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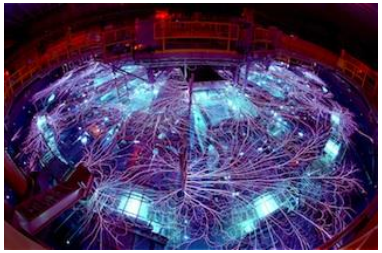

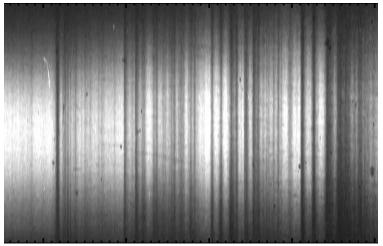

Systematic measurements of opacity dependence on temperature, density, and atomic number at stellar interior conditions

Jim Bailey

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

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.

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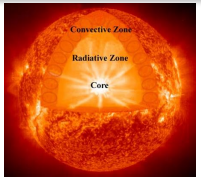
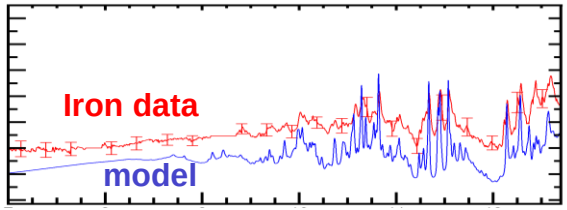
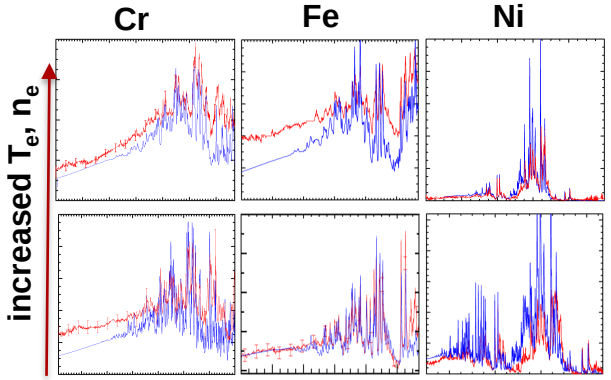
- **Solar interior predictions don't match helioseismology**
  → **Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?**
- **Z experiments have measured iron plasma opacity at near-solar-interior conditions**
- **The measured high temperature/density iron opacity 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**

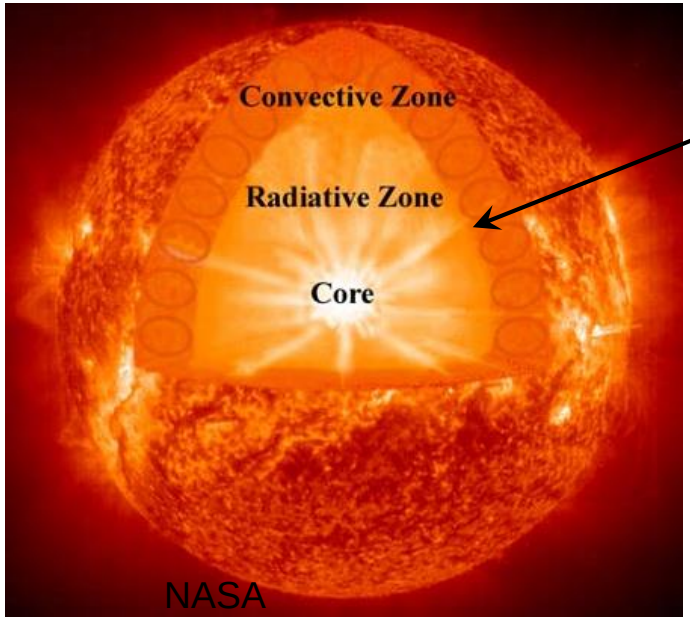






Bailey *et al.*, *Nature* 2015

Models for solar interior structure disagree with helioseismology observations.



