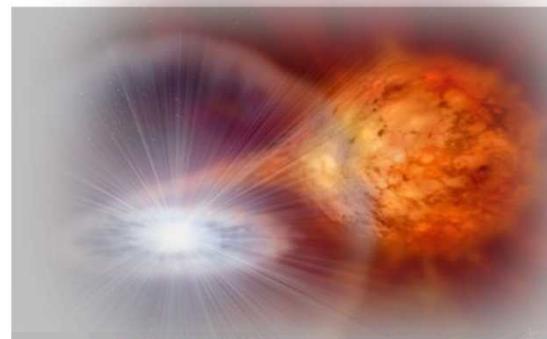
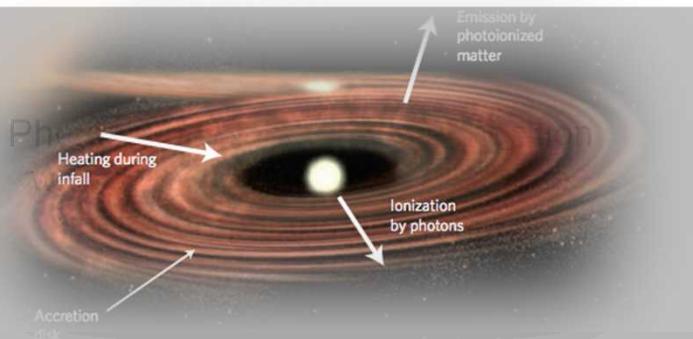


Exceptional service in the national interest



ZAPP: The Z Astrophysical Plasma Properties Collaboration

Gregory A. Rochau

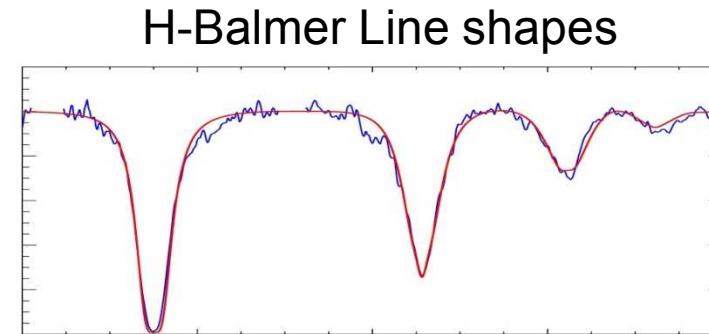
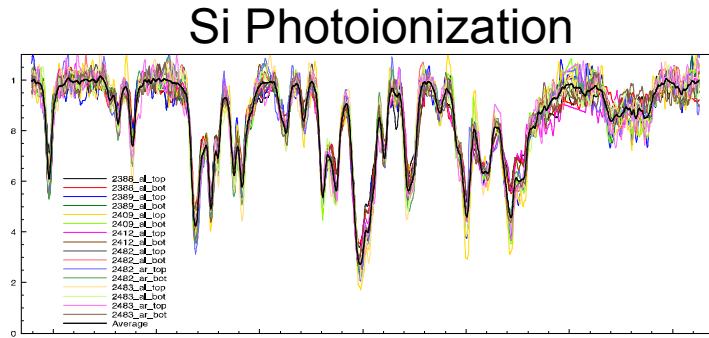
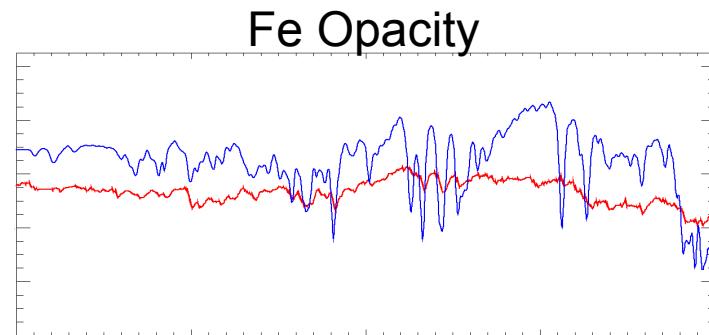
Presented at the 55th Annual Meeting of the APS Division
of Plasma Physics – November 11-15, 2013



Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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 \sim 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



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



Jim Bailey, Taisuke Nagayama,
Guillaume Loisel, Stephanie Hansen,
Dave Bliss, Tom Nash

Sandia National Laboratories



Roberto Mancini, Iain Hall, Tom
Lockard, Dan Marks

University of Nevada – Reno



Don Winget, Mike Montgomery, Ross
Falcon, Thomas Gomez, Alan Wooton,
Jennifer Ellis, Sean Moorhead, Roger
Bengtson

University of Texas – Austin



Anhil Pradhan, C. Orban, Mark
Pinsonneault, and S.N. Nahar

Ohio State University



Mark Koepke
West Virginia University



Duane Leidahl, Carlos Iglesias, Brian Wilson
Lawrence Livermore National Laboratory



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

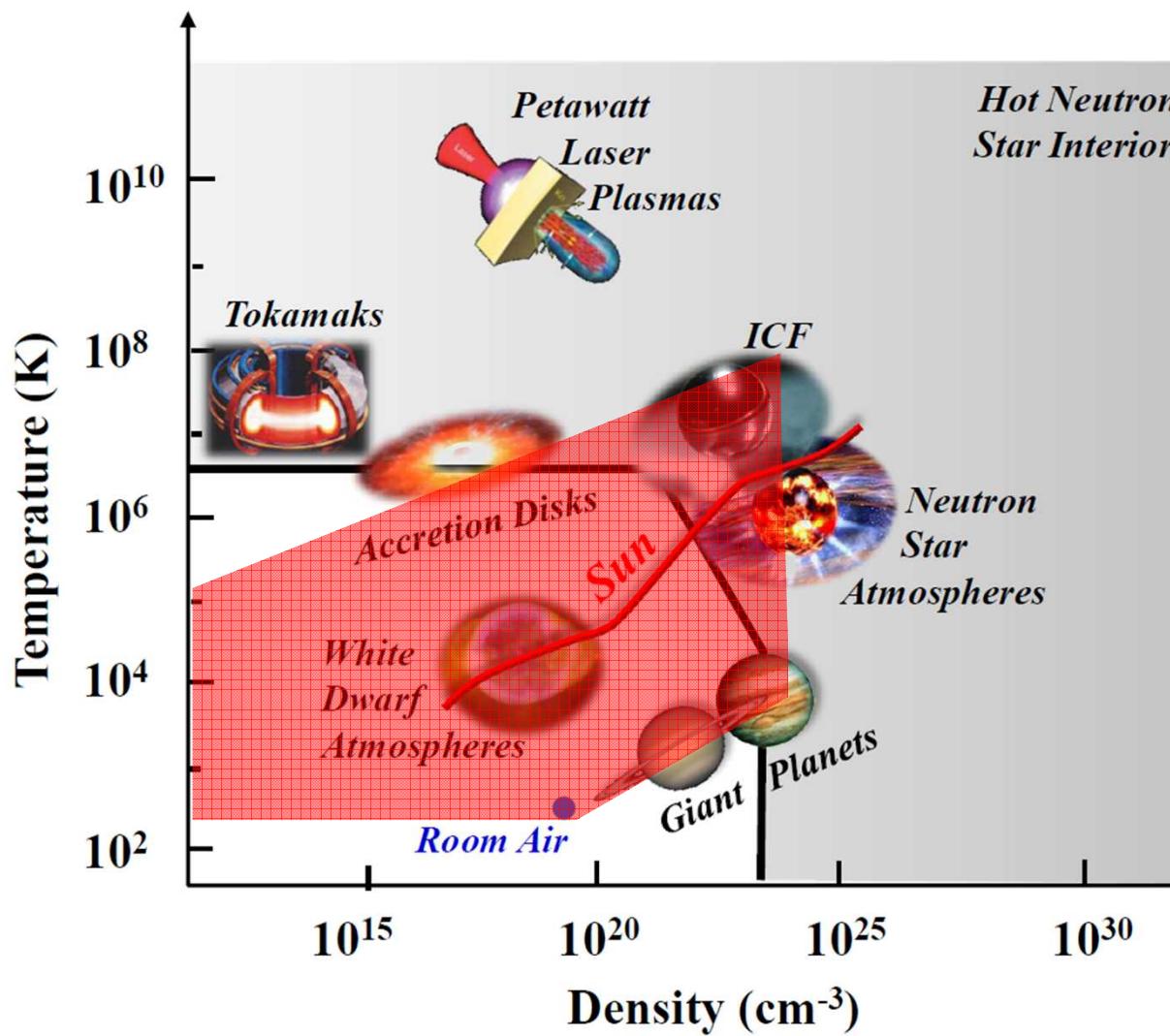


C. Blancard, Ph. Cosse, G. Faussurier, F.
Gilleron, J.C. Pain
French Alternative Energies and Atomic Energy Commission (CEA)



Joe MacFarlane, Igor Golovkin
Prism Computational Sciences

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

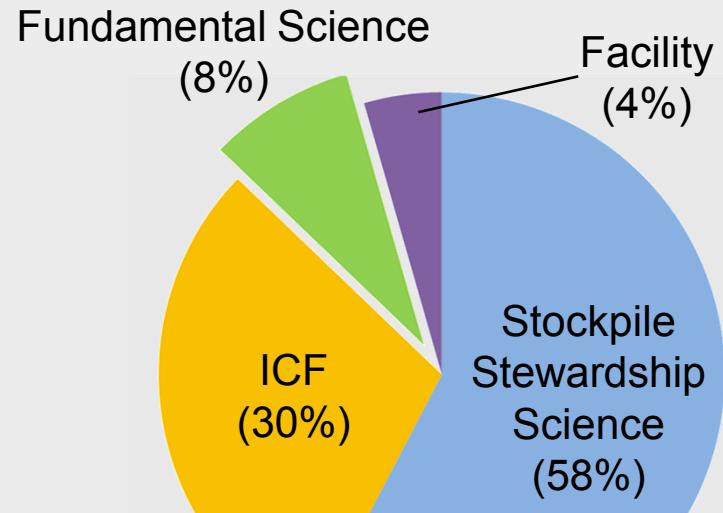


The fundamental science program is an essential part of the research portfolio on Z

Fundamental science collaborations provide:

- Peer review and critique on methods and results
- New ideas
- Growth in the HED science community
- A talent pool of trained HED experimental and theoretical scientists

Distribution of Shot Days in FY13

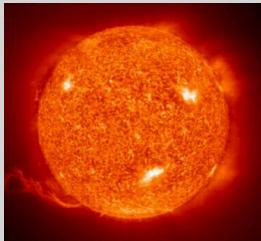


Programmatic science can leverage the intellectual and financial investments made by the world-wide fundamental science community

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



Solar Opacity



Question:

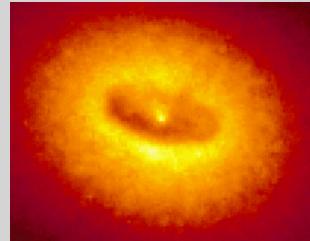
Why can't we predict the location of the convection zone boundary in the Sun?

Achieved Conditions:

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



Photoionized Plasmas



Question:

How does ionization and line formation occur in accreting objects?

