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Sandia National Laboratories

Updates on stellar opacity project

Taisuke Nagayama

Wootton Center for Astrophysical Plasma Properties
DOE/NNSA Stockpile Stewardship Academic Alliance Program
Center External Review, Oct 14, 2021

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

Sandia National Laboratories

J.E. Bailey, T. Nagayama, G.P. Loisel, G.A. Rochau, S.B. Hansen, G.S. Dunham, R. More, T. Gomez
Sandia National Laboratories, Albuquerque, NM, 87185-1196

D. Mayes, M. Kao, D. Winget, M. Montgomery
University of Texas, Austin, TX

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

C. Blancard, Ph. Cosse, G. Faussurier, F. Gilleron, J.-C. Pain
CEA, France

C.A. Iglesias and B. Wilson
Lawrence Livermore National Laboratory, Livermore, CA, 94550

J. Colgan, C.J. Fontes, D.P. Kilcrease, and M.E. Sherrill
Los Alamos National Laboratory, Los Alamos, NM 87545

J.J. MacFarlane and I. Golovkin
Prism Computational Sciences, Madison, WI

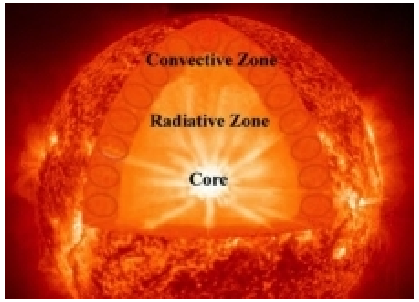
Stellar opacity research continues to advance experiment, analysis, and theory towards resolving the solar problem

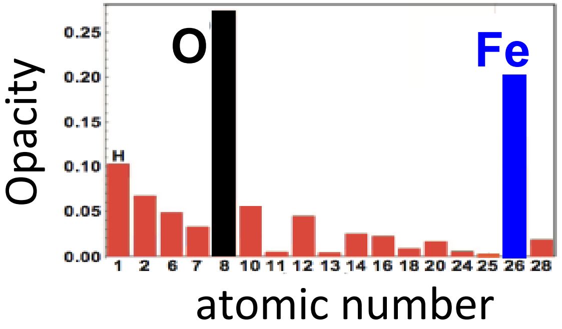
Motivation: solar models disagree with observations

→ Can we model solar opacity correctly?

L-shell Fe: Billions of L-shell lines

K-shell O: Density effects





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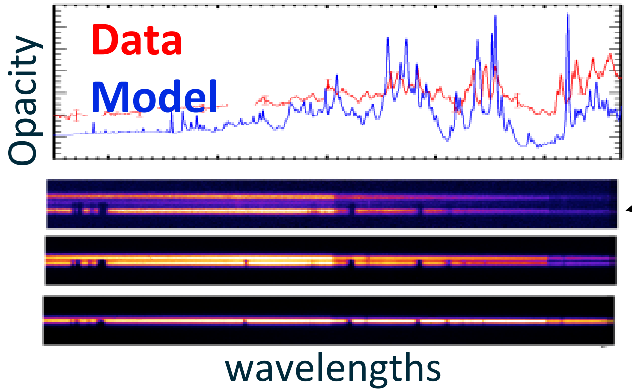

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- **Experiments**

  Time-resolved measure.

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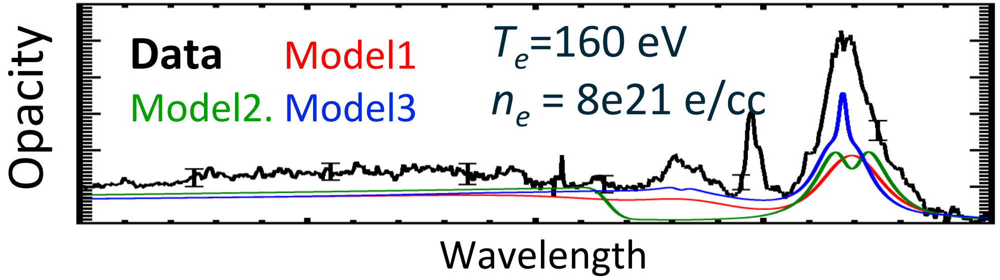
- **Theory**

O opacity: Measured for the first time

→ Showing interesting disagreements



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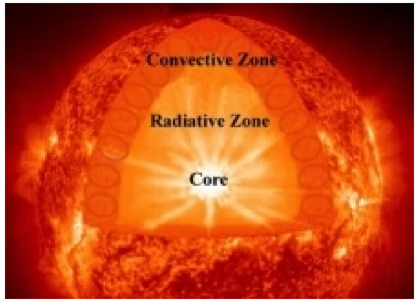

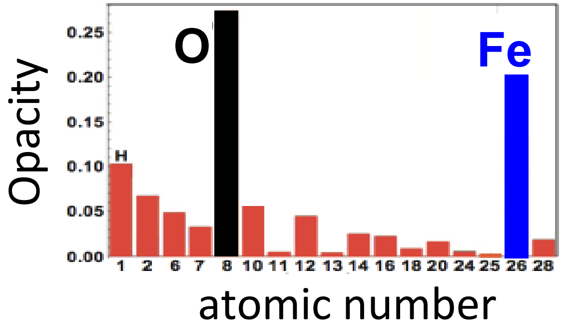

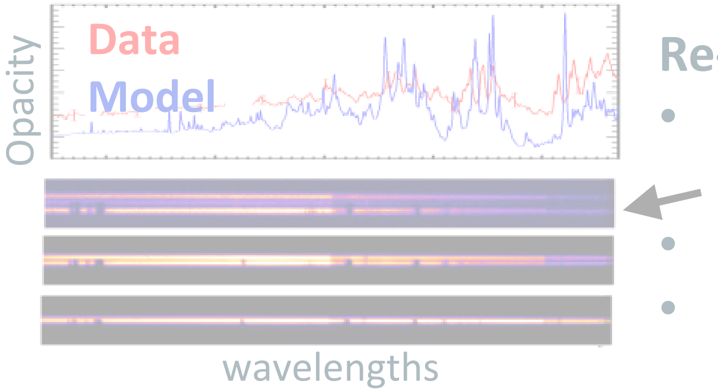

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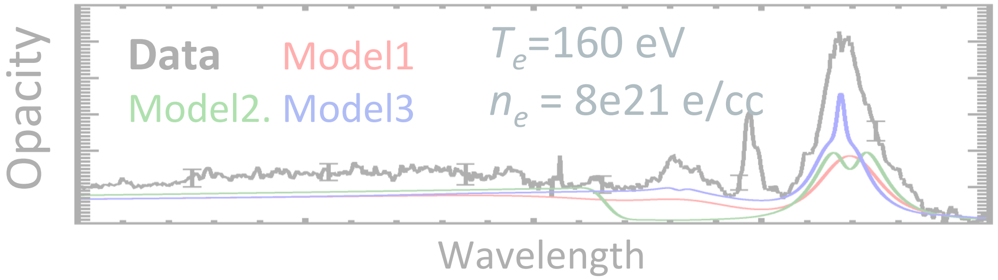

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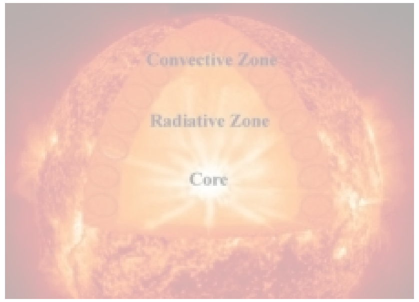

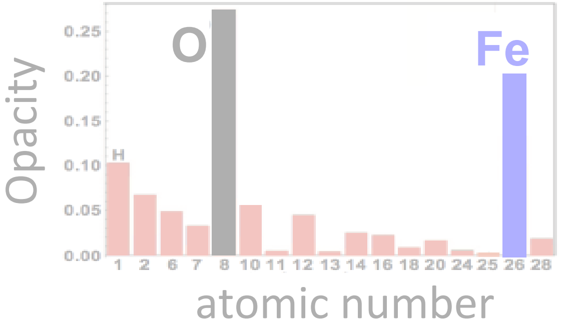

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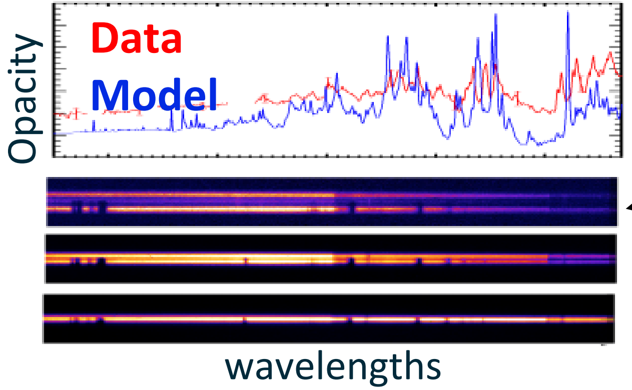

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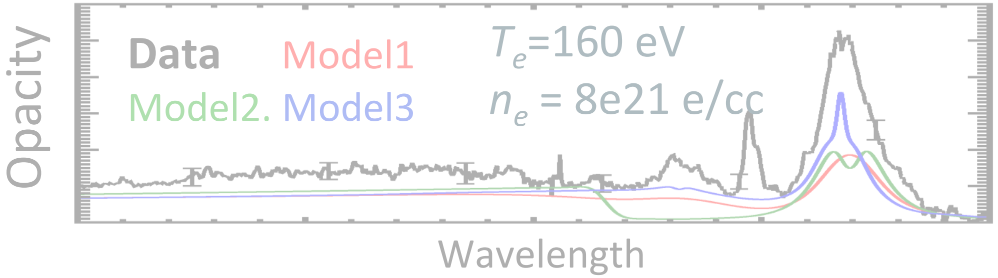

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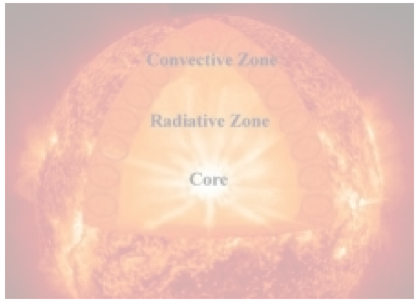

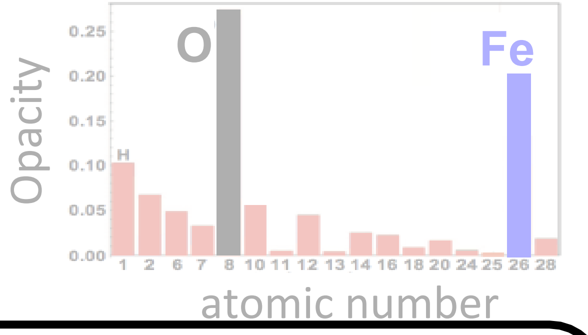

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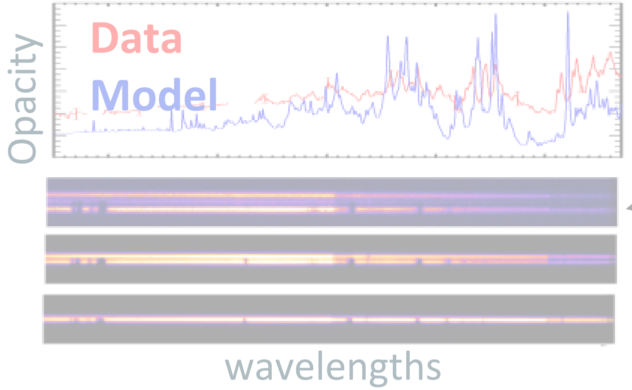

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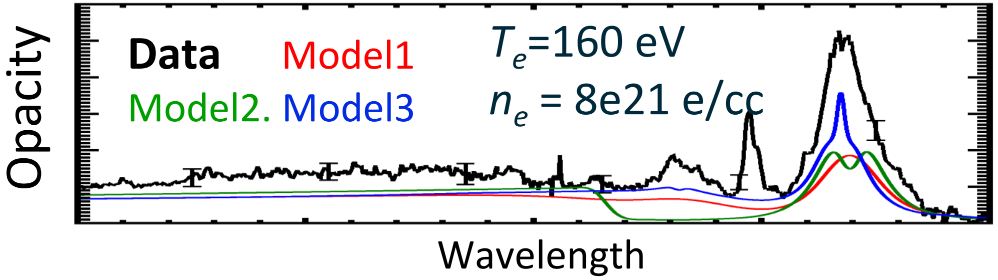

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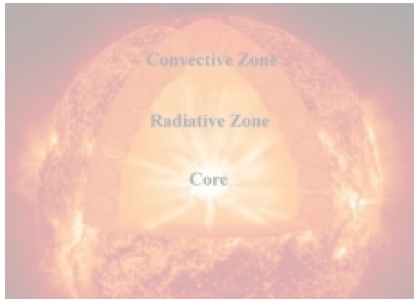

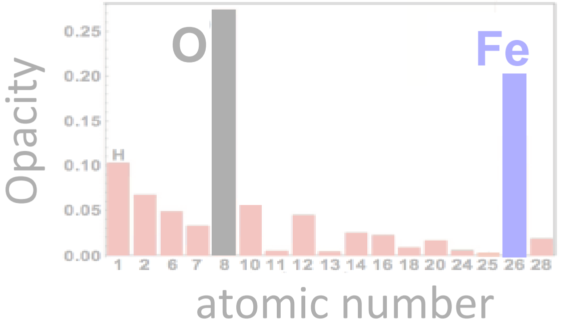

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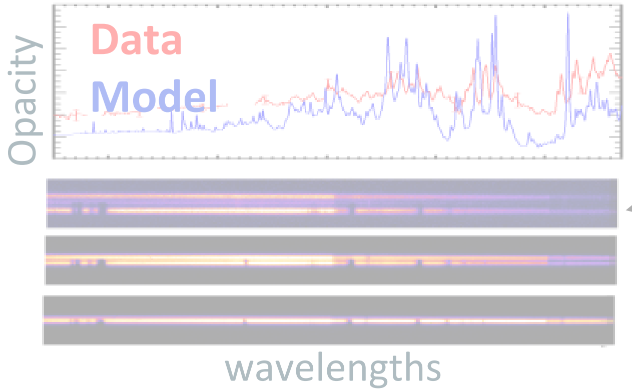

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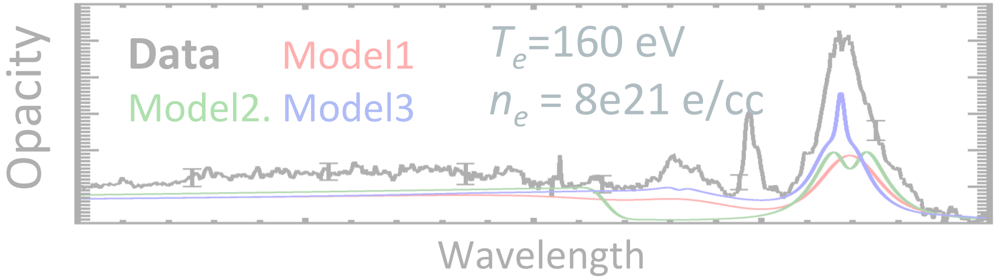

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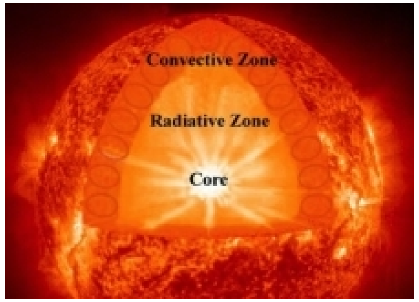

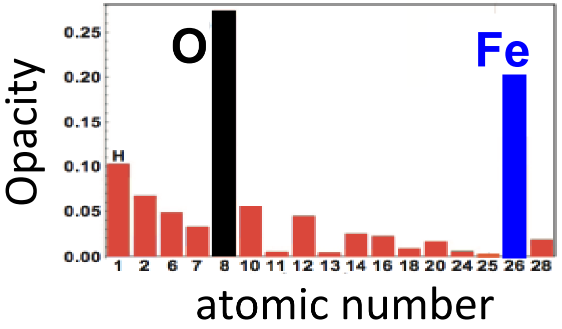

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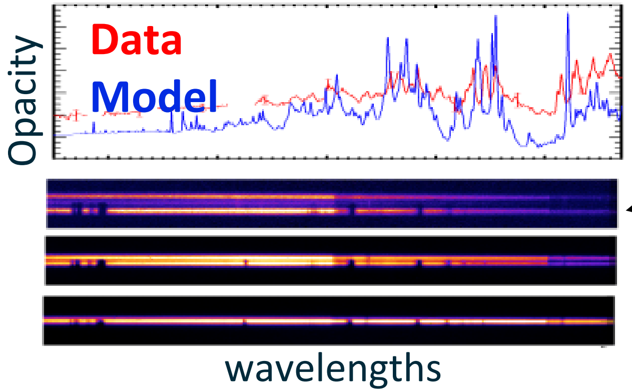

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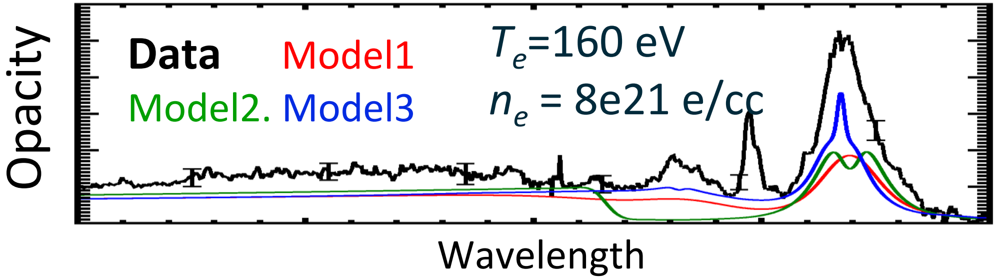

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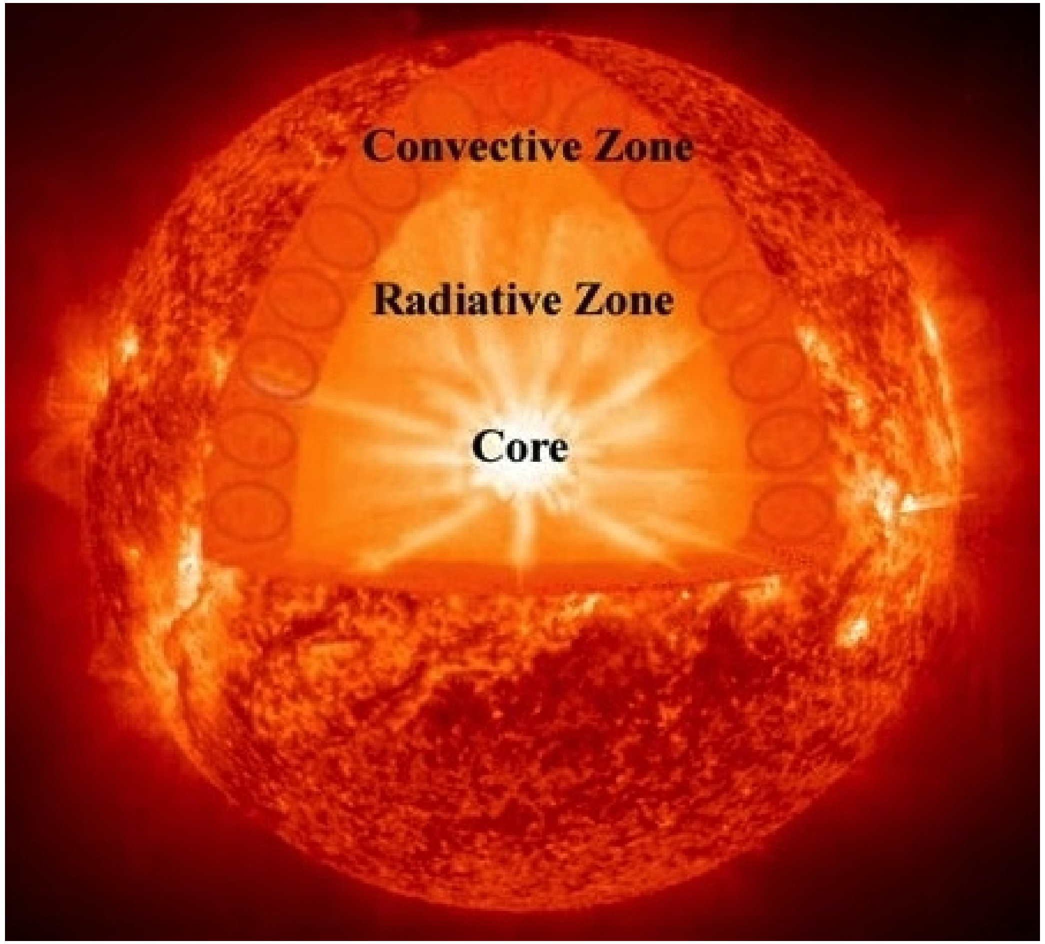
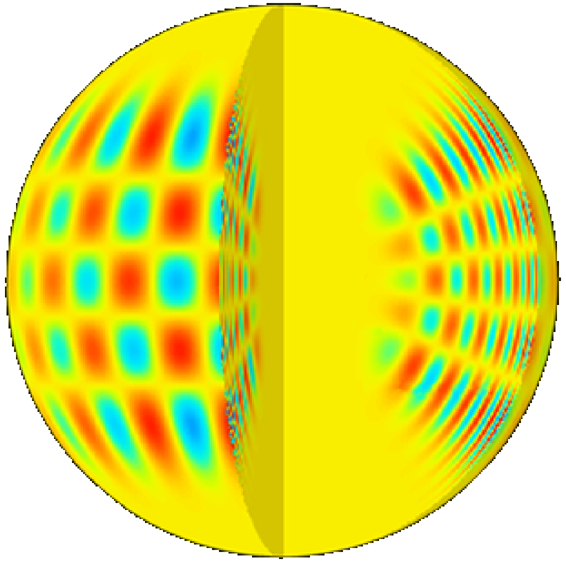


- **Simulation: Standard solar model**

  Inputs:

  - Abundance
  - EOS
  - Opacity
  - Etc.

- **Measurements: Helioseismology**



Analysis of 2D-resolved pulsation reveals the solar structure

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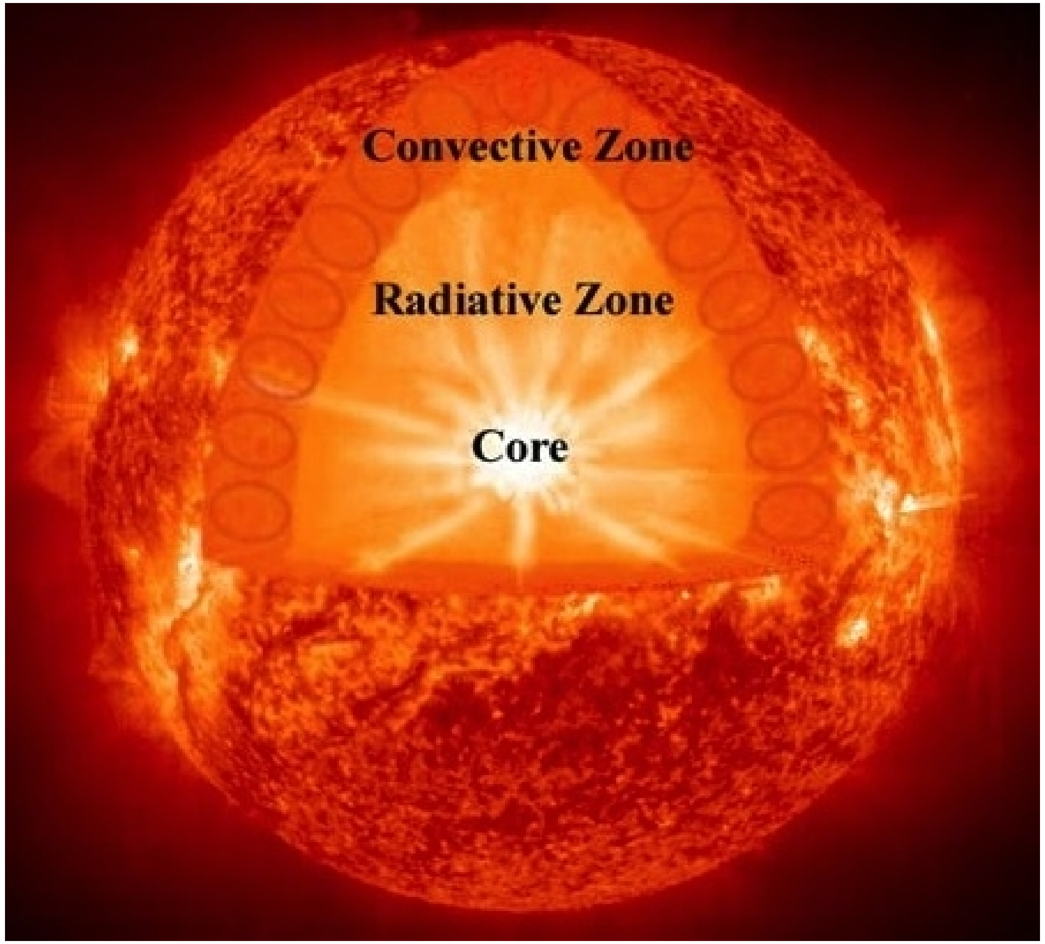

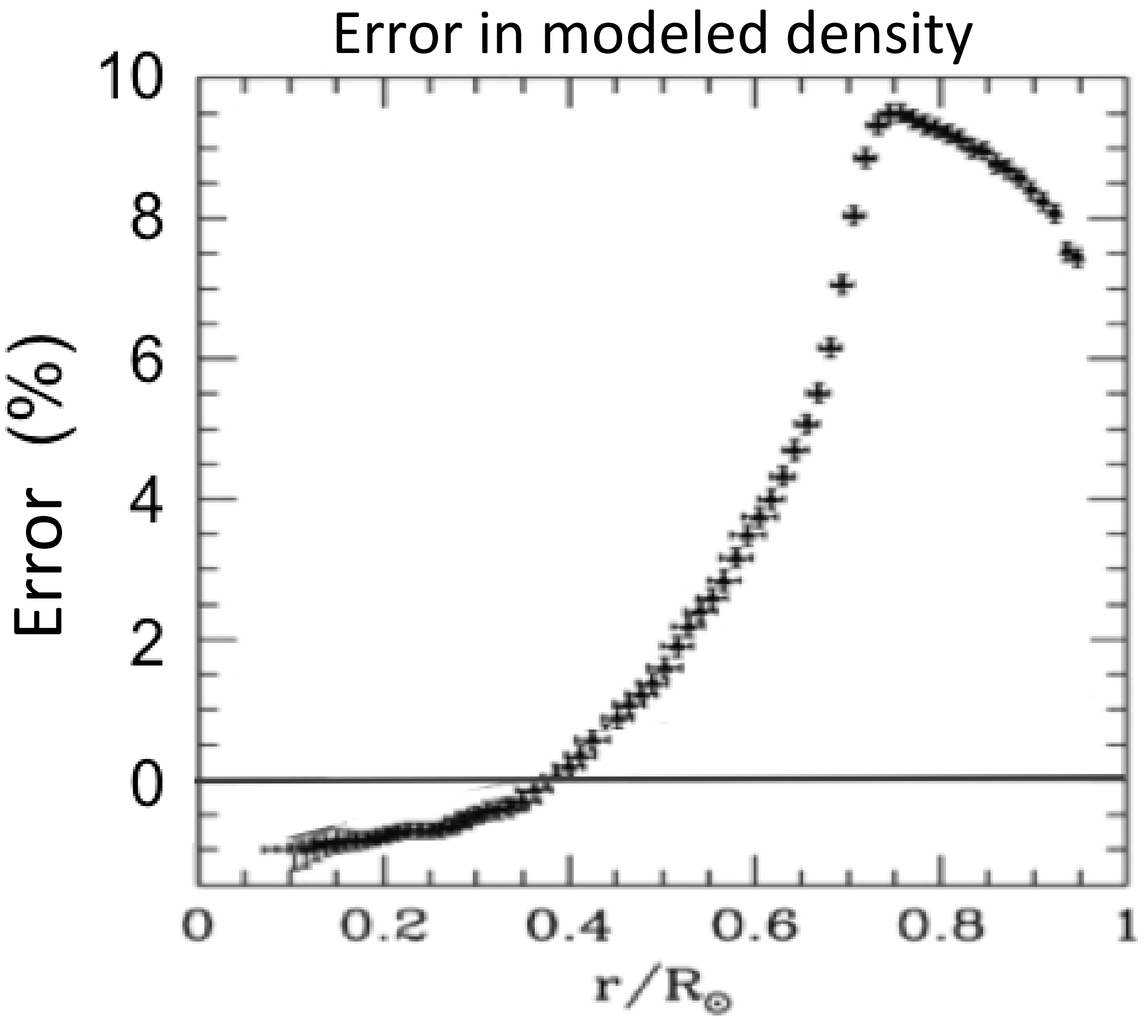

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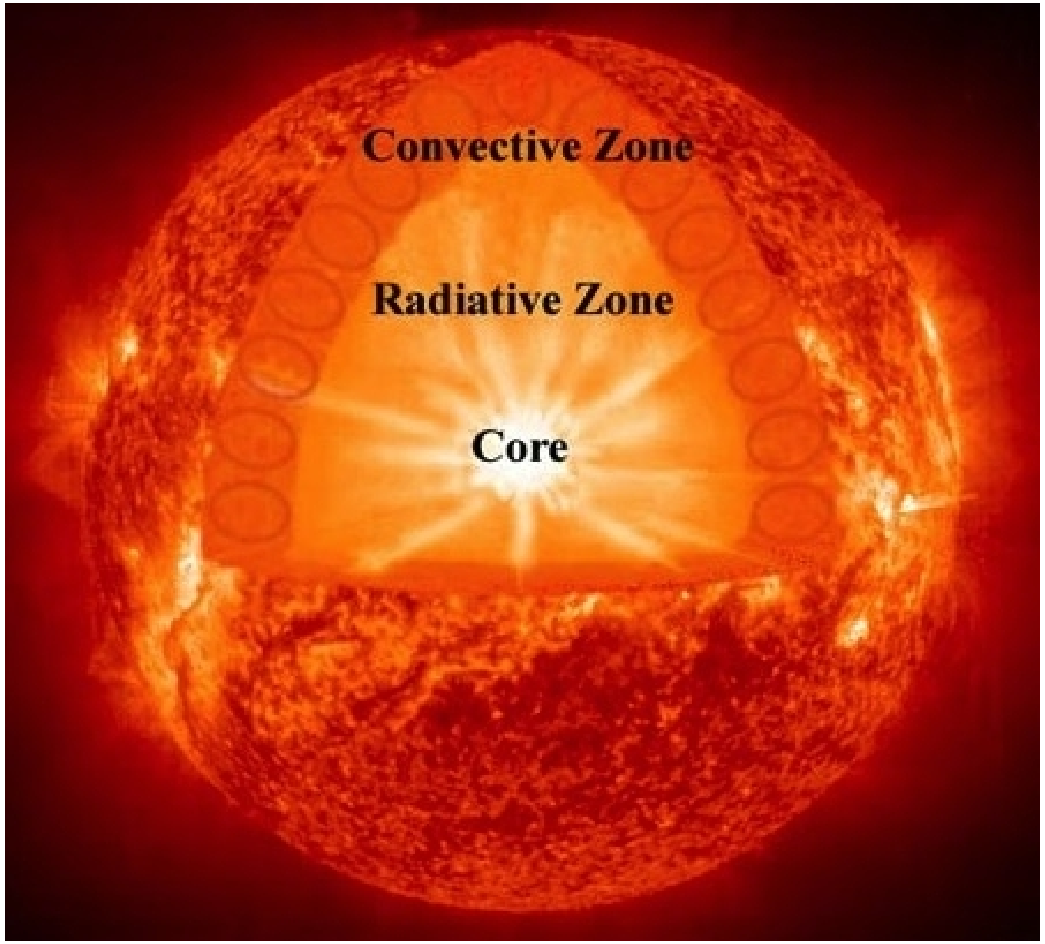

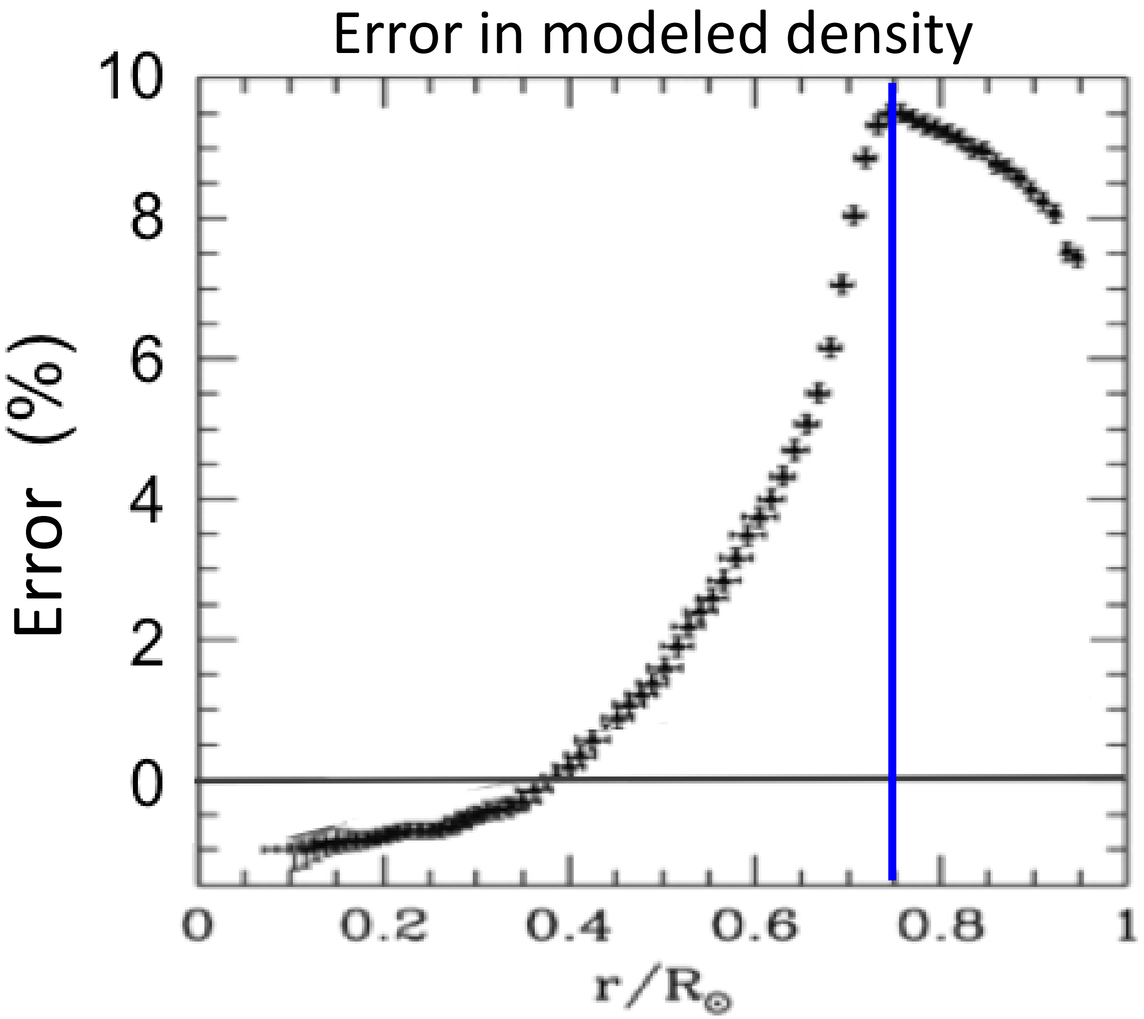

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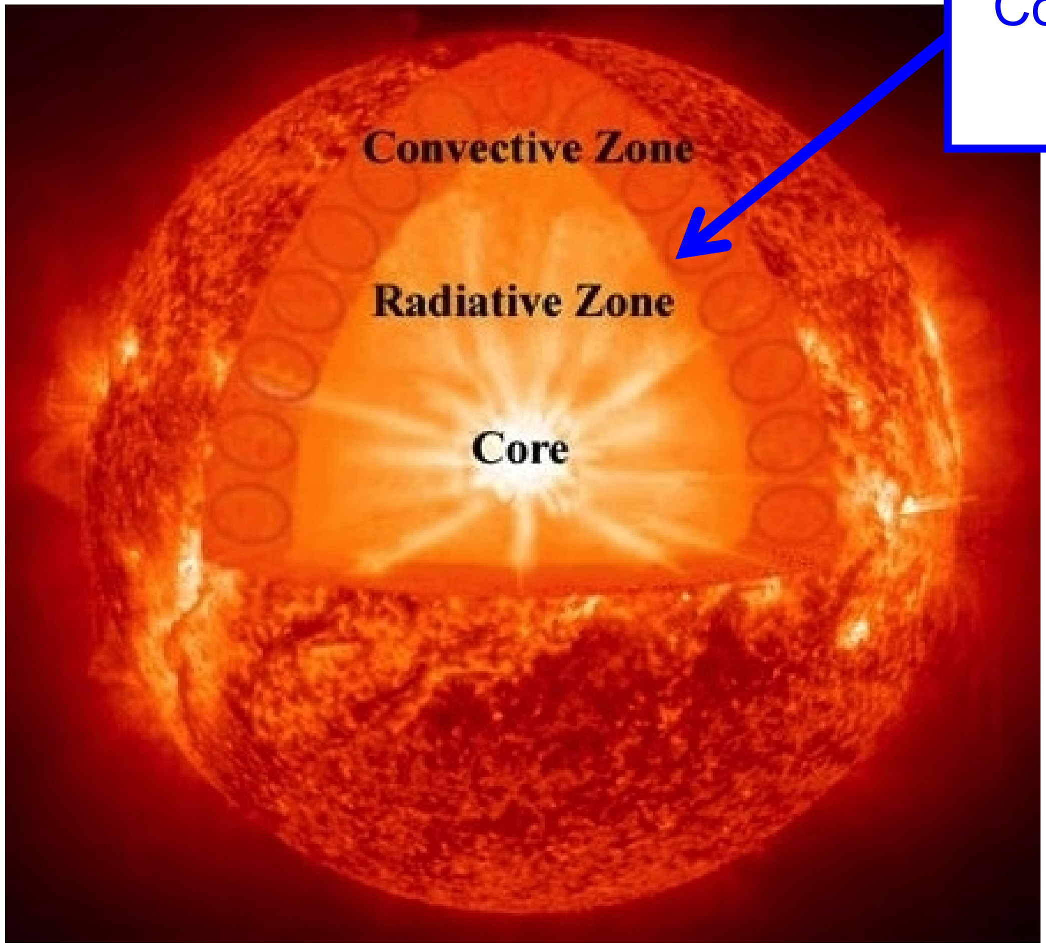
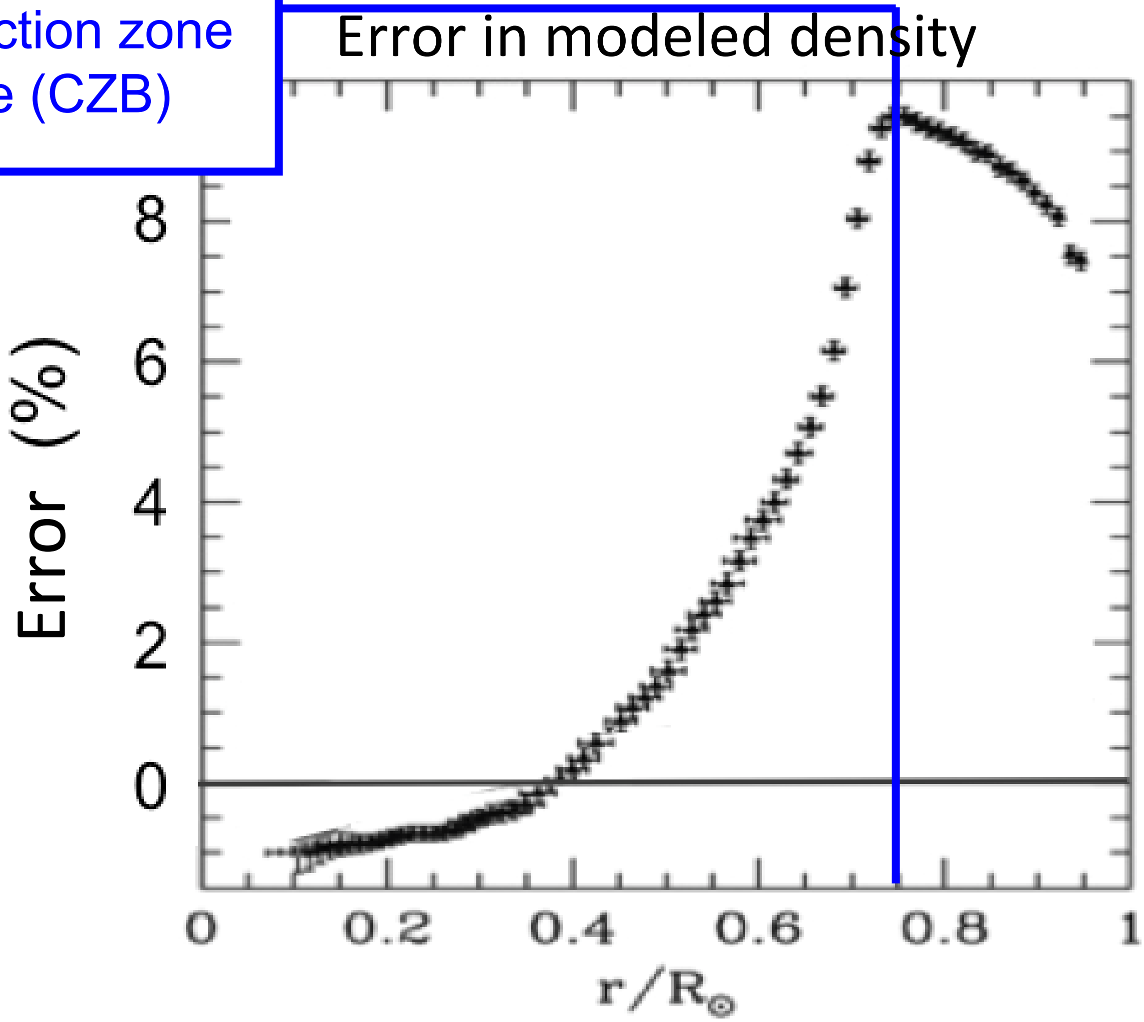
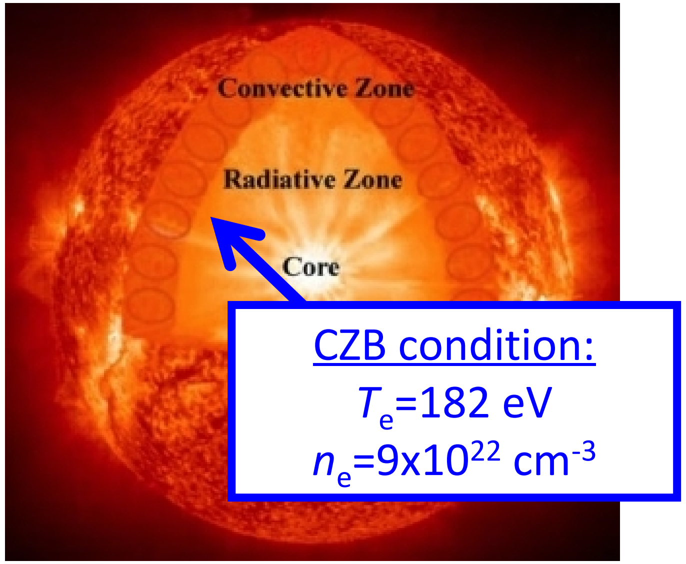


