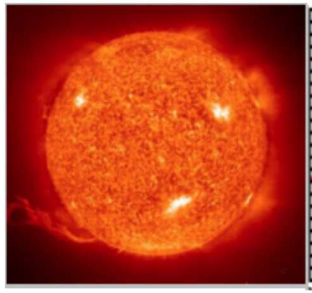
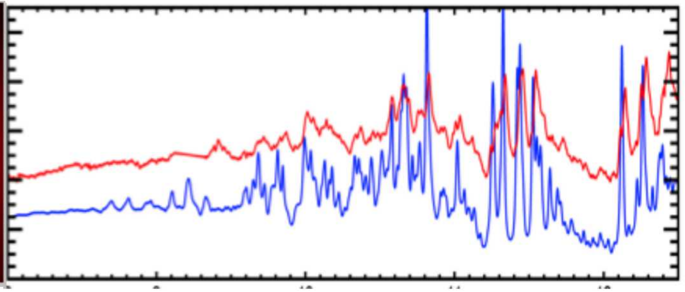
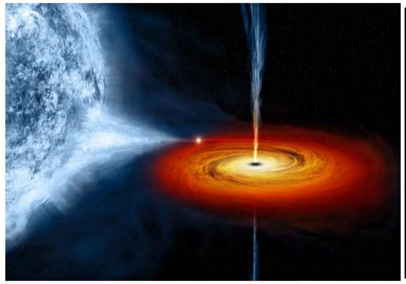
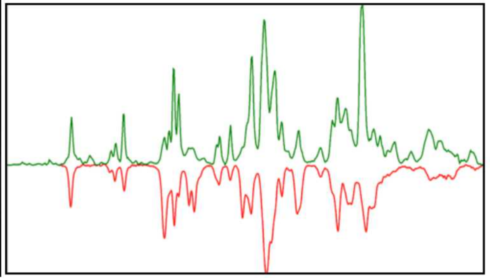
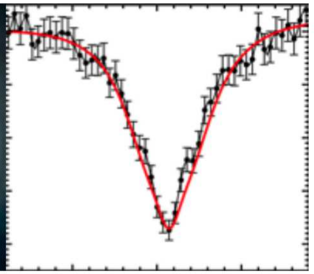
SAND2019-6101PE

ZAPP: Z Astrophysical Plasma Property collaboration



Guillaume Loisel

CEA DAM DIF seminar
June 4th 2019
Arpajon, France

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

ZAPP is a collaboration among a large number of scientists from national labs and the academia

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Prism Computational Sciences

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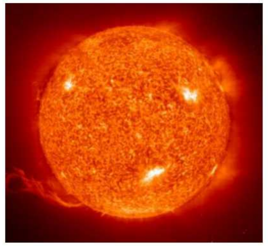
Nuclear Research Center Negev, Israel

ZAPP experiments measure fundamental properties of atoms in plasmas to solve important astrophysical puzzles

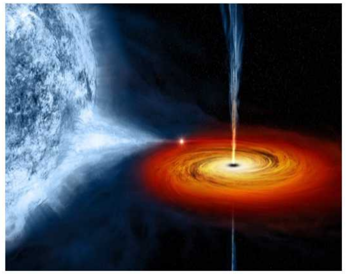
- Astrophysics relies on *plasma spectral models* in two ways:
  - Spectra analysis (e.g., from accretion disk, white dwarfs)
  - Fundamental properties (e.g., opacity, equation of state)
- ZAPP (= Z Astrophysical Plasma Properties) collaboration uses terra-watt x-ray source to replicate astrophysics-relevant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



Solar Fe opacity:

T=200 eV

n_e=5e22 cm^{-3}



Accretion disk spectra:

ξ = 20-200 erg cm/s

T=30 eV

n_e=1e19 cm^{-3}

White dwarf mass:

T=1 eV

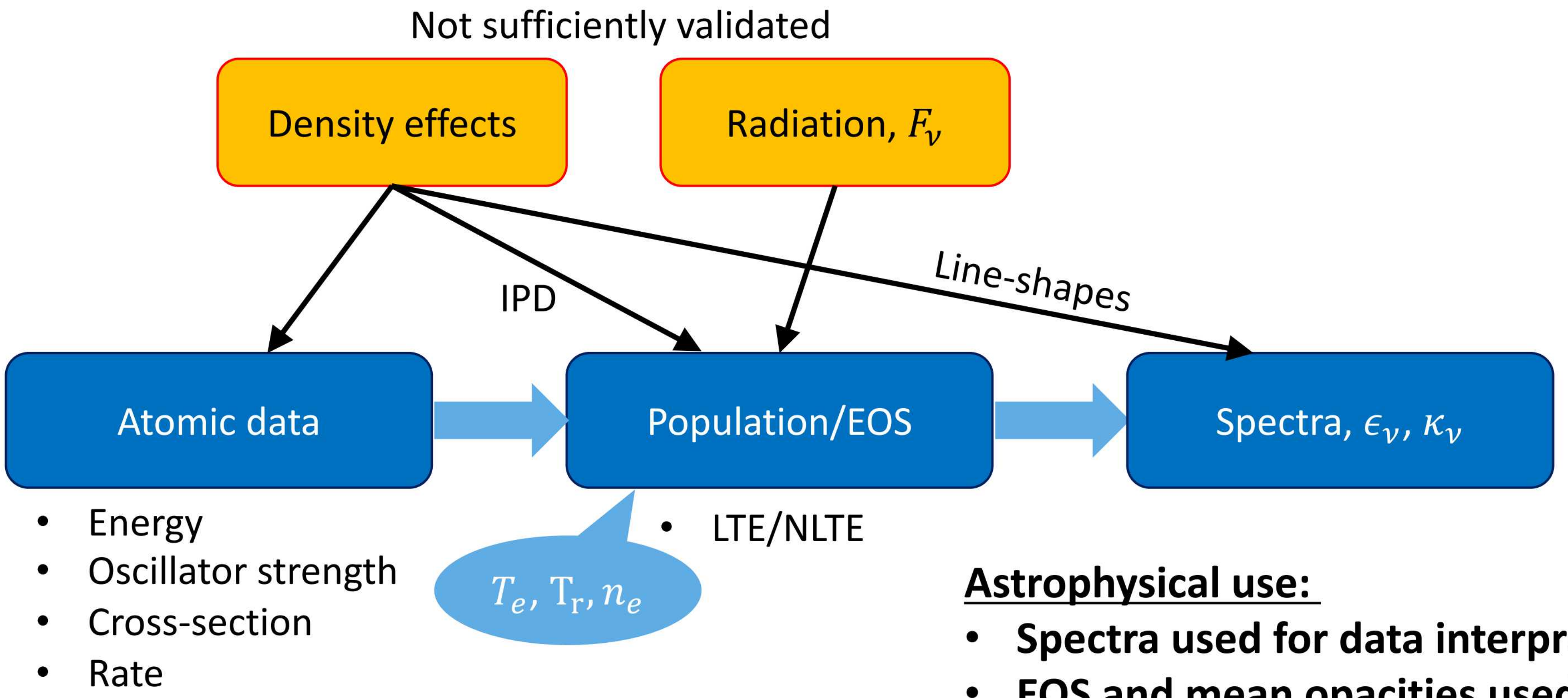
n_e=1e17 cm^{-3}

- Laboratory astrophysics requires special knowledge: i) astrophysical importance, ii) model approximations and limitations, and iii) experiment feasibility

→ Collaboration and education are key ingredients for success

Success of satellite missions require validated models, making benchmark experiments invaluable.

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

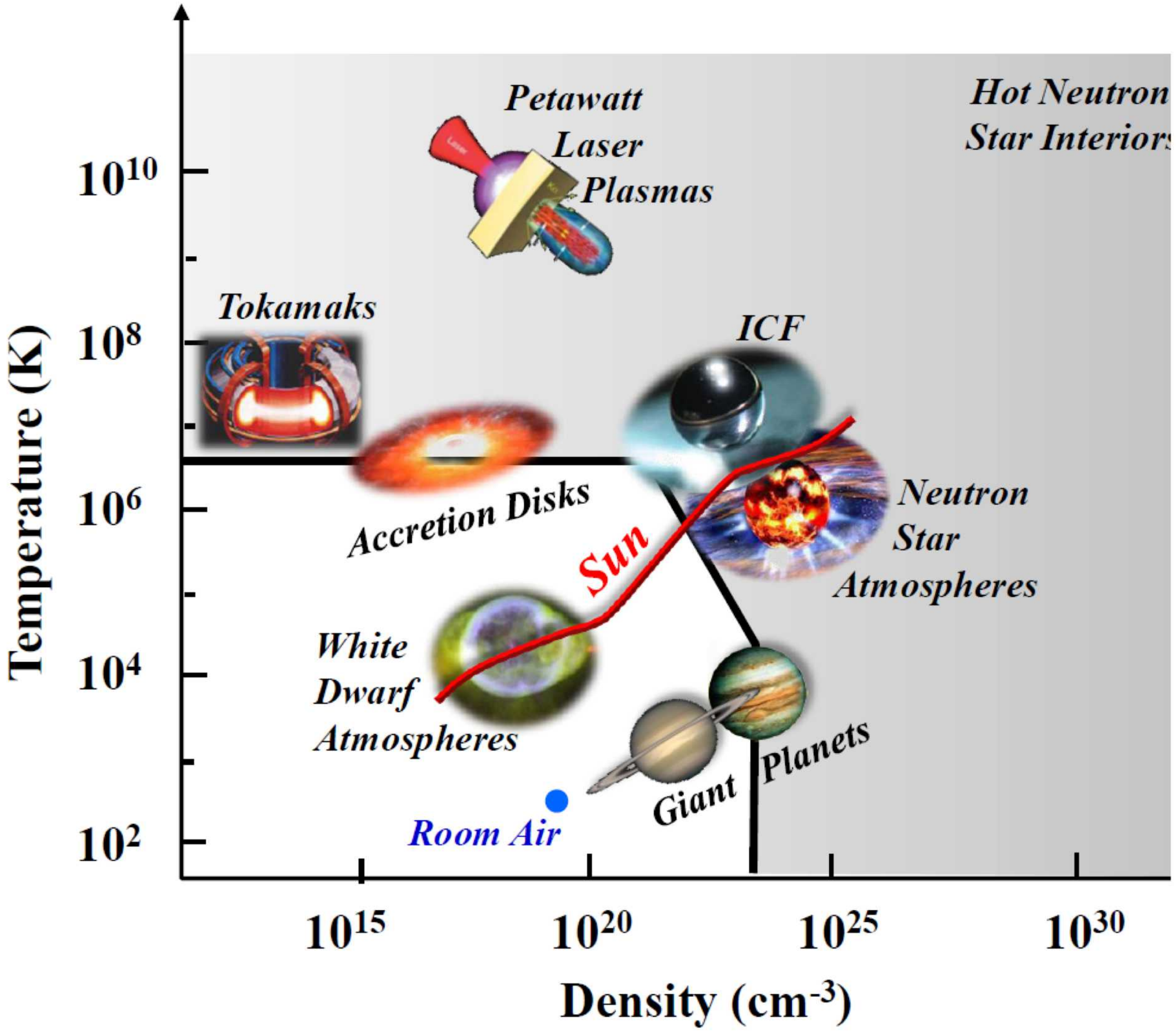


Astrophysical use:

- **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**

NNSA-sponsored mega-joule-class laboratories produce extreme conditions for many years, but …

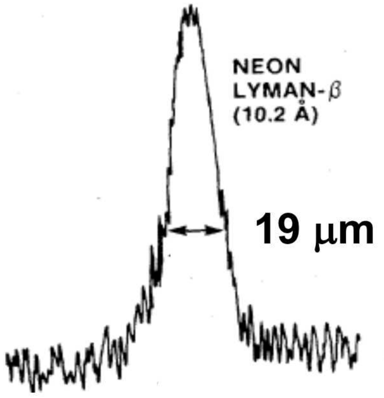


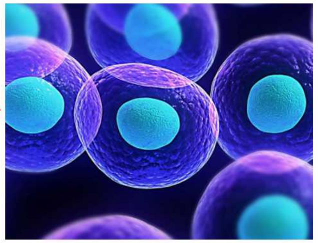
Problem: Sample size used to be so small for benchmark experiments

e.g., Laser fusion capsule[1]

T=3.5x10^6 K,
ρ=0.26 g/cc } Exotic

Size: 19 μm

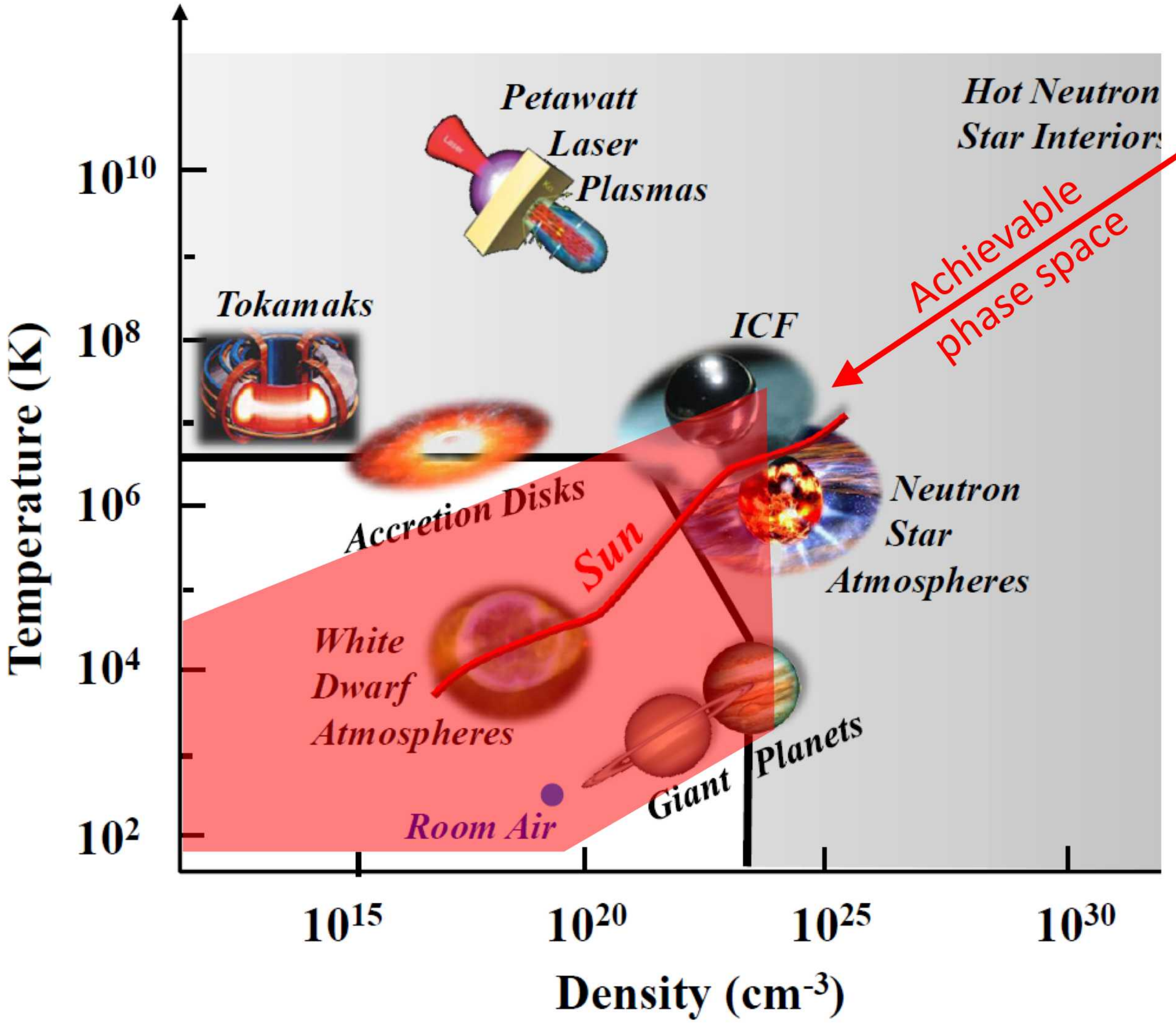




size of cell

[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*

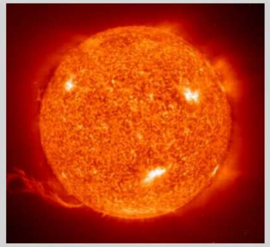
Achieved conditions:
T=(1.5-2.0)x10^6 K
n_e=(1-10)x10^{22} e/cm^3

Z White Dwarf samples: ~ size of a phone

Achieved conditions:
T=(1-3)x10^4 K
n_e=(5-100)x10^{16} e/cm^3

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

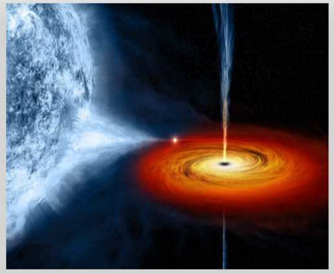
Solar Opacity



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

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

Photoionized Plasma



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

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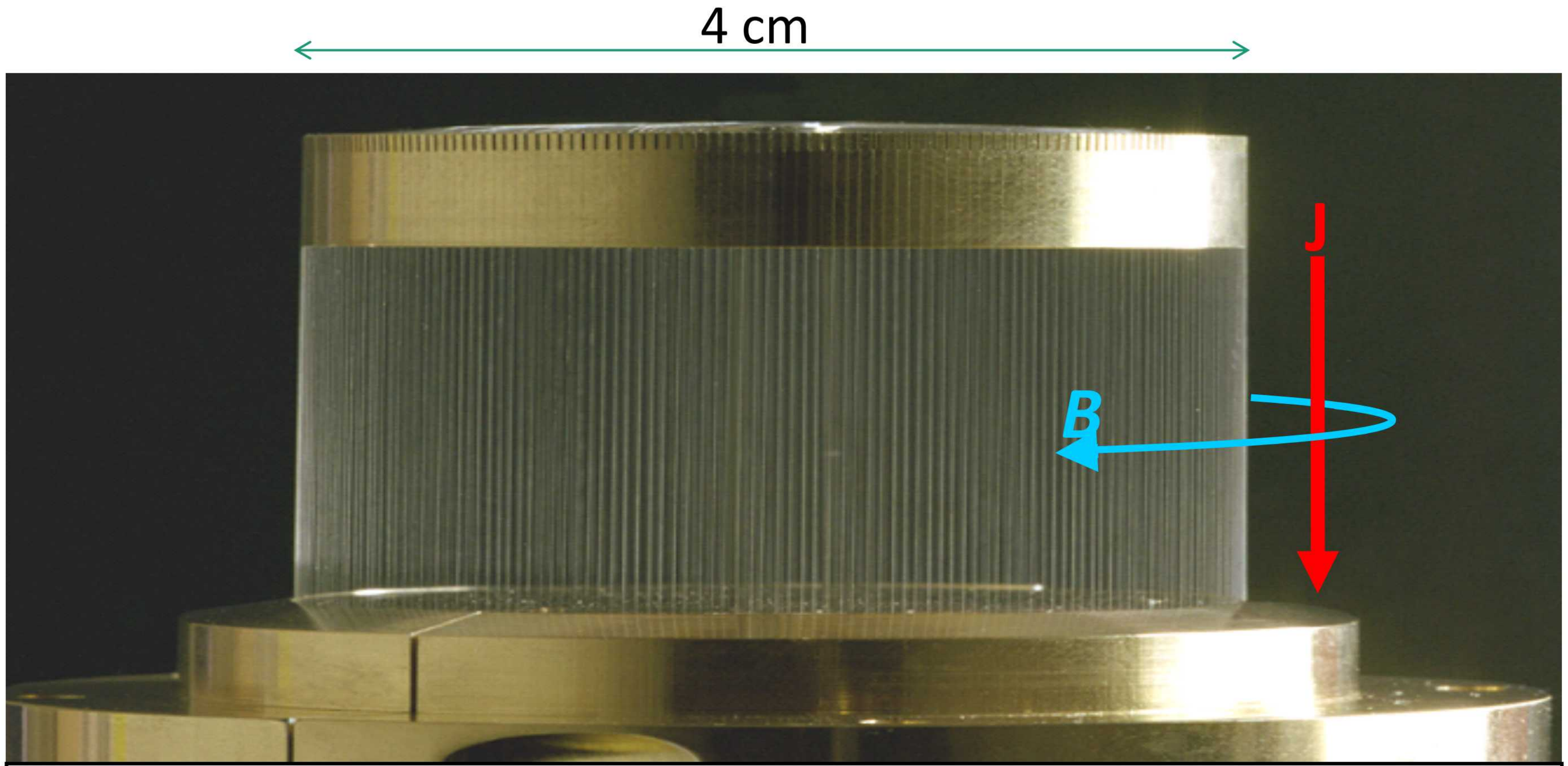
T_e ~ 20 eV, n_e ~ 10^{19} cm^{-3}

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}

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)

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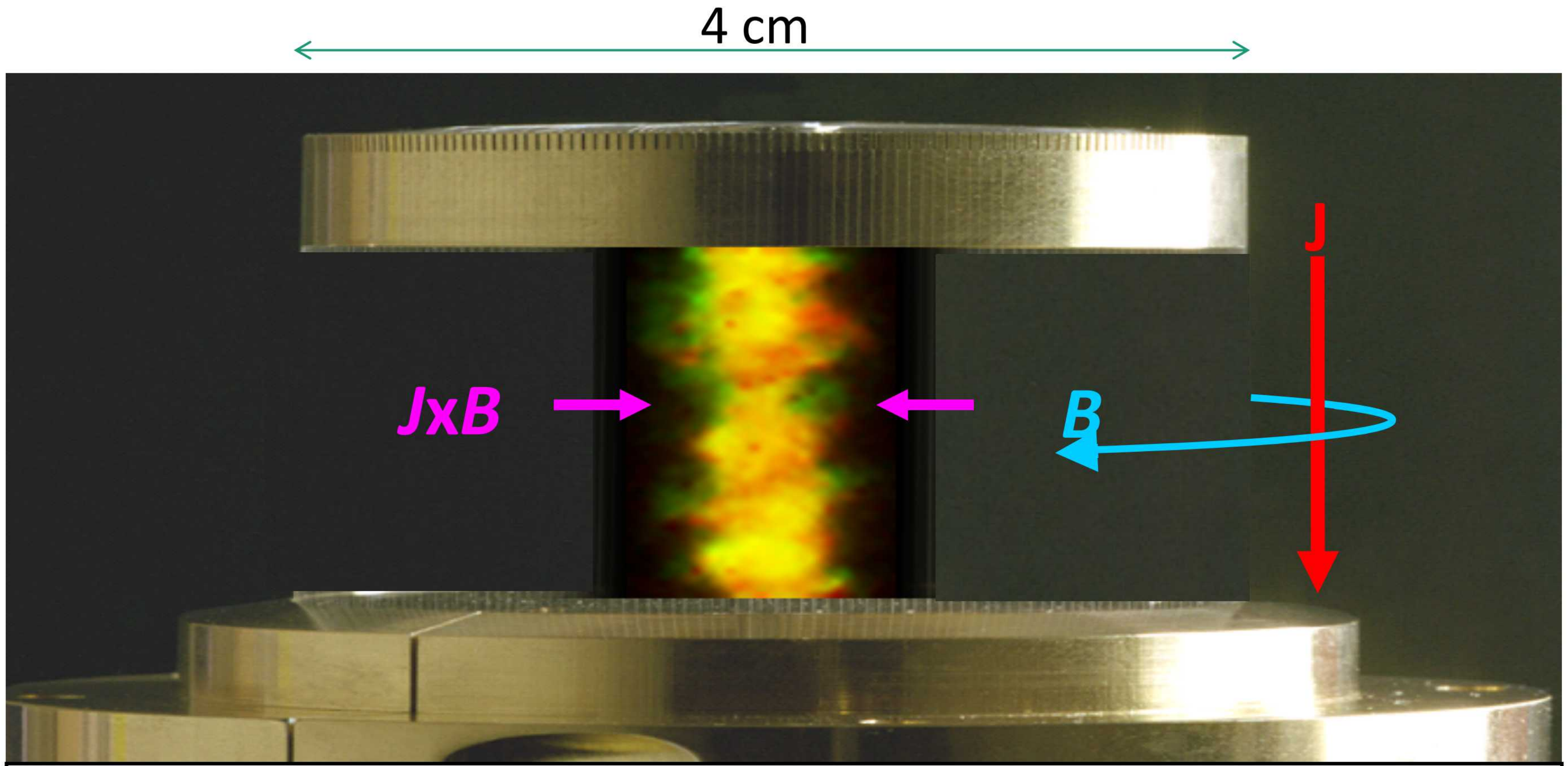

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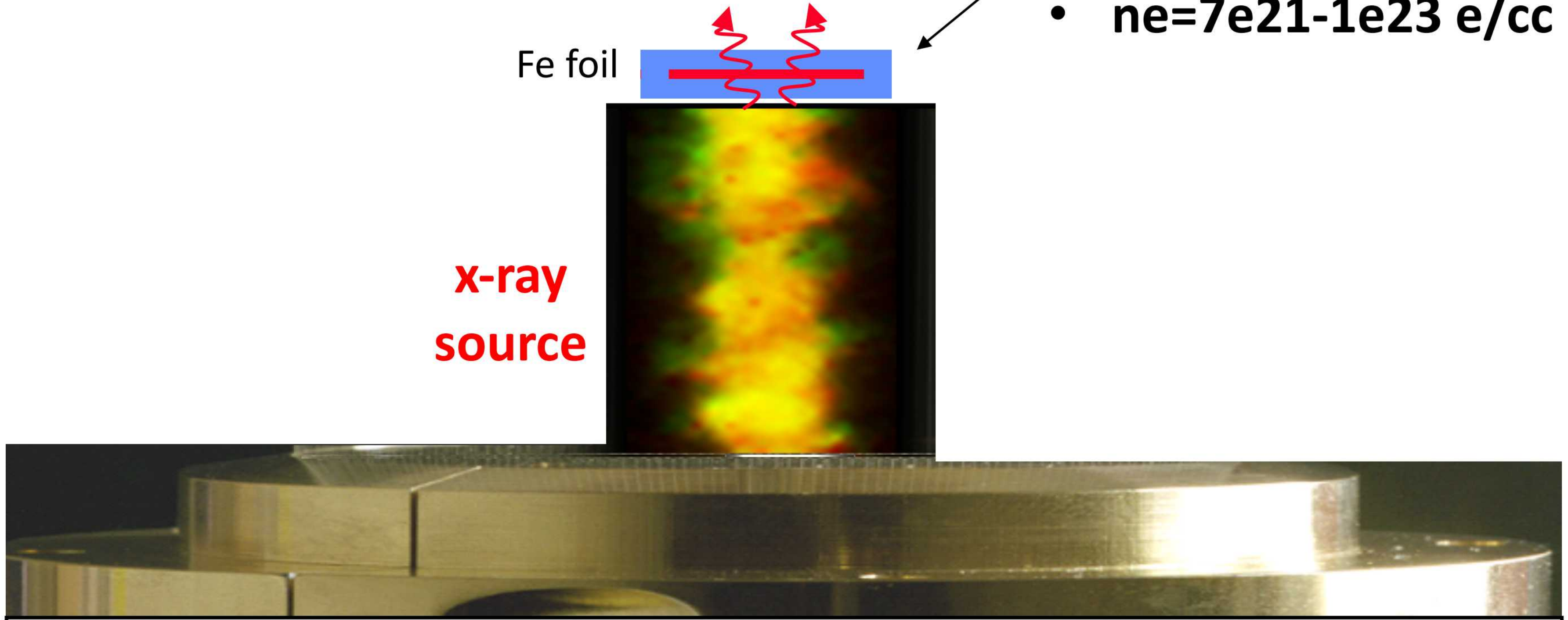
The SNL Z machine uses 27 million Amperes to create x-rays, and perform multiple benchmark experiments simultaneously

Solar opacity sample

- **T=150-200 eV**
- **ne=7e21-1e23 e/cc**



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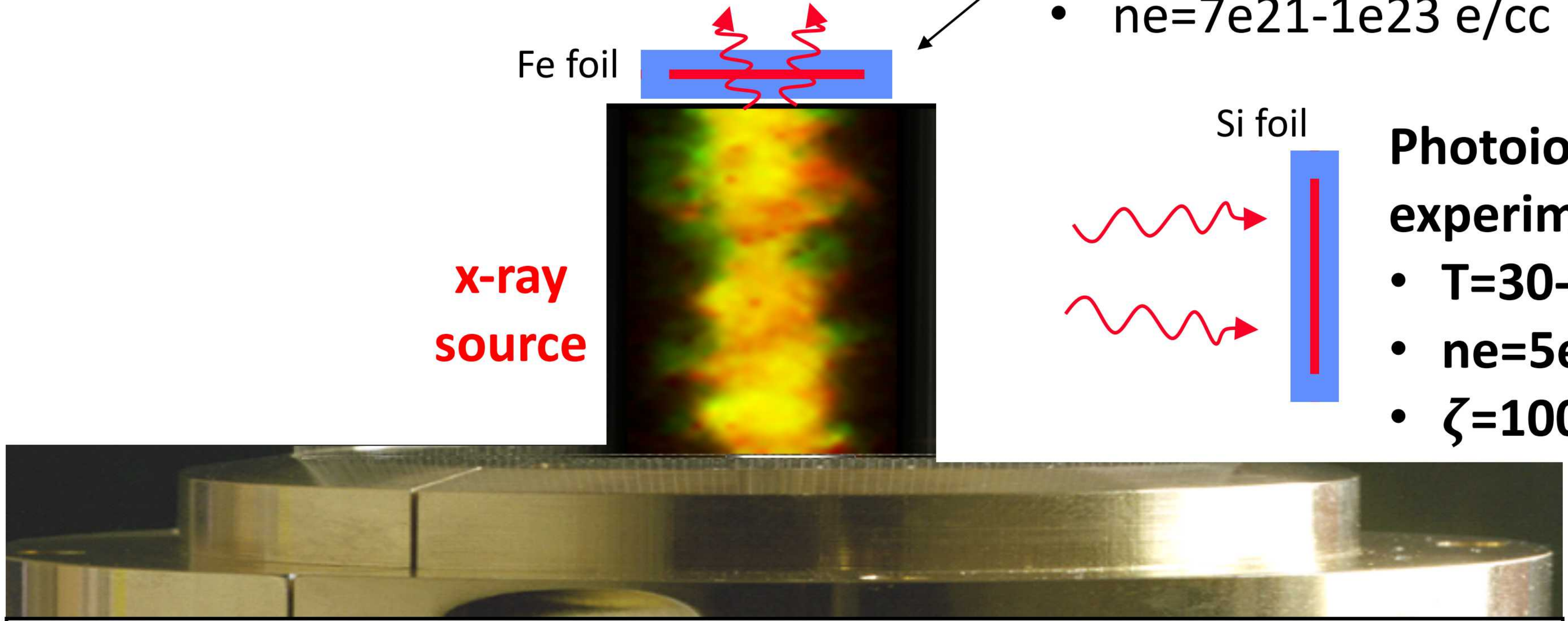


Photoionized plasma experiments
- **T=30-40 eV**
- **ne=5e16-1e17 e/cc**
- **ζ=100-1000**

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

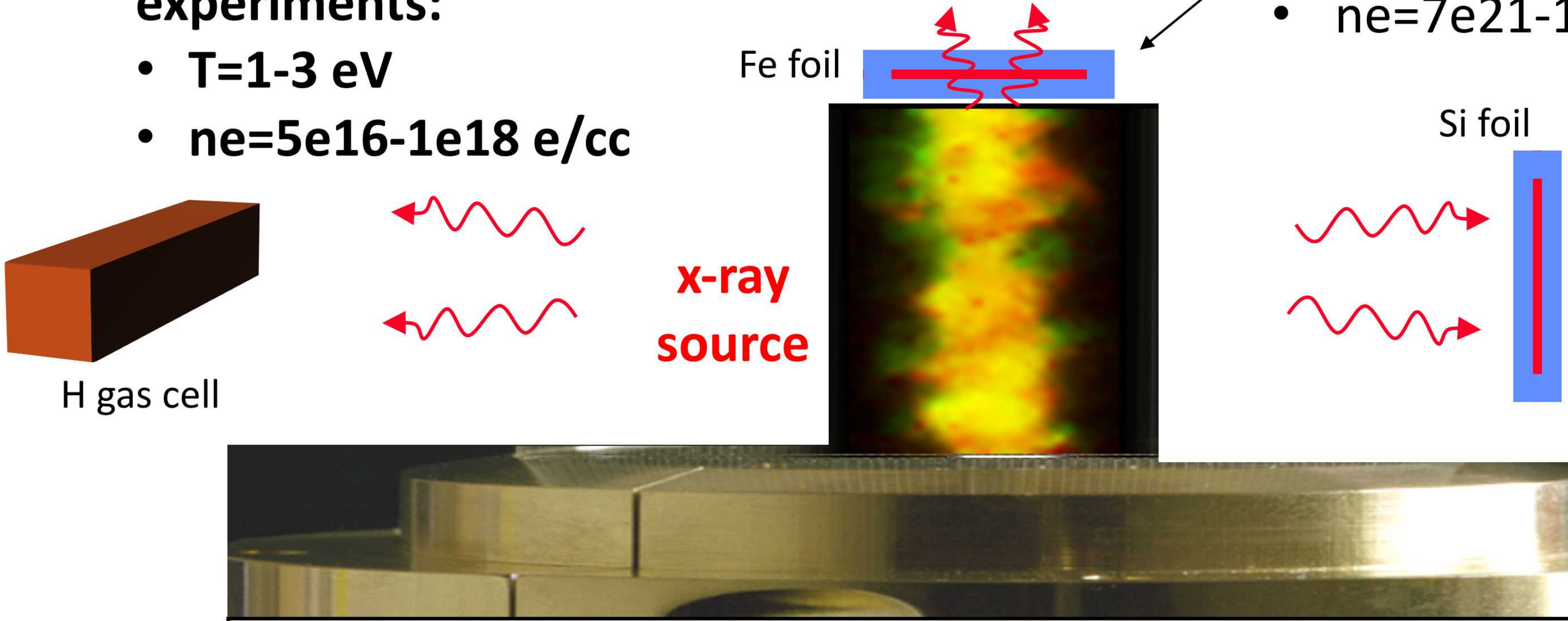
Sanford, *PoP* (2002); Bailey et al., *PoP* (2006); Slutz et al., *PoP* (2006); Rochau et al., *PPCF* (2007)

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

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=20-200



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

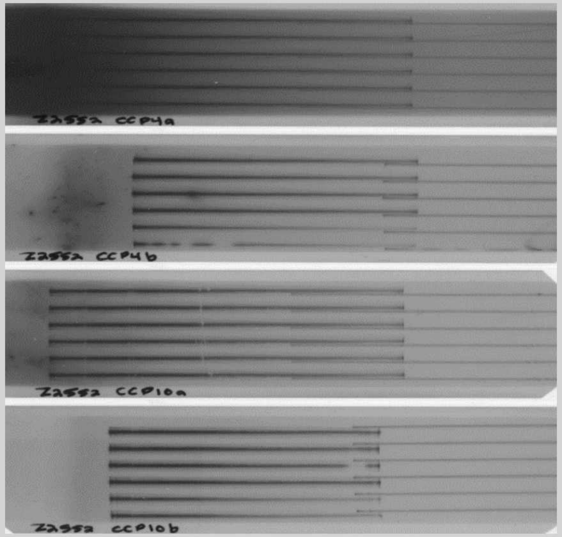
Single shot can perform multiple experiments at T=1-200 eV and ne=5e16-1e23 e/cc

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

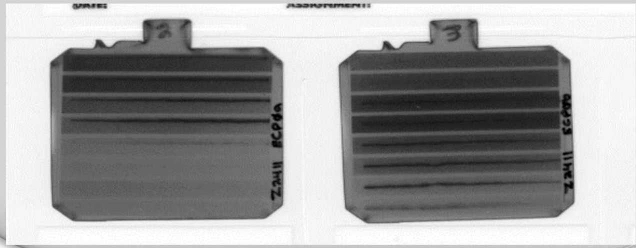
ZAPP campaigns acquire up to 60 spectra on a single shot

Solar Opacity

24 Space-Resolved
Fe Absorption Spectra

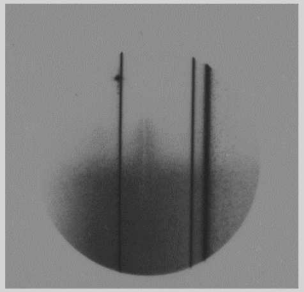


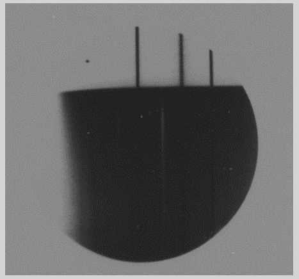
16 Time-Resolved
Fe Absorption Spectra



White Dwarf Line-Shapes

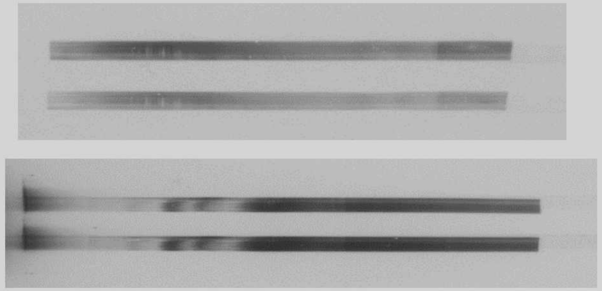
3 Streaked
H Absorption/emission Spectra



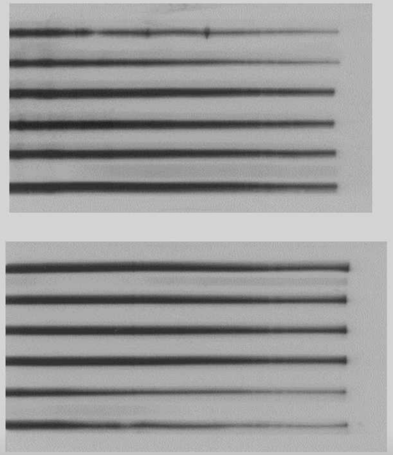


Photoionized Plasma

4 Space-Resolved
Si Absorption Spectra



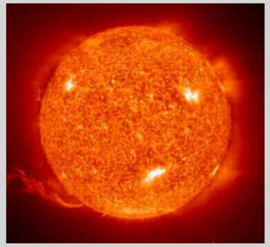
12 Space-Resolved
Ne Absorption Spectra



We can repeat experiments to ensure results. We can modify experiments to test hypotheses

ZAPP campaigns simultaneously study multiple issues

Solar Opacity



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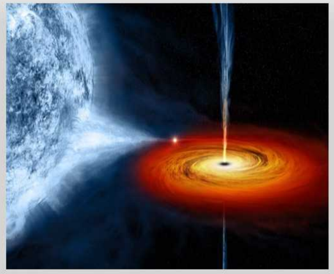

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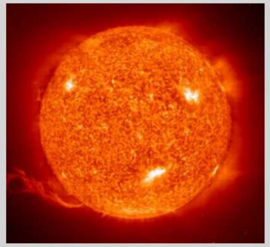

