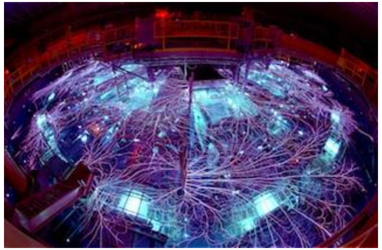

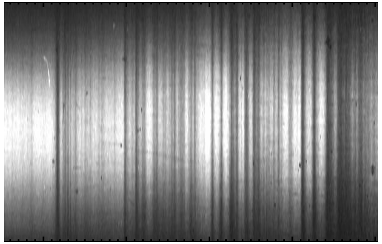

Systematic measurements of opacity dependence on temperature, density, and atomic number at stellar interior conditions

Jim Bailey

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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

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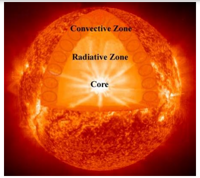
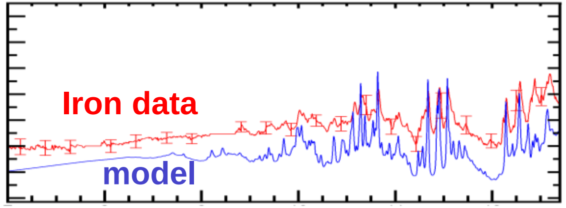
Z opacity experiments refine our understanding of photon absorption in high energy density stellar matter.

- **Solar interior predictions don't match helioseismology**
  → **Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?**

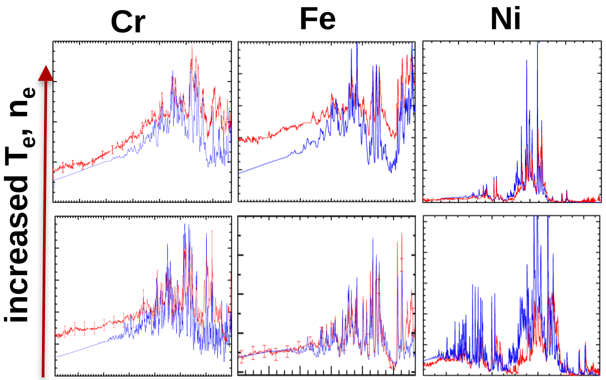


- **Z experiments have measured iron plasma opacity at near-solar-interior conditions**



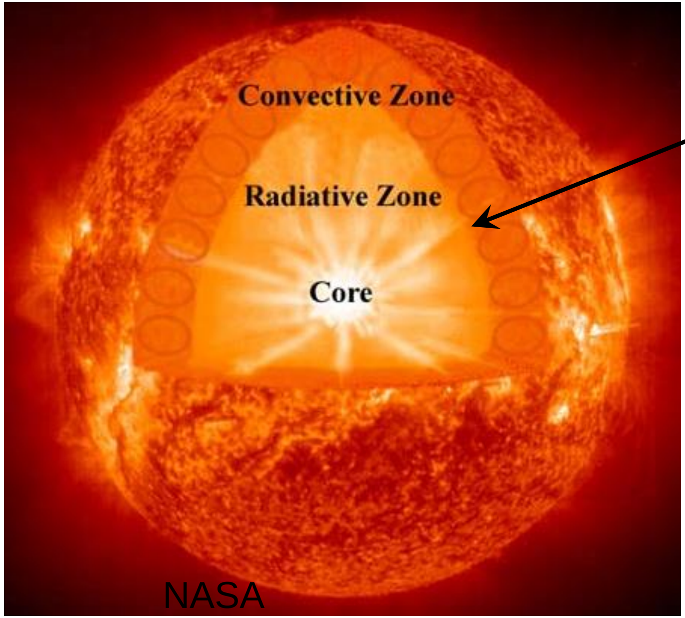
- **The measured high temperature/density iron opacity is higher than predictions**
  → **helps resolve the solar problem, but we need to understand what causes the discrepancy**

- **Systematic measurements of opacity dependence on temperature, density, and atomic number will test hypotheses for the model-data discrepancy**



Bailey *et al.*, *Nature* 2015

Models for solar interior structure disagree with helioseismology observations.



Convection-Zone (CZ) Boundary

Models are off by 10-30 σ

Models depend on:

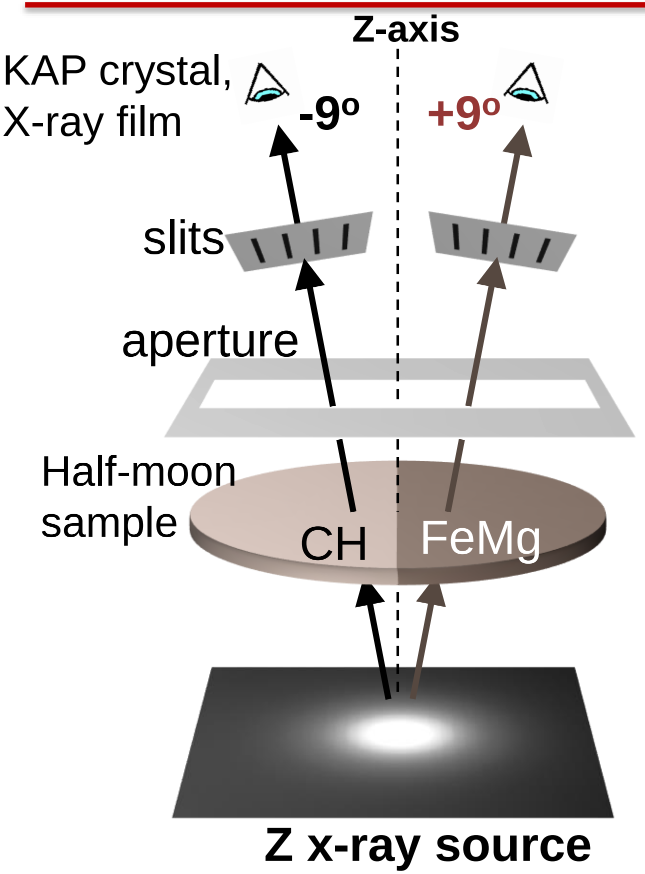
- **Composition (revised in 2000*)**
- **EOS as a function of radius**
- **The solar matter *opacity***
- **Nuclear cross sections**

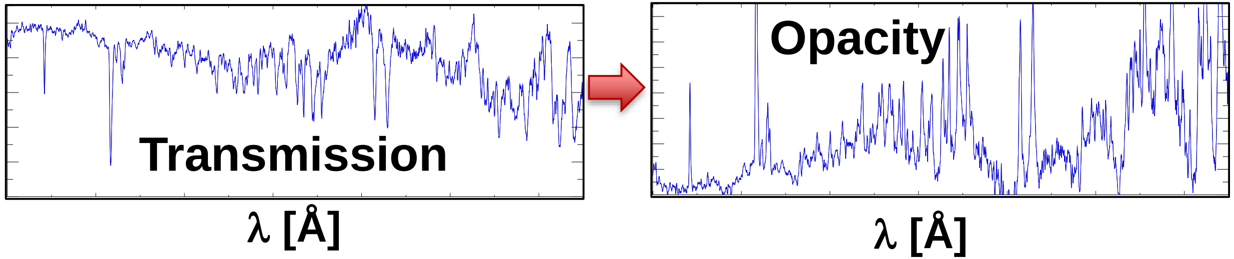
Question: Is opacity uncertainty the cause of the disagreement?