Convection zone base (CZB)



10-17% 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

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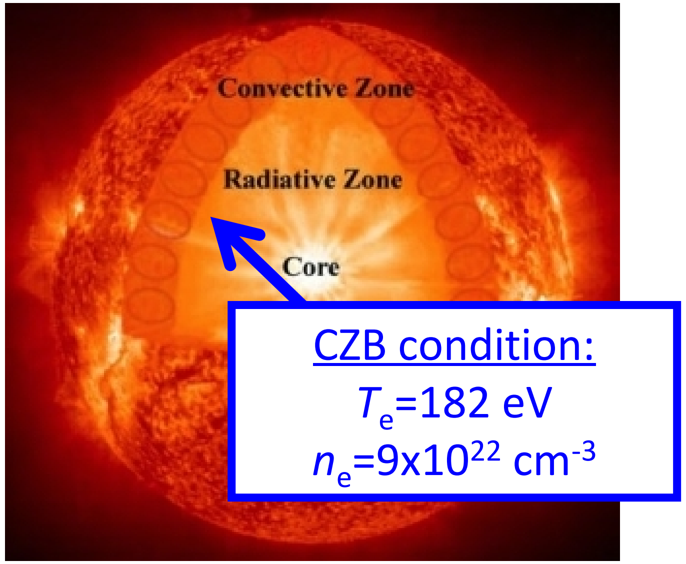

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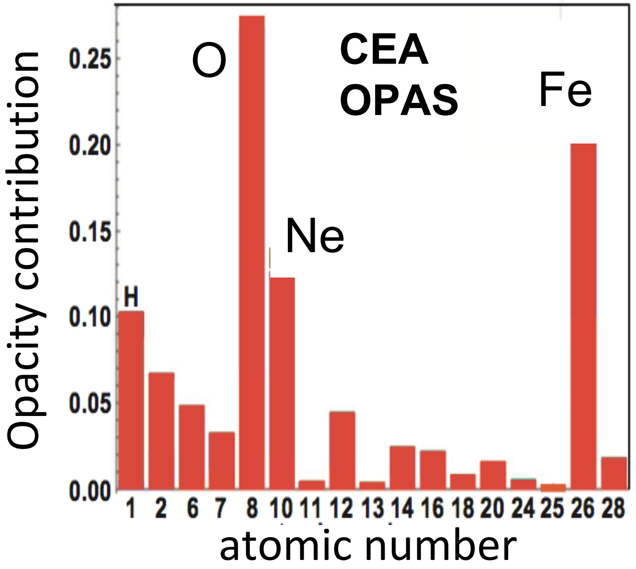
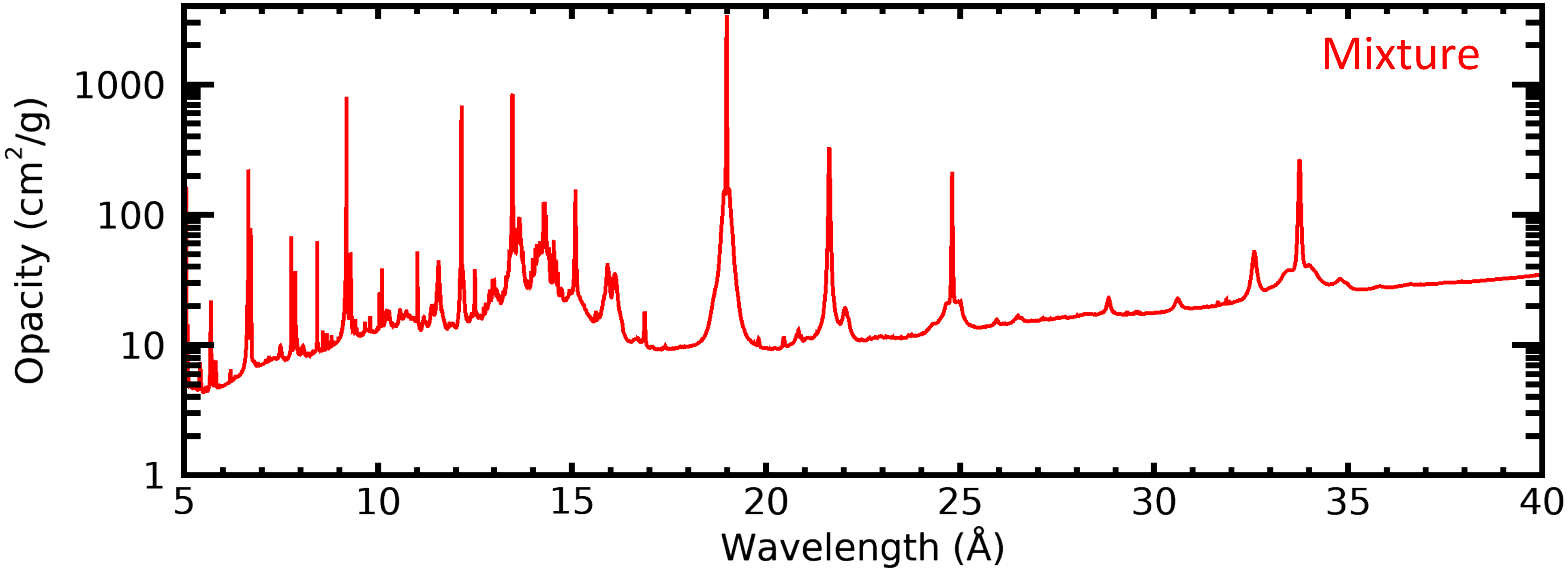


Solar mixture opacity at Convection Zone Base (CZB)



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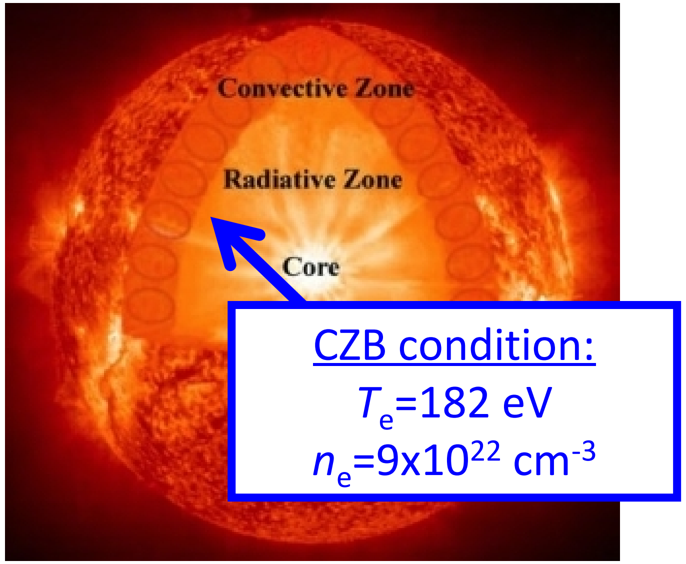

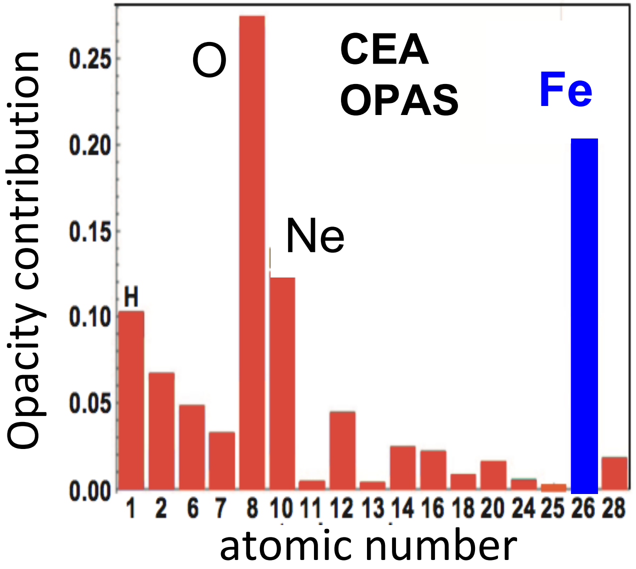

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- 2nd largest contribution
- Most difficult to model

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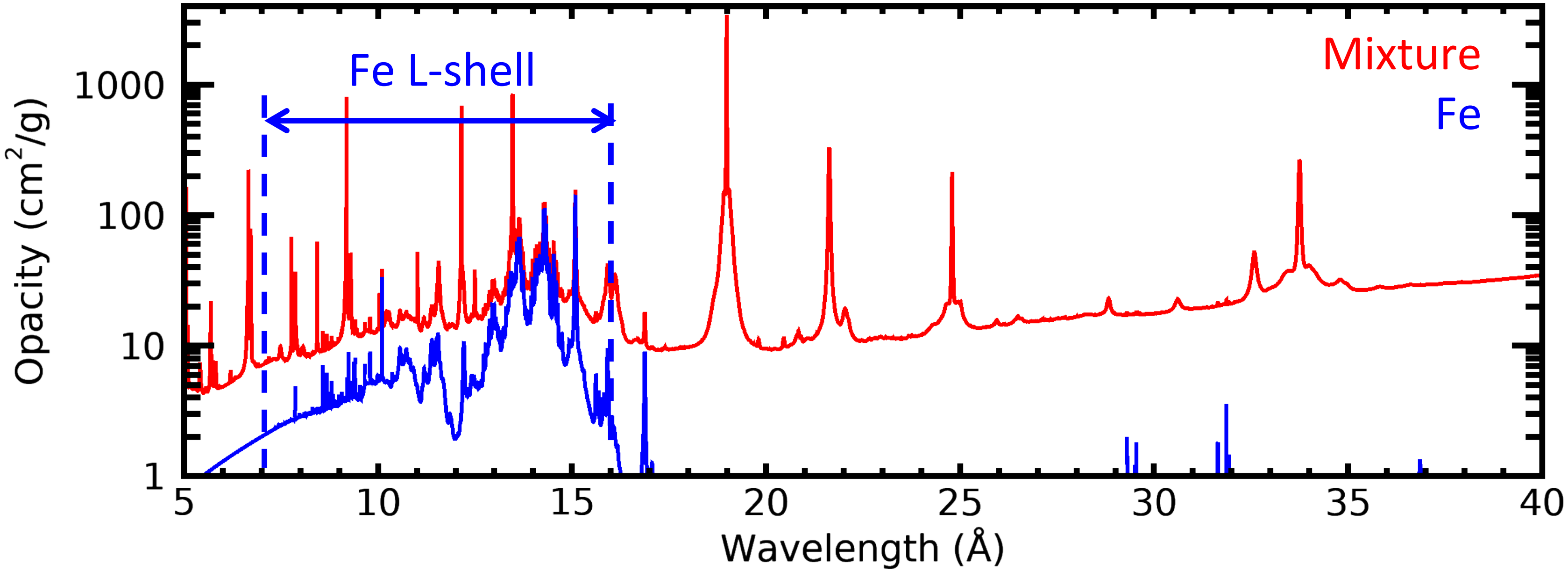

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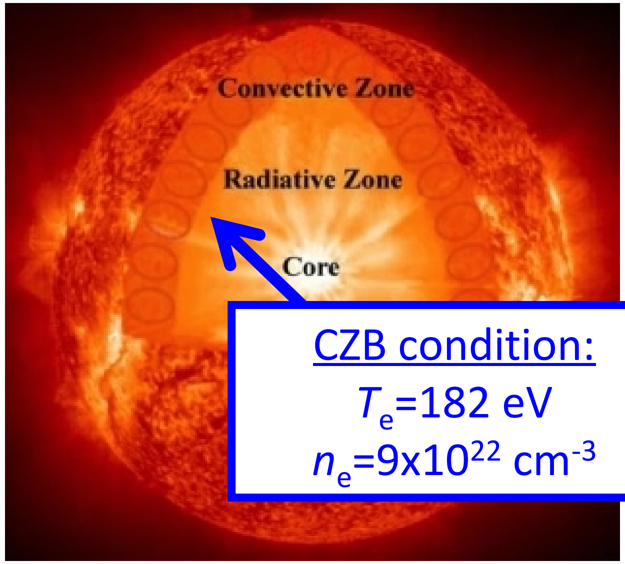

CZB condition:
T_e=182 eV
n_e=9x10^{22} cm^{-3}

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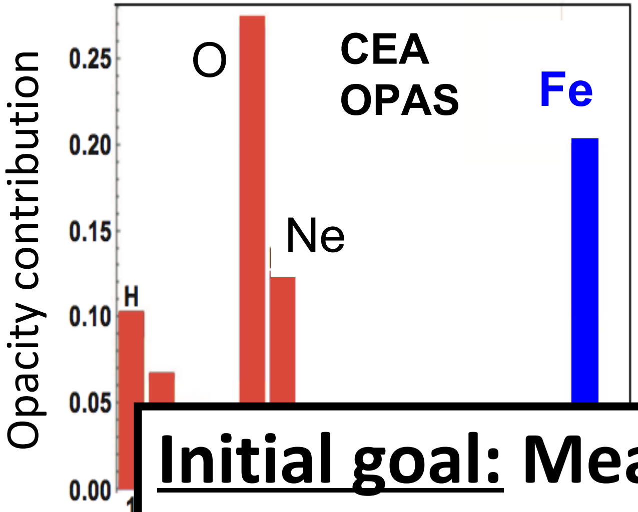

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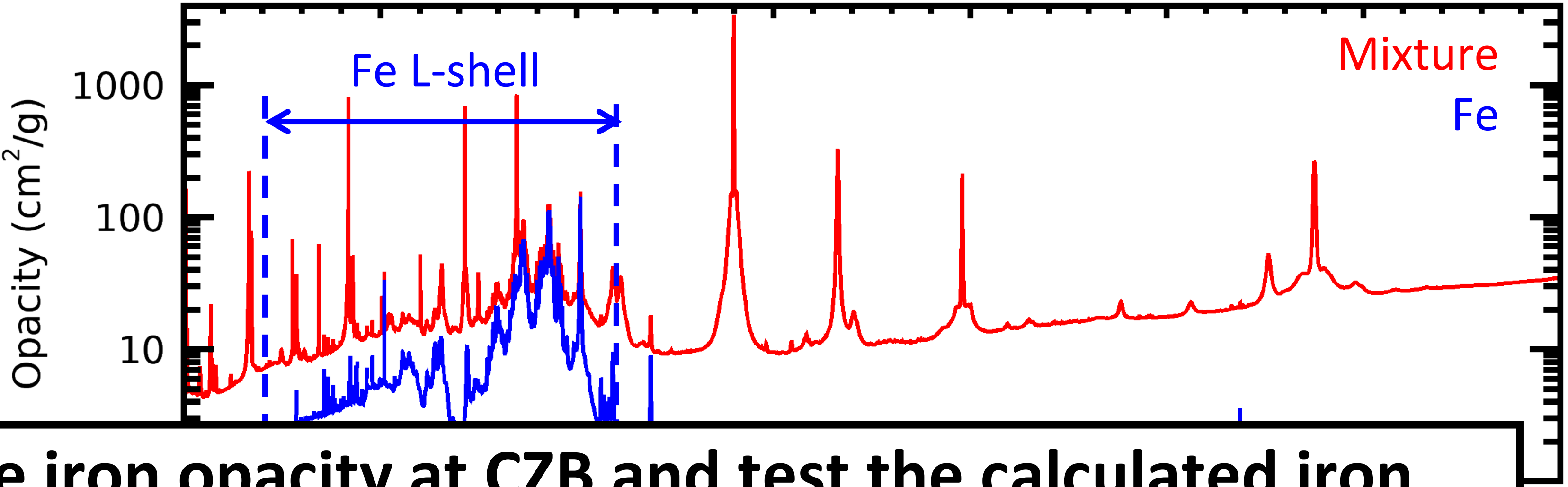
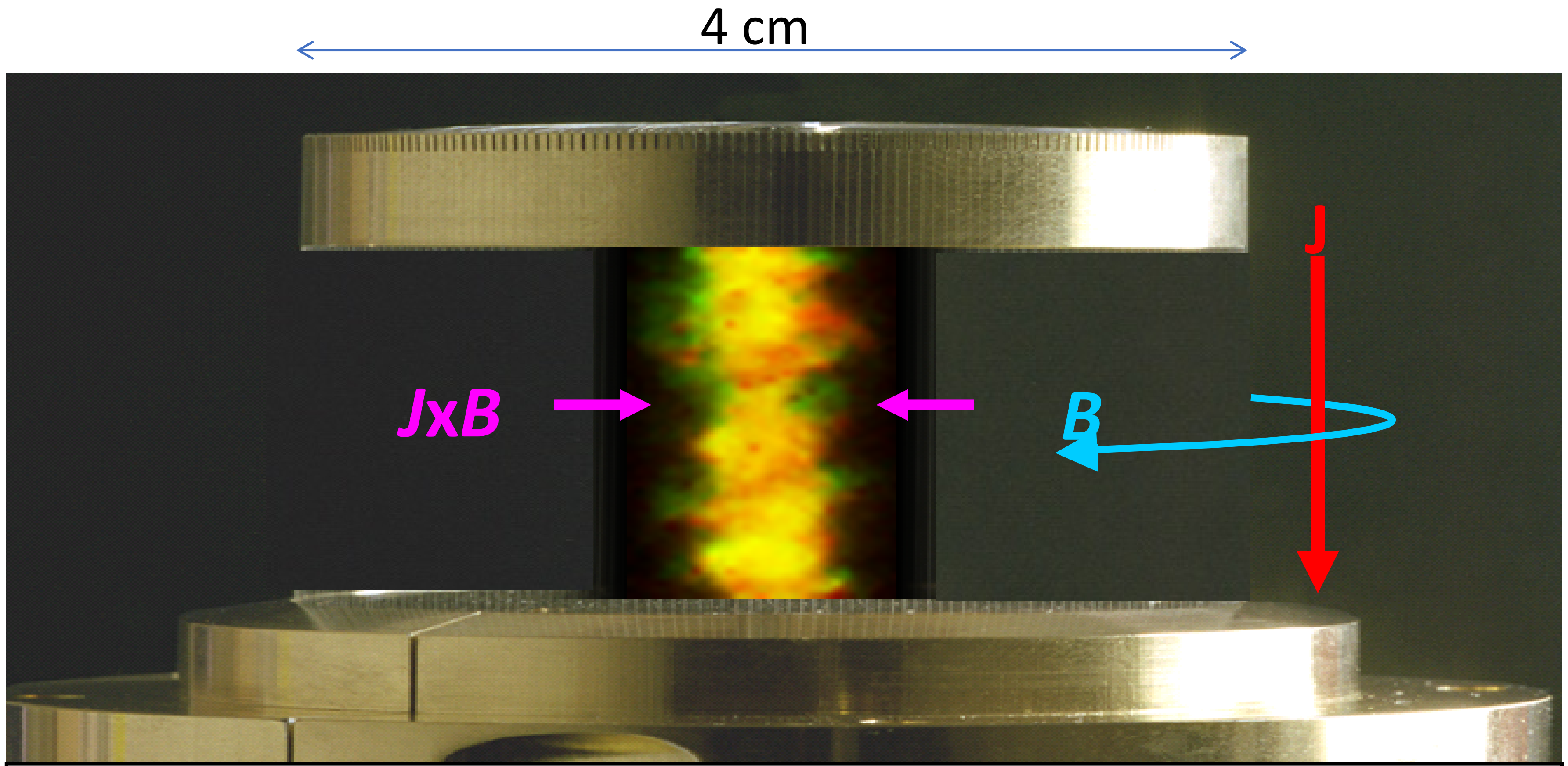


Initial goal: Measure iron opacity at CZB and test the calculated iron opacity

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

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



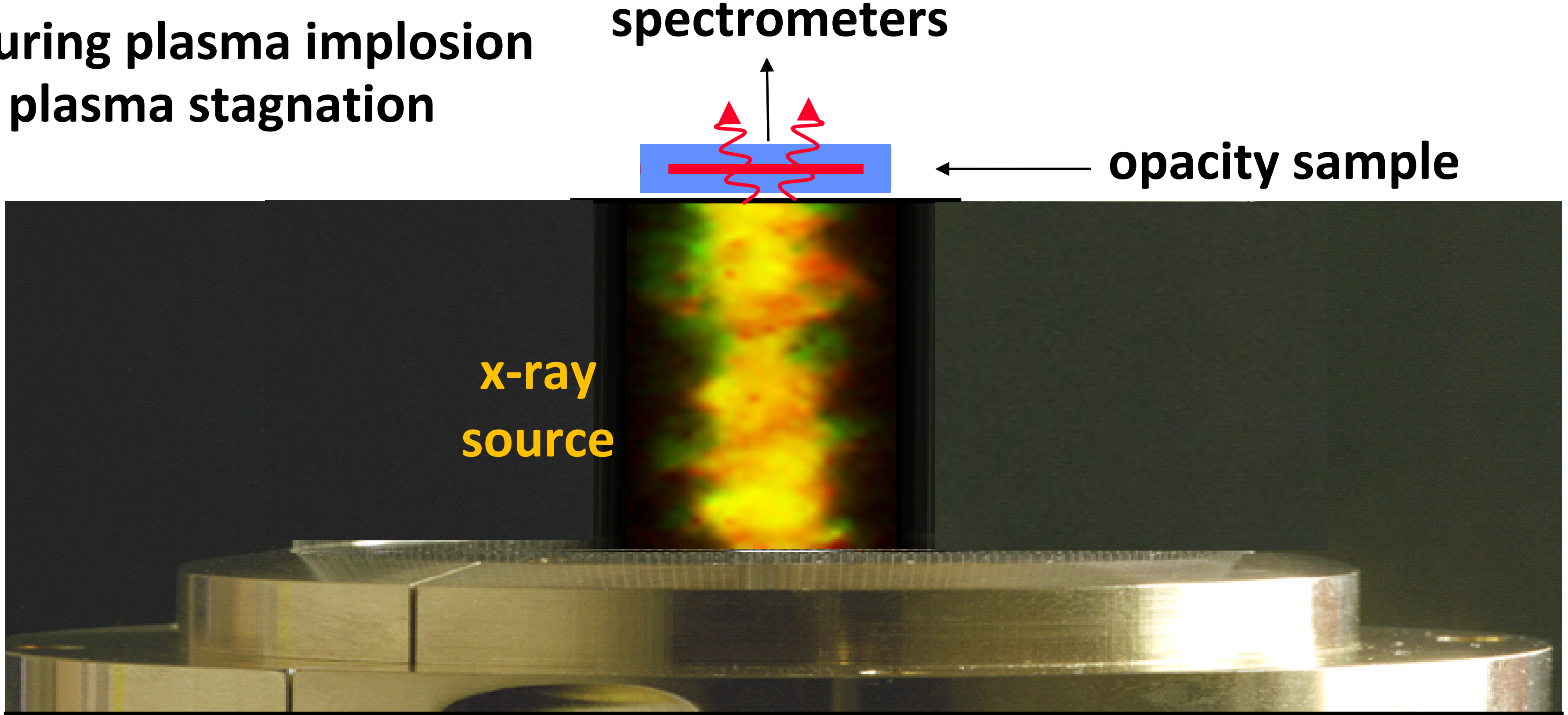
P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

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

The Z x-ray source both heats and backlights samples to stellar interior conditions.

Sample is:

- Heated during plasma implosion
- Backlit at plasma stagnation



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High-temperature Fe opacities are measured using the Z-Pinch opacity science platform

Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements

Z-p ... ce

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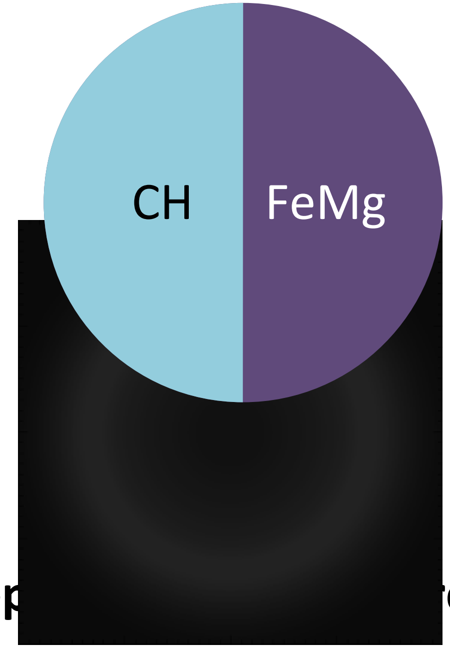

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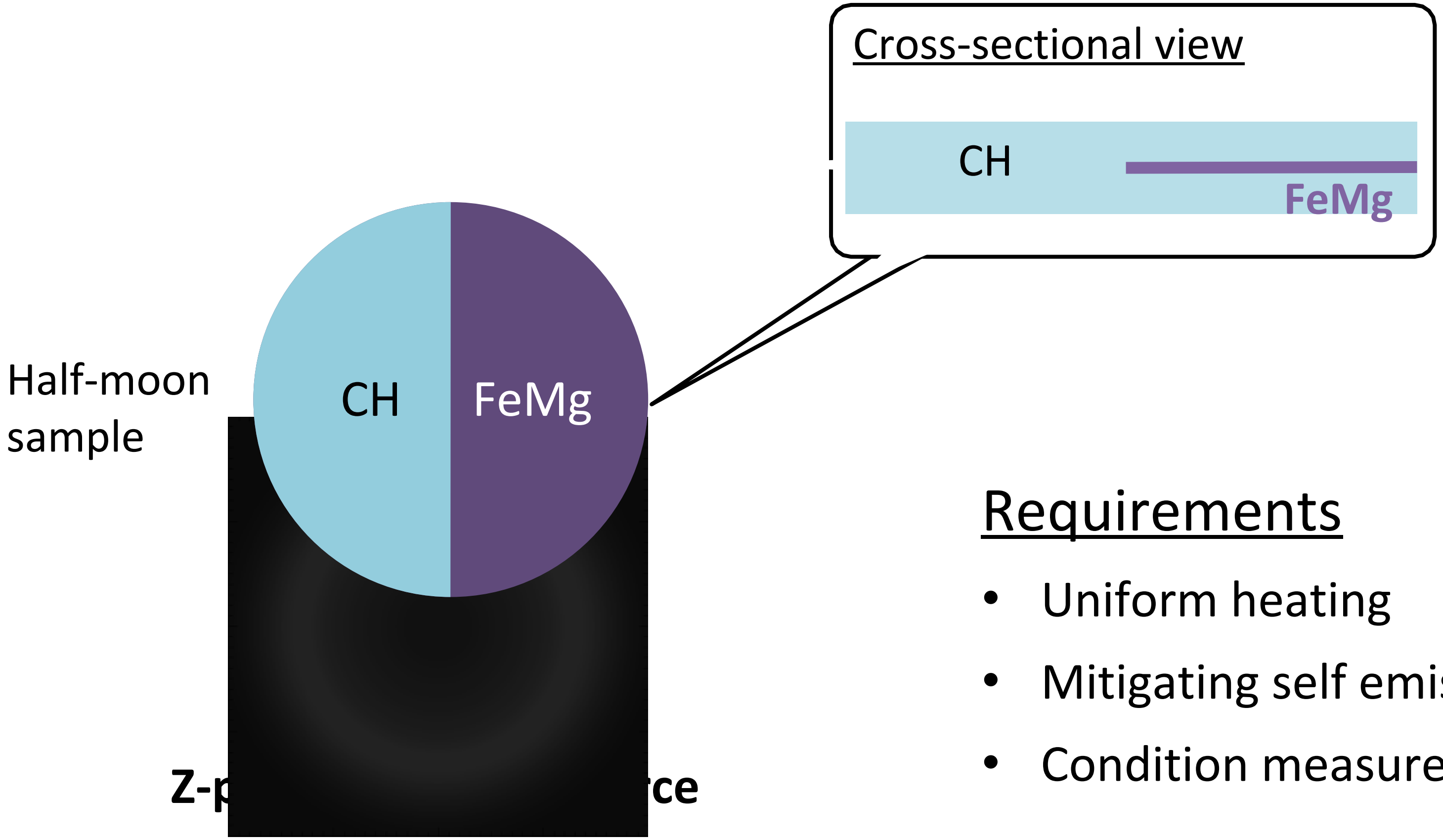

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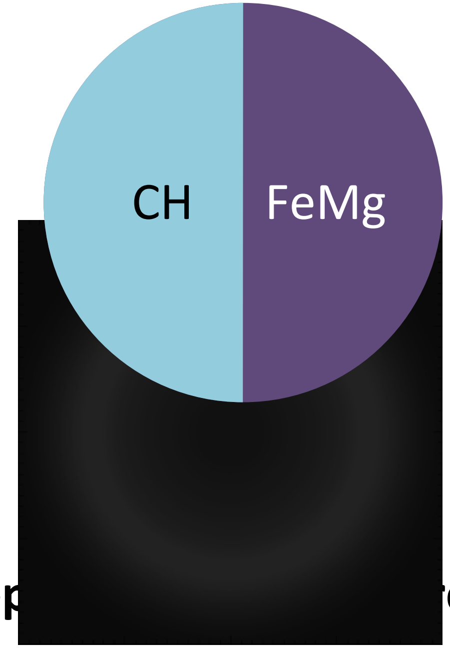
Half-moon sample



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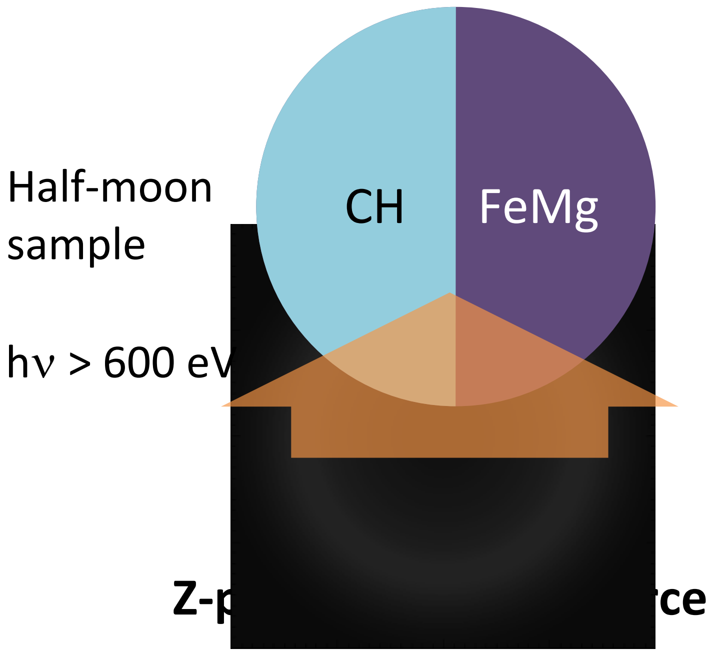

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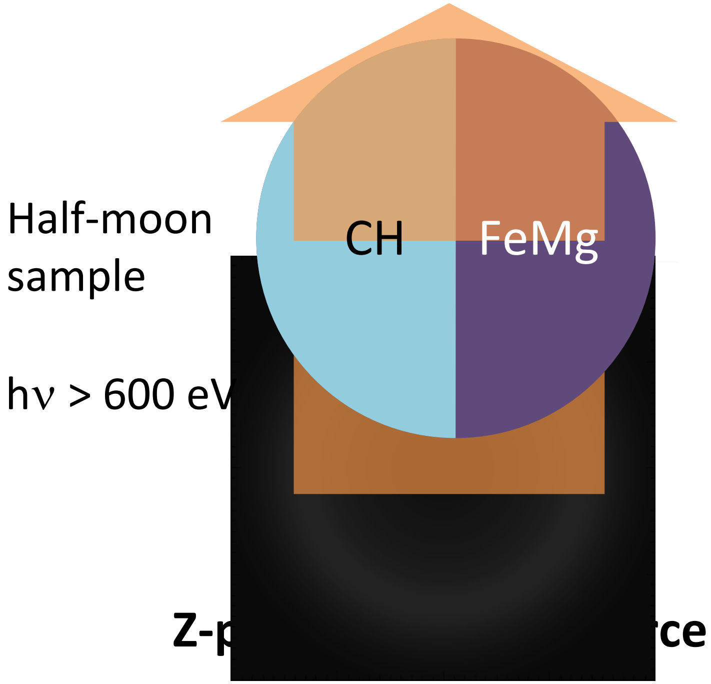

Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements

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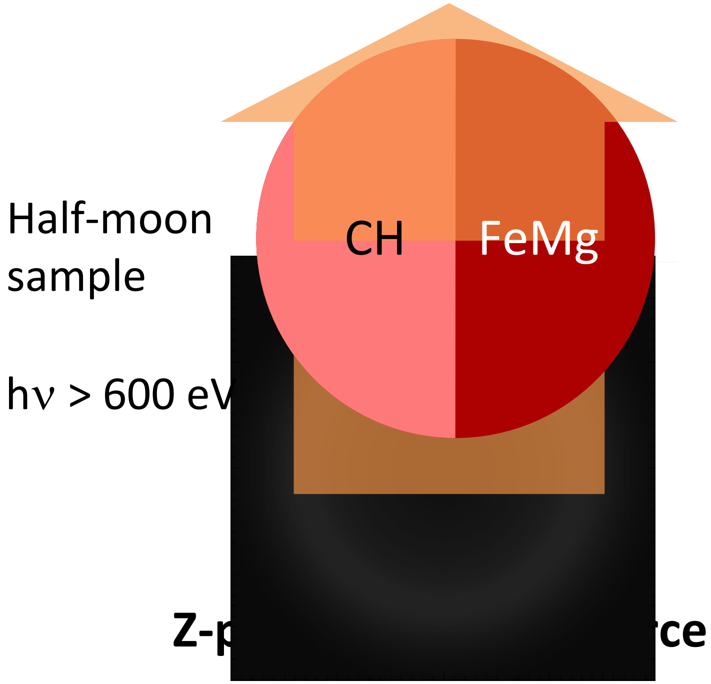

<u>Requirements</u>

- Uniform heating → Volumetric heating
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<u>SNL Z satisfies:</u>

Volumetric heating

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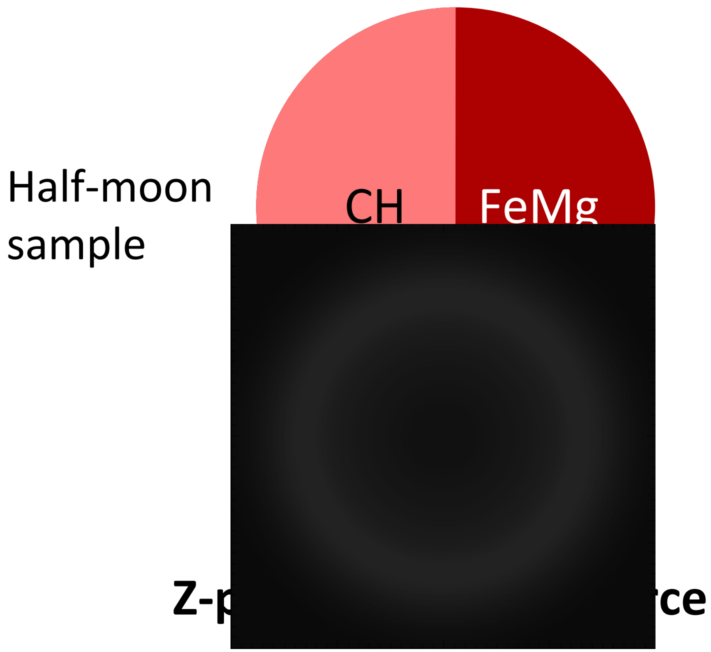

