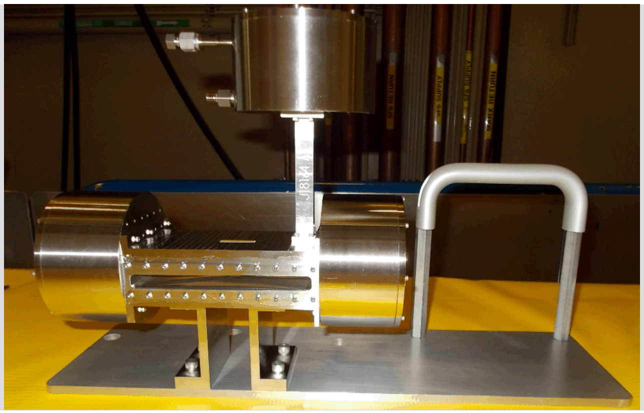
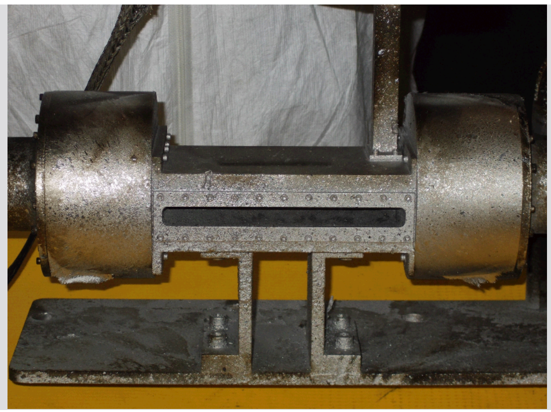
SAND2016-7071C

Exceptional service in the national interest

Sandia National Laboratories





Reaching Higher Densities with our Laboratory White Dwarf Photospheres

Ross E. Falcon

20th European White Dwarf Workshop
University of Warwick, United Kingdom
07.26.2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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. SAND NO. 2011-XXXXP

Our project is a collaboration between national lab and university

Sandia National Laboratories

Ross E. Falcon
Taisuke Nagayama
James E. Bailey
Gregory A. Rochau
Guillaume Loisel
Dave E. Bliss
Dan Scoglietti

Sandia National Laboratories

Thomas A. Gomez
Marc Schaeuble
Michael H. Montgomery
Don Winget
Zach Swindle
Sean Moorhead
Travis Pille

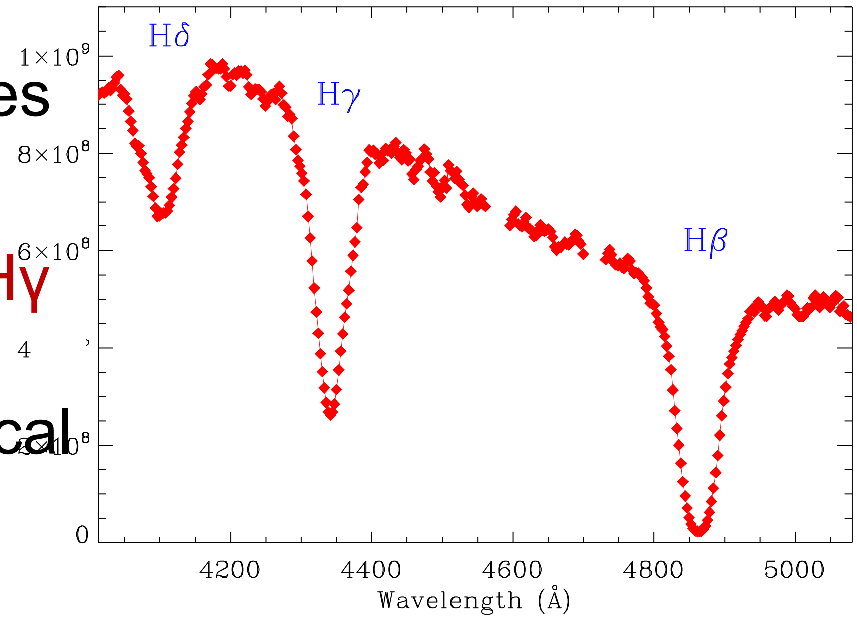
University of Texas – Austin

Summary: we extend our experimental platform to measure white dwarf plasmas at higher electron densities

Sandia National Laboratories

- At these higher electron densities, Hβ as a diagnostic now disagrees between theories

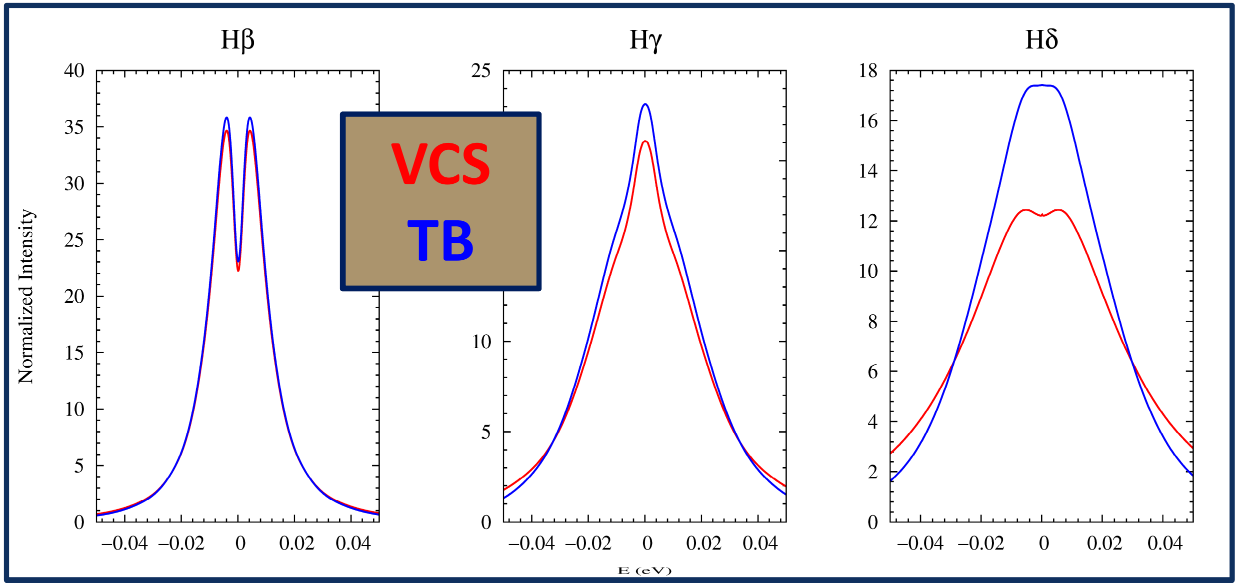
- Our measured line profiles of Hγ and Hβ show relative disagreement with the theoretical profiles
  - *Shape*
  - *Strength* (occupation probability)



Line profiles used in WD atmosphere models are very *precise*, but are they *accurate*?

- Precision of the *spectroscopic method* (see, e.g., Bergeron et al. 1992):
  - $\delta T_{eff}/T_{eff} \sim 5\%$
  - $\delta \log g / \log g \sim 1\%$
- Used for 10,000s of WDs

- In WD community, Stark-broadened H line profiles by Tremblay & Bergeron (TB) now replace Vidal, Cooper, & Smith (1973; VCS) profiles as tabulated by Lemke (1997)
  - Initially resulted in systematic increases:
    - $\Delta T_{eff} \sim 200$—1000 K
    - $\Delta \log g \sim 0.04$—0.1
    - $\Delta M \sim 0.03\ M_{Sun}$
    - For 250 WDs from the Palomar-Green Survey
- VCS and TB profiles disagree with increasing principal quantum number, n, and with increasing electron density, n_e

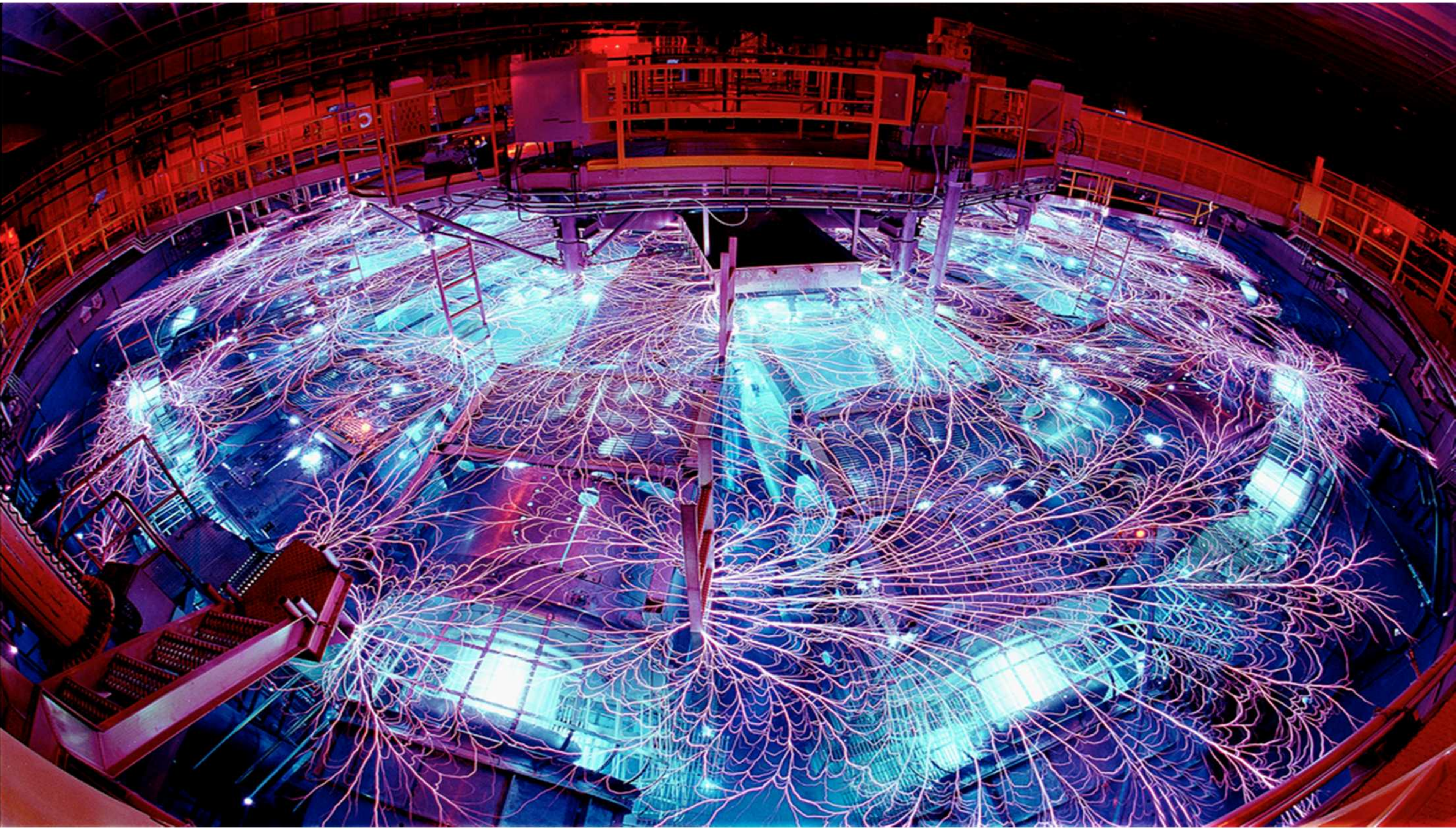


Calculated at T_e = 1 eV and $n_e = 10^{17}$ cm^{-3}

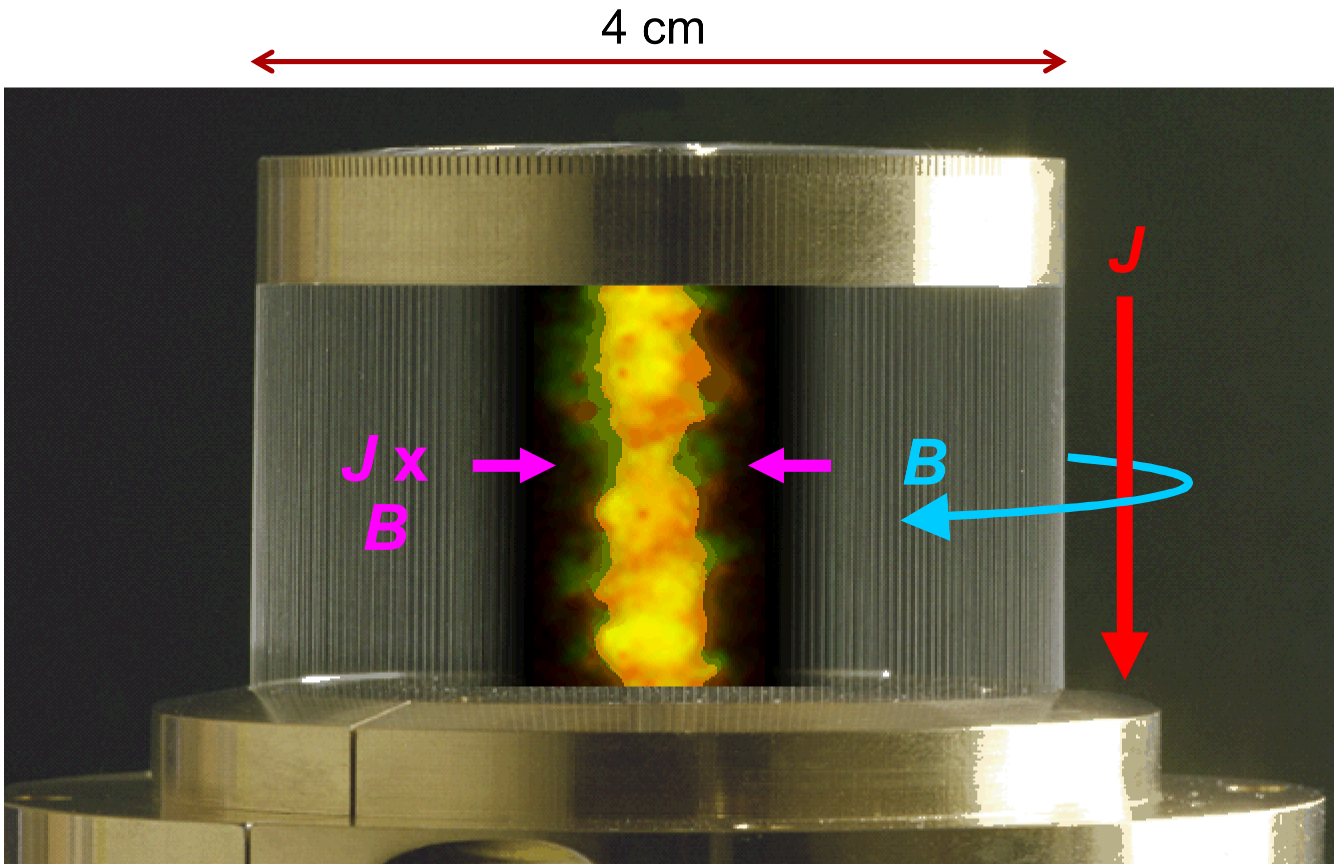
We can test these line shapes in the laboratory

