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Sandia National Laboratories

Laboratory tests of stellar opacity models

PRESENTED BY

Taisuke Nagayama

U.S. DEPARTMENT OF ENERGY | NNSA

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

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

Holistic scrutiny in experiments, analyses, and theories made significant progress towards resolving the solar problem

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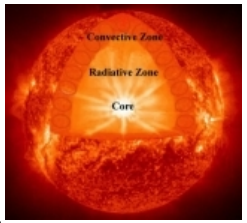

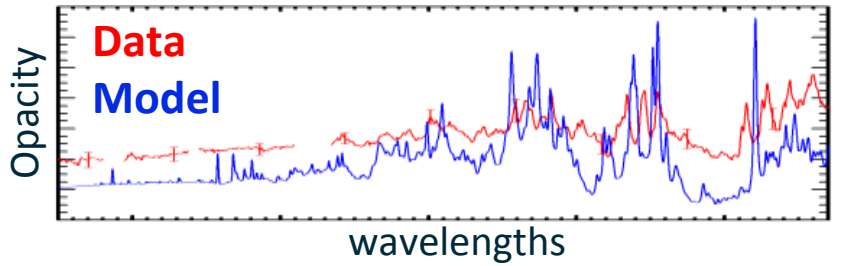

Revisit Fe results: Re-scrutiny in experiments, analyses, theories

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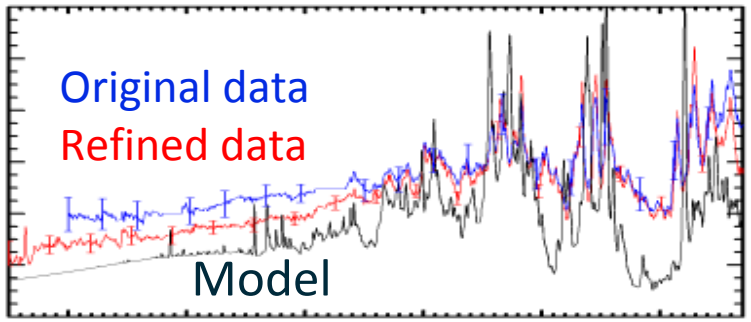

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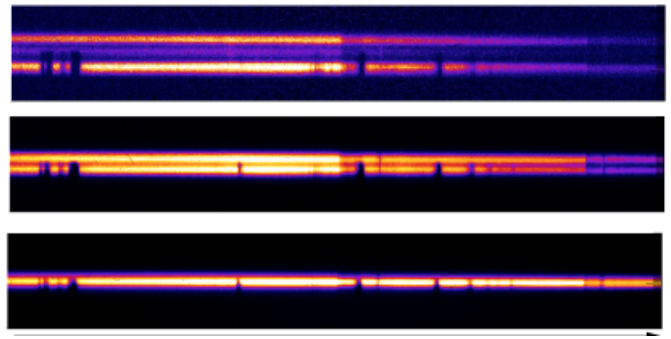
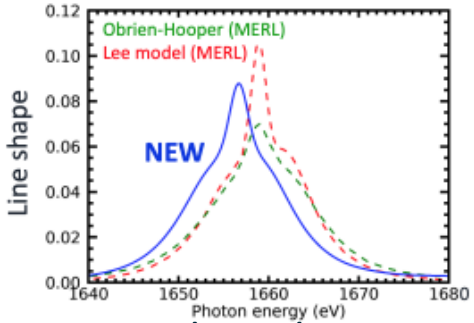


Refined theories



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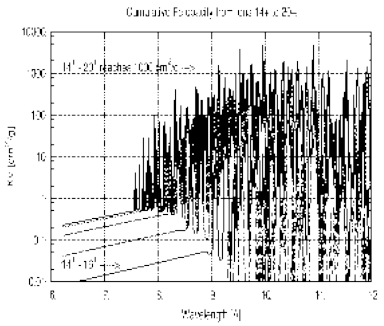

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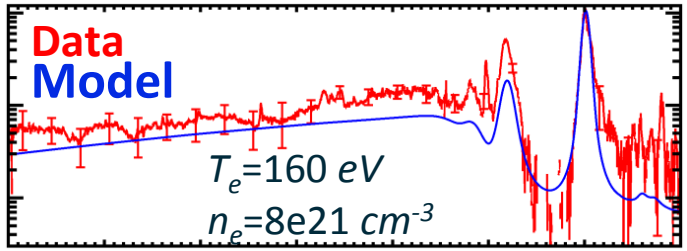

Recruiting student & po[illegible]: Malia Kao (student), Dan Mayes (Postdoc)

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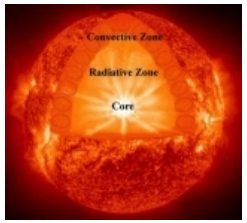

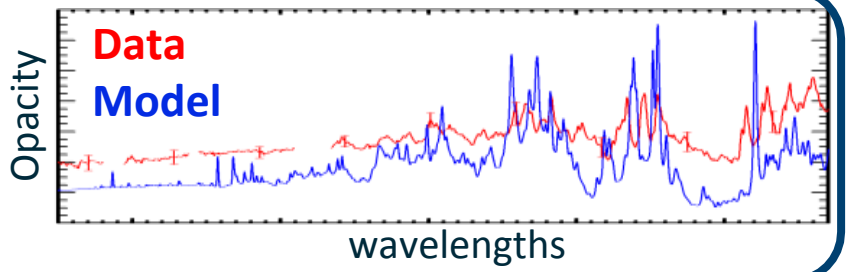

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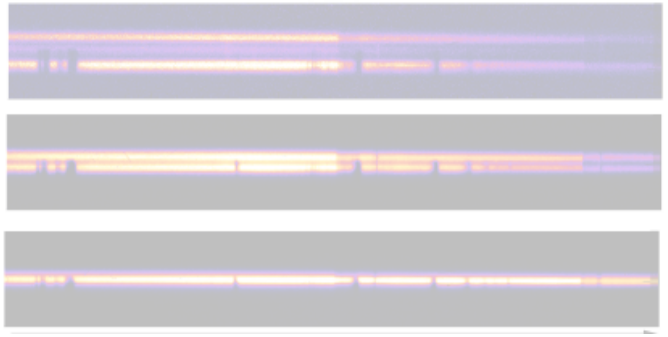

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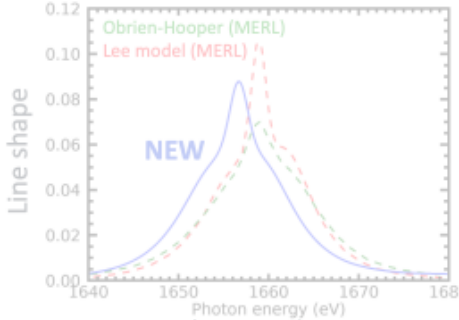

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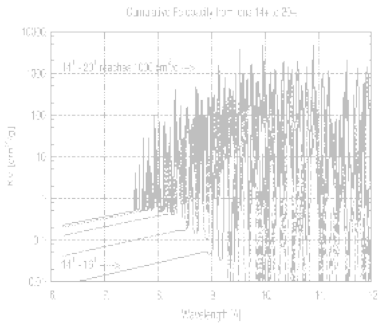

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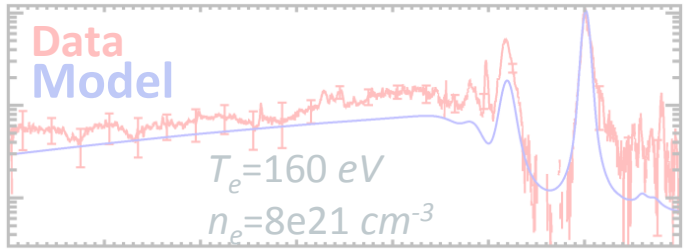

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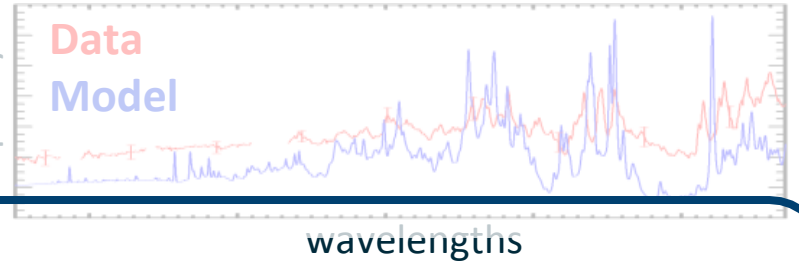

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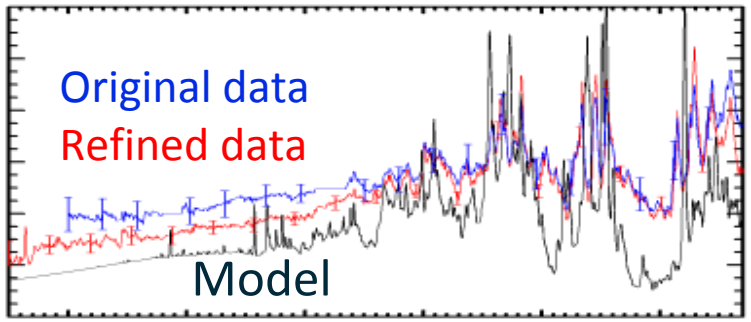

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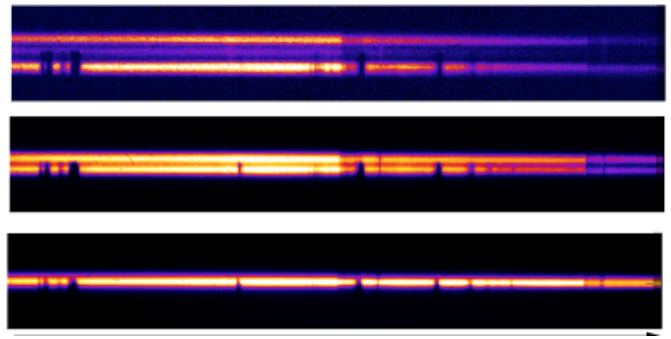

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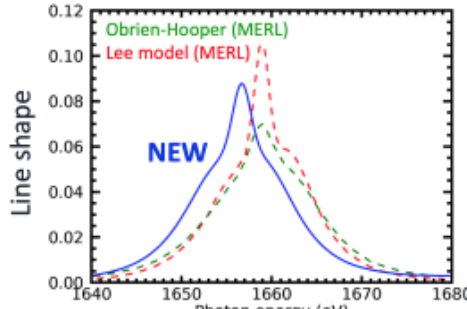

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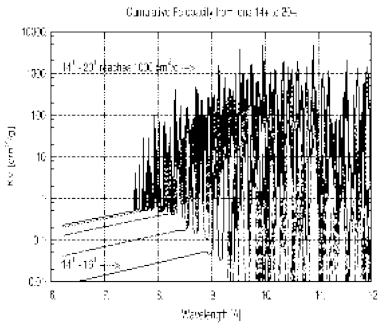

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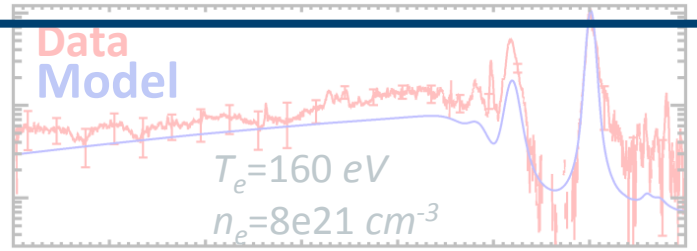

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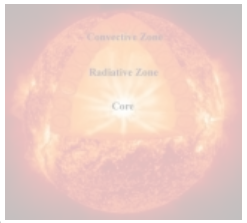

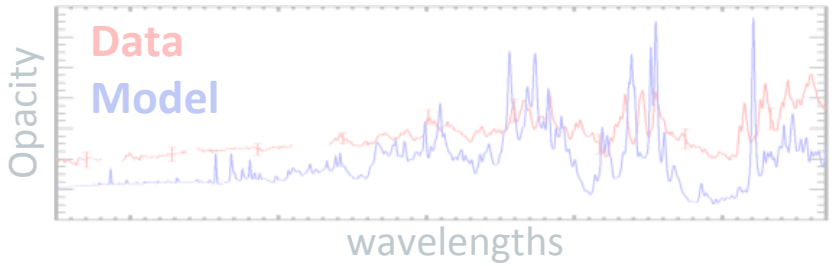

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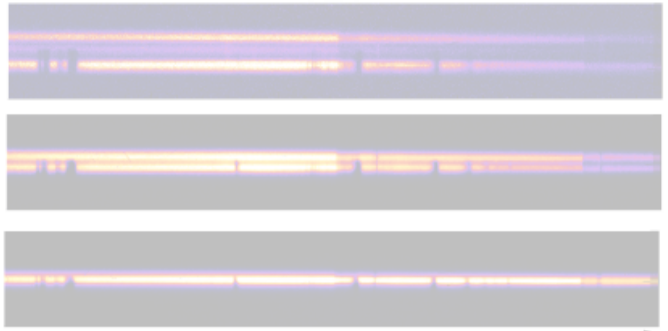

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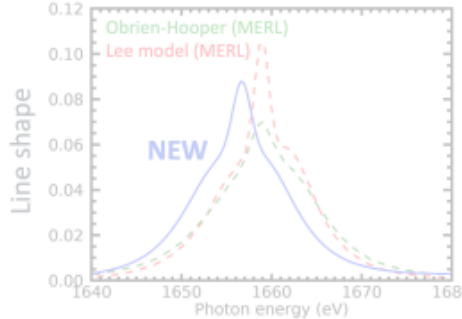

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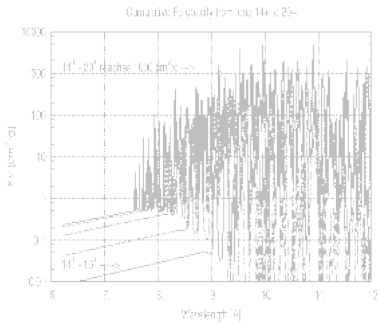

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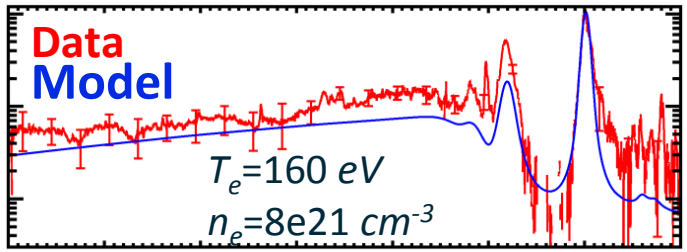

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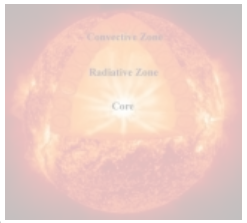

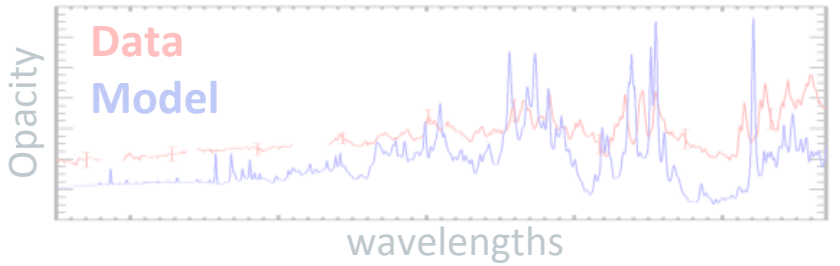

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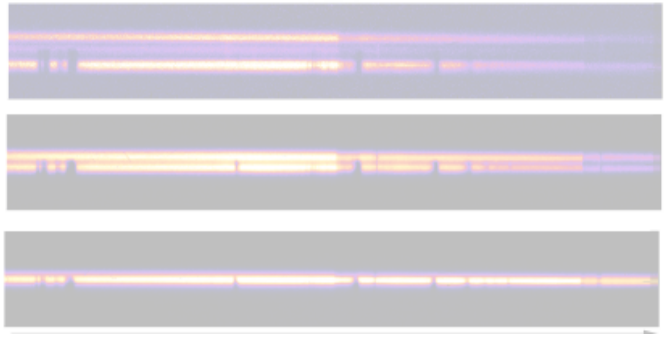

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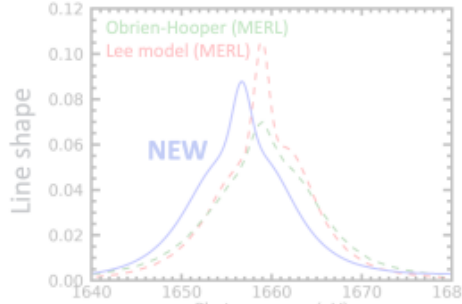

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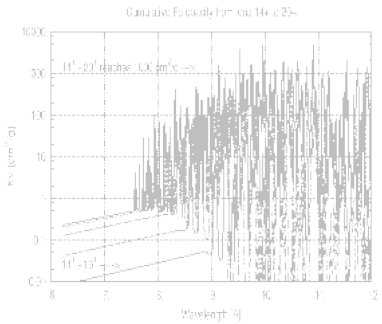

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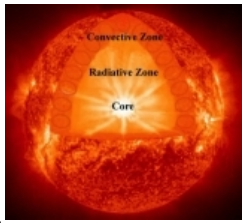

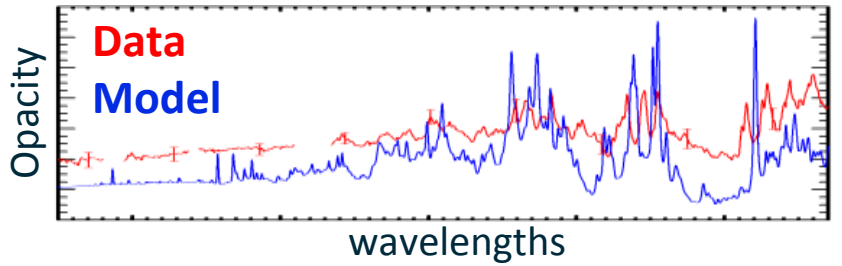

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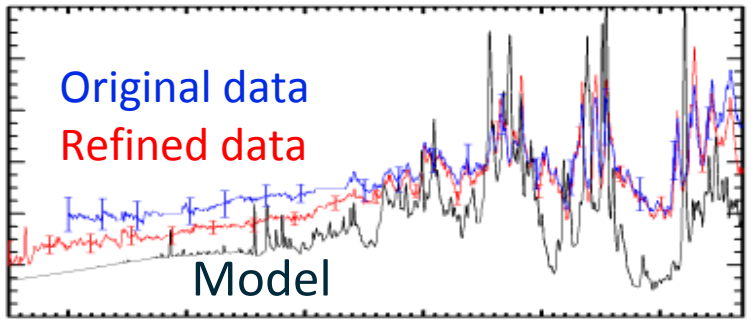

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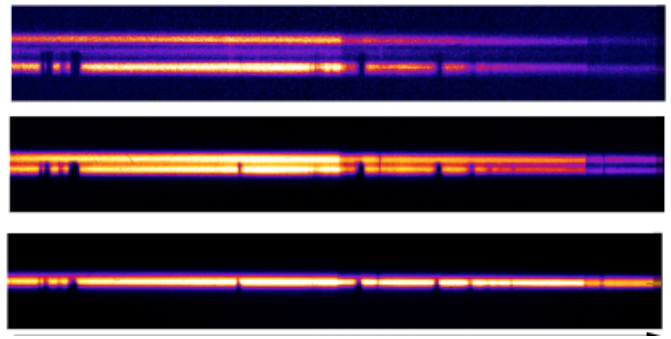

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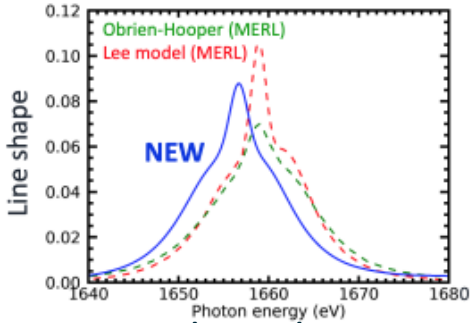

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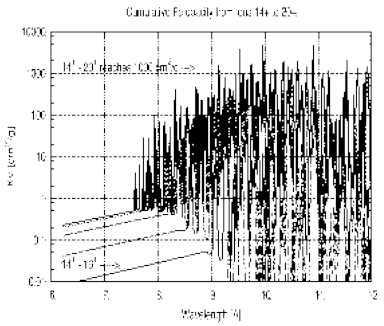

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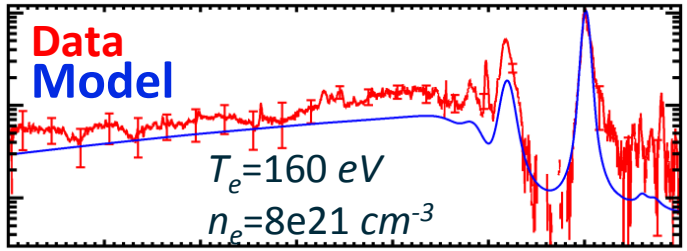

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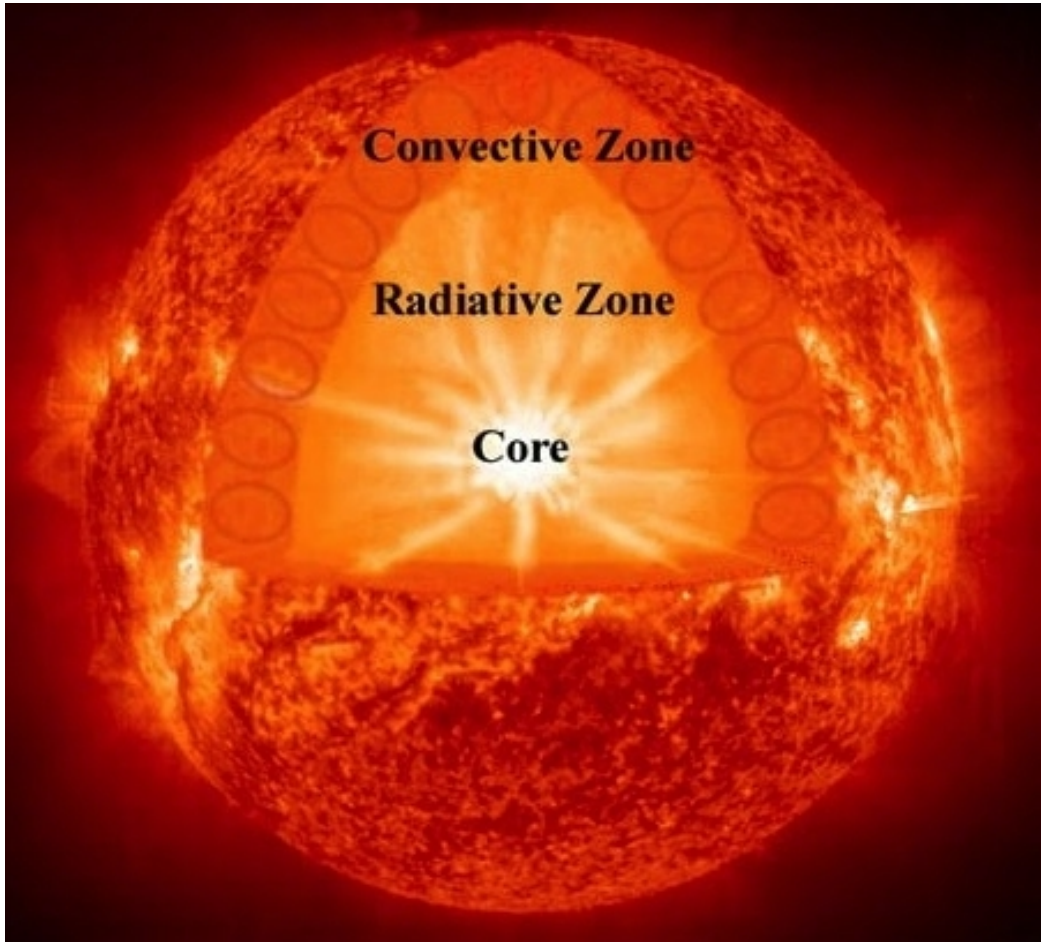
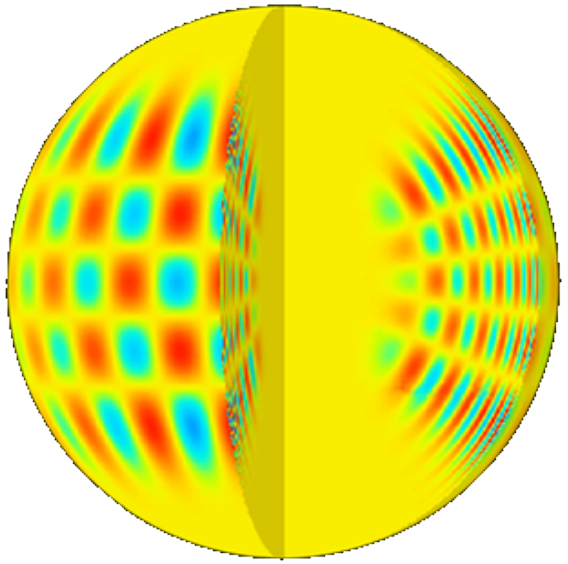


