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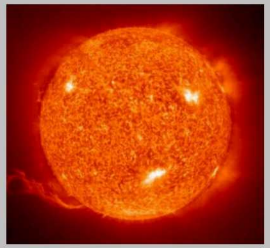
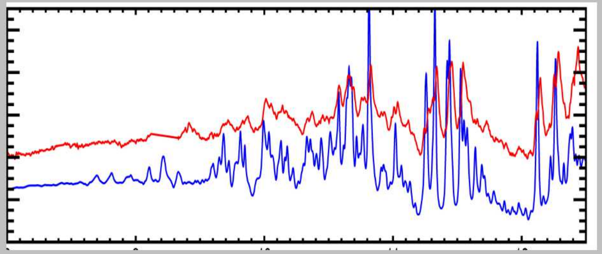

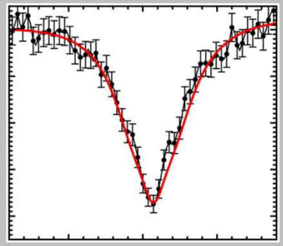
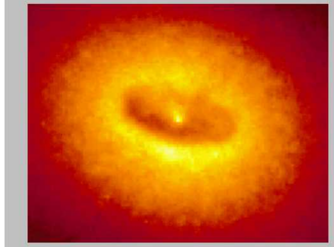
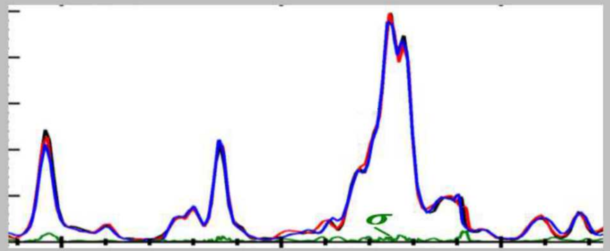

Importance and challenges of benchmark experiments for astrophysics
-- ZAPP: Z Astrophysical Plasma Property Collaboration --

Taisuke Nagayama

7/31/2019

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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ZAPP represents a collaboration among a large number of scientists from the national labs and the academic community

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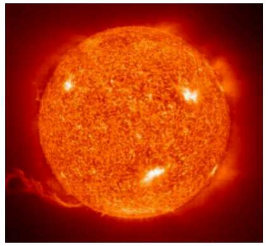
Plasma spectral models used for astrophysics are not extensively tested; Benchmark experiments are essential though challenging

- Astrophysics relies on *plasma spectral models* in two ways:
  - Spectra analysis (e.g., from accretion disk, white dwarfs)
  - Fundamental properties (e.g., opacity, equation of state)
- ZAPP (= Z Astrophysical Plasma Properties) collaboration uses terra-watt x-ray source to replicate astrophysics-relevant plasma and check the accuracy of spectral models

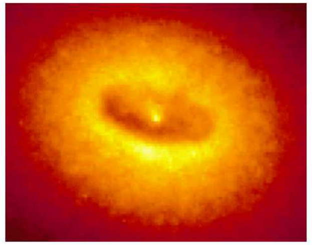


Solar Fe opacity:

T=200 eV
n_e=5e22 cm^{-3}

White dwarf mass:

T=1 eV
n_e=1e17 cm^{-3}

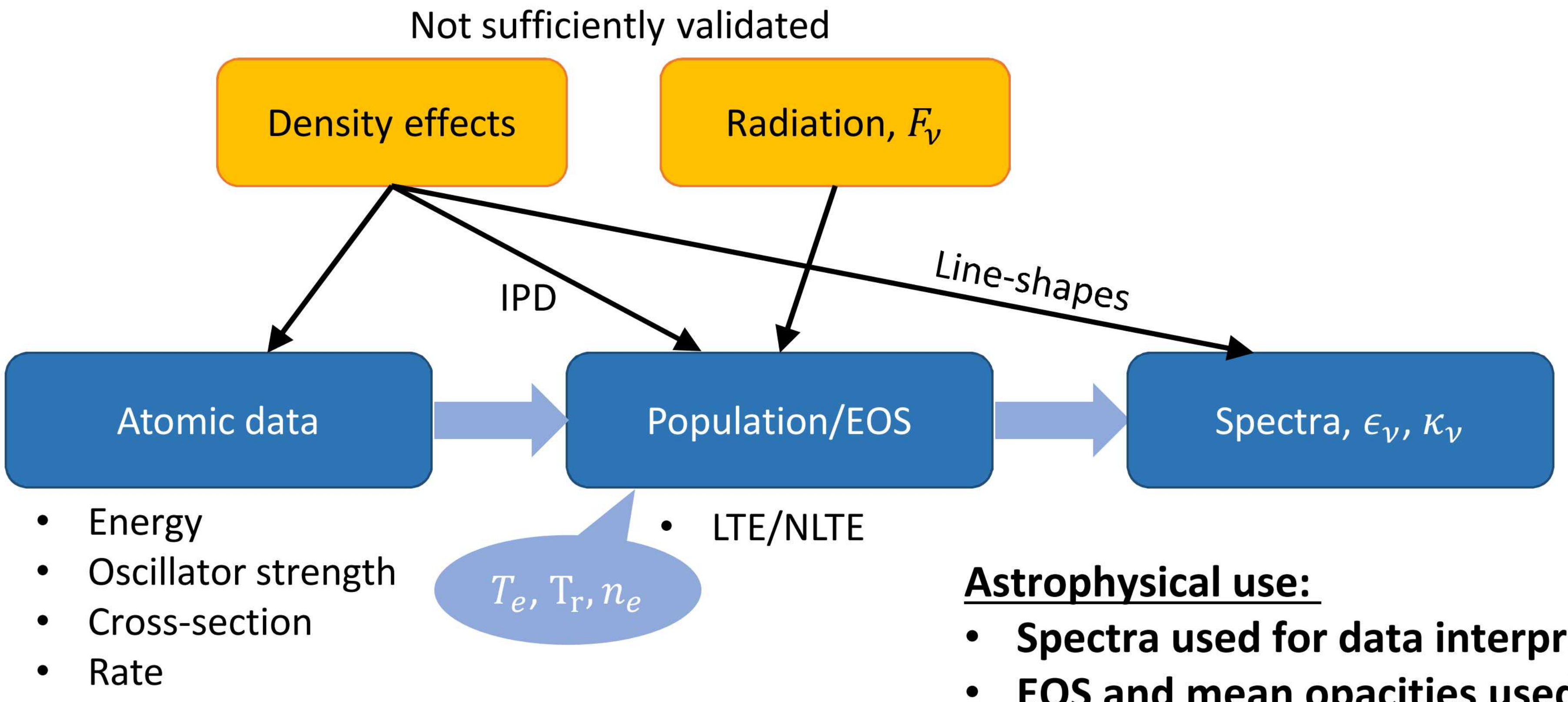


Accretion disk spectra:
ξ = 20-1000 erg cm/s
T=30 eV
n_e=1e19 cm^{-3}

- HED science needs more benchmarks, though challenging:
  - Experimentalist: a decade of diligent work for reliable platform and hypothesis testing
  - Theorists: openness for criticism, eagerness for testing untested approximations
  - Management: continuous support and encouragement for checking reproducibility

Diligent benchmark-experiment collaborations will advance astrophysics and HED science

Plasma property and spectra calculations are complex and contain many approximations with limited validations

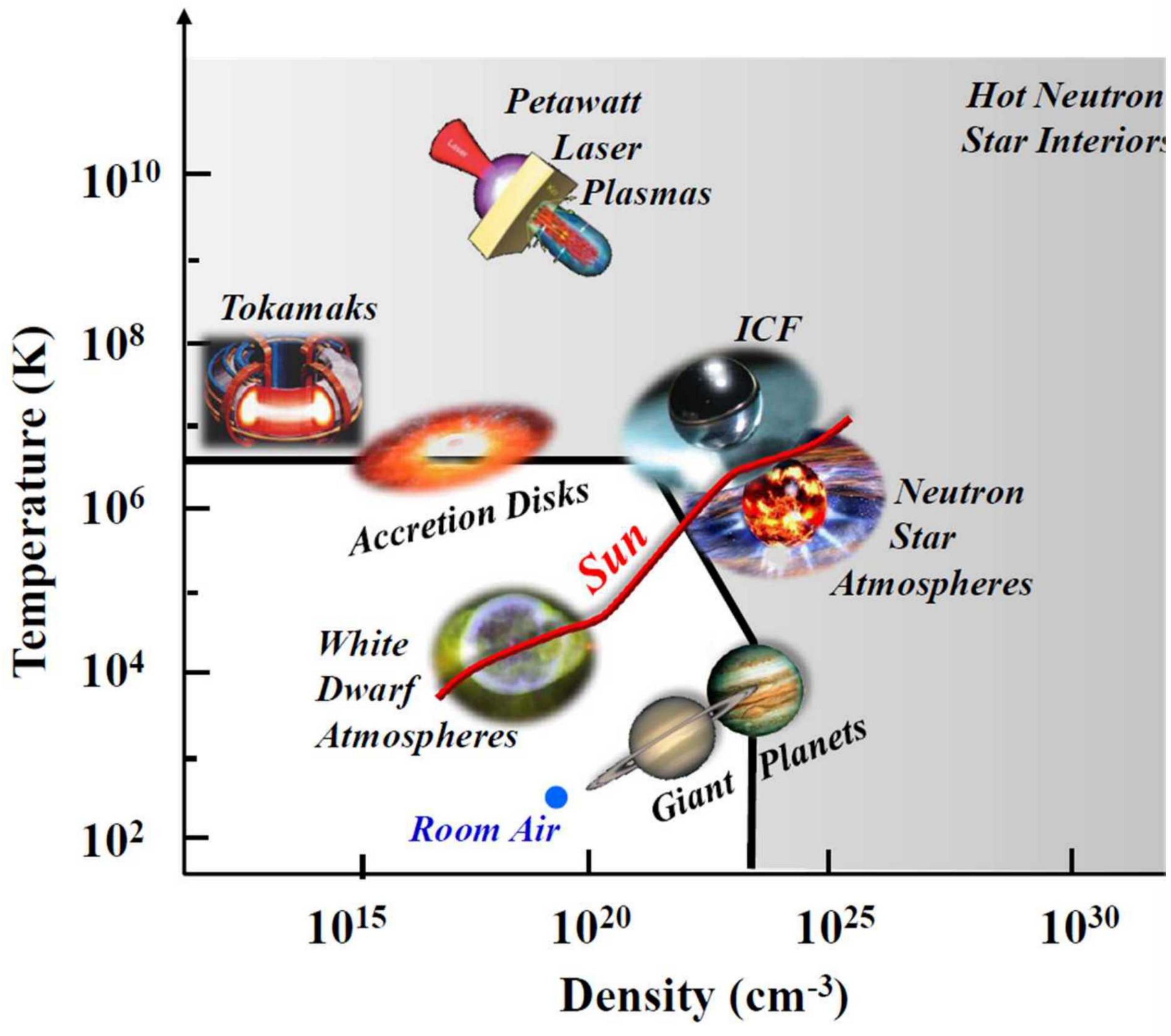


Astrophysical use:

- **Spectra used for data interpretation**
- **EOS and mean opacities used for modeling**

- **Limited validations available for approximations at extreme conditions**
- **This produces unknown uncertainty to the data interpretations and model predictions**

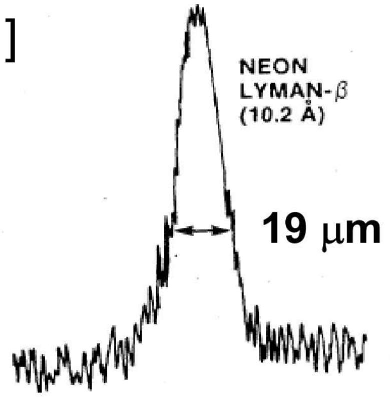
Mega-joule-class HED laboratories produce extreme conditions for many years, but …

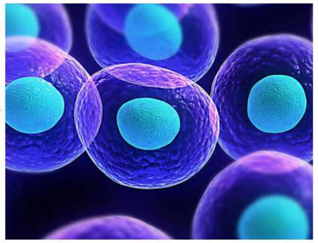


Problem: Sample size used to be so small for benchmark experiments

e.g., Laser fusion capsule [1]

T=300 eV,
ρ=0.26 g/cc } Exotic
Size: 19 μm

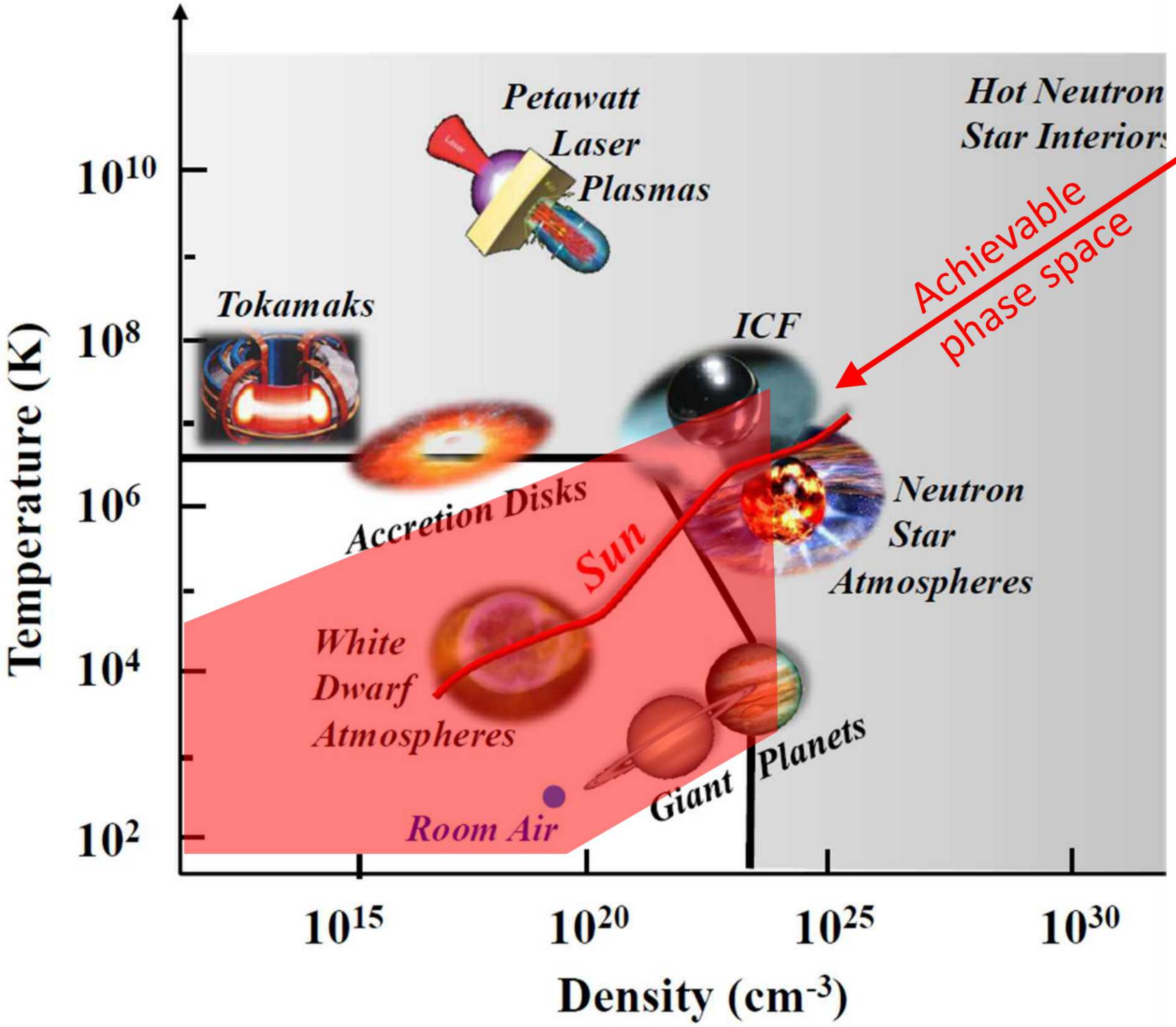




size of cell

[1] Yaakobi, PRL, 1977

What's new: now, we can create macroscopic enough quantities of astrophysical matter for detailed studies



Z machine at Sandia National Lab creates macroscopic plasma at fairly exotic conditions

Fe opacity samples: ***Size ~ 1 mm sand grain***

Achieved conditions:
T=150-200 eV
n_e=(1-10)x10^{22} e/cm^3

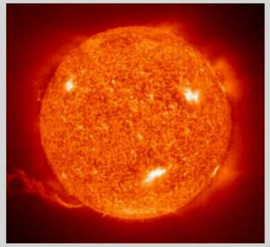
Z White Dwarf samples: ~ size of a phone

Achieved conditions:
T=1-3 eV
n_e=(5-100)x10^{16} e/cm^3

ZAPP campaigns simultaneously study multiple issues spanning 200x in temperature and 10^6x in density

Sandia National Laboratories

Solar Opacity



Question:
Why can't we predict solar structure accurately enough?

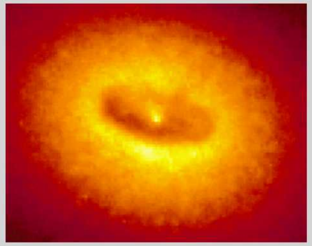
Achieved Conditions:
T_e ~ 200 eV, n_e ~ 10^{23} cm^{-3}

White Dwarf Line-Shapes

Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

Achieved Conditions:
T_e ~ 1 eV, n_e ~ 10^{17} cm^{-3}

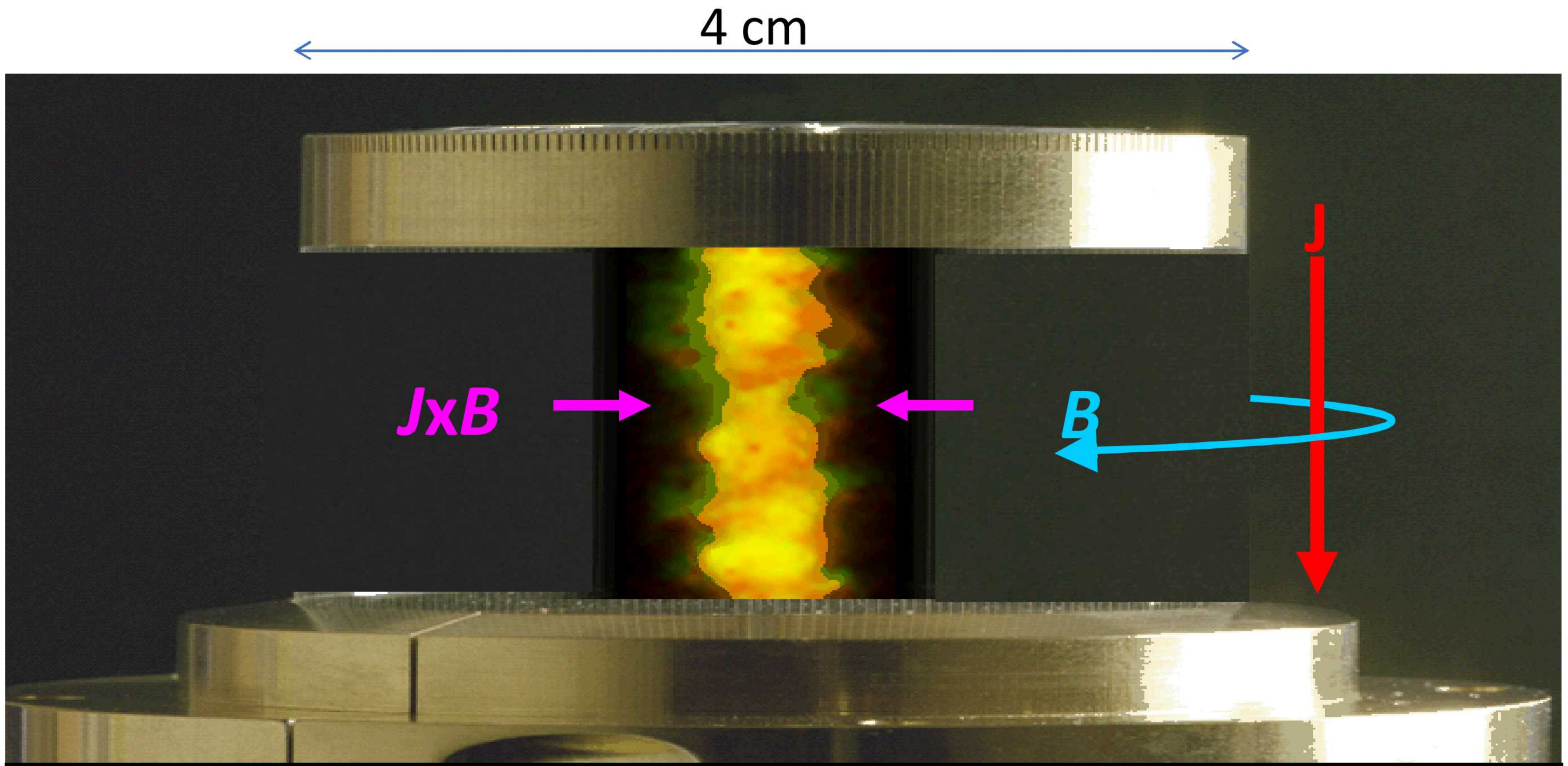
Photoionized Plasma



Question:
How does ionization and line formation occur in accreting objects?

