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SAND2022-10563C

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Challenges of HED opacity and its implication on solar/stellar applications

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U.S. DEPARTMENT OF ENERGY NNSA

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HED opacity is challenging in theory, experiments, and translating its implications to solar/stellar applications

Q. What is high-energy-density (HED) plasma?

Q. Experiments: Why is HED opacity experiments challenging?

Q. Theory: Why is HED opacity theory (Fe, O) challenging?

Q. Impact on astrophysics: Why is assessing the impact challenging?

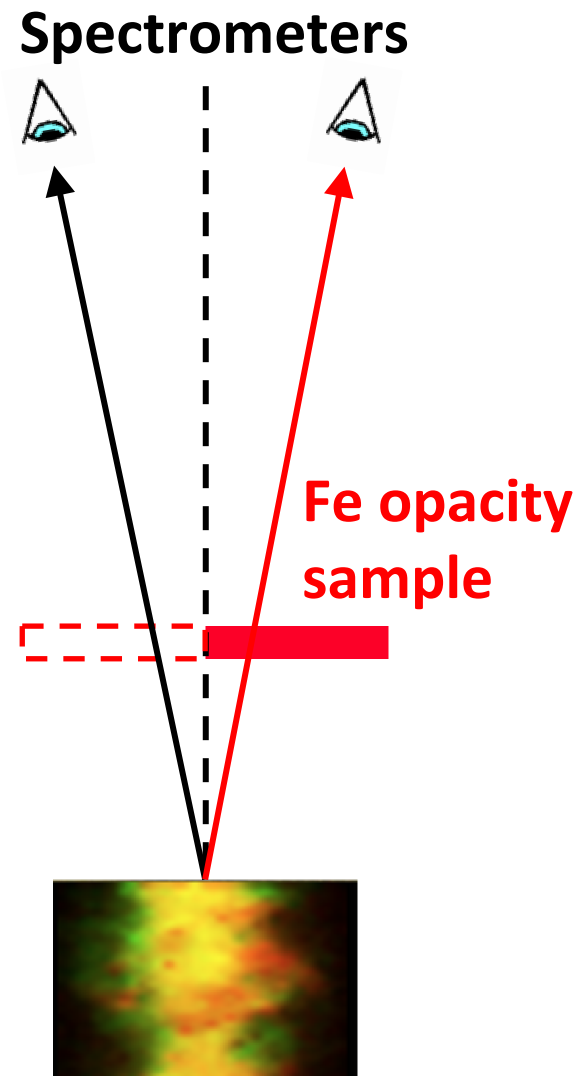
Questions to Solar physicists → Aldo Serenelli

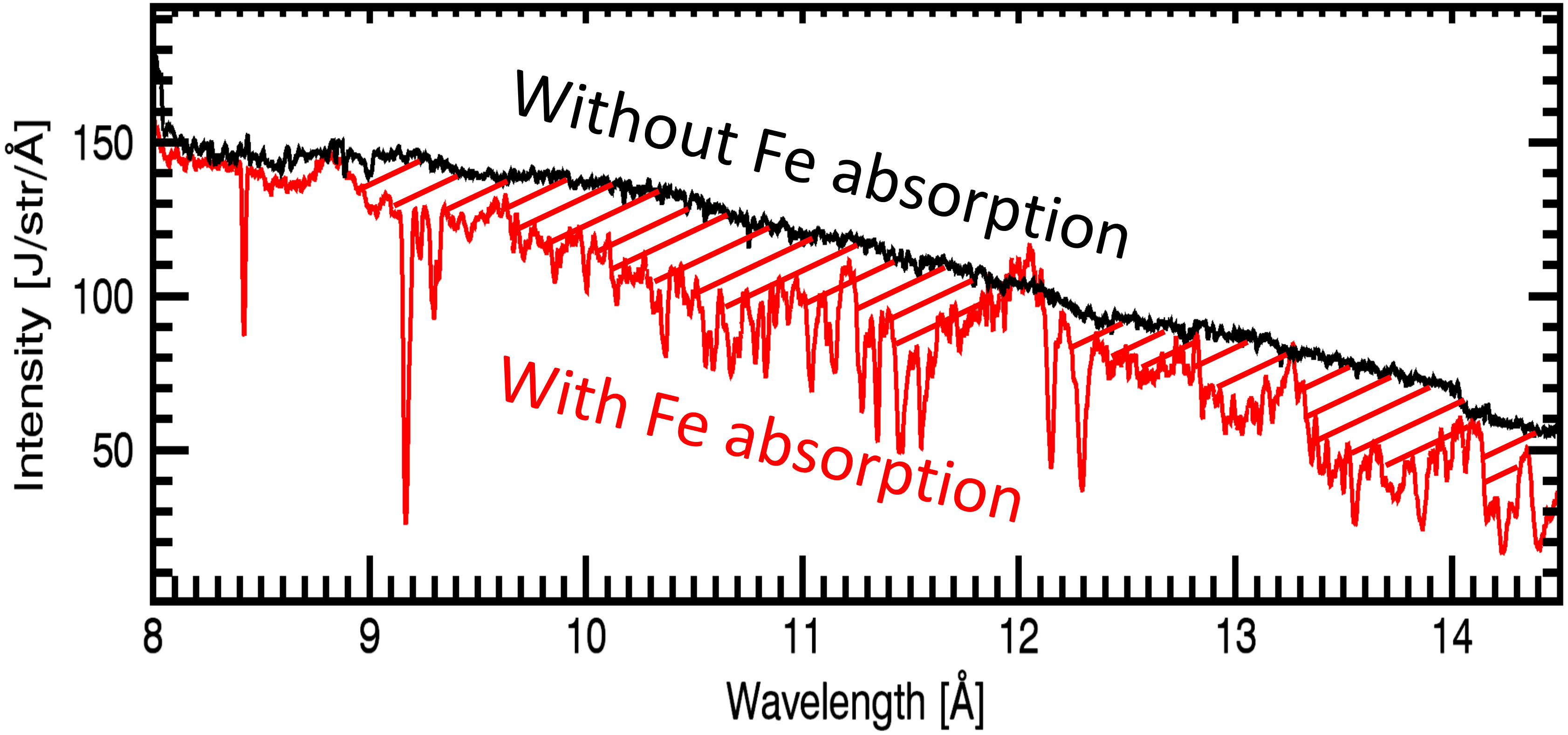
Topics to cover

- How opacity experiments work
- Oxygen opacity
  - Why is oxygen opacity challenging?
  - Preliminary status of oxygen opacity measurement
- Why is assessing astrophysical impact challenging?

  → Solar Rosseland-mean opacity error would change with radius

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





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

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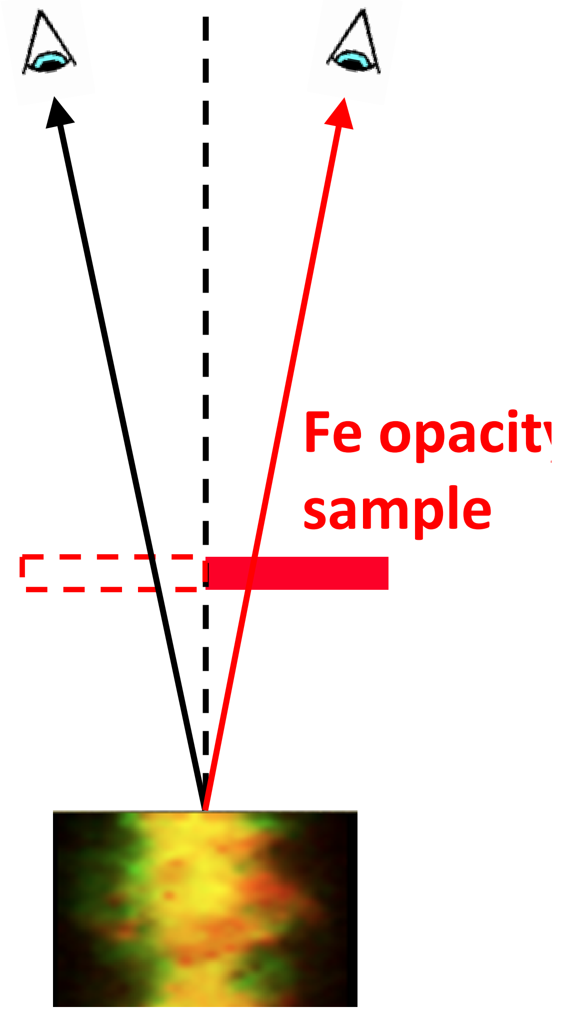
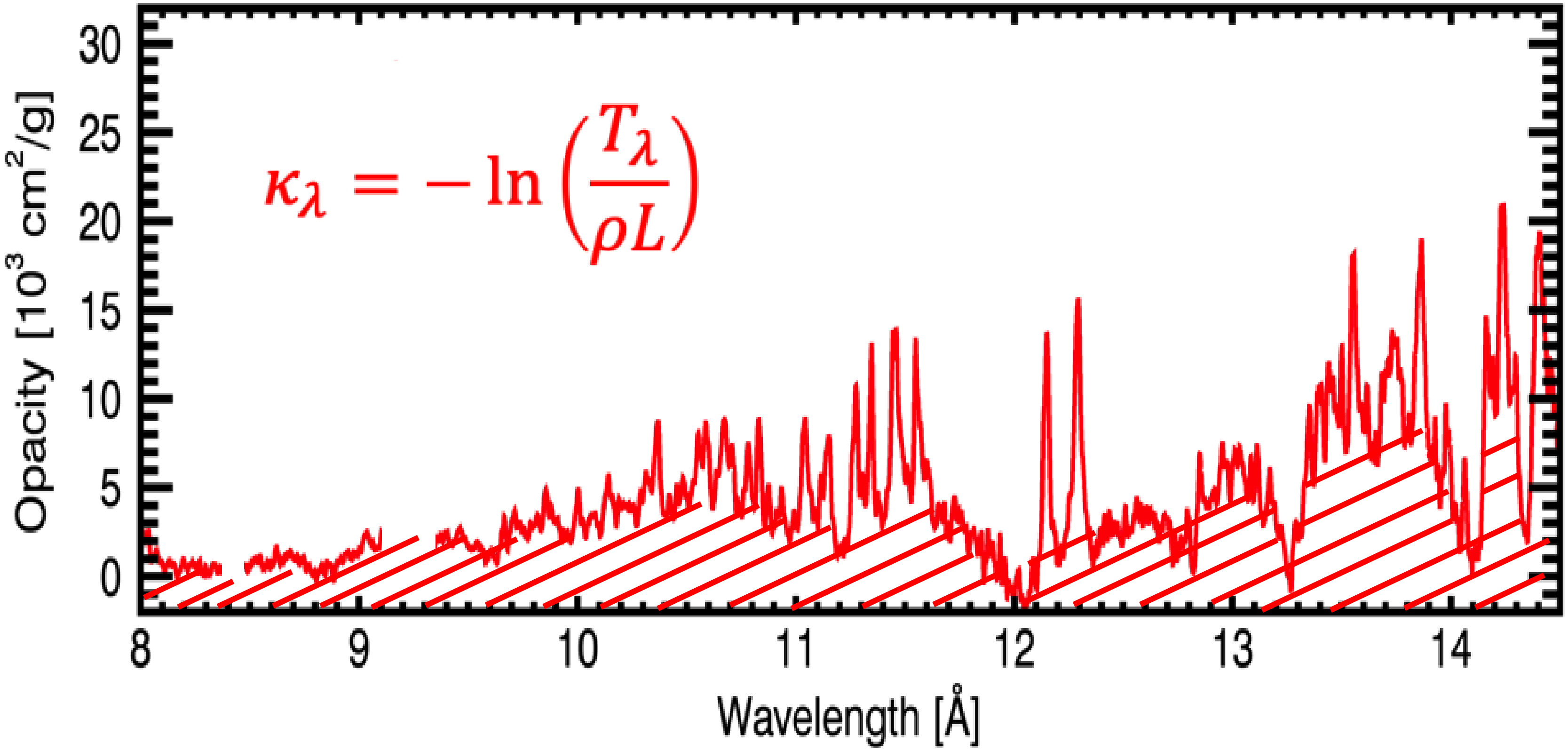
Spectrometers





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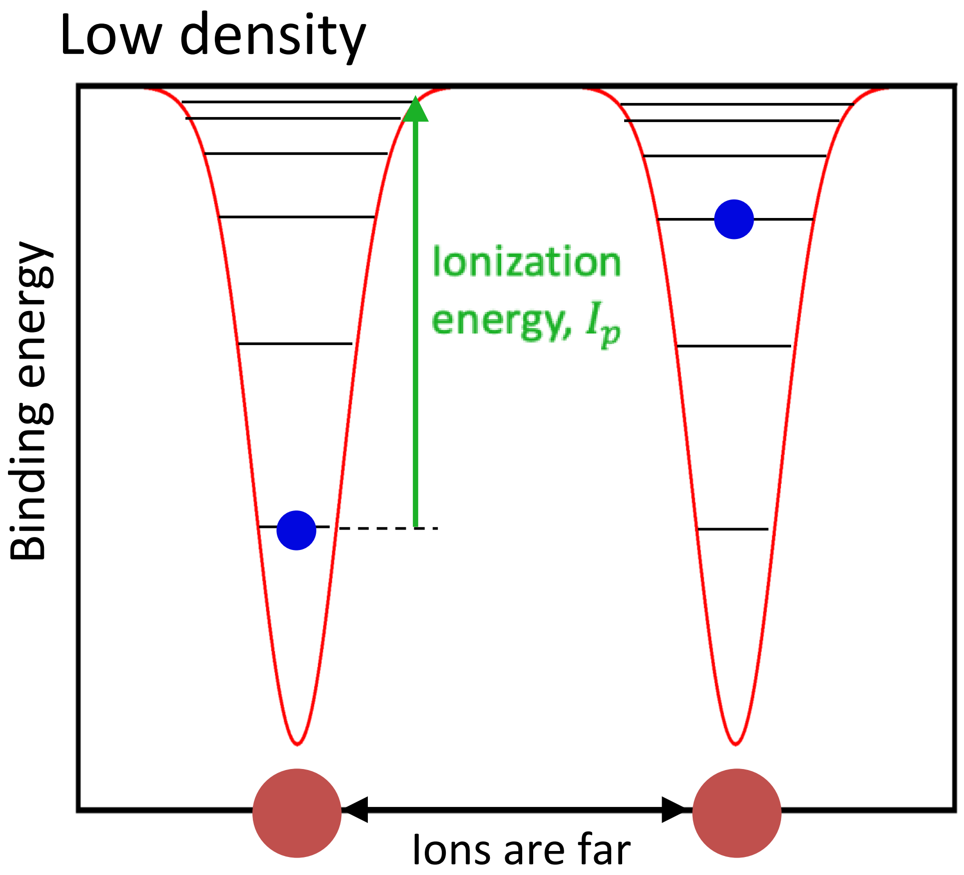
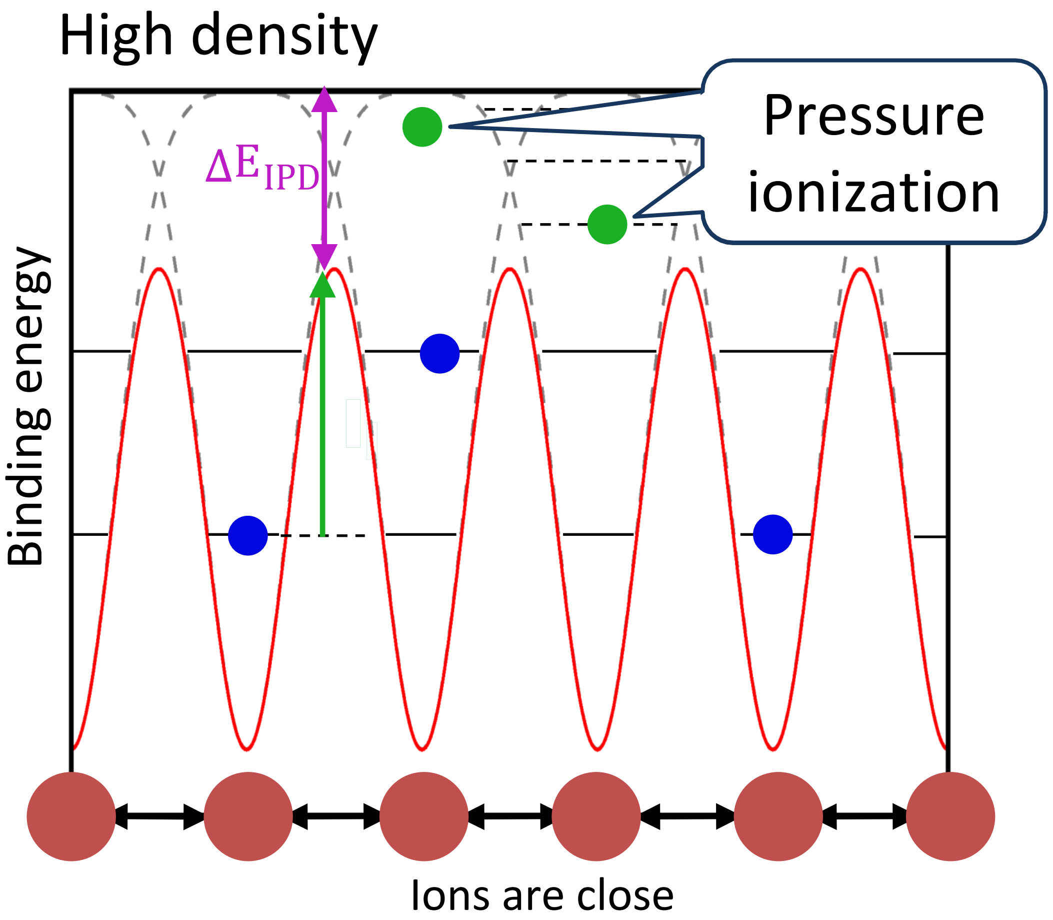
HED theory is challenging due to: (i) too many excited states and **(ii) density effects**