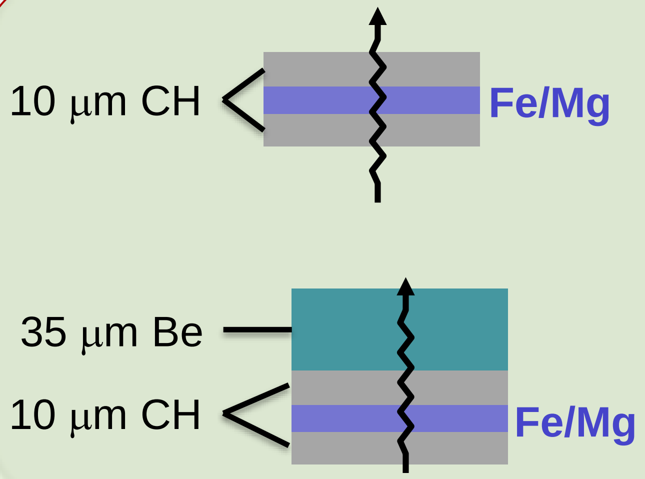
*M. Asplund *et al*, Annu. Rev. Astro. Astrophys. 43, 481 (2005).

Serenelli, *ApJ* 2009

Z experiments provide opacity measurements at multiple conditions







"Anchor 1" sample

$T_e \sim 160$ eV

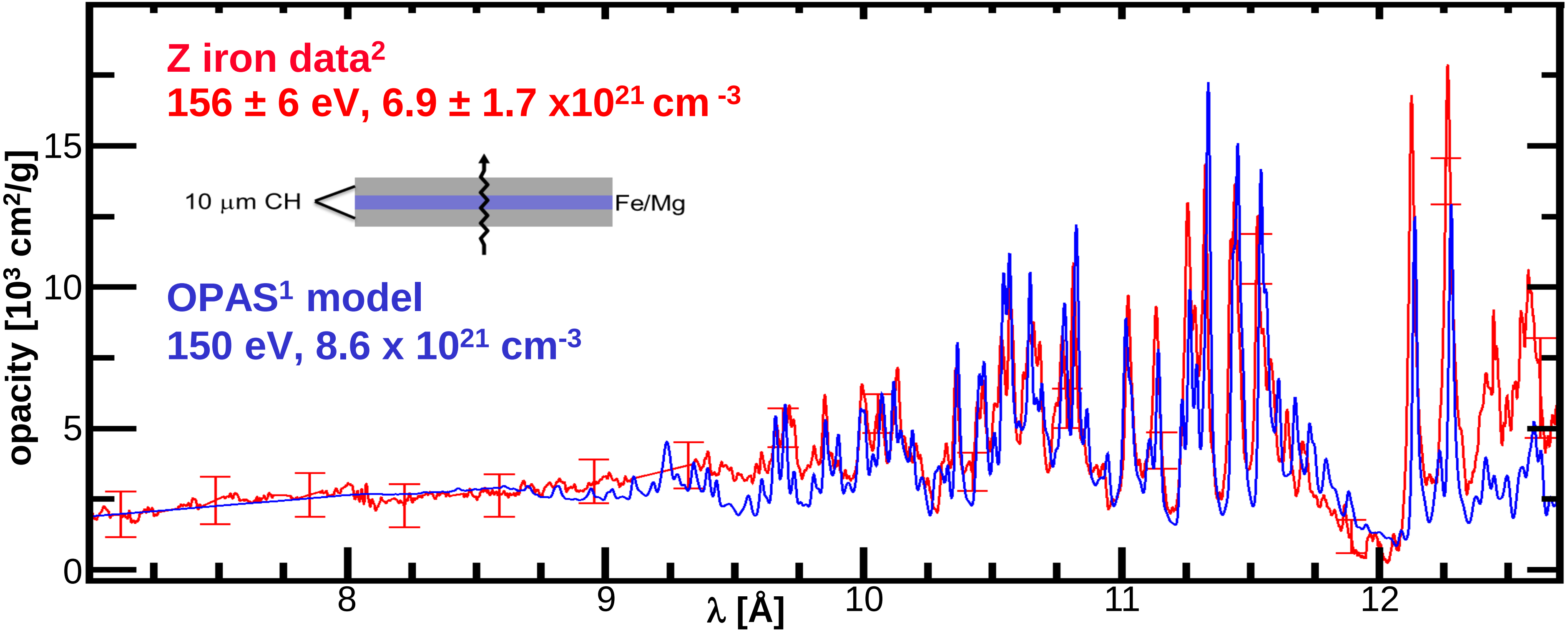
$n_e \sim 7 \times 10^{21}$ cm^{-3}

"Anchor 2" sample

$T_e \sim 185$ eV

$n_e \sim 3 \times 10^{22}$ cm^{-3}

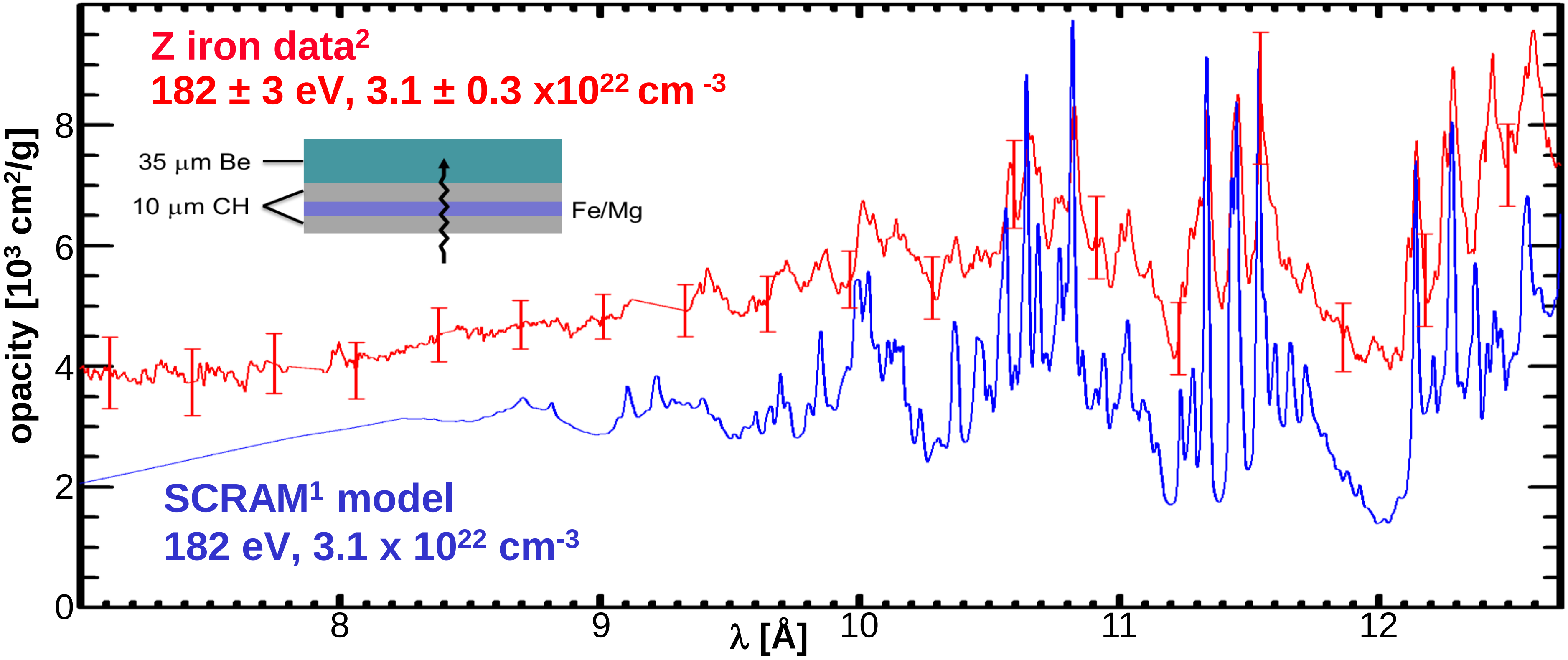
Modern best-effort models agree very well with the Z iron data at Anchor 1 conditions



