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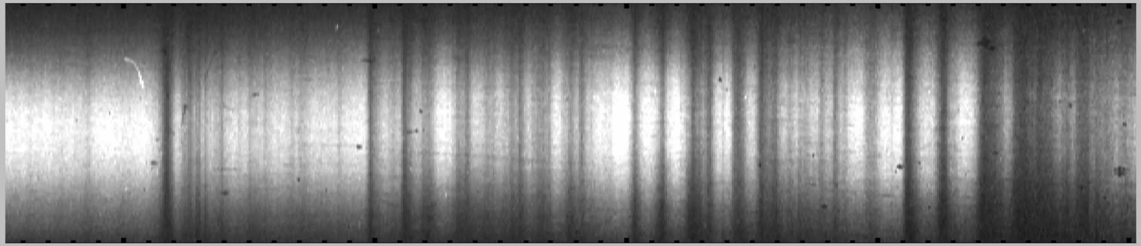

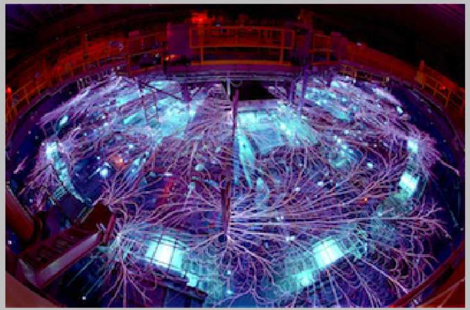

Revised laboratory measurements of iron opacity for stellar interiors

Jim Bailey, Tai Nagayama, Guillaume Loisel, Stephanie Hansen, Greg Dunham, and Greg Rochau

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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APS Division of Plasma Physics, October 21, 2019, Ft. Lauderdale, Florida

New iron opacity experiments and analysis are in progress, but model-data discrepancies at 2-10 σ remain

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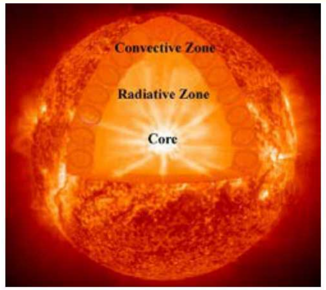
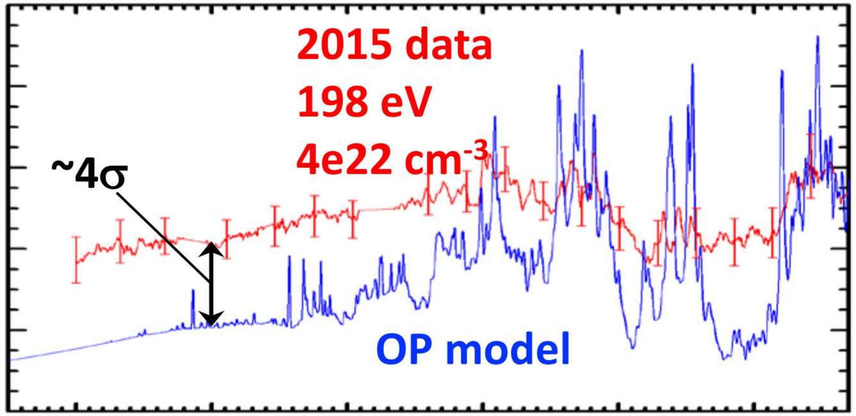
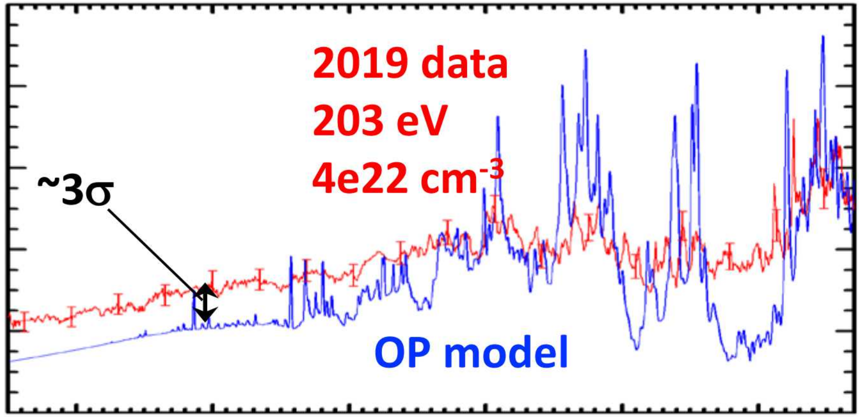
- **Experiments published in 2015 are impactful**
  - **Help reconcile Solar model and helioseismology**
  - **Change understanding of photon absorption in HED matter**
- **No opacity theory has yet matched the data**
- **A systematic study published this year shows opacity behavior is complex**
- **Continued re-examination of experiments is warranted**
  - **New iron experiments**
  - **Revised analysis methods**
- **Refined results reduce, but do not resolve, the model data discrepancy**