High density alters the atomic structure





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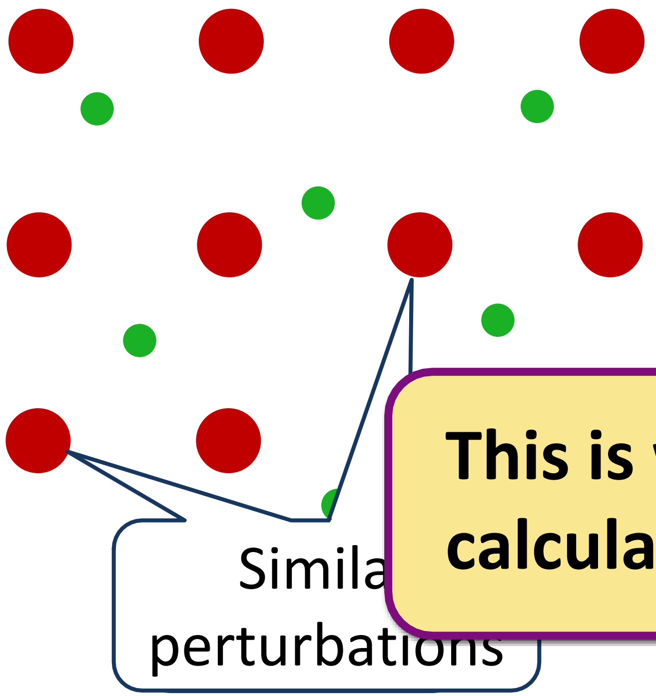
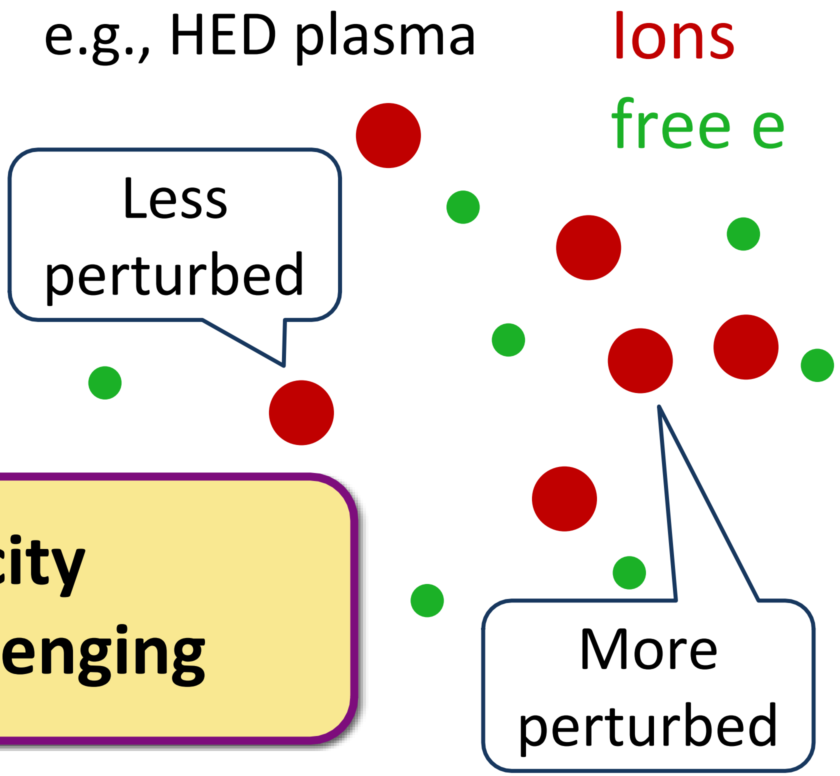
<u>High temperature introduces randomness in perturbation</u>

Low temperature
e.g., Condensed matter



High temperature
e.g., HED plasma

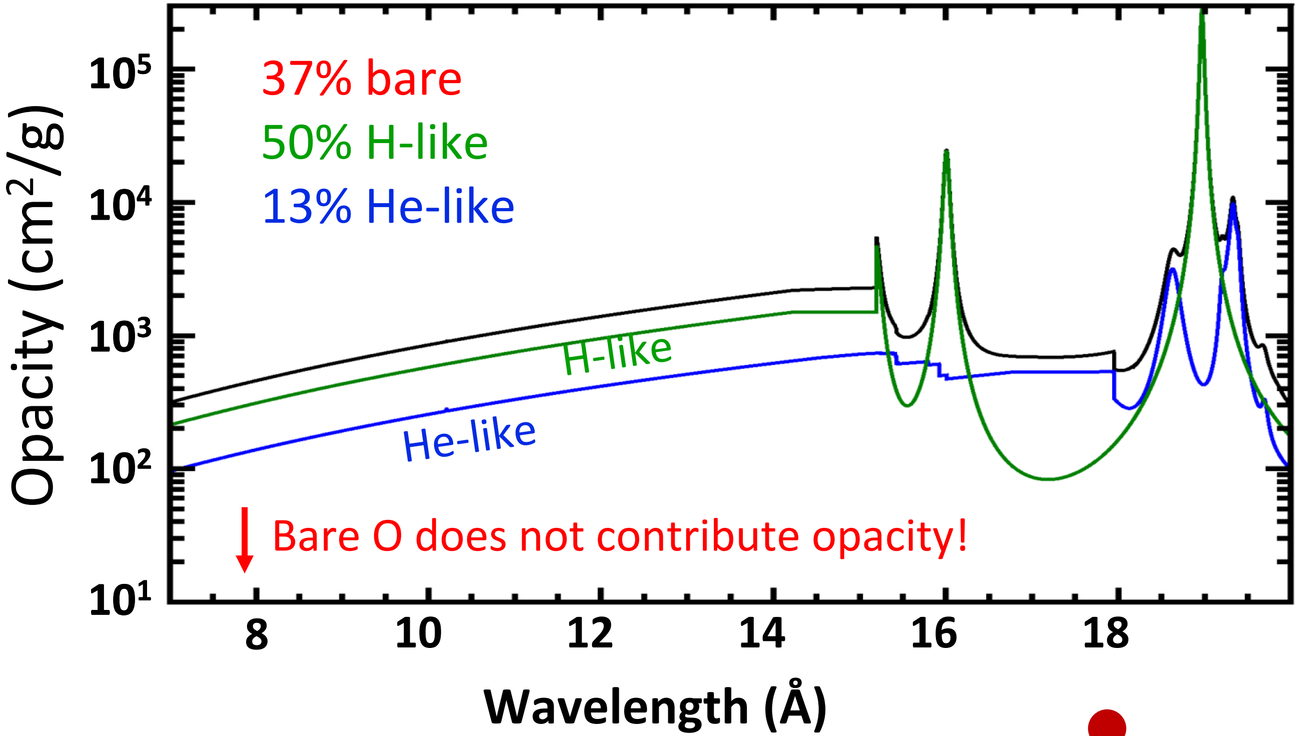


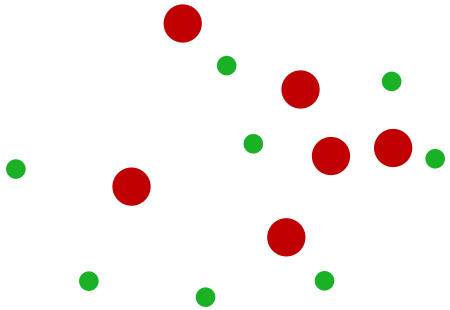
This is why O opacity calculation is challenging

HED effects complicates ionization calculation and line-broadening calculation

Oxygen opacity depends on accuracy of density effects

Oxygen opacity calculated at CZB conditions*





- Bound-free opacity depends on IPD

  3x IPD → -3% in κ_R

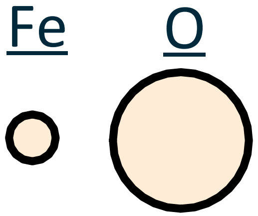
- Opacity window depends on line shapes

  3x broader lines → +6% in κ_R

- Density effect is severer on O than Fe

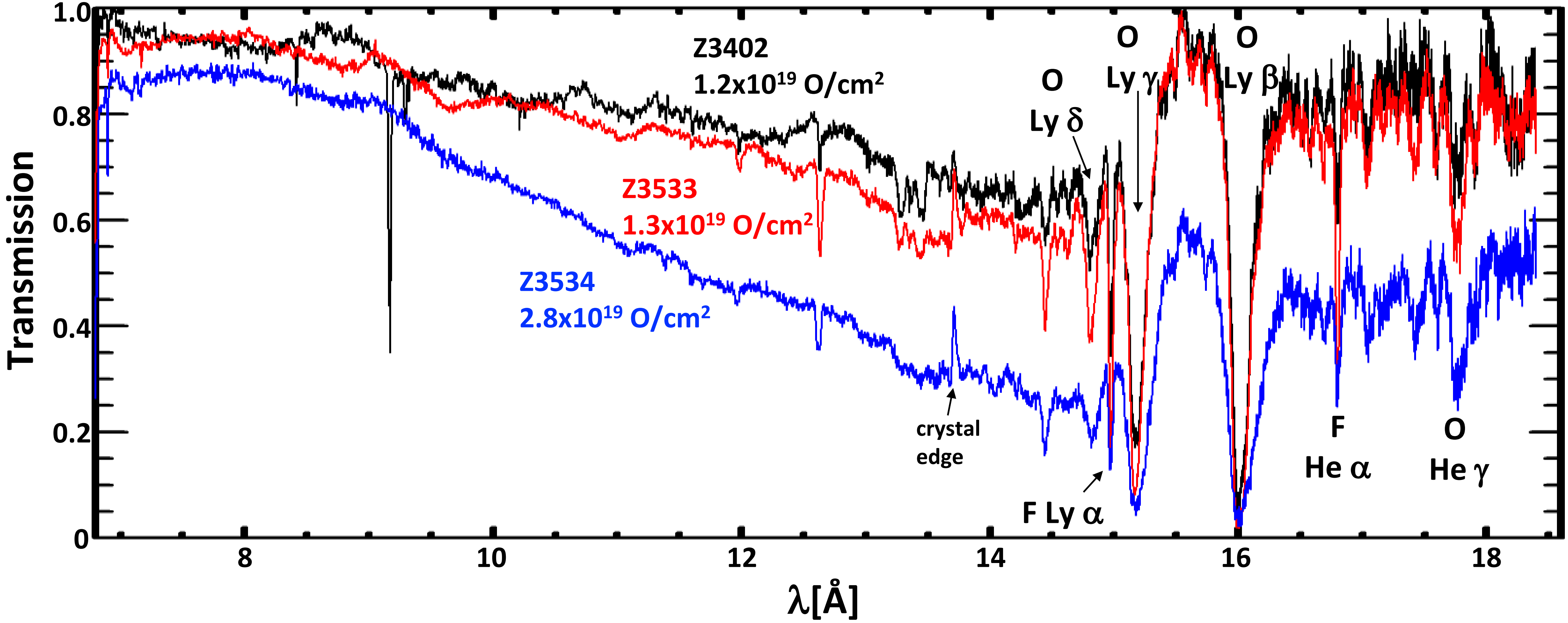
  Atomic radius $\propto 1/Z$

  → **O is 3x larger**



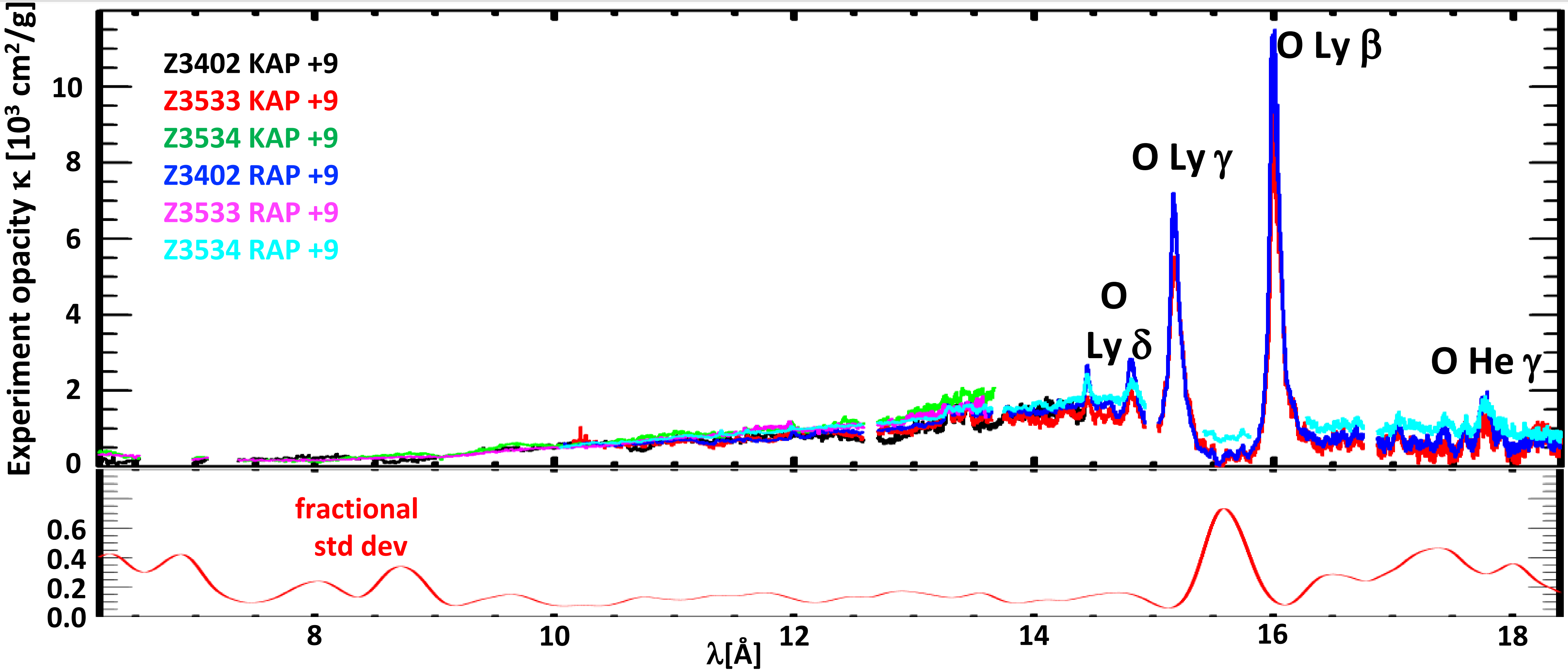
  - Stronger perturbation
  - Higher-order effect is important