[1]Blancard *et al.*, Astrophys. J. (2012)

[2]Bailey *et al.*, PRL (2007)

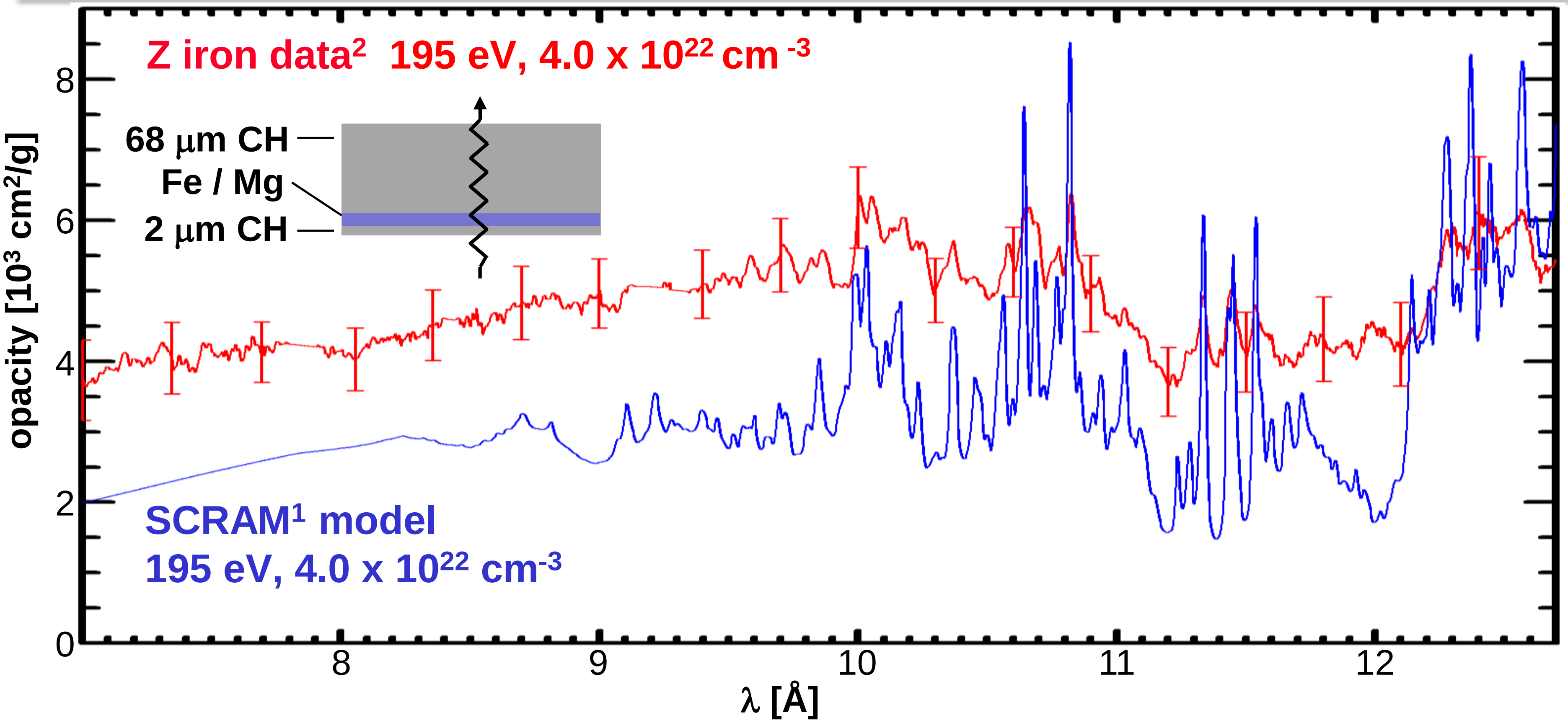
Modern best-effort models disagree with the Z iron data at Anchor 2 conditions



[1]Hansen *et al.*, HEDP (2007)

[2]Bailey *et al.*, Nature (2015)

Modern best-effort models also disagree with the Z iron data at the highest temperature/density conditions



[1]Hansen *et al.*, HEDP (2007)

[2]Bailey *et al.*, Nature (2015)

A solar mixture plasma using Z iron data has ~ 7% higher Rosseland mean opacity than using OP iron

