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Opacity measurements for stellar interiors

PRESENTED BY

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Z Fundamental Science Workshop 2020

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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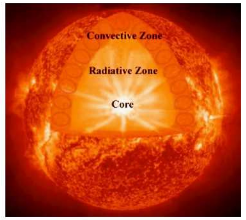
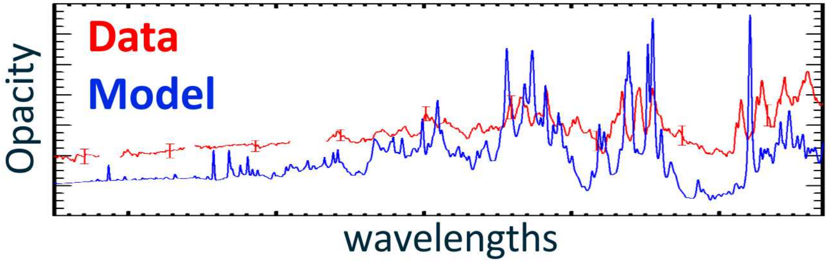
Nuclear Research Center Negev, Israel

Holistic approach including new experiments, new analysis, new theories will help resolve the solar problem





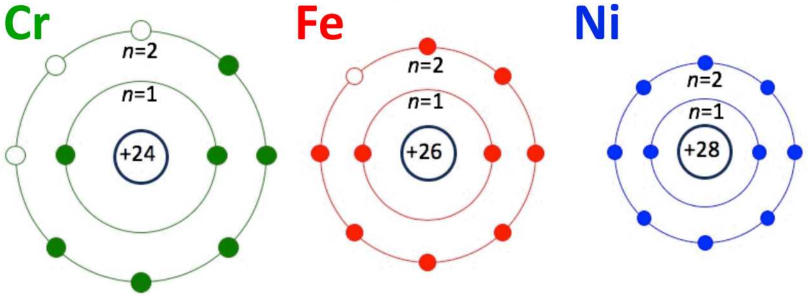
<u>Puzzle: Measured stellar iron opacity higher than predicted</u>

→ Both experiment and theory need to be scrutinized

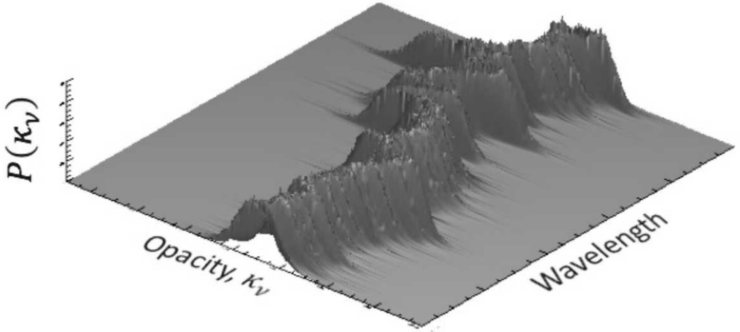
<u>Experiment scrutiny</u>

- **Systematic study of Cr, Fe, and Ni**

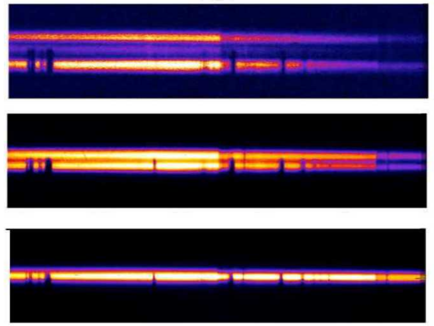
  → Narrow down hypotheses



- **Refined analysis method**

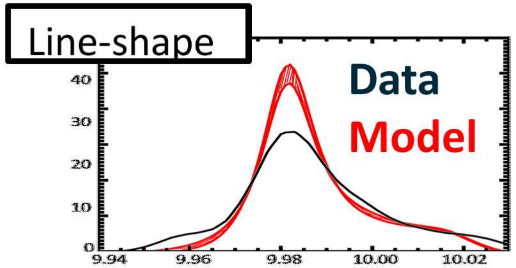


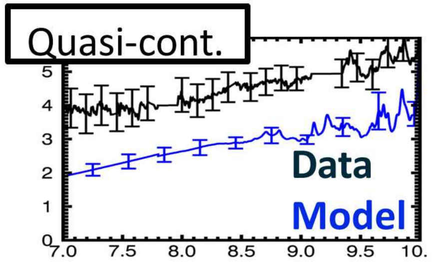
- **Time-resolved data**



<u>Theoretical scrutiny</u> stimulates atomic-physics discussions

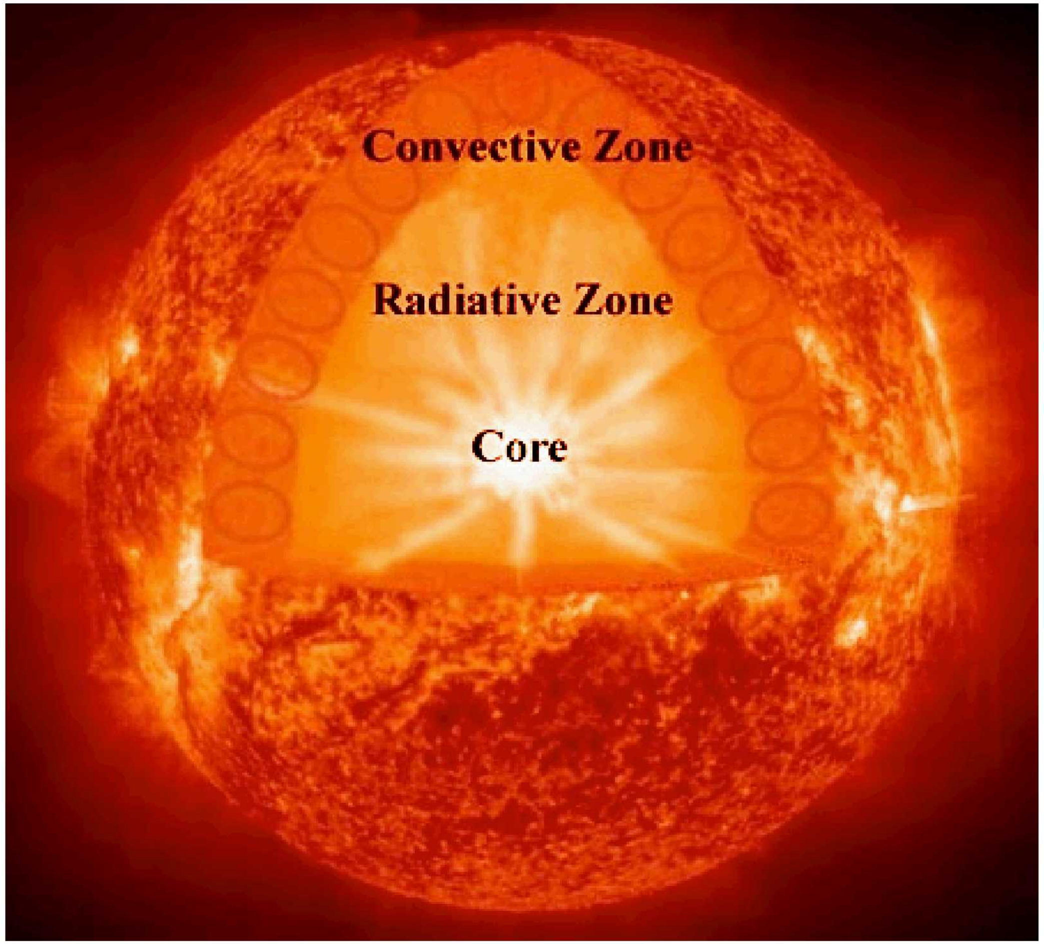
- **Spectral line shapes:** Ion, electron, satellites
- **Quasi-continuum:** new theories





Continued experimental and theoretical research is needed for understanding photon-atom interactions in High-Energy-Density matter

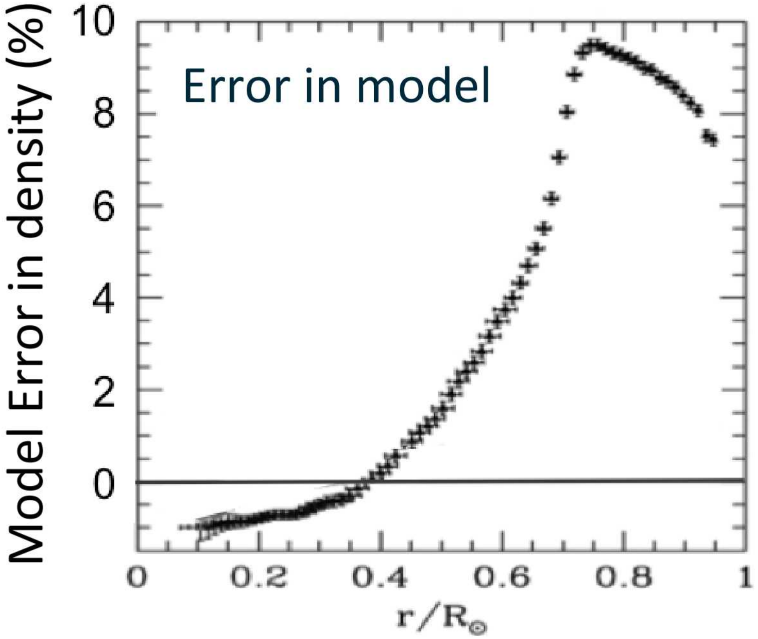
Modeled solar structure disagree with observations; 10-30% mean opacity increase needed in the model



Standard solar model

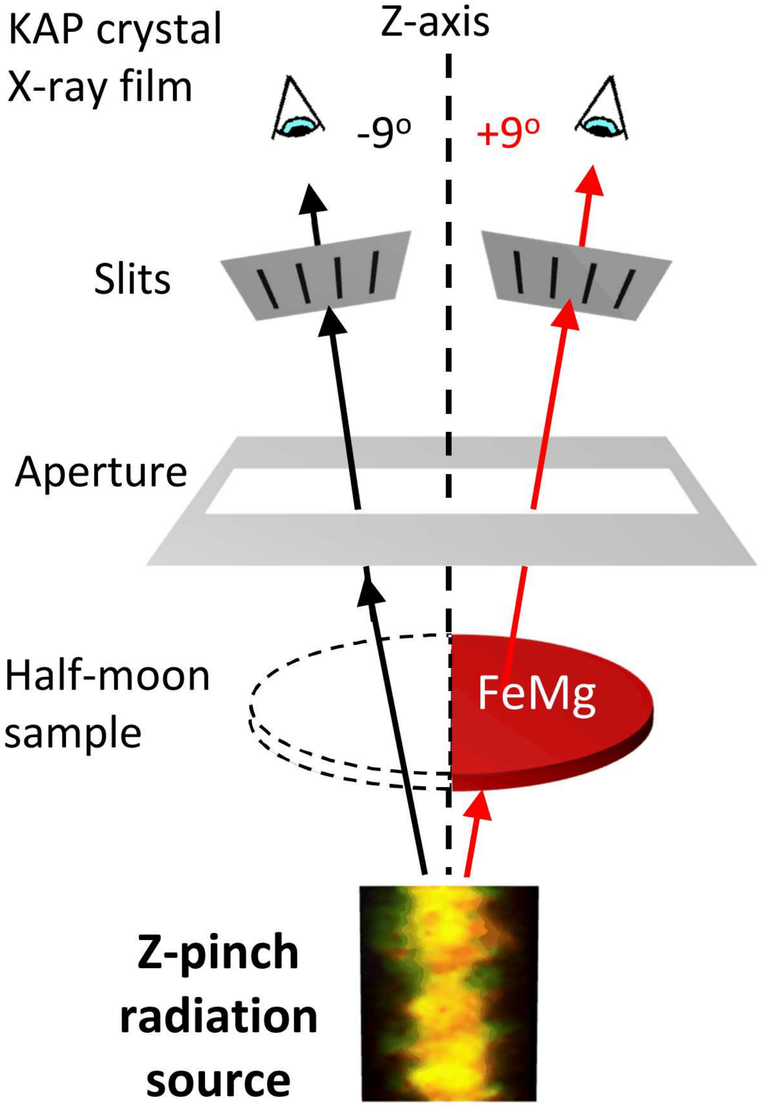
Inputs:

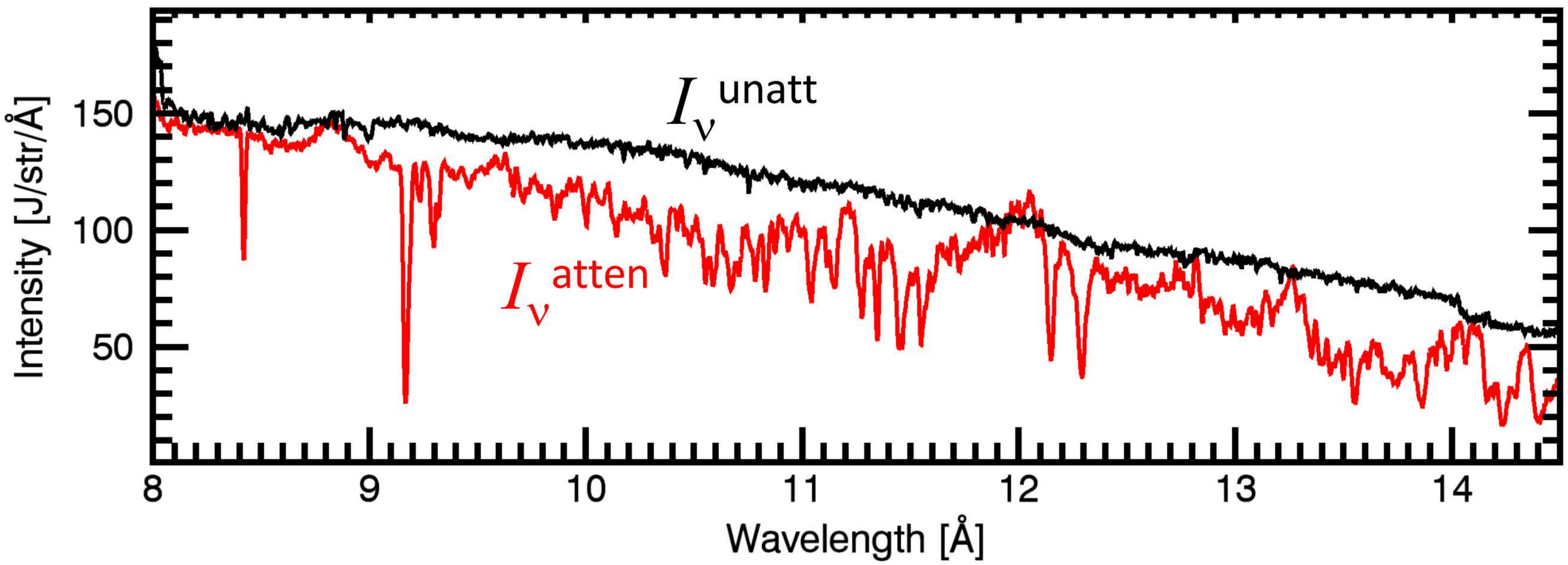
- Abundance
- EOS
- Opacity
- Etc.



Hypothesis: calculated iron opacity is underestimated at solar interior conditions

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)
[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

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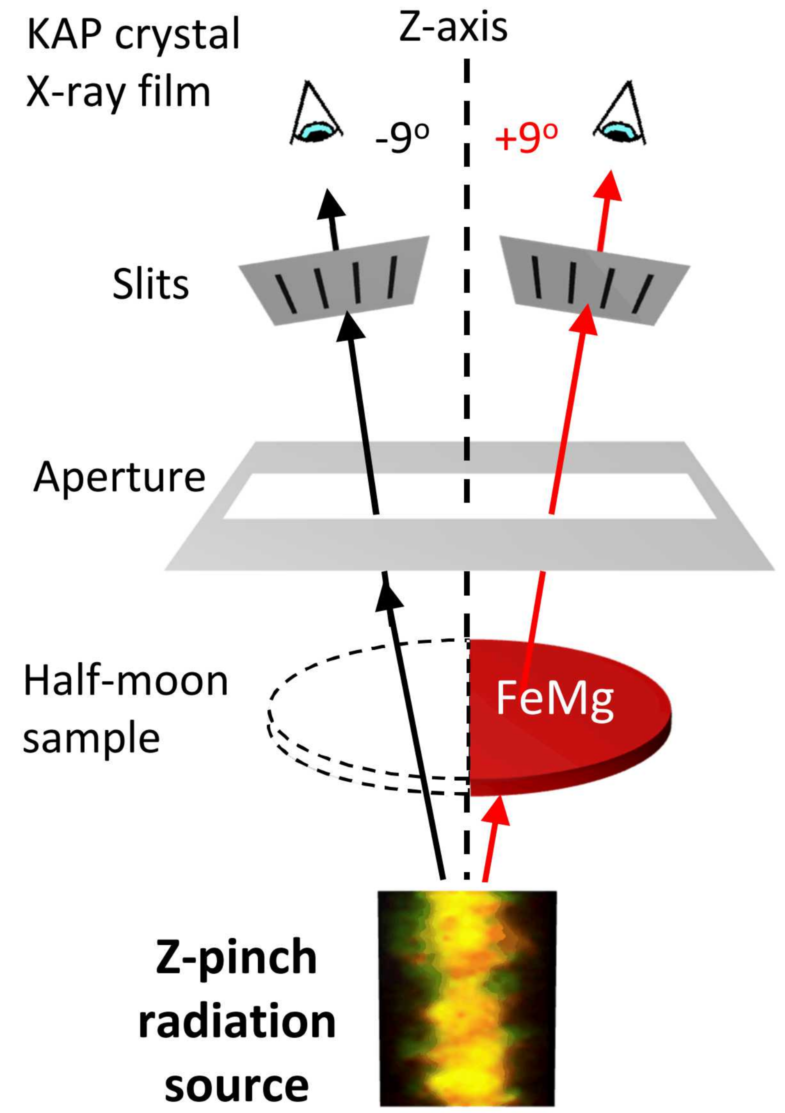

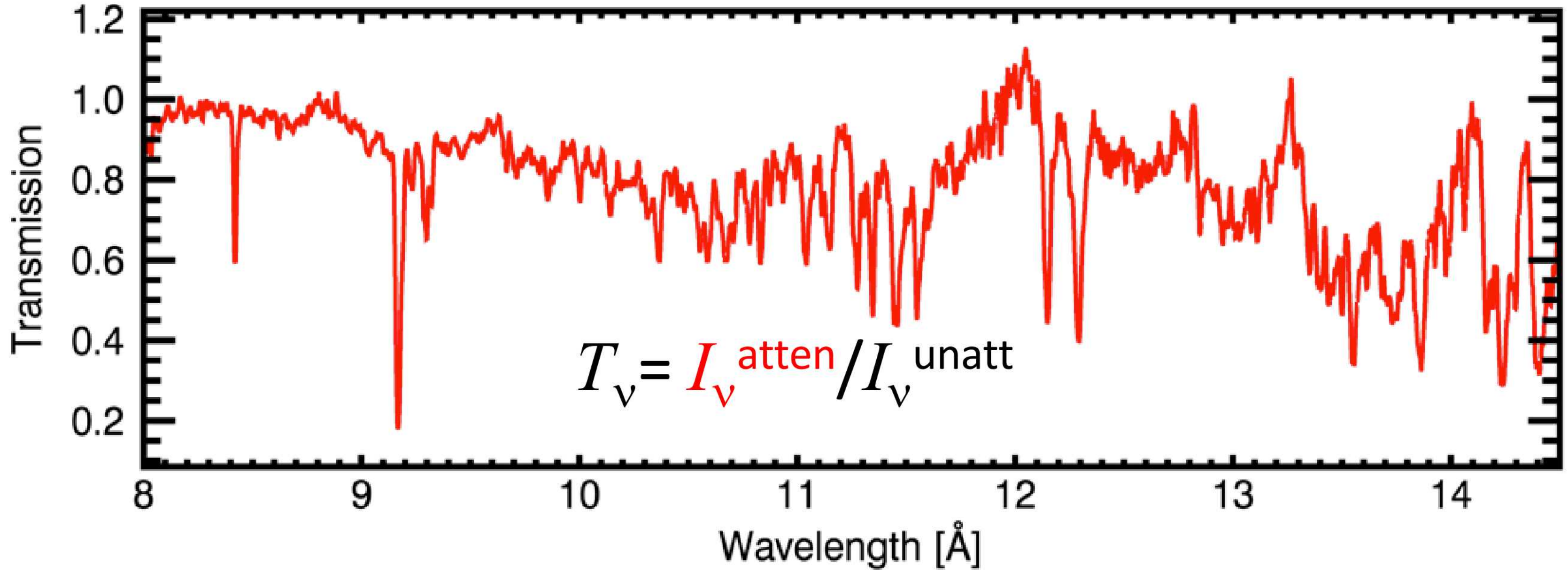

$$T_\nu = I_\nu^{atten} / I_\nu^{unatt}$$

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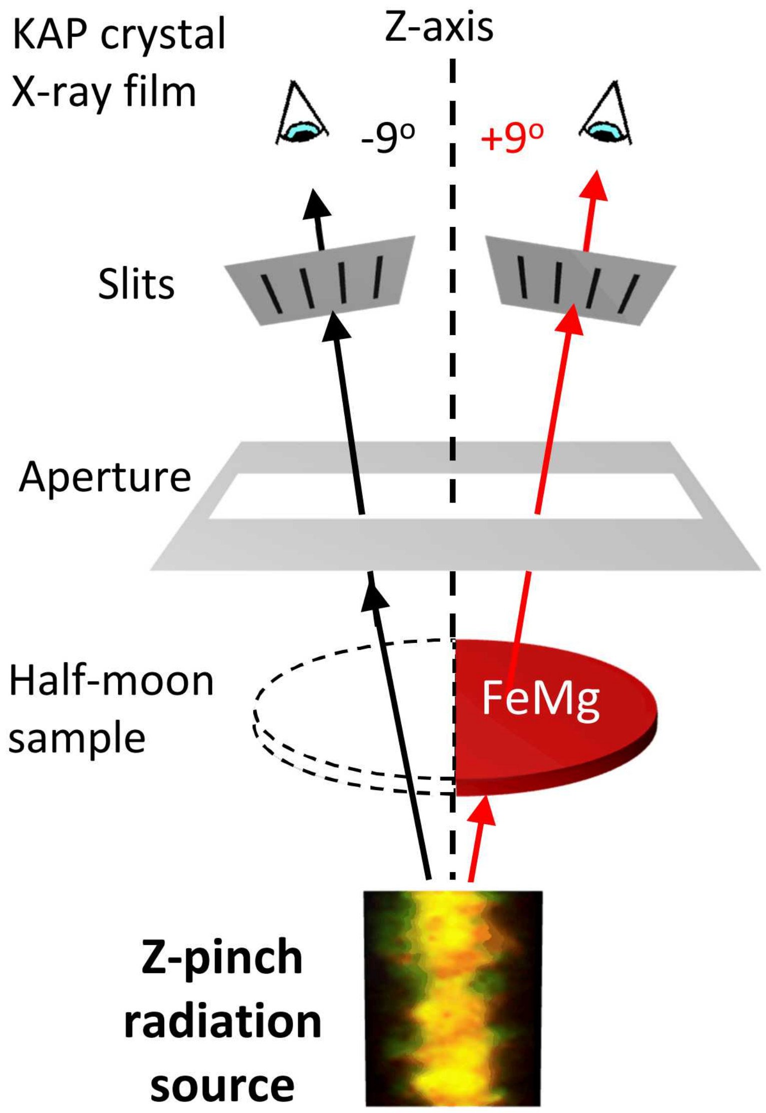