- Simulation: Standard solar model
  Inputs:
  - Abundance
  - EOS
  - Opacity
  - Etc.
- Measurements: Helioseismology



Analysis of 2D-resolved pulsation reveals the solar structure

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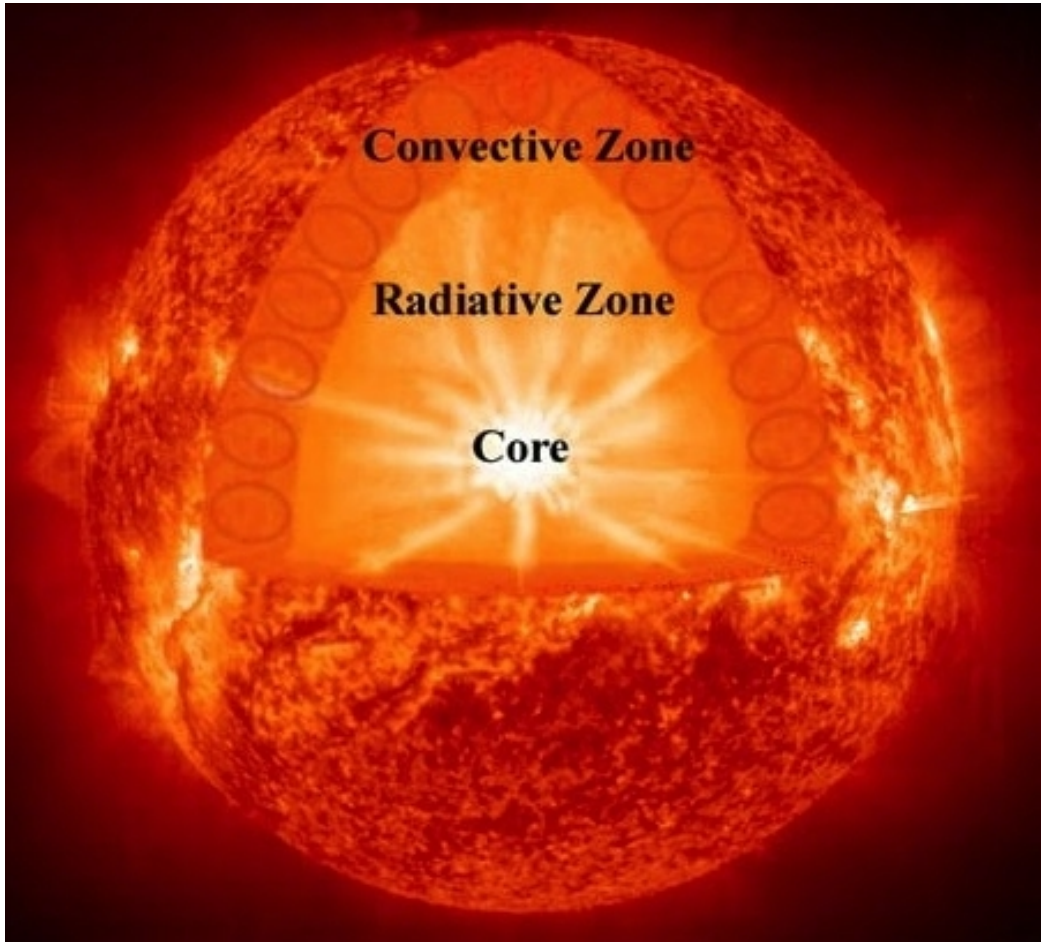

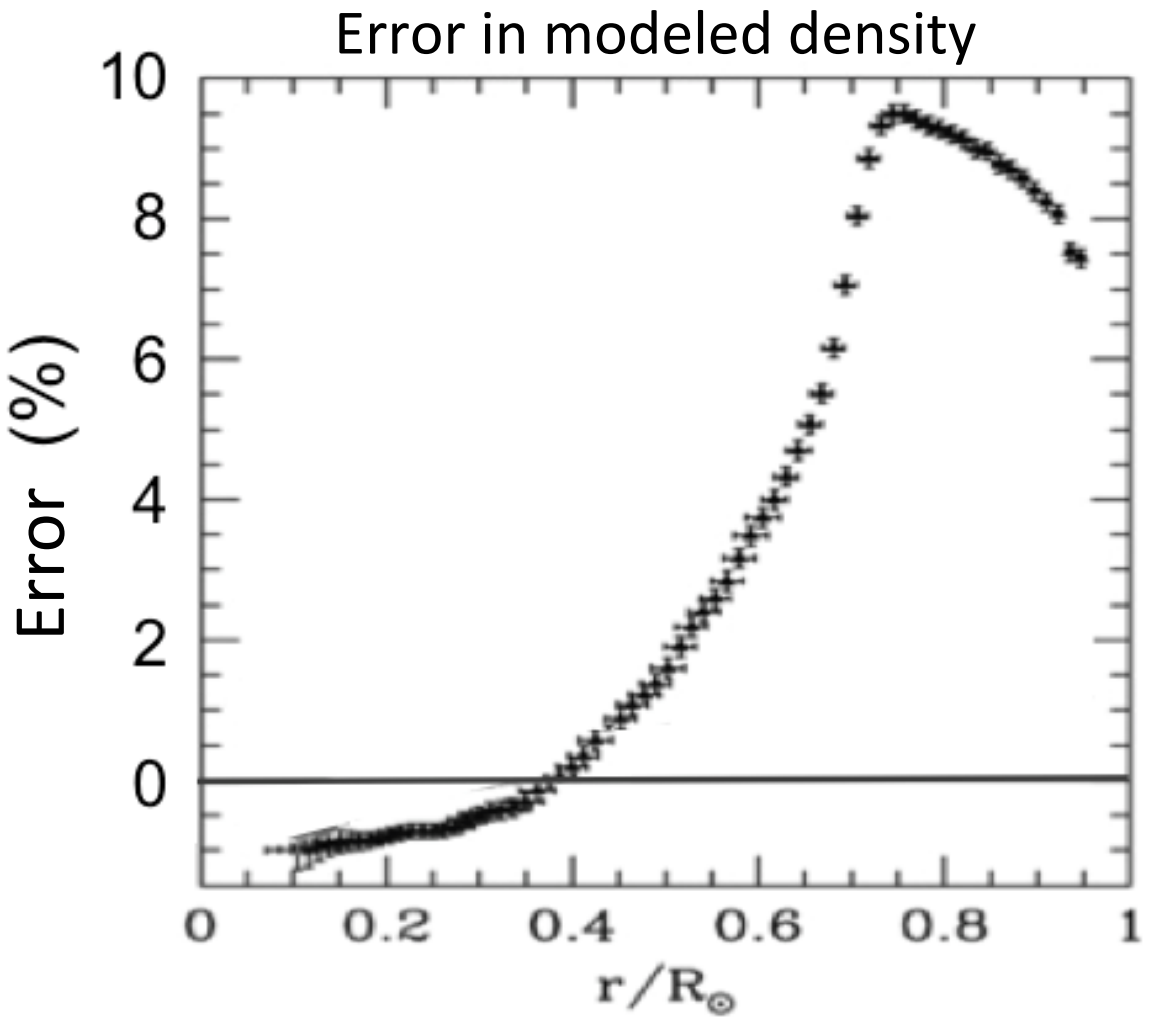

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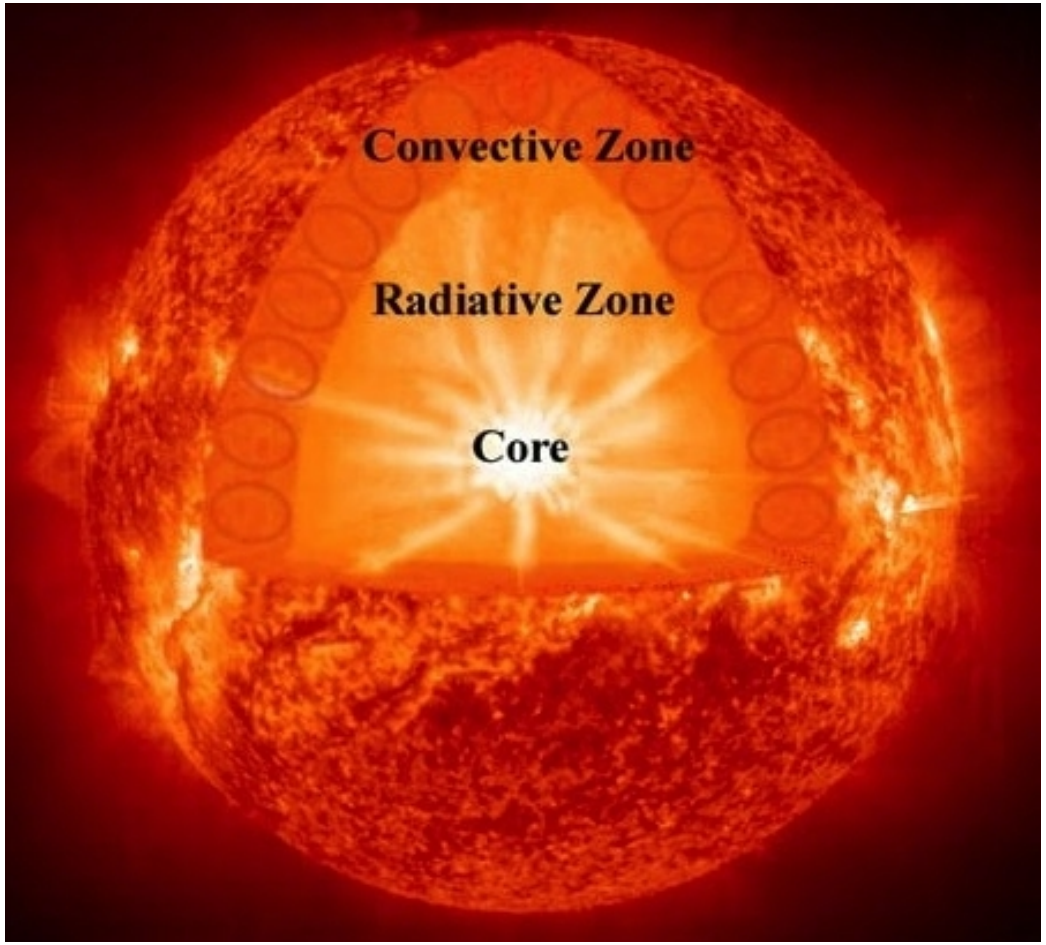

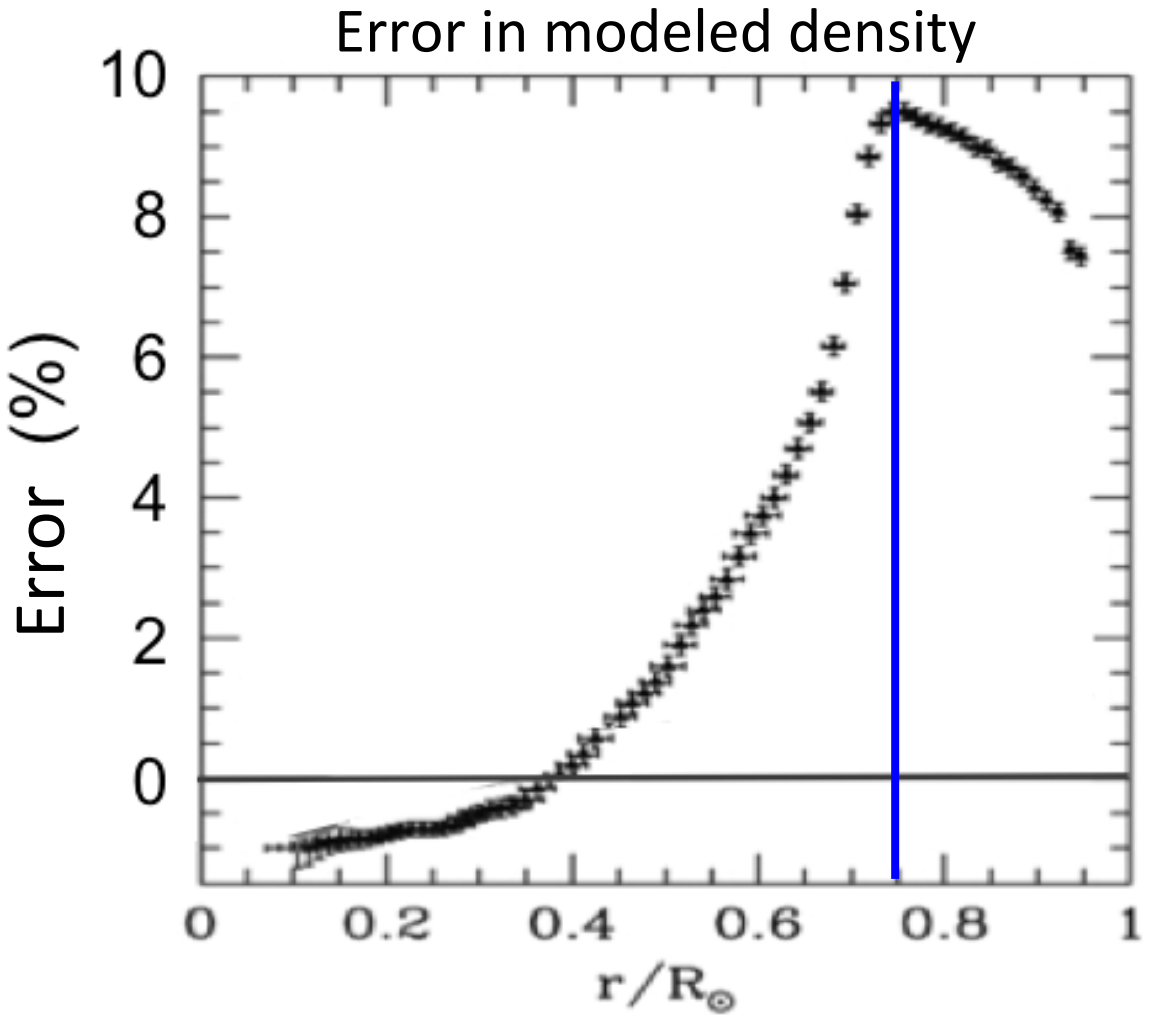

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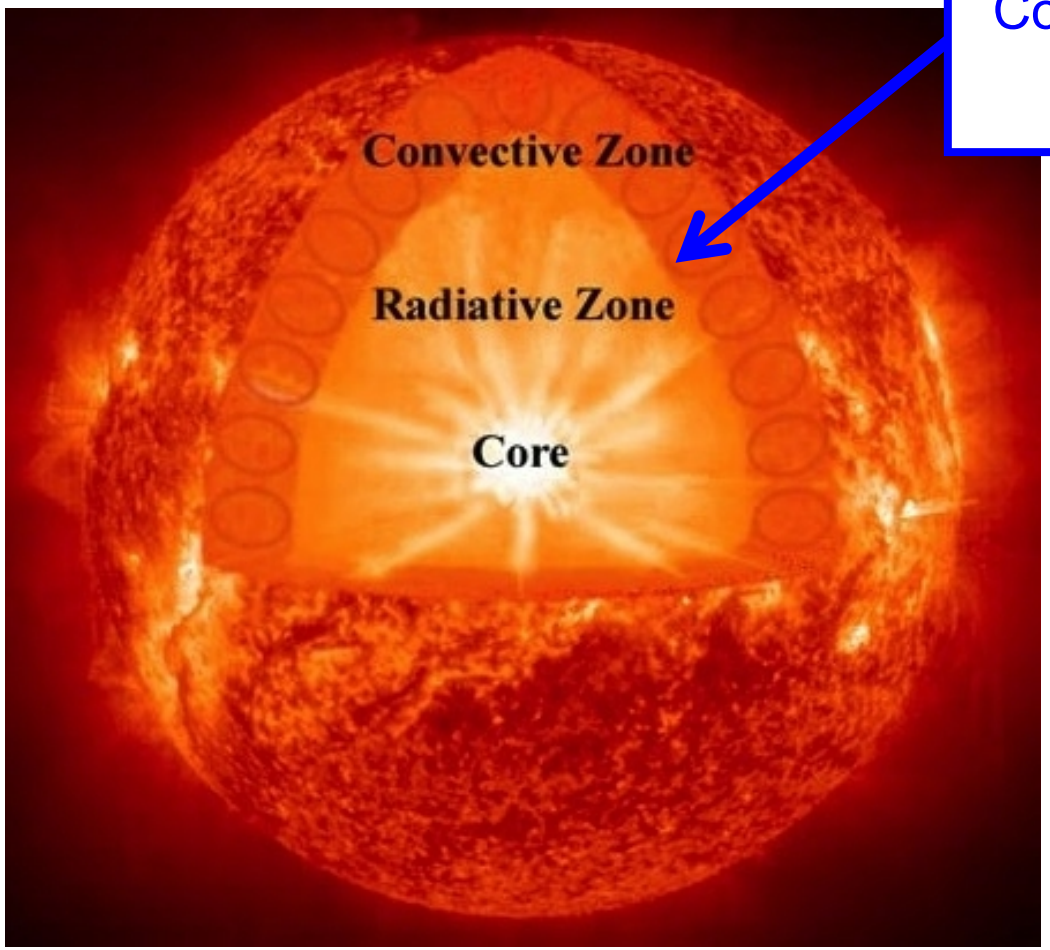
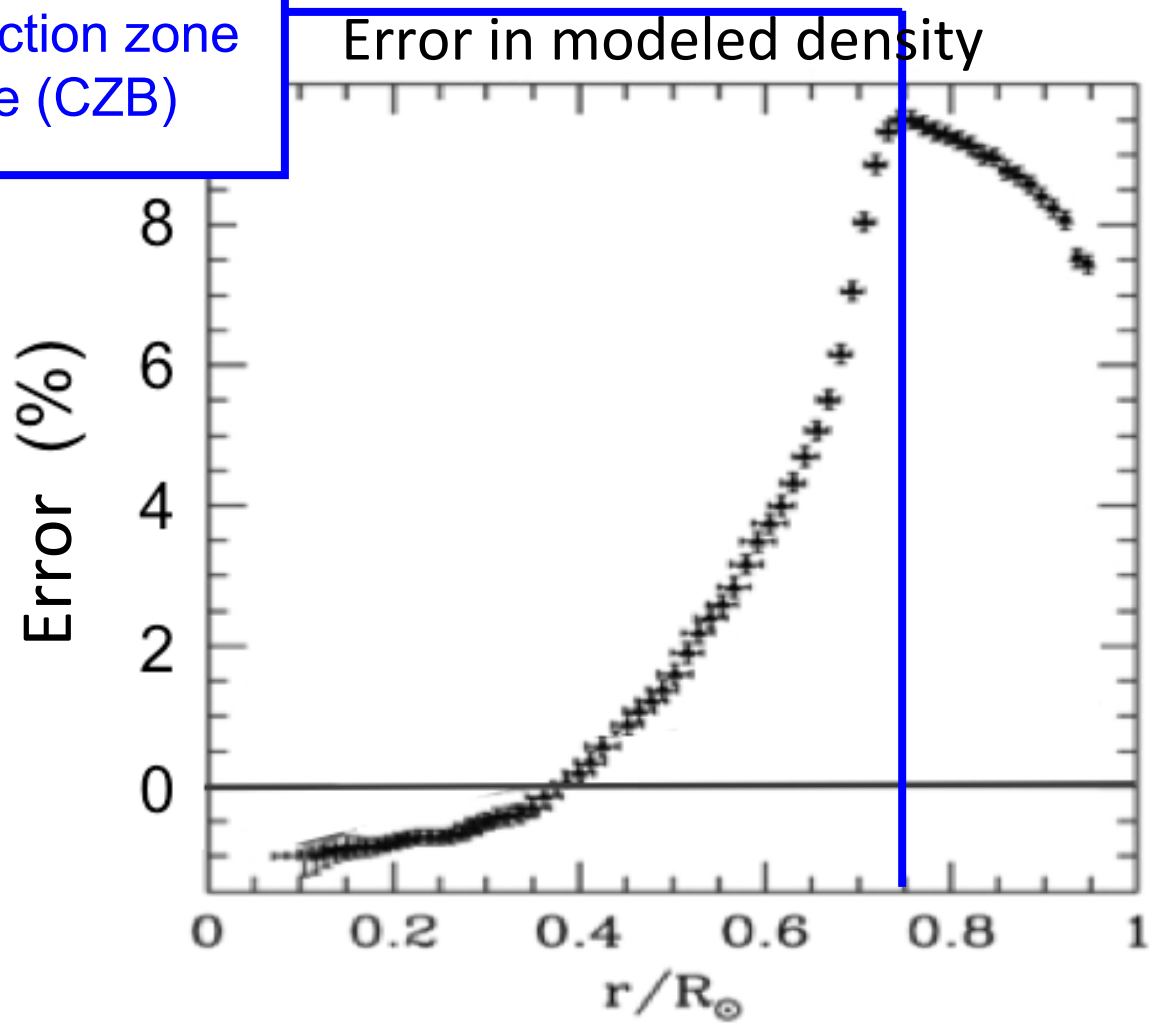
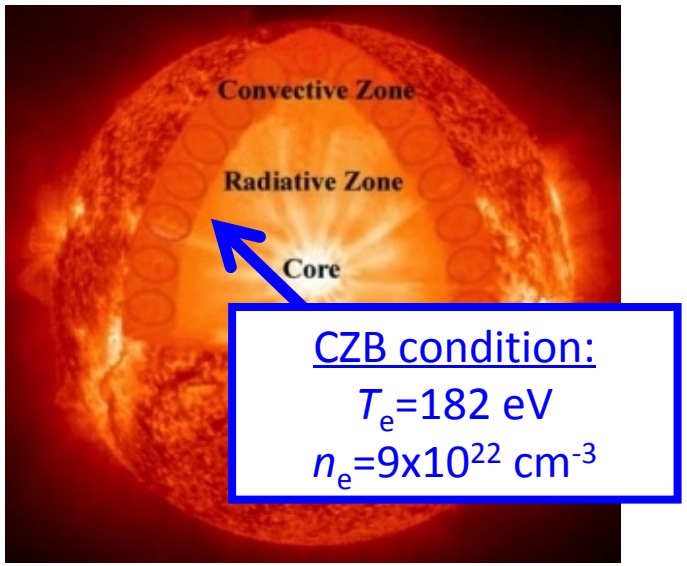
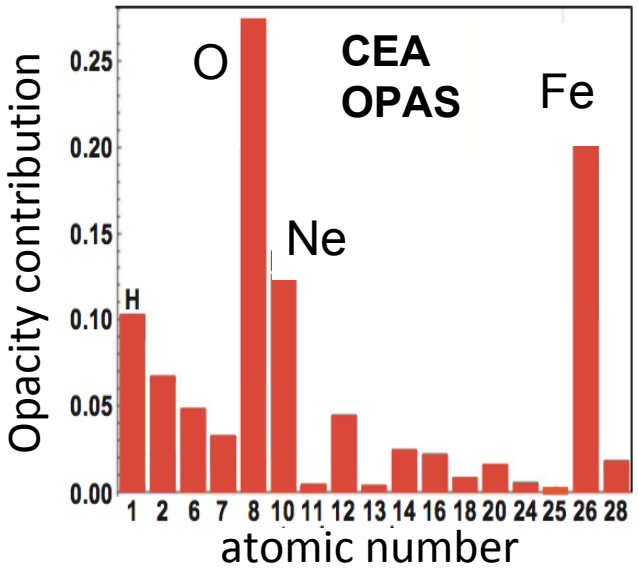


Convection zone base (CZB)



10-30% mean-opacity increase in the solar model is needed to resolve this discrepancy