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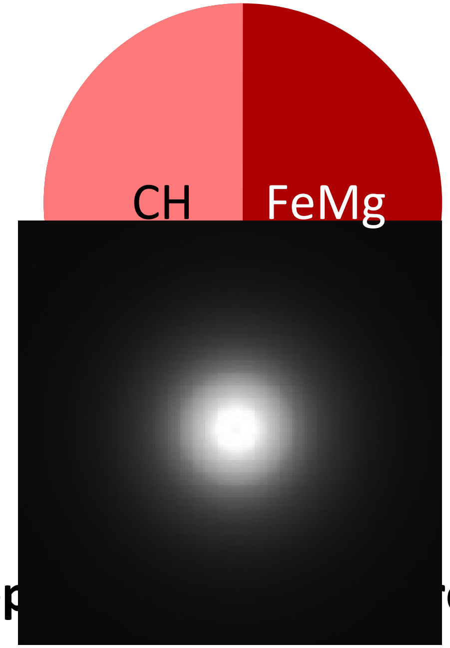
Half-moon sample



Z-p … **rce**

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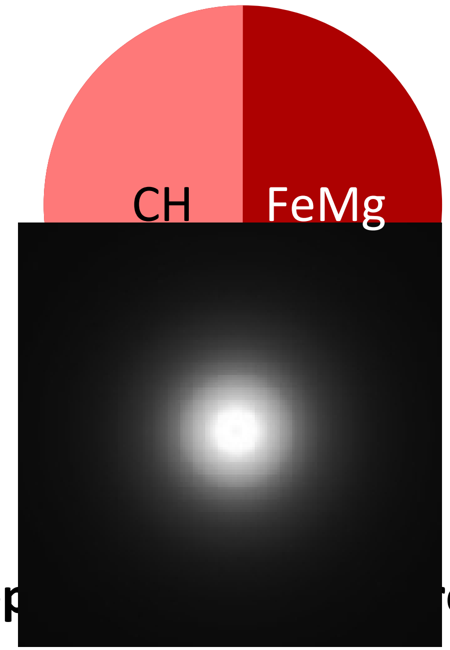

<u>Requirements</u>

- Uniform heating → Volumetric heating
- Mitigating self emission → 350 eV Planckian backlight
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<u>SNL Z satisfies:</u>

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350 eV Planckian backlight

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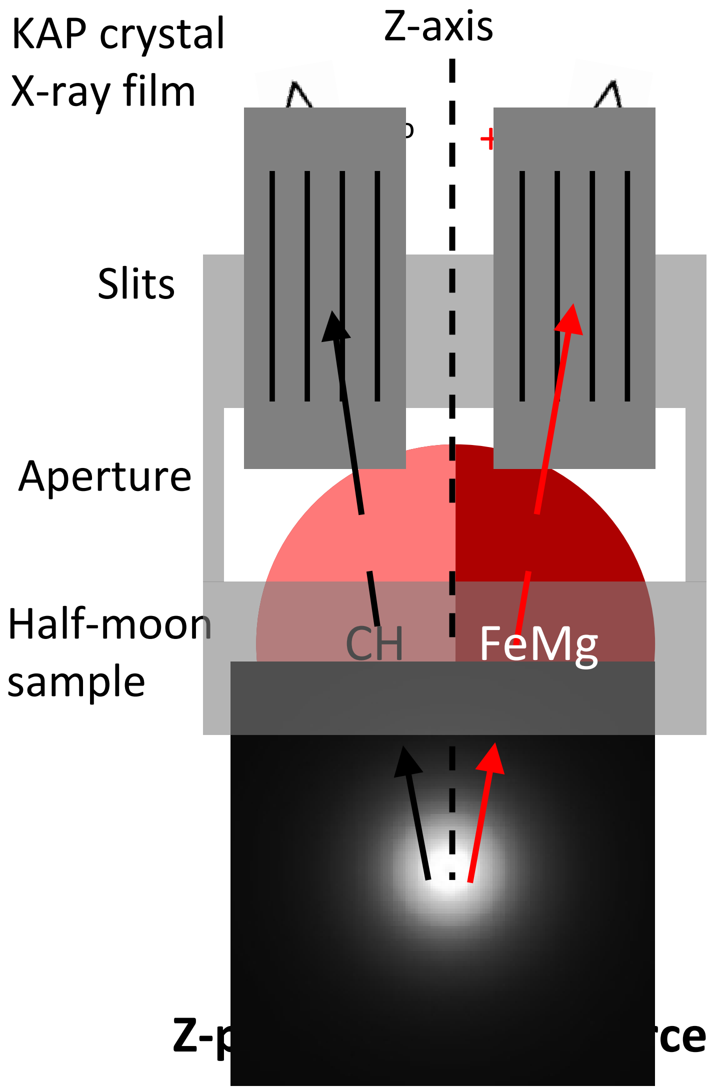

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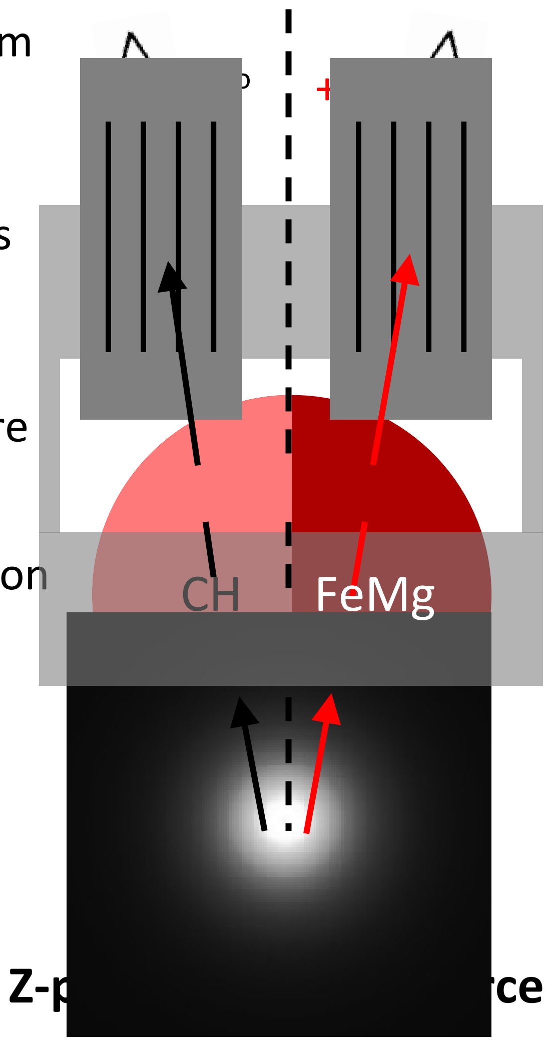

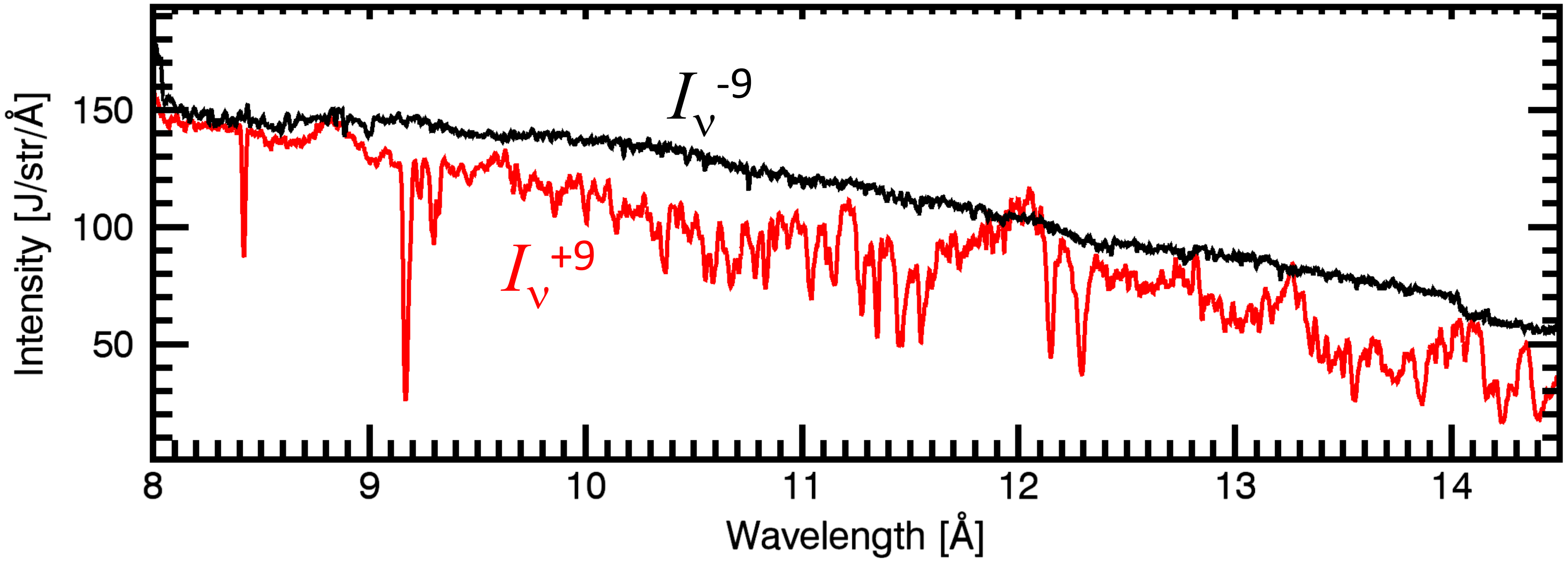

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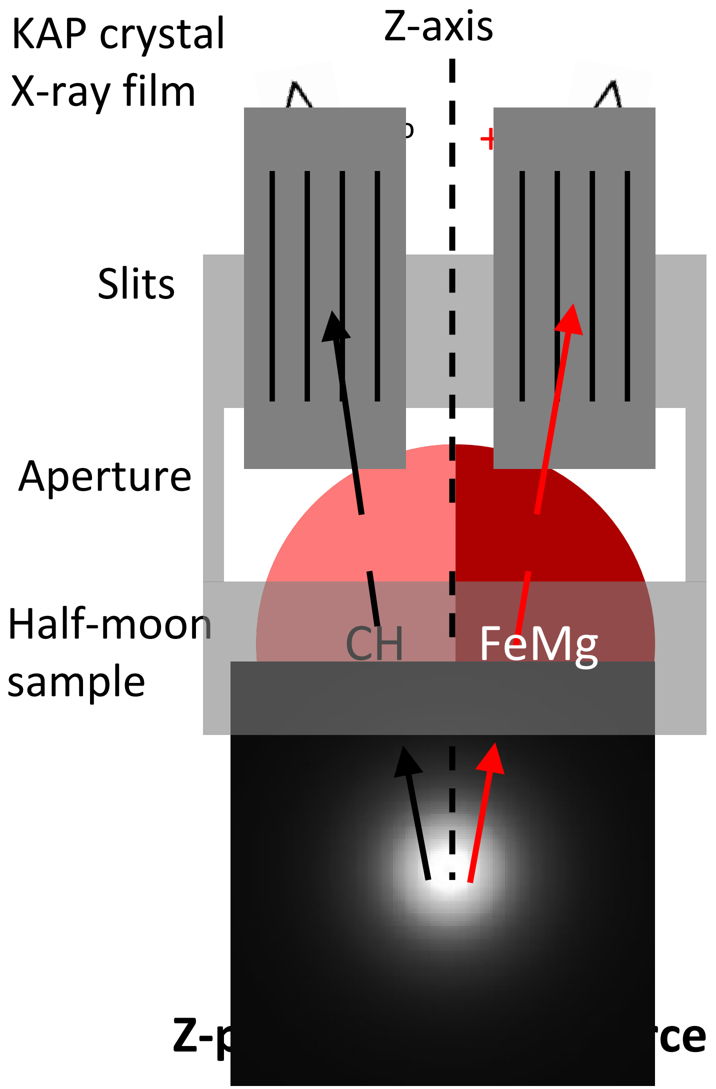

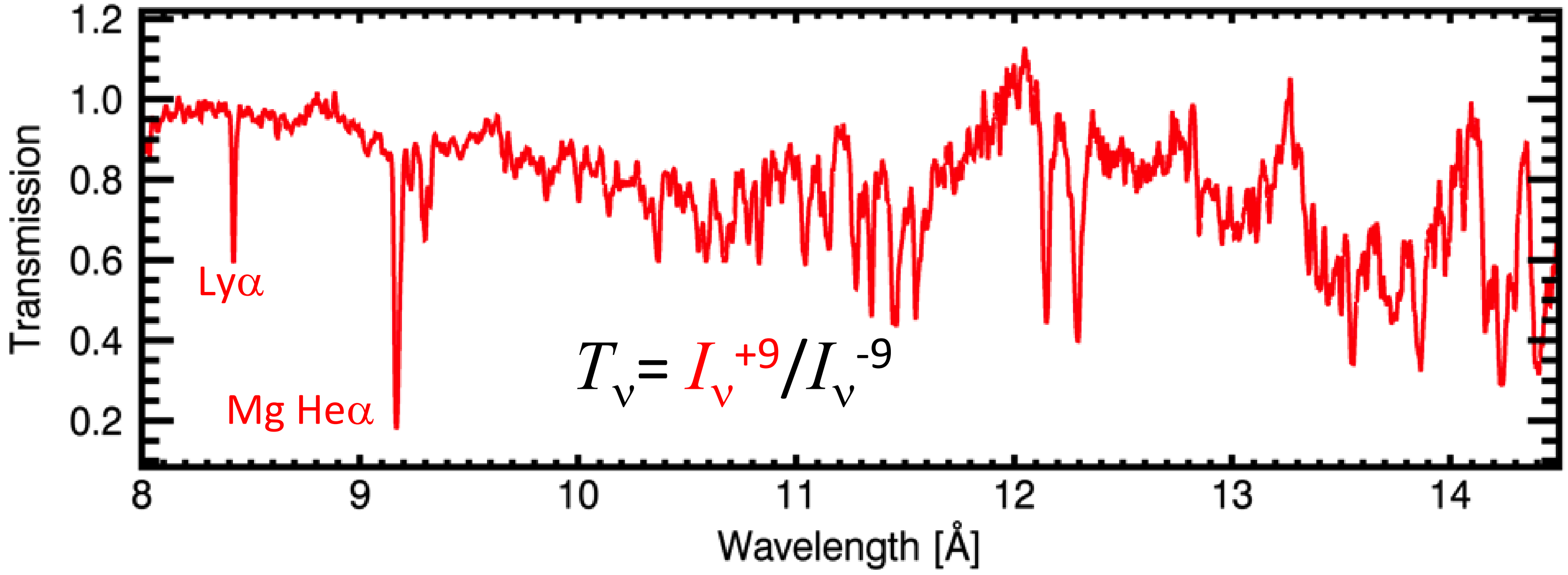

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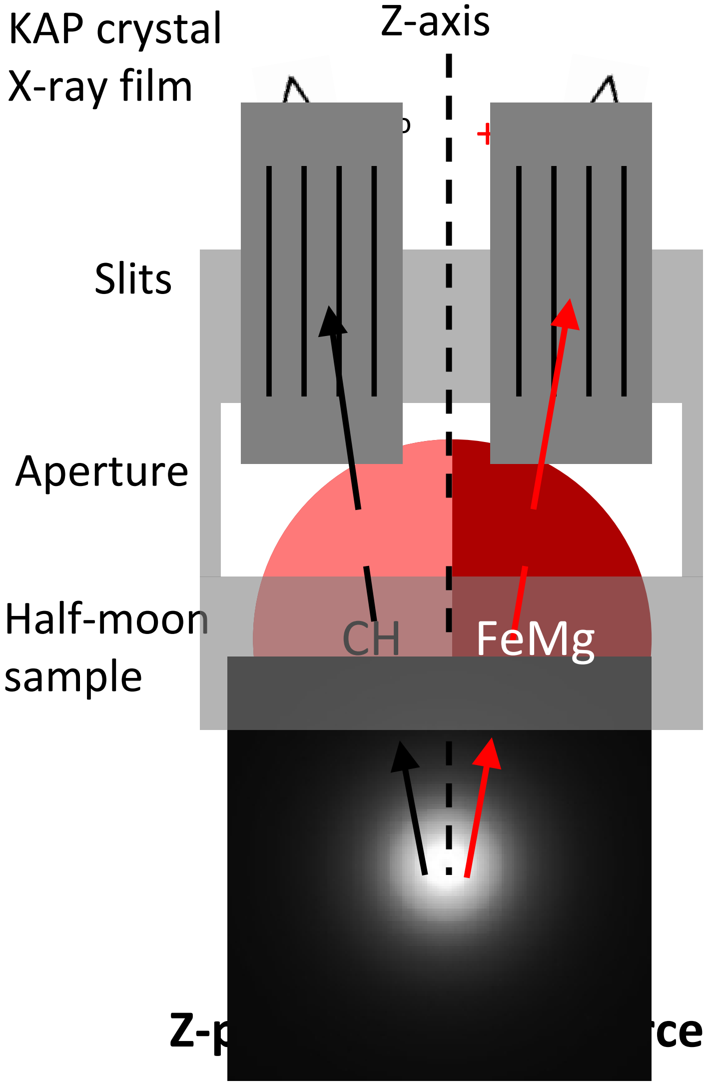

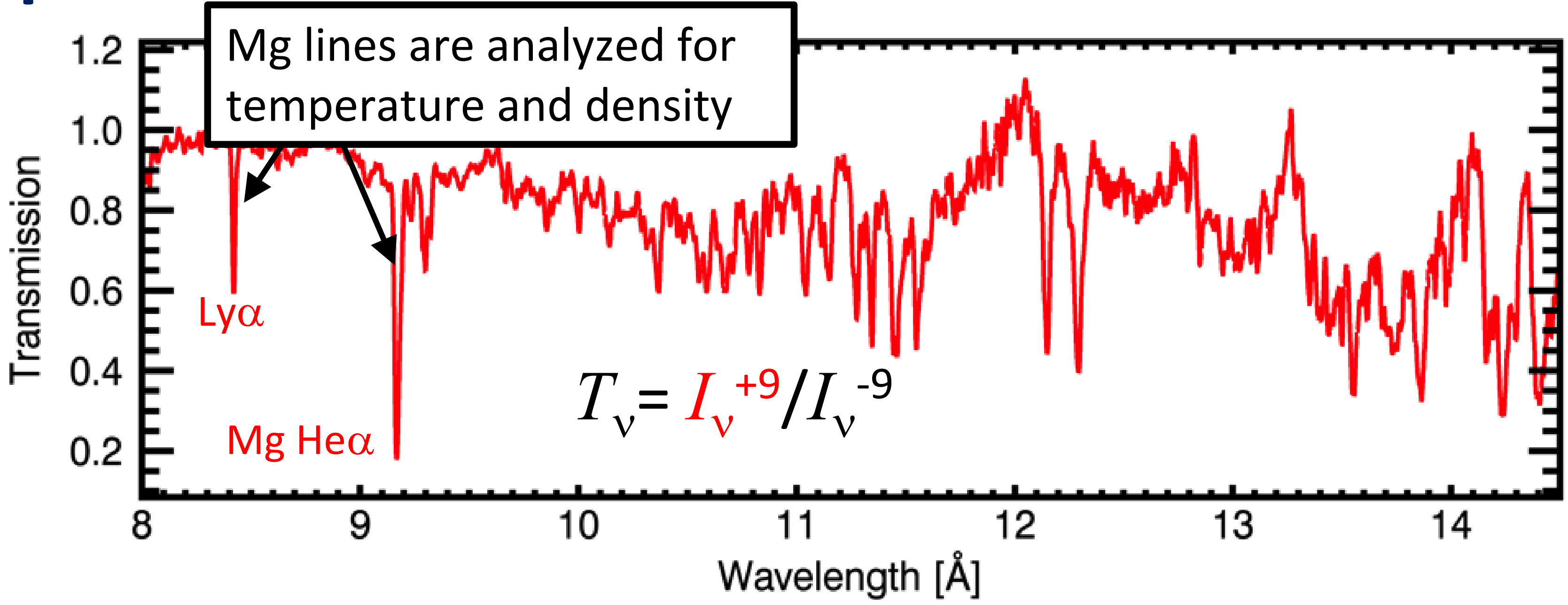

Requirements	SNL Z satisfies:
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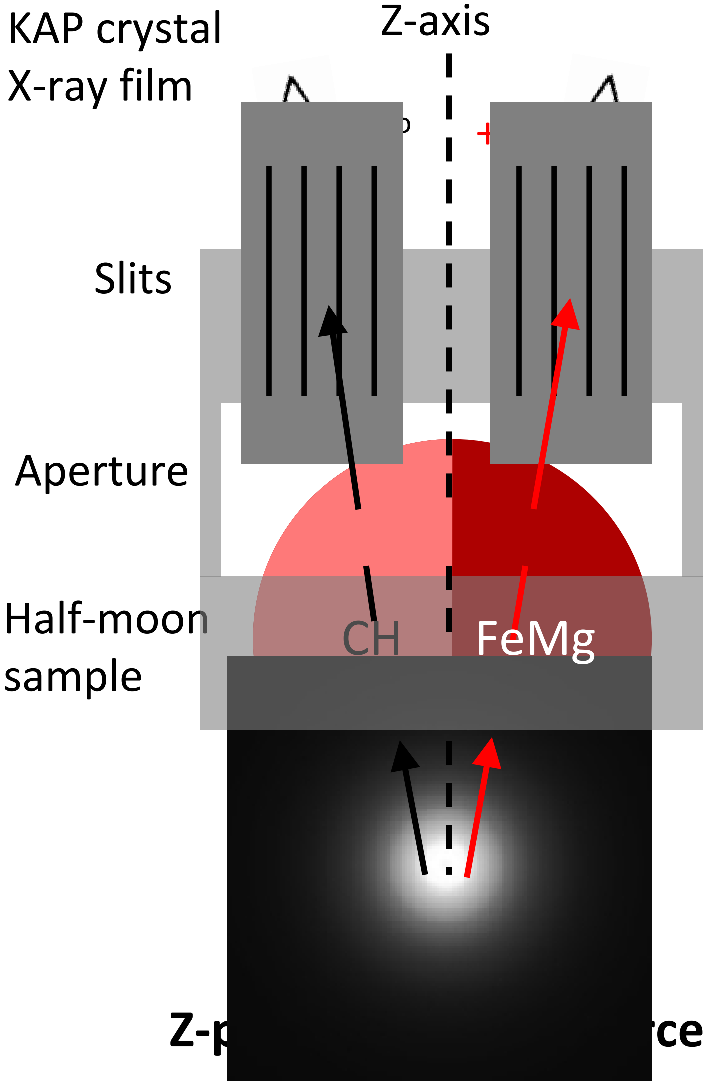

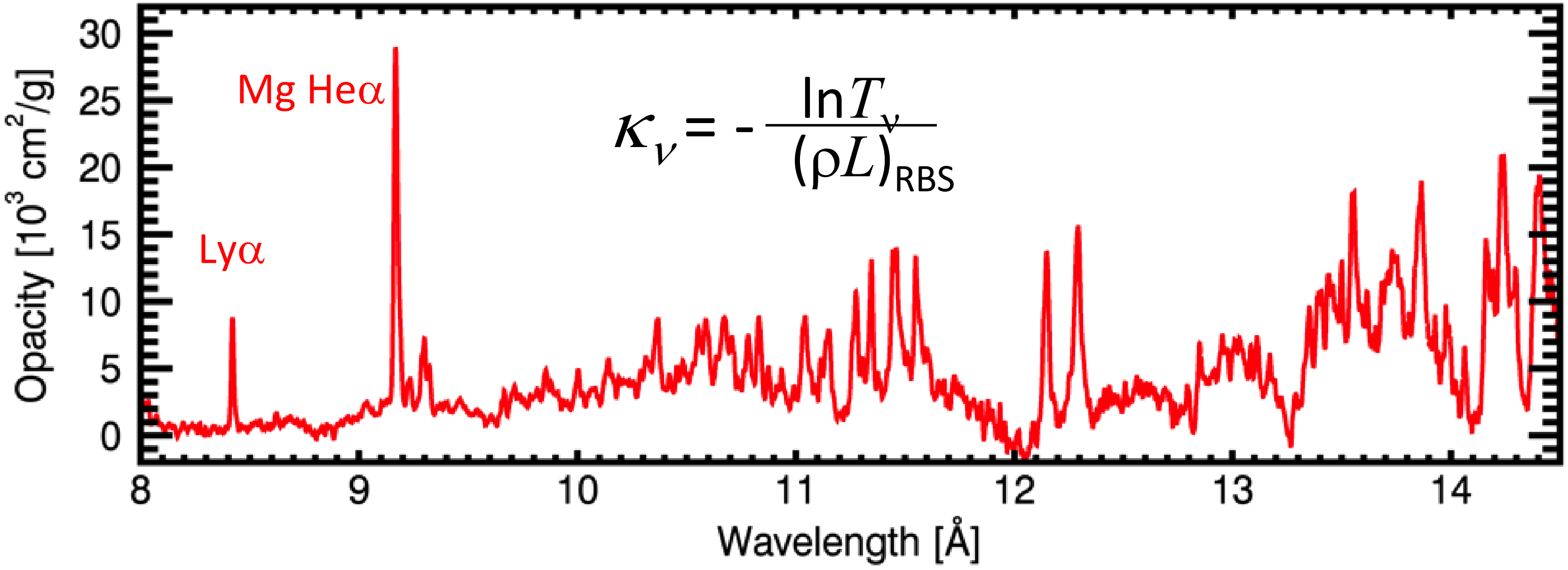

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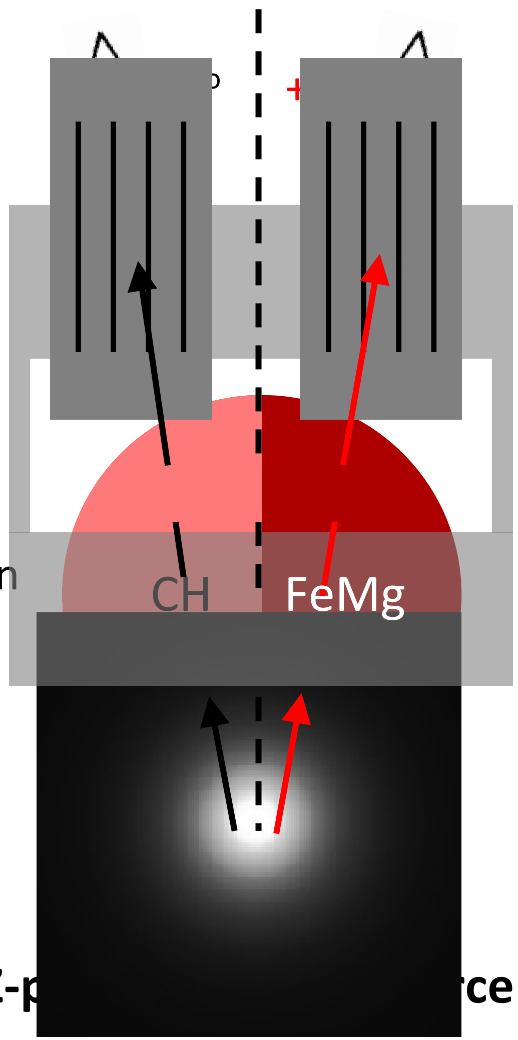

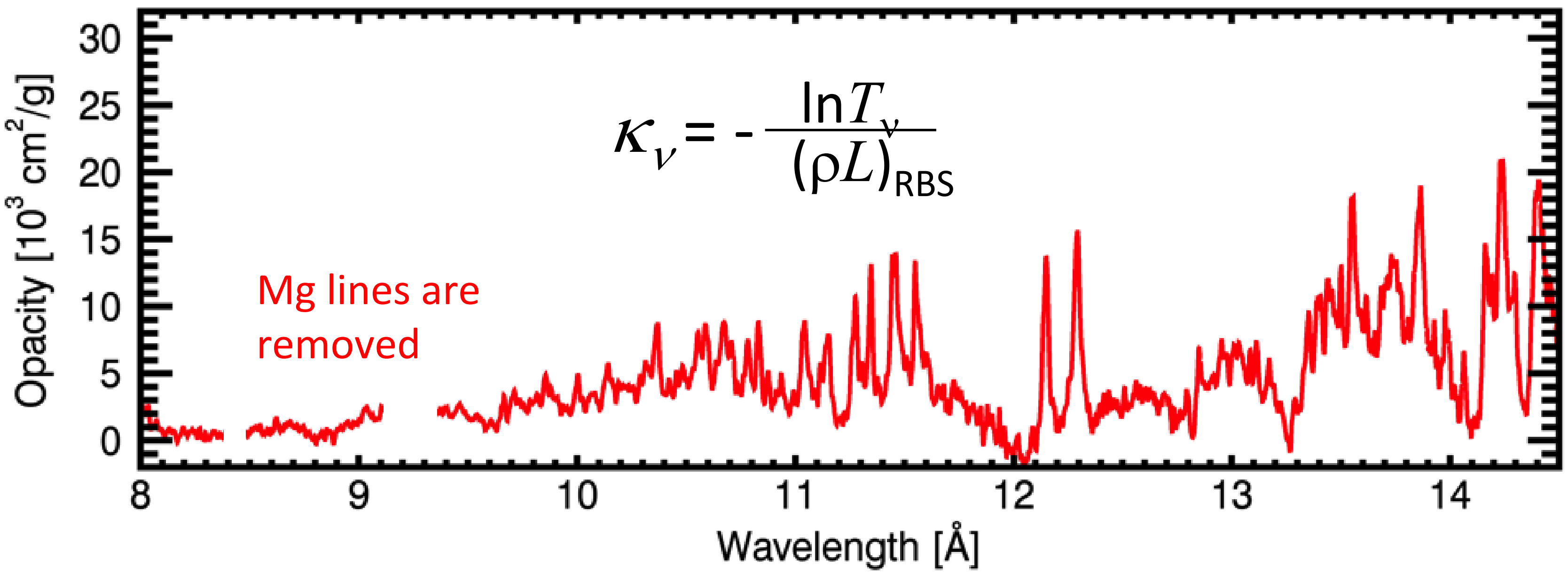

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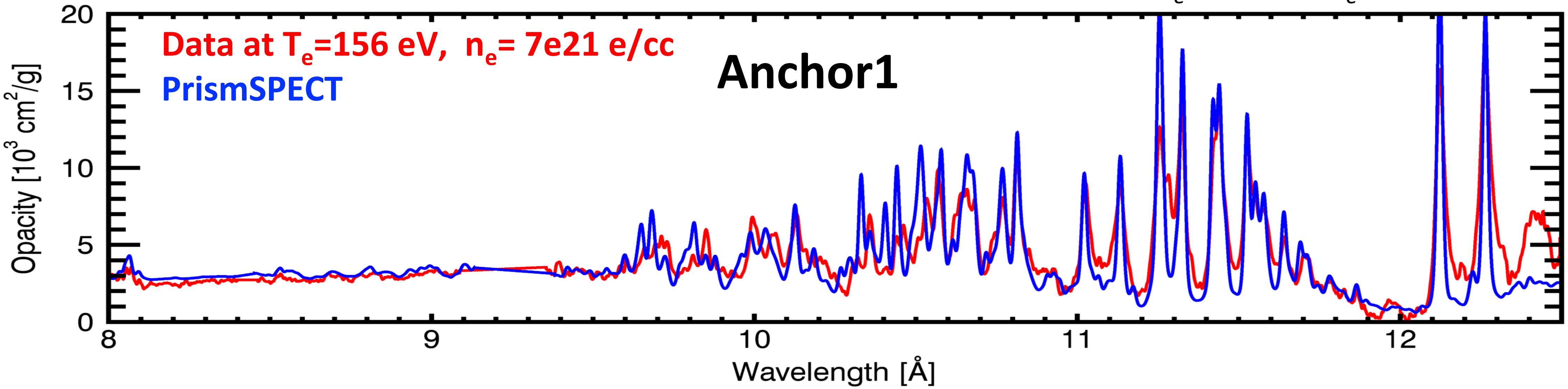
Opacity models disagree with the Z iron data as the condition approaches the solar CZB conditions

Convection Zone Base: T_e=185 eV, n_e = 90e21 e/cc



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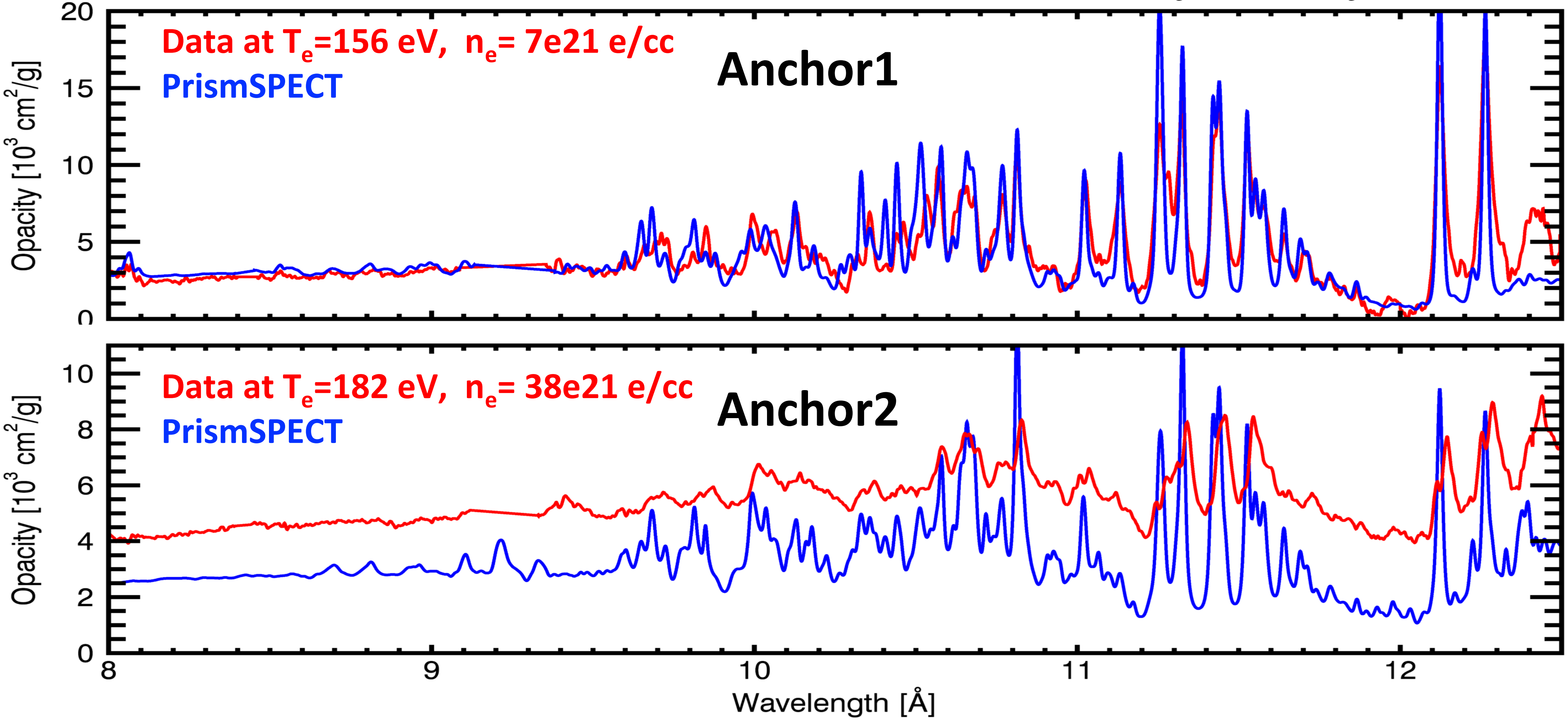

[1] Bailey et al., Nature 517, 56 (2015)

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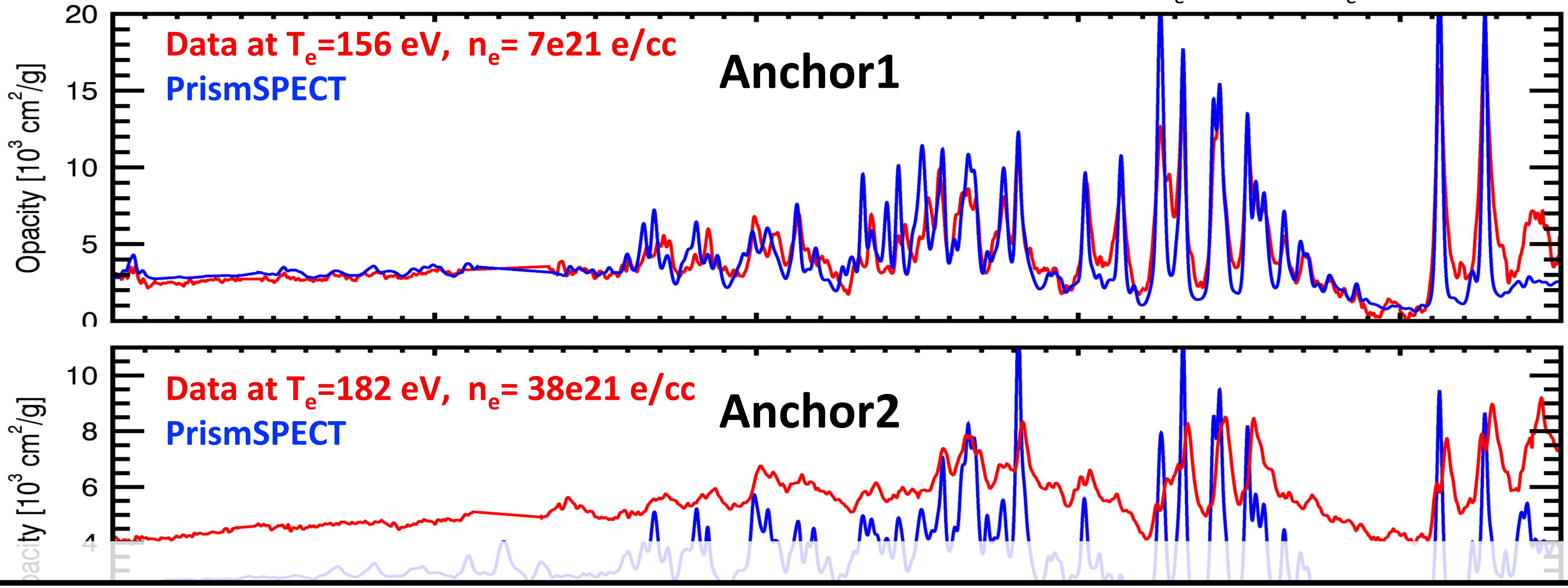
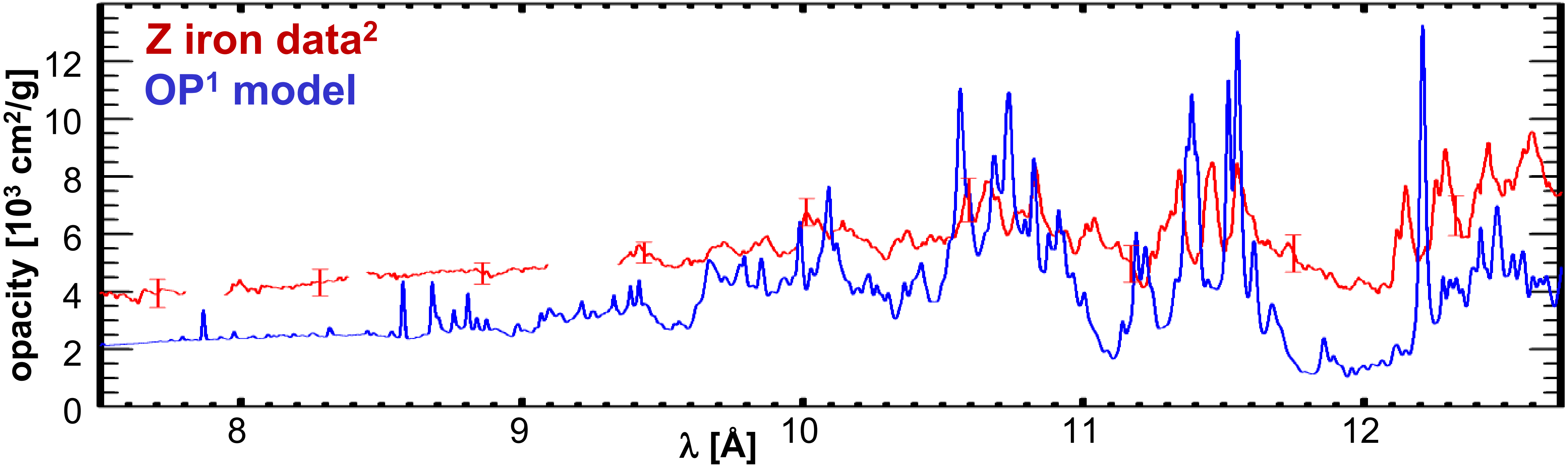


If true, it accounts for about ½ the opacity increase needed to resolve the solar problem

→ But, why do they disagree?

