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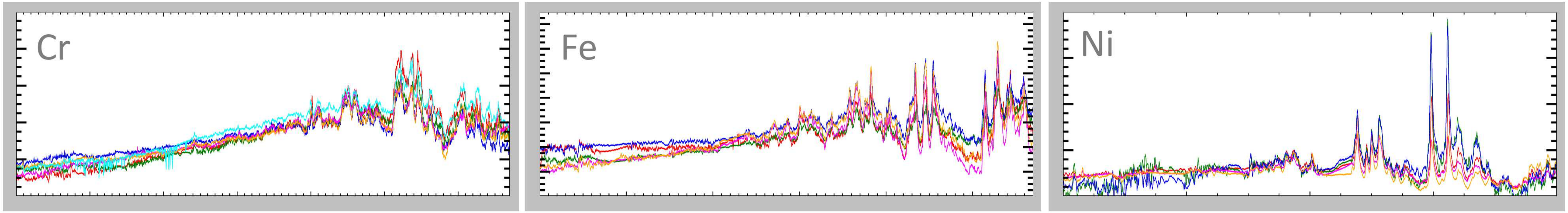

Opacity measurements for stellar interiors

Taisuke Nagayama

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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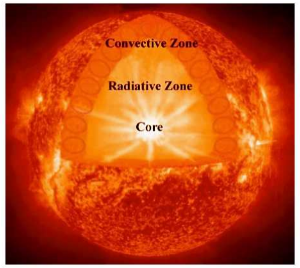
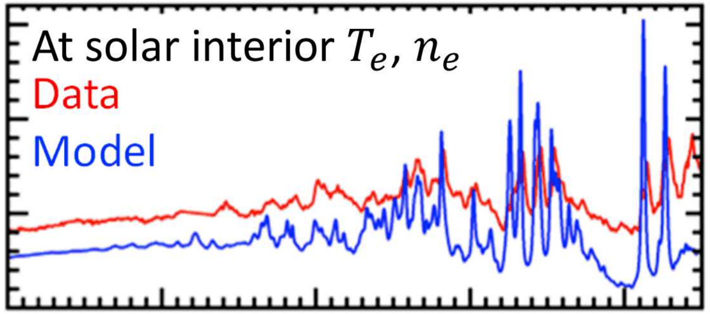
L-shell opacities of Cr, Fe, and Ni were systematically measured, providing unprecedented constraints for resolving solar problem

- **Modeled solar structure is not sufficiently accurate**

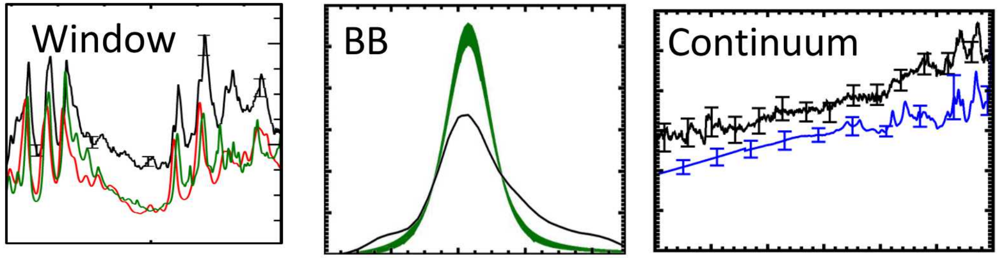
  → Is calculated iron opacity accurate?





- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**

- **Systematic measurement of Cr, Fe, and Ni opacities suggests model refinements in three areas**
  - <u>Window:</u> Challenge associated with open L-shell config.
  - <u>BB:</u> Inaccurate treatment of density effects
  - <u>Continuum:</u> Peculiar dependence on atomic number

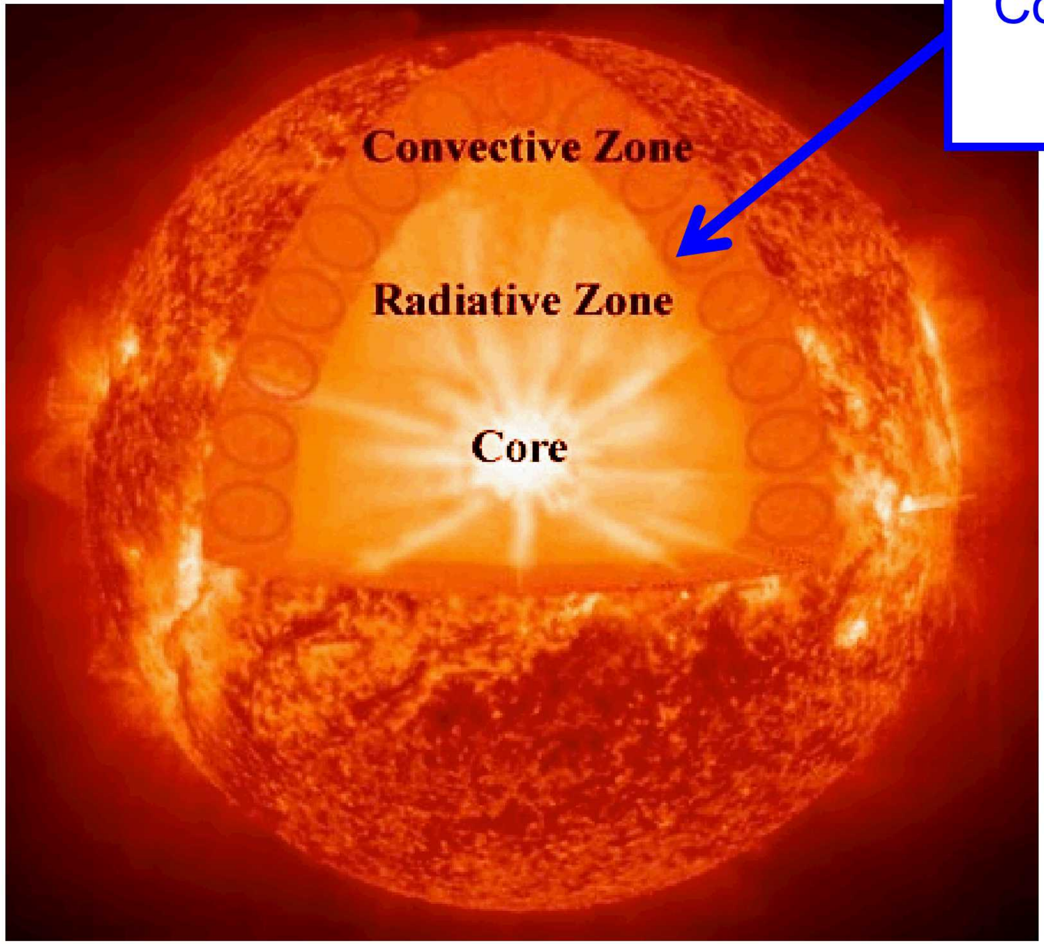


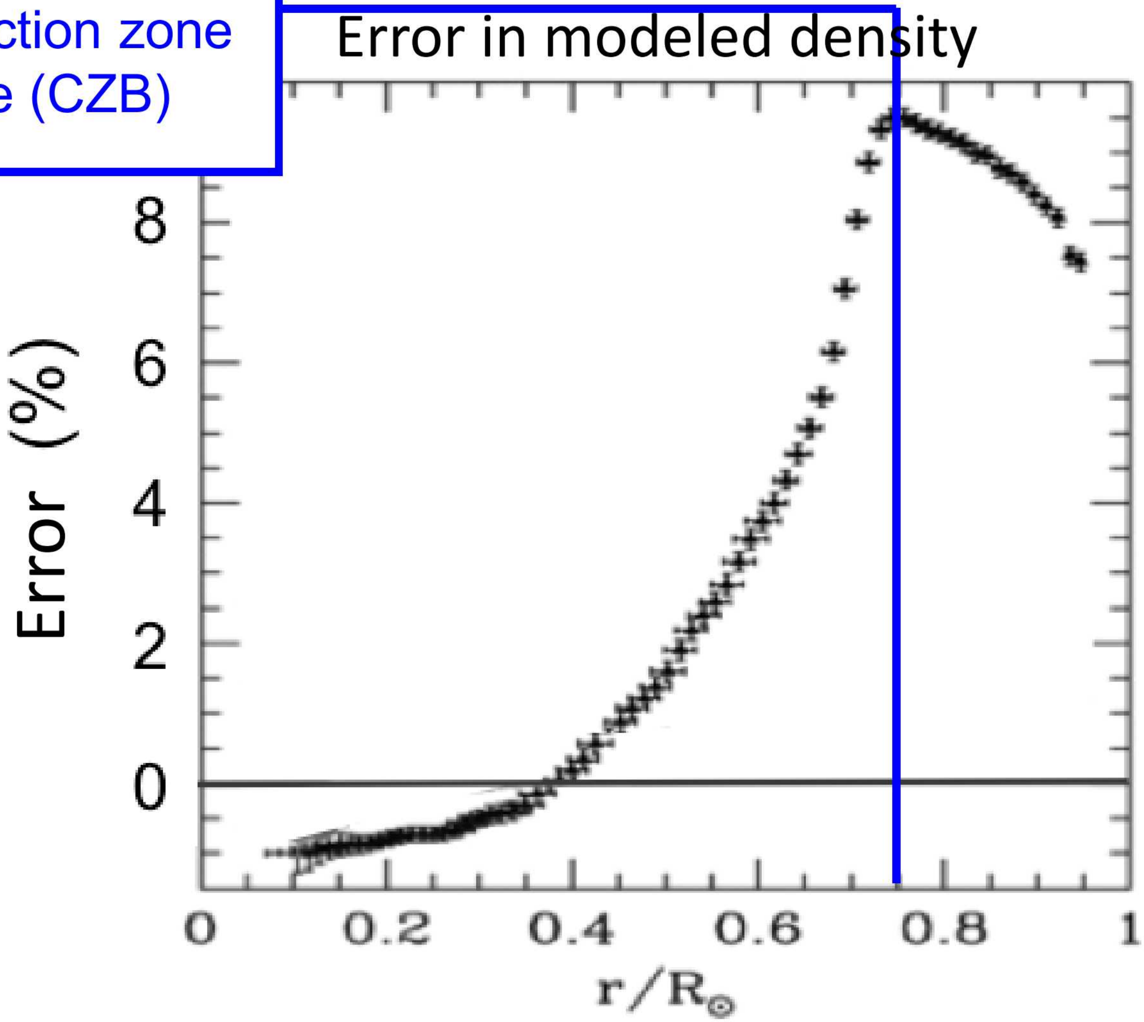
- **More exciting measurements are on the horizon**

Diligent experiment and analysis are leading us steadily towards resolution

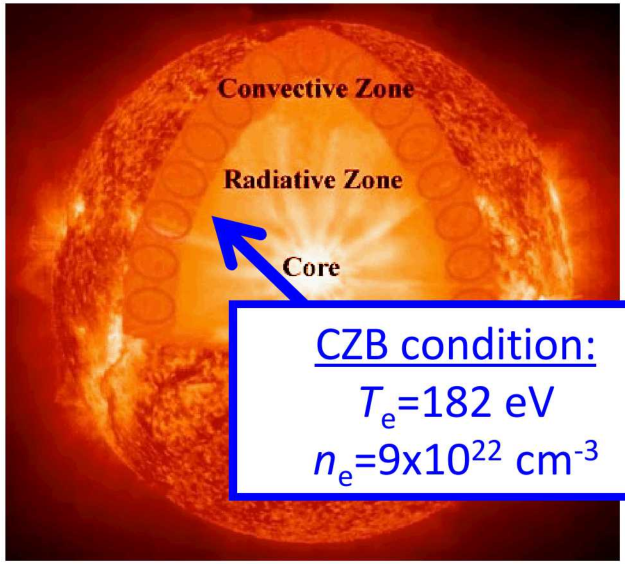
Modeled solar structure disagrees with observations

Convection zone base (CZB)





10-30% mean-opacity increase in the solar model is needed to resolve this discrepancy



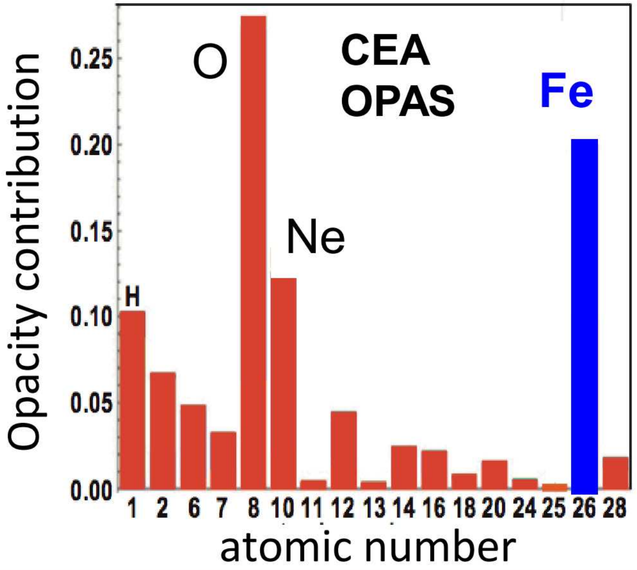
CZB condition:
T_e=182 eV
n_e=9x10^{22} cm^{-3}

Opacity: κ_ν

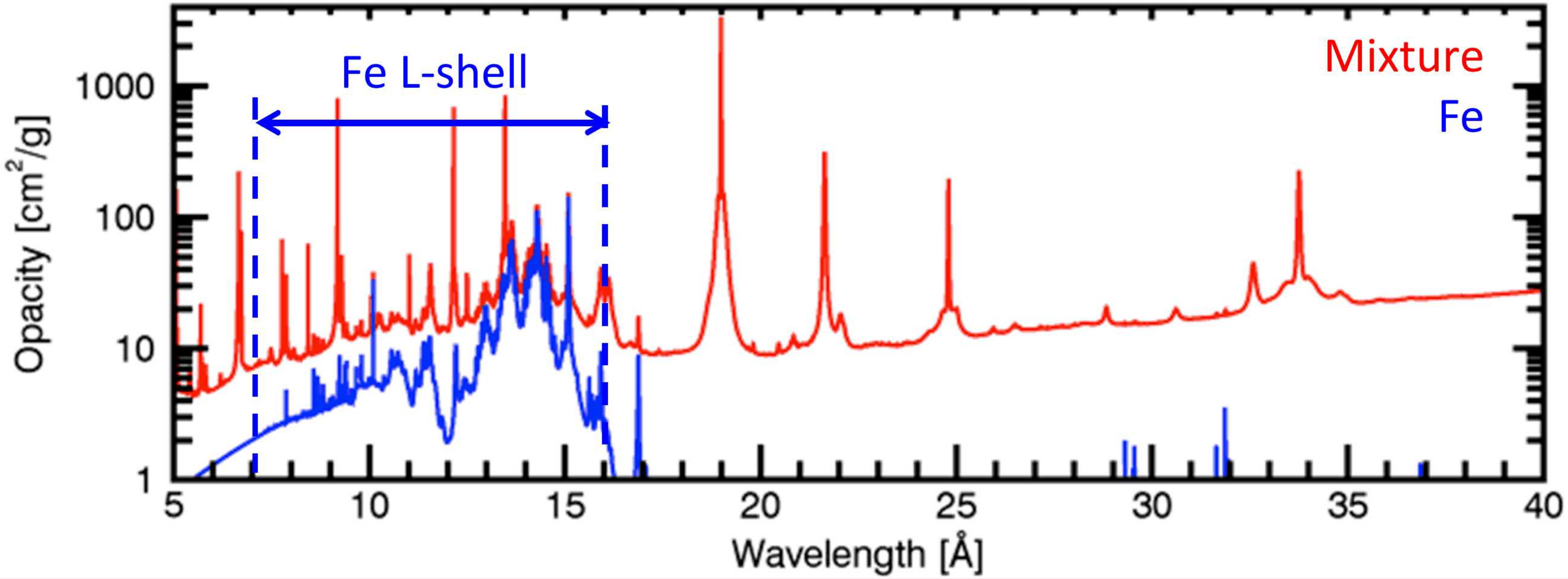
- Quantifies radiation absorption
- $\kappa_\nu(T_e, n_e)$ … input for solar models
- Opacity models have never been tested

Fe is a likely suspect:

- 2nd largest contribution
- Most difficult to model

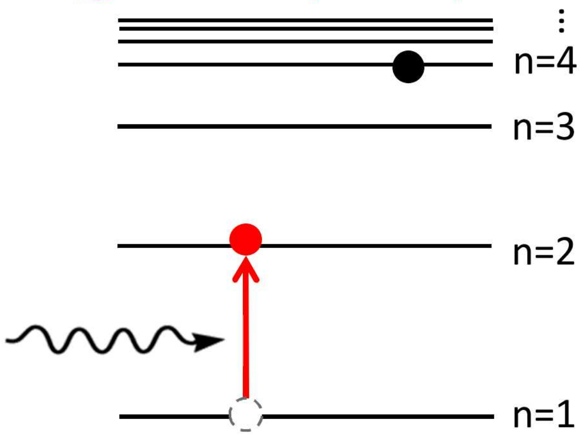


Solar mixture opacity at Convection Zone Base (CZB)