- Measure *multiple* H Balmer lines *simultaneously* at a range of electron density, n_e
  - Use Hβ to diagnose plasma conditions; experimentally validated (Kellerher et al. 1993)
  - Include up to at least Hδ
- Use Wiese et al. (1972) to validate ($n_e < 10^{17}$ cm^{-3}), then extend to higher n_e ($> 10^{17}$ cm^{-3})
  - Arc-discharge experiment
  - Benchmark for H line shapes for >40 years
  - Only experiment to measure multiple H Balmer lines at these conditions

Welcome to the Z Pulsed Power Accelerator



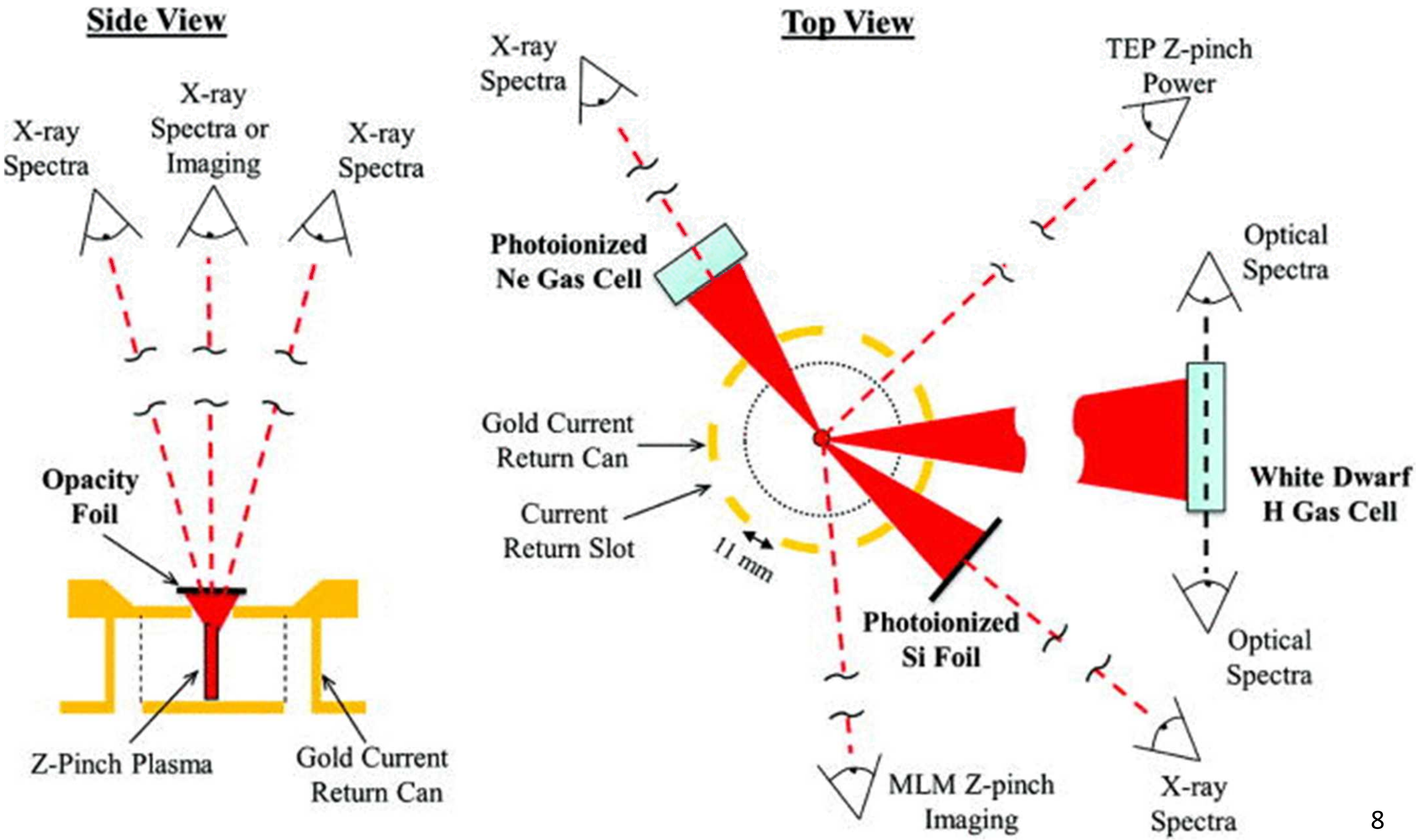
Z Accelerator uses 27 million Amperes to create x rays



$P_{rad} \lesssim 330$ TW, $Y_{rad} \lesssim 2$ MJ

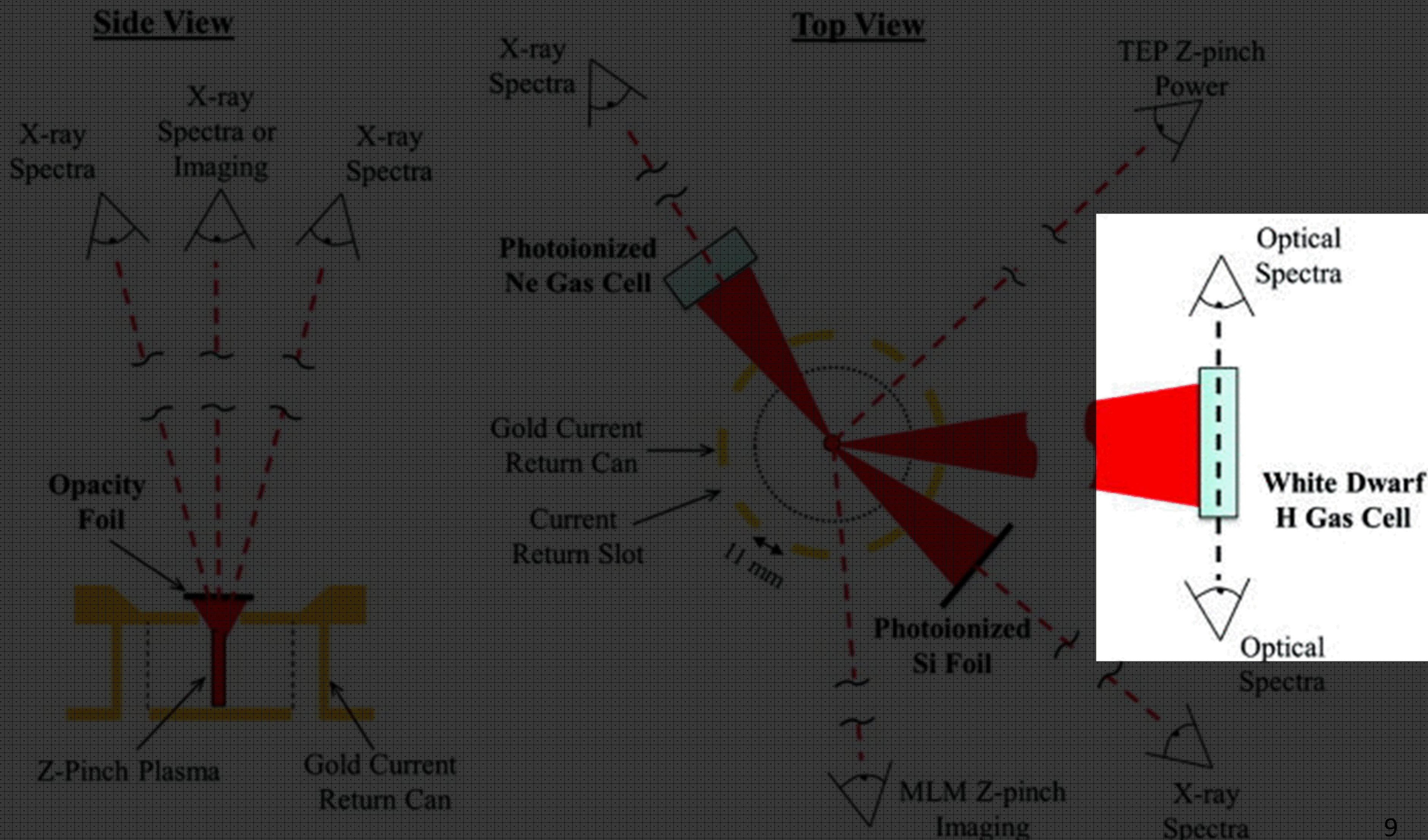
Sandford et al. (2002), *PoP*, **9**, 3573; Bailey et al. (2006), *PoP*, **13**, 056301; Slutz et al. (2006), *PoP*, **13**, 102701

X-ray source simultaneously drives multiple experiments inside vacuum chamber



Rochau et al. (2014), *PoP*, **21**, 056308

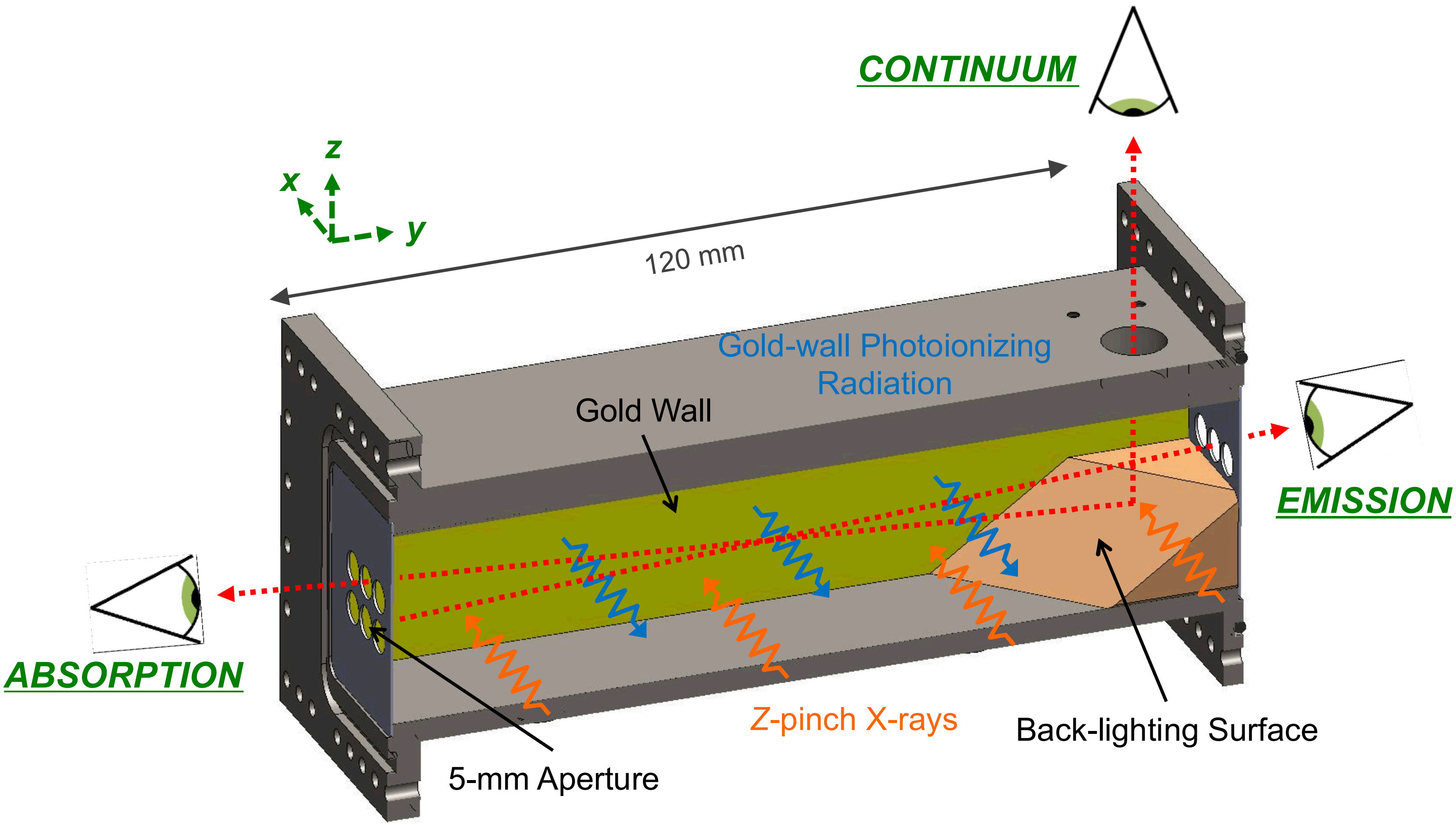
X-ray source simultaneously drives multiple experiments inside vacuum chamber



