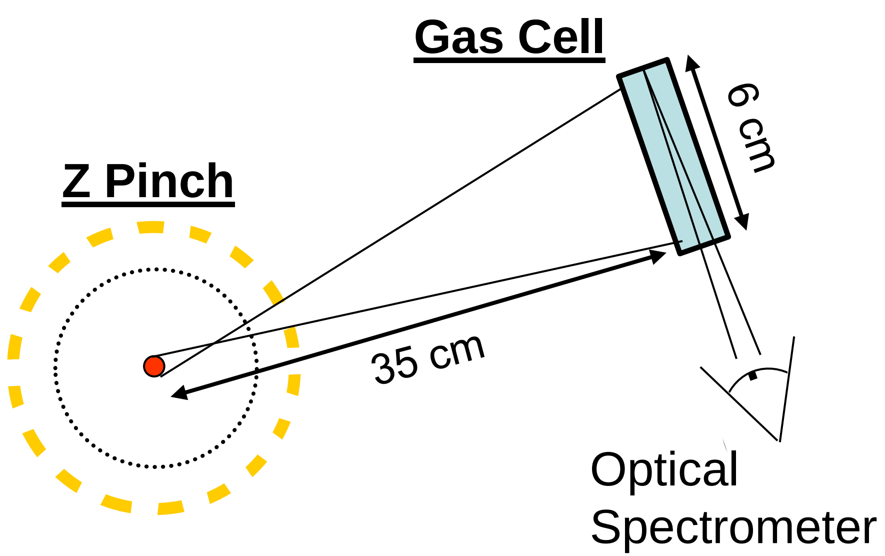
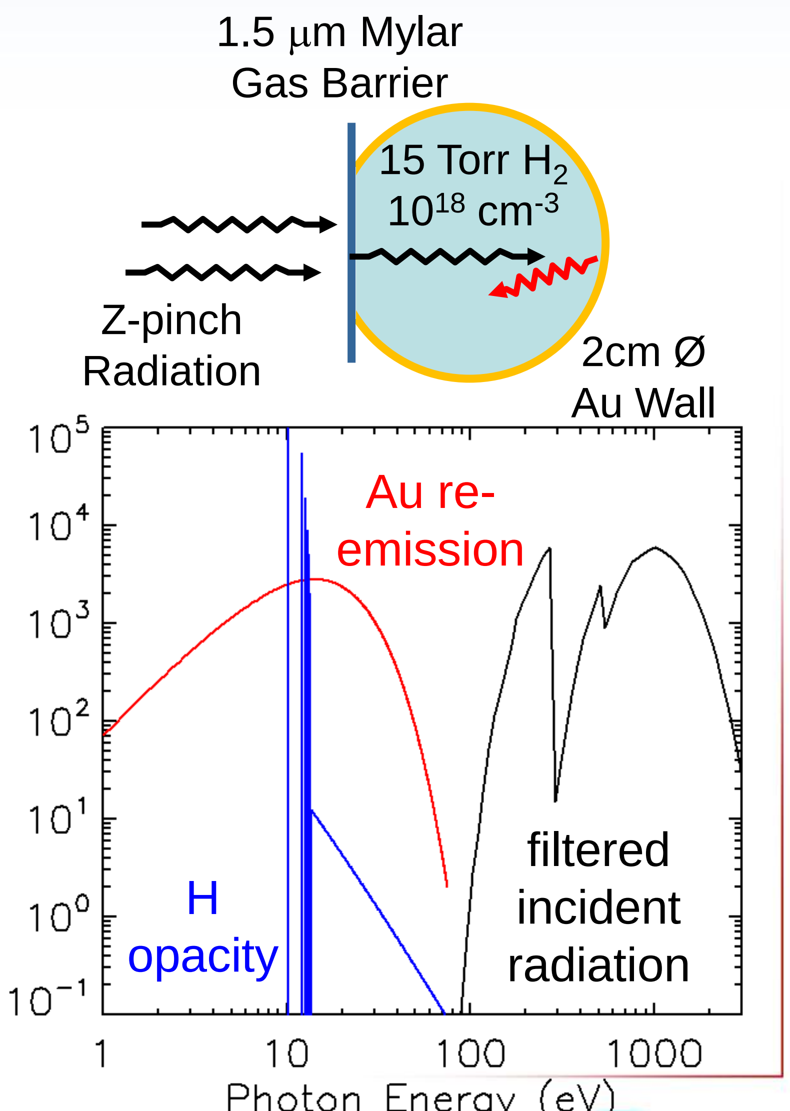
The first implementation of this platform is to study H Balmer lines for the white dwarf photosphere problem

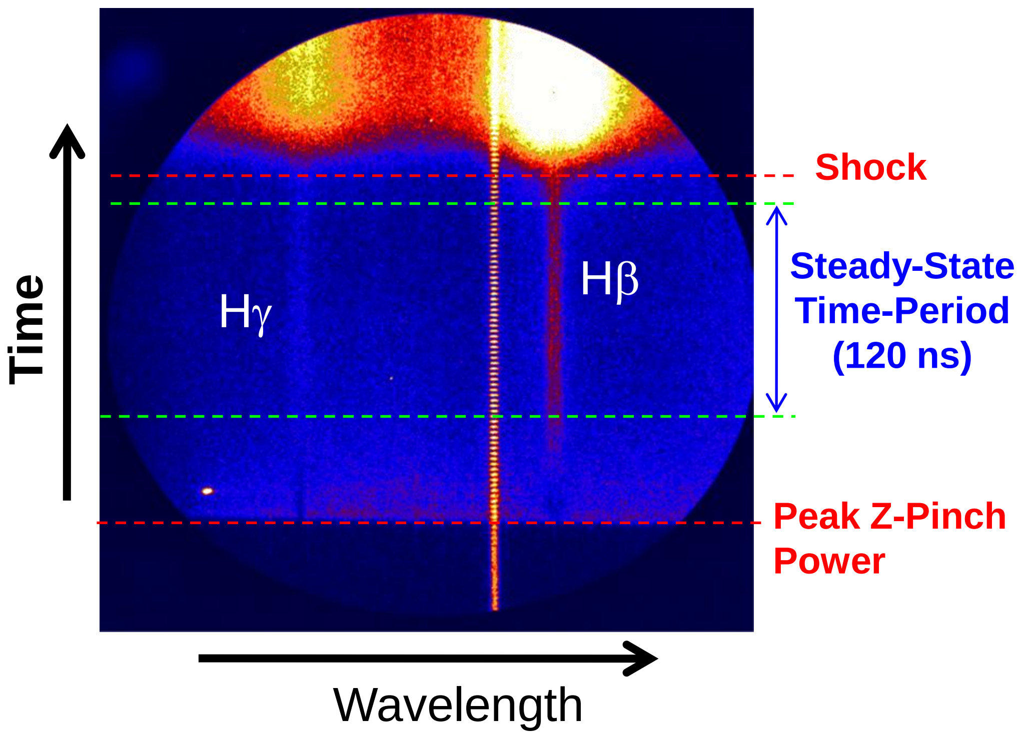
- Incident Z-pinch radiation is only partially transmitted through the gas barrier.
- Transmitted radiation doesn't heat H, but heats the Au wall up to a few eV.
- Blackbody Radiation from Au wall heats the H up to ~1 eV through photoionization.



