An Experimental Platform for Creating White Dwarf Photospheres in the Laboratory

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White Dwarfs ≈ Retired Stars

- End point of stellar evolution for most stars, including our Sun
- Compact object
  - $\sim 2/3\ M_{\mathrm{Sun}}$, $\sim 1\ R_{\mathrm{Earth}}$
  - Electron degenerate core, stratified envelope
- No nuclear fusion in core
  - Electron degeneracy pressure provides support against gravity
  - Star exponentially cools with time

White Dwarf Atmospheric Parameters

- Effective temperature (T_{eff})
- Surface gravity (log g)
- Composition, Magnetism

Cosmochronology

Image: FORS, 8.2-m VLT Antu, ESO

Asteroseismology

EOS

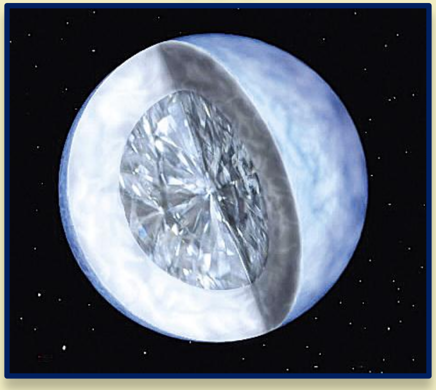


Illustration: Harvard-Smithsonian Center for Astrophysics/Travis Metcalfe, Ruth Bazinet

Initial-Final Mass Relation

Image: H. Bond (STScI), R. Ciardullo (PSU), WFPC2, HST, NASA, F. Hamilton

Type Ia Supernovae

Illustration: David A. Hardy, PPARC

Intergalactic Distances

Dark Energy

Determining WD Atmospheric Parameters

- Compare observed spectra with synthetic spectra from WD atmosphere models
- The *spectroscopic method* (see, e.g., Bergeron et al. 1992) is:
  - Precise
    - $\delta T_{\text{eff}}/T_{\text{eff}} \sim 5\%$
    - $\delta \log g/\log g \sim 1\%$
  - Widely-used; more than 30,000 WDs
    - Palomar-Green Survey
    - Sloan Digital Sky Survey
    - SPY
    - HETDEX

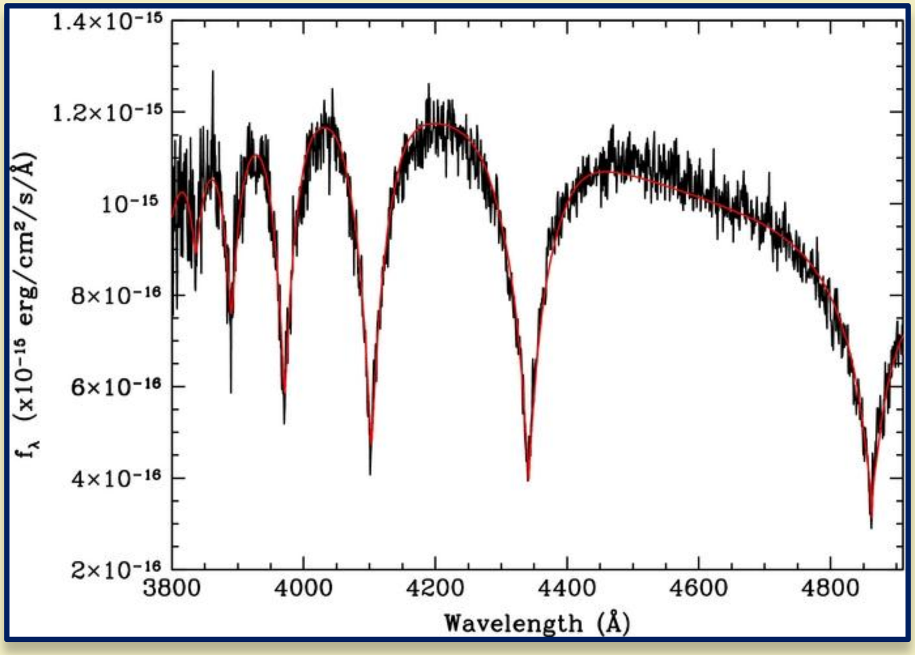


Figure from Hermes et al. (2011): KPNO spectrum of WD J1916+3938

The Spectroscopic Method Isn't Perfect?

- The "Log *g* Upturn"
  - Unphysical mass increase at lower T_{eff}
  - Appears in *all* large spectroscopic surveys

