SAND2022-10416C

Laboratory Tests of Stellar Interior Opacity Models

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University of Texas at Austin – Department of Astronomy

Z Fundamental Science Workshop

2022/08/03

Z Fundamental Science

NIF Discovery Science

National Nuclear Security Administration

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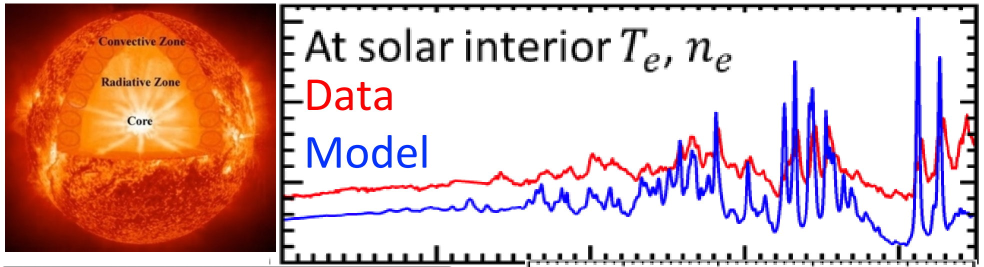
This work was sponsored in part by the Wootton Center for Astrophysical Plasma Properties under U.S. Department of Energy cooperative agreement number DE-NA0003843, the Z Facility's Fundamental Science Program of Sandia National Laboratories, and the National Ignition Facility's Discovery Science Program of Lawrence Livermore National Laboratory.

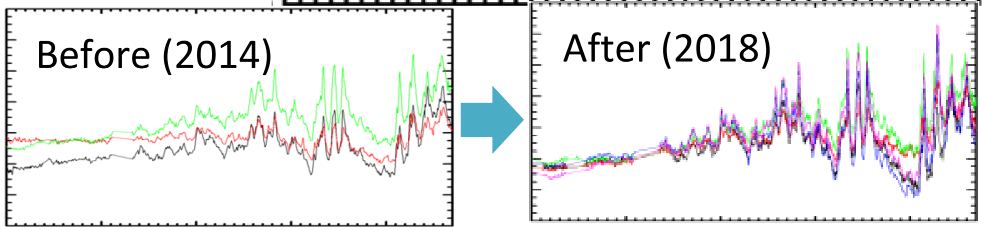
Executive summary: Novel opacity research advances HED physics and its astrophysical and laboratory applications

- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**

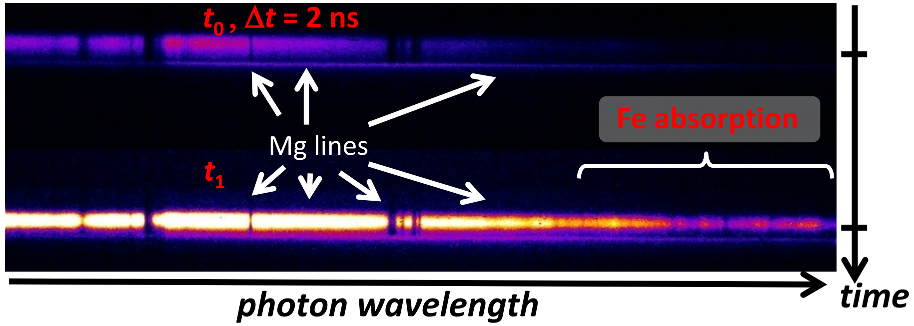
  → Is opacity theory wrong? Is experiment flawed?



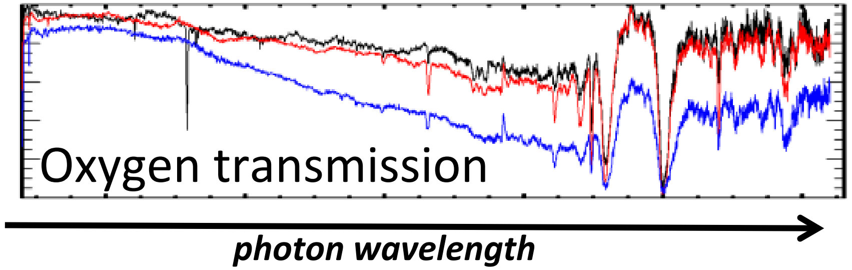
- **Refined analysis improved shot-to-shot reproducibility, demonstrating opacity experiment reliability**



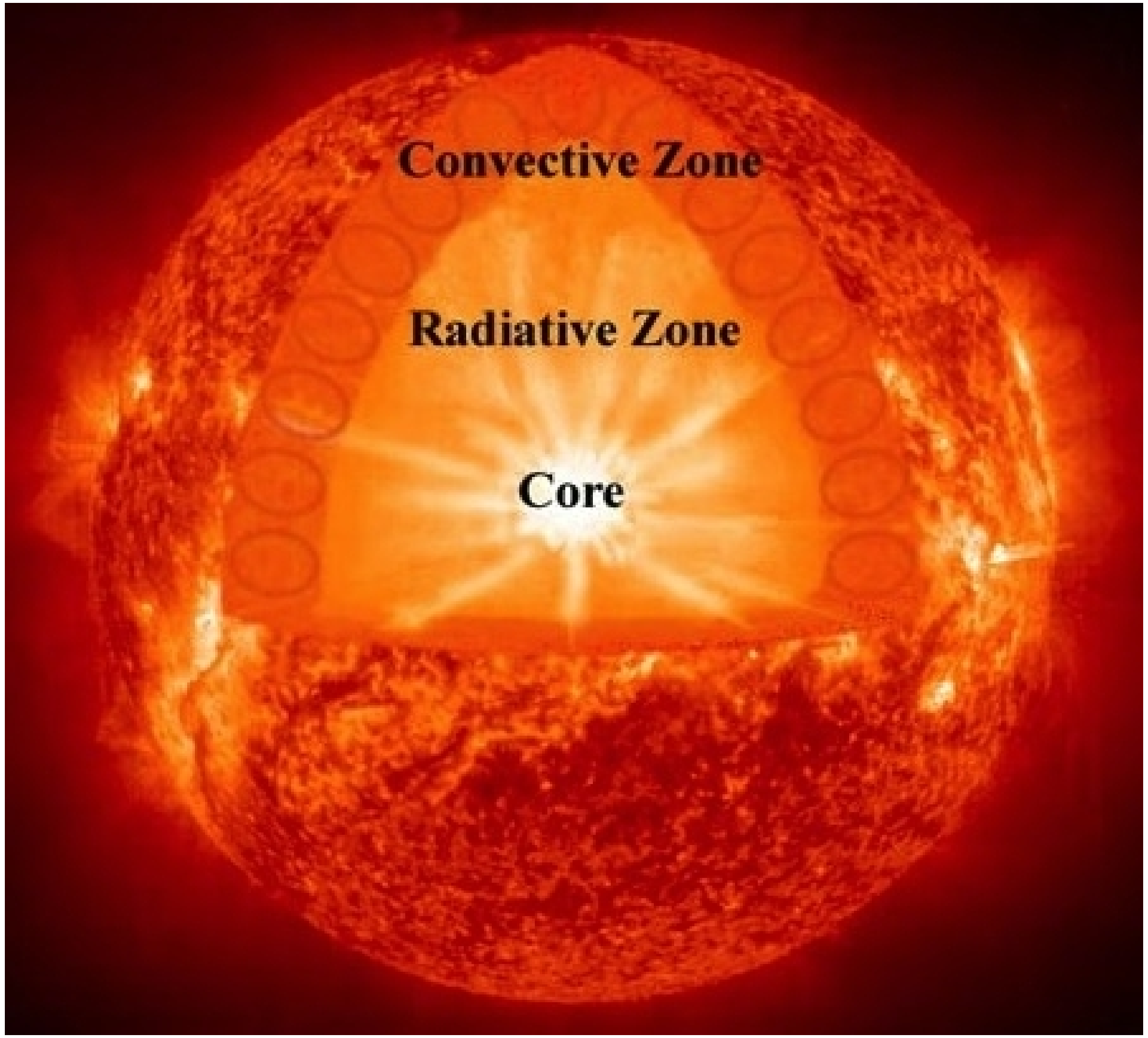
- **Systematic measurement of Cr, Fe, and Ni opacities suggests model refinements**
- **Time-resolved measurements augment the capabilities of the Z opacity platform and allow novel test of time-dependent effects**



- **Oxygen opacity measurements near CZB conditions are under development with interesting initial observations**



Solar models compute the internal structure of the Sun based on many interacting processes

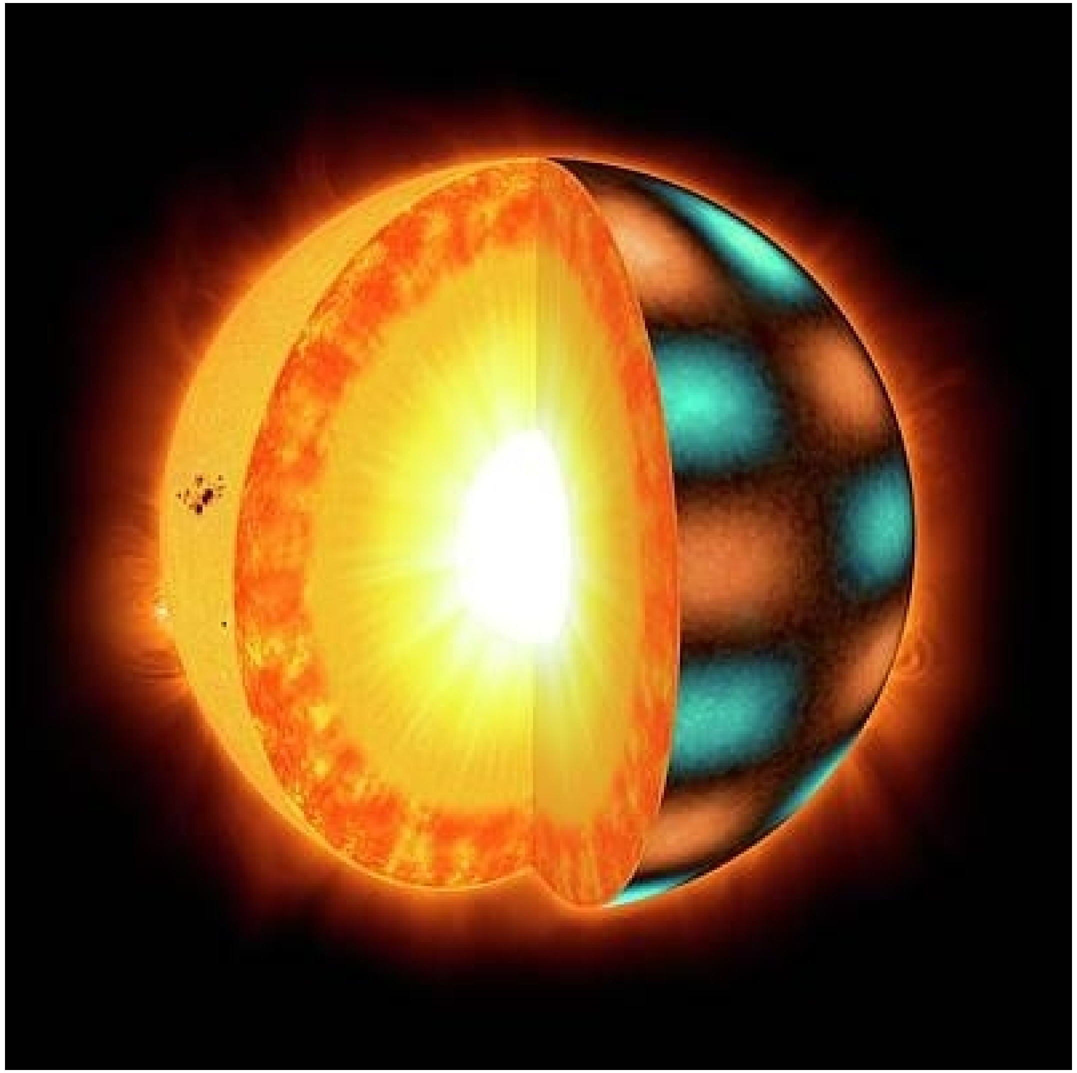


- These models use the theory of stellar structure and evolution to model the Sun.
- Our proximity to the Sun allows much higher accuracy measurements compared with other stars.
- This places greater constraints on solar models than general stellar models.
- Required input include:
  - Abundances
  - Opacities
  - Equation of state
  - Nuclear reaction rates
  - Etc.

Basu and Antia, *Phys Reports* (2008)

Helioseismology provides a different approach to measure the Sun's interior structure

- Helioseismology uses pulsations observed in the Sun to measure its properties.
- This allows for high accuracy measurements of the Sun's internal structure.
- For some time, solar models and helioseismic measurements agreed reasonably.



Basu and Antia, *Phys Reports* (2008); Serenelli, *ApJ* (2009); Basu, *J Phys Conf Series* (2013)

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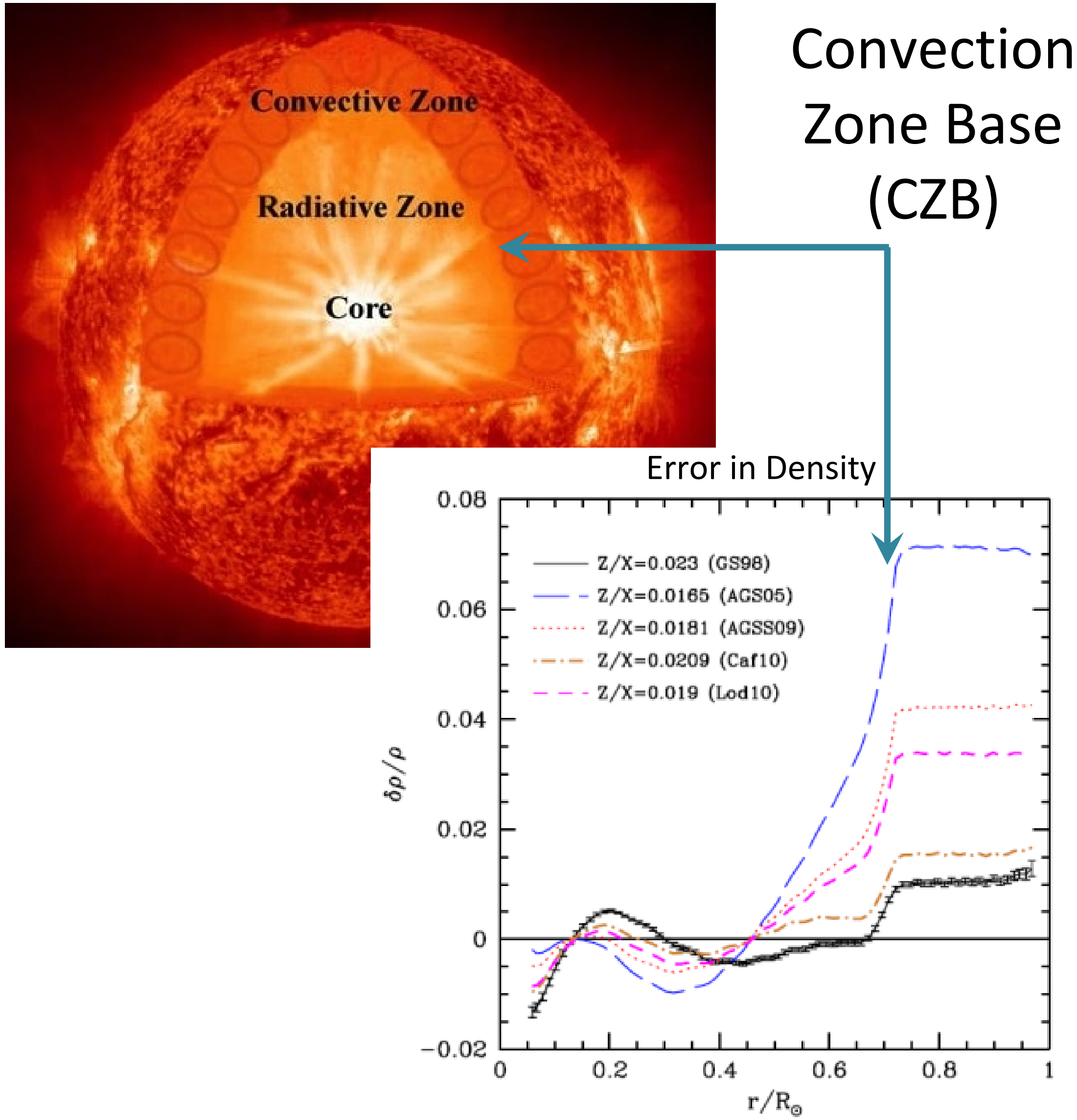


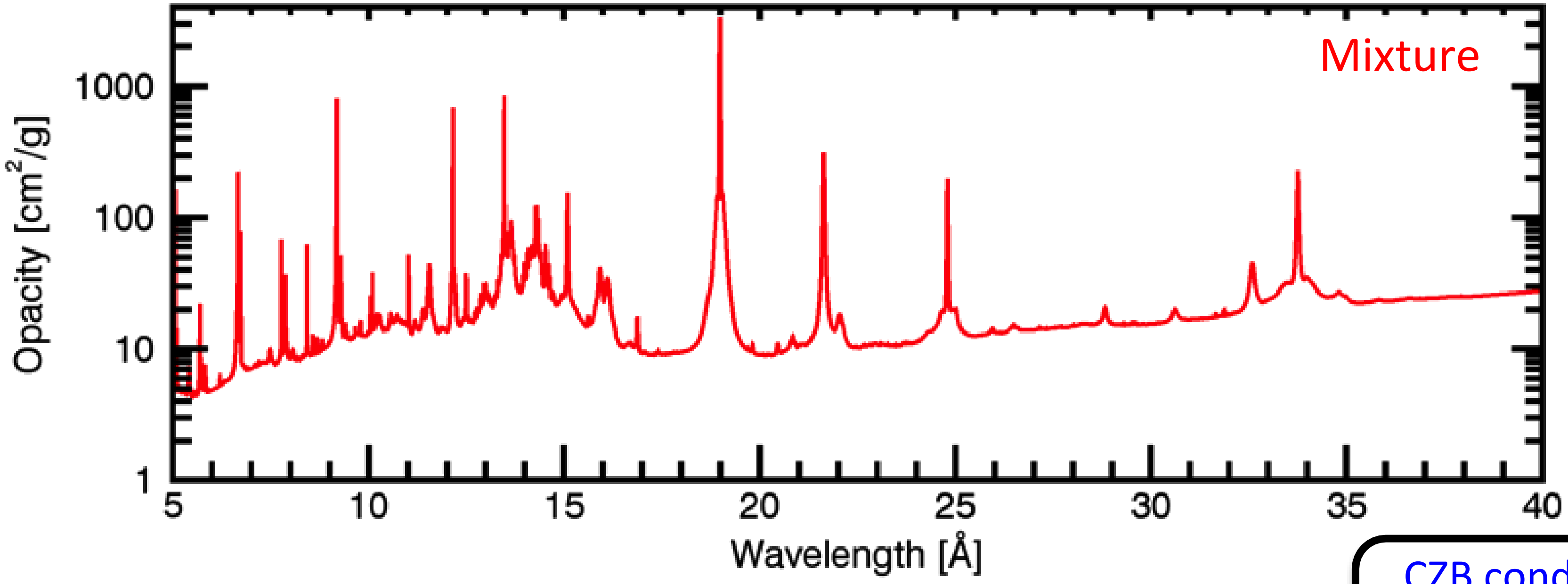
<u>The Solar Problem:</u>

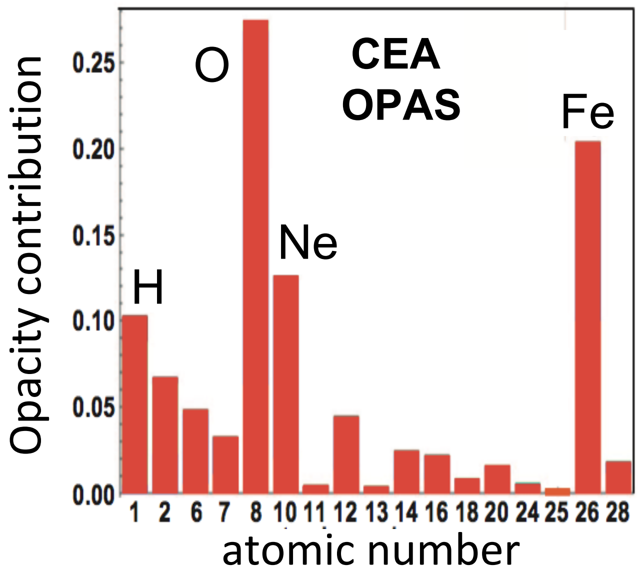
- Revised measurements of abundances reduced the inferred solar metallicity.
- When used as input to solar models, it brings the models out of agreement with the helioseismic measurements.
- Affected quantities include:
  - Sound speed
  - Densities
  - **Location of the base of the convection zone**

Basu and Antia, *Phys Reports* (2008); Serenelli, *ApJ* (2009); Basu, *J Phys Conf Series* (2013)

The discrepancy could be resolved if opacities are higher than models predict

Solar mixture opacity at Convection Zone Base (CZB)

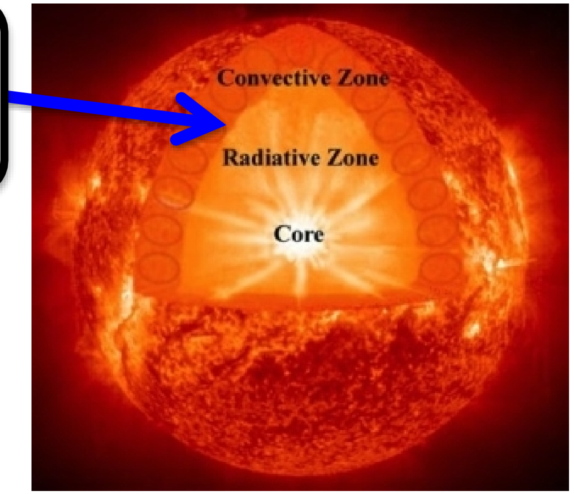




CZB conditions:

T_e ~ 180 eV

n_e ~ 9×10^{22} e^-/cc

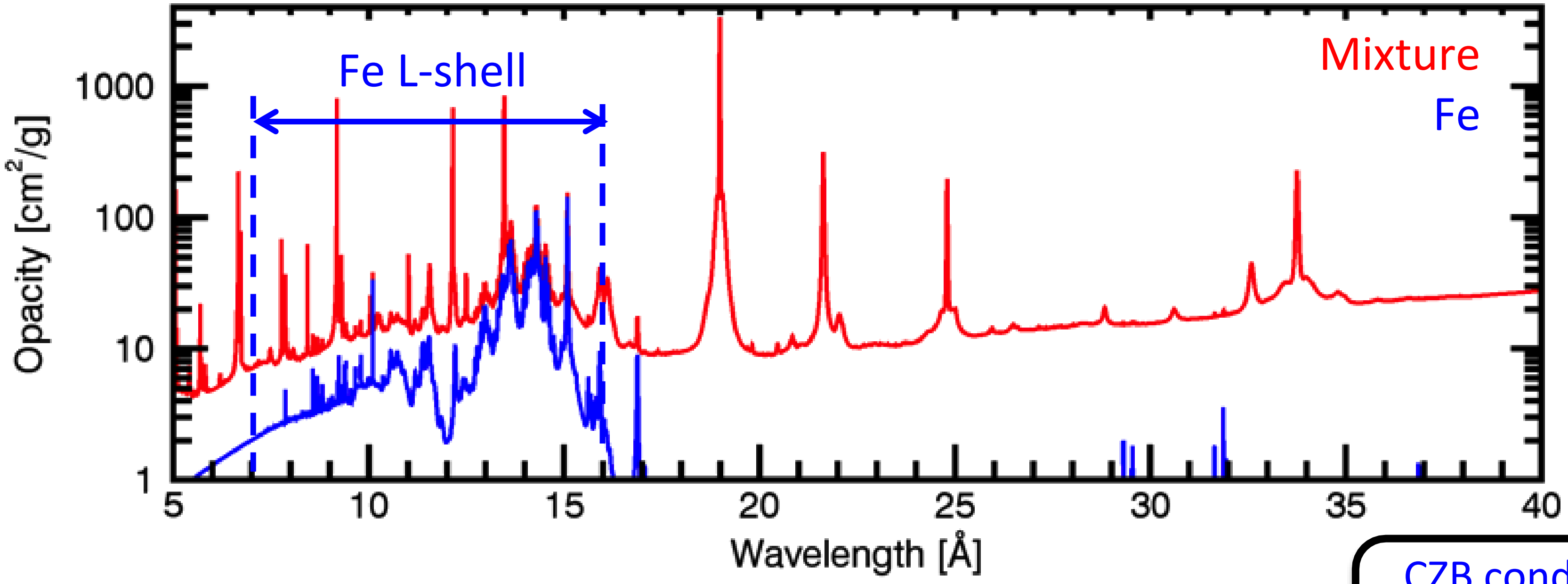


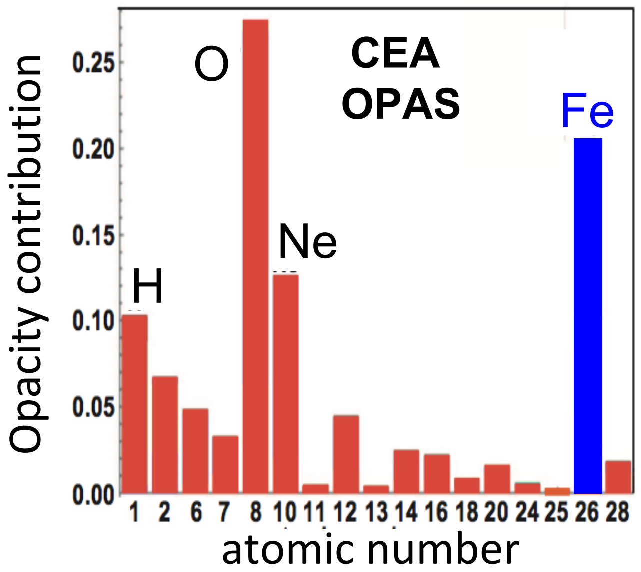
Opacity: κ_ν

- Quantifies radiation absorption
- $\kappa_\nu(T_e, n_e)$: Input for solar models
- Opacities affect the CZB location
- Opacity models are untested at CZB conditions

The discrepancy could be resolved if opacities are higher than models predict

Solar mixture opacity at Convection Zone Base (CZB)





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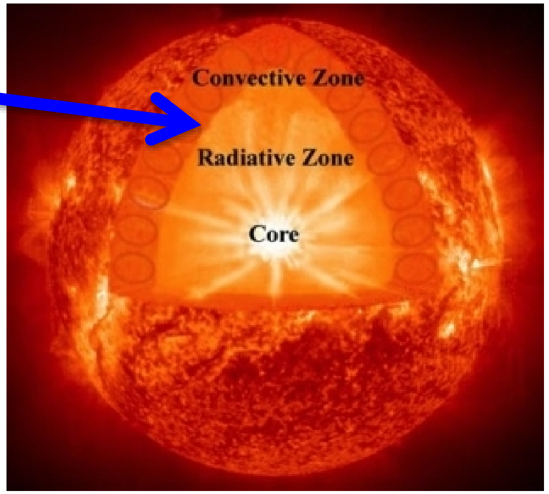
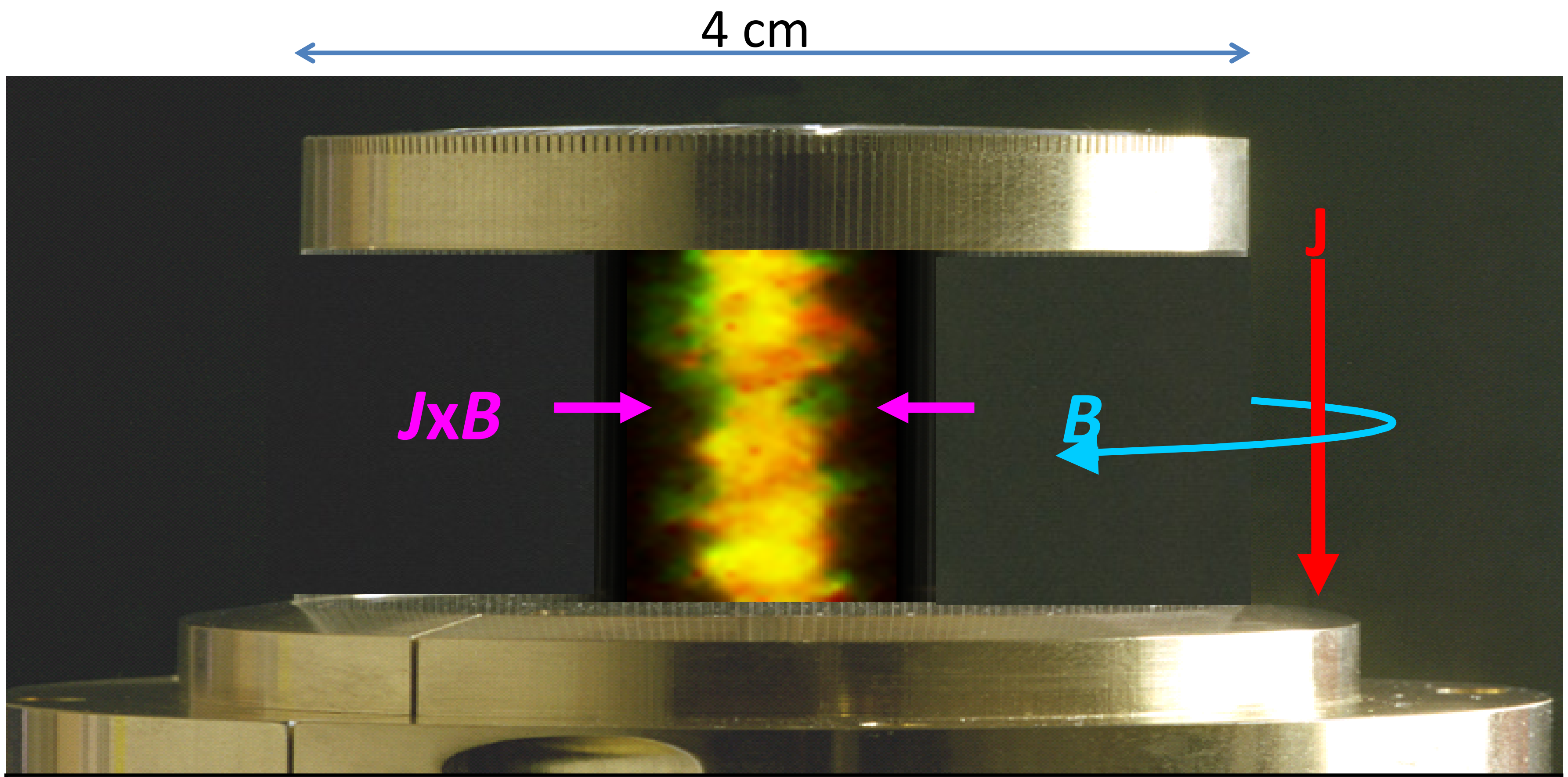