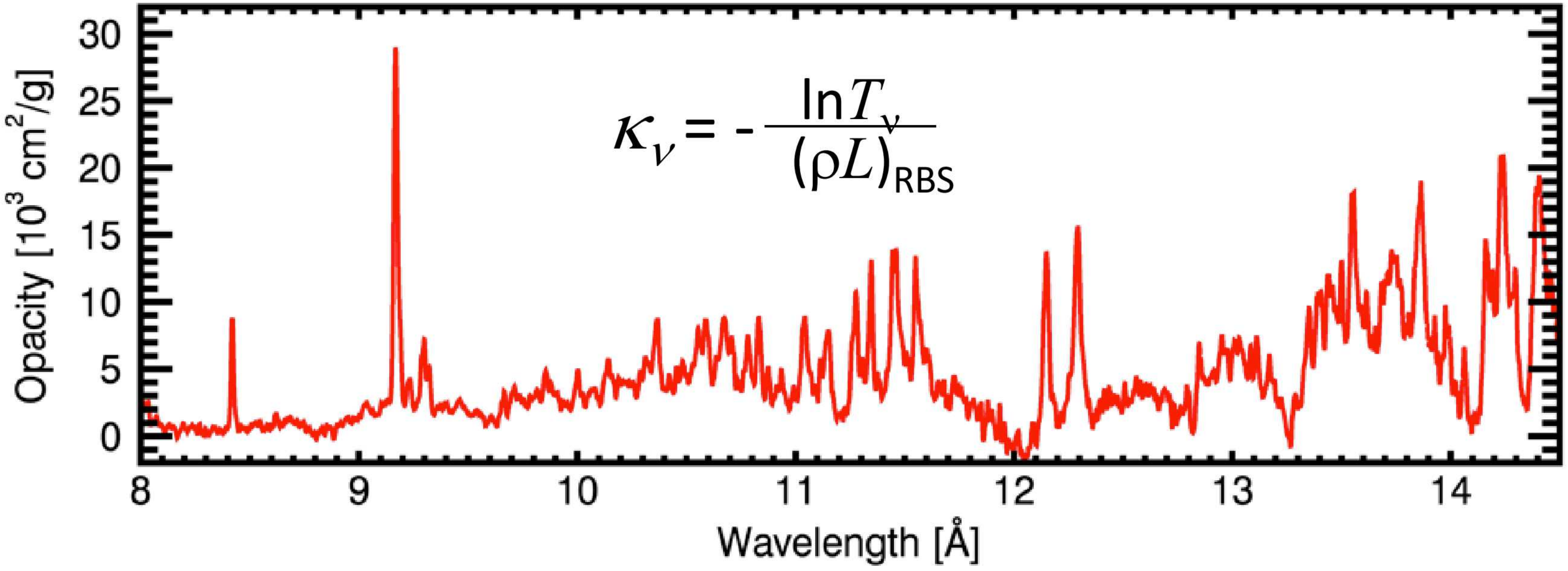

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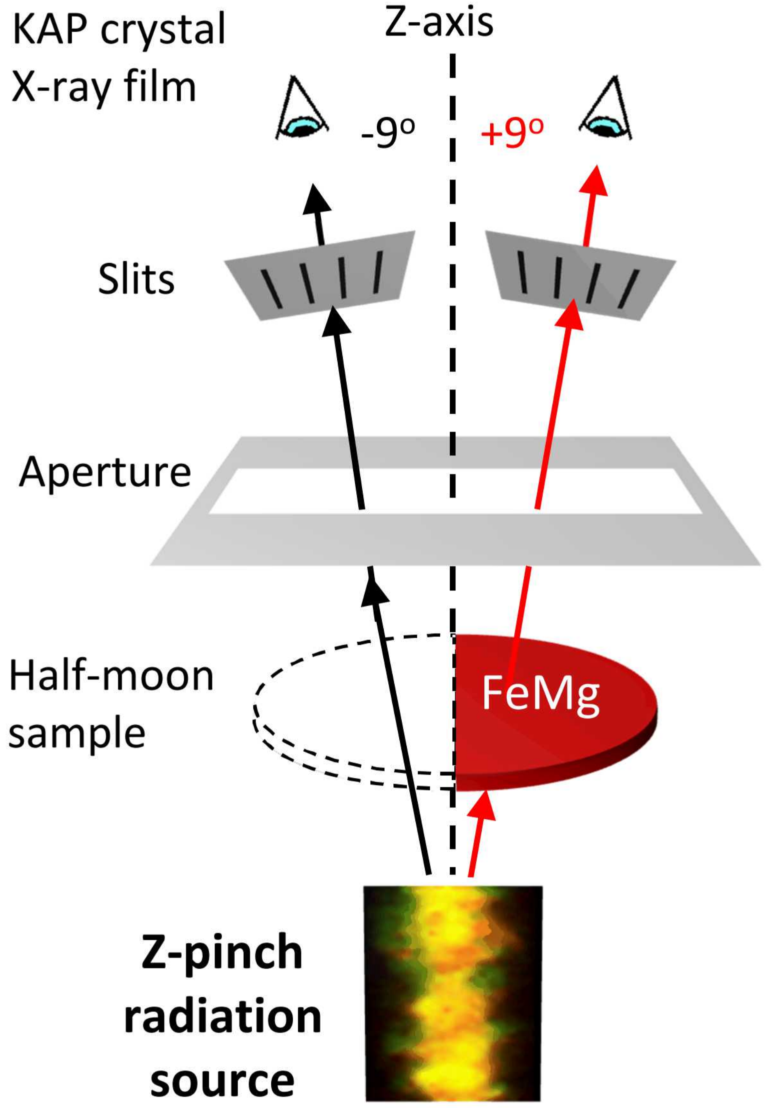

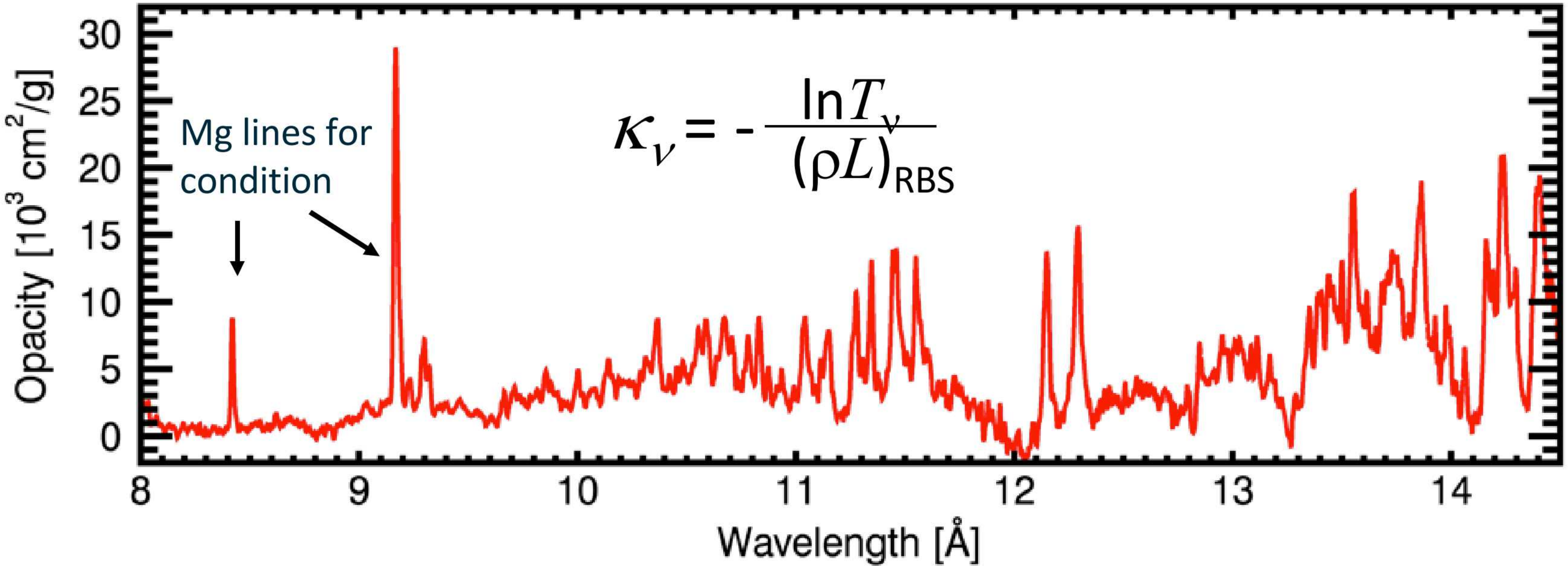

$$\kappa_\nu = -\frac{\ln T_\nu}{(\rho L)_{RBS}}$$

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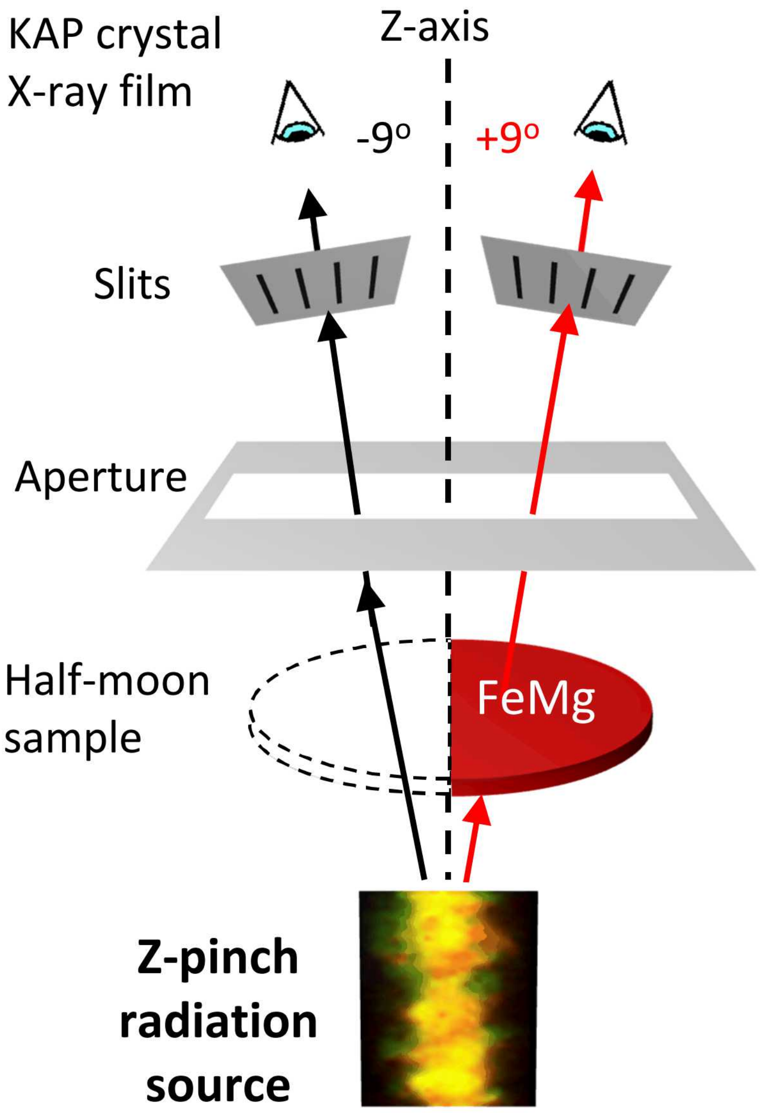

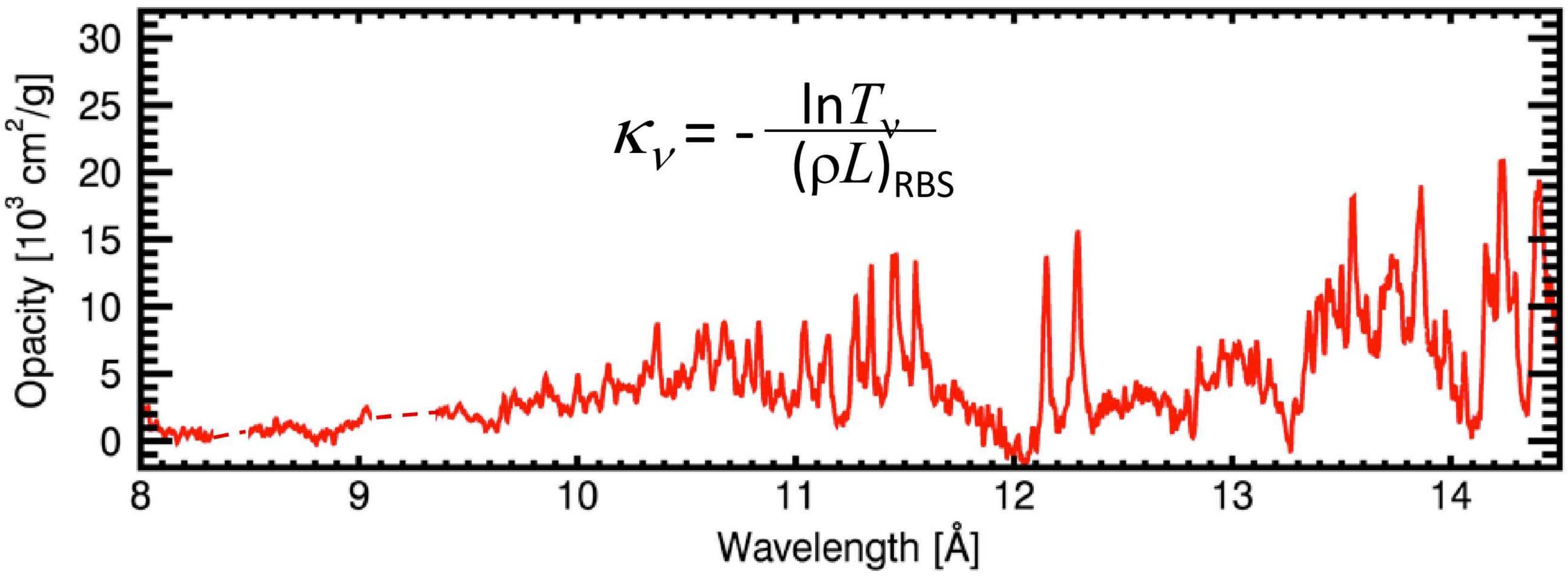

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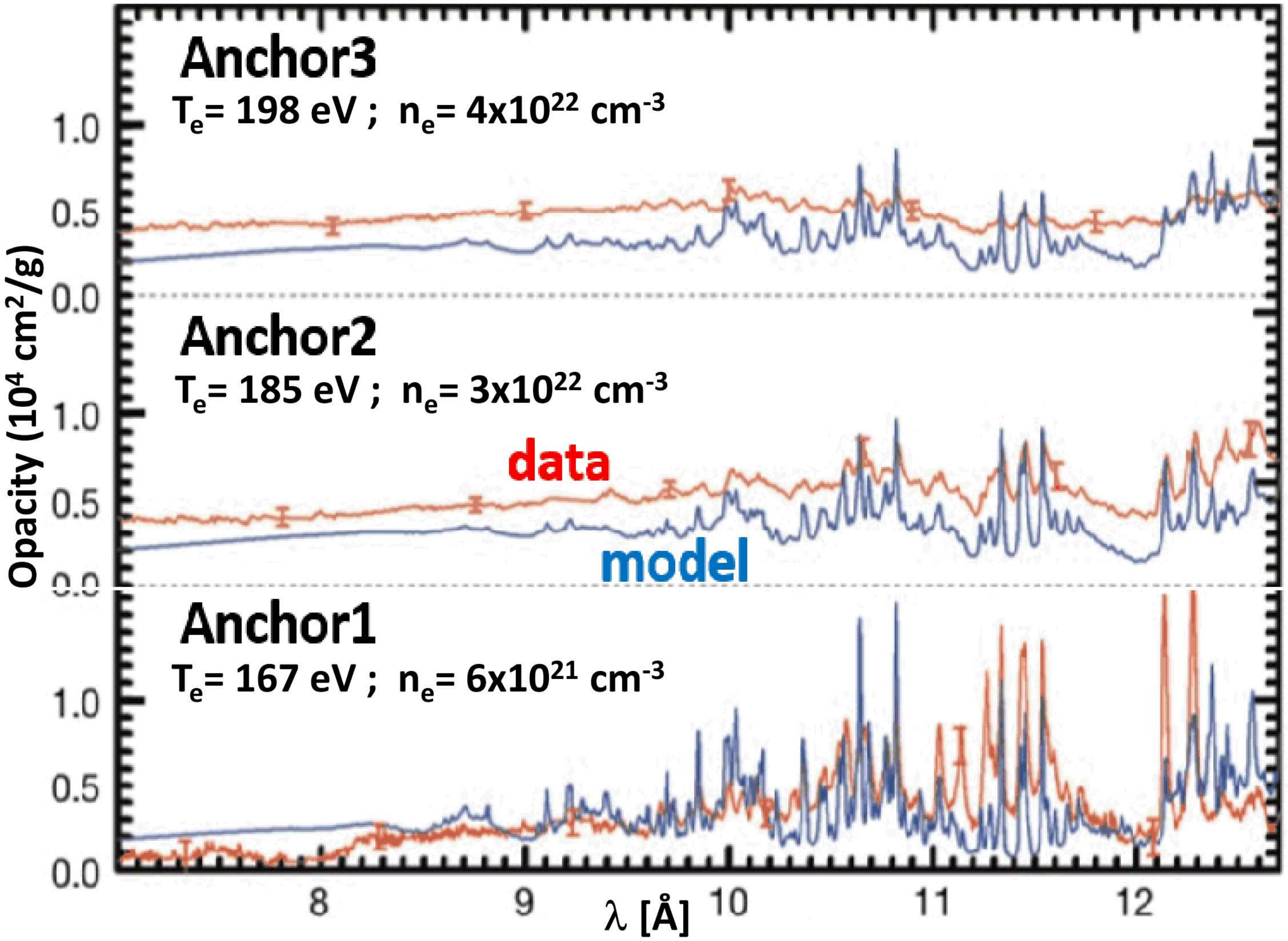
Calculated iron opacities are significantly lower than measurements as T_e, n_e approach solar interior values

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



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

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

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

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

High-energy-density (HED) science is challenging for both theory and experiment

What is high-energy-density?

Ideal gas law

$$PV = Nk_bT$$

⬇

$$\mathrm{P} = \left(\frac{N}{V}\right) k_bT$$

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Density (particles/cm^3)

Temperature in unit of energy (eV)

How much energy per volume

or

Energy density

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Density (particles/cm^3) — $\left(\frac{N}{V}\right)$

Temperature in unit of energy (eV) — k_bT

How much energy per volume

or

Energy density

High energy density (HED) plasma

||

High pressure (> 1Mbar) plasma

||

High temperature, high density plasma

||

Hot, dense plasma

They are used interchangeably

High-energy-density (HED) science is challenging for both theory and experiment

Experiments: Hard to diagnose, hard to repeat

HED plasma is created by compressing energy in space and time

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Easy to say
Hard to do

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Small size: $10^{-5} - 10^{-3}\ m$
$\boldsymbol{\mu m, mm}$
Short duration: $10^{-15} - 10^{-9}$ s
fs, ps, ns

→ Hard to diagnose

Expensive
Limited resource

→ Hard to get opportunity to check reproducibility

High-energy-density (HED) science is challenging for both theory and experiment

Theory: High temperature, high density effects complicate modeling

Challenge 1: Involves many excited states

Challenge 2: Density effects with thermal fluctuation

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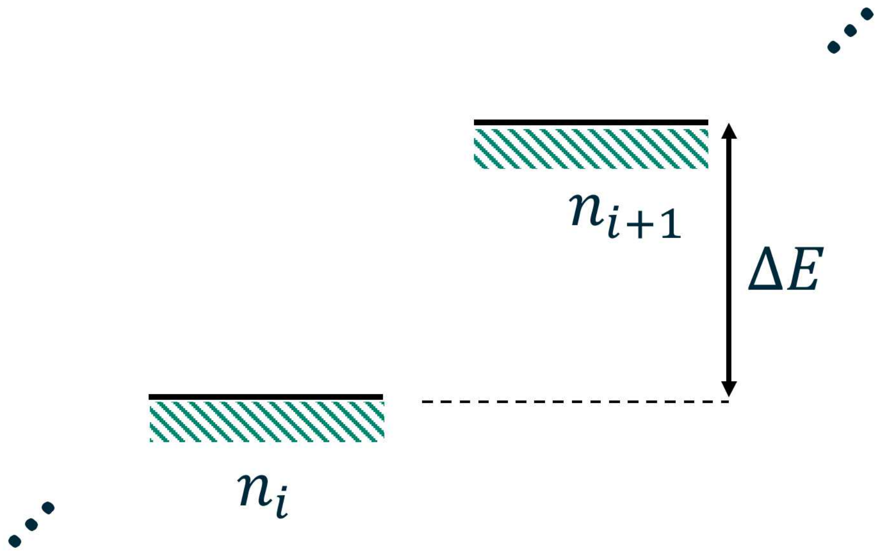

<u>Ionization by the Saha equation</u>

$$\frac{n_{i+1}}{n_i} \propto \frac{\exp(-\Delta E/T_e)}{n_e}$$

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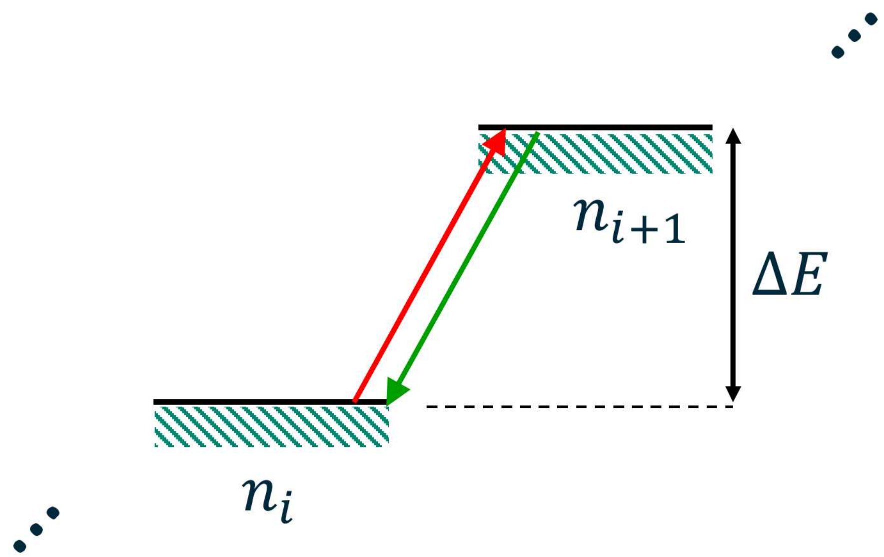

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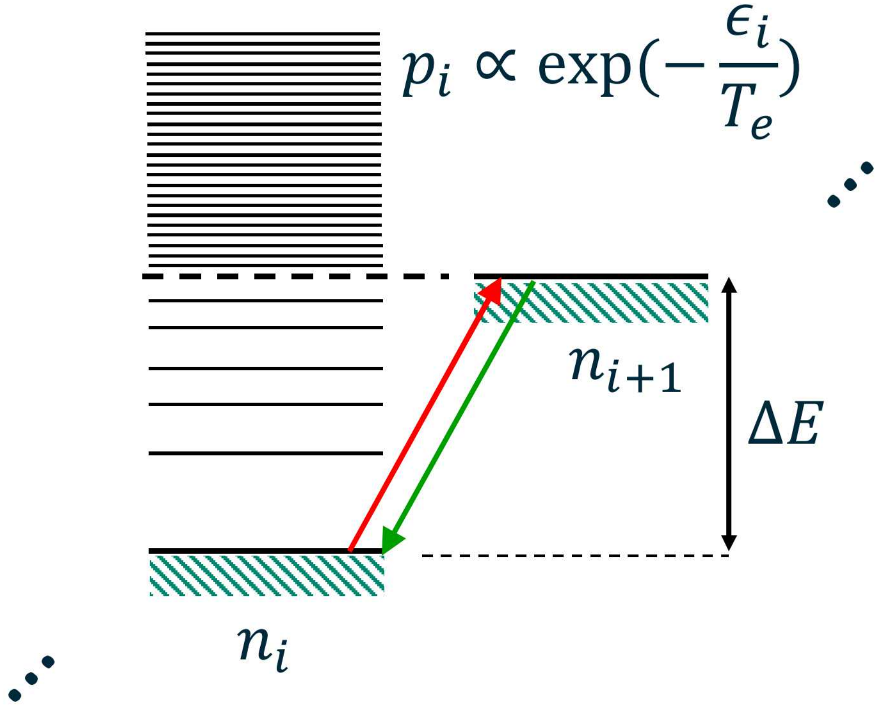

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- Increasing density promotes recombination

HED plasma can have similar ionization to low temperature, low density plasma, but …

- **Significant population in excited states!**
- **Complete inclusion of excited states is crucial**