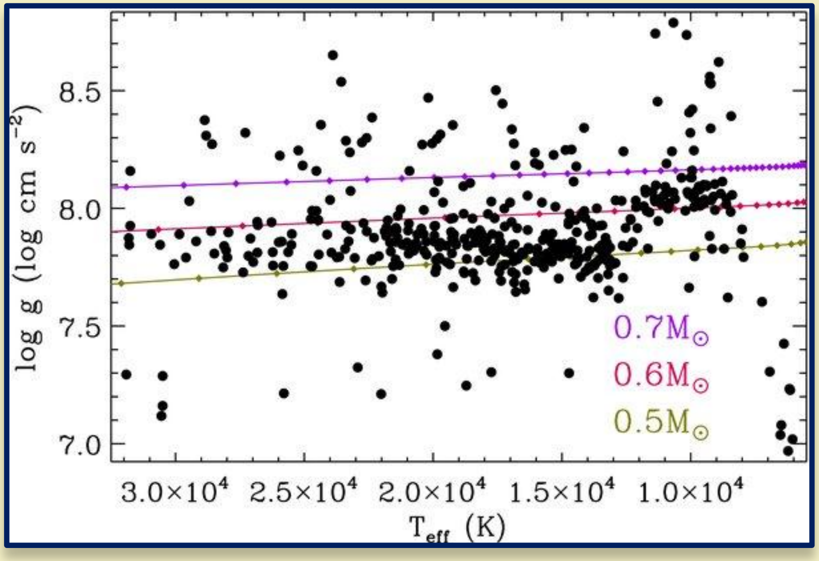


Figure from Falcon et al. (2010a): 419 DA WDs from SPY

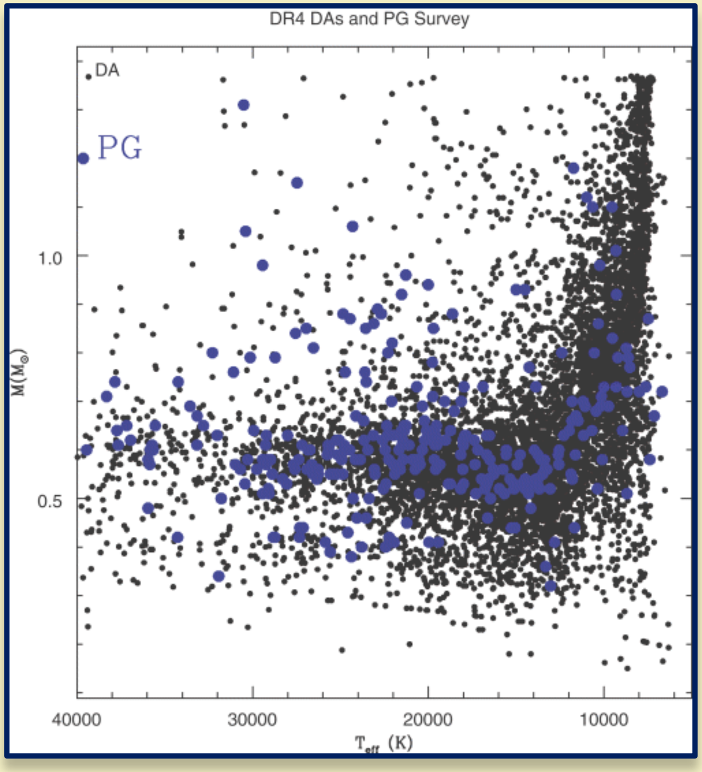


Figure from Kepler et al. (2007): 3595 DA WDs from SDSS DR4 and 348 DA WDs from the PG survey (Liebert et al. 2005)

The Spectroscopic Method Isn't Perfect?

- Mean mass discrepancy at all T_{eff}
  - From gravitational redshift of ensemble of WDs (Falcon et al. 2010a)

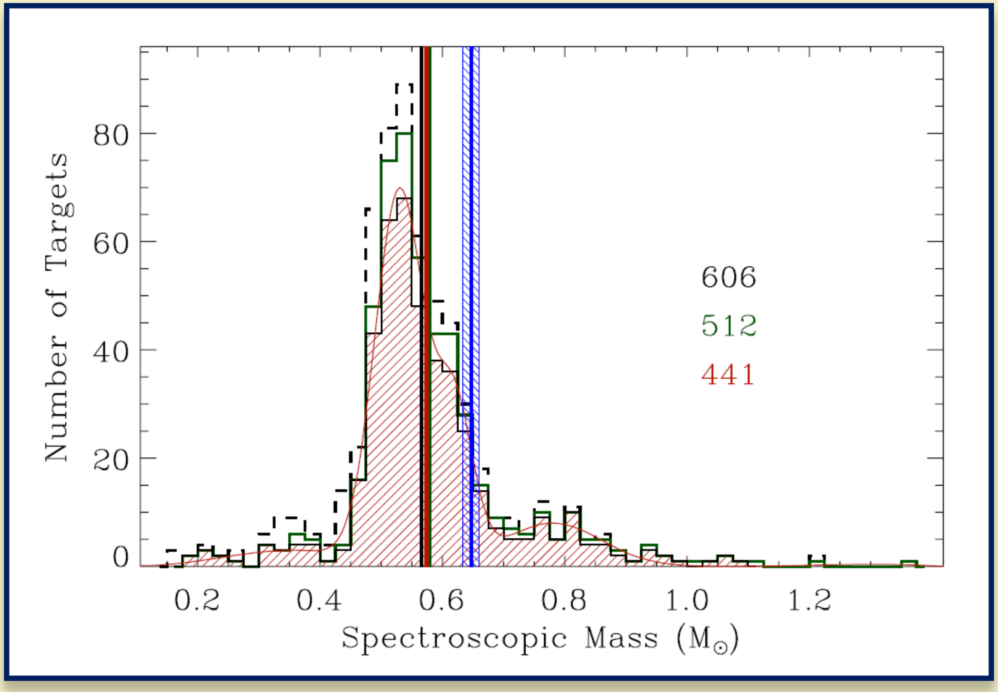


Figure from Falcon et al. (2010a): Spectroscopic mass distribution from SPY. The means of the spectroscopic masses (vertical lines) differ significantly from the mean mass from gravitational redshift (vertical, blue line).

The Spectroscopic Method Isn't Final?

