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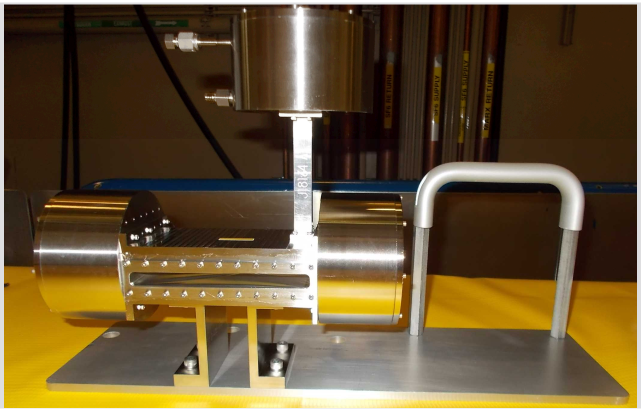
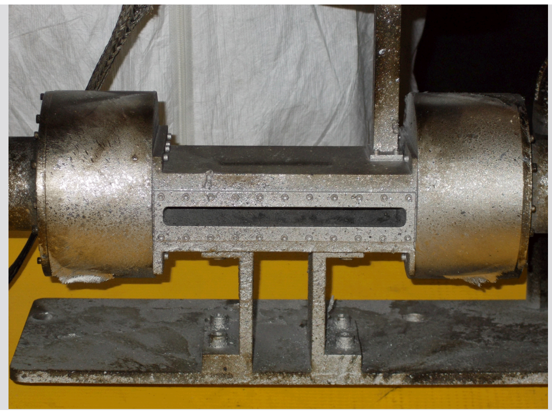


Laboratory White Dwarf Photospheres

Ross E. Falcon

Current Challenges on the Physics of White Dwarf Stars
Santa Fe, NM
2017.06.15

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Our project is a collaboration between national lab and university

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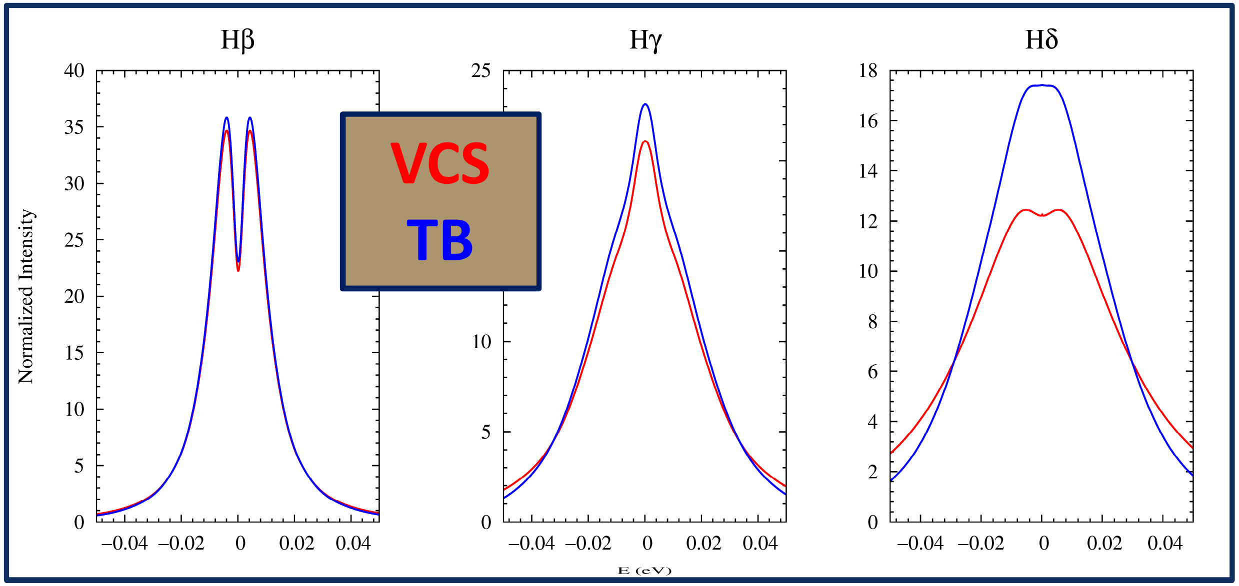
Line profiles used in white dwarf (WD) atmosphere models are very *precise*, but are they *accurate*?

- Precision of the *spectroscopic method* (see, e.g., Bergeron et al. 1992):
  - Effective temperature ($\delta T_{eff}/T_{eff}$) ~ 5%
  - Surface gravity ($\delta \log g/\log g$) ~ 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:
    - ΔT_{eff} ~ 200—1000 K
    - $\Delta \log g$ ~ 0.04—0.1
    - ΔM ~ 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



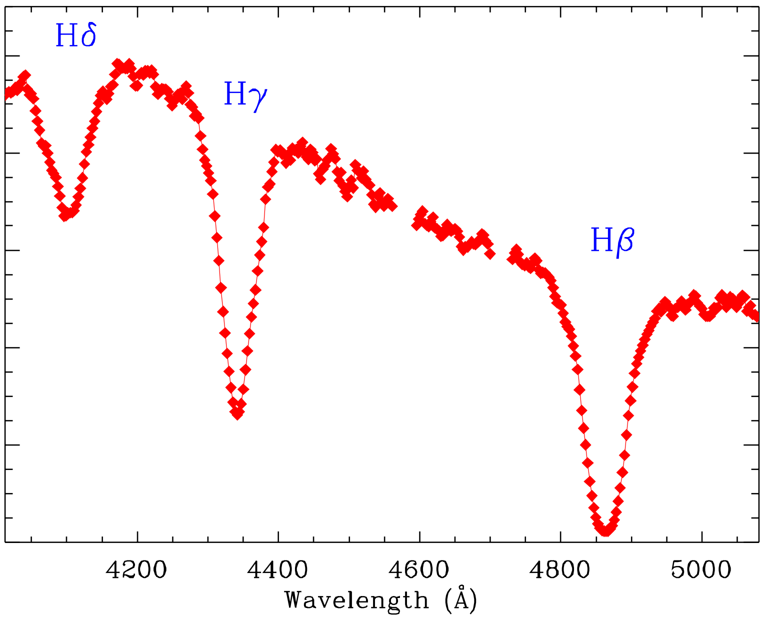
Calculated at T_e = 1 eV and n_e = 10^{17} cm^{-3}

We can test these line shapes in the laboratory

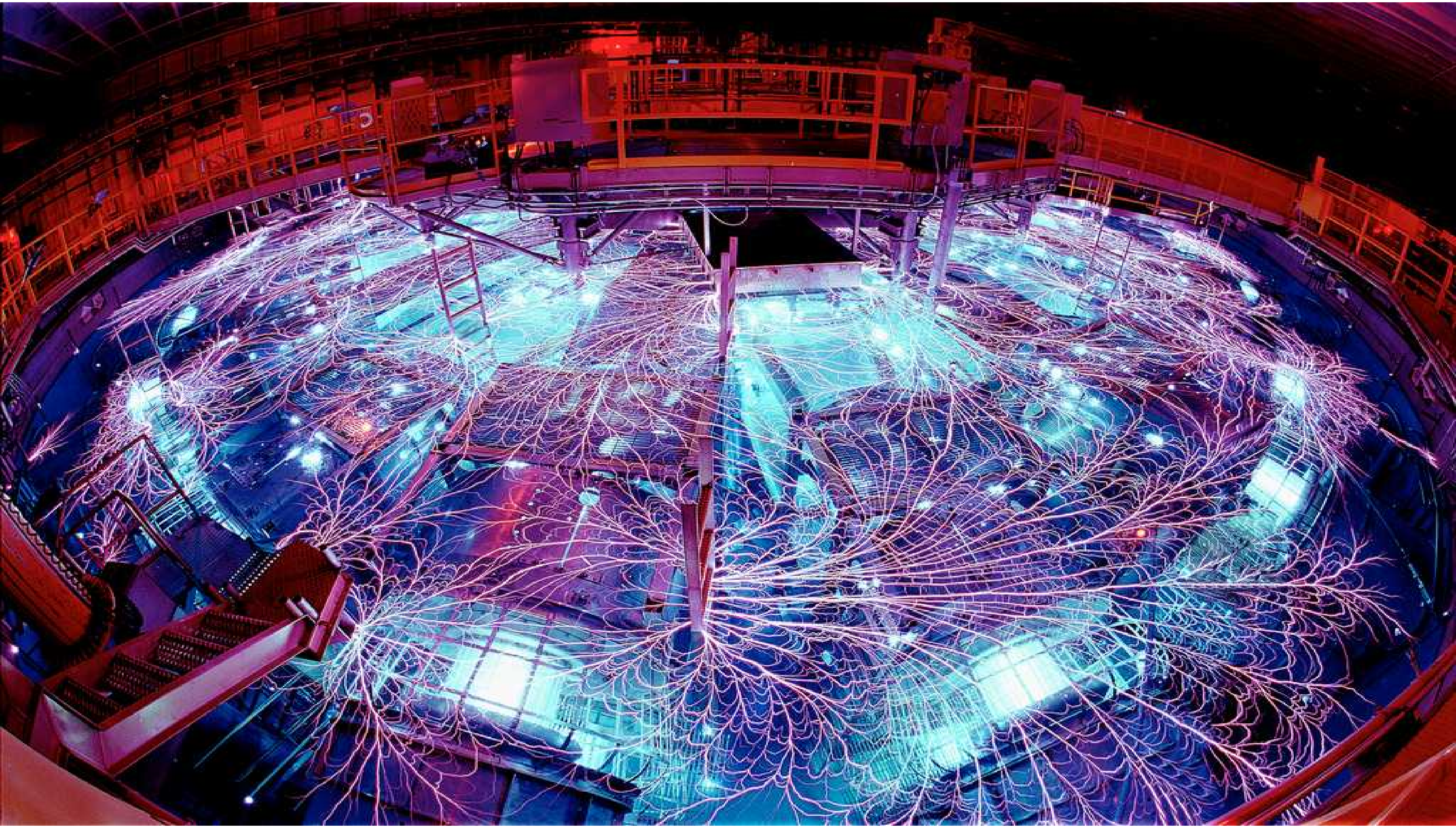
- Measure *multiple* H Balmer lines *simultaneously* at a range of electron density, n_e
  - Use Hβ to diagnose plasma conditions; experimentally validated (Kellerher et al. 1993)
  - Include up to at least Hδ
- Use Wiese et al. (1972) to validate (n_e < 10^{17} cm^{-3}), then extend to higher n_e (> 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

Summary: we extend our experimental platform to measure WD plasmas at higher electron densities than previously measured

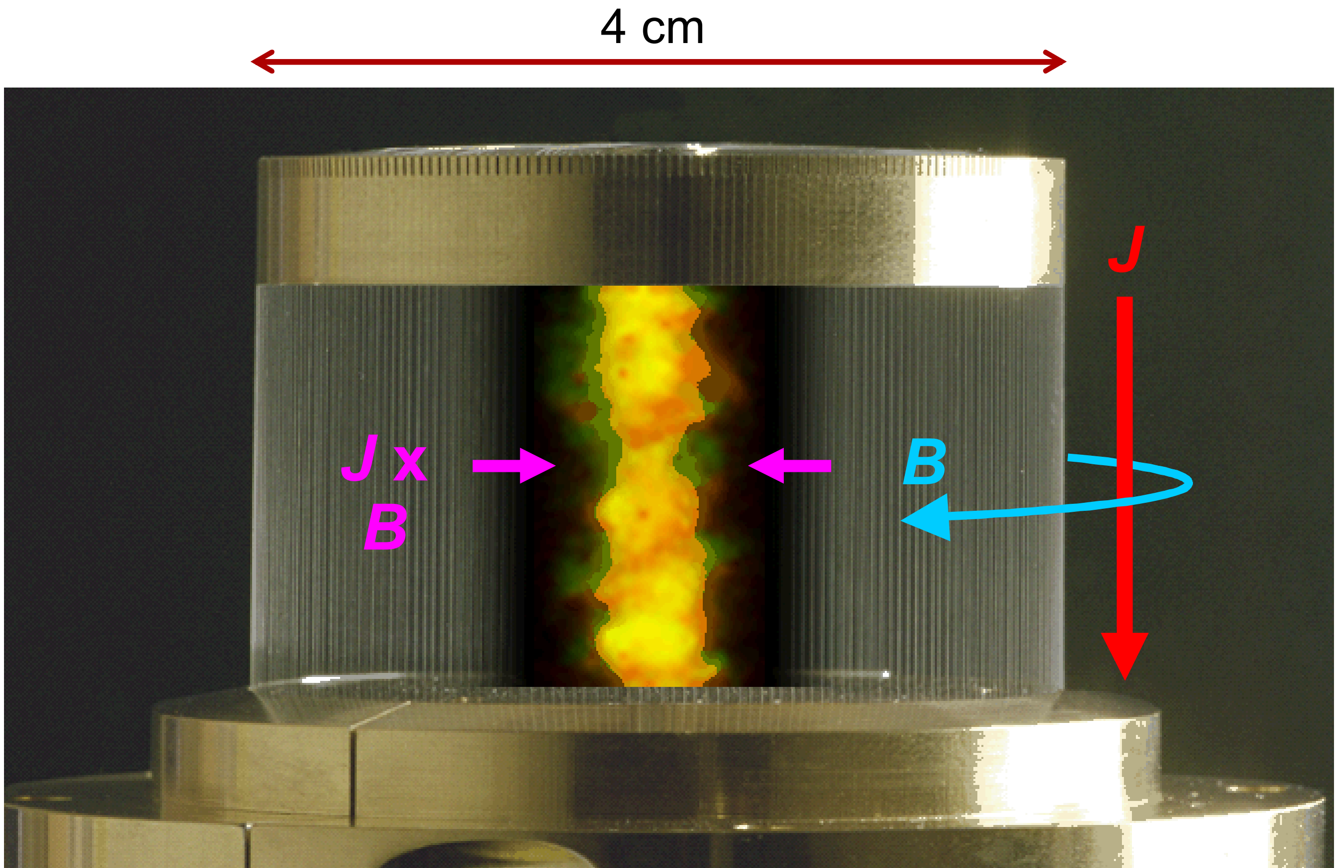
- At these higher electron densities, Hβ as a diagnostic now disagrees between theories
- Our measured line profiles of Hγ and Hβ show relative disagreement with the theoretical profiles
  - *Shape*
  - *Strength* (occupation probability)