Rochau et al. (2014), *PoP*, **21**, 056308

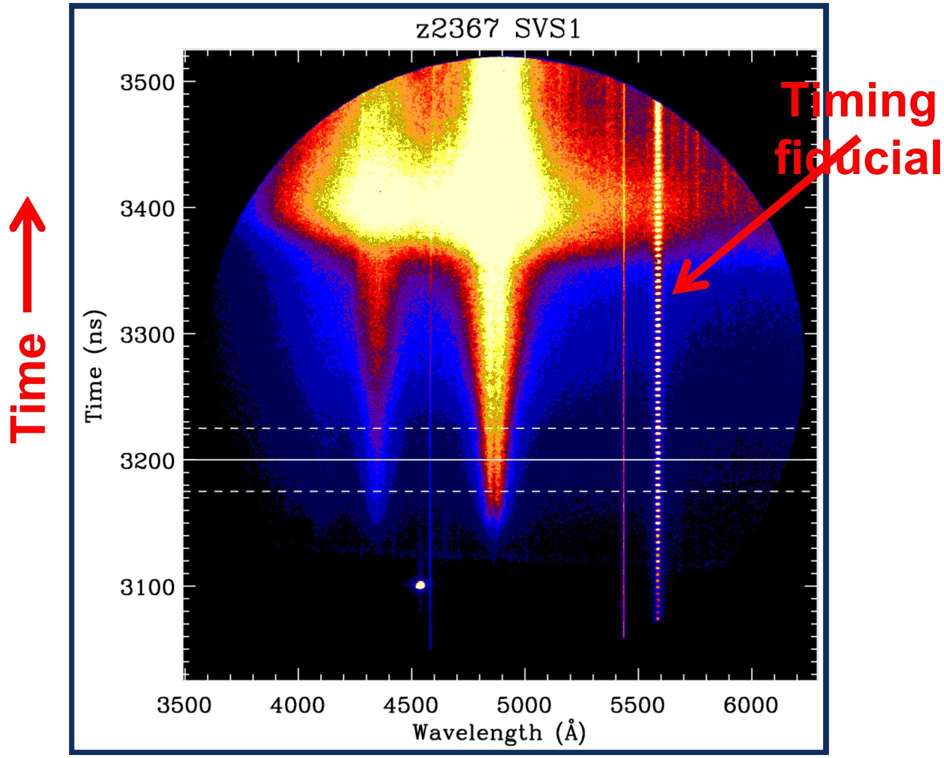
Observe plasma along 3 lines of sight

Sandia National Laboratories

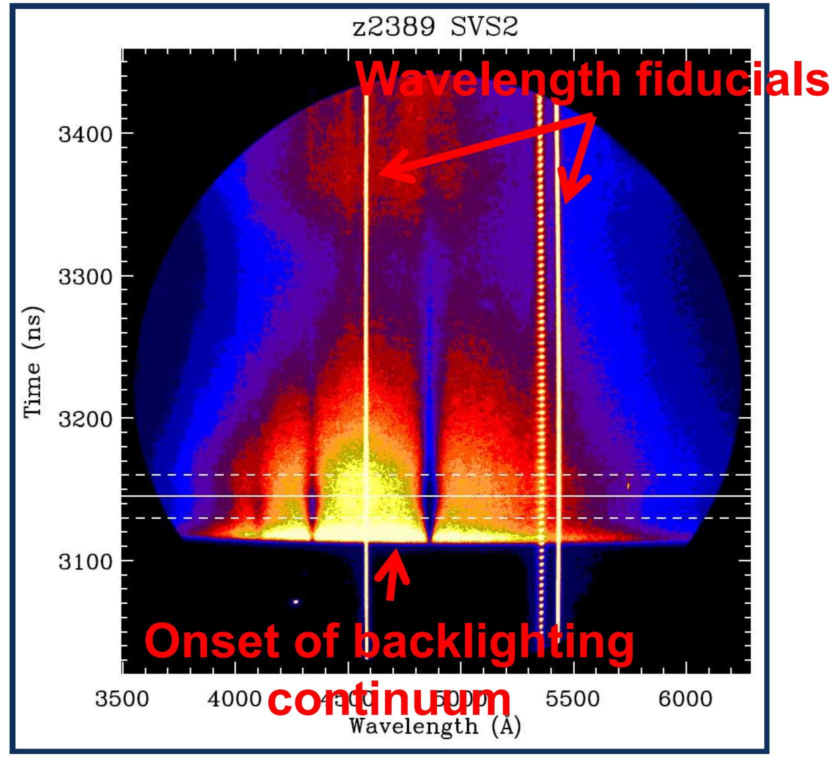


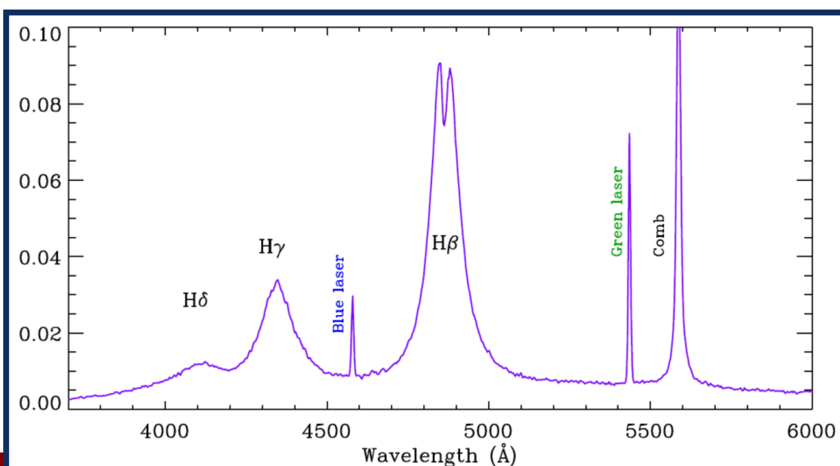
Falcon et al. (2015), *ApJ*, **806**, 214

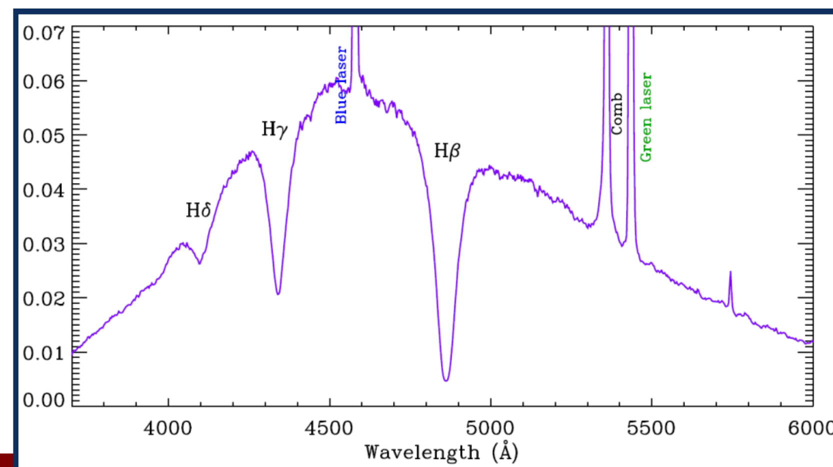
Emission



Absorption

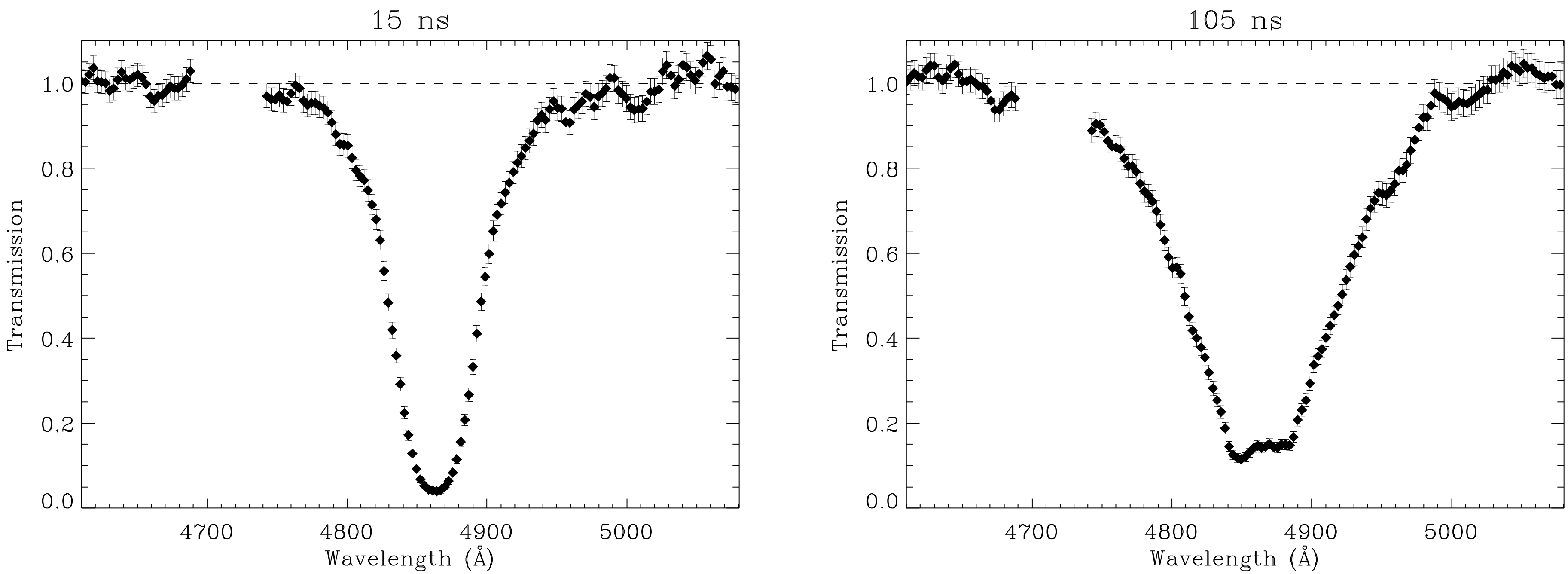






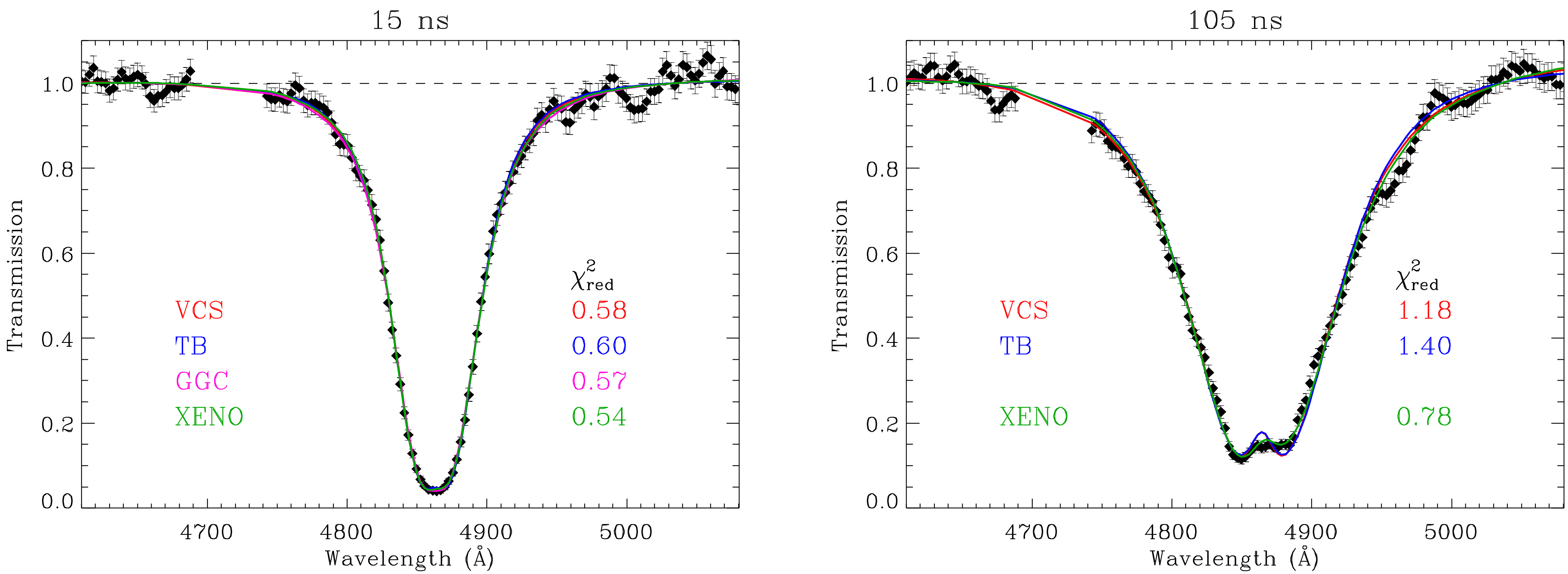
We **measure** and fit the Hβ transmission line throughout the duration of our experiment

- Measured profile widens and develops more structure with time



We measure and **fit** the Hβ transmission line throughout the duration of our experiment

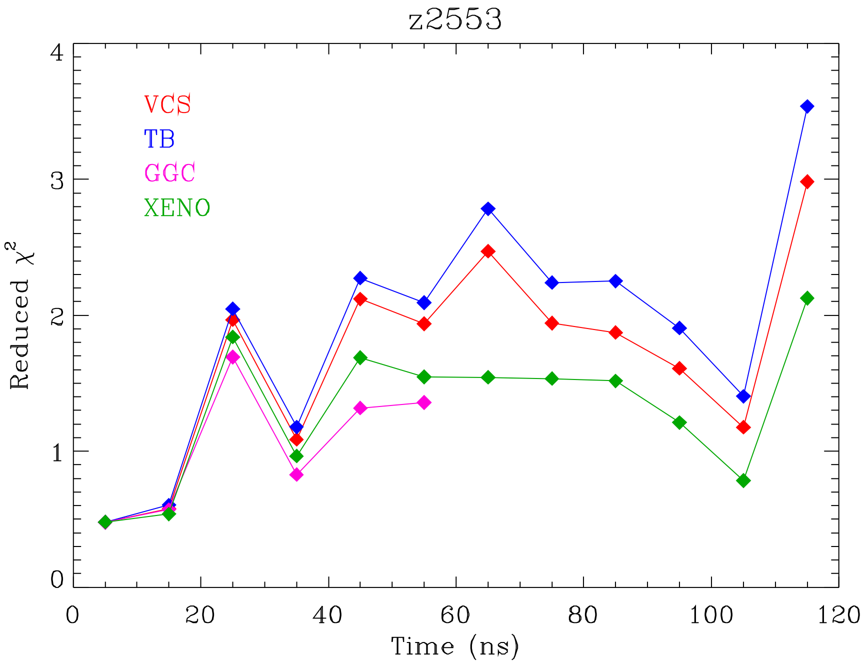
- Measured profile widens and develops more structure with time