Bailey et al, *Nature* 2015; Nagayama et al, *Phys Rev Lett* 2019

Solar models disagree with helioseismology, prompting astrophysicists to ask if the true opacity might be higher than predicted

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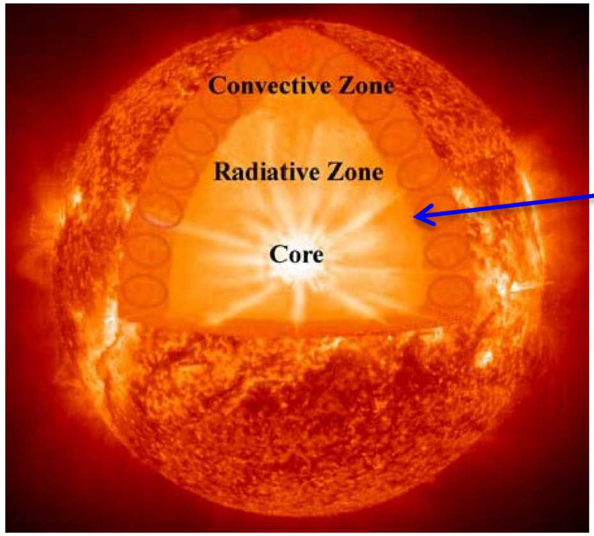

CZB condition:
T_e=182 eV
2.075x10^6 K
n_e=9x10^{22} cm^{-3}

- **Solar abundances reduced for some elements beginning ~ 2000**
- **Leads to lower total opacity**
- **Causes disagreements between helioseismology and solar models**
- **Agreement is restored if we assume opacity is 15-30% higher than predicted**

Is this explanation correct?

solar models rely on opacity predictions that have never been directly measured until now

Basu and Antia, *Phys. Reports* 2008; Serenelli, *ApJ* 2009

The first iron opacity measurements at stellar interior temperatures help resolve a longstanding problem in solar physics.

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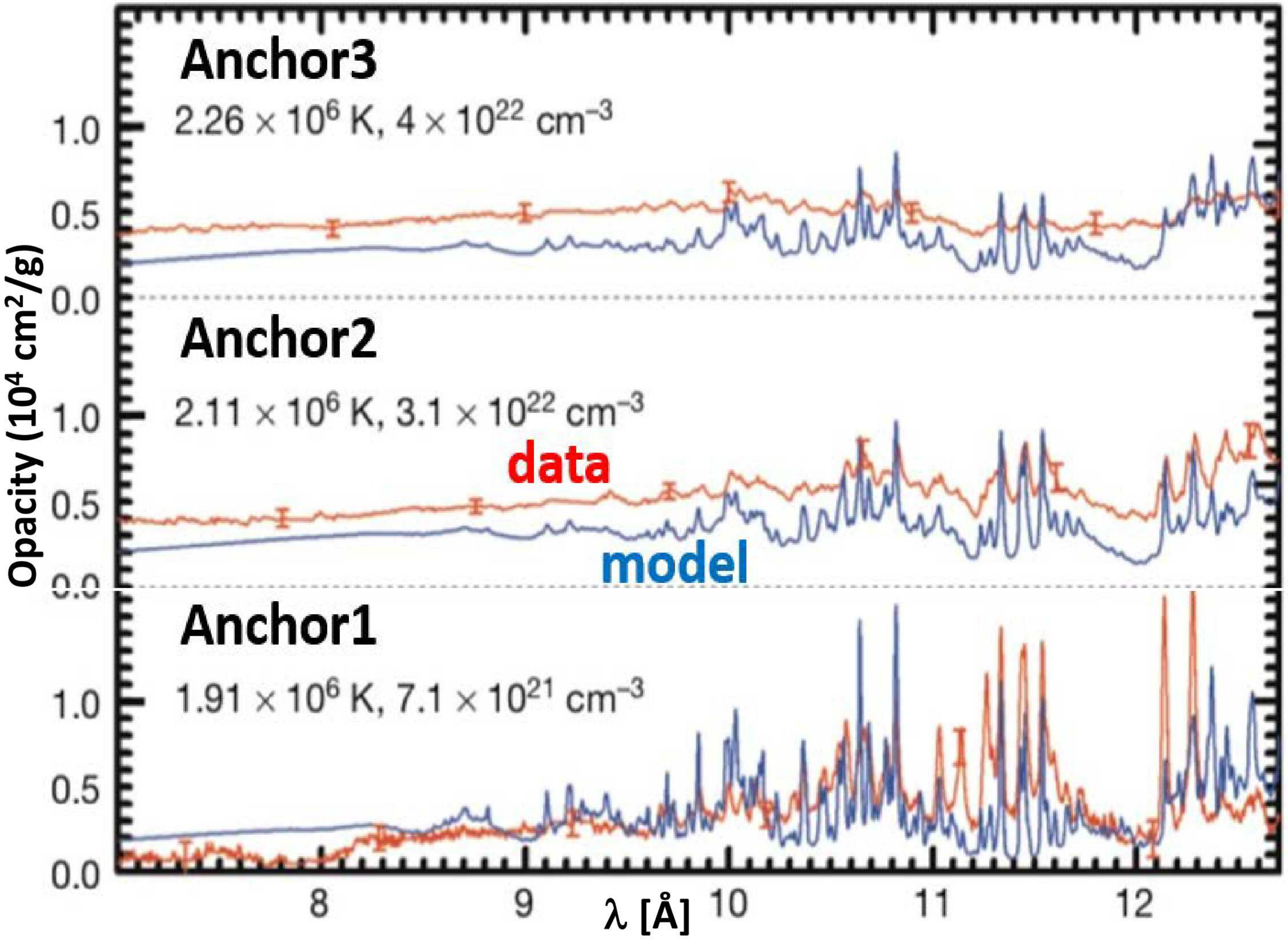
Bailey, Nagayama, Loisel, Rochau *et al.*, *Nature* 2015