Convection-Zone (CZ) Boundary
Models are off by 10-30 σ

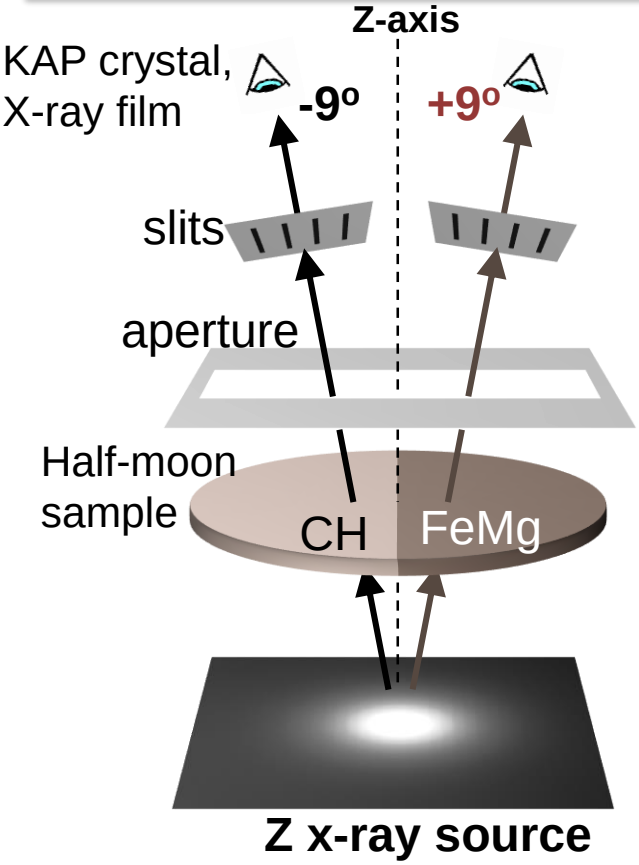
Models depend on:

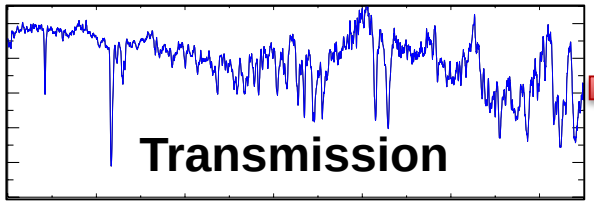
- **Composition (revised in 2000*)**
- **EOS as a function of radius**
- **The solar matter *opacity***
- **Nuclear cross sections**

Question: Is opacity uncertainty the cause of the disagreement?

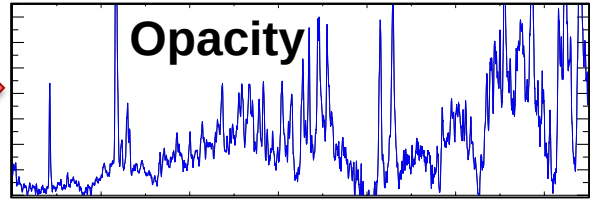
*M. Asplund *et al*, Annu. Rev. Astro. Astrophys. 43, 481 (2005). Serenelli, *ApJ* 2009

Z experiments provide opacity measurements at multiple conditions

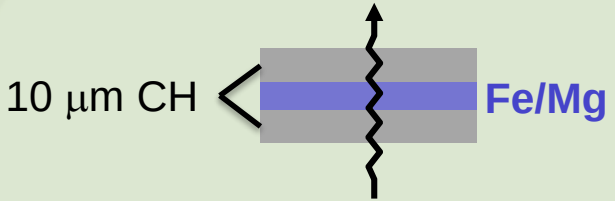




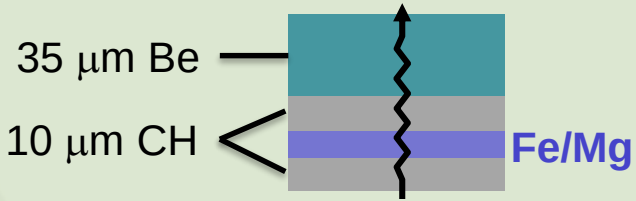
λ [Å]



λ [Å]



"Anchor 1" sample
T_e ~ 160 eV
n_e ~ 7x10 ^{21} cm^{-3}



"Anchor 2" sample
T_e ~ 185 eV
n_e ~ 3x10 ^{22} cm^{-3}

Bailey *et al* PoP (2009); Nagayama *et al* POP (2014)