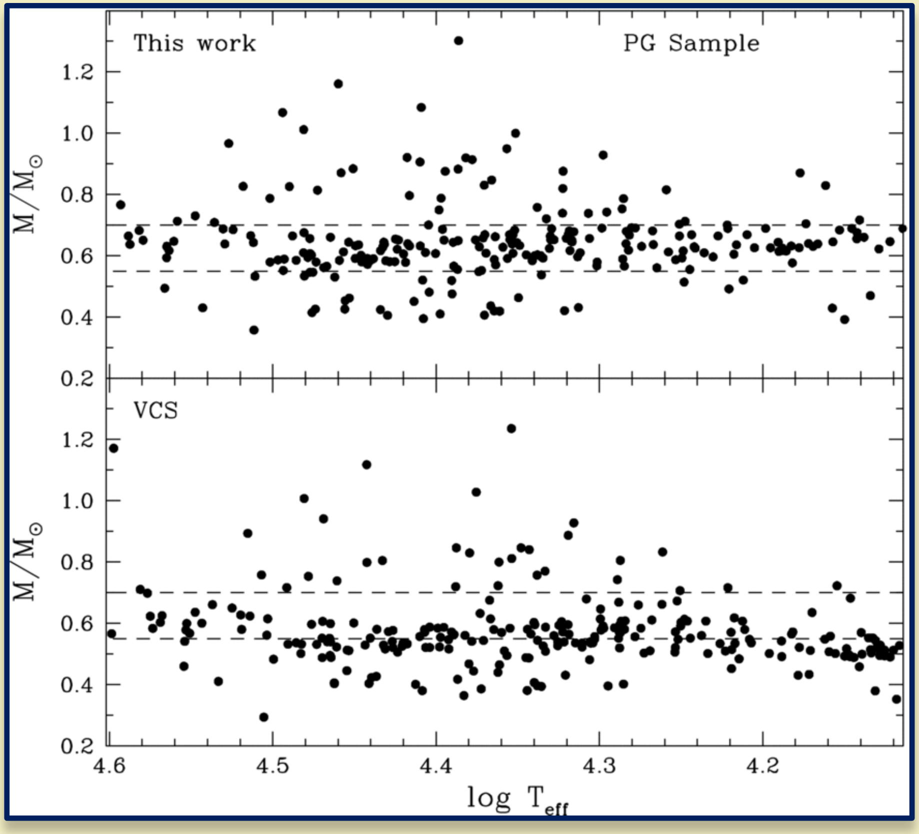
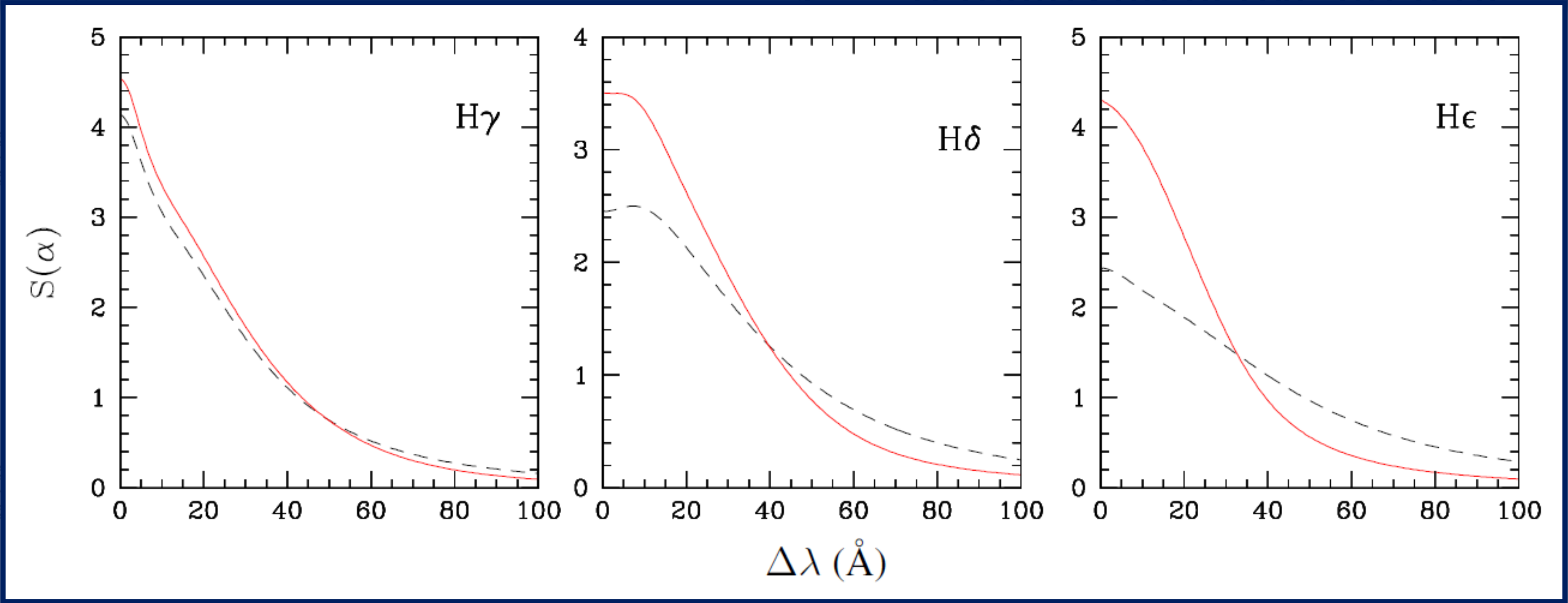


Figure from Tremblay & Bergeron (2009): Difference in fit results using WD atmosphere models with improved Stark broadened line profiles

- WD atmosphere modeling remains an active area of research
- Recent "improved" Stark broadened H line profiles (Tremblay & Bergeron 2009) resulted in systematic increases:
  - $\Delta T_{\mathrm{eff}} \sim 200 - 1000$ K
  - $\Delta \log g \sim 0.04 - 0.1$ dex
- Inclusion of opacity of H Ly-α significantly improved cool WD models (Kowalski & Saumon 2006)

The Spectroscopic Method Isn’t Final?