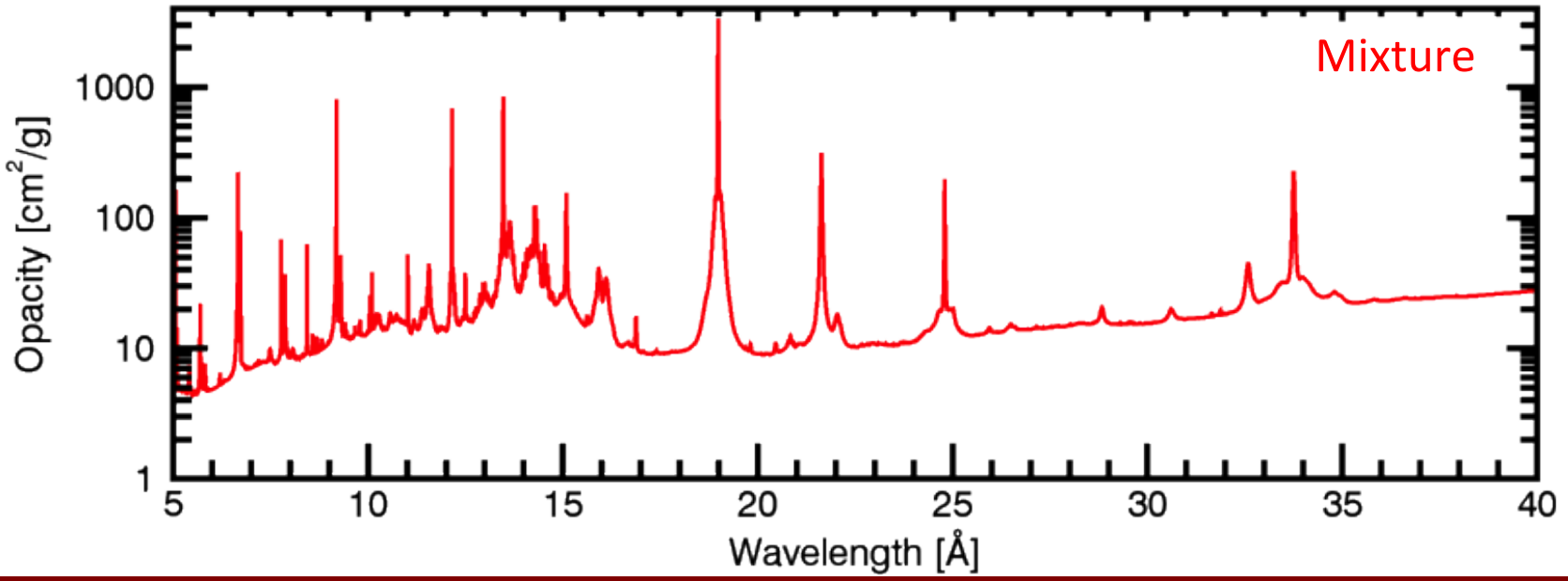




Opacity: κ_ν

- Quantifies radiation absorption
- $\kappa_\nu(T_e, n_e)$ … input for solar models
- Opacity models have never been tested

Solar mixture opacity at Convection Zone Base (CZB)



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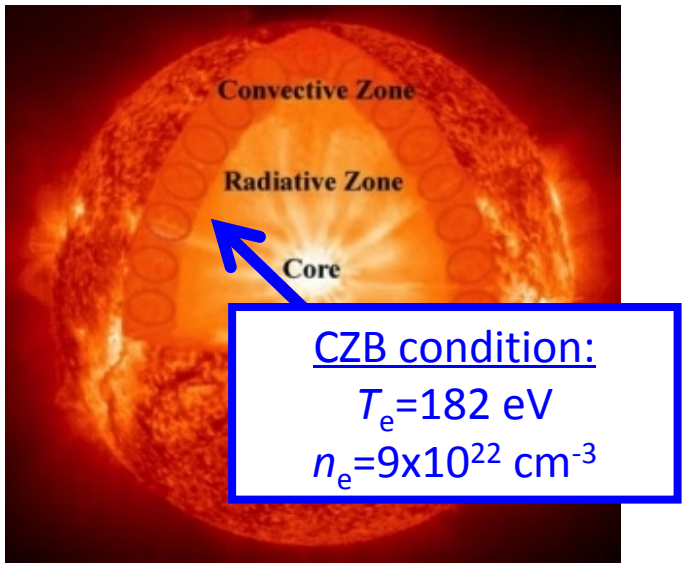

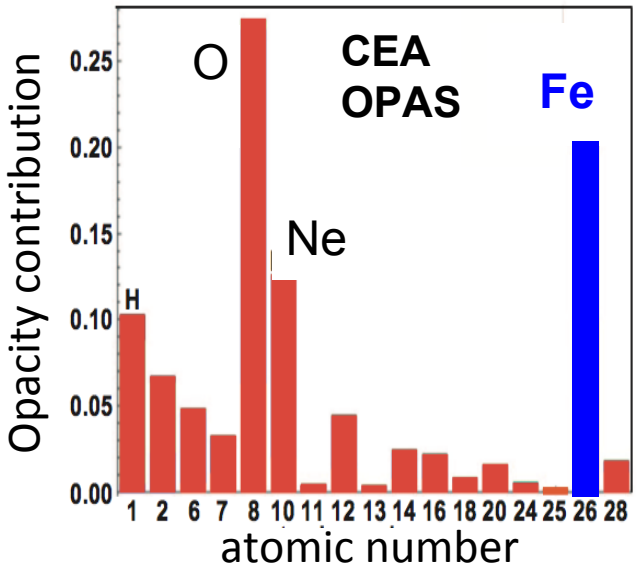

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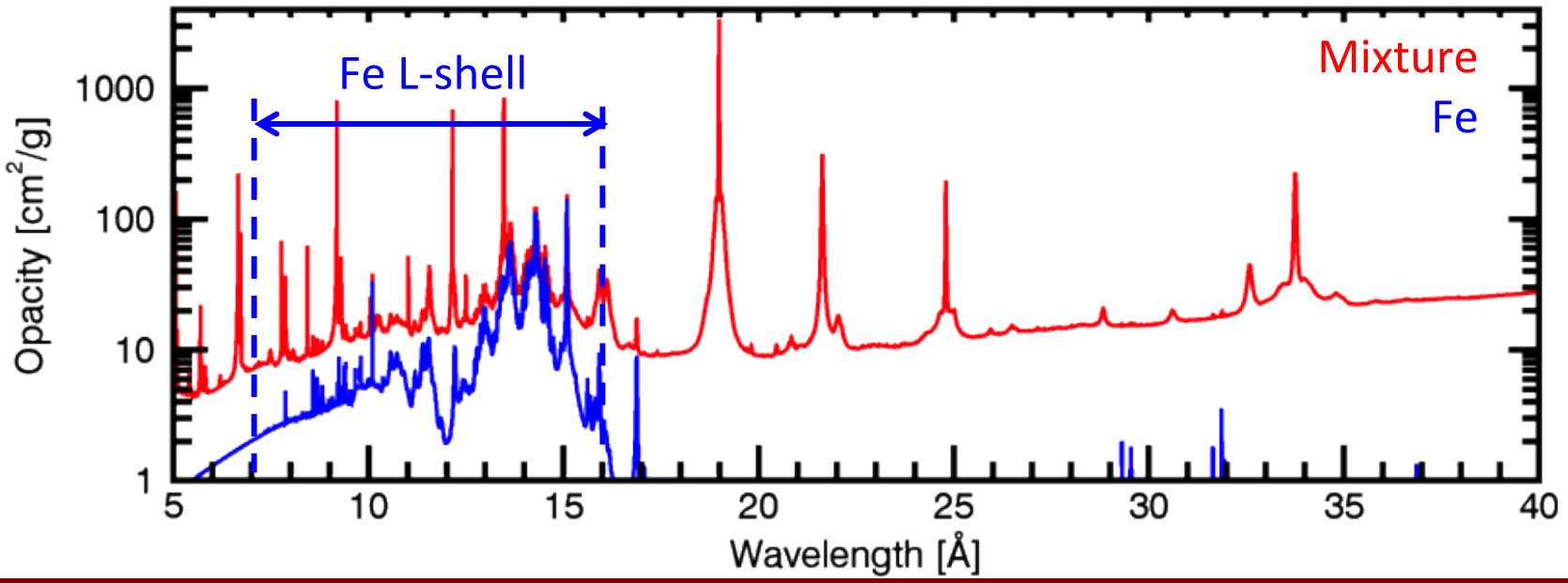
Fe is a likely suspect:

- 2nd largest contribution
- Most difficult to model

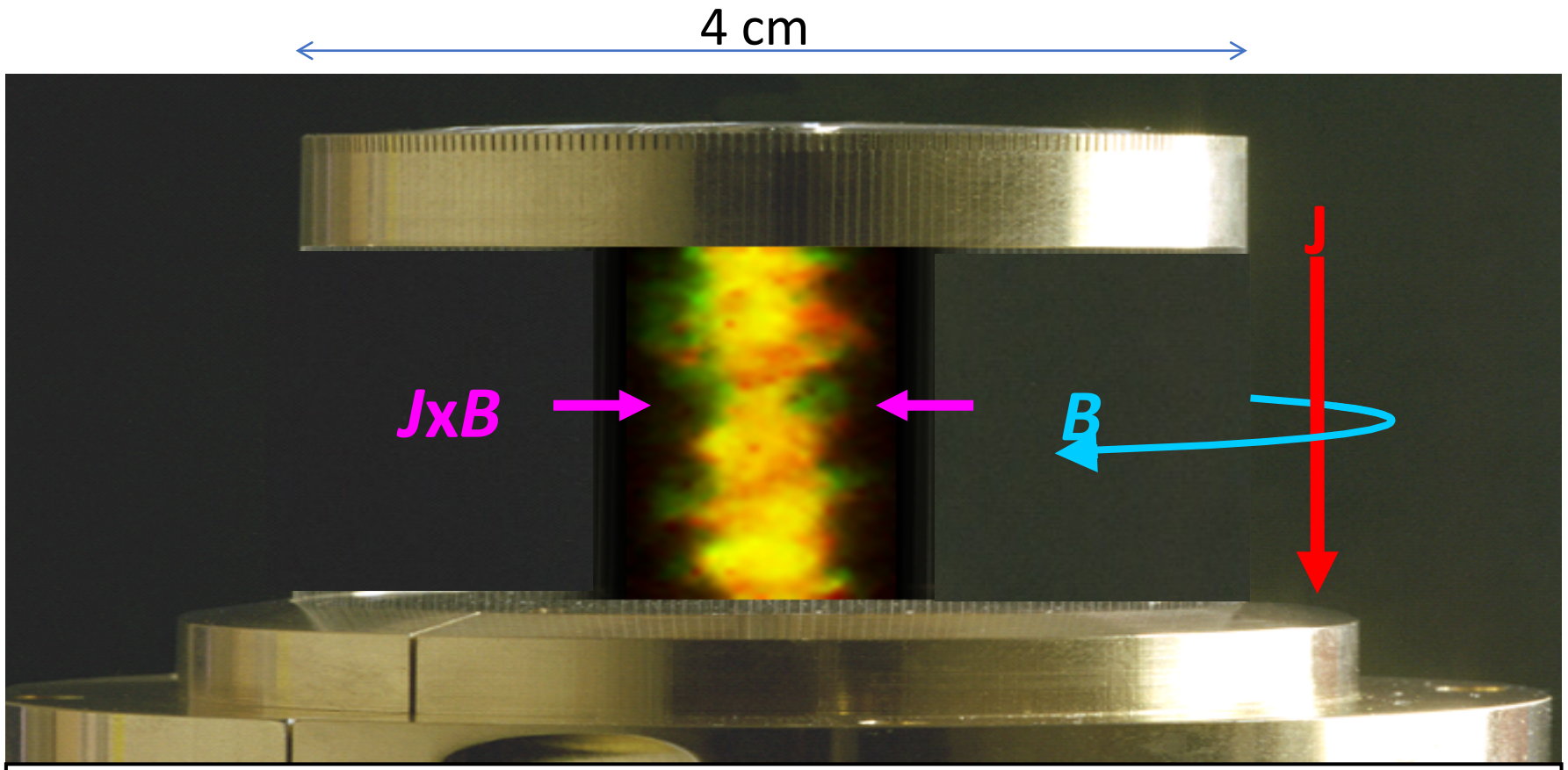
Solar mixture opacity at Convection Zone Base (CZB)



C. Blancard et al., *The Astrophysical Journal* 745, 10 (2012)

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

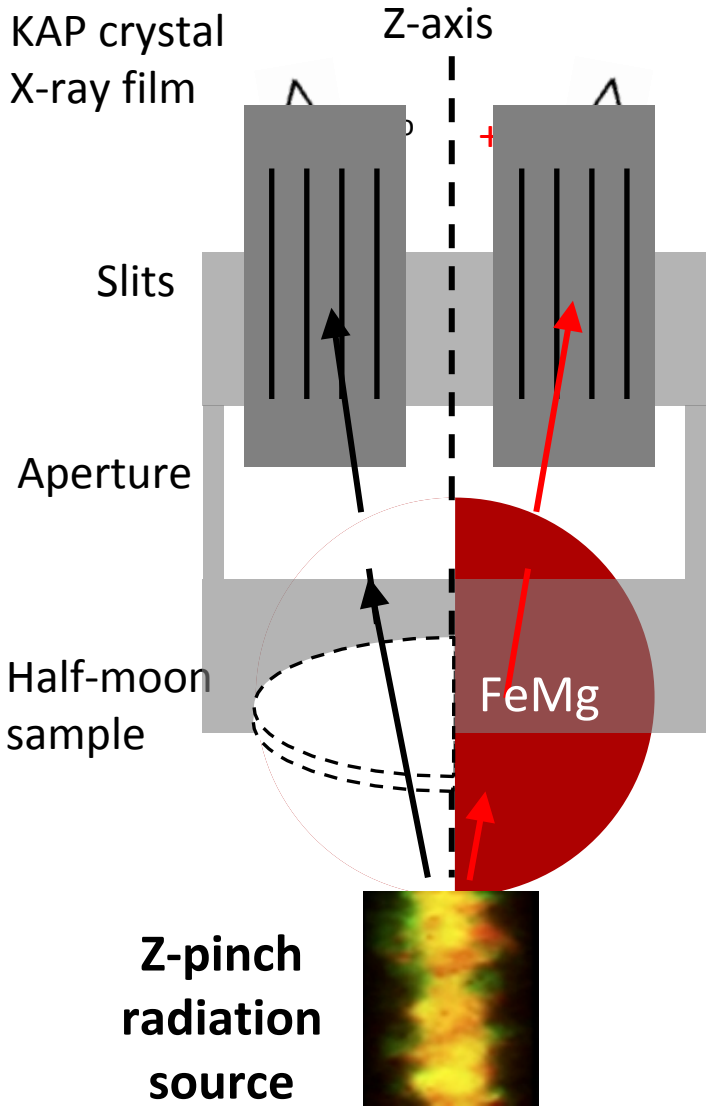
Sandia National Laboratories

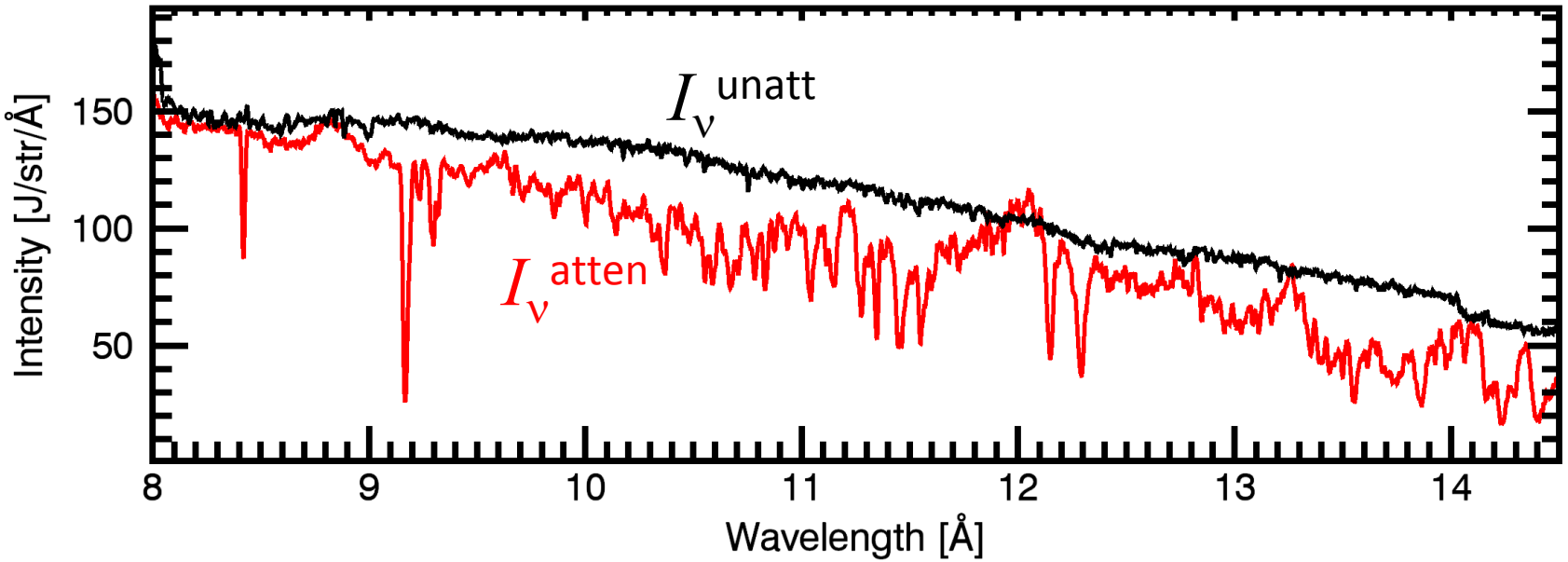


P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

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

[1] Bailey et al., *Phys Plasmas* 16, 058101 (2009)

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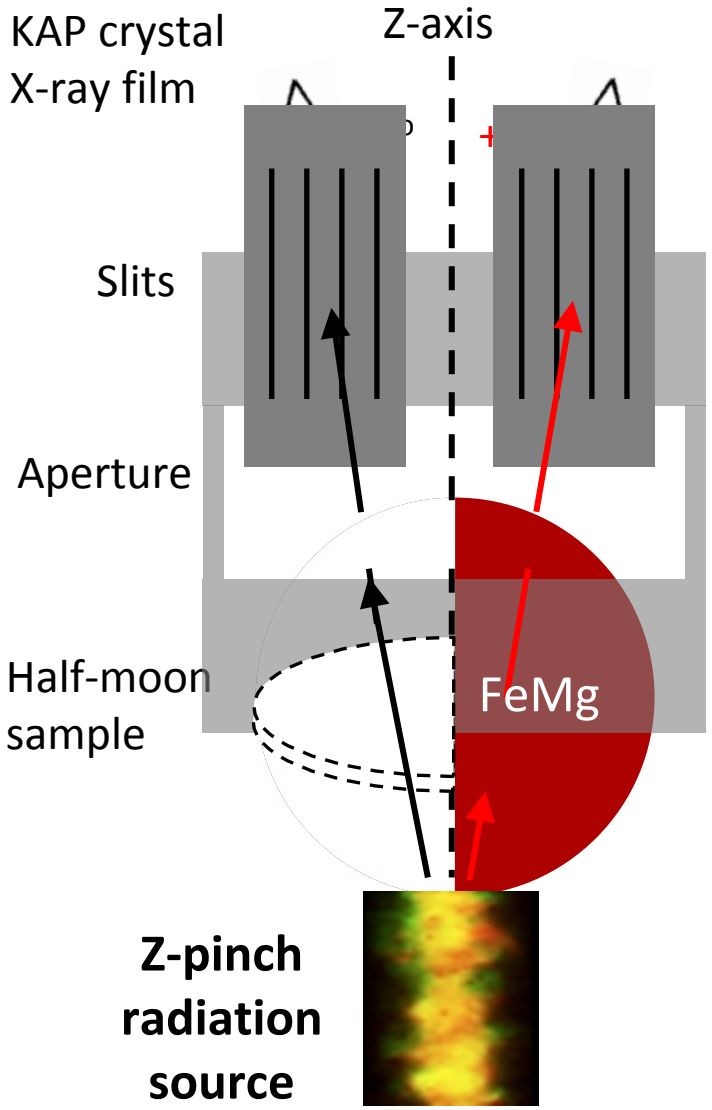

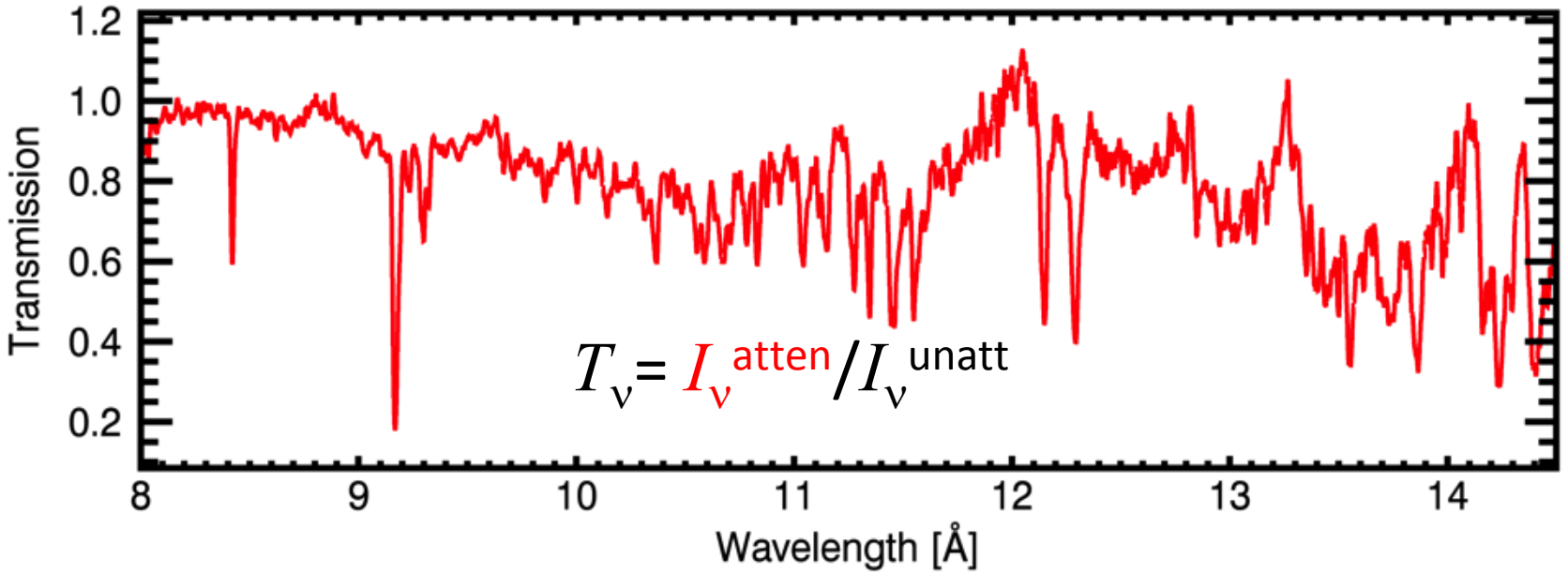

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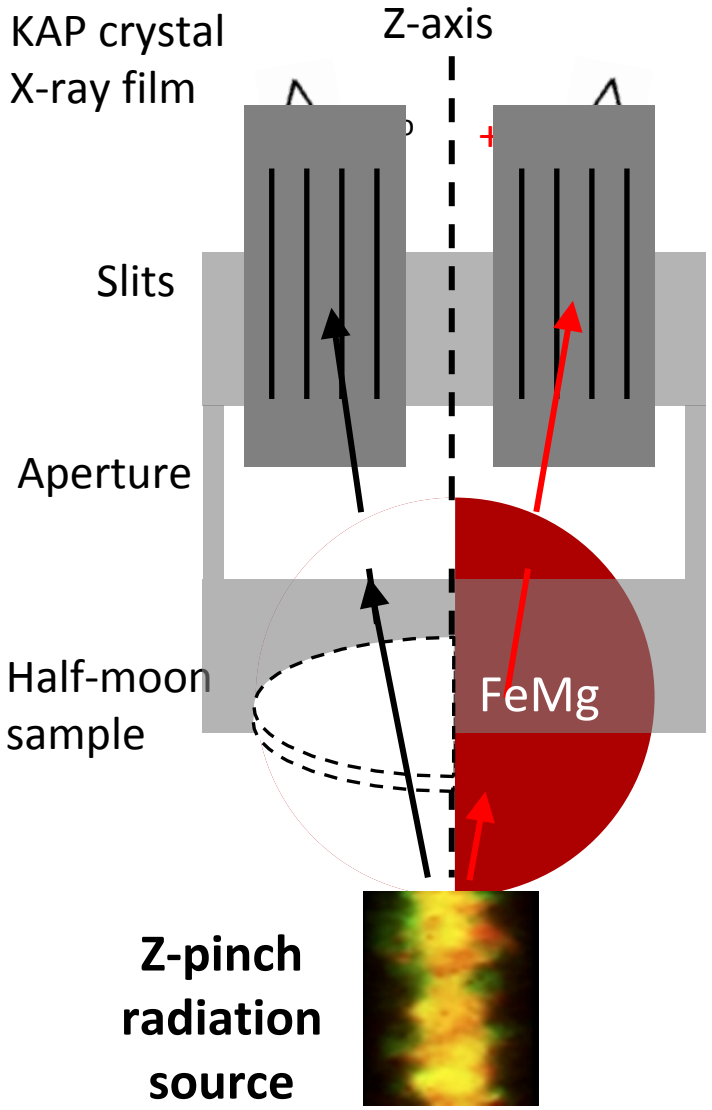