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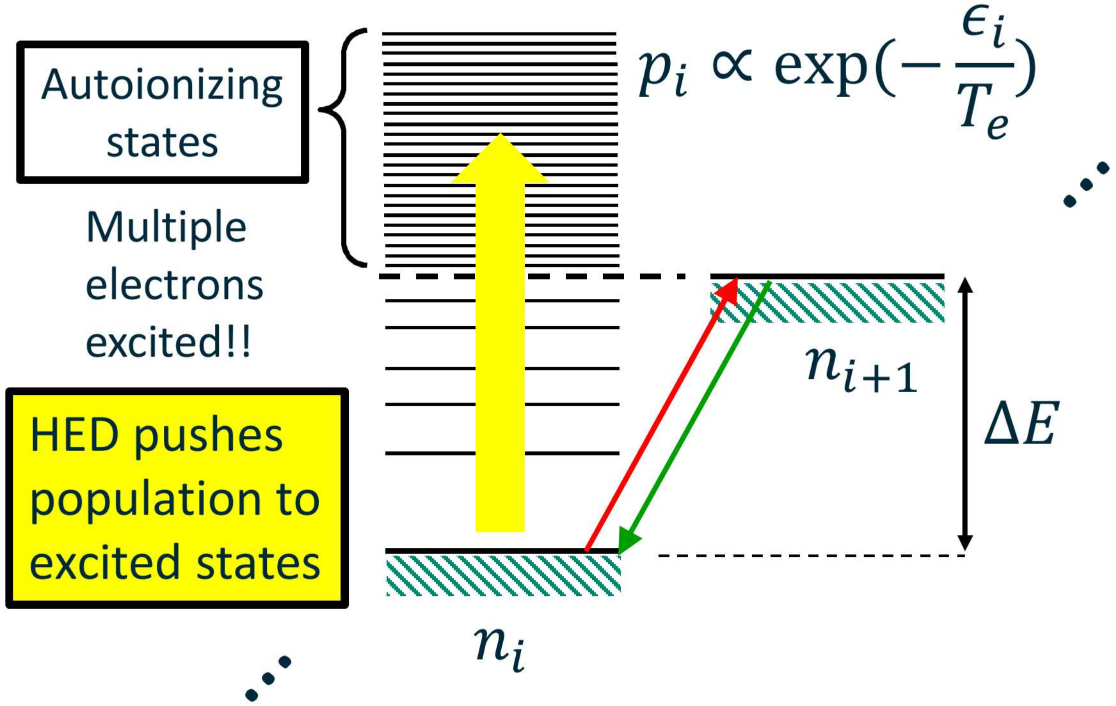

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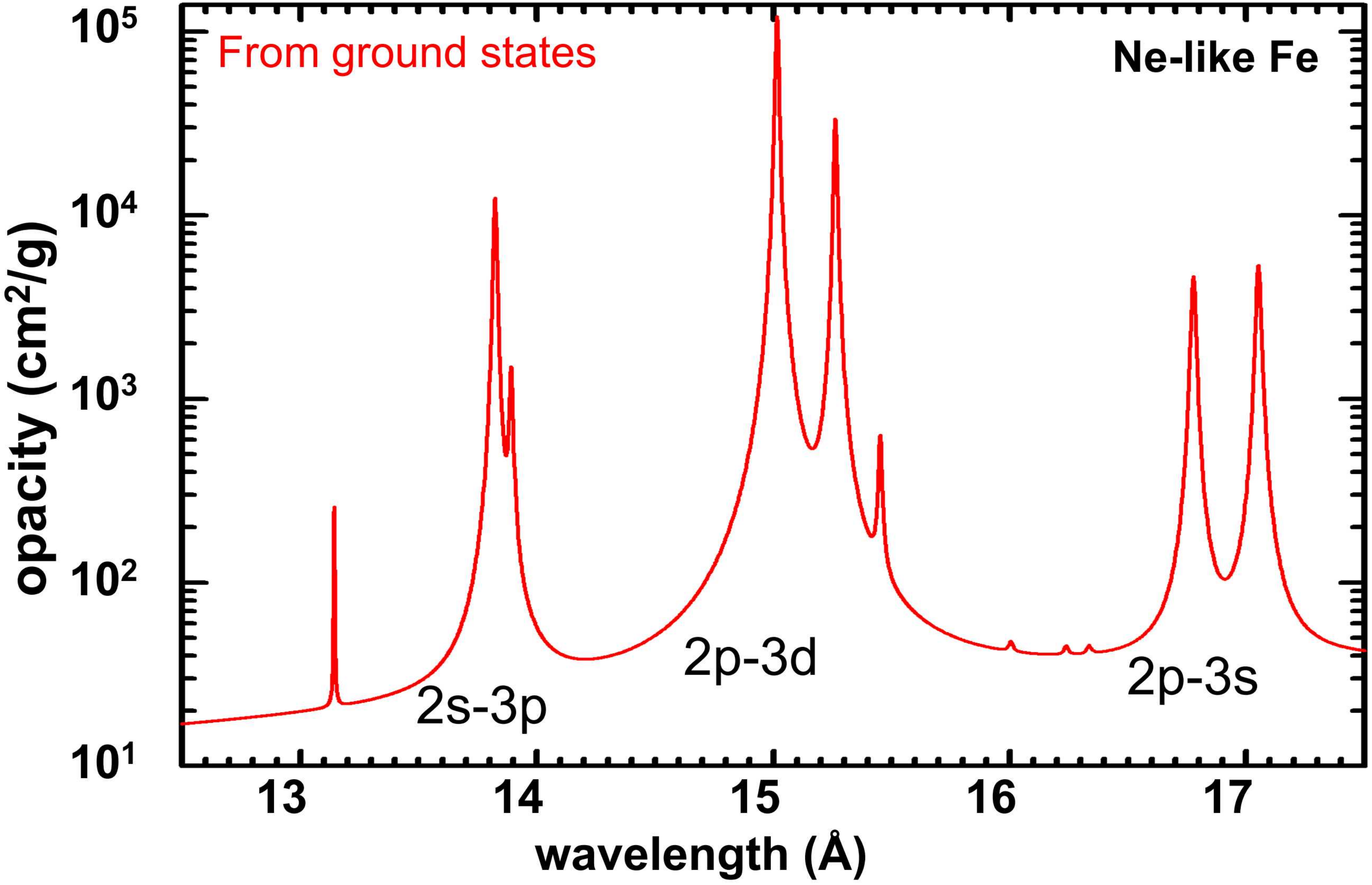
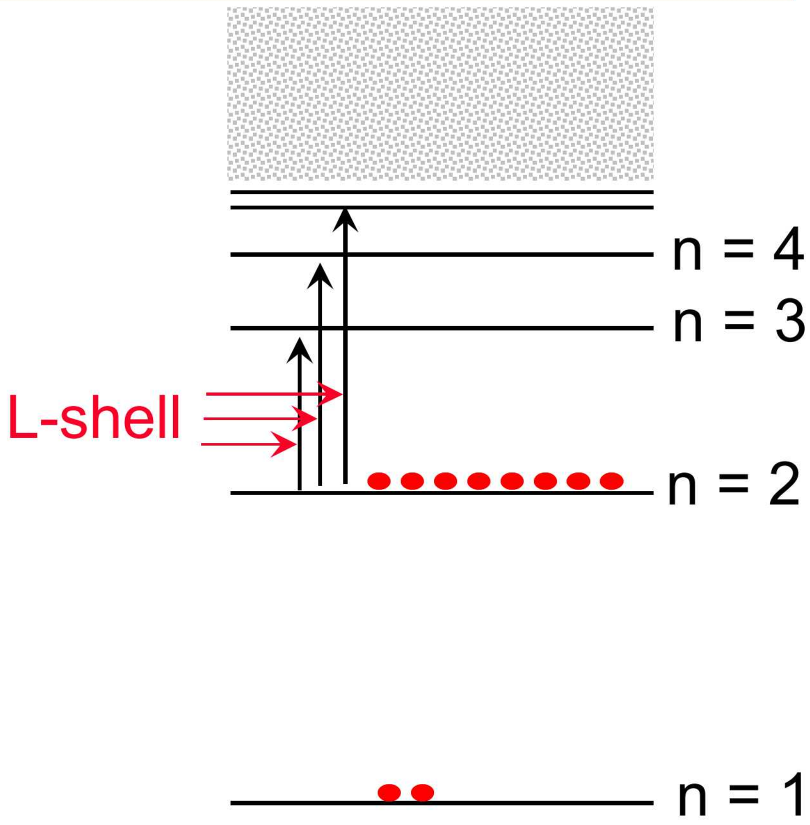
Opacity contribution from ground states are relatively simple

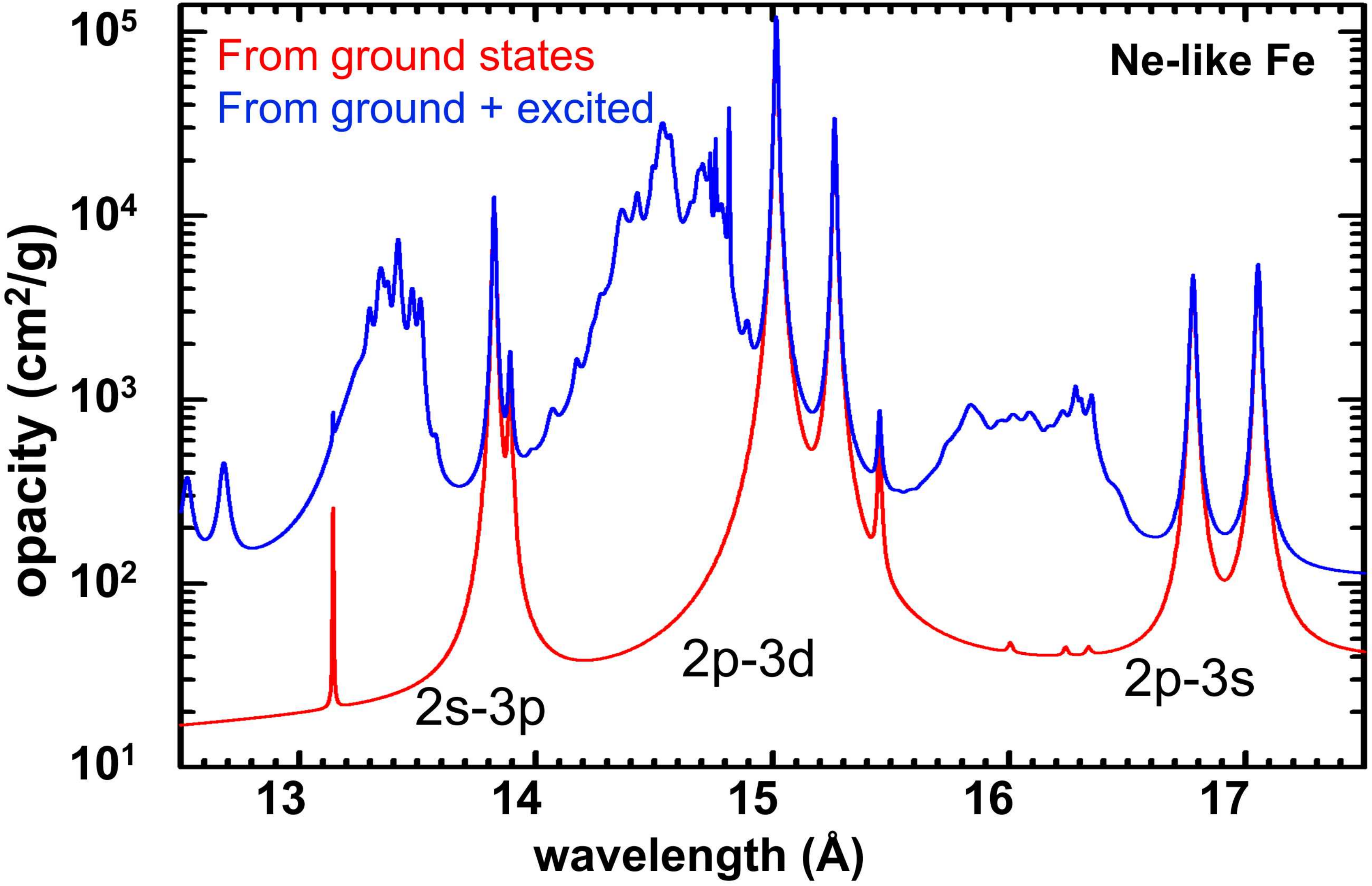


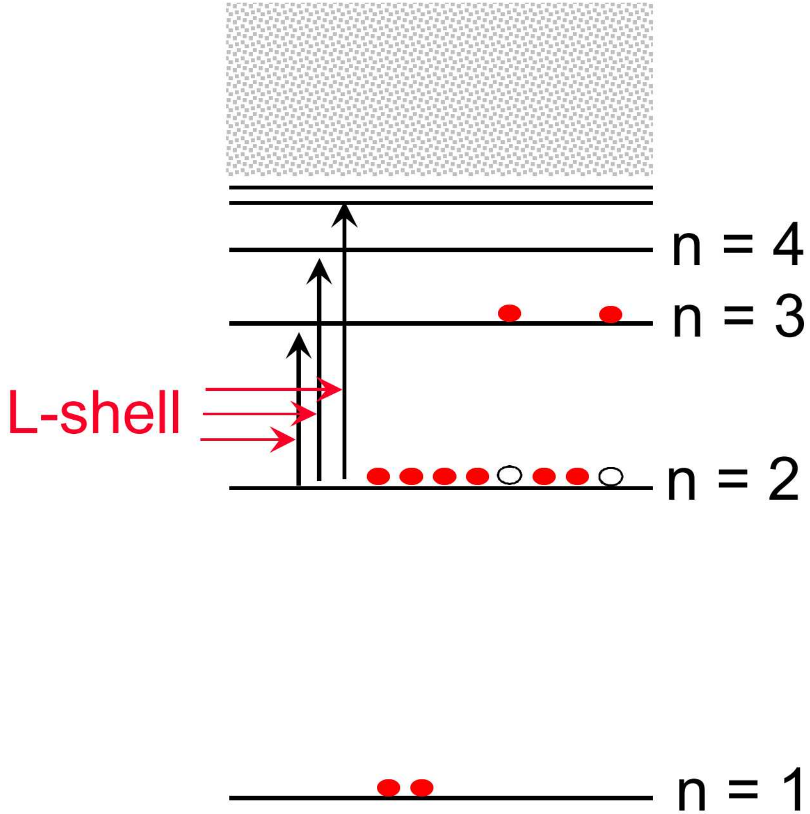


Fe^{+16} : $1s^2 2s^2 2p^6$

Ne-like

Contribution from excited states significantly adds complexity





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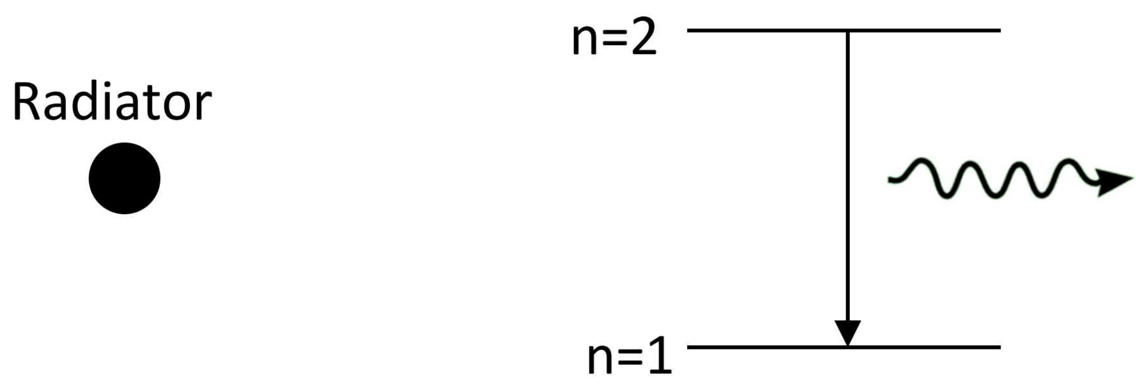
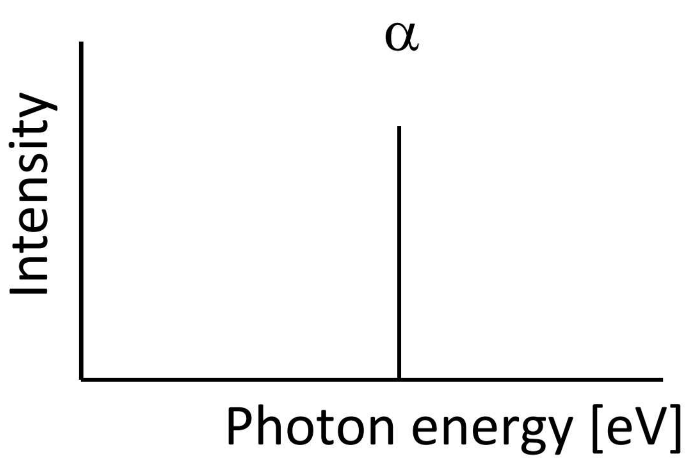
Example:
- **Line broadening [1]**
- Level depletion
  → Occupation probability [2]

Isolated atom

Unperturbed transition energies





[1] Griem, Spectral Line Broadening by Plasmas (1974)
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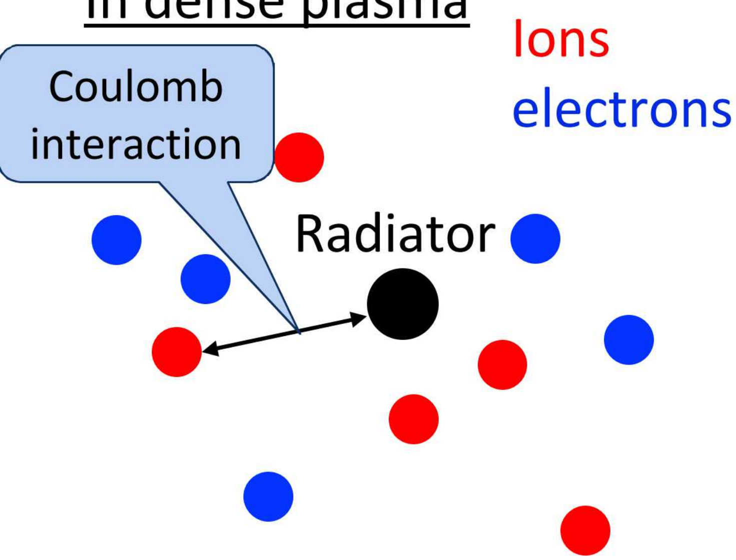
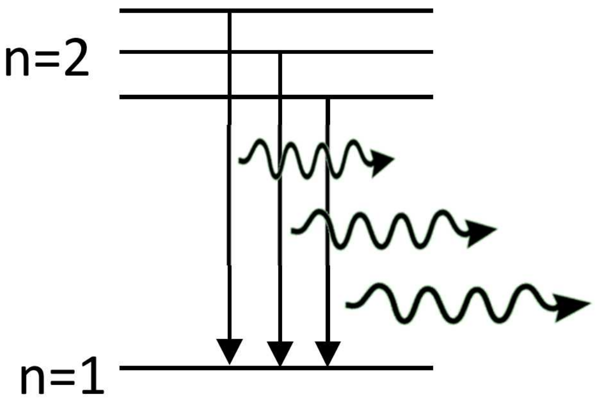
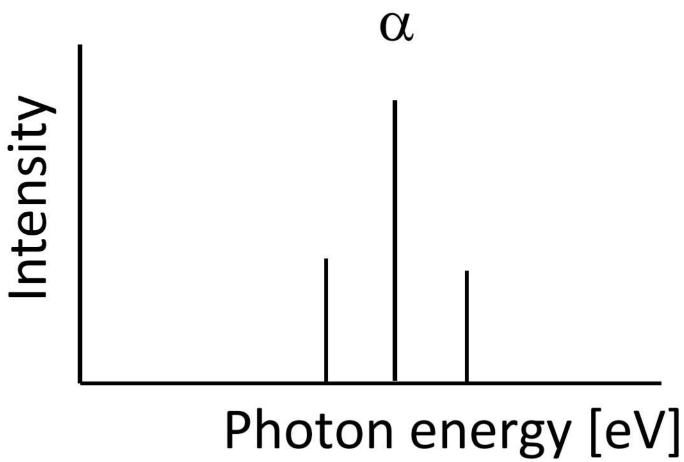
In dense plasma



Energy splits due to Stark effects





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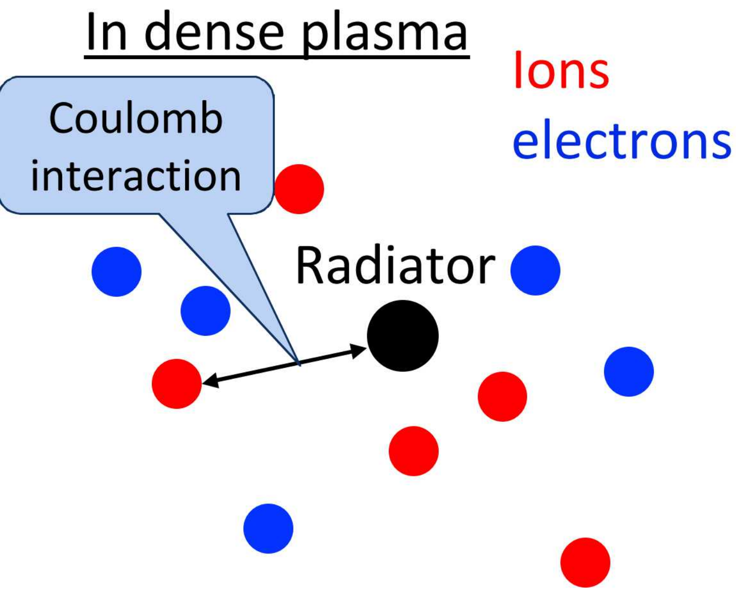

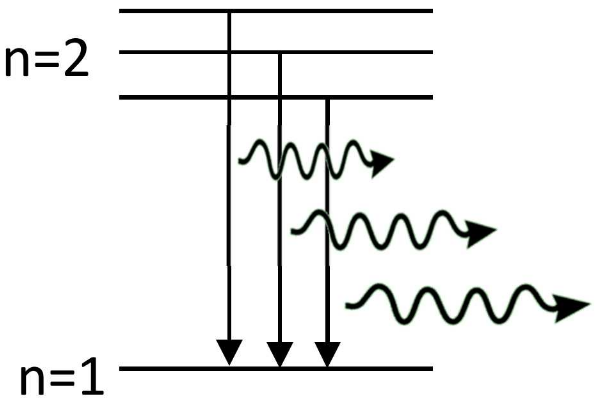

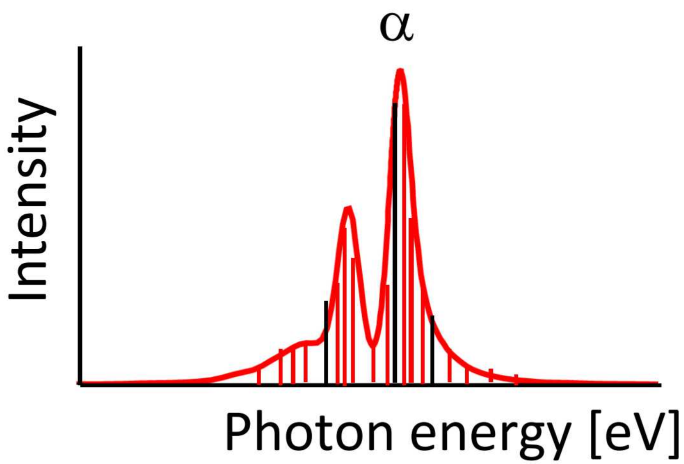

Observation is the ensemble of the random perturbations

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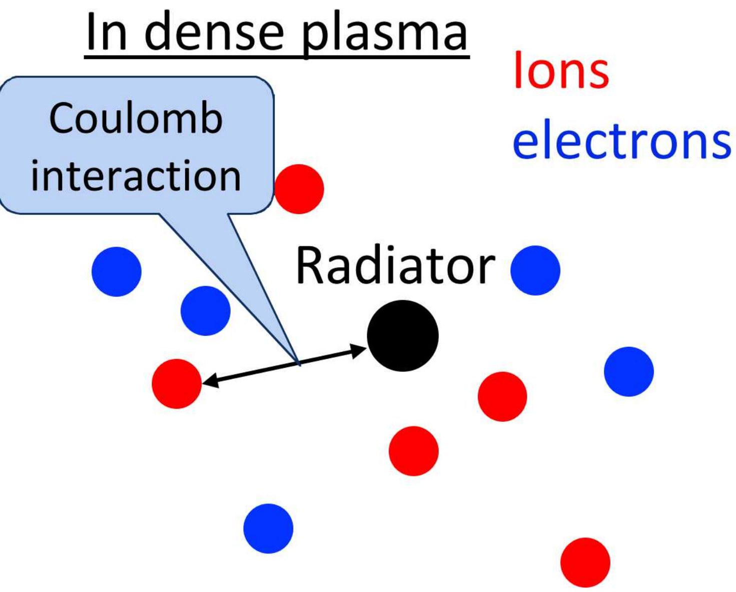
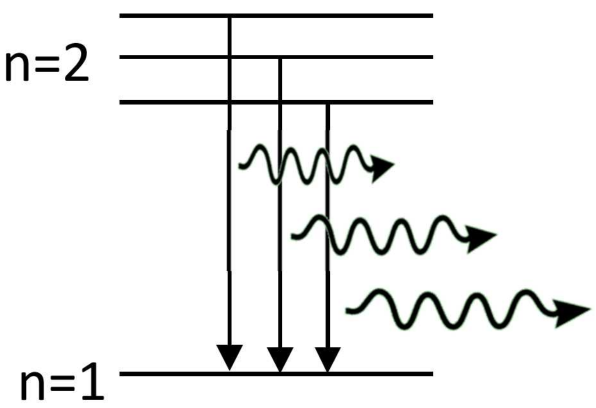
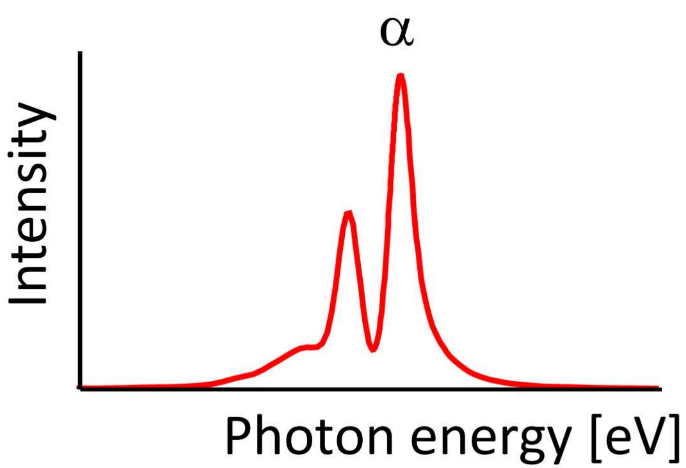






Spectral lines are broadened due to the ensemble of random perturbations

[1] Griem, Spectral Line Broadening by Plasmas (1974) [2] Hummer and Mihalas, Astrophys. J. 331, 794 (1988)

High-energy-density (HED) science is challenging for both theory and experiment

What is high-energy-density science?