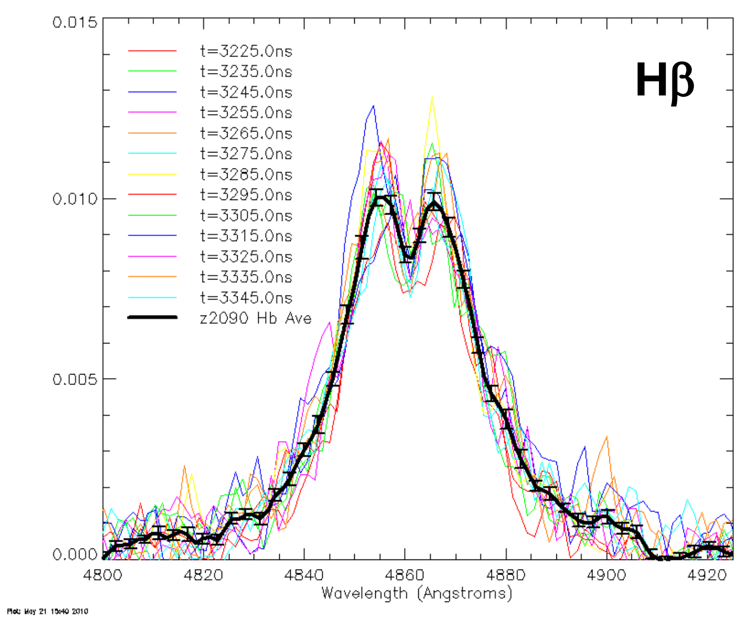


This platform is providing interesting data relevant to the white dwarf photosphere problem

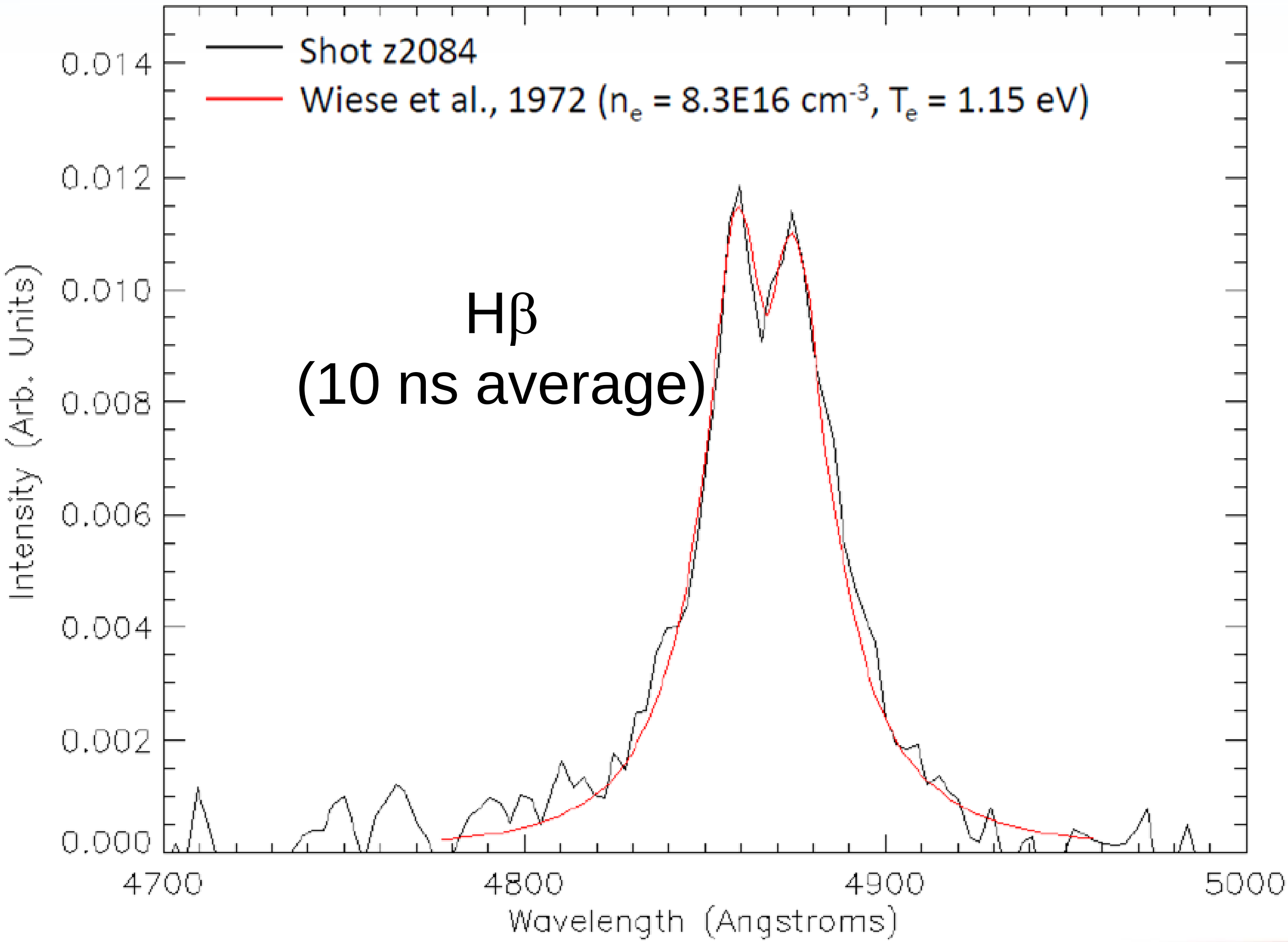
- Balmer line intensities increase over ~80 ns as the levels populate (time-dependent kinetics).
- Slow cooling rates provide steady-state emission over >> 100 ns.
- Steady-state emission is disrupted by a shock from the exploded gas barrier