Fe is a likely suspect:

- 2nd largest contribution
- Most difficult to model

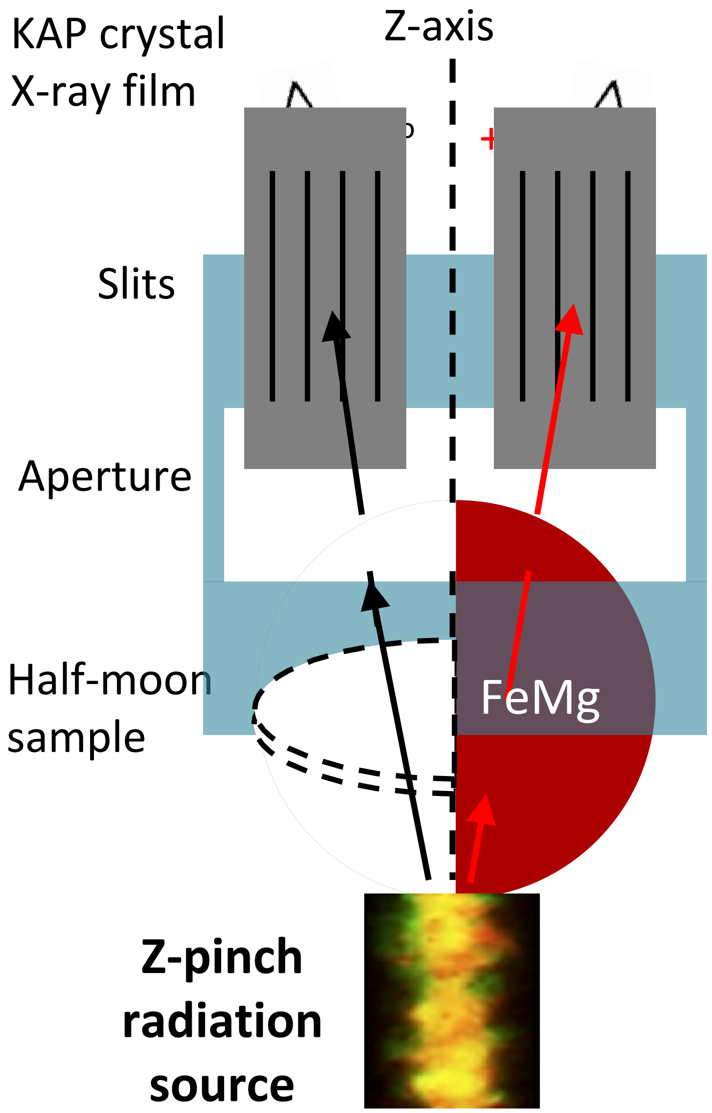
The SNL Z machine uses 27 million Amperes to create x-rays

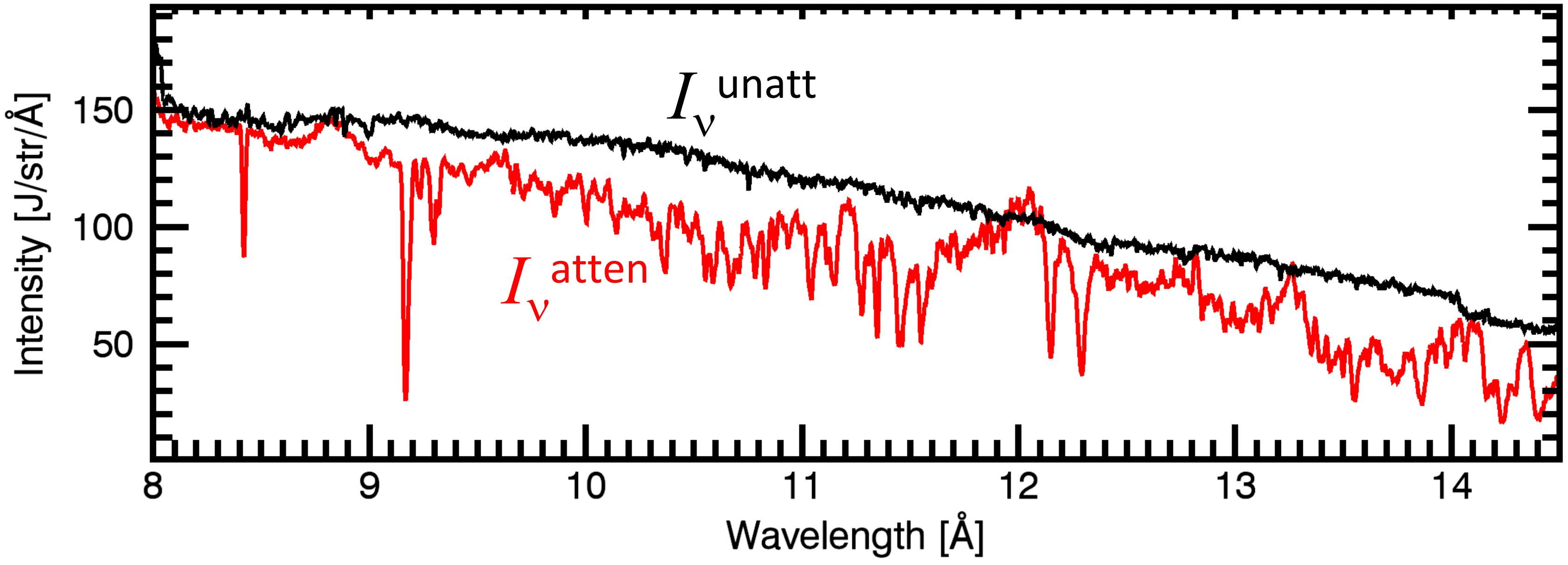


P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

Sanford, *PoP* (2002); Bailey et al., *PoP* (2006); Slutz et al., *PoP* (2006); Rochau et al., *PPCF* (2007)

Iron opacity at solar interior conditions is measured using bright radiation generated by Z-pinch

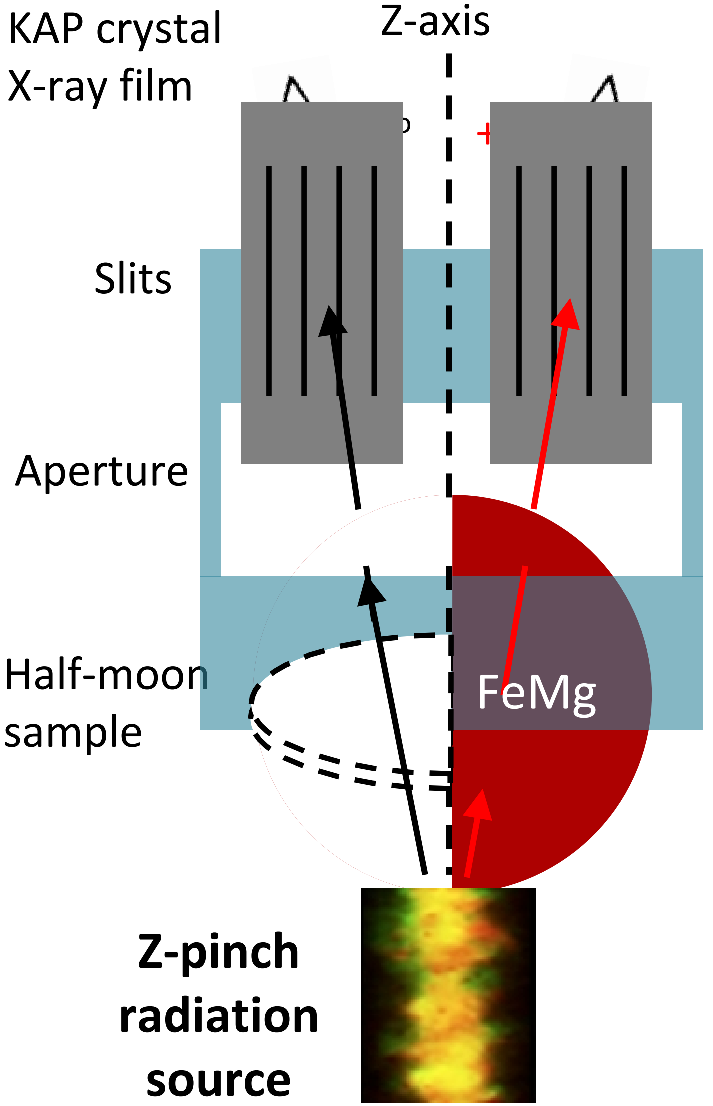


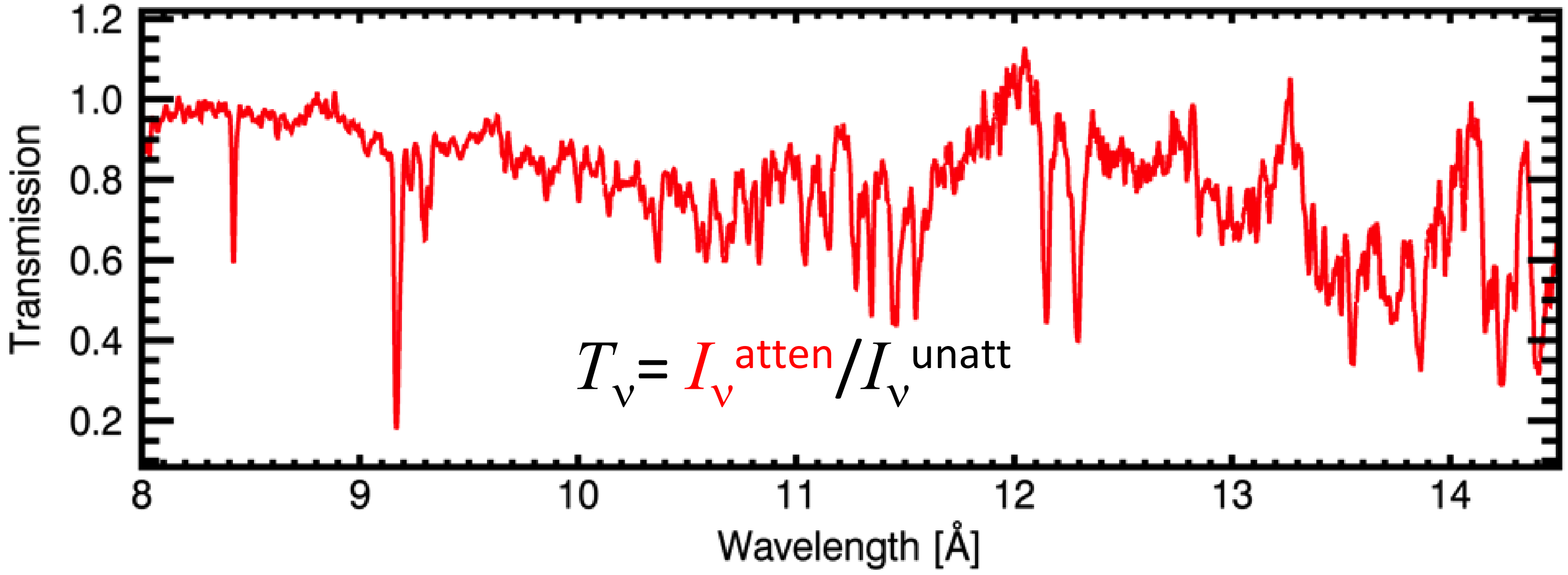


Z experiment satisfies challenging requirements:

- Uniform heating
- Mitigating self emission
- Condition measurements
- Checking reproducibility

Iron opacity at solar interior conditions is measured using bright radiation generated by Z-pinch





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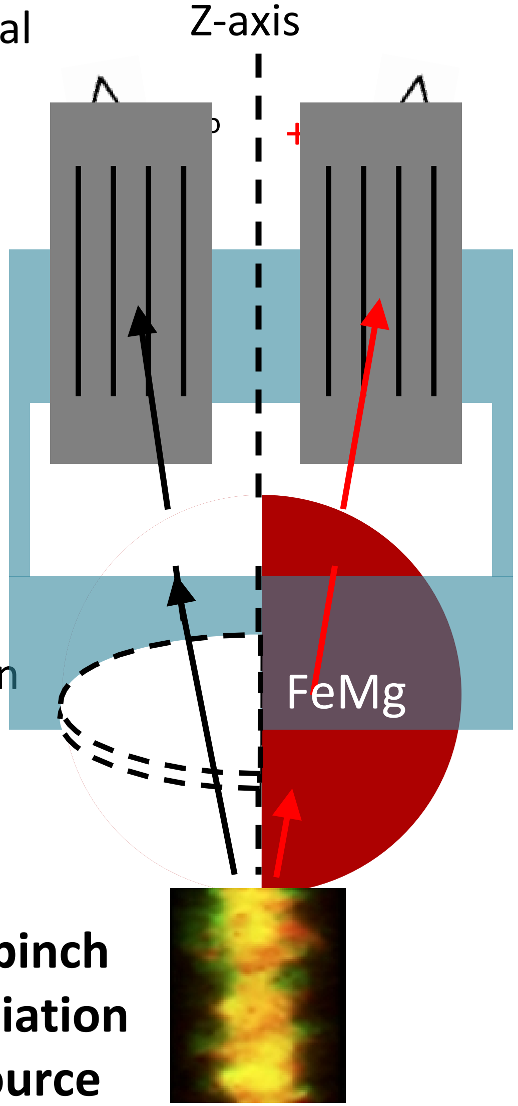

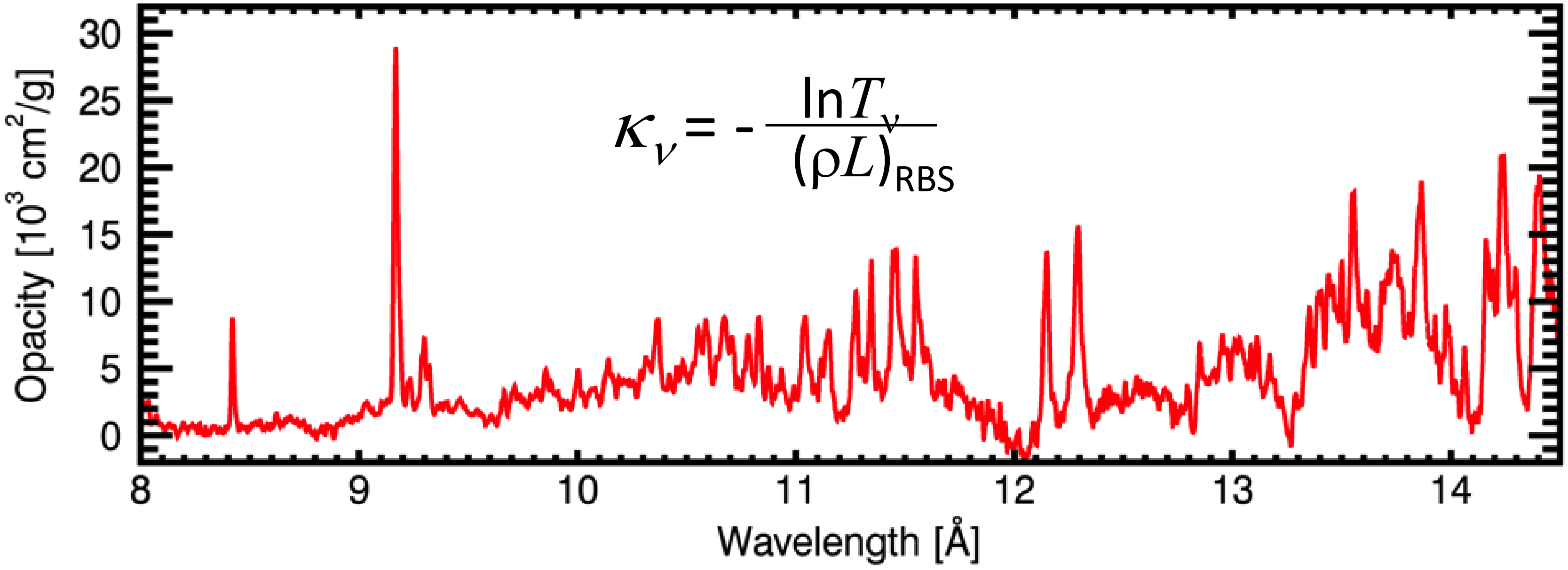

$$\kappa_\nu = -\frac{\ln T_\nu}{(\rho L)_{RBS}}$$

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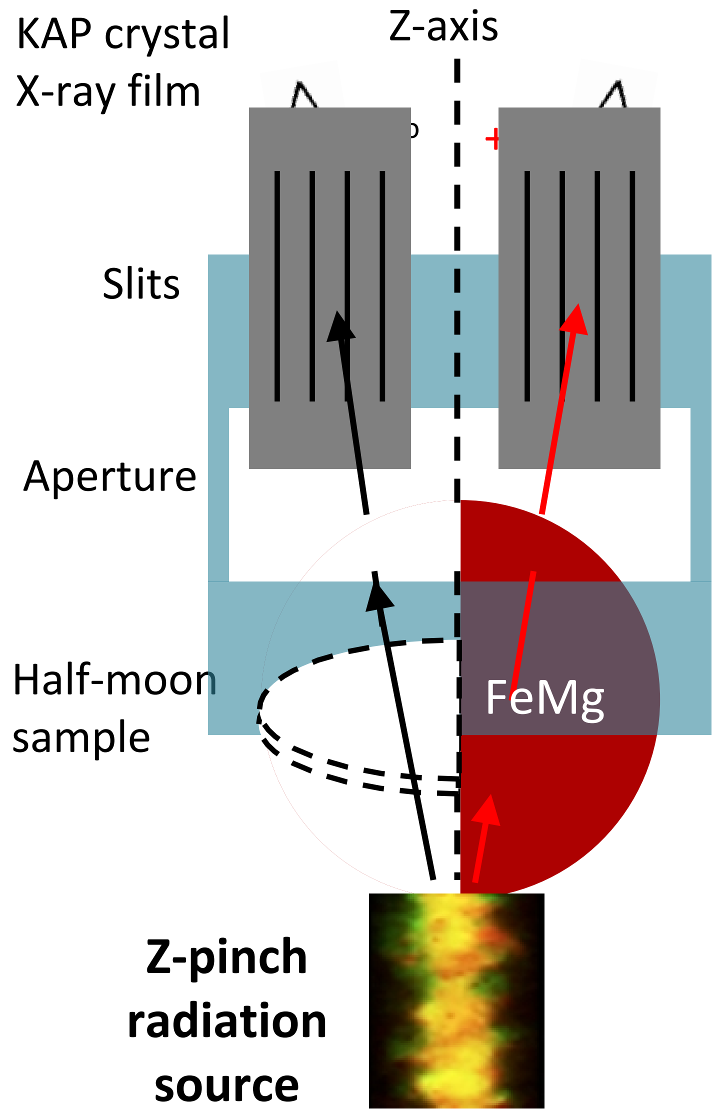

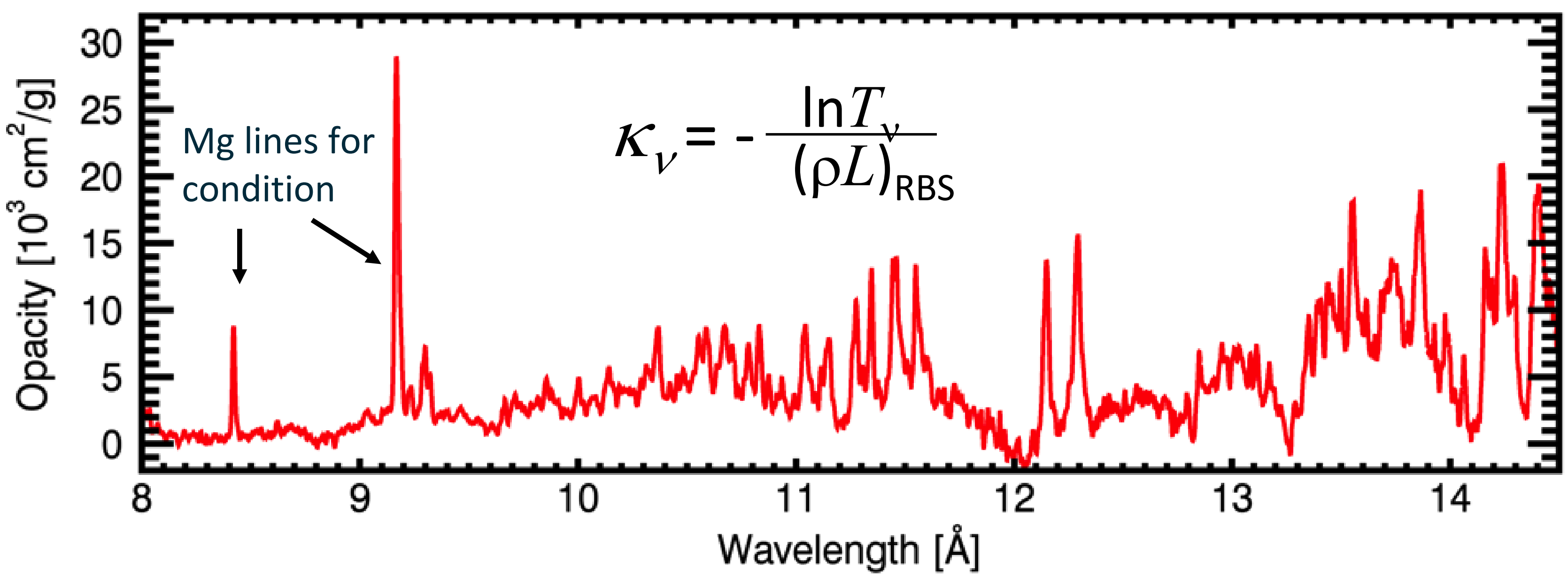

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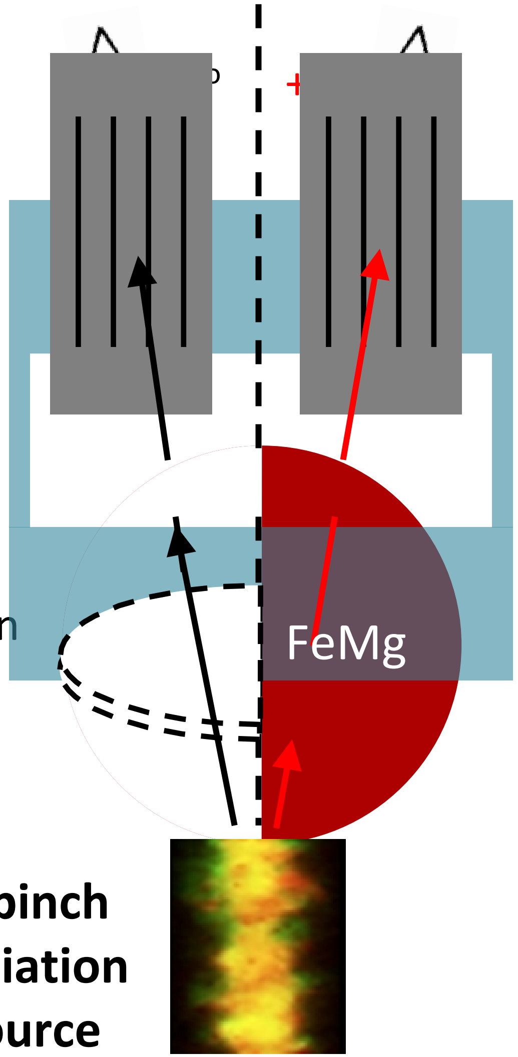

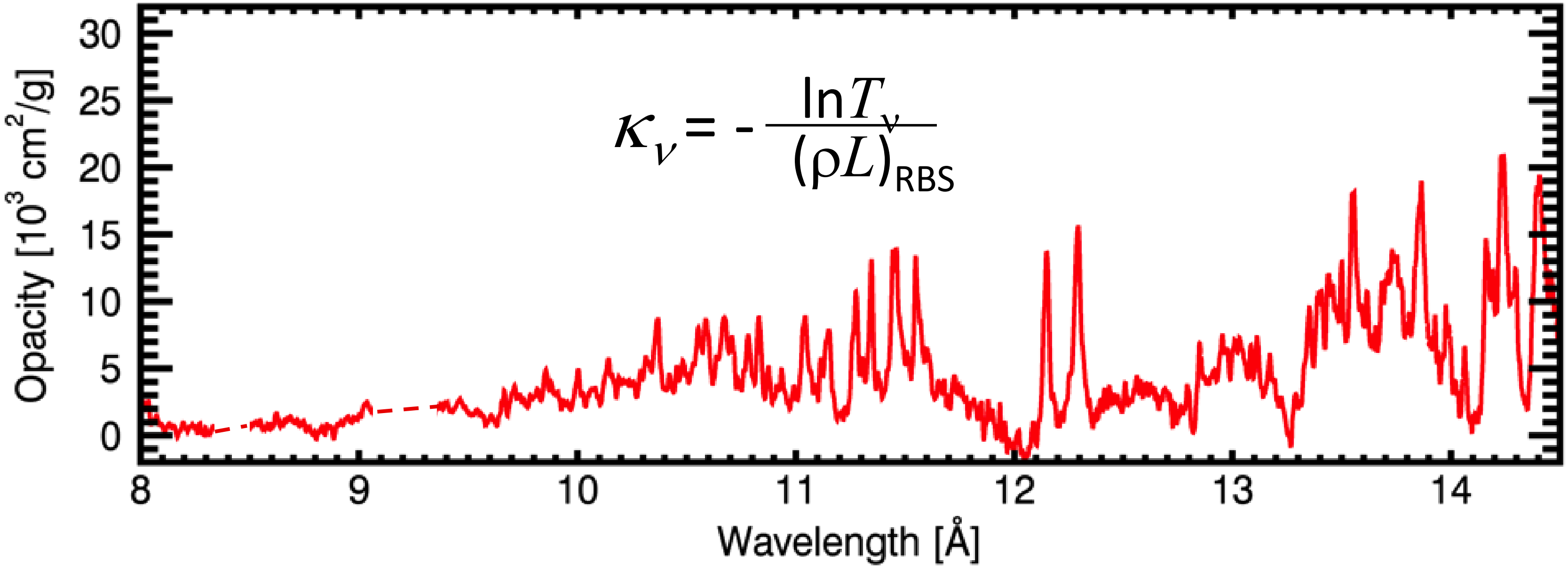

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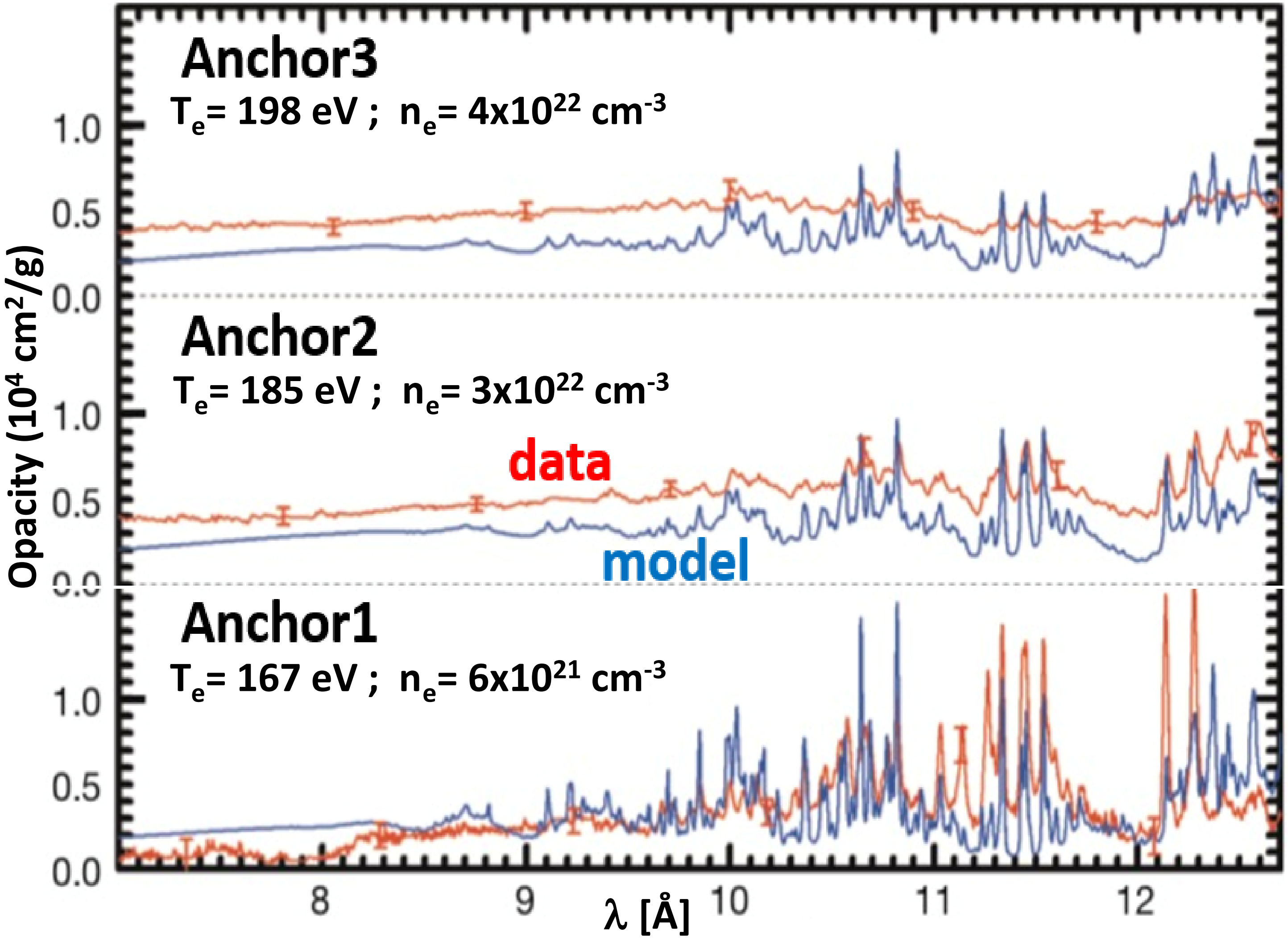
Calculated iron opacities are significantly lower than measurements as T_e, n_e approach solar interior values