- WD atmosphere modeling remains an active area of … Ly α significantly improved cool WD models (Kowalski & Saumon 2006)



Courtesy of P.-E. Tremblay: Theoretical hydrogen line profiles as a function of distance from the line center, Δλ. The plasma conditions assumed are T = 10,000 K and n_e = 10^{17} cm^{-3}. The recent calculations of Tremblay & Bergeron are shown as the solid (red) lines, and the previous Vidal-Cooper-Smith (VCS) calculations are shown as the dashed (black) lines.

Figure from Tremblay & Bergeron (2009): Difference in fit results using WD atmosphere models with improved Stark broadened line profiles

What’s Been Done (in the Lab)

History of Experiments

Year	Authors	Plasma Source
1962	Berg et al.	Shock tube
1965	McLean et al.	Shock tube
1967	Hill et al.	Arc discharge
1968	Morris et al.	Arc discharge
1968	Shumaker et al.	Arc discharge
1969	Griffith et al.	Arc discharge
1969	Birkeland et al.	Arc discharge
1969	Bengtson et al.	Shock tube
1972	Wiese et al.	Arc discharge
1980	Baessler & Kock	Arc discharge
1981	Helbig & Nick	Arc discharge
1990	Uhlenbusch & Viöl	Laser-induced discharge
1995	Parigger et al.	Laser-induced breakdown
2000	Escarguel et al.	Laser-induced breakdown
2003	Flih et al.	Laser-induced breakdown
2003	Parigger et al.	Laser-induced breakdown
2008	Parigger et al.	Laser-induced breakdown
2010	Falcon et al.	Radiation-driven

- Driving the experiments
  - `60s, `70s
    - Theory
  - `80s and on
    - Theory
    - Diagnostic methods
  - Now
    - Theory
    - Diagnostic methods
    - Astronomical observation

A New, Unique Perspective

- Radiation-driven experiment
  - As opposed to shocks (e.g., Bengtson et al. 1969), discharges (e.g., Wiese et al. 1972)
  - Uses large x-ray flux from z-pinch
    - Not available many places other than Z Pulsed Power Facility
- Continuum backlighter ⟶ absorption spectra

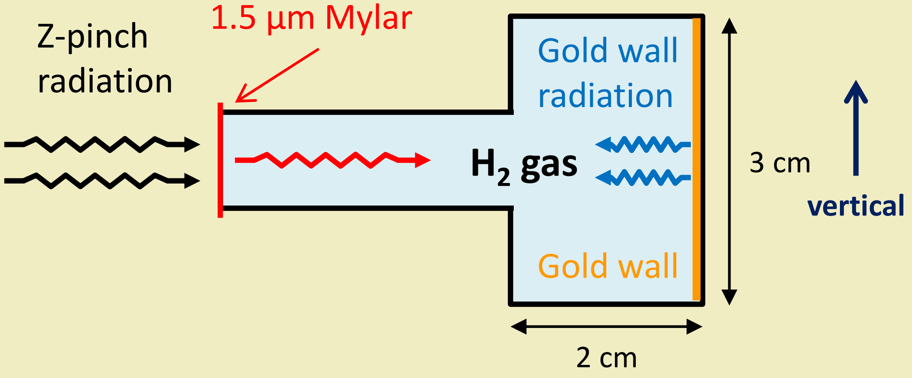
Plasma Source	Homogenous	Stationary	Emission	Absorption
Shock-heated	X		X	
Arc Discharge		X	X	
Laser-induced Breakdown		Smooth	X	
Radiation-driven	X	Smooth	X	X

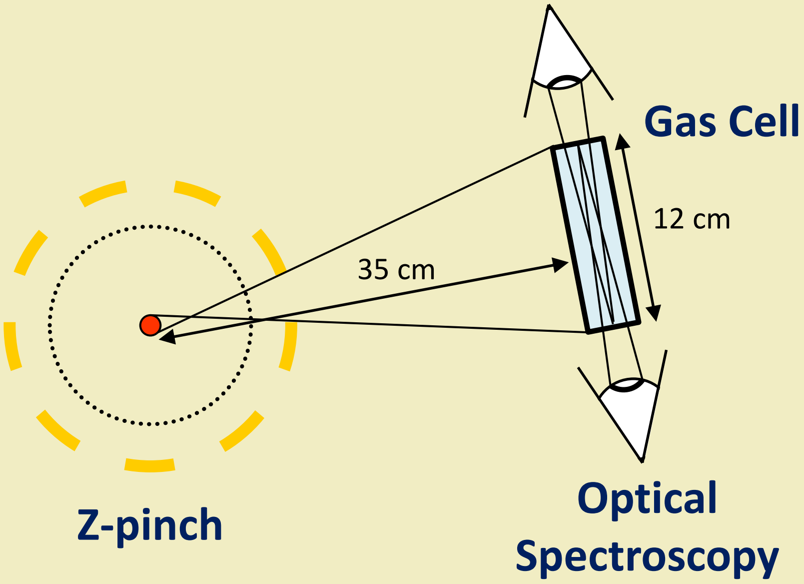
For plasmas at $T \sim 0.5 - 2$ eV and $n_e \sim 10^{17}$ cm^{-3}