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



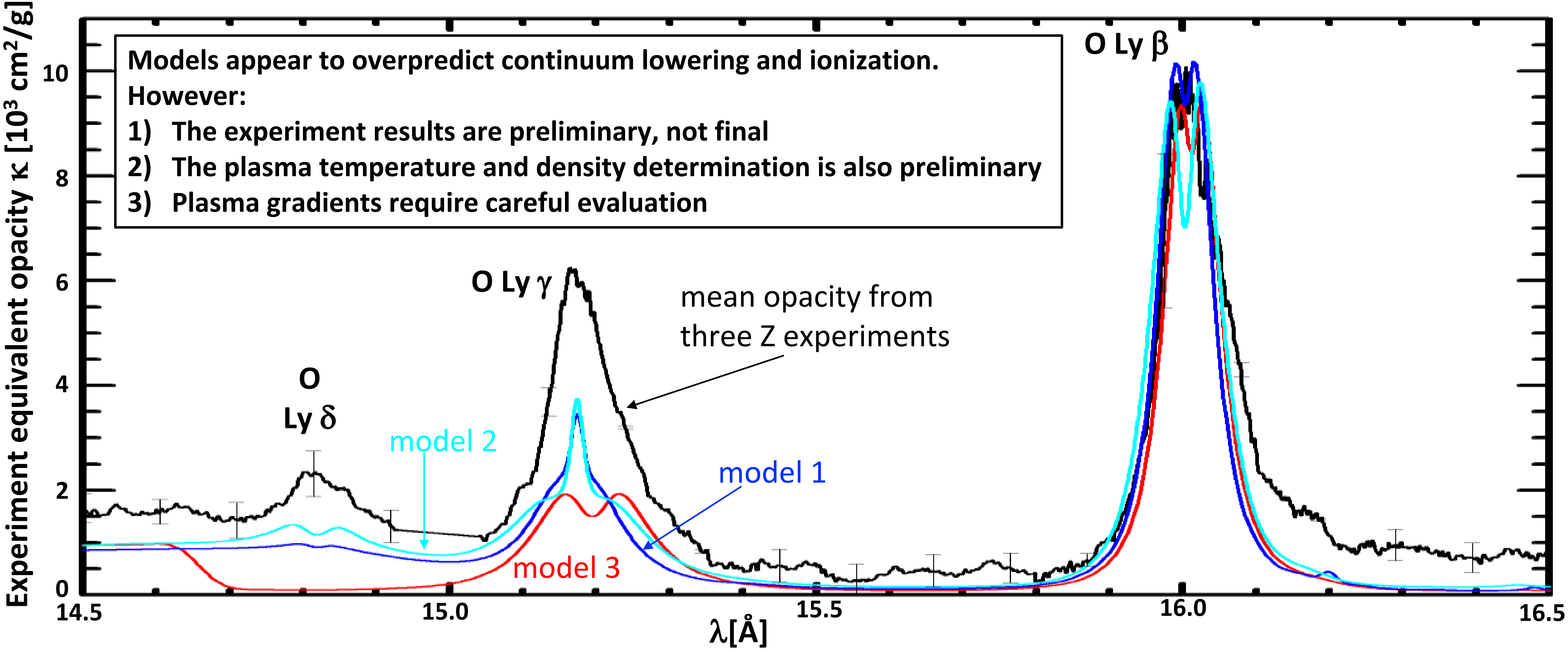
- Multiple experiments test reproducibility
- Different areal densities help assess accuracy and expand dynamic range

Preliminary oxygen opacity measurements are reproducible



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

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



The models don't even agree with each other

Topics to cover

- How opacity experiments work
- Oxygen opacity
  - Why oxygen opacity challenging?
  - Current status
- Why is assessing astrophysical impact challenging?
  → Solar Rosseland-mean opacity error would change with radius

Uncertainty of solar Rosseland mean opacity is complex due to multiple sources of uncertainty

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- **Single-model uncertainty:** How can we propagate uncertainties in different aspect of theory to final opacity calculation?

- **Model-model inconsistency:** How can we incorporate the differences between opacity models into solar Rosseland-mean opacity uncertainty?

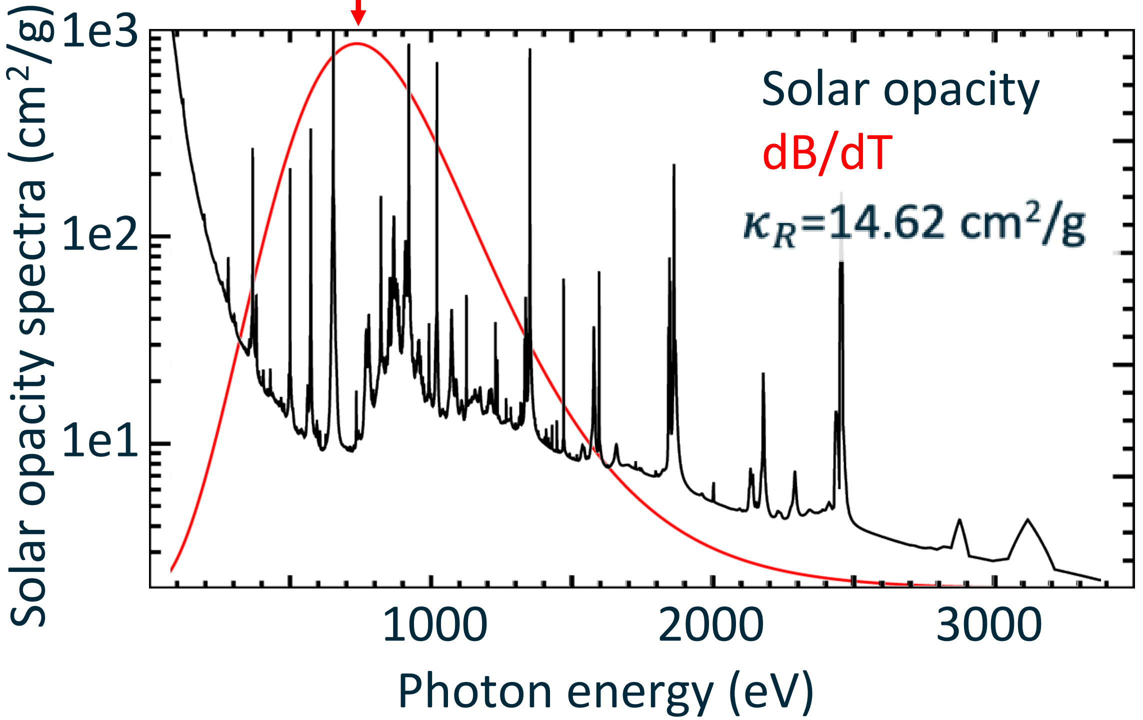
- **Model-data discrepancy:** How can we propagate model inaccuracy inferred by measurements to solar Rosseland-mean opacity (RMO) uncertainty?
  - Model-data discrepancy in frequency-resolved opacity can reveal model weaknesses
  - Experiments cannot test opacities of all elements at all conditions
  - Propagating the measured model-data discrepancy to solar RMO uncertainty at all radii seems infeasible

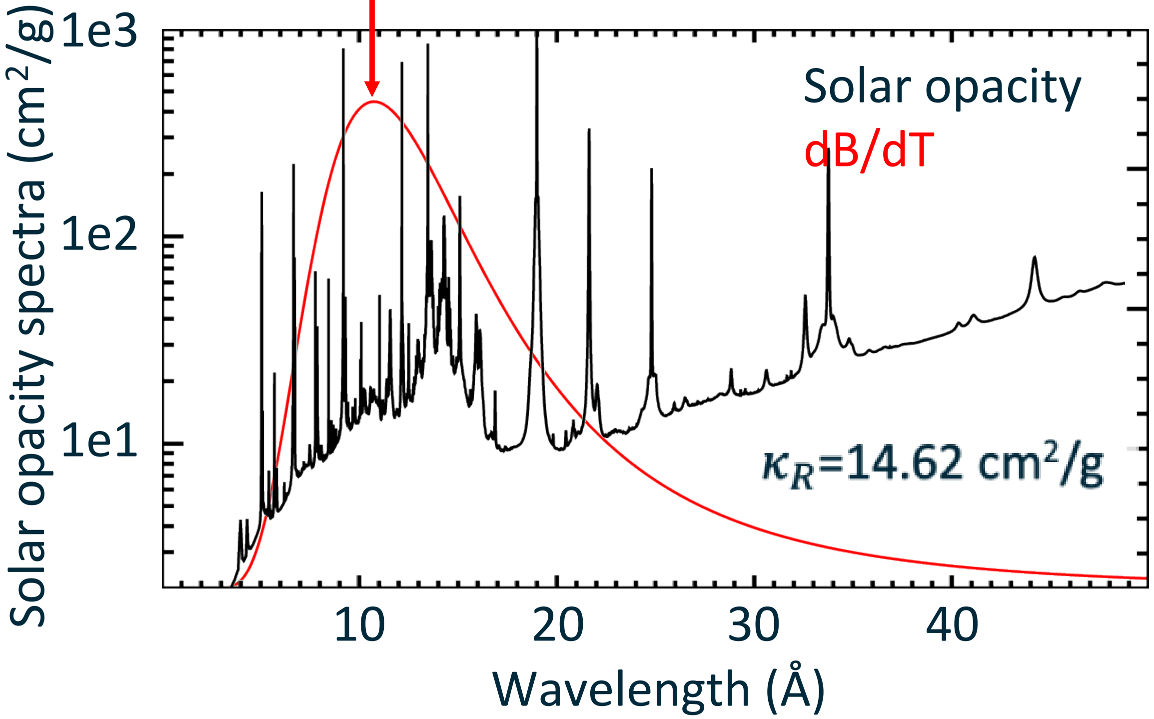
We use experiments to test opacity physics and use validated opacity models to provide accurate solar models

CZB solar opacity is most important at 18Å
… this is not exactly correct

dB/dT peak location depends on its abscissa.
Its peak location has limited meaning ….

T=193 eV, n_e=1e23



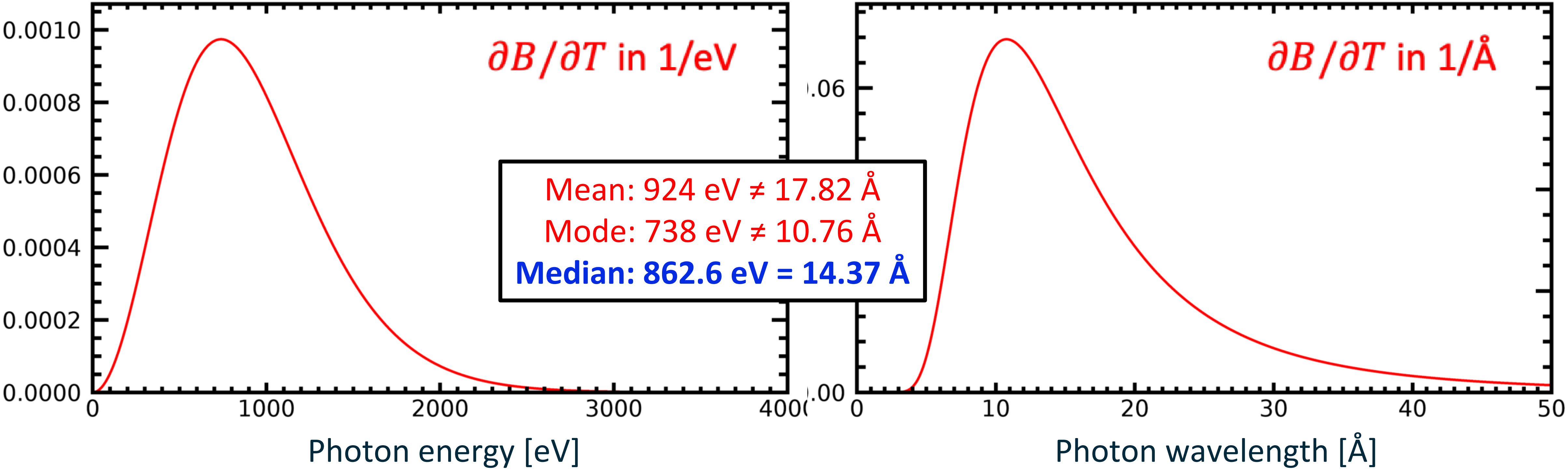


What's conserved is the probability, i.e., dB/dT x dx: → $\frac{\partial B}{\partial T}(E)\,dE = \frac{\partial B}{\partial T}(\lambda)\,d\lambda$

Wrong: Opacity at 18Å is most important

Correct: 68% of dB/dT curve falls between [494, 1353] eV
or. [9.16, 25.1] Å

Caution in interpreting probability density, e.g., dB/dT. Median and mode have limited meanings …



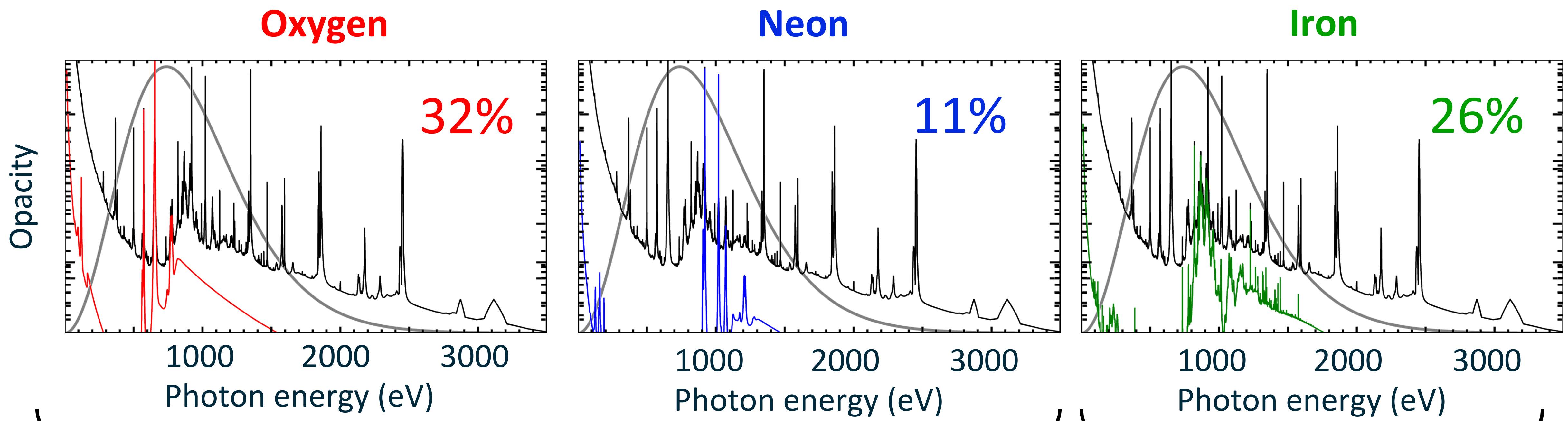
$$\lambda[\text{Å}] = \frac{12398.42}{E\,[eV]}$$

Only percentiles or probability between some interval have physical meaning.