Bailey, Nagayama, Loisel, Rochau *et al*., *Nature* 2015



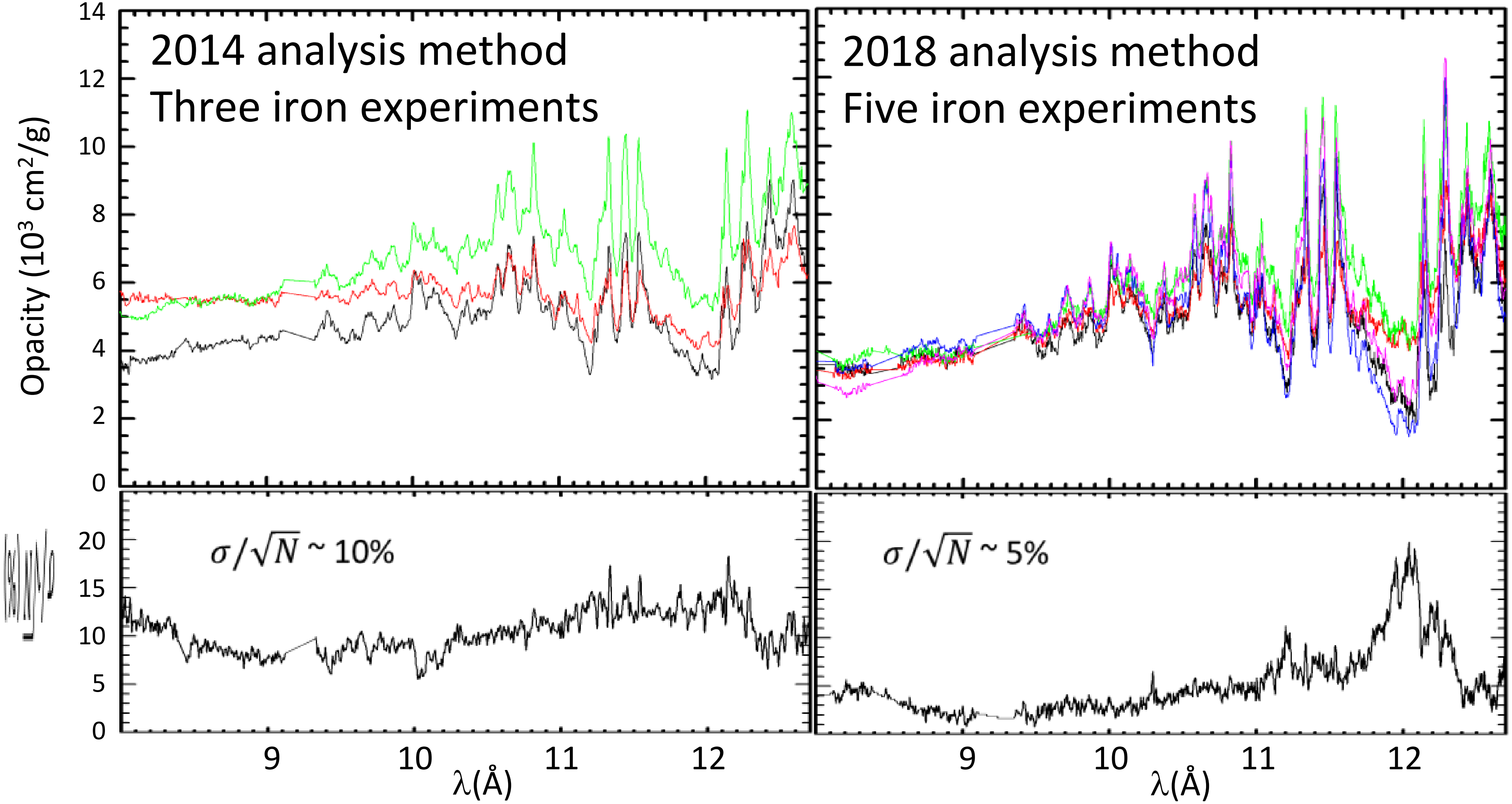
- If true, it accounts for about ½ the opacity increase needed to resolve the solar problem

<u>But what's causing the discrepancy?</u>

- Inaccuracy of theory?
- Flaws in experiment?

Both theory and experiment are challenging in HED science; Neither should be ruled out.

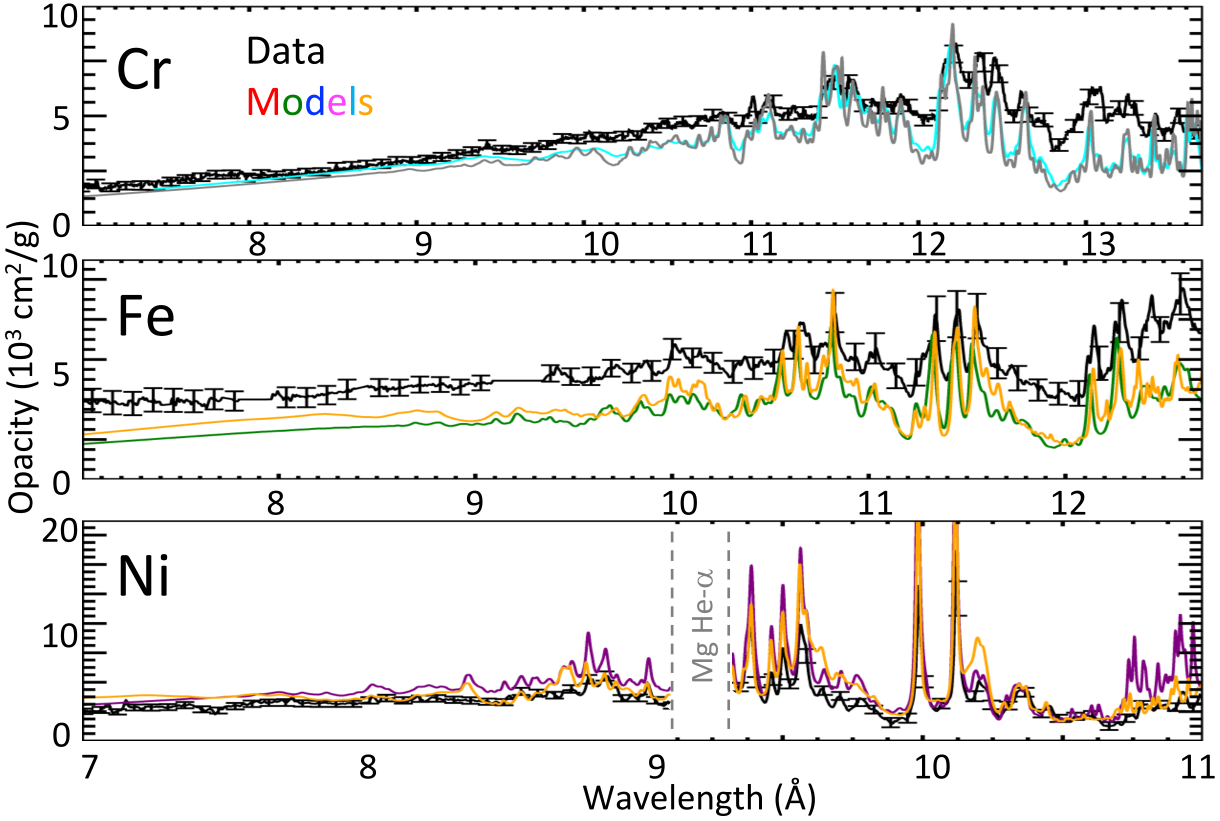
Both refined analysis and more experiments helped to improve shot-to-shot agreement on Anchor-2 Fe



Solar mean opacity update: +7% → +5%

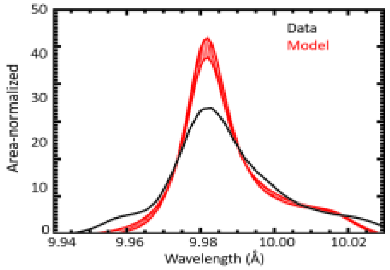
Systematic opacity measurements with Cr, Fe, and Ni identified three main opacity model-data discrepancies

Anchor2: $T_e \sim 180$ eV, $n_e \sim 30 \times 10^{21}$ cm^{-3}



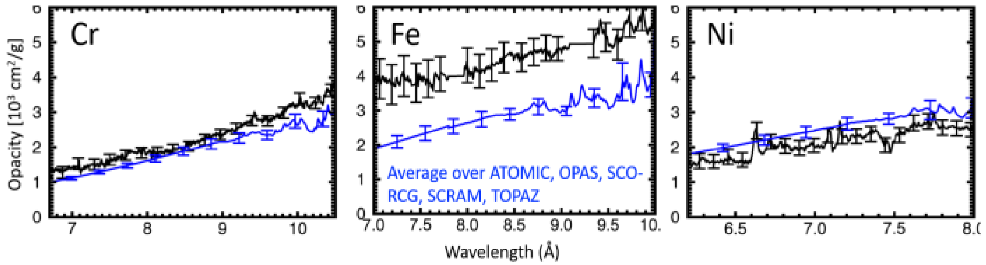
How models and data disagree …

Discrepancy1: Narrower lines



Inaccurate line-broadening?
Missing satellite lines?

Discrepancy2: Lower quasi-continuum only from Fe



Discrepancy3: Lower opacity valleys from Fe, Cr

What's causing the discrepancies? Experiments? Analyses? Theories?

Time-dependent effects are a potential source of systematic error on opacity measurements

Potential systematic errors[1]:

- Error in T_e and n_e determination
- Sample areal density error
- Sample spatial gradients
- Sample self-emission
- Background determination

⋮

Time dependent effects:

Effect 1: Transient kinetics. Excluded from high density and agreement at anchor 1.

Effect 2: Integration of opacity over multiple plasma conditions (temporal gradients).

→ First approach: field ultra-fast detector to assess the Z opacity sample evolution

Time-resolved measurements can also augment the outcomes of the opacity research on Z

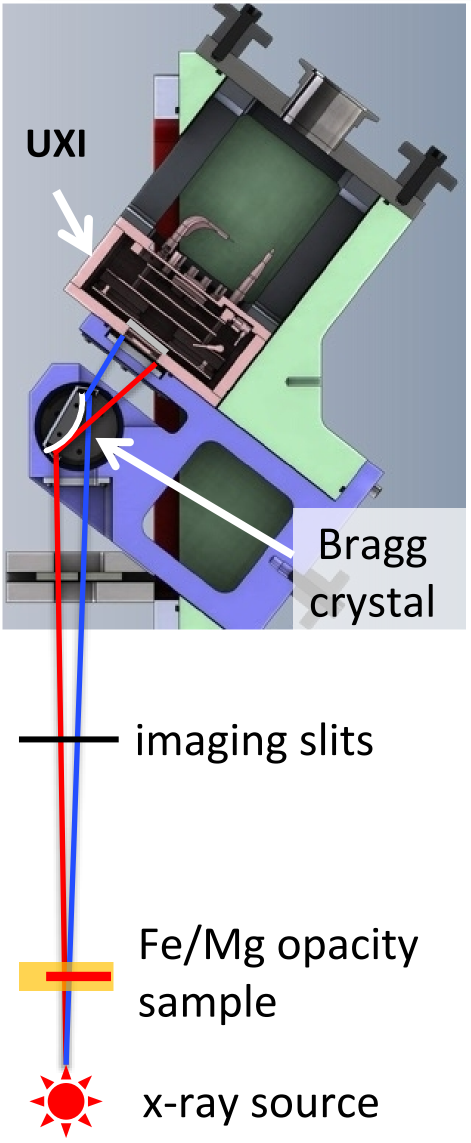
- ***Testbed for radiation-hydrodynamics simulations***

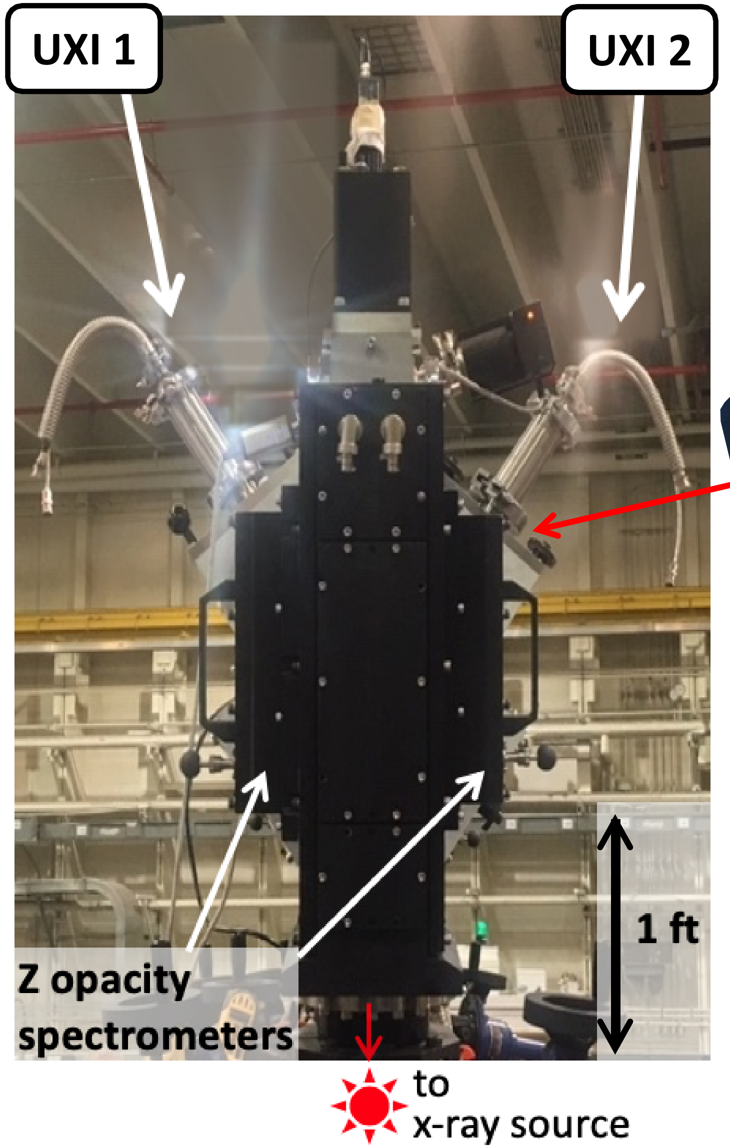
- ***Evaluate proposed model refinements that address the model-data discrepancies***
  → line broadening
  → 2-photon absorption
  → excited states distribution

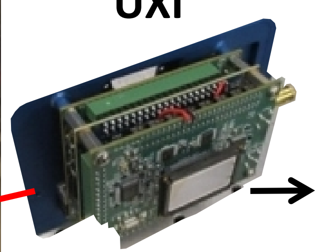
- ***Better understanding of how opacity experiments work***
  → better control of sample conditions
  → reach higher T_e, n_e

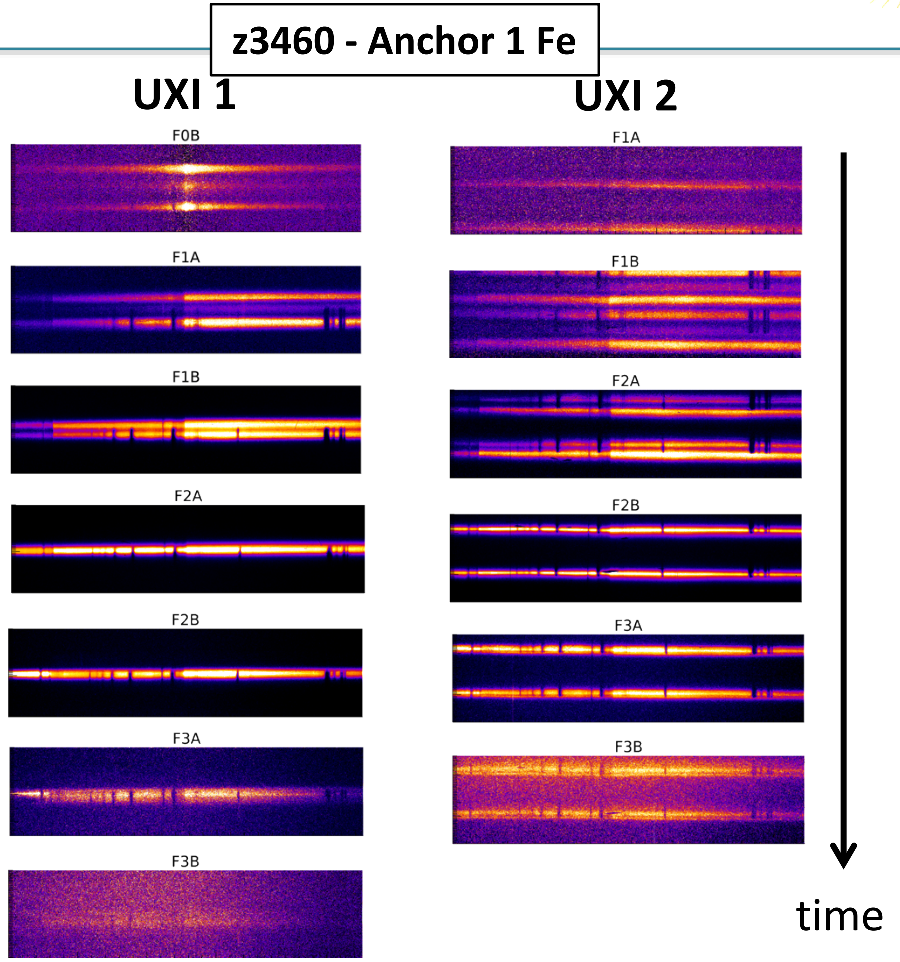
- ***Increase efficiency of absolute opacity measurements***
  → multiple opacity measurements over different T_e, n_e within a single experiment

UXI* detector successfully fielded in Z opacity spectrometers



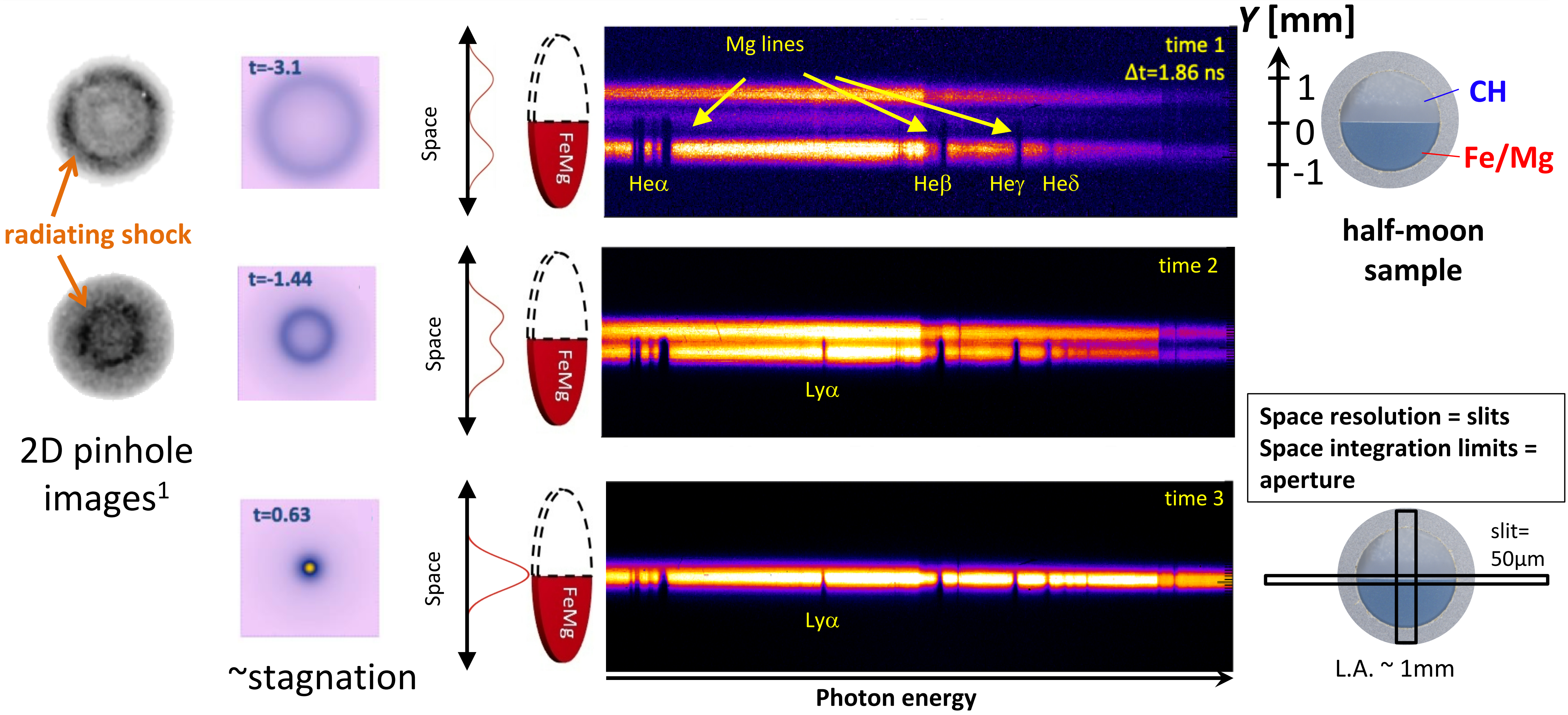






- ➢ Average of 8 frames per shot, with max of 13 frames on a single shot with 2 UXI cameras.
- ➢ March 2022: 39 images on 3 shots

Our first goal is to measure the sample conditions evolution using Mg K-shell absorption *space-resolved*



2D pinhole images[1]

~stagnation

half-moon sample

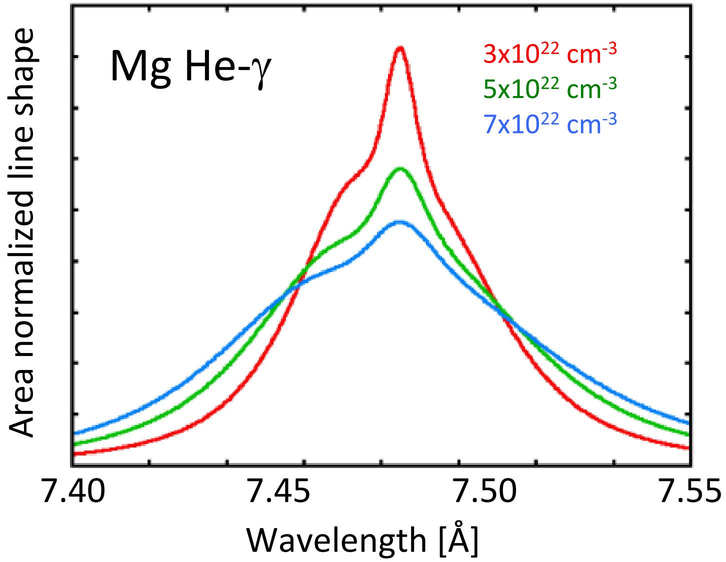
Space resolution = slits
Space integration limits = aperture

➤ The reproducible (320 km/s ± 8%) radiating shock is used to cross-time datasets[1]

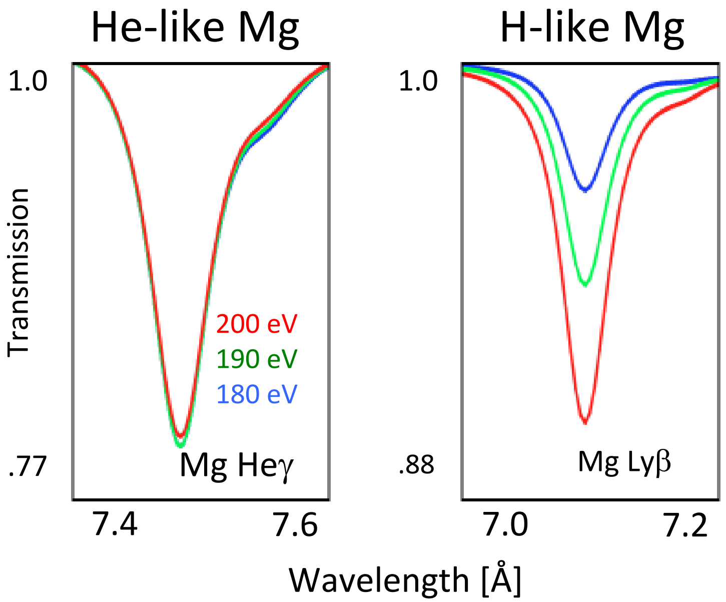
[1]G. Rochau *et al.*, *PRL* (2008)

n_e and T_e are inferred from measured Mg K-shell line absorption spectrum

- Line shape: sensitive to electron density, n_e



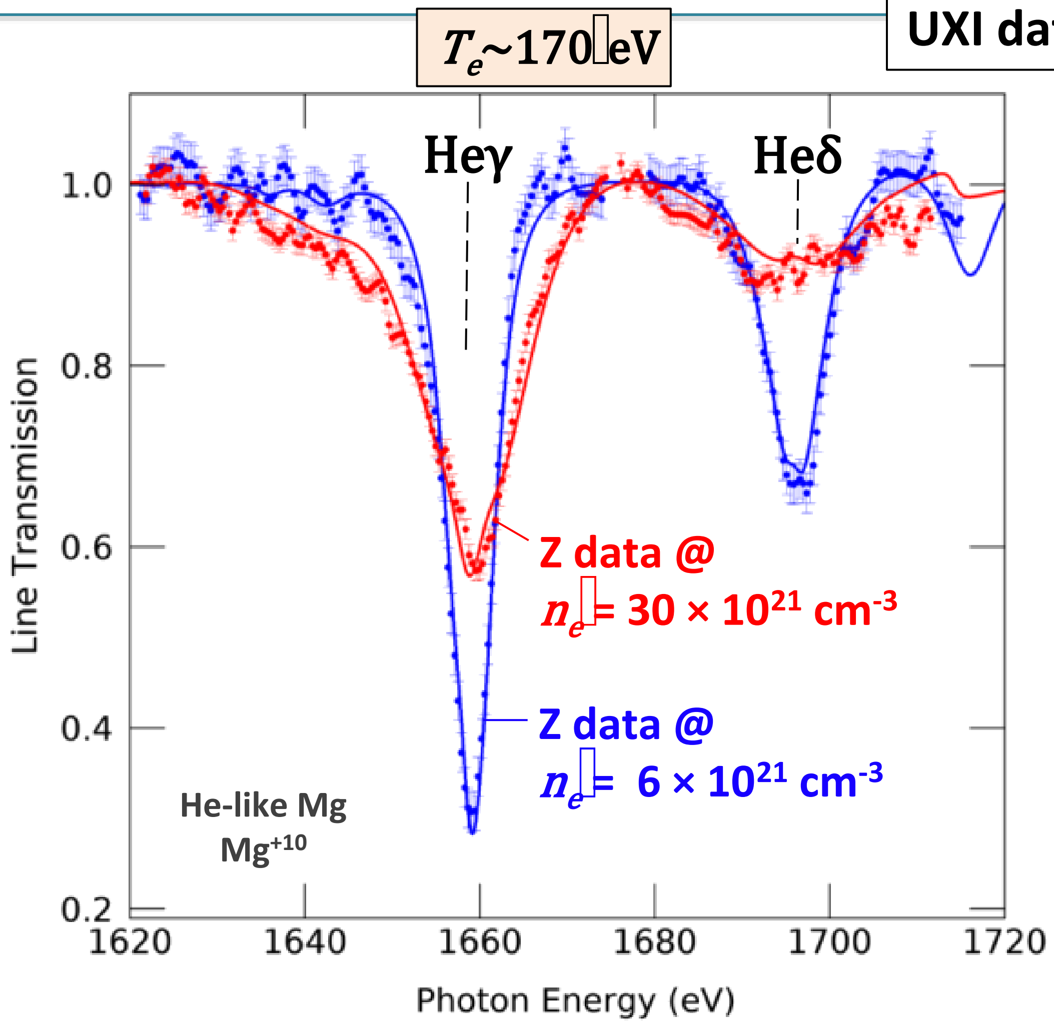
- Line ratio: sensitive to electron temperature, T_e