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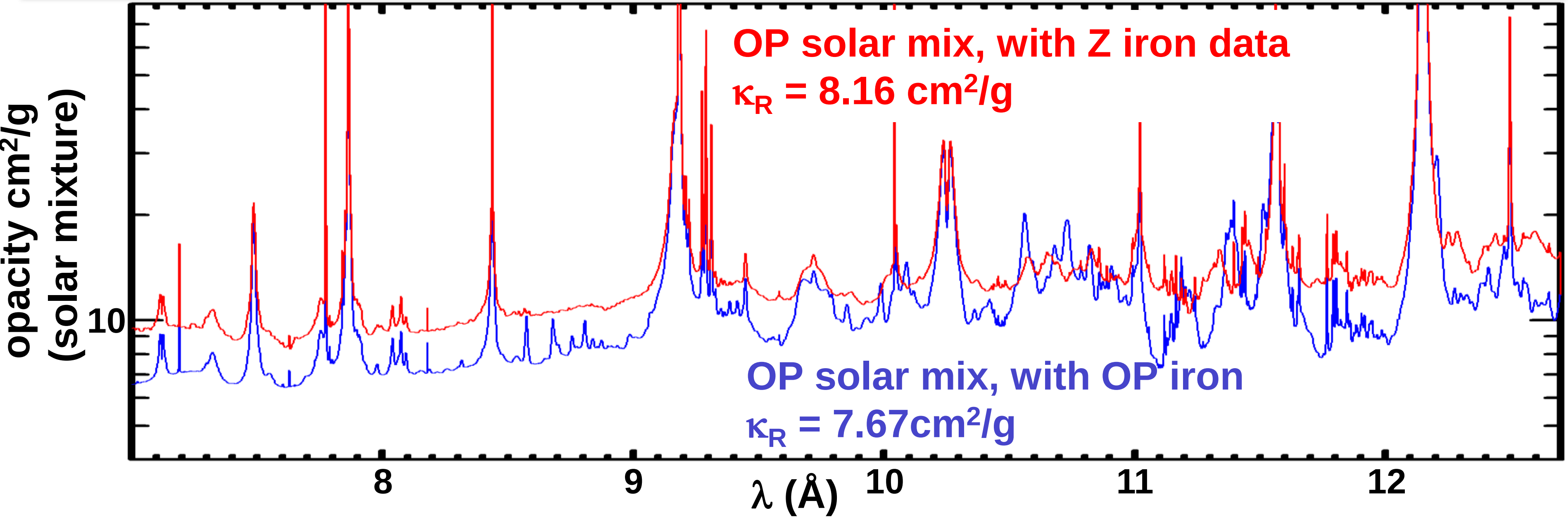

- A 7% Rosseland increase partially resolves the solar problem, but the measured iron opacity by itself cannot account for the entire discrepancy
- Other elements and regions deeper in the sun could contribute

193 eV, 3.3 e22 e/cc Asplund09 solar abundances   Badnell *et al.*, MNRAS 2005

The higher-than-predicted short-λ continuum and window filling have comparable impact on solar opacity

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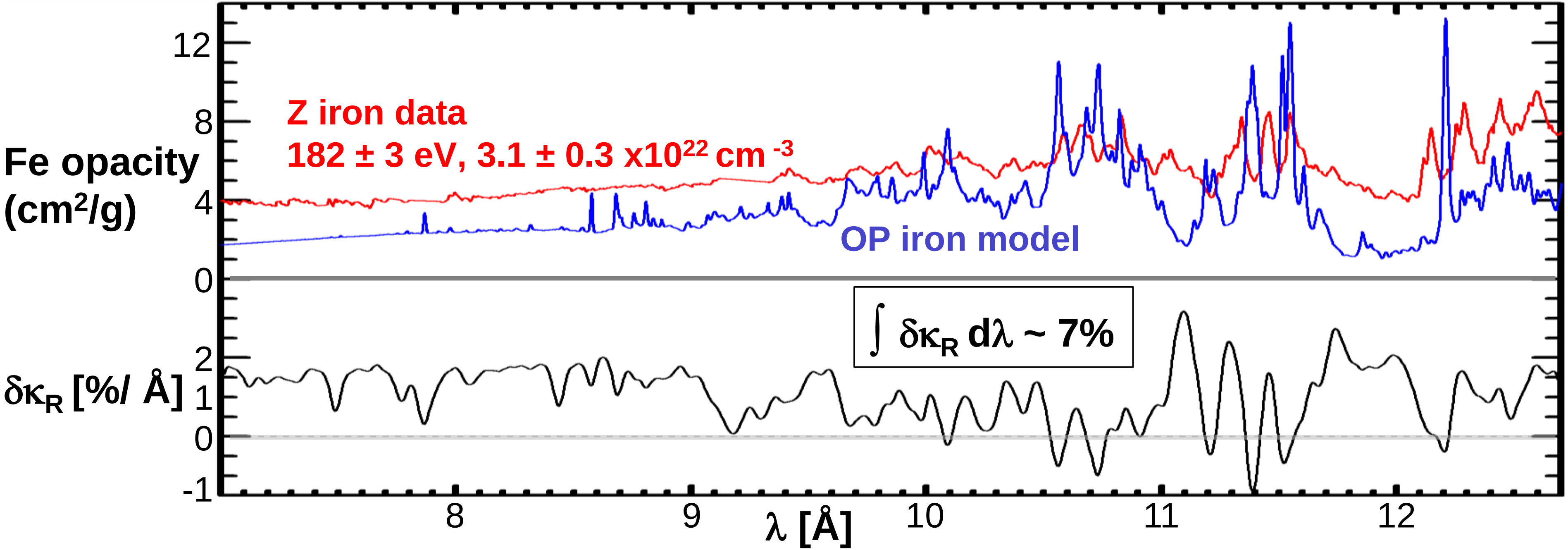
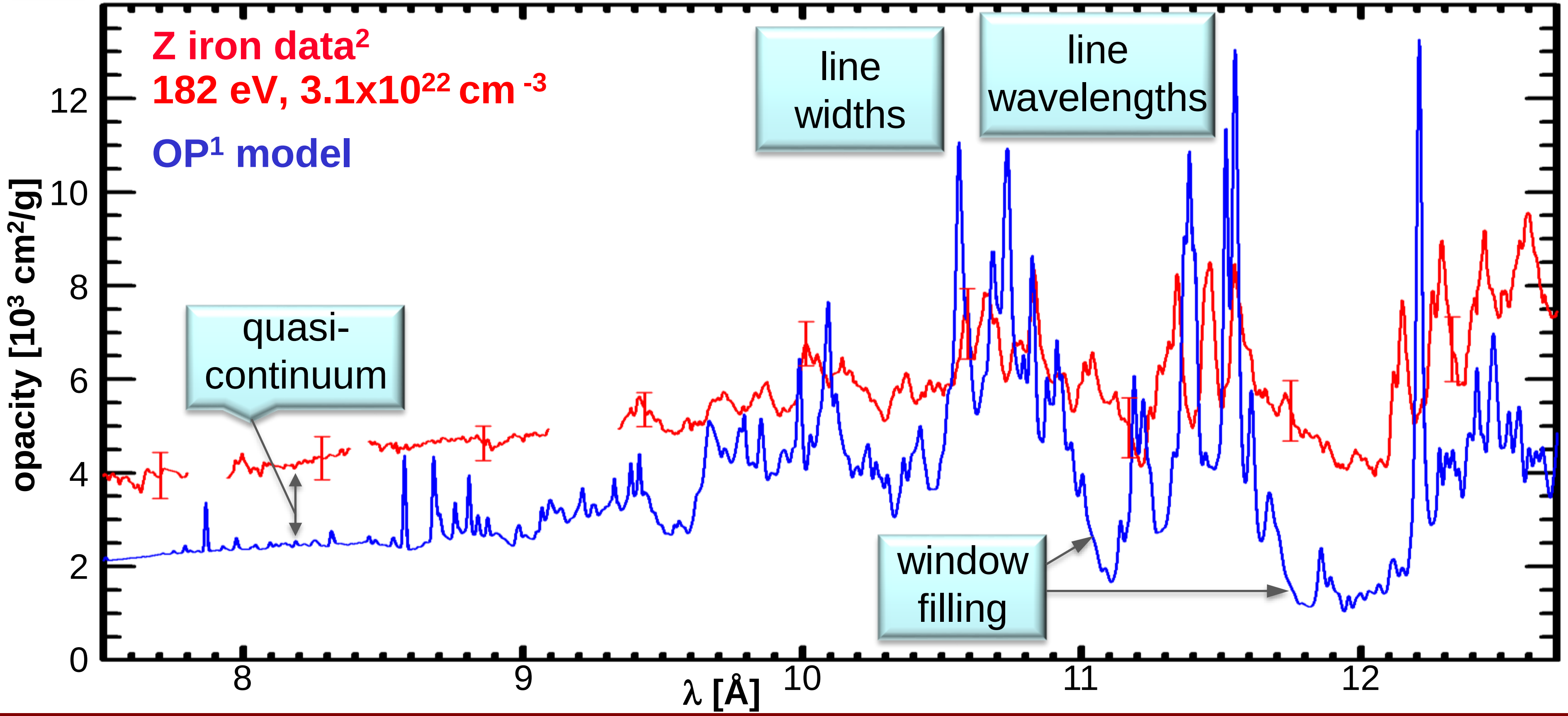