*** Bayesian analogy: uniform prior in photon-energy axis is not uniform in wavelength axis.**

What are three major opacity donors at the convection-zone base?

Solar Rosseland-mean opacity at CZB is dominated by …



<u>K-shell</u>

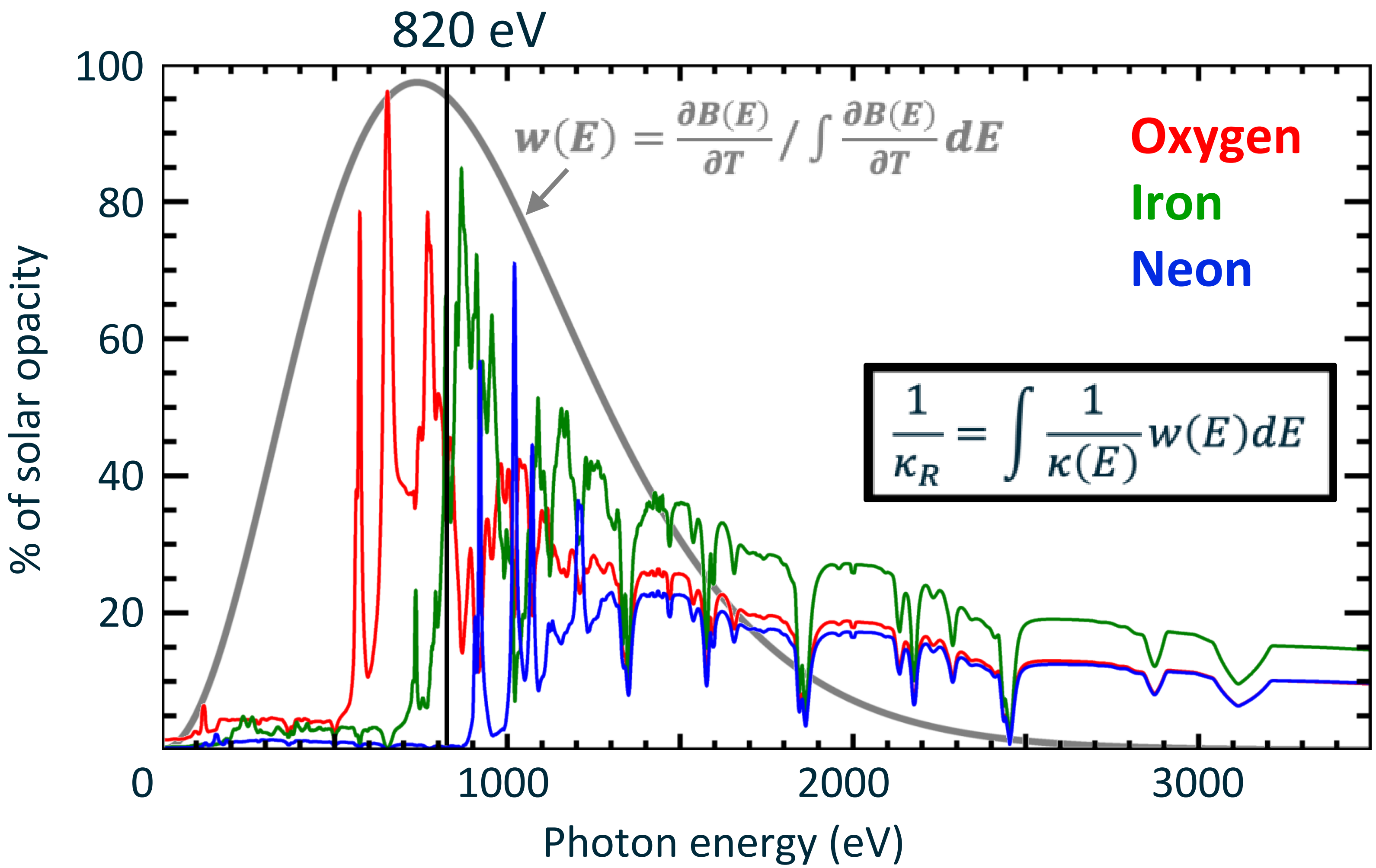
- Accurate ionization (IPD)
- Accurate line shapes

<u>L-shell</u>

- Accurate treatment of multi-excited states and billions of satellite lines

Which one dominates at each photon energy (or wavelength)?

Oxygen is more important below 820 eV (> 15 Å); Iron is more important above 820 eV (< 15 Å)



Unimportant when κ_ν is high

Peak depends on axis

Their importance for Rosseland mean is not clear due to complexity of $1/\kappa_\nu$, w(E)

Spare slides

HED opacity is challenging in theory, experiments, and translating its implications to solar/stellar applications

Q. What are high-energy-density (HED) plasmas?

A. HED plasmas are hot, dense plasmas

Q. Experiments: Why is HED opacity experiments challenging?

A. HED experiments are hard to diagnose or hard to get opportunities

Q. Theory: Why is HED opacity theory (Fe, O) challenging?

A1. HED plasmas could have billions of bound-bound transitions (Fe)

A2. HED plasmas have complex density effects (O)

Q. Impact on astrophysics: Why is assessing the impact challenging?

A. Solar opacity depends on composition, temperature, density, and frequency in a complex way

Questions to Solar physicists → Aldo Serenelli

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What is high-energy-density?

Ideal gas law

$$PV = N k_B T$$

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What is high-energy-density?

Ideal gas law

[illegible] = [illegible]

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Energy-density

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High energy-density (HED) plasma

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High pressure (> 1Mbar) plasma

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High temperature, high density plasma

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Hot, dense plasma

They are used interchangeably

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Easy to say
Hard to do

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Easy to say
Hard to do

HED plasmas are created by <u>compressing energy in space and time</u>

<u>Small size:</u> $10^{-5} - 10^{-3}\ m$

<u>Short duration:</u> $10^{-15} - 10^{-9}$ s

fs, ps, ns

Hard to diagnose

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Easy to say
Hard to do

HED plasmas are created by compressing energy in space and time

Small size: $10^{-5} - 10^{-3}\ m$

Short duration: $10^{-15} - 10^{-9}$ s

fs, ps, ns

Hard to diagnose

Expensive
Limited resource

Hard to get opportunity to check reproducibility

In fact, there are many potential sources of systematic errors in our experiments too

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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 [1,2]
- 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 [1]
- 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 → Quantified amount do not explain the discrepancy (Tamper self emission and Extraneous background)

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

Condition reproducibility: [1] Nagayama et al, Phys Plasmas (2014) [2] Nagayama et al, HEDP (2016)

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Numerical evidence

- Plasma T_e and n_e errors → Suggested n_e error did not explain the discrepancy
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(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, *High Energ Dens Phys* (2016)
Iglesias et al, *High Energ Dens Phys* (2016)

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

- **We have checked everything the best we can, with dedicated experiments and simulations.**
- **Experiments are difficult enough that people will question them until discrepancies are gone.**

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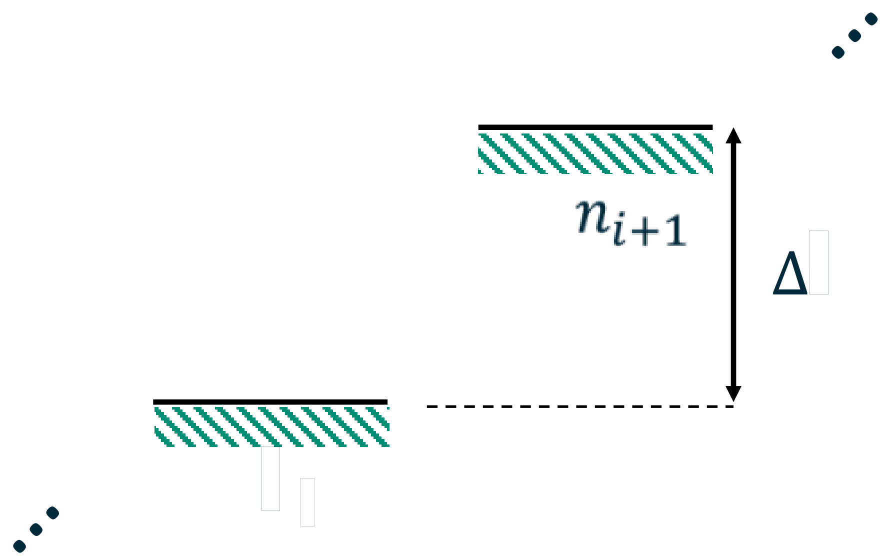

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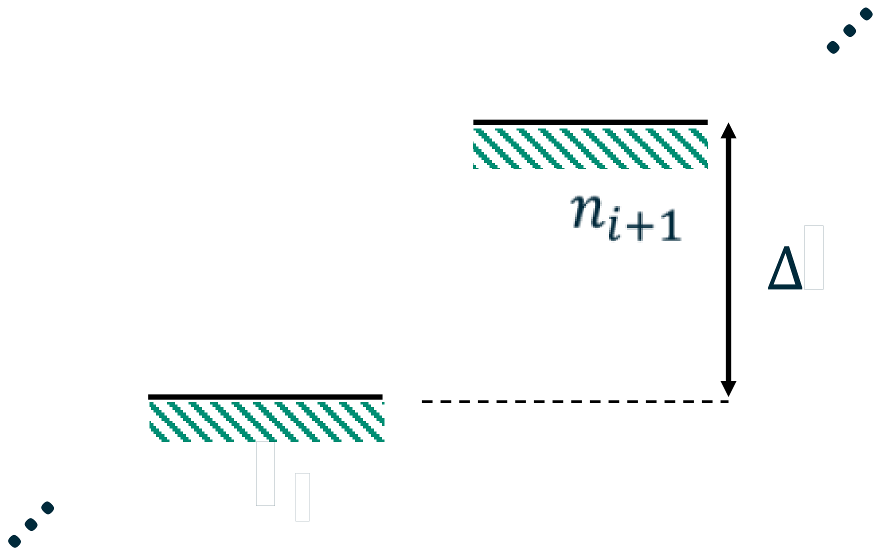

Ionization by the Saha equation

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

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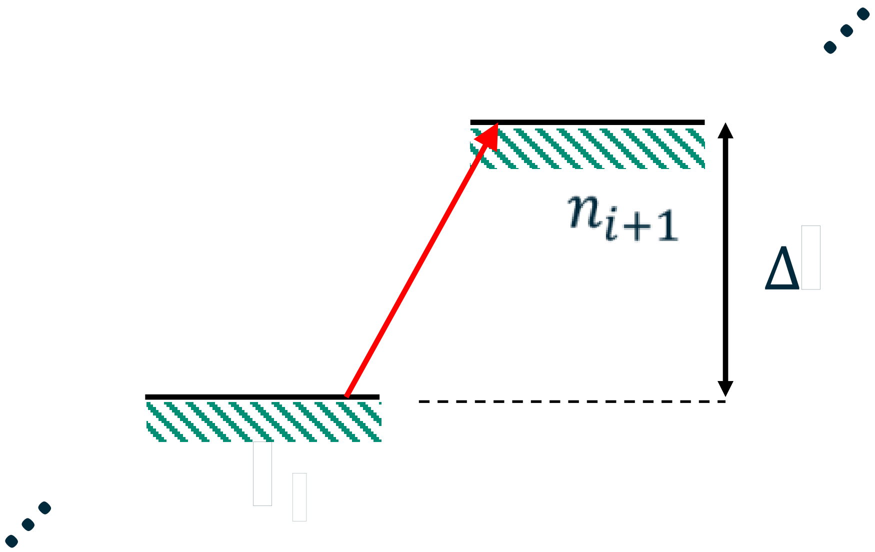

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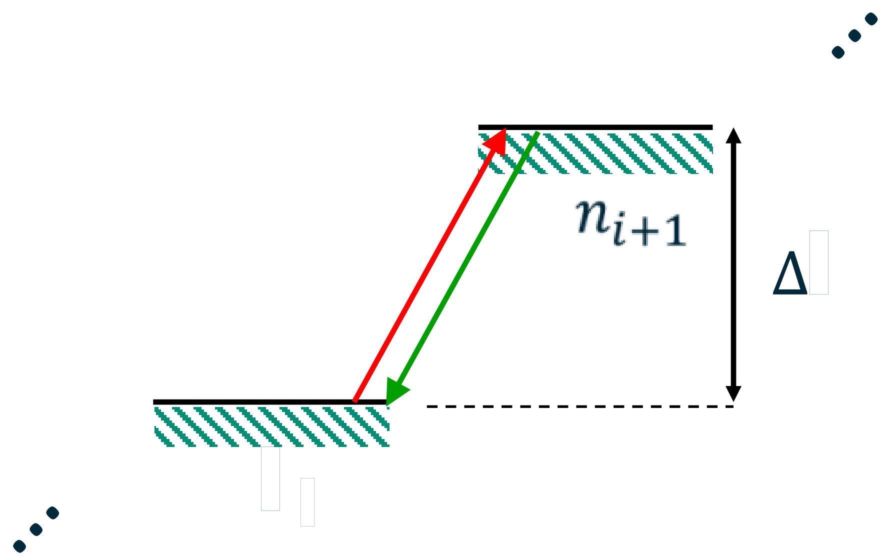

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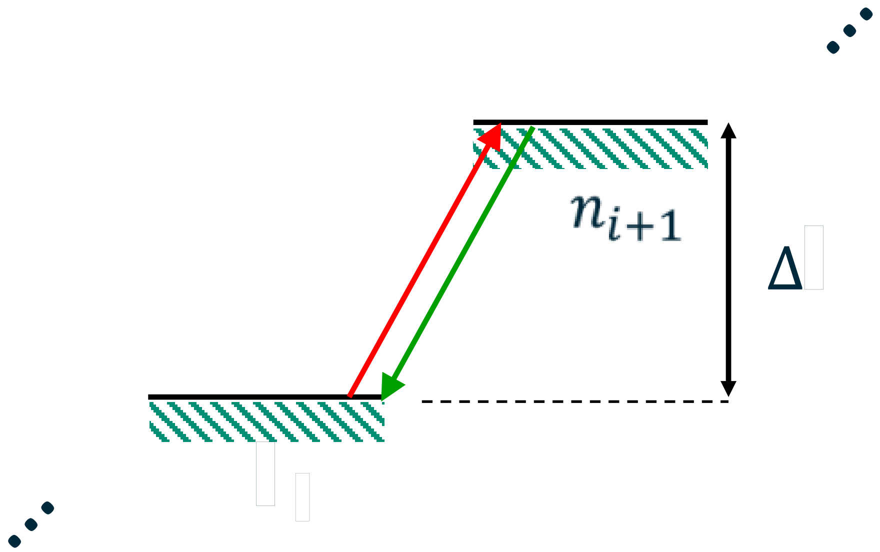

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HED plasma can have similar ionization to low temperature, low density plasma, but …

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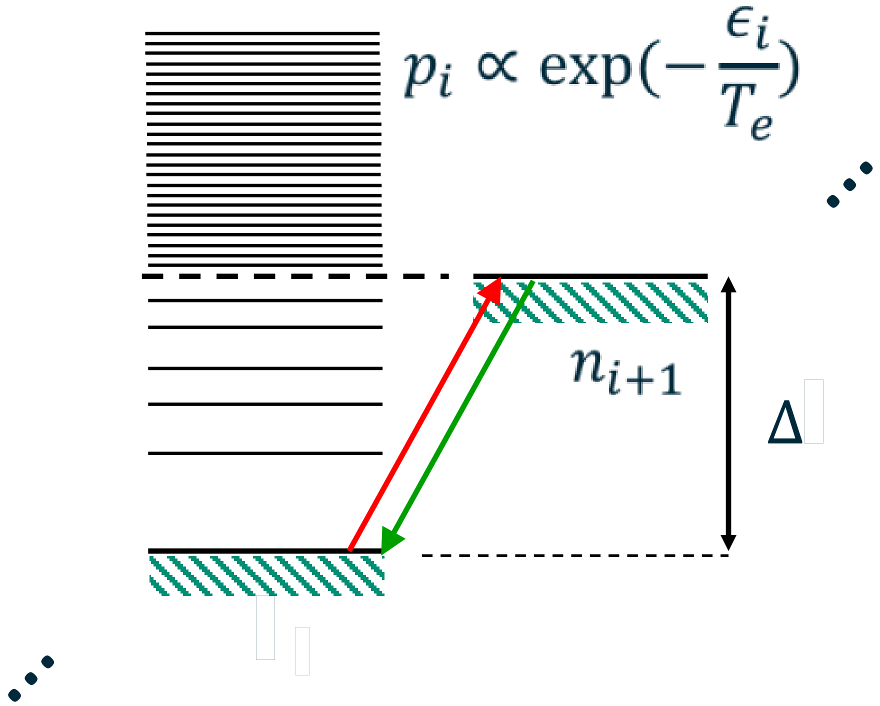

