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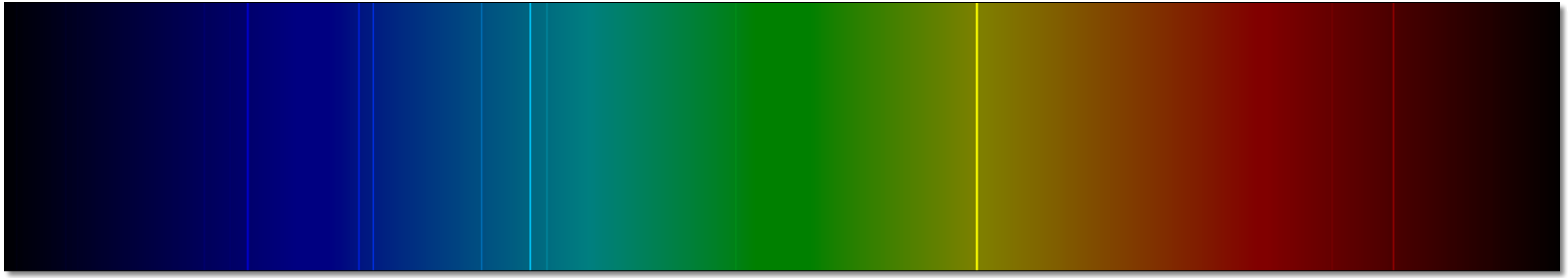


The White Dwarf Photosphere Experiment

at

Sandia National Laboratories’ *Z*-machine

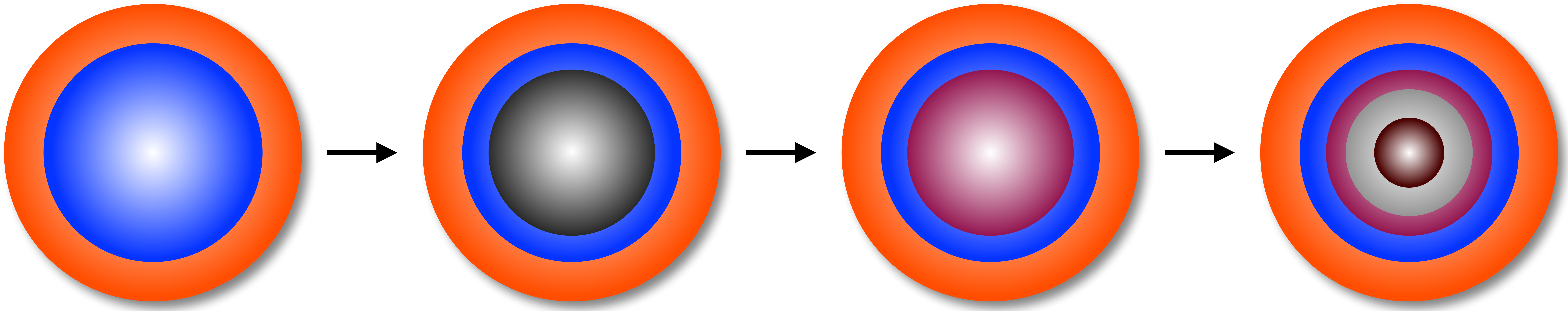
Marc-Andre Schaeuble
University of Texas at Austin

10/16/2017

Outline

- What is a White Dwarf (WD)?
- How are WDs used in astrophysics?
- What are the current limitations of our understanding of WDs?
- How are we using the *Z*-machine to help?
- Summary

What is a WD?

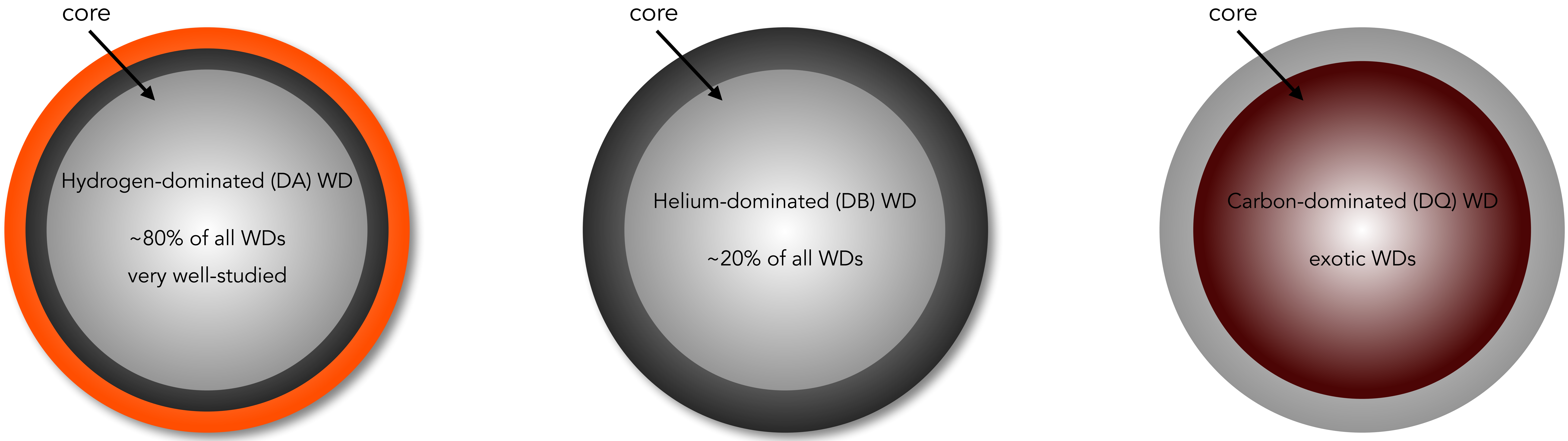


Main Sequence	Red Giant	Horizontal Branch	Asymptotic Giant
H fusion	H fusion Inert He	H fusion He fusion	H fusion He fusion C/O fusion

- inert H
- inert He
- H fusion
- He fusion
- inert C/O or C fusion
- inert O/Mg/Ne

Not drawn to scale.

What is a WD?



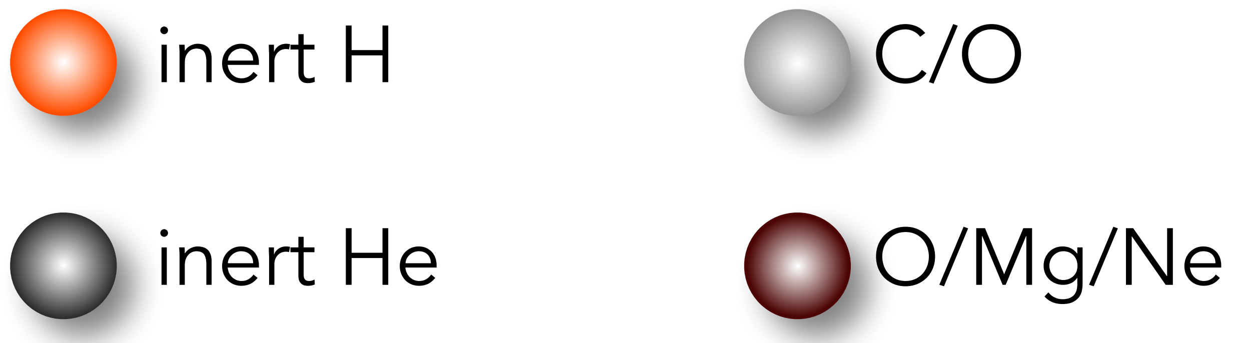
Typical WD parameters:

Surface temperature (T_{eff}): 10,000 K (~1 eV)

Surface gravity (log g): 10^8 cm/s^2 (n_e ~10^{17} cm^{-3})

Radius: r_{earth}

Mass: ~2/3 M_{sun}



Not drawn to scale.

WDs in astrophysics

An overview

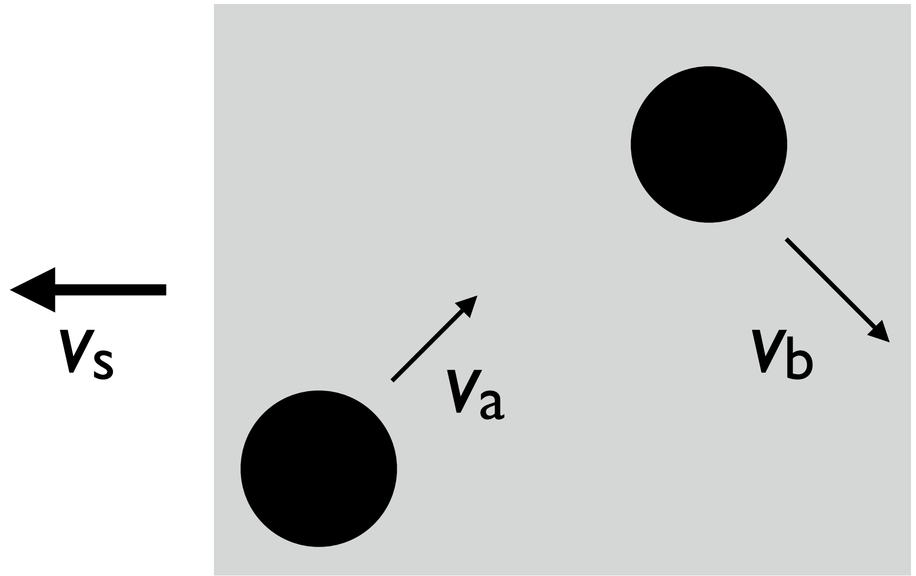
	DA	DB	DQ
Astronomical use	‣ age of Galaxy and universe ‣ composition of extrasolar planets ‣ stellar initial/final mass relation	‣ test stellar evolution models ‣ constrain model atmospheres ‣ evaluate He atomic models	‣ insight into massive stars in early Galaxy ‣ test stellar evolution models ‣ confirm theoretical Stark width calculations
Required data	accurate DA masses	accurate DB masses	accurate DQ masses

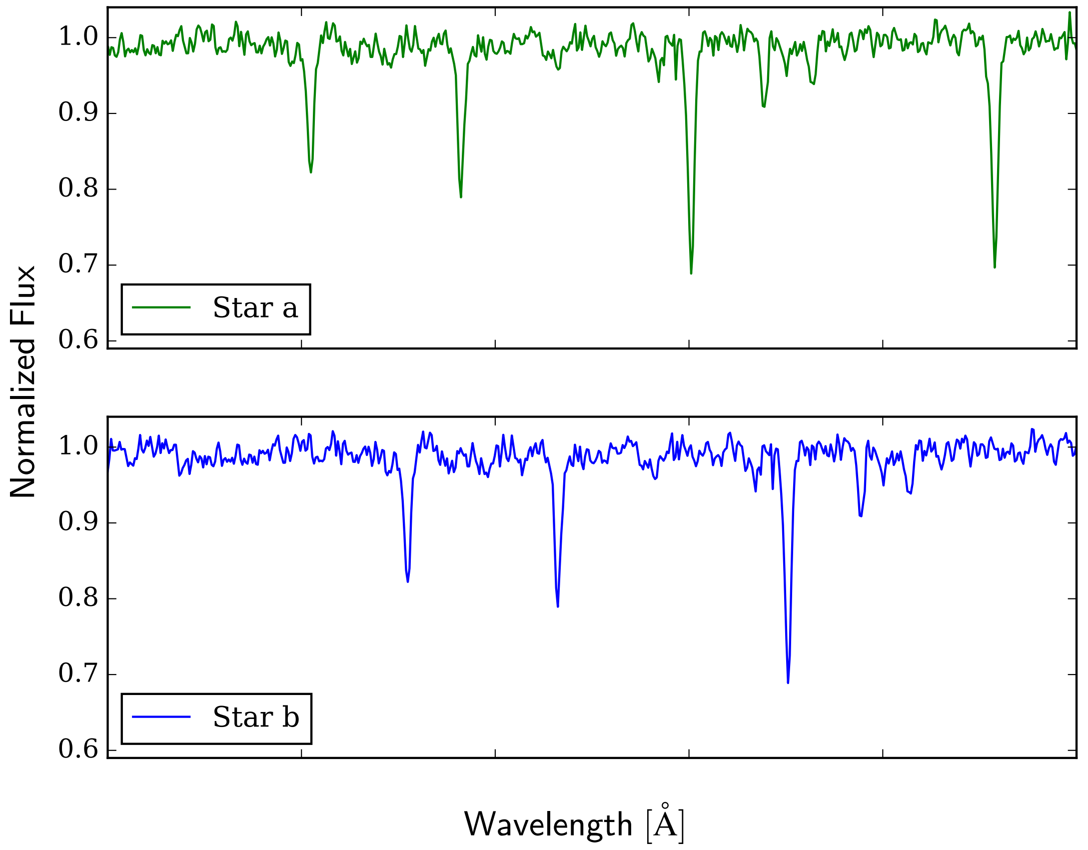
Accurate WD masses are needed.

WDs in astrophysics

Mass determination methods

Gravitational redshift (GR)





averaging over random motions (v_a, v_b)

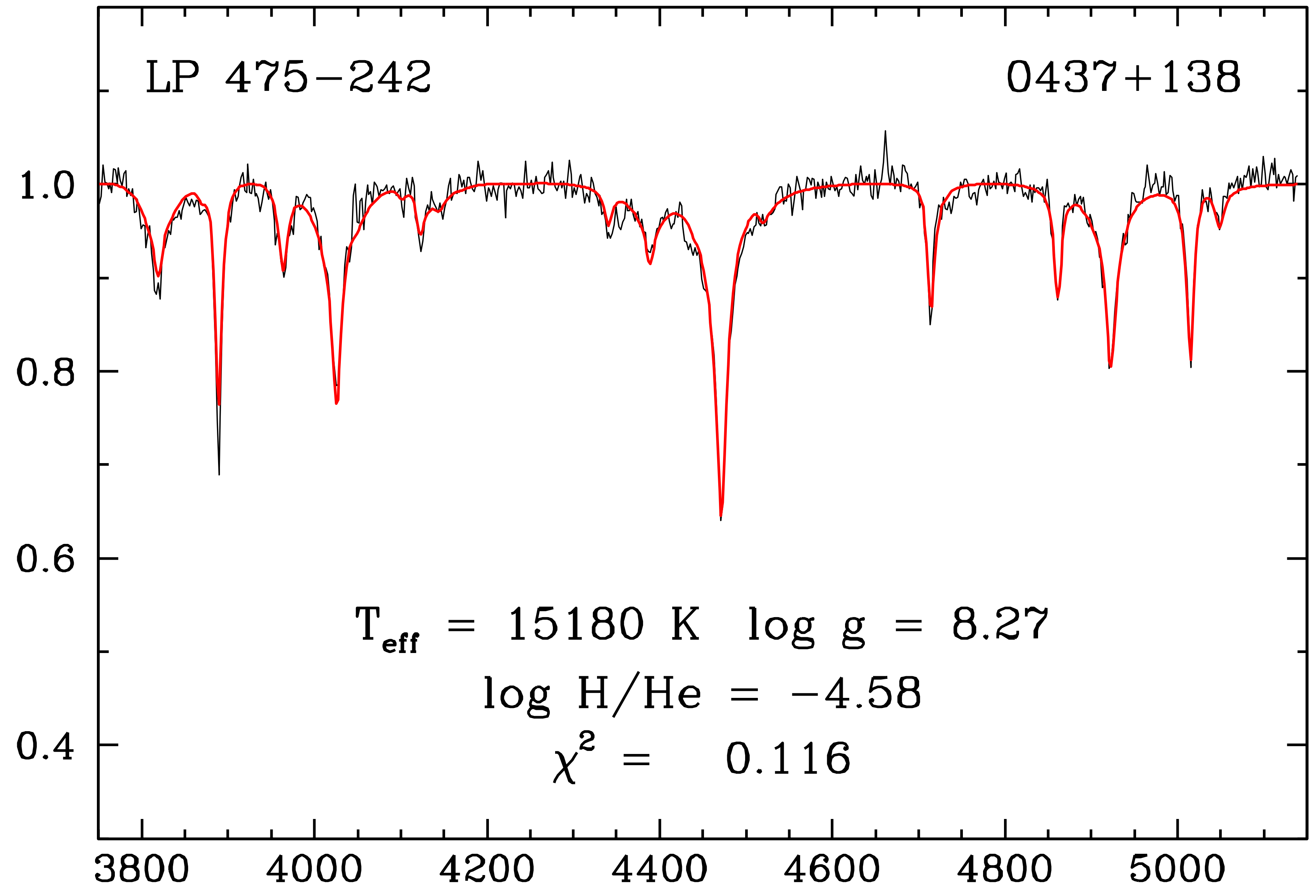
correcting for bulk motion (v_s)

$$v_g = \frac{c\Delta\lambda}{\lambda} = \frac{GM}{Rc}$$

$$\Delta\lambda_{GR,\,WD} \sim 1\ \text{Å}$$

- relies on ***centroid*** of spectral lines
- can only be applied to collections of stars

Spectroscopic

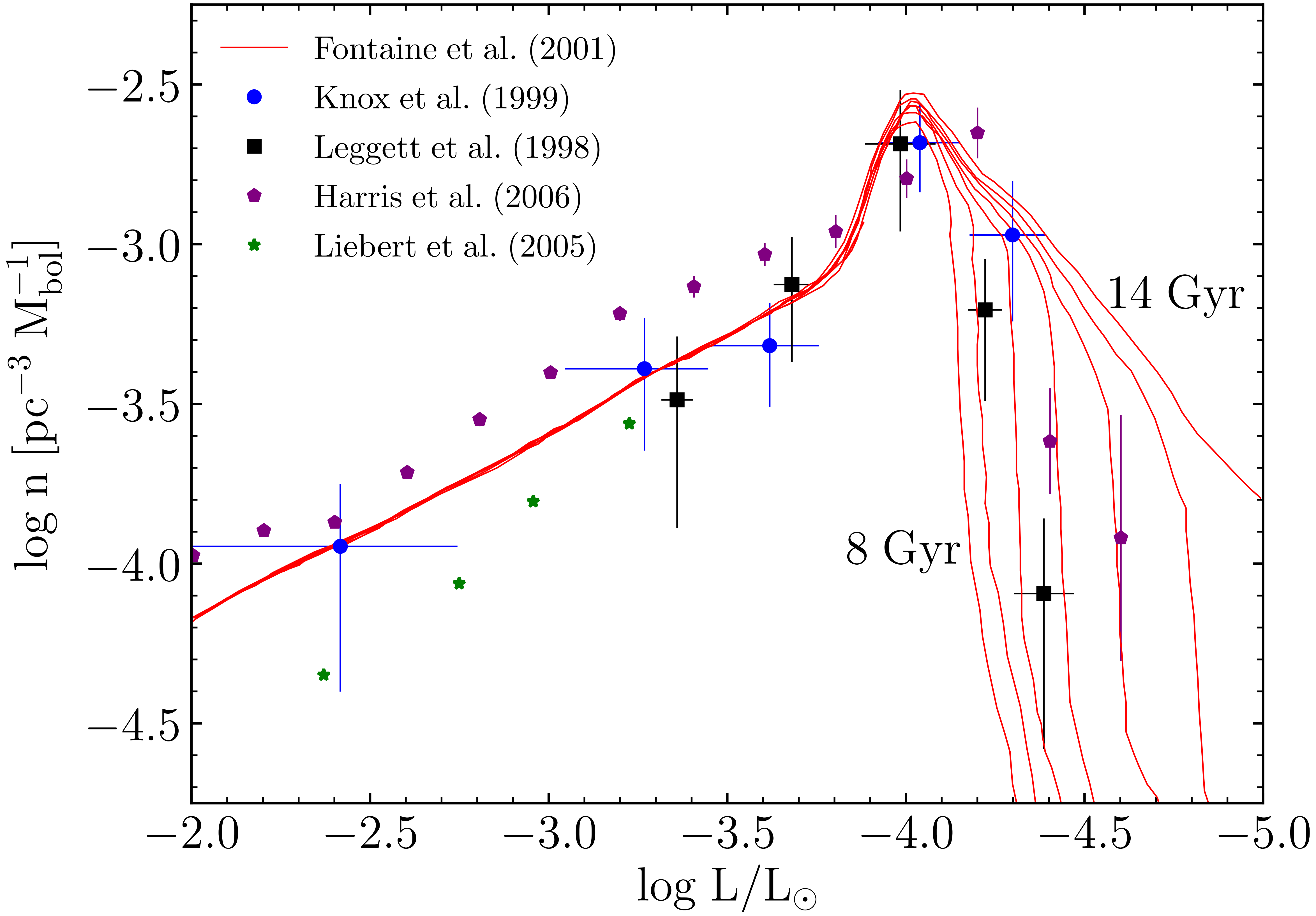


Bergeron et al. (2011)