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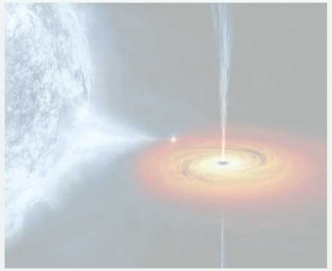

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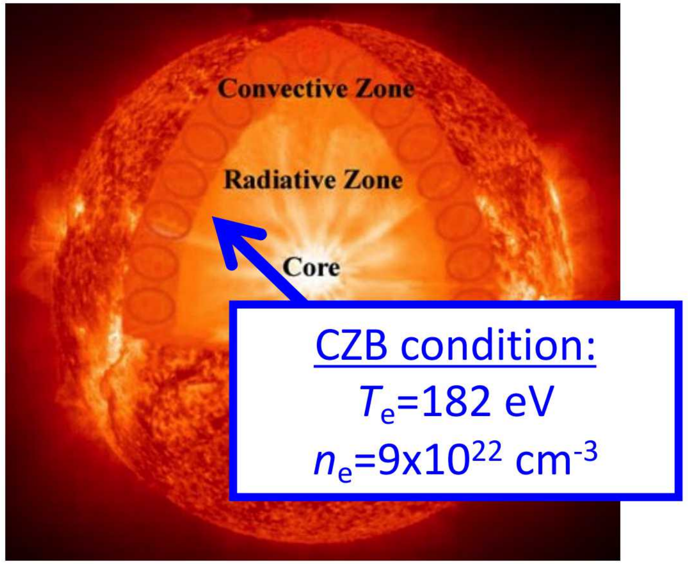
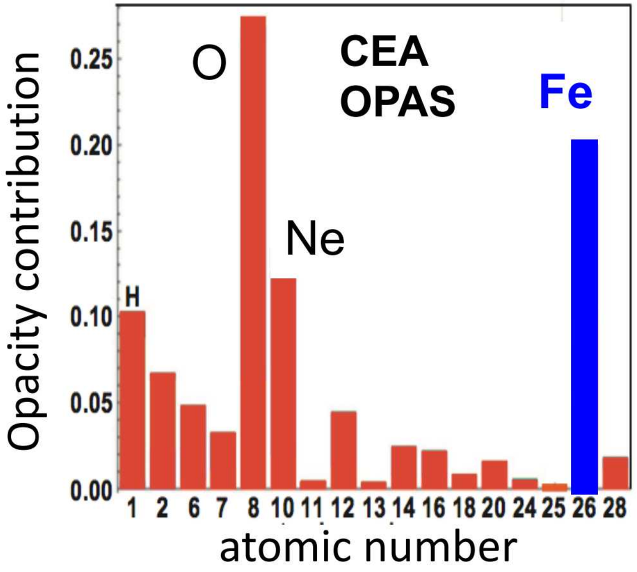
10-30% mean-opacity increase in the solar model is needed to resolve this discrepancy





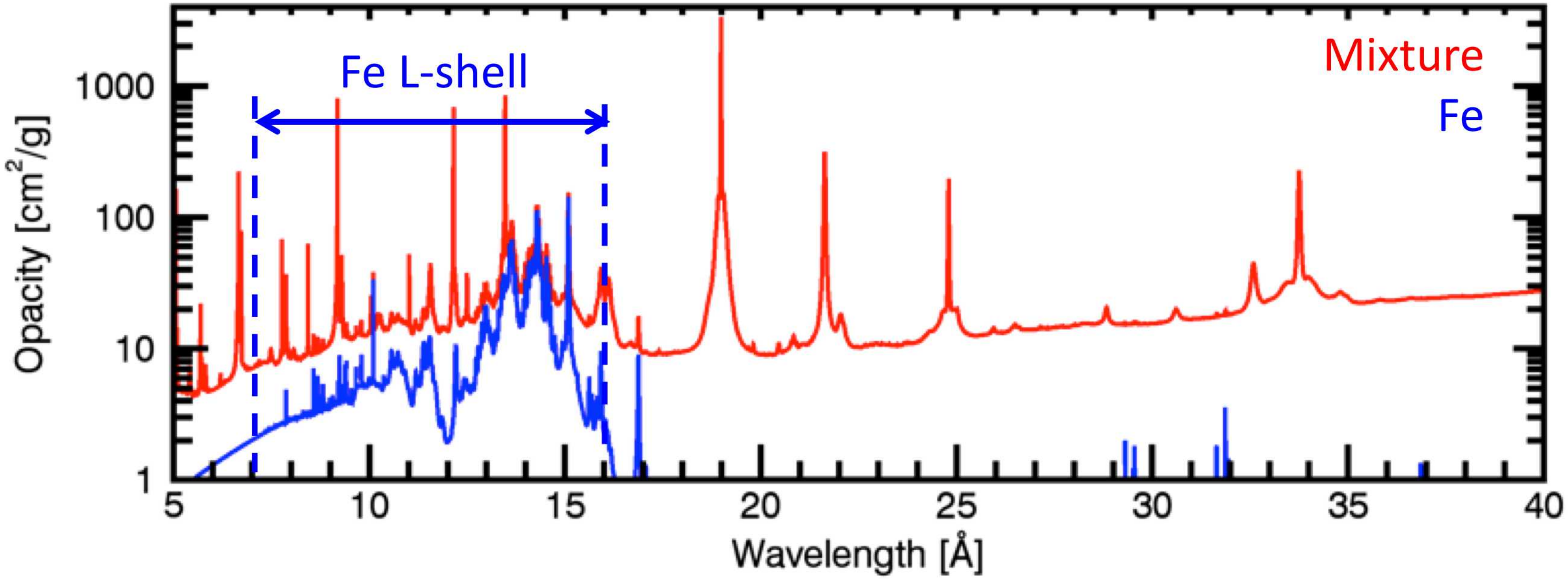
Opacity: κ_ν

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

Fe is a likely suspect:

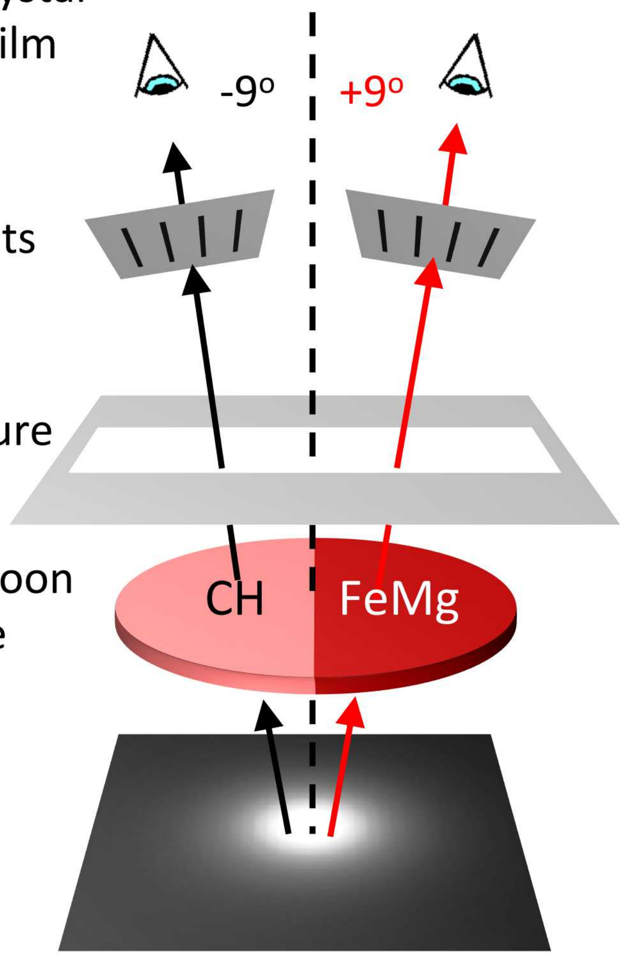
- 2nd largest contribution
- Most difficult to model

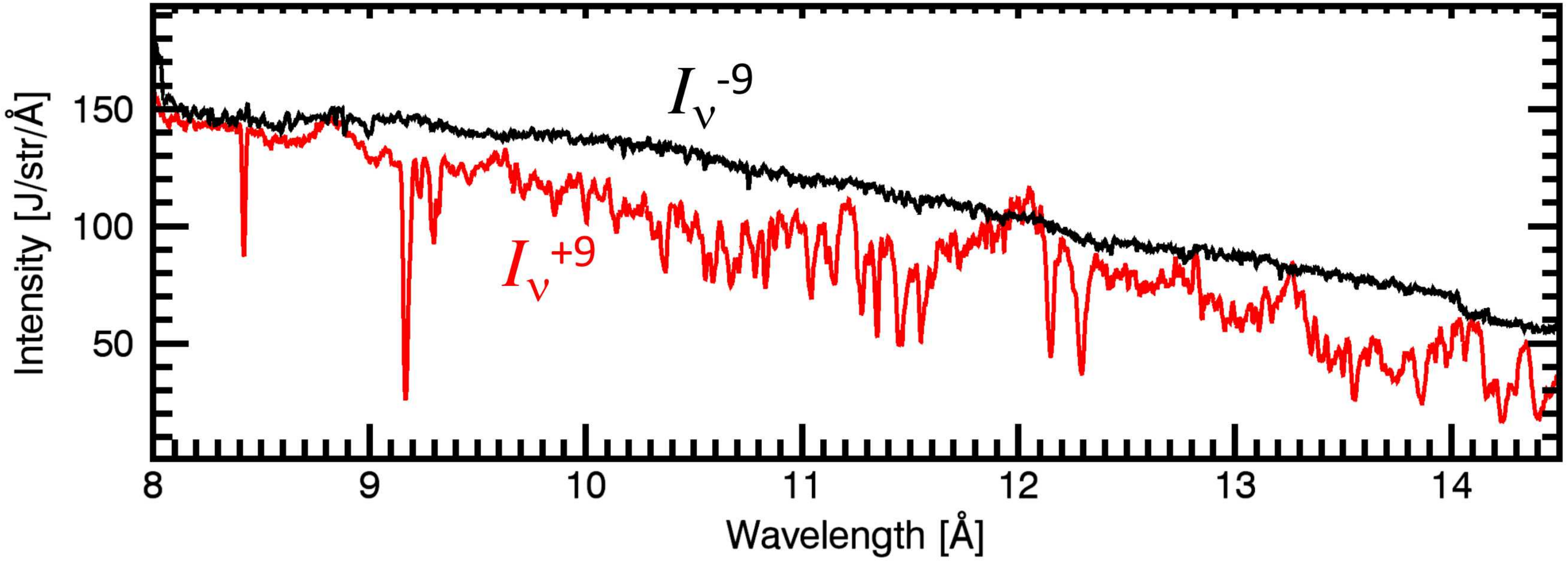
Solar mixture opacity at Convection Zone Base (CZB)



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

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 (>> 200eV sample self-emission)
• Condition measurements	
• Checking reproducibility	

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

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

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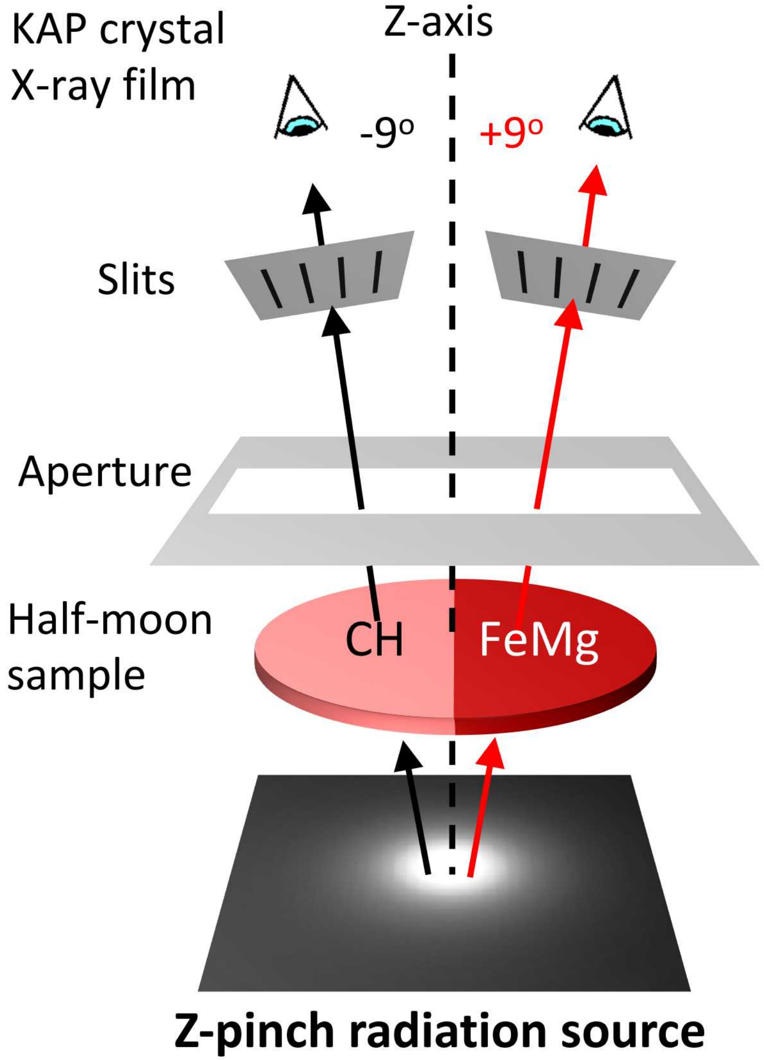

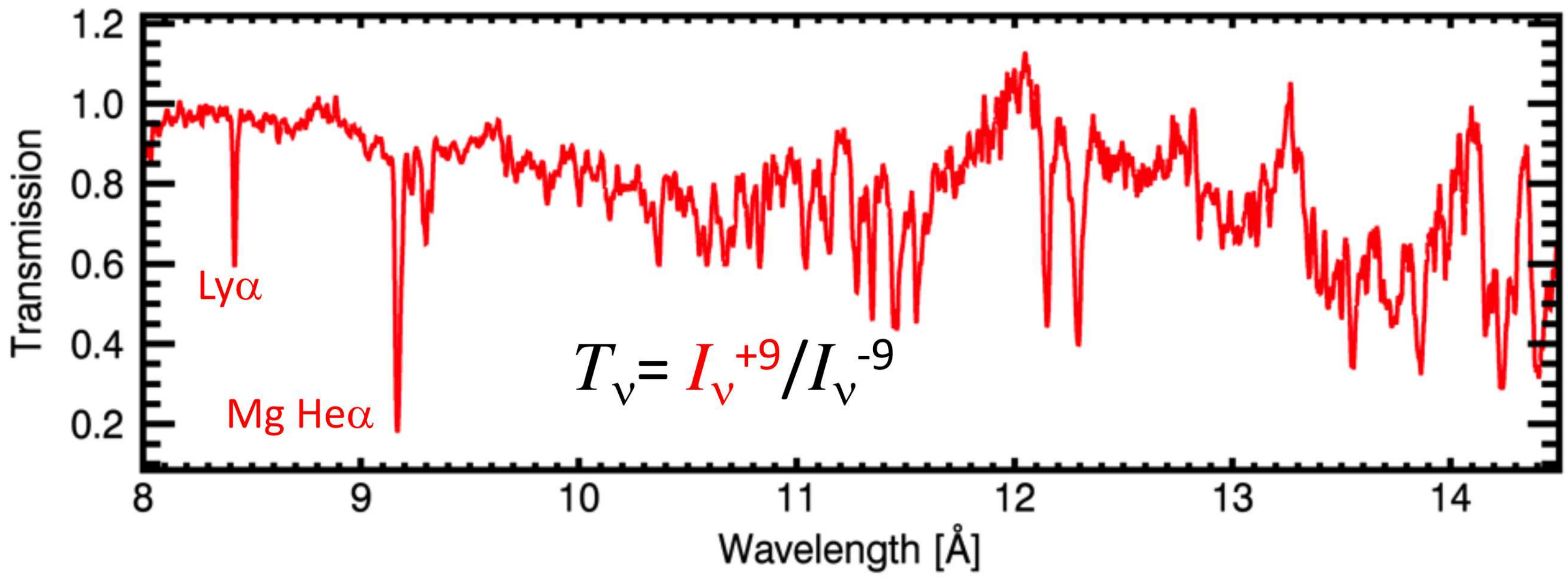

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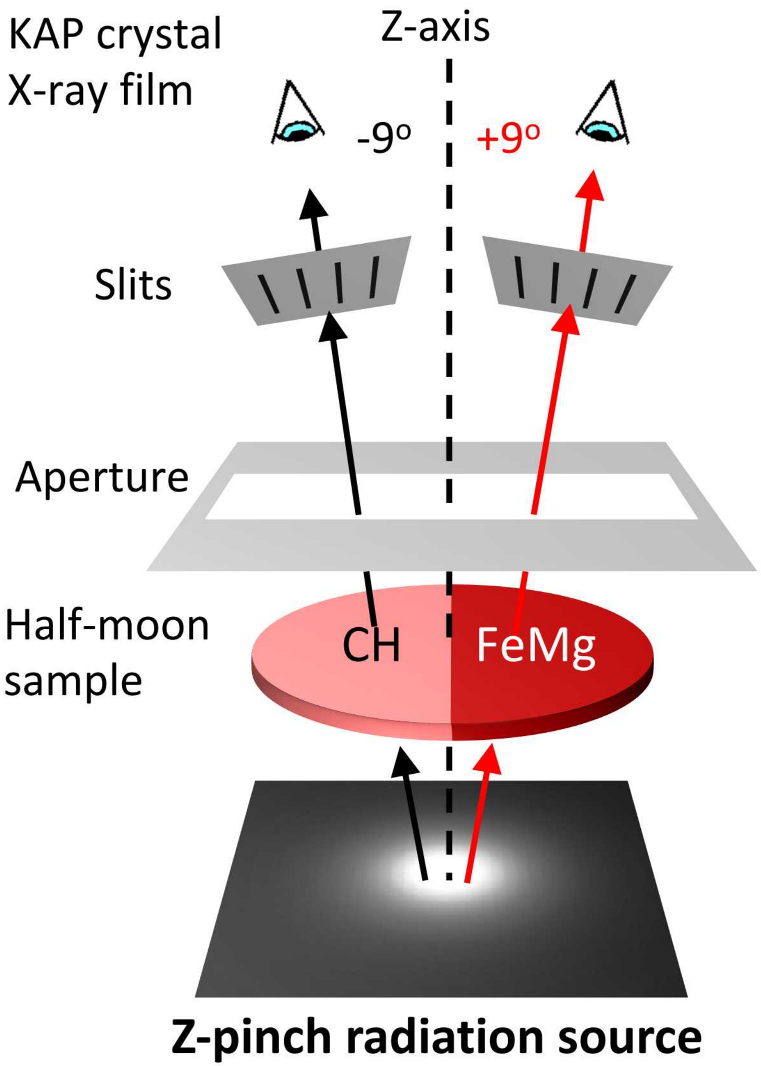

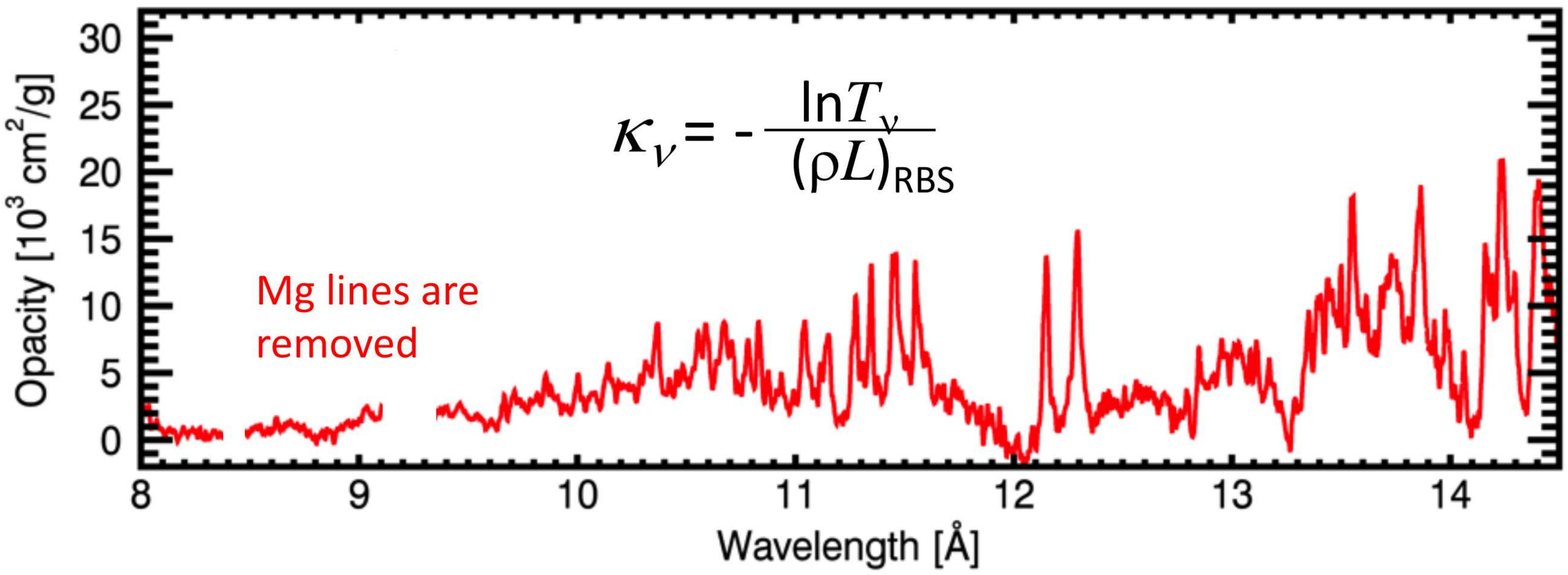

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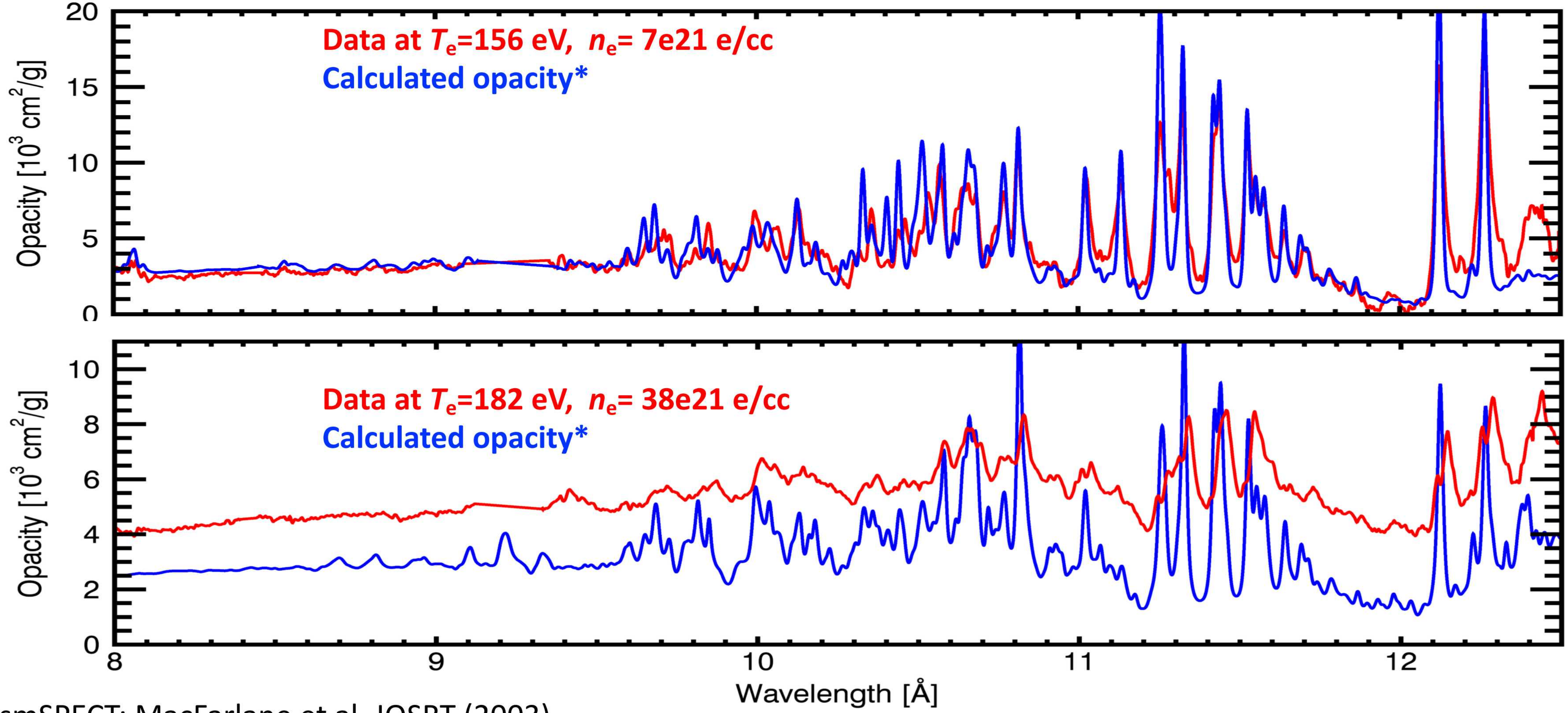
[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

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

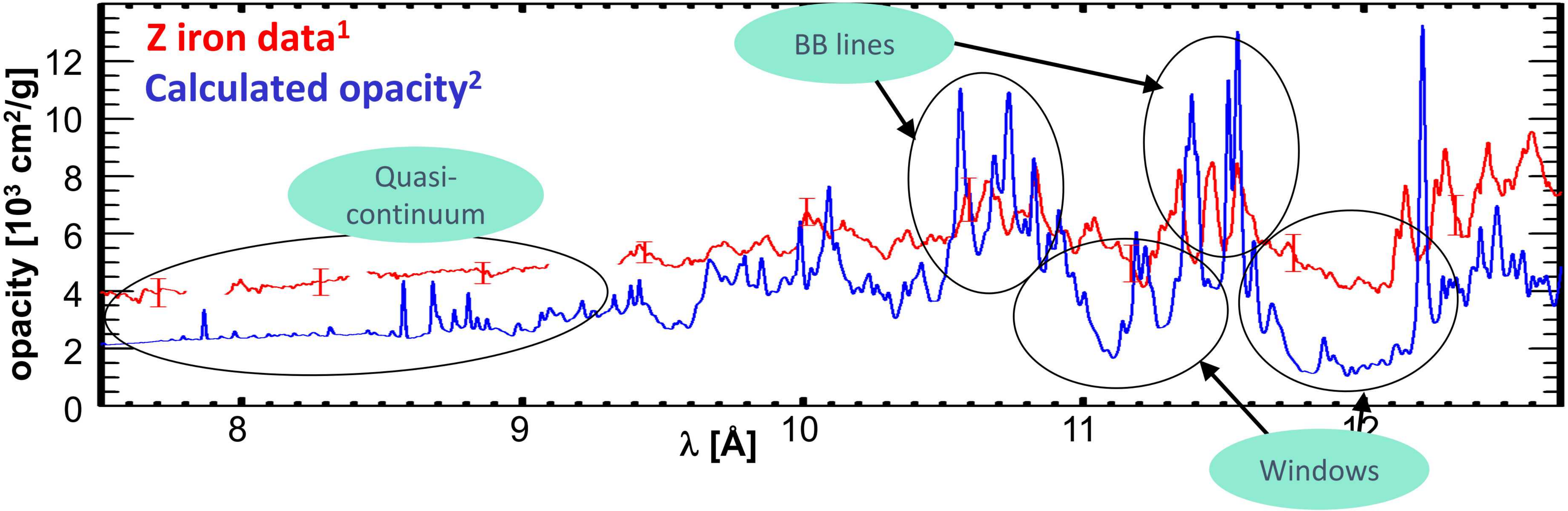


* PrismSPECT: MacFarlane et al, JQSRT (2003)

[1] Bailey et al., *Nature* 517, 56 (2015)

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

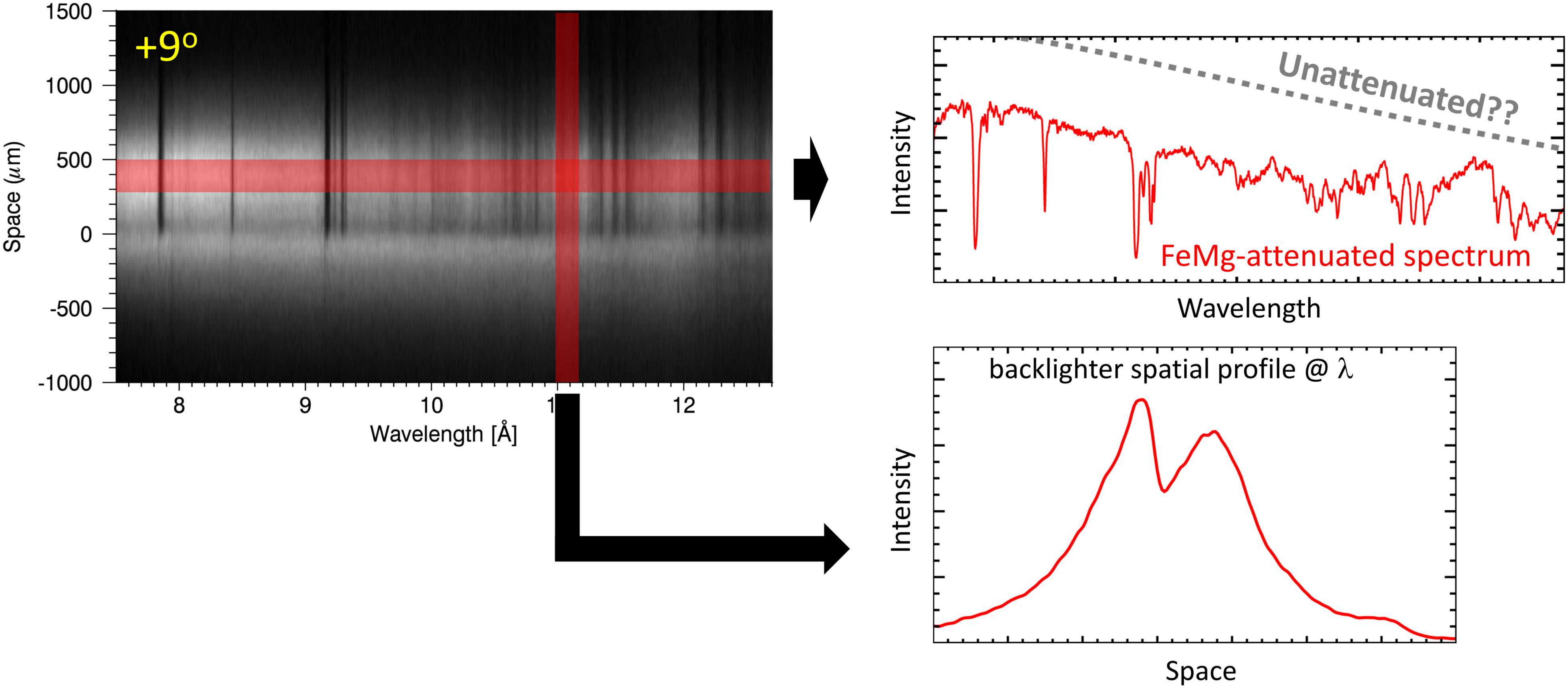
Reported opacity discrepancy is complex and deserves further scrutiny



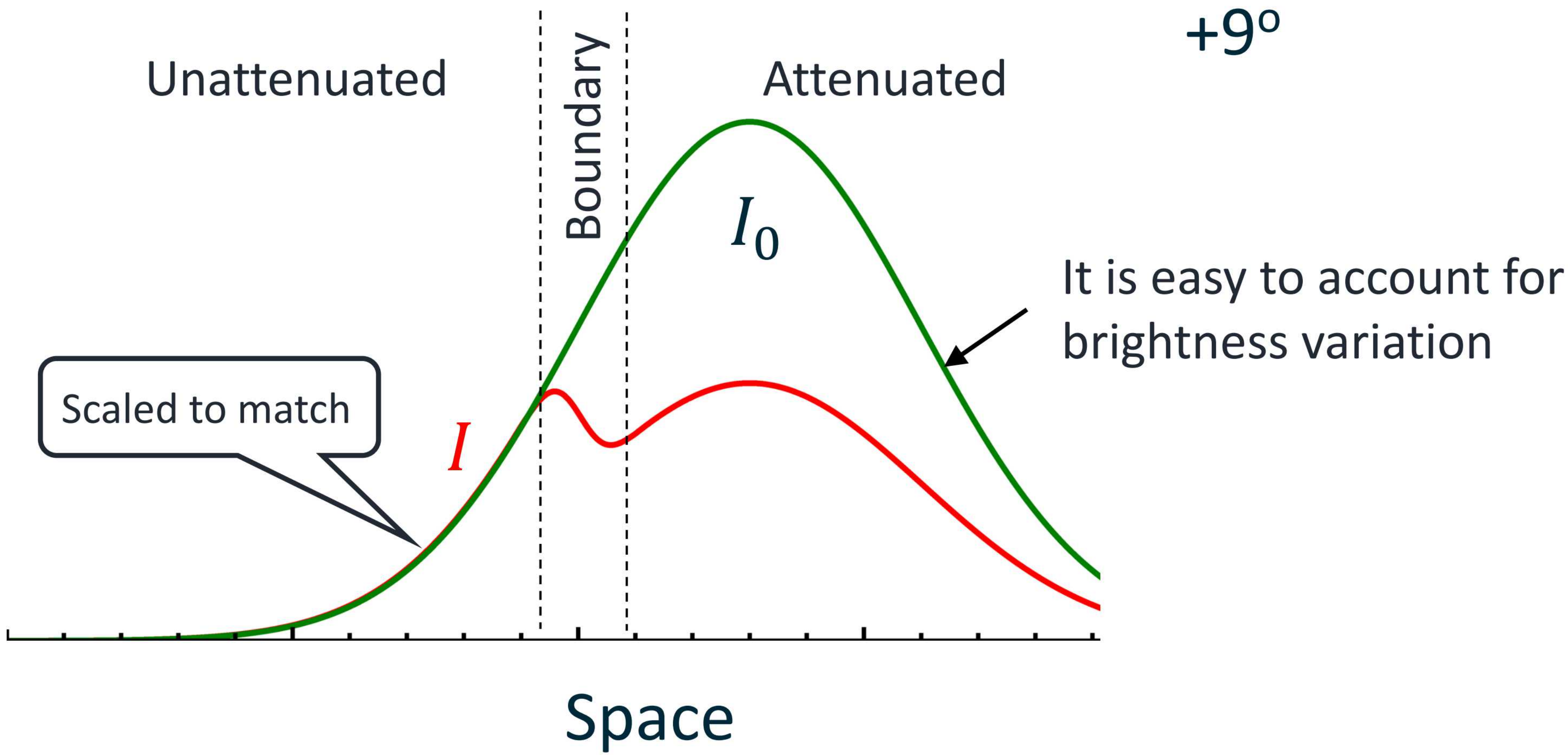
Is opacity theory inaccurate?
Is opacity experiment flawed?