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HED plasma can have similar ionization to low temperature, low density plasma, but …
- **Significant population in excited states!**
- **Complete inclusion of excited states is crucial**

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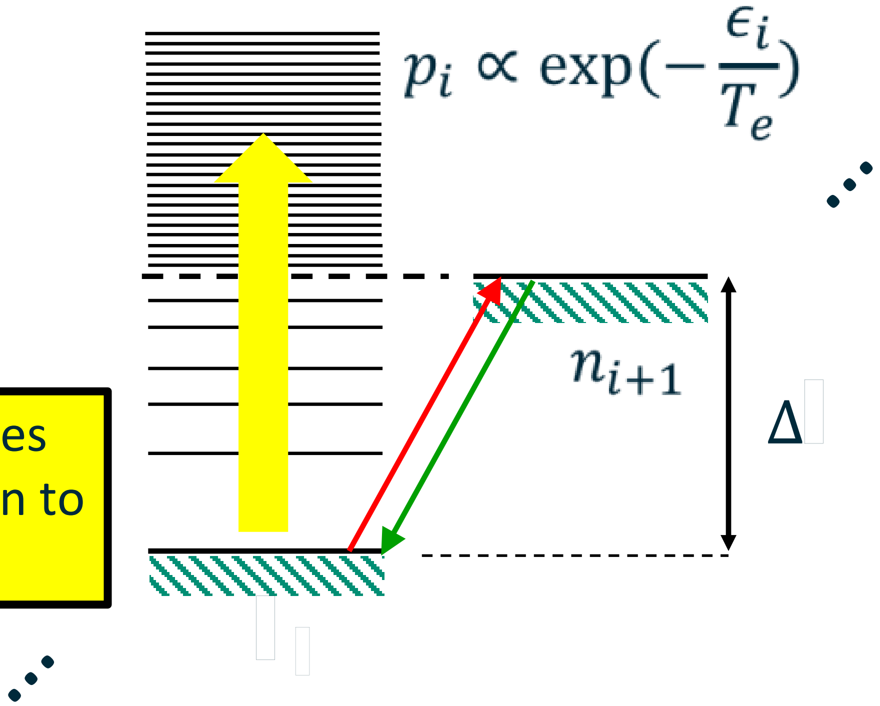

HED pushes population to excited states

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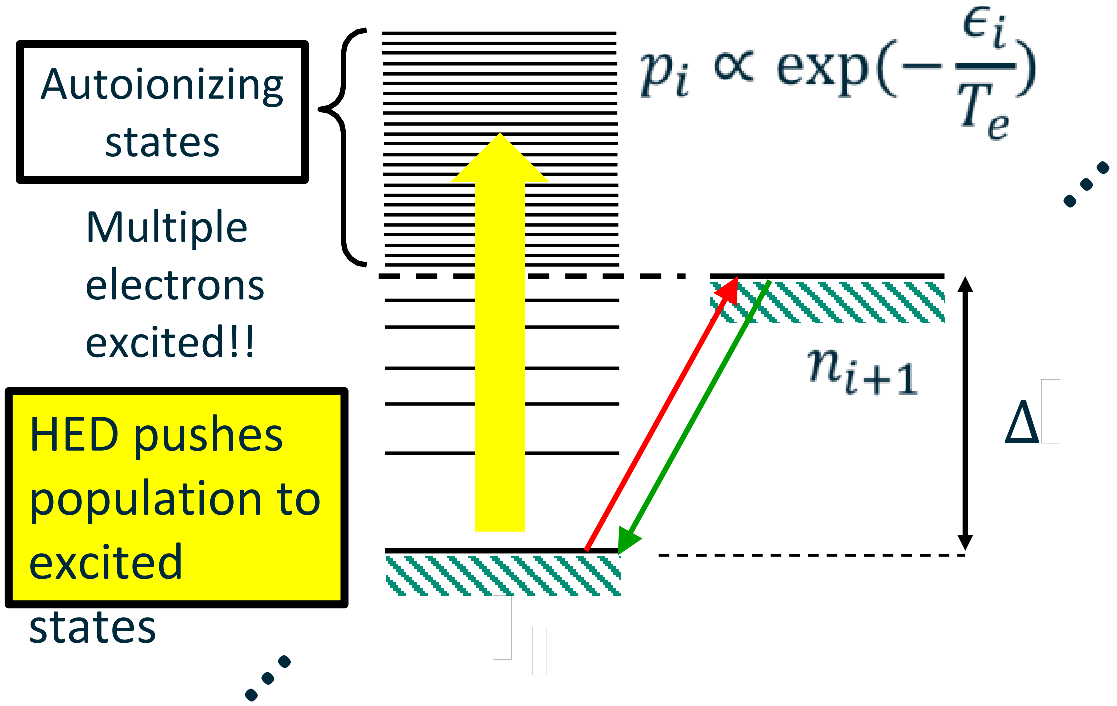

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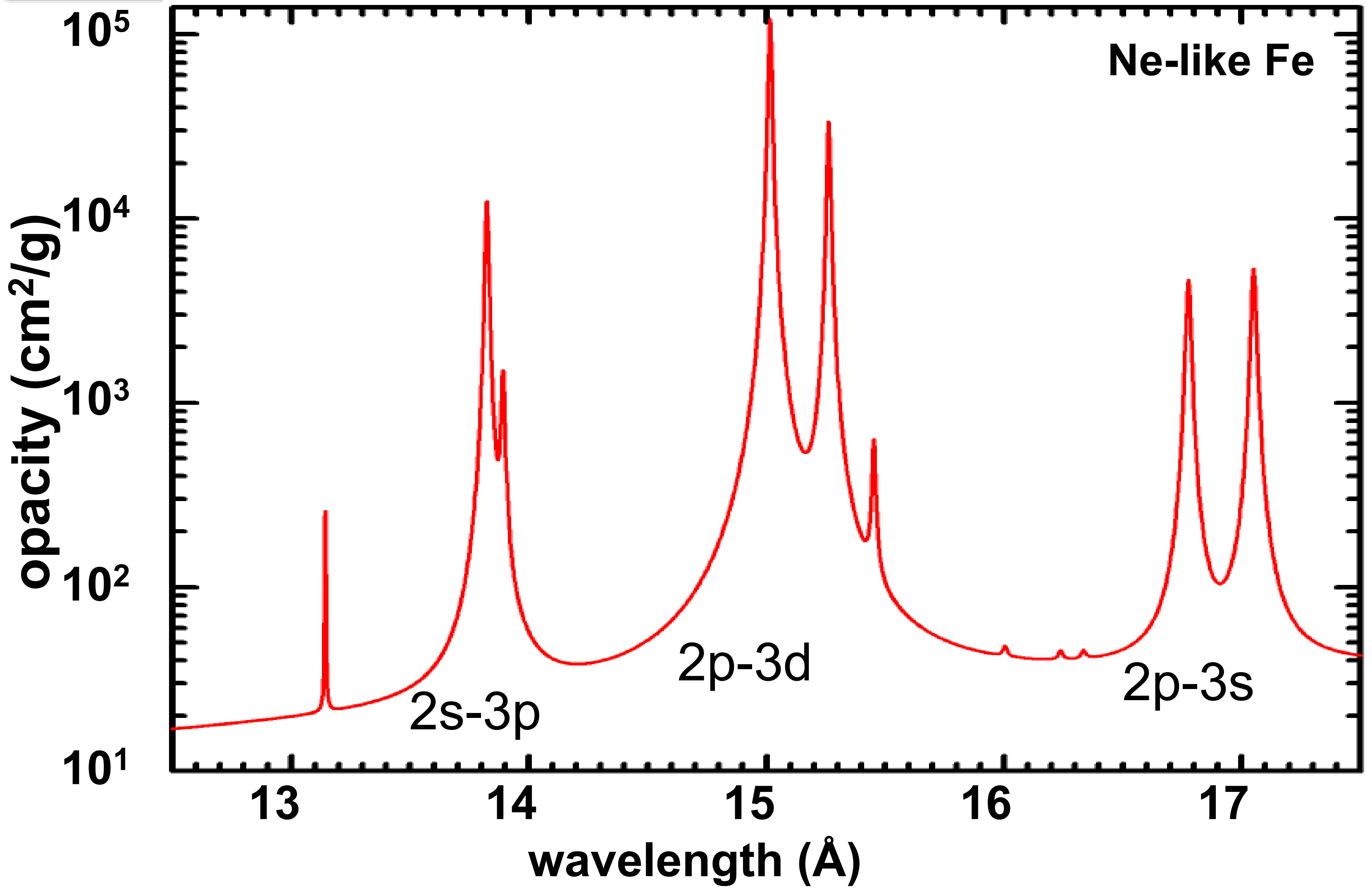
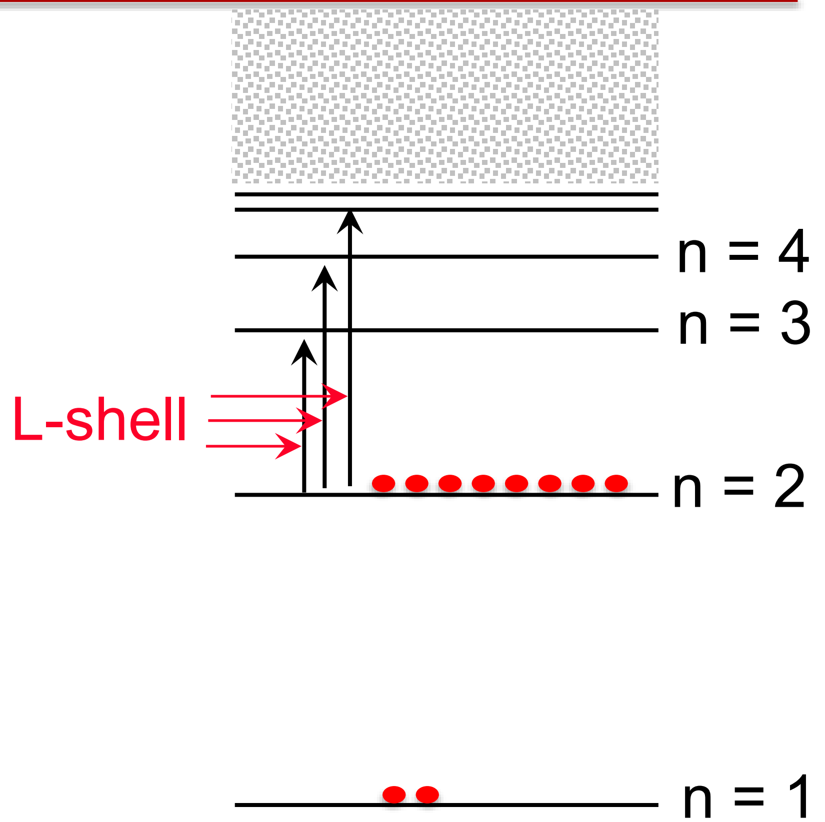
Opacity contribution from ground states are relatively simple