[1] Bailey et al., Nature 517, 56 (2015)
[2] Nagayama et al., Phys Plasmas 21, 056502 (2014)

Opacity disagreement is disturbing and most likely caused by multiple sources



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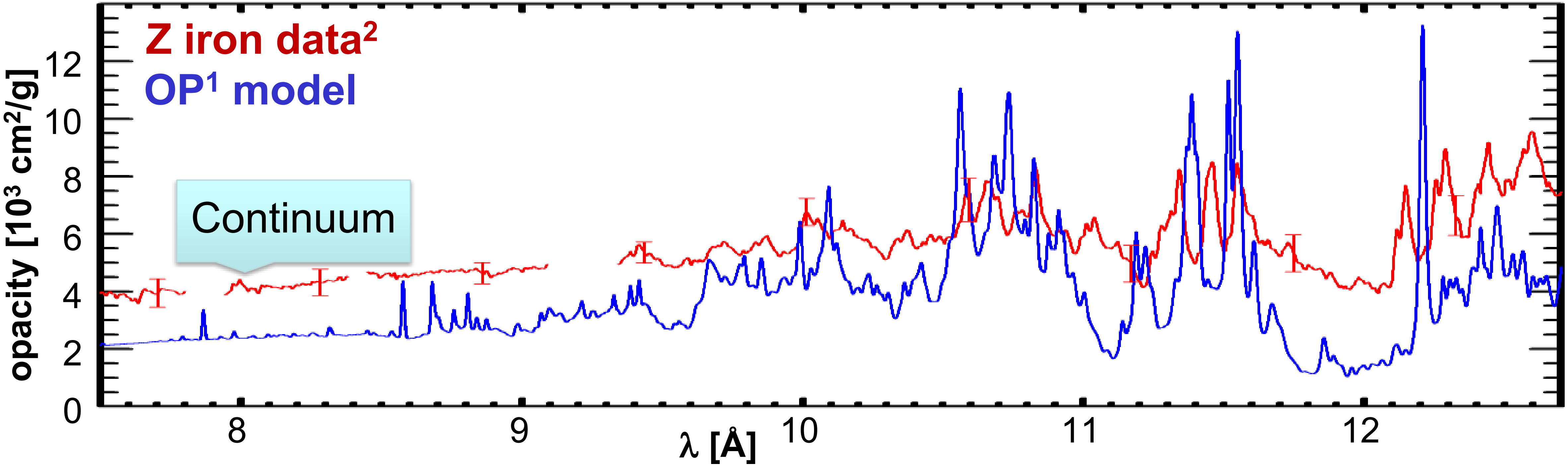

Calculations are:

- **Lower in continuum (Continuum)**

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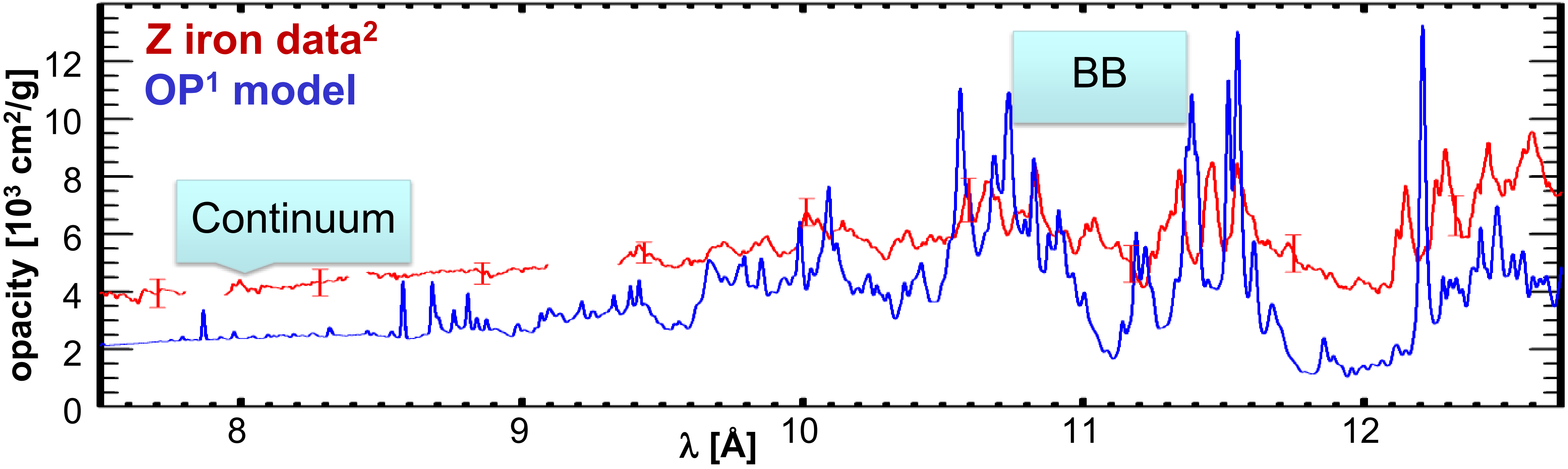

Calculations are:

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- **Narrower in bound-bound lines (BB)**

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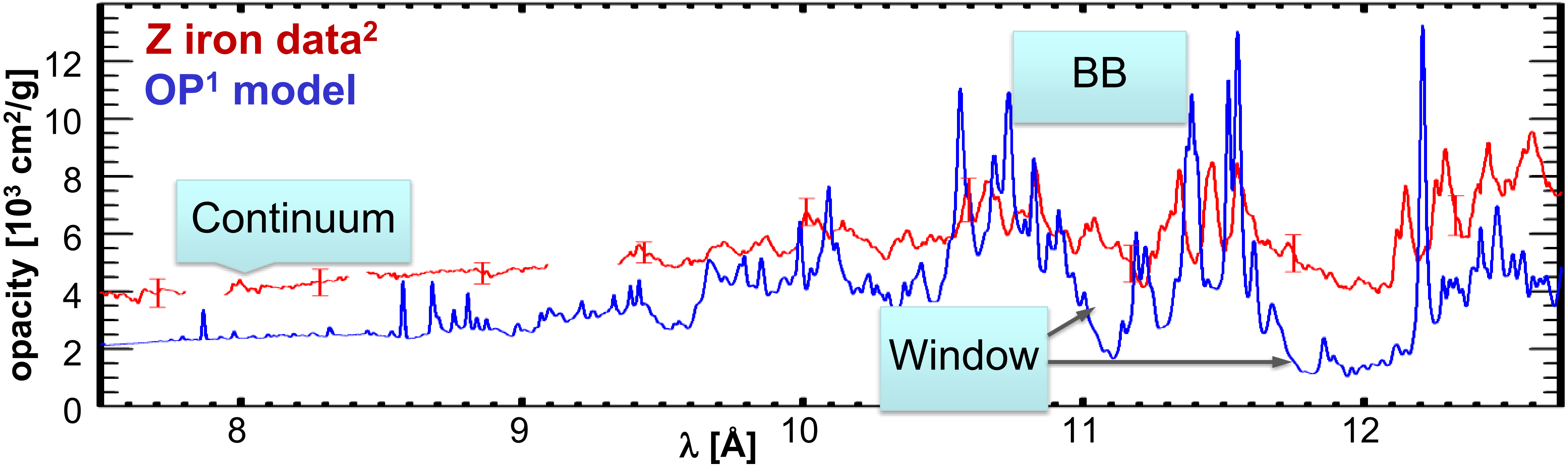

Calculations are:

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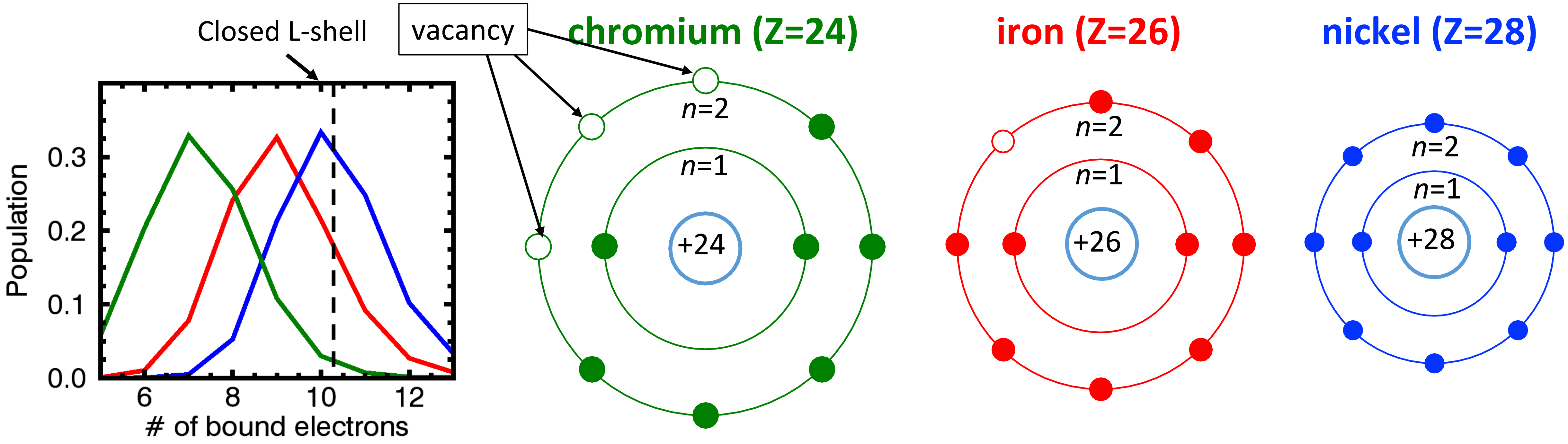
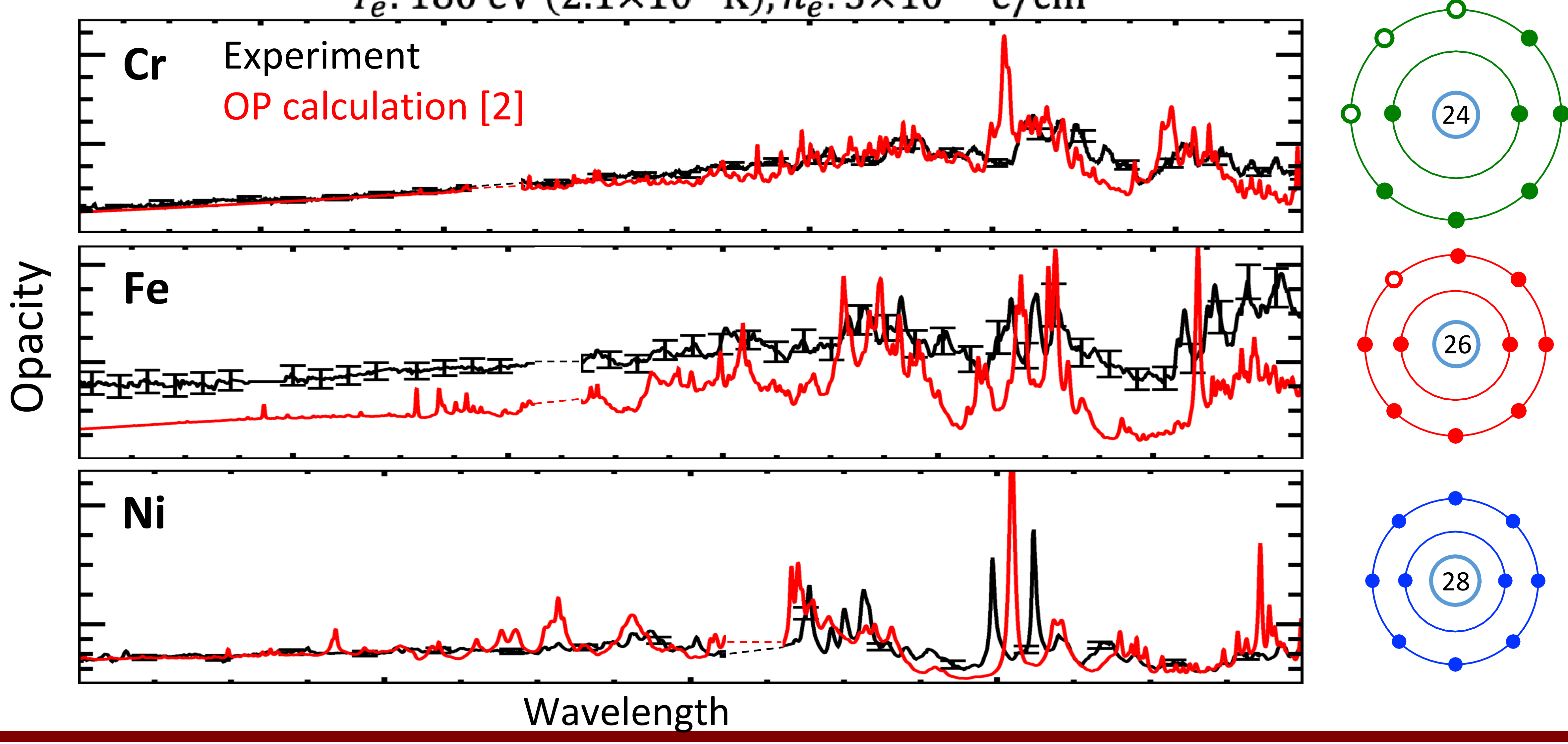
- **Lower in opacity valleys (Windows)**

First systematic study of high-temperature L-shell opacities were performed for Cr, Fe, and Ni at two conditions



First systematic study of high-temperature L-shell opacities narrowed down hypotheses for the discrepancies

T_e: 180 eV (2.1×10^6 K), n_e: 3×10^{22} e/cm^3



[1] Nagayama et al PRL (2019)
[2] Badnell et al, Mon. Not. R. Astron. Soc. (2005)

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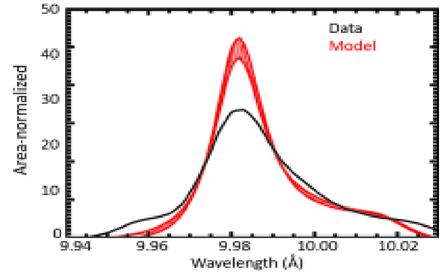
Sandia National Laboratories

BB: Measured lines are broader

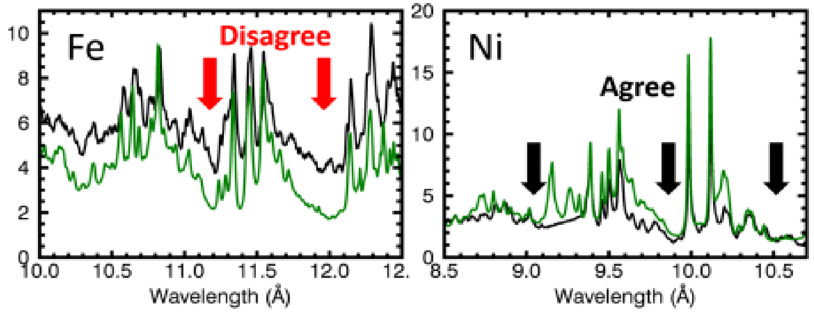
→ Inaccurate line-shapes **OR**

→ Insufficient satellite lines



Windows: Disagreement happens for Cr and Fe

→ Calculation becomes less accurate as # of L-shell vacancies increases



Quasi-continuum: Severe disagreement only on Fe

→ **Experiment:** Undetected flaw in anchor2 Fe

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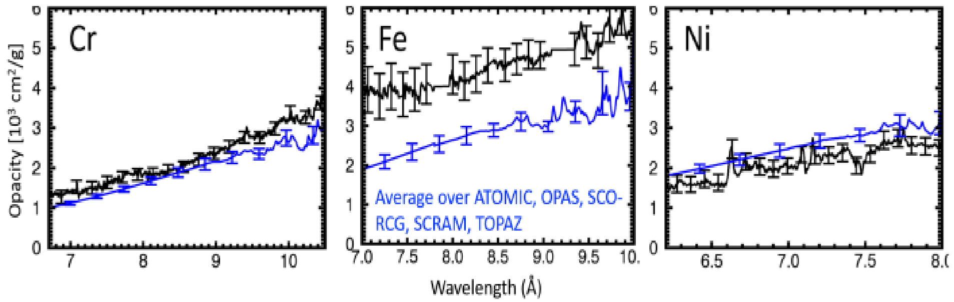

Systematic study results are guiding our current investigations

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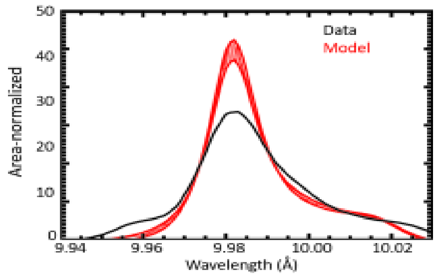

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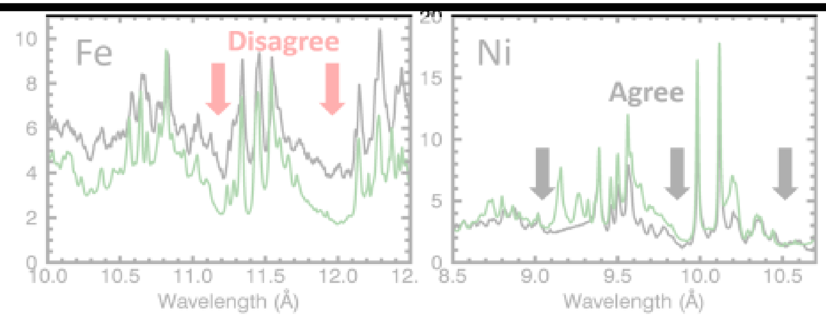

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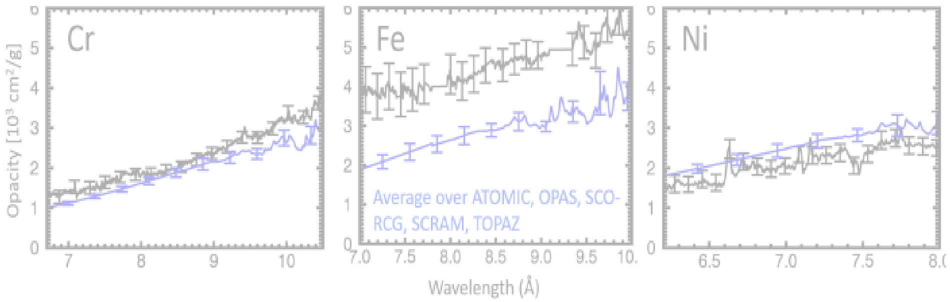

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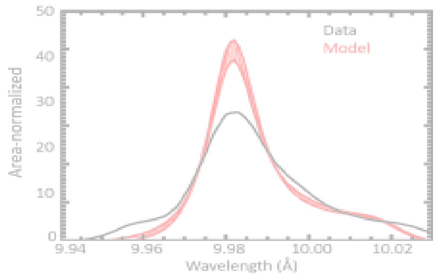

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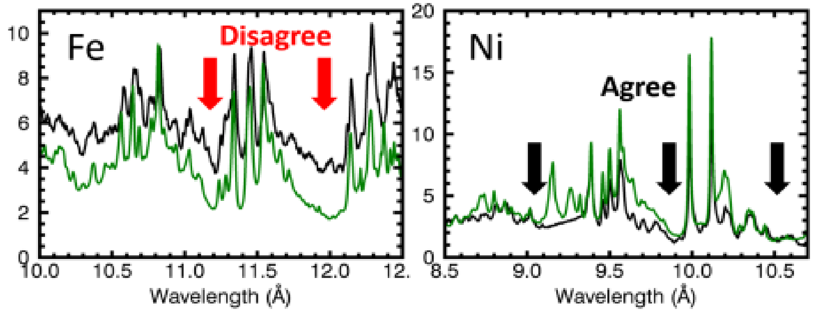

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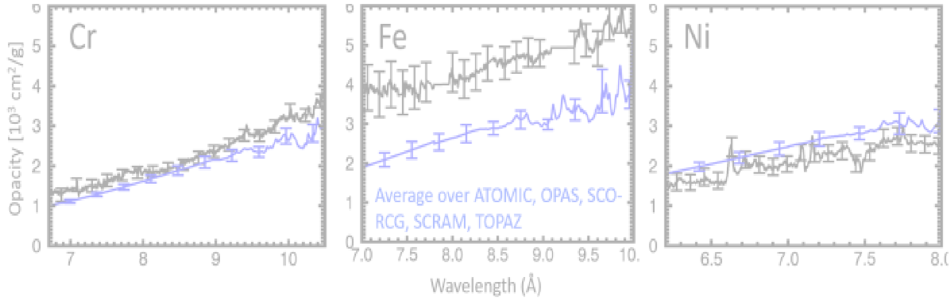

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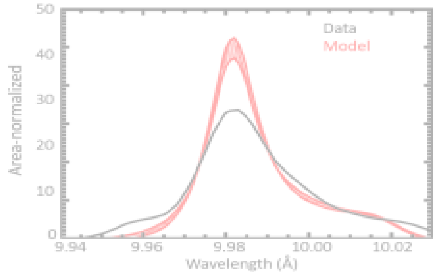

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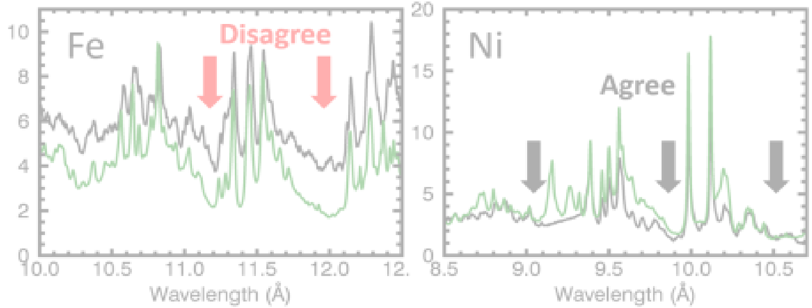

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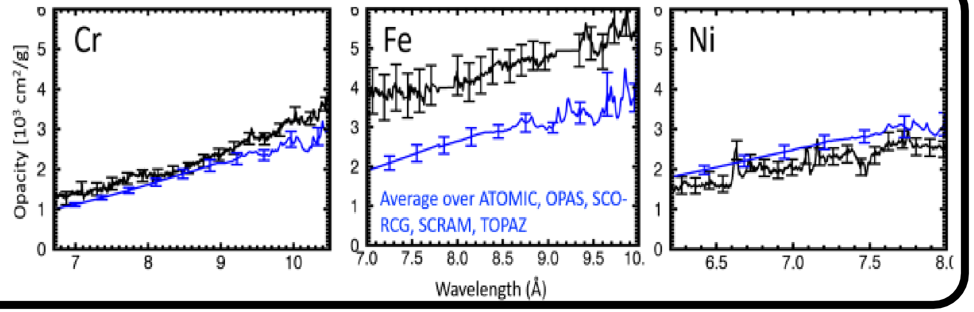

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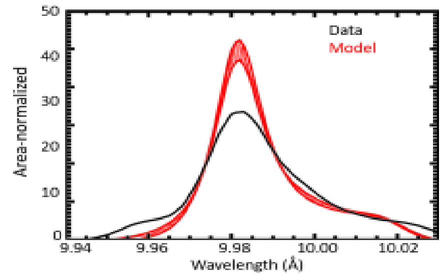

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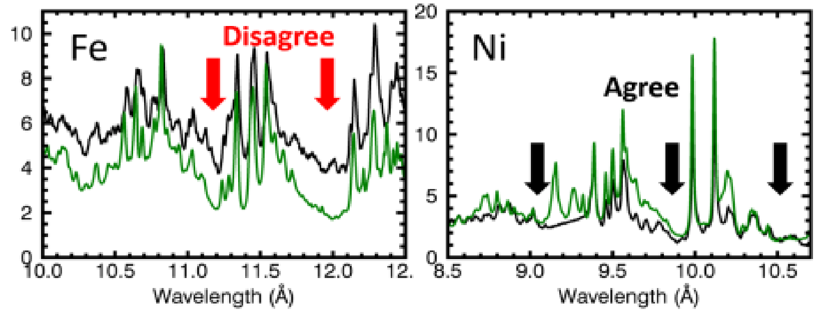

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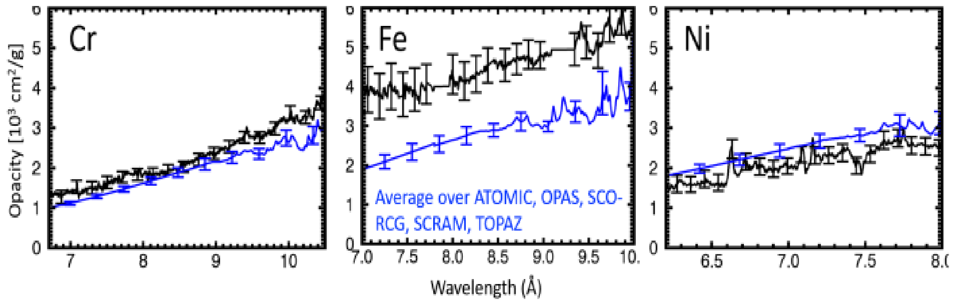

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Over the last few years, we have advanced opacity science in experiments, analyses, and theory for resolving the solar problem

Experiments

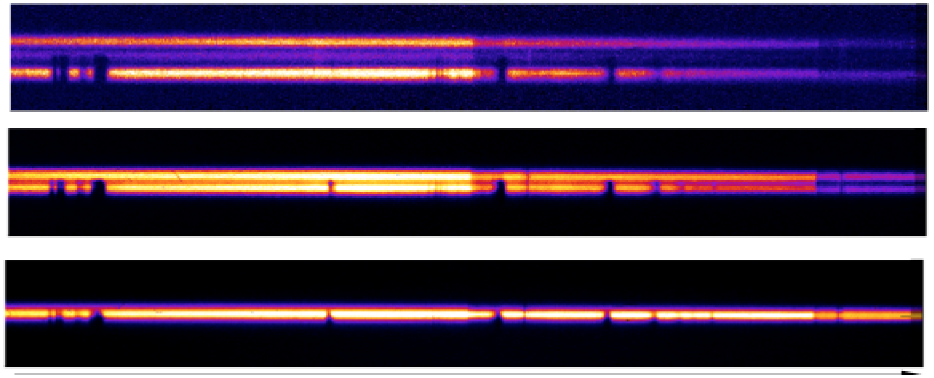
- More iron experiments
- Time-resolved spectroscopy
- Oxygen opacity experiments

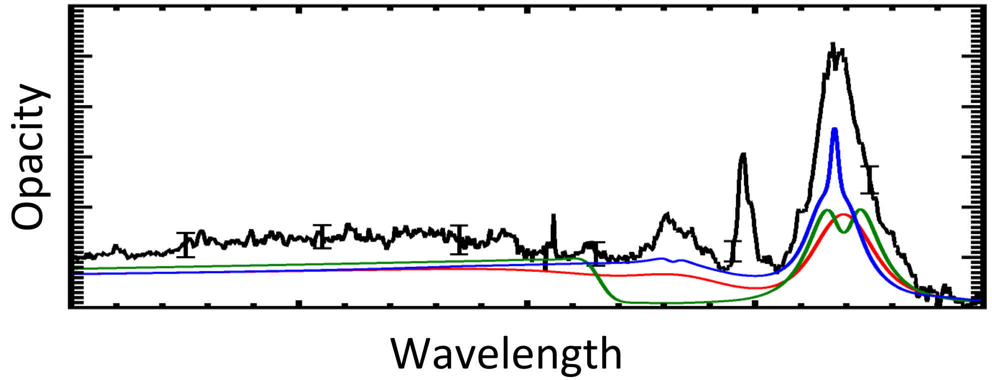
Analyses

- Opacity analysis
- Background analysis [3]
- T_e and n_e analysis

Theory

- Two-photon opacity [1]
- Spectral line shapes [2]





WCAPP students and postdocs will be trained in HEDP atomic physics and spectroscopy through state-of-the-art stellar opacity research and will help resolve the solar problem

[1] R. More HEDP (2019) [2] T. Gomez PRL (2020, 2021?) [3] G. Dunham RSI (2021)

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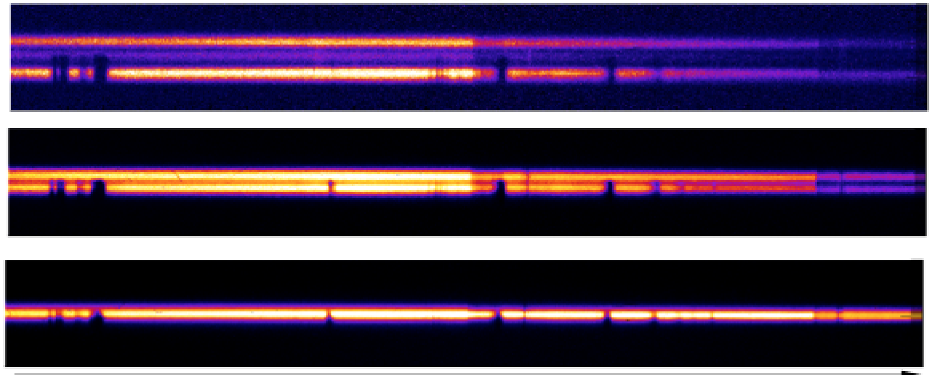

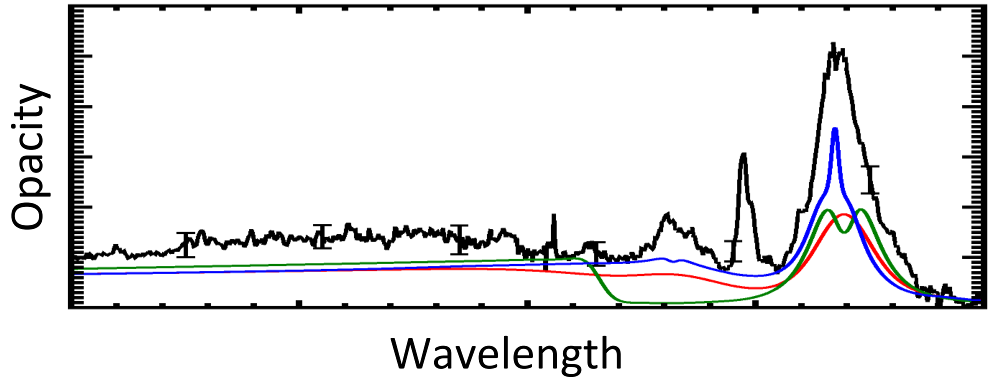

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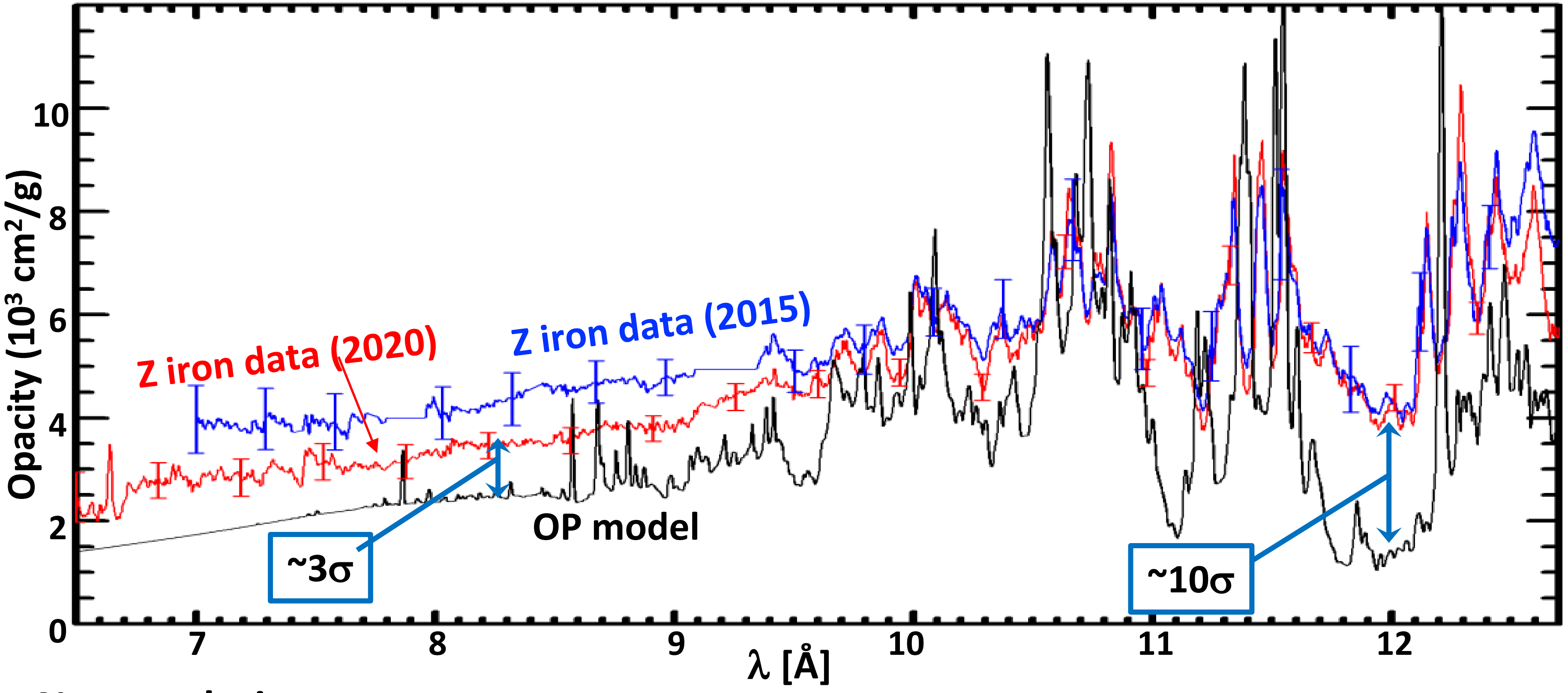
More experiments and reanalysis reduced the model-discrepancy for Anchor 2 iron, but ~ 3-10 σ differences remain



Quasi continuum discrepancy

2015: ~ 1800 cm2/g; ~4σ

2020: ~ 960 cm2/g; ~3σ

Window discrepancy

2015: ~ 2900 cm2/g; ~ 5σ

2020: ~ 2700 cm2/g; ~ 10σ

We found similar results for Fe at anchor3

New analysis:

- Statistically analyze backlight using large volume of calibration data
- Propagate three sources of opacity uncertainty (backlight, background, areal density)

➔ Opacity probability distribution as a function of wavelength

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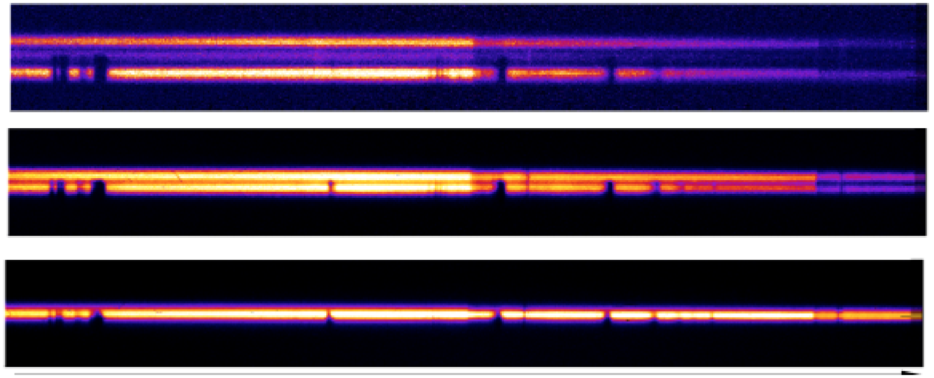

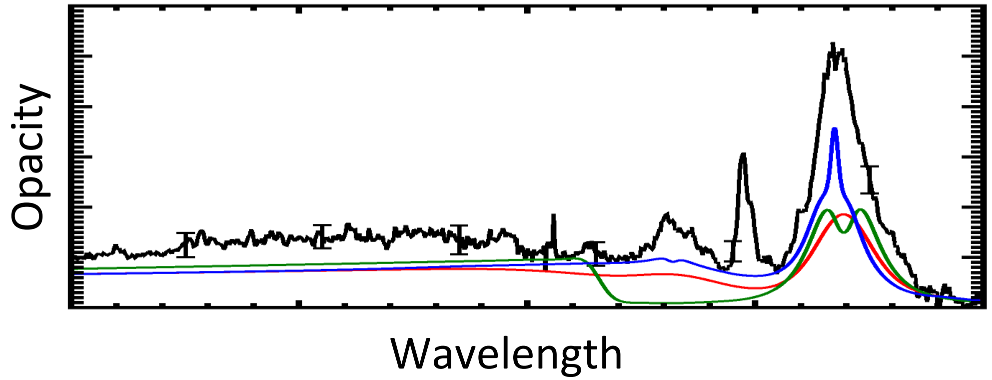

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Over the last few years, we have advanced opacity science in experiments, analyses, and theory for resolving the solar problem

Experiments

- More iron experiments
- **Time-resolved spectroscopy**
- Oxygen opacity experiments

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- T_e and n_e analysis

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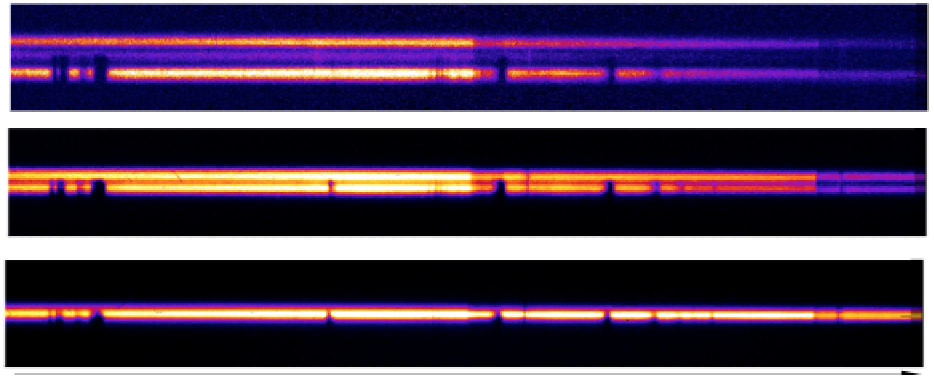
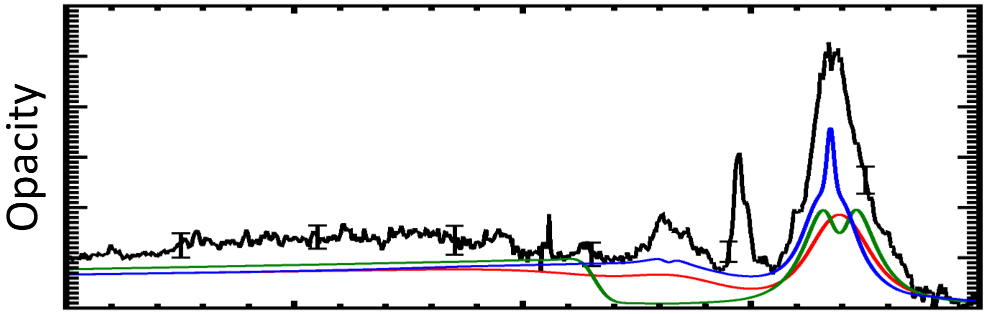
- Two-photon opacity [1]
- Spectral line shapes [2]