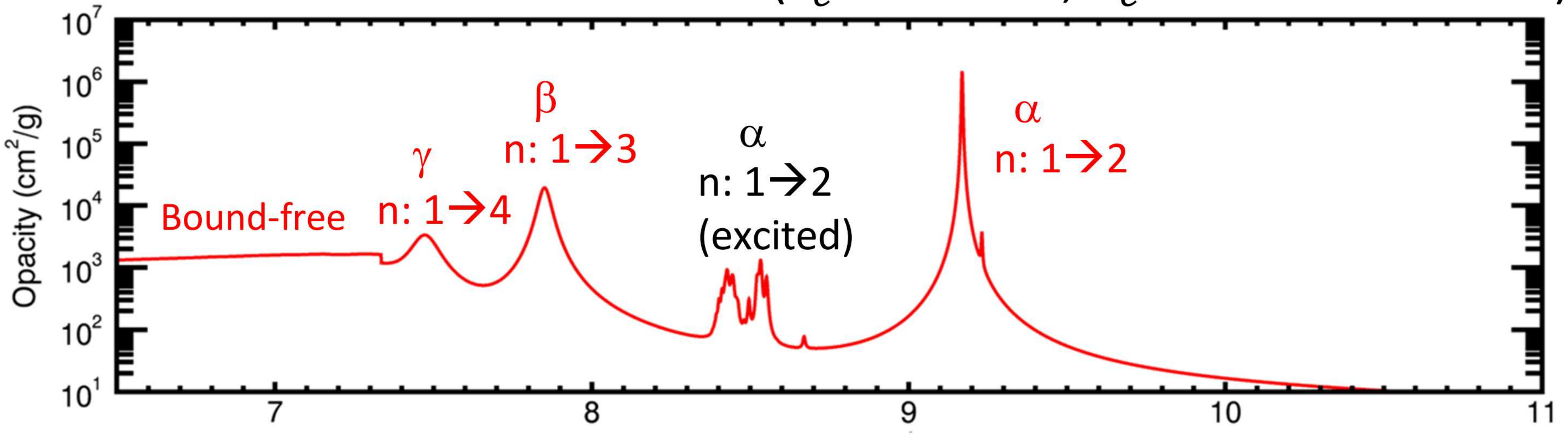


Opacity calculation at Convection-Zone Base is easier for lower atomic number elements

Mg at CZB (Z=12)



CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)



Take-away:

- Opacity calculation is relatively easy with a few bound electrons
- Transitions from excited states add significantly more lines

Iron opacity at Convection-Zone Base is challenging due to large contribution from excited states

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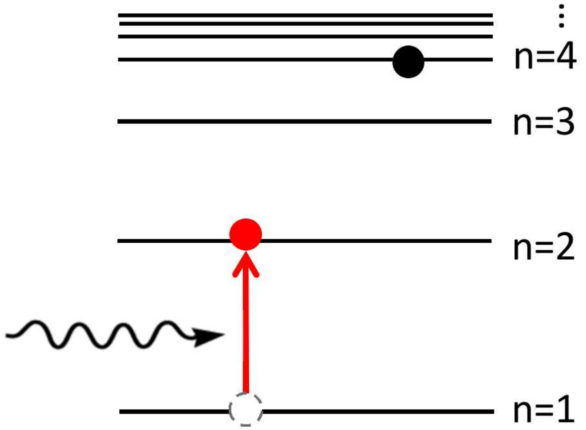
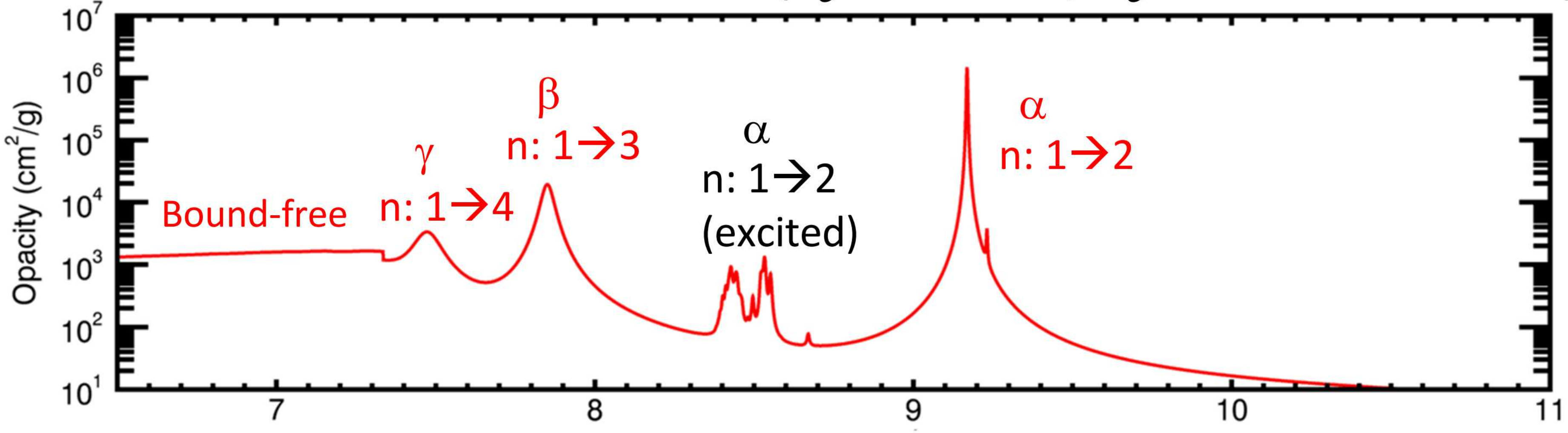
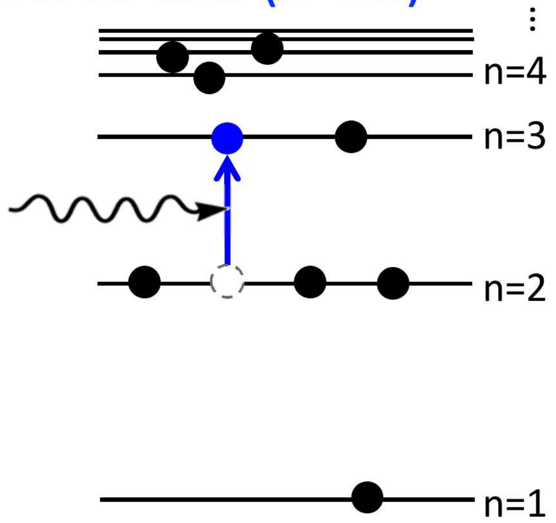
CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)

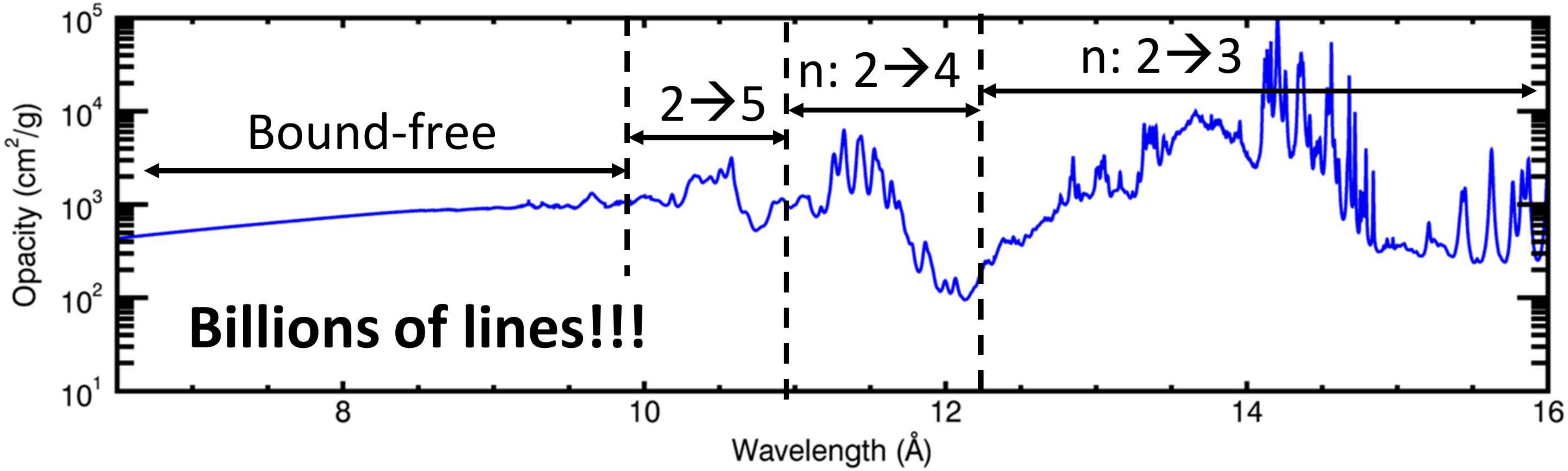
Mg at CZB (Z=12)



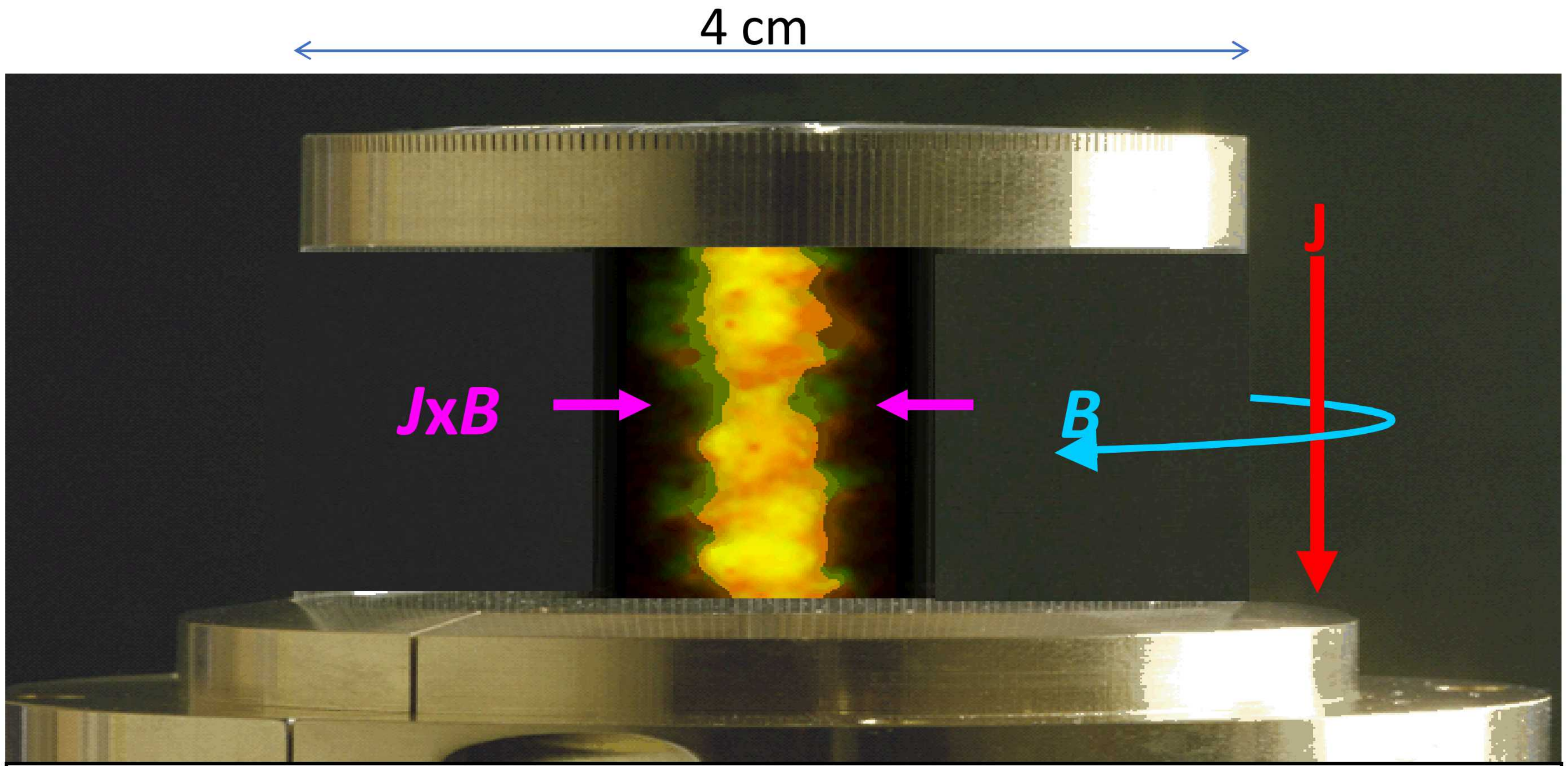


Fe at CZB (Z=26)





The Z machine uses 27 million Amperes to create x-rays



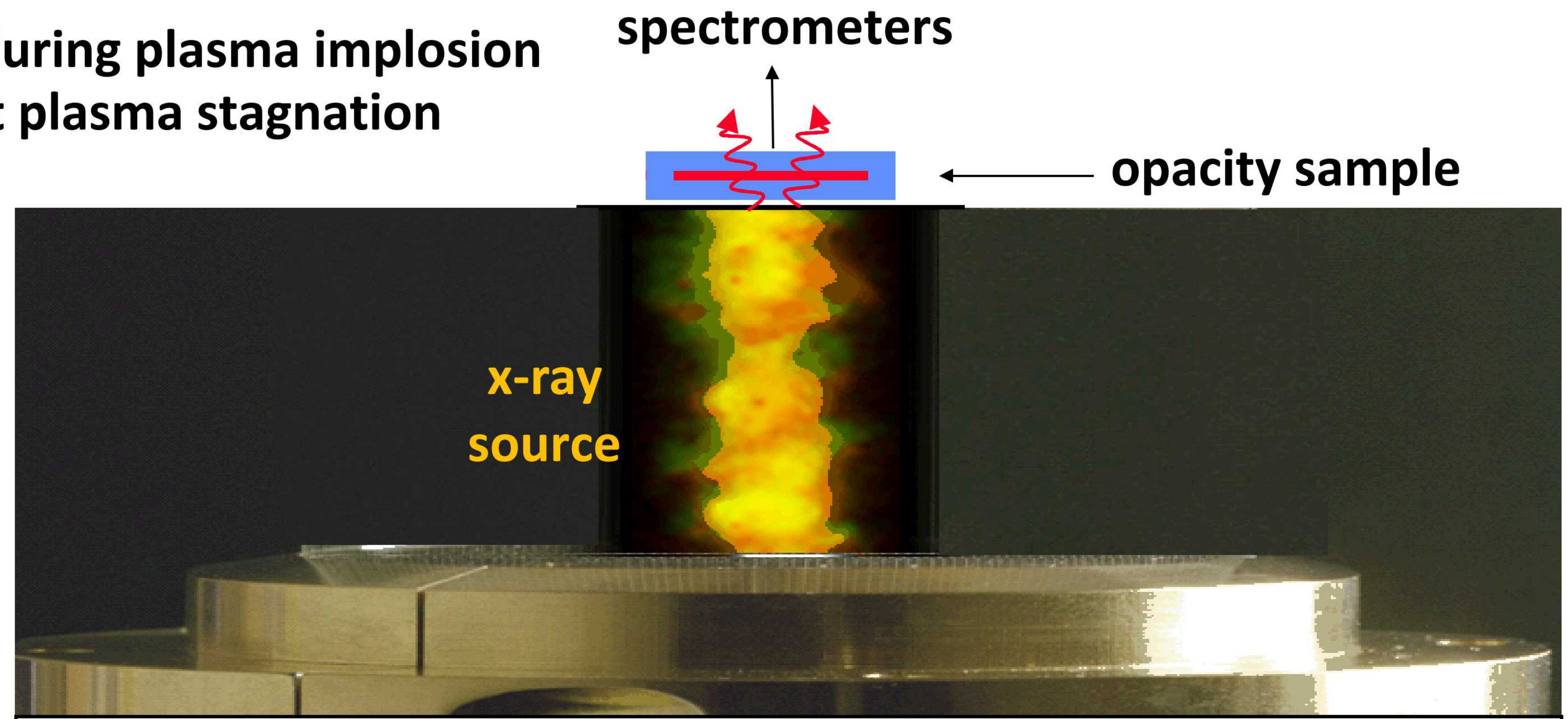
P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

Sanford, *PoP* (2002); Bailey et al., *PoP* (2006); Slutz et al., *PoP* (2006); Rochau et al., *PPCF* (2007)

The Z x-ray source both heats and backlights samples to stellar interior conditions.