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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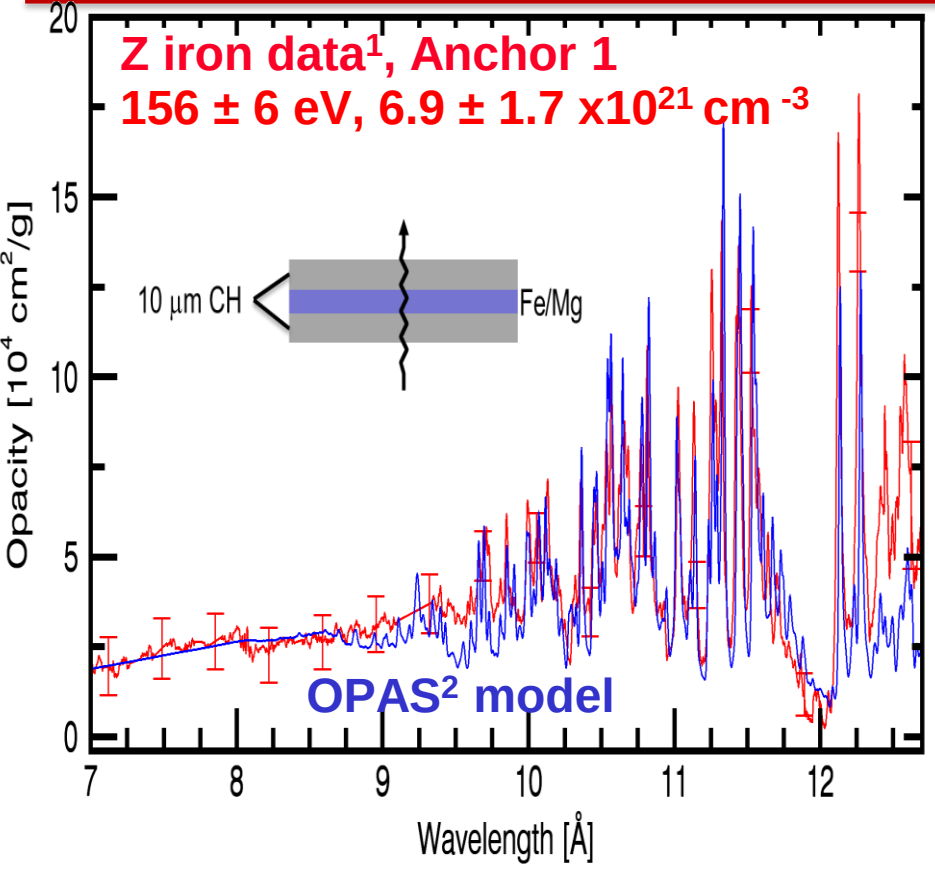

