SAND2018-3976C

Photos placed in horizontal position
with even amount of white space
between photos and header

ZAPP: Z Astrophysical Plasma Property Collaborations

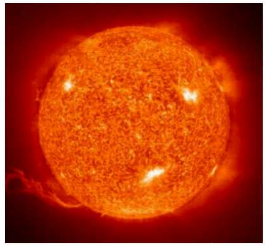
Taisuke Nagayama

4/11/2018

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and 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-NA-0003525.

ZAPP experiments benchmark plasma properties and spectra calculations and checks the accuracy of astrophysics interpretations

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

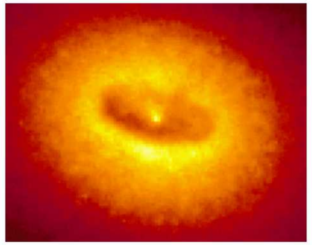


<u>Solar Fe opacity:</u>

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

<u>White dwarf mass:</u>

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



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

- Laboratory astrophysics requires special education: i) astrophysical importance, ii) model limitations, and iii) experiment feasibility → (Center of Astrophysical Plasma Properties)

Success of satellite missions require validated models, making benchmark experiments and healthy collaboration between astrophysicists and physicists invaluable.

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

J.E. Bailey, T. Nagayama, G.P. Loisel, G.A. Rochau, S.B. Hansen, G.S. Dunham, R. More, T.A. Gomez
Sandia National Laboratories

R.C. Mancini, D Mayes
University of Nevada – Reno

D.E. Winget, M.H. Montgomery, R.E. Falcon, A. Wootton
University of Texas – Austin

A.K. Pradhan, C. Orban, and S.N. Nahar
Ohio State University

M. Koepke, T. Lane
West Virginia University

C.A. Iglesias, D.A. Liedahl, B. Wilson
Lawrence Livermore National Laboratory

J. Colgan, C. Fontes, D. Kilcrease, and M. Sherrill
Los Alamos National Laboratory

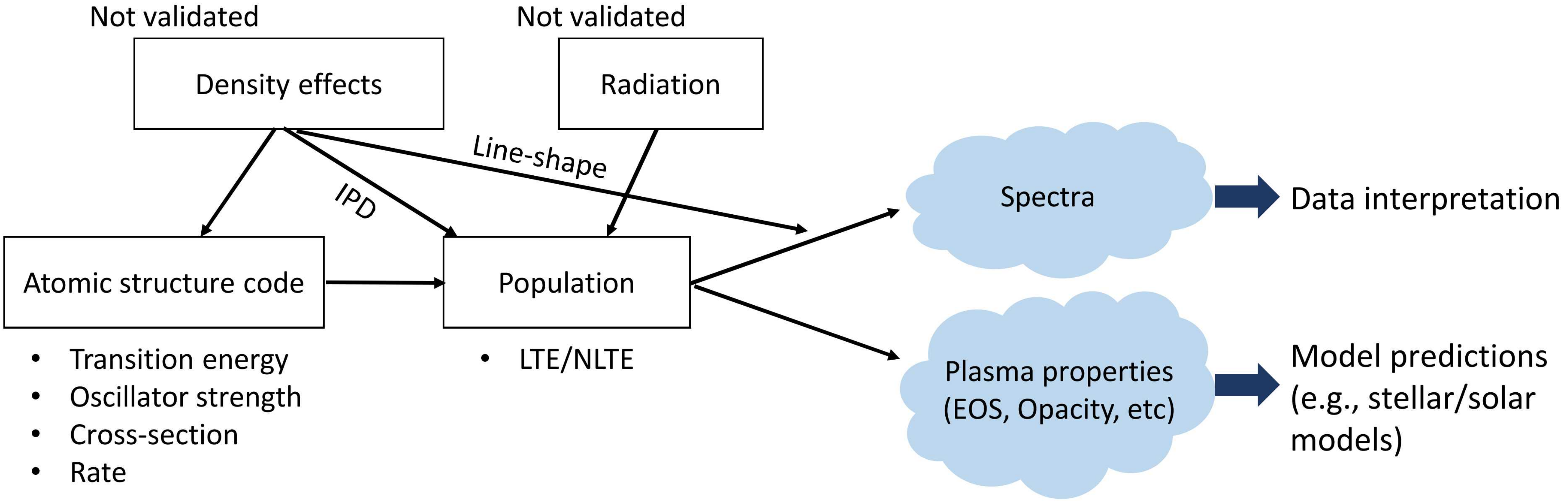
C. Blancard, Ph. Cosse, G. Faussurier, F. Gilleron, J.C. Pain
French Alternative Energies and Atomic Energy Commission (CEA)

J.J. MacFarlane, I.E. Golovkin
Prism Computational Sciences

T. Kallman
Goddard Space & Flight Center NASA, Maryland

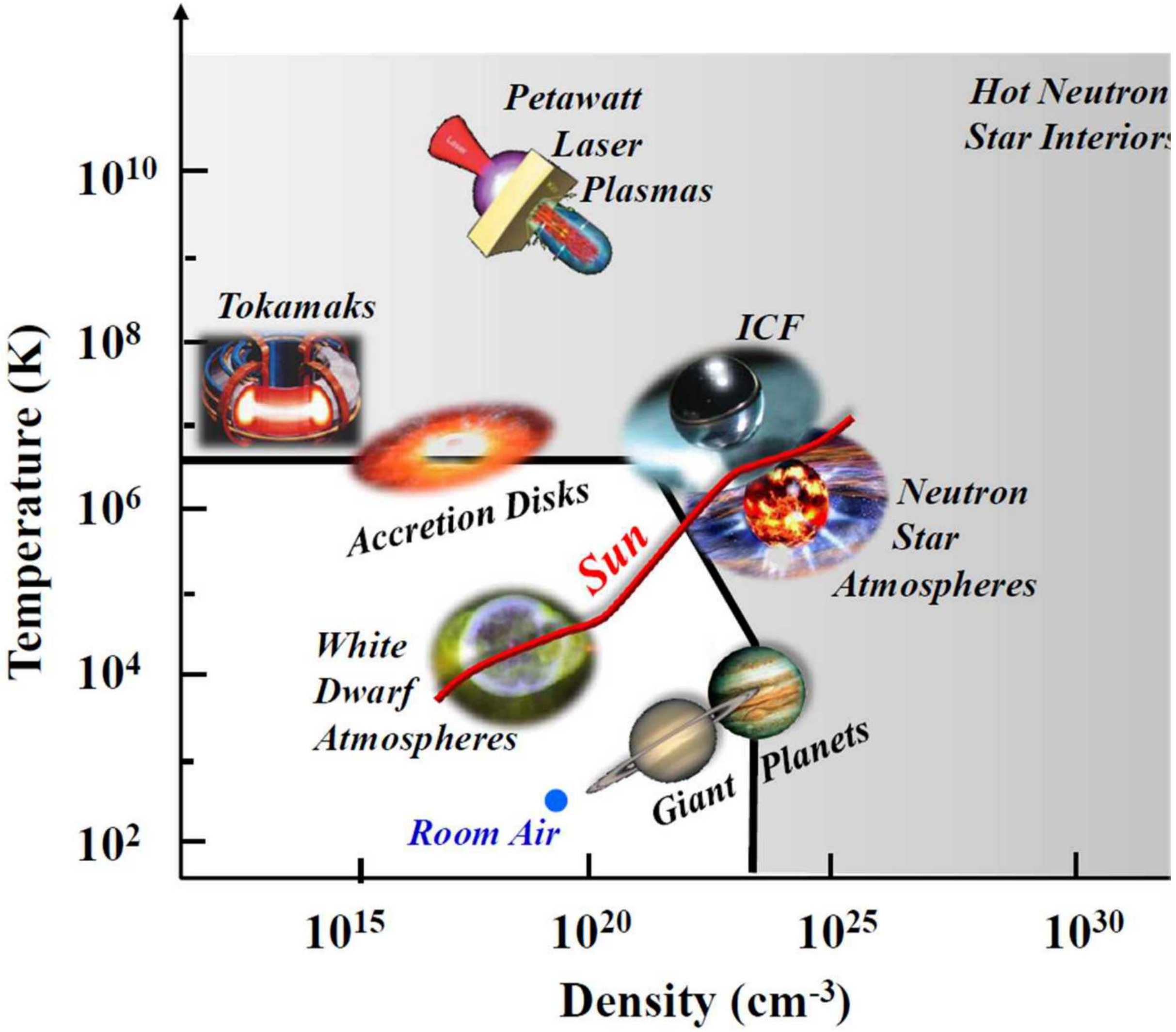
Y. Kurzweil and G. Hazak
Nuclear Research Center Negev, Israel

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



- **Limited/no validations available for approximations for extreme conditions**
- **This produces unknown uncertainty to the model predictions and data interpretations**

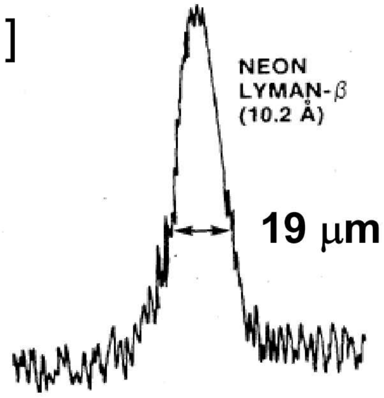
NNSA-sponsored mega-joule-class laboratories produce extreme conditions for many years, but …



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
Size: 19 μm



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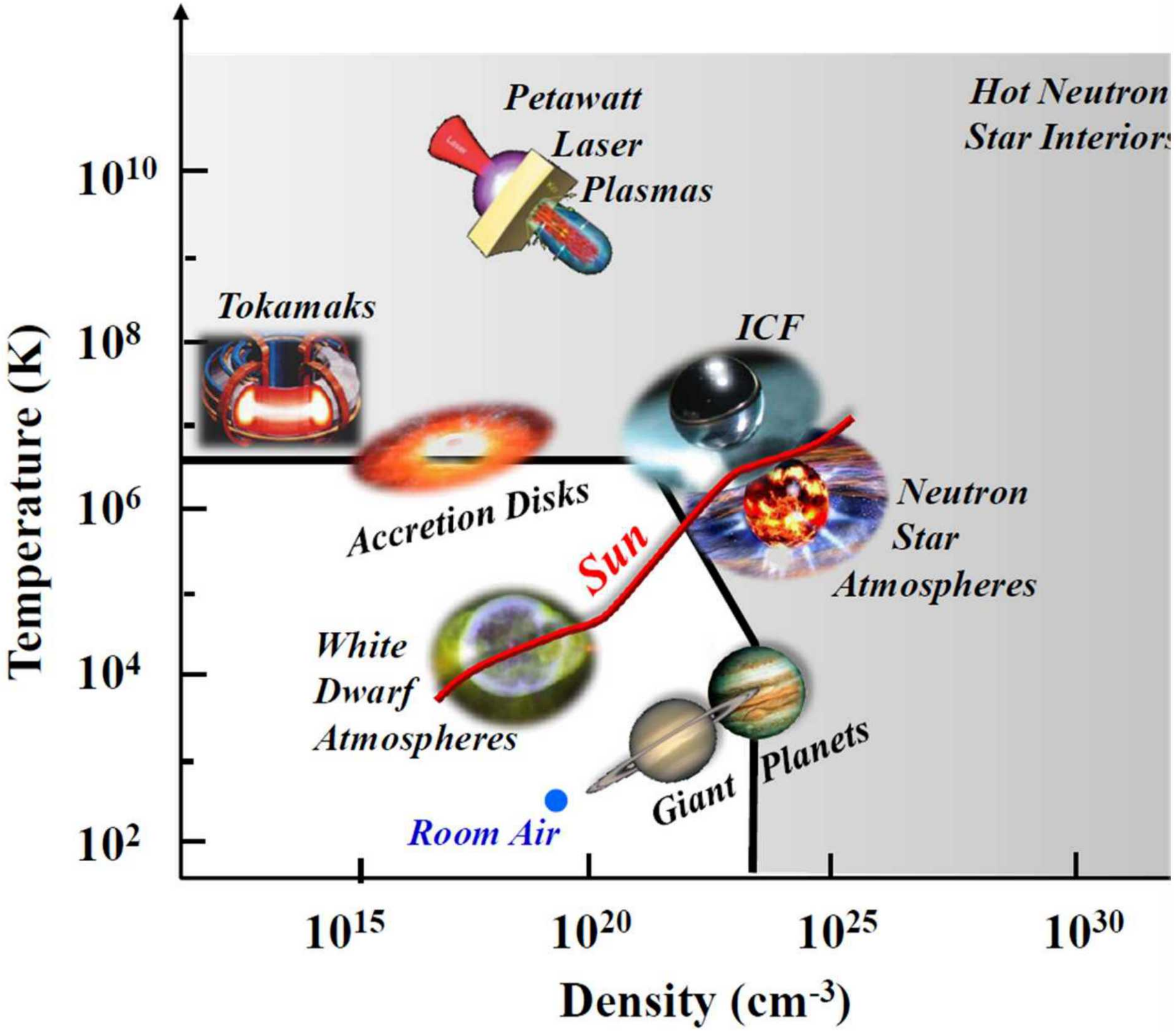

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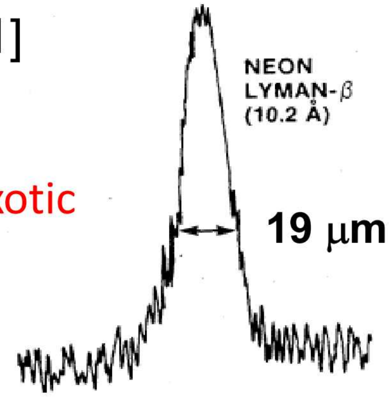
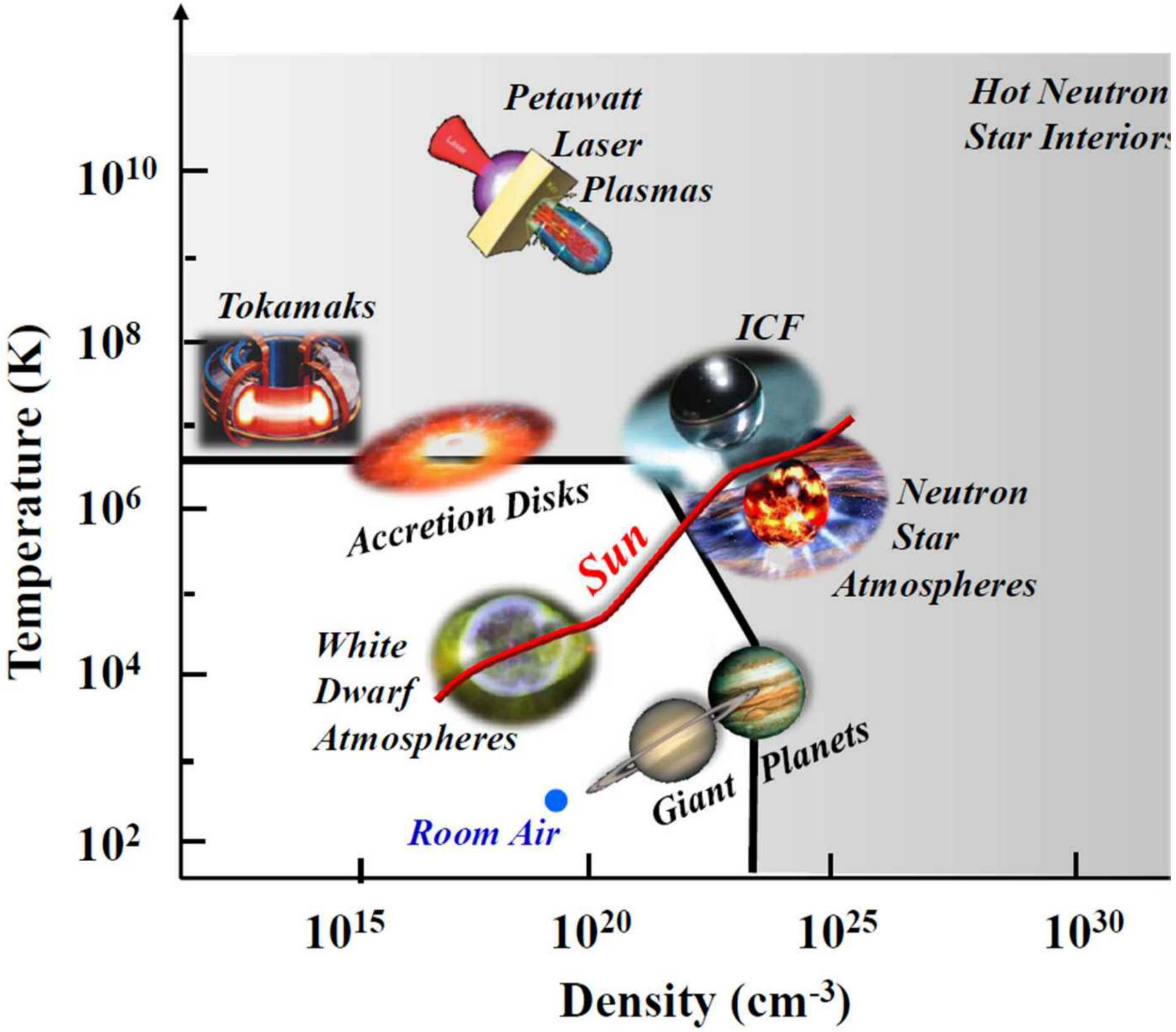
Fairly exotic



[1] Yaakobi, PRL, 1977

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



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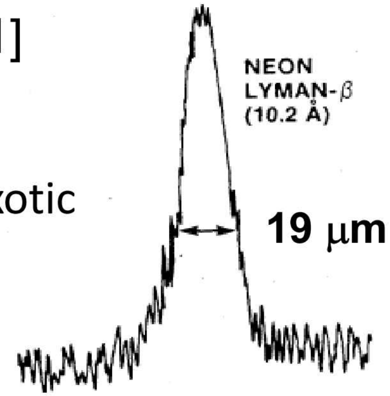

$T=3.5\times10^{6}$ K, $\rho=0.26$ g/cc } Fairly exotic

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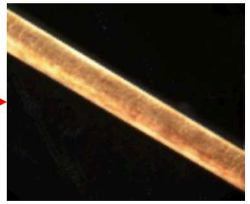
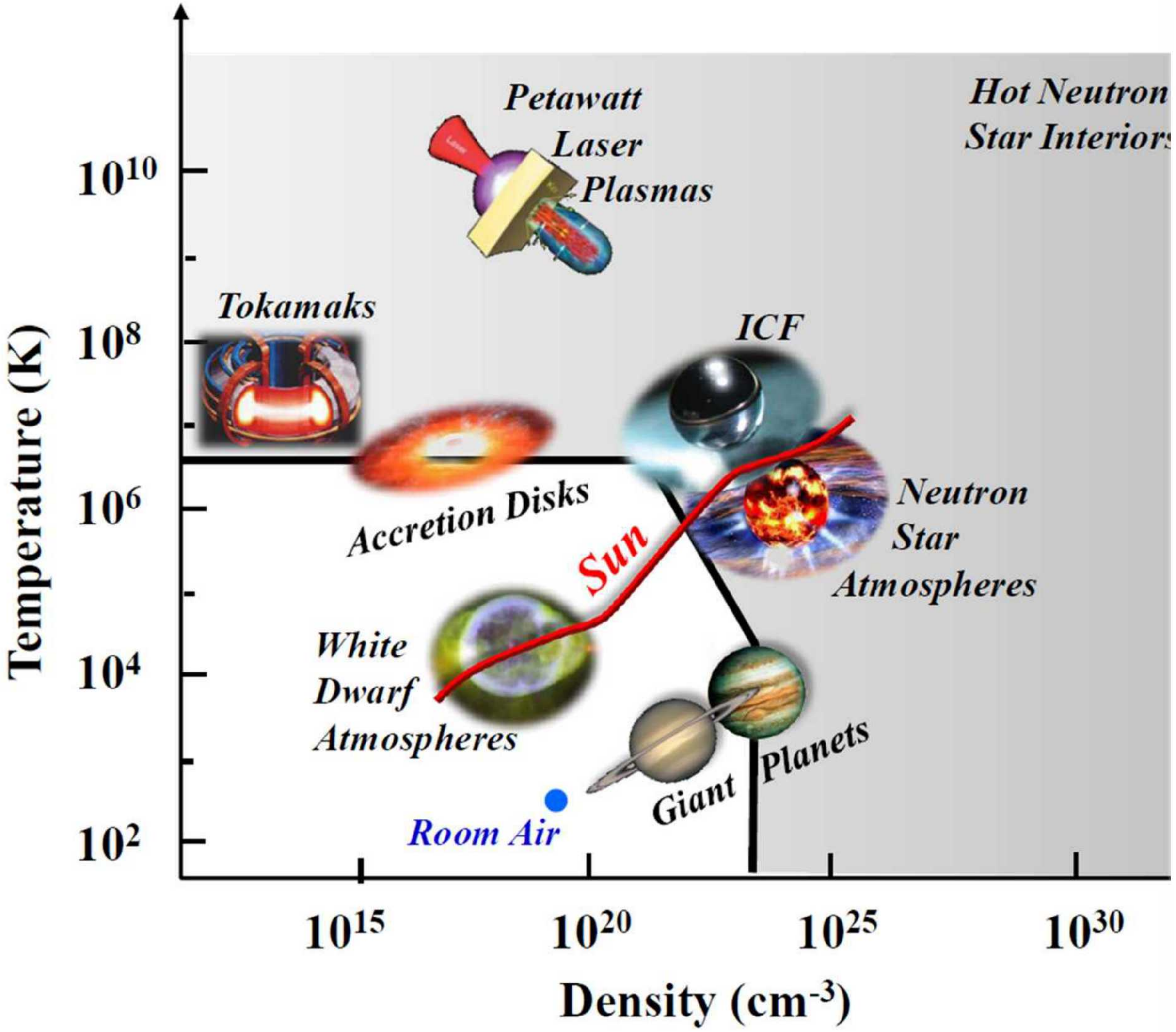


size of human hair

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

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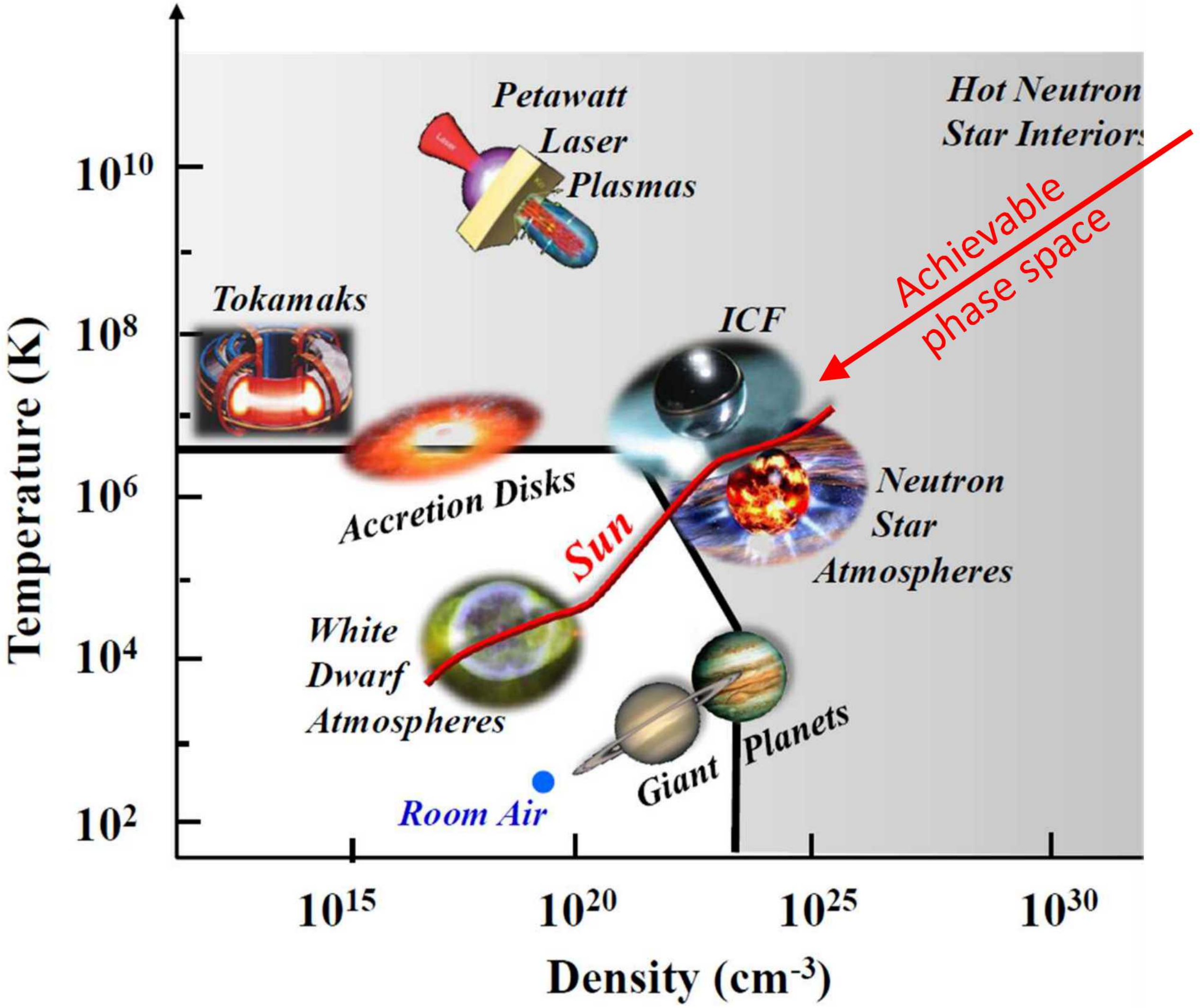

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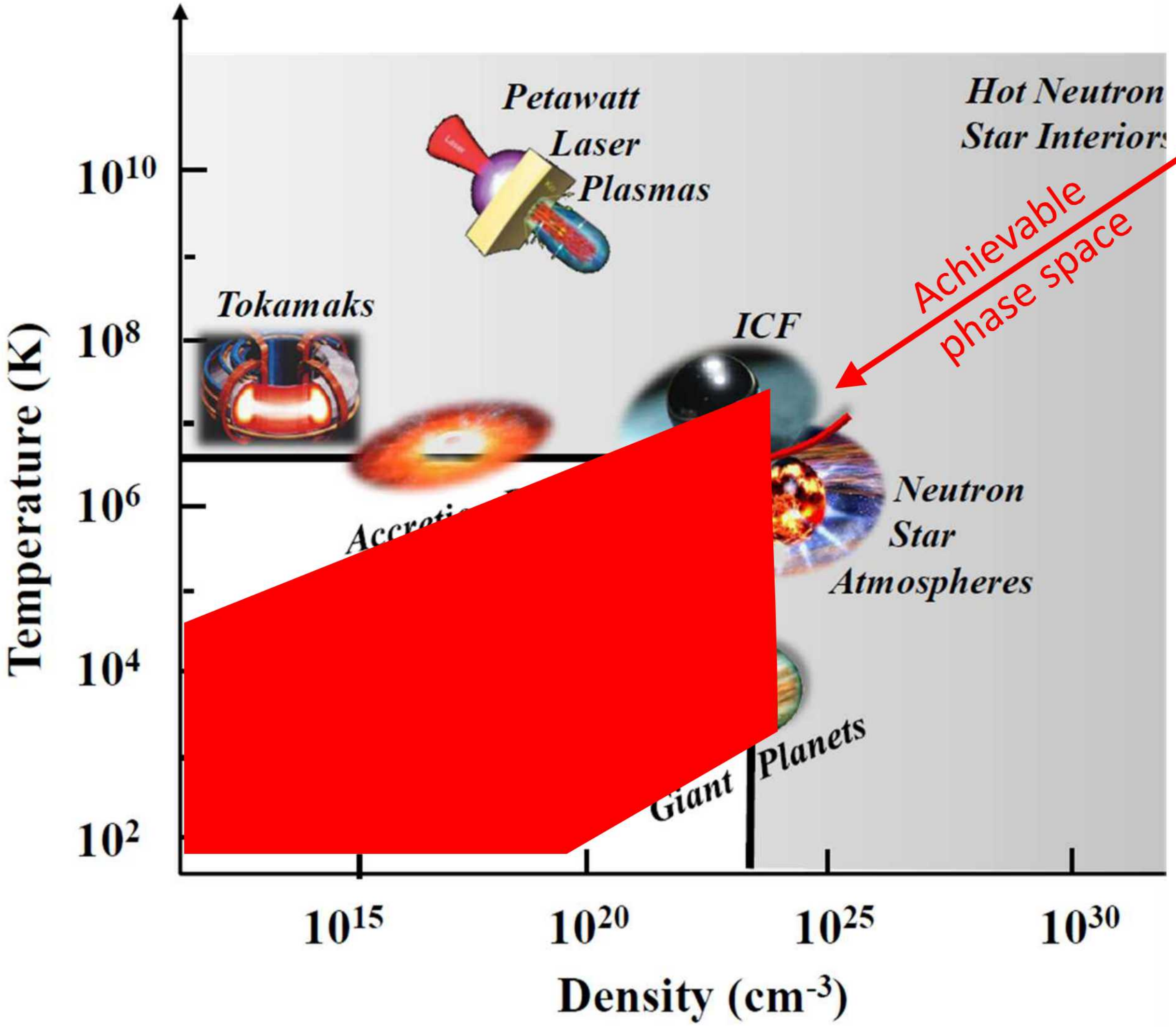

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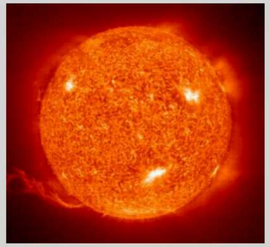
ZAPP campaigns simultaneously study multiple issues spanning 200x in temperature and 10^6x in density

Solar Opacity



Question:
Why can't we predict the location of the convection zone boundary in the Sun?