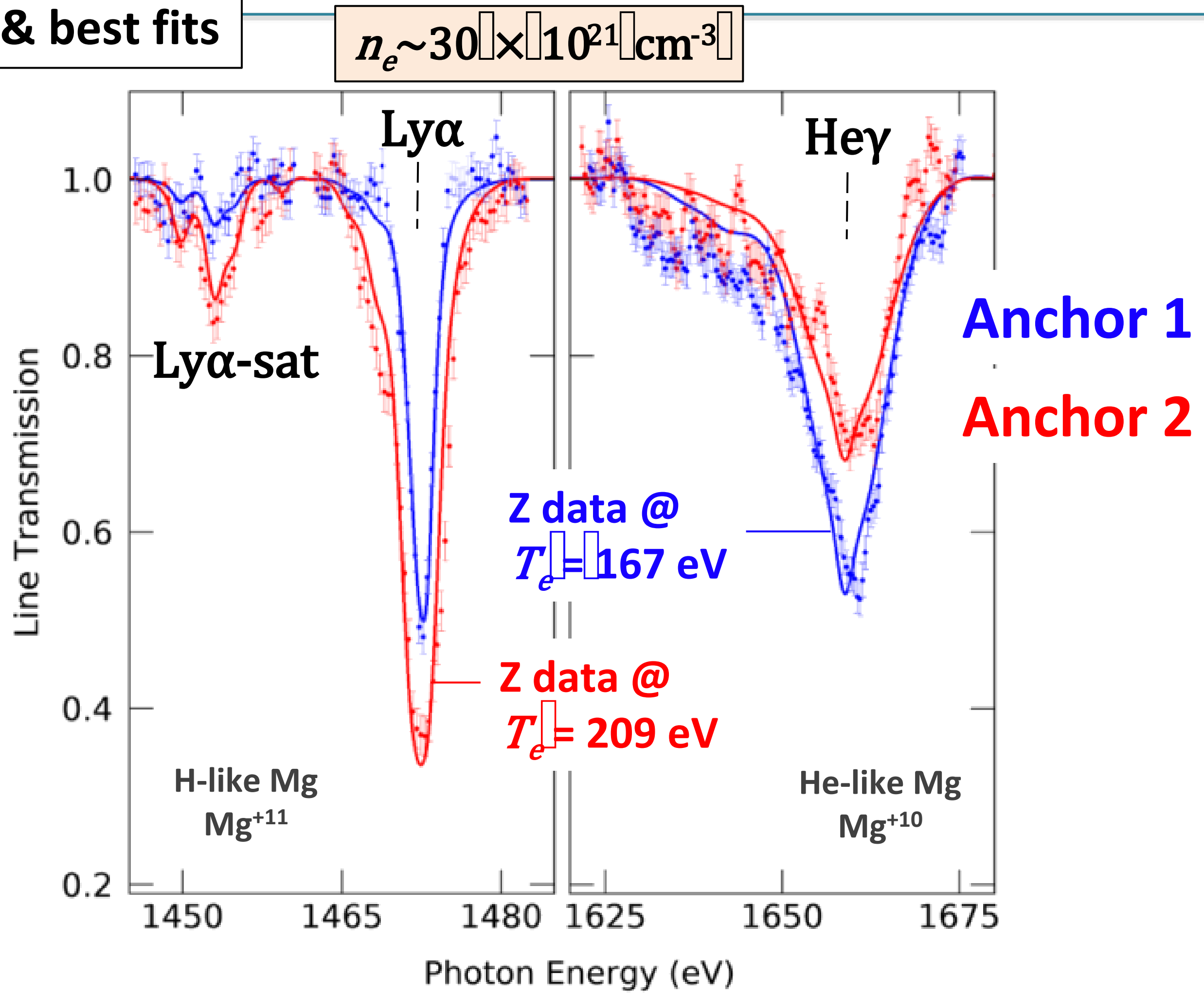


Plasma T_e and n_e can be extracted by reproducing measured spectra with spectral models

Conditions were obtained for both anchor 1 & 2

UXI data & best fits



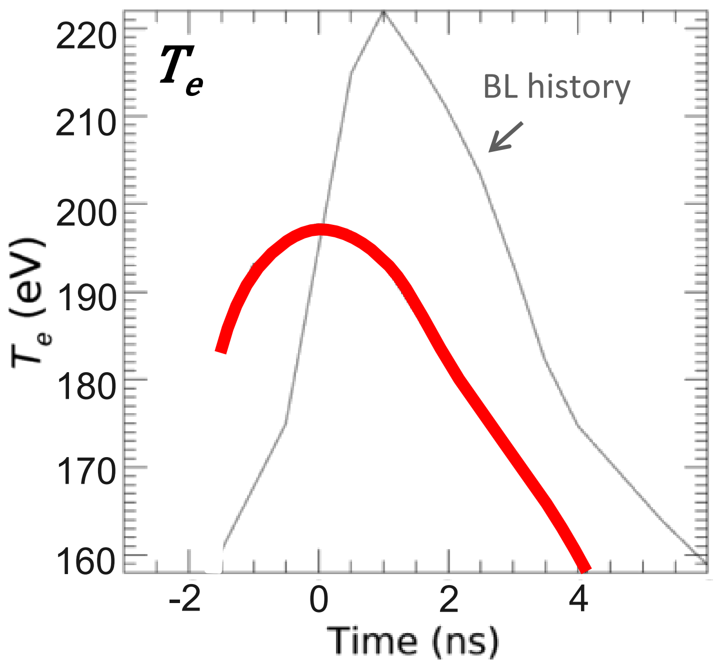


- High-n He-like (γ, δ) lines are broader with higher n_e

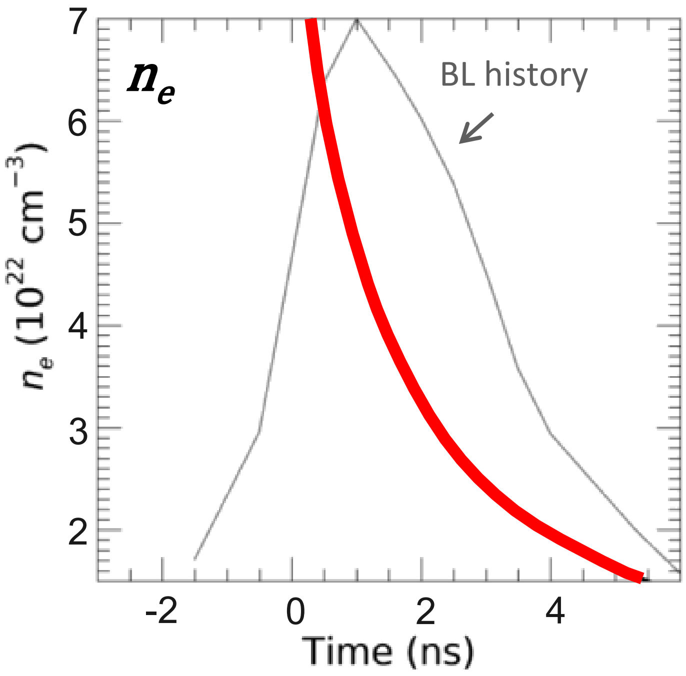
- H-like to He-like line ratios increase with T_e at fixed n_e

Simulations* predict T_e , n_e evolution for Anchor-2 Fe

Anchor 2 T_e



Anchor 2 n_e

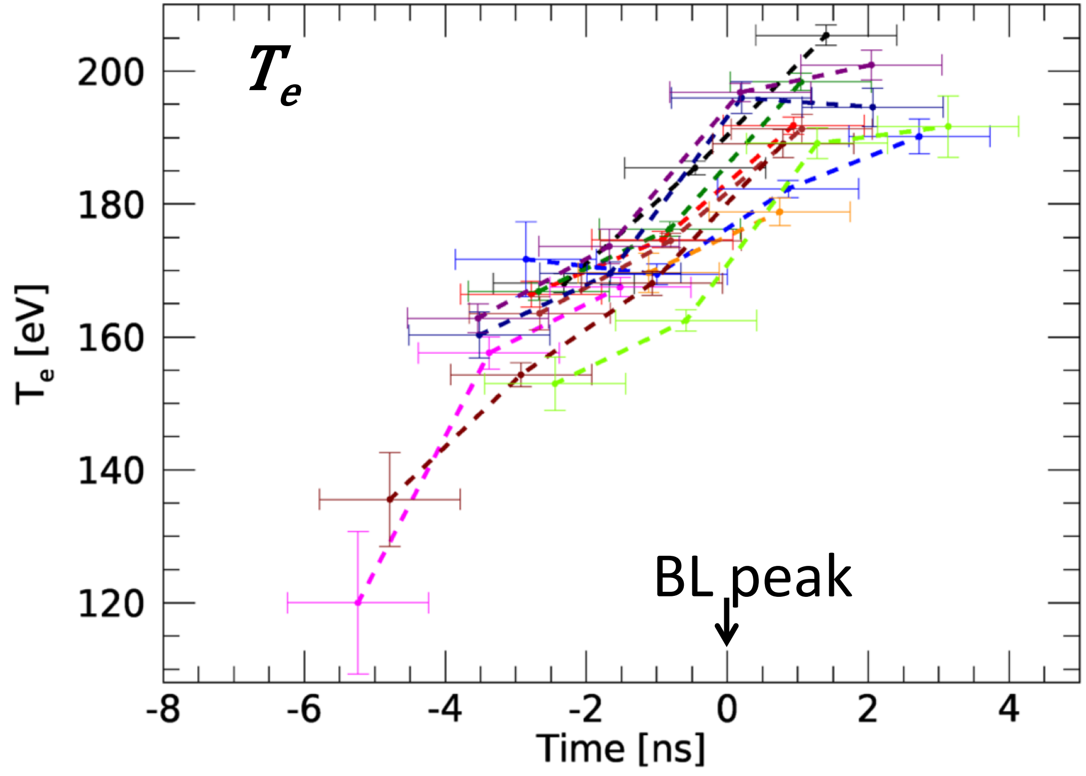


*Nagayama et al., PRE, 93 (2016)

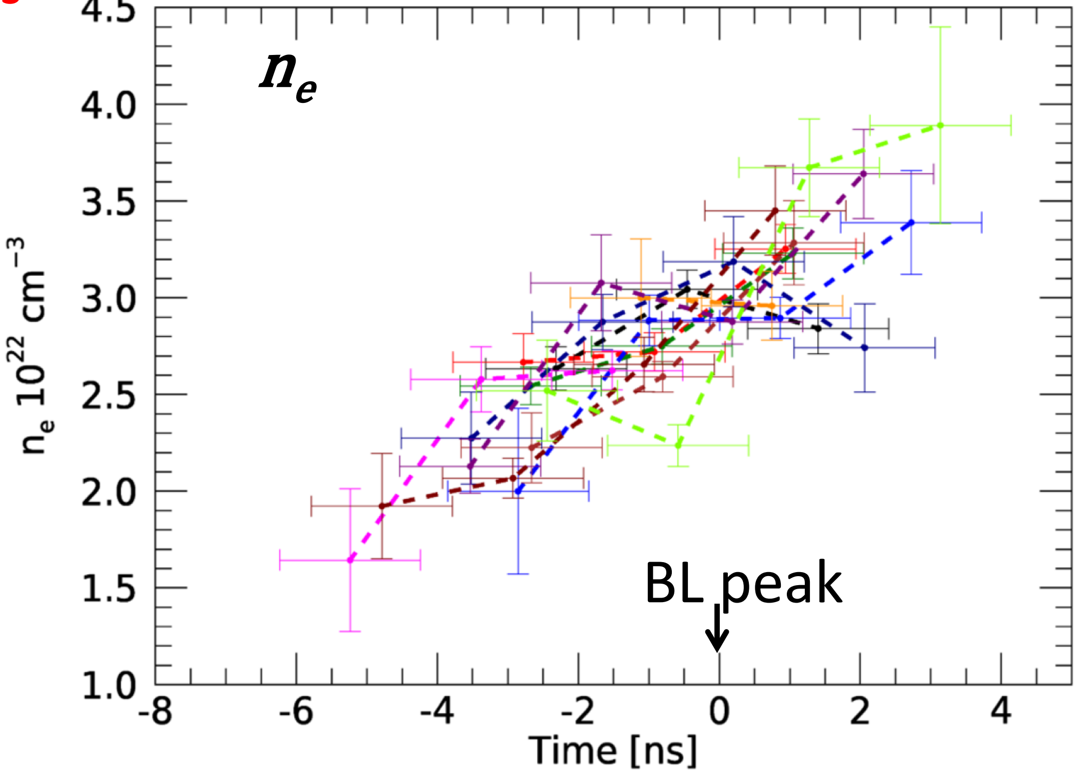
Anchor 2 Fe conditions evolution trends disagree with simulation predictions - PRELIMINARY

11 datasets
7 Z shots

Anchor 2 T_e



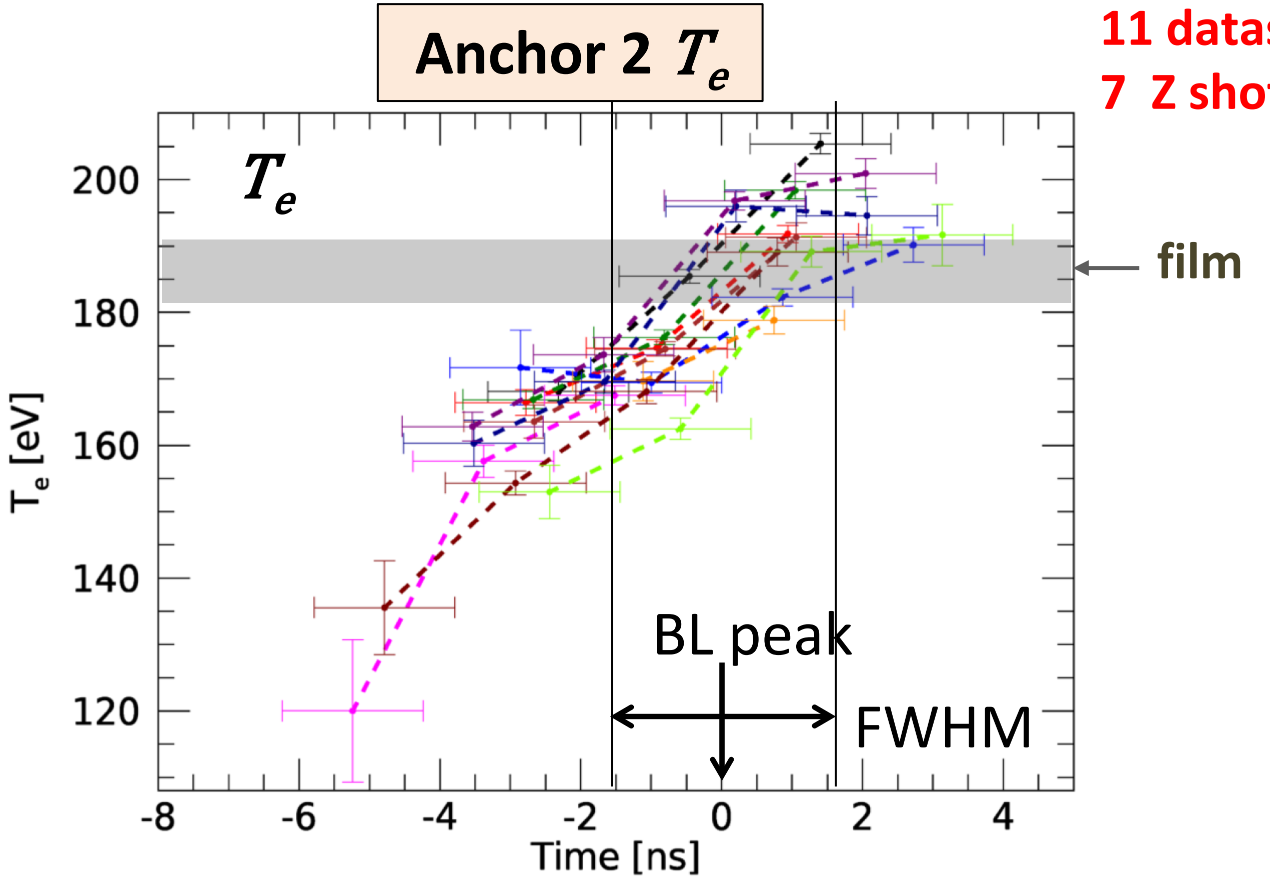
Anchor 2 n_e

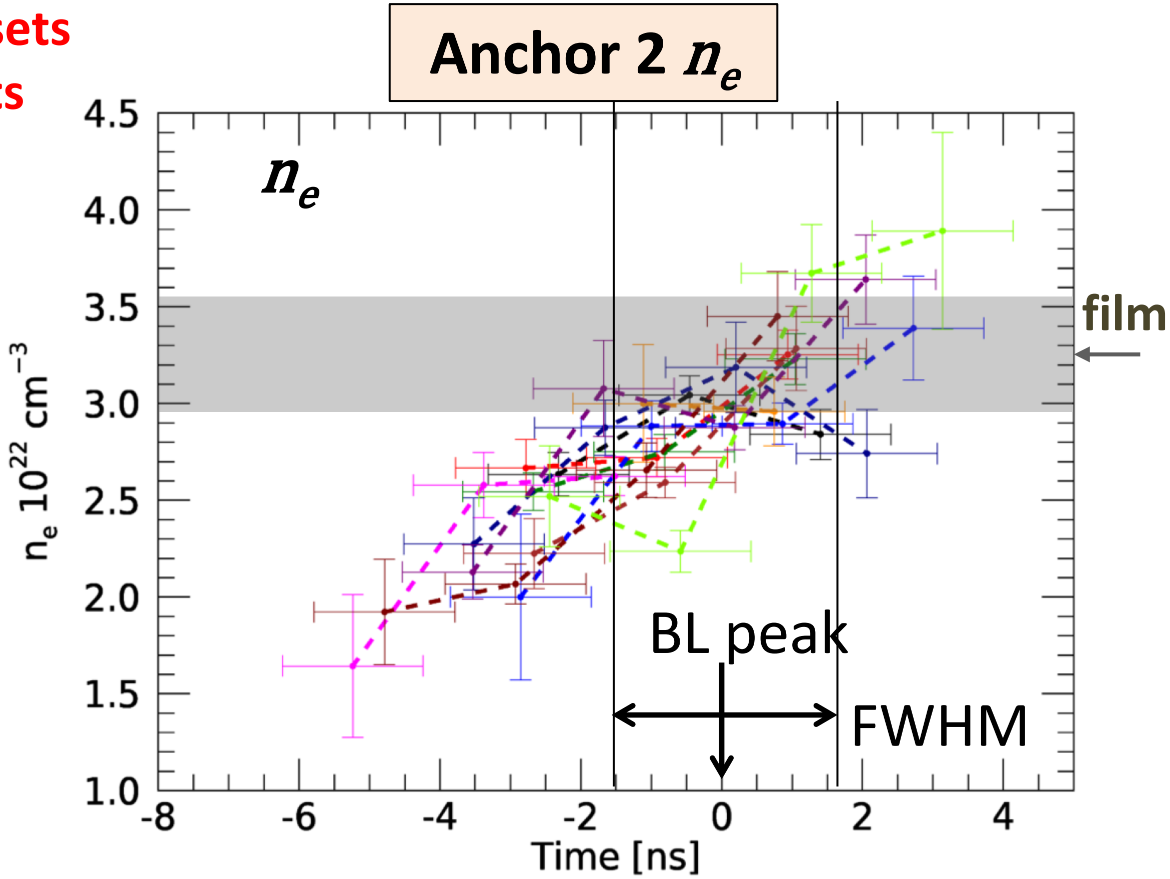


- ➢ **Inclusion of multiple datasets helps assure reliability of novel measurements, allows for clearer trends**
- ➢ **Condition fitting algorithm being scrutinize (preliminary results)**

Anchor 2 Fe conditions evolution trends disagree with simulation predictions - PRELIMINARY

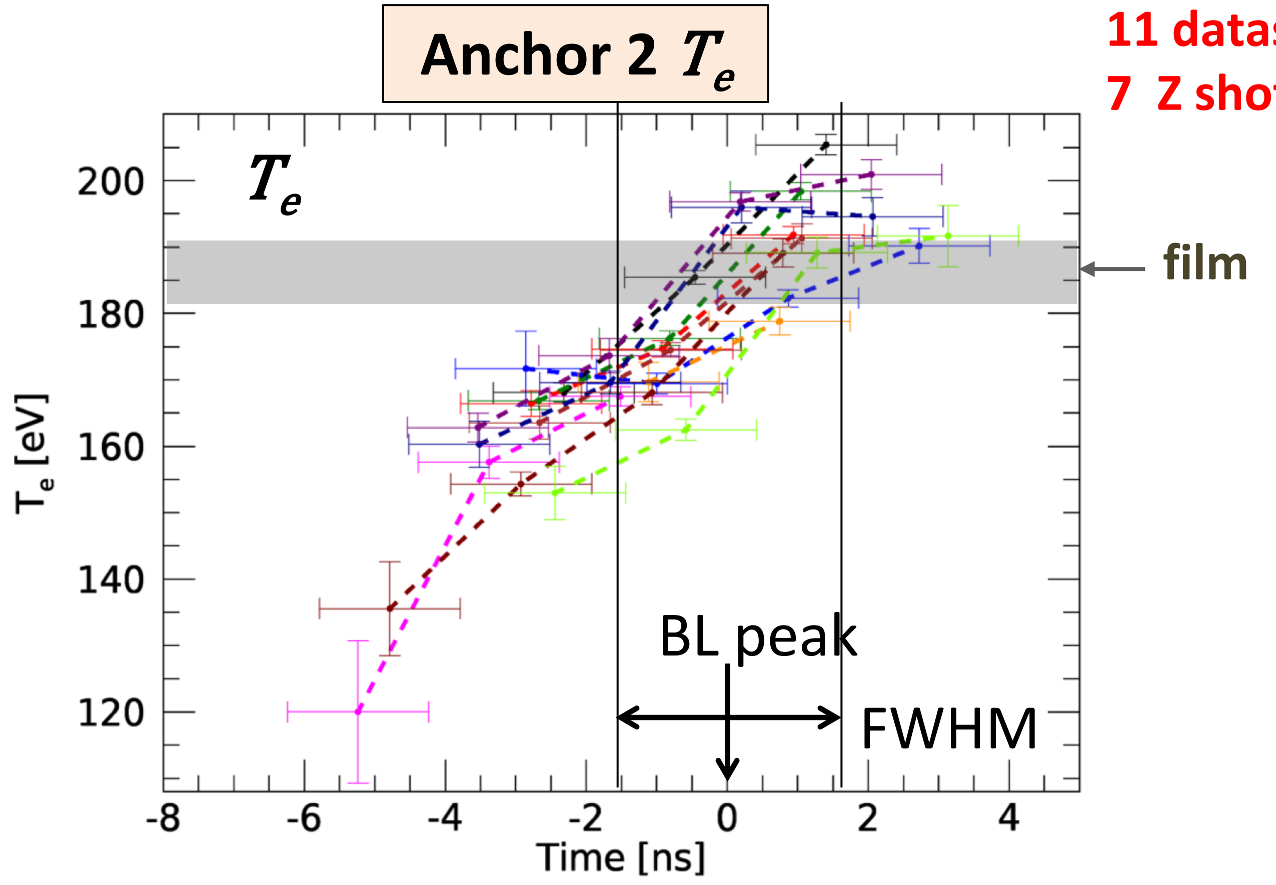
11 datasets
7 Z shots





➢ **Sample evolution is consistent with past conditions inferred on film-based measurements**

Anchor 2 Fe conditions evolution trends disagree with simulation predictions - PRELIMINARY



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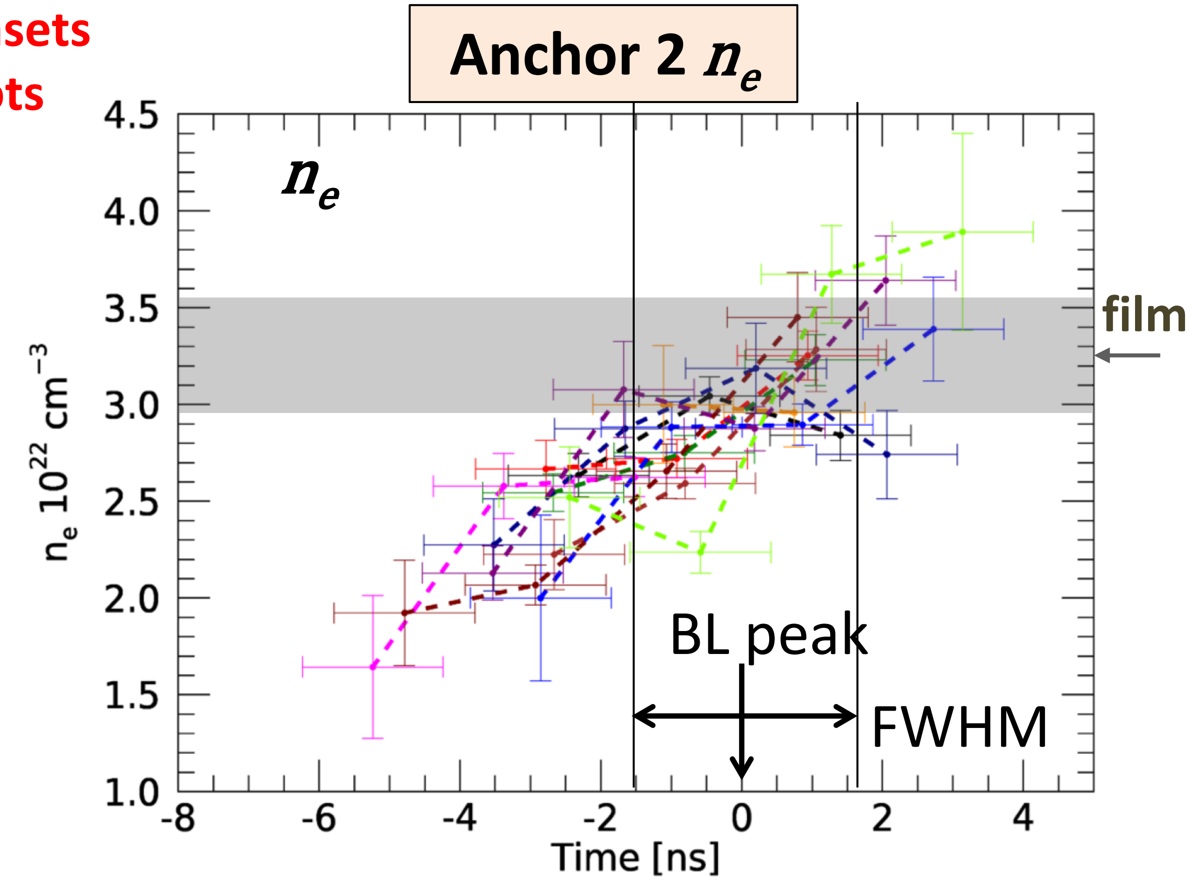