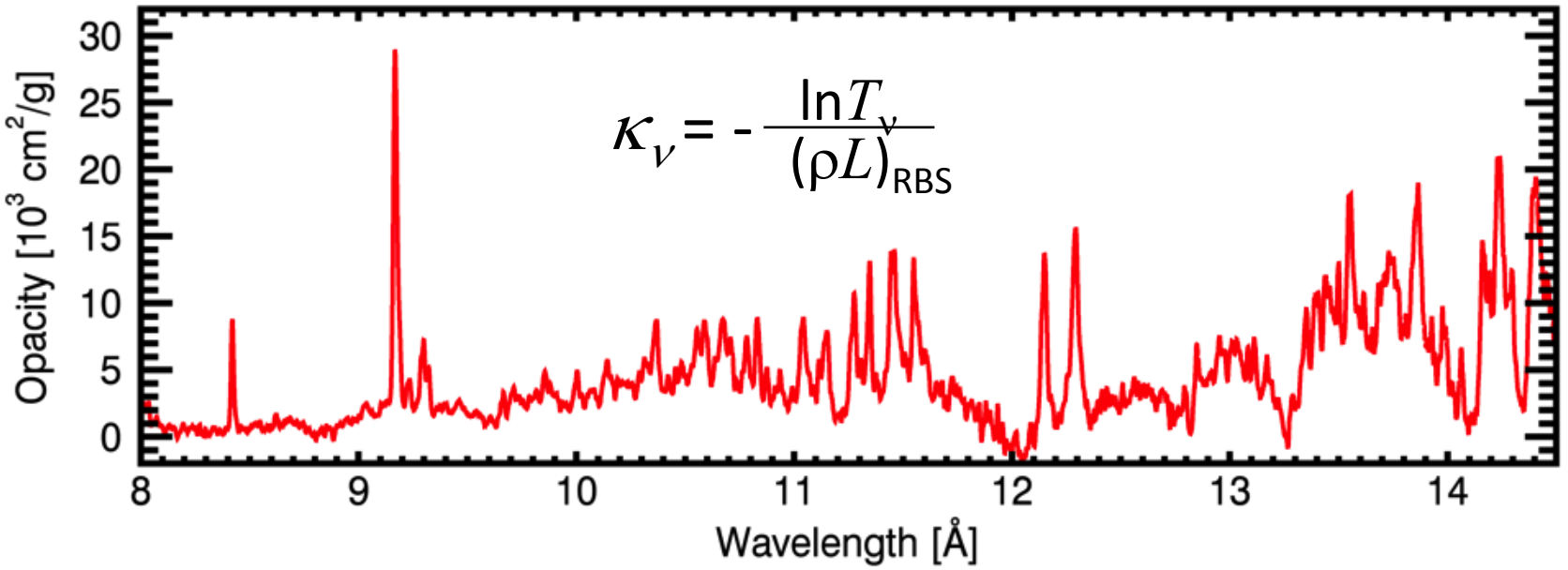

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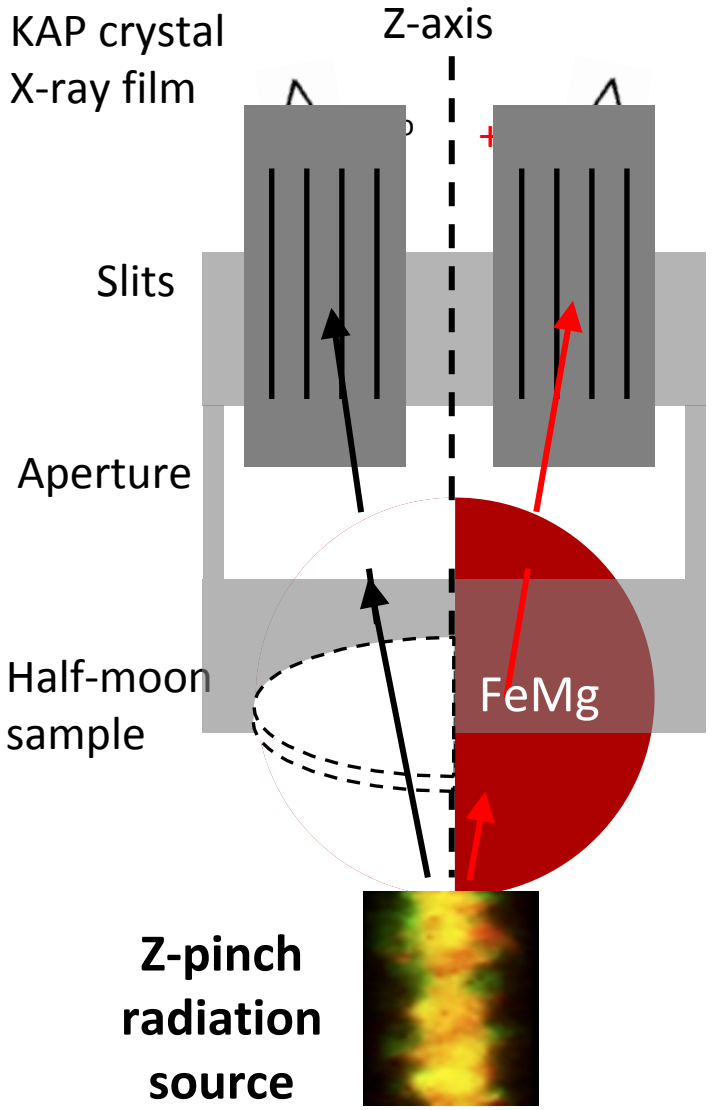

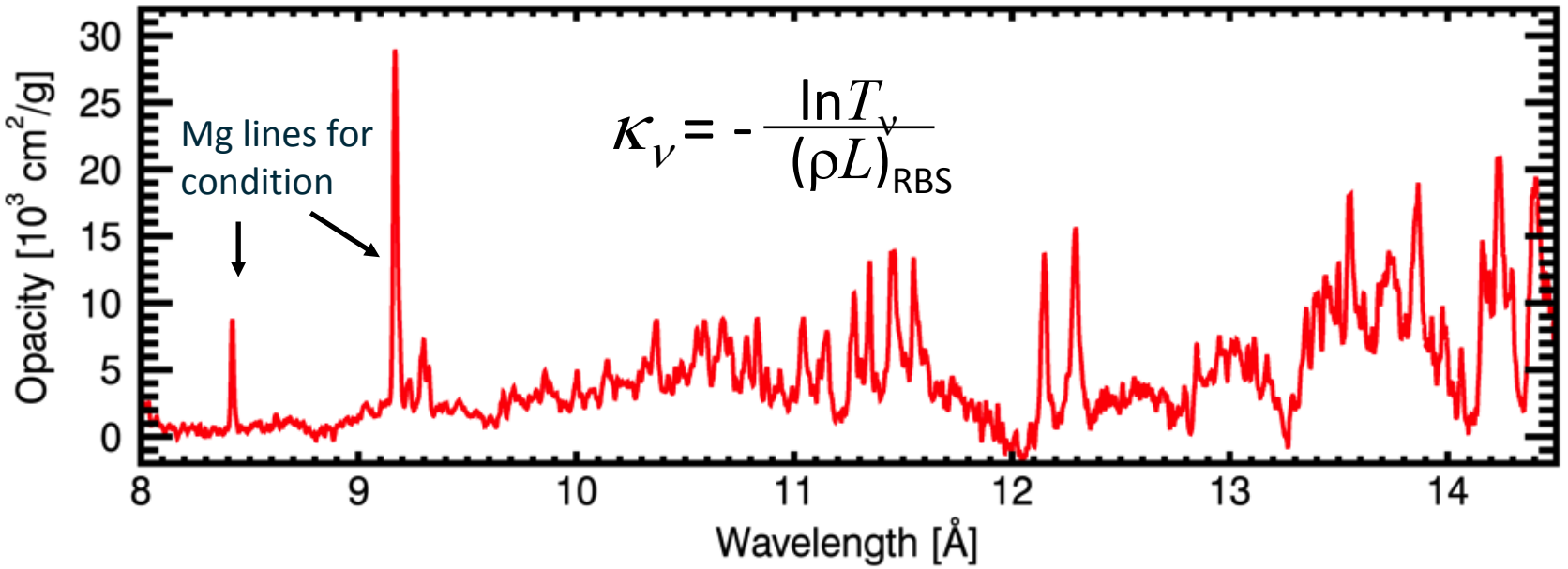

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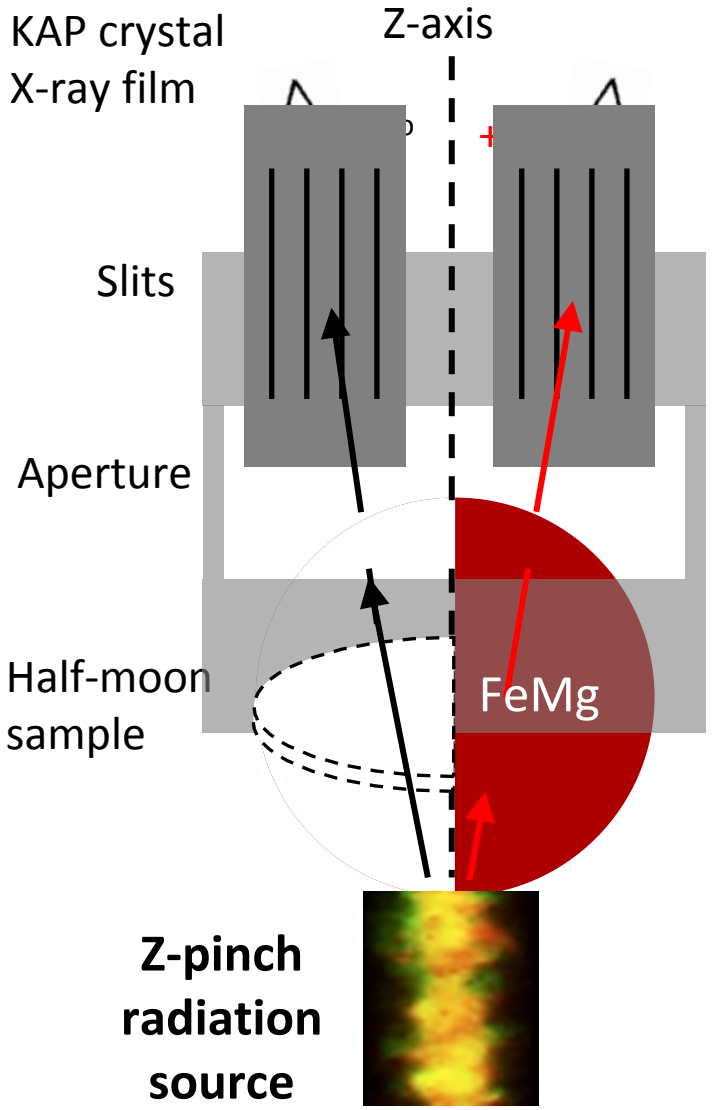

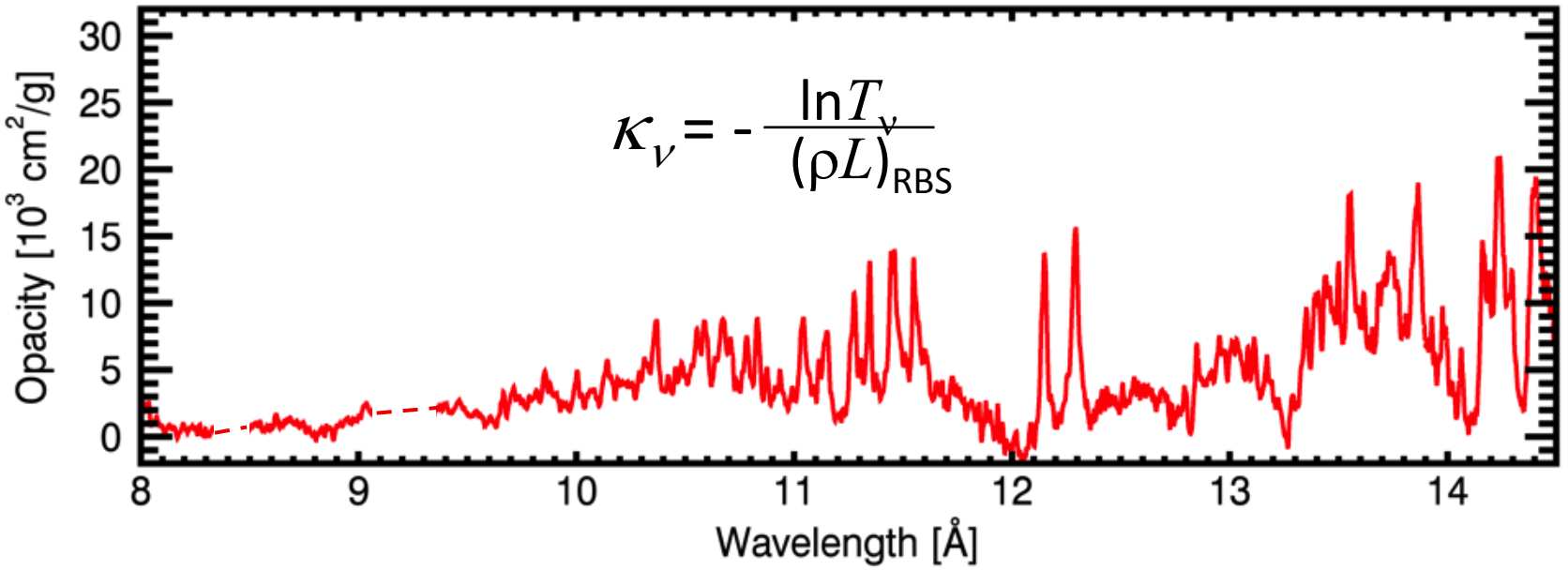

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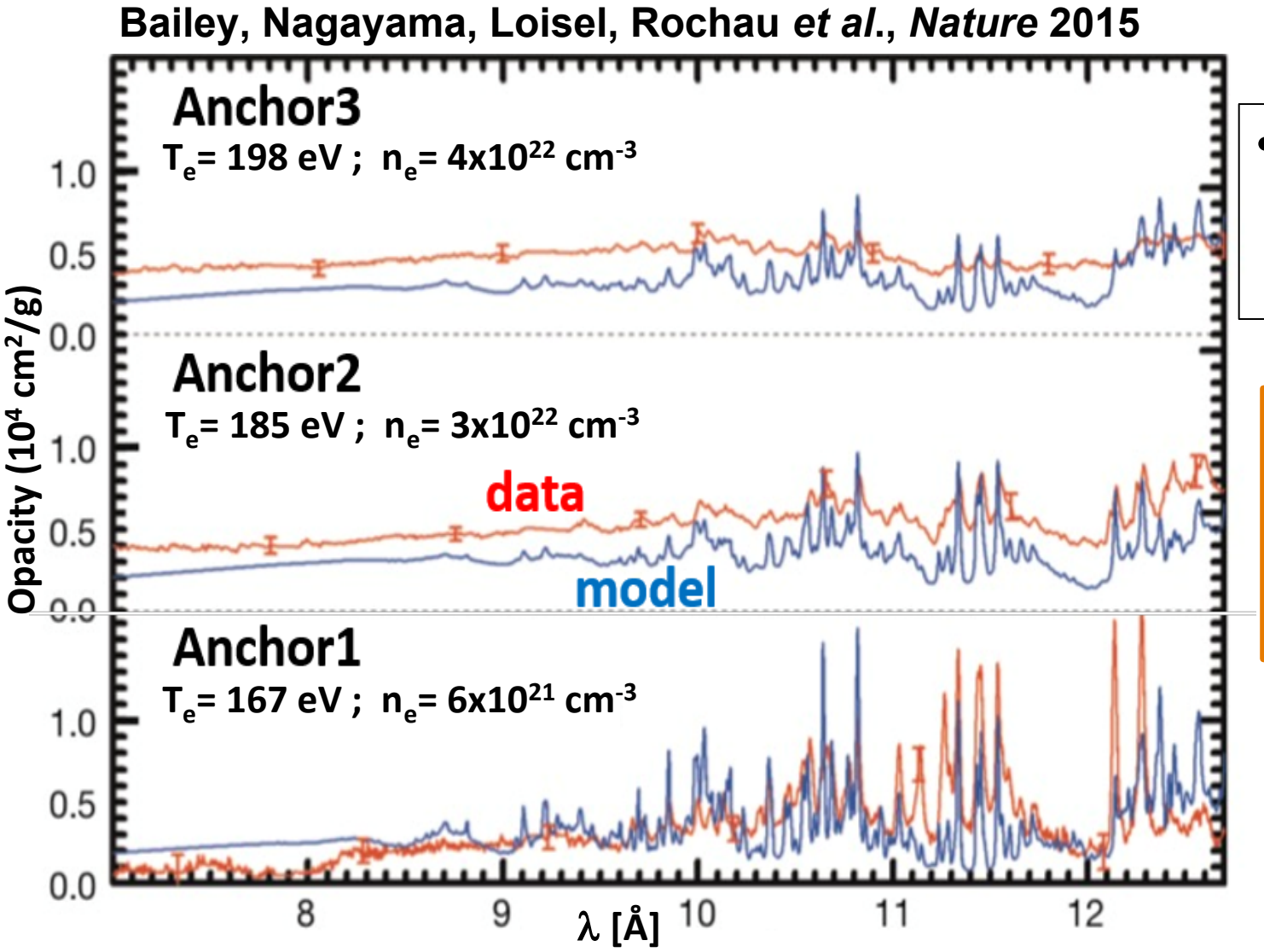
Calculated iron opacities are significantly lower than measurements as T_e, n_e approach solar interior values



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

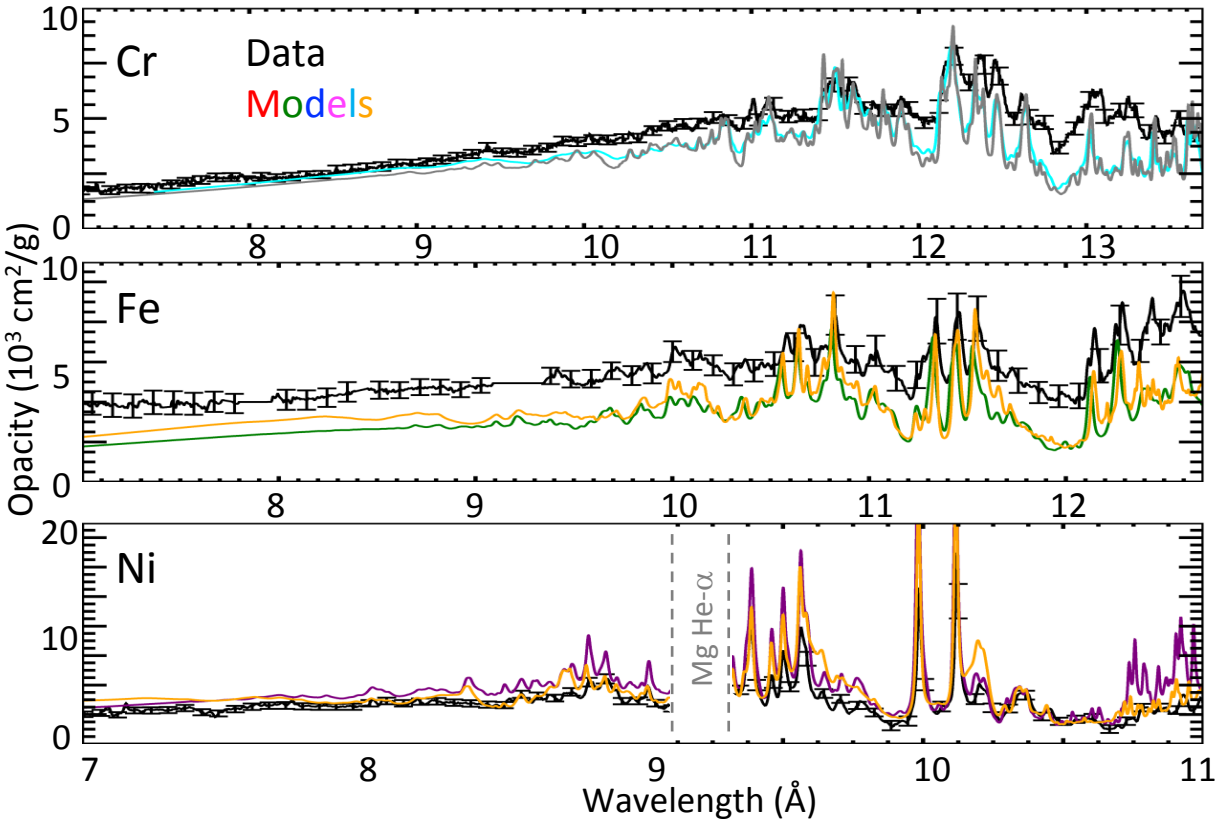
<u>But what's causing the discrepancy?</u>

- **Inaccuracy of theory?**
- **Flaws in experiment?**

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

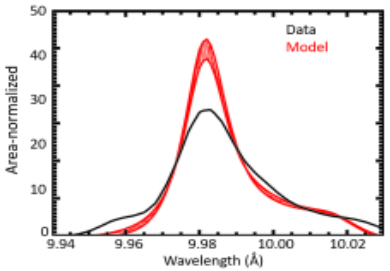
Systematic opacity measurements with Cr, Fe, and Ni identified three main opacity model-data discrepancies

Anchor2: $T_e \sim 180$ eV, $n_e \sim 30\times10^{21}$ cm^{-3}



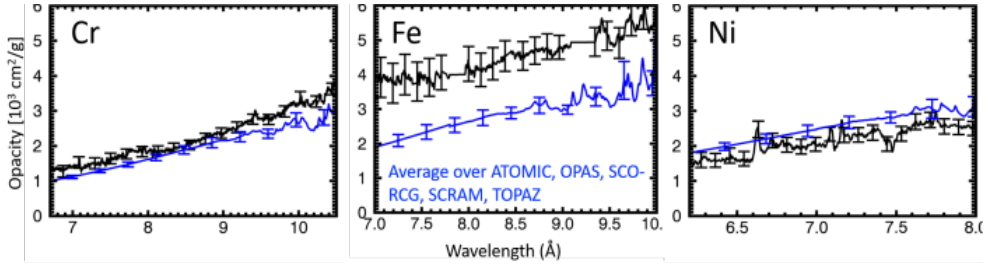
How models and data disagree …

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?

