This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2015-2413C

Exceptional service in the national interest

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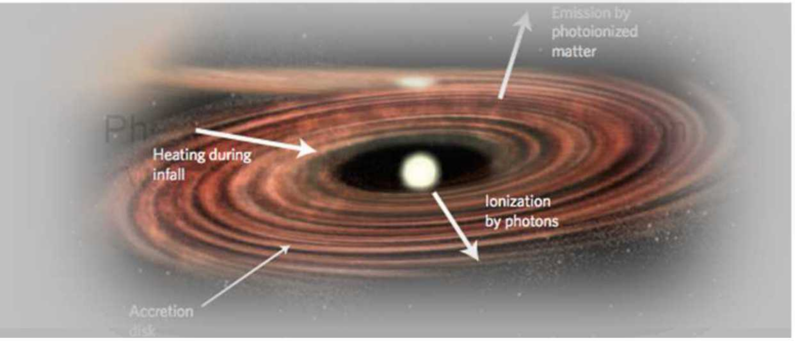

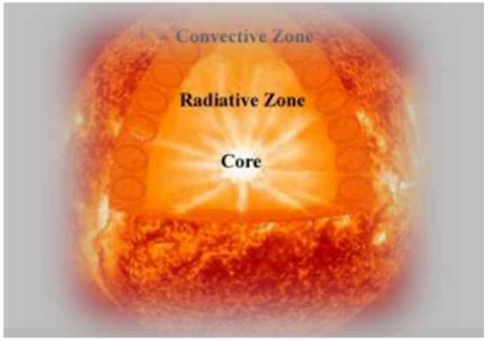

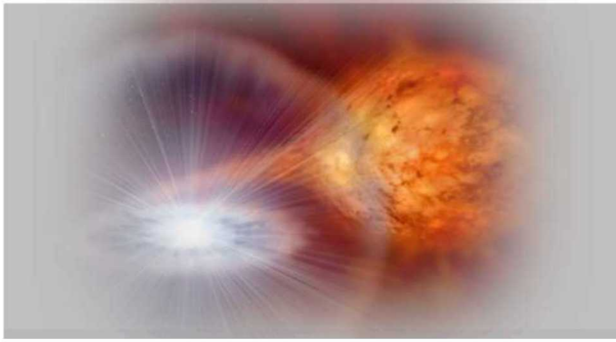

ZAPP: The Z Astrophysical Plasma Properties Collaboration

Gregory A. Rochau

Presented at the Electromagnetic Driven High Energy Density Physics Workshop – Chengdu, China

April 13-14, 2015

SAND No.

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

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Rochau et al., POP 21 (2014)

ZAPP represents a large collaboration between the NNSA labs and the academic community

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Sandia National Laboratories

Roberto Mancini, Iain Hall, Tom Lockard, Dan Mayes
University of Nevada – Reno

Don Winget, Mike Montgomery, Ross Falcon, Thomas Gomez, Alan Wootton, Jennifer Ellis, Sean Moorhead, Roger Bengtson
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Anhil Pradhan, C. Orban, Mark Pinsonneault, and S.N. Nahar
Ohio State University

Mark Koepke, Ted Lane, Matt Flaugh
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Lawrence Livermore National Laboratory

Manolo Sherrill, Heidi Tierney ,Chris Fontes, James Colgan, Dave Kilcrease
Los Alamos National Laboratory

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

Joe MacFarlane, Igor Golovkin
Prism Computational Sciences

<u>Summary</u>: ZAPP experiments measure fundamental properties of atoms in plasmas to solve important astrophysical puzzles.

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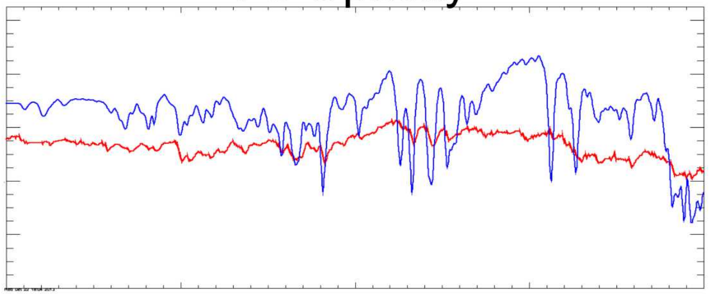
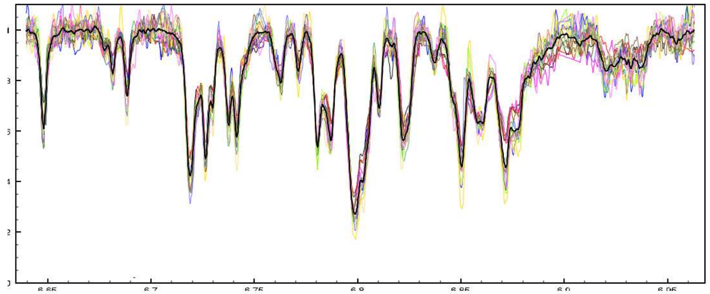
- Why can't we predict the location of the convection zone boundary in the Sun?
  - ➢ Opacity of Fe at ~200 eV

Fe Opacity



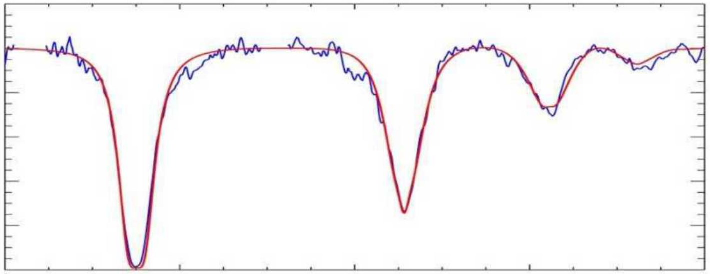
- How does ionization and line formation occur in accreting objects and warm absorbers?
  - ➢ Ionization distribution and spectral properties of photoionized Ne and Si

Si Photoionization



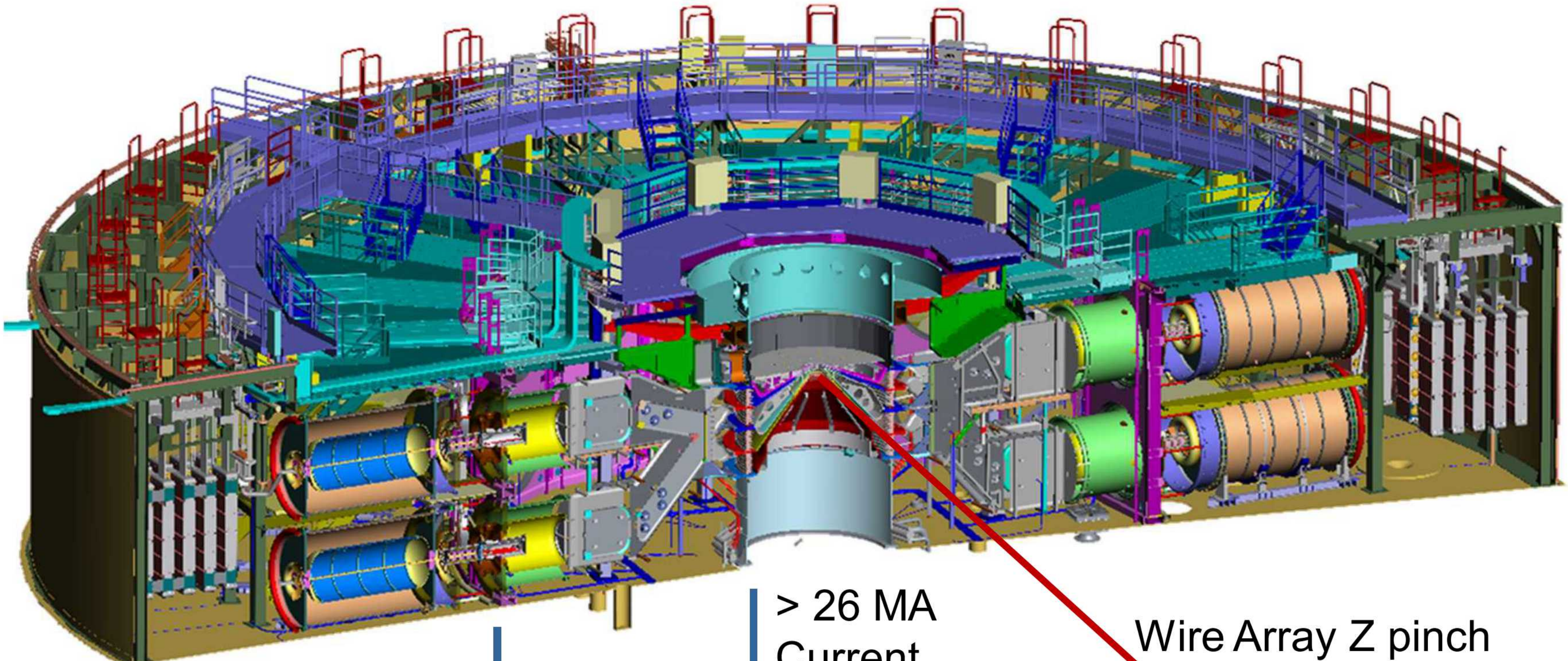
- Why doesn't spectral fitting provide the correct properties for White Dwarfs?
  - ➢ Stark-broadened H-Balmer line profiles

H-Balmer Line shapes



The Z facility at Sandia National Laboratories is the most powerful pulsed power machine in the world.

Sandia National Laboratories



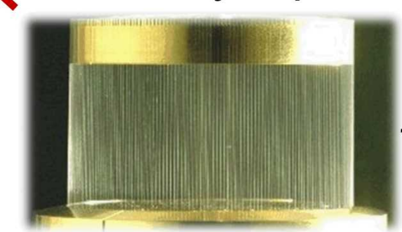
23 MJ Electrical

80 TW Electrical

> 26 MA Current

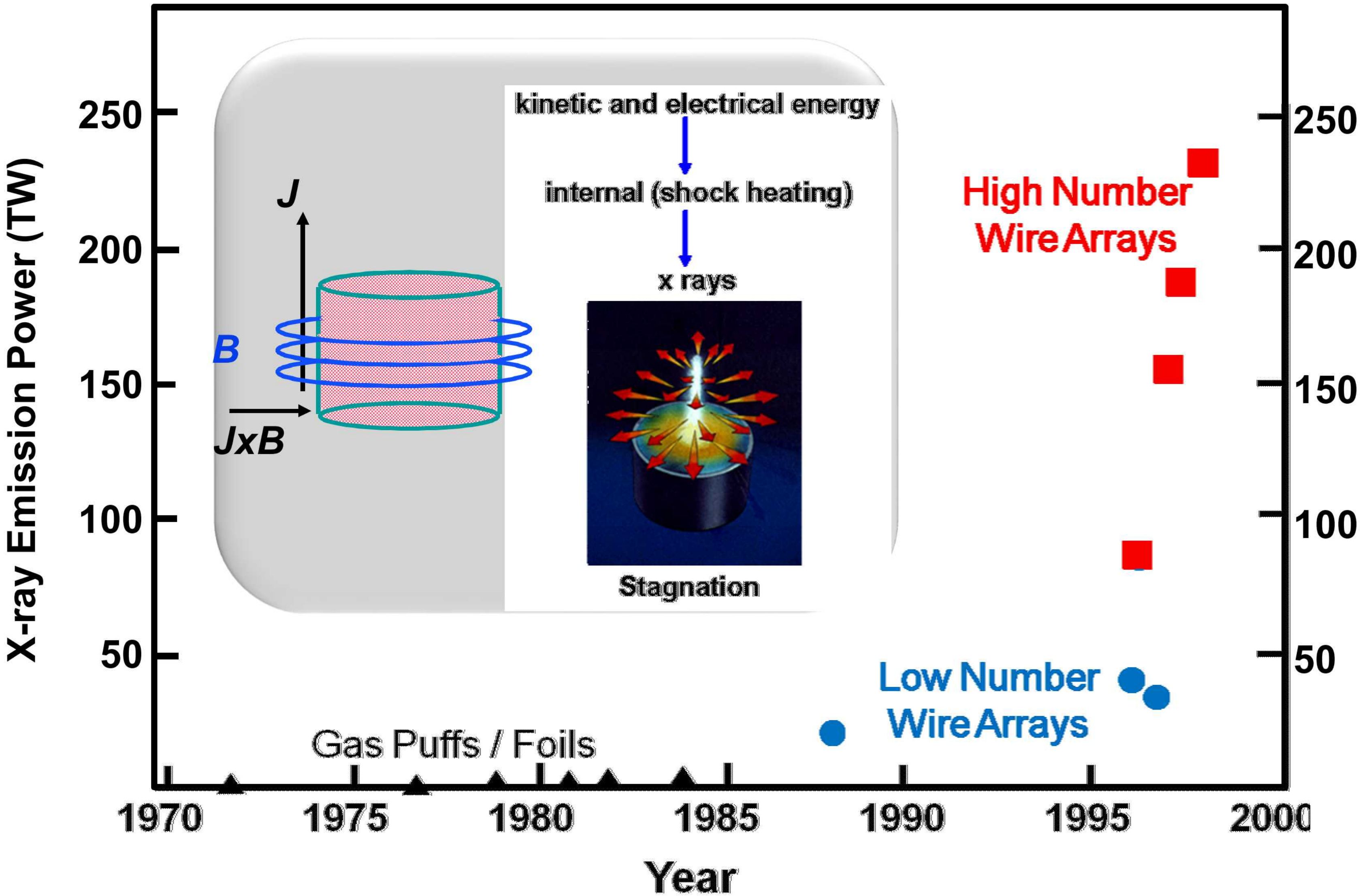
<u>X-ray Output</u>
>300 TW
> 2 MJ

Wire Array Z pinch



$E_{x\text{-}ray} \sim 10\%\ E_{Electric}$

Breakthroughs in Z-pinch technology enabled the study of high-temp HED plasmas using Pulsed Power.