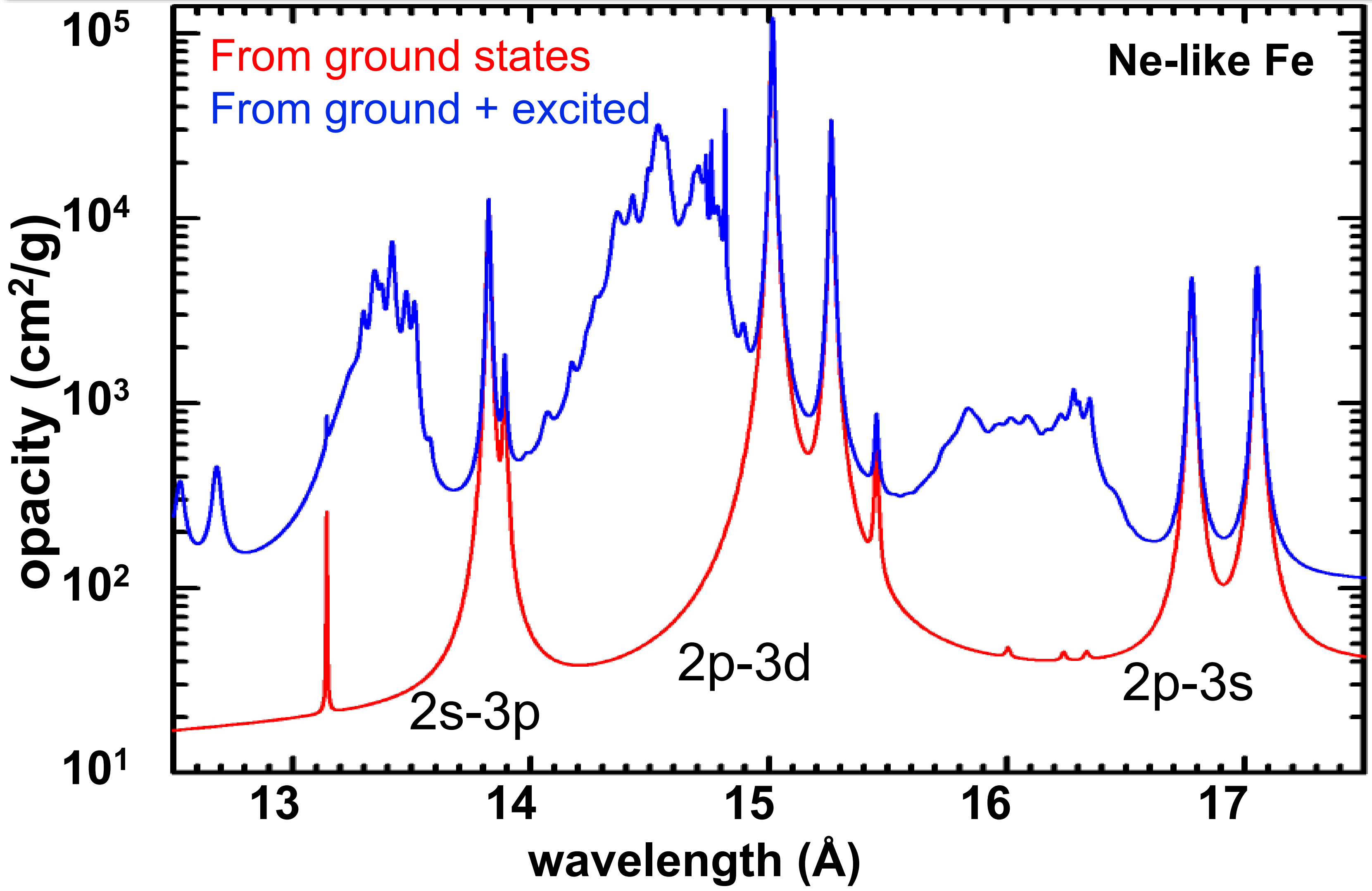


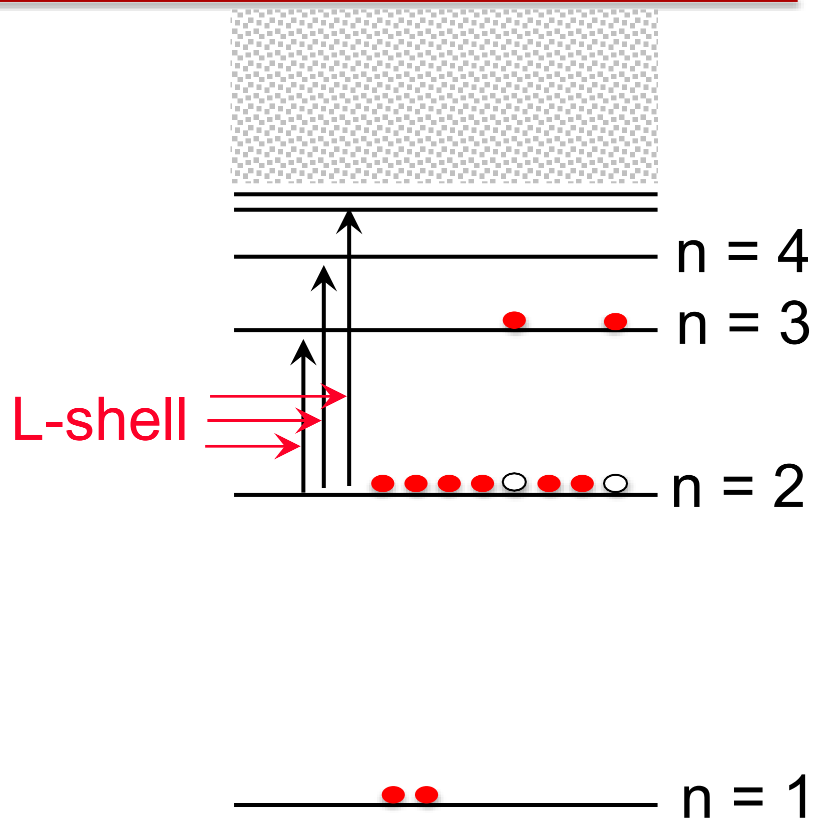


Fe^{+16} : $1s^2 2s^2 2p^6$

Ne-like

Contribution from excited states significantly adds complexity





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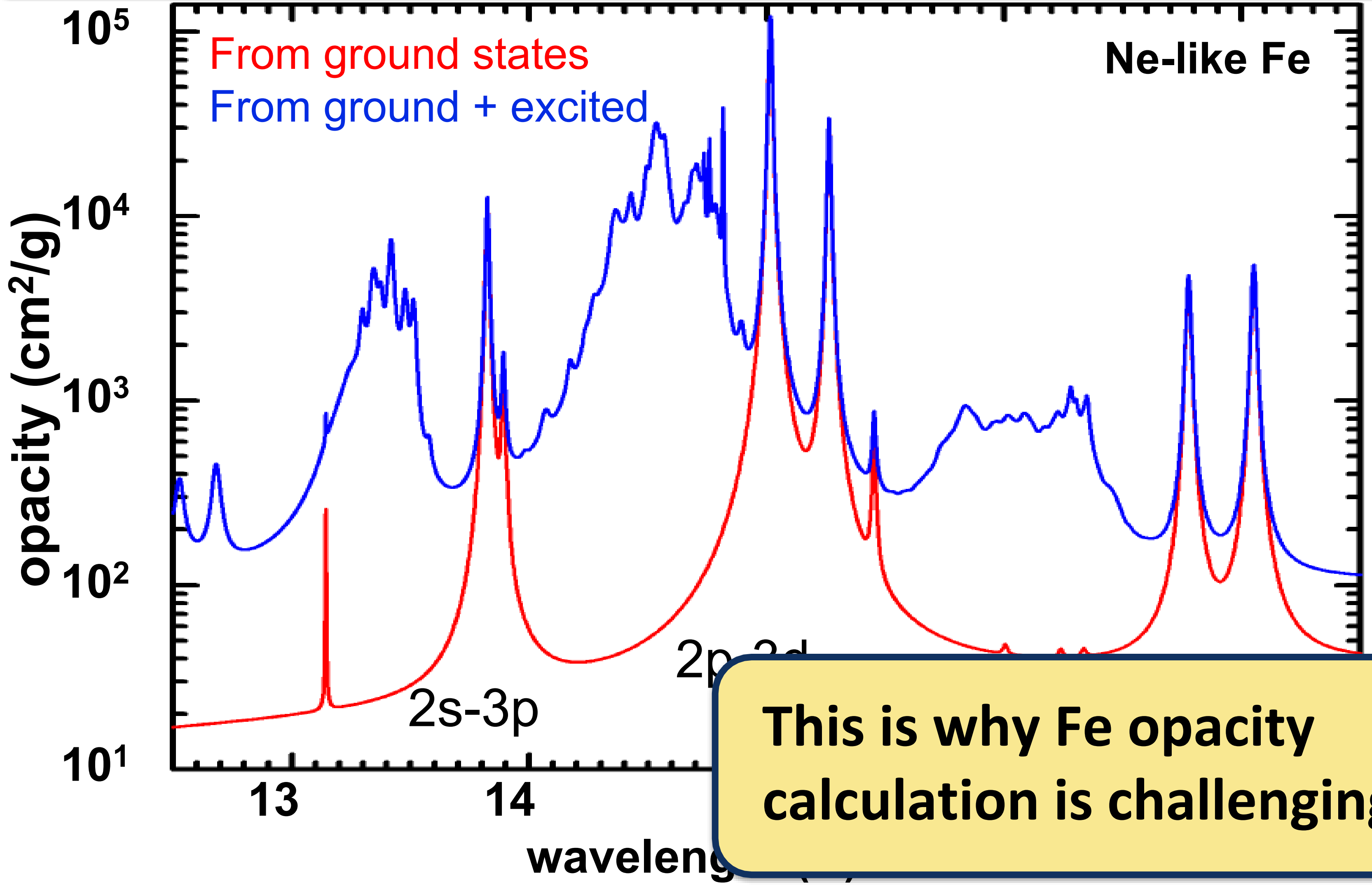
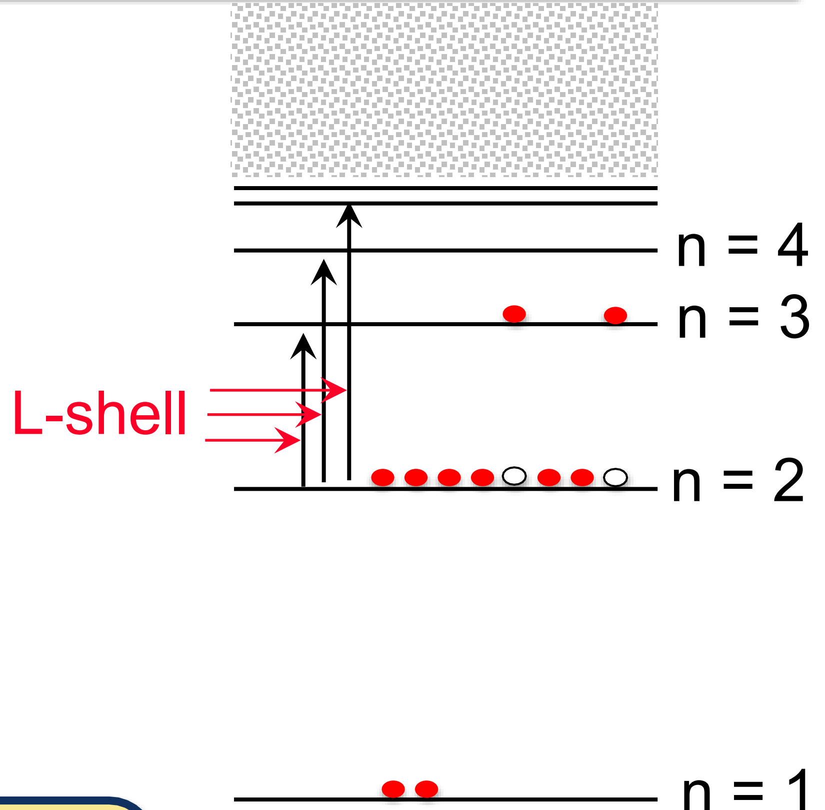




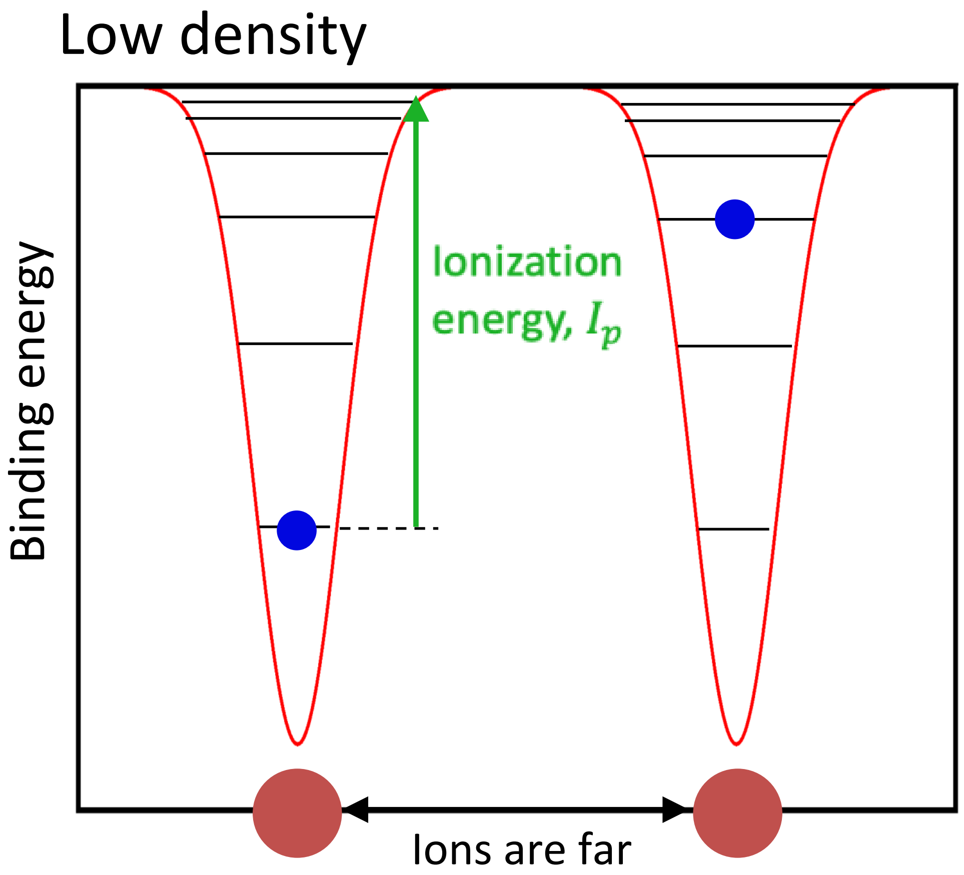
Fe^{+16} : $1s^2 2s^2 2p^6$

Ne-like

This is why Fe opacity calculation is challenging

HED theory is challenging due to: (i) too many excited states and **(ii) density effects**

High density alters the atomic structure



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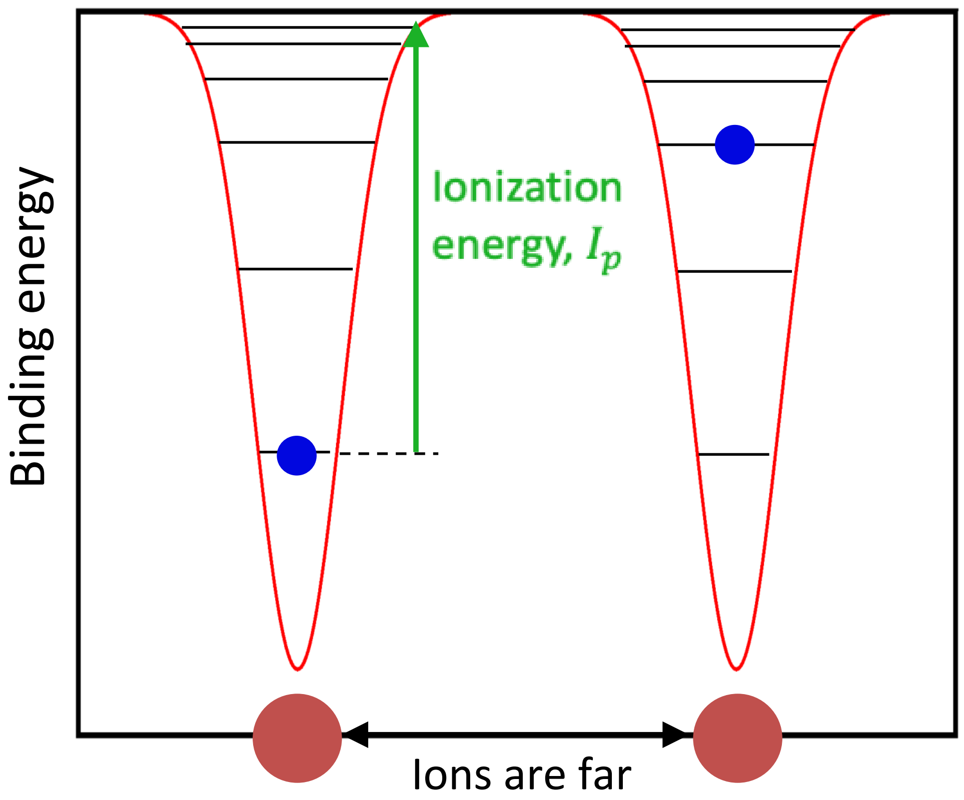
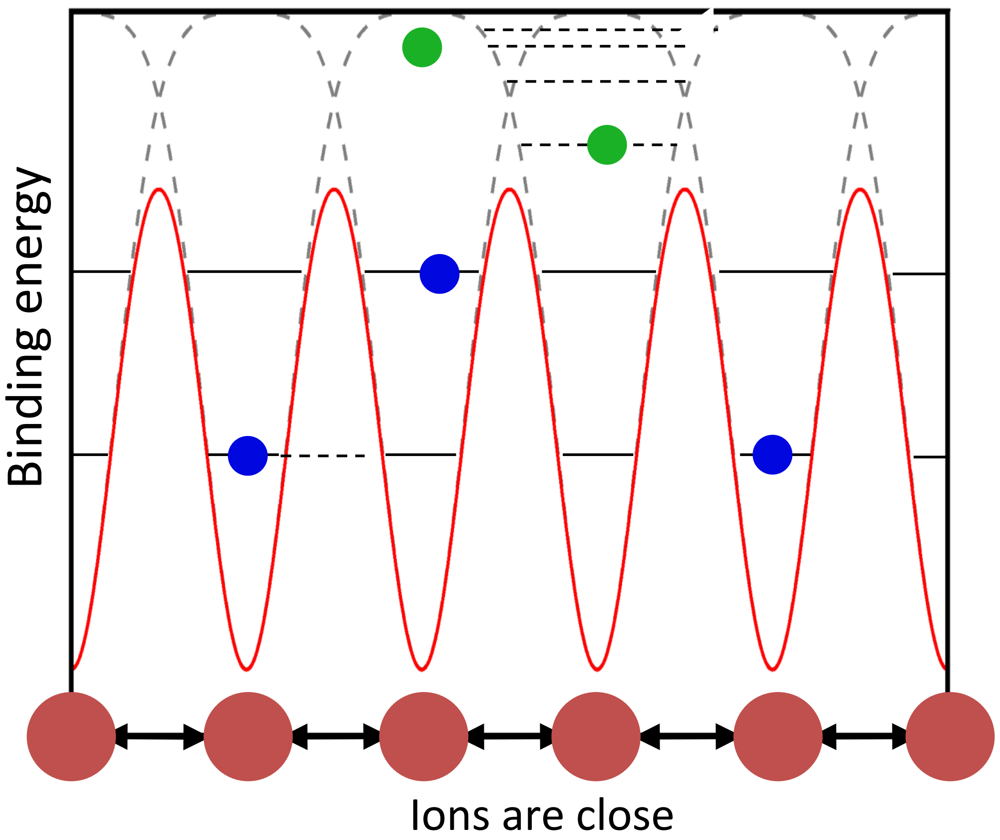
High density alters the atomic structure