- **Predictions diverge from iron opacity measurements as the temperature approaches solar interior value**
- **Accounts for about ½ the opacity increase needed to resolve the solar problem**
- **But why?**

Hypotheses for the discrepancy define a strategy to reconcile theory and experiment

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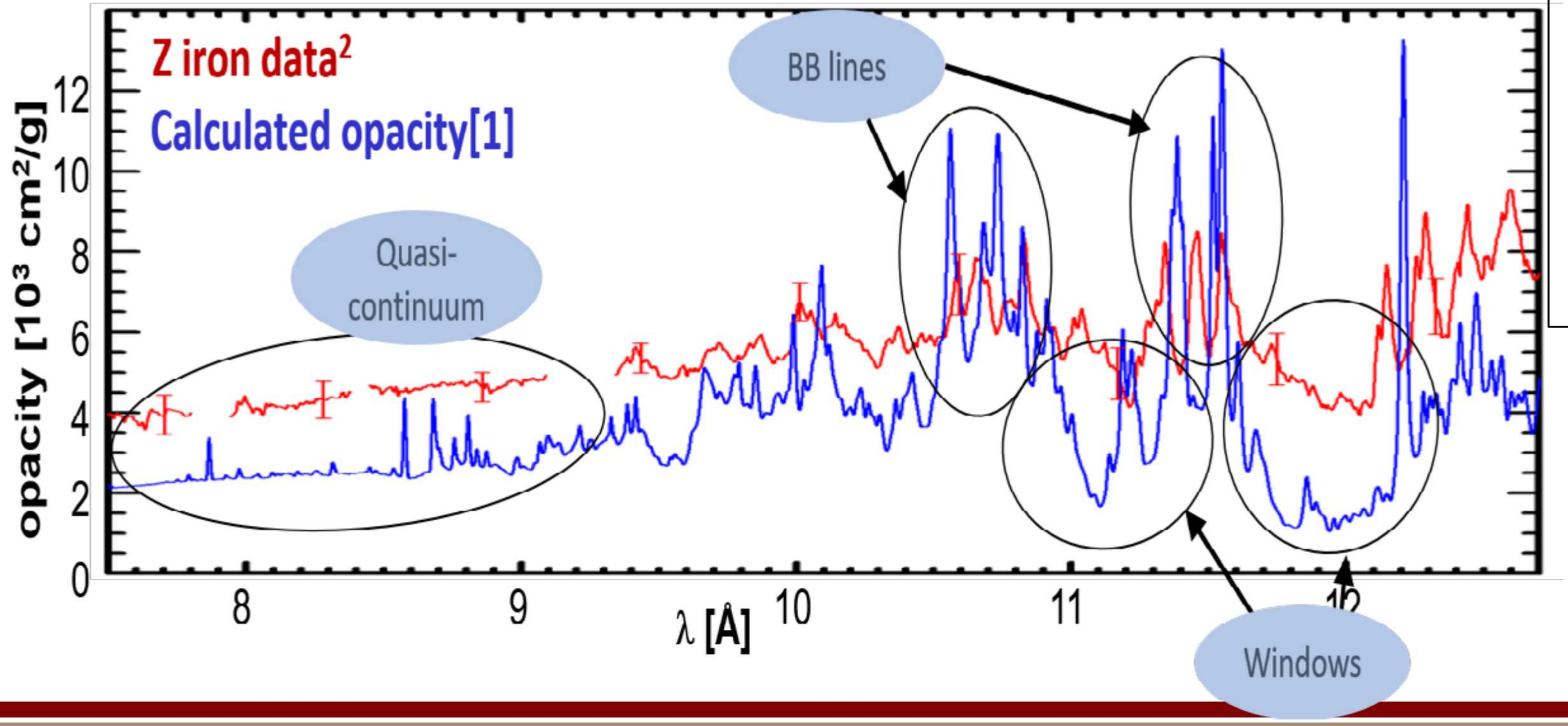
Two hypothesis categories:
EITHER
Photon absorption in stellar matter is different from previously believed
OR
Experiments are flawed in some undetected manner