Statistically speaking, the line shape and strength is identical over 120 ns.



Early data show a promising tie to existing published lineshape data



Significant effort can transform the line profile platform into a true benchmark capability

Proof of principle measurements show:

- We can create the plasma
- We can measure lineshapes

True bench measurements require:

- Independent plasma diagnostics
- Uniformity measurements
- Both absorption and emission spectra

Additional aspects:

- The platform may enable time dependent kinetics studies under controlled conditions
- LTE is desirable but not essential

High energy density science and lab astrophysics on Z are expected to grow in the future

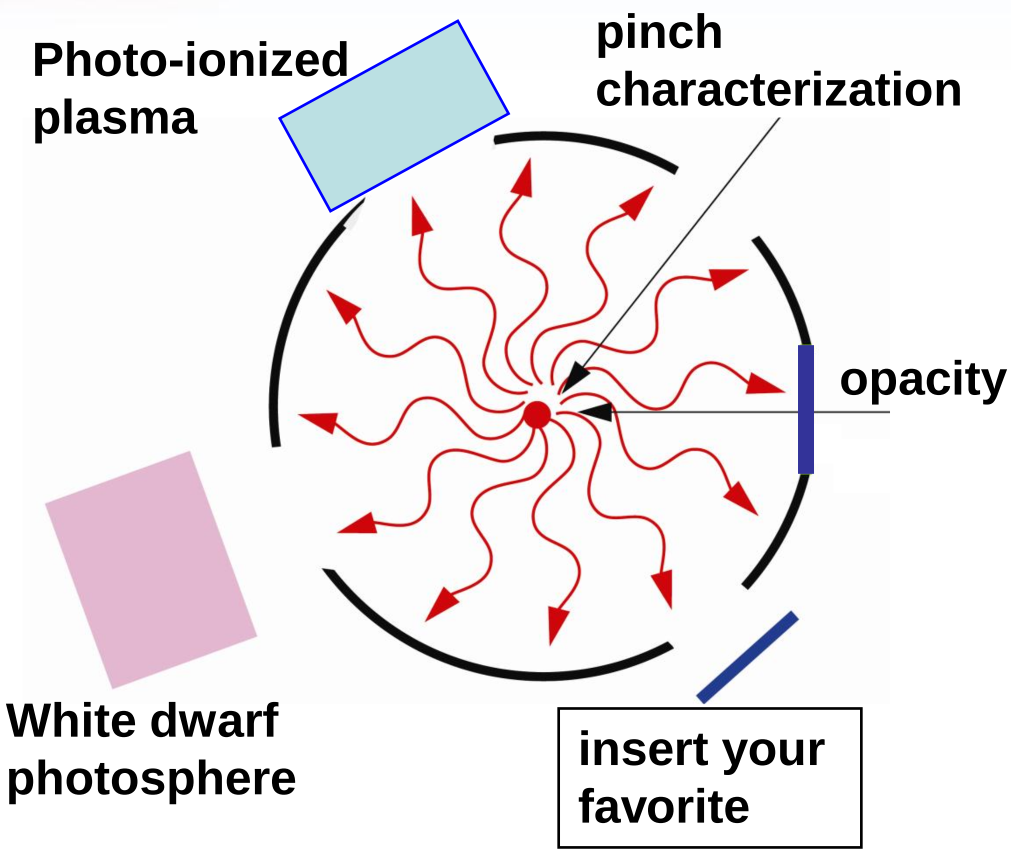
1) Facility upgrades are undergoing commissioning
   - Full capability on upgraded Z doubled electrical energy
   - Combined experiments with Z and a Petawatt laser

2) Growing support within DOE/NNSA for HED science and laboratory astrophysics
   - Recent NAS studies identify these as critical areas
   - Formation of Texas/Sandia Joint Institute for High Energy Density Science

3) Grasping this opportunity requires careful topic selection from myriad possibilities

4) Examples help illustrate research possibilities

Experiments dedicated to fundamental science drive multiple physics packages



The possibilities for experiments exceeds the number of Z shots

Presently we field three physics experiments per shot

We want to increase that number

There are many topics that provide “grand-challenge” level basic science opportunities

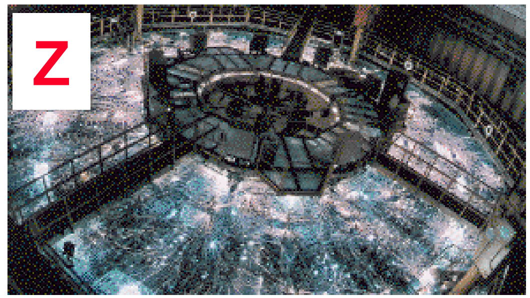
Grand-Challenge extensions of past work:

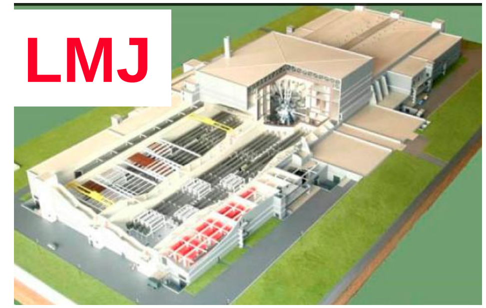
Stellar opacity
Photoionized plasma kinetics
White dwarf photosphere and composition