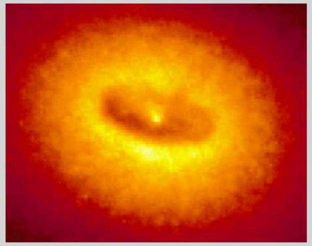
Achieved Conditions:
$T_e \sim 200$ eV, $n_e \sim 10^{23}$ cm^{-3}

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}

Accretion Disk Spectra

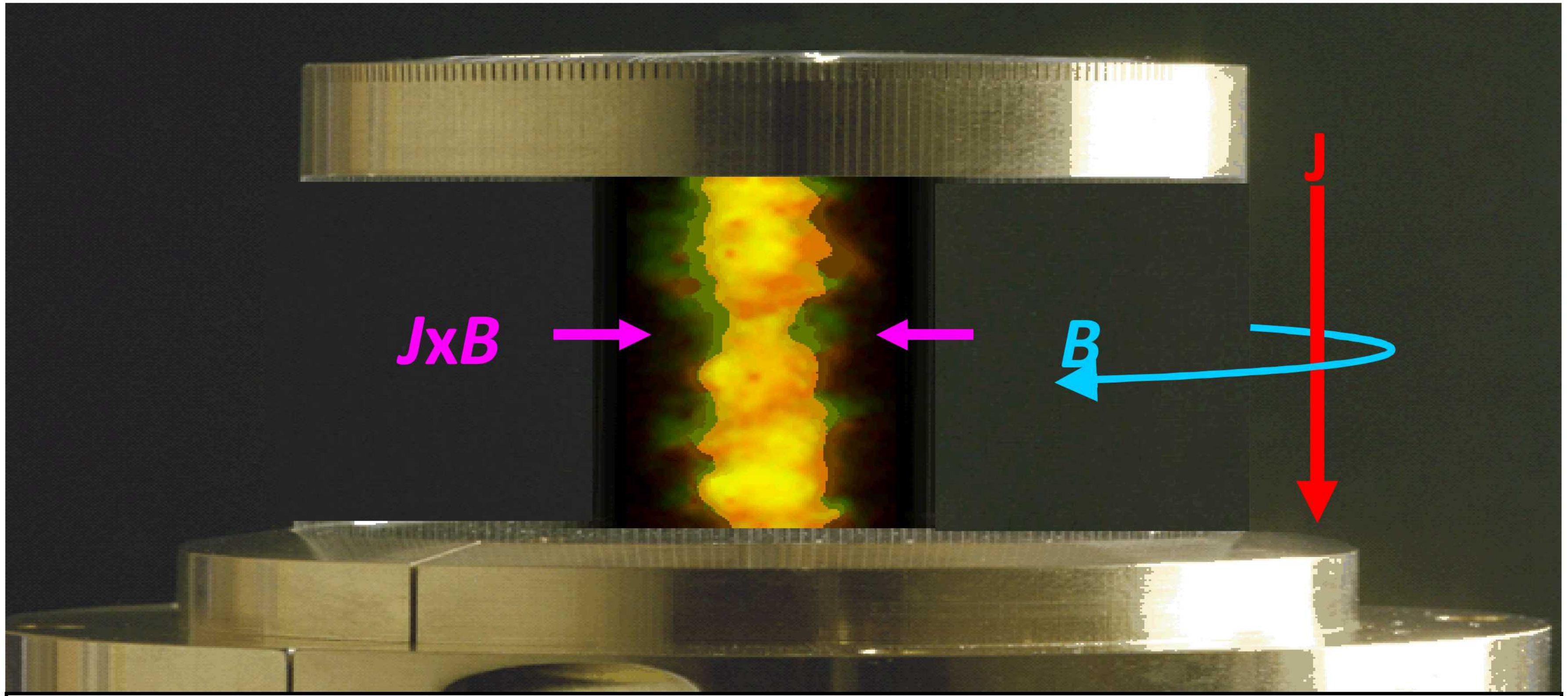


Question:
How does ionization and line formation occur in accreting objects?

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

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

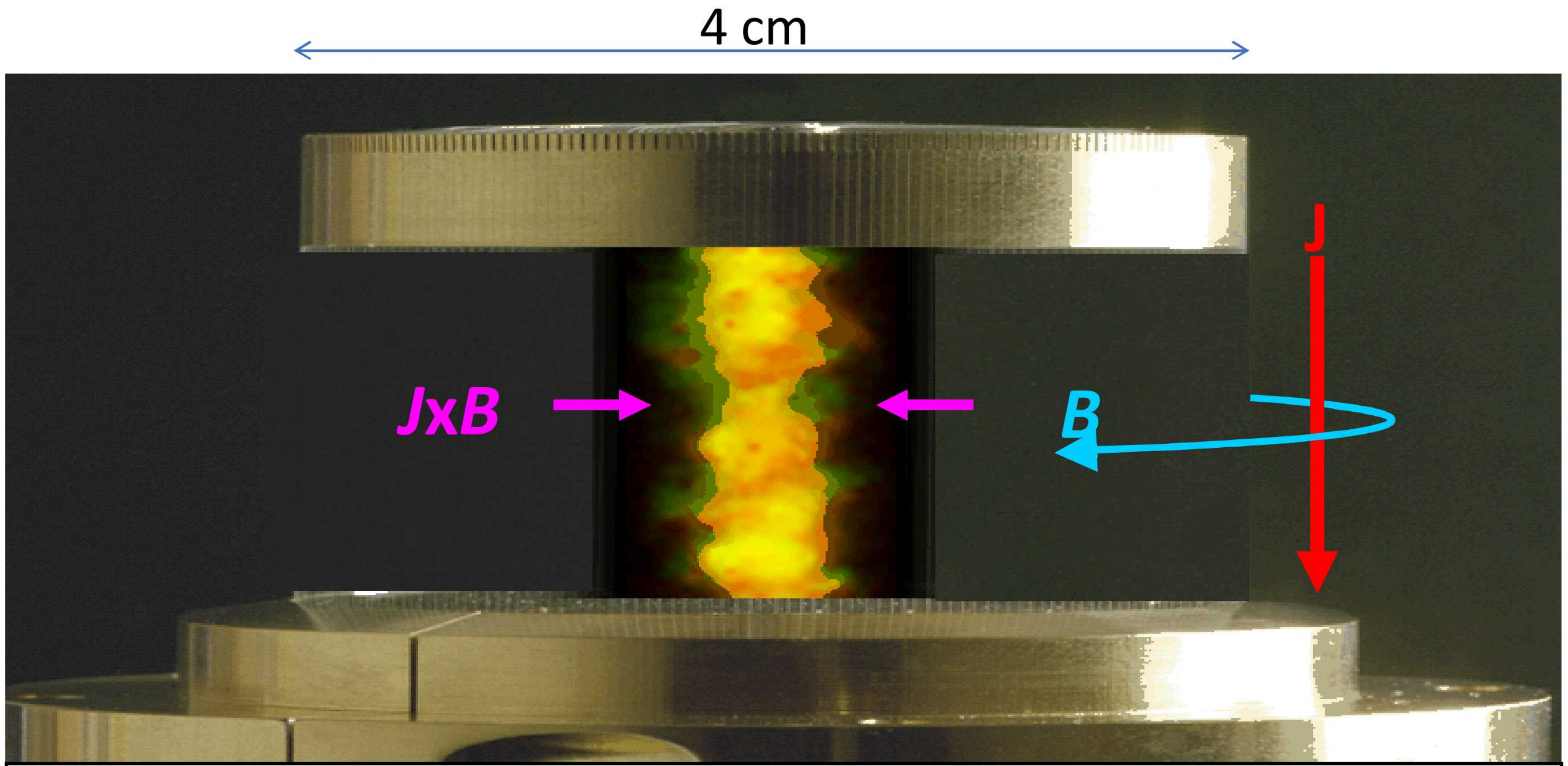
4 cm



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

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

Sandia National Laboratories



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

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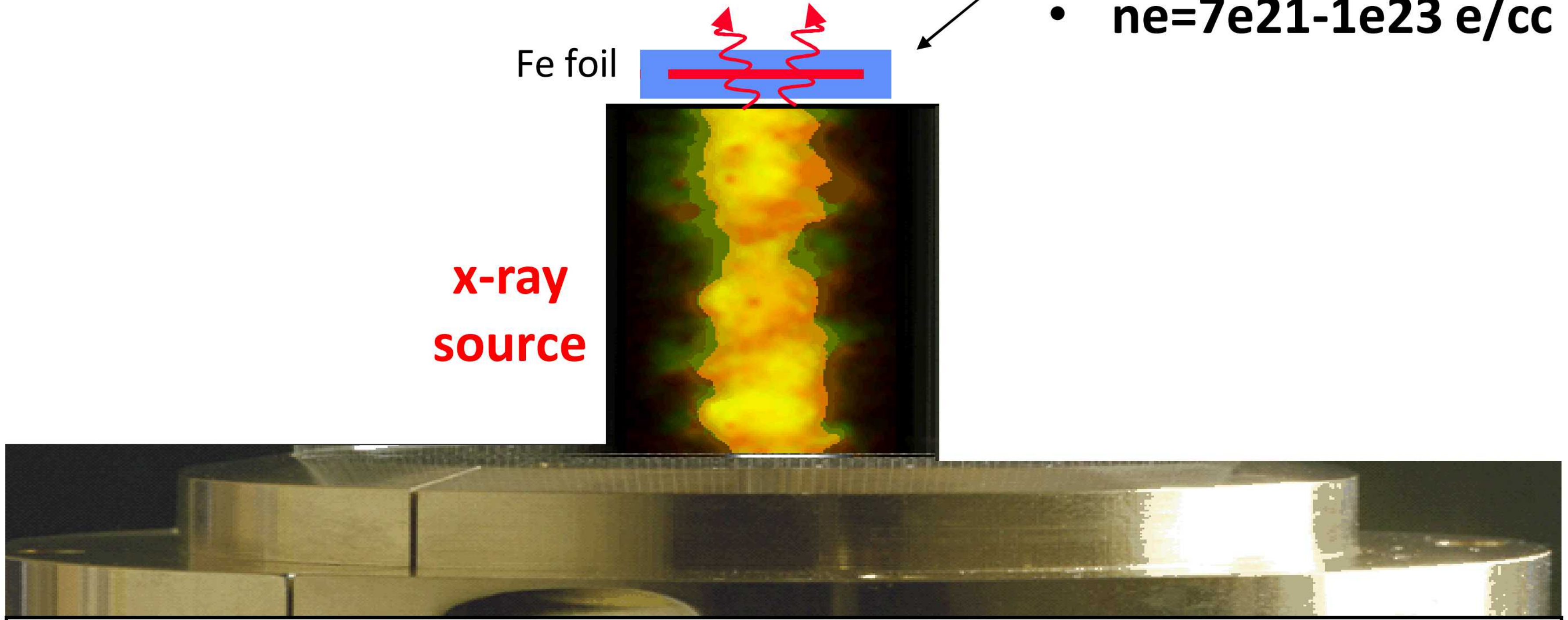

Solar opacity sample

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

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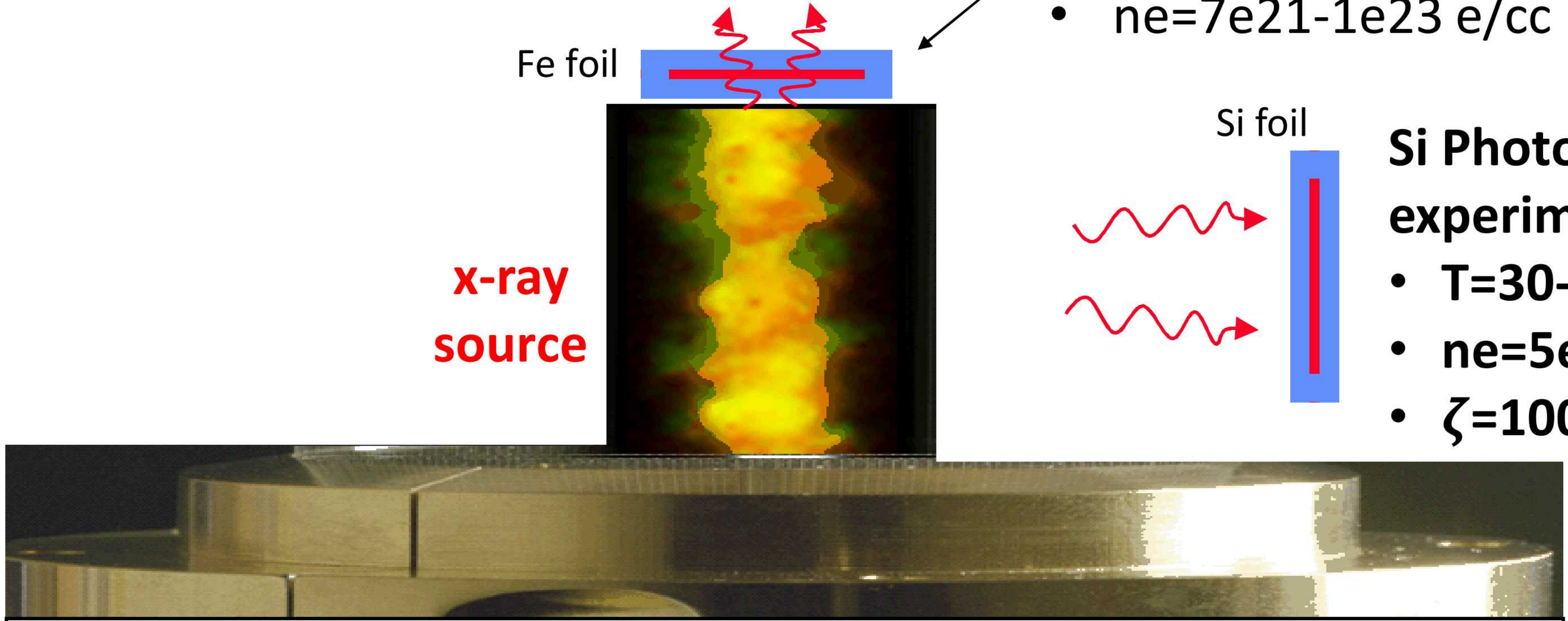

Si Photoionized experiments
- **T=30-40 eV**
- **ne=5e16-1e17 e/cc**
- **ζ=100-1000**

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

Solar opacity sample
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Si Photoionized experiments
- T=30-40 eV
- ne=5e16-1e17 e/cc
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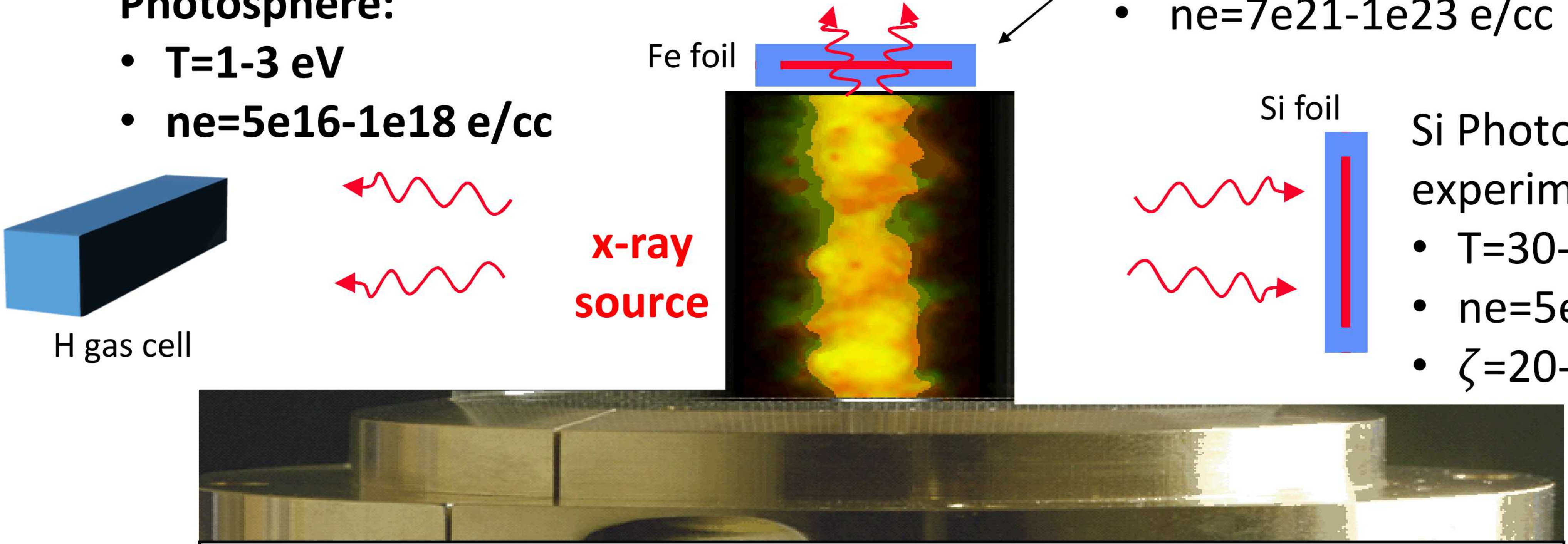

P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

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

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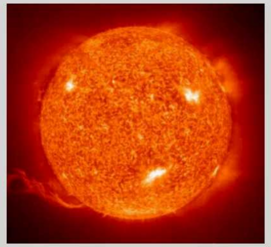
ZAPP campaigns simultaneously study multiple issues

Solar Opacity



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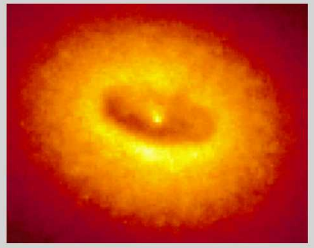

Question:
How does ionization and line formation occur in accreting objects?

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ZAPP campaigns acquire up to 60 spectra on a single shot

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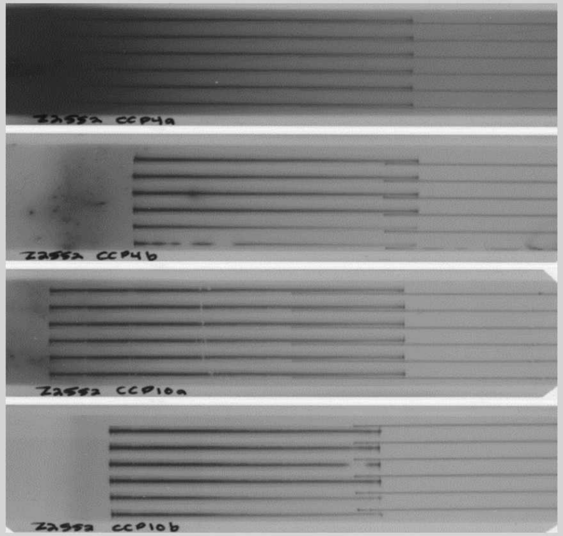
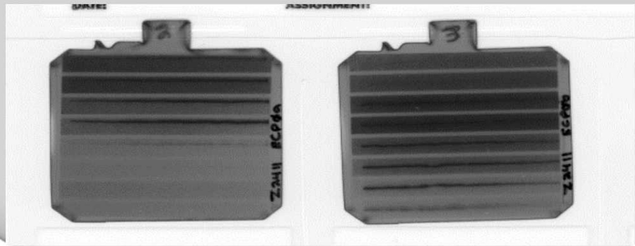
Solar Opacity

24 Space-Resolved
Fe Absorption Spectra

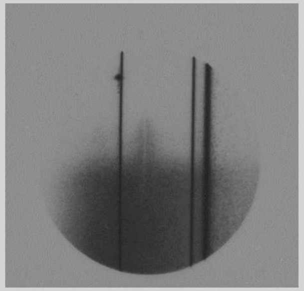


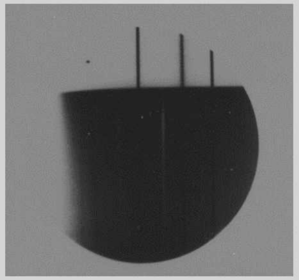
16 Time-Resolved
Fe Absorption Spectra



White Dwarf Line-Shapes

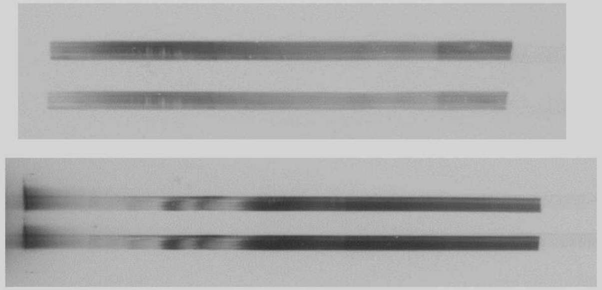
3 Streaked
H Absorption Spectra



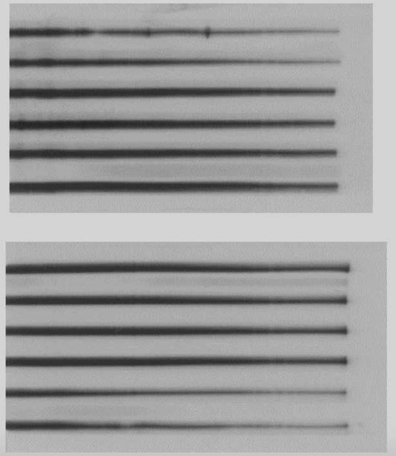


Accretion Disk Spectra

4 Space-Resolved
Si Absorption Spectra



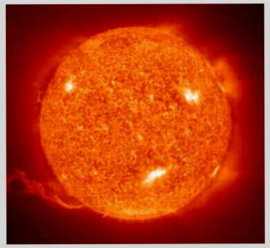
12 Space-Resolved
Ne Absorption Spectra



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

ZAPP campaigns simultaneously study multiple issues

Solar Opacity



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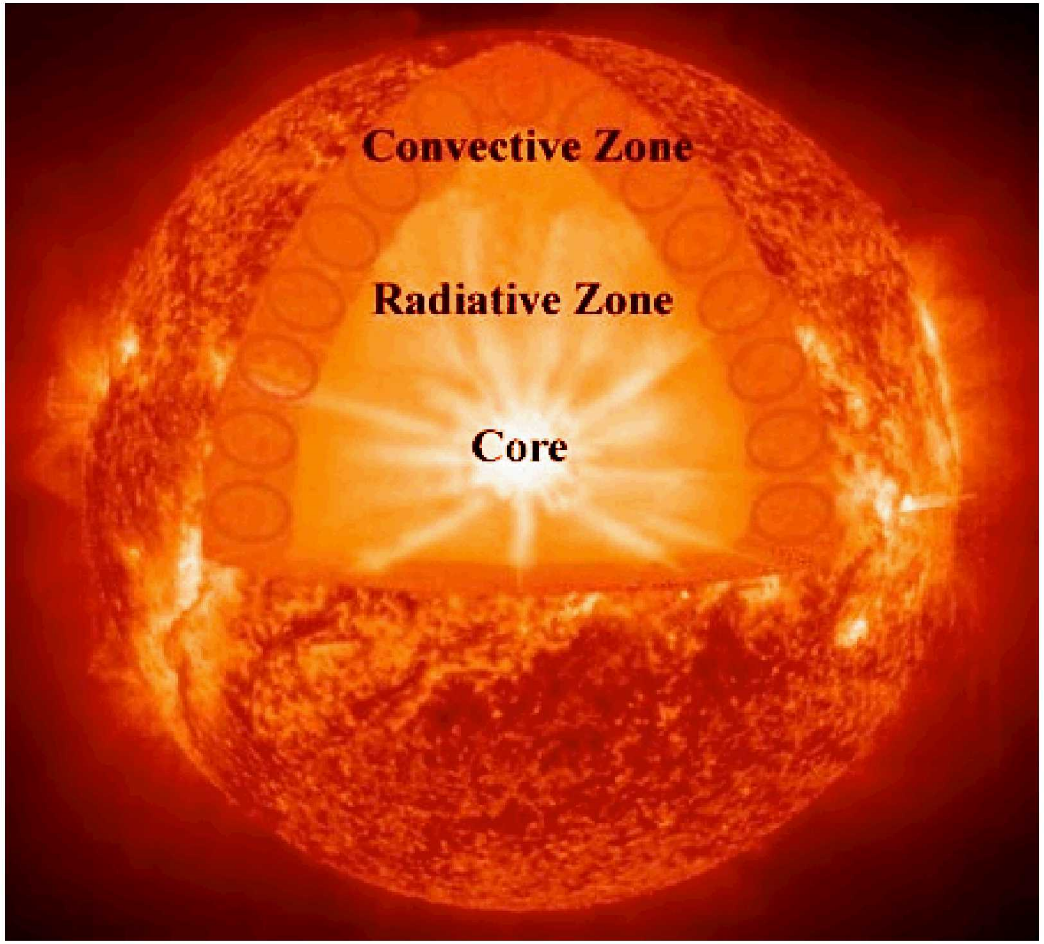
Achieved Conditions:
T_e ~ 200 eV, n_e ~ 10^{23} cm^{-3}

Modeled solar structure disagrees with observations

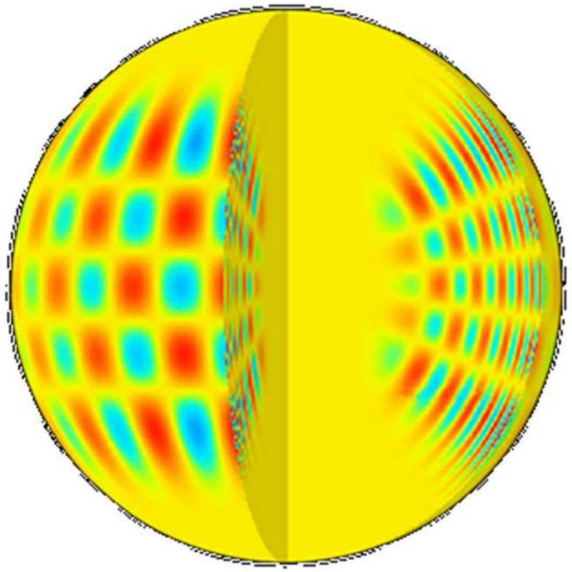


- Simulation: Standard solar model

  Inputs:

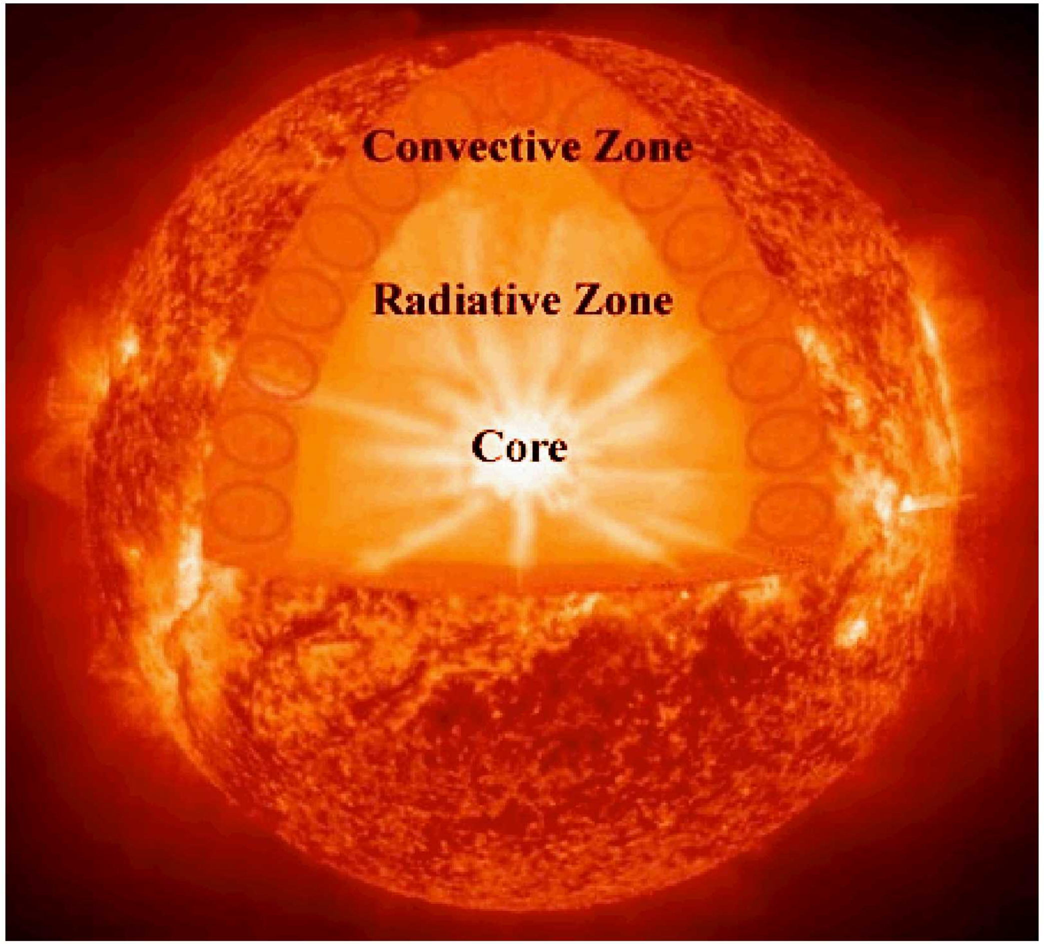
  - Abundance
  - EOS
  - Opacity
  - Etc.