<u>**Sample is:**</u>

- **Heated during plasma implosion**
- **Backlit at plasma stagnation**



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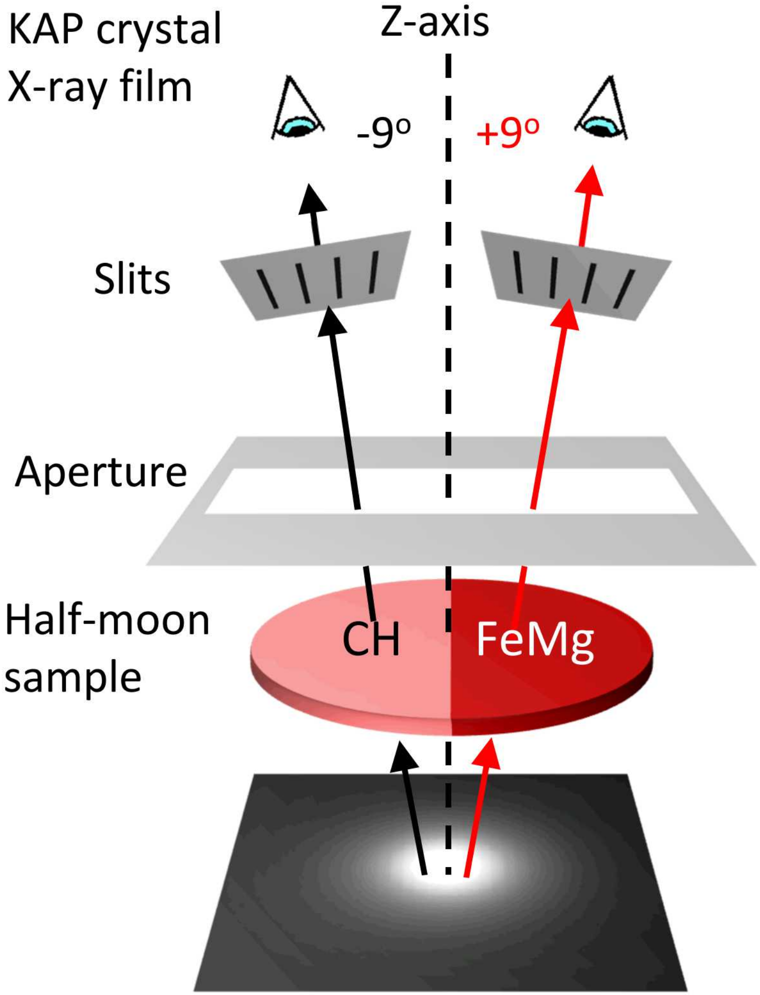
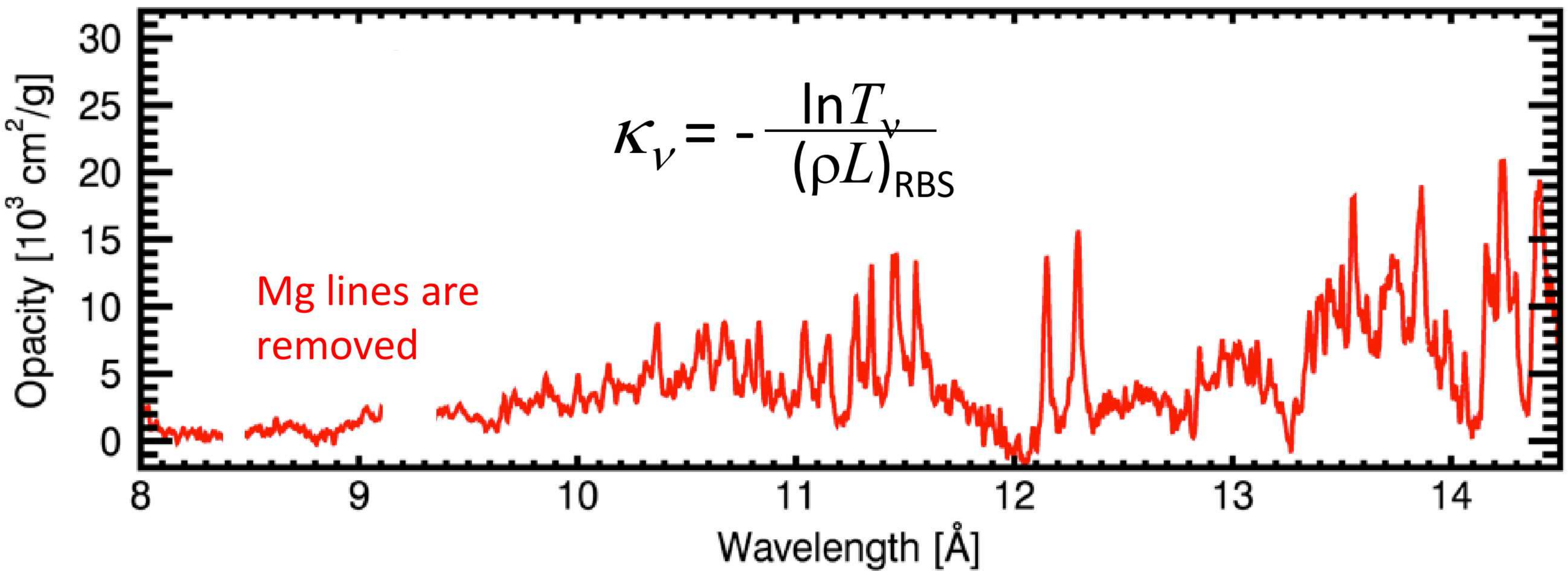
High-temperature Fe opacities are measured using the Z-Pinch opacity science platform





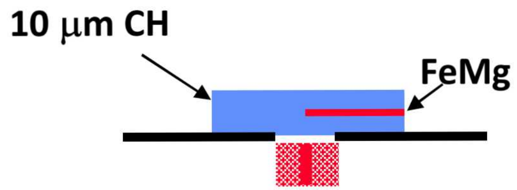
$$\kappa_\nu = -\frac{\ln T_\nu}{(\rho L)_{RBS}}$$

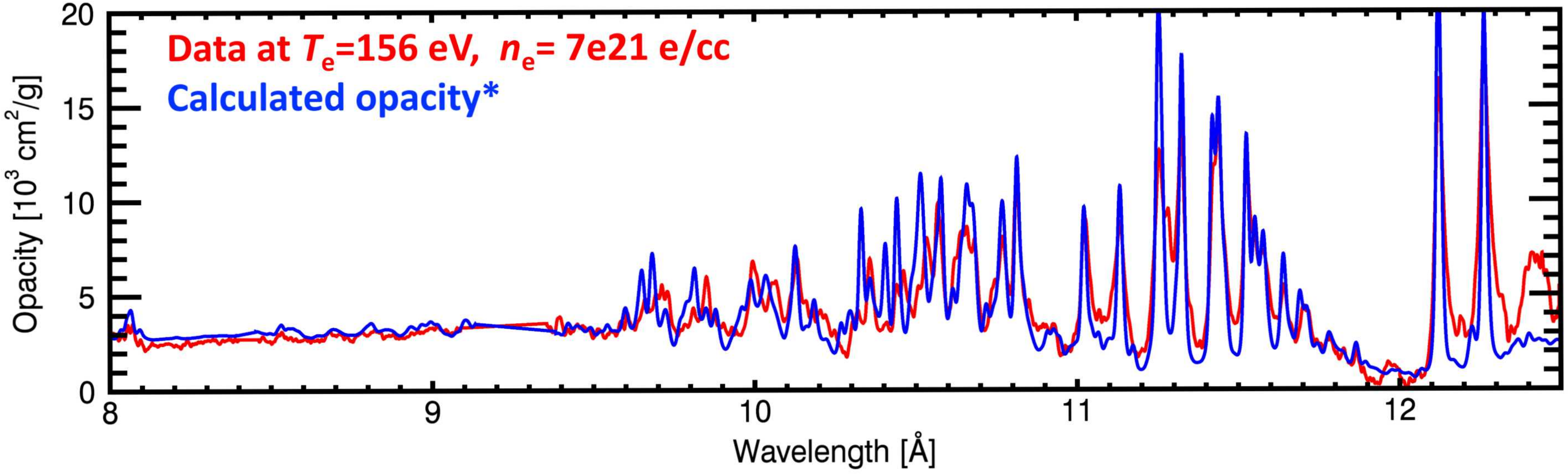
Requirements	SNL Z satisfies:
• Uniform heating →	Volumetric heating
• Mitigating self emission →	350 eV Planckian backlight
• Condition measurements →	Mg K-shell spectroscopy
• Checking reproducibility →	$\geq$ 5 shots

[1] Bailey et al., *Phys Plasmas* 16, 058101 (2009)
[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

Modeled opacity agrees well with the Z iron data at lower temperature T_e and lower density n_e than solar interior

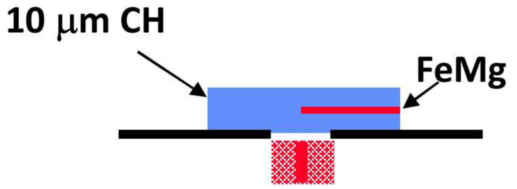
Convection Zone Base: T_e=185 eV, n_e = 90e21 e/cc



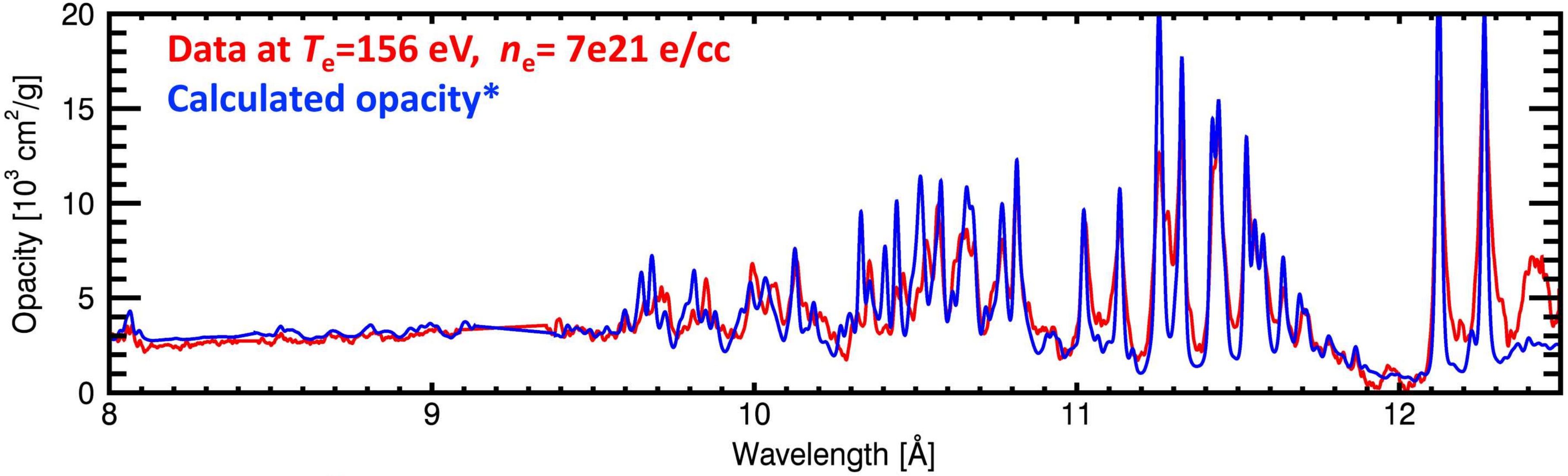


* PrismSPECT: MacFarlane et al, JQSRT (2003)

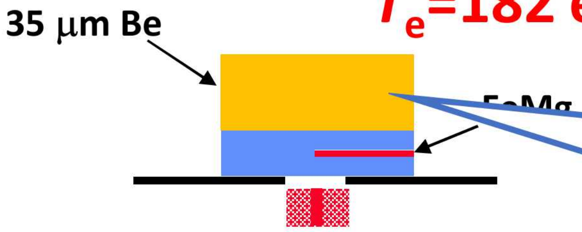
Extra mass on the top helps to increase both T_e and n_e



Convection Zone Base: T_e=185 eV, n_e = 90e21 e/cc



T_e=182 eV, n_e= 38e21 e/cc

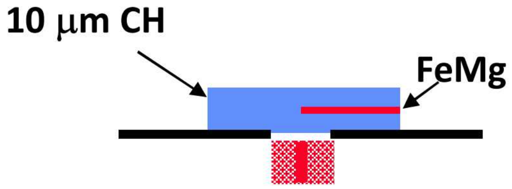


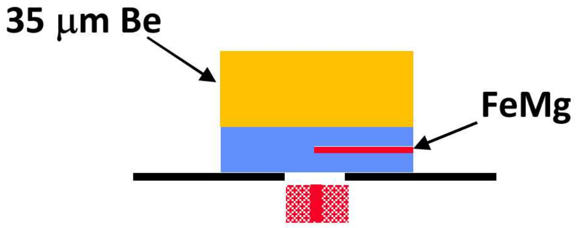
Slows down sample expansion → Higher n_e

Slows down upward sample motion → Higher T_e

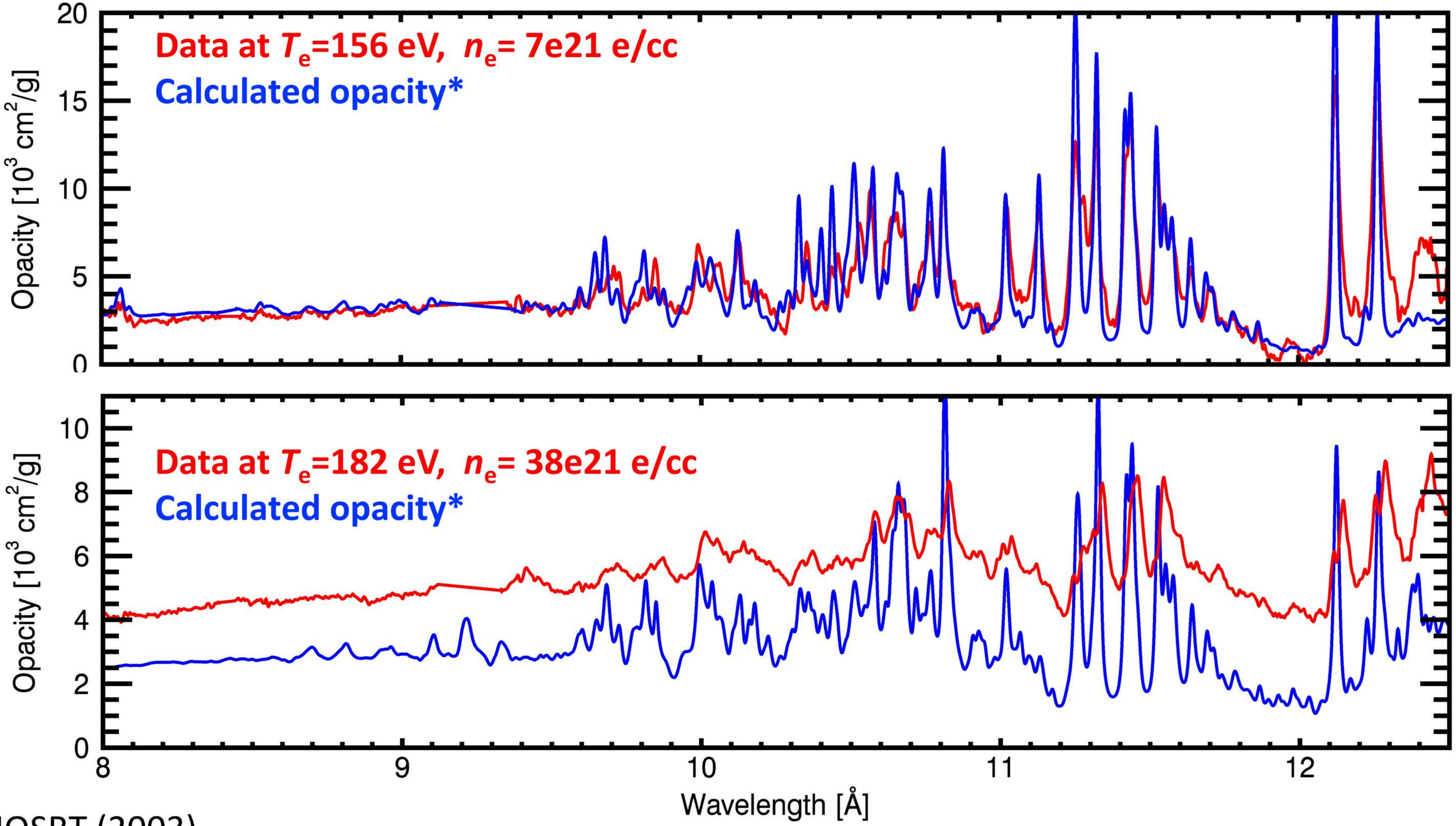
* PrismSPECT: MacFarlane et al, JQSRT (2003)

Modeled opacity shows severe disagreement as T_e and n_e approach solar interior conditions



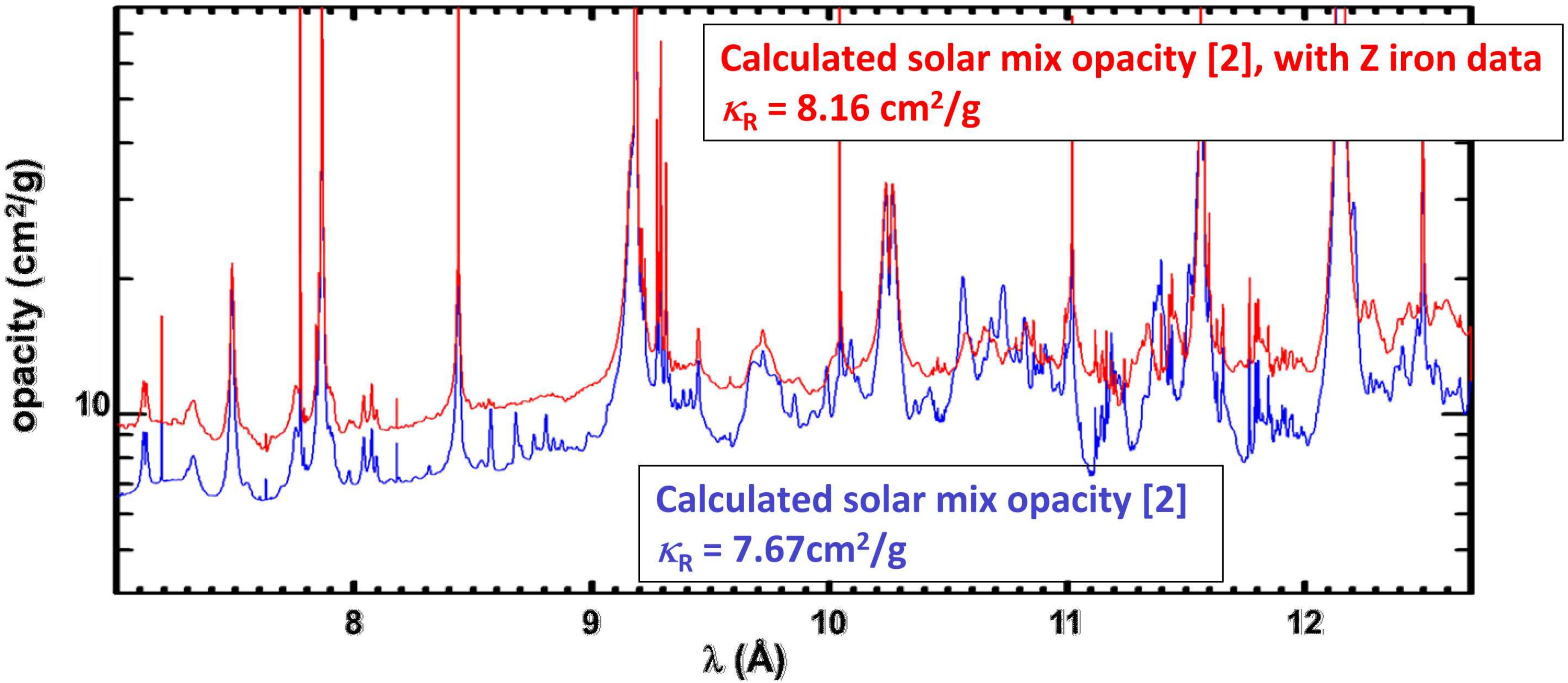


Convection Zone Base: T_e=185 eV, n_e = 90e21 e/cc



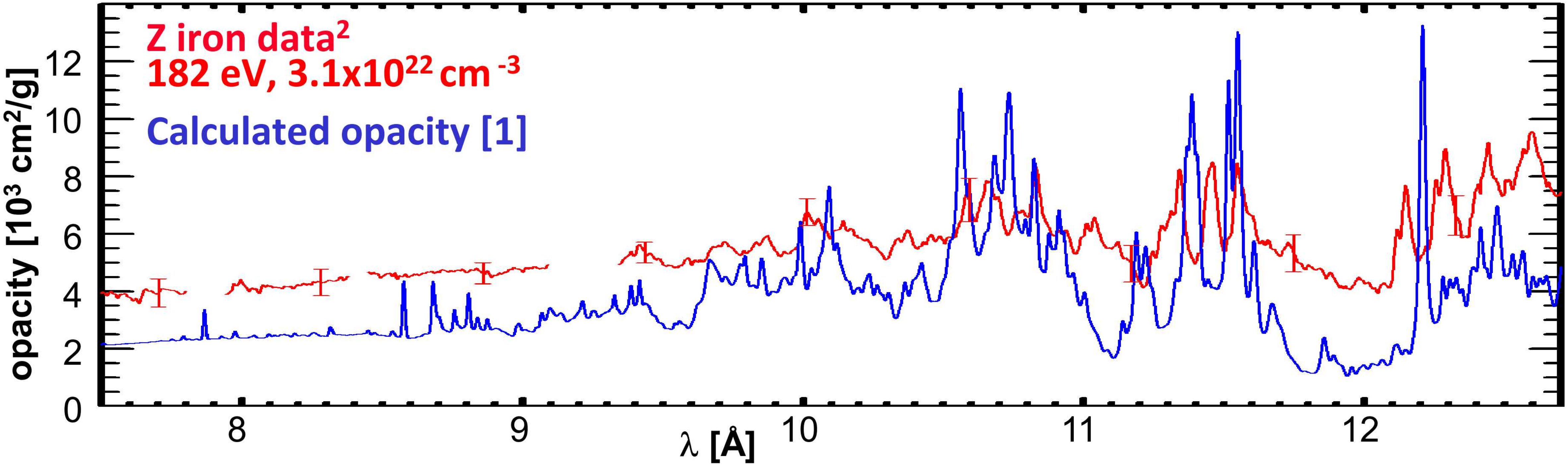
* PrismSPECT: MacFarlane et al, JQSRT (2003)