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Time resolved measurements are attractive for three reasons

1. Experimentally test the temporal gradient effects

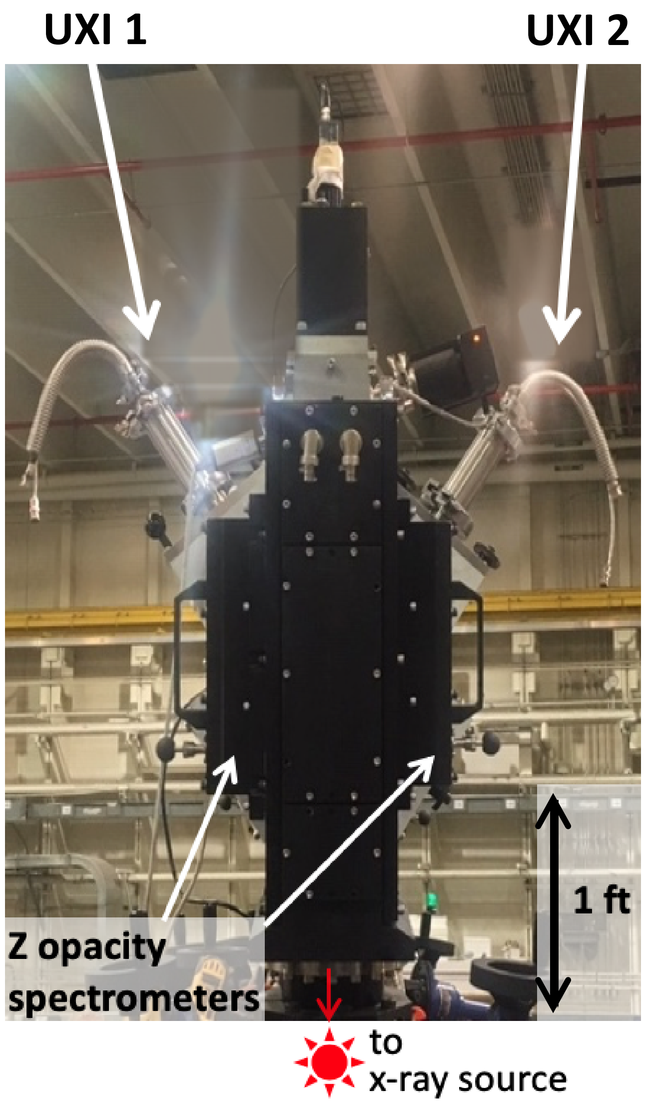
2. Understand and refine our experiments

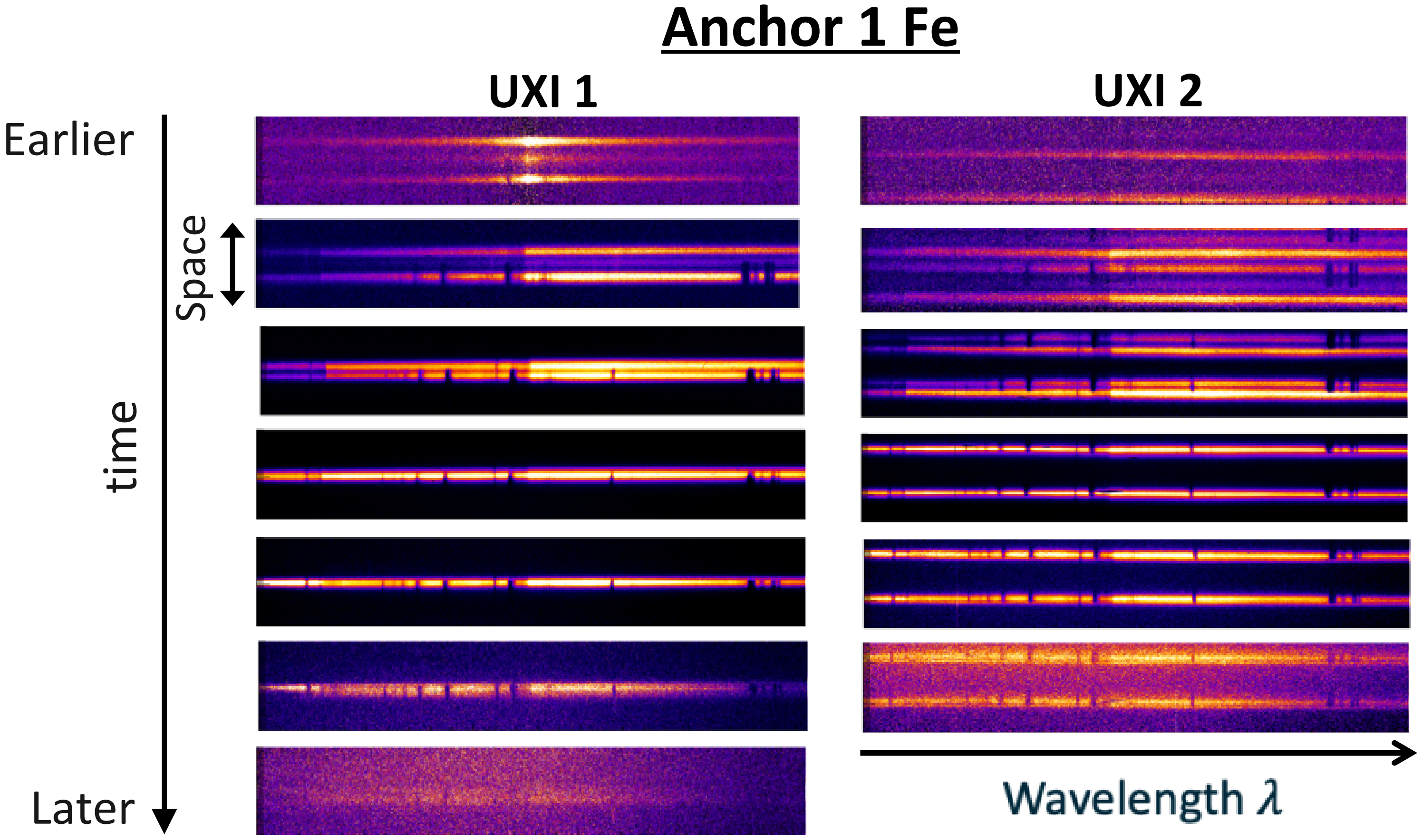
3. Perform time-resolved opacity experiments

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

Sandia developed Ultrafast X-ray Imagers (UXI) were fielded to measure time-resolved FeMg absorption spectral images

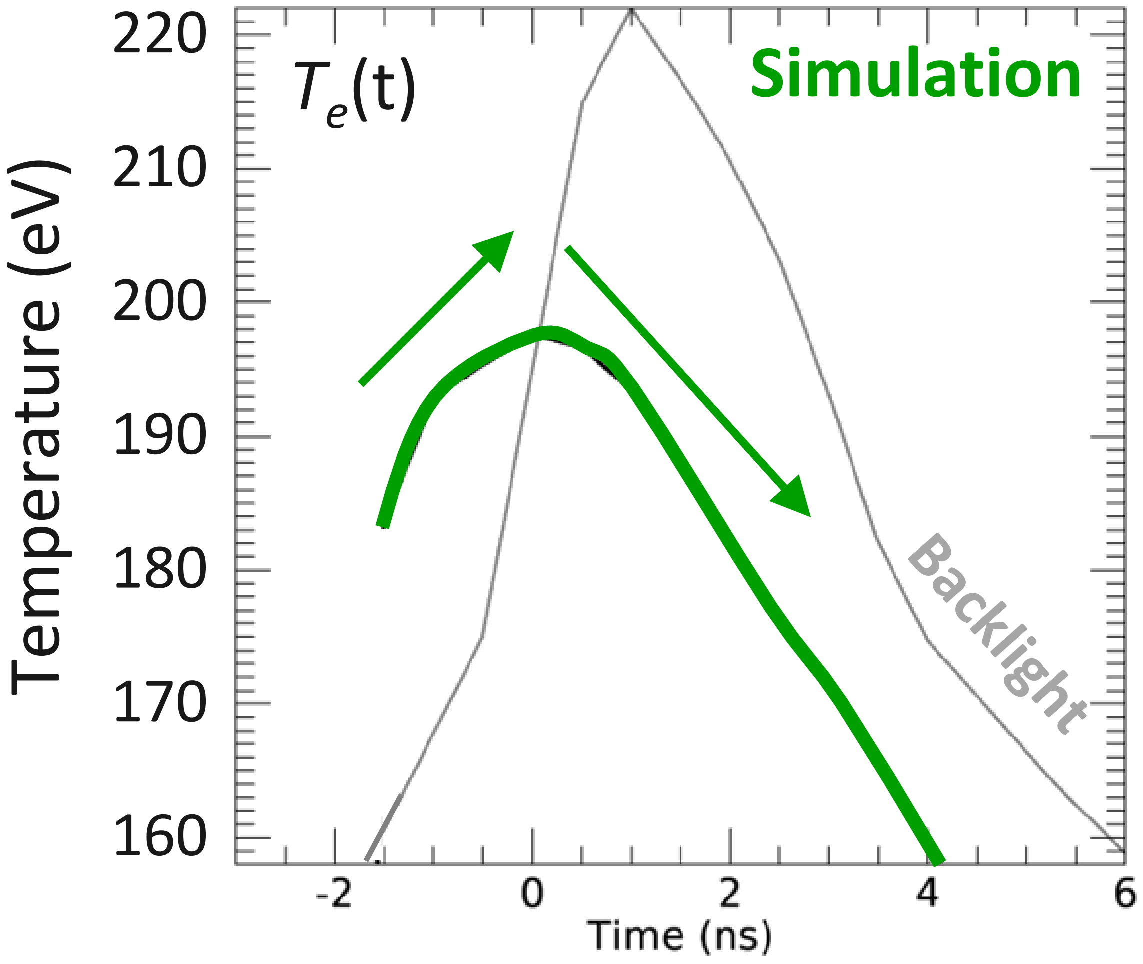


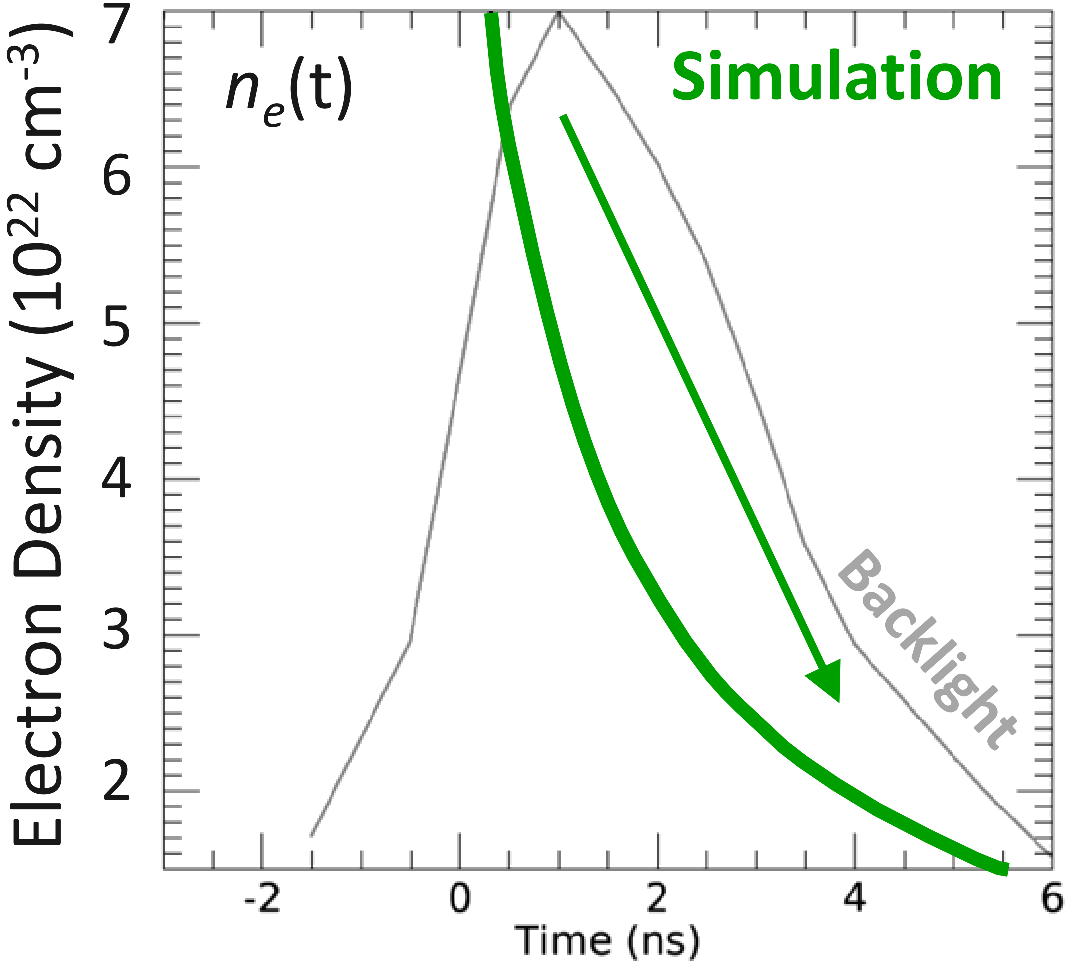


Mg spectra → $T_e(t)$ and $n_e(t)$

Fe spectra→ Time resolved Fe opacity

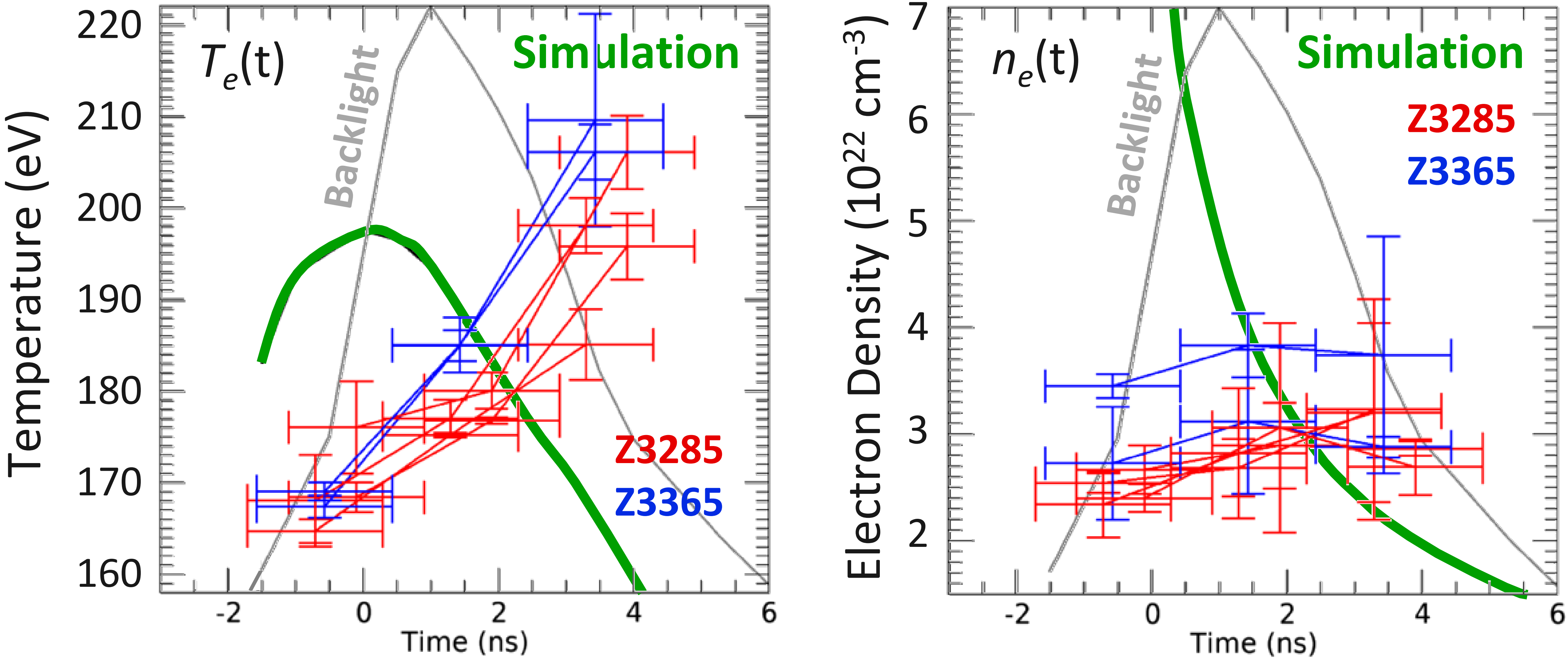
Simulations* predicted that sample temperature goes up and down while density monotonically decreases





* Nagayama et al PRE (2016)

Time-resolved measurement suggested different sample evolution



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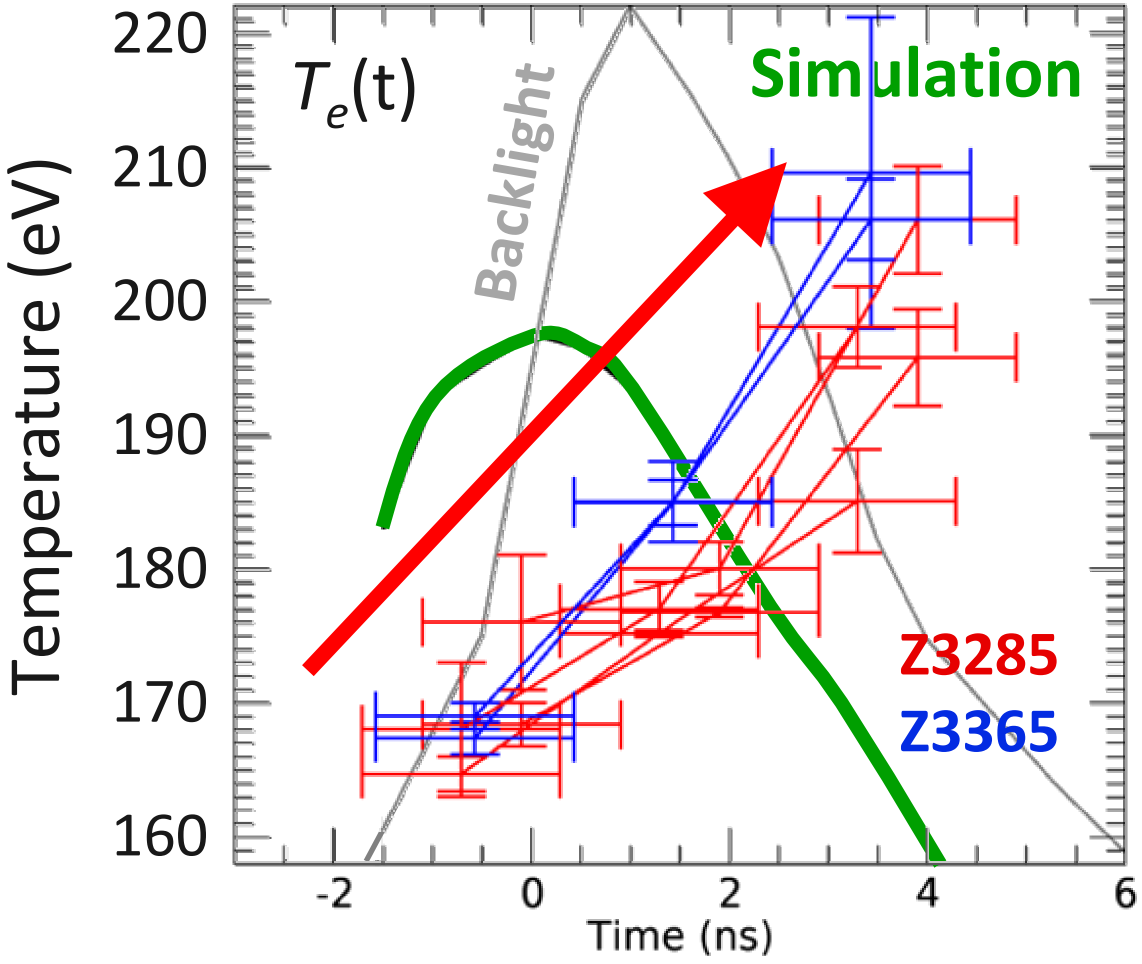

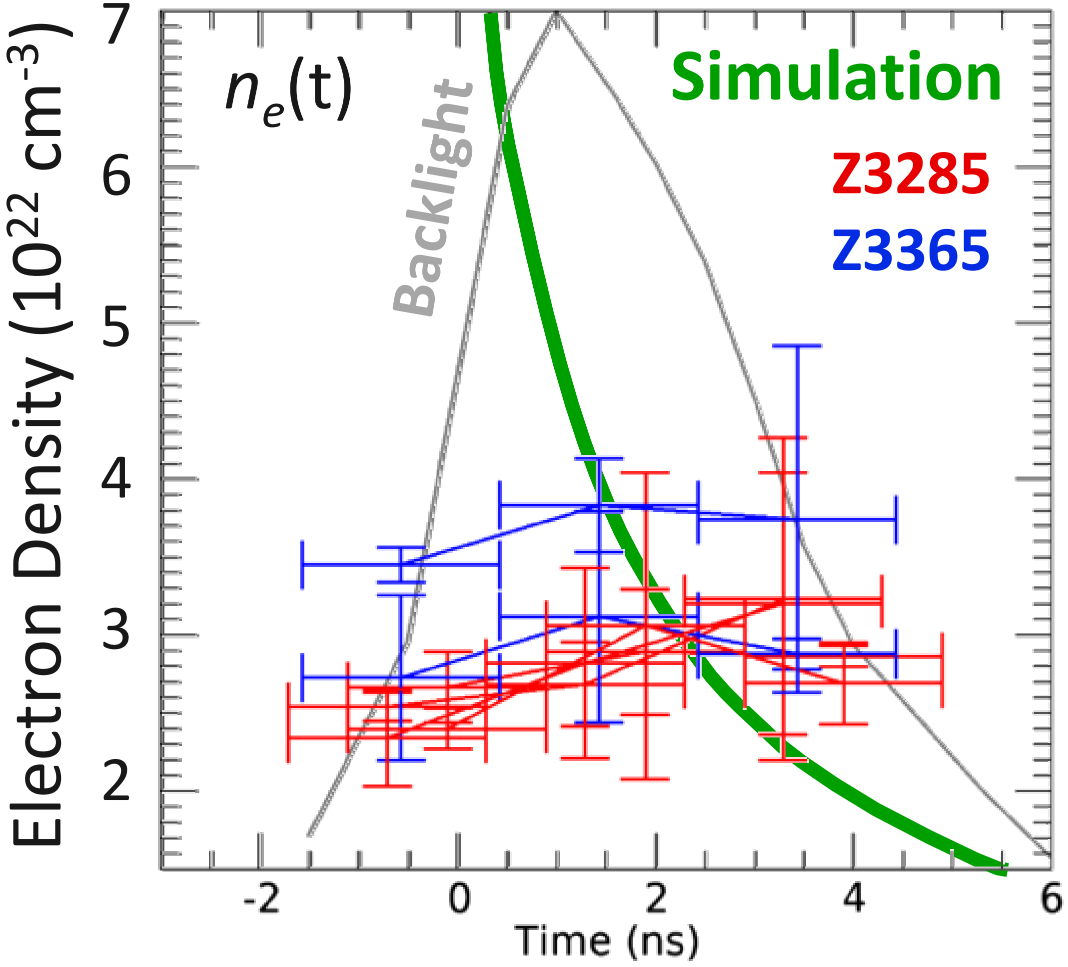

Temperature: Monotonically increasing → Is the sample approaching to the Z pinch?

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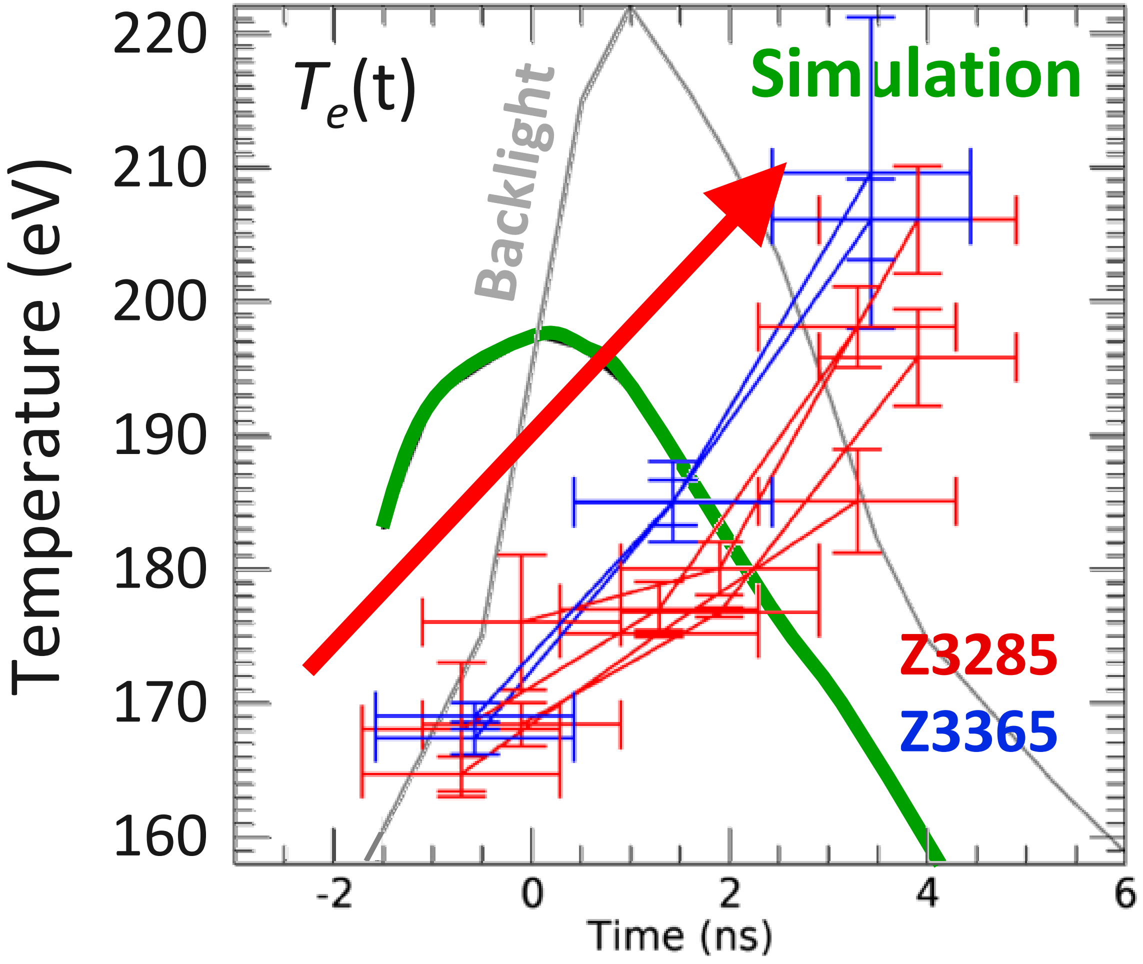
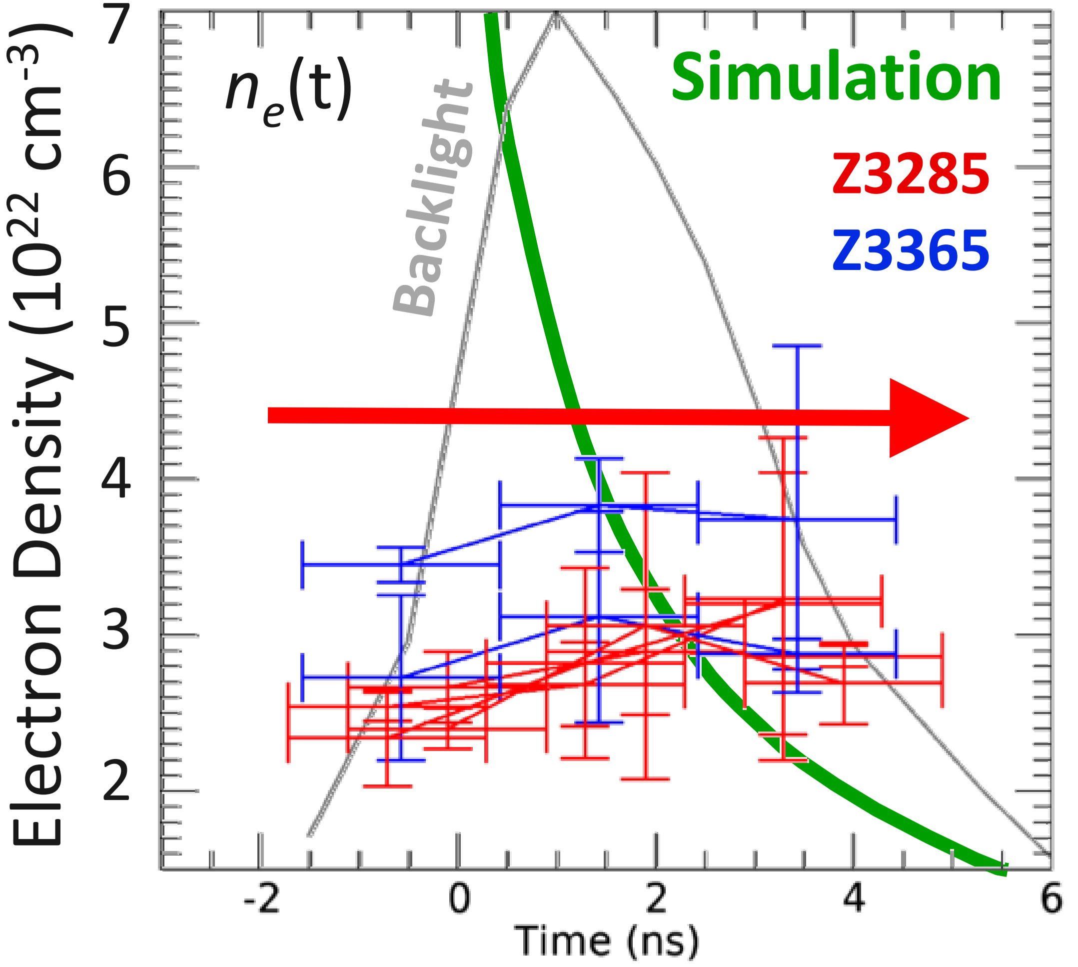


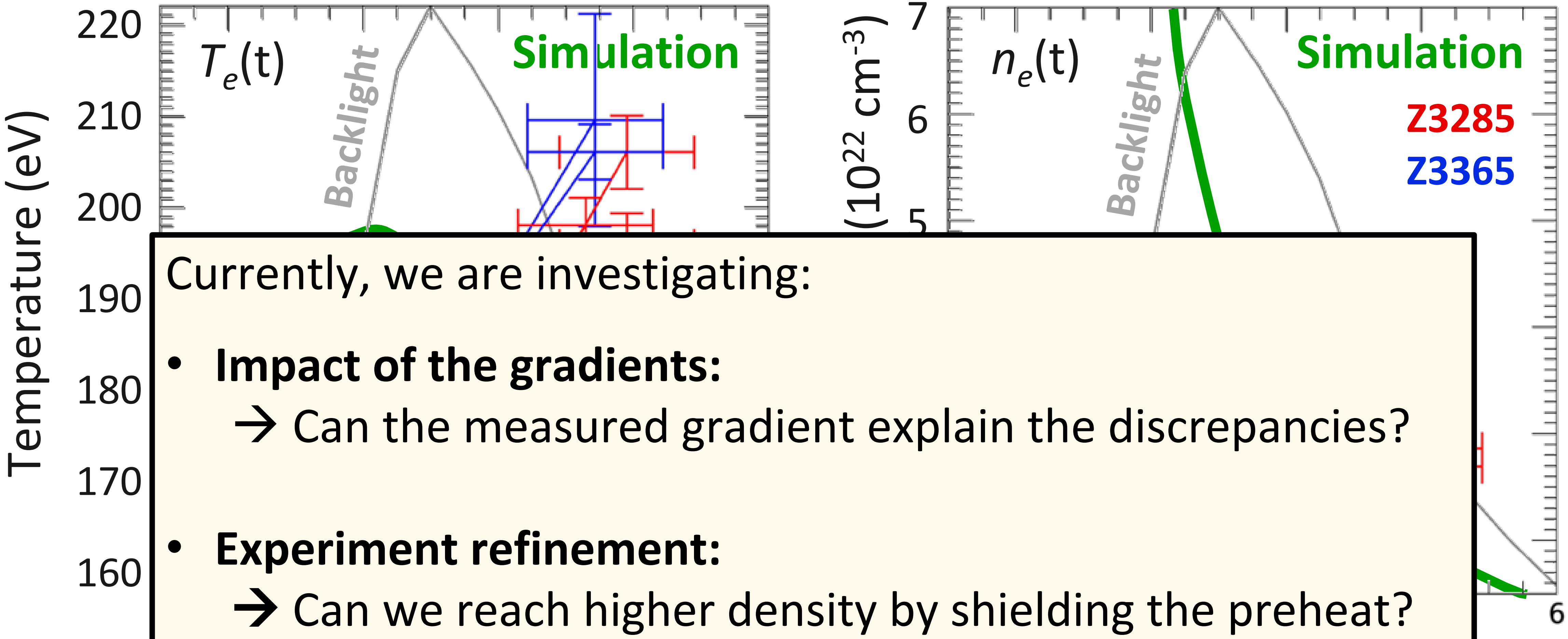


Temperature: Monotonically increasing → Is the sample approaching to the Z pinch?

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

* Nagayama et al PRE (2016)

Time-resolved measurement suggested different sample evolution



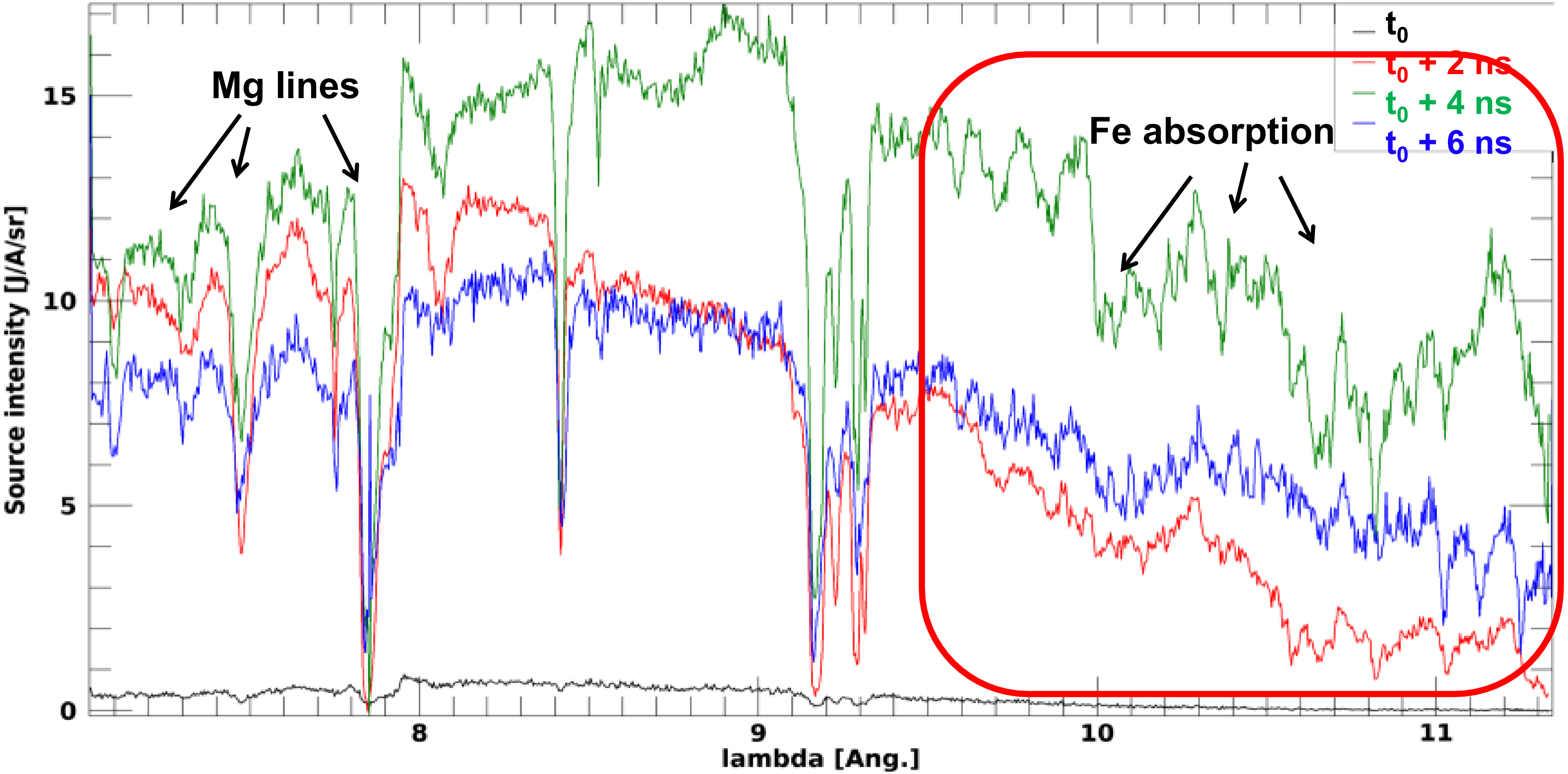
Currently, we are investigating:

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

Temper... ...h?