Welcome to the Z Pulsed Power Accelerator



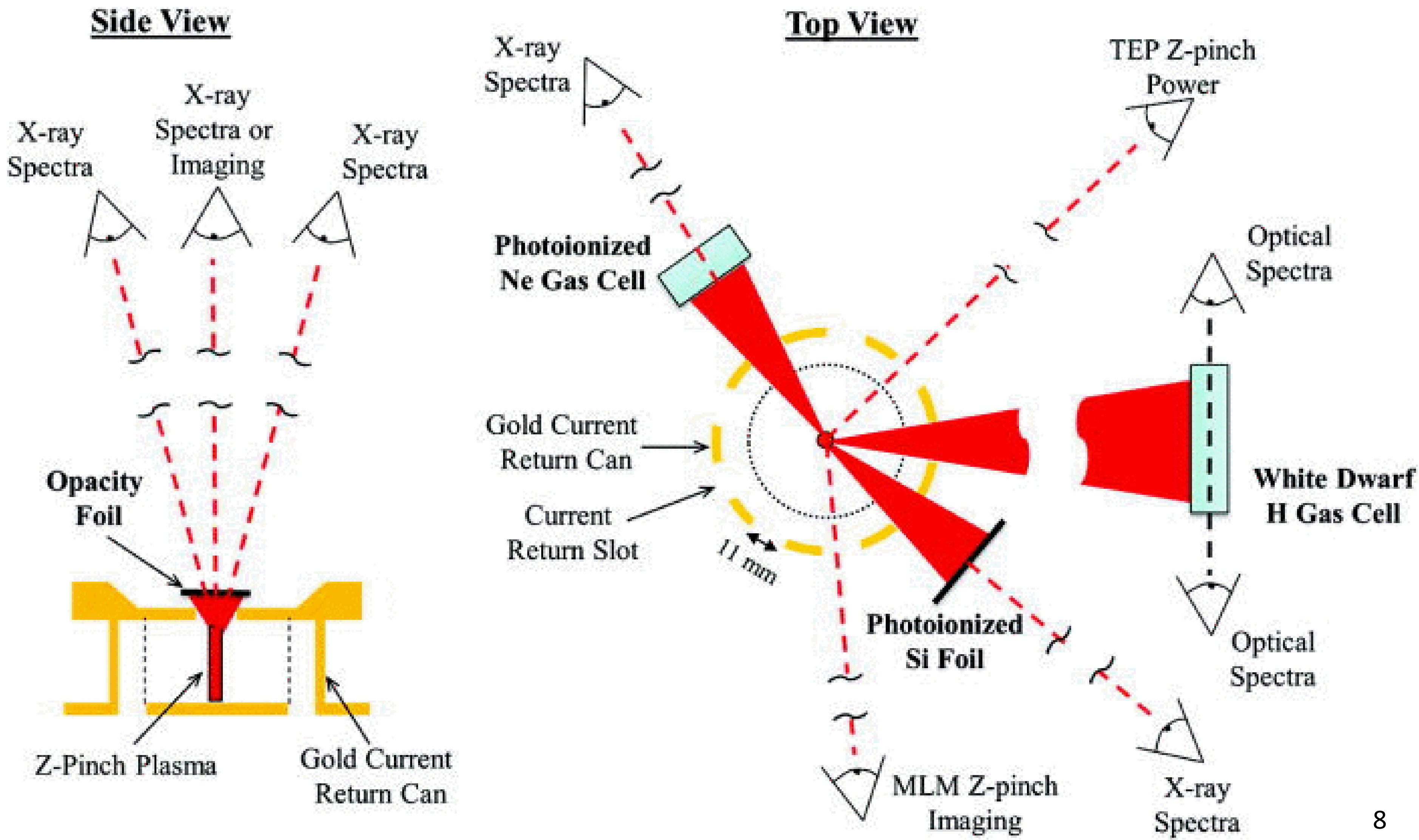
Z Accelerator uses 27 million Amperes to create x-rays



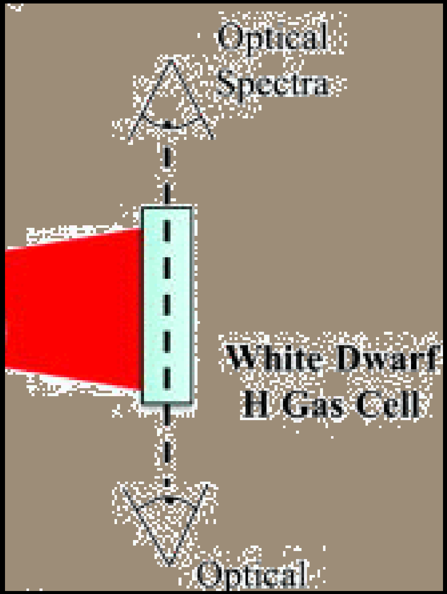
$P_{rad} \lesssim 330$ TW, $Y_{rad} \lesssim 2$ MJ

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

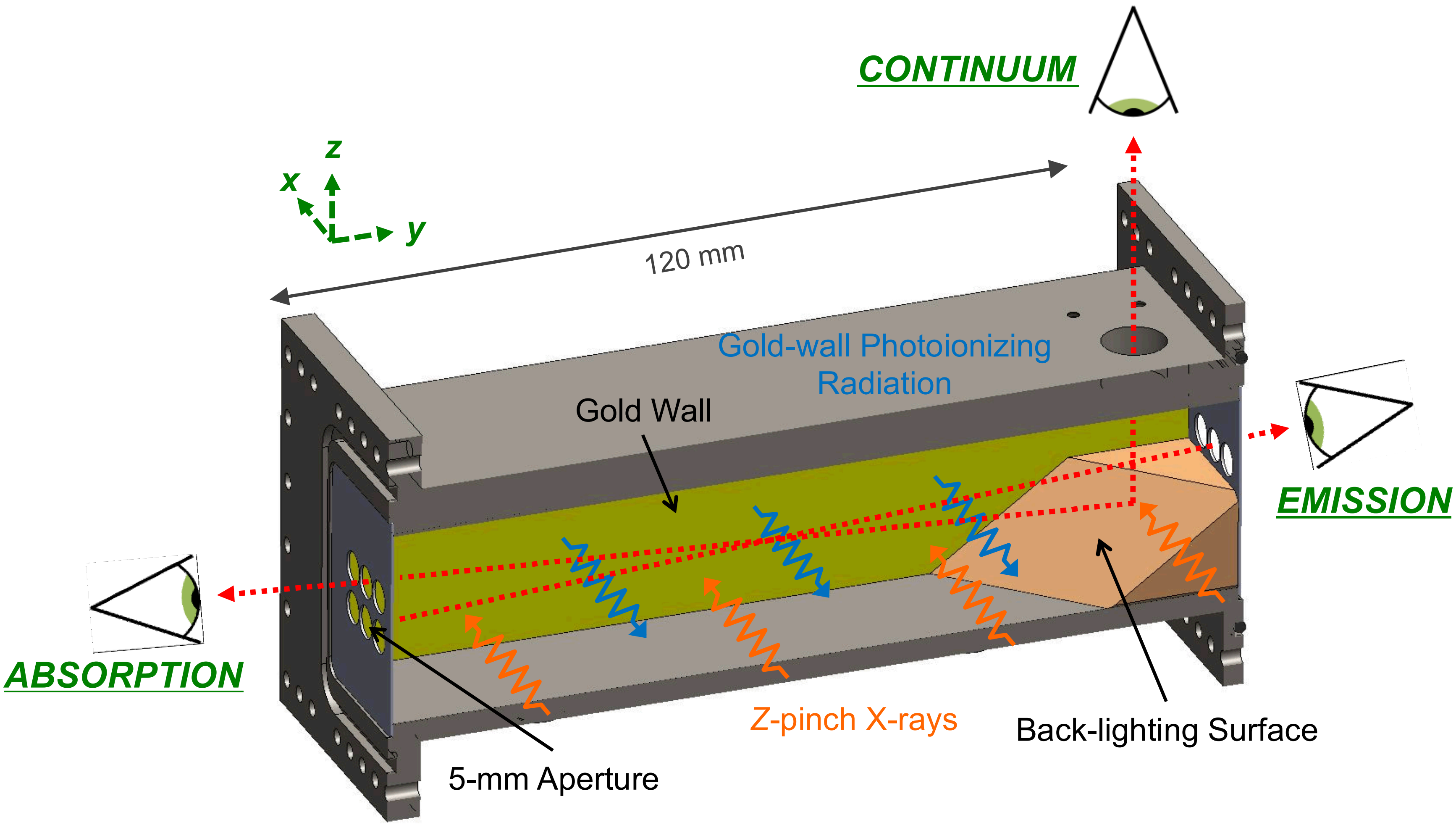


Rochau et al. (2014), *PoP*, **21**, 056308



Optical
Spectra
White Dwarf
H Gas Cell
Optical

Observe plasma along 3 lines of sight

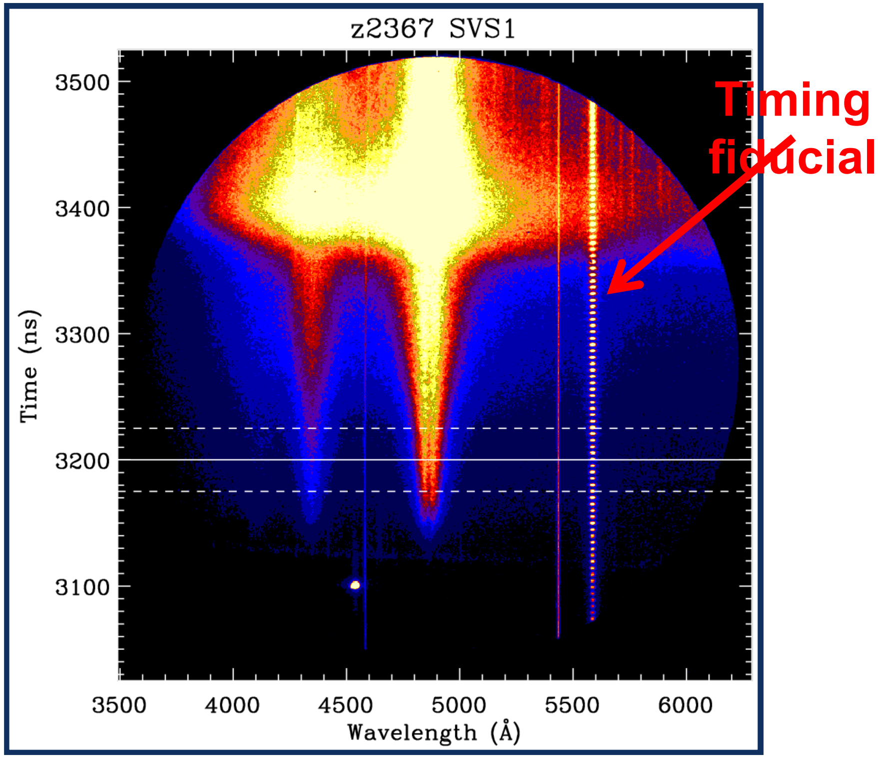


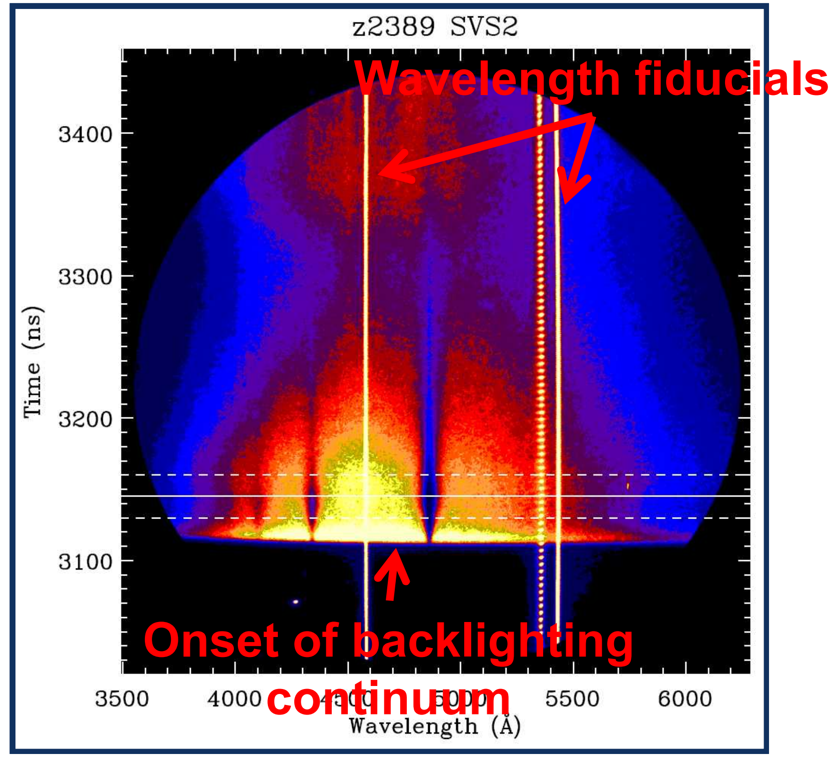
Falcon et al. (2015), *ApJ*, **806**, 214