A solar mixture opacity using Z iron data has ~ 7% higher Rosseland-mean opacity than using calculated iron opacity[1]



- A 7% Rosseland-mean increase partially resolves the solar problem
- Revision of opacity has significant impact on many astrophysical applications

Reported opacity discrepancy is disturbing and deserves further scrutiny



Inaccuracy in theory?

Flaws in experiment?

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

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

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

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 → (Tamper self emission, Extraneous background) Quantified amount do not explain the discrepancy

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

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

Numerical evidence

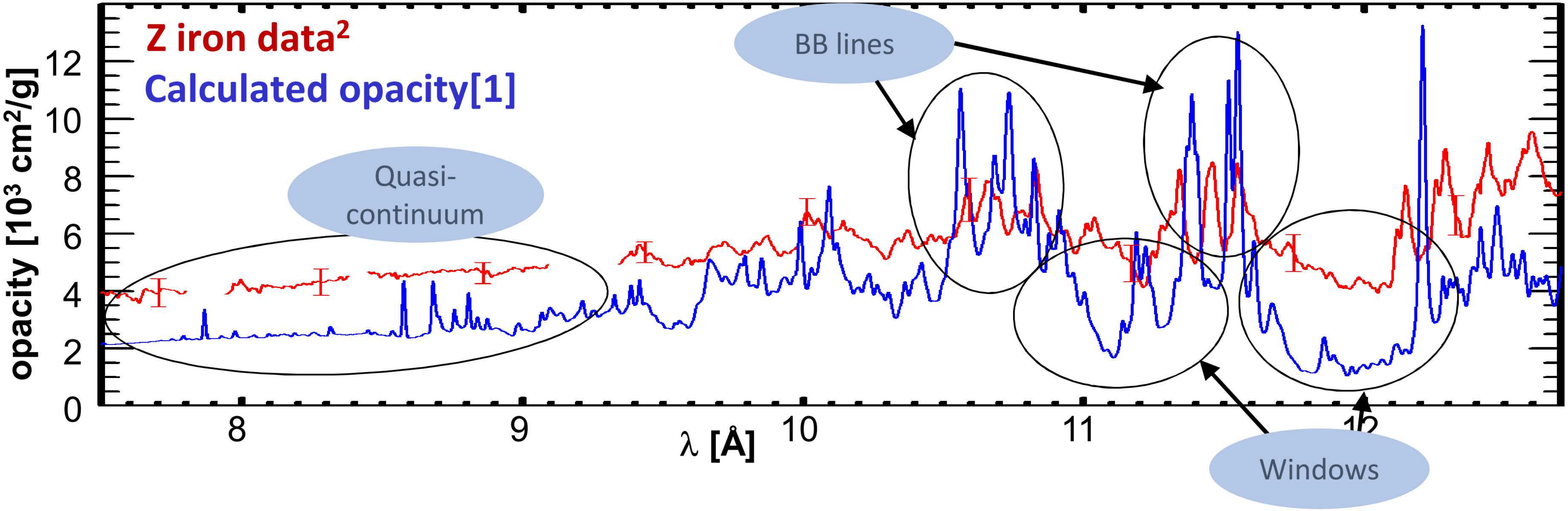
- Plasma T_e and n_e errors → Suggested n_e error did not explain the discrepancy
- Sample areal density errors
- Transmission errors
- Spatial non-uniformities
- Temporal non-uniformities
- Departures from LTE
- Fe self emission
- Tamper self emission
- Extraneous background
- Sample contamination
- Tamper transmission difference

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)

Both opacity calculation and reported model-data discrepancy are so complex; more constraints needed



Both opacity calculation and reported model-data discrepancy are so complex; more constraints needed

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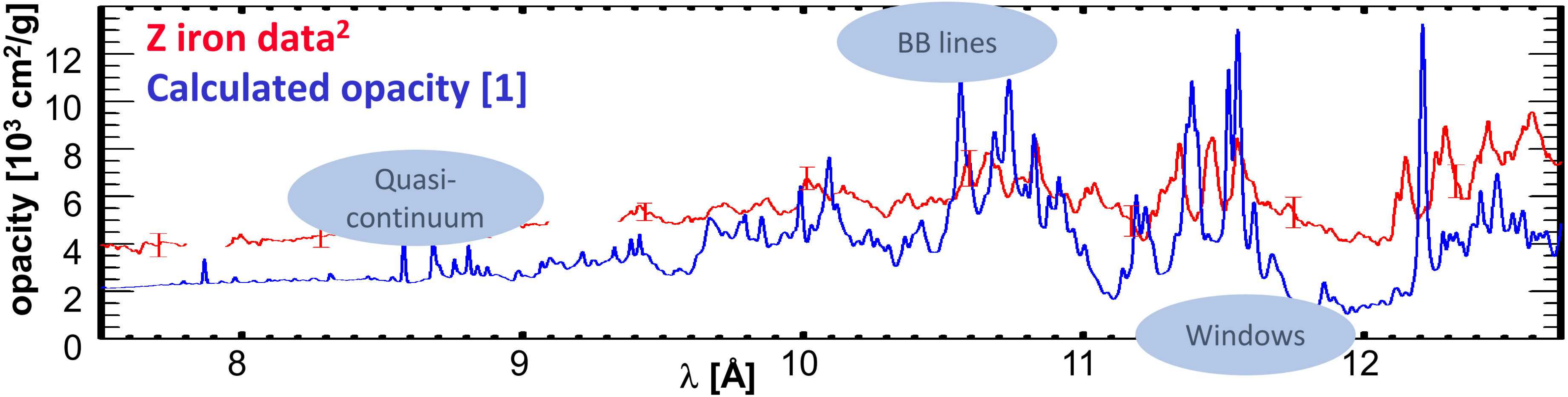
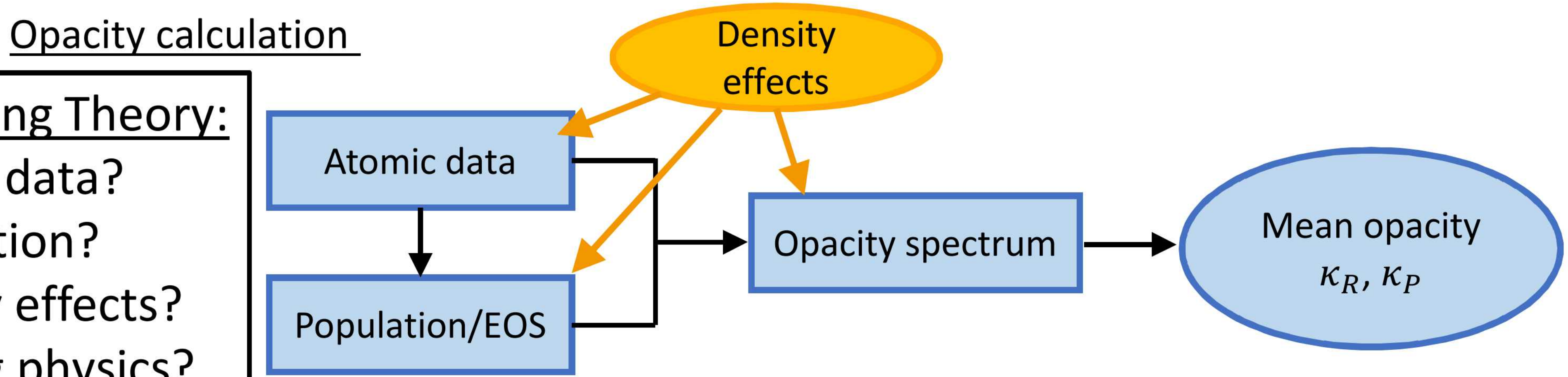


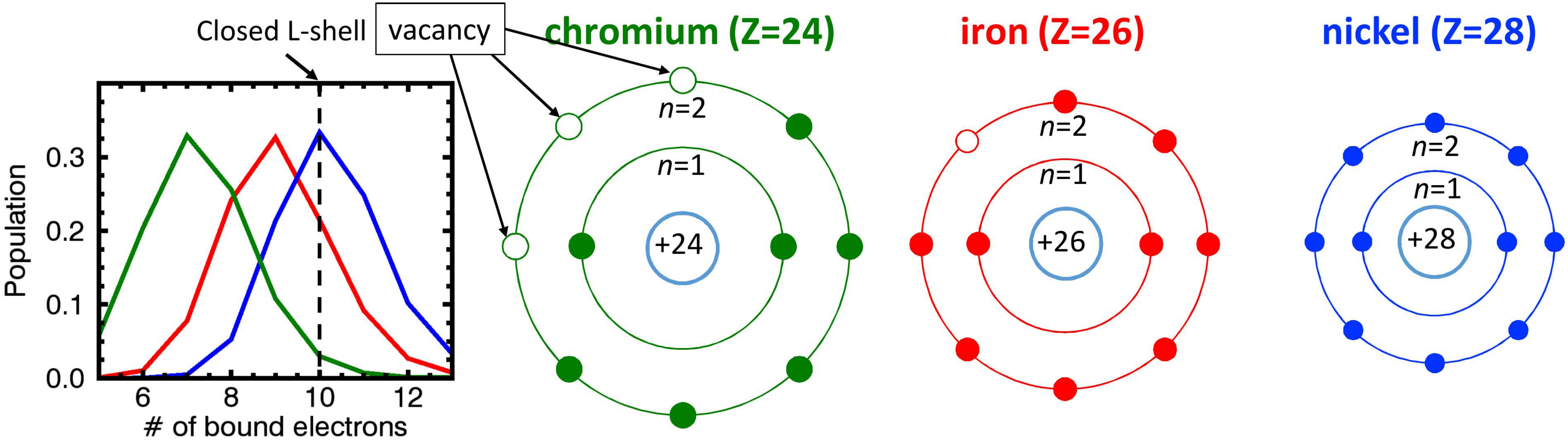


Questioning Theory:

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

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

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



Questioning Theory:

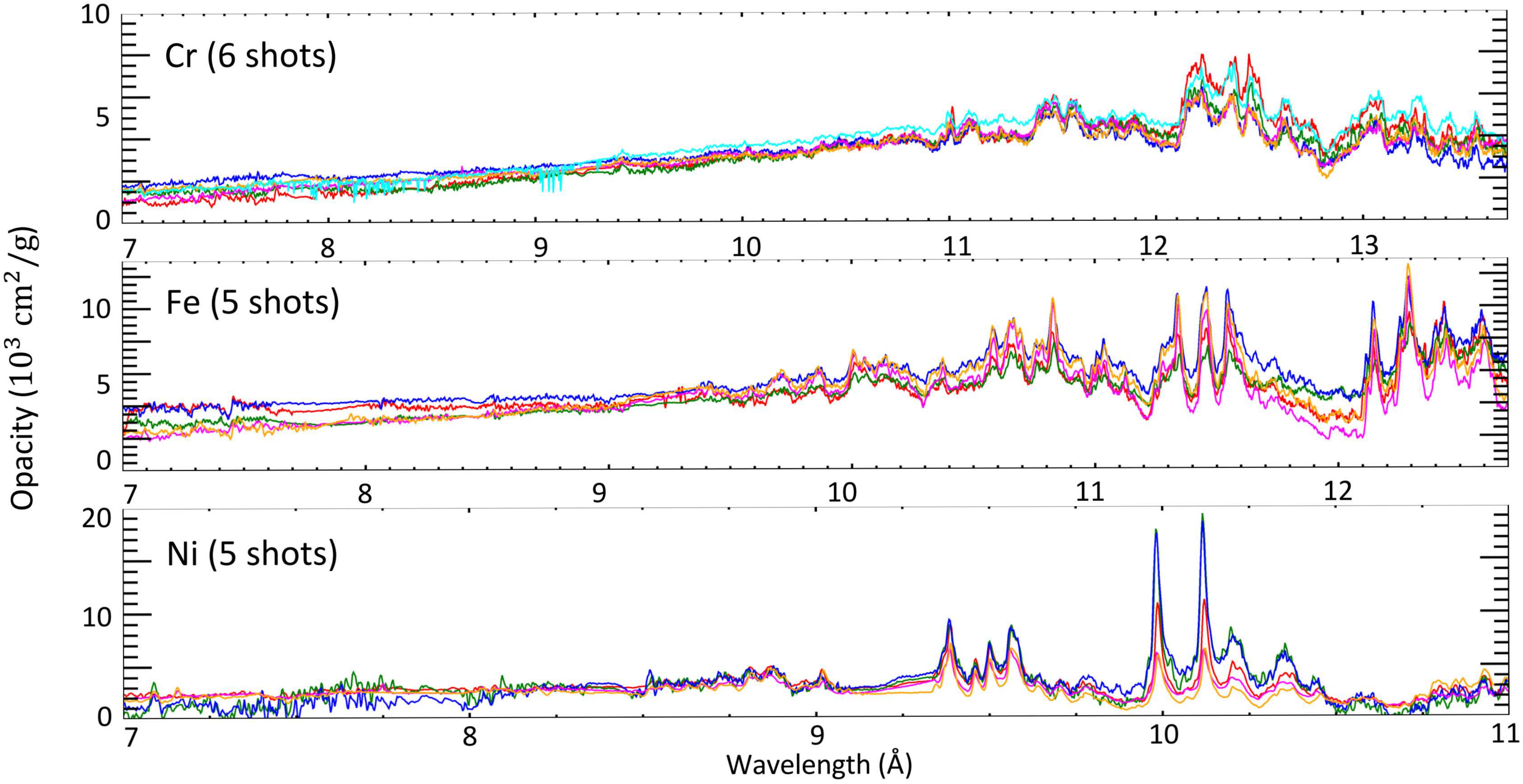
- Atomic data?
- Population?
- Density effects?
- Missing physics?