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

We successfully measured time-resolved Fe absorption spectra; More work needed for time-resolved opacity



variation in shape of features

Need to collect more time-resolved calibration data for accurate opacity determination

Over the last few years, we have advanced opacity science in experiments, analyses, and theory for resolving the solar problem

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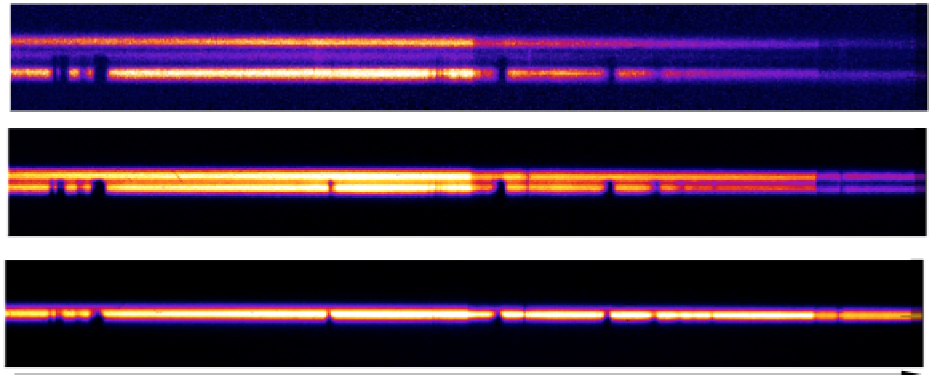

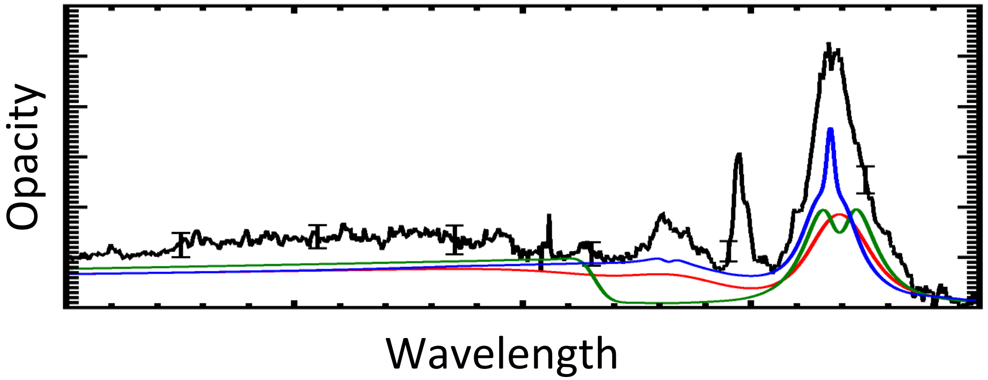

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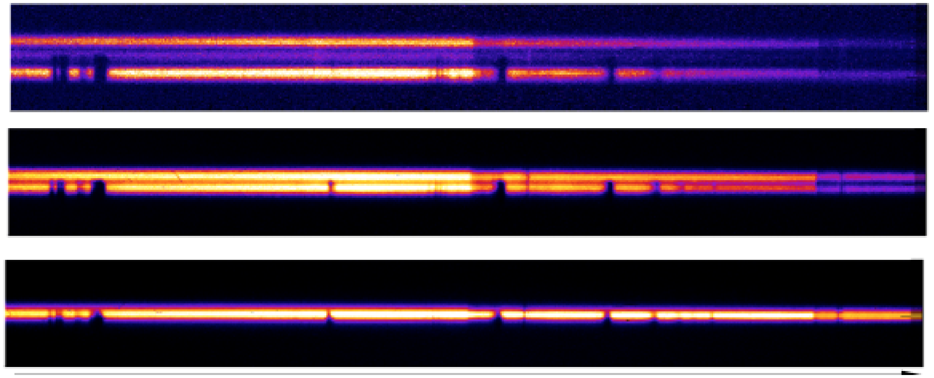

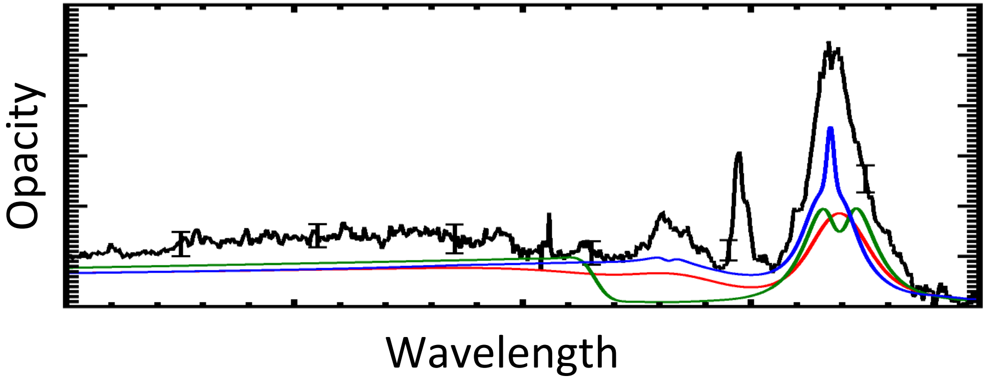

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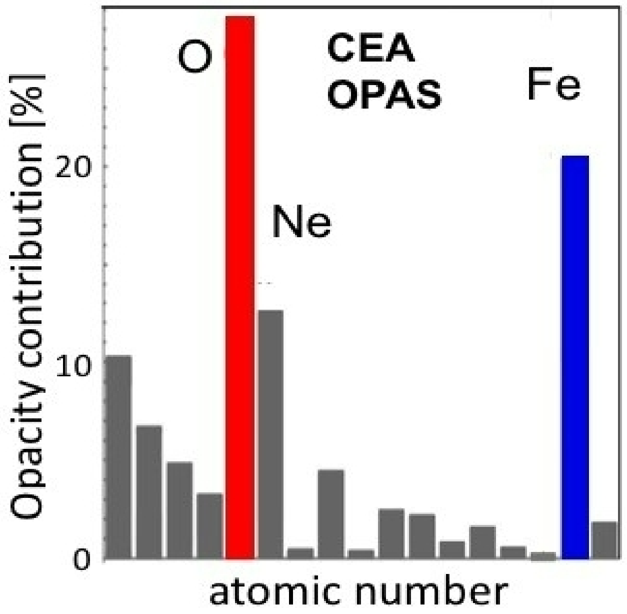
Oxygen x-ray opacity was measured for the first time;
More experiments will be performed at more relevant conditions



Why important?

Reason1: Oxygen is the dominant source of solar opacity

Reason2: K-shell calculation is difficult due different reason, i.e., density effects

WCAPP postdoc, Dan Mayes, will lead this project together with NIF oxygen opacity

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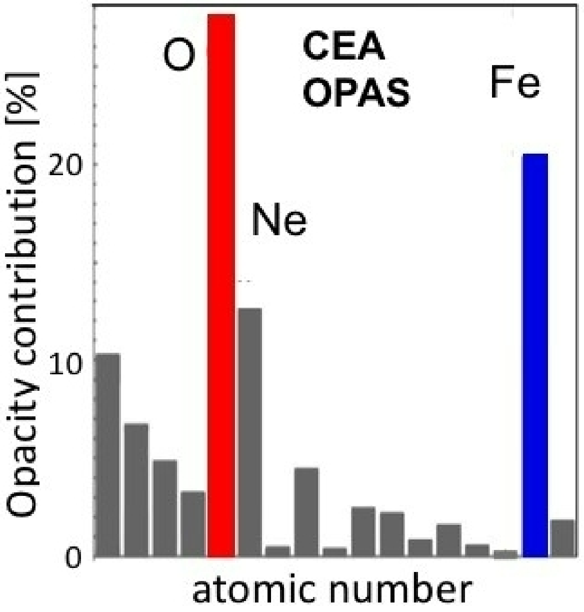

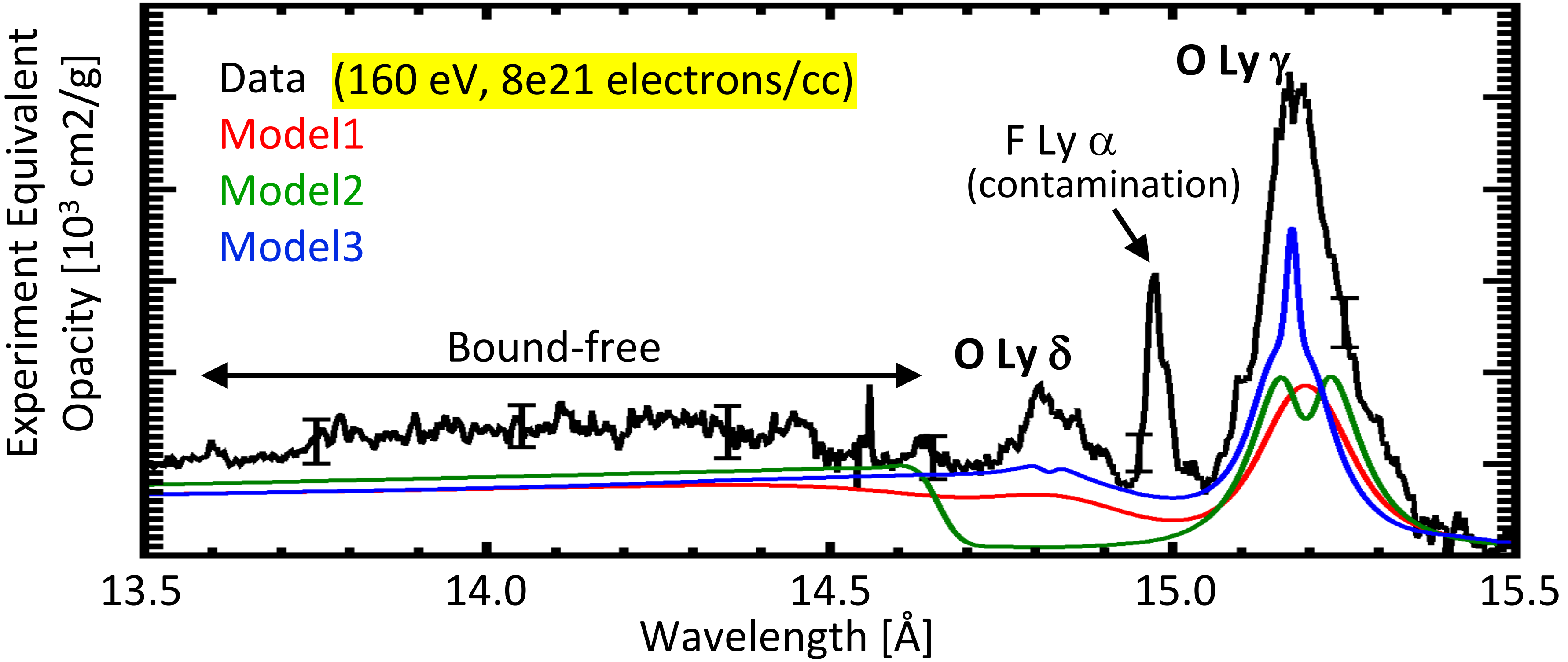

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Basu and Antia, *Phys. Reports* 2008; Serenelli, *ApJ* 2009; Blancard ApJ 2012; Seaton MNRAS 1994

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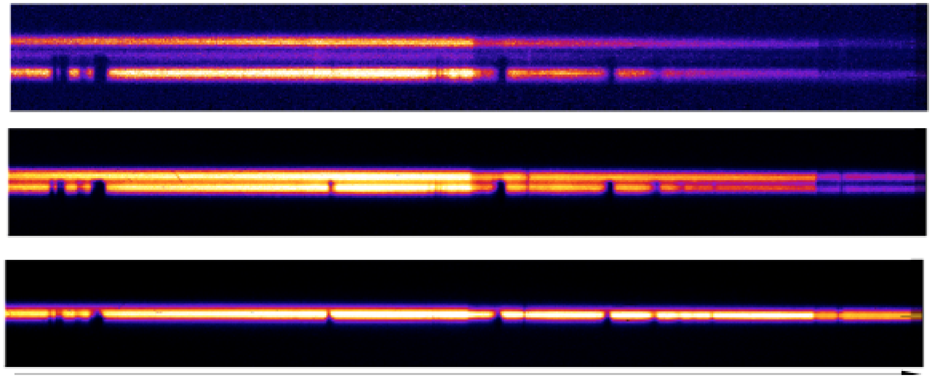

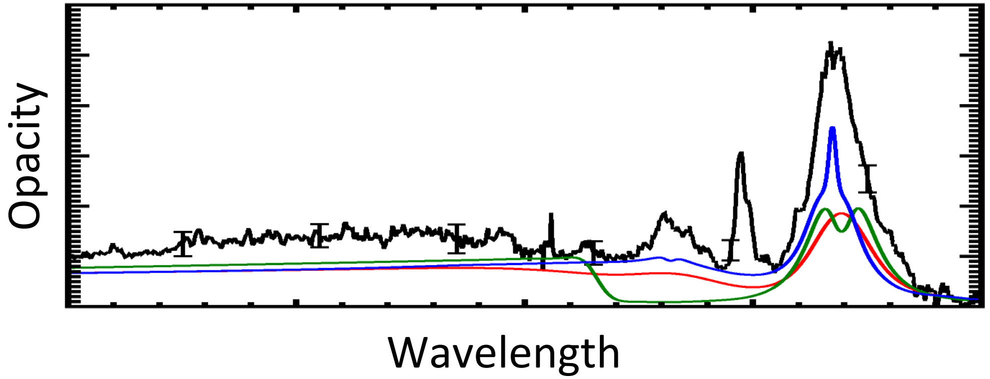

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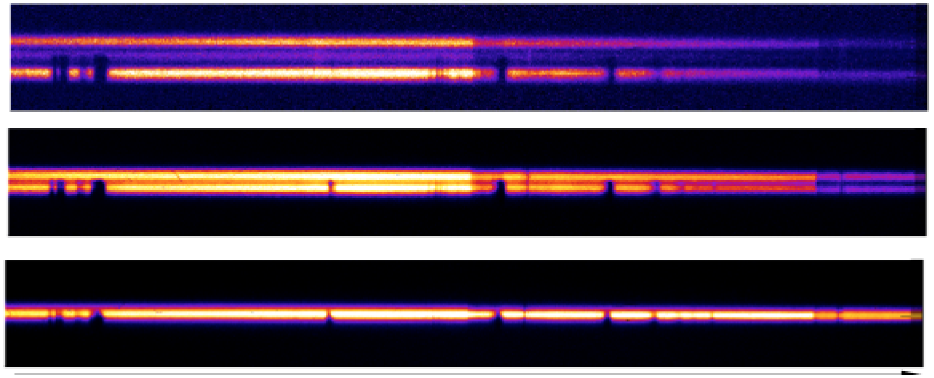

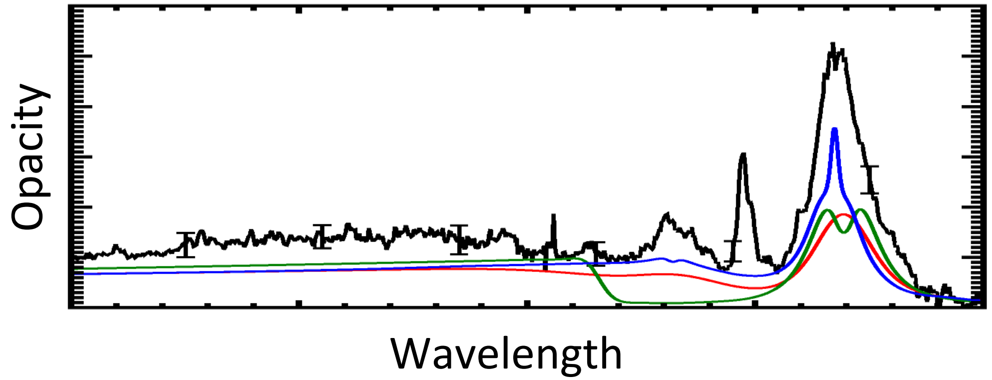

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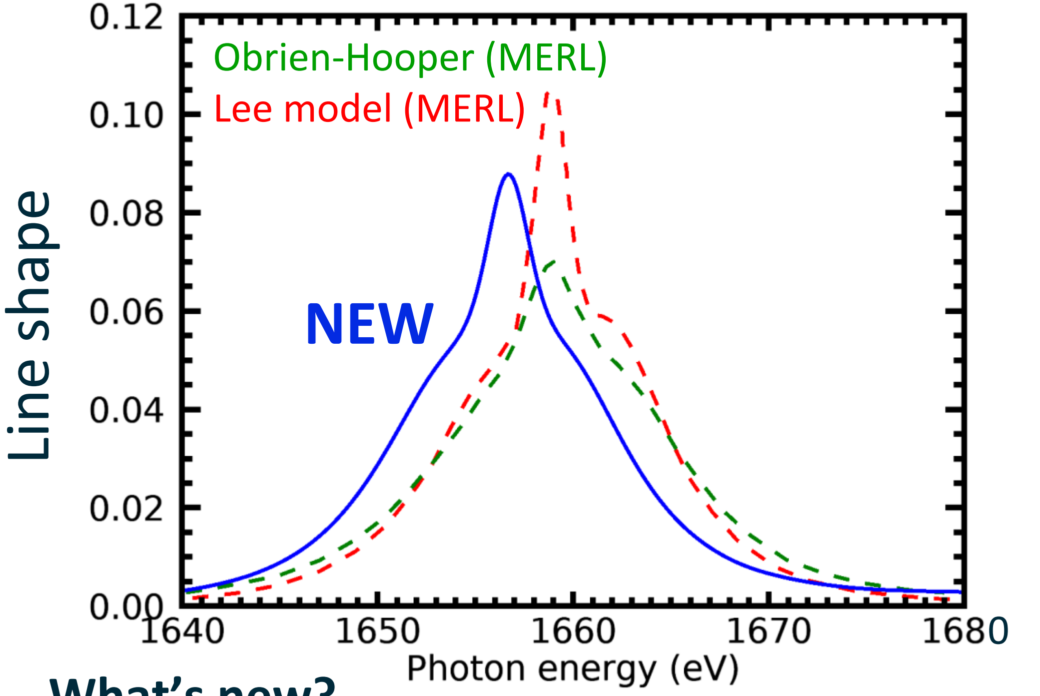
Two relevant theories were scrutinized and refined significantly for resolving the Fe model-data discrepancies

Spectral line broadening [1,2]

→ Plasma diagnostics

→ BB line-width discrepancy

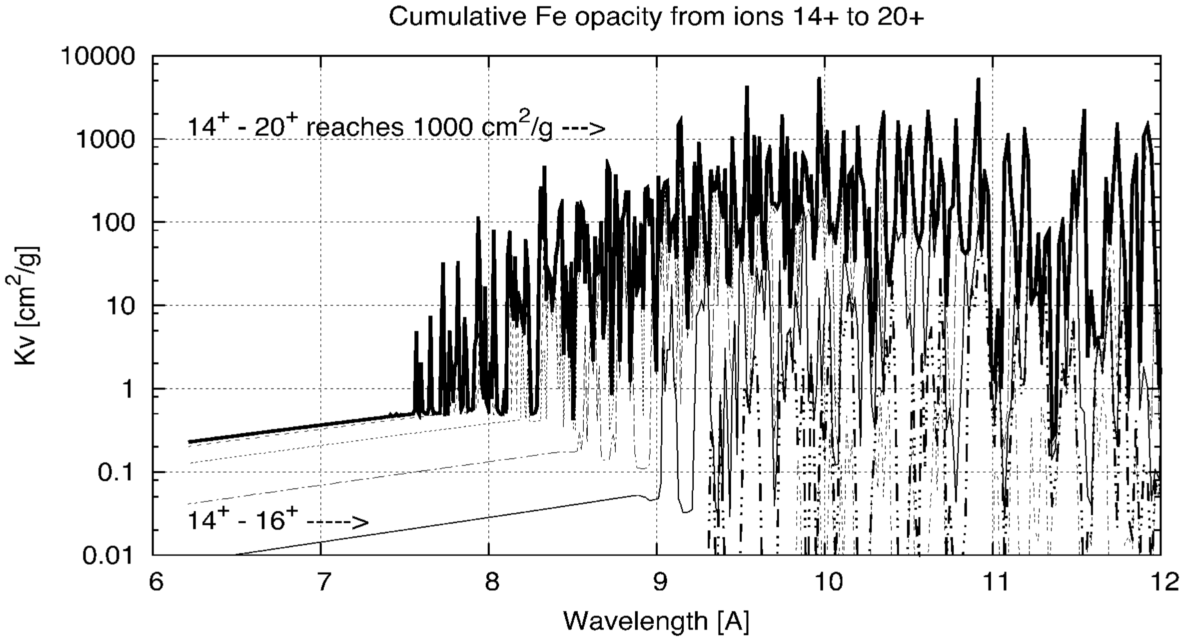


What's new?

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

Two-photon opacity [3]

→ BB, BF discrepancies



What's new?

- TPO is omitted from existing opacity models
- Performed most complete calculations ever

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

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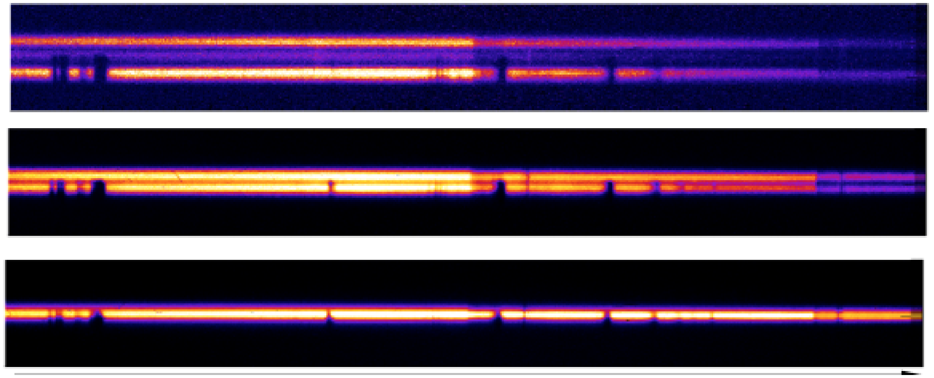

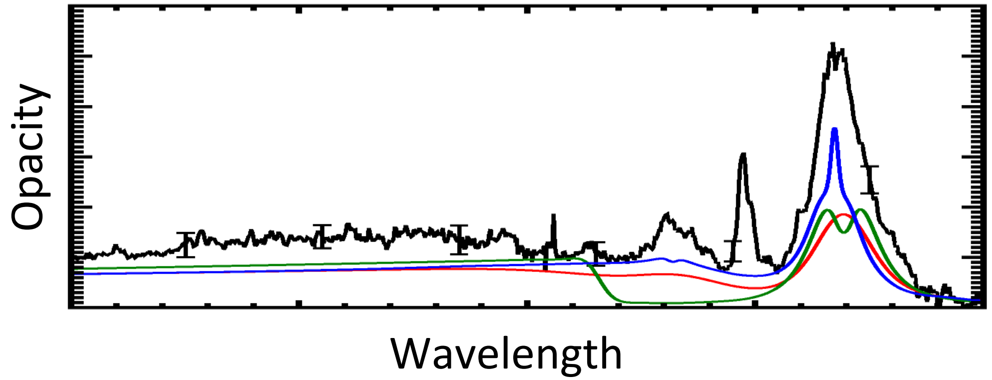

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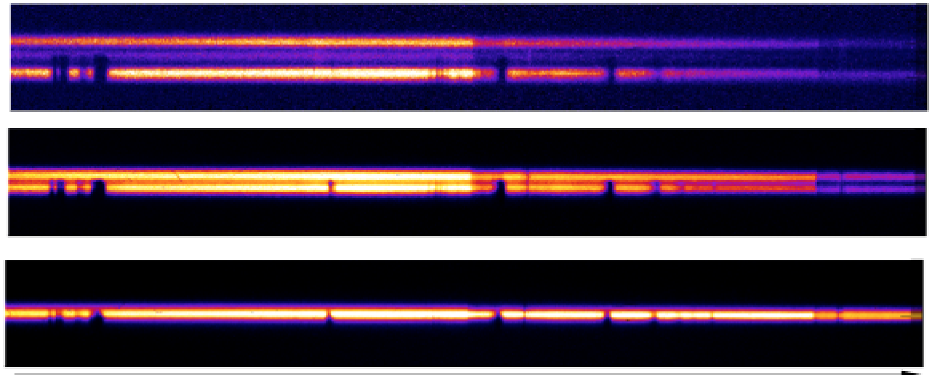

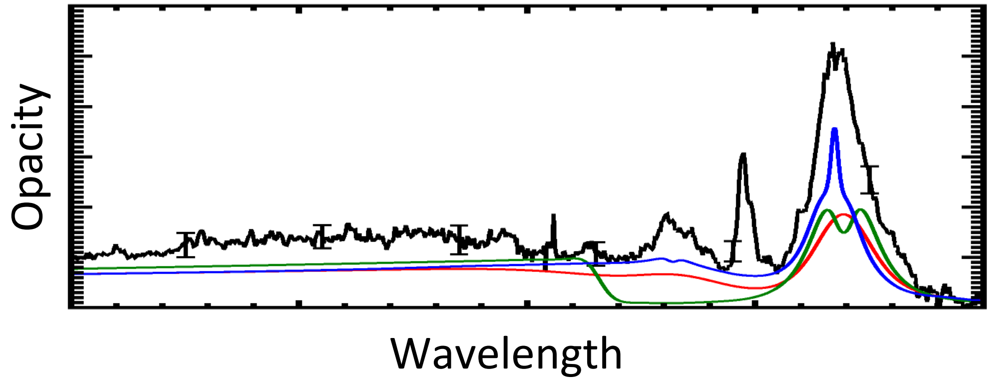

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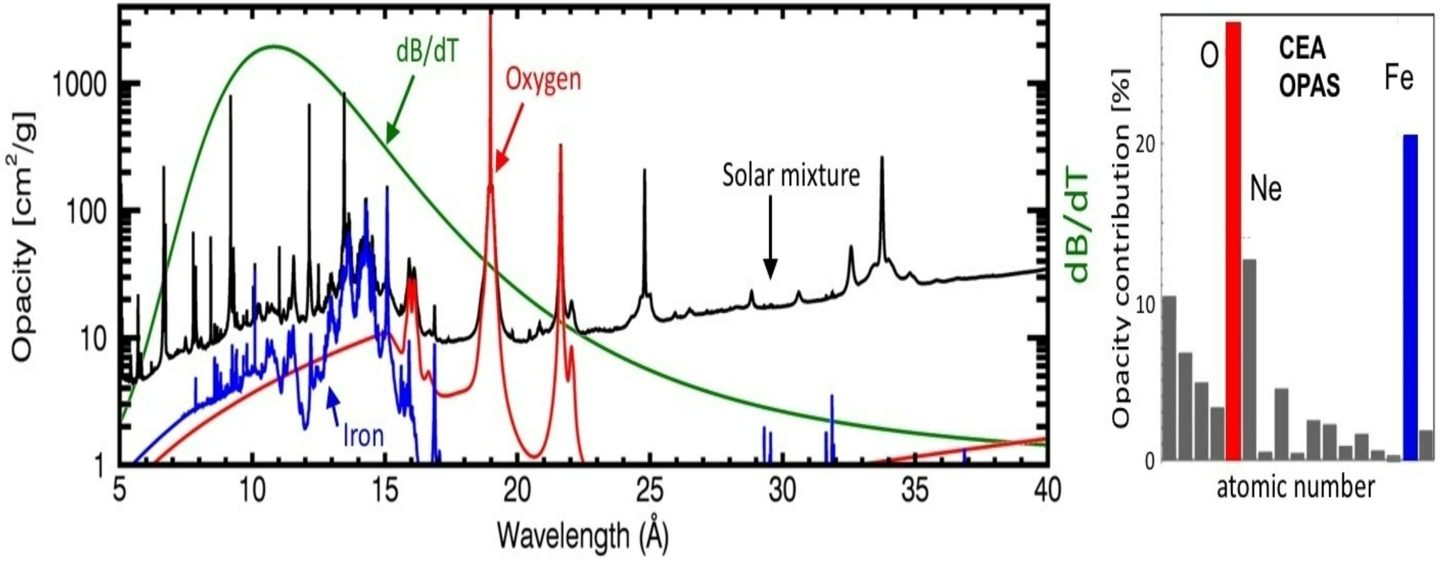
Postdoc: Dan Mayes has working knowledge of spectroscopy and will work on oxygen opacity research

Dan Mayes:

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

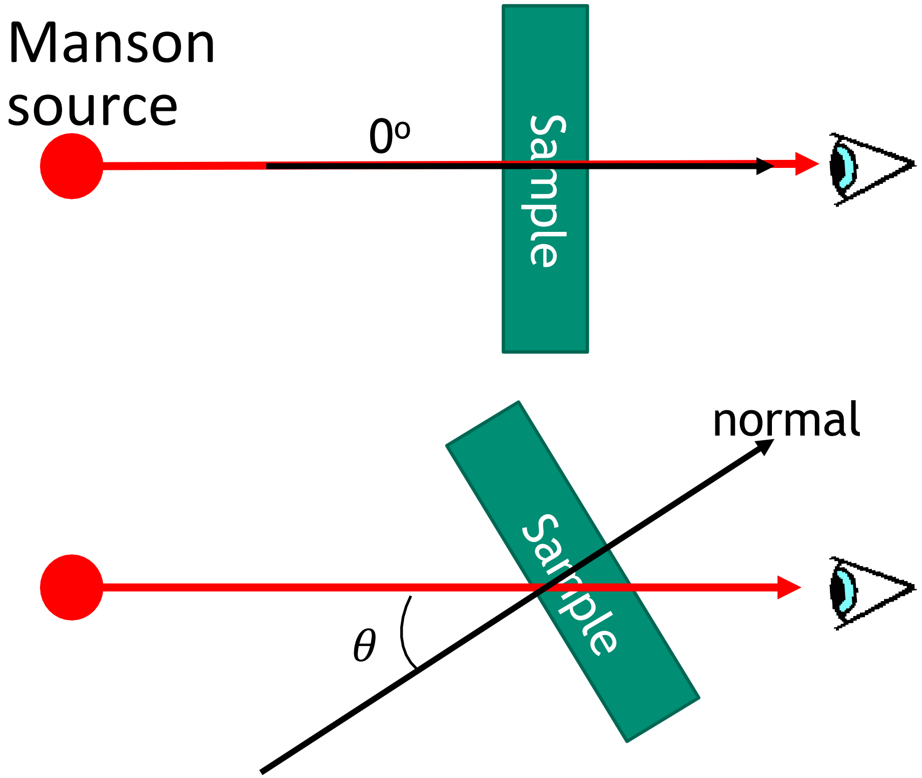
Working knowledge in:
- **X-ray spectroscopy**
- **SNL Z experiments**

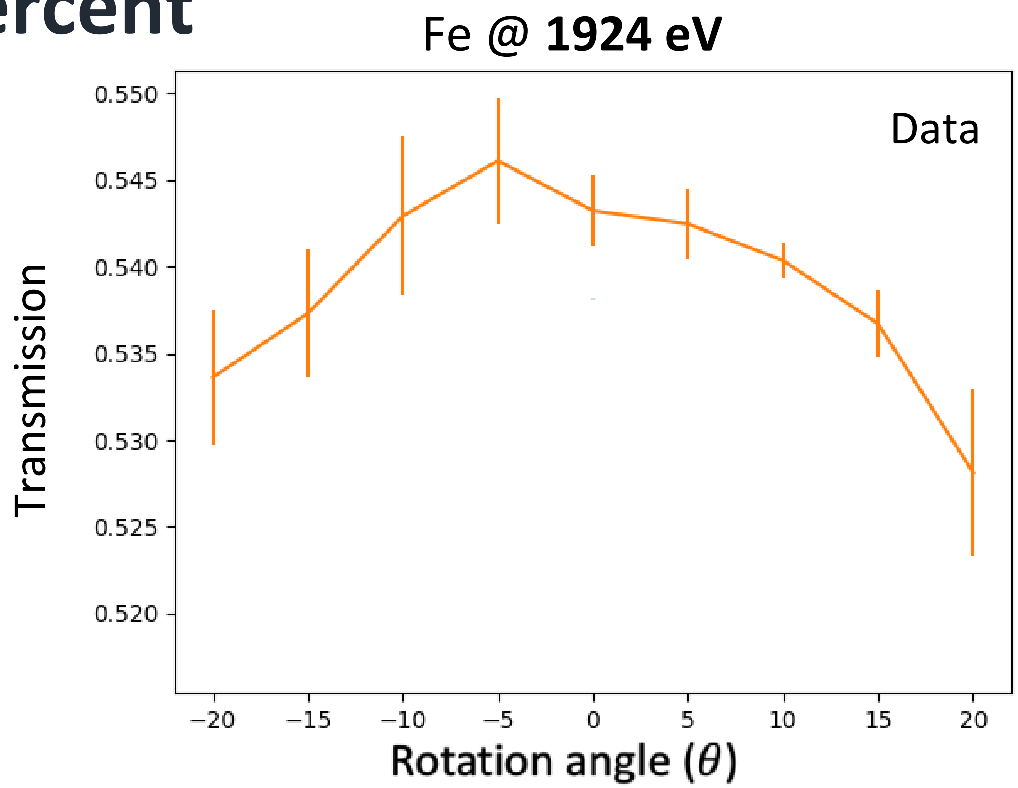
He will work on oxygen opacity



Postdoc hiring has been challenging due to lack of good candidates in atomic physics and spectroscopy. Dan is an excellent HED spectroscopist trained through WCAPP.

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

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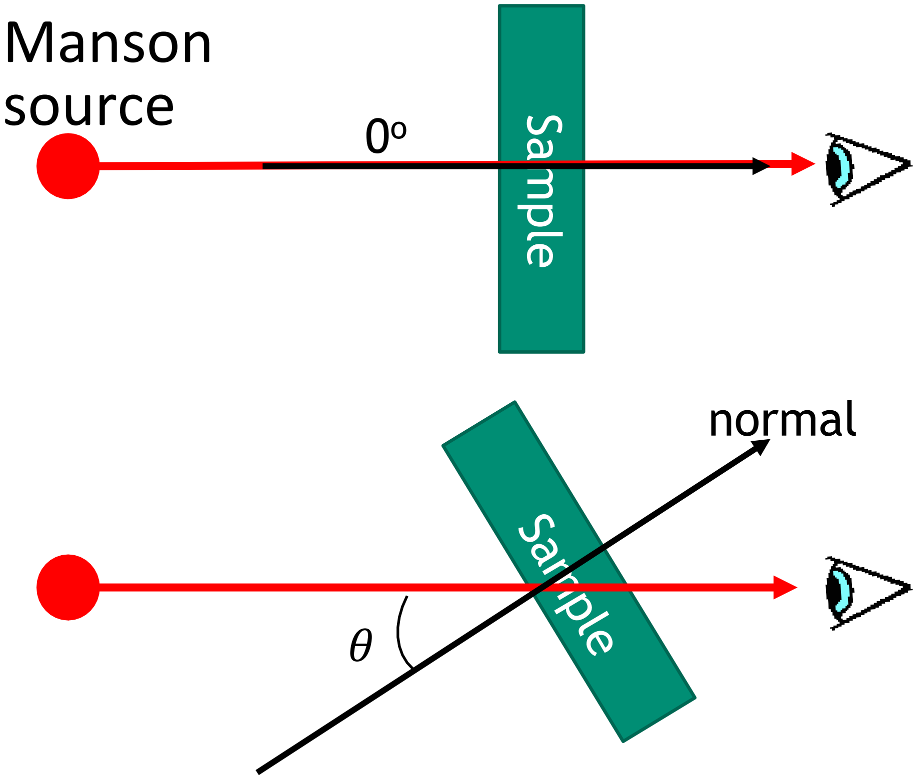

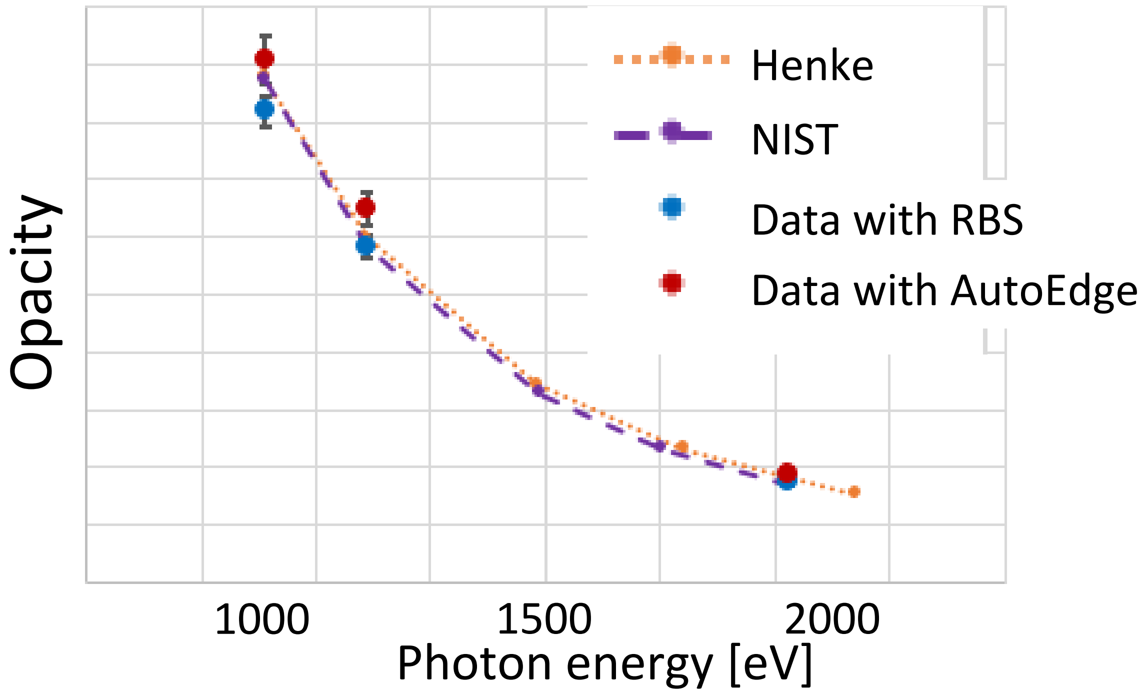

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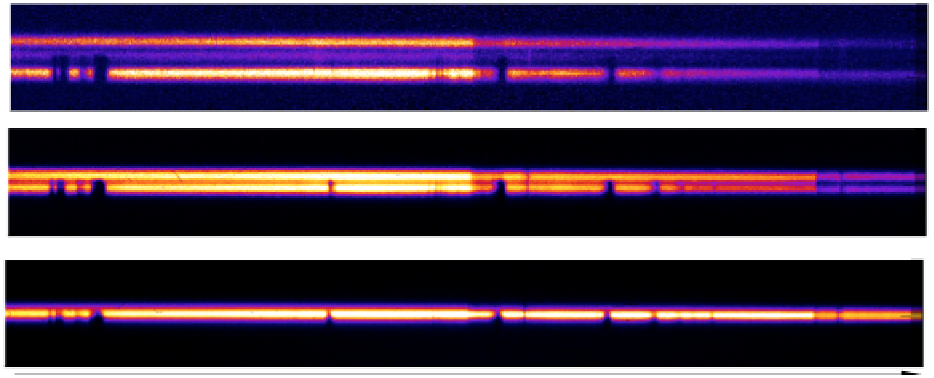

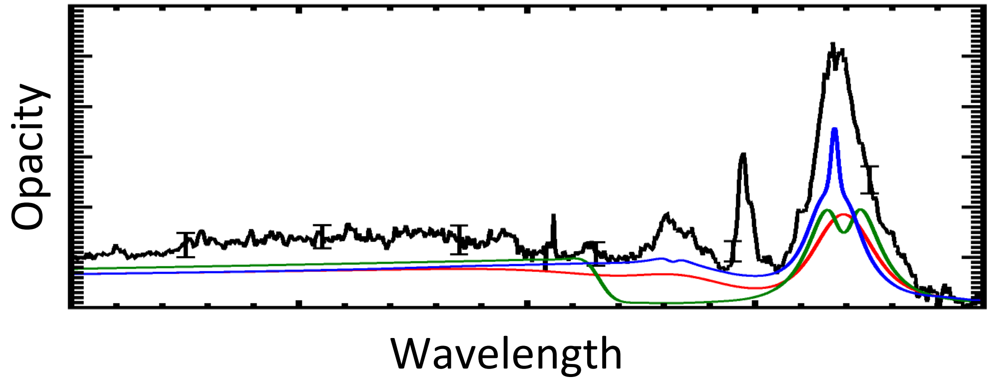

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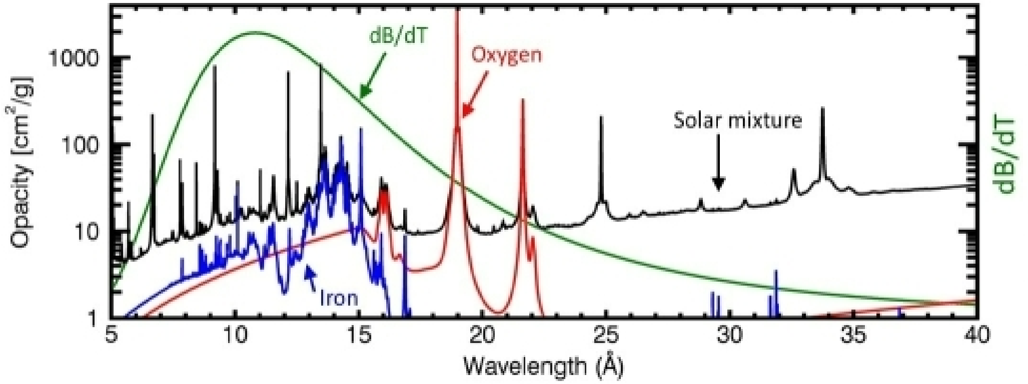
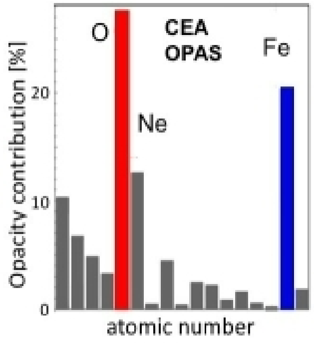
Exciting stellar-opacity research is on the horizon

Measure oxygen opacity at solar interior conditions for the solar problem





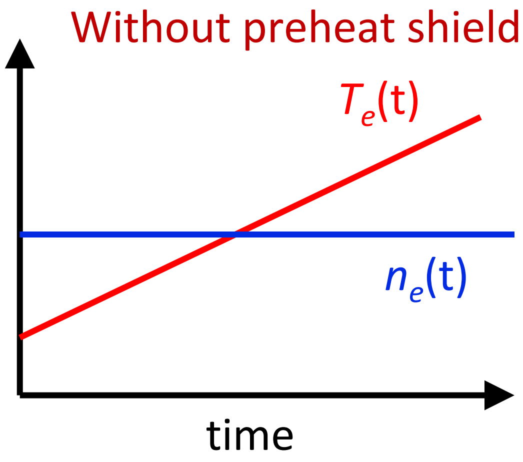
Anchor1

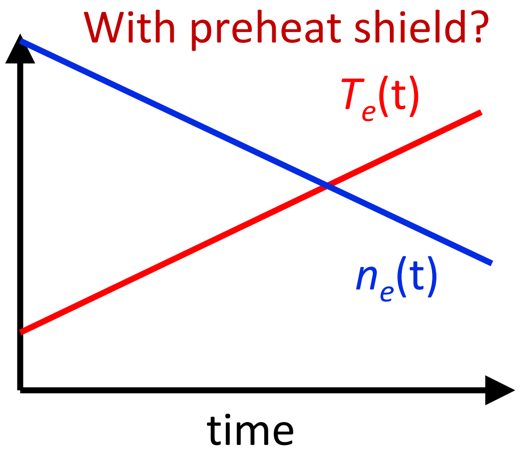
(160 eV, 8e21 cm^{-3})

Anchor2

(180 eV, 3e22 cm^{-3})

Transform opacity science on Z using novel time-resolved spectroscopy





- **Opacity as a function of temperature or density from a single experiment**
- **Minimize temporal-gradient concern**

WCAPP students and postdocs will be trained in HEDP atomic physics and spectroscopy through the stellar opacity research and will help resolve the solar problem

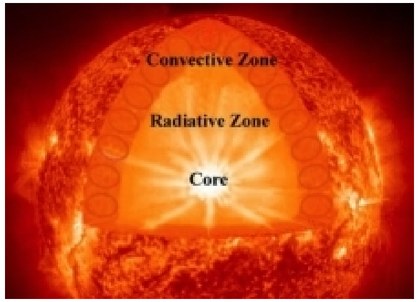
Stellar opacity research continues to advance experiment, analysis, and theory towards resolving the solar problem

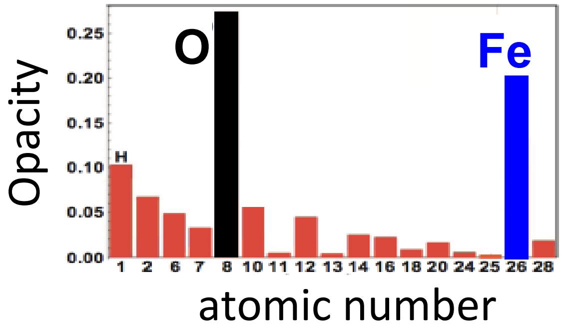
Motivation: solar models disagree with observations

→ Can we model solar opacity correctly?