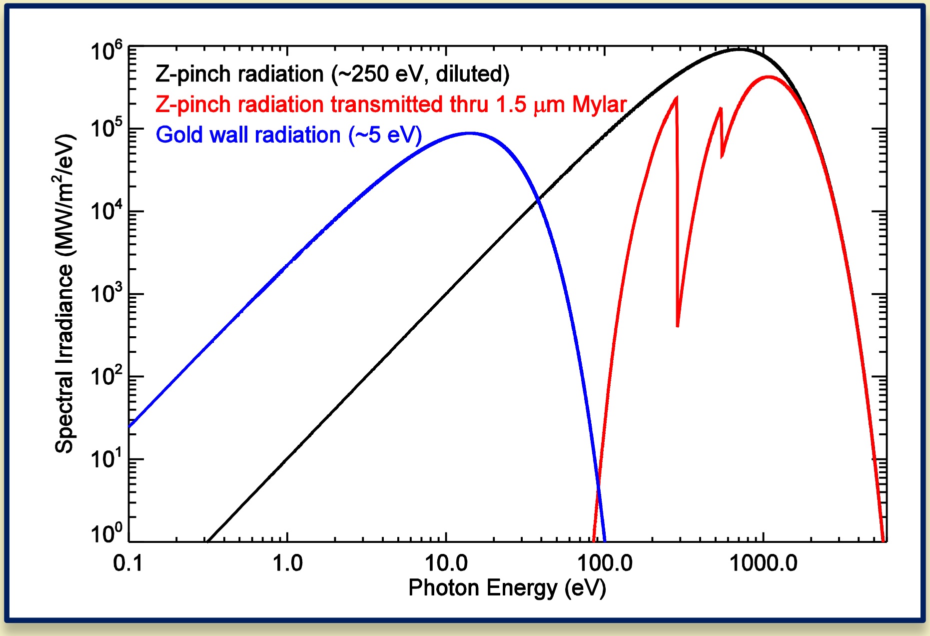
Experimental Setup

- Z-pinch x-rays uniformly irradiate gold wall in gas cell
- Gold wall radiation couples well to hydrogen gas to heat through photoionization
- Total particle density set by initial fill pressure