Achieved Conditions:
T_e ~ 20 eV, n_e ~ 10^{19} cm^{-3}

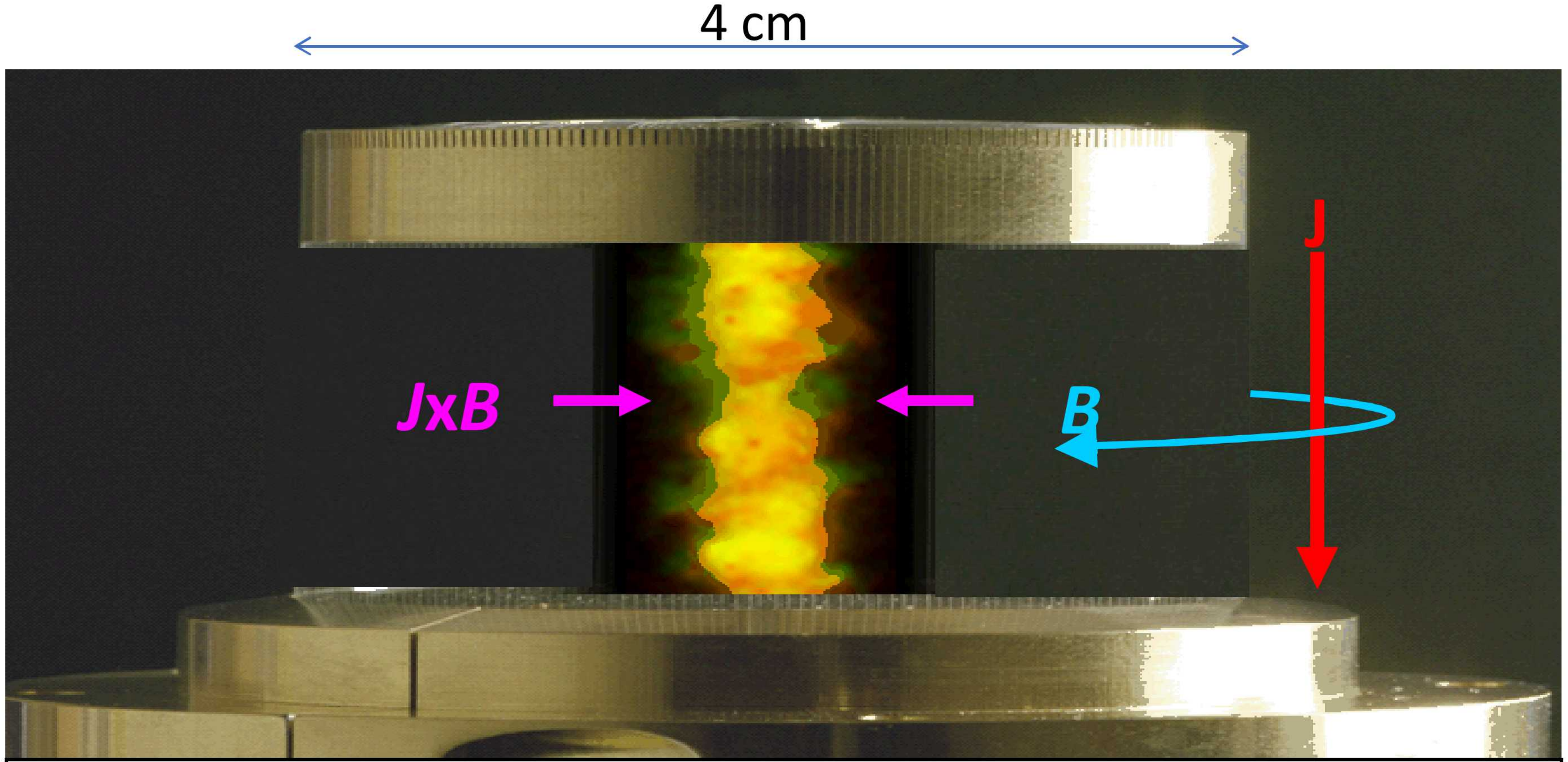
The SNL Z machine uses 27 million Amperes to create x-rays



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 SNL Z machine uses 27 million Amperes to create x-rays, and perform multiple benchmark experiments simultaneously



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The SNL Z machine uses 27 million Amperes to create x-rays, and perform multiple benchmark experiments simultaneously

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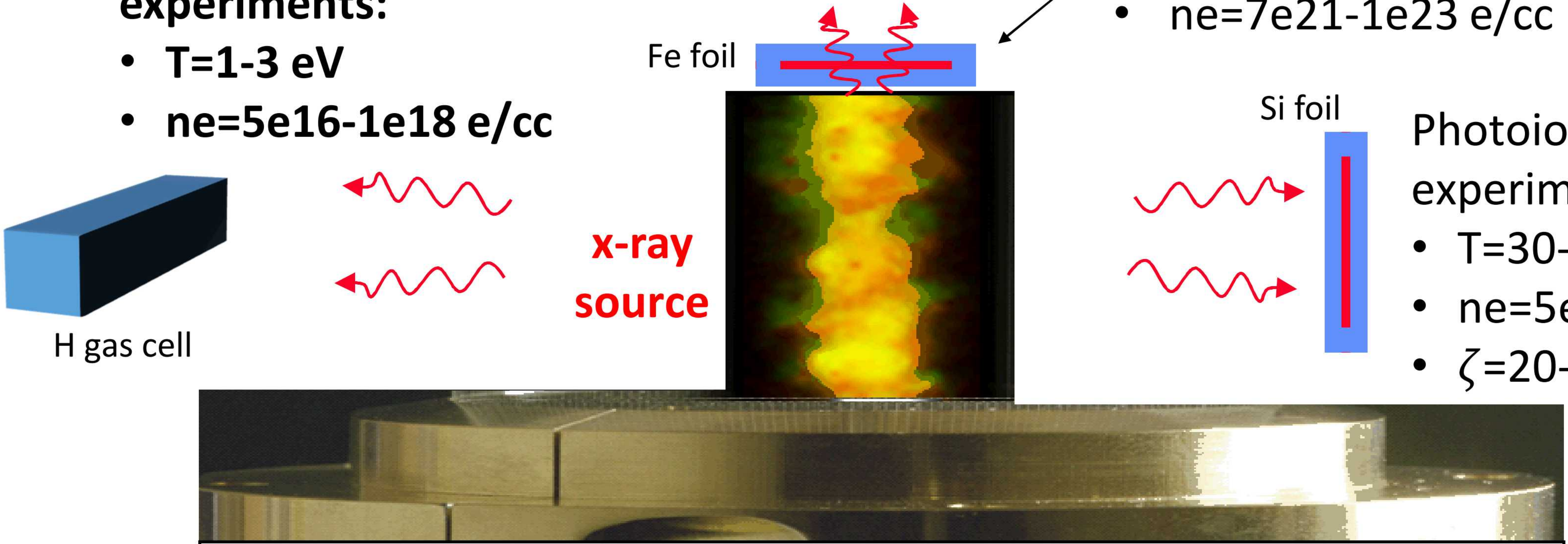
White Dwarf experiments:
- **T=1-3 eV**
- **ne=5e16-1e18 e/cc**

Solar opacity sample
- T=150-200 eV
- ne=7e21-1e23 e/cc

Photoionized plasma experiments
- T=30-40 eV
- ne=5e16-1e17 e/cc
- ζ=20-1000



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

Single shot can perform multiple experiments at T=1-200 eV and ne=5e16-1e23 e/cc

ZAPP campaigns simultaneously study multiple issues

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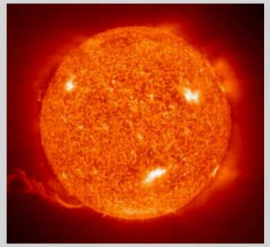
Solar Opacity



Question:
Why can't we predict solar structure accurately enough?

Achieved Conditions:
$T_e \sim 200$ eV, $n_e \sim 10^{23}$ cm^{-3}

White Dwarf Line-Shapes

Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

Achieved Conditions:
$T_e \sim 1$ eV, $n_e \sim 10^{17}$ cm^{-3}

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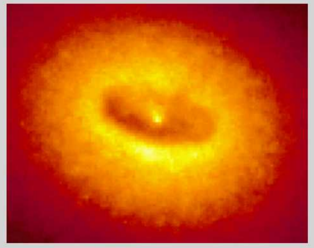

Question:
How does ionization and line formation occur in accreting objects?

Achieved Conditions:
$T_e \sim 20$ eV, $n_e \sim 10^{19}$ cm^{-3}

ZAPP campaigns acquire up to 60 spectra on a single shot

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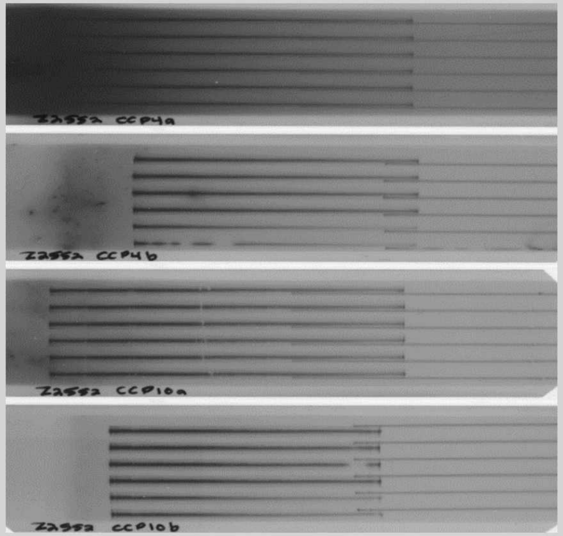
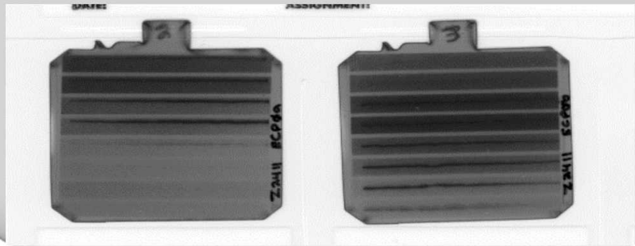
Solar Opacity

24 Space-Resolved
Fe Absorption Spectra

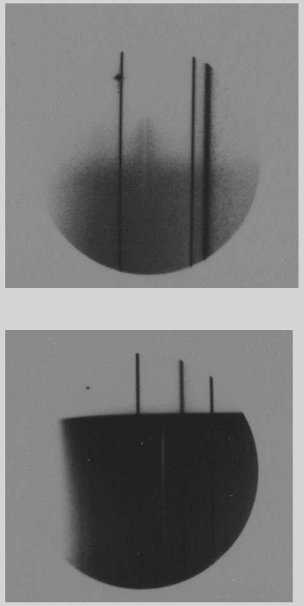


16 Time-Resolved
Fe Absorption Spectra



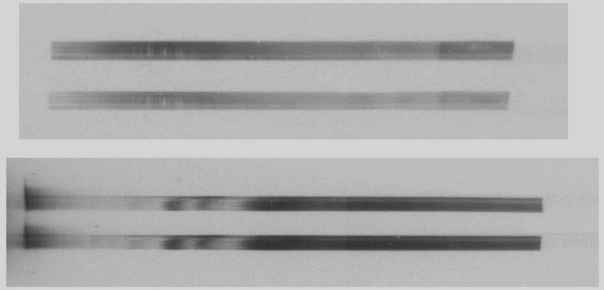
White Dwarf Line-Shapes

3 Streaked
H Absorption Spectra

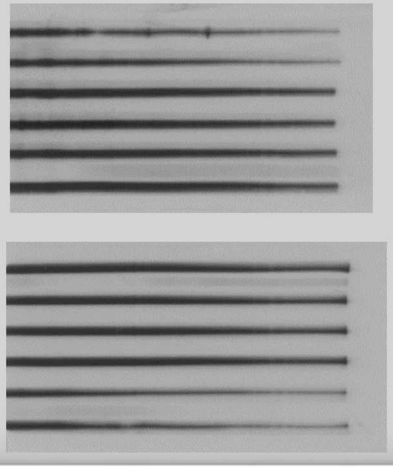


Photoionized Plasma

4 Space-Resolved
Si Absorption Spectra



12 Space-Resolved
Ne Absorption Spectra



We can repeat experiments to make sure the result; we can modify experiments to test hypotheses

ZAPP campaigns simultaneously study multiple issues

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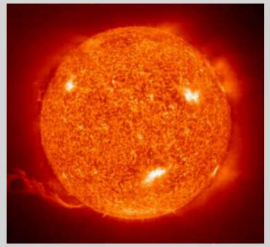
Solar Opacity



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Why doesn't spectral fitting provide the correct properties for White Dwarfs?

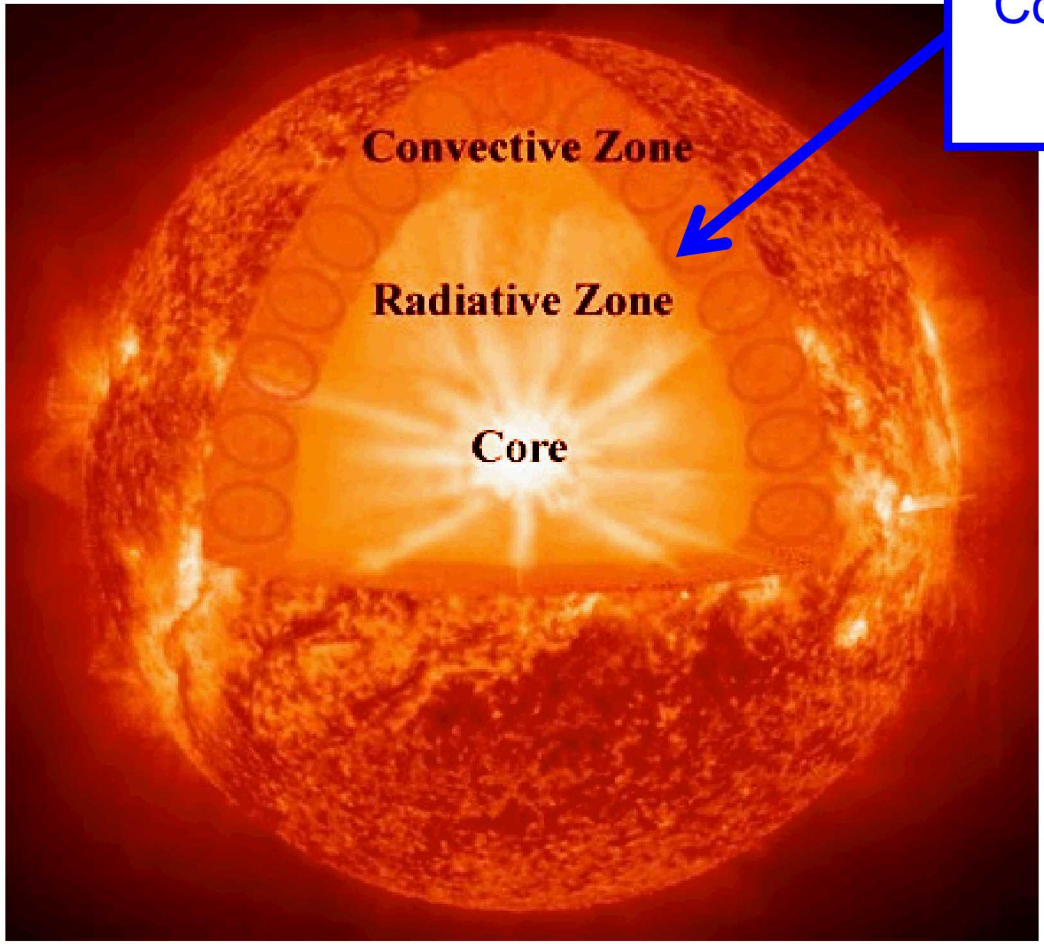
Achieved Conditions:
T_e ~ 1 eV, n_e ~ 10^{17} cm^{-3}

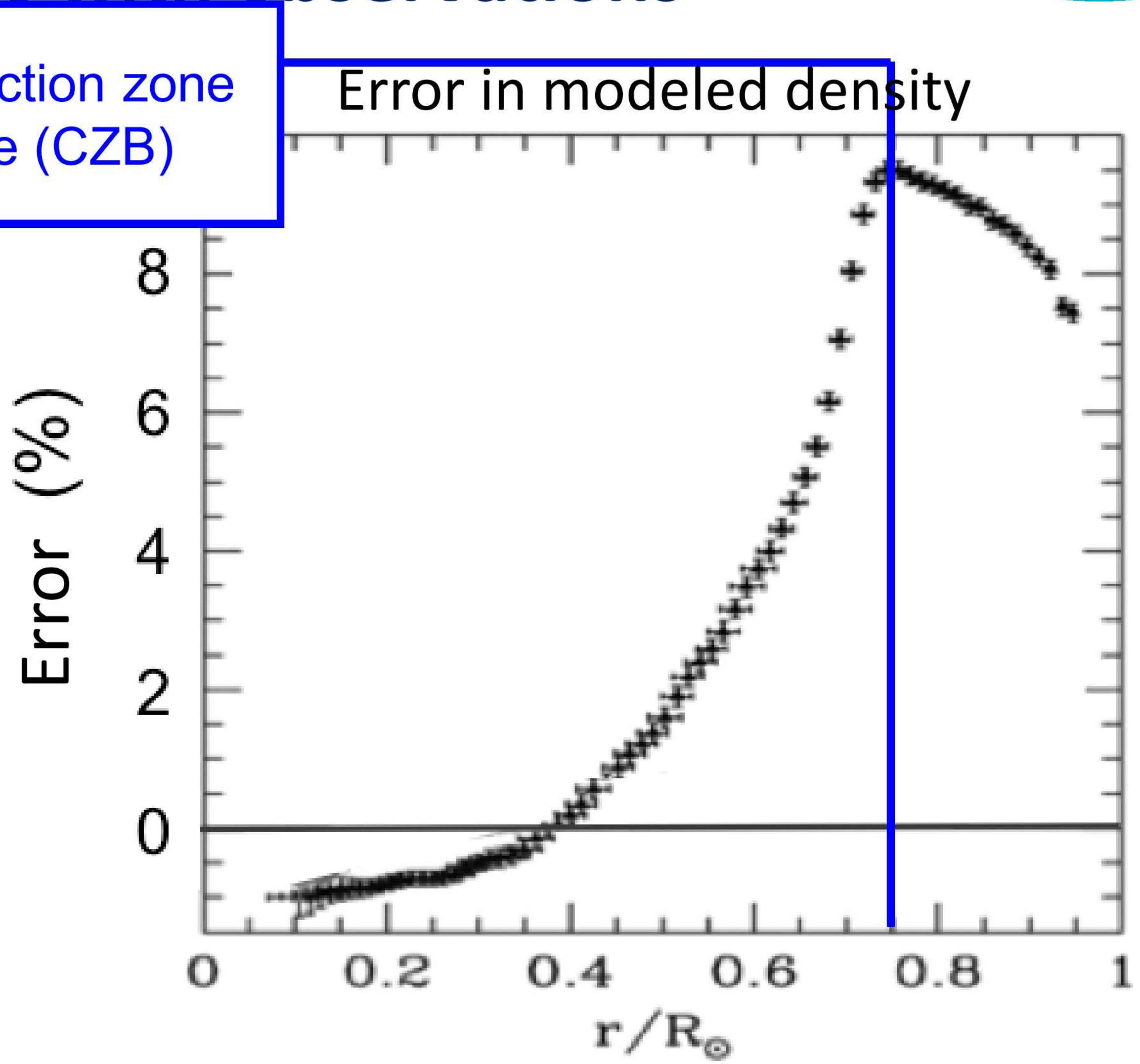
Photoionized Plasma

Question:
How does ionization and line formation occur in accreting objects?

Achieved Conditions:
T_e ~ 20 eV, n_e ~ 10^{18} cm^{-3}

Modeled solar structure disagrees with observations





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

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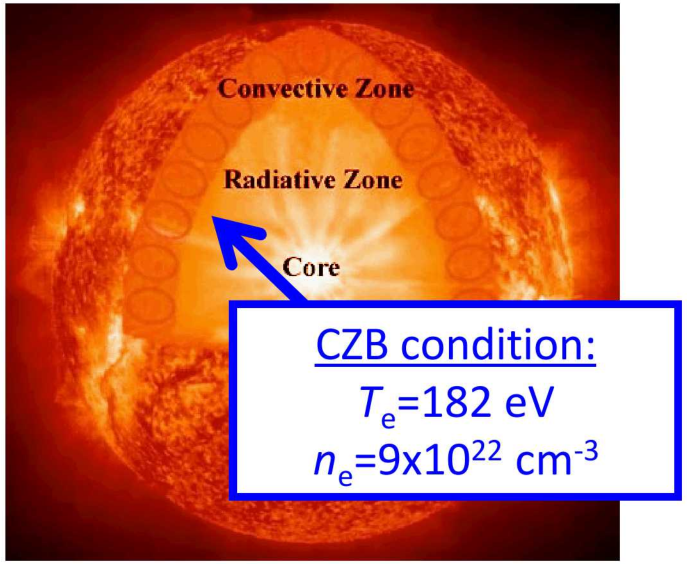
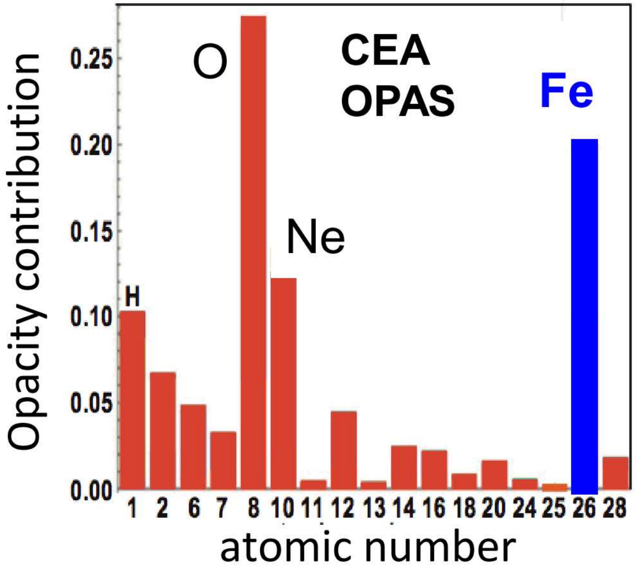




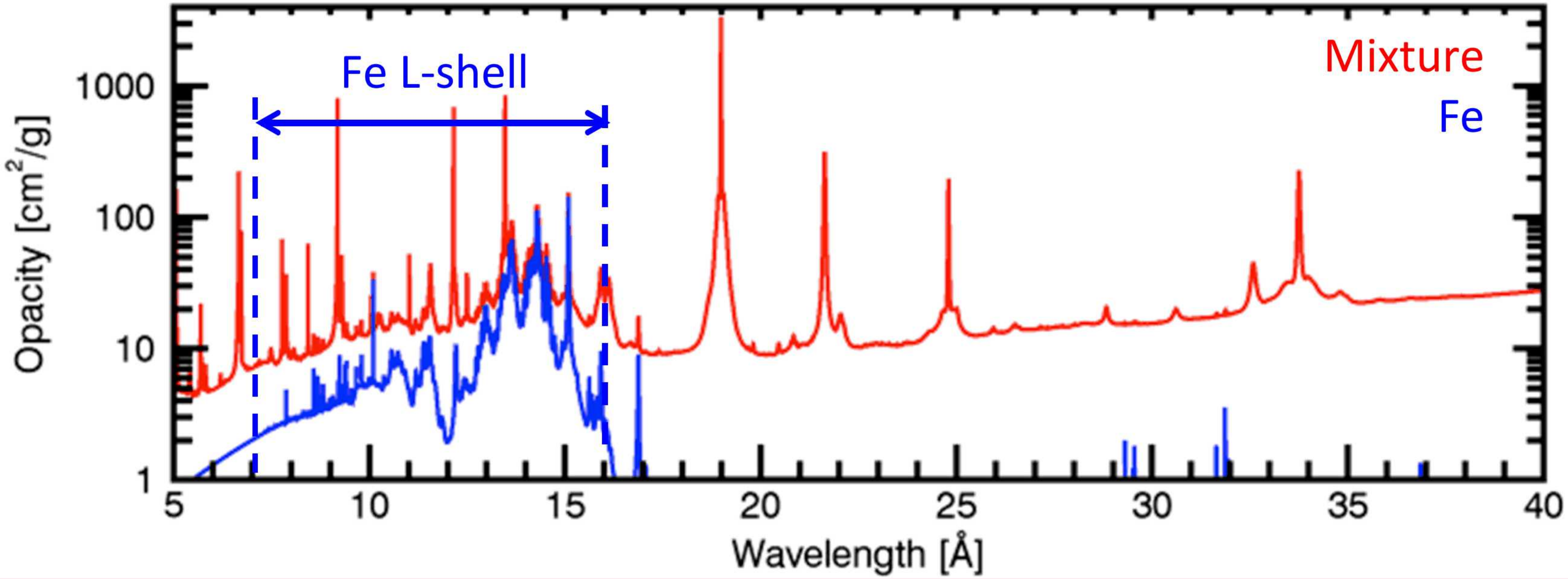
Opacity: κ_ν

- 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)