Low density



High density



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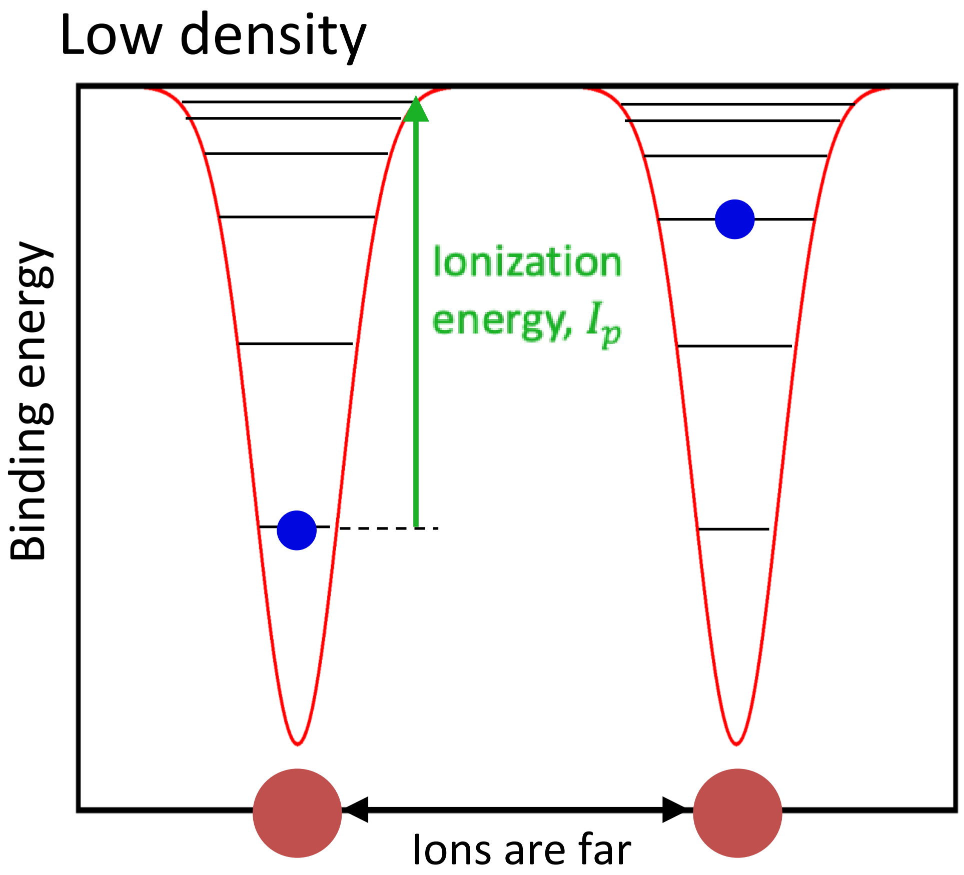

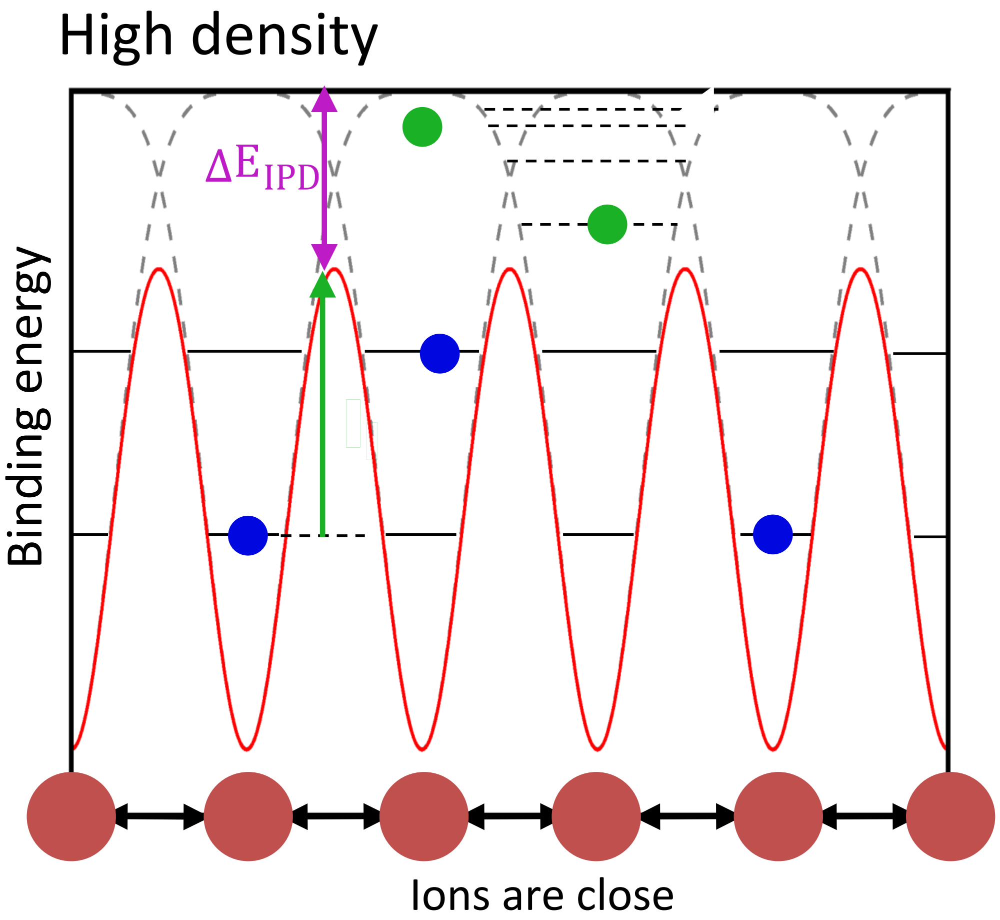

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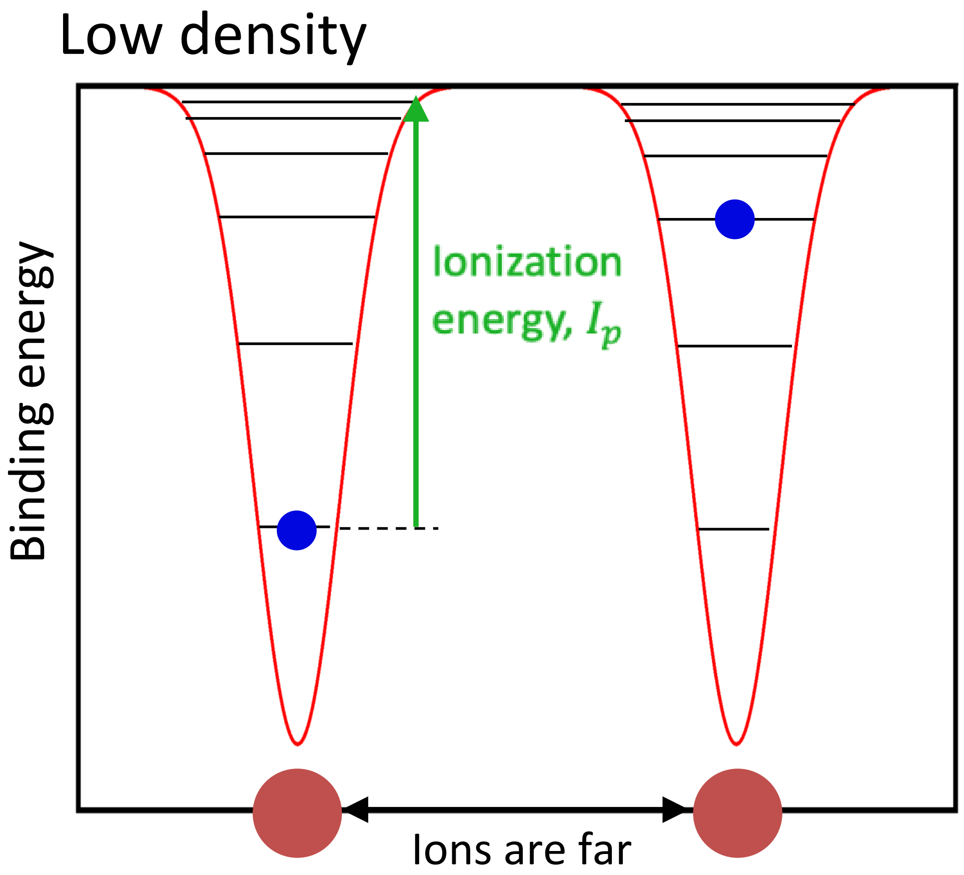
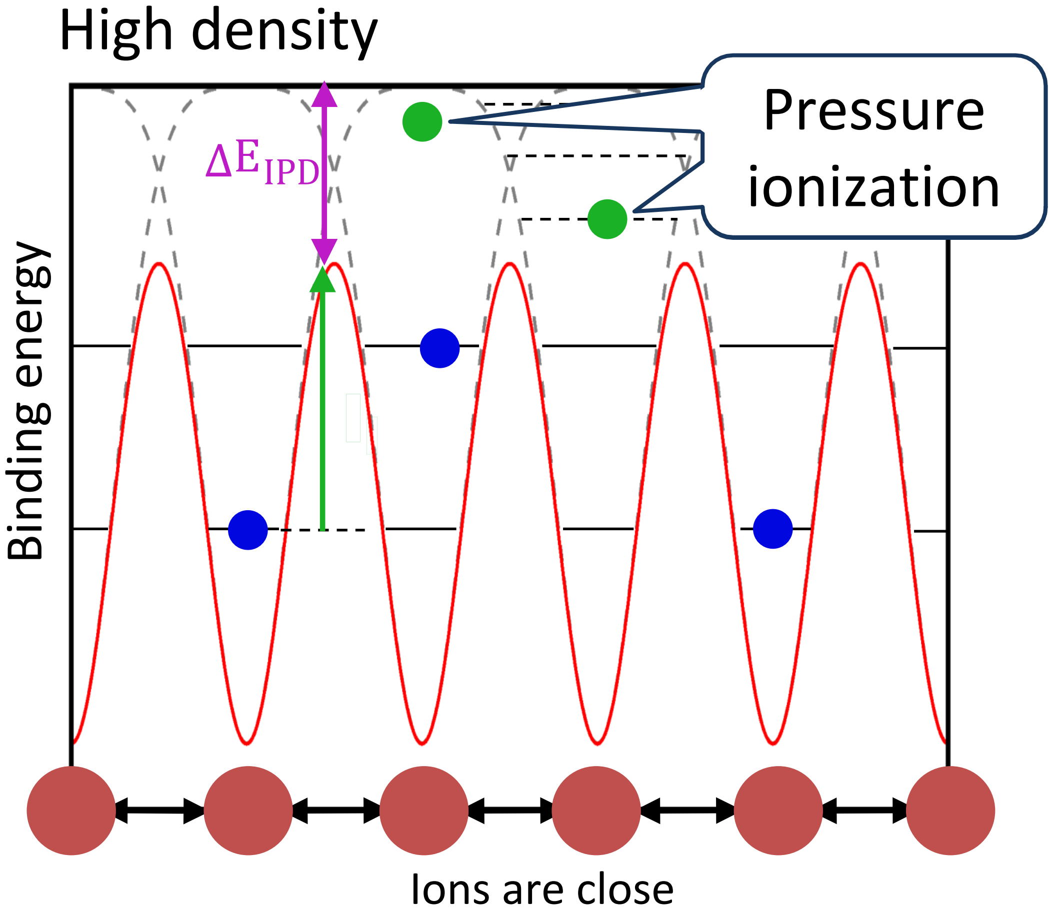


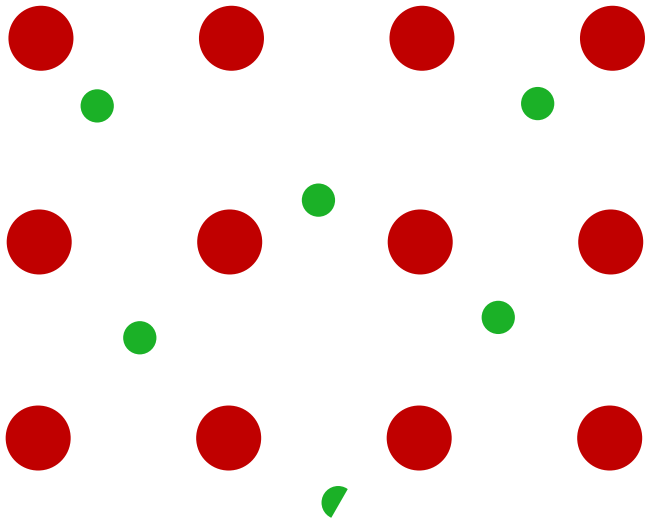


HED theory is challenging due to: (i) too many excited states and **(ii) density effects**

High temperature introduces randomness in perturbation

Low temperature

e.g., Condensed matter



HED effects complicates ionization calculation and line-broadening calculation

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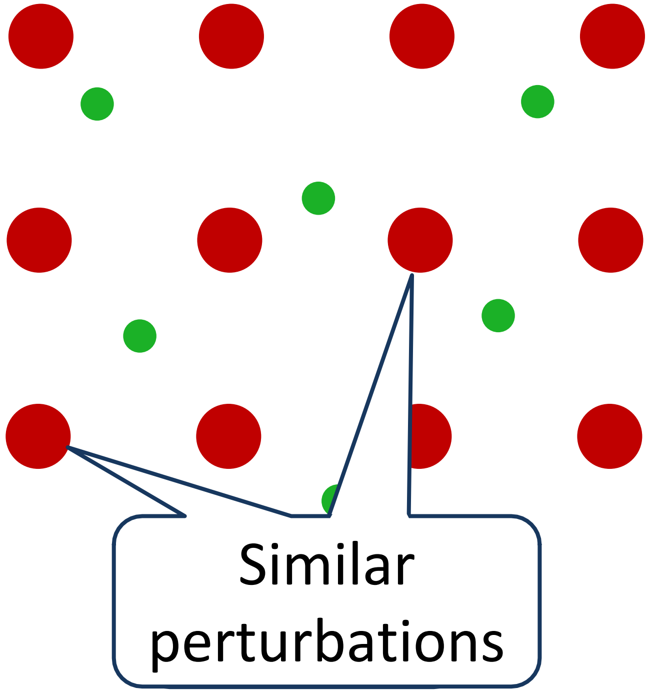