L-shell vacancies

More ← # of excited states — Less

Density effects

Excellent reproducibility is confirmed from all three elements, demonstrating experiment/analysis reliability



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

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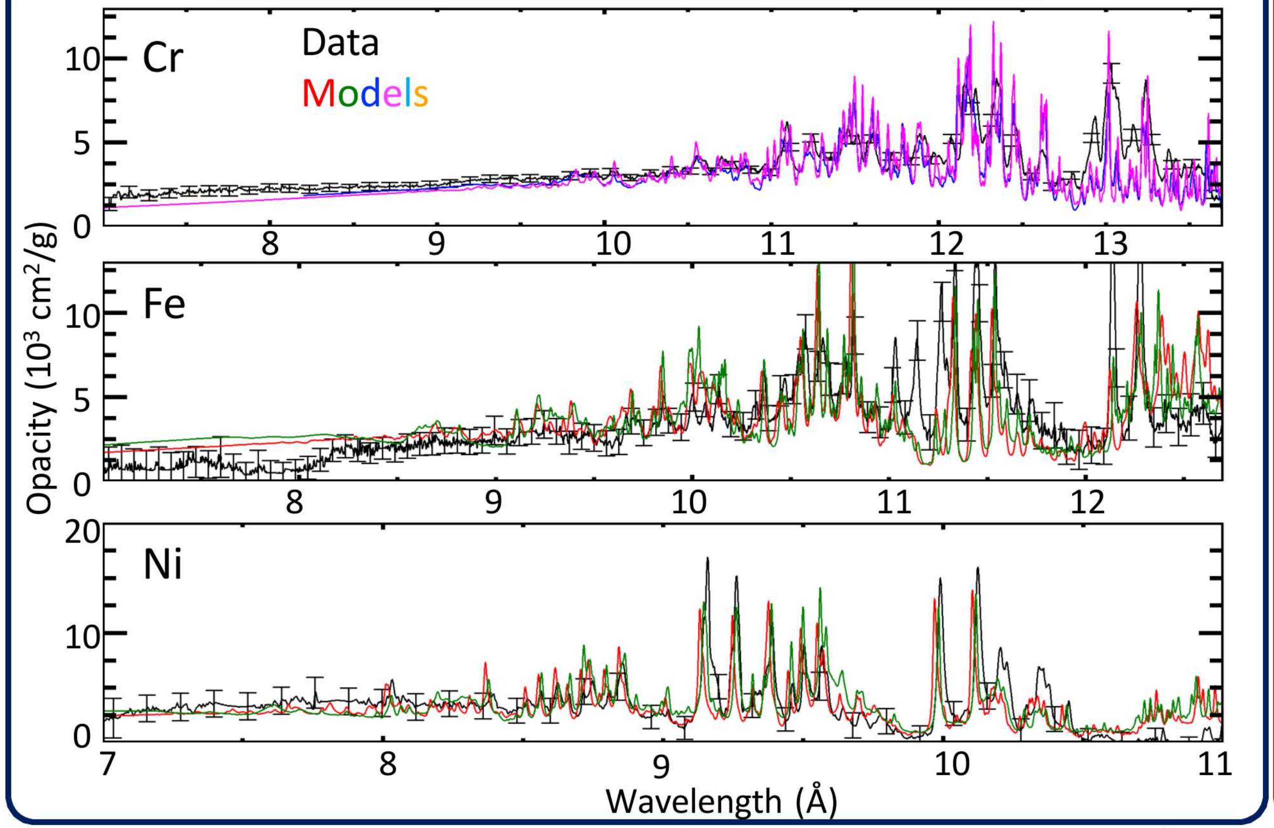
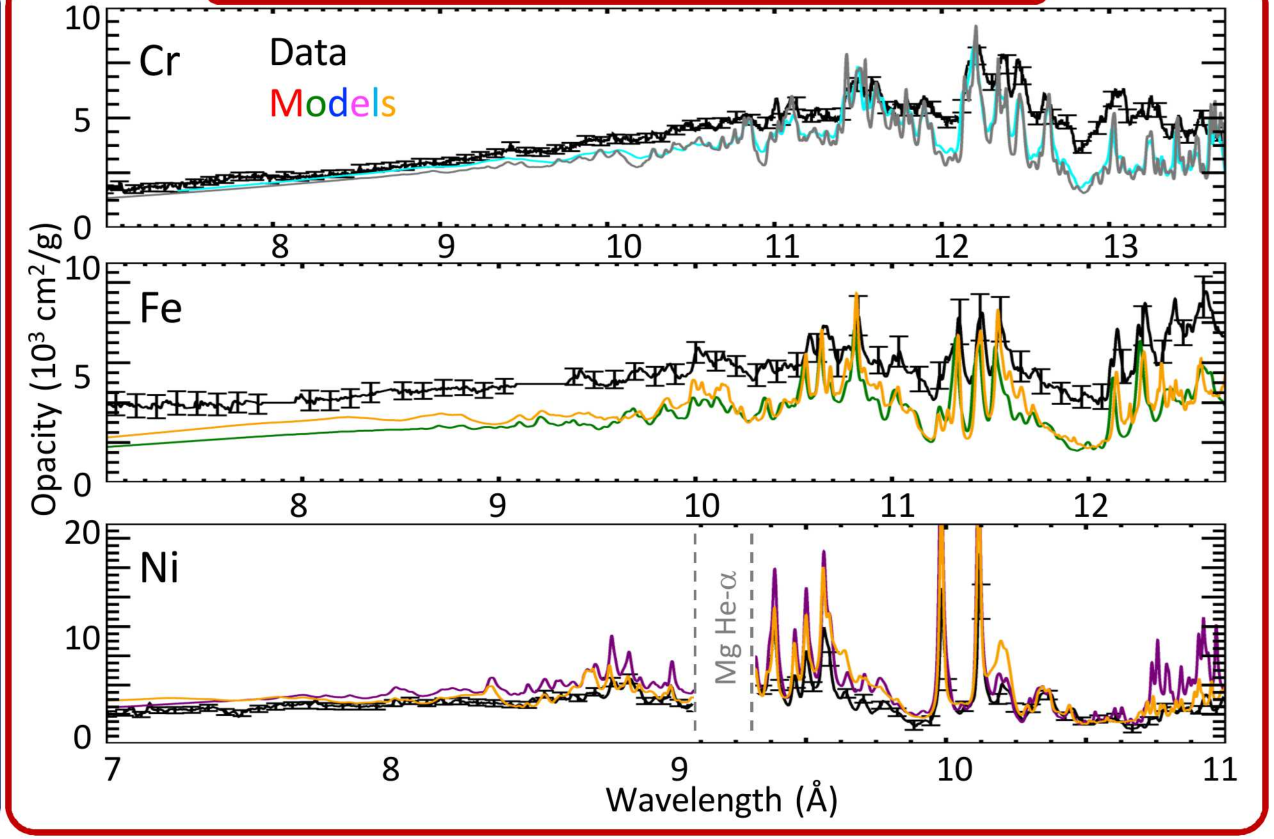
Anchor1: $T_e \sim 165$ eV, $n_e \sim 7 \times 10^{21}$ cm^{-3}



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



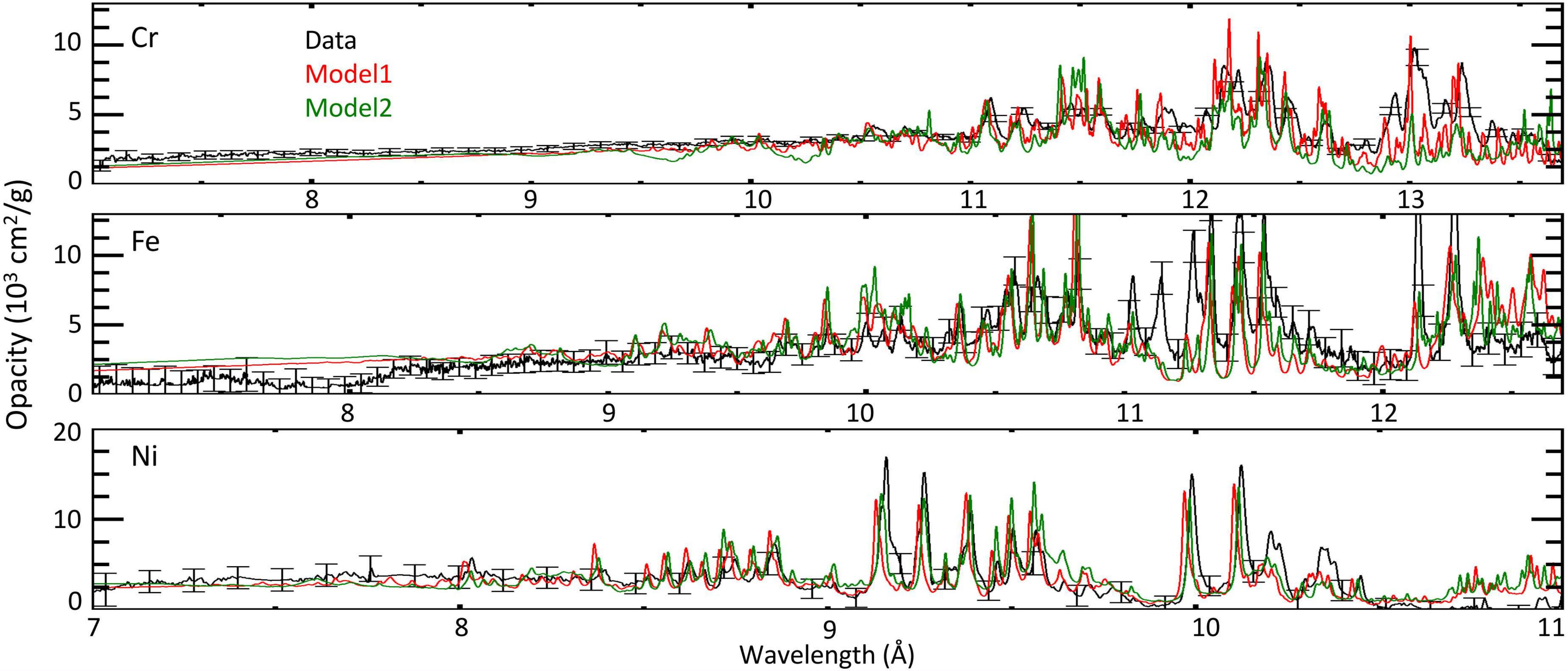
- **Opacities are measured at $T_e > 150$ eV**
- **T_e and n_e are diagnosed independently**
- **Reproducibility is confirmed**

Systematically performed for Cr, Fe, Ni at two conditions

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

Anchor1: Modeled and measured opacities agree reasonably well at lower temperature and density

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



Anchor2: Interesting element-dependent disagreement appears as approaching to stellar interior conditions

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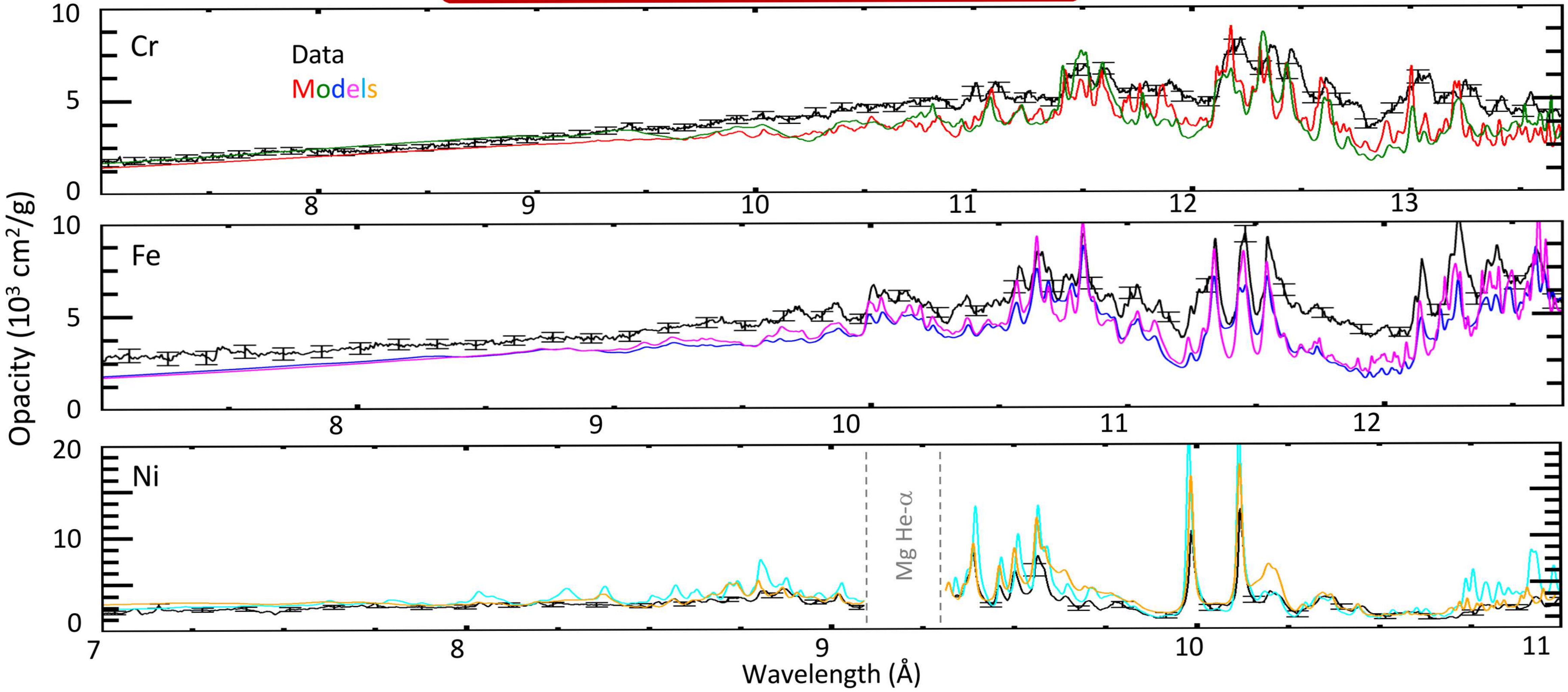
$T_e \sim 180 \text{ eV}, n_e \sim 30 \times 10^{21} \text{ cm}^{-3}$



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

Systematic study successfully narrowed down sources of *BB* and *Window* while deepening the mystery on *BF*

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Systematic Study of L-Shell Opacity at Stellar Interior Temperatures

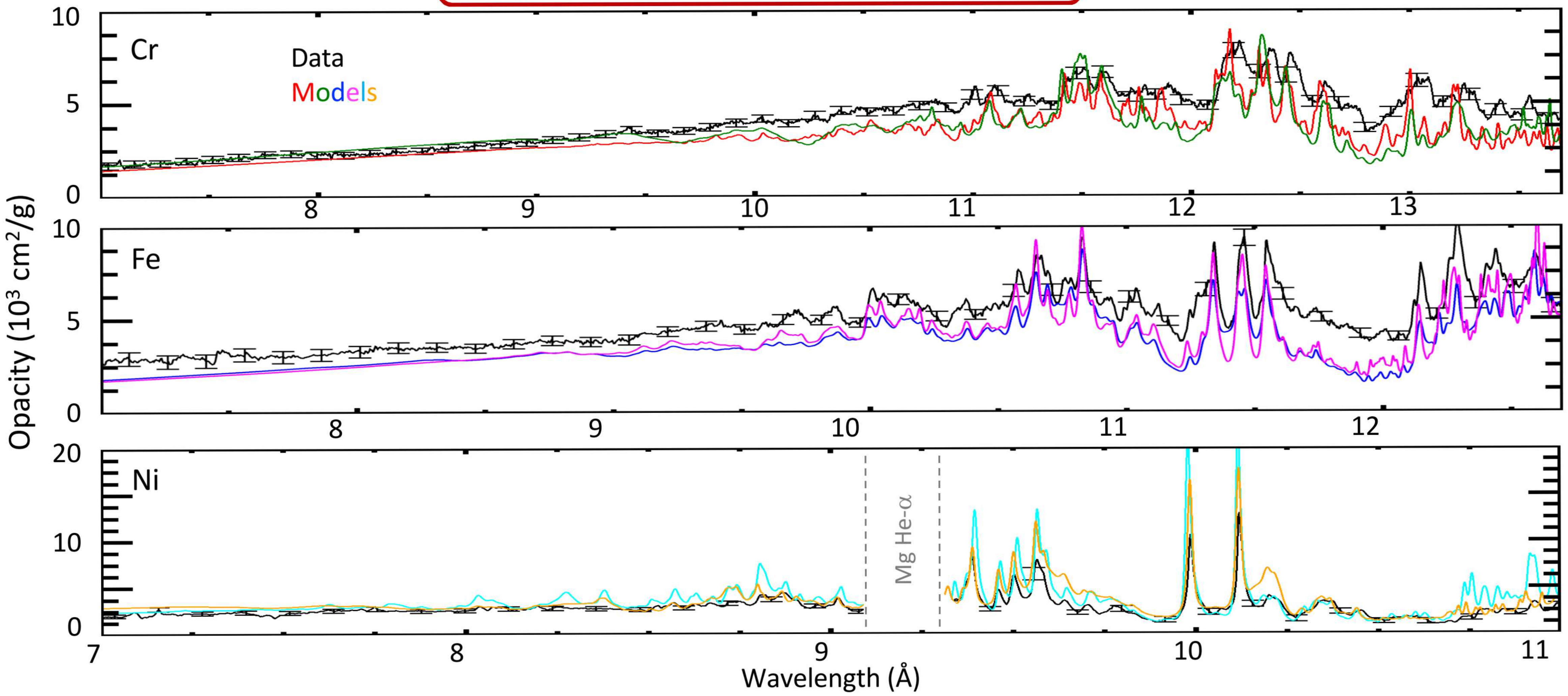
T. Nagayama, J. E. Bailey, G. P. Loisel, G. S. Dunham, G. A. Rochau, C. Blancard, J. Colgan, Ph. Cossé, G. Faussurier, C. J. Fontes, F. Gilleron, S. B. Hansen, C. A. Iglesias, I. E. Golovkin, D. P. Kilcrease, J. J. MacFarlane, R. C. Mancini, R. M. More, C. Orban, J.-C. Pain, M. E. Sherrill, and B. G.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

Phys. Rev. Lett. 122, 235001 – Published 10 June 2019

Physics See Viewpoint: Plot Thickens in Solar Opacity Debate

Anchor2: Interesting element-dependent disagreement appears as approaching to stellar interior conditions

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



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

Anchor2: Interesting element-dependent disagreement appears as approaching to stellar interior conditions