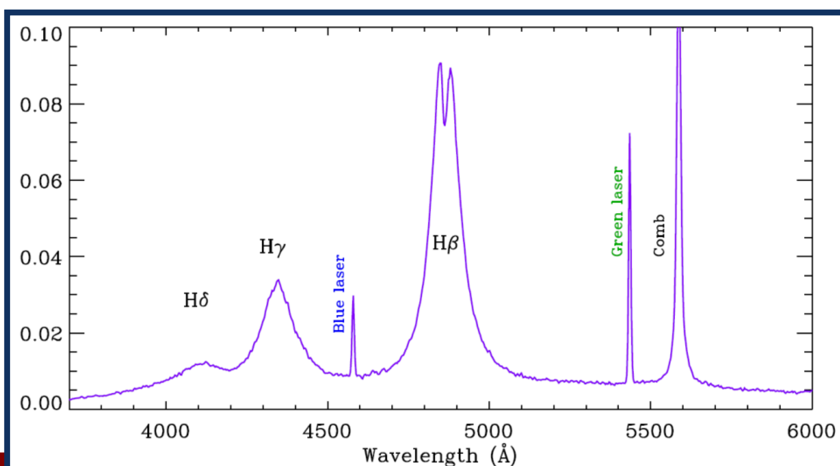
Emission

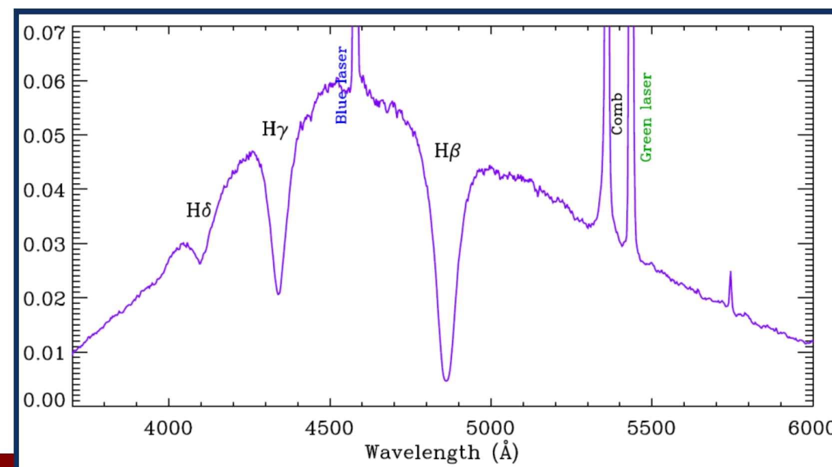
Absorption

Time



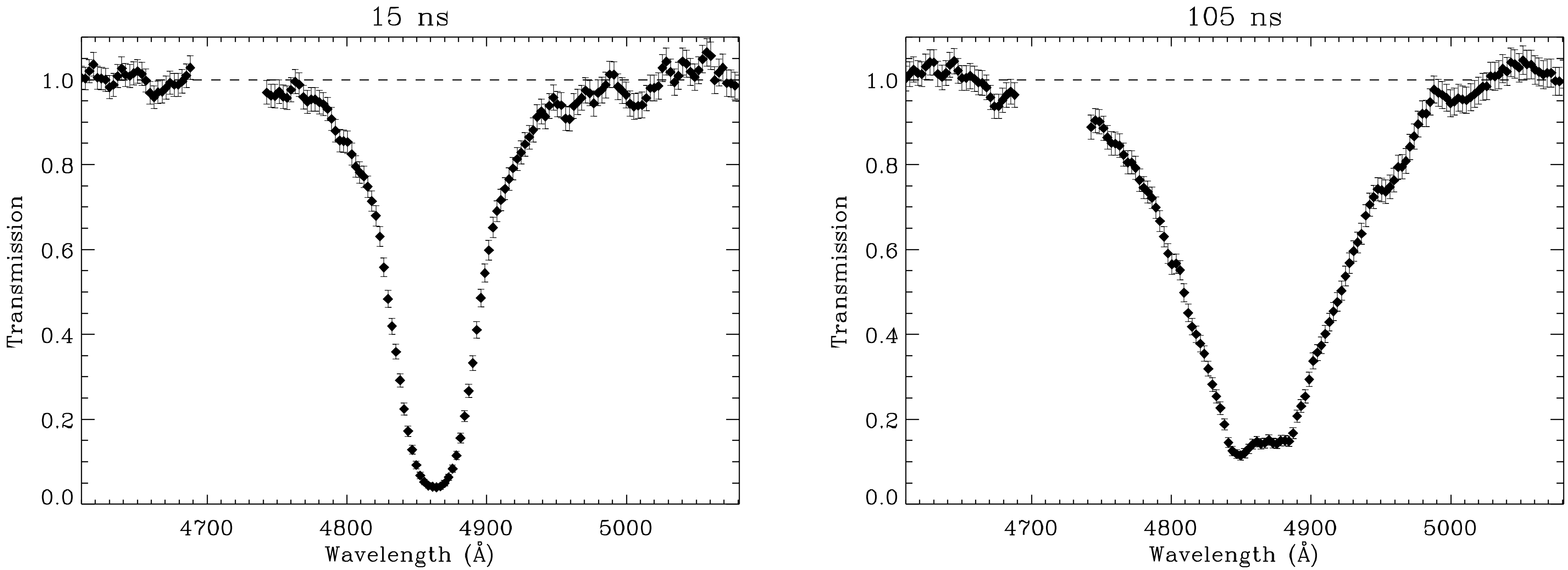






We **measure** and fit the Hβ transmission line throughout the duration of our experiment

- Measured profile widens and develops more structure with time



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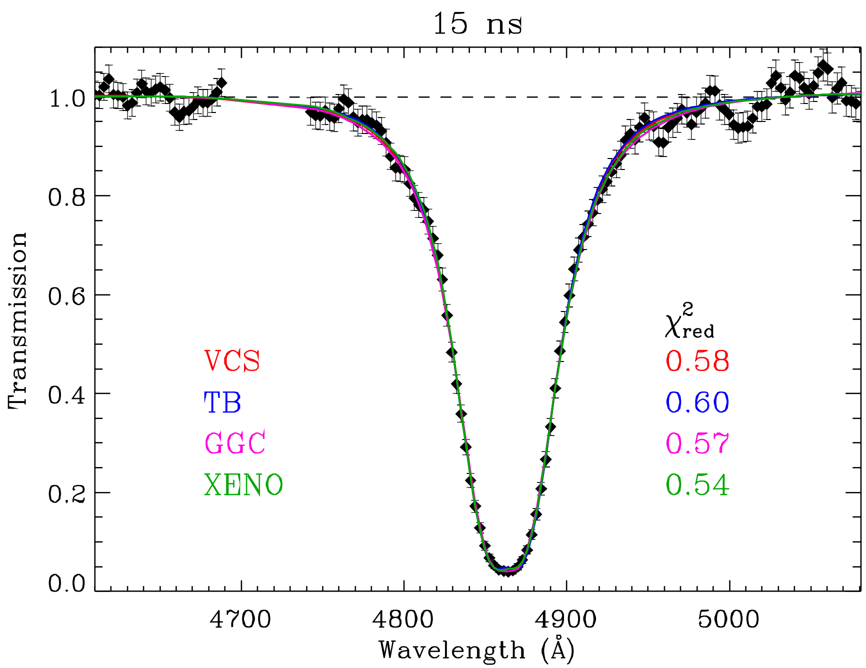
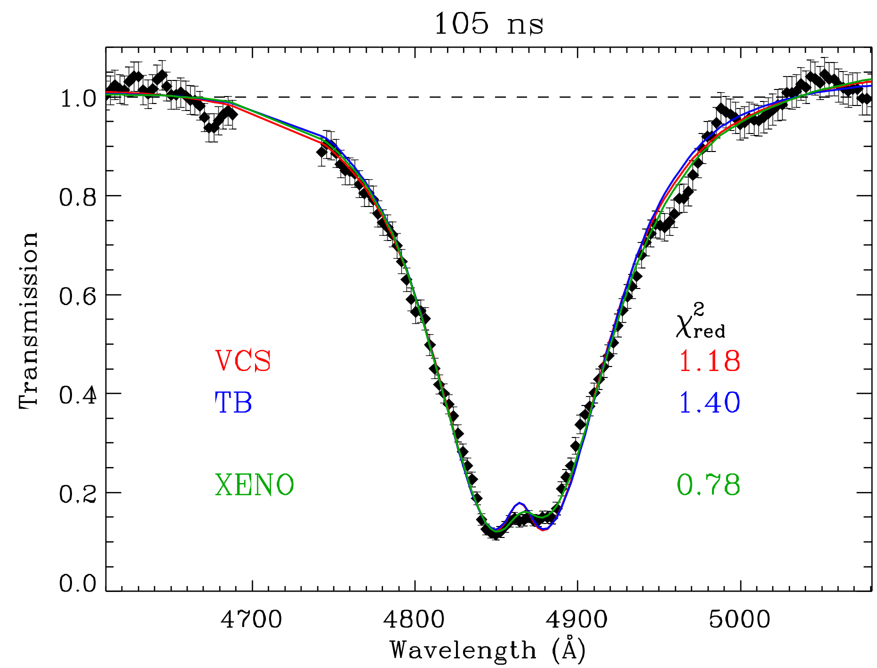
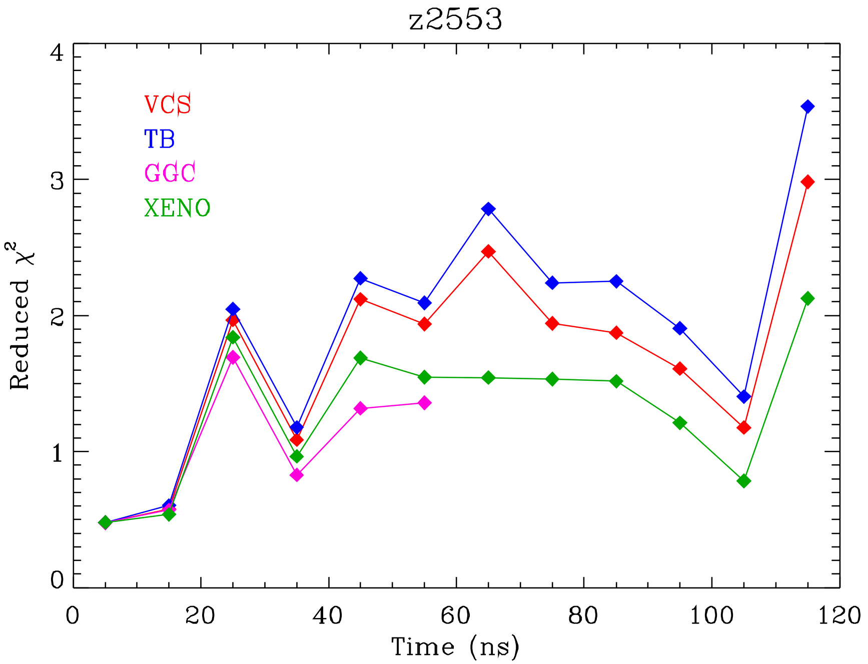




- Theoretical line-profile theories used
  - Vidal, Cooper & Smith (1973, **VCS**)
  - Tremblay & Bergeron (2009, **TB**)
  - Gigosos et al. (2003, **GGC**)
  - Gomez et al. (Xenomorph or **XENO**)

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

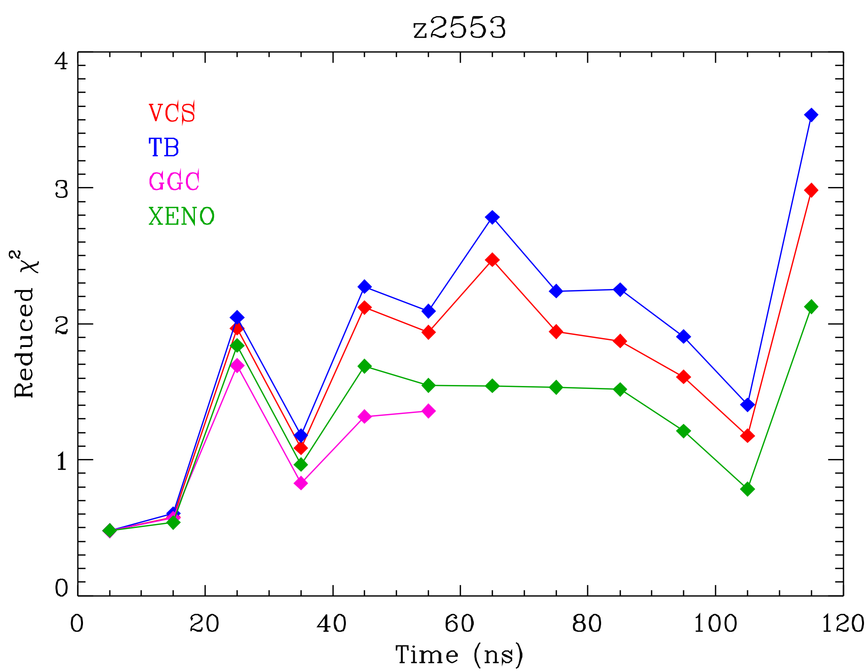
- VCS and now TB used in WD astronomy community
- What else is there?
  - Computer-simulated calculations
  - i.e., Gigosos et al. (2003, GGC), Gomez et al. (Xenomorph)

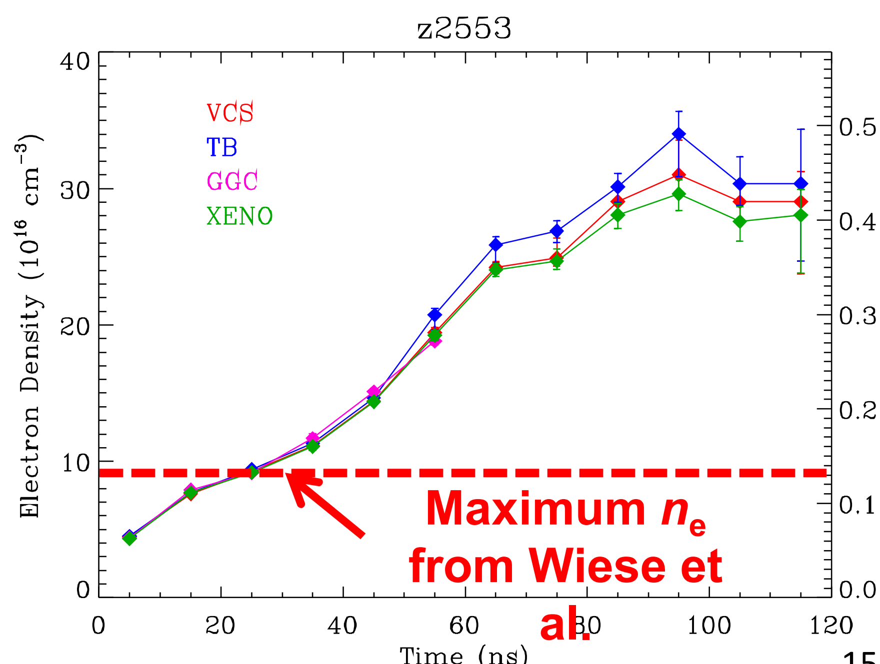


Falcon et al. (2015), *ApJ*, **806**, 214

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

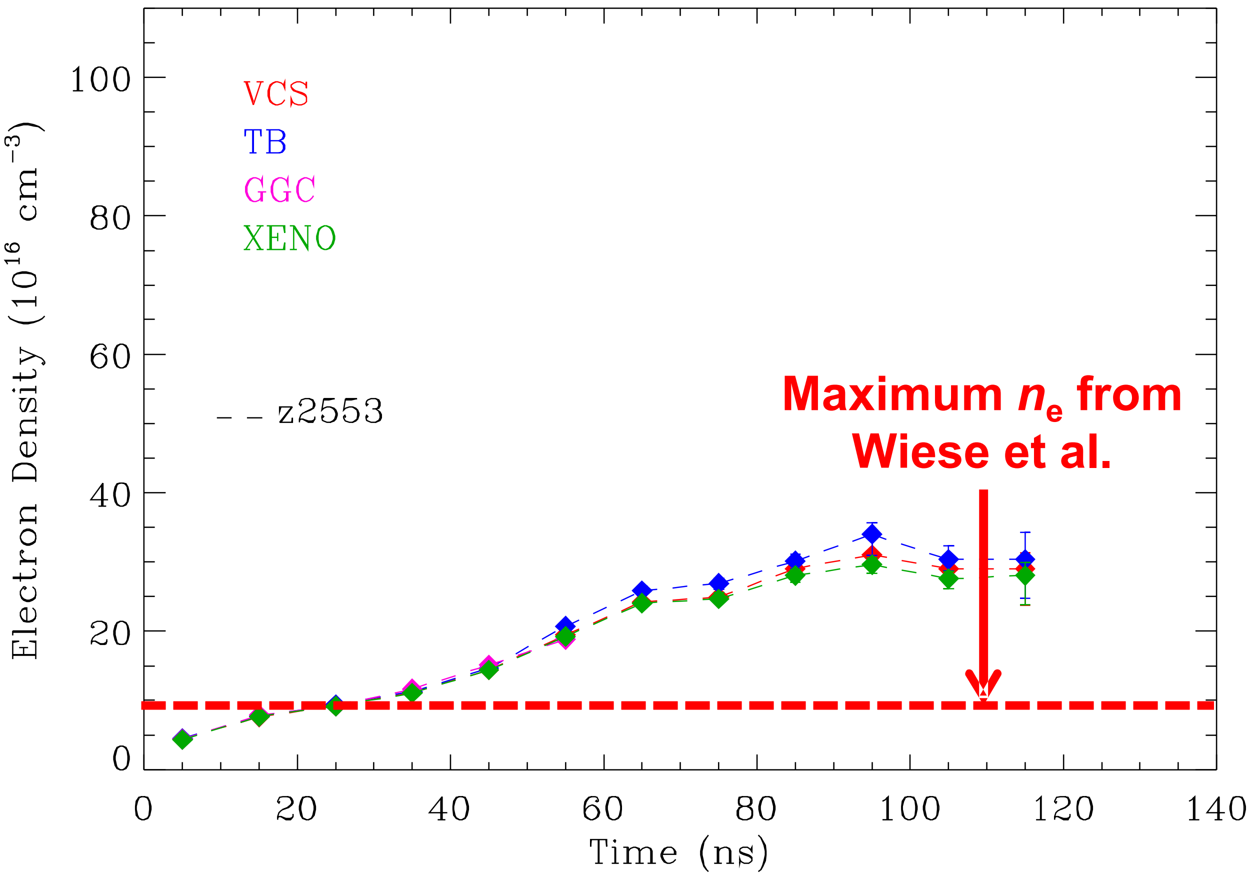
- VCS and now TB used in WD astronomy community
- What else is there?
  - Computer-simulated calculations
  - i.e., Gigosos et al. (2003, GGC), Gomez et al. (Xenomorph)
- Agreement over a range of electron density (analogous to surface gravity) not previously tested