[1] Bailey et al., *Nature* 517, 56 (2015), [2] Seaton et al., *MNRAS* (1994)

Paradigm shift: Spectral lineout → Spatial lineout



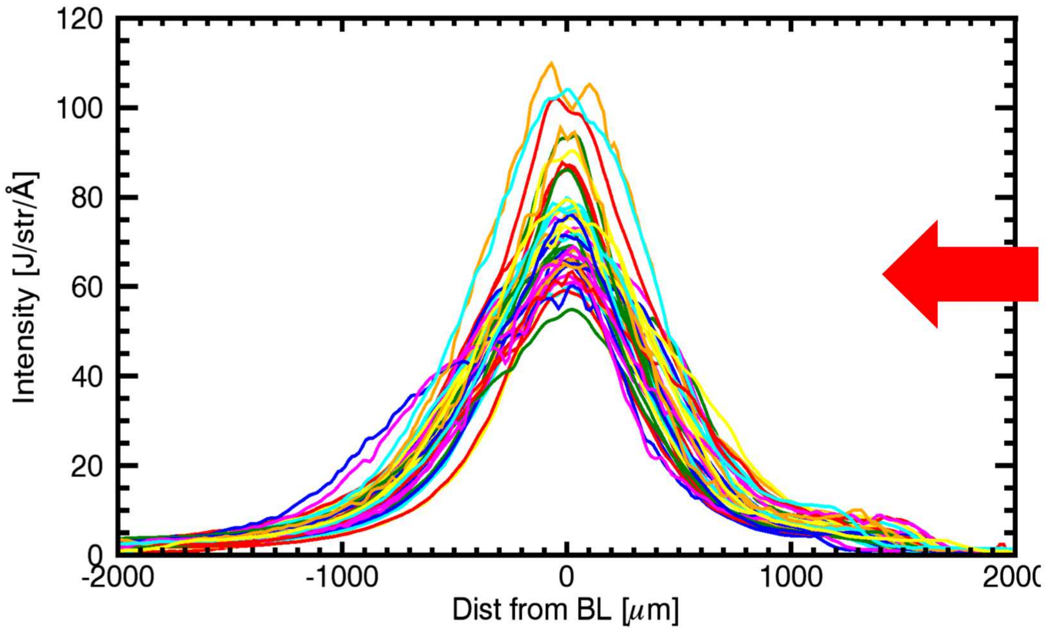
Half-moon spatial profile has both attenuated and unattenuated intensities, enabling accurate analysis



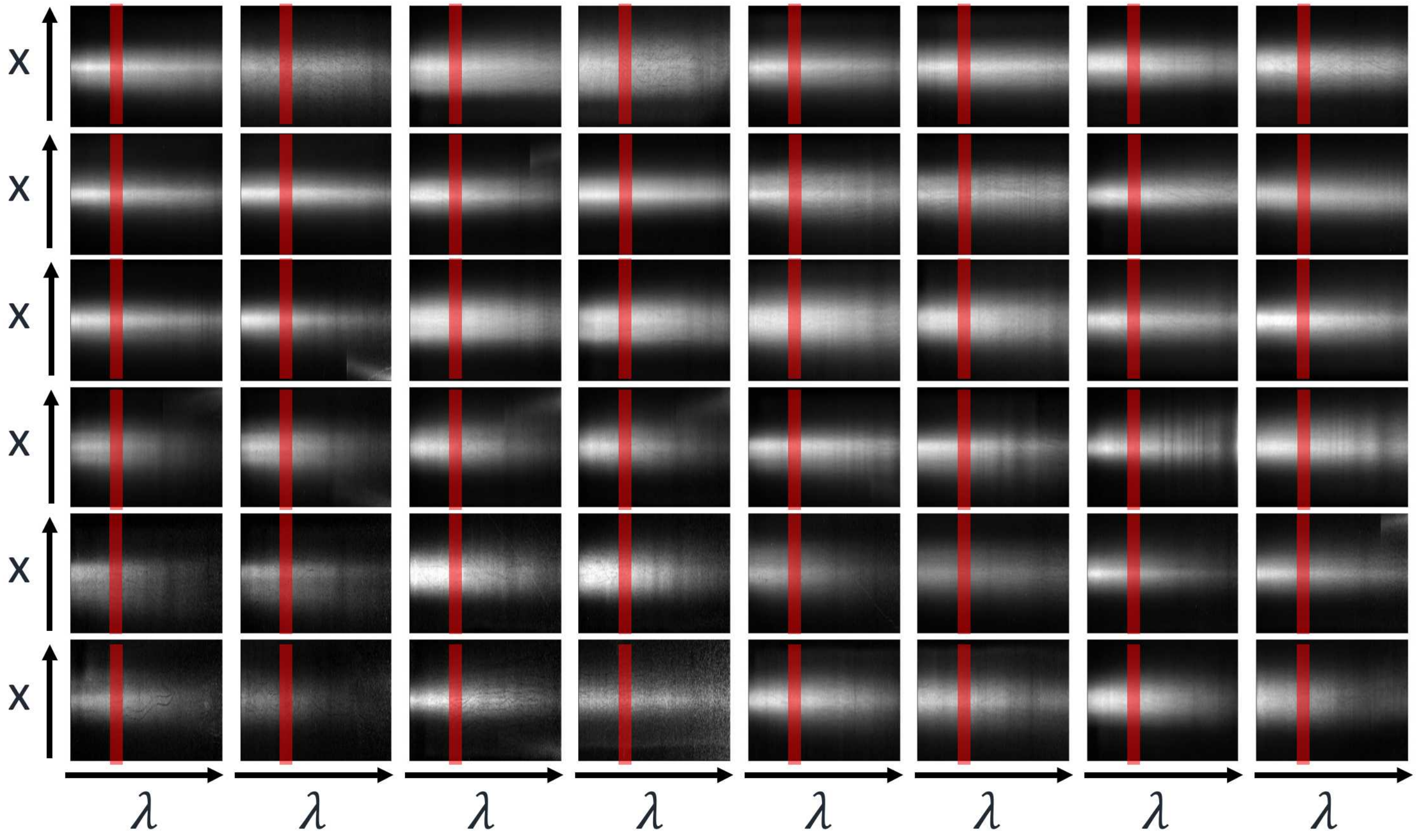
If the unattenuated shape is known, we can determine FeMg transmission accurately

The unattenuated shape comes from a large ensemble of tamper-only shot measurements

Reproducibility in unattenuated spatial shape and brightness

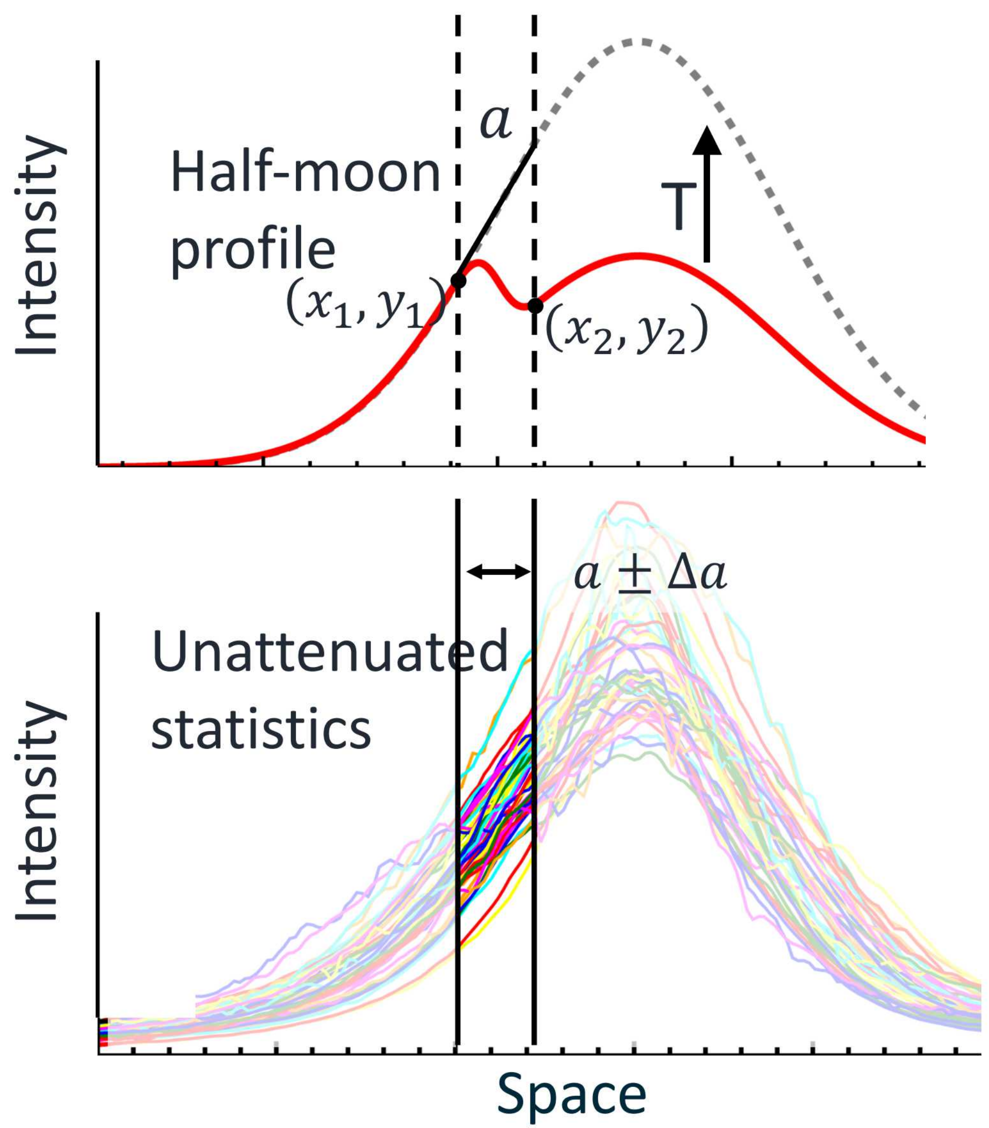


48 spectral images from 12 calibration shots collected over a decade

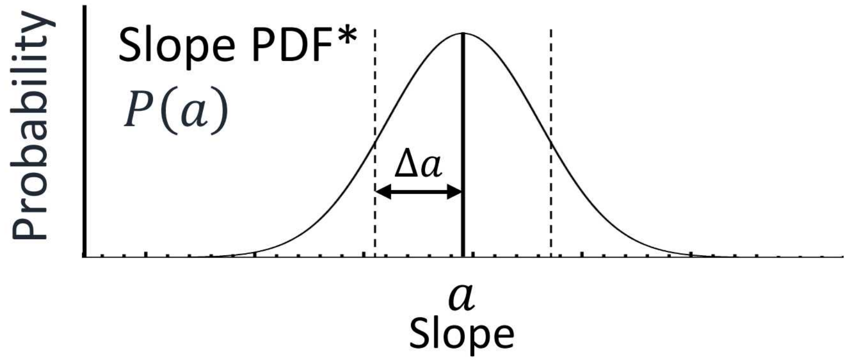


We can use this statistics to determine FeMg transmission

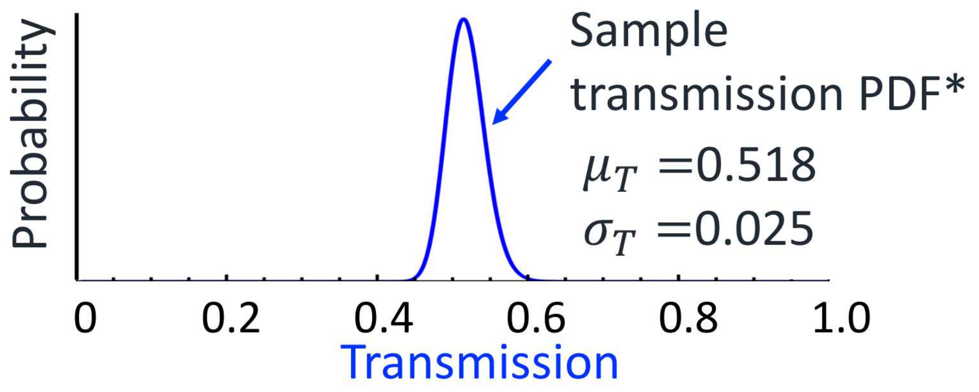
New method: The transmission is derived from boundary-slope statistics



$$T = \frac{y_2}{y_1 + a(x_2 - x_1)}$$

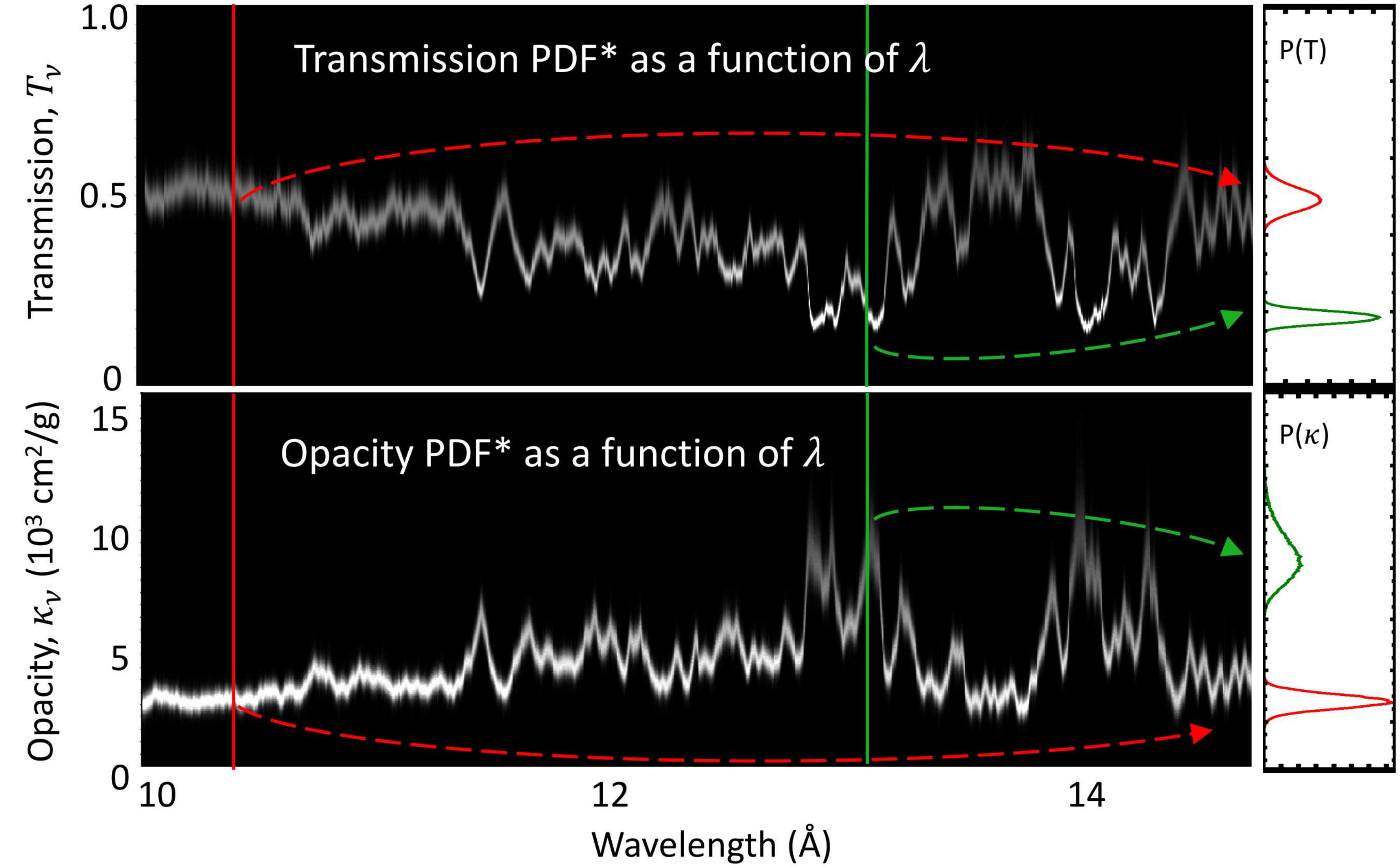


$$P(T) = P(a)\frac{da}{dT}$$



*PDF = Probability distribution function

Transmission PDF is converted to opacity PDF using Monte-Carlo technique, propagating various uncertainties

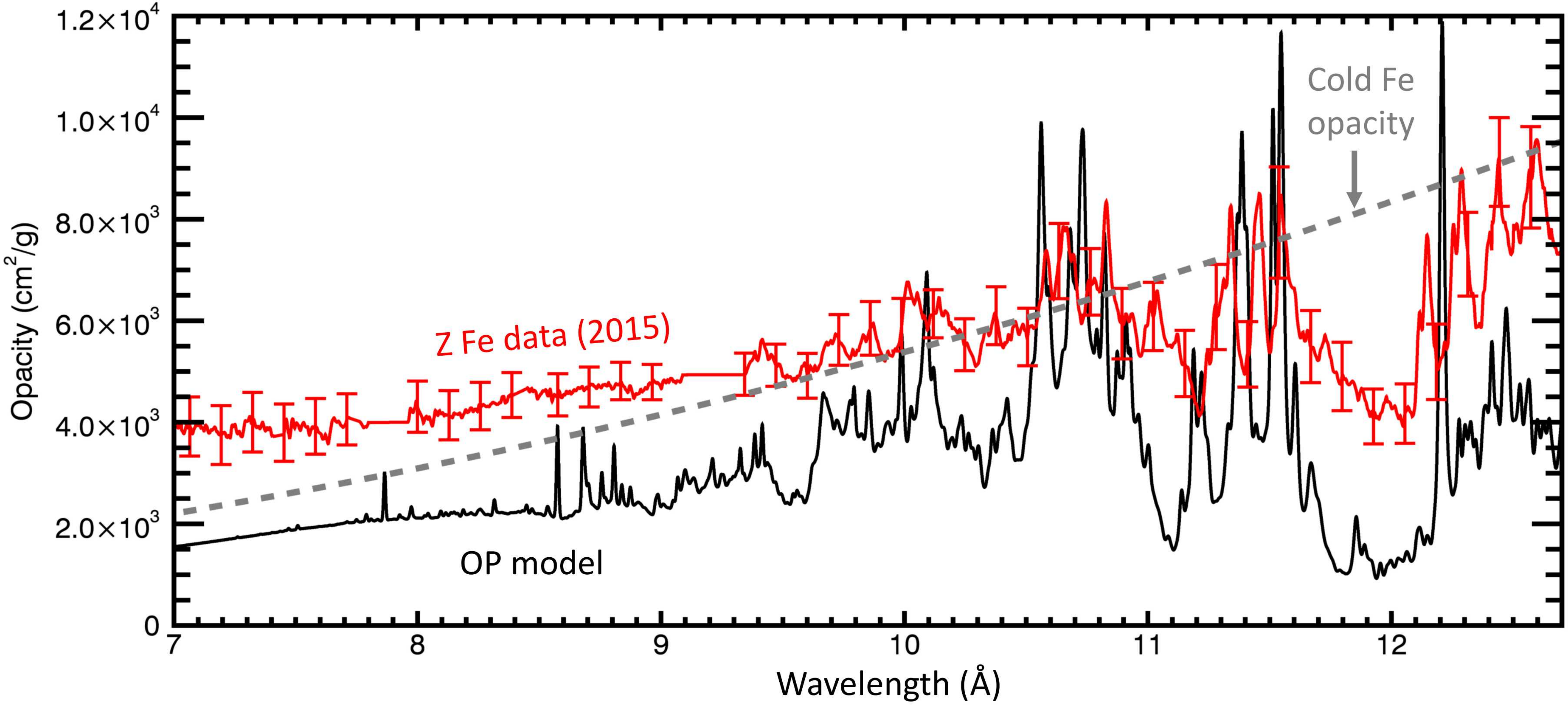


Monte-Carlo to propagate errors:

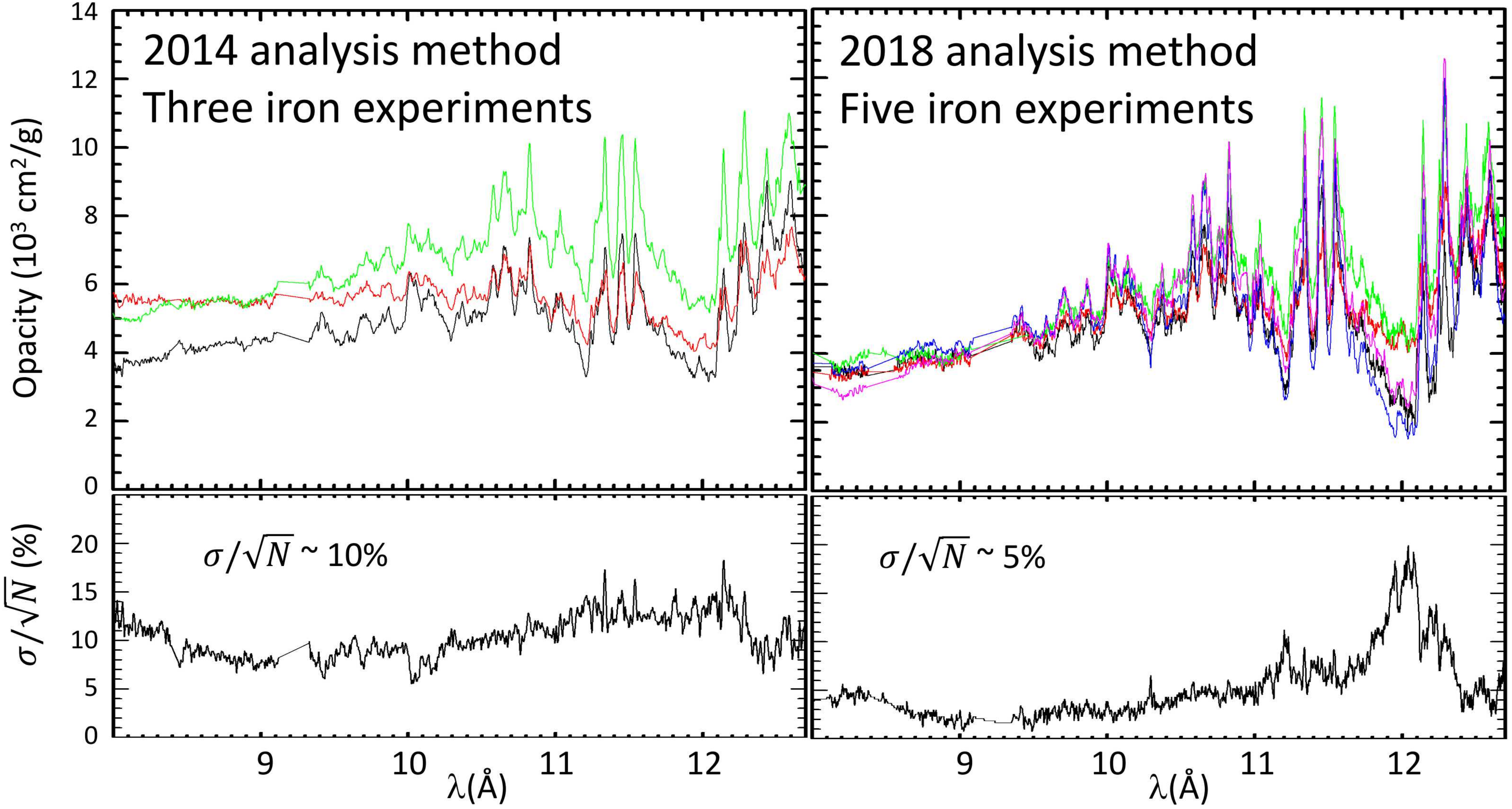
- Transmission error
- Background subtraction error
- Areal density error

*PDF = Probability distribution function

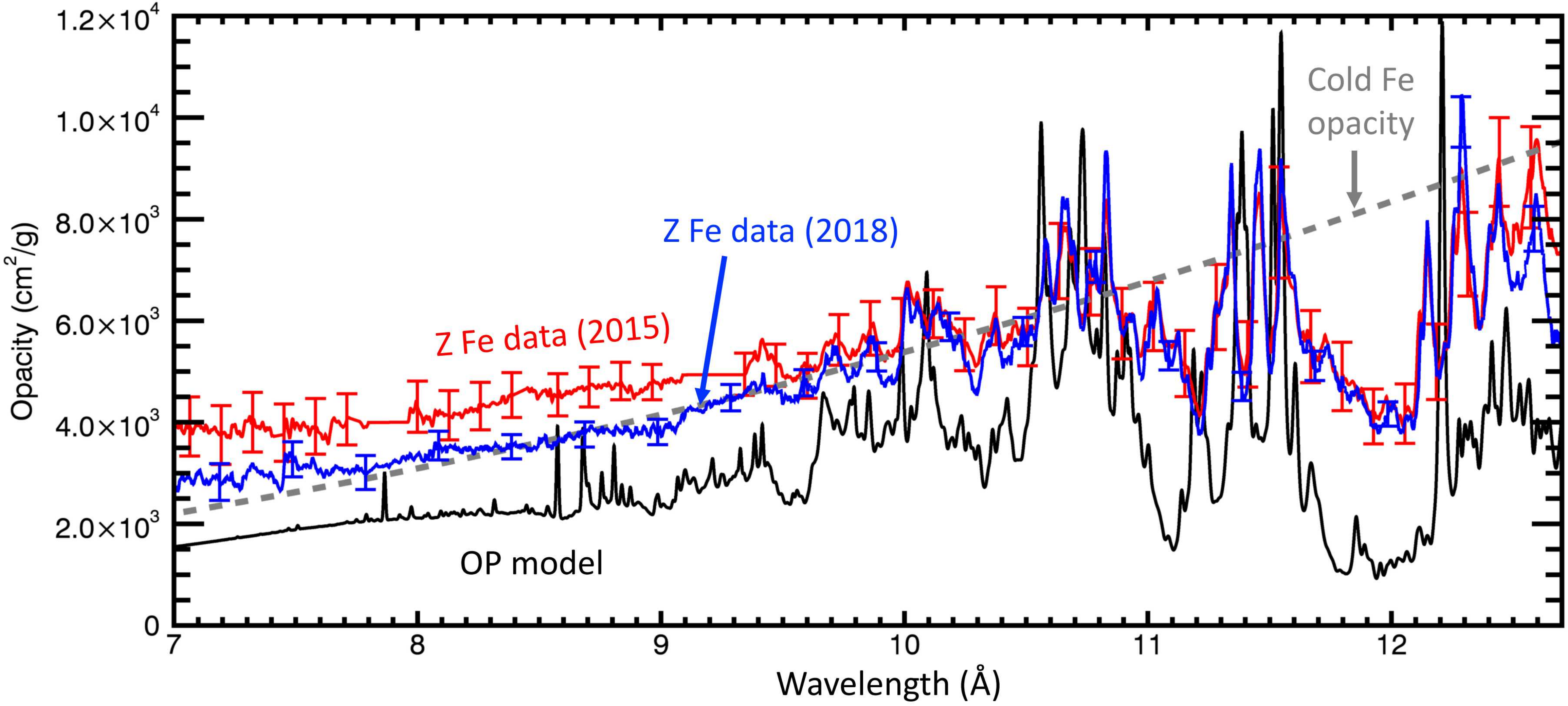
Analysis from 2015 showed 2x higher quasi-continuum opacity than astrophysical opacity-model prediction



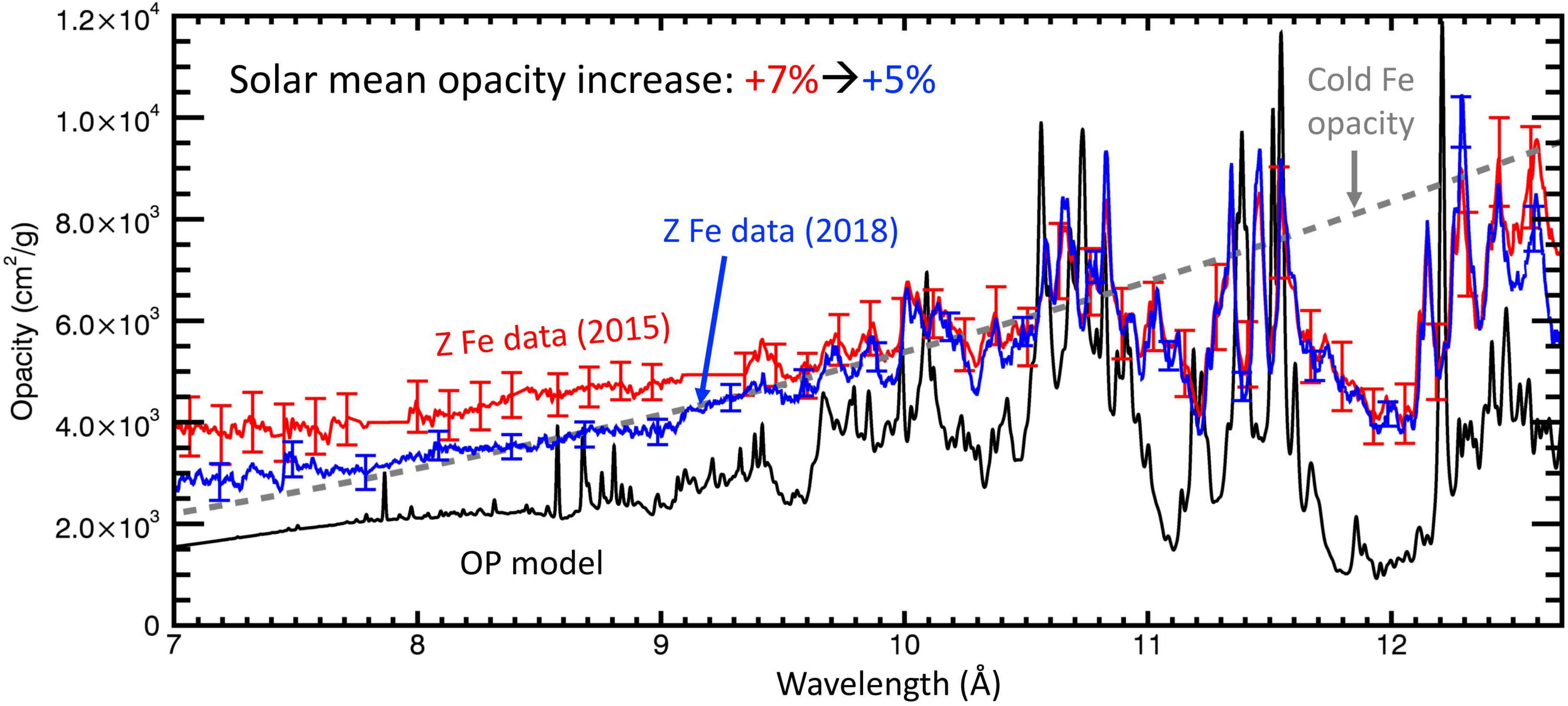
Both refined analysis and more experiments helped to improve shot-to-shot agreement on Anchor2 Fe



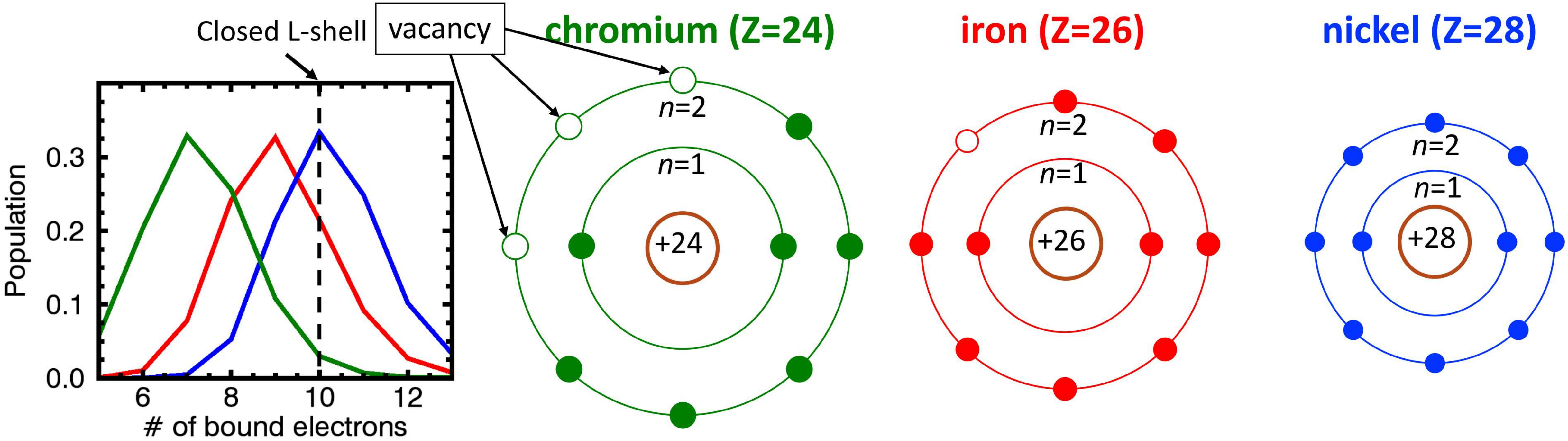
New analysis reduced the quasi-continuum disagreement from 2.0x to 1.6x, approaching to cold Fe opacity limit



New analysis reduced the quasi-continuum disagreement from 2.0x to 1.6x, approaching to cold Fe opacity limit

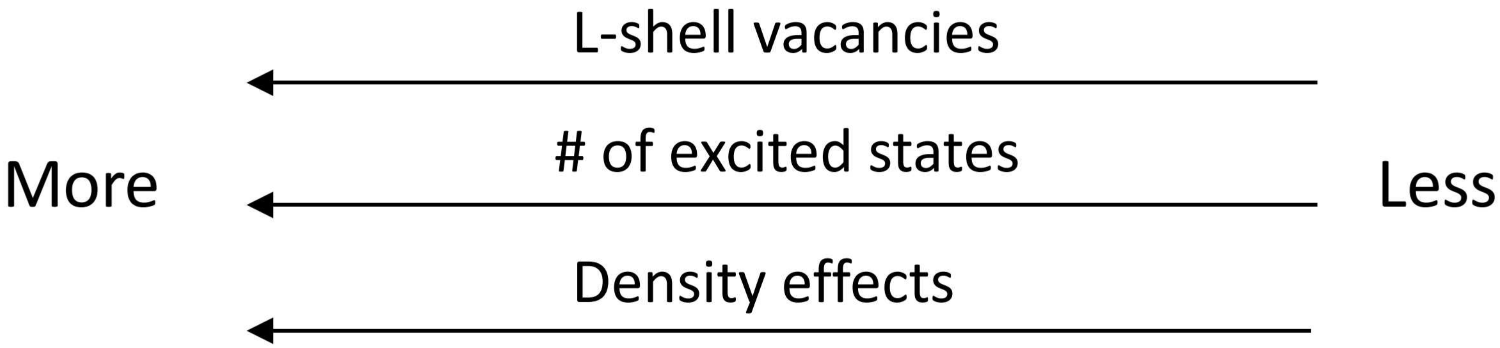


Different elements interact with plasma differently, providing unprecedented constraints for testing theory and experiments

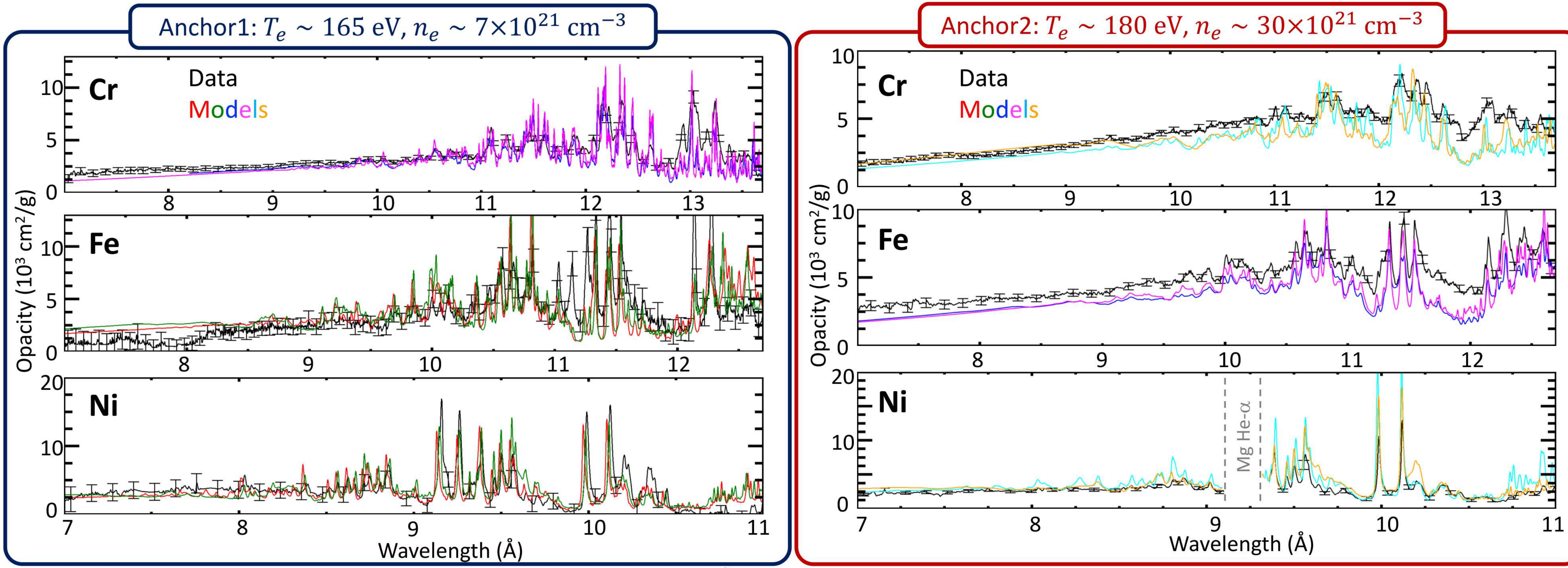


<u>Questioning Theory:</u>

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



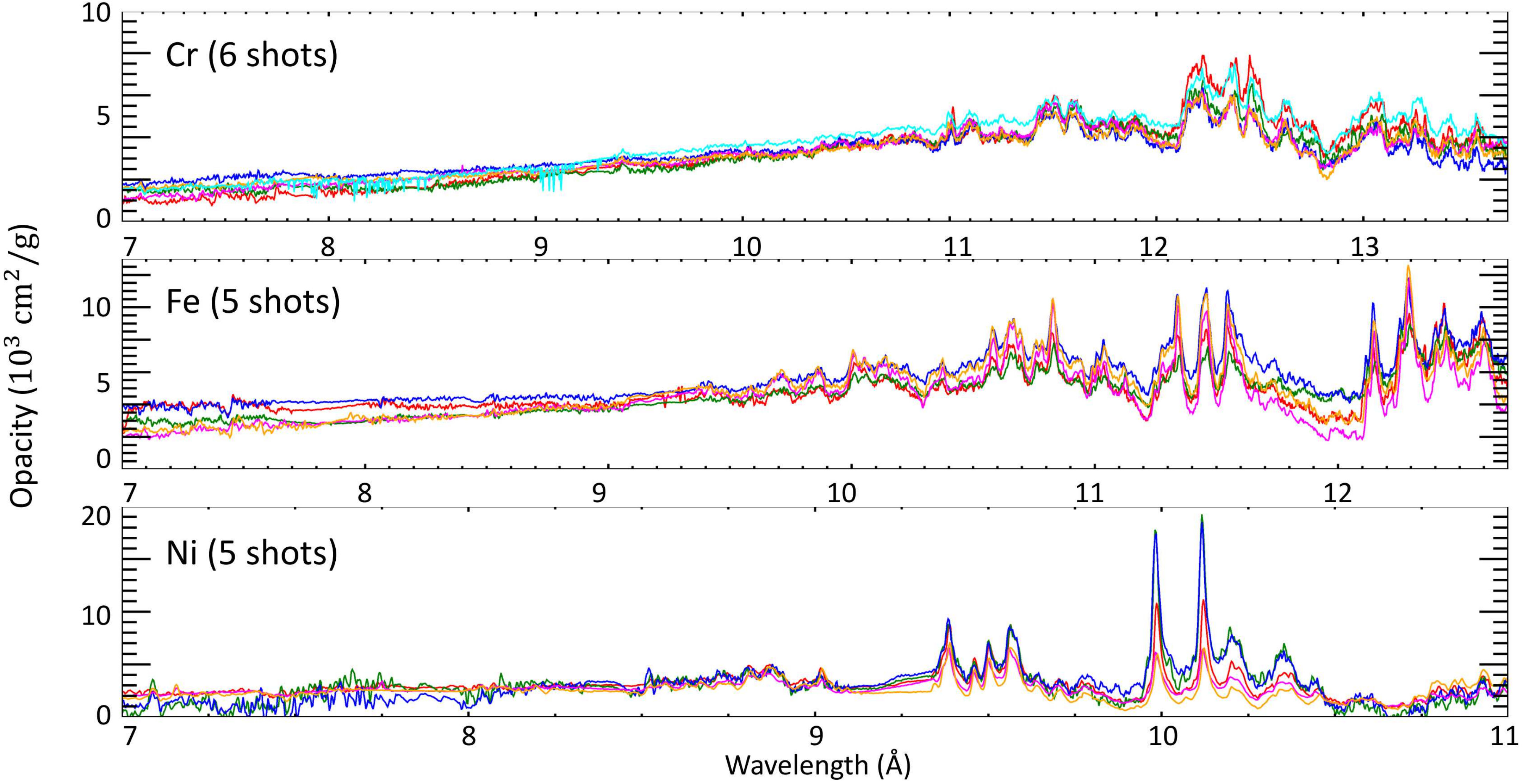
First systematic study of high-temperature L-shell opacities were performed for Cr, Fe, and Ni at two conditions



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

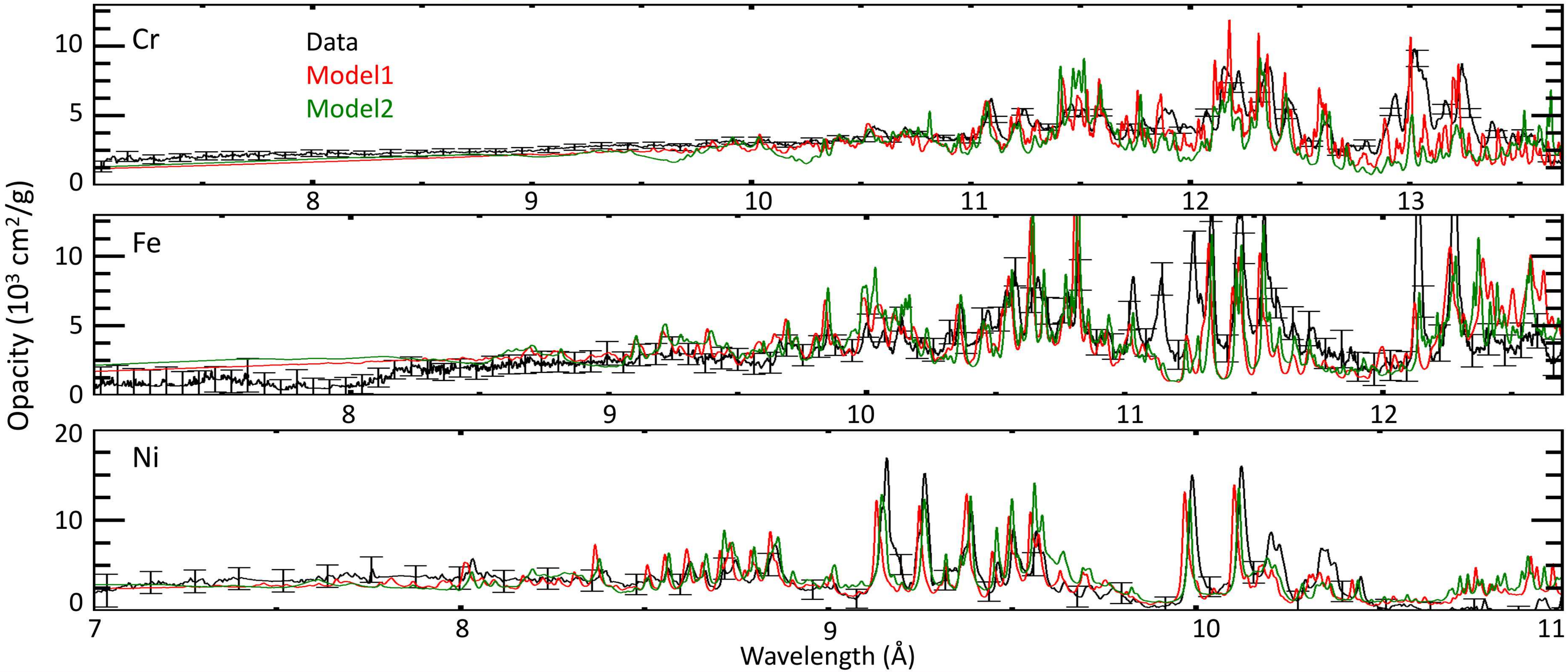
Systematically performed for Cr, Fe, Ni at two conditions