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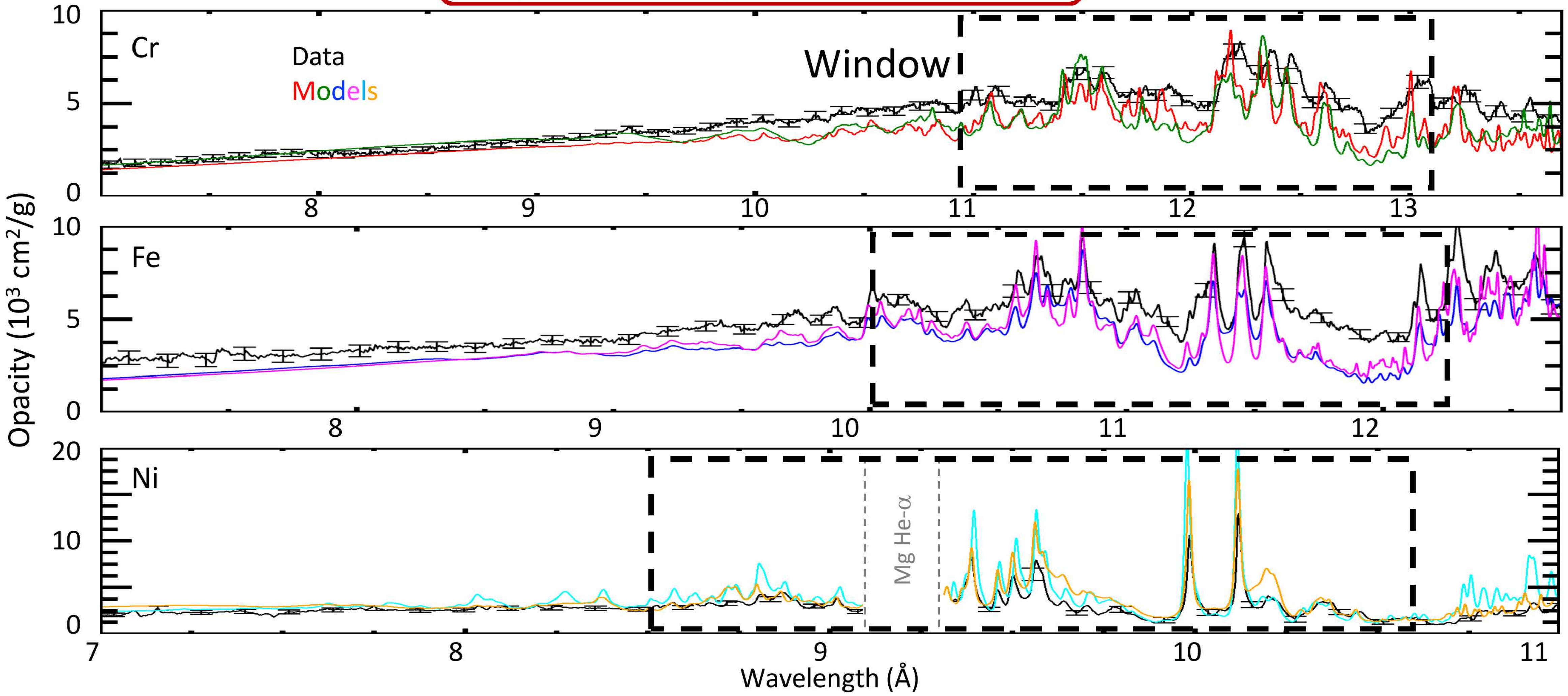
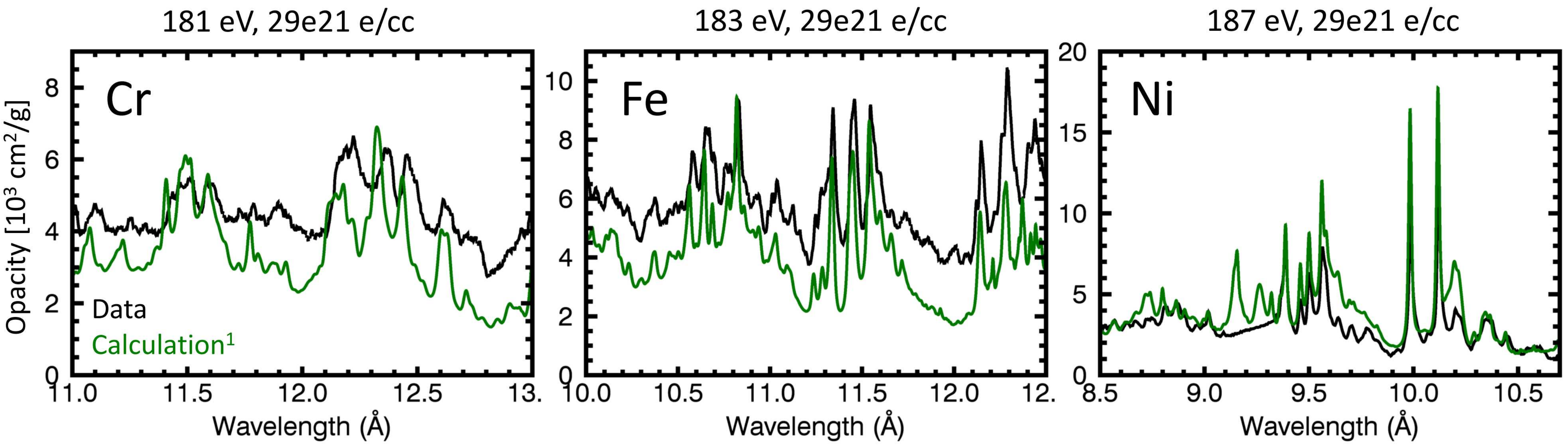
$T_e \sim 180$ eV, $n_e \sim 30 \times 10^{21}$ cm^{-3}

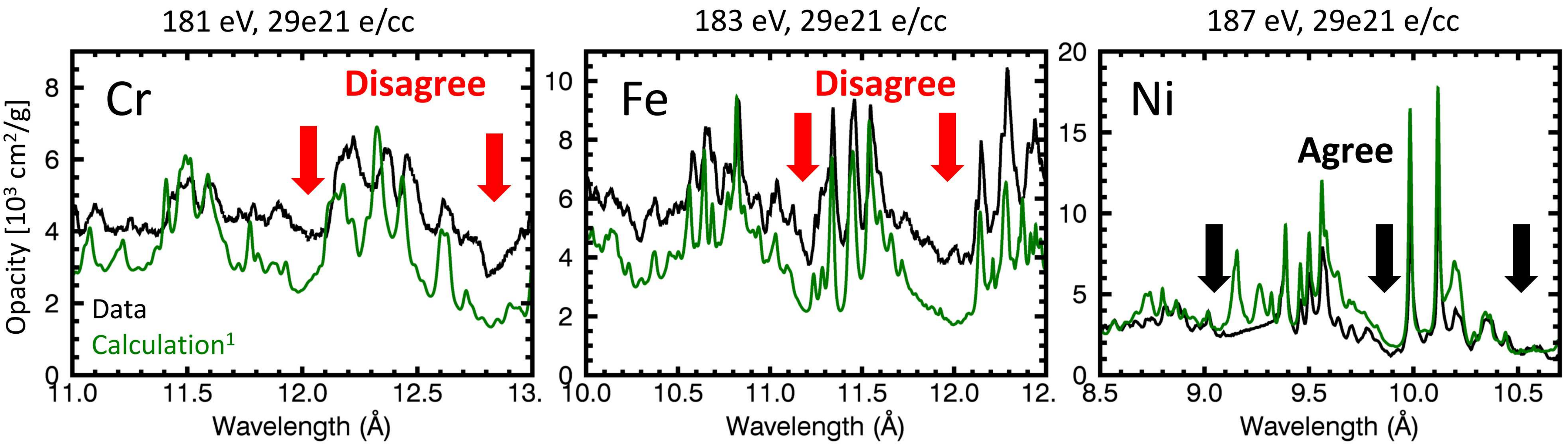


MODELS: ATOMIC, NOMAD, OPAS, SCO-RCG, SCRAM, TOPAZ

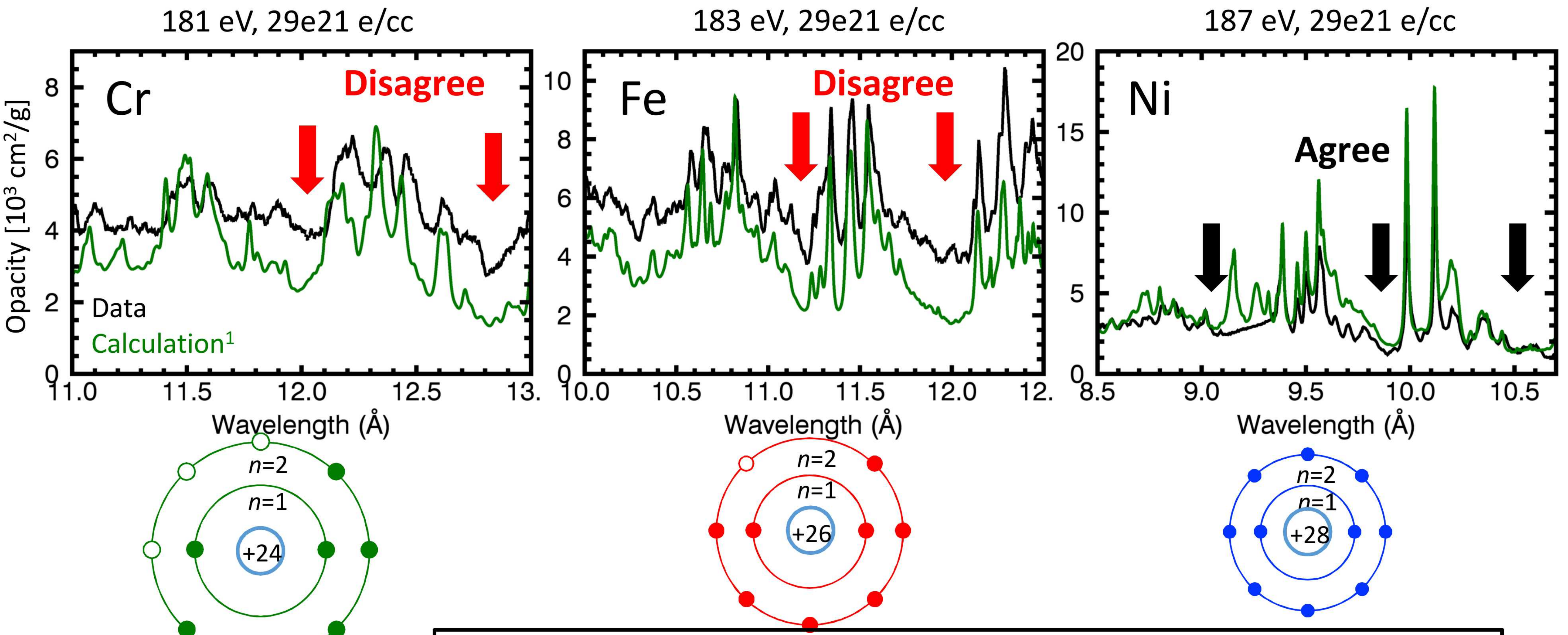
Window: Filled window observed from Cr and Fe, but not Ni



Window: Filled window observed from Cr and Fe, but not Ni



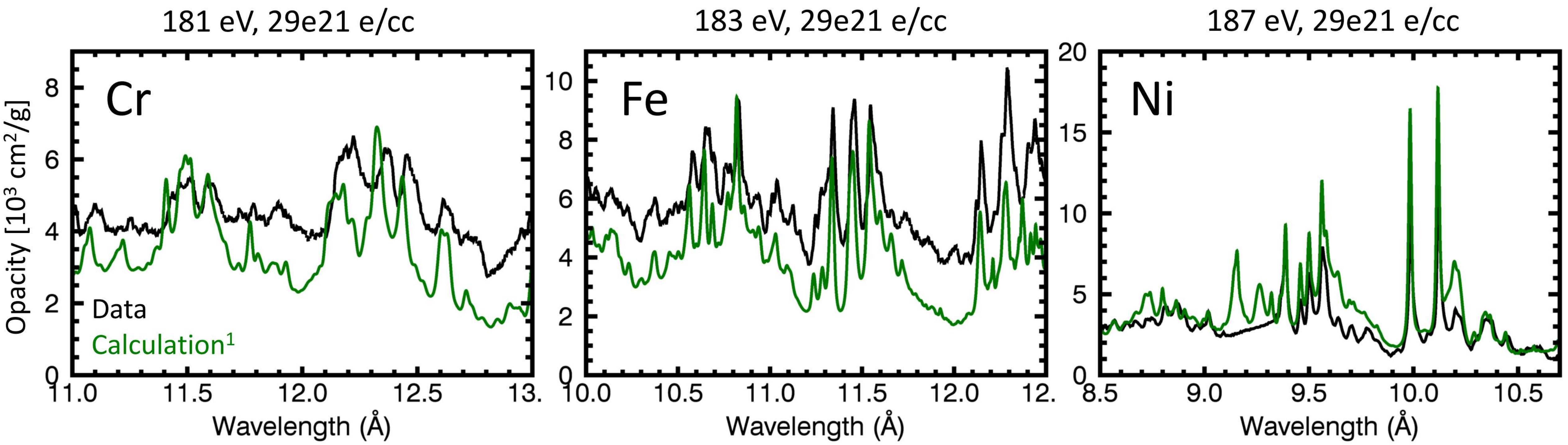
Window: Filled window observed from Cr and Fe, but not Ni



Hypothesis: Challenge associated with open L-shell configuration

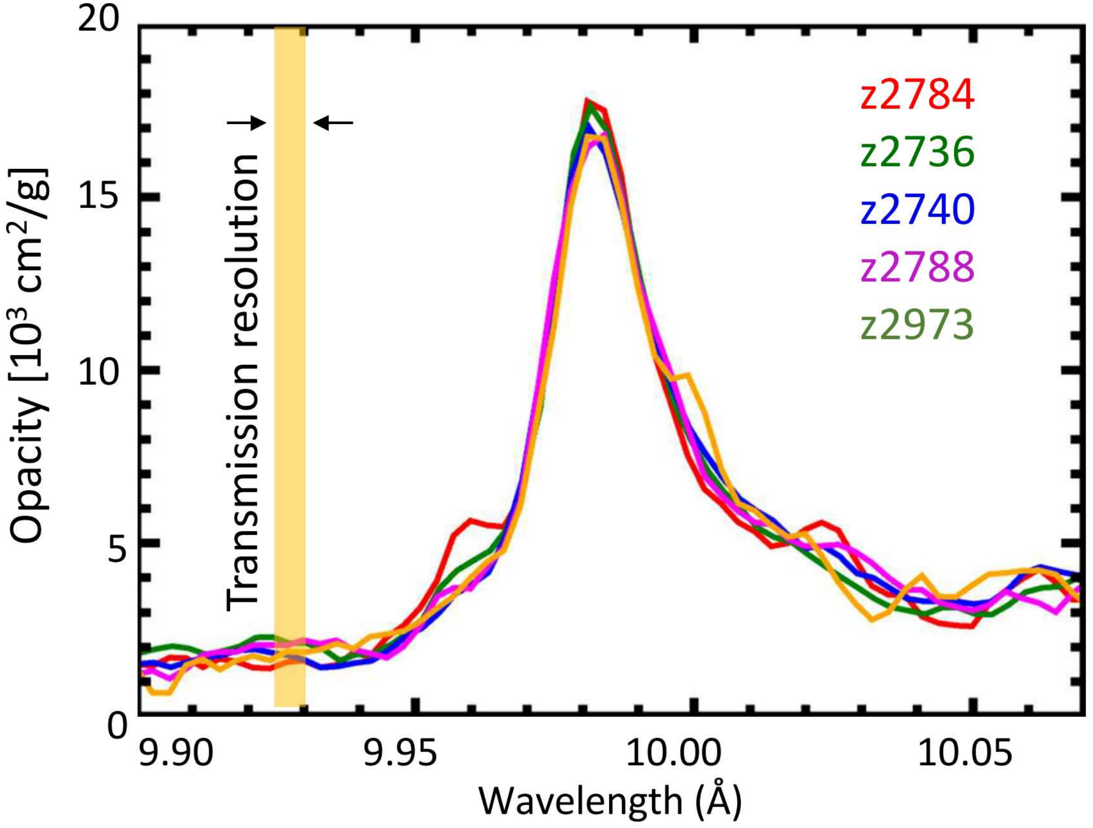
[1] SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

Can we check accuracy of modeled line shapes?