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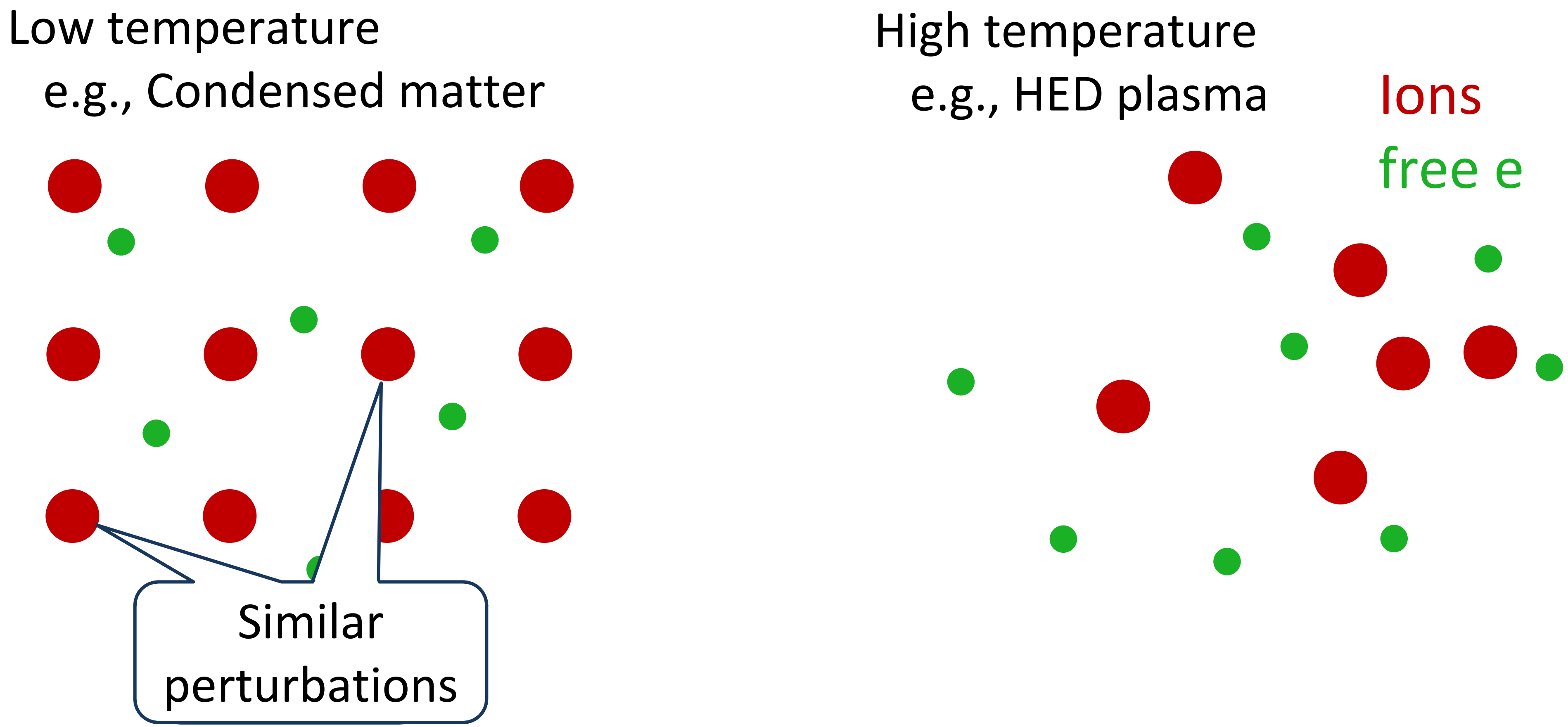


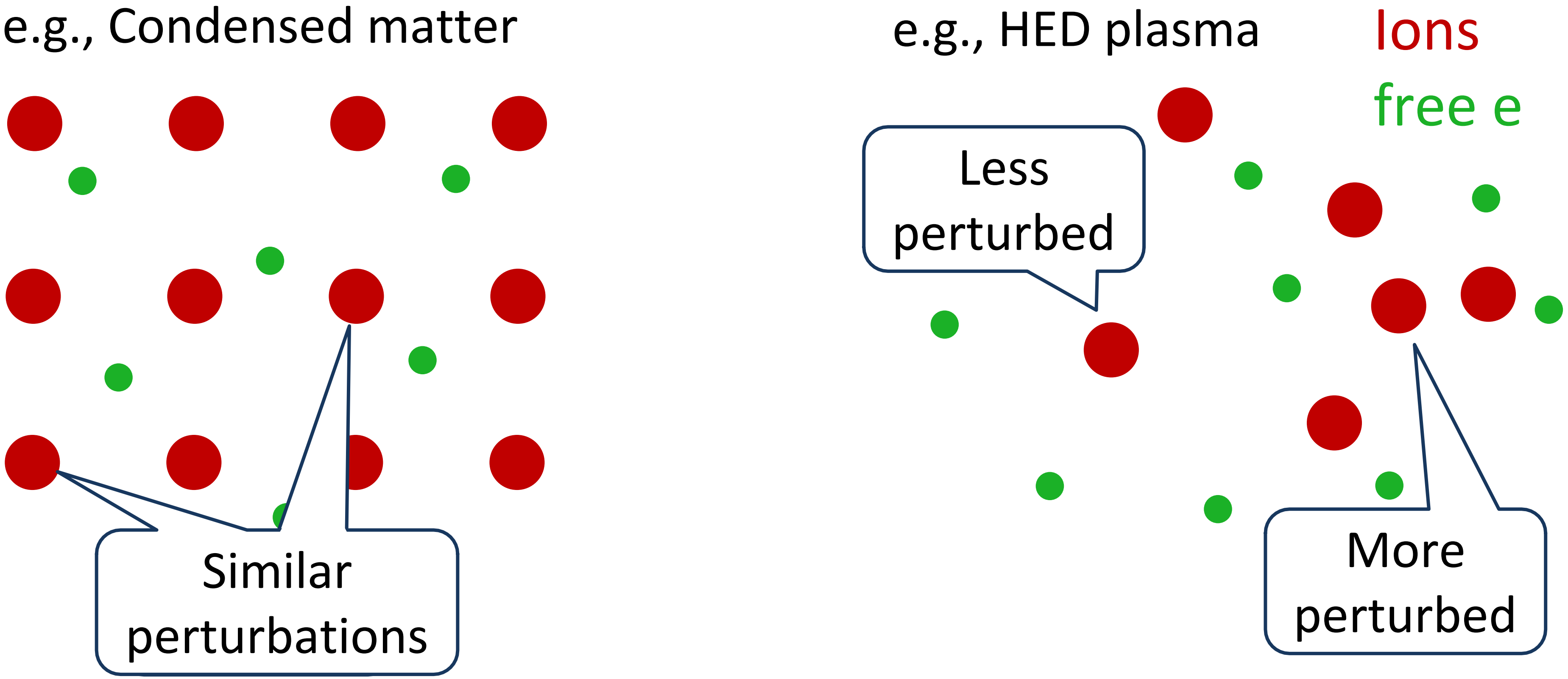
HED effects complicates ionization calculation and line-broadening calculation

HED theory is challenging due to: (i) too many excited states and **(ii) density effects**

High temperature introduces randomness in perturbation

Low temperature
e.g., Condensed matter

High temperature
e.g., HED plasma



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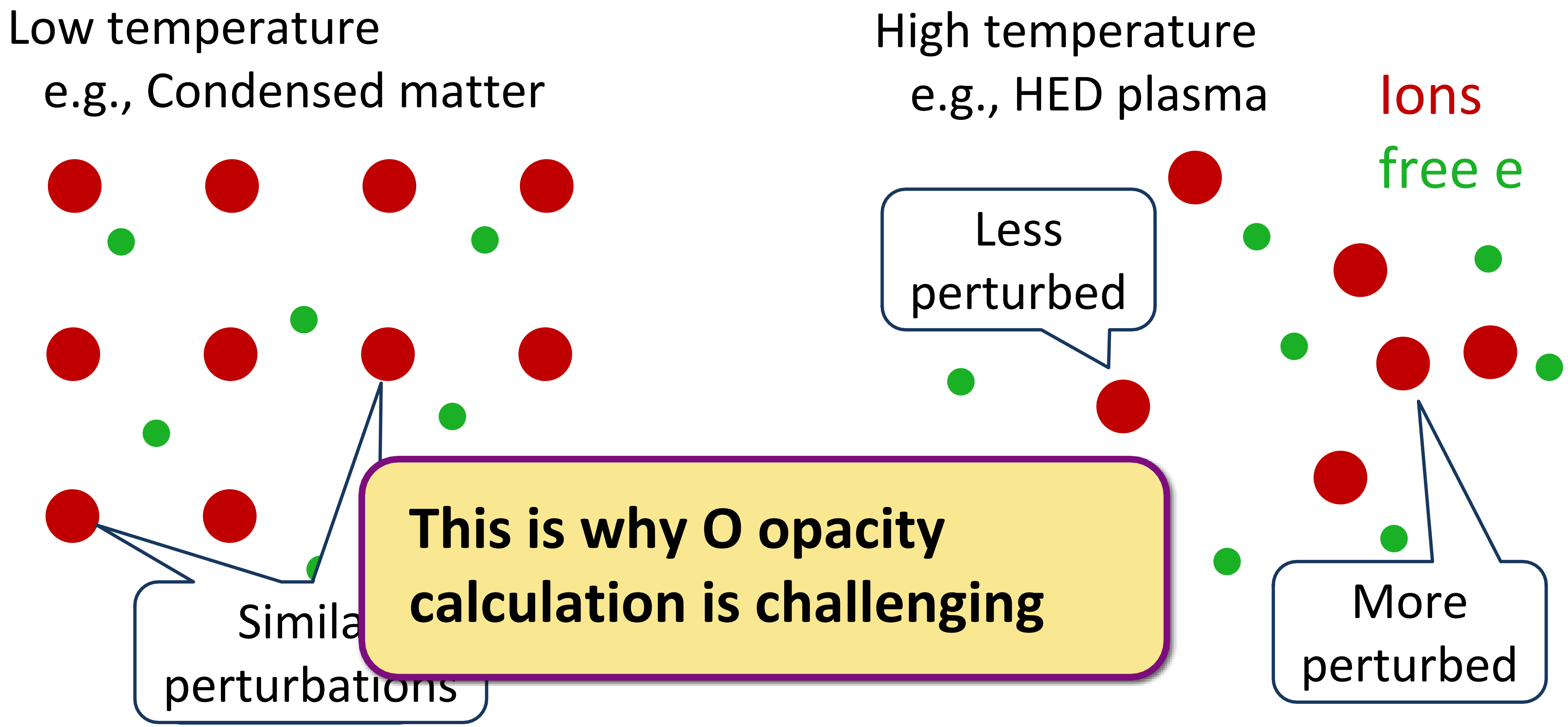
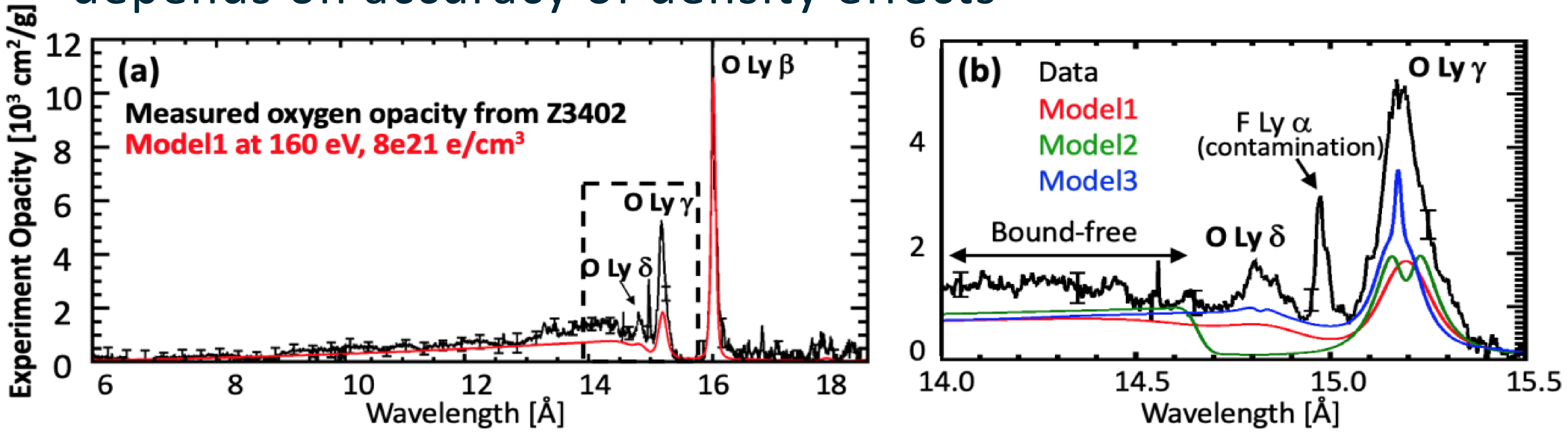
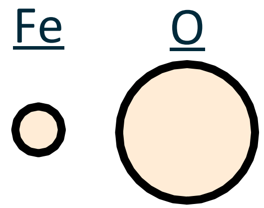


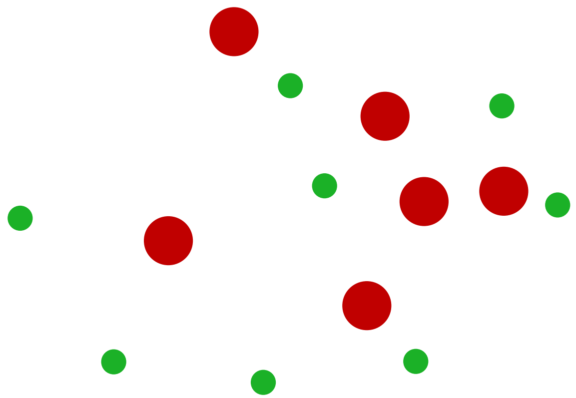
HED effects complicates ionization calculation and line-broadening calculation

Oxygen opacity at the base of the solar convection zone depends on accuracy of density effects



- **O opacity depends on density effects (IPD and line-shape)**
  - → BF accuracy depends on pressure ionization (1 bound e)
  - → Window accuracy depends on line-shape accuracy
- **Oxygen atoms are more perturbed than Fe**
  - → O is roughly 3x bigger ($R \propto 1/Z$)
  - → Higher order perturbation may be important





HED opacity is challenging in theory, experiments, and translating its implications to solar/stellar applications

Q. What are high-energy-density (HED) plasmas?

A. HED plasmas are hot, dense plasmas

Q. Experiments: Why is HED opacity experiments challenging?

A. HED experiments are hard to diagnose or hard to get opportunities

Q. Theory: Why is HED opacity theory (Fe, O) challenging?

A1. HED plasmas could have billions of bound-bound transitions (Fe)
A2. HED plasmas have complex density effects (O)

Q. Impact on astrophysics: Why is assessing the impact challenging?

A. Solar opacity depends on composition, temperature, density, and frequency in a complex way

Questions to Solar physicists → Aldo Serenelli

Uncertainty of solar Rosseland mean opacity is complex due to multiple sources of uncertainty

- Single-model uncertainty: How can we propagate uncertainties in different aspect of theory to final opacity calculation?

- Model-model inconsistency: How can we incorporate the differences between opacity models into solar Rosseland-mean opacity uncertainty?

- Model-data discrepancy: How can we propagate model inaccuracy inferred by measurements to solar Rosseland-mean opacity (RMO) uncertainty?
  - Model-data discrepancy in frequency-resolved opacity can reveal model weaknesses
  - Experiments cannot test opacities of all elements at all conditions
  - Propagating the measured model-data discrepancy to solar RMO uncertainty at all radii seems infeasible

We use experiments to test opacity physics and use validated opacity models to provide accurate solar models

HED opacity is challenging in theory, experiments, and translating its implications to solar/stellar applications

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Questions to Solar physicists → Aldo Serenelli

Various questions that we asked to Aldo Serenelli

Q1. What are some astrophysical applications of interest to you that rely heavily on opacity accuracy?

- Elements, conditions, and spectral ranges?
- How does opacity inaccuracy affect your conclusions?

Q2. What are a few of the most common opacity-dependent methods to infer ages of stars, galaxies, or the universe? What role does opacity play in these methods?

Q3. What opacity models (e.g., OP, OPAL) are widely used by stellar/solar physicists?

Q4. How complete are solar/stellar models (e.g. tachocline, convection behavior, rotation, 3D effects)? How does opacity or variance in opacity affect different aspects of a model?

More questions on solar abundance problem

Two latest solar-abundance analyses disagree with each other:

- Asplund21: $Z/X = 0.0187$
- Magg22: $Z/X = 0.0225$ (≈ GS98 before the revision)

Q1. Why do Magg22 believes in their results over Asplund21?

Q2. Which one do astrophysicists believe and why?