Cross-section of Gas Cell

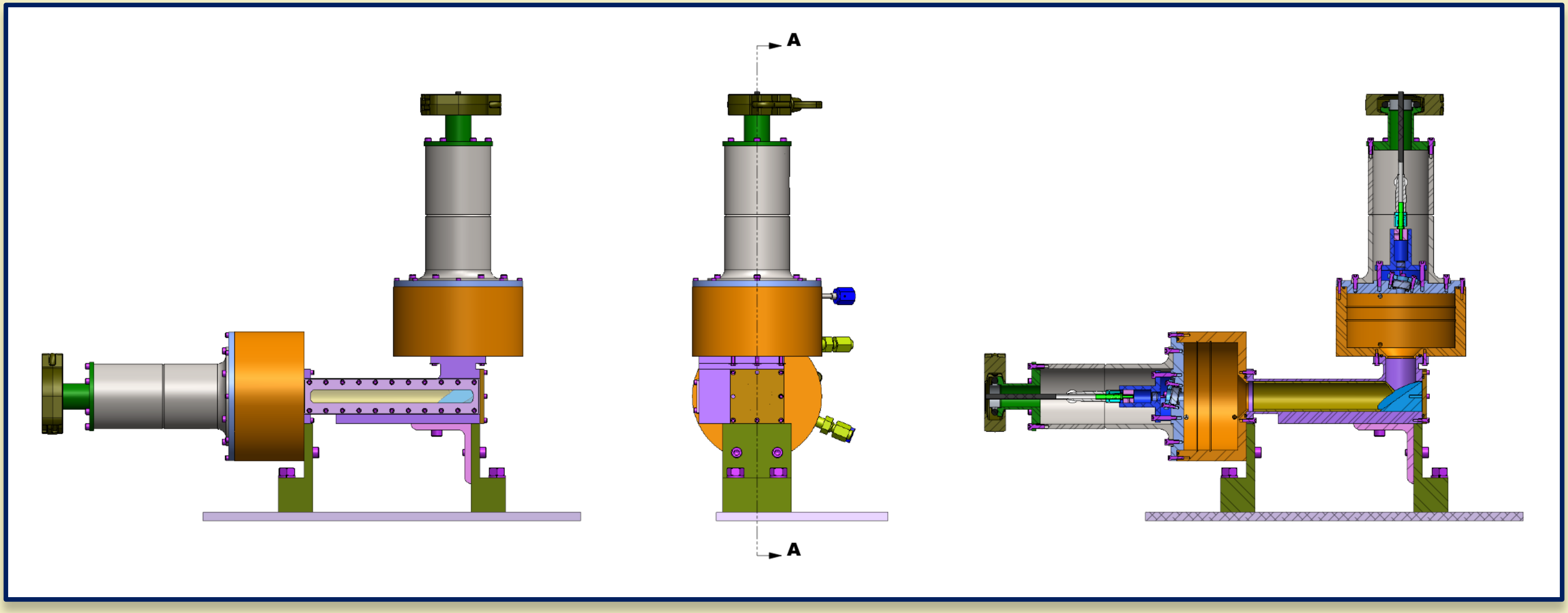




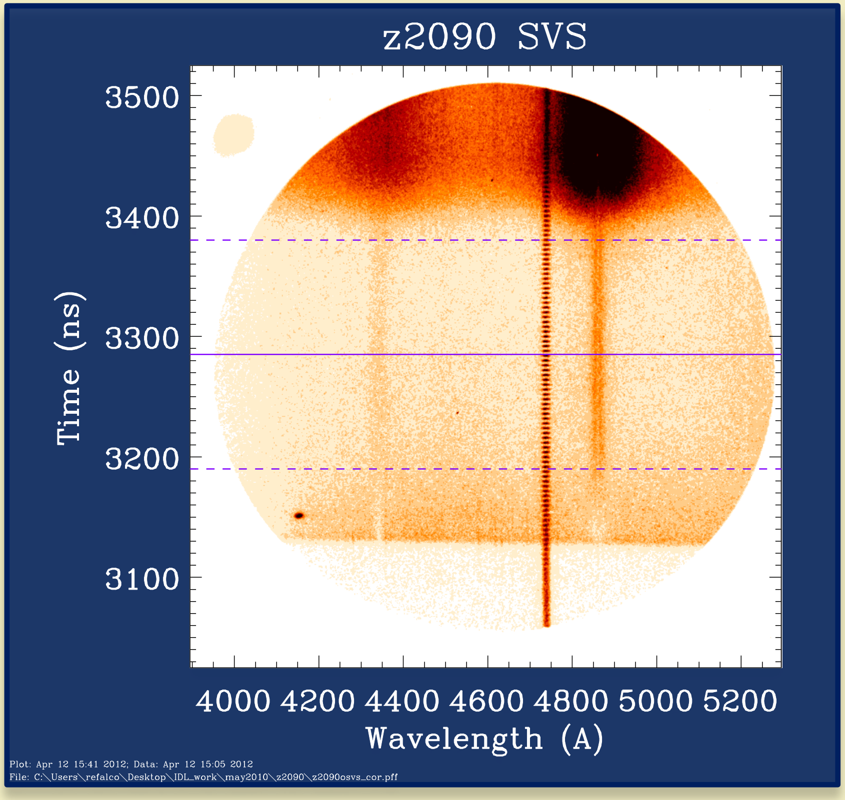


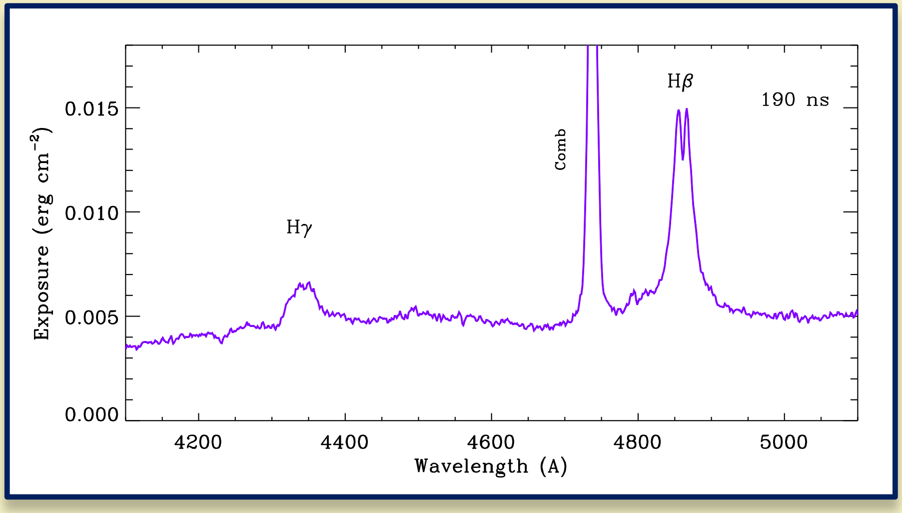
Gas Cell

- Alternate designs allow for different (and multiple) LOS options
  - Emission
  - Absorption
  - Distance from gold wall
  - Length of plasma