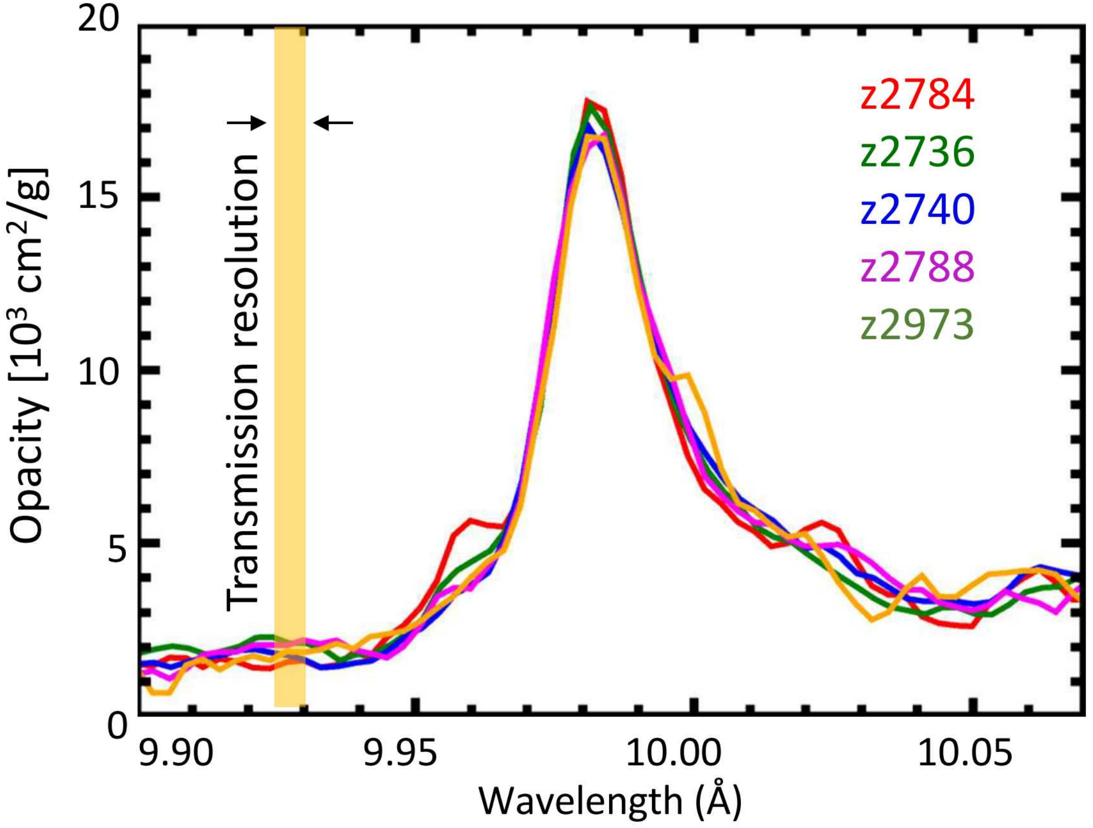
[1] SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

Line-shape of Ne-like Ni 2p-4d is accurately measured and appropriate to test approximations used in models

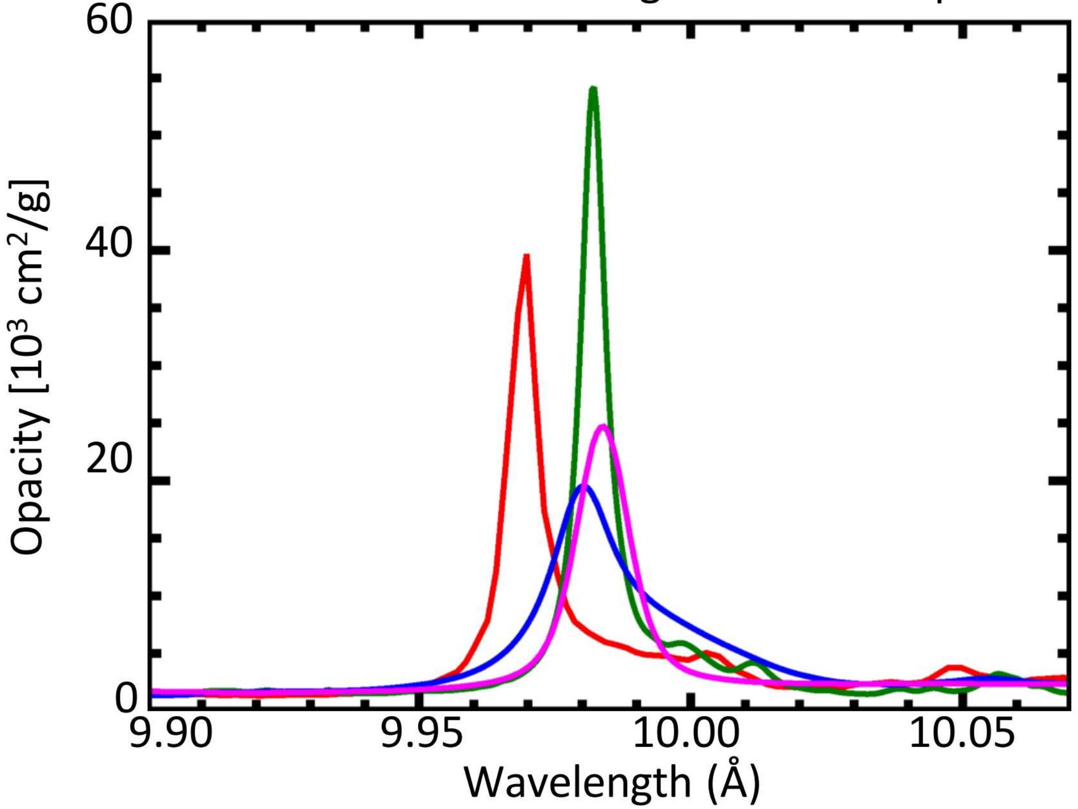


- This line-shape is reproduced by five experiments
- Models employ simple approximations for L-shell line shapes, which are not tested.
    - Electron broadening
    - Static ion broadening
    - Satellite contributions

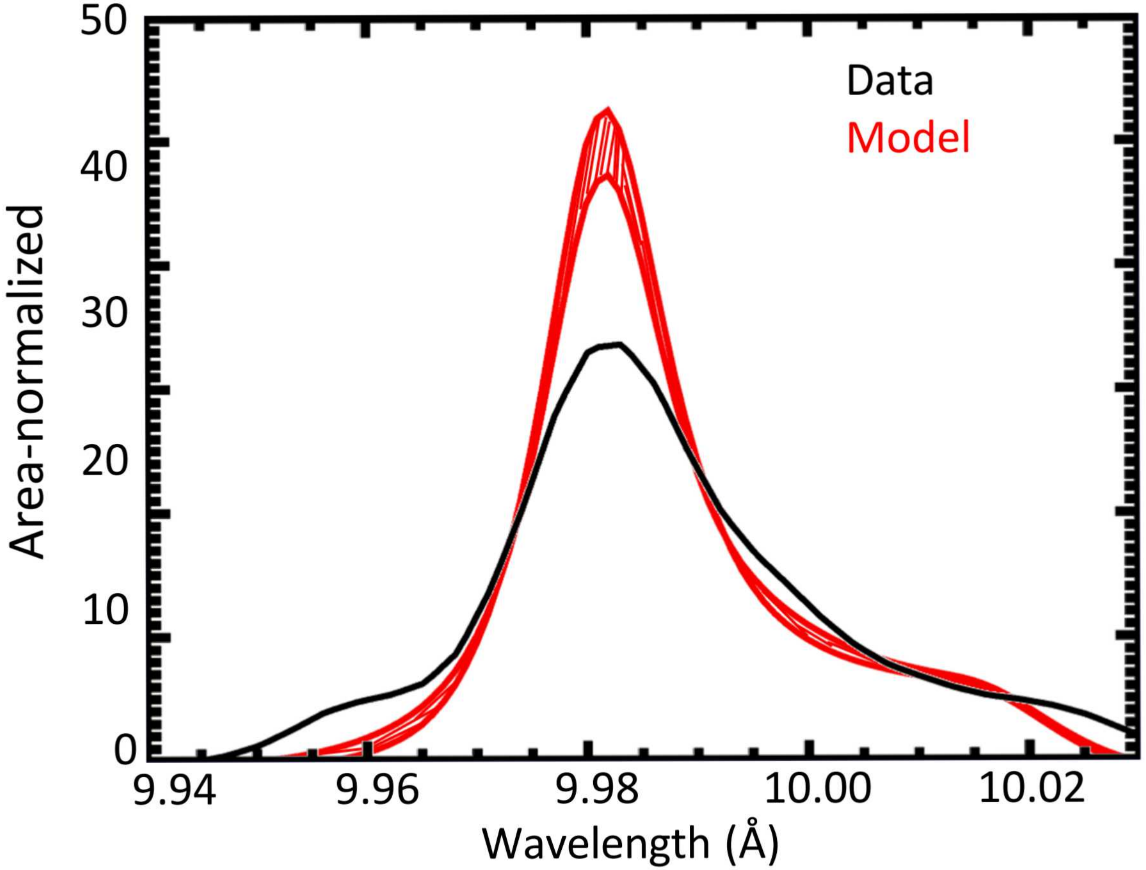
Line-shape of Ne-like Ni 2p-4d is accurately measured and appropriate to test approximations used in models



Different models disagree in line shapes

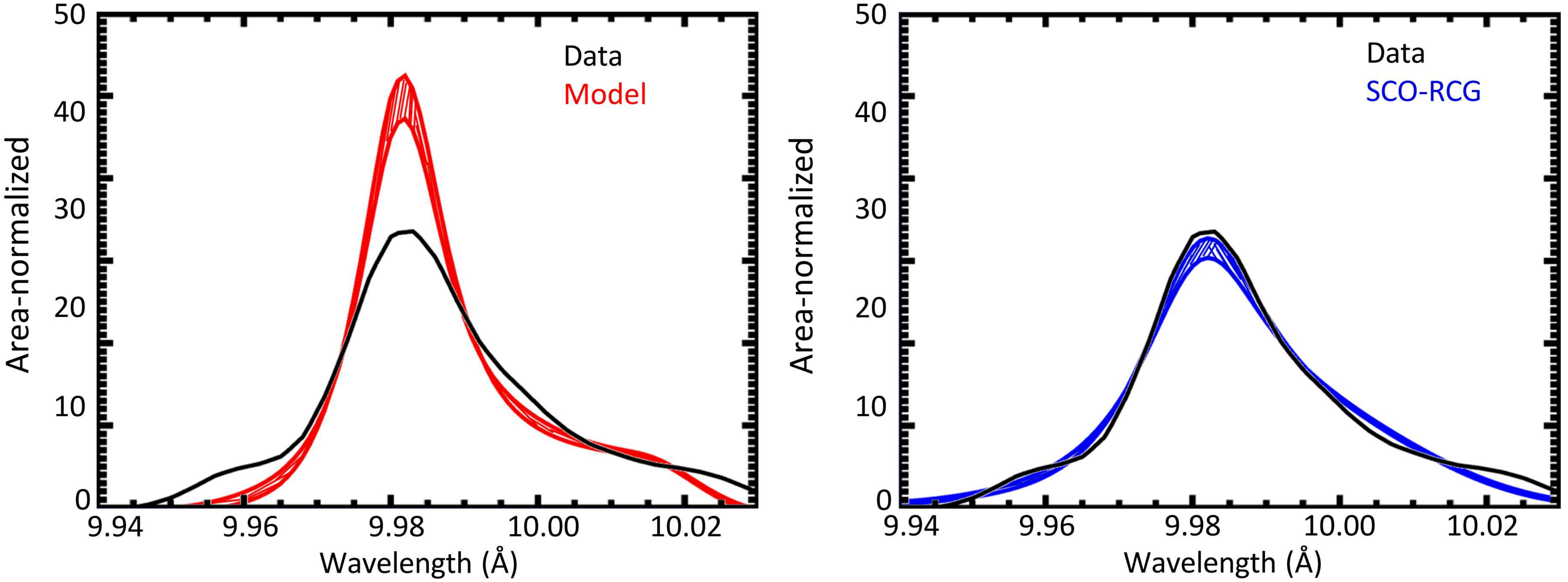


Most models underestimate the L-shell line widths



Models need to refine treatment of atomic interaction with plasma and excited states.

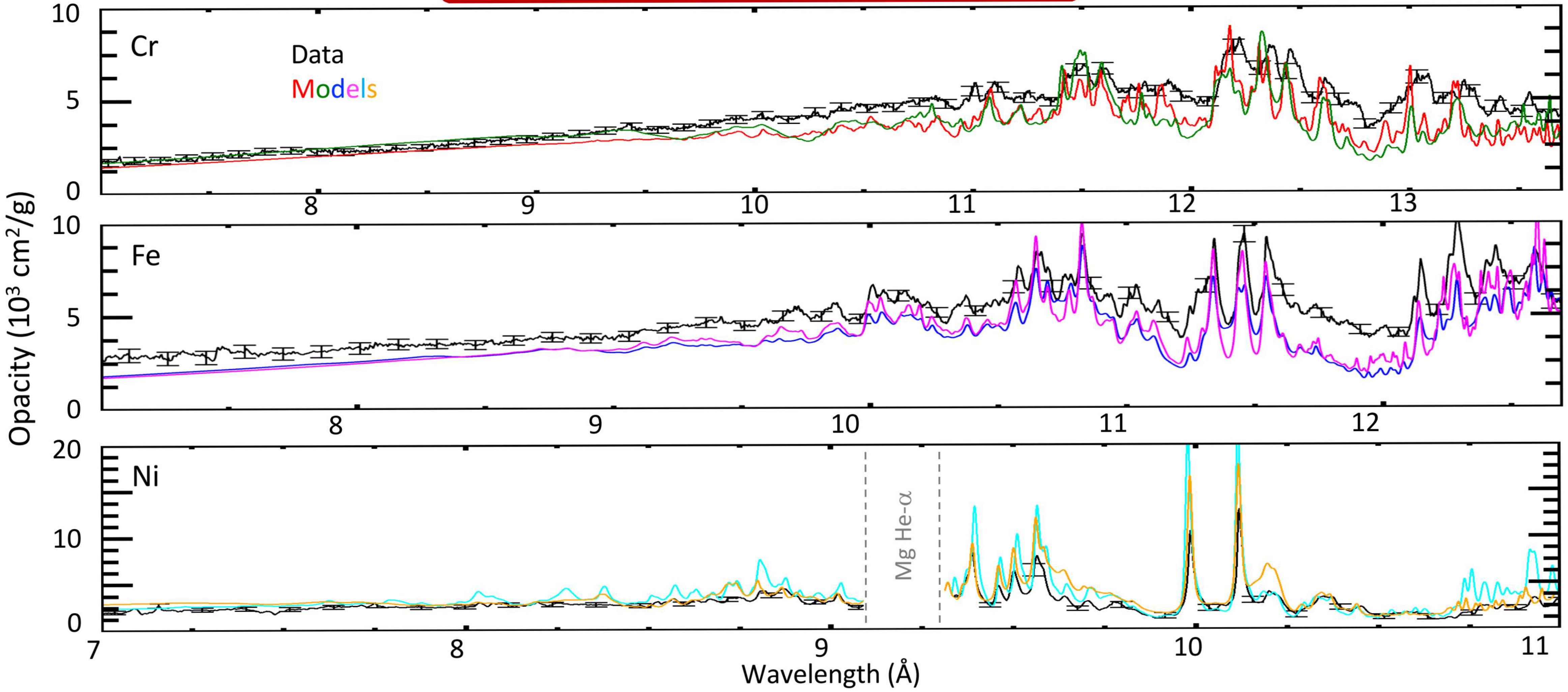
SCO-RCG model predicted the measured L-shell line width reasonably well



Models need to refine treatment of atomic interaction with plasma and excited states.

Anchor2: Interesting element-dependent disagreement appears as approaching to stellar interior conditions

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



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

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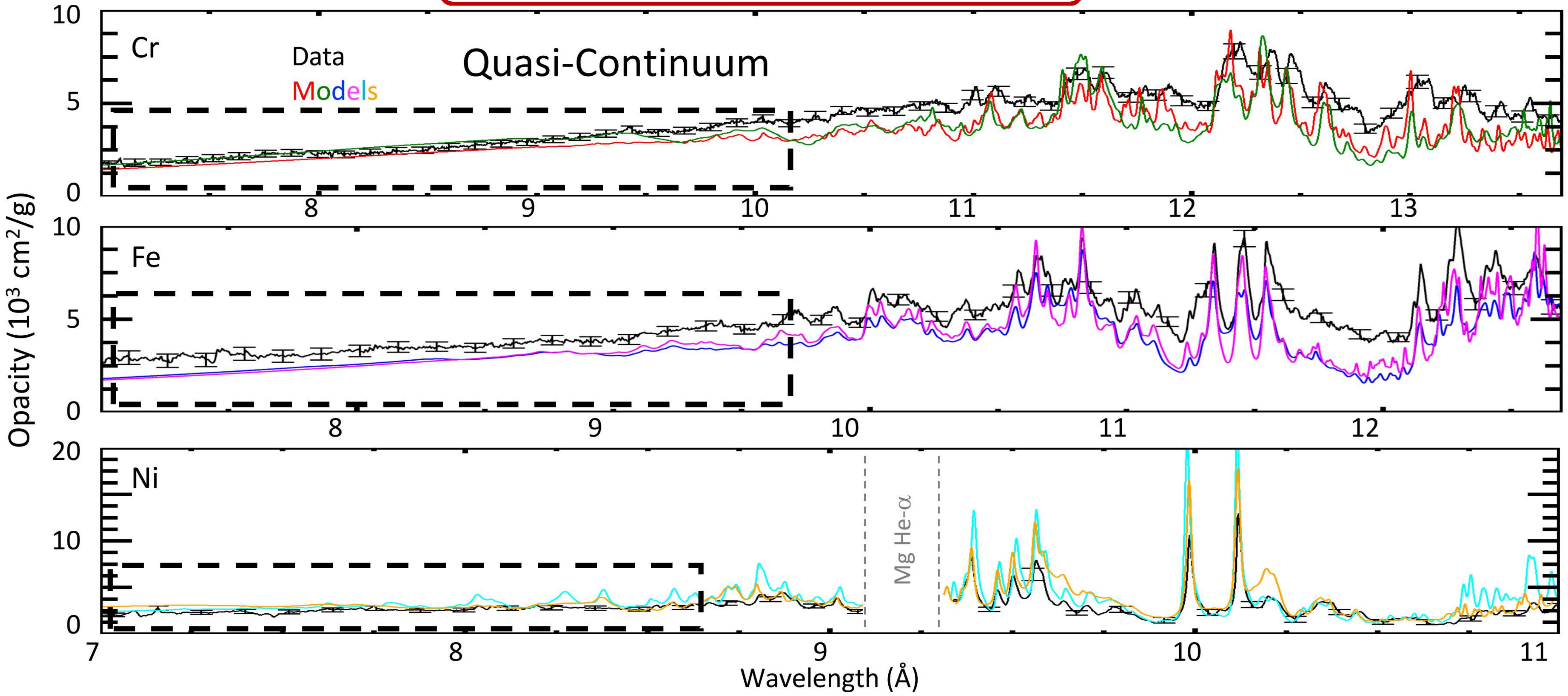
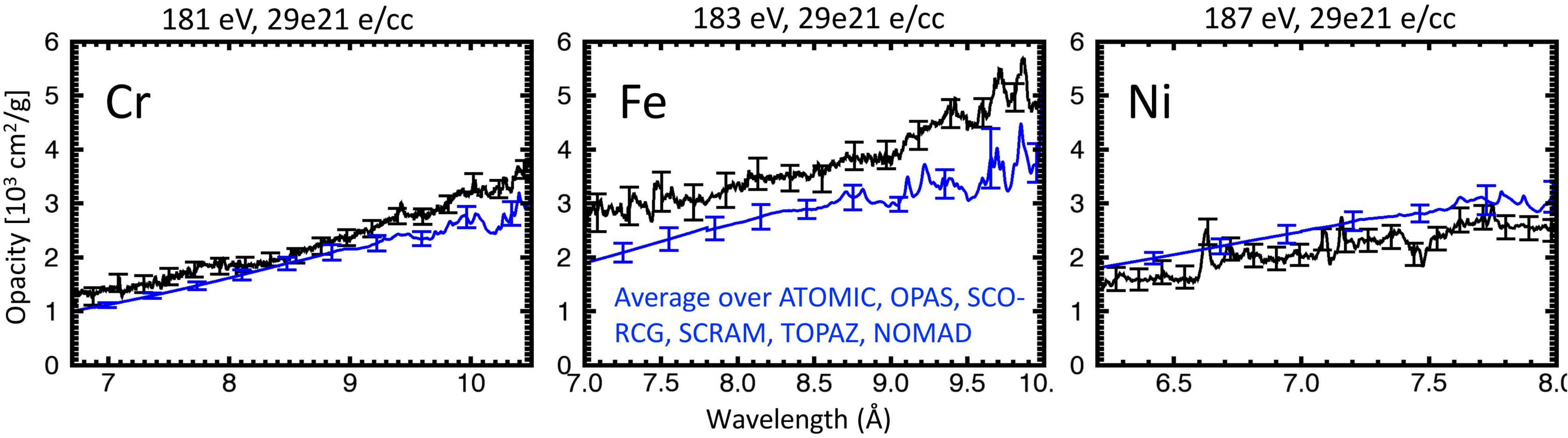