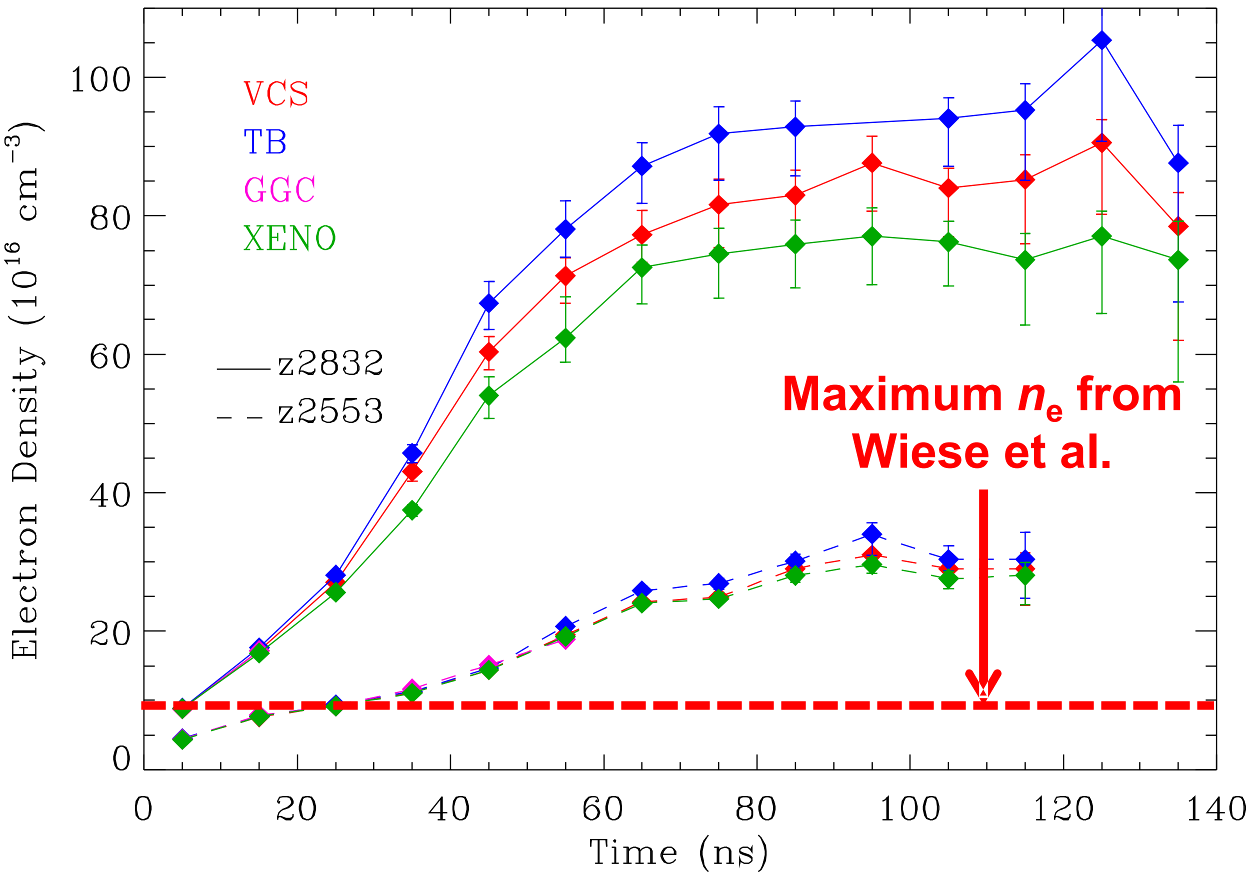


Falcon et al. (2015), *ApJ*, **806**, 214

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



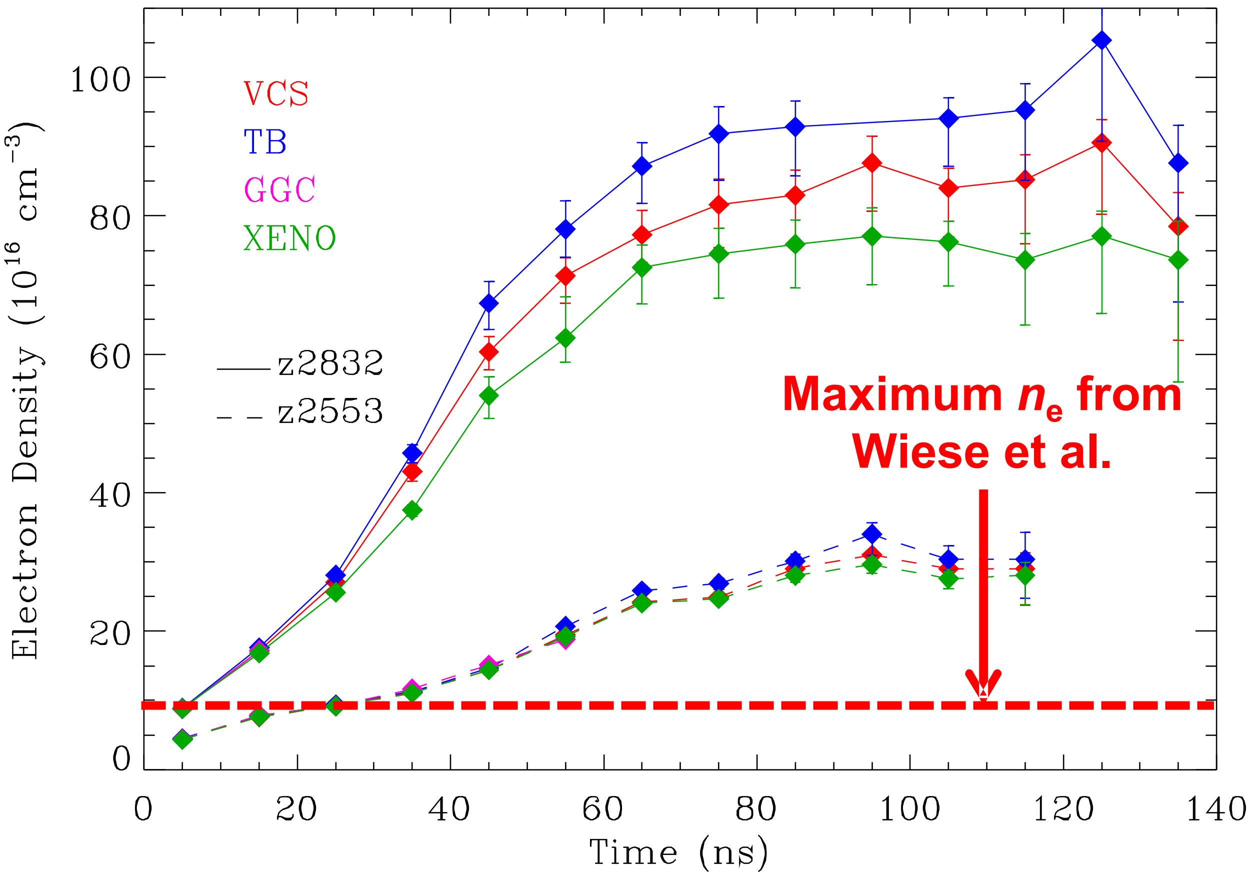
At ***higher*** electron densities, diagnosis from Hβ diverges between different line-shape theories



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

Falcon et al. (2017), *ASPC,* **509**, 149

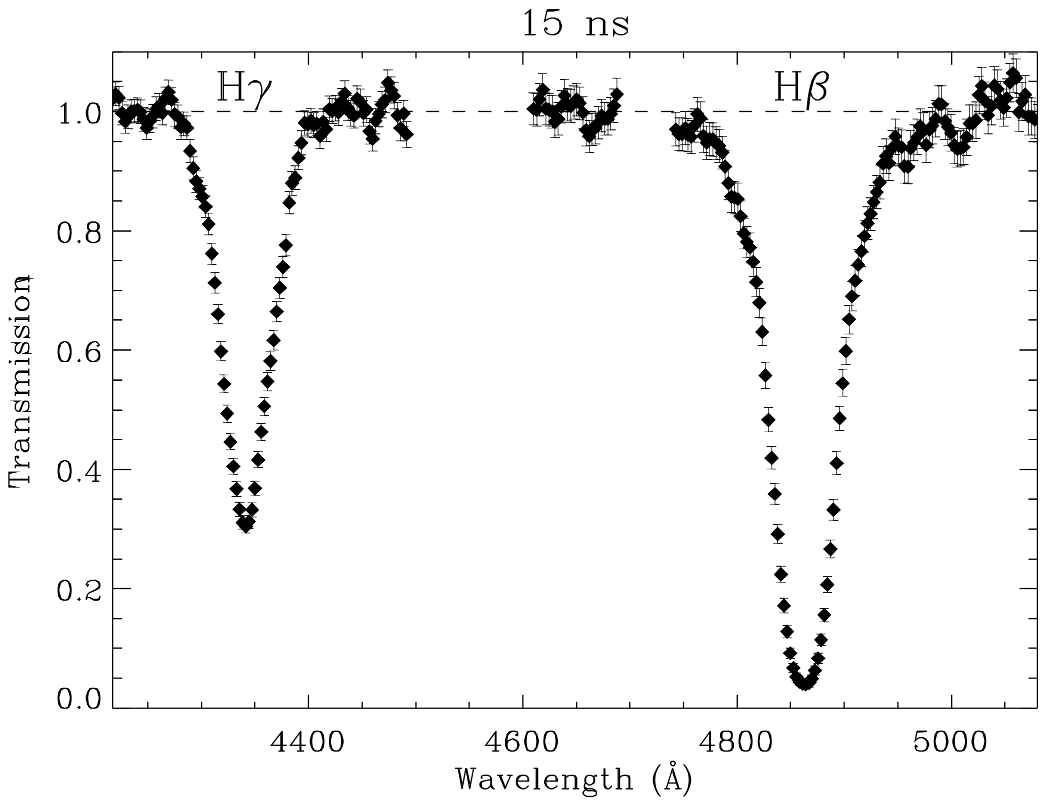
At ***higher*** electron densities, diagnosis from Hβ diverges between different line-shape theories



- 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
  - **Recent experiments measure helium and carbon**

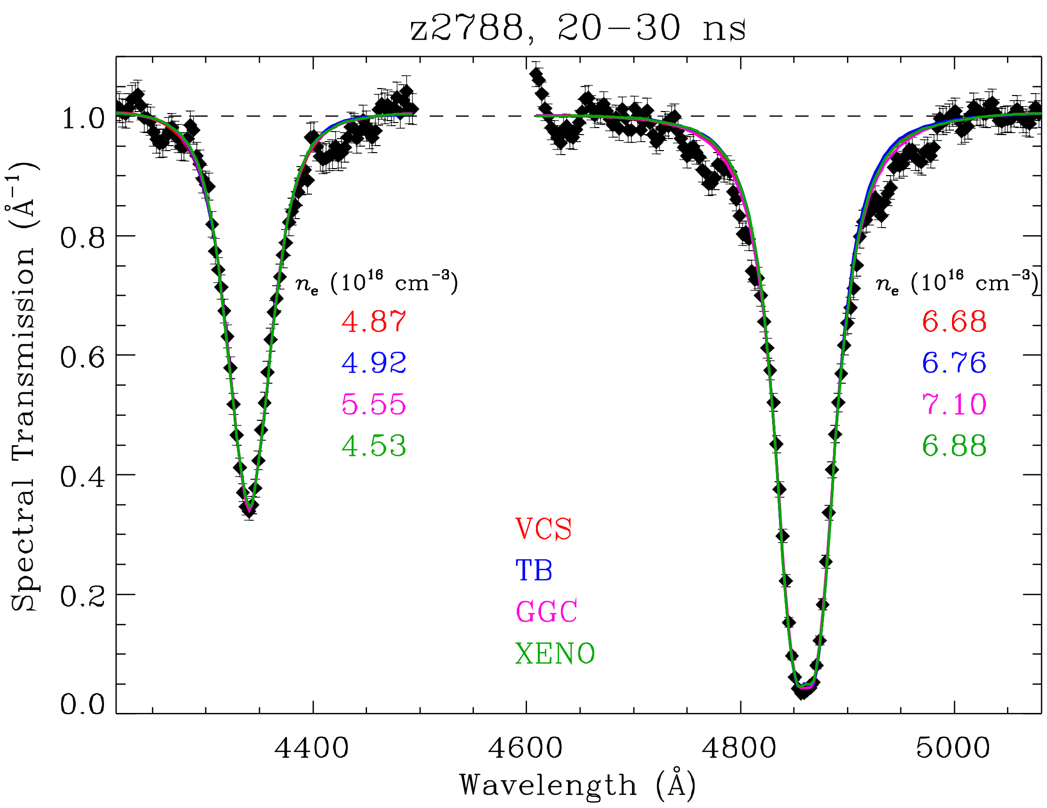
Falcon et al. (2017), *ASPC*, **509**, 149