Hypothesis tests require identifying the nature of the discrepancy



Strategy

Systematic measurements: Z, T_e, n_e

Refine the high T_e/n_e Fe experiment

Directly measure temporal evolution

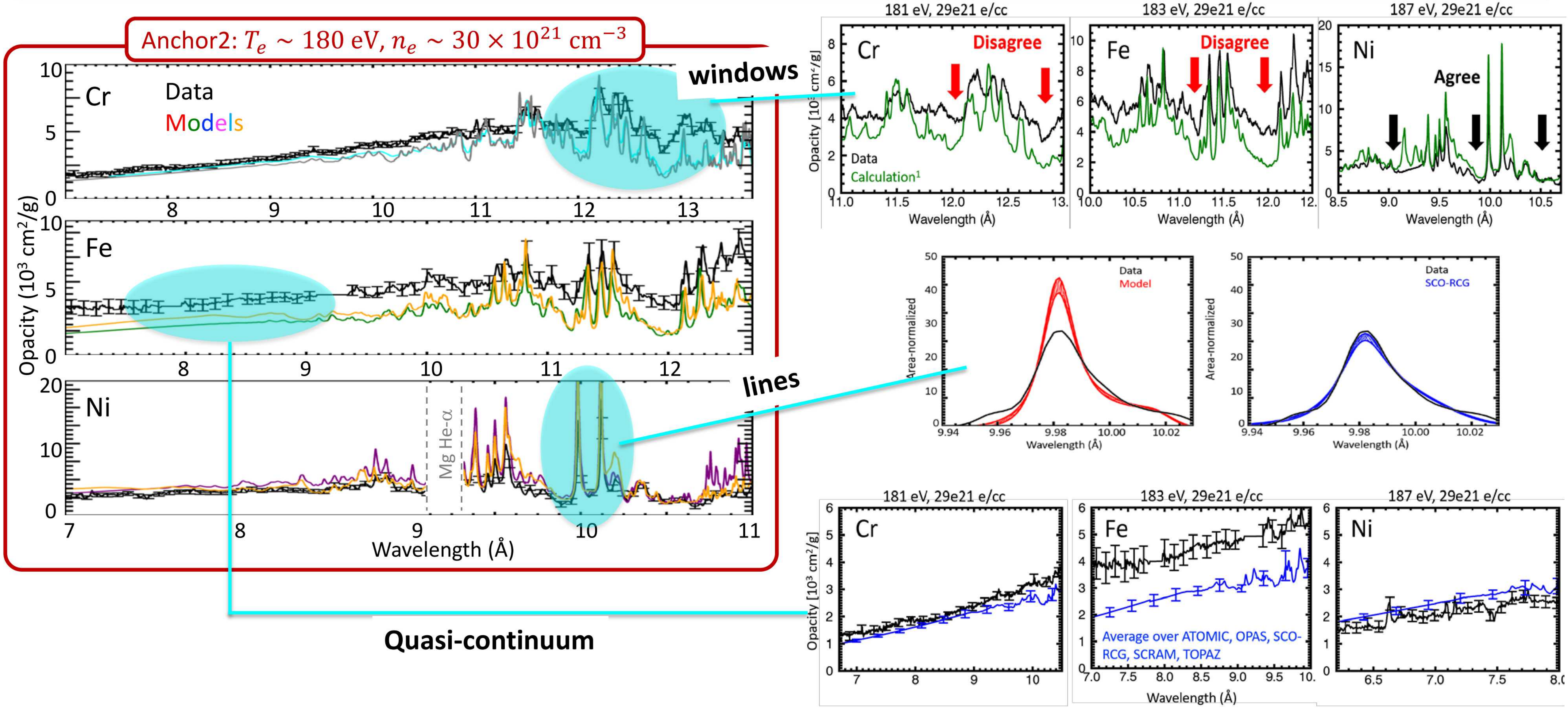
New experiments at the NIF

Examine possible theory revisions

- **Line broadening**
- **Two photon absorption**
- **Open shell physics**

[1] OP: Astrophysics opacity code by Seaton *et al.*, *MNRAS* (1994)