Science for high temperature, high density plasma

Experiment:

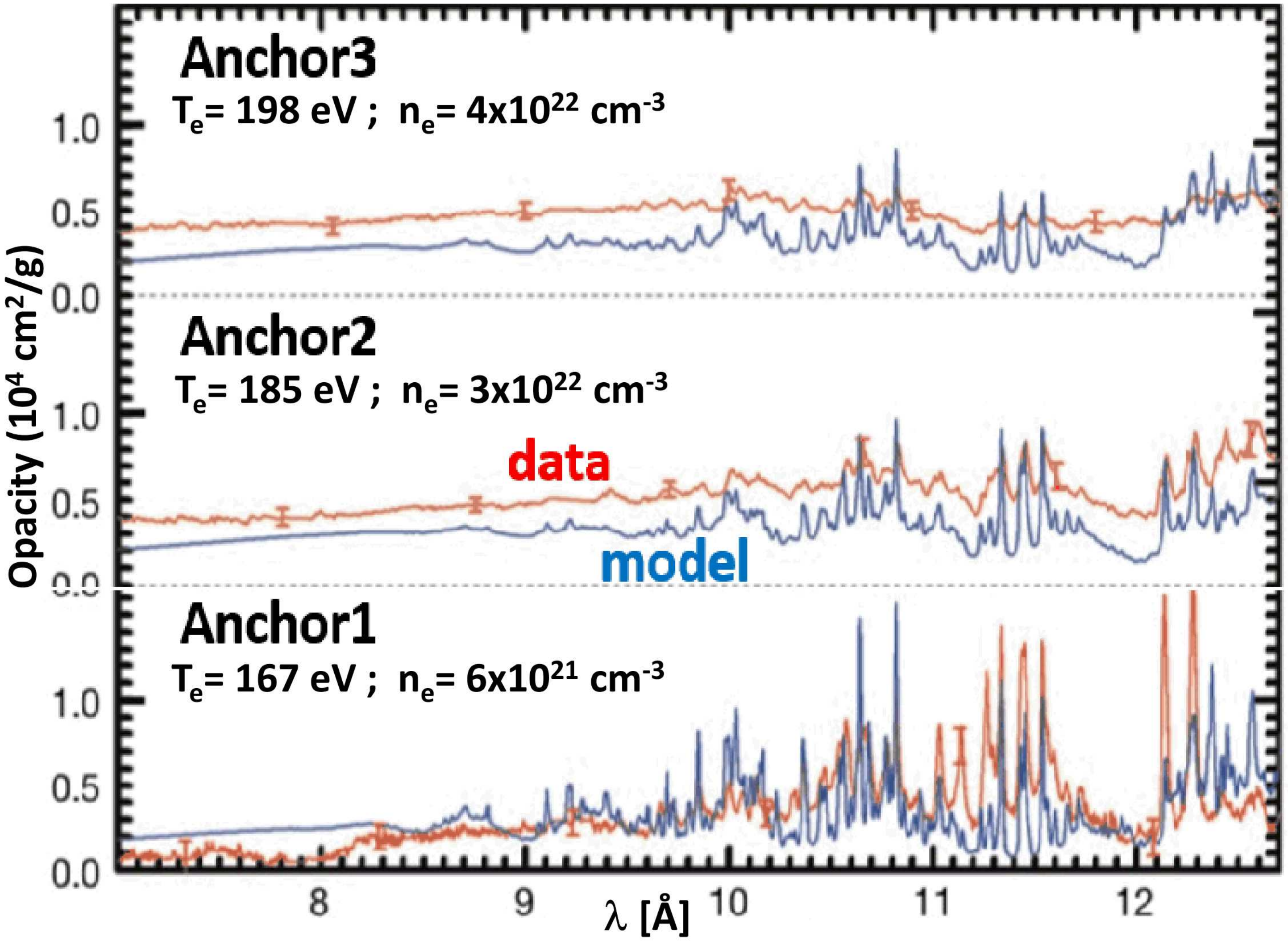
- Diagnose: Hard to **diagnose** due to extremely small, short-lived plasma
- Limited resource: Not easy to get funding to repeat experiments for **checking reproducibility**

Theory:

- Significant population in **excited states**
- **Density effects** with thermal fluctuation (line shape, level depletion)

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

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



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

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

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

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

No systematic error has been found that explains the model-data discrepancies

Random error:

→ Average over many spectra from multiple experiments

Systematic error evaluation:

→ Evaluated with experiments and simulations

- Plasma T_e and n_e errors
- Sample areal density errors
- Transmission errors
- Spatial non-uniformities
- Temporal non-uniformities
- Departures from LTE

- Fe self emission
- Tamper self emission
- Extraneous background

- Sample contamination
- Tamper transmission difference

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Experimental evidence

- Plasma T_e and n_e errors → $\pm 4\%$ and $\pm 25\%$, respectively [1]
- Sample areal density errors → RBS measurements agree with Mg spectroscopy
- Transmission errors → Transmission analysis on null shot shows $\pm$5%
- Spatial non-uniformities → Al and Mg spectroscopy
- Temporal non-uniformities → Backlight radiation lasts 3ns
- Departures from LTE

- Fe self emission → Measurement do not show Fe self-emission
- Tamper self emission
- Extraneous background → (with Tamper self emission) Quantified amount do not explain the discrepancy

- Sample contamination → RBS measurements show no contamination
- Tamper transmission difference

Condition reproducibility: [1] Nagayama et al, Phys Plasmas (2014)

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Numerical evidence

- Plasma T_e and n_e errors → Suggested n_e error did not explain the discrepancy
- Sample areal density errors
- Transmission errors
- Spatial non-uniformities
- Temporal non-uniformities
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- Fe self emission
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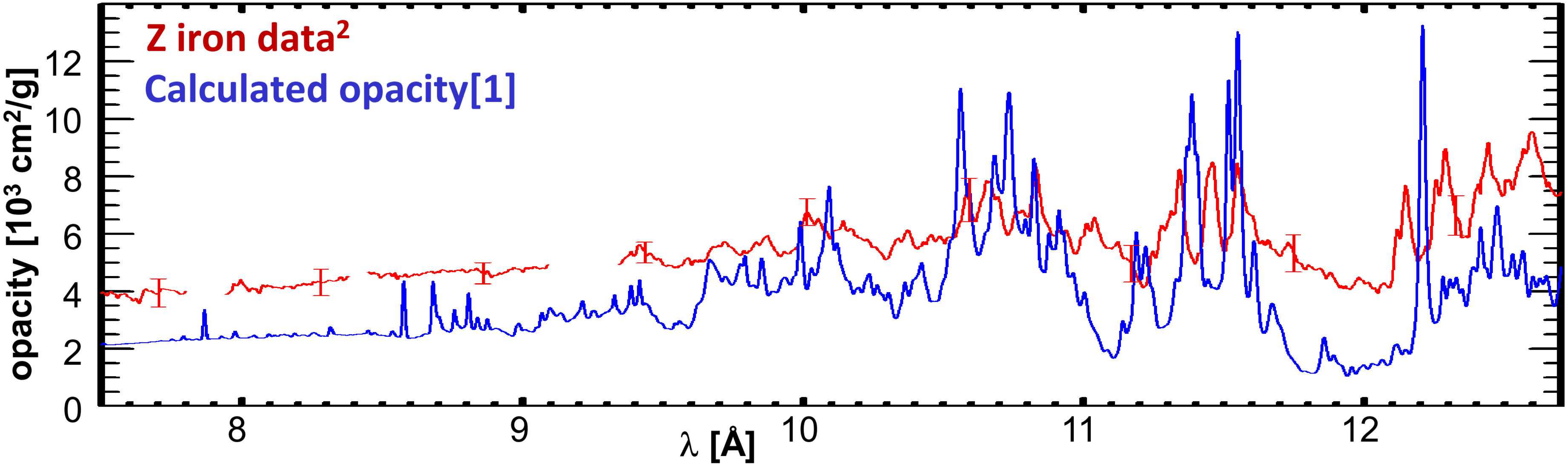
Nagayama et al, *High Energ Dens Phys* (2016)
Iglesias et al, *High Energ Dens Phys* (2016)

Spatial non-uniformities, Temporal non-uniformities, Departures from LTE, Fe self emission, Tamper self emission, Tamper transmission difference → Simulation found they were negligible

Nagayama et al, *Phys Rev E* **93**, 023202 (2016)
Nagayama et al, *Phys Rev E* **95**, 063206 (2017)

Opacity disagreement is complex and most likely caused by multiple sources



[1] Seaton et al., *MNRAS* (1994)

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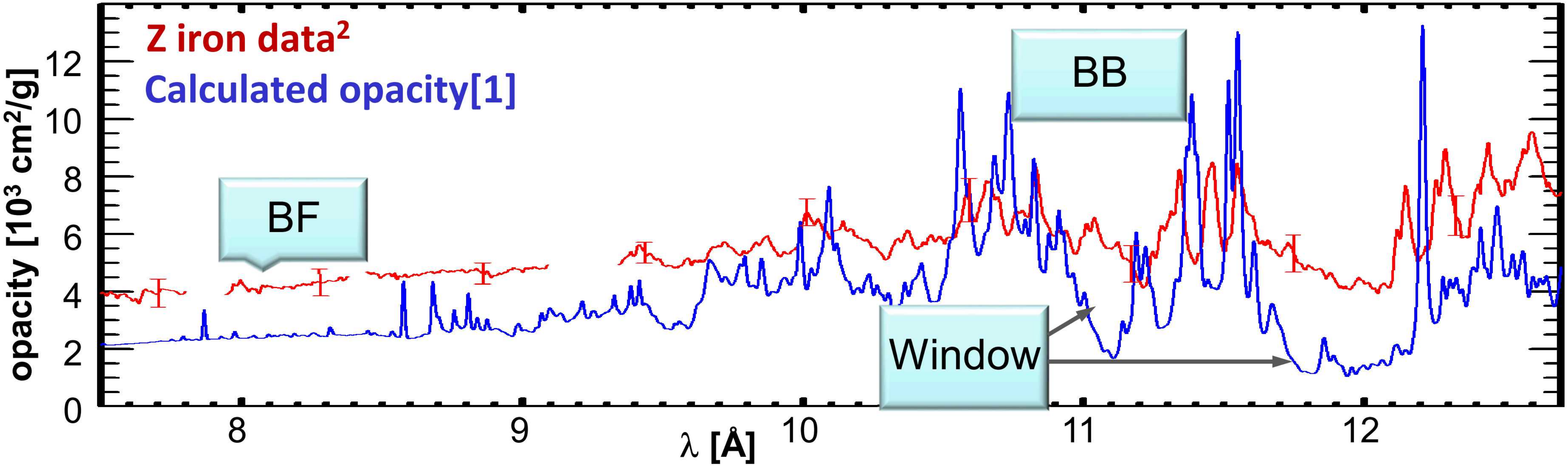

<u>BF: bound-free/quasi-continuum:</u>

- Bound-free (b-f) cross-section?
- Missing lines from multi-excited states?
- Multi-photon processes?

<u>BB: bound-bound line features*</u>

- Line location → Atomic structure
- Strength → Oscillator strength?
Population?
- Line width → Line shape?
Missing lines?

<u>Window filling:</u>

- Broader line shape filling the window?
- Missing lines from multi-excited states?
- Multi-photon processes?

[1] Seaton et al., *MNRAS* (1994)

*ATOMIC, OPAS, SCO-RCG, SCRAM, and TOPAZ show much better agreement in line locations

Questioning theory comes down to atomic data, population, density effects, or missing physics

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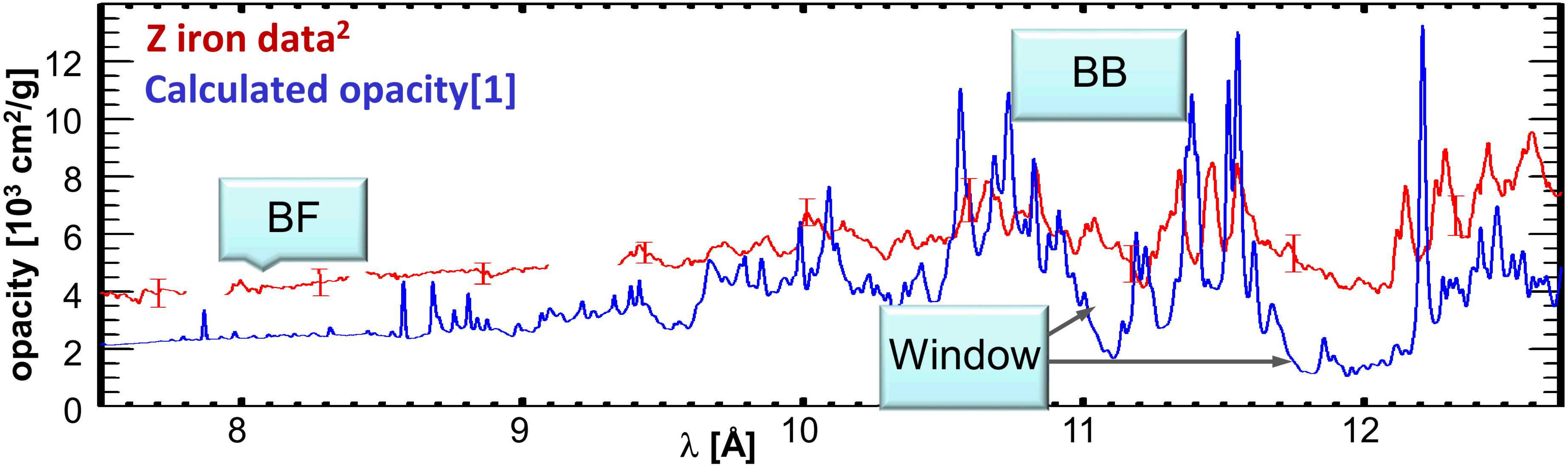

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Experiments with different elements are a rich source of opacity model tests as well as experiment-platform test

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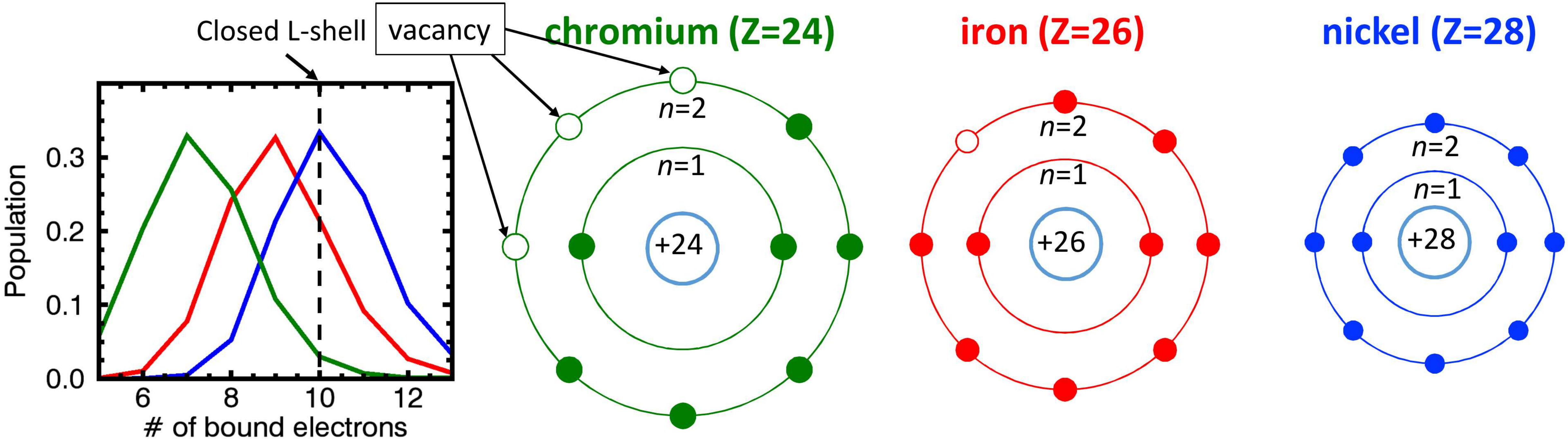


<u>Questioning Theory:</u>

- Atomic data?
- Population?
- Density effects?
- Missing physics?

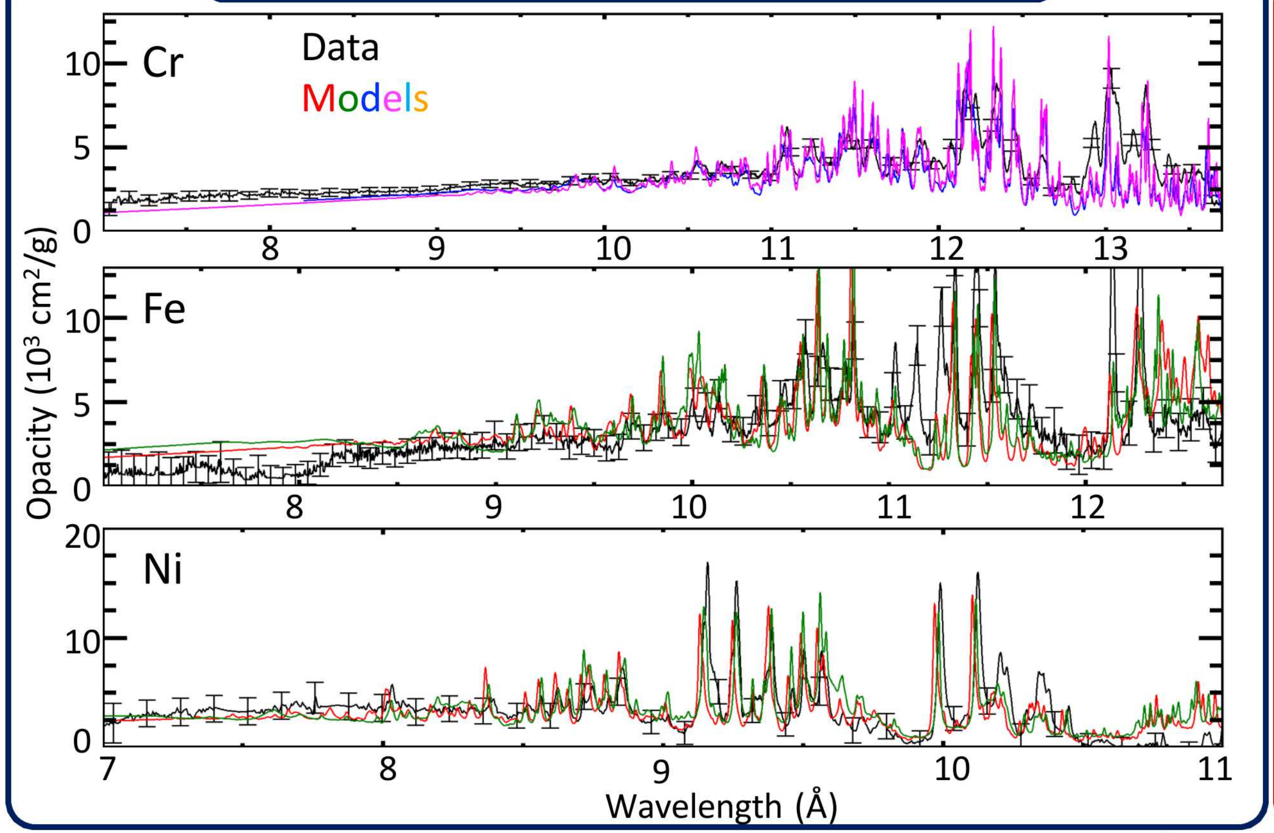
More ← L-shell vacancies — Less

More ← # of excited states — Less

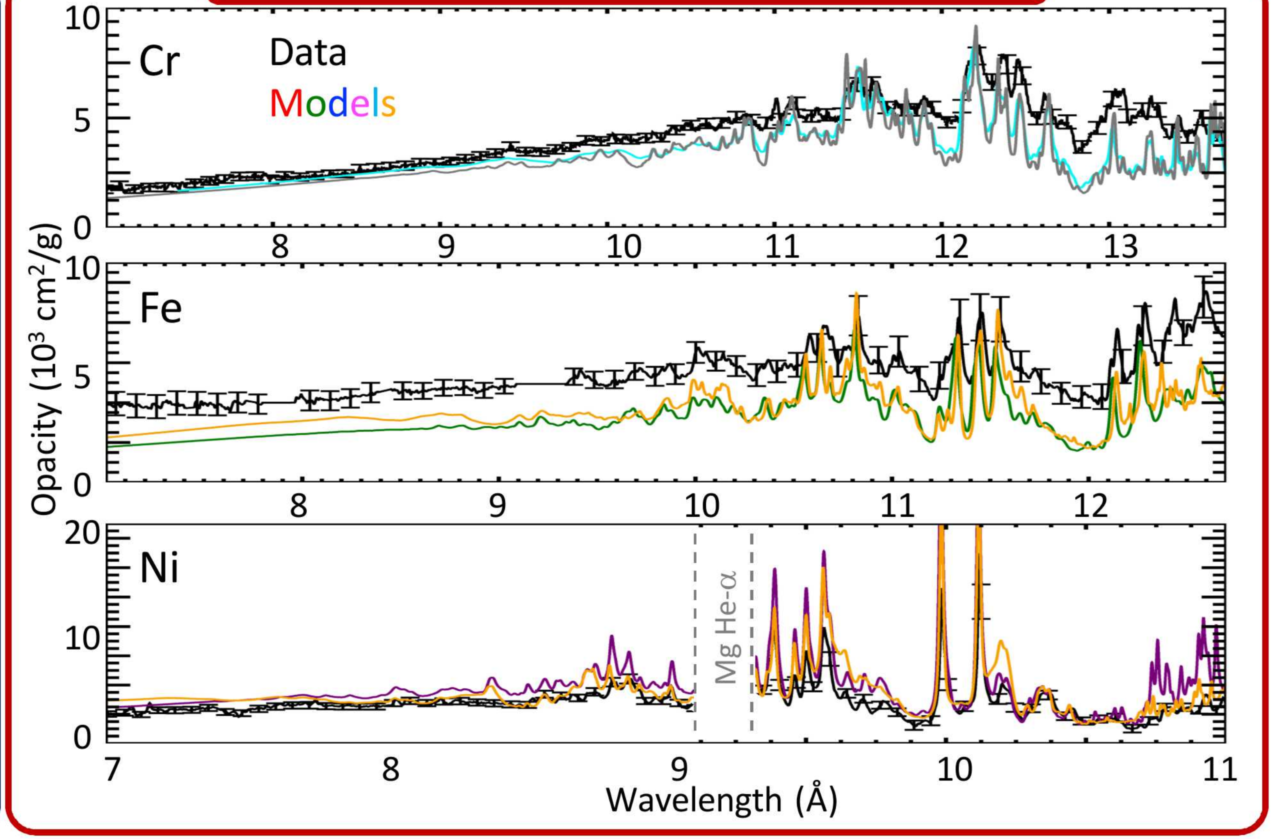
More ← Density effects — Less

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

Anchor1: $T_e \sim 165$ eV, $n_e \sim 7 \times 10^{21}$ cm^{-3}



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



- **Opacities are measured at $T_e > 150$ eV**
- **T_e and n_e are diagnosed independently**
- **Reproducibility is confirmed**

Systematically performed for Cr, Fe, Ni at two conditions

MODELS: ATOMIC, NOMAD, OPAS, SCO-RCG, SCRAM, TOPAZ

Systematic opacity model-data comparisons for three elements narrowed down hypotheses for discrepancies

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PHYSICAL REVIEW LETTERS **122,** 235001 (2019)