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



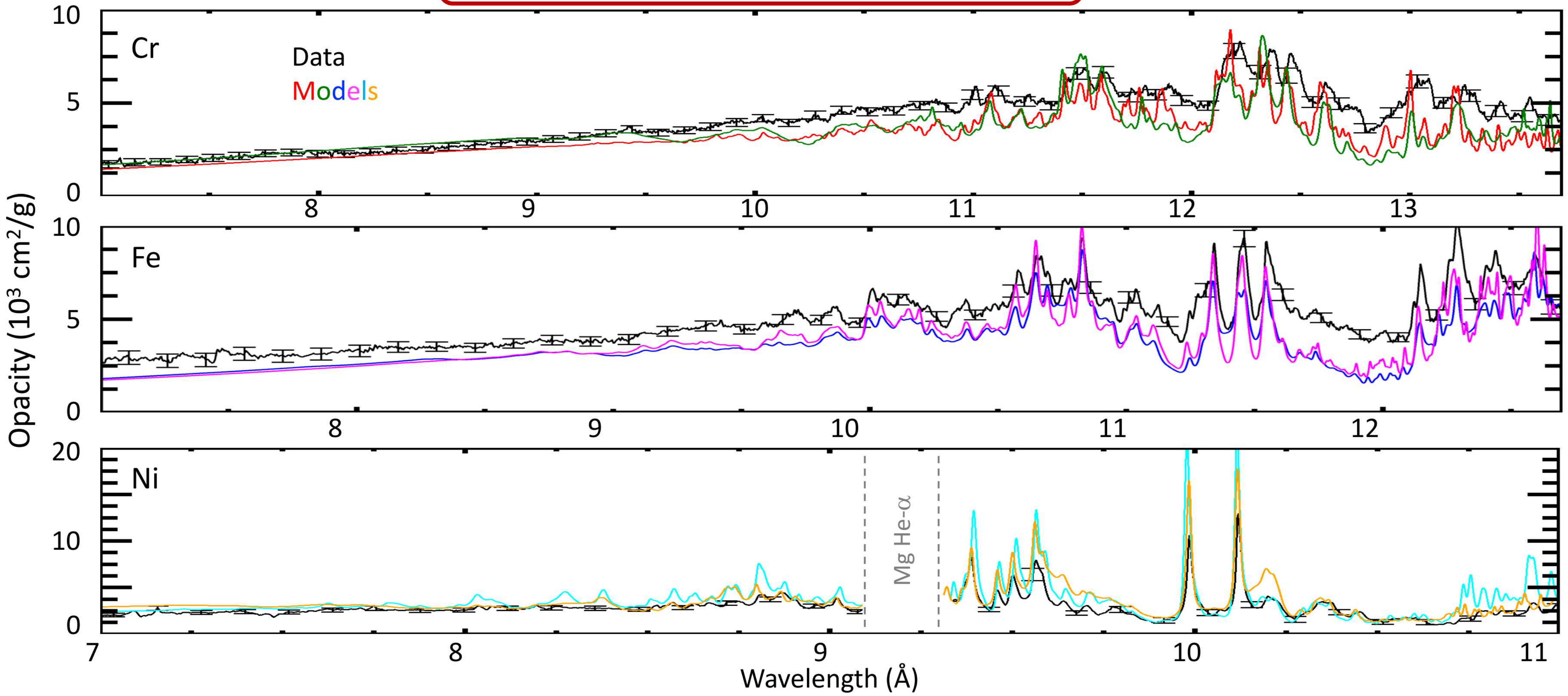
Anchor1: Modeled and measured opacities agree reasonably well at lower temperature and density

$T_e \sim 165$ eV, $n_e \sim 7\times10^{21}$ cm^{-3}

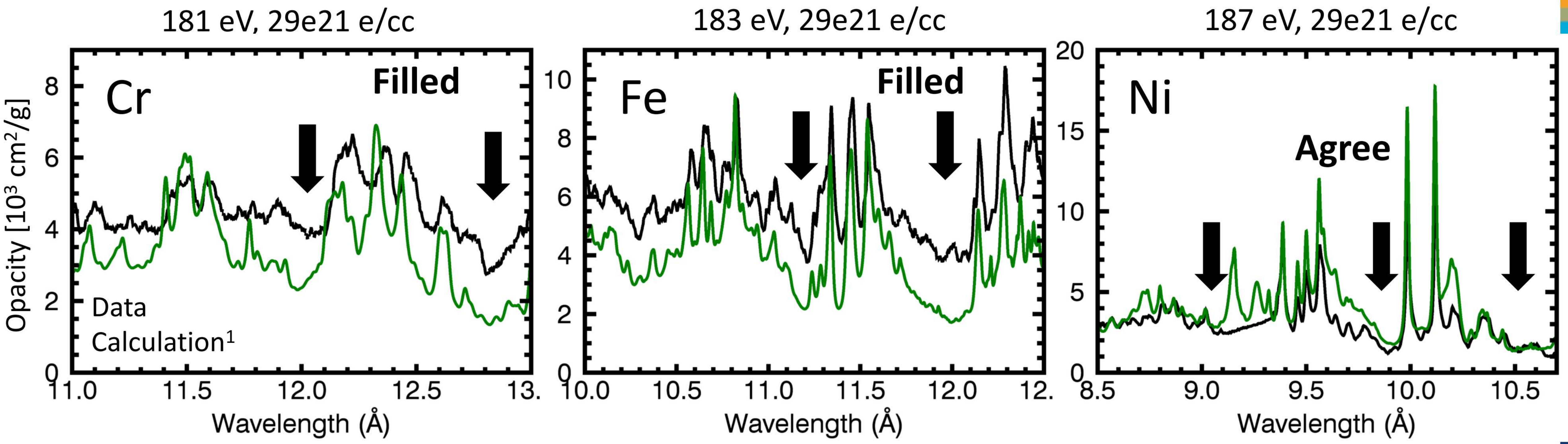


Anchor2: Interesting element-dependent disagreement appears as approaching to stellar interior conditions

$T_e \sim 180$ eV, $n_e \sim 30\times10^{21}$ cm^{-3}

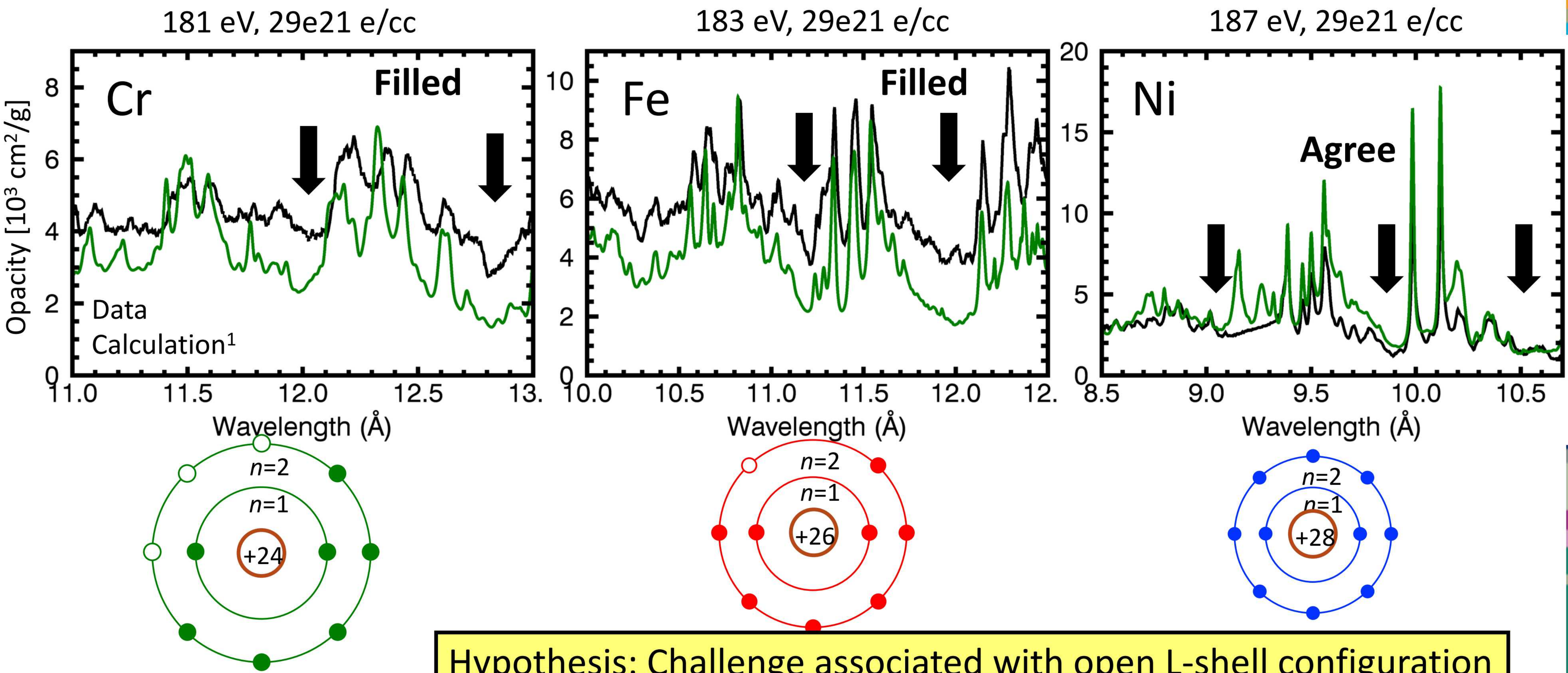


Window: Filled window observed from Cr and Fe, but not Ni



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

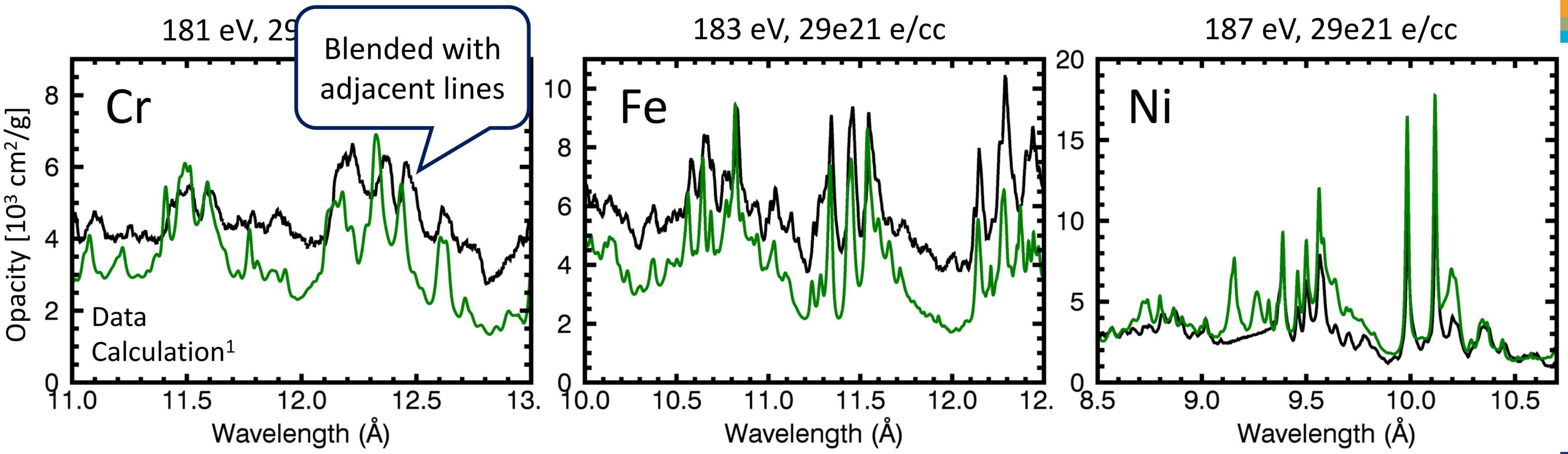
Window: Filled window observed from Cr and Fe, but not Ni



Hypothesis: Challenge associated with open L-shell configuration

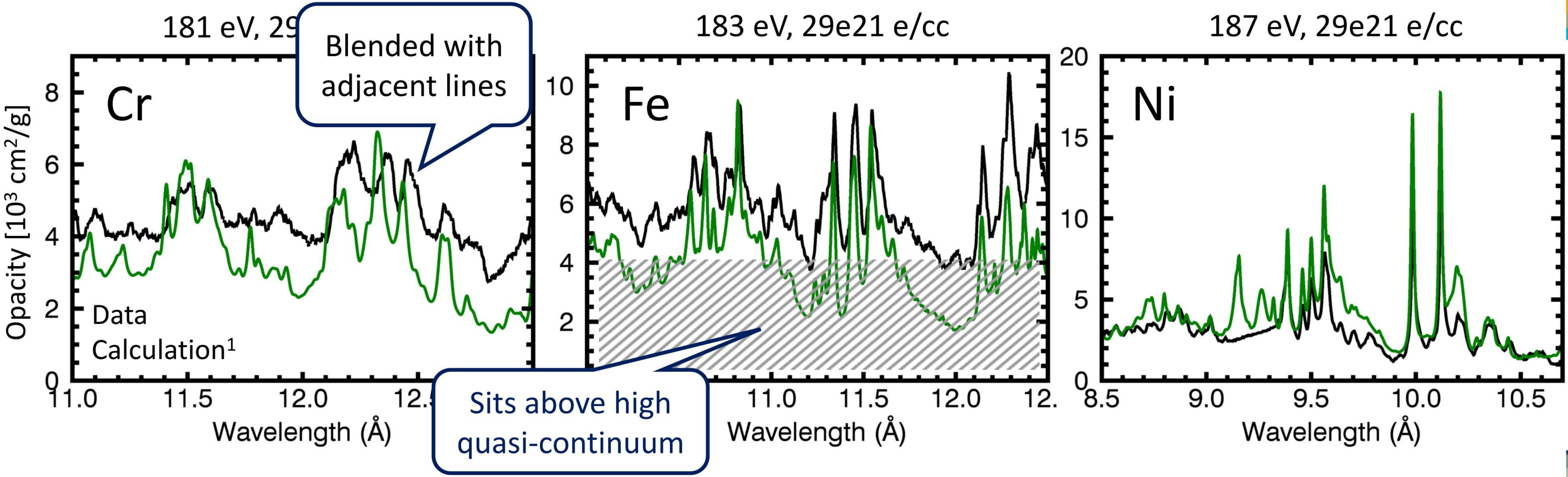
SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

Can we check accuracy of modeled line shapes?



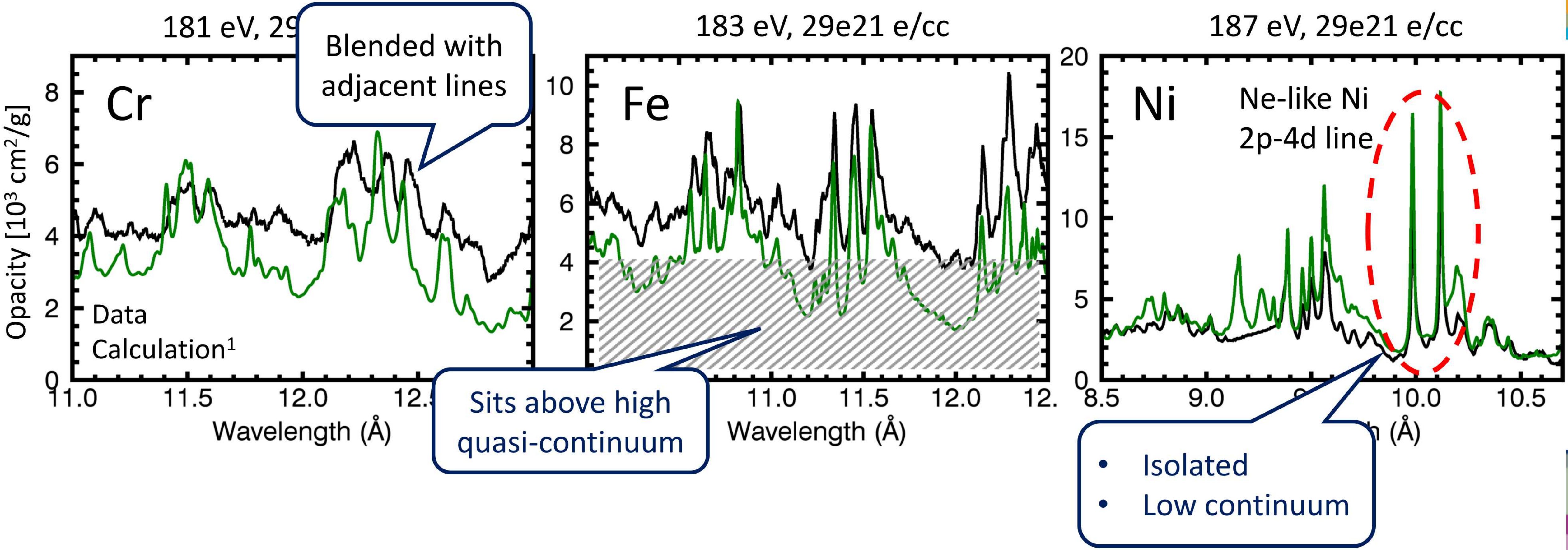
SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

Can we check accuracy of modeled line shapes?



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

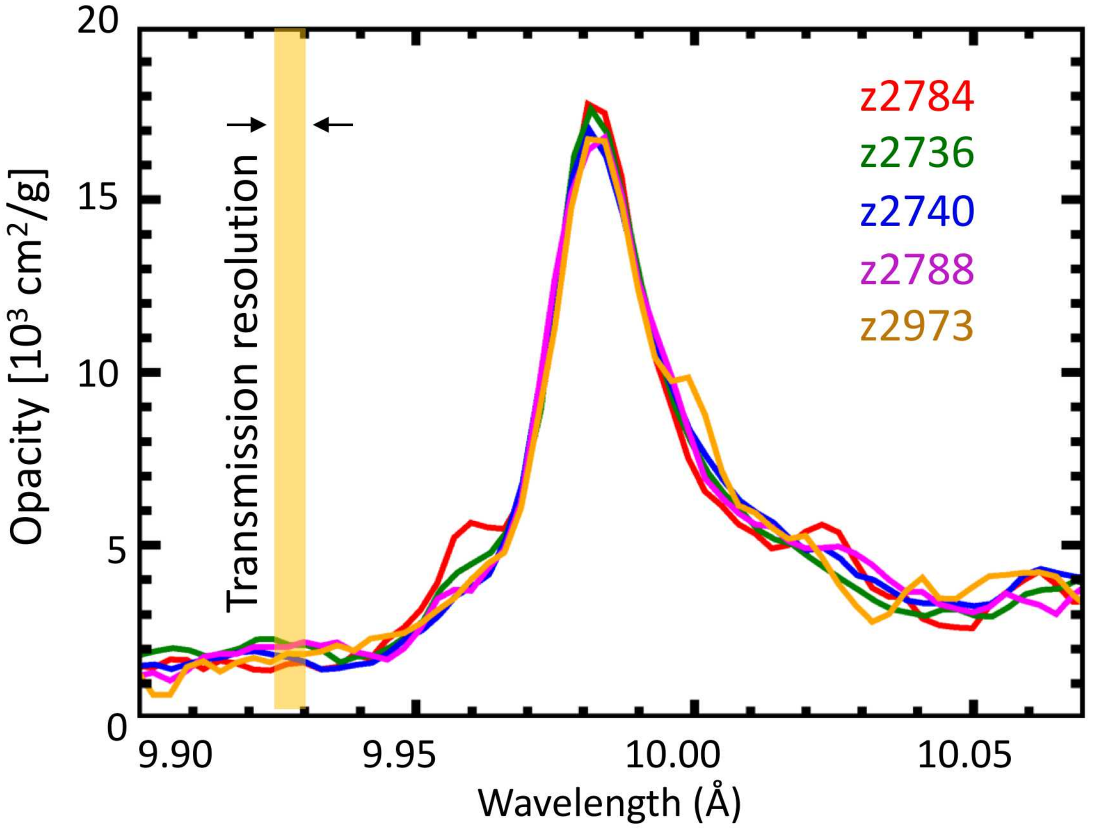
Can we check accuracy of modeled line shapes?



We use n=2 → 4 lines from Ne-like Ni to assess the accuracy of calculated line shape

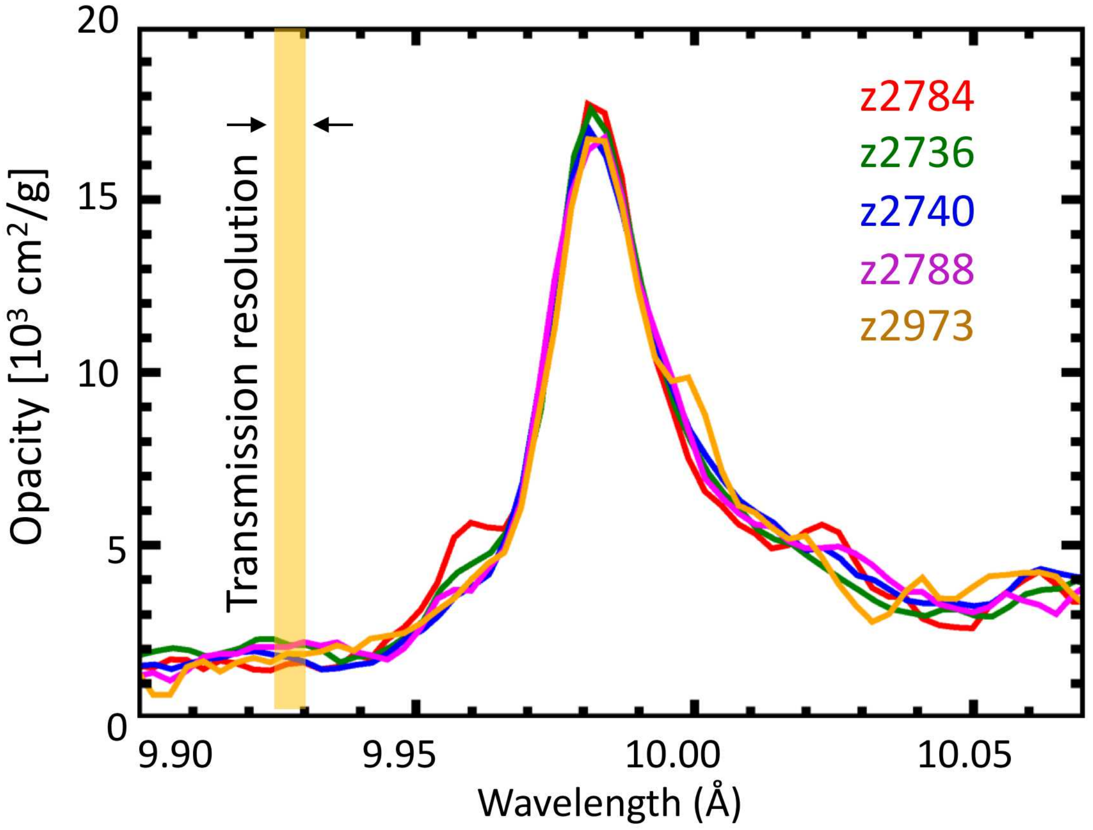
SCRAM: S. Hansen et al, *High Energ Dens Phys* 3 (2007) 109.

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

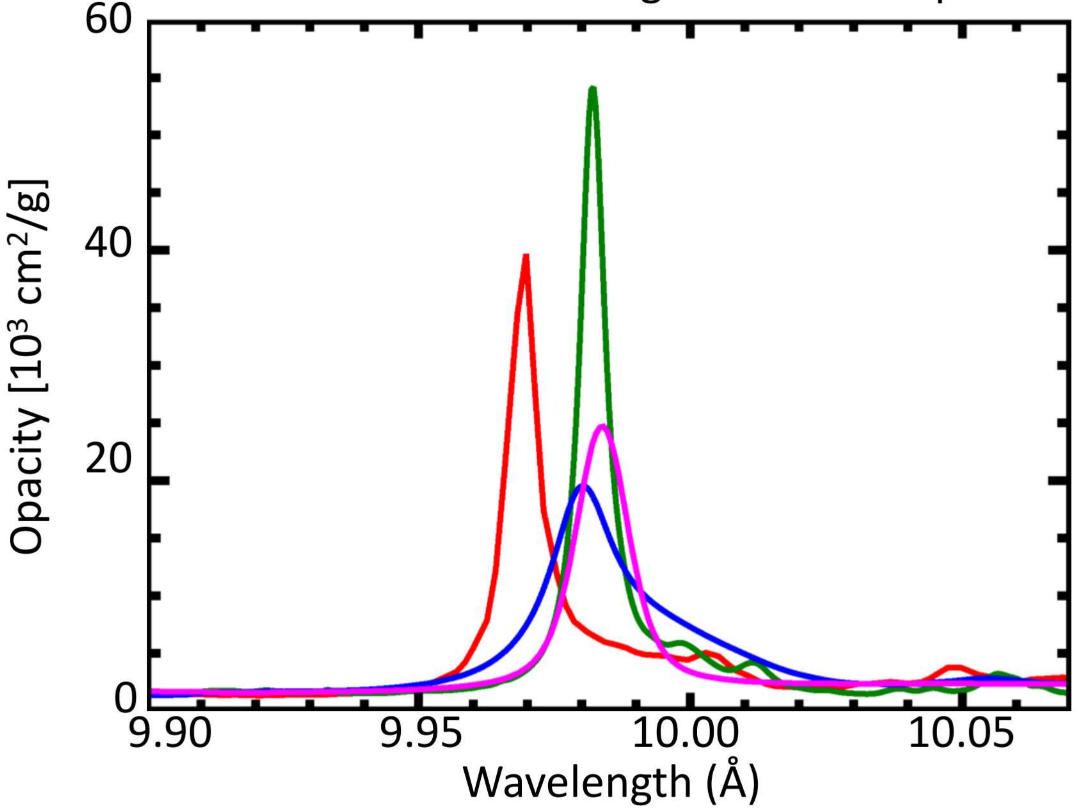


- This line-shape is reproduced by five experiments
- Models employ simple approximations for L-shell line shapes, which are not tested.
  - Electron broadening
  - Static ion broadening
  - Satellite contributions

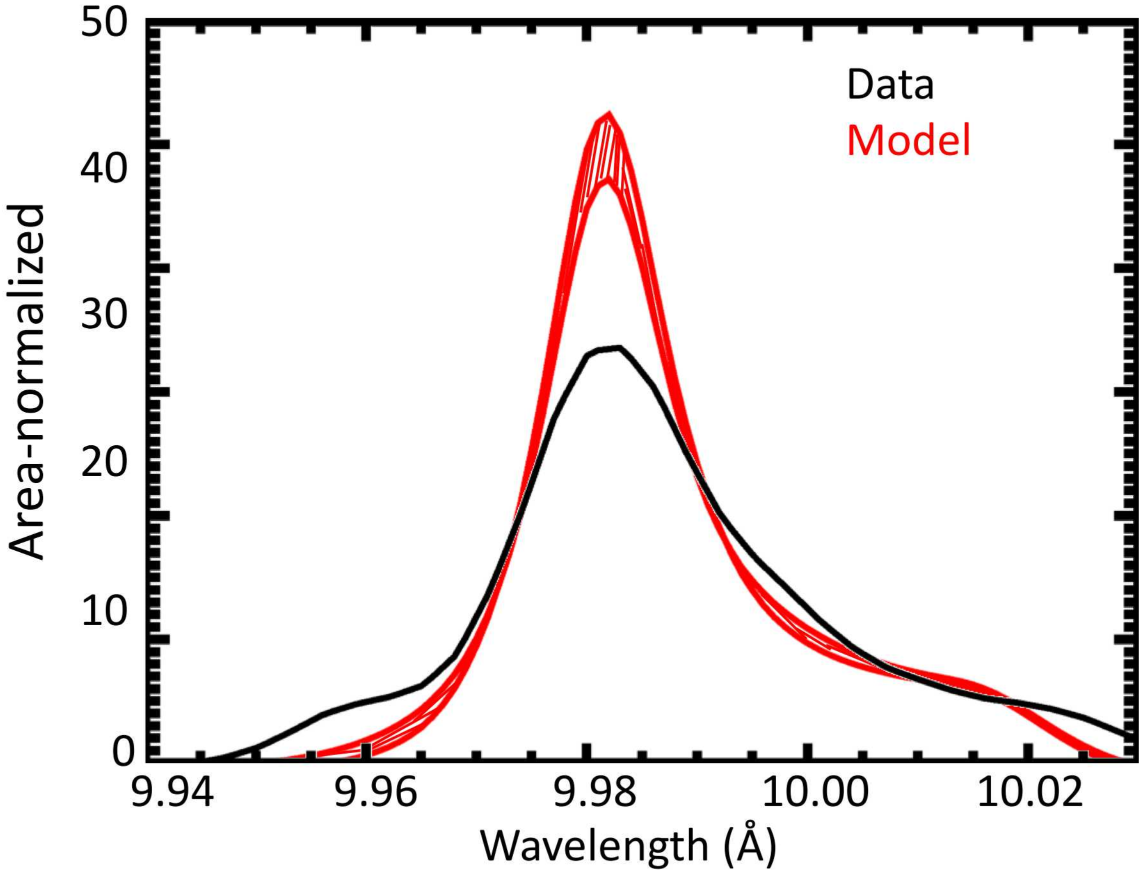
Line-shape of Ne-like Ni 2p-4d is accurately measured and appropriate to test approximations used in models



Different models disagree in line shapes

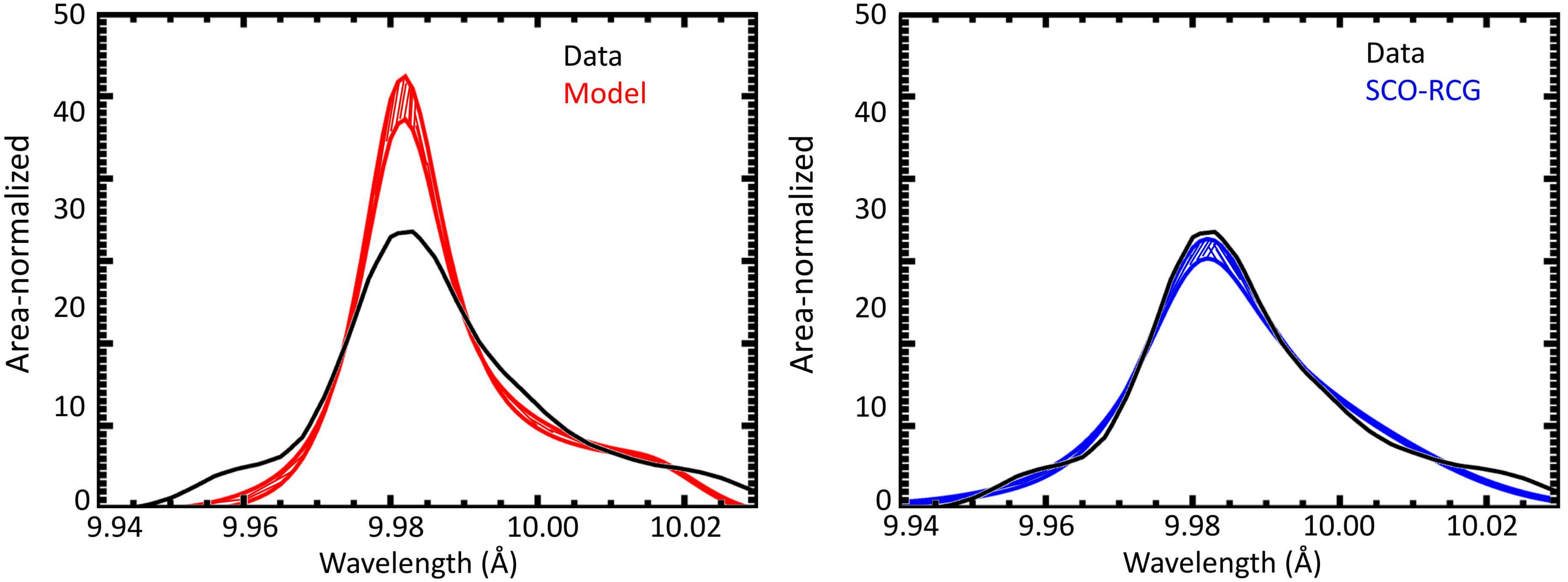


Most models underestimate the L-shell line widths



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

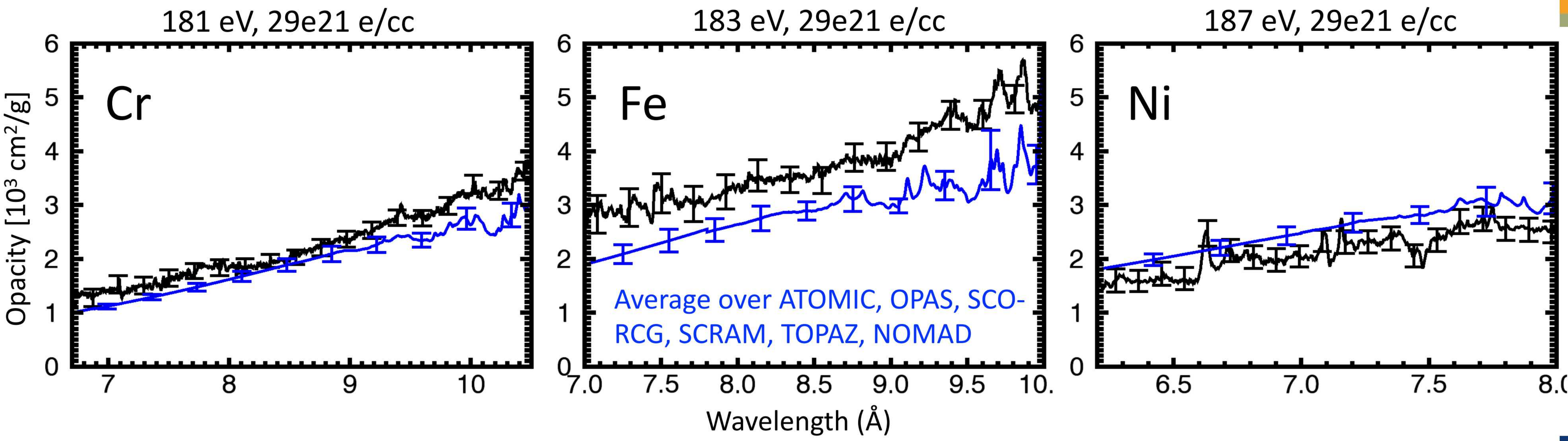
SCO-RCG model predicted the measured L-shell line width reasonably well



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

J.-C. Pain, F. Gilleron, High Energy Density Physics, 15, 30 (2015)

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

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

Future work: exciting new investigations and further scrutiny are on the horizon

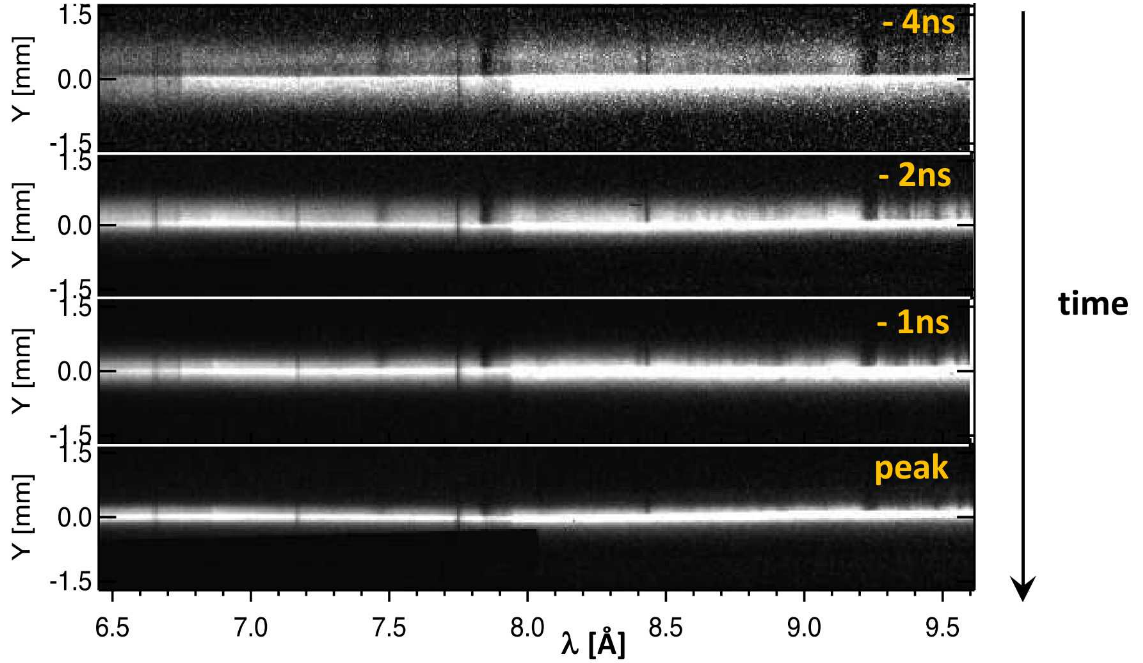
New investigations:

- Opacity at higher T_e and n_e:
  - Higher T_e:
    - Window disagreement
  - Higher n_e
    - Line-shape disagreement
    - Closer to solar CZB conditions
- O opacity for solar problem
- Time-resolved measurement (UXI*)
  - Comparable S/N to x-ray film
  - Potentially, T_e and n_e points from single experiment, in progress

*UXI = Ultra-fast X-ray Imager

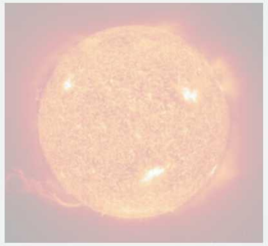
Further scrutiny:

- Fe quasi-continuum puzzle
  - Anchor1, 2, 3
- Revisiting errors
  - Areal density
  - Background



ZAPP campaigns simultaneously study multiple issues

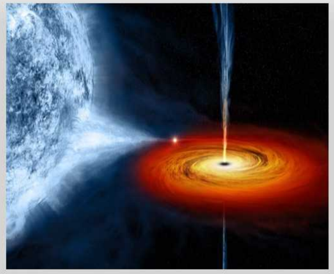
Solar Opacity



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

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

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}

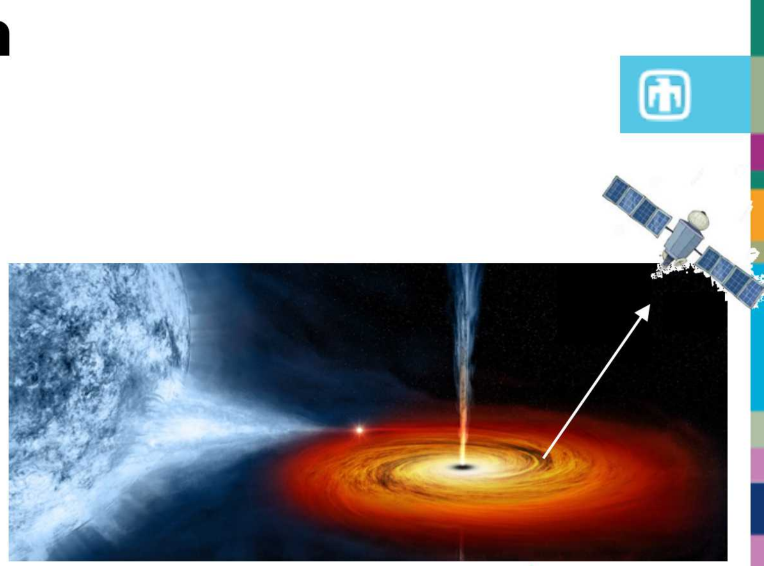
White Dwarf Line-Shapes

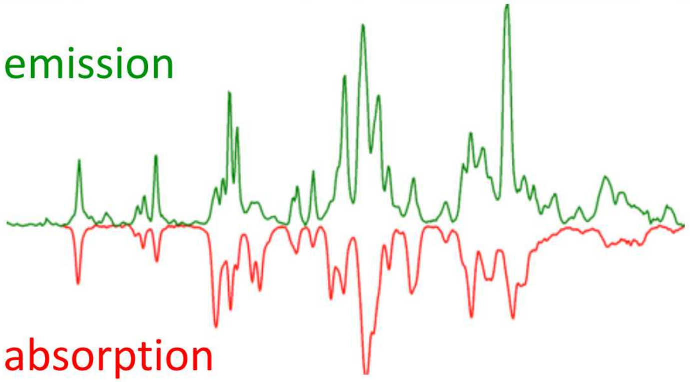
Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

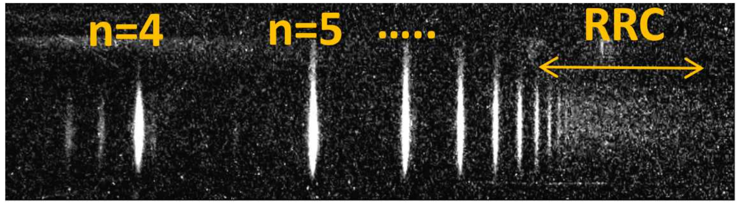
Achieved Conditions:
$T_e \sim 1$ eV, $n_e \sim 10^{17}$ cm^{-3}

Z data can benchmark models of emission from photoionized accretion-powered plasmas

- Understanding X-ray Binaries and AGN accretion disks requires complex models that interpret observed spectra
  - → These models are largely untested in the laboratory
  - → Need benchmark quality data
- A photoionized silicon plasma with a measured drive radiation spectrum, density and temperature was created on Z
  → the column density is adjustable, testing radiation transport
- Spectral absorption and emission are measured to high reproducibility enabling benchmark code comparison
- Presently, models do not reproduce neither relative or absolute emission
- First terrestrial RRC from a photoionized plasma was obtained on Z enabling test of astrophysical temperature diagnostics





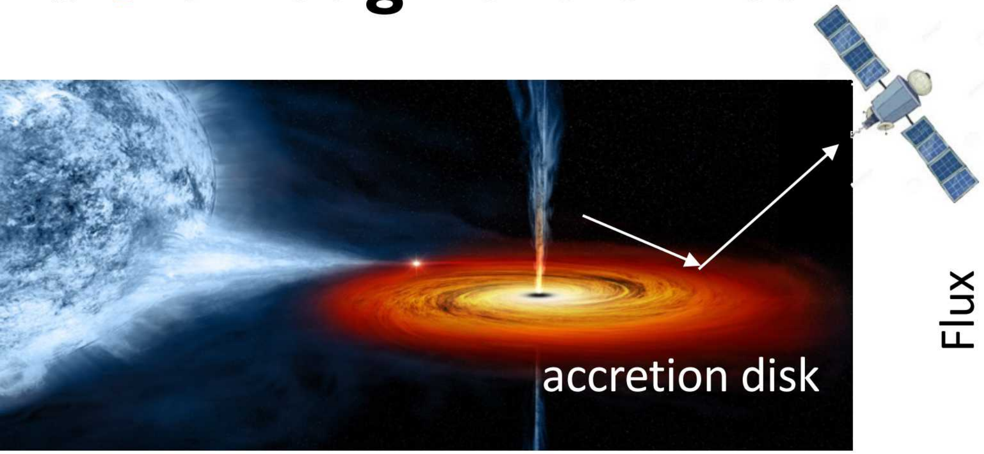


Si He-like emission

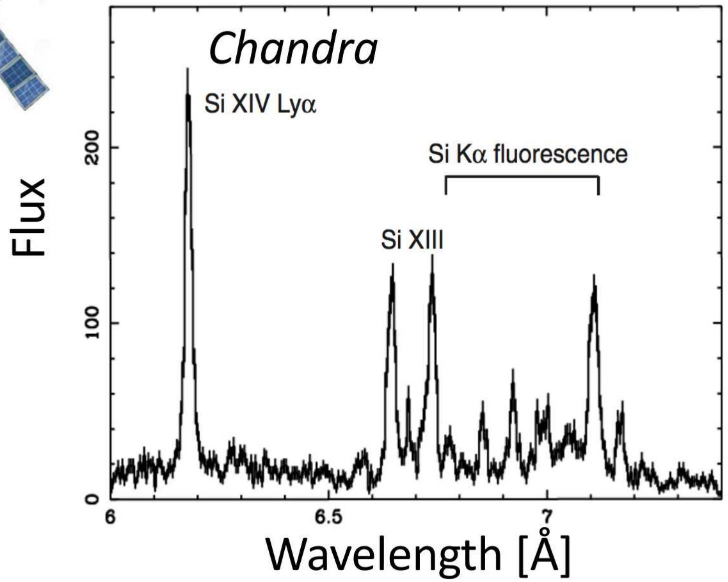
The difficulty to model emission raises questions about the suitability of models used to interpret astrophysical observations

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

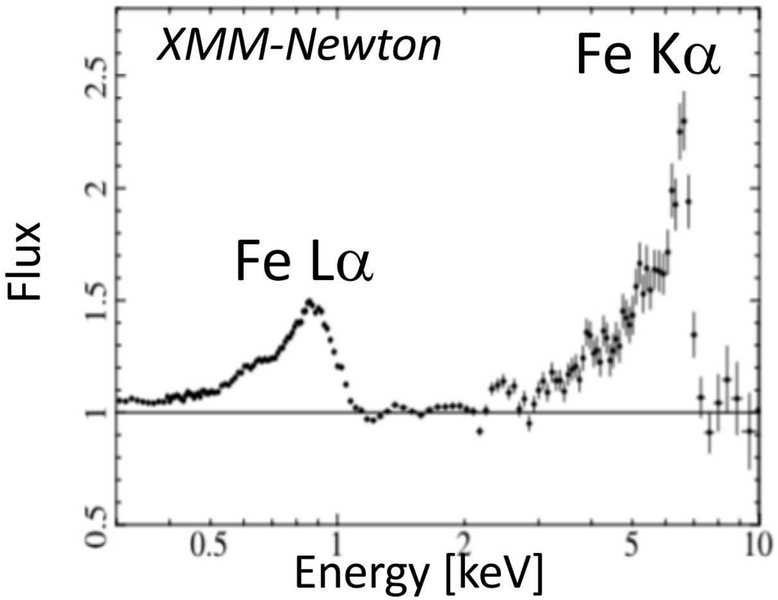
Active Galactic Nuclei and X-ray Binaries are revealed through the emission from their accretion disk



Neutron star Vela X-1



AGN 1H0707-495



XMM-Newton - ESA

Chandra - NASA

Suzaku – JAXA

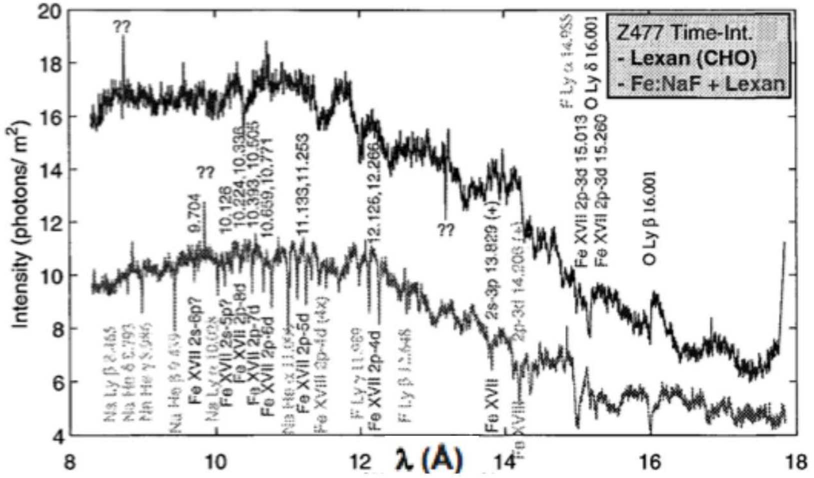
Challenges:

- Line identification
- Blended spectra from multiple elements
- Spatial and temporal integration
- Limited spectral resolution
- Limited signal-to-noise

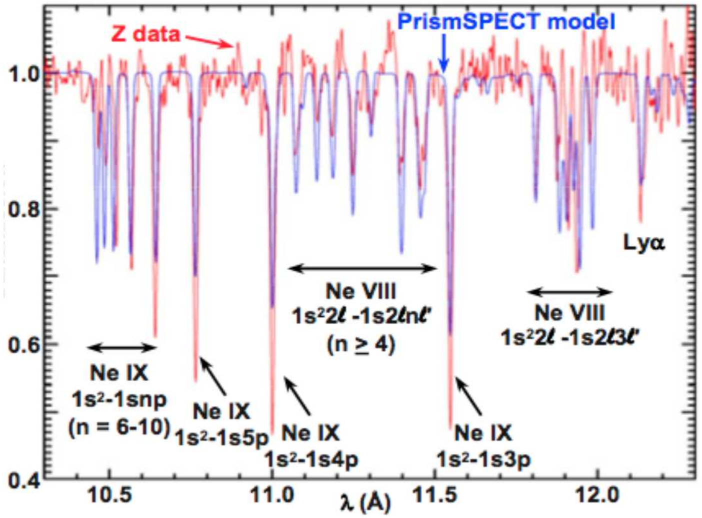
Liedahl, X-ray Diagnostics of Astrophysical Plasmas (2005), Ross & Fabian, Nature (2009)

Few photoionized plasma experiments exist

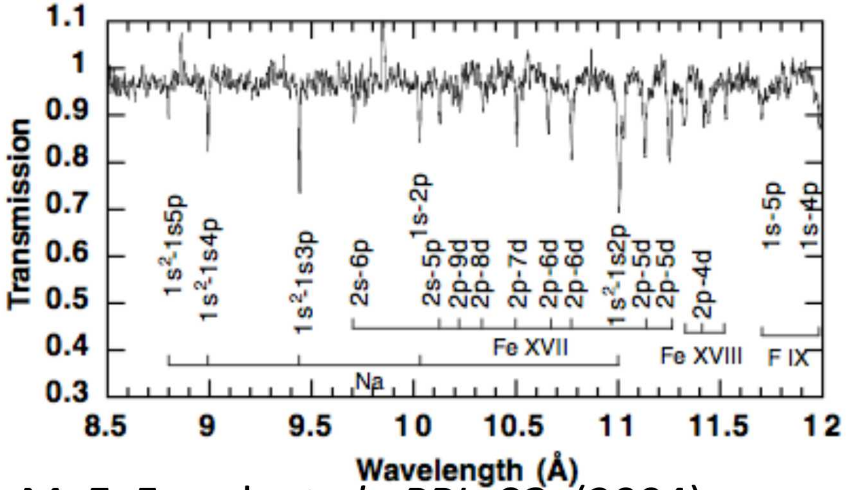
Absorption



R. F. Heeter, J. E. Bailey, M. E. Cuneo, *et al.*, AIP CP, **547**, (2000).

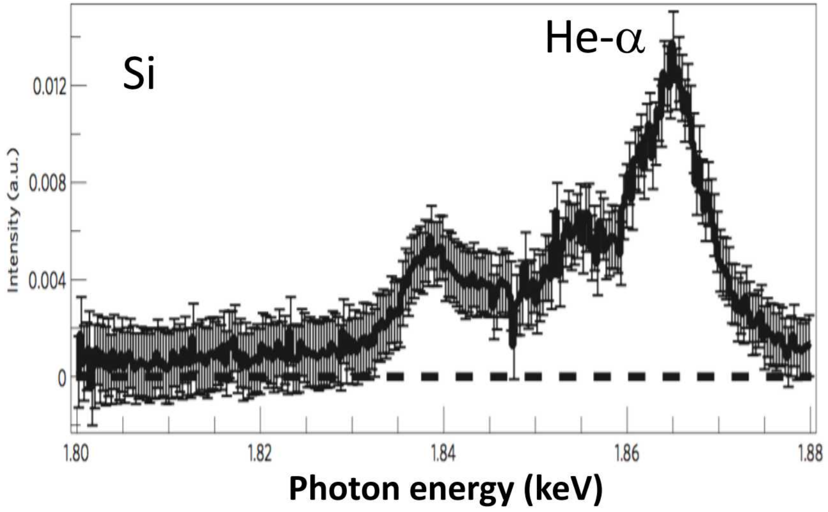


R. C. Mancini, J. E. Bailey *et al.*, *PoP*, **16**, (2009).



M. E. Foord, *et al.*, *PRL*, **93**, (2004).

Emission



S. Fujioka et al. Nature Phys. **5**, (2009)

→ **Absorption measurements revealed first photoionized plasma spectra and allowed test of ionization models.**
→ **Emission spectra was first observed in a laser experiment, although short timescale and important radiation dilution.**

Benchmark requirements to emission experiment

Experimental requirements for model benchmarking:

- large volumes for uniformity
- long duration x-ray drive for steady state
- demonstrated reproducibility
- independent diagnosis of plasma conditions *and* x-ray driving radiation
- demonstrated photoionization regime (CSD vs T_e, $\xi > 1$ erg.cm/s)

Specifically for *emission*:

- Large column density for high S/N

Since column = density × length , density < 10^{19} e^-/cc → large ~1cm plasma size

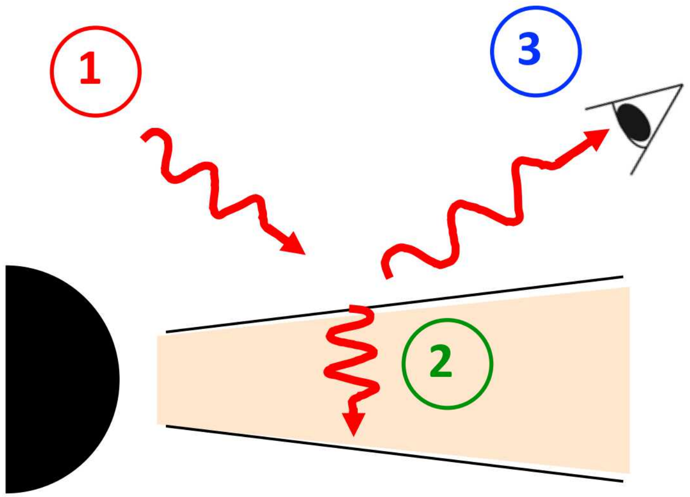
Experiments on the Z Facility can meet these criteria.

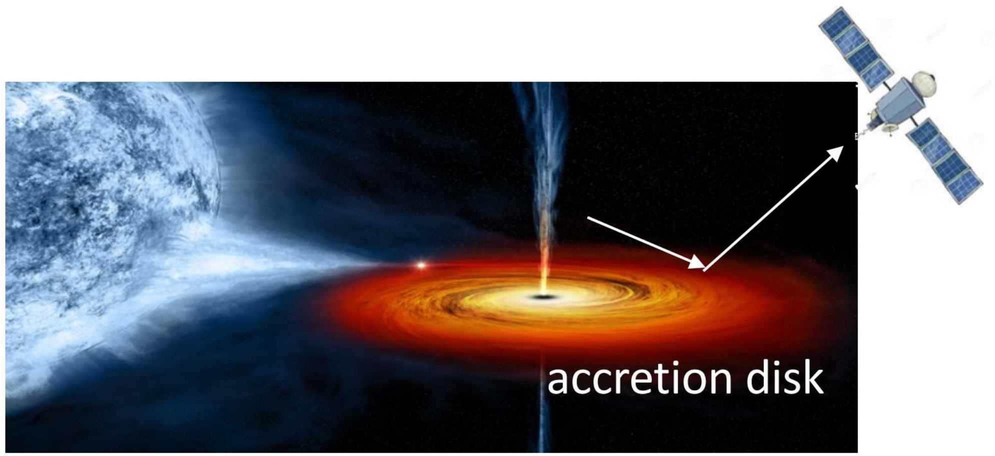
G. Loisel, J. Bailey, D. Liedahl et al., PRL 119 (2017)

Goal: build a laboratory analog for accretion disk X-ray emission

1. X-ray illumination
2. Photon ionization and atomic kinetics
3. Plasma emission

accretion disk





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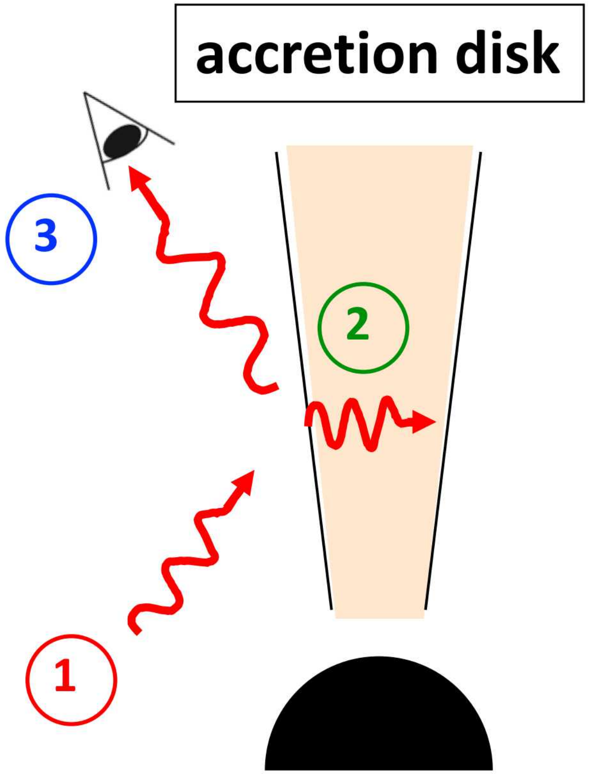

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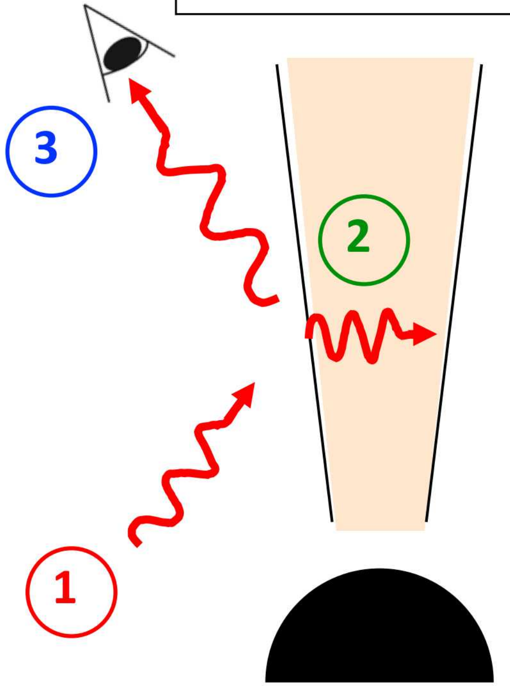
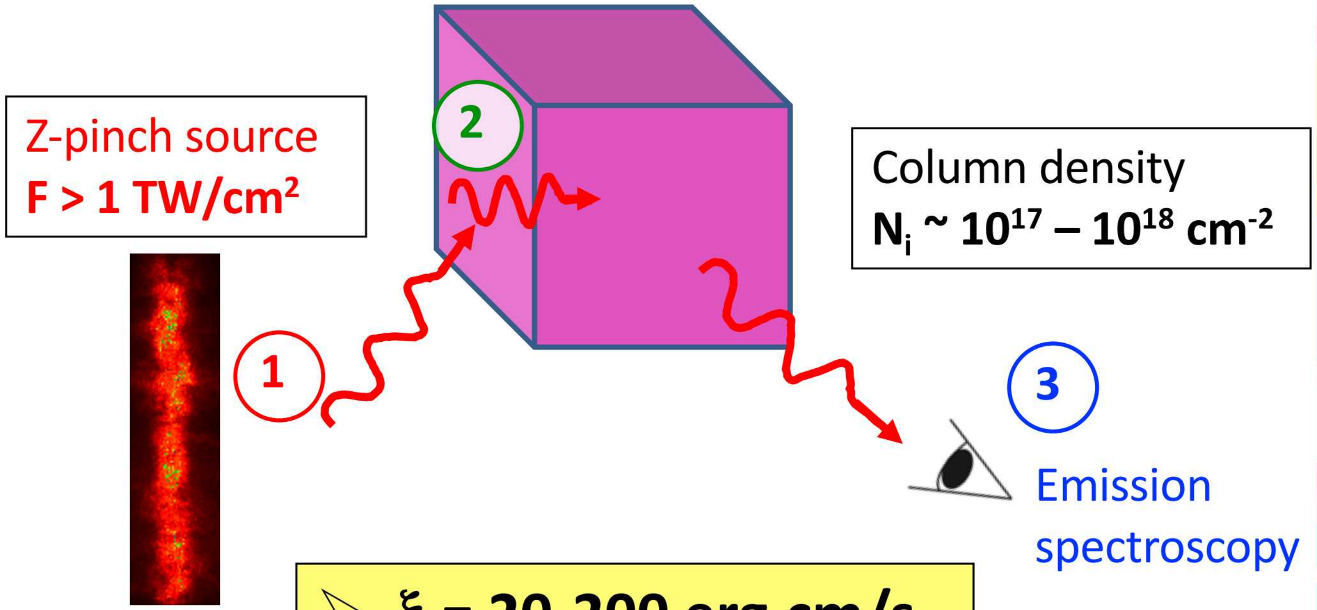


laboratory

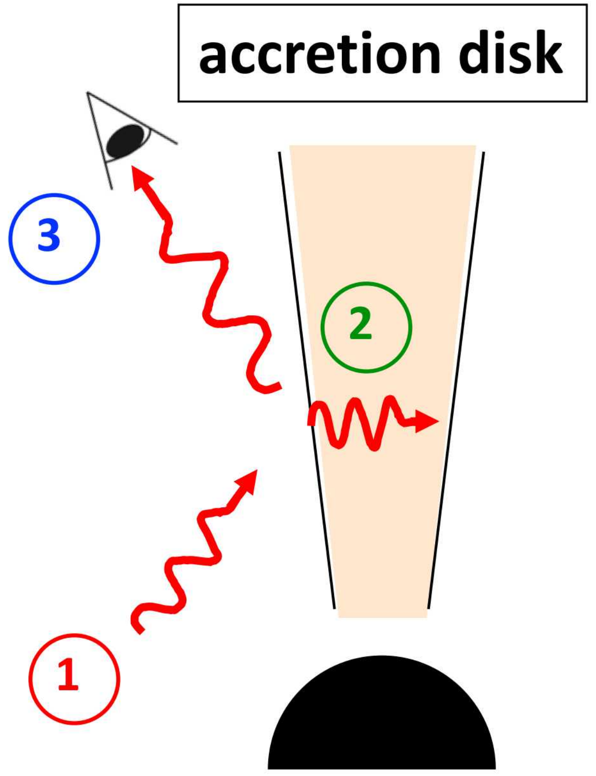
Temperature T_e = **20-40 eV**
Density n_i **~ 10^{17} – 10^{18} cm^{-3}**

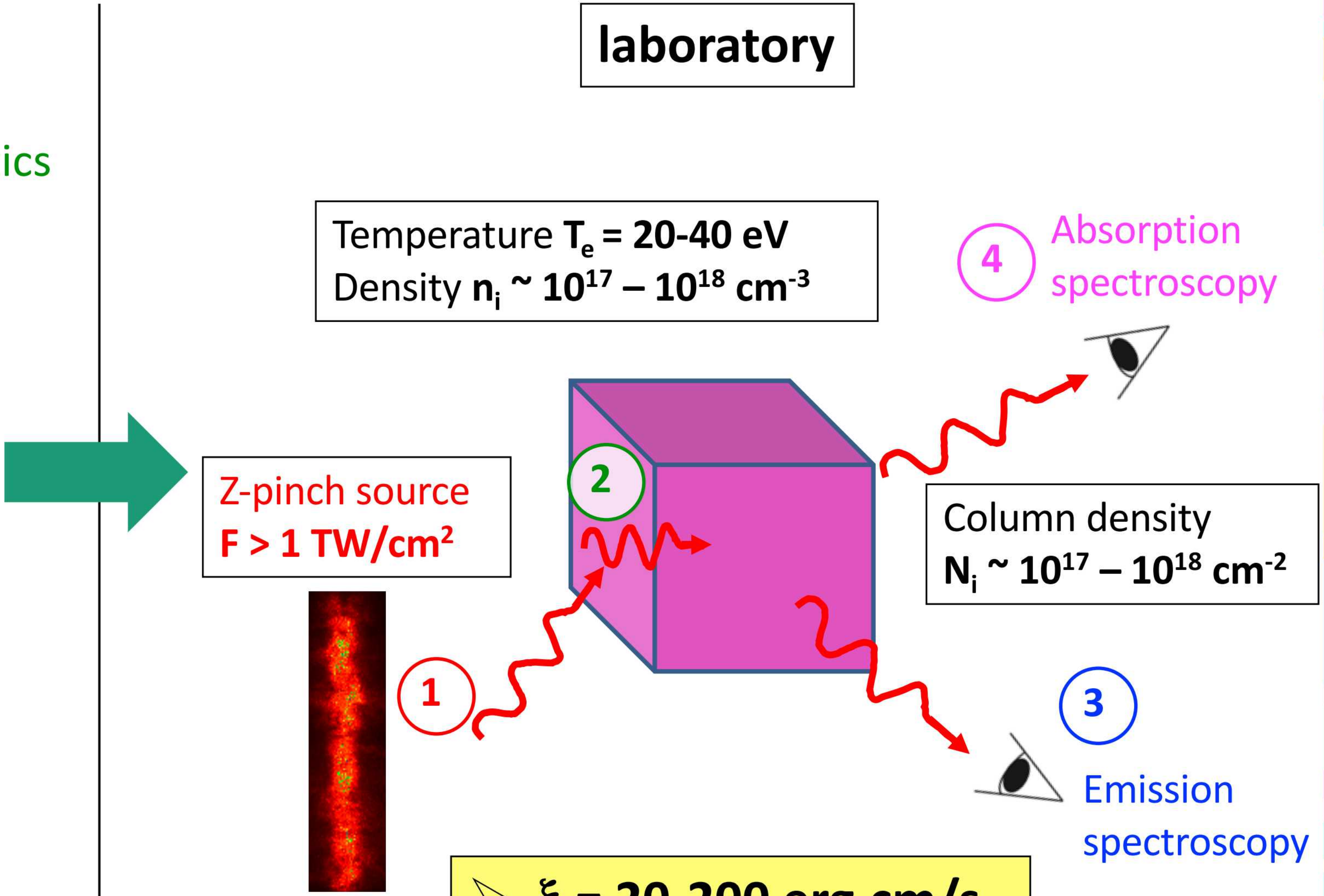


- **ξ = 20-200 erg.cm/s**

Goal: build a laboratory analog for accretion disk X-ray emission

1. X-ray illumination
2. Photon ionization and atomic kinetics
3. Plasma emission





➢ **ξ = 20-200 erg.cm/s**

Goal: build a laboratory analog for accretion disk X-ray emission

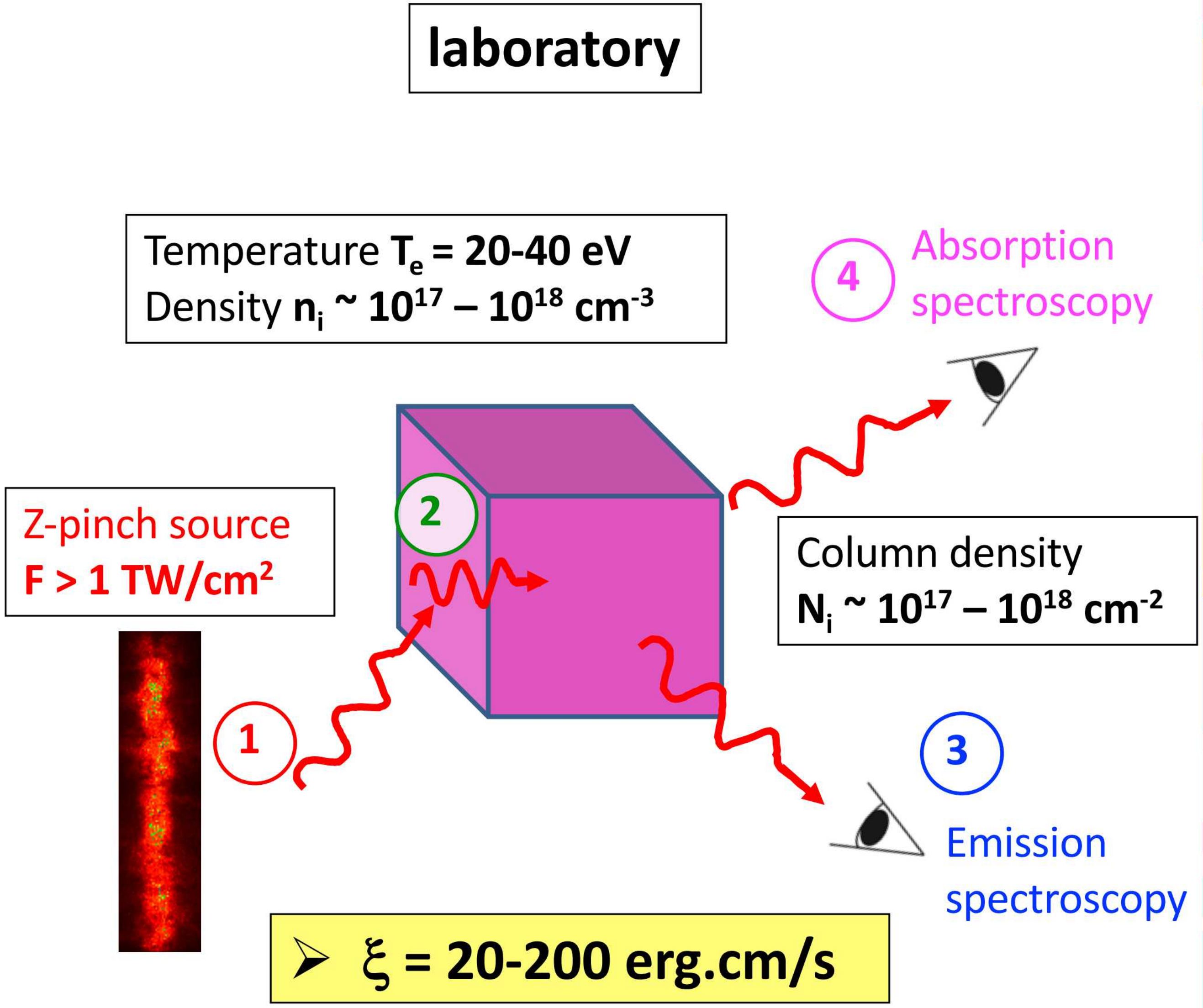
1 X-ray illumination

2 Photon ionization and atomic kinetics

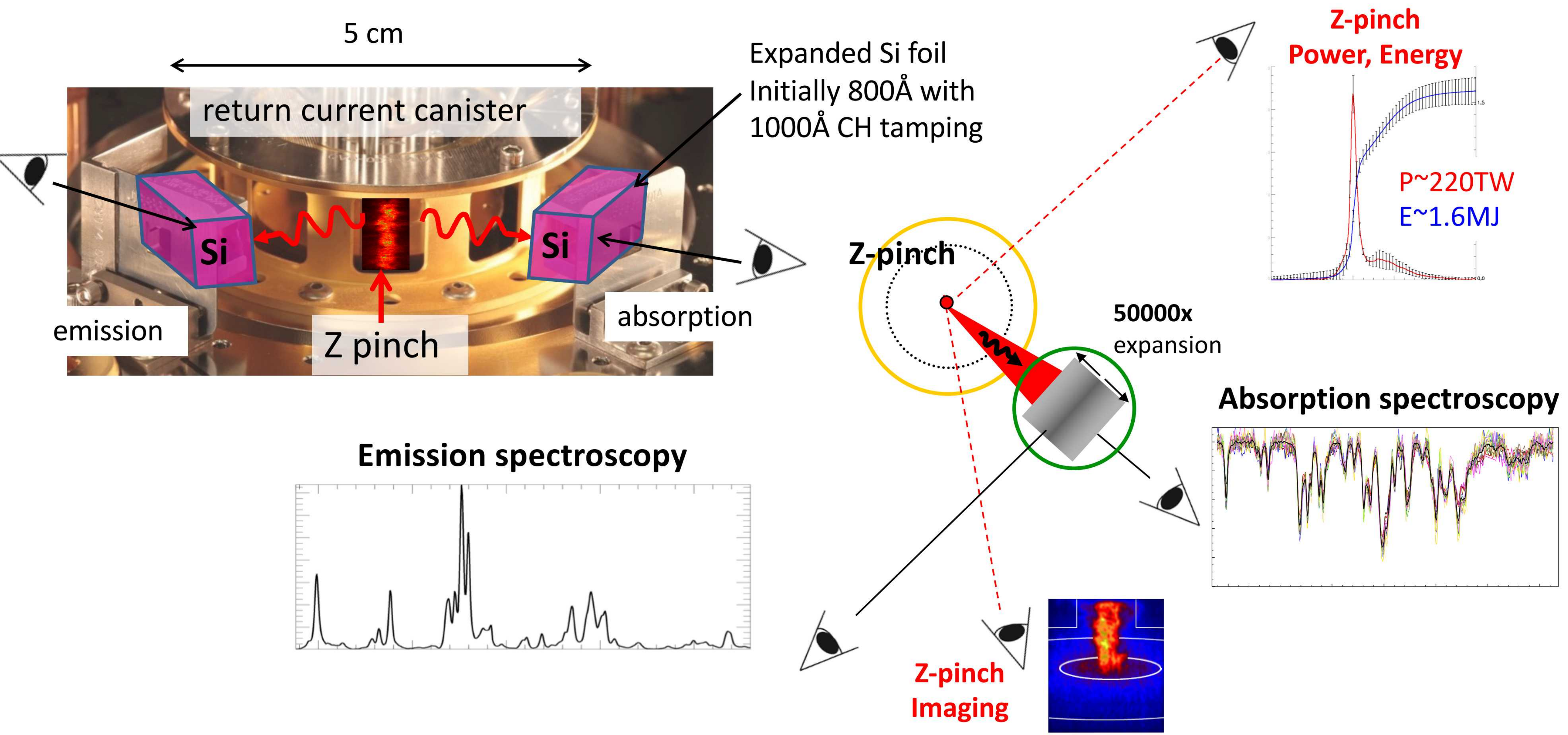
3 Plasma emission

Advantages
- study individual process 1 2 3
- single element
- known drive
- controlled uniform plasma size
- higher spectral resolution
- higher signal to noise

Challenges
- dynamic evolution
- ensure higher density doesn't impact results
- measurements accuracy
- residual non-uniformities

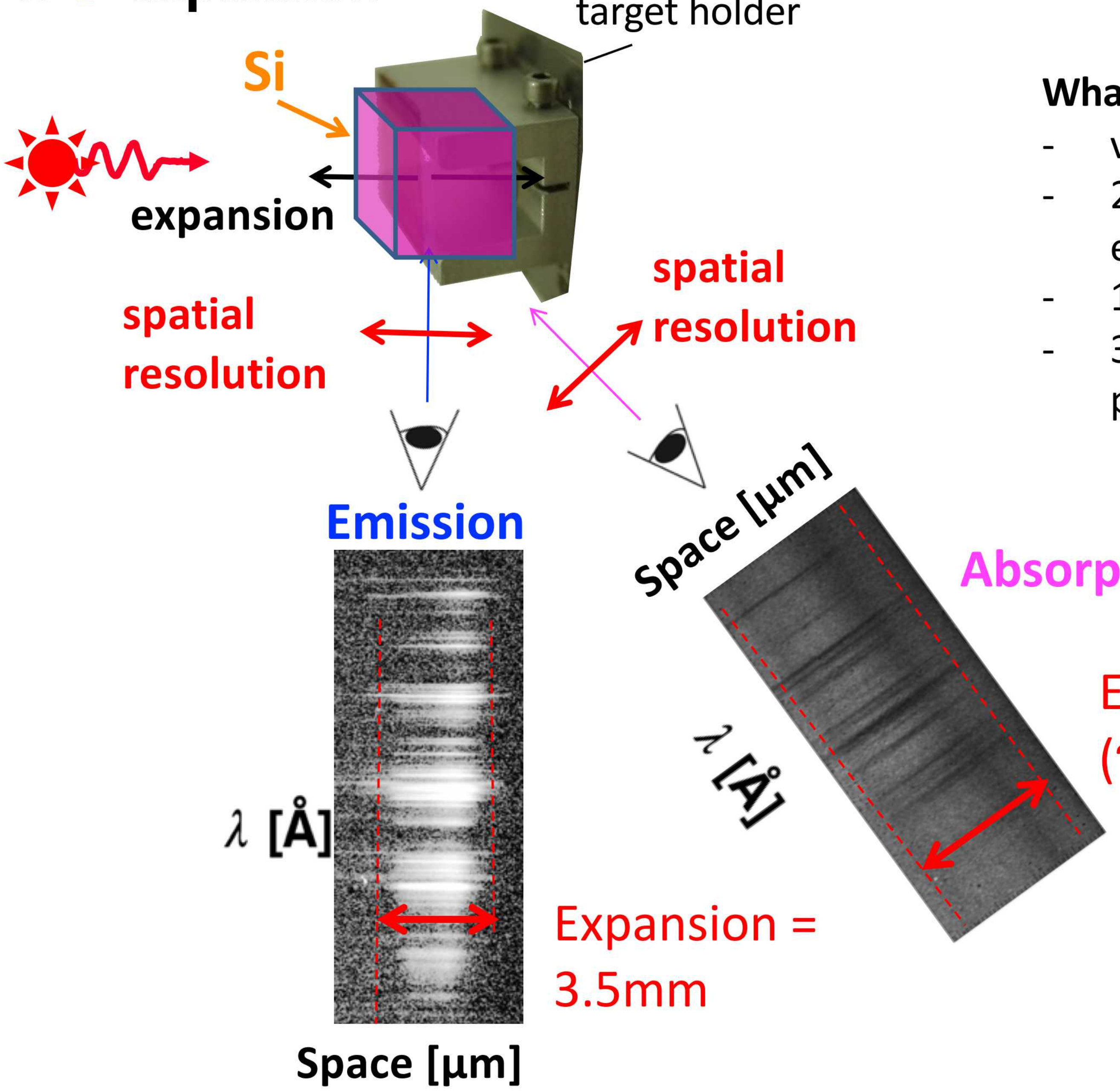


All required inputs are obtained on a single Z shot, confirm the plasma is photoionized and at relevant regime



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

Ion density is measured from the sample areal mass and sample expansion

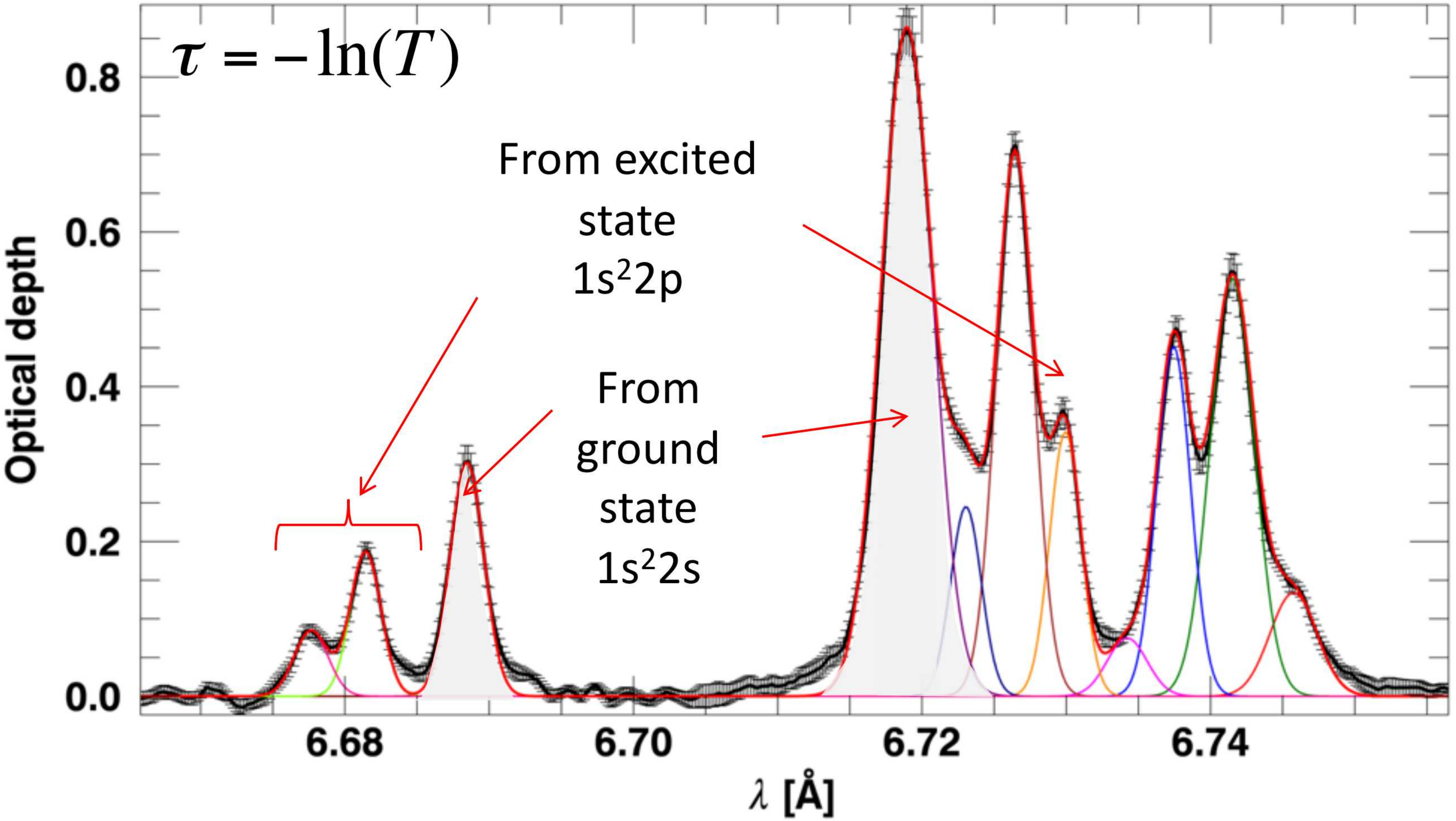


What is helping with uniformity?