C. Deeney et al, Phys. Rev. Lett. 81, 4883 (1998) ; R.B. Spielman et al, Phys. Plasmas 5, 2105 (1998)

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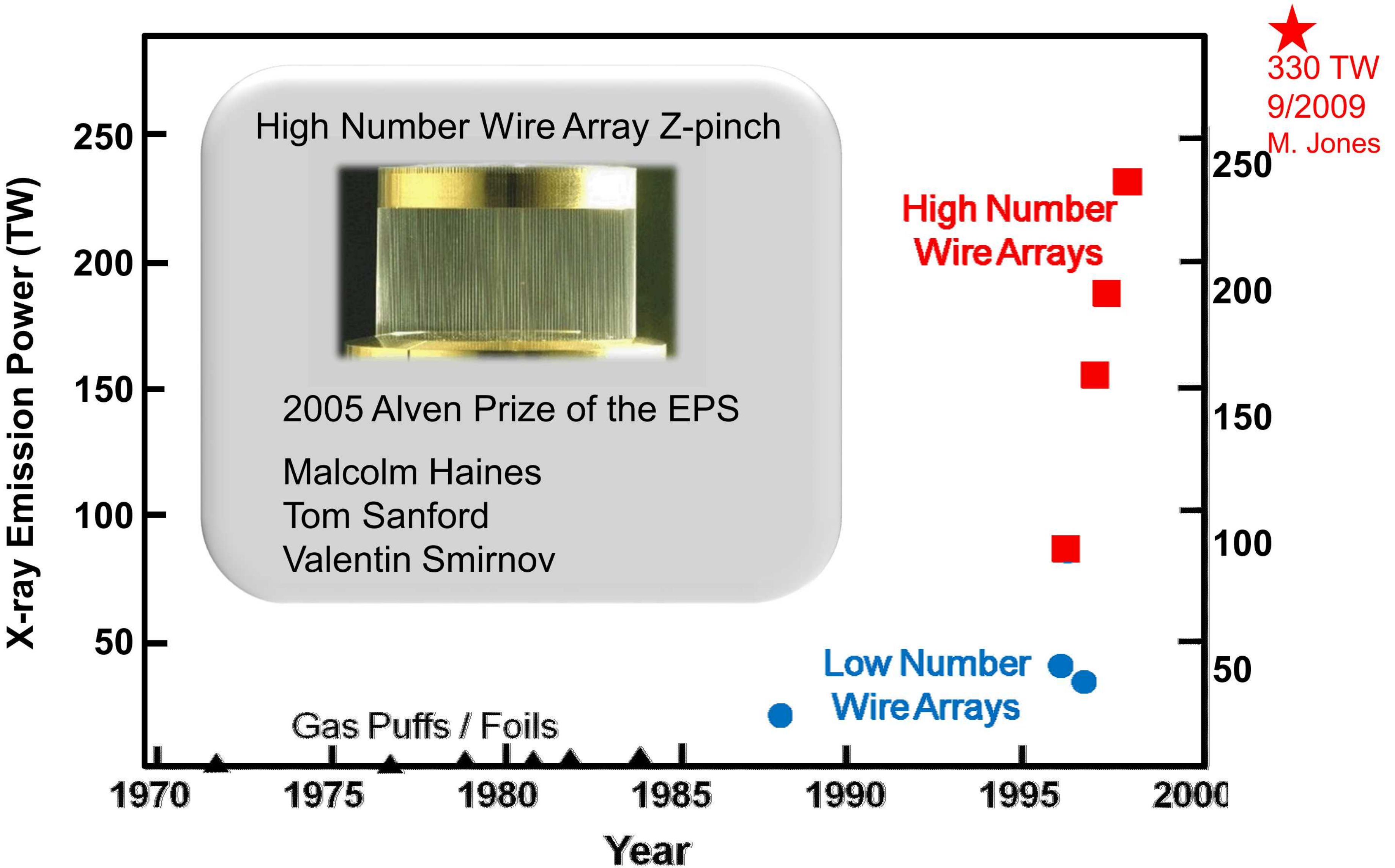
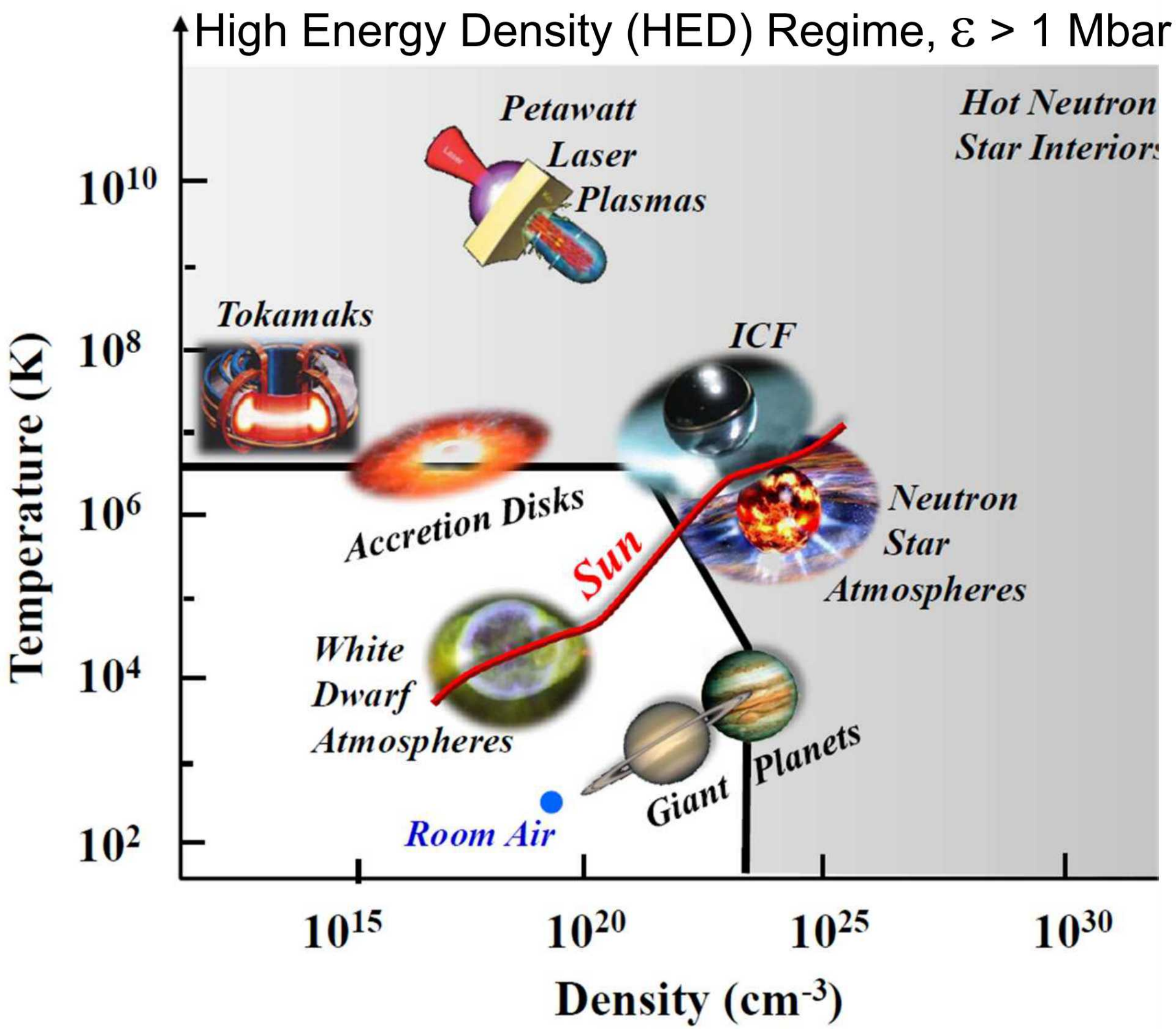
Sandia National Laboratories

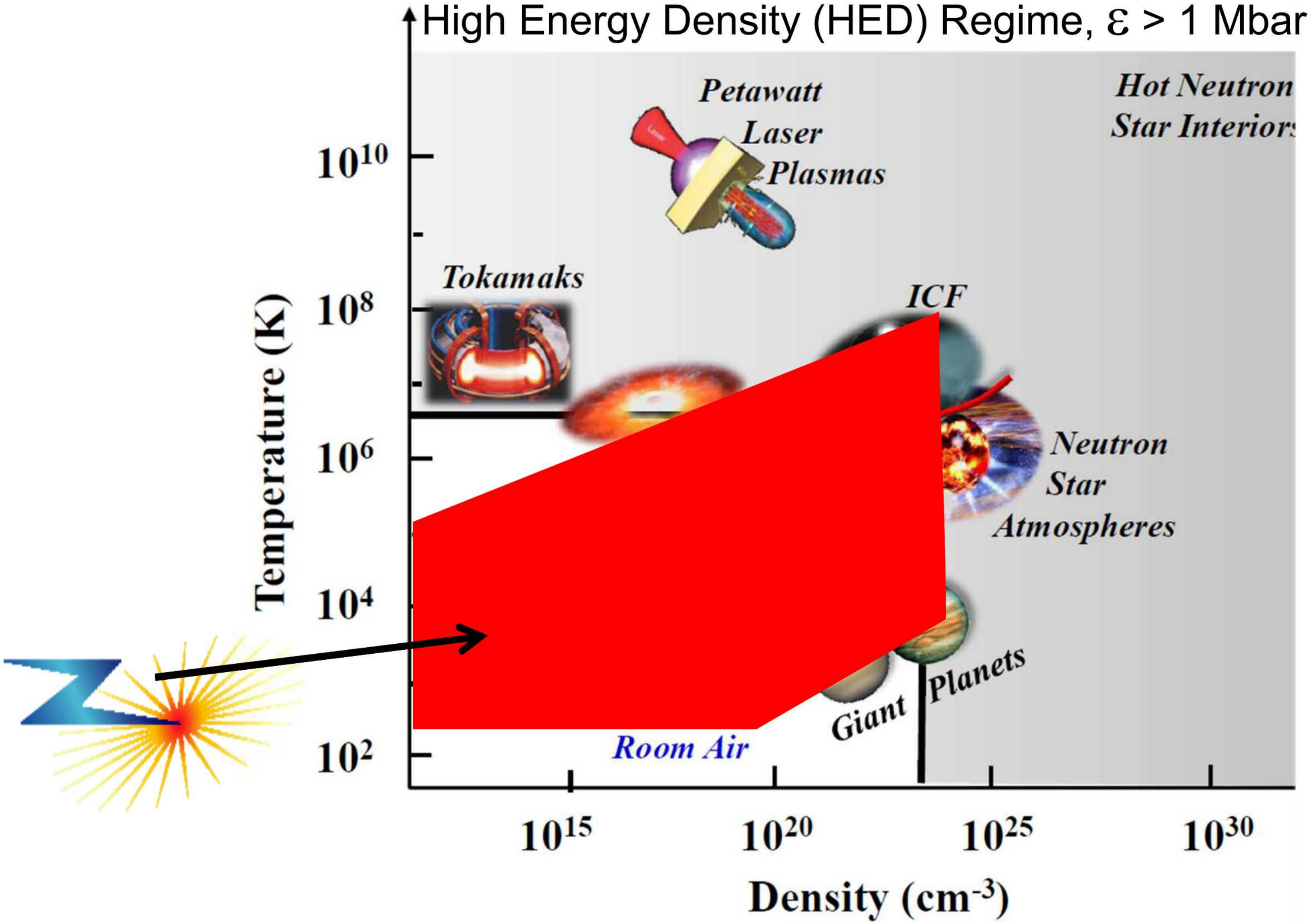


C. Deeney et al, Phys. Rev. Lett. 81, 4883 (1998) ; R.B. Spielman et al, Phys. Plasmas 5, 2105 (1998)

Experiments on Z access a broad range of the energy-density phase space

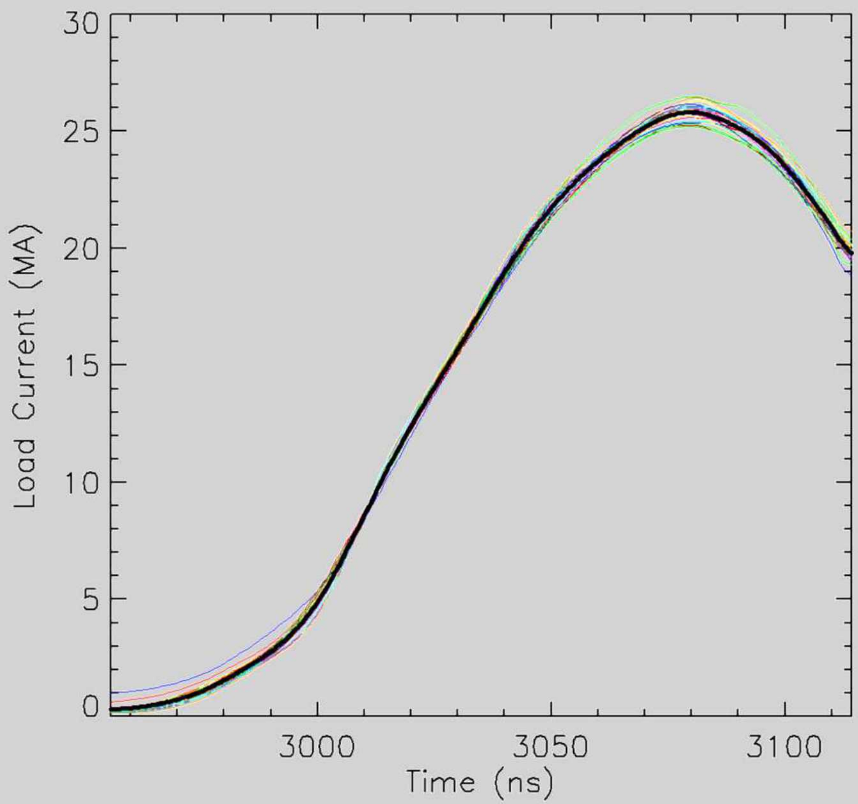


Experiments on Z access a broad range of the energy-density phase space

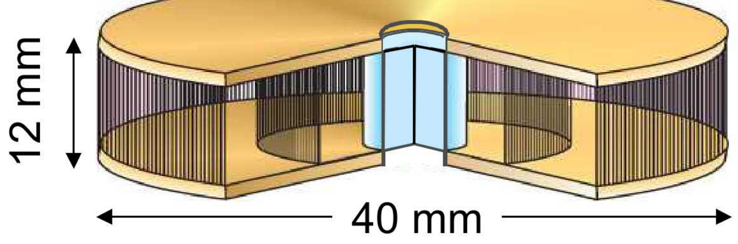


The z-pinch dynamic hohlraum (ZPDH) produces record currents of 25.8 MA with 1.5% reproducibility

Load Currents (20 shot average)