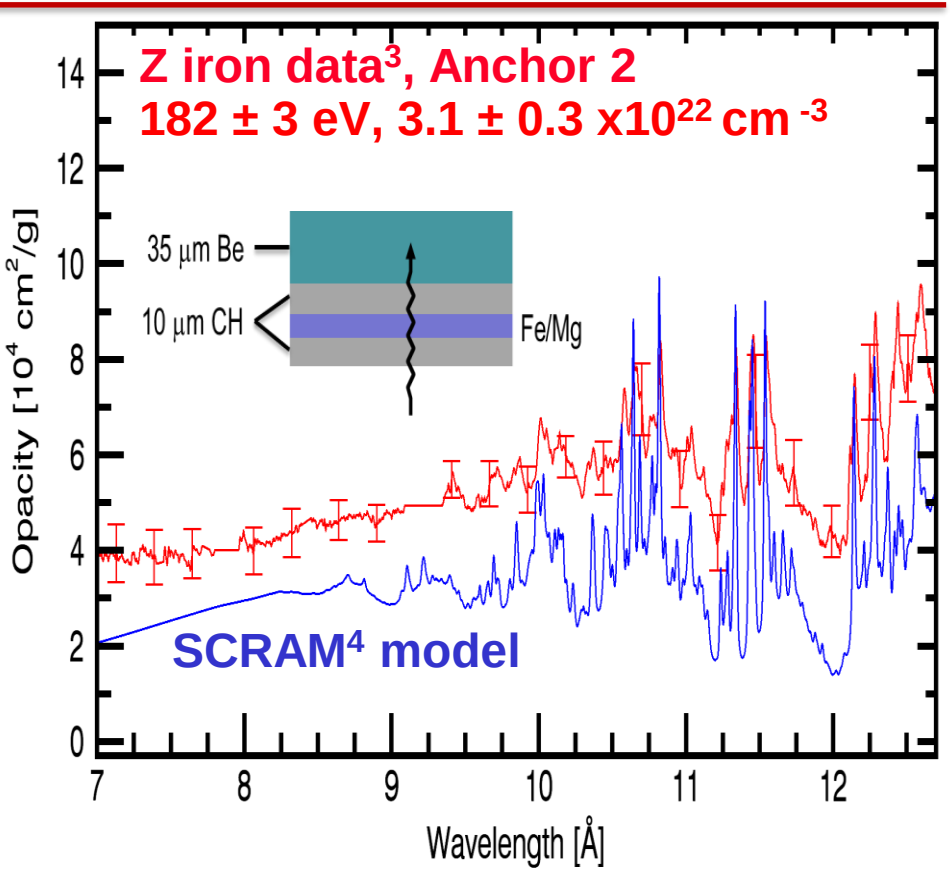

[1]Bailey *et al.*, PRL (2007); [2]Blancard *et al.*, ApJ (2012); [3]Bailey et al., *Nature* 2015; [4]Hansen et al., HEDP (2007)