- volumetric heating (line absorption)
- 2x 1000Å CH tamped along the heating direction →1D expansion
- 1mm CH tamping in the other dimension
- 3mm-apertured measurement over ~10mm plasma dimensions

The temperature has been obtained from Li-like absorption from low-lying state assuming partial LTE

Li-like Si^{+11} features



The ratio of lines from ground state and low lying states is a temperature diagnostic

→ T_e= 33 ± 7 eV

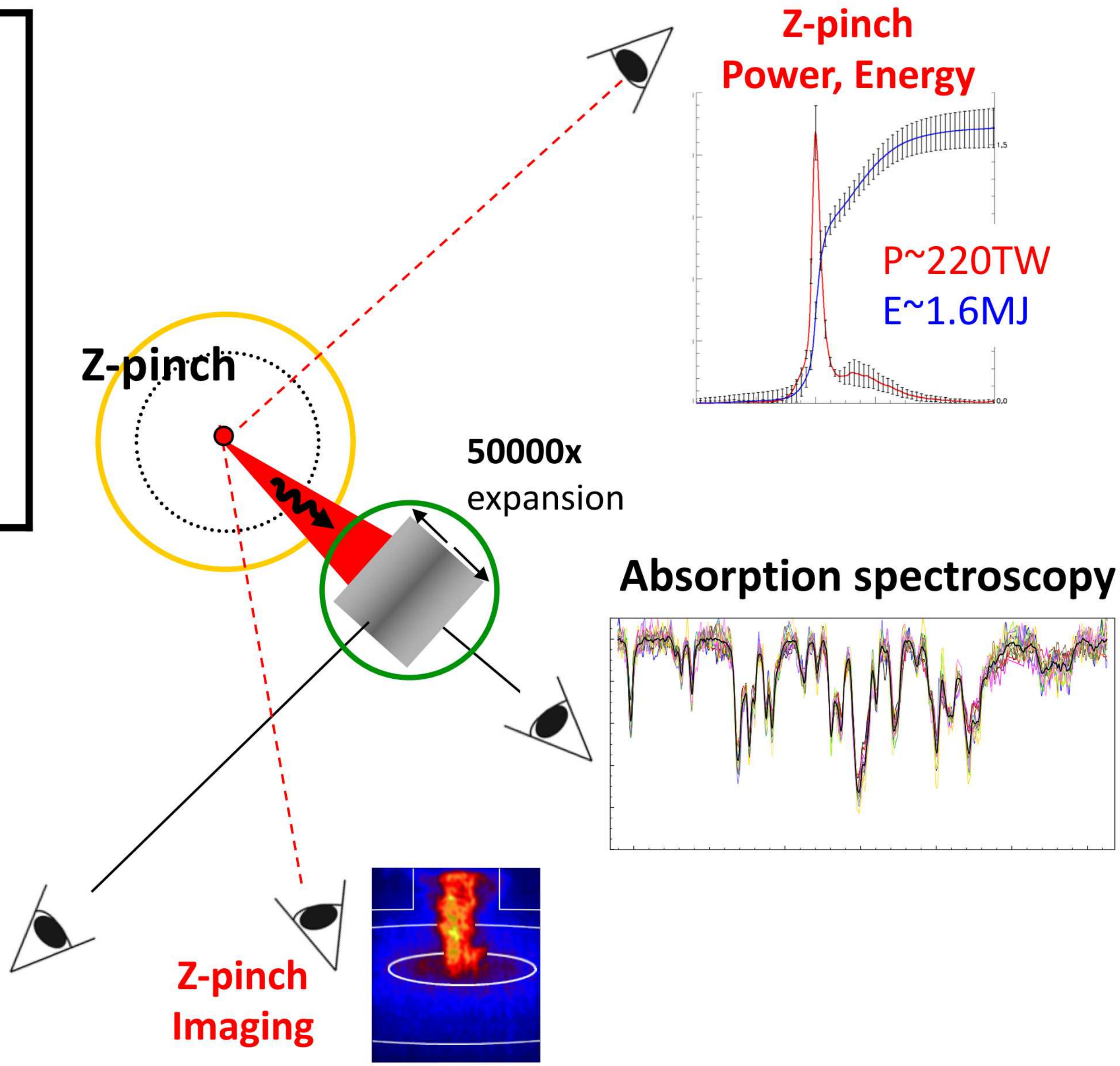
$\bar{Z}$ = 10.3 with radiation

$\bar{Z}$ = 5.3 without radiation

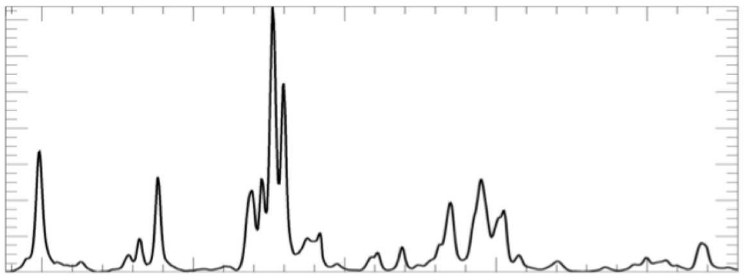
The plasma is over-ionized compared to collisional plasma at the same temperature

All required inputs are obtained on a single Z shot, confirm the plasma is photoionized and at relevant regime

X-ray drive, flux and shape	F ~ 1.3 10^{19} erg/cm^2/s T_{color}= [45, 80, 170] eV
Average charge	Z* ~ 10 , Si^{+10}
Electron density	n_e = 8 x 10^{18} e^-/cm^3
Photoionization parameter	ξ ~ 20-300 erg.cm/s
Column density (adjustable)	N_i ~ 2.5 - 10 10^{17} Si/cm^2
Electron temperature	T_e = 26 - 40 eV

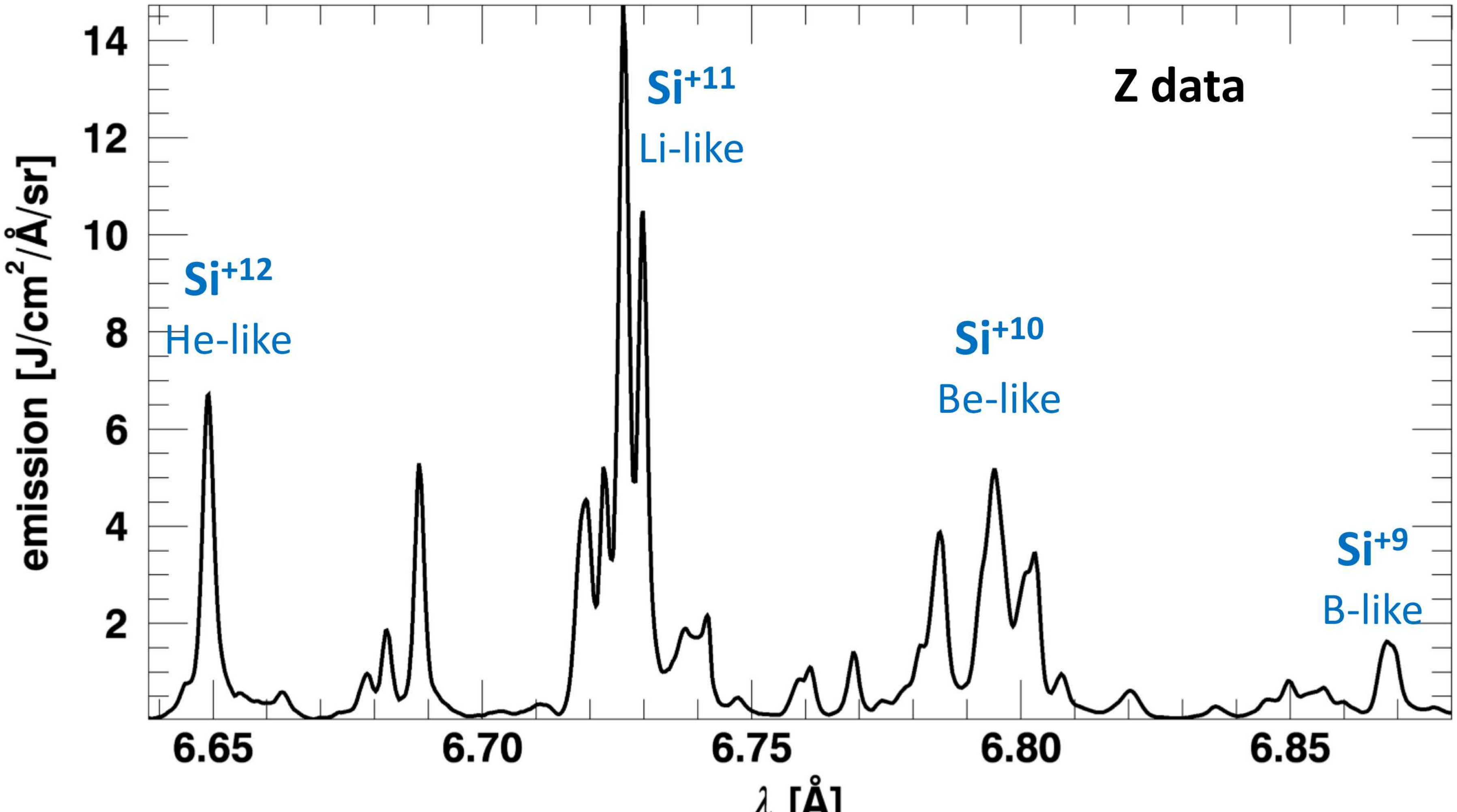


Emission spectroscopy



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

The emission data shows contributions from different charge states

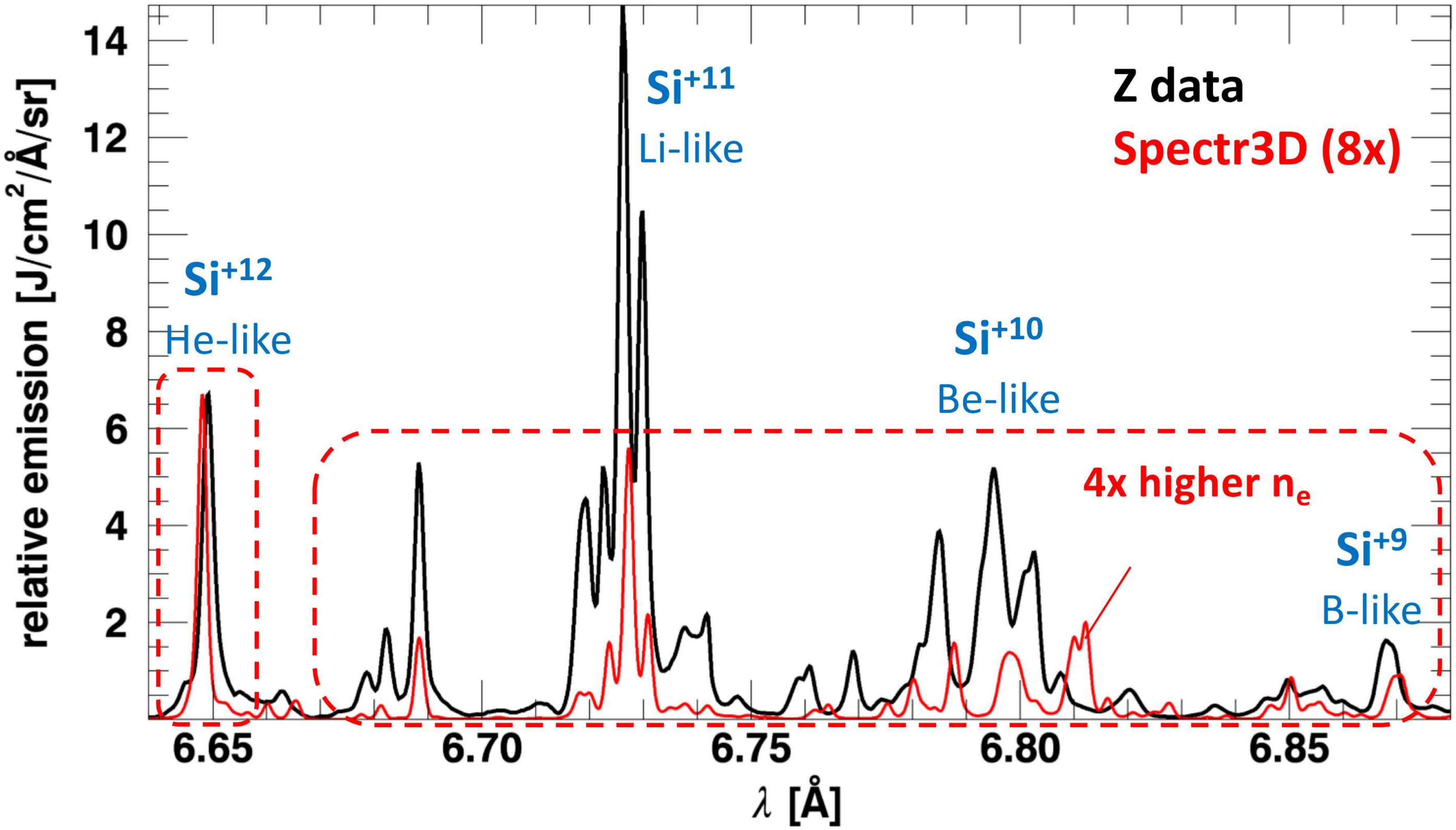


5.2% rel. unc.
$\lambda/\delta\lambda$ ~ 4400

Simultaneous line observation contradicts an assumption used to interpret black hole spectra*

**Ross and Fabian, MNRAS, 278 (1996), Loisel et al., PRL 119 (2017)*

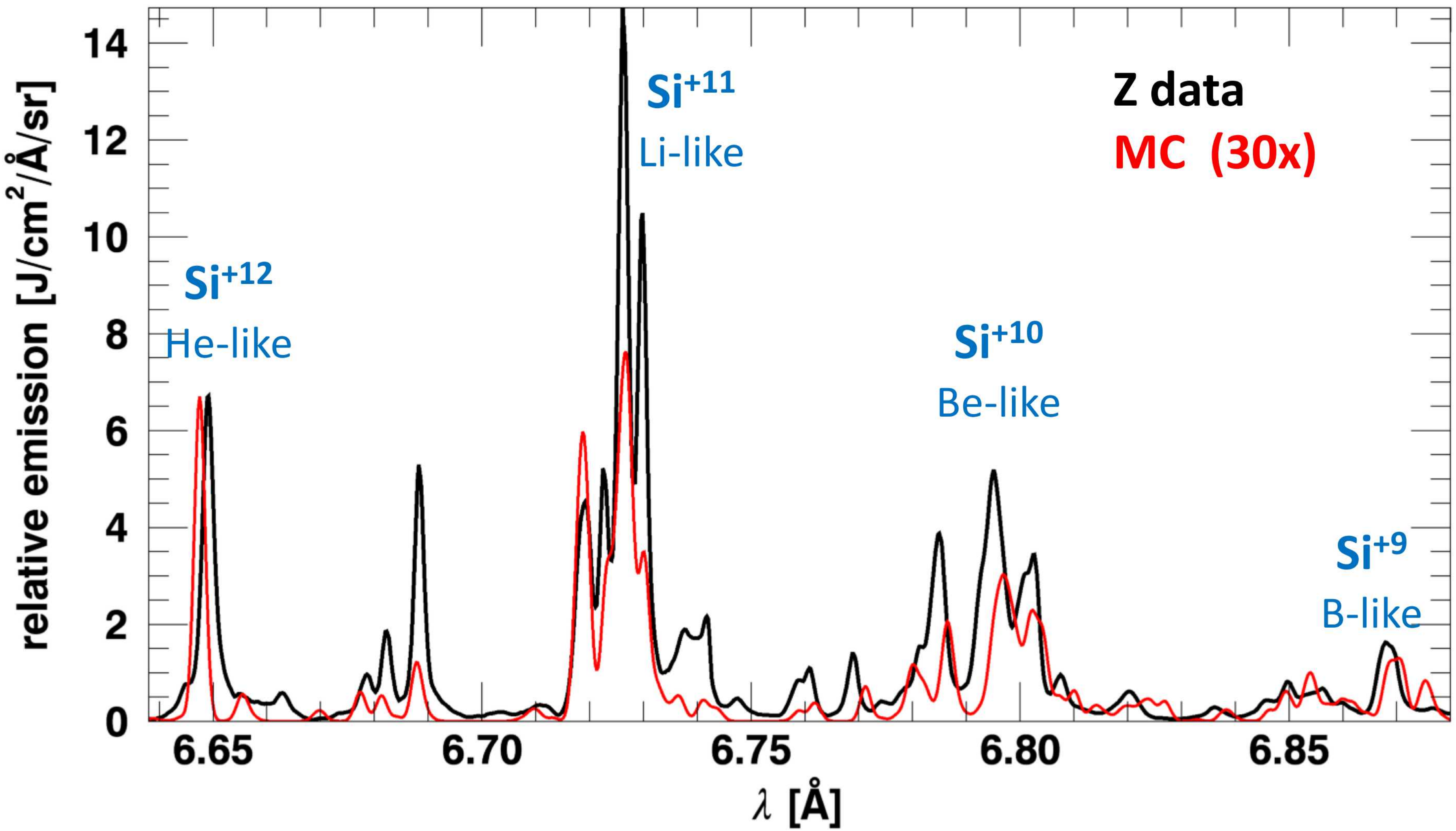
The emission is not reproduced by any model even with conditions adjusted to match absorption spectra



With normalization to Si^{+12} (Heα) models under predict lines from lower charge state

Spectr3D: Prism Computational Software

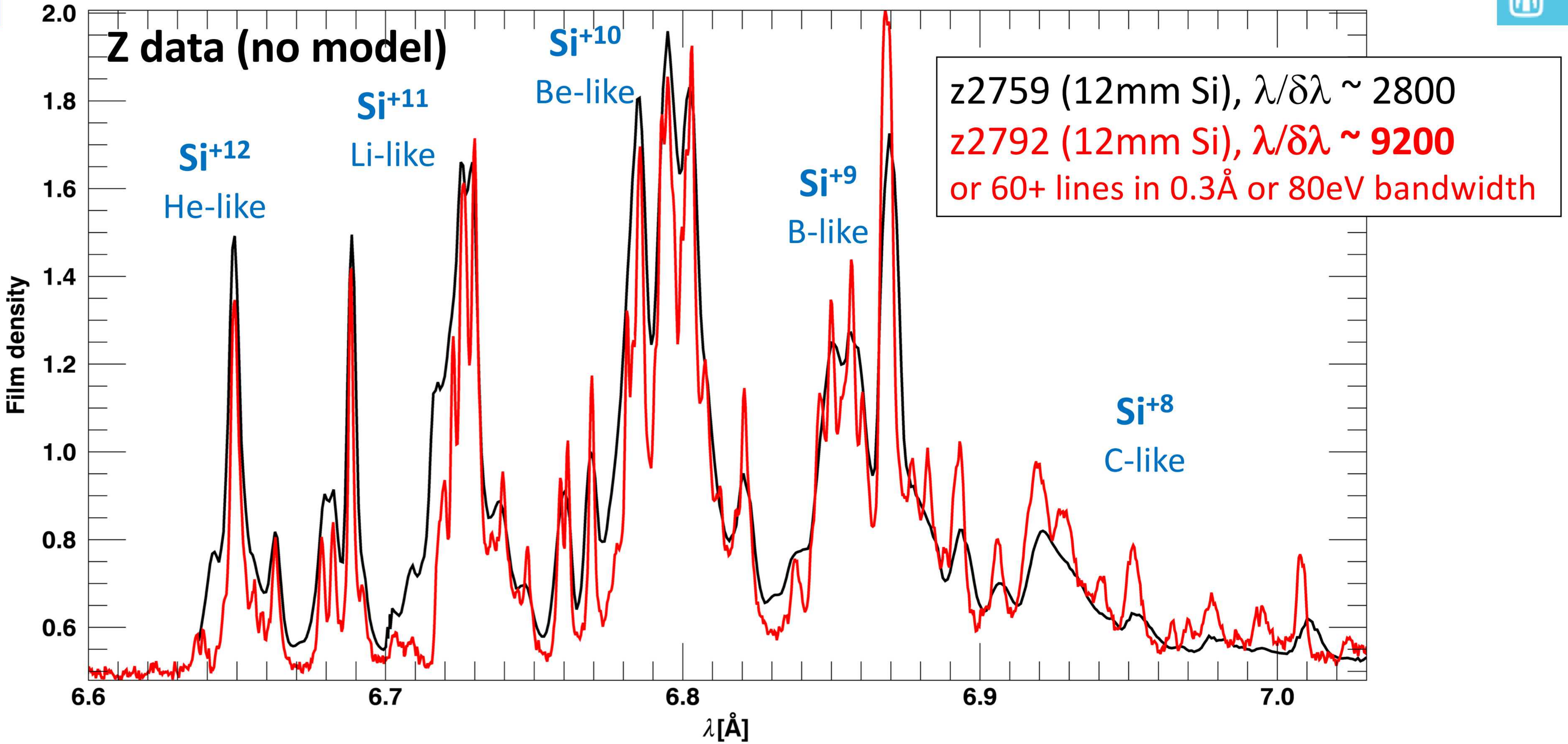
Comparison with a Monte Carlo radiation transport code exhibits improved agreement



The effect of the different atomic physics data must also be evaluated

MC: Monte Carlo radiation transport code, D. Liedahl

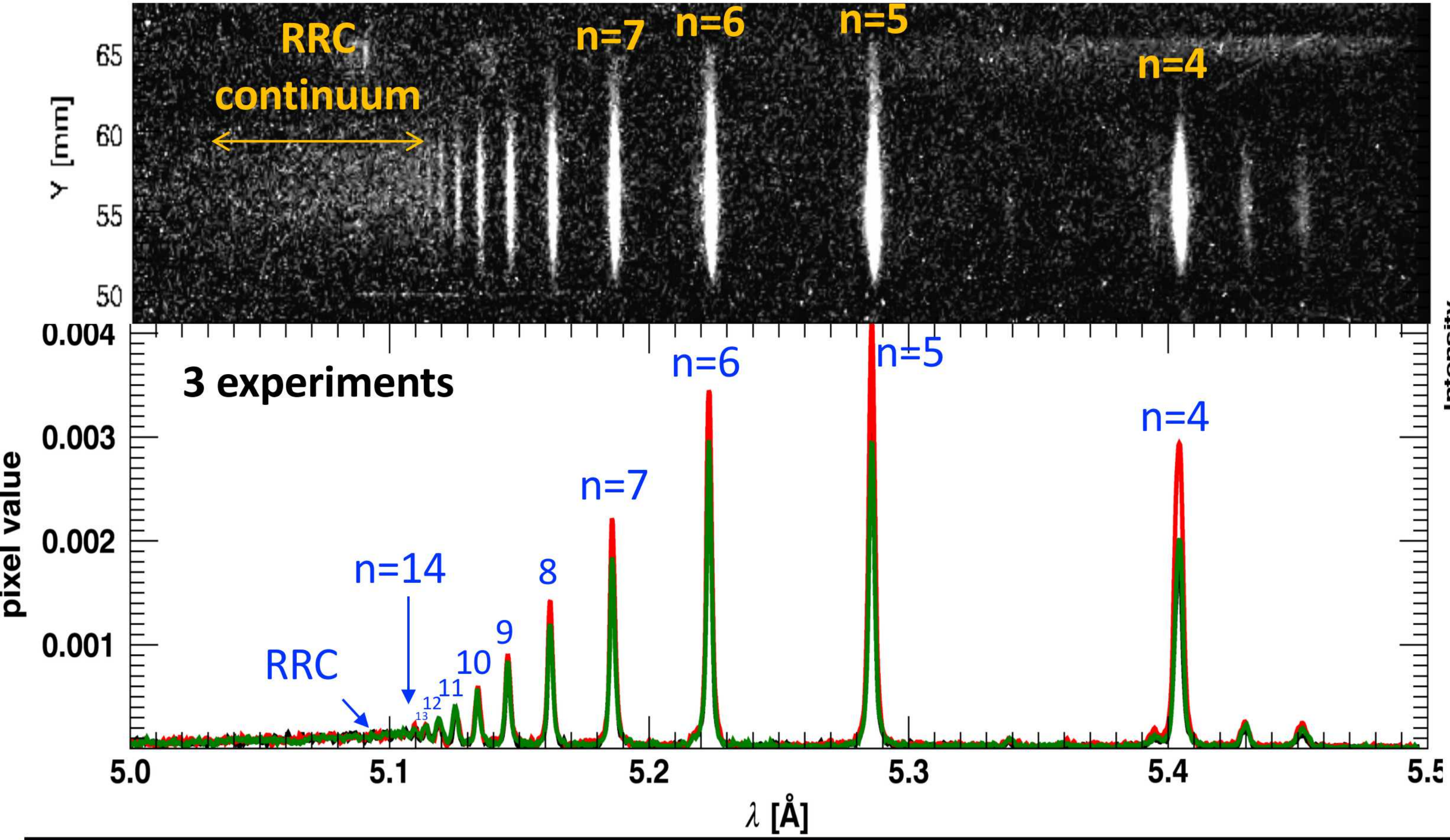
Emission spectra are also measured at very high spectral resolution

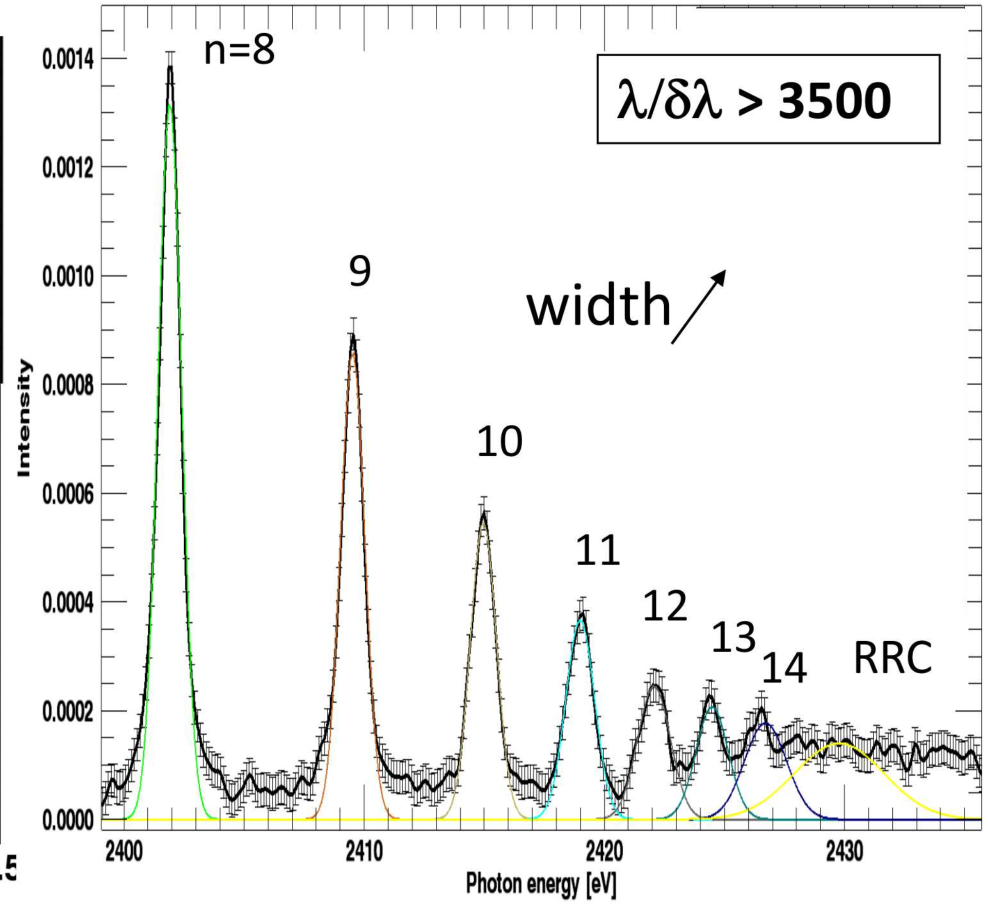


We can study very detailed level structure and more precise radiation transport effects on lines that have variable optical depth.

High-n, $n \leq 14$, He-like transitions with merging into the continuum first obtained in a laboratory photoionized plasma

Silicon closer to the x-ray source

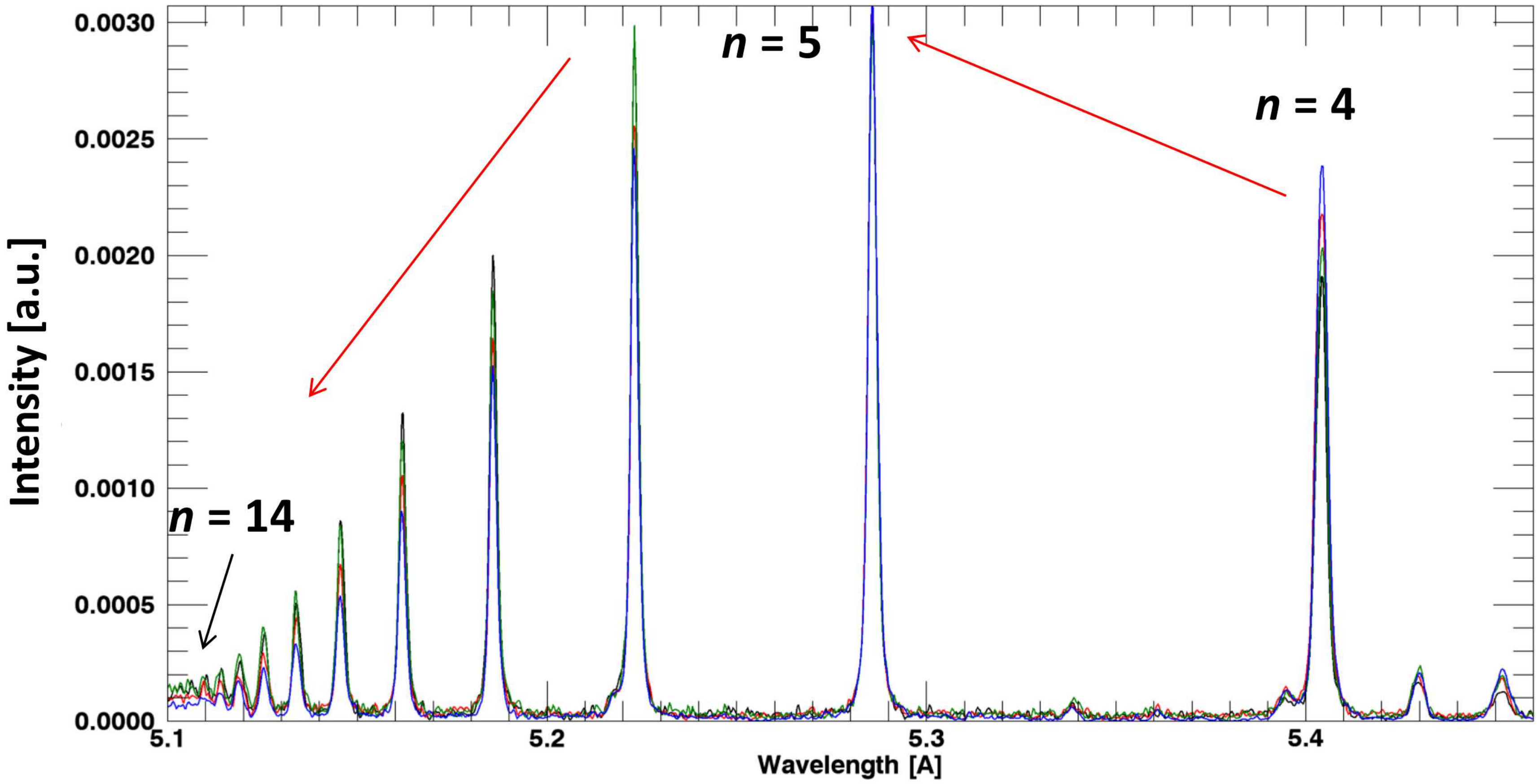




→ **Effect of line shape, line broadening, continuum lowering on the RRC can be studied. High-n lines getting broader with n → density sensitivity.**

The high-n lines are not systematically decreasing with principal quantum number

Silicon closer to the x-ray source



Initial upper states can be populated either by:

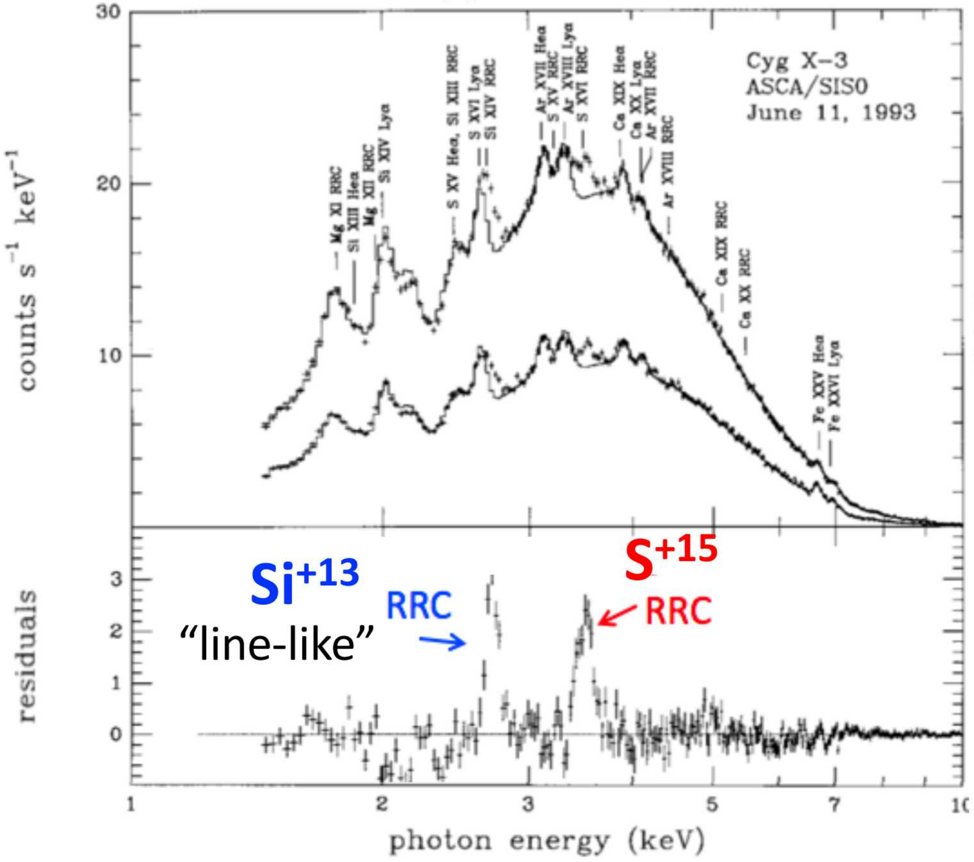
- **recombination following photoionization**
- **or photoexcitation**

Also line intensity is affected by radiation transport.