Editors' Suggestion   Featured in Physics

Systematic Study of *L*-Shell Opacity at Stellar Interior Temperatures

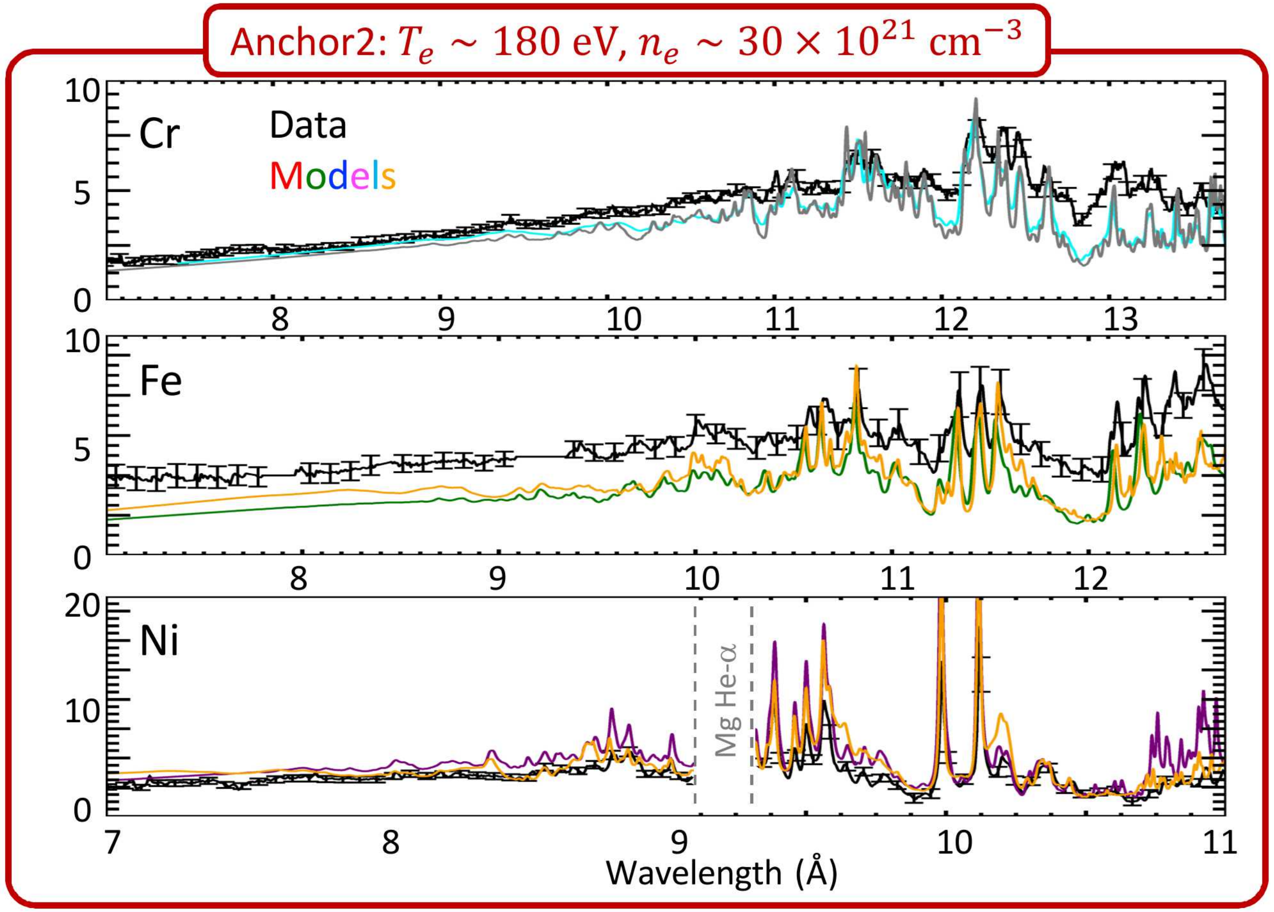
T. Nagayama,[1] J. E. Bailey,[1] G. P. Loisel,[1] G. S. Dunham,[1] G. A. Rochau,[1] C. Blancard,[2] J. Colgan,[3] Ph. Cossé,[2] G. Faussurier,[2] C. J. Fontes,[3] F. Gilleron,[2] S. B. Hansen,[1] C. A. Iglesias,[4] I. E. Golovkin,[5] D. P. Kilcrease,[3] J. J. MacFarlane,[5] R. C. Mancini,[6] R. M. More,[1,*] C. Orban,[7] J.-C. Pain,[2] M. E. Sherrill,[3] and B. G. Wilson[4]

[1]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*
[2]*CEA, DAM, DIF, F-91297 Arpajon, France*
[3]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[4]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[5]*Prism Computational Sciences, Madison, Wisconsin 53711, USA*
[6]*University of Nevada, Reno, Nevada 89557, USA*
[7]*Ohio State University, Columbus, Ohio 43210, USA*

(Received 7 March 2019; published 10 June 2019)

The first systematic study of opacity dependence on atomic number at stellar interior temperatures is used to evaluate discrepancies between measured and modeled iron opacity [J. E. Bailey *et al.*, Nature (London) **517**, 56 (2015)]. High-temperature (> 180 eV) chromium and nickel opacities are measured with ±6%–10% uncertainty, using the same methods employed in the previous iron experiments. The 10%–20% experiment reproducibility demonstrates experiment reliability. The overall model-data disagreements are smaller than for iron. However, the systematic study reveals shortcomings in models for density effects, excited states, and open *L*-shell configurations. The 30%–45% underestimate in the modeled quasicontinuum opacity at short wavelengths was observed only from iron and only at temperature above 180 eV. Thus, either opacity theories are missing physics that has nonmonotonic dependence on the number of bound electrons or there is an experimental flaw unique to the iron measurement at temperatures above 180 eV.

DOI: 10.1103/PhysRevLett.122.235001



Nagayama et al, *Phys Rev Lett 122, 235001* (2019)

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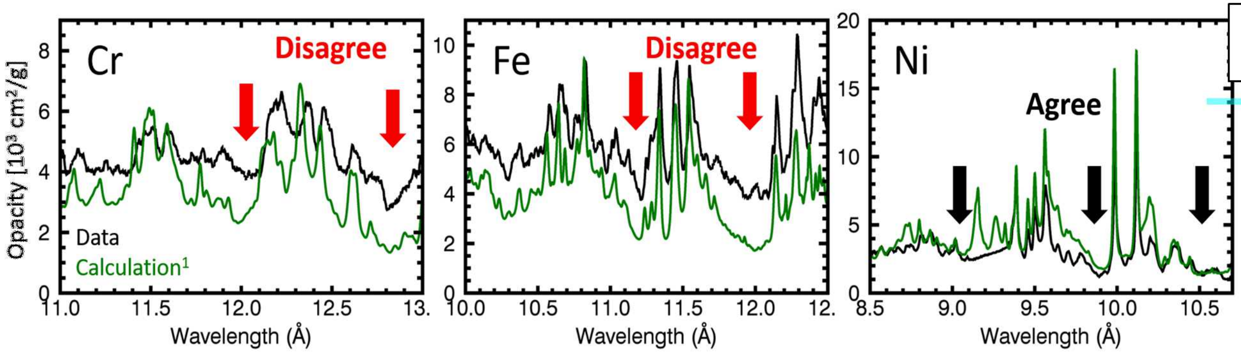
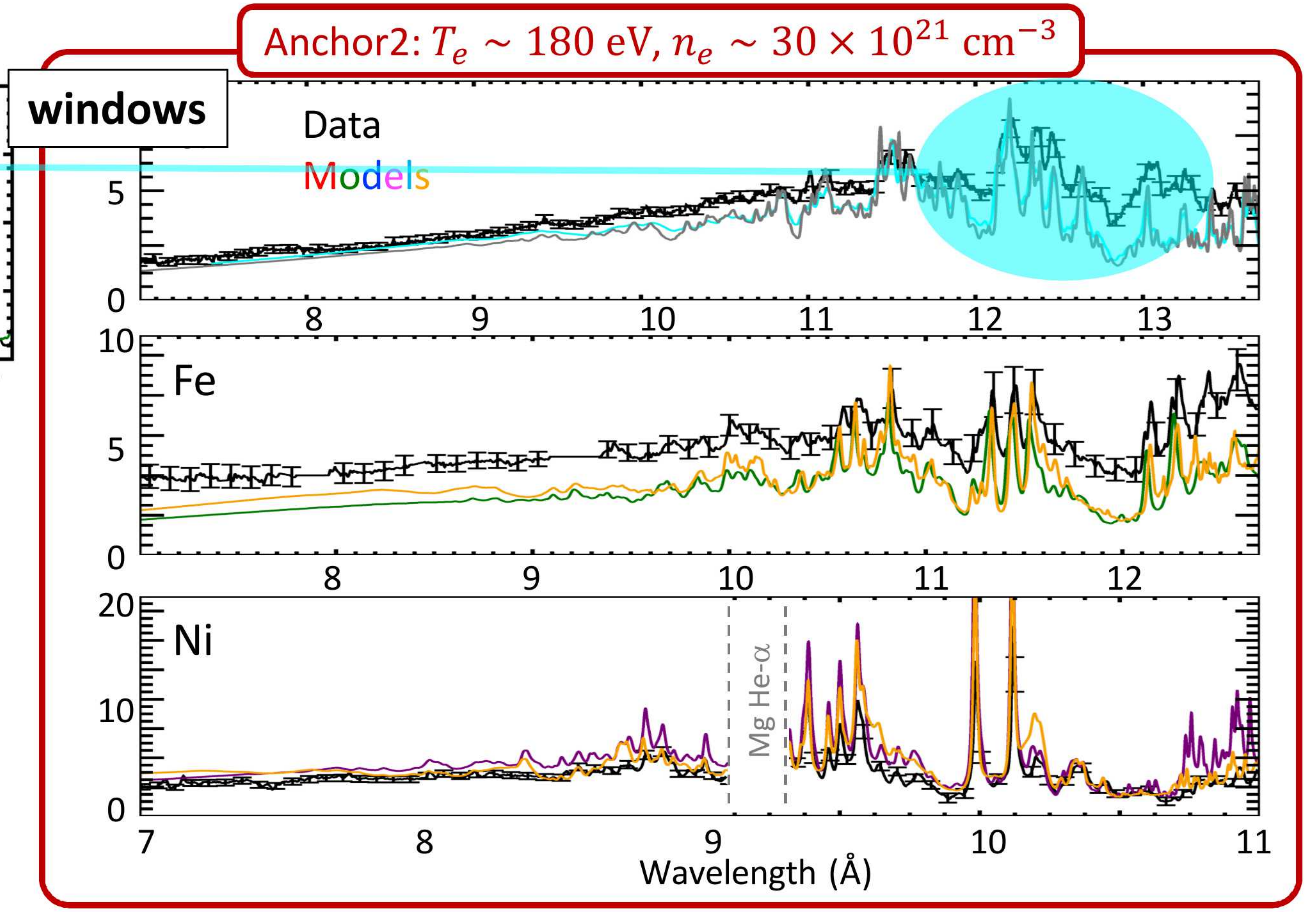
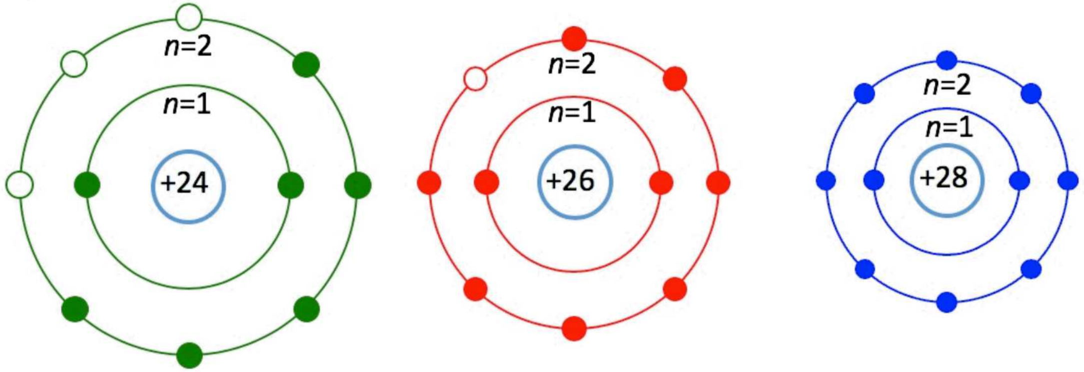




Found: Window disagreement appears in open L-shell configuration



Hypothesis: Challenge in population calculation at open L-shell configuration

Nagayama et al, *Phys Rev Lett 122, 235001* (2019)

Systematic opacity model-data comparisons for three elements narrowed down hypotheses for discrepancies

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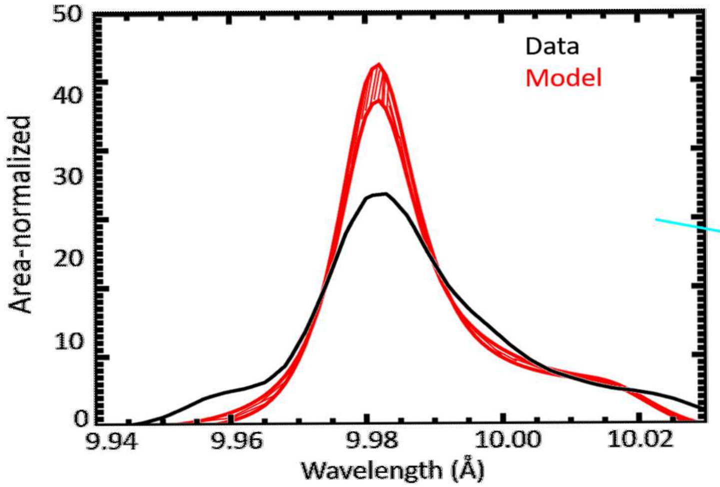

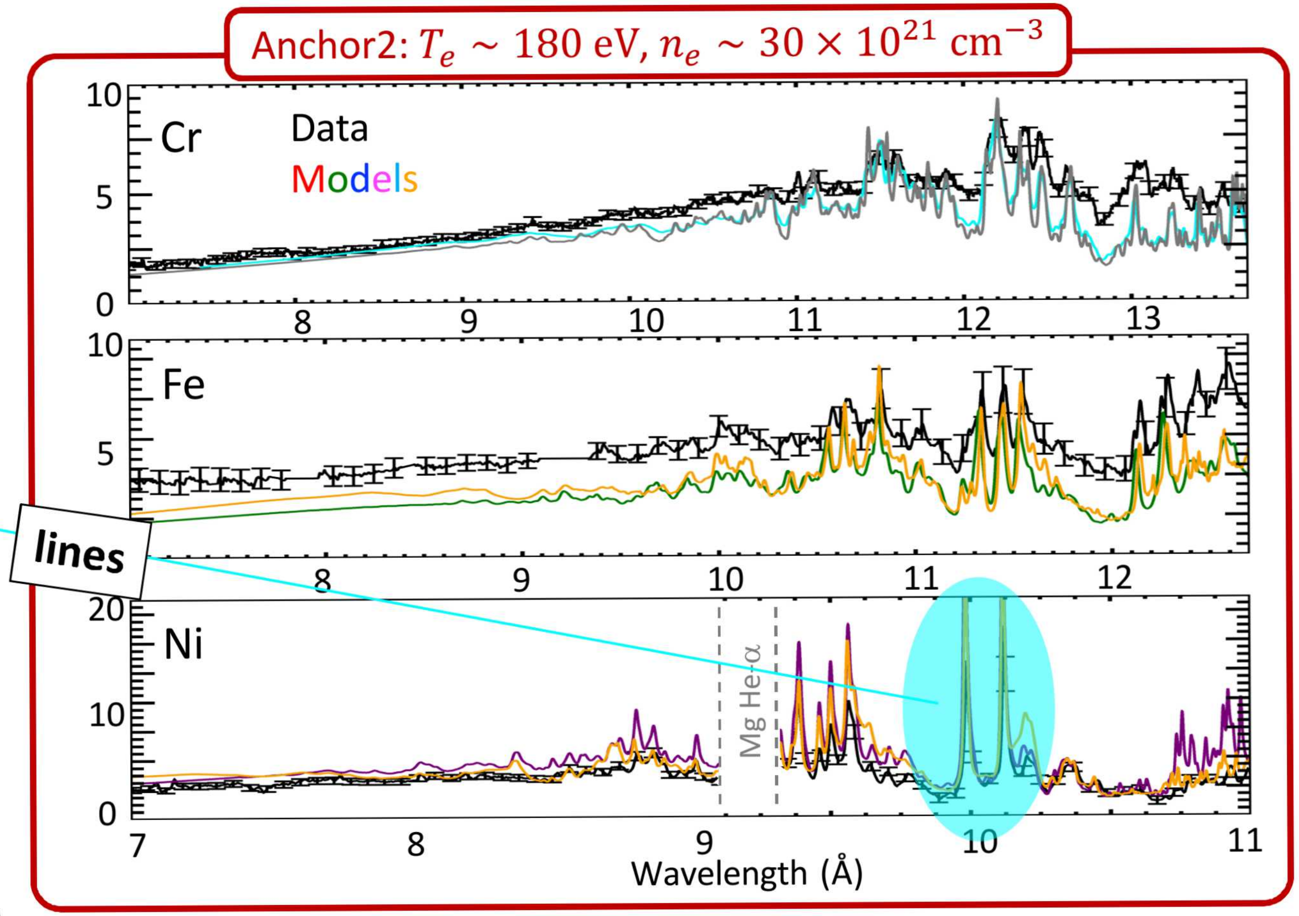

Found: Most models significantly under-predict line broadening

Hypothesis: Line-shape theory is not sufficiently accurate

Systematic opacity model-data comparisons for three elements narrowed down hypotheses for discrepancies

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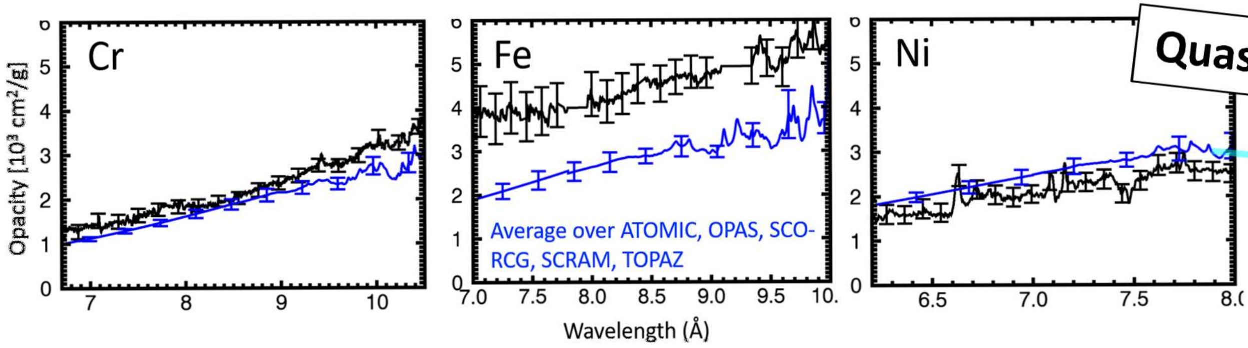
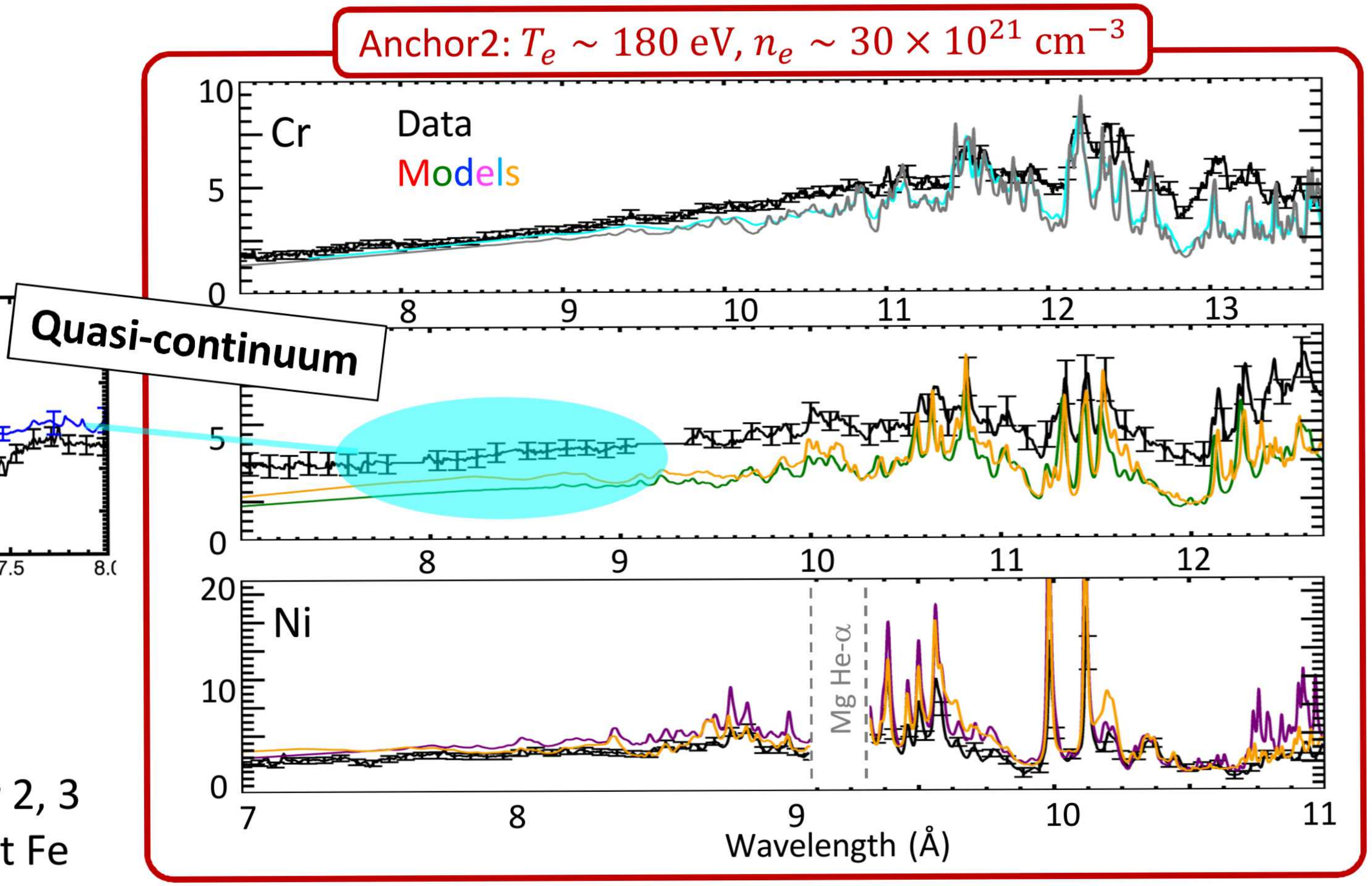


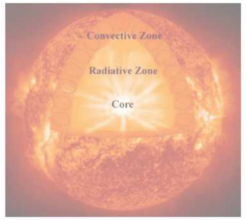


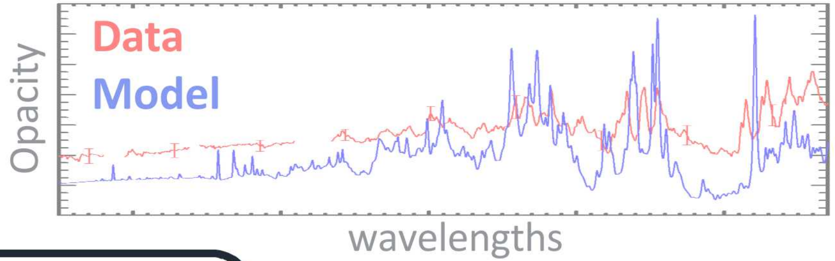
Found: Only Fe shows severe discrepancy

Hypotheses:

- Fe experiments or **data analysis** are flawed at anchor 2, 3
- Missing physics becomes important at conditions that Fe achieved

Holistic approach including new experiments, new analysis, new theories will help resolve the solar problem



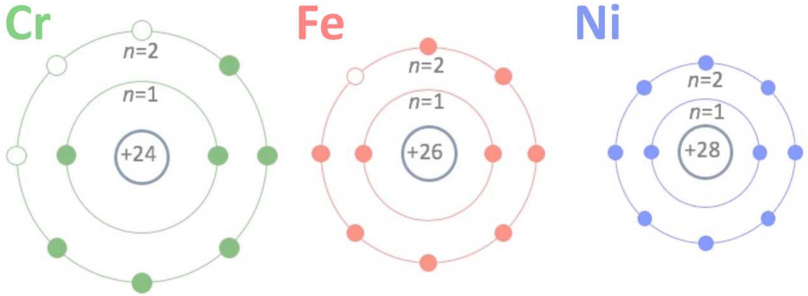


Puzzle: Measured stellar iron opacity higher than predicted

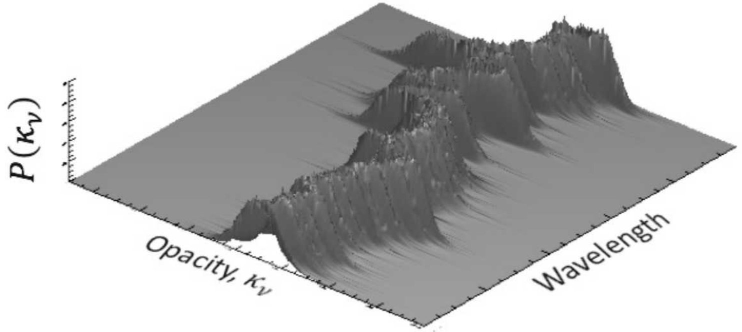
→ **Both experiment and theory need to be scrutinized**