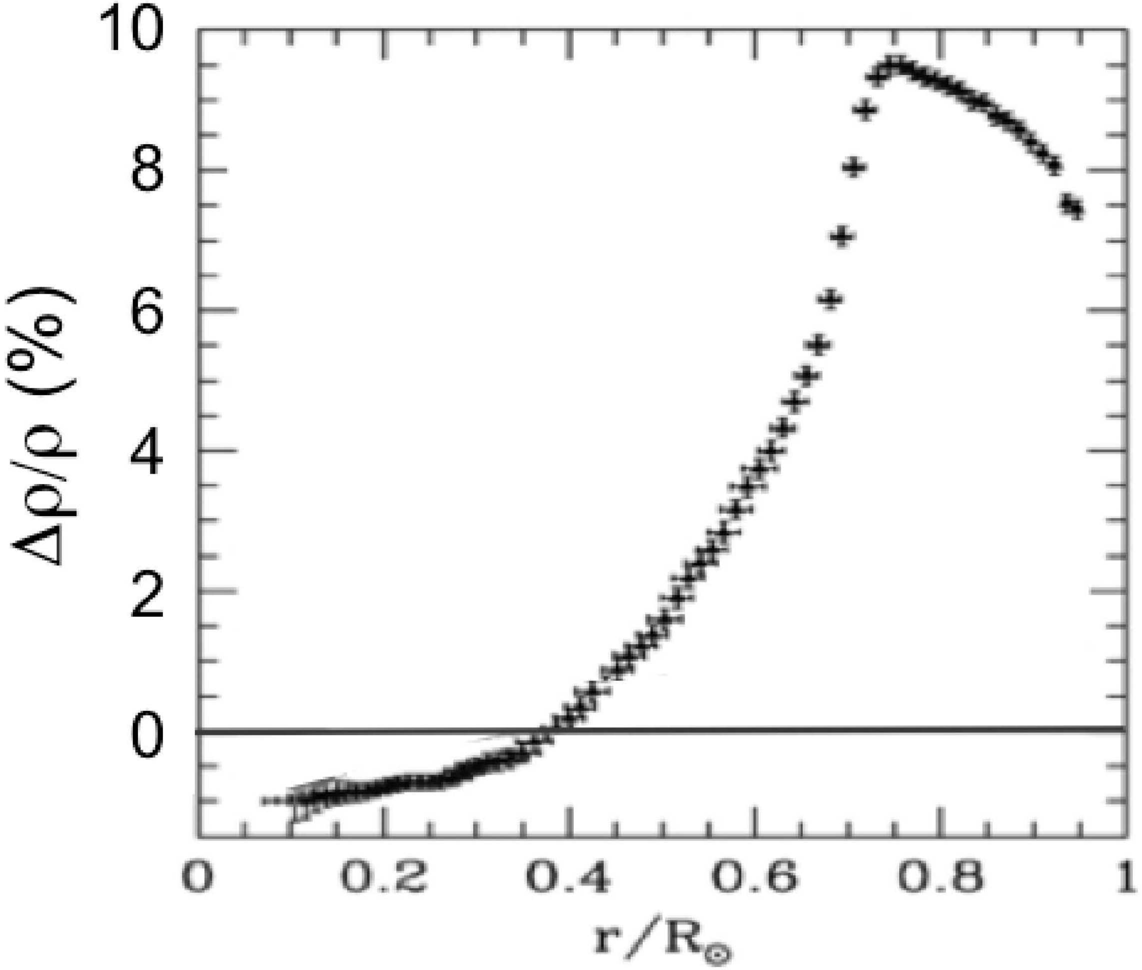
- Measurements: Helioseismology



Analysis of 2D-resolved pulsation reveals the solar structure

Modeled solar structure disagrees with observations





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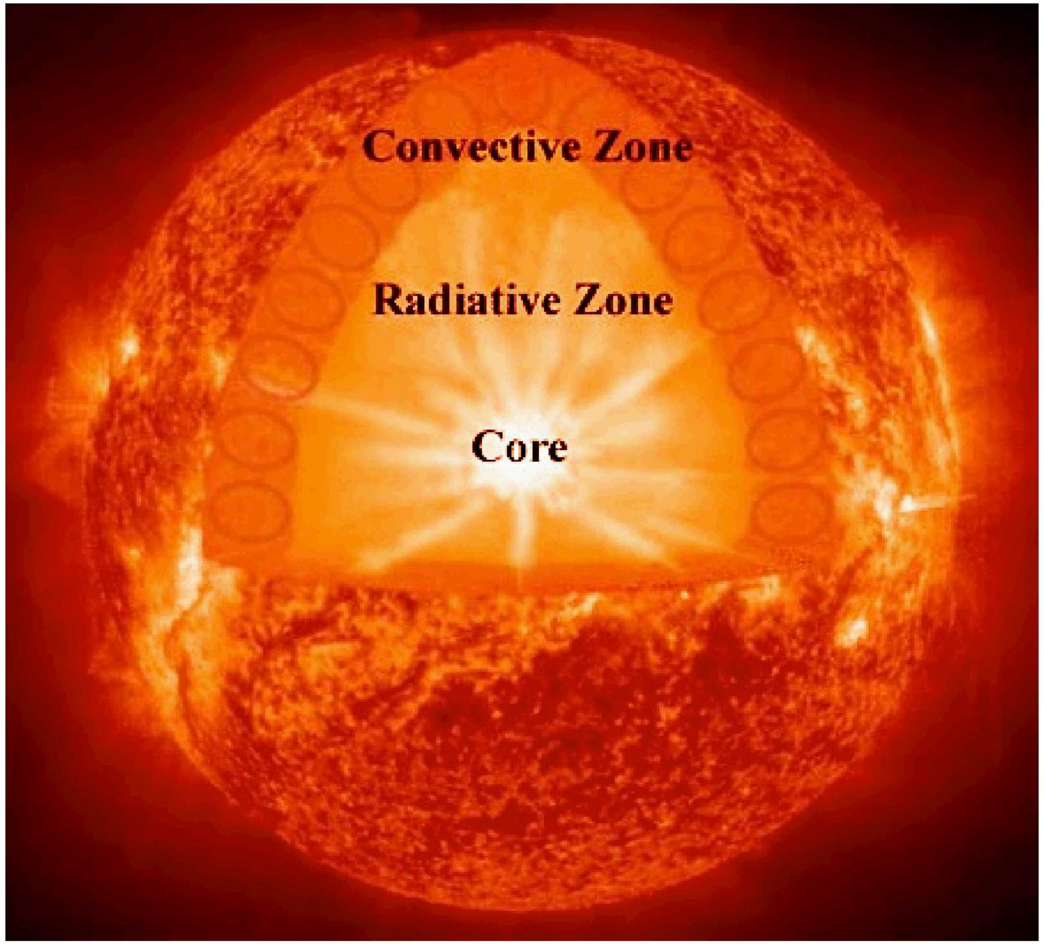

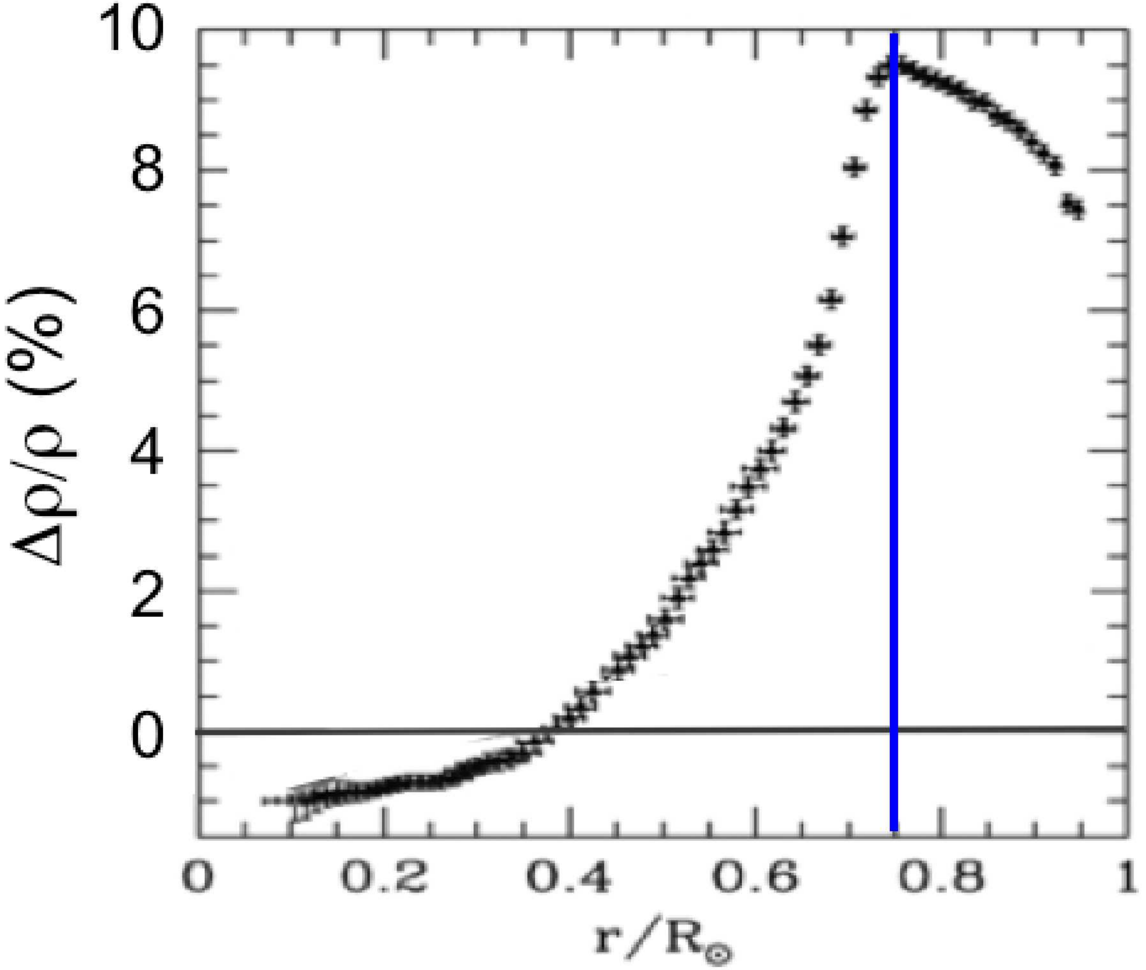

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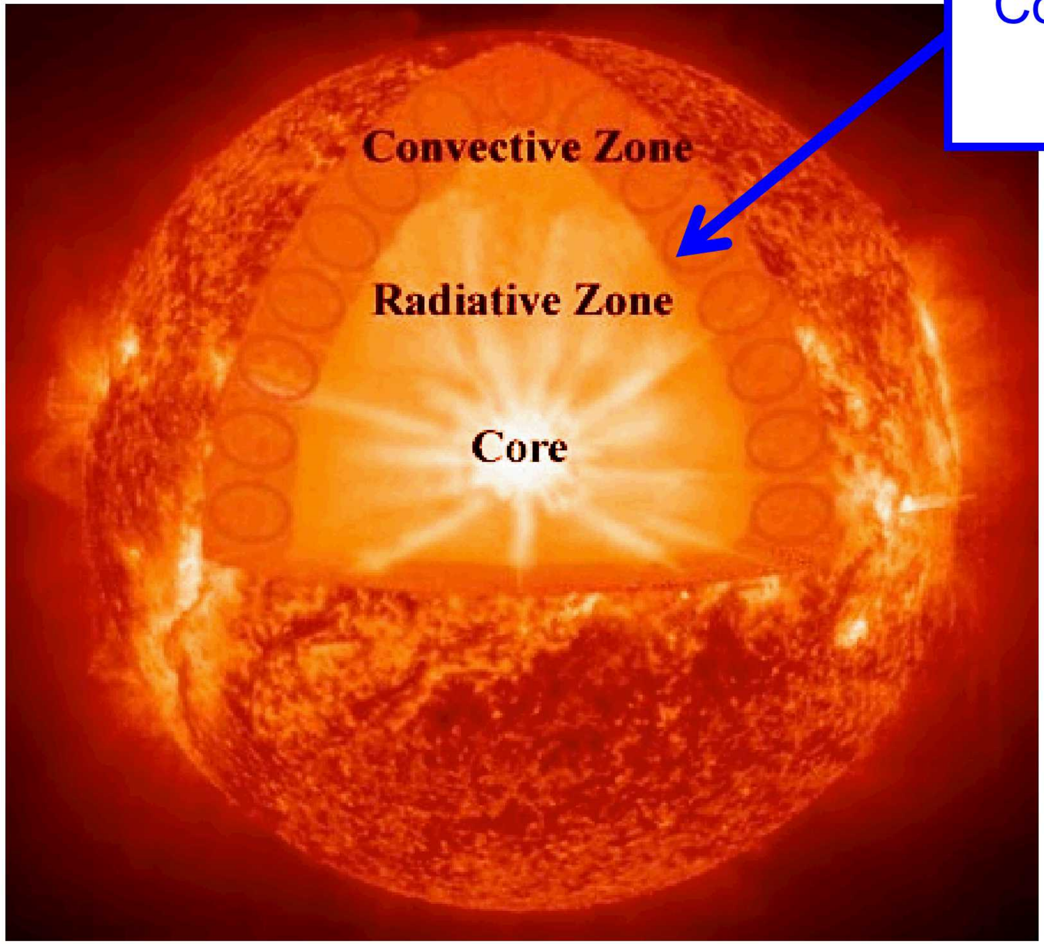
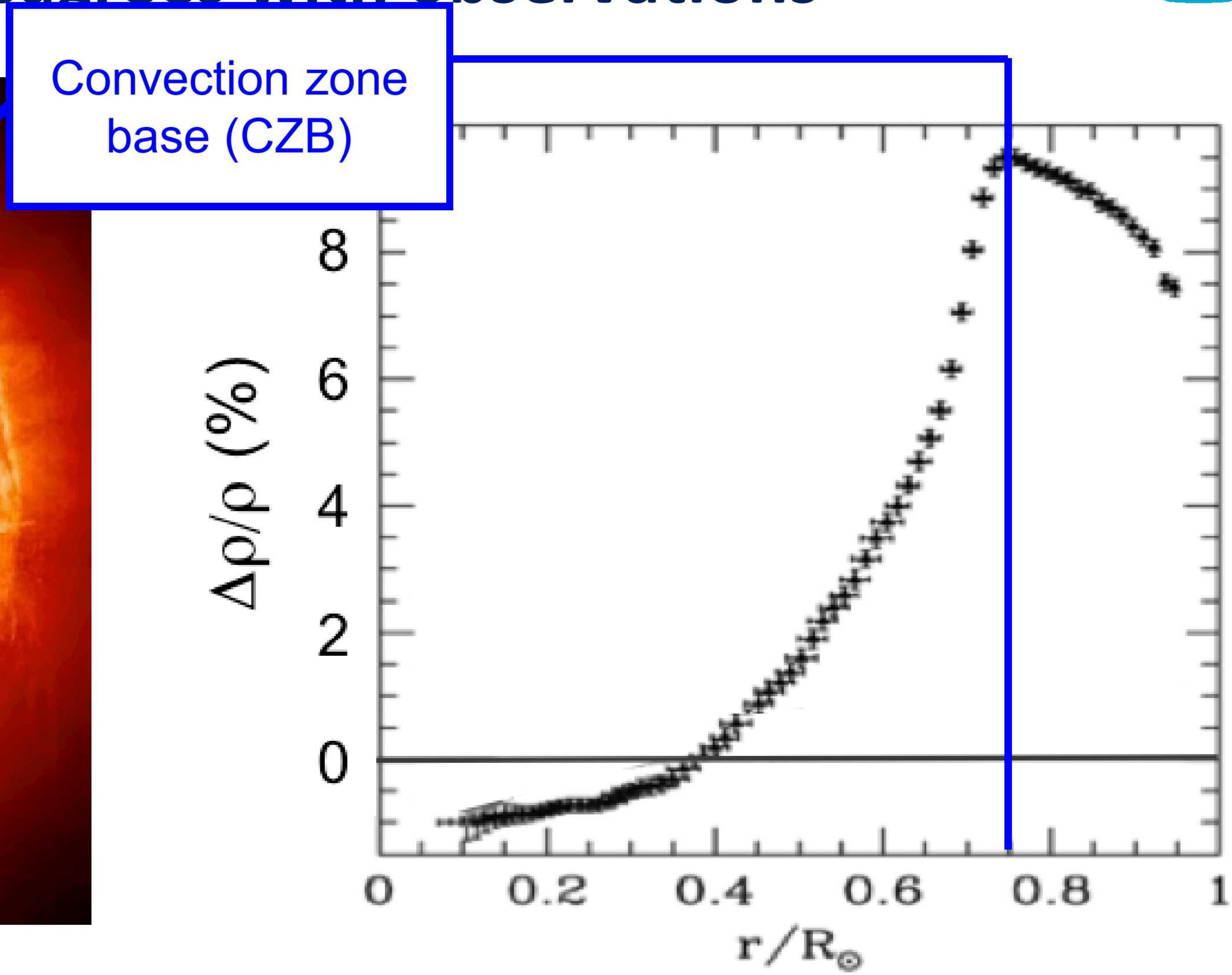
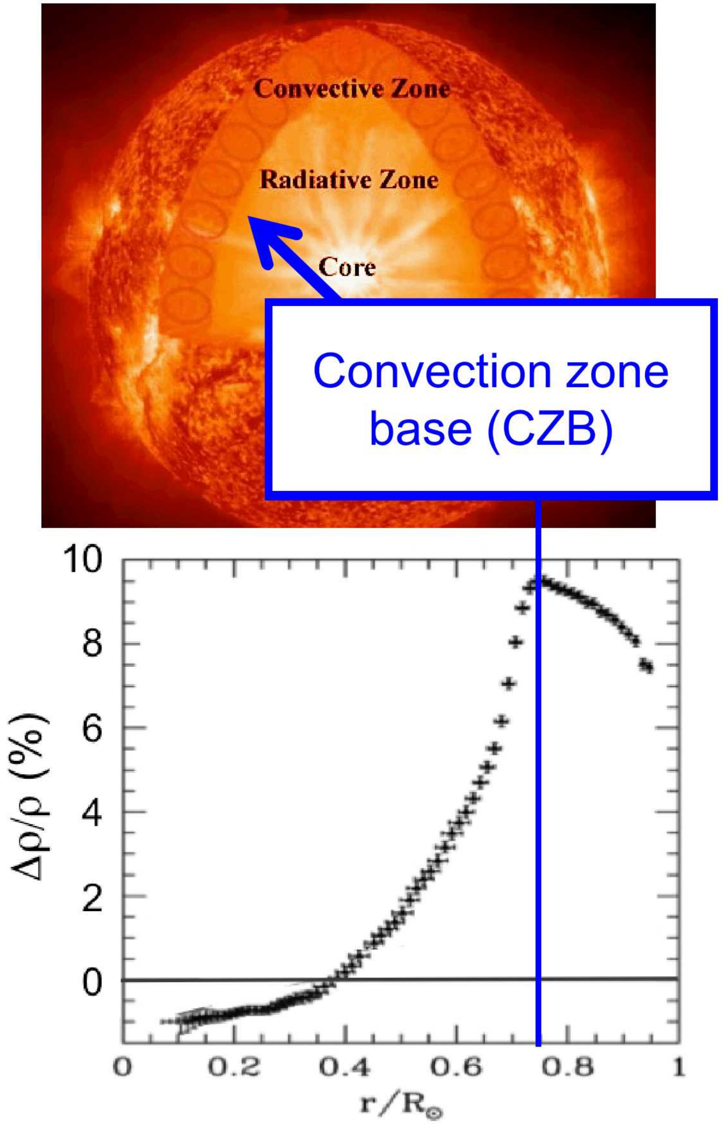




Modeled convection-zone base location disagrees by 30 σ

17% 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

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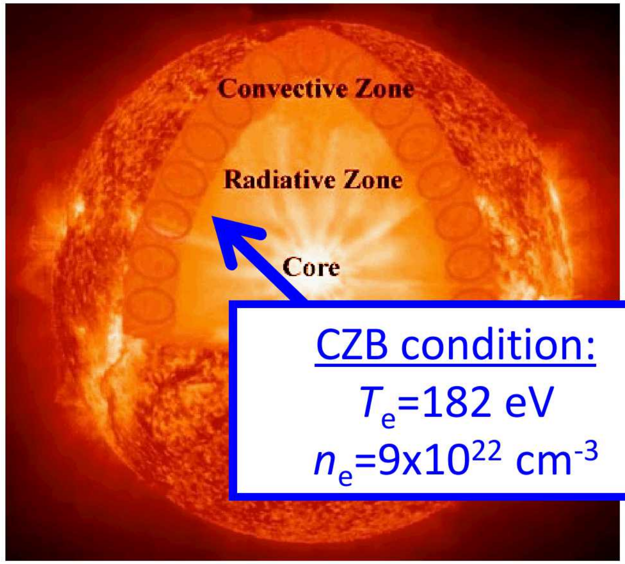
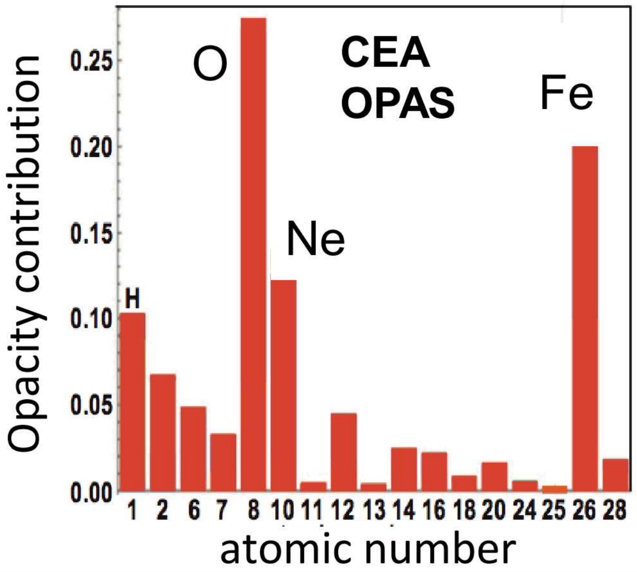


CZB condition:
T_e=182 eV
n_e=9x10^{22} cm^{-3}



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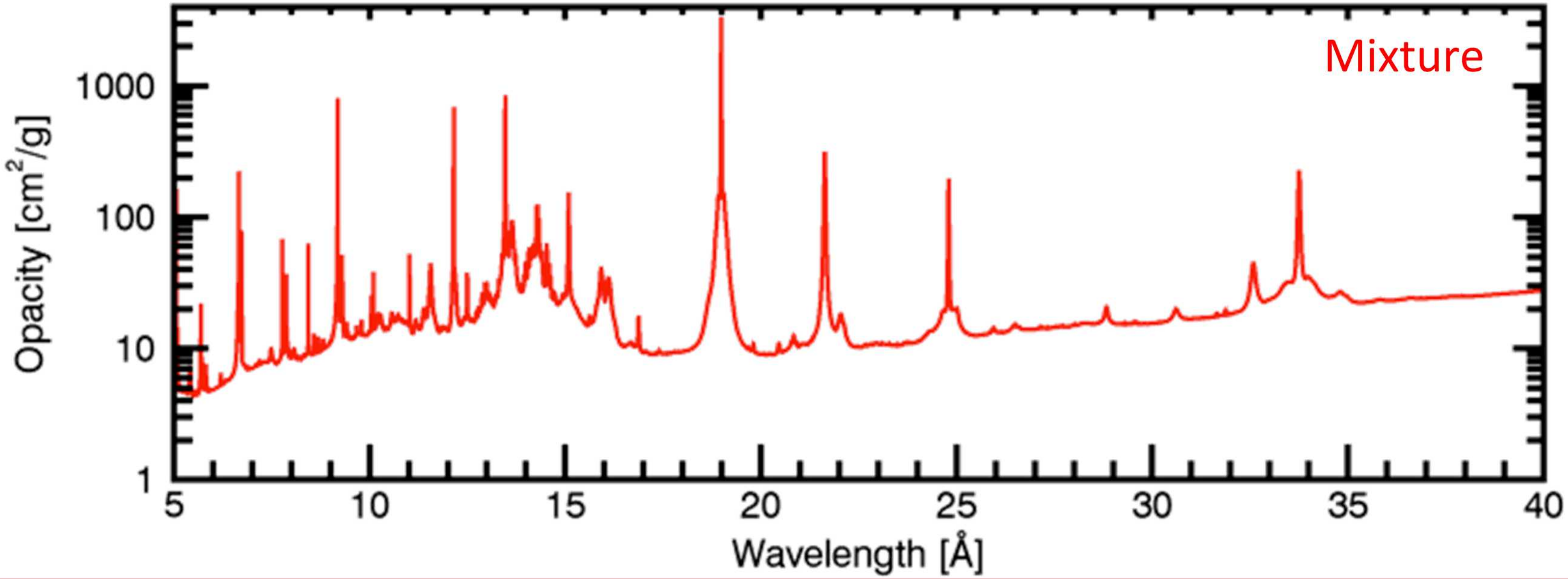
Solar mixture opacity at Convection Zone Base (CZB)



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

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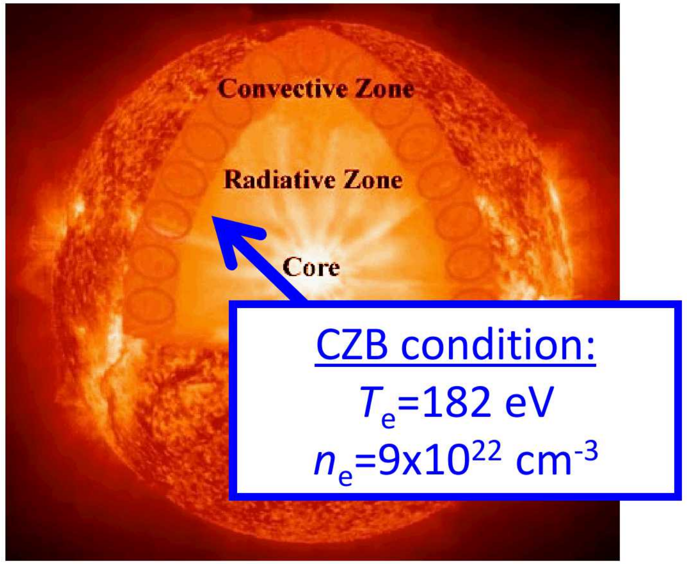

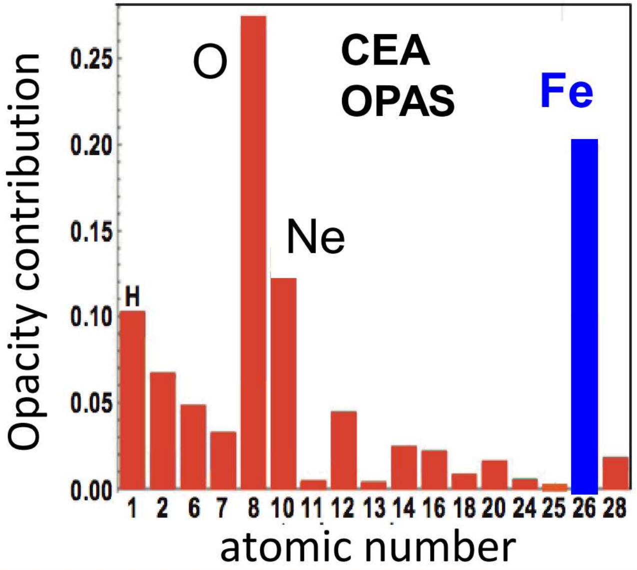

Opacity: κ_ν

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Fe is a likely suspect:

- 2nd largest contribution
- Most difficult to model

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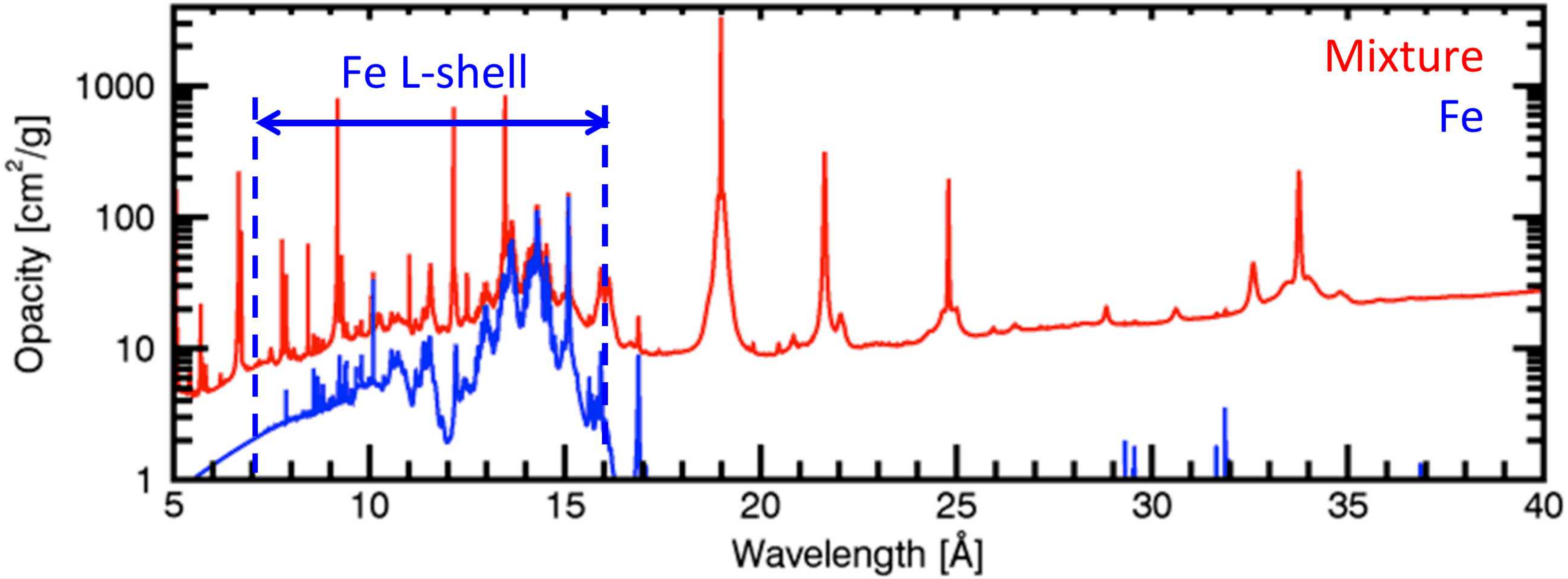
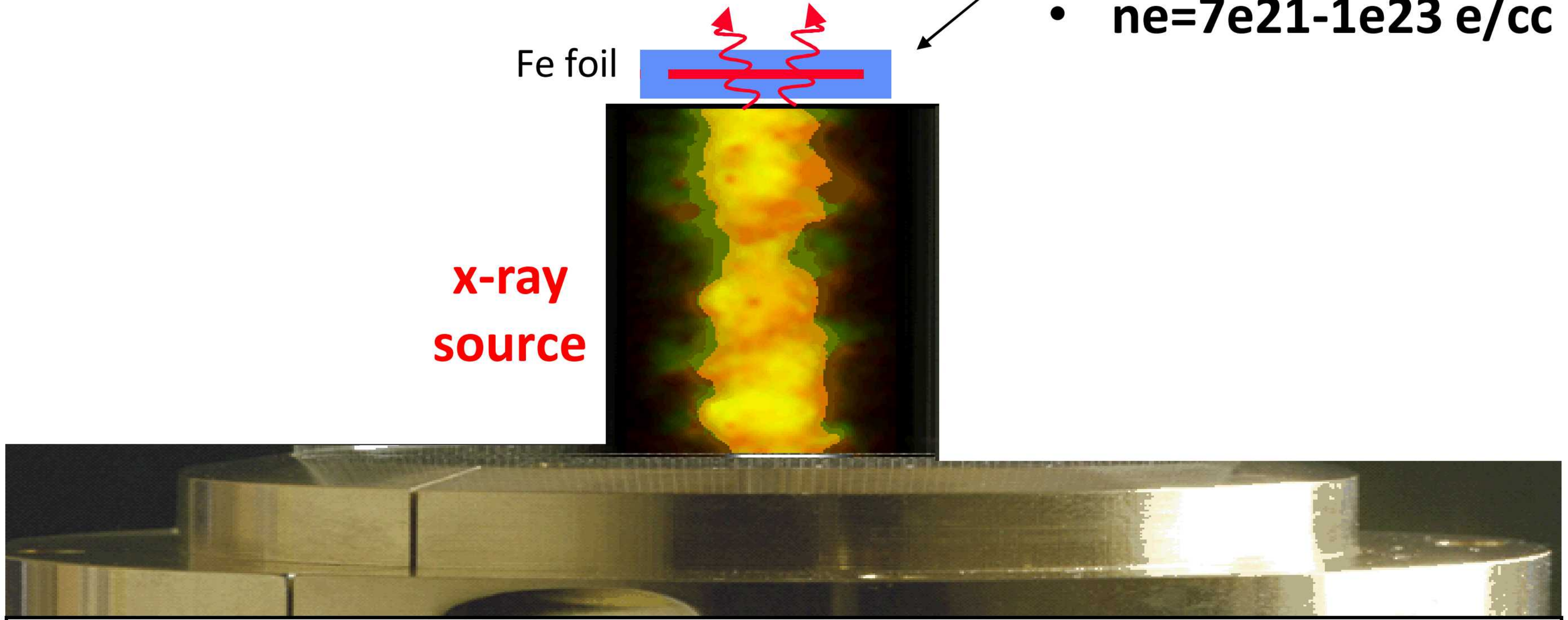


The SNL Z machine uses 27 million Amperes to create x-rays, and perform multiple benchmark experiments simultaneously

Solar opacity sample

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



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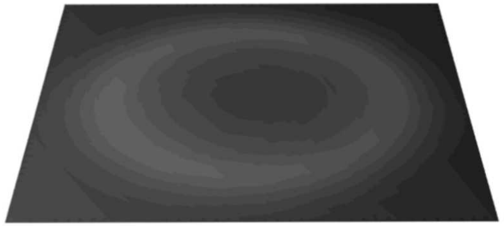
High-temperature Fe opacities are measured using the Z-Pinch opacity science platform



Z-pinch radiation source

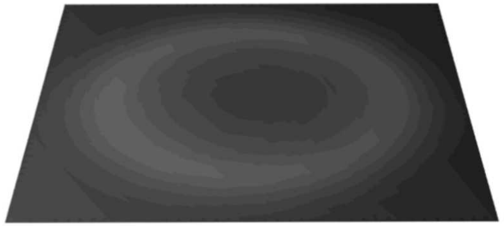
<u>Requirements</u>

- Uniform heating
- Mitigating self emission
- Condition measurements

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

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

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



Z-pinch radiation source

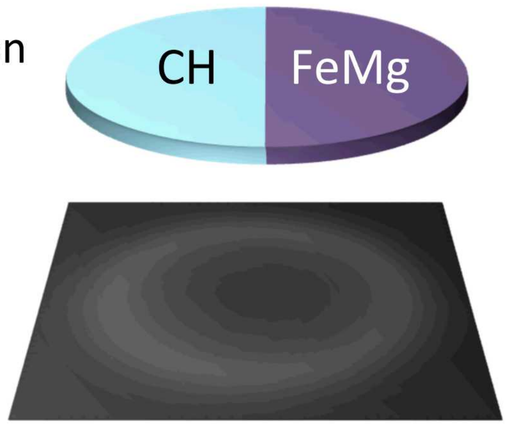
<u>Requirements</u>

- Uniform heating
- Mitigating self emission
- Condition measurements

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

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

Half-moon sample



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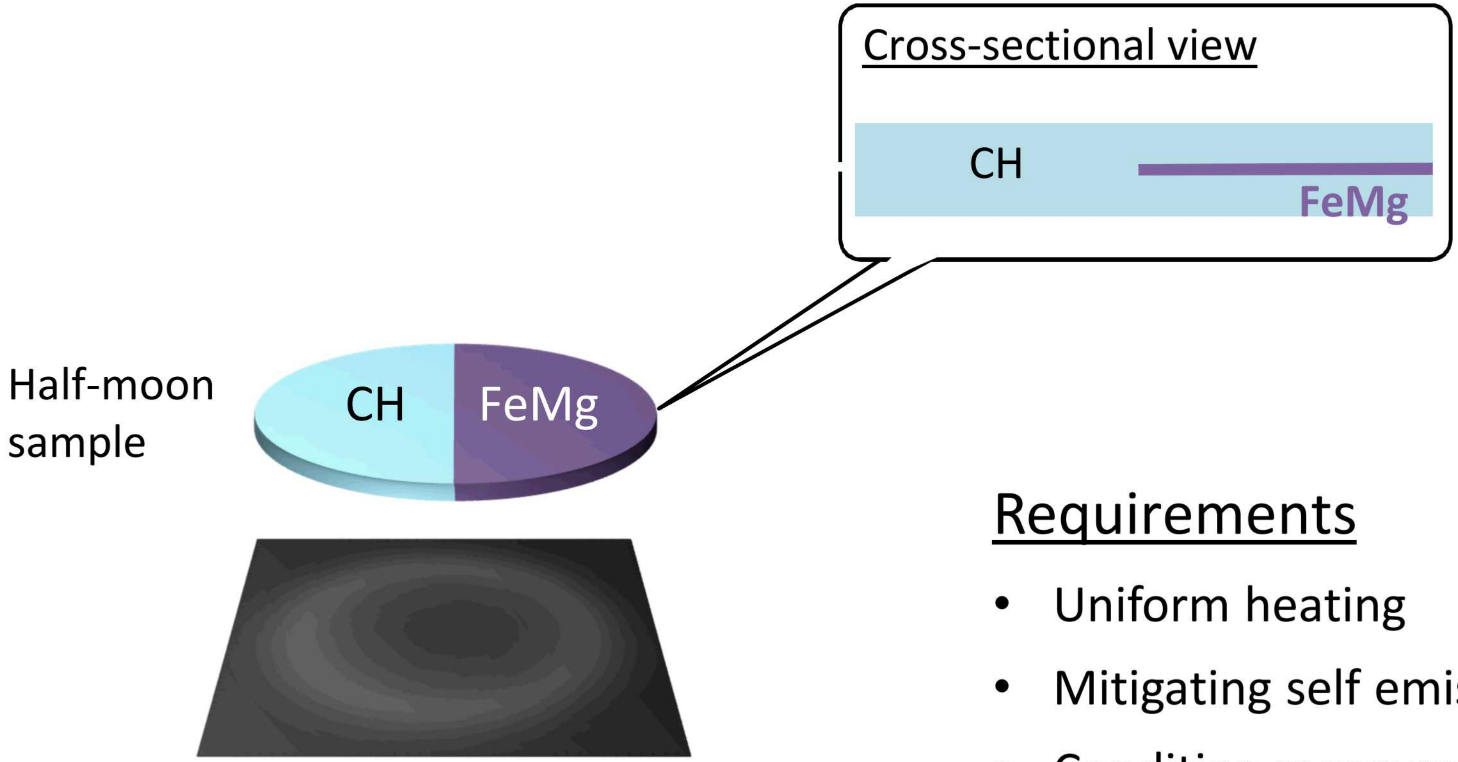

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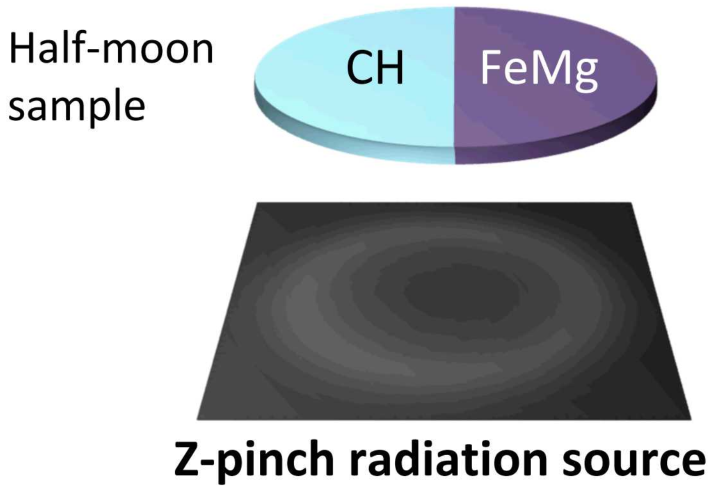

<u>Requirements</u>

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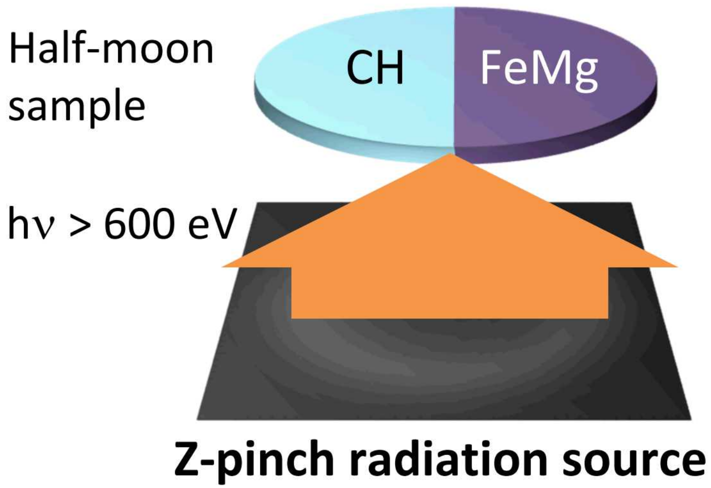

Requirements

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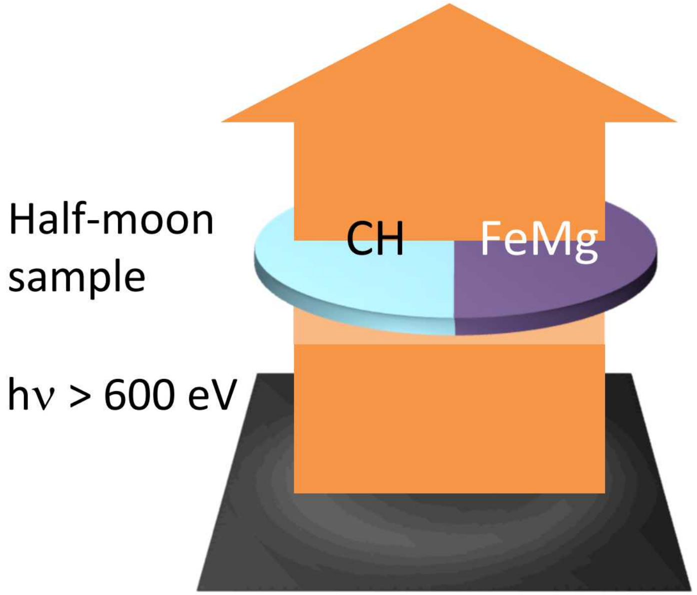

Z-pinch radiation source

Requirements

- Uniform heating
- Mitigating self emission
- Condition measurements

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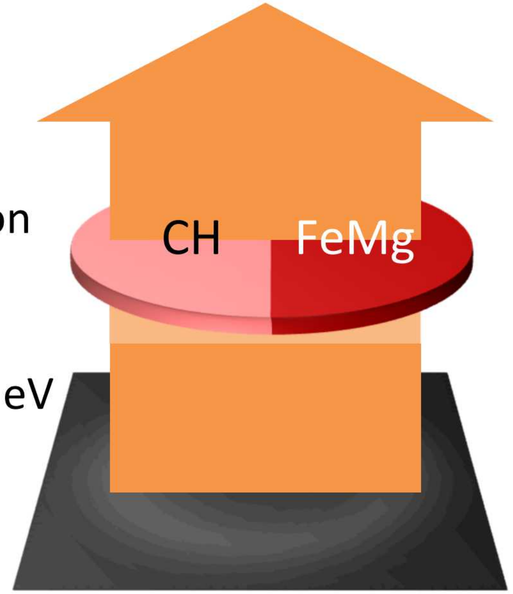


Z-pinch radiation source

Requirements

- Uniform heating → Volumetric heating
- Mitigating self emission
- Condition measurements

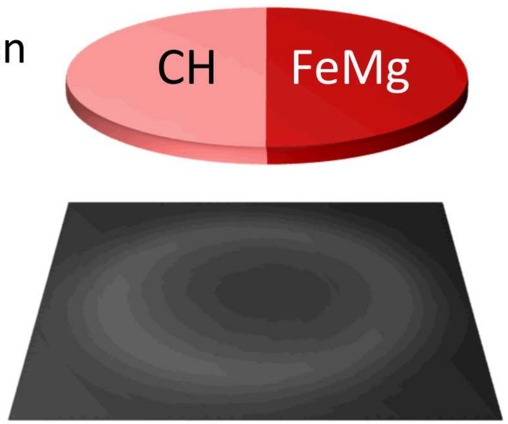
SNL Z satisfies:

Volumetric heating

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

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

Half-moon sample



Z-pinch radiation source

<u>Requirements</u>

- Uniform heating → Volumetric heating
- Mitigating self emission
- Condition measurements

<u>SNL Z satisfies:</u>

Volumetric heating

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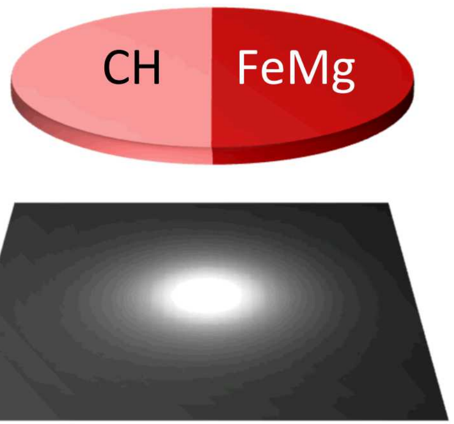
Half-moon sample



Z-pinch radiation source

Requirements	SNL Z satisfies:
• Uniform heating →	Volumetric heating
• Mitigating self emission	
• Condition measurements	

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

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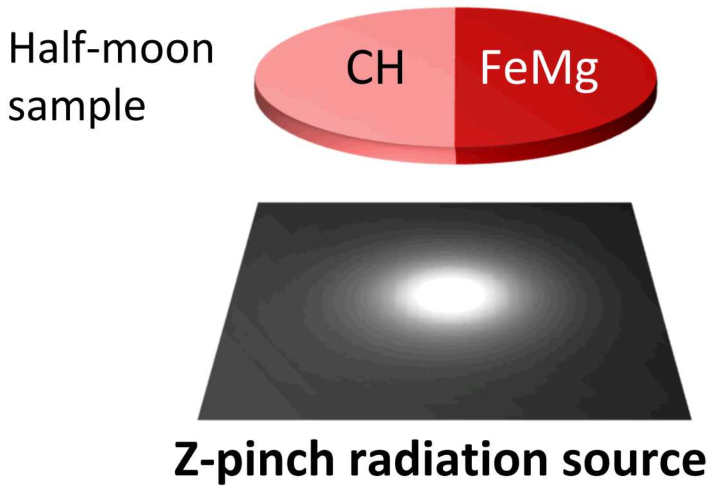

Requirements	SNL Z satisfies:
• Uniform heating →	Volumetric heating
• Mitigating self emission →	350 eV Planckian backlight
• Condition measurements	

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

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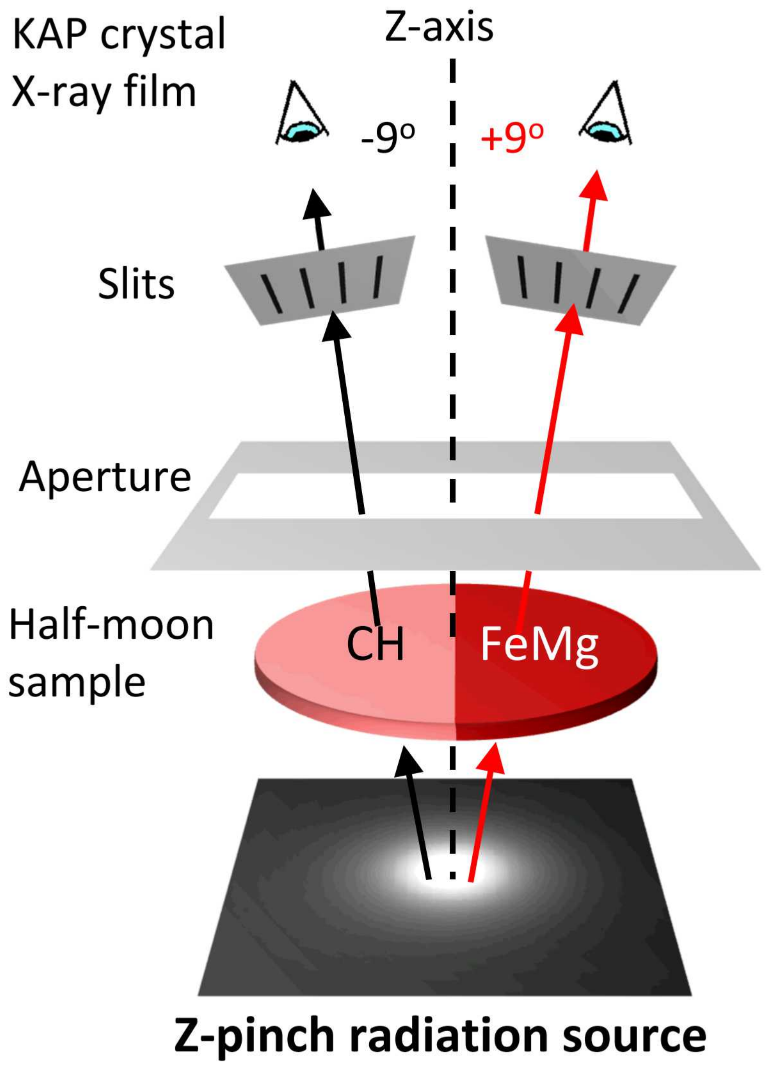

Requirements		SNL Z satisfies:
• Uniform heating	→	Volumetric heating
• Mitigating self emission	→	350 eV Planckian backlight
• Condition measurements		

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

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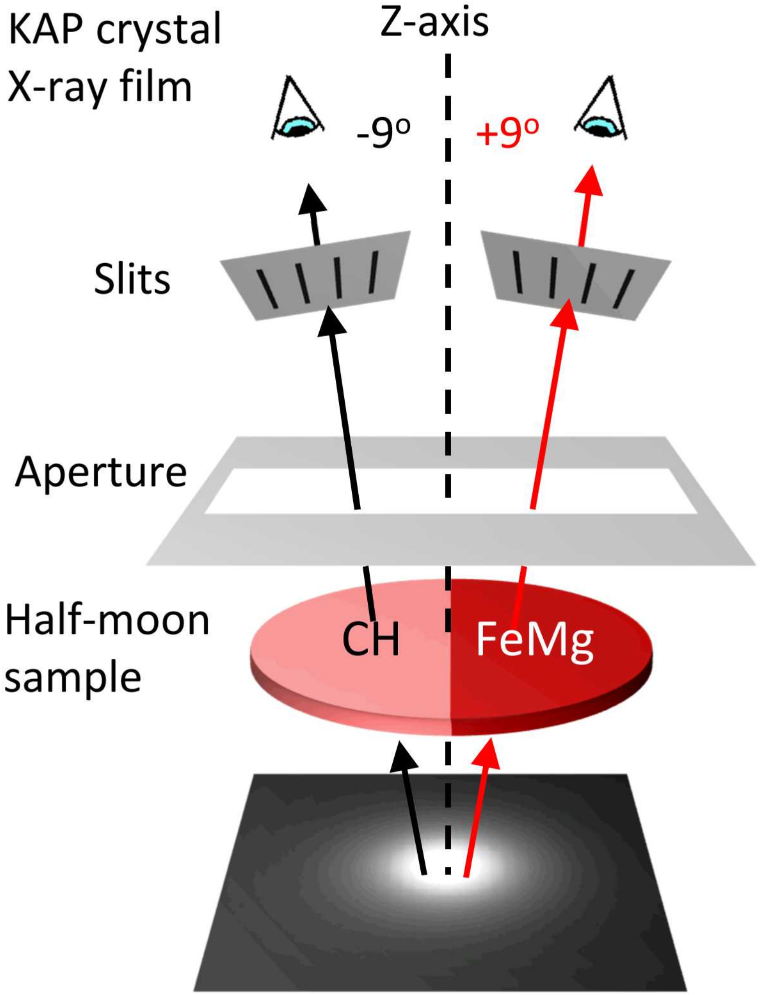
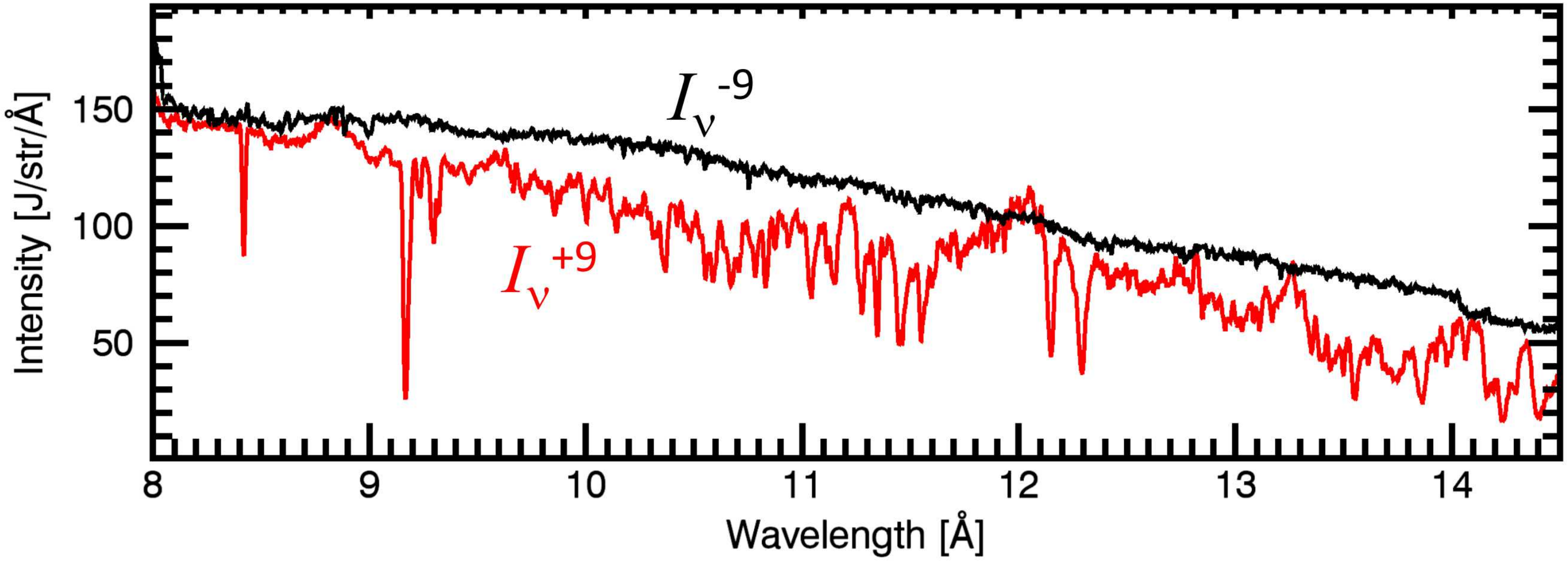


Z-pinch radiation source



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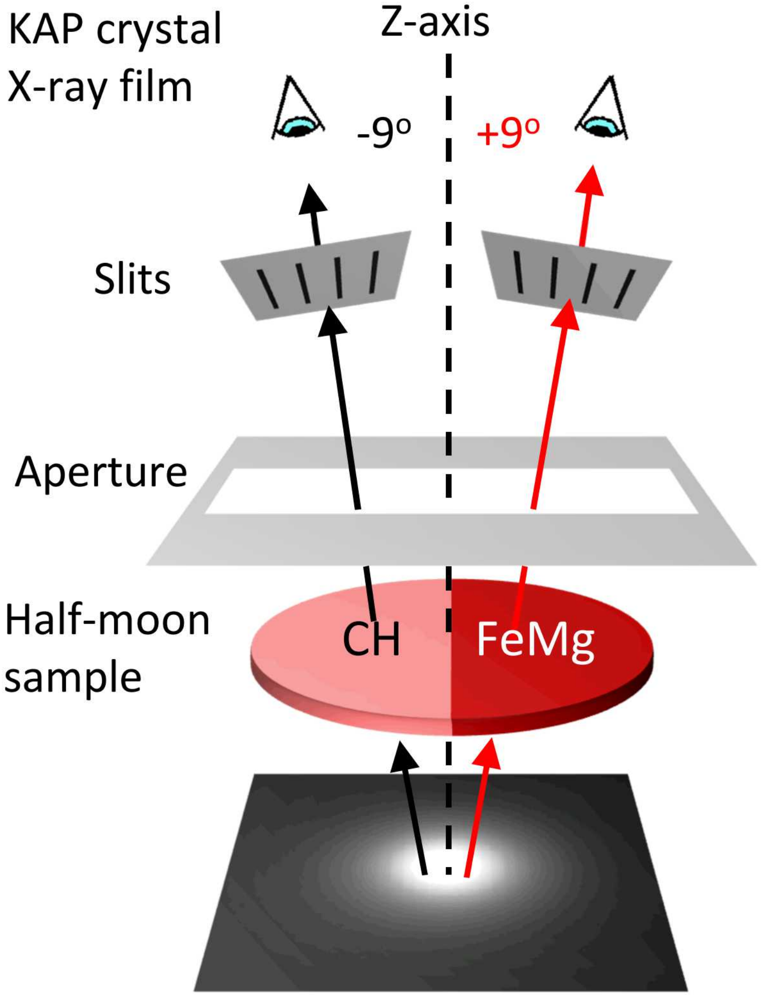