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



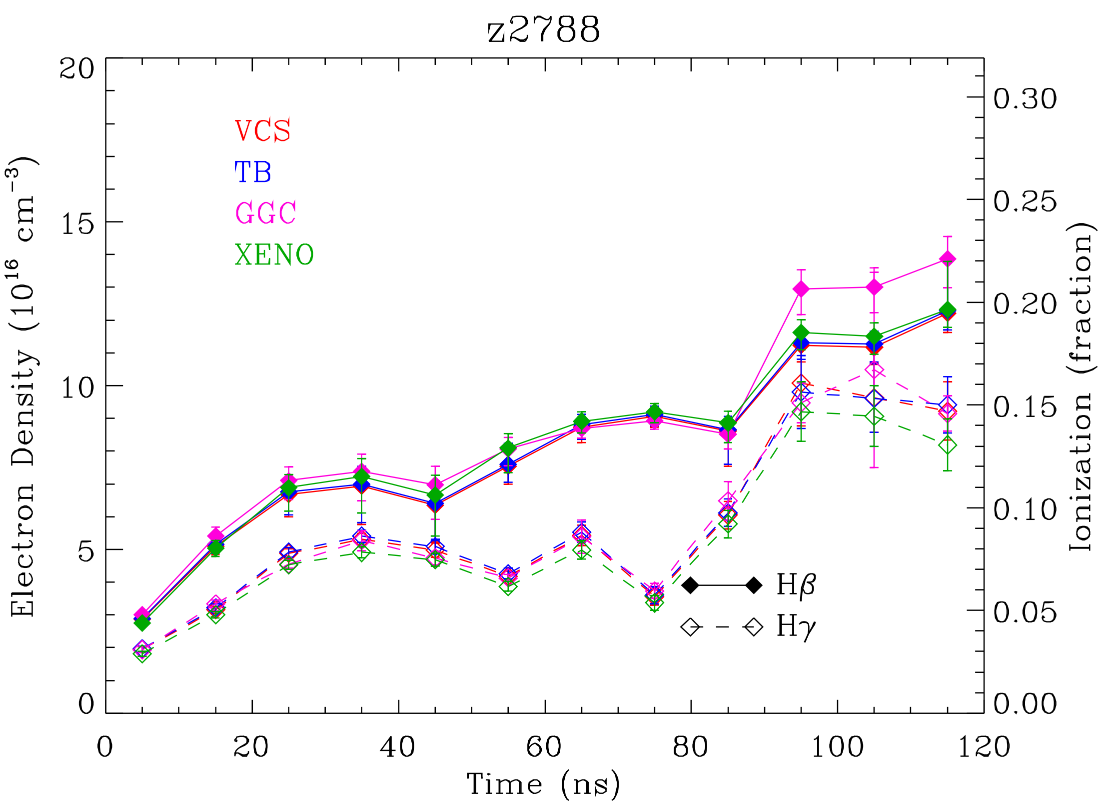
- We measure multiple spectral lines at the ***same*** time from the ***same*** plasma

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



- We measure multiple spectral lines at the ***same*** time from the ***same*** plasma
- Fits here are **not** simultaneous

Transmission fits for Hγ infer different electron densities than for Hβ



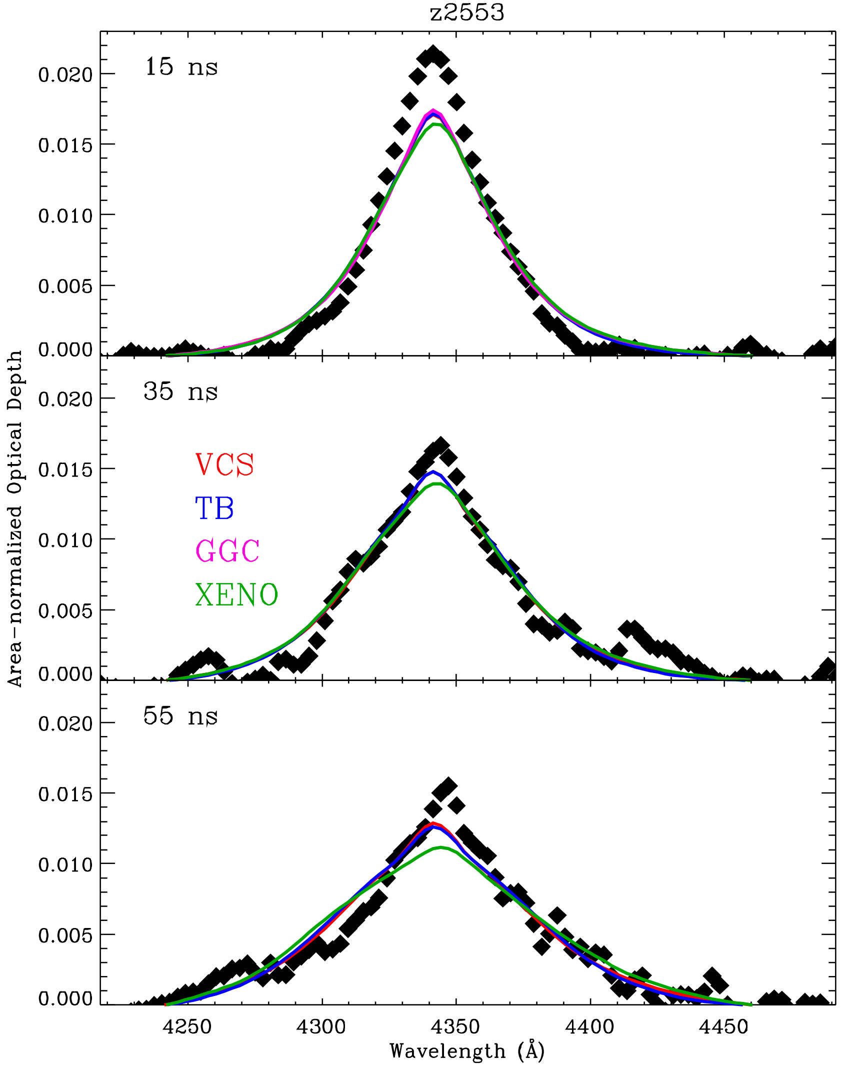
- BUT data are poorer for Hγ than for Hβ
  - Less signal (especially for emission data)
  - Fewer spectral points
- Need to confirm that emission-fitting technique is valid

Let us investigate measured **emission**

- Recall that we simultaneously measure both **absorption** and **emission** as part of our method to infer **transmission**

- Here I *overplot* the area-normalized ***measured*** (from z2553) Hɣ emission with the ***calculated*** Hɣ
  - Calculated using *transmission* fit parameters

- Definitely saw a difference in *shape*
  - I suspect due to spectral resolution (number of data points)



Let us confirm that my fitting method is valid by fitting the Wiese data (calibration standard)

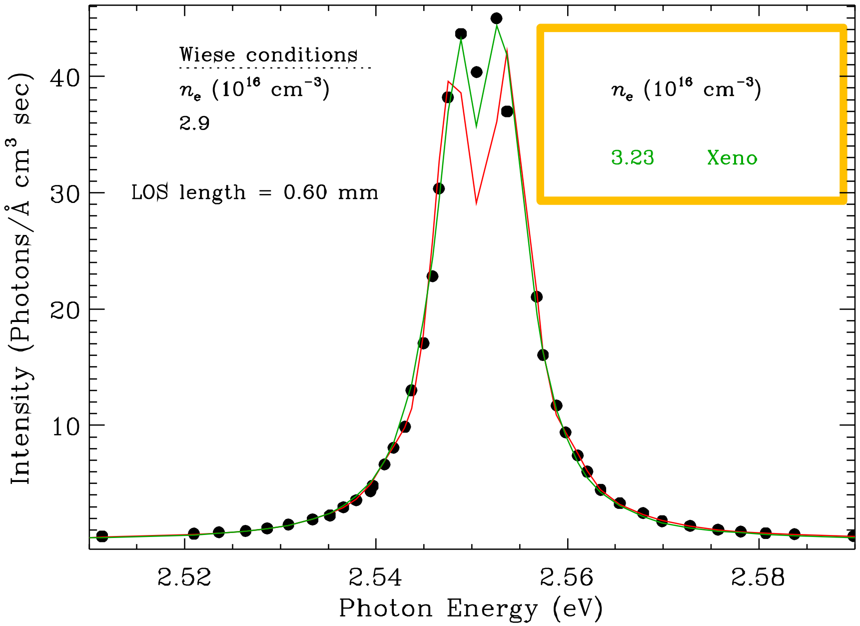
- Of the four conditions plotted in Wiese et al. (1972), I’ll show you three
  - For some conditions, the fits had difficulty converging

- Fit parameters:
  - **n_e (electron density)**
  - Background continuum (polynomial)

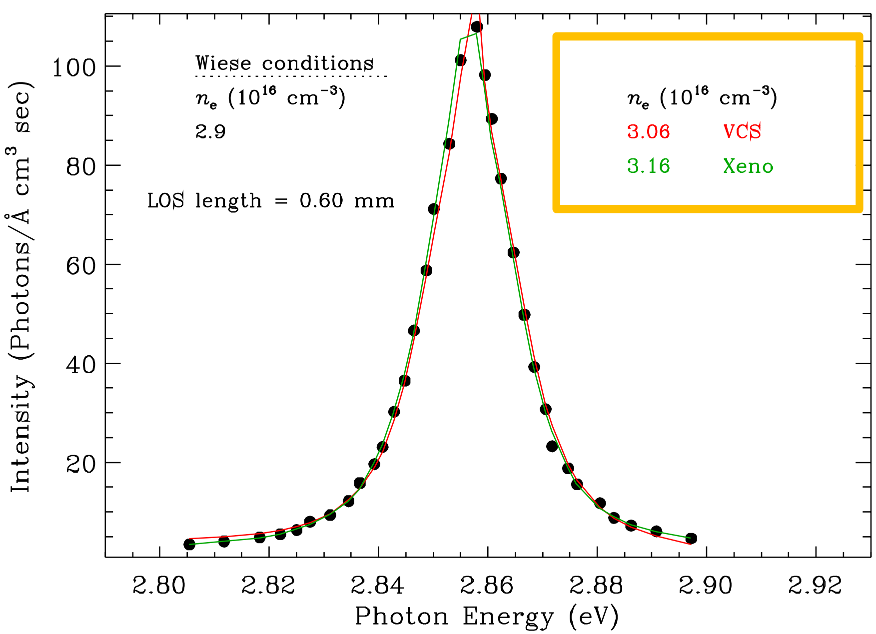
- Used Thomas Gomez’s digitized Wiese data