- Theoretical line-profile theories used
  - Vidal, Cooper, & Smith (1973, **VCS**)
  - Tremblay & Bergeron (2009, **TB**)
  - Gigosos et al. (2003, **GGC**)
  - Gomez et al. (Xenomorph or **XENO**)

Theoretical line profiles used by WD astronomers do ***not*** fit as well as others

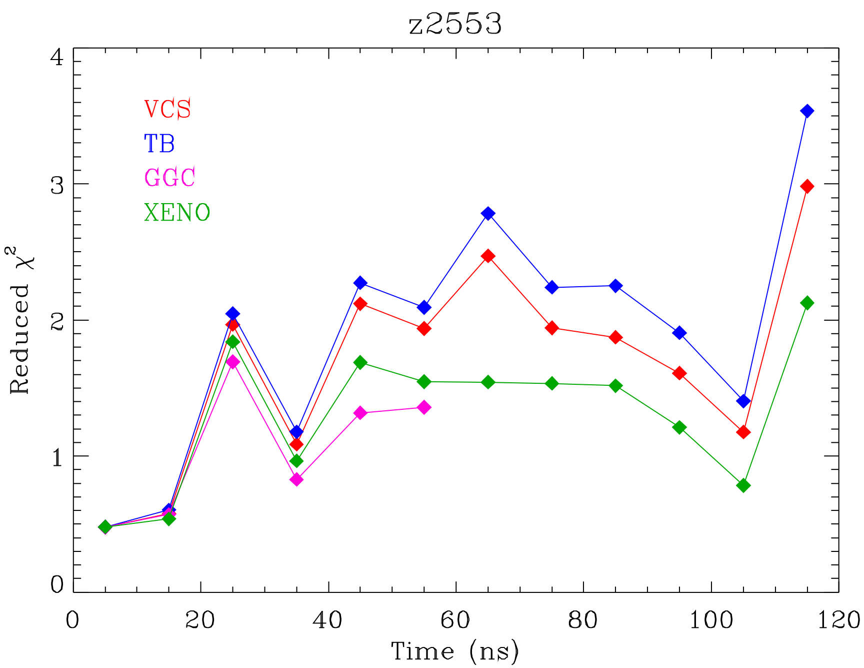
- VCS and now TB used in WD astronomy community
- What else is there?
    - Computer-simulated calculations
    - i.e., Gigosos et al. (2003, GGC), Gomez et al. (Xenomorph)

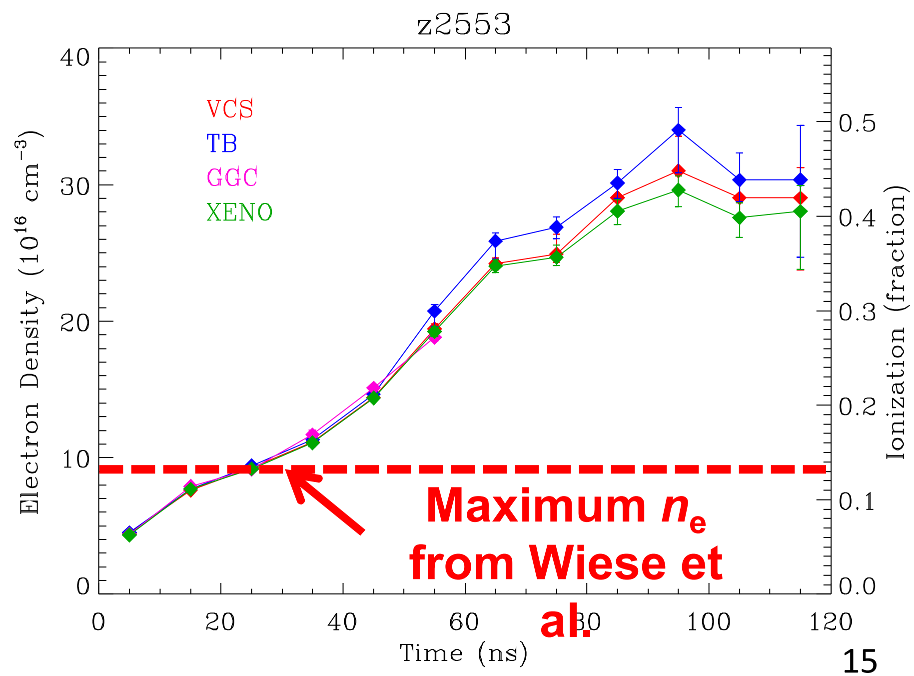


Falcon et al. (2015), *ApJ*, **806**, 214

BUT, the inferred conditions ***agree***!

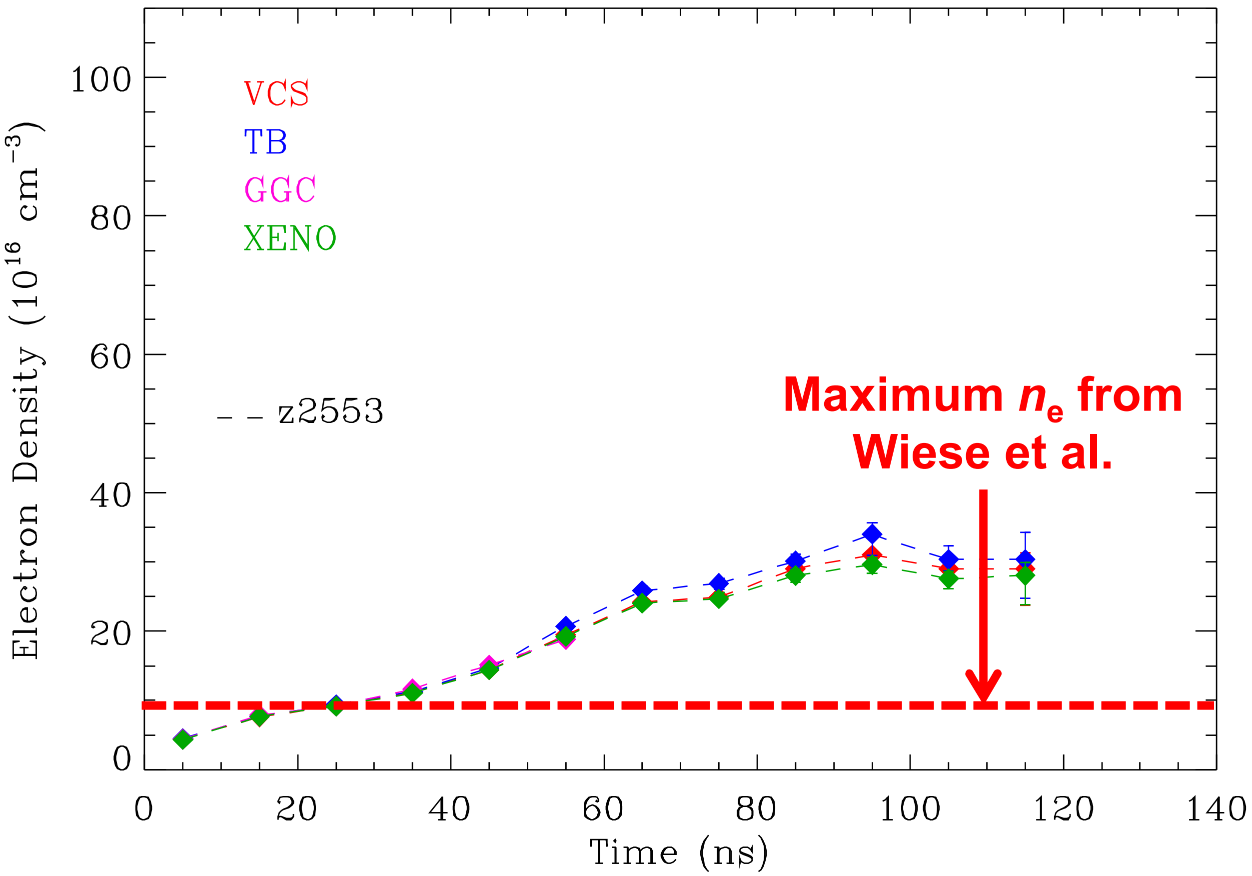
- VCS and now TB used in WD astronomy community
- What else is there?
  - Computer-simulated calculations
  - i.e., Gigosos et al. (2003, GGC), Gomez et al. (Xenomorph)
- Agreement over a range of electron density (analogous to surface gravity) not previously tested



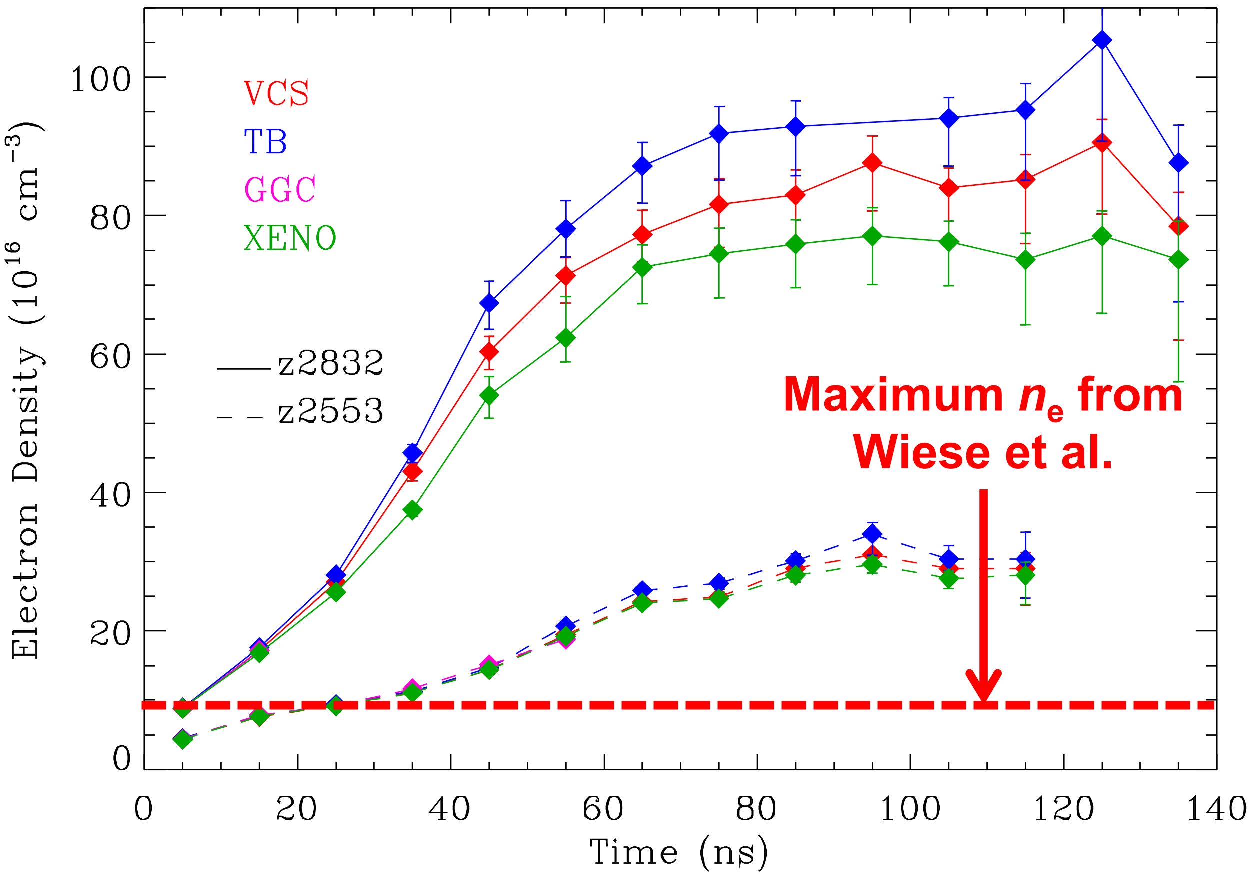


Falcon et al. (2015), *ApJ*, **806**, 214

At ***lower*** electron densities, diagnosis from Hβ agrees between different line-shape theories