C. Blancard et al., *The Astrophysical Journal* 745, 10 (2012)

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

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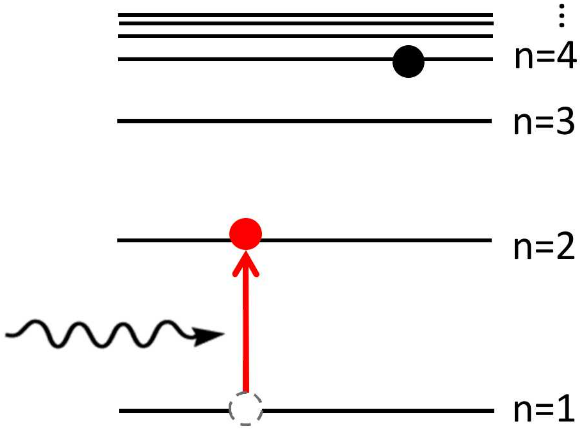
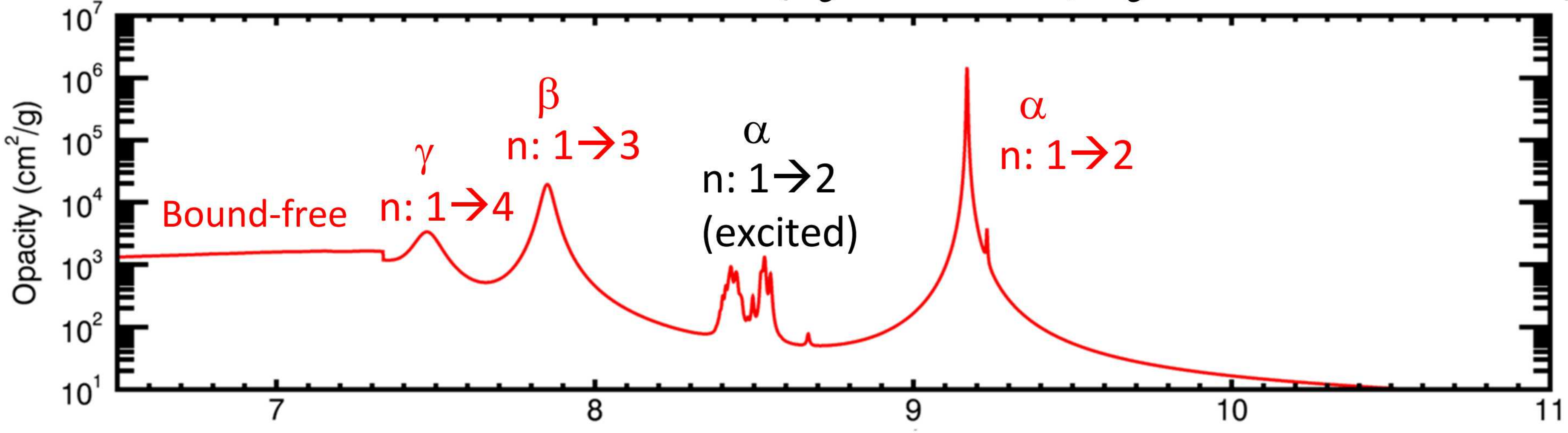
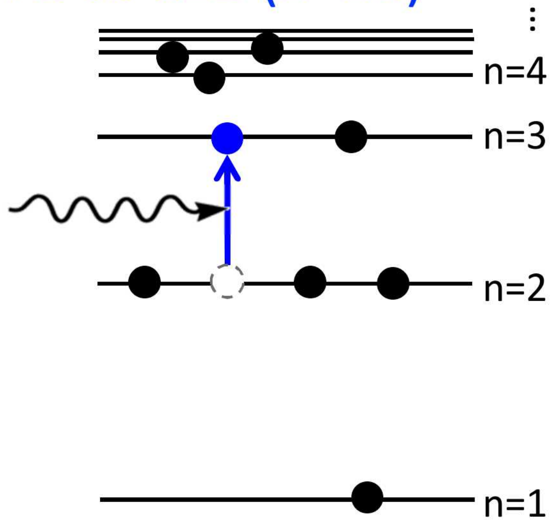
Mg at CZB (Z=12)

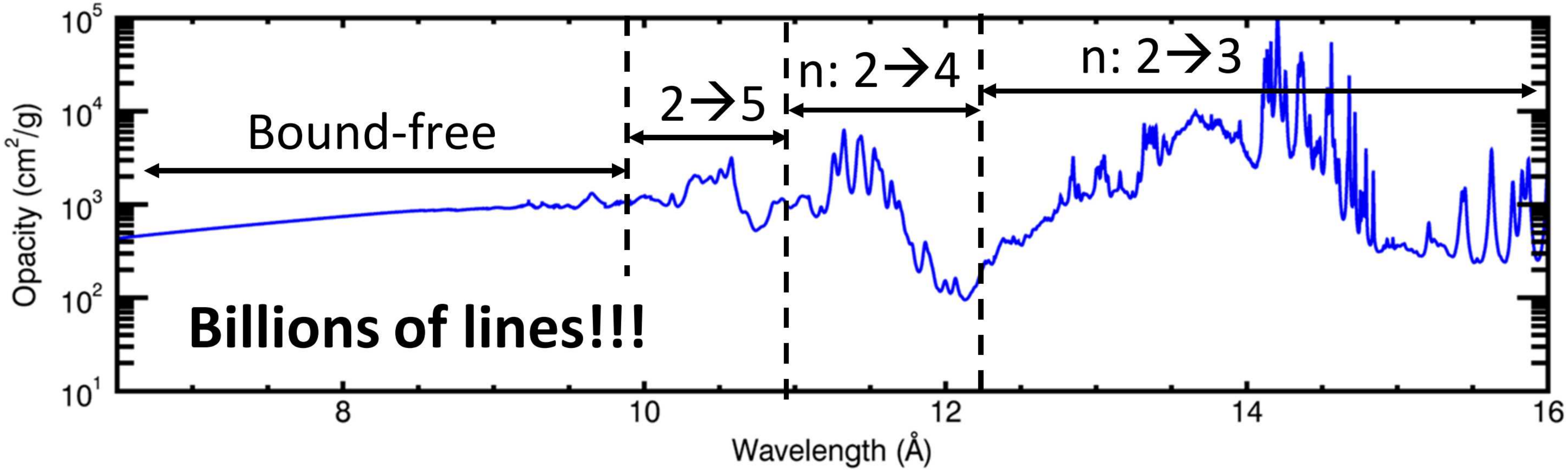


CZB = Convection Zone Base ($T_e = 182$ eV, $n_e = 9 \times 10^{22}\ cm^{-3}$)

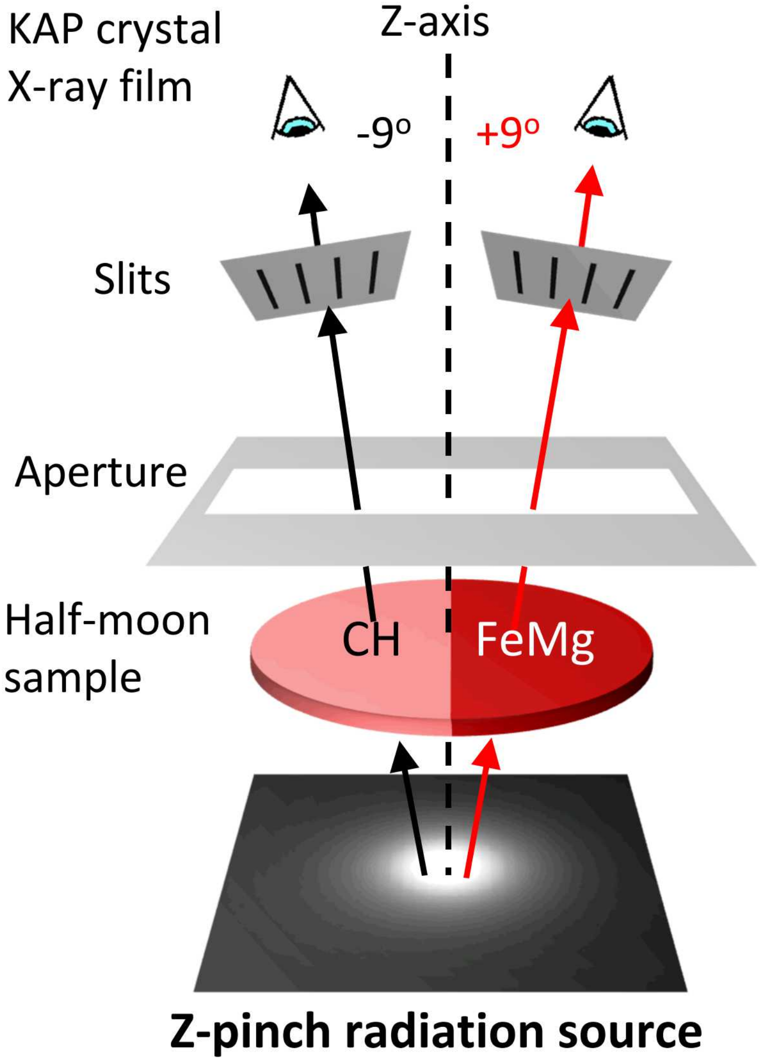


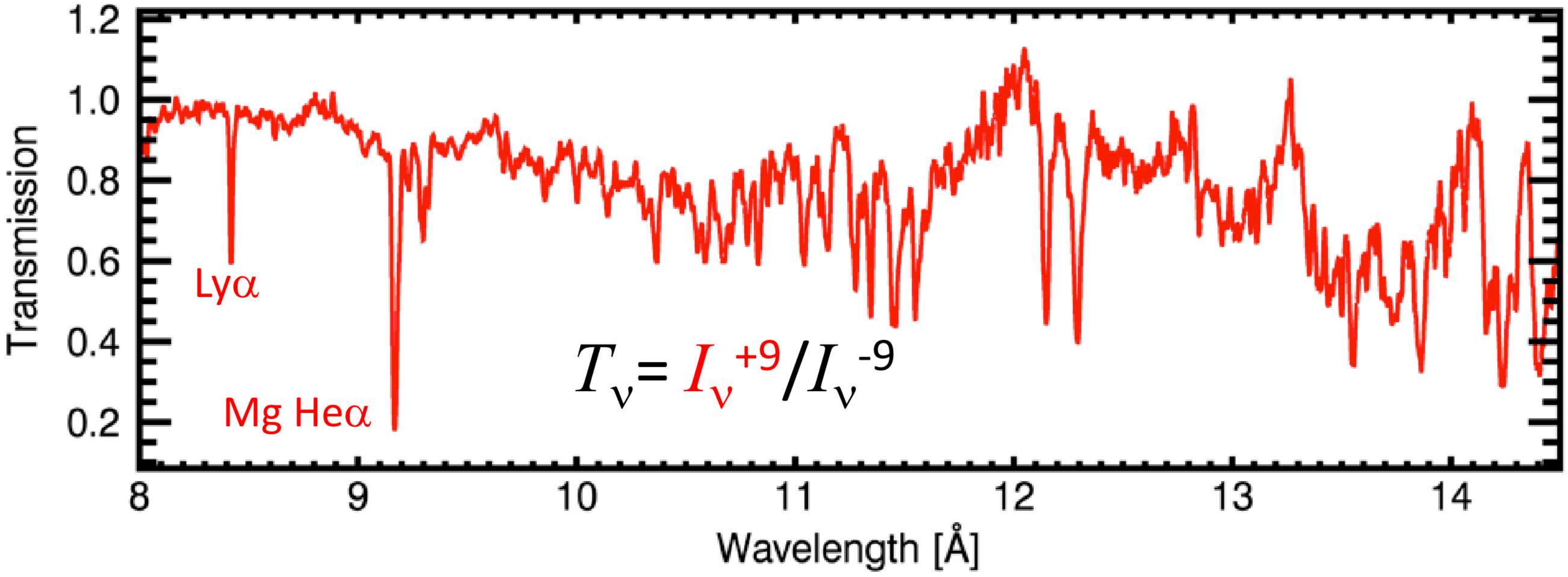
Fe at CZB (Z=26)





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





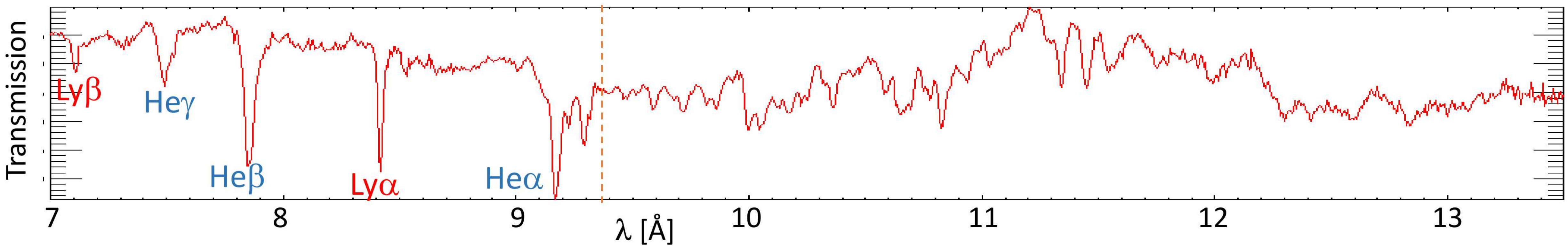
Requirements	SNL Z satisfies:
• Uniform heating →	Volumetric heating
• Mitigating self emission →	350 eV Planckian backlight
• Condition measurements →	Mg K-shell spectroscopy
• Checking reproducibility	

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

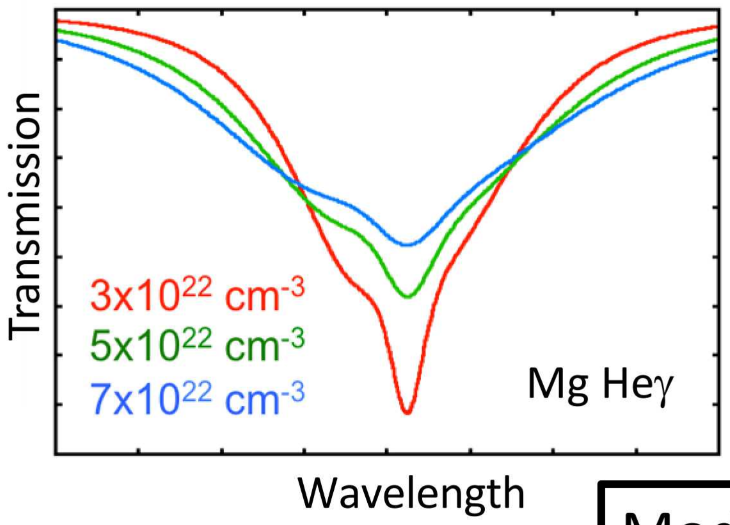
n_e and T_e are inferred from their line ratios and widths, assuming He-like/H-like spectra are accurately modeled

Mg K-shell

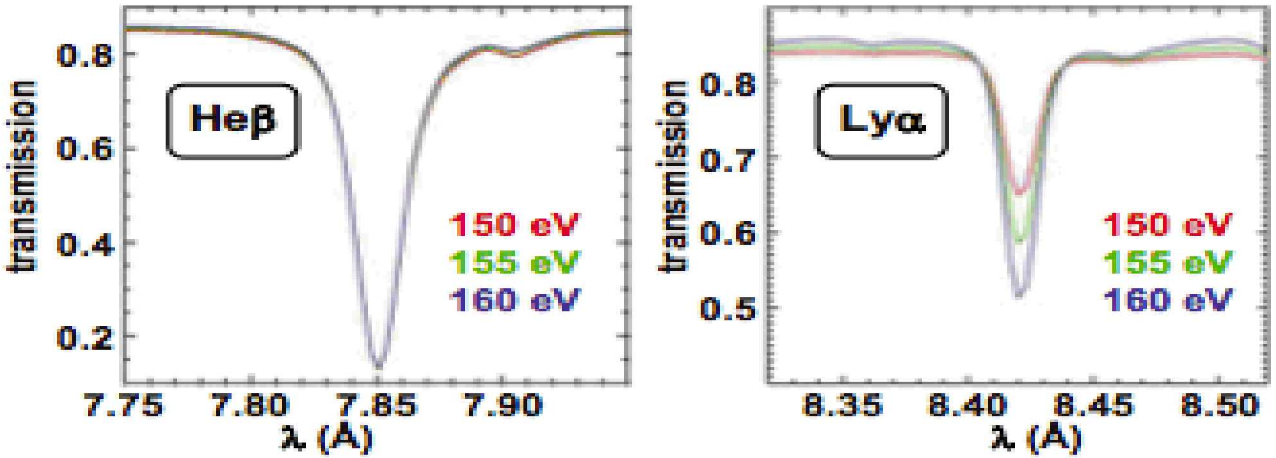
Fe L-shell



Line broadened with electron density, n_e

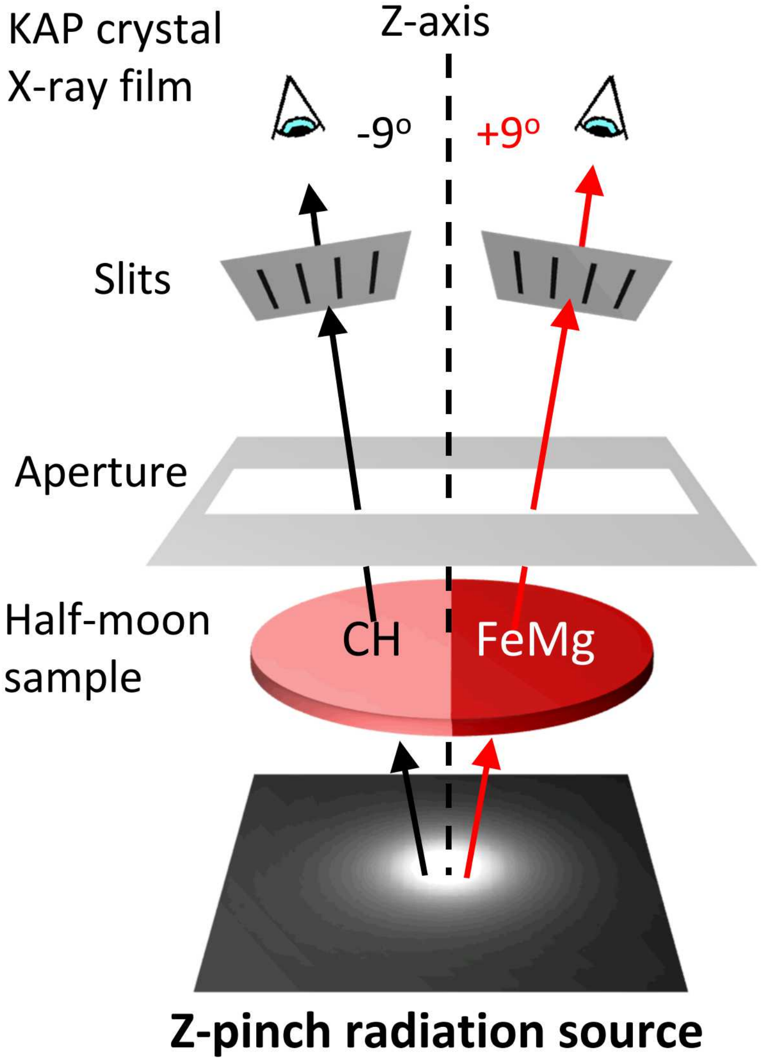


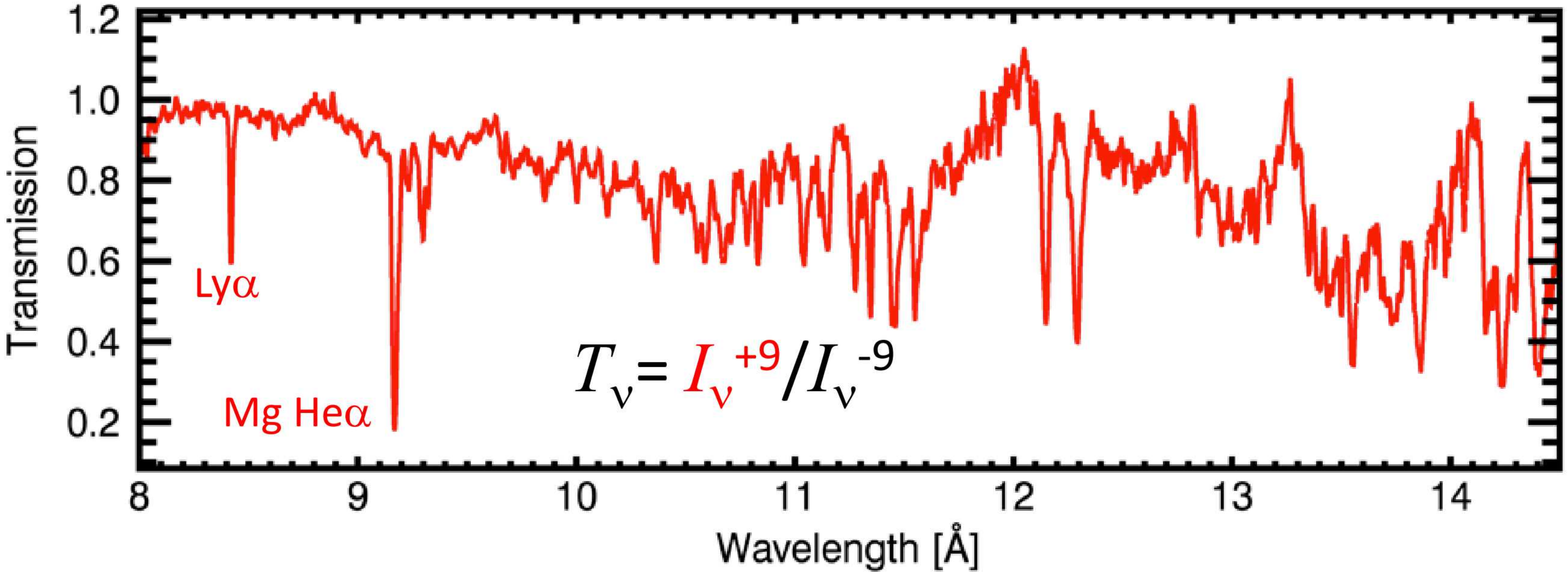
Line ratio changes with temperature, T_e