Also: new platform researched to reach highest density to date ~ x2

The requirements are more stringent for measuring time-resolved opacity $\kappa_\upsilon(t)$ than sample conditions $n_e(t)$, $T_e(t)$

$n_e(t)$, $T_e(t)$ requirements

- Accurate Mg ***line*** transmission measured
  - high S/N absorption spectrum
  - linear photon intensity
  - avoiding line saturation
  - reproducibility demonstrated
- Multiple time-steps to observe actual evolution
- Inference using fitting techniques to line transmission

→ **Measuring absolute opacity requires calibration shots (BL) at enough time-steps**

opacity $\kappa_\upsilon(t)$ requirements

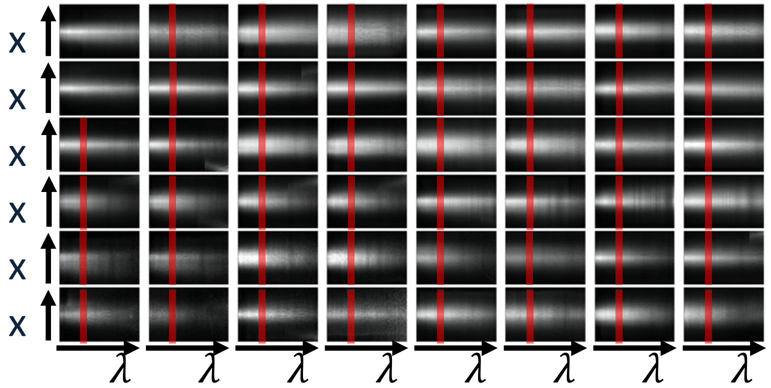
- Typical requirements for opacity measurement:

Bailey *et al.*, *PoP*, **16** (2009)

- uniformity
- freedom from self-emission, background
- multiple areal densities
- measured plasma conditions
- reproducibility demonstrated
- …

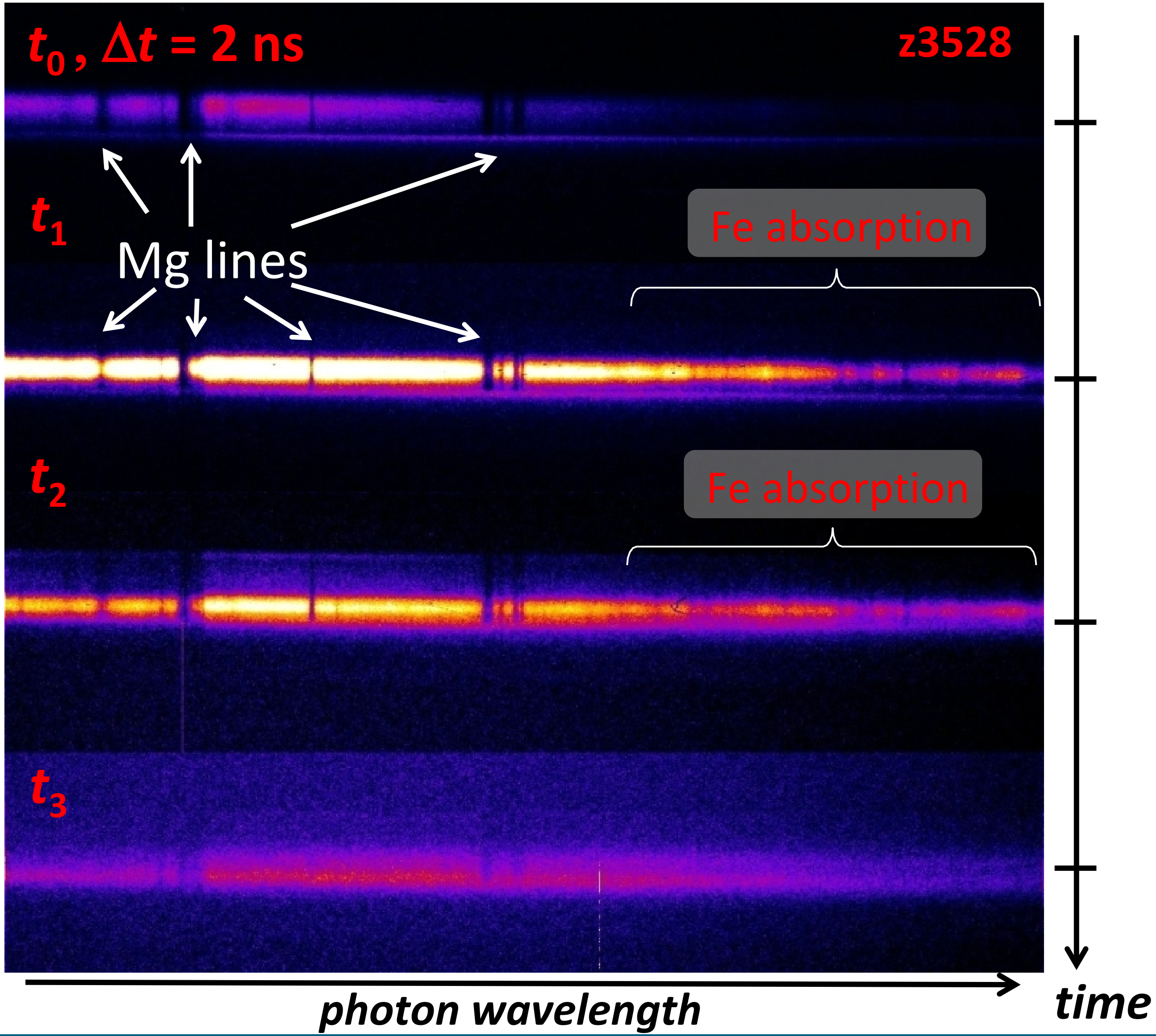
- Accurate ***absolute*** transmission measurements

→ *requires tamper-only statistics for accurate analysis*



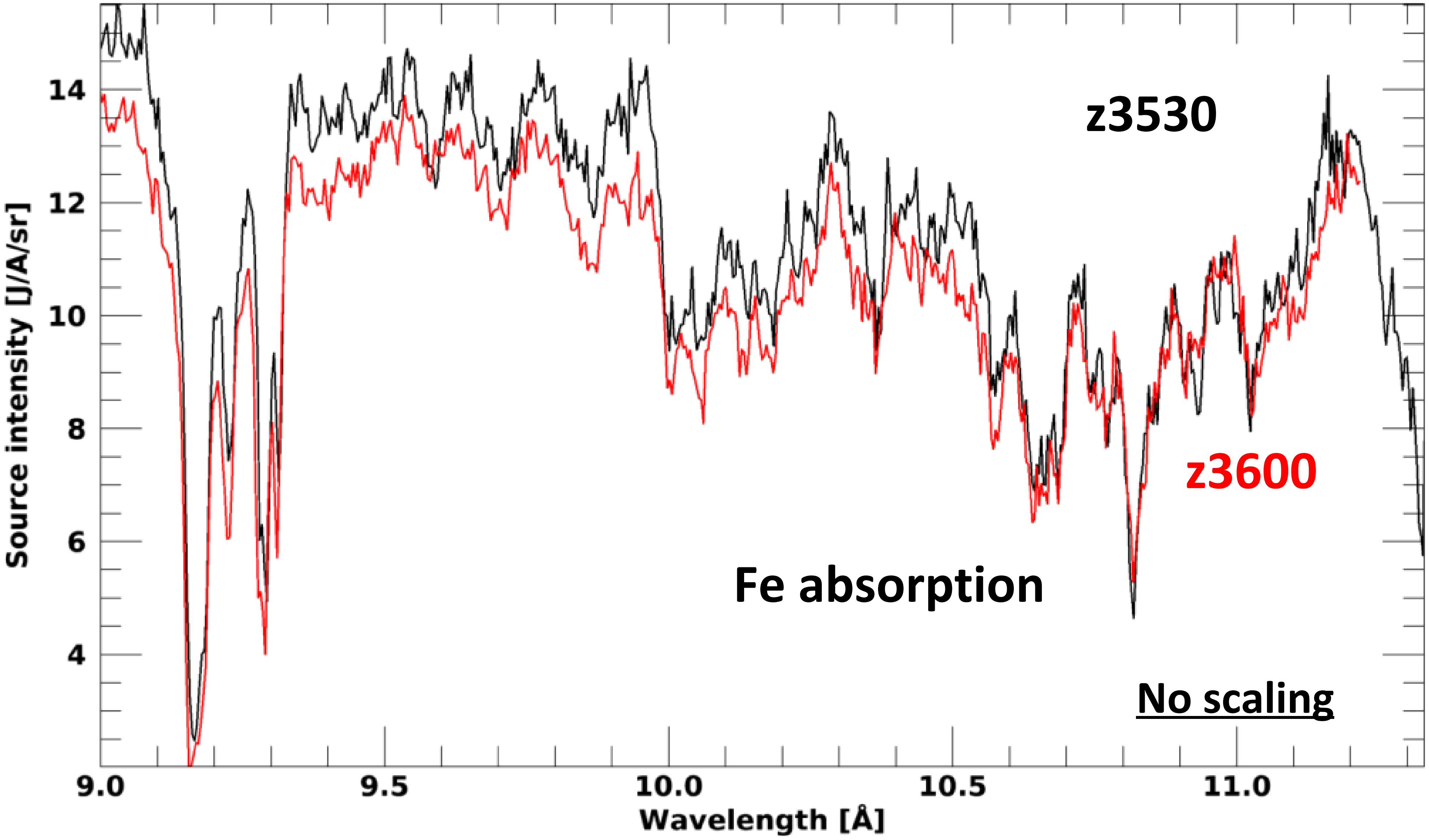
→ Evaluate how many to repeat due to spatial-distribution temporal variation

We have started to measure data for time-dependent absolute opacity measurements

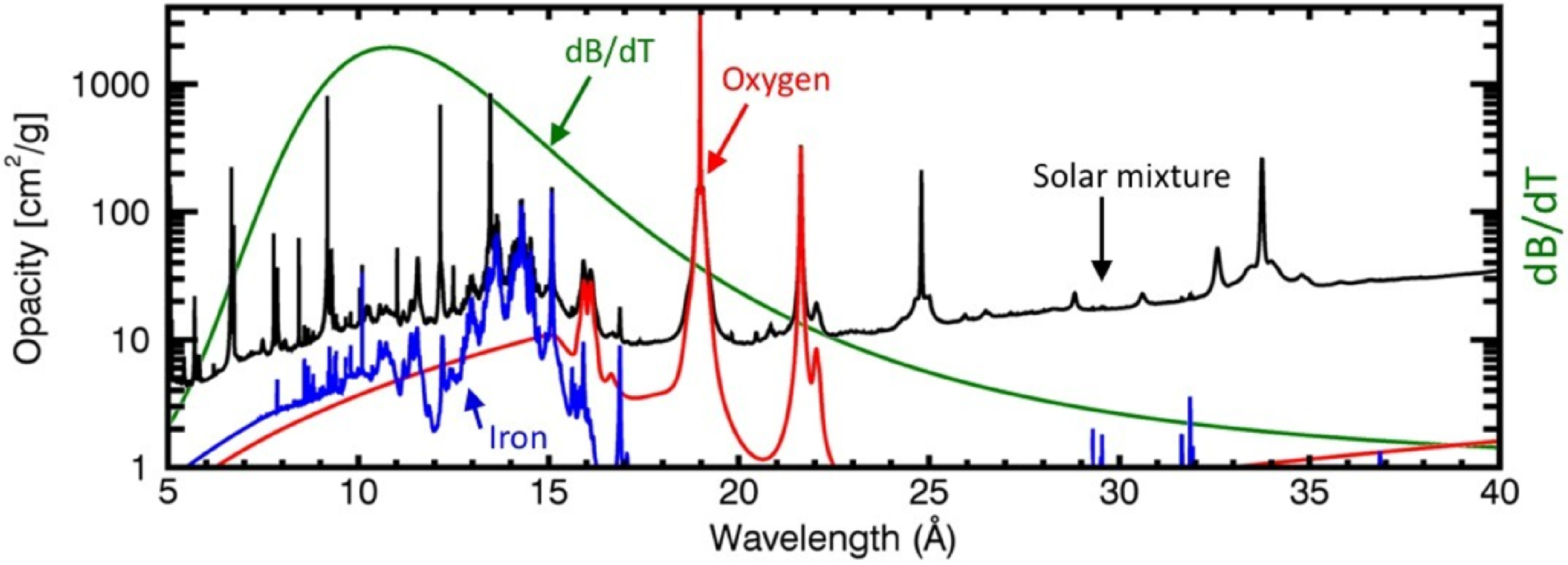


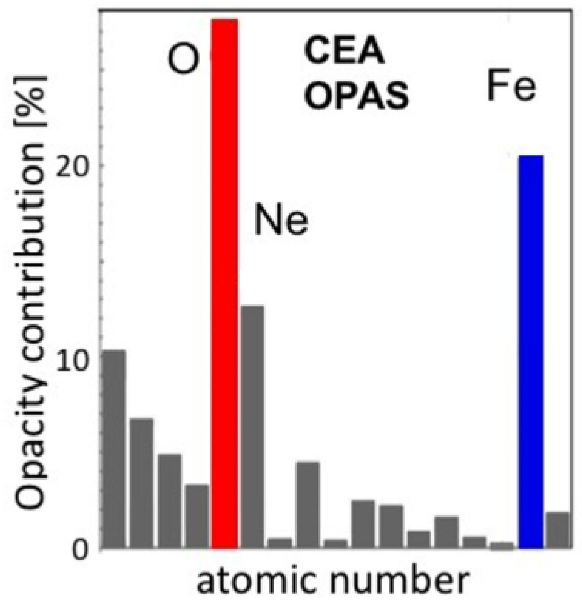
- First time-resolved Fe absorption spectra in 9/2020
- Technical challenges had to be overcome (EMP, debris…)
- Dataset is being built to obtain absolute time-resolved opacity

Initial reproducibility has been observed and is encouraging

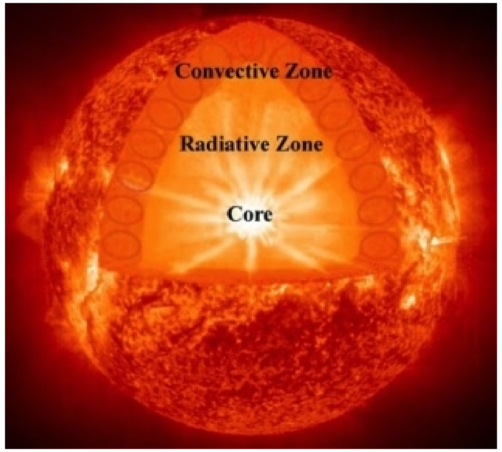


Oxygen opacity measurements are essential to resolve the solar problem



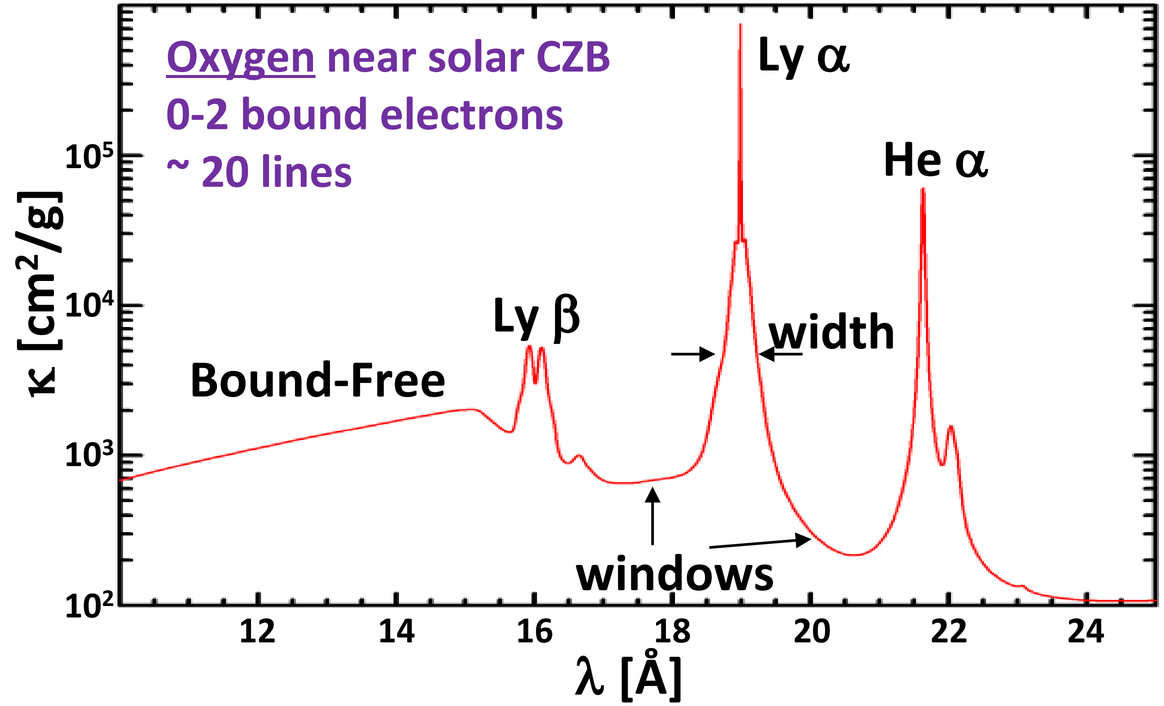


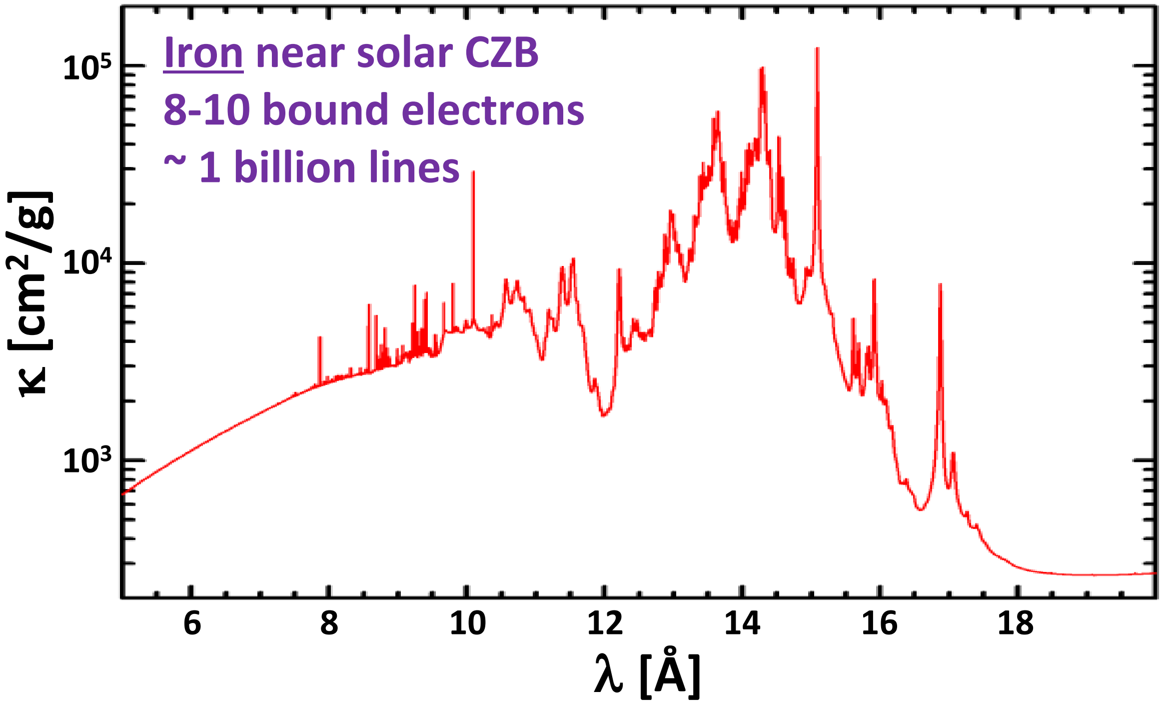
- Oxygen is a dominant source of opacity near the convection zone base (CZB).
- The spectrum is much simpler than Fe.
  - It could help understand sources of discrepancy in the more complex atoms.
- If measured O opacity is higher, it could further help resolve the solar problem.



Oxygen opacity spectra are challenging because they are strongly affected by approximations for plasma density effects

OP model; T_e = 192 eV; n_e = 1e23 e/cc



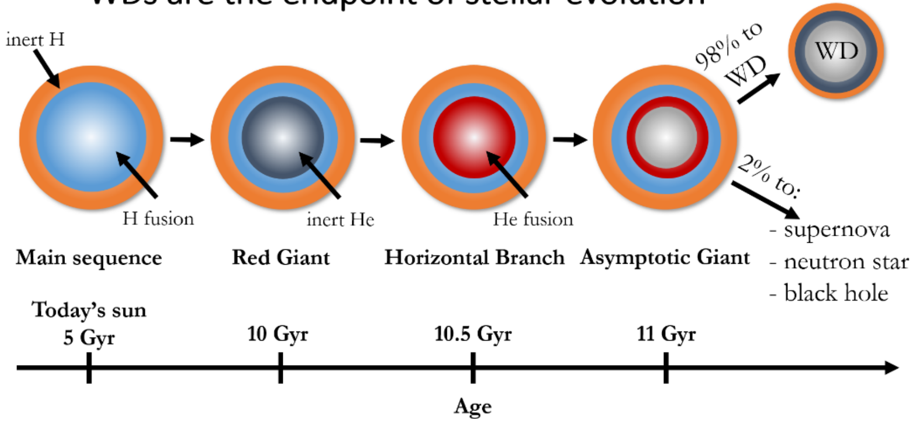


- Bare atoms do not have bound-bound or bound-free absorption.
  - ***Oxygen opacity is highly dependent on level of ionization.*** Iron is less affected by small ionization changes.
- <u>Density effects:</u> → <u>Affected features:</u>
  - Line broadening · · · · > Opacity windows
  - Ionization potential depression · · · · > Bound-free absorption
  - Occupation probability · · · · > Ionization balance

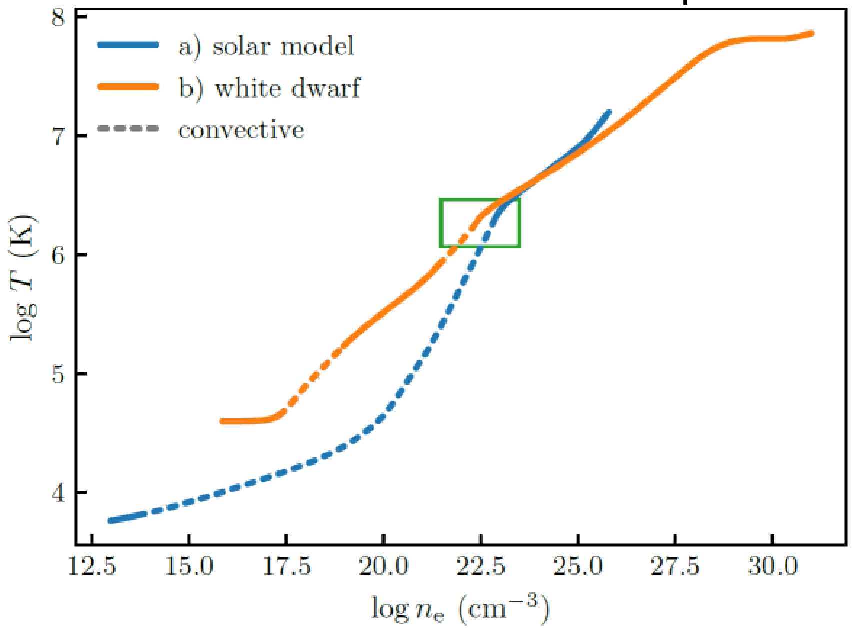
Stellar evolution and the age of the universe can be constrained using WD stars; Accurate oxygen opacity is important for WD cooling models

- White dwarfs (WDs) are "burned out" remnants of stars.
  - 98% of all stars will become WDs, including the Sun.
  - Cores are ~ 50:50 mixture of Carbon and Oxygen.
- WDs only cool with time, so surface temperature reveals their age.
  - WD cooling models constrain the age of our galaxy[1].
  - **Accurate opacities are required for WD cooling models.**
- "DQ" class WDs have Carbon and often Oxygen in their atmospheres.
  - These may be "failed Type Ia supernovae".
  - Studying them may help us understand how Type Ia supernovae are produced.
  - **DQ WD convection zone base (CZB) conditions have similar temperature and density as the solar CZB.**

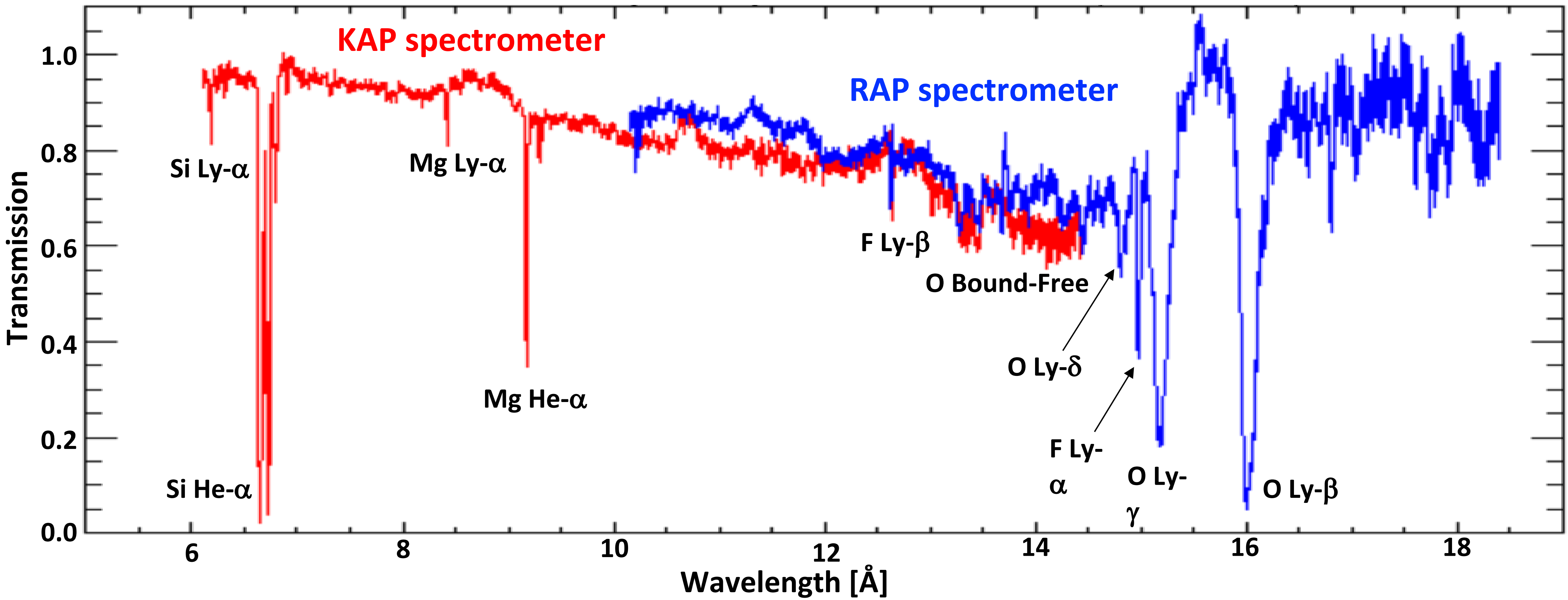
WDs are the endpoint of stellar evolution



Stellar Interior Tracks in EOS plane



Oxygen and Silicon transmission have been successfully measured



- Accurate opacity is only obtained for T ~ 0.15-0.85.
- Multiple experiments to test reproducibility.
- Spectrometer ranges have been extended to shorter λ (~ 5.1 Å) for Si and to longer λ (~ 19.5 Å) for O.