Systematic opacity model-data comparisons for three elements at several temperatures and densities revealed unexpected complexity



Nagayama et al, *Phys Rev Lett* 2019

Opacity experiment requirements determine what should be checked, re-checked, and re-checked again to ensure accurate results

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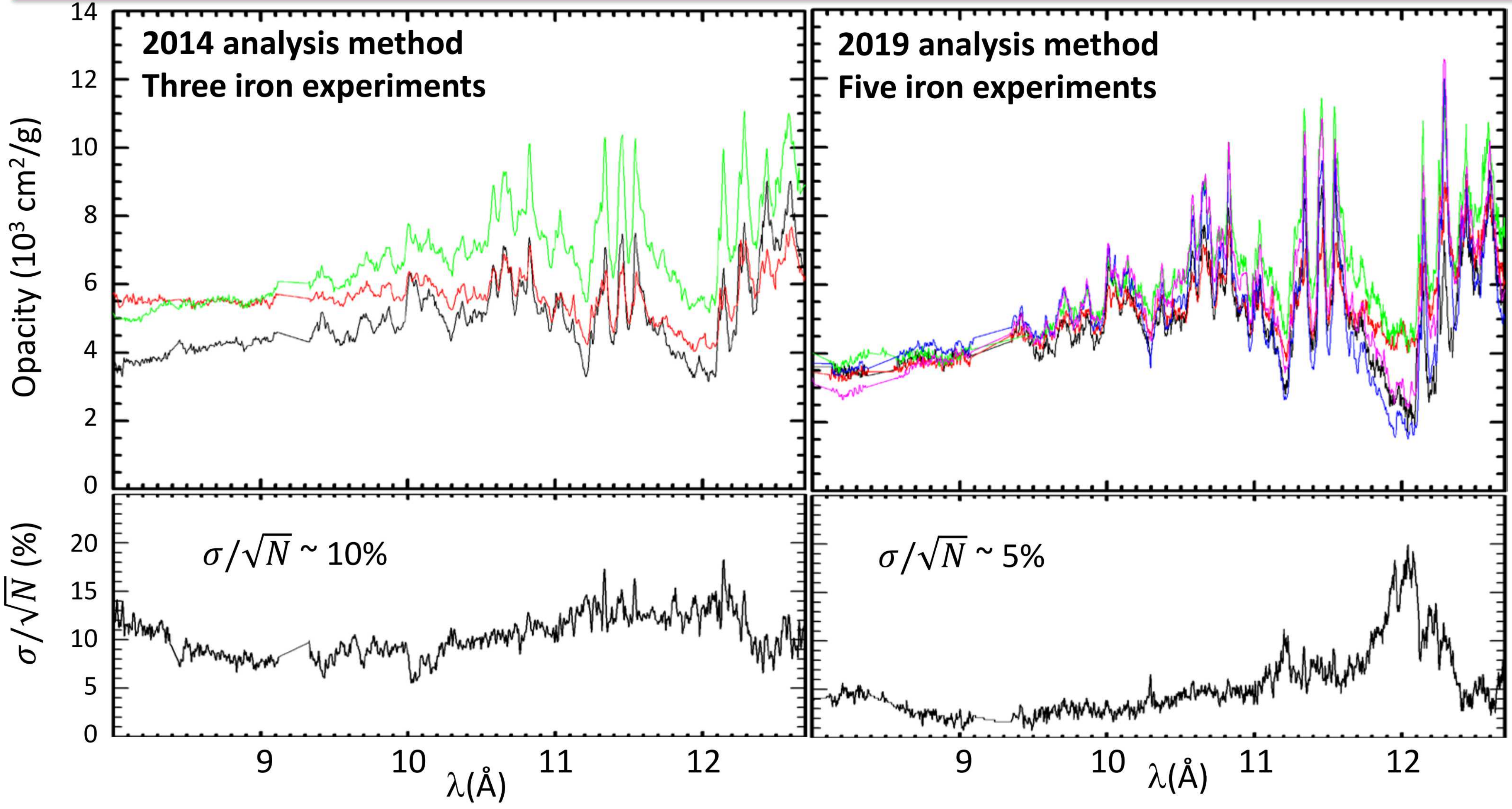
Experiment requirements:

1. Accurate transmission measurements (~ ± 5%)
2. Demonstrated uniformity – spatial and temporal
3. Reliable plasma diagnostics
4. Freedom from self emission
5. Freedom from background contamination
6. Multiple areal densities
7. Thorough sample characterization
8. An evaluation of how suitable the LTE approximation is
9. Multiple T_e, n_e conditions, to aid disentangling physical effects
10. Multiple atomic number elements, to aid disentangling physical effects and help verify robustness against systematic errors
11. Multiple experiments of each type, to confirm reproducibility
12. Peer review and documentation