Model dependence*: 5% in T_e and 25% in n_e

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





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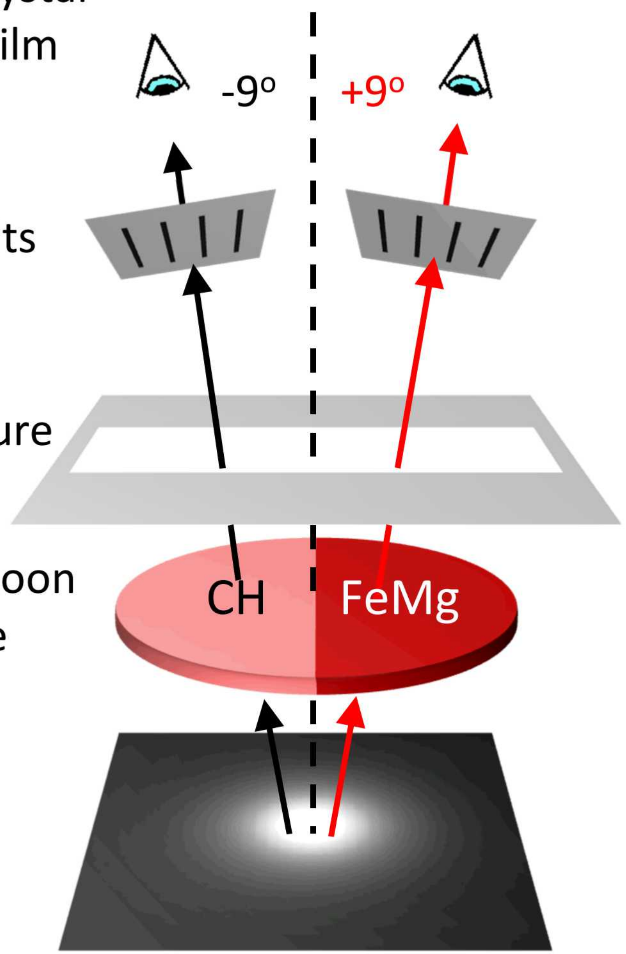

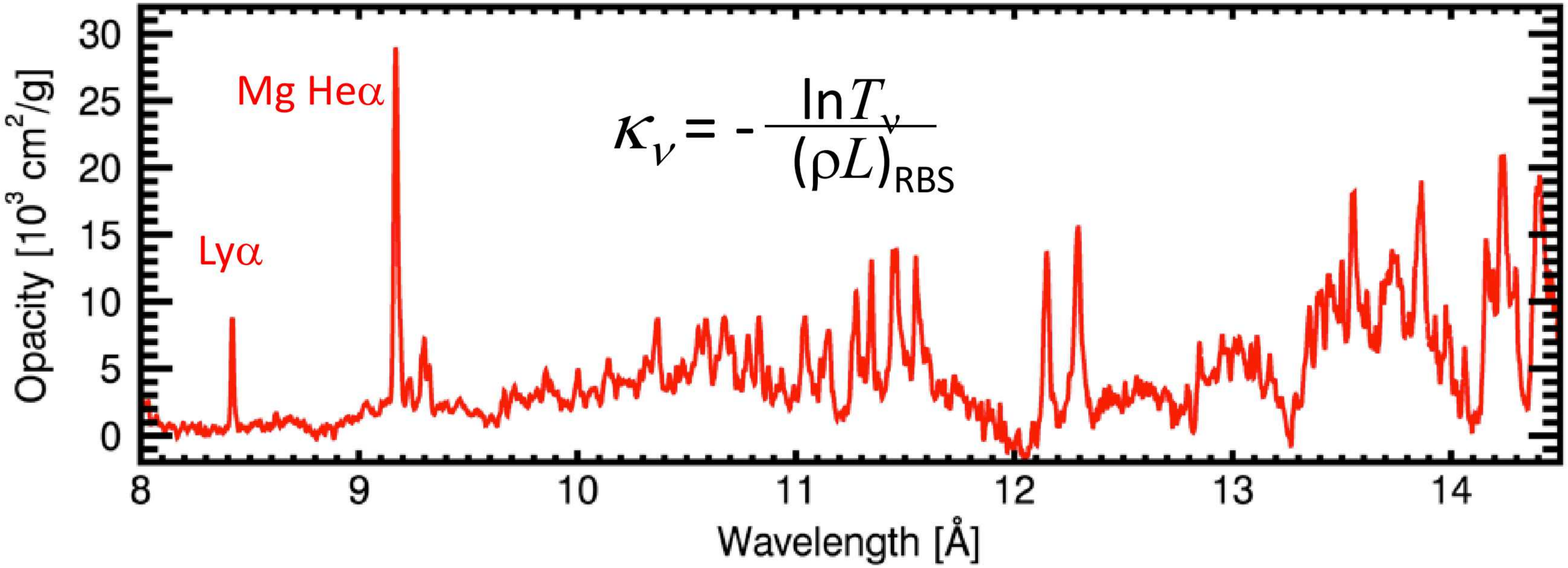

Requirements	SNL Z satisfies:
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[1] Bailey et al., *Phys Plasmas* 16, 058101 (2009)
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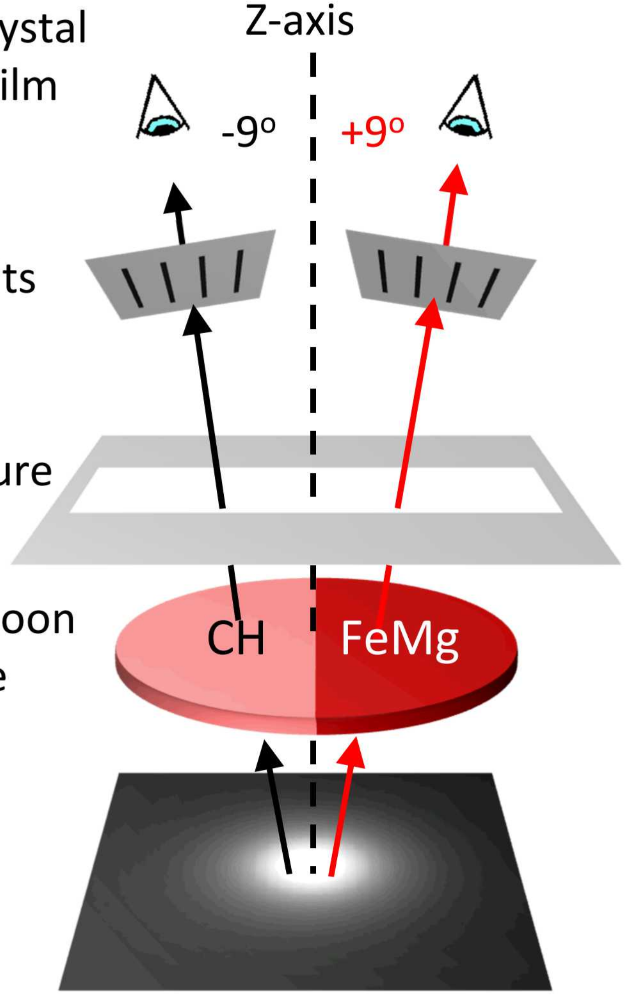

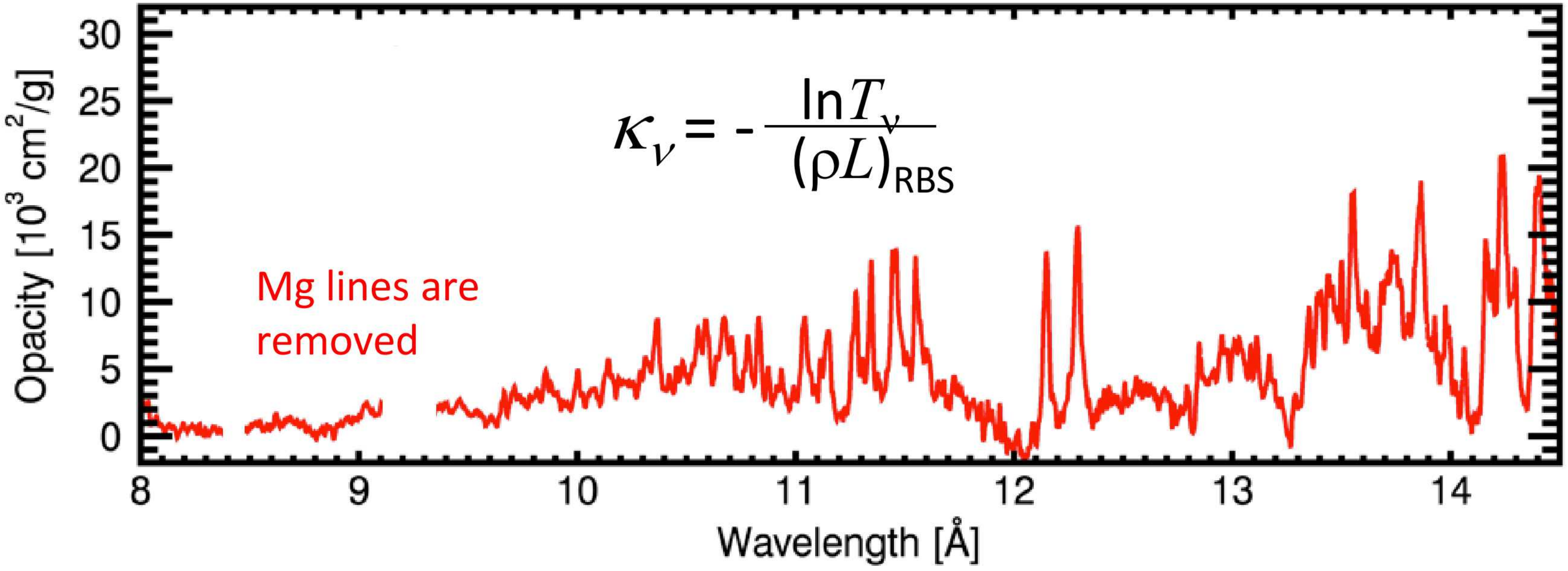

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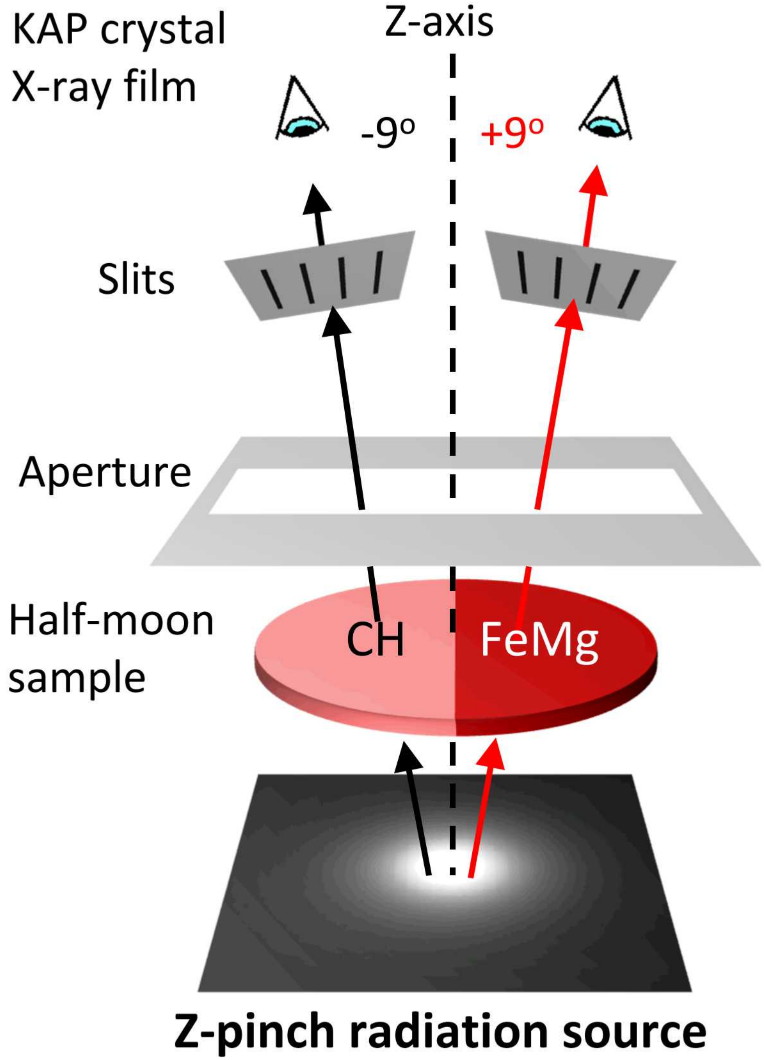
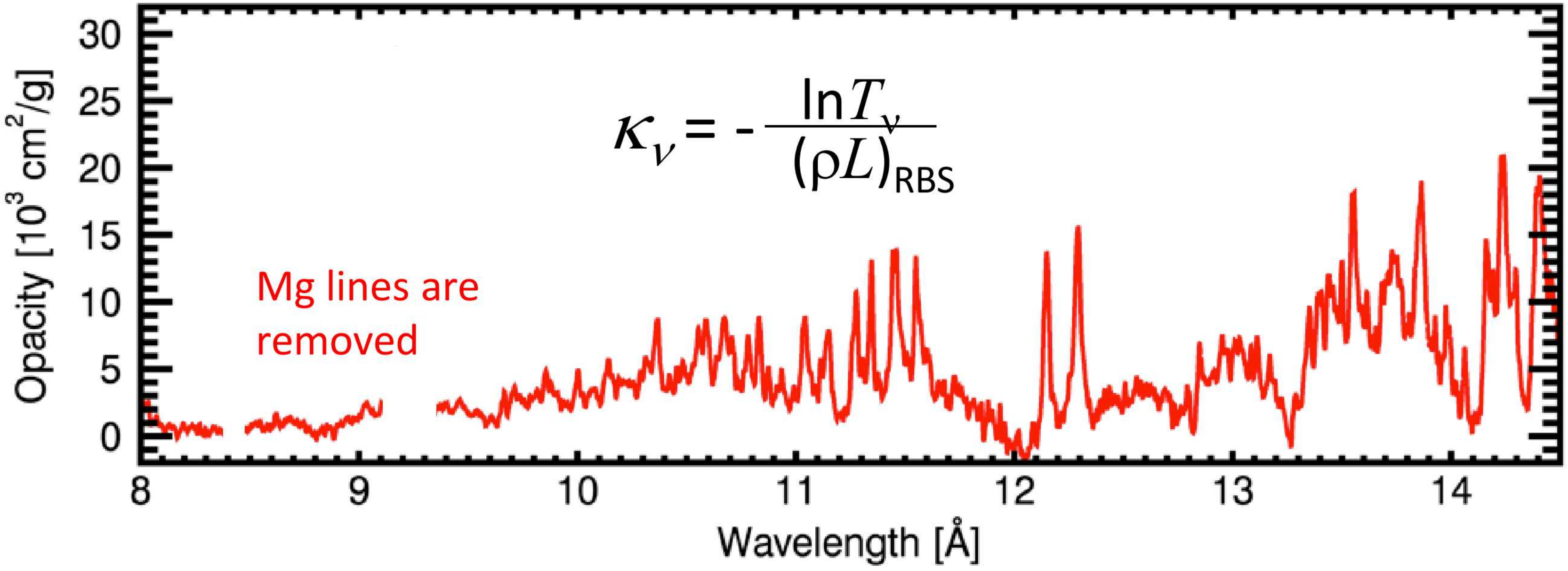


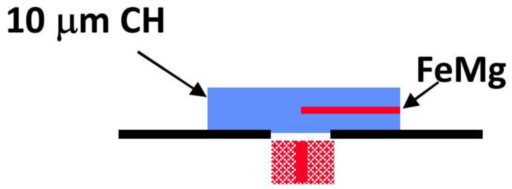


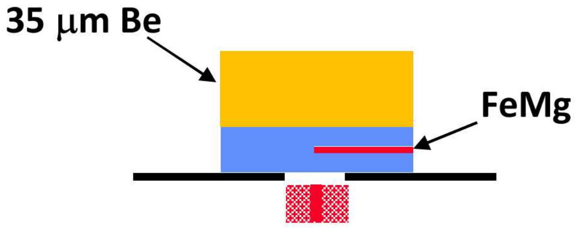
Requirements	SNL Z satisfies:
• Uniform heating →	Volumetric heating
• Mitigating self emission →	350 eV Planckian backlight
• Condition measurements →	Mg K-shell spectroscopy
• Checking reproducibility →	$\geq$ 5 shots

[1] Bailey et al., *Phys Plasmas* 16, 058101 (2009)

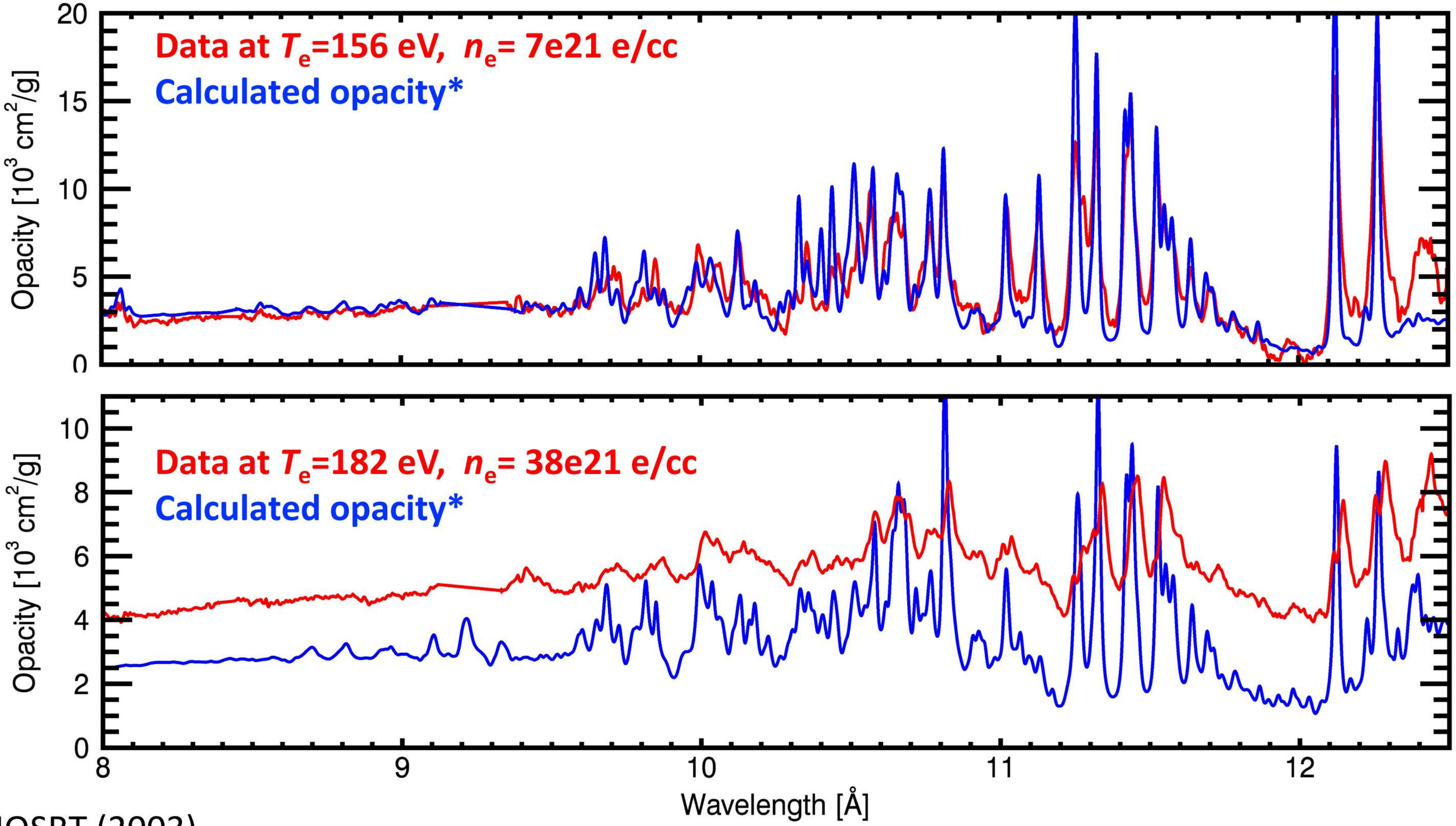
[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

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





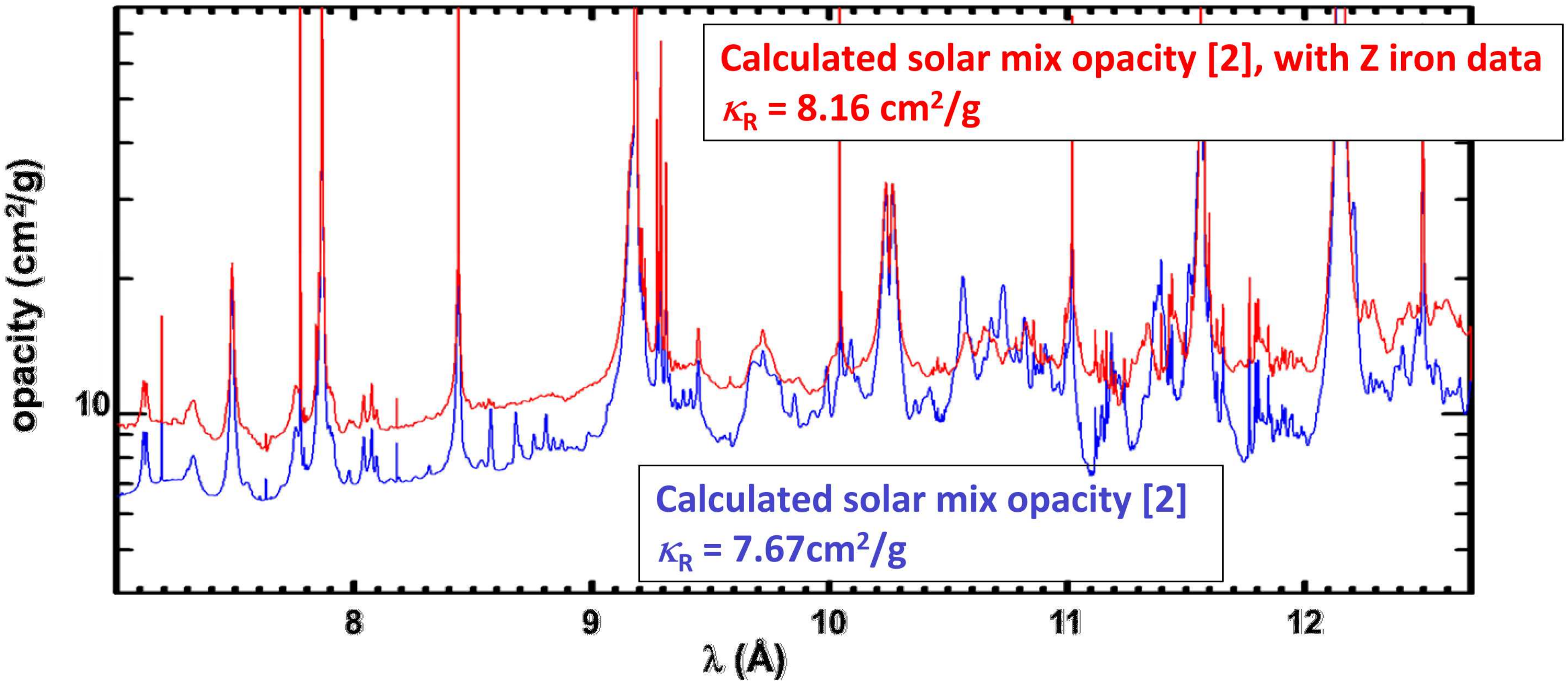
Convection Zone Base: T_e=185 eV, n_e = 90e21 e/cc



* PrismSPECT: MacFarlane et al, JQSRT (2003)

[1] Bailey et al., *Nature* 517, 56 (2015)
[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