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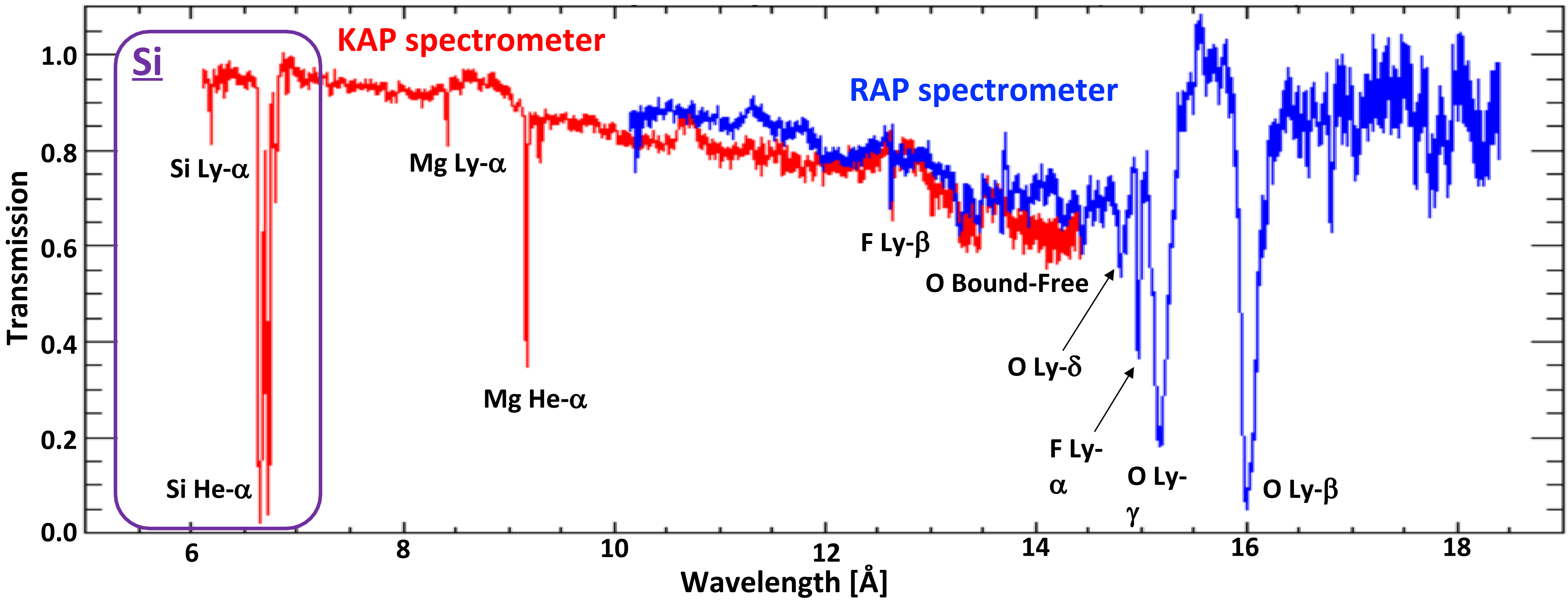

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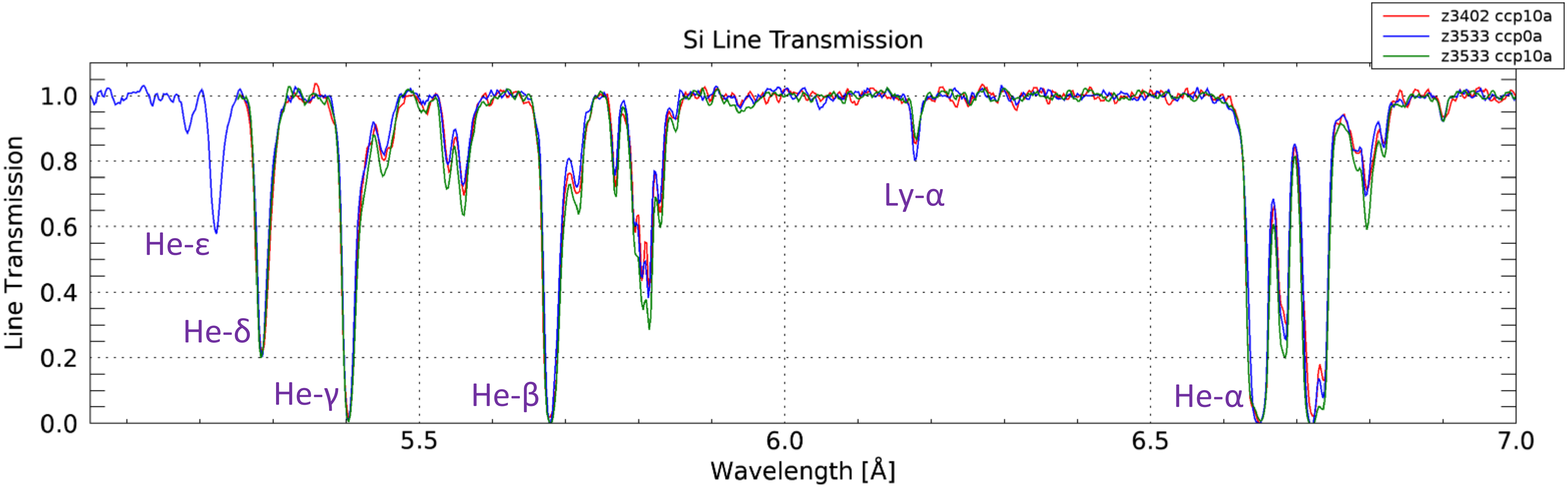
Silicon line transmission is used to diagnose the plasma conditions (T_e and n_e)



- To test opacity models, we need 3 things:
  - Opacity measurement
  - Accurate T_e and n_e
- We rely on measurements of T_e and n_e to produce opacity model comparisons with experimental data.
- The plasma conditions must be well understood.

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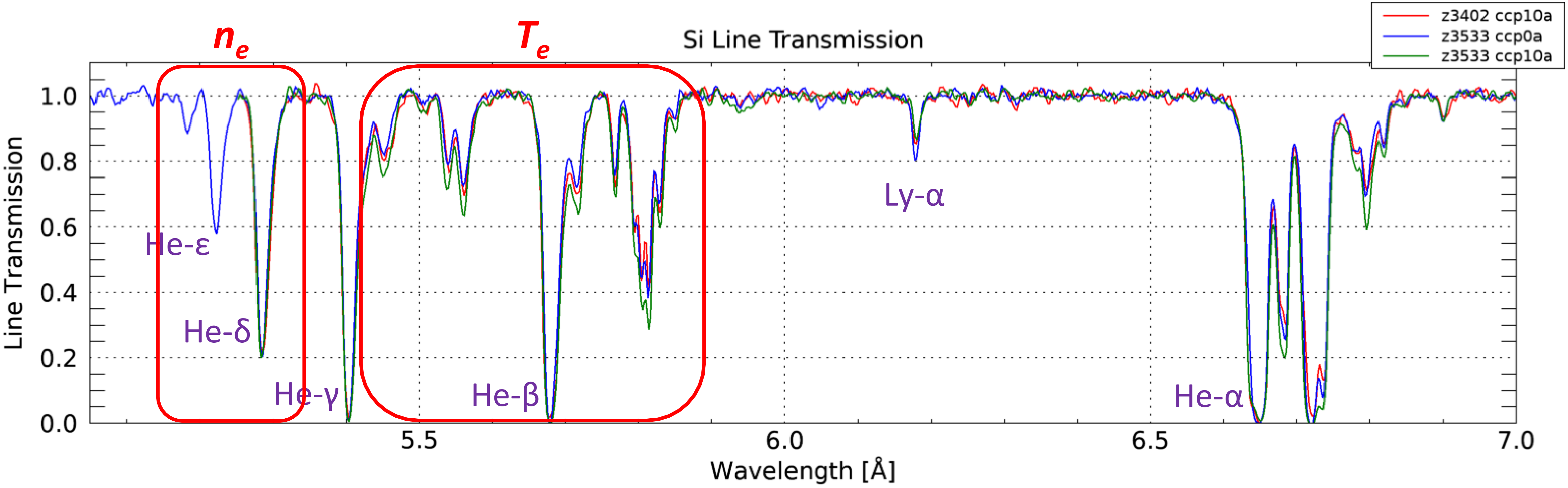

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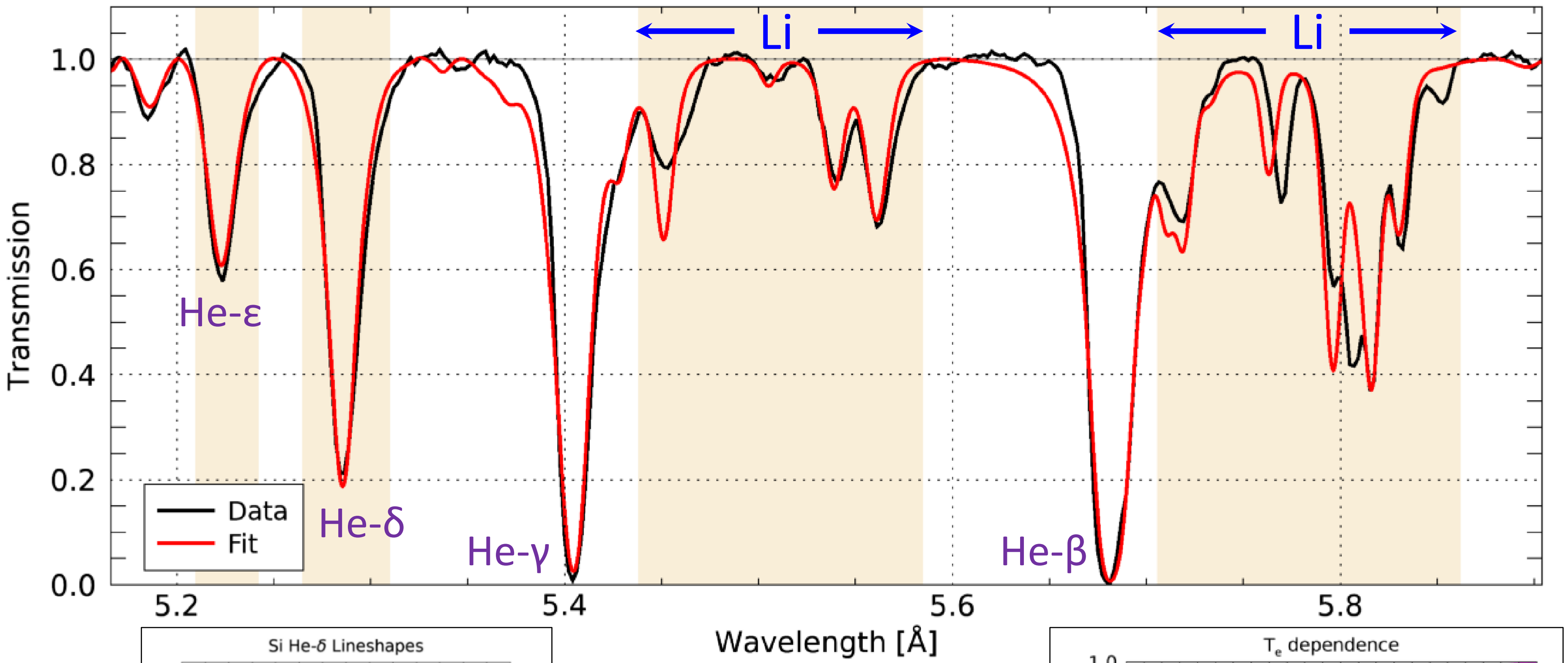
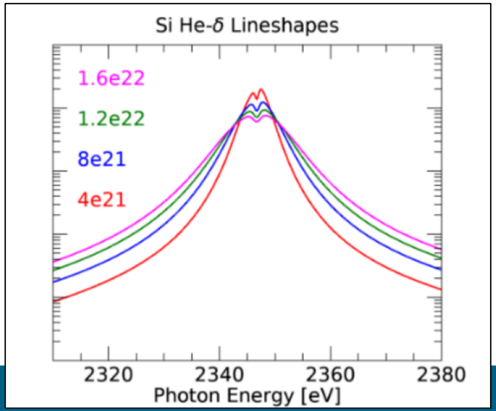
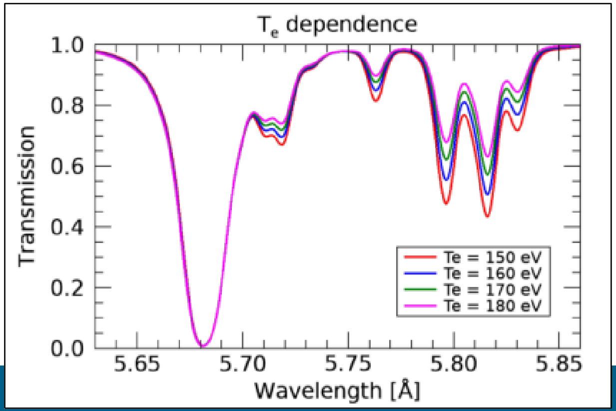
Preliminary conditions inferred from Si lines: T_e ~ 160 eV, n_e ~ 8e21 e/cc.



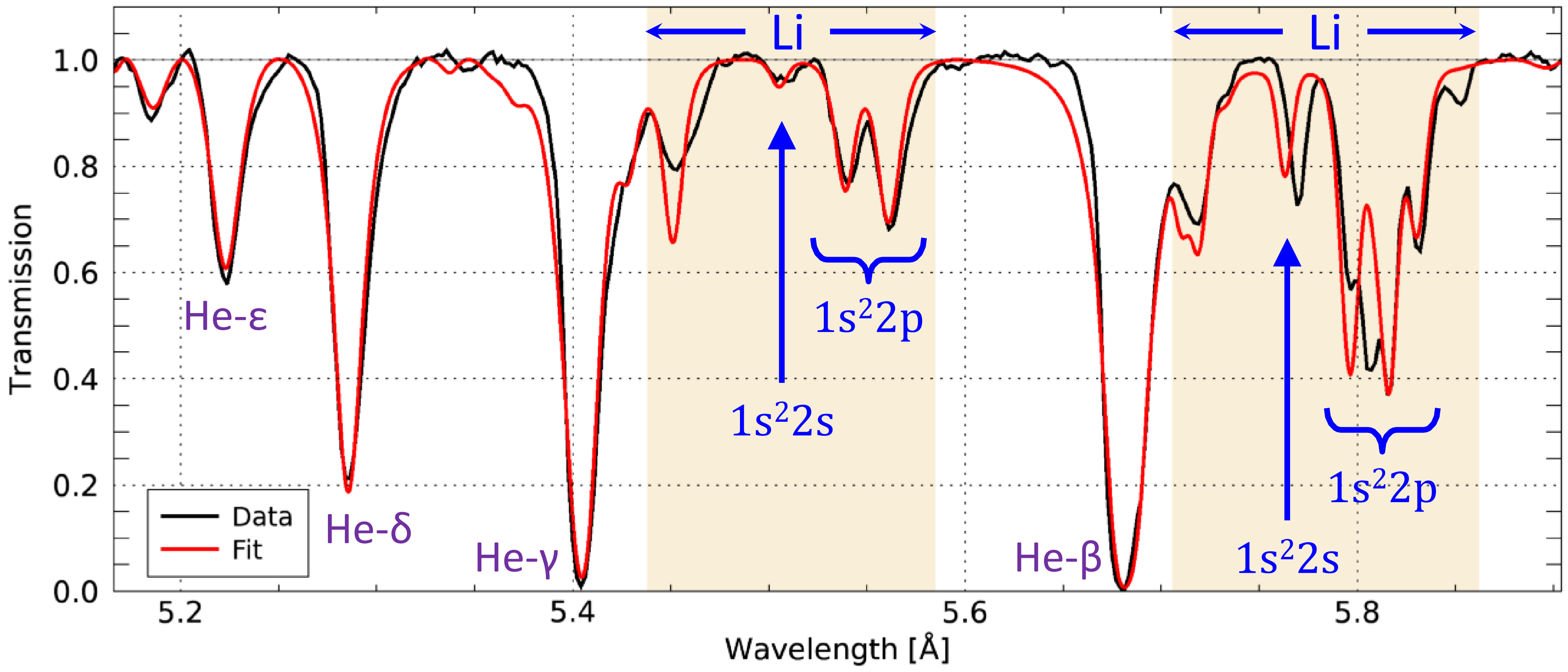


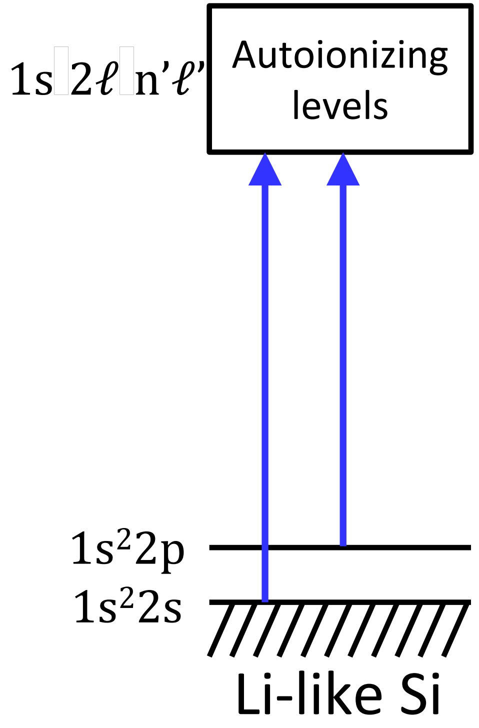
← n_e is constrained by line widths.



← T_e is inferred from ratio of Li-like to He-like lines.

Novel method to infer temperature from population ratios of Li-like satellites.





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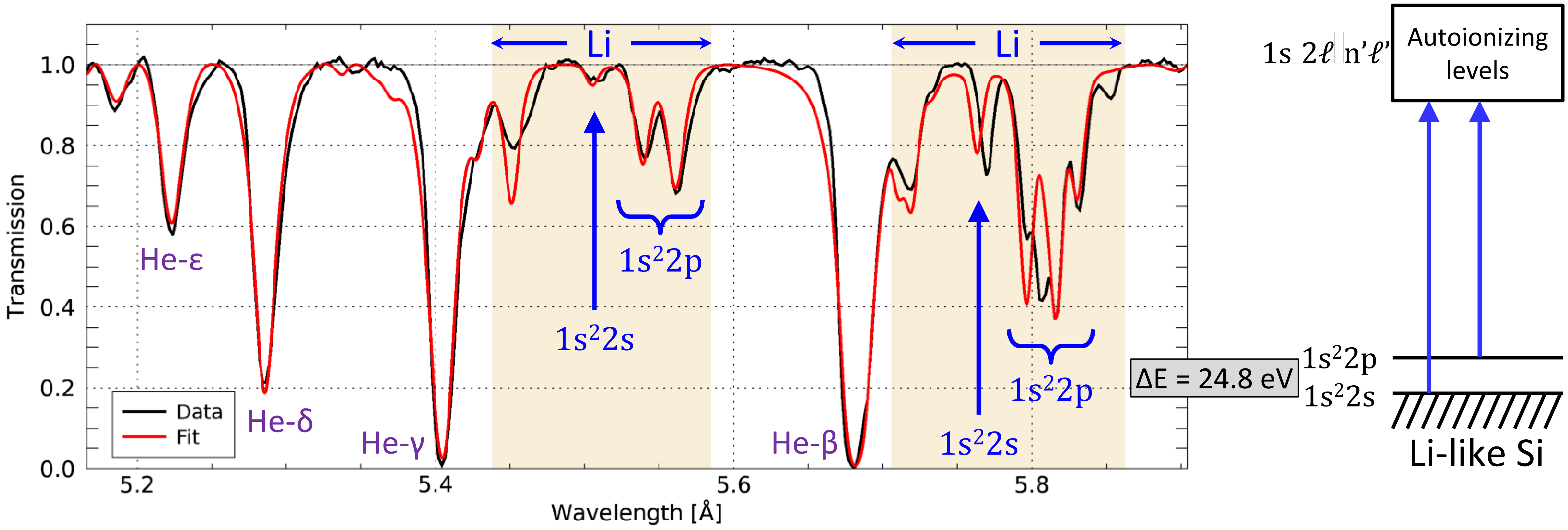

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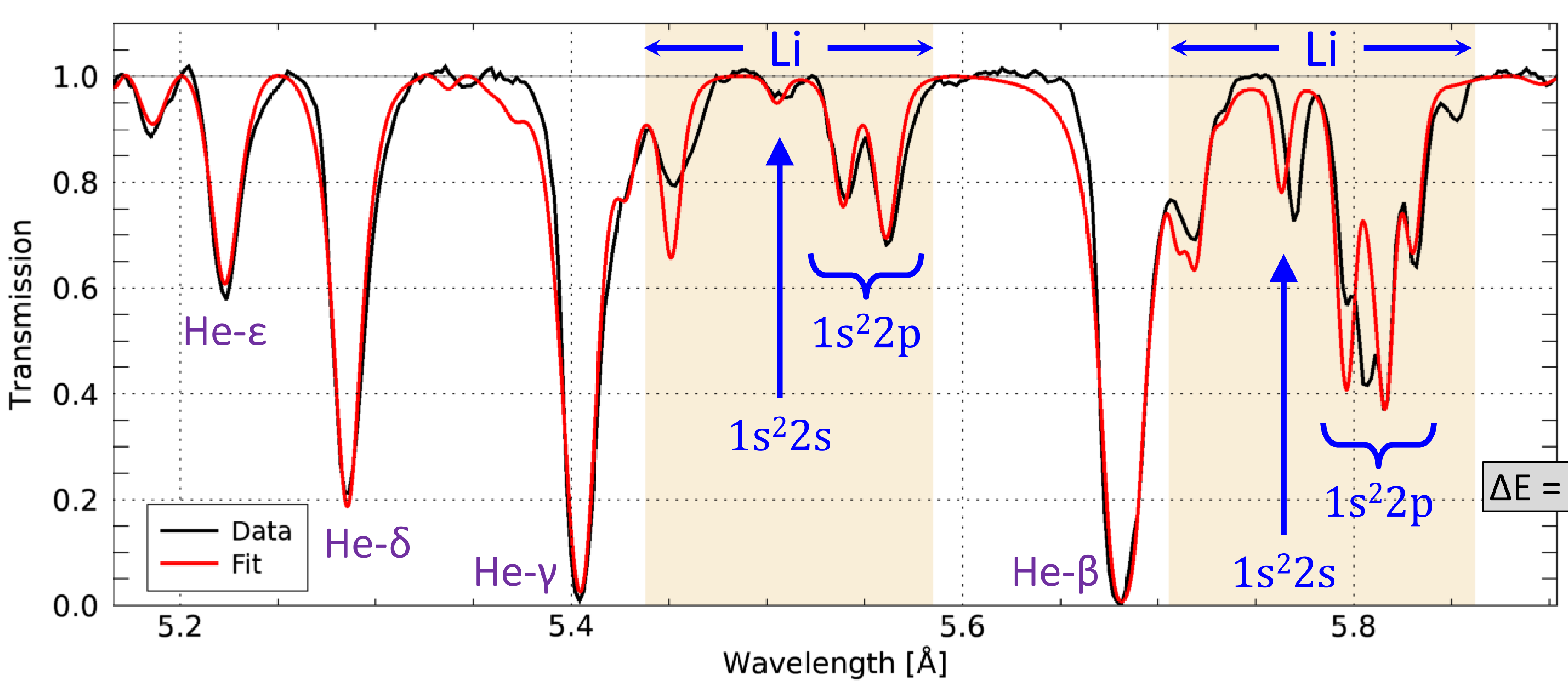

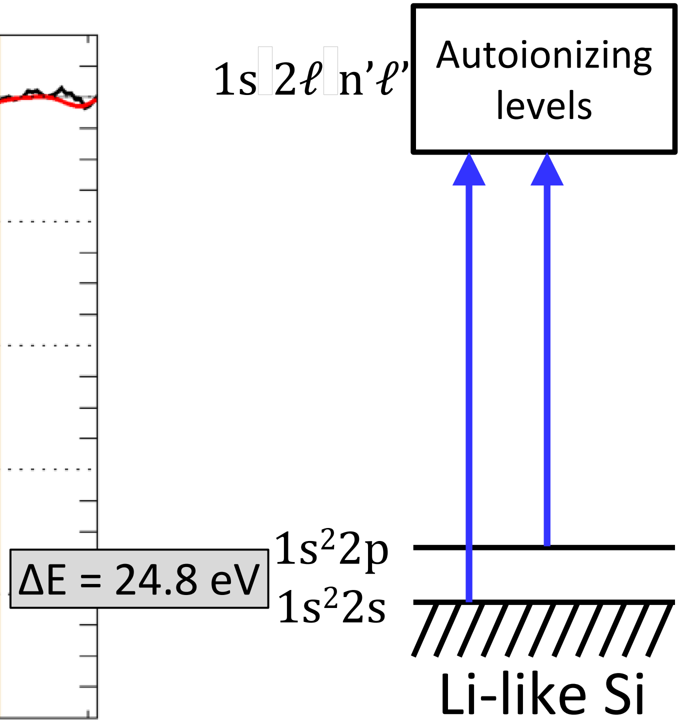

- Measure the relative population in each Li-like configuration.
- The ratio of populations in different configurations depends on T_e.

$$\frac{P_{2p}}{P_{2s}} = \frac{g_p \exp\left(\frac{-E_p}{kT}\right)}{g_s \exp\left(\frac{-E_s}{kT}\right)}$$

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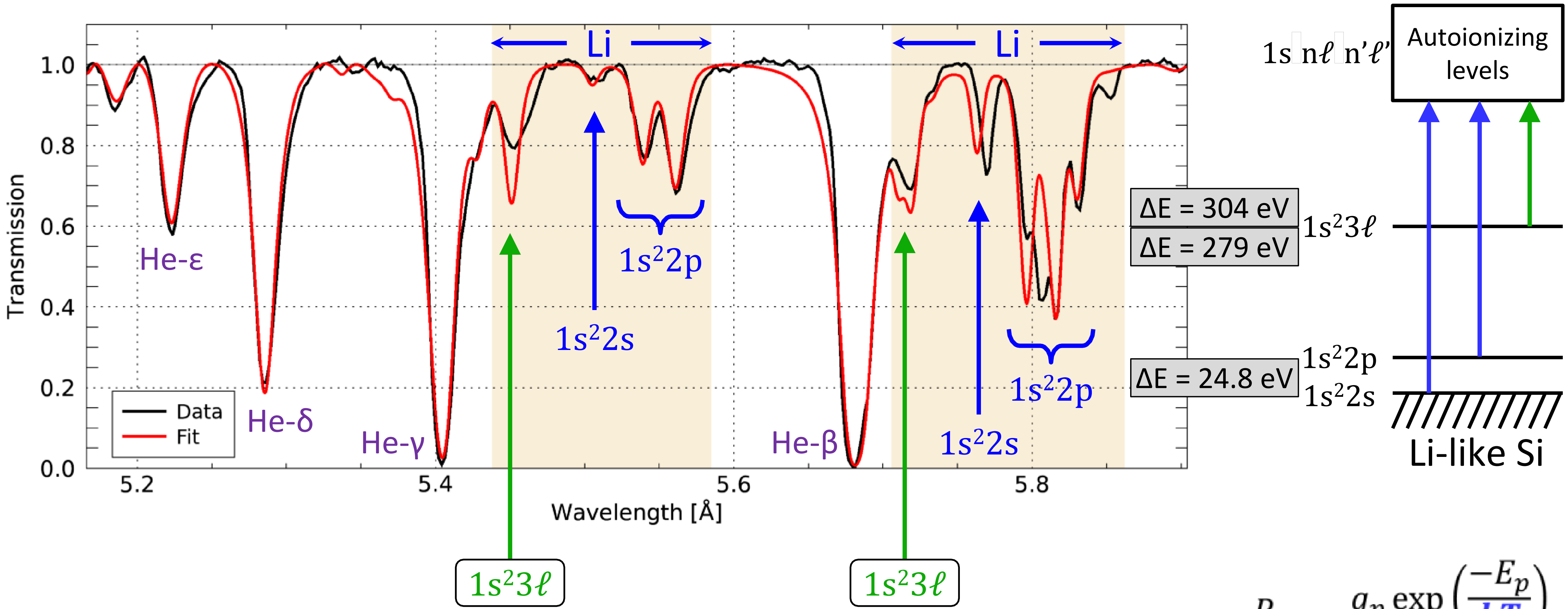