Reproducibility is difficult at large HED facilities
But essential for all benchmark science measurements

Experiments continually surprise us:
confidence in uncertainties is elusive without repeated identical experiments

Both refined analysis and more experiments improve reproducibility for Anchor2 Fe



Anchor 2:

T_e ~ 184 eV

n_e ~ 3×10^{22} cm^{-3}

Areal Densities
$\times10^{18}$ Fe/cm^2

1.04, 1.91, 0.93 — 2014

1.31, 1.31 — 2015

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

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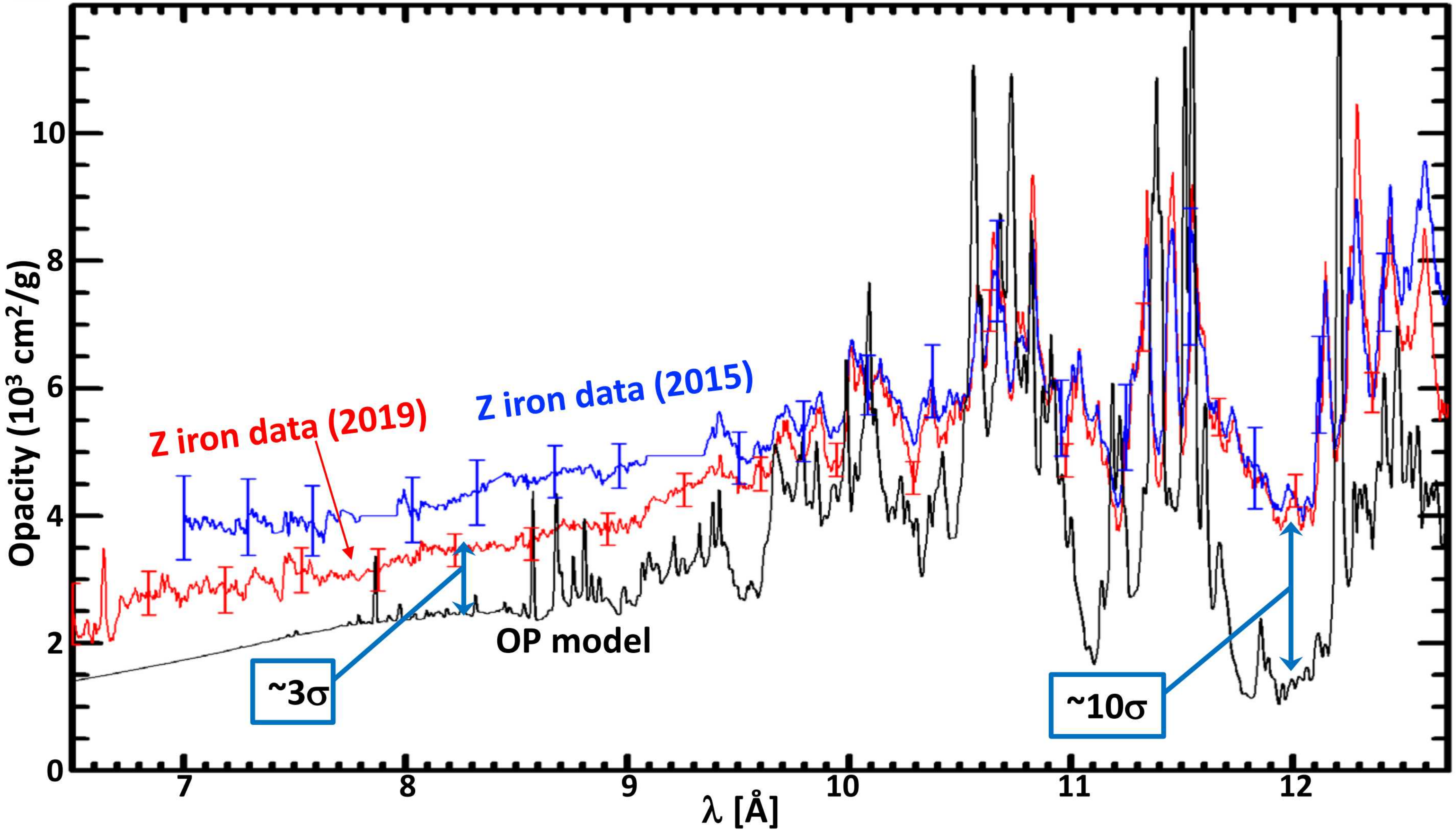