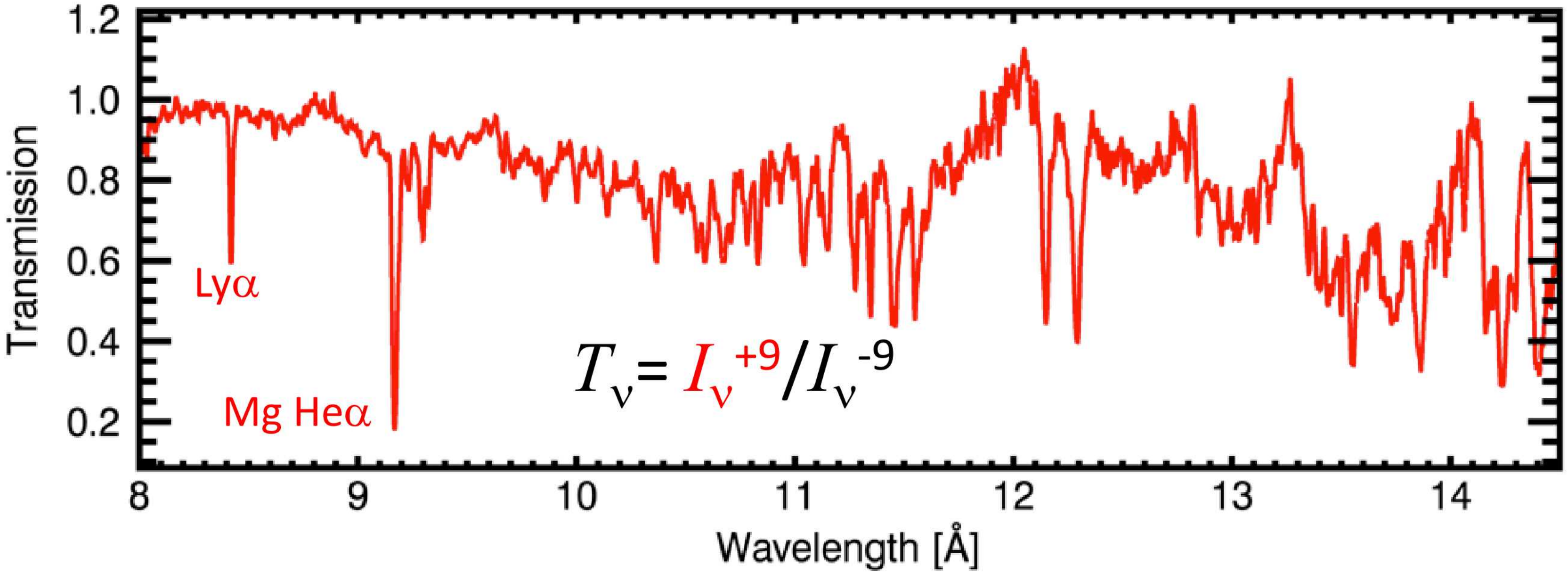

Requirements		SNL Z satisfies:
• Uniform heating	→	Volumetric heating
• Mitigating self emission	→	350 eV Planckian backlight
• Condition measurements		

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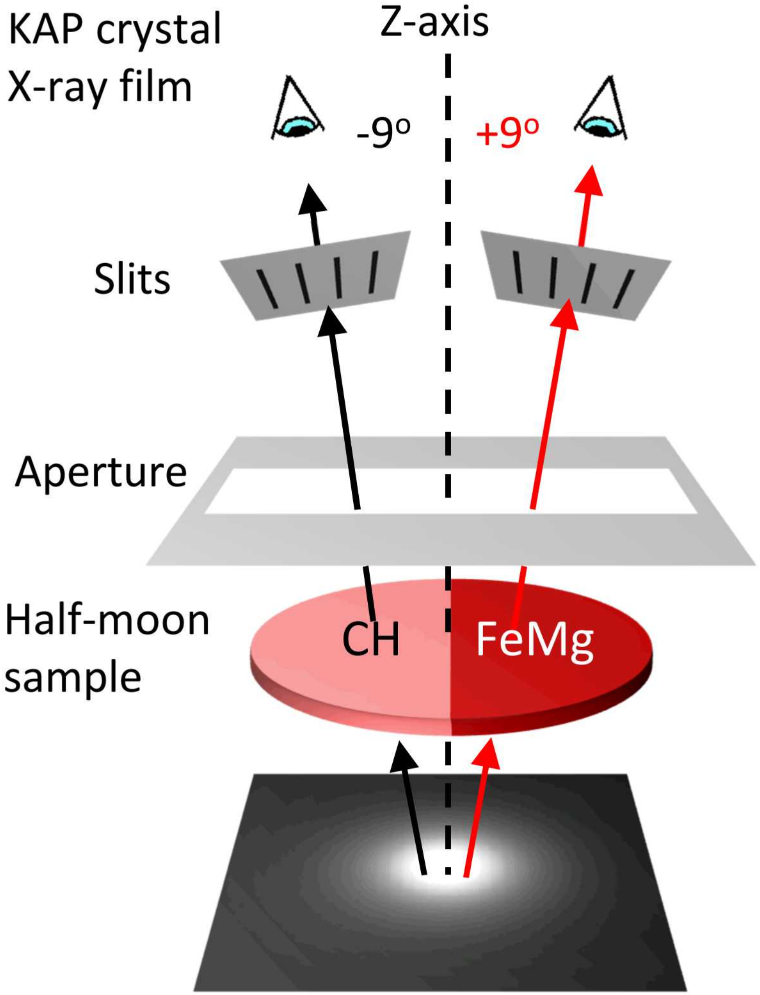
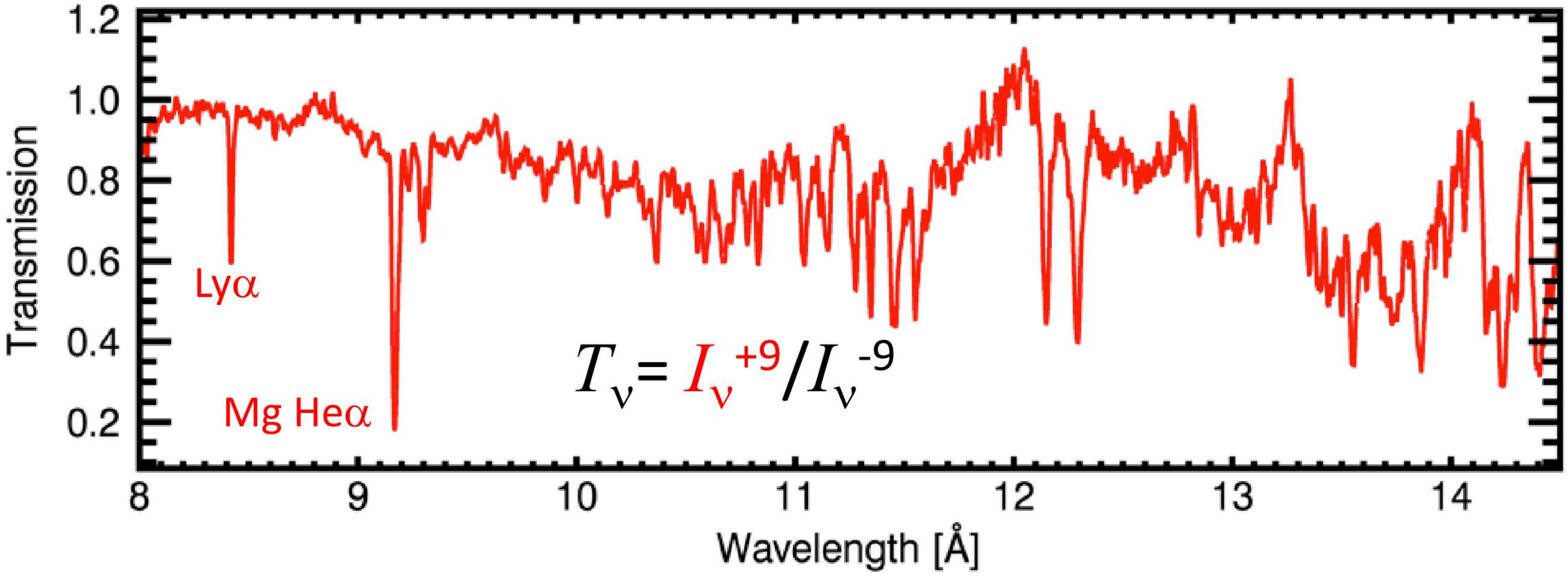
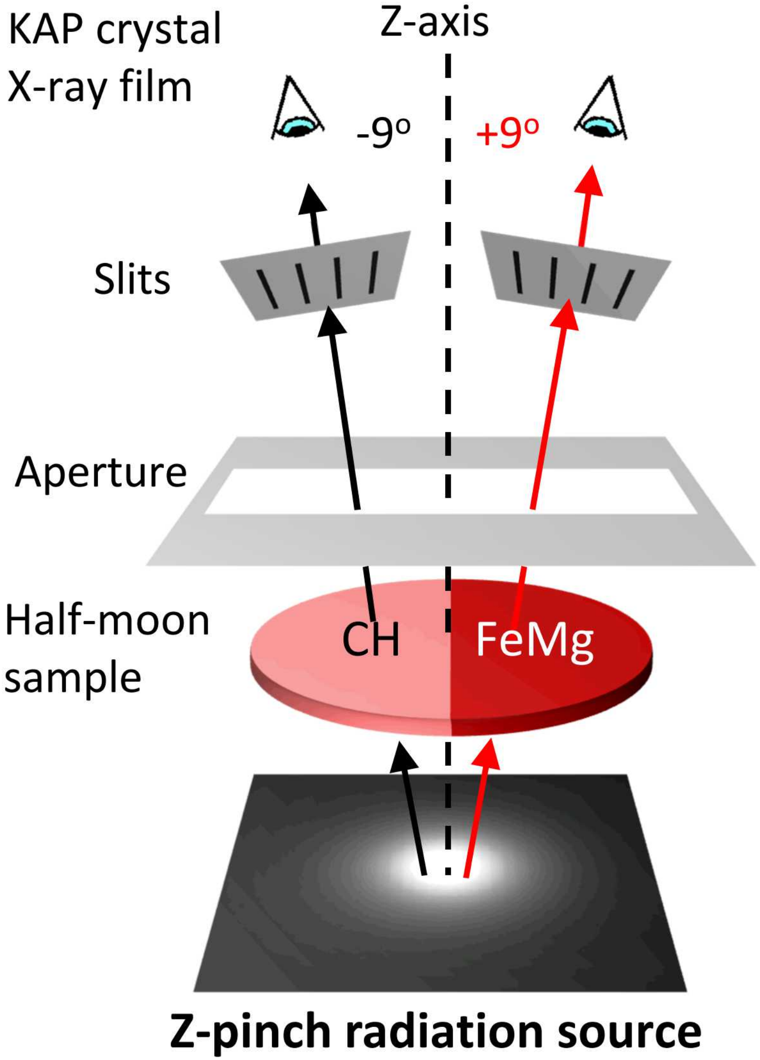


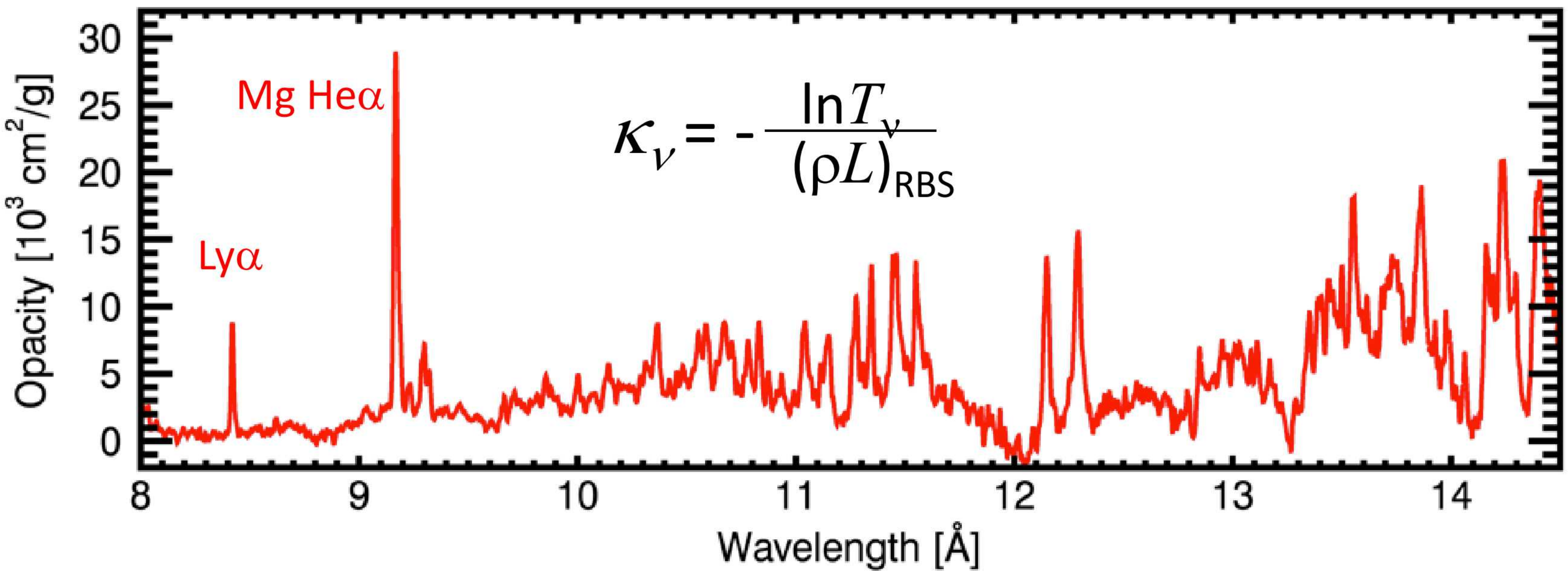


Requirements	SNL Z satisfies:
• Uniform heating →	Volumetric heating
• Mitigating self emission →	350 eV Planckian backlight
• Condition measurements →	Mg K-shell spectroscopy

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

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





Requirements	SNL Z satisfies:
• Uniform heating →	Volumetric heating
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• Condition measurements →	Mg K-shell spectroscopy

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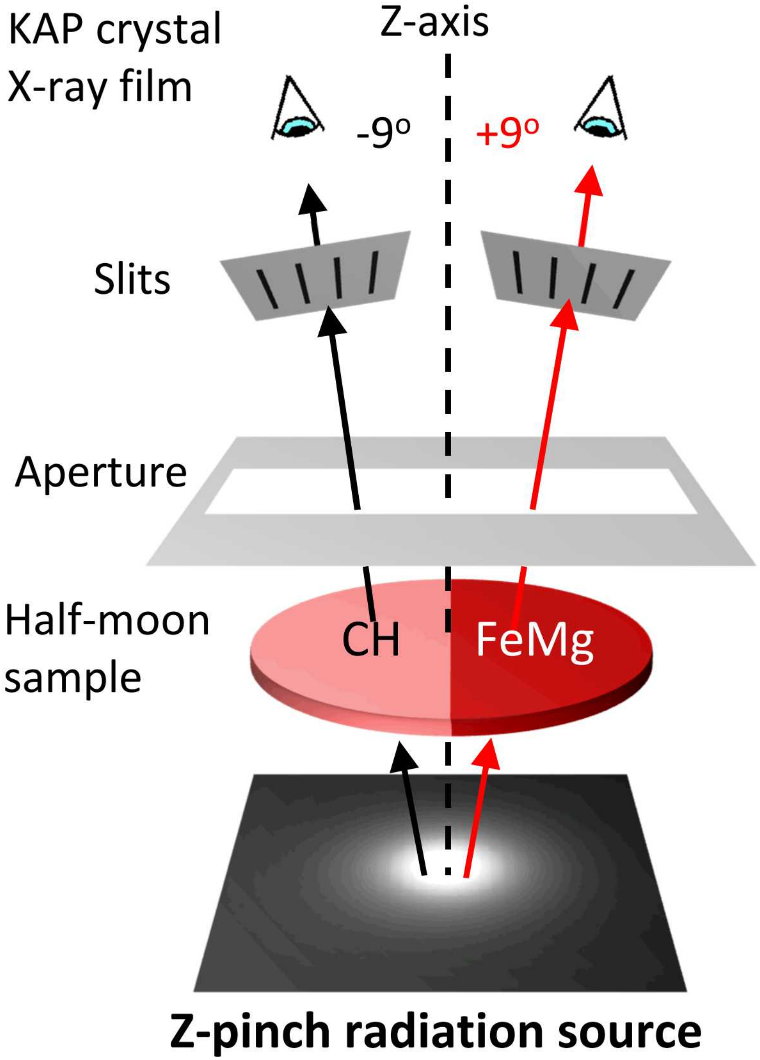
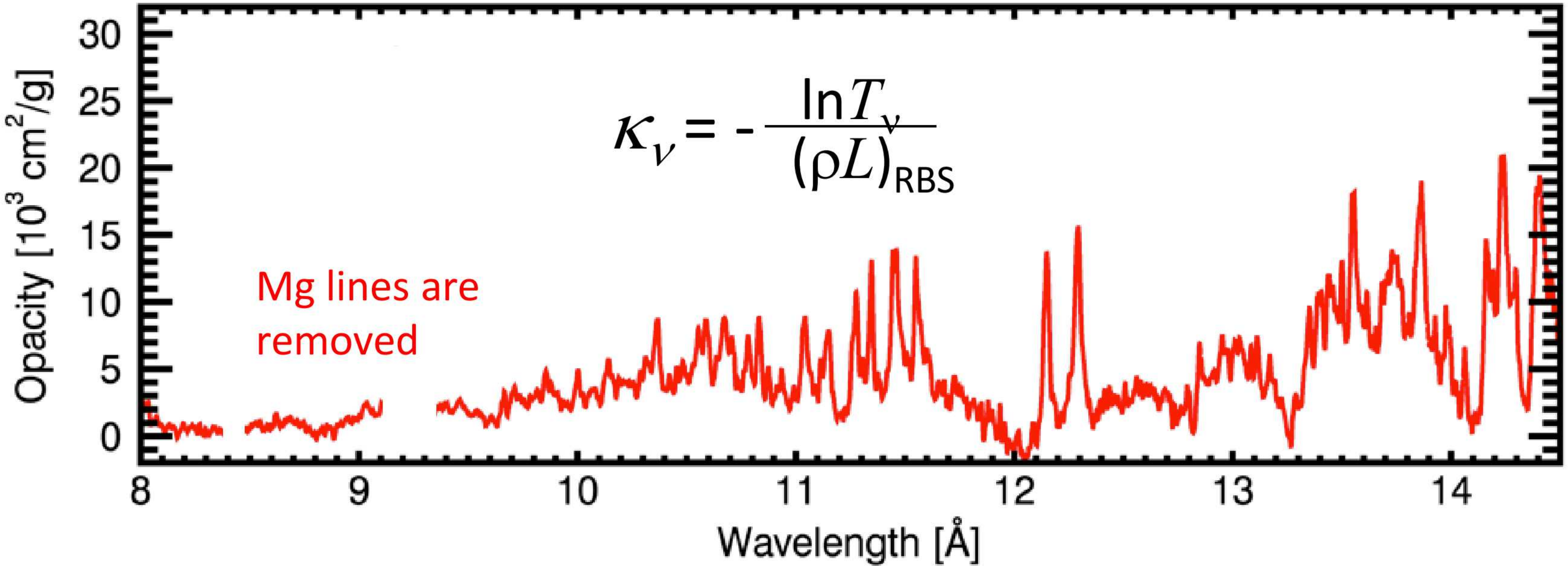


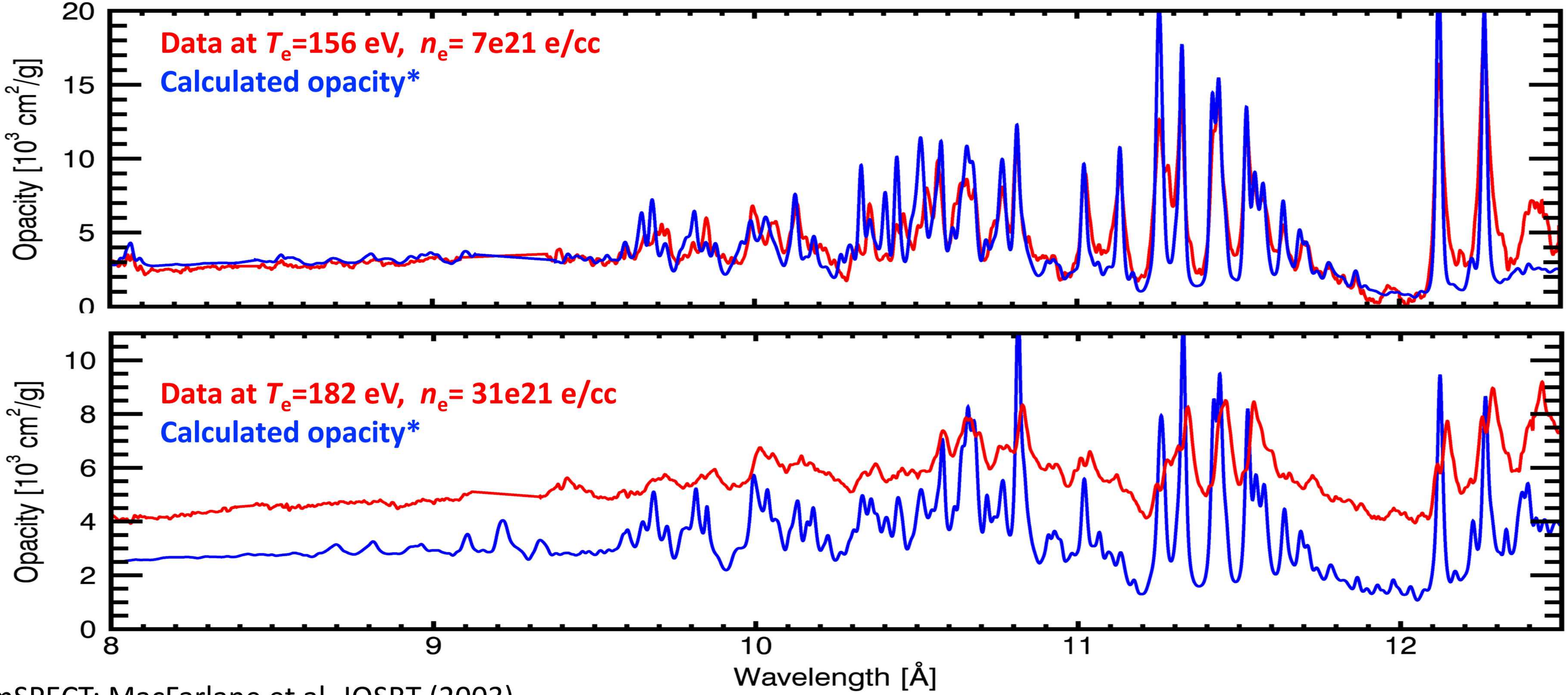


Requirements		SNL Z satisfies:
• Uniform heating	→	Volumetric heating
• Mitigating self emission	→	350 eV Planckian backlight
• Condition measurements	→	Mg K-shell spectroscopy

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

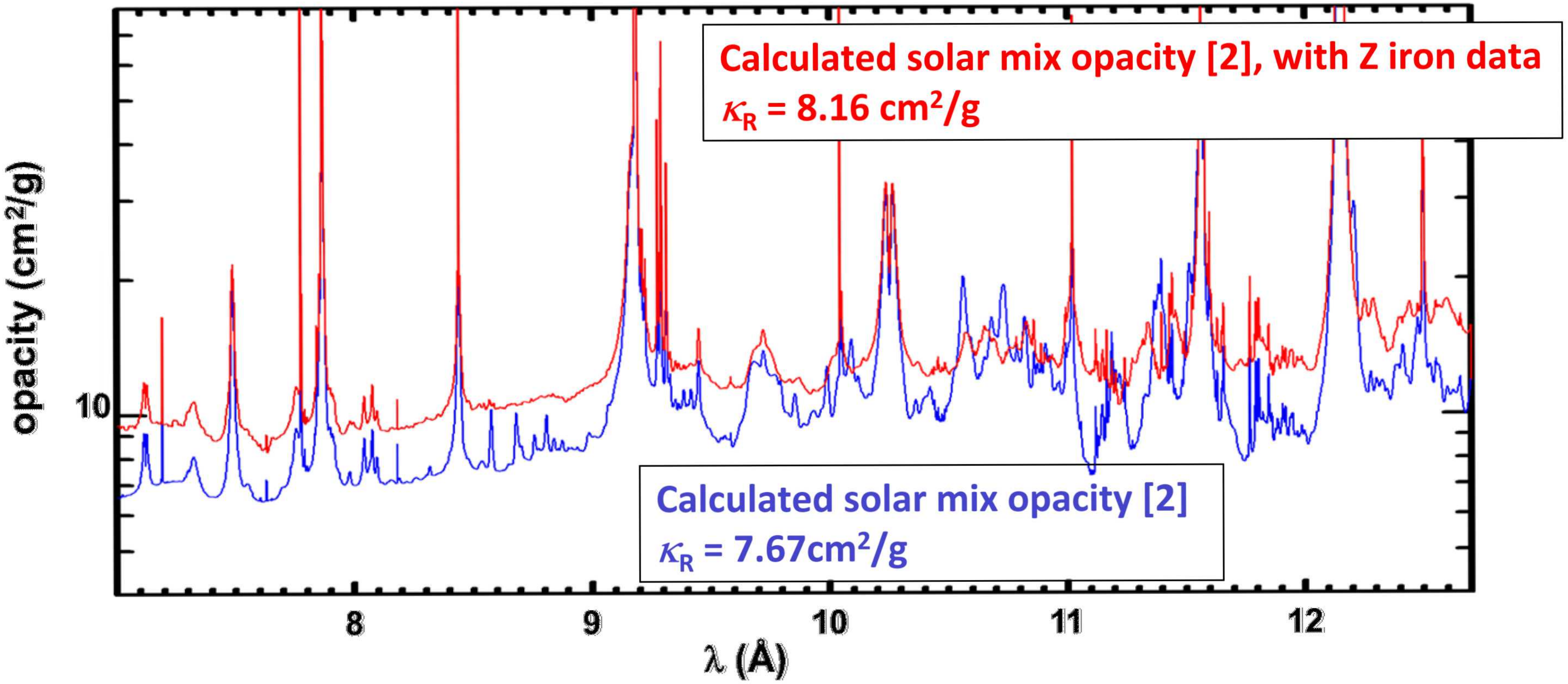
Modeled opacity shows severe disagreement as T_e and n_e approach solar interior conditions

Convection Zone Base: T_e=182 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 increase partially resolves the solar problem
- But the measured iron opacity by itself cannot account for the entire discrepancy
- We need to extend our measurement in spectral range, elements, and conditions

The impact of revising opacity go beyond the Sun

- Finding the discrepancies is just a beginning
  - Is existing theory wrong?
    - Atomic physics?
    - Population?
    - Density effects?
    - Missing physics?
  - Are experiments flawed?
    - Why not flawed at lower Te and rho?
  - We are investigating by measuring opacities of Cr and Ni at higher Te and ne
- Revising opacity has high impact on astrophysics
  - Understanding host stars of exoplanets
  - Neutron star atmosphere
  - Radiative acceleration
    - Gravity pushes inward, radiative acceleration pushes outward
    - Radiative acceleration is important in some stars
  - Biggest uncertainty source for the age of the stars is opacity (Serenelli)

ZAPP campaigns simultaneously study multiple issues

White Dwarf Line-Shapes

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

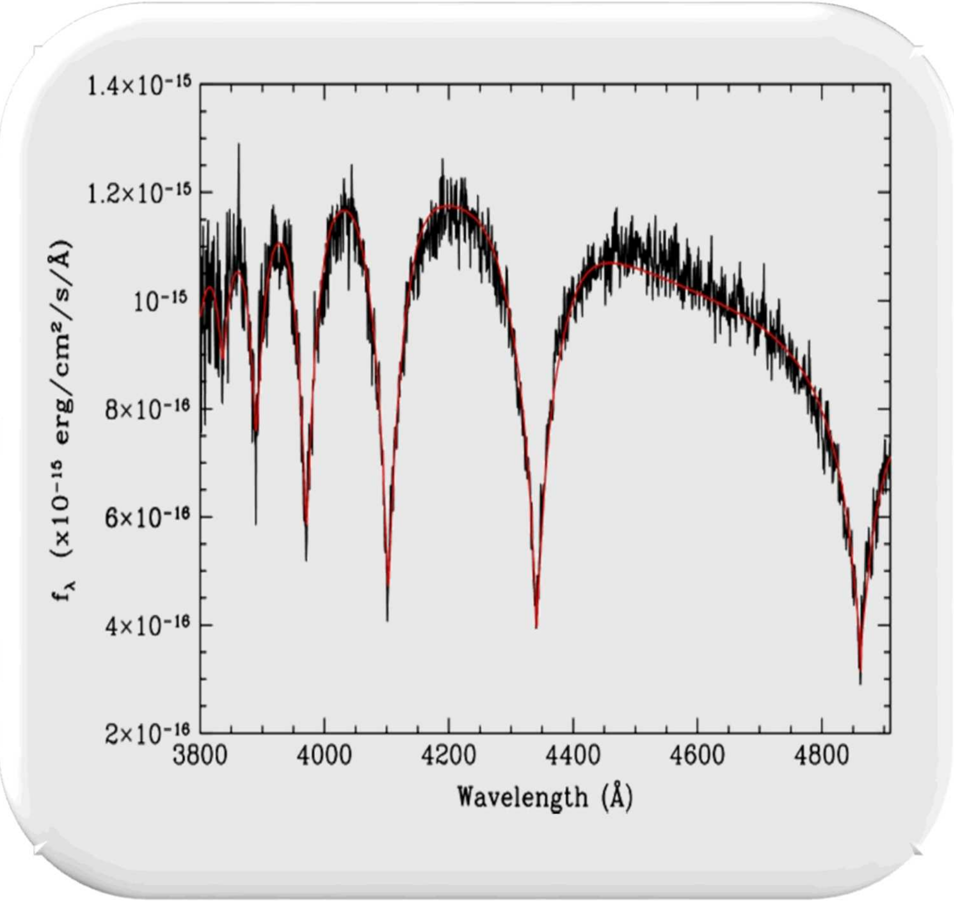
Achieved Conditions:
$T_e \sim 1$ eV, $n_e \sim 10^{17}$ cm^{-3}

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

- White Dwarfs are fundamentally important
  - Evolutionary endpoint for ~98% of stars
  - Simple in structure and evolution
  - Cosmic laboratories (cosmochronology)

- WD surface temperature and total mass are usually determined by fitting the observed spectra