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Remaining 7 shots will help us accomplish more

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- Background [1]
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Theory:

- Line broadening [2,3]
- Two-photon opacity [4]

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- First oxygen x-ray opacity measurement
  - T_e=160 eV, n_e=8e21 e/cc (anchor1)
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- Prepared for anchor2 but not performed

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Despite of the significant progresses, more work needed to resolve the solar problem

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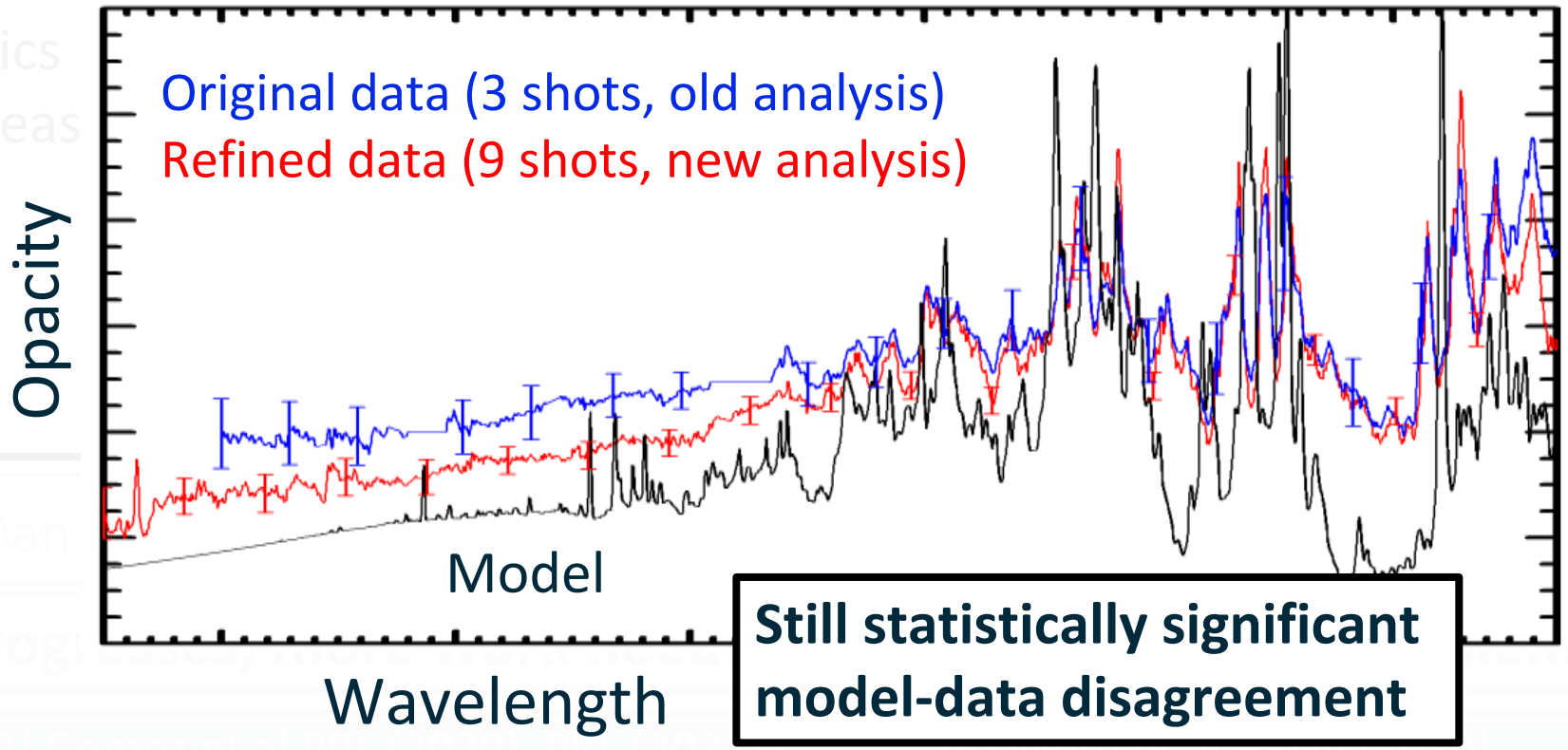
Result from last ZFS workshop



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Time resolved measurements are attractive for three reasons

1. Experimentally test the temporal gradient effects

2. Understand and refine our experiments

3. Perform time-resolved opacity experiments

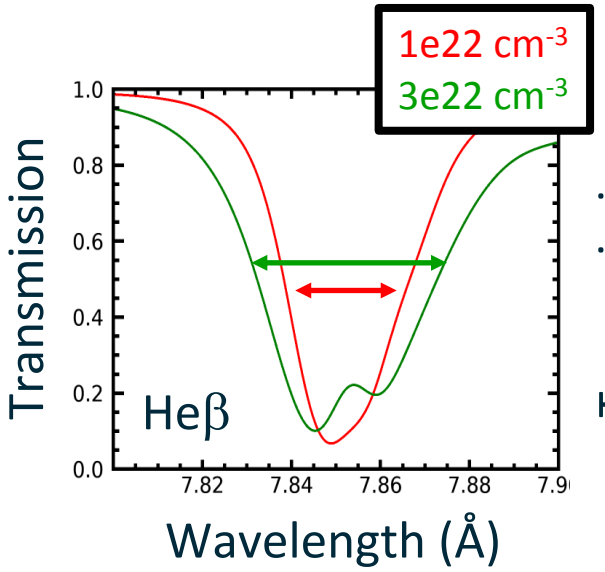
i. Minimize temporal gradient concern
ii. Fe opacity at multiple conditions from a single experiment
iii. Fe opacity at higher temperature and/or density

Let's adopt Sandia Ultra-fast X-ray Imager (UXI) to our experiments

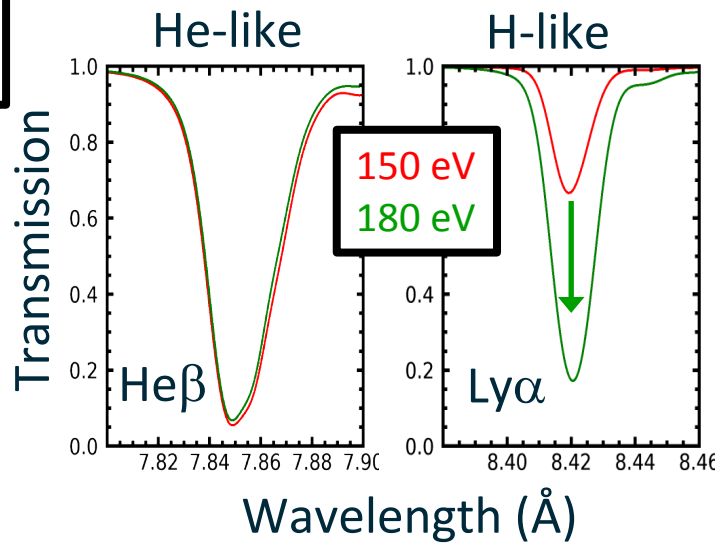
Two UXI cameras were successfully installed to record up to 16 frames

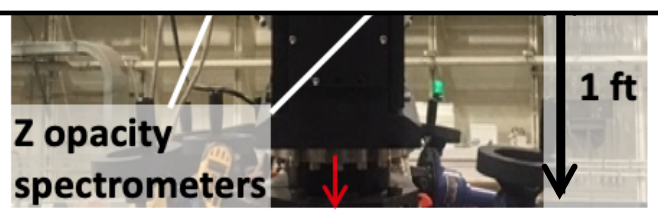
Mg K-shell spectroscopy

Density from line width



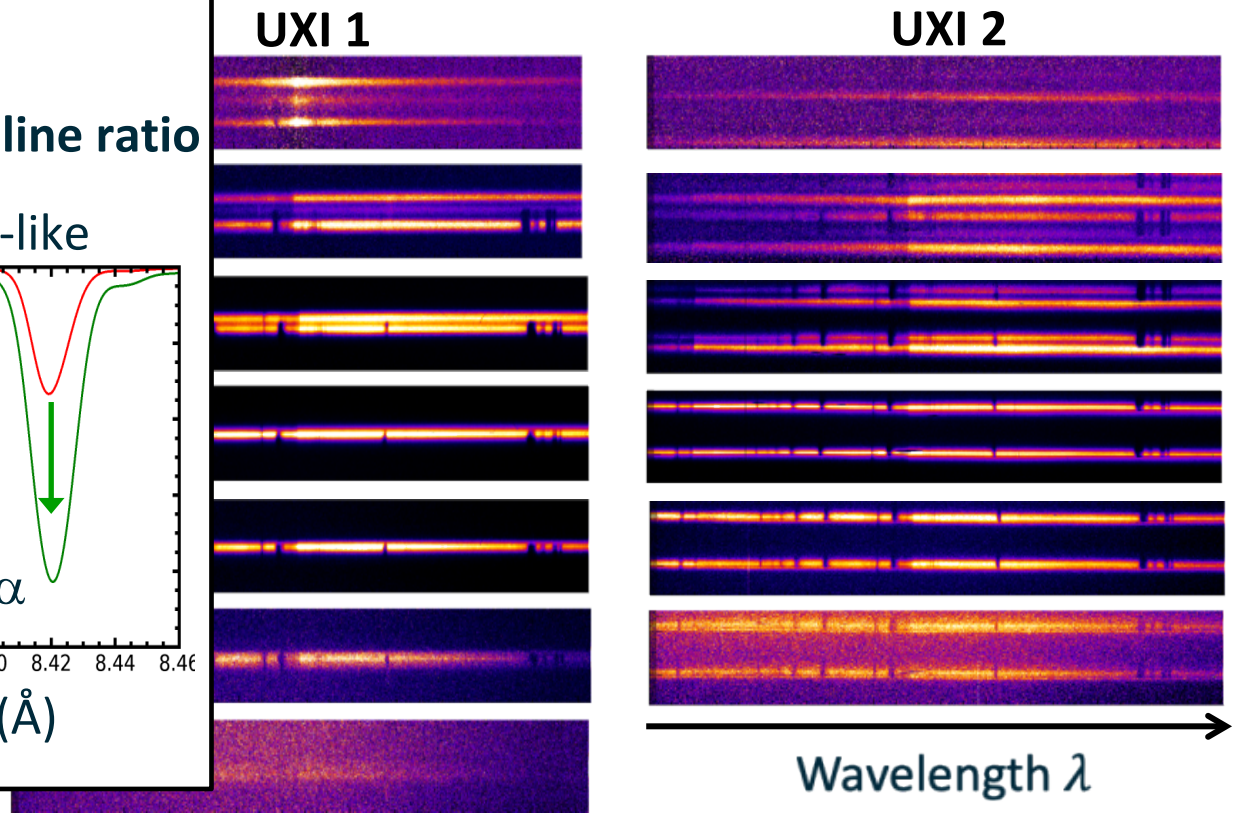
Temperature from line ratio





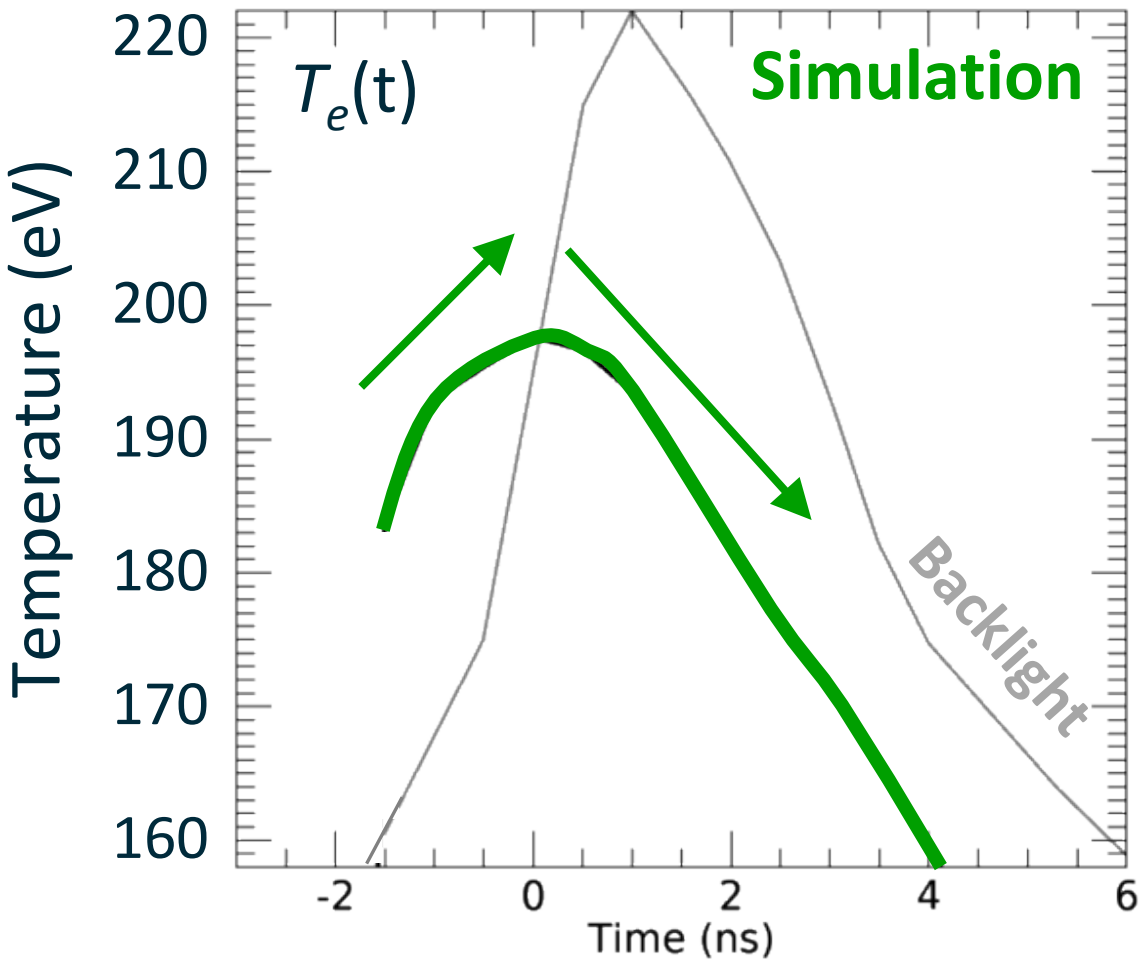
to
x-ray source

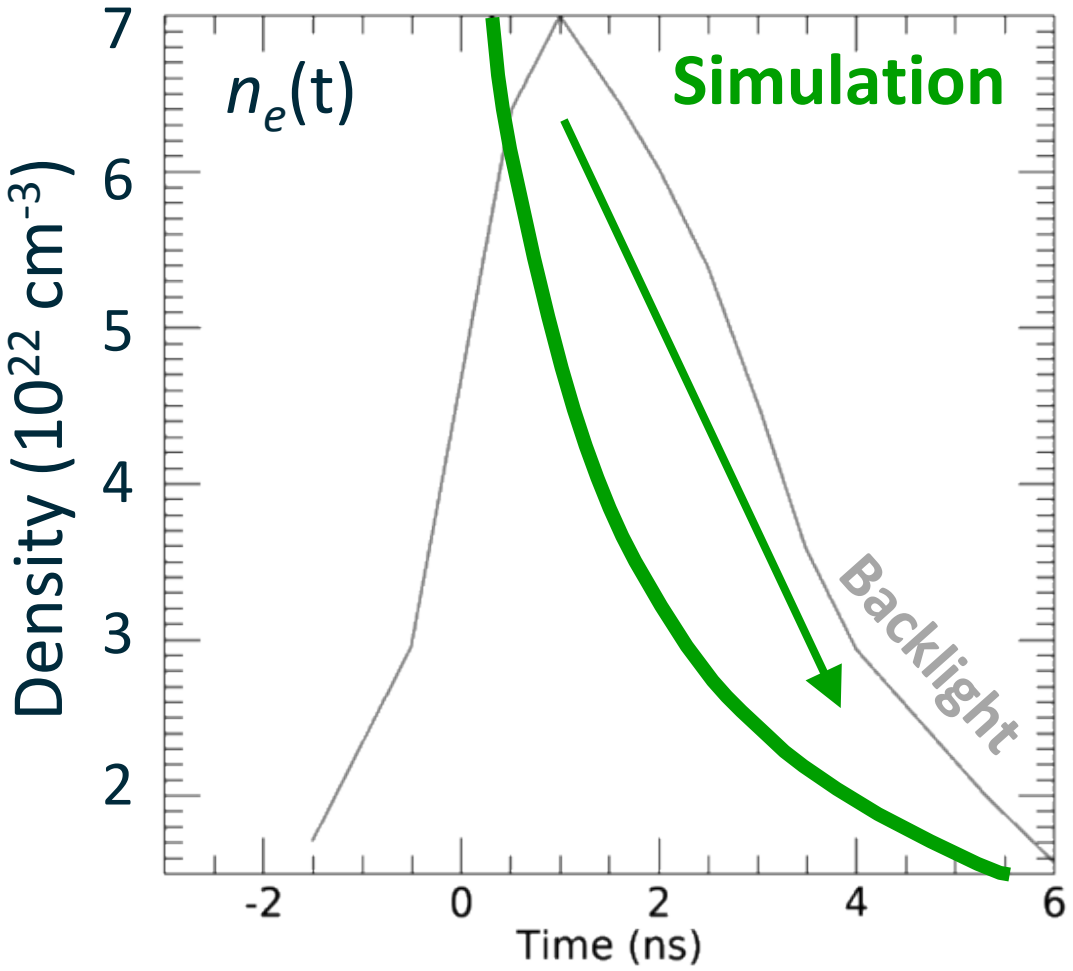
Anchor 1 Fe



We can study how FeMg sample was heated by analyzing time-resolves Mg spectra

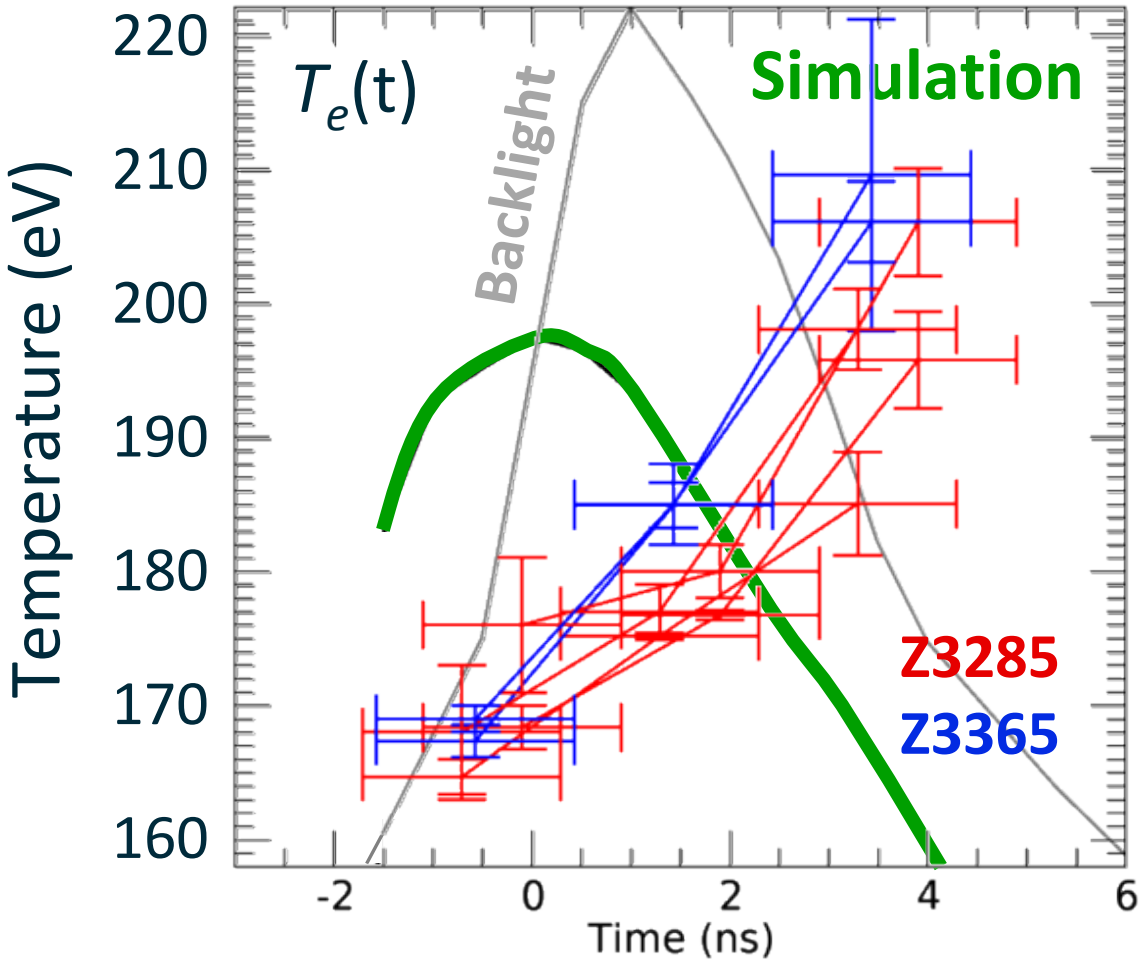
Simulations* predicted that sample temperature goes up and down while density monotonically decreases

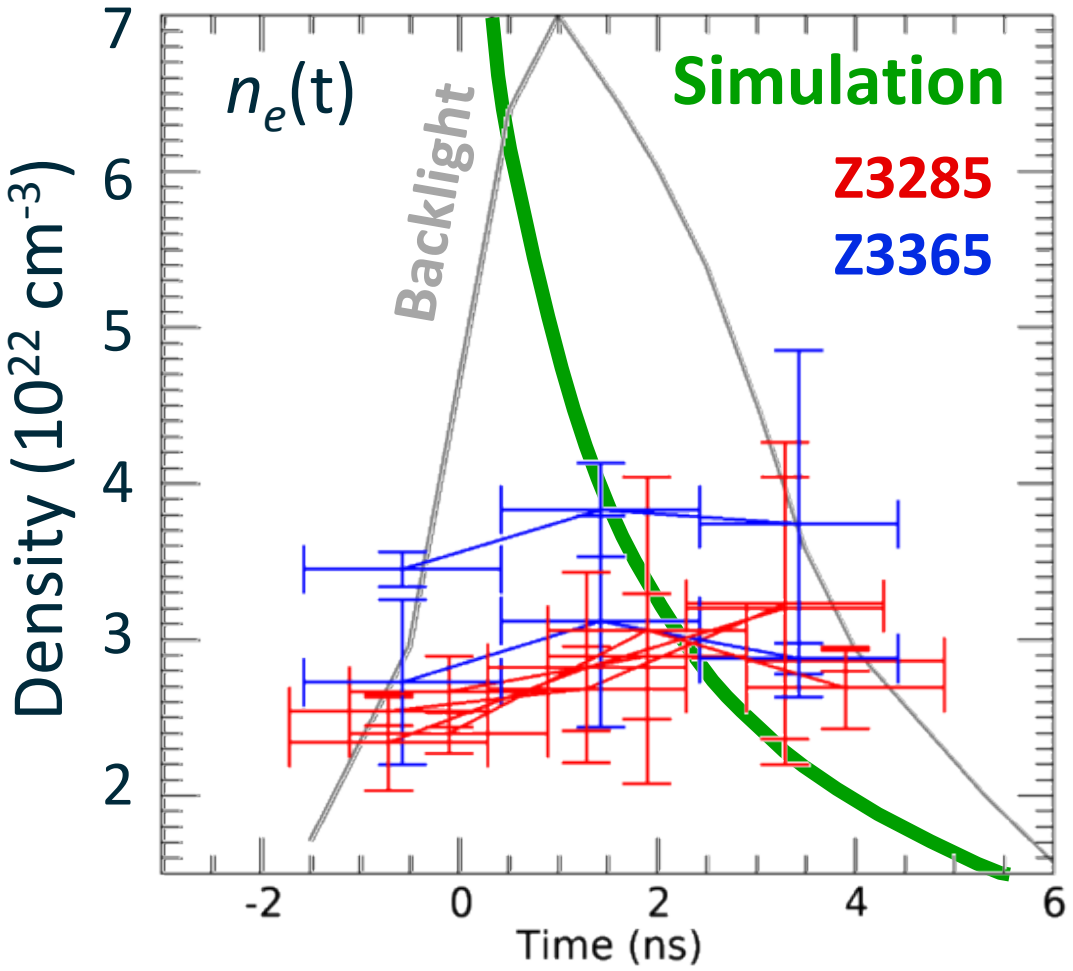




* Nagayama et al PRE (2016)