Z-pinch Dynamic Hohlraum



Standard ZPDH Characteristics

360 W wires – 11.4 μm diameter

m = 8.5 mg W total

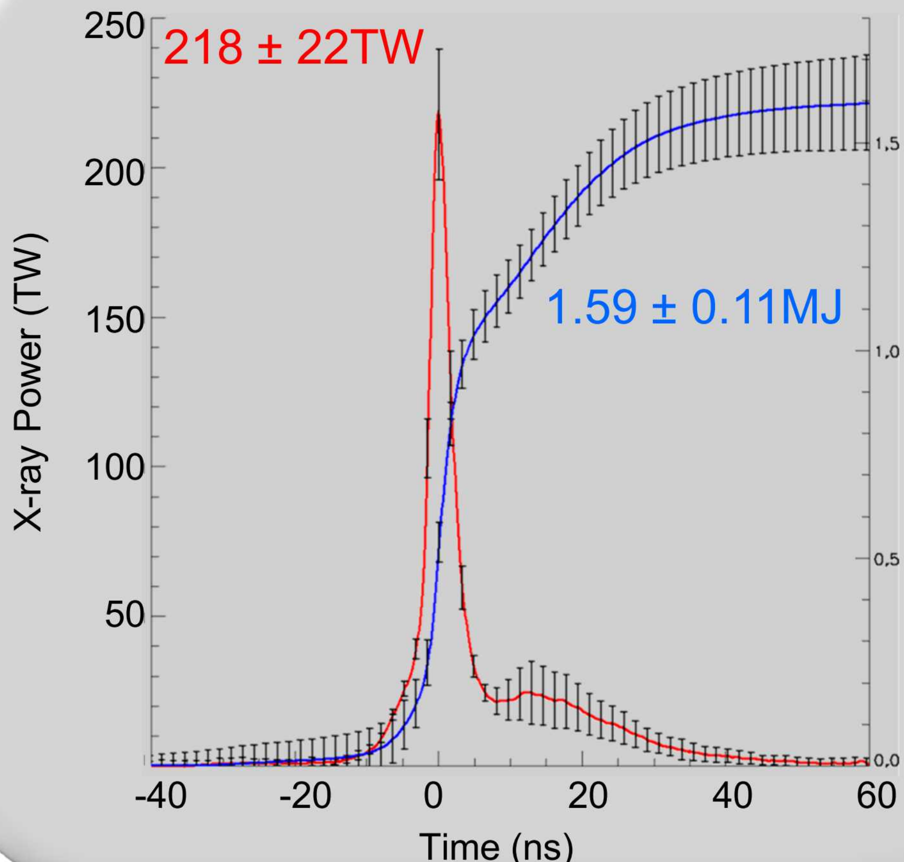
V_{marx} = 85 kV (20.3 MJ)

I_p = 25.8 ± 0.4 MA [20 shots]

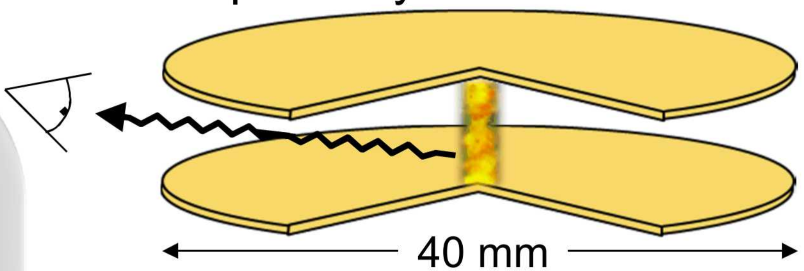
Sanford et al., POP 9 (2002)
Lemke et al., POP 12 (2004)
Bailey et al., POP 13 (2006)
Slutz et al., POP 13 (2006)
Rochau et al., PRL 100 (2008)

The ZPDH x-ray emission is reproducible to ± 10% in peak power and ± 7% in energy

Radial X-ray Power and Energy
(20 shot average)

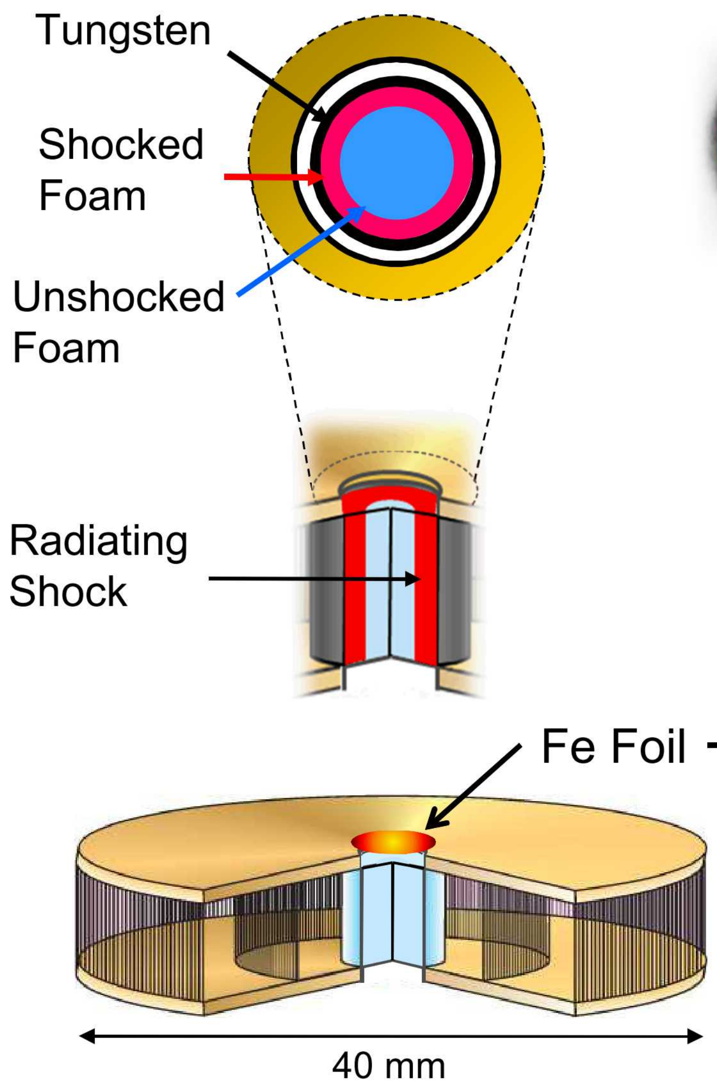


Z-pinch Dynamic Hohlraum

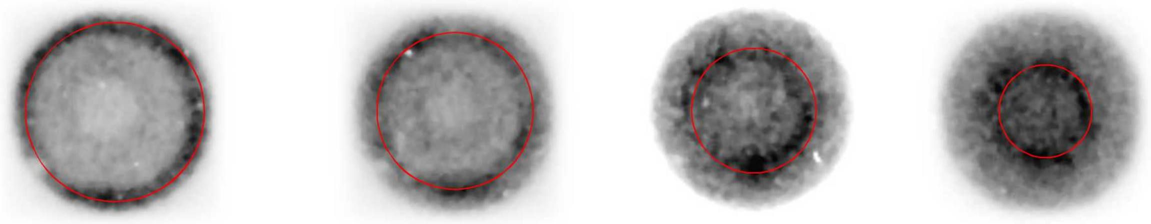


	ZR >2011	Z <2007
Marx Energy	20.3 MJ	11.4 MJ
Ipeak	25.8 MA (1.5%)	21.7 MA* (2.1%)
Mass	8.5 mg	3.8 mg
Peak Power	220 TW (10%)	120 TW (14%)
Radiated Energy	1.6 MJ (7%)	0.82 MJ (17%)

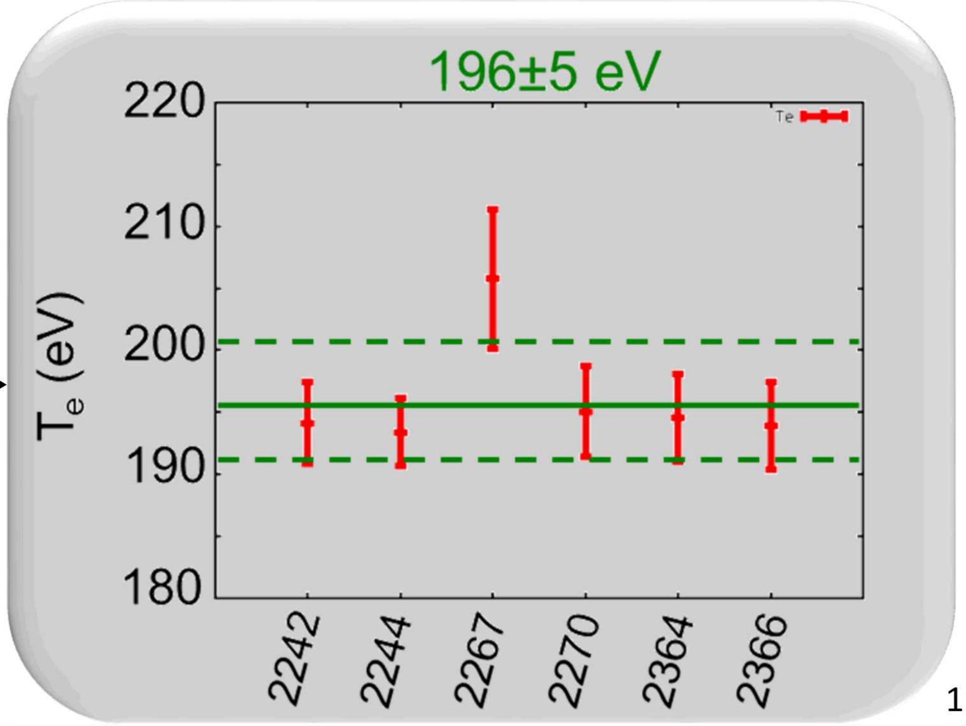
The ZPDH can also radiatively heat samples placed above the z-pinch to T_e~200 eV.