Quasi continuum discrepancy

2015: ~ 1800 cm2/g; ~4σ

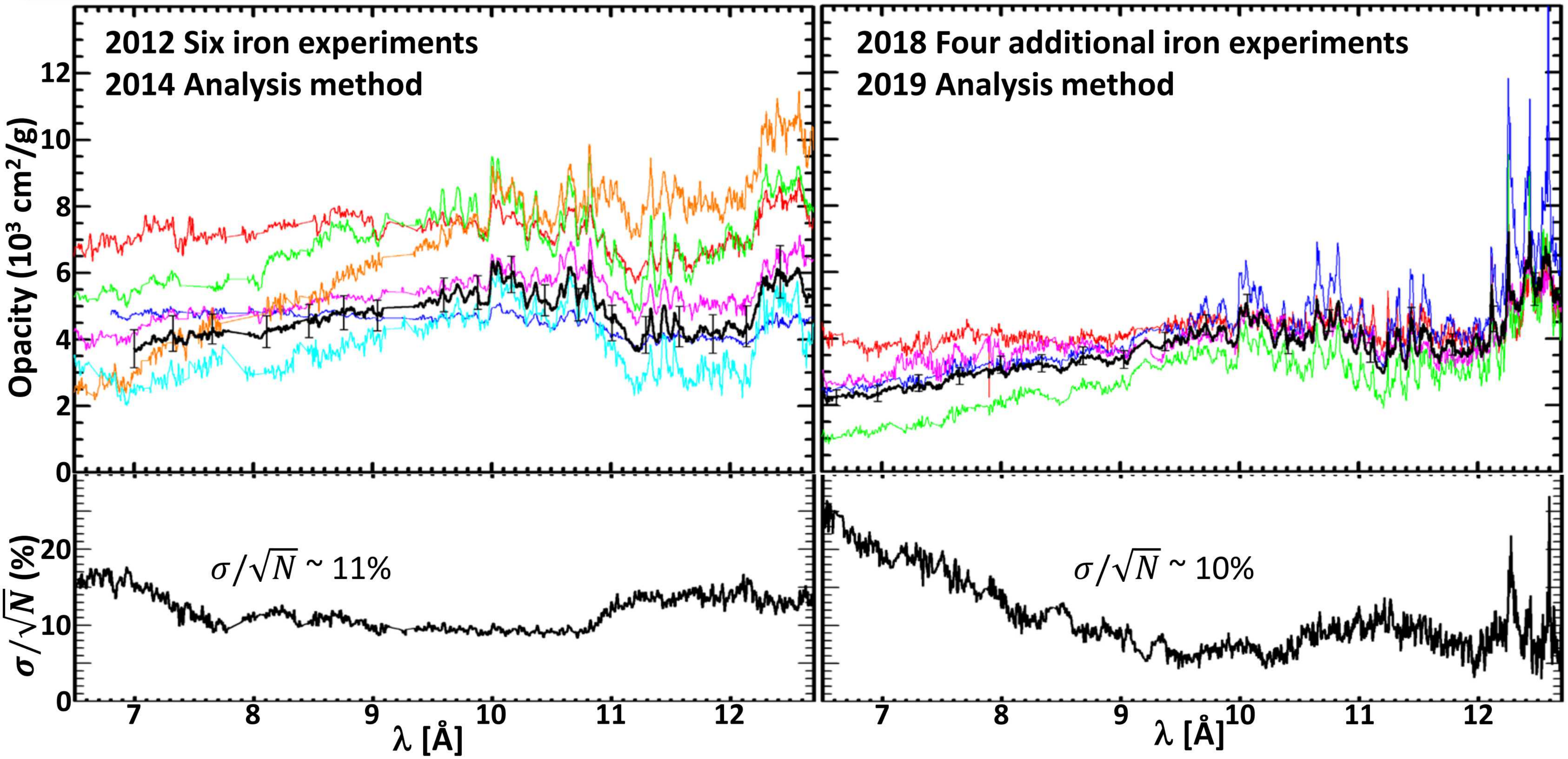
2019: ~ 960 cm2/g; ~3σ

Window discrepancy

2015: ~ 2900 cm2/g; ~ 5σ

2019: ~ 2700 cm2/g; ~ 10σ

Both refined analysis and more experiments improve reproducibility for Anchor 3 Fe



Anchor 3:

T_e ~ 200 eV

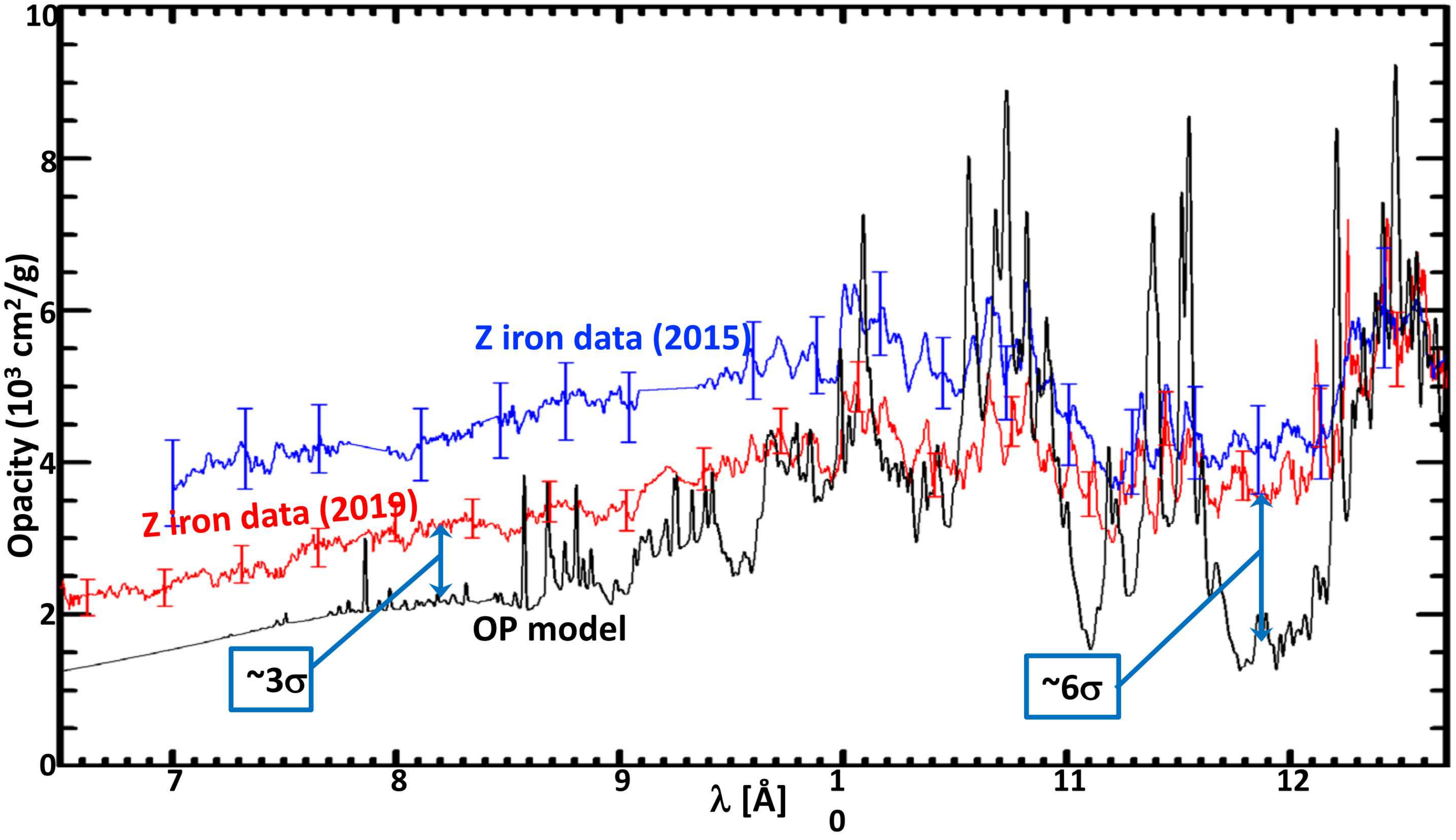
n_e ~ 4×10^{22} cm^{-3}

Areal Densities $\times10^{18}$ Fe/cm^2

1.31, 2.97, 2.84, 1.28, 0.66, 0.66 — 2011-2012

2.37, 2.96, 2.89, 2.37 — 2018

New results have lower model-discrepancy for Anchor 3 iron, but ~3σ differences remain; reanalysis of 2012 experiments in progress



Quasi continuum discrepancy

2015: ~ 2200 cm2/g; ~4σ

2019: ~ 900 cm2/g; ~3σ

Window discrepancy

2015: ~ 2600 cm2/g; ~4σ

2019: ~2000 cm2/g; ~6σ

Stellar astrophysics and HED science require continued research to obtain benchmarked opacity models

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Status / Path Forward

Systematic measurements for Cr, Fe, Ni published {Nagayama et al., PRL 2019} More results coming…

Planned measurements with O, Br will test new aspects of opacity science

High T_e/n_e Fe experiment refined, but 2012 data re-analysis still in progress

Temporal evolution measurements in progress {Loisel *et al*., next talk}

New experiments at the NIF {Perry *et al*., poster CP10.00043, Monday afternoon}

{Johns *et al*., Invited talk PI2.00002, Wednesday afternoon}

Continue to examine possible theory revisions

- Line broadening
- Two photon absorption
- Open shell physics