Time-resolved measurement suggested different sample evolution





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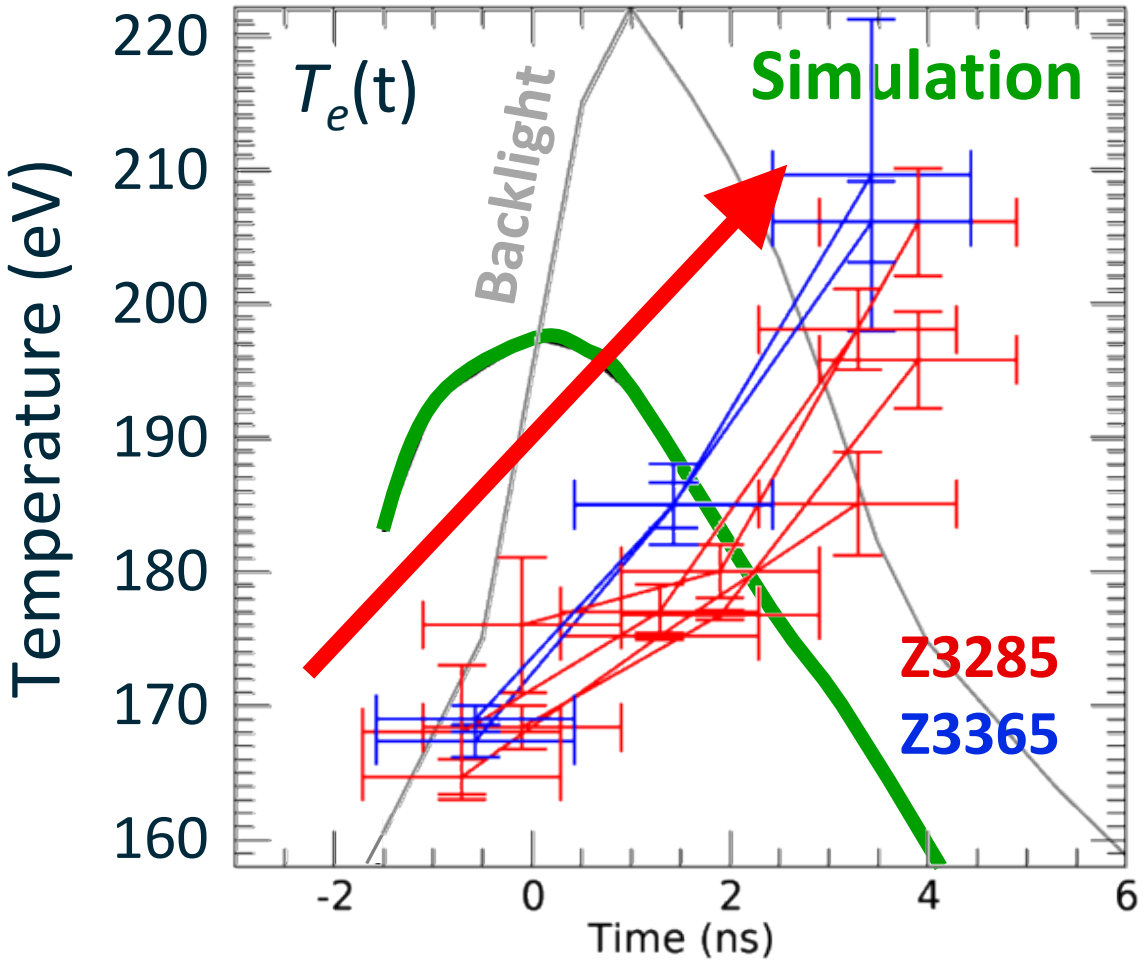

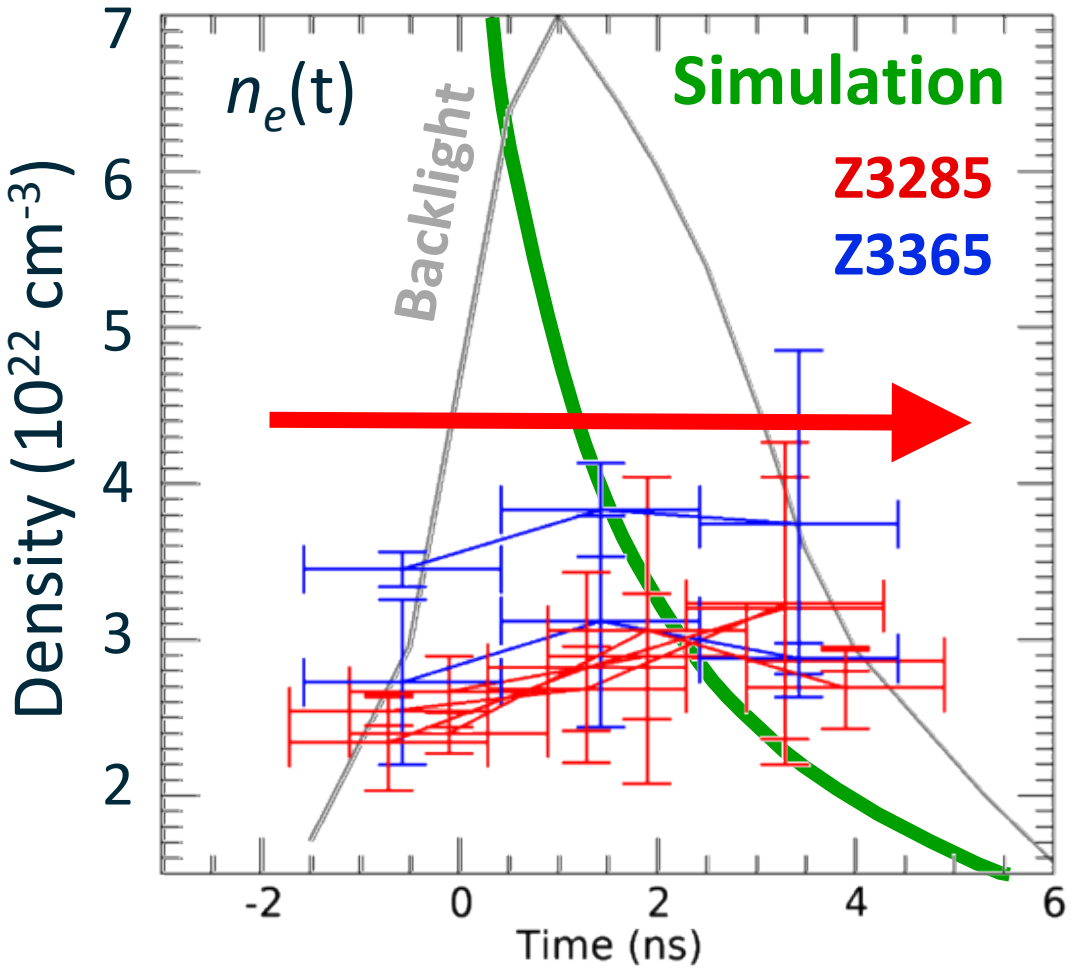

Temperature: Monotonically increasing → Is the sample approaching to the Z pinch?

Density: Constantly low → Is the sample expanded much earlier? Preheat?

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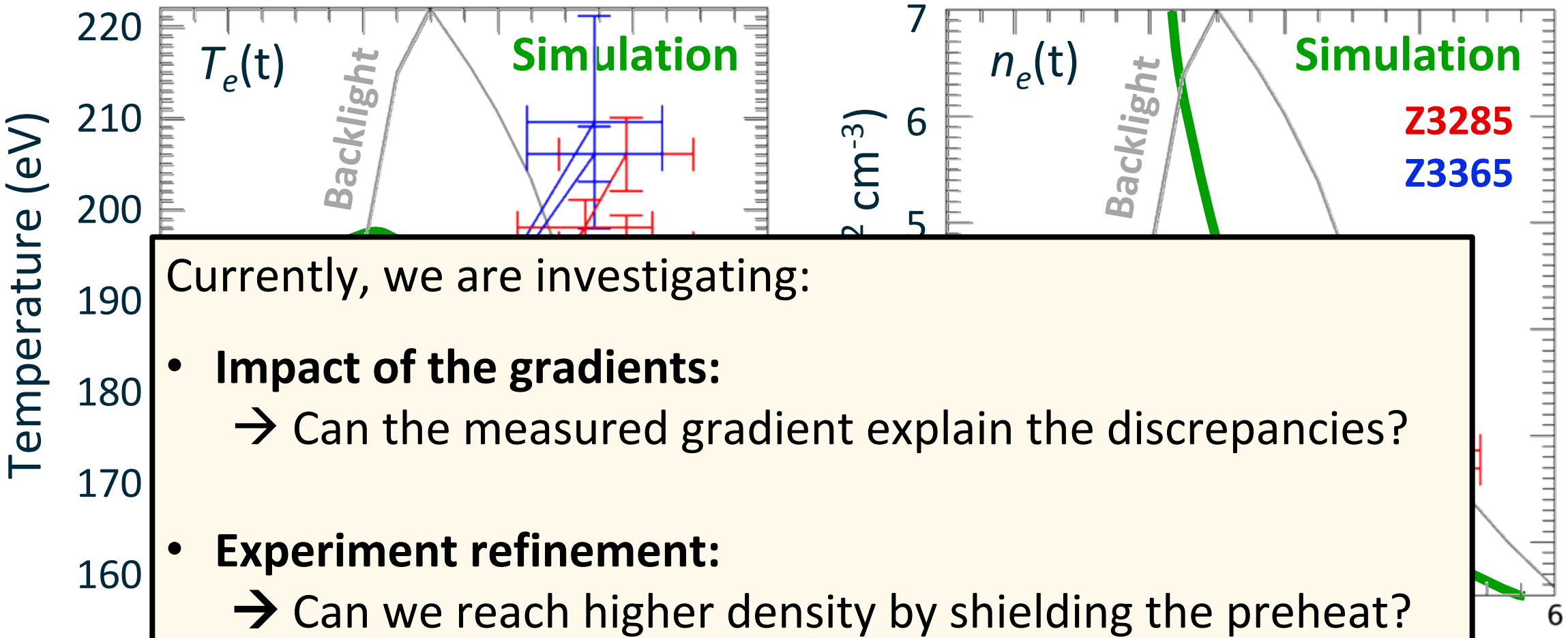

Currently, we are investigating:

- **Impact of the gradients:**
  → Can the measured gradient explain the discrepancies?
- **Experiment refinement:**
  → Can we reach higher density by shielding the preheat?

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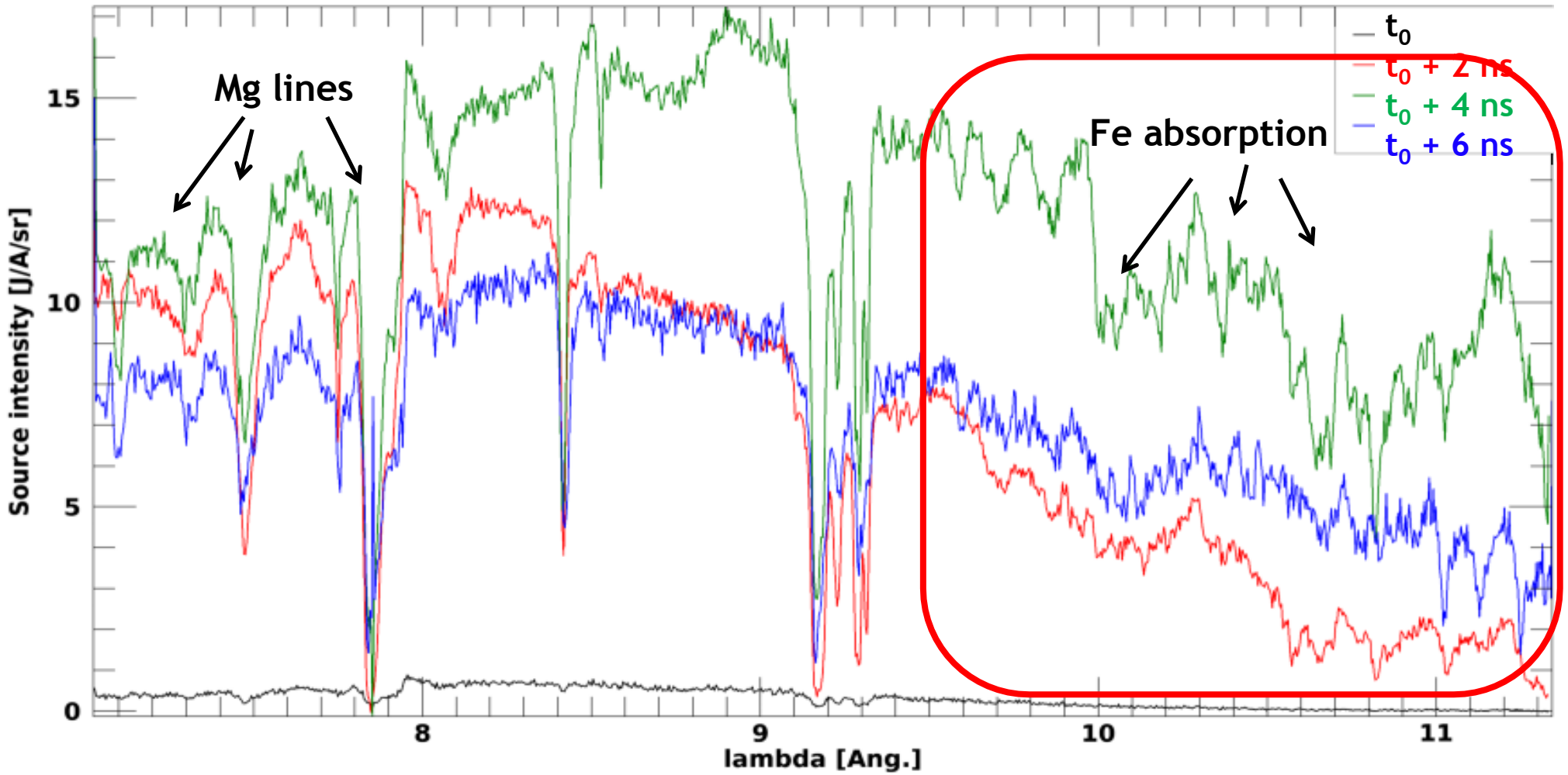
We moved UXI cameras at regular spectrometer positions and successfully measured time-resolved Fe absorption spectra



variation in shape of features

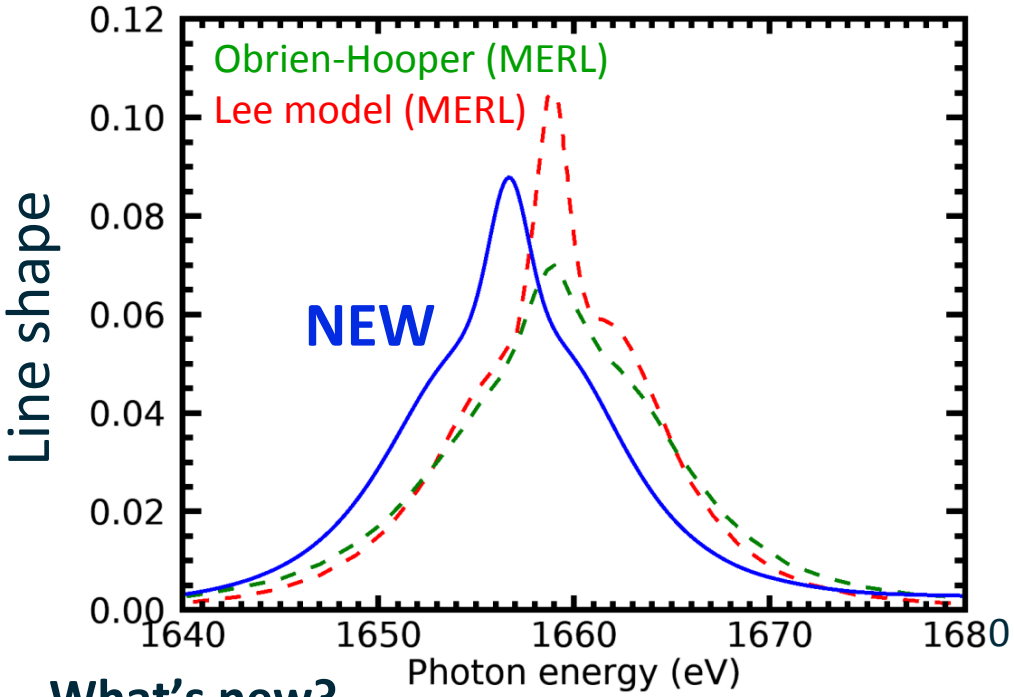
Time-resolved opacity determination requires a large volume of time-resolved calibration data

Two relevant theories were scrutinized and refined significantly for resolving the Fe model-data discrepancies

Spectral line broadening [1,2]

→ Plasma diagnostics

→ BB line-width discrepancy

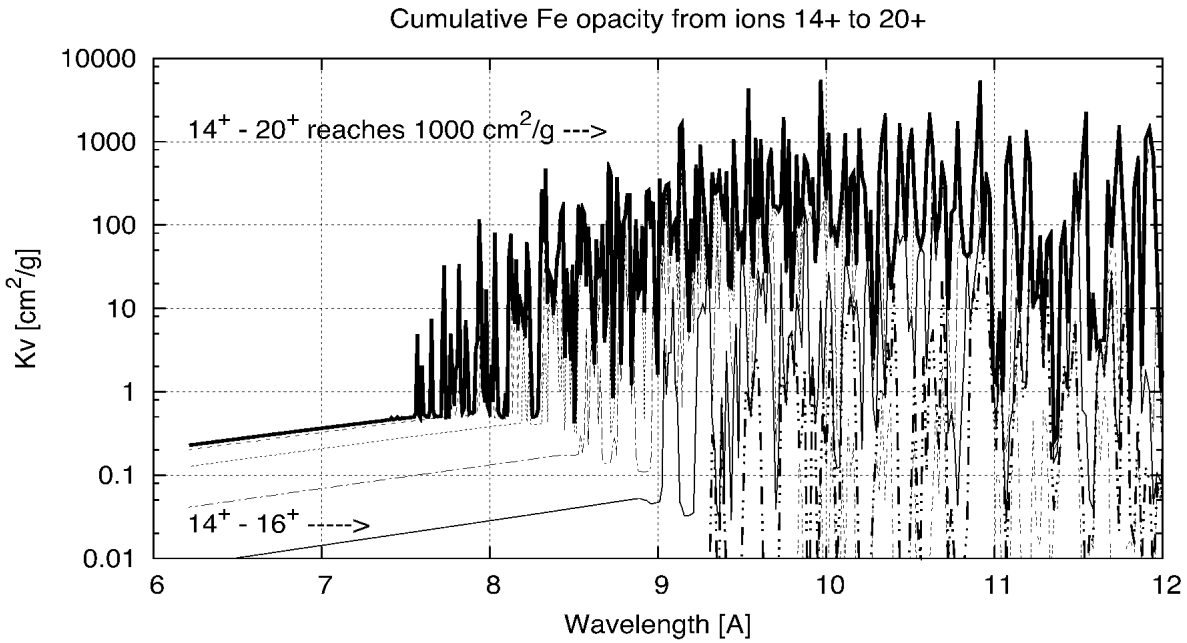


What's new?

- Electron capture [1]
- Remove 3 approximations [2]

Two-photon opacity [3]

→ BB, BF discrepancies



What's new?

- Omitted from existing opacity models
- Performed most complete calculations ever

[1] Gomez et al PRL (2021). [2] Gomez et al submitted to PRL (2021). [3] More et al HEDP (2020)

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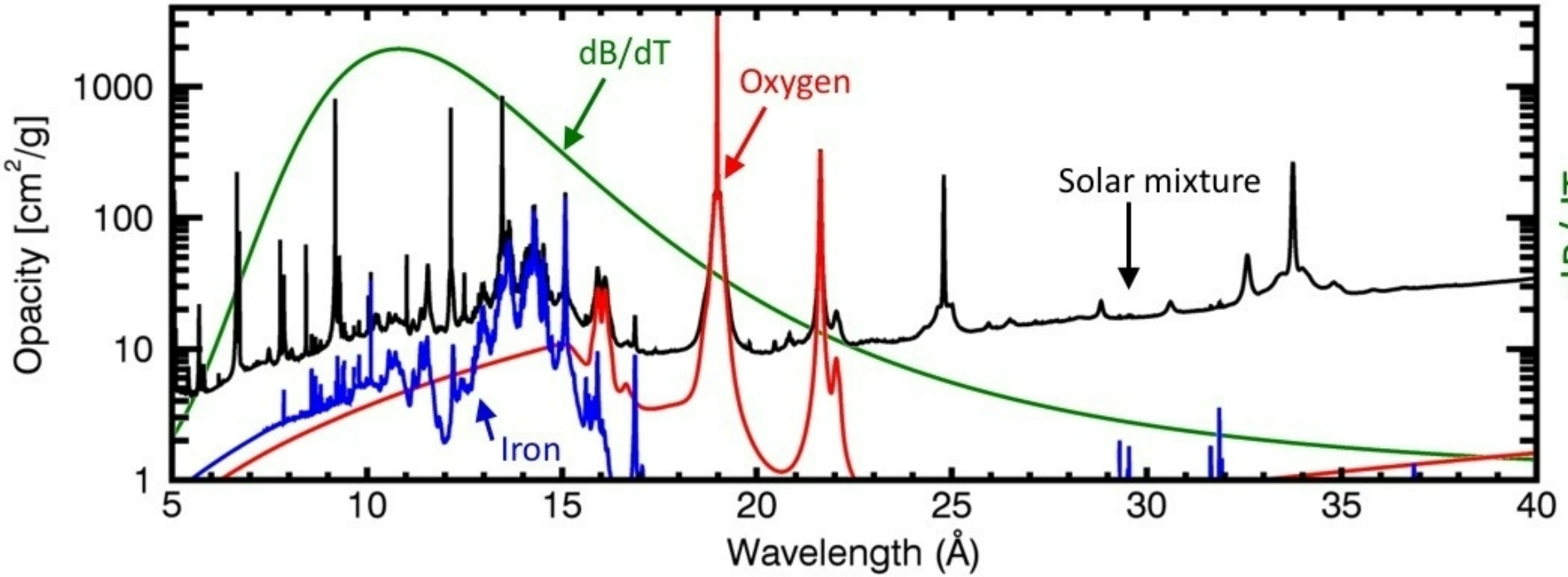
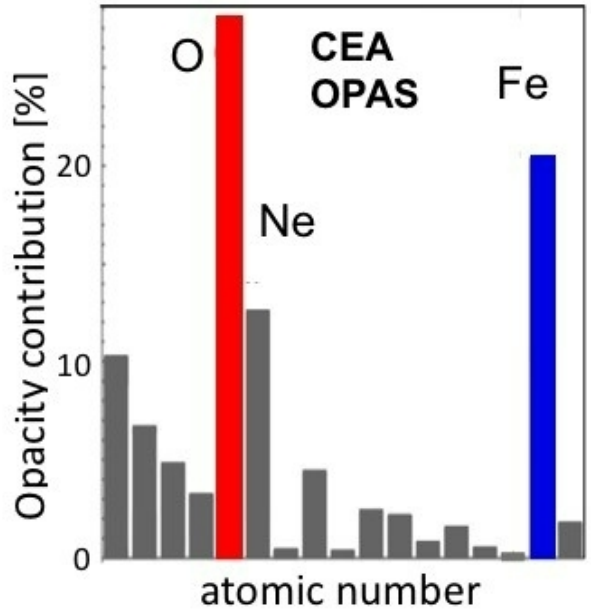
Oxygen opacity measurements are essential to resolve the solar problem