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

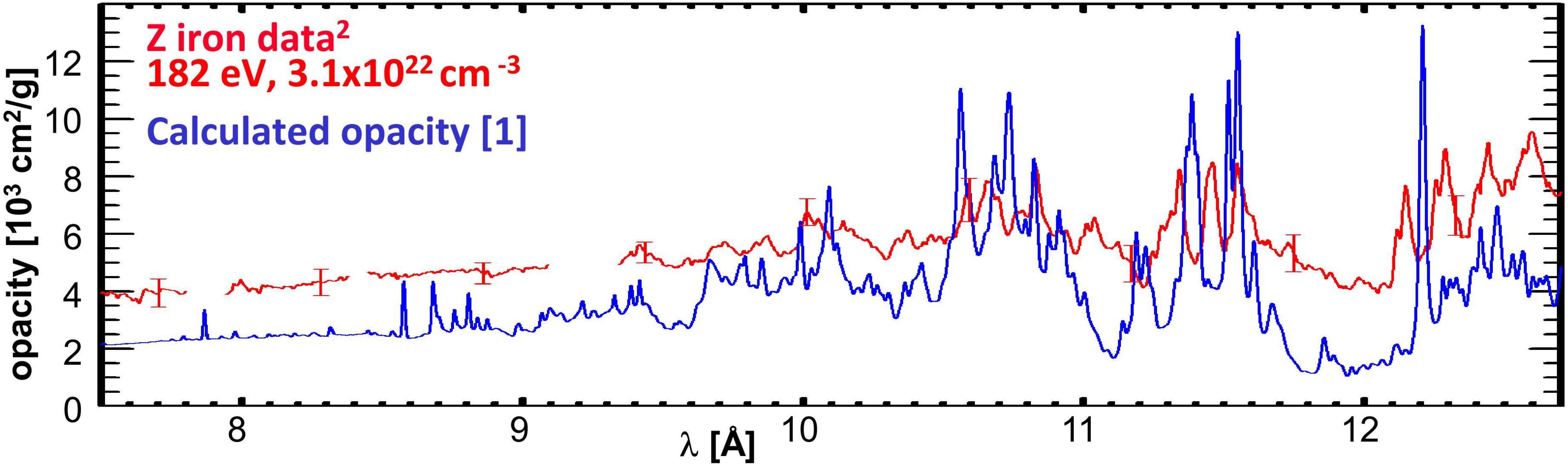


- A 7% Rosseland-mean increase partially resolves the solar problem
- Revision of opacity has significant impact on many astrophysical applications

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

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

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:

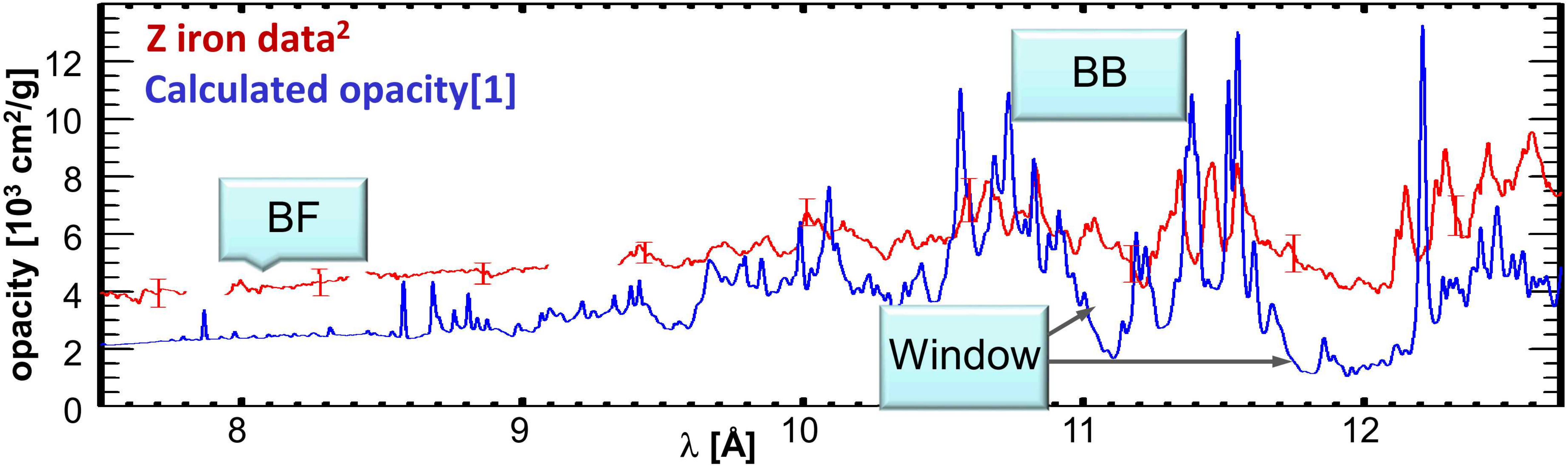
→ Evaluated with experiments and simulations

- 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

Opacity disagreement is complex and most likely caused by multiple sources



BF: bound-free/quasi-continuum:

- Bound-free (b-f) cross-section?
- Missing lines from multi-excited states?
- Multi-photon processes?

BB: bound-bound line features*

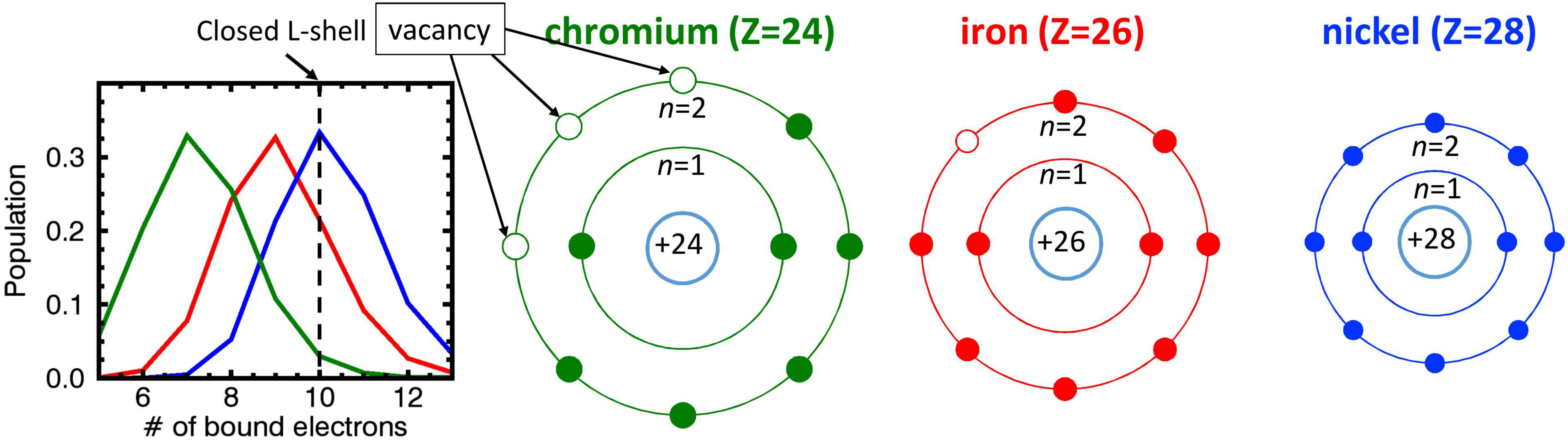
- Line location → Atomic structure
- Strength → Oscillator strength? Population?
- Line width → Line shape? Missing lines?

Window filling:

- Broader line shape filling the window?
- Missing lines from multi-excited states?
- Multi-photon processes?

[1] Seaton et al., *MNRAS* (1994) *ATOMIC, OPAS, SCO-RCG, SCRAM, and TOPAZ show much better agreement in line locations

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



<u>Questioning Theory:</u>

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

More ← L-shell vacancies ← Less

More ← # of excited states ← Less

More ← Density effects ← Less

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

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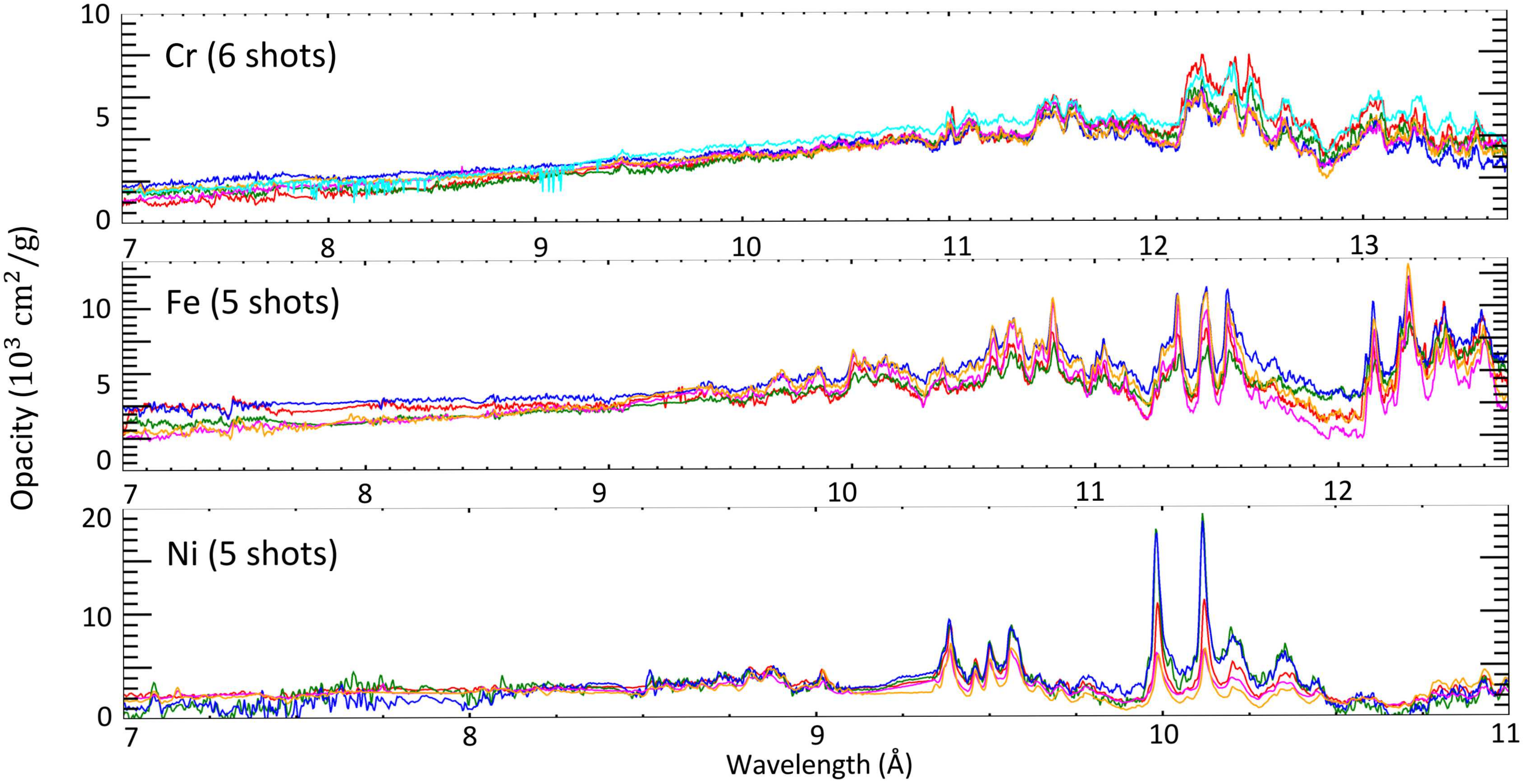
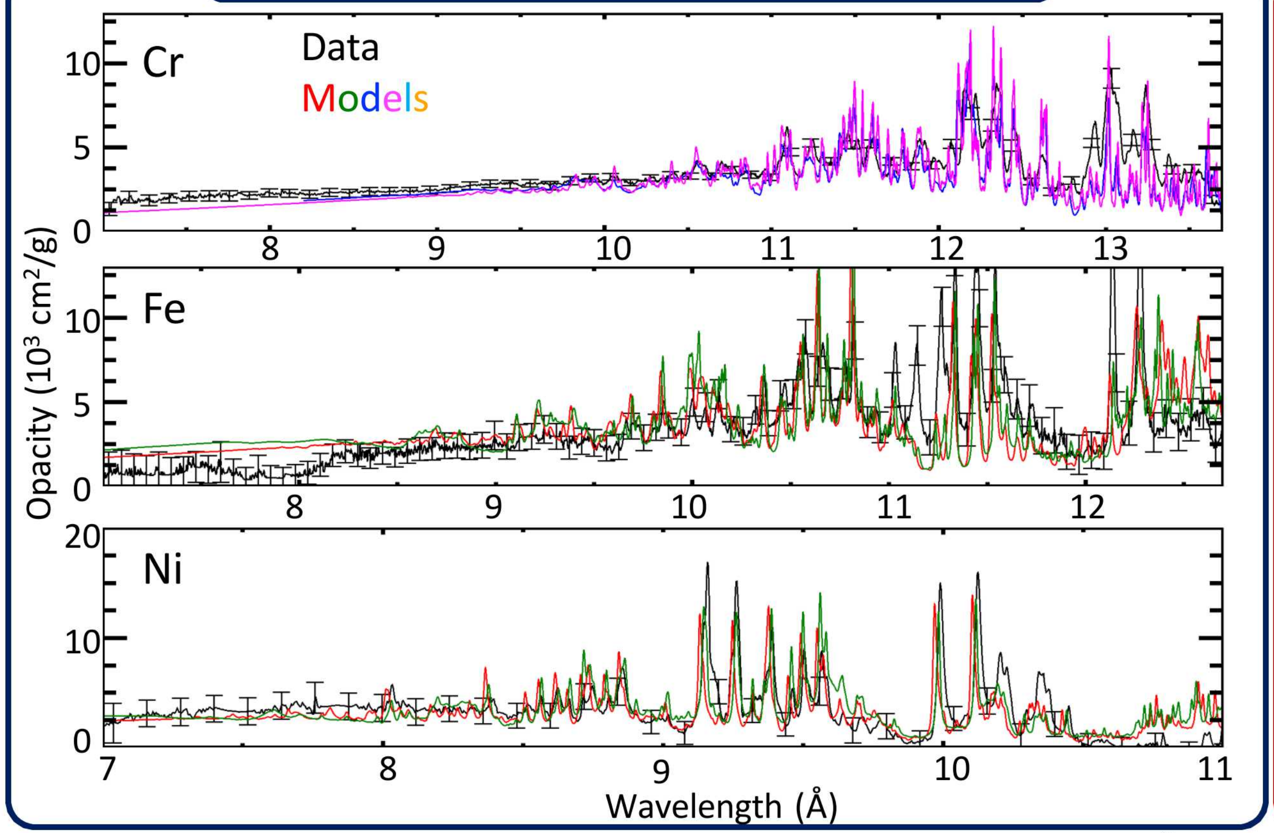
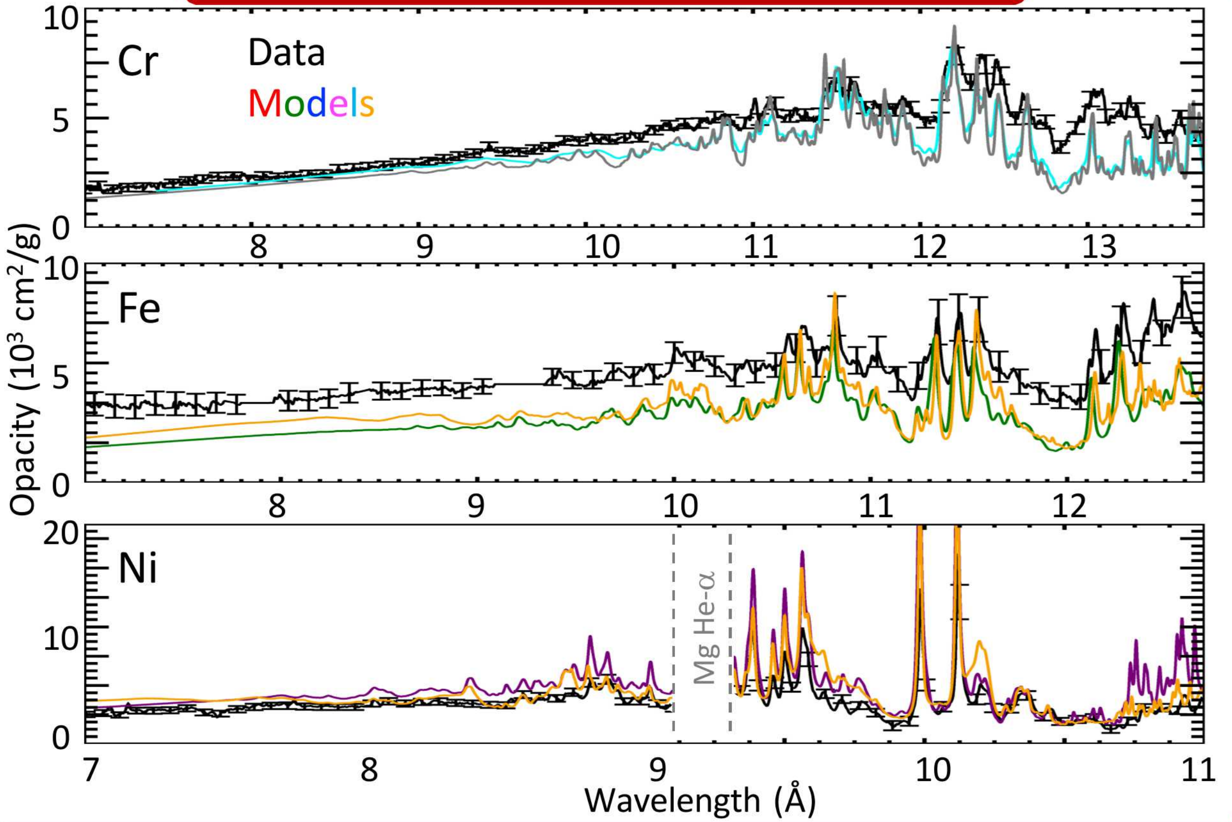


First systematic study of high-temperature L-shell opacities were performed for Cr, Fe, and Ni at two conditions

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

ZAPP campaigns simultaneously study multiple issues

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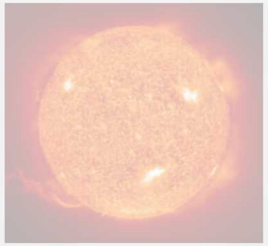
Solar Opacity



Question:
Why can't we predict solar structure accurately enough?

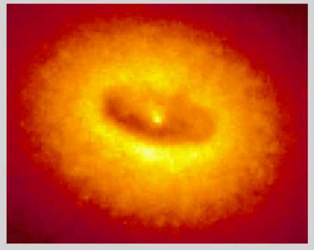
Achieved Conditions:
$T_e \sim 200$ eV, $n_e \sim 10^{23}$ cm^{-3}

White Dwarf Line-Shapes

Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

Achieved Conditions:
$T_e \sim 1$ eV, $n_e \sim 10^{17}$ cm^{-3}

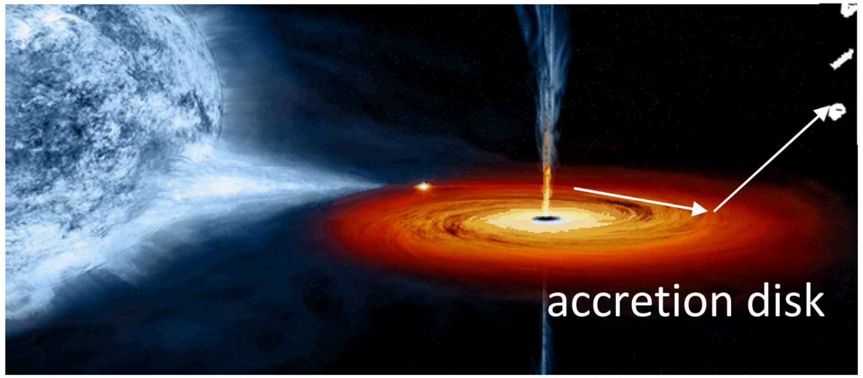
Photoionized Plasma



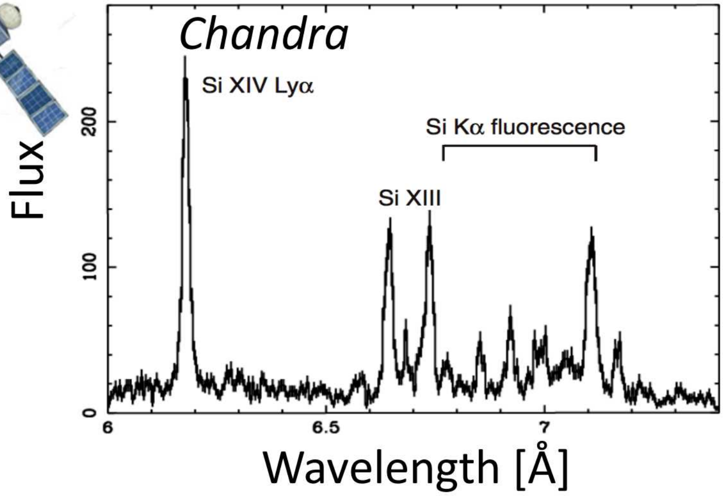
Question:
How does ionization and line formation occur in accreting objects?