Experiment scrutiny

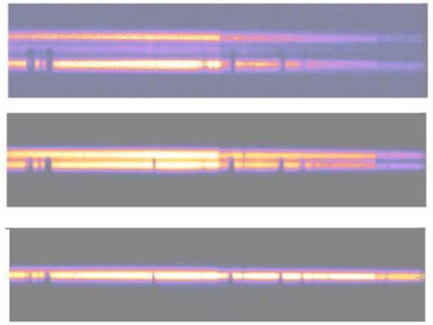
- **Systematic study of Cr, Fe, and Ni**
  → Narrow down hypotheses



- **Refined analysis method**

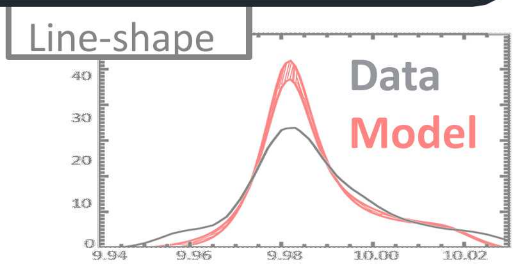


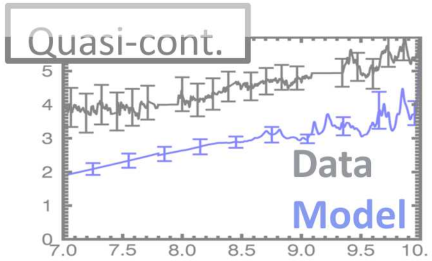
- **Time-resolved data**



Theoretical scrutiny stimulates atomic-physics discussions

- **Spectral line shapes:** Ion, electron, satellites
- **Quasi-continuum:** new theories



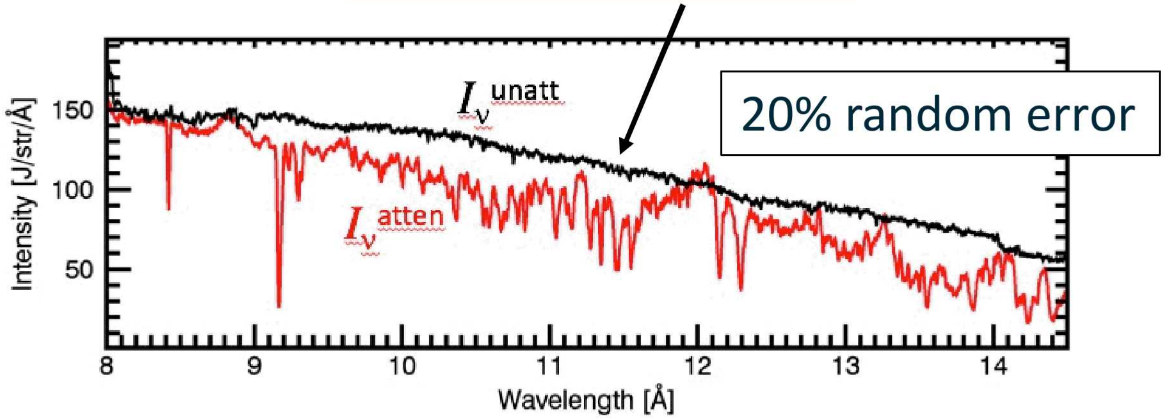


Continued experimental and theoretical research is needed for understanding photon-atom interactions in High-Energy-Density matter

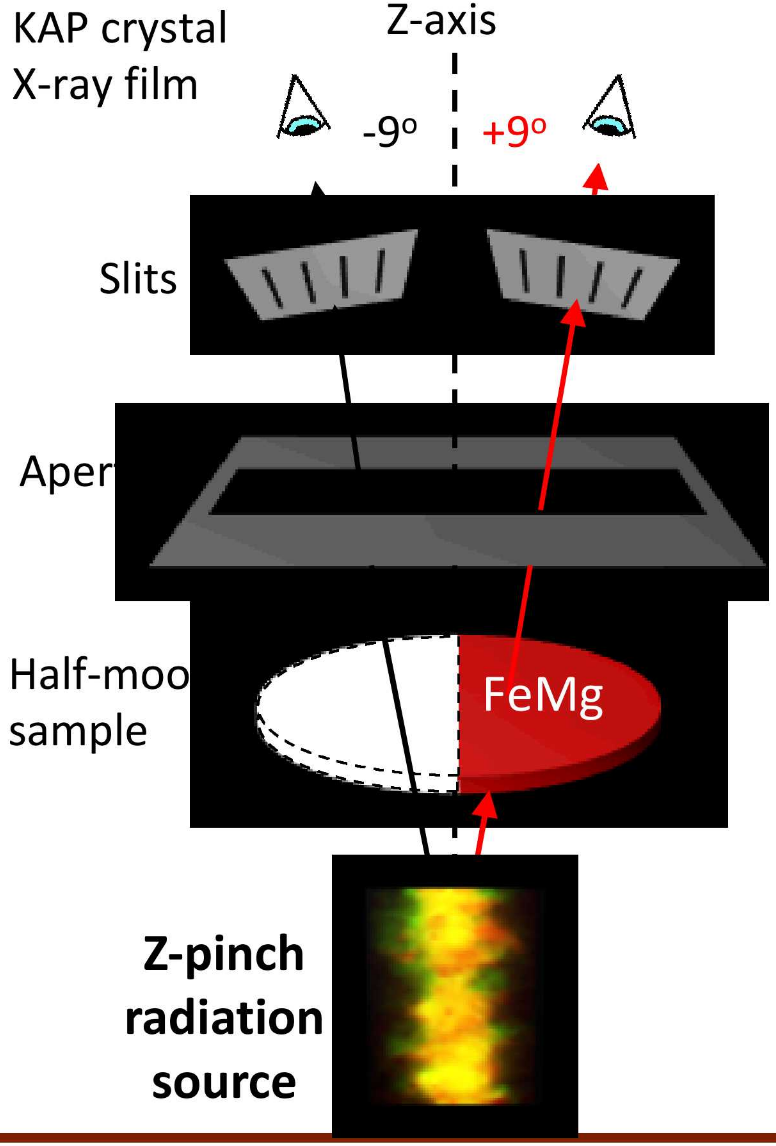
Analysis method is refined in (1) determining unattenuated spectrum, (2) propagating errors

<u>Two challenges in opacity analysis:</u>

1. Determination unattenuated spectrum



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



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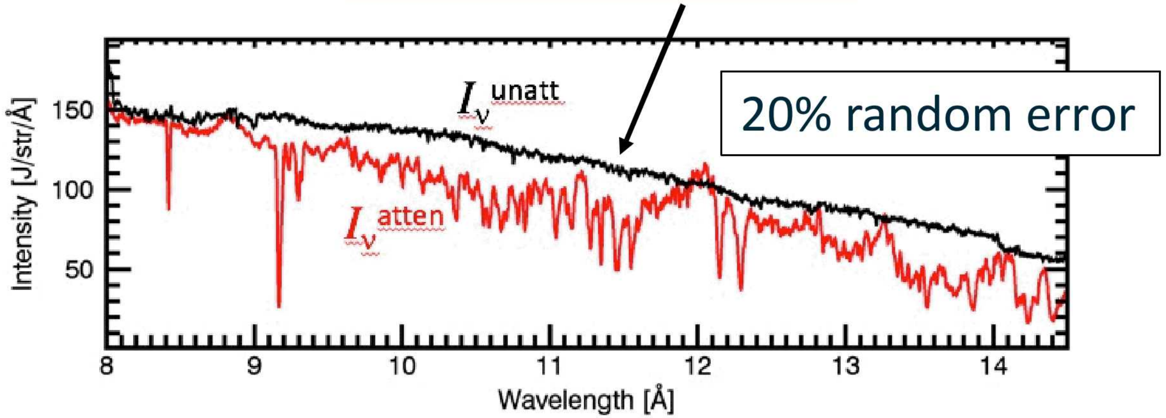
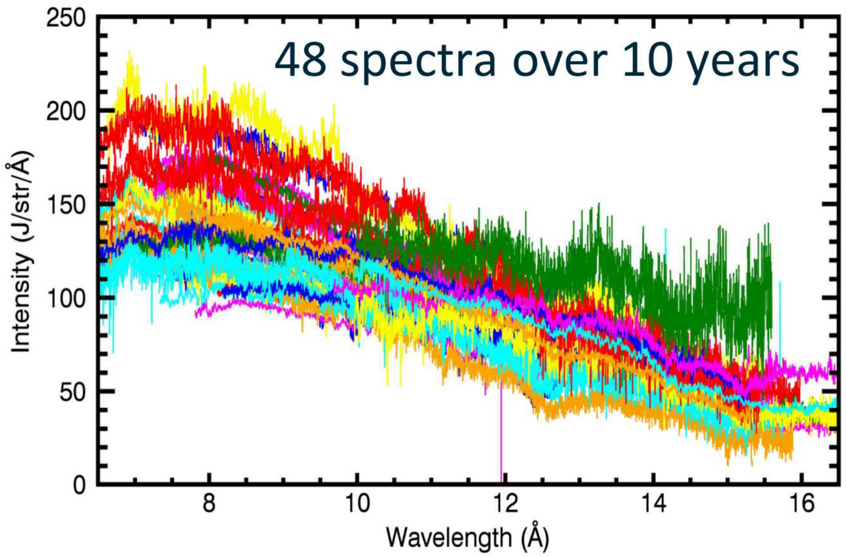


2. Propagating multiple errors
   - Unattenuated spectrum
   - Background subtraction
   - Areal density

Solution:

Calibration shot stats → Unattenuated PDF*



*** PDF = probability distribution function**

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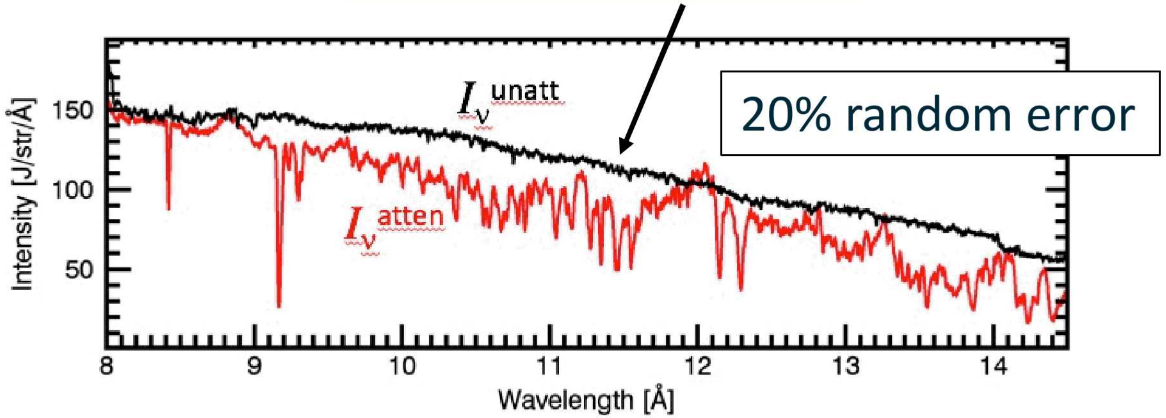

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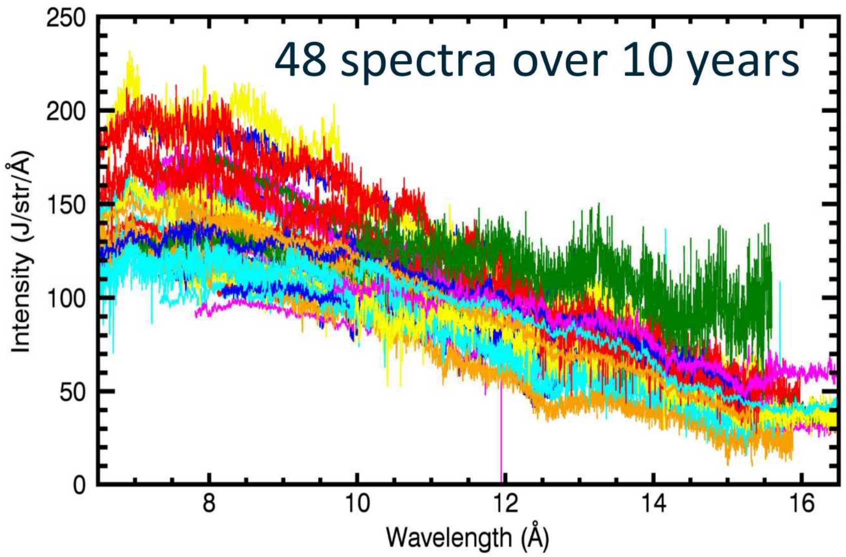


Monte-Carlo sampling

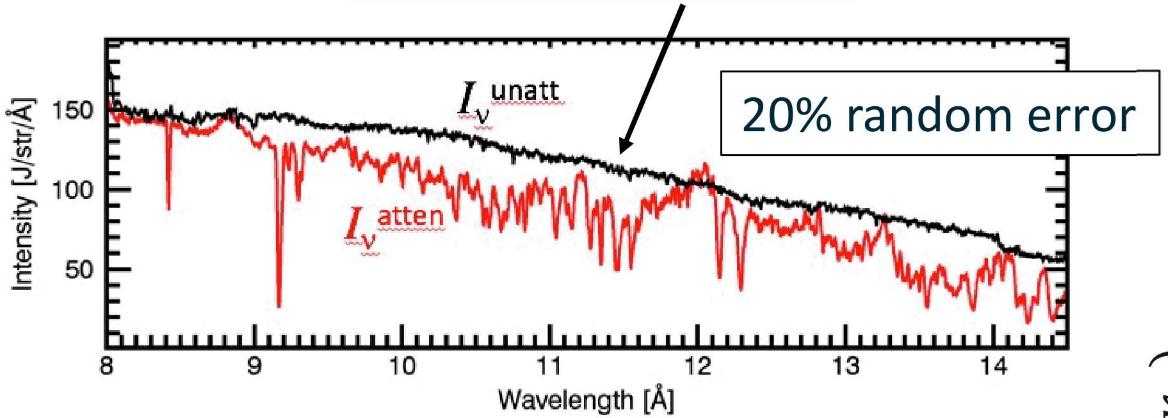
This can easily handle multiple sources of errors and non-linearity.

*** PDF = probability distribution function**

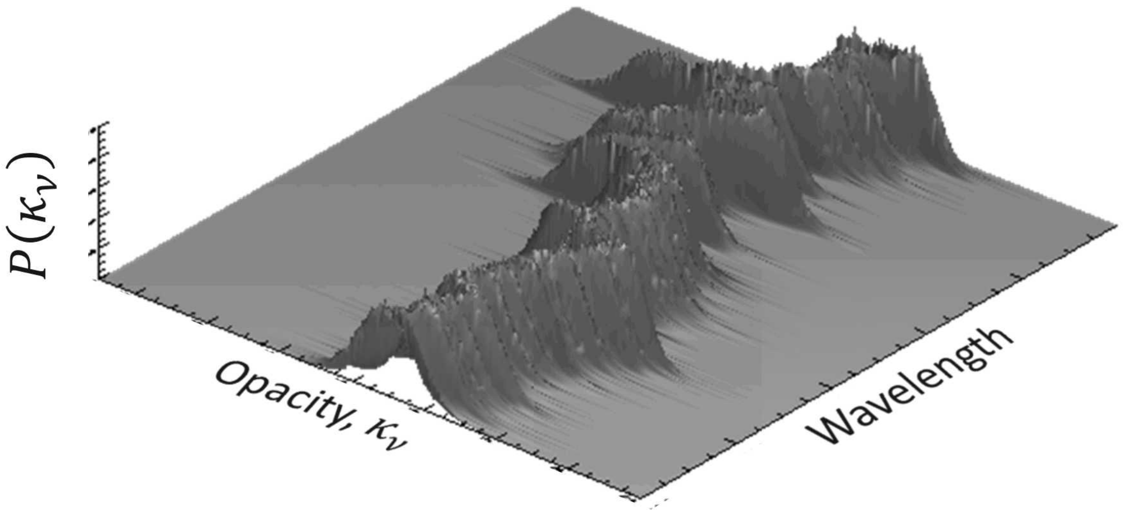
New analysis returns asymmetric non-Gaussian opacity PDF* as a function of wavelengths

Two challenges in opacity analysis:

1. Determination unattenuated spectrum



Opacity probability distribution function



2. Propagating multiple errors
   - Unattenuated spectrum
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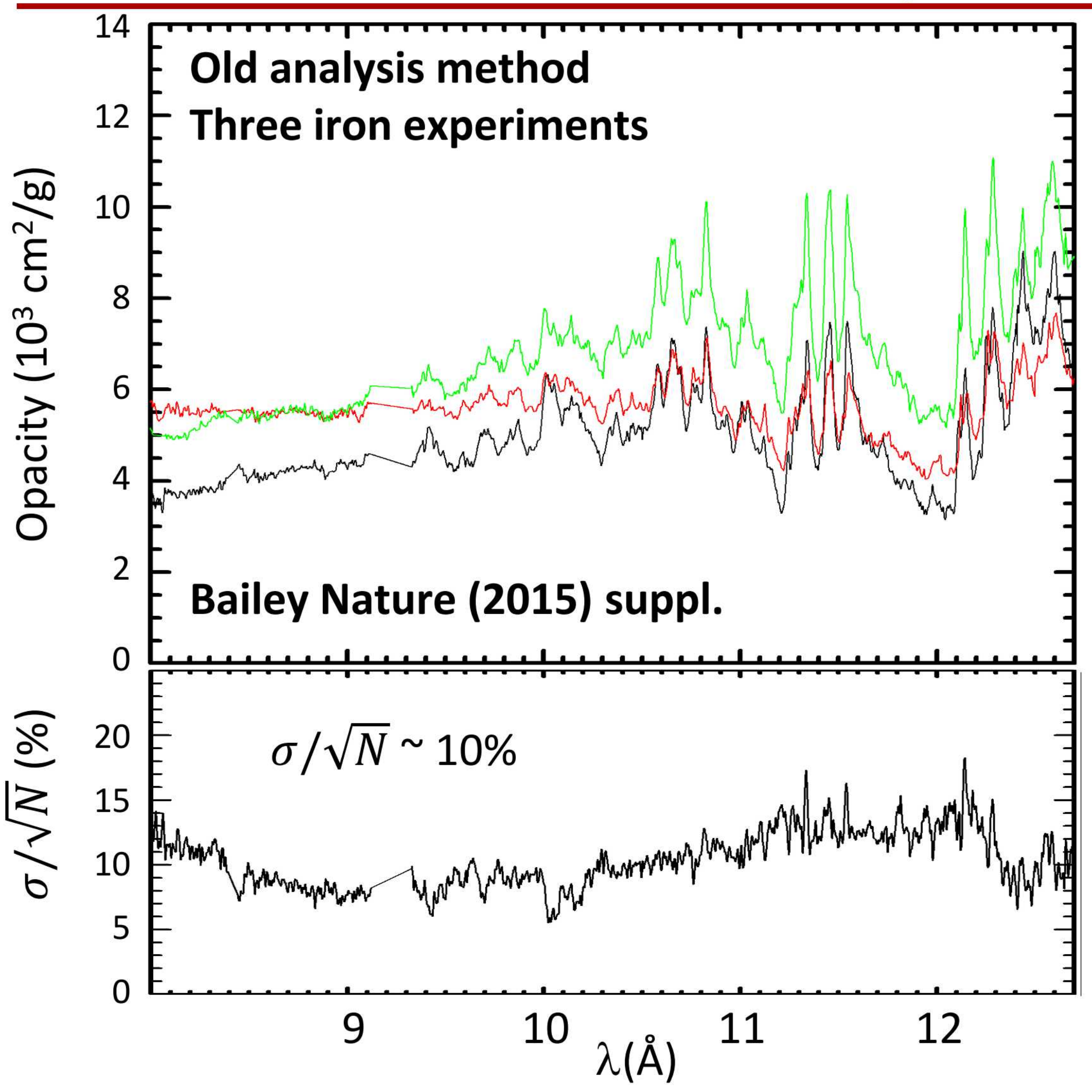
   - Areal density

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 ~ $3x10^{22}$ cm^{-3}

Areal Densities
$x10^{18}$ Fe/cm^2

1.04
1.91
0.93
} 2014

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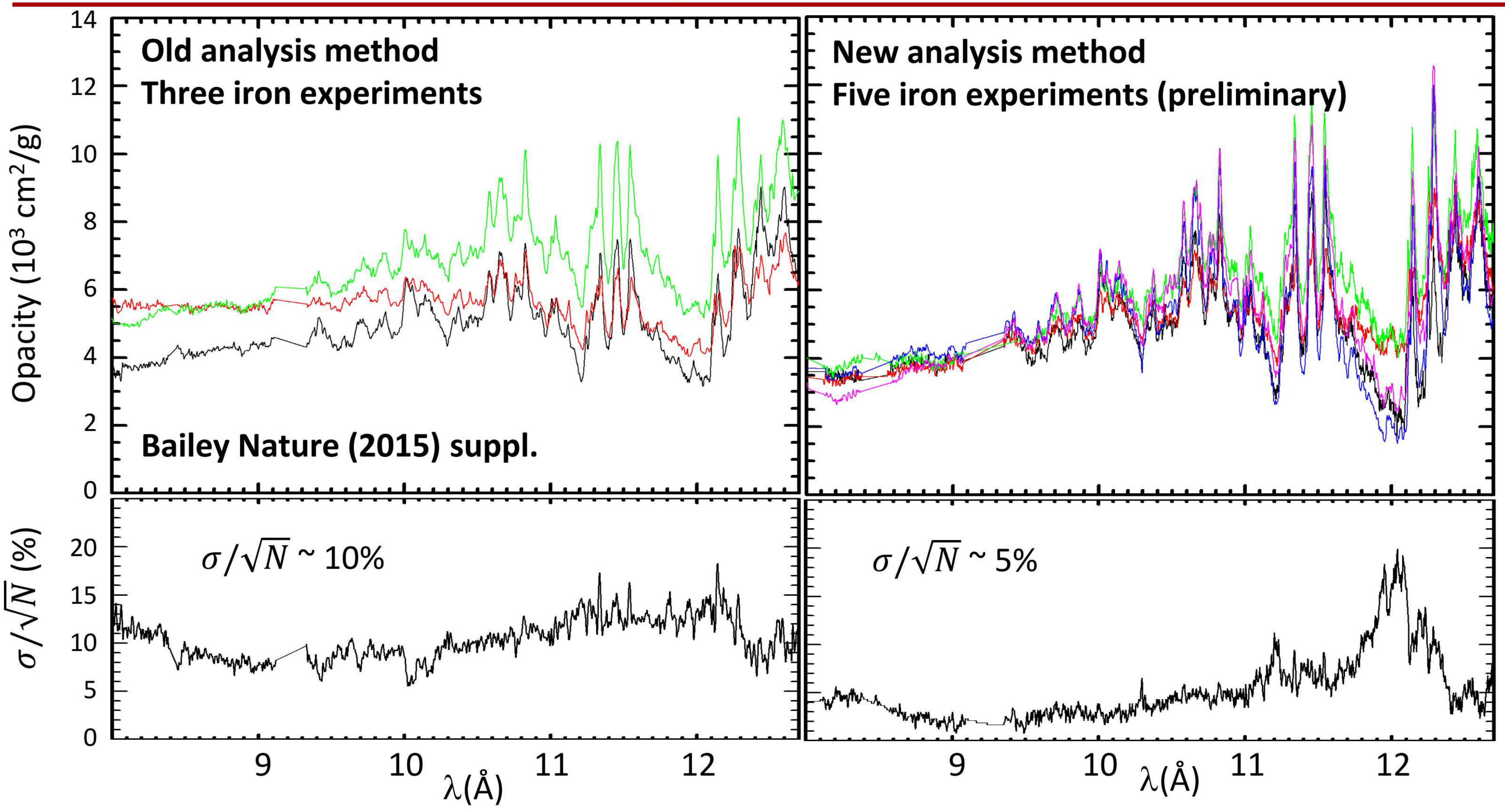