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

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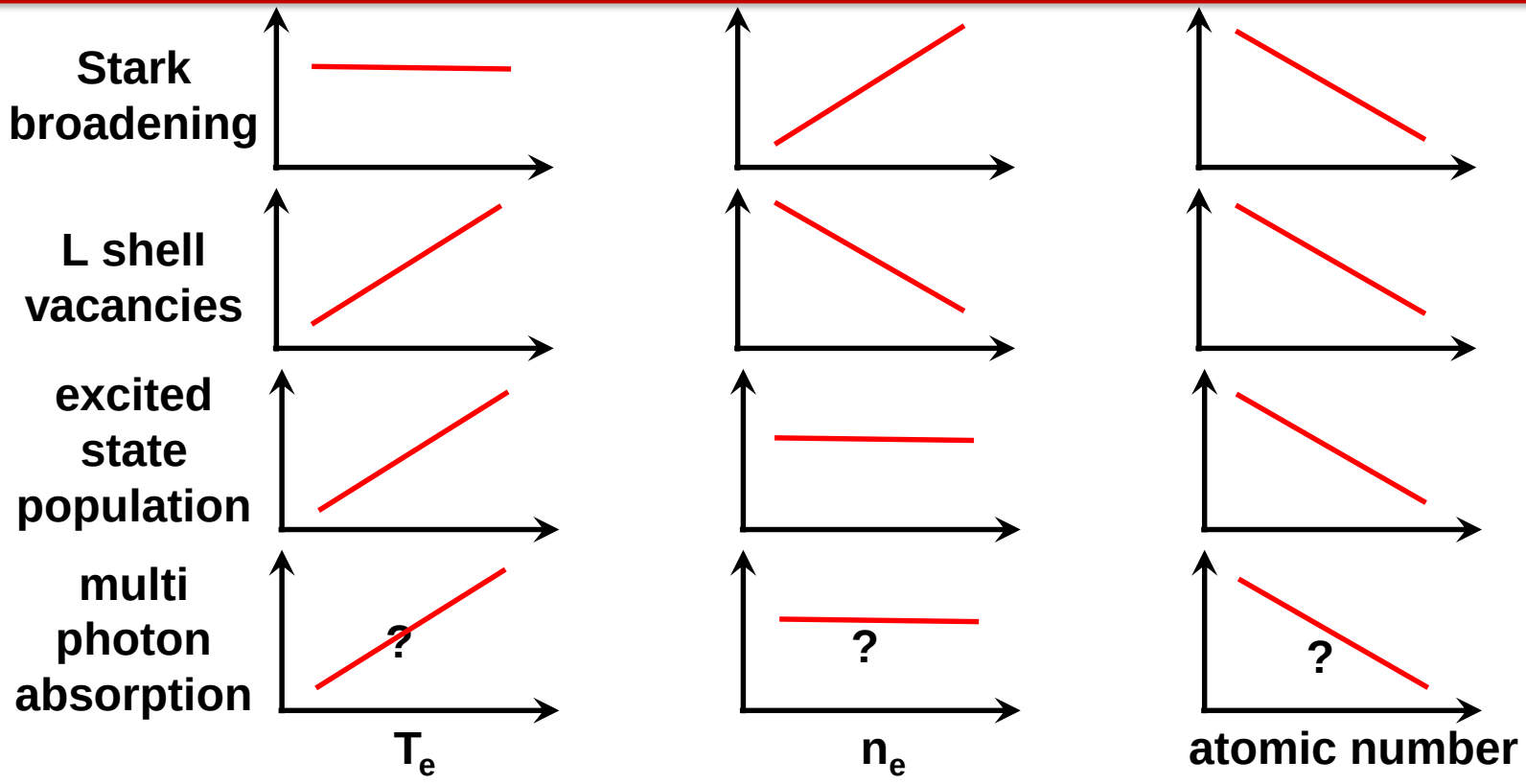
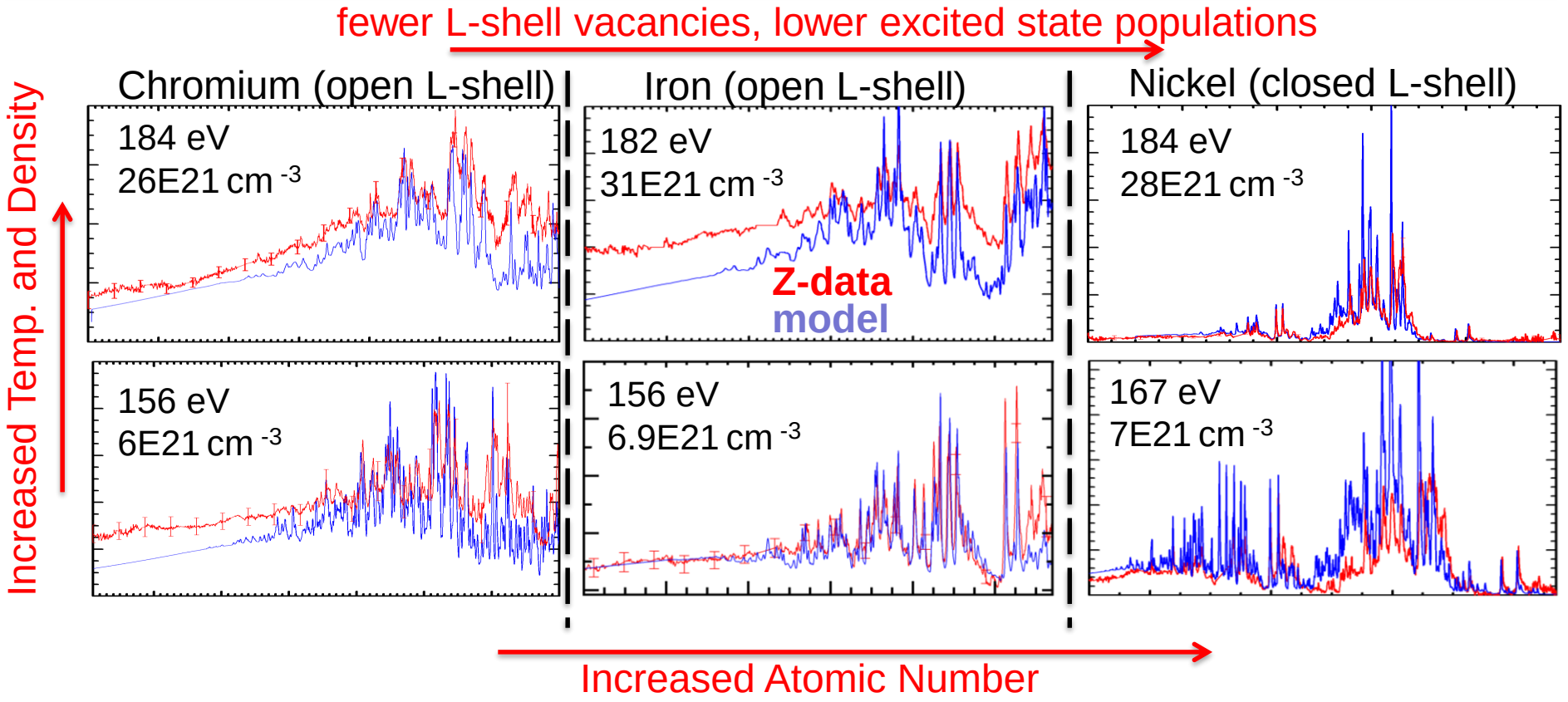
7 questions we should answer for stellar opacity understanding:

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?**

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

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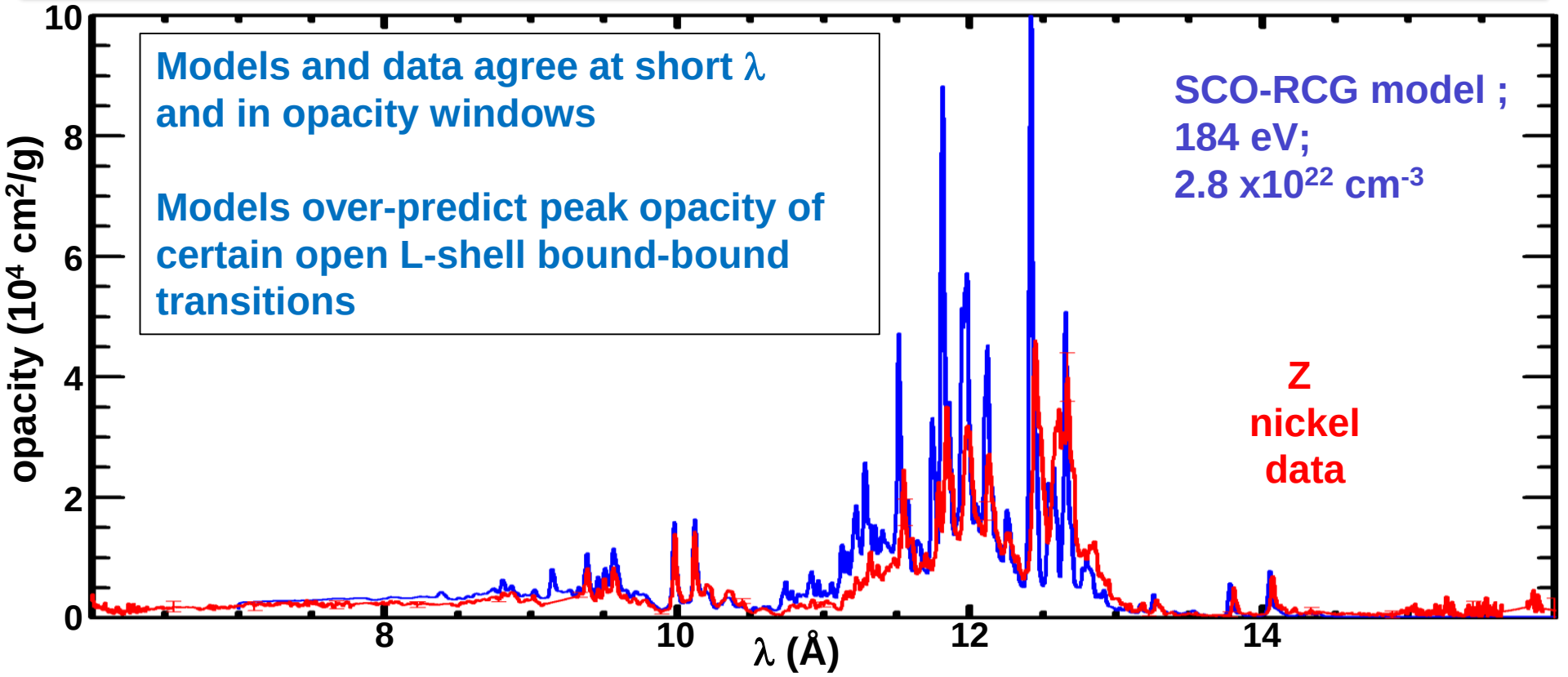