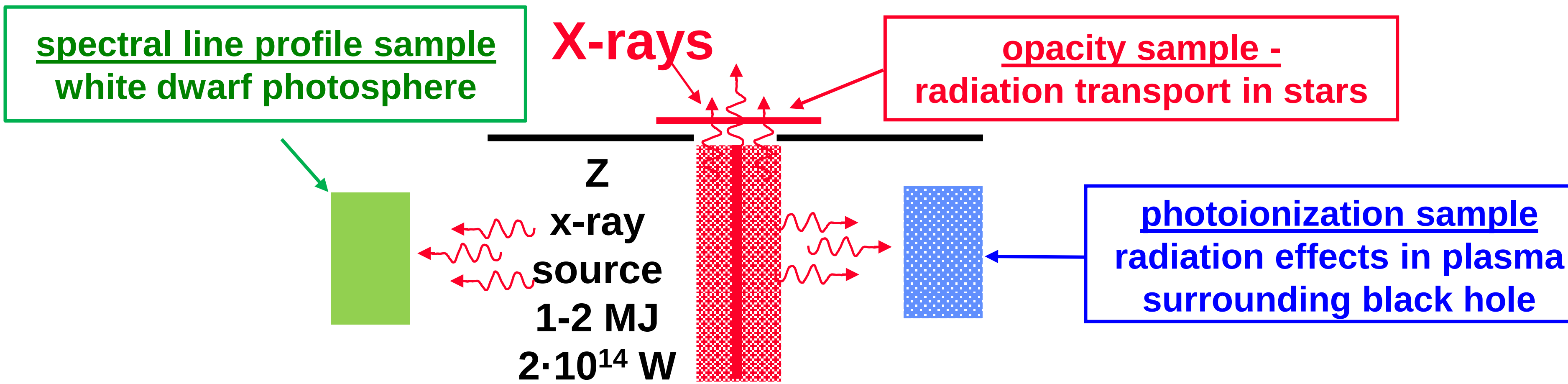
Possible new Grand Challenges (more speculative!):

Equation of state for the earth’s interior
Test spectral synthesis models used to infer stellar composition
Radiative levitation in stars
Atoms in strong fields
Photoionization and excitation cross sections
Ionization of shocked solid density matter
Properties of solid density plasmas
Conversion of magnetic energy into thermal energy
Lattice dynamics of shocked materials
Jets
Radiative shocks

The new generation of High Energy Density facilities can *create* and *diagnose* astrophysical matter on earth



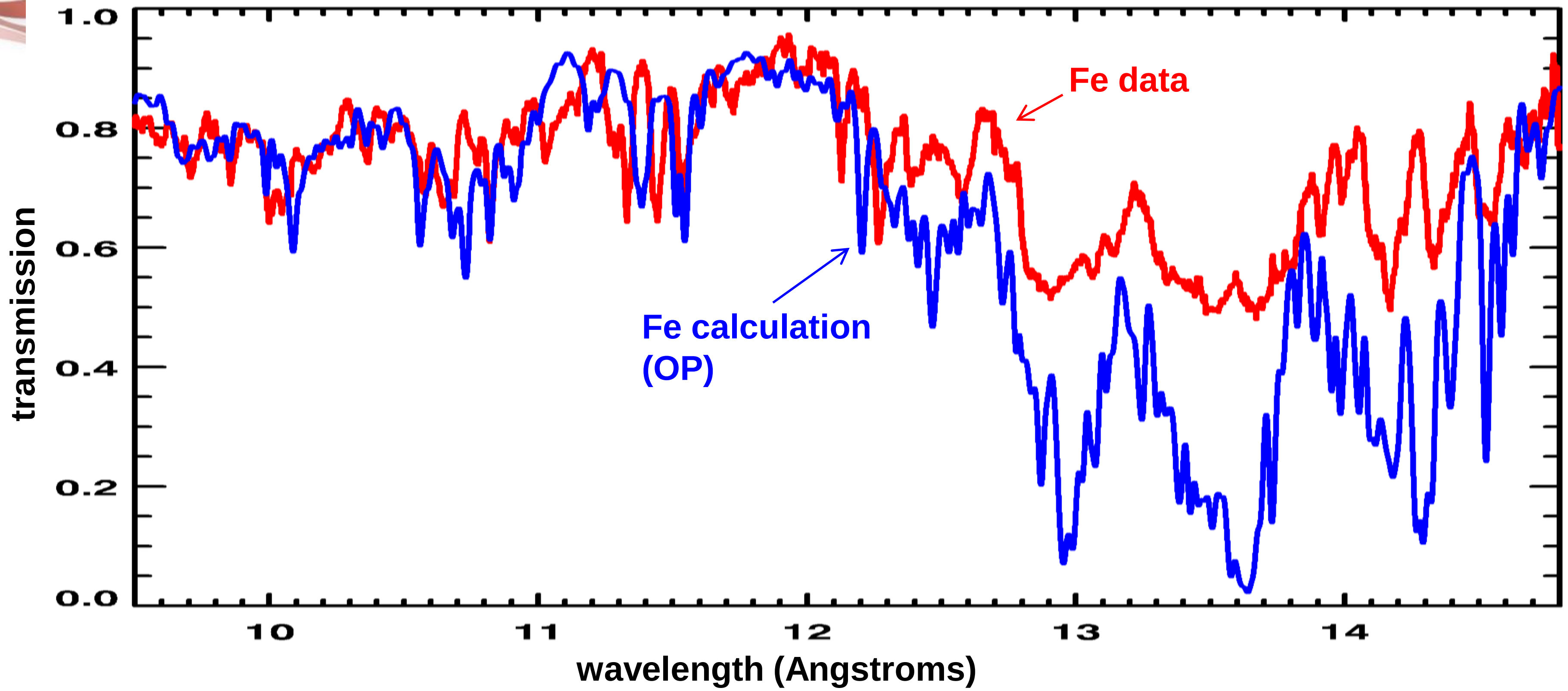




Mega-Joule class facilities create *macroscopic enough* quantities of astrophysical matter for detailed measurements