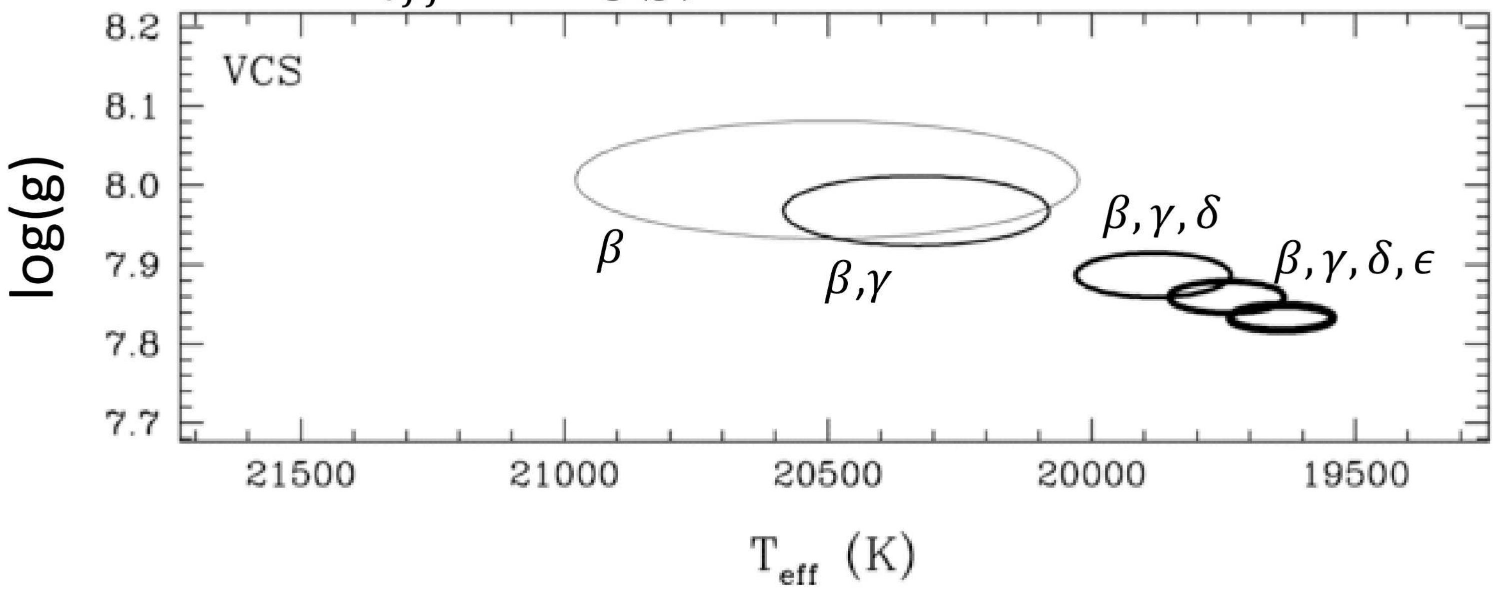
- The spectroscopic method and gravitational redshift disagree by >10% in the stellar mass

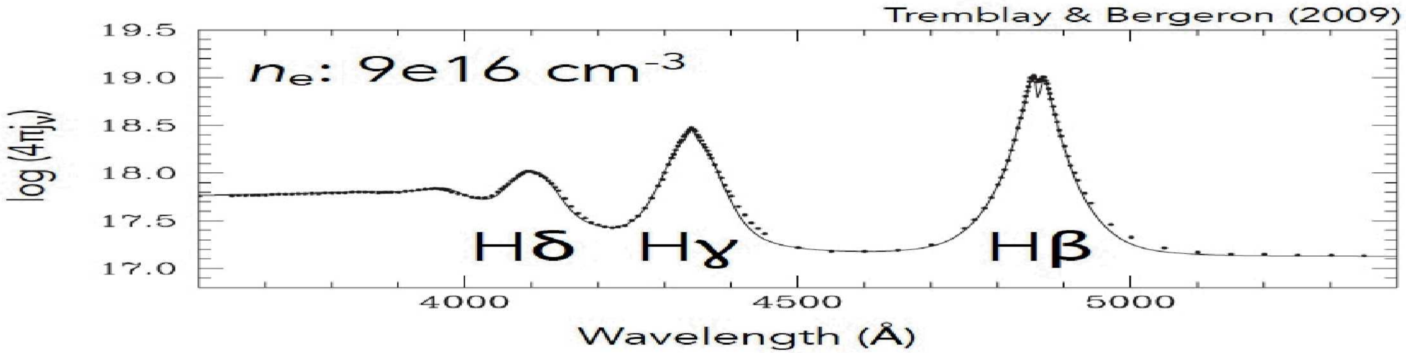


This 10% uncertainty in mass yields 0.5 G year difference for the age of galaxy

There are inconsistencies in mass inferred from different lines while Wiese emission measurements validated the models

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





Puzzling facts:

- Higher lines lower the inferred $\log(g)$
- VCS was validated against Wiese's benchmark emission spectra

Limitation of Wiese's data:

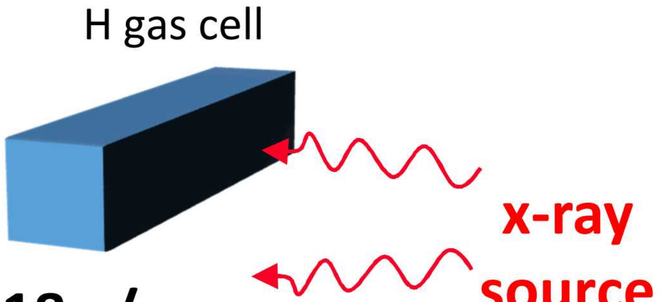
- Available only up to 1×10^{17} cm^{-3}
- Measured emission spectra

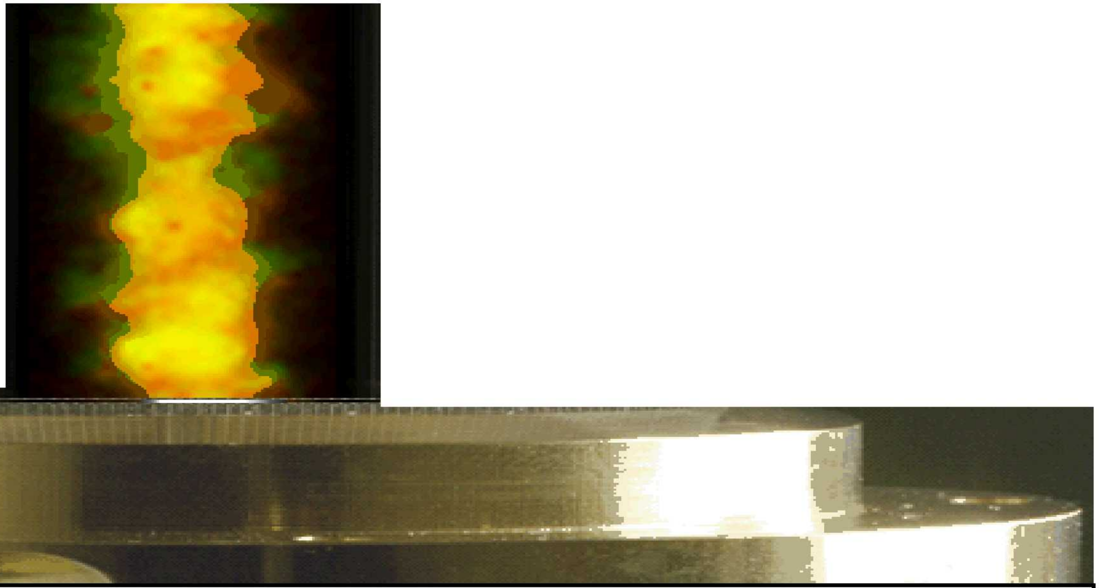
Need to measure line shapes both in emission and absorption up to higher density

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

White Dwarf Photosphere:

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



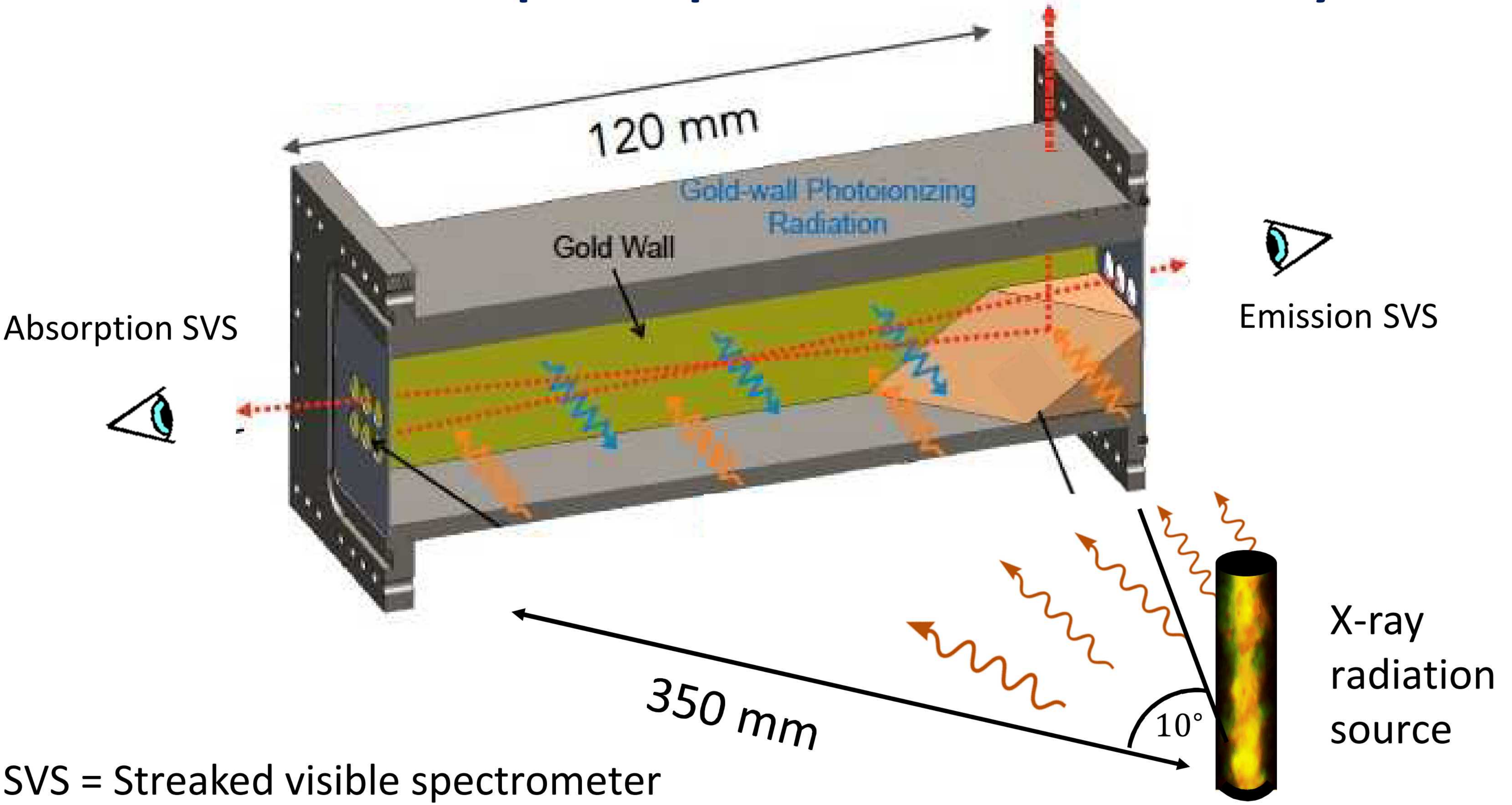


P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

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

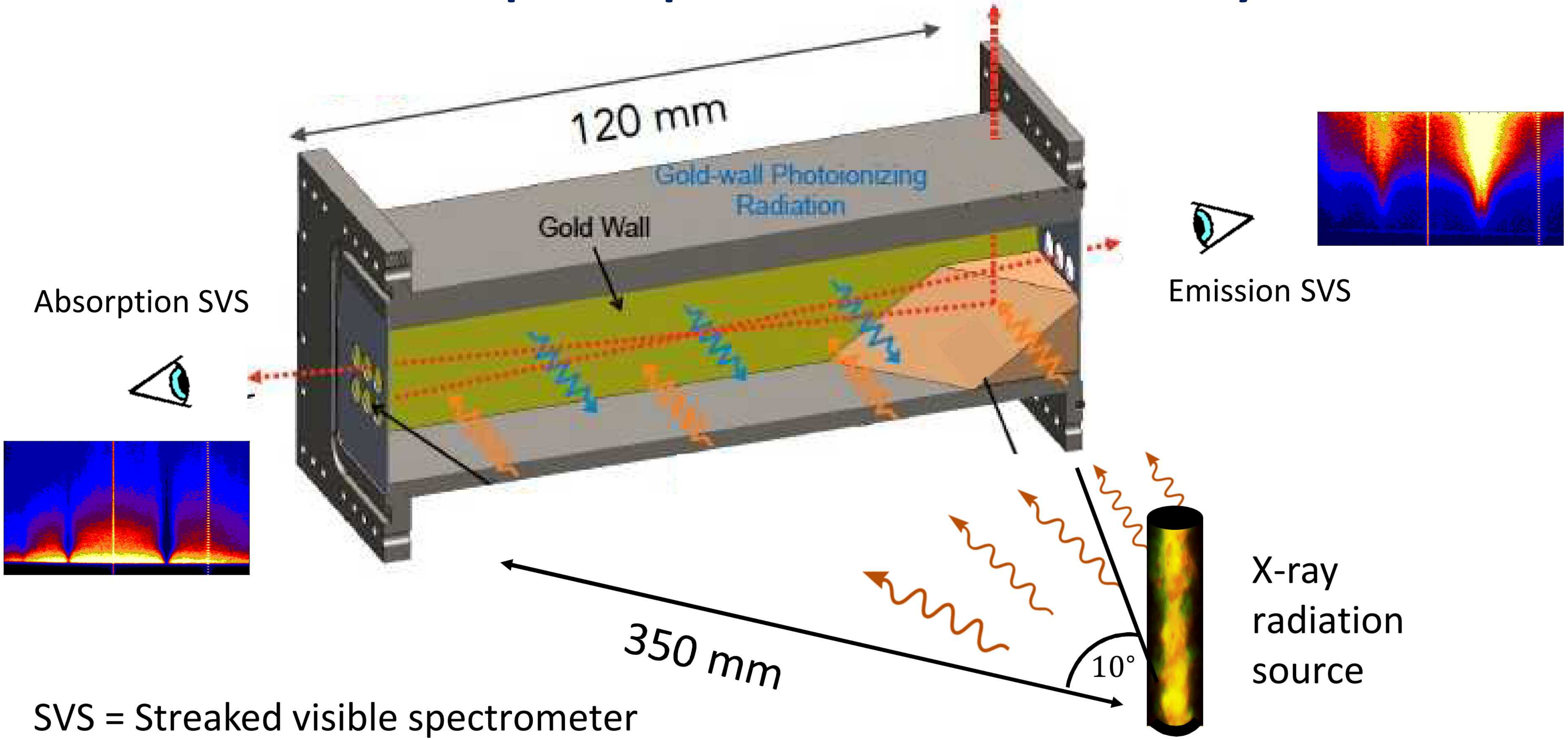
Sanford, *PoP* (2002); Bailey et al., *PoP* (2006); Slutz et al., *PoP* (2006); Rochau et al., *PPCF* (2007)

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



SVS = Streaked visible spectrometer

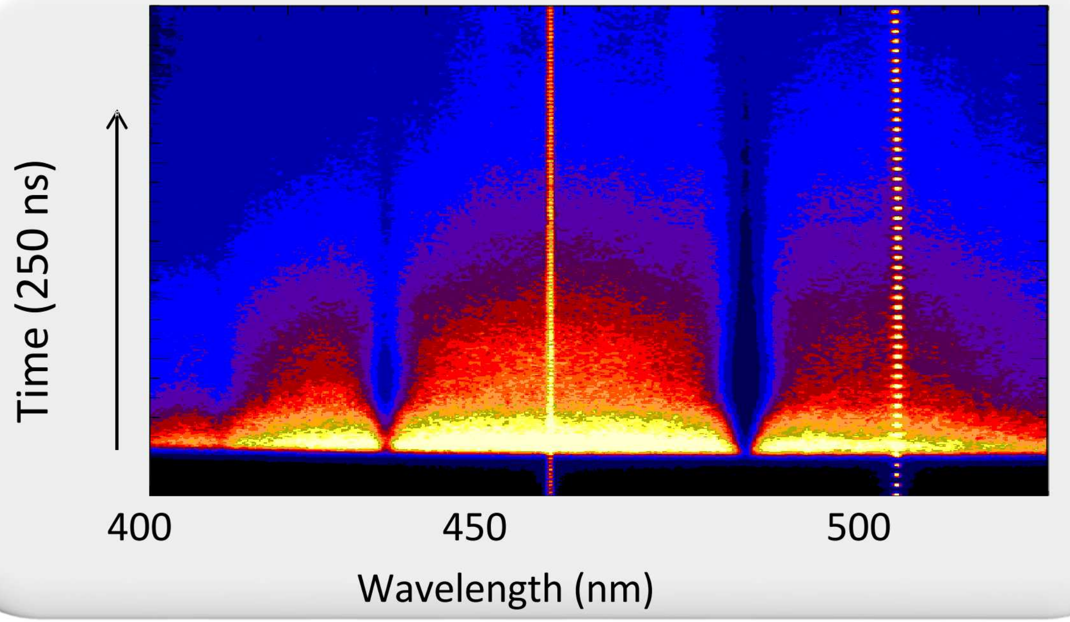
Hydrogen gas is heated by reemission from the gold wall; Its emission and absorption spectra are simultaneously observed



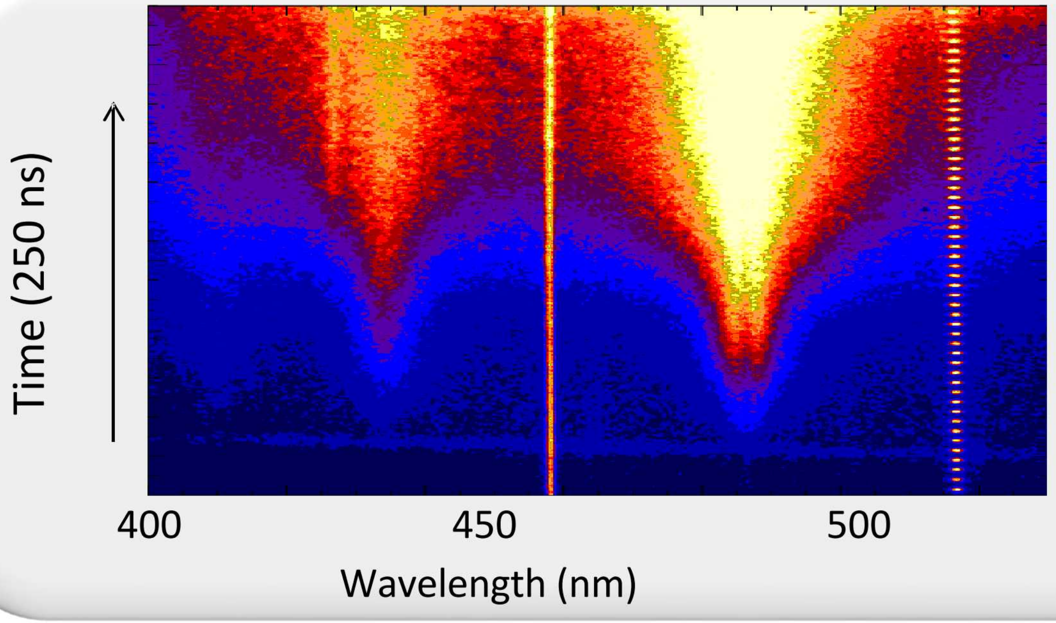
SVS = Streaked visible spectrometer

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

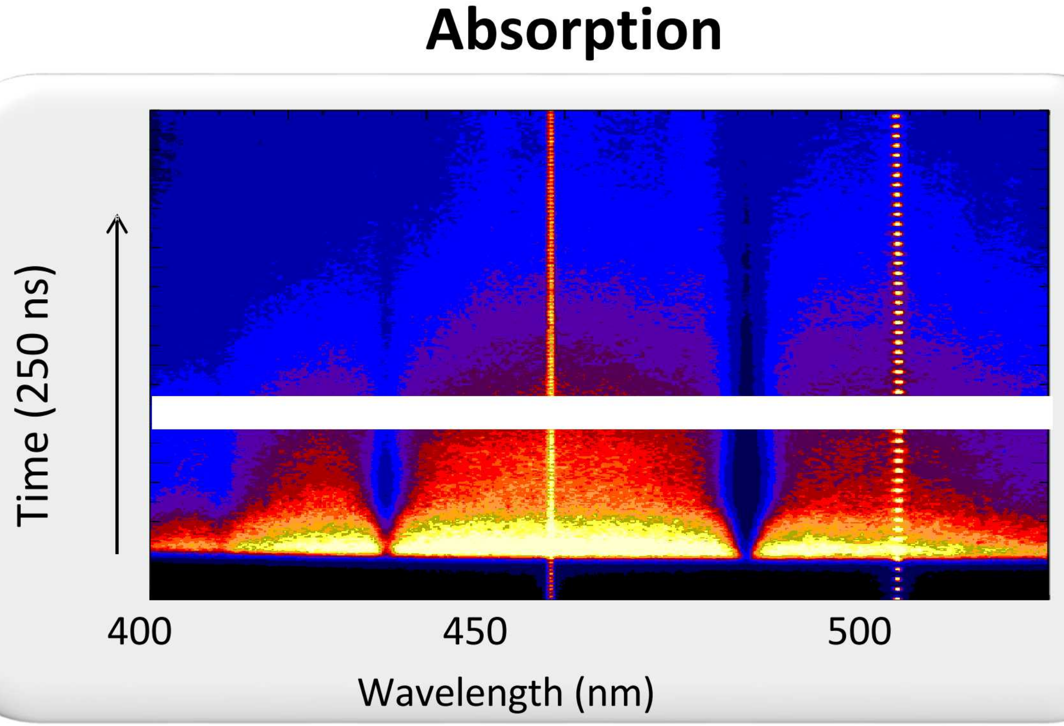
Absorption

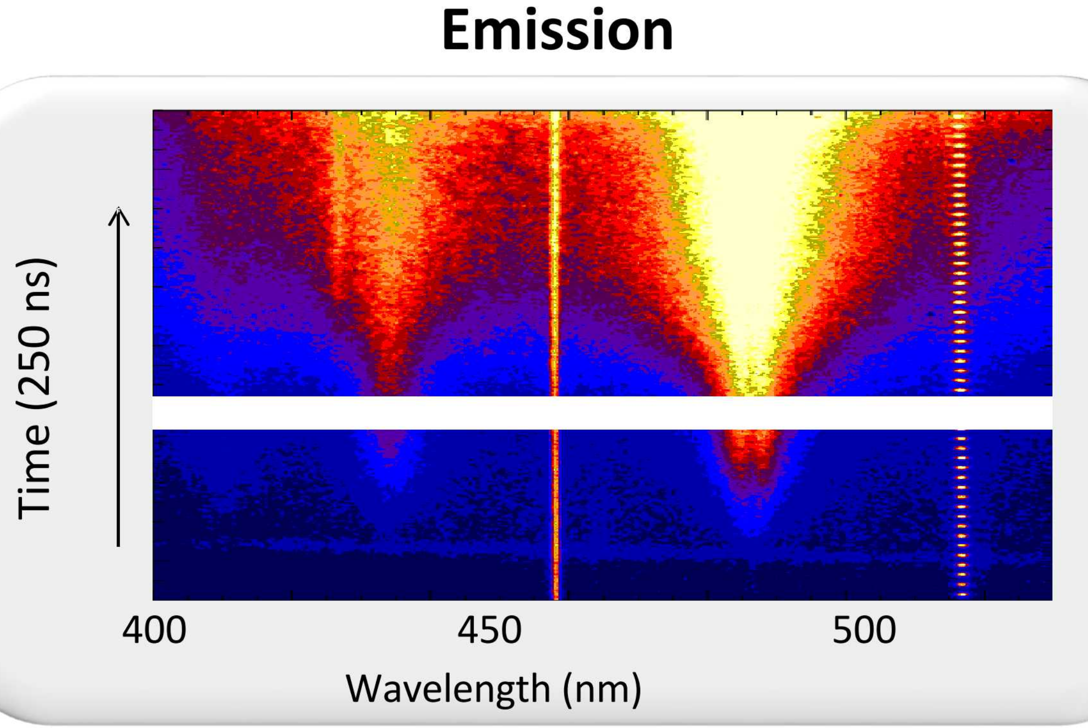


Emission



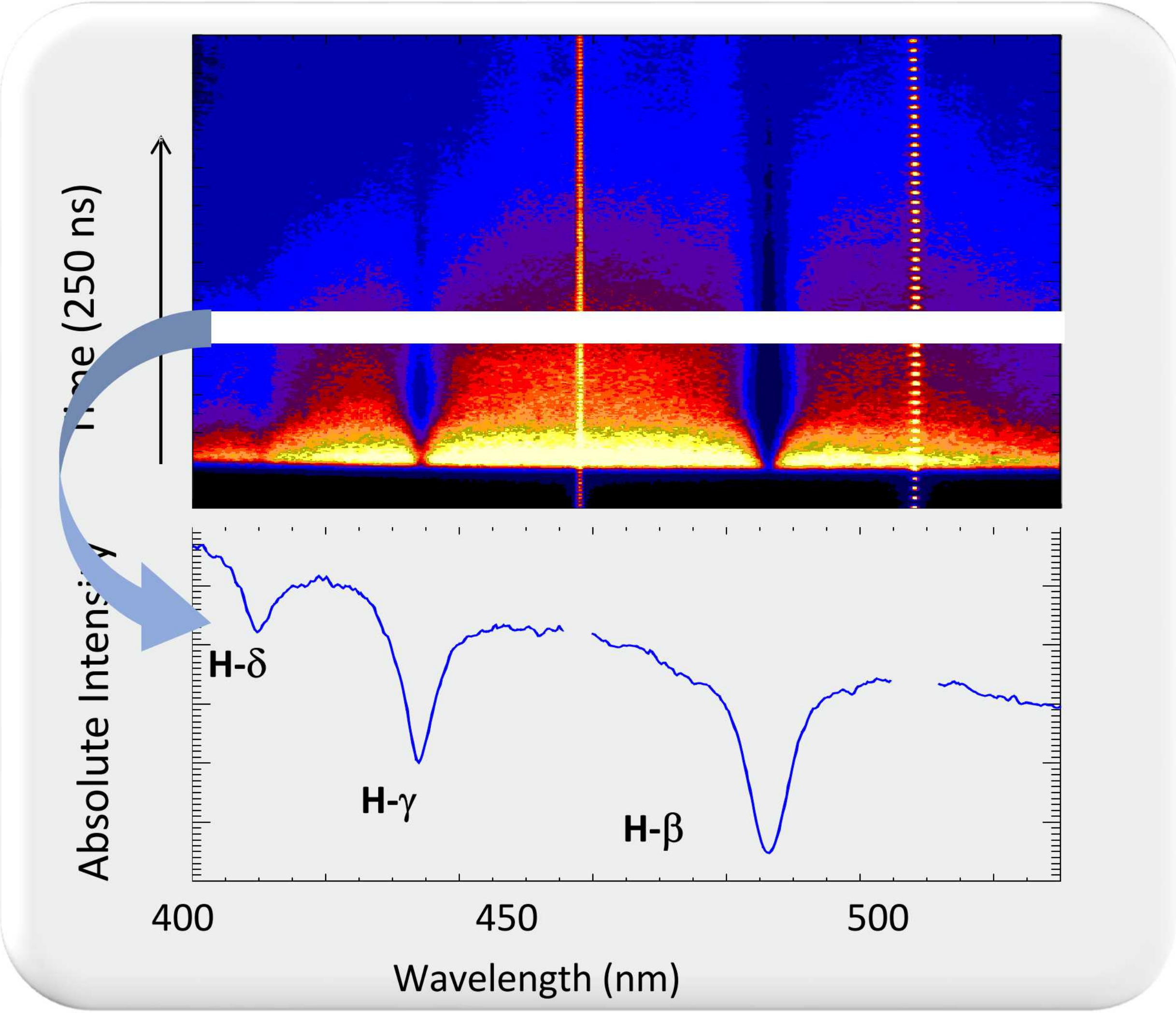
Hydrogen gas is heated by reemission from the gold wall; Its emission and absorption spectra are simultaneously observed