Achieved Conditions:
$T_e \sim 20$ eV, $n_e \sim 10^{19}$ cm^{-3}

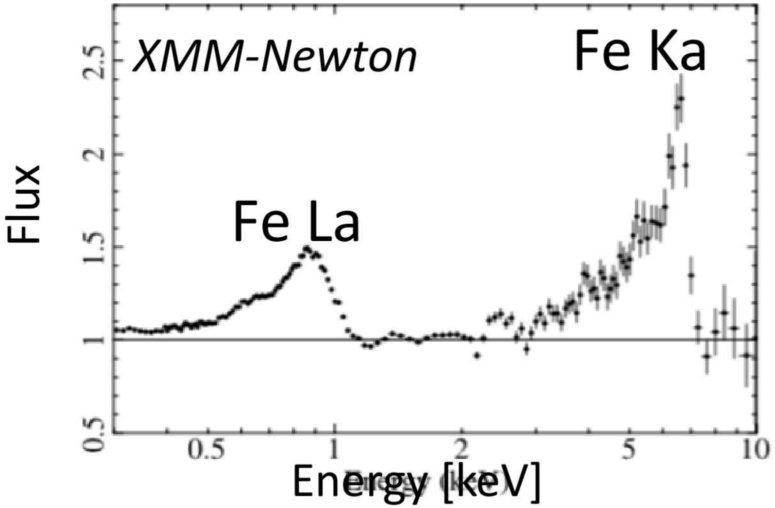
Active Galactic Nuclei and X-ray Binaries are revealed through the emission from their accretion disk



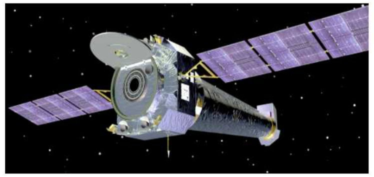
Neutron star Vela X-1



AGN 1H0707-495

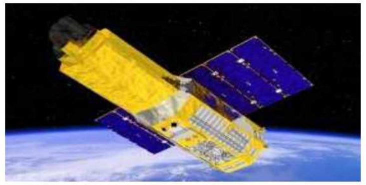


Chandra - NASA



XMM-Newton - ESA

Suzaku – JAXA



Liedahl, X-ray Diagnostics of Astrophysical Plasmas (2005), Ross & Fabian, Nature (2009)

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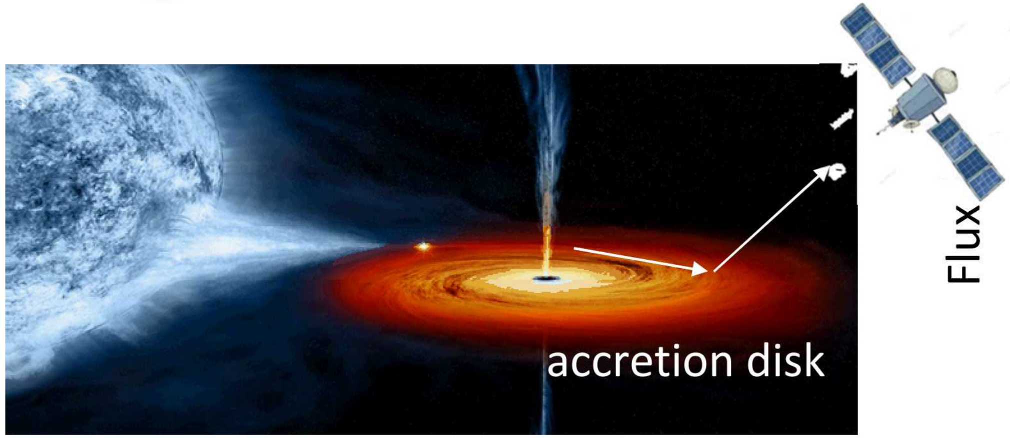
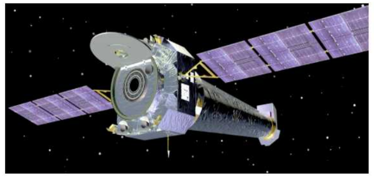
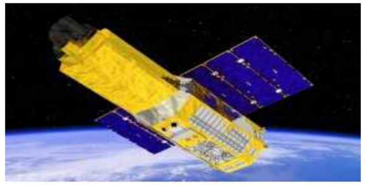


Chandra - NASA



Suzaku – JAXA



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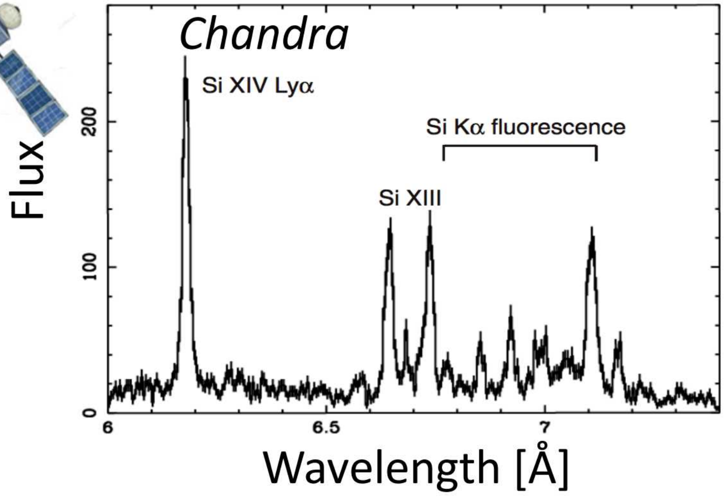
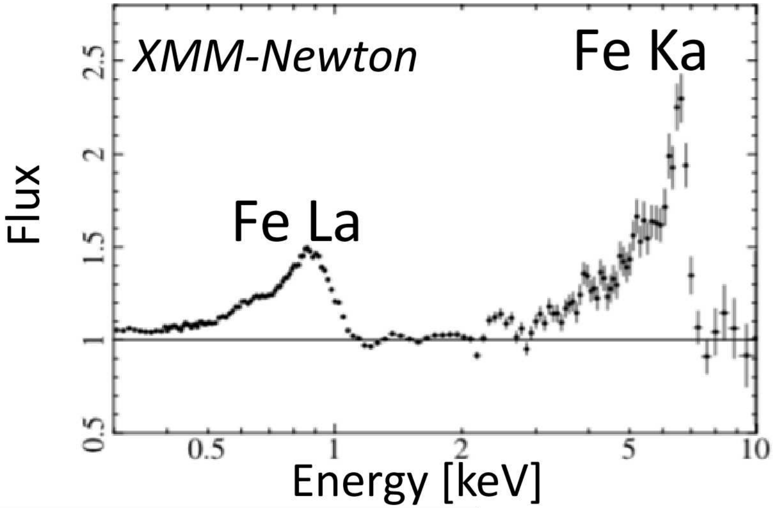


AGN 1H0707-495



Challenges:
- Line identification
- Limited spectral resolution
- Blended spectra from multiple elements
- Spatial and temporal integration

- **Modeling of photoionzed plasma is not sufficiently tested**
- **Extraordinary observation deserves benchmarked models**

Liedahl, X-ray Diagnostics of Astrophysical Plasmas (2005), Ross & Fabian, Nature (2009)

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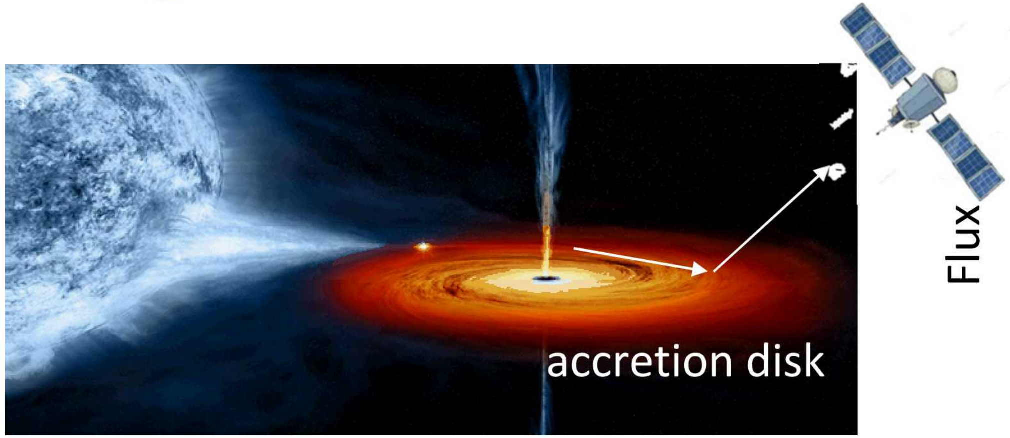

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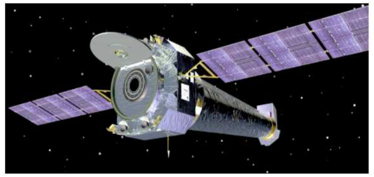

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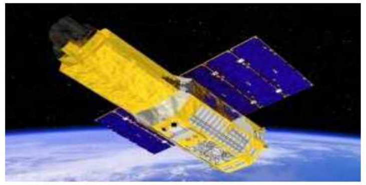

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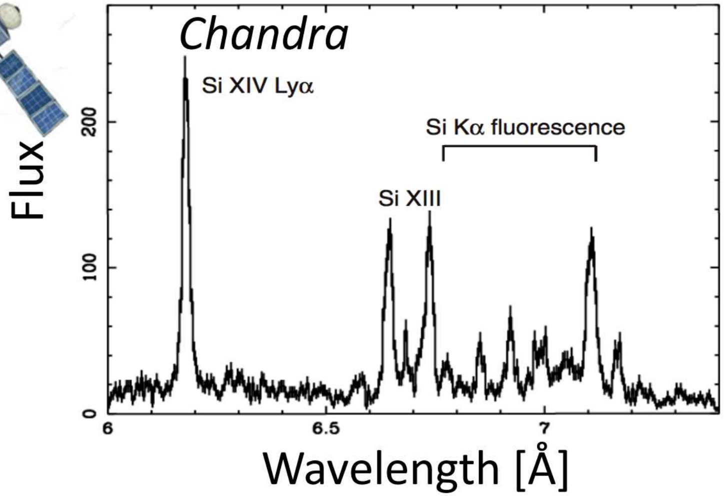

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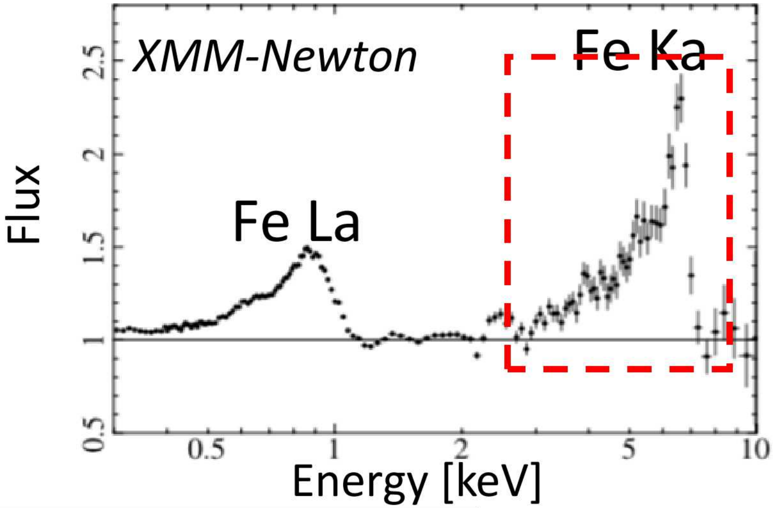

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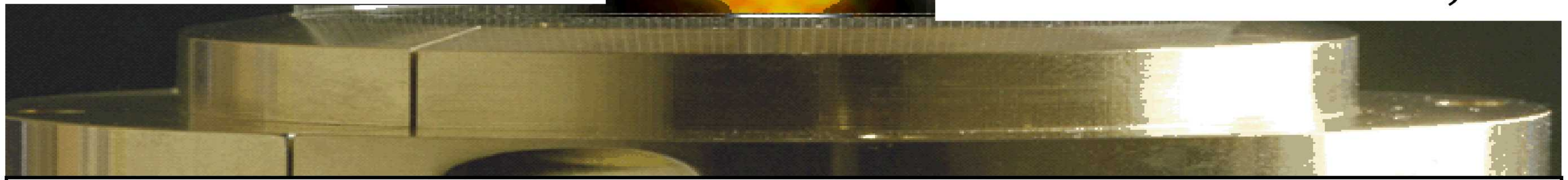
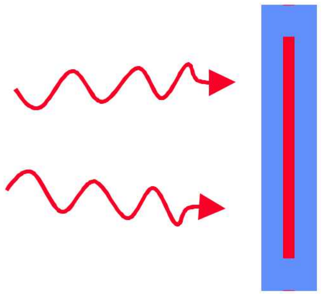
Liedahl, X-ray Diagnostics of Astrophysical Plasmas (2005), Ross & Fabian, Nature (2009)

Z-pinch radiation heats and expands Si foil and achieve photoionization parameter, ξ=20-1,000



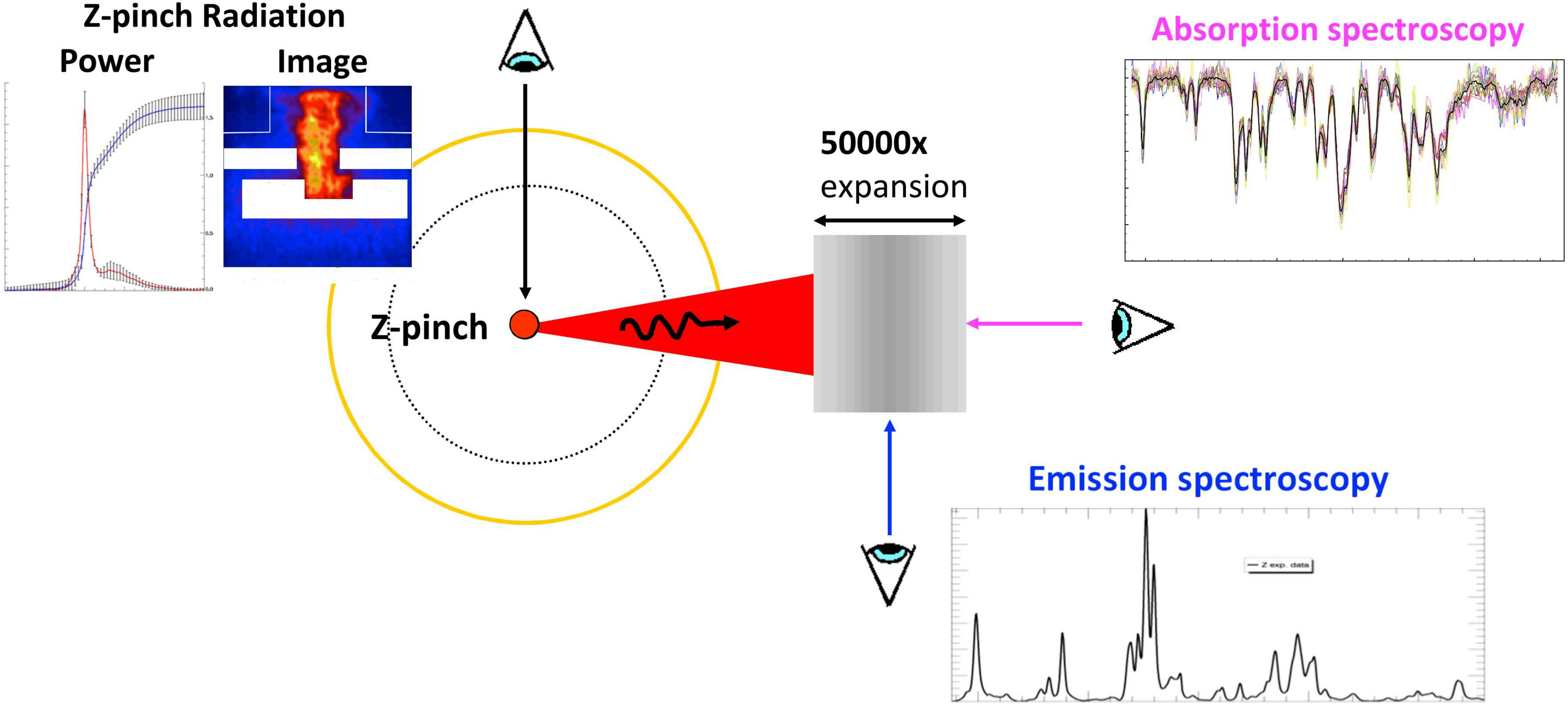
Accretion disk experiments

- T=30-40 eV
- ne=5e16-1e17 e/cc
- ξ=20-1000

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)

Numerous requirements for benchmark emission measurements are met at Sandia National Lab



G. Loisel, J. Bailey, D. Liedahl et al., PRL 119 (2017)

Numerous requirements for benchmark emission measurements are met at Sandia National Lab

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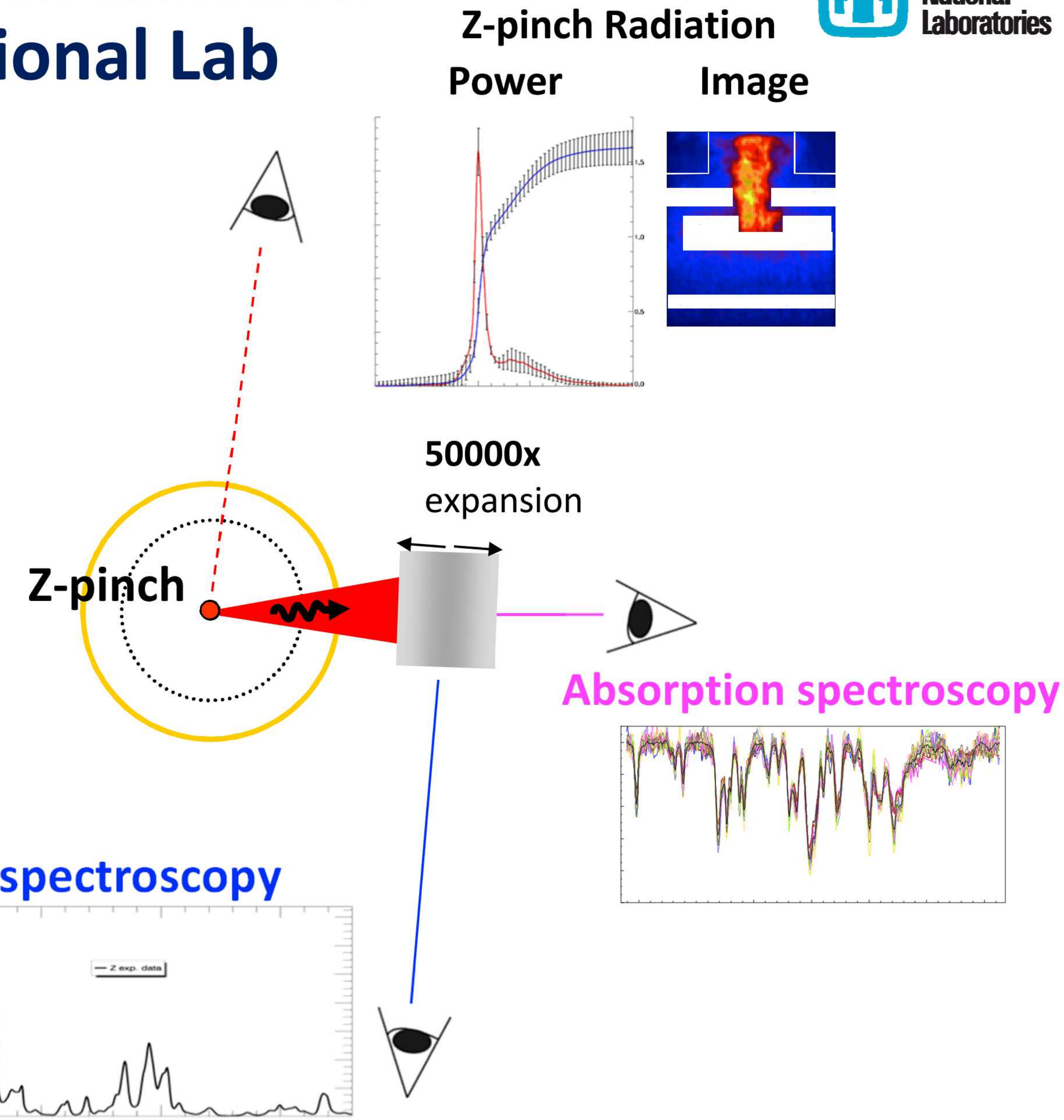
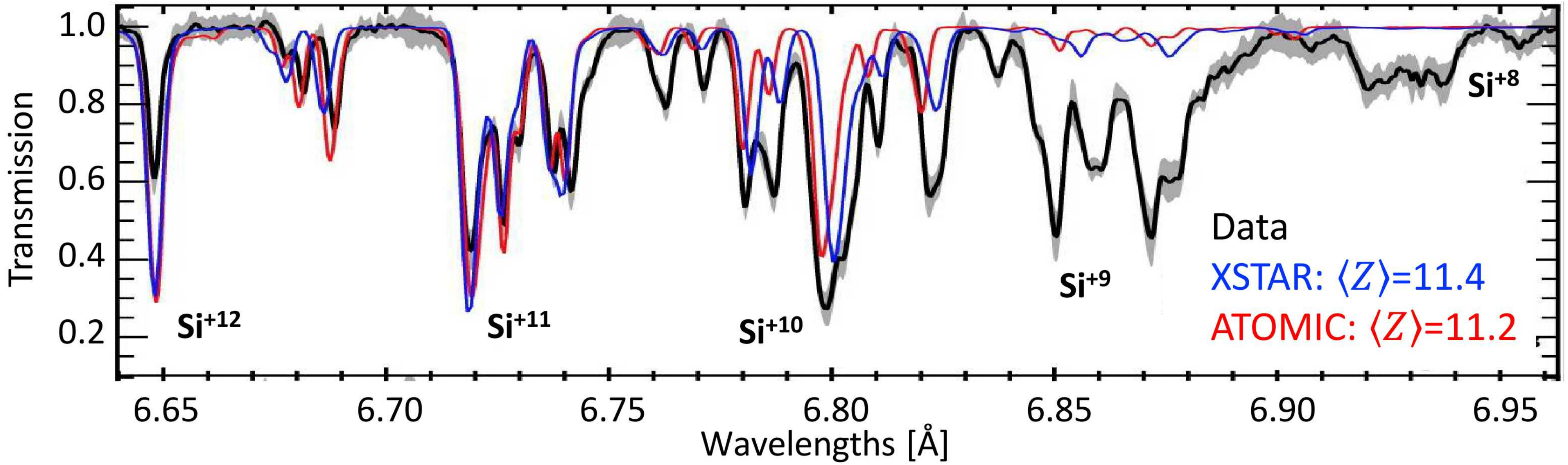
Experimentally constrained parameters

X-ray drive, flux and shape	$F \sim 1.3\ 10^{19}$ erg/cm^2/s T_{color}= [45, 80, 170] eV
Ion density	$n_i = 8 \times 10^{17}$ cm^{-3}
Column density (adjustable)	N_i = [2.5, 5, 10] x 10^{17} cm^{-2}
Average charge	$Z \sim 10$, Si^{+10}
Electron temperature	T_e = 26 - 40 eV
Photoionization parameter	ξ = 20-1000 erg.cm/s



Modeled absorption spectra overpredict the ionization at inferred conditions



Hypotheses:

Experiment:

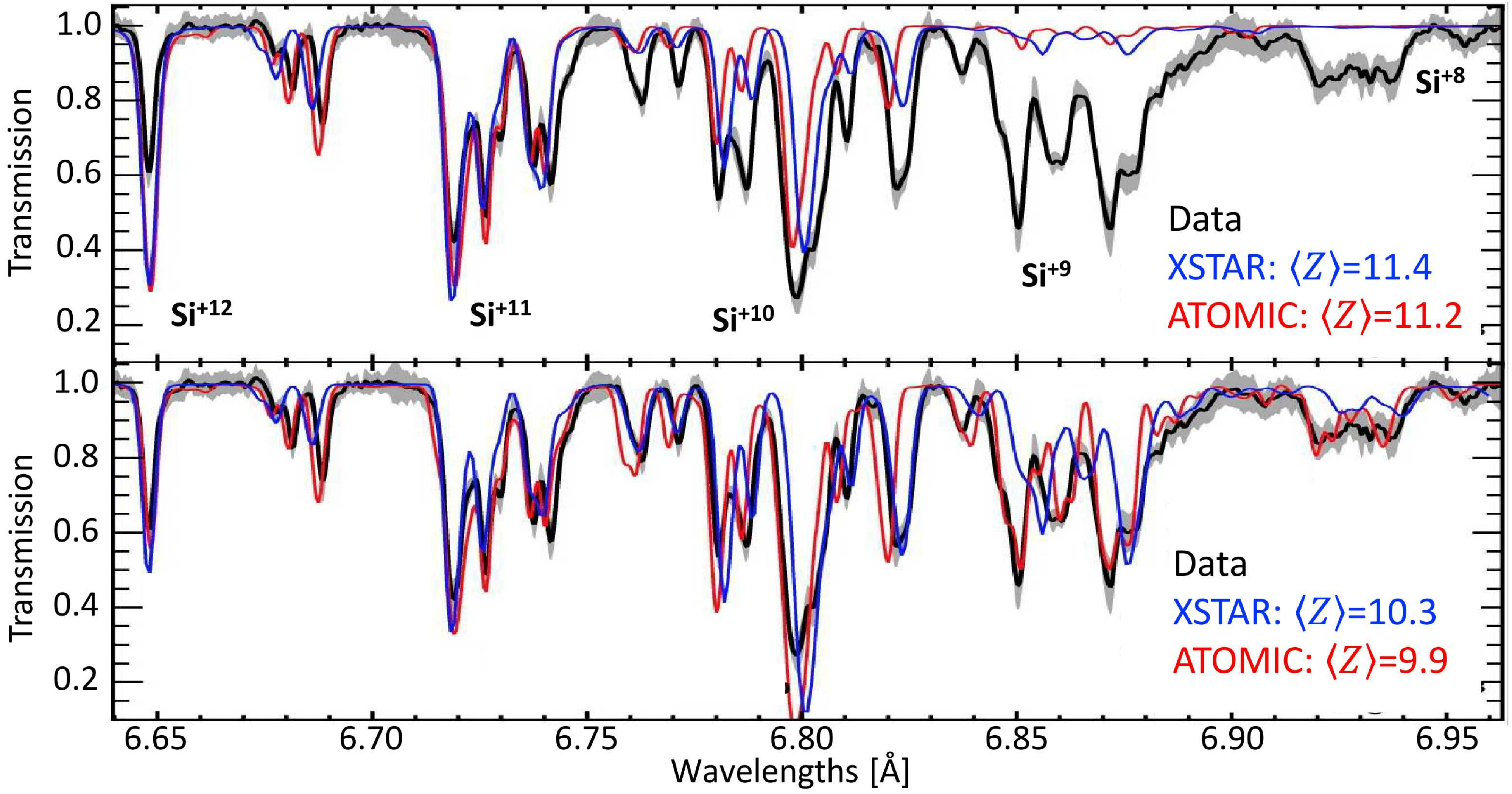
- Higher n_e?
- Lower F_ν?