Achieved Conditions:

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



White Dwarf Line-Shapes



Question:

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

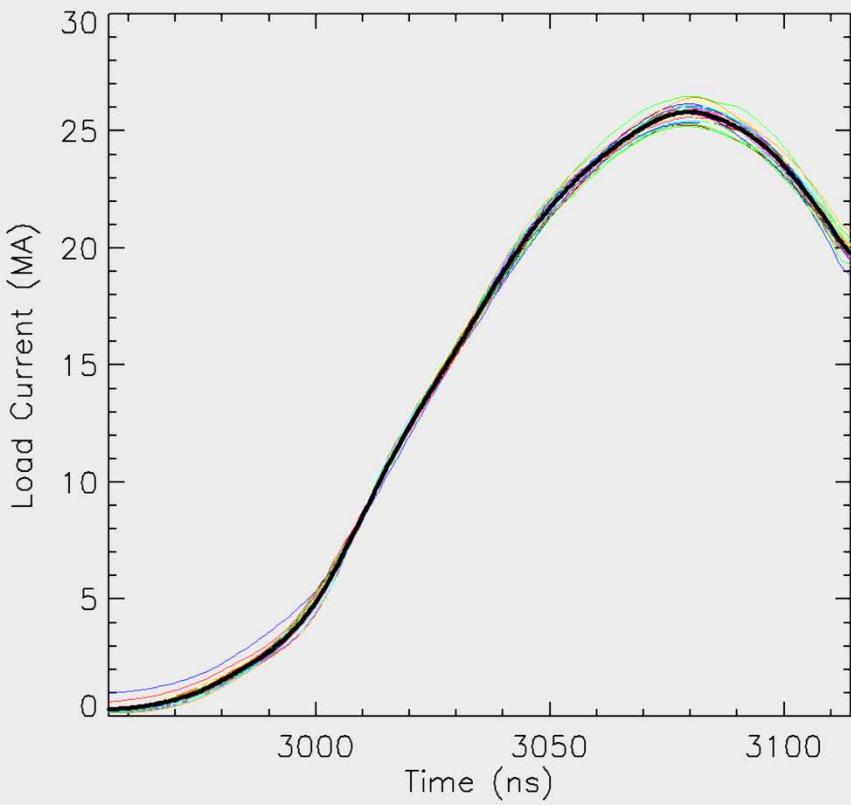
Acheived Conditions:

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

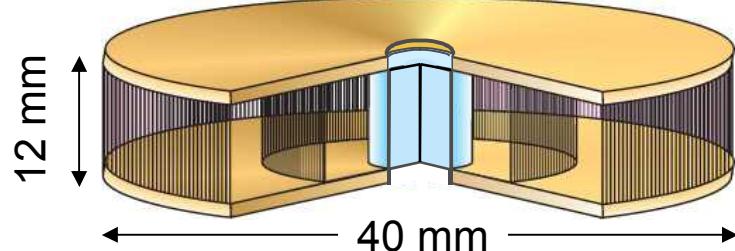


The z-pinch dynamic hohlraum (ZPDH) produces record currents of 25.8 MA with 1.5% reproducibility

Load Currents (20 shot average)



Z-pinch Dynamic Hohlraum



Standard ZPDH Characteristics

360 W wires – 11.4 μ m diameter

$m = 8.5$ mg W total

$V_{\text{marx}} = 85$ kV (21 MJ)

$I_p = 25.8 \pm 0.4$ MA [20 shots]

Sanford et al., POP 9 (2002)

Bailey et al., POP 13 (2006)

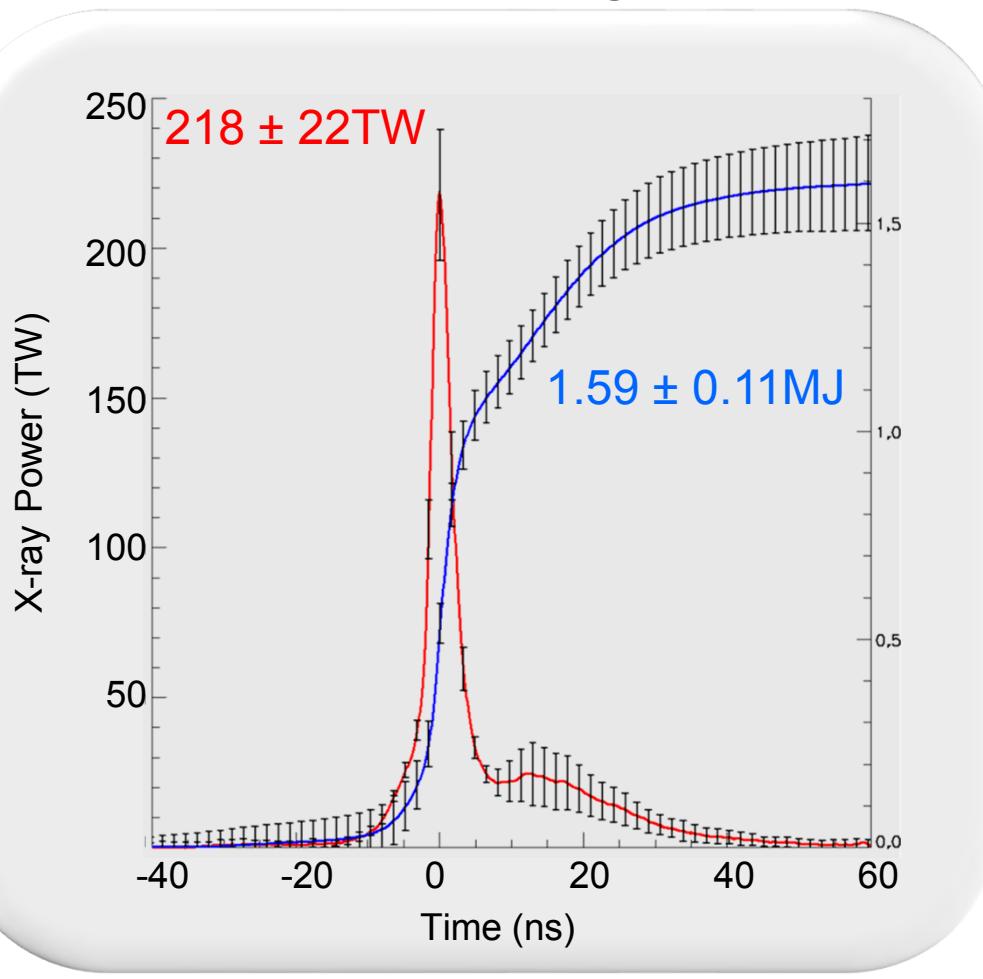
Lemke et al., POP 12 (2004)

Slutz et al., POP13 (2006)

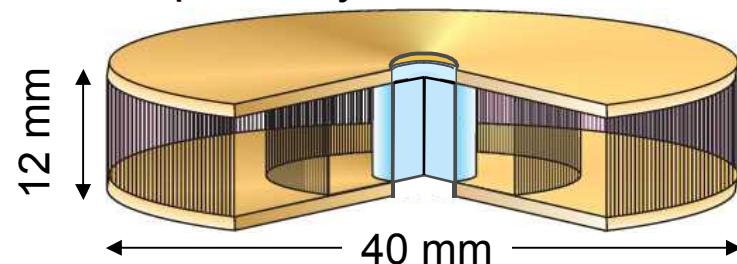
Rochau et al., PPCF 49 (2007)

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

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



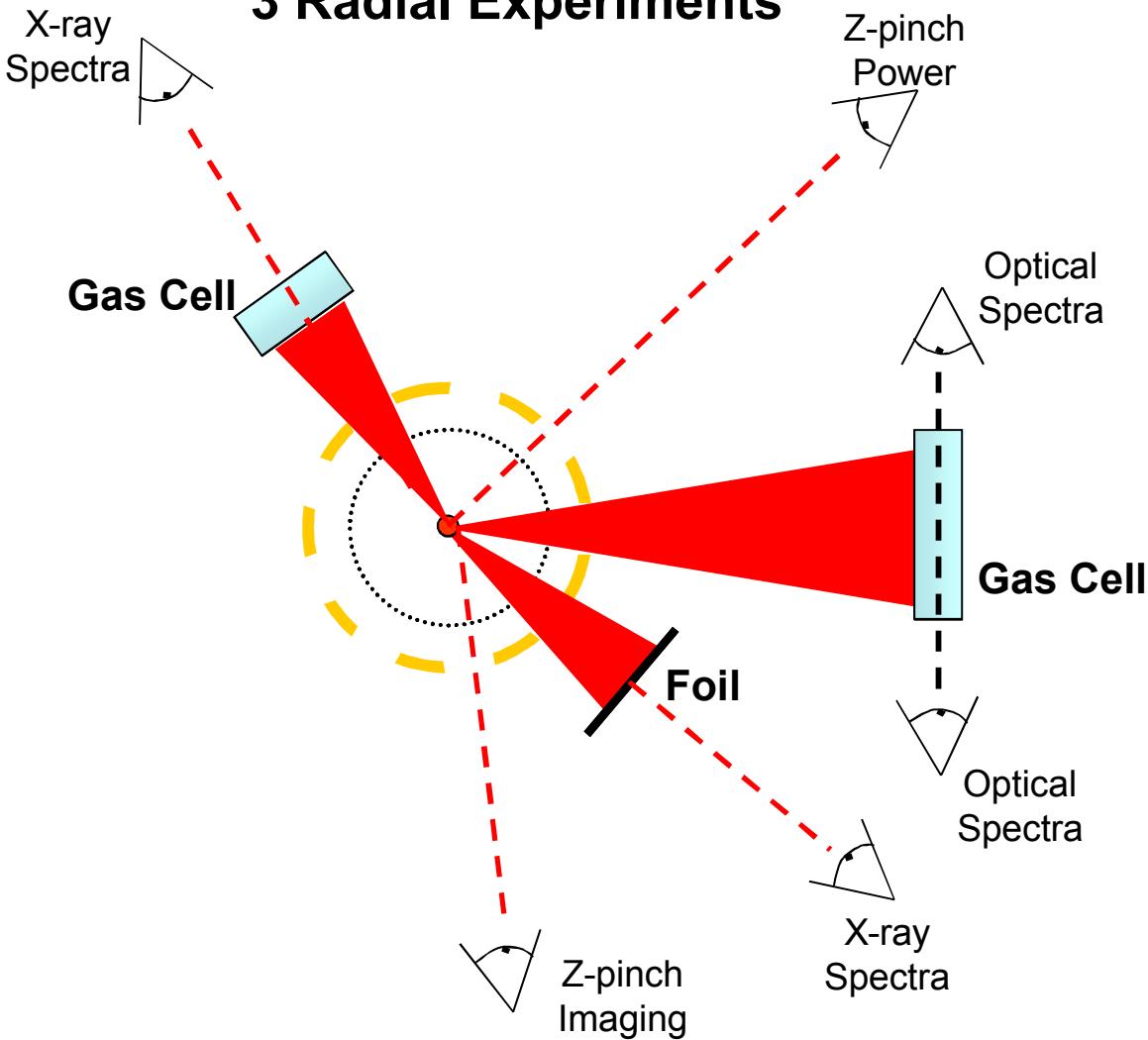
Z-pinch Dynamic Hohlraum



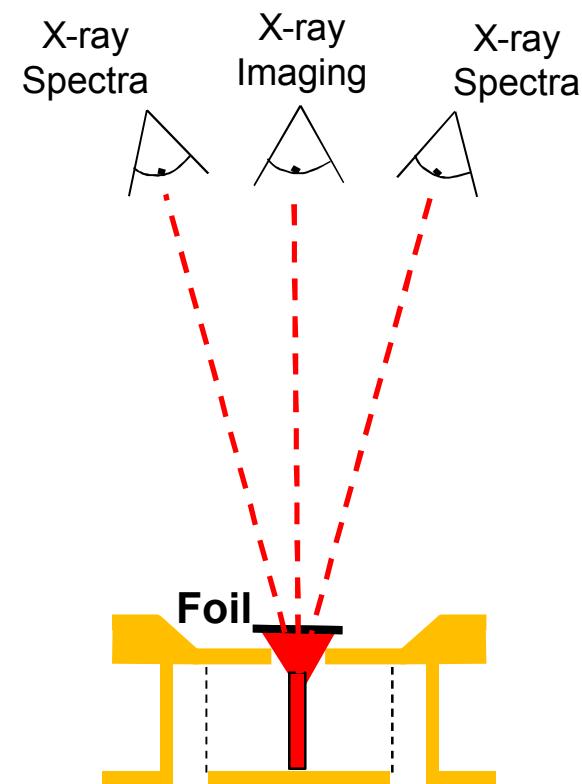
	ZR	Z
Marx Energy	21 MJ	12 MJ
Ipeak	25.8 MA	21.8 MA
Mass	8.5 mg	3.8 mg
Peak Power	220 TW (10%)	120 TW (14%)
Radiated Energy	1.6 MJ (7%)	0.82 MJ (17%)