Condition 2 = 2.9e16 cm^{-3}

Hβ



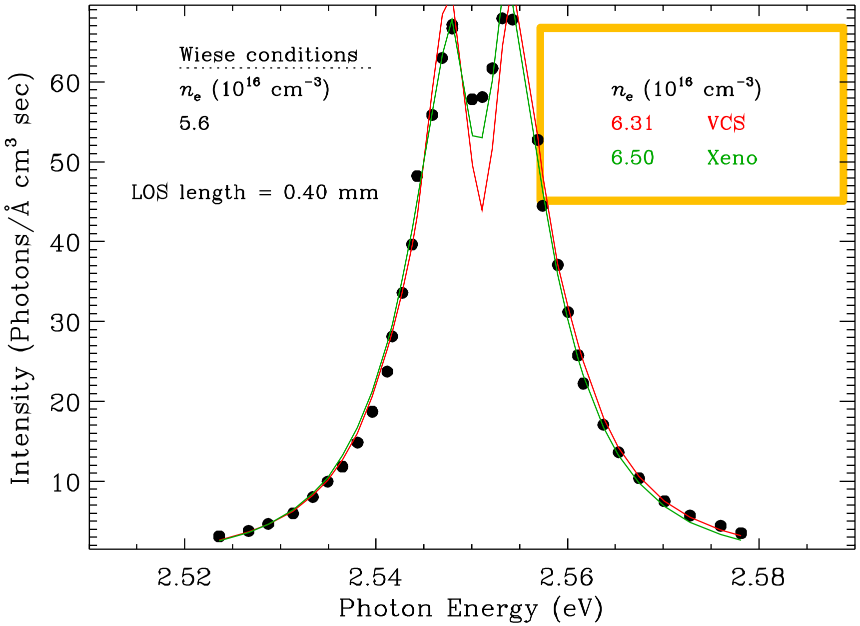
Hγ



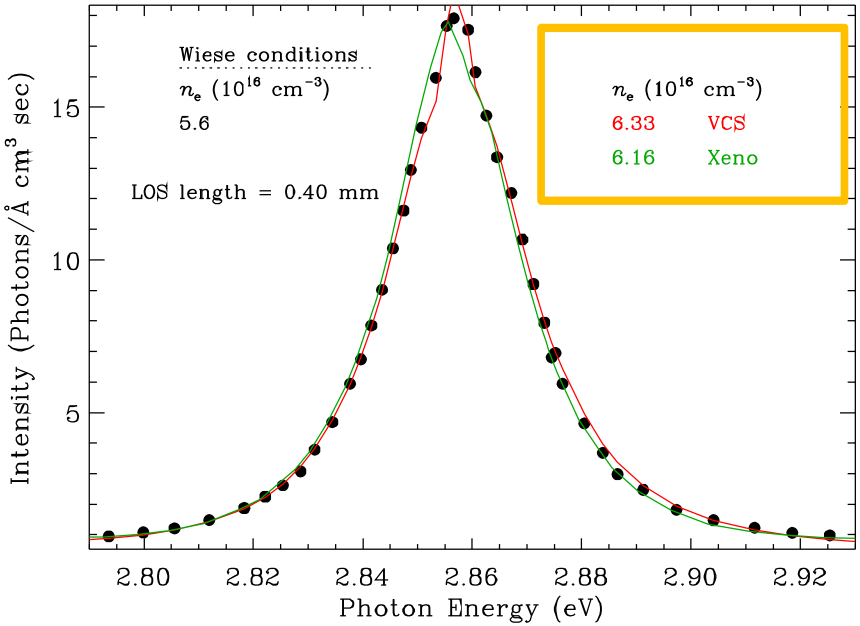
VCS fit does not converge

Condition 3 = 5.6e16 cm^{-3}

Hβ

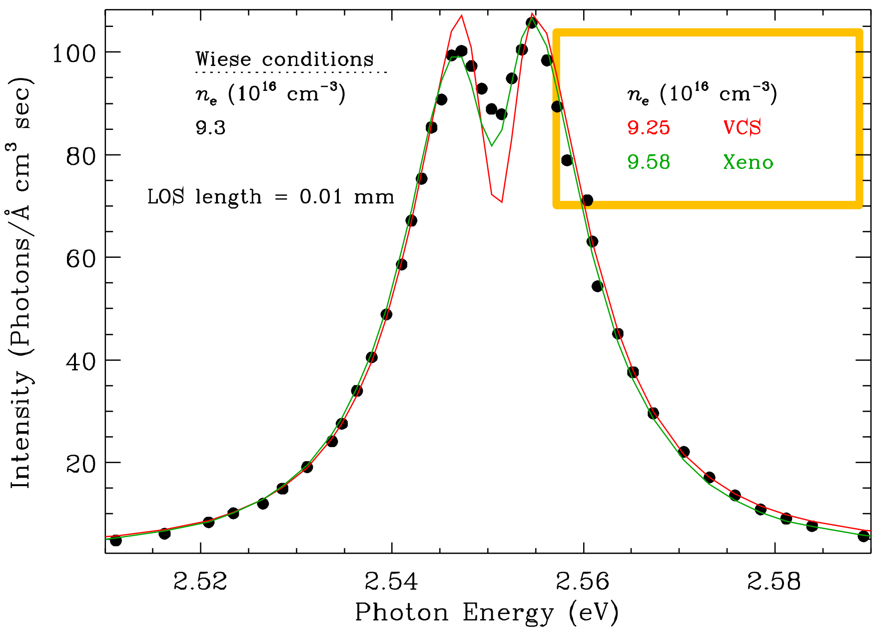


Hγ

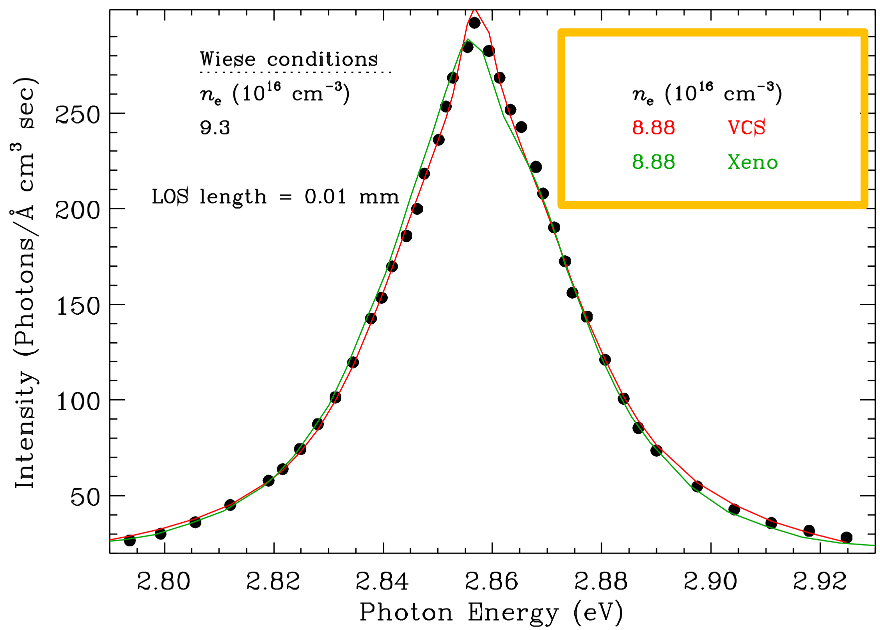


Condition 4 = 9.3e16 cm^{-3}

Hβ



Hγ



From Wiese fits, I cannot confirm that the emission fitting works *precisely*

- For now, I have inconclusive results
  - No consistent trend in either direction (larger or smaller)
  - Sometimes the fit is a bit large
  - Sometimes the fit is a bit small

- VCS fit for Condition 2 does not converge

- But, I conclude that the emission fitting works *generally*
- So I still find that the **transmission** fits for Hγ infer different electron densities than for Hβ

Intriguing trend seen in spectroscopic fits to observed WD spectra

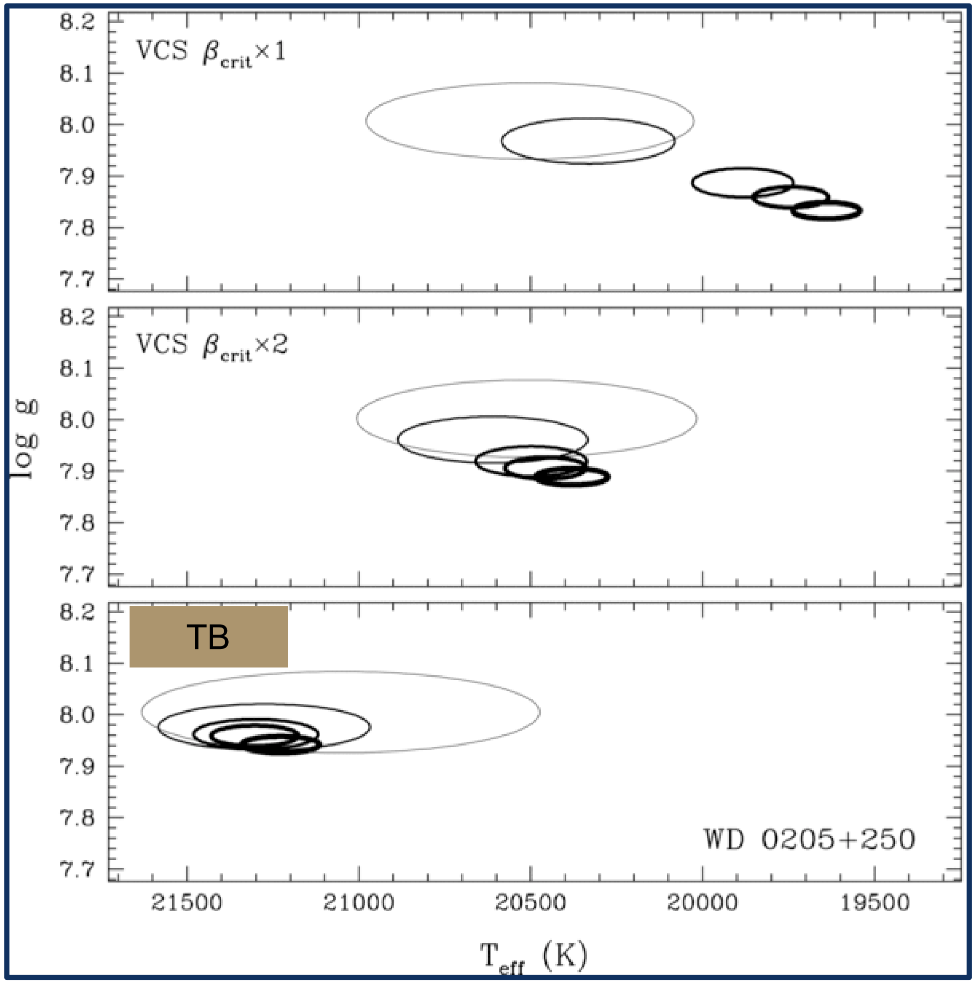


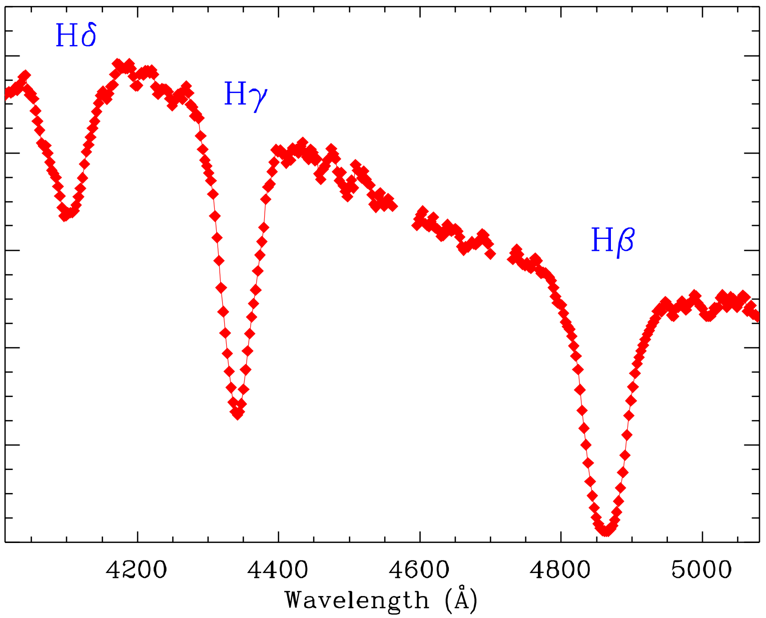
Figure from Tremblay & Bergeron (2009)

- 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)

Summary: we extend our experimental platform to measure WD plasmas at higher electron densities than previously measured

- 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…

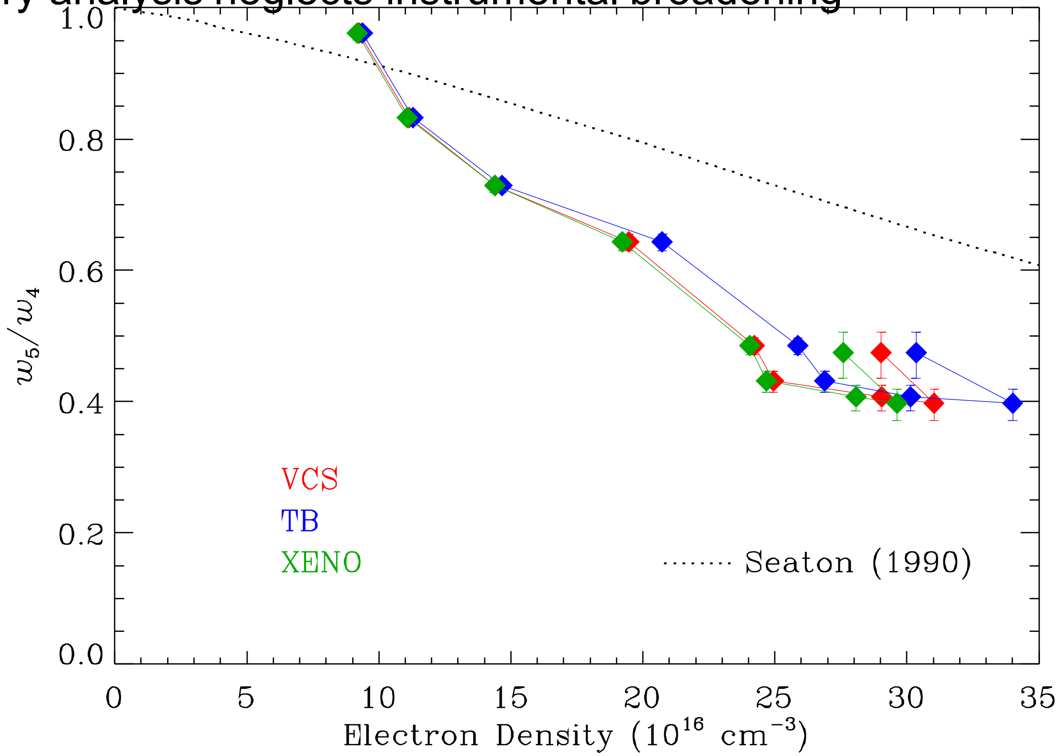
By measuring line *strengths*, our data provide new, unique measurements of occupation probabilities

- $$\frac{\kappa^{H\gamma}}{\kappa^{H\beta}} \propto \frac{f_{2\to5} w_5(n_e)}{f_{2\to4} w_4(n_e)}$$

  Use published oscillator strengths (Baker 2008)

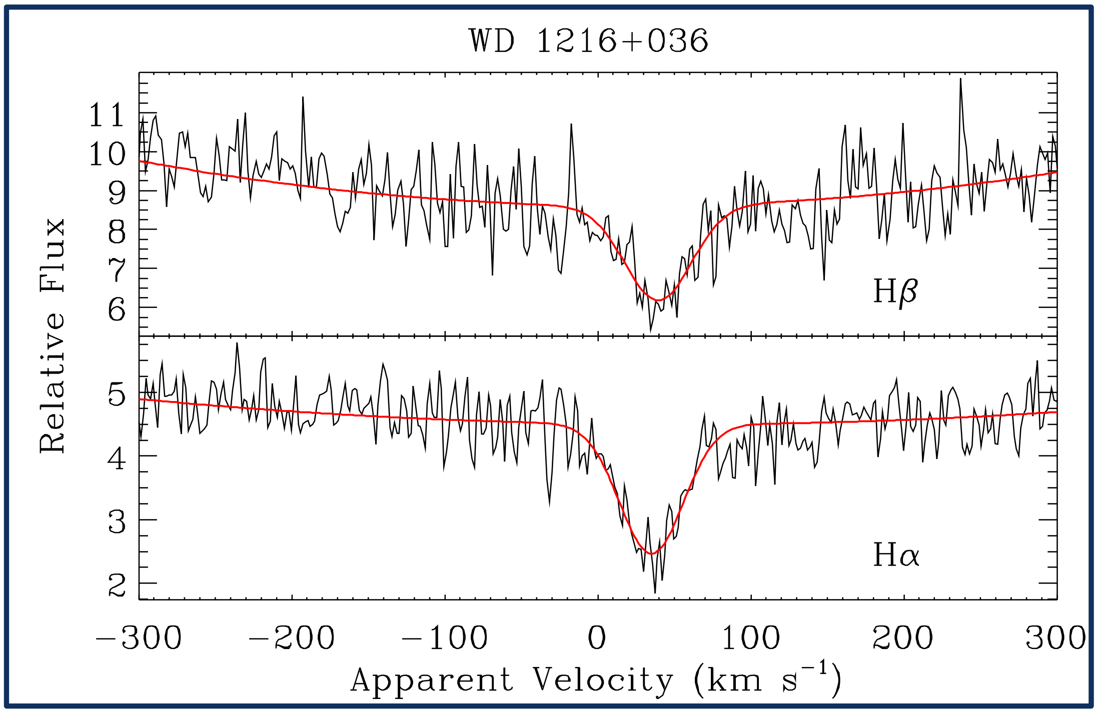
  Occupation probabilities

- Measured curve falls off with n_e more steeply than predicted by Seaton (1990)
  - Preliminary analysis neglects instrumental broadening



