SAND2022-11271C

WOOTTON CAPP

The White Dwarf Photosphere Experiment

Bart Dunlap, UT Austin

Z Fundamental Science Workshop

August 3, 2022

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TEXAS
The University of Texas at Austin

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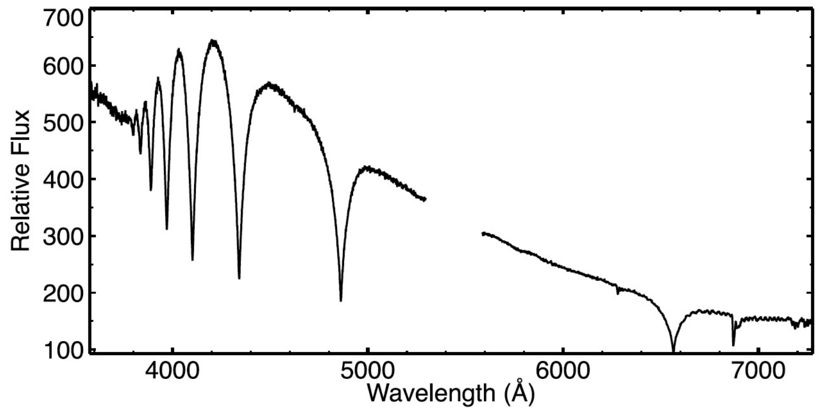
U.S. DEPARTMENT OF ENERGY
Office of Science

NSF

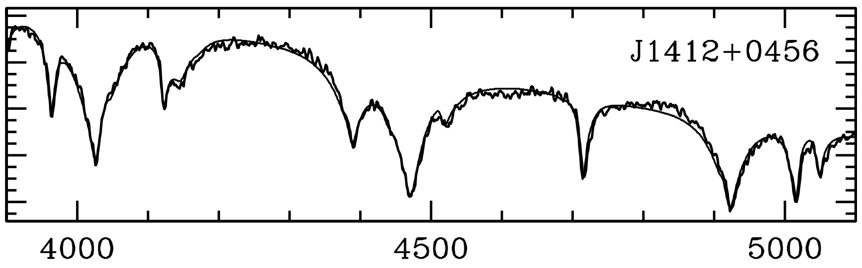
Overview

- What do white dwarf spectra tell us?
  - Mass, Temperature, Atmospheric Composition
- How do white dwarfs help answer broader astrophysical questions?
  - Ages of stellar populations, exoplanets, cosmology
- Why do we think there are problems with spectroscopic mass determinations?
  - Independent mass estimates disagree
- What developments are underway with the white dwarf photosphere experiment?
  - Achieving higher densities in hydrogen
  - Developing independent electron density diagnostic (PDV)
  - Measuring Stark broadening of He I 5015 & 5876 lines
  - Theory update: screening, continuum lowering/occupation probability, H_2 quasi-molecular features

The Importance of White Dwarf Spectra



H



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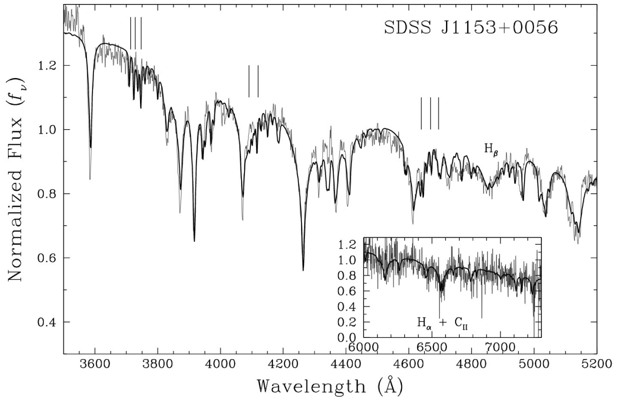

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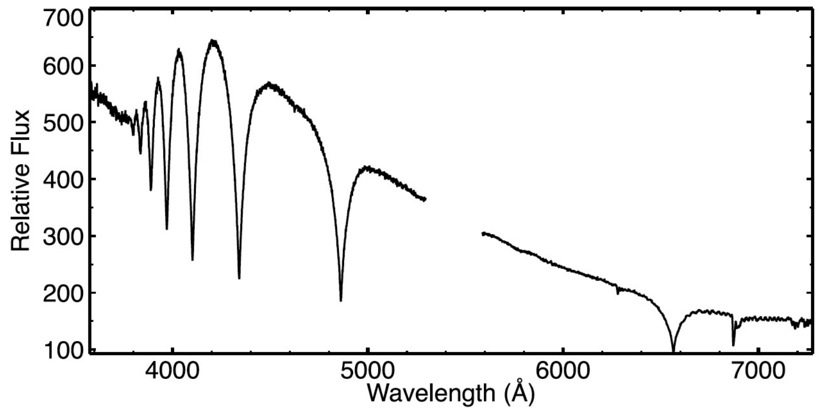
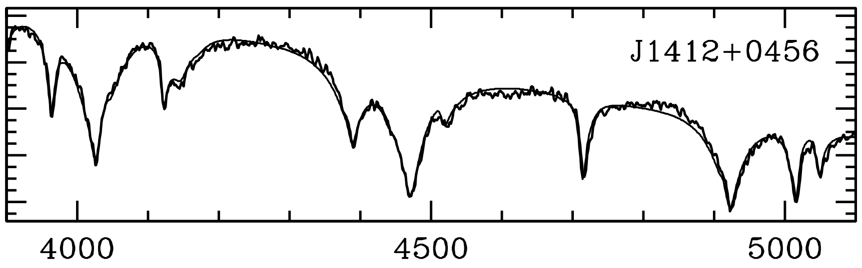
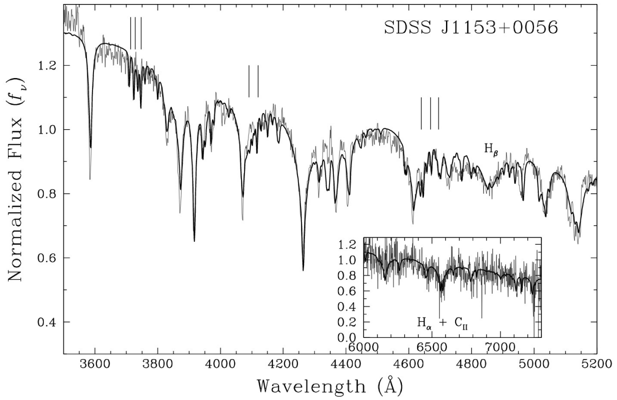
What do they tell us?

White Dwarf Spectra → Composition, Mass, & Temperature







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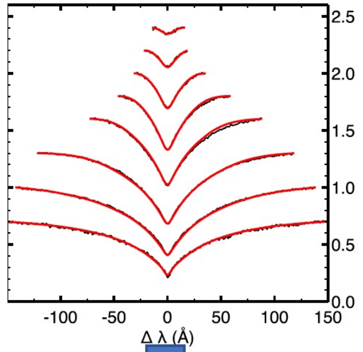


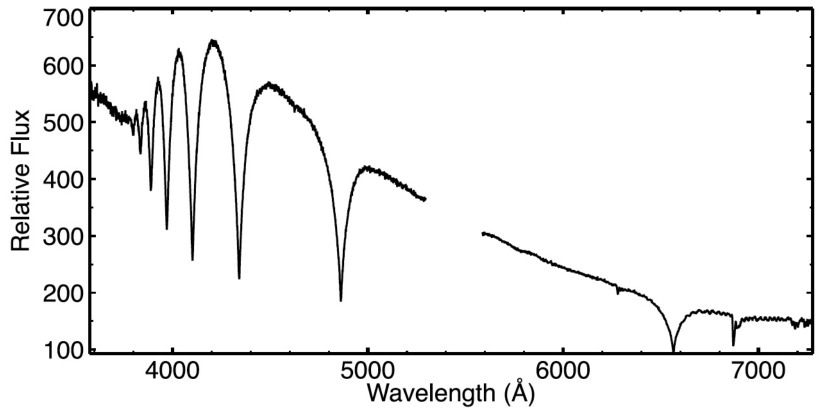
Model Fits to
WD **Spectral Lines**

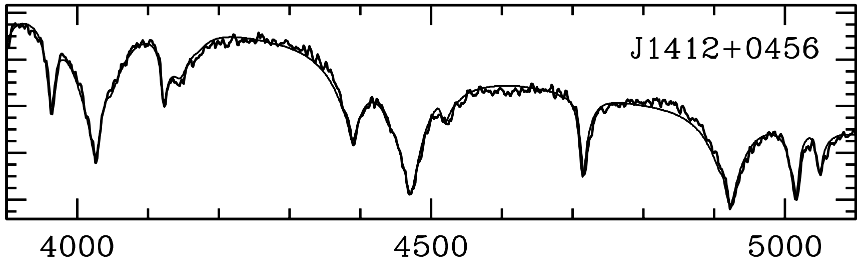
log g => Mass
Temperature
Composition

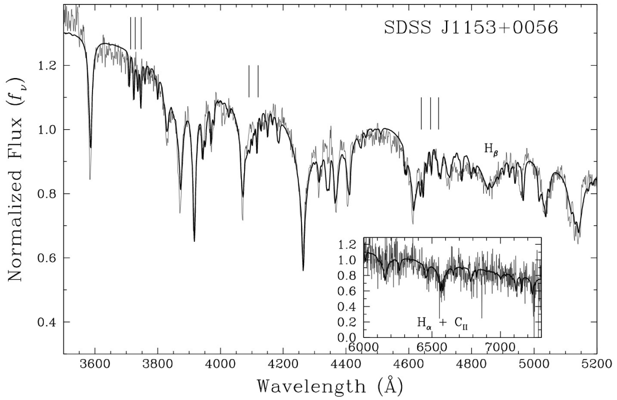
(b/c more massive WDs have smaller radii)

What good are these?

White Dwarf Spectra → Composition, Mass, & Temperature







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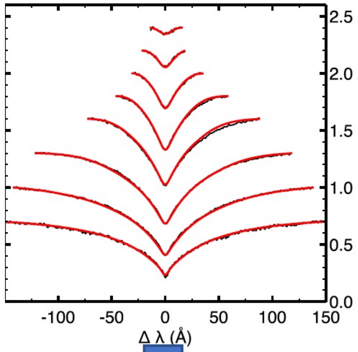


Model Fits to WD **Spectral Lines**

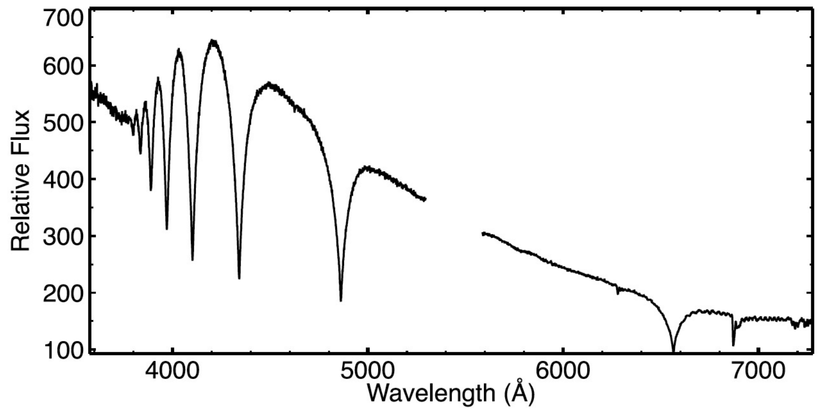
log g => Mass
Temperature
Composition

Age & History of the Galaxy

Interior Composition of Exoplanets

Supernova Formation/ Precision Cosmology

White Dwarf Spectra → Composition, Mass, & Temperature



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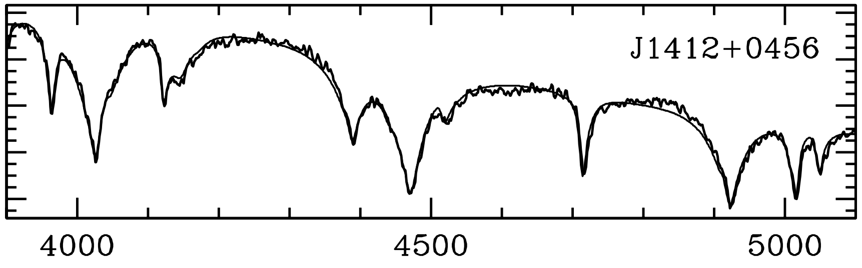

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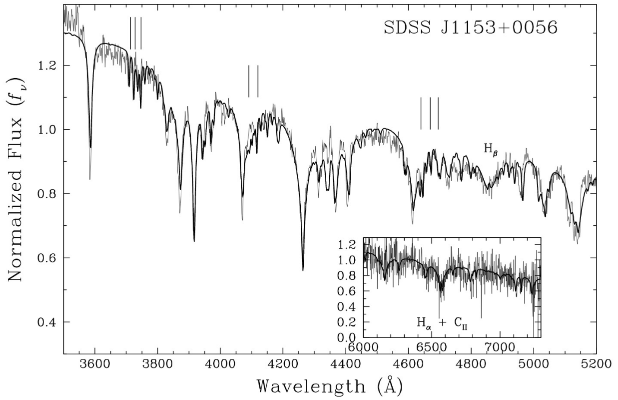

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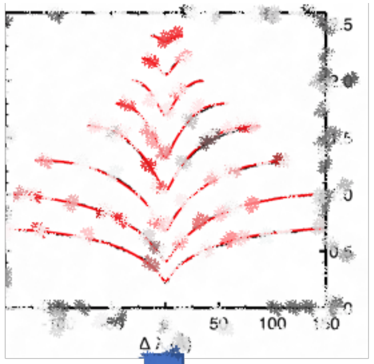

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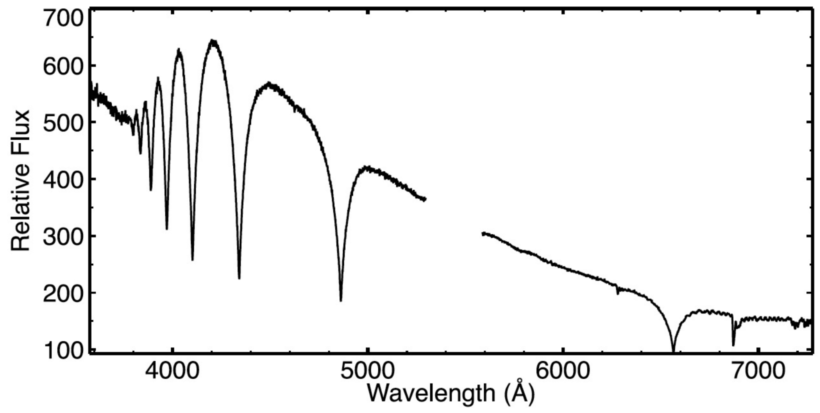

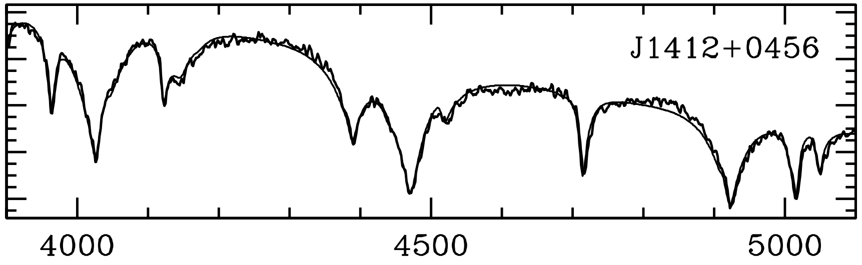

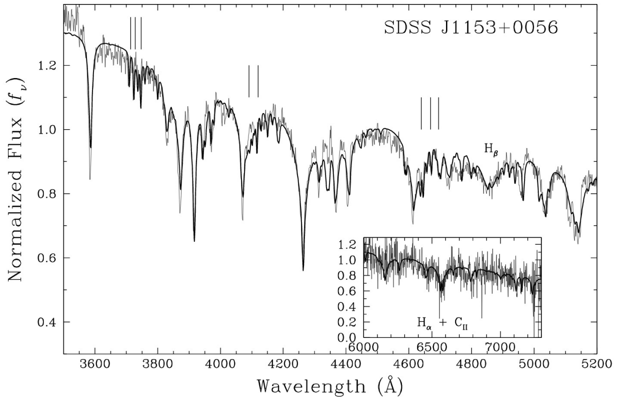

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He

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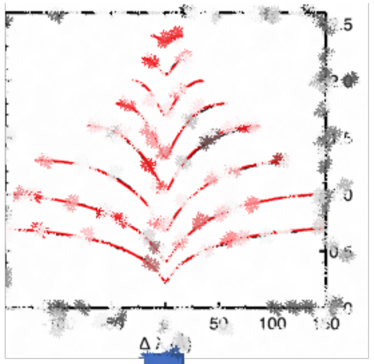

Model Fits to WD **Spectral Lines**

log g => Mass
Temperature
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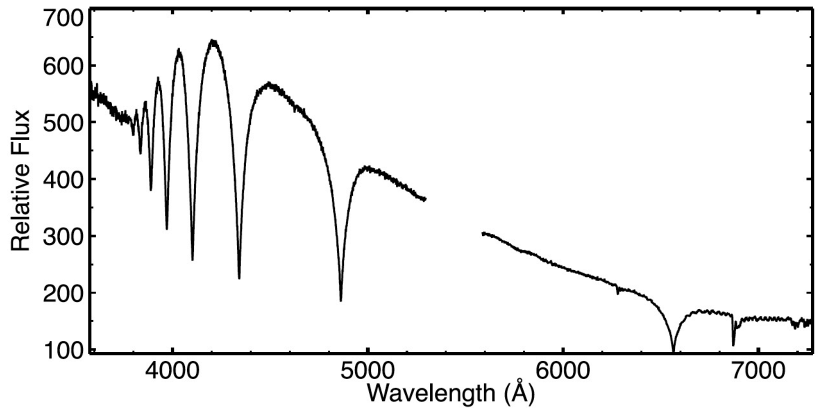
Age & History of the Galaxy

Interior Composition of Exoplanets

Supernova Formation/ Precision Cosmology

Z Measurements focused on 3 main types



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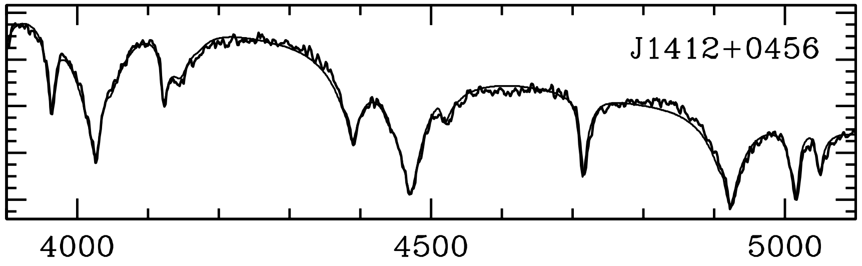

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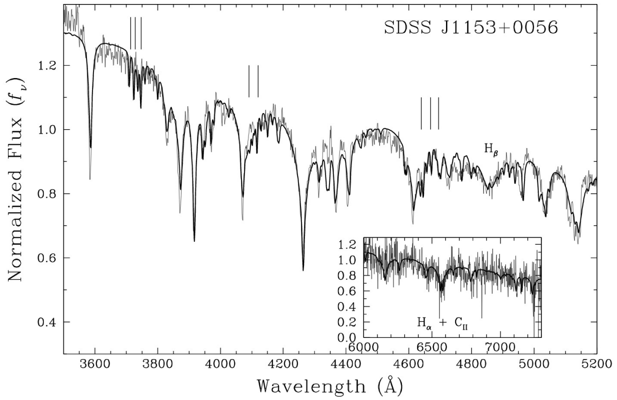

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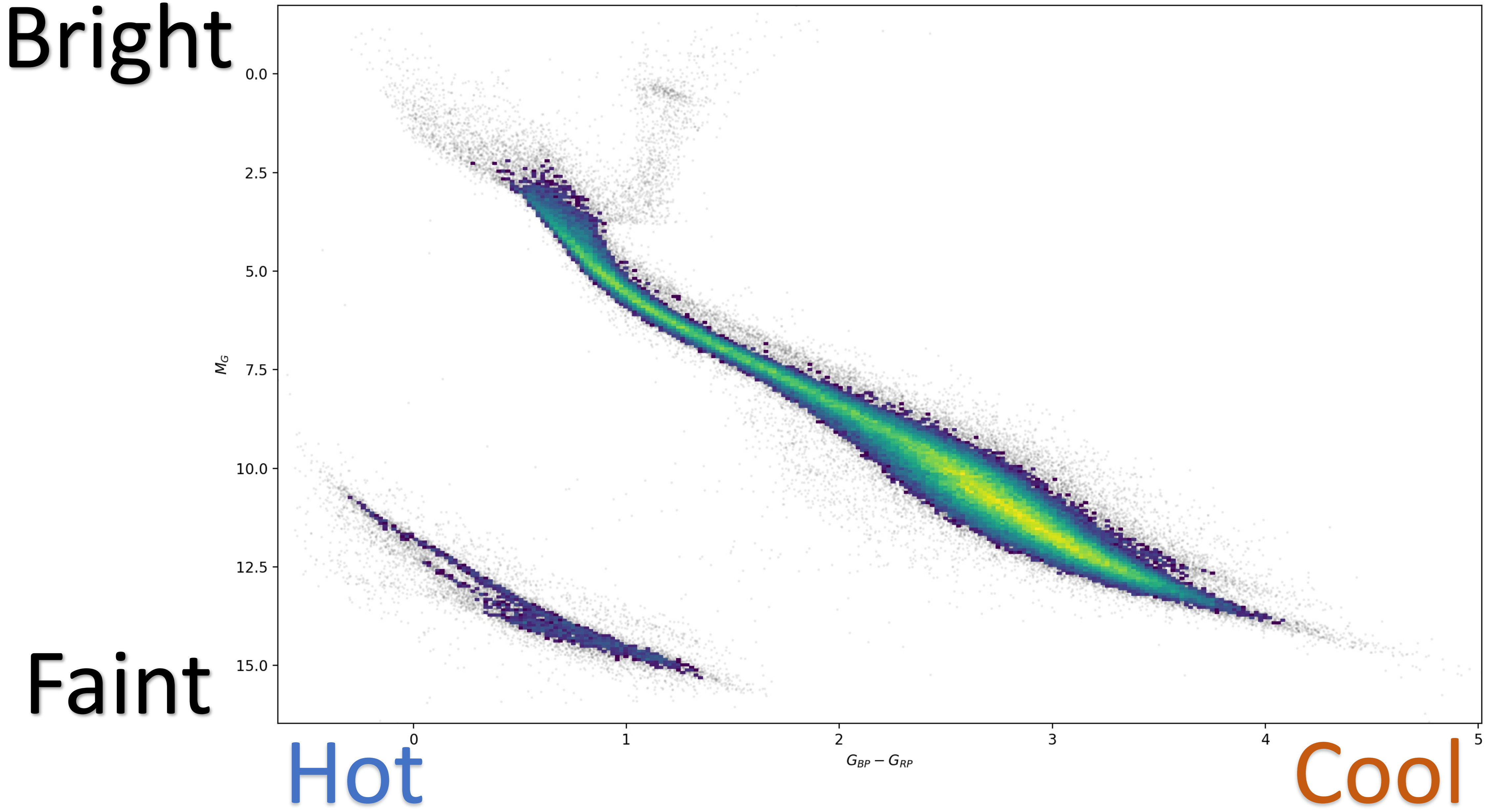
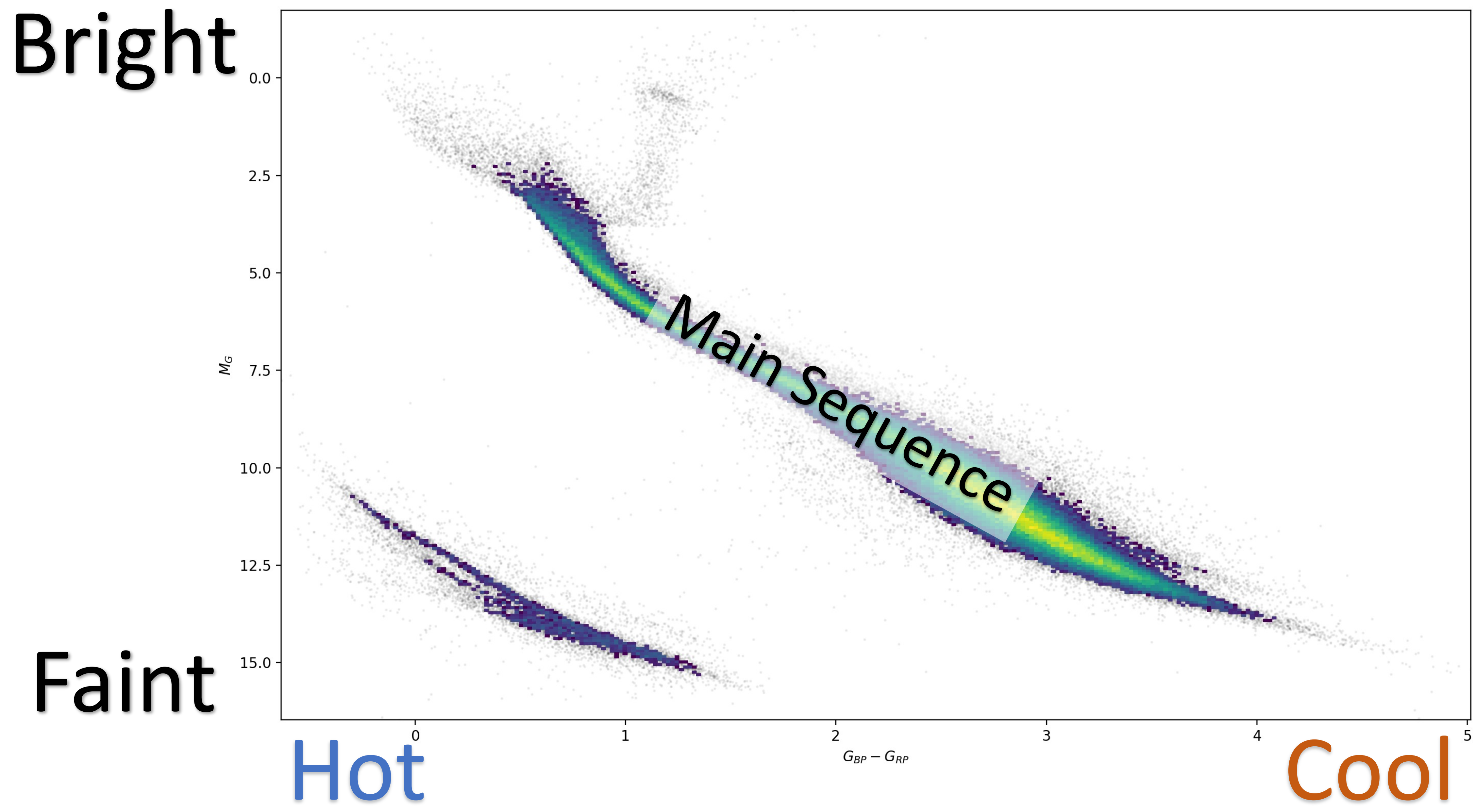
Benchmark measurements of Balmer lines.

Measuring He I Stark/neutral broadening.

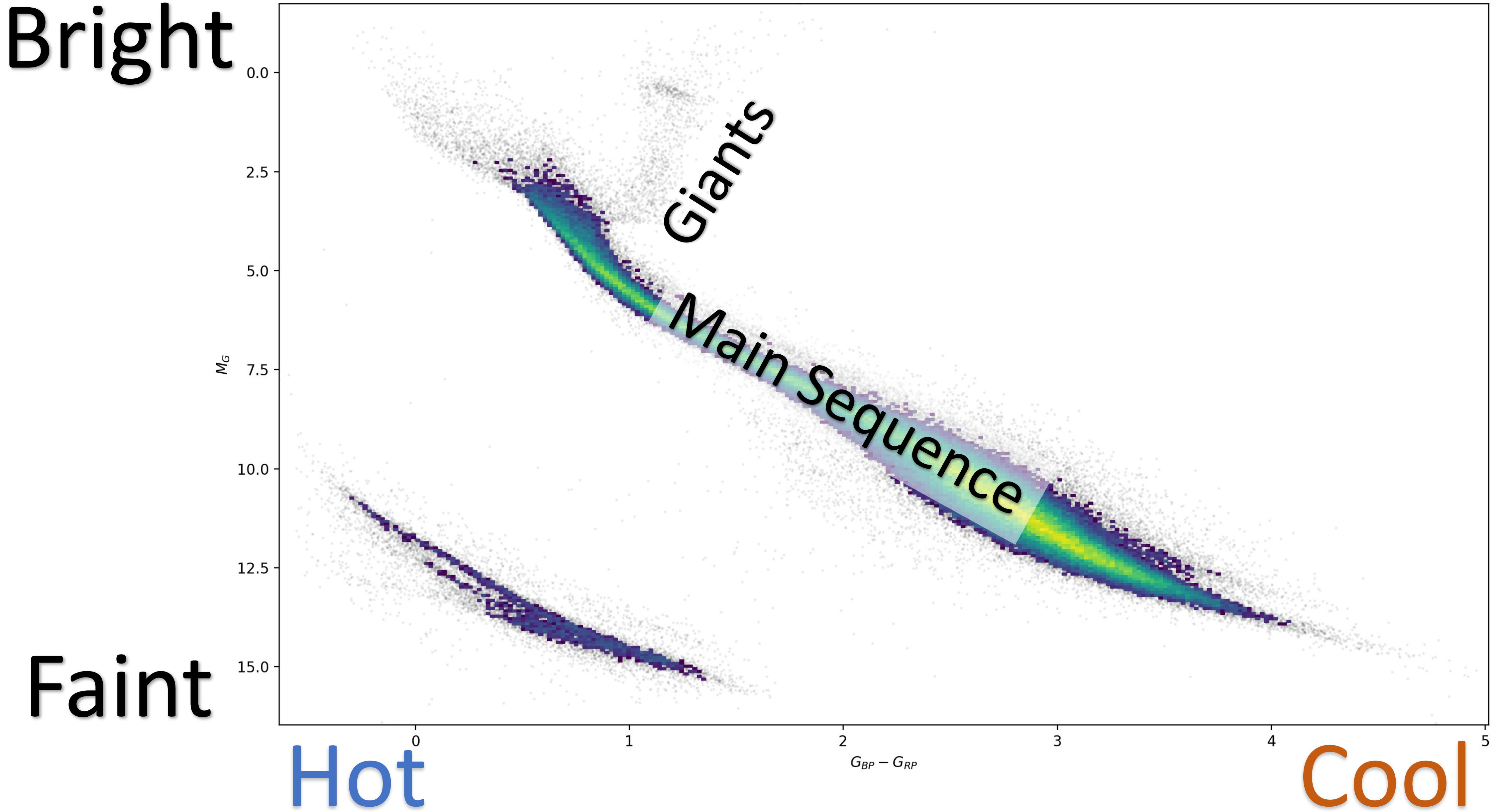
Measuring hotter hot DQ conditions (CII lines)

White Dwarfs and Stellar Evolution





Bright
Faint
Hot
Cool
Main Sequence
M_G
$G_{BP} - G_{RP}$
0.0
2.5
5.0
7.5
10.0
12.5
15.0
0
1
2
3
4
5



Bright
Faint
Hot
Cool
Giants
Main Sequence
M_G
0.0
2.5
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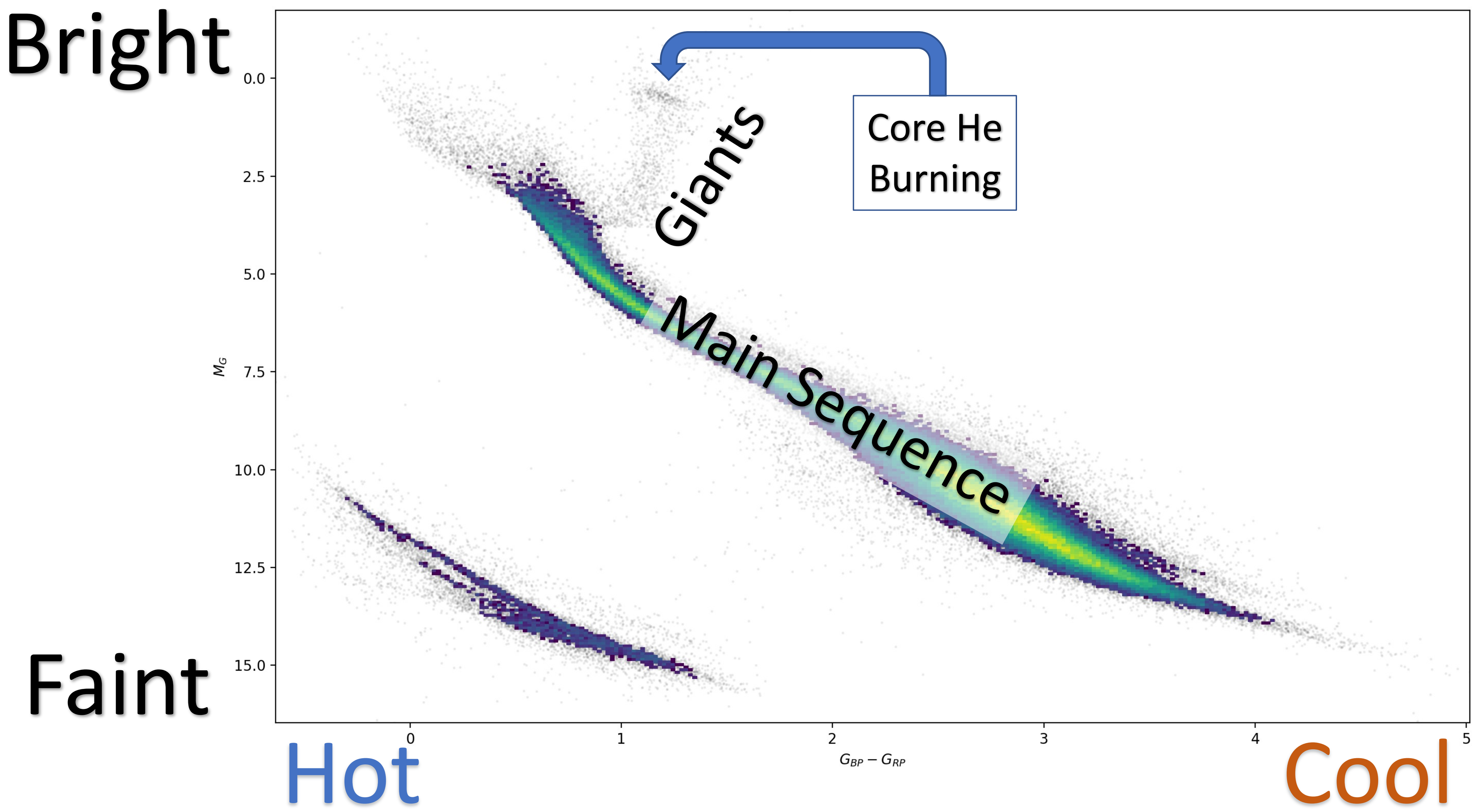
$G_{BP} - G_{RP}$



Bright
Faint
Hot
Cool
Core He Burning
Giants
Main Sequence
0.0
2.5
5.0
7.5
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M_G
0
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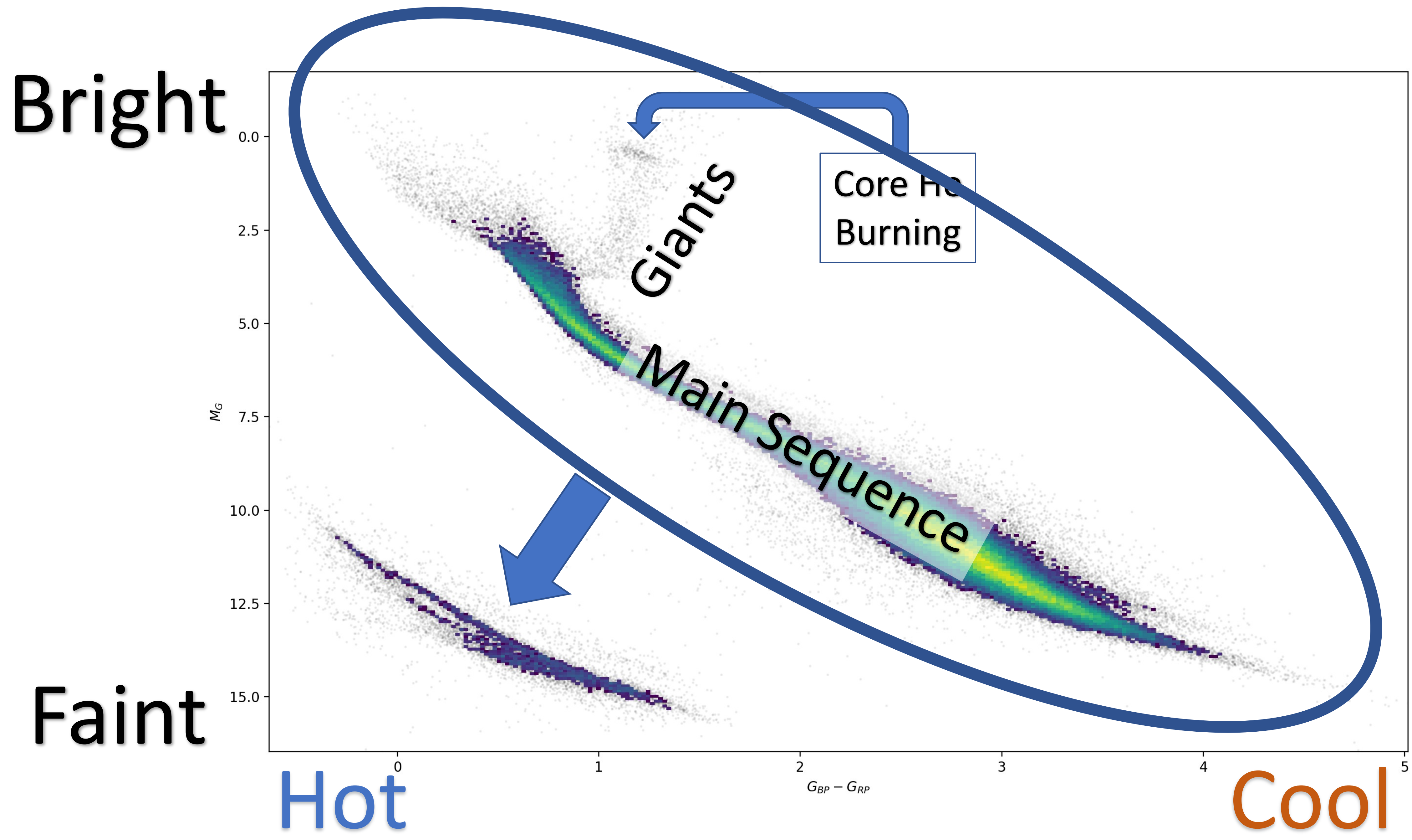
$G_{BP} - G_{RP}$


Bright
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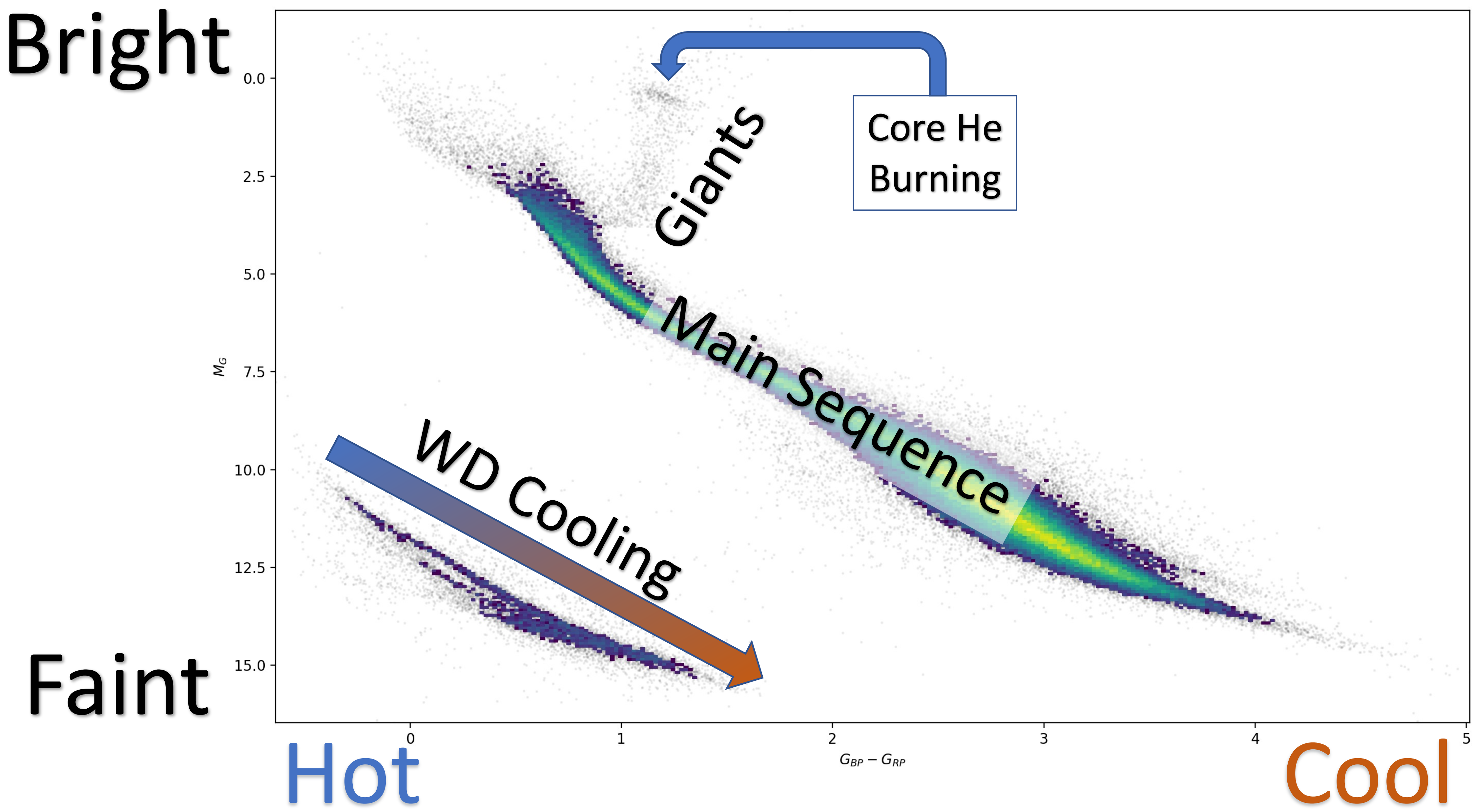
Bright
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Main Sequence
WD Cooling
M_G
$G_{BP} - G_{RP}$
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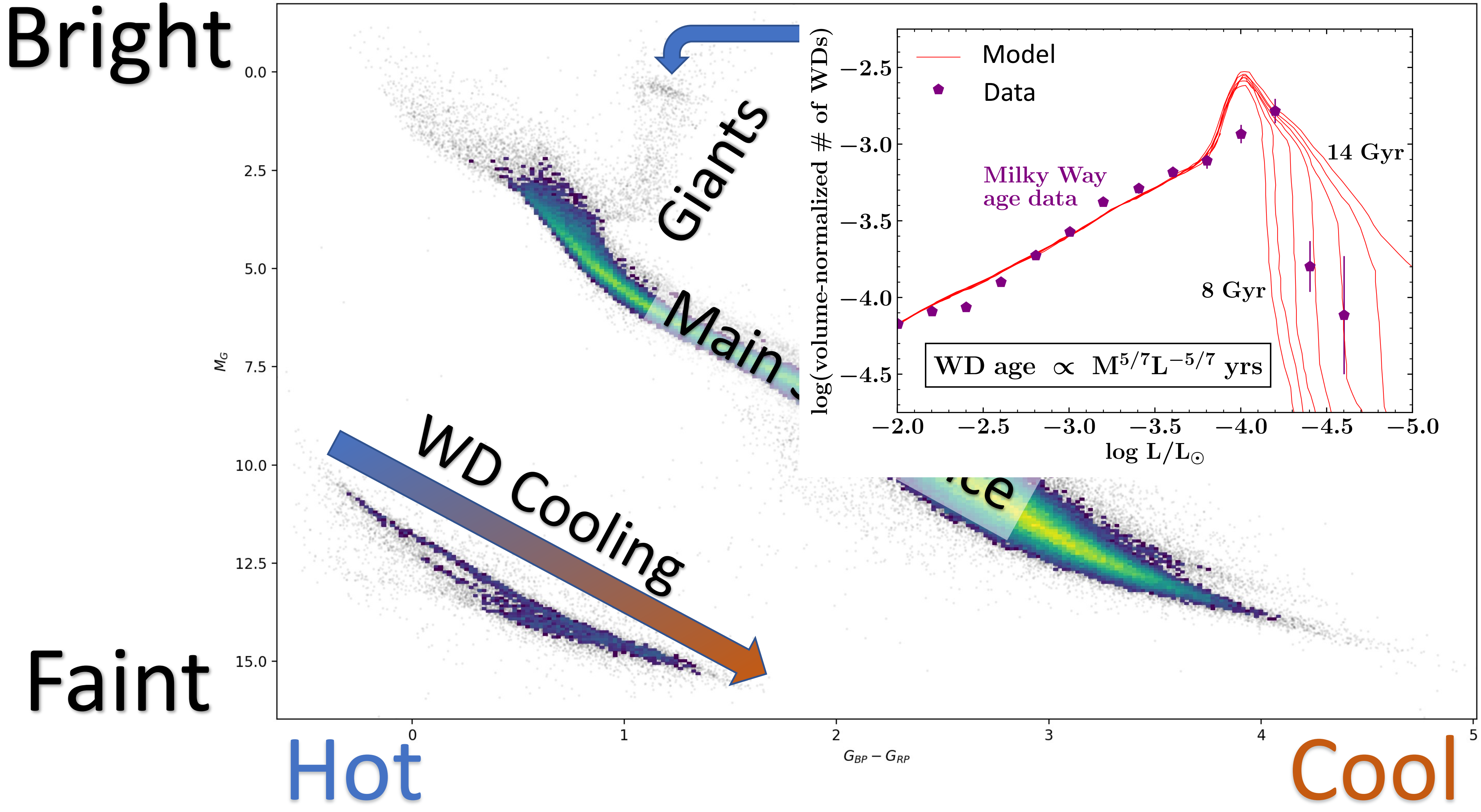
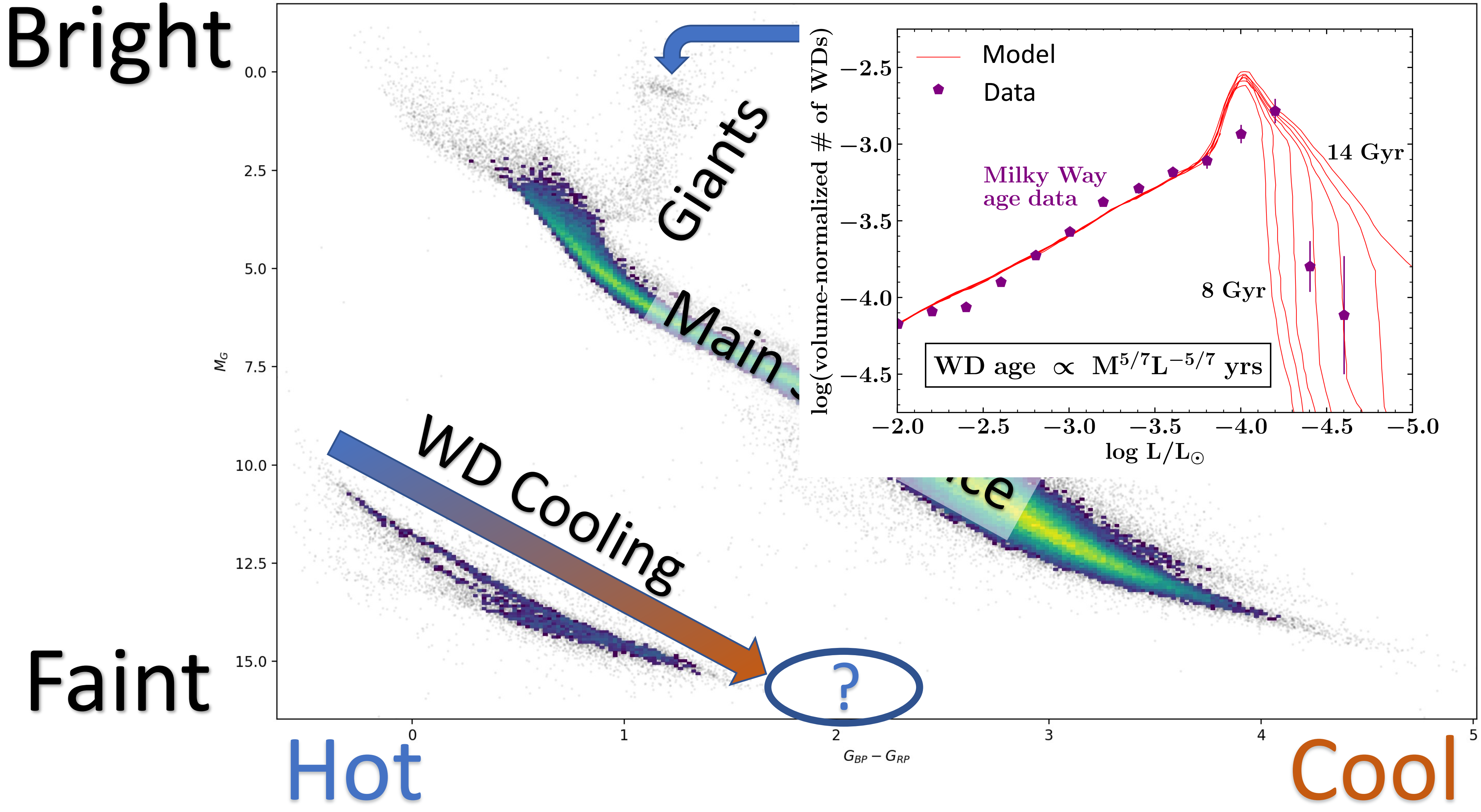
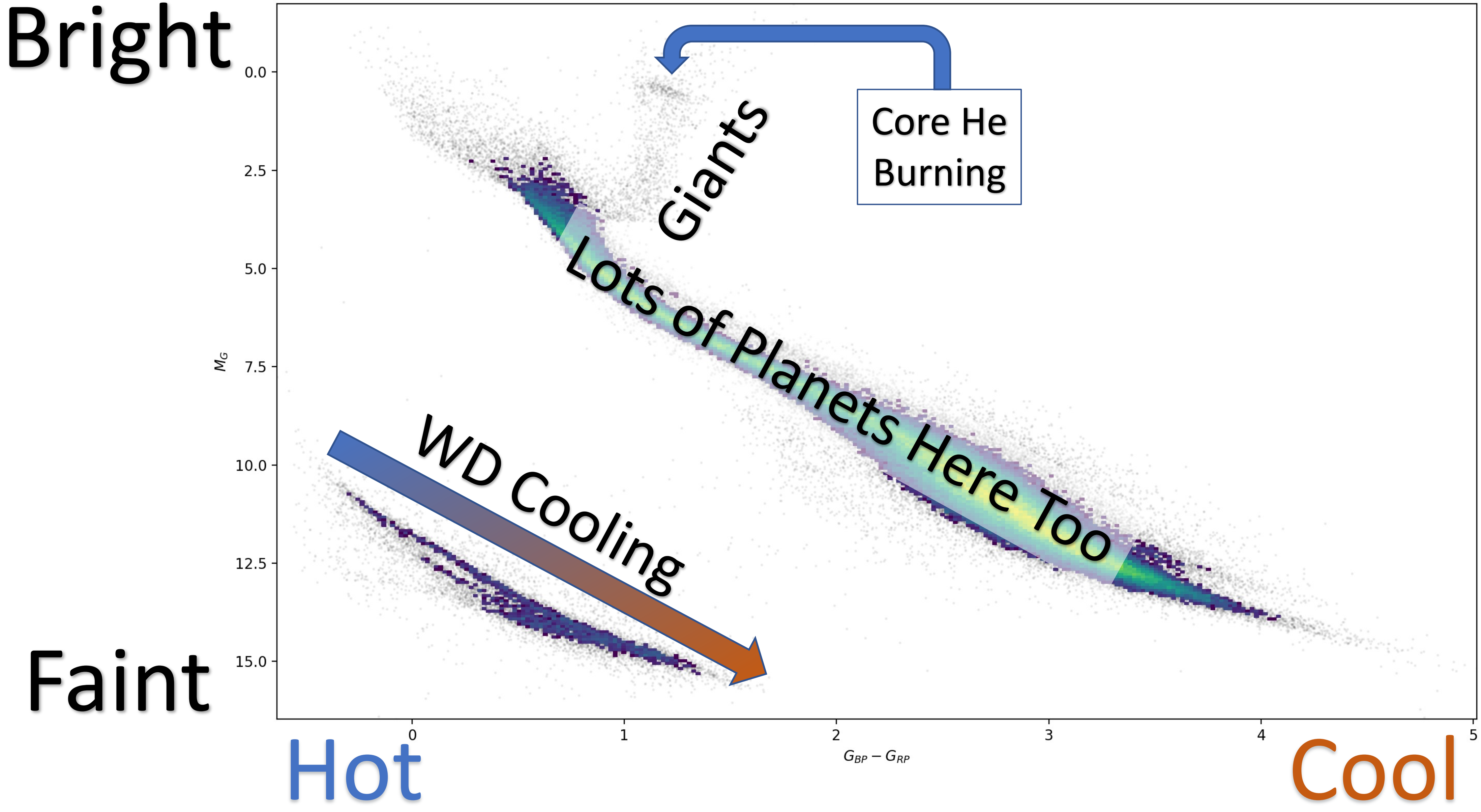
White Dwarfs Constrain Ages of Stellar Populations



White Dwarfs Constrain Ages of Stellar Populations



White Dwarfs Provide Unique Insights on Exoplanets



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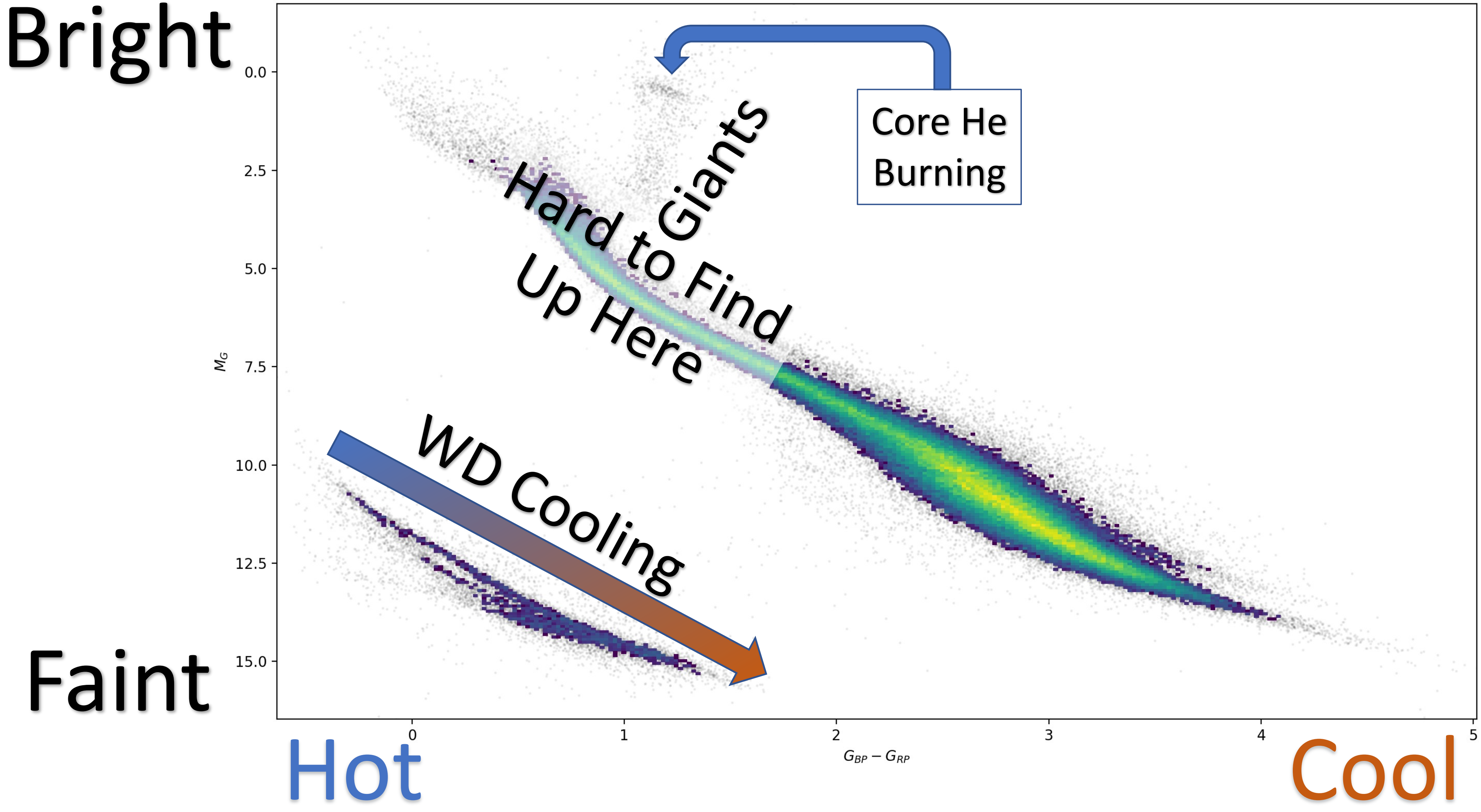
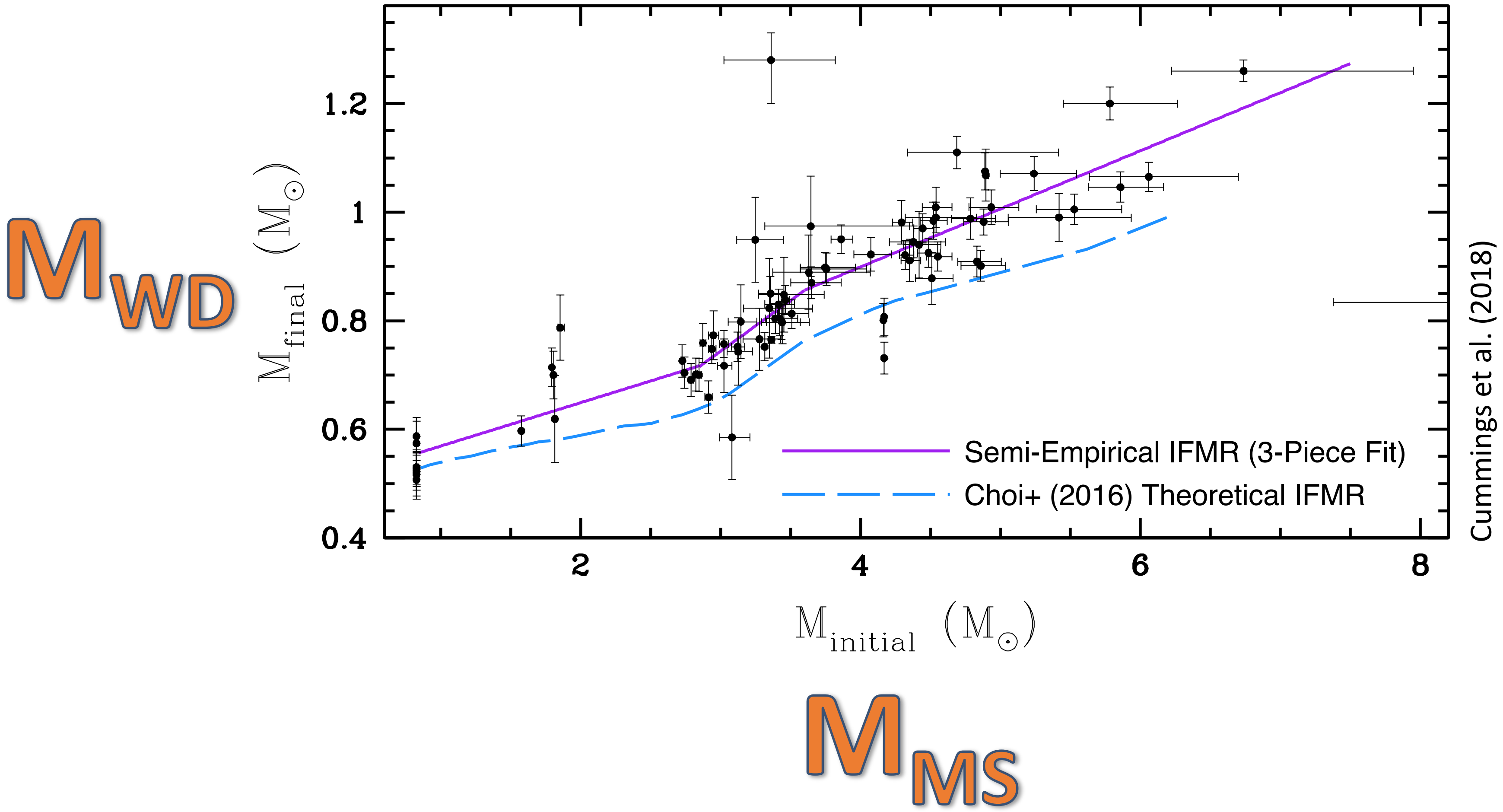
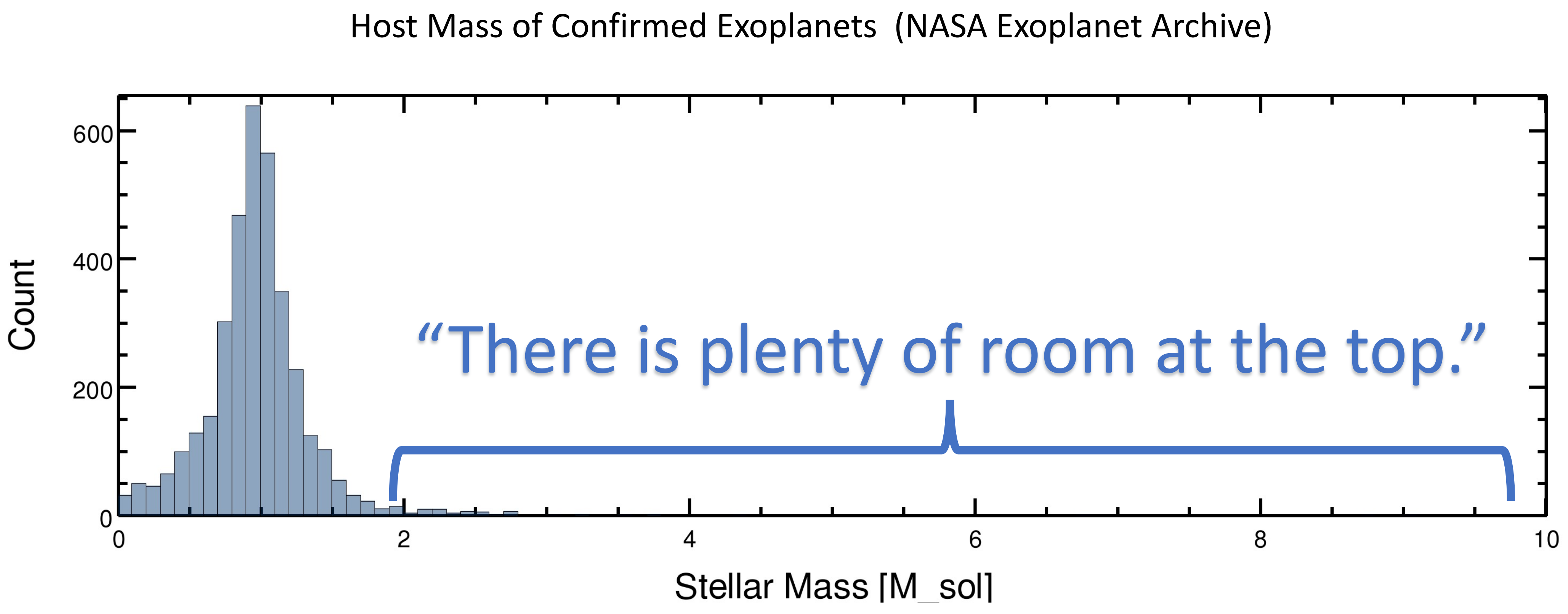


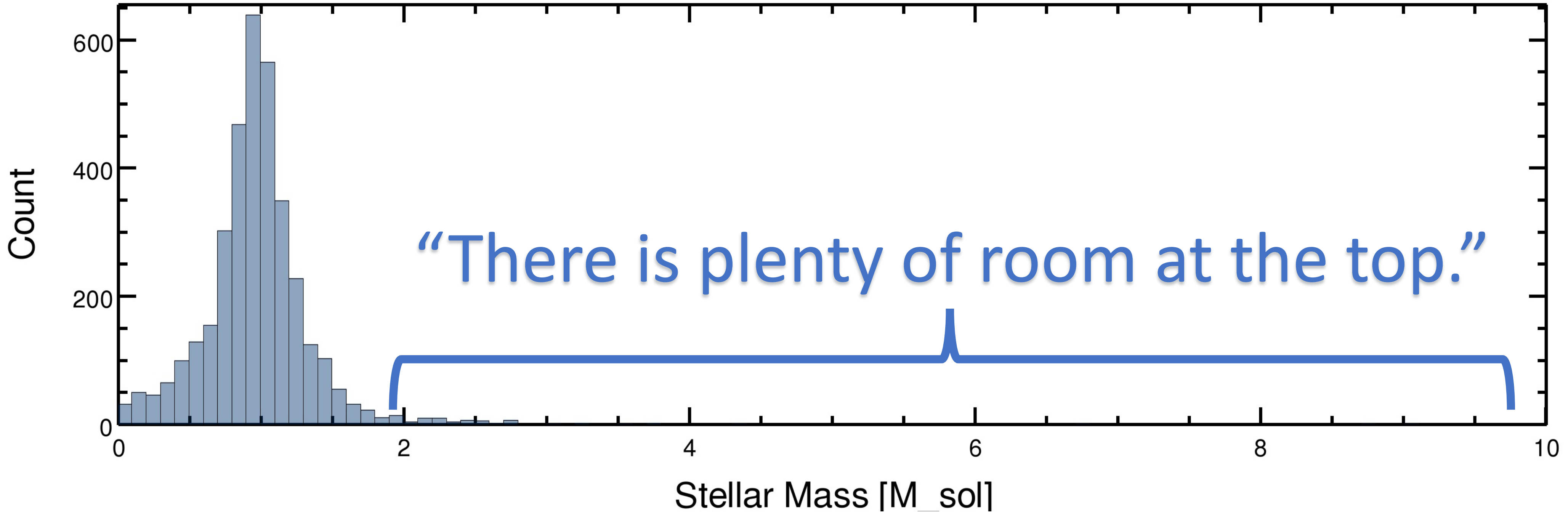
Initial-Final Mass Relation allows us to infer progenitor mass from white dwarf mass





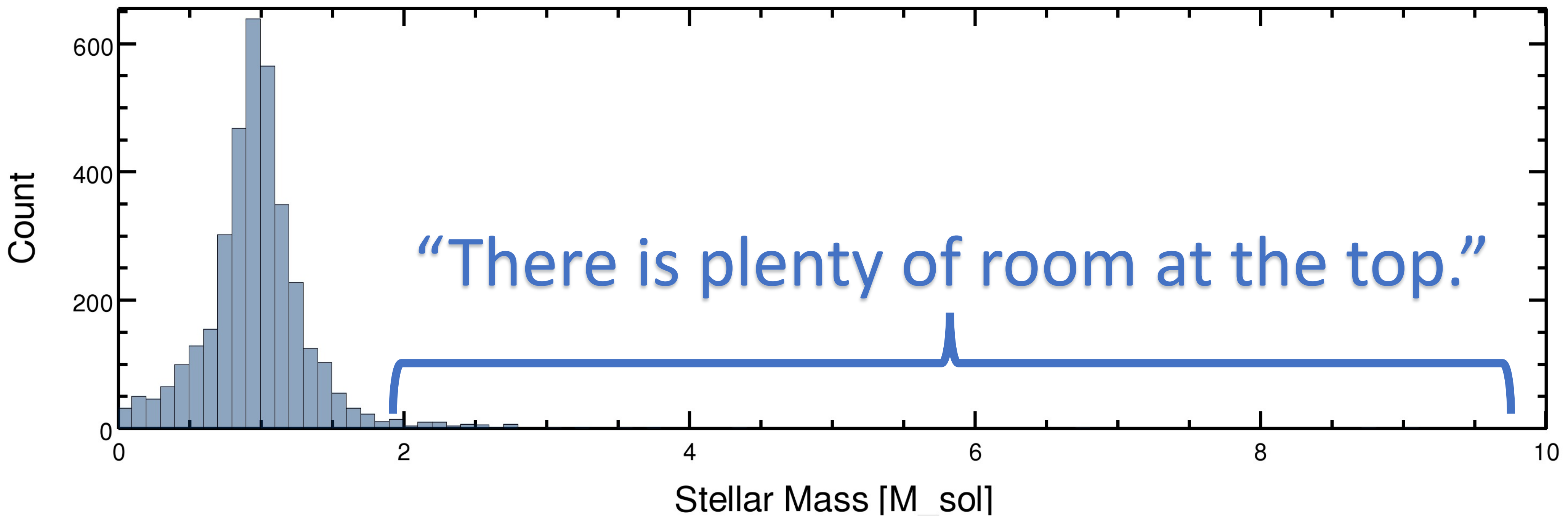
Planetary detection on the main sequence is particularly hard at high mass.

Host Mass of Confirmed Exoplanets (NASA Exoplanet Archive)



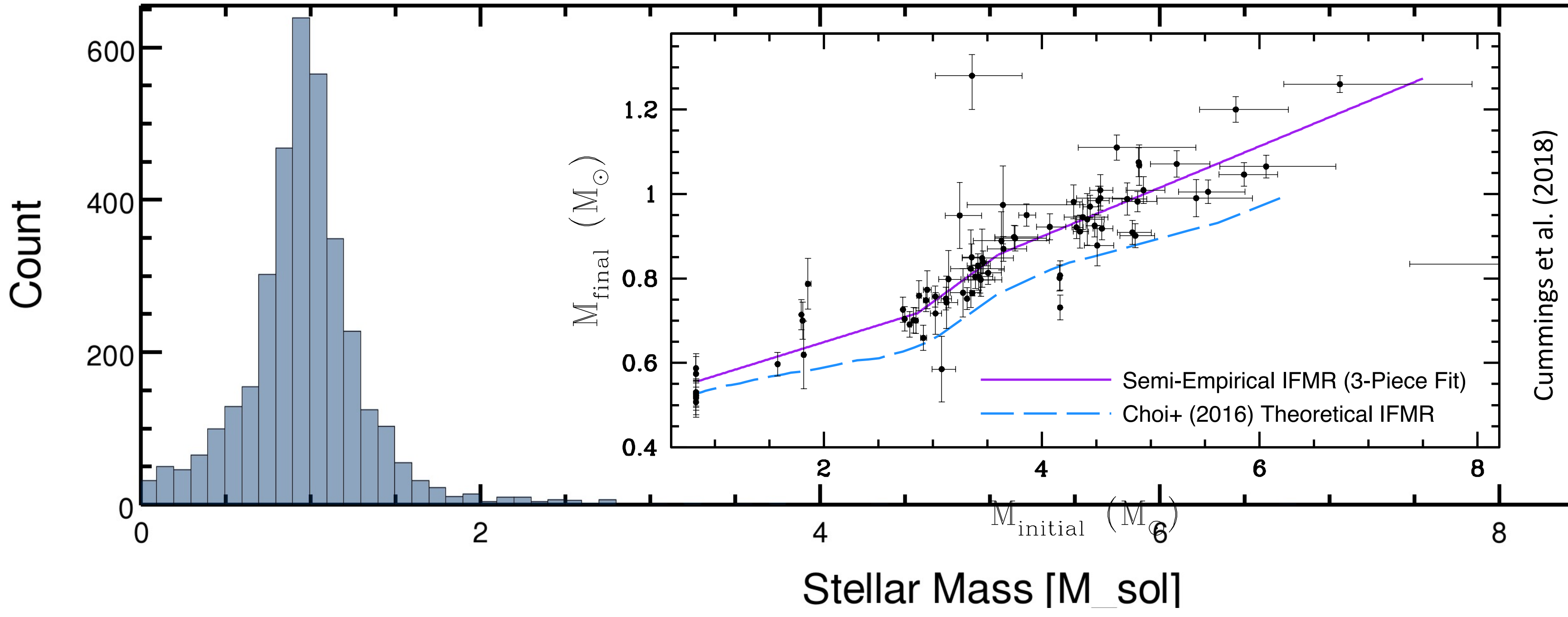
White Dwarfs allow us to probe this regime much more easily.

Host Mass of Confirmed Exoplanets (NASA Exoplanet Archive)



The Initial Final Mass relation lets us translate knowledge of white dwarf planetary systems to previous stages of stellar evolution.

Host Mass of Confirmed Exoplanets (NASA Exoplanet Archive)



The Initial Final Mass relation lets us translate knowledge of white dwarf planetary systems to previous stages of stellar evolution.

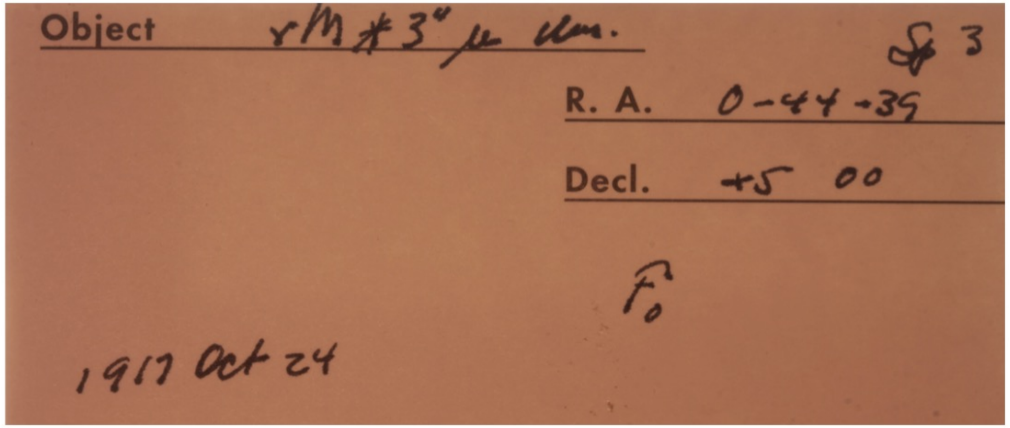
White Dwarfs Reveal Planetary Interiors

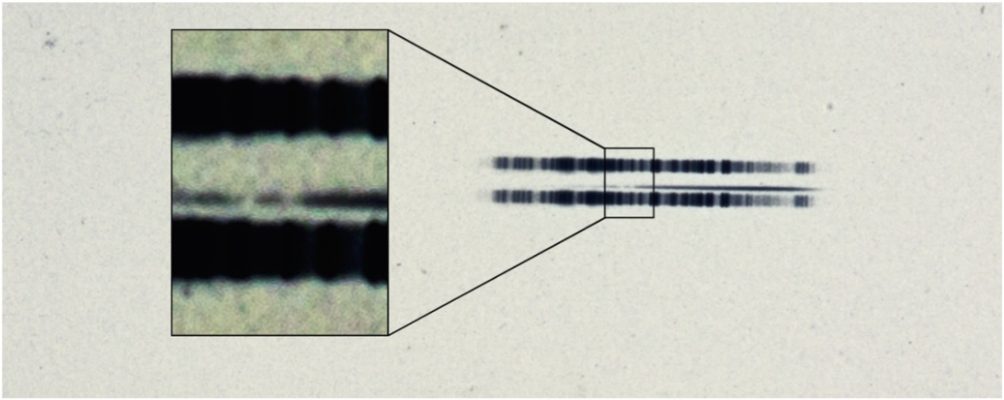
They Crush Exoplanetary Rocky Debris & Accrete It

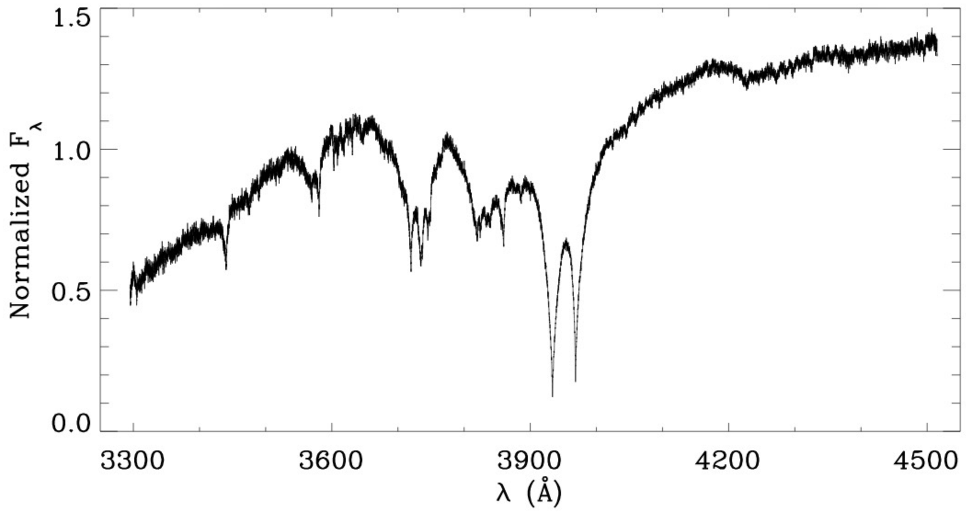
Spectra Give Abundances

Accurate log g Necessary to Infer Composition

For more on planetary material in white dwarf atmospheres, see the breakout session talk by Simon Blouin this afternoon.







Farihi 2016

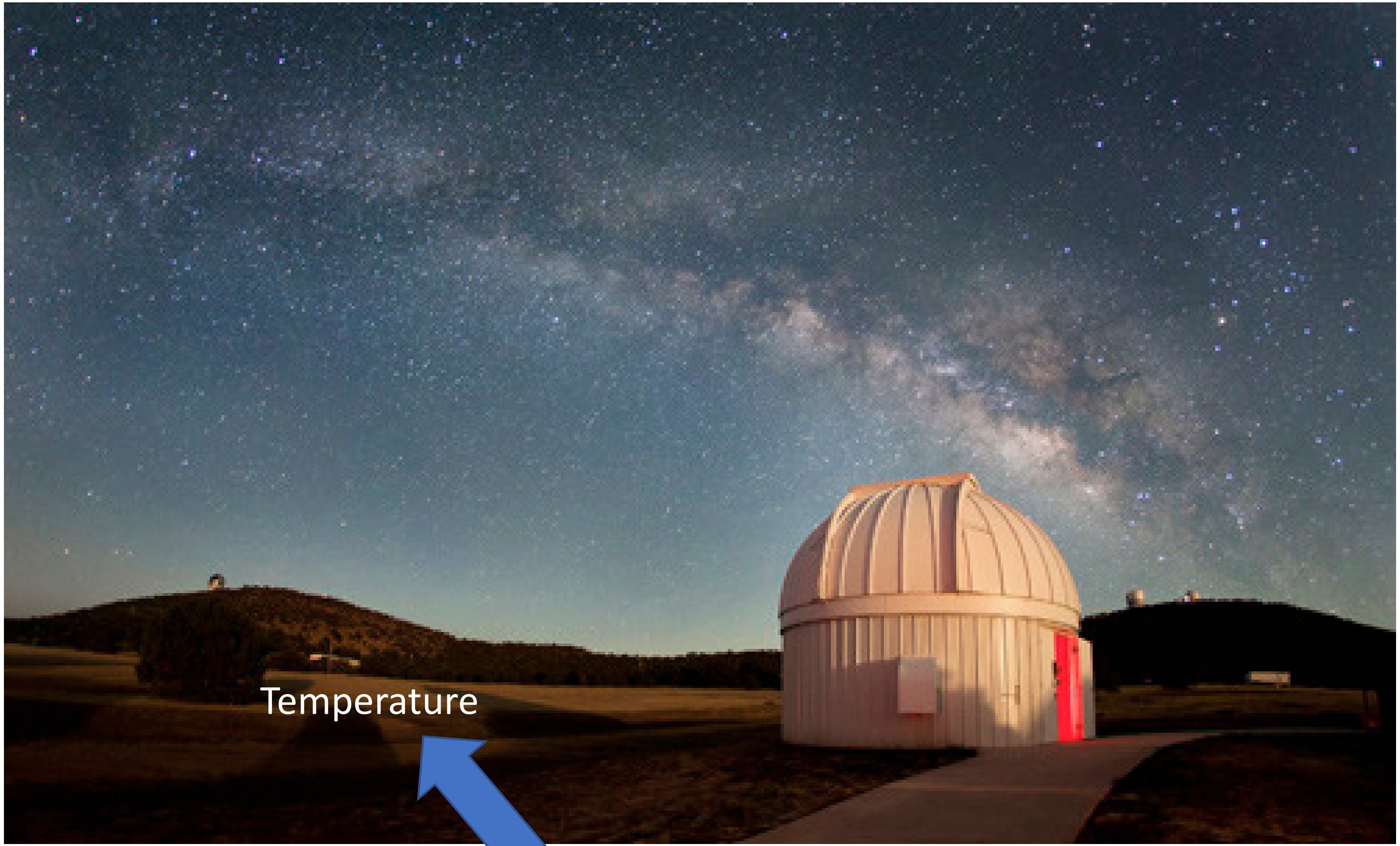
Evidence of Inaccurate Mass & Temperature Determinations


Why are some of these stars brighter than others?

Why are some of these brighter than others?

$$\mathbf{f_{Earth} \propto F_{star} \times (Radius/Dist)^2}$$

Why are some of these brighter than others?



$$f_{Earth} \propto F_{star} \times (Radius/Dist)^2$$

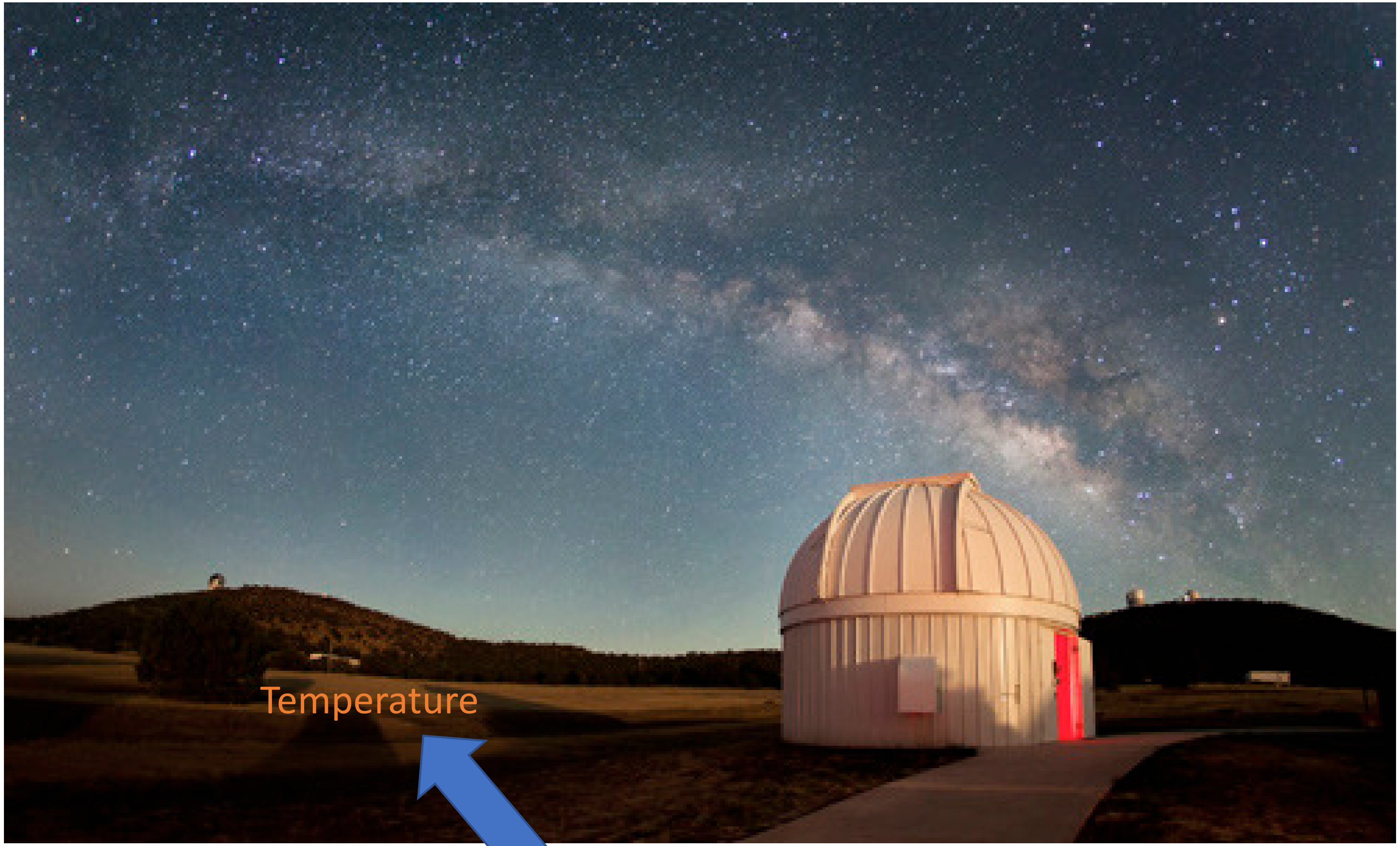
Why are some of these brighter than others?

$$f_{Earth} \propto F_{star} \times (\text{Radius}/\text{Dist})^2$$

Why are some of these brighter than others?

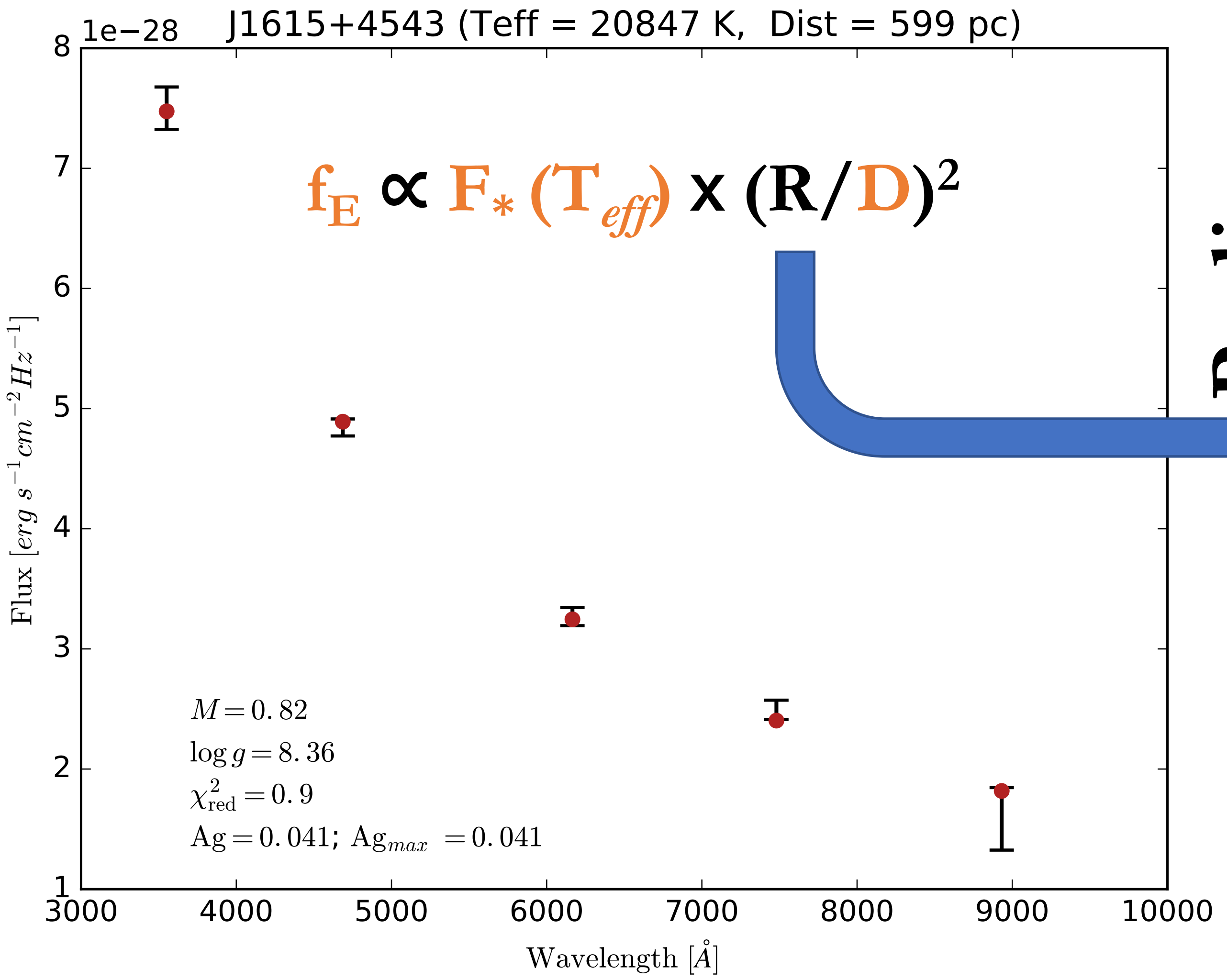
$$f_{Earth} \propto F_{star} \times (Radius/Dist)^2$$

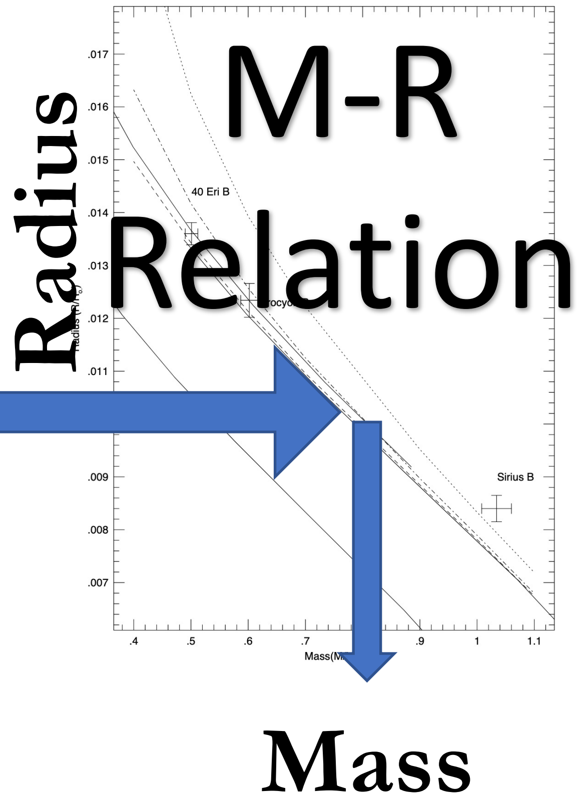
If we measure all of these, we can determine radius



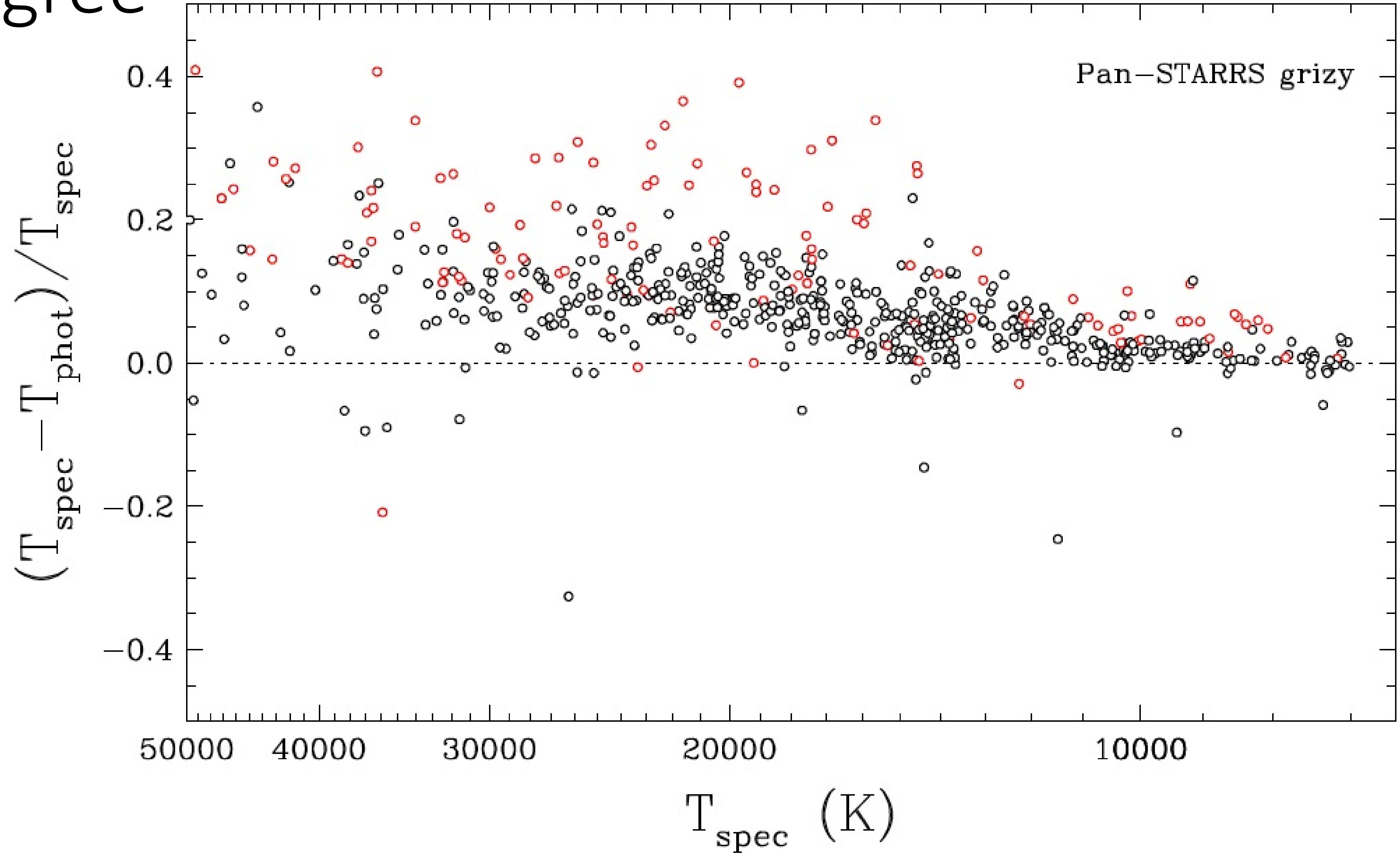
$$f_{Earth} \propto F_{star} \times (Radius/Dist)^2$$

Mass & T_{eff} from Broadband Photometry + Gaia Distances



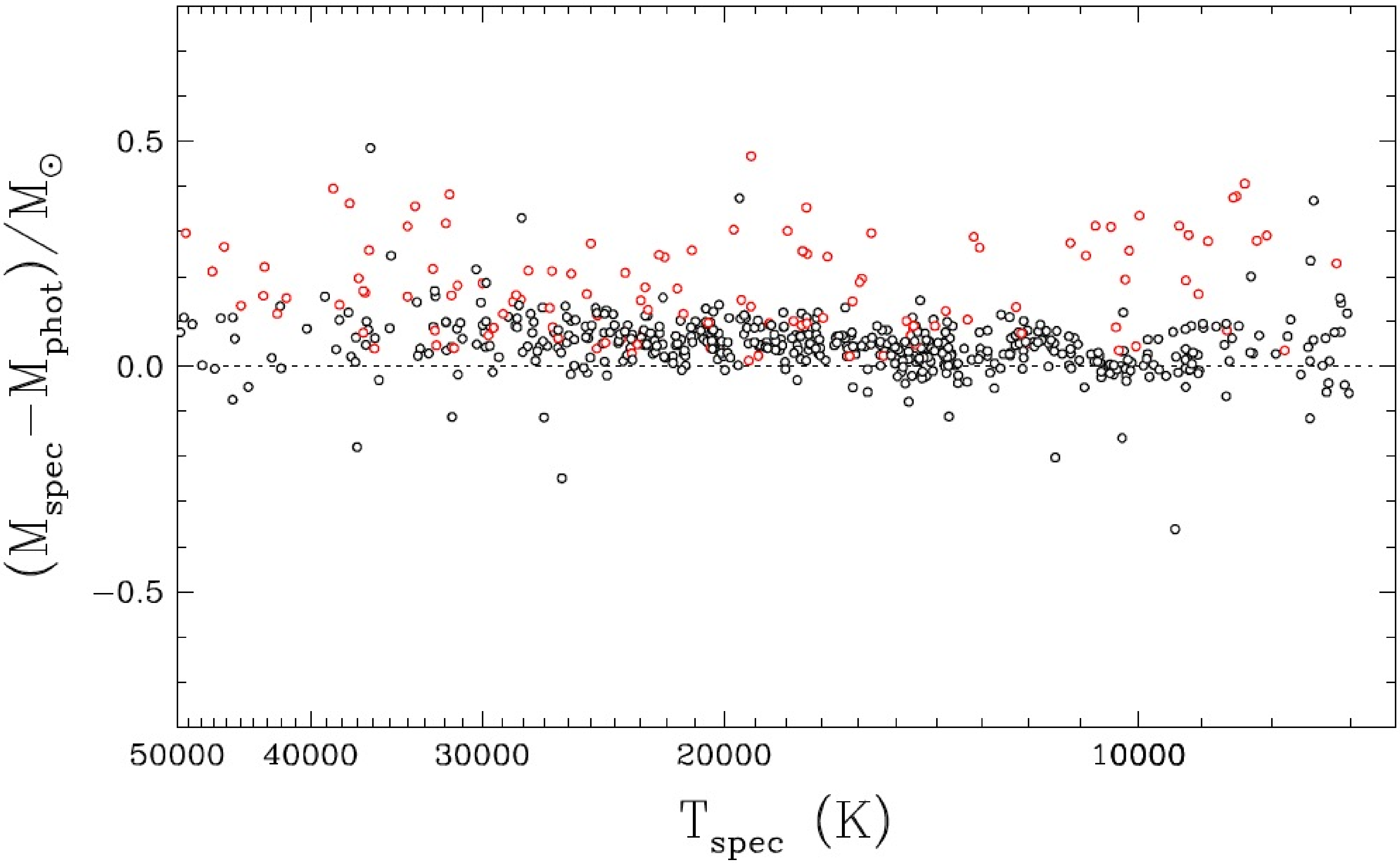


Photometric and Spectroscopic Temperatures Disagree



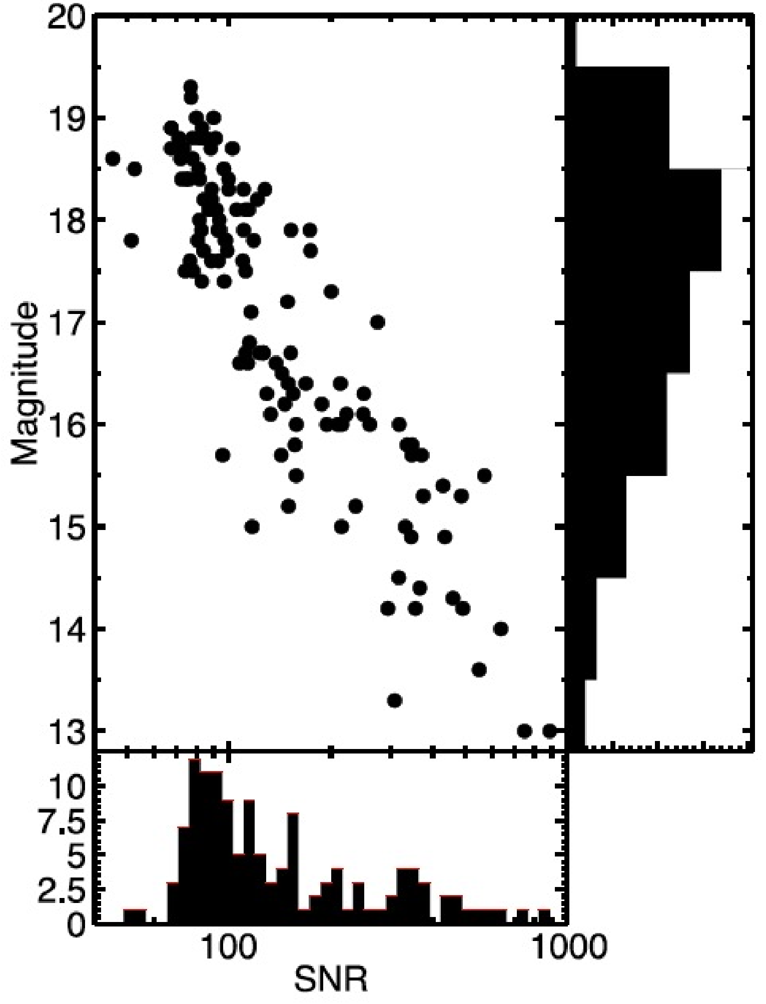
Bergeron et al. 2019

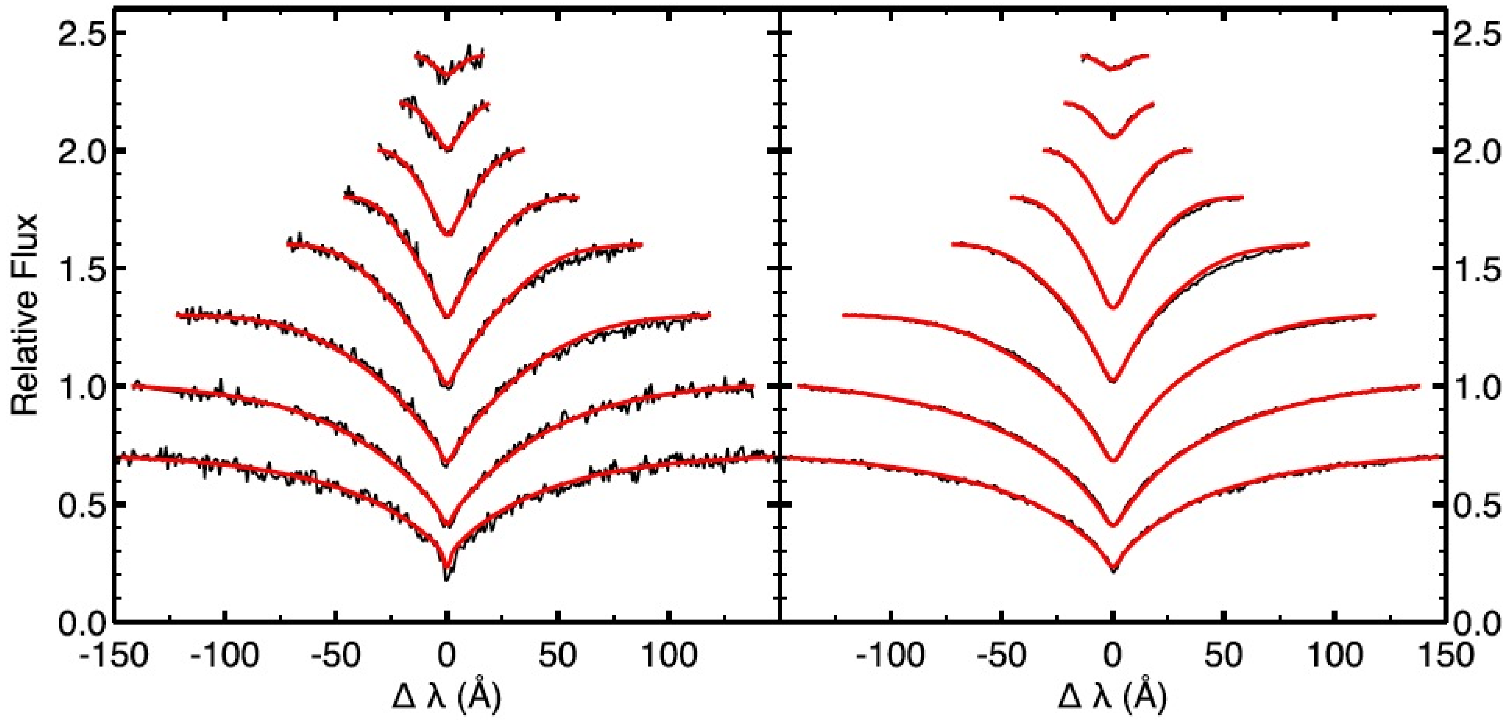
Photometric and Spectroscopic Masses Disagree



Bergeron et al. 2019

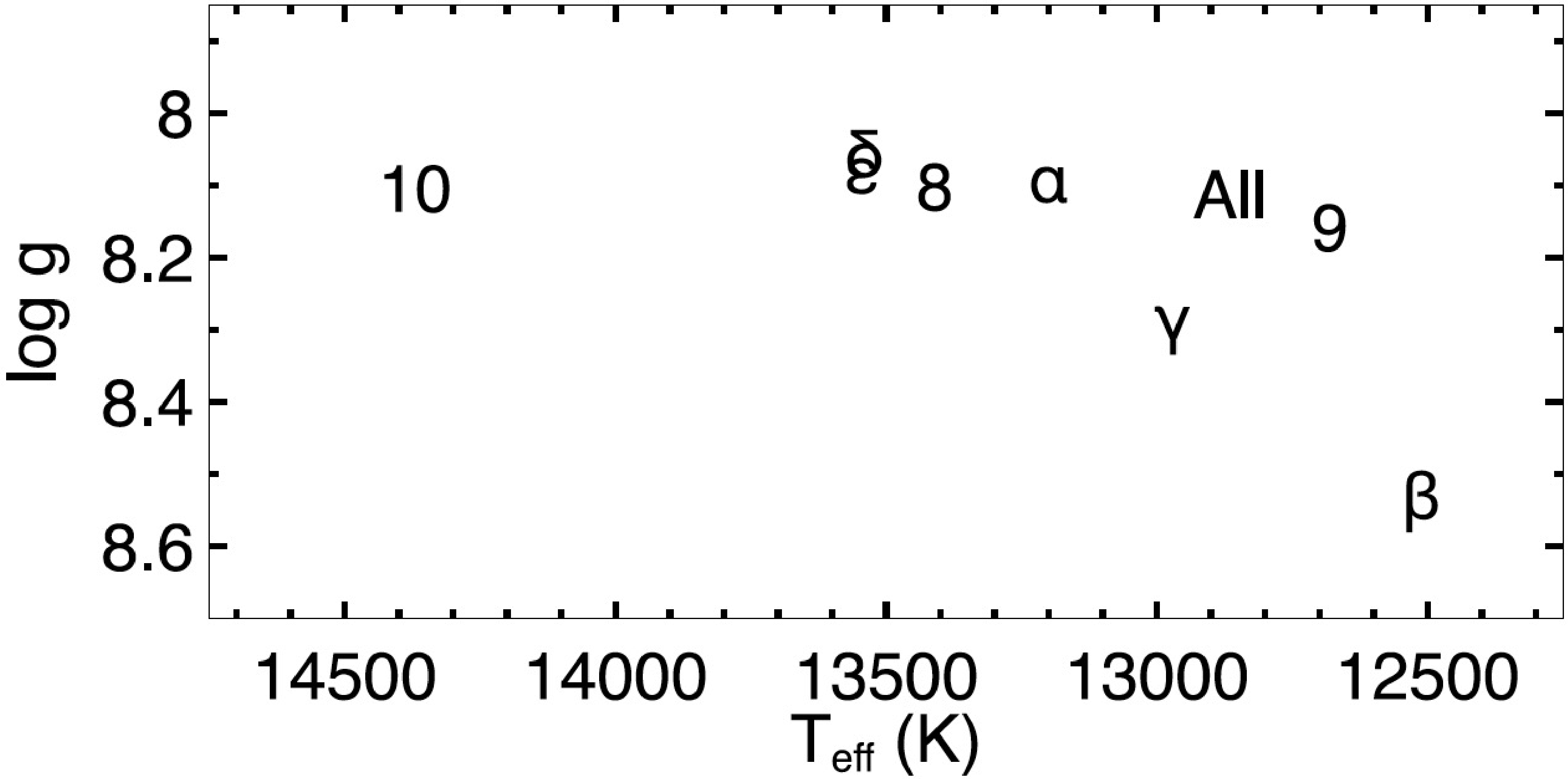
Fits to white dwarf spectral lines look pretty good, but…





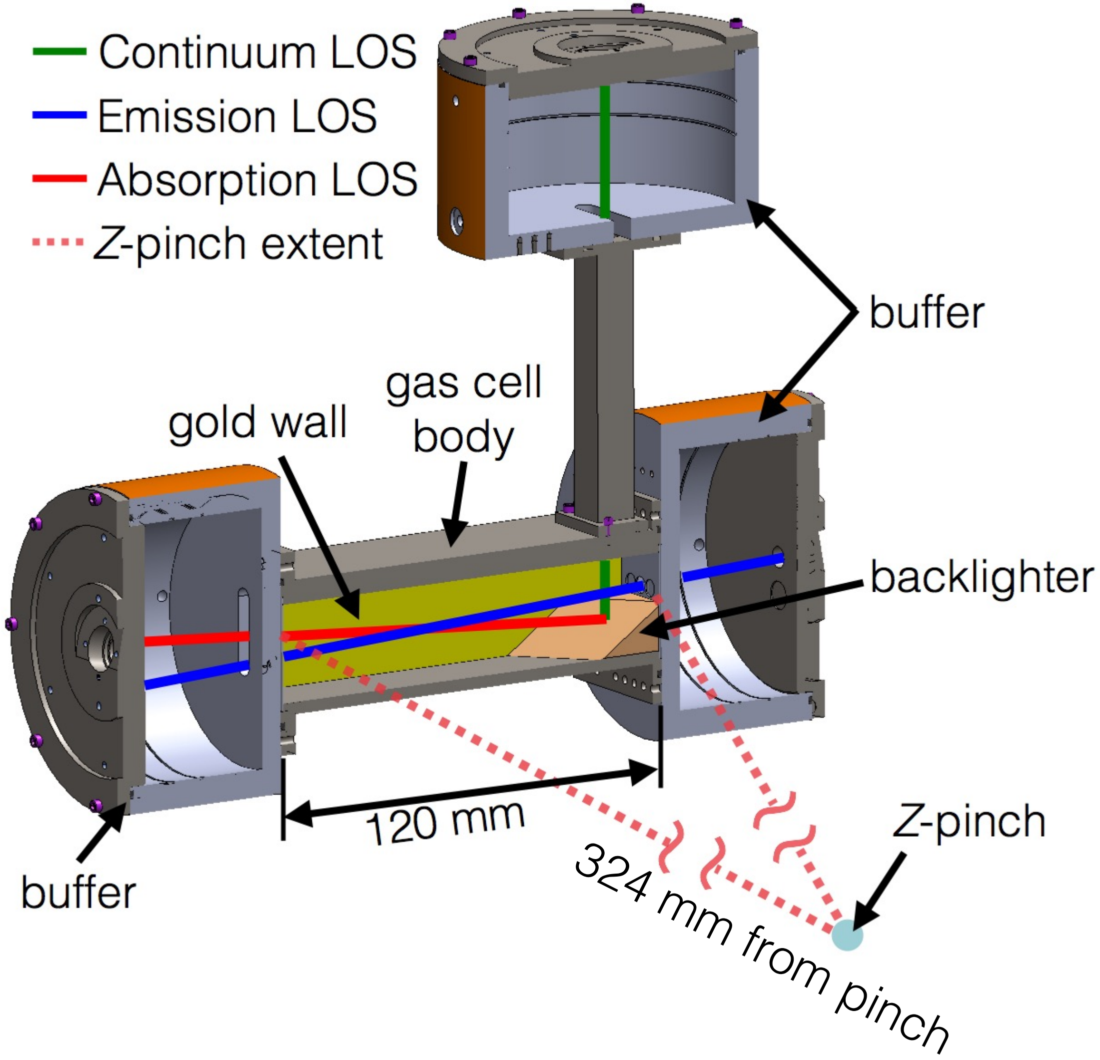
High S/N spectroscopy of 129 DAs in and around the DAV pulsational instability strip (Fuchs et al. in prep)

Individual Balmer lines give different results

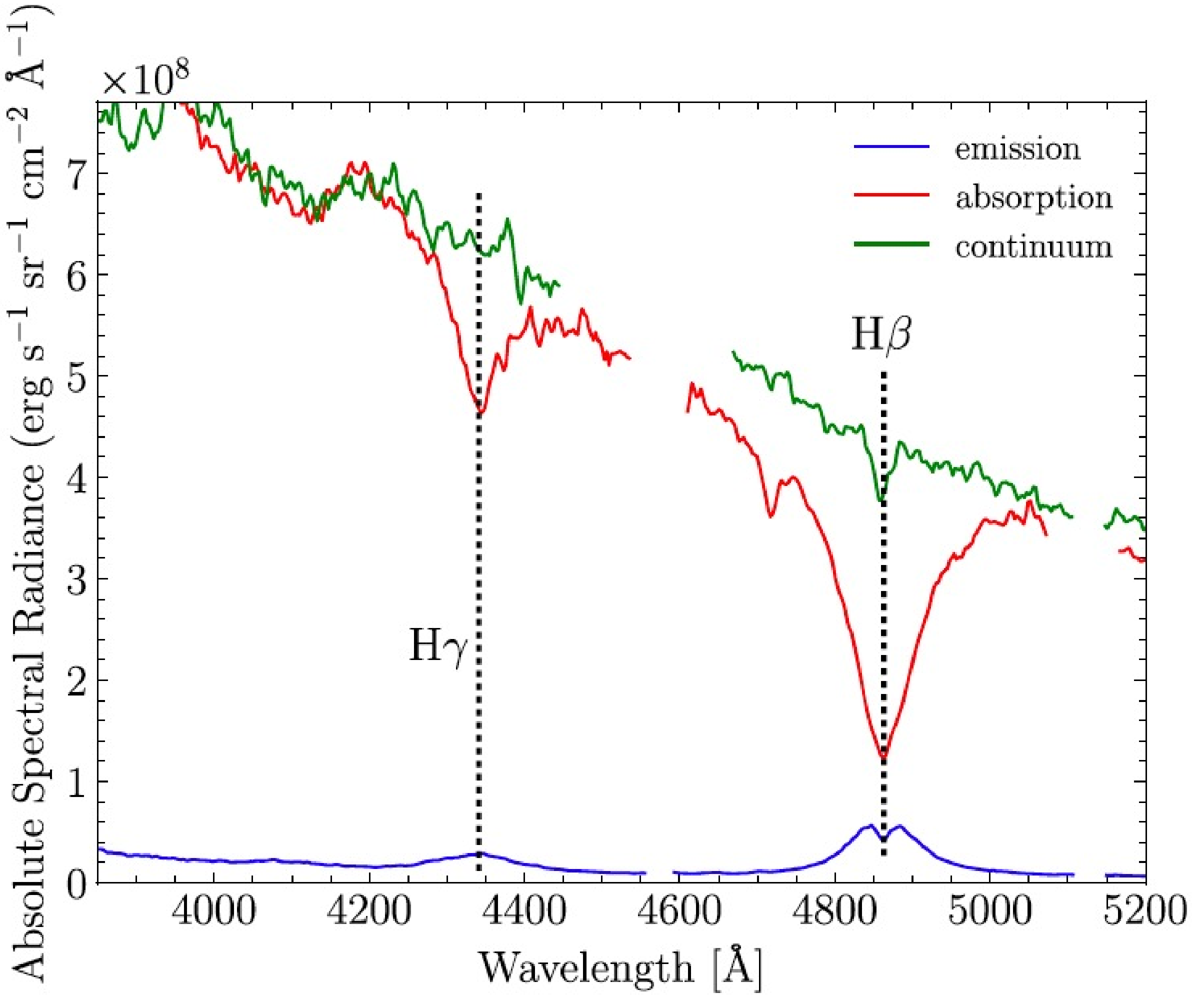


Fuchs et al.

The White Dwarf Photosphere Experiment Measures



Schaeuble et al. (2019)



Schaeuble et al. (2019)

The White Dwarf Photosphere Experiment
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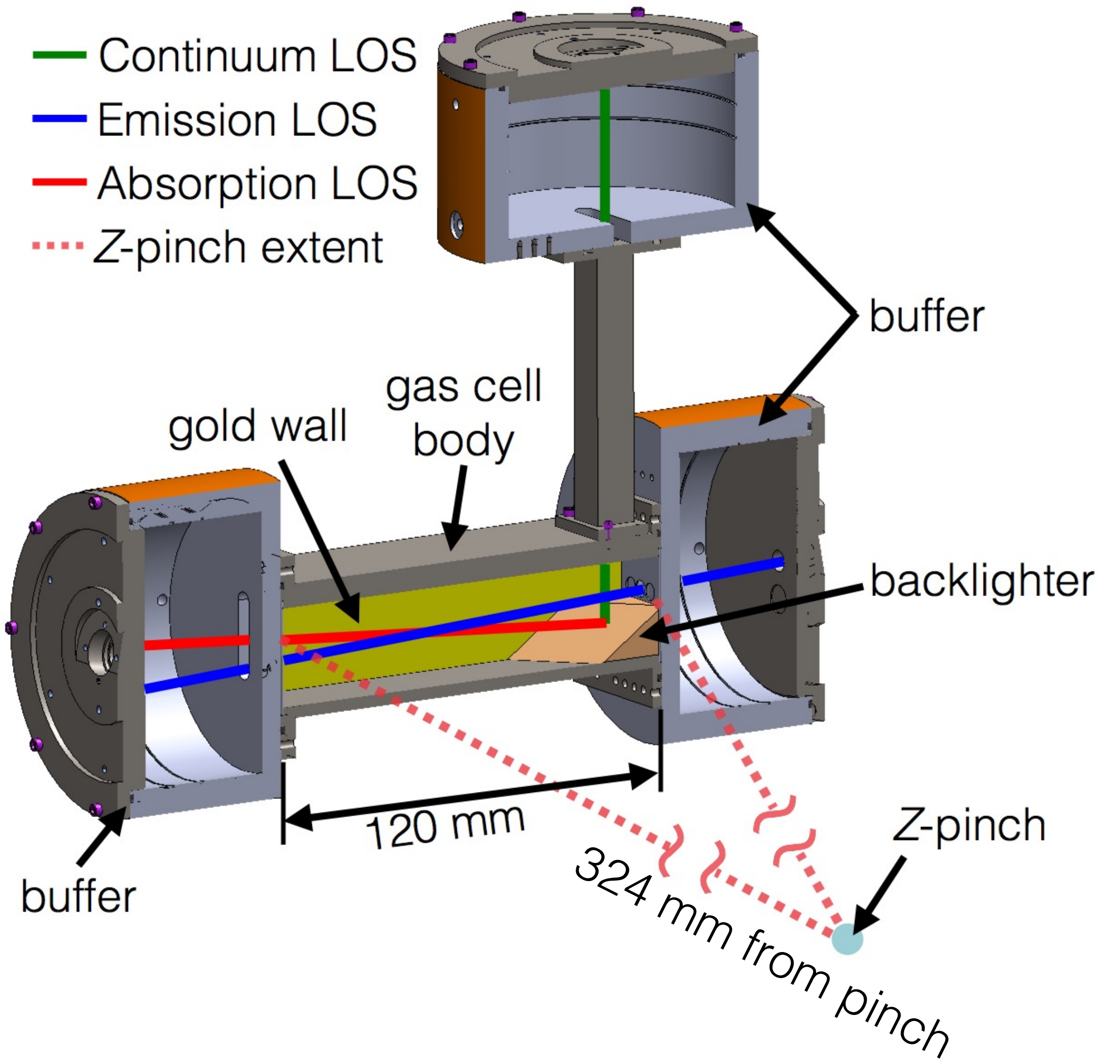
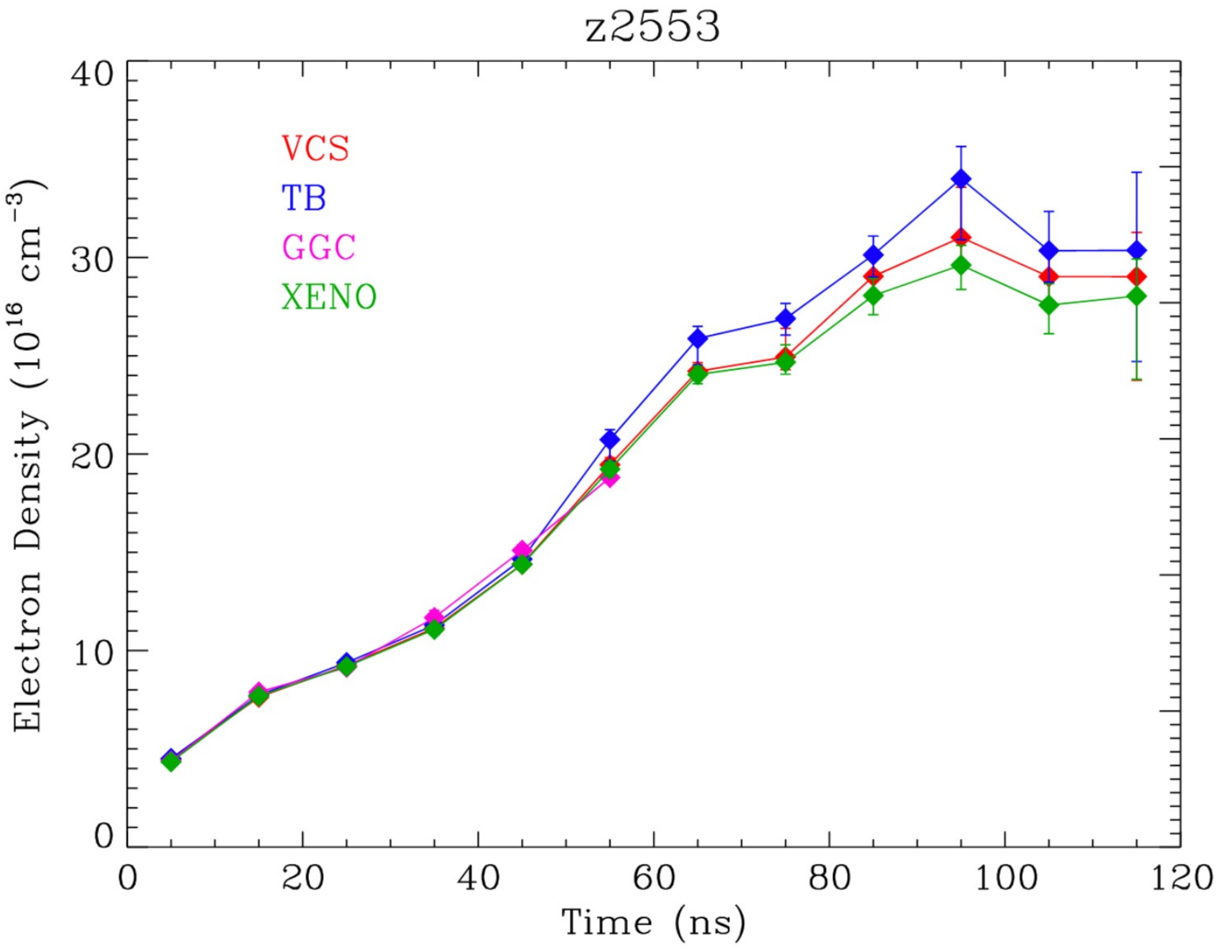


Schaeuble et al. (2019)

Across a range of n_e during each experiment.



Falcon et al. ApJ (2015)

Hydrogen data at higher densities can more easily test theories of line shapes and occupation probability

Previous data at higher densities showed larger disagreement among theories.

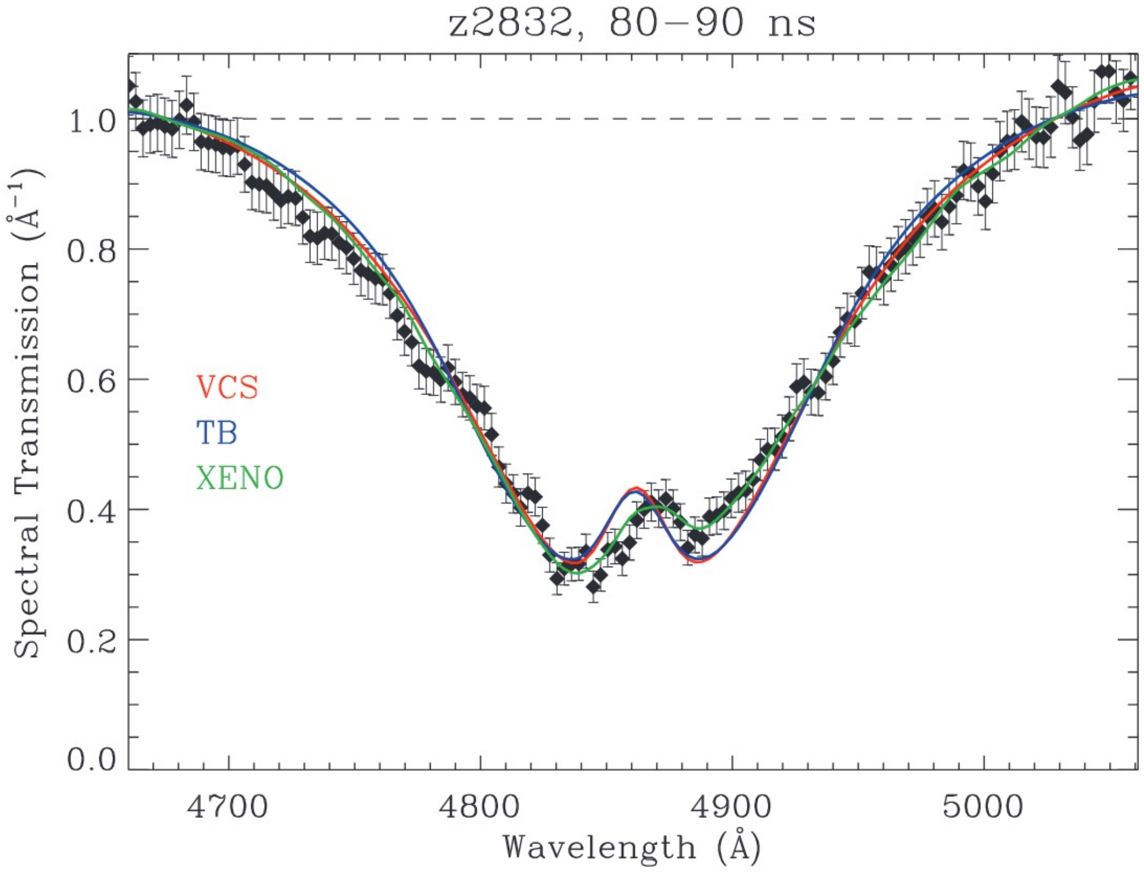


Figure 2. Measured Hβ spectral transmission at 80–90 ns during experiment z2832. We fit using different theoretical line-profile calculations (n_e ~ 83, ~ 93, and ~ 76×10^{16} cm^{-3} for VCS, TB, and XENO, respectively) and show the goodness of fit (reduced χ^2).

Falcon et al. 2017

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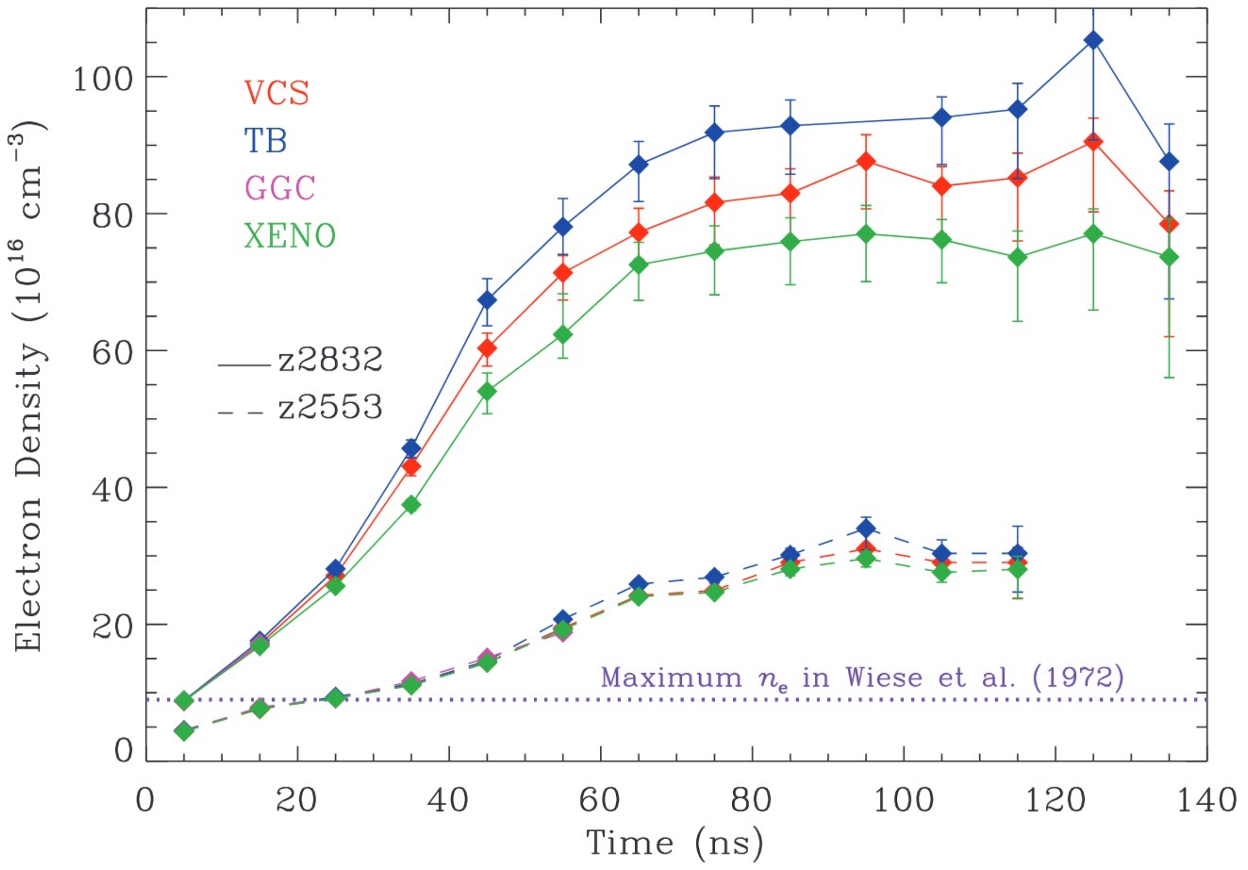
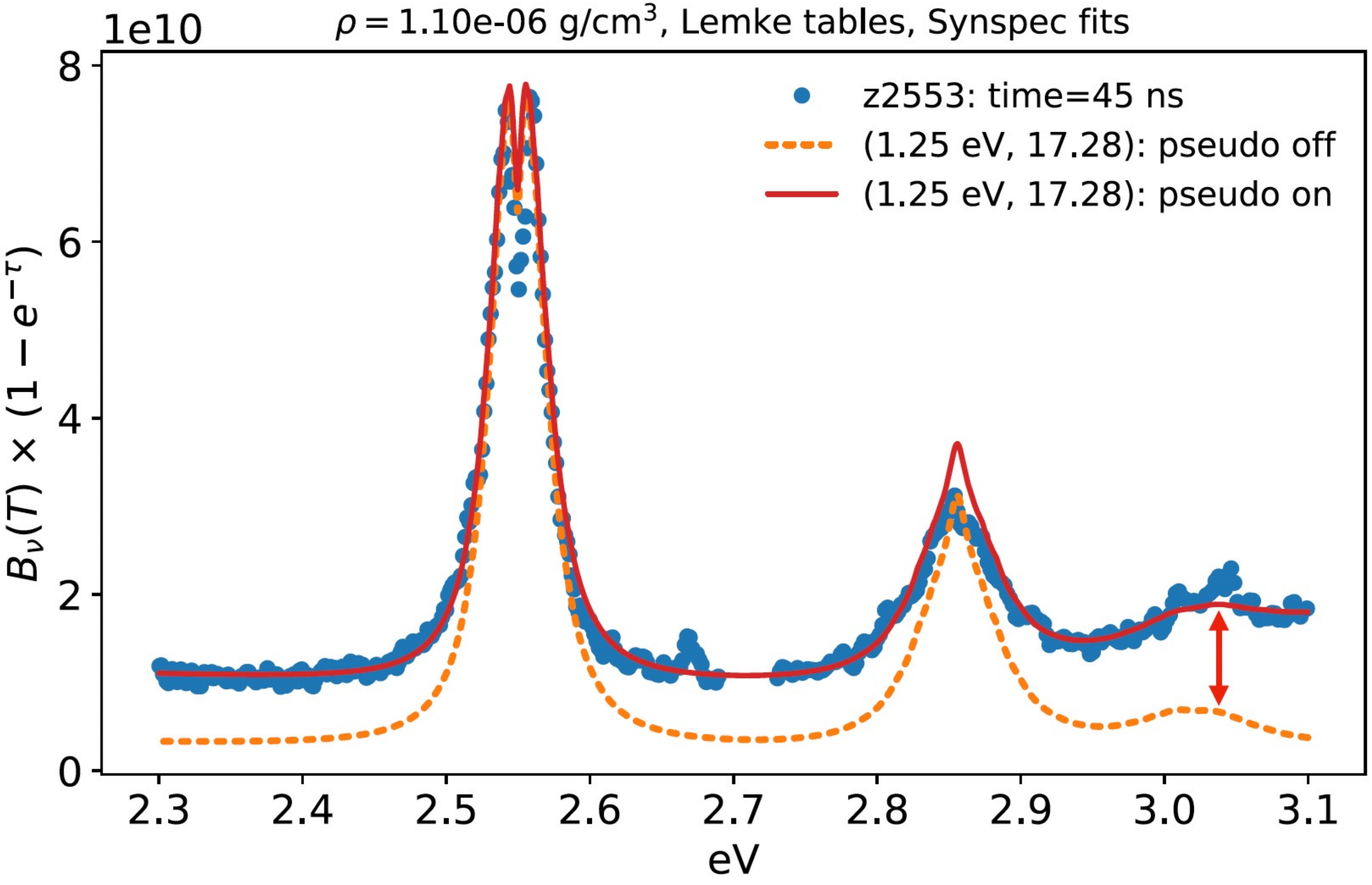


Figure 1. Electron density, n_e, as a function of time throughout our experiments z2553 and z2832. We infer n_e using different theoretical line-profile calculations.

Falcon et al. 2017

Differences in “pseudo-continuum” opacity should be more pronounced at higher n_e

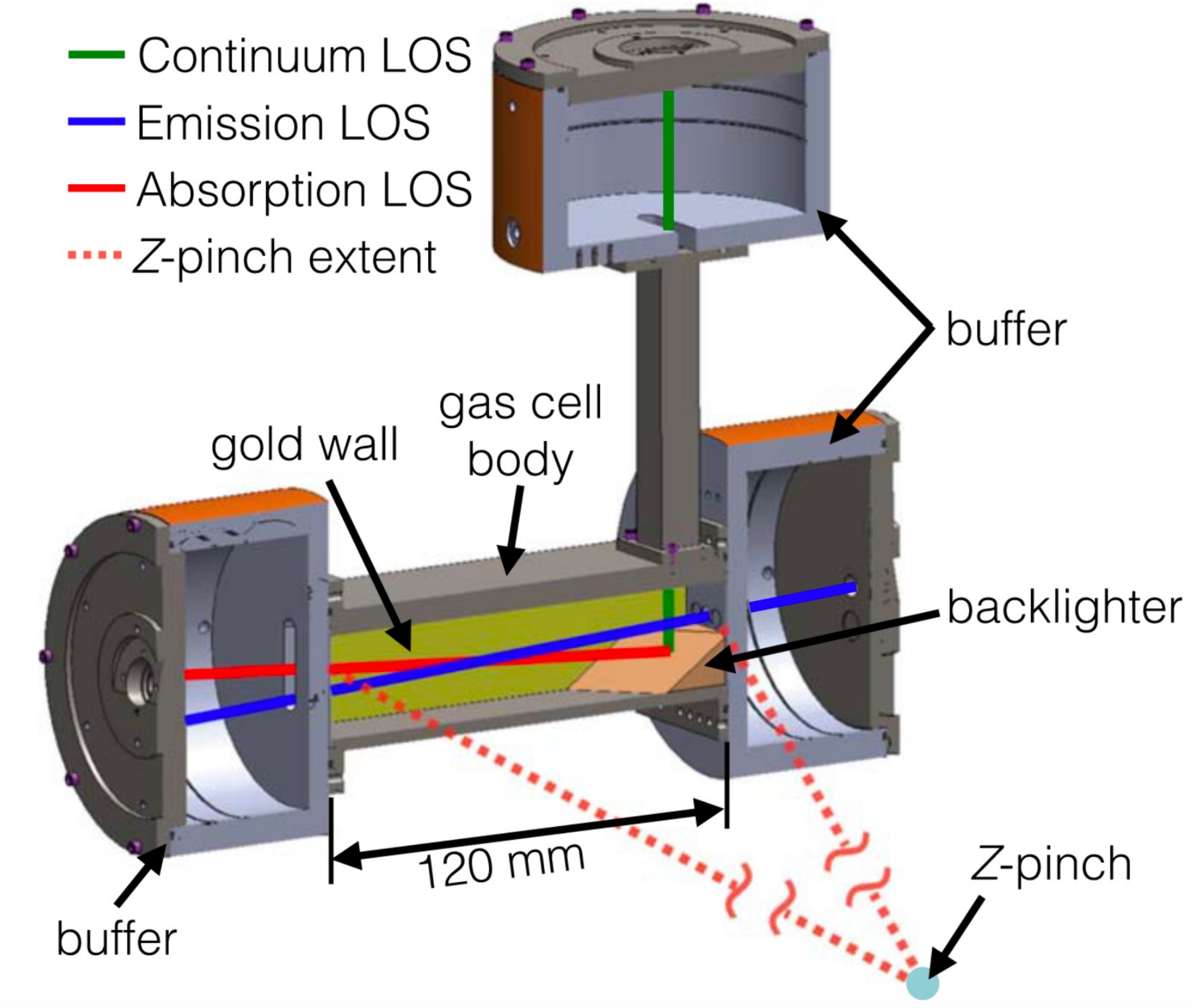


These calculations use the code *Synspec*, part of the *Tlusty* suite (Ivan Hubeny), which is used to fit the observed spectra of white dwarf stars.

Previous attempts at higher n_e had to move closer to the back wall

Previous data at higher densities showed larger disagreement among theories.

Higher fill pressure did not result in higher n_e at the 10 mm LOS.

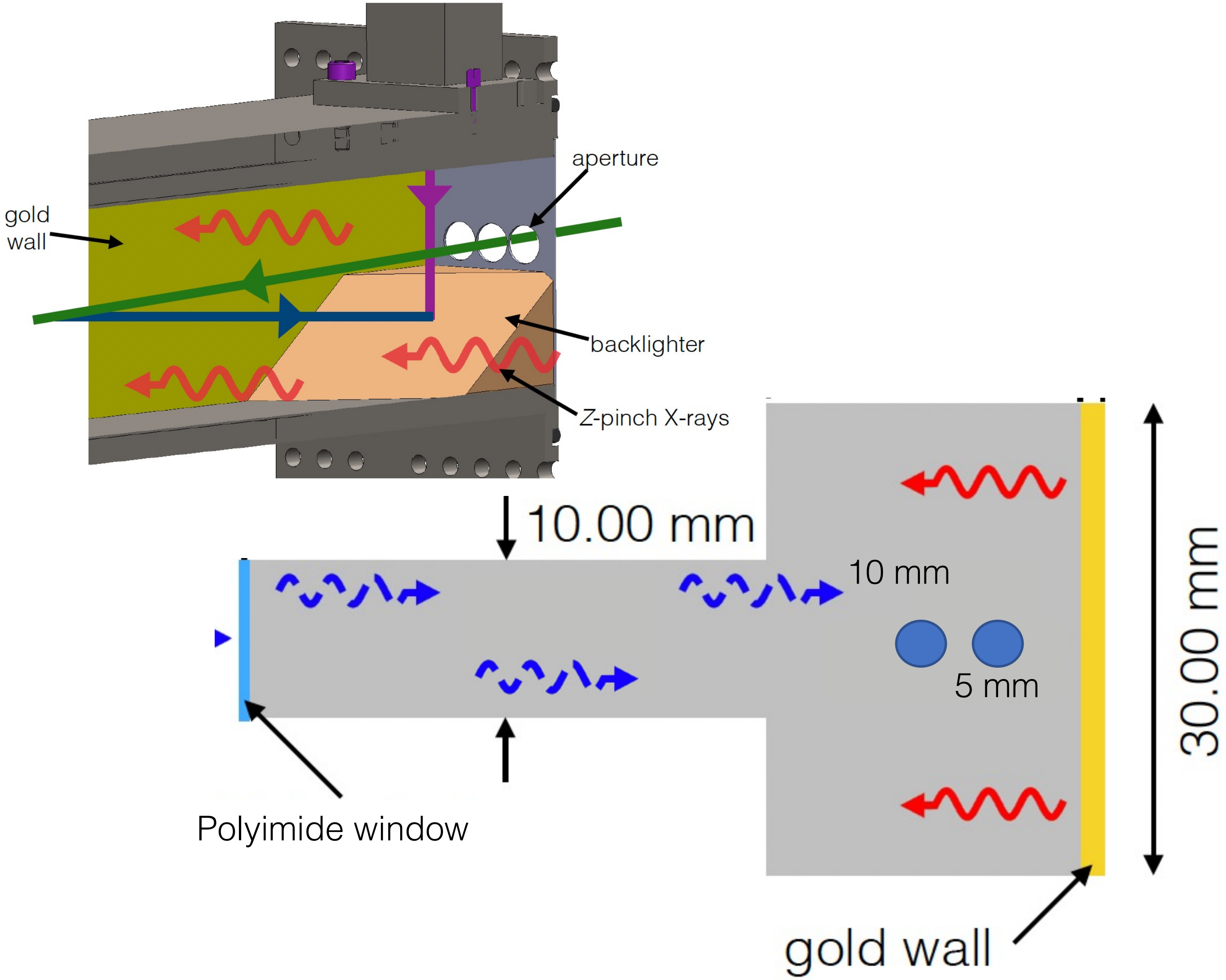


Previous attempts at higher n_e had to move closer to the back wall

Previous data at higher densities showed larger disagreement among theories.

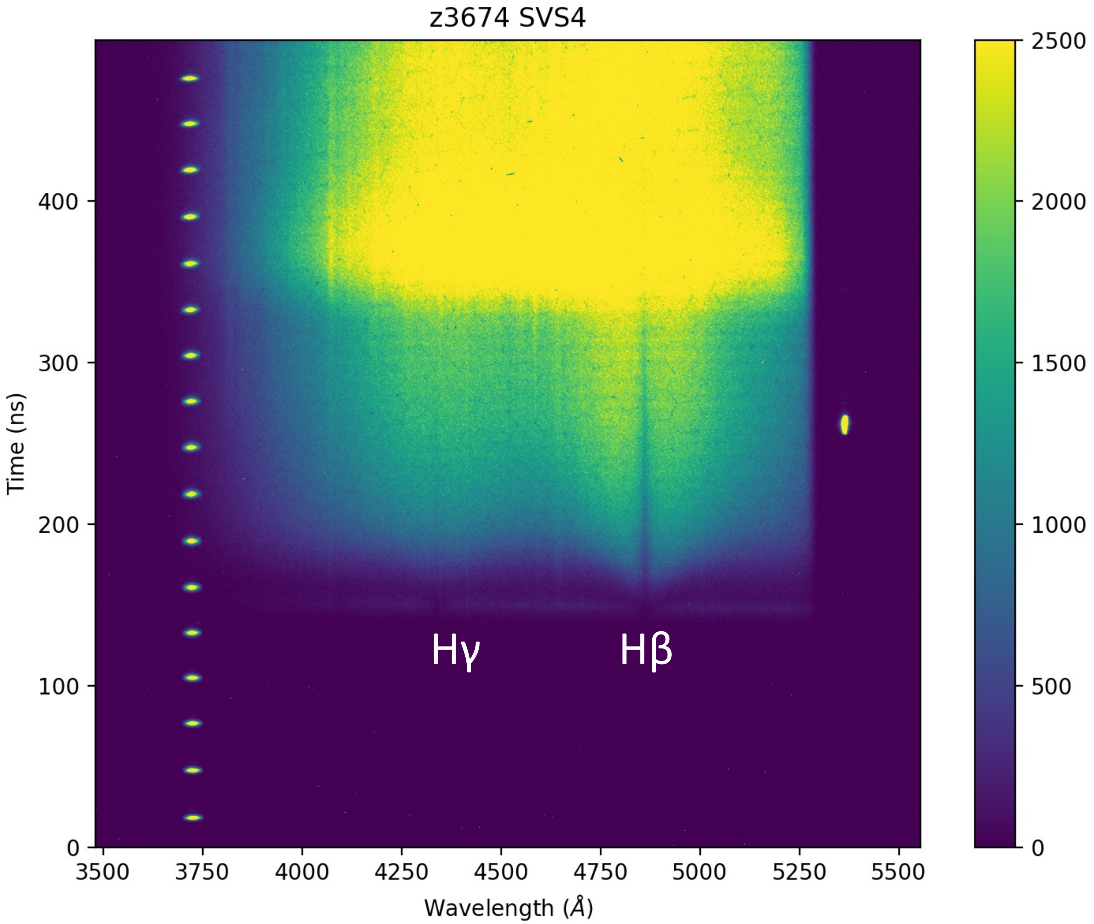
Higher fill pressure did not result in higher n_e at the 10 mm LOS.

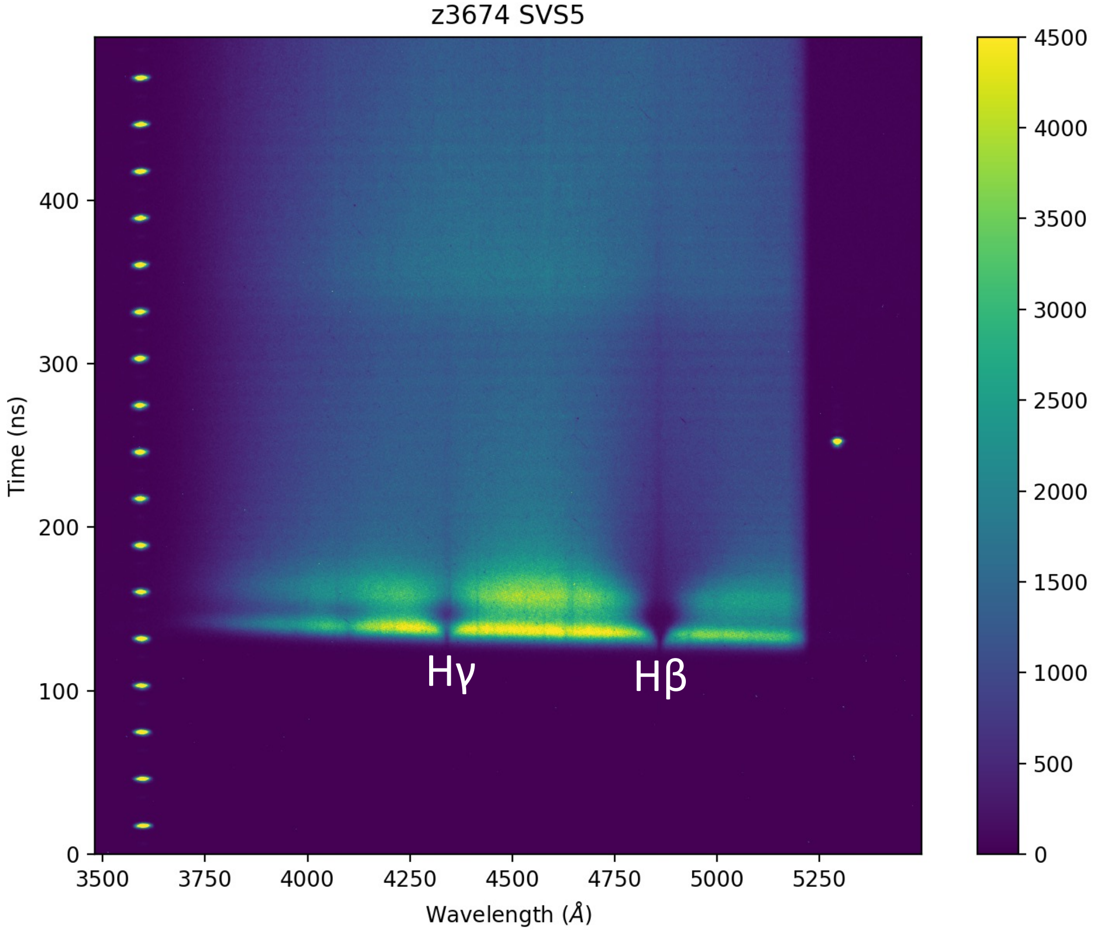
Data had to be taken at the 5 mm line of sight, where **gradients across the beam are larger**.



Achieved higher n_e in H at 10 mm line of sight

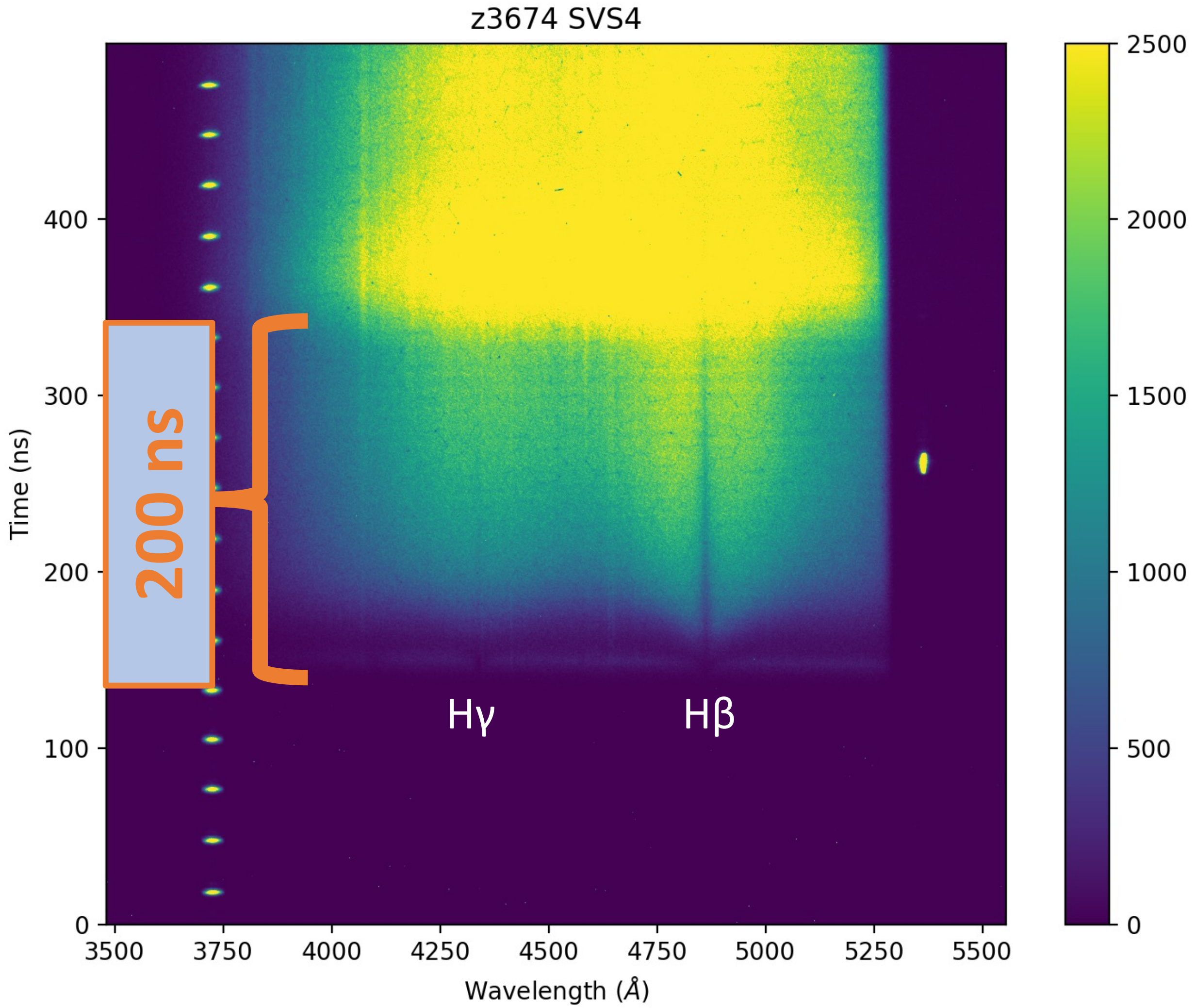
Increased pressure (from 10 Torr to 25 Torr) **and**
Decreased window thickness (from 1.4 µm to 0.7 µm)

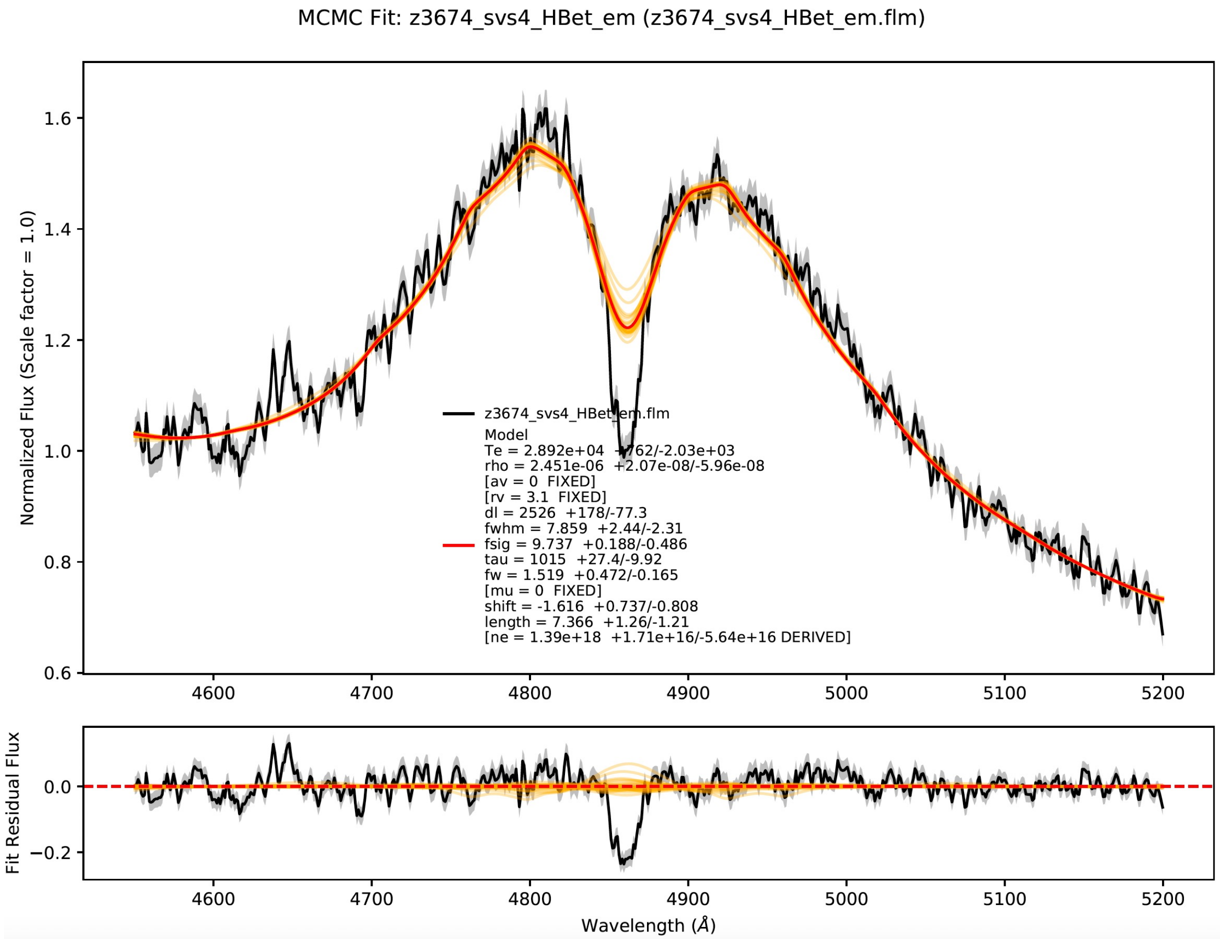




Fits to Hβ suggest $n_e > 10^{18}$ cm^{-3}

Hitting upper bounds of our current model grid.
Cf. our typical $n_e \sim 5 \times 10^{16} – 3 \times 10^{17}$.



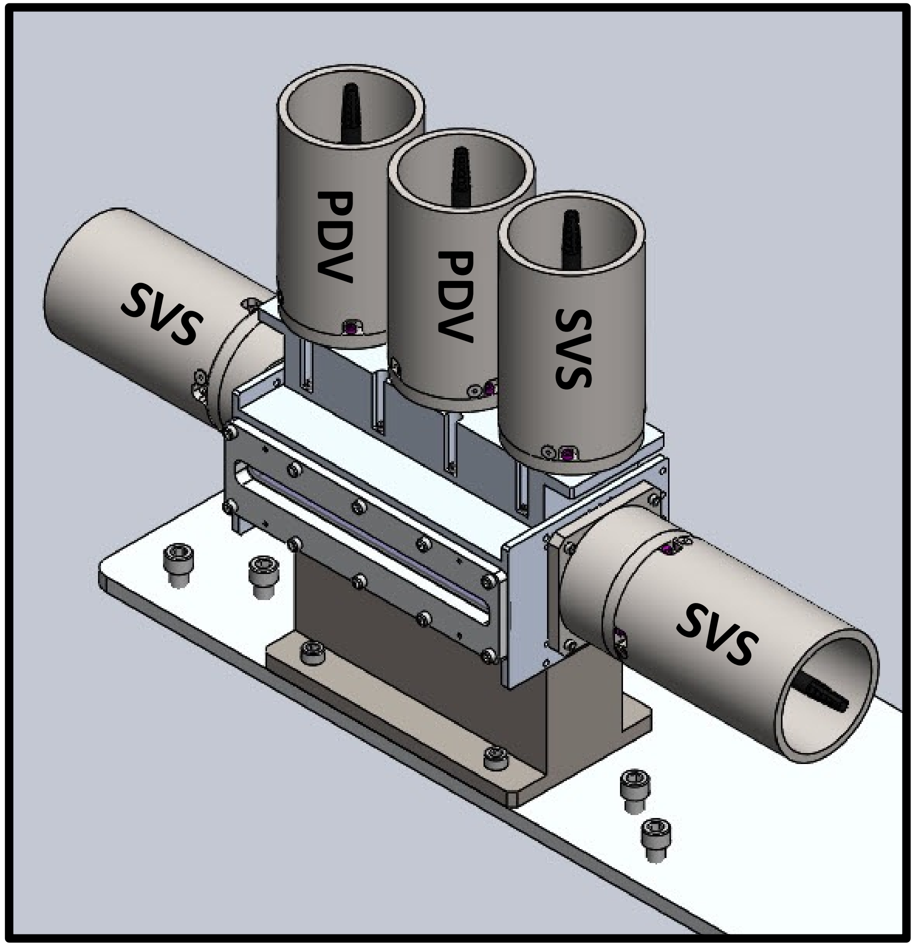


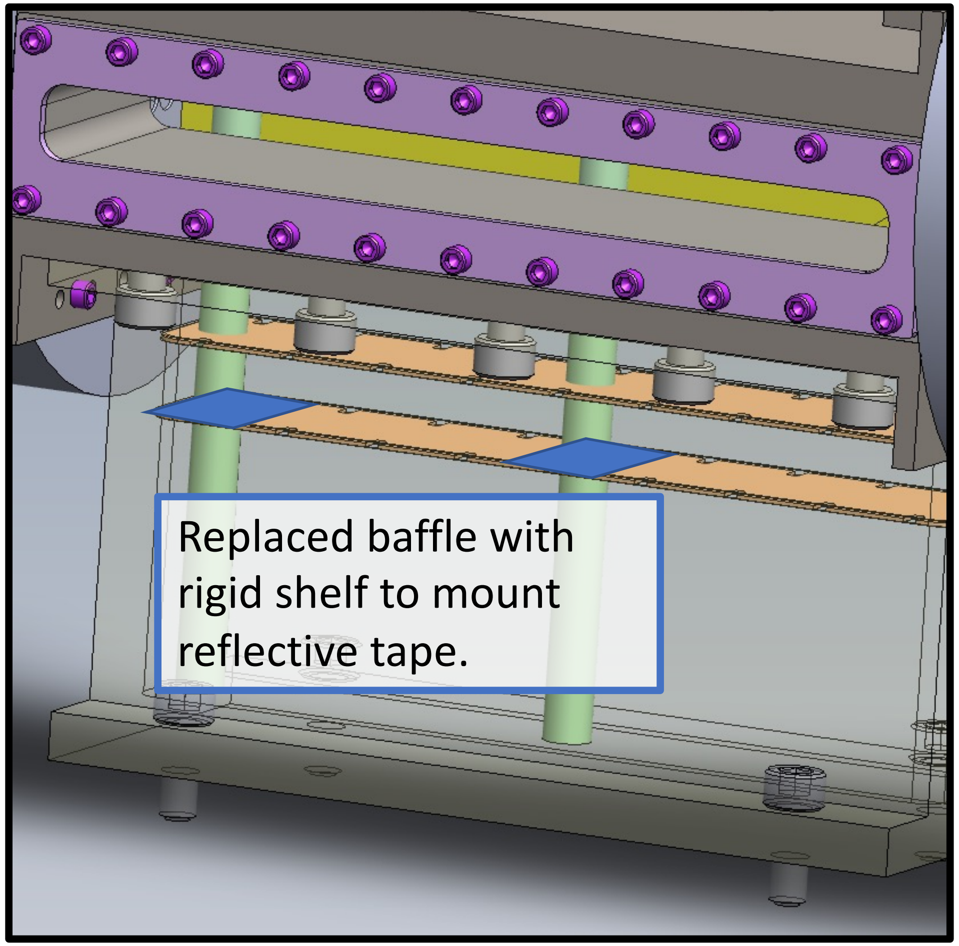
An independent n_e diagnostic is important

- We don’t want to have to rely on theoretical Hβ lineshapes
- This is especially important at higher densities
- We don’t always have Hβ
  - Carbon and C/O experiments
  - Pure He experiments
  - Wavelength range

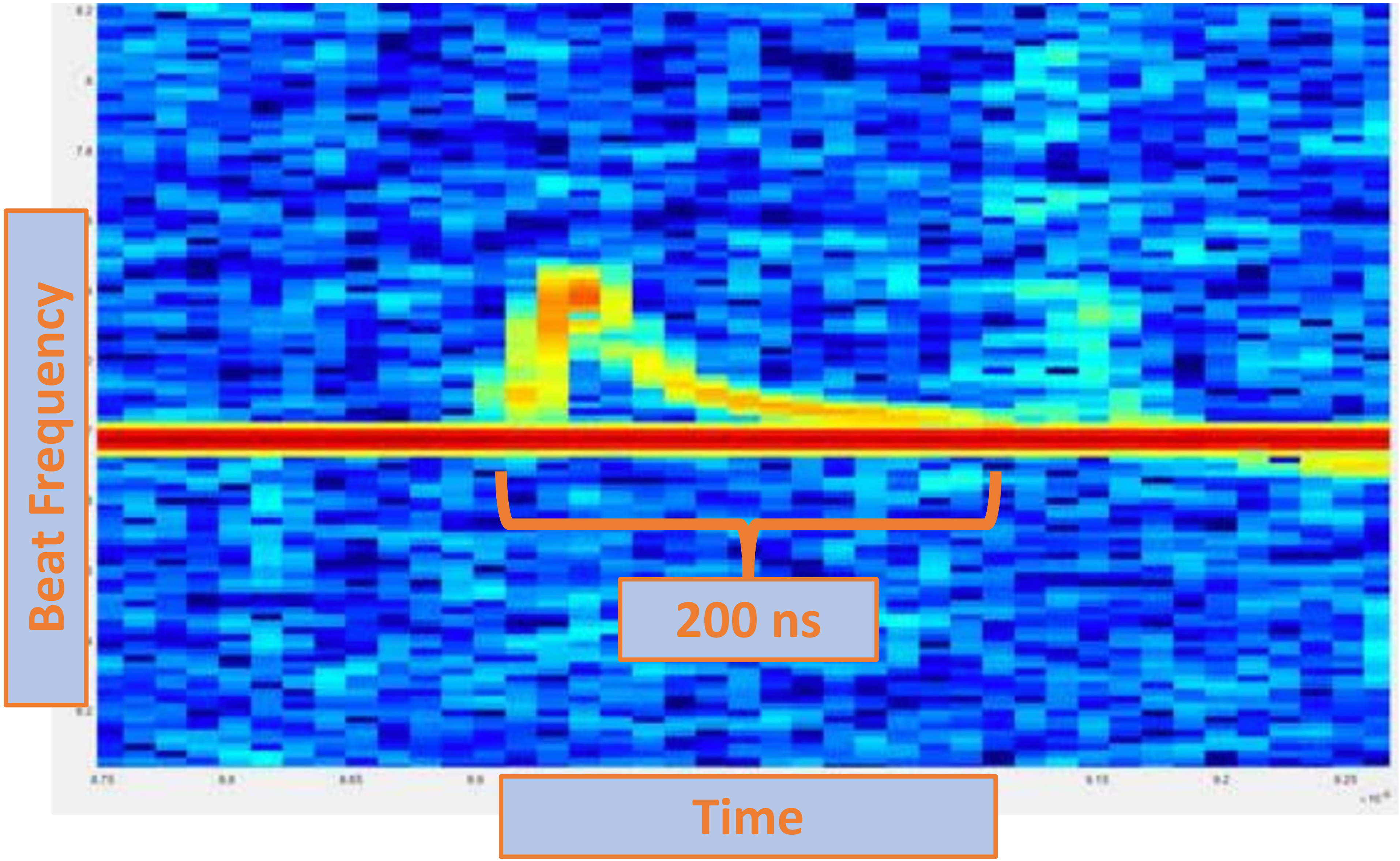
Photonic Doppler Velocimetry (PDV) provides an independent measure of n_e

PDV is sensitive to changes in the index of refraction.
The index of refraction changes as n_e changes.





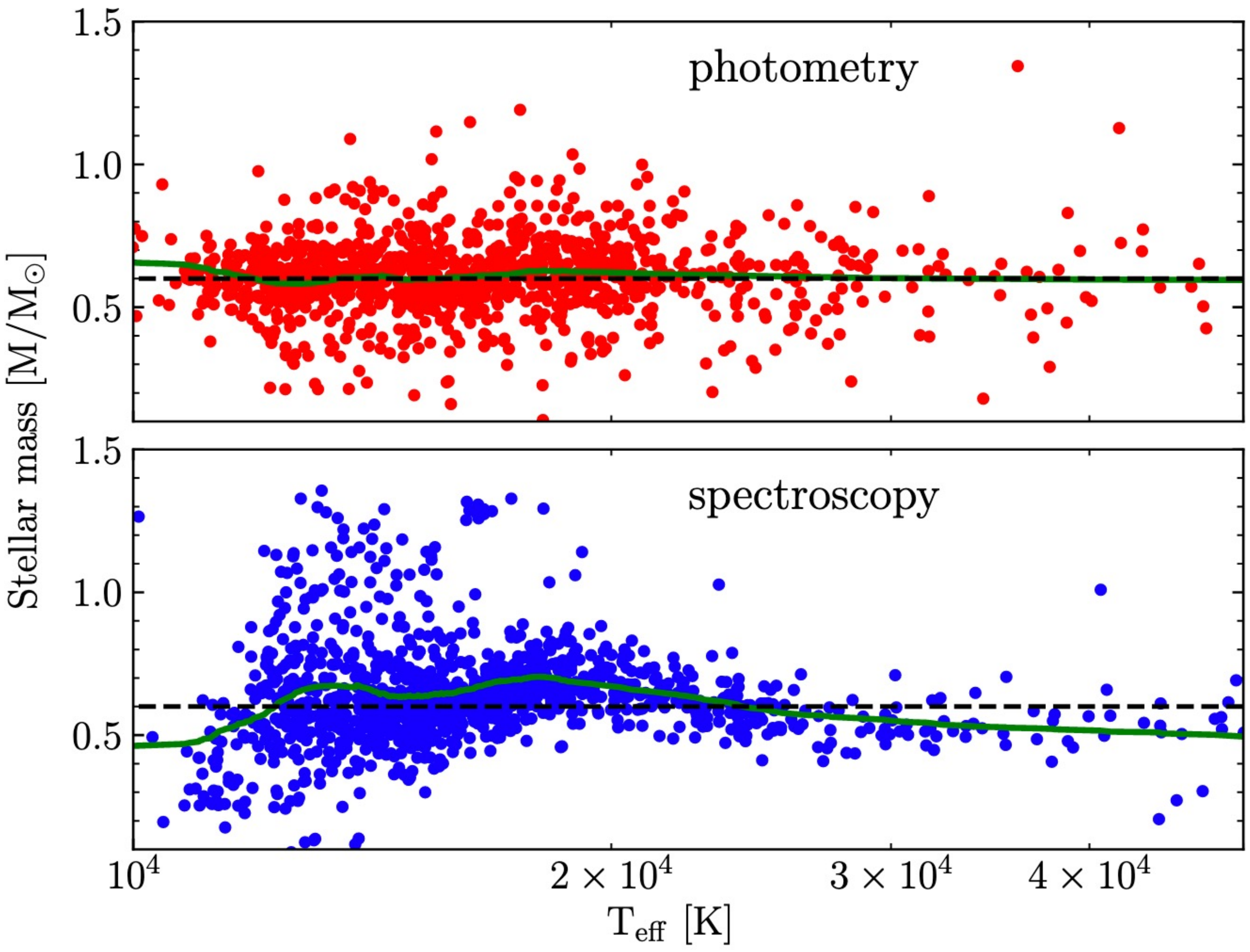
Acquired first PDV results last week (z3721)



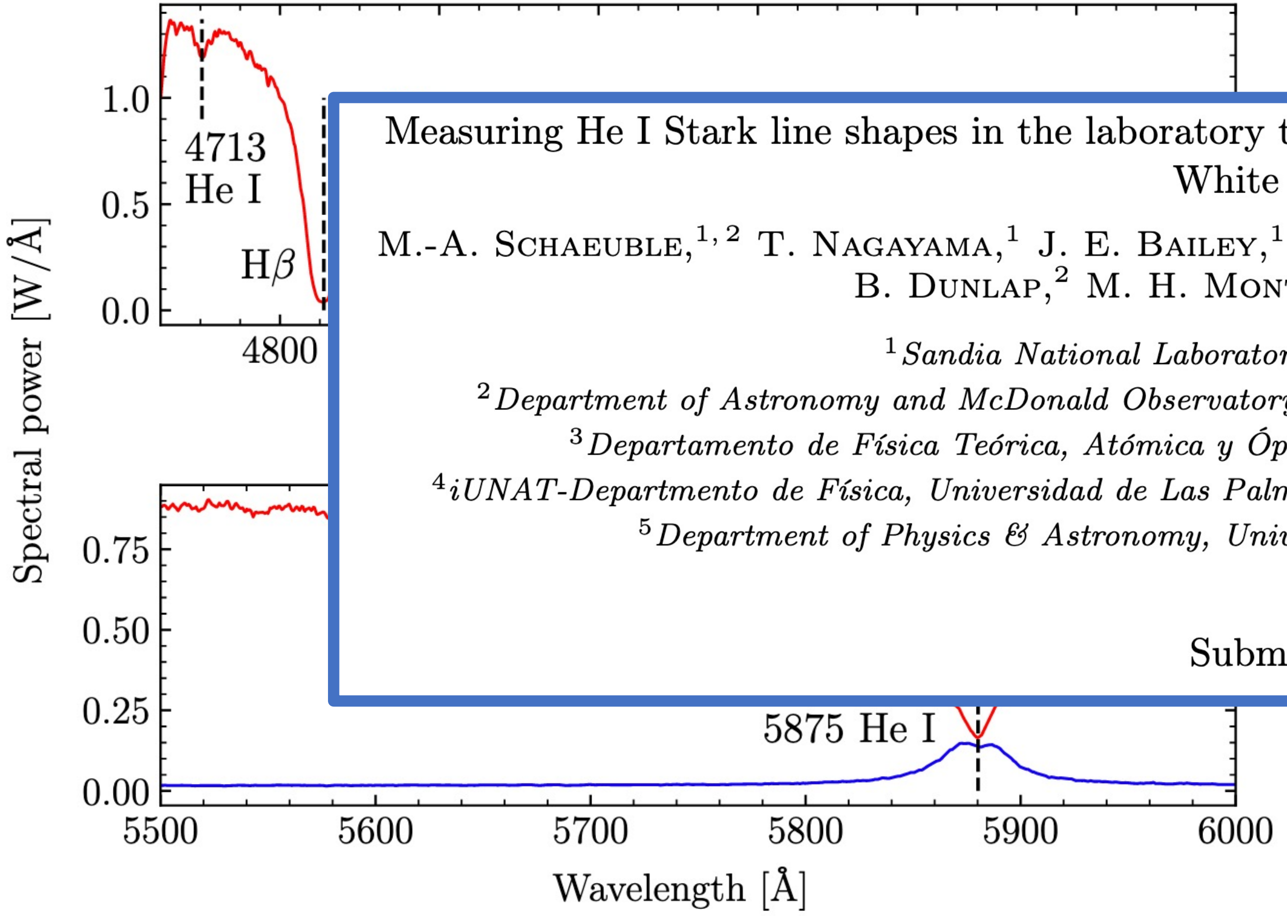
Thank you:
Chris Delacruz
Tom Avila
Kyle Swanson
Georges Jaar
Dan Dolan

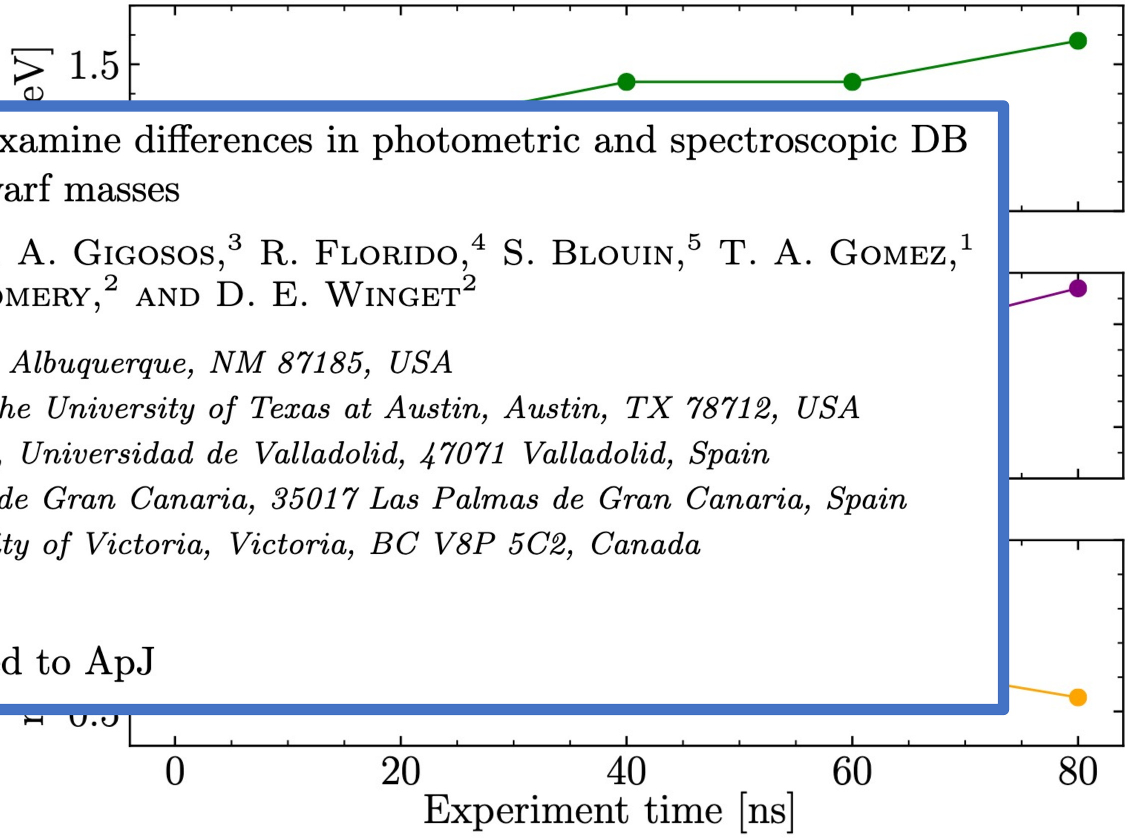
Helium Results

Helium atmosphere (DB) white dwarfs also show problems with spectroscopic mass



Measuring Helium lines with the WDPE on Z





Measuring He I Stark line shapes in the laboratory to examine differences in photometric and spectroscopic DB White Dwarf masses

M.-A. Schaeuble,[1,2] T. Nagayama,[1] J. E. Bailey,[1] M. A. Gigosos,[3] R. Florido,[4] S. Blouin,[5] T. A. Gomez,[1] B. Dunlap,[2] M. H. Montgomery,[2] and D. E. Winget[2]

[1] *Sandia National Laboratories, Albuquerque, NM 87185, USA*

[2] *Department of Astronomy and McDonald Observatory, The University of Texas at Austin, Austin, TX 78712, USA*

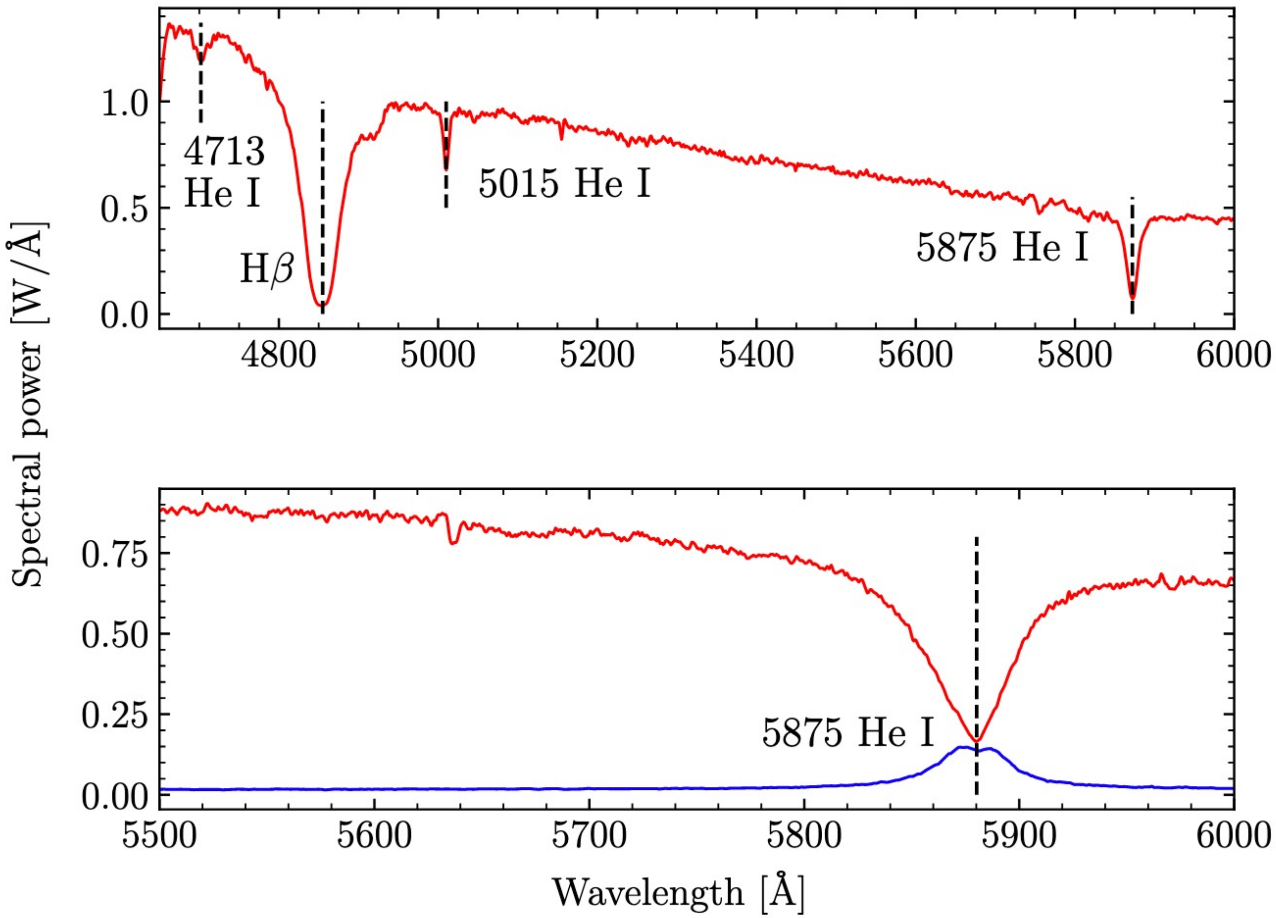
[3] *Departamento de Física Teórica, Atómica y Óptica, Universidad de Valladolid, 47071 Valladolid, Spain*

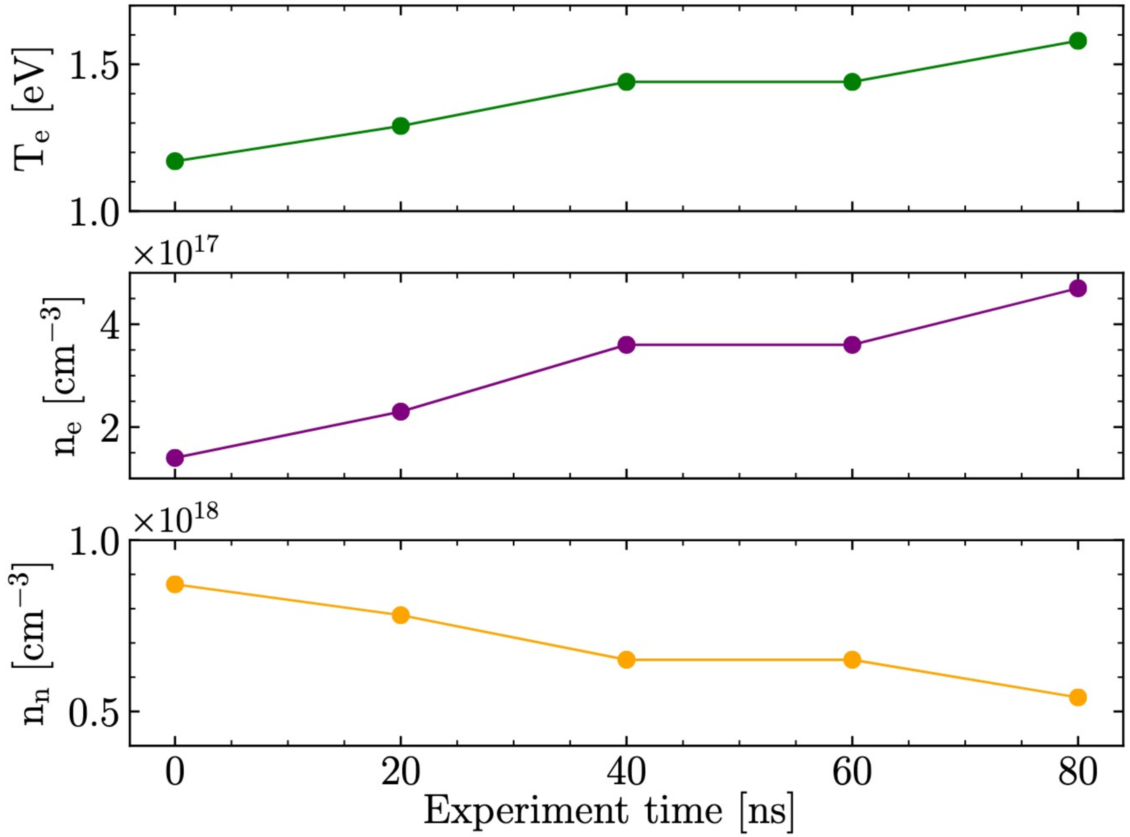
[4] *iUNAT-Departmento de Física, Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain*

[5] *Department of Physics & Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*

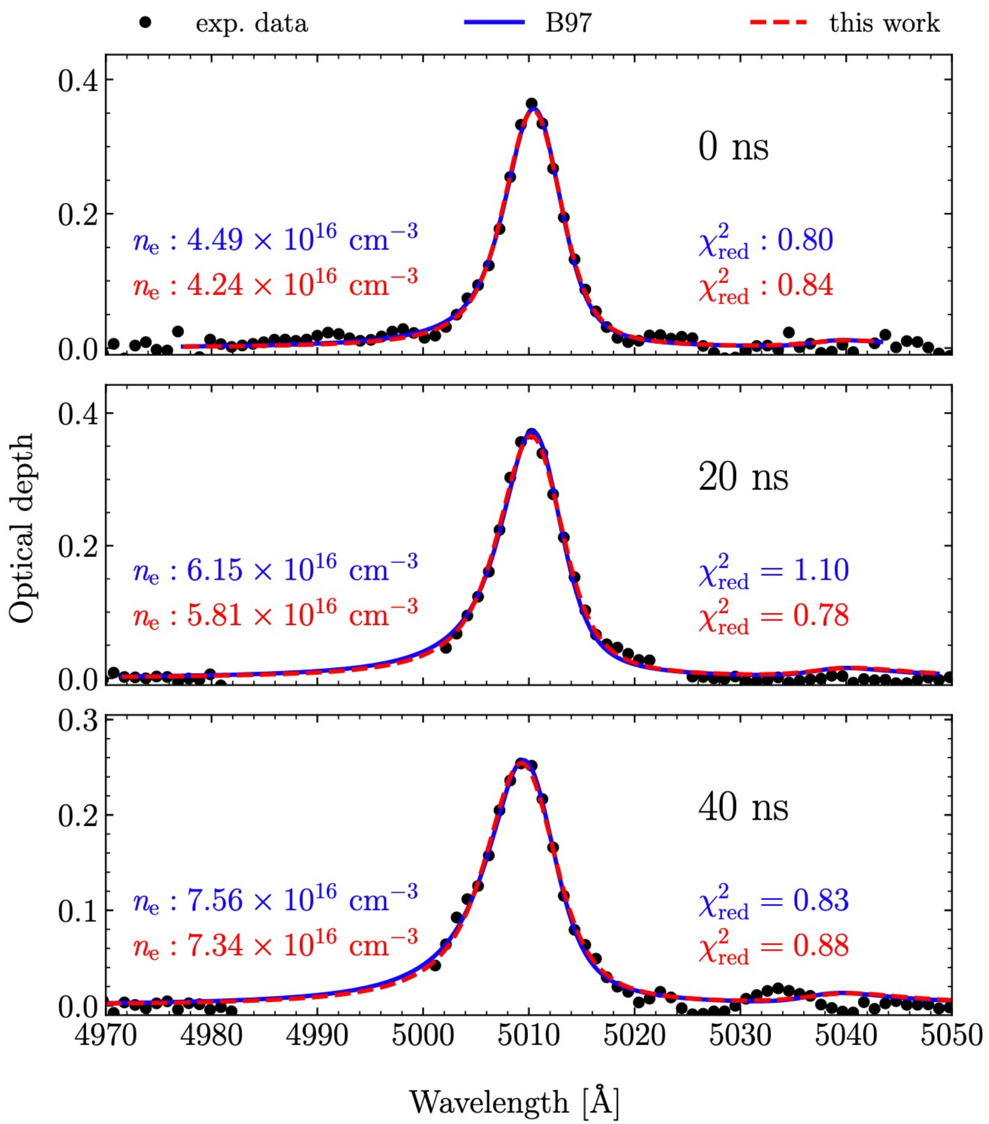
Submitted to ApJ

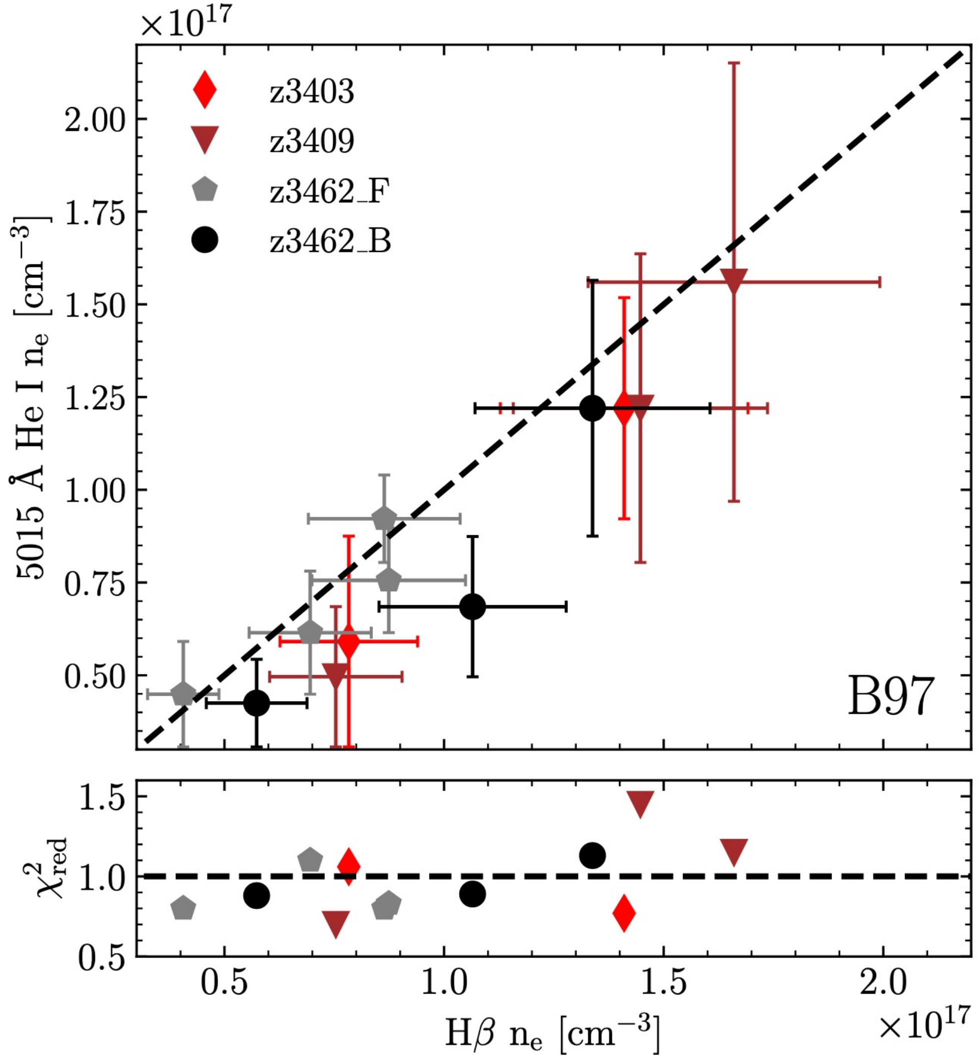
Measuring Helium lines with the WDPE on Z



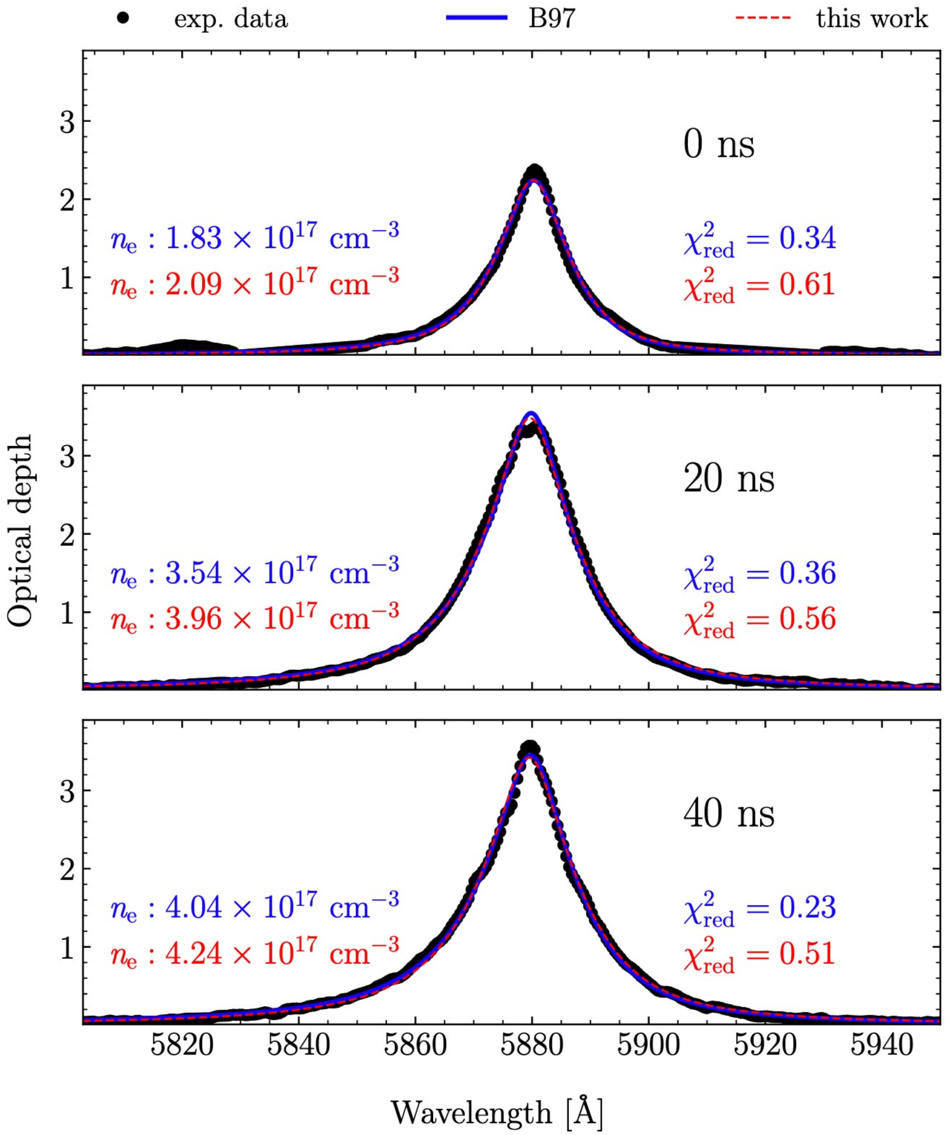


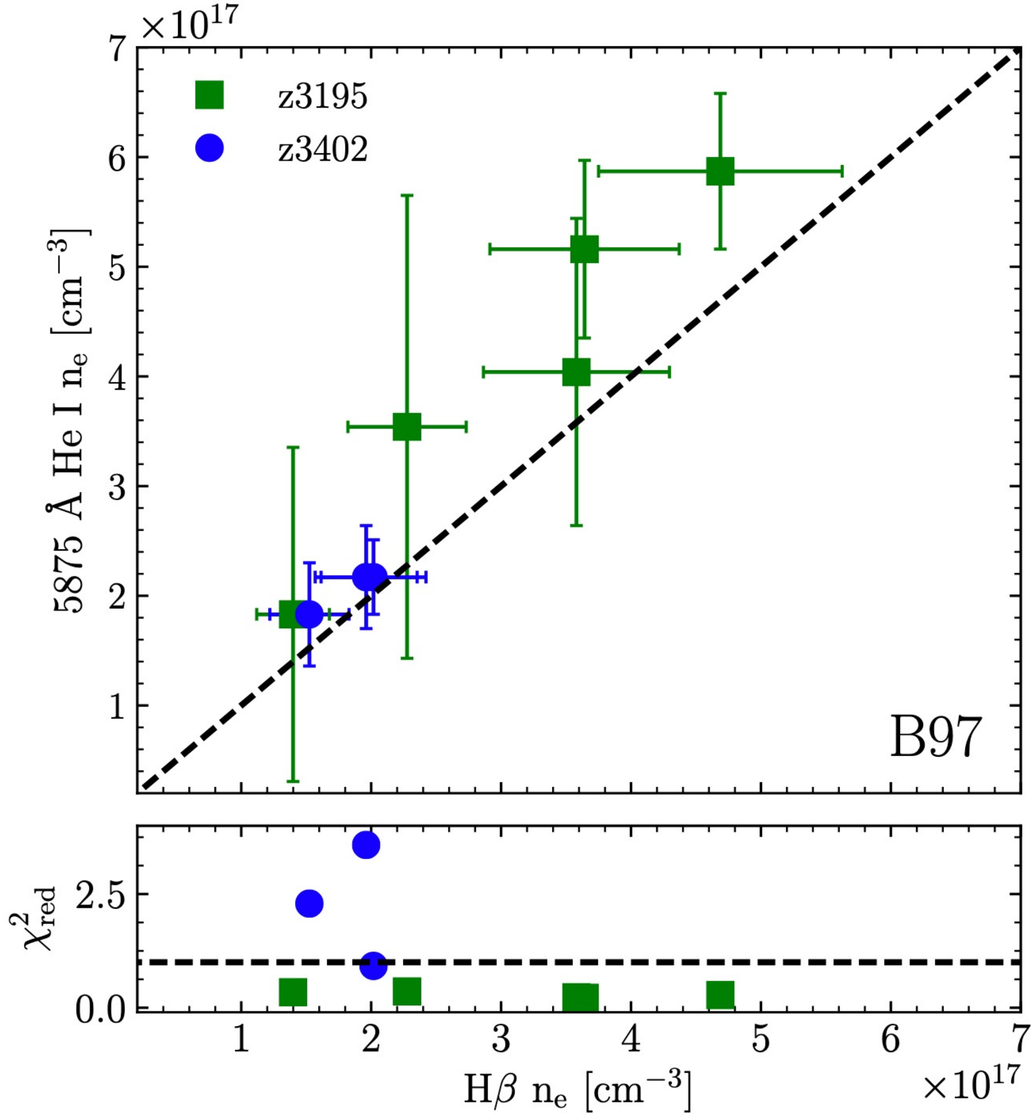
Fits to He I 5015 give n_e in agreement with Hβ





Fits to He I 5875 give n_e in agreement with Hβ





Theoretical Developments

Screening matters

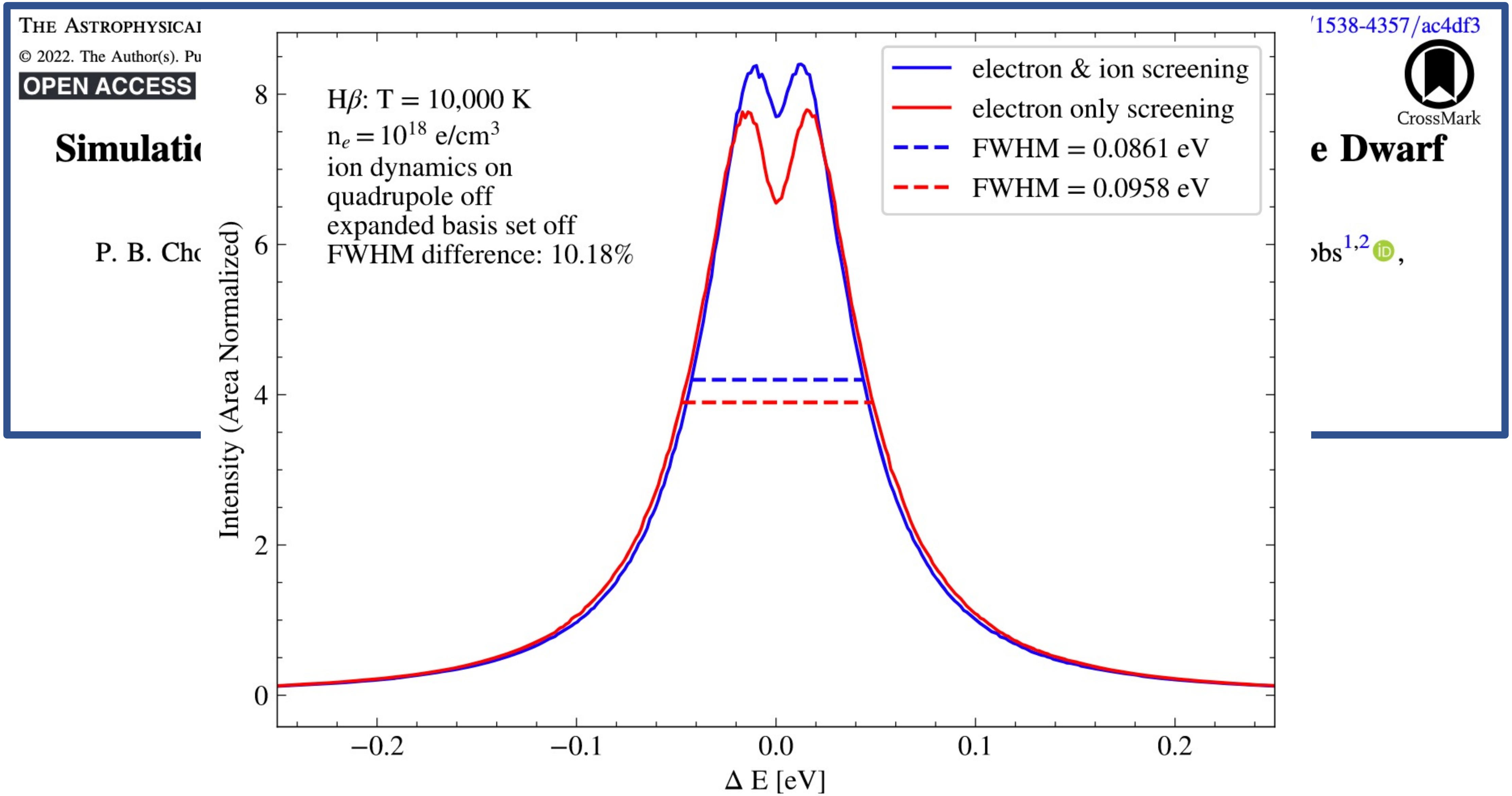
The Astrophysical Journal, 927:70 (20pp), 2022 March 1 https://doi.org/10.3847/1538-4357/ac4df3

Simulation of Stark-broadened Hydrogen Balmer-line Shapes for DA White Dwarf Synthetic Spectra

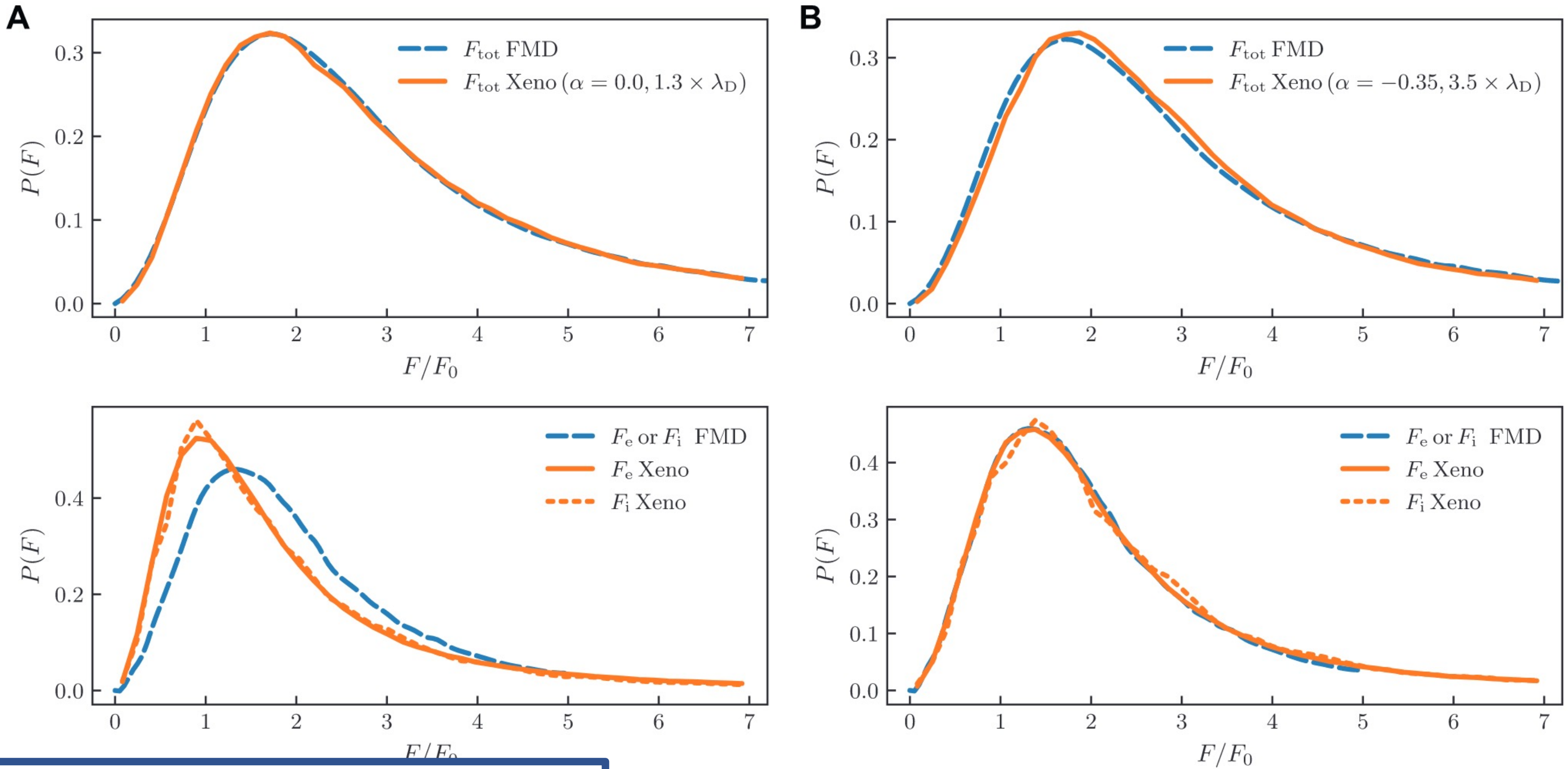
P. B. Cho[1,2,3], T. A. Gomez[3], M. H. Montgomery[1,2], B. H. Dunlap[1,2], M. Fitz Axen[1,2], B. Hobbs[1,2], I. Hubeny[4], and D. E. Winget[1,2]

[1] Department of Astronomy, University of Texas at Austin, Austin, TX-78712, USA; patricia.cho@utexas.edu
[2] McDonald Observatory, Fort Davis, TX-79734, USA
[3] Sandia National Laboratories, Albuquerque, NM-87123, USA
[4] Department of Astronomy and Steward Observatory, University of Arizona, Tucson, AZ-85721, USA
Received 2021 August 27; revised 2022 January 13; accepted 2022 January 20; published 2022 March 7

Screening matters



A non-interacting simulation can be parameterized to mimic a fully interacting simulation



Hydrogen Line Shape Uncertainties in White Dwarf Model Atmospheres

M. H. Montgomery[1], B. H. Dunlap[1], P. B. Cho[1] and T. A. Gomez[2]*

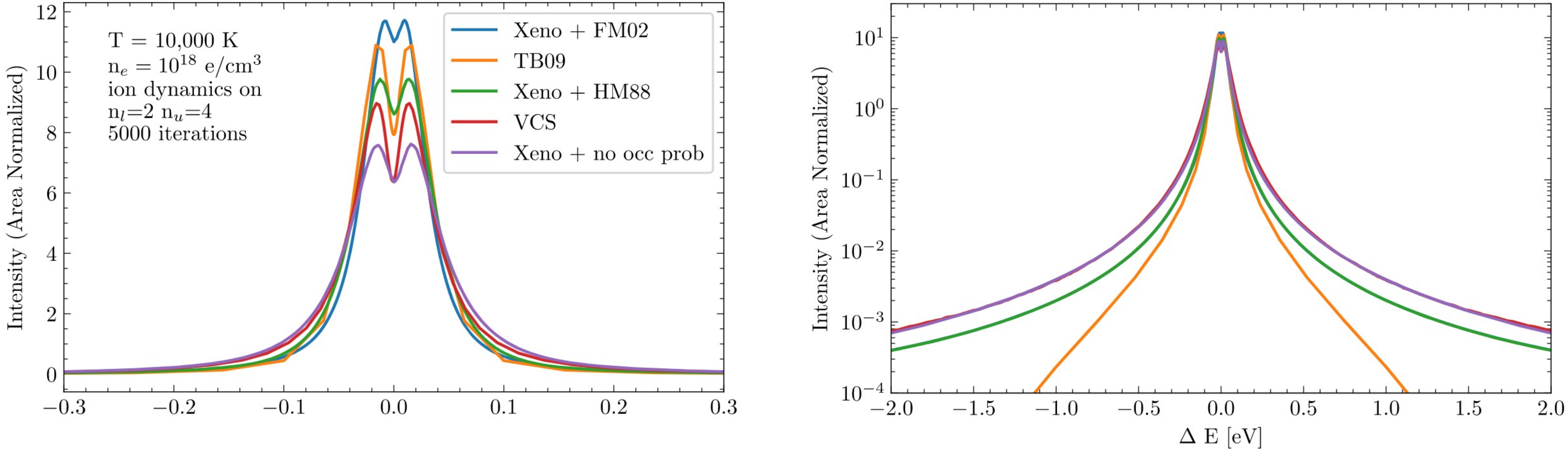
[1]Department of Astronomy, University of Texas at Austin, Austin, TX, United States, [2]Sandia National Laboratories, Albuquerque, NM, United States

Frontiers in Astronomy & Space Science, 17 February 2022

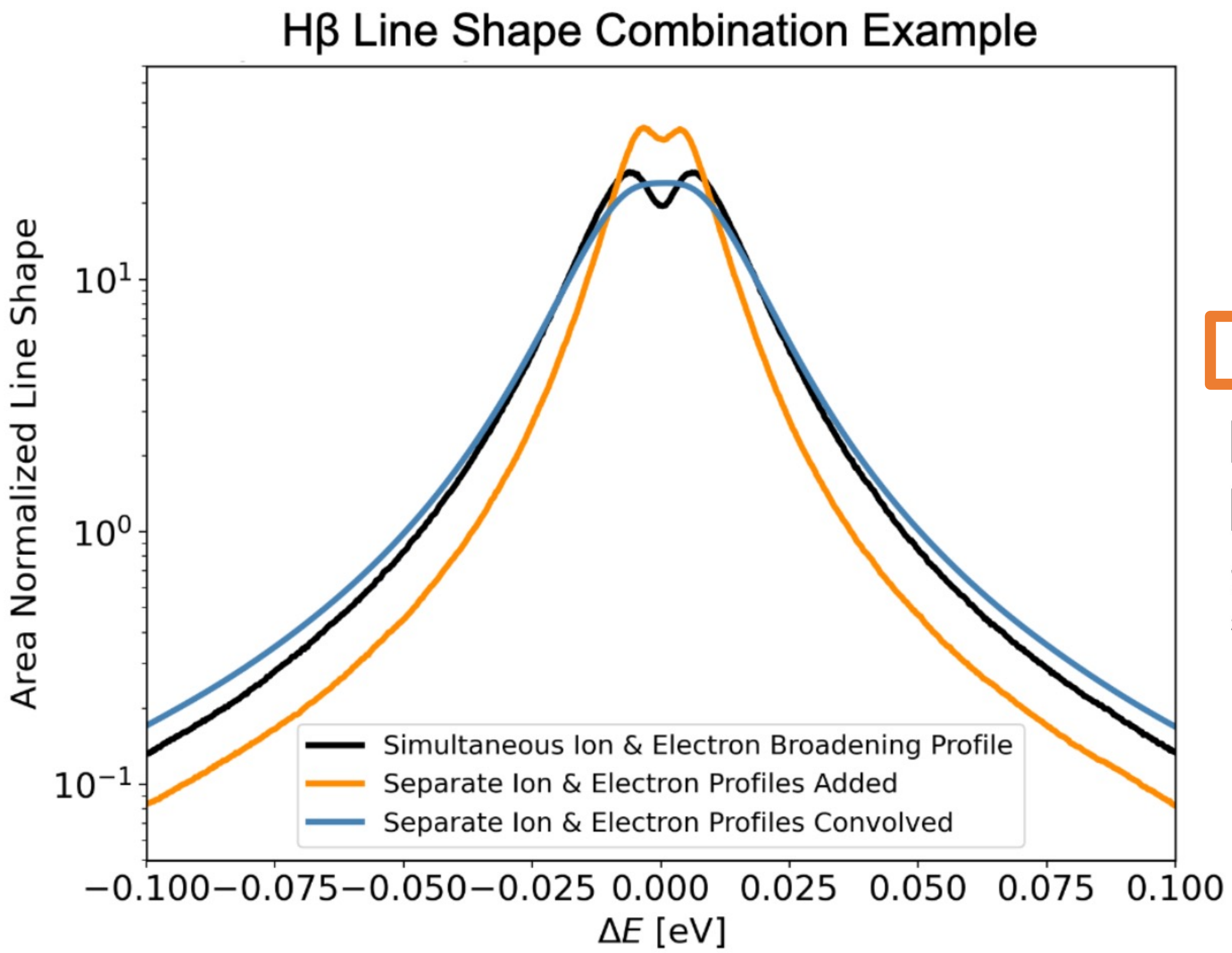
Occupation probability prescription matters

THE ASTROPHYSICAL JOURNAL, 927:70 (20pp), 2022 March 1 https://doi.org/10.3847/1538-4357/ac4df3

Simulation of Stark-broadened Hydrogen Balmer-line Shapes for DA White Dwarf Synthetic Spectra



H_2 quasi-molecular features



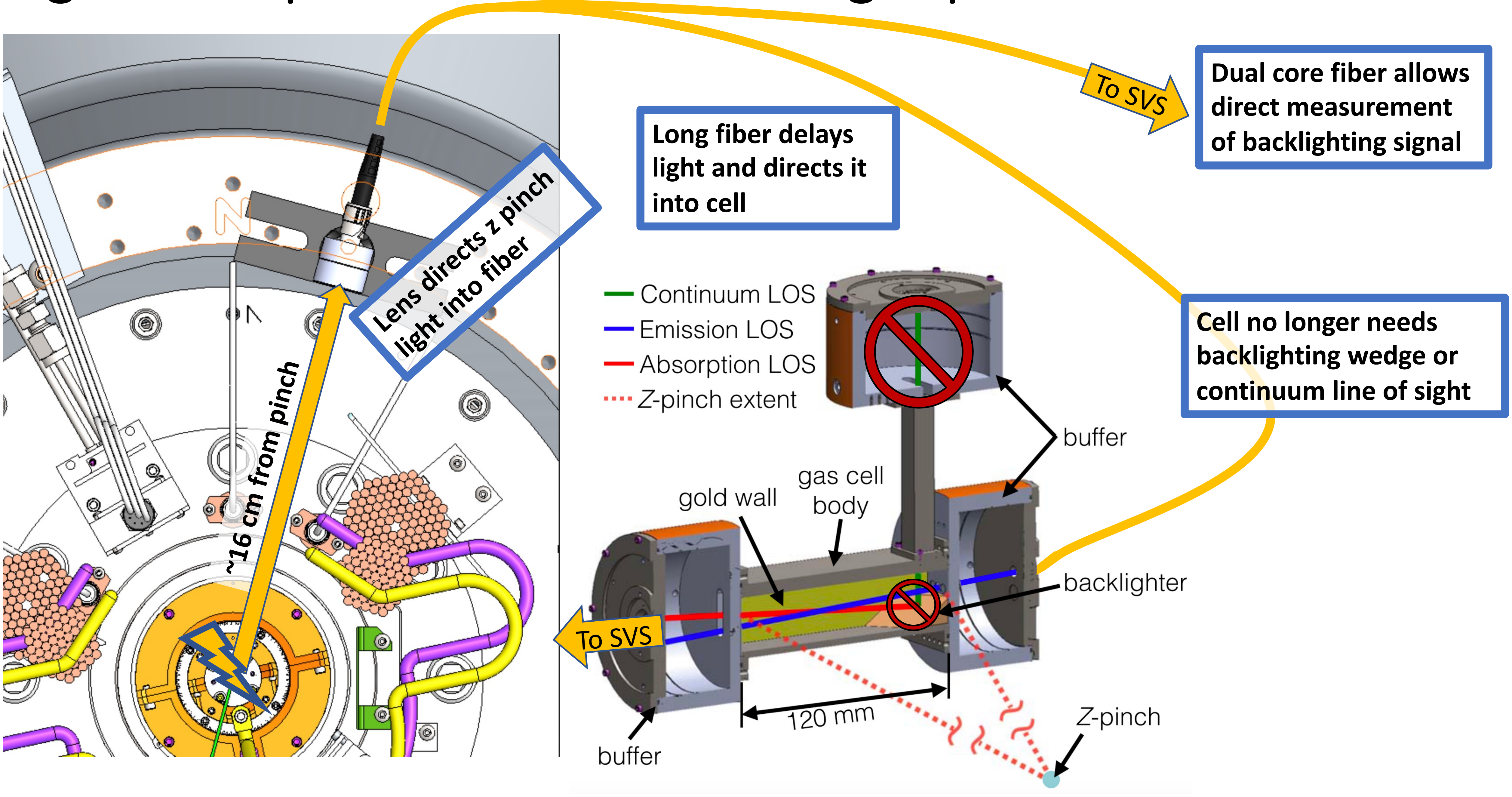
See poster by Jackson White!

H2+ Quasi Molecular Line Shape Profiles in Stellar Atmospheres

Jackson White[1], Thomas Gomez[1,2], Mike Montgomery[1], Bart Dunlap[1]
[1]Department of Astronomy, University of Texas at Austin
[2]Sandia National Laboratory

Platform Development

Light from pinch is used to backlight plasma in cell



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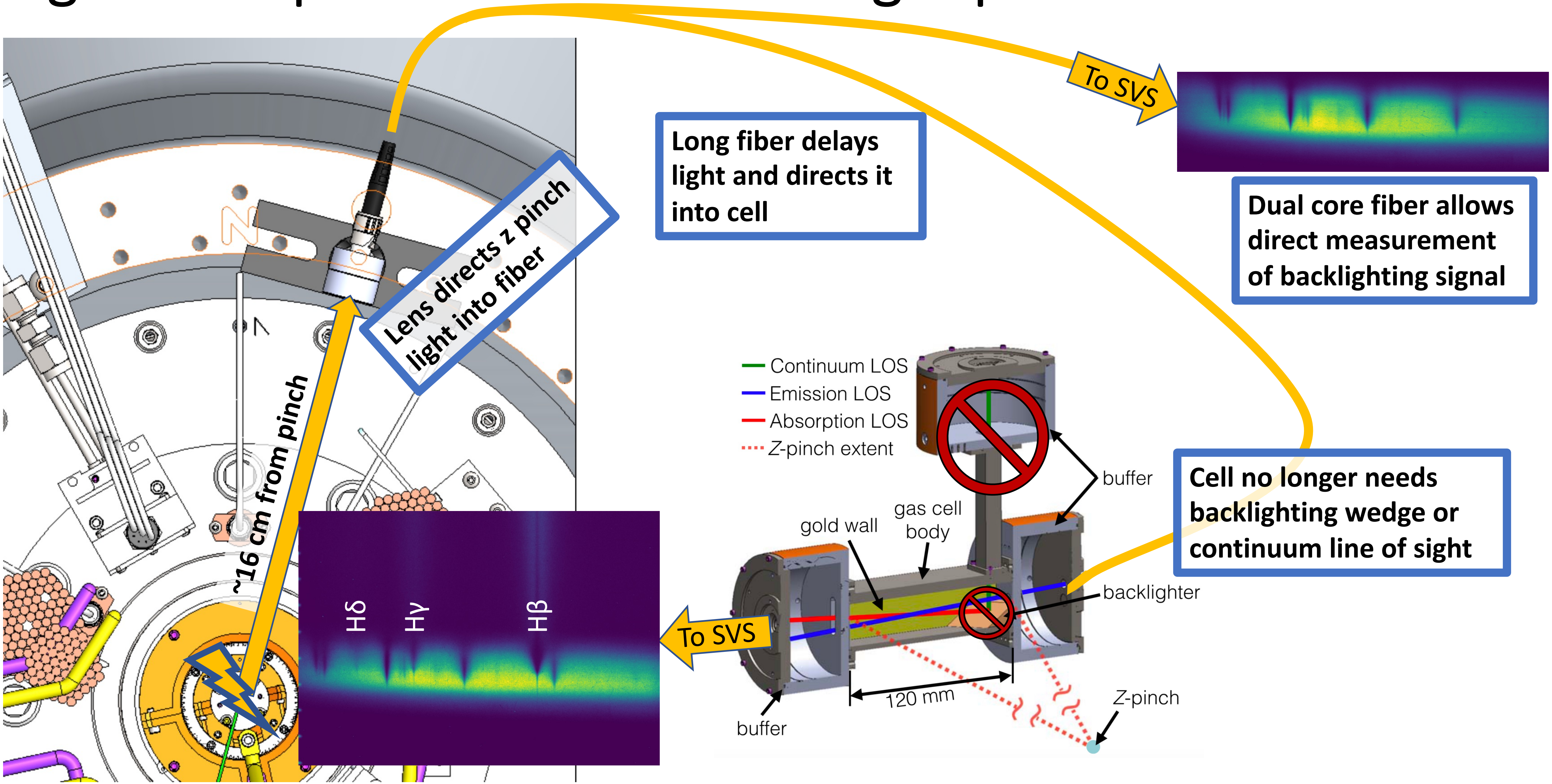
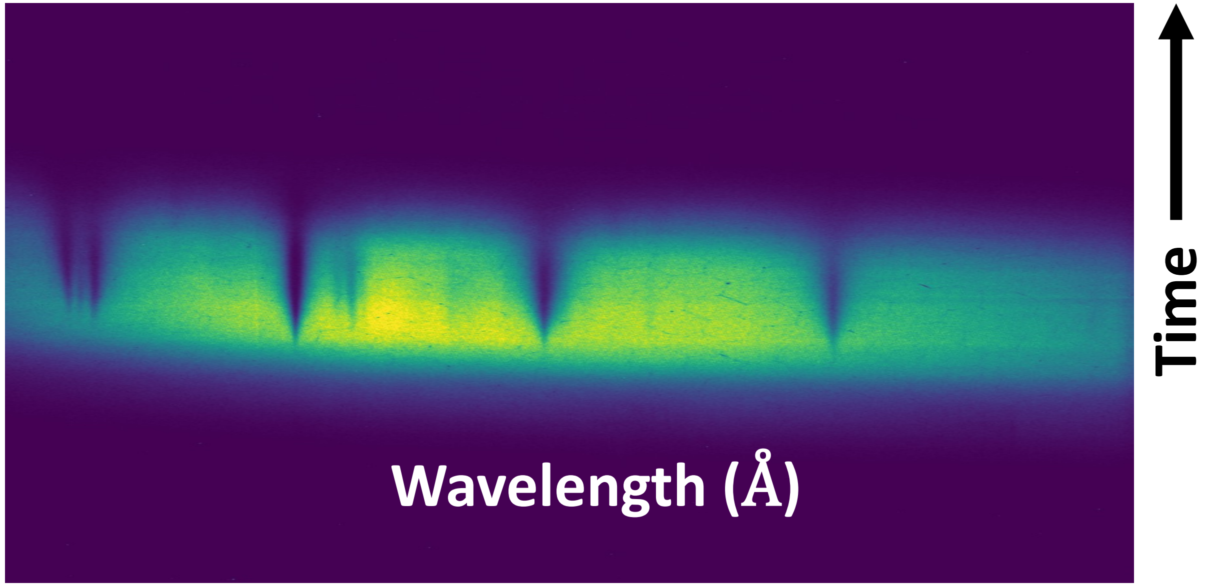
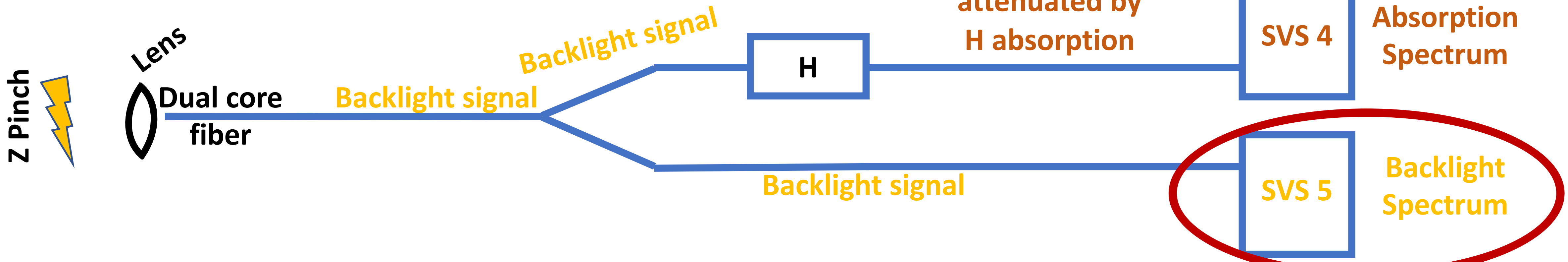


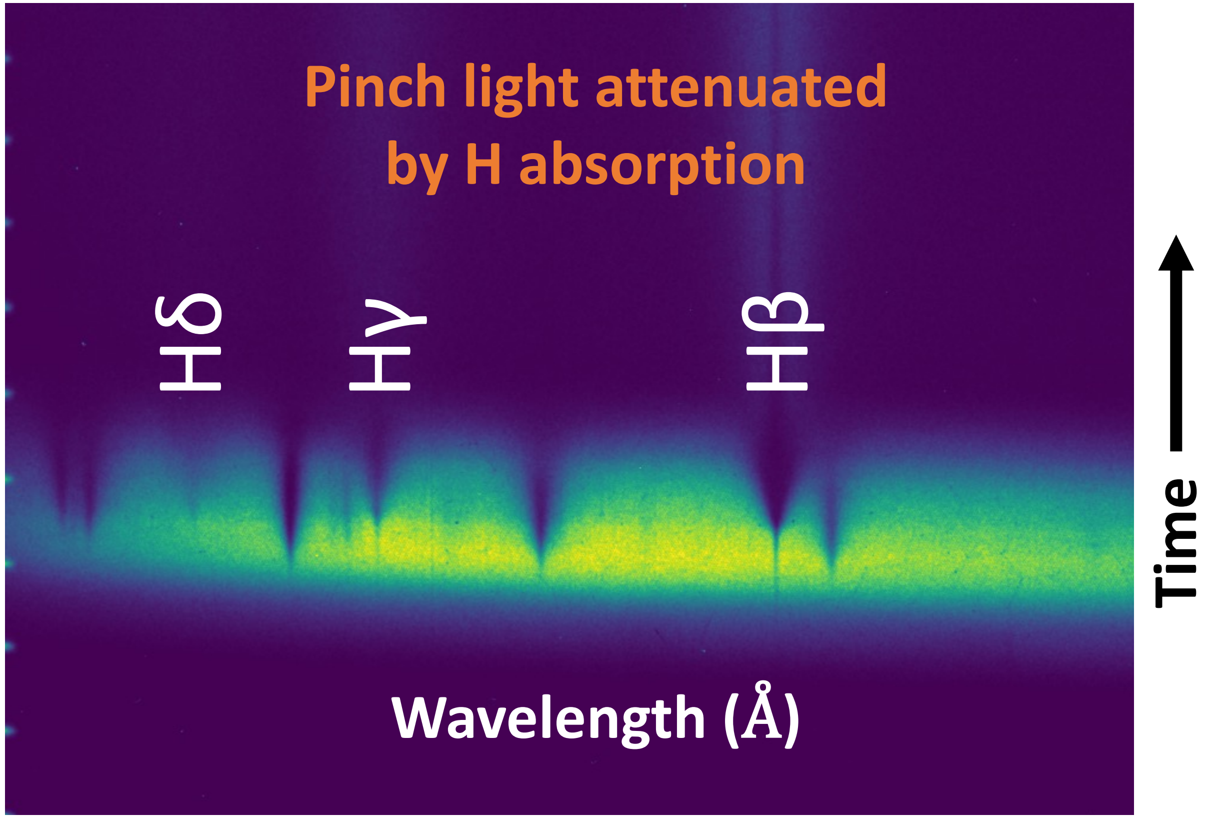
Pinch light successfully fielded as backlight for absorption spectrum

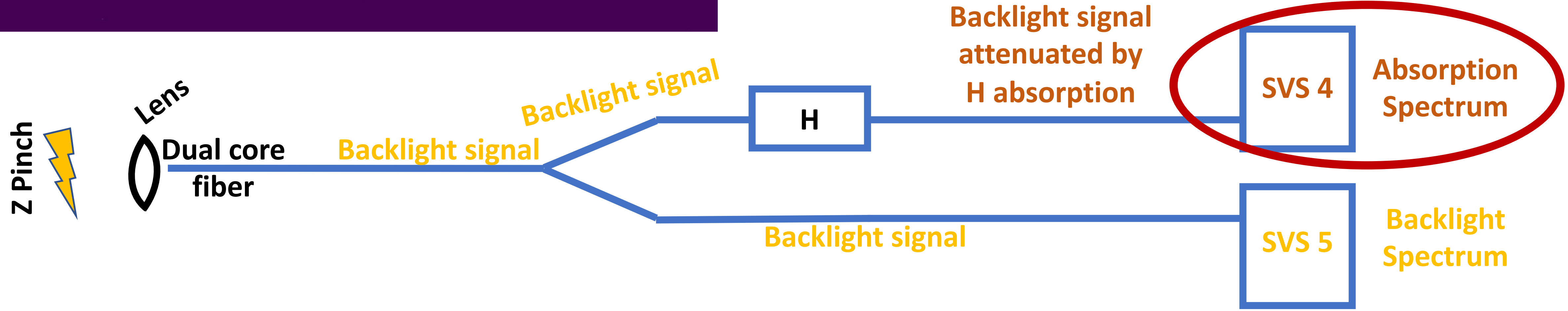
Pinch light direct to SVS





Pinch light successfully fielded as backlight for absorption spectrum



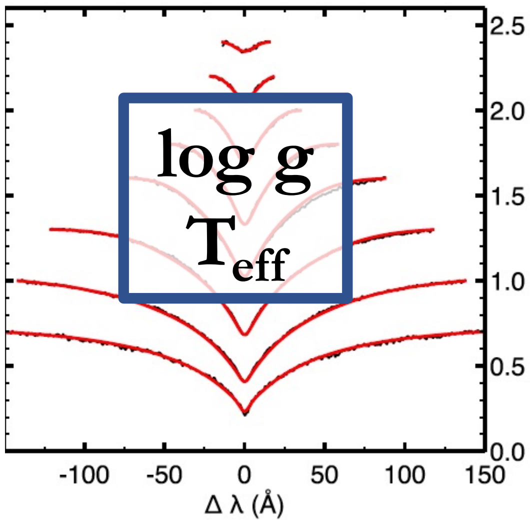


Overview

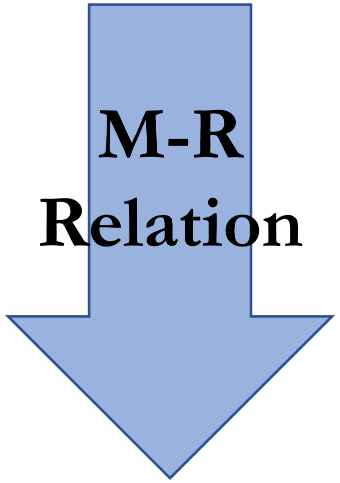
- What do white dwarf spectra tell us?
  - Mass, Temperature, Atmospheric Composition
- How do white dwarfs help answer broader astrophysical questions?
  - Ages of stellar populations, exoplanets, cosmology
- Why do we think there are problems with spectroscopic mass determinations?
  - Independent mass estimates disagree
- What developments are underway with the white dwarf photosphere experiment?
  - Achieving higher densities in hydrogen
  - Developing independent electron density diagnostic (PDV)
  - Measuring Stark broadening of He I 5015 & 5876 lines
  - Theory update: screening, continuum lowering/occupation probability, H_2 quasi-molecular features

Extra Slides

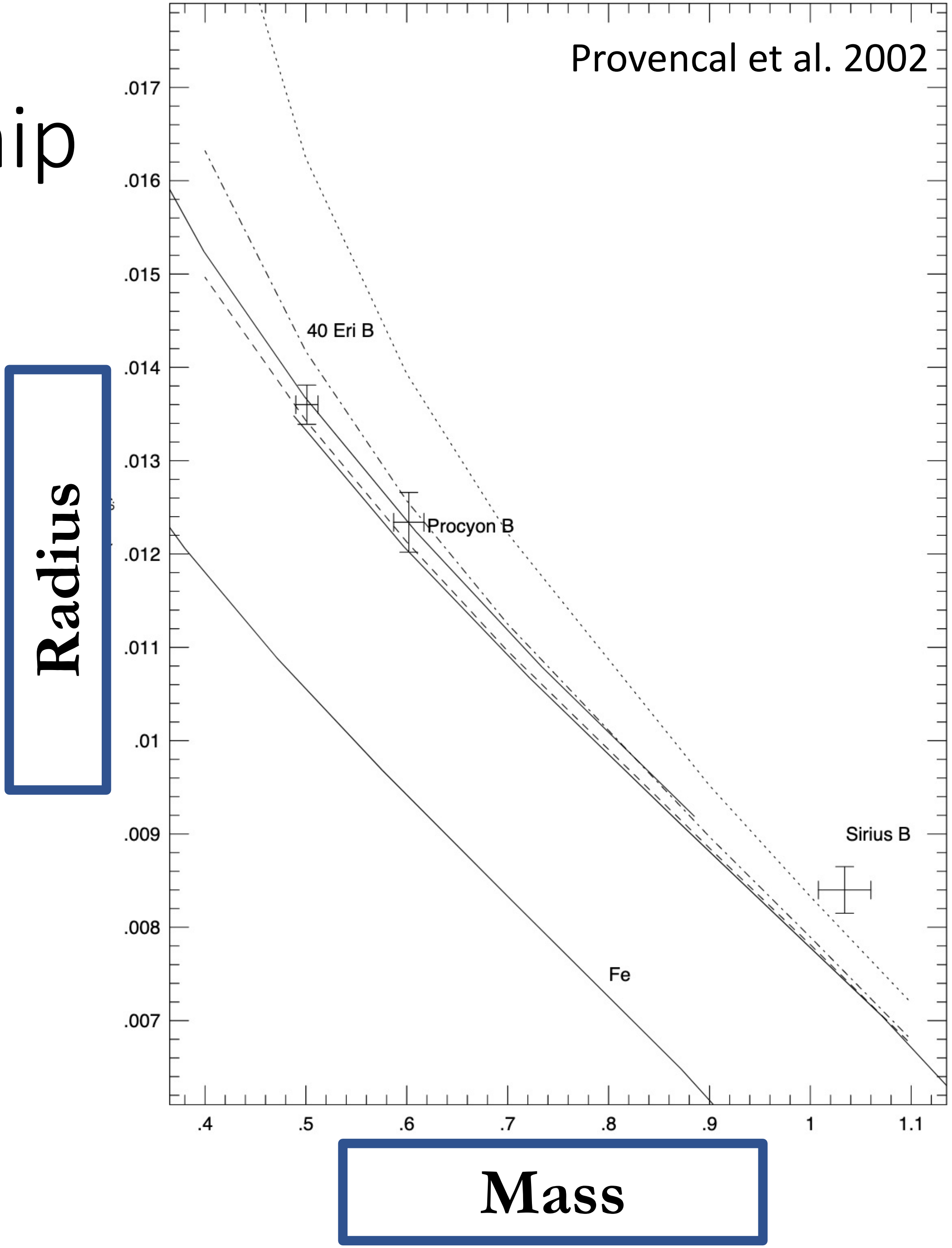
Converting surface gravity to mass via mass-radius relationship



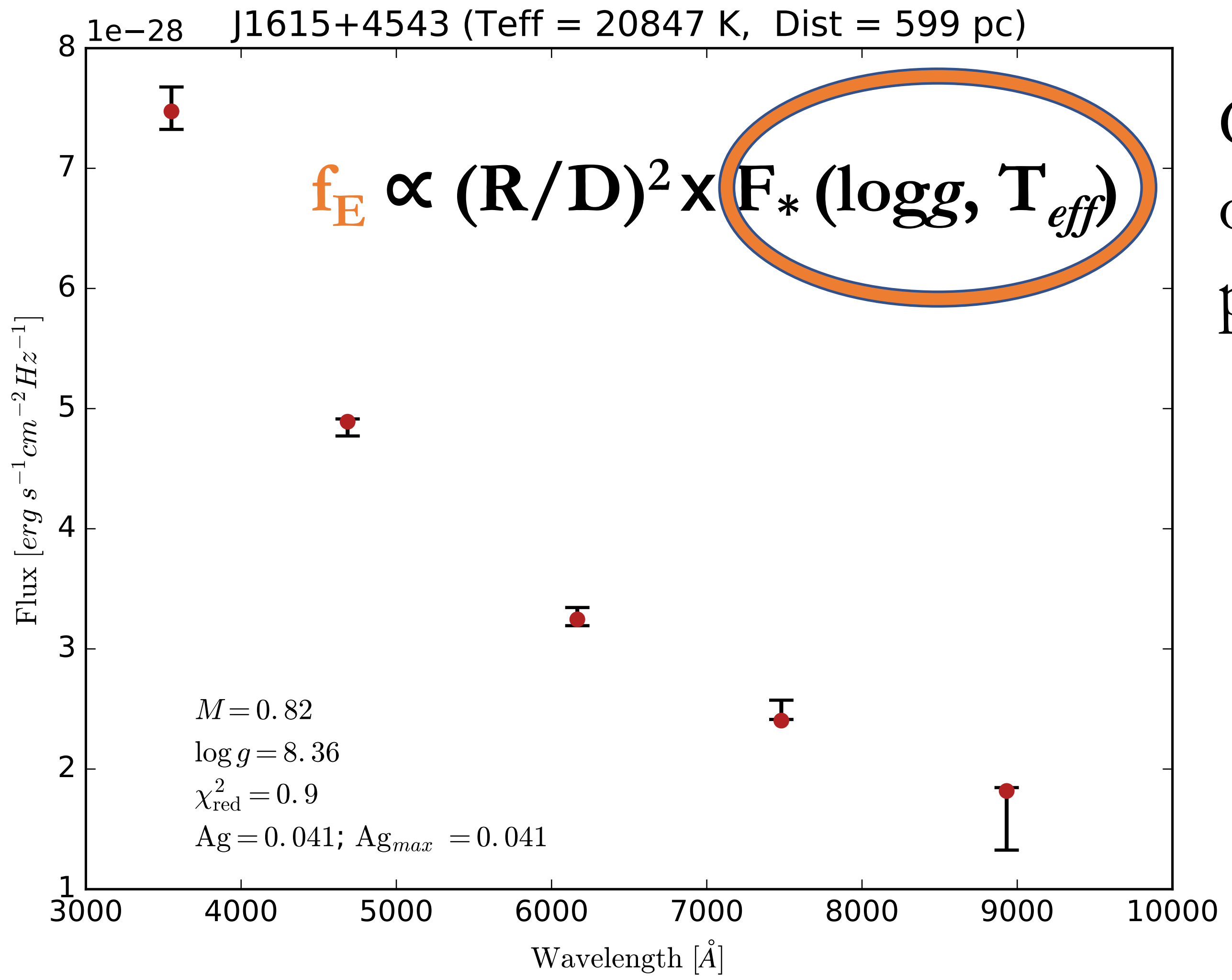
$g \propto M/R^2$



Mass



Mass & T_{eff} from Broadband Photometry + Gaia Distances

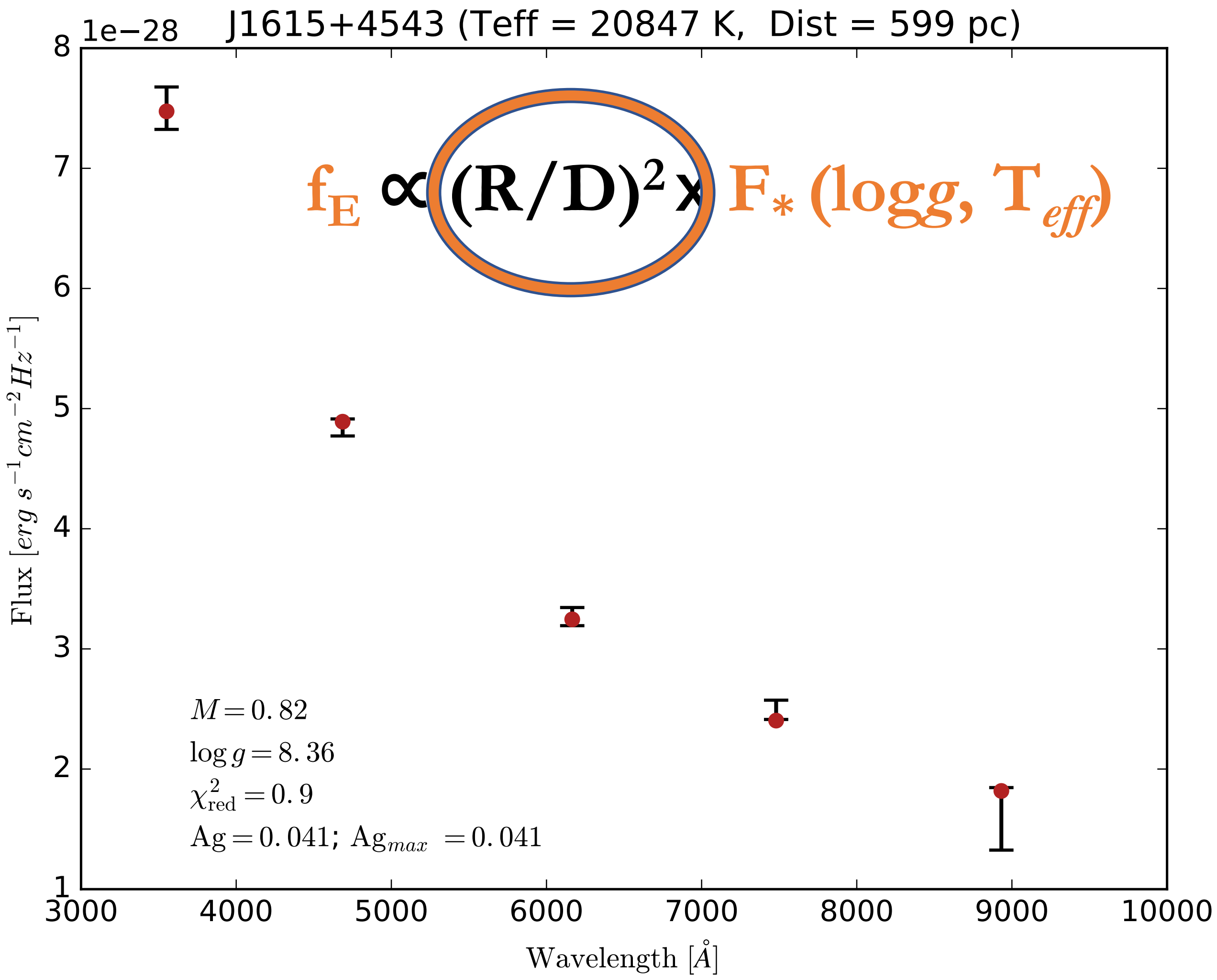


Constrained by *shape* of the broadband photometry.

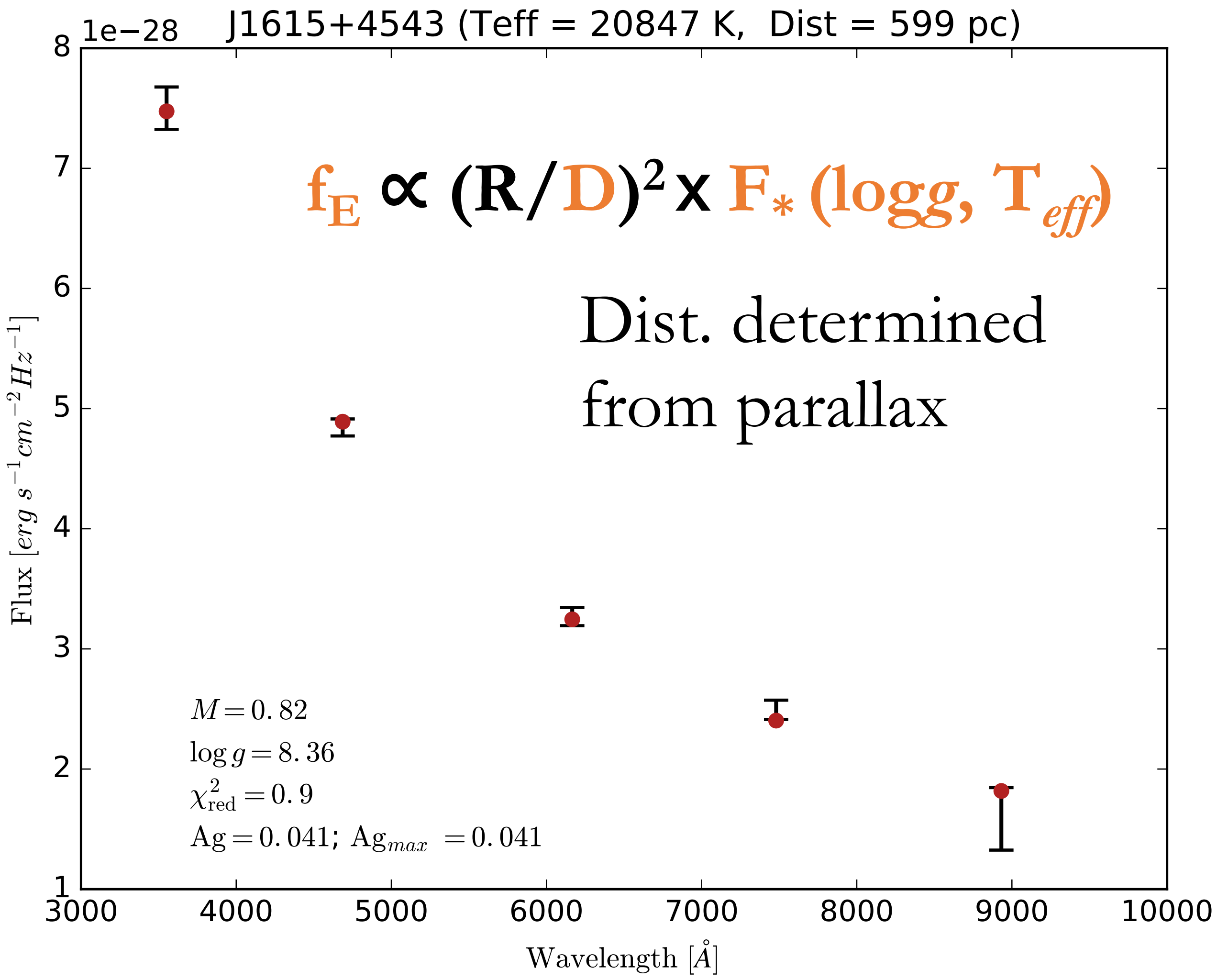
Mass & T_{eff} from Broadband Photometry + Gaia Distances

Constrained by absolute flux level

Depends on angular size of the star on the sky

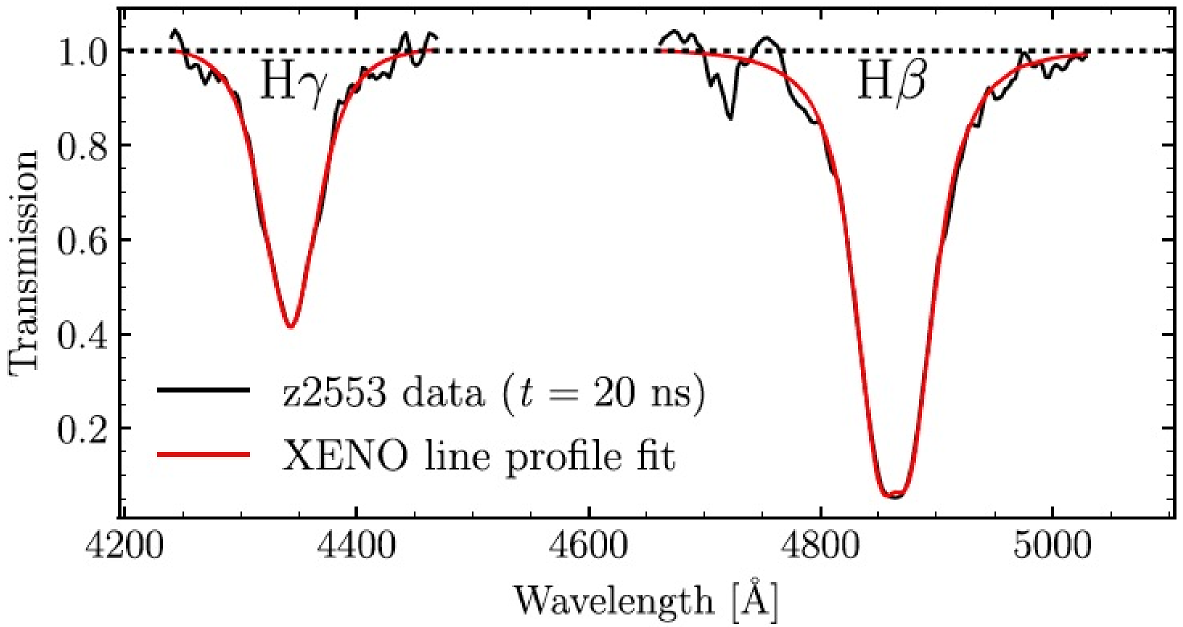


Mass & T_{eff} from Broadband Photometry + Gaia Distances

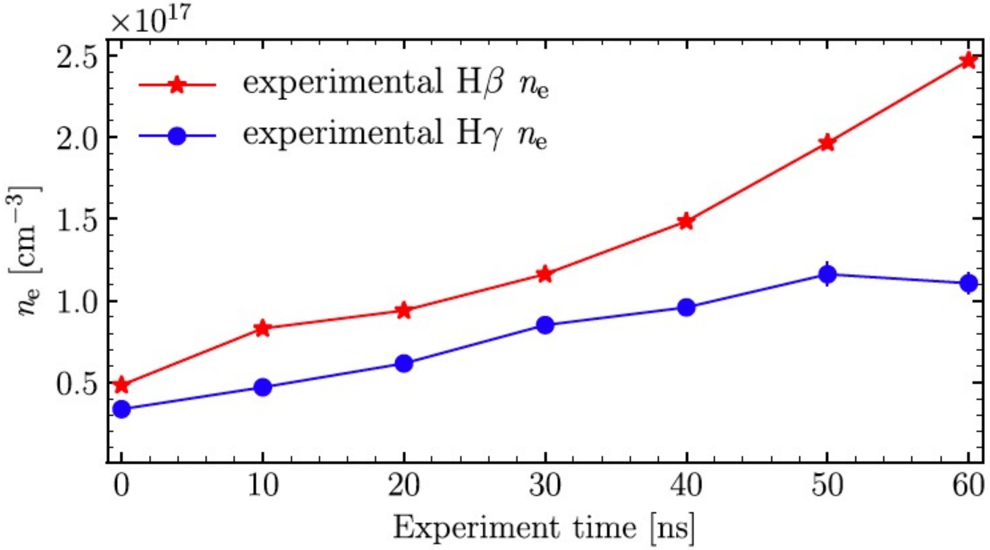


Analysis of the WDPE absorption spectra reveal trends similar to those observed in stellar spectra

Schaeuble et al. (2019)



Line fits to absorption spectra.
These are used to extract n_e values.

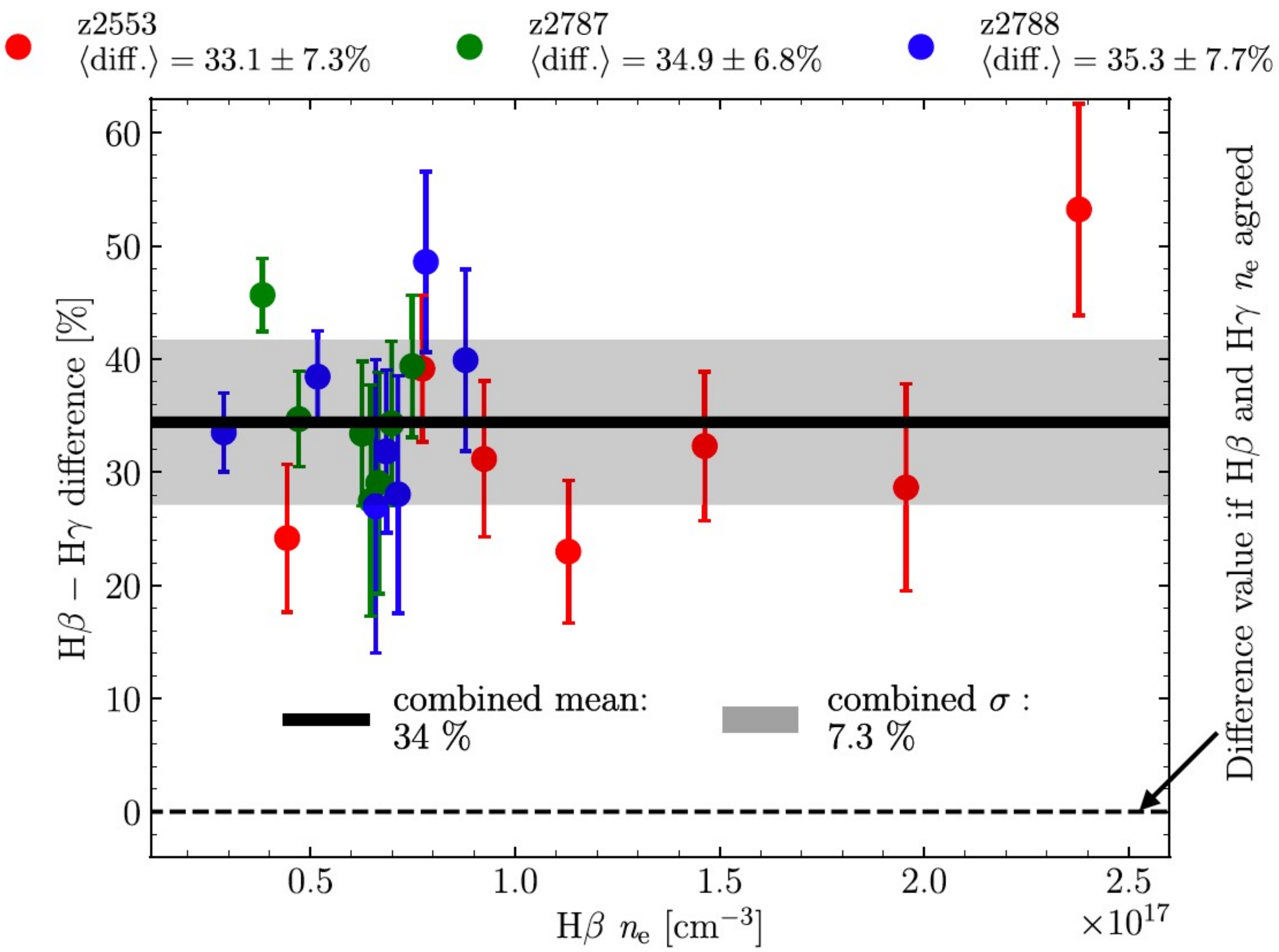


Hβ and Hγ n_e values differ by ~30%.

Analysis of the WDPE absorption spectra reveal trends similar to those observed in stellar spectra

Hβ and Hγ n_e values differ by ~30%.

This difference is consistent across multiple shots.



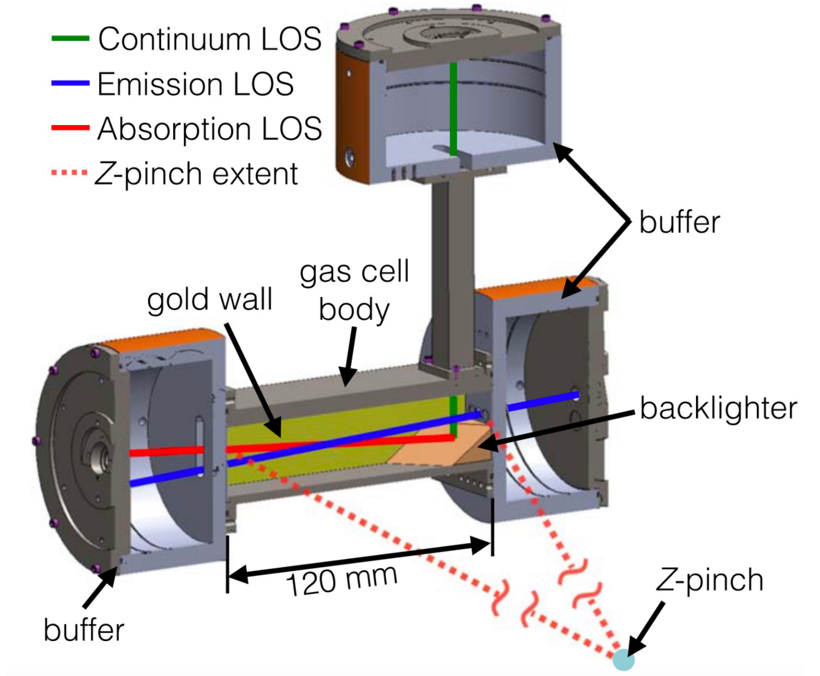
Schaeuble et al. (2019)

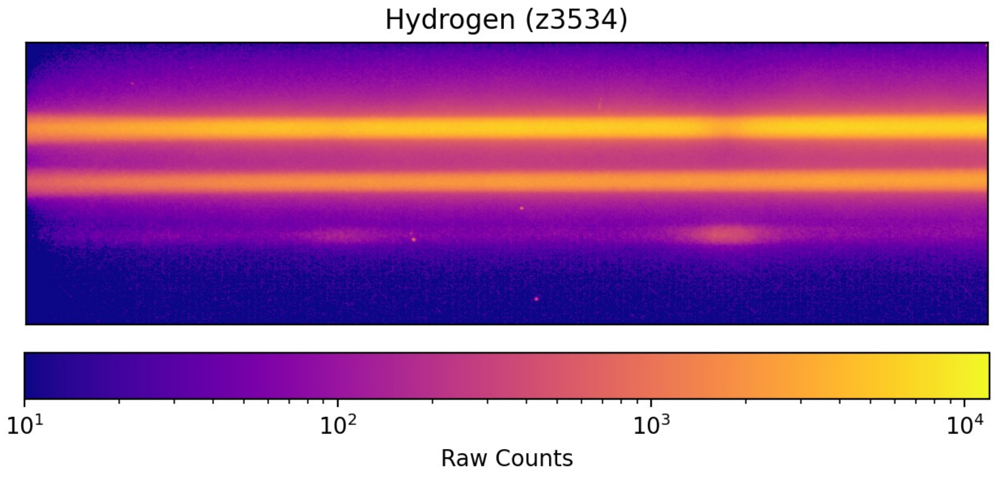
Hydrogen data at higher densities can more easily test theories of line shapes and occupation probability

Previous data at higher densities showed larger disagreement among theories.

Data had to be taken at the 5 mm line of sight, where gradients across the beam are larger.

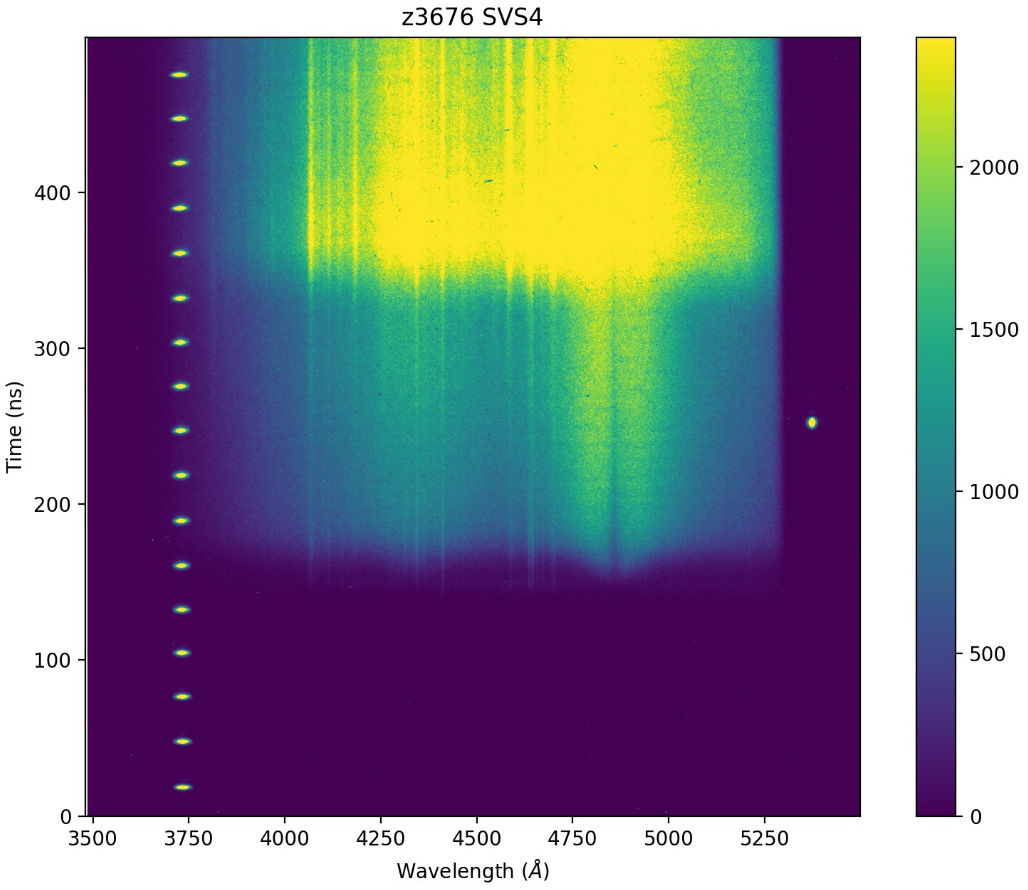
Continuum data not collected simultaneously, which limits the ability to test theories of occupation probability.

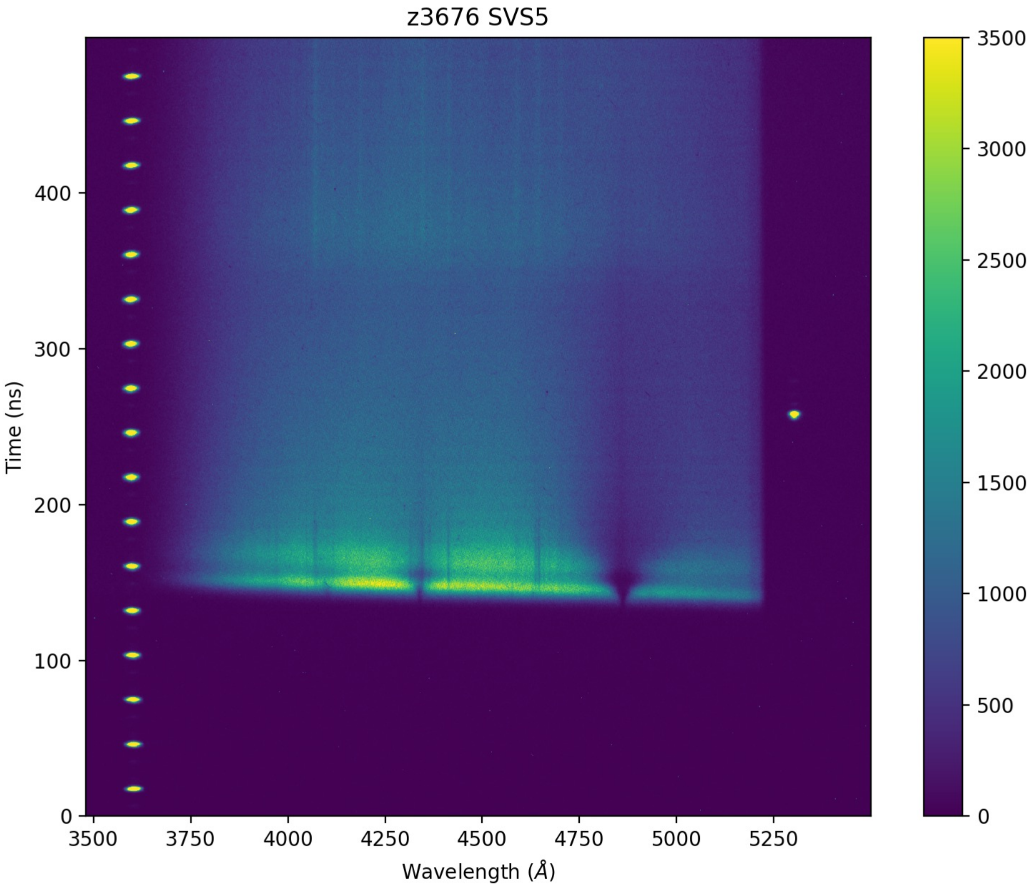




Achieved higher n_e in H at 10 mm line of sight

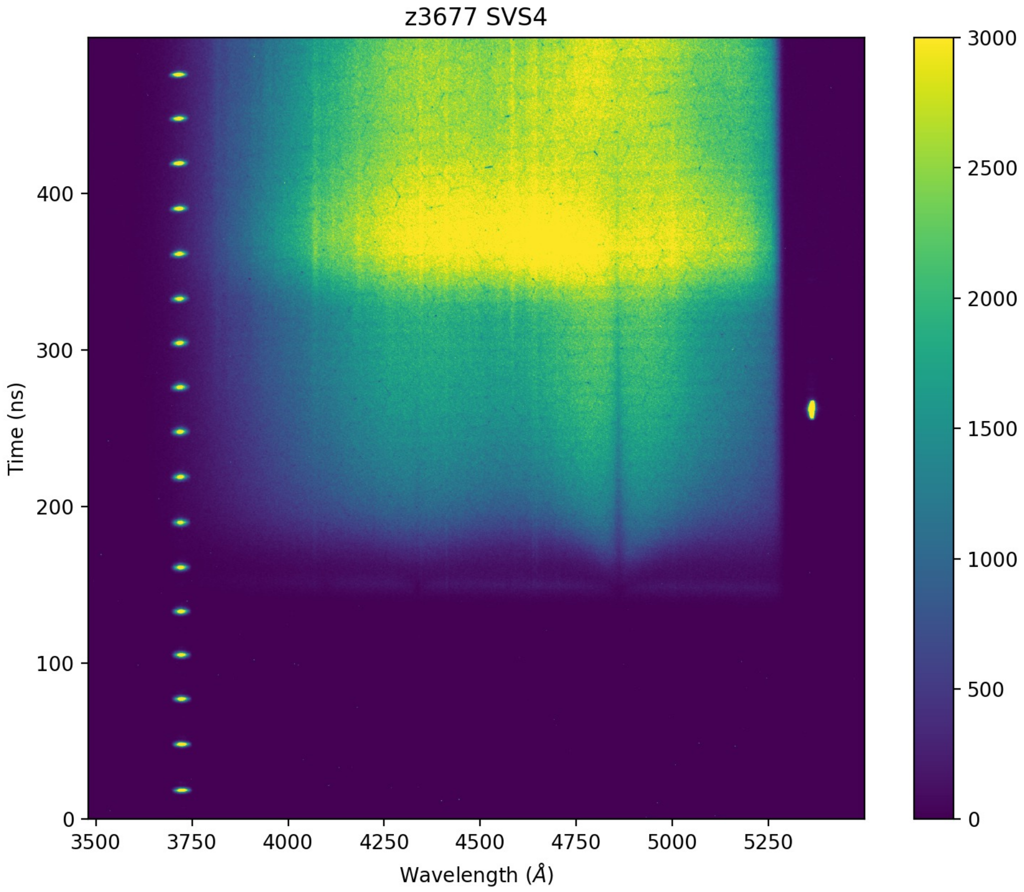
- Fill pressure = 18 Torr.
- More contamination visible.
- Cell sensor indicated increase in pressure after lockup; gas cabinet sensor did not show increase.

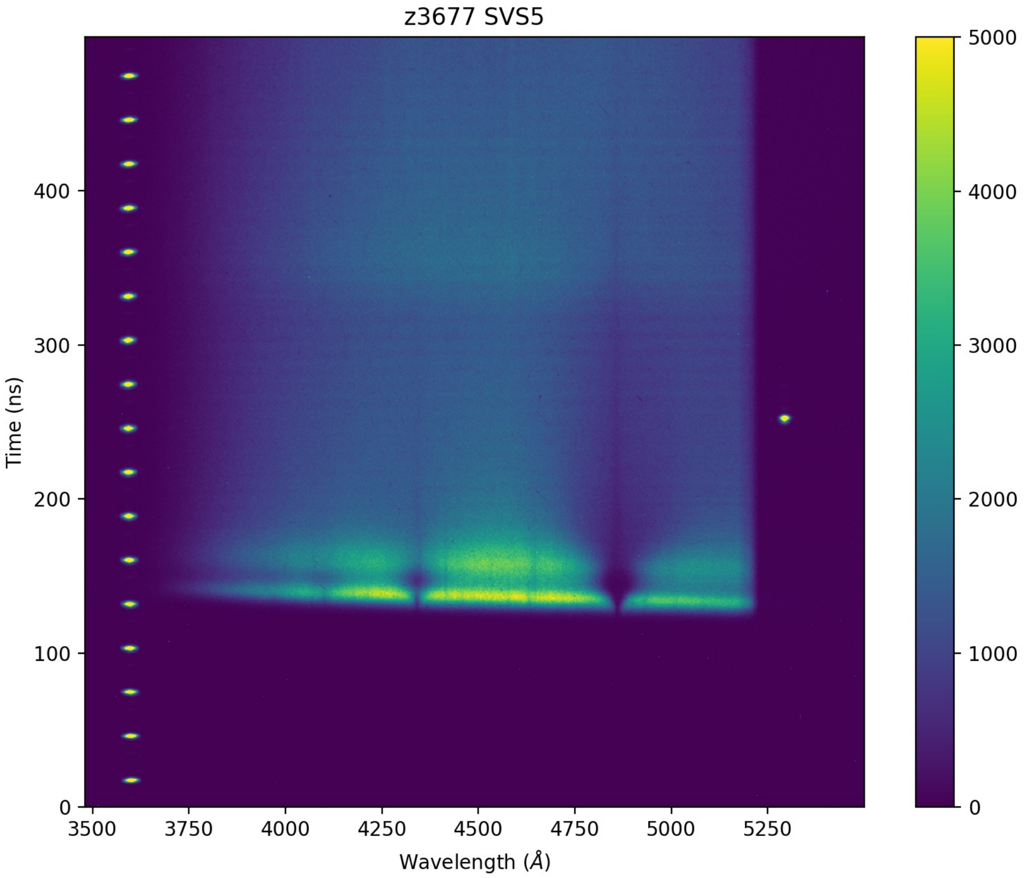




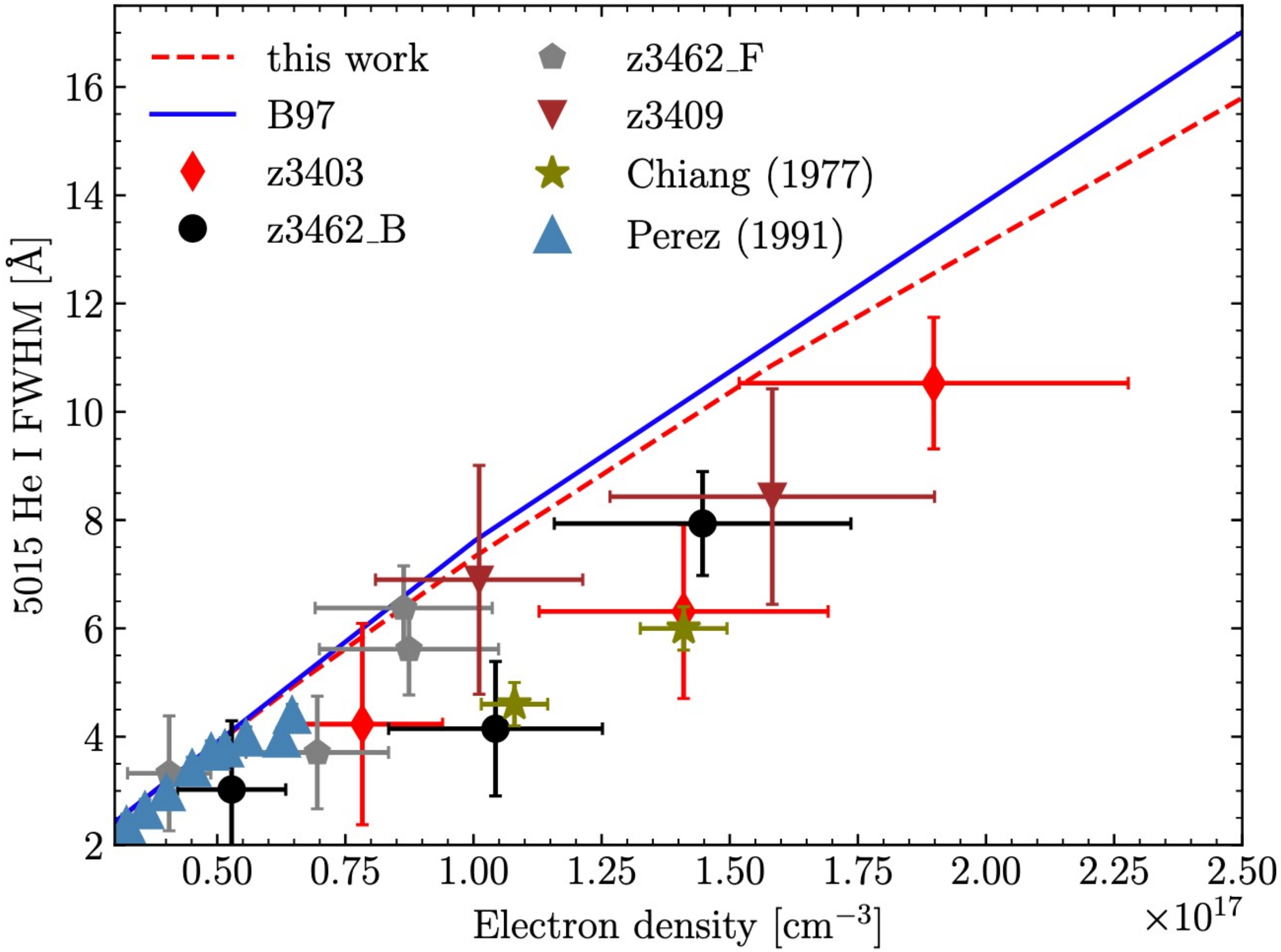
Achieved higher n_e in H at 10 mm line of sight

- Fill pressure = 35 Torr

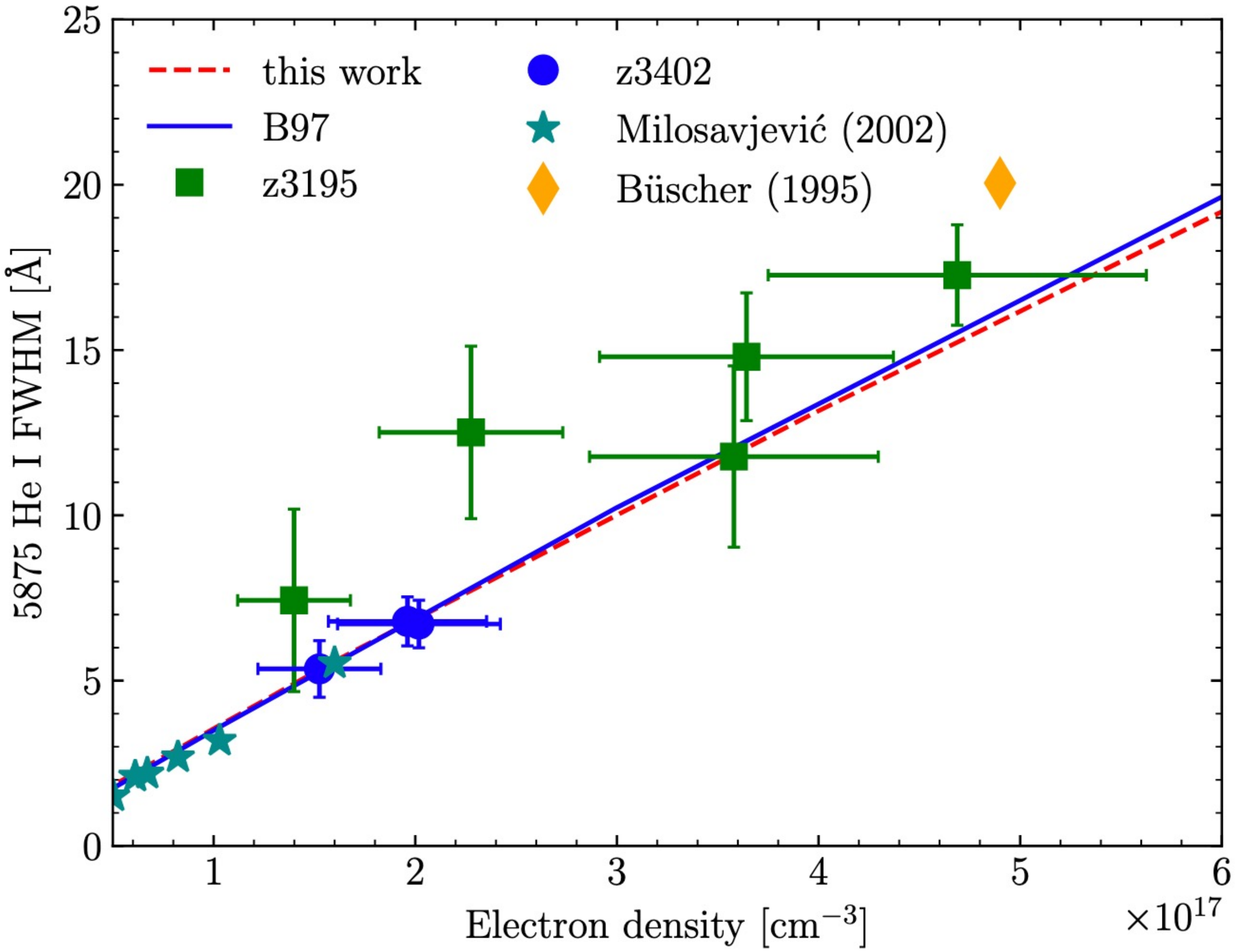




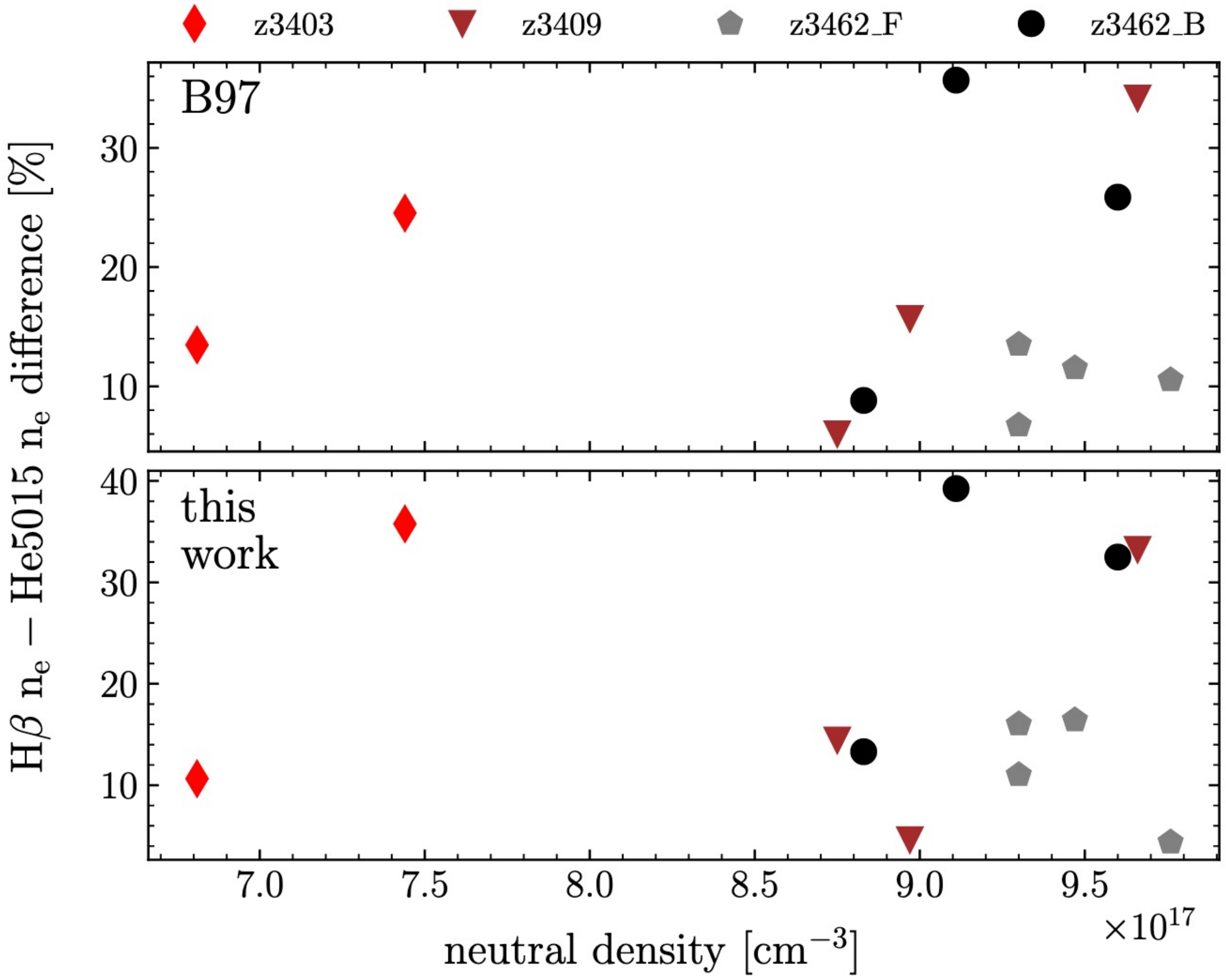
He I 5015 line widths compared to theory



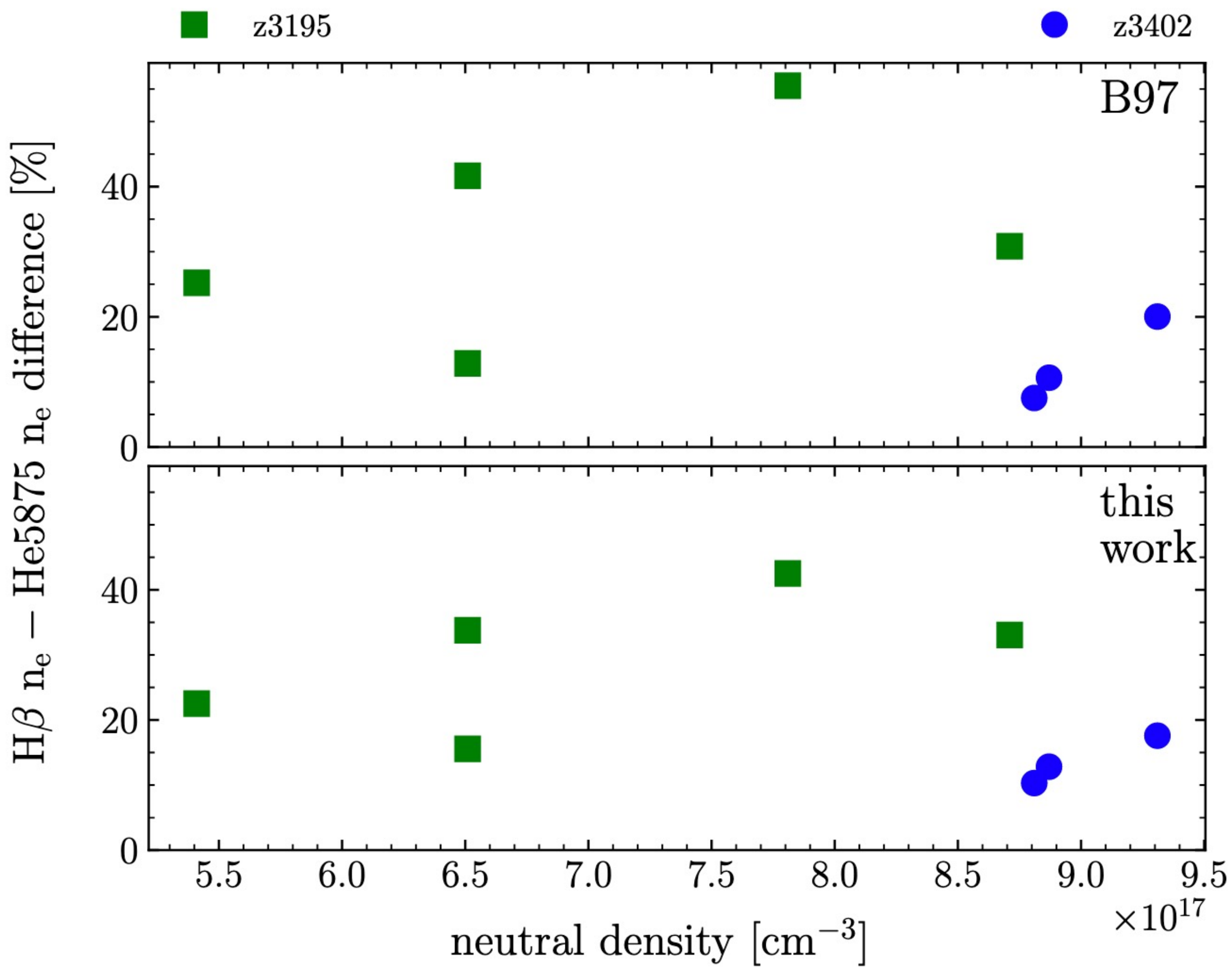
He I 5875 line widths compared to theory



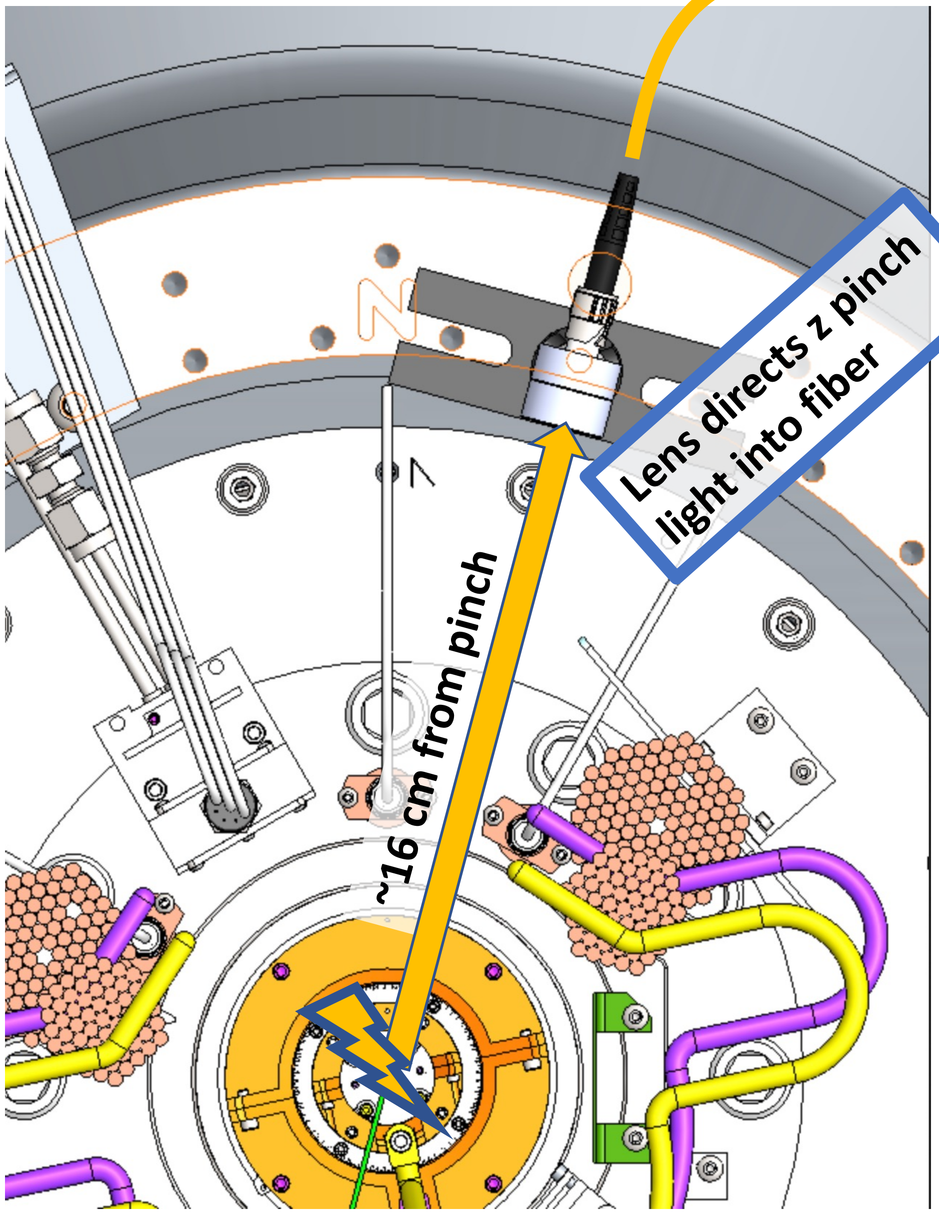
Effect of neutral density



Effect of neutral density



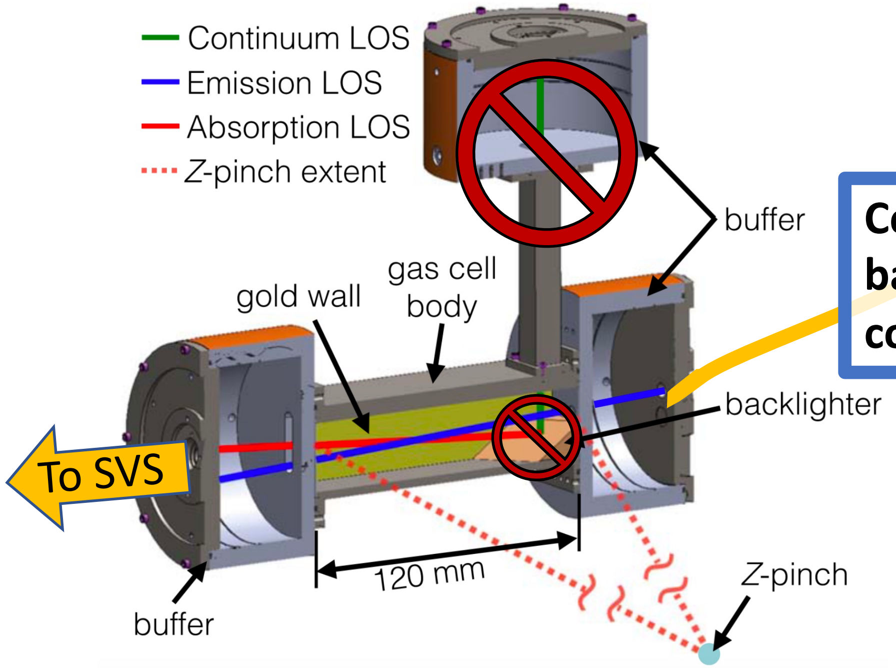
Light from pinch is used to backlight plasma in cell



Long fiber delays light and directs it into cell

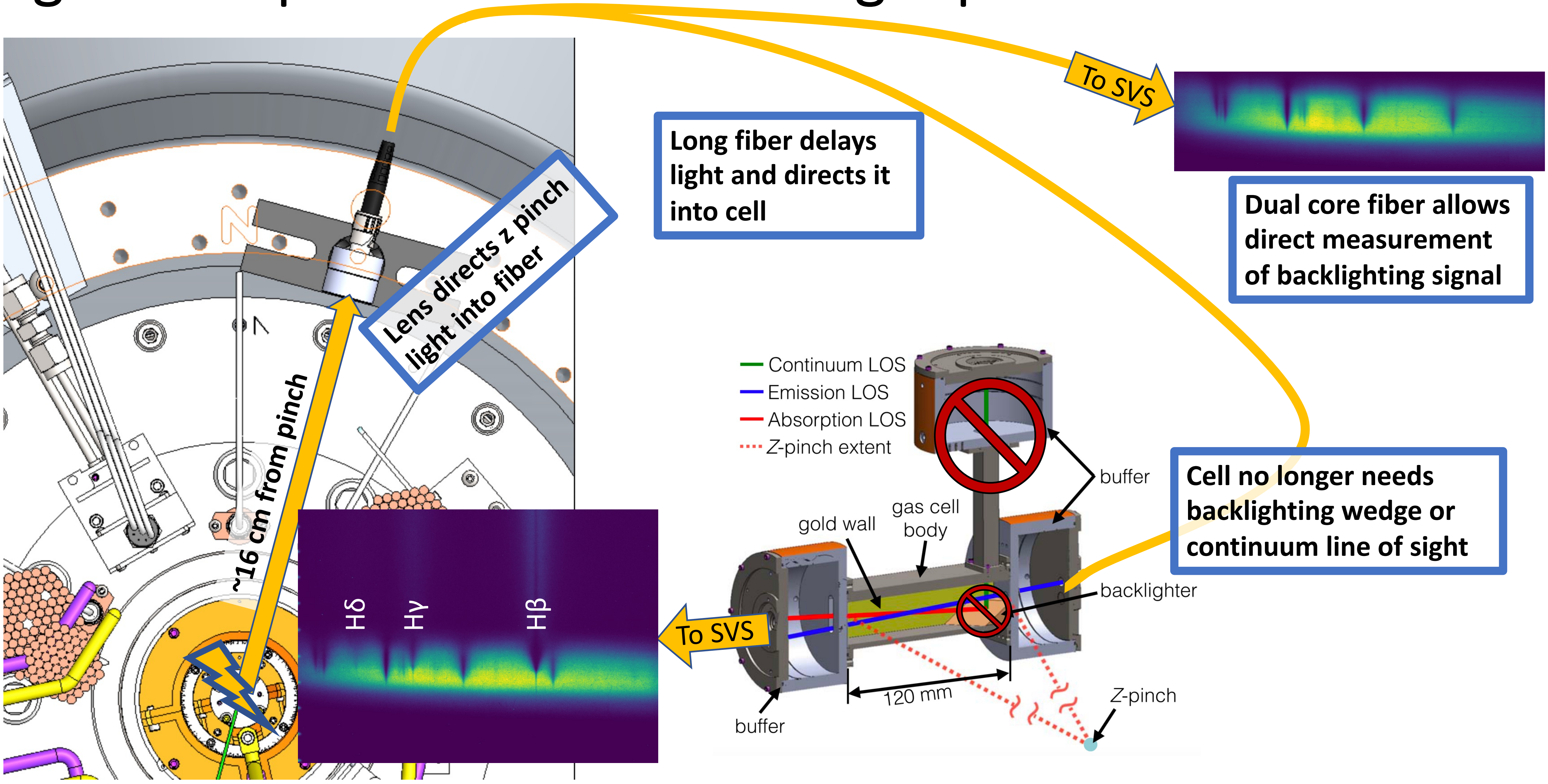
Dual core fiber allows direct measurement of backlighting signal

To SVS



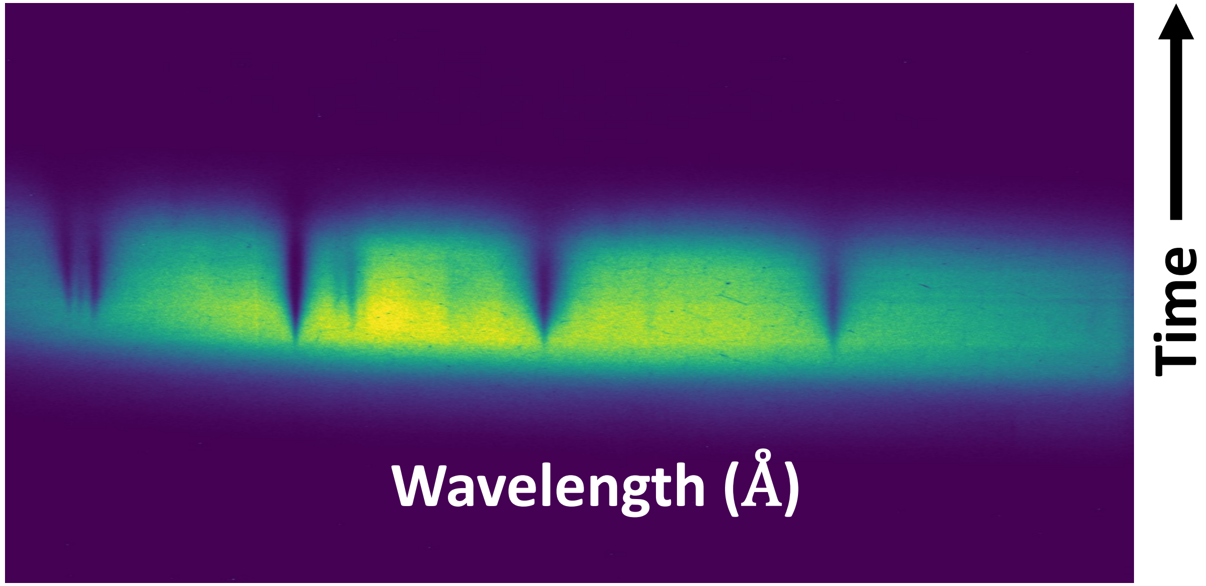
Cell no longer needs backlighting wedge or continuum line of sight

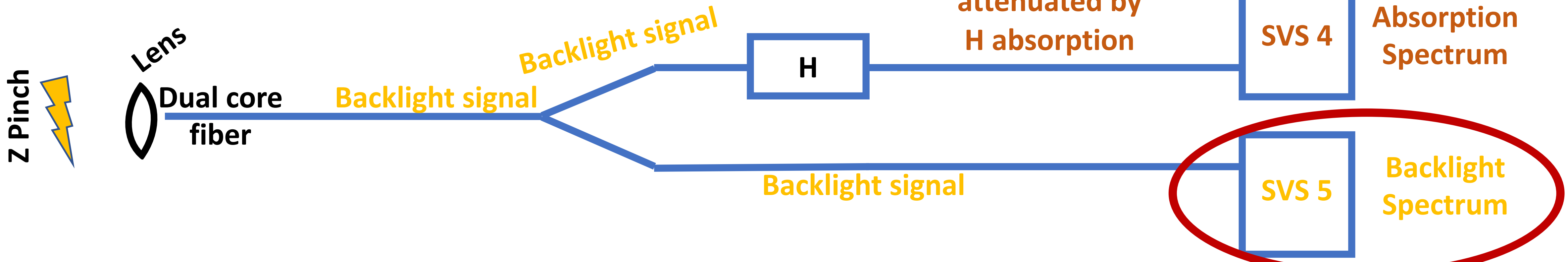
Light from pinch is used to backlight plasma in cell



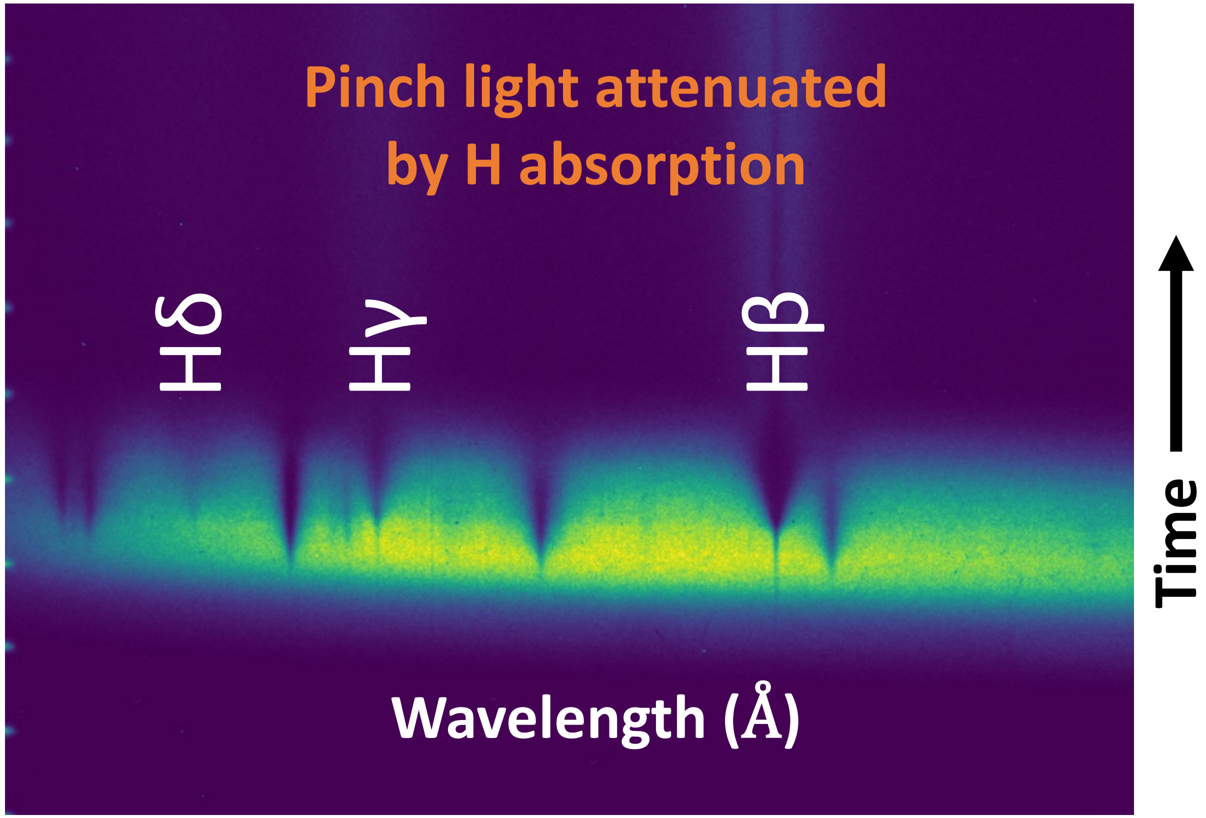
Pinch light successfully fielded as backlight for absorption spectrum

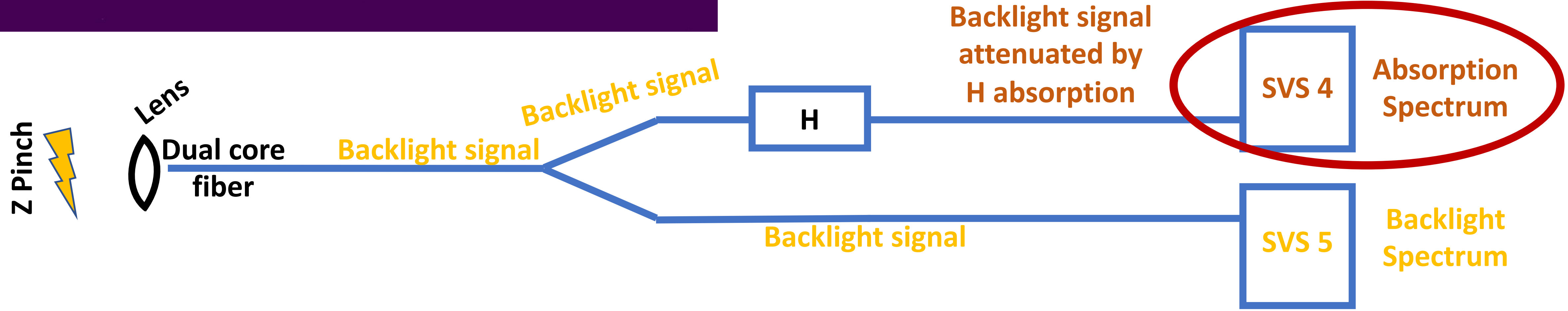
Pinch light direct to SVS





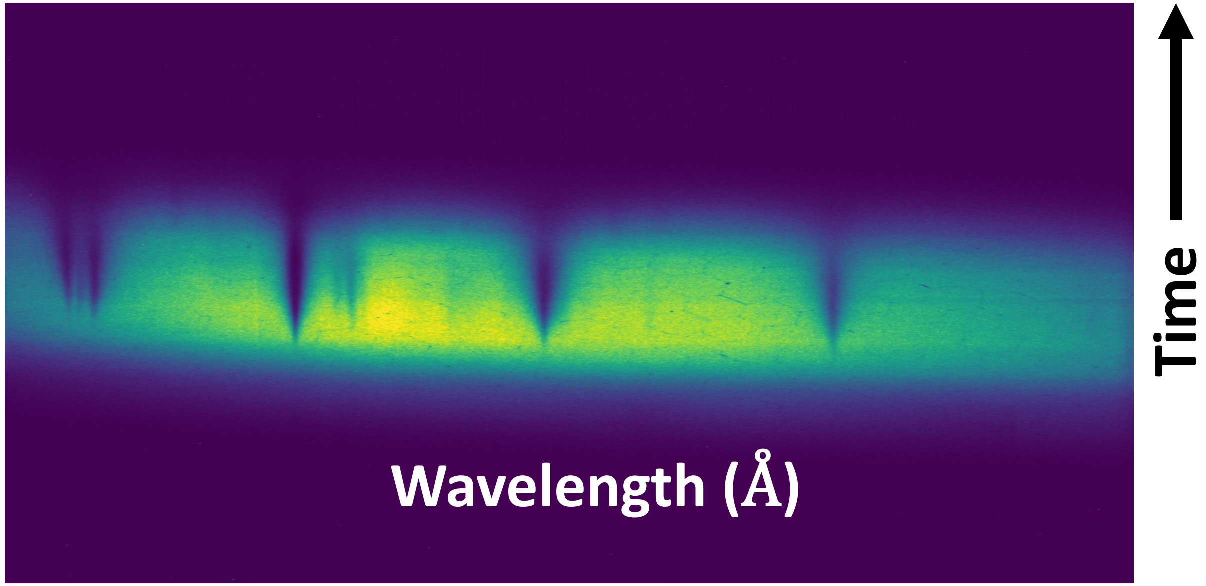
Pinch light successfully fielded as backlight for absorption spectrum

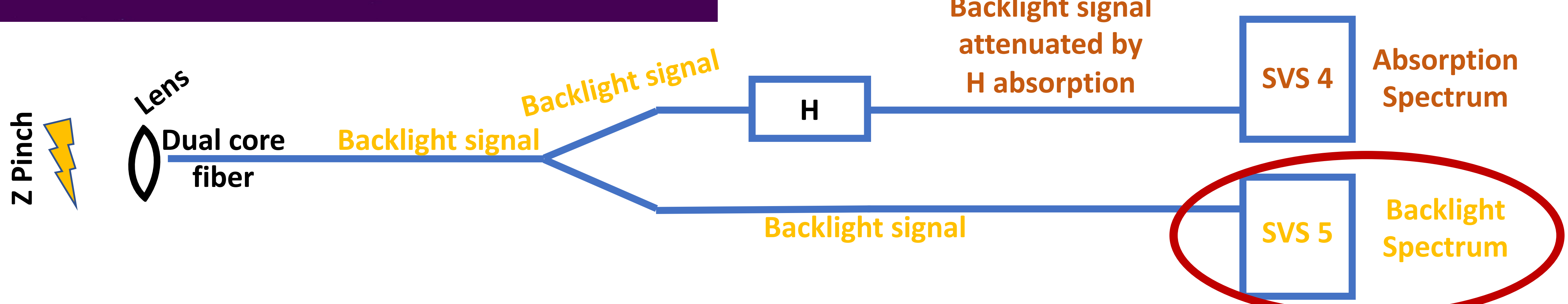




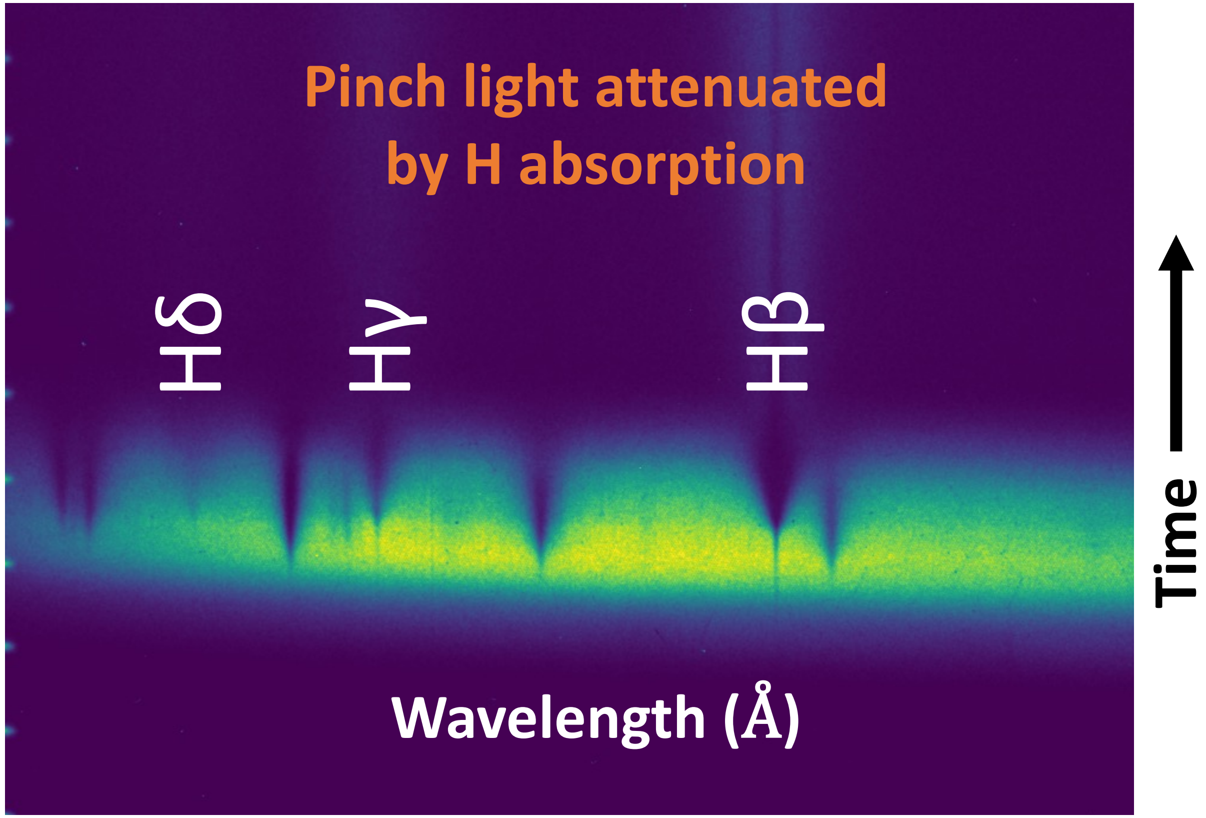
Pinch light successfully fielded as backlight for absorption spectrum

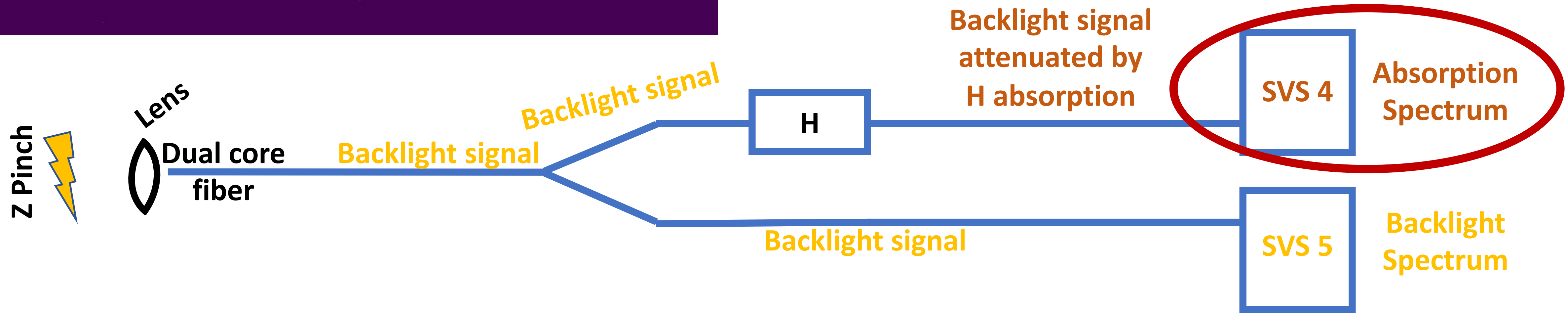
Pinch light direct to SVS



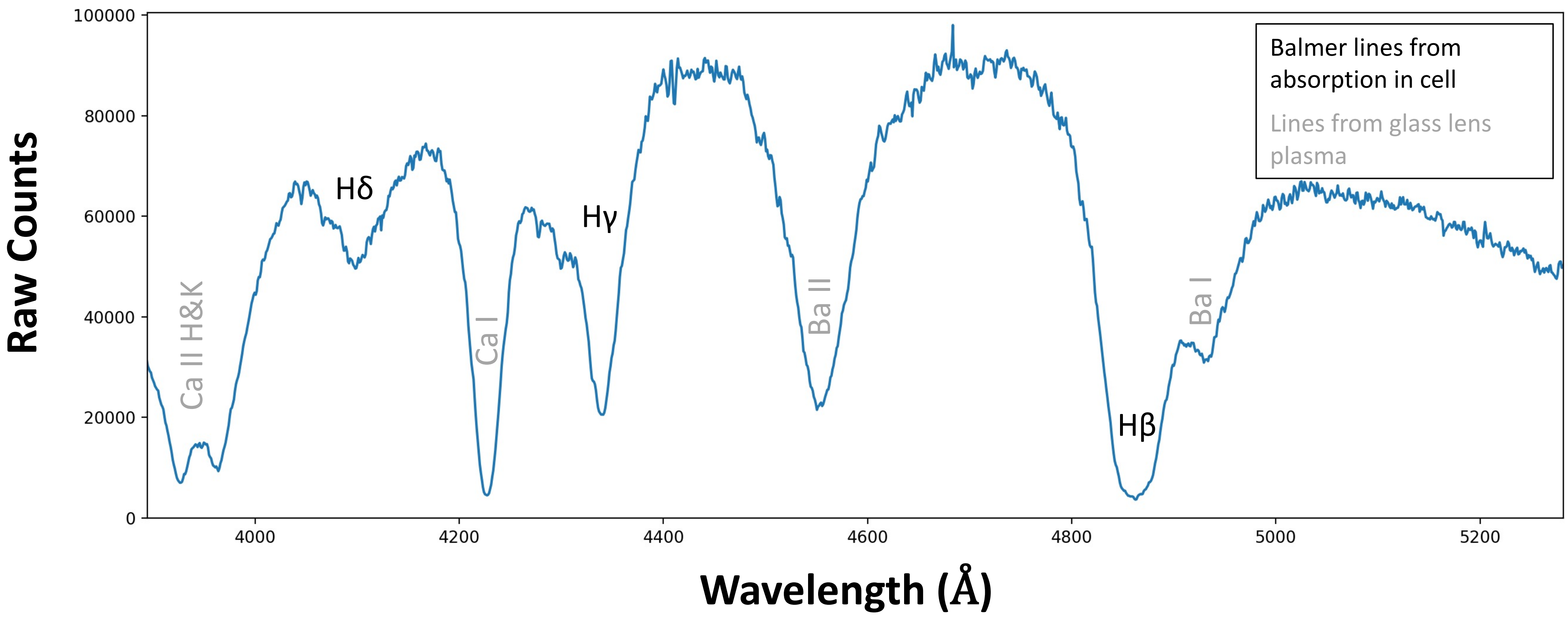


Pinch light successfully fielded as backlight for absorption spectrum





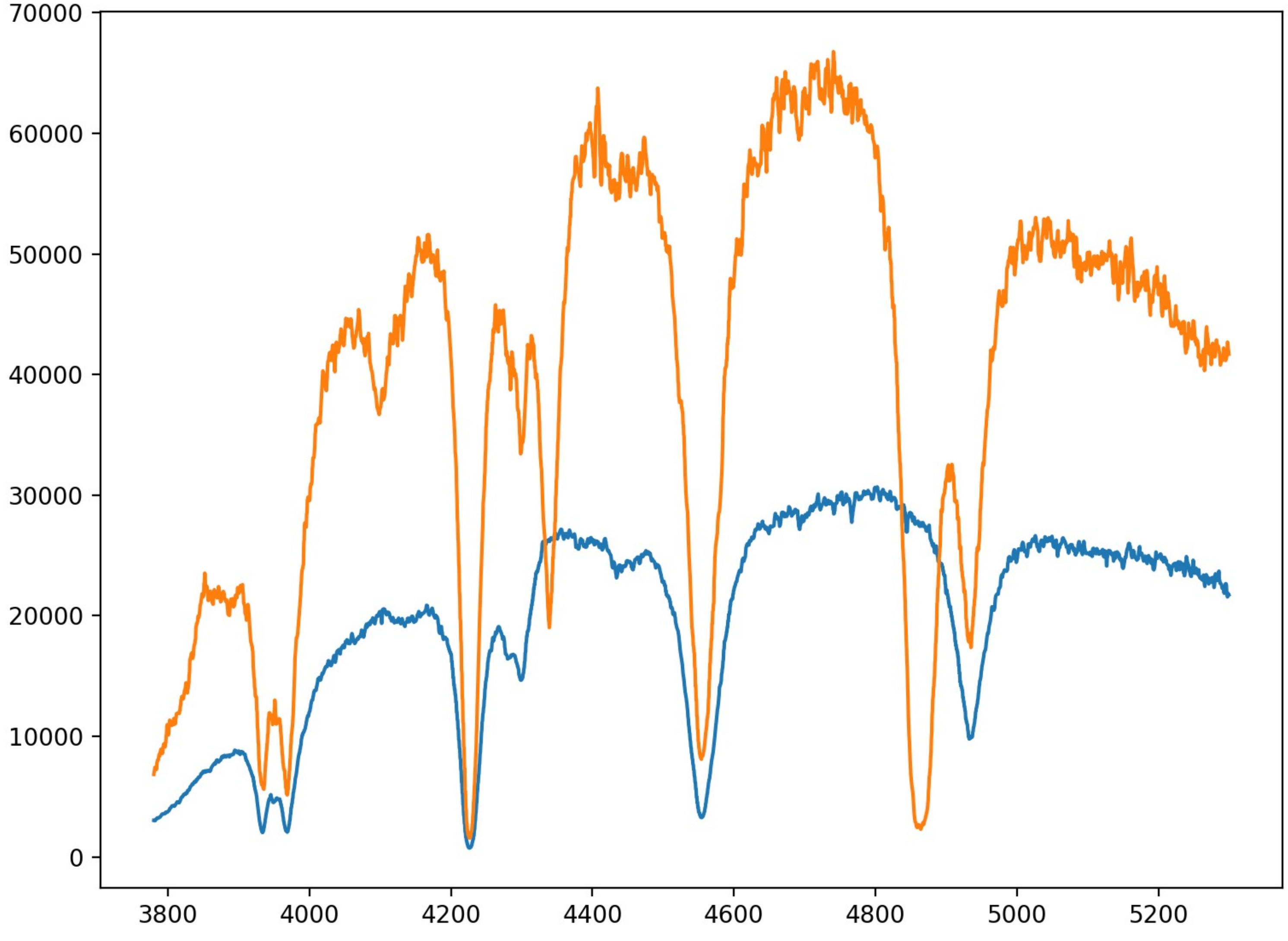
Hydrogen absorption measured with backlight from z pinch



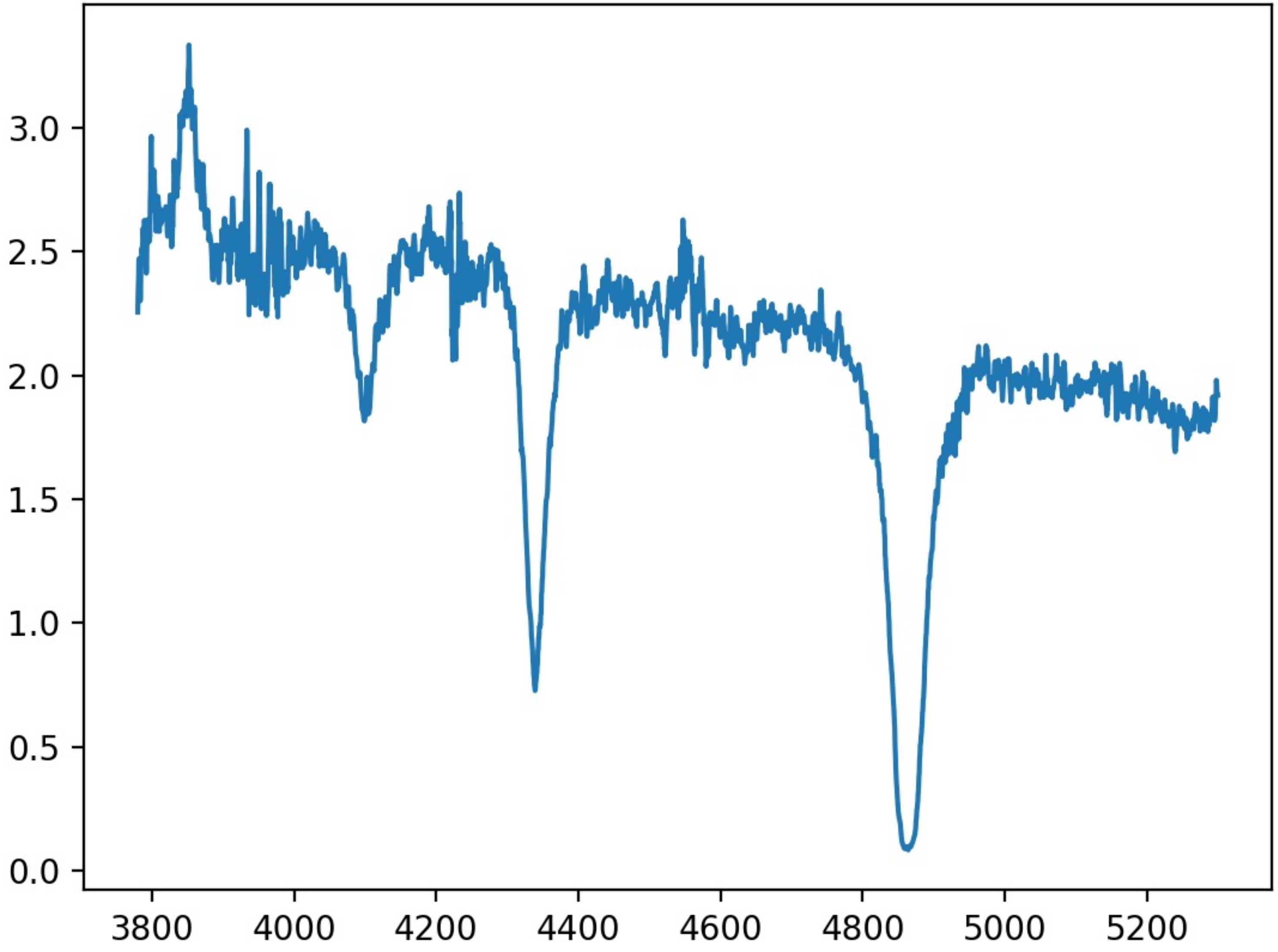
Pinch as backlight enables several possibilities

- It should **increase signal-to-noise** and **remove self-emission uncertainty**
- Allows **absorption measurement at late time** when our standard backlighting wedge has cooled off
- Allows the possibility of **high S/N absorption** measurements along other lines of sight (e.g., downward lines of sight with short plasma lengths)
- With more shielding or distance, we should be able to capture peak brightness for a significant gain in S/N.
- Capturing the peak would also allow for a brief **backlighting pulse,** which could allow **absorption and emission on the same system and LOS**.

Naïve application shows attenuated spectrum brighter than backlight spectrum



Spectral lines from lens are removed ~ well in resulting transmission spectrum



Spectra can be scaled based on early-time data