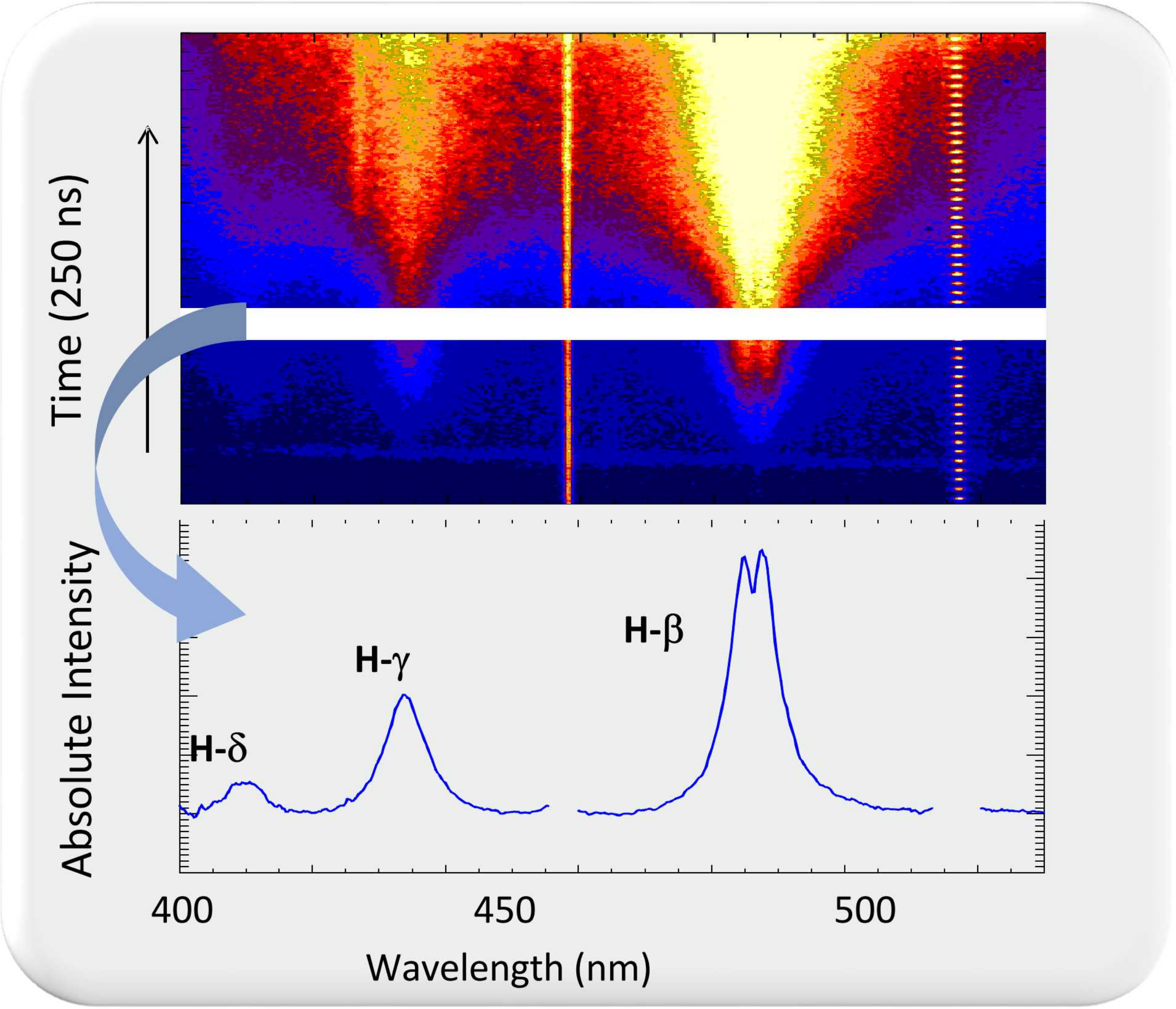


Hydrogen gas is heated by reemission from the gold wall; Its emission and absorption spectra are simultaneously observed

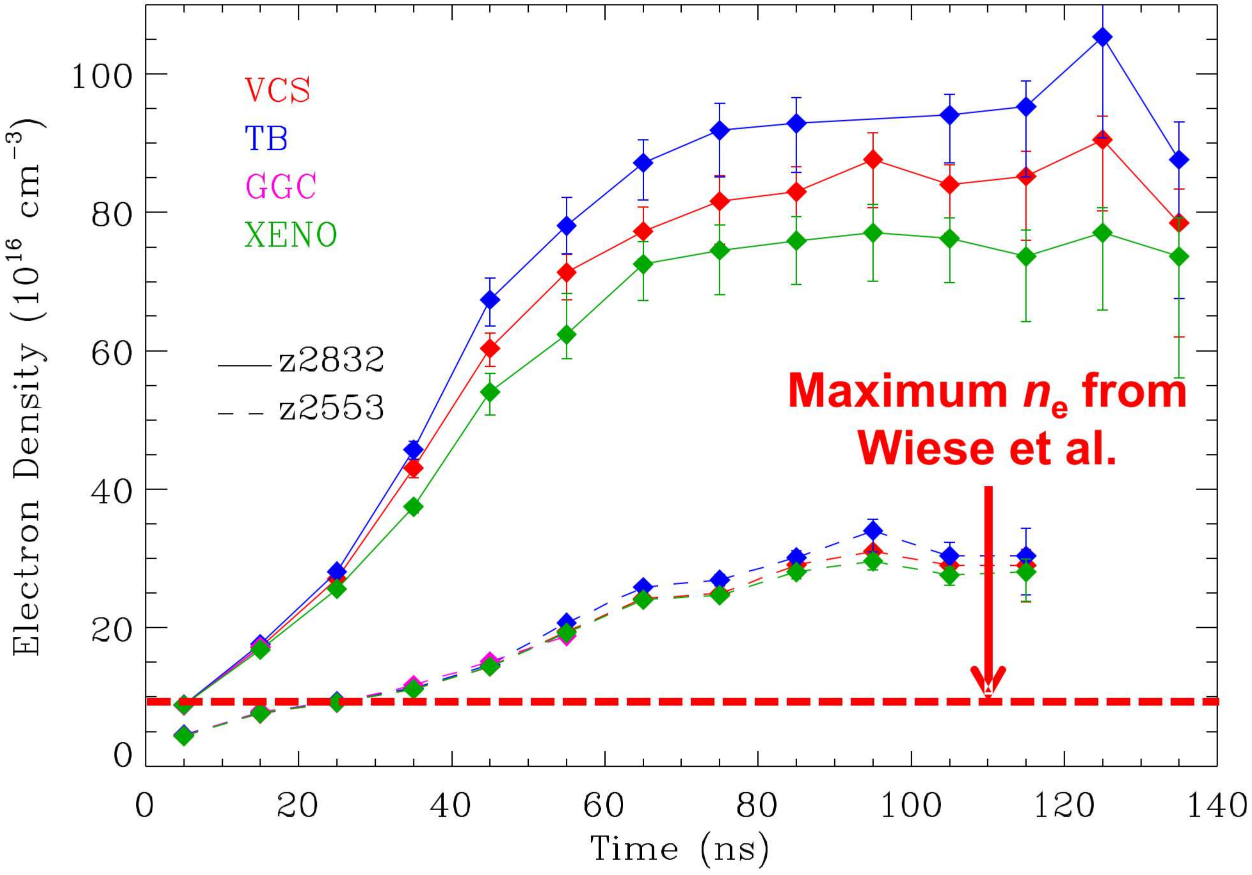
Absorption

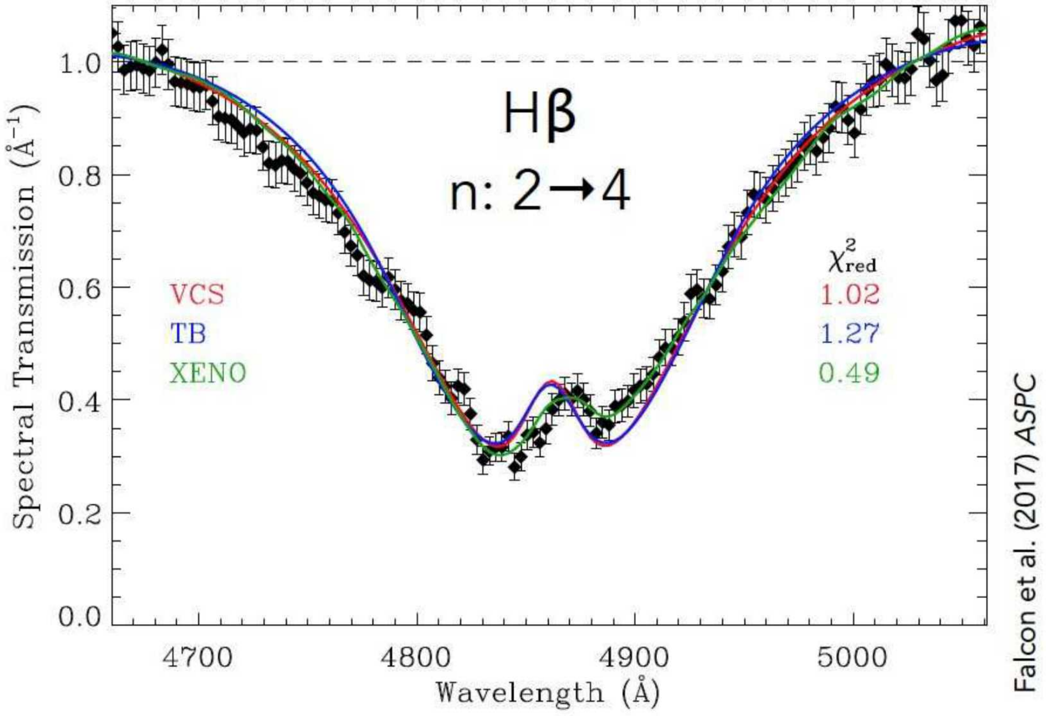


Emission



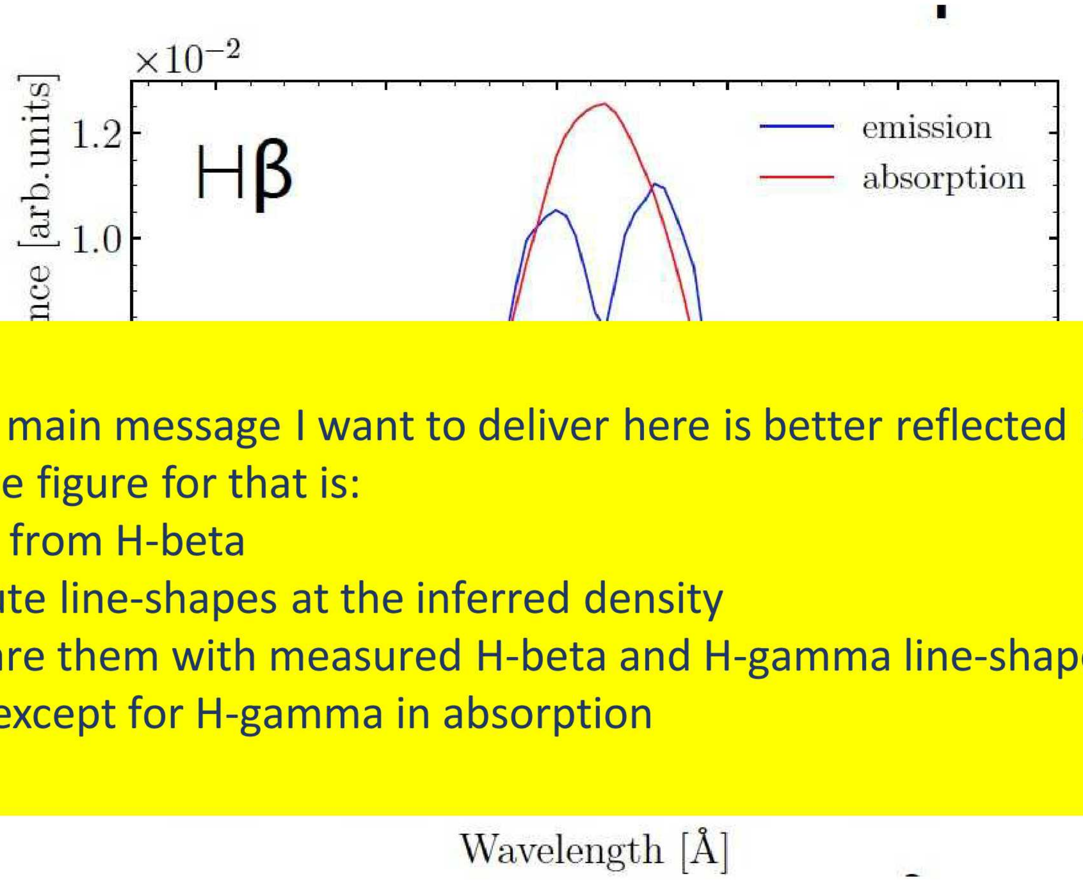
Line-shapes were measured up to 10x higher density than previously available, discriminating between theories

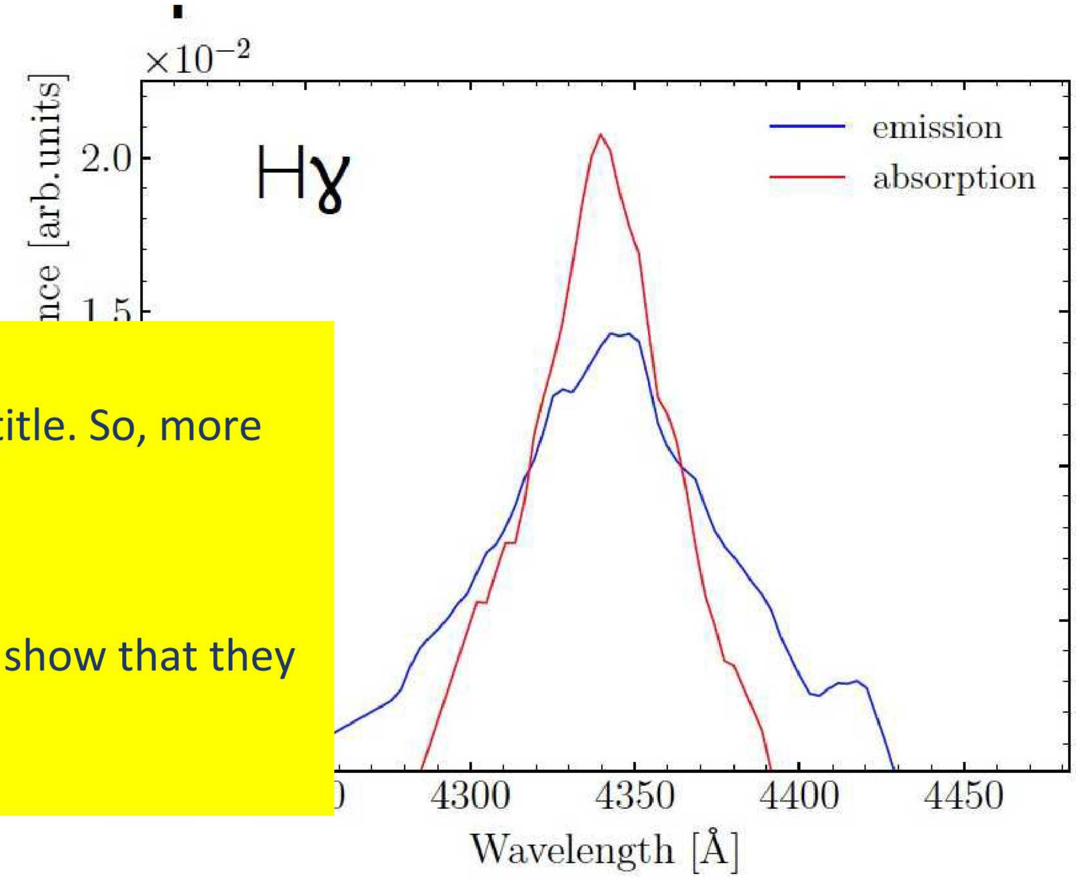




Sample spectrum of recent hydrogen experiment.
Differences in theory are apparent.

Measurements confirmed model-data consistency in emission spectra, but not in absorption spectra



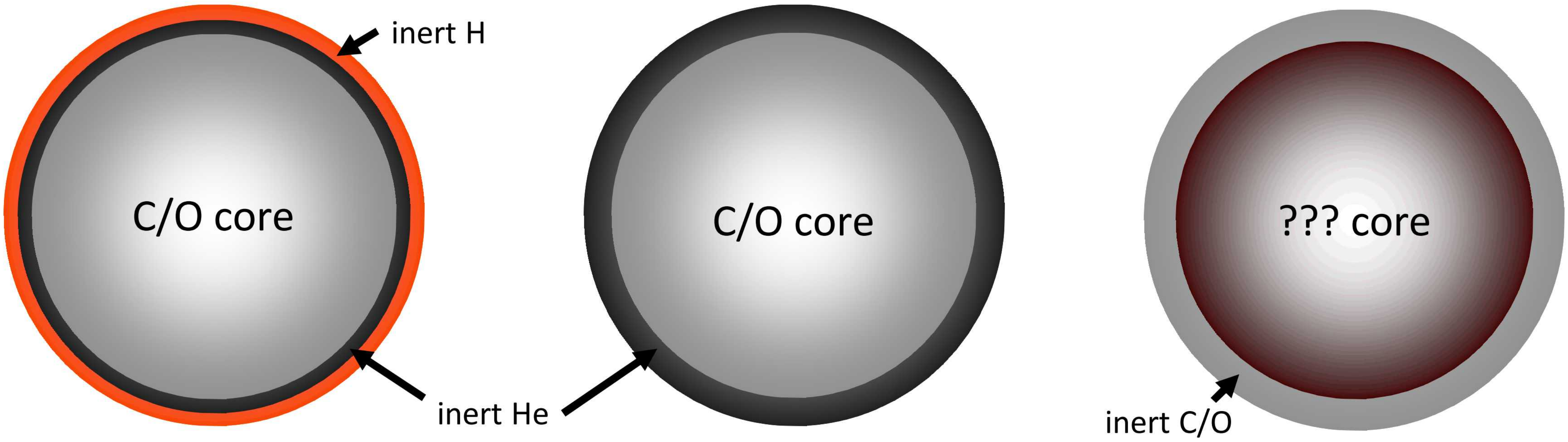


k the main message I want to deliver here is better reflected in the title. So, more
opriate figure for that is:
et ne from H-beta
ompute line-shapes at the inferred density
ompare them with measured H-beta and H-gamma line-shapes and show that they
gree except for H-gamma in absorption

The disagreement cannot be explained by inhomogeneity, suggesting inaccuracy in line-shape theory

Helium and carbon white-dwarf-photosphere experiments can answer different astrophysical puzzles

~80% H WD | ~20% He WD | < 1% C, O WD



Question:
What's the true mean mass?

Question:
How is He WD created?

Question:
What's the core made of?

Validating line-shape and -shift models can provide strong constraints to answer these questions

Helium and carbon white dwarf photosphere experiments can answer different astrophysical puzzles

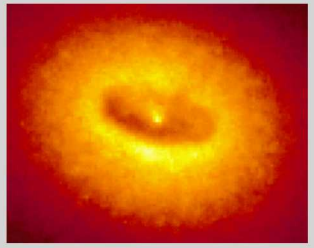
Sandia National Laboratories

	hydrogen WD	helium WD	carbon WD
Astronomical use	age of Galaxy and universe	test stellar evolution models	insight into origins of Type Ia supernovae
Required data	accurate hydrogen WD masses	accurate helium WD masses	accurate carbon WD masses
Astronomical problem	GR and spectroscopic masses do ***not*** agree	GR and spectroscopic methods are deficient	Unverified atomic physics used in model atmospheres
Physics problem	H line shapes are still poorly modeled	Line-broadening and shift models are inadequate	C Stark widths are unknown
experimental goal	verify H line profiles	determine He I line shifts and widths	measure atomic C Stark widths

Benchmark spectra line broadening and shift models will advance our understanding of WD and galaxy

ZAPP campaigns simultaneously study multiple issues

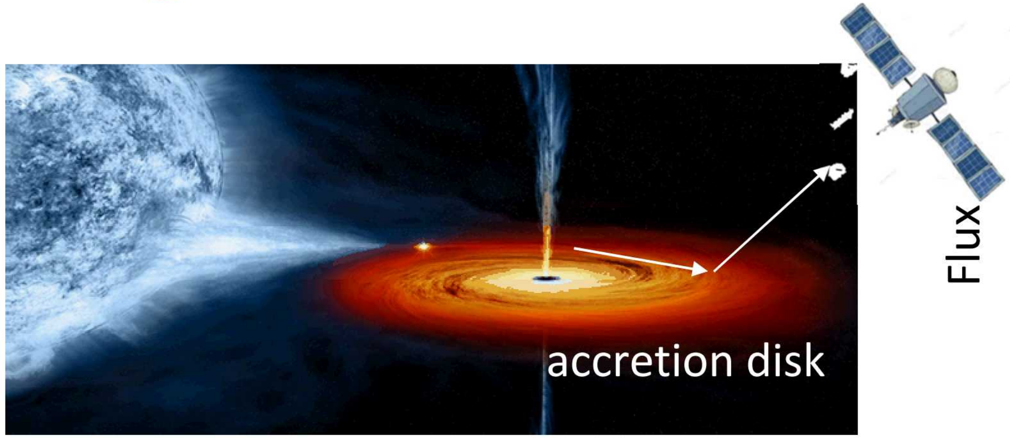
Accretion Disk Spectra



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

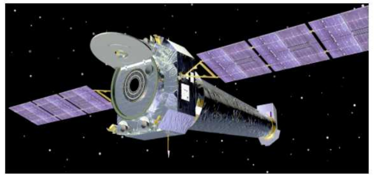
Achieved Conditions:
$T_e \sim 20$ eV, $n_e \sim 10^{18}$ cm^{-3}

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

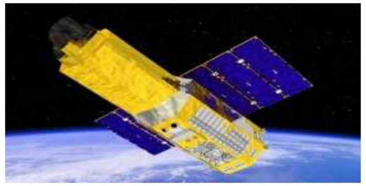


XMM-Newton - ESA

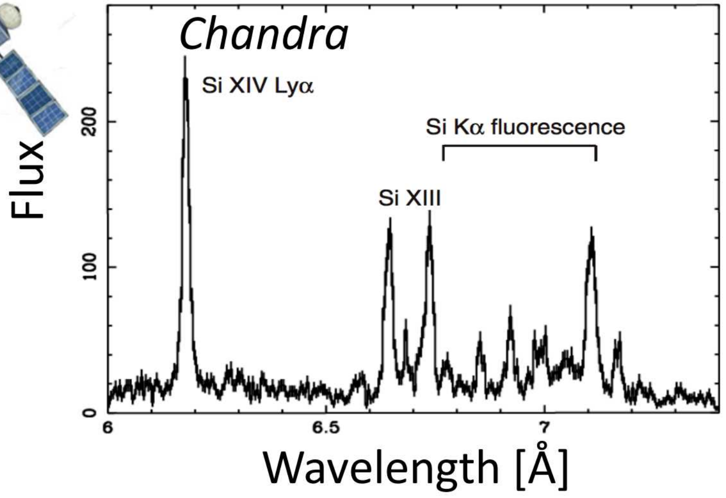
Chandra - NASA



Suzaku – JAXA



Neutron star Vela X-1



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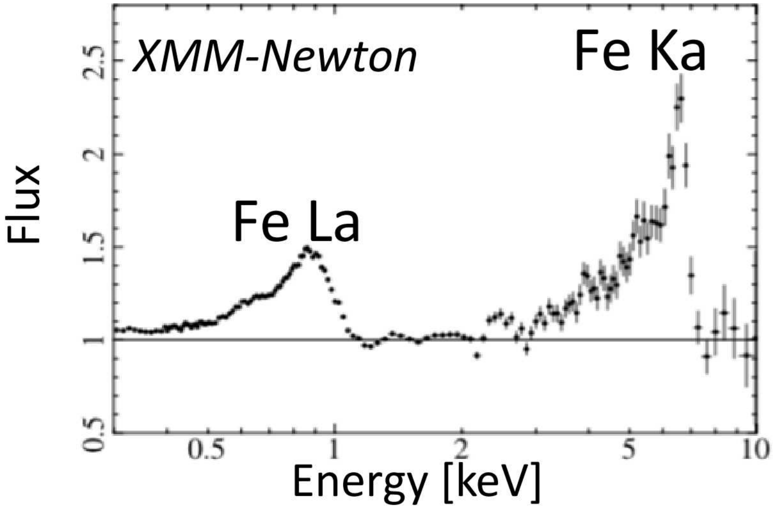
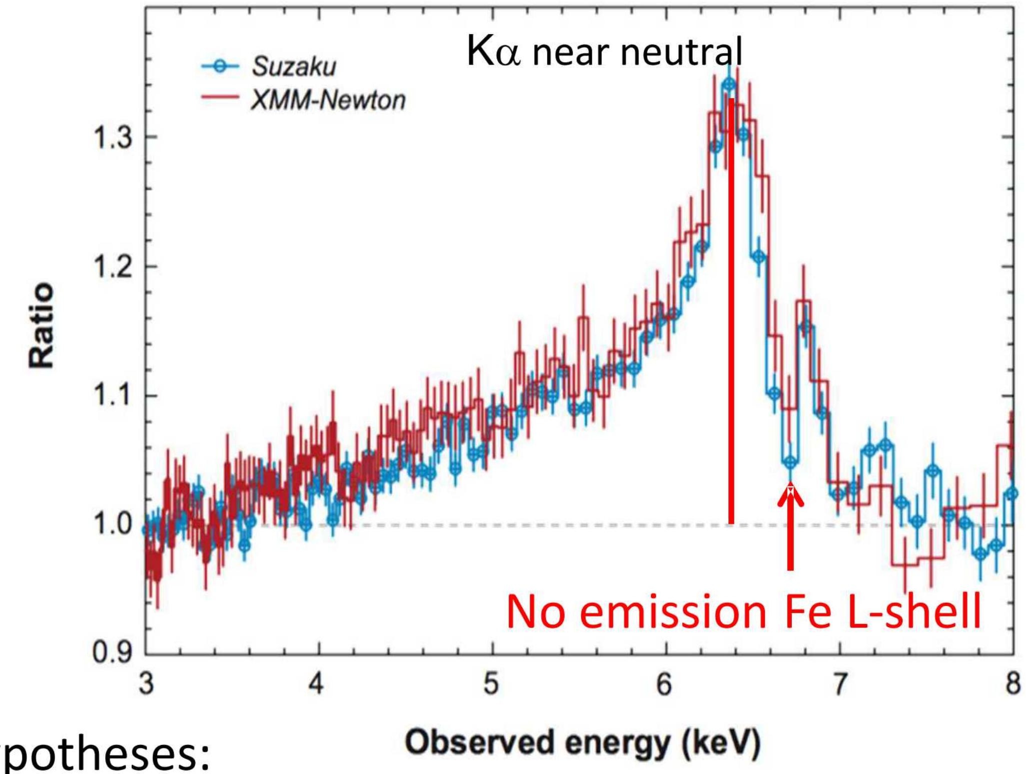


Challenges:

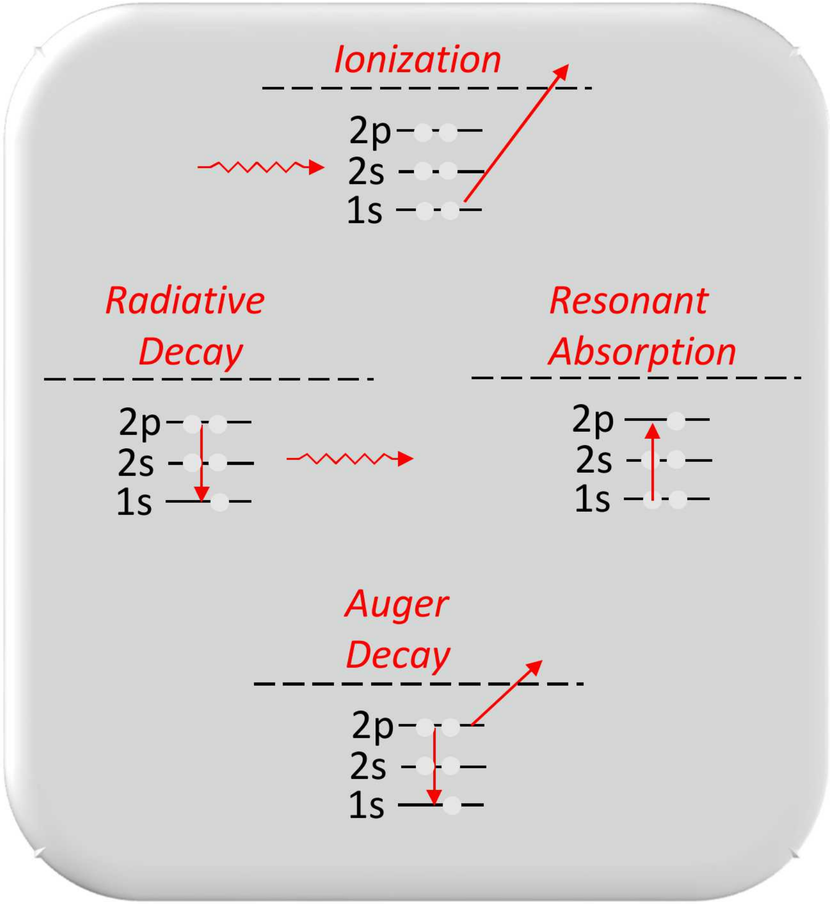
- Line identification
- Blended spectra from multiple elements
- Spatial and temporal integration
- Radiation transport
- Limited spectral resolution

Accretion disk is photoionized plasma where models are not sufficiently tested

Lack of L-shell emission from accretion disk raised speculations



Is Resonant Auger Destruction (RAD) the Reason?