- The bottom panel is % change in solar mixture Rosseland mean opacity vs. λ
- Helps identify which model-data discrepancies most affect the solar problem

We have identified four categories of model-data differences



Z opacity measurements help resolve the solar problem, but we must learn what causes the model data discrepancy

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7 questions we should answer for stellar opacity understanding:

1. Is the experiment systematically biased despite all our effort?
2. How do L-shell vacancies influence opacity?
3. How do excited states influence opacity?
4. Is there a re-distribution of photon absorption from long λ to short λ?
5. Is Stark broadening accurately accounted for in opacity models?
6. Are there BB transitions not presently accounted for in opacity models?
7. Is multi photon absorption larger than previously believed for L-shell ions?

Modern best-effort models agree very well with the Z iron data at Anchor 1, but disagree at Anchor 2 conditions

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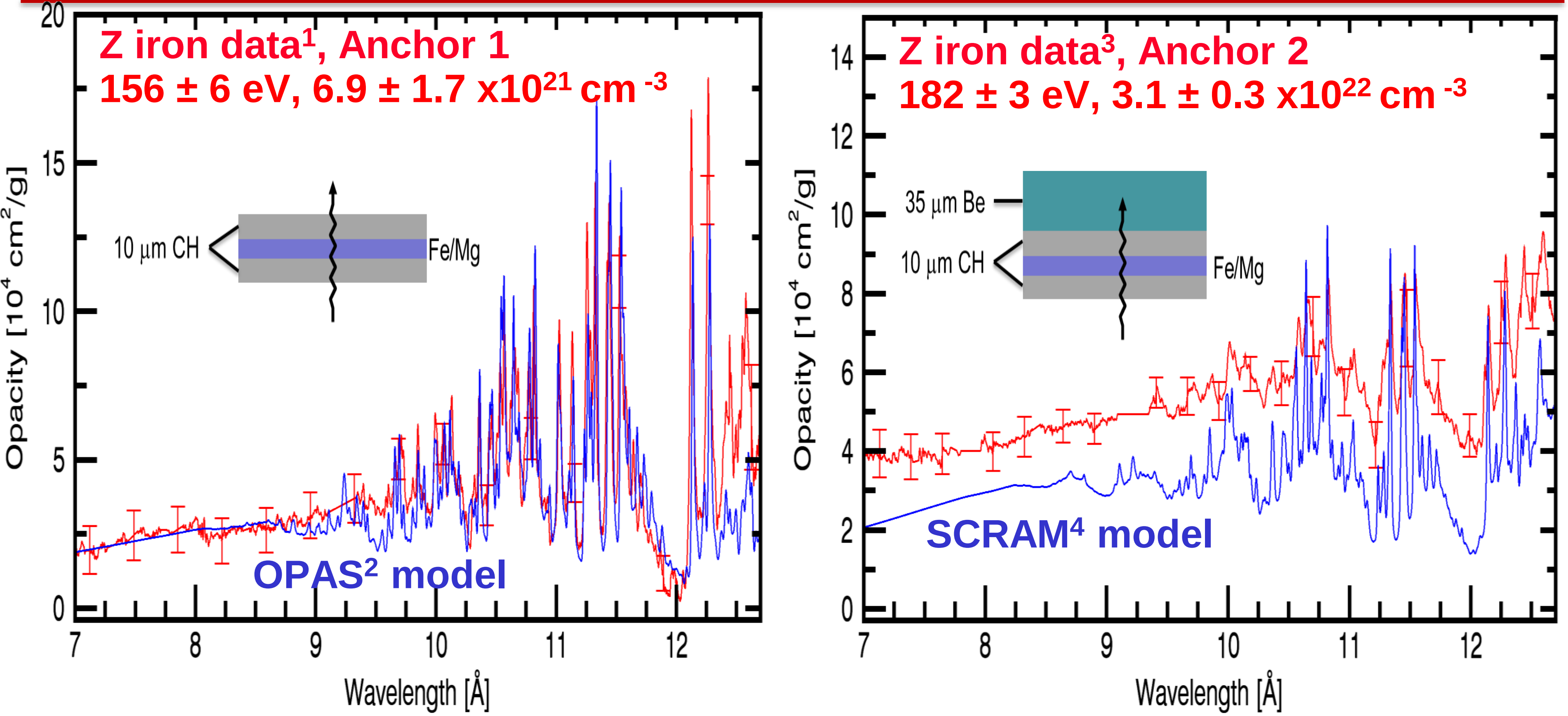
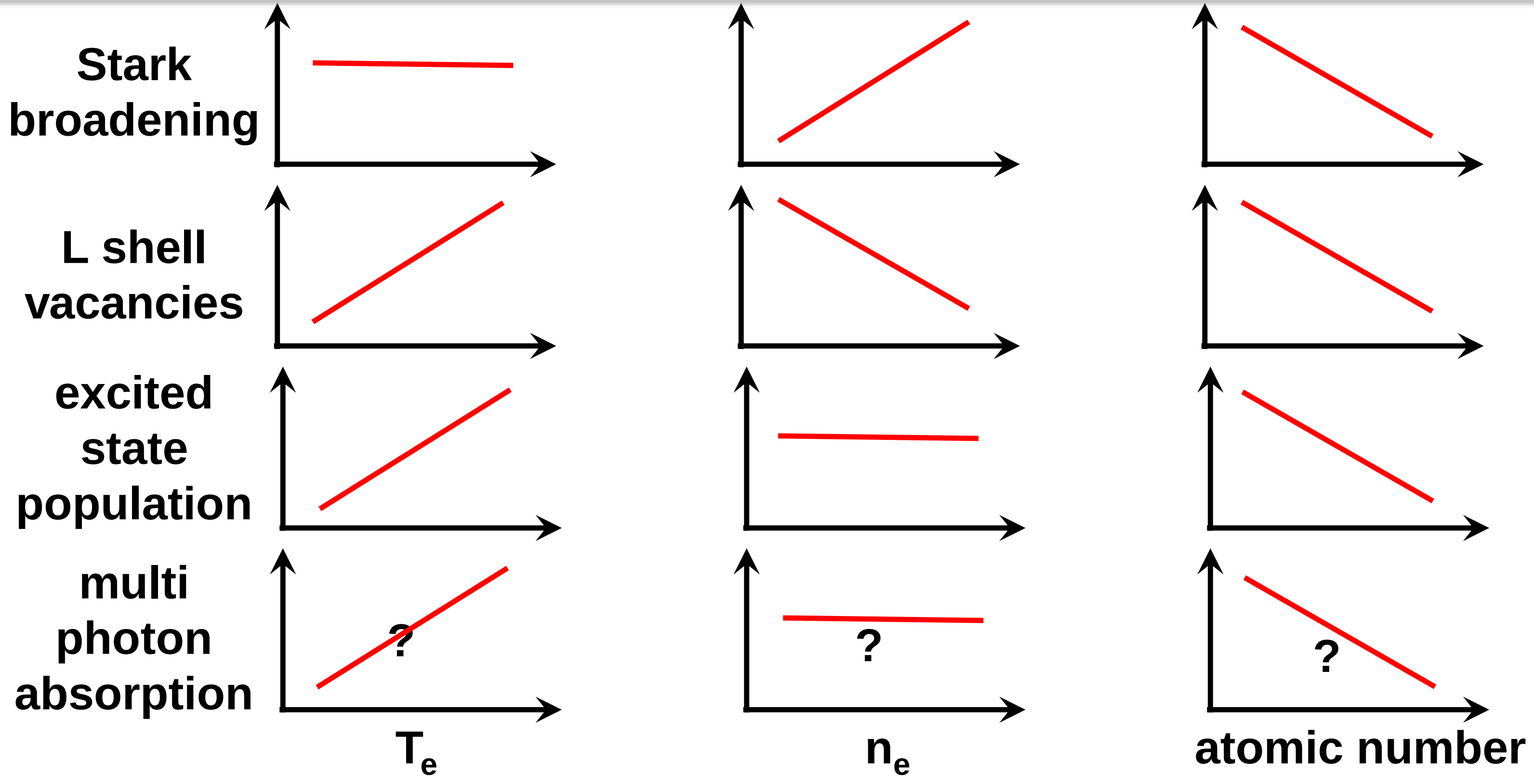
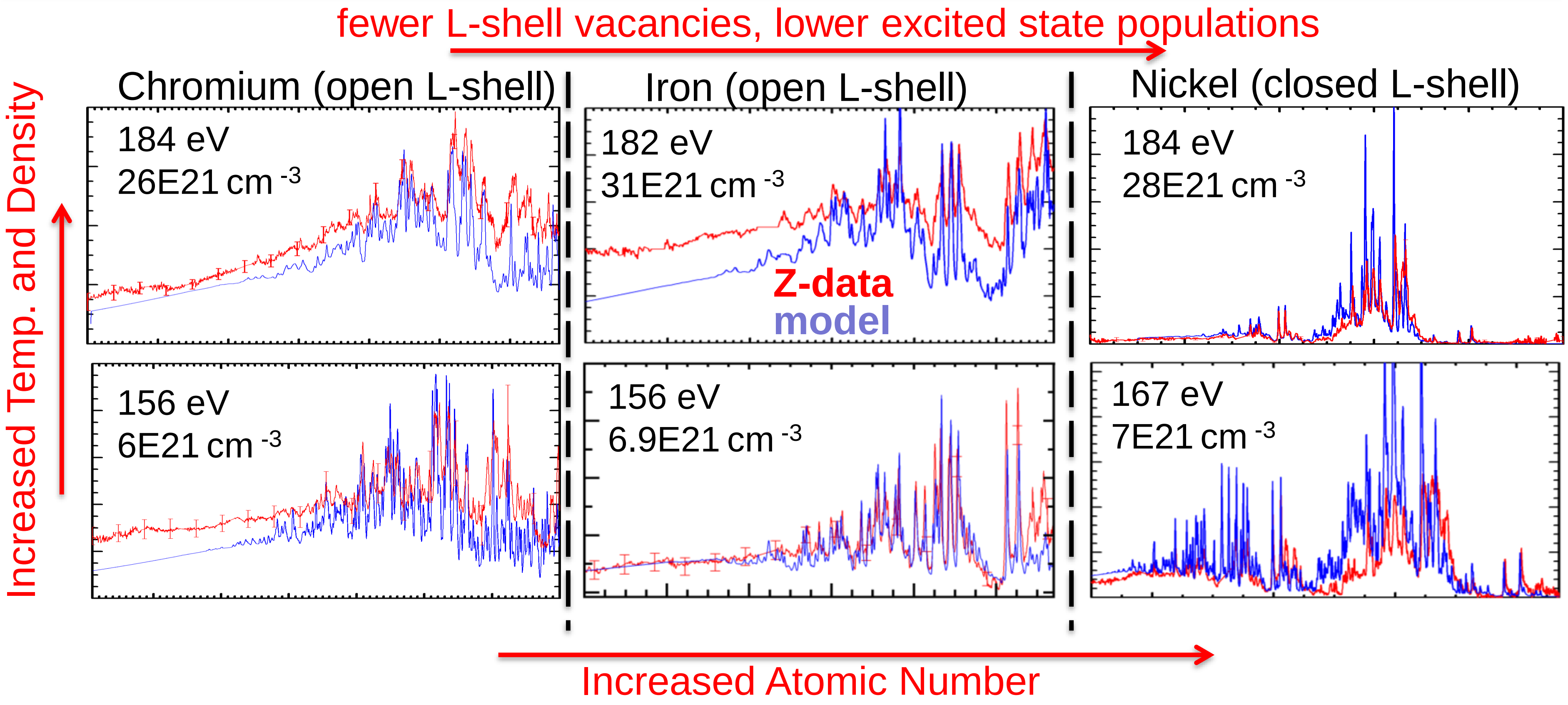