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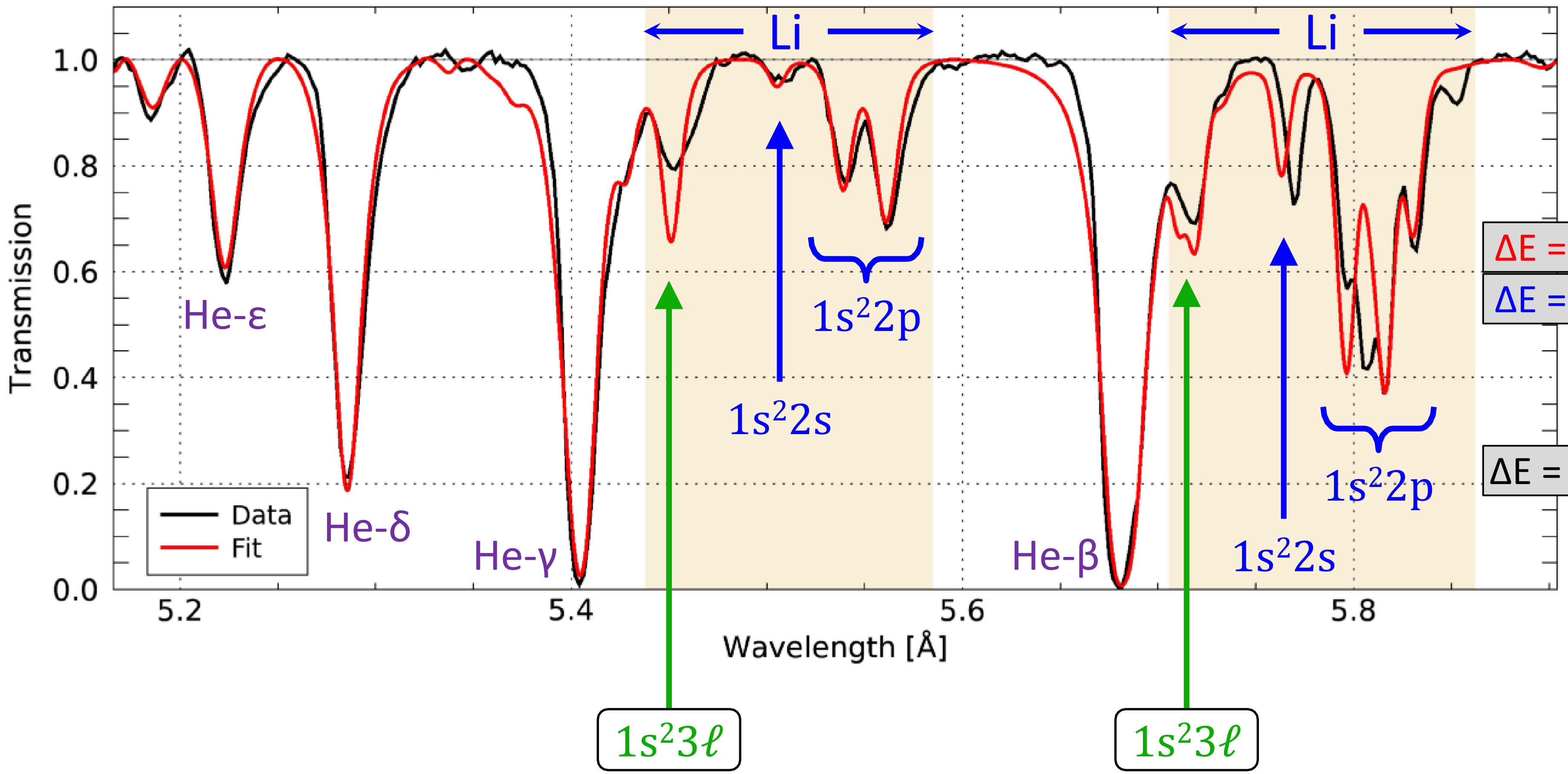
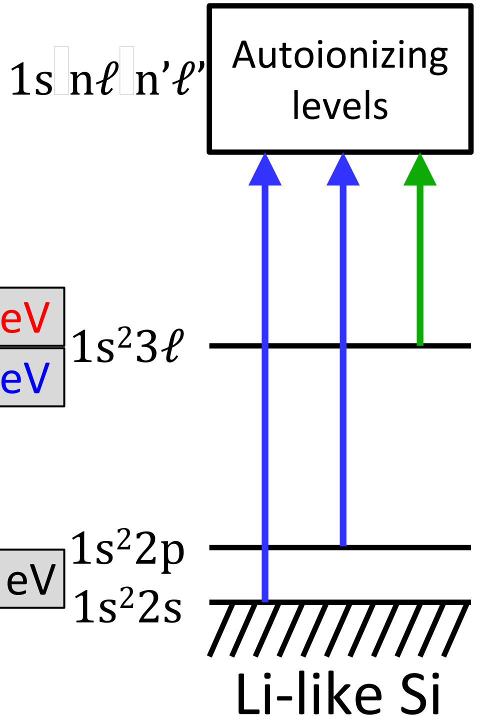
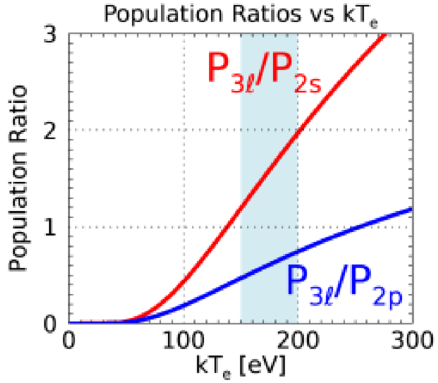
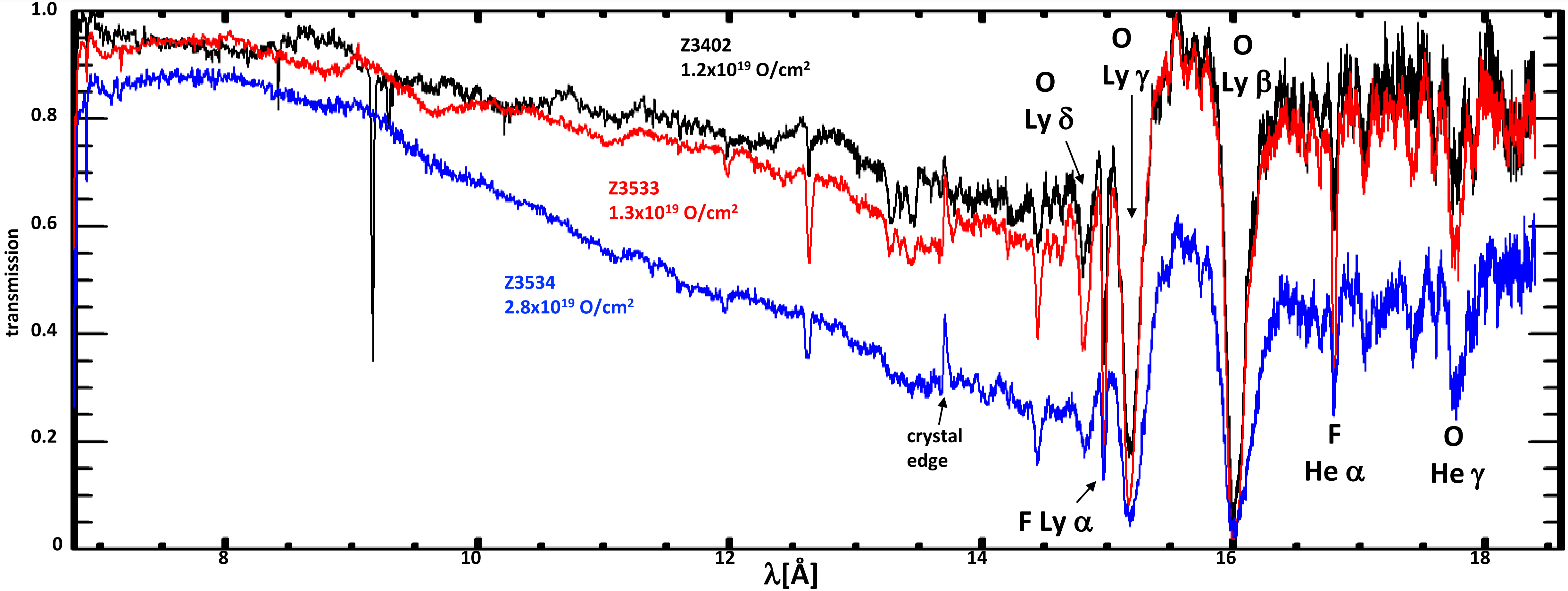






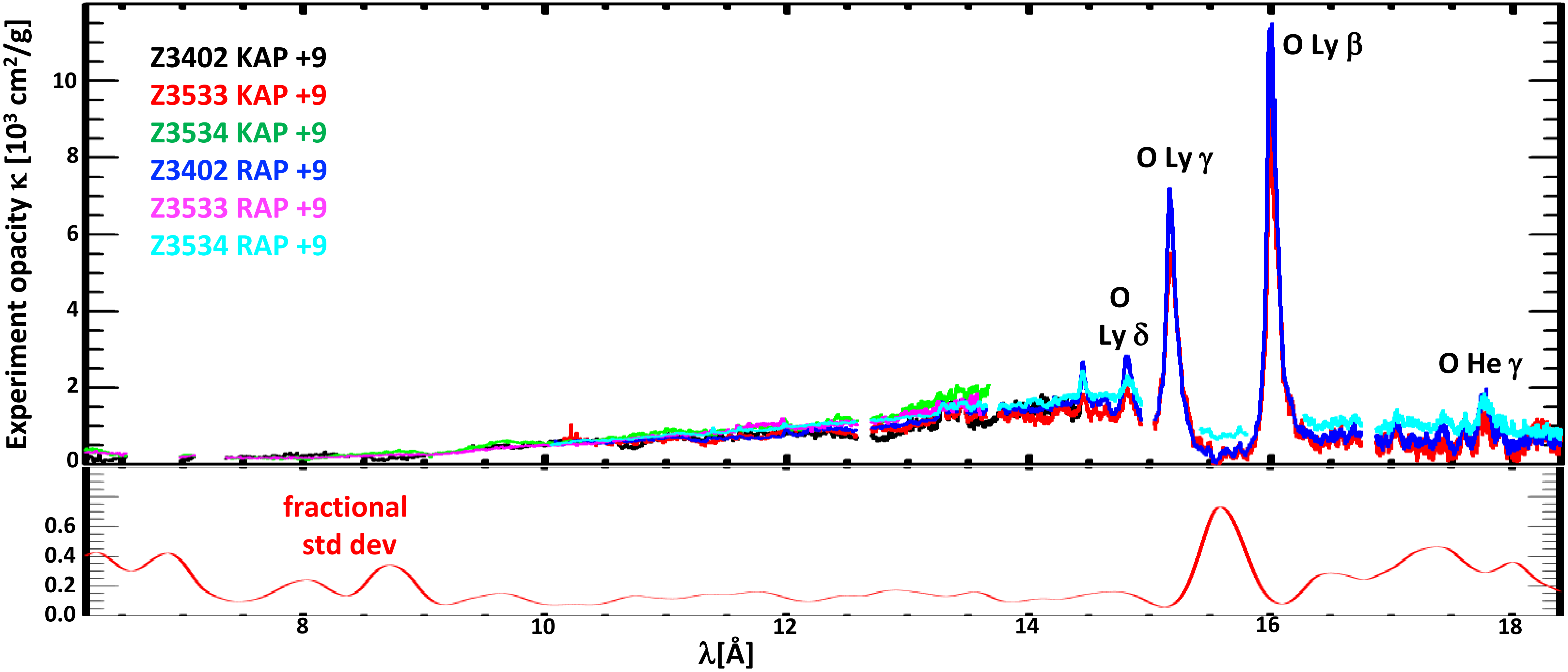
- Measure the relative population in each Li-like configuration.
- The ratio of populations in different configurations depends on T_e.

Preliminary analysis provides transmission from three oxygen opacity experiments at two different areal densities



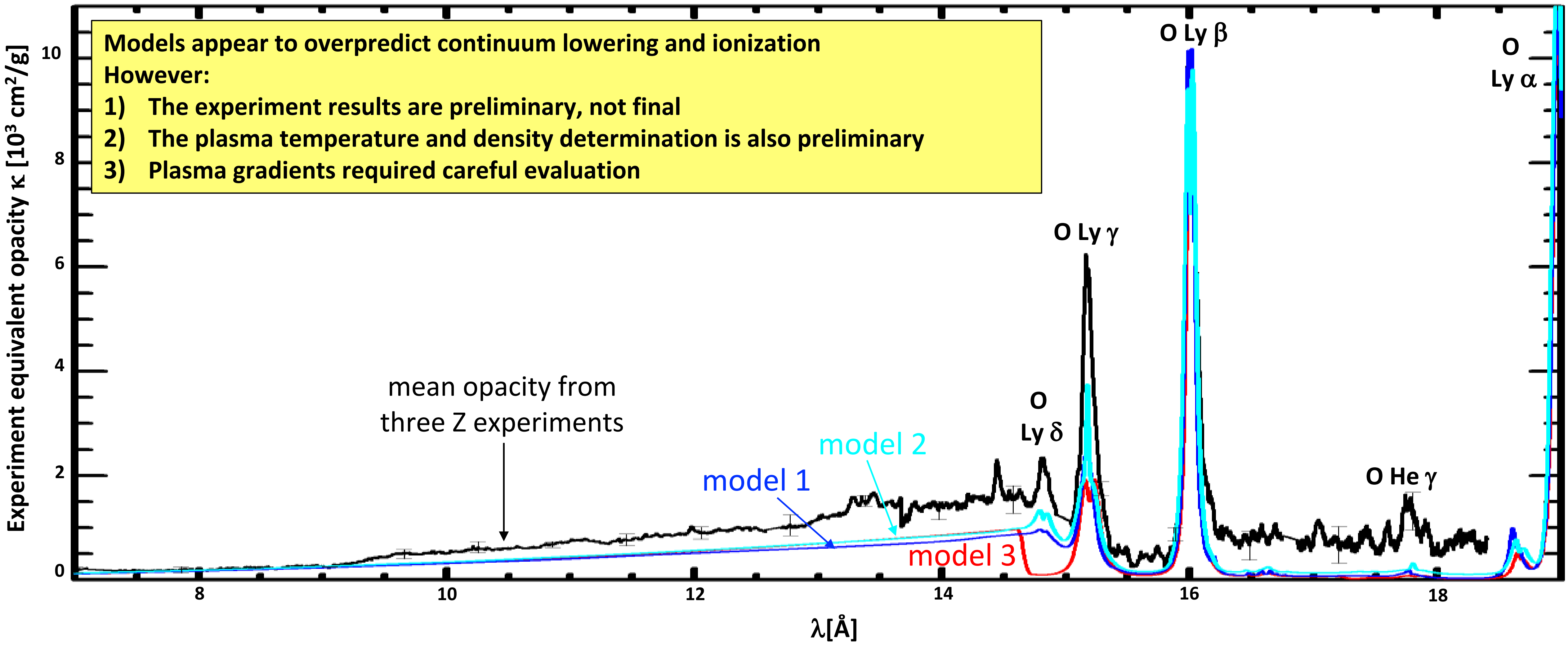
- **Multiple experiments test reproducibility**
- **Different areal densities help assess accuracy and expand dynamic range**

Preliminary oxygen opacity measurements are reproducible



Preliminary reproducibility better than +/- 10% over 9-15 Angstroms
Refined analysis in progress
There are 12 more spectra to include from these three shots

Preliminary Z measurements provide the first tests of oxygen opacity models at high energy density conditions



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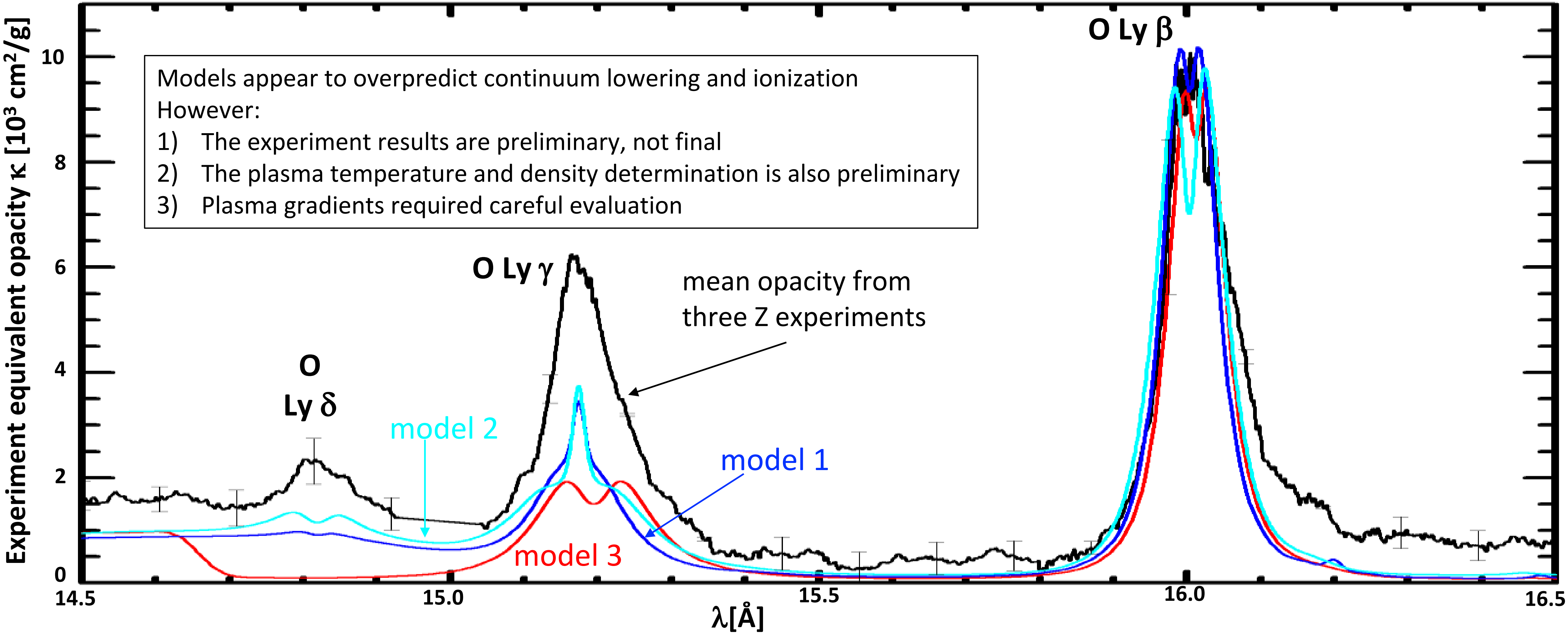
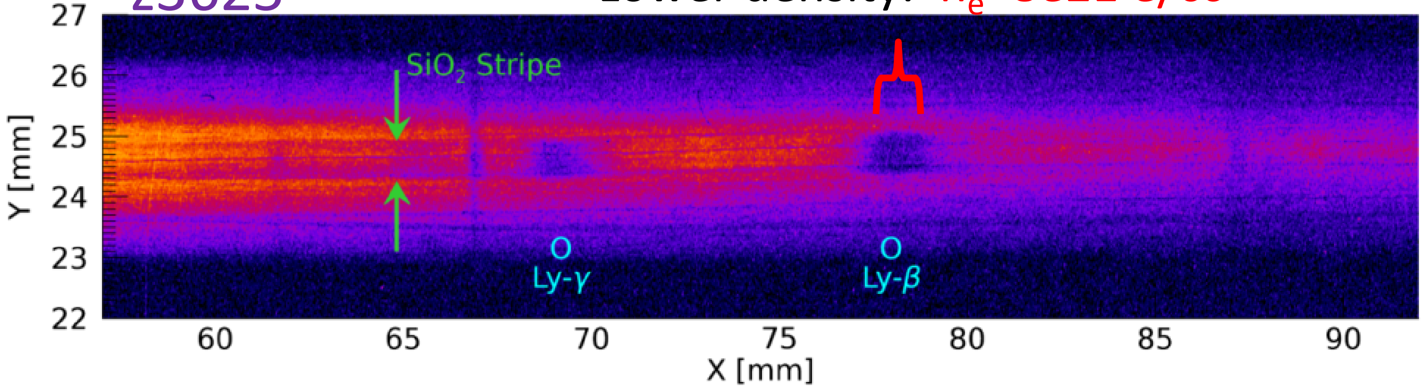


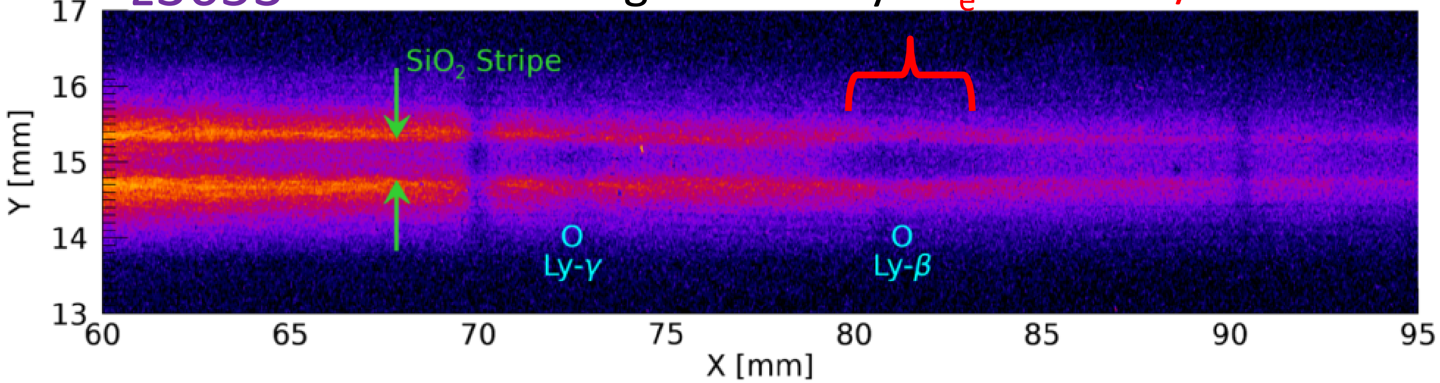
Results from two recent tests look promising:
1) Reaching higher T_e and N_e conditions, 2) New stripe-style samples.

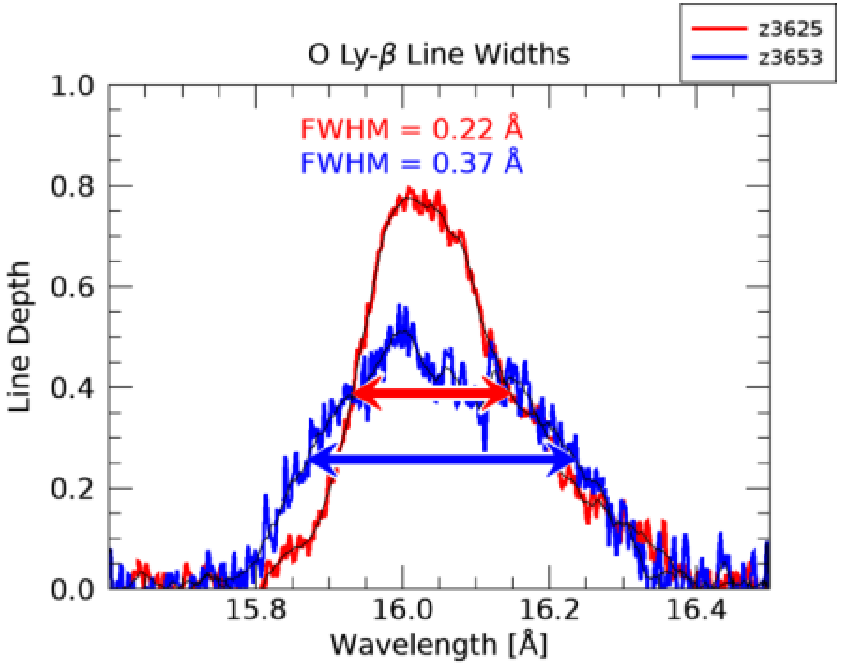
- The first oxygen opacity measurements made were at lower T_e and N_e than CZB.
  - It's important for the solar problem to reach higher T_e and N_e.
- Stripe-style sample can help to constrain transmission measurement better.

z3625 Lower density: n_e~8e21 e/cc



z3653 Higher density: n_e~30e21 e/cc





Wider line indicates higher density.

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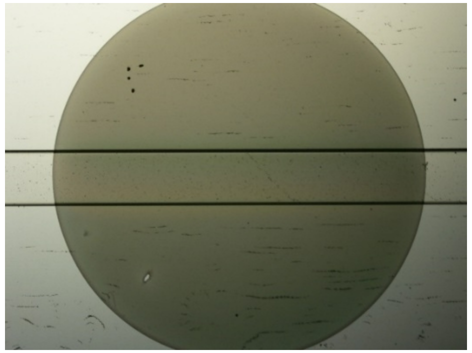

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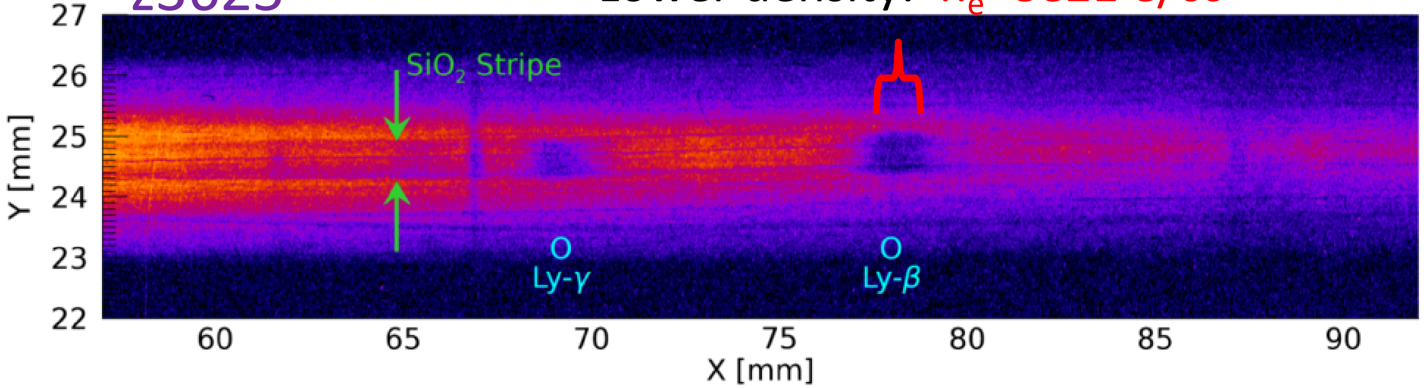

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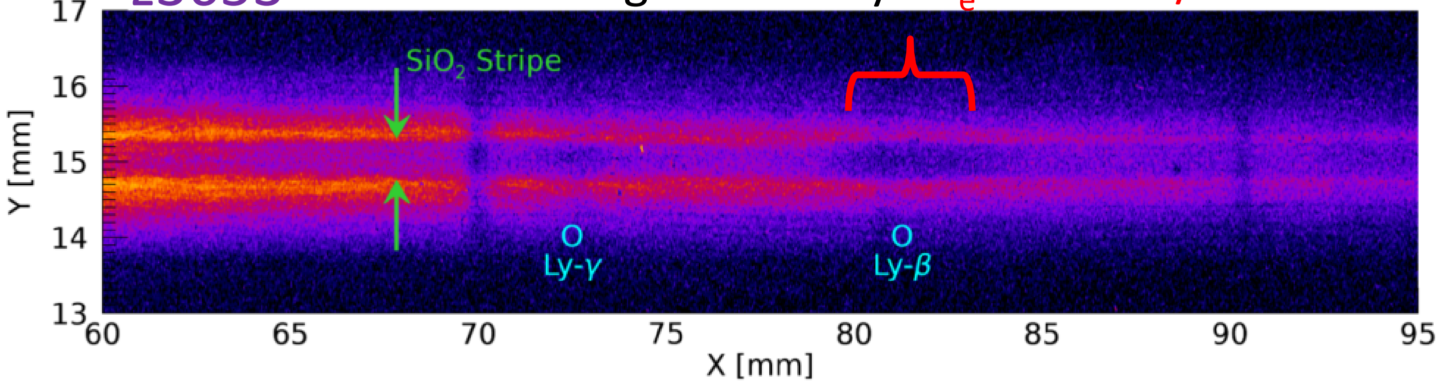
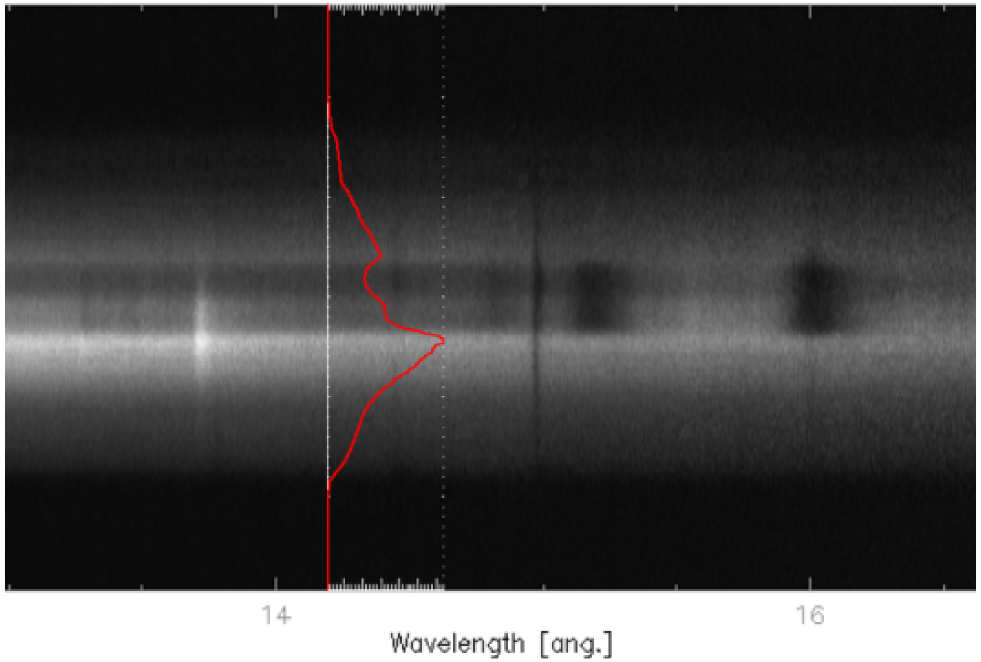
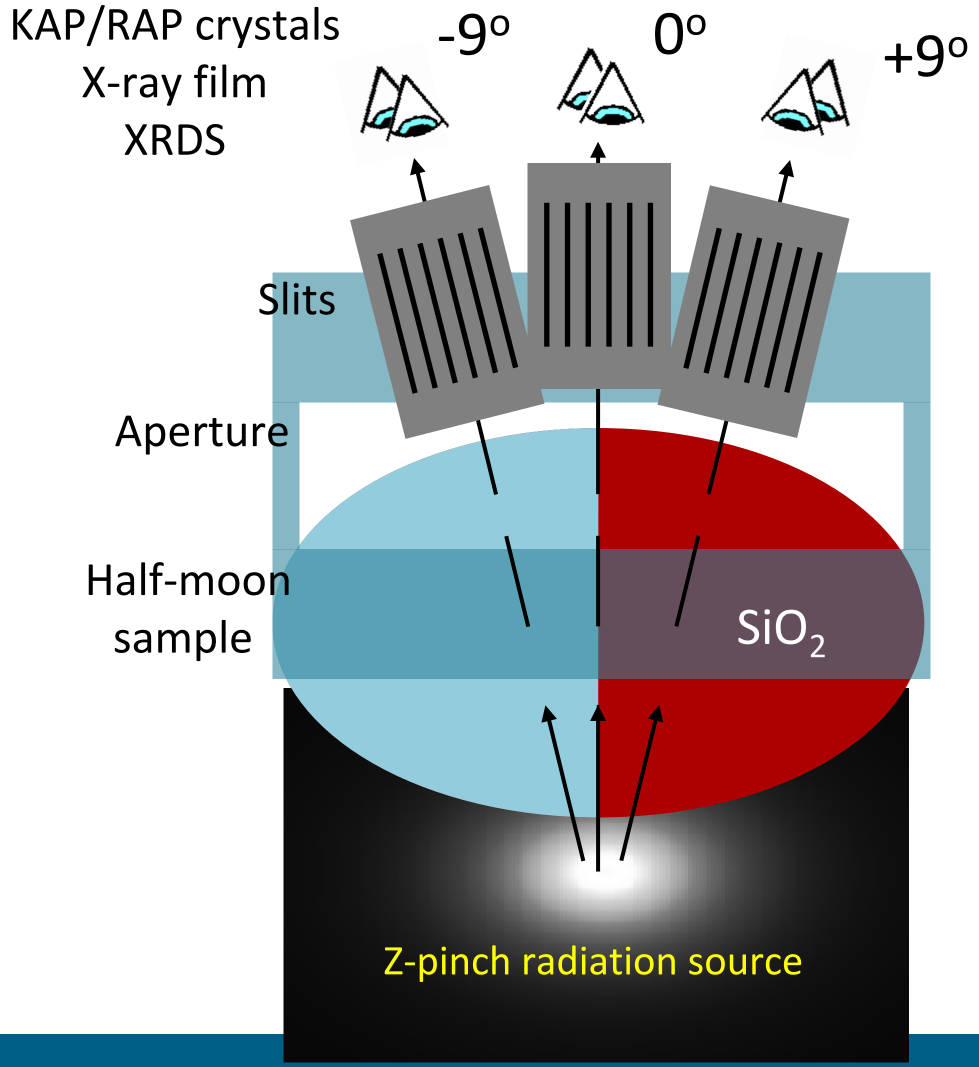


