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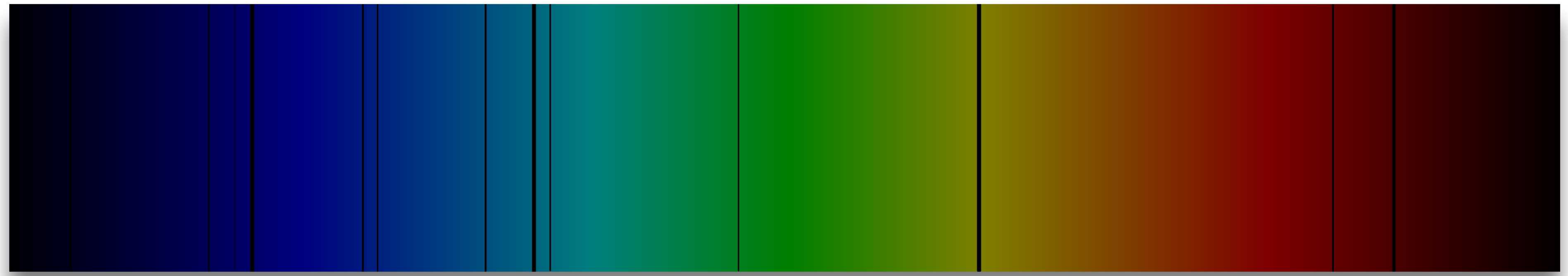


The Behavior Hydrogen and Helium at White Dwarf Photosphere Conditions

Marc-Andre Schaeuble
University of Texas at Austin

11/02/2018
Austin, TX

Outline

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

White Dwarfs (WDs) are the endpoint of stellar evolution

Not drawn to scale.

DA: hydrogen atmosphere **DB: helium atmosphere** **DQ: carbon atmosphere**

Q: Age of the Galaxy? Q: Stellar evolution? Q: Failed supernovae?

Accurate WD masses are needed to answer these questions!

Not drawn to scale.

DA: hydrogen atmosphere

DB: helium atmosphere

DQ: carbon atmosphere

Q: Age of the Galaxy?

Q: Stellar evolution?

Q: Failed supernovae?

Focus of this talk

Not drawn to scale.

White Dwarfs are earth-sized objects with masses comparable to the sun

Typical WD parameters:

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

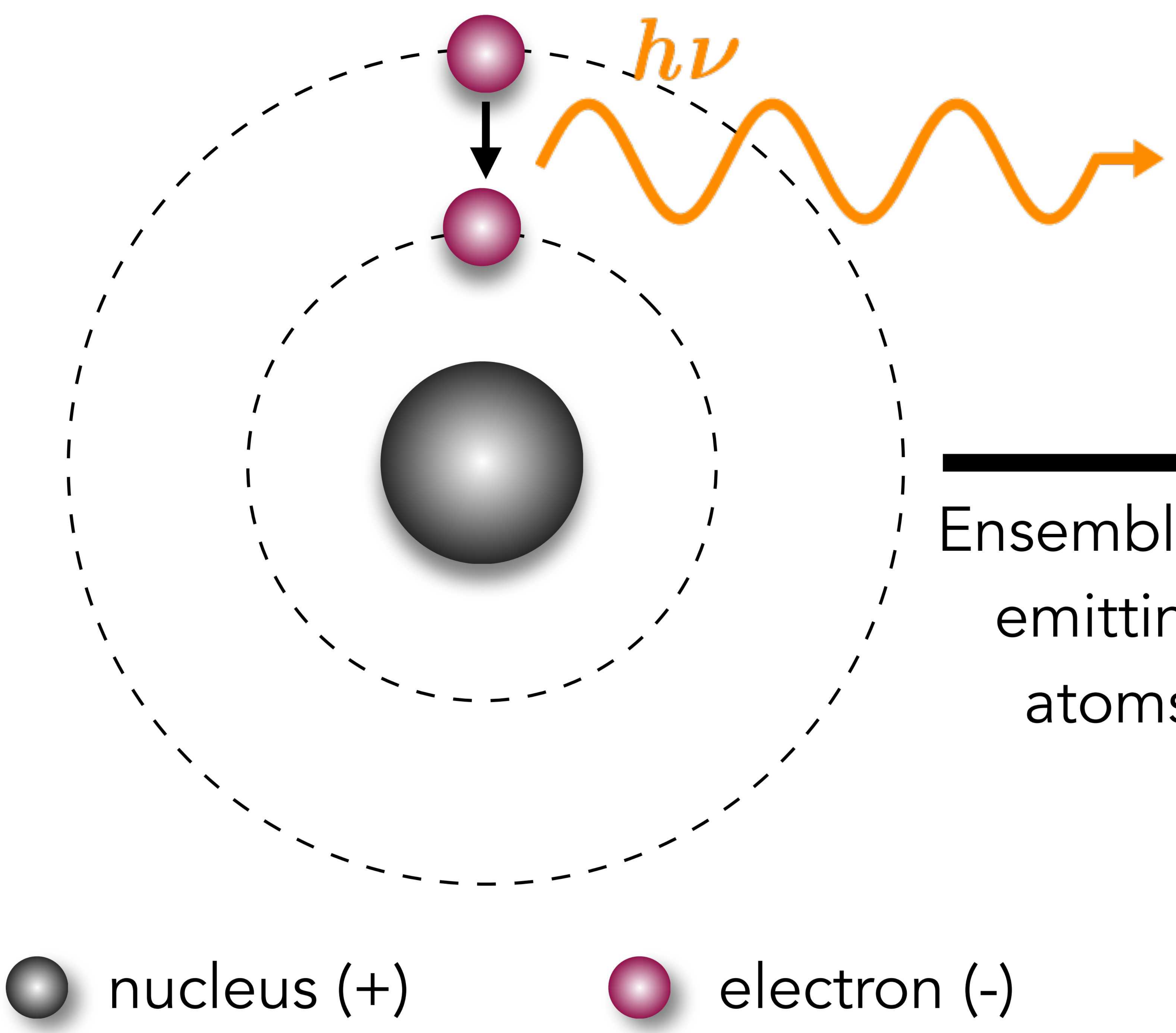
Surface gravity (log g): 10^8 cm/s^2 (n_e ~10^{17} cm^{-3})

Radius: r_{earth}

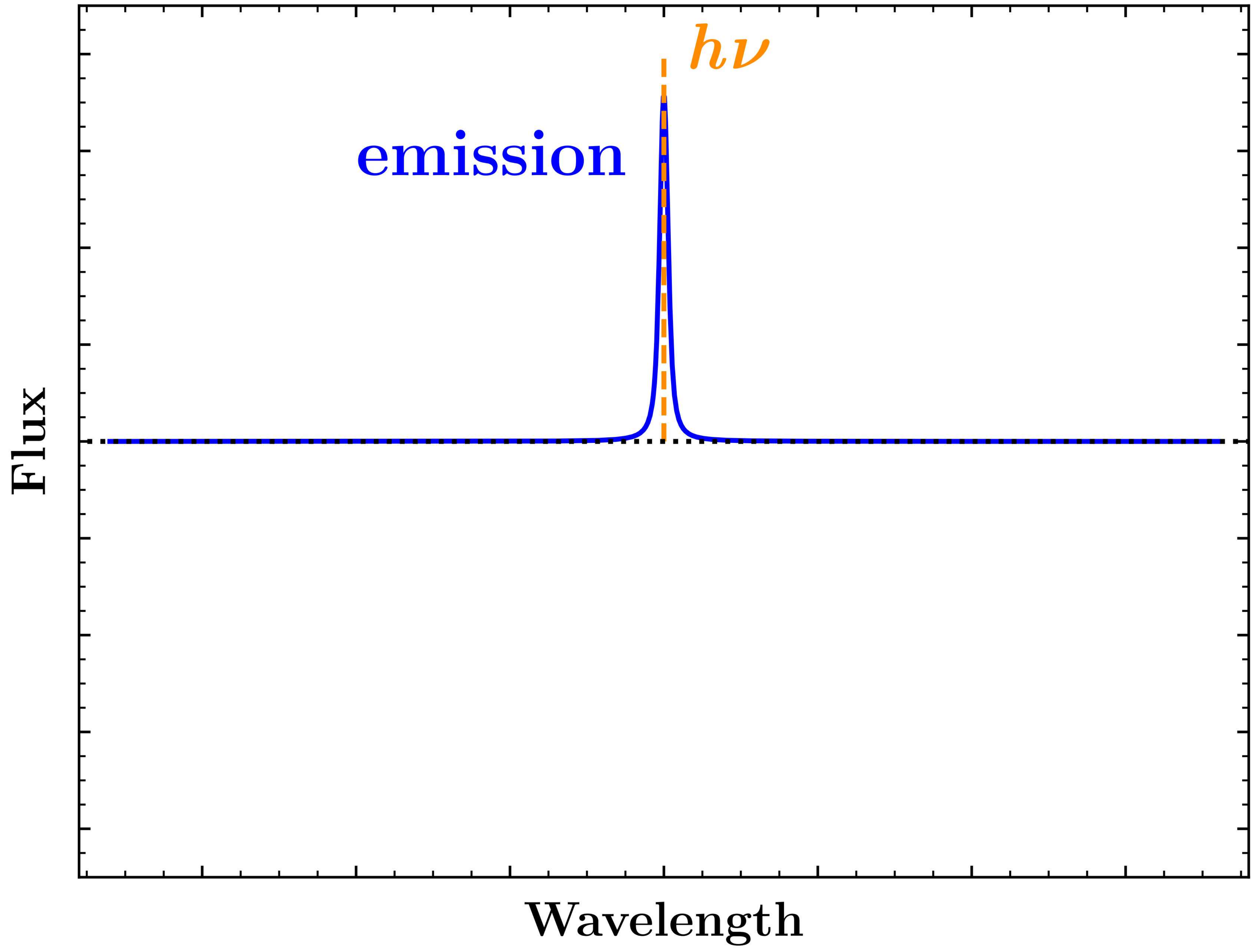
Mass: ~2/3 M_{sun}

WD masses are derived using spectroscopy

The emission process



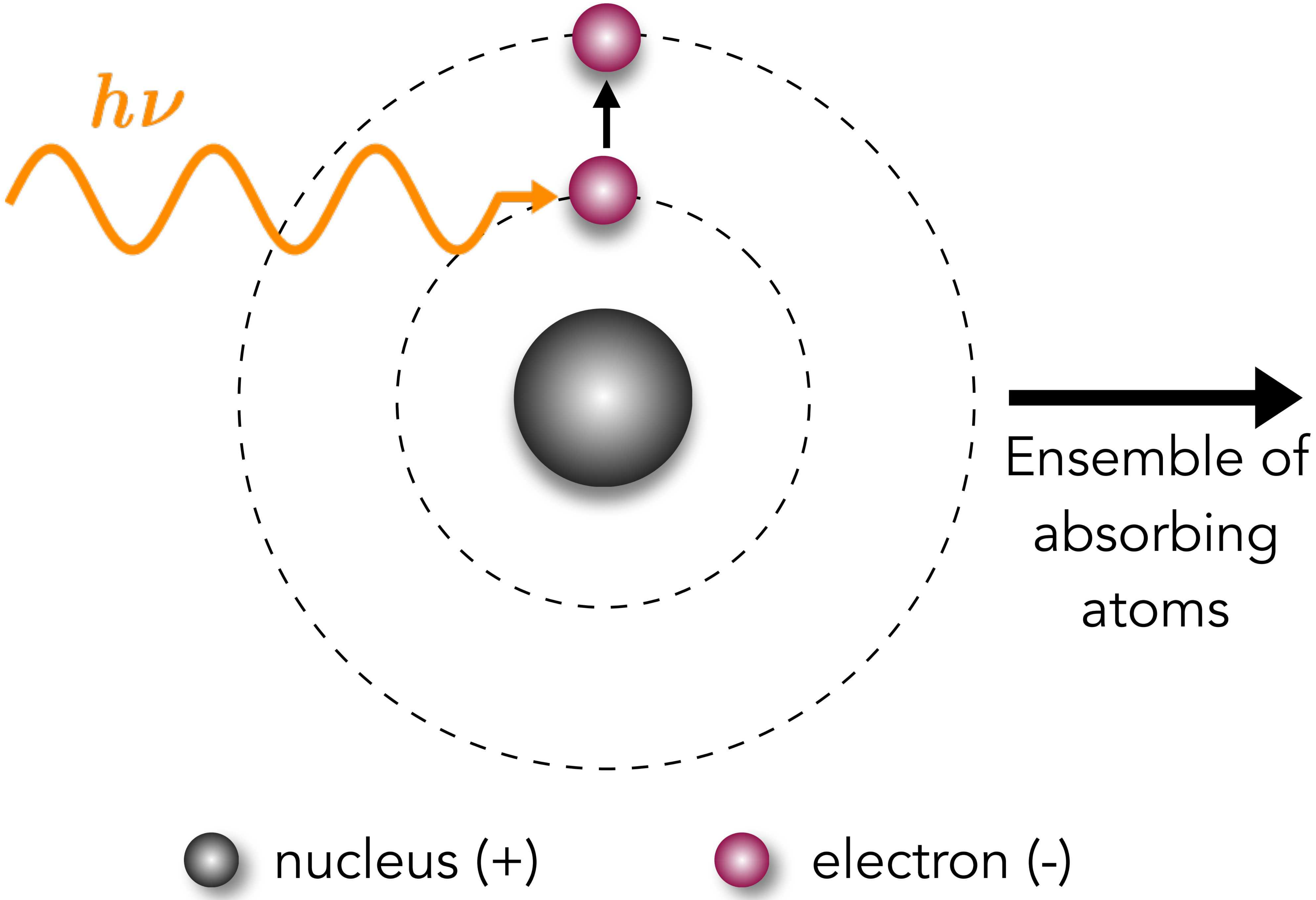
Ensemble of emitting atoms

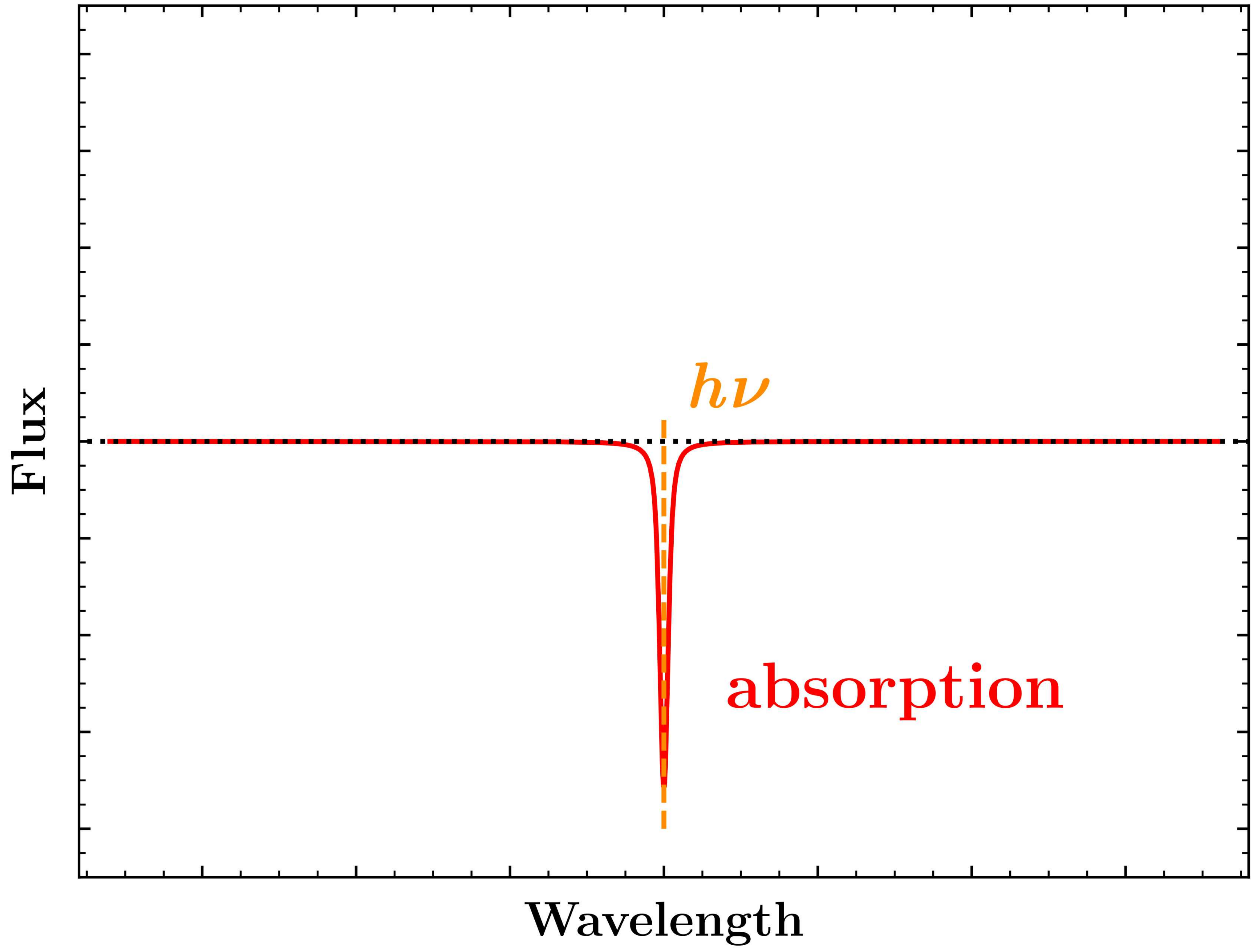


Emission profile created by addition of energy to continuum.

WD masses are derived using spectroscopy

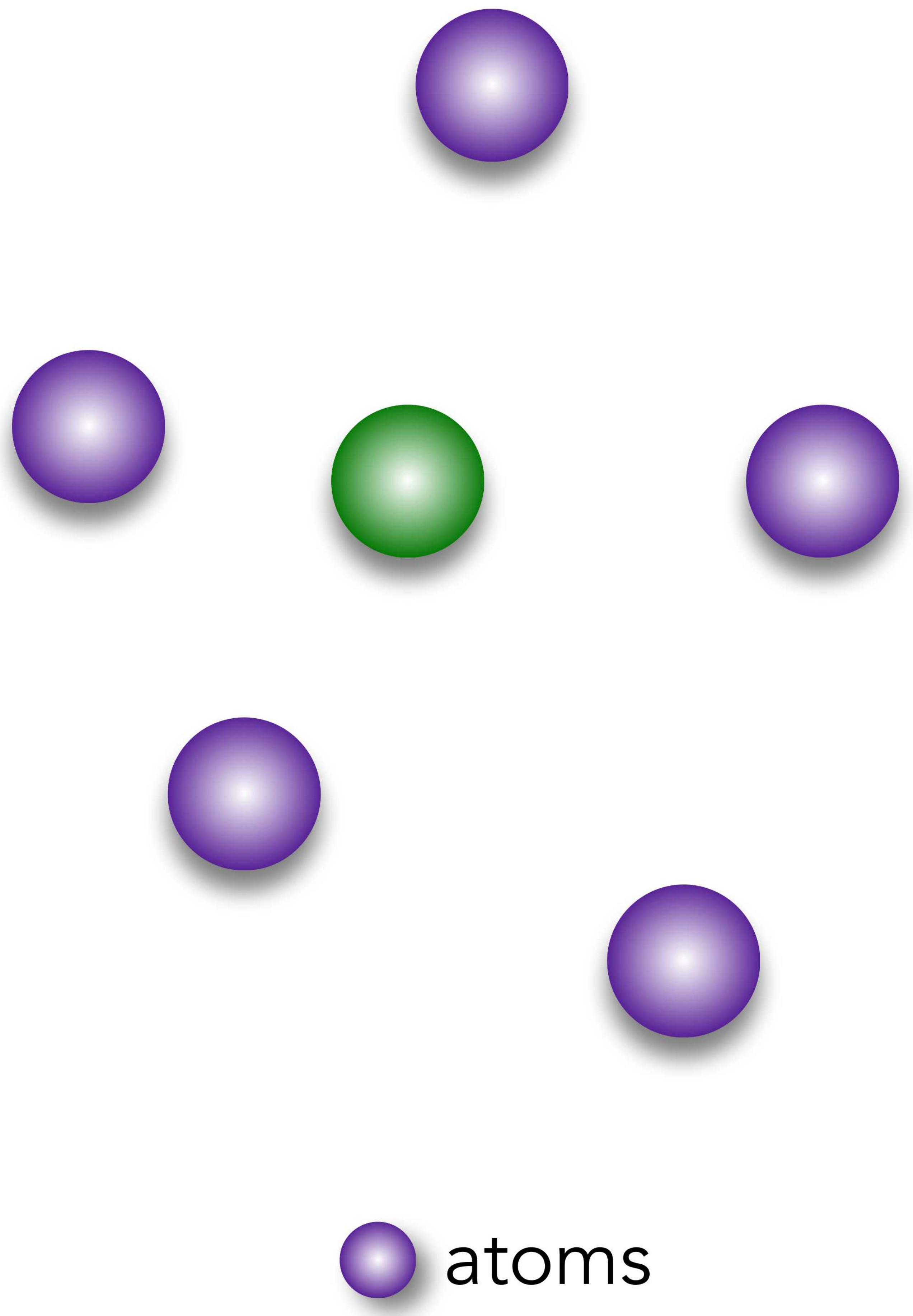
The absorption process



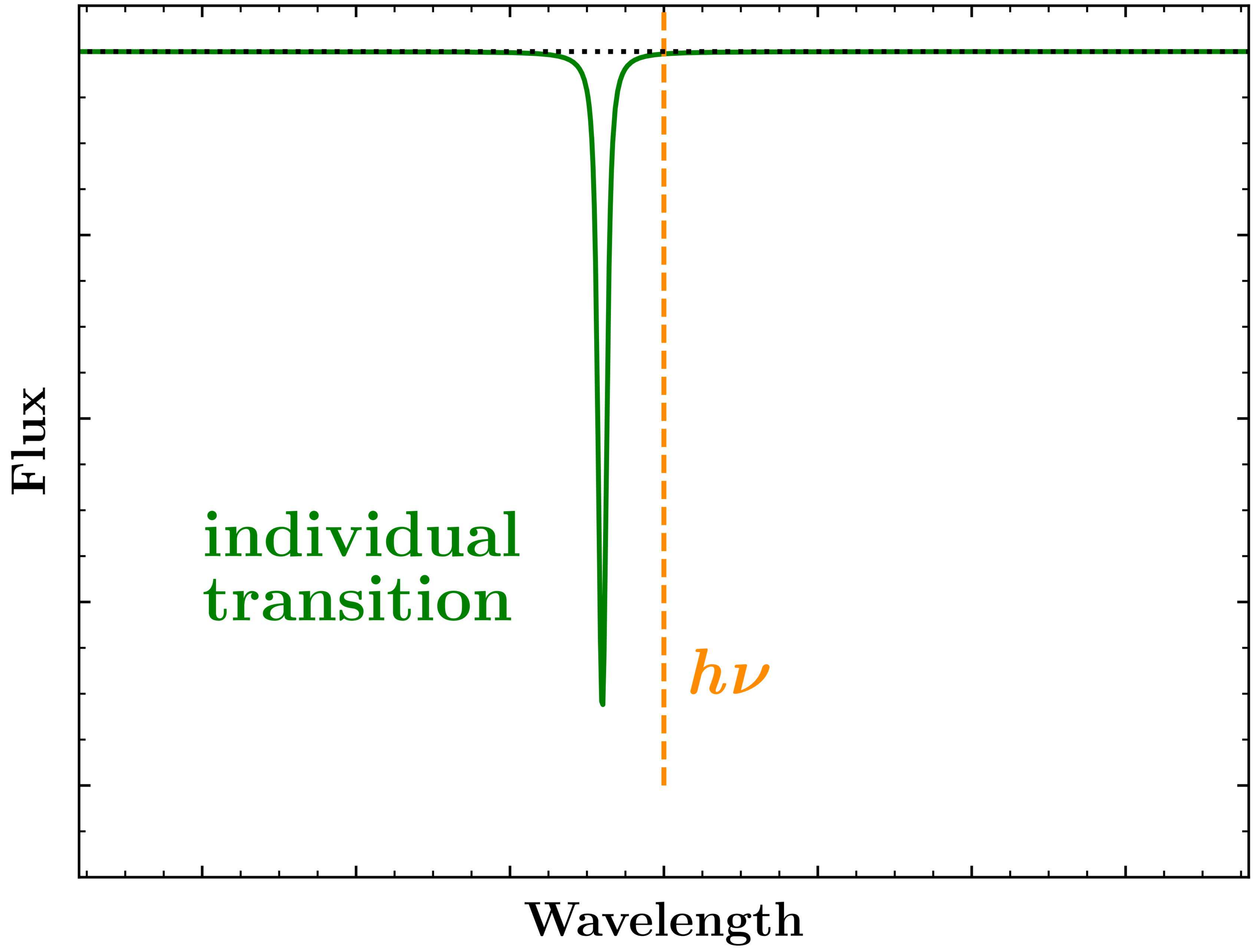


Absorption profile created by removal of energy from continuum.

Density effects control width and shifts of spectral lines

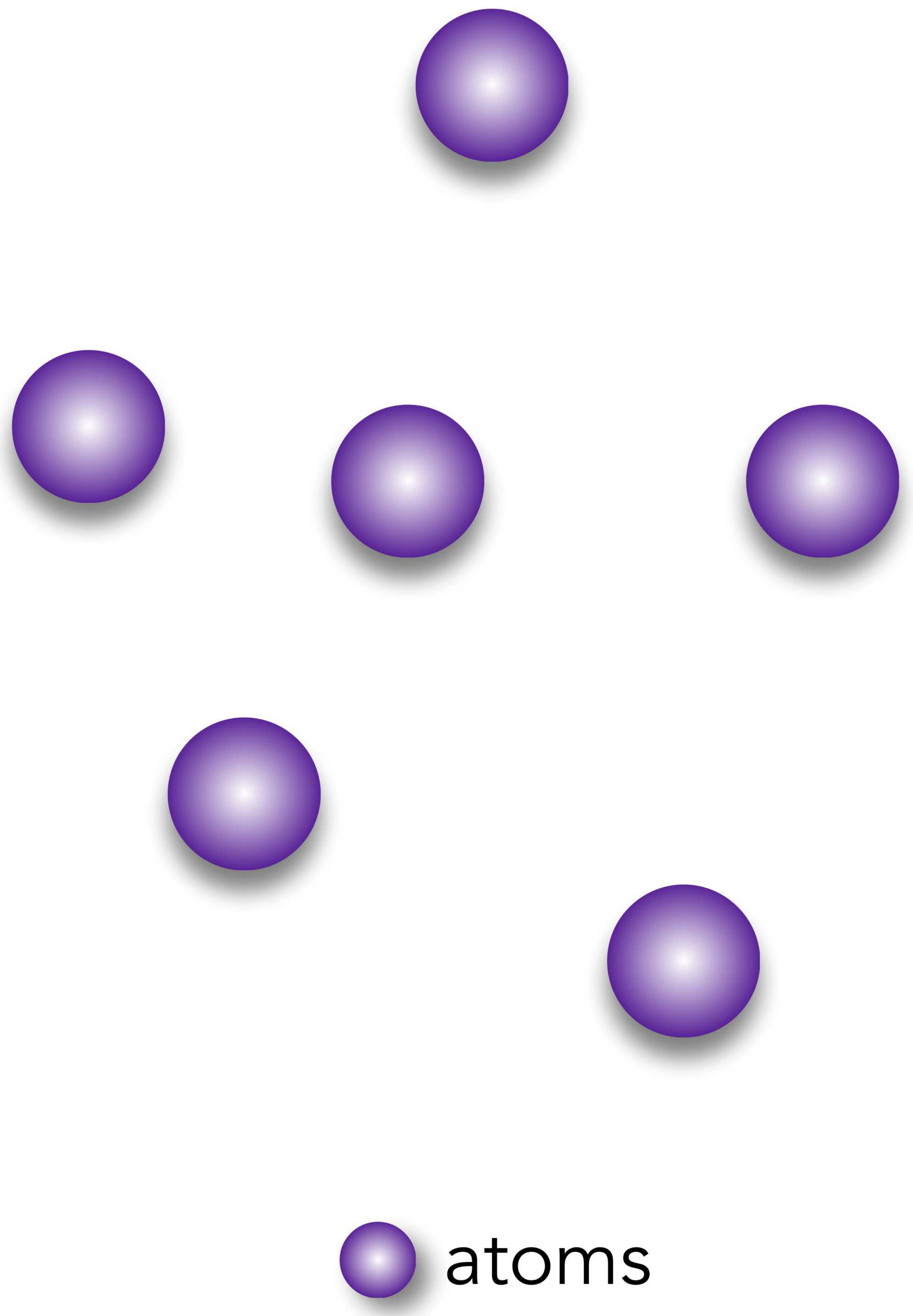


Atomic system perturbed by electrons, ions, and neutrals in the plasma



Individual transition by each atom in the plasma form the observed spectral line.

Density effects control width and shifts of spectral lines



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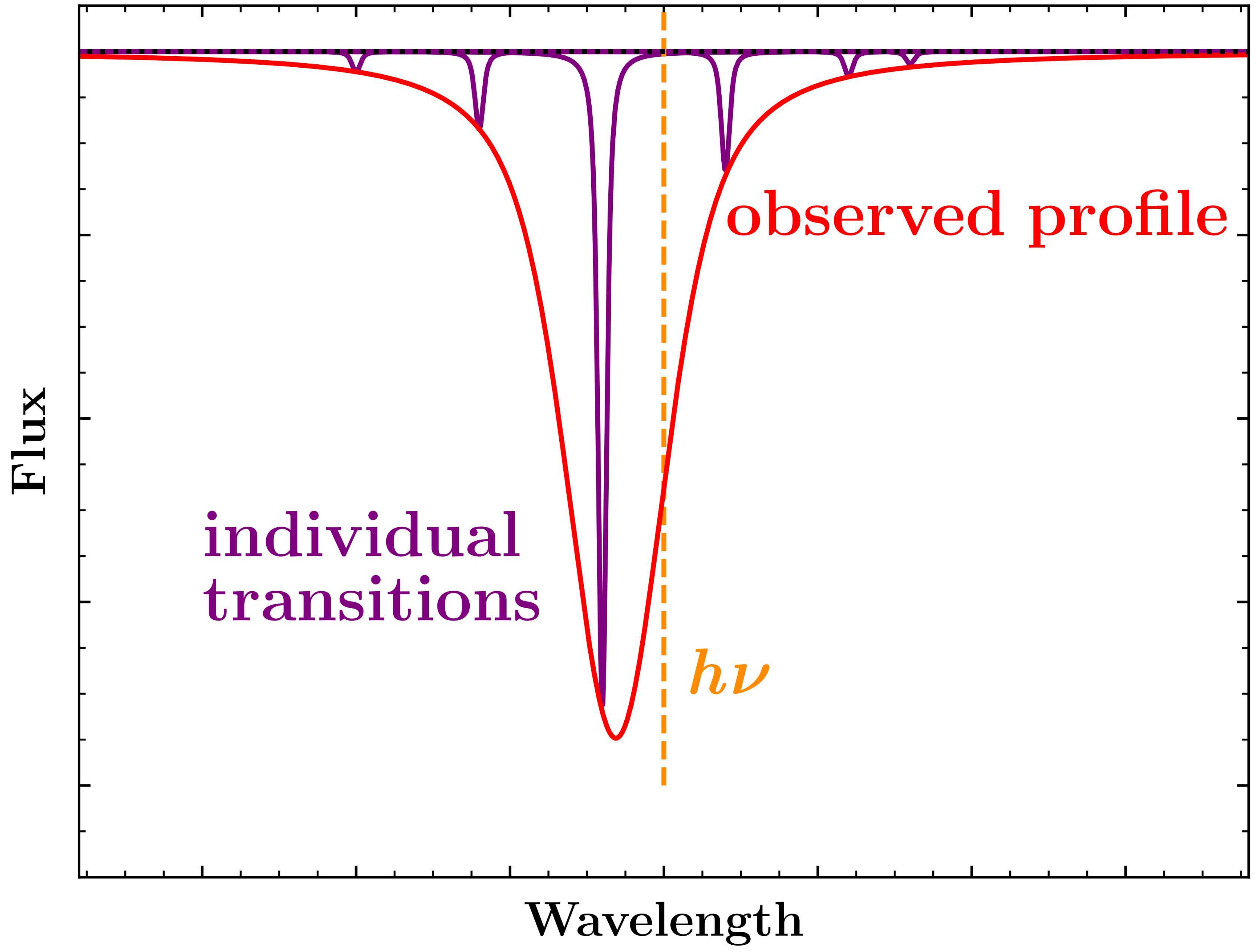

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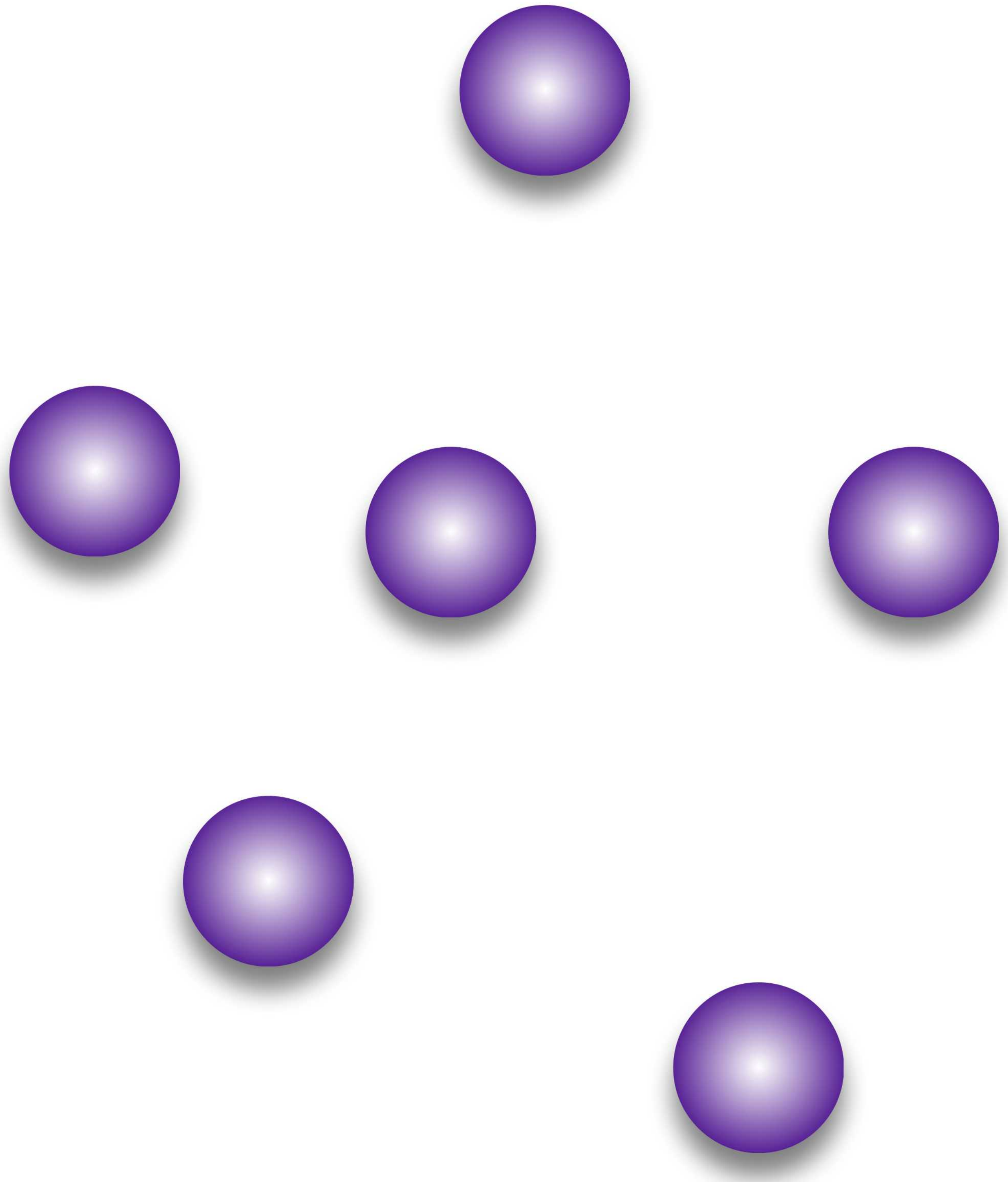
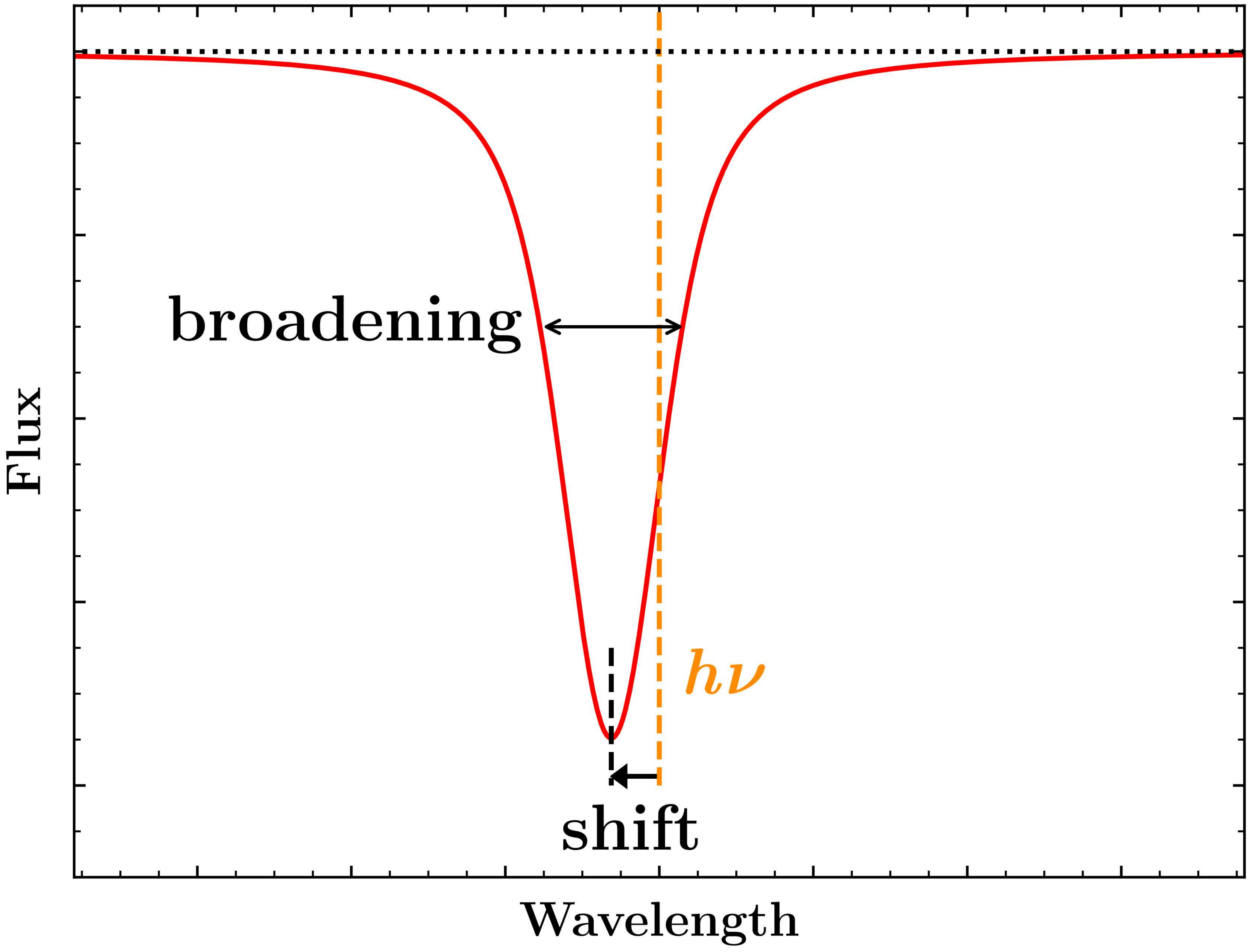


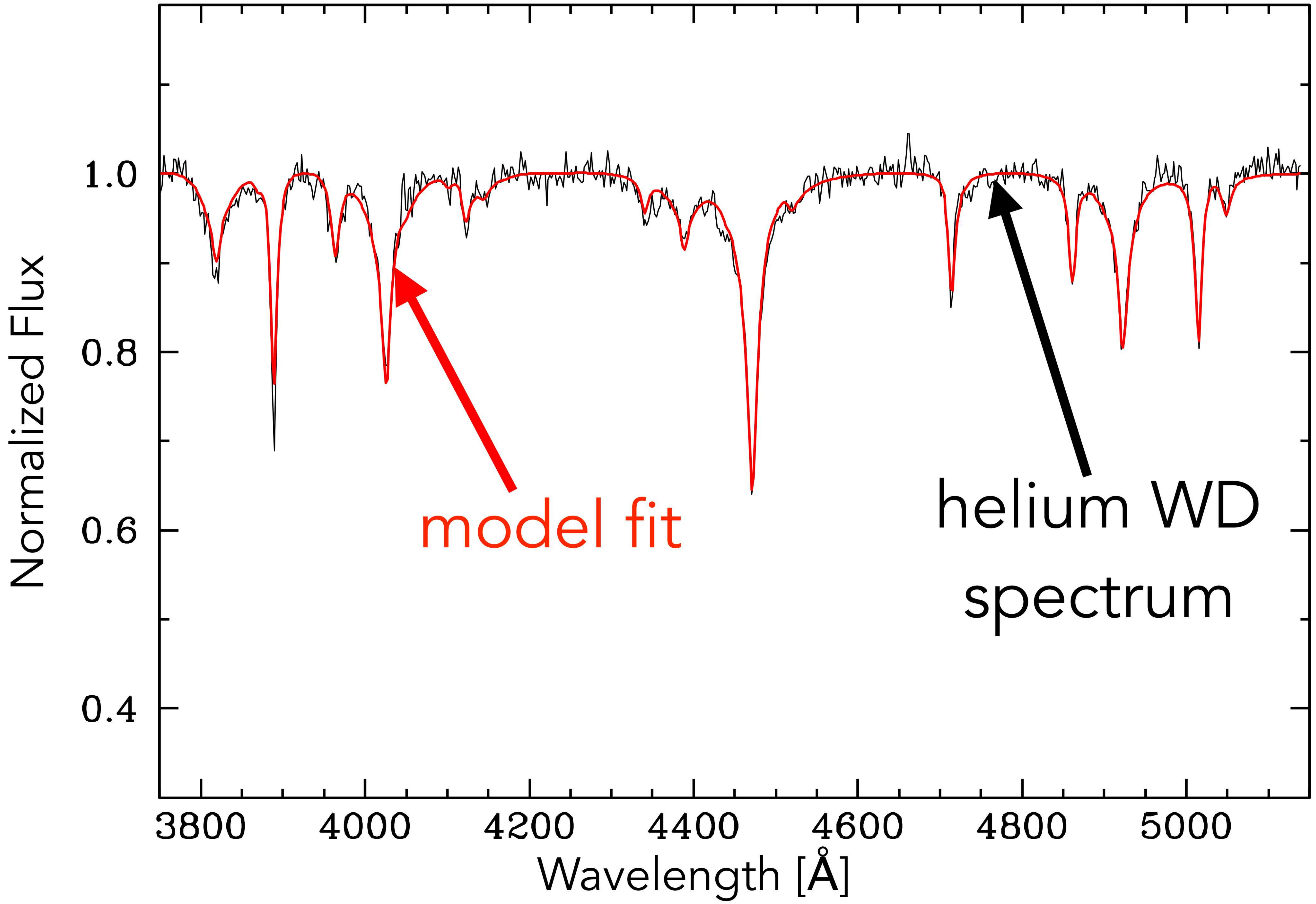
atoms

Atomic system perturbed by electrons, ions, and neutrals in the plasma



Density effects shift and broadened the observed spectral line.

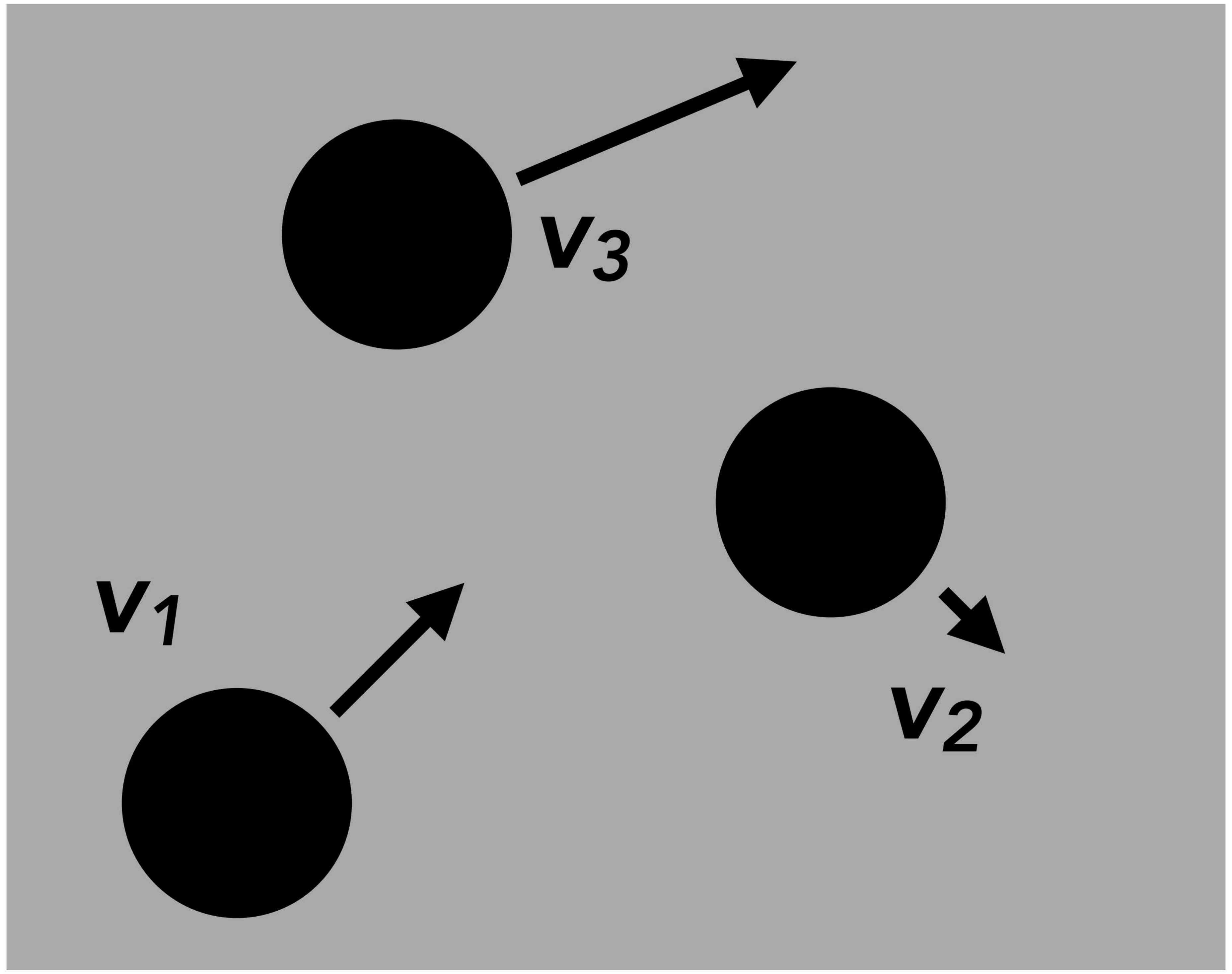
Fitting model atmospheres to observed WD spectra leads to stellar masses



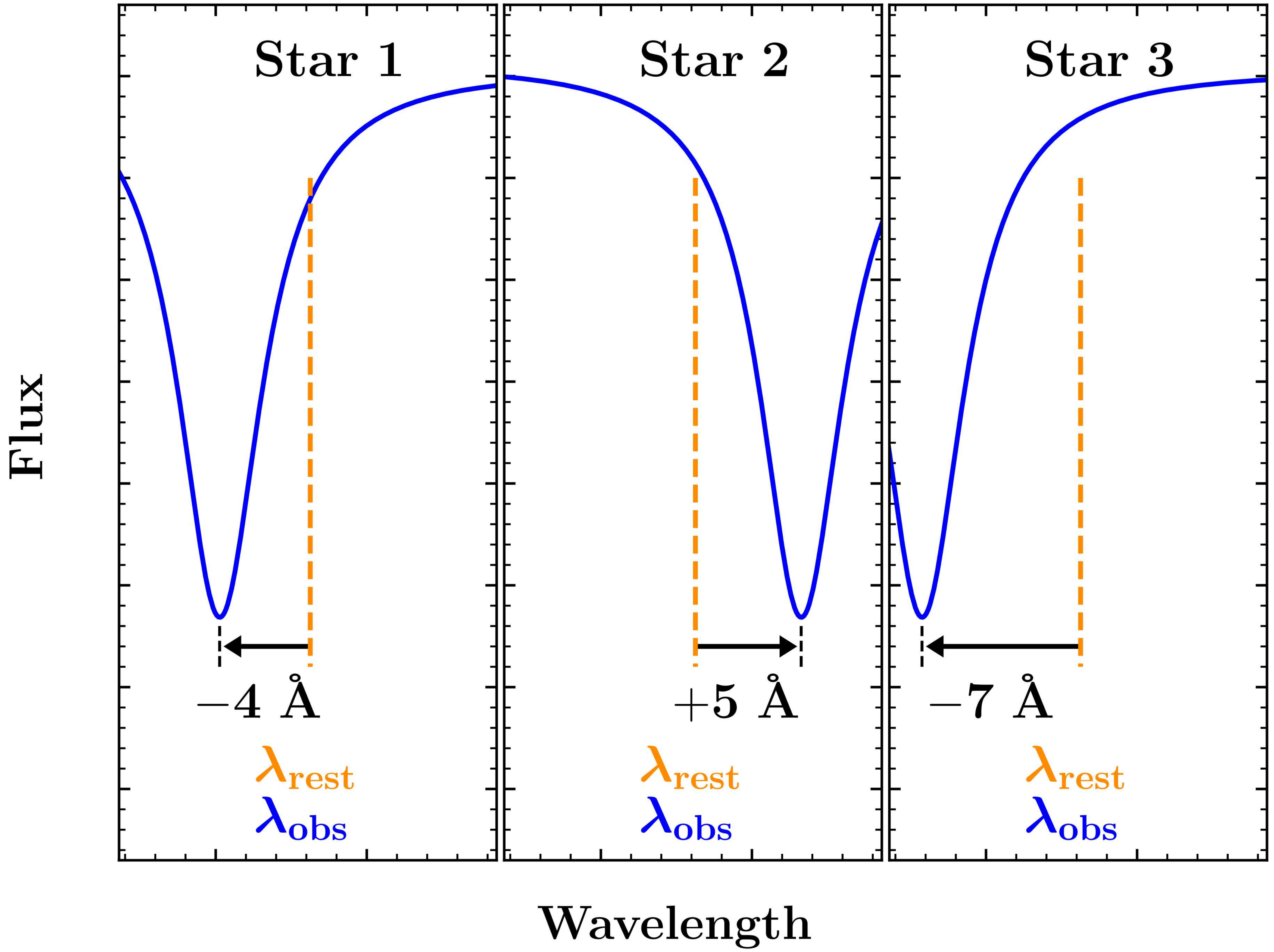
Bergeron et al. (2011) *ApJ*

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

WD masses can be determined by gravitational redshift

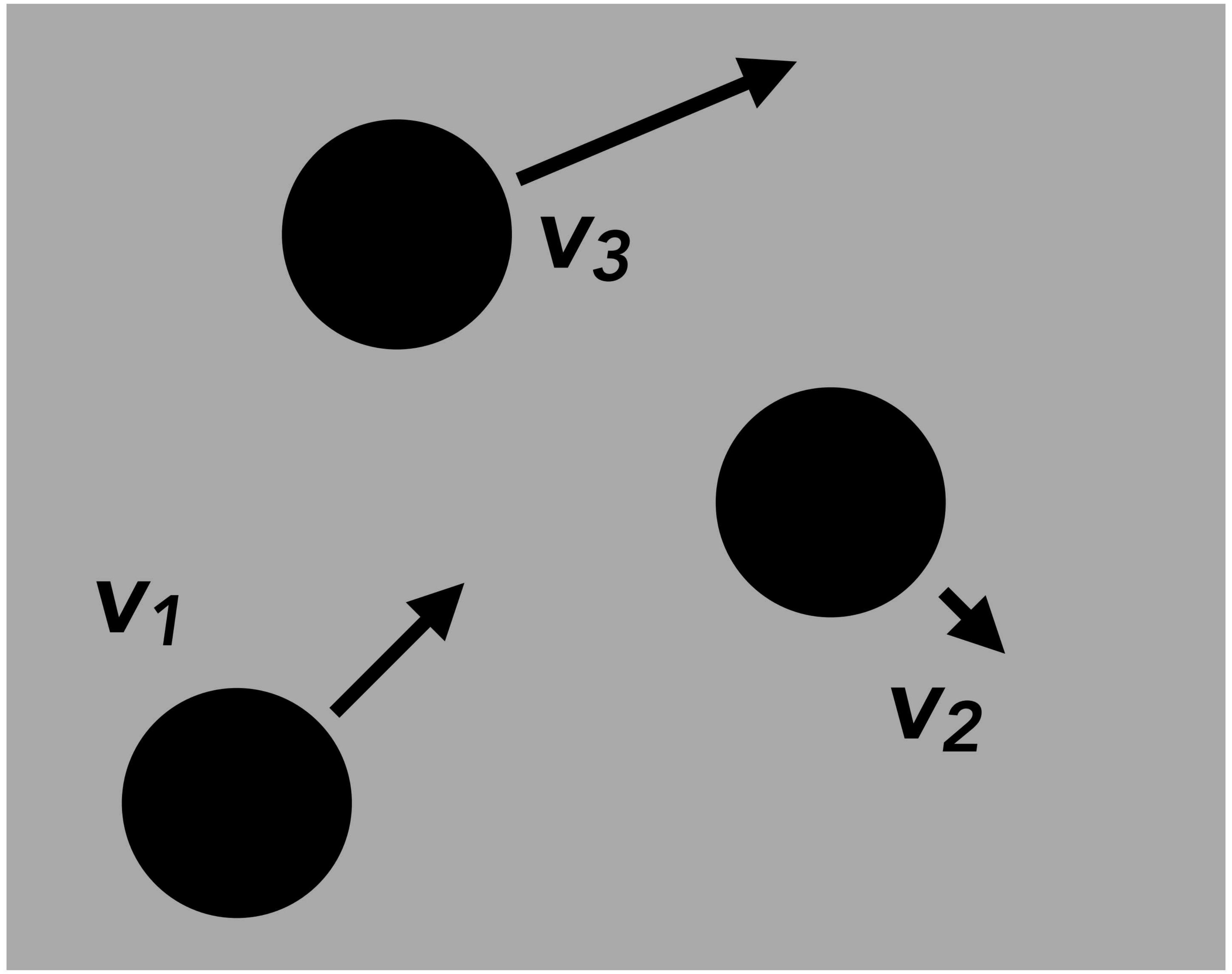


A sample of WDs

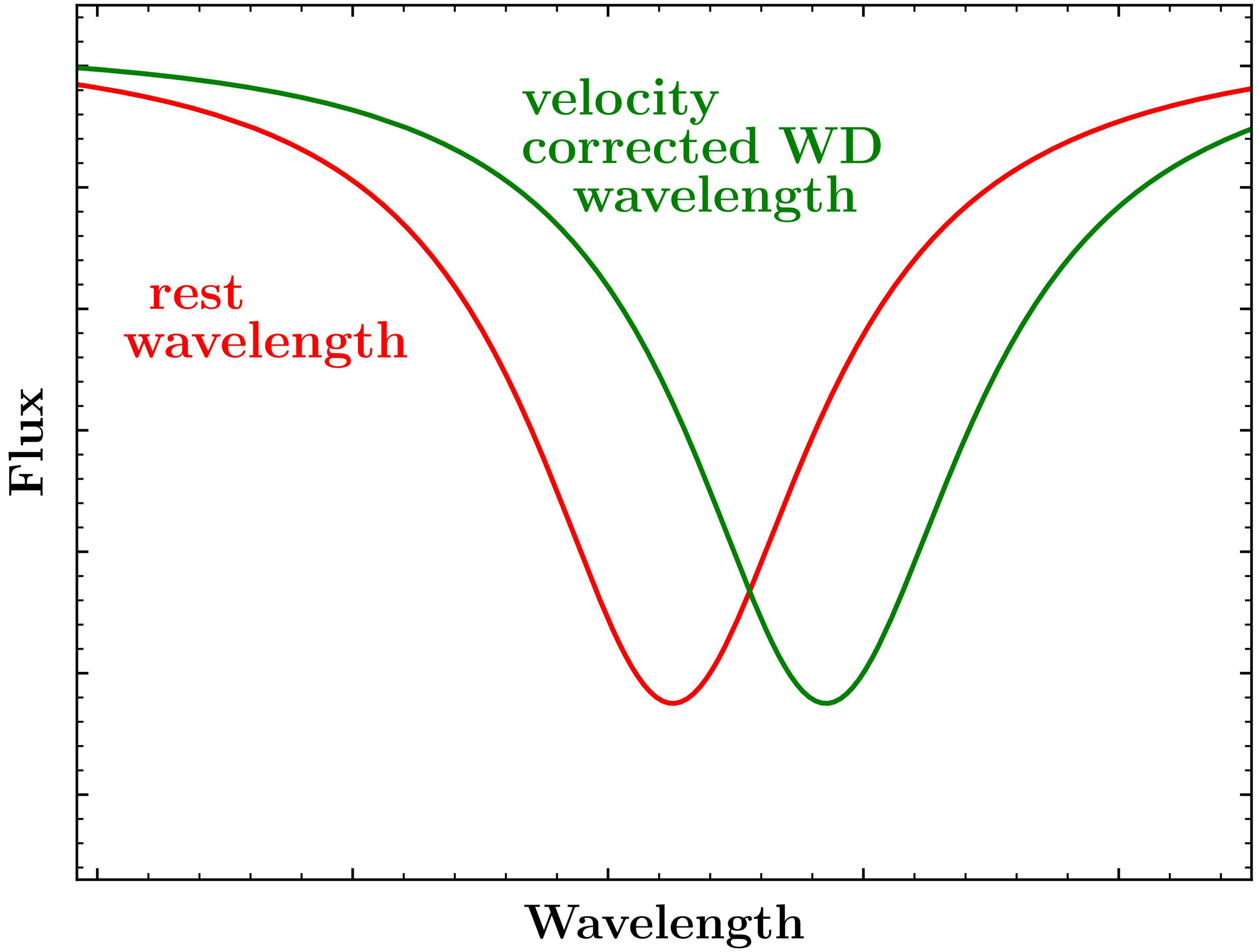


Observed spectra of the sample WDs

WD masses can be determined by gravitational redshift

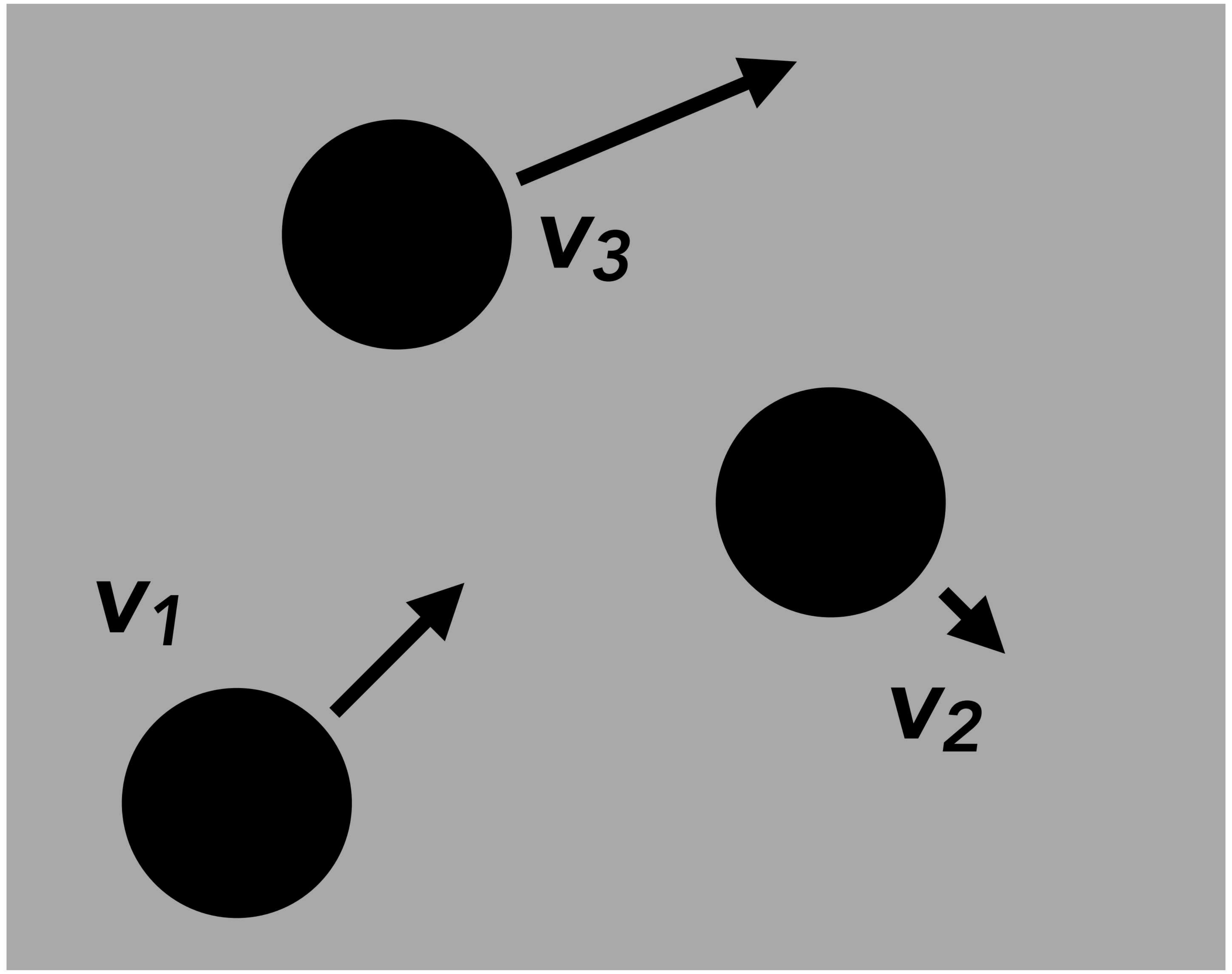


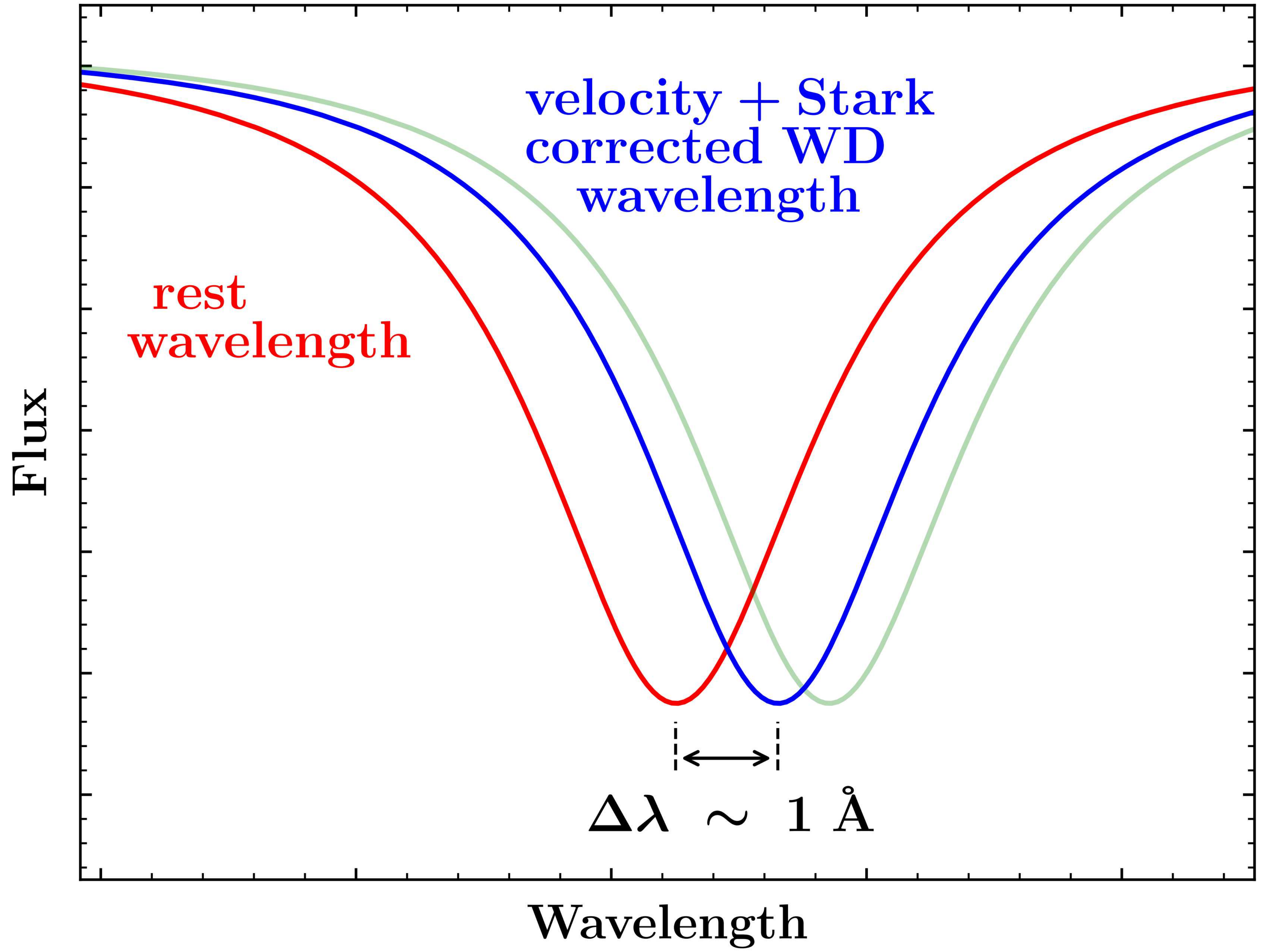
- average over individual motions $\boldsymbol{v_1}$, $\boldsymbol{v_2}$, and $\boldsymbol{v_3}$



Comparison of spectral feature at rest (red) and that determined by velocity correction of observed WD spectra (green)

WD masses can be determined by gravitational redshift



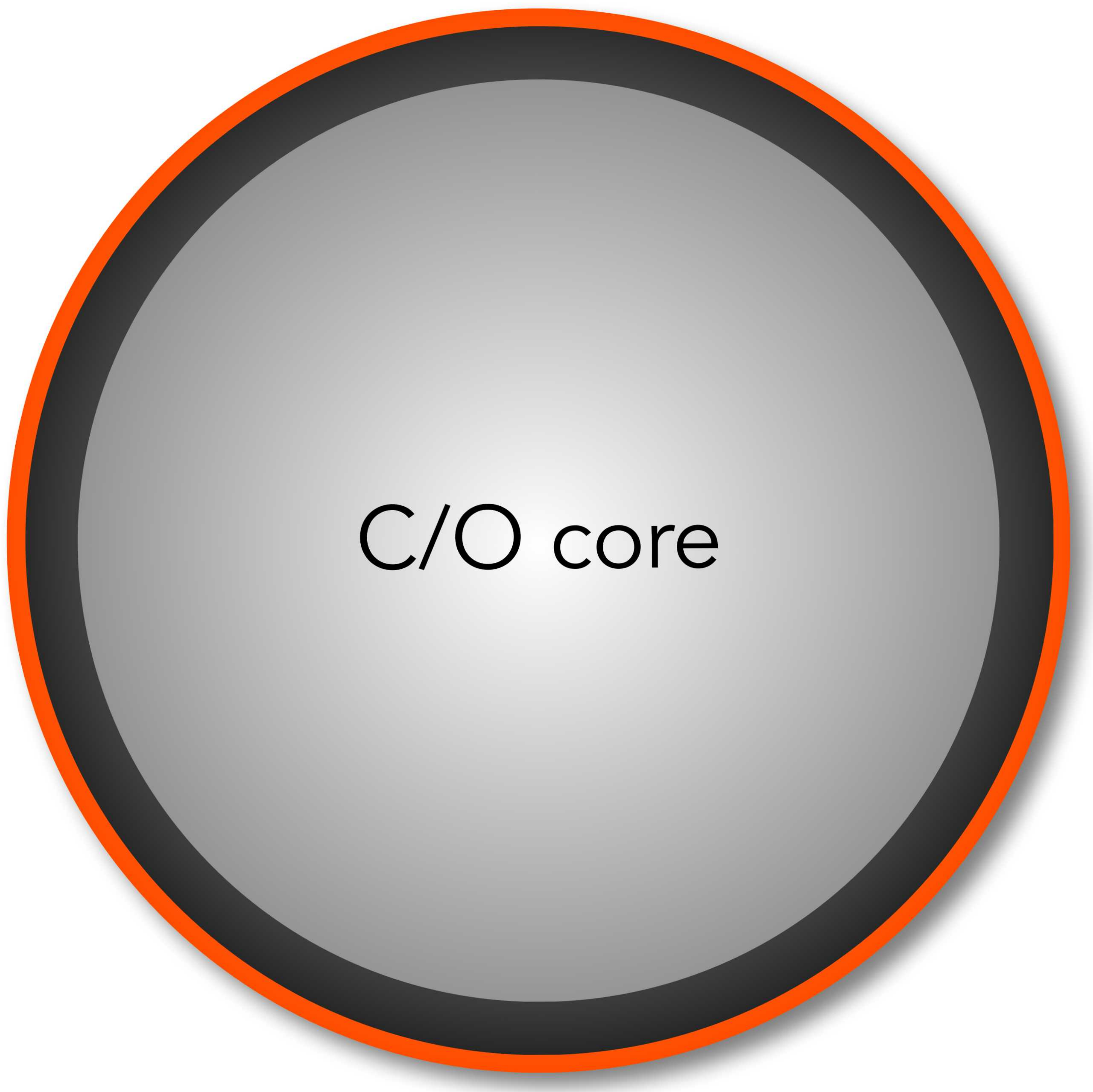


- average over individual motions $\boldsymbol{v_1}$, $\boldsymbol{v_2}$, and $\boldsymbol{v_3}$
- if important, correct for Stark ***shift*** of spectral line

Wavelength shift caused by mass of WD

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

DA: hydrogen atmosphere



Q: Age of the Galaxy?

DB: helium atmosphere

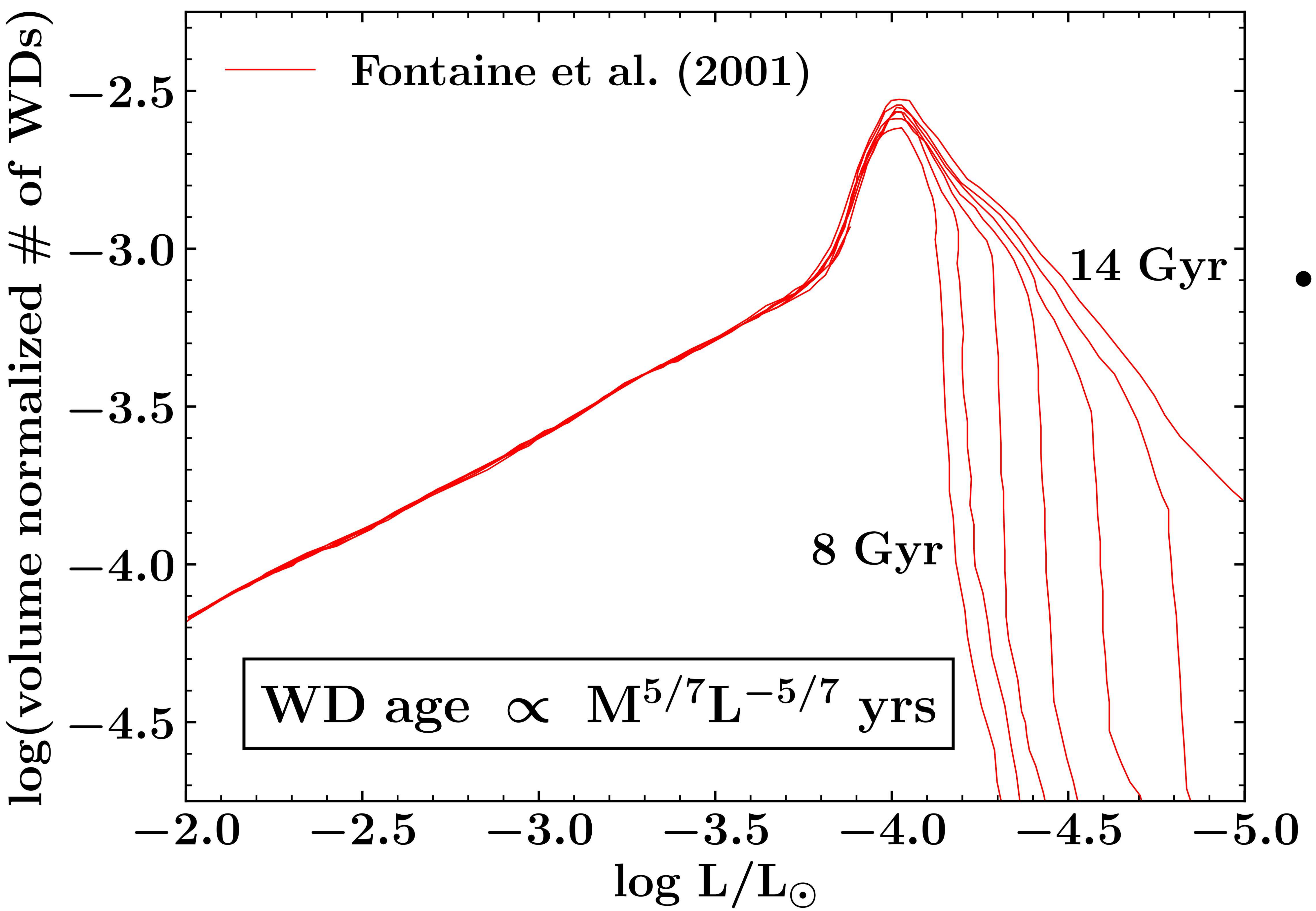
Q: Stellar evolution?

DQ: carbon atmosphere

Q: Failed supernovae?

Not drawn to scale.

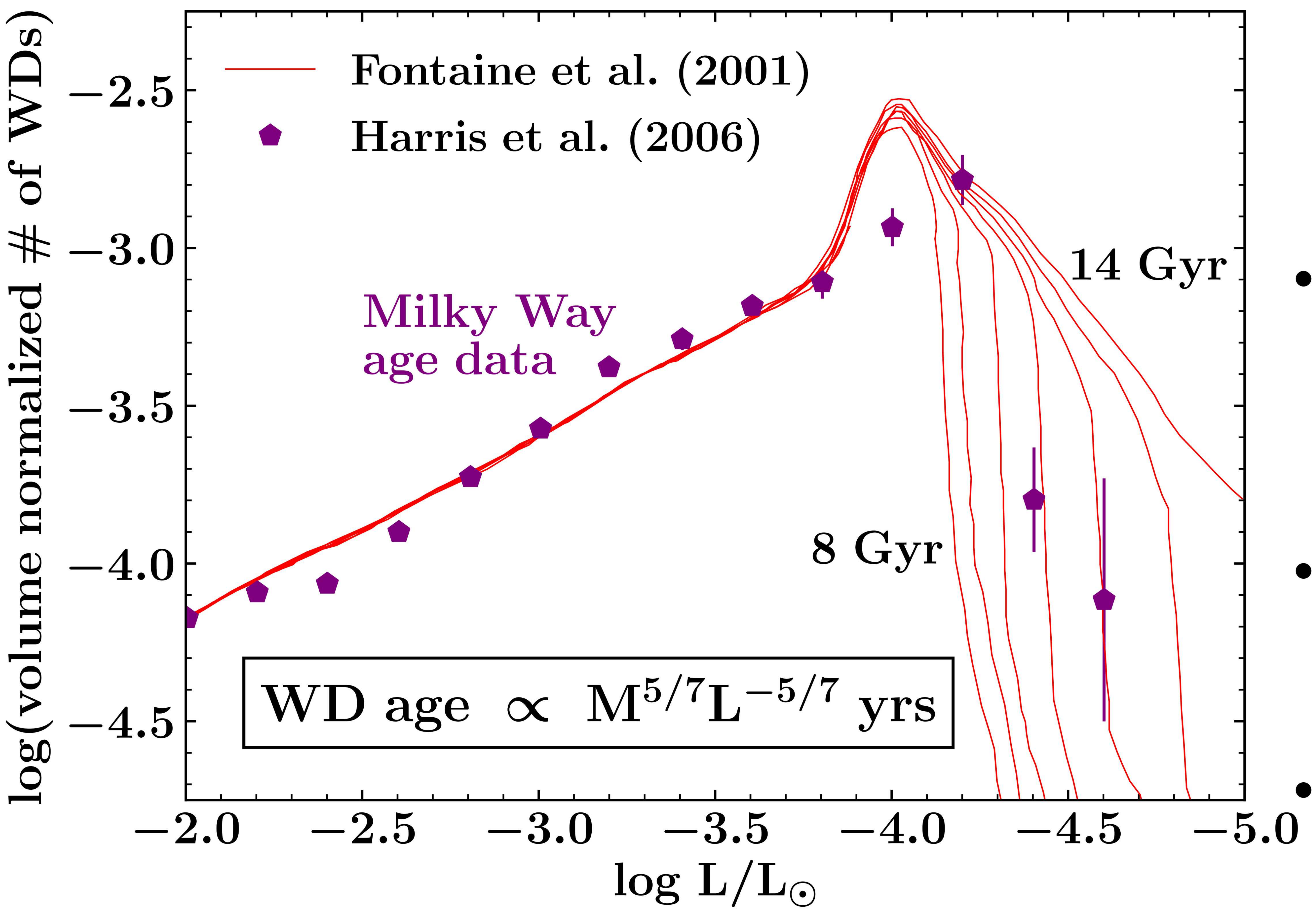
Hydrogen WDs and the age of the Galaxy



1 pc = 3.26 light years

- Fontaine et al. (2001) predicted the number of WDs as a function of luminosity
- Calculations depend on:
  - input age
  - mean WD mass

Hydrogen WDs and the age of the Galaxy



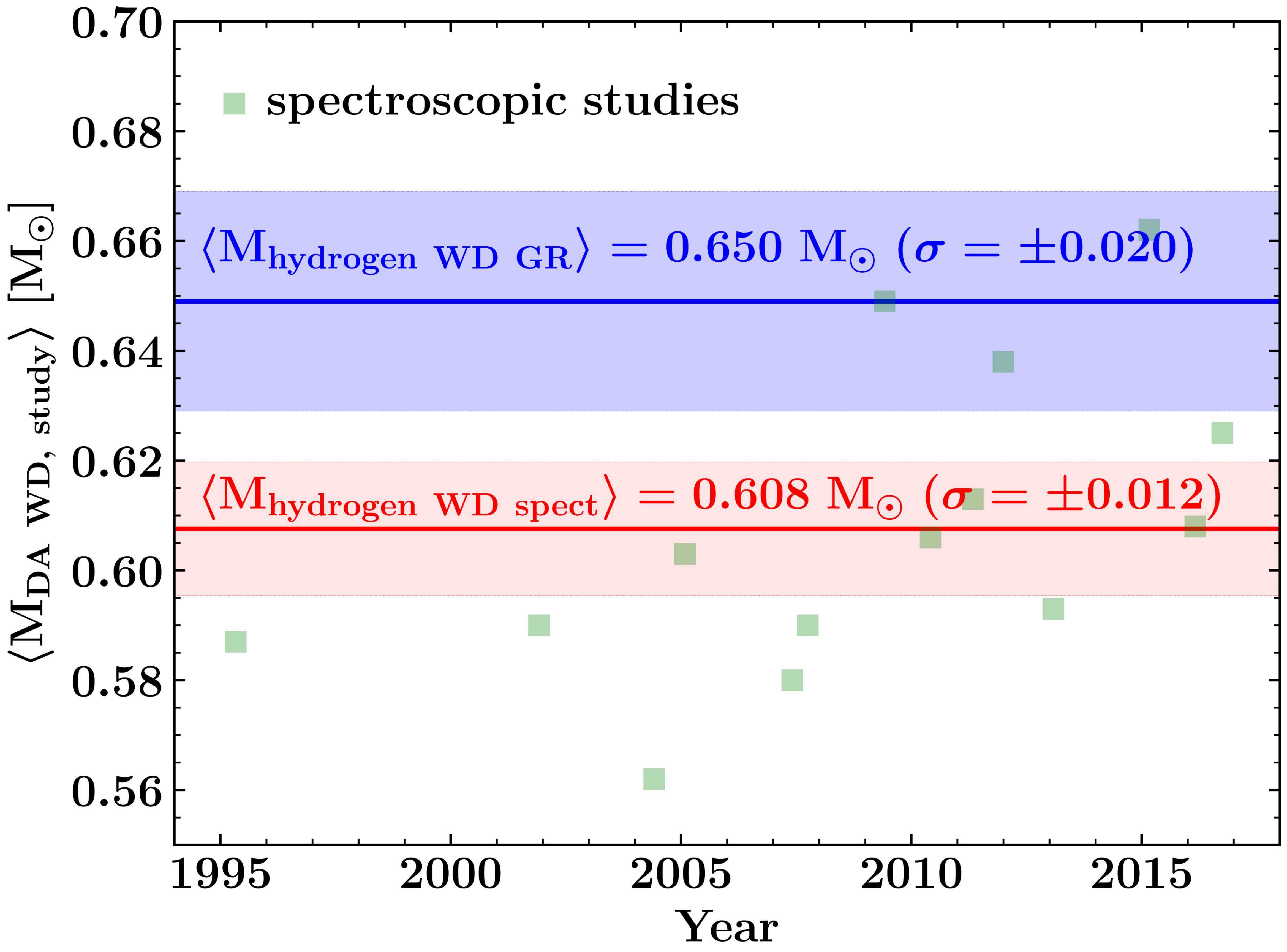
1 pc = 3.26 light years

- Fontaine et al. (2001) predicted the number of WDs as a function of luminosity
- Calculations depend on:
  - input age
  - mean WD mass
- WDs contrain the age of Galaxy to:
  11.5 ± 0.7 Gyr
- Other methods:
  12.5 ± 3.0 Gyr (Th/Ur ratio)
  13.5 ± 3.5 Gyr (stellar isochrone)

Hydrogen WD masses obtained from the GR and spectroscopic method disagree

- current mass differences in spectroscopic and GR method result in age differences of ~0.5 Gyrs

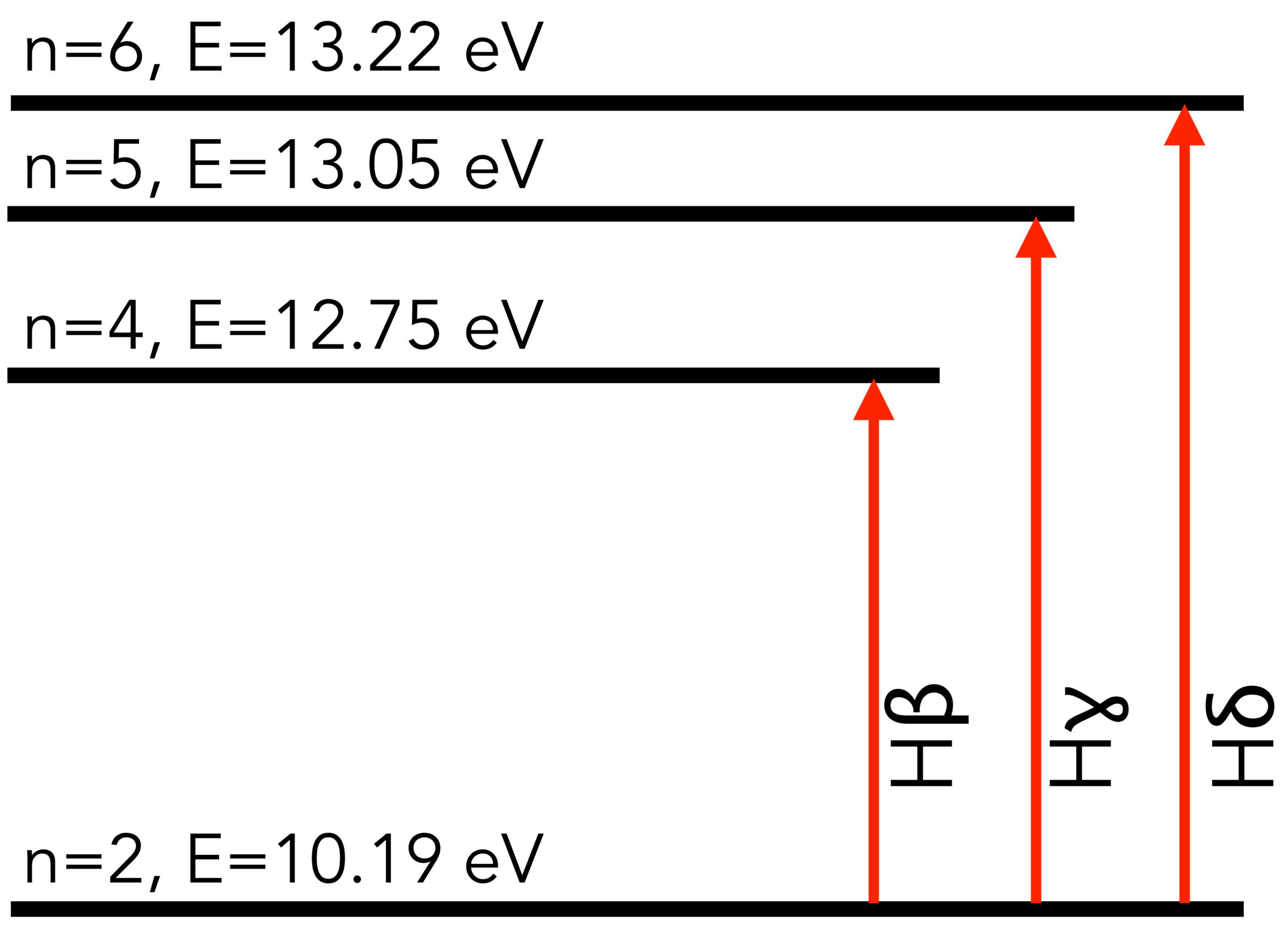
- such age discrepancies have large implications for our understanding of chemical and kinematic evolution of our Galaxy



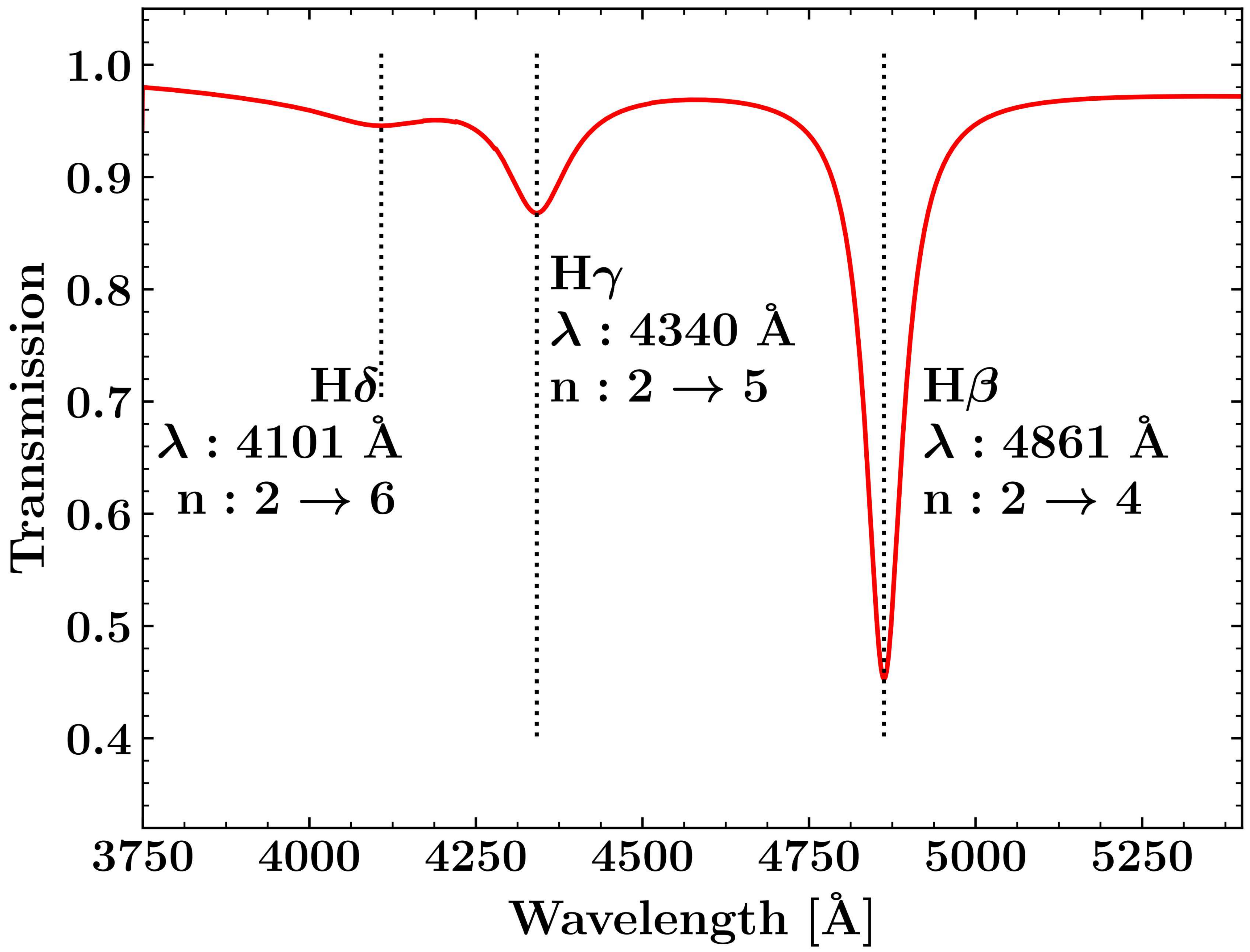
Falcon et al. (2010) *ApJ*

Gravitational redshift and spectroscopic masses in comparison. The difference is larger than the stated uncertainties.

Masses of H WDs are inferred using the Balmer series

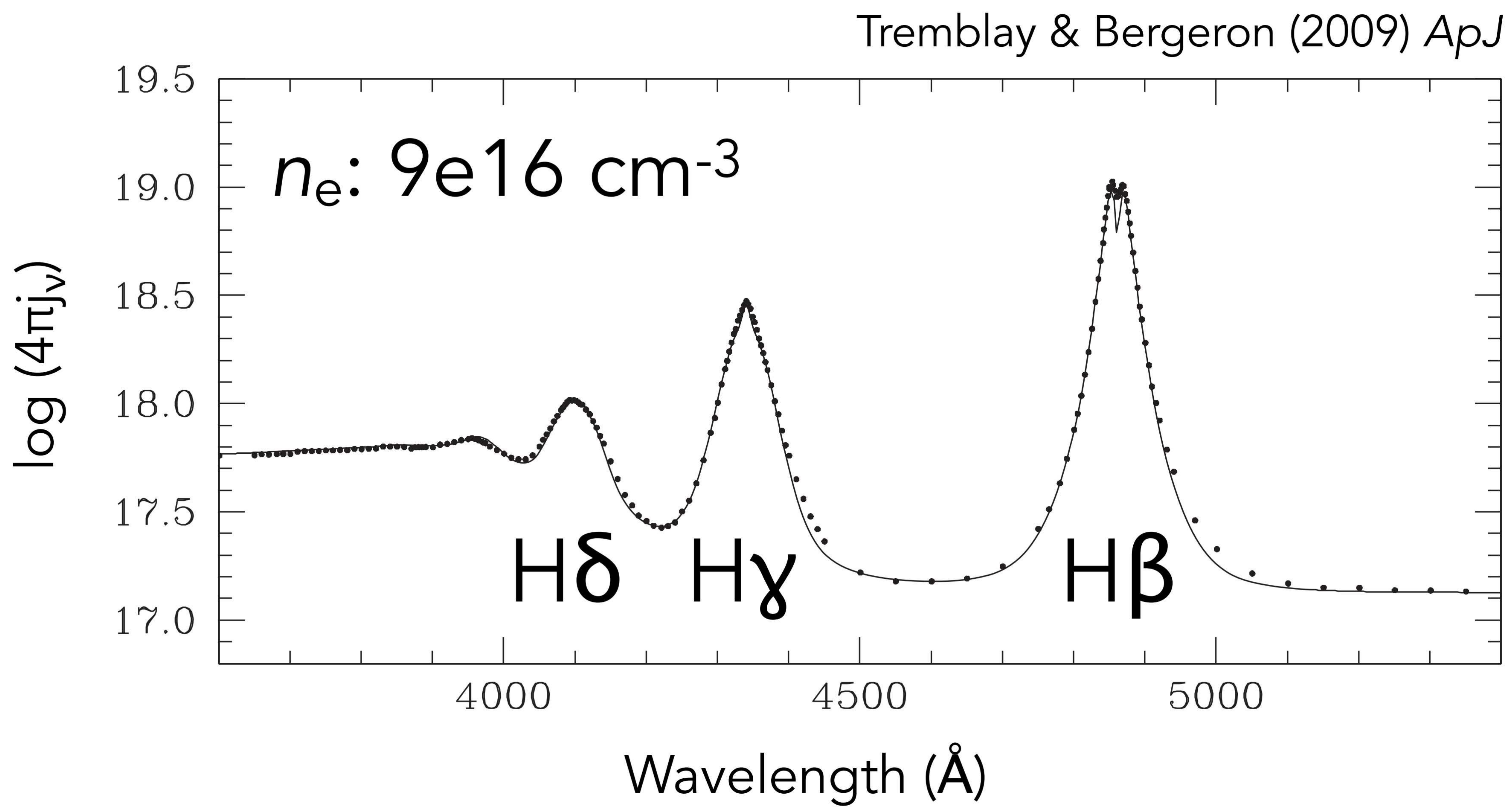


Energy structure of hydrogen



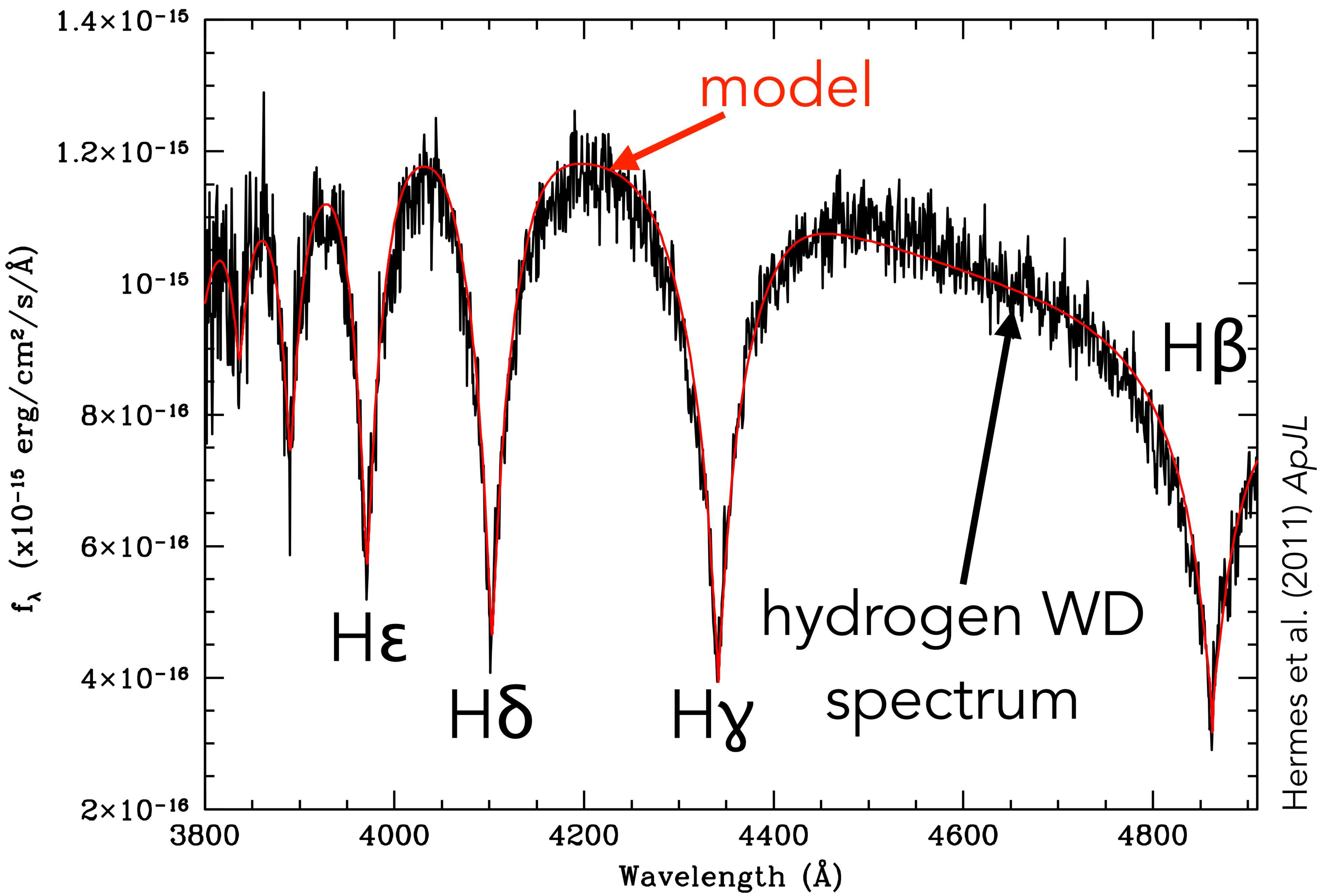
Spectrum of various Balmer lines

Emission validated hydrogen line-profile theories applied to WD absorption spectra allow for mass measurements



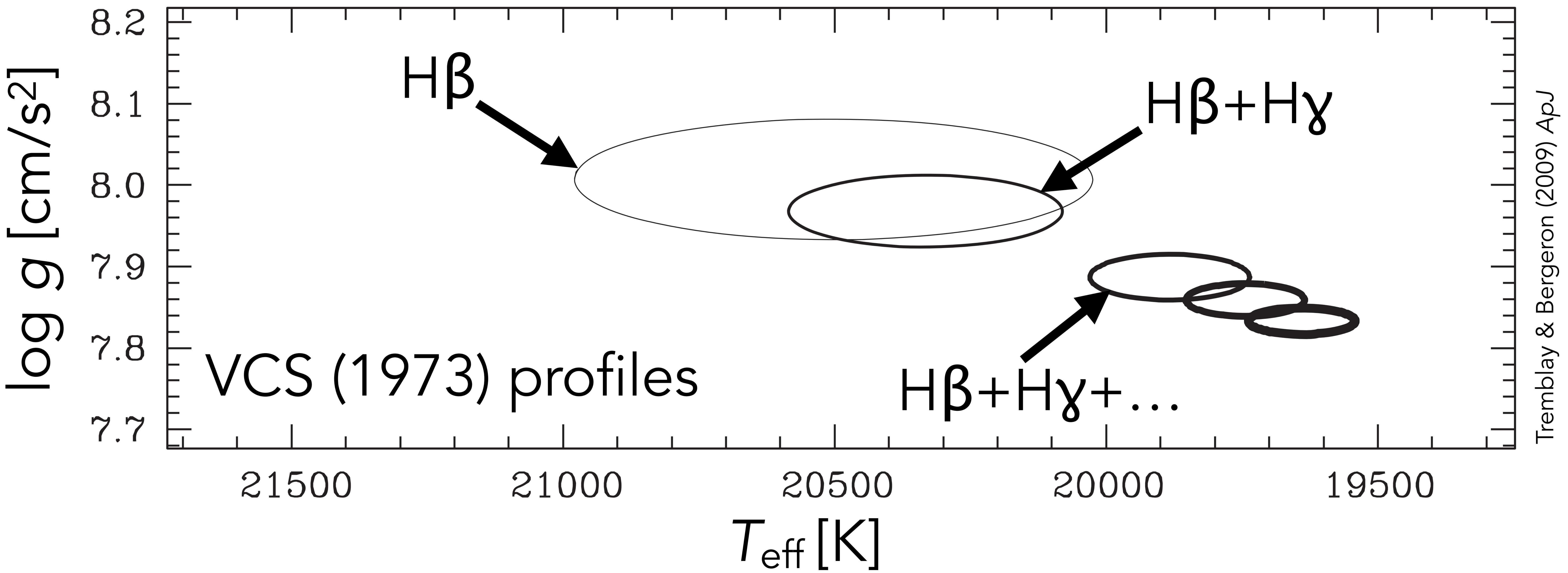
Comparison of current WD line shape theory to ***emission*** experiment of Wiese et al. (1972).

dots: experiment ***line: model***



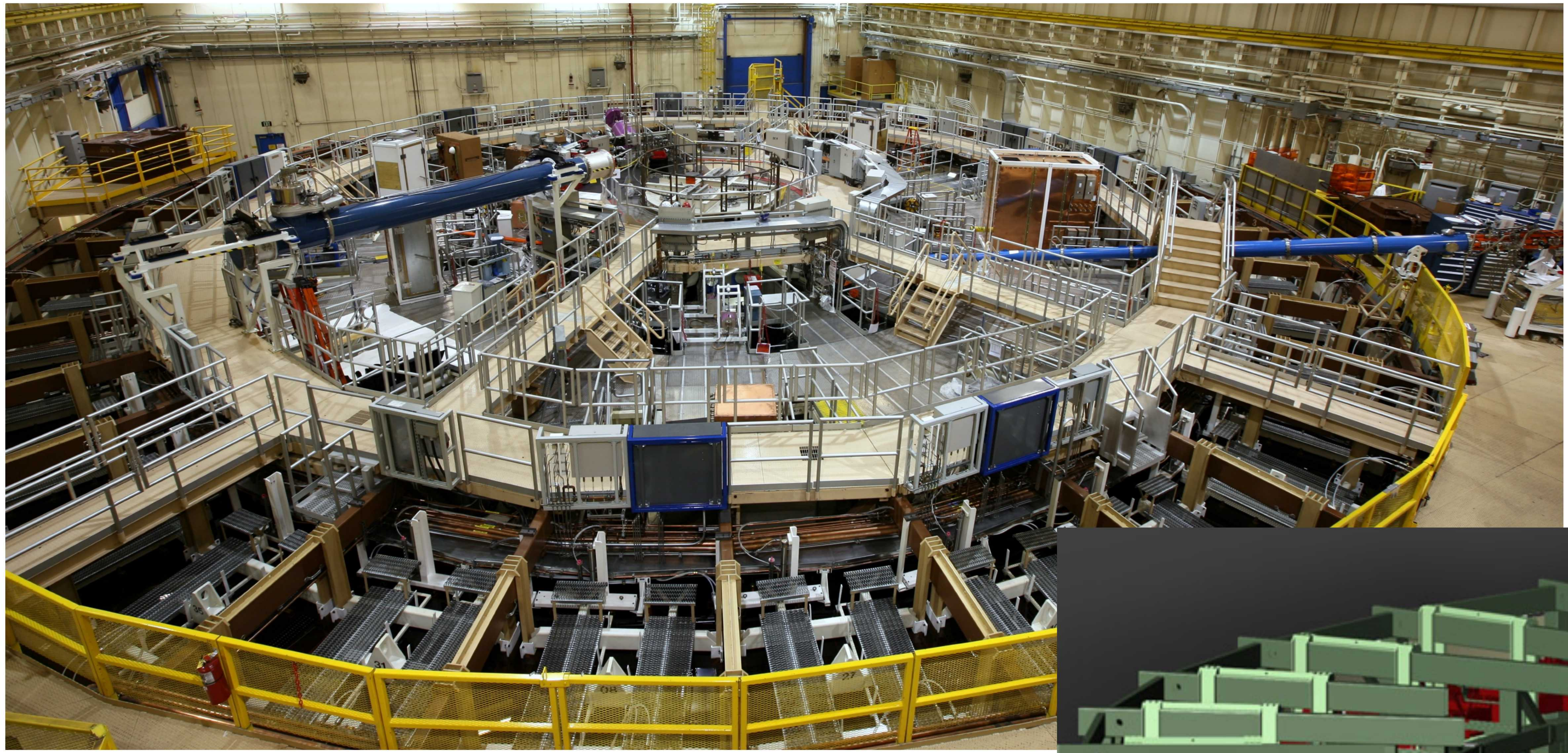
Fit of model atmosphere (red) to an observed hydrogen WD spectrum (black).
Fits and observations are in ***absorption***.

Fitting WD absorption spectra with emission-validated theories produces unexpected results

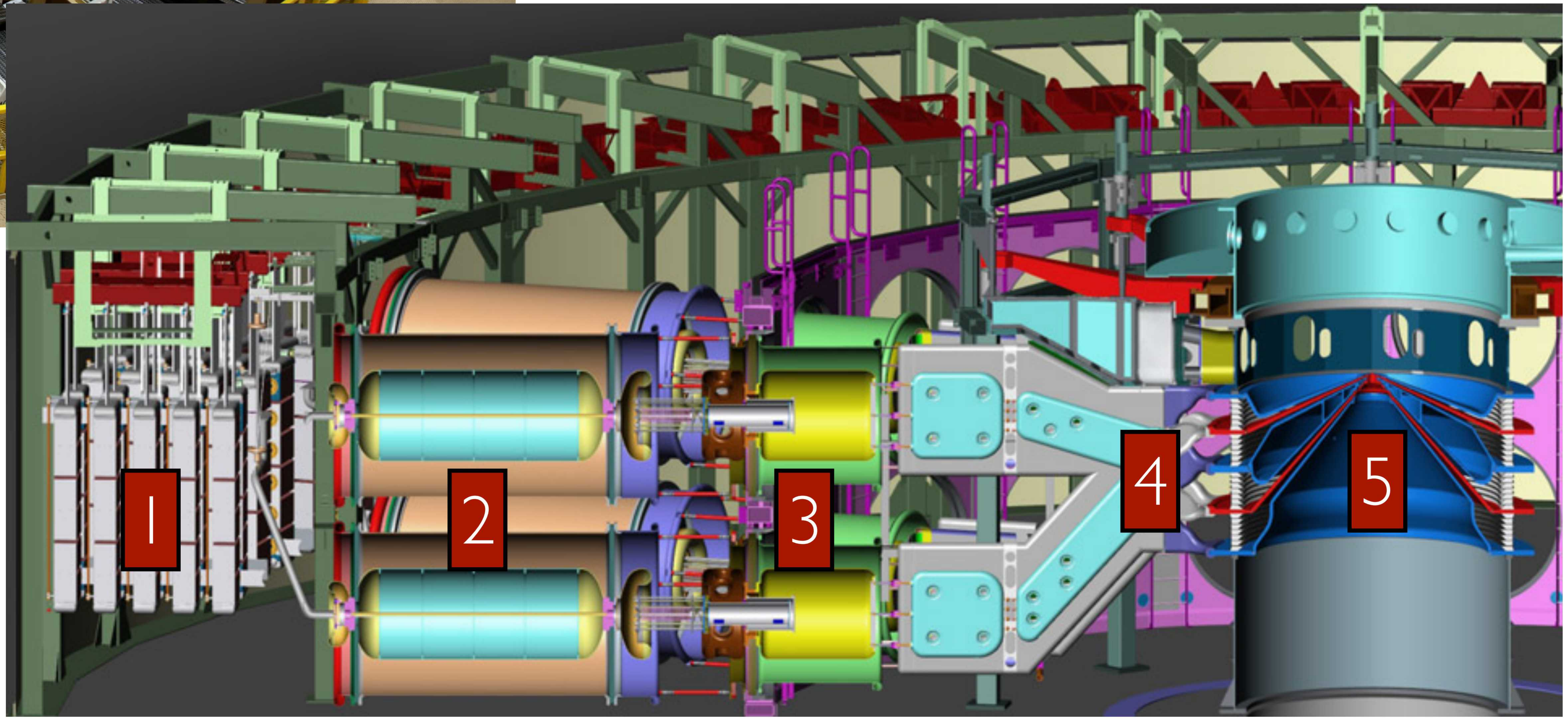


Are line-shape models inaccurate in absorption?

Sandia National Laboratories’ Z-machine

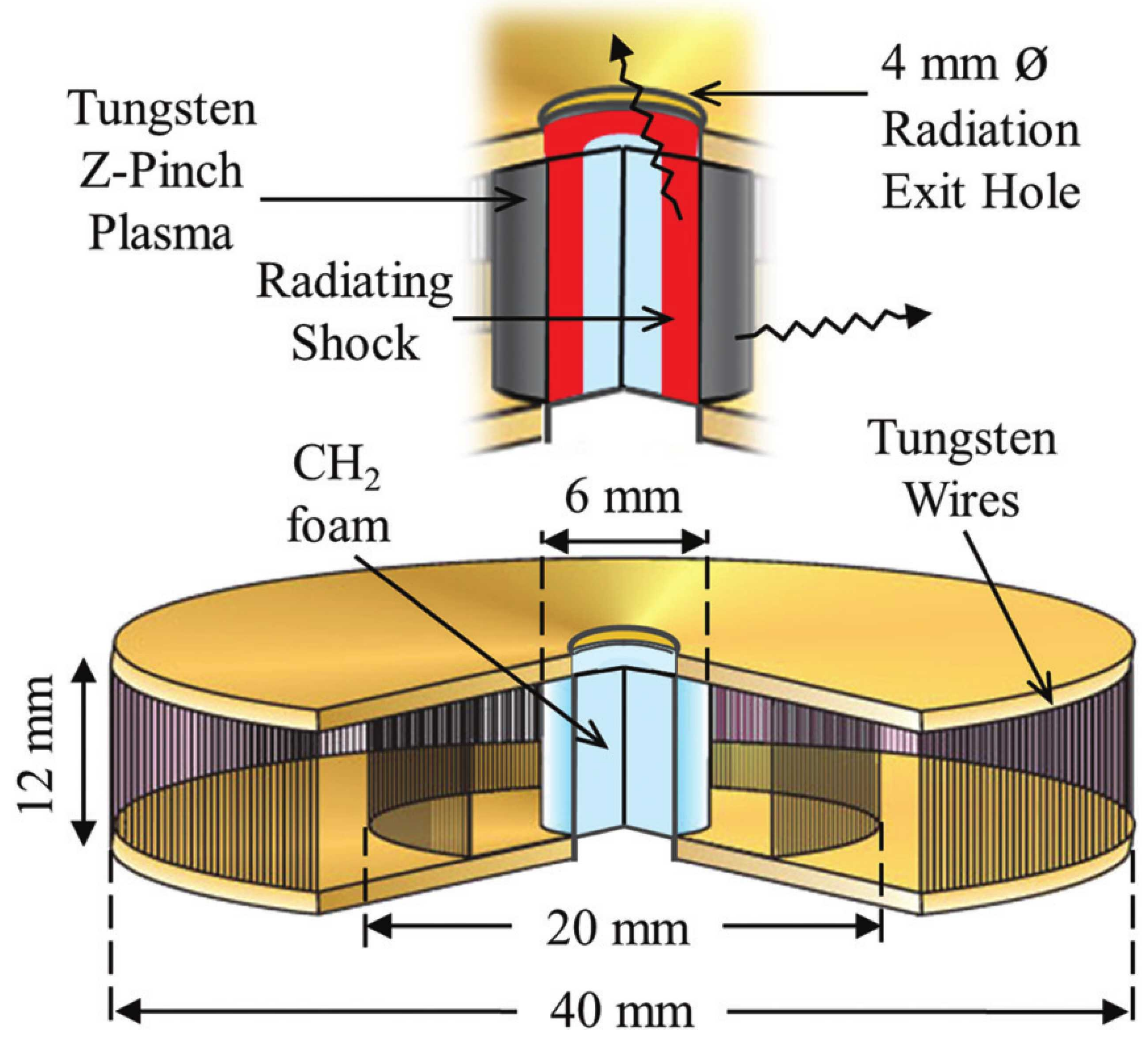


- 36 Marx bank generators at 85 kV
- current gets compressed in time and space
- x-ray output energy: 2 MJ
- broadband x-ray spectrum from 0.1 - 3 keV



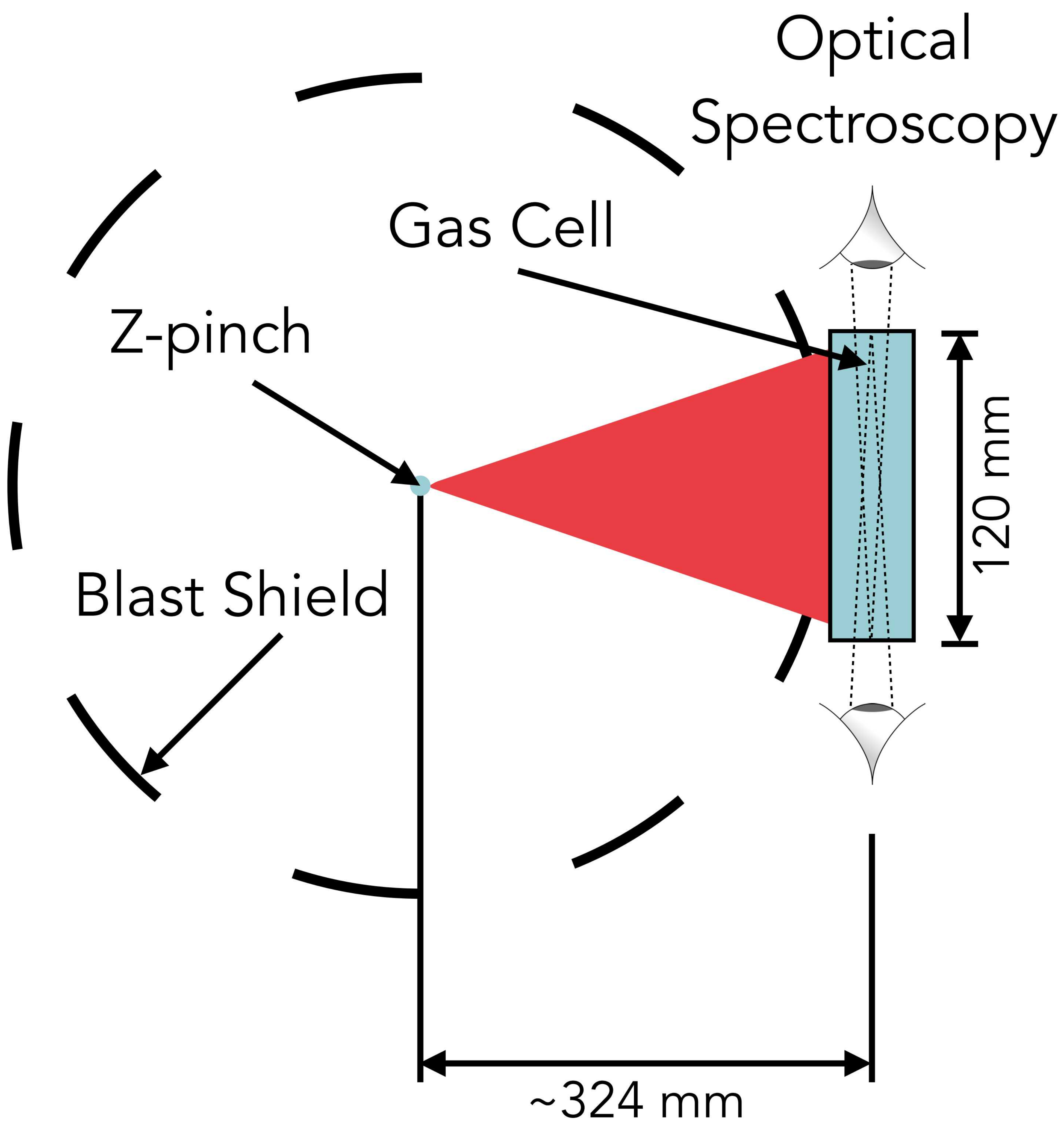
1 - 3: capacitors with decreasing rise times
4: transmission lines
5: vacuum chamber with dynamic hohlraum

Sandia National Laboratories' Z-machine



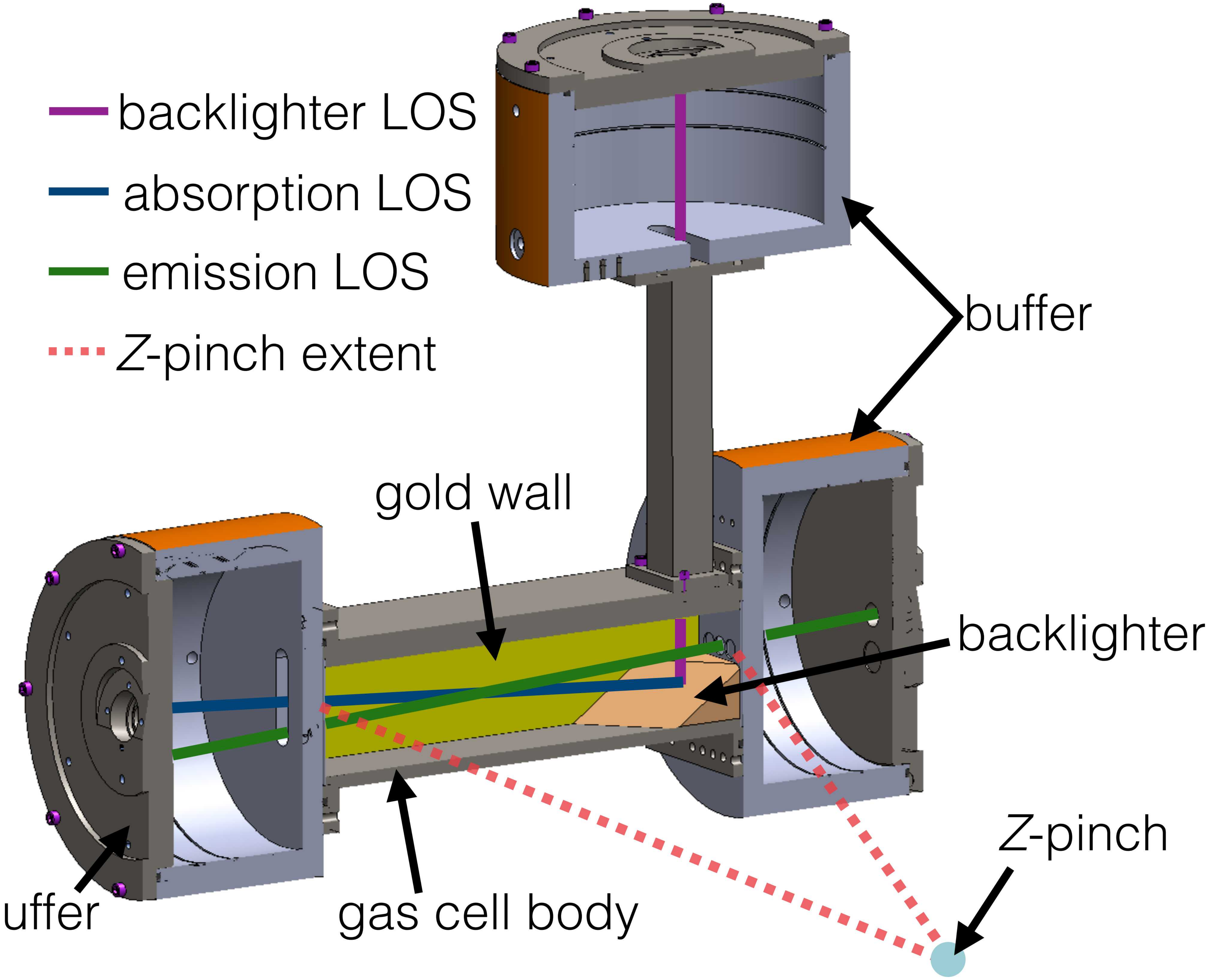
Rochau et al. (2014)

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.



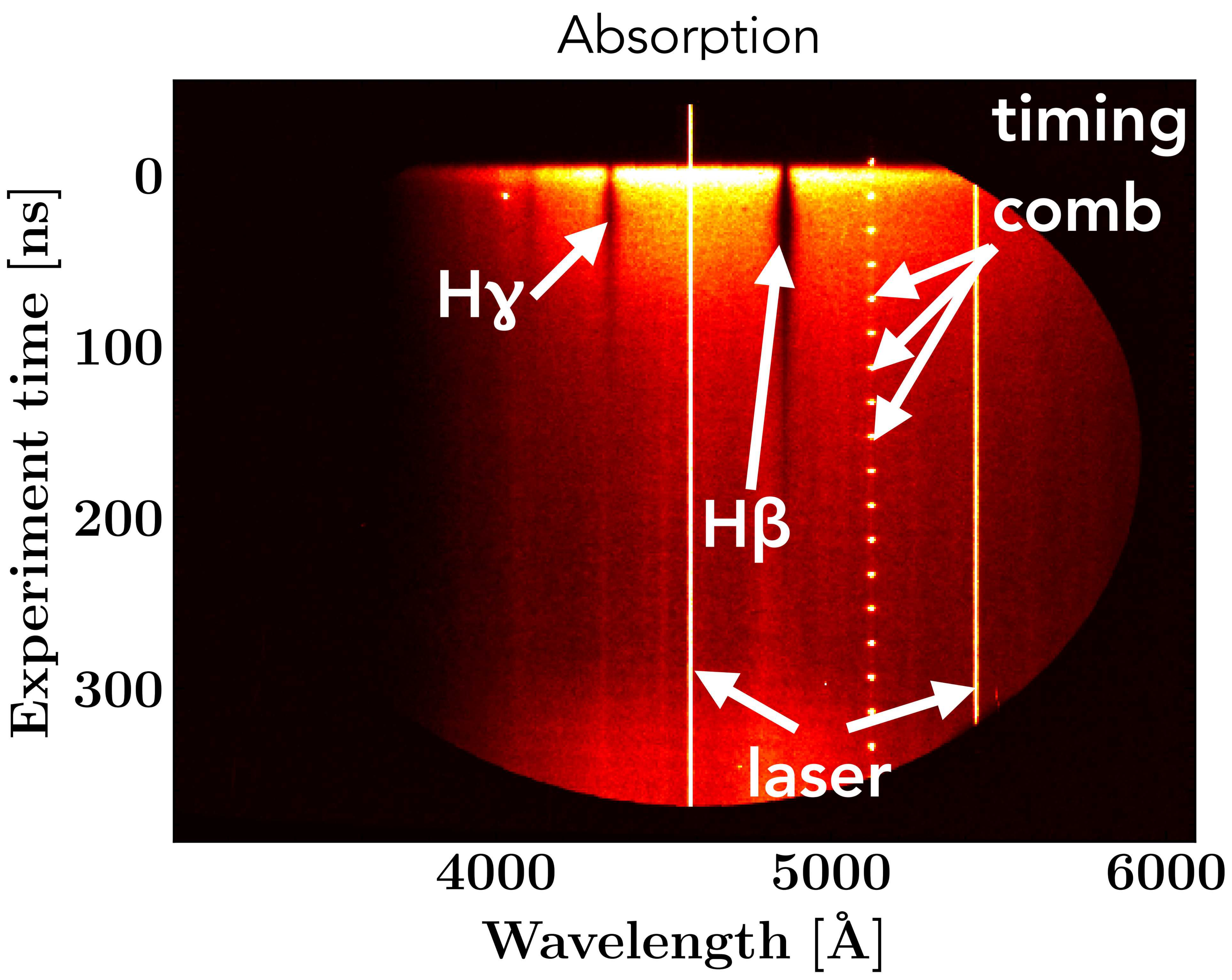
Location of WDPE gas cell with respect to the *Z*-pinch.

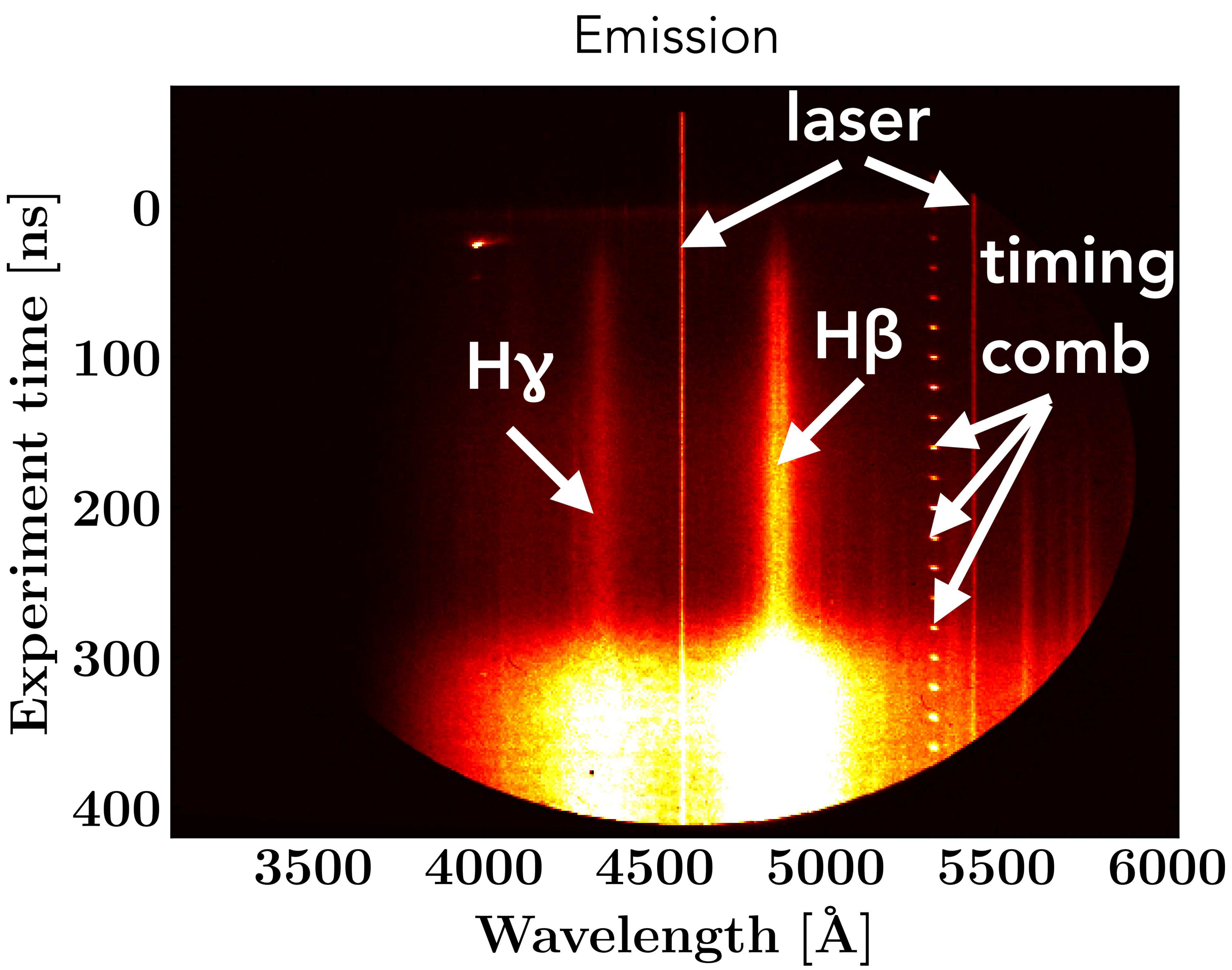
The White Dwarf Photosphere Experiment on *Z*



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 ~6eV, heating the gas in the gas cell.

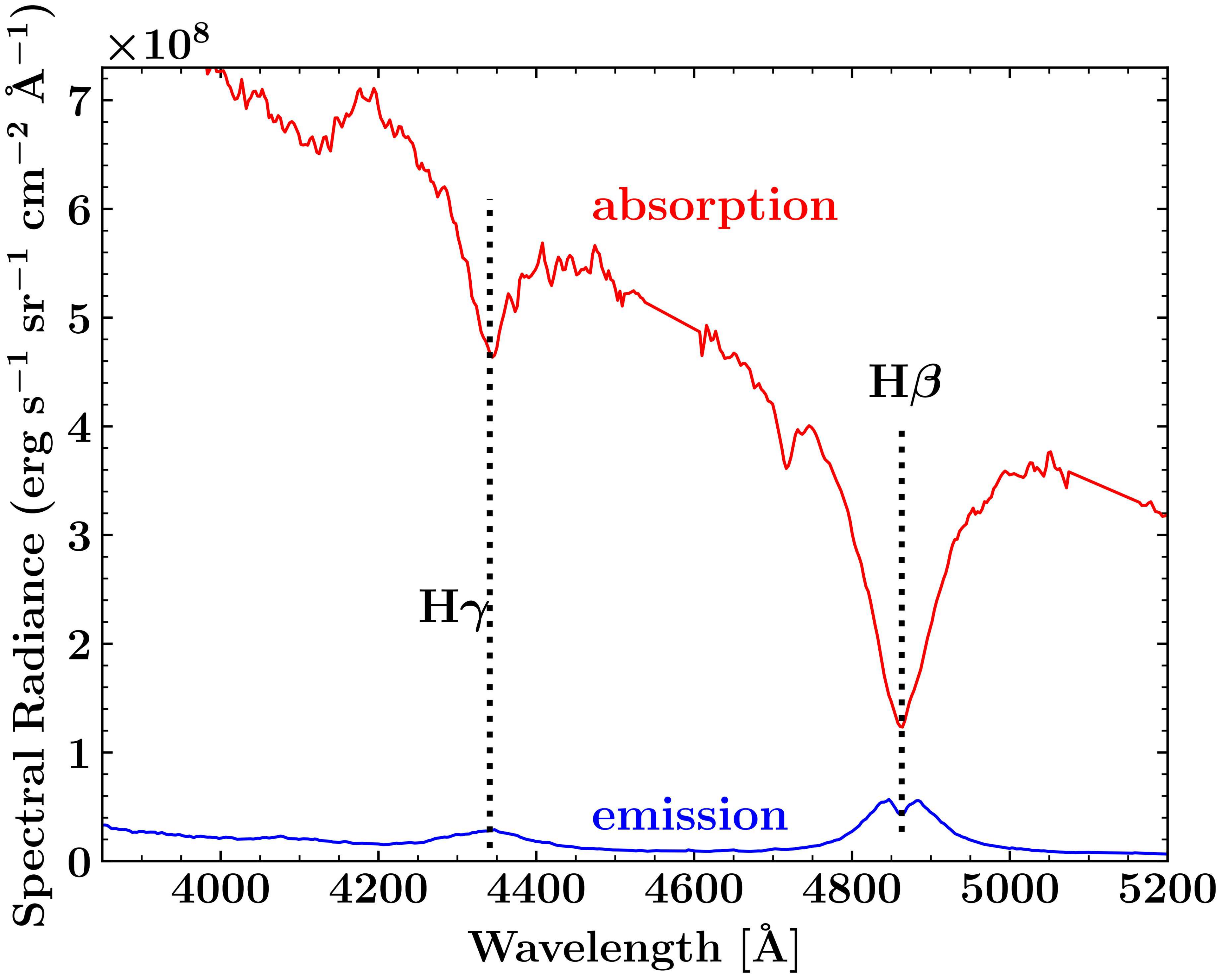
Hydrogen experimental data



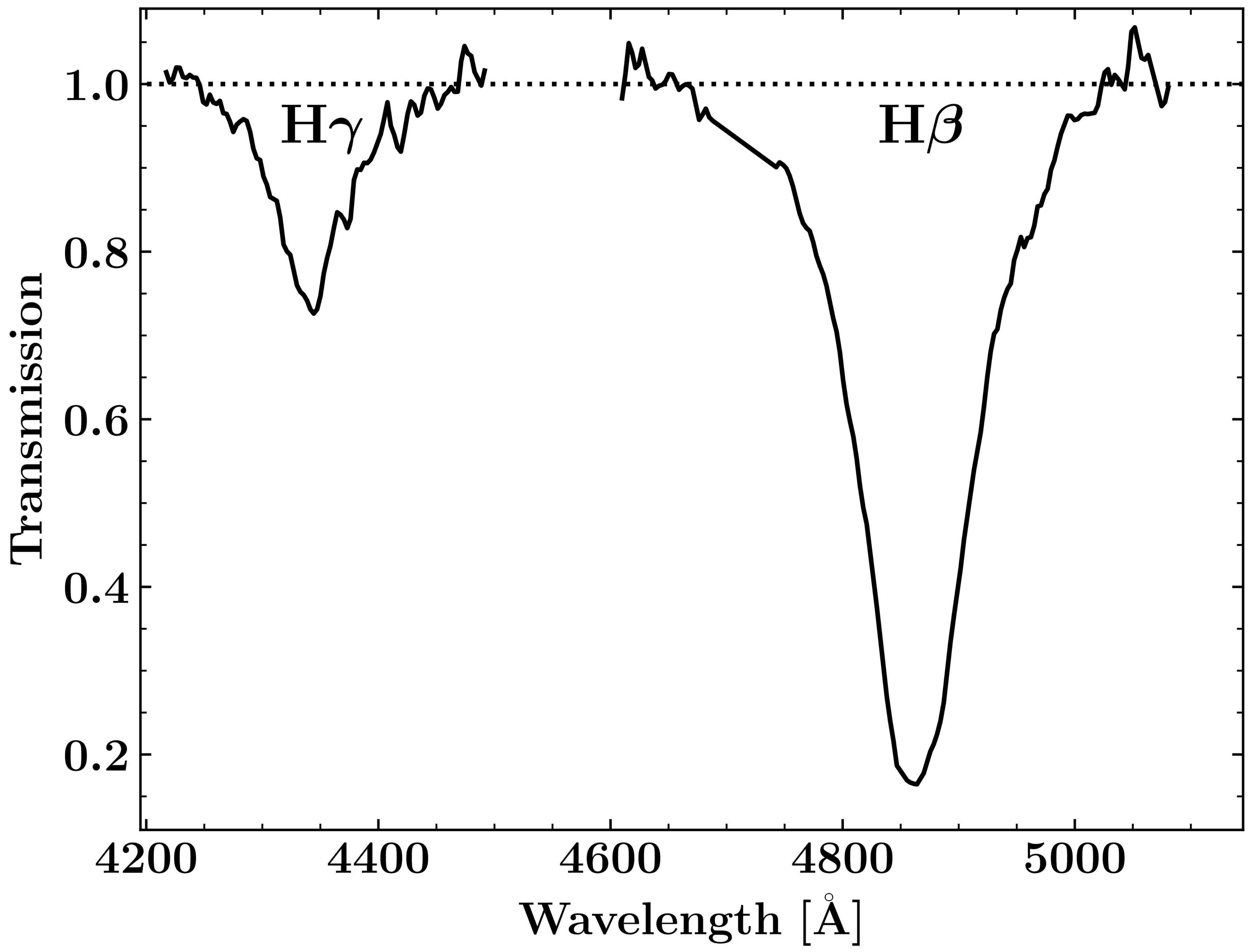


I combine the absorption and emission data to extract a transmission spectrum.

Z hydrogen data resemble real WD observations

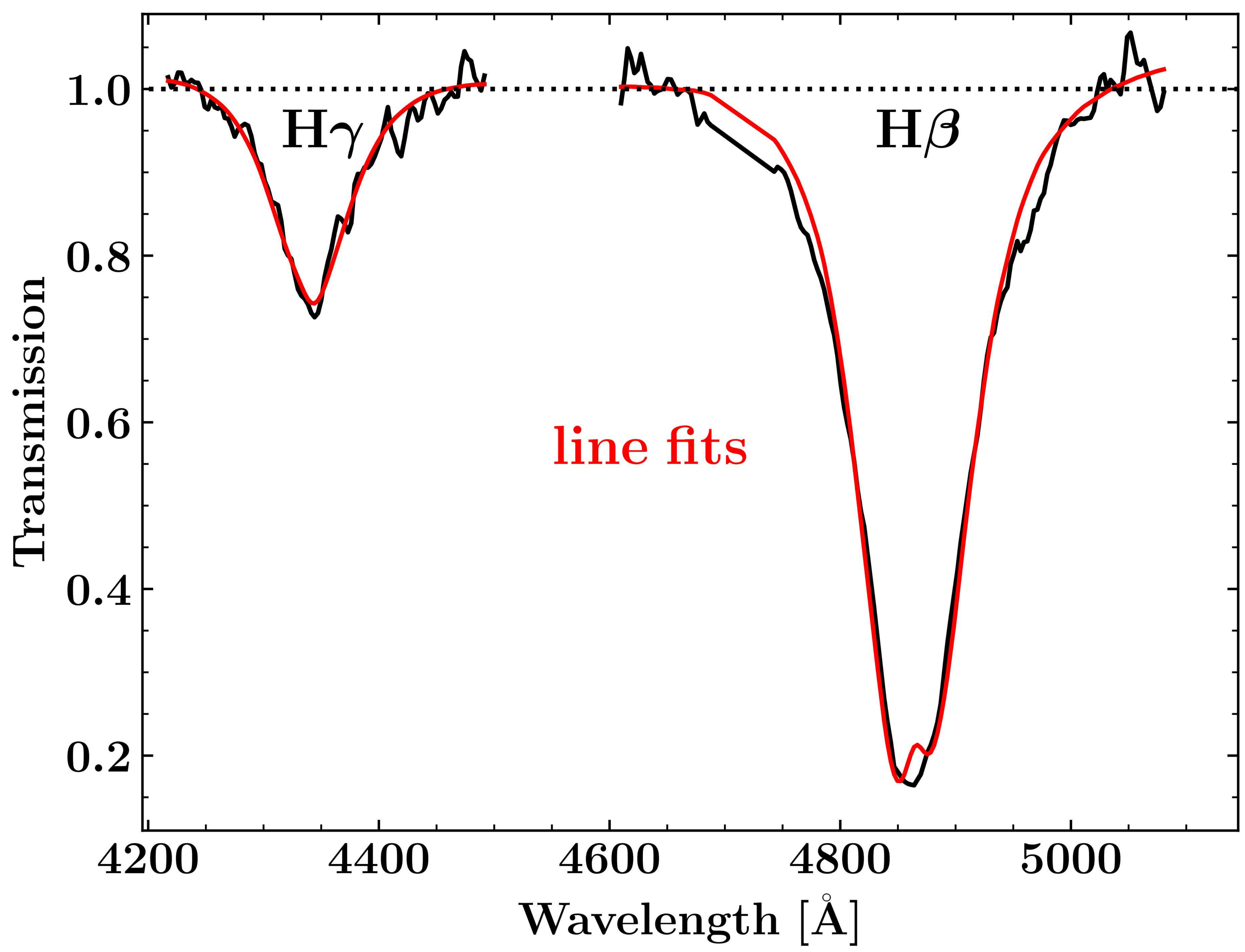


I collect absorption (blue) and emission (red) data, which are subtracted to give a transmission spectrum

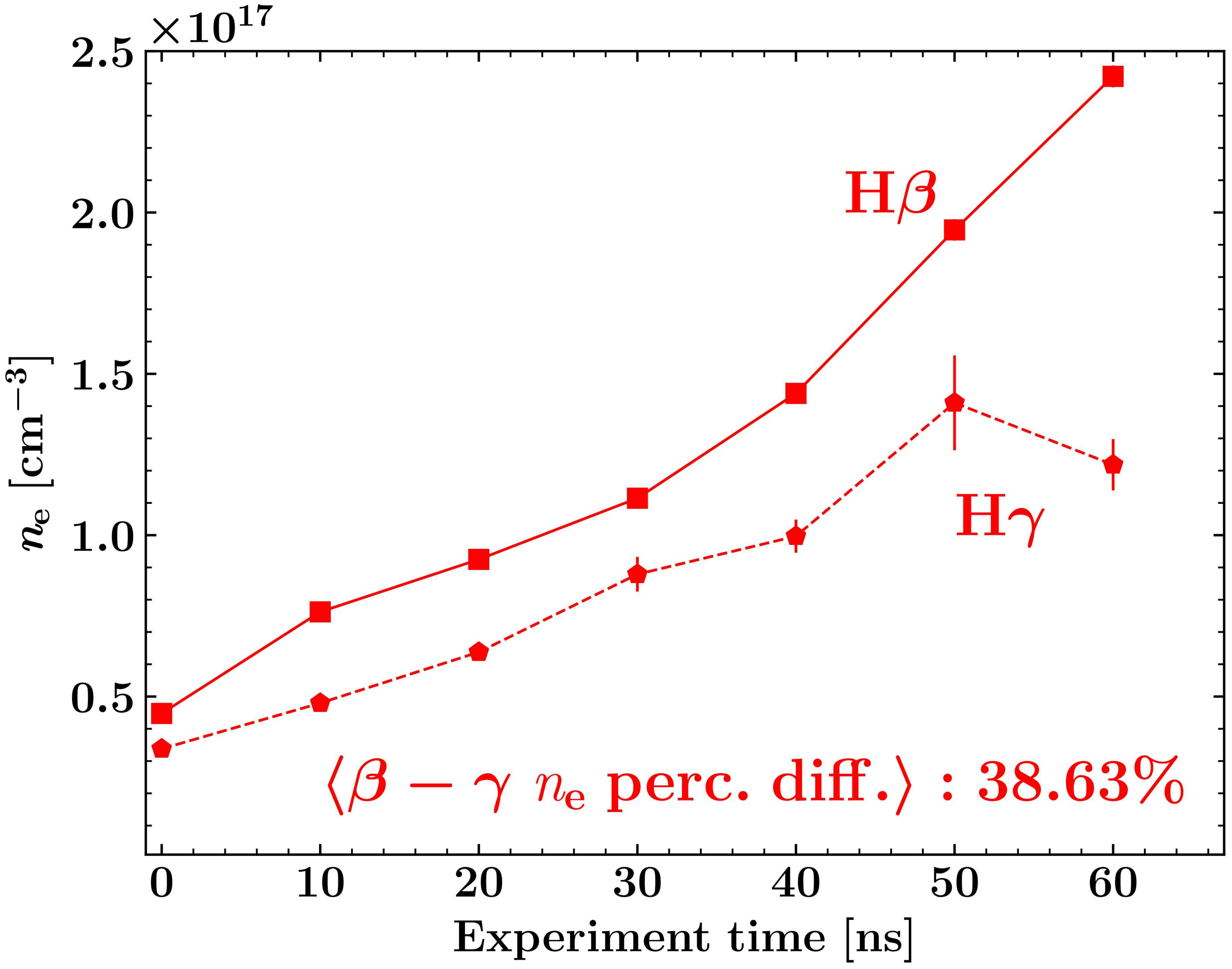


Extracted emission-corrected transmission spectra

Z hydrogen results reproduce observed WD n_e trends



Line fits to transmission spectra. These are used to extract plasma n_e values.



Inferred n_e values of Hβ and Hγ differ by almost 40%.
This effect is also observed in fits to hydrogen WDs.

What could cause the Hβ-Hγ n_e disagreement in transmission?

- Are plasma inhomogeneities in the WDPE platform causing these differences?

- Is there a fundamental physical difference between emission and absorption?

What could cause the Hβ-Hγ n_e disagreement in transmission?

- ***Are plasma inhomogeneities in the WDPE platform causing these differences?***

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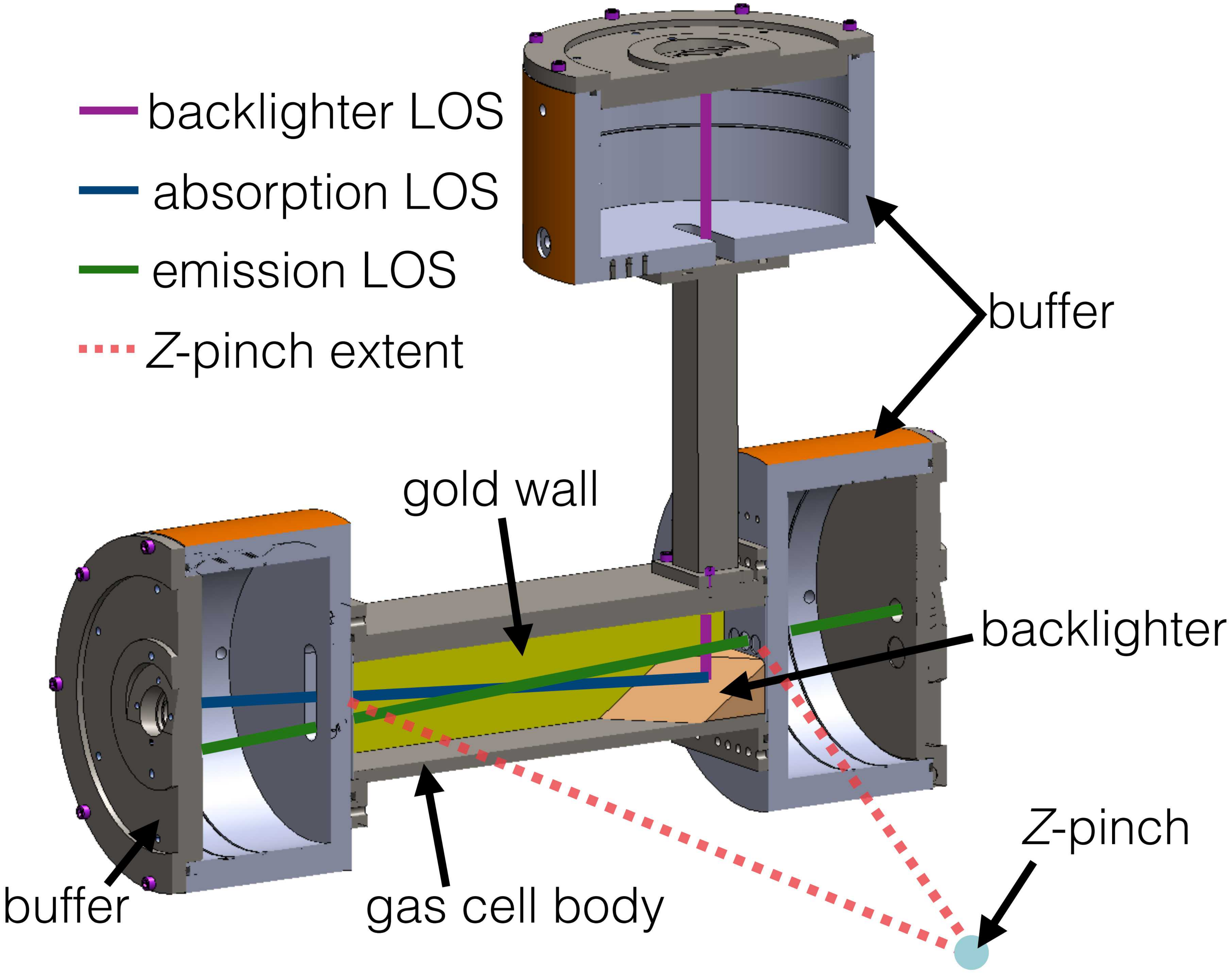
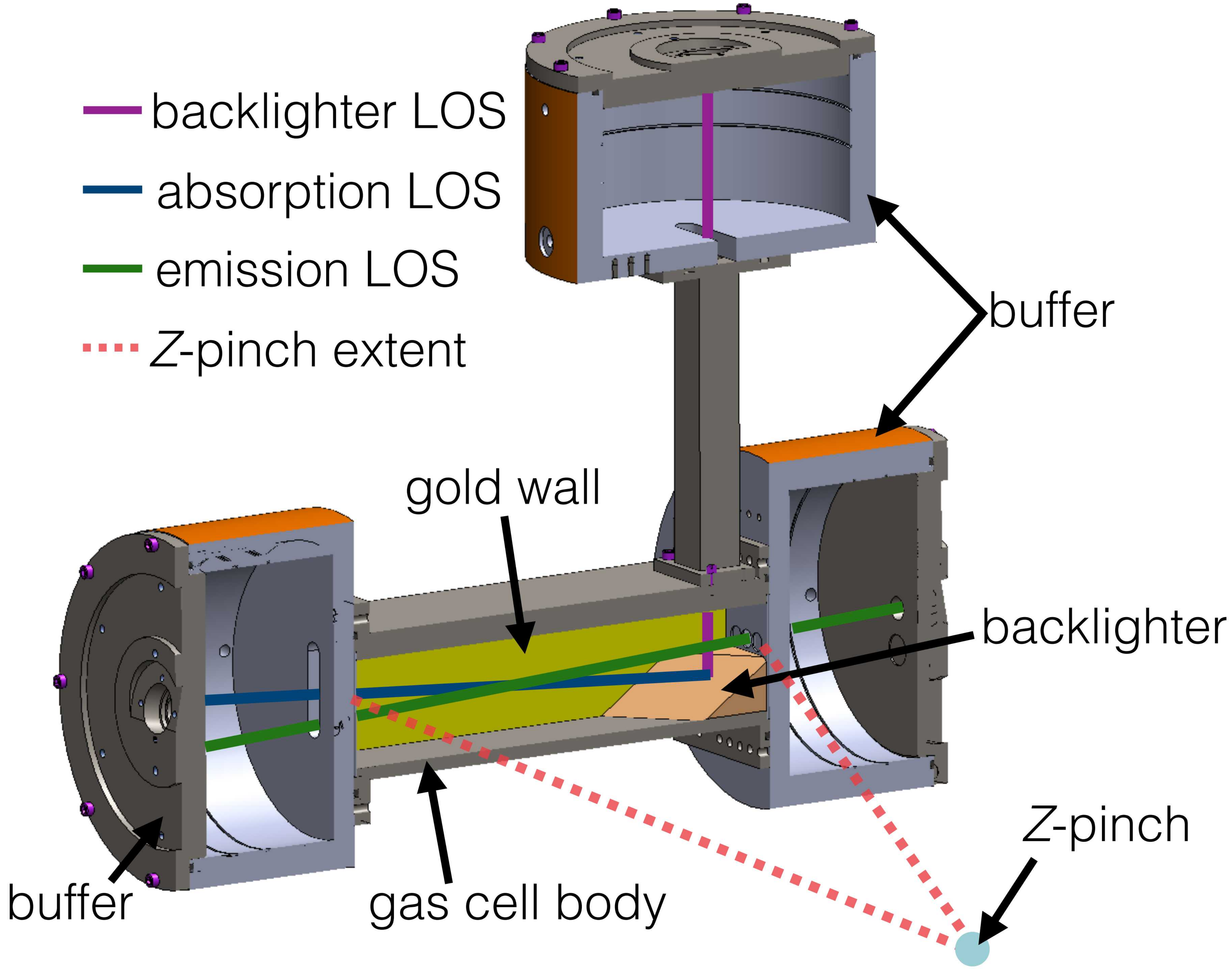
Plasma inhomogeneities in the WDPE gas cell



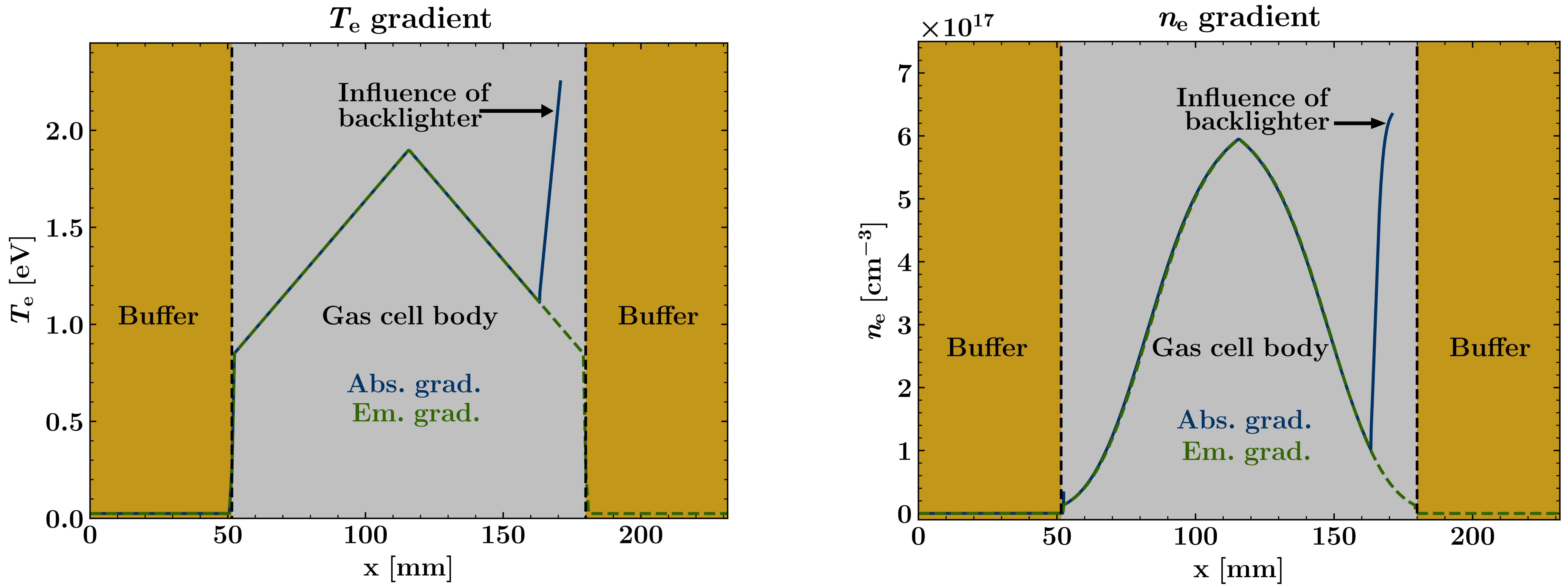
- Potential gradient sources:
  - interaction of Z-pinch with buffers
  - influence of backlighter on absorption data
  - cooler edge plasmas
  - gradient along gold wall due to view factor effects

Plasma inhomogeneities in the WDPE gas cell



- Potential gradient sources:
  - ~~interaction of Z-pinch with buffers~~
  - ~~influence of backlighter on absorption data~~
  - ~~cooler edge plasmas~~
  - ***gradient along gold wall due to view factor effects***

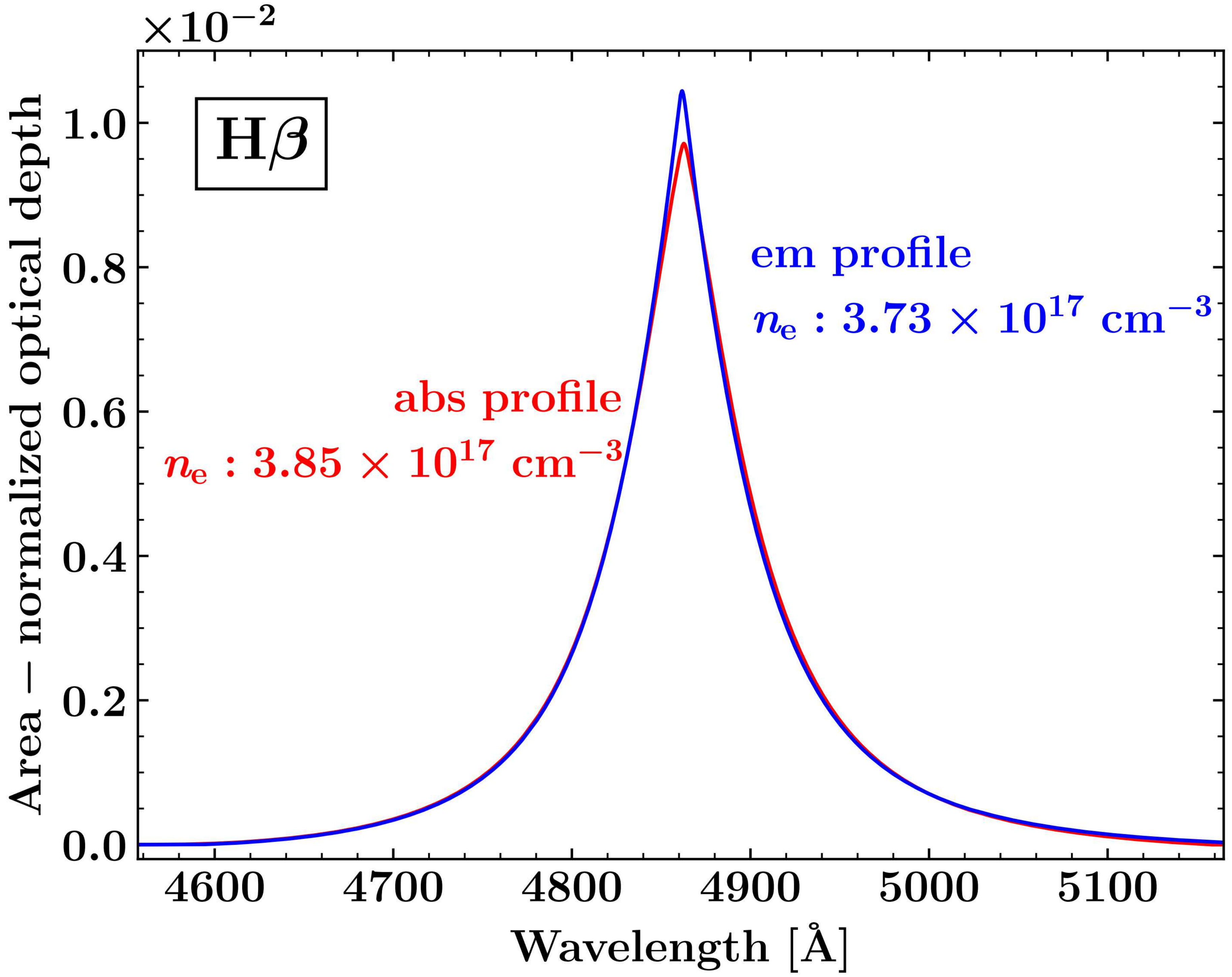
Extreme plasma inhomogeneities in the WDPE gas cell

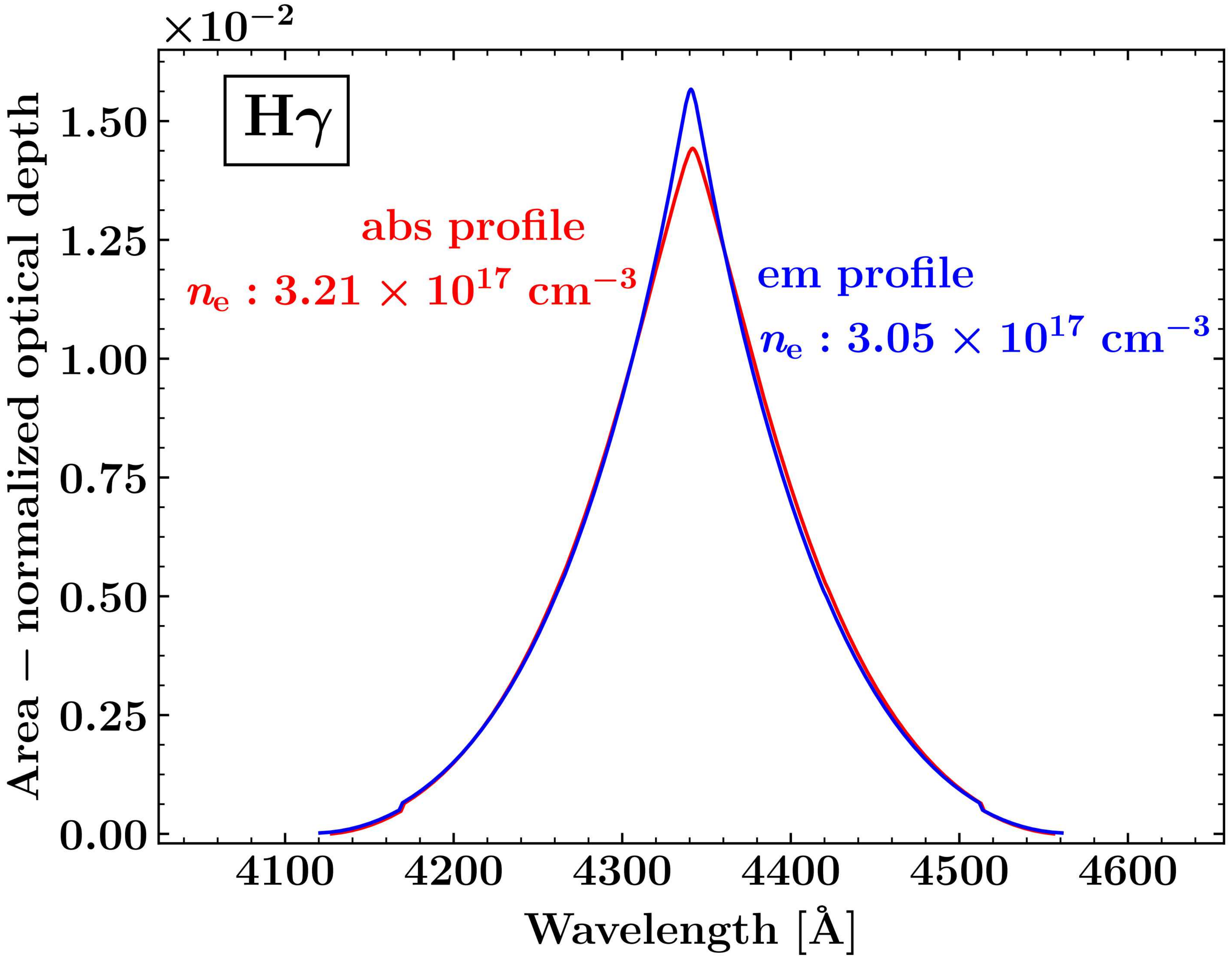


T_e range: 0.85 eV < T_e < 1.90 eV

n_e range: 0.3×10^{16} cm^{-3} < n_e < 6.0×10^{17} cm^{-3}

Effects of extreme gradients on Hβ and Hɣ line profiles





Area-normalized Hβ and Hɣ emission and absorption profiles resulting from gradient simulations

Inhomogeneities can only explain about half of the observed n_e difference.

Where is the remaining difference coming from?

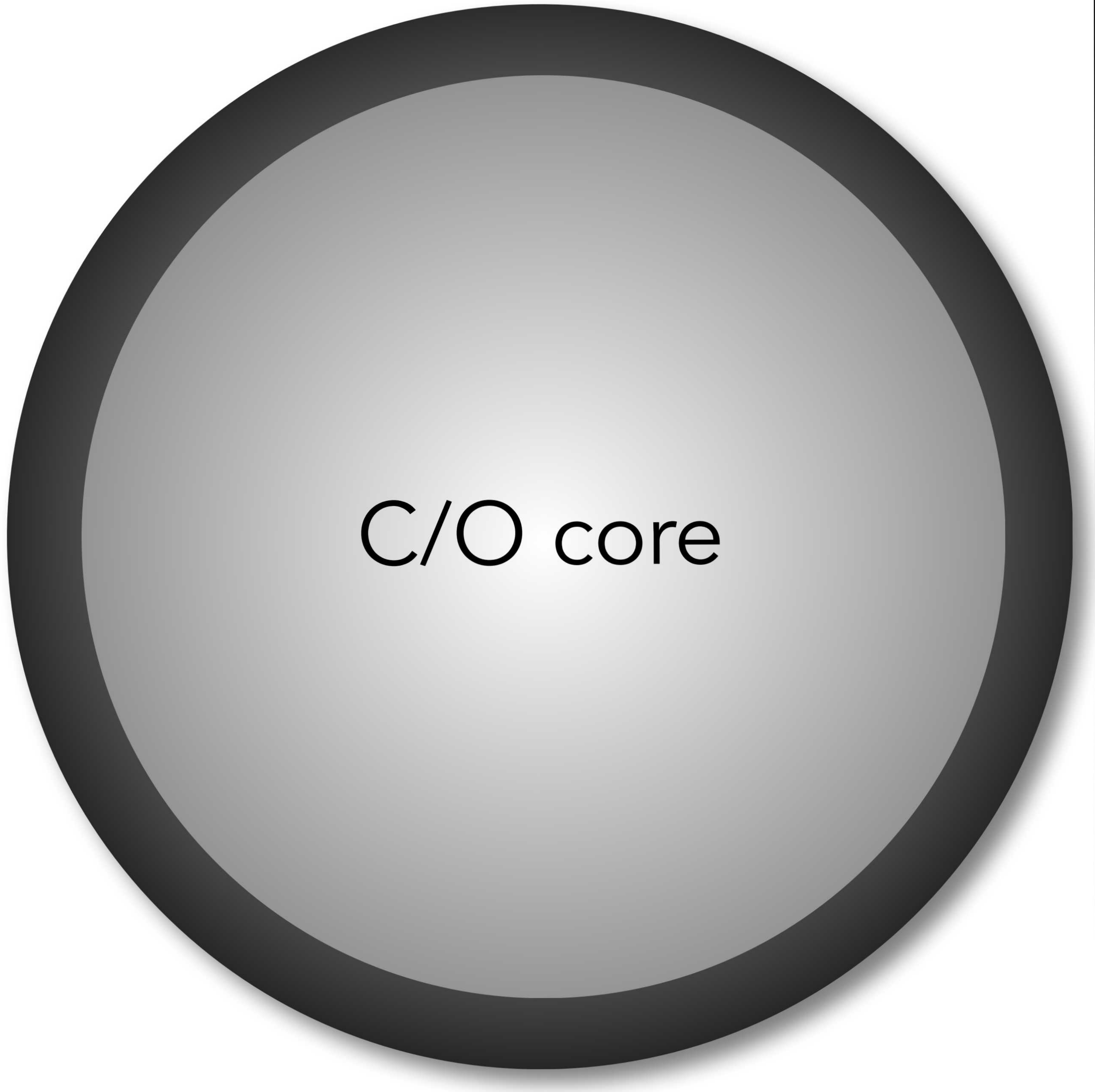
If real, how does this affect WD ages?

What does this mean for emission and absorption line profiles?

DA: hydrogen atmosphere

Q: Age of the Galaxy?

DB: helium atmosphere



Q: Stellar evolution?

DQ: carbon atmosphere

Q: Failed supernovae?

Not drawn to scale.

What is the evolutionary history of helium WDs?

Hypothesis	Predicted mass signatures
atmospheric diffusion/convection	

Atmospheric diffusion/convection mechanism

Hypothesis 1: All WDs are 'born' with a hydrogen and helium layer.
These layers convectively mix as the WD cools, producing a DB.

What is the evolutionary history of helium WDs?

Hypothesis	Predicted mass signatures
atmospheric diffusion/convection	$\langle M_{\text{helium WD}} \rangle = \langle M_{\text{hydroden WD}} \rangle$

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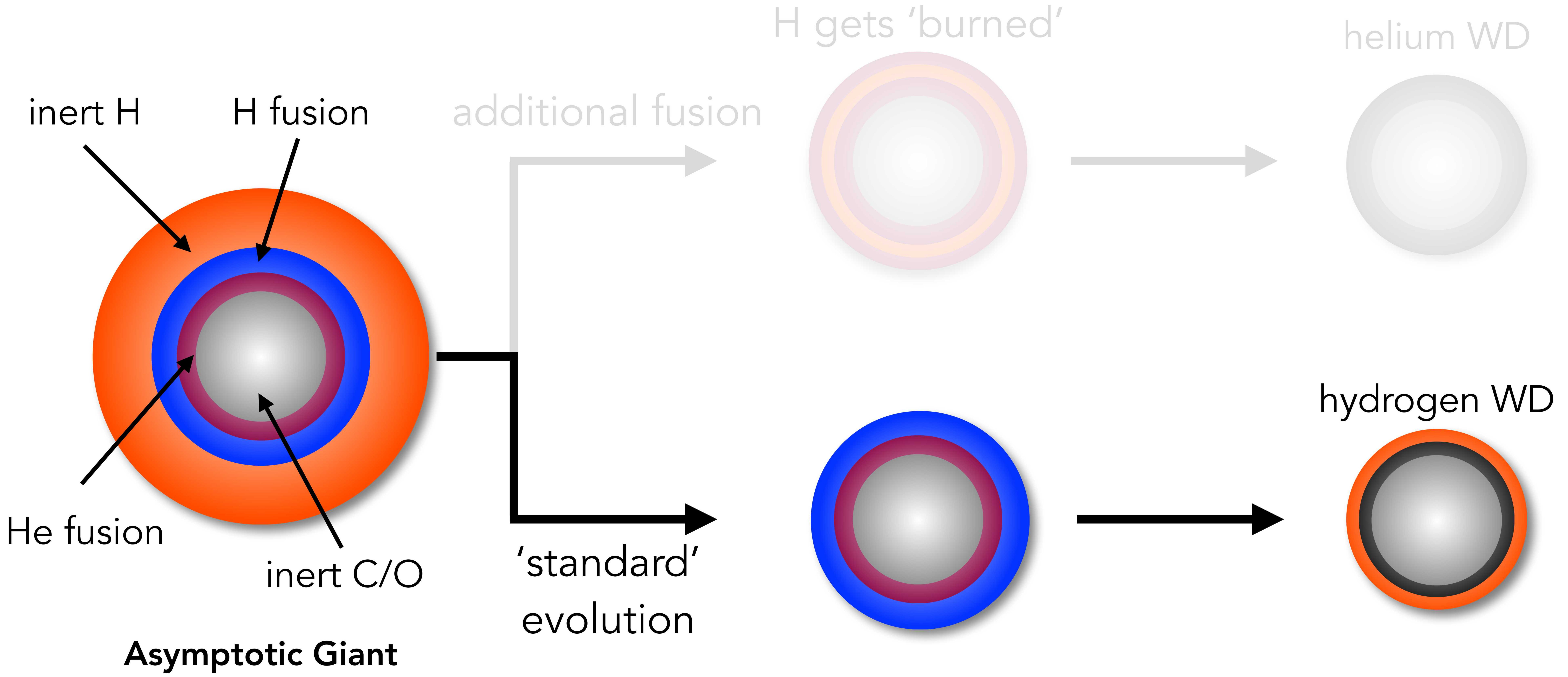
additional WD progenitor fusion	

WD progenitor fusion mechanism

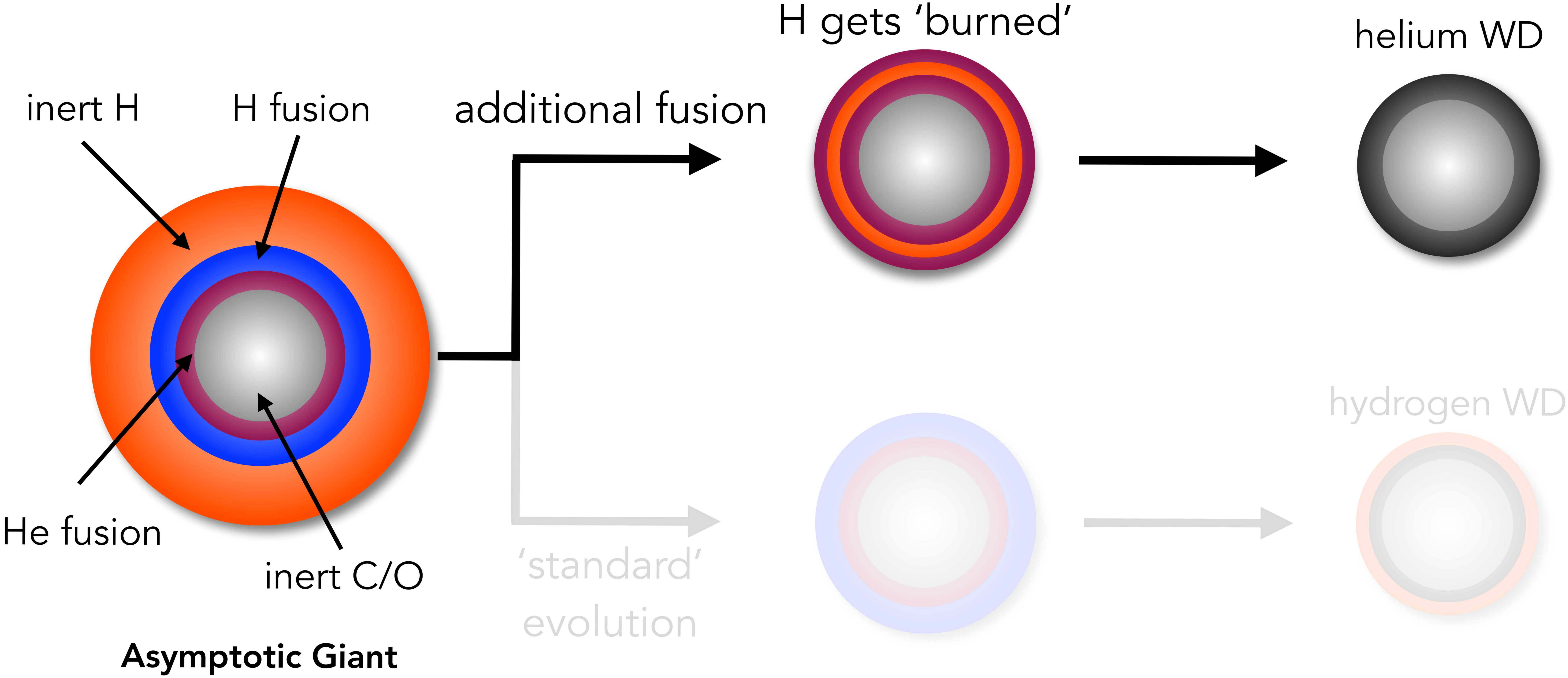
Not drawn to scale.

WD progenitor fusion mechanism



Not drawn to scale.

WD progenitor fusion mechanism



Not drawn to scale.

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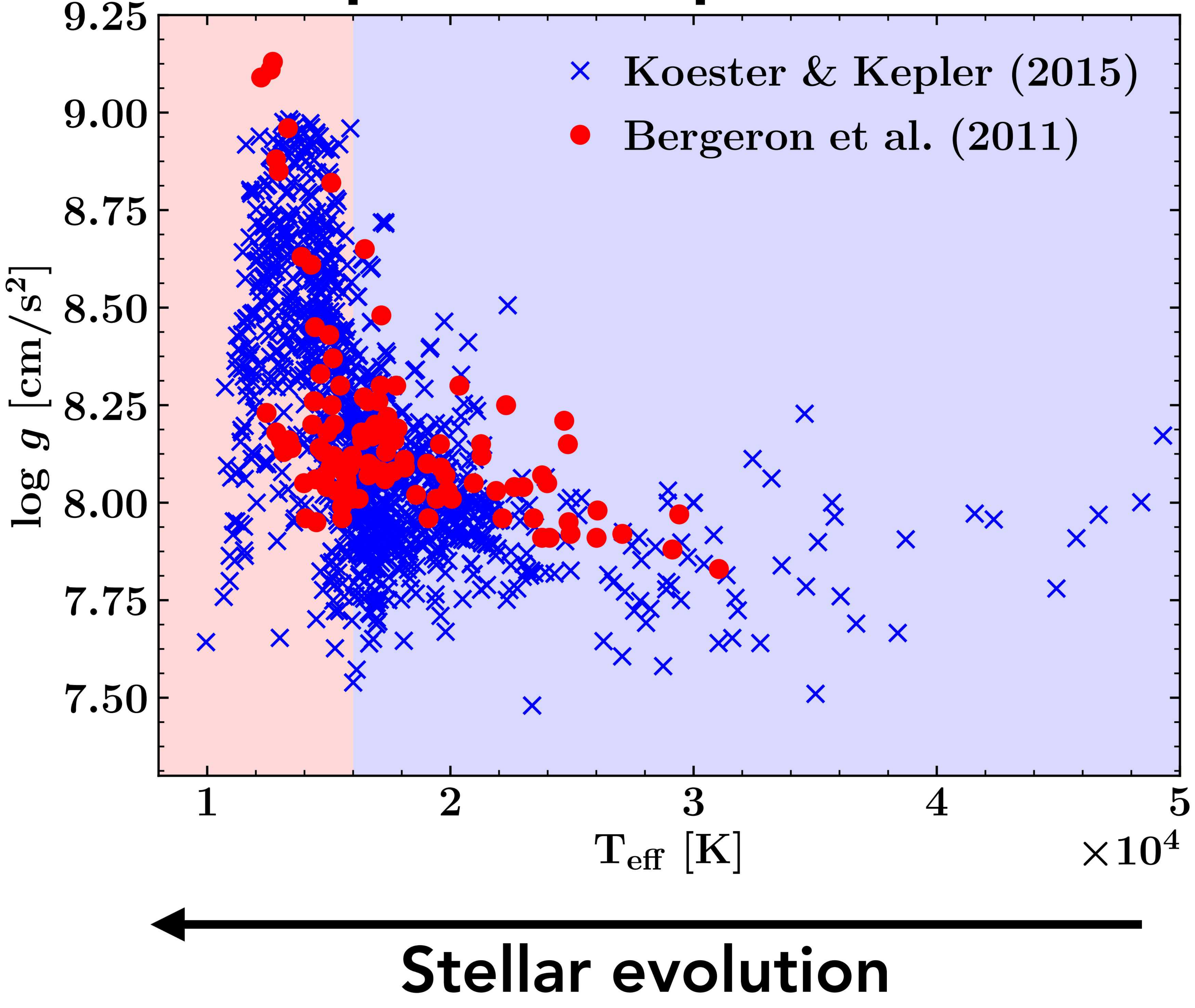
Hypothesis	Predicted mass signatures
atmospheric diffusion/convection	$\langle M_{\text{helium WD}} \rangle = \langle M_{\text{hydroden WD}} \rangle$
additional WD progenitor fusion	$\langle M_{\text{helium WD}} \rangle \neq \langle M_{\text{hydrogen WD}} \rangle$
binary evolution	$\langle M_{\text{helium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

Nather et al. (1987) *ApJ*
Koester & Kepler (2015) *A&A*
Werner et al. (2006) *PASP*

Accurate DB mass distributions are needed to distinguish between hypotheses.

Problems with all He WD mass determination methods prevents studying their evolutionary history

Spectroscopic mass



spectroscopically determined masses seem to imply that:

- older (cooler) WDs are more massive

  OR

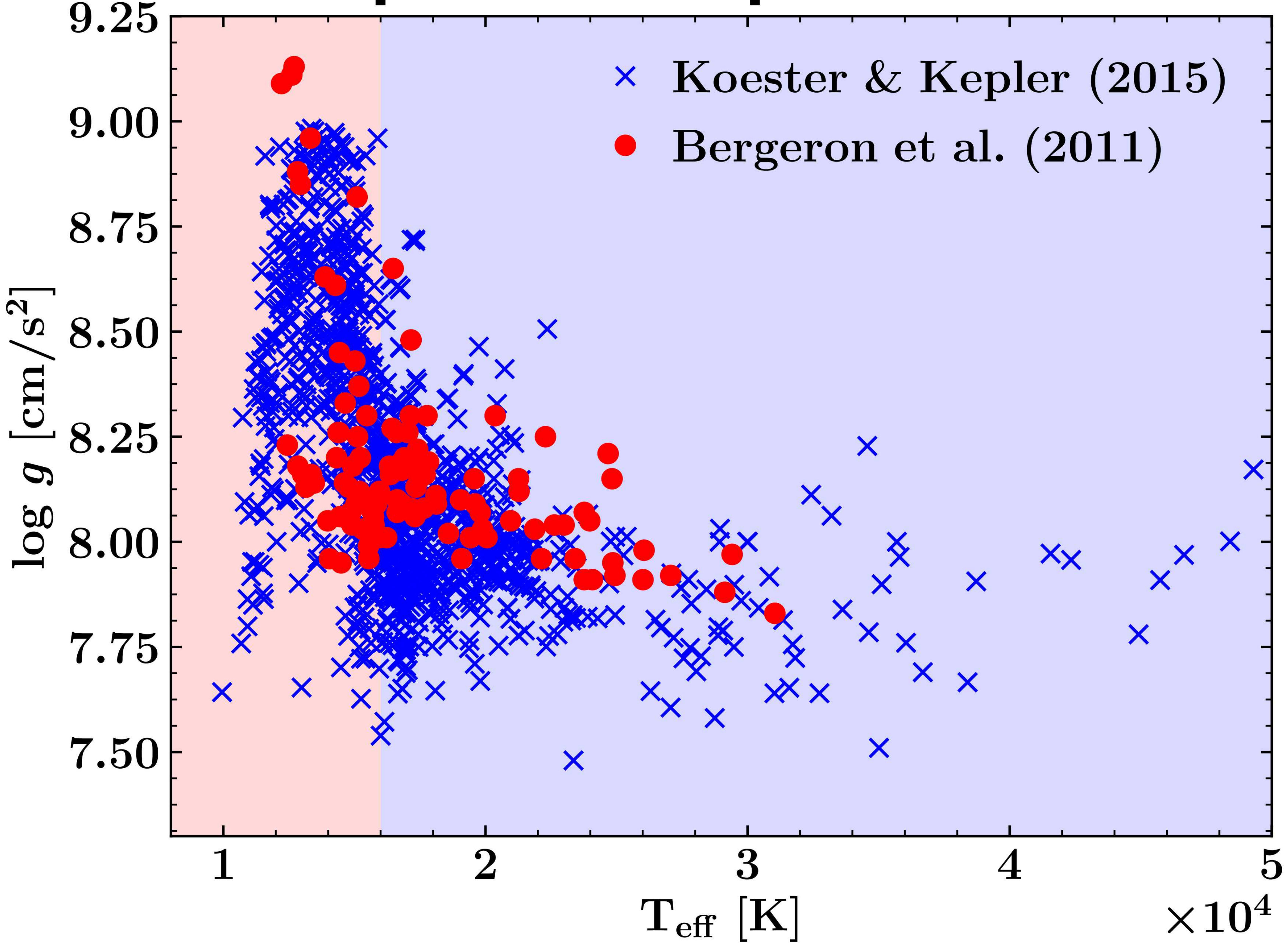
- stars gain mass as they age

  OR

- missing atomic physics in the models is responsible (i.e. neutral broadening)

Problems with all He WD mass determination methods prevents studying their evolutionary history

Spectroscopic mass



Spectroscopically determined DB surface gravities as a function of surface temperature.

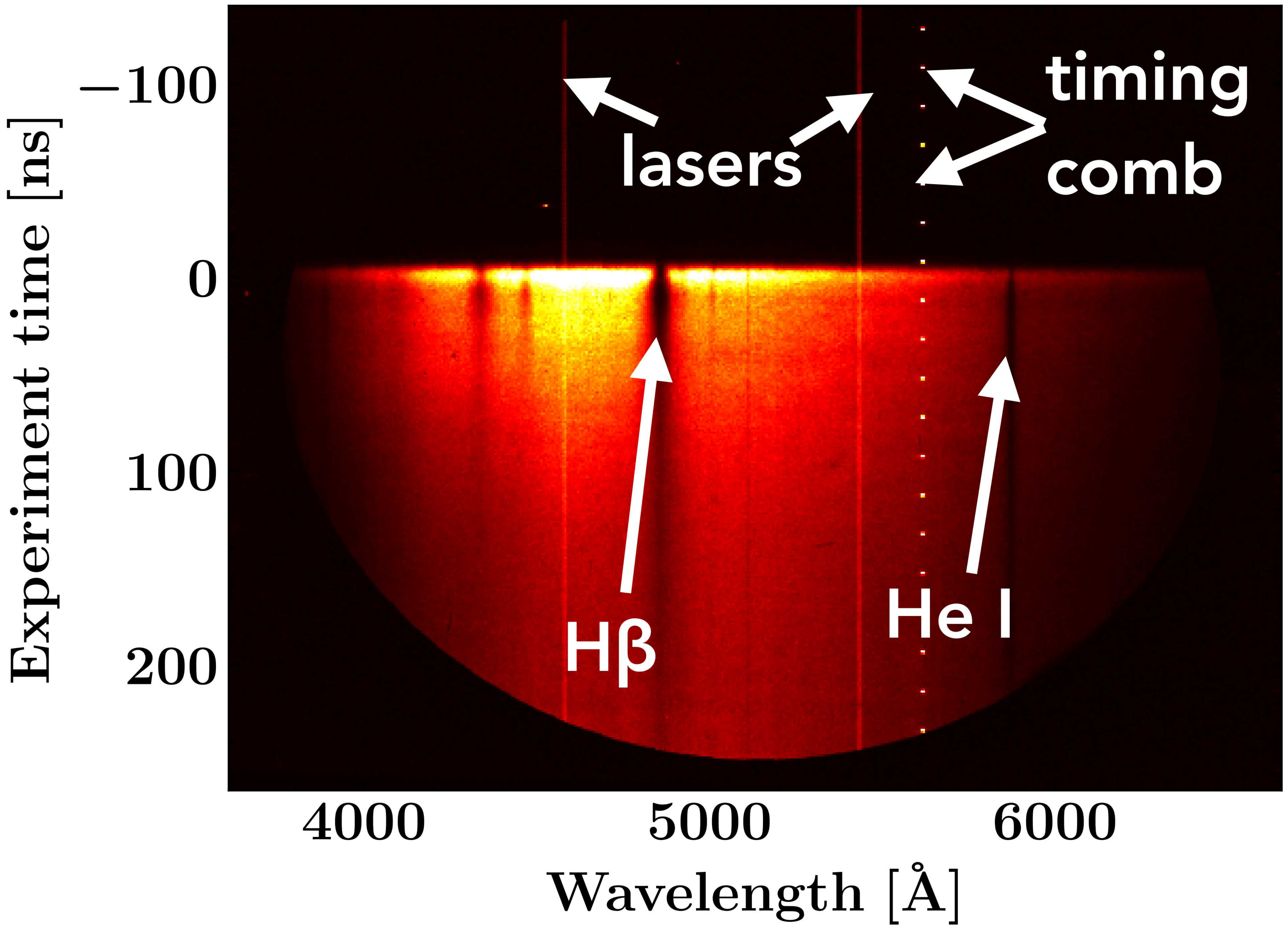
GR mass:

not available due to uncertain pressure shifts of He lines

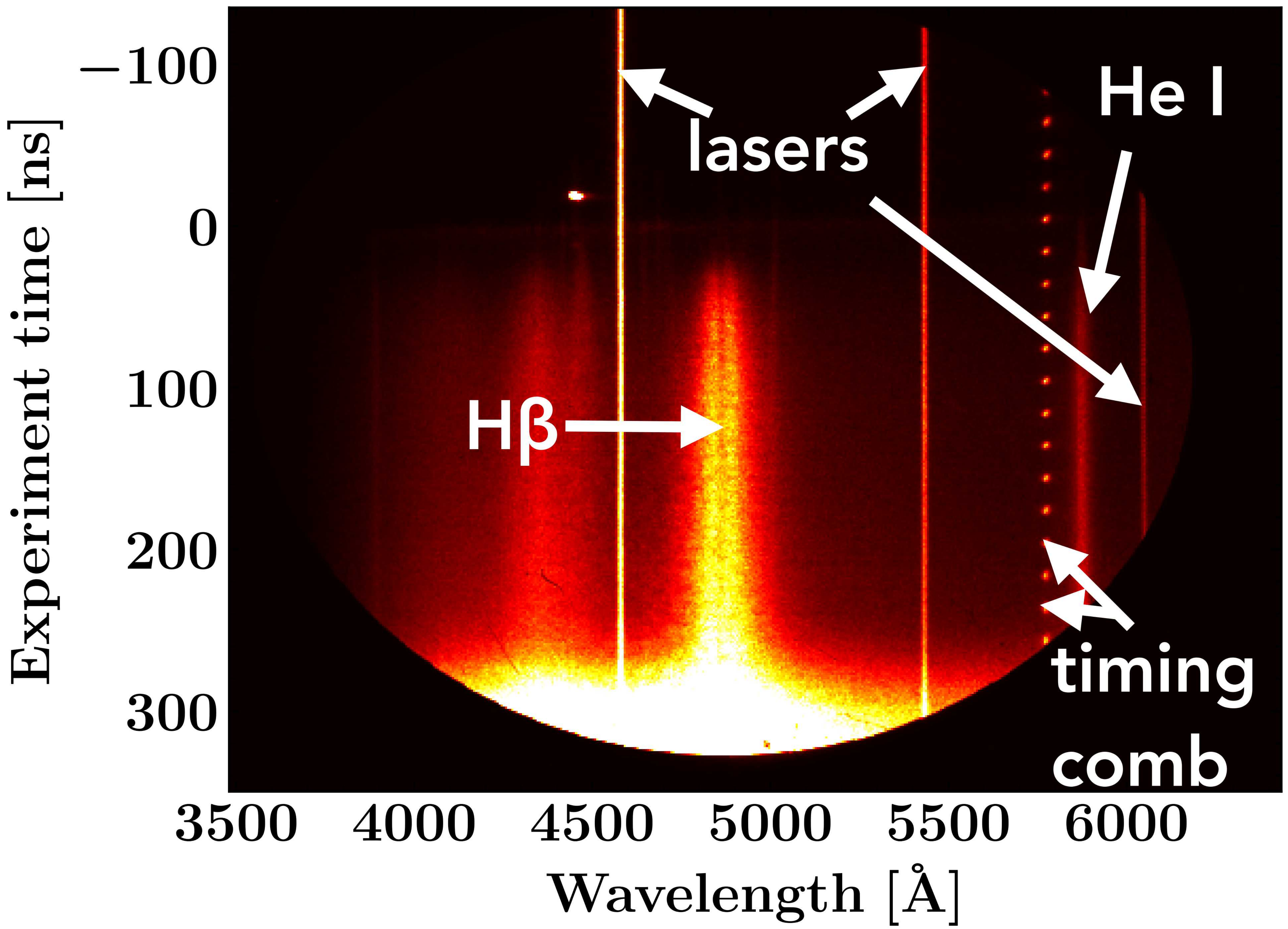
Both the spectroscopic and GR mass determination methods are flawed. We are therefore unable to determine their masses.

Low-resolution He experimental data

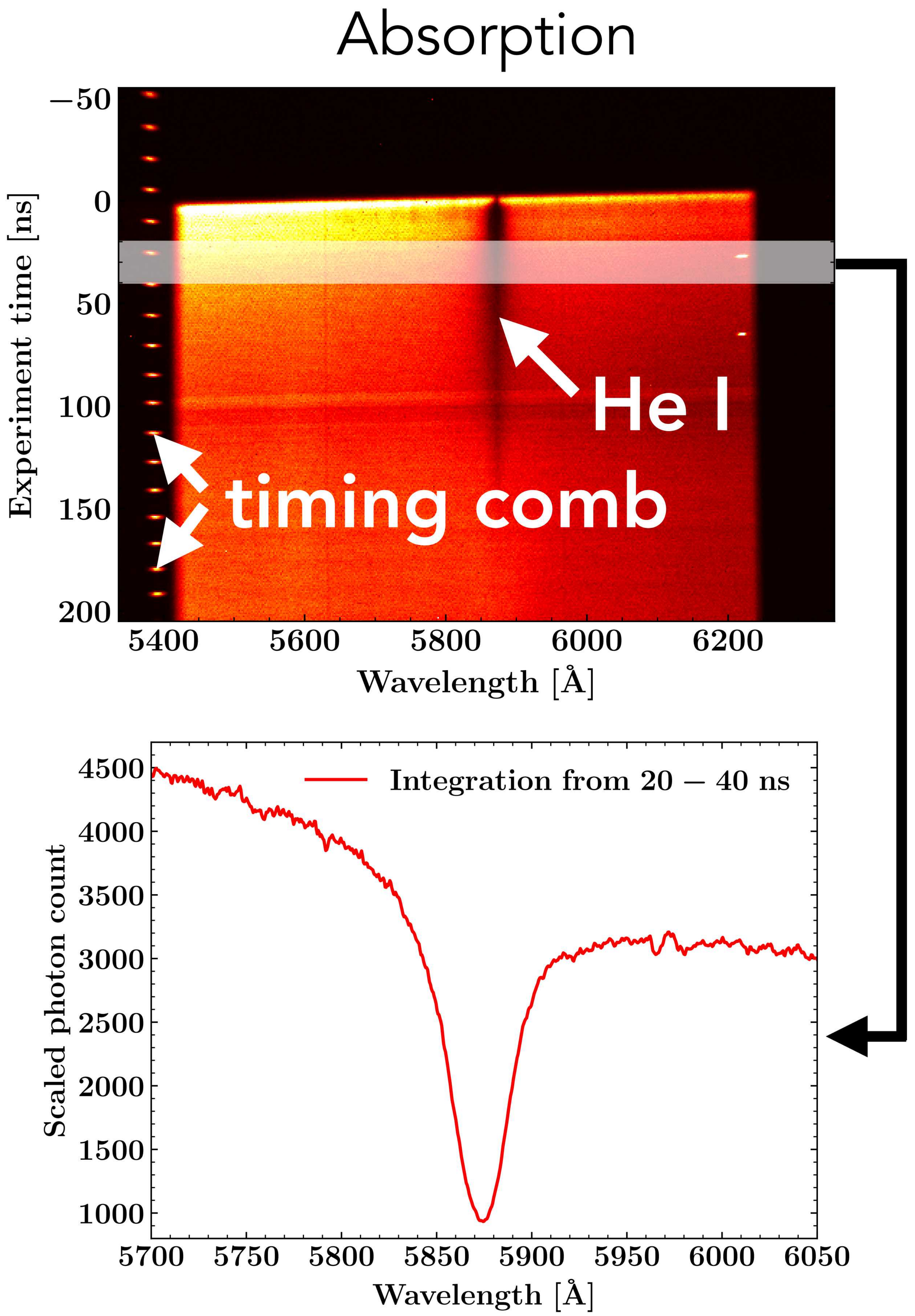
Absorption

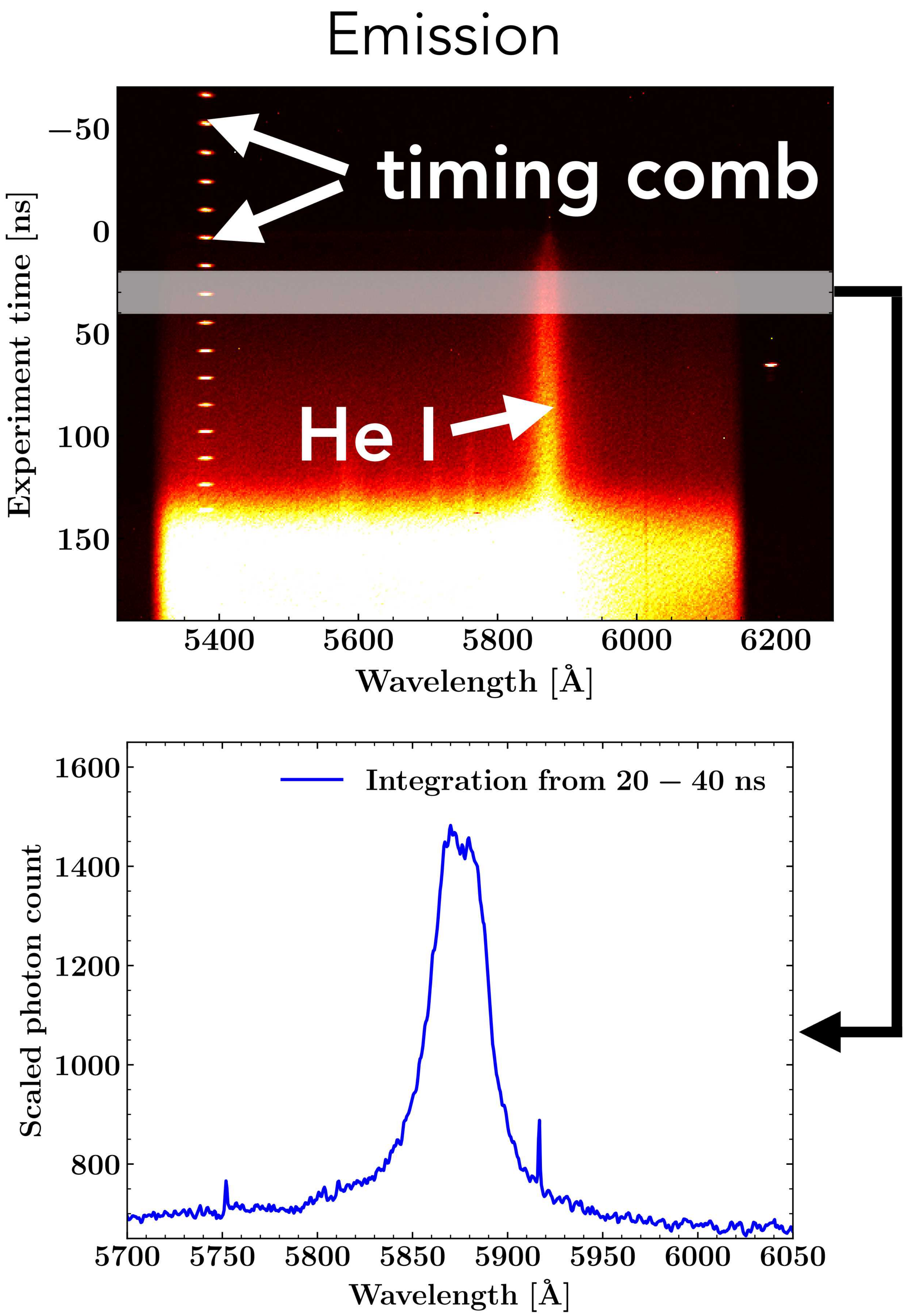


Emission



High-resolution helium experimental data

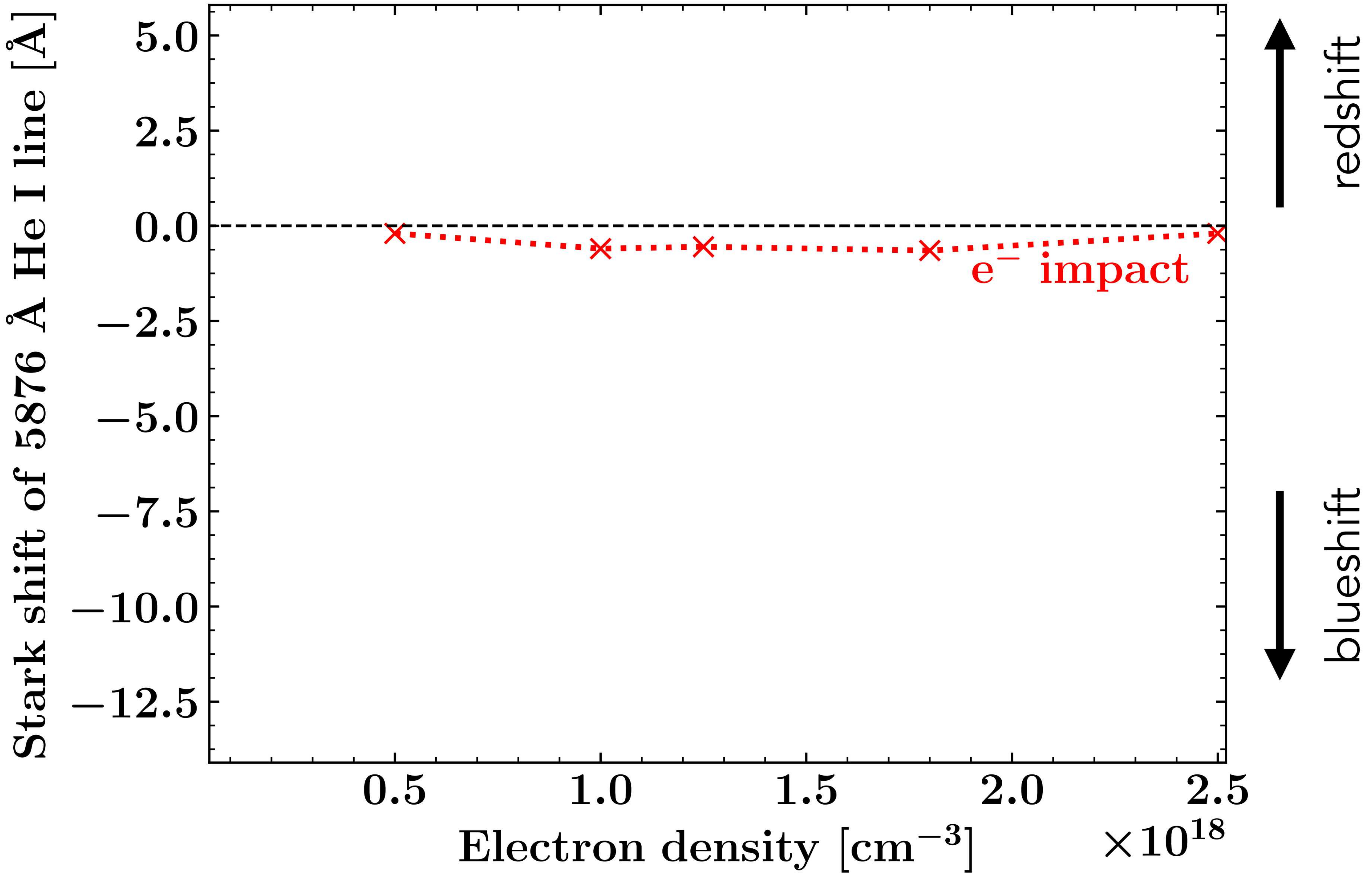




History of *3d* → *2p* He I 5876 Å Stark shift calculations

- Spectroscopic masses are uncertain - why not use the GR method to constrain the helium WD masses? → Stark shifts.

- The *3d* → *2p* He I 5876 Å line is the most prominent feature in the optical spectra of helium WDs



Griem et al. (1962) *Phys. Rev.*

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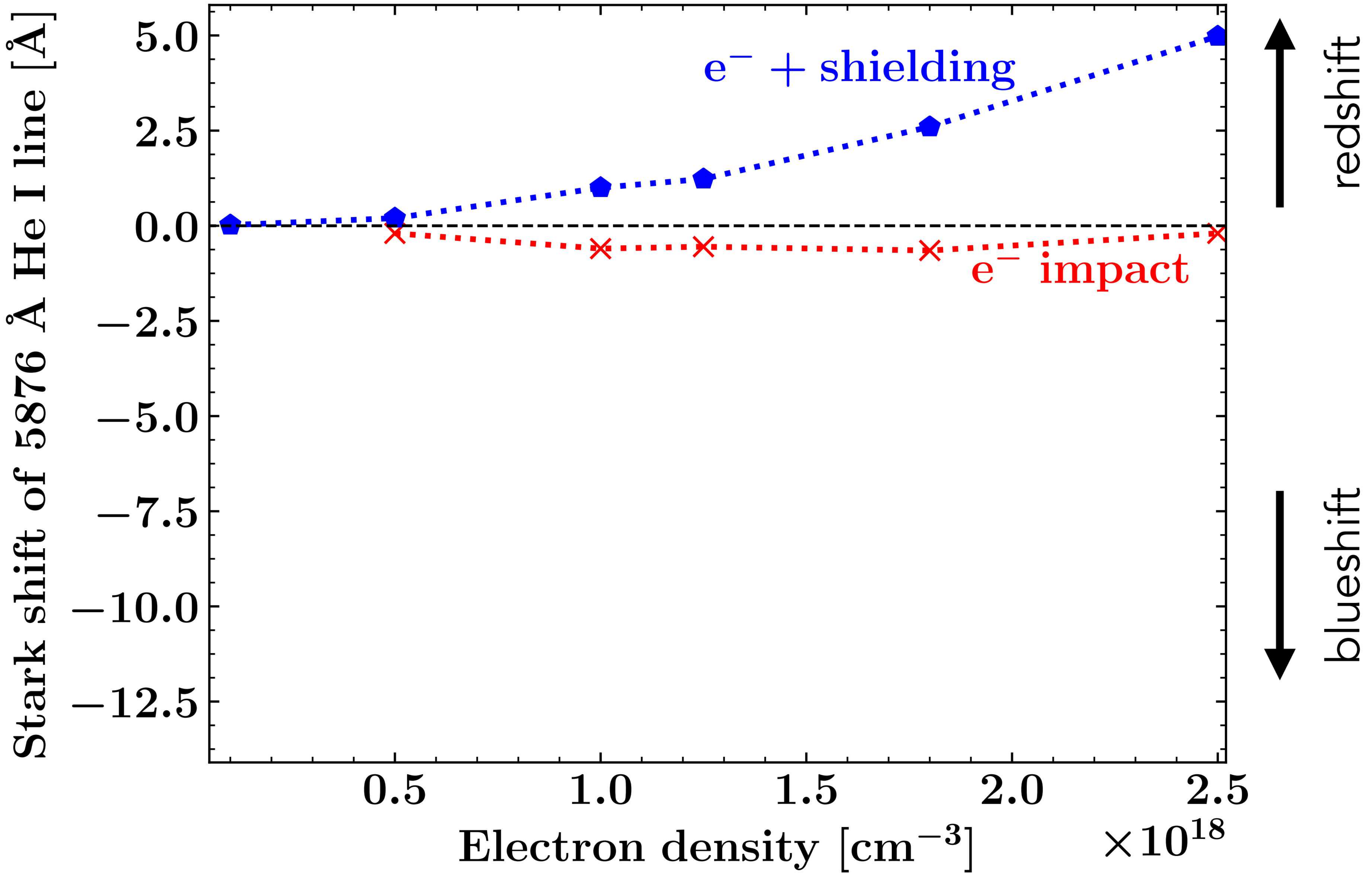

Griem et al. (1962) *Phys. Rev.*
Cooper et al. (1969) *Phys. Rev.*

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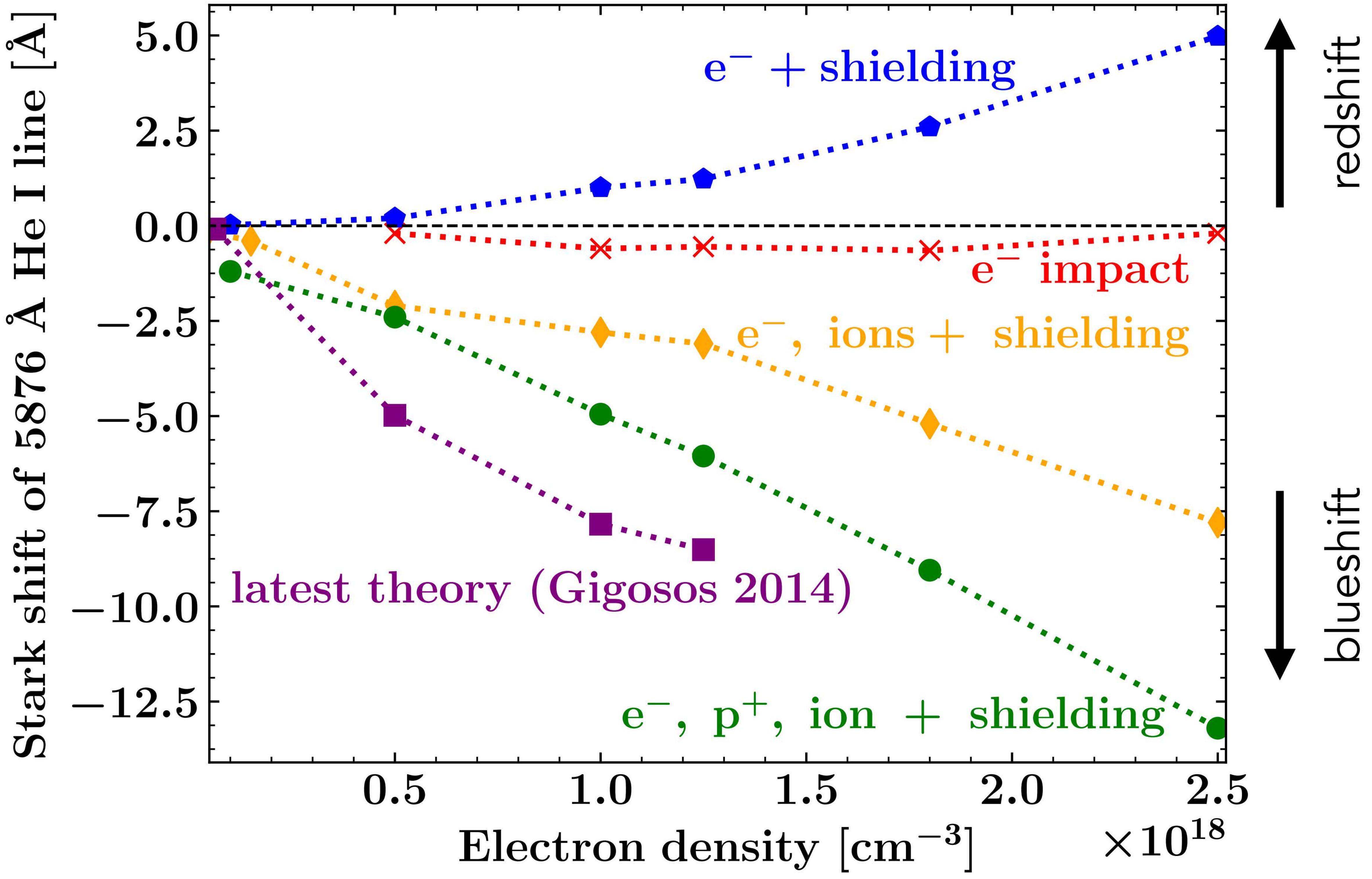
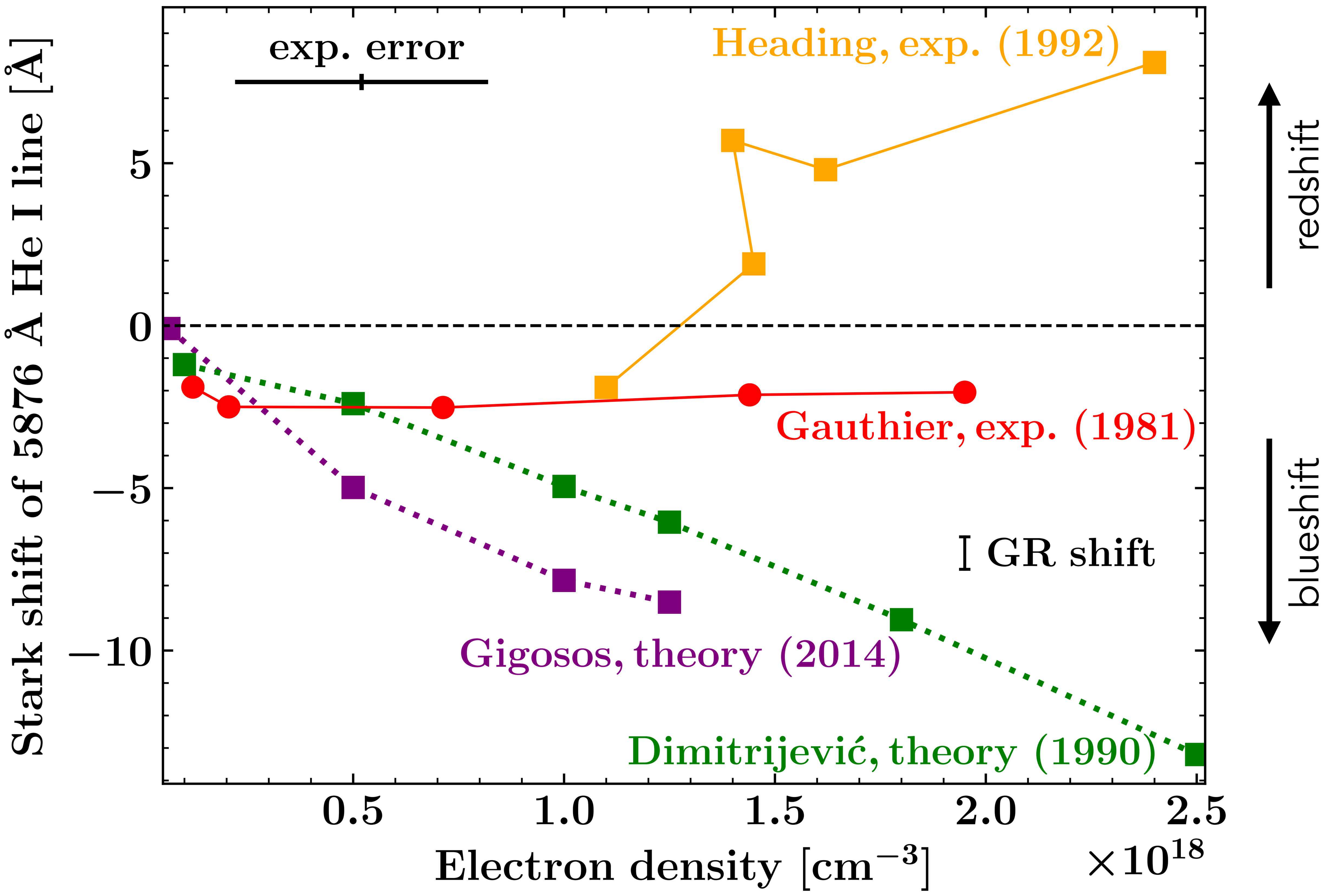


Griem et al. (1962) *Phys. Rev.*
Cooper et al. (1969) *Phys. Rev.*
Griem (1974)
Dimitrijević and Sahal-Bréchot (1990) *ApJS*
Gigosos et al. (2014) *A&A*

History of *3d* → *2p* He I 5876 Å Stark shift calculations



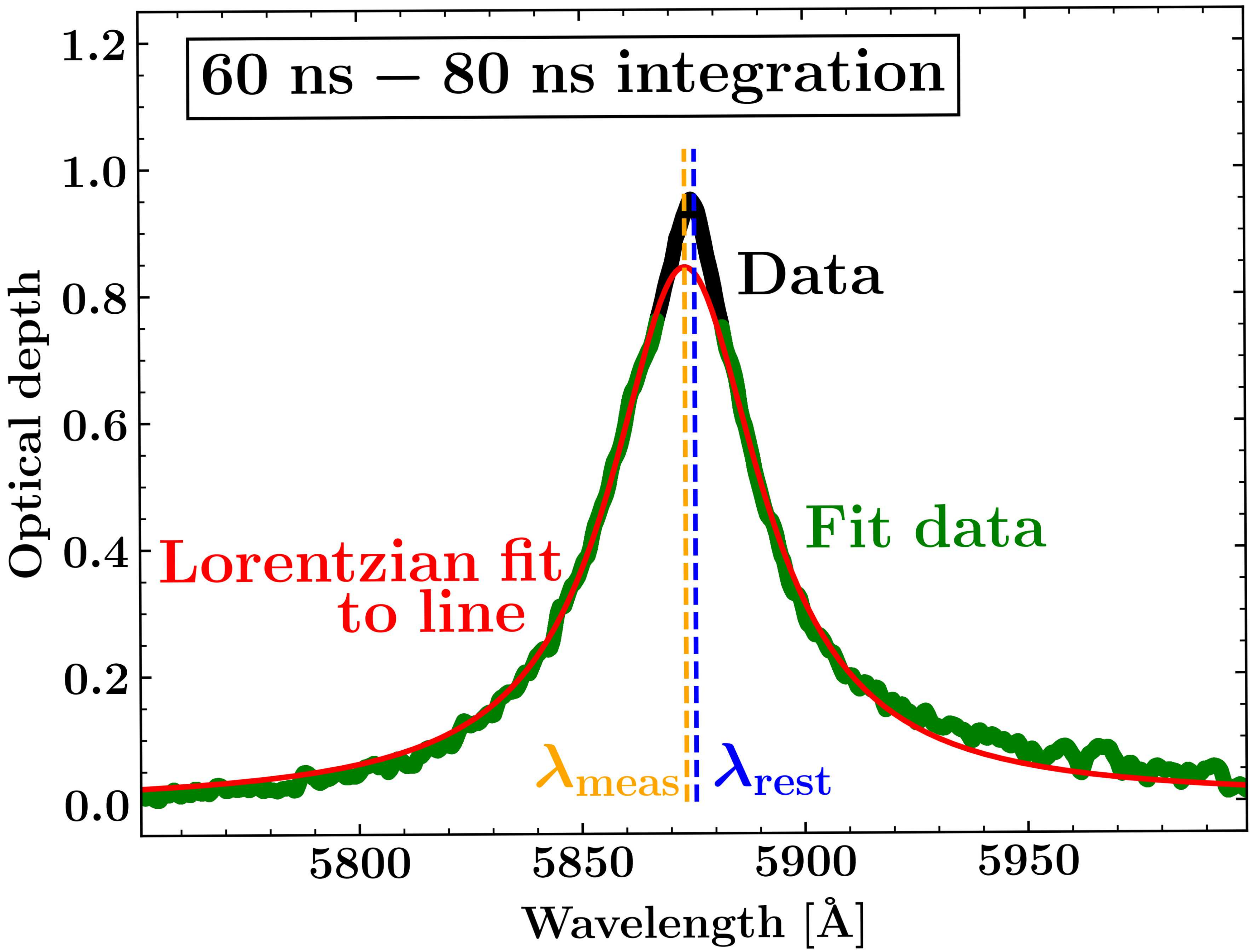
Heading et al. (1992) *J. Phys. B*
Gauthier et al. (1981) *J. Phys. B*

The WDPE employs a fundamentally different approach to extract He shift measurements

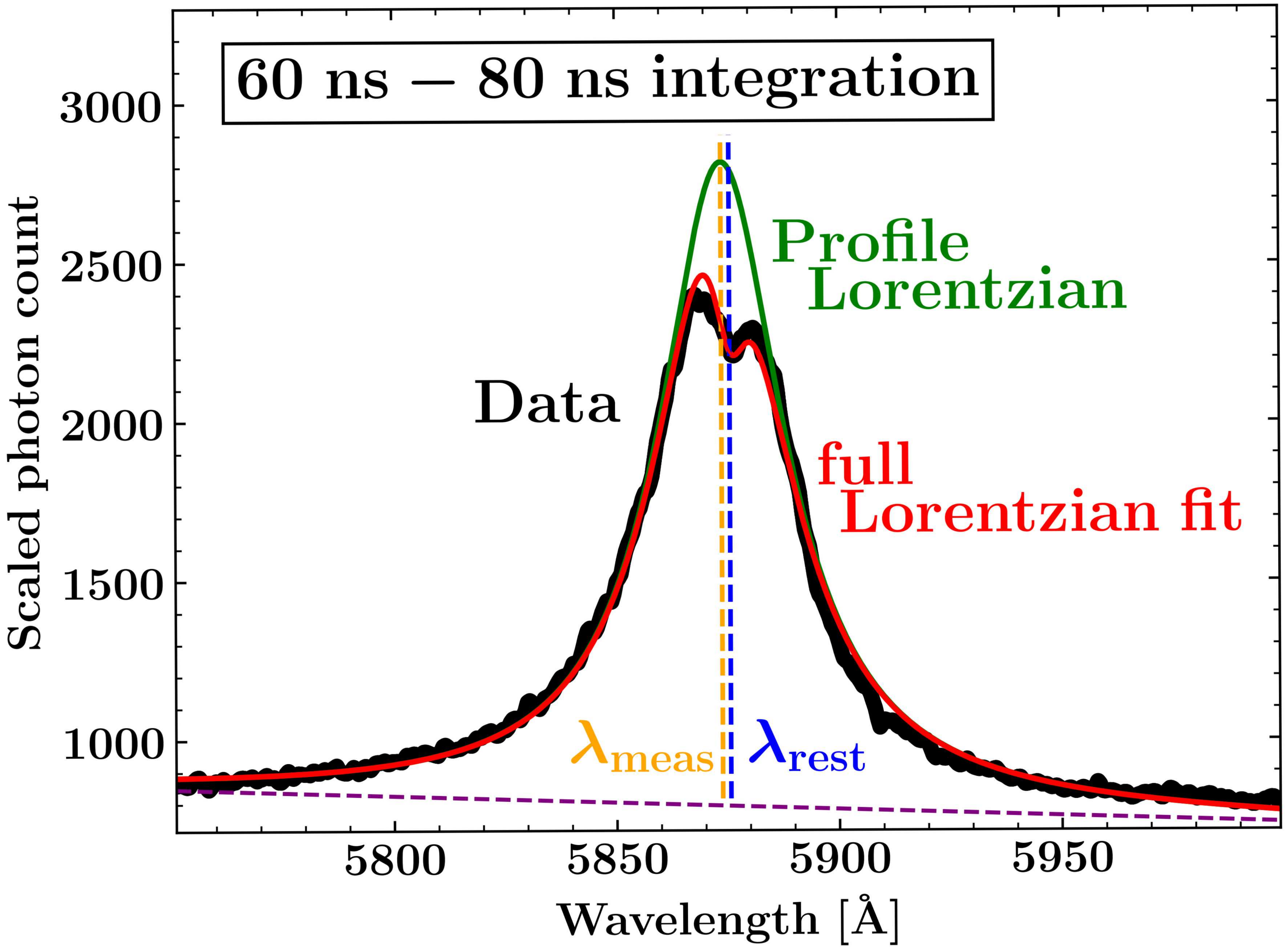
Experimental problems	My experiment (WDPE)
influence of self-absorption	emission ***and*** absorption data
multiple co-added datasets	sufficient S/N in single experiment
uncertain n_e and T diagnostics	hydrogen tracer lines
influence of Doppler shifts	no Doppler shifts
plasma non-uniformities	use of Z allows creation of large, uniform plasma

Büscher et al. (1995) *JQRST*

Performing the 5876 Å He I shift measurement

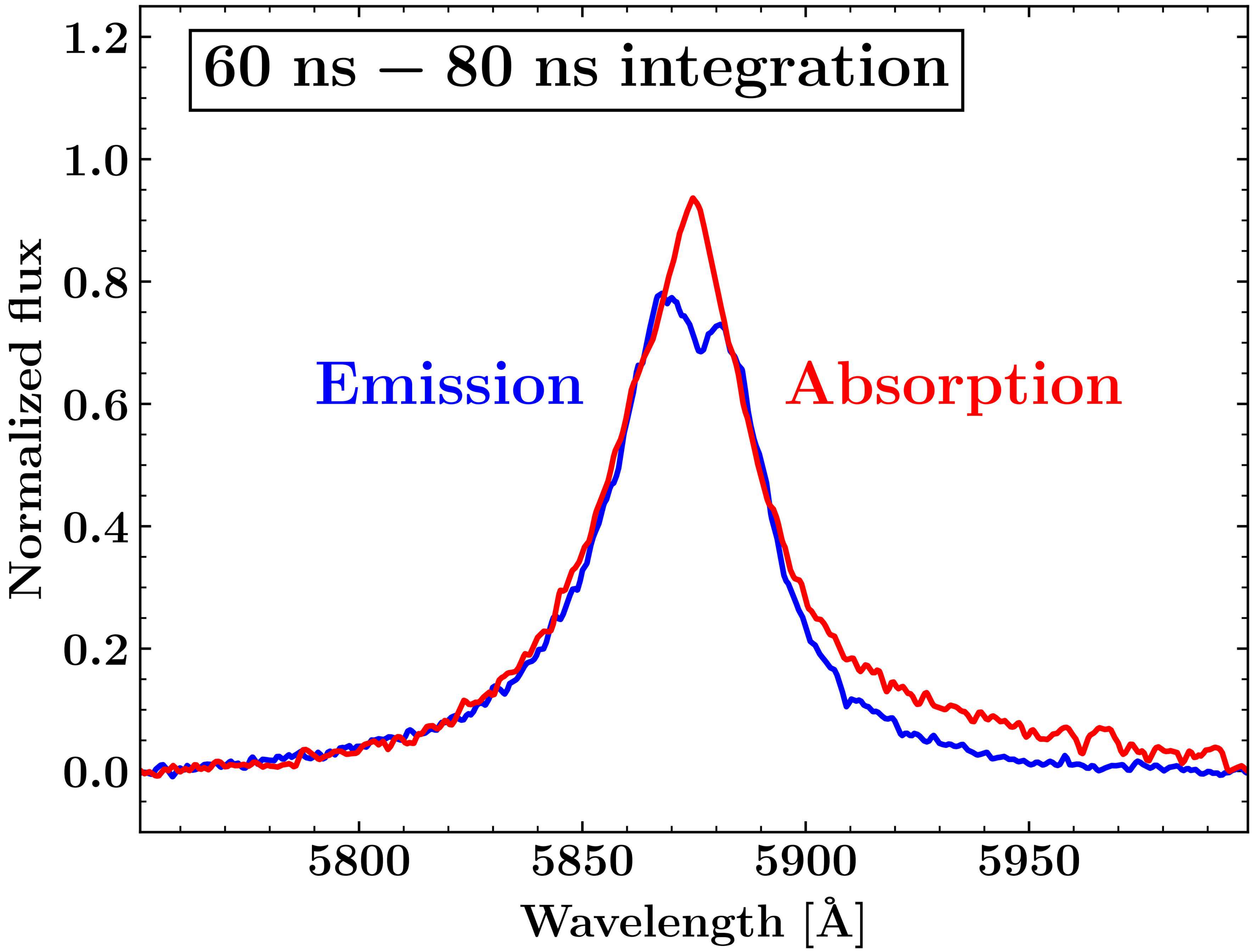


The experimental *3d* → *2p* He I 5876 Å absorption profile. I fit a Lorentzian with the core excluded to obtain my shift measurement.

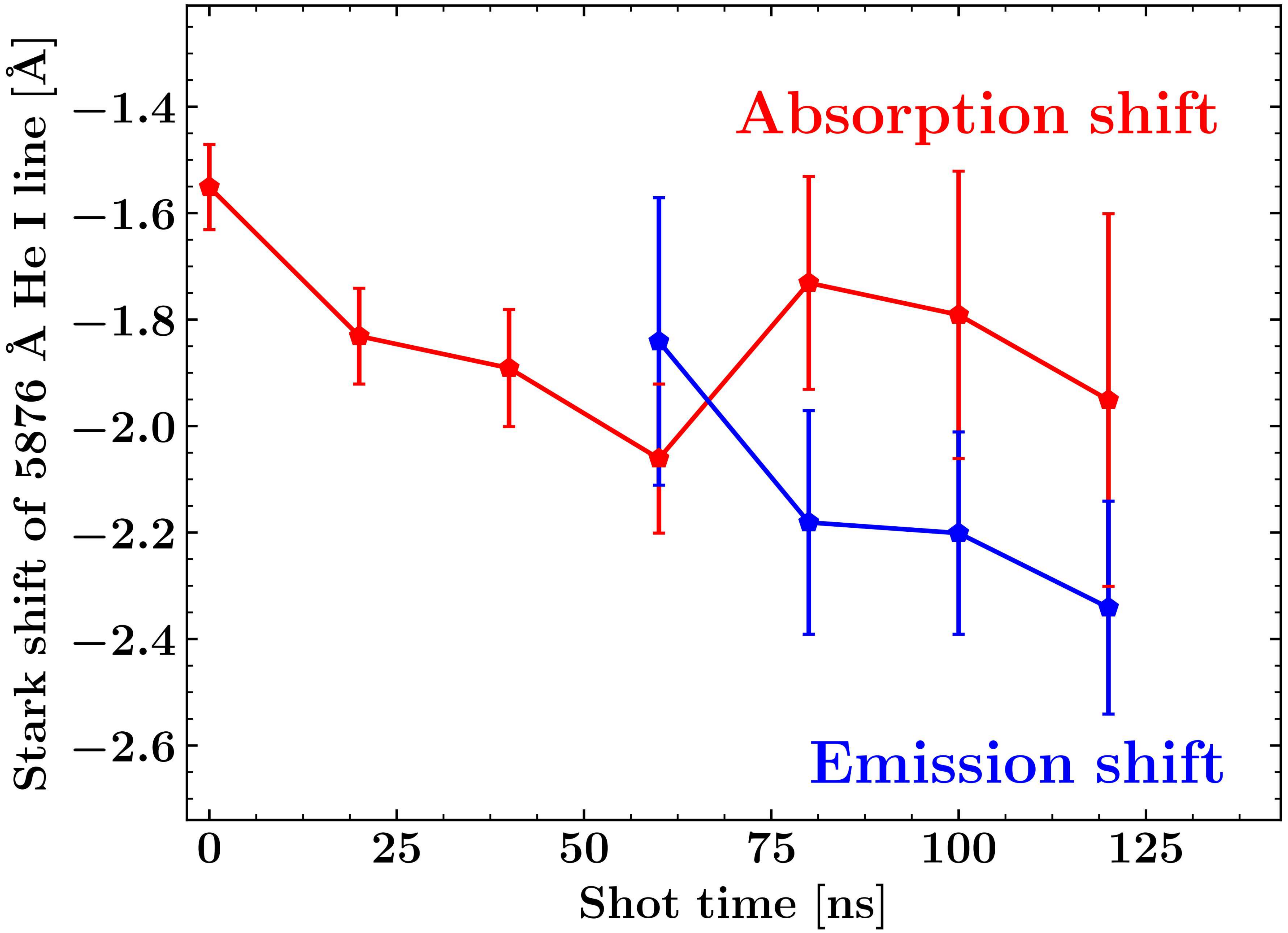


The experimental *3d* → *2p* He I 5876 Å emission profile. I fit two Lorentzians to account for self-absorption to obtain my shift measurement.

Comparison of absorption and emission shifts

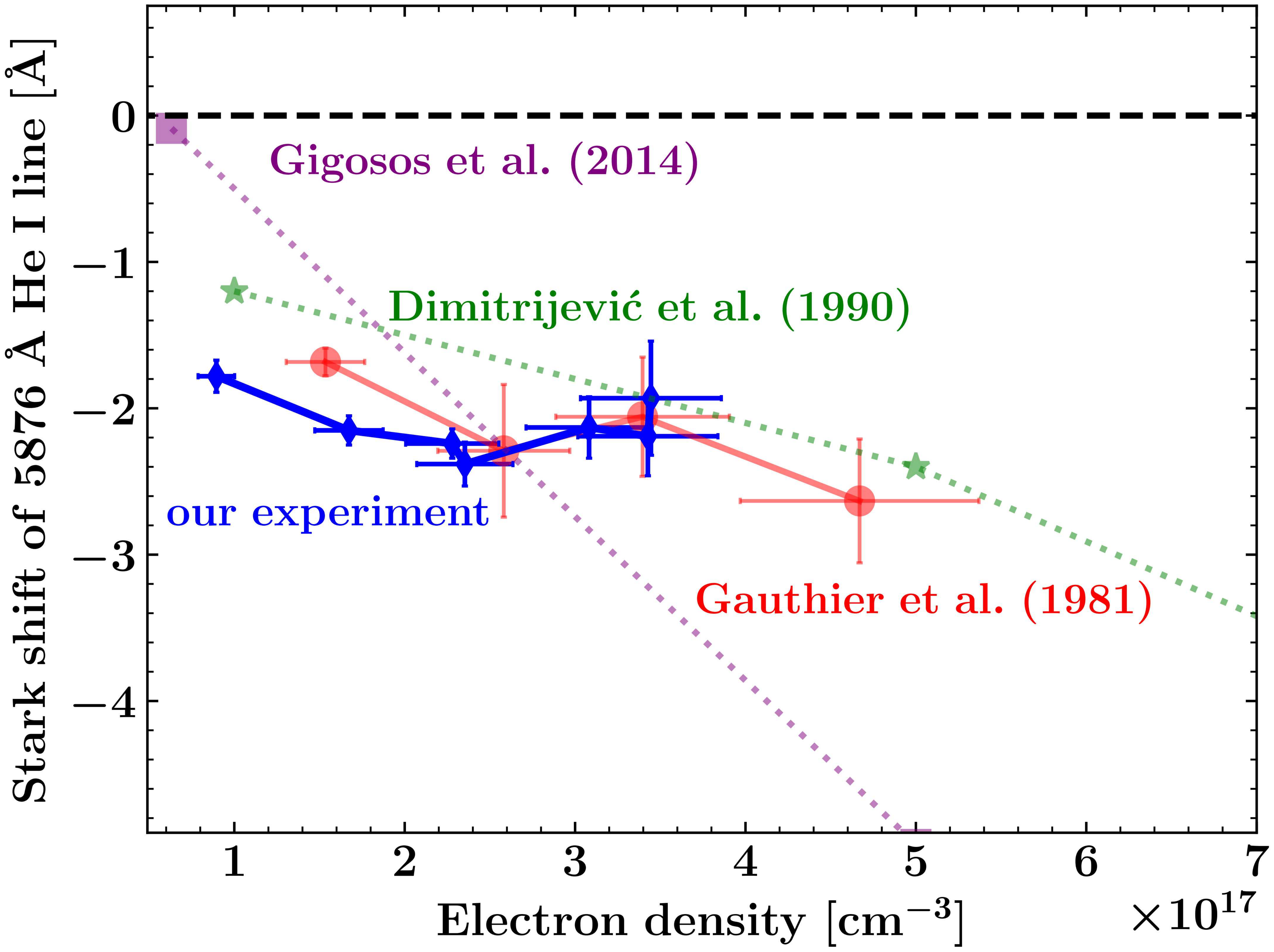


A comparison of emission and absorption profiles at the same experiment time



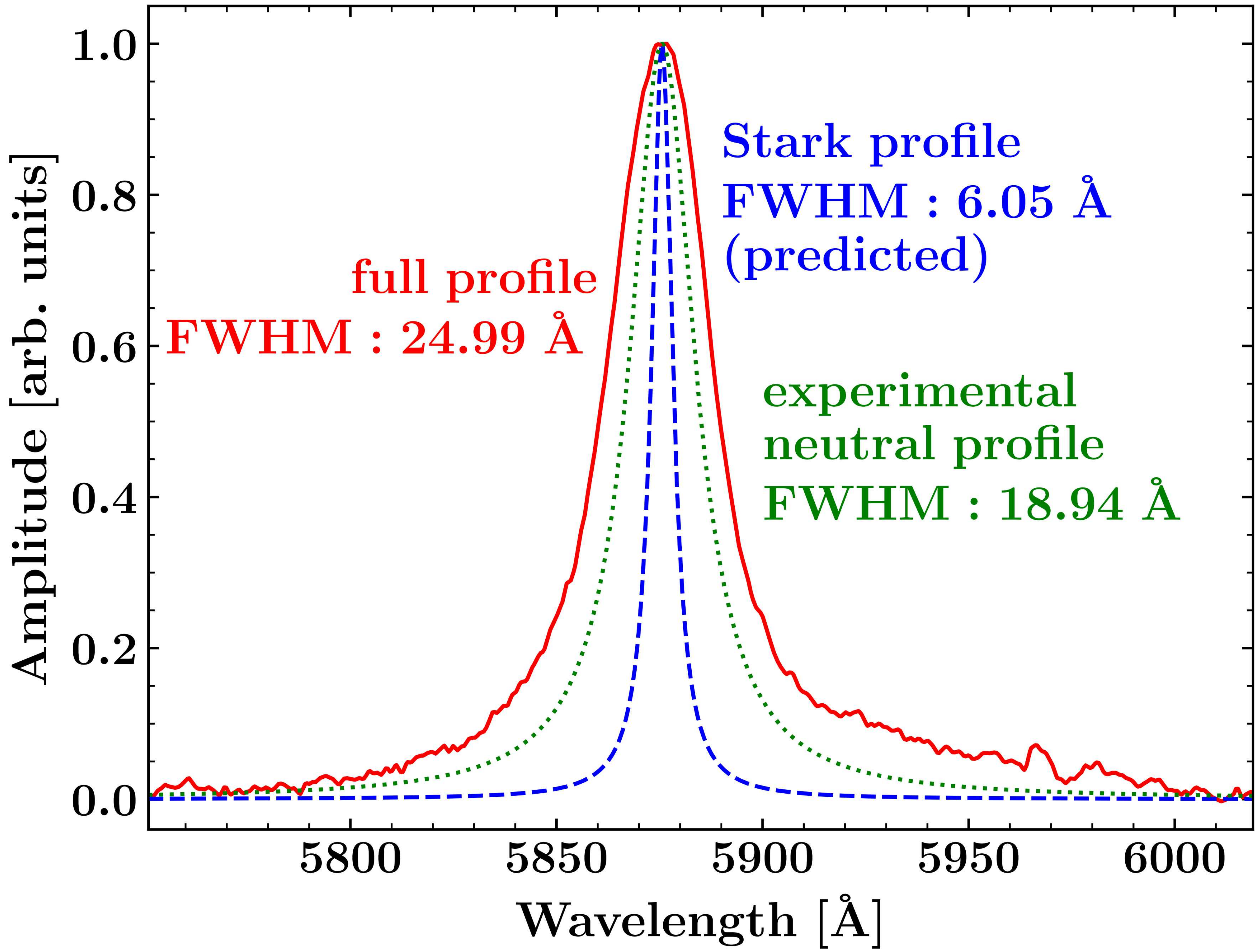
WDPE absorption and emission shift measurements. Despite the different shift extraction methods, the measurements agree.

My $2p \rightarrow 3d$ He I 5876 Å Stark shift measurement



My shift measurements match previous experiments and show that theory for this line is still deficient.

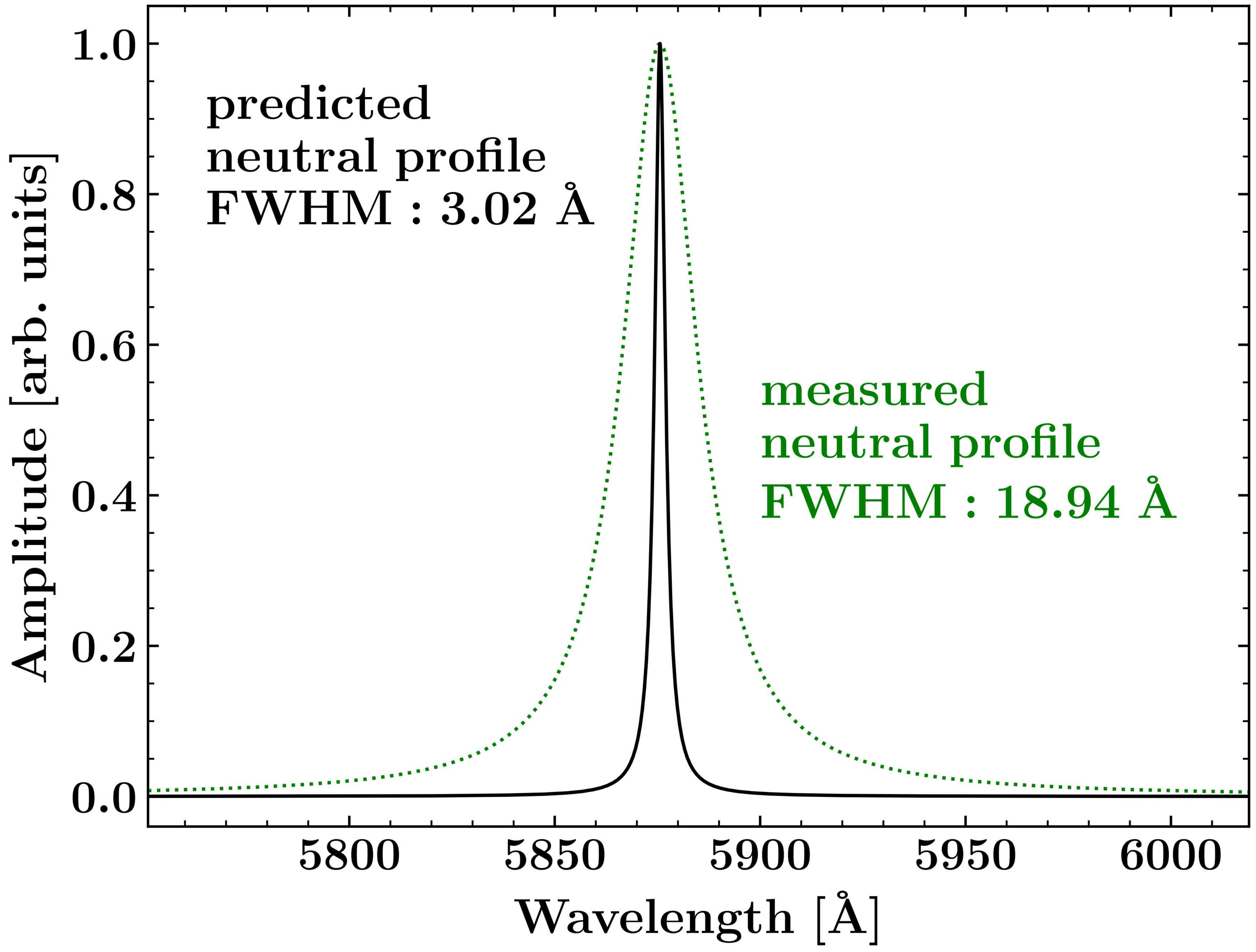
Influence of neutral broadening on 5876 Å He I



Measurement of electron and neutral broadening of He I 5876 Å

- Deridder & Van Rensbergen (1976) is the experimentally unverified neutral broadening theory used in WD astronomy
- I can use my data to test this theory

Influence of neutral broadening on 5876 Å He I



Comparison of predicted and measured neutral widths

- Deridder & Van Rensbergen (1976) is the experimentally unverified neutral broadening theory used in WD astronomy
- I can use my data to test this theory
- My measured neutral widths are ***larger than the predicted values by a factor of 6***
- WD measurements spectra also show severe shortcomings in neutral broadening

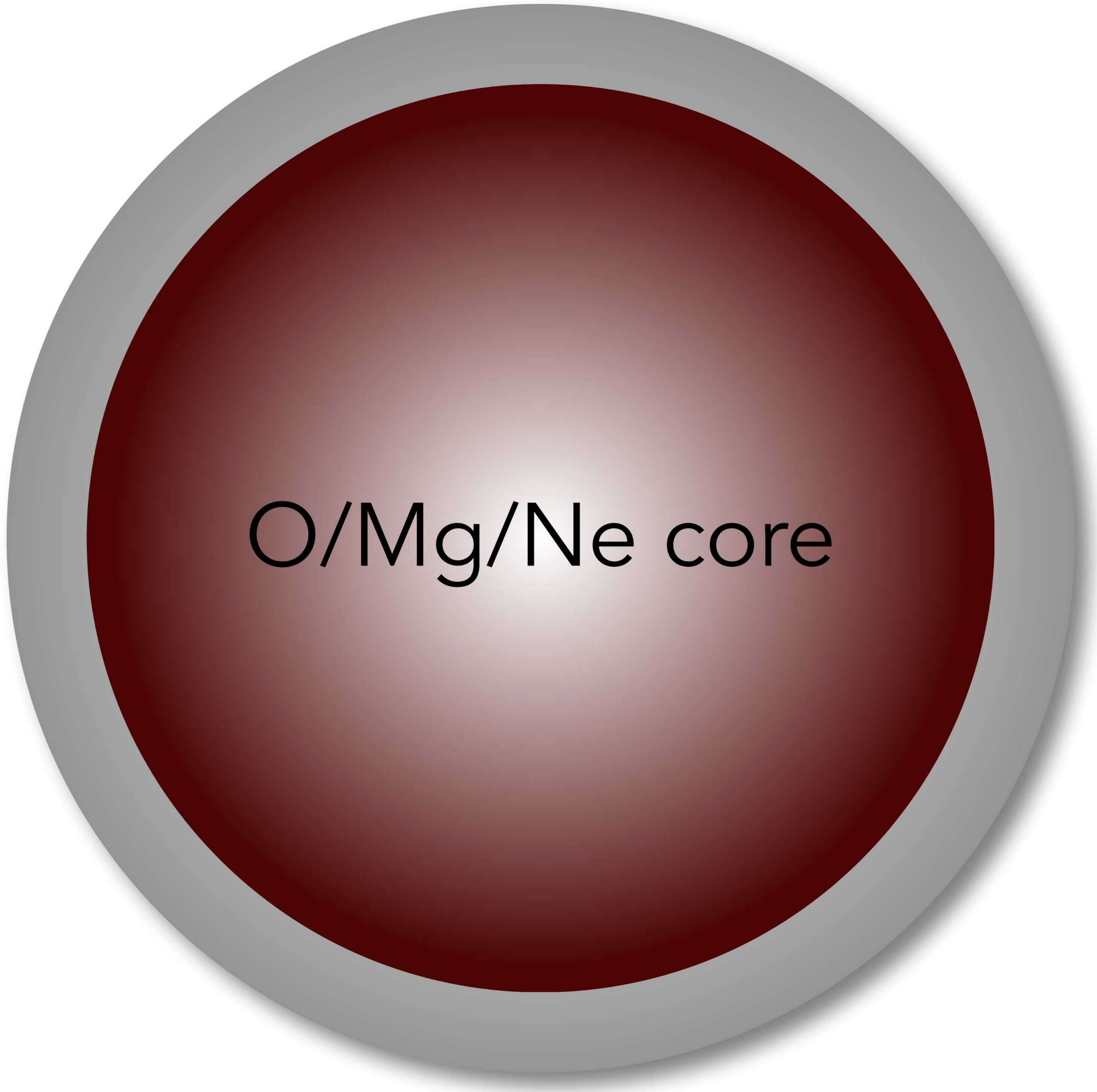
DA: hydrogen atmosphere

Q: Age of the Galaxy?

DB: helium atmosphere

Q: Stellar evolution?

DQ: carbon atmosphere



Q: Failed supernovae?

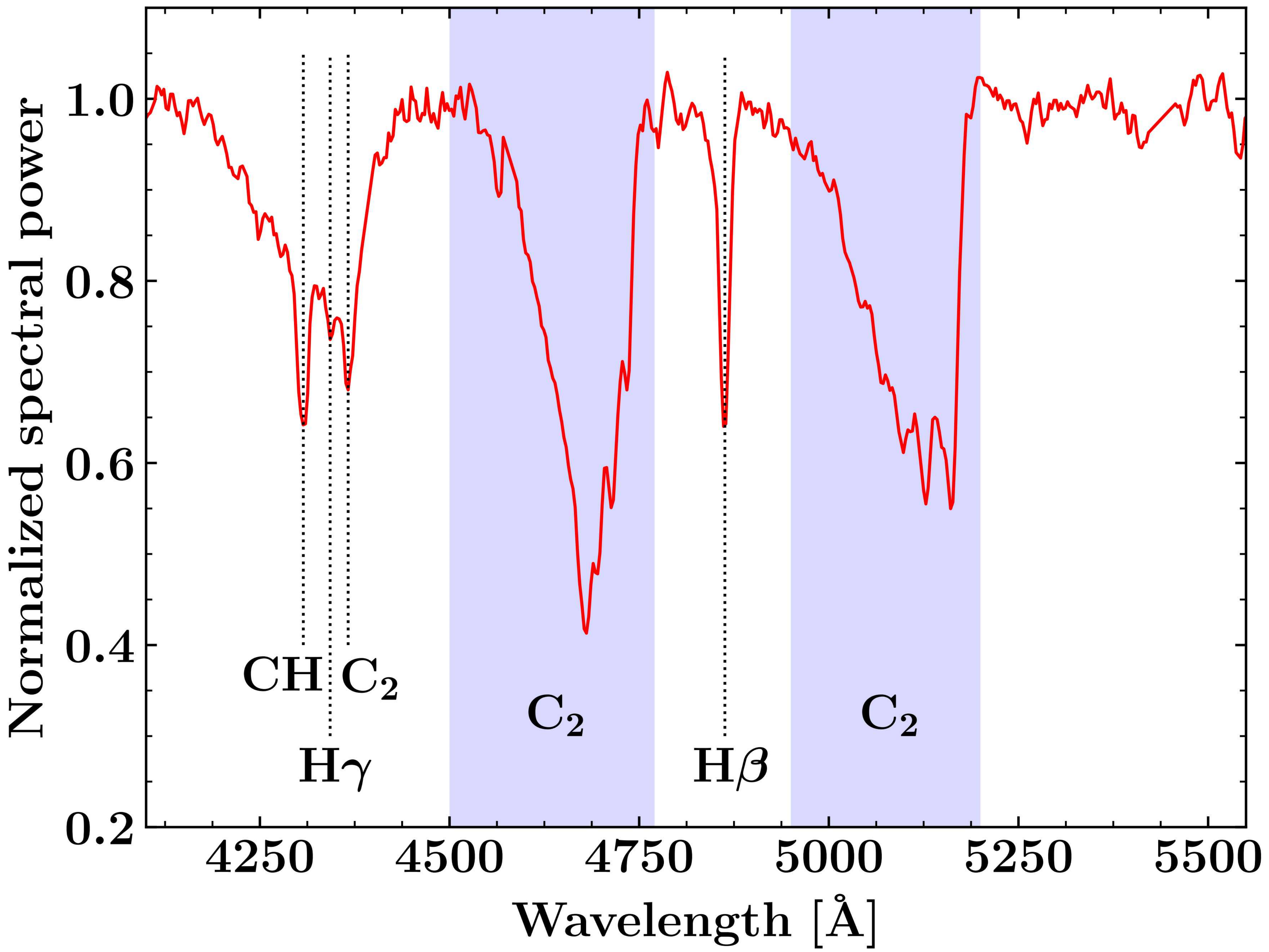
Not drawn to scale.

Experimental investigation of C at WD conditions

- Scientific goals: measure Stark widths of C at WD conditions

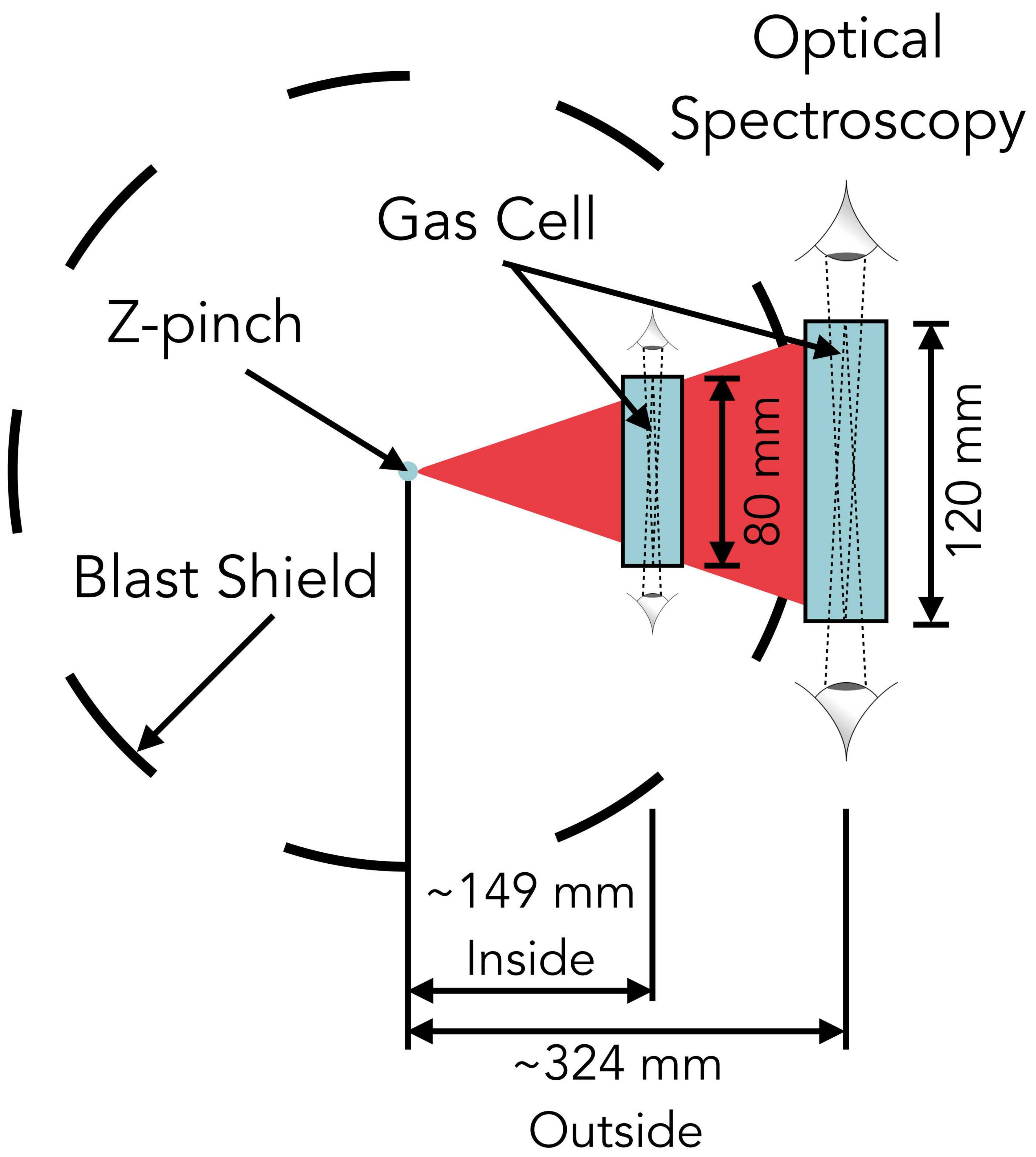
- Challenges:
  - Carbon WDs have higher surface temperatures, requiring higher experimental temperatures

- Risks:
  - platform needs to be altered, which could lead to unexpected results

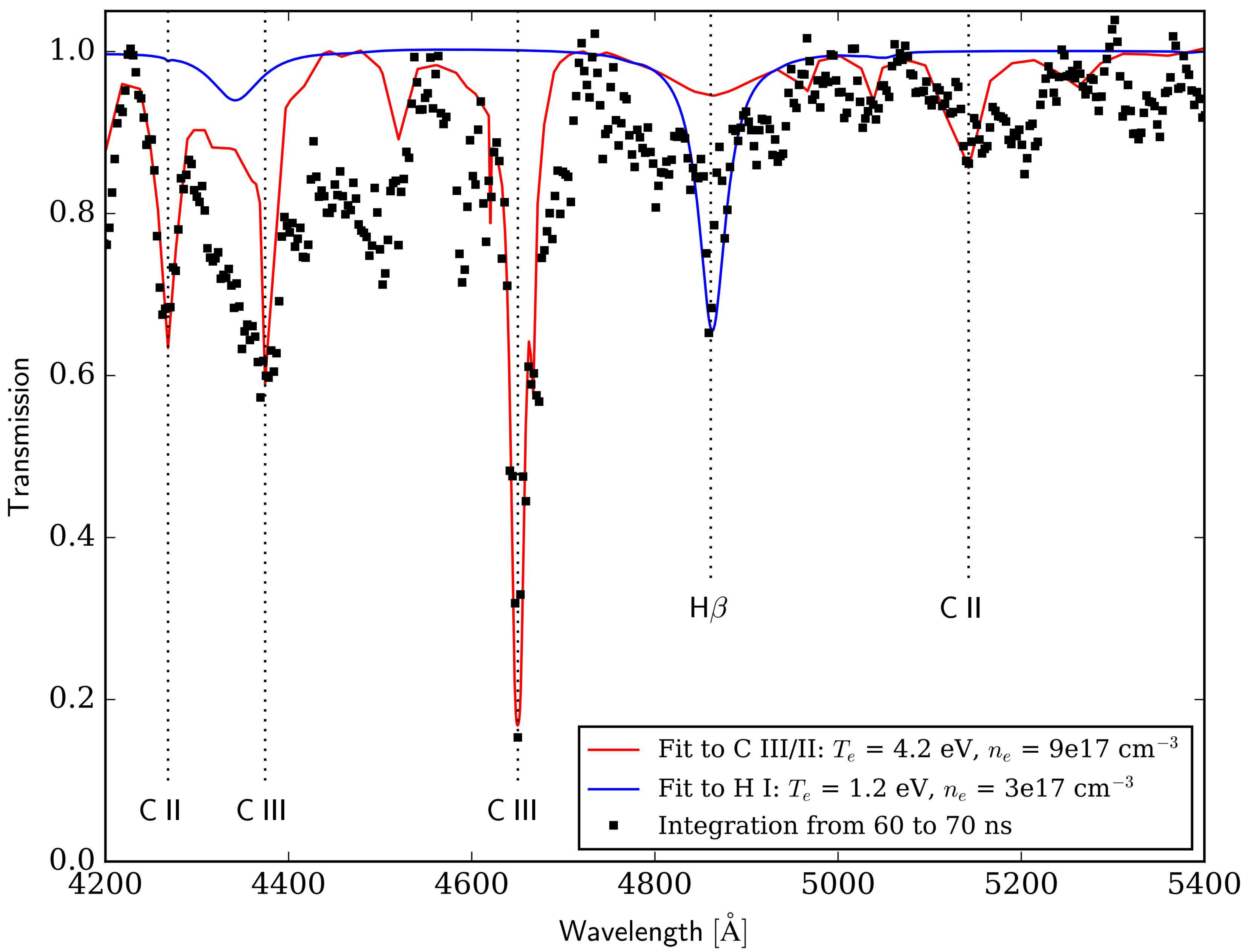


Experimental spectra collected using our old platform

Extending the plasma parameters of the WDPE



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



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

Summary

	Hydrogen	Helium	Carbon
Experimental discovery	n_e inferred from Hβ and Hɣ ***transmission*** disagree	He shifts and neutral widths are incorrect	Stark widths for C may not be accurate
(Astro)physical consequences	inferred WD masses are suspect fundamental assumptions about atomic processes may be flawed	helium GR measurements are currently impossible models for He are deficient	masses for carbon WDs are uncertain Type Ia supernovae remain a mystery
Future experiments	obtain data with a cell design that purposely increases gradients	collect more shift and width data to guide new theory	update hardware to eliminate two component plasma

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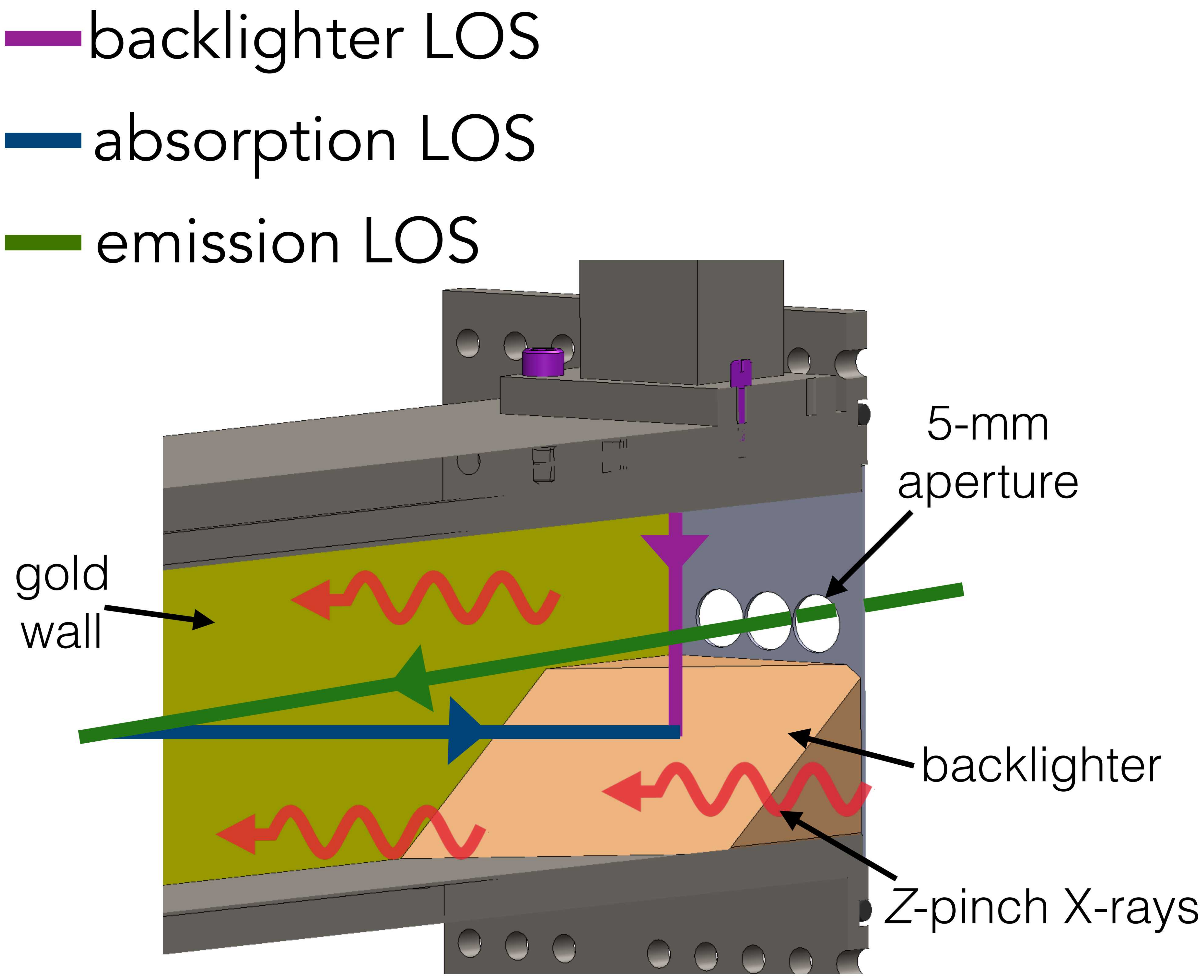
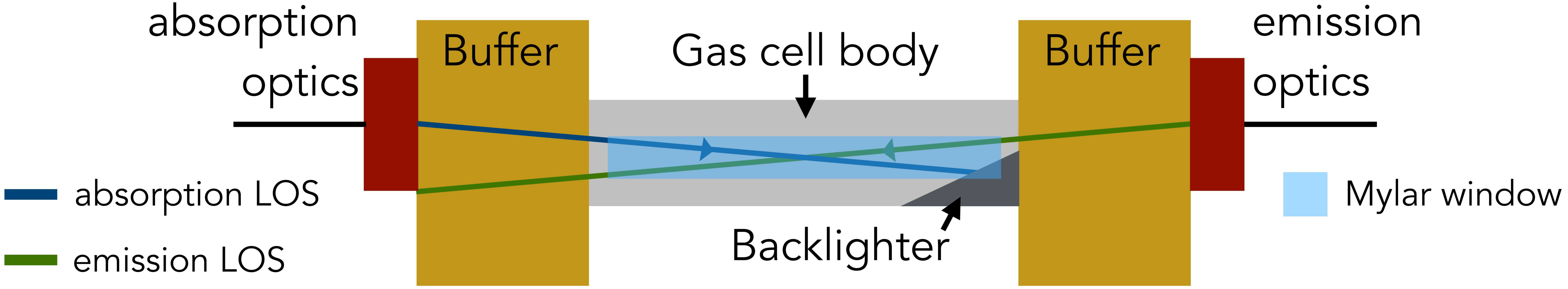
Constraining gradients in the WDPE gas cell



Detailed view of the backlighting surface

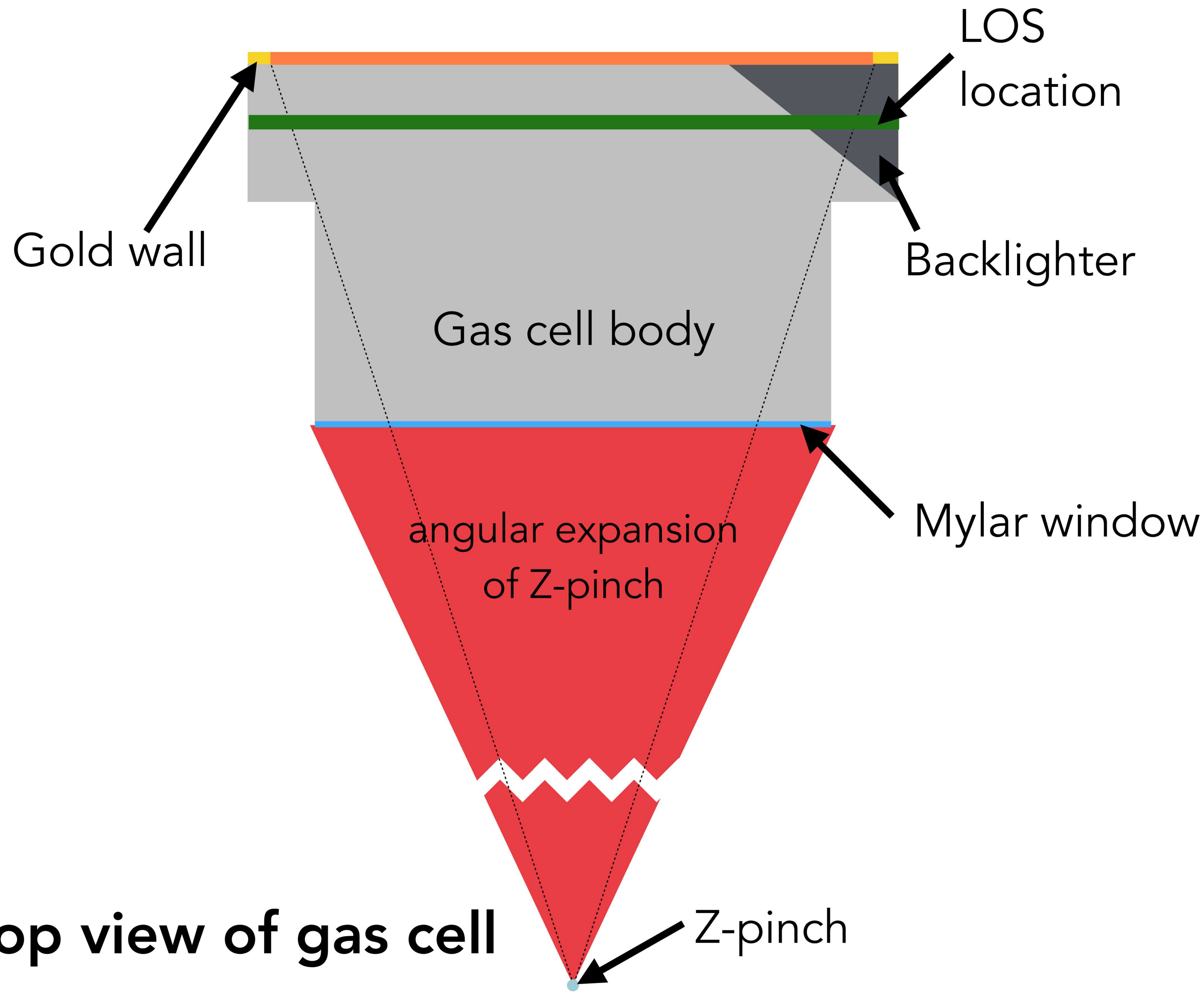
- Like the gold wall, the backlighter is heated by the *Z*-pinch
- The absorption (blue) and backlighter (purple) LOS end on the backlighting surface. The emission LOS does not.
- Since we perform an emission-correction of our absorption data, could this explain the n_e discrepancy?

Constraining gradients in the WDPE gas cell



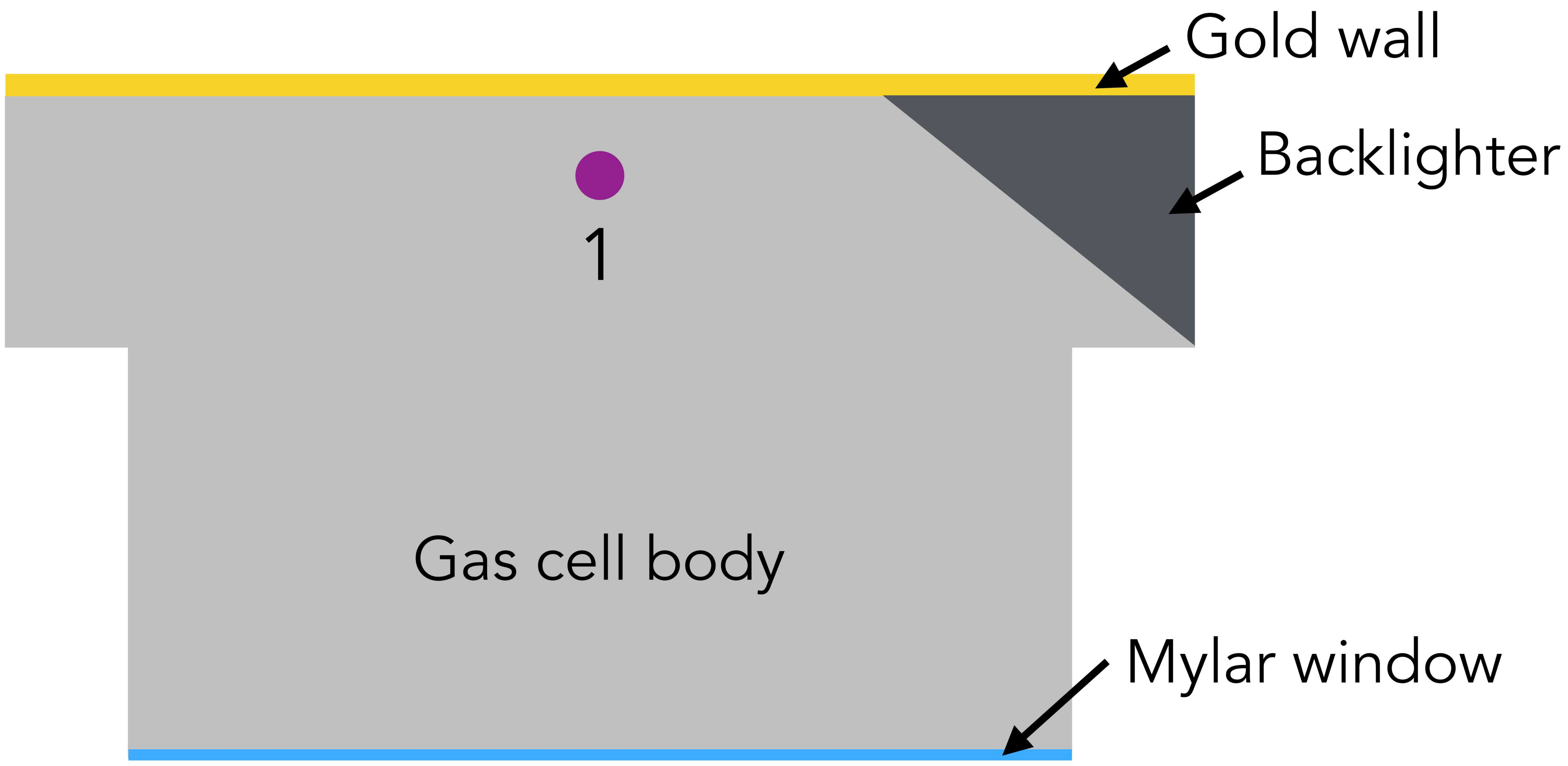
- Stainless steel buffers are attached to each end of the gas cell to protect our optics
- Buffers are also filled with experimental gas, which can turn into a plasma
- Could a potential plasma in the buffers explain the observed n_e difference?

Constraining gradients in the WDPE gas cell



Top view of gas cell

Constraining gradients in the WDPE gas cell



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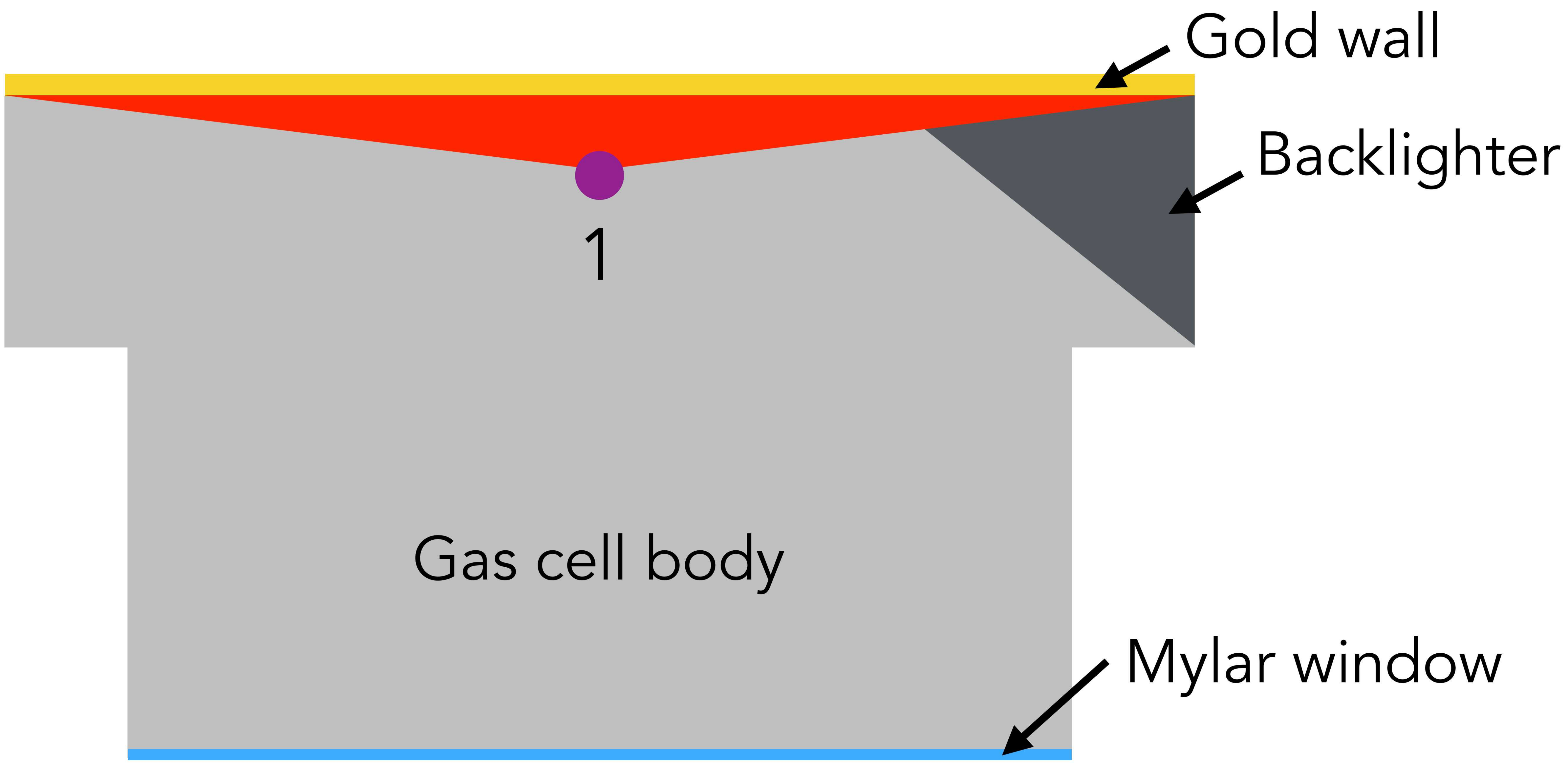

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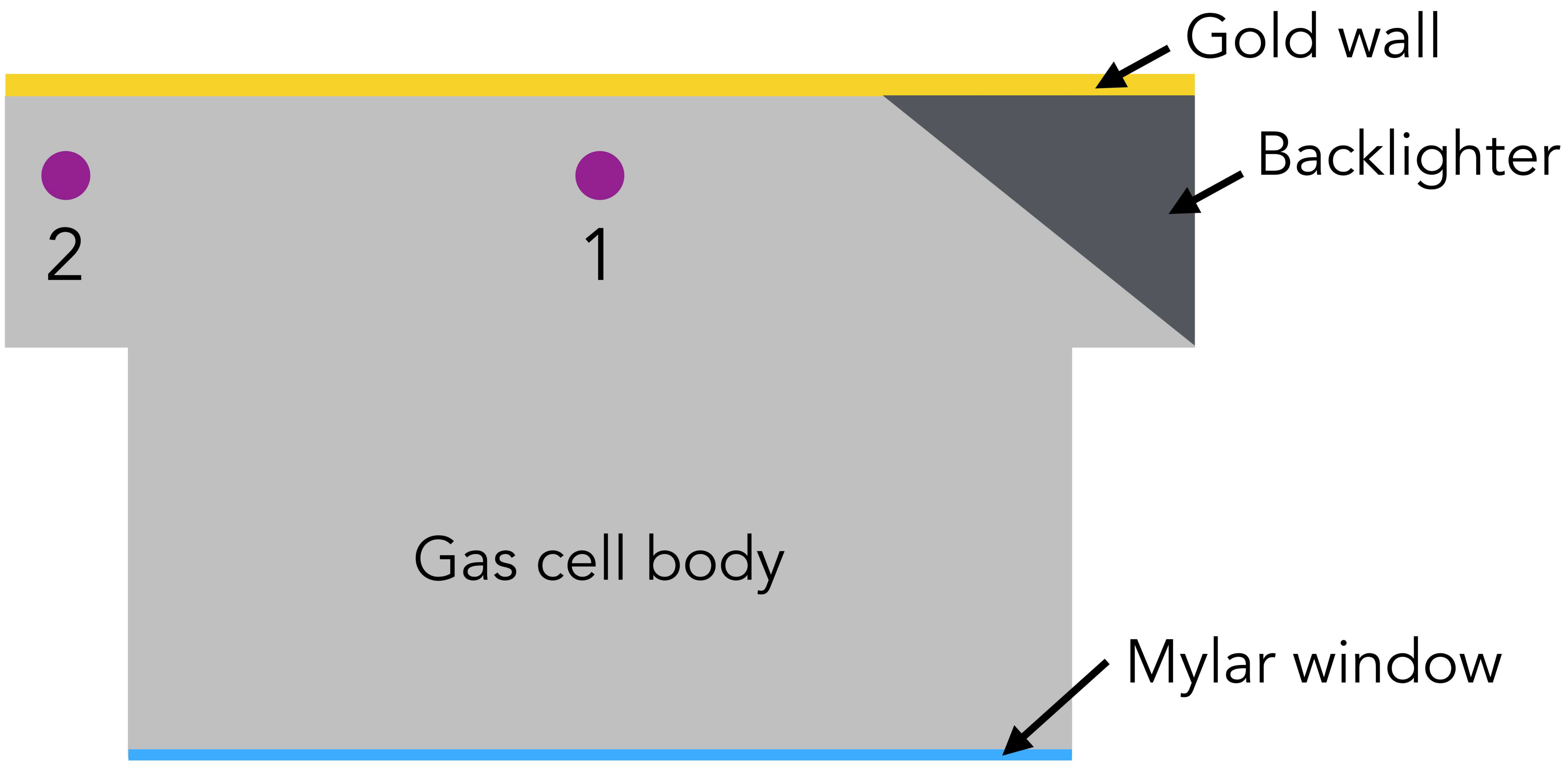

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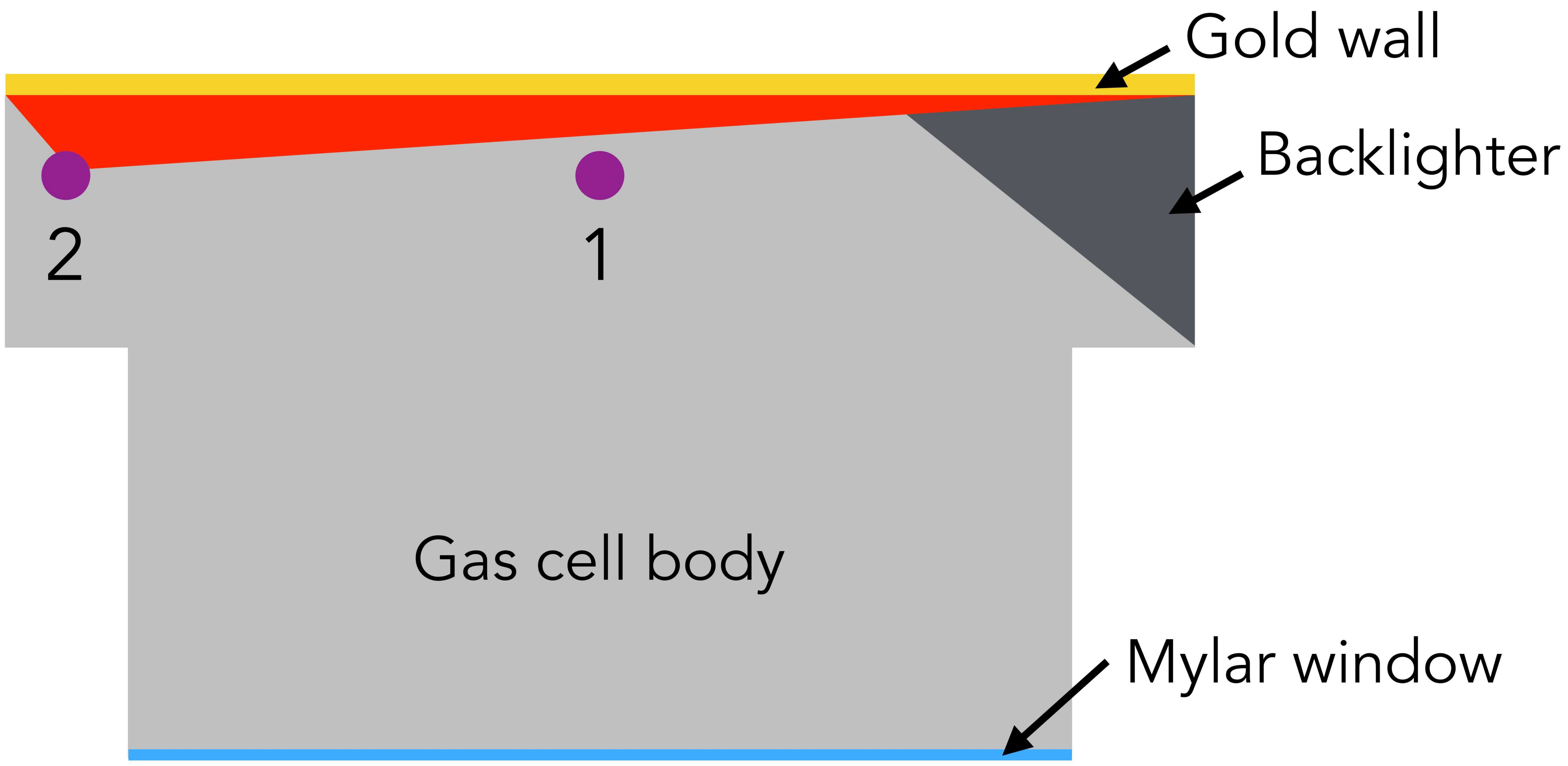

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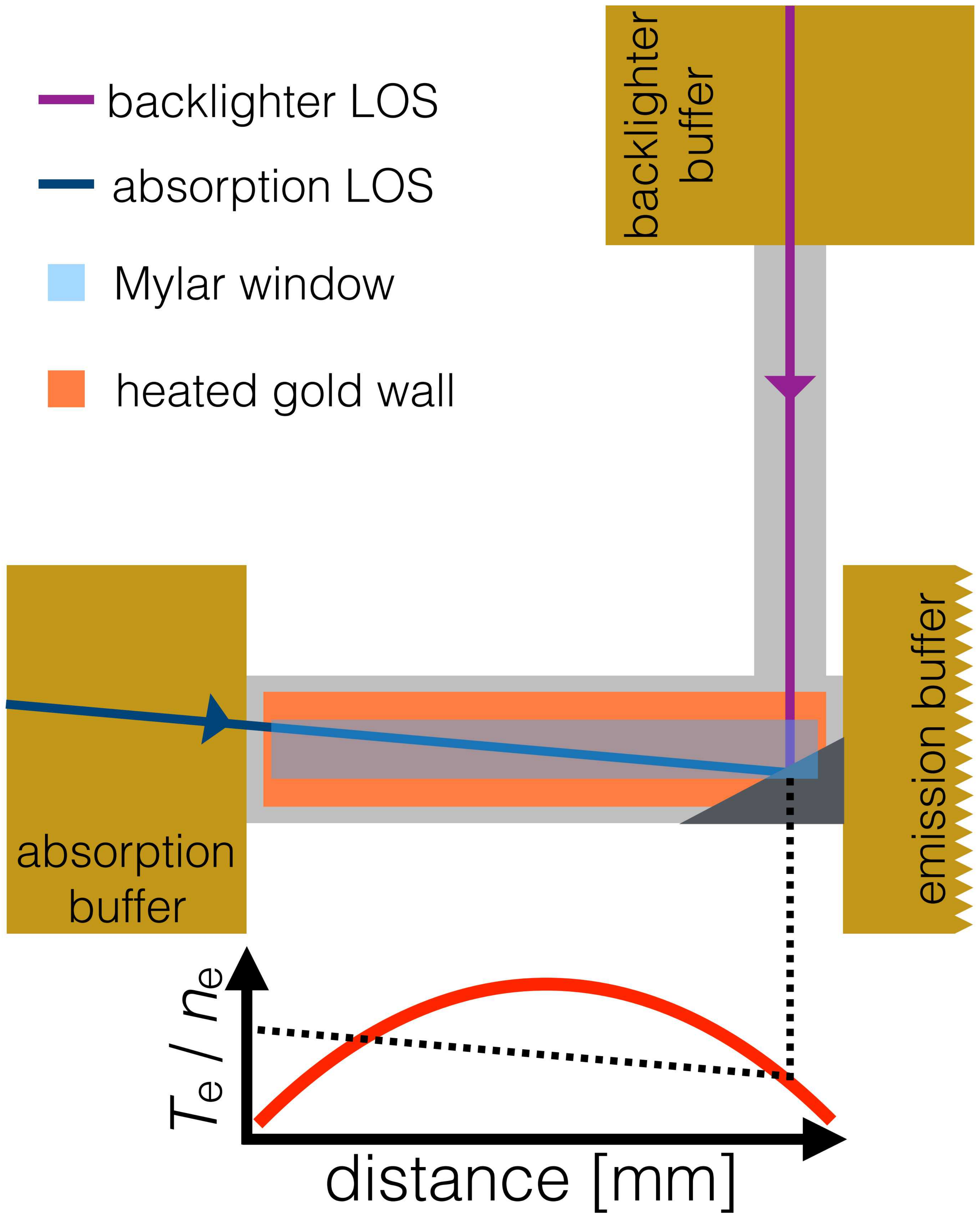
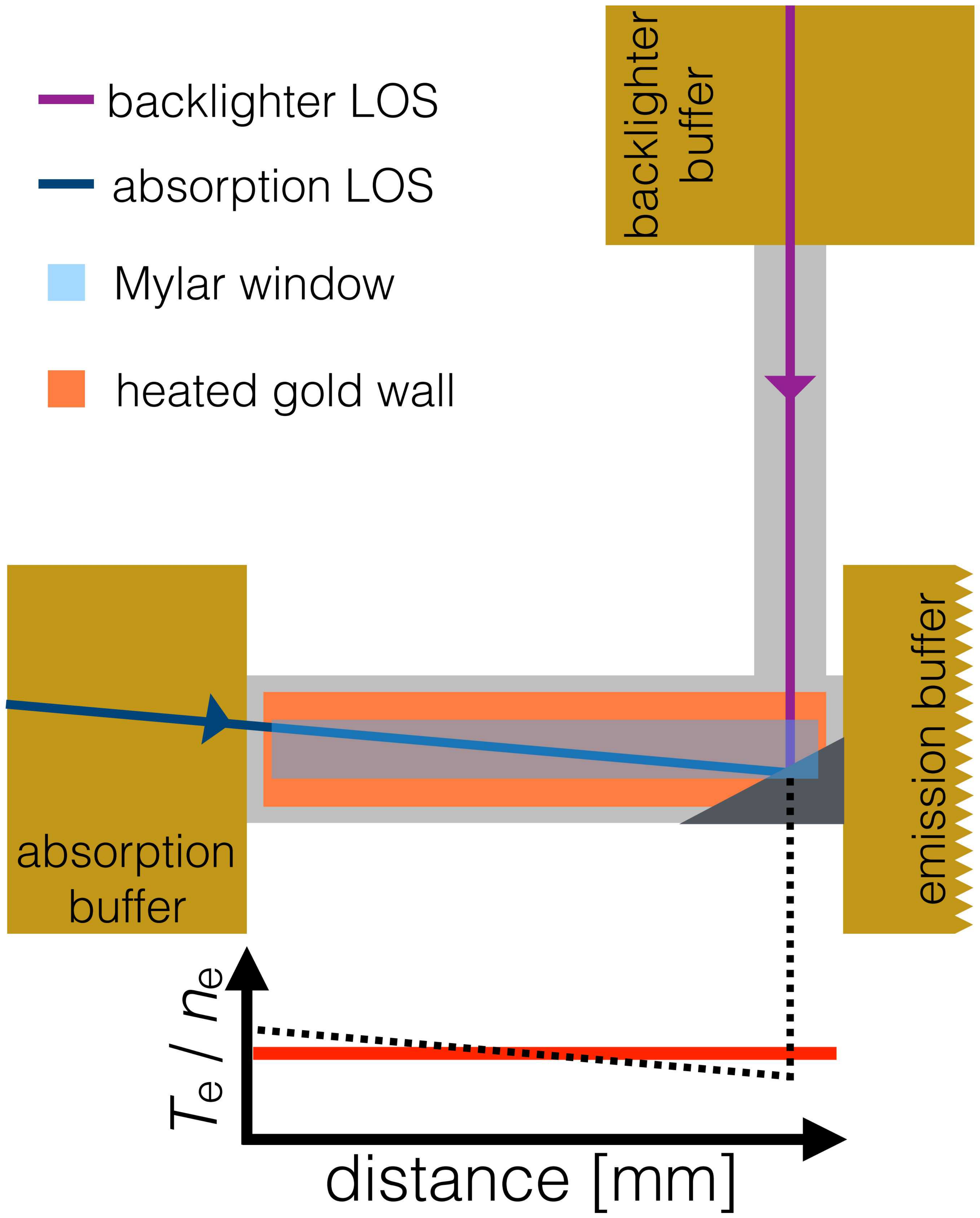


- Since my experiments investigate hydrogen plasmas, there's a direct and simple connection between T_e and n_e
- I can check for gradients by comparing the backlighter LOS data to the absorption LOS data
- If differential heating is important, the inferred n_e will differ

Constraining gradients in the WDPE gas cell



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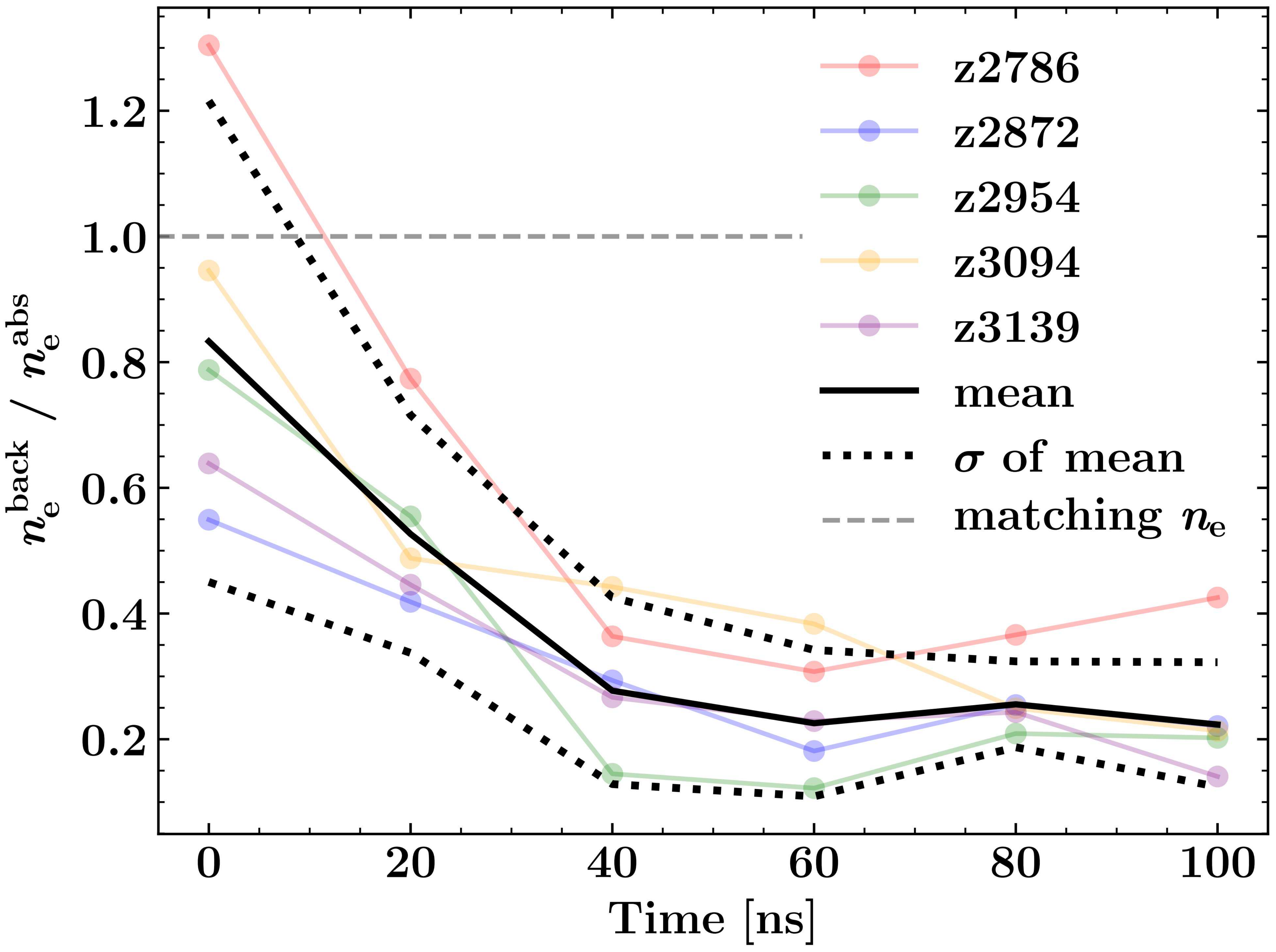
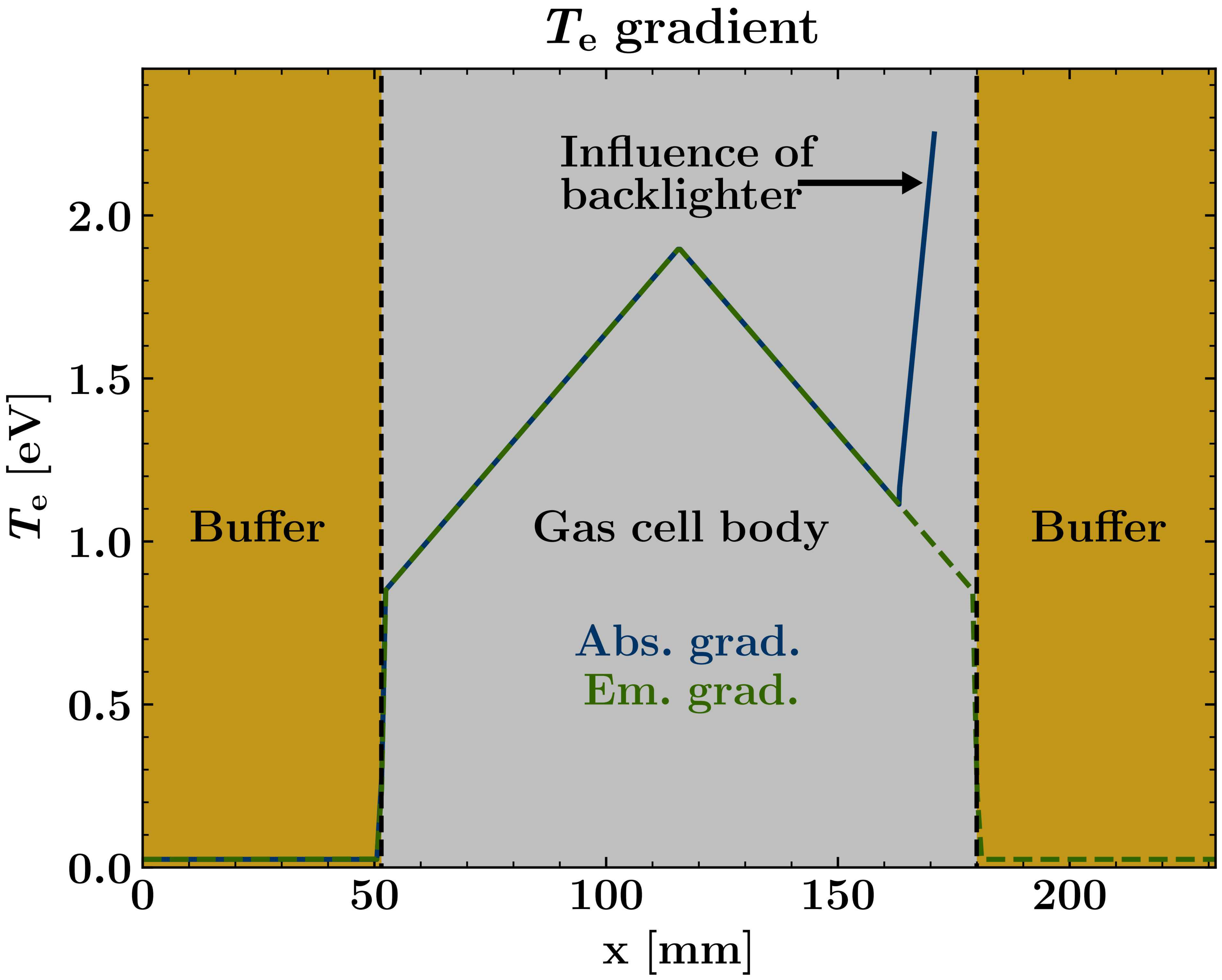
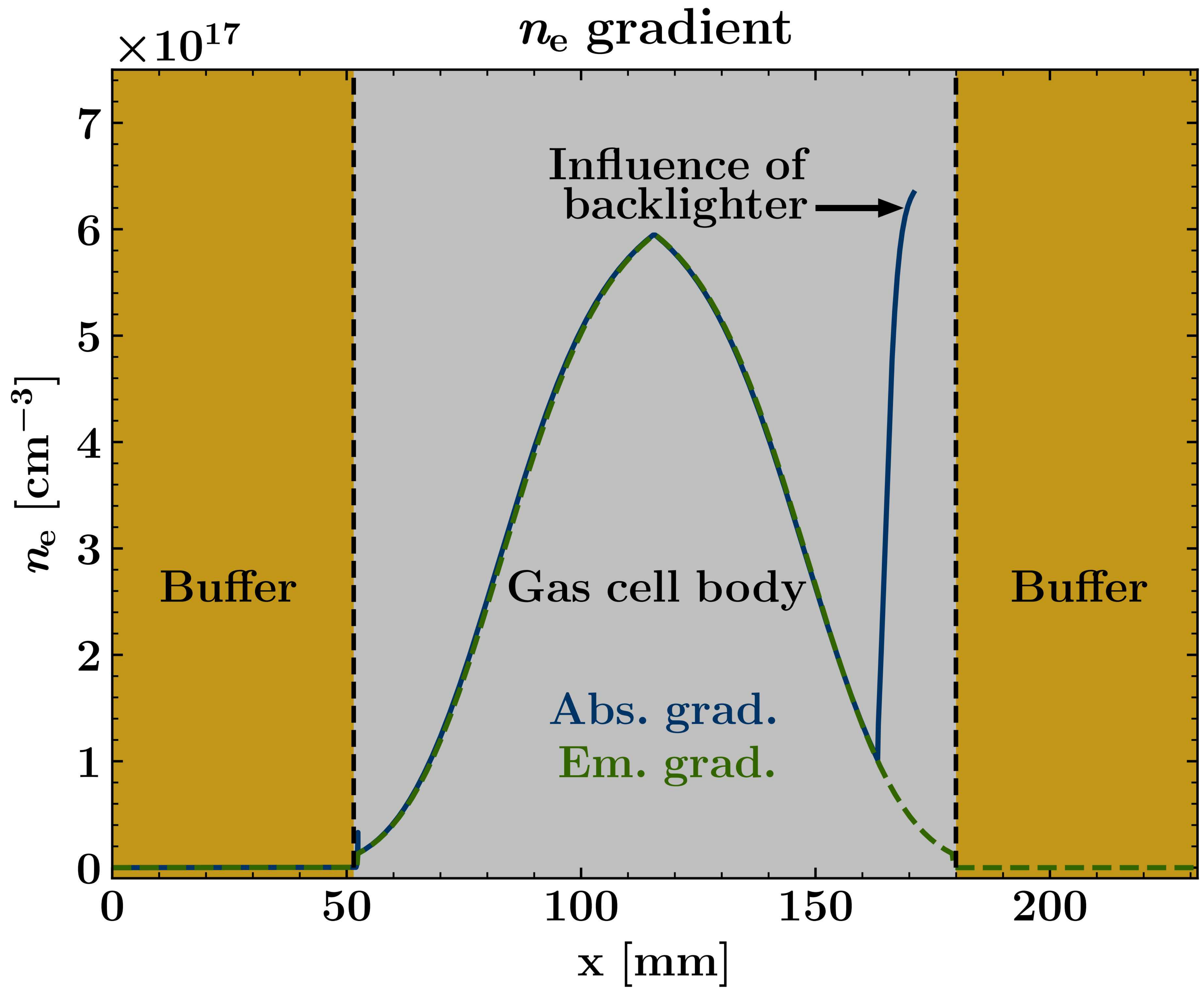


- An analysis of five shots performed over 2 years reveals a difference between the absorption and continuum LOS
- This difference is a function of experiment time, indicating further physics at work
- The lowest backlighter/absorption ratio is used to derive a plasma gradient

The most extreme gradients in the WDPE platform

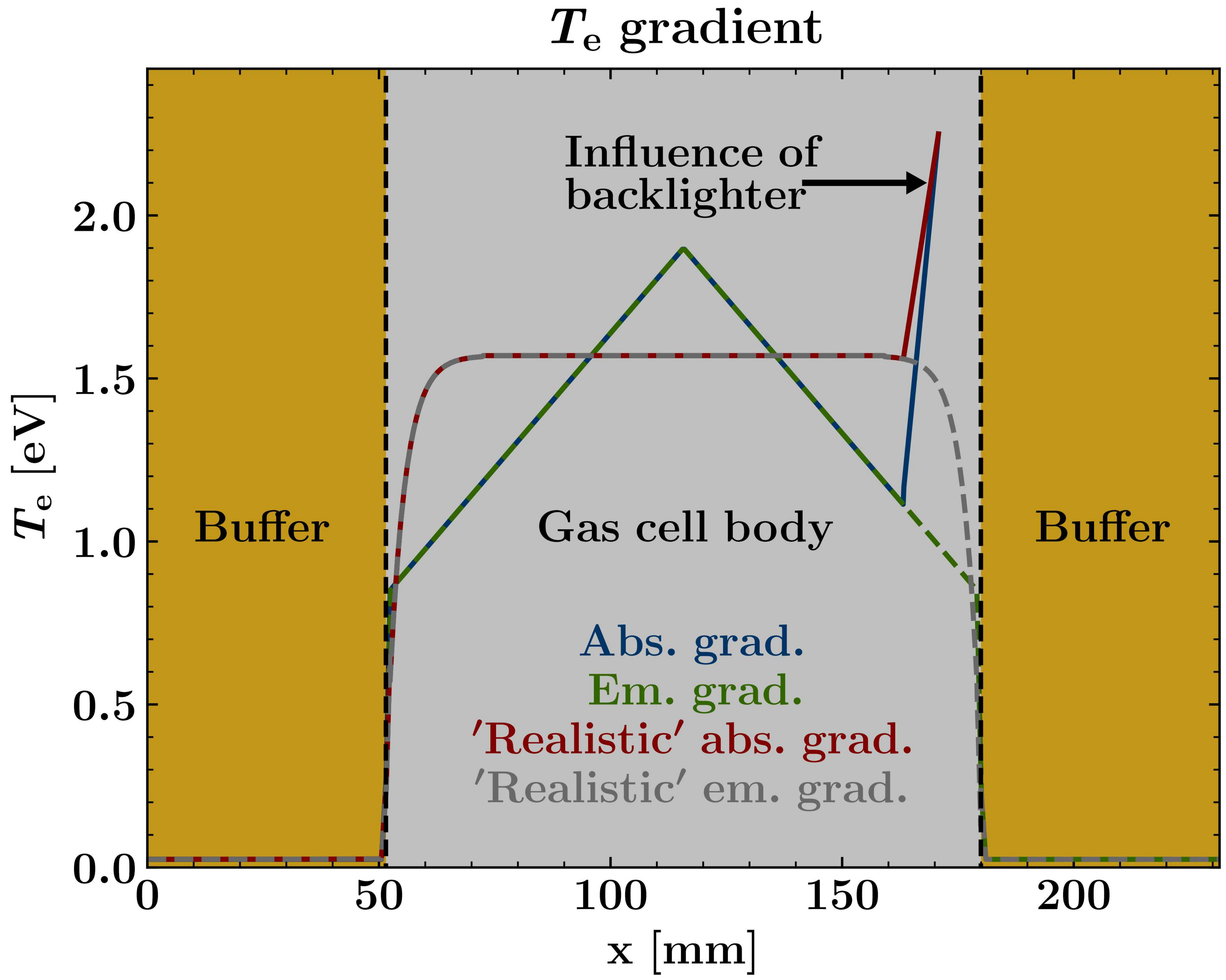


The temperature gradient along the emission and absorption LOS. This temperature structure was used in Spect3D simulations.



The electron density gradient along the emission and absorption LOS. This results directly from the temperature gradient shown on left.

'Realistic' gradients in the WDPE



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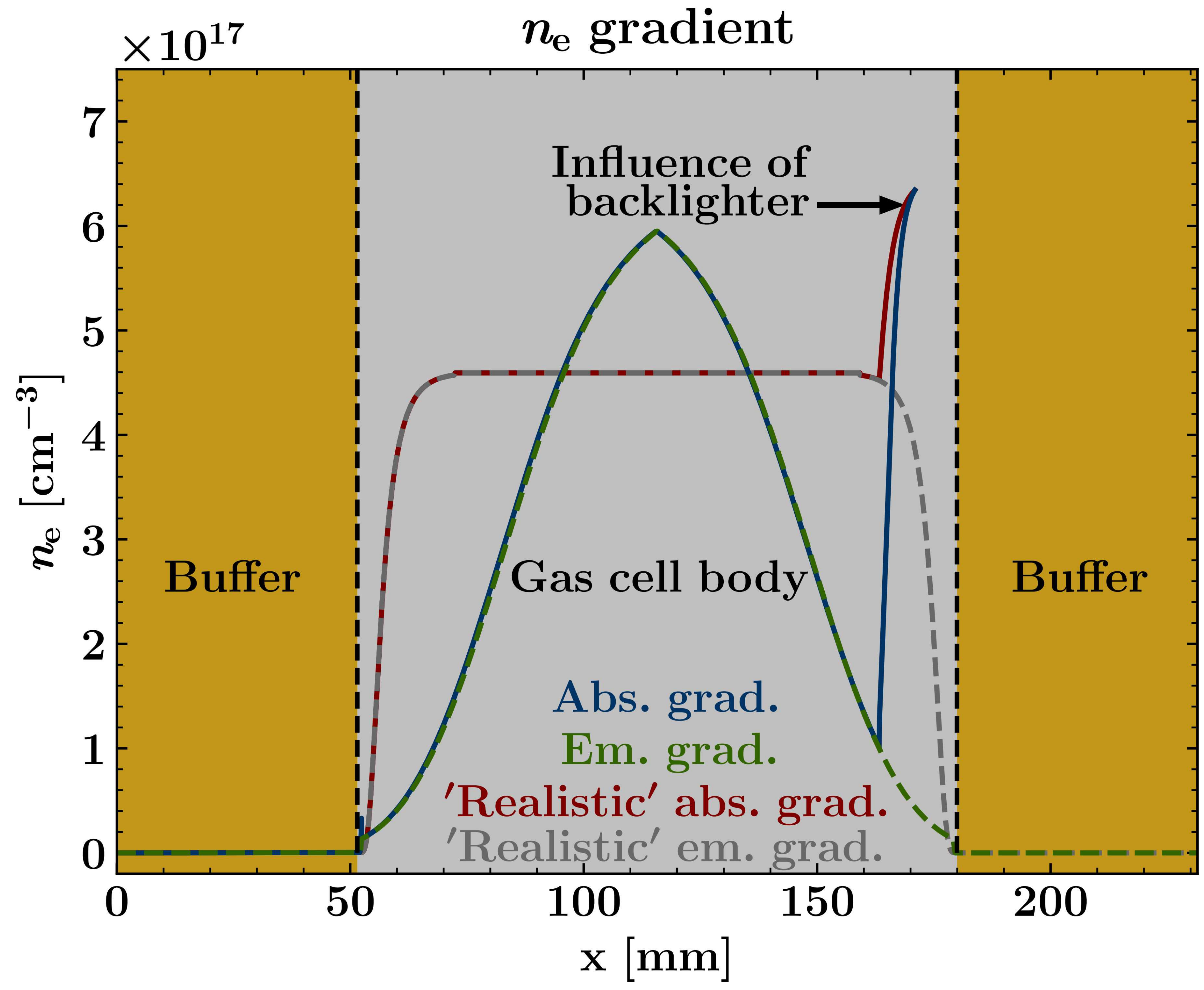

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