Theory:

- Higher dielectronic recombination rate?

Models agree when we assume higher ne, lower radiation, or higher DR rate

Agreement improves by assuming higher n_e, weaker radiation, or higher DR rate



Hypotheses:

Experiment:

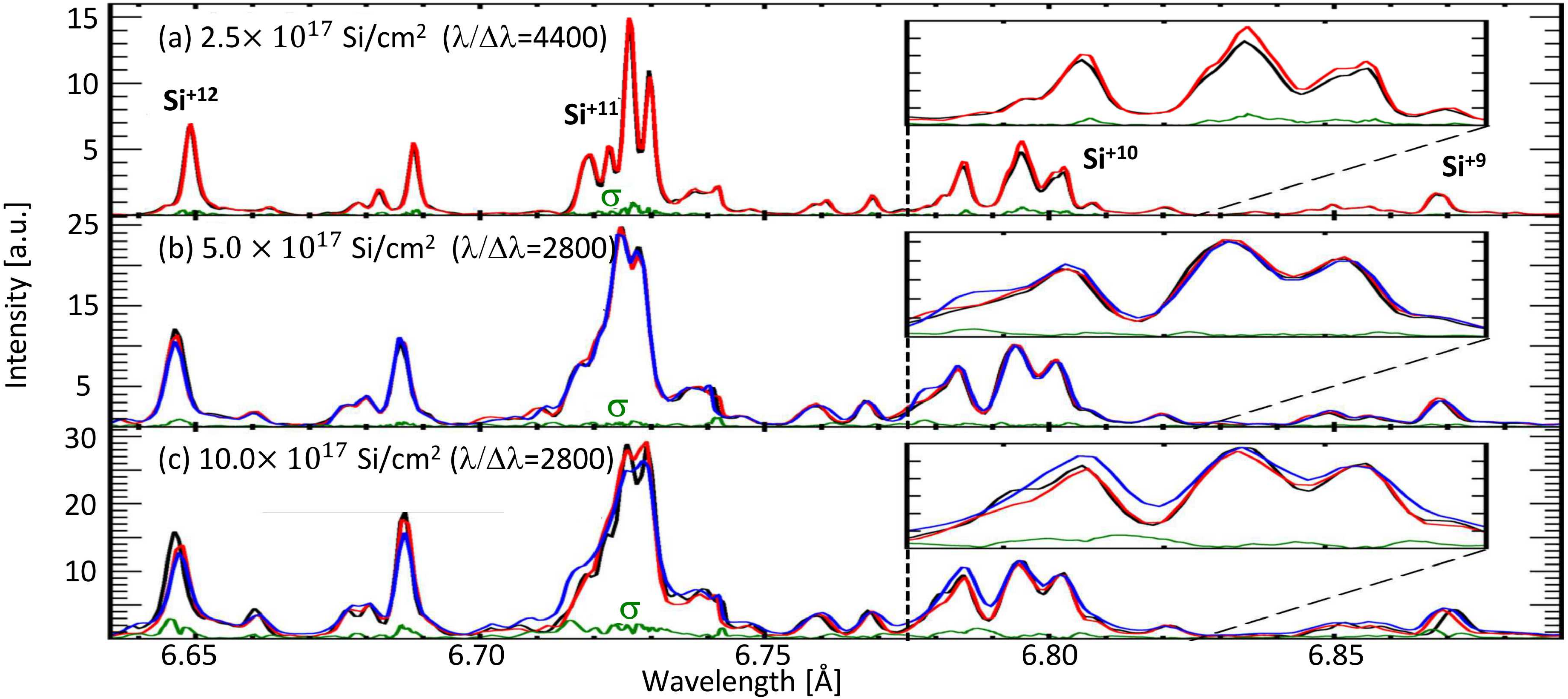
- Higher n_e?
- Lower F_ν?

Theory:

- Higher dielectronic recombination rate?

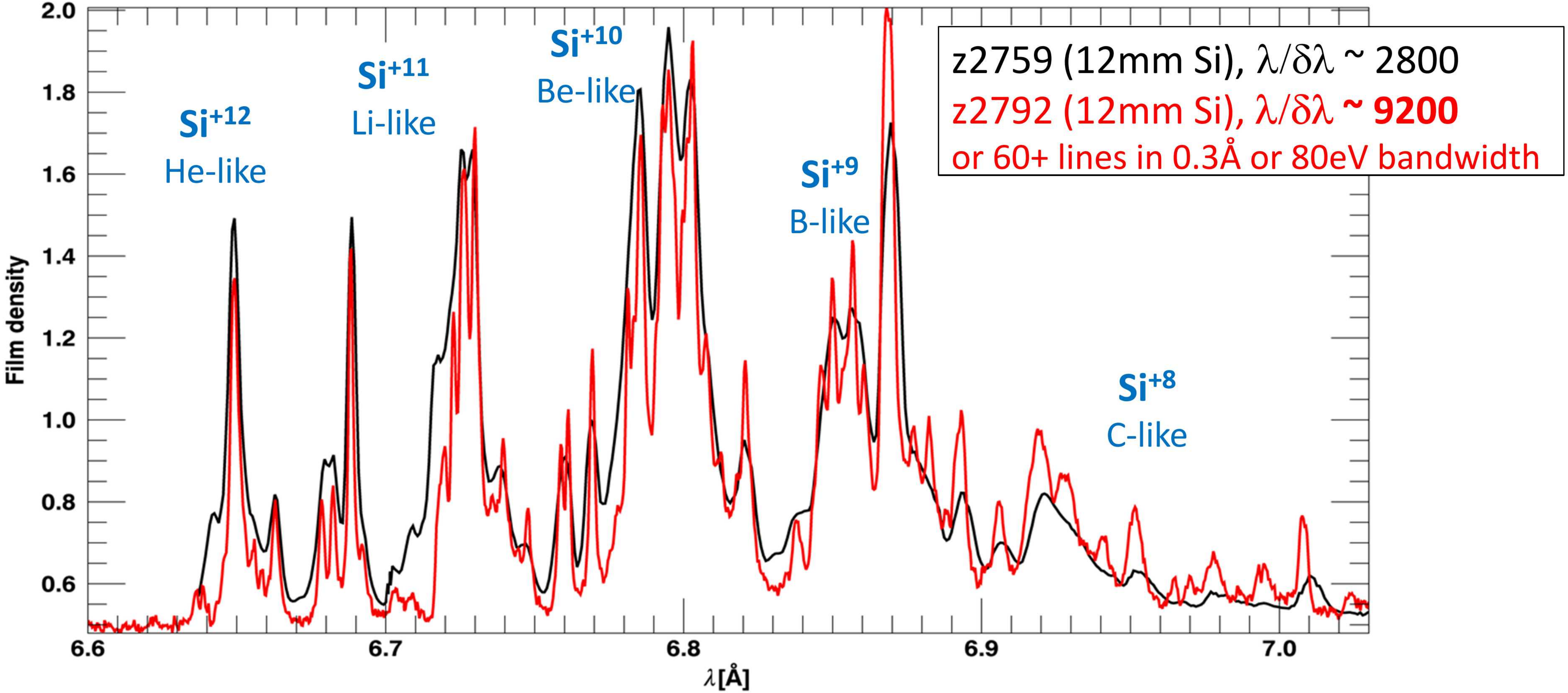
We need extra measurements to double-check the accuracy of n_e and F_ν

Photoionized plasma emission were measured with high resolution for the first time through 3 different column densities



K emission from L-shell ions increases with column density → RAD is not appropriate

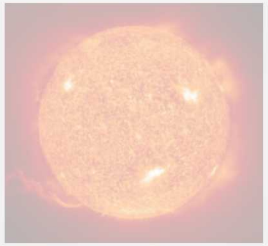
We recently measured emission at very high spectral resolution



Comparison with the EBIT measurements will be exciting.

ZAPP campaigns simultaneously study multiple issues

Solar Opacity



Question:
Why can't we predict solar structure accurately enough?

Achieved Conditions:
T_e ~ 200 eV, n_e ~ 10^{23} cm^{-3}

White Dwarf Line-Shapes

Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

Achieved Conditions:
T_e ~ 1 eV, n_e ~ 10^{17} cm^{-3}

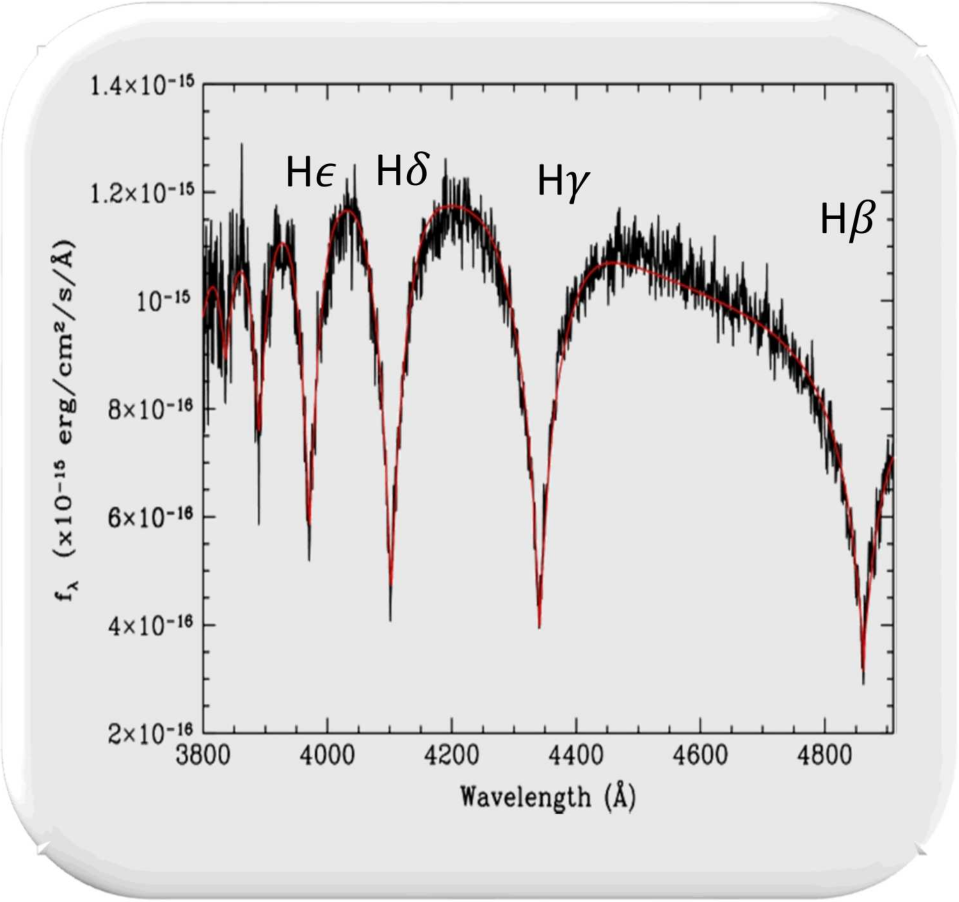
Photoionized Plasma

Question:
How does ionization and line formation occur in accreting objects?

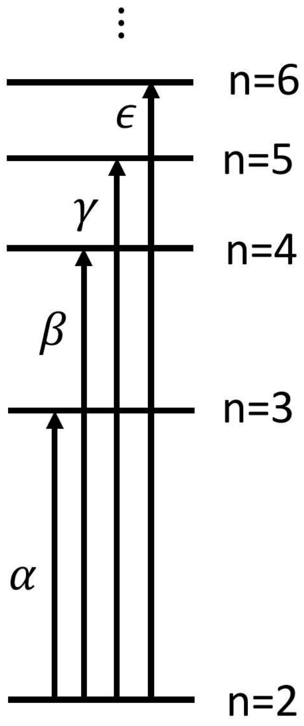
Achieved Conditions:
T_e ~ 20 eV, n_e ~ 10^{19} cm^{-3}

The properties of White Dwarfs are determined by spectral fitting, but disagrees with other methods

- White Dwarfs are evolutionary endpoint for ~98% of stars
- WD surface temperature and total mass are usually determined by fitting the observed spectra
- **<u>Problem:</u>** The mean WD mass inferred by fitting and by gravitational-red-shift disagree by 10%



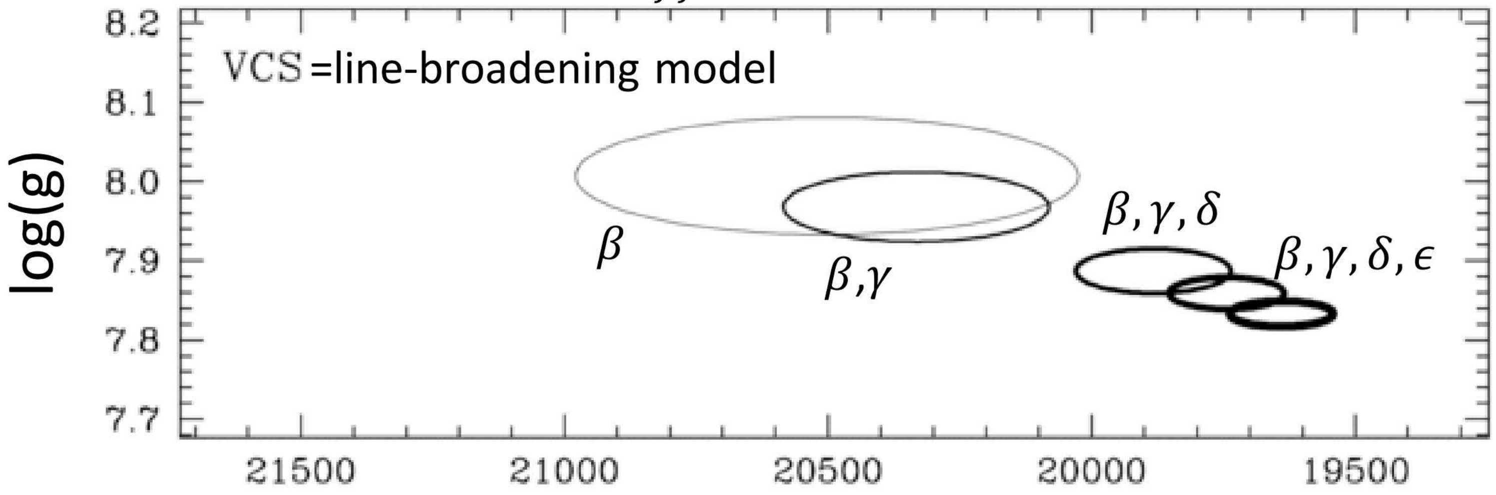
Balmer lines

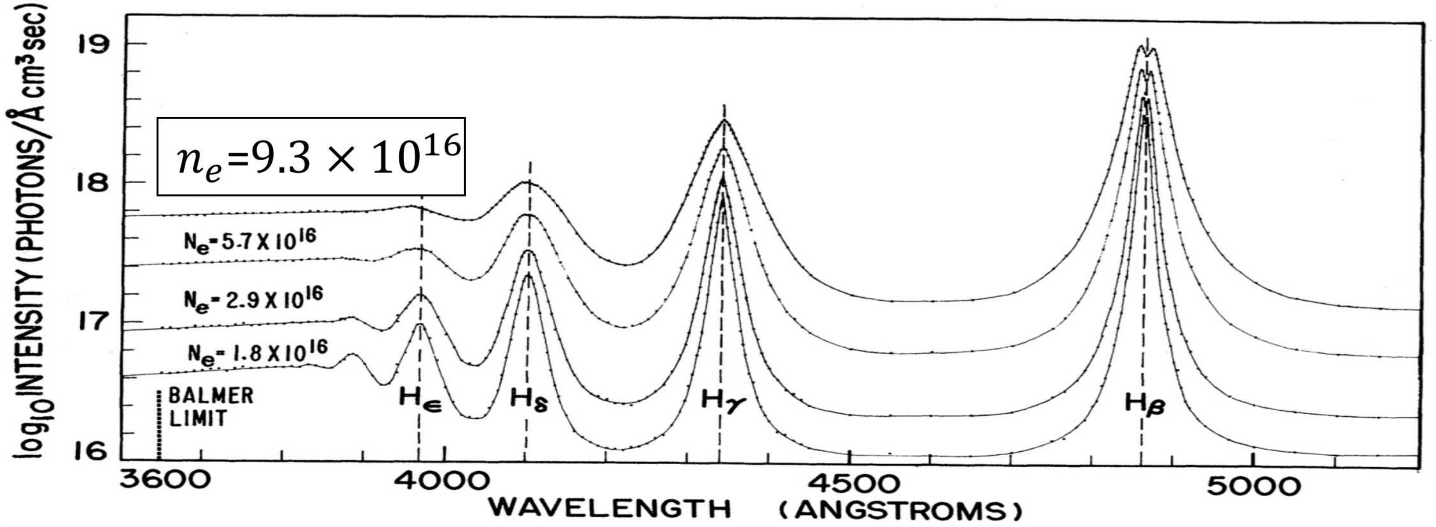


This 10% uncertainty in mass yields 0.5 G year difference for the age of galaxy

There are inconsistencies in mass inferred from different lines while VCS model was validated by measurements

$\log(g)$ and T_{eff} inferred from different lines [1]





Puzzling facts:

- Higher lines lower the inferred $\log(g)$
- VCS was validated by Wiese [2]

Limitation of Wiese's data:

- Available only up to 1×10^{17} cm^{-3}*
- Measured emission spectra

Need to measure line shapes both in emission and absorption up to higher density

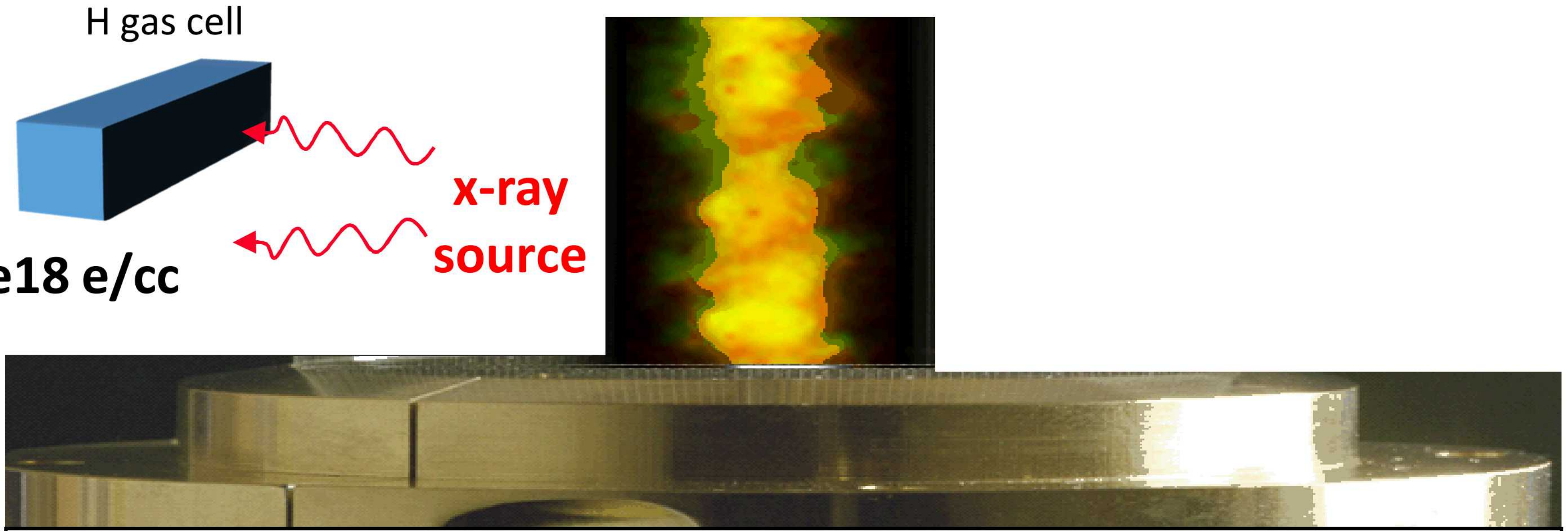
[2] Wiese et al, Physical Review A 6, 1132 (1972).