→ Test predominance of photoexcitation versus photoionization in populating He-like states

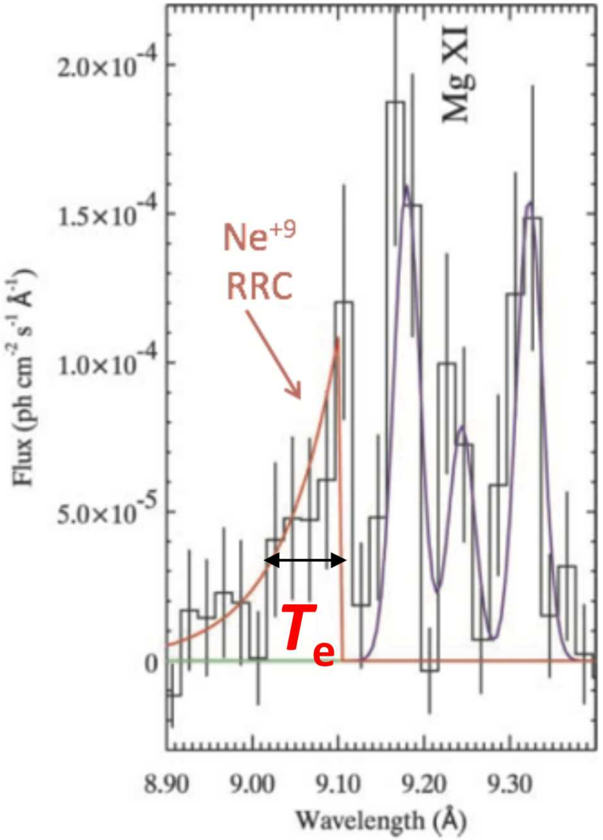
First RRC (~10^{-8} Z-pinch energy) in a photoionized plasma in a terrestrial laboratory was recorded

Cygnus X-3



T_e = 5-50 eV [1]

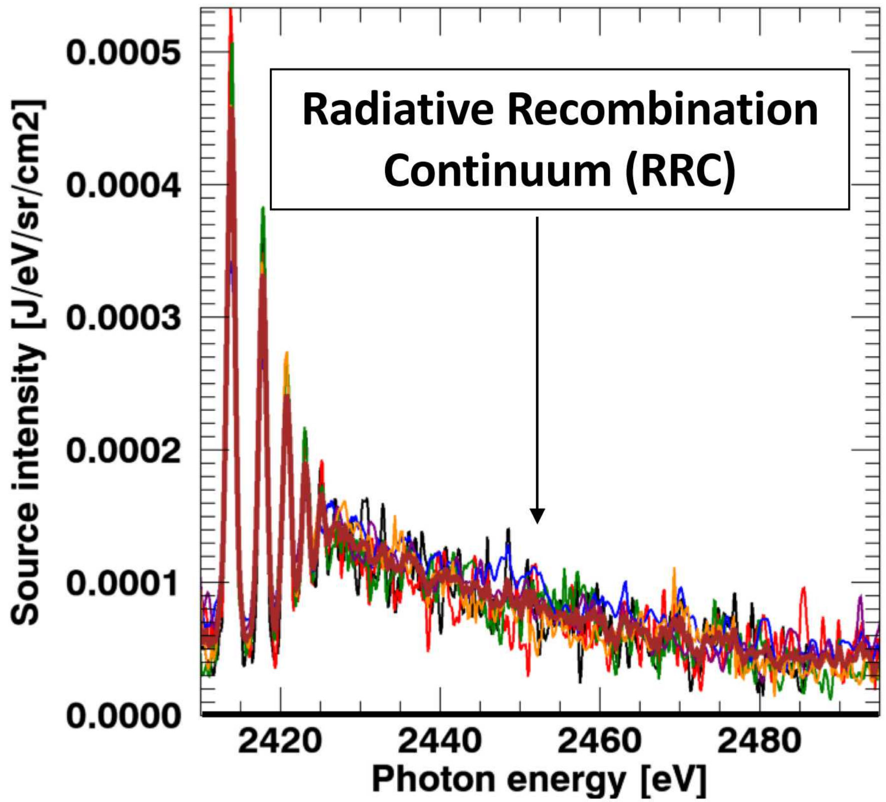
Vela X-1



$T_e = 10 \pm 2$eV [2]

$T_e = 6.6 \pm 2$eV [3]

Earth: Z plasma



exp. slope => T_e

→ ~Maxwellian e^- distribution

→ RRC visibility with highly charged ions supports the photoionized nature of the emitting matter

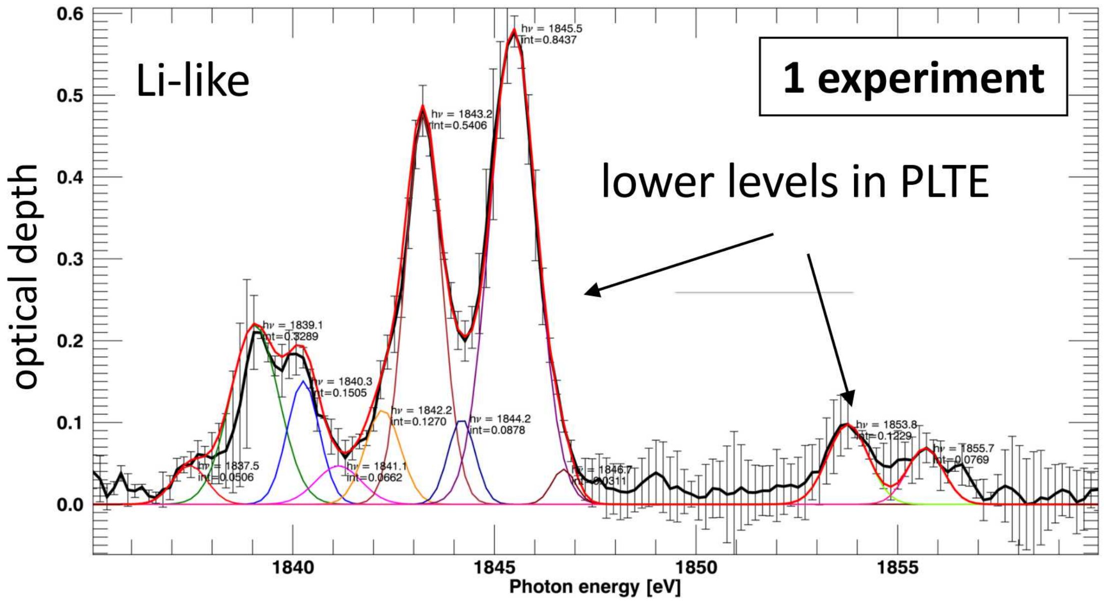
→ Untested in the laboratory in a well-characterized photoionized plasma.

[1] Liedahl, Paerels et al. (1996), [2] Schulz et al., Ap. J. Letters 564 (2002). [3] Watanabe et al., Ap. J. 651 (2006)

Preliminary: temperature inferred from line absorption agreed with the RRC slope

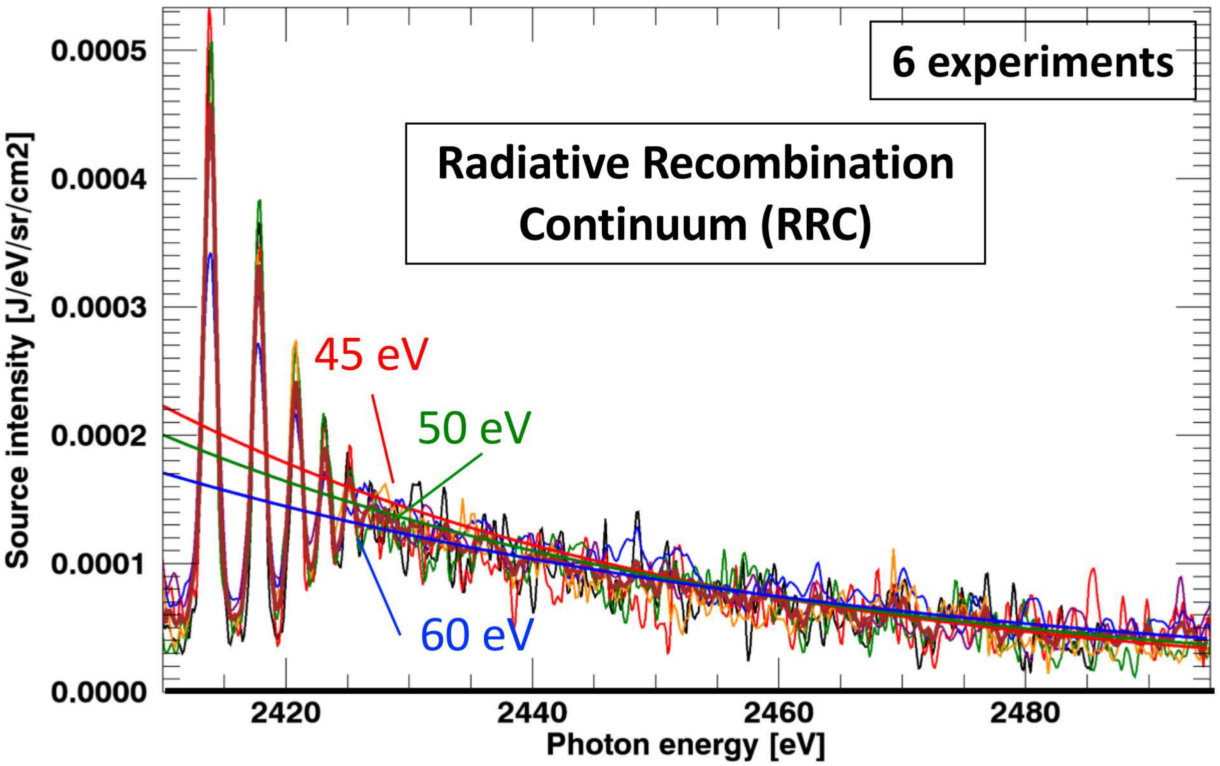
Silicon closer to the x-ray source

Absorption



Absorption initial level	Oscillator strength code	Temperature T_e [eV]
$1s^2\,2p_{1/2}$	PRISM	51 ± 21
$1s^2\,2p_{3/2}$	PRISM	57 ± 19
$1s^2\,2p_{1/2}$	CATS	39 ± 13
$1s^2\,2p_{3/2}$	CATS	55 ± 35

Emission

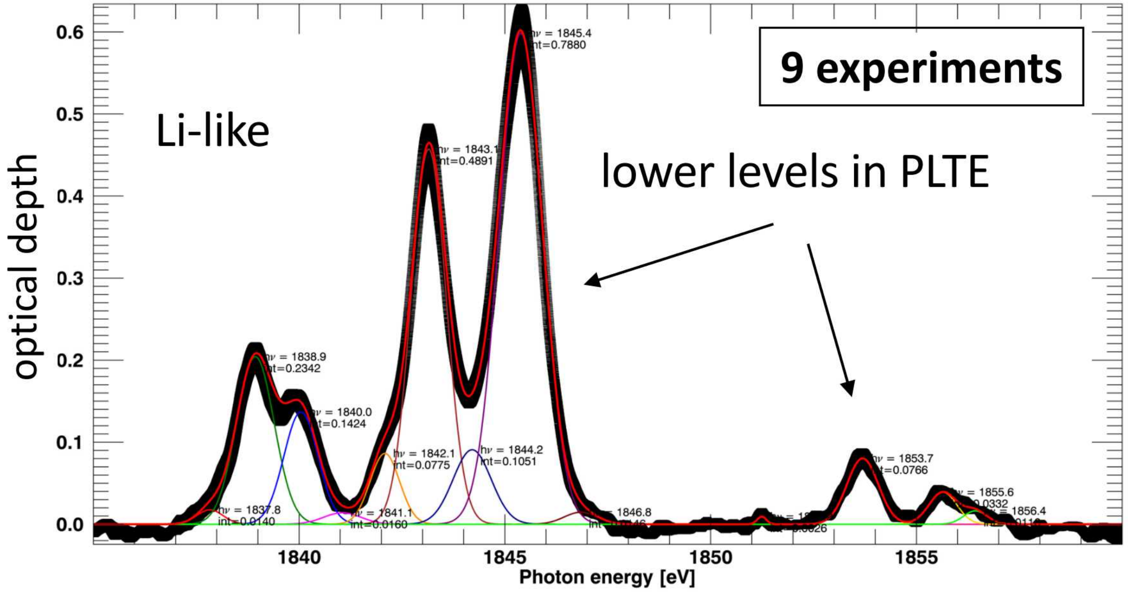


RRC slope → T_e = 52 ± 7 eV
Initial abs. data → T_e ~ 39 – 60 eV

not anymore? [preliminary]

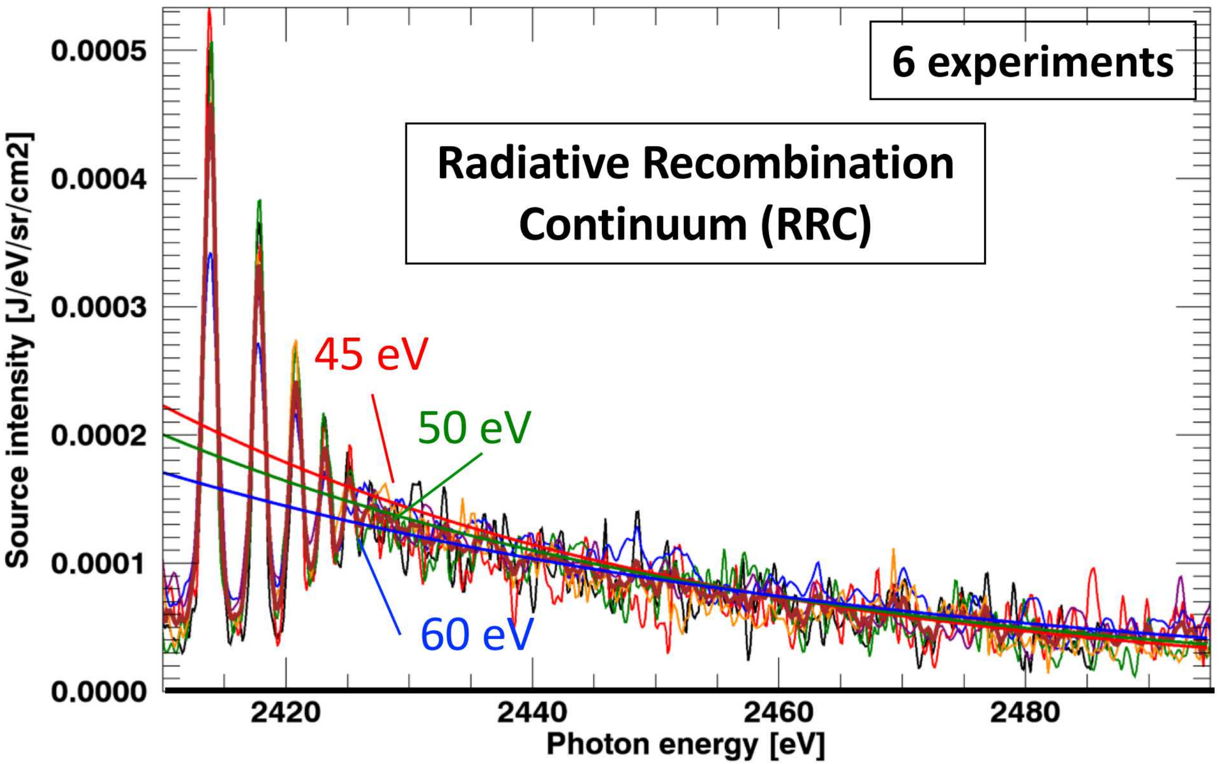
Silicon closer to the x-ray source

Absorption



Absorption initial level	Oscillator strength code	Temperature T_e [eV]
$1s^2\,2p_{1/2}$	PRISM	33.3 ± 1.46
$1s^2\,2p_{3/2}$	PRISM	33.4 ± 1.30
$1s^2\,2p_{1/2}$	CATS	33.2 ± 1.83
$1s^2\,2p_{3/2}$	CATS	32.6 ± 1.55

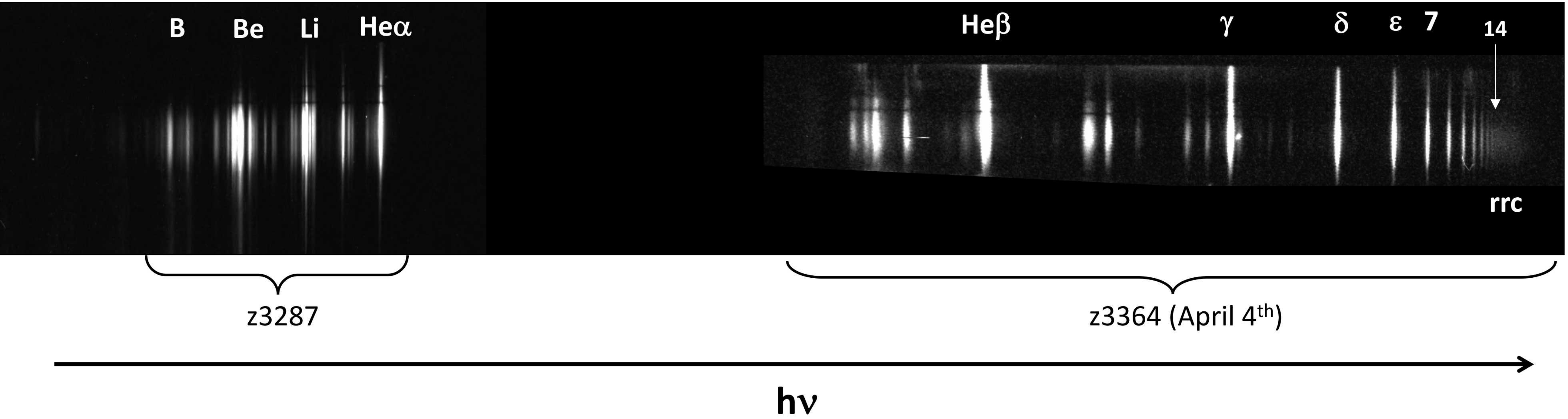
Emission



RRC slope → T_e = 52 ± 7 eV
Li-like sat. ratio → T_e ~ 33±2 eV
Data need more scrutiny

The complete He-like series up to n=14 was recently measured

Silicon closer to the x-ray source



The complete He-like series will facilitate model/data comparison
Measurement needs to be repeated

How much of the predictive difficulty is unique to our experiments and how does it impact astrophysical objects?

Possible needed improvements in understanding the experiment

- Could electron density be higher than the value measured with radiography?
- *Transient kinetics appear relatively unimportant, but further evaluation is needed*
- *The bulk of x-ray drive in 0.1 - 1 keV is measured to ±20%, but accuracy in >1.7keV photon spectrum needs more evaluation.*
- Accounting for geometrical dilution of drive requires attention
- Velocity impact on line optical depths appears small

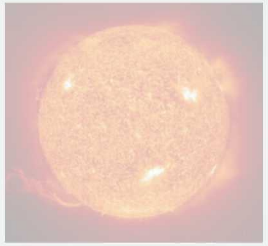
Scrutiny is required for the models

- Accuracy of the recombination rates? dielectronic recombination rates?
- Is the atomic data complete?
- Are approximations in the radiation transport valid?
  e.g. escape factors, escape geometry, self-consistency…

Scrutiny for the 2018-2020 Z fundamental science proposal

ZAPP campaigns simultaneously study multiple issues

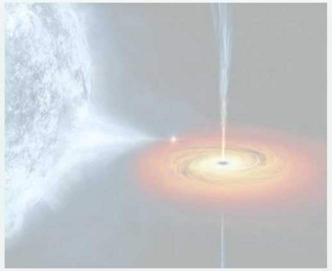
Solar Opacity



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

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

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}

White Dwarf Line-Shapes

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

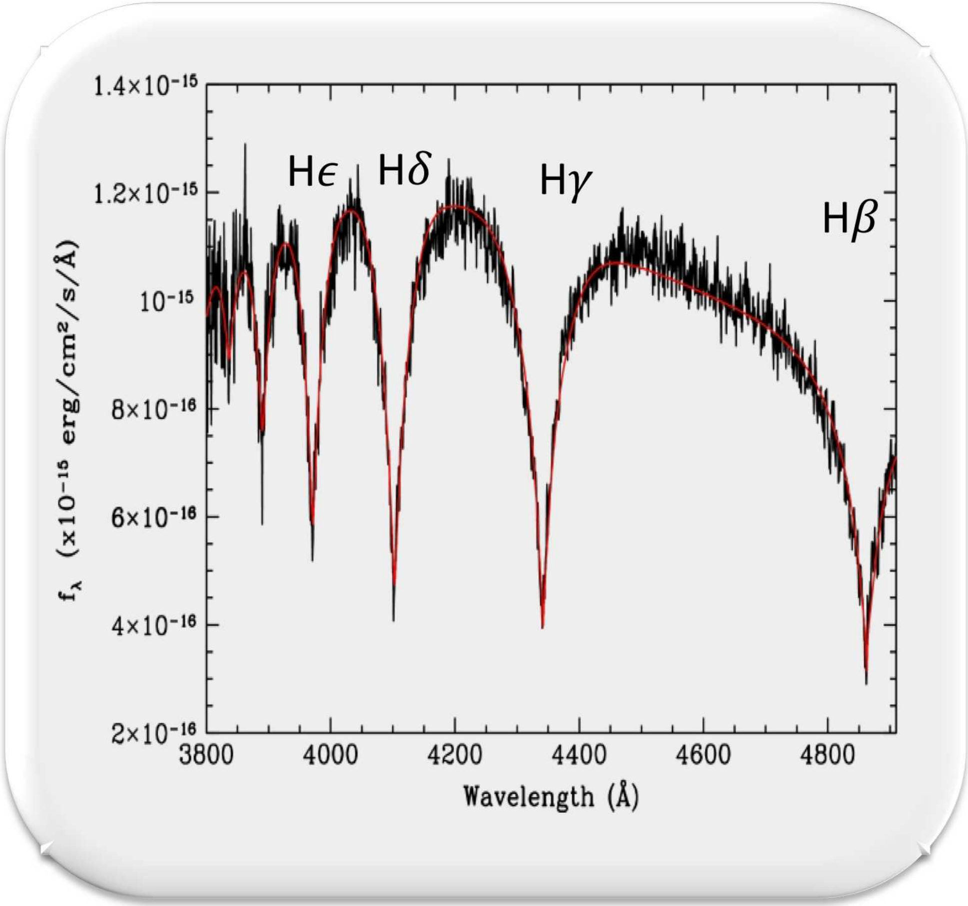
Achieved Conditions:
$T_e \sim 1$ eV, $n_e \sim 10^{17}$ cm^{-3}

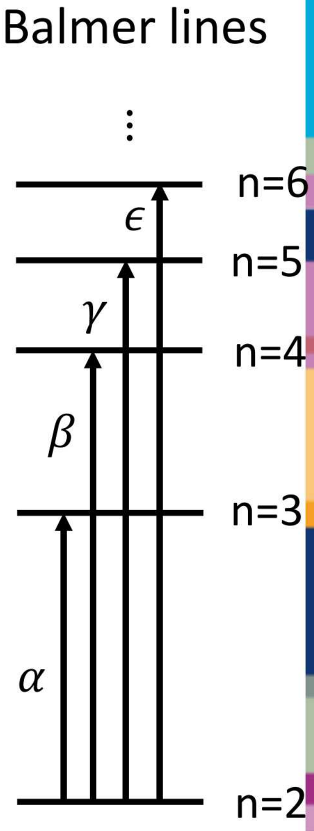
The properties of White Dwarfs are determined by spectral fitting, but disagrees with other methods

- 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%

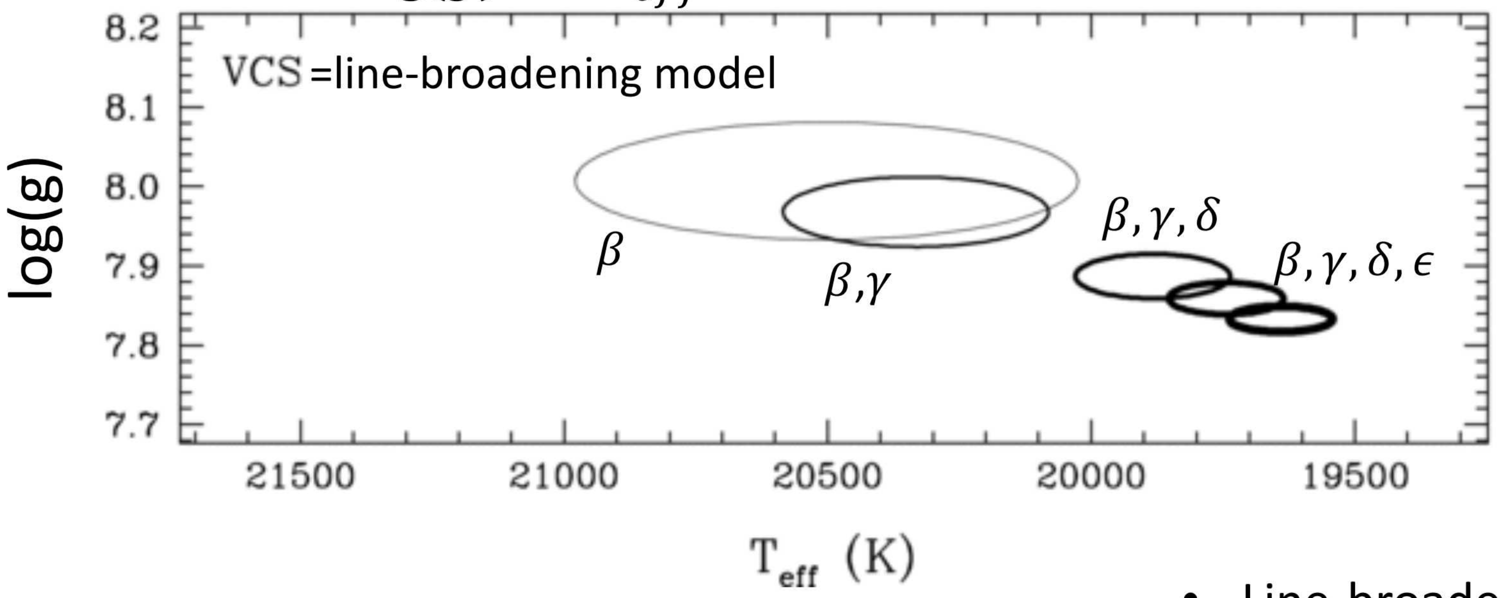




This 10% uncertainty in mass yields 0.5 G year difference for the age of galaxy

There are inconsistencies in mass inferred from different lines

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



Puzzling facts:

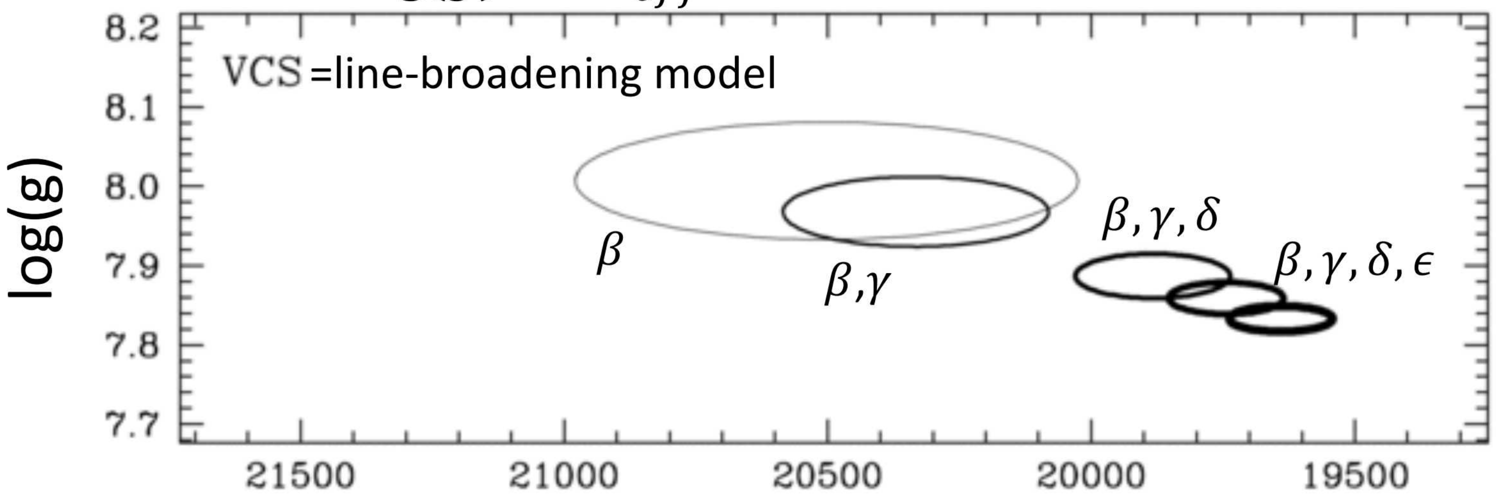
- Higher lines lower the inferred $\log(g)$

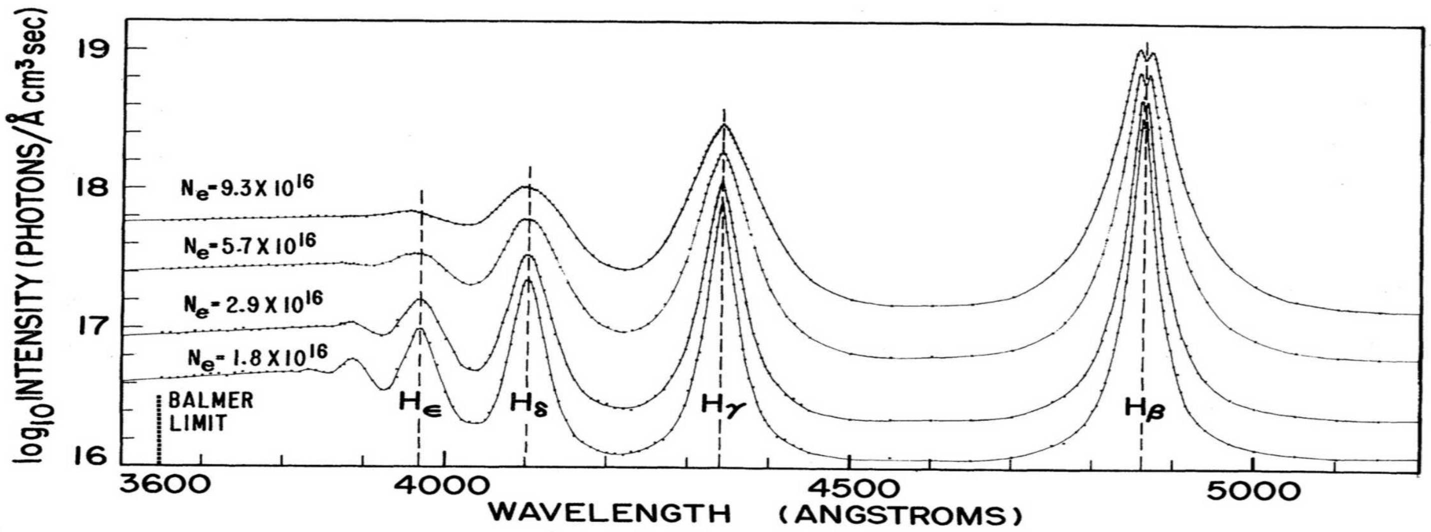
- Line-broadening is often used for density diagnostics
- This trend implies you would infer higher density from β than from γ

[1] P.-E. Tremblay, Ap.J. 696, 1755 (2009).

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]





<u>Puzzling facts:</u>

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

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

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

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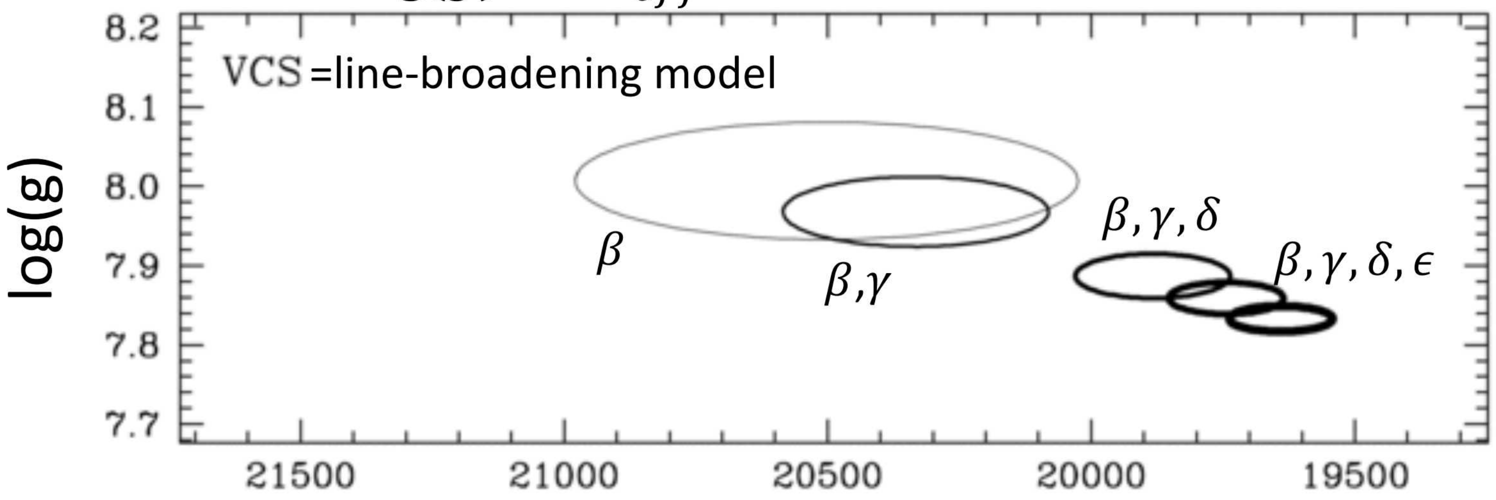
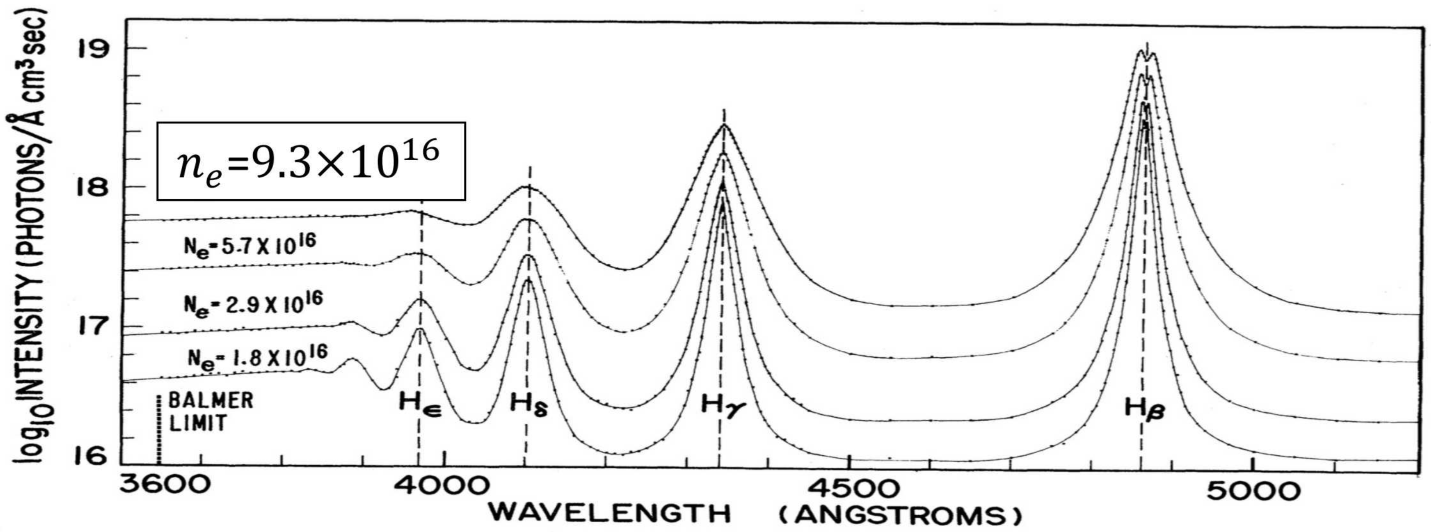




Puzzling facts:
- Higher lines lower the inferred $\log(g)$
- VCS was validated by Wiese [2]

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

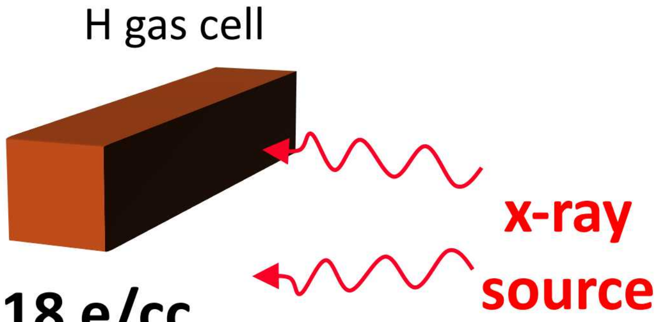
[2] Wiese et al, Physical Review A 6, 1132 (1972).