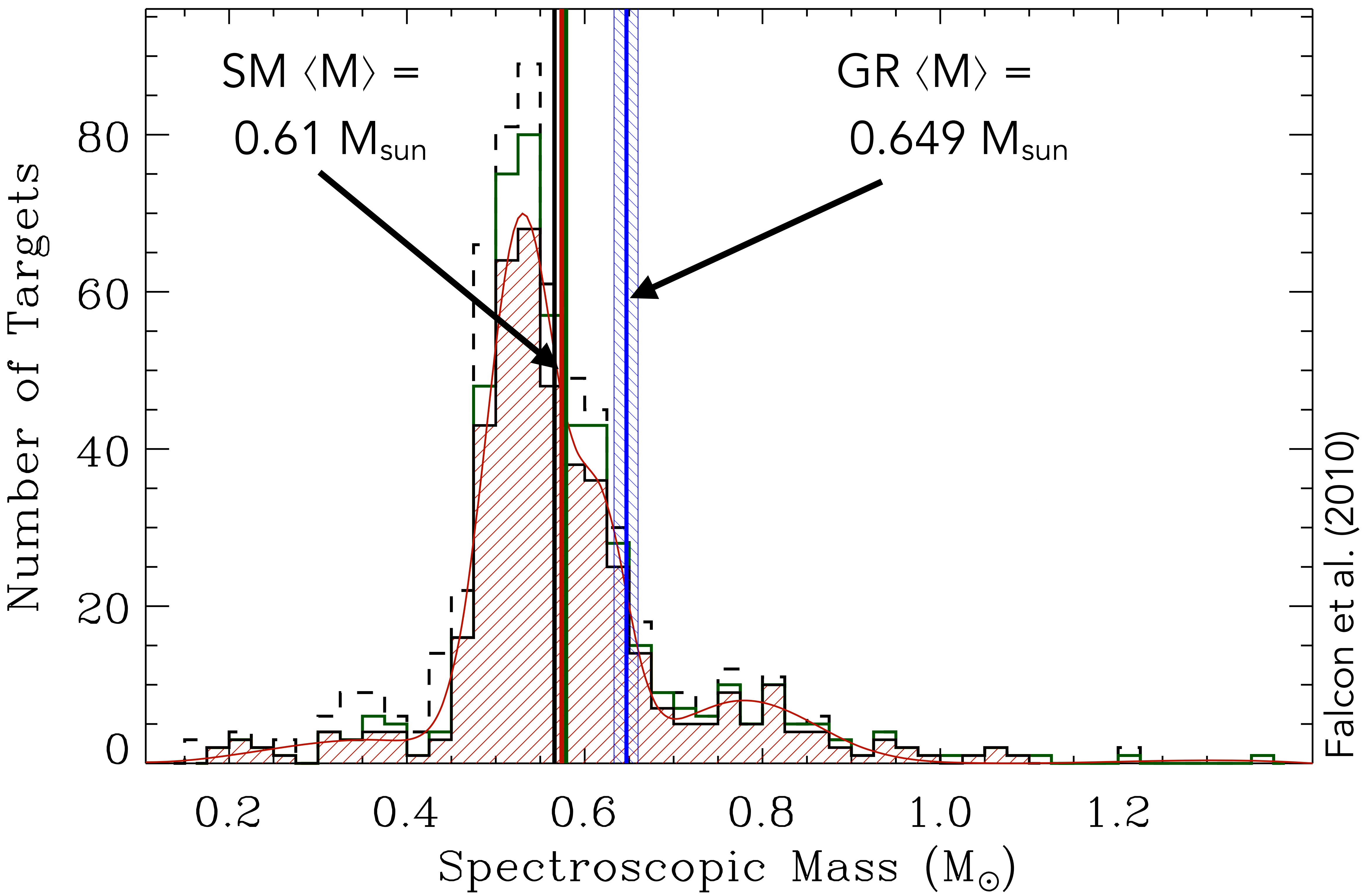
- relies on ***width*** of spectral lines
- can be applied to individual stars

WDs in astrophysics

The DAs



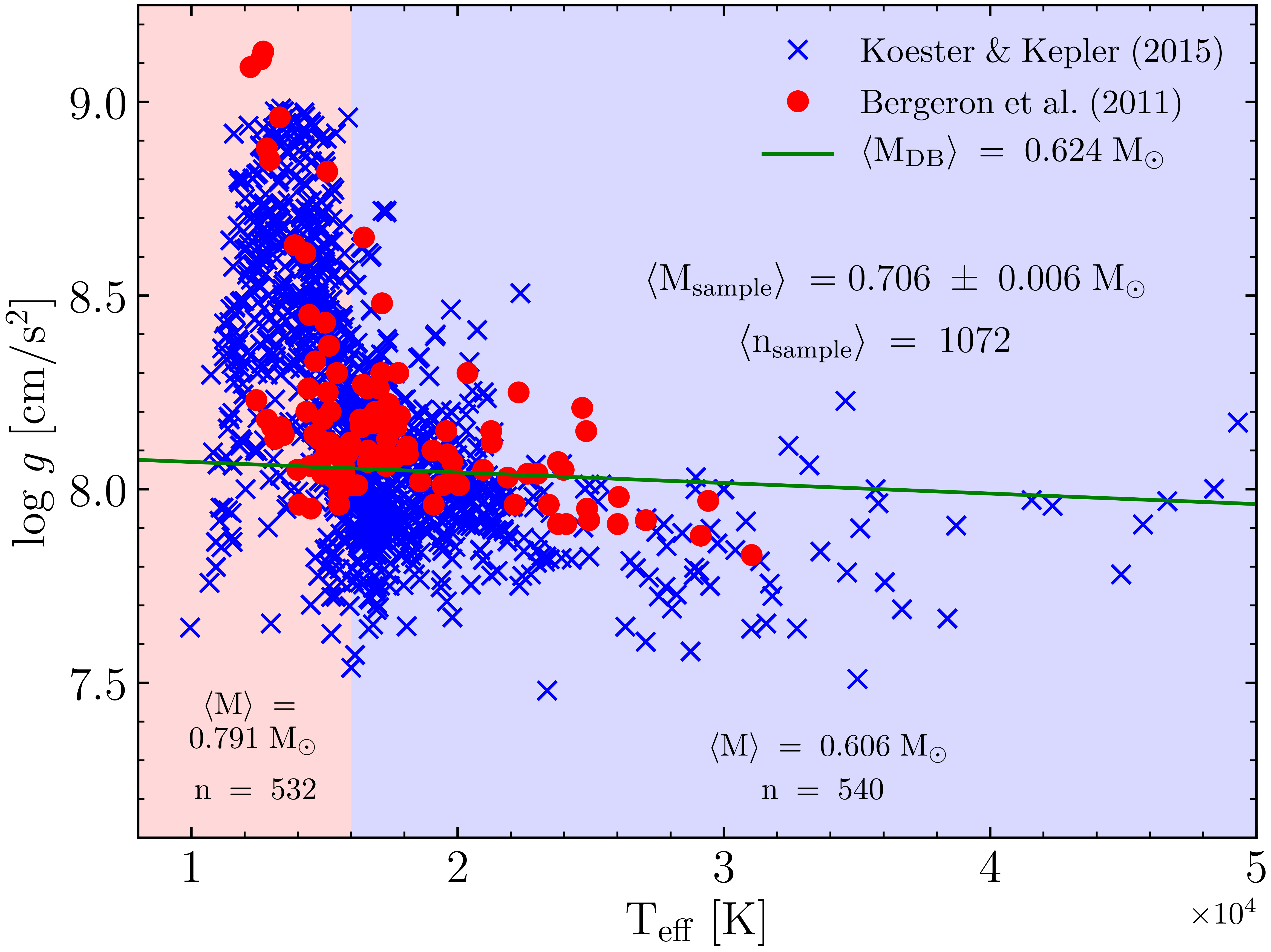
Comparison of observed and theoretical WD luminosity functions. These can be used to determine the age of stellar populations, the Galaxy, and the universe.



Gravitational redshift and spectroscopic masses in comparison. The difference is much larger than the stated uncertainties and would result in a Galactic age adjustment of 0.5 x 10^9 years.

WDs in astrophysics

The DBs



Spectroscopically determined DB surface gravities as a function of surface temperature. Problems are evident.

GR mass:

$\langle M_{DB} \rangle = 0.74 \pm 0.08\ M_{sun}$ using the 5876 Å He I line

Problems:

- spectroscopy is unreliable due to upturn in log *g* at low temperatures

- GR is unreliable due to unknown pressure shifts of 5876 Å He I line

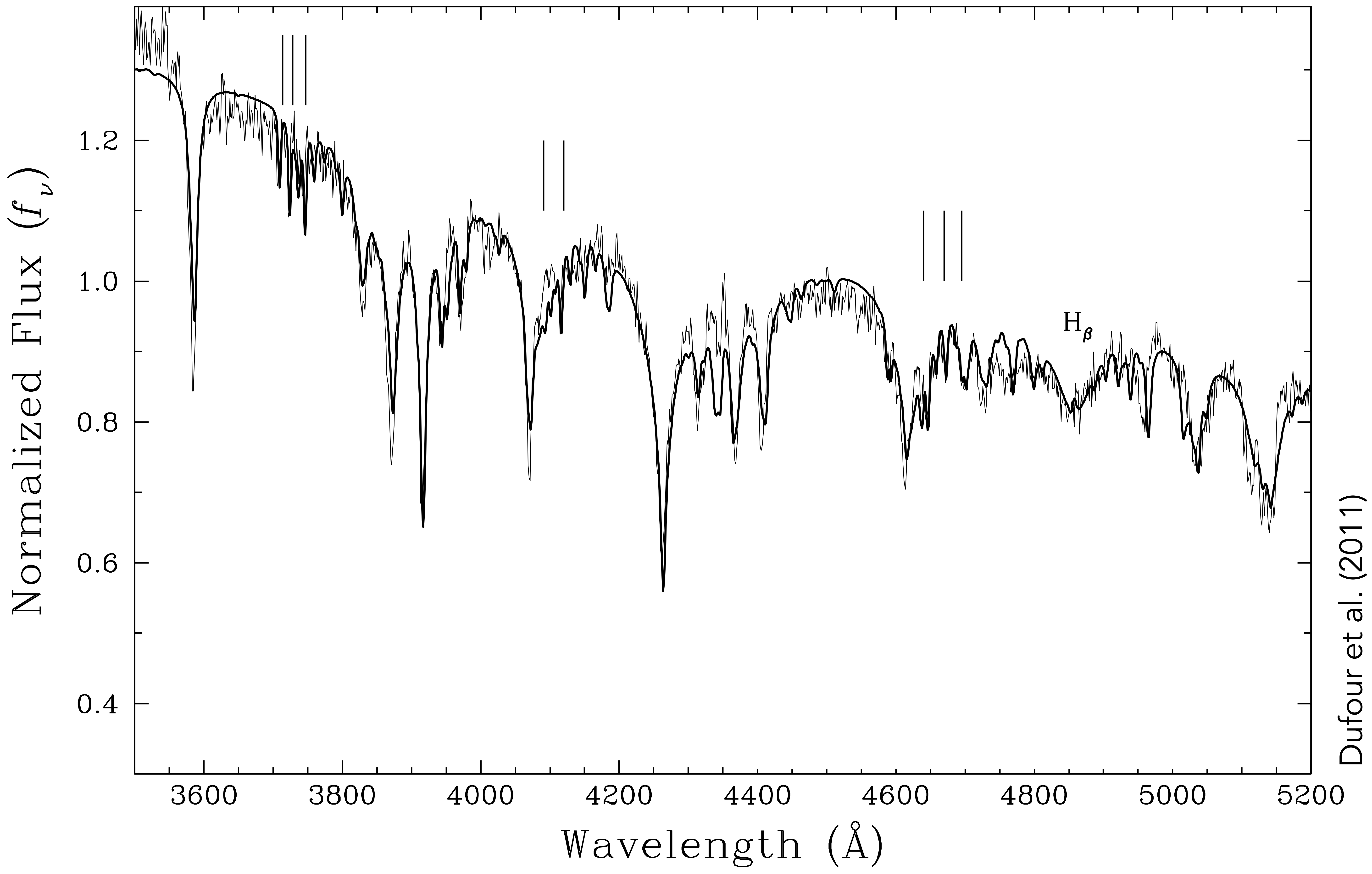
WDs in astrophysics

The DBs

Hypothesis	Predicted mass signatures
atmospheric convection/diffusion	$\langle M_{DB} \rangle = \langle M_{DA} \rangle$
additional WD progenitor fusion	$\langle M_{DB} \rangle \neq \langle M_{DA} \rangle$
binary evolution	$\langle M_{DB} \rangle = \langle M_{DA} \rangle$ $\sigma(\langle M_{DB} \rangle) \neq \sigma(\langle M_{DA} \rangle)$
combination of progenitor fusion and binary evolution	$\langle M_{DB} \rangle \neq \langle M_{DA} \rangle$ $\sigma(\langle M_{DB} \rangle) \neq \sigma(\langle M_{DA} \rangle)$

WDs in astrophysics

The DQs

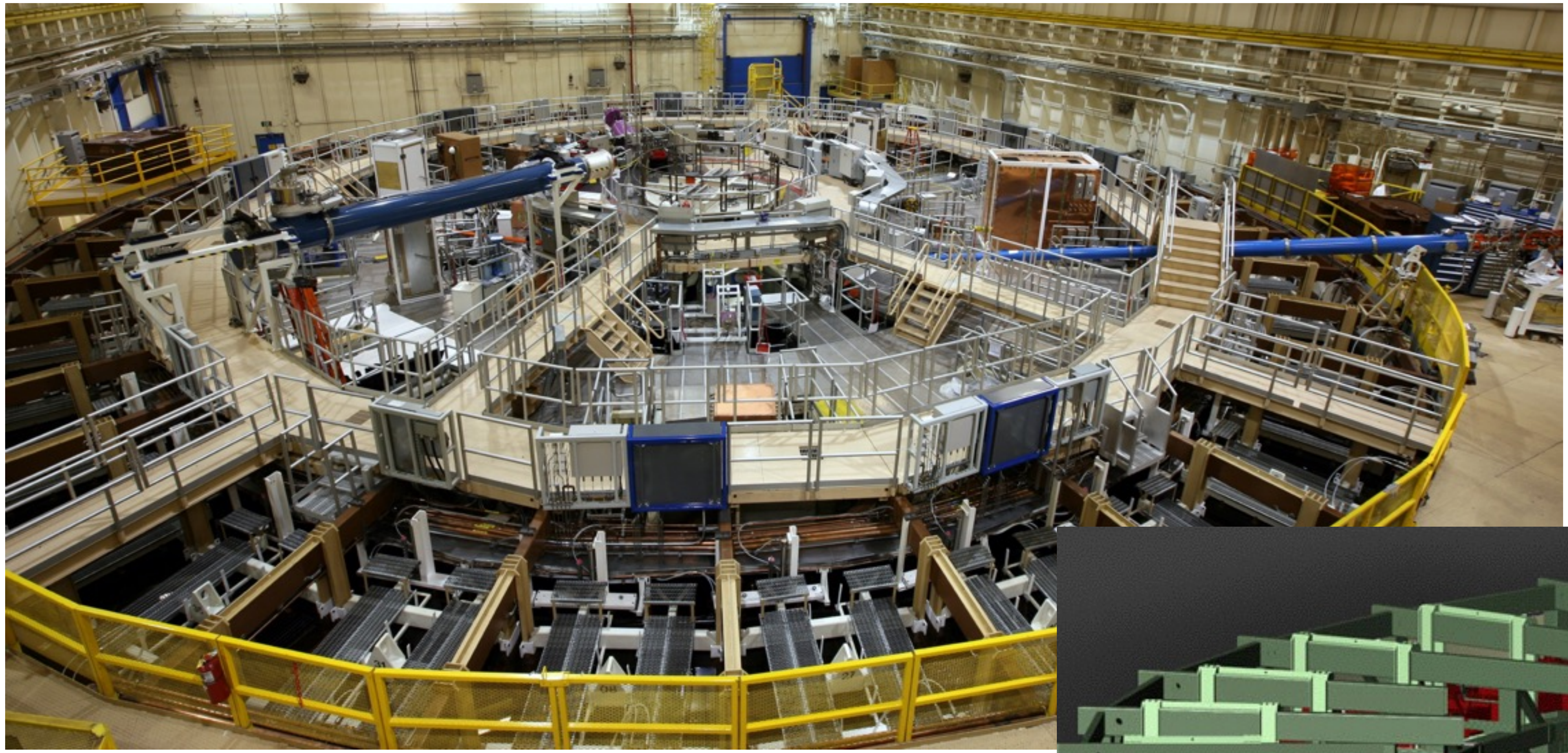


Dufour et al. (2011)

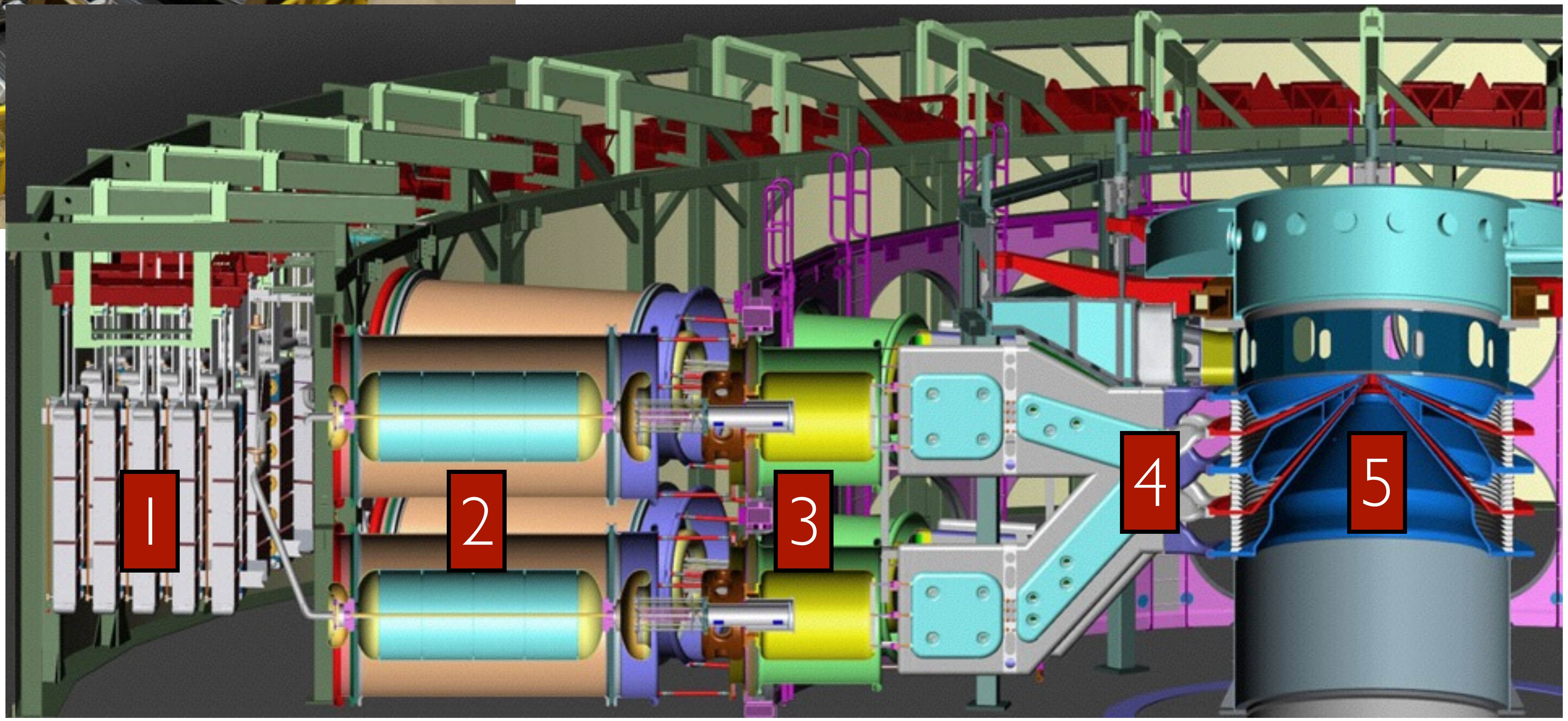
Spectroscopic fits to hot DQ WD SDSS J1153+0056.