[1]Bailey *et al.*, PRL (2007); [2]Blancard *et al.*, ApJ (2012); [3]Bailey et al., *Nature* 2015; [4]Hansen et al., HEDP (2007)

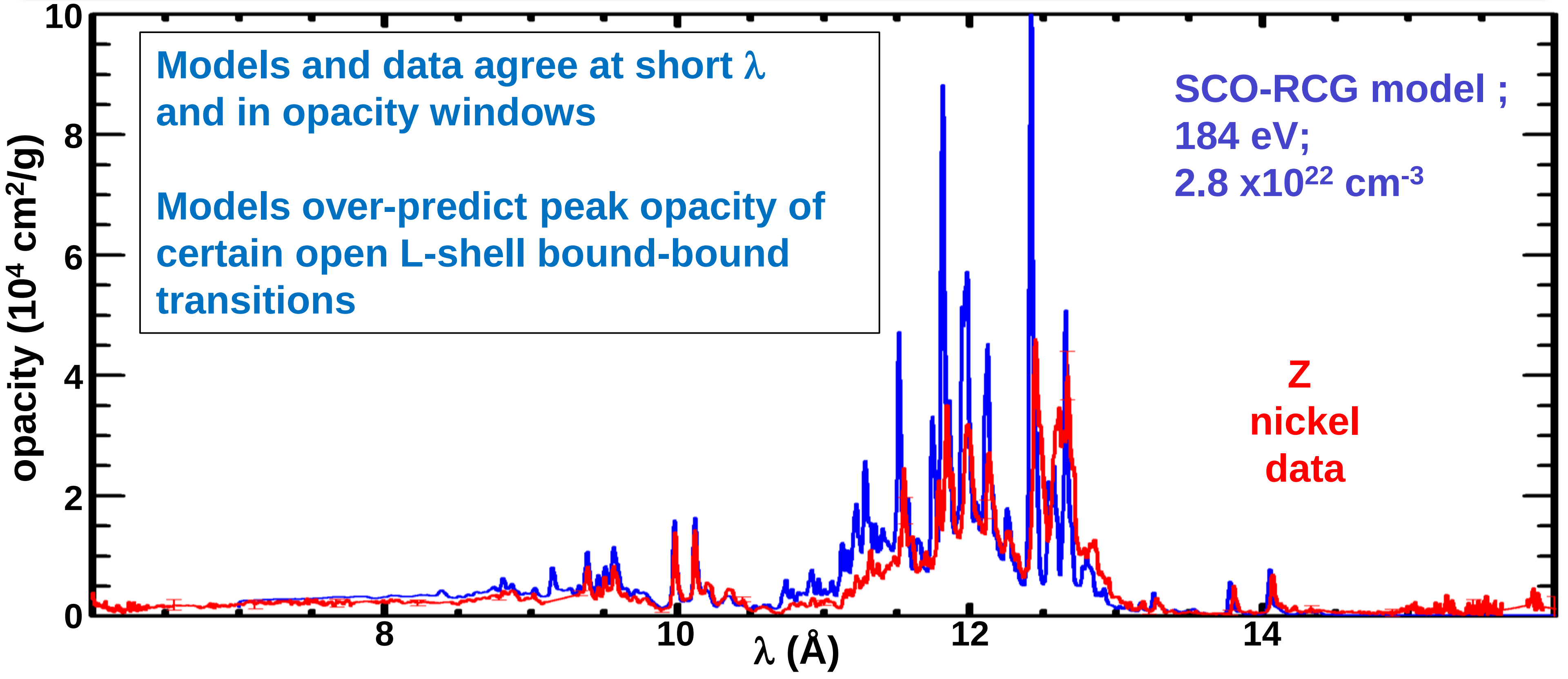
Measurements with varying T_e, n_e, and element help isolate and test understanding of relevant physical processes



Work is in progress to perform the first systematic opacity measurements with varying T_e, n_e, and atomic number