Framing Pinhole Camera Images

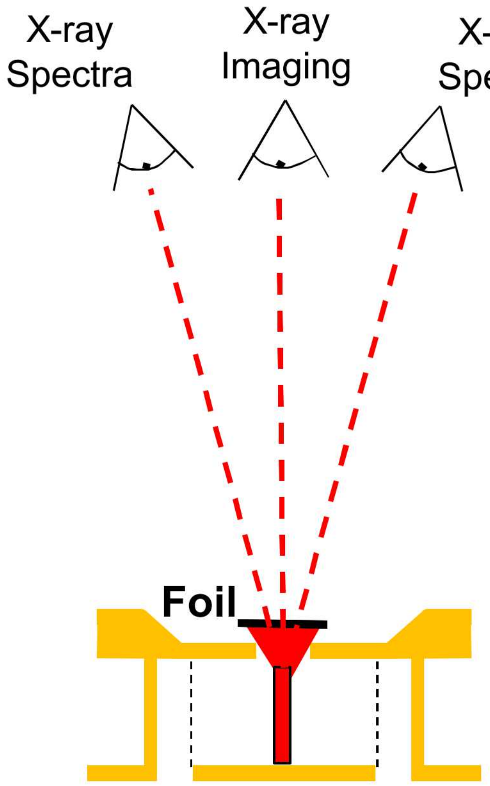


Axial Fe Foil Temperature

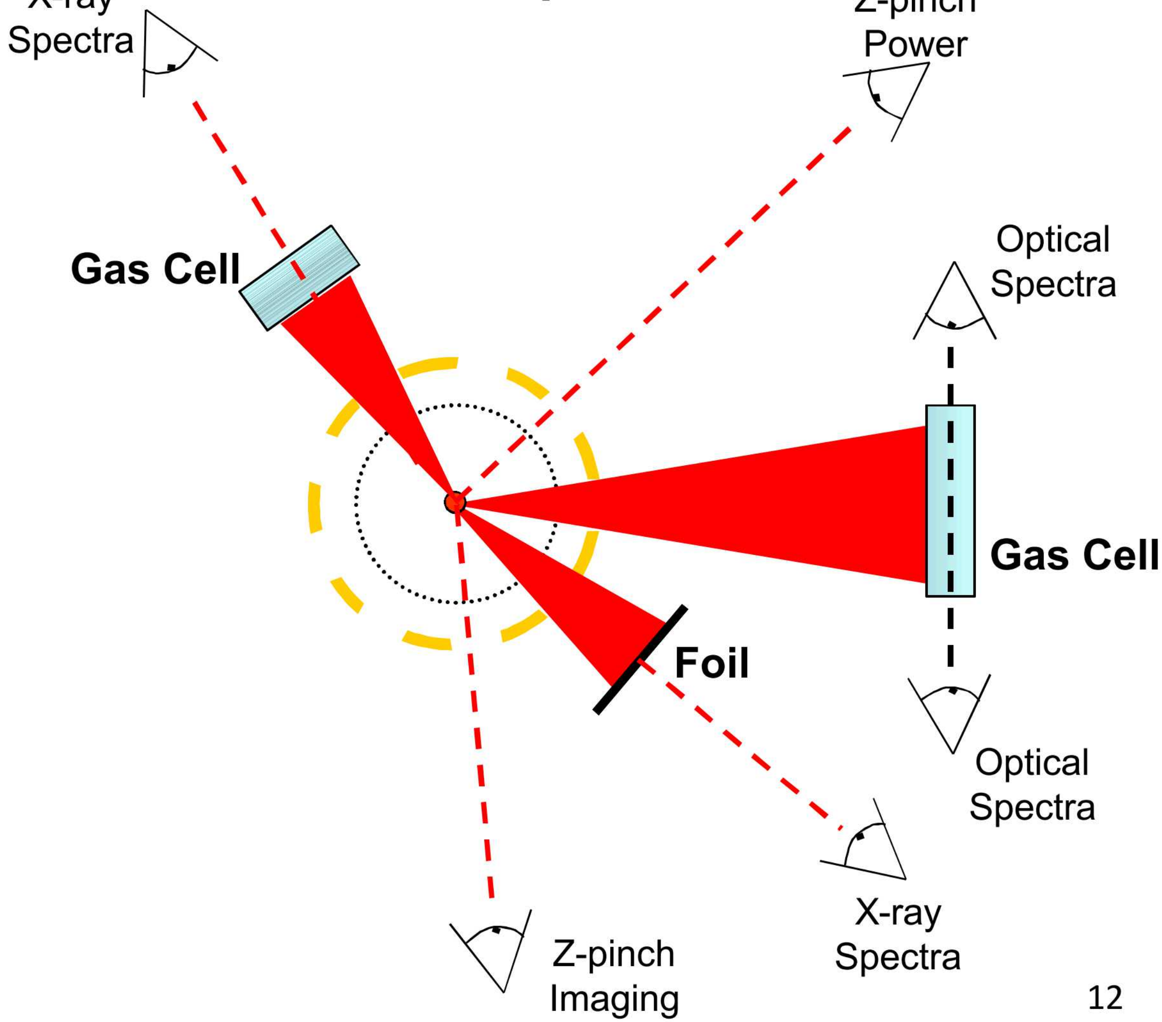


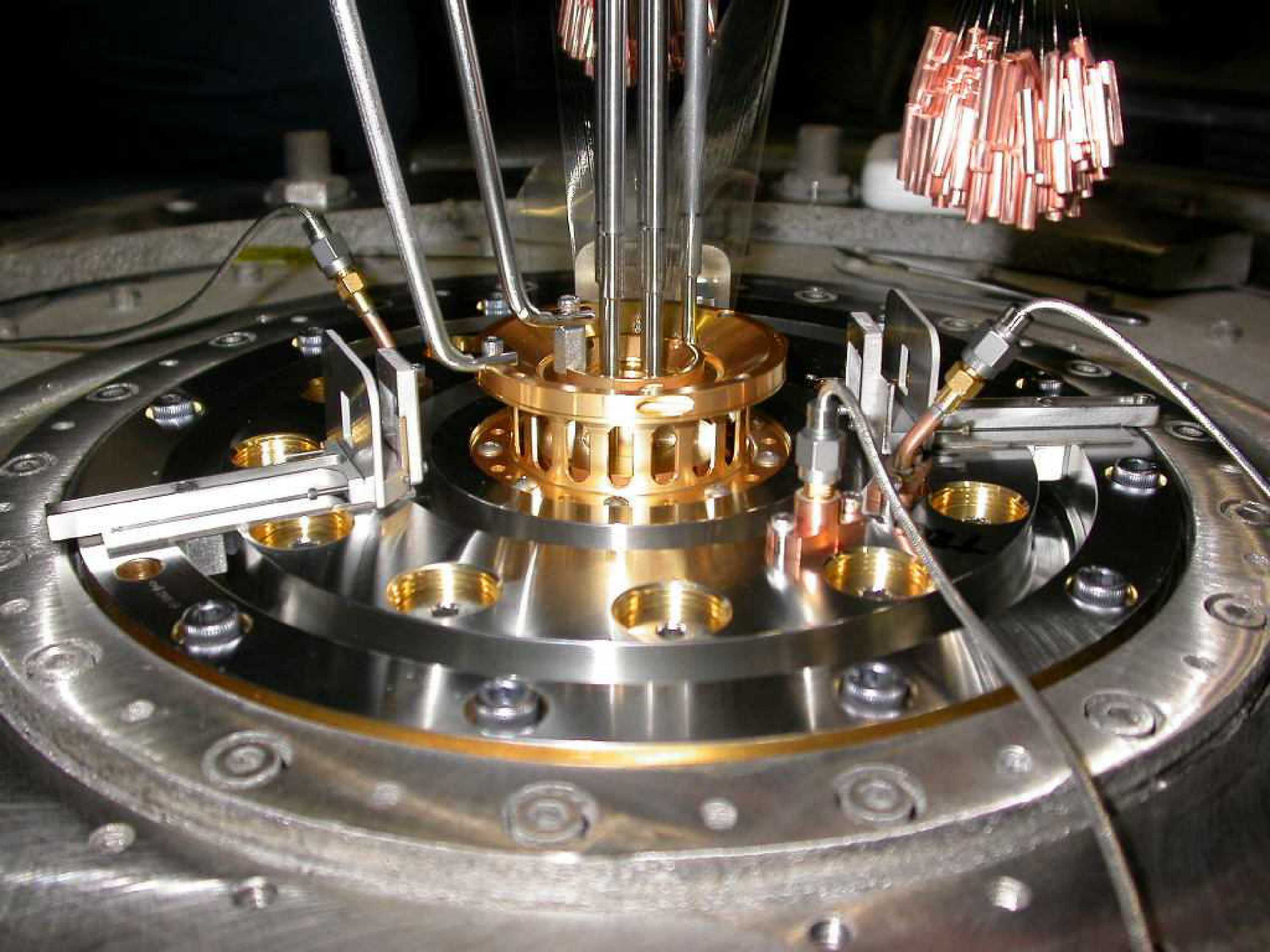
The ZPDH simultaneously drives four independent experiments on a single ZAPP shot

1 Axial Experiment



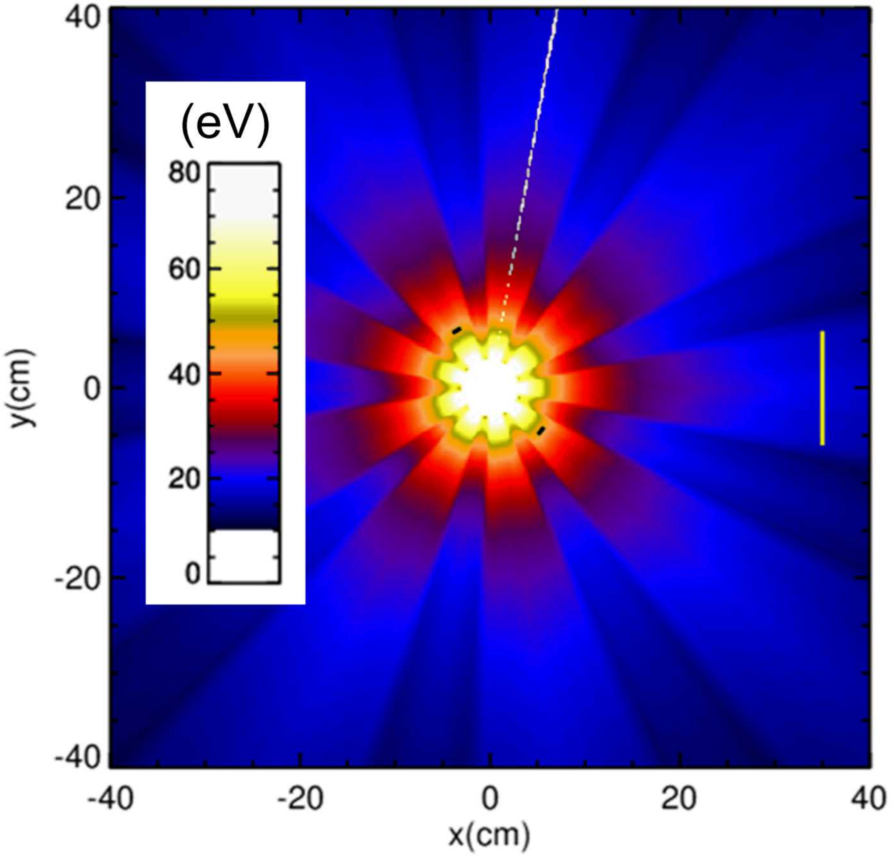
3 Radial Experiments



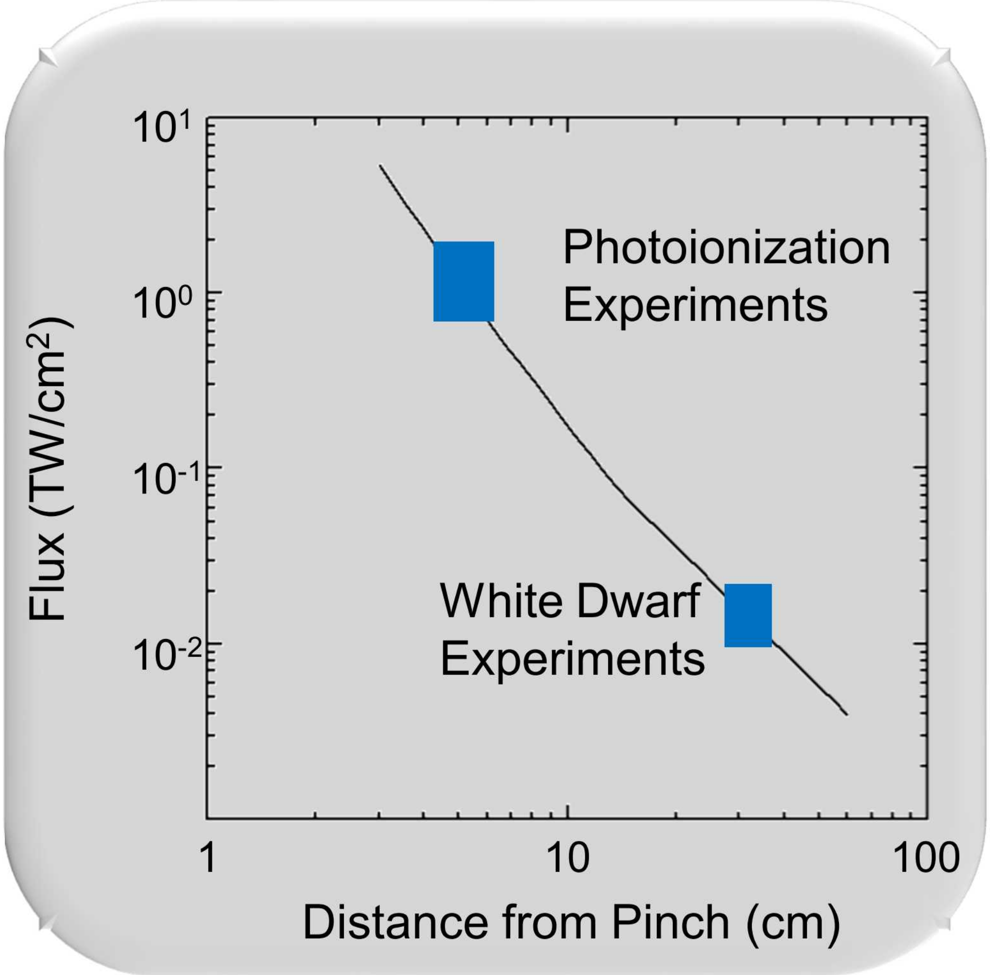


Placing samples at multiple distances from the z pinch provides a broad range of drive flux.

r-θ Peak Brightness Temperature Contours Around Z Pinch

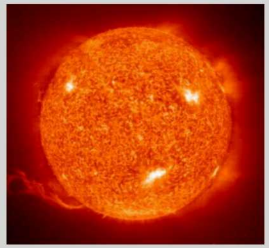


Peak Drive Flux on a Sample



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

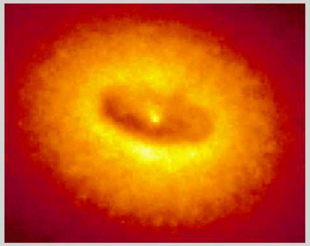
Solar Opacity



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}

Photoionized Plasmas



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}

White Dwarf Line-Shapes

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

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

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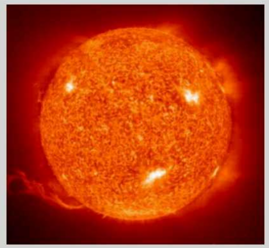

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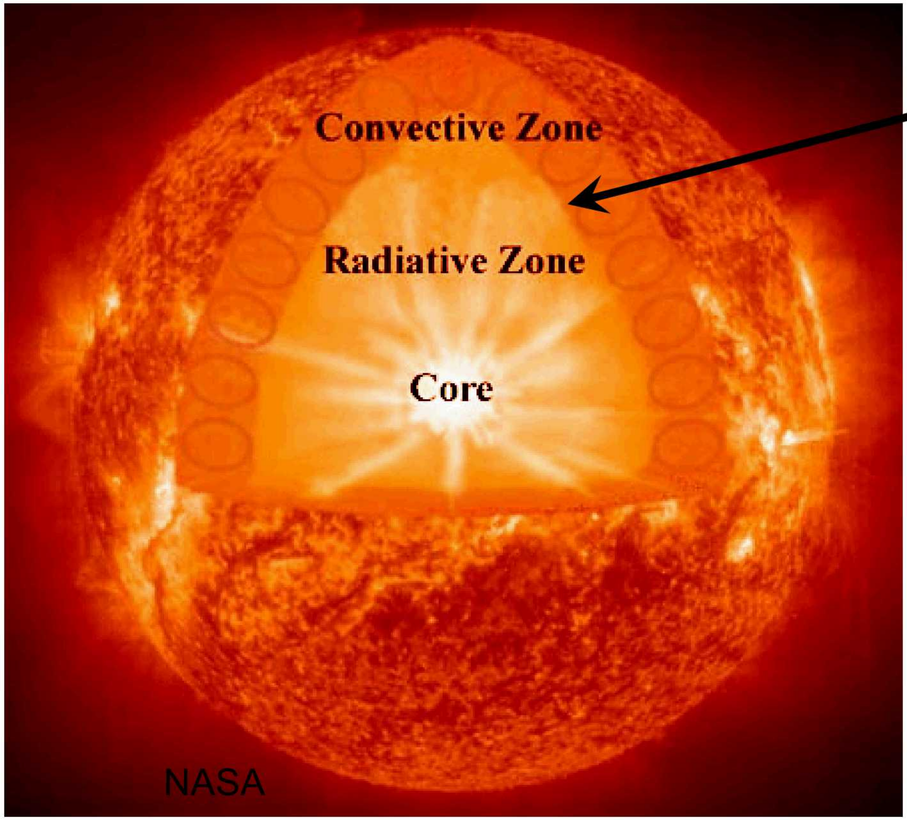
Models for solar interior structure disagree with helioseismology observations.



Convection-Zone (CZ) Boundary
Models are off by 10-30 σ

Models depend on:

- **Composition (revised in 2005*)**
- **EOS as a function of radius**
- **The solar matter *opacity***
- **Nuclear cross sections**

Question: Is opacity uncertainty the cause of the disagreement?

Objective: Measure Fe opacity at CZ base conditions.

*M. Asplund *et al*, Annu. Rev. Astro. Astrophys. **43**, 481 (2005).

The ZPDH radiating shock is used to both heat and backlight samples to stellar interior conditions.

