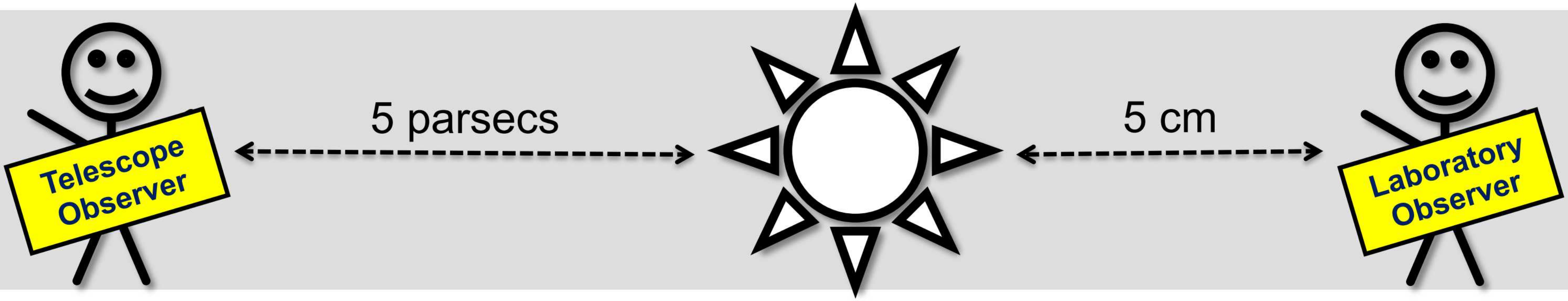
SAND2015-3061PE

Exceptional service in the national interest

Sandia National Laboratories



Creating and Measuring White Dwarf Photospheres in a Terrestrial Laboratory

Ross E. Falcon

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Performing experiments at a major facility requires many talented individuals: here are a few…

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

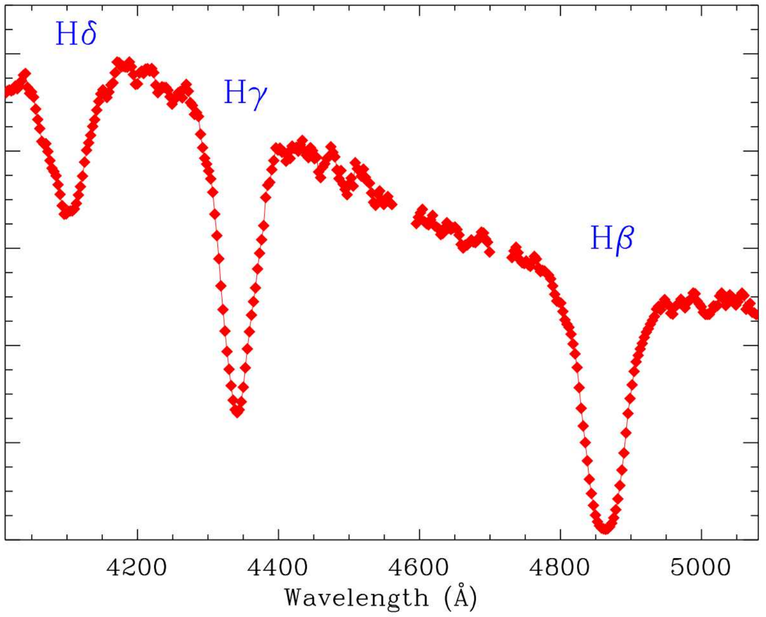
Sandia National Laboratories

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

University of Texas – Austin

Summary: Our experimental platform has matured, produces important results, and continues to develop

- Theoretical line *shapes* used by white dwarf astronomers are valid for Hβ
  - What about higher-order lines?
- We also measure line *strengths* (occupation probabilities)
- We are now exploring other compositions, such as carbon



Nearly all stars are or will become white dwarfs

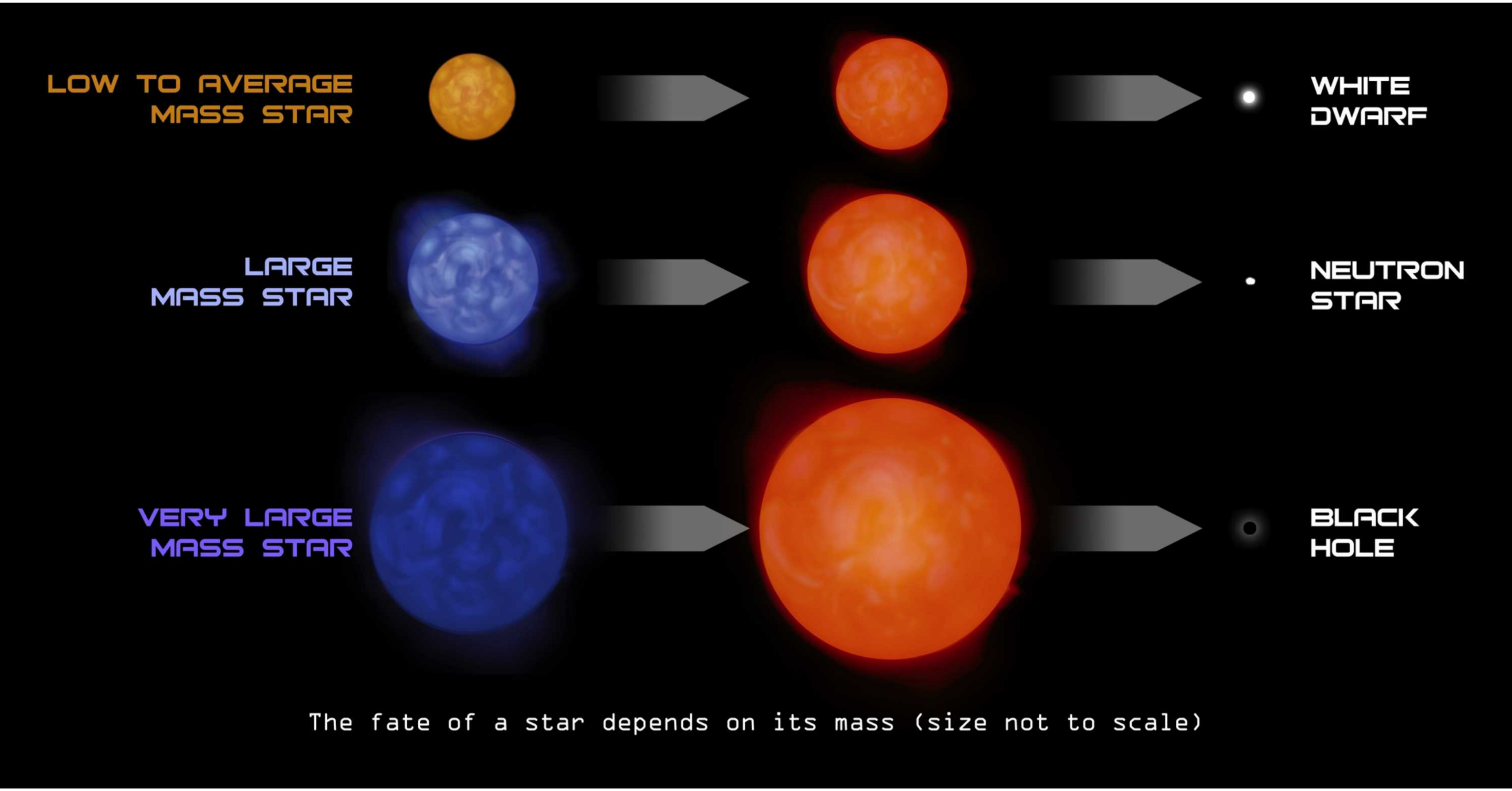
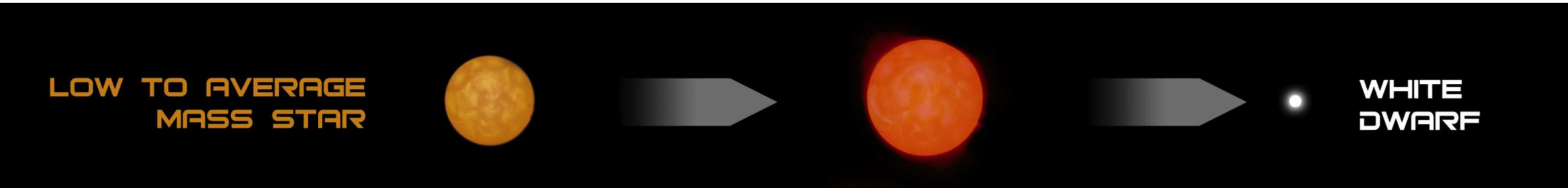


Image: *NASA / CXC/ M. Weiss*

Nearly all stars are or will become white dwarfs



- End point of stellar evolution for most stars, including our Sun
- Compact object
  - $\approx 2/3\ M_{\mathrm{Sun}}$, $\approx 1\ R_{\mathrm{Earth}}$
  - Electron degenerate core, stratified envelope
- Relatively simple
  - No nuclear fusion in core
  - Electron-degeneracy pressure provides support against gravity
  - Star cools with time
  - Foundation for much more science

Image: *NASA / CXC/ M. Weiss*

White Dwarf Atmospheric Parameters

- Effective temperature (T_{eff})
- Surface gravity (log g)
- Mass (M)
- Composition

Cosmochronology

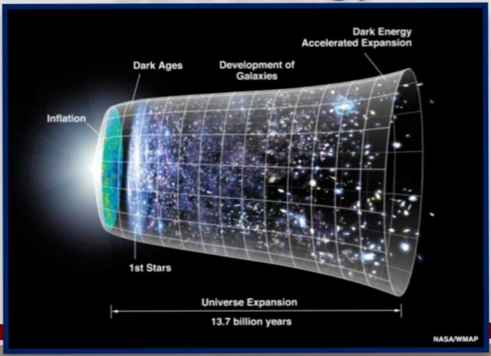
Image: FORS, 8.2-m VLT Antu, ESO

Type Ia Supernovae

Illustration: David T Hardy

Intergalactic Distances

Dark Energy



Graphic: *NASA / WMAP*

Asteroseismology

Nuclear Fusion

Dark Matter

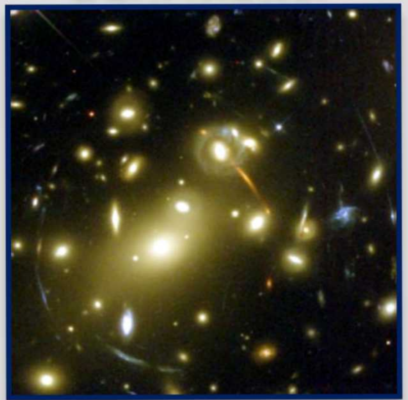


Image: *NASA / A. Fruchter / STScI*

EOS

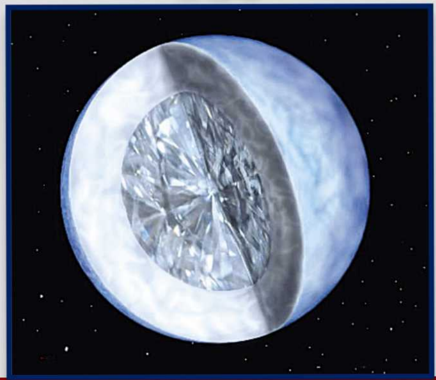


Illustration: Harvard-Smithsonian Center for Astrophysics/Travis Metcalfe, Ruth Bazinet

Fit spectral lines to infer WD atmospheric parameters

- Compare observed spectra with synthetic spectra from WD atmosphere models
- The *spectroscopic method* (see, e.g., Bergeron et al. 1992) is :
  - Precise
    - $\delta T_{\mathrm{eff}}/T_{\mathrm{eff}} \sim 5\%$
    - $\delta \log g/\log g \sim 1\%$
  - Widely used; more than 30,000 WDs
    - Palomar-Green Survey
    - Sloan Digital Sky Survey
    - SPY

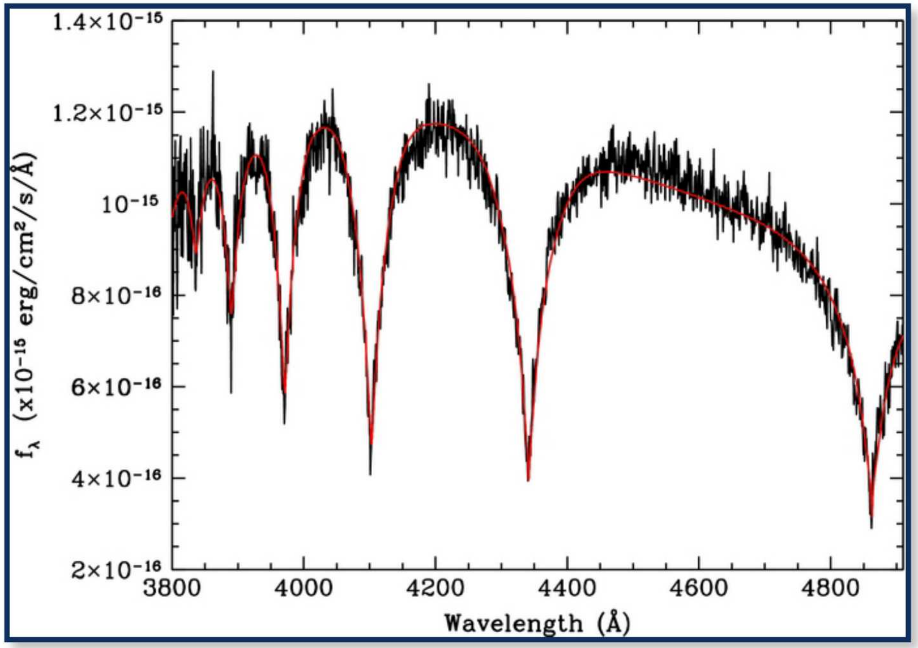


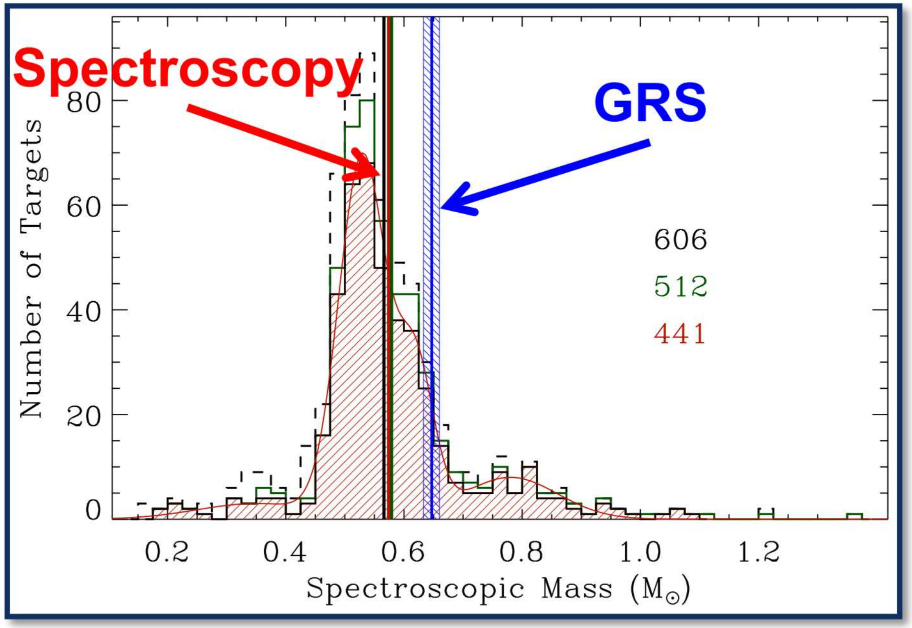
Figure from Hermes et al. (2011): KPNO spectrum of WD J1916+3938

Newer line profiles infer larger masses

- Stark-broadened H line profiles (Tremblay & Bergeron 2009) result in systematic increases:
  - $\Delta T_{\mathrm{eff}} \sim 200$—$1000$ K
  - $\Delta \log g \sim 0.04$—0.1
  - $\Delta M \sim 0.03\ M_{\mathrm{Sun}}$
  - For 250 WDs from the Palomar-Green Survey
- In WD community, Tremblay & Bergeron (TB) line profiles now replaced Vidal, Cooper, & Smith (1973; VCS) profiles as tabulated by Lemke (1997)

Mean mass from gravitational redshift disagrees with the spectroscopic method

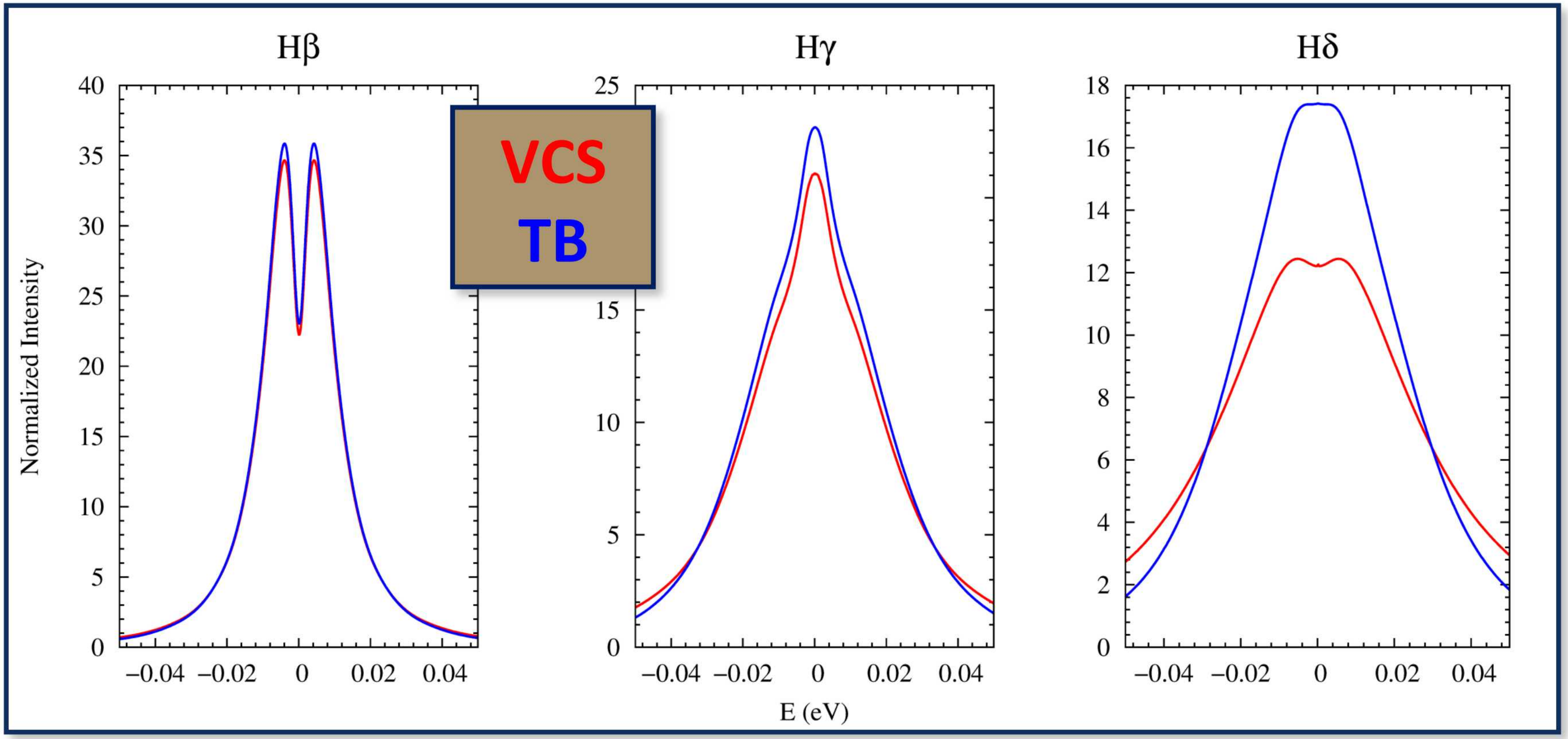
- Gravitational-redshift method independent from line profiles
- GRS
  - <M> = 0.649 +/- 0.014 M_{Sun}
  - 449 DA stars
- Spectroscopy
  - <M> = 0.575 +/- 0.002 M_{Sun} using VCS profiles
  - <M> ~ 0.61 M_{Sun} using TB profiles
  - 441 DA stars



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

Are the line profiles used in WD atmosphere models accurate?

VCS and TB profiles disagree with increasing principal quantum number, *n*, and with increasing electron density, n_e



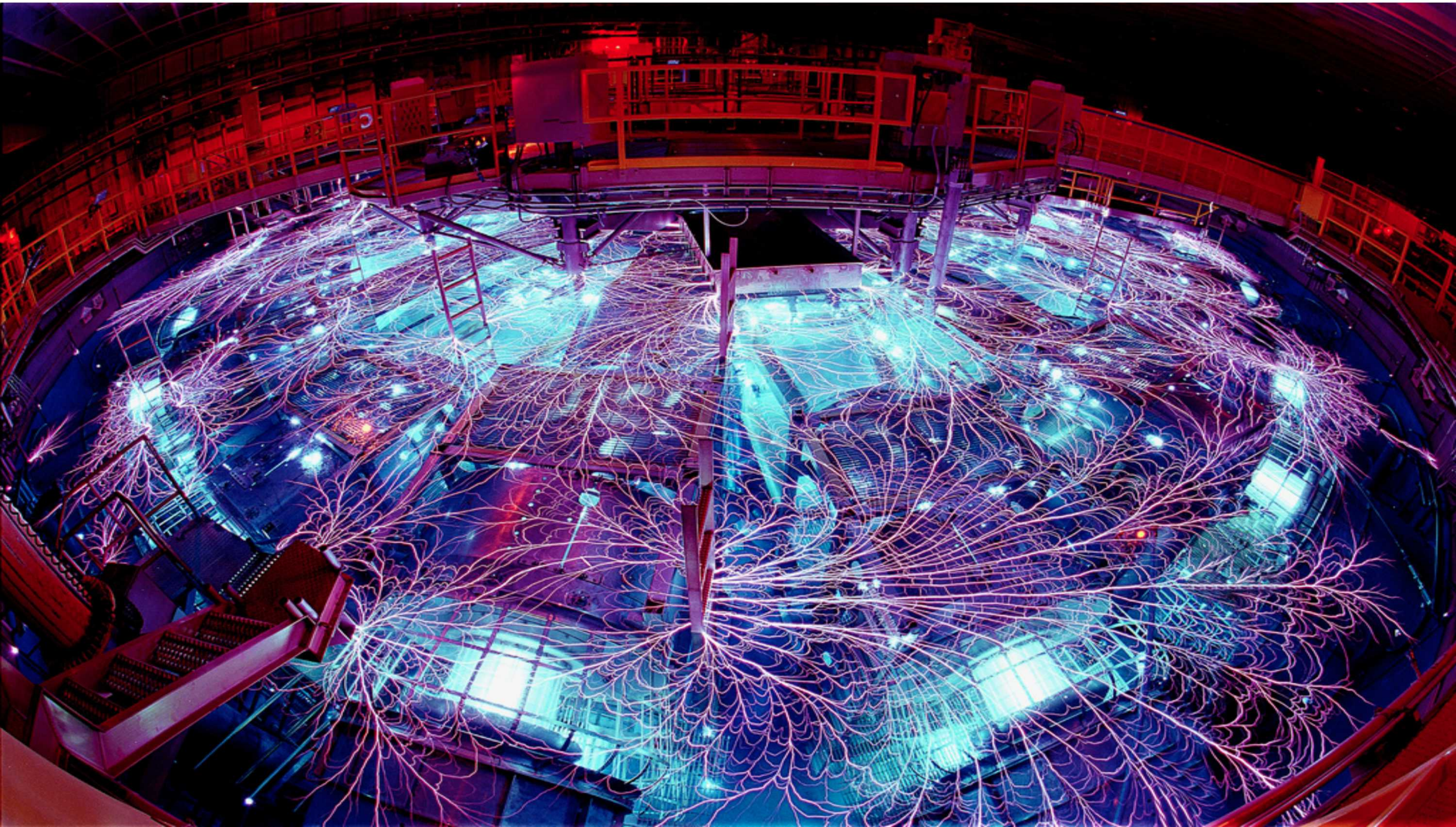
Calculated at T_e = 1 eV and $n_e = 10^{17}$ cm^{-3}

We can test these line shapes in the laboratory

- Measure *multiple* Balmer lines *simultaneously* at a range of electron density, n_e
  - Use Hβ to diagnose plasma conditions
  - Include up to at least Hδ

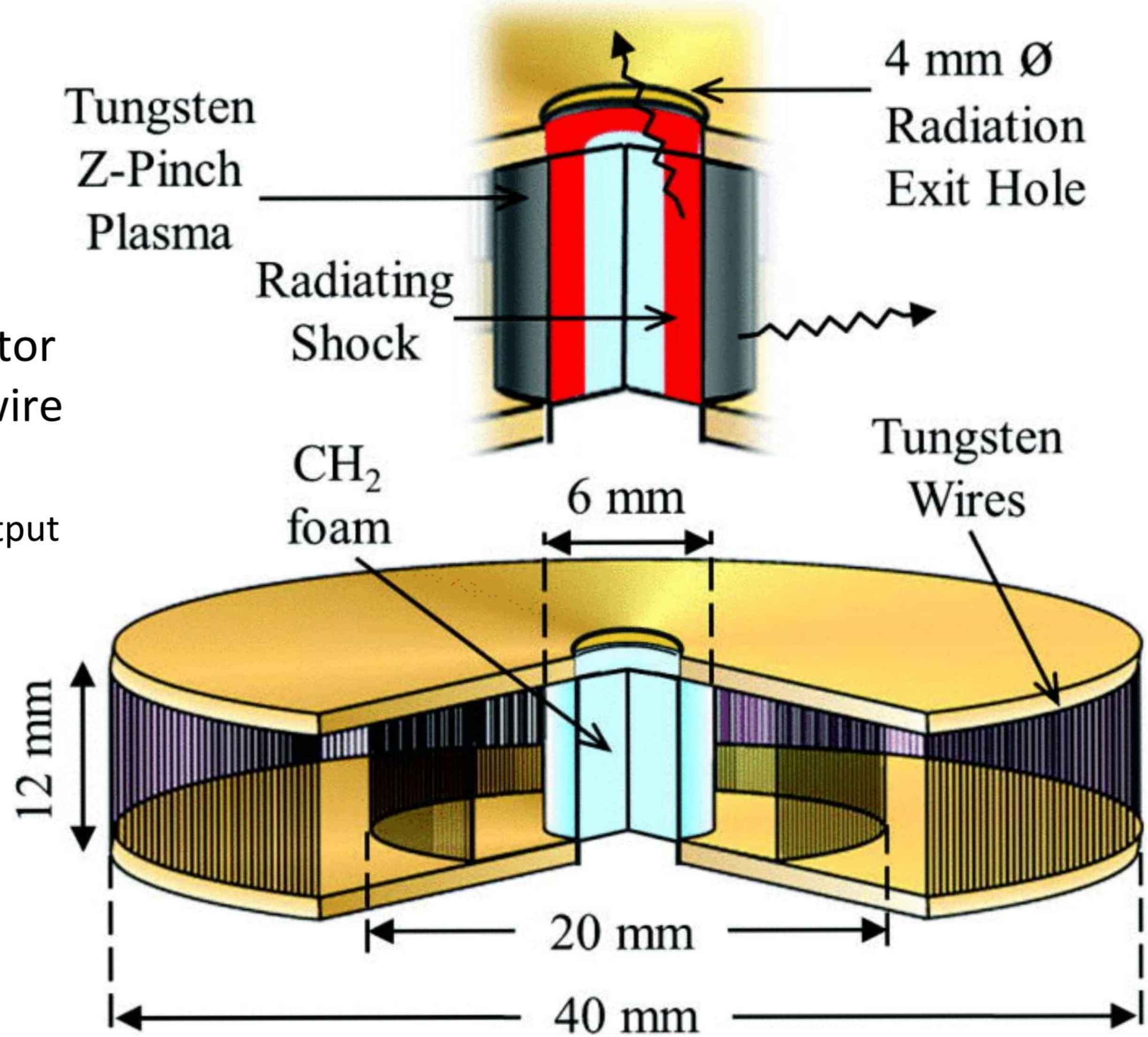
- Use Wiese et al. (1972) to validate ($n_e < 10^{17}$ cm^{-3}), then extend to higher n_e ($> 10^{17}$ cm^{-3})
  - Arc-discharge experiment
  - Benchmark for H line shapes for >40 years
  - Only experiment to measure multiple H Balmer lines at these conditions

Welcome to the Z Pulsed Power Accelerator