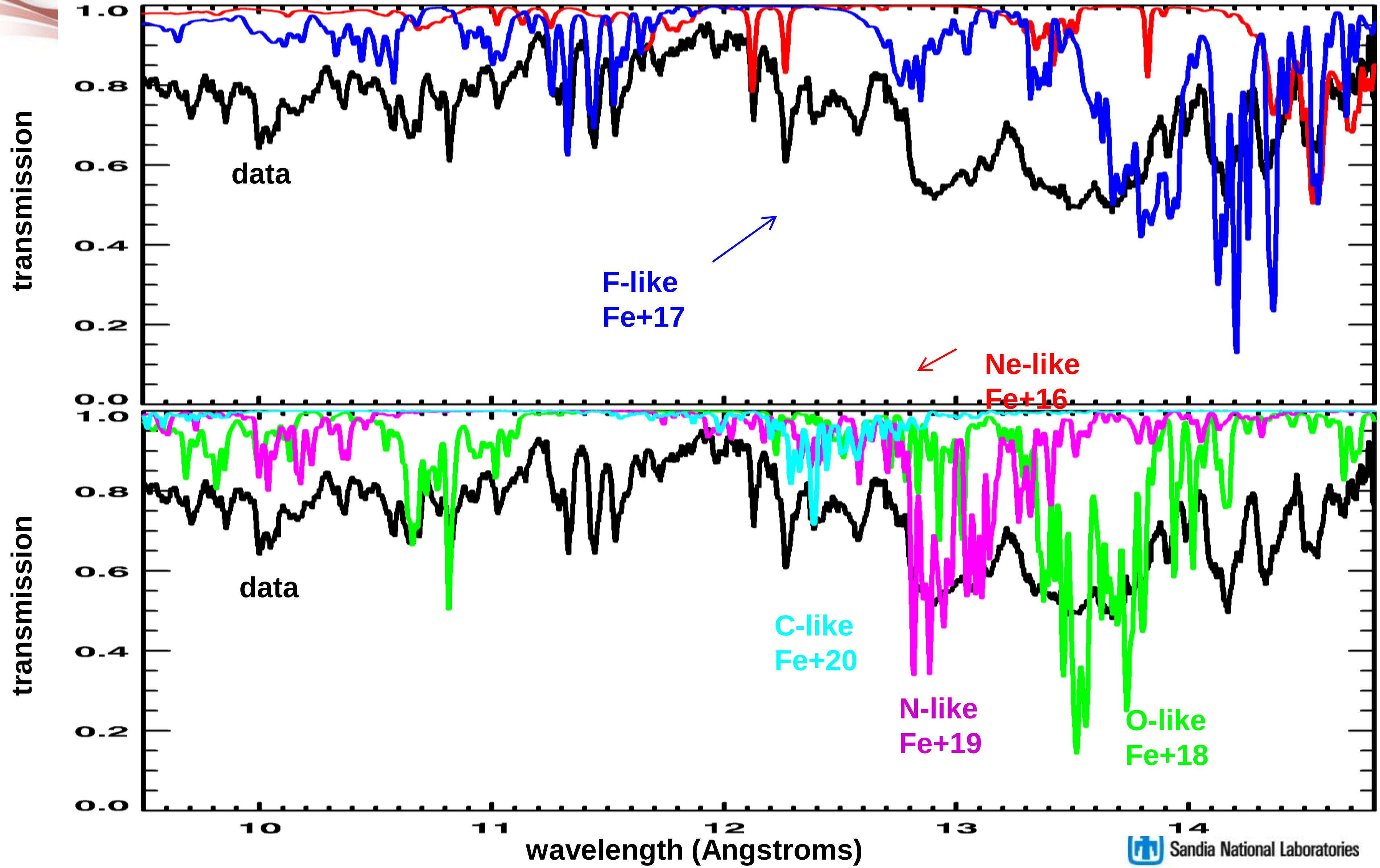
Supplemental Slides

Serious discrepancies exist in comparisons with the Opacity Project model



This model is actively used in stellar interior calculations

PrismSPECT comparisons enable feature identification