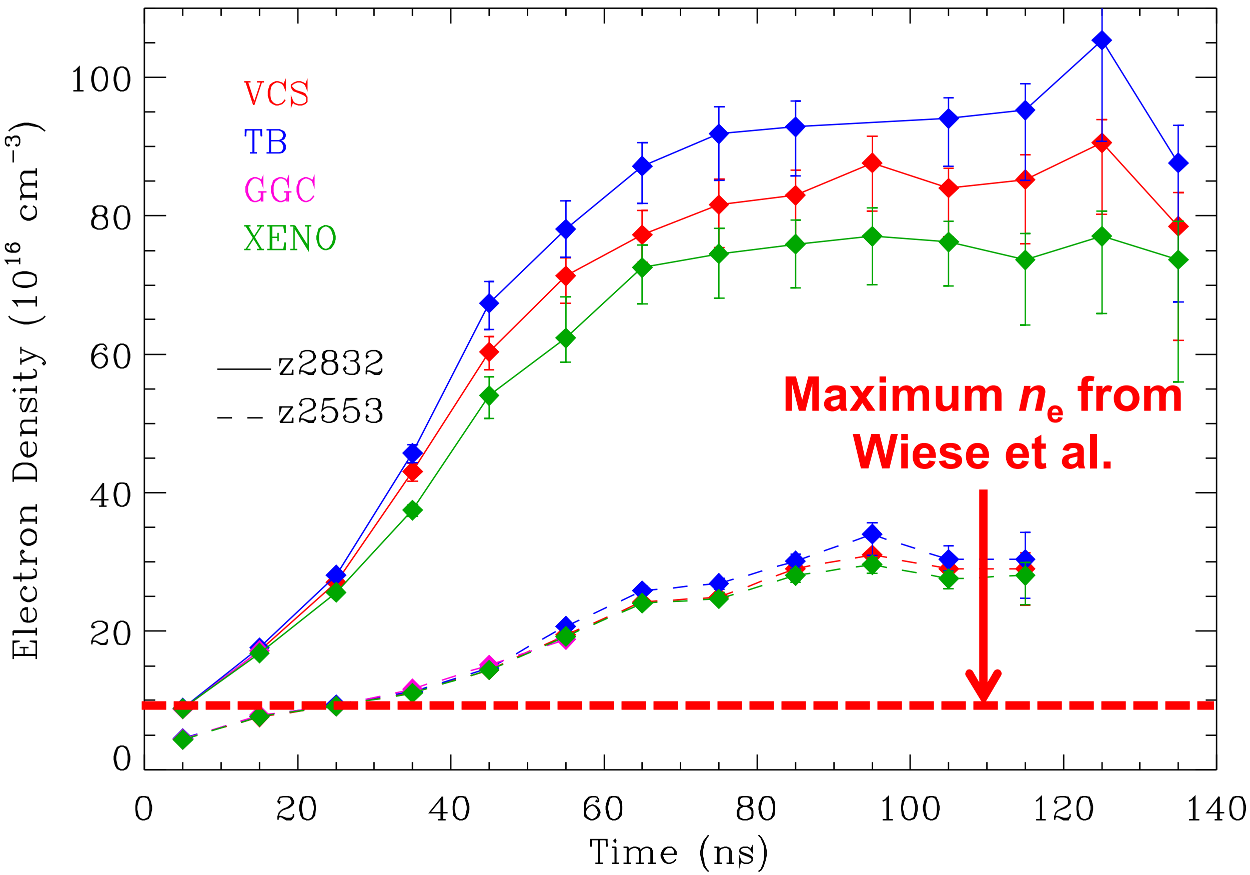


At ***higher*** electron densities, diagnosis from Hβ diverges between different line-shape theories



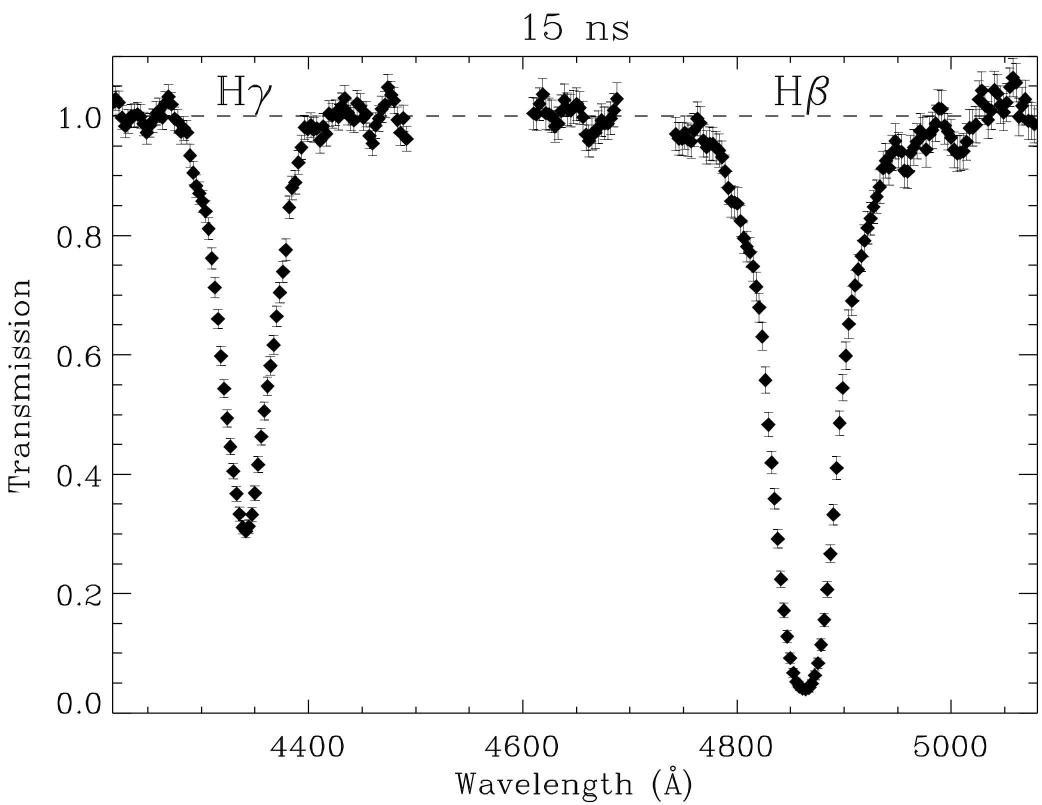
- Same gas cell
- Changed gas-fill pressure
- Decreased LOS distance from radiating gold wall

At higher electron densities, diagnosis from Hβ diverges between different line-shape theories



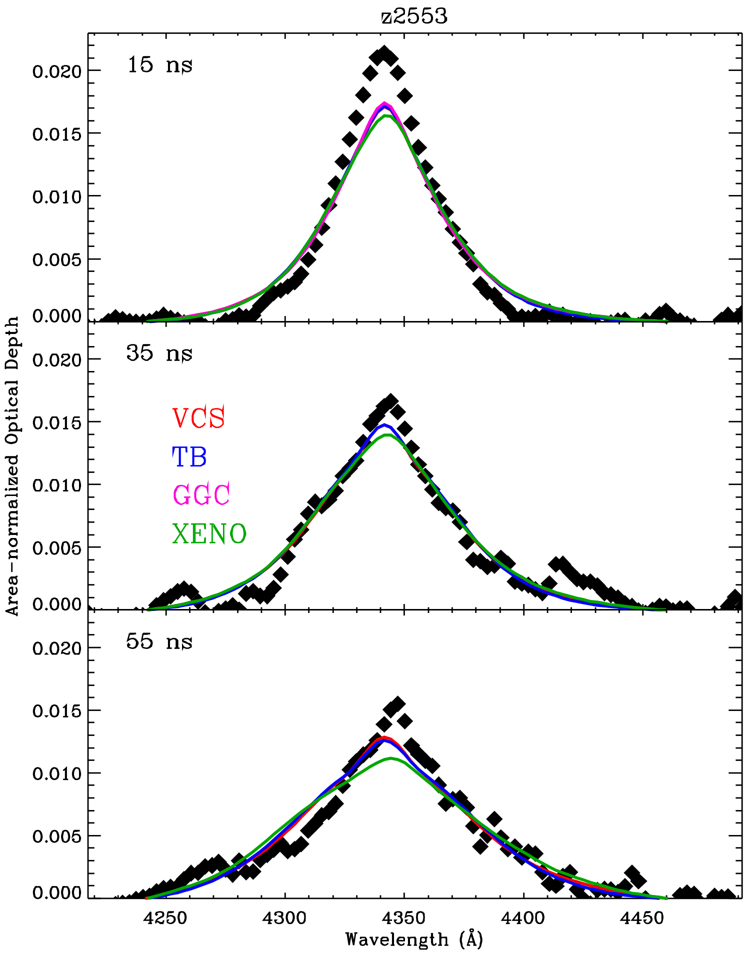
- Same gas cell
- Changed gas-fill pressure
- Decreased LOS distance from radiating gold wall
- We can increase ***temperature*** by moving gas cell closer to x rays
  - **See poster by Marc Schaeuble**
    - Helium
    - Carbon

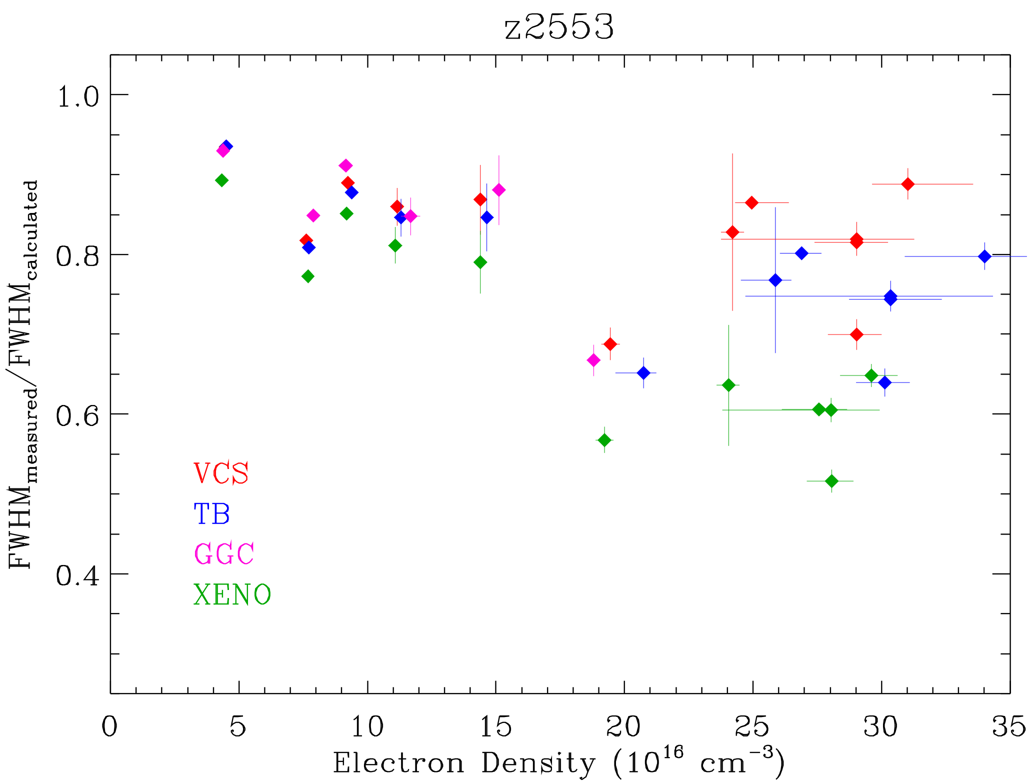
What do other Balmer lines (i.e., Hγ) have to say?



- We measure multiple spectral lines at the ***same*** time from the ***same*** plasma

Measured Hγ line shape does not agree with calculated line shape (using Hβ electron density)





Intriguing trend seen in spectroscopic fits to observed WD spectra

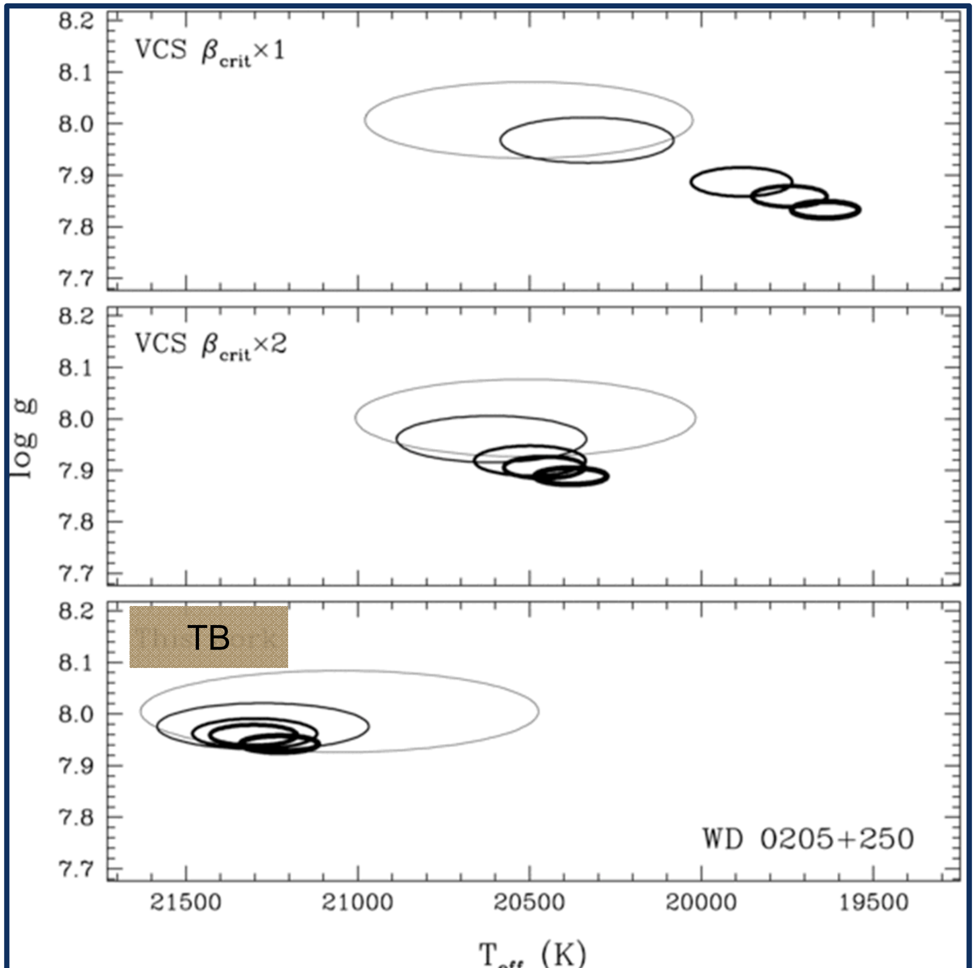
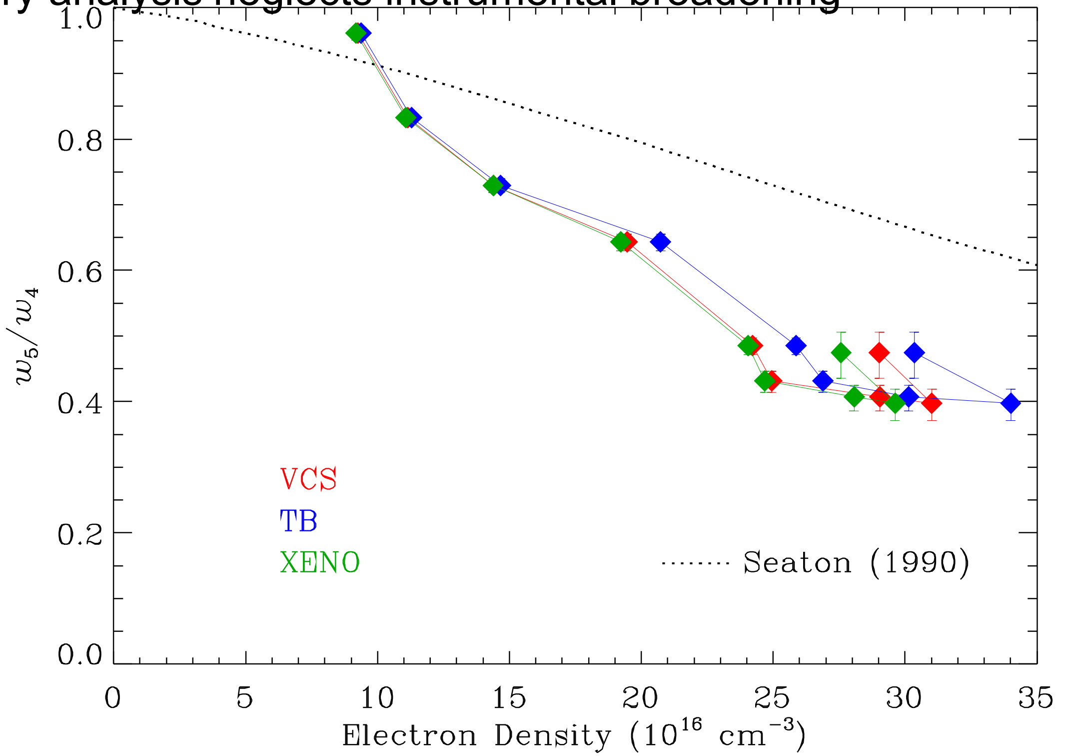