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

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



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

- Apparent velocity has 2 components

  0

  - $\langle v_{app} \rangle = \langle v_r \rangle + \langle v_g \rangle$

- For a nearby, co-moving sample, space velocities are random

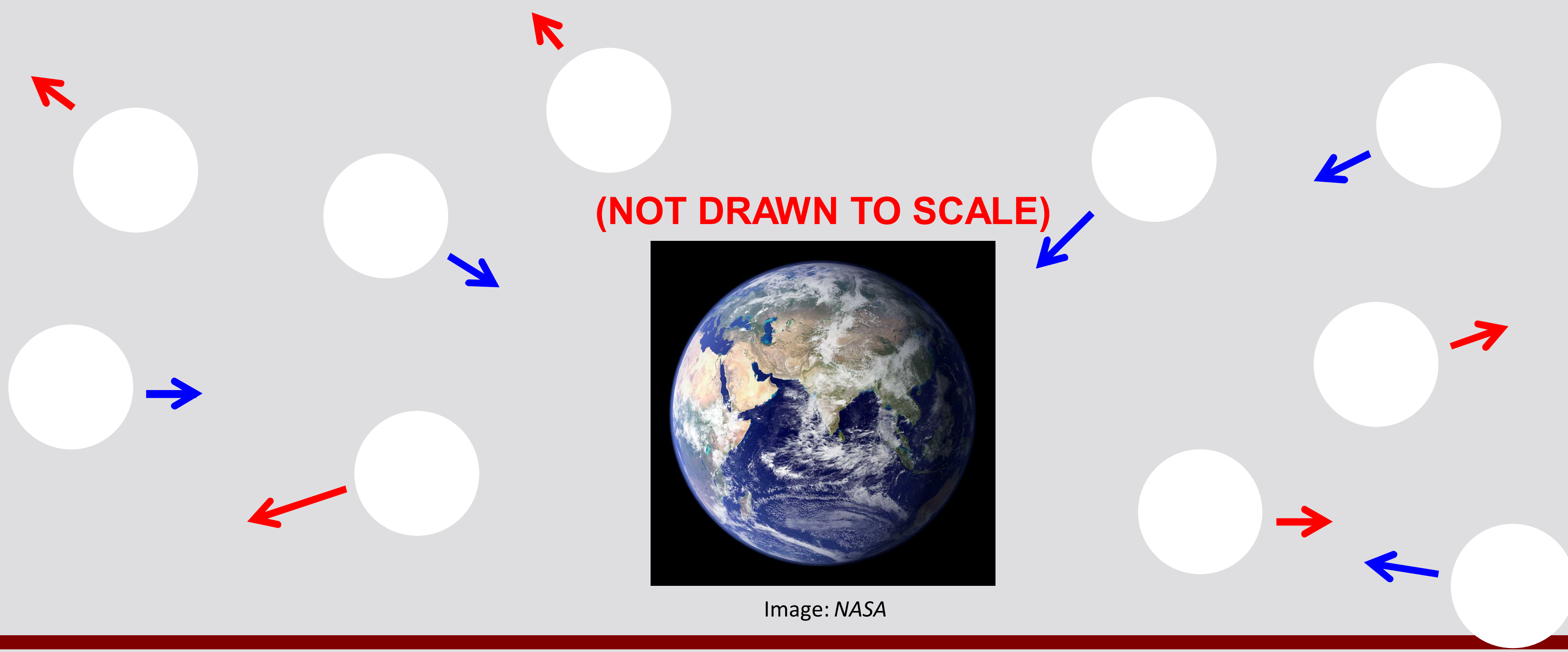
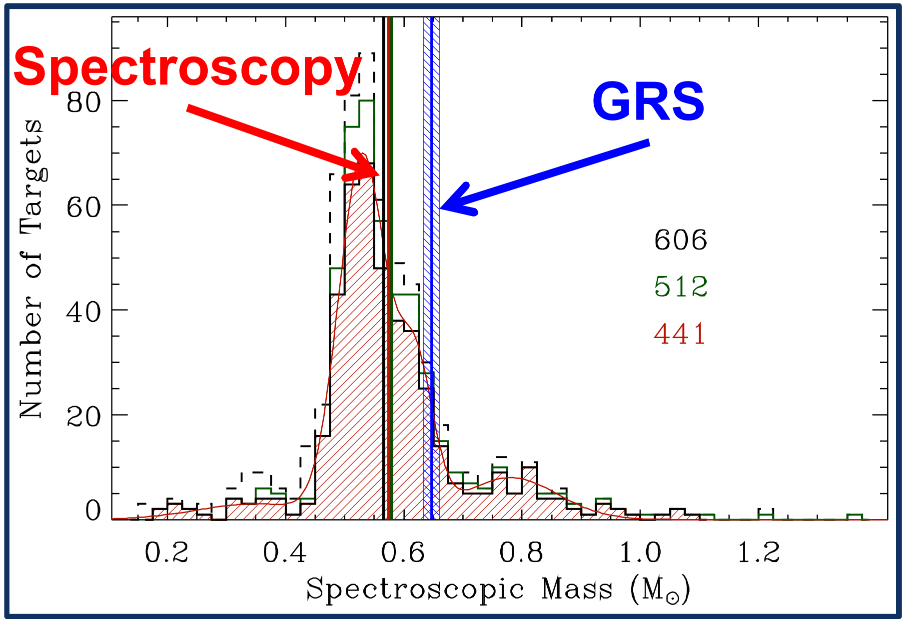


Image: *NASA*

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

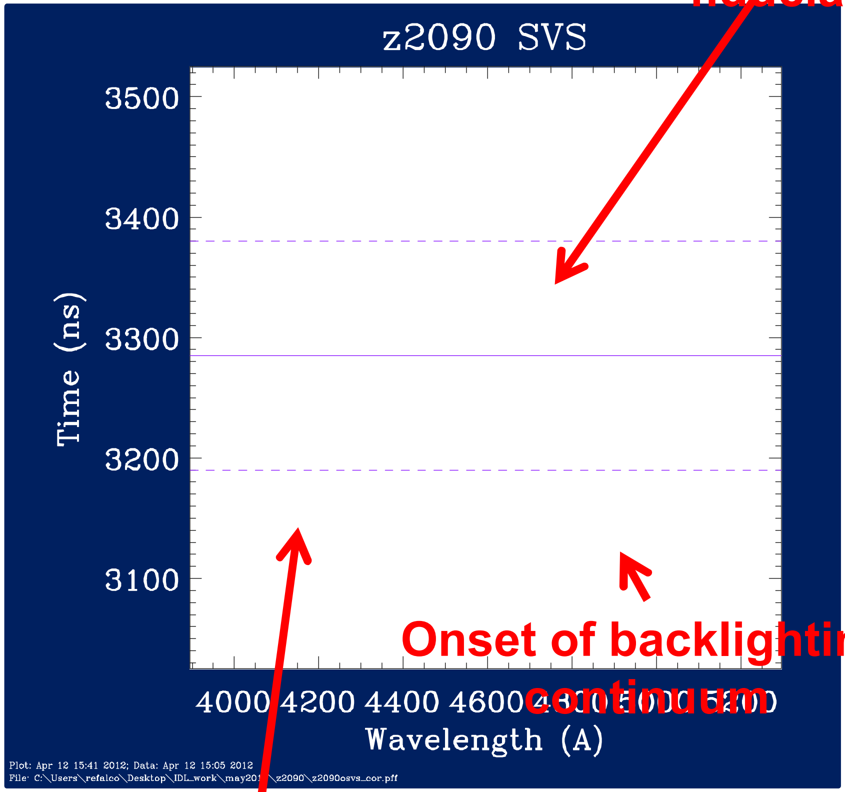


Falcon et al. (2010), *ApJ*, **712**, 585

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

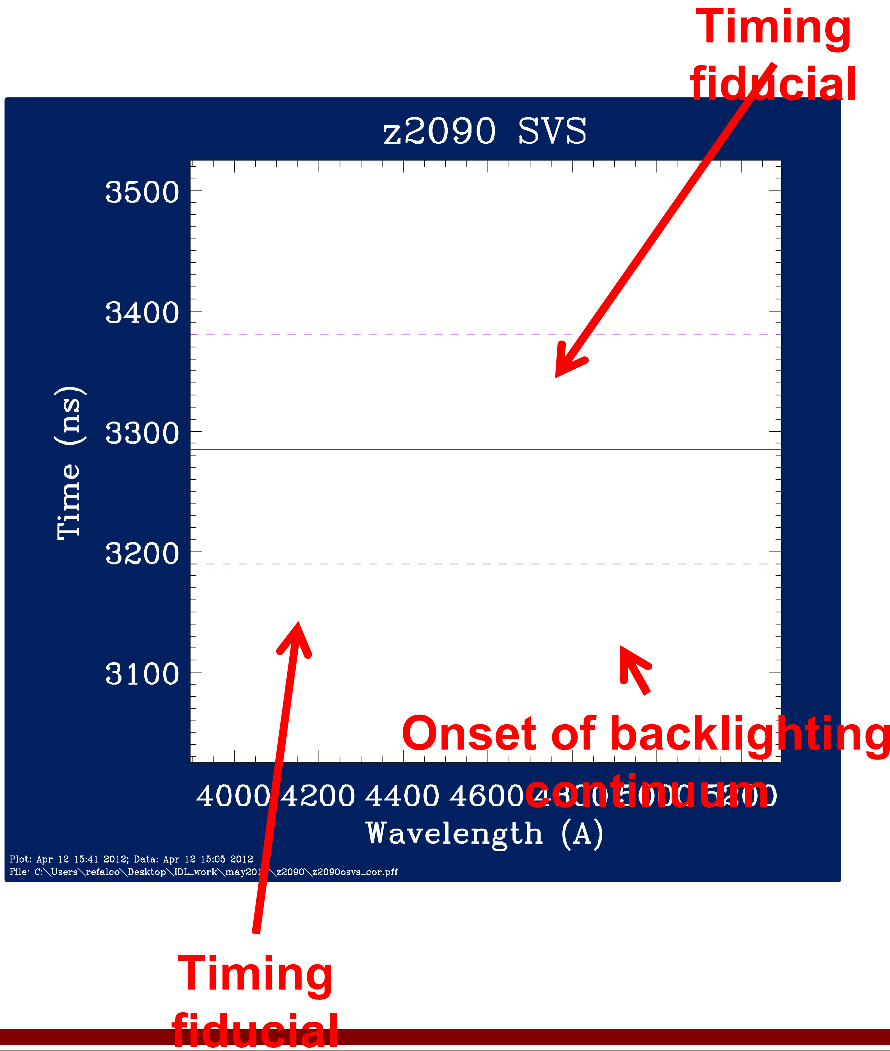


Timing fiducial

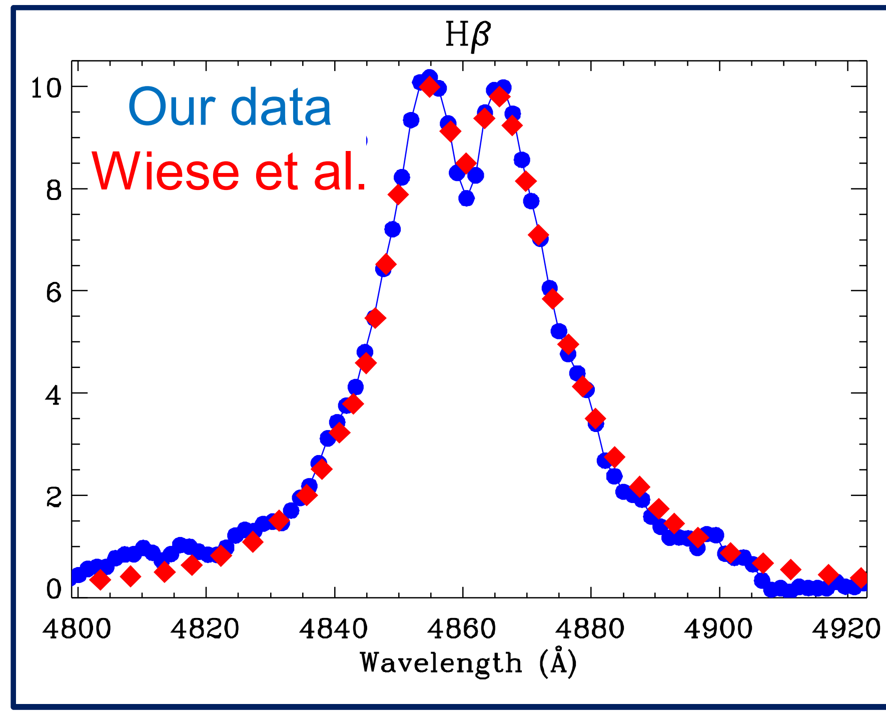
Onset of backlighting continuum

Timing fiducial

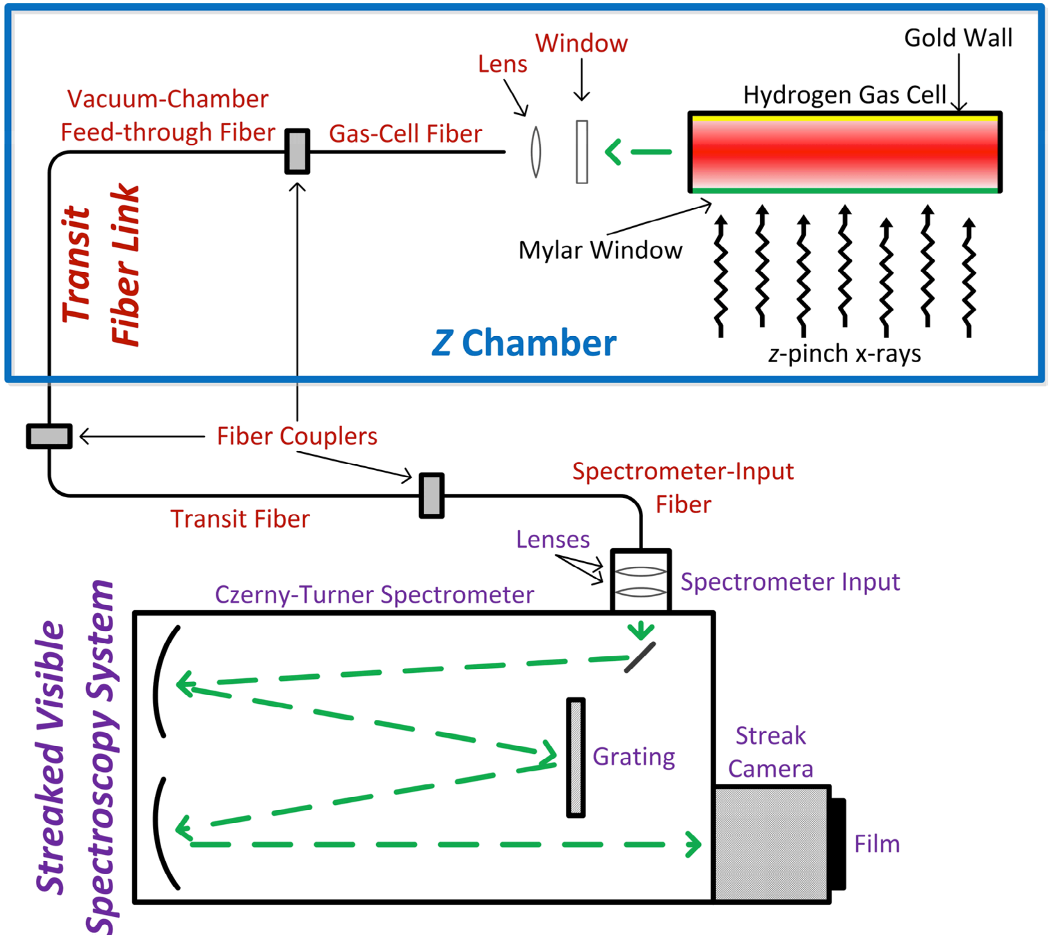
Hβ-emission-line agreement with Wiese et al. shows we achieve desired conditions