The ZPDH can simultaneously drive four independent experiments on a single ZAPP shot

3 Radial Experiments



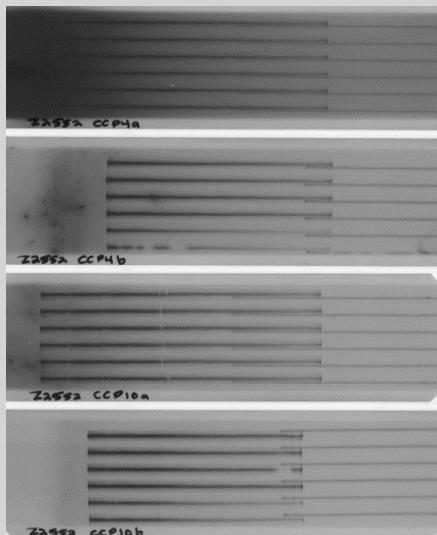
1 Axial Experiment



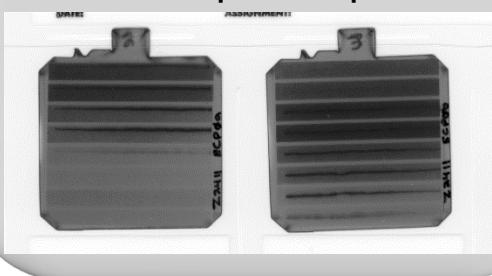
ZAPP campaigns acquire up to 59 spectra on a single shot

Solar Opacity

24 Space-Resolved
Fe Absorption Spectra

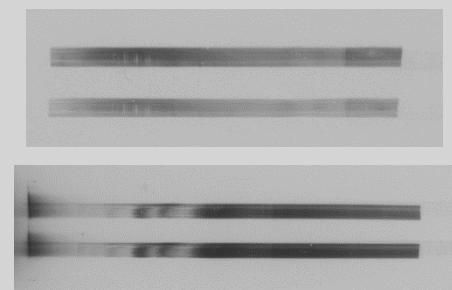


16 Time-Resolved
Fe Absorption Spectra

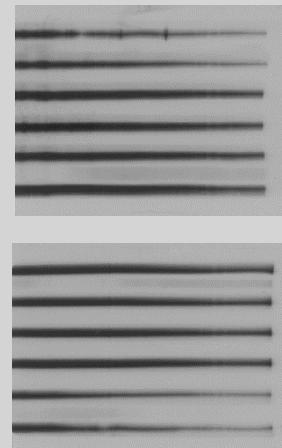


Photoionized Plasmas

4 Space-Resolved
Si Absorption Spectra

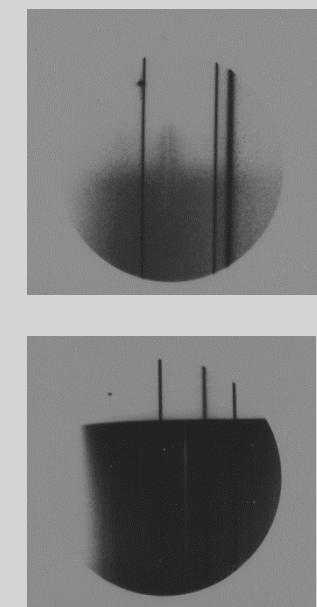


12 Space-Resolved
Ne Absorption Spectra



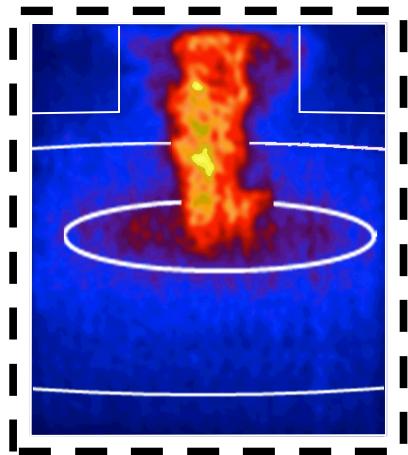
White Dwarf Line-Shapes

3 Streaked
H Absorption Spectra

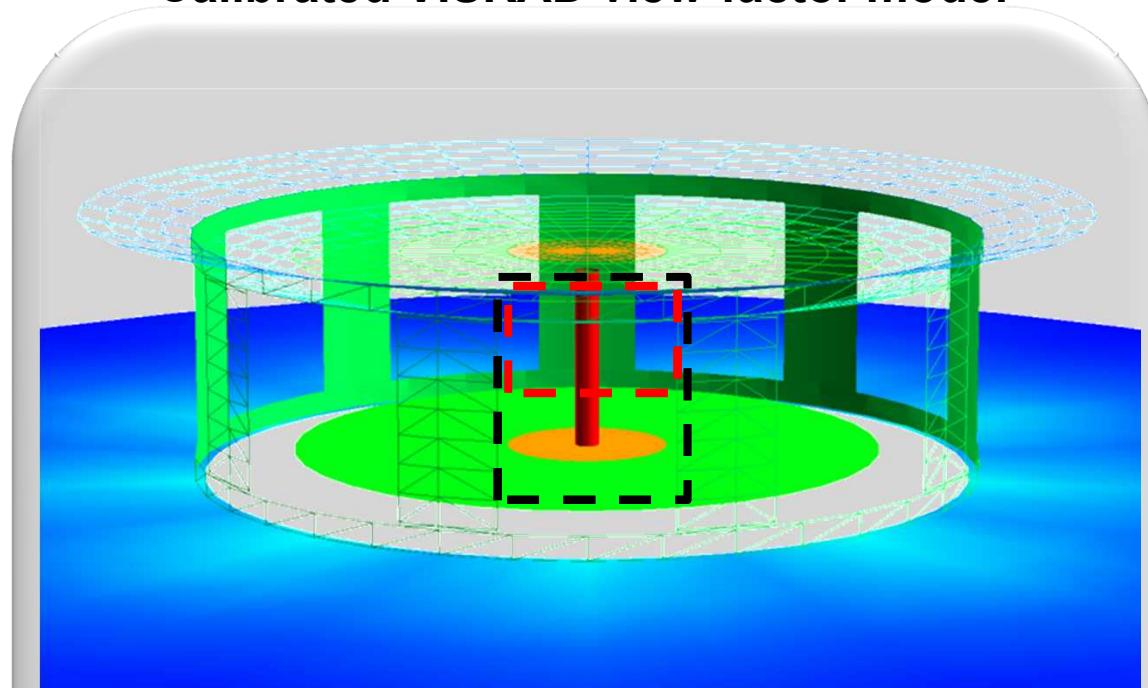


The x-ray drive on radial samples needs to be corrected for the view-factor

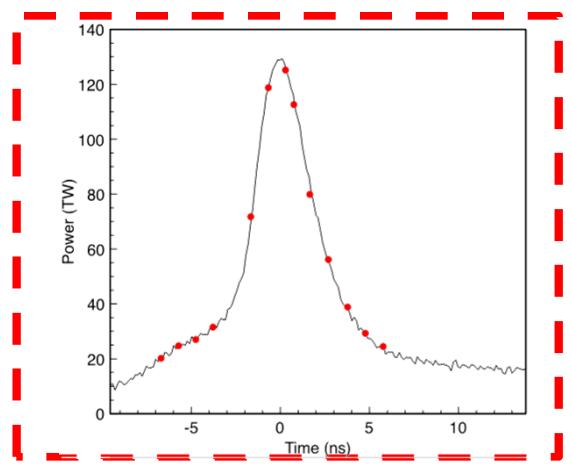
Monochromatic Images (277 eV)



Calibrated VISRAD view-factor model



Absolute Power Measurements

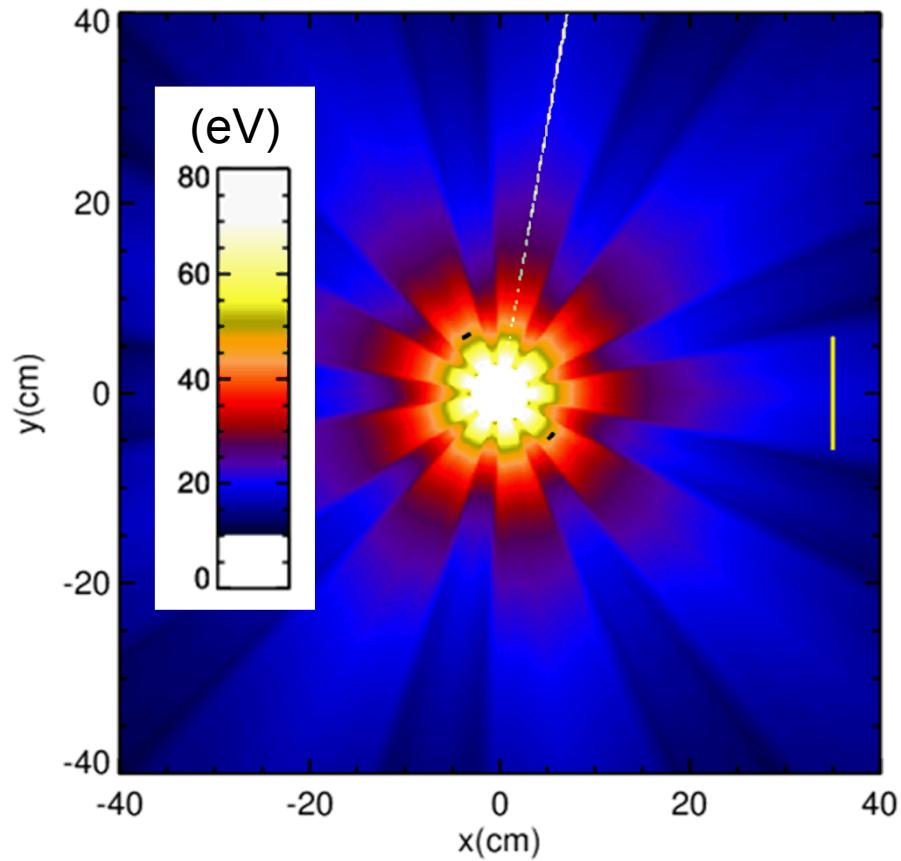


Assumption:

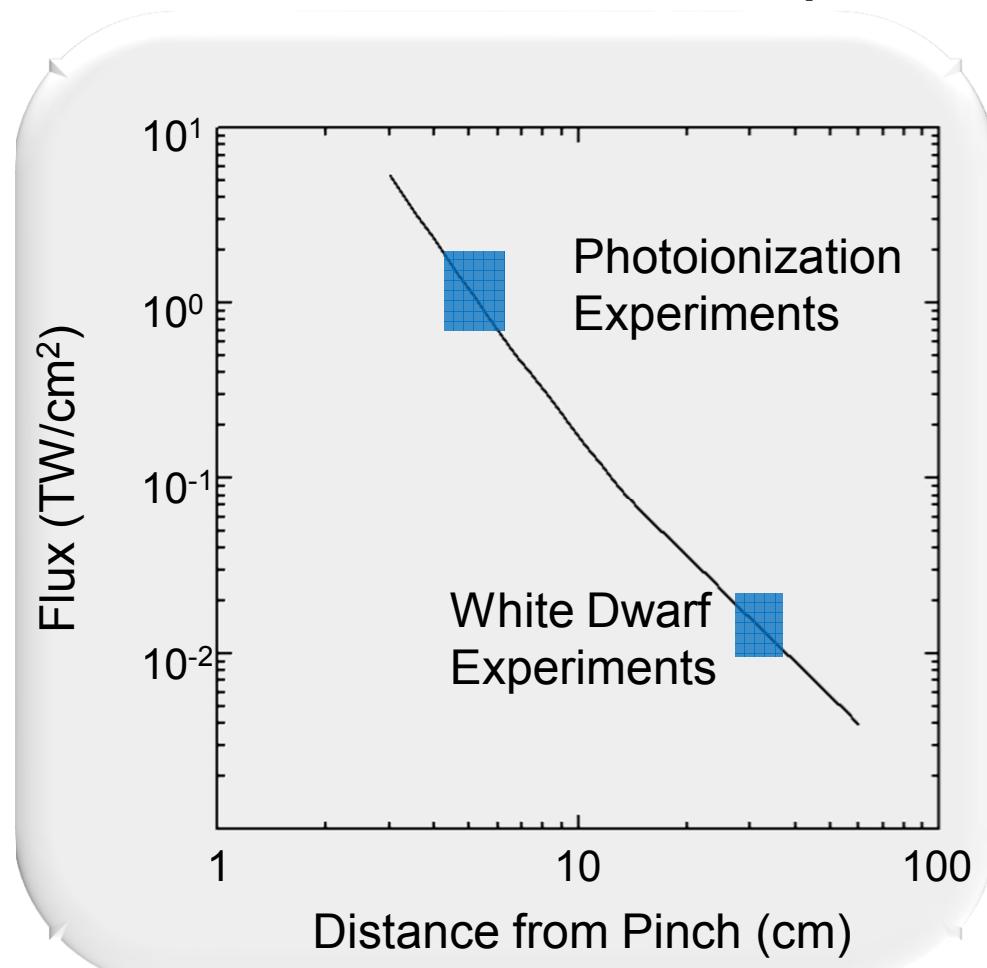
Each 'pixel' emits a Planckian spectrum at its characteristic T_r

The calibrated VISRAD model is used to infer the radiation drive spectrum at each sample

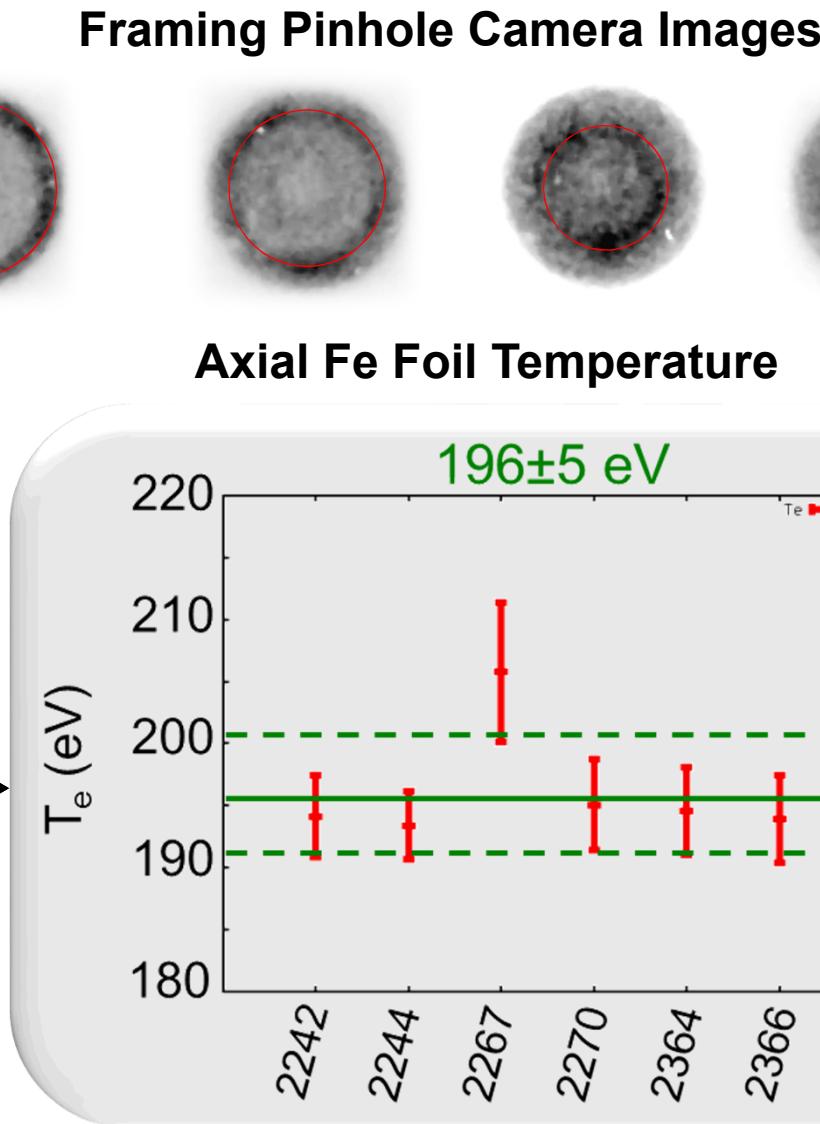
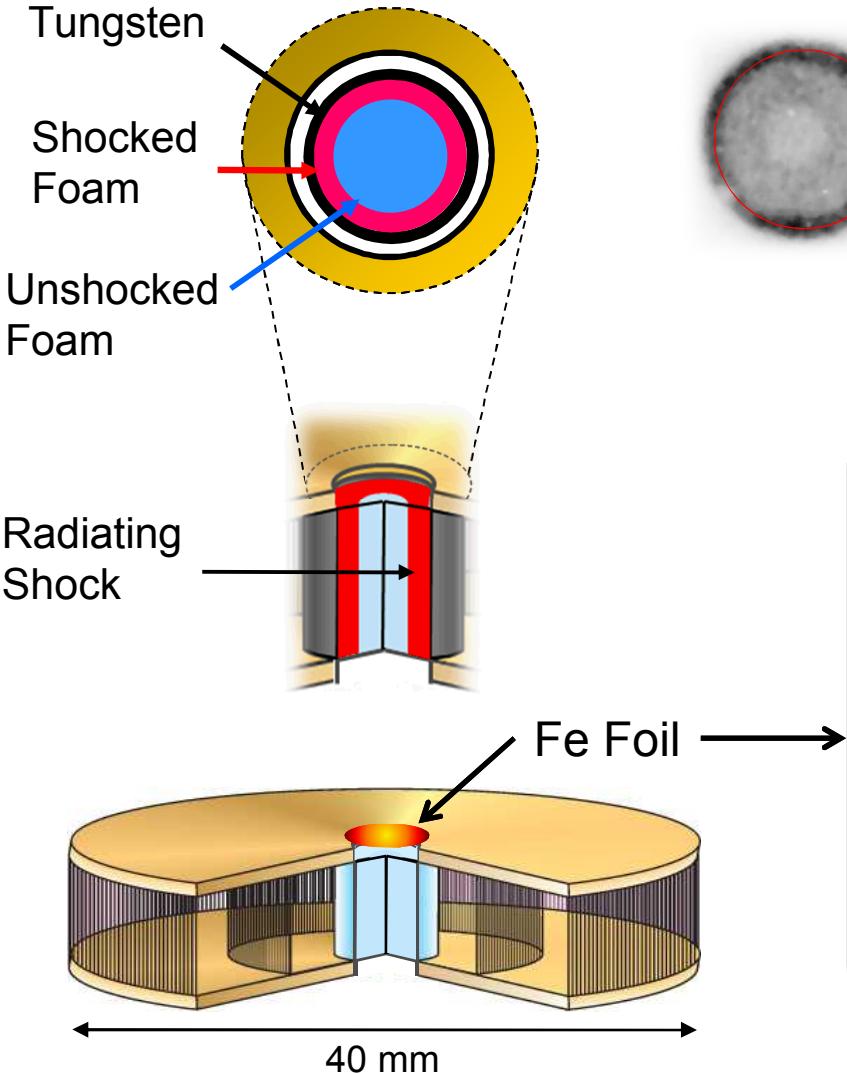
**r-θ Peak Brightness
Temperature Contours**



Peak Drive Flux on a Sample

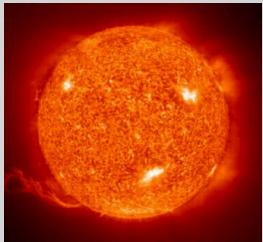


The ZPDH can also radiatively heat samples placed above the z-pinch to $T_e \sim 200$ eV.



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

Solar Opacity



Question:

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

Achieved Conditions:

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



Photoionized Plasmas



Question:

How does ionization and line formation occur in accreting objects?

Achieved Conditions:

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



White Dwarf Line-Shapes



Question:

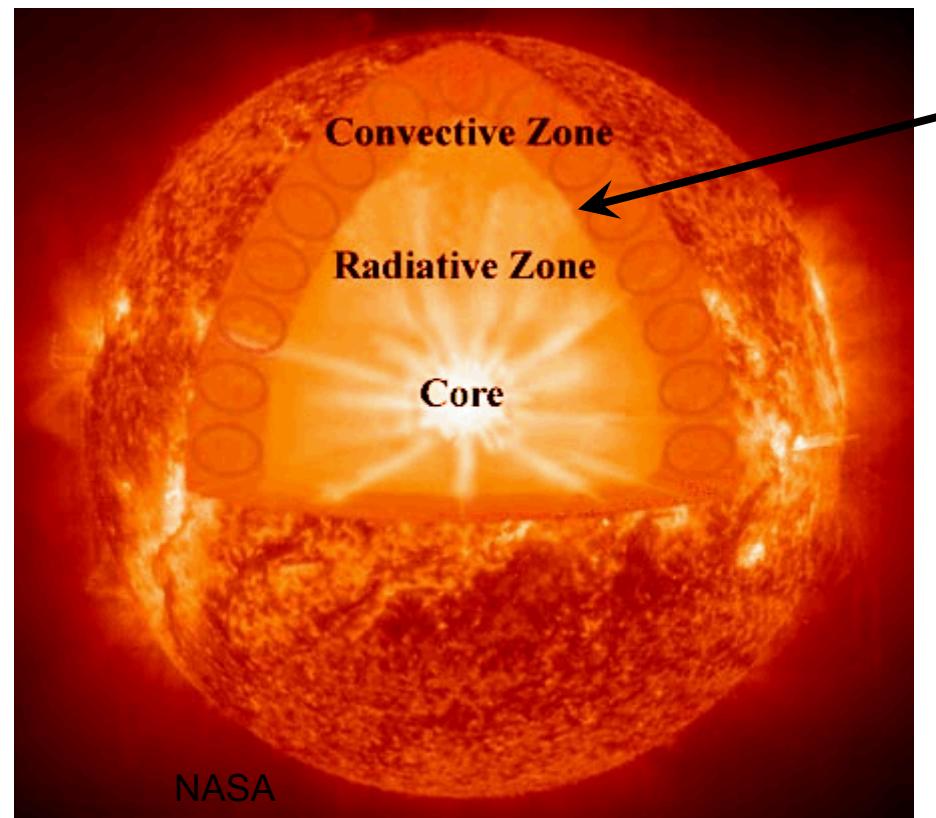
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

Acheived Conditions:

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



Models for solar interior structure disagree with helioseismology observations.



Convection-Zone (CZ) Boundary
Models are off by $10\text{-}30 \sigma$

Models depend on:

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

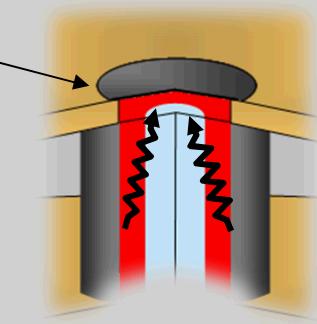
Question: Is opacity uncertainty the cause of the disagreement?

Objective: Measure Fe opacity at CZ base conditions.