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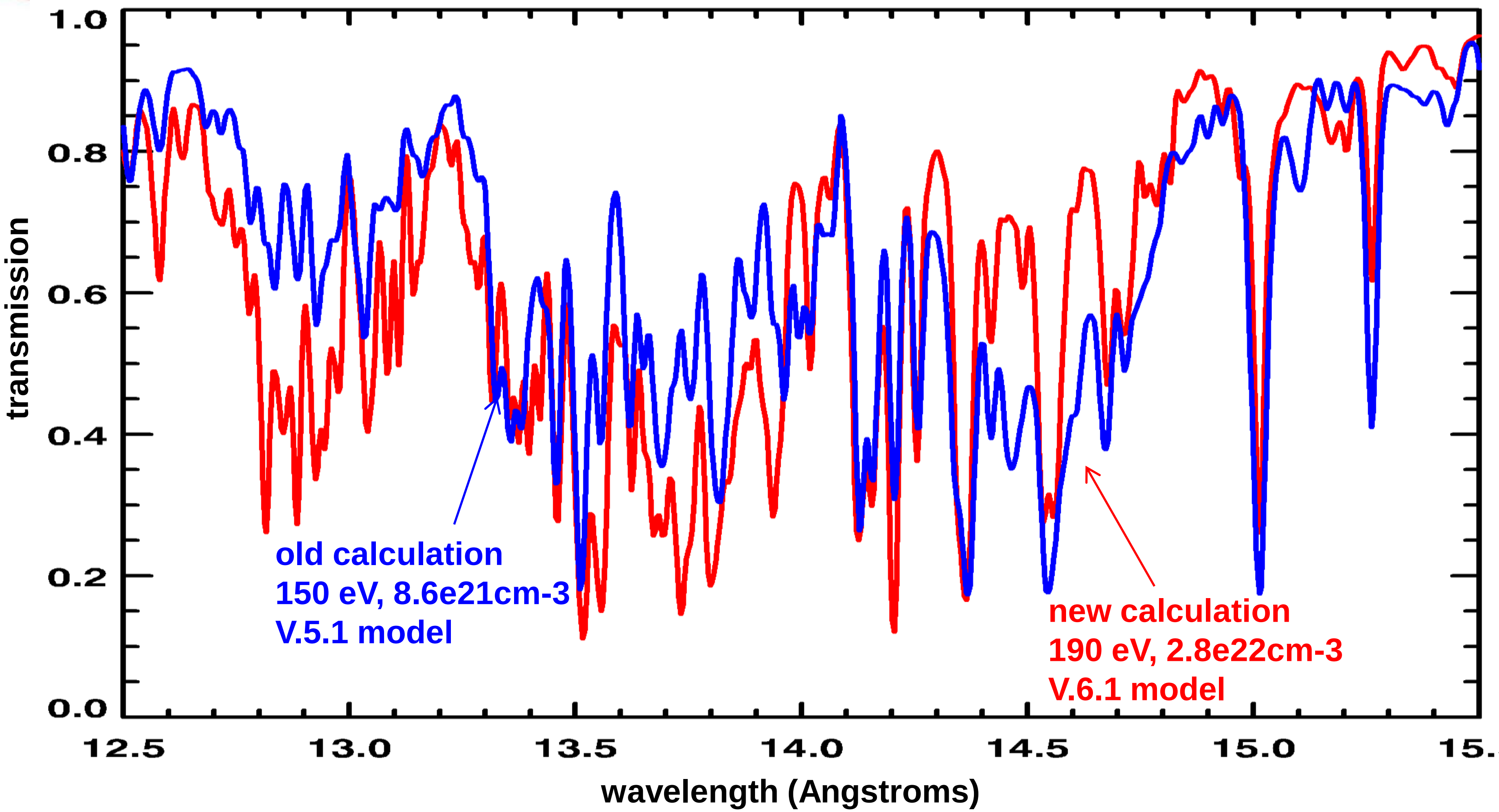
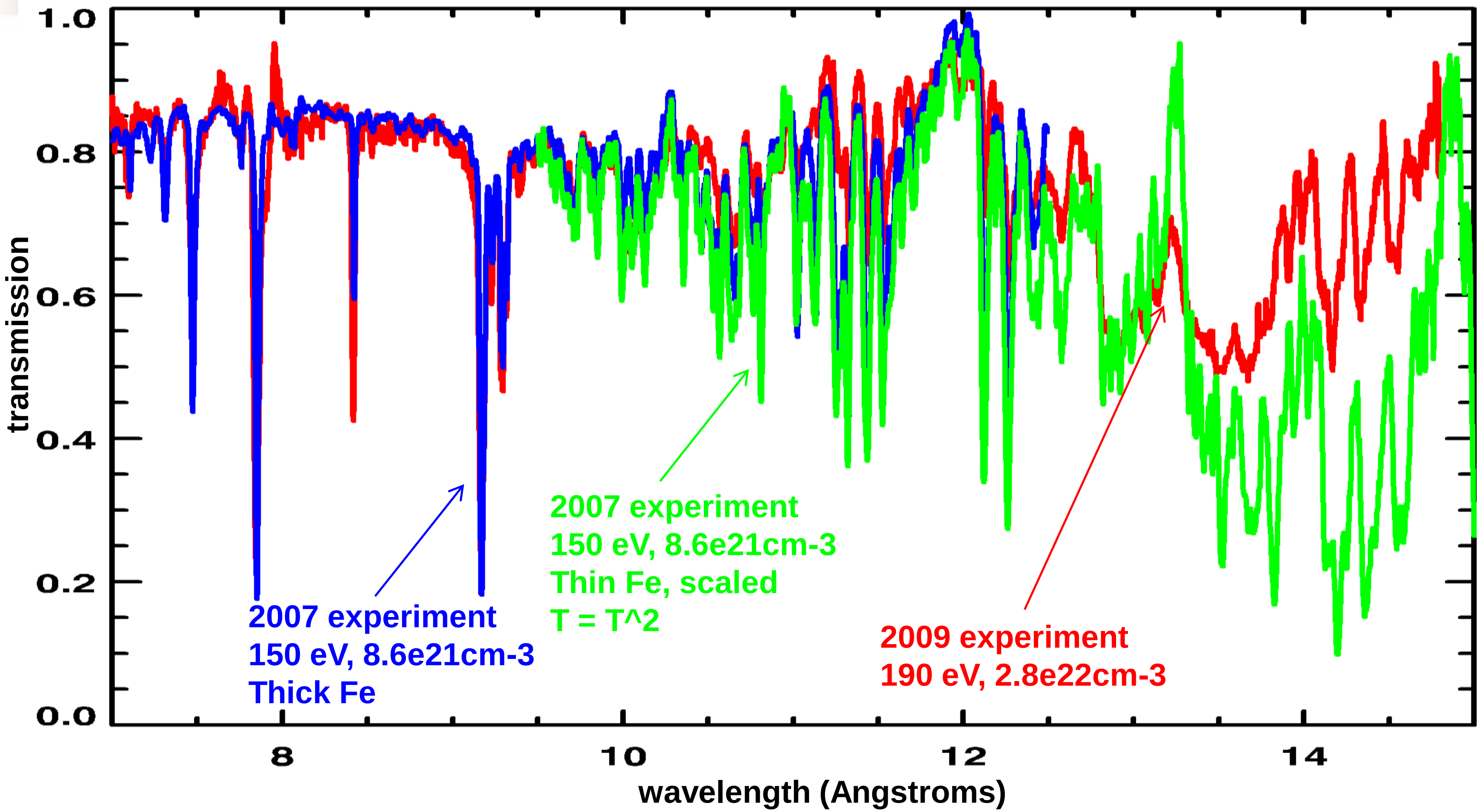
PrismSPECT calculations predict significant changes as the conditions change