n_e = 5.7e16 cm^{-3}

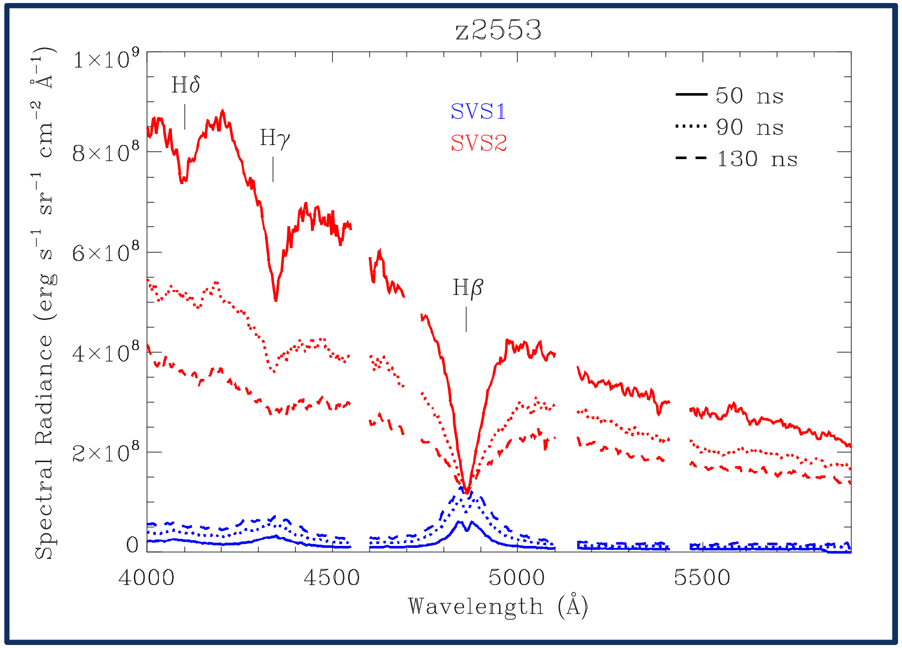


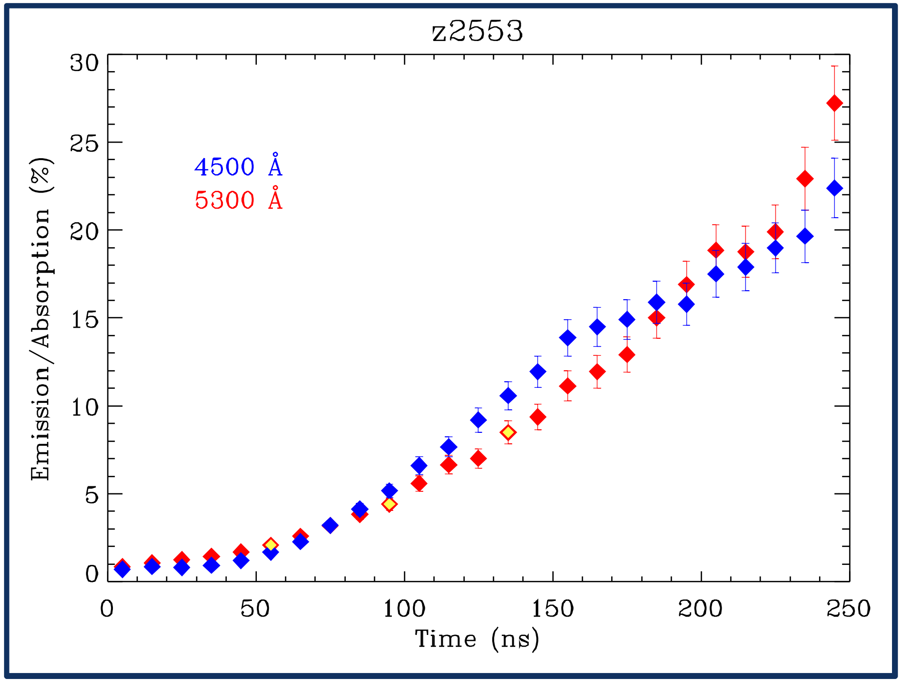
Combining data from multiple spectrometer systems requires calibrations



- 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

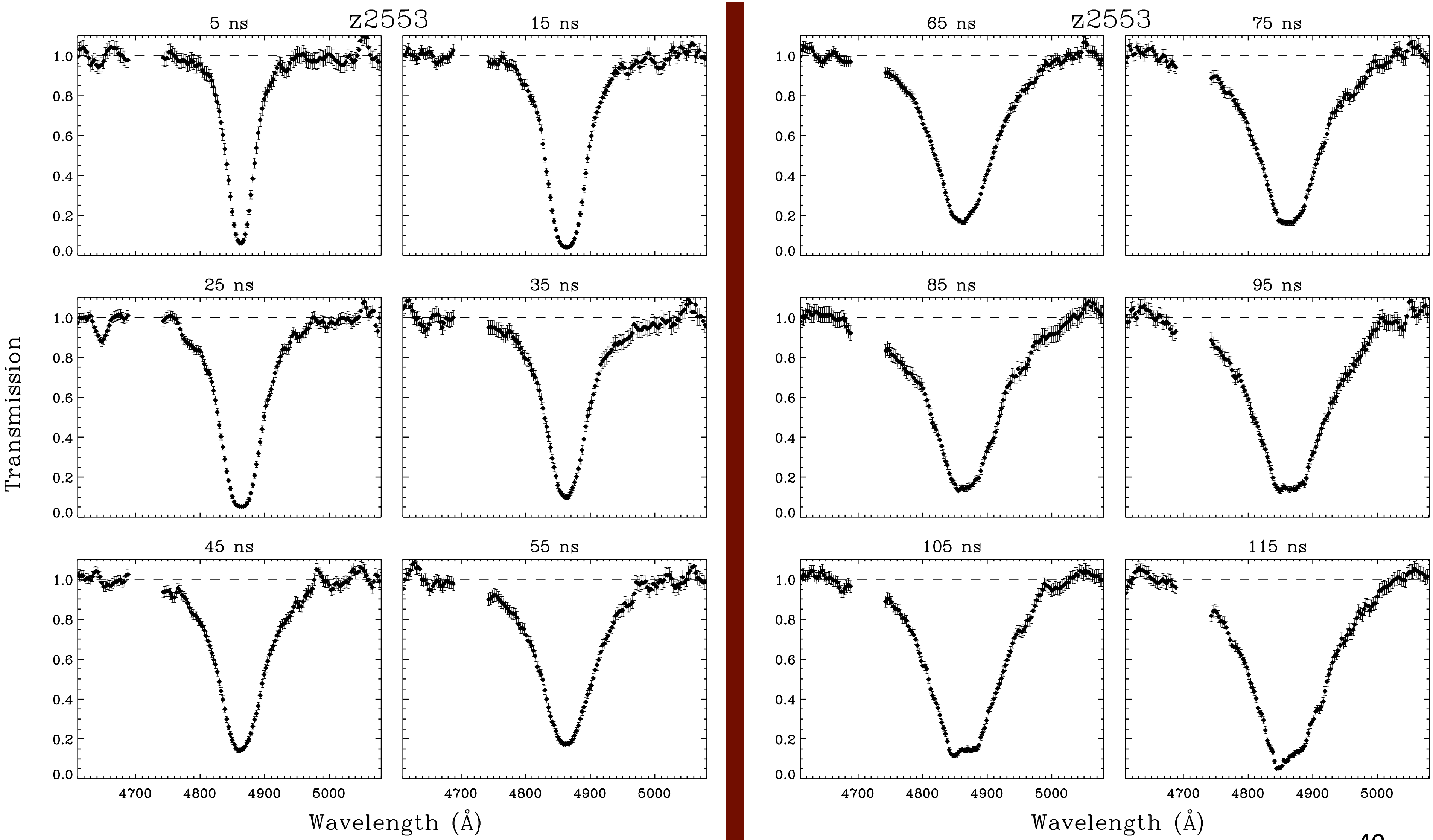




- Most significant for Hβ line

Falcon (2014), PhD Thesis

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



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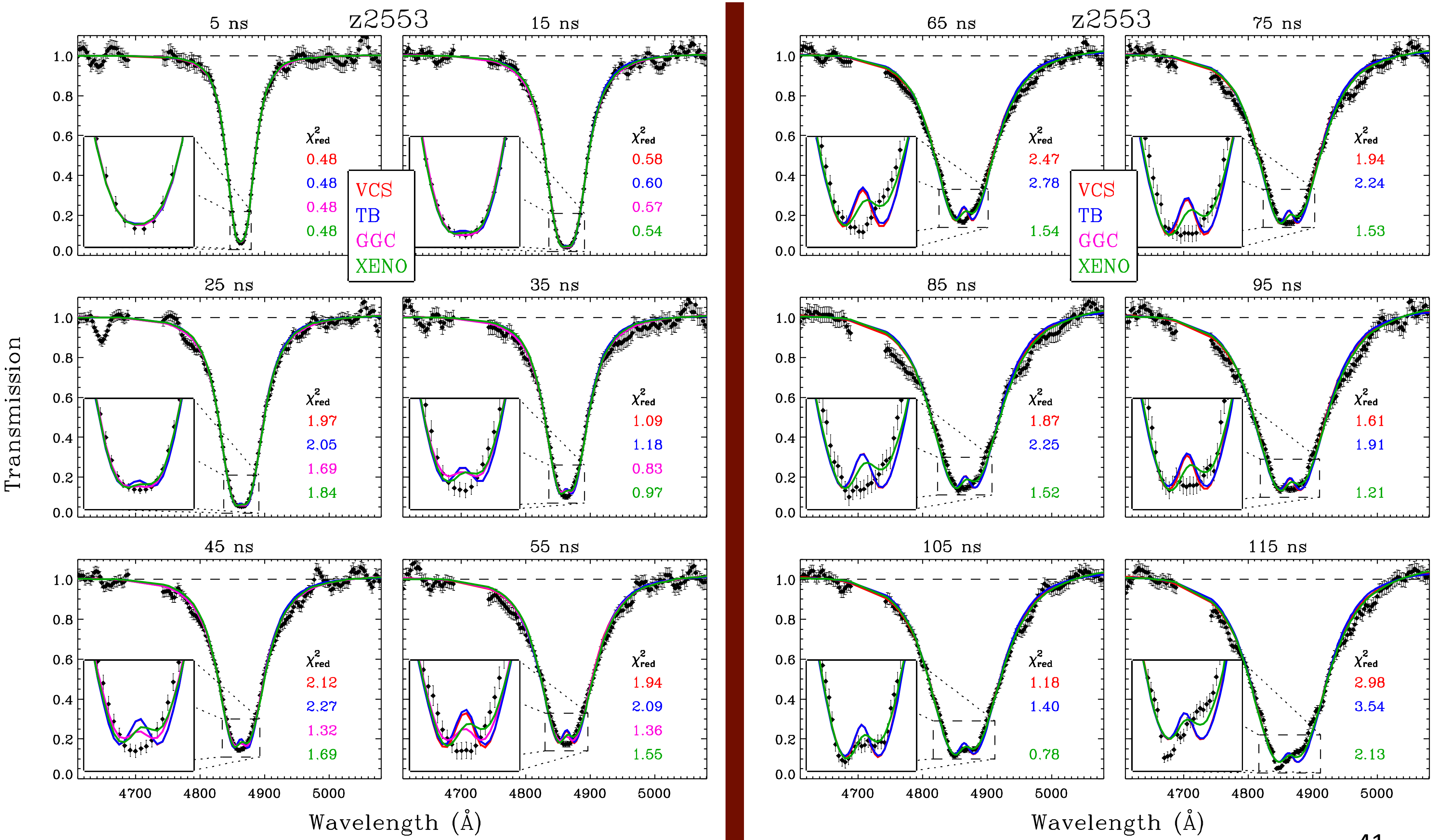
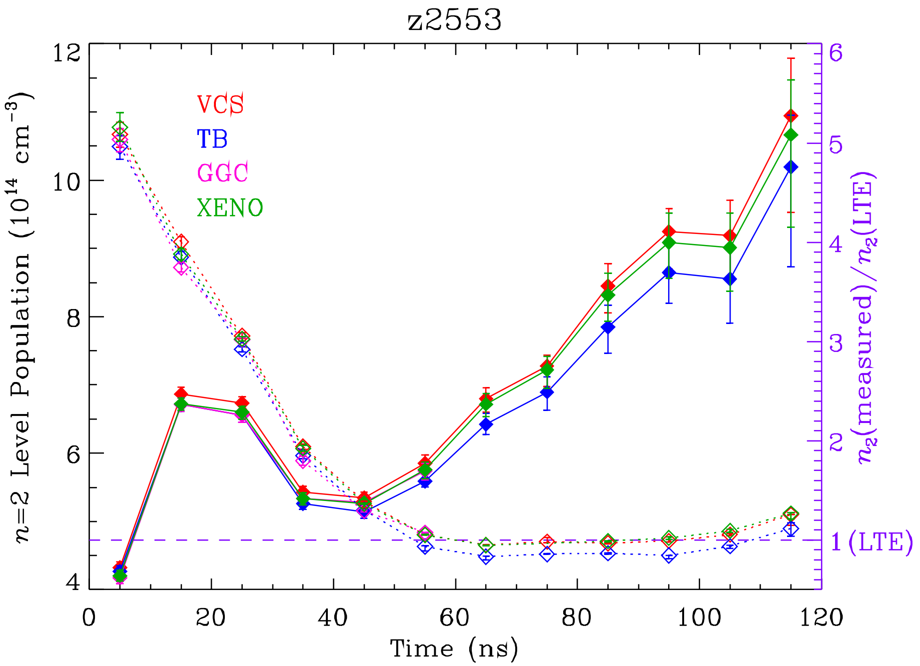
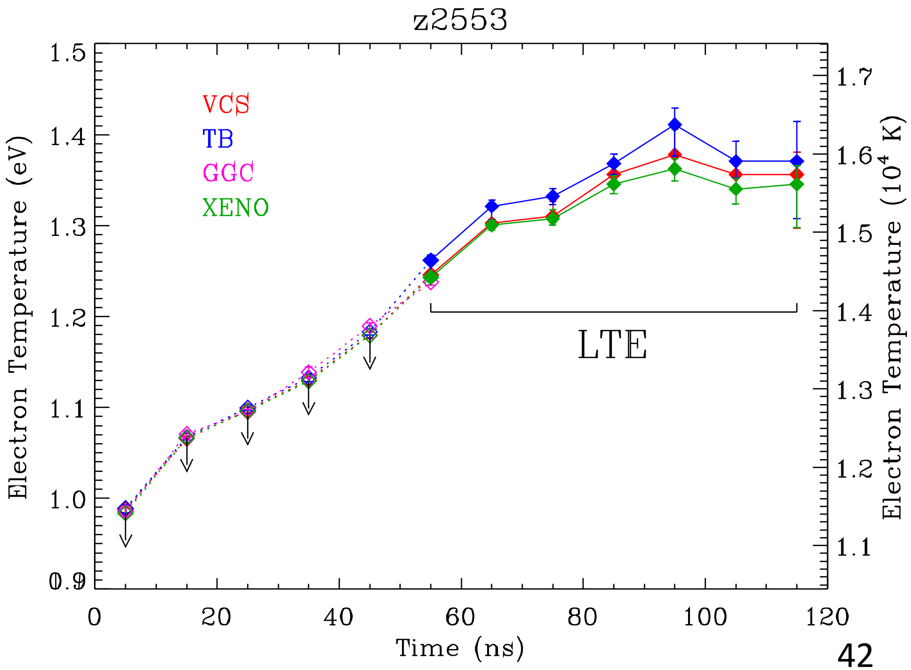


Falcon et al. (2015), *ApJ*, **806**, 214

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