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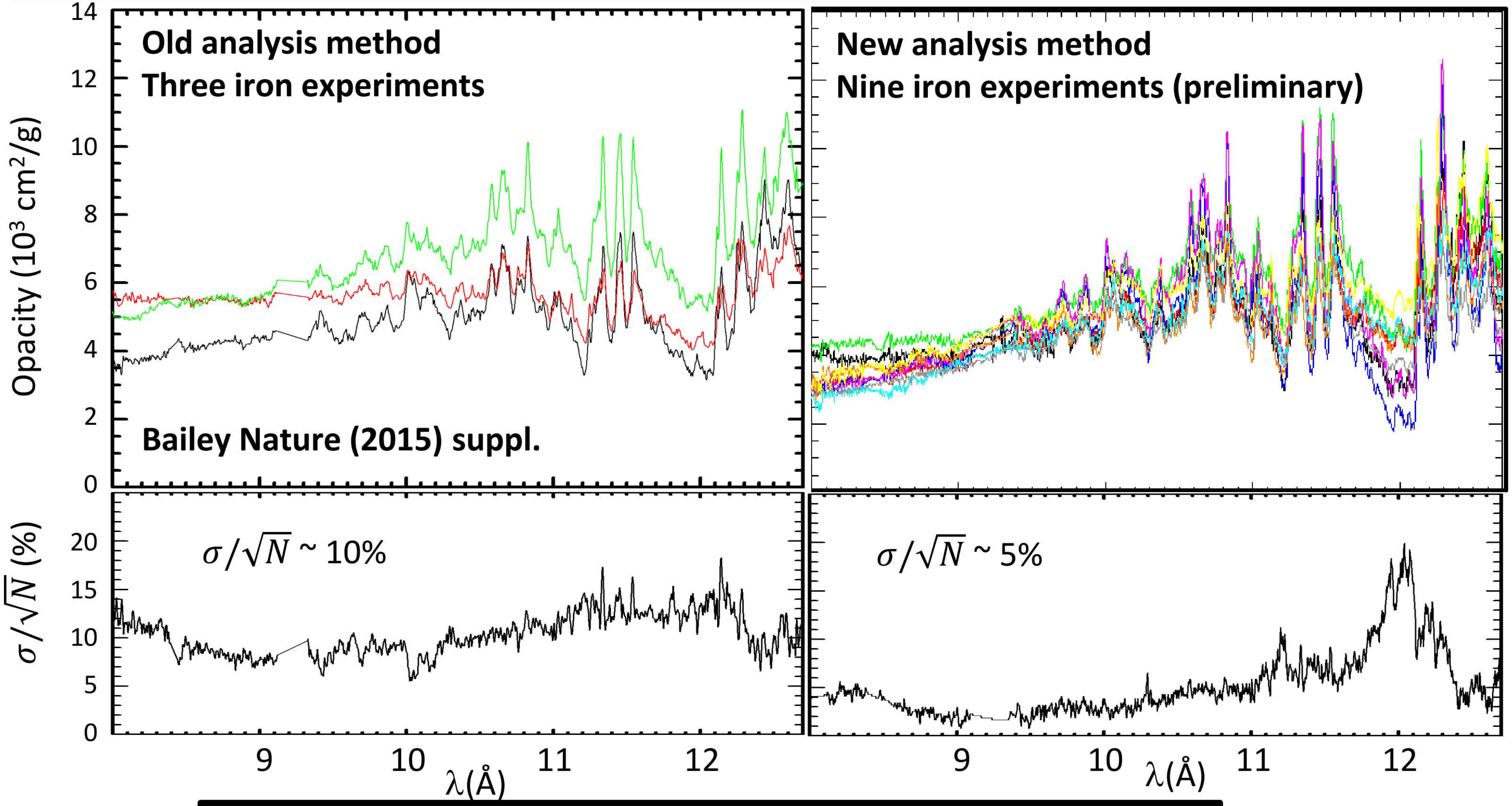

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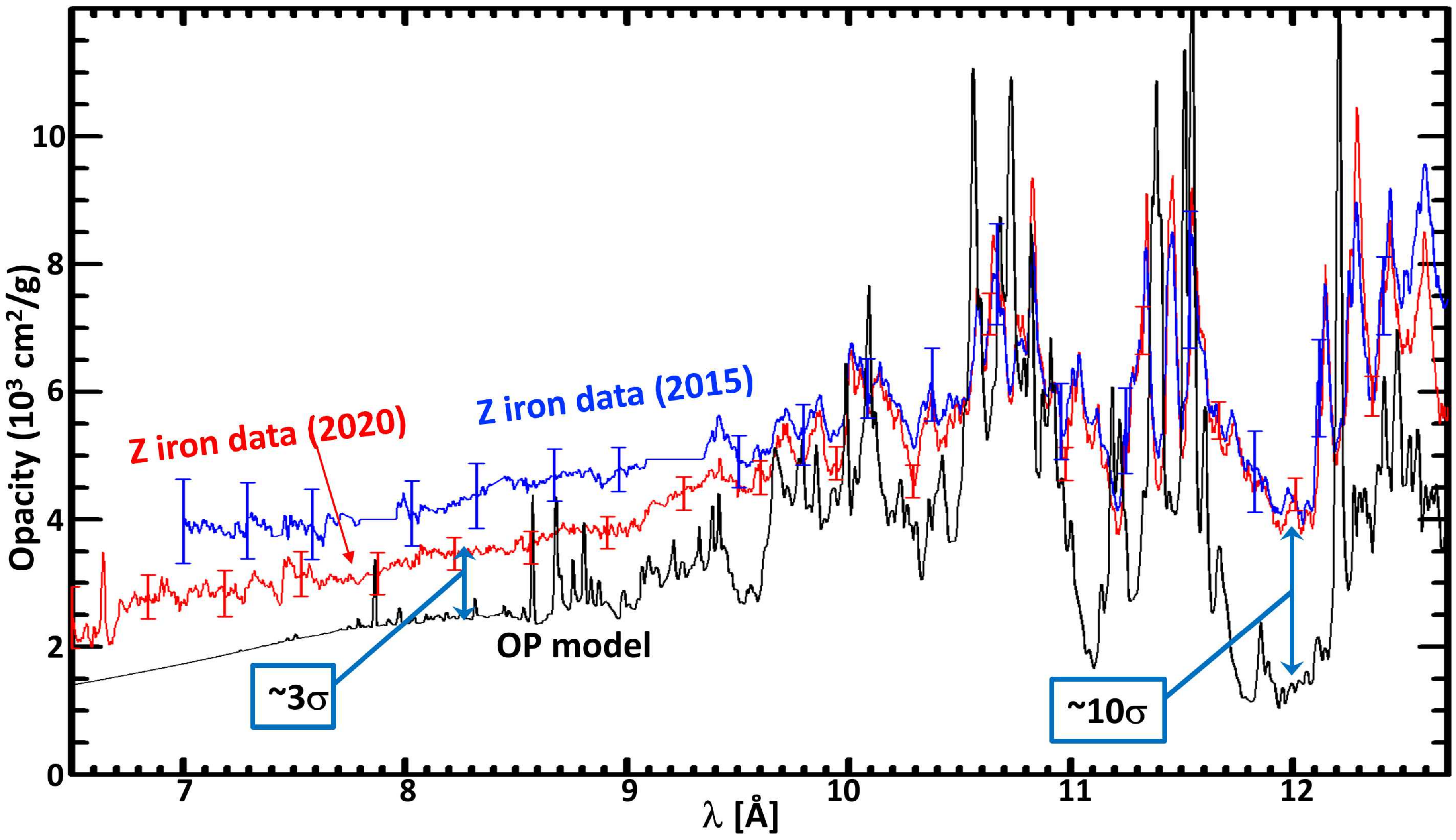
$\text{x}10^{18}$ Fe/cm^2

1.04	2014
1.91	2014
0.93	2014
1.31	2015
1.31	2015
2.18	2017
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



Quasi continuum discrepancy

2015: ~ 1800 cm2/g; ~4σ

2019: ~ 960 cm2/g; ~3σ

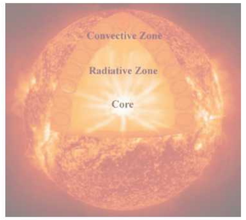
Window discrepancy

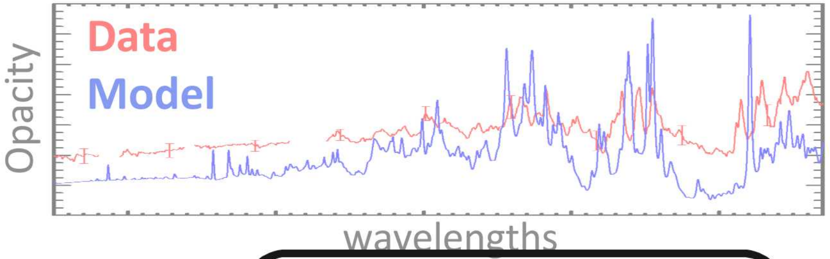
2015: ~ 2900 cm2/g; ~ 5σ

2019: ~ 2700 cm2/g; ~ 10σ

We found similar results for Fe at anchor3

Holistic approach including new experiments, new analysis, new theories will help resolve the solar problem





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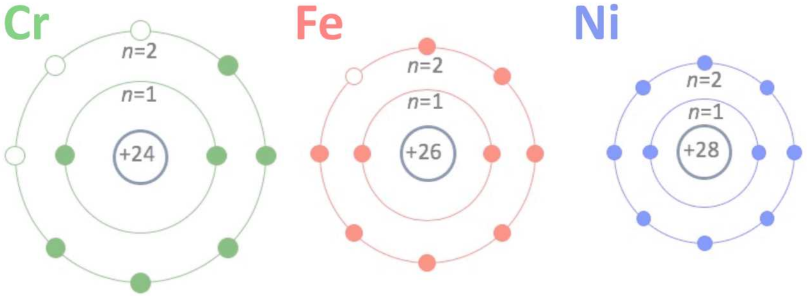

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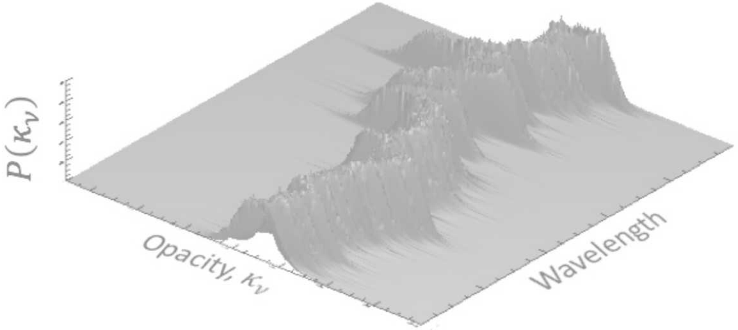
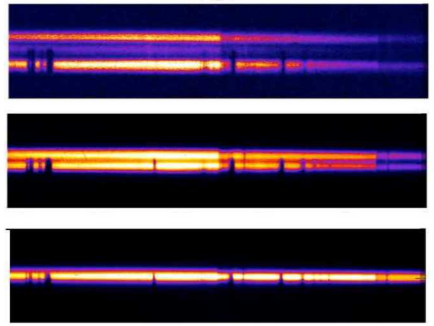


- Time-resolved data



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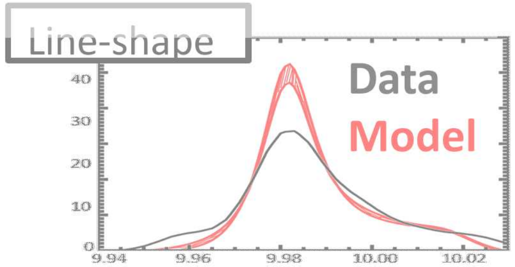
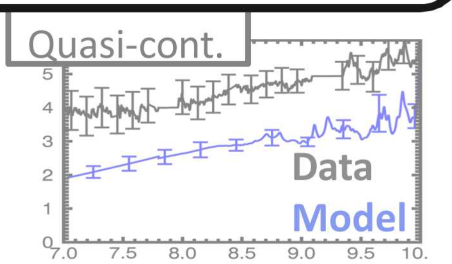
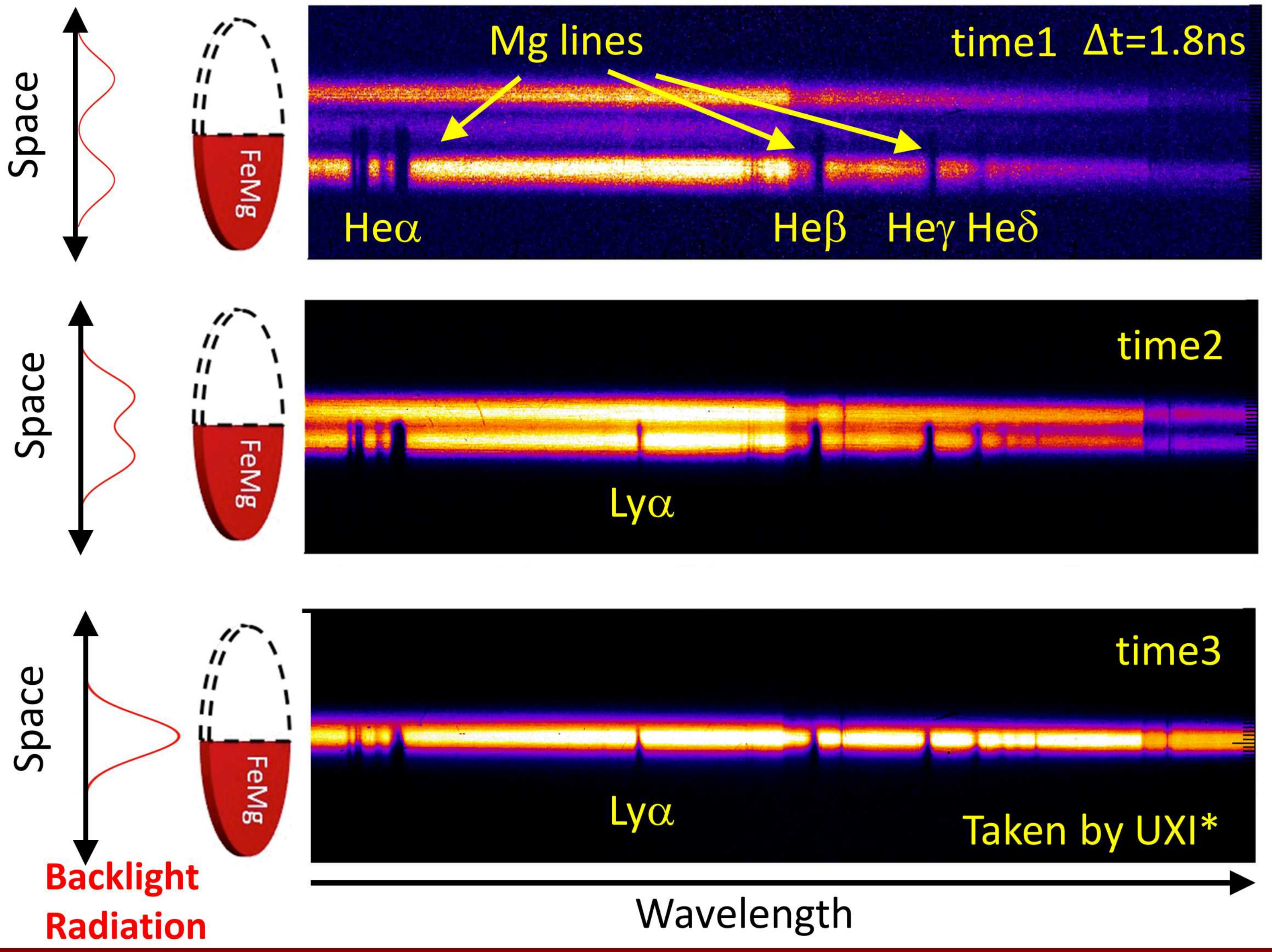




Continued experimental and theoretical research is needed for understanding photon-atom interactions in High-Energy-Density matter

Time resolved measurements with a unique Sandia-developed detector are in progress to further strengthen the data



Impact on opacity research

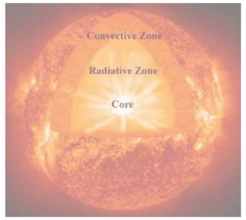
- Assess the impact of temporal gradient
- Time-resolved opacity measurements
  - Free from temporal gradient
  - Multiple conditions in a single shot

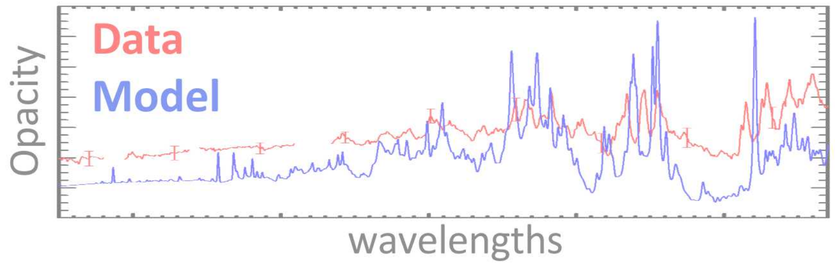
Impact on atomic physics:

- Study how changing temperature, density, and radiation field affect:
  - Line broadening and shift
  - Excited state populations
  - Two-photon opacity

* UXI = Ultrafast X-ray Imager. It employs CMOS detector, recording up to 8 frames on the same pixel.

Holistic approach including new experiments, new analysis, new theories will help resolve the solar problem





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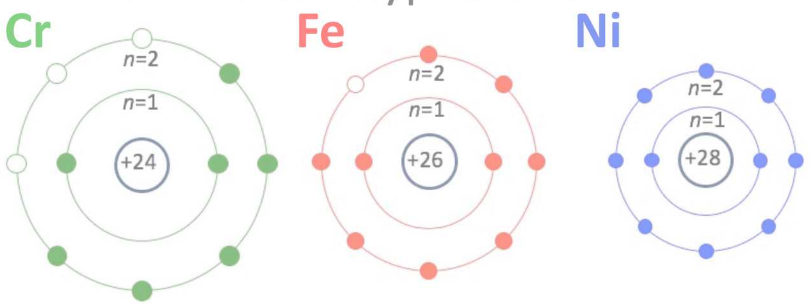

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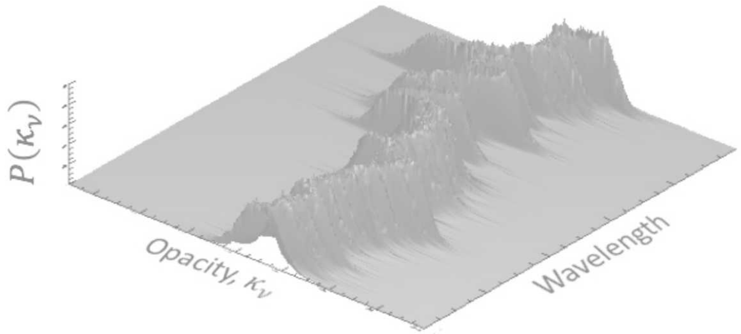

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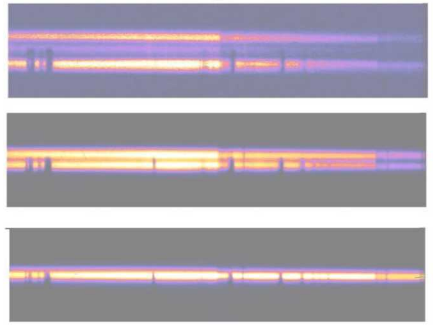

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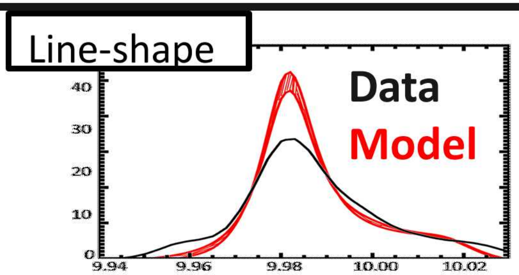

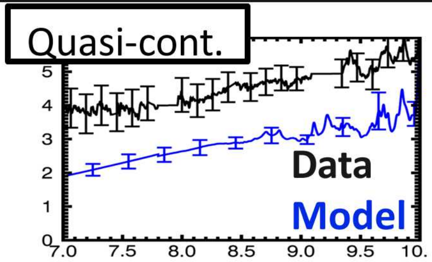

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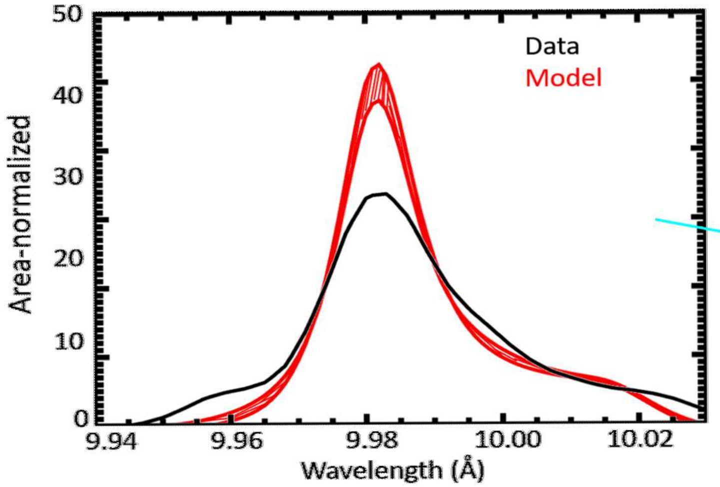

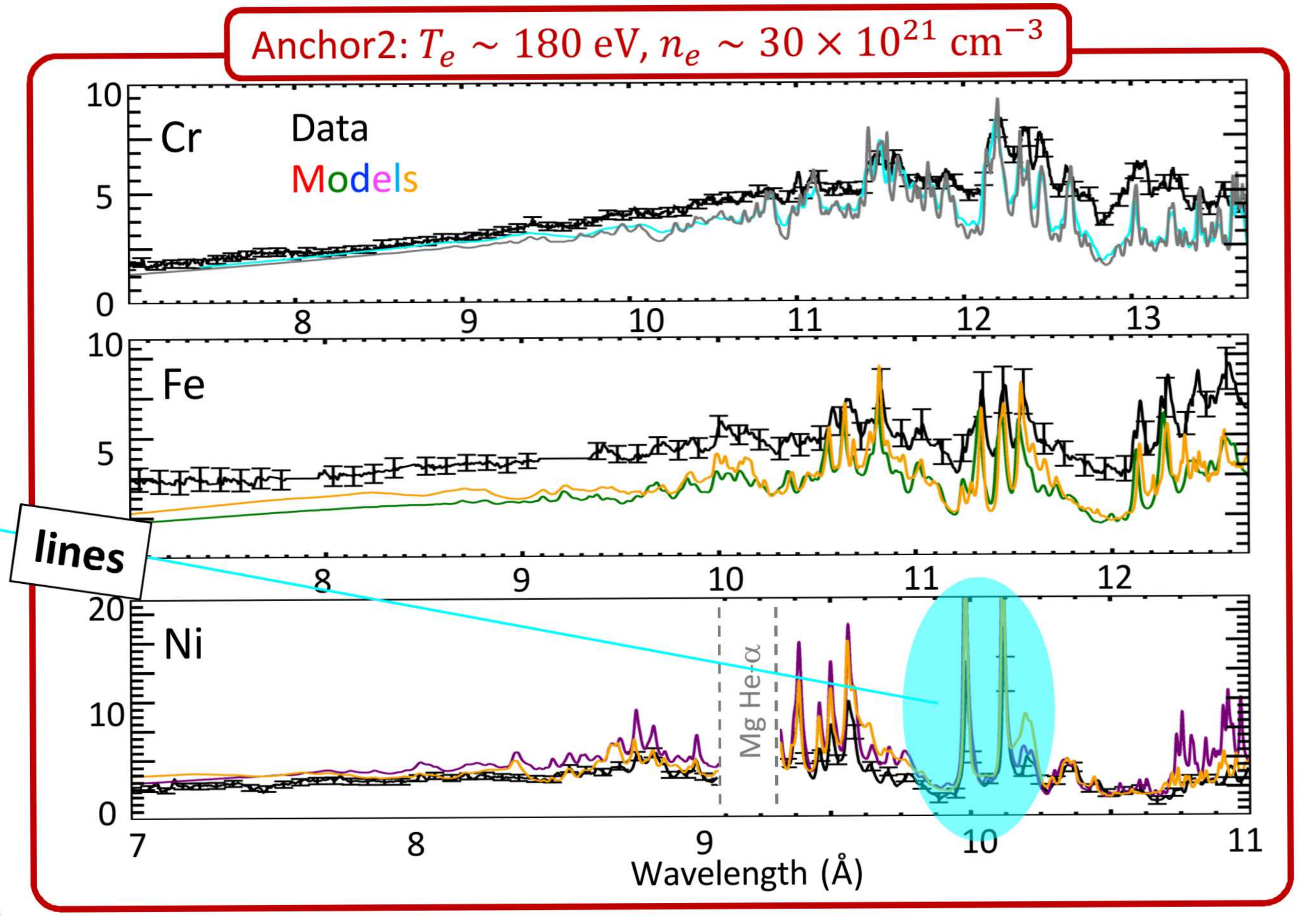

Found: Most models significantly under-predict line broadening

Hypothesis: Line-shape theory is not sufficiently accurate

Systematic opacity model-data comparisons for three elements narrowed down hypotheses for discrepancies

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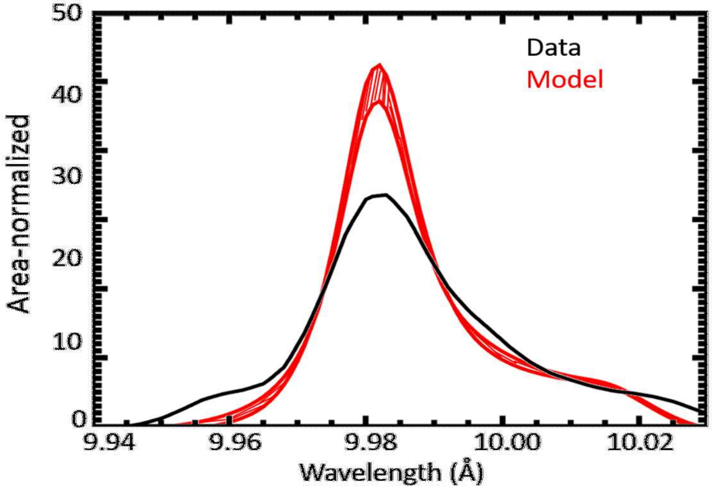
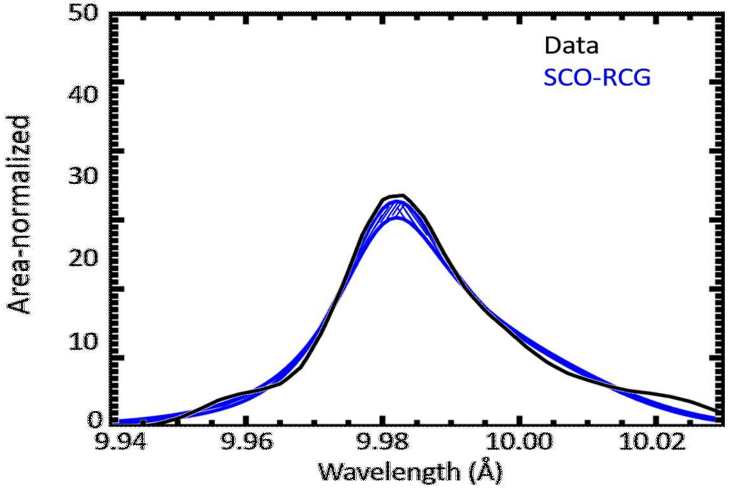




Due to better treatment in satellite?