I need to determine how much of the differences are from the atomic model version

The change in plasma conditions causes significant changes in transmission



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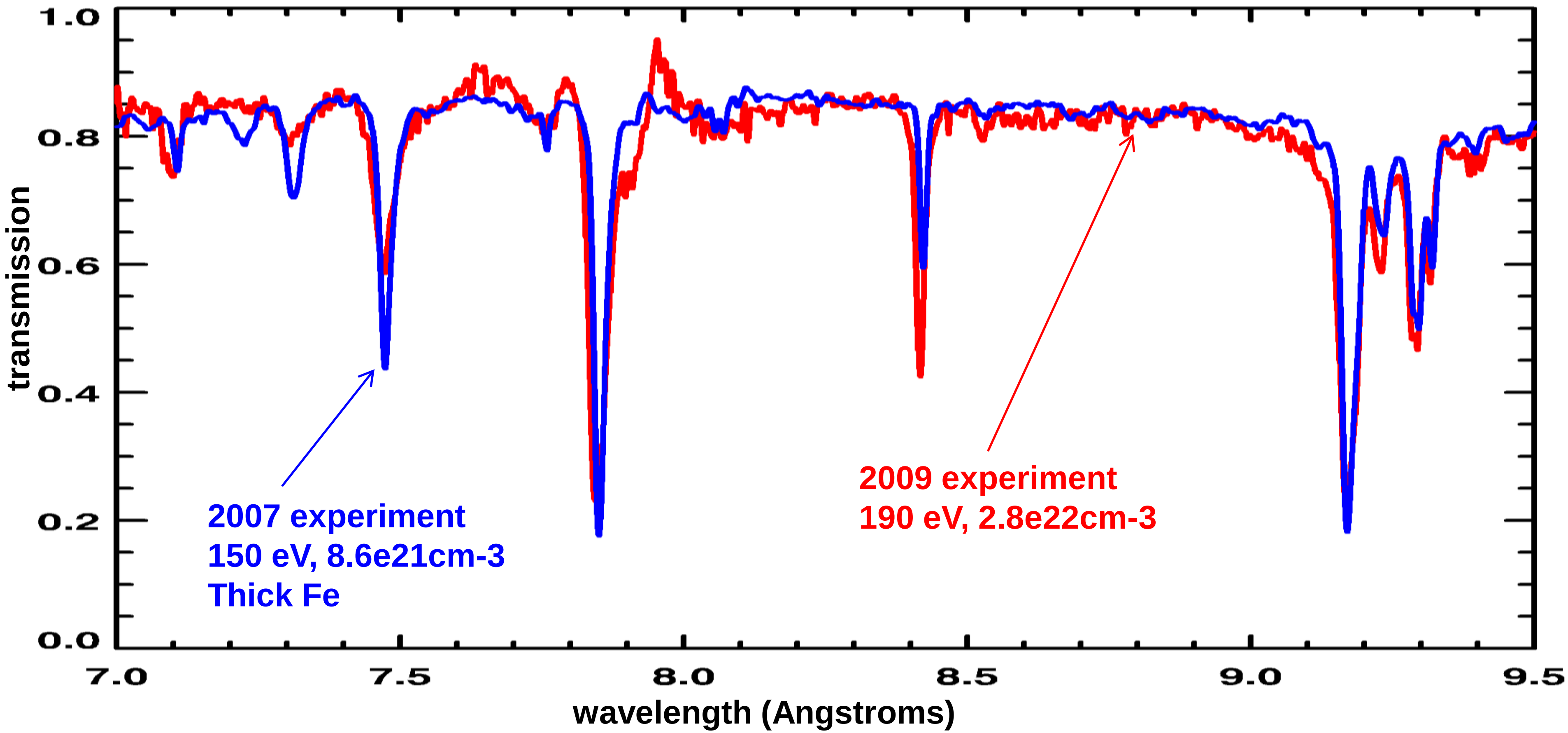
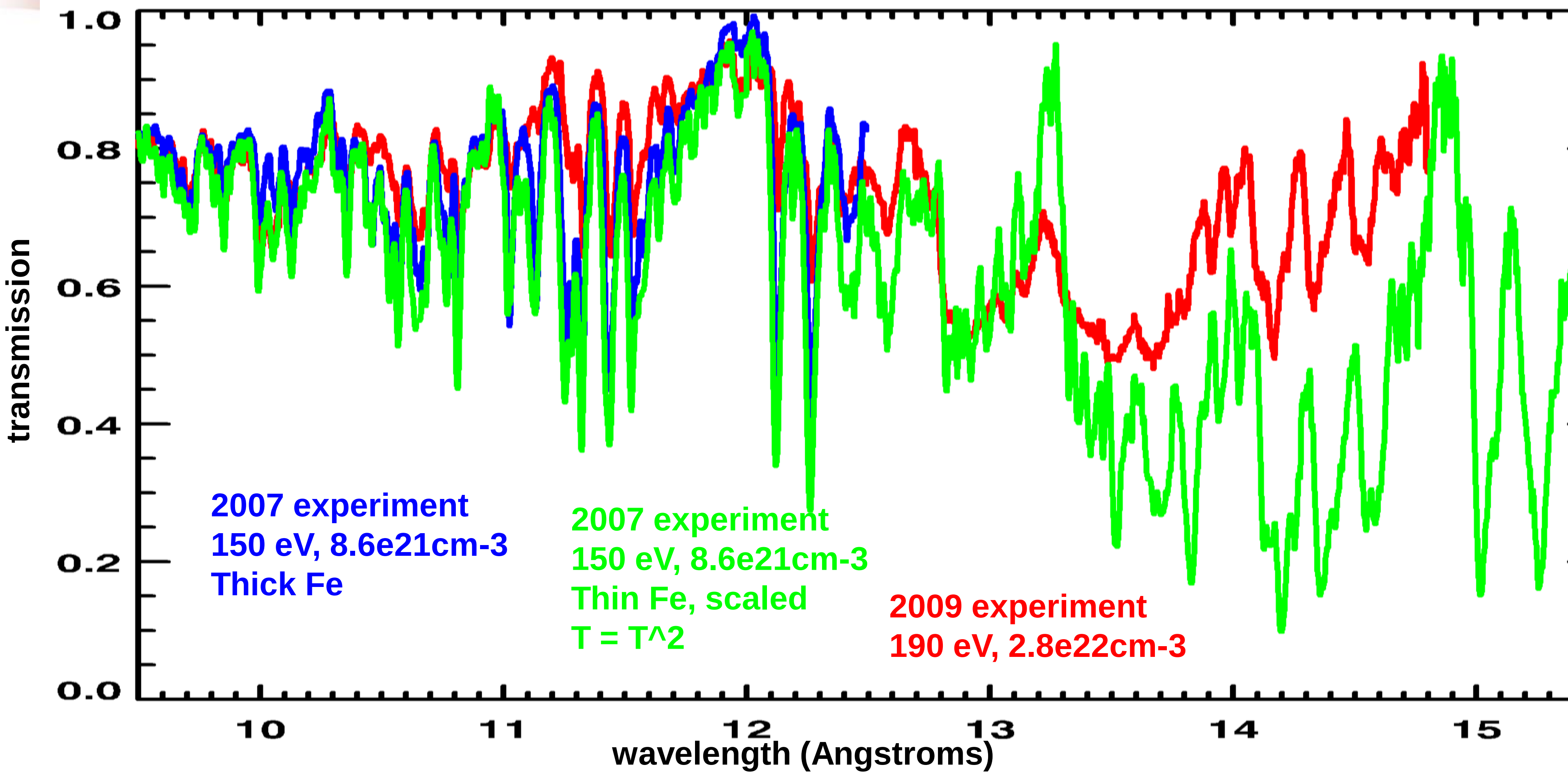
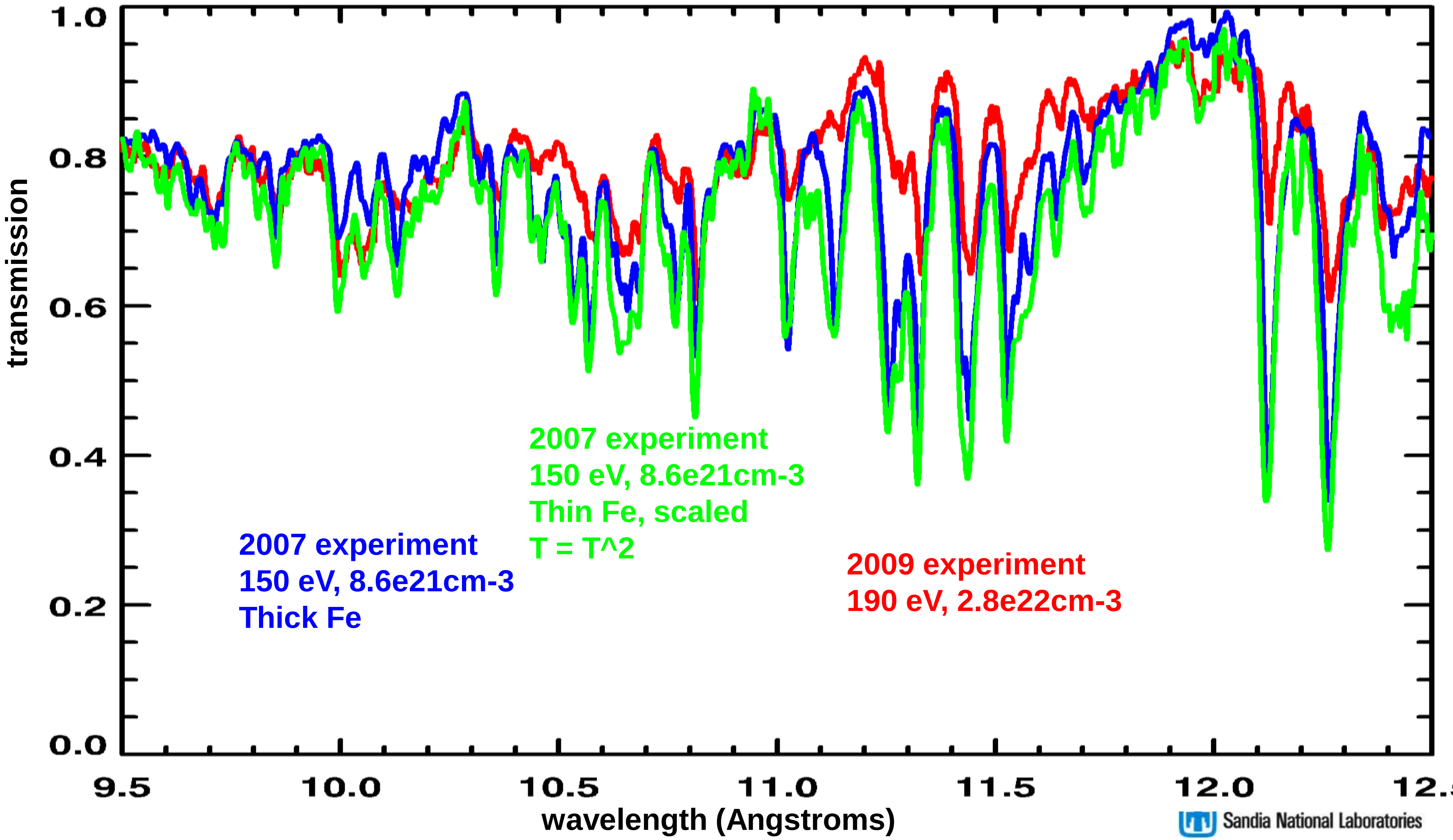
The change in plasma conditions causes significant changes in transmission



The change in plasma conditions causes significant changes in transmission



The change in plasma conditions causes significant changes in transmission



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The change in plasma conditions causes significant changes in transmission