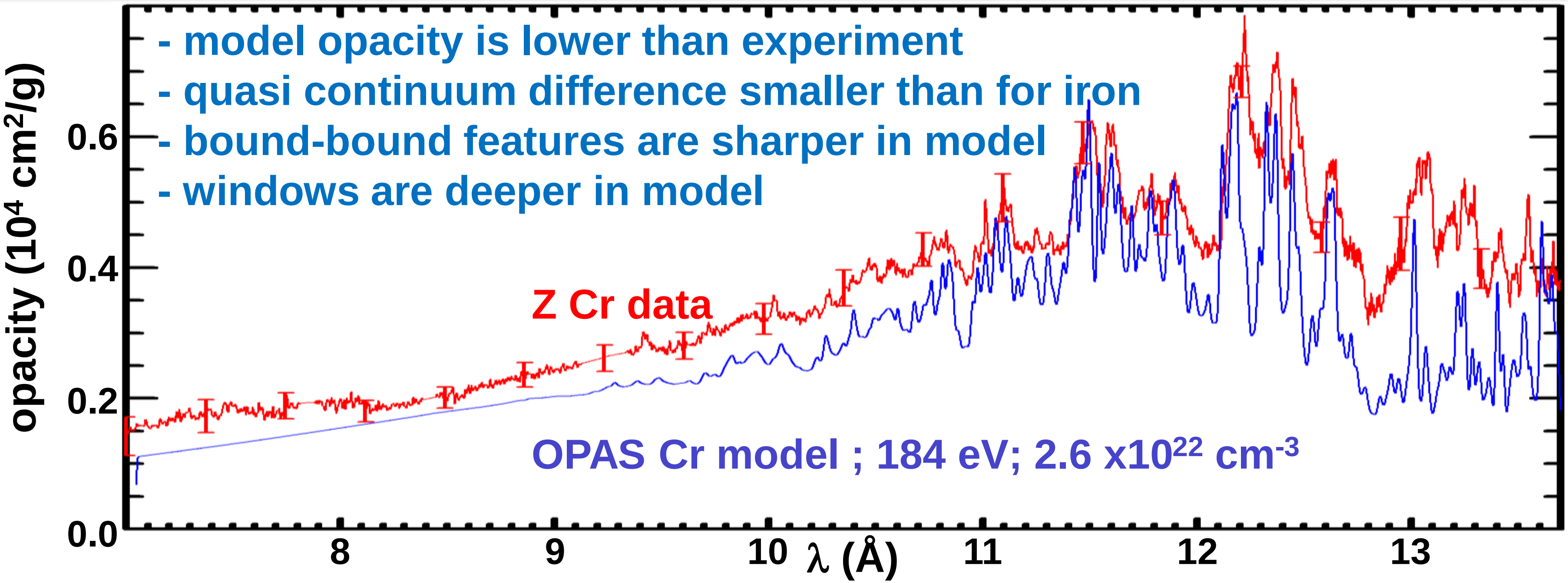


Ni data confirms Z experiments are not systematically biased to measure higher-than-predicted opacity



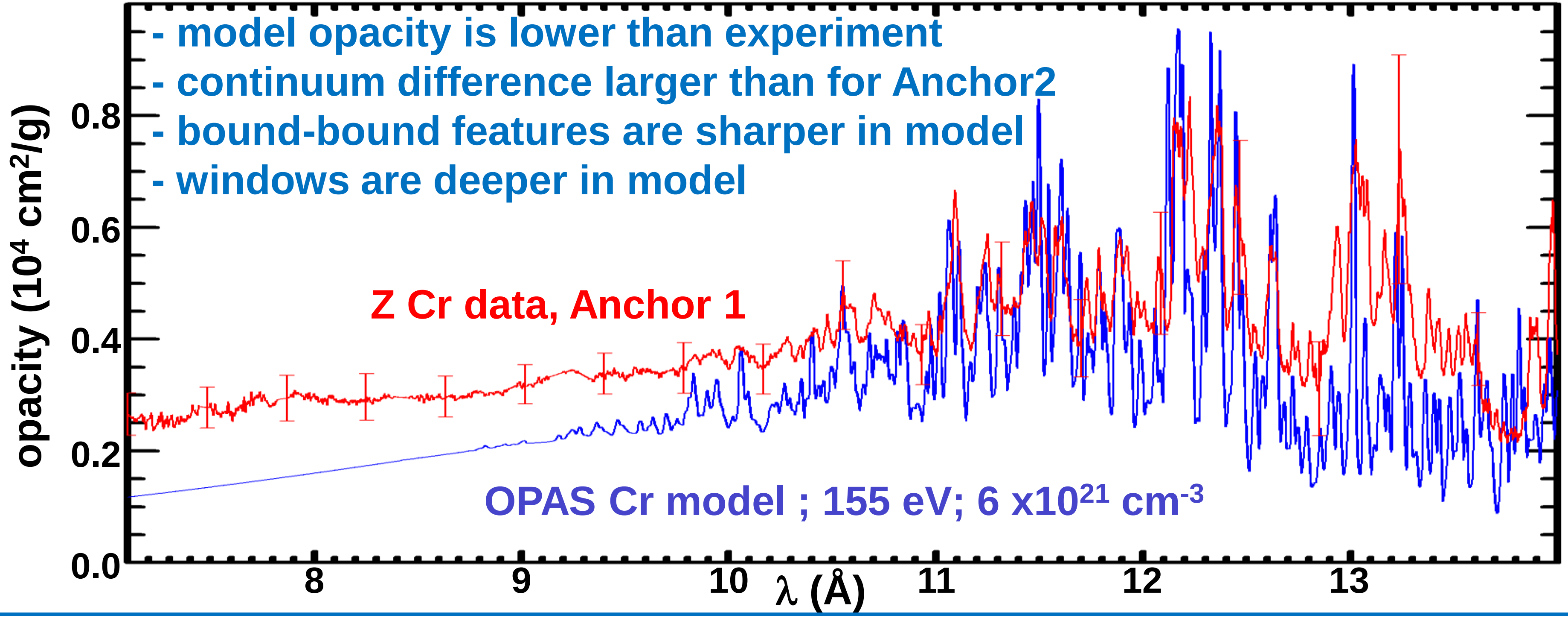
SCO-RCG: J.-C. Pain *et al.*, 2013

Chromium opacity measurements at Anchor 2 conditions are higher than predictions, similar to iron



This generally supports the iron data validity
We need to use the data ensemble to test ideas for what might cause the differences

Unlike iron, preliminary chromium measurements at Anchor 1 conditions are higher than predictions



If corroborated, these results could provide important clues for what caused the model-data discrepancy in iron

We will continue to scrutinize these results and extend the measurements. Future work will include:

- Additional Ni and Cr measurements for improved confidence and precision.
- Time-gated opacity measurements
- Extend wavelength range to enable sum-rule evaluation
- Develop capability to change T_e and n_e independently of each other
- Multi-dimensional radiation-hydrodynamics simulations including the integrated z-pinch source formation, sample heating, and backlighting.
  - Search for effects we aren't presently considering
- Complementary experiments on the NIF.
  - First measurements of Fe at Anchor 1 scheduled for 2017, Anchor 2 in 2018.

Z opacity experiments refine our understanding of photon absorption in high energy density stellar matter.

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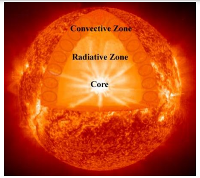

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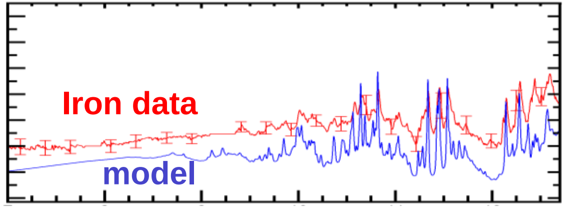

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