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

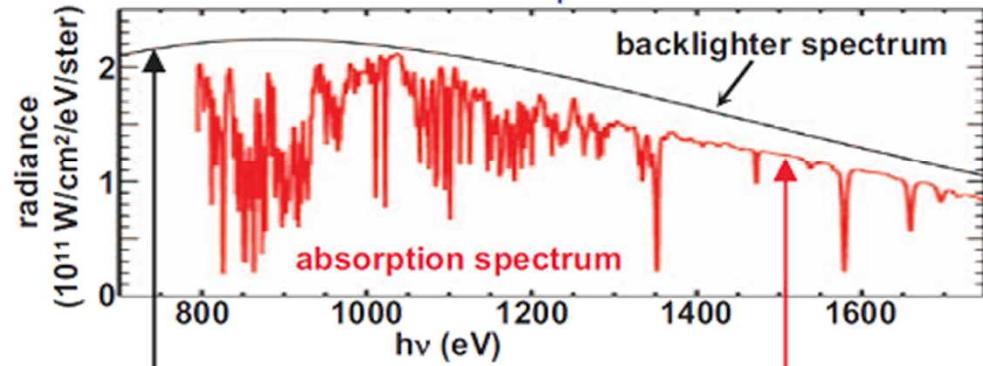
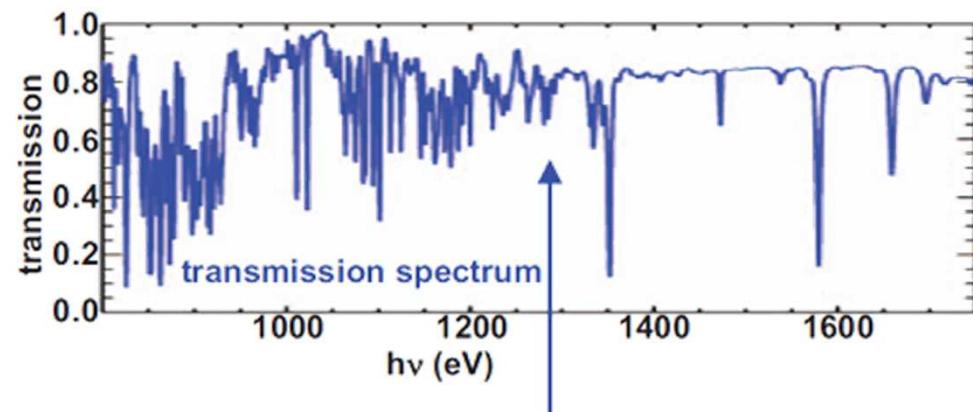
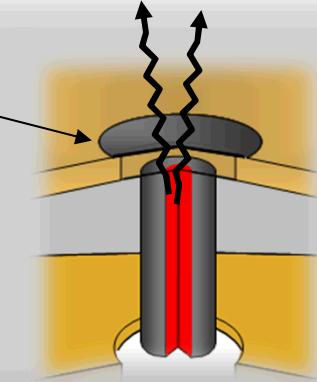
Foil is heated during the ZPDH implosion

Thin Foil



Foil is backlit at shock stagnation

Thin Foil



Z data without iron

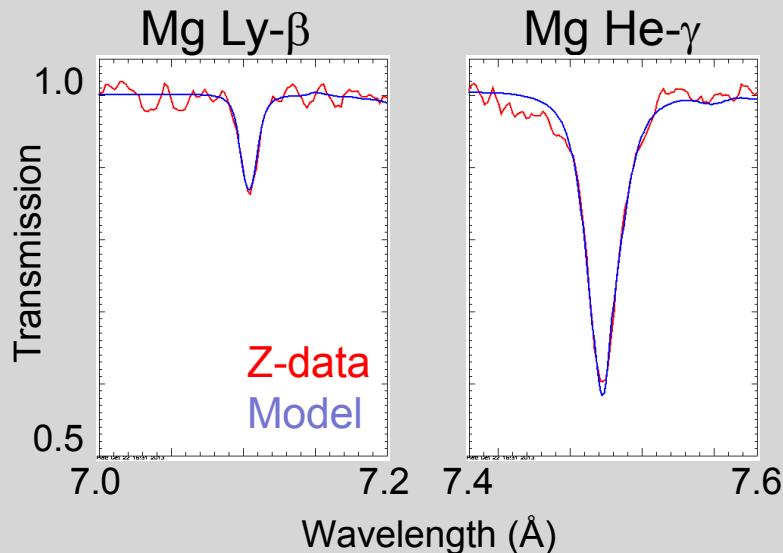
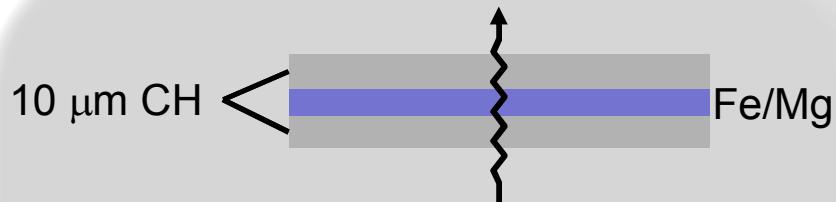
hv →

Z data with iron

hv →

The achieved temperature and density depend on the target design.

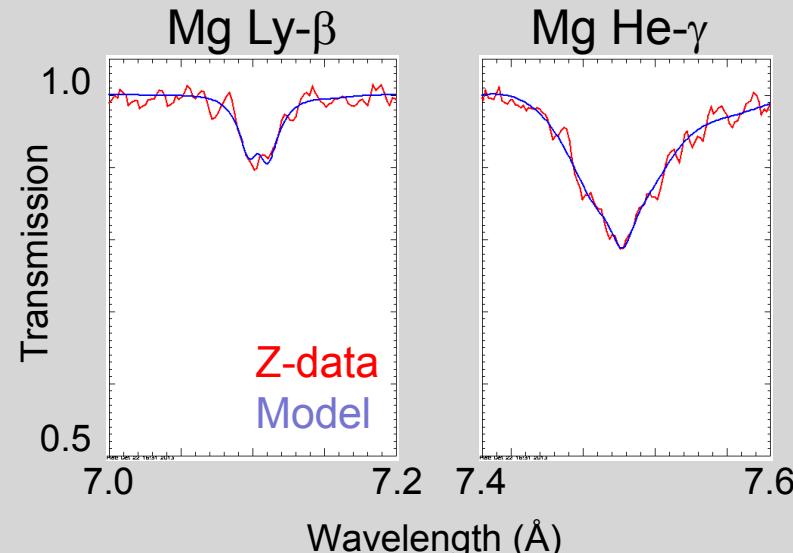
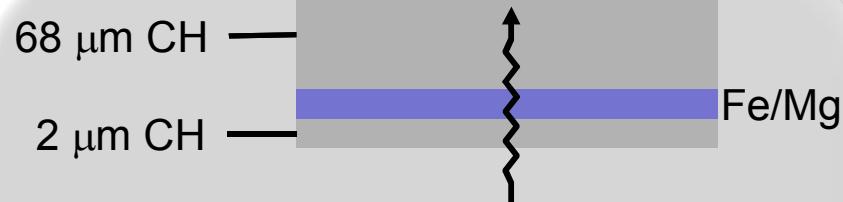
Thin Tamper



$$T_e = 156 \pm 6 \text{ eV}$$

$$n_e = 6.9 \pm 1.7 \times 10^{21} \text{ cm}^{-3}$$

Thick Tamper

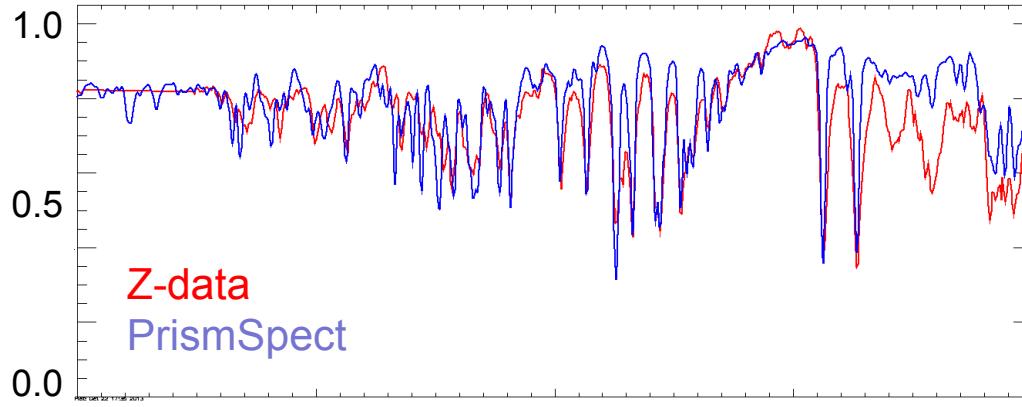


$$T_e = 196 \pm 5 \text{ eV}$$

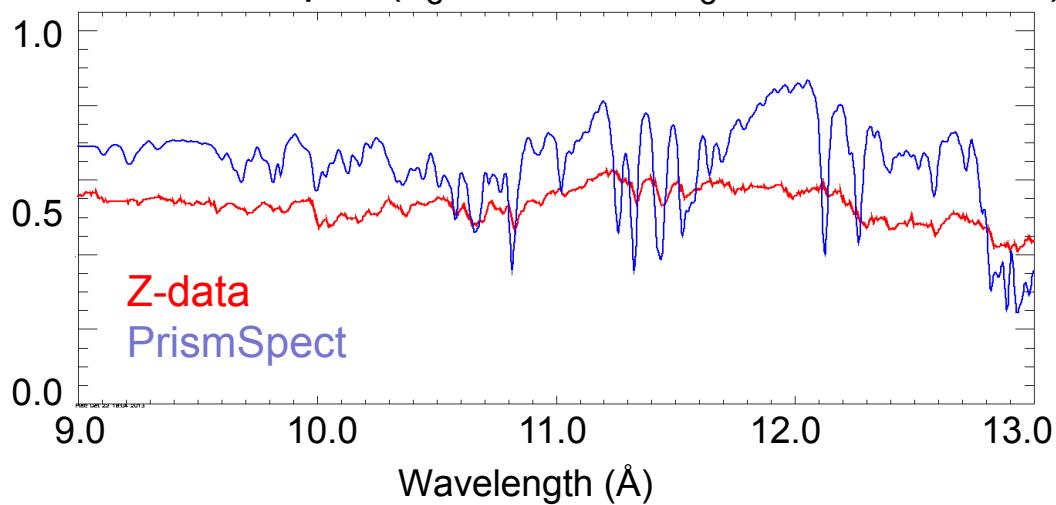
$$n_e = 39. \pm 9. \times 10^{21} \text{ cm}^{-3}$$

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

Thin Tamper ($T_e = 156$ eV, $n_e = 6.9 \times 10^{21} \text{ cm}^{-3}$)



Thick Tamper ($T_e = 196$ eV, $n_e = 39 \times 10^{21} \text{ cm}^{-3}$)



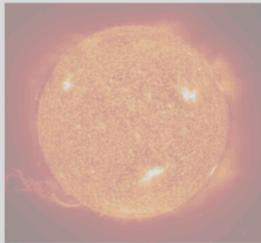
Present Status

- 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... more scrutiny of the data is prudent.

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



Solar Opacity



Question:

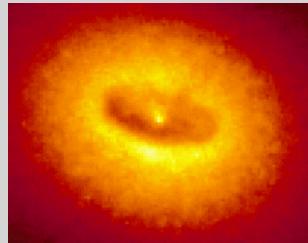
Why can't we predict the location of the convection zone boundary in the Sun?

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?