SCO-RCG: J.-C. Pain *et al.*, 2013

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

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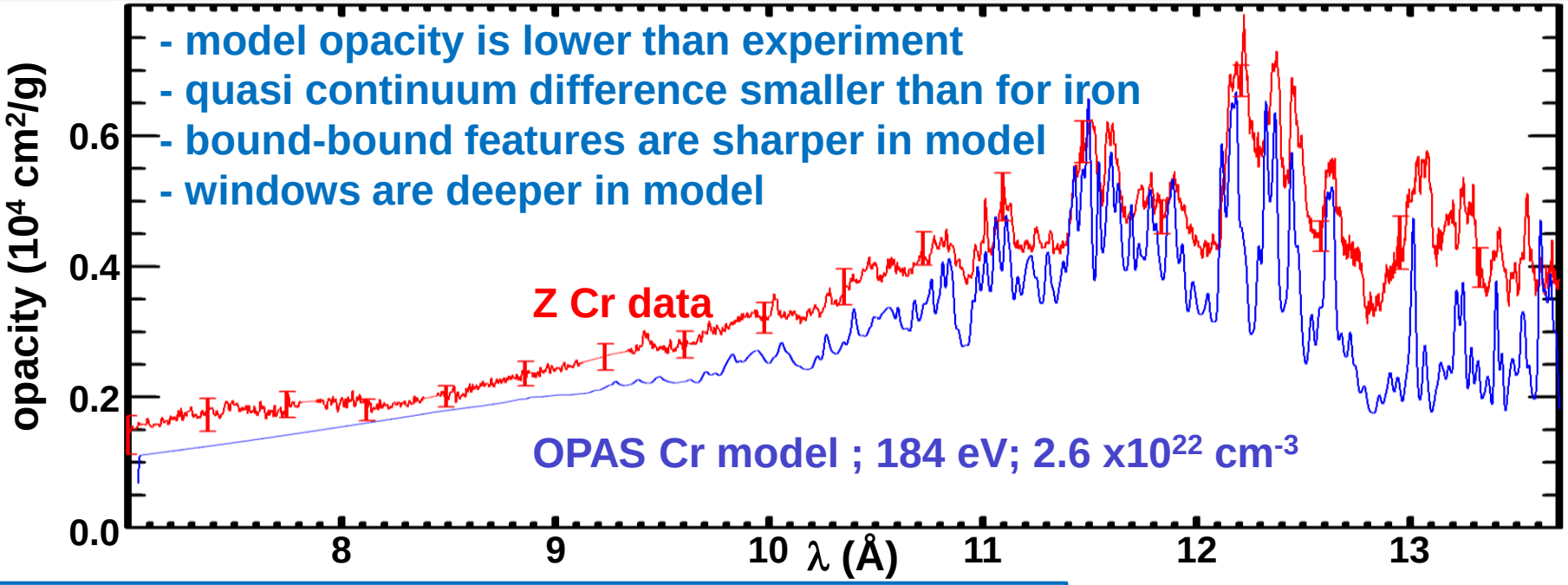

This generally supports the iron data validity
We need to use the data ensemble to test ideas for what might cause the differences