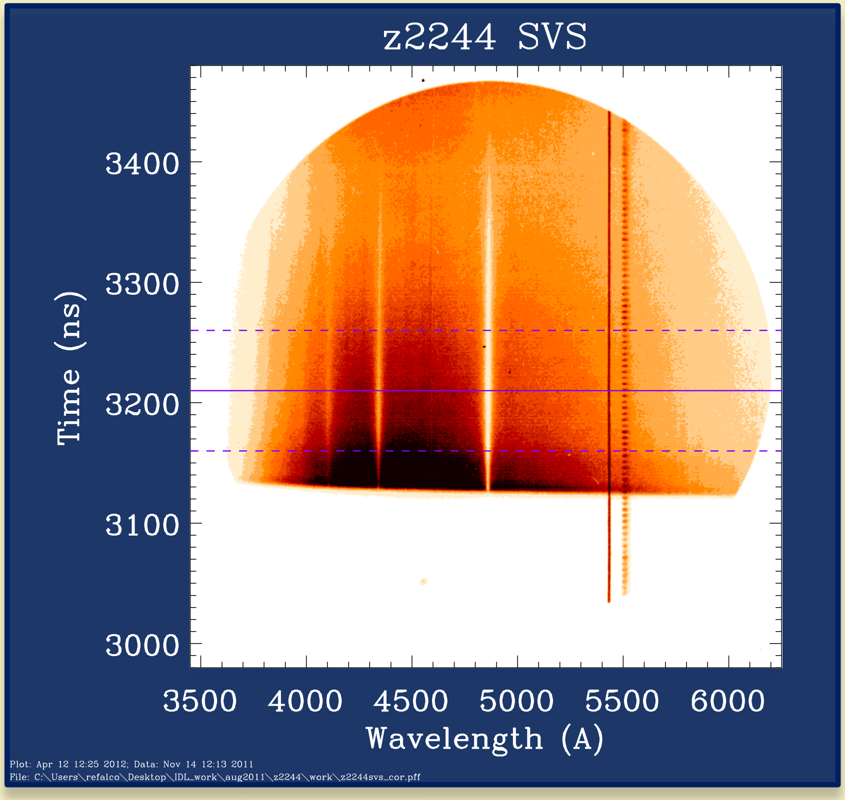


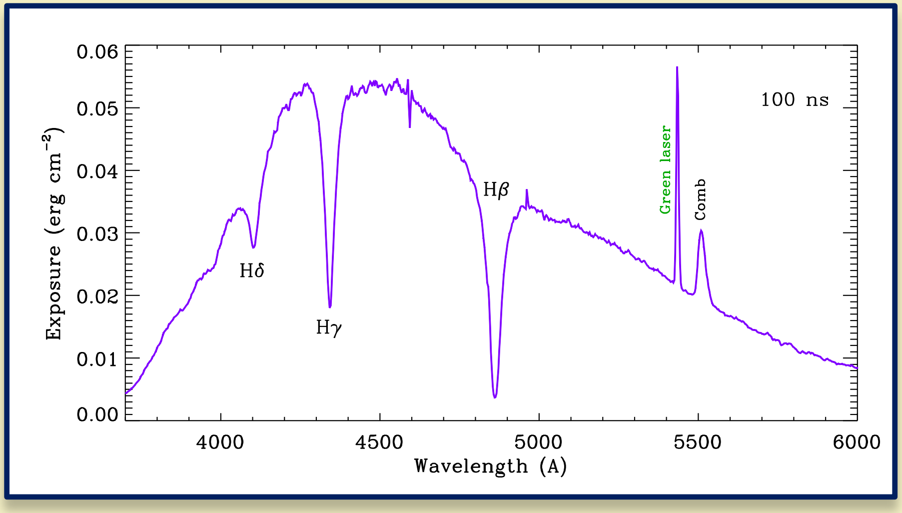
Emission



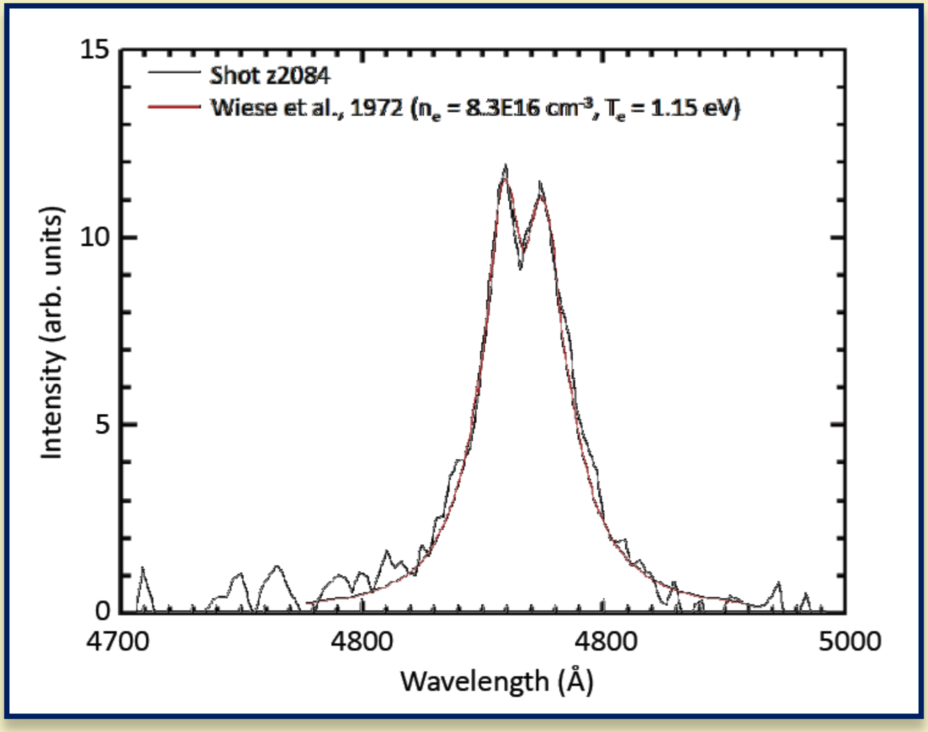


Absorption

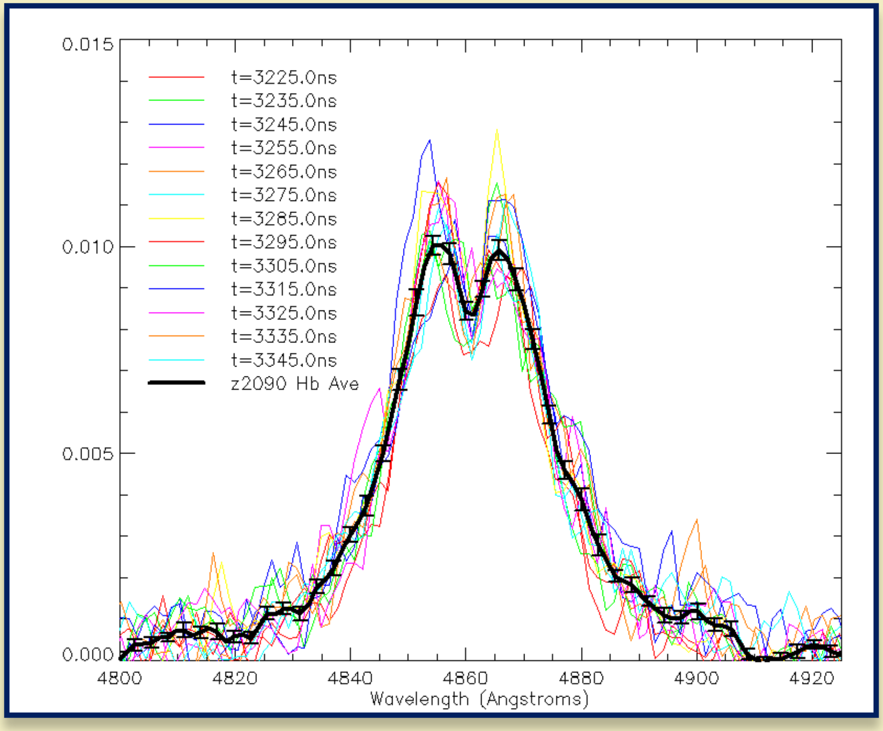




Hβ, the Standard



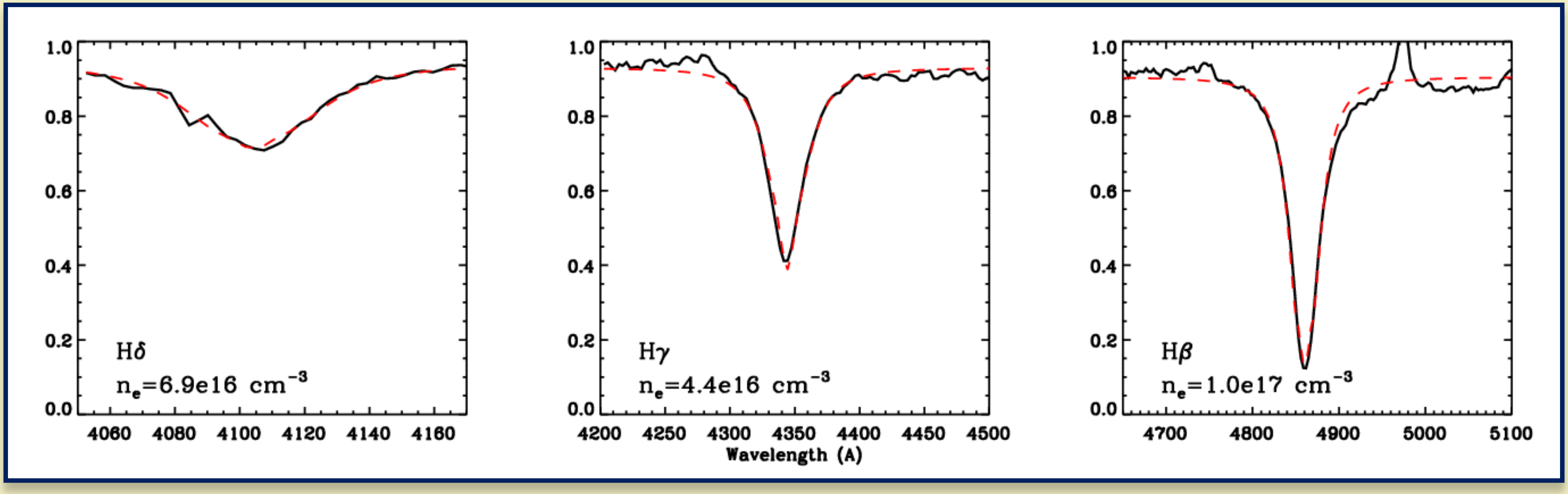
- First shot displayed agreement with arc discharge experiment of Wiese et al. (1972)



- Hβ shows stability in time

Spectroscopic Line Fits

- Using VCS theory
  - Neglecting optical depth effects
- First fits to absorption data from experiment
- Sufficient quality to begin discriminating between theories



120 ns integration from shot z2267

(Near-term) Strategy

- Measure relative line shapes of Hβ, Hγ, Hδ, (Hε) for H plasma at WD photospheric conditions ($T \sim 1$ eV, $n_\mathrm{e} \sim 10^{17}$ cm^{-3})
  - Gas fill temperature, pressure → total particle density
  - Hβ line shape → electron density n_e
  - Gold wall temperature → radiation temperature T_r
  - Absolute intensity, absorption, emission → level populations
- Compare to VCS, TB09, other *theoretical* line shapes
  - WD test case at recent Spectral Line Shapes in Plasmas Workshop in Vienna
- Compare to Wiese et al., other *experimental* line shapes

Pros/Cons of Platform

- Strengths/Potential
  - Continuum backlighter (*for absorption measurements*)
  - Additional plasma diagnostics in development
  - Ability to investigate other gases (*He, CO_2, etc.*)
  - Ability to explore time-dependent, non-LTE, collisional/radiative atomic kinetics
- Weaknesses/Limitations
  - Harsh environment – hard radiation, debris
  - Experiment lasts 10s to 100s of ns

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