Hypotheses:

- RAD is 100% efficient, and no L-shell emission expected
- Complex radiation transport explains this missing emission
- We cannot see it due to resolution limitation

Experimental objective: Measure L-shell emission from photoionized plasma

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

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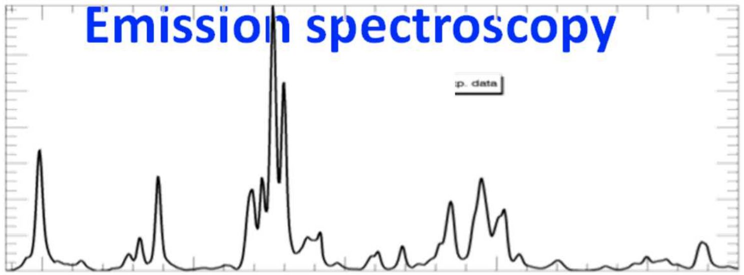
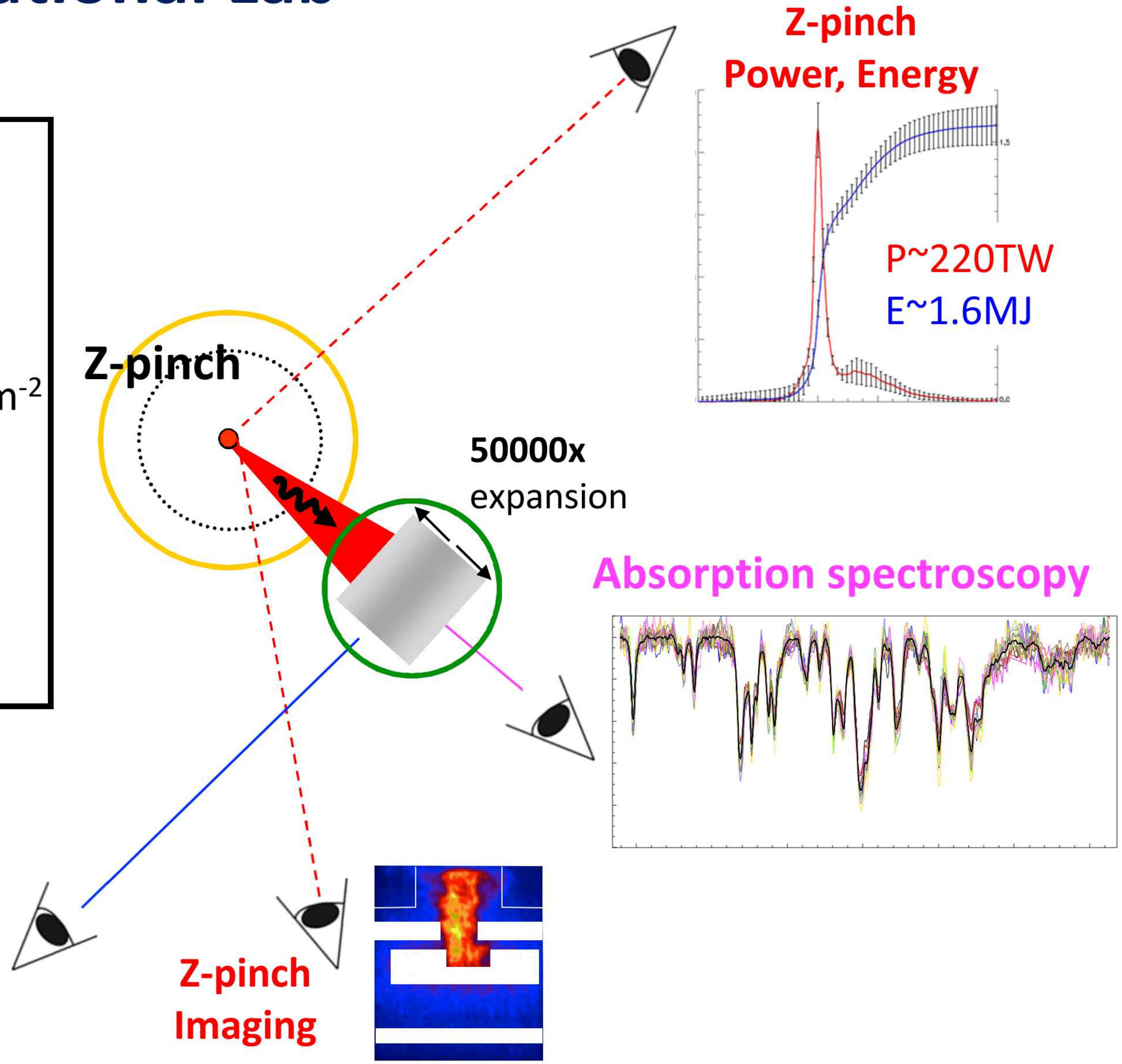
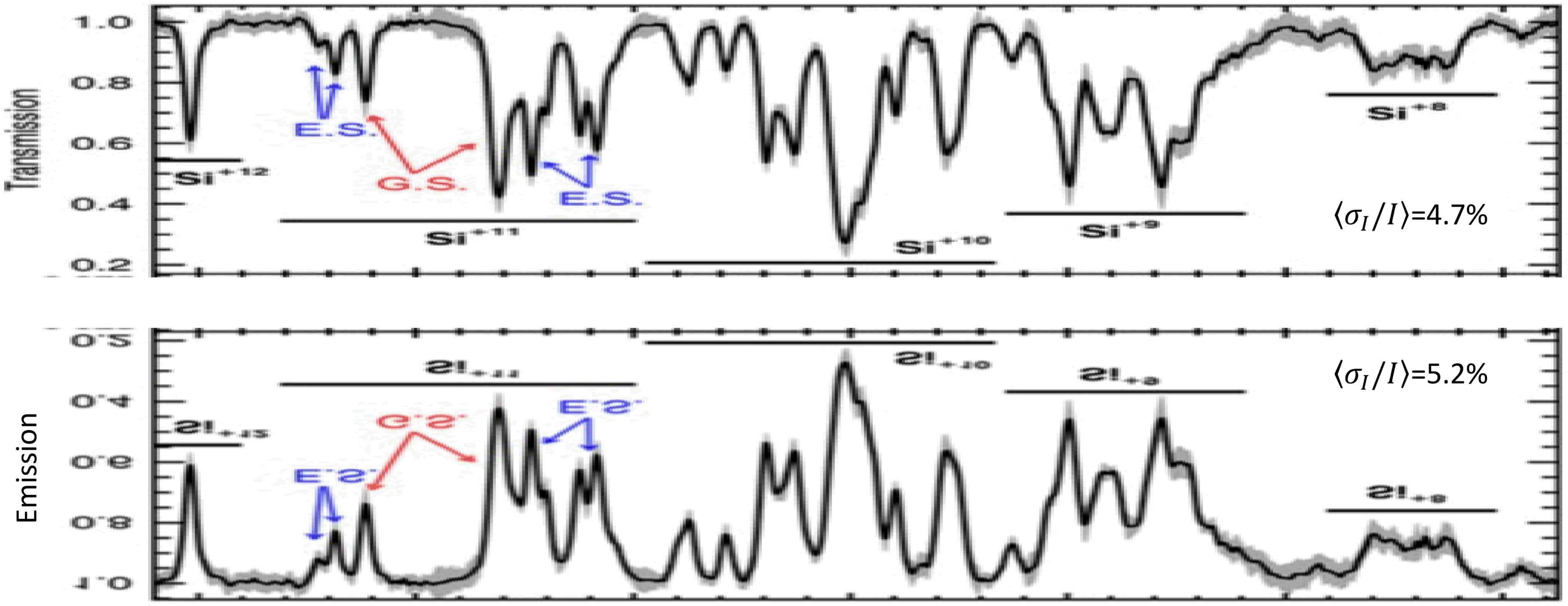
Experimentally constrained parameters

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 x 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



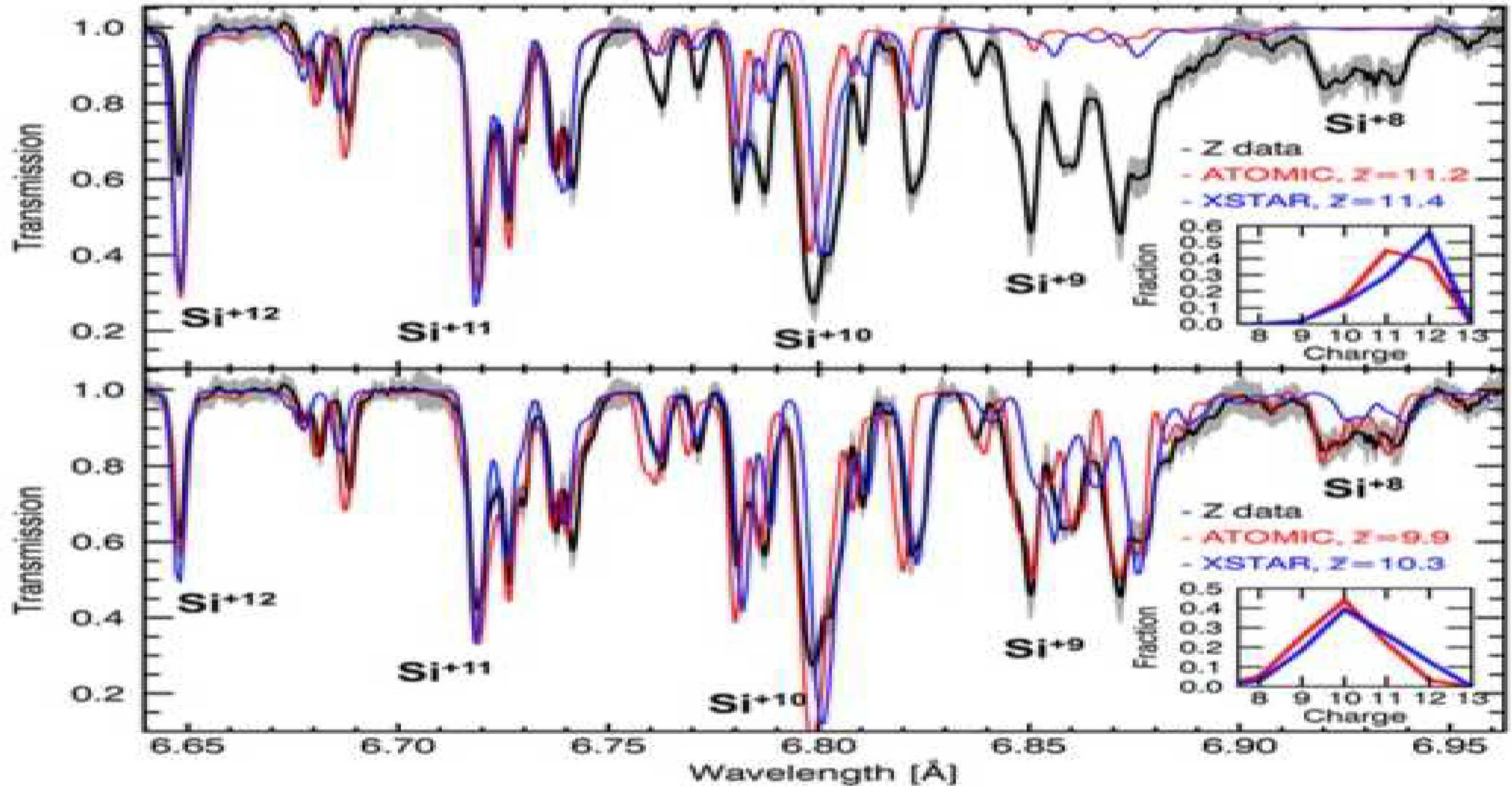


Absorption and emission spectra are simultaneously measured with high reproducibility



Excellent reproducibility and spectral resolution provide strong constraints for photo-ionized plasma modeling

Finding 1: Absorption spectra computed at inferred conditions underpredict the ionization



Hypotheses:

Experiment:

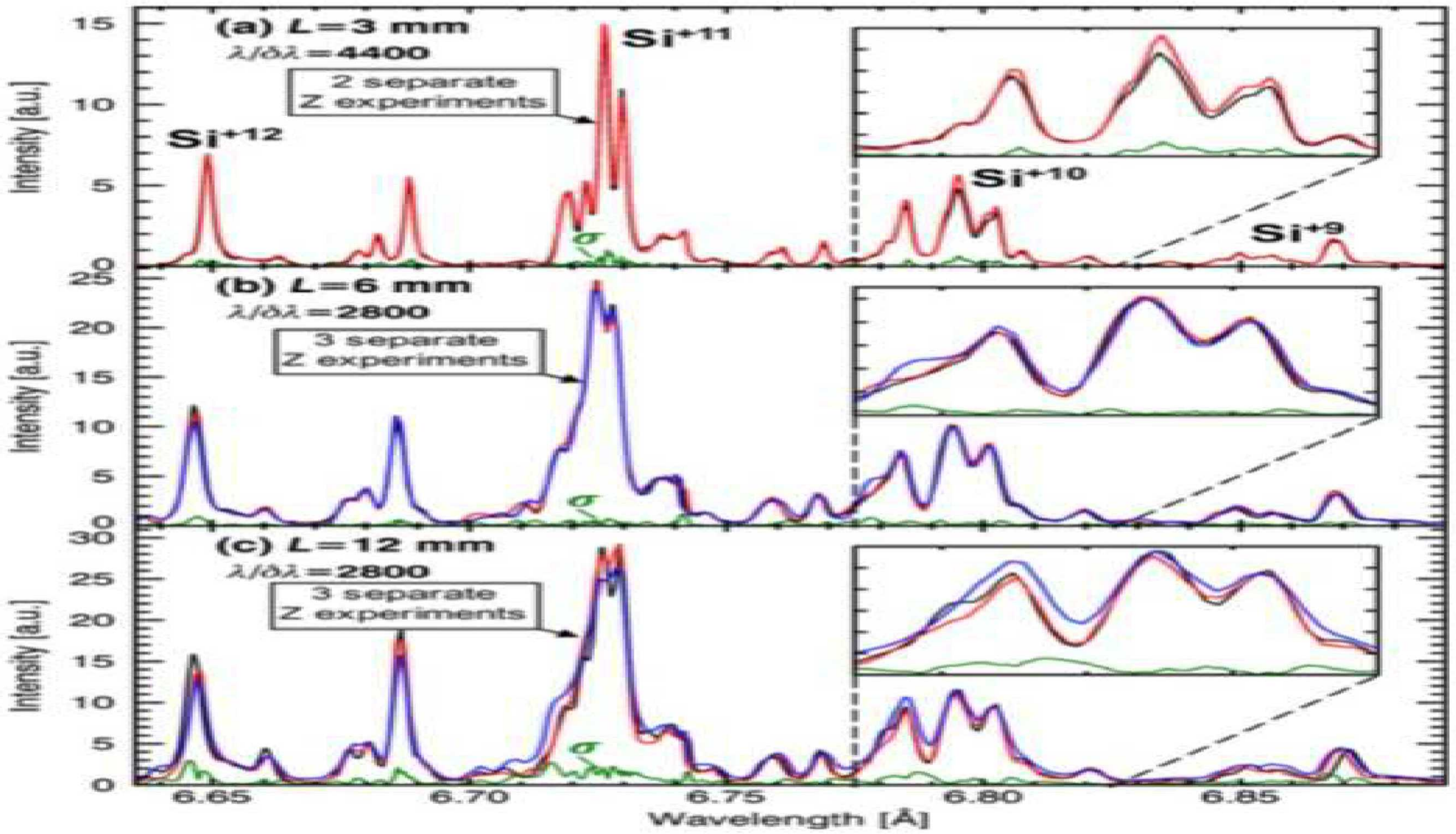
- Higher n_e?
- Lower F_ν?

Theory:

- Higher dielectronic recombination rate?

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

Finding 2: First high-resolution emission measurements discriminate RAD hypothesis



NL=??

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

Open questions

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

Possible needed improvements in understanding the experiment

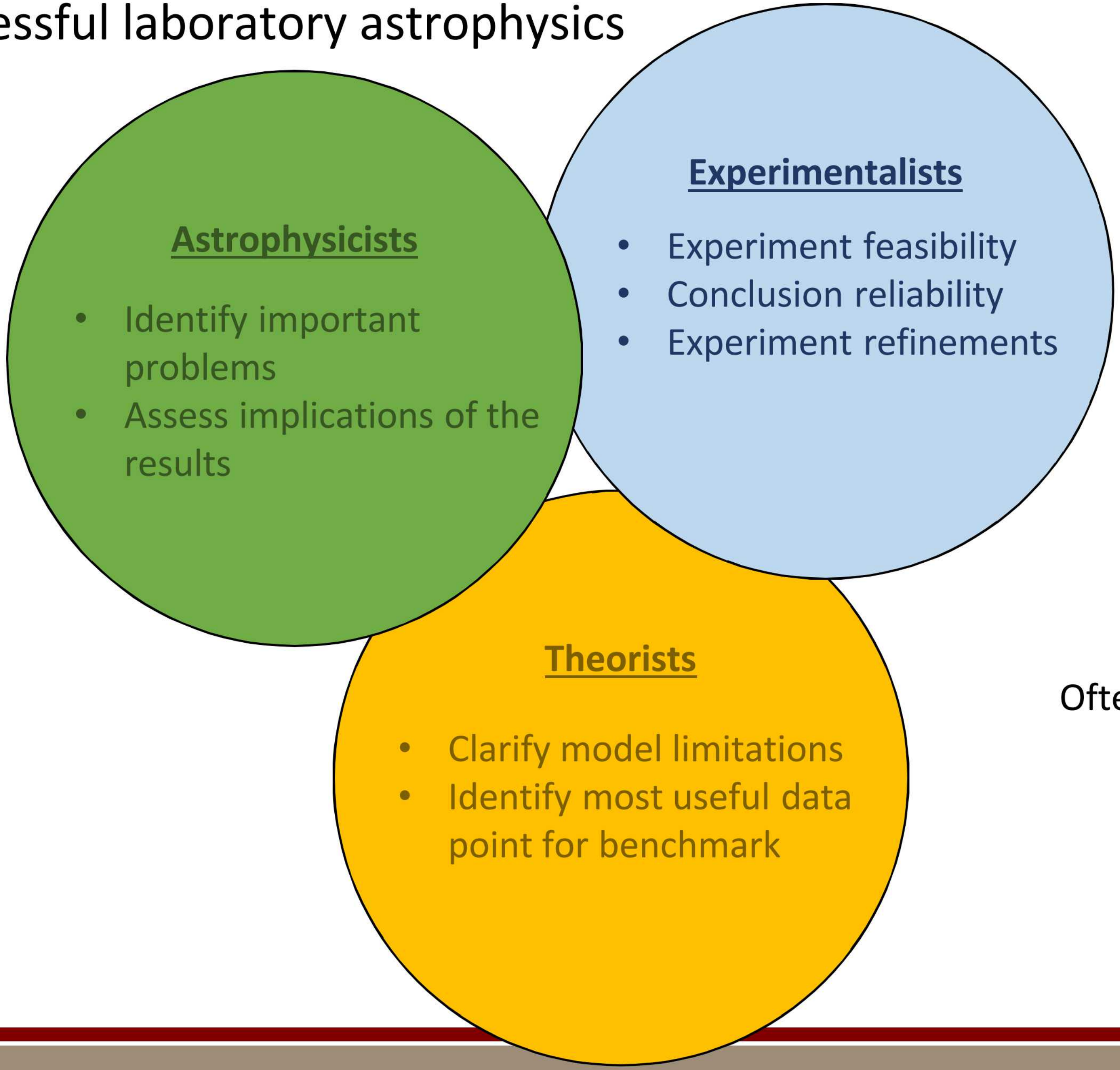
- Could electron density be higher than the value measured with radiography?
- Transient kinetics appear relatively unimportant, but further evaluation is needed
- The bulk of x-ray drive in 0.1 -1keV is measured to ±20%, but accuracy in >1.7keV photon spectrum needs more evaluation.
- Accounting for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

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…

Good collaboration between astrophysicists, experimentalists, and theorists is essential for successful laboratory astrophysics



Often, there is little overlap …

Good collaboration between astrophysicists, experimentalists, and theorists is essential for successful laboratory astrophysics

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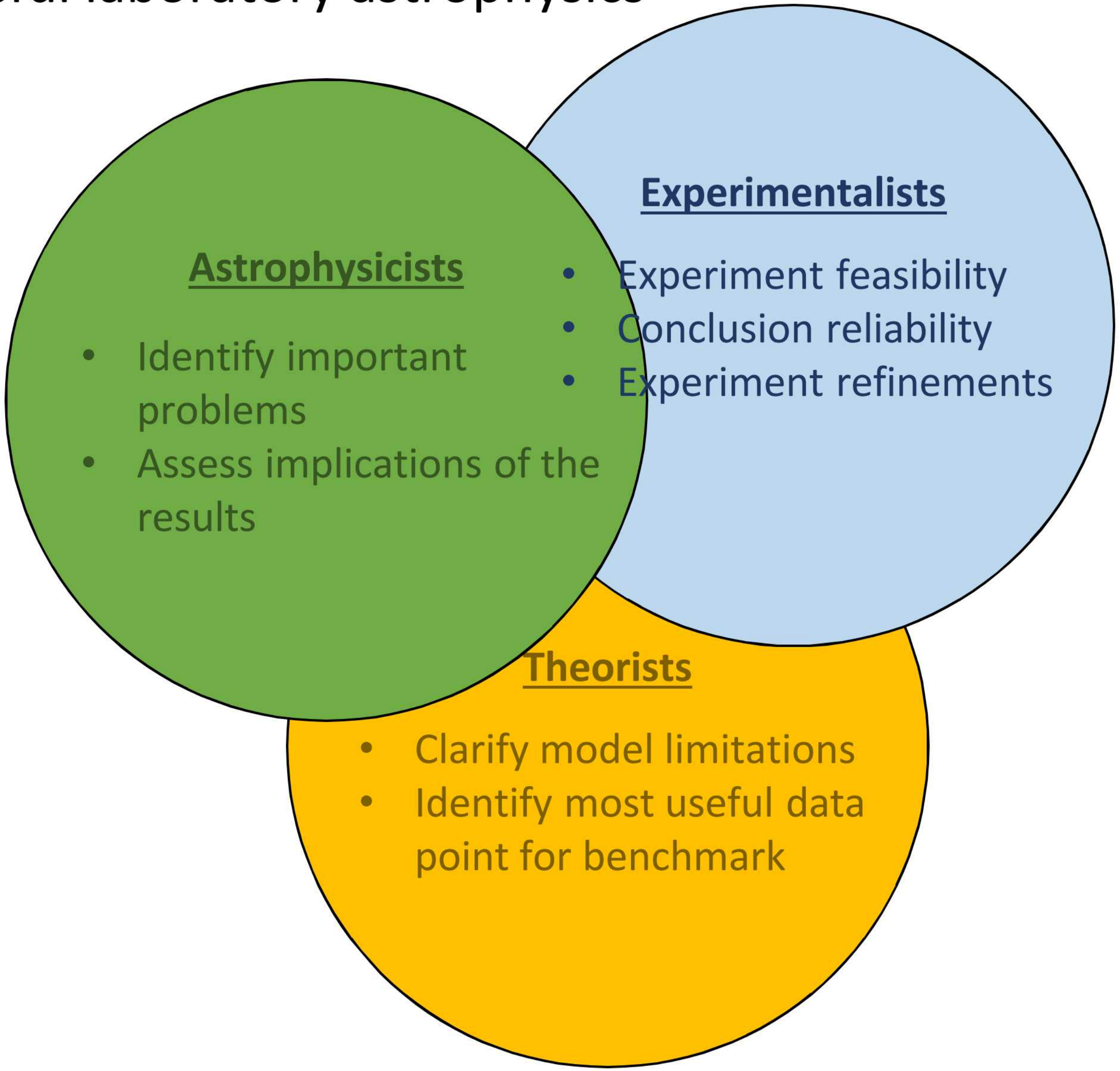

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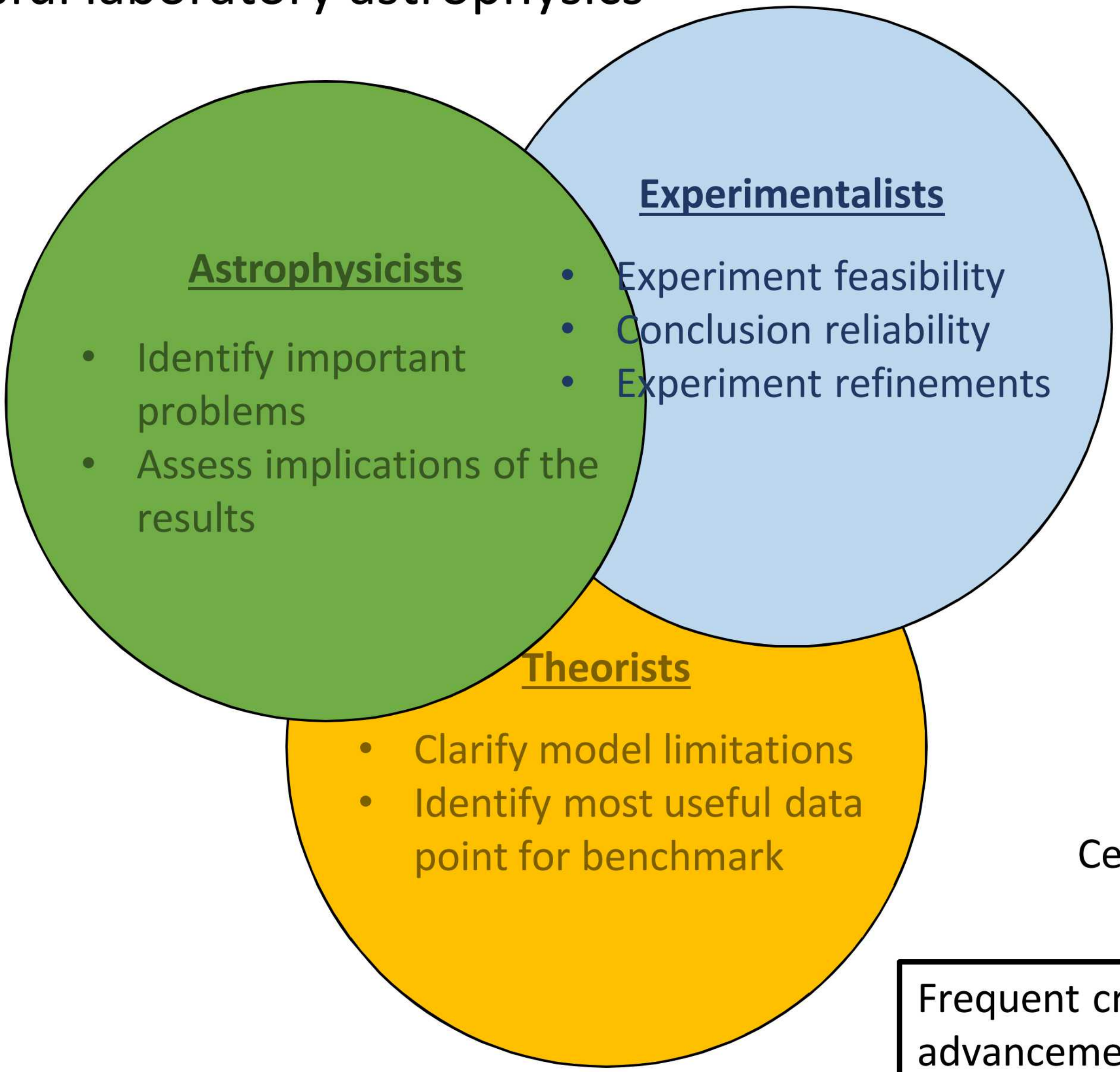

Close collaboration will improve:
- Astrophysical relevance of the experiments
- Clarity of the impact

provides

Certainty in astrophysical conclusions

Frequent cross-talk is very important for healthy advancement of astrophysics

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

- Lab astrophysics requires special knowledge who understand:
  i. Astrophysical impact,
  ii. Model limitations,
  iii. Experimental feasibility and limitations

- CAPP provides:
  - Sustained funding to train students for continuous growth of laboratory astrophysics
  - Resource and connection to good astrophysicists, theorists, and experimentalists.

Importance of HEDP facility and Z next

- While two of the three projects are not in the regime of HED plasma, it is still considered HED experiments because we often need HED facility for benchmark experiments
  - Larger sample size for long duration (uniformit, steady sate)
  - Example:
    - WD: to have Te and ne as WDP, we need large cell size to produce measurable absorption and emission
    - Fe, Si, WD:
      - Need large size to ensure the edge-gradient effect to be negligible
      - Need nanosecond hydrodynamics for plasma to reach steady state; otherwise, transient effect can be significant and any conclusions are skeptical.

- Also, HED facility enables us to perform at scale experiments:
  - Example:
    - Opacity at CZB
    - Photoionization of ζ =1000
  - We are promoting to upgrade to Z-next → How important?
    - Fe opacity at R=?
    - Photoinization of ζ=??s

ZAPP experiments benchmark plasma properties and spectra calculations and checks the accuracy of astrophysics interpretations

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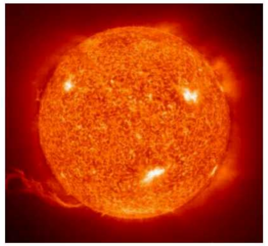
- Astrophysics relies on *unbenchmarked* atomic-physics models in two ways:
  - Fundamental properties (e.g., EOS, opacity)
  - Spectra analysis (e.g., accretion disk, white dwarfs)
- ZAPP (= Z Astrophysical Plasma Properties) collaboration uses terra-watt x-ray source to replicate astrophysics-relevant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



Solar Fe opacity:

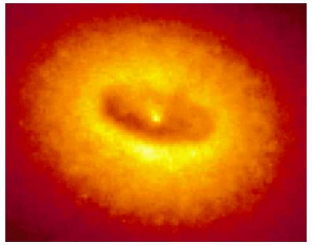
T=200 eV

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}

- Laboratory astrophysics requires special education: i) astrophysical importance, ii) model limitations, and iii) experiment feasibility → (Center of Astrophysical Plasma Properties)

Success of satellite missions require validated models, making benchmark experiments and healthy collaboration between astrophysicists and physicists invaluable.