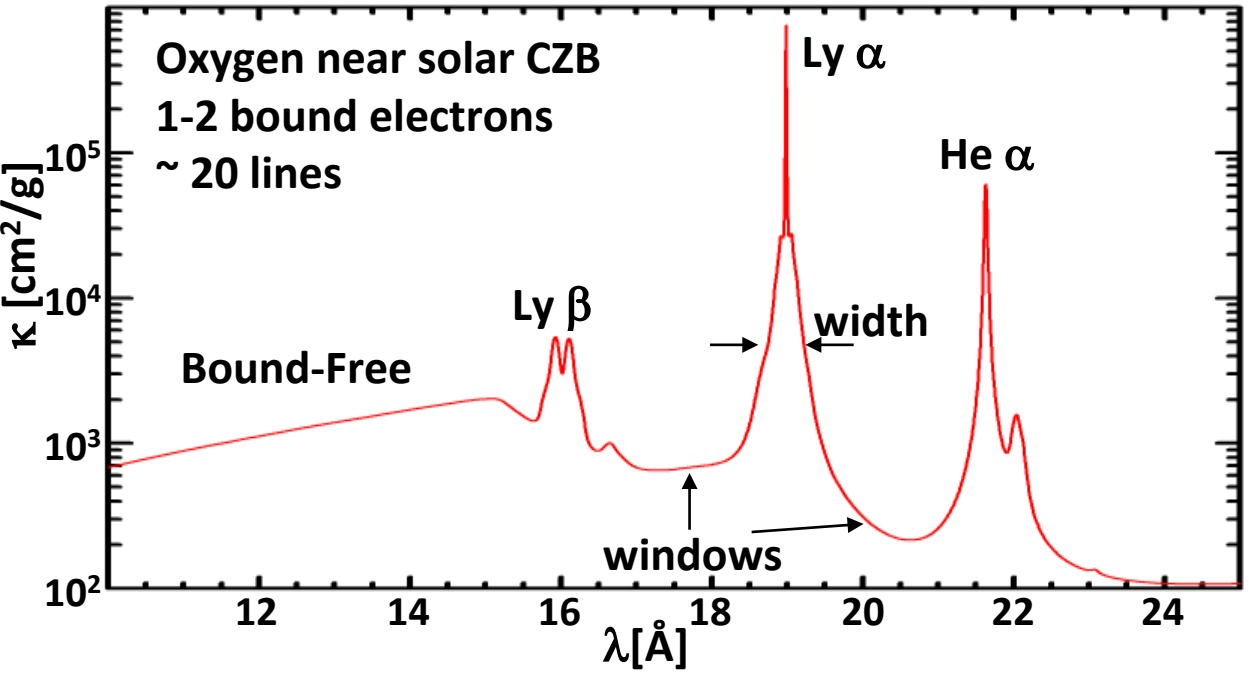


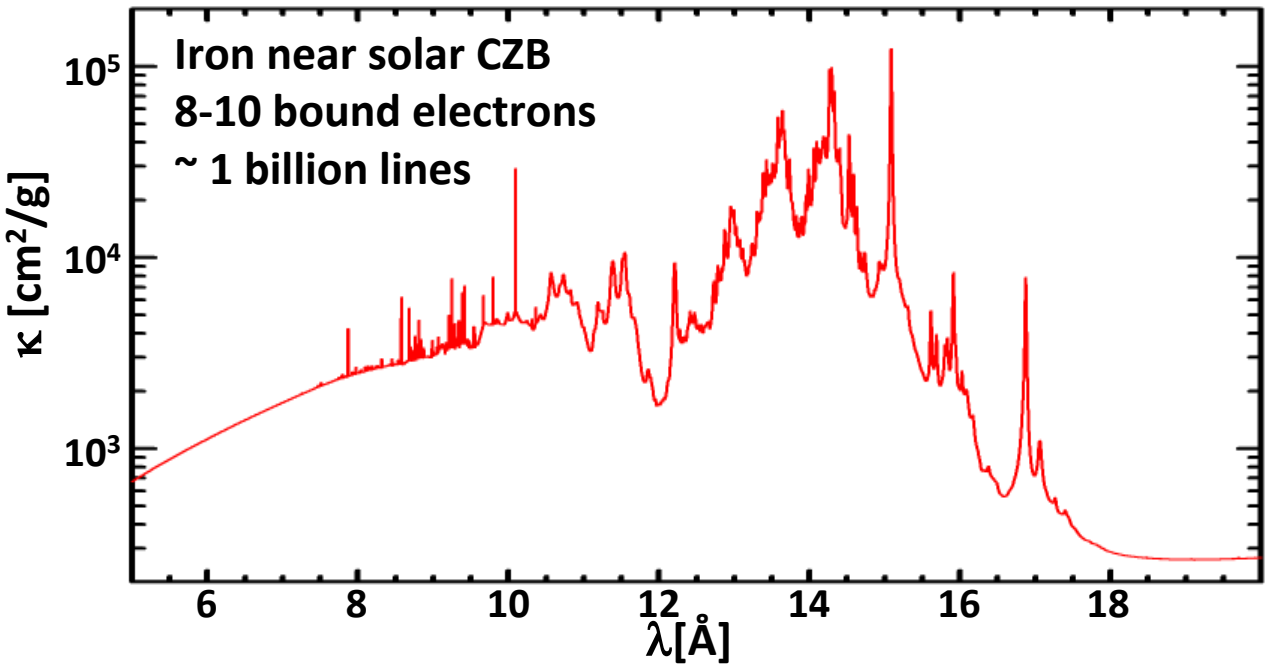
If oxygen measurements are lower than models predict, it could partially cancel the improved agreement between solar models and helioseismology resulting from past Z iron opacity experiments [Bailey *et al.*, *Nature* 2015]

If oxygen measurements are higher than predicted, it will further help resolve the solar problem

Basu and Antia, *Phys. Reports* 2008; Serenelli, *ApJ* 2009; Blancard ApJ 2012; Seaton MNRAS 1994

Oxygen opacity spectra are relatively simple, but strongly affected by approximations for plasma density effects





Important physics:
- Opacity window
- Bound-free opacity

Important physics:
- Billions of bound-bound line features
- Bound-free opacity

Bare atoms have no bound-bound and bound-free opacity

→ Oxygen opacity is strongly affected by small ionization changes

Seaton MNRAS 1994; Badnell MNRAS 2005; Mendoza 2007

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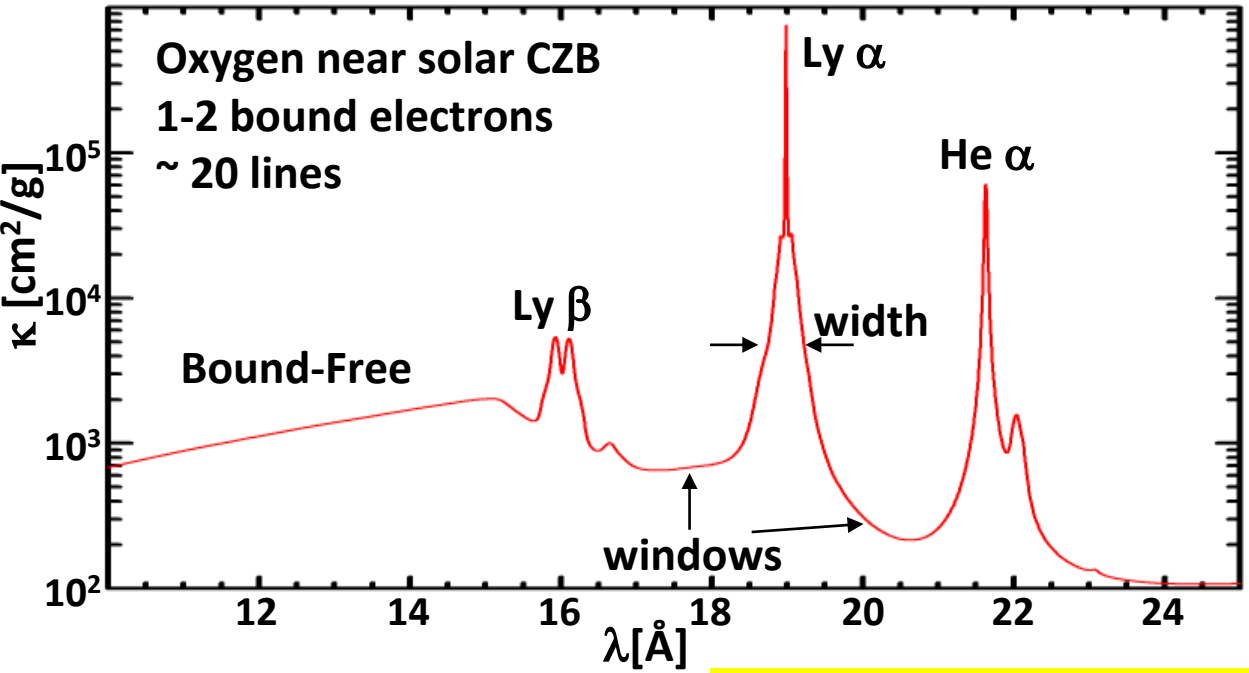

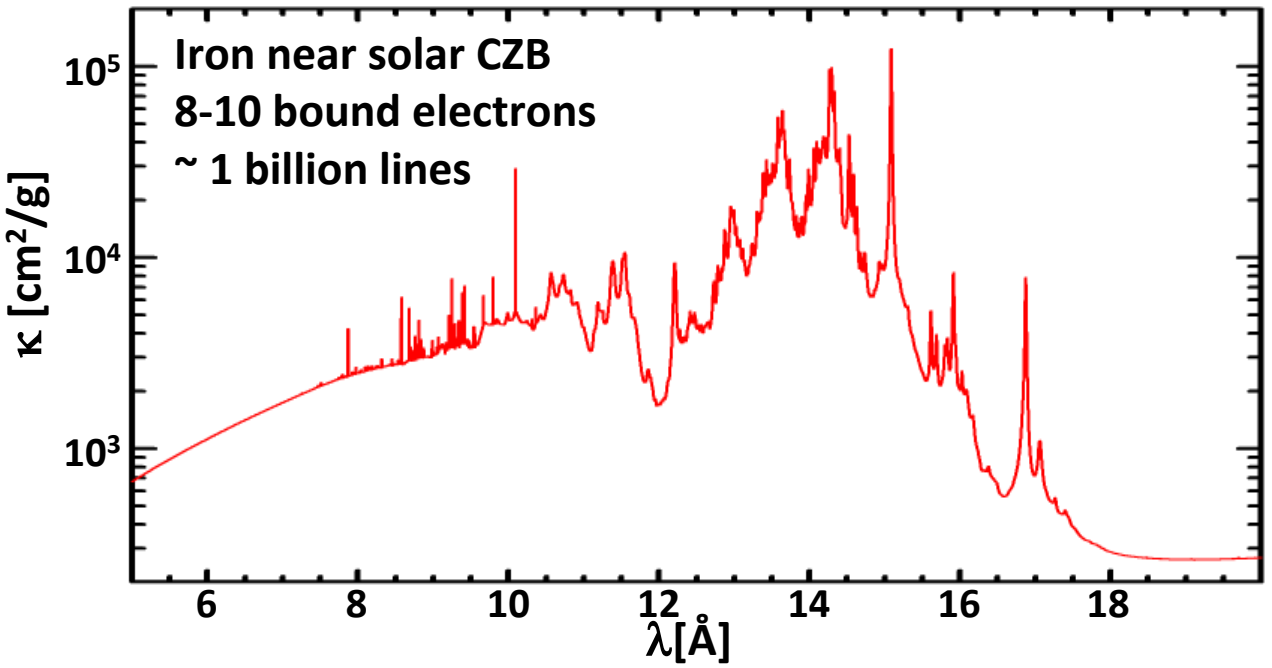

Important physics:
- Opacity window
- Bound-free opacity

Affected by density effects
- Line-broadening
- Ionization potential depression
- Occupation probability

Important physics:
- Billions of bound-bound line features
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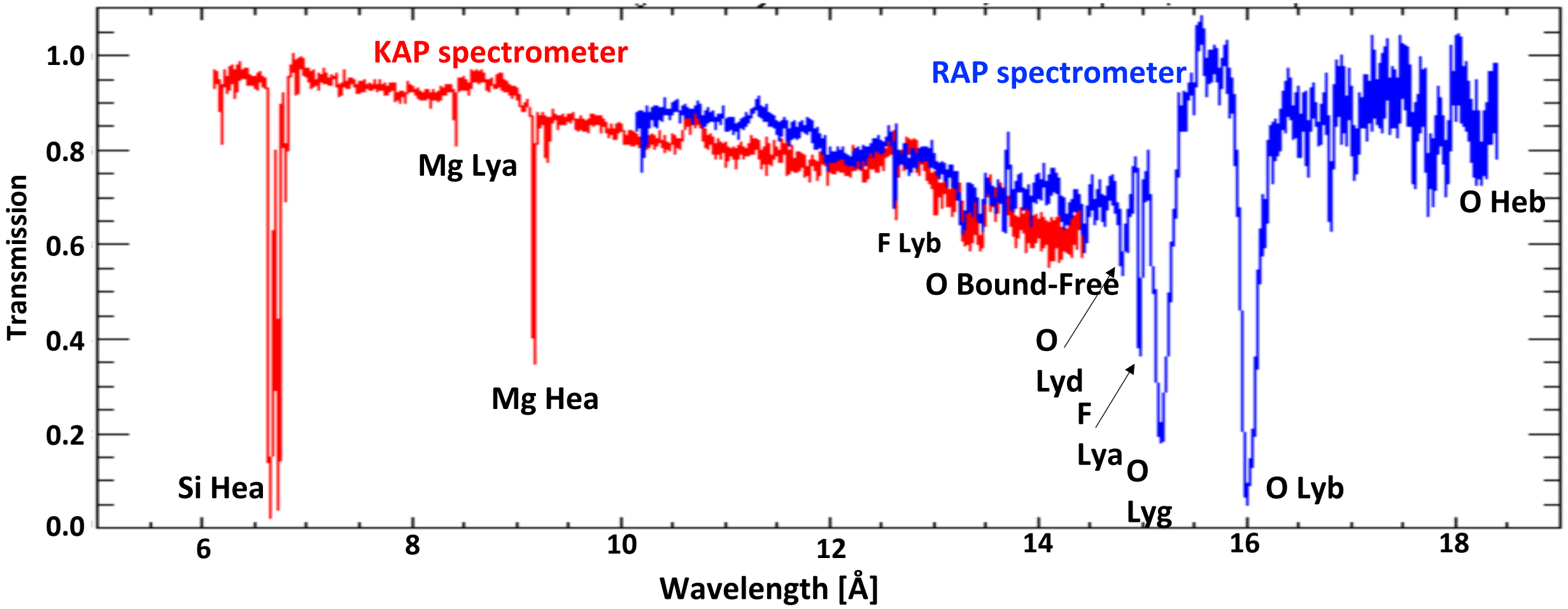
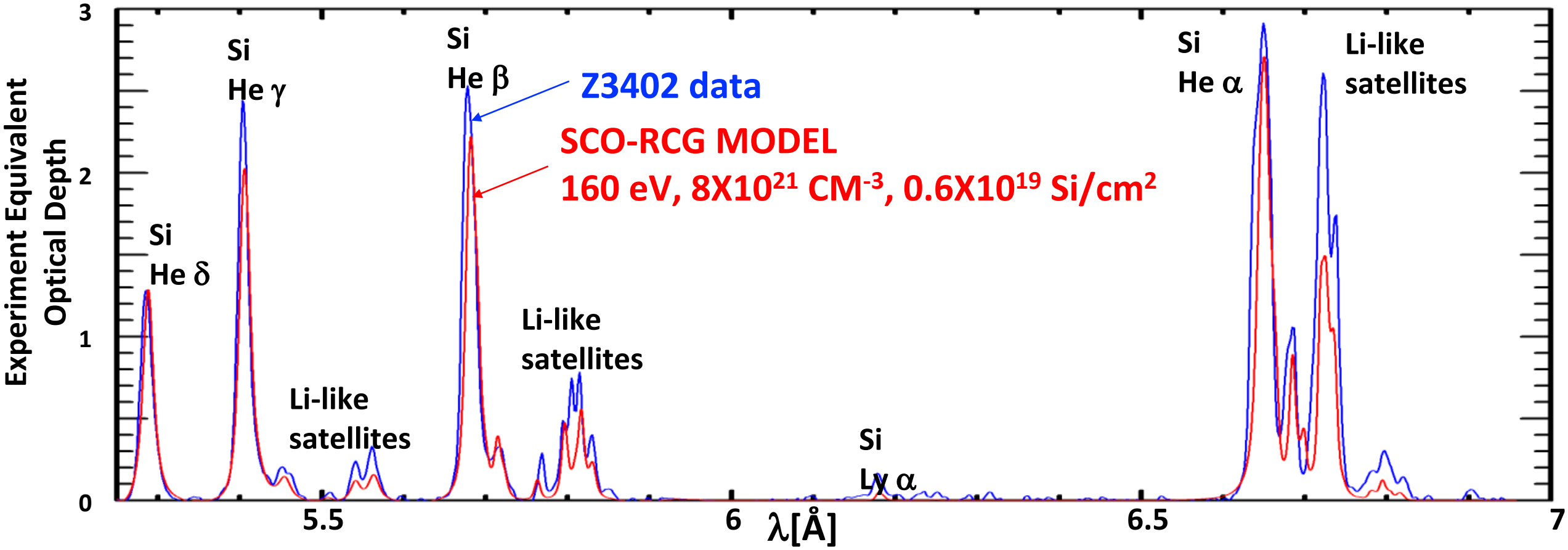
Oxygen and silicon transmission spectra were successfully measured



Accurate opacity is only obtained for T ~ 0.15-0.85

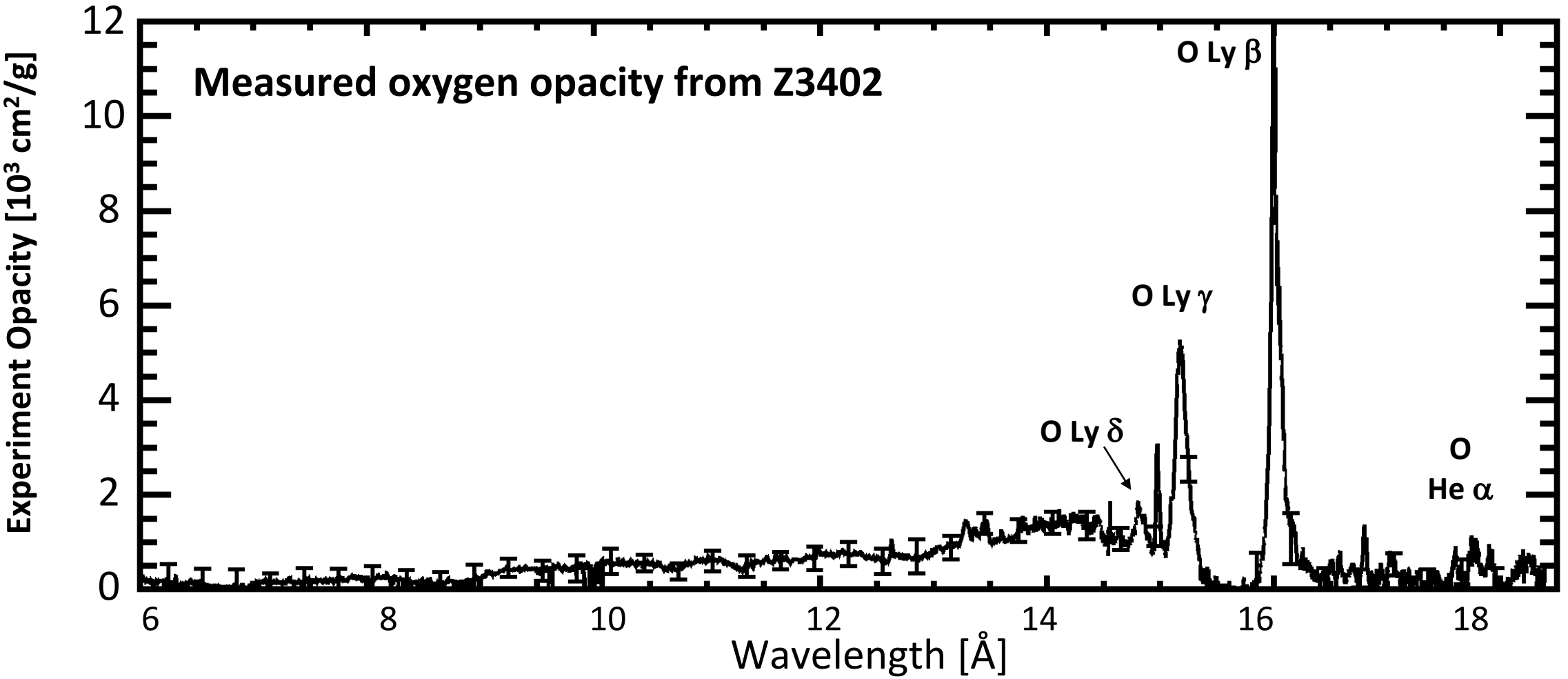
Preliminary plasma conditions inferred from Si lines were T_e ~ 160 eV and n_e ~ 8x10^{21} cm^{-3}



n_e: Si He δ line broadening, T_e: He-like/Li-like Si line ratios, ratios of Li-like satellites

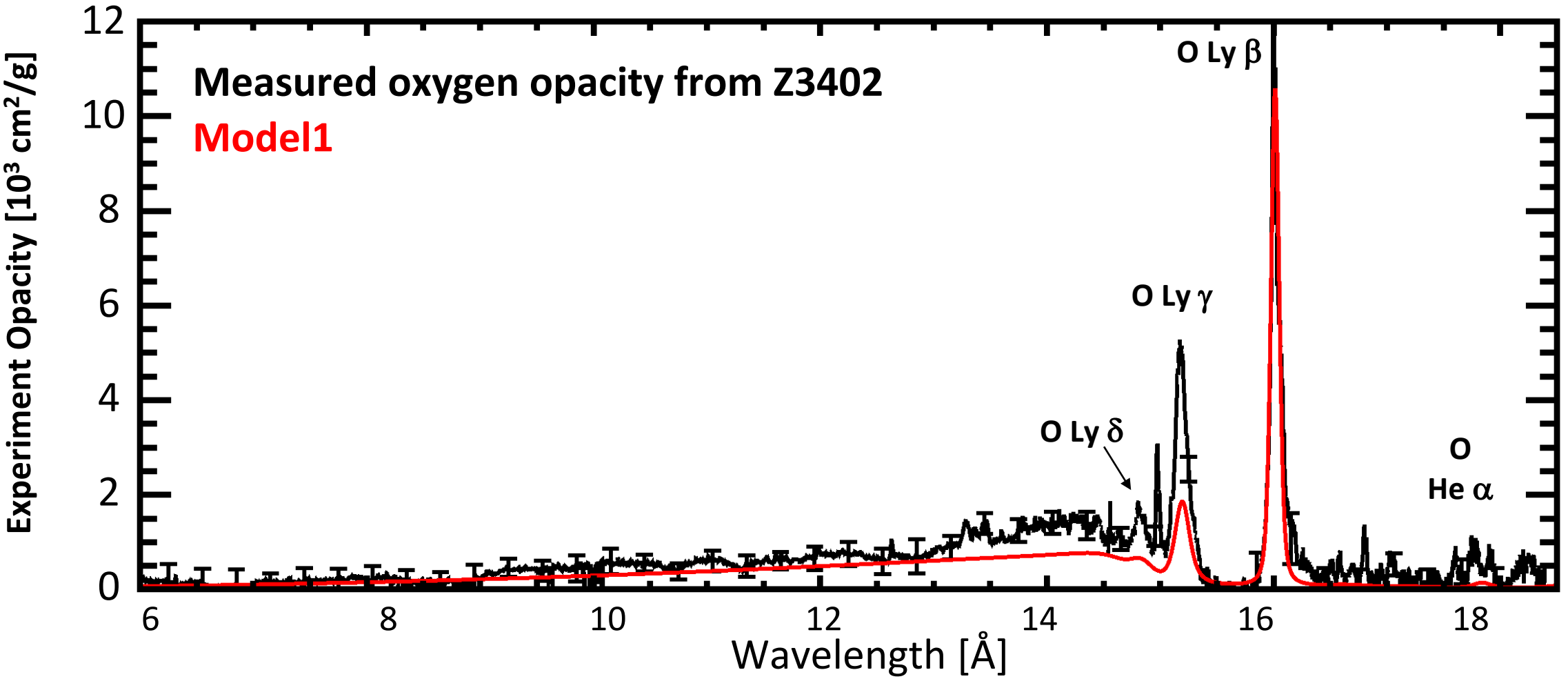
Plasma condition needs to be re-analyzed by using the refined line shapes and by accounting for model uncertainties.