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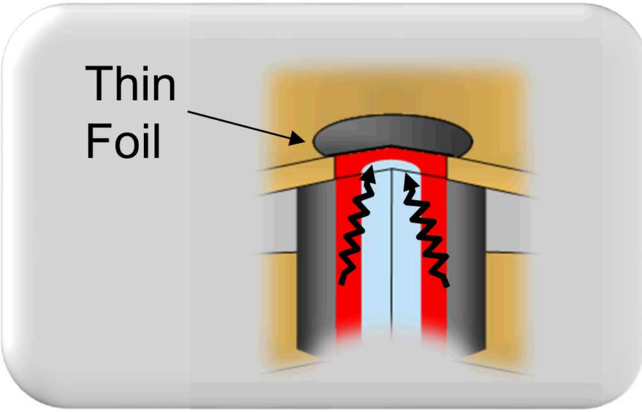
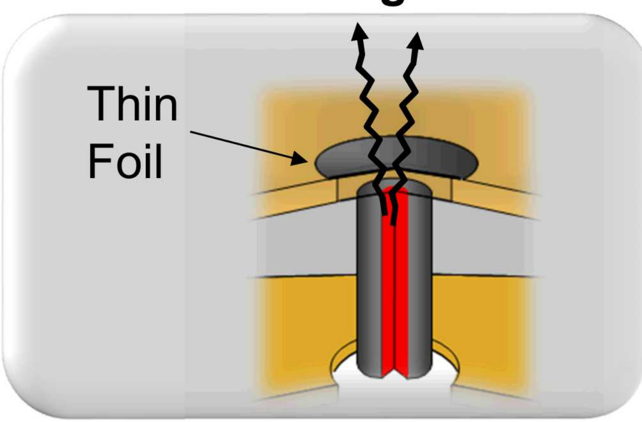
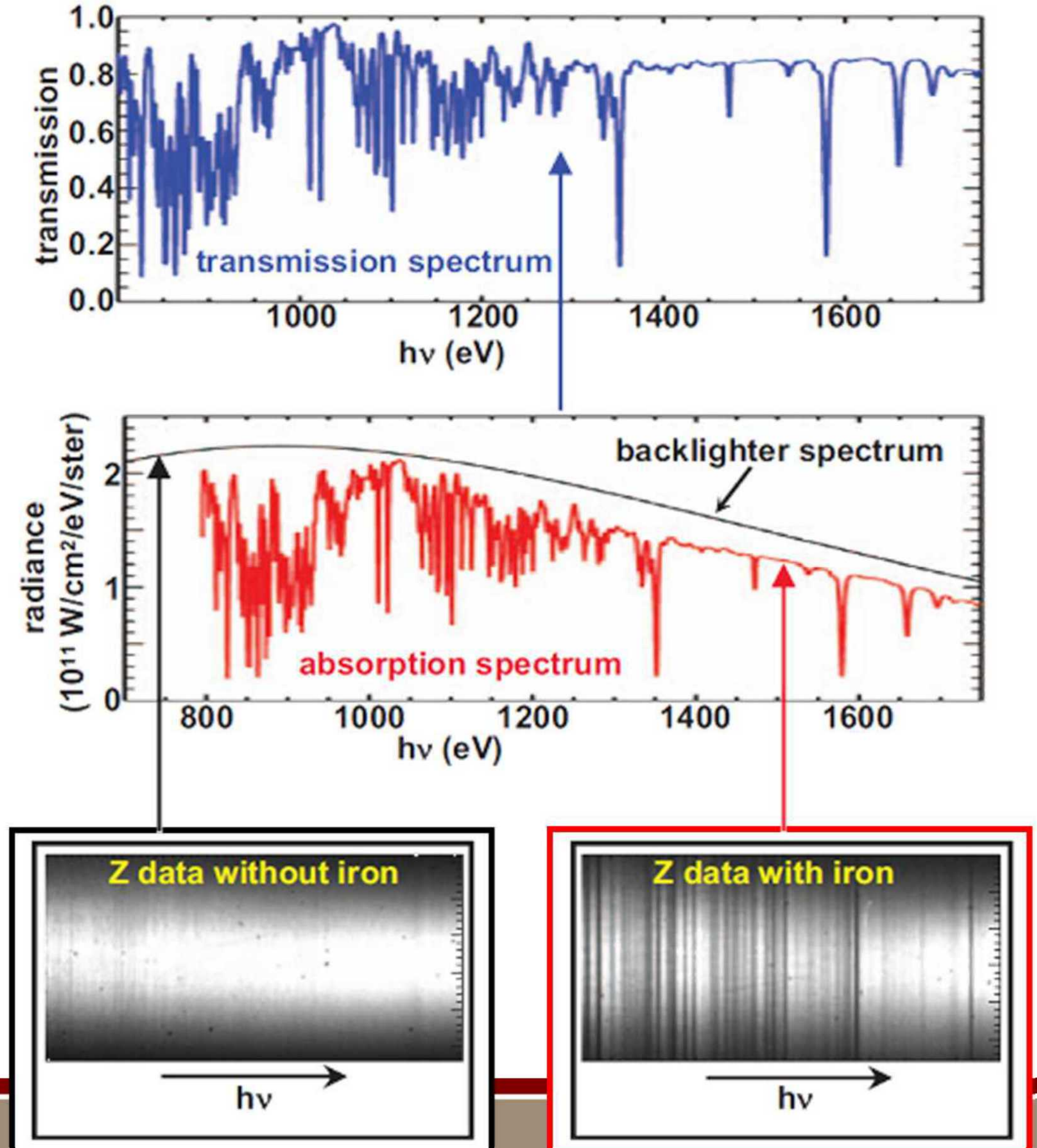
Foil is heated during the ZPDH implosion



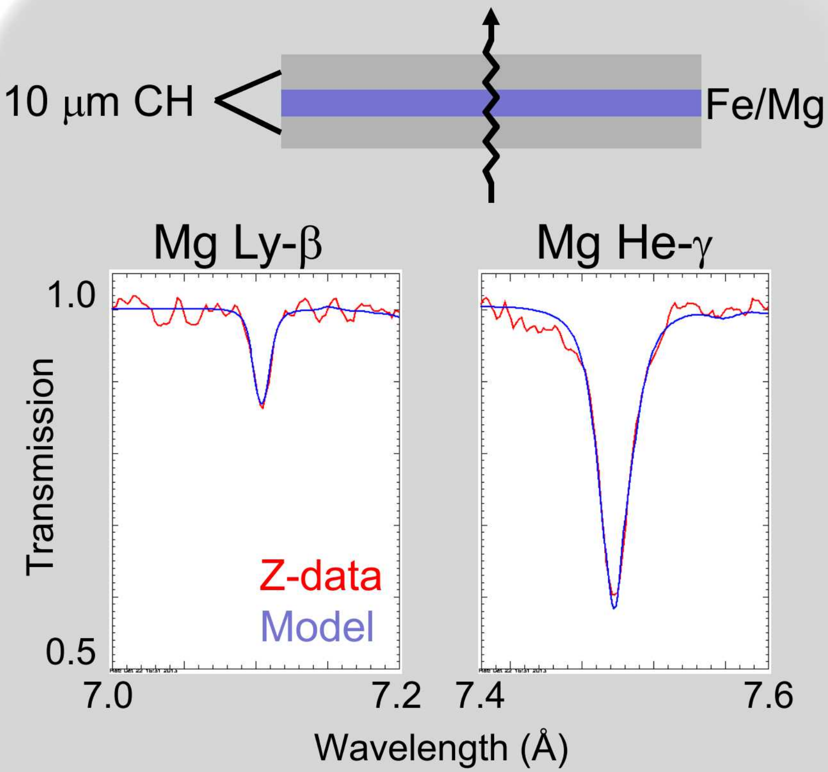
Foil is backlit at shock stagnation





The achieved temperature and density depend on the target design.

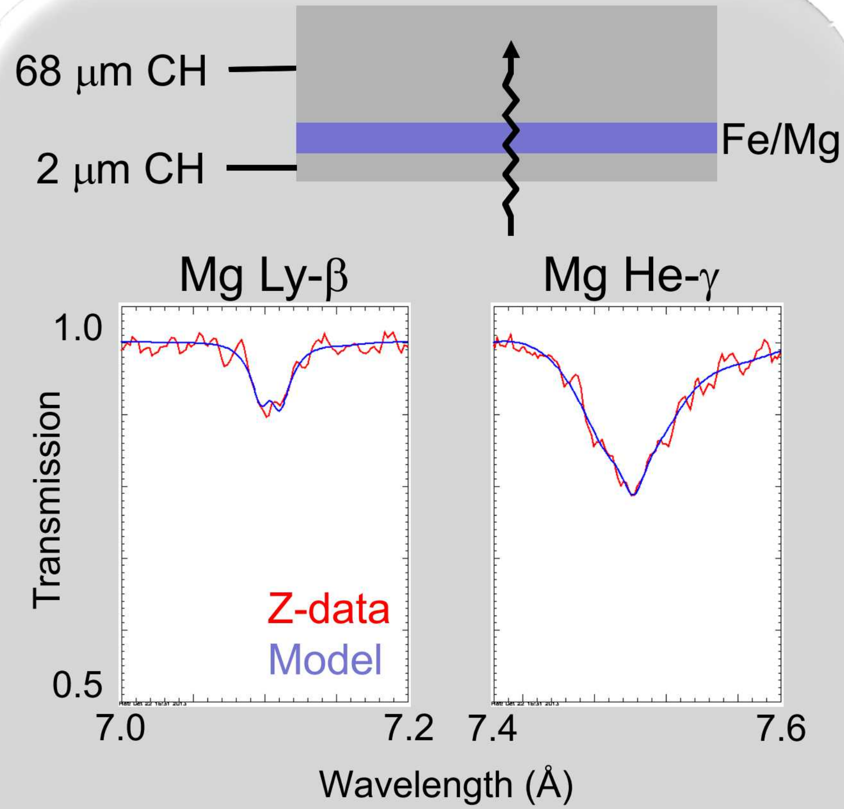
Thin Tamper



T_e = 156 ± 6 eV

n_e = 6.9 ± 1.7 x10^{21} cm^{-3}

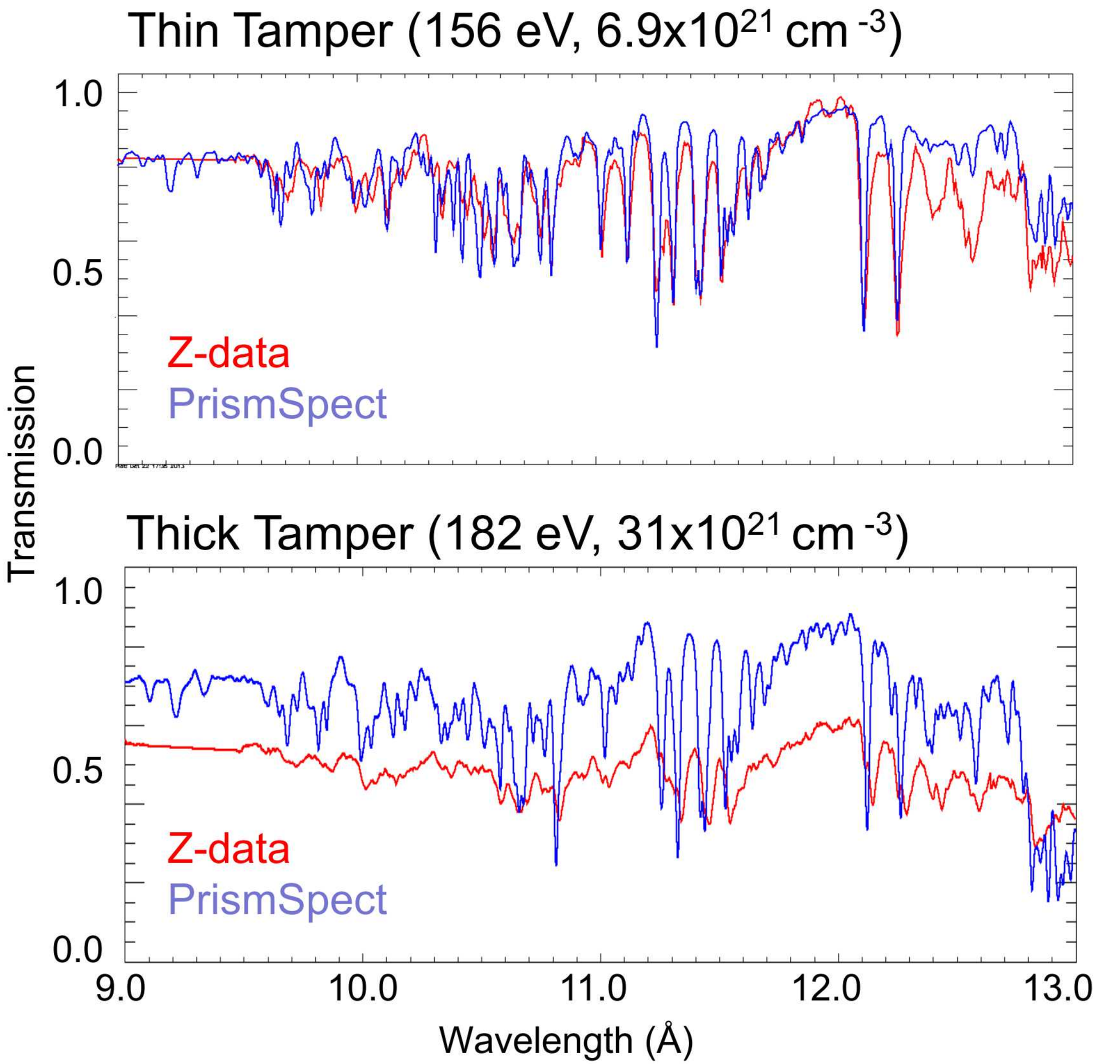
Thick Tamper



T_e = 196 ± 5 eV

n_e = 39. ± 9. x10^{21} cm^{-3}

Modern computations of Fe opacity show large disagreements with data at CZ base conditions



Present Status*

- Agreement between data and computation becomes worse at increasing temp. and dens.
- Disagreements at CZ base conditions can partially explain the CZ boundary problem.
- The differences are probably not unique to Fe
- Presently investigating Cr & Ni

*Bailey et al., Nature (2015)

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

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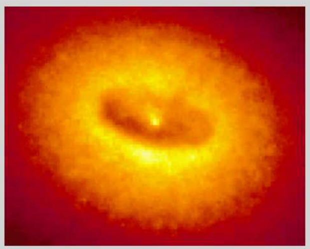
Solar Opacity

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}

Photoionized Plasmas



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How does ionization and line formation occur in accreting objects?

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

White Dwarf Line-Shapes

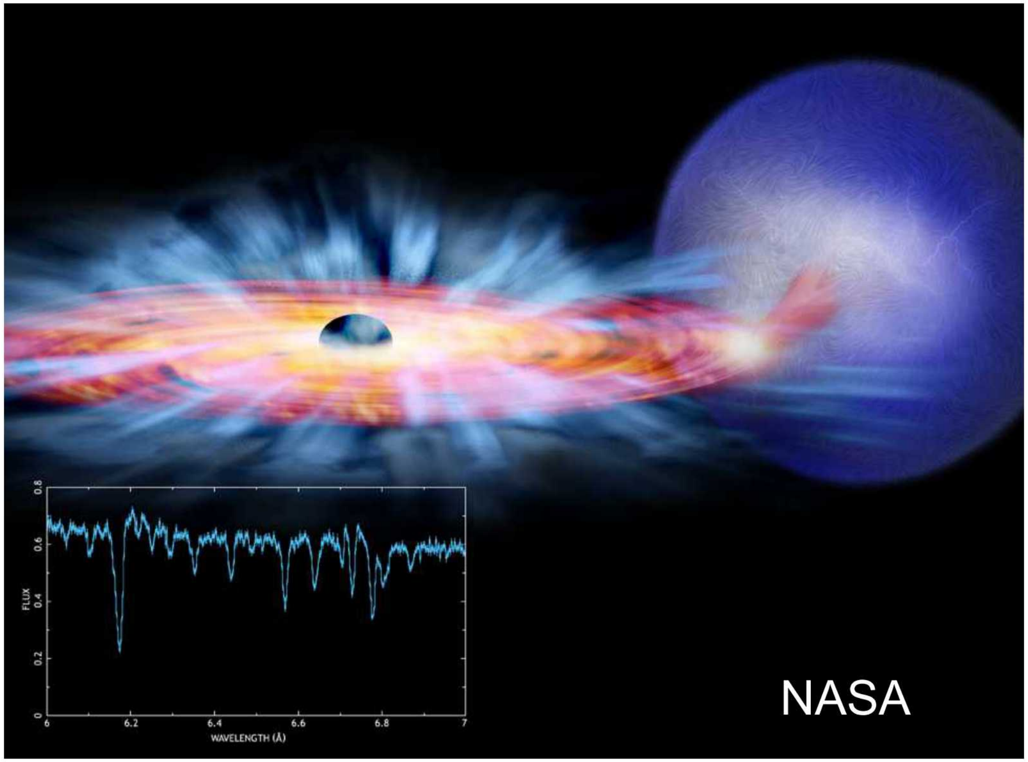
Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

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

We learn about black holes from the matter falling into them – these are photoionized plasmas

Conceptual Picture of a Black-Hole Accretion Disk

ξ ~ 10 – 10,000 erg.cm.s^{-1}



Photoionization parameter

$$\xi \equiv \frac{4\pi F}{n_e} \; [\mathrm{erg.cm.s^{-1}}]$$

Laboratory Plasmas

n_e ~ 10^{19} cm^{-3}

F > 1 TW/cm^2 for ξ > 10

- Can we model the ionization?
- Can we model the line emission?

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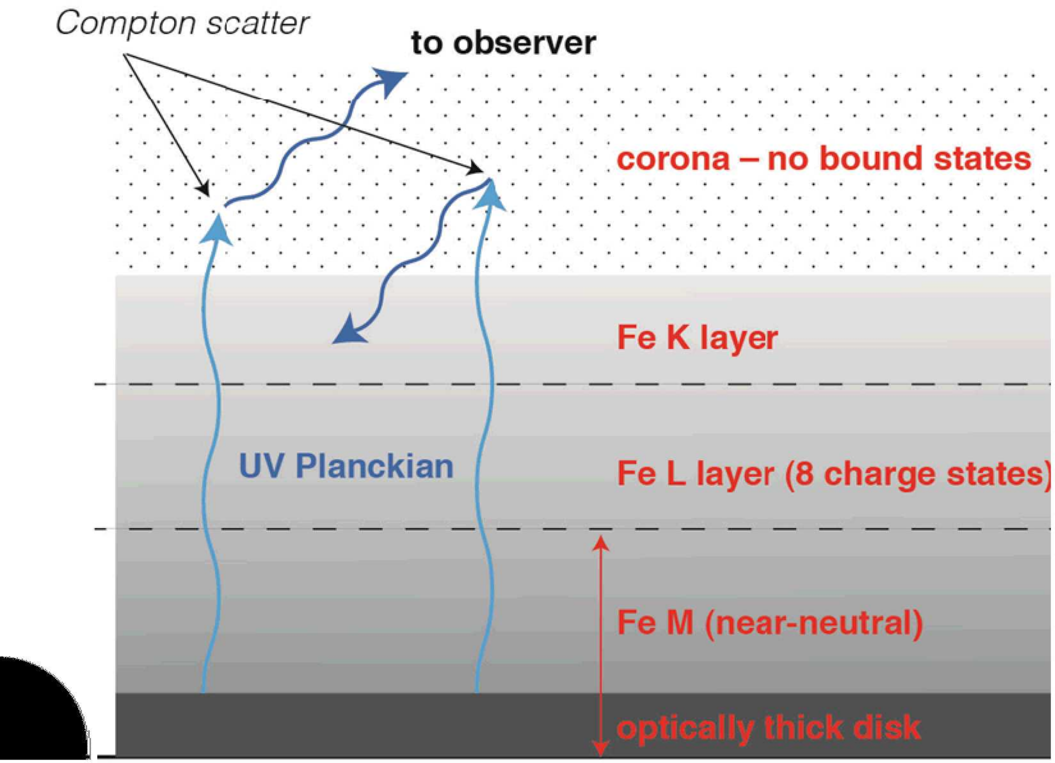

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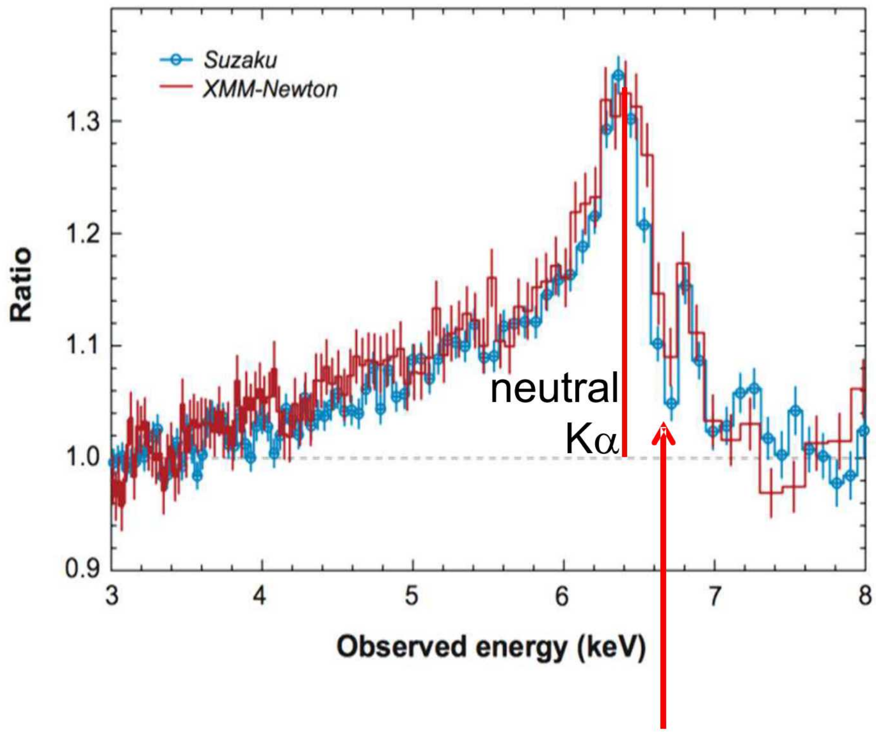
- Can we model the ionization?
- Can we model the line emission?

A Specific Problem: Emission from L-shell ions is not seen in some prominent black-hole accretion disks.

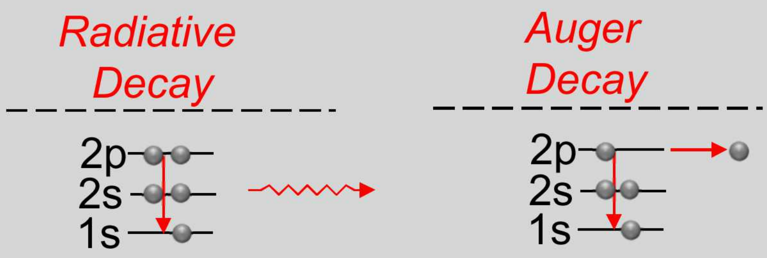
Measured Fe Emission from MCG 6-30-15



No observed emission from Fe ionized to the L-shell

Resonant Auger Destruction (RAD) was accepted as the reason*

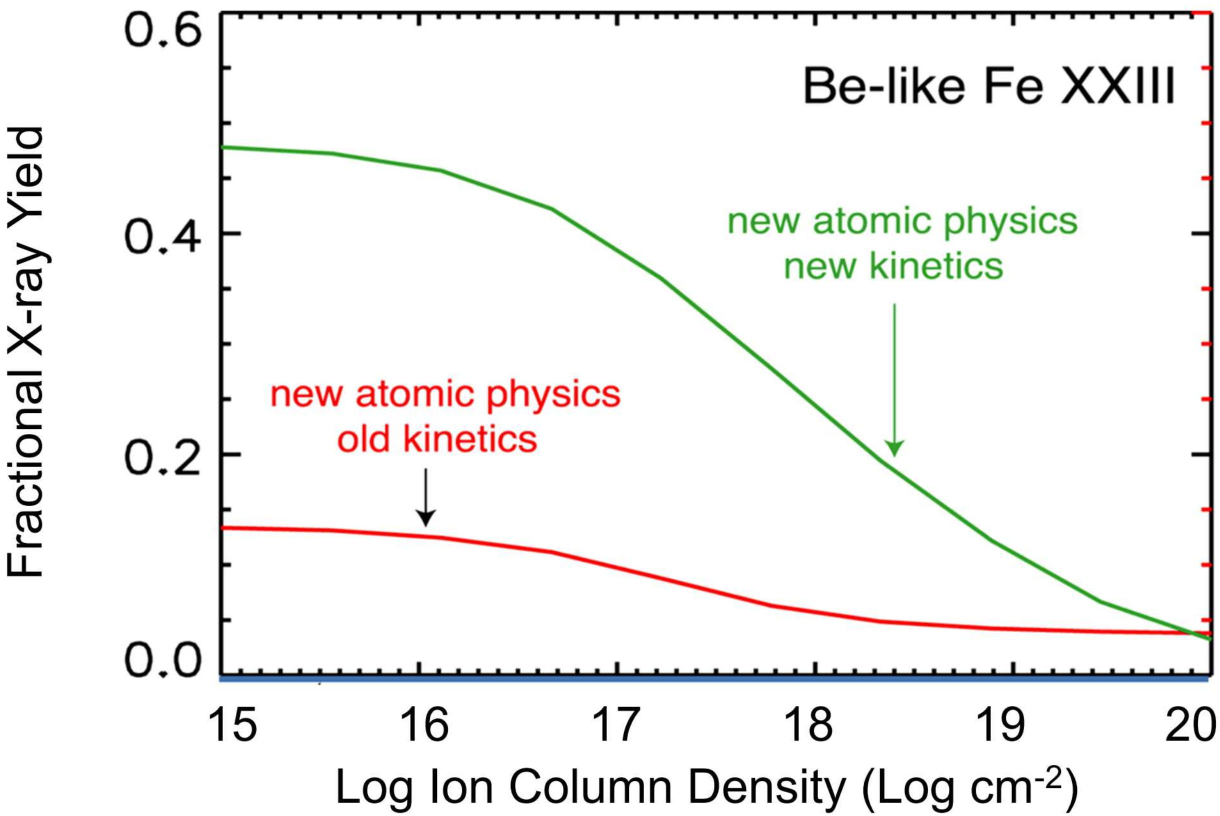
- 2 competing processes for the de-excitation of L-shell ions:



- **Thin Plasma:** high probability of observing the photon
- **Thick Plasma:** high probability of the photon being resonantly absorbed
  → Higher probability of Auger Decay for the ensemble

*Ross, Fabian and Brandt, MNRAS, 1996

New models* suggest that RAD may not be as efficient as previously thought.



Question: Is Resonant Auger Destruction the reason we don't see emission from L-shell ions in some black-hole accretion disks?

Objective: Measure spectra in a highly photo-ionized lab plasma.

*Liedahl, *X-ray Diag. of Astrophysical Plasmas (2005)*

ZAPP experiments achieve $\xi \sim 20$ at the correct column depths to study the RAD question.

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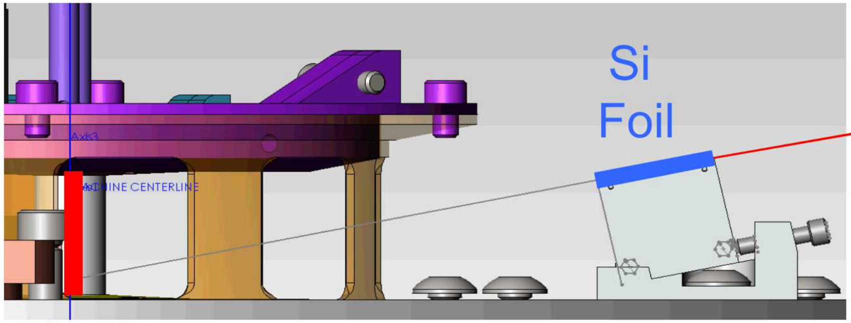
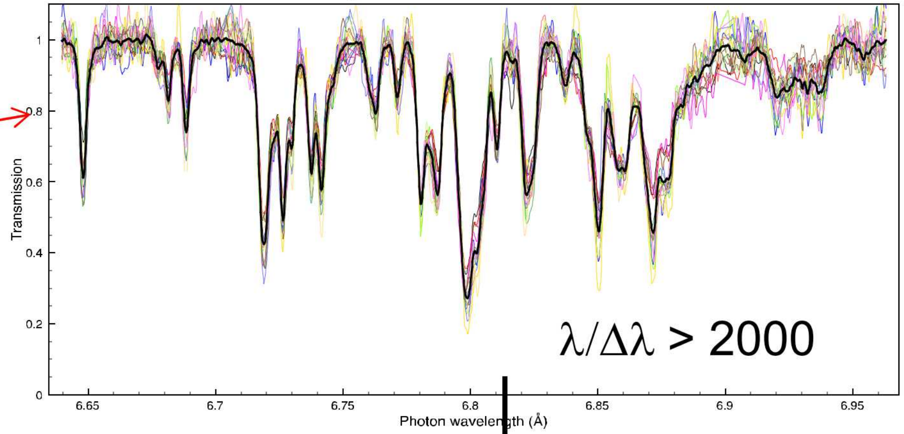


Pinch

Si Absorption Measurements



Measured Quantities

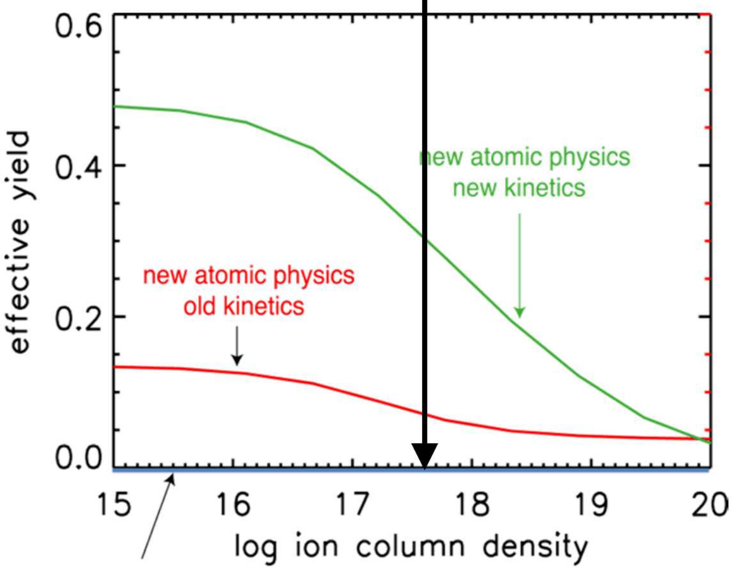
Flux……………………F = 1.3 TW/cm^2

Electron Density…………….n_e = 8.5 10^{18} e^-/cm^3

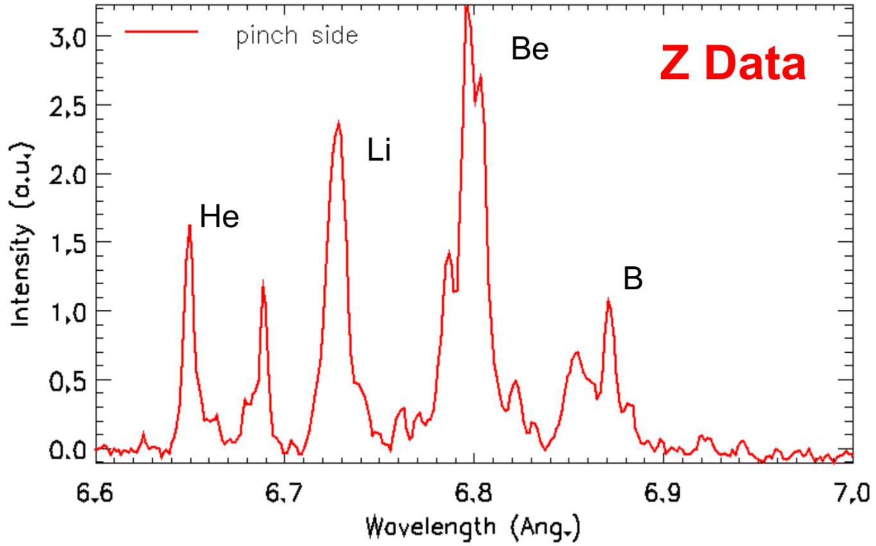
Photoionization Parameter………...ξ = 19 erg.cm.s^{-1}

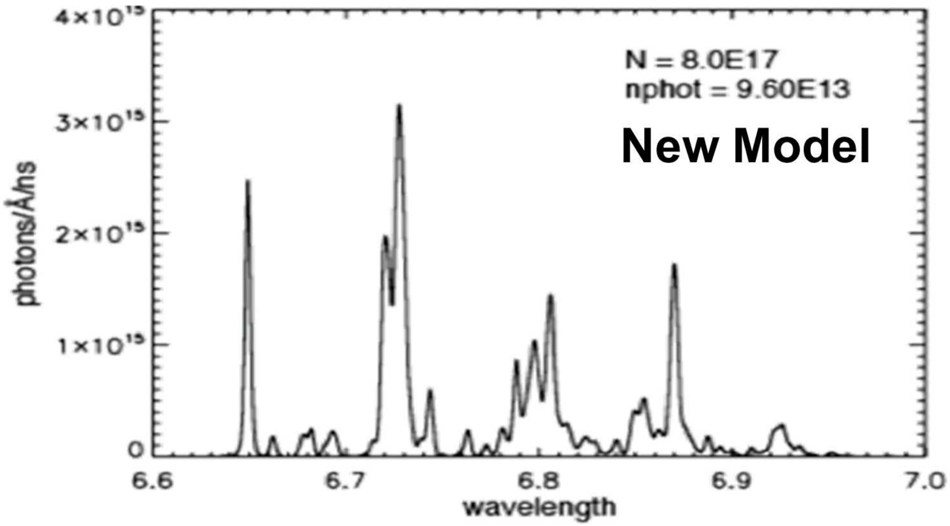
Column Density…..N_i = 5 10^{17} at/cm^2

Electron Temp…….T_e = 19.5 eV



Recent emission measurements demonstrate that L-shell emission is not 100% quenched by RAD.





Present Status

- Z Data demonstrates that L-shell emission does escape at column depths >1E17 at/cm^2.
- Present data can discriminate between models of the ionization distribution AND relative line strengths.
- Absolute intensity is needed to determine efficiency of RAD process.

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Los Alamos NATIONAL LABORATORY

cea

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THE UNIVERSITY OF TEXAS AT AUSTIN

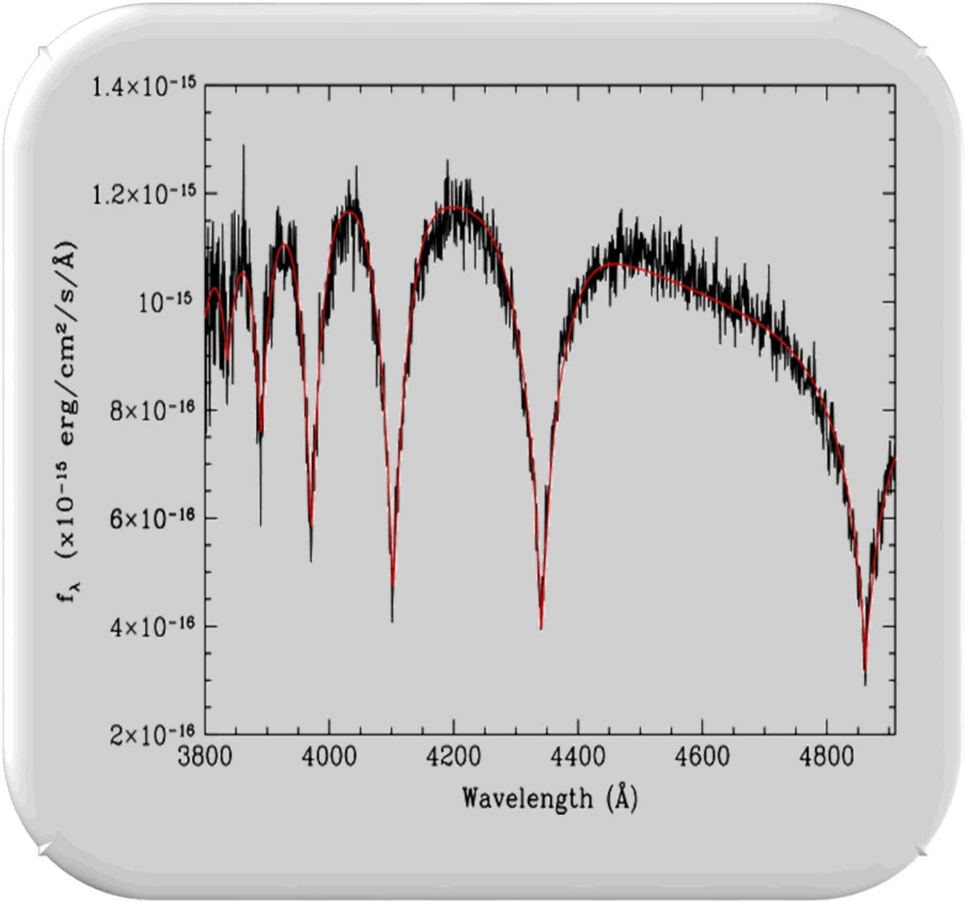
The properties of White Dwarfs are determined by spectral fitting, but disagrees with other methods

- 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

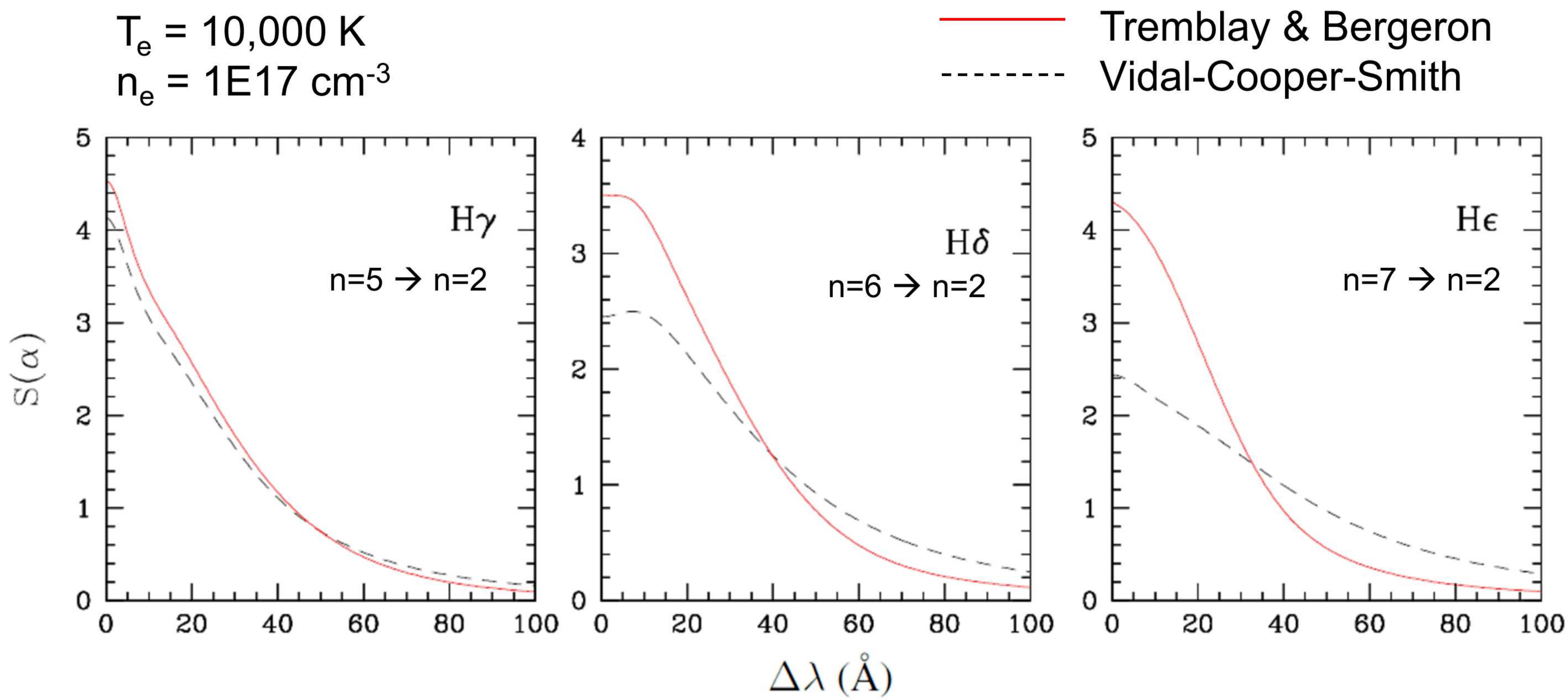
- The spectroscopic method and gravitational redshift disagree by >10% in the stellar mass

Spectral fit of WD J1916+3938*



*Hermes et al. (2011)

New Stark broadened line-shape calculations* partially fix the problem – are they right?



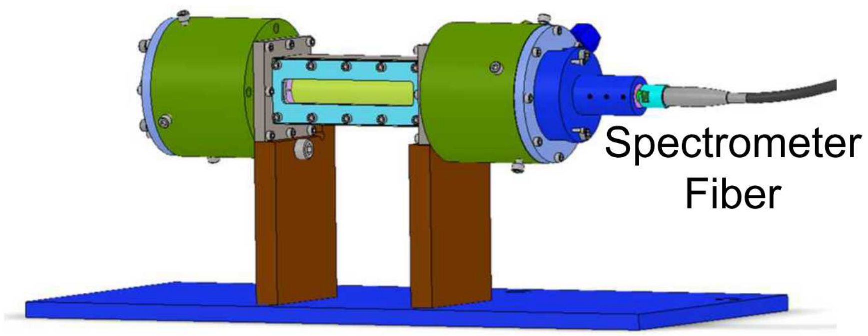
Question: Are inaccurate H-Balmer line shapes responsible for the inaccurate determination of WD mass?

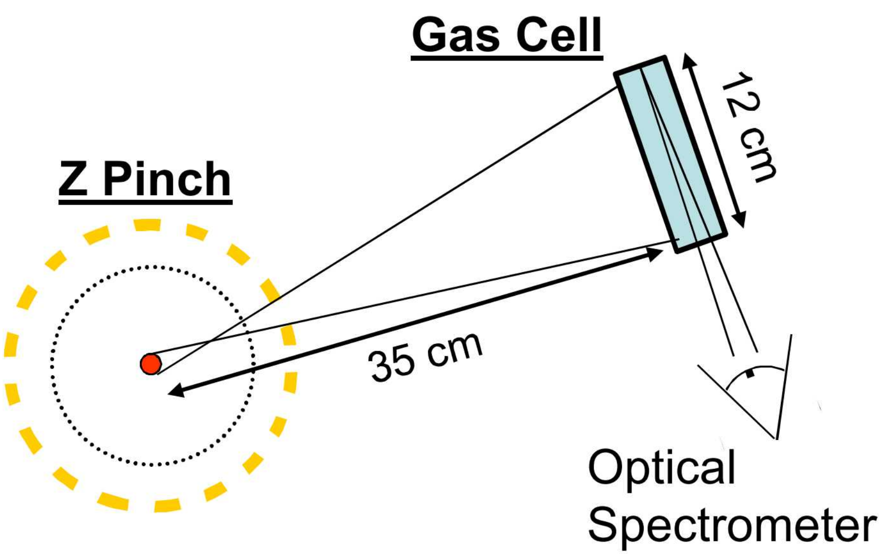
Objective: Measure H-Balmer line shapes at relevant temperature and density.

ZAPP experiments utilize radiatively heated gas cells to provide benchmark data for the WD problem

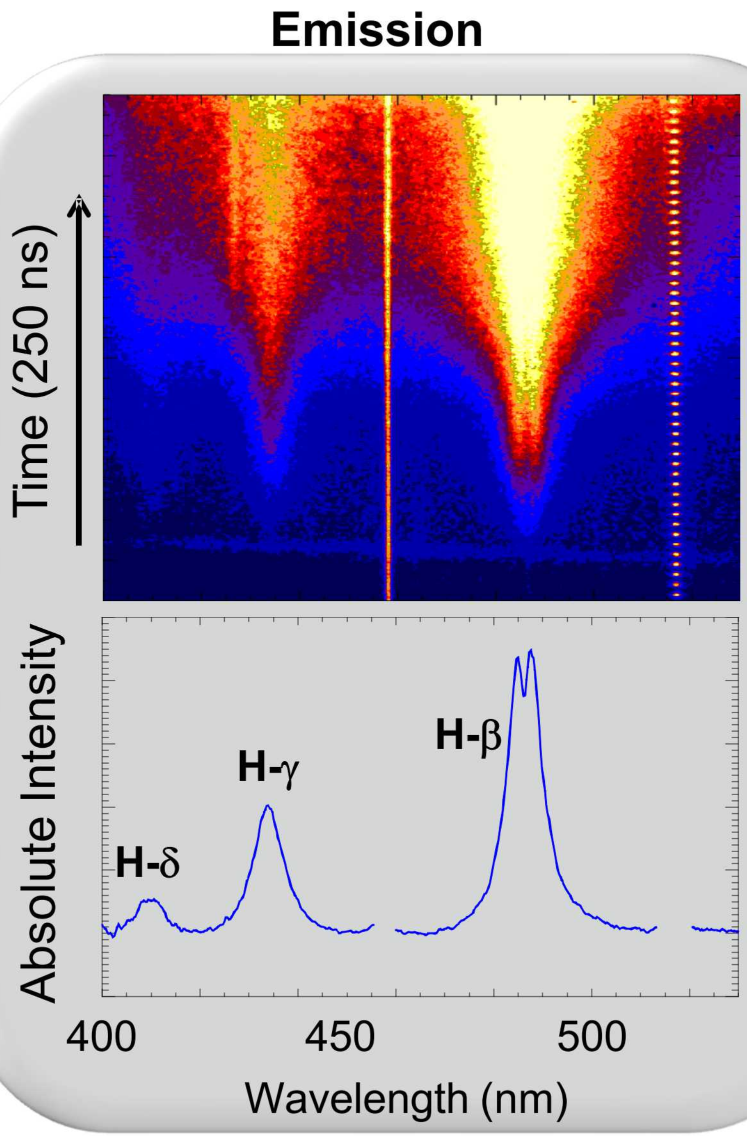
- Gas cells provide a precisely known atom density
- Large cell size provides optical depths needed for high-n lines
- Large cell minimizes the effect of boundary layers
- Long fielding distance provides uniform heating flux

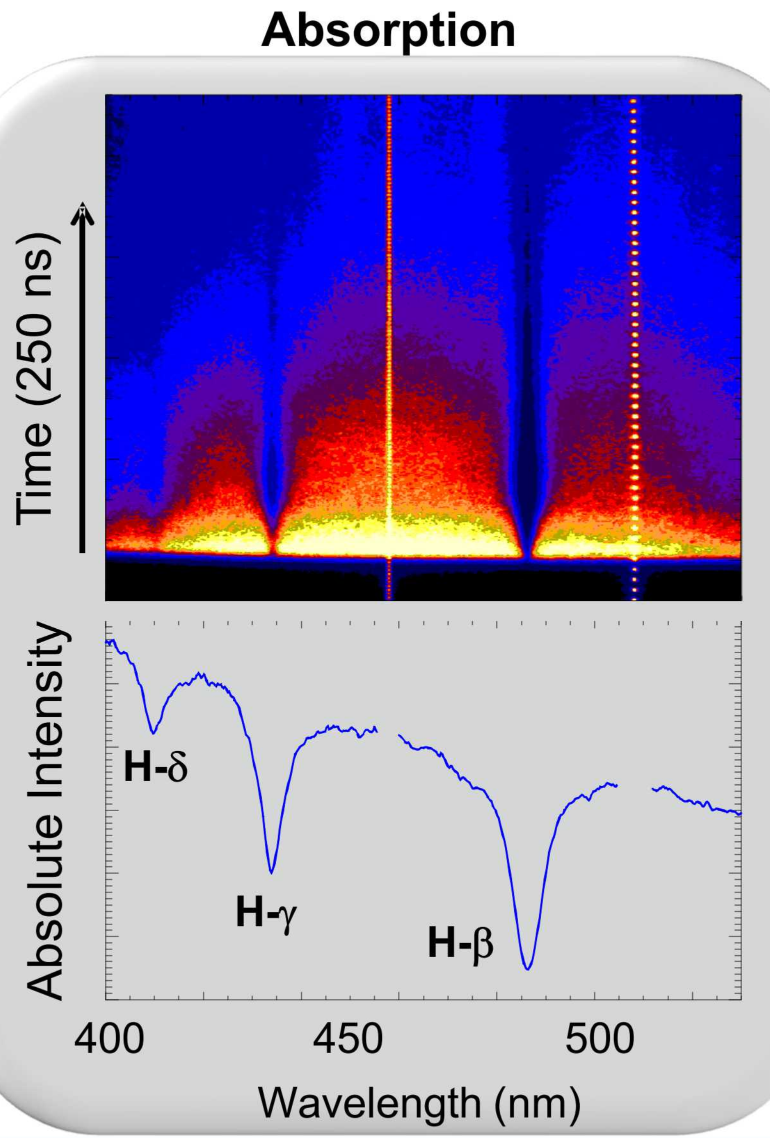
Gas Cell Model



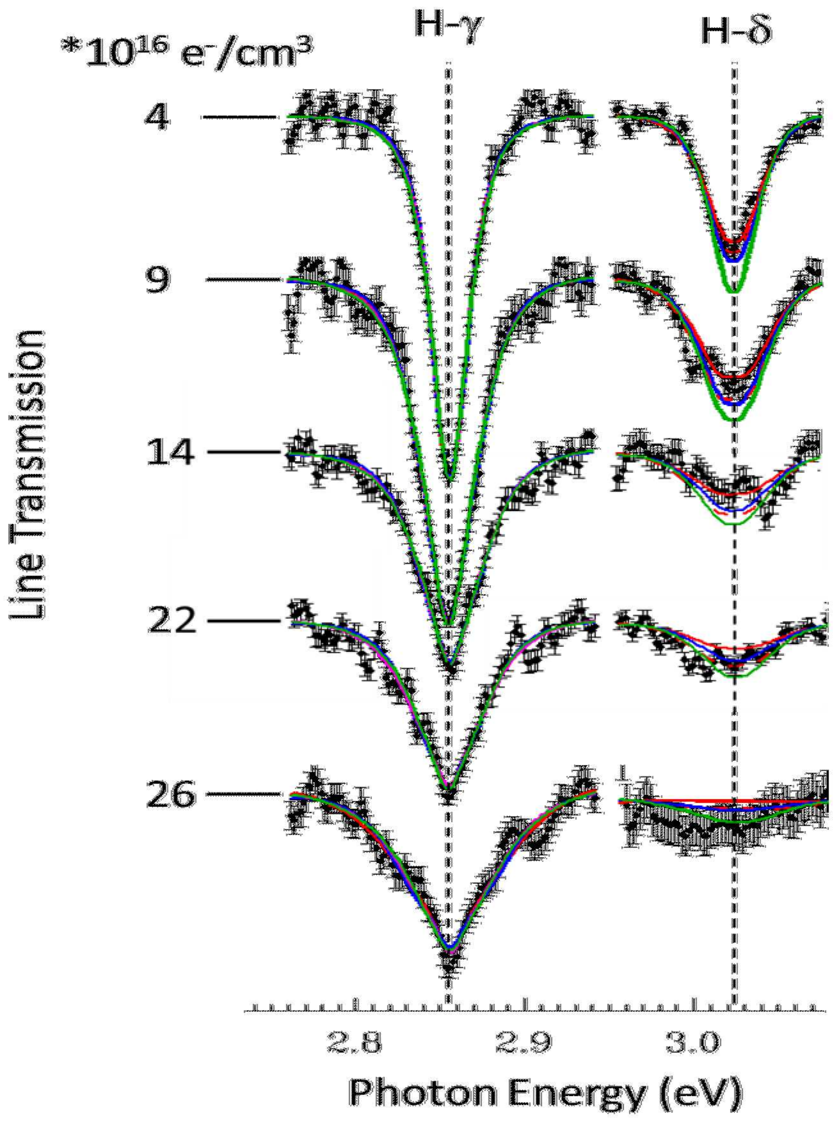


Simultaneous streaked absorption and emission in absolute units provide a unique capability





The measured evolution of H-Balmer line shapes provides tight constraints on models



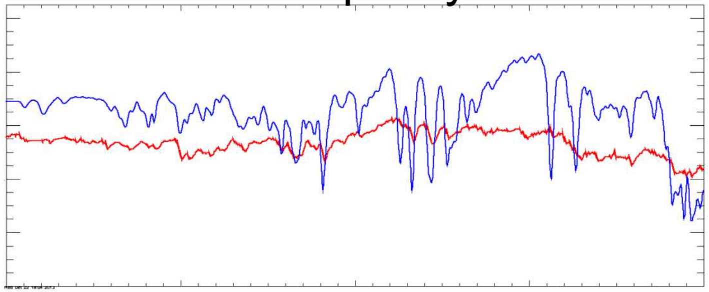
Present Status

- Measurement of relative line-shapes up to n=7 provides a strong constraint on models
- Additional measurements at higher density may be required to fully address the WD problem
- Continued scrutiny on the data is prudent:
  - Reproducibility of the result
  - Plasma uniformity

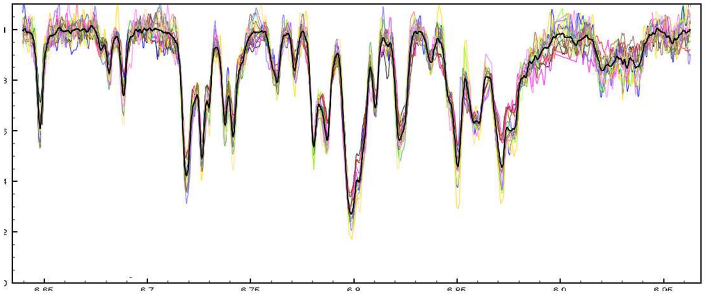
Summary: ZAPP experiments measure fundamental properties of atoms in plasmas to solve important astrophysical puzzles.

- Why can't we predict the location of the convection zone boundary in the Sun?
  - ➢ Opacity of Fe at ~200 eV
- How does ionization and line formation occur in accreting objects and warm absorbers?
  - ➢ Ionization distribution and spectral properties of photoionized Ne and Si
- Why doesn't spectral fitting provide the correct properties for White Dwarfs?
  - ➢ Stark-broadened H-Balmer line profiles

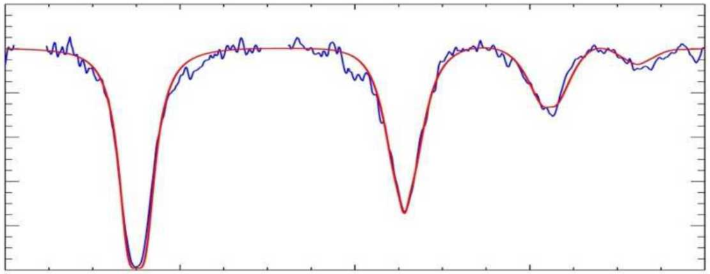
Fe Opacity



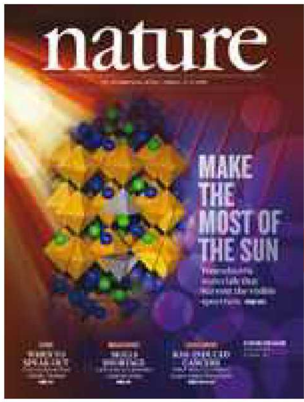
Si Photoionization



H-Balmer Line shapes



ZAPP experiments inform *and challenge* the interpretation of spectral data from the world's multi-billion dollar x-ray observatories.



NATURE Editorial: November, 2013

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POISON Strawberry-frog parents give protection to kids p.441

Nailing fingerprints in the stars

Laboratory-based experiments are sorely needed to complement the rapidly proliferating spectral data originating from observations by the latest space telescopes.

What are stars made of? After astronomers detected a bright-yellow, unknown spectral line in sunlight in 1868, they named the new element helium after the Greek Sun god Helios. But it was some 30 years before physicists on Earth managed to detect — and so confirm the discovery of — helium in a laboratory.

It is a pattern that has been repeated many times since: the indirect detection of elements and molecules through spectral signatures in quantum mechanics. But heavier elements have many electrons that can participate in transitions — iron has 26, making the probabilities of possible transitions between levels too complex to calculate accurately. Measuring emissions in the lab is the only alternative. Physicists can use tunable lasers to excite electrons into more levels and measure further transitions. This information can then feed back to the astronomical observations. Extra funds would significantly improve this

Chandra

XMM-Newton

Suzaku

"Laboratory-based experiments are sorely needed to complement the rapidly proliferating spectral data originating from the latest space telescopes"

*Nature editor, Nature 503 (2013)