* Photosphere continues up > 1×10^{18} cm^{-3}

Hydrogen gas is heated by reemission from the gold wall; Its emission and absorption spectra are simultaneously observed

White Dwarf experiments:

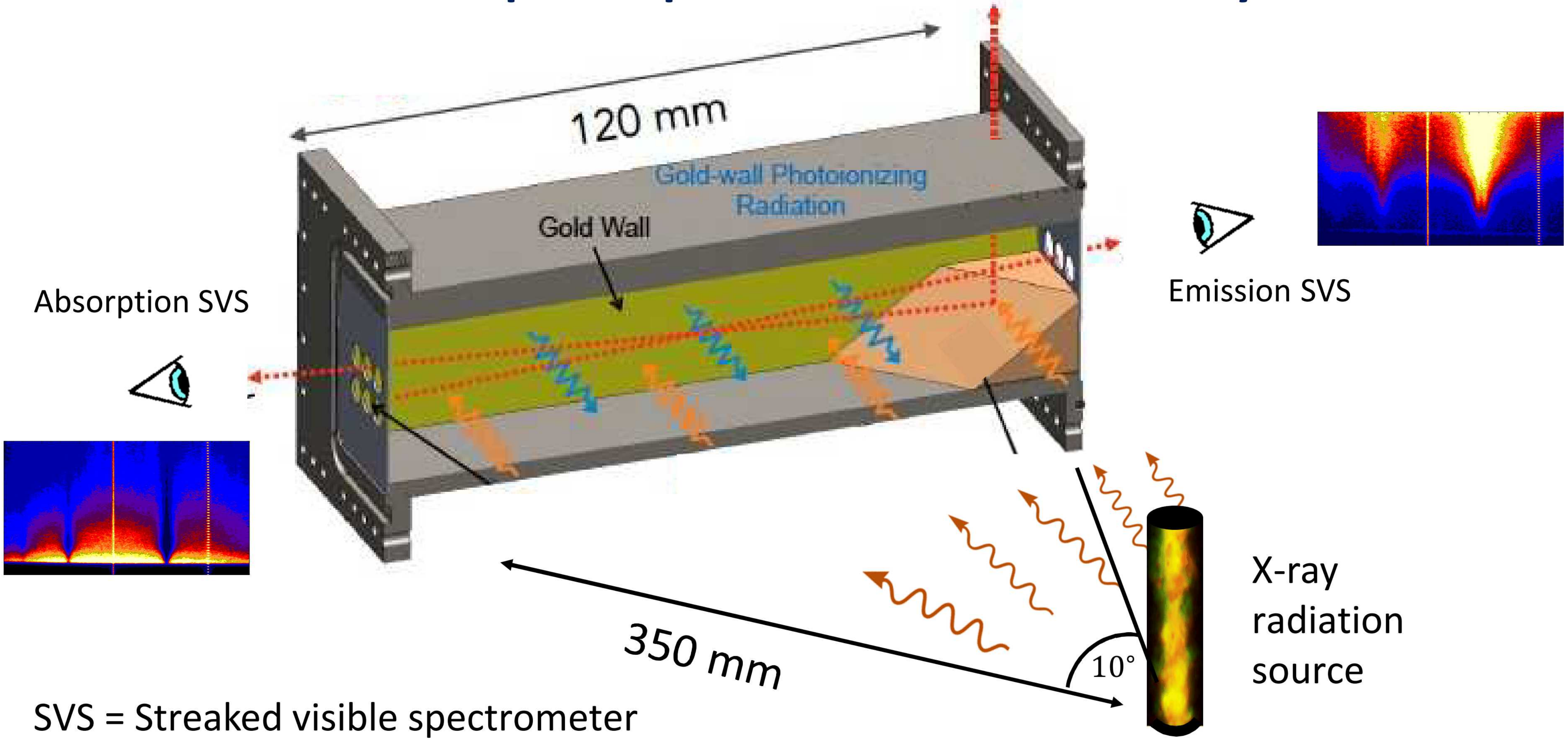
- **T=1-3 eV**
- **ne=5e16-1e18 e/cc**



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

Single shot can perform multiple experiments at T=1-200 eV and ne=5e16-1e23 e/cc

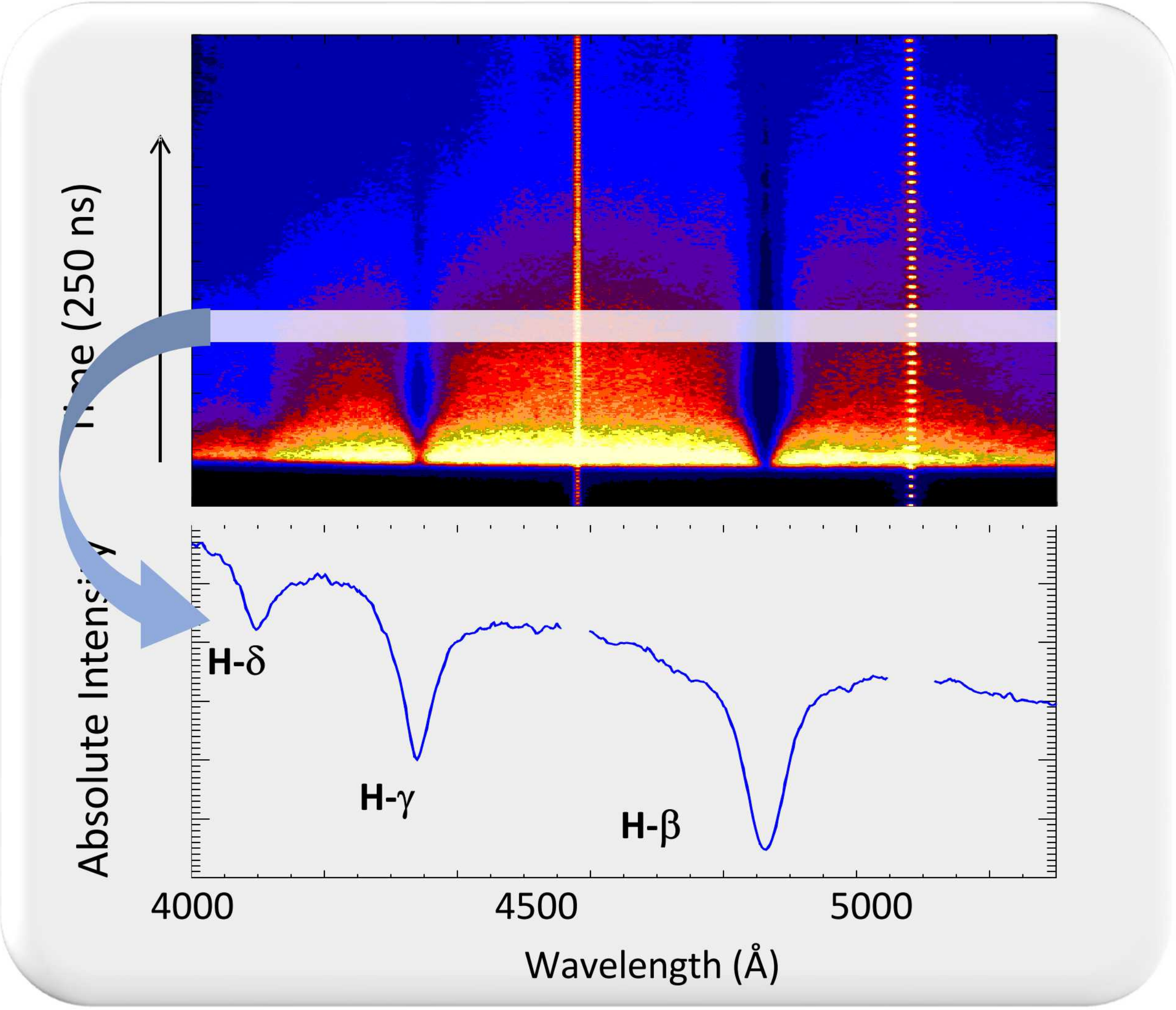
Hydrogen gas is heated by reemission from the gold wall; Its emission and absorption spectra are simultaneously observed



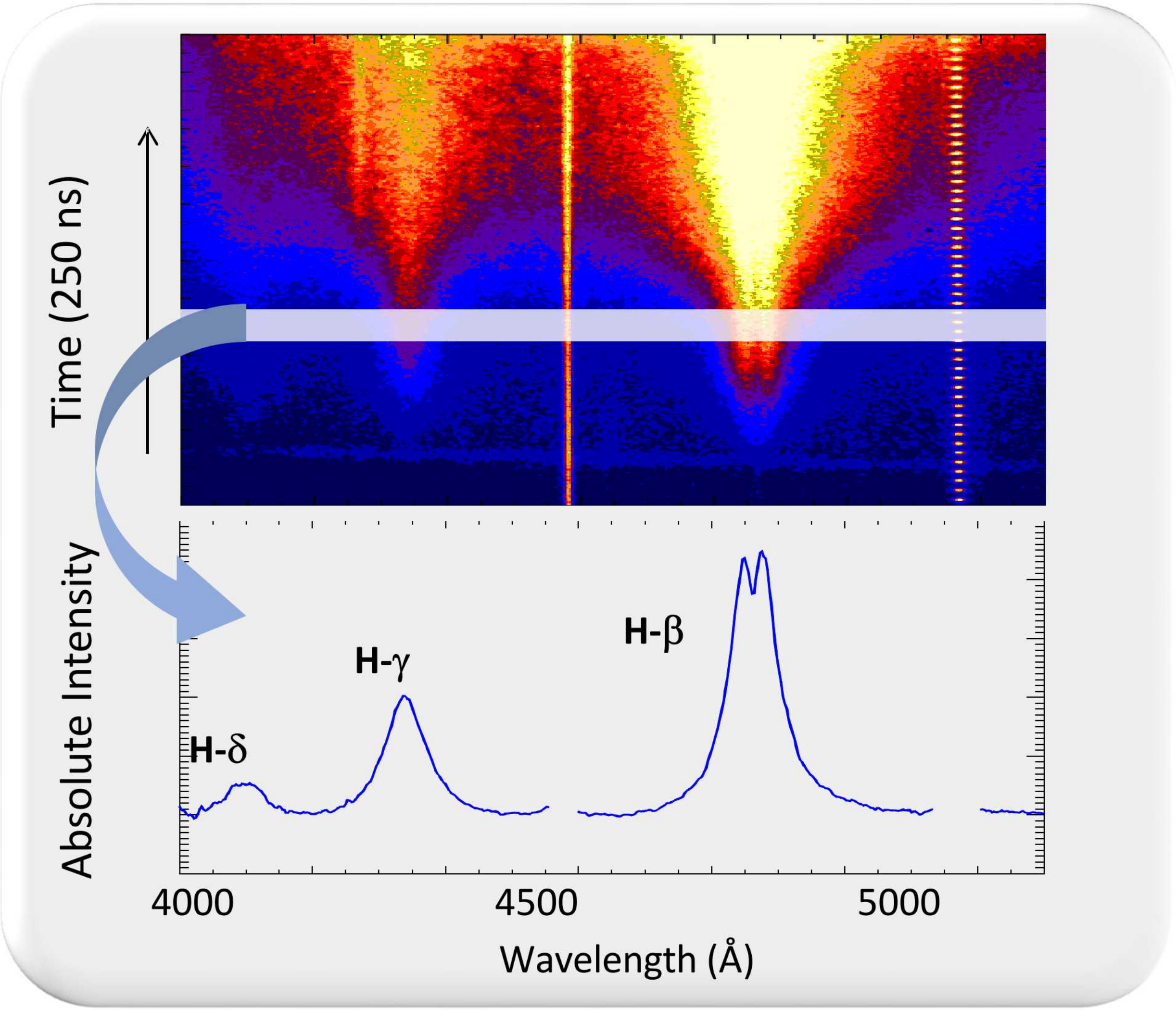
SVS = Streaked visible spectrometer

Hydrogen gas is heated by reemission from the gold wall; Its emission and absorption spectra are simultaneously observed

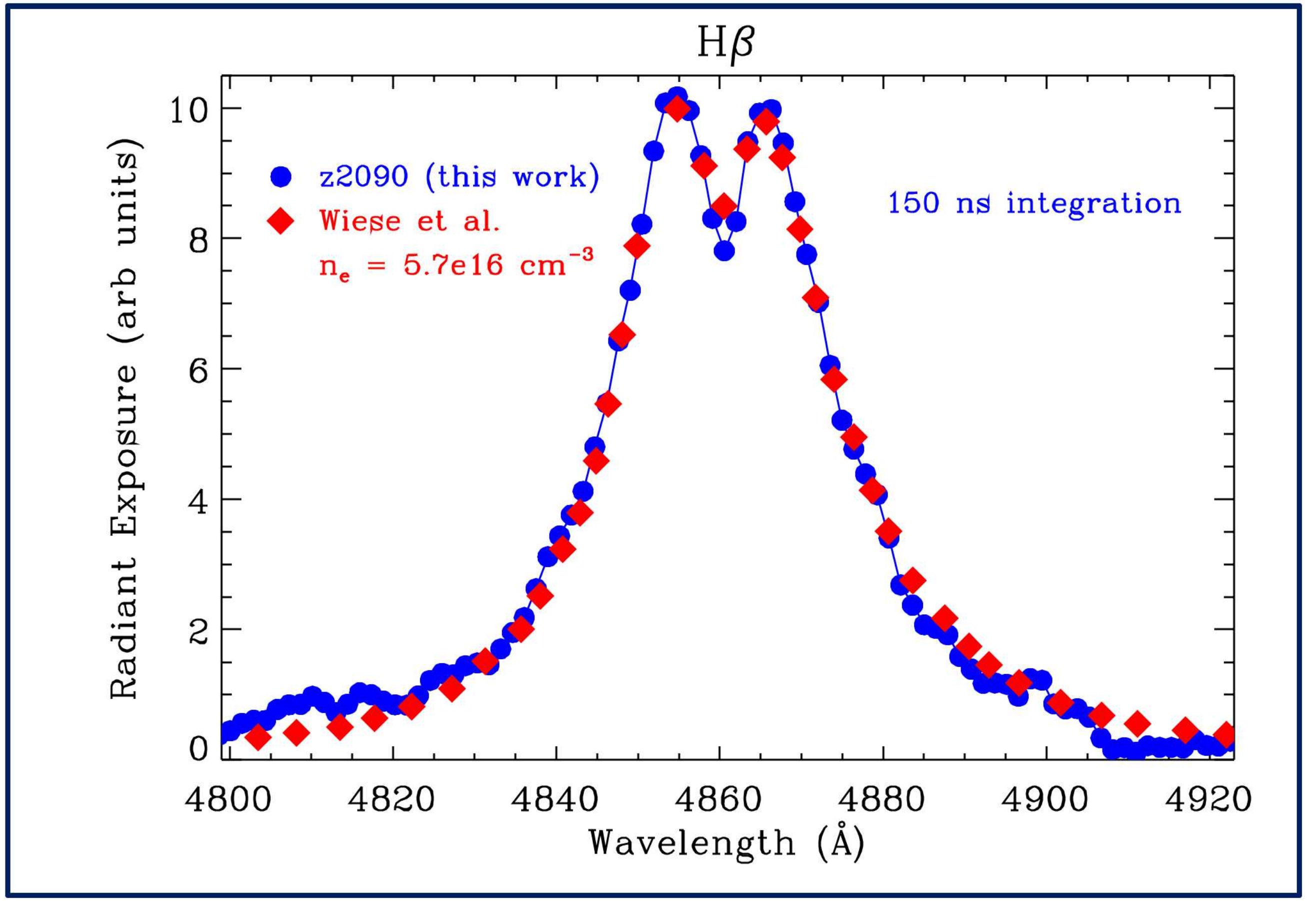
Absorption

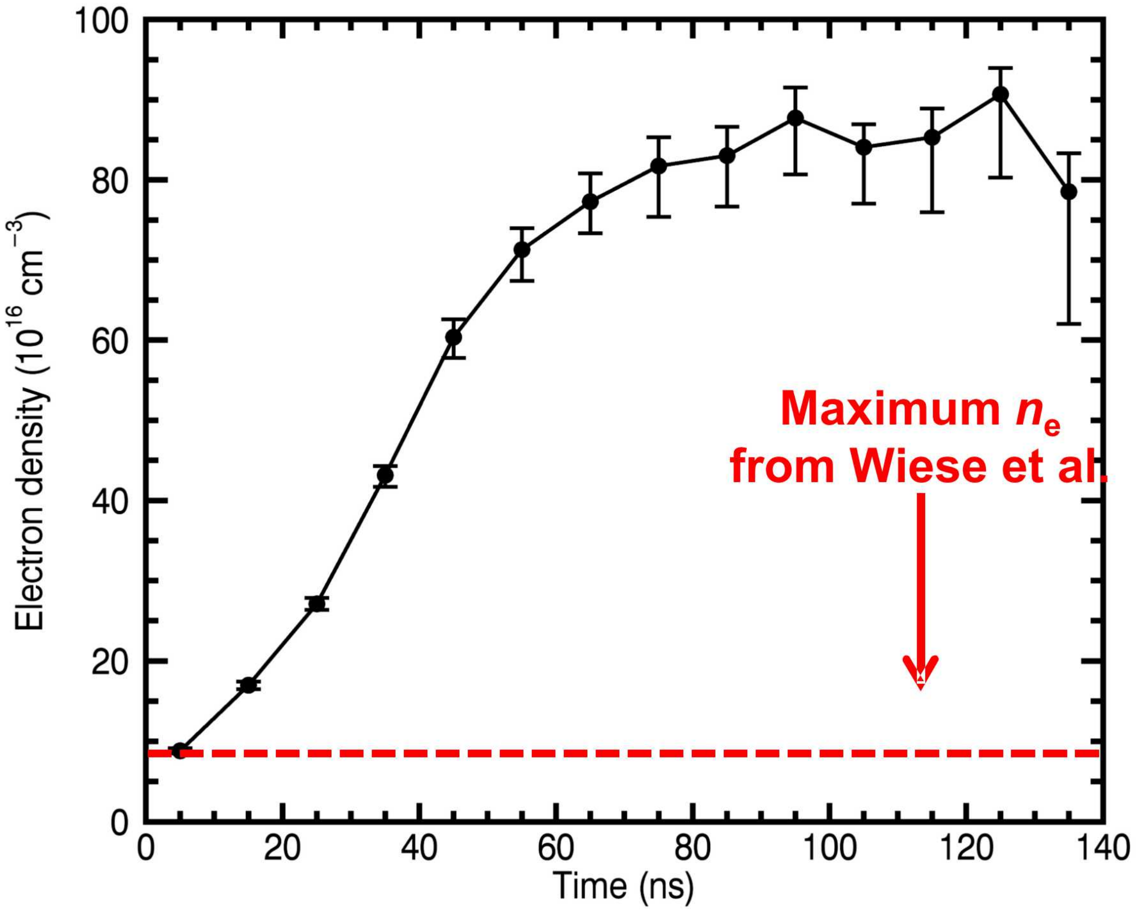


Emission



Z experiment reproduced previous line-shape benchmark experiments by Wiese [1], and measured up to 10x higher n_e

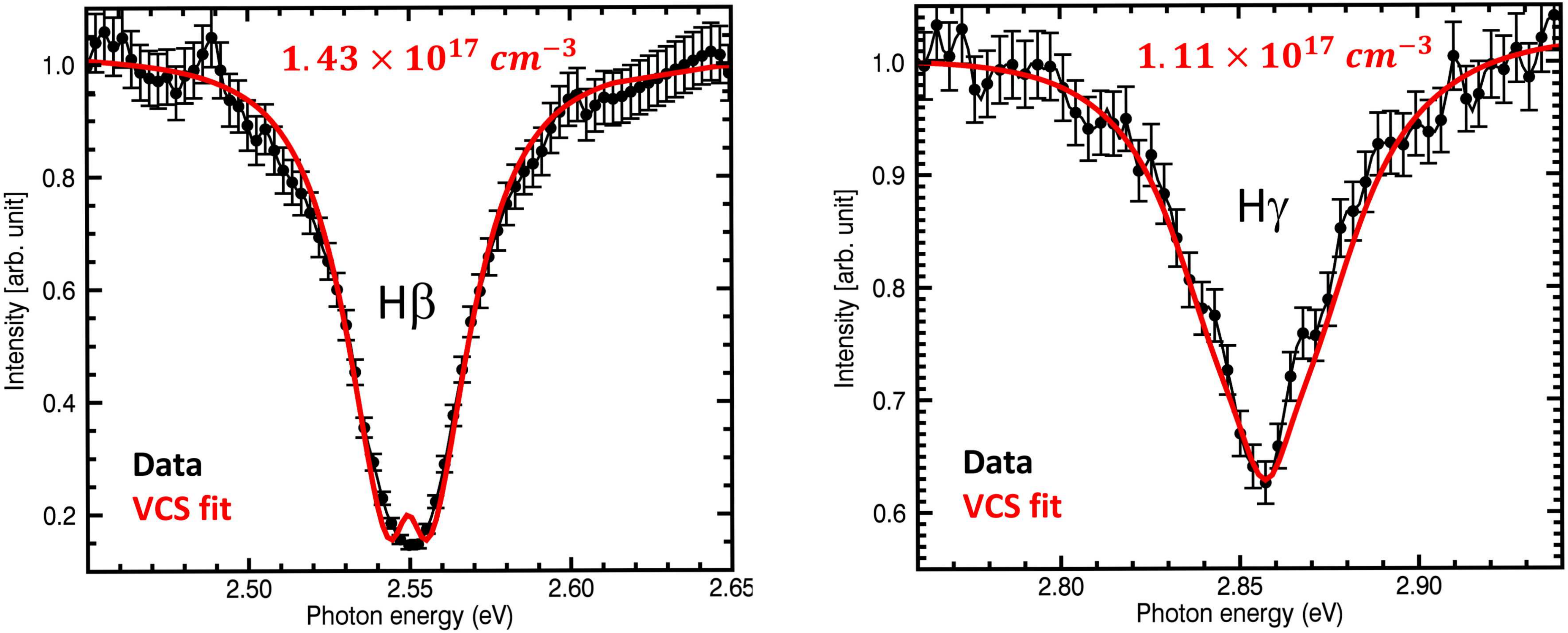




Let's check inferred density consistency between different lines

[1] Wiese et al, Physical Review A 6, 1132 (1972).

Density inferred from Hβ line is 30% higher than that from Hγ line



- **Density inferred by Hβ and Hγ of preliminary emission spectra agree**
- **The data suggest that line-broadening is different for absorption lines**
- **Line-shapes measured over wide range of n_e allows us to investigate more**

Center for Astrophysical Plasma Properties (CAPP) provides sustained funding to train laboratory astrophysicists

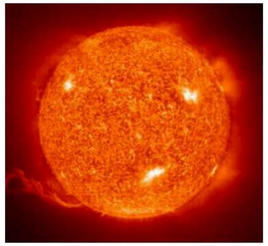
- Lab astrophysicists require specialized knowledge; they must understand:
  i. Astrophysical impact,
  ii. Model approximations and limitations,
  iii. Experimental feasibility and limitations

- CAPP* at University of Texas at Austin, provides:
  - Sustained funding to train students/postdocs for continuous growth of laboratory astrophysics
  - Resources and connections to experts in astrophysics, theory, and experiment

* Contact Don Winget (dew@astro.as.utexas.edu) and Mike Montgomery (mikemon@astro.as.utexas.edu) for details

Plasma spectral models used for astrophysics are not extensively tested; Benchmark experiments are essential though challenging

- Astrophysics relies on *plasma spectral models* in two ways:
  - Spectra analysis (e.g., from accretion disk, white dwarfs)
  - Fundamental properties (e.g., opacity, equation of state)
- ZAPP (= Z Astrophysical Plasma Properties) collaboration uses terra-watt x-ray source to replicate astrophysics-relevant plasma and check the accuracy of spectral models

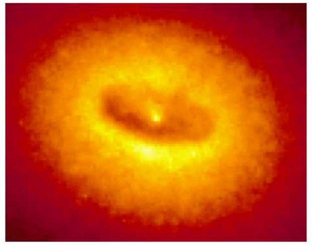


Solar Fe opacity:

T=200 eV
n_e=5e22 cm^{-3}

White dwarf mass:

T=1 eV
n_e=1e17 cm^{-3}



Accretion disk spectra:
ξ = 20-1000 erg cm/s
T=30 eV
n_e=1e19 cm^{-3}

- HED science needs more benchmarks, though challenging:
  - Experimentalist: a decade of diligent work for reliable platform and hypothesis testing
  - Theorists: openness for criticism, eagerness for testing untested approximations
  - Management: continuous support and encouragement for checking reproducibility

Diligent benchmark-experiment collaborations will advance astrophysics and HED science