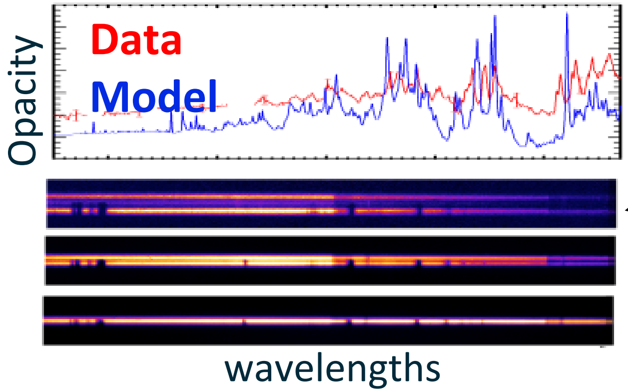
L-shell Fe: Billions of L-shell lines

K-shell O: Density effects





Fe opacity: Data was significantly higher



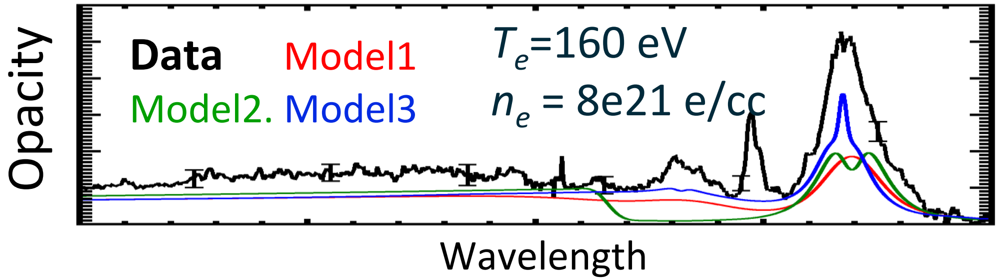
Re-scrutiny in:

- **Experiments**

  Time-resolved measure.
- **Data analysis**
- **Theory**

O opacity: Measured for the first time

→ Showing interesting disagreements



We will measure oxygen opacity at higher T_e and n_e

Student/postdoc involvement:

- **Dan Mayes (postdoc) was trained under WCAPP and will lead oxygen opacity**
- **Malia Kao (student) performed excellent cold iron-opacity measurements and joined WCAPP**

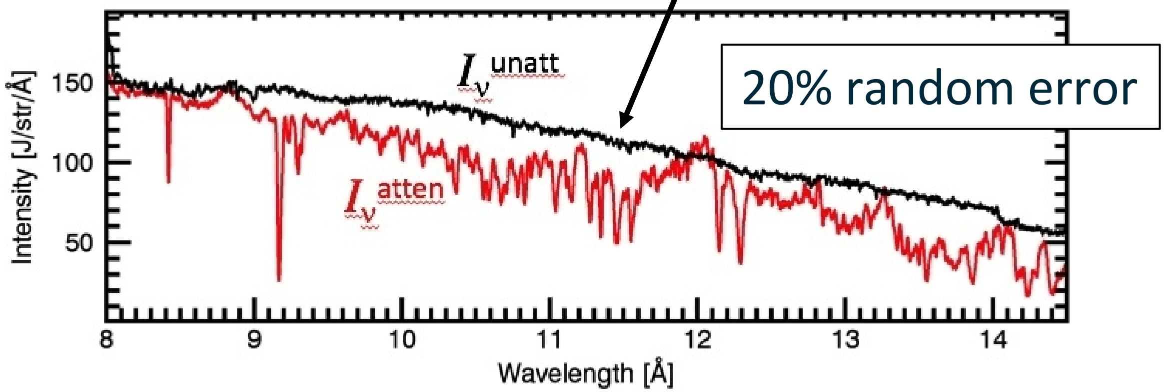
More students and postdocs will be trained and lead stellar-opacity research to help refine our understanding of atomic behavior in HED plasmas

Spare slides

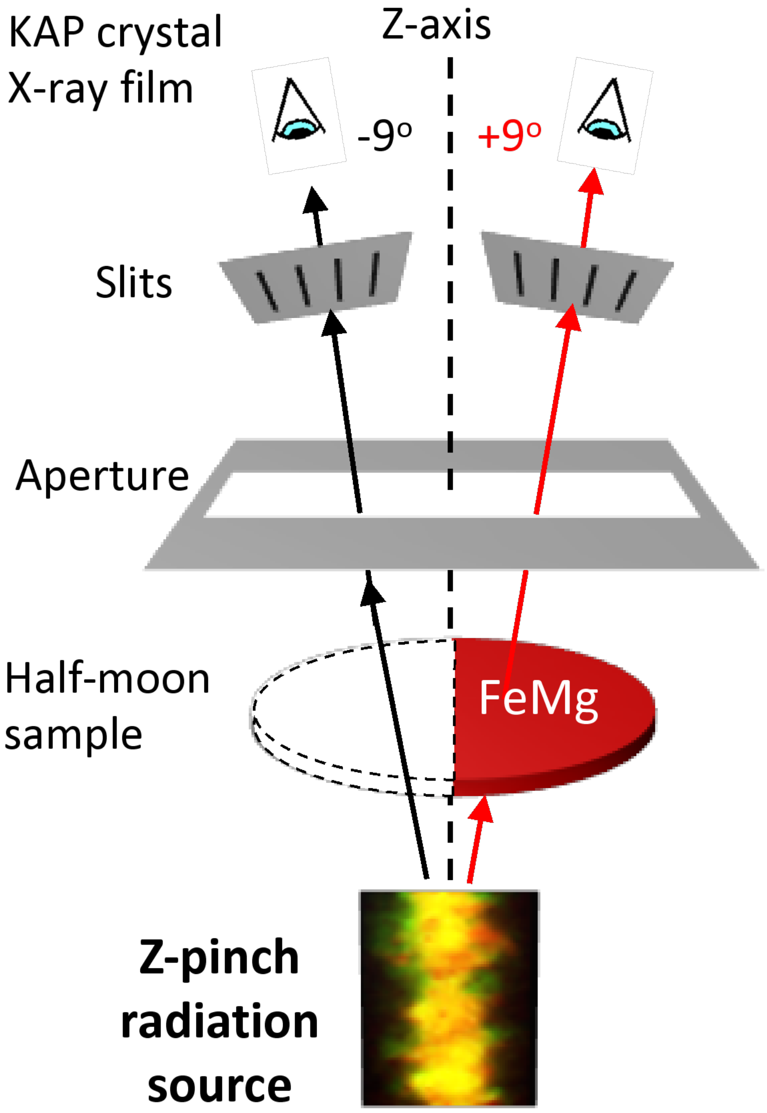
Analysis method is refined in (1) determining unattenuated spectrum, (2) propagating errors

Two challenges in opacity analysis:

1. Determination unattenuated spectrum



2. Propagating multiple errors
   - Unattenuated spectrum
   - Background subtraction
   - Areal density



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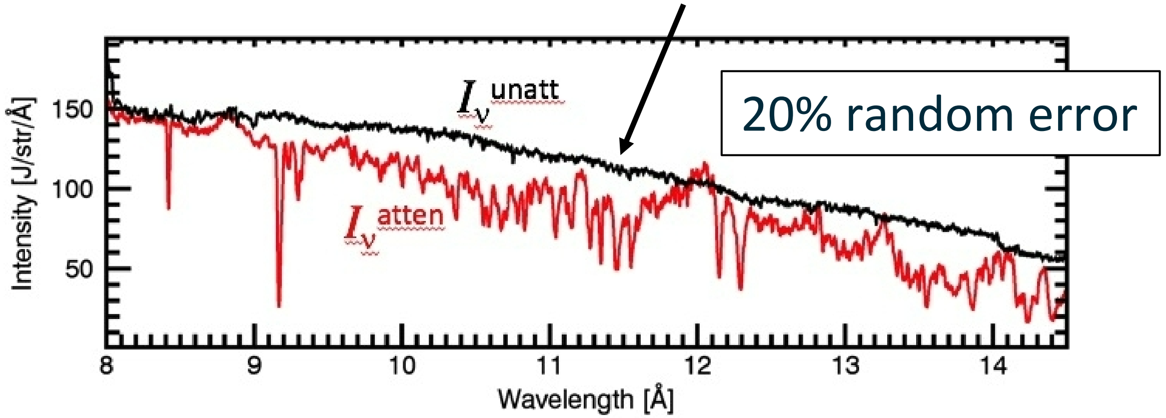

2. Propagating multiple errors
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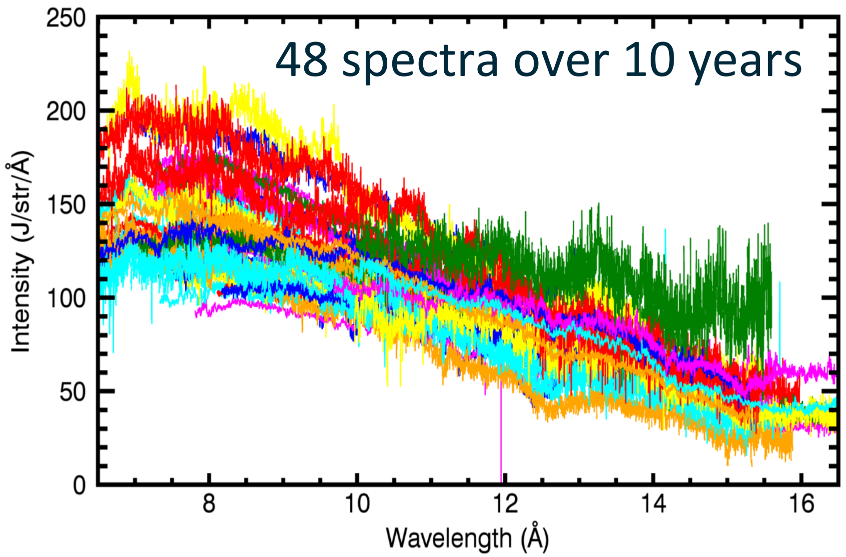
Solution:

Calibration shot stats → Unattenuated PDF*

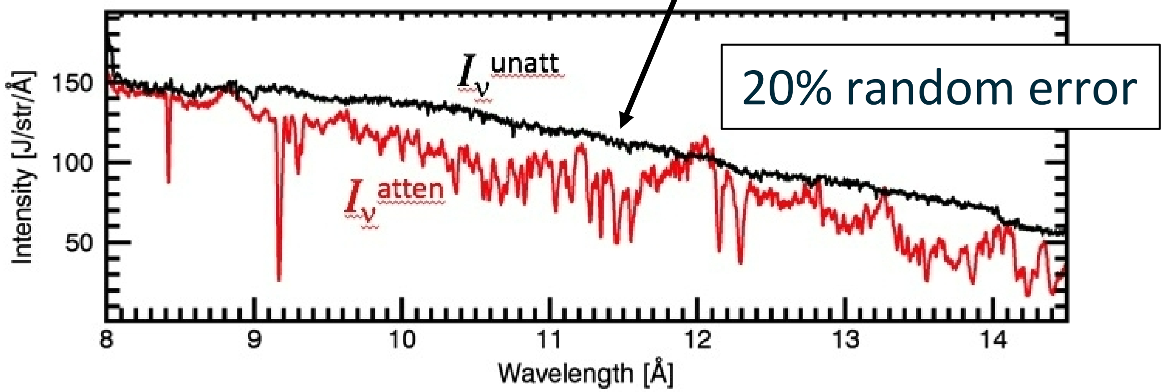


*** PDF = probability distribution function**

Analysis method is refined in (1) determining unattenuated spectrum, (2) propagating errors

Two challenges in opacity analysis:

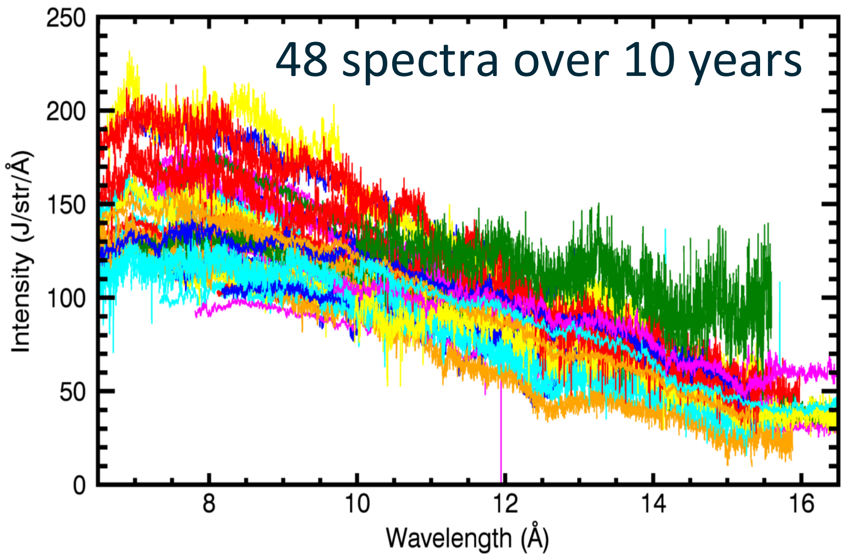
1. Determination unattenuated spectrum



2. Propagating multiple errors
   - Unattenuated spectrum
   - Background subtraction
   - Areal density

Solution:

Calibration shot stats → Unattenuated PDF*



Monte-Carlo sampling

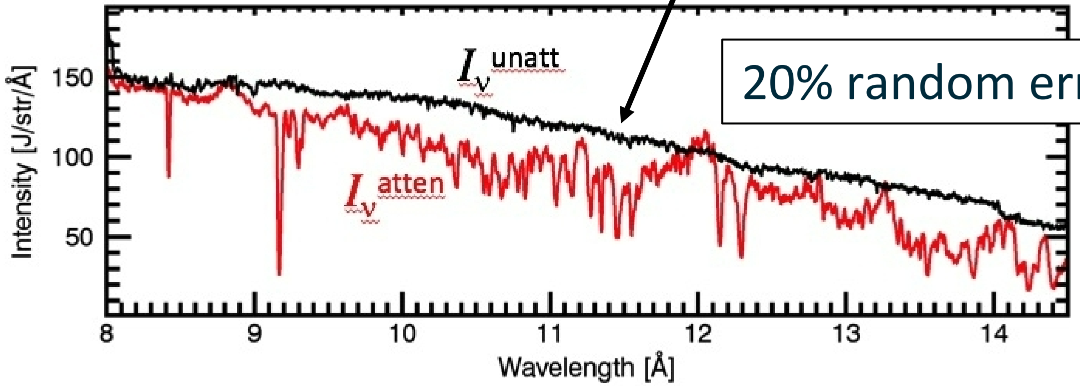
This can easily handle multiple sources of errors and non-linearity.

*** PDF = probability distribution function**

New analysis returns asymmetric non-Gaussian opacity PDF* as a function of wavelengths

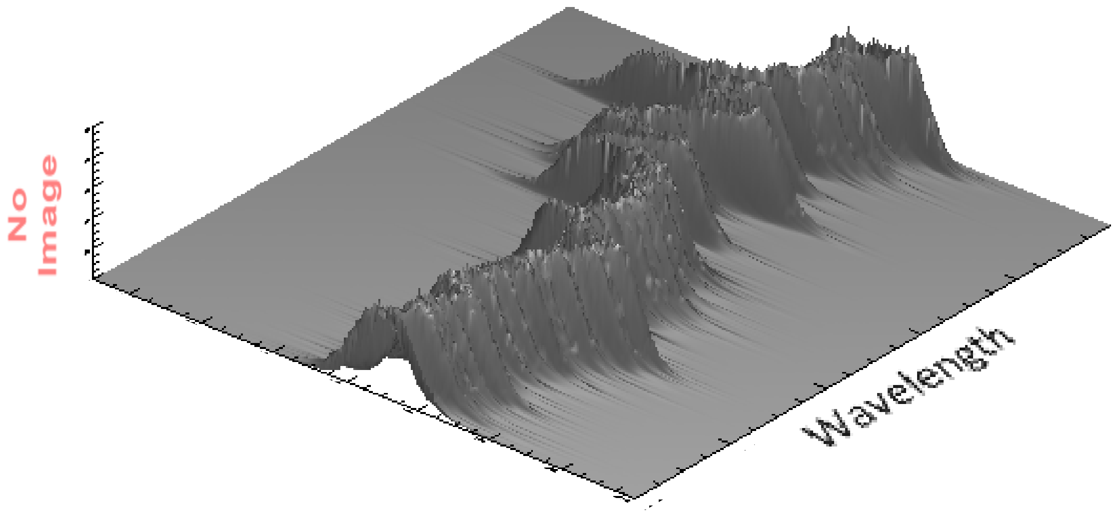
Two challenges in opacity analysis:

1. Determination unattenuated spectrum



20% random error

Opacity probability distribution function

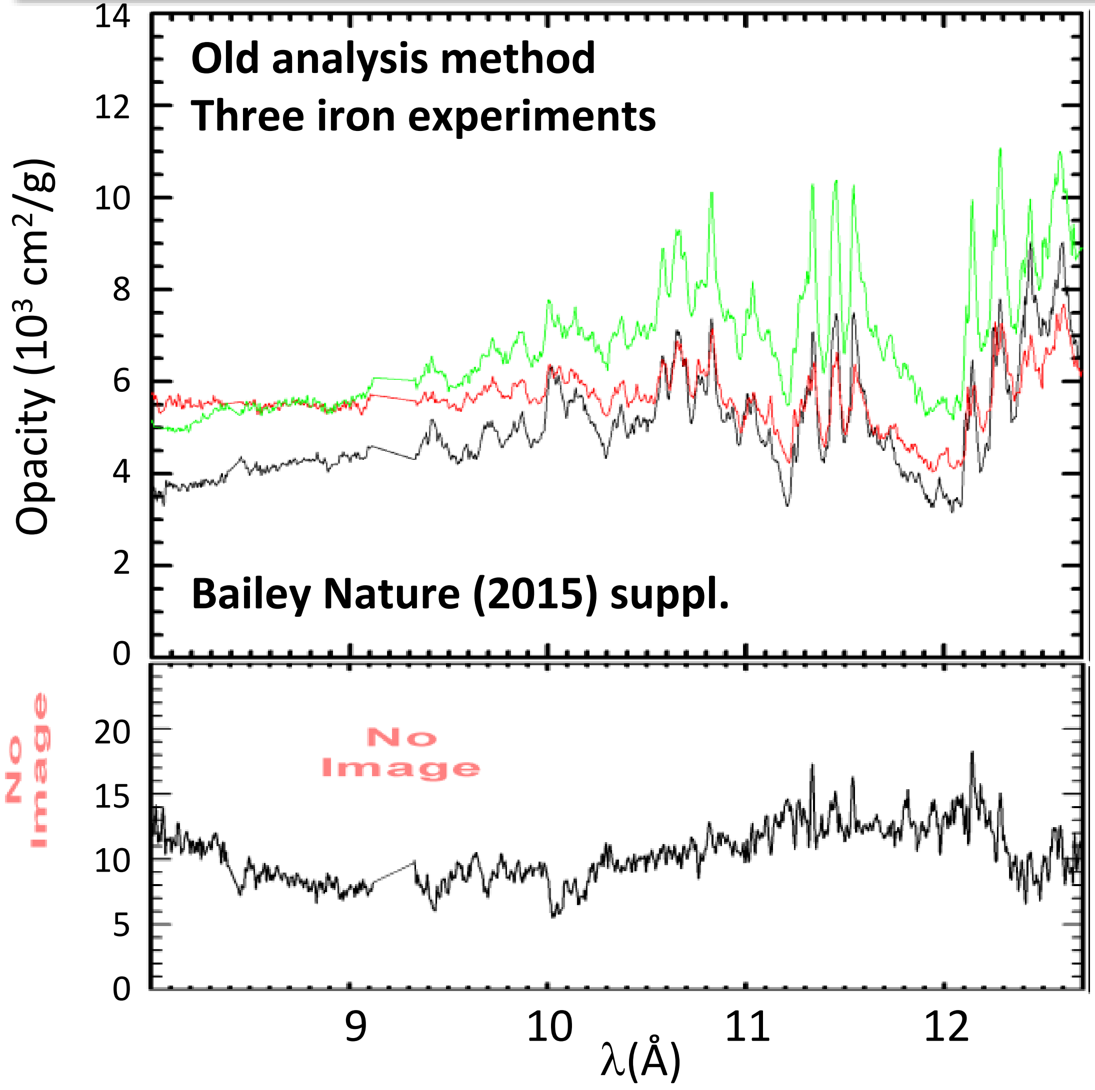


2. Propagating multiple errors
   - Unattenuated spectrum
   - Background subtraction
   - Areal density

Analysis accuracy is confirmed through synthetic-data tests and calibration-shot data

* PDF = probability distribution function

New-analysis method revealed experiment reproducibility is better than we believed (σ=20%→10%)



Anchor 2:

T_e ~ 184 eV

n_e ~ 3×10^{22} cm^{-3}

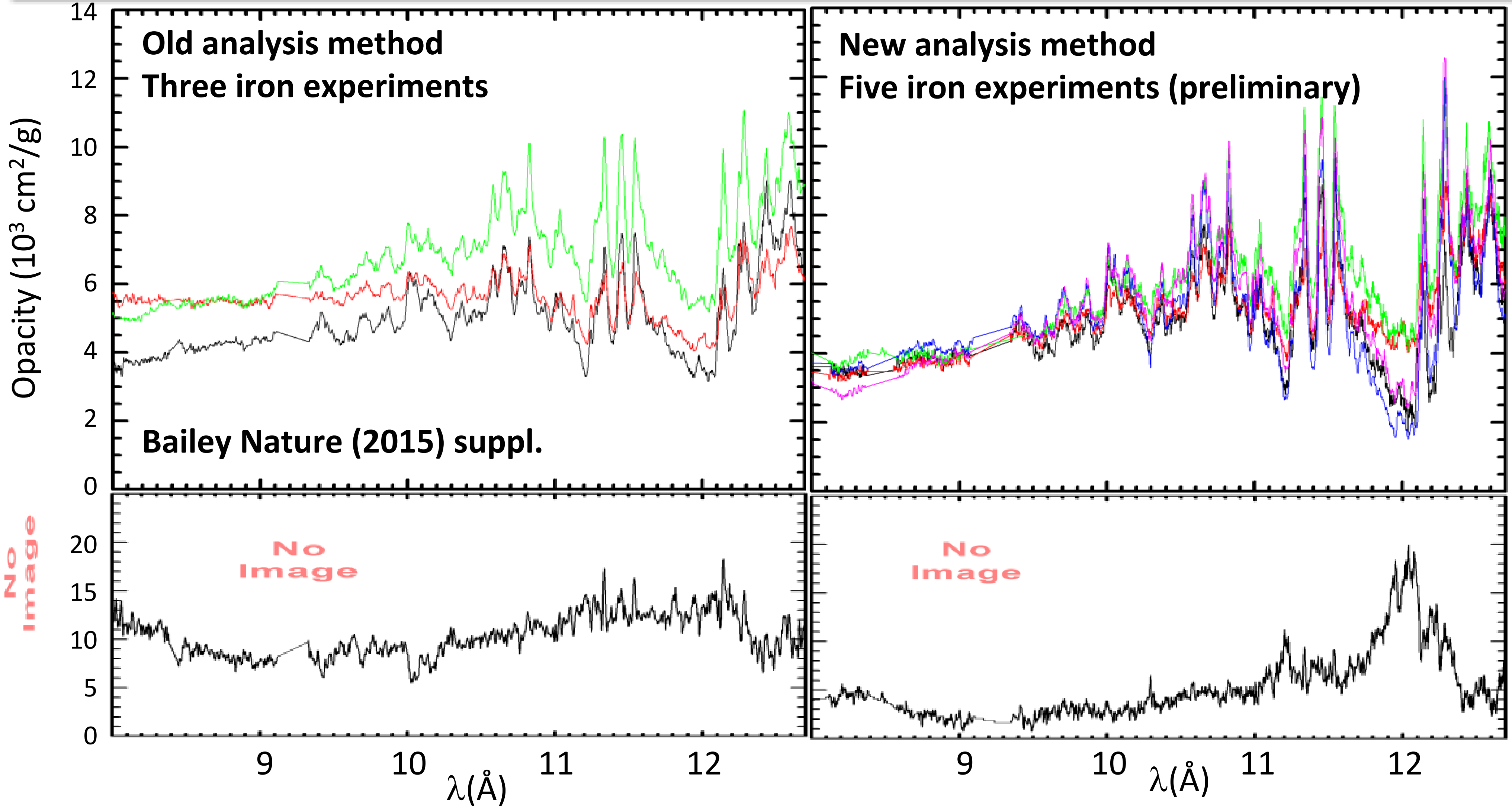
Areal Densities

$\times 10^{18}$ Fe/cm^2

1.04
1.91
0.93

} 2014

New-analysis method revealed experiment reproducibility is better than we believed (σ=20%→10%)



Anchor 2:
T_e ~ 184 eV
n_e ~ $3x10^{22}$ cm^{-3}

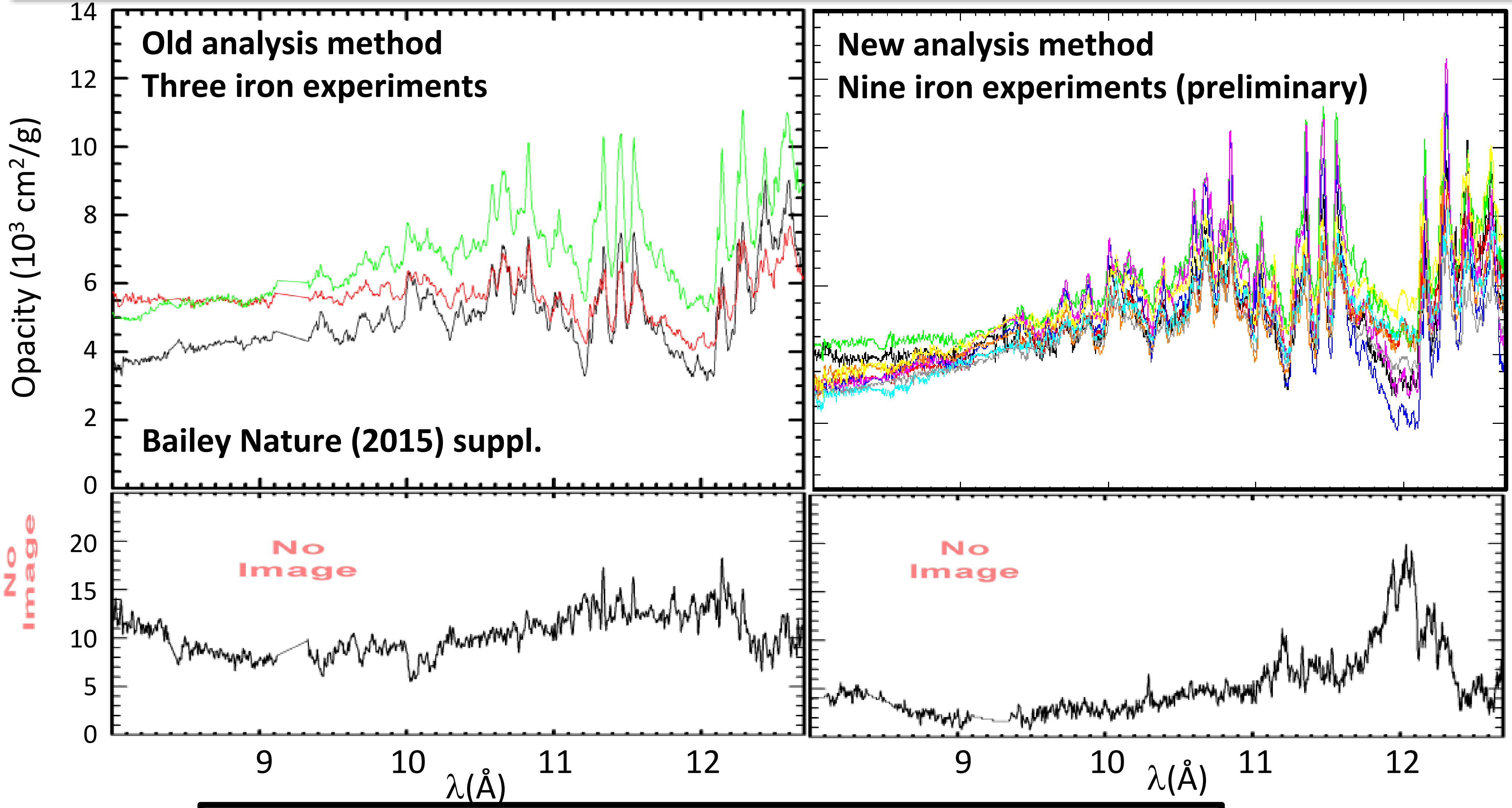
Areal Densities x10^{18} Fe/cm²

1.04, 1.91, 0.93 — 2014

1.31, 1.31 — 2015

New-analysis method revealed experiment reproducibility is better than we believed (σ=20%→10%)

Sandia National Laboratories



Anchor 2:

T_e ~ 184 eV

n_e ~ 3×10^{22} cm^{-3}

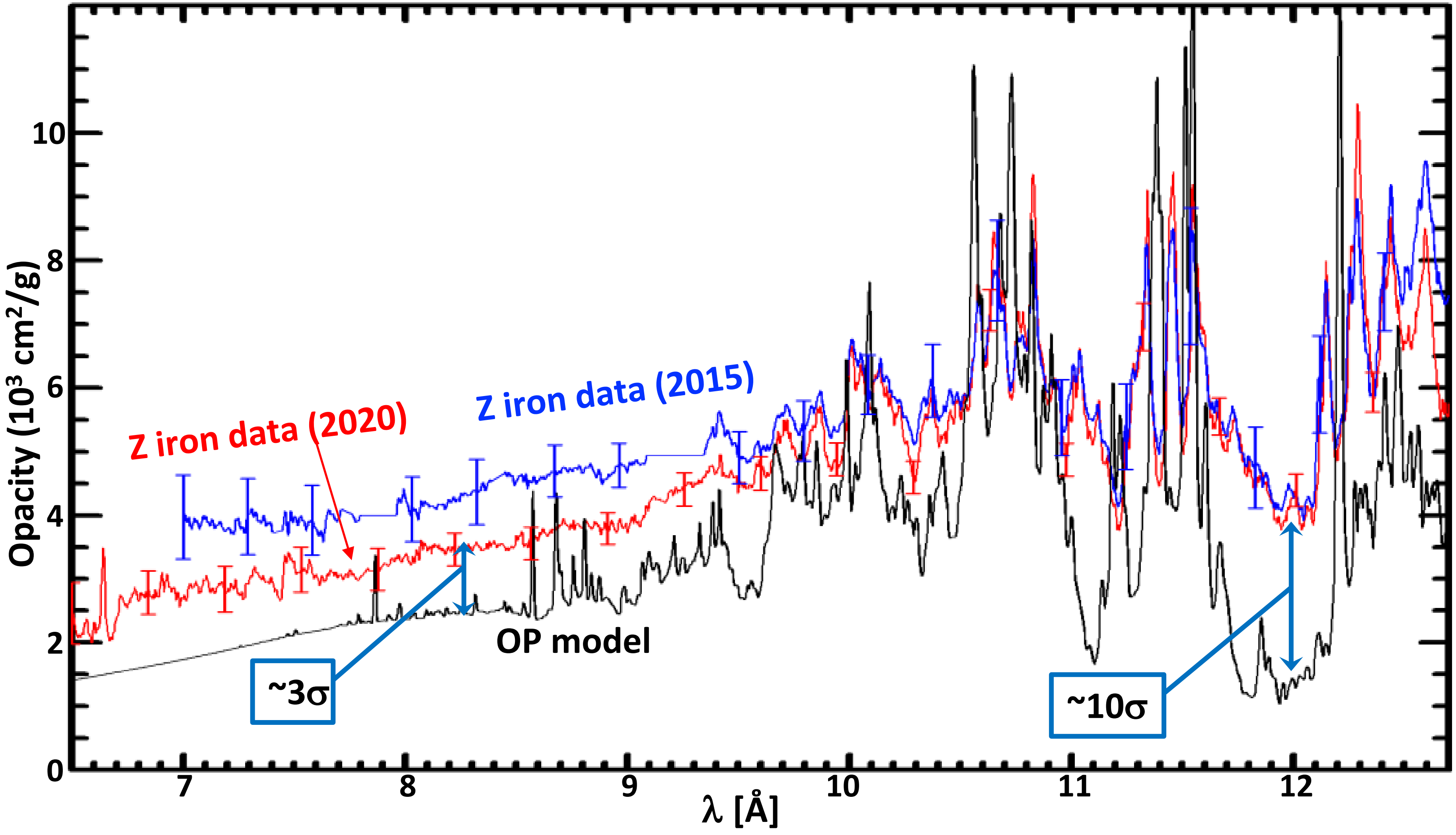
Areal Densities

$\times 10^{18}$ Fe/cm^2

1.04 1.91 0.93	2014
1.31 1.31	2015
2.18 2.18	2017
2.38	2018
2.78	2019

We are collecting more Fe data to re-scrutinize the Fe results

New experiments and analysis reduced the model-discrepancy for Anchor 2 iron, but ~ 3-10 σ differences remain