Figure from Tremblay & Bergeron (2009)

- Including higher-order lines in fits infers lower surface gravity
  - Tremblay & Bergeron provide consistency, but trend still exists
- If Hβ is indeed more accurate, then WD surface gravities (and masses) are ***underestimated***
- Implies masses should be larger, as suggested by gravitational-redshift masses (Falcon et al. 2010)

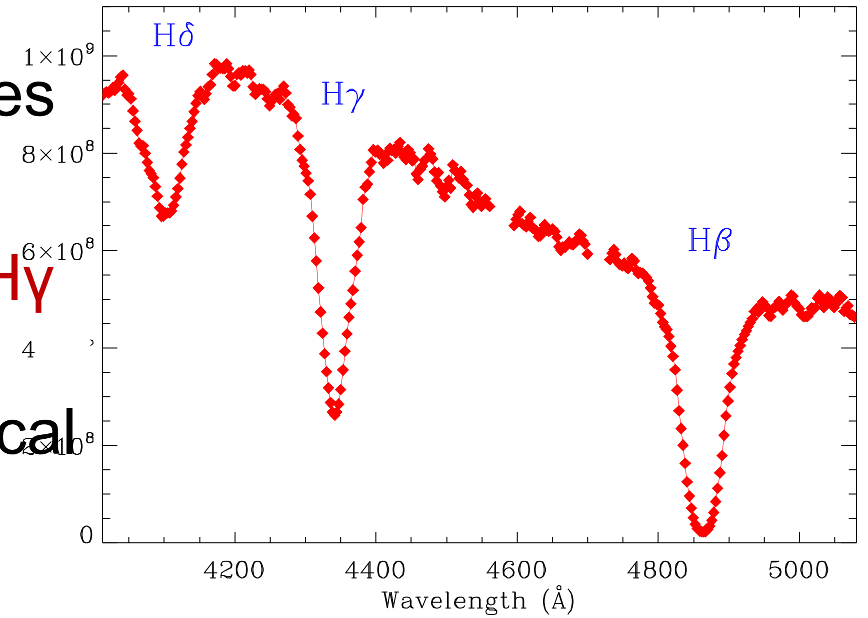
By measuring line *strengths*, our data provide new, unique measurements of occupation probabilities

- $$\frac{\kappa^{H\gamma}}{\kappa^{H\beta}} \propto \frac{f_{2\rightarrow 5} w_5(n_e)}{f_{2\rightarrow 4} w_4(n_e)}$$
  Use published oscillator strengths (Baker 2008)
  Occupation probabilities
- Measured curve falls off with n_e more steeply than predicted by Seaton (1990)
  - Preliminary analysis neglects instrumental broadening



Summary: we extend our experimental platform to measure white dwarf plasmas at higher electron densities

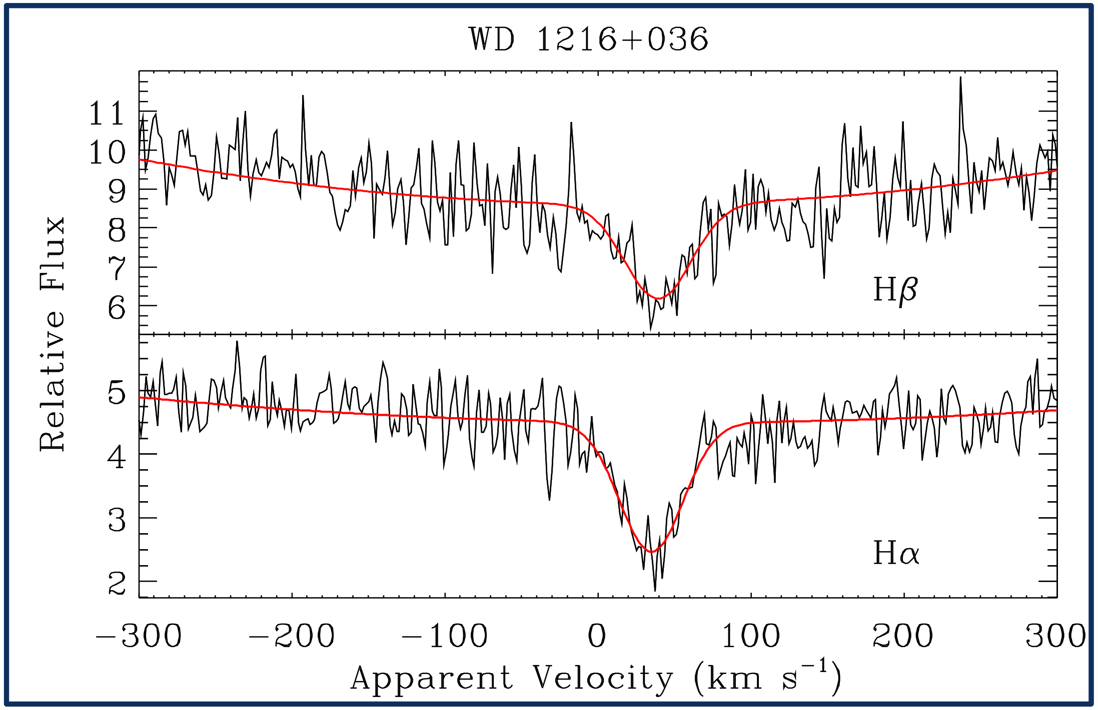
- At these higher electron densities, Hβ as a diagnostic now disagrees between theories
- Our measured line profiles of Hγ and Hβ show relative disagreement with the theoretical profiles
  - *Shape*
  - *Strength* (occupation probability)



Additional details…

Gravitational redshifts are observed in WD spectra due to high surface gravity

- Apparent velocity has 2 components
  - $v_{app} = v_r + v_g$
    - v_r: **Stellar radial velocity**
    - v_g: **Gravitational redshift**
- Cannot be separated for a single, non-binary WD



Falcon et al. (2010), *ApJ*, **712**, 585

Gravitational redshifts provide a way to measure a *mean* mass

- Apparent velocity has 2 components
  - $\langle v_{app} \rangle = \cancel{\langle v_r \rangle}^{\,0} + \langle v_g \rangle$
- For a nearby, co-moving sample, space velocities are random

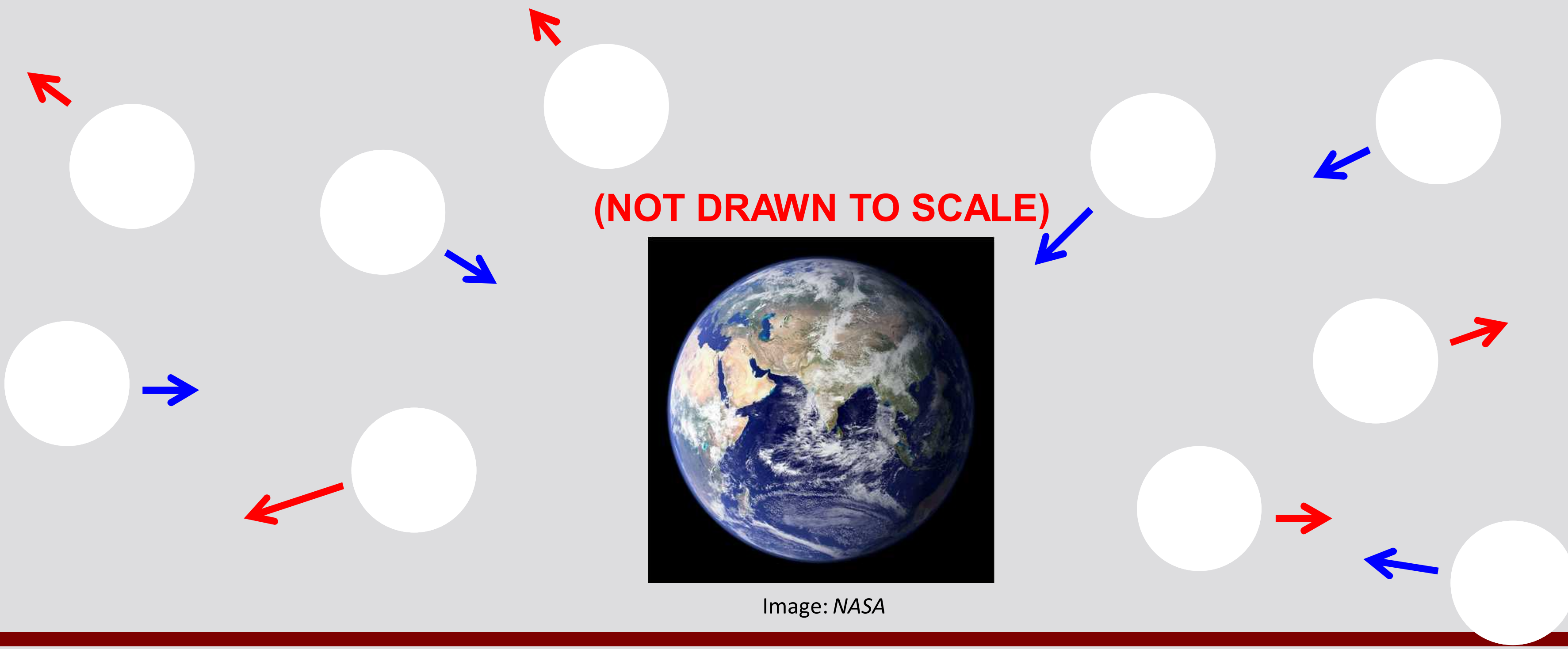
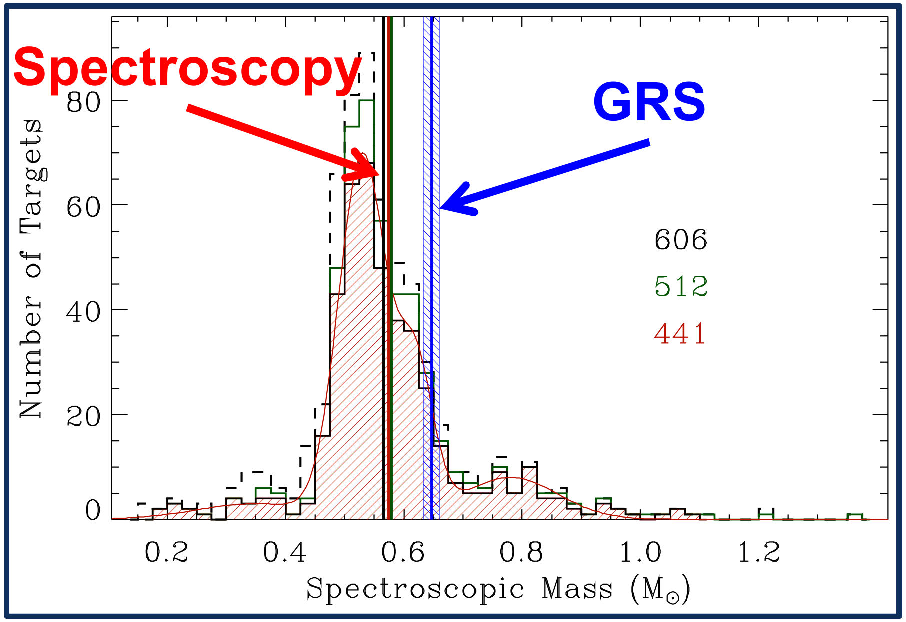