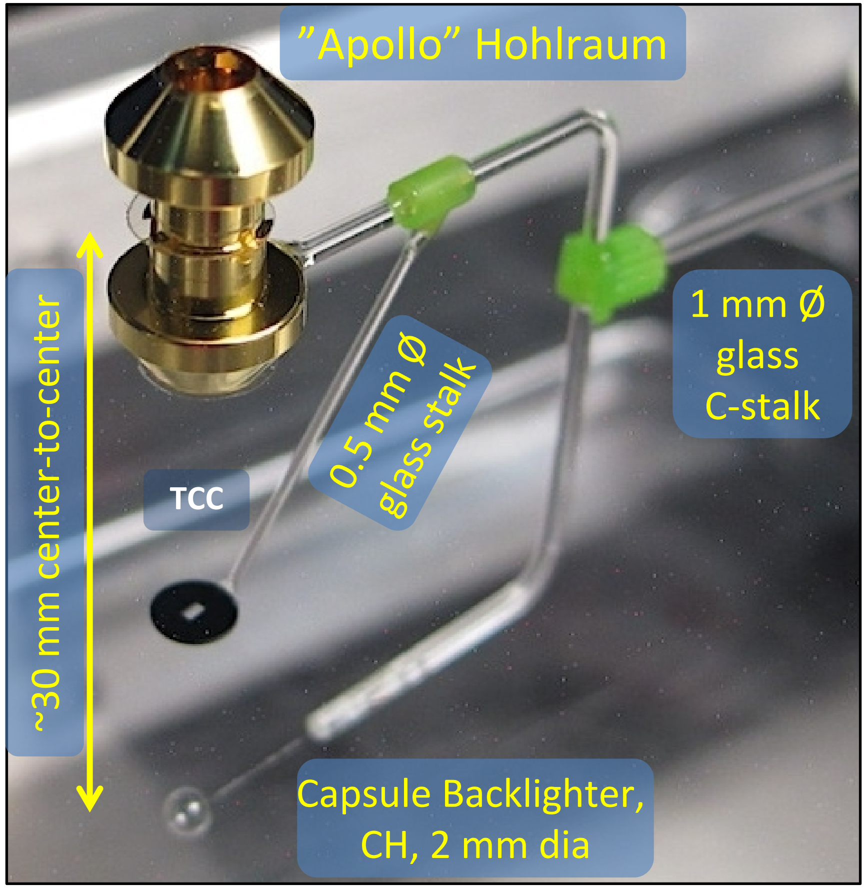


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

Z Opacity Platform

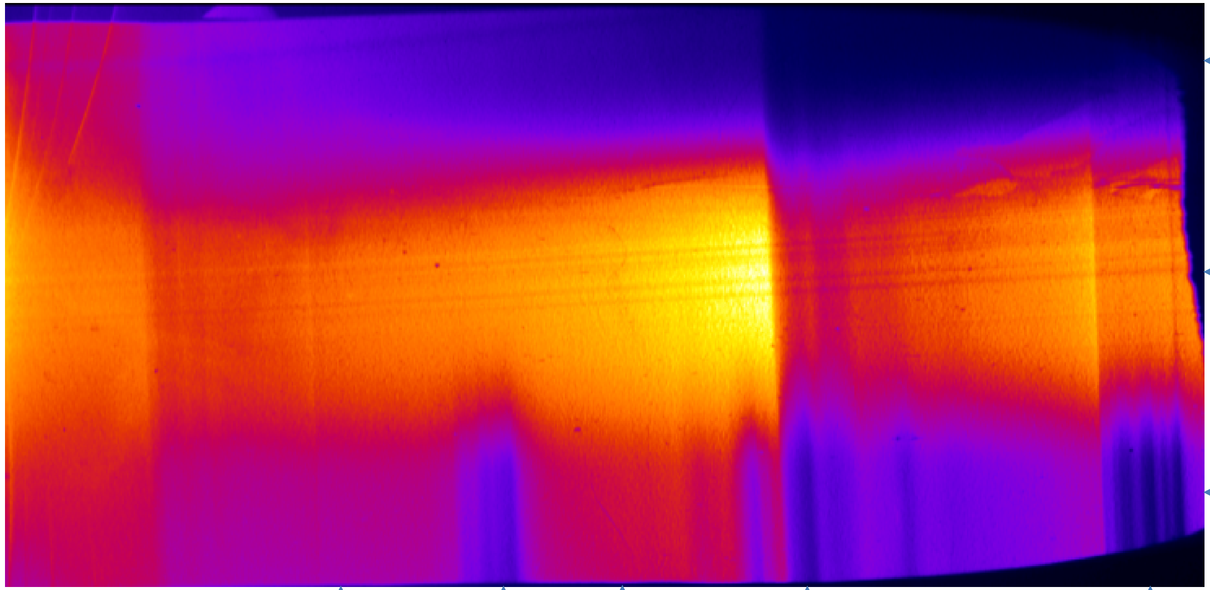


NIF Opacity Platform



At NIF, the spectrometer records absorption, backlight, and emission simultaneously

Sample: $MgO + SiO_2$ layers tamped with plastic



Self-emission and background

Unattenuated backlighter spectrum

Sample absorption spectrum

~1000 eV

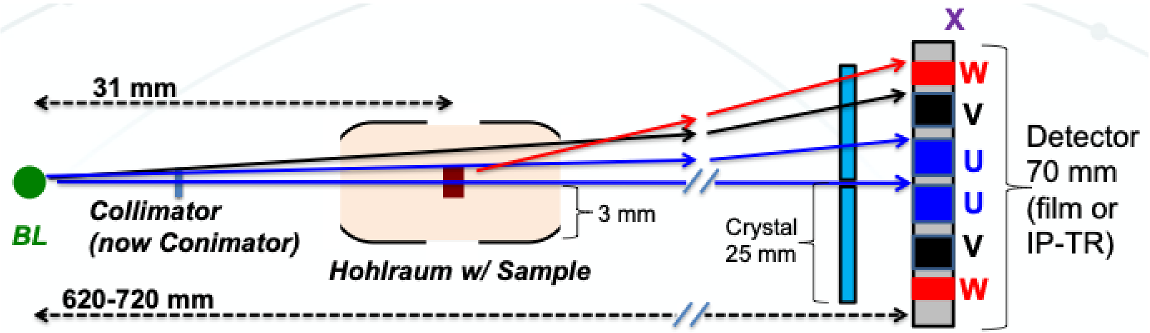
Mg He-α

Mg He -β

Si He -α

~2000 eV

Oxygen continuum absorption



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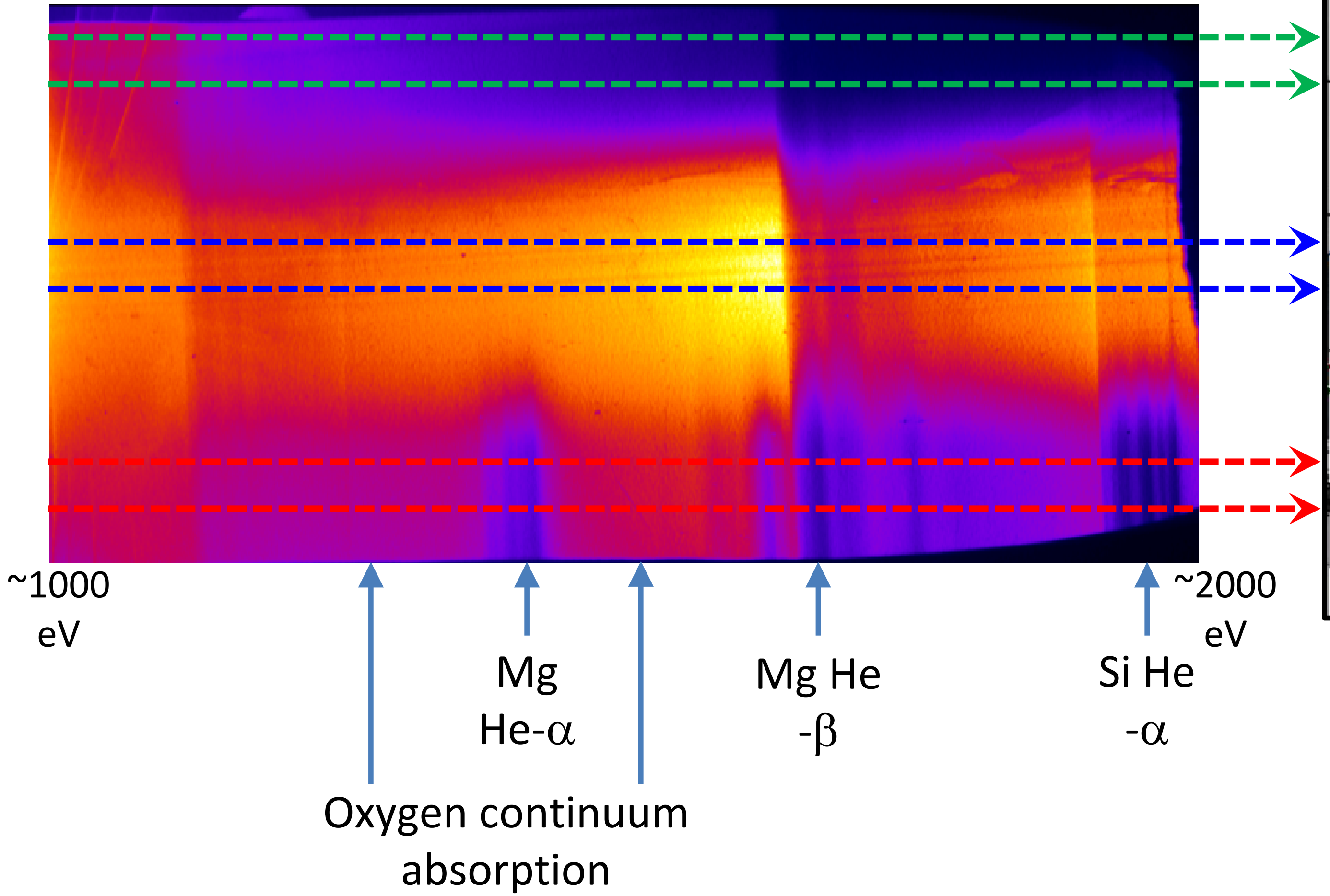
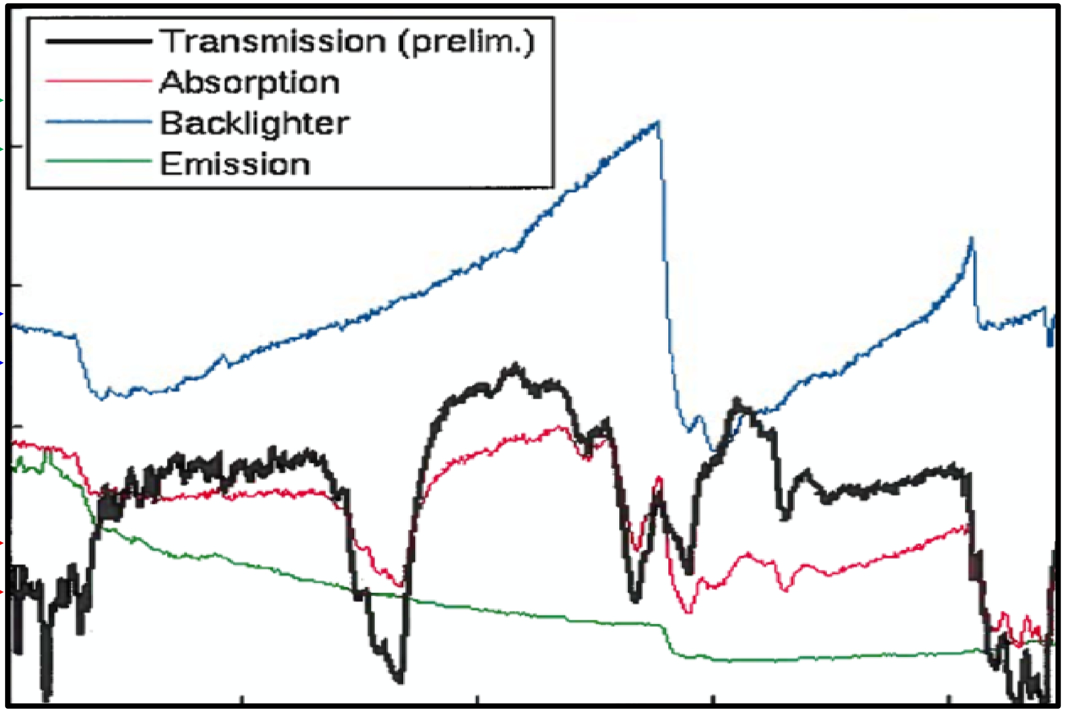


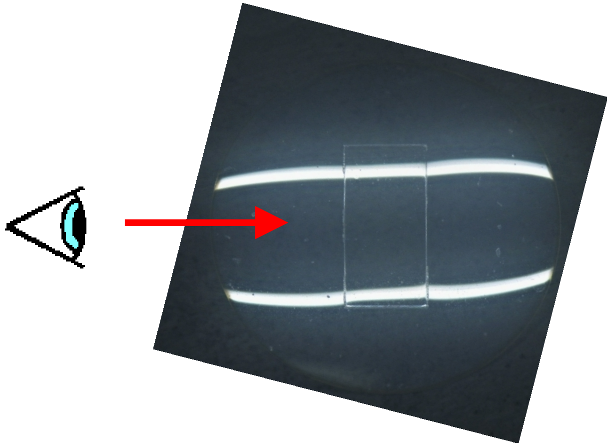


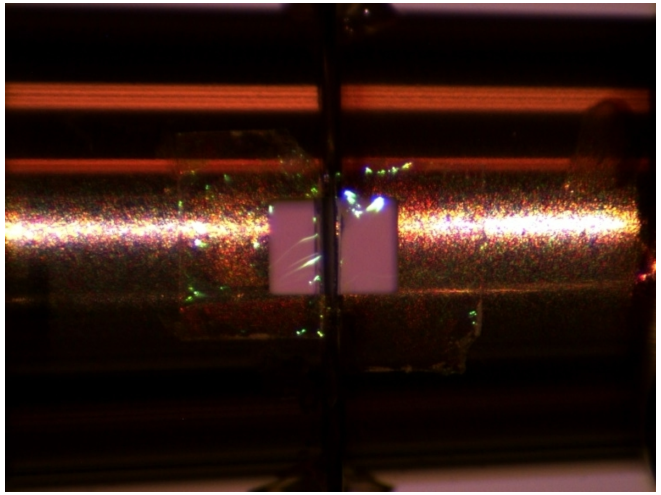
$$\text{Transmission} = \frac{\text{Absorption} - \text{Emission}}{\text{Backlighter} - \text{Emission}}$$

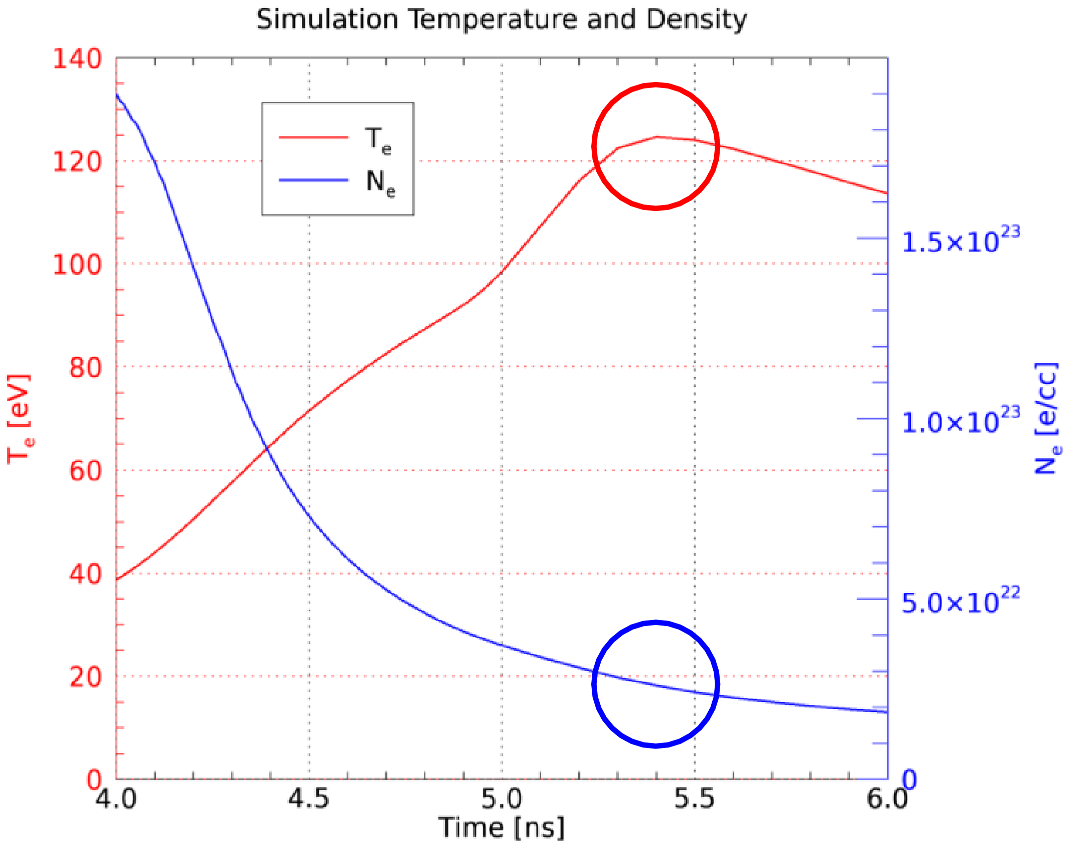
Some penumbral corrections are also applied.

Plasma conditions are inferred through a combination of experimental measurements and simulations.

- Estimated plasma conditions:
  - T_e ~ 125 eV and n_e ~ 2×10^{22} e/cc.
  - Electron temperature inferred from Dante instrument data coupled with a simulation.
  - Electron density inferred from simulation results. (GXD data was obscured by tamper material.)





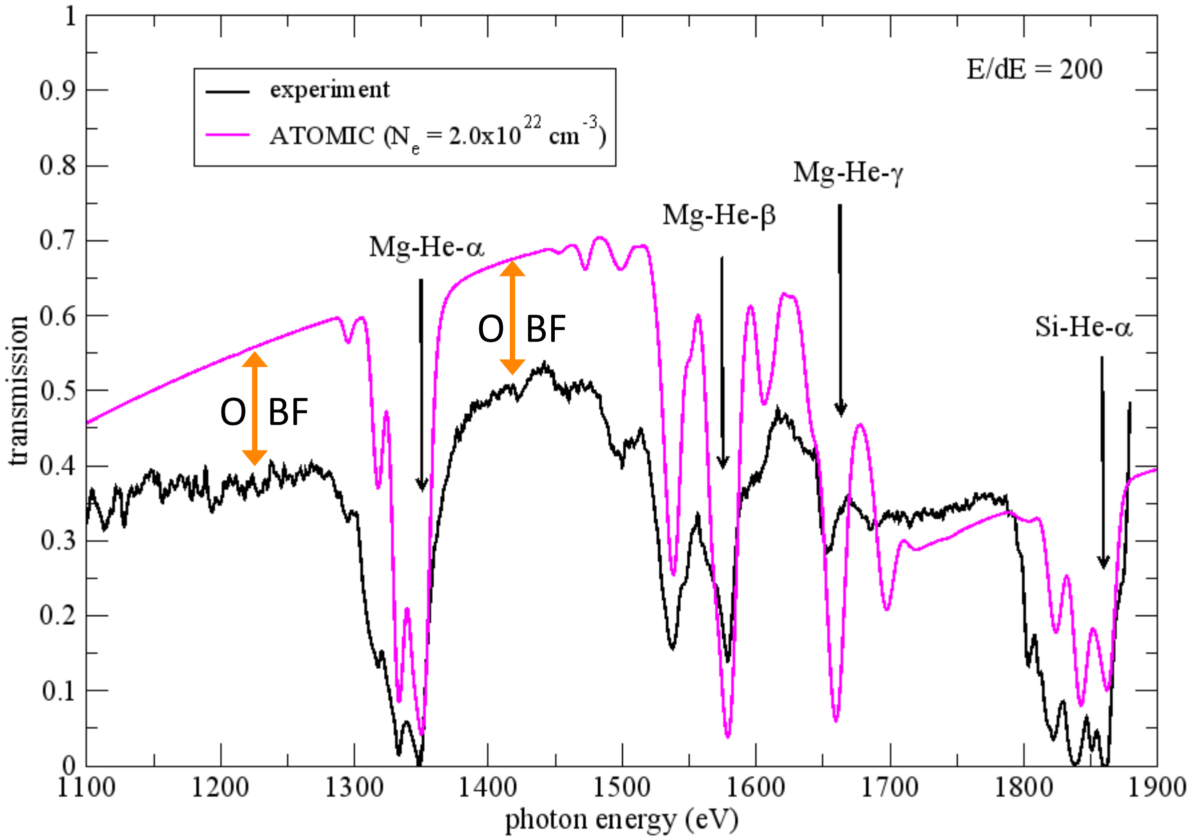


Preliminary analysis of experimental data shows possible disagreement with theory

**** CAUTION! ****

- The oxygen bound-free opacity is very sensitive to plasma conditions
- Potential sources of uncertainty:
  - How well do we know the plasma conditions?
  - Have we correctly accounted for all background and self-emission?
  - How uniform is the plasma?
  - How large are temporal gradients?

Si+O+Mg transmission



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NIF

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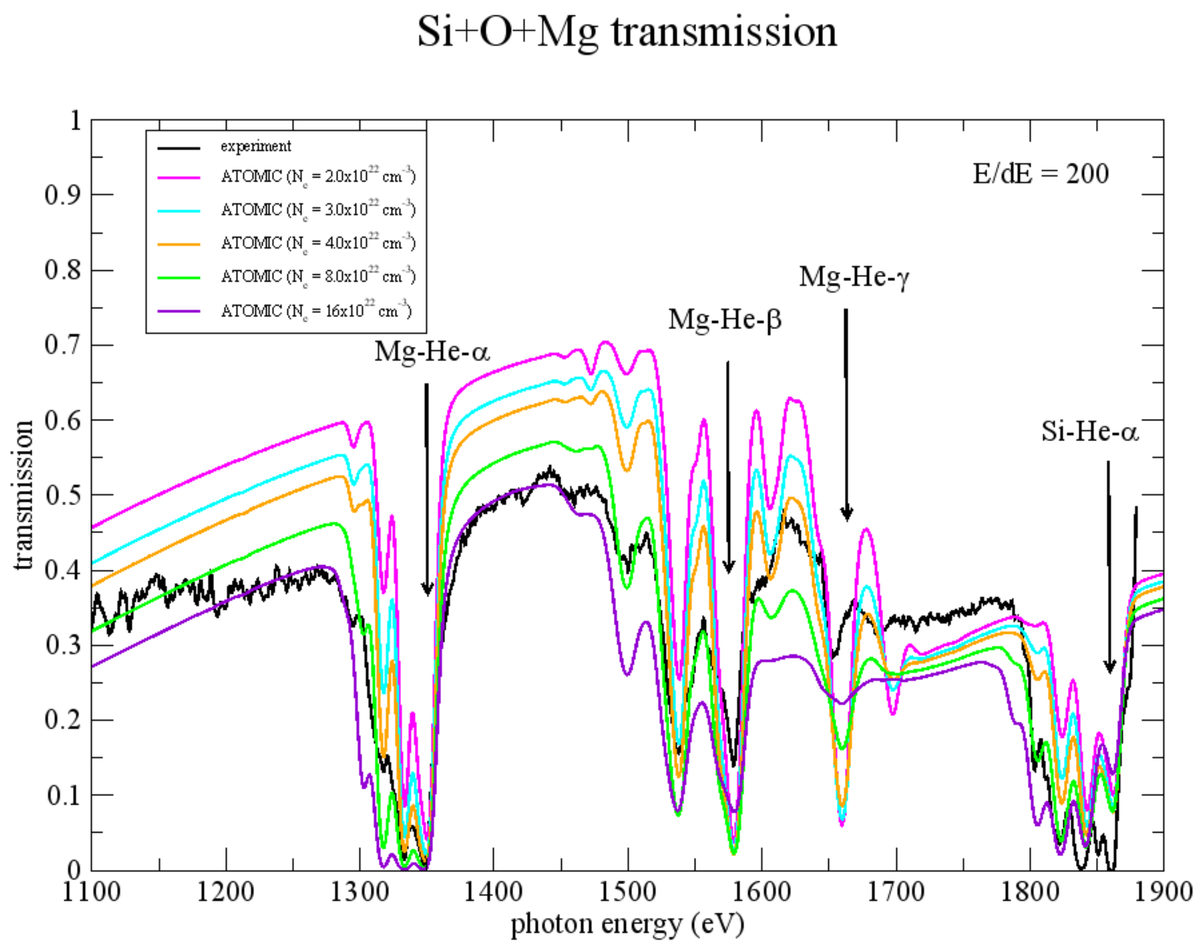

The opacity research has many future exciting opportunities

Fe opacity

- Update statistical analysis techniques and report
- Include additional ~20 datasets

Time-resolved opacity

- Finalize condition analysis using latest algorithm, publication
- Finalize dataset collection for first absolute opacity measurements time-resolved
- Evaluate importance of time-dependent effects on previously reported data
- Request support for shorter duration measurements (~1ns)

Oxygen opacity

- Finalize oxygen measurements for accurate O opacity
- Finalize oxygen platform condition analysis
- Comparison with models, publication

High-density opacity

- Test preheat suppression idea to reach highest density ever ~10^{23} e^-/cc (CZB) – most anticipated stress on models

Cross-comparison effort with NIF opacity

- Fe opacity, define comparison technique
- Study the effect of changing density for a given Te.
- Oxygen opacity – Do we see the same model-data comparison trend