<u>Quasi continuum discrepancy</u>

2015: ~ 1800 cm2/g; ~4σ

2019: ~ 960 cm2/g; ~3σ

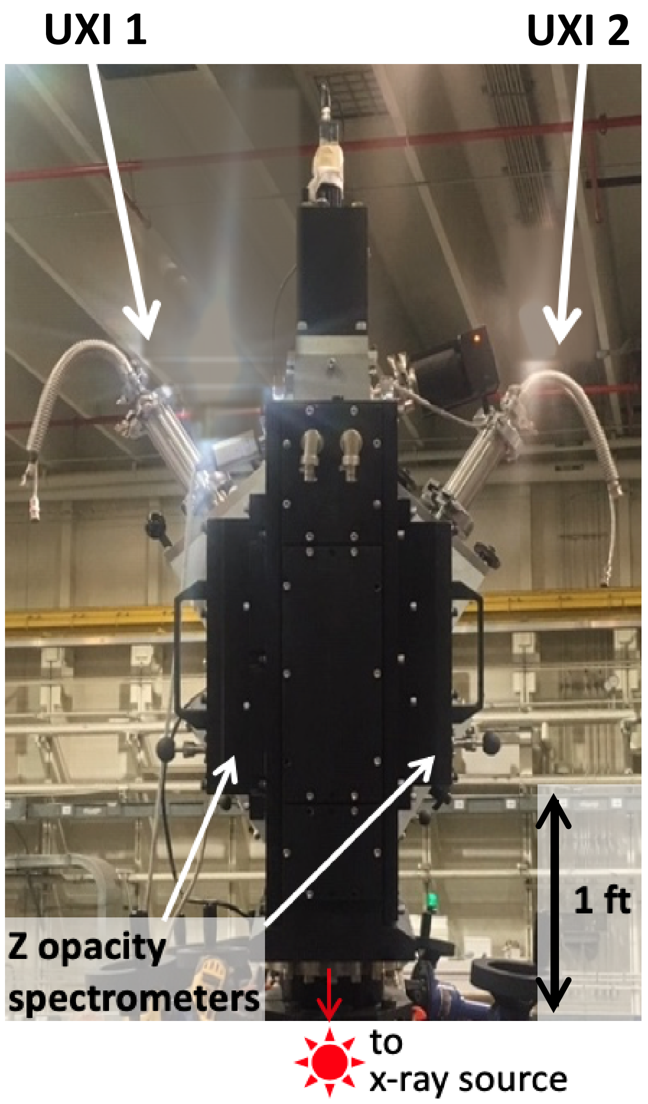
<u>Window discrepancy</u>

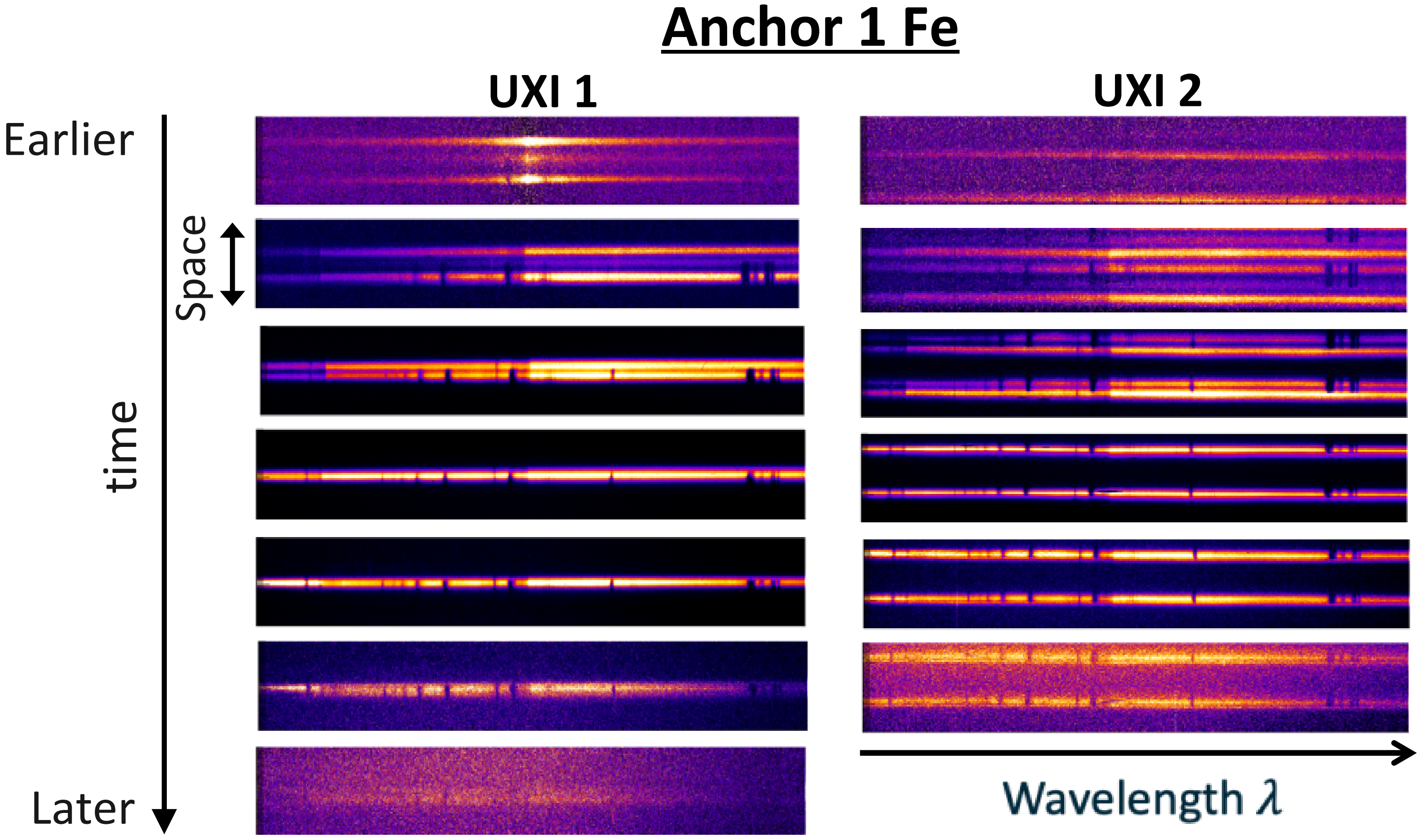
2015: ~ 2900 cm2/g; ~ 5σ

2019: ~ 2700 cm2/g; ~ 10σ

We found similar results for Fe at anchor3

Sandia developed Ultrafast X-ray Imagers (UXI) were fielded to measure time-resolved FeMg absorption spectral images

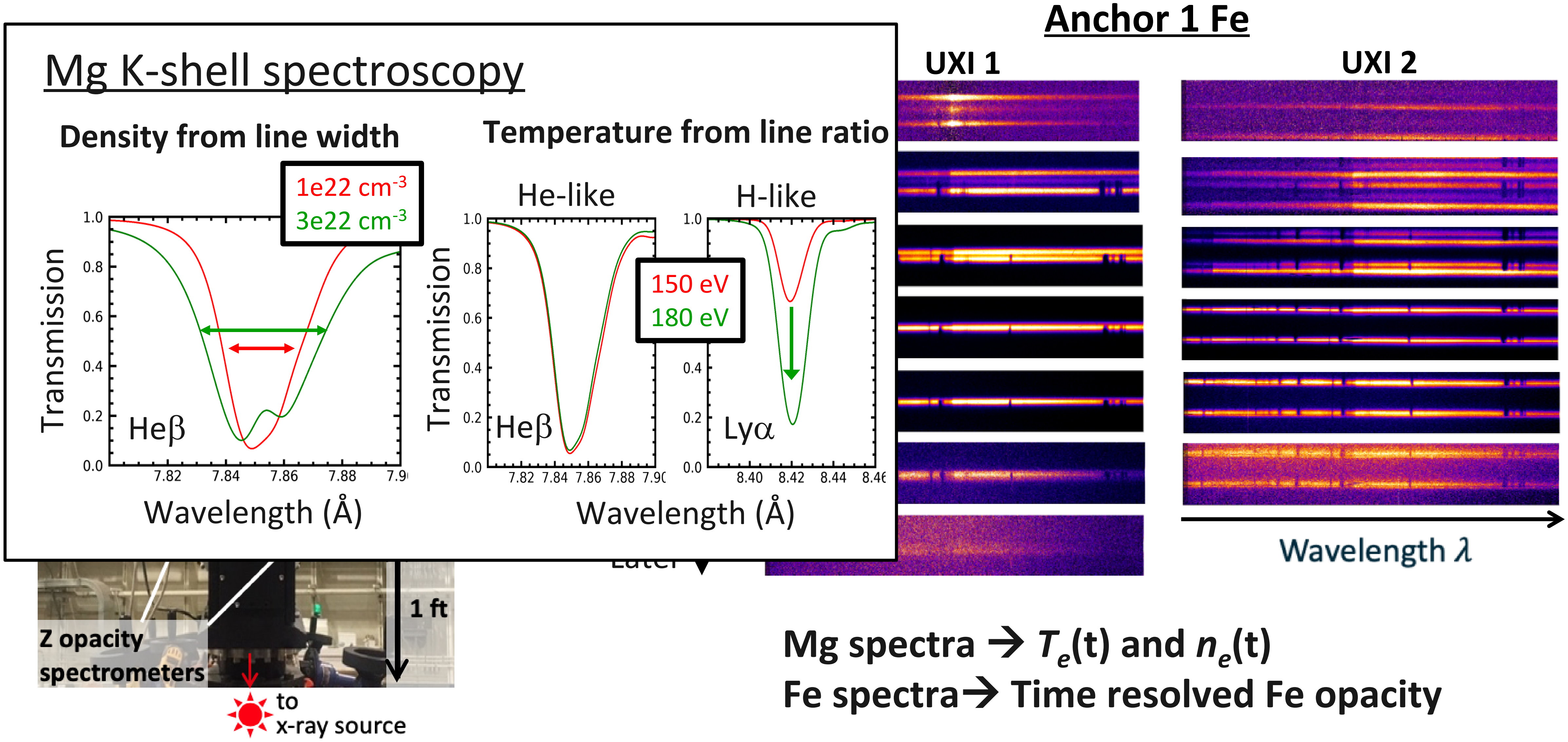




Mg spectra → $T_e(t)$ and $n_e(t)$

Fe spectra→ Time resolved Fe opacity

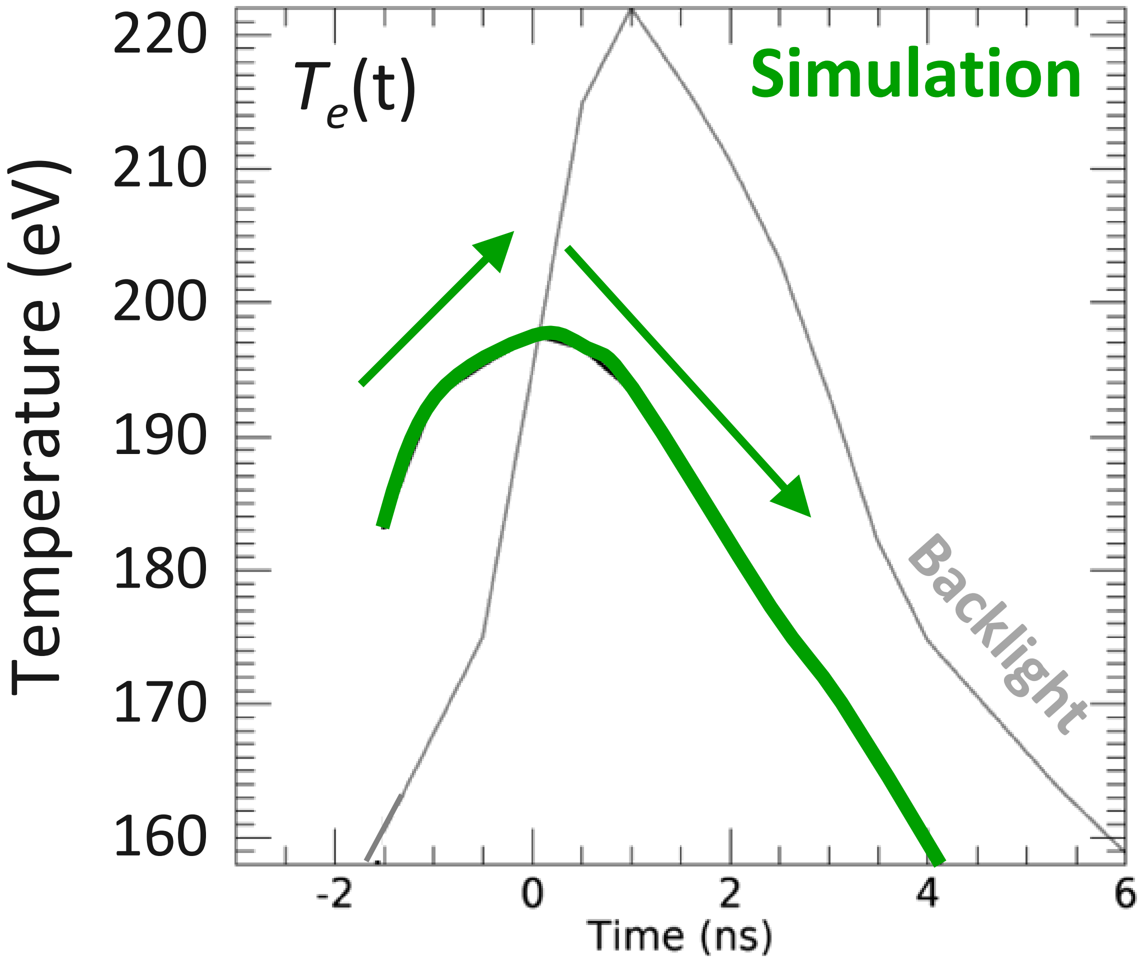
Sandia developed Ultrafast X-ray Imagers (UXI) were fielded to measure time-resolved FeMg absorption spectral images

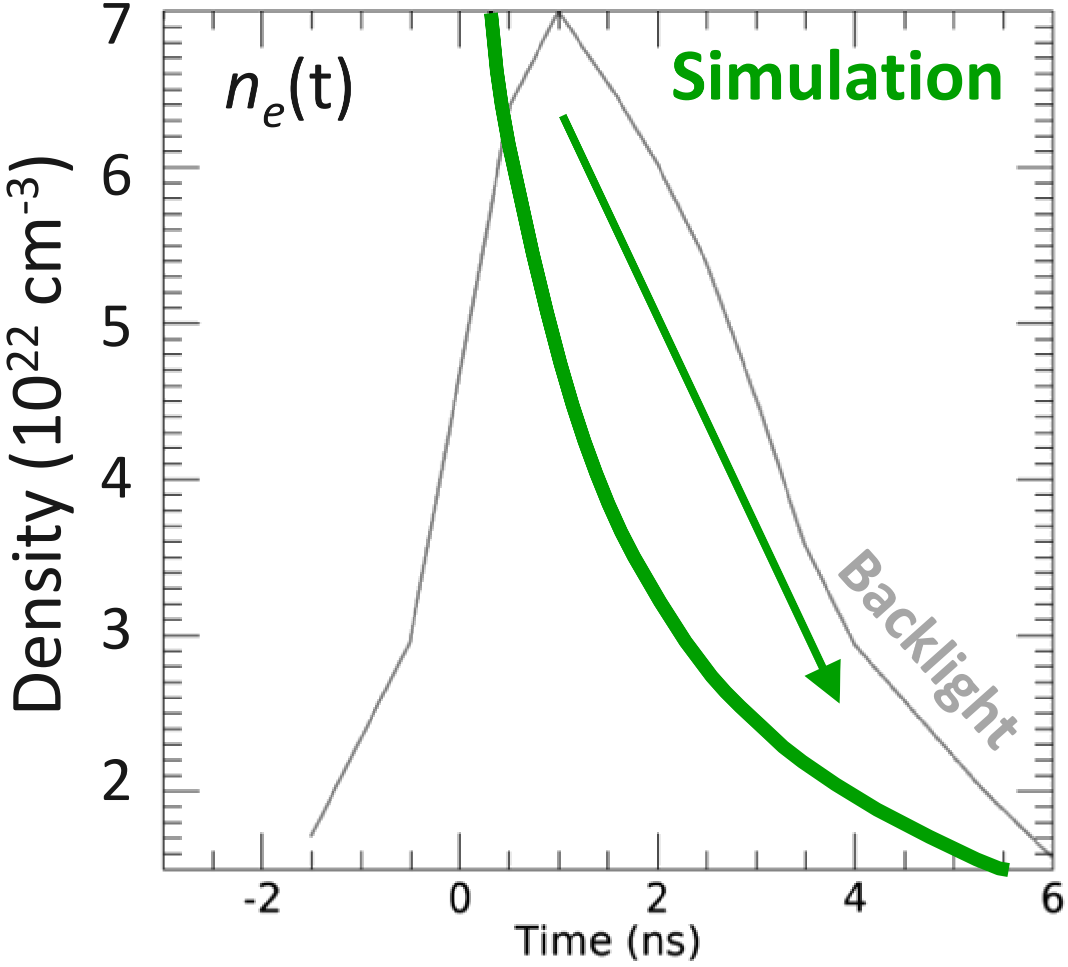


Mg spectra → $T_e(t)$ and $n_e(t)$

Fe spectra→ Time resolved Fe opacity

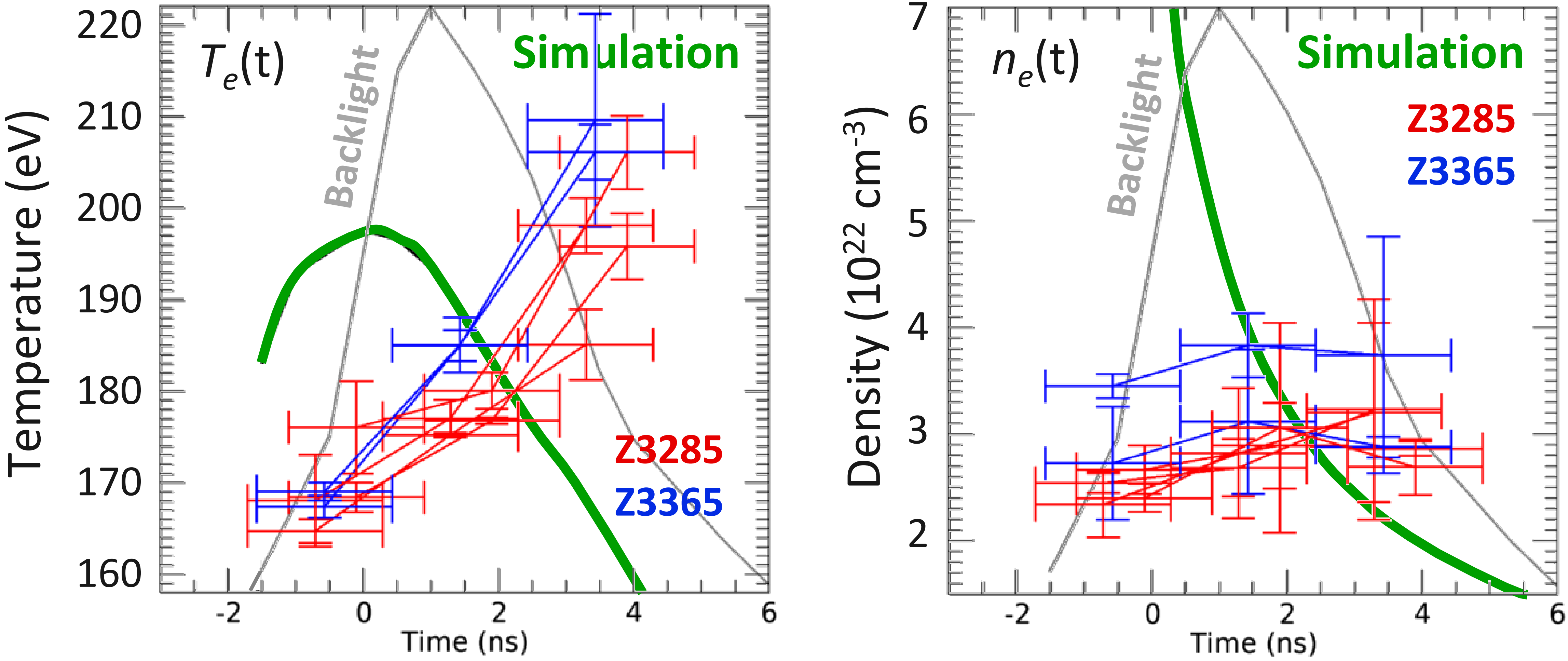
Simulations* predicted that sample temperature goes up and down while density monotonically decreases





* Nagayama et al PRE (2016)

Time-resolved measurement suggested different sample evolution



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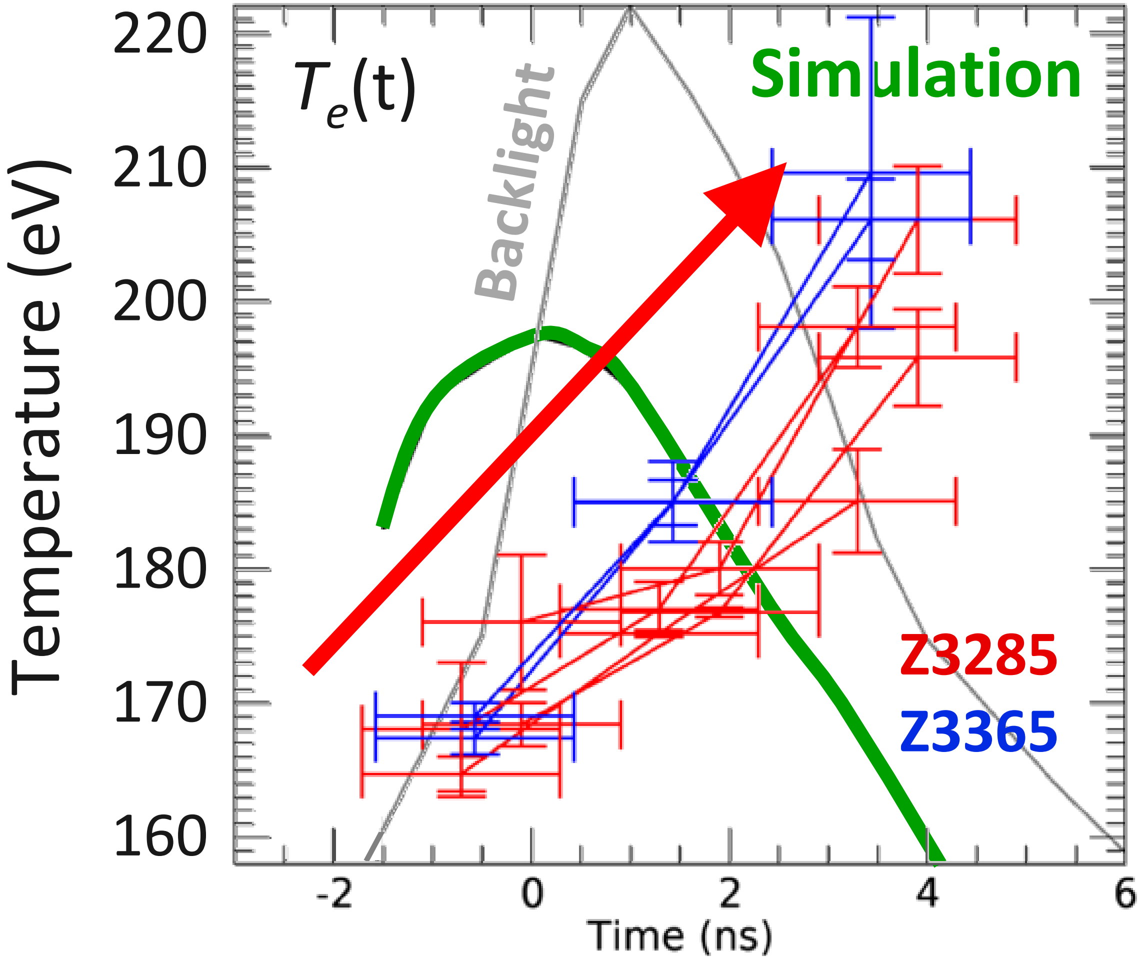
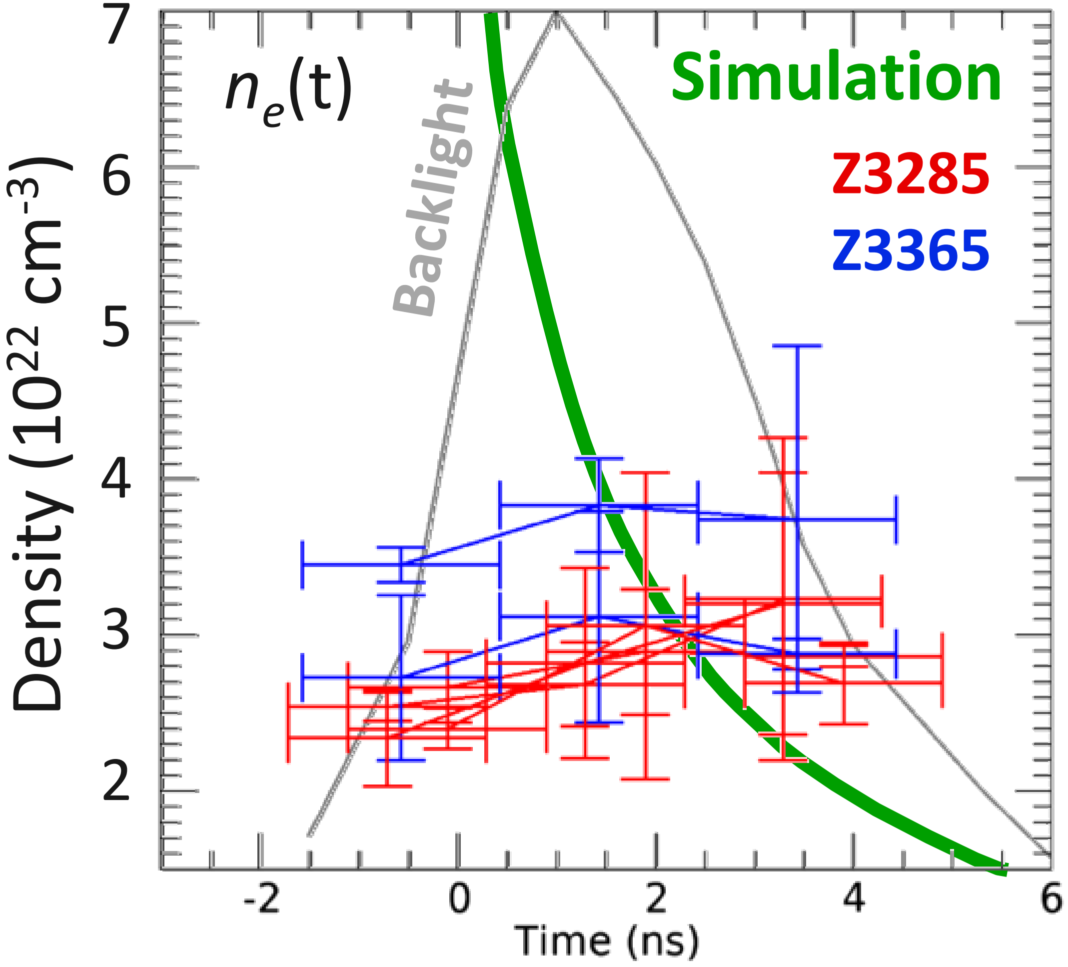
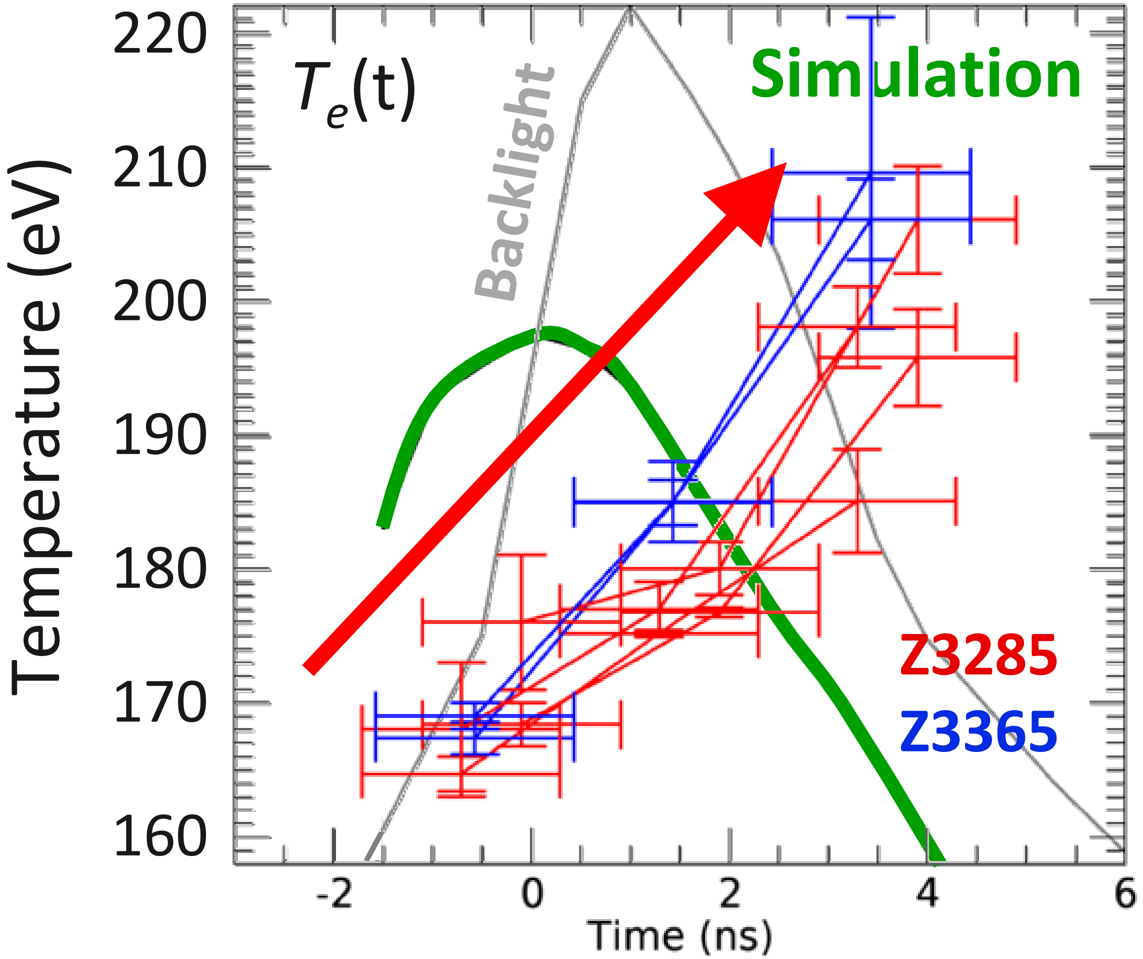
Time-resolved measurement suggested different sample evolution

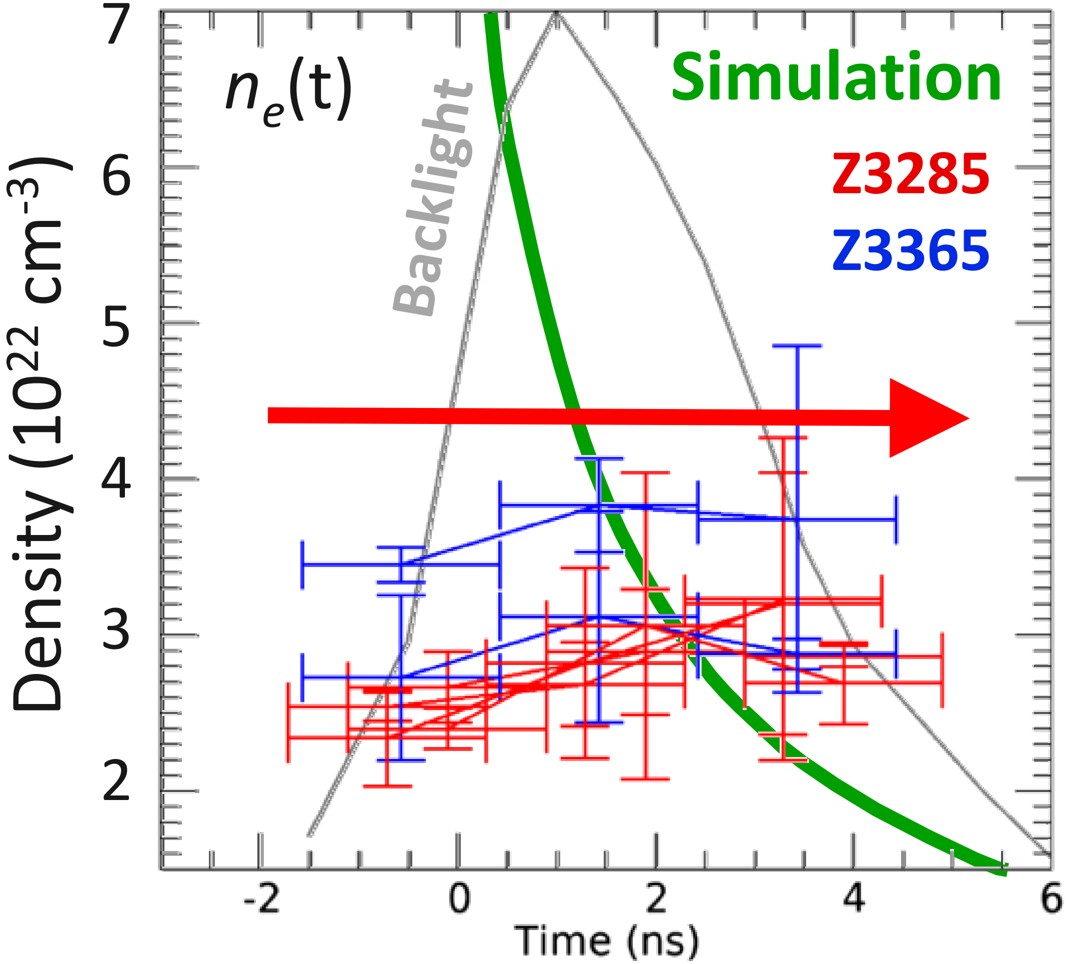




Temperature: Monotonically increasing → Is the sample approaching to the Z pinch?

Time-resolved measurement suggested different sample evolution

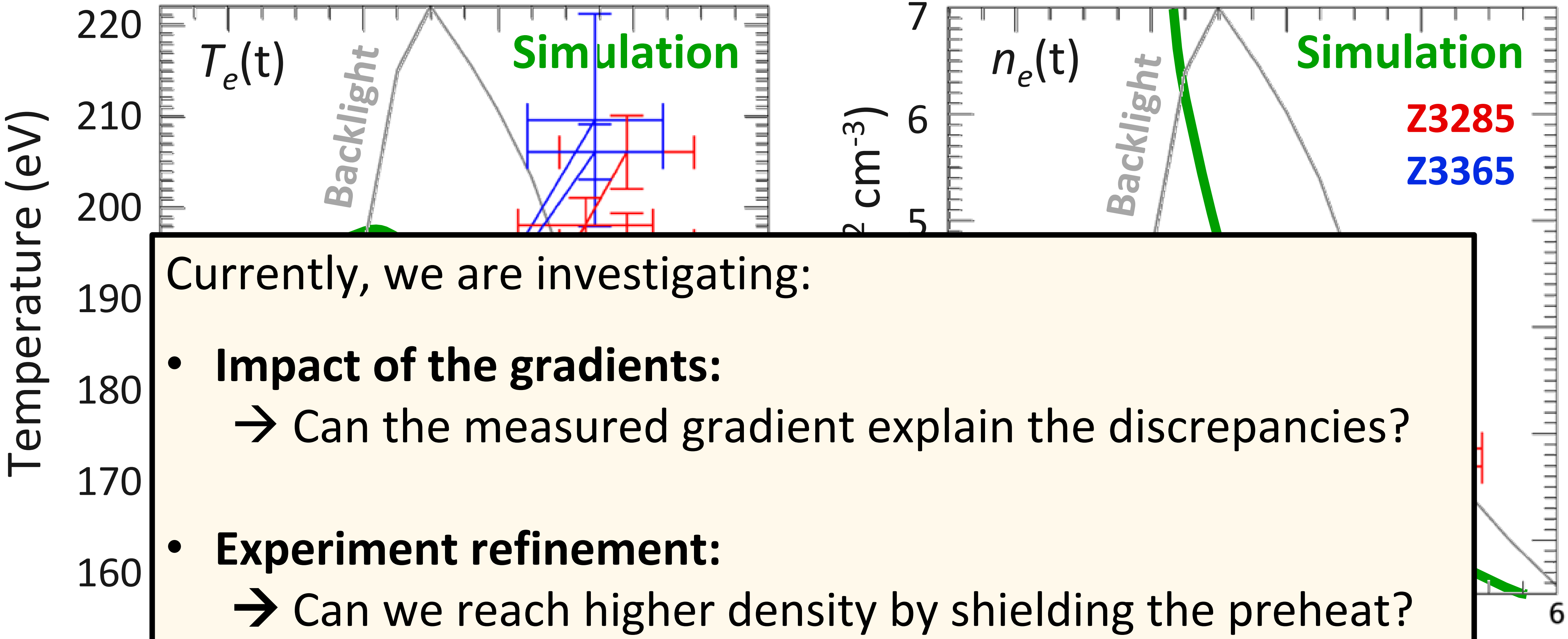




Temperature: Monotonically increasing → Is the sample approaching to the Z pinch?

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

Time-resolved measurement suggested different sample evolution



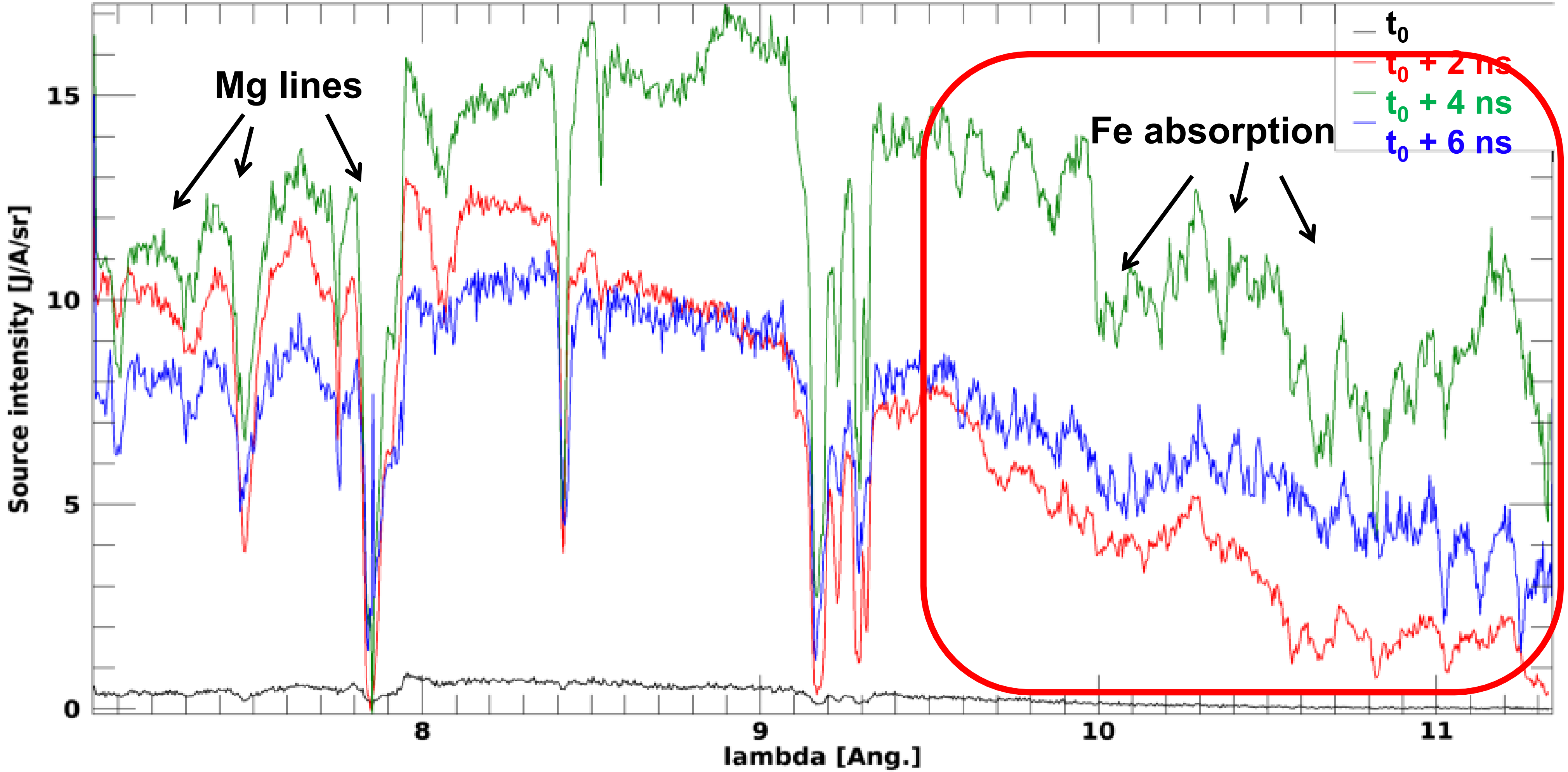
Currently, we are investigating:

- **Impact of the gradients:**
  → Can the measured gradient explain the discrepancies?

- **Experiment refinement:**
  → Can we reach higher density by shielding the preheat?

Temperature: Monotonically increasing → Is the sample approaching to the Z pinch?
Density: Constantly low → Is the sample expanded much earlier? Preheat?

We successfully measured time-resolved Fe absorption spectra; More work needed for time-resolved opacity



variation in shape of features

Need to collect more time-resolved calibration data for accurate opacity determination

Time-resolved opacity measurements can transform our stellar opacity research in a few important ways

1. Minimal gradient concern

2. Multiple opacity measurements from a single experiment

- Great leverage for HED experiments
- We can study how opacity changes with T_e and n_e?

3. Iron opacity at more extreme conditions

- Density effect is not tested at solar-interior density

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