Image: *NASA*

Mean mass from gravitational redshift disagrees with the spectroscopic method

- Gravitational-redshift (GRS) method independent from line profiles
- GRS
  - <*M*> = 0.649 +/- 0.014 M_{Sun}
  - 449 DA stars
- Spectroscopy
  - <*M*> = 0.575 +/- 0.002 M_{Sun} using VCS profiles
  - <*M*> ~ 0.61 M_{Sun} using TB profiles
  - 441 DA stars

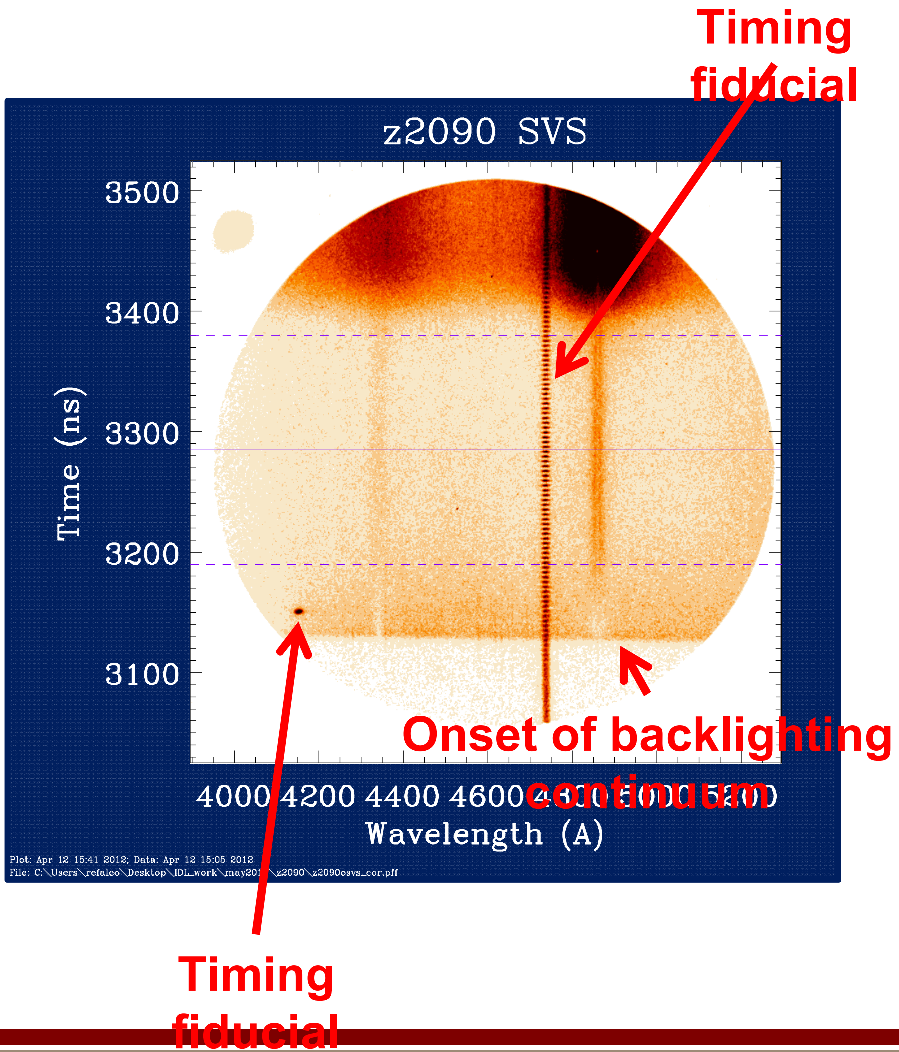


Falcon et al. (2010), *ApJ*, **712**, 585

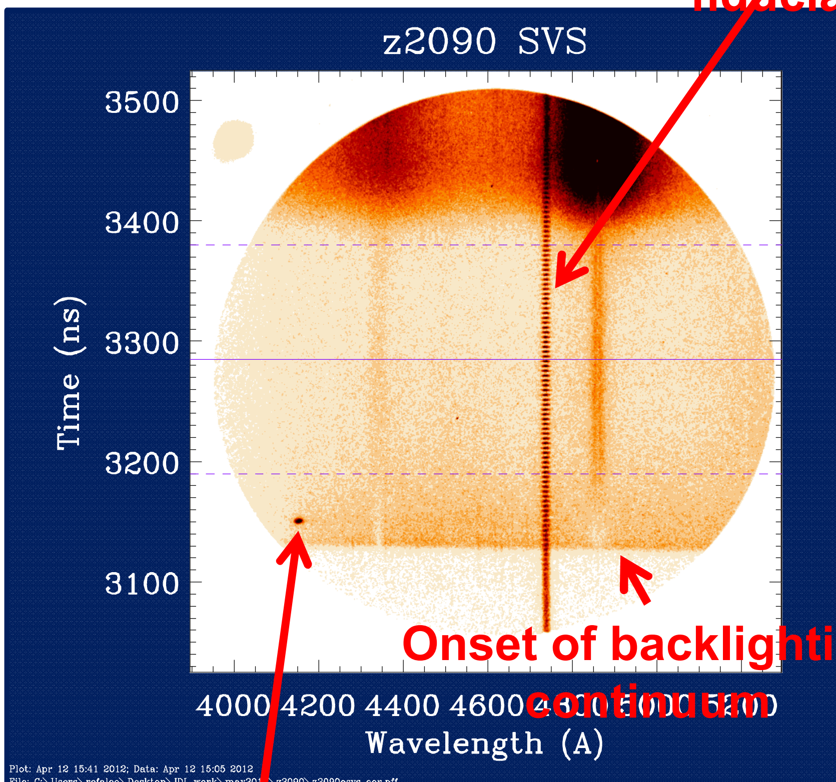
What does such an experiment require?

- Relevant plasma conditions
  - Composition
  - Electron density
  - Temperature
- Large plasma
  - Observe long line of sight to achieve optical depths
  - Stationary or non-dynamic; steady
  - Homogeneous (minimal gradients in plasma conditions)
- Measure multiple Balmer lines

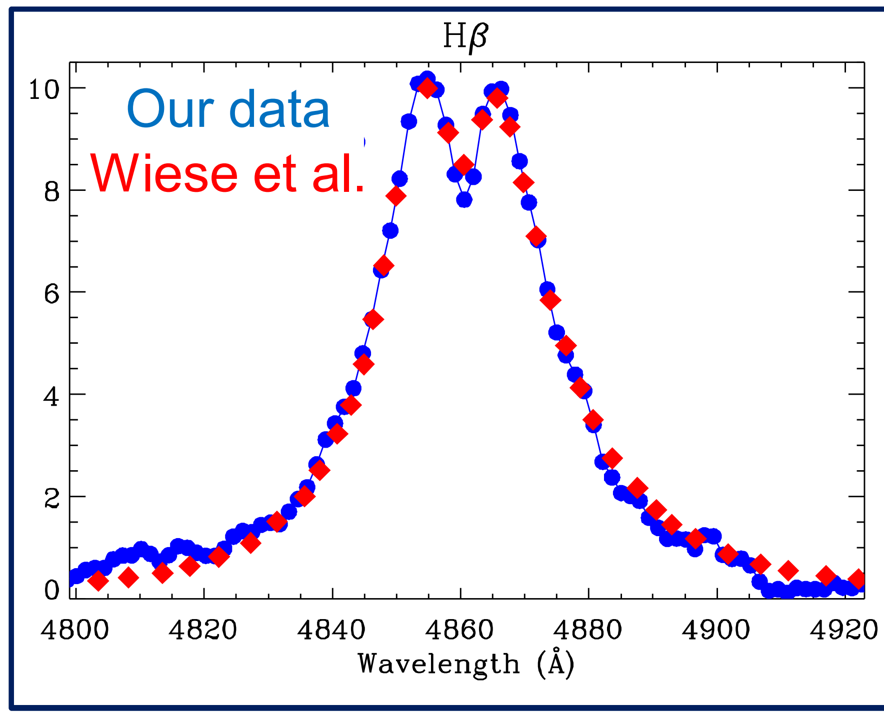
Time-resolved optical spectroscopy shows that our plasma is steady in time



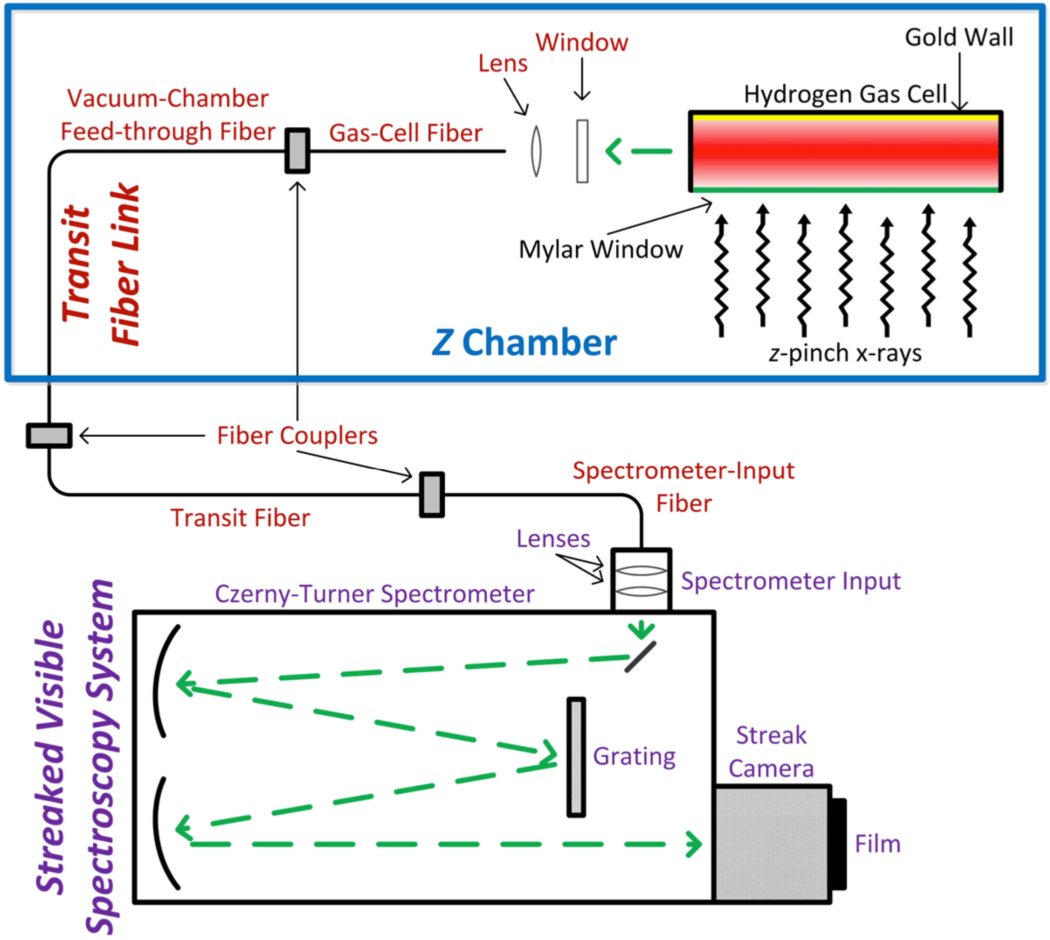
Hβ-emission-line agreement with Wiese et al. shows we achieve desired conditions



n_e = 5.7e16 cm^{-3}

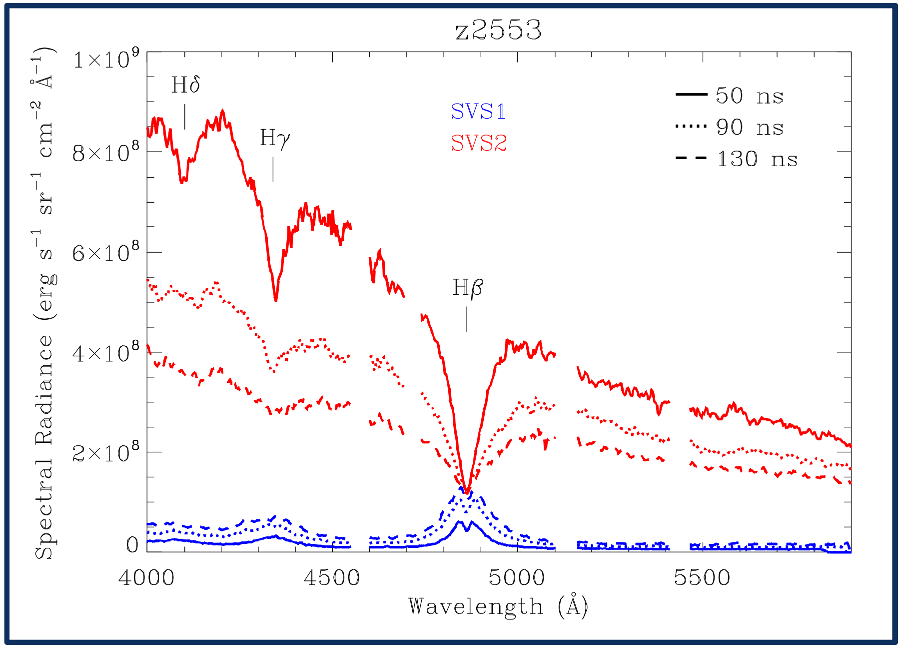


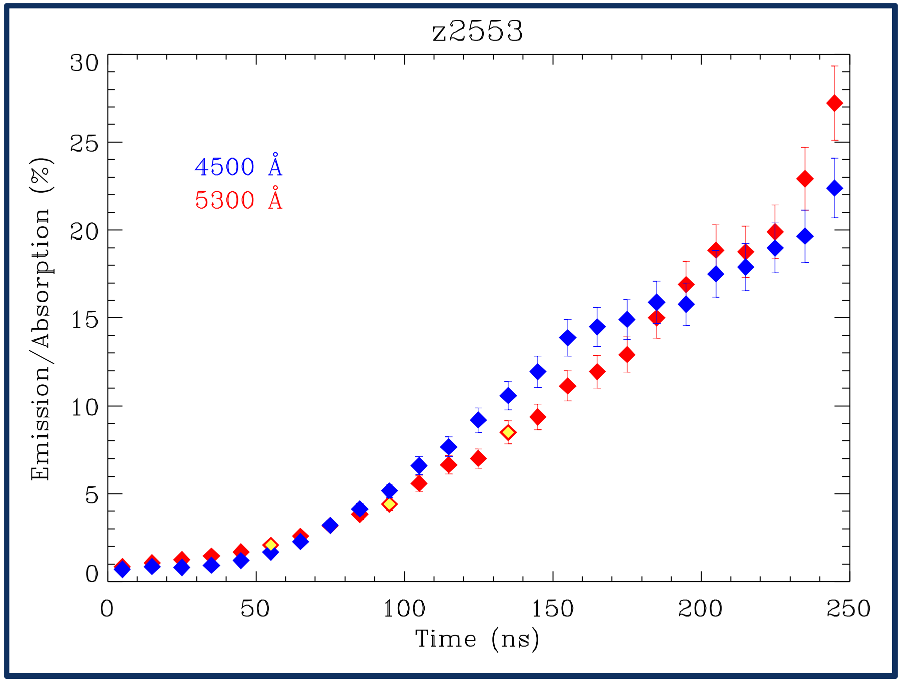
Combining data from multiple spectrometer systems requires calibrations