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

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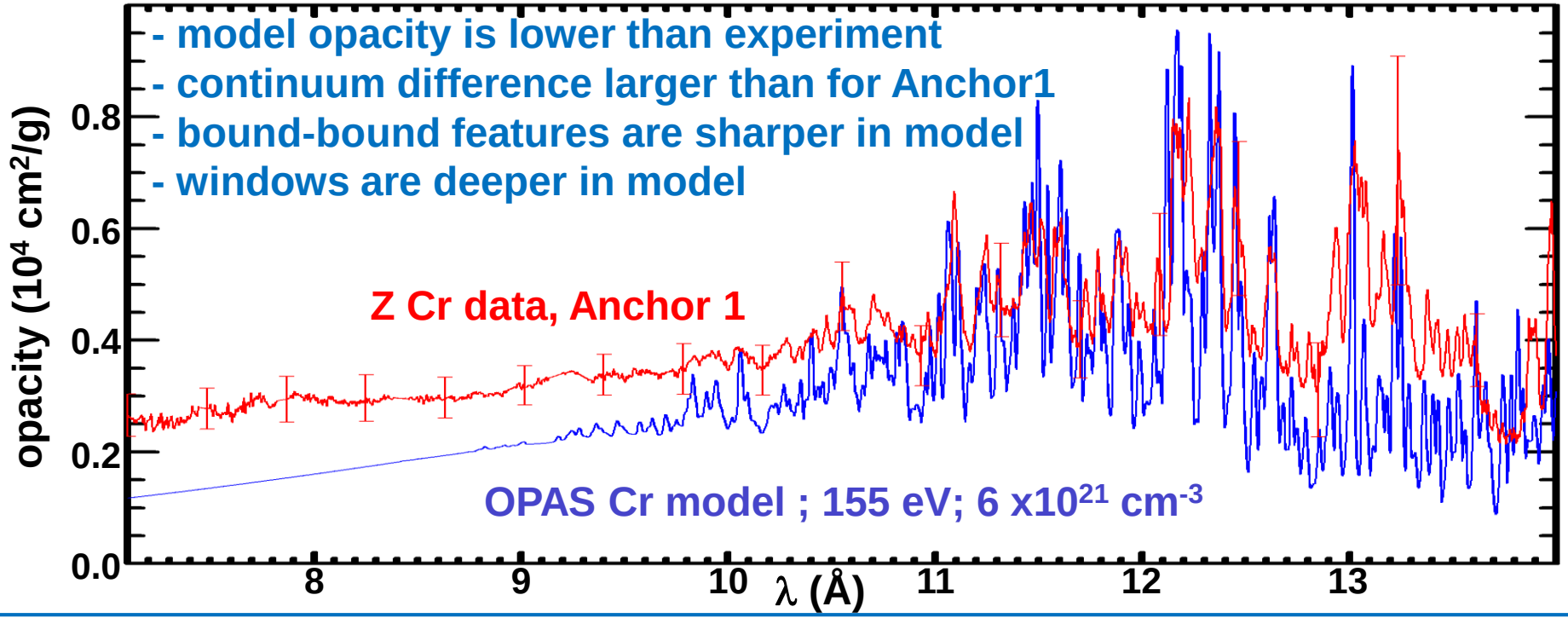

If corroborated, these results could provide important clues for what caused the model-data discrepancy in iron

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

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- 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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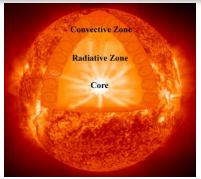

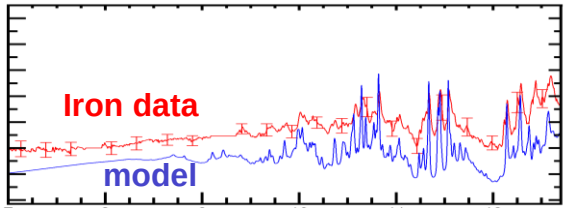

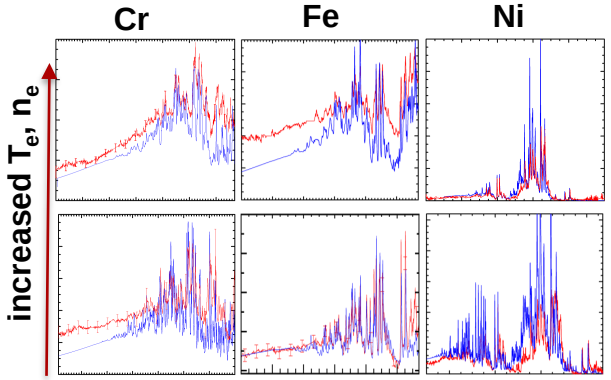

Bailey *et al.*, *Nature* 2015