Oxygen opacity inferred with roughly +/-20% uncertainty in 11-15.5 Å range; Recent experiments will check the reproducibility



Two additional experiments were performed in October 2020, analysis underway

Preliminary oxygen opacity measurements may provide useful model tests, even at initial Te &ne that are below the solar values



Future experiments will examine reproducibility, quantify uncertainties, and extend measurements to higher Te and ne

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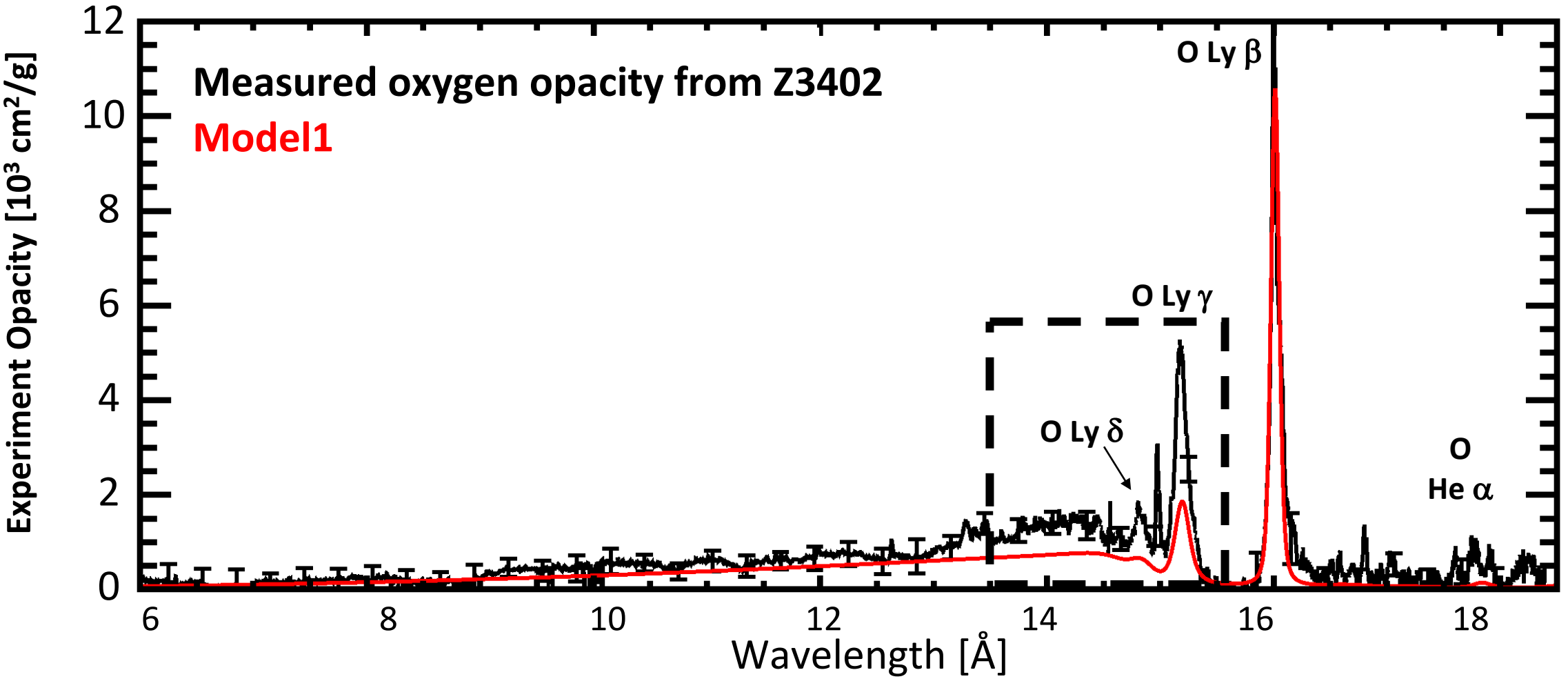
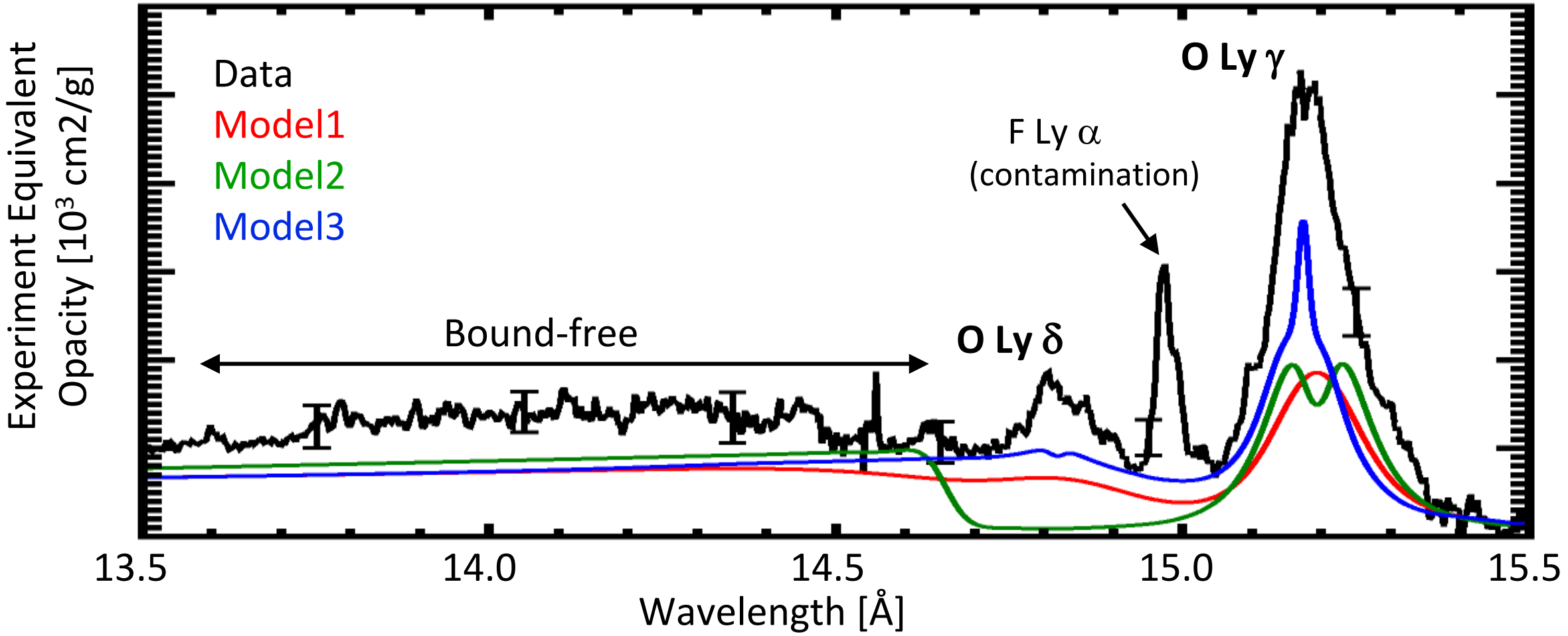


Future experiments will examine reproducibility, quantify uncertainties, and extend measurements to higher Te and ne

Preliminary oxygen opacity measurements show significant disagreement in line shapes and bound-free features



Future experiments will examine reproducibility, quantify uncertainties, and extend measurements to higher Te and ne

Last two years: We made significant progresses by re-scrutinizing Fe results, measuring first O opacity, and recruiting young scientists

Revisiting Fe results:

Remaining 7 shots will help us accomplish more

Experiments:

- More experiments for Fe at anchor2, 3 [in prep.]
- Time-resolved measurements
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  - Fe absorption measurements

Analyses:

- Opacity [in prep.]
- Background [1]
- T_e and n_e [in prep.]

Theory:

- Line broadening [2,3]
- Two-photon opacity [4]

First O opacity

- First oxygen x-ray opacity measurement
  - T_e=160 eV, n_e=8e21 e/cc (anchor1)
  - 3 shots with different O amount
- Prepared for anchor2 but not performed

Successful recruiting: Dan Mayes (postdoc), Malia Kao (grad. student)

Despite of the significant progresses, more work needed to resolve the solar problem

[1] Dunham et al RSI (2021) [2,3] Gomez et al PRL (2020), PRL (2021)? [4] More et al HEDP (2020)

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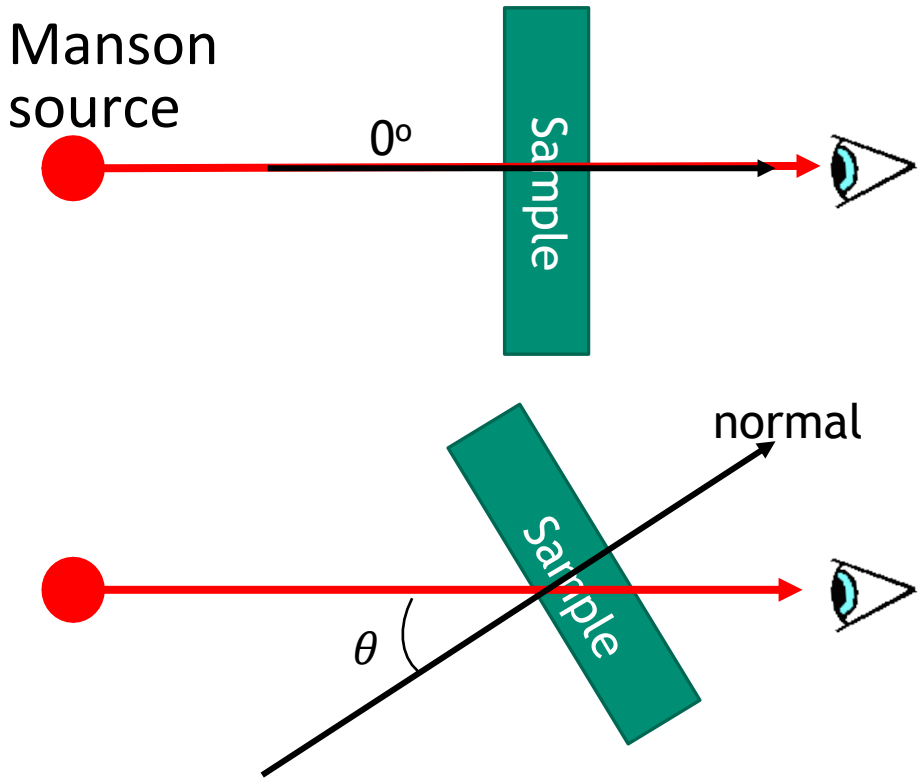
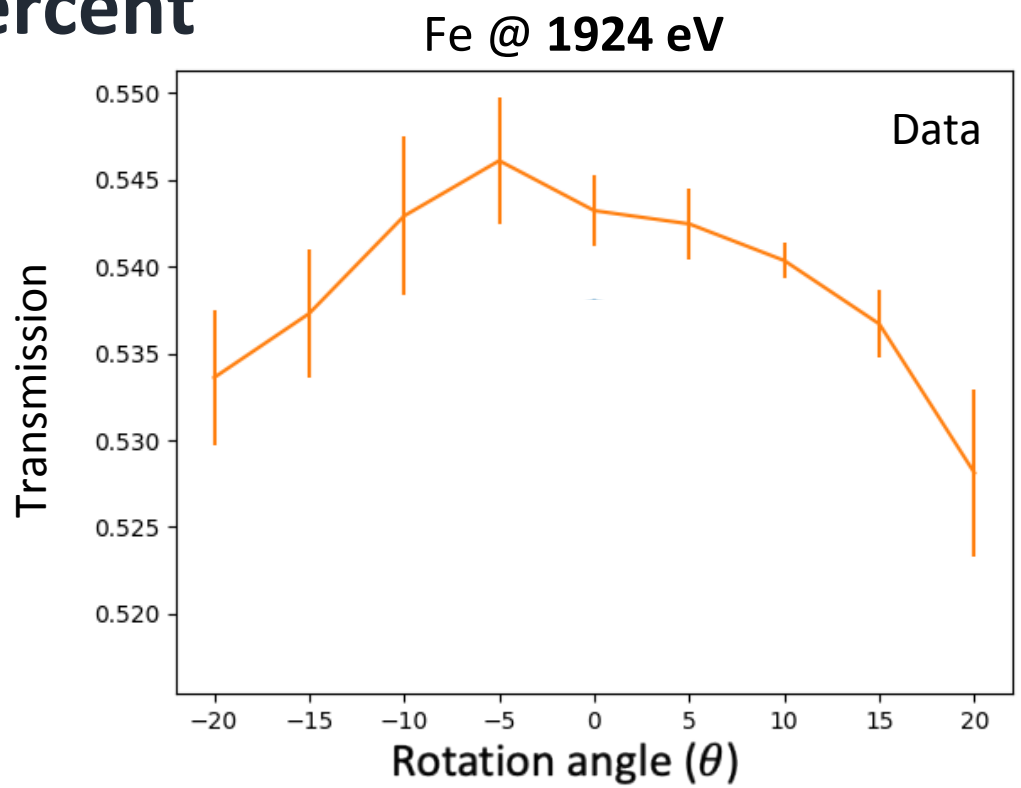
Student: Malia Kao successfully measured room-temperature Fe transmission within a few percent





- Also measured at **1012 eV** and **1188 eV**
- Biggest source of opacity uncertainty
  = Sample thickness (i.e., areal density)

- **Works with target-characterization labs at SNL and GA for accurate opacity**
- **Recently joined the center of our academic collaborator WCAPP***

*** Wootton Center for Astrophysical Plasma Properties**

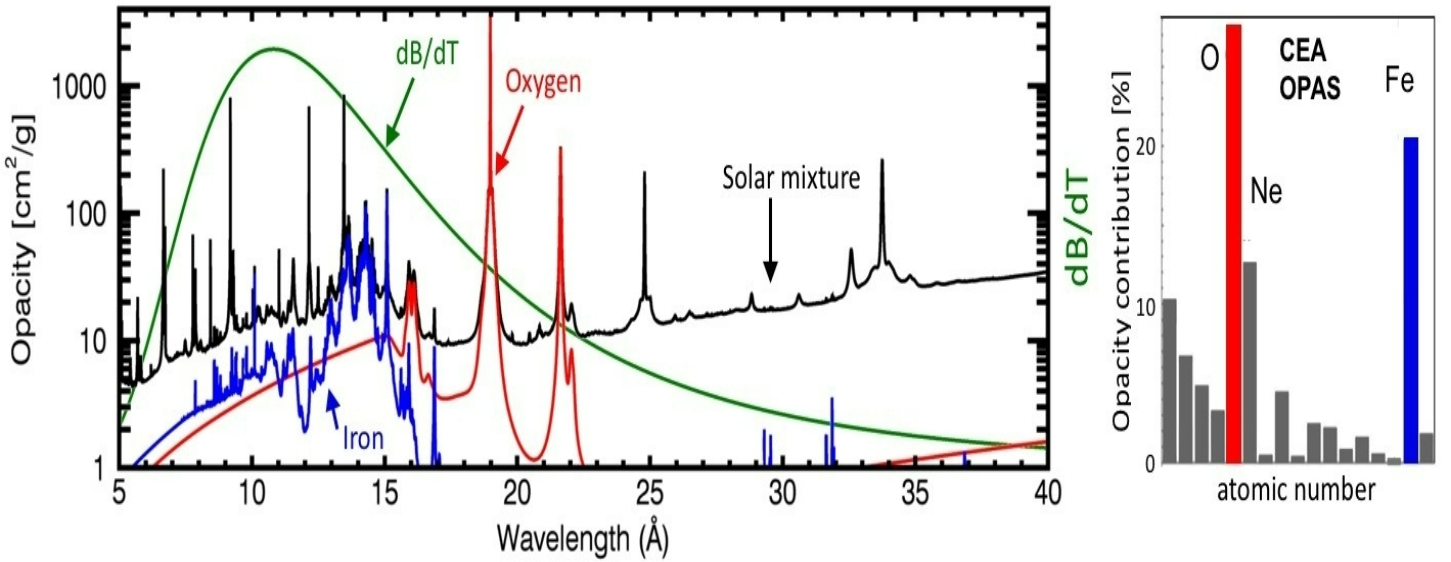
Postdoc: Dan Mayes has working knowledge of spectroscopy and will work on oxygen opacity research

Dan Mayes:

- Member of WCAPP* since 2018
- Defended in Dec 2020
  University of Nevada, Reno
  Advisor: **Roberto Mancini**
- Joined opacity team in Jan 2021

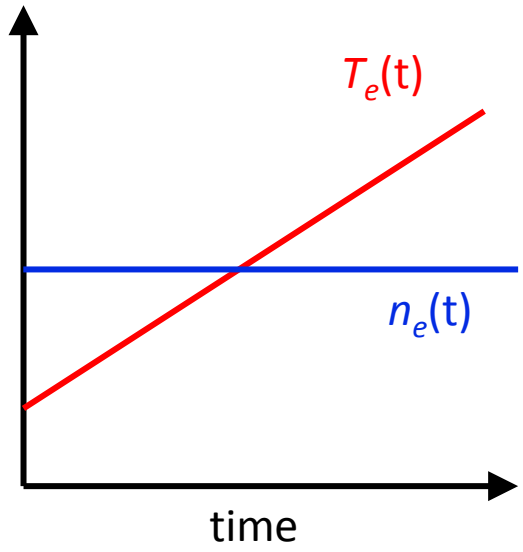
Working knowledge in:
- **X-ray spectroscopy**
- **SNL Z experiments**

He will work on oxygen opacity



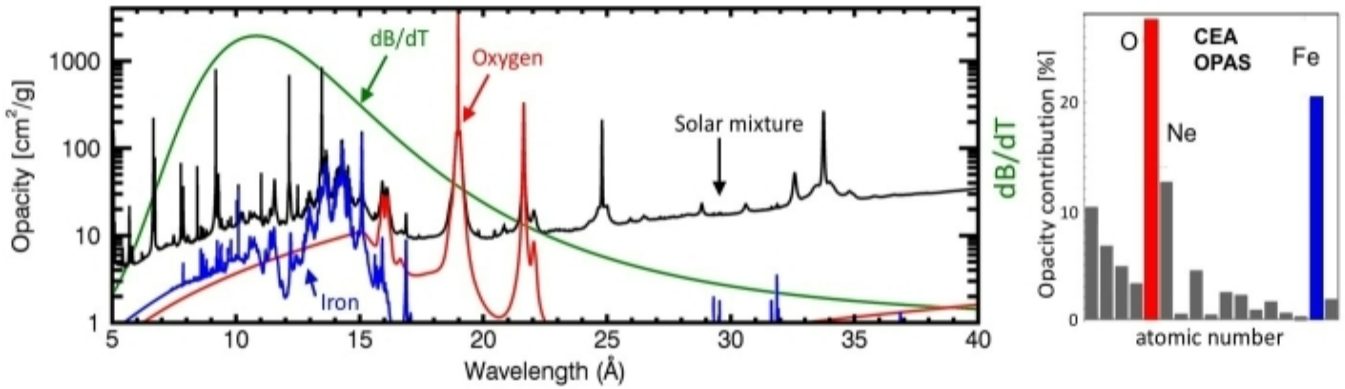
Exciting stellar-opacity research is on the horizon

Transform opacity science on Z using novel time-resolved spectroscopy



Based on time-resolved
Mg spectroscopy

Measure oxygen opacity at solar interior conditions for the solar problem



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Need to be measured at stellar interior conditions, i.e., 180 eV, 1e23 cm^{-3}

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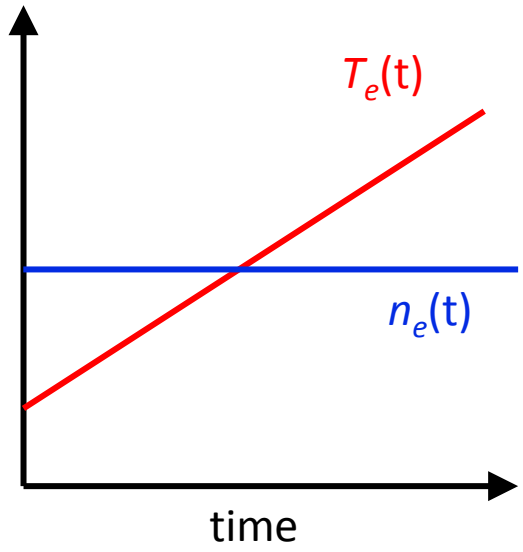

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- **Minimize temporal-gradient concern**
- **Study how opacity changes with temperature**

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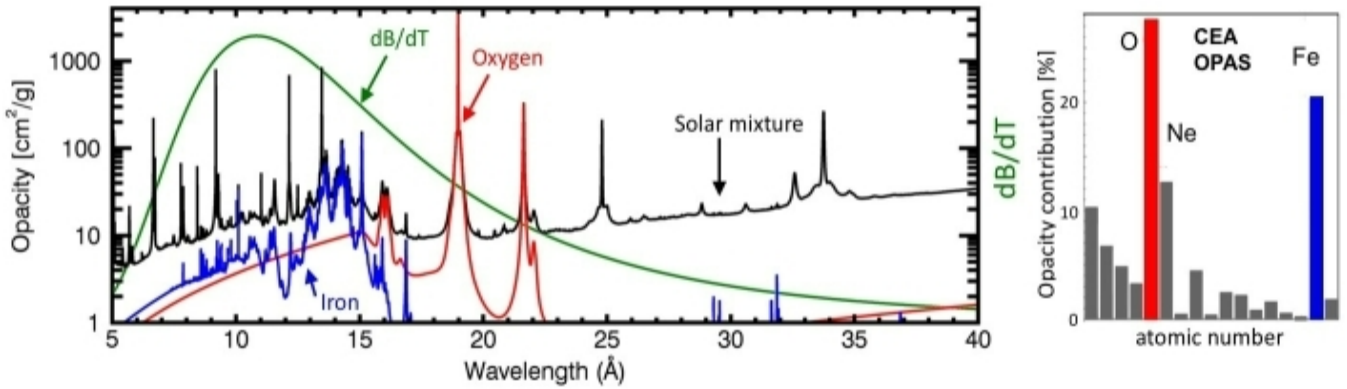

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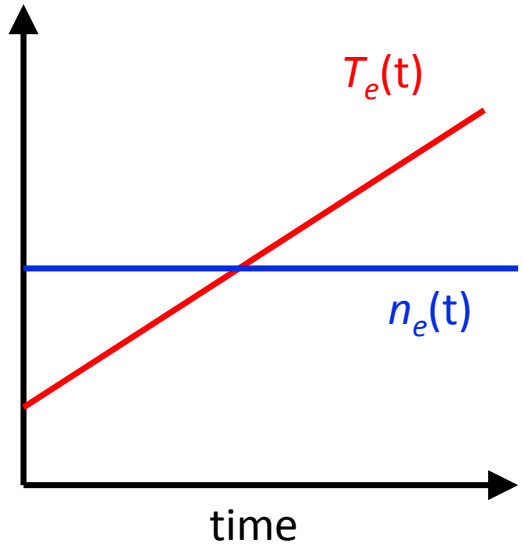
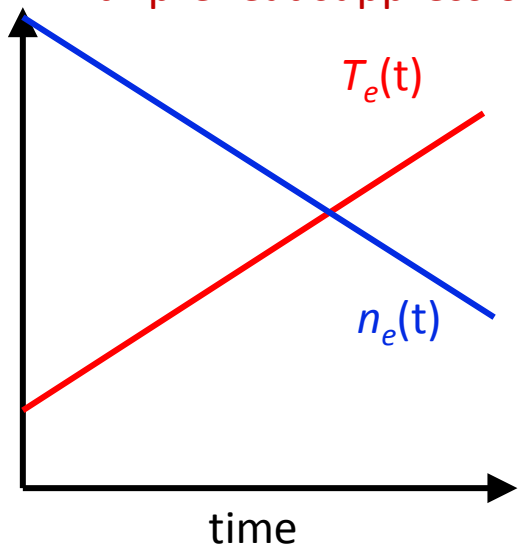
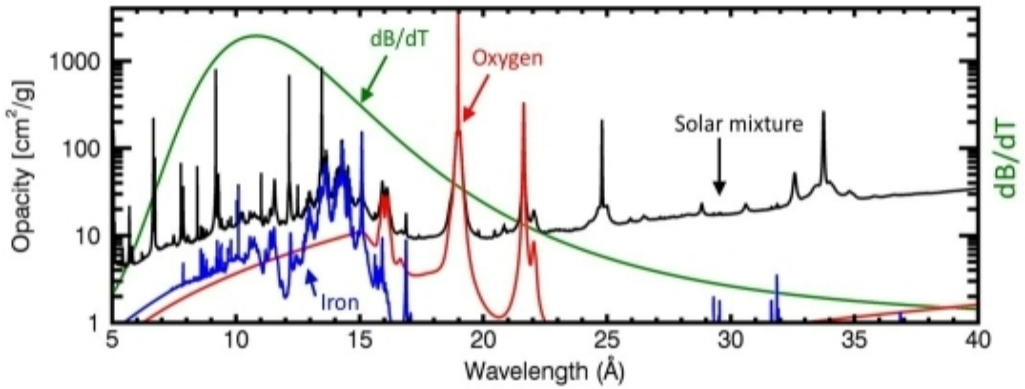


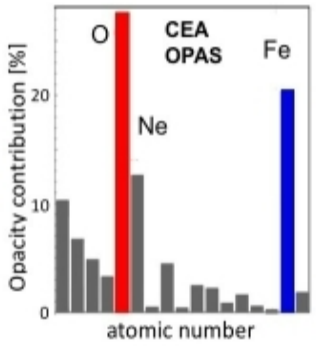
With preheat suppression



- **Opacity at multiple conditions from a single experiment**
- **Minimize temporal-gradient concern**
- **Study how opacity changes with temperature**
- With preheat suppression:
  - Measure opacity at highest density
  - Study how opacity changes with density

Measure oxygen opacity at solar interior conditions for the solar problem





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