- Correct data for:
  - Wavelength-dependent instrumental efficiency
  - Light attenuation during transit from experiment (gas cell)
  - Observed geometry within gas cell

Importance of emission correction increases as backlighter cools



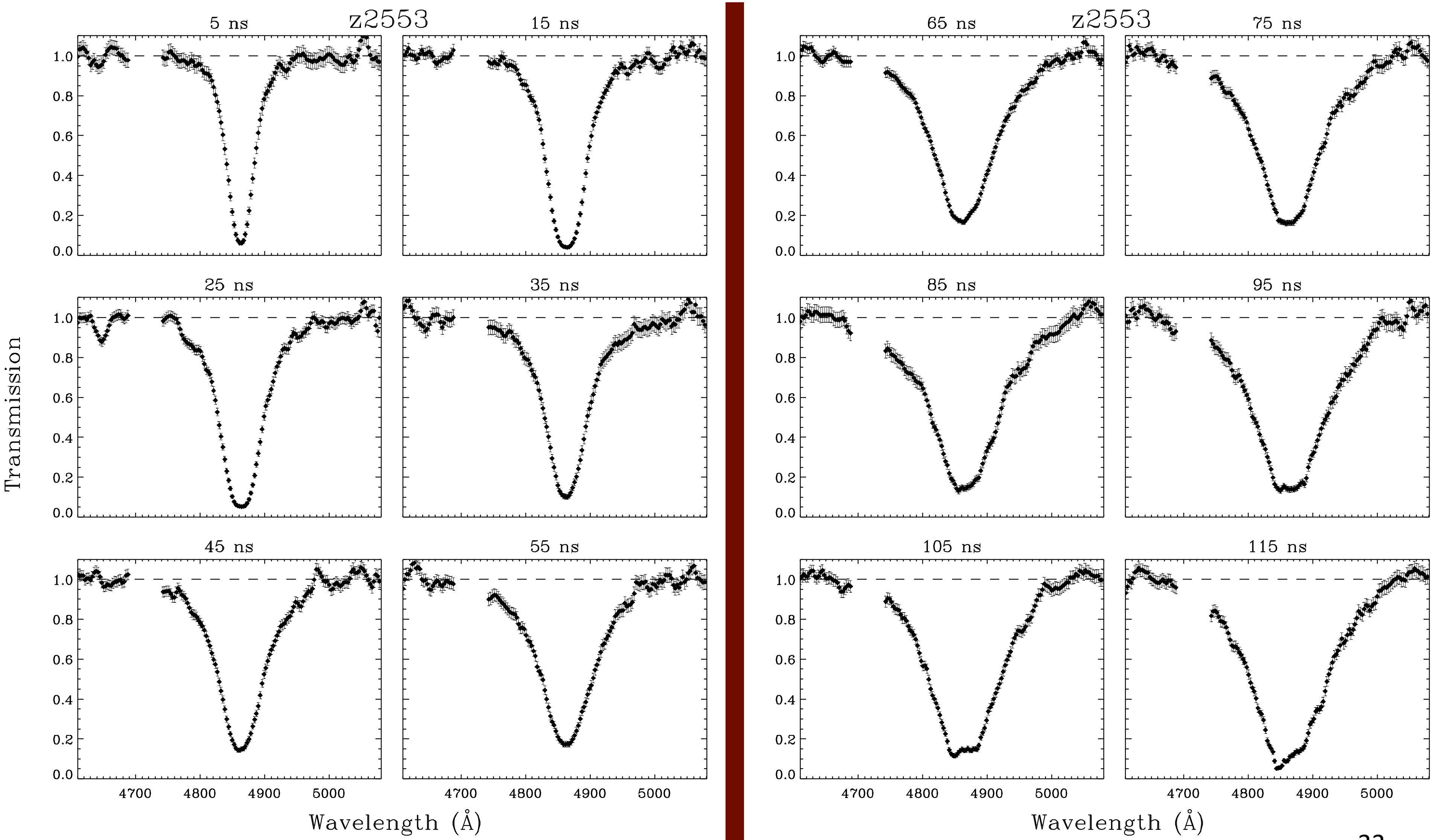


- Most significant for Hβ line

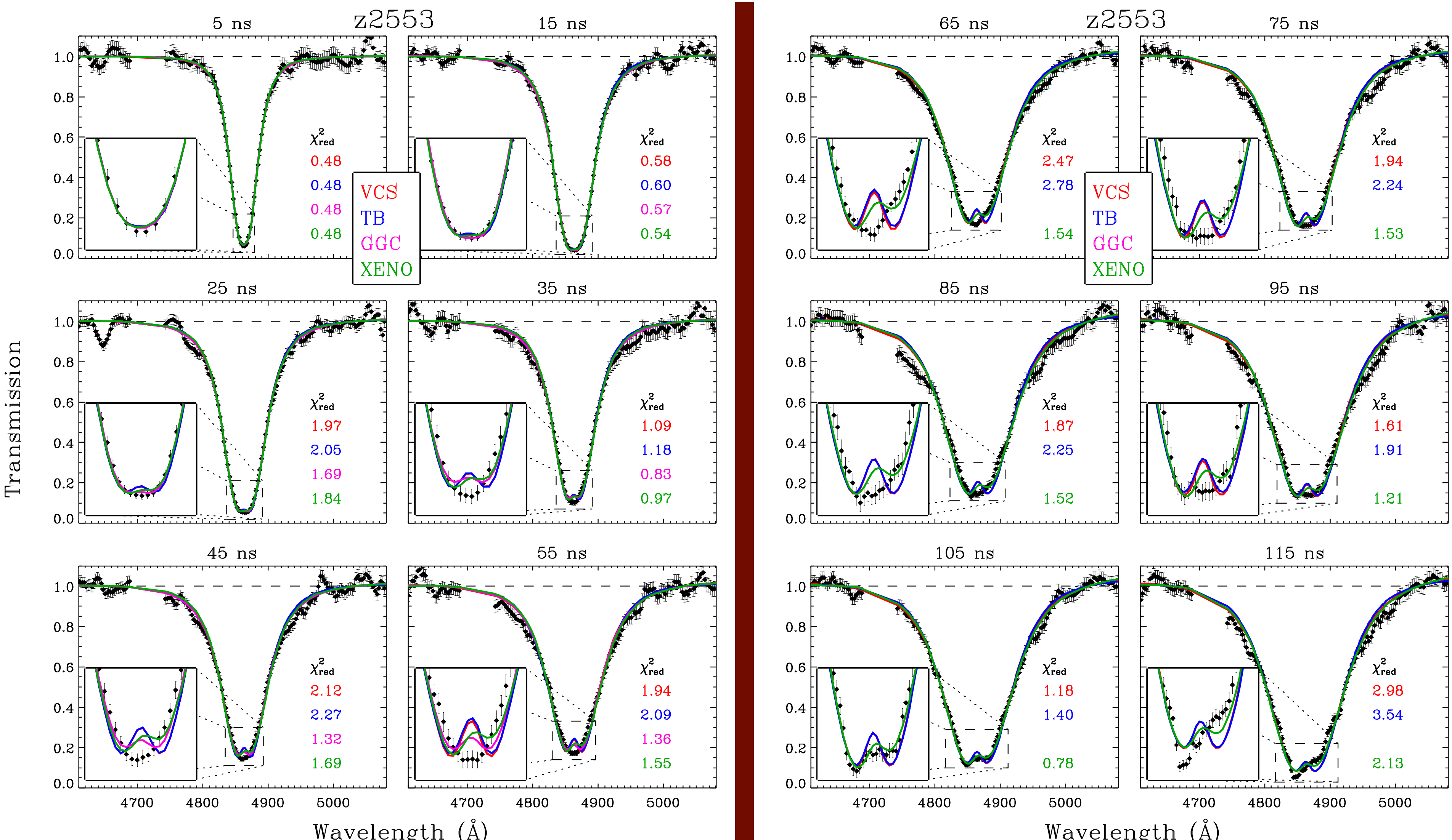
Falcon (2014), PhD Thesis

We measure and fit the Hβ transmission line throughout the duration of our experiment

Sandia National Laboratories



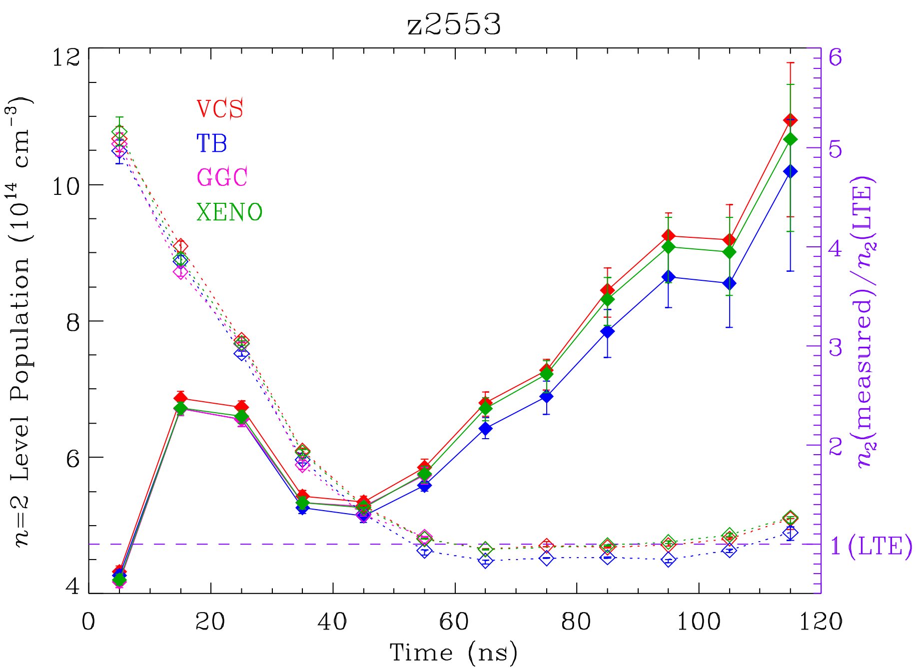
We measure and fit the Hβ transmission line throughout the duration of our experiment

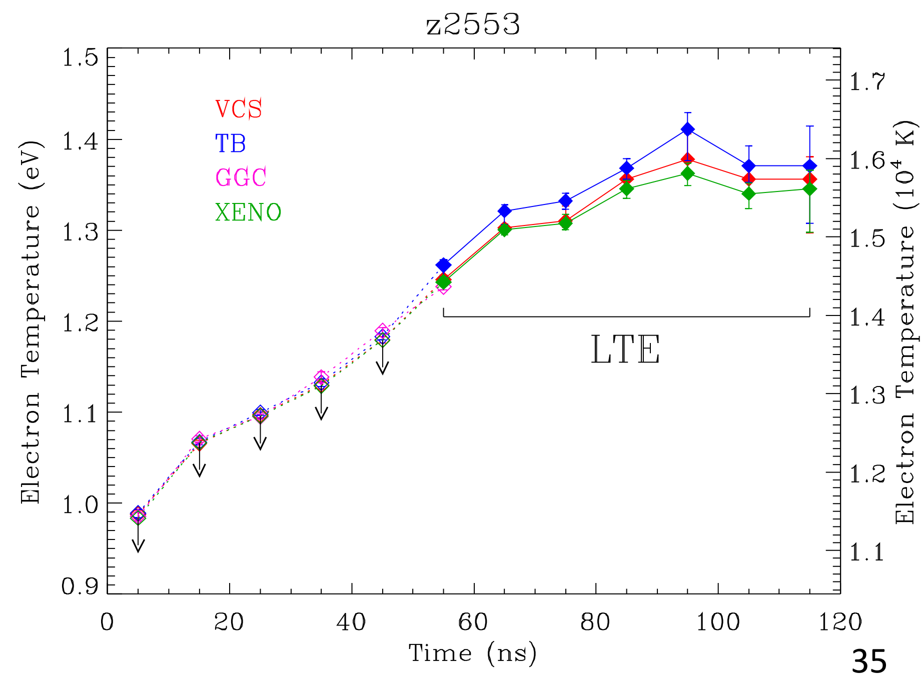


Falcon et al. (2015), *ApJ*, **806**, 214

Our diagnosis continues

- Lower (n = 2) level population, n_2, allows us to infer electron temperature, T_e
  - Measured line strength includes a measurement of occupation probabilities!
- We witness our plasma relax into LTE





Falcon et al. (2015), *ApJ*, **806**, 214

Our experimental platform can explore other compositions relevant to other WD atmospheres

- Molecular carbon (C_2) features are observed in cool-DQ spectra (e.g., Dufour et al. 2005)

- Preliminary experimental data
  - Not "flux"-calibrated
  - C_2 and CH features
  - Recombining plasma