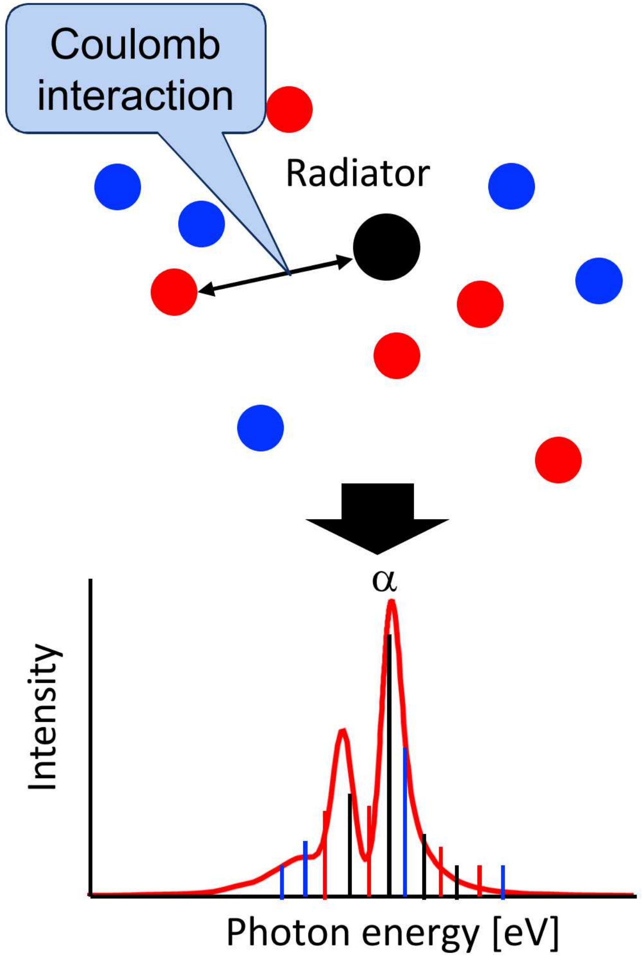
Line-shape theory has many approximations to be scrutinized

Found: Most models significantly under-predict line broadening

Hypothesis: Line-shape theory is not sufficiently accurate

Many line-shape approximations were recently revisited; More investigations are underway

Line is broadened due to ensemble of random perturbations



Common Approximations

Coulomb interactions:

- Dipole approximation
- Limited basis sets

Electrons:

- 2^{nd} order
- Classical
- Neglect or ad-hoc
  - Penetration/Strong coll.
  - Exchange
  - Electron capture

Ion:

- Crudely approximated
- Static

Satellites

Some were revisited

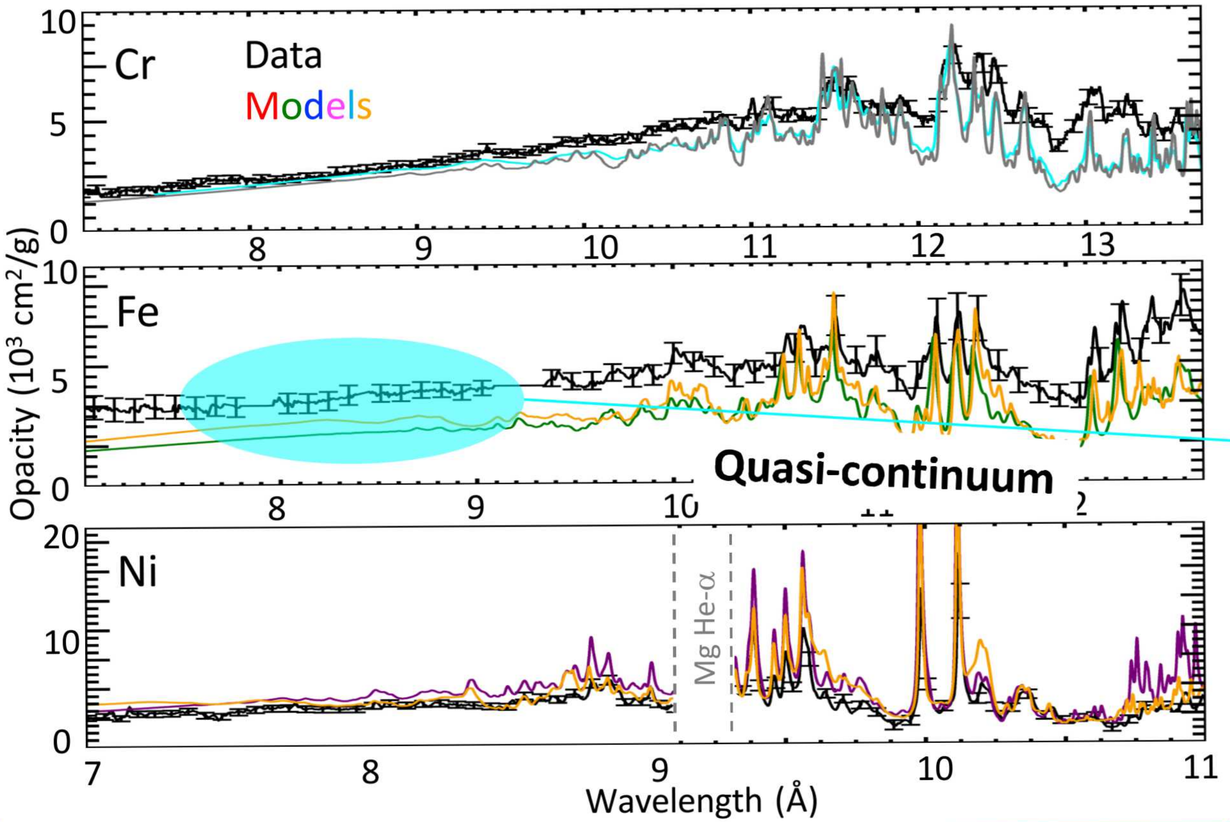
Coulomb interactions → Gomez PRA (2016)

Electrons → Gomez PRA (2018), Gomez PRL (2020), Iglesias HEDP (2016), Iglesias HEDP (2020)

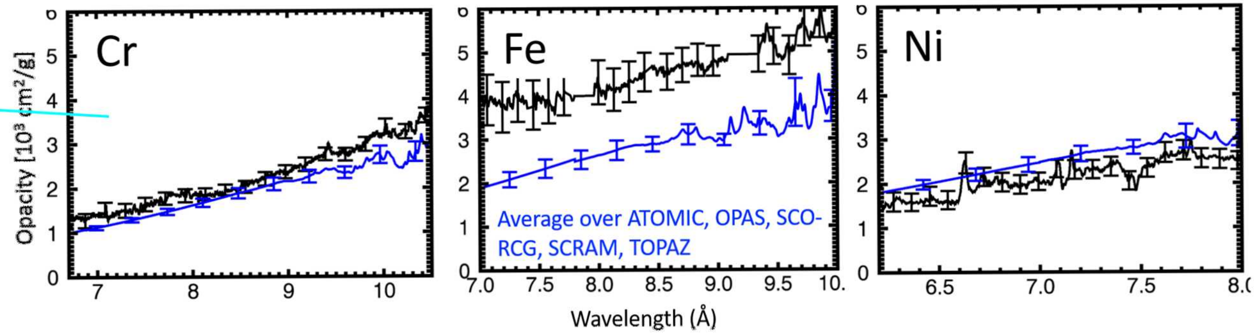
Ion → Mancini JPCS (2016)

Two impacts: (1) Fe line shapes in opacity model (2) Density diagnostics

Systematic opacity model-data comparisons for three elements revealed unexpected complexity

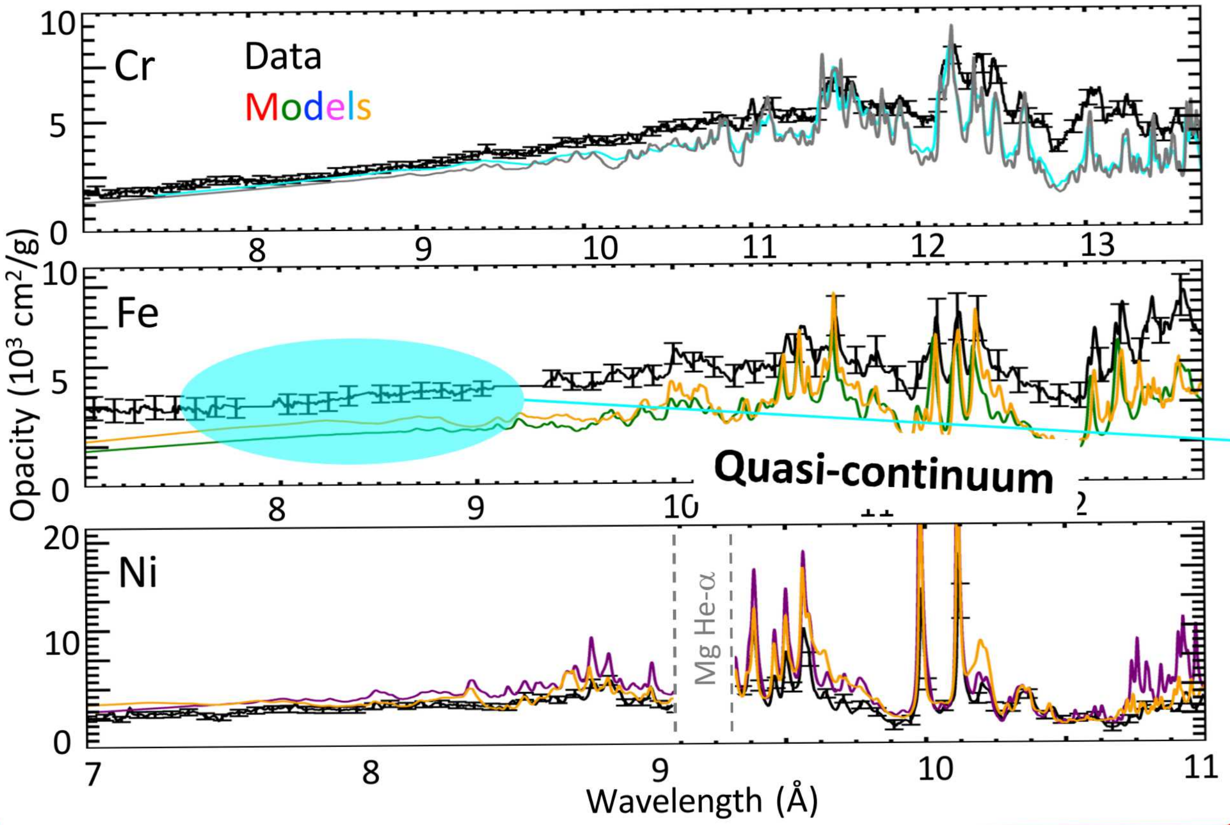


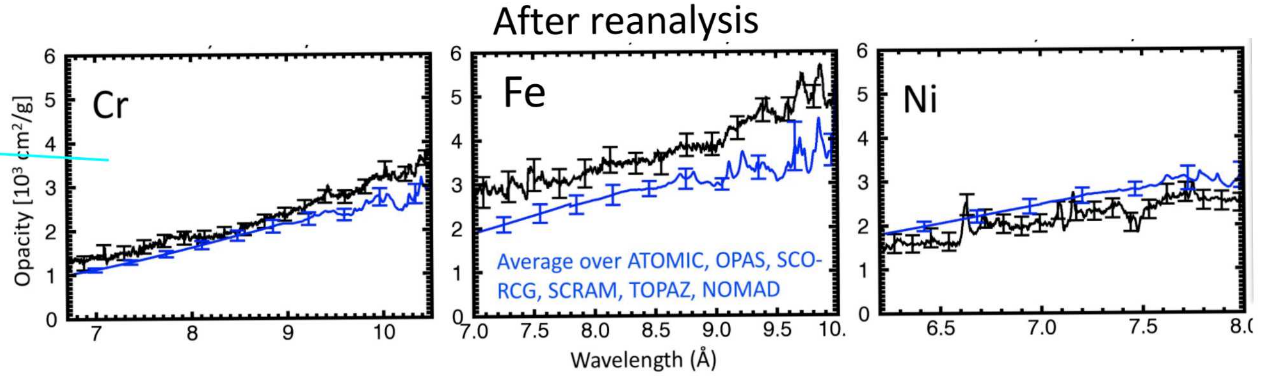
Before reanalysis



Anchor2: $T_e \sim 184$ eV, $n_e \sim 3 \times 10^{22}$ cm^{-3}

Systematic opacity model-data comparisons for three elements revealed unexpected complexity





Anchor2: $T_e \sim 184$ eV, $n_e \sim 3 \times 10^{22}$ cm^{-3}

Can quasi-continuum puzzle be explained by missing physics? Three new theories are proposed …

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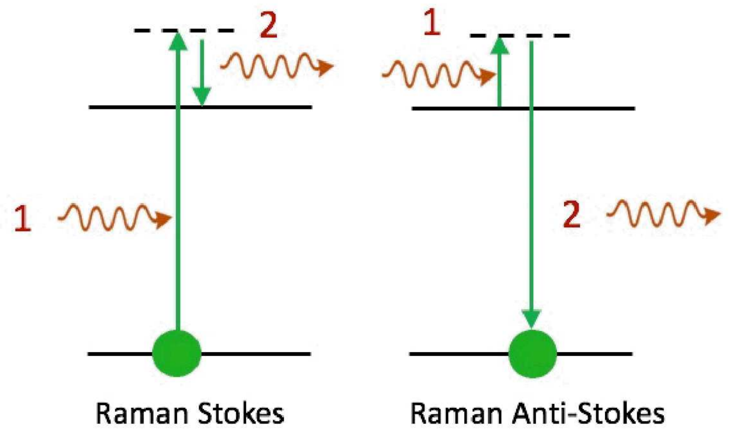
Two-photon opacities

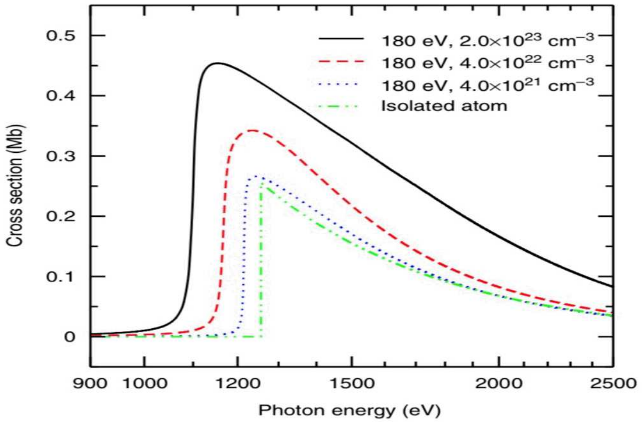


Two photons can simultaneously interact with the atom

For: More HEDP (2017)
More HEDP (2019)

Against:
Kruse HEDP (2019)
Pain HEDP (2018)

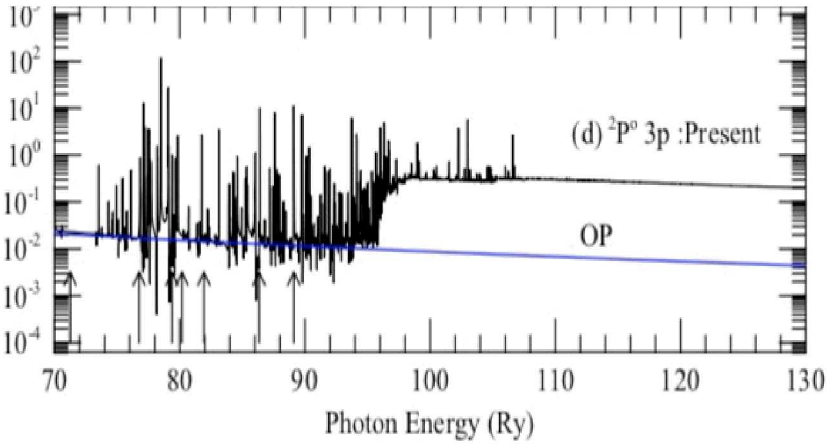
Transient space-localization of electron



Ejected electrons stay close to ion, contributing extra absorption

For: Liu Comm. Phys. (2018)

Resonances



Resonances are neglected

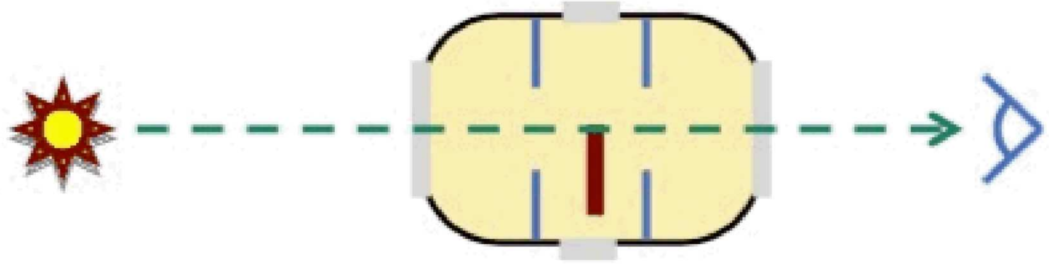
For: Nahar PRL (2016)

Against:
Blancard PRL (2016)
Iglesias Ap.J. (2016)

Opacity calculations need to be performed and compared with the data systematically across Cr, Fe, and Ni

Other facilities play crucial role in resolving the opacity puzzles

National Ignition Facility is independently testing the Fe opacity at similar conditions



[1] R. Heeter et al, Atoms 6, 57 (2018).

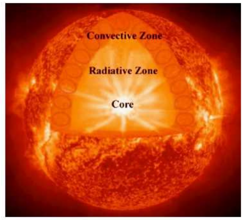
[2] T. S. Perry et al, HEDP 23, 223 (2017).

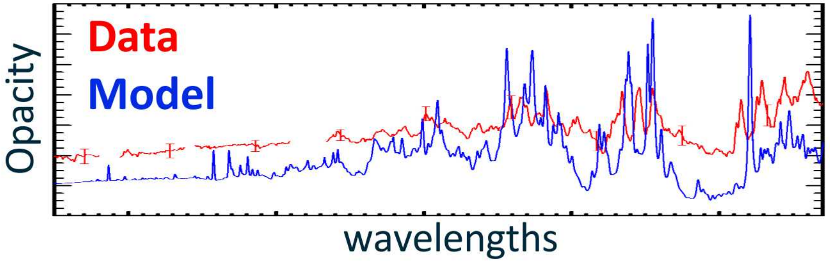
[3] R. F. Heeter et al J. Plasma Phys. 83, 5617 (2017).

X-ray free-electron lasers:

- **Oscillator strengths of highly-ionized Fe**
- **Mono-energetic two-photon process cross-sections**

Holistic approach including new experiments, new analysis, new theories will help resolve the solar problem





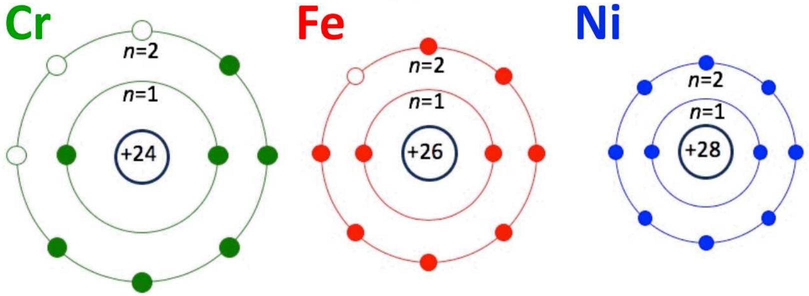
Puzzle: Measured stellar iron opacity higher than predicted

→ **Both experiment and theory need to be scrutinized**

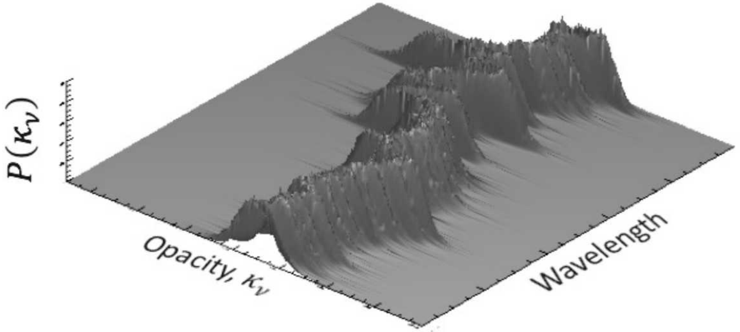
Experiment scrutiny

- **Systematic study of Cr, Fe, and Ni**

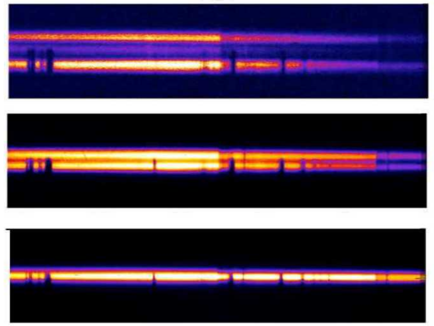
  → Narrow down hypotheses



- **Refined analysis method**

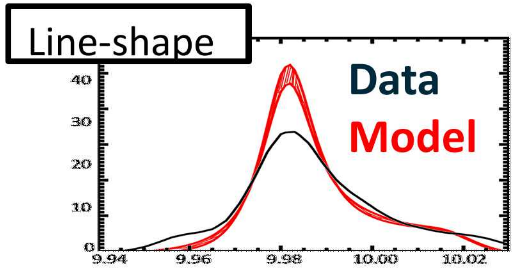


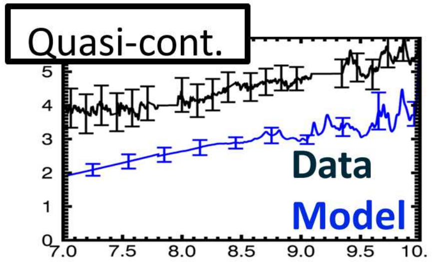
- **Time-resolved data**



Theoretical scrutiny stimulates atomic-physics discussions

- **Spectral line shapes:** Ion, electron, satellites
- **Quasi-continuum:** new theories





Continued experimental and theoretical research is needed for understanding photon-atom interactions in High-Energy-Density matter