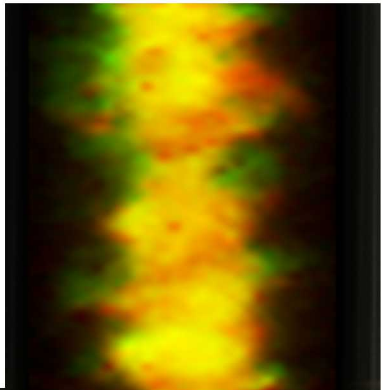
* Photosphere continues up > $1\times10^{18}\ \mathrm{cm}^{-3}$

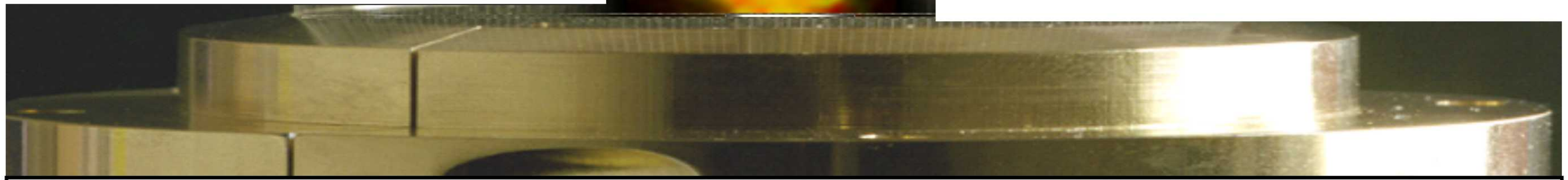
Hydrogen gas is heated by reemission from the gold wall; Its emission and absorption spectra are simultaneously observed

White Dwarf experiments:

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





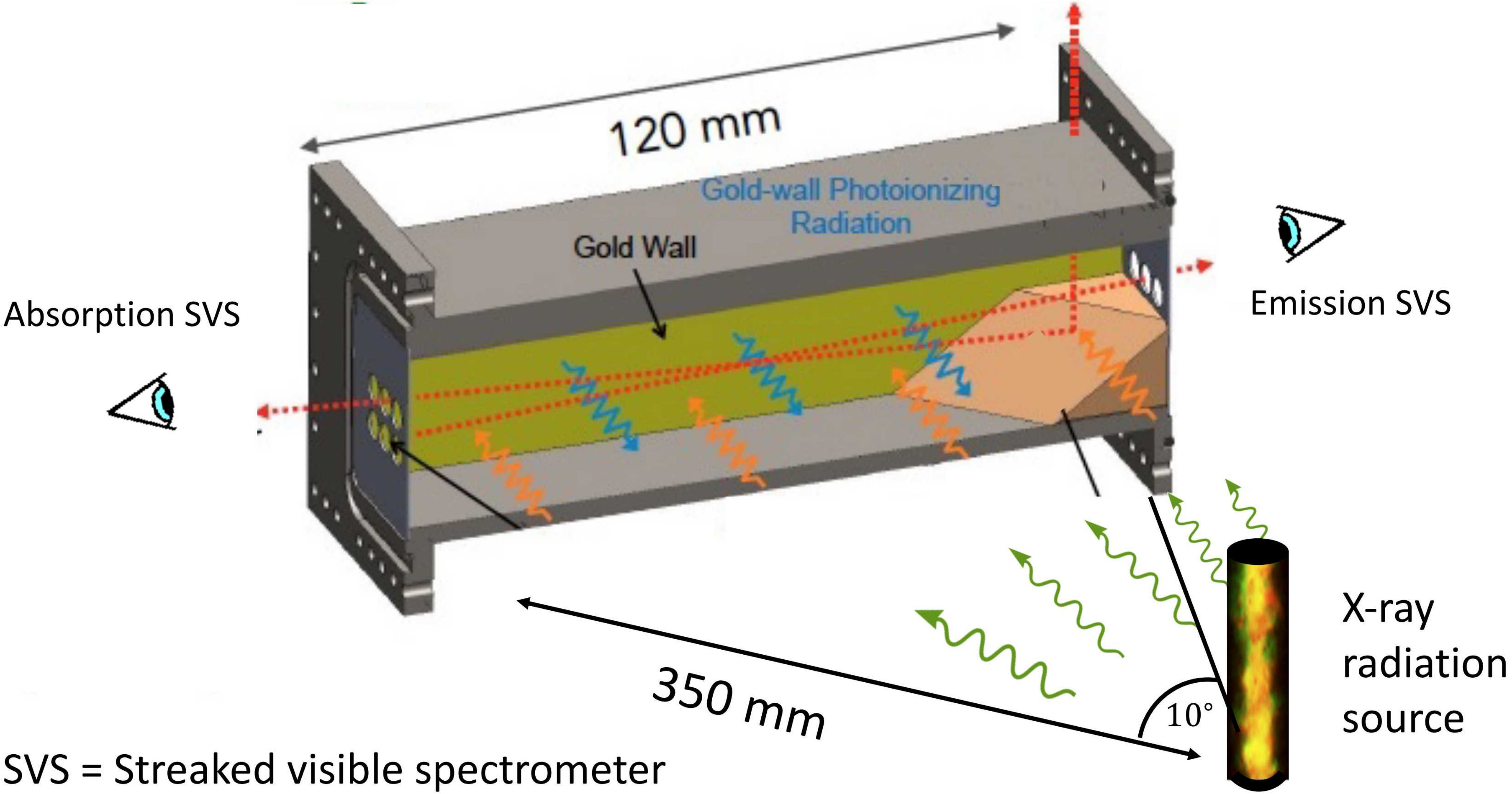


P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

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

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

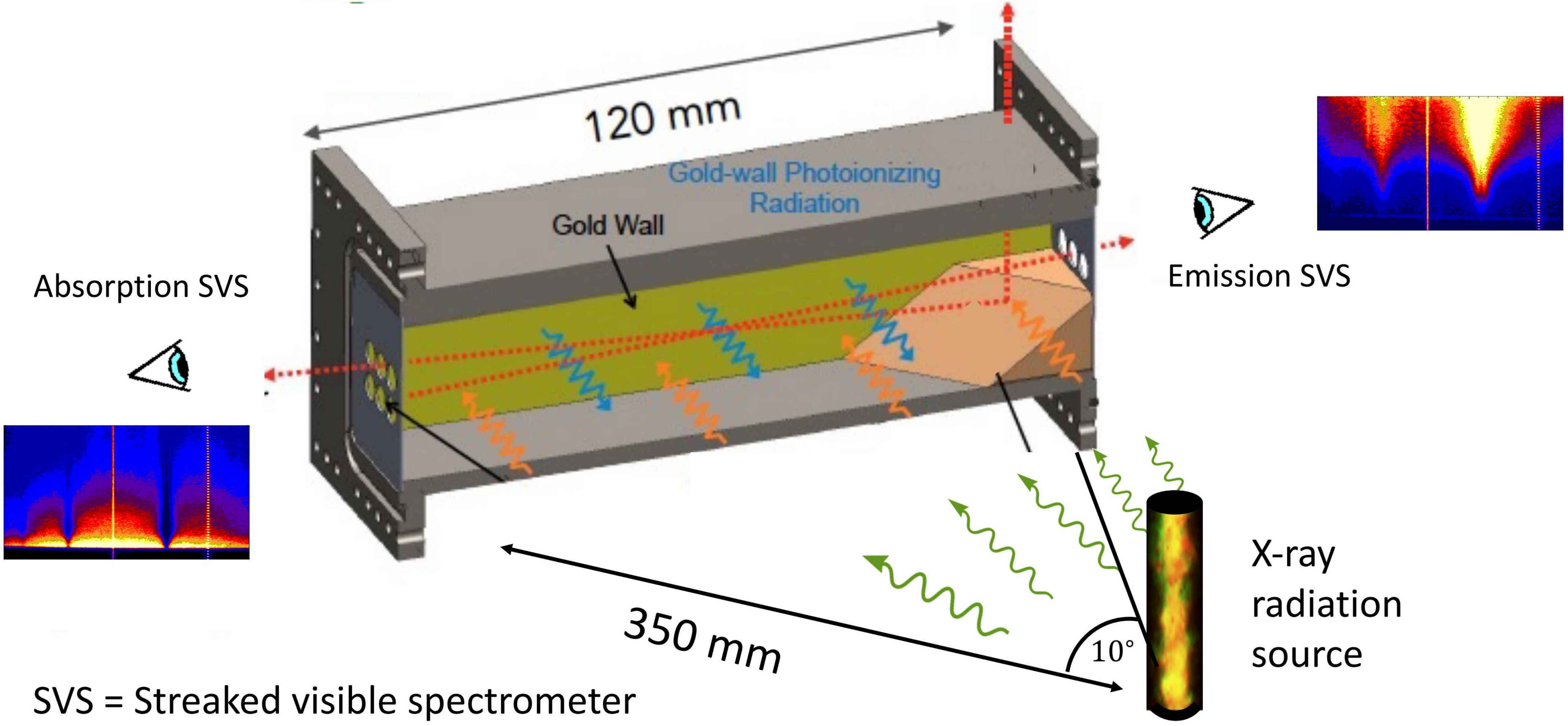
Hydrogen gas is heated by reemission from the gold wall; Its emission and absorption spectra are simultaneously observed



SVS = Streaked visible spectrometer

Falcon et al. (2015) ApJ

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



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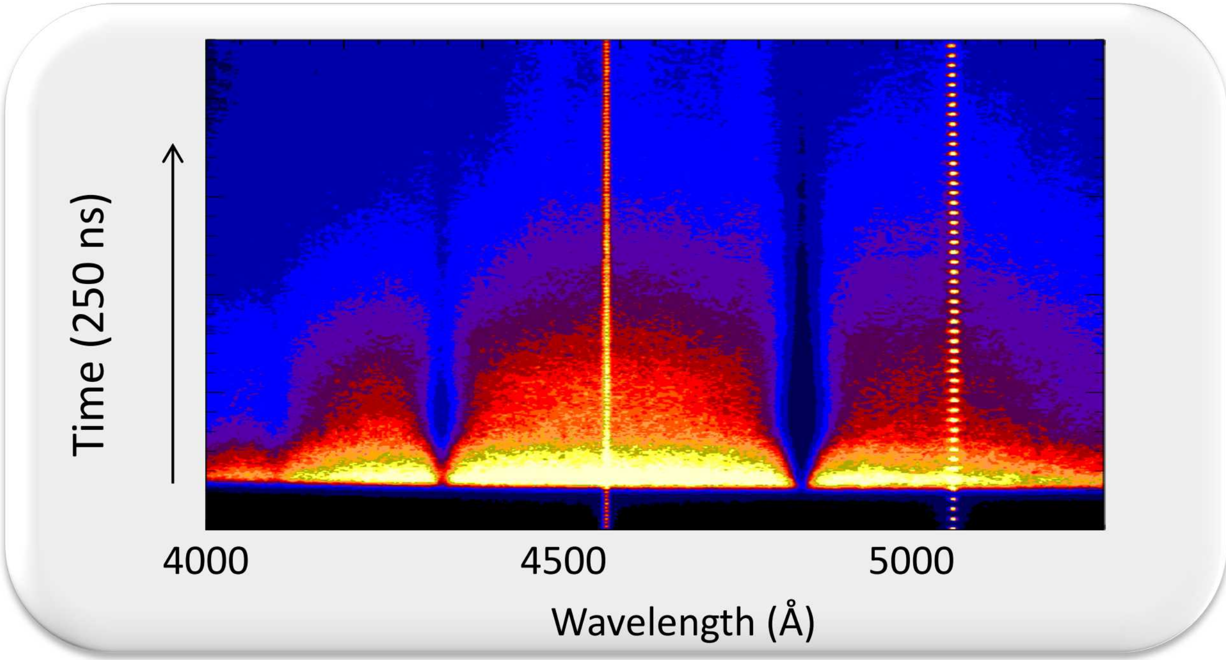
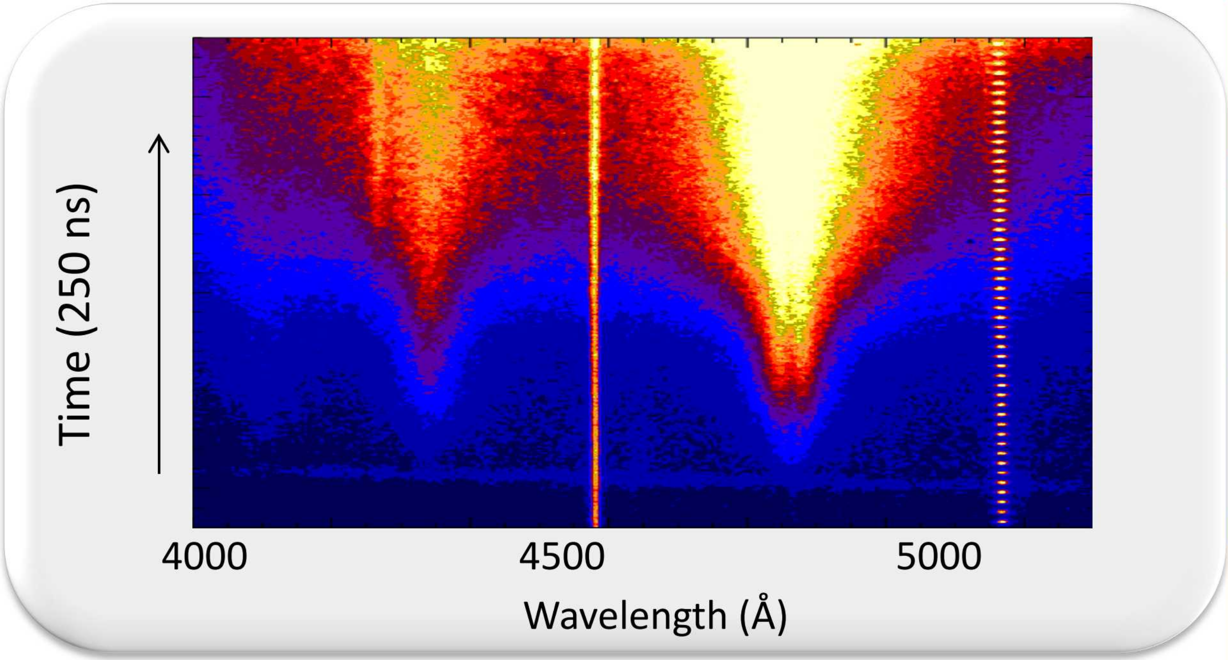
Hydrogen gas is heated by reemission from the gold wall; Its emission and absorption spectra are simultaneously observed

Absorption

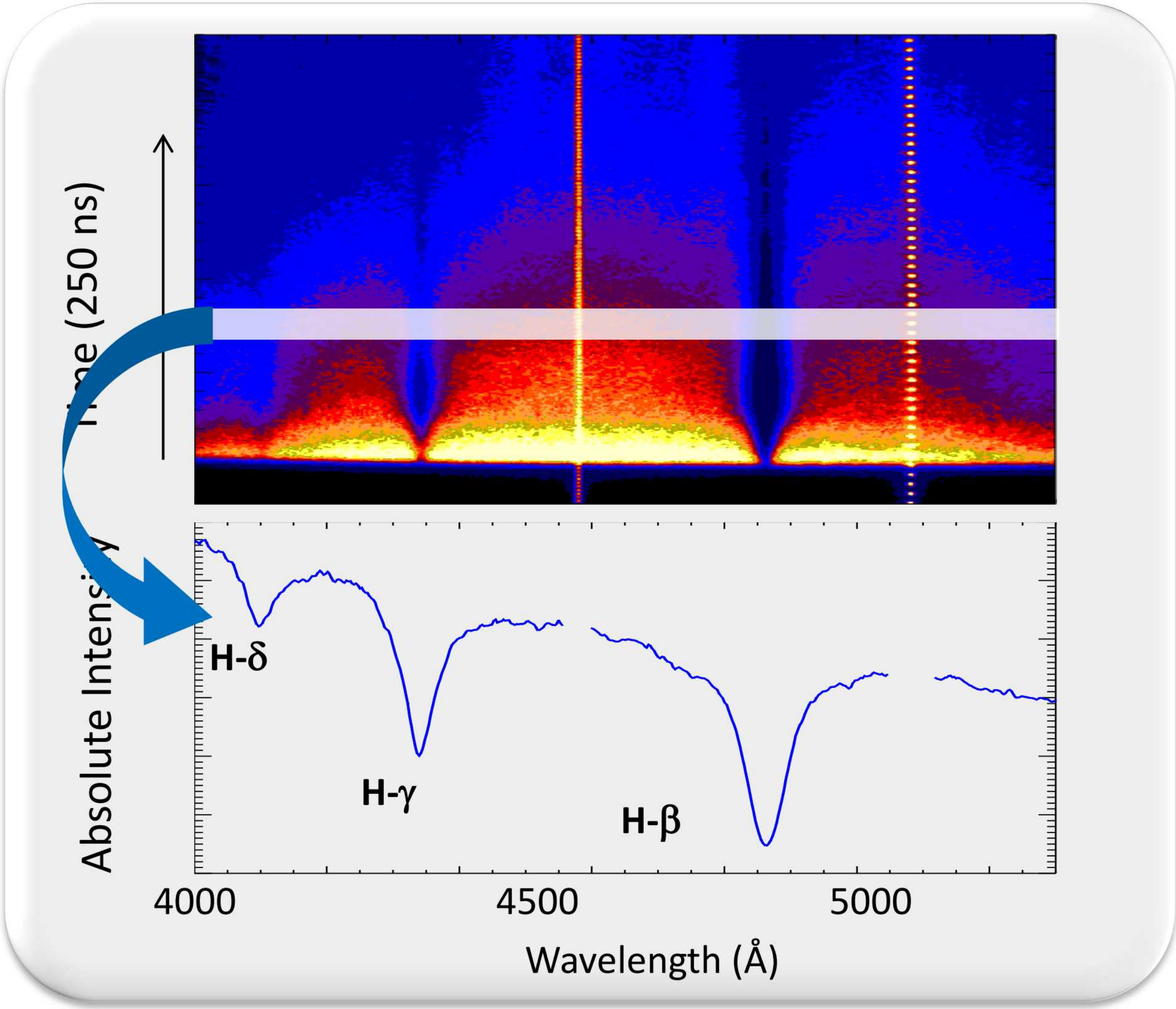


Emission

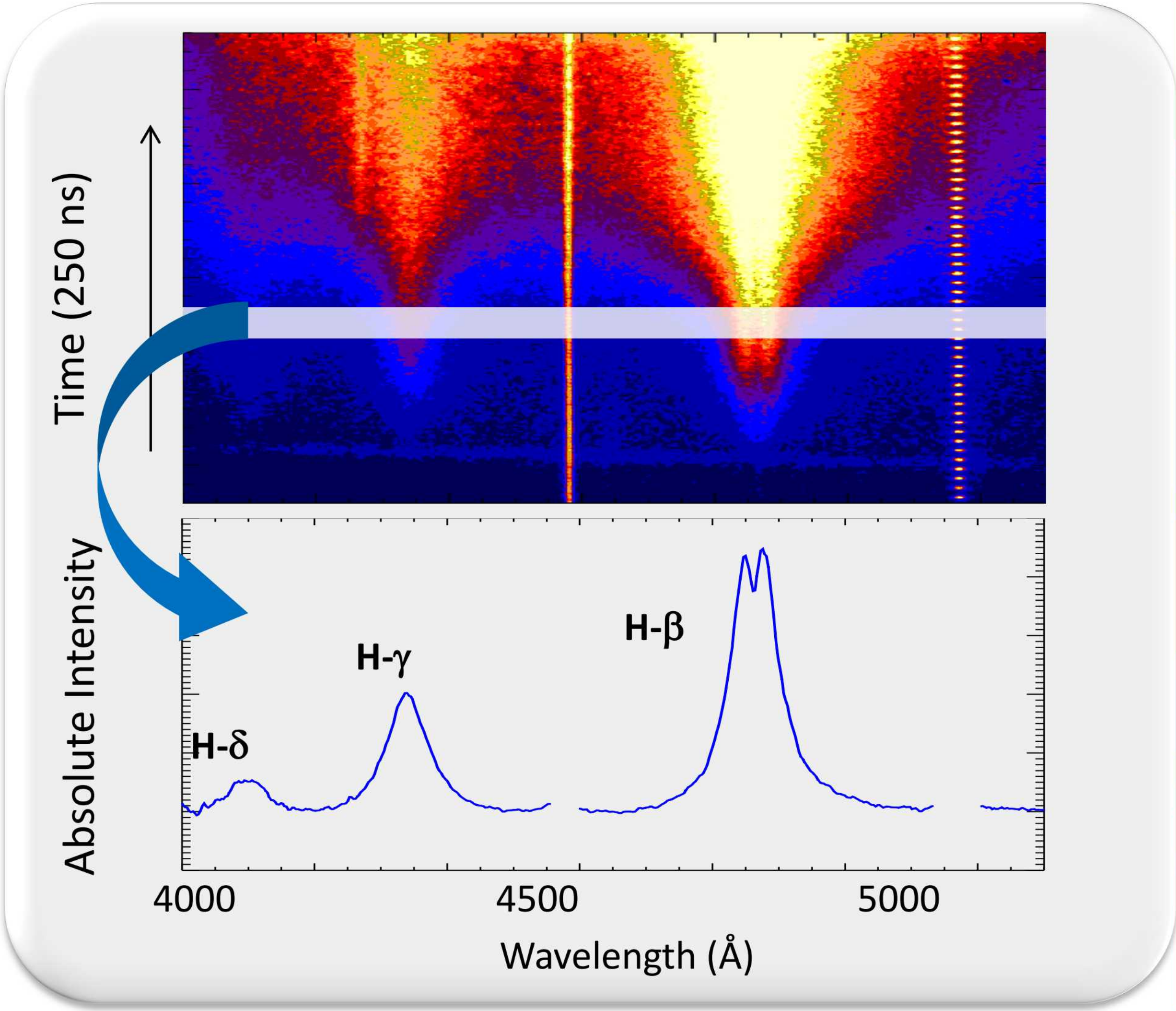


Hydrogen gas is heated by reemission from the gold wall; Its emission and absorption spectra are simultaneously observed

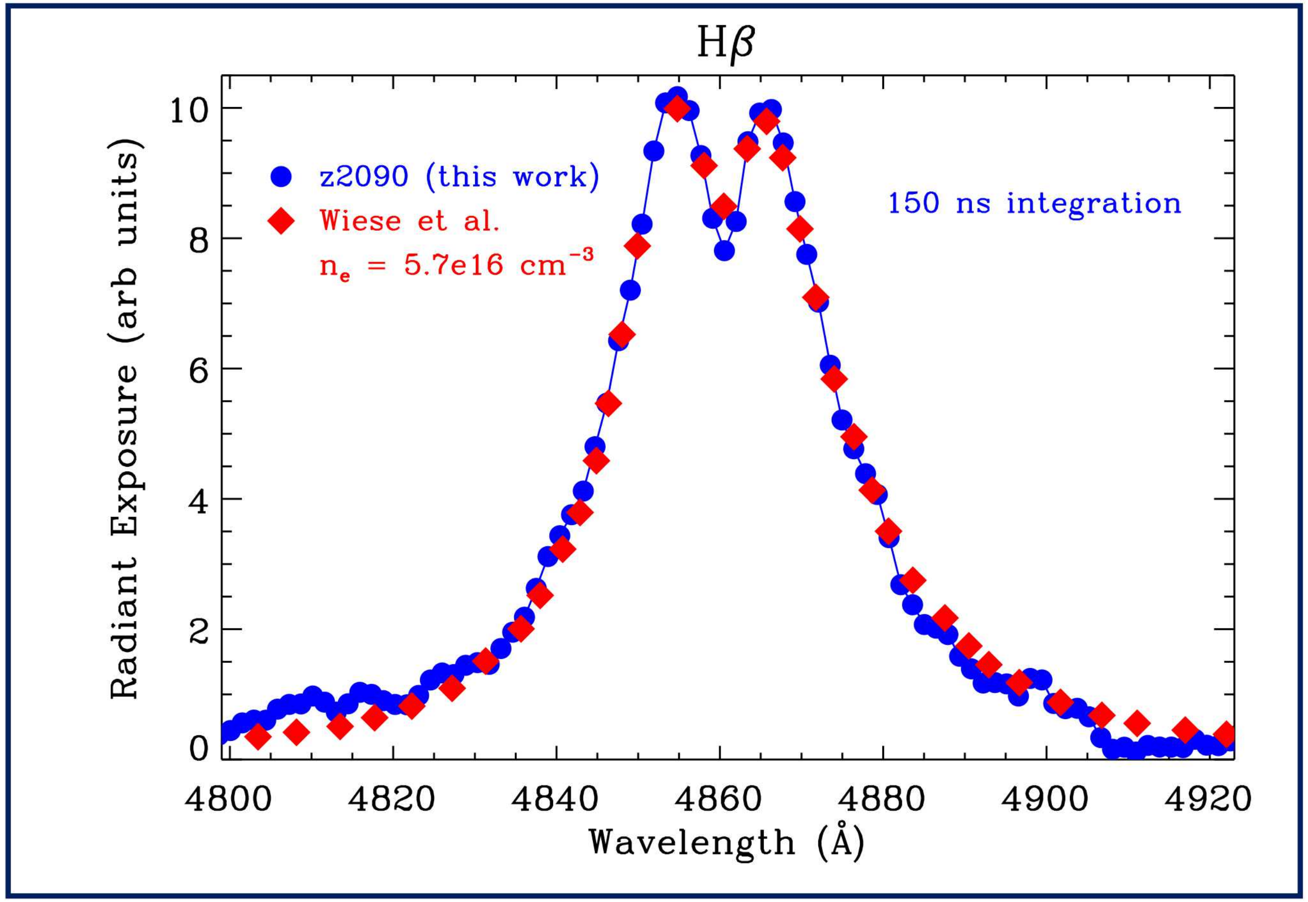
Absorption



Emission



Z experiment reproduced previous line-shape benchmark experiments by Wiese[1]



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

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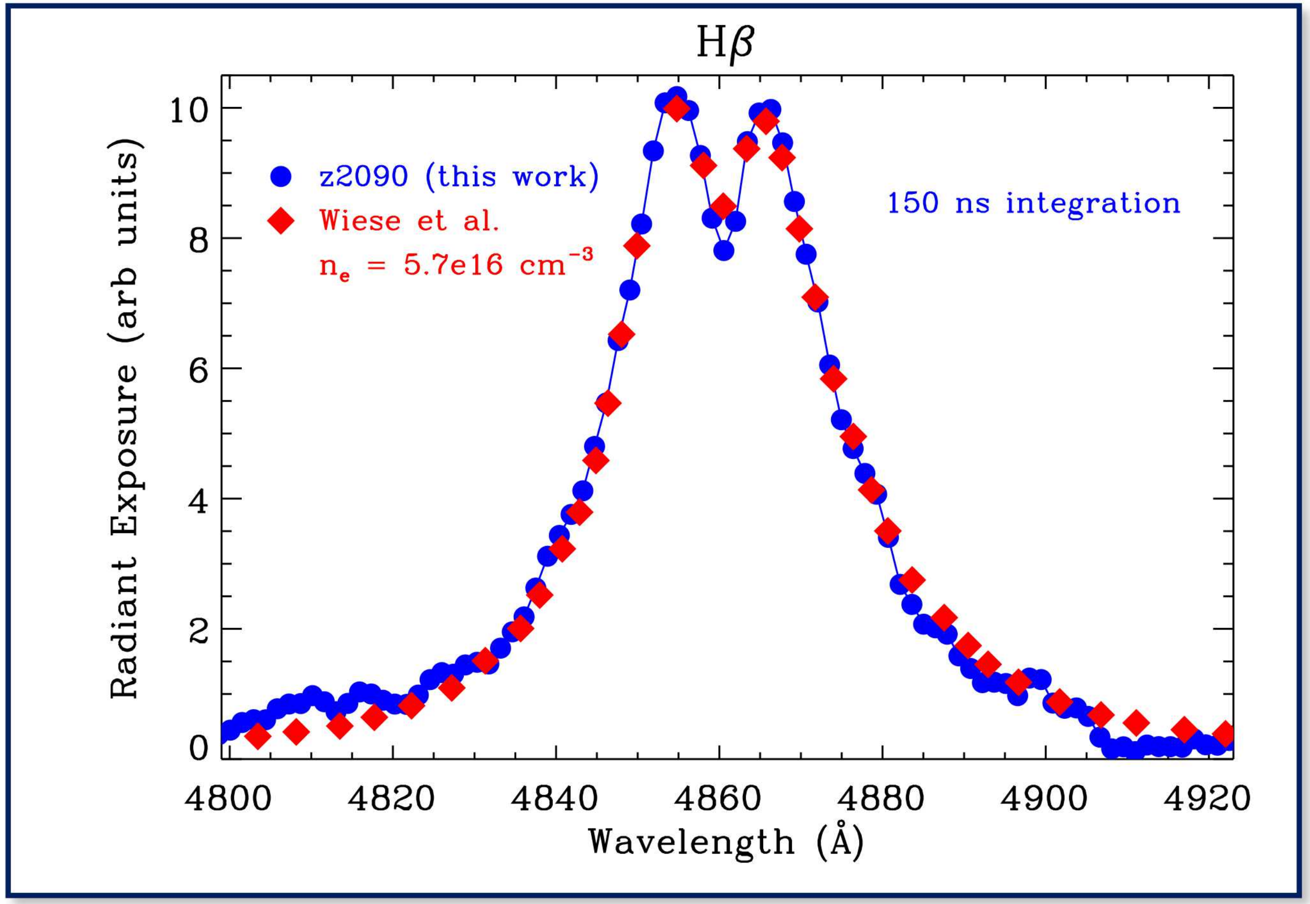
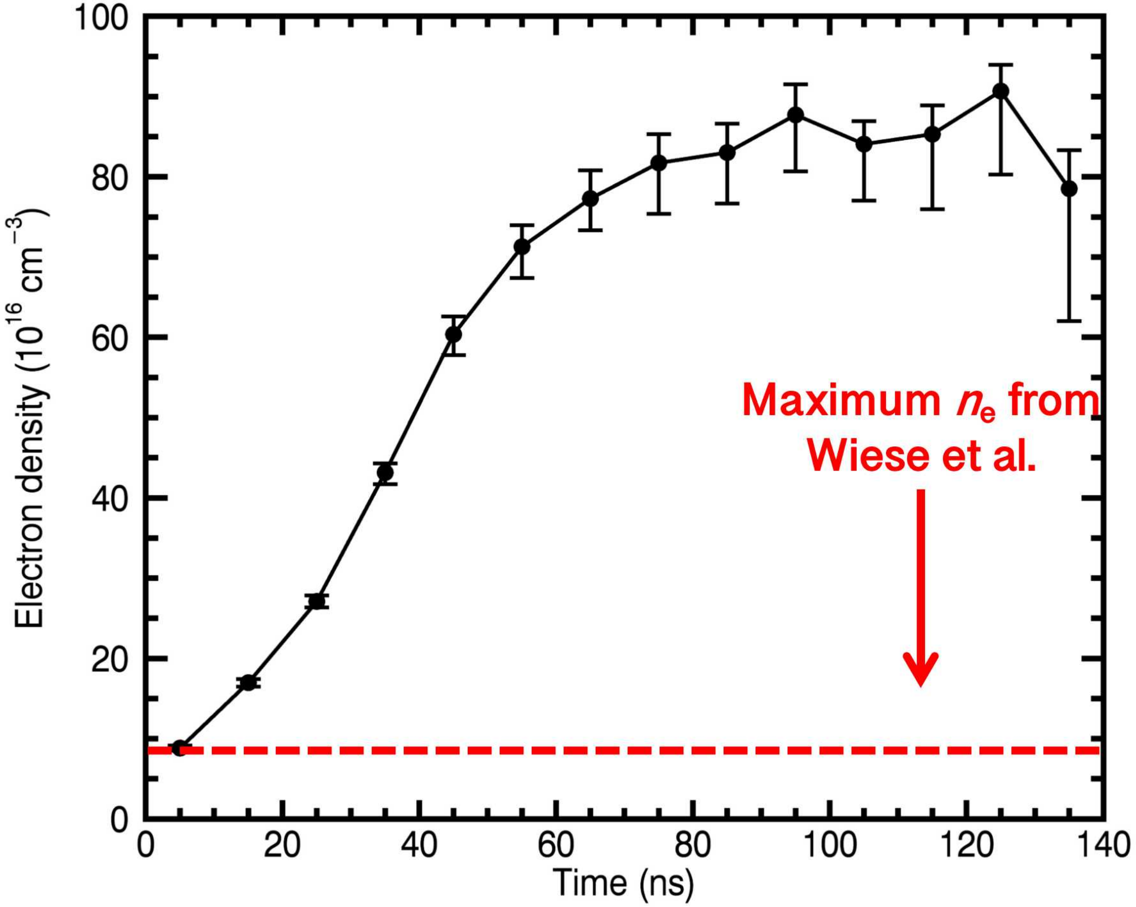
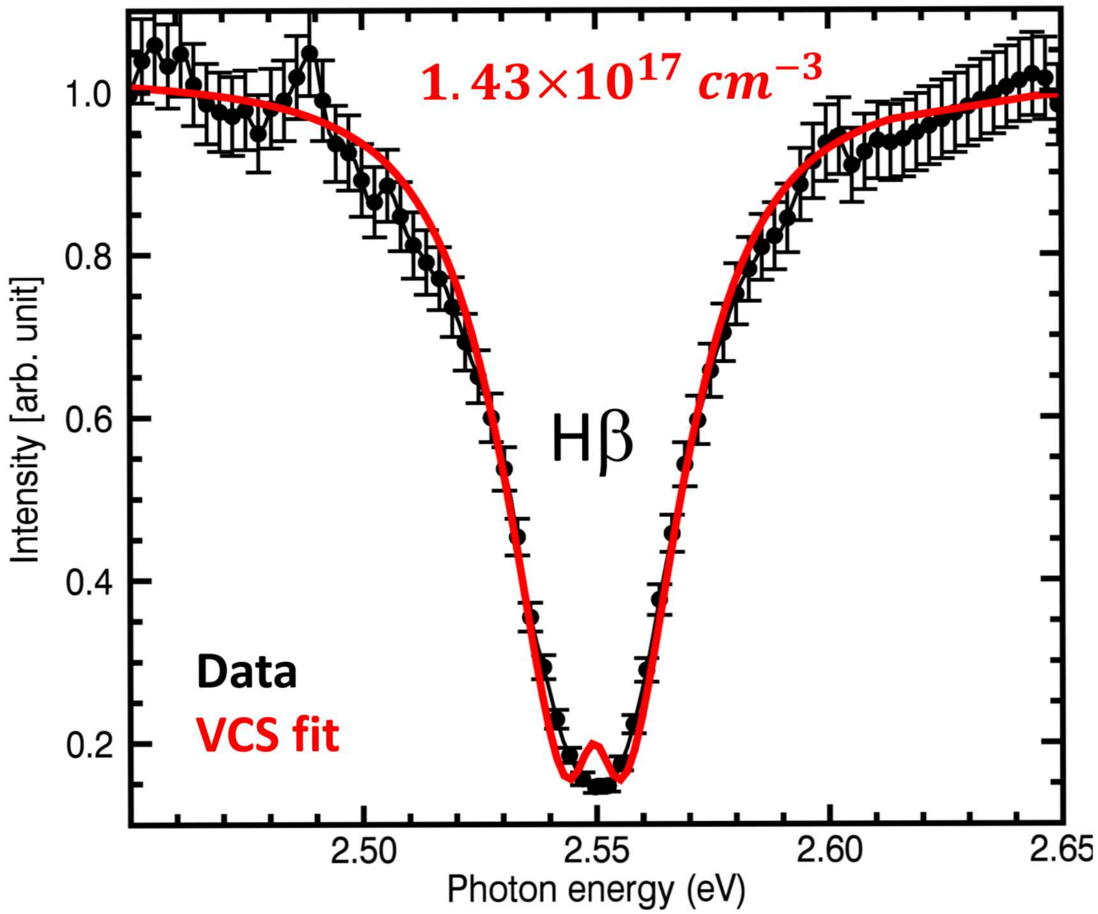


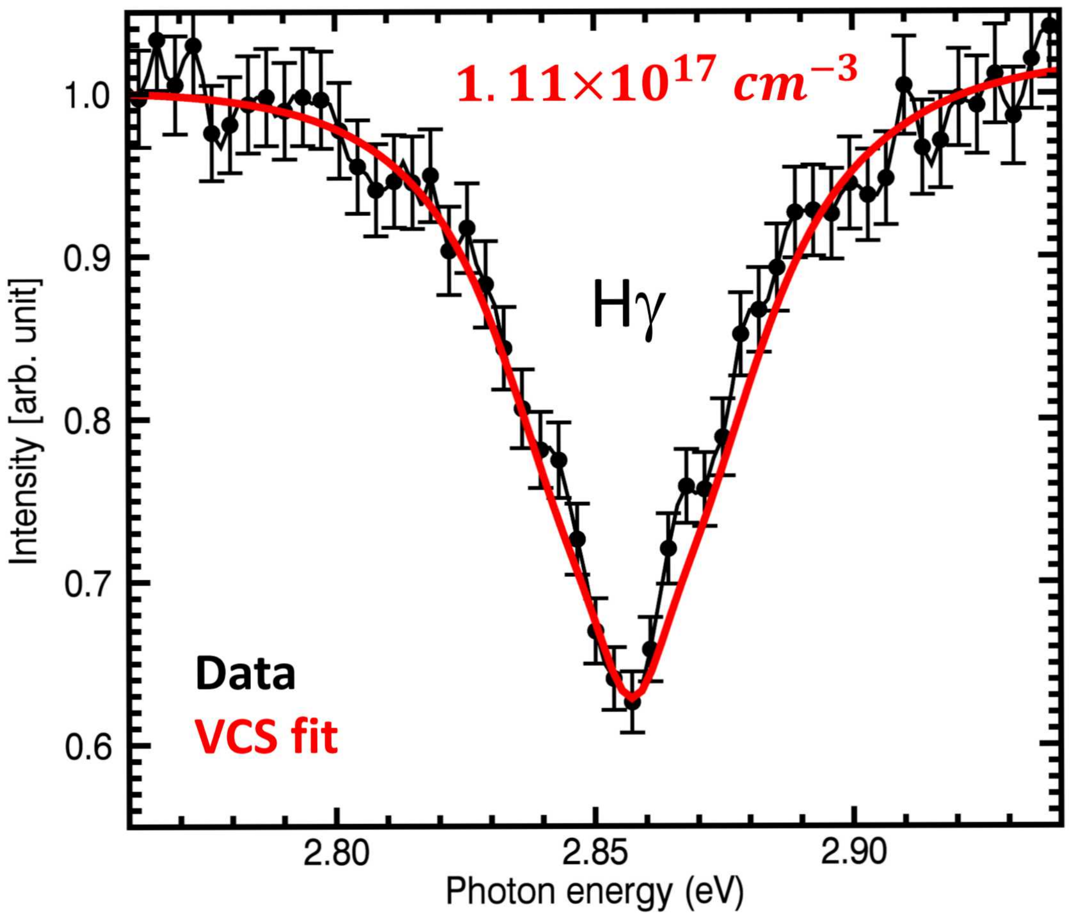


Let's check inferred density consistency between different lines

[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

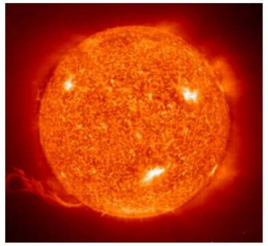
McDonald Observatory
THE UNIVERSITY OF TEXAS AT AUSTIN

U.S. DEPARTMENT OF ENERGY
Office of Science

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

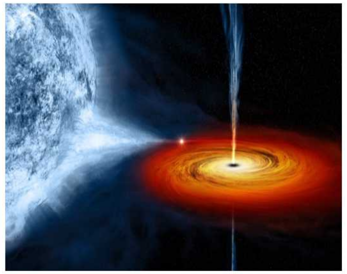
ZAPP experiments measure fundamental properties of atoms in plasmas to solve important astrophysical puzzles

- 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}



Accretion disk spectra:
ξ = 20-200 erg cm/s
T=30 eV
n_e=1e19 cm^{-3}

White dwarf mass:

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

- Laboratory astrophysics requires special knowledge: i) astrophysical importance, ii) model approximations and limitations, and iii) experiment feasibility

→ Collaboration and education are key ingredients for success

Success of satellite missions require validated models, making benchmark experiments invaluable.