Masses derived from such fits are crucial in understanding Type Ia supernovae and massive stars in the Galaxy.

Sandia National Laboratories’ Z-machine

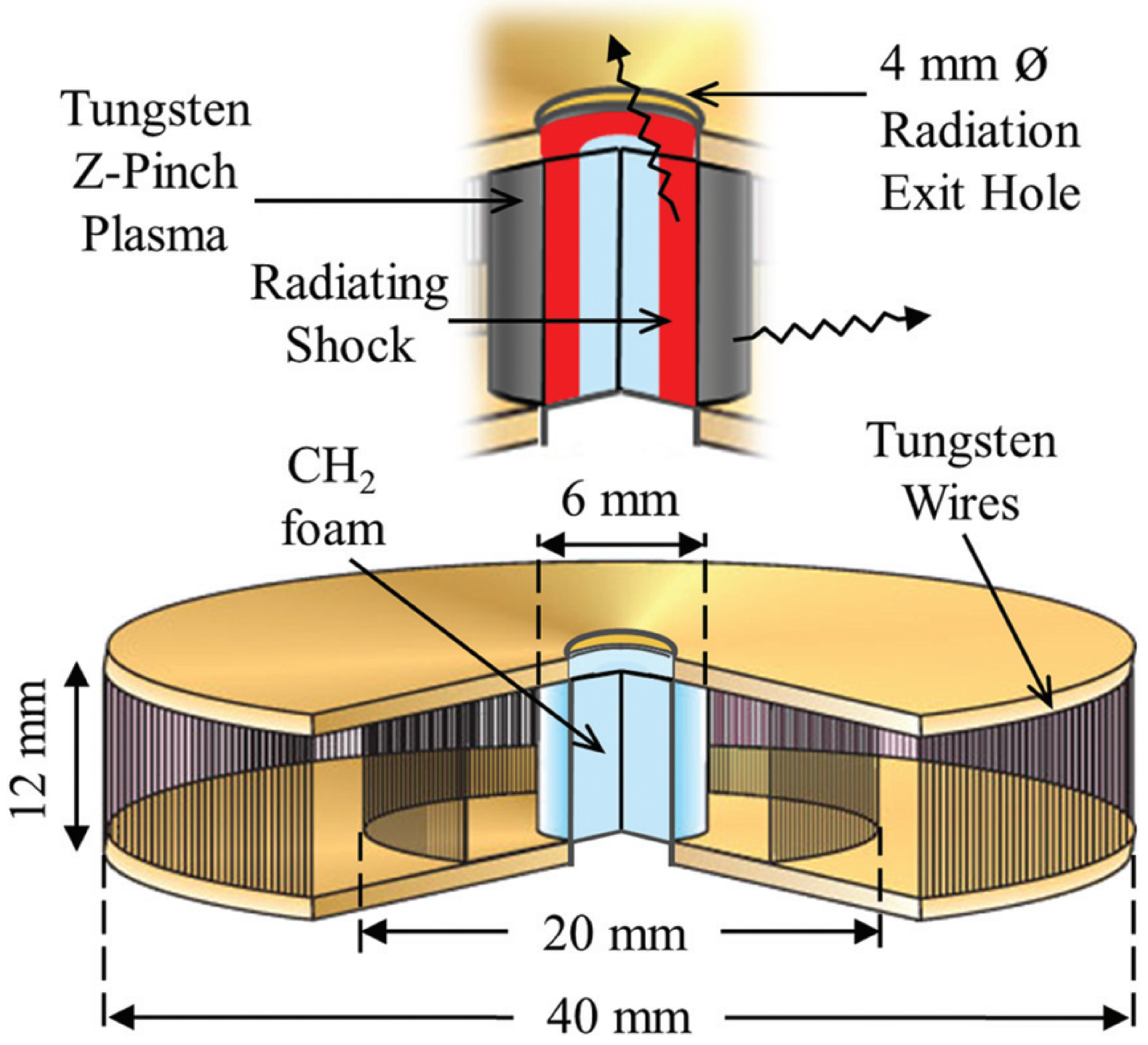


- 36 Marx bank generators at 85 kV
- current gets compressed in time and space
- x-ray output energy: 2 MJ
- broadband x-ray spectrum from 0.1 - 3 keV



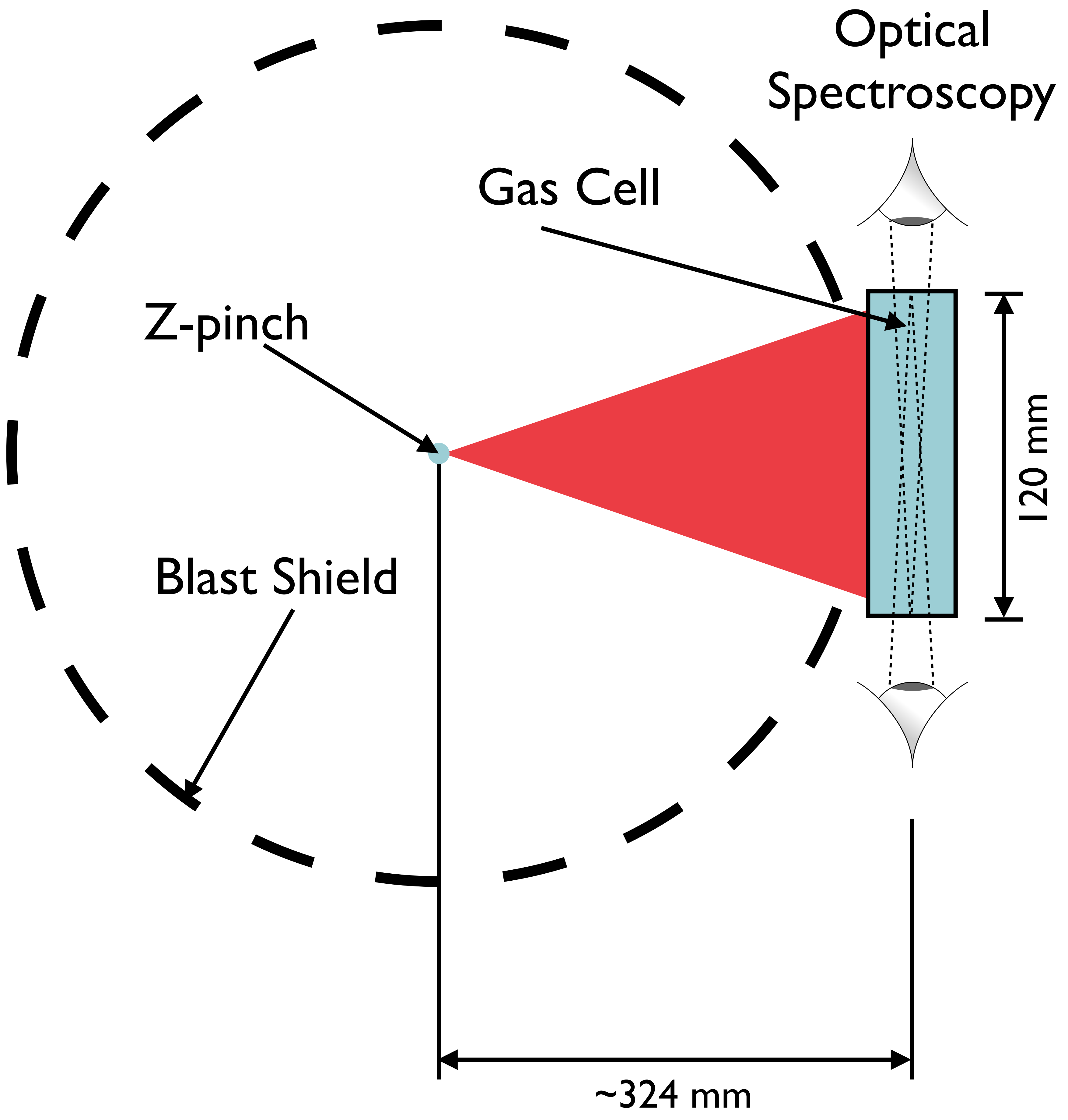
1 - 3: capacitors with decreasing rise times
4: transmission lines
5: vacuum chamber with dynamic hohlraum

Sandia National Laboratories' Z-machine



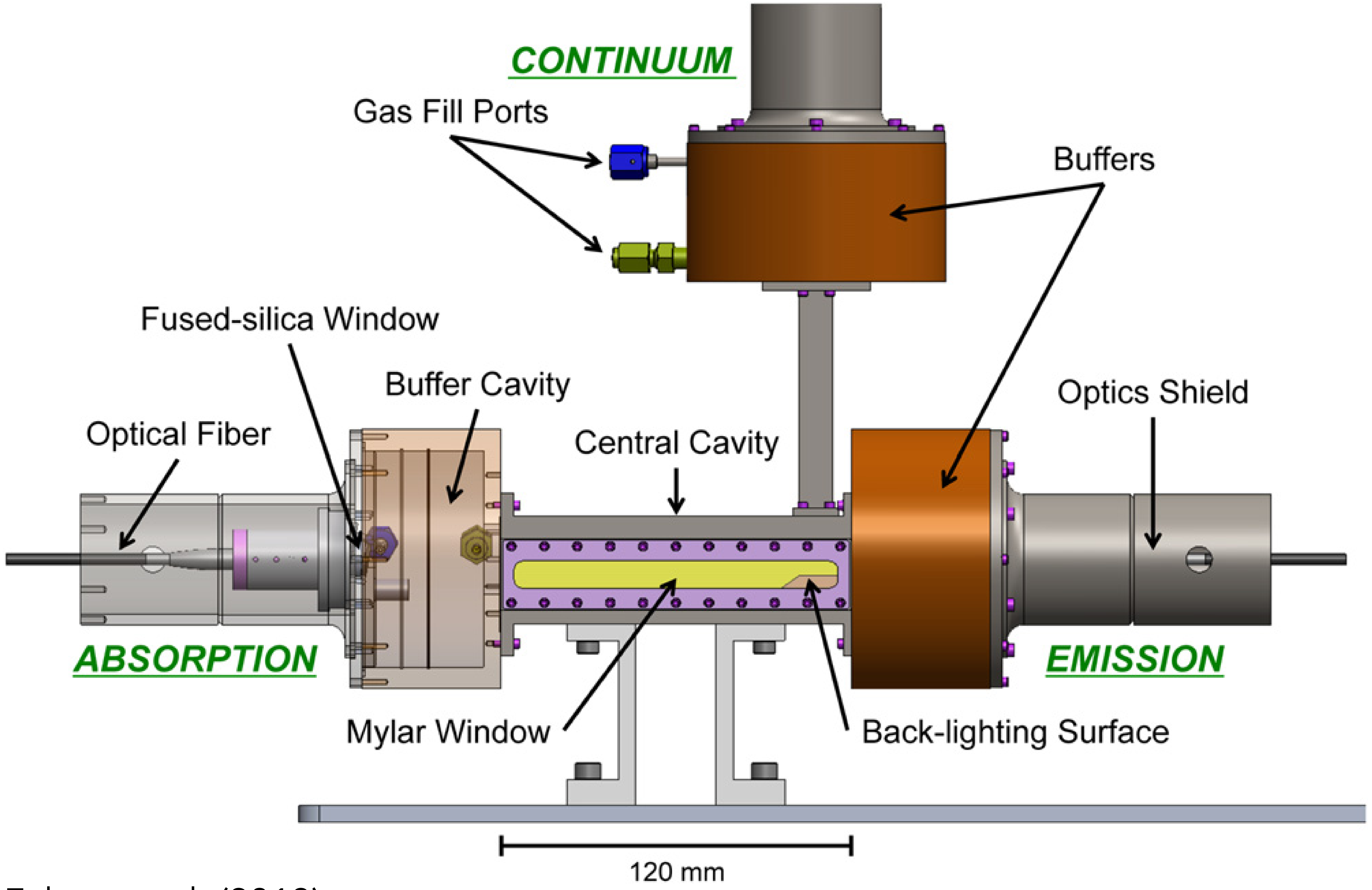
Rochau et al. (2014)

The dynamic hohlraum located at the center of the vacuum chamber. The current travels up tungsten wires, turning them into a plasma. The magnetic force pulls the plasma particles toward the CH_2 foam and produces a broadband x-ray drive.



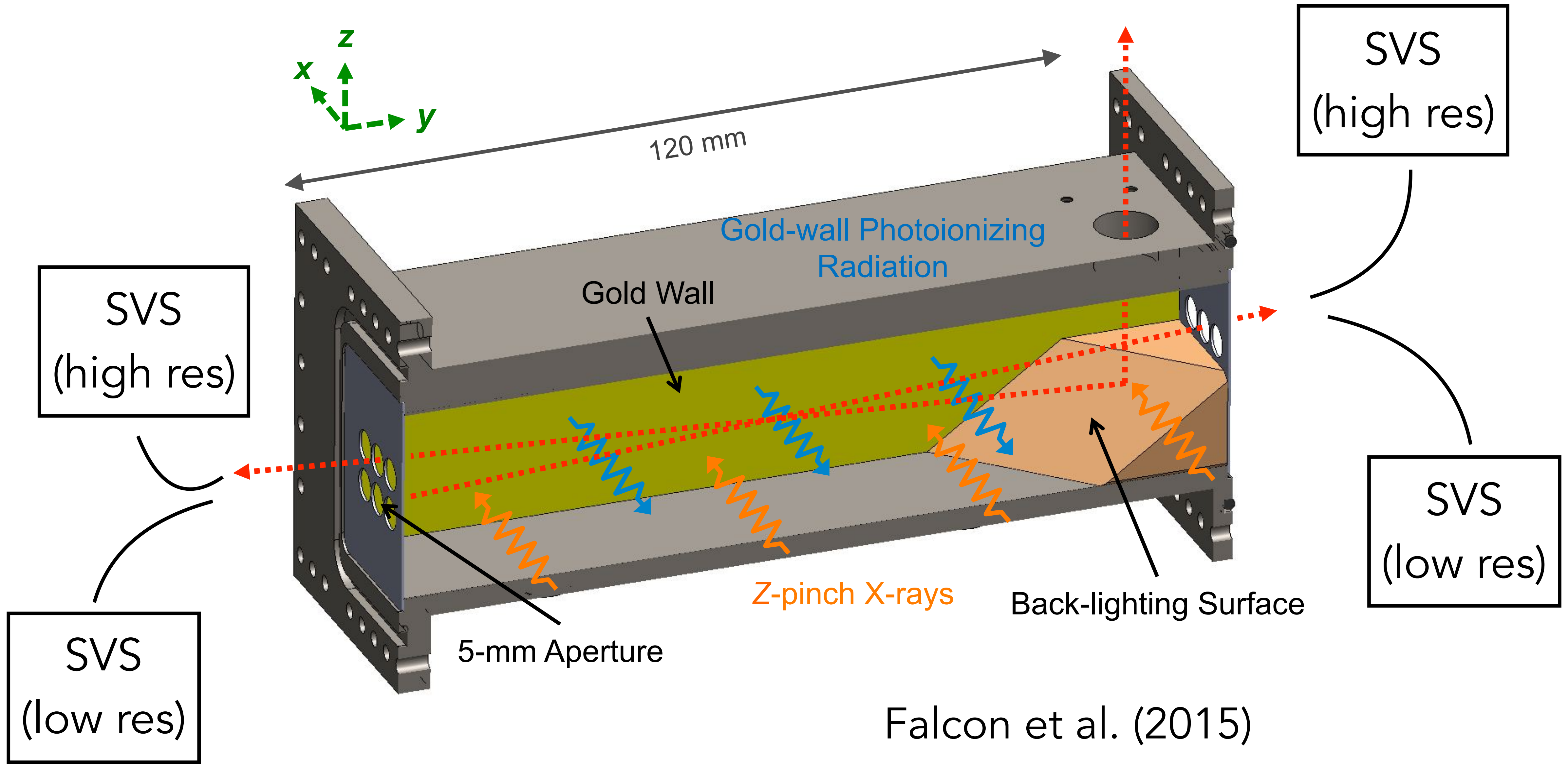
Location of WDPE gas cell with respect to the *Z*-pinch.

The WDPE gas cell



Falcon et al. (2013)

The WDPE gas cell. X-rays enter our gas cell through the Mylar window and heat up the gold wall. The optics are protected by the buffers.



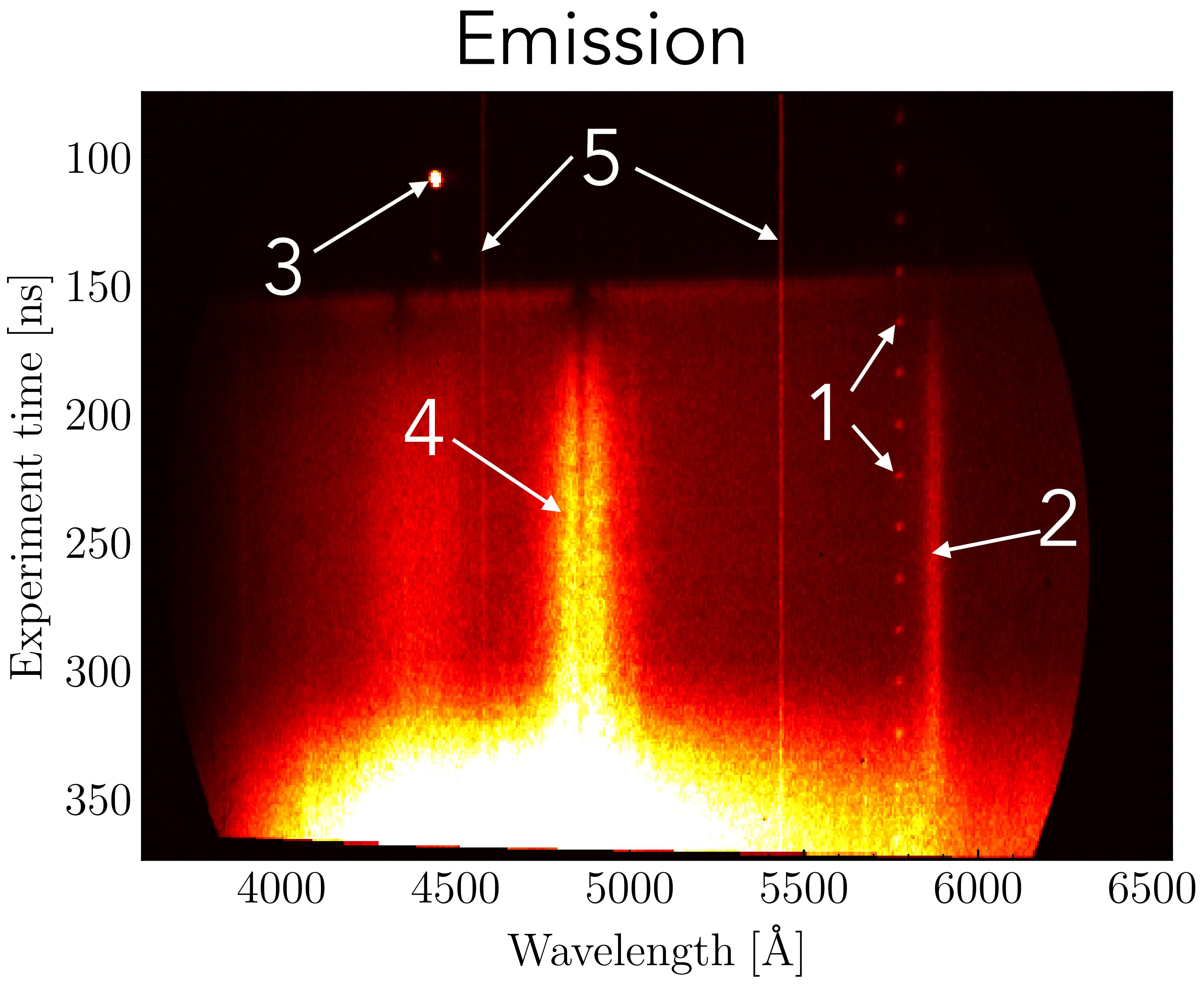
Falcon et al. (2015)

The 'meat' of the WDPE gas cell. Filtered Z-pinch x-rays enter the cell and heat up the gold wall. This wall then emits a Planckian of ~10eV, heating the gas in the gas cell.

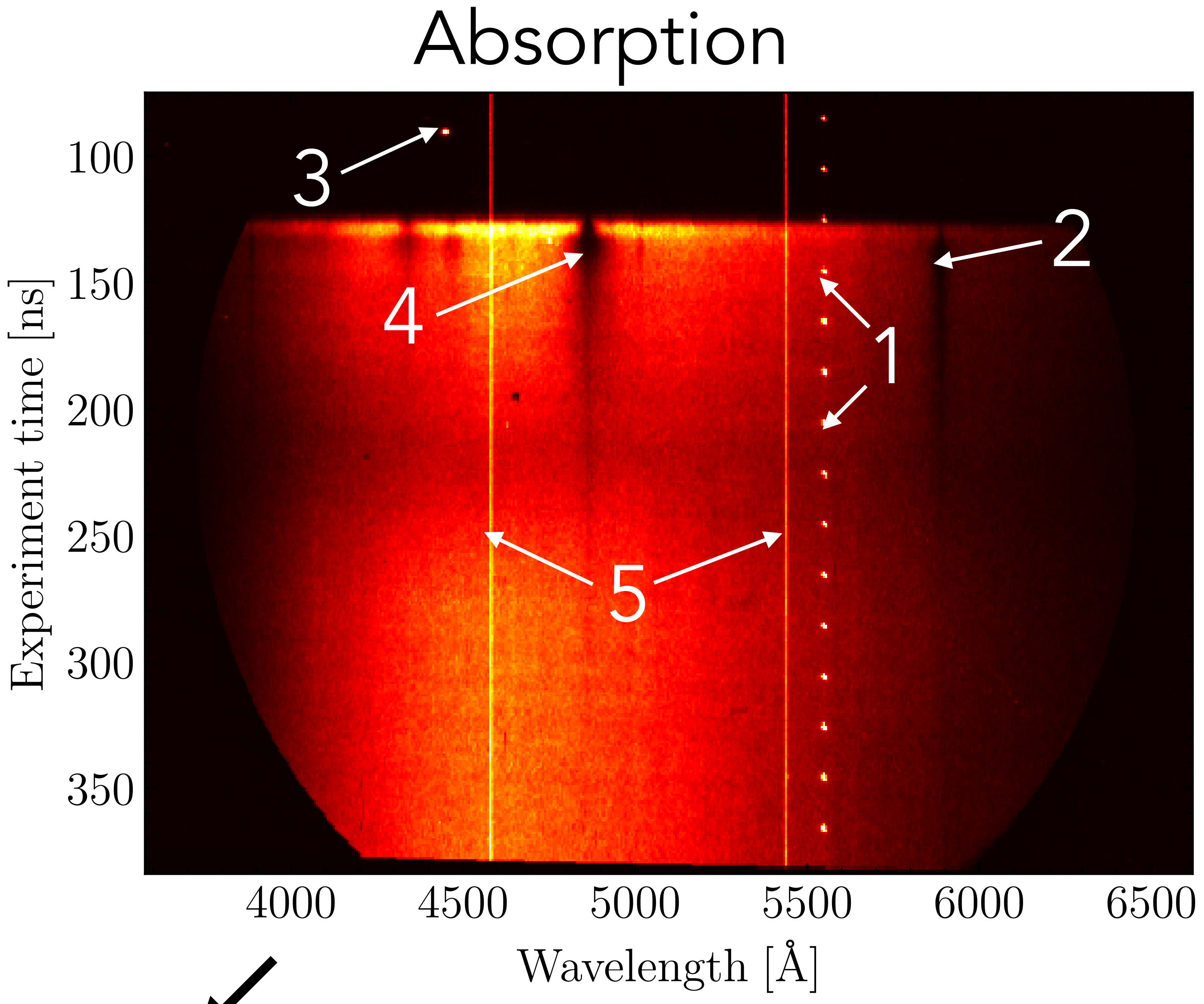
SVS: streaked visible spectrometer

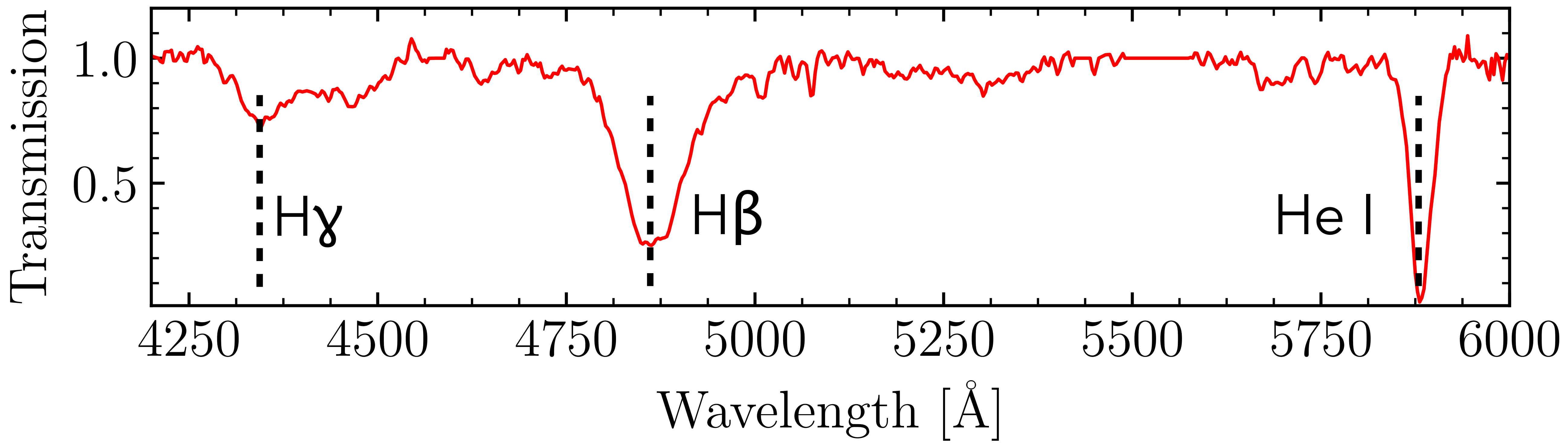
Experimental data - low resolution

Film data



1: timing comb
2: 5876 Å He I
3: impulse
4: Hβ
5: laser fiducial

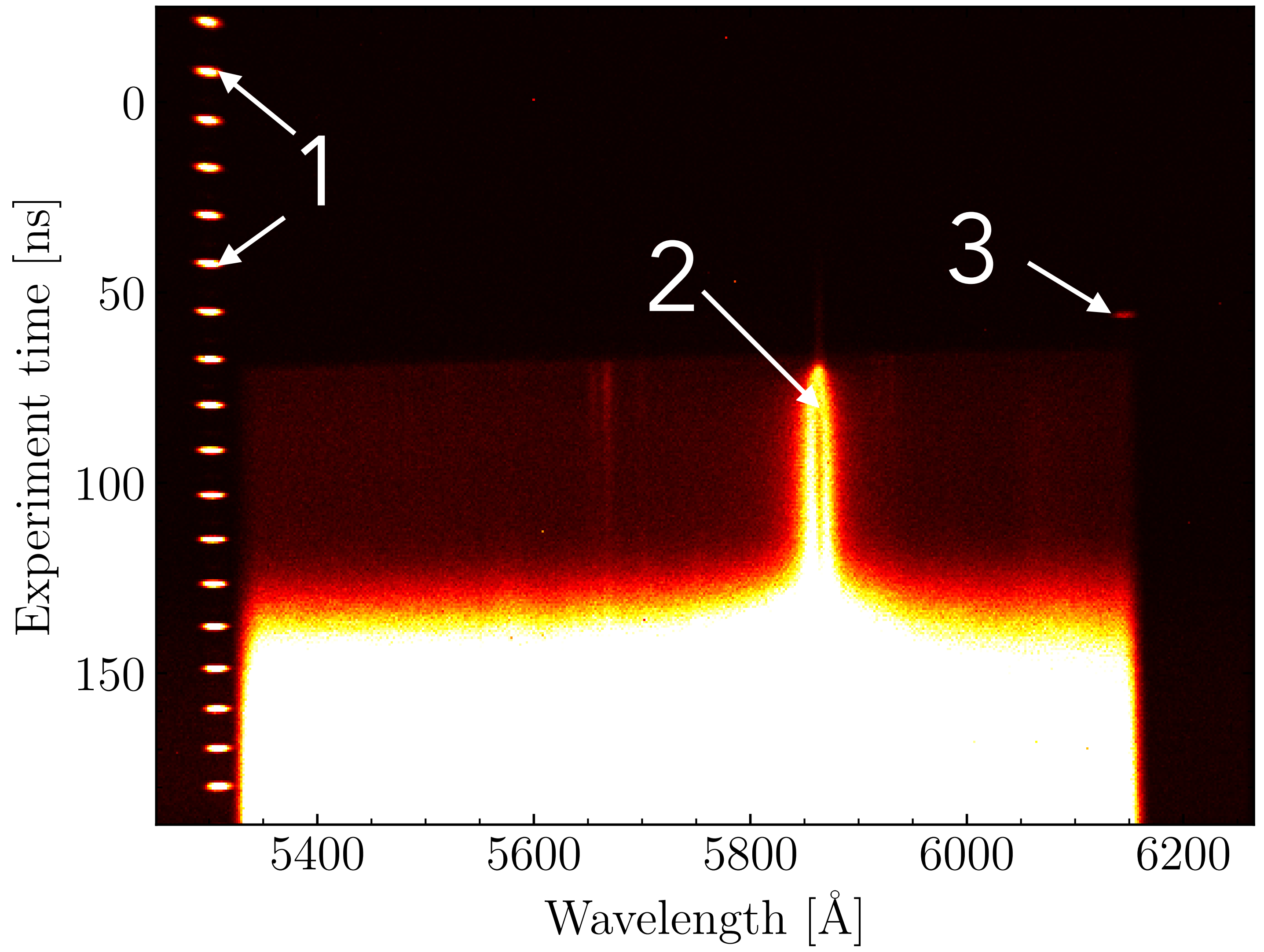


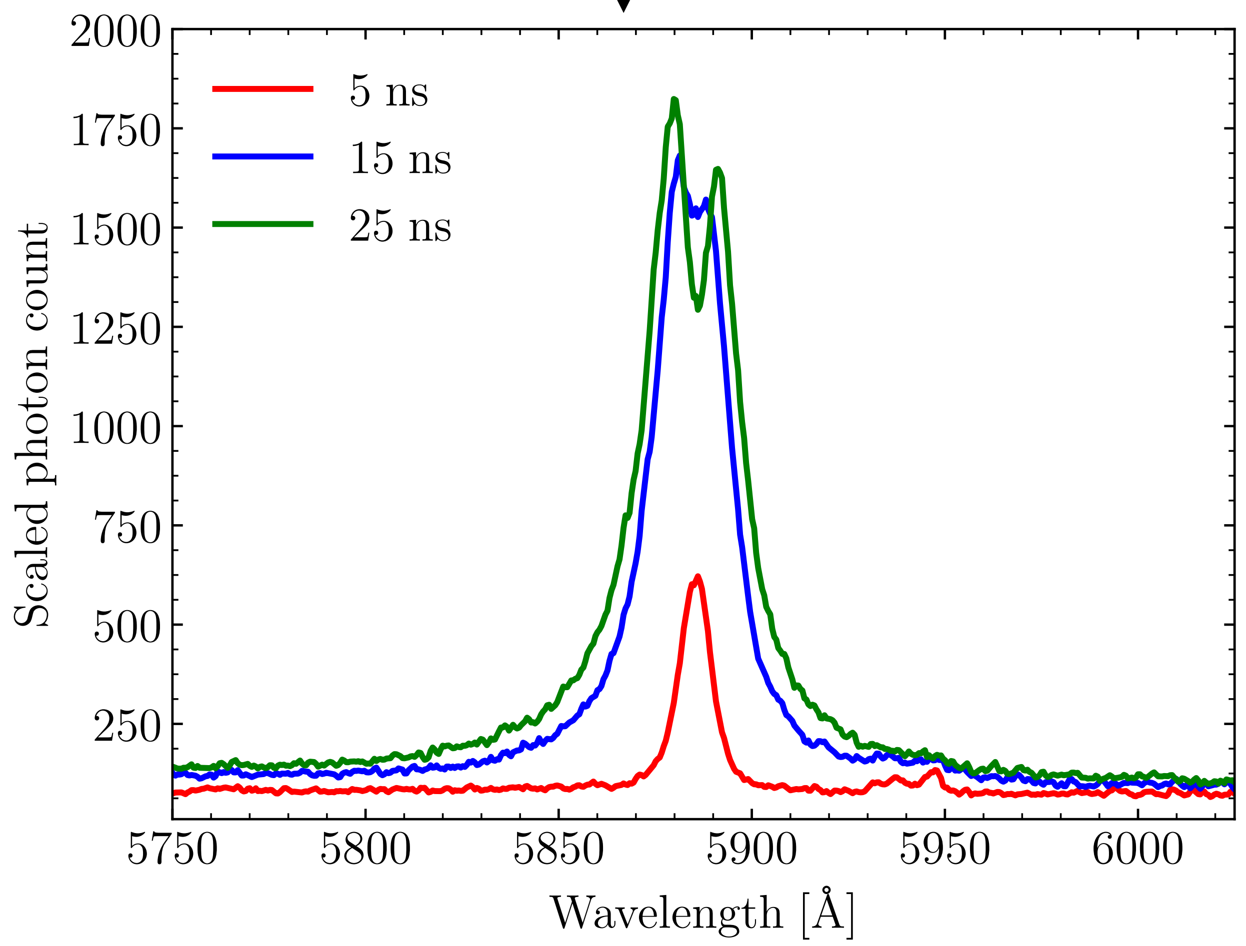


Experimental data - high resolution

CCD data

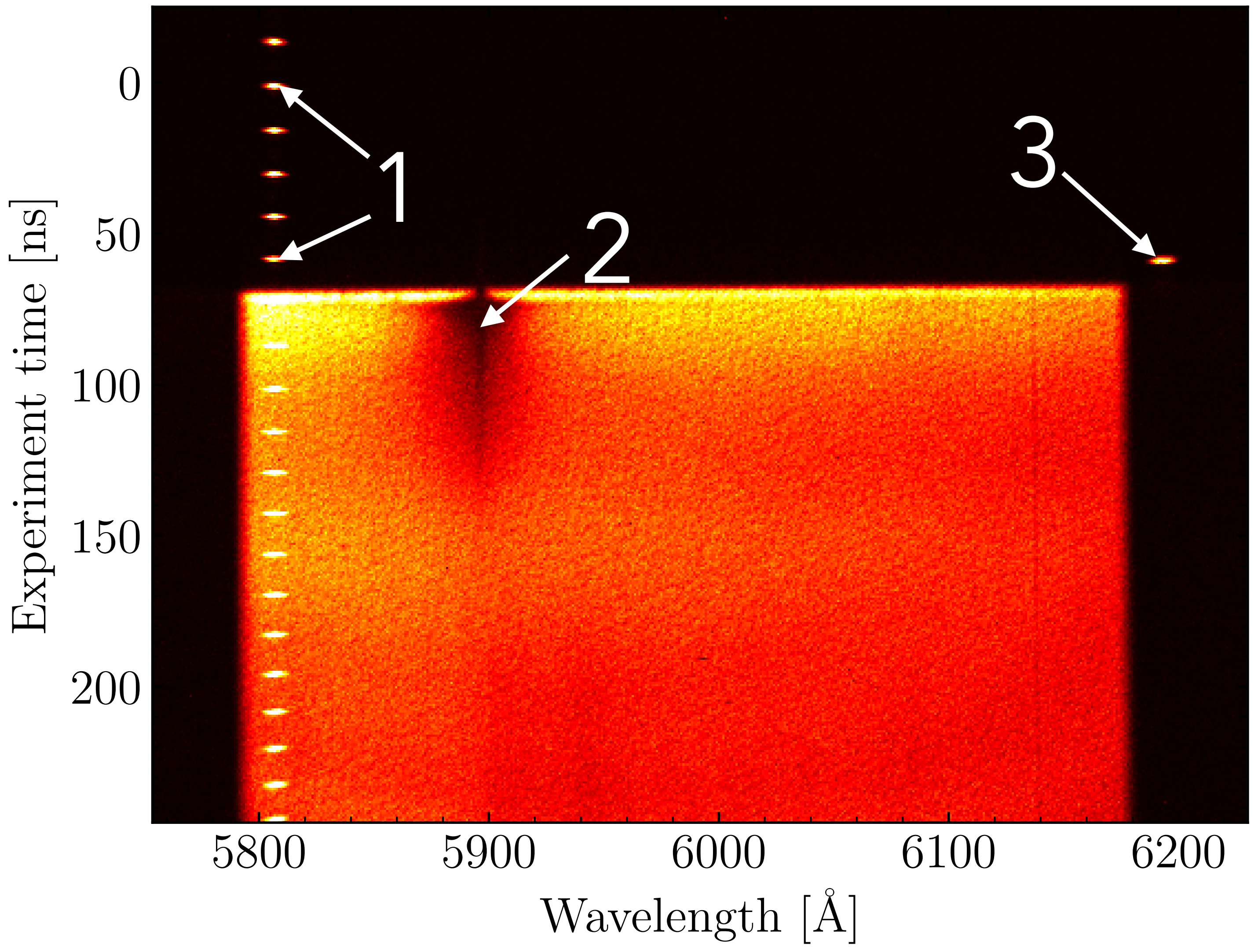
Emission

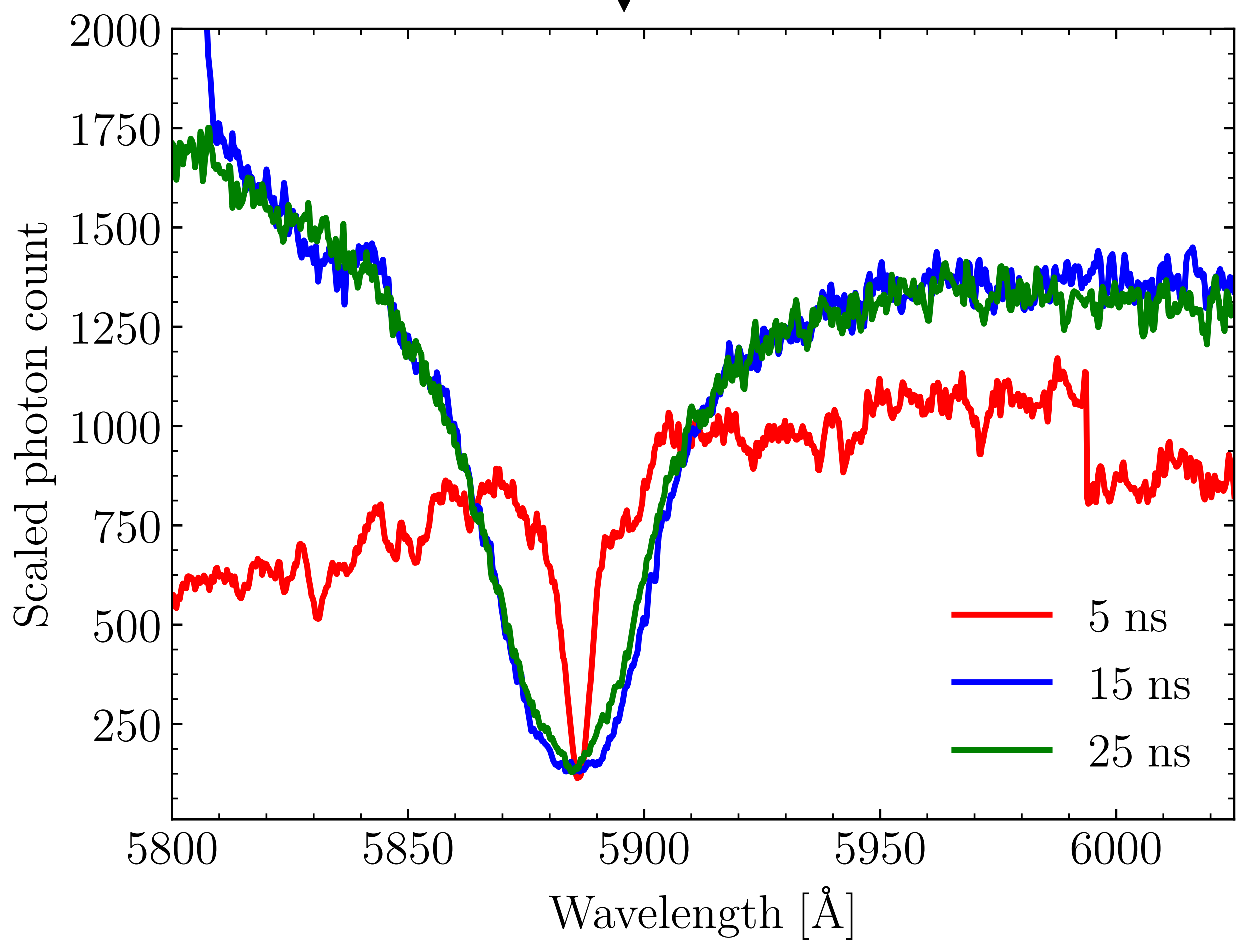




1: timing comb
2: 5876 Å He I
3: impulse

Absorption



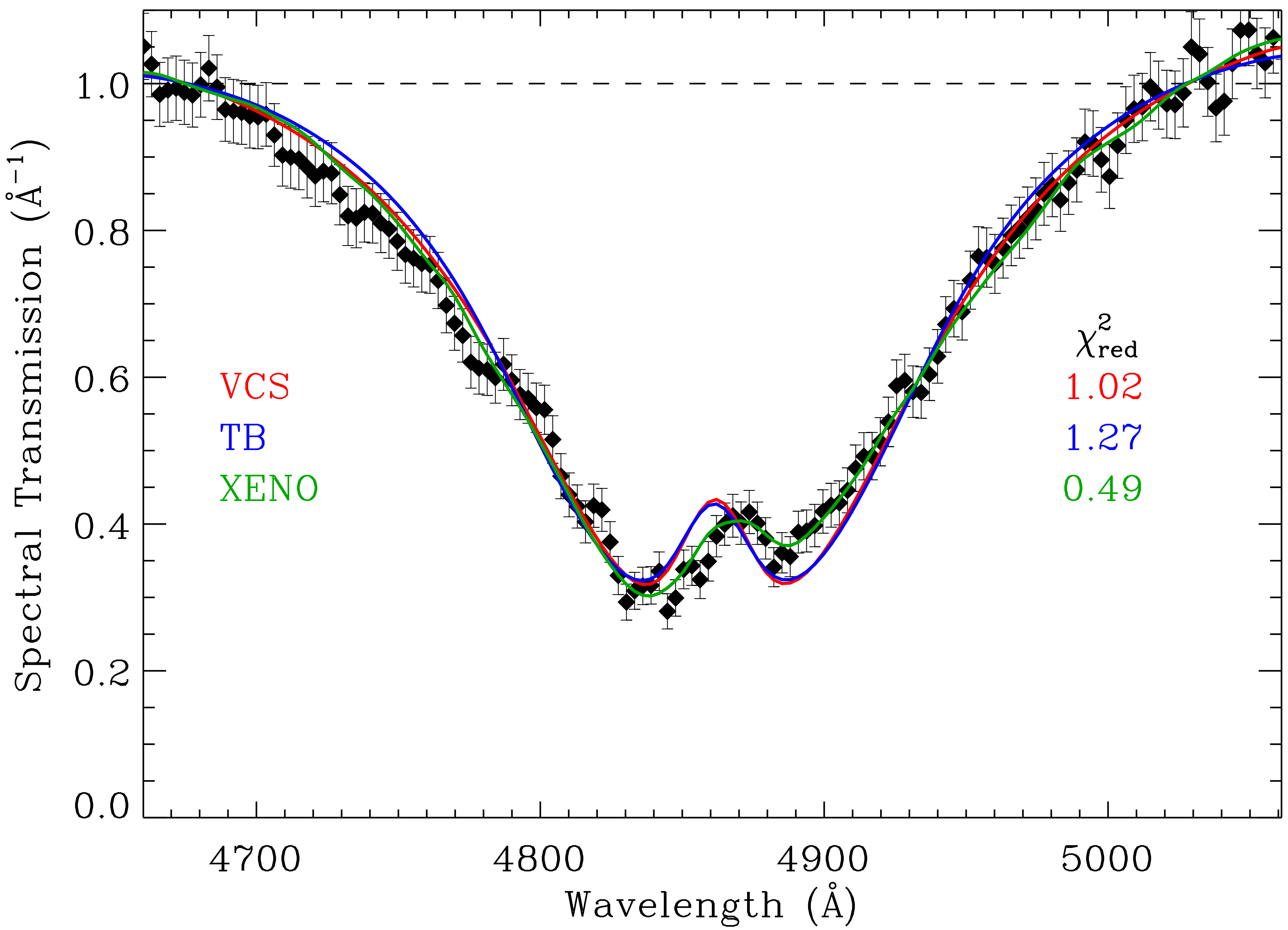


The hydrogen data - line shapes

- WDPE hydrogen data has guided theoretical developments for hydrogen line shapes used in model atmospheres

- differences at low densities (n_e > 3e17 cm^{-3}) between theories are negligible; high-density regime is problematic

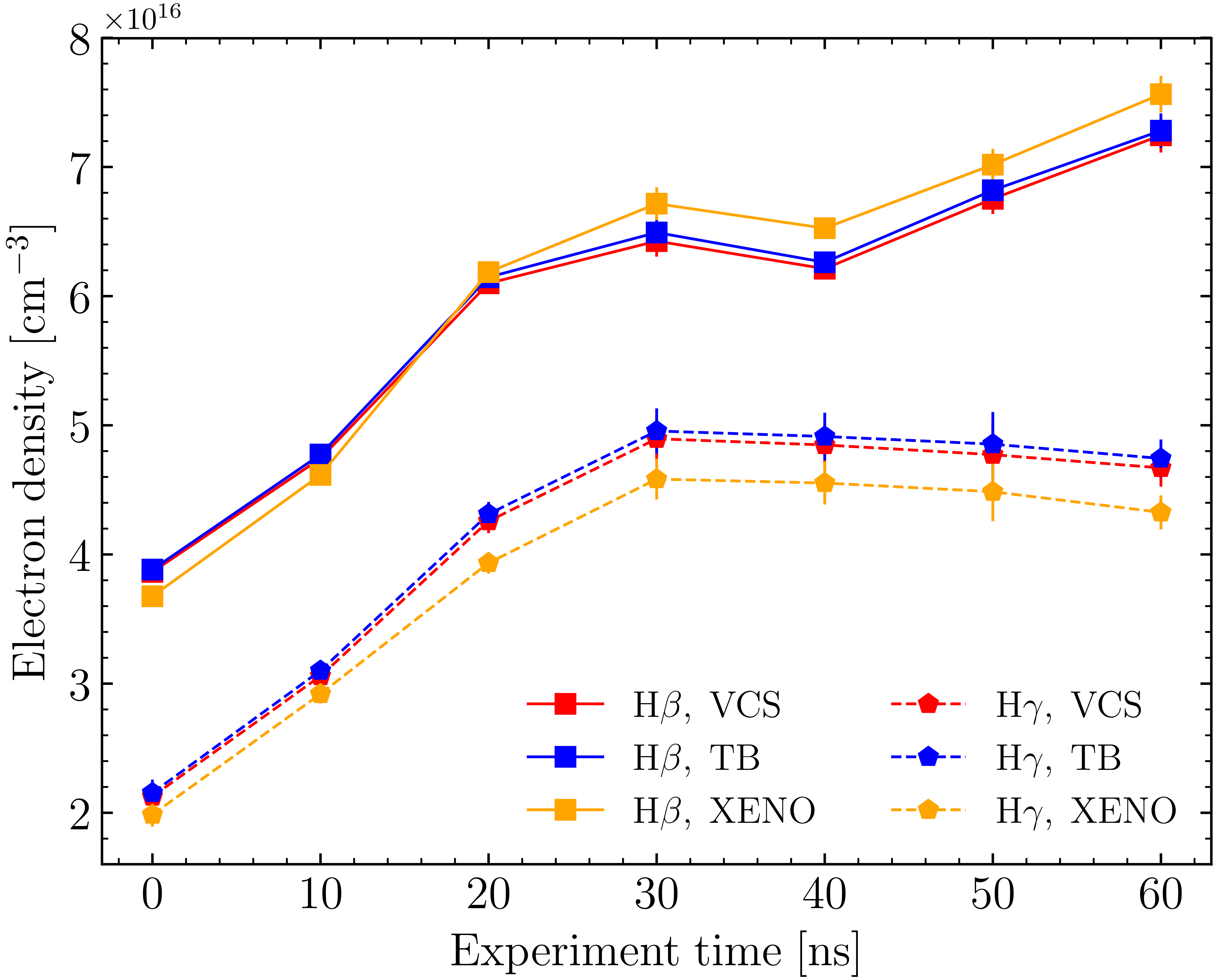
- new hydrogen line shapes result in an increased WD mass (~5%) at all temperatures

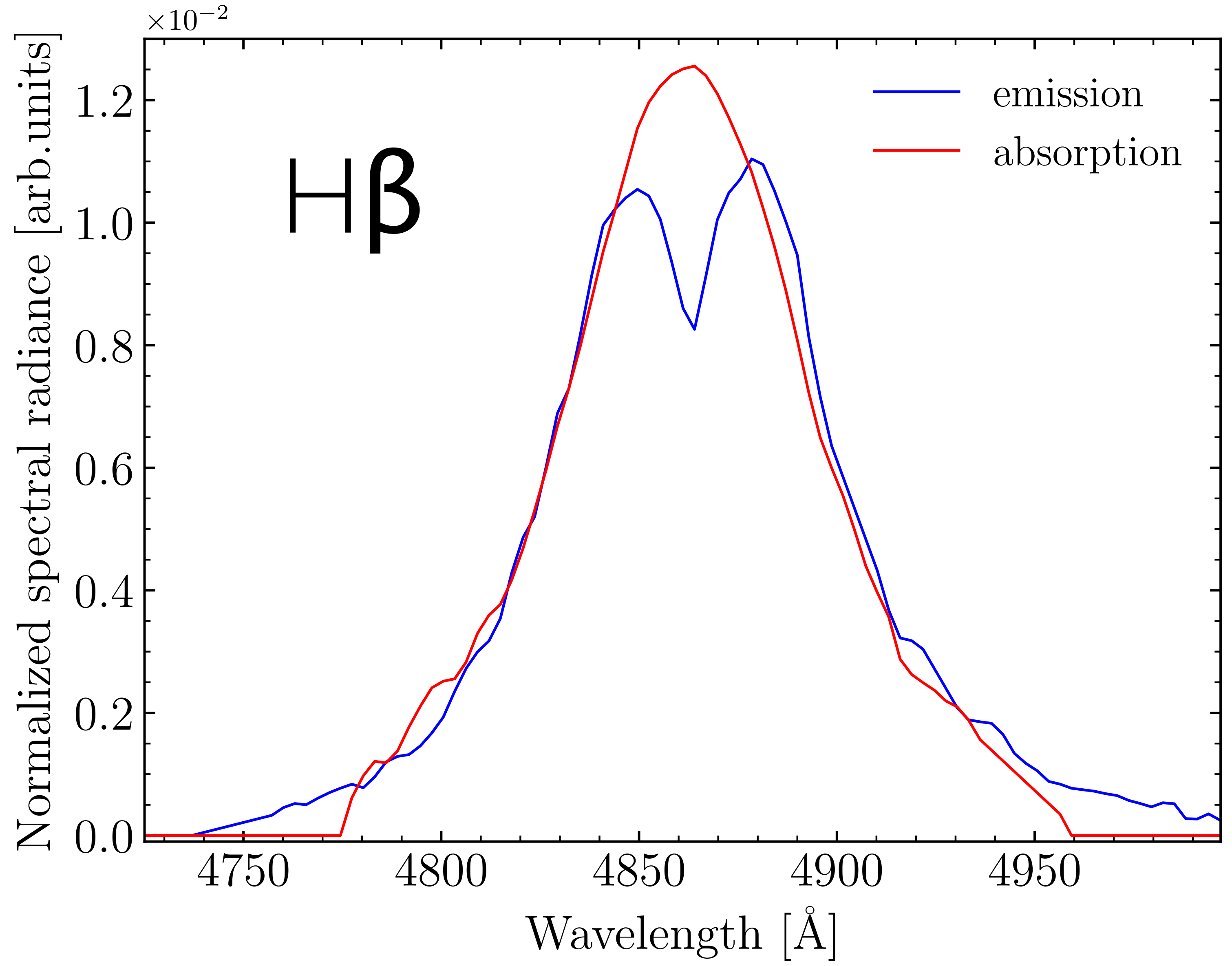


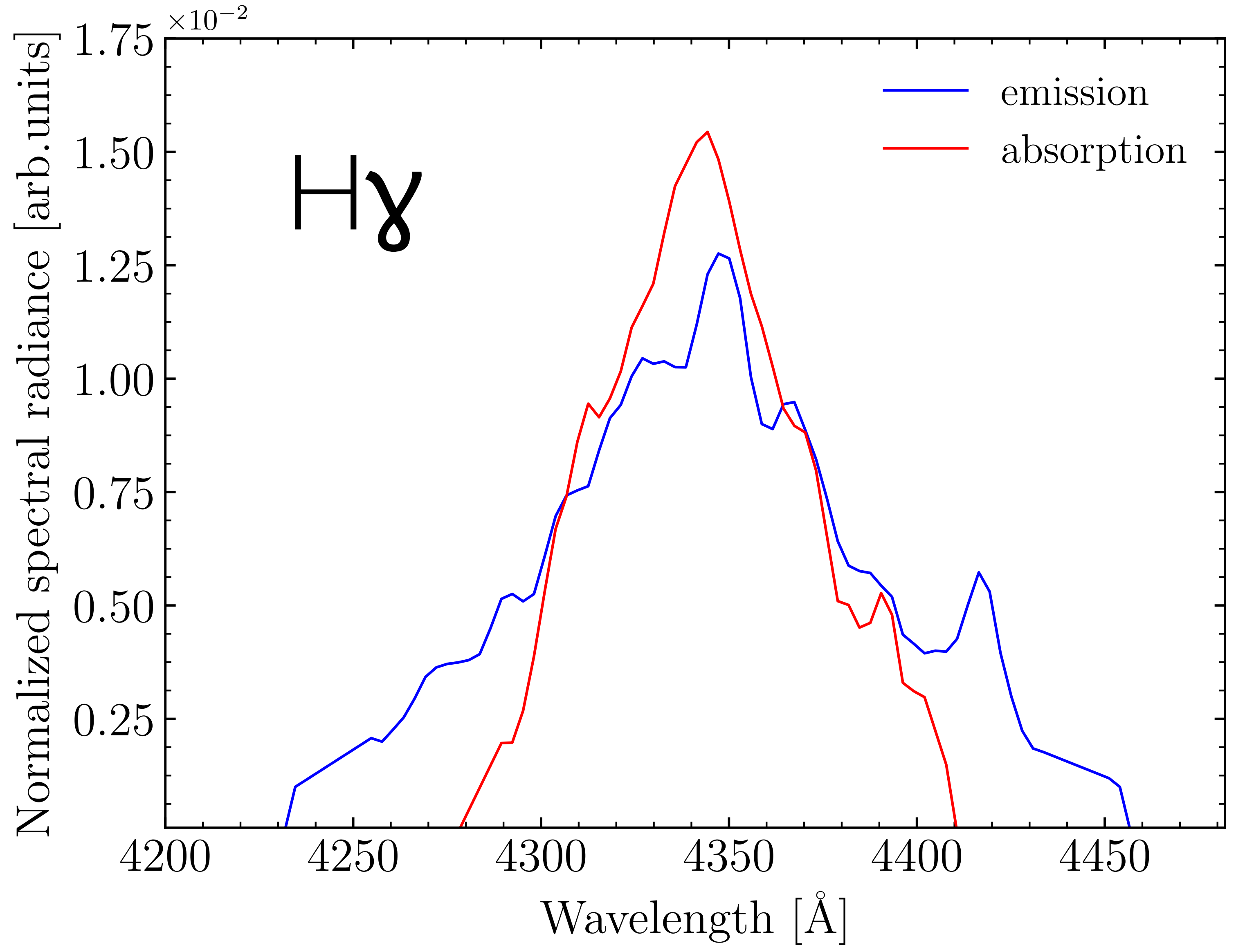
Falcon et al. (2017)

Sample spectrum of recent hydrogen experiment. Differences in theory are apparent.

The hydrogen data - emission and absorption



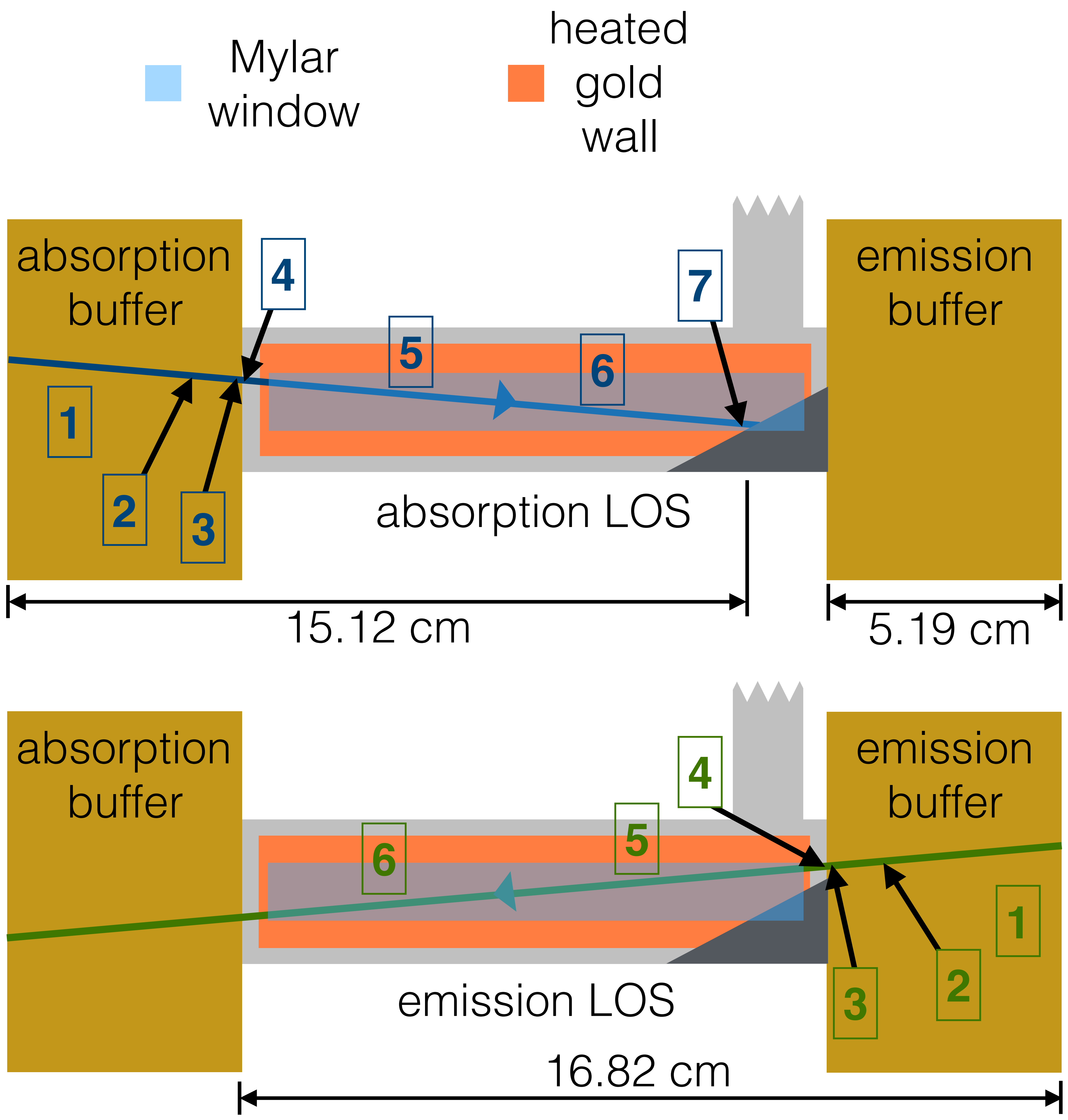




Line shapes for Hβ and Hγ disagree across a variety of electron densities and shots.

Inferred n_e values of Hβ and Hγ differ by roughly 30%, which translates to ΔFWHM of 20%.

The hydrogen data - simulations



Identifier	Name	Extent [cm]	Simulated Temperature [eV]
1	Outer buffer	0.00 - 4.00	0.025
2	Buffer transition	4.00 - 5.00	0.025 - 0.050
3	Hot buffer	5.00 - 5.12	0.050 - 0.85
4	Unheated Plasma	5.12 - 6.26	0.85 - 1.70
5	Heated Plasma Rising	6.26 - 11.54	1.10 - 1.70
6	Heated Plasma Falling	11.54 - 14.12	1.70 - 1.40
7	Backlighter	14.12 - 15.12	1.40 - 2.20

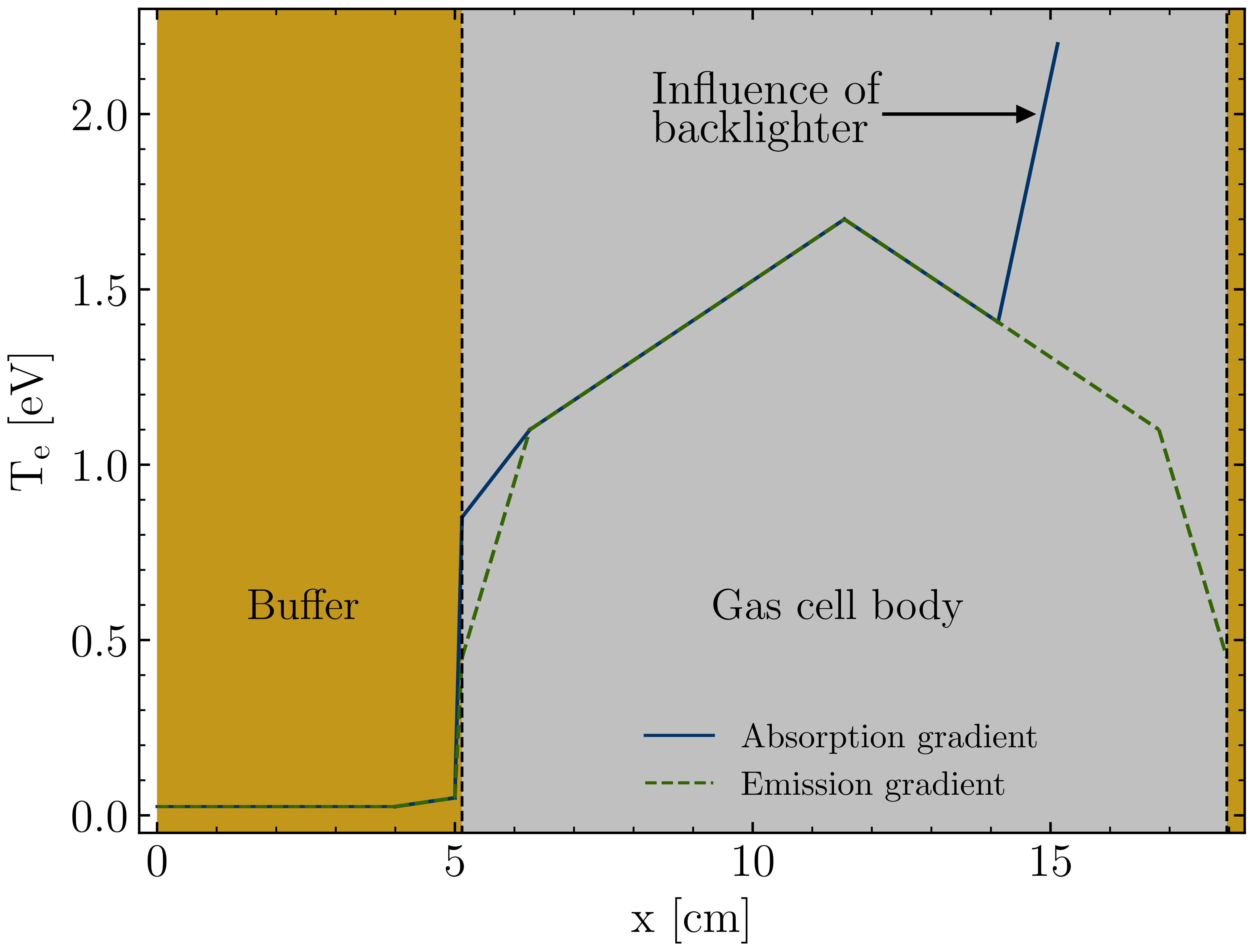
absorption LOS

Identifier	Name	Extent [cm]	Simulated Temperature [eV]
1	Outer buffer	0.00 - 4.00	0.025
2	Buffer transition	4.00 - 5.00	0.025 - 0.050
3	Hot buffer	5.00 - 5.12	0.050 - 0.45
4	Unheated Plasma	5.12 - 6.26	0.45-1.1
5	Heated Plasma Rising	6.26 - 11.54	1.1 - 1.7
6	Heated Plasma Falling	11.54 - 16.82	1.7 - 1.1

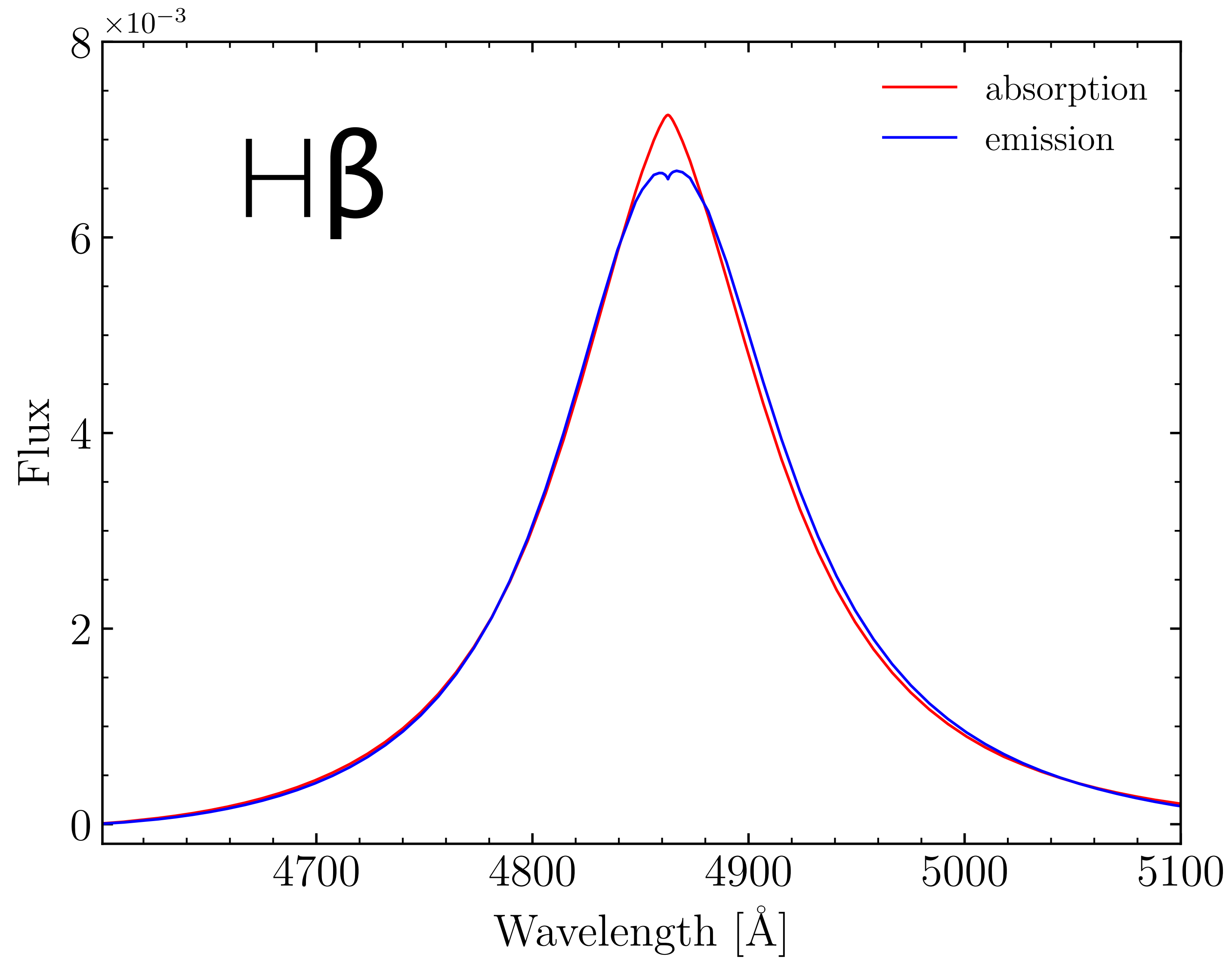
emission LOS

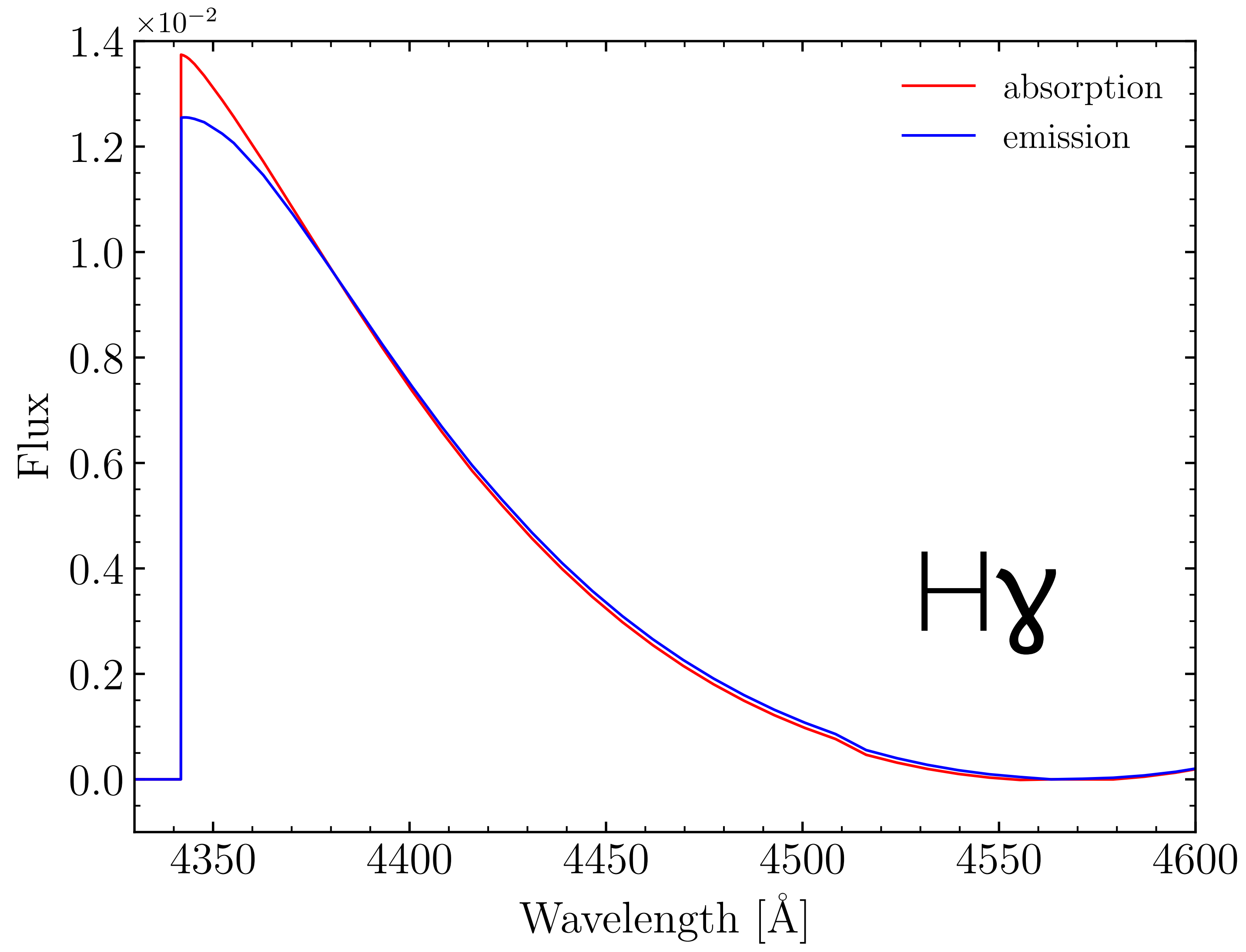
Results of VisRad and Helios simulations along the emission and absorption lines-of-sight (LOS).

The hydrogen data - simulations



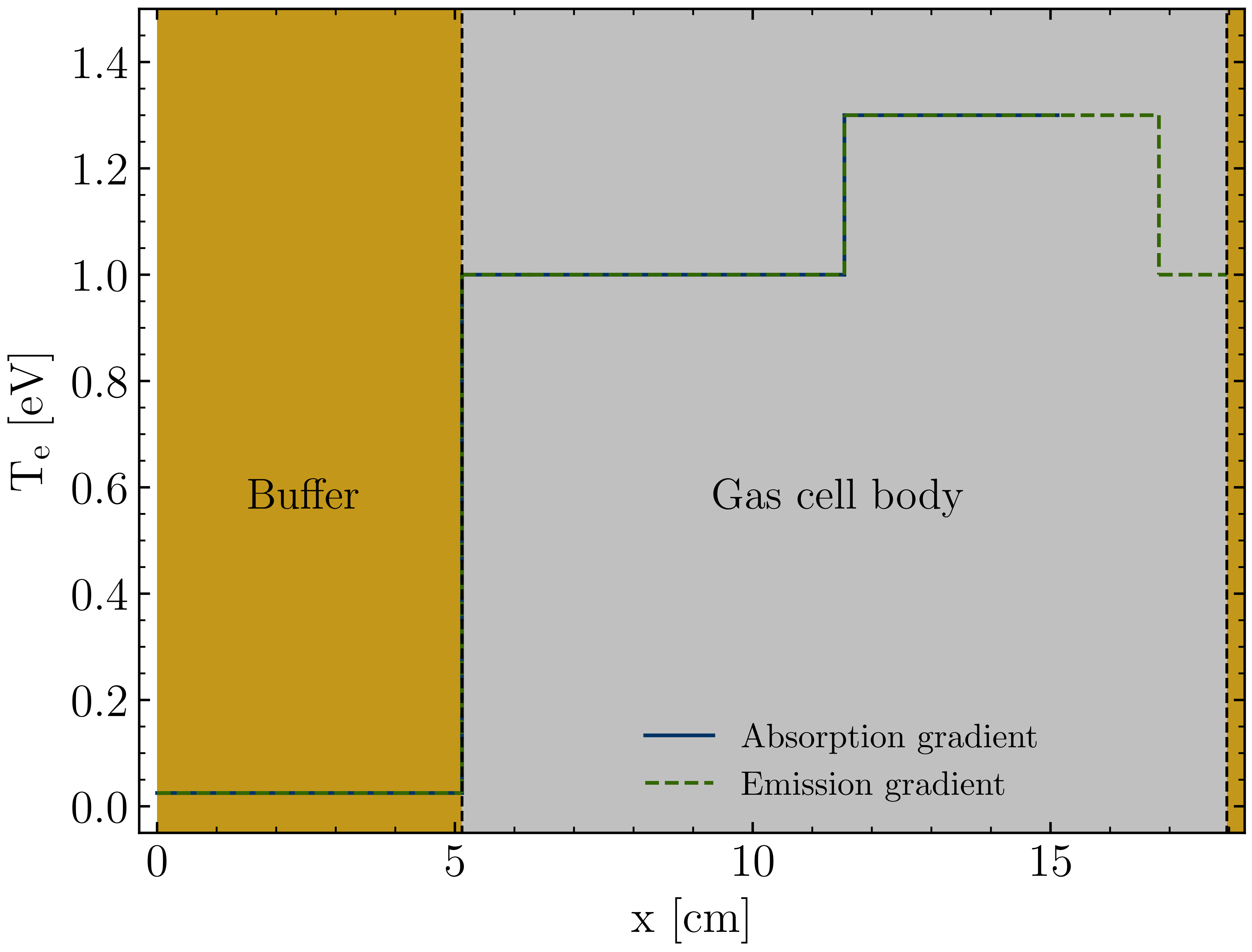
The 'nominal' gradient along the emission and absorption LOS. This temperature structure was used in Spect3D simulations.



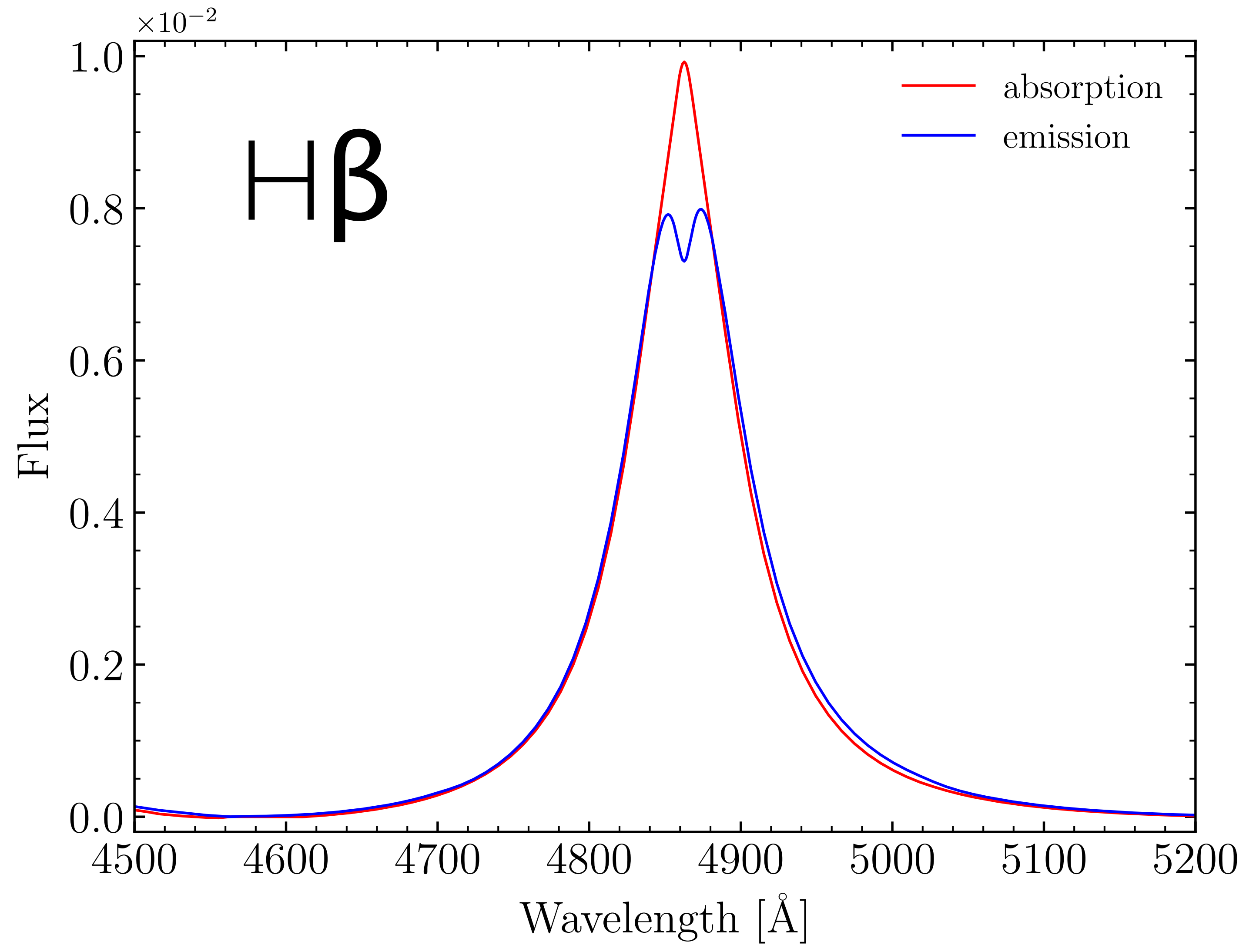


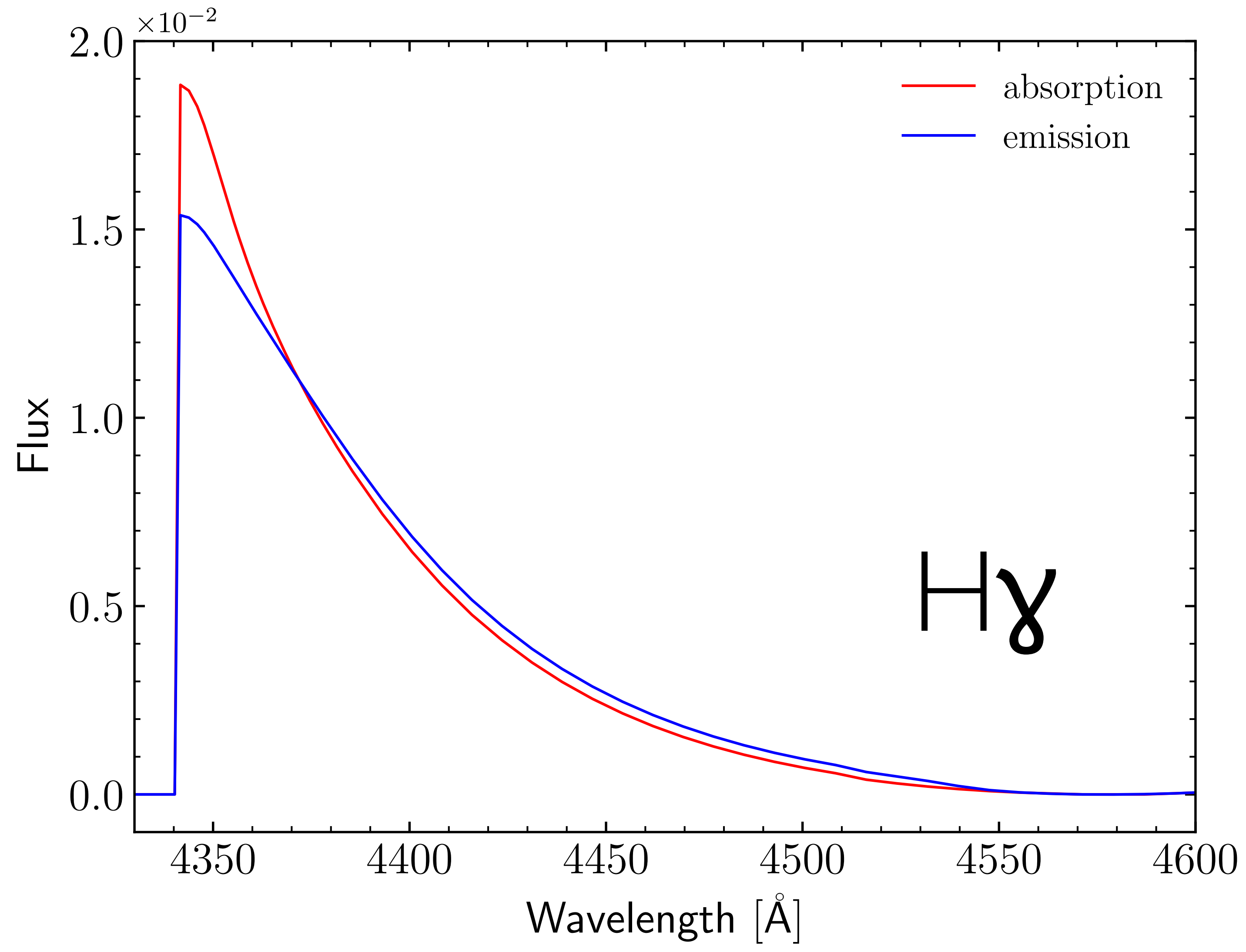
Area-normalized Hβ and Hɣ emission and absorption profiles resulting from Spect3D simulations. The effect of inhomogeneities cannot explain the observed difference of emission of absorption.

The hydrogen data - simulations



The 'altered' gradient that can reproduce the needed ΔFWHM of 20% between Hɣ emission and absorption, while leaving Hβ untouched.





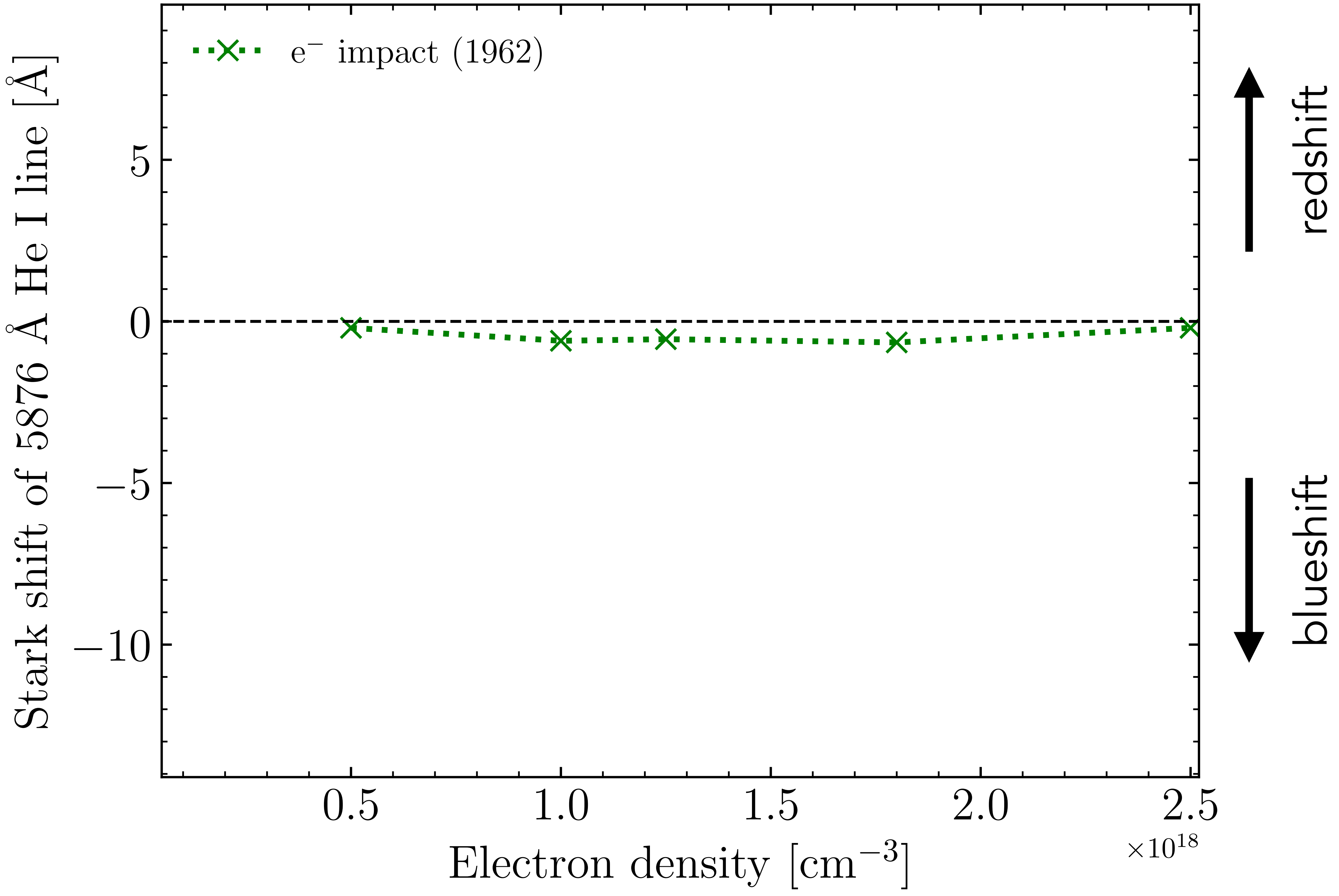
Area-normalized Hβ and Hɣ emission and absorption profiles resulting from Spect3D simulations. These profiles achieve the desired change in FWHM, but do not resemble the data.

The helium data - Stark shift calculations

- spectroscopic masses are uncertain - why not use the GR method to constrain the DB masses? → Stark shifts.

- He I 5876 Å line is the most prominent in the optical spectra of DBs

- theory and experiment agree very poorly on the Stark shift for that line



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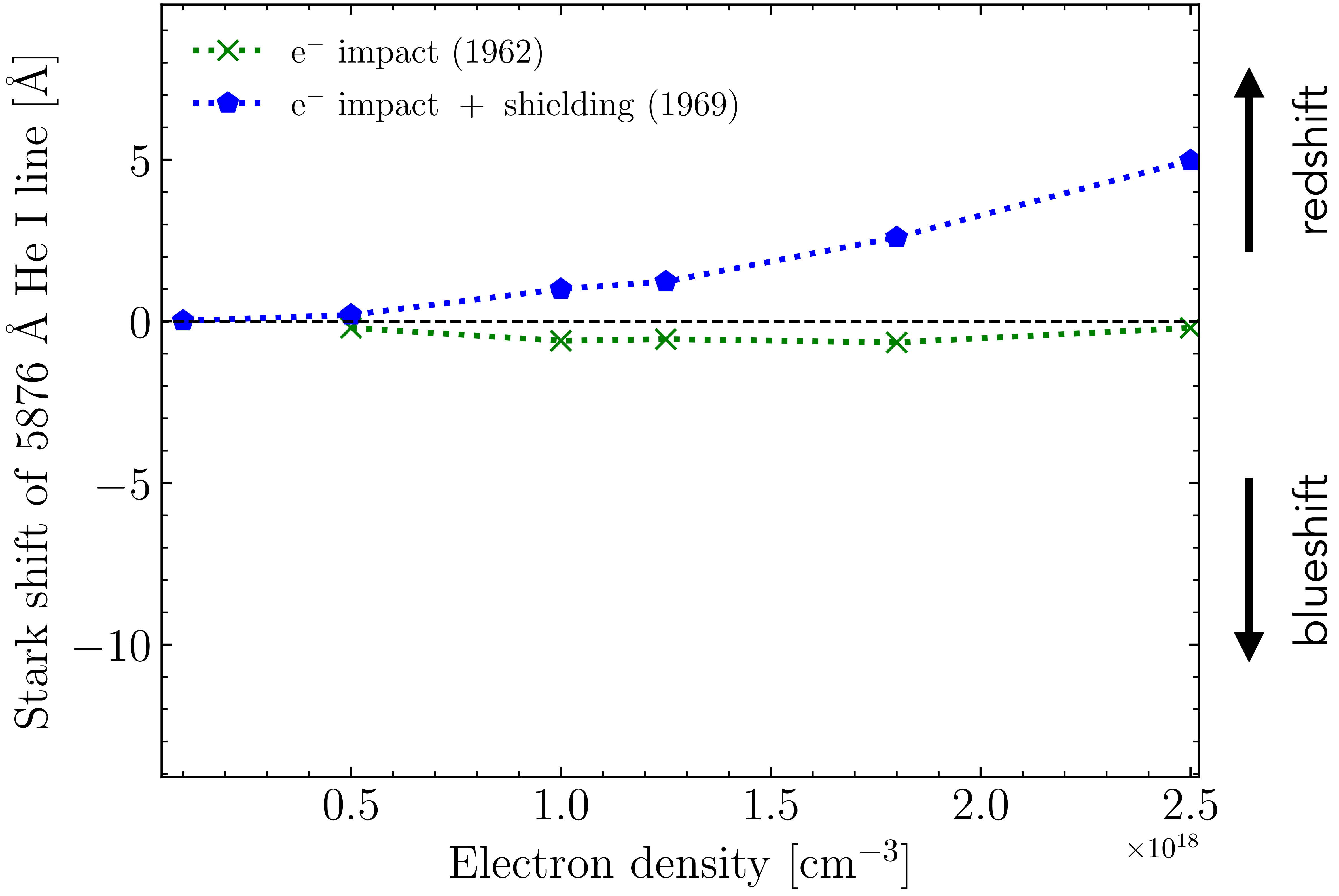

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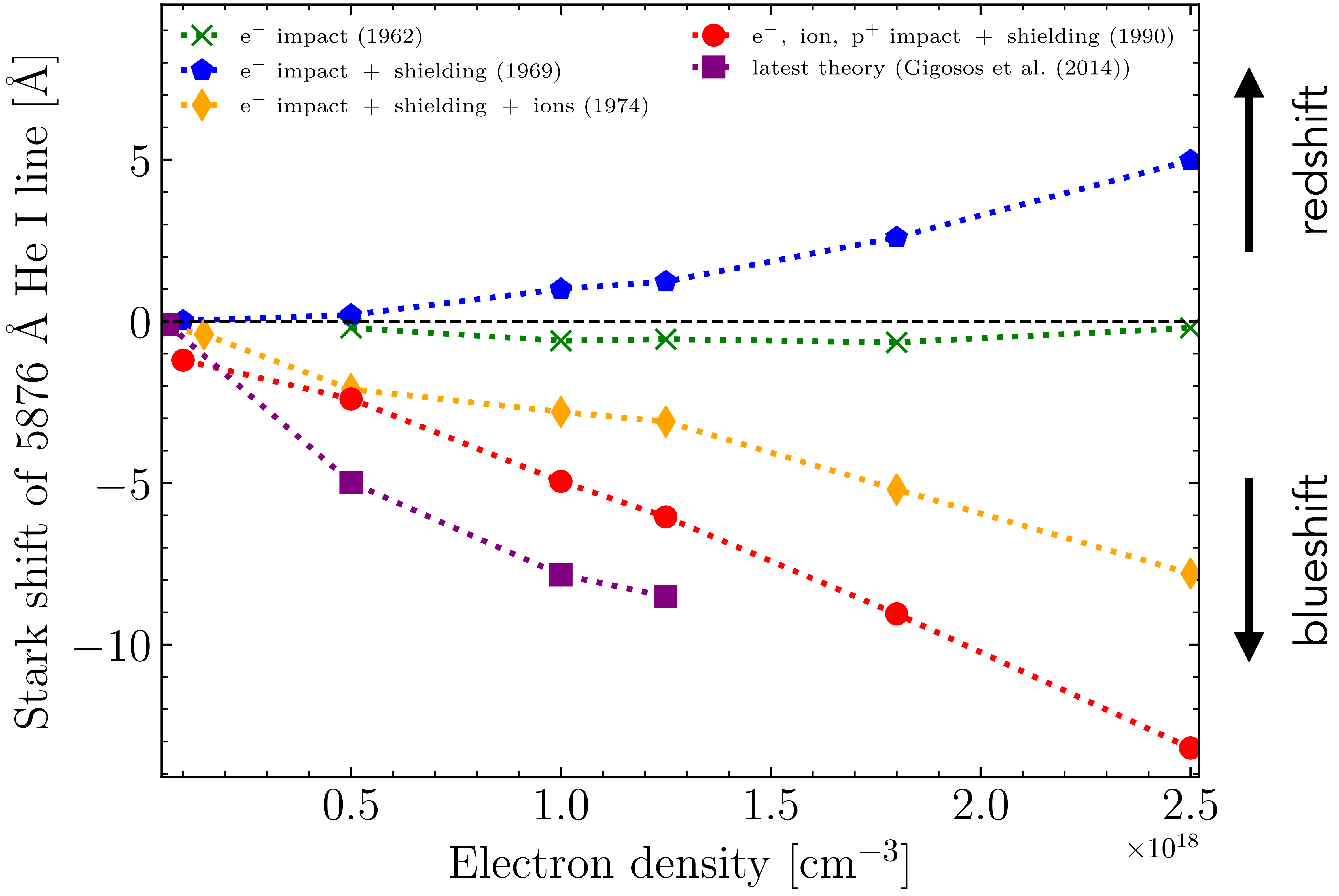
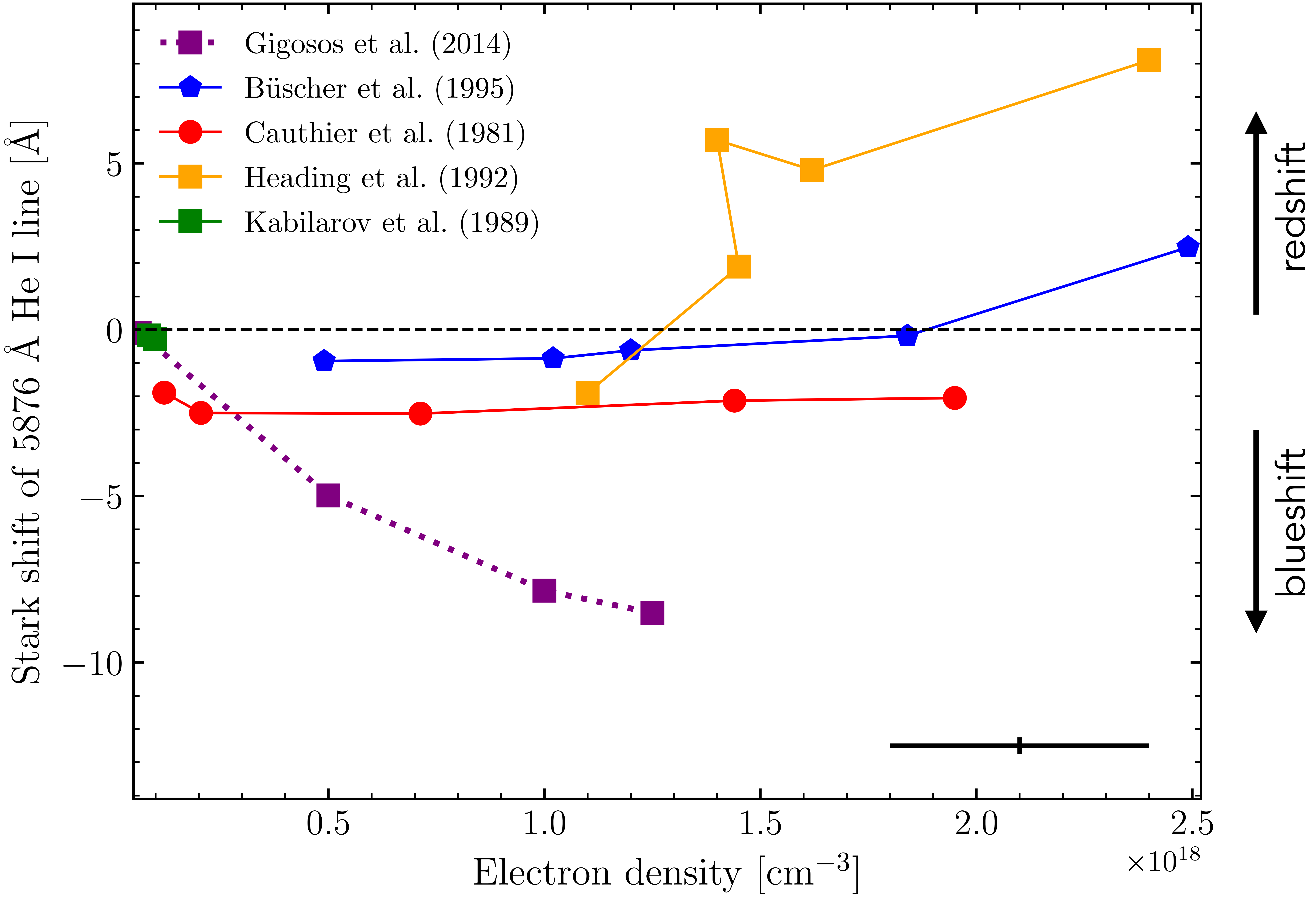


The helium data - previous experiments

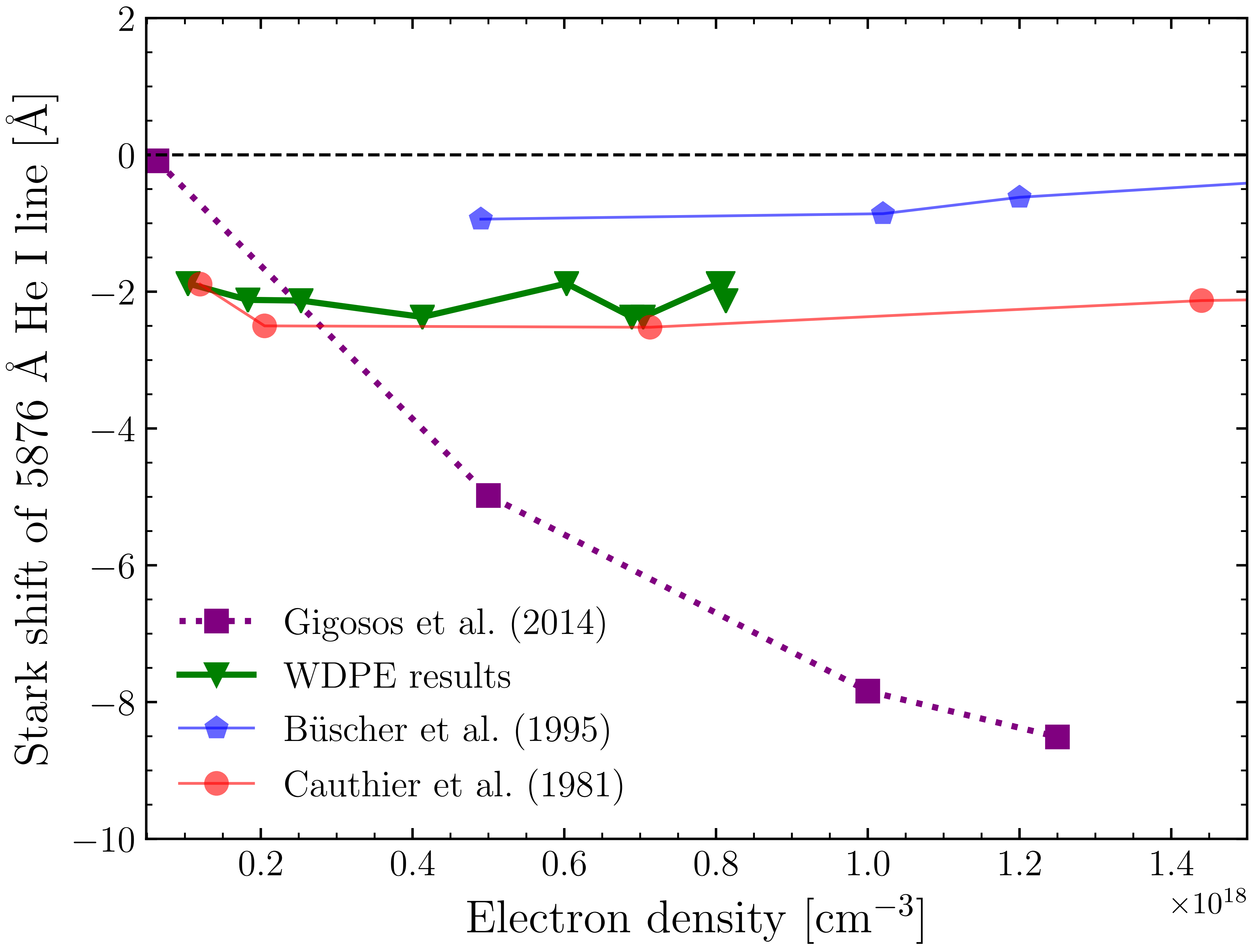


The helium data - experimental concerns

Concern	Our experiment (WDPE)
influence of self-absorption	emission and absorption data
single data points	range of n_e and T
uncertain n_e and T diagnostics	use of well-studied Hβ line profiles
influence of Doppler shifts	no Doppler shifts
plasma non-uniformities	use of Z allows creation of large, uniform plasma

The helium data - WDPE results

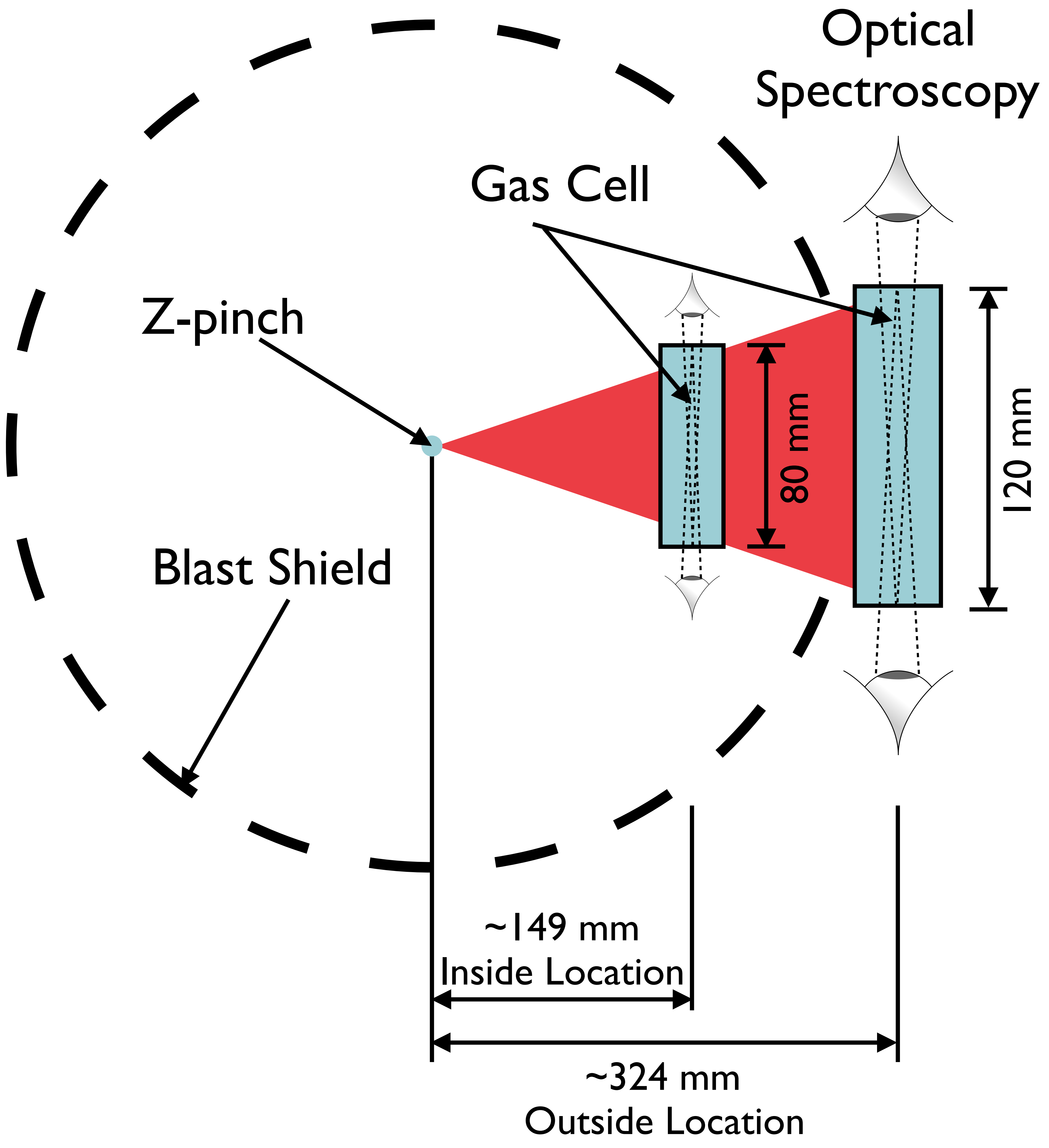
- emission and absorption data give the same shift
- transmission shift has yet to be determined
- magnitude of shift is still preliminary, but it is consistent with other experiments and flat as function of electron density



The carbon data - experimental setup

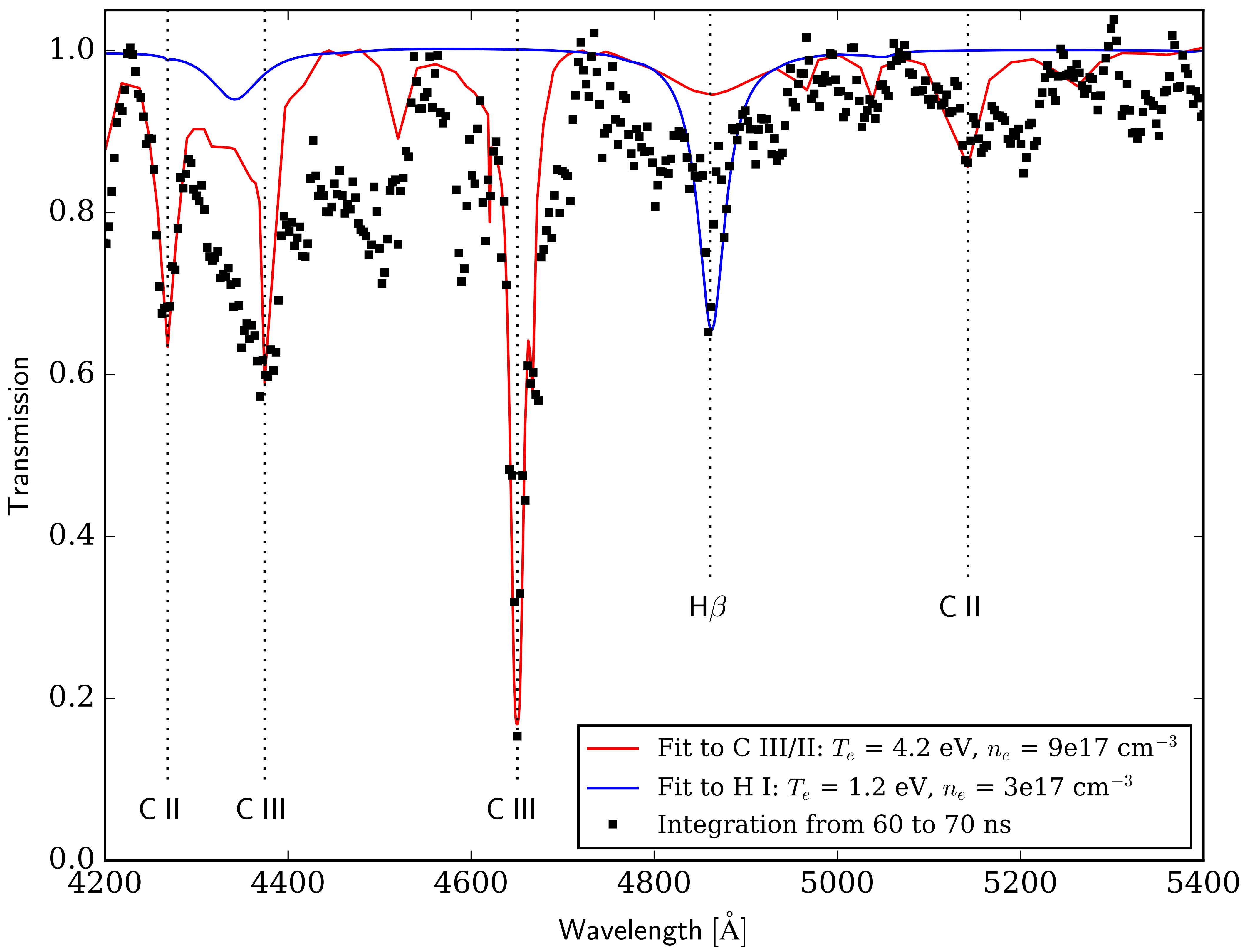
- DQ stars have surface temperatures ranging from 18,000 to 23,000 K, a bit higher than the garden variety DA or DB.

- Significant hardware changes were implemented to reach required conditions.

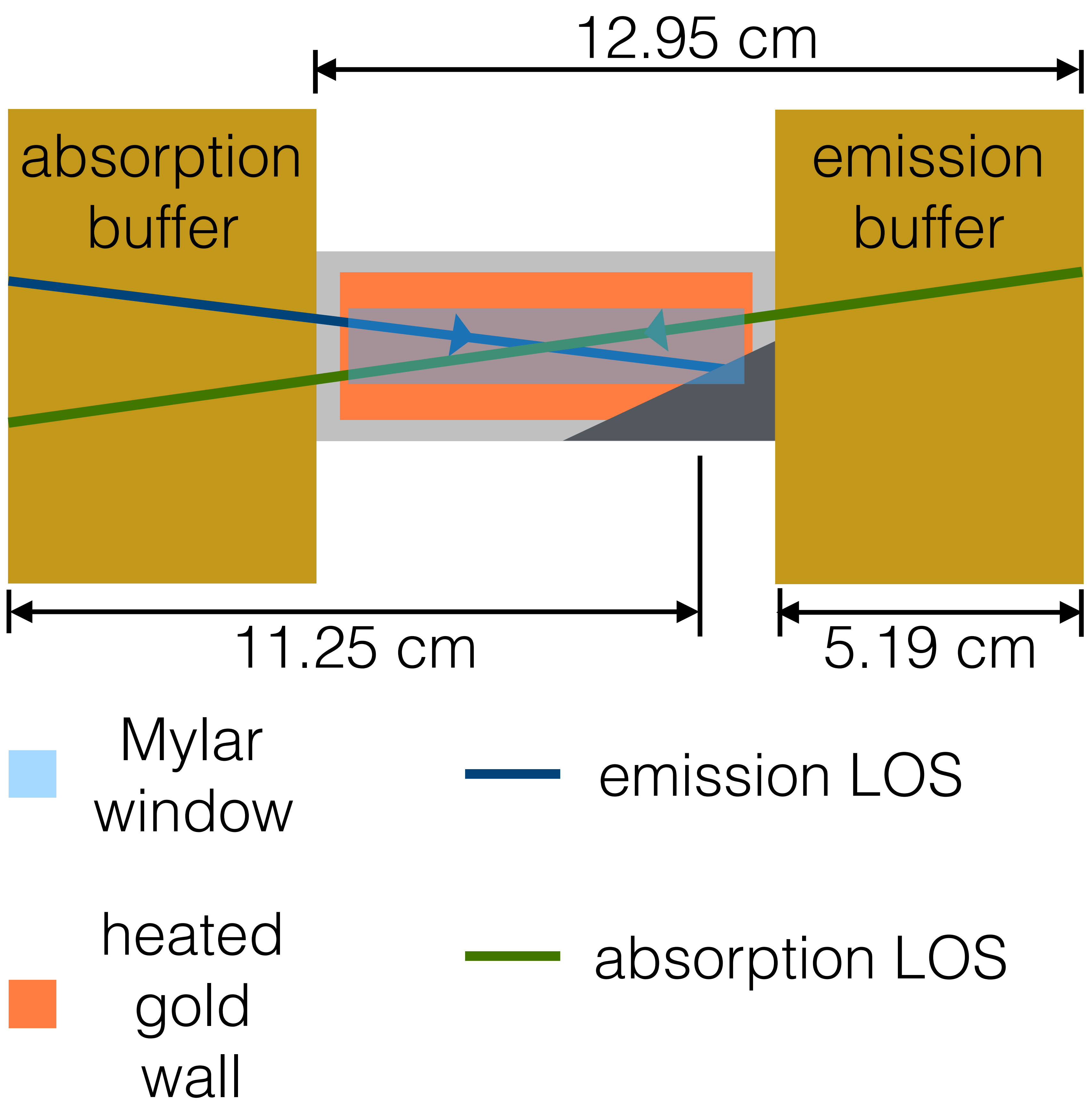


Altered location of WDPE gas cell with respect to Z pinch.

The carbon data - experimental results



PrismSPECT fits to the CH_4 data. Two plasma components are evident.



Altered platform design for CH_4 experiments.

Summary

- The WDPE at Sandia National Laboratories' *Z*-machine has uncovered theoretical weaknesses in atomic models for hydrogen and helium.
- Recent re-analysis of the emission and absorption data for multiple members of the H-Balmer series reveals that there may be problems in our understanding of these atomic processes.
- Proof-of-concept CH_4 experiments have shown that we can also address weaknesses in our understanding of multiple-electron. Further future hardware developments will be needed to solidify our current results.