MODELS: ATOMIC, NOMAD, OPAS, SCO-RCG, SCRAM, TOPAZ

Refined analysis on Fe does not fully remove the reported quasi-continuum disagreement

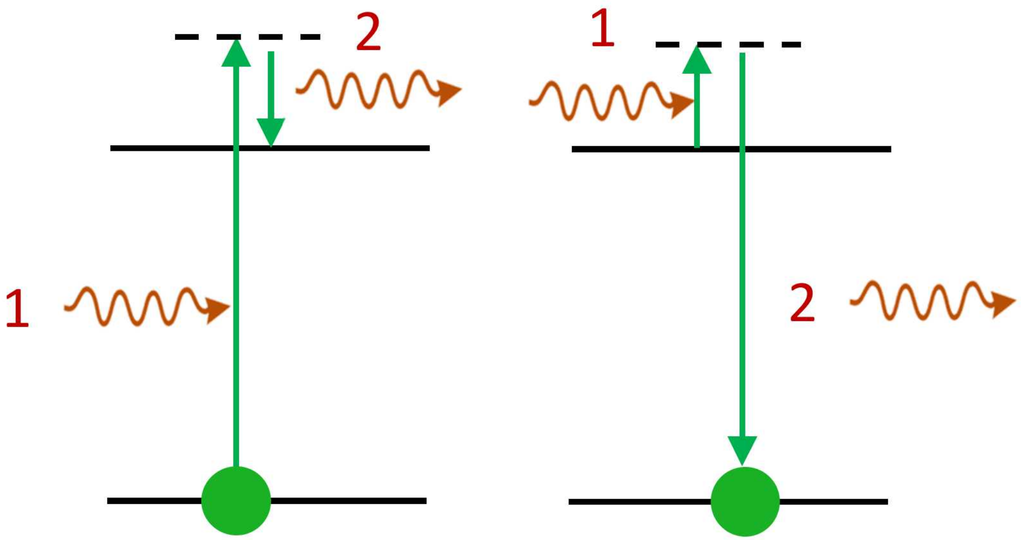


- Reanalysis on Fe reduced data/<model> from +60% to +30%, still statistically significant
- Excellent reproducibility in all three elements suggests the Fe discrepancy is real
- Can the discrepancy be explained by two-photon opacity?

Any hypothesis has to explain not only Fe discrepancy but also better agreement in Cr and Ni

Is b-f discrepancy explained by missing physics?

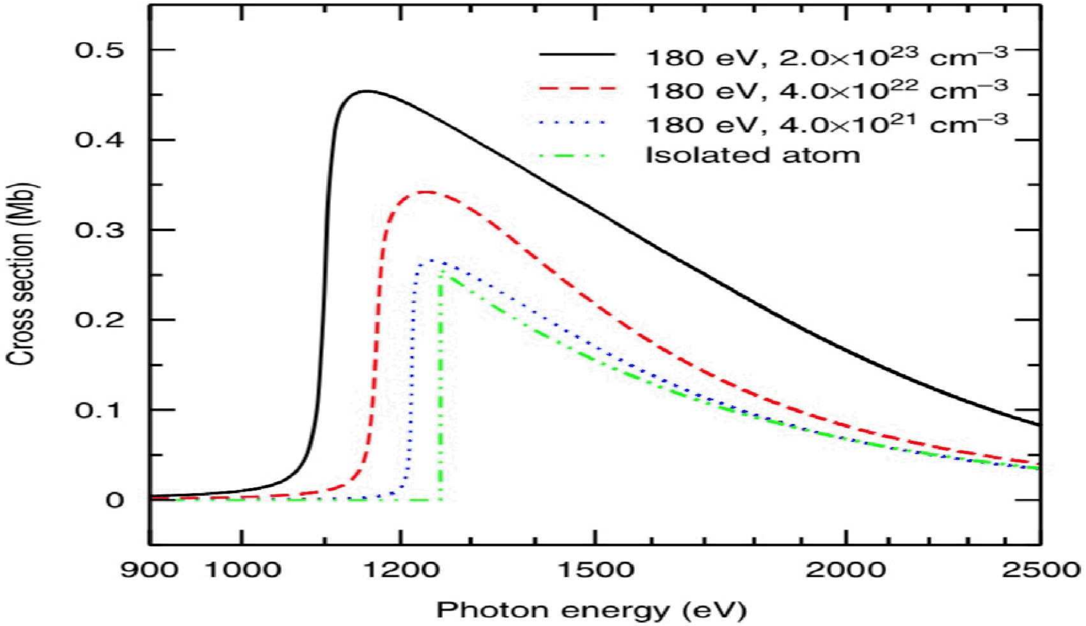
- **Two-photon processes?**



Raman Stokes   Raman Anti-Stokes

SNL, LANL, LLNL predict different conclusions

- **Transient space localization of electrons?**



[1] P. Liu et al, Communications Physics **1**, 95 (2018).

"Transient space localization of electrons ejected from continuum atomic processes in hot dense plasma"

Any hypothesis has to explain not only Fe discrepancy but also better agreement in Cr and Ni

We published >13 papers*, demonstrating high-impact of our work and strategic efforts for resolving the discrepancies

	Journal (1st Author)	Findings
2019	PRL (Nagayama)	First systematic study suggests potential weaknesses of opacity models
2017	PRE (Nagayama)	Commonly proposed hypotheses cannot explain the discrepancy
2016	PRE (Nagayama)	Calibrated simulations reproduce measured Te and ne and backlighter
	HEDP (Nagayama)	T_e and n_e error due to spectral model is 5% and 25%, respectively
2015	Nature (Bailey)	Calculated Fe opacity may be significantly underestimated at solar interior
2014	RSI (Nagayama)	Sample temperature is controlled by source-to-sample distance
	PoP (Nagayama)	Sample condition is uniform and controlled by tamping configuration
	PoP (Rochau)	Review paper on Z Astrophysical Plasma Property collaboration
2012	RSI (Loisel)	Our spectrometer provides good resolving power, $E/\Delta E$, > 1000
	RSI (Nagayama)	Gradient can be studied spectroscopically using Al and Mg dopant
2009	PoP (Bailey)	Review on opacity-experiment challenges
2008	RSI (Bailey)	Te and ne diagnostics using Mg spectroscopy
2007	PRL (Bailey)	Z can perform high-temperature opacity measurement

* Excluding >10 papers published by collaborators

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High Impact

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Sandia National Laboratories

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Investigation/ development

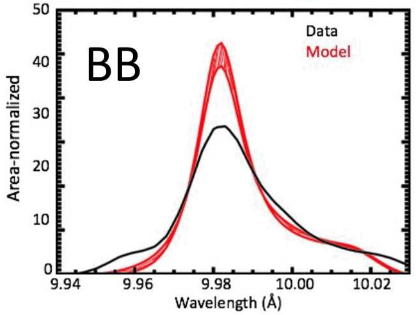
*** Excluding >10 papers published by collaborators**

Future experiments will test more hypotheses for resolving discrepancies and refine our understanding of experiments

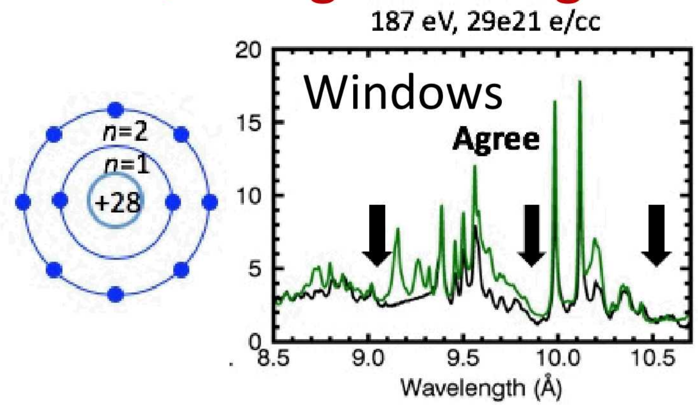
- <u>Ni opacity at higher T_e and n_e</u>

  → Testing BB and Window further

  Q. Worse at higher n_e ?

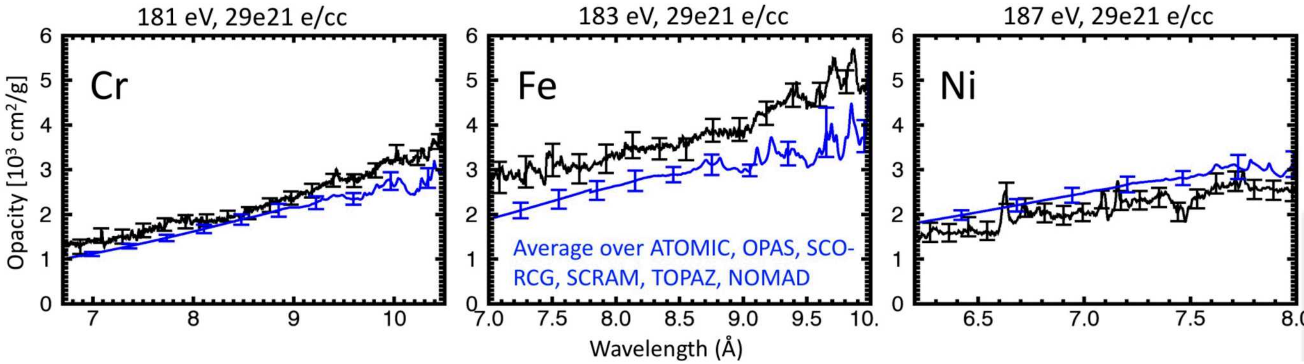


  Q. Disagree at higher T_e ?

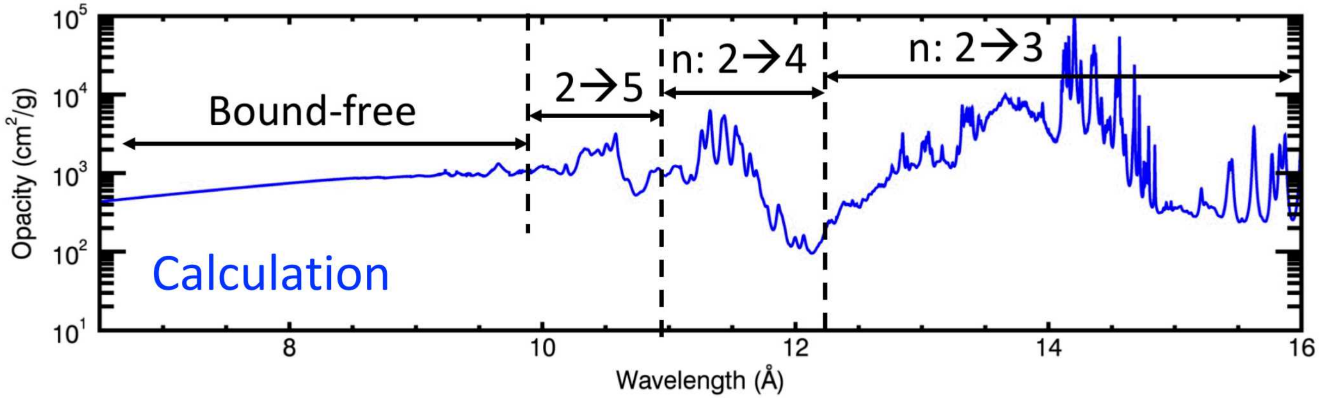


- <u>Revisiting Fe</u>

  Q. Is Fe BF flawed?



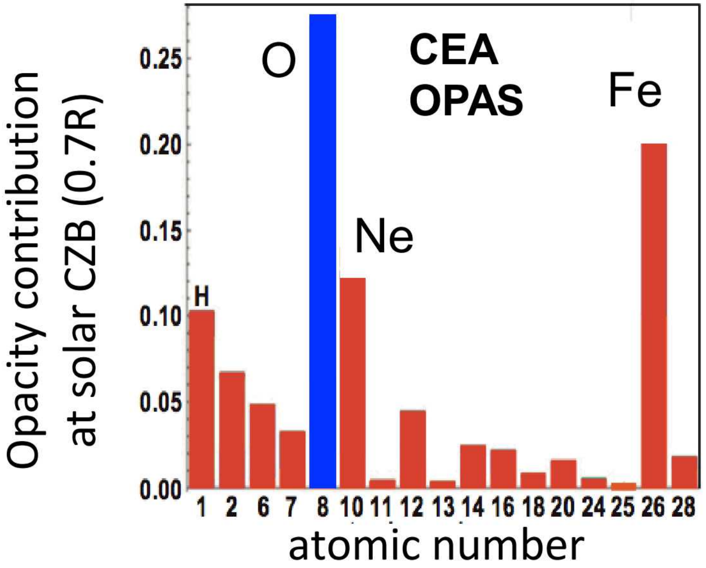
  Q. Can we report n=2→3 lines? Sum rule?



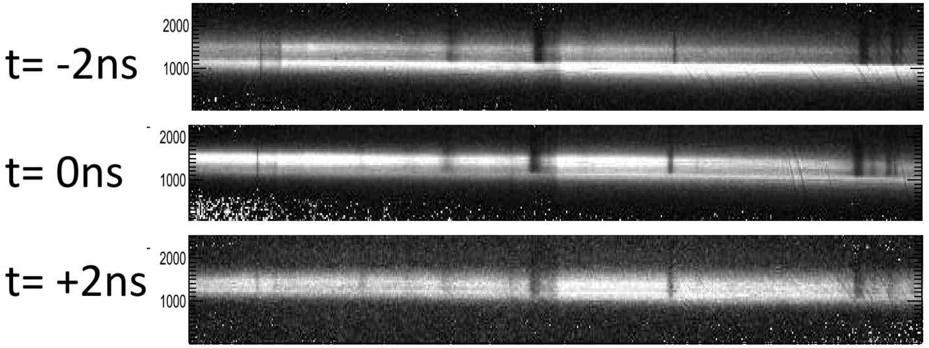
Future experiments will test more hypotheses for resolving discrepancies and refine our understanding of experiments

- O opacity at stellar interior

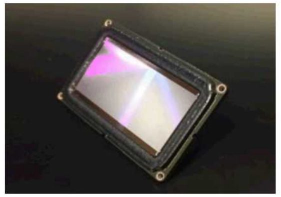
Q. Is O causing the solar problem?



- Time-resolved measurements



CMOS detector



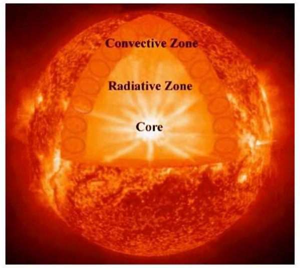
Q. Is our understanding of experiment correct [1]?

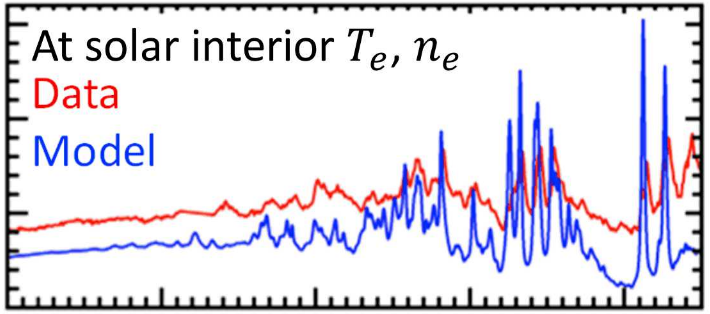
Q. Can we measure opacities at multiple conditions in single experiment?

L-shell opacities of Cr, Fe, and Ni were systematically measured, providing unprecedented constraints for resolving solar problem

- **Modeled solar structure is not sufficiently accurate**

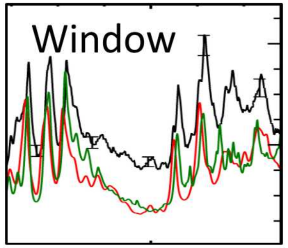
  → Is calculated iron opacity accurate?

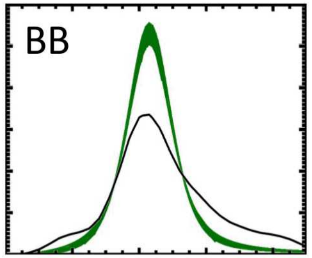


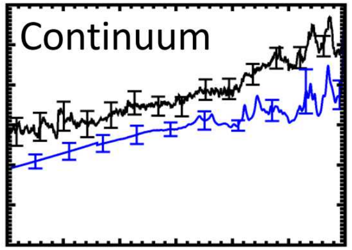


- **Fe L-shell opacity is measured at solar interior conditions and revealed severe model-data discrepancy**

- **Systematic measurement of Cr, Fe, and Ni opacities suggests model refinements in three areas**
  - <u>Window:</u> Challenge associated with open L-shell config.
  - <u>BB:</u> Inaccurate treatment of density effects
  - <u>Continuum:</u> Peculiar dependence on atomic number







- **More exciting measurements are on the horizon**

Diligent experiment and analysis are leading us steadily towards resolution