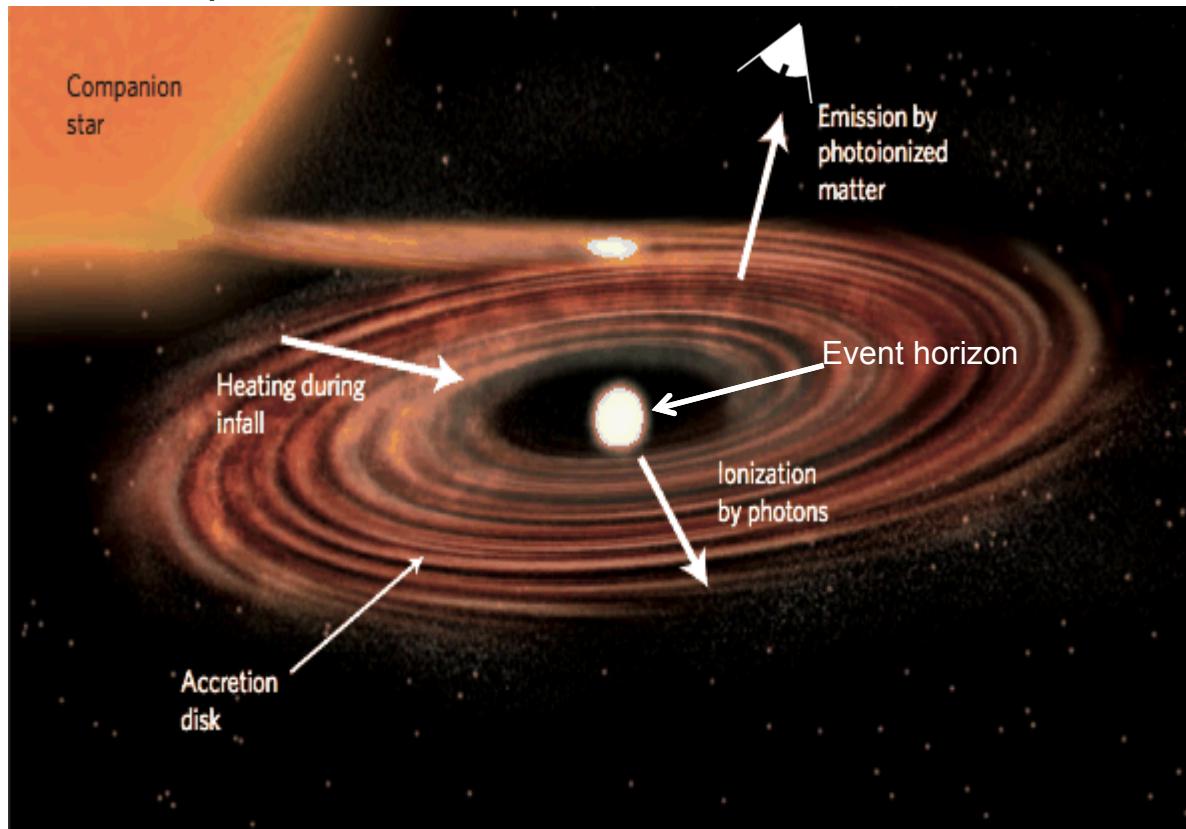
Achieved Conditions:

$T_e \sim 1$ 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



Photoionization parameter

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

Accretion Disks

$$\xi \sim 10 - 10,000 \text{ erg.cm.s}^{-1}$$

Laboratory Plasmas

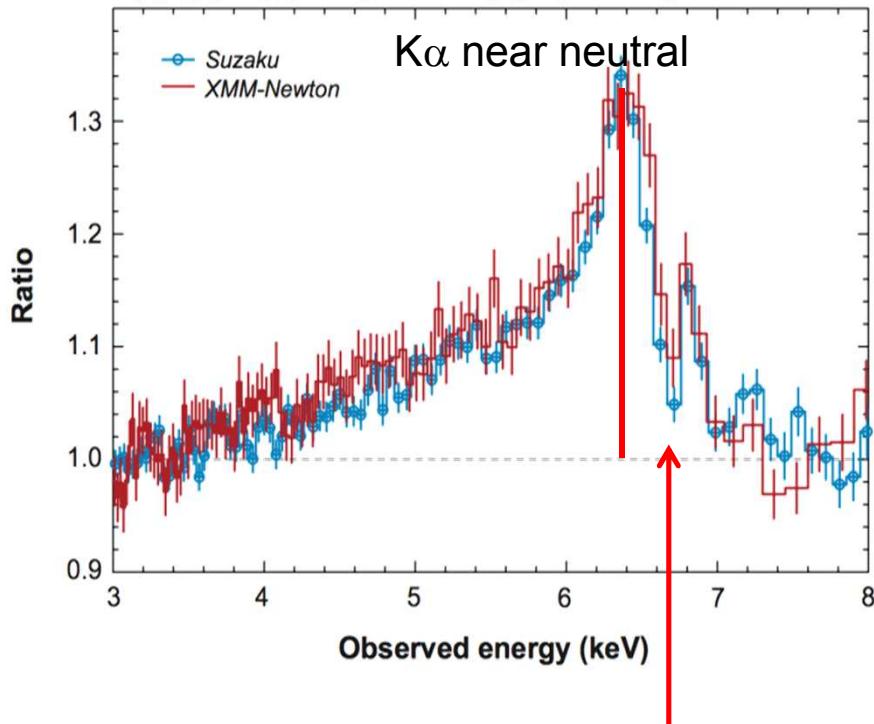
$$n_e \sim 10^{19} \text{ cm}^{-3}$$

$$F > 10^{19} \text{ erg/cm}^2/\text{s}$$

$$> 1 \text{ TW/cm}^2 \text{ for } \xi > 10$$

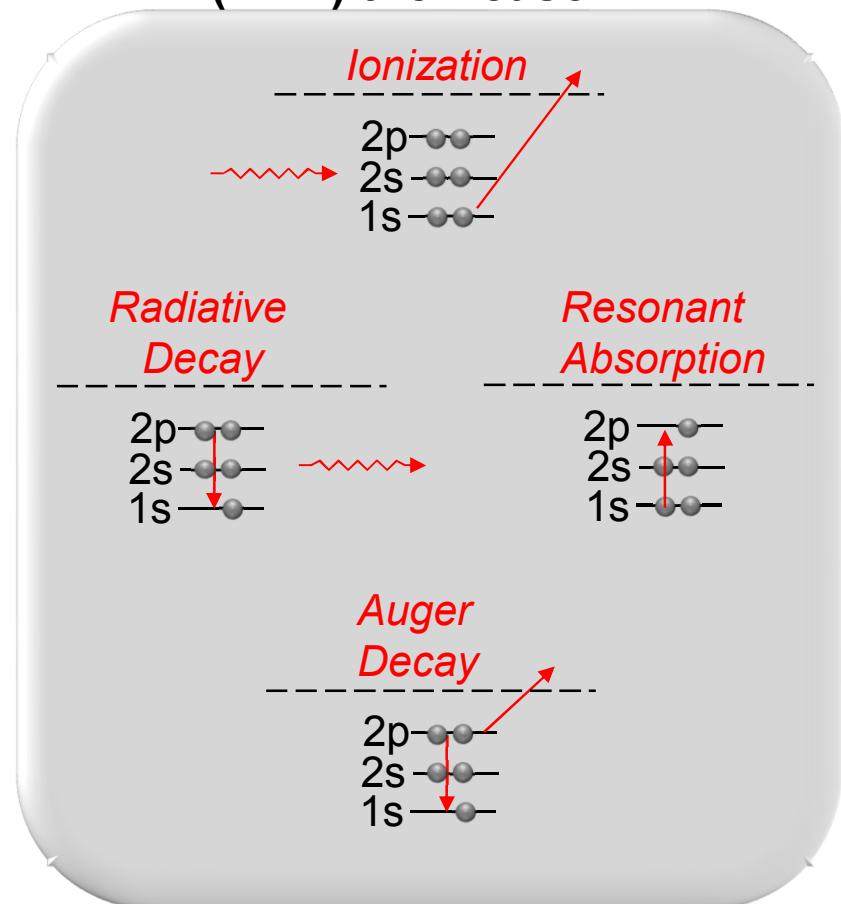
A Specific Problem: Emission from L-shell ions is not seen in some prominent black-hole accretion disks.

Measured Fe Emission from ???

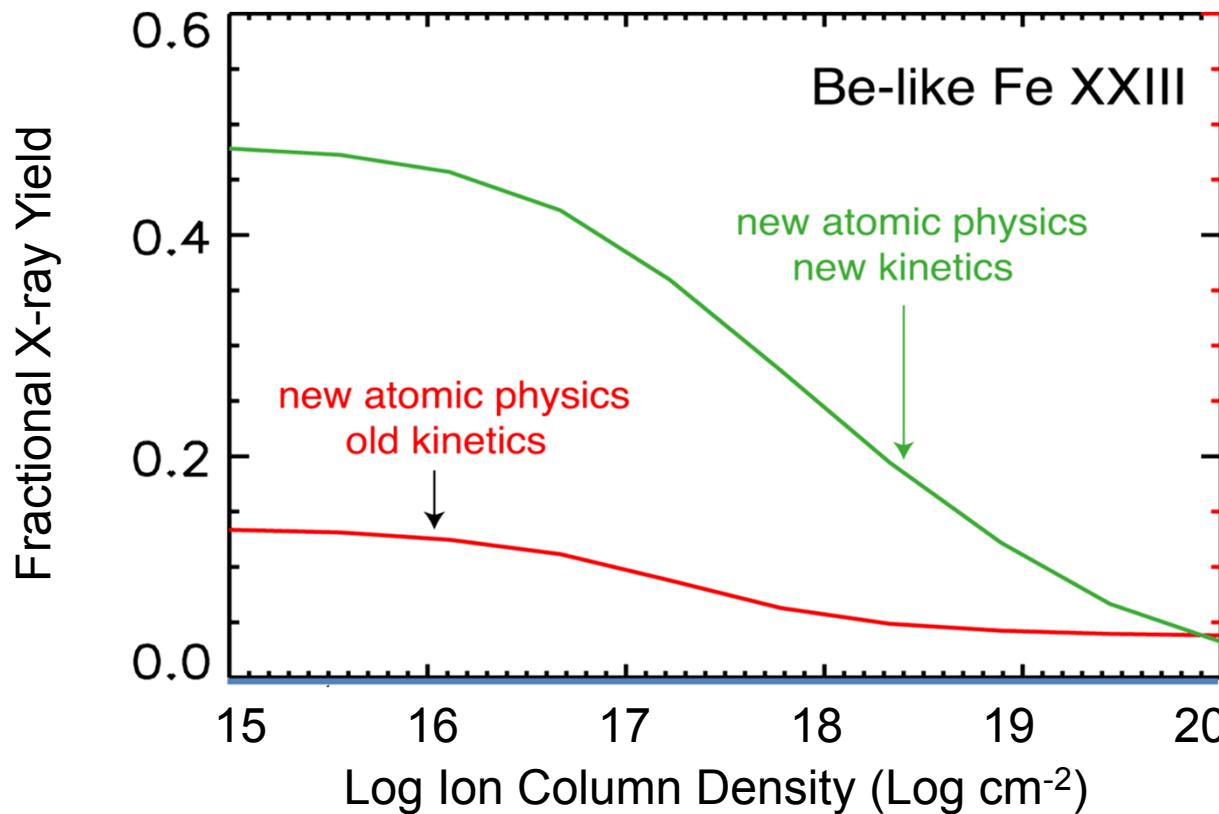


No observed emission from Fe ionized to the L-shell

Is Resonant Auger Destruction (RAD) the Reason?



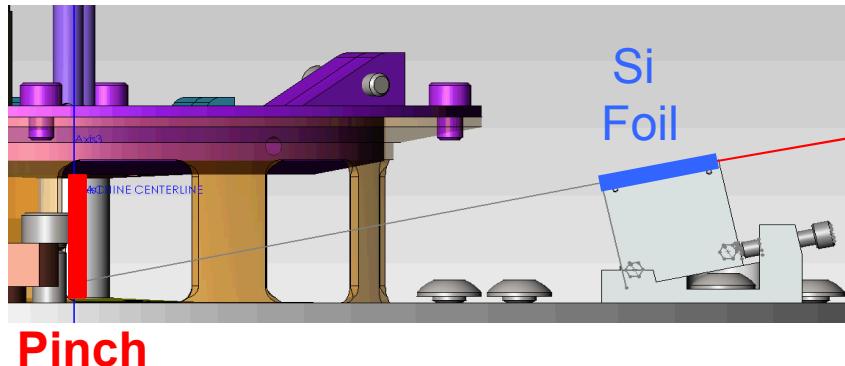
New models suggest that RAD may not be as efficient as previously thought.



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.

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



Measured Quantities

Flux..... $F = 1.3 \text{ TW/cm}^2$

Electron

Density..... $n_e = 8.5 \cdot 10^{18} e^-/\text{cm}^3$

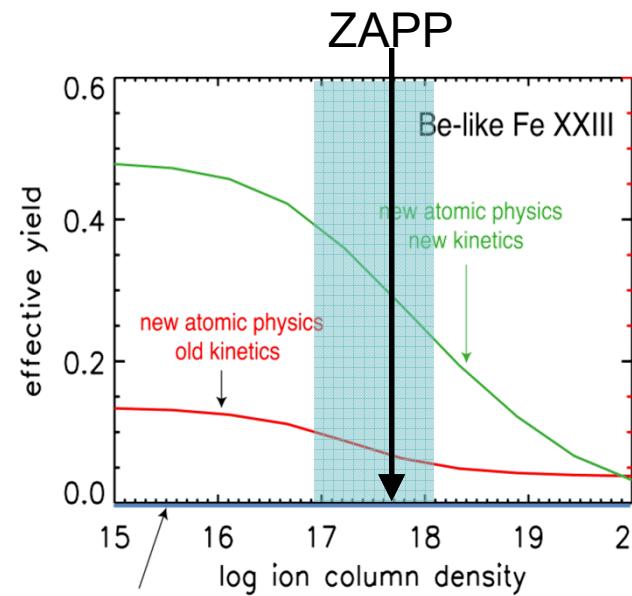
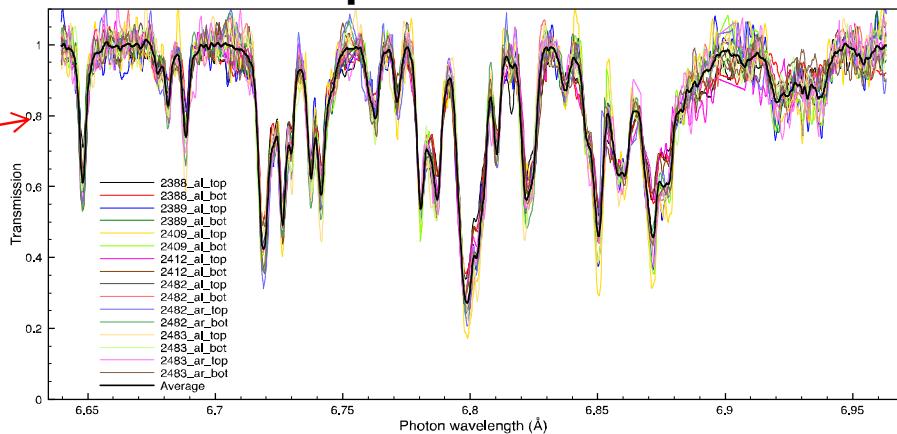
Photoionization

Parameter..... $\xi = 19 \text{ erg.cm.s}^{-1}$

Column Density..... $N_i = 5 \cdot 10^{17} \text{ at/cm}^2$

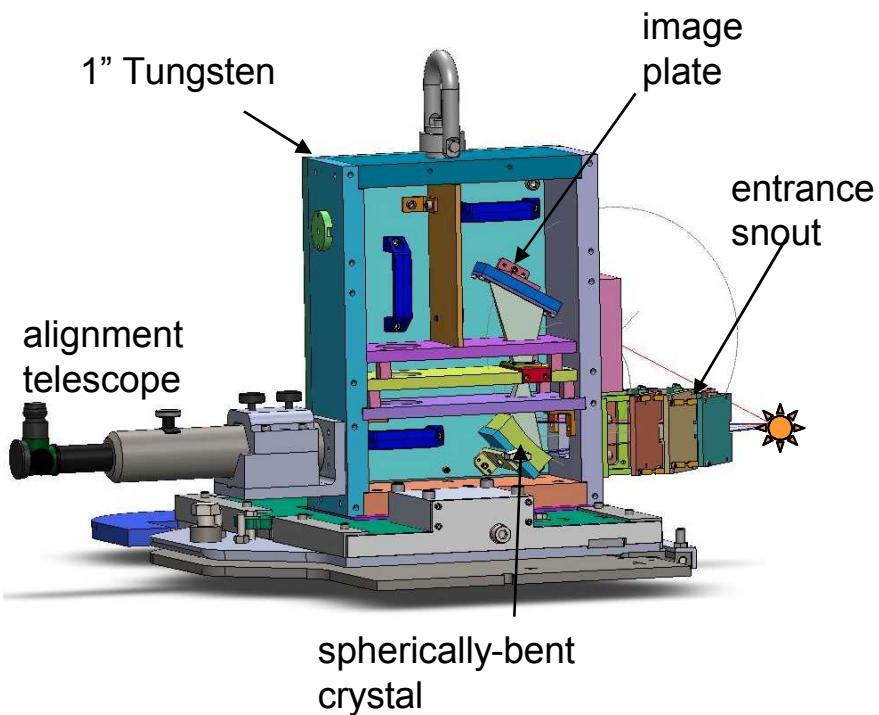
Electron Temp..... $T_e = 19.5 \text{ eV}$

Si Absorption Measurements



Emission measurements in FY14 will measure the quenching due to RAD.

New Spherically-Bent Crystal Spectrometer



If RAD-affected lines are quenched:

- New atomic modeling methods will need to be re-evaluated
- we will have strong experimental support for current assumptions used in accretion disk modeling

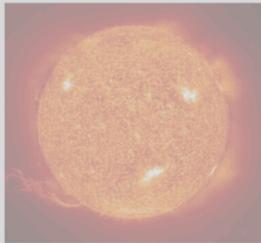
If RAD-affected lines aren't quenched:

- L-shell ionization zones cannot be there, counter to accretion models
- data archive will need re-examination

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

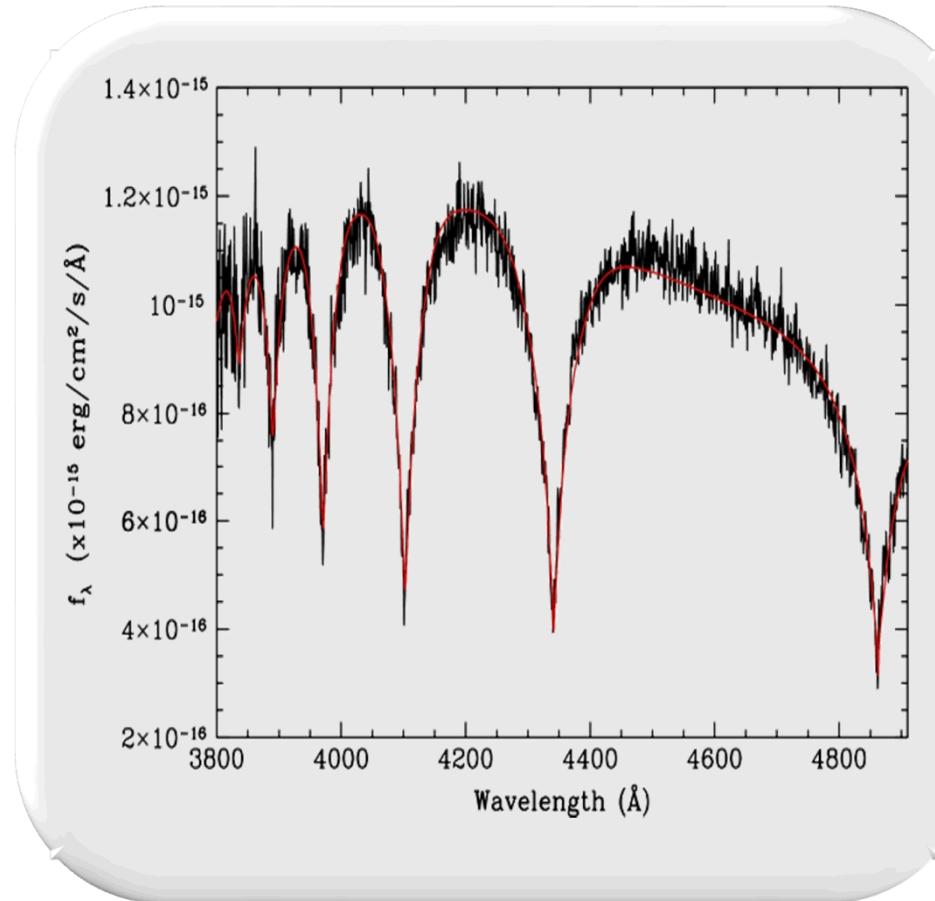
Achieved Conditions:

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



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

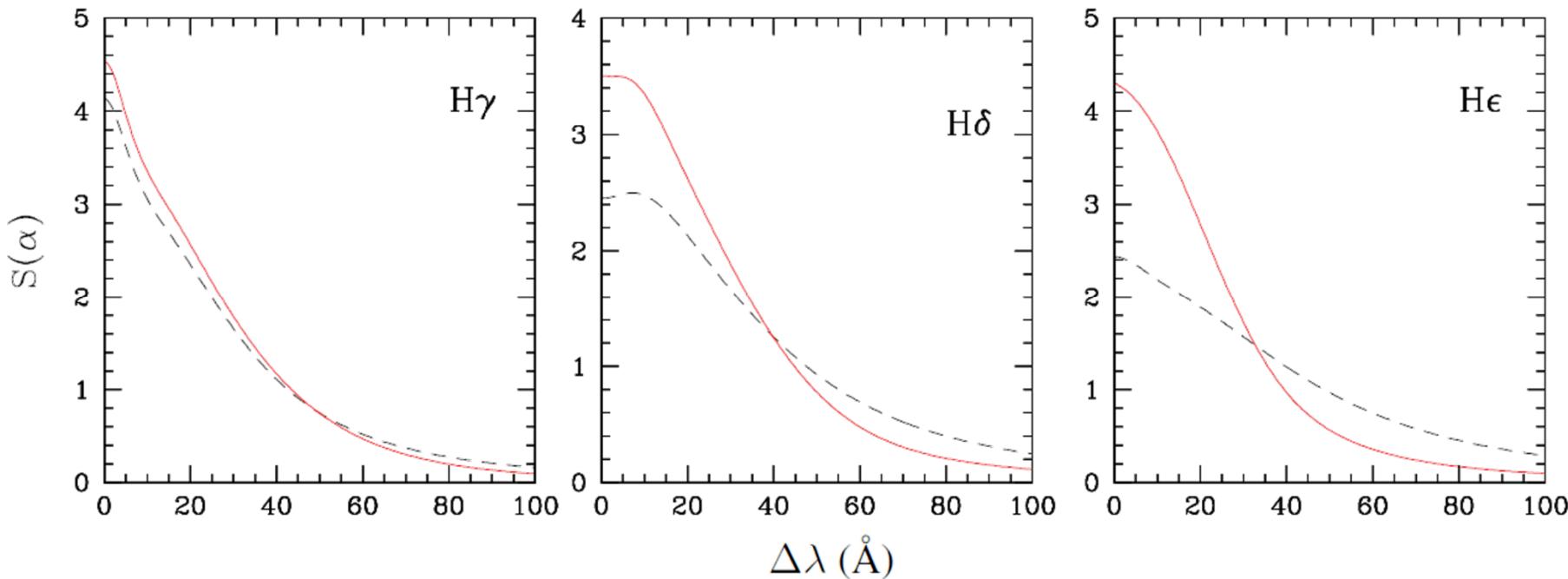
- White Dwarfs are fundamentally important
 - Evolutionary endpoint for ~98% of stars
 - Simple in structure and evolution
 - Cosmic laboratories (cosmochronology)
- WD surface temperature and total mass are usually determined by fitting the observed spectra
- The spectroscopic method and gravitational redshift disagree by >10% in the stellar mass



Recent line-profile calculations partially fix the problem – are they right?

$$T_e = 10,000 \text{ K}$$
$$n_e = 1E17 \text{ cm}^{-3}$$

— Tremblay & Bergeron
- - - - - Vidal-Cooper-Smith



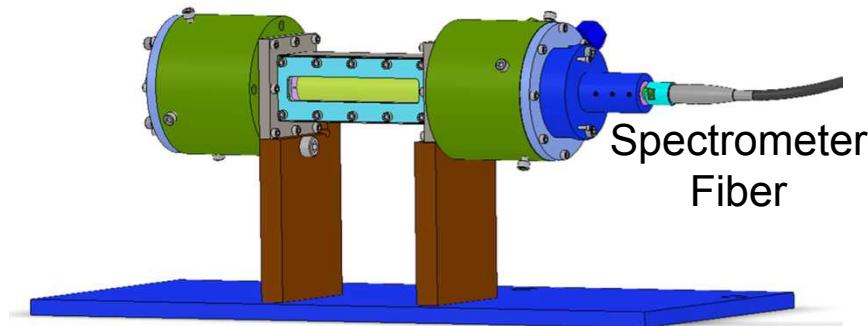
Question: Are inaccurate H-Balmer line shapes responsible for the inaccurate determination of WD mass?

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

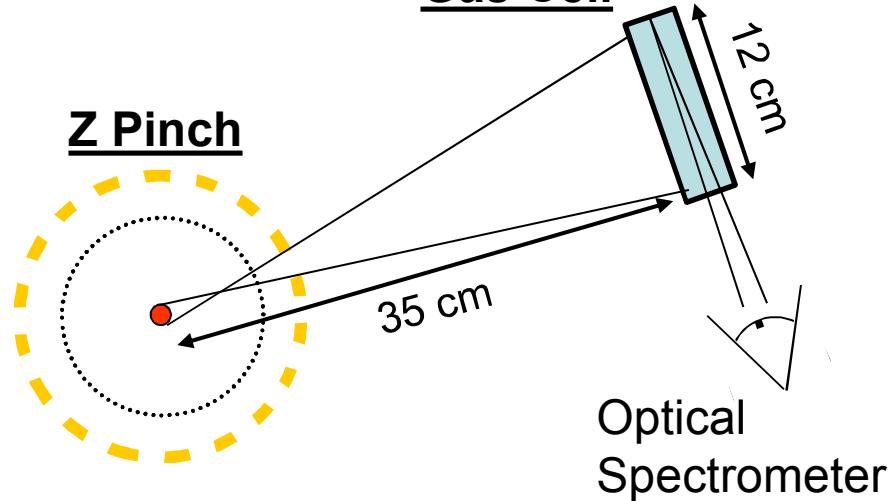
ZAPP experiments utilize radiatively heated gas cells to provide benchmark data for the WD problem

- 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

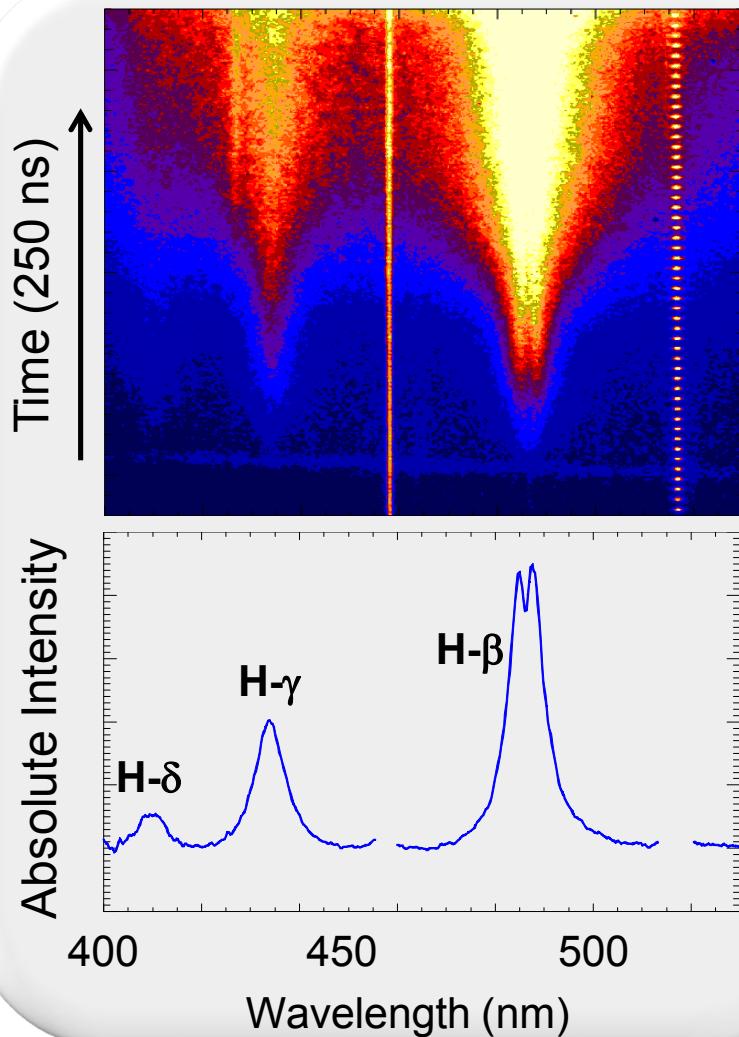


Gas Cell

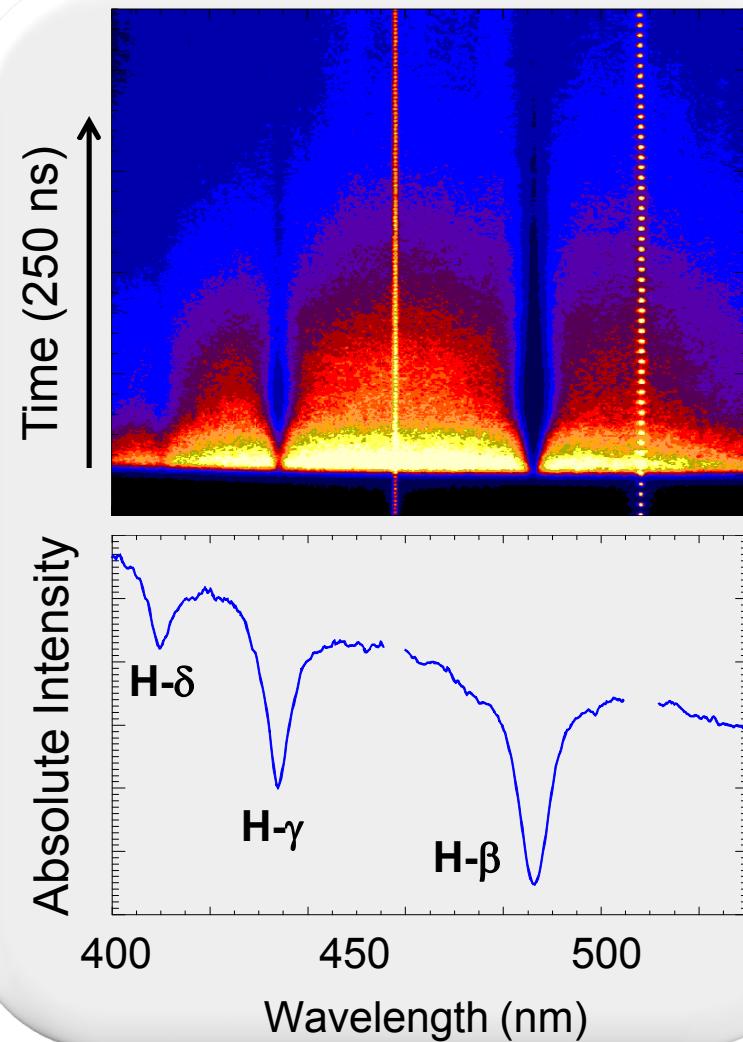


Simultaneous streaked absorption and emission in absolute units provide a unique capability

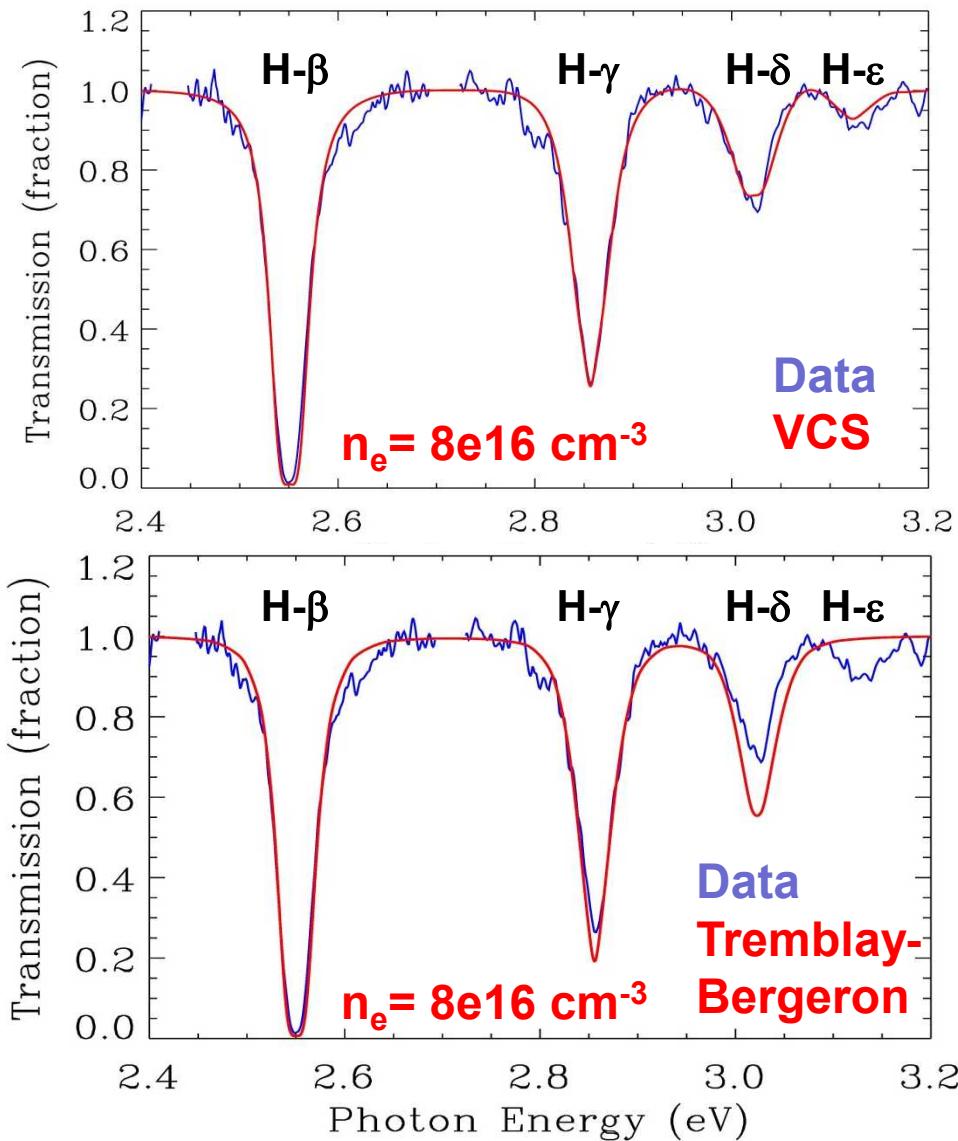
Emission



Absorption



Measured H-Balmer line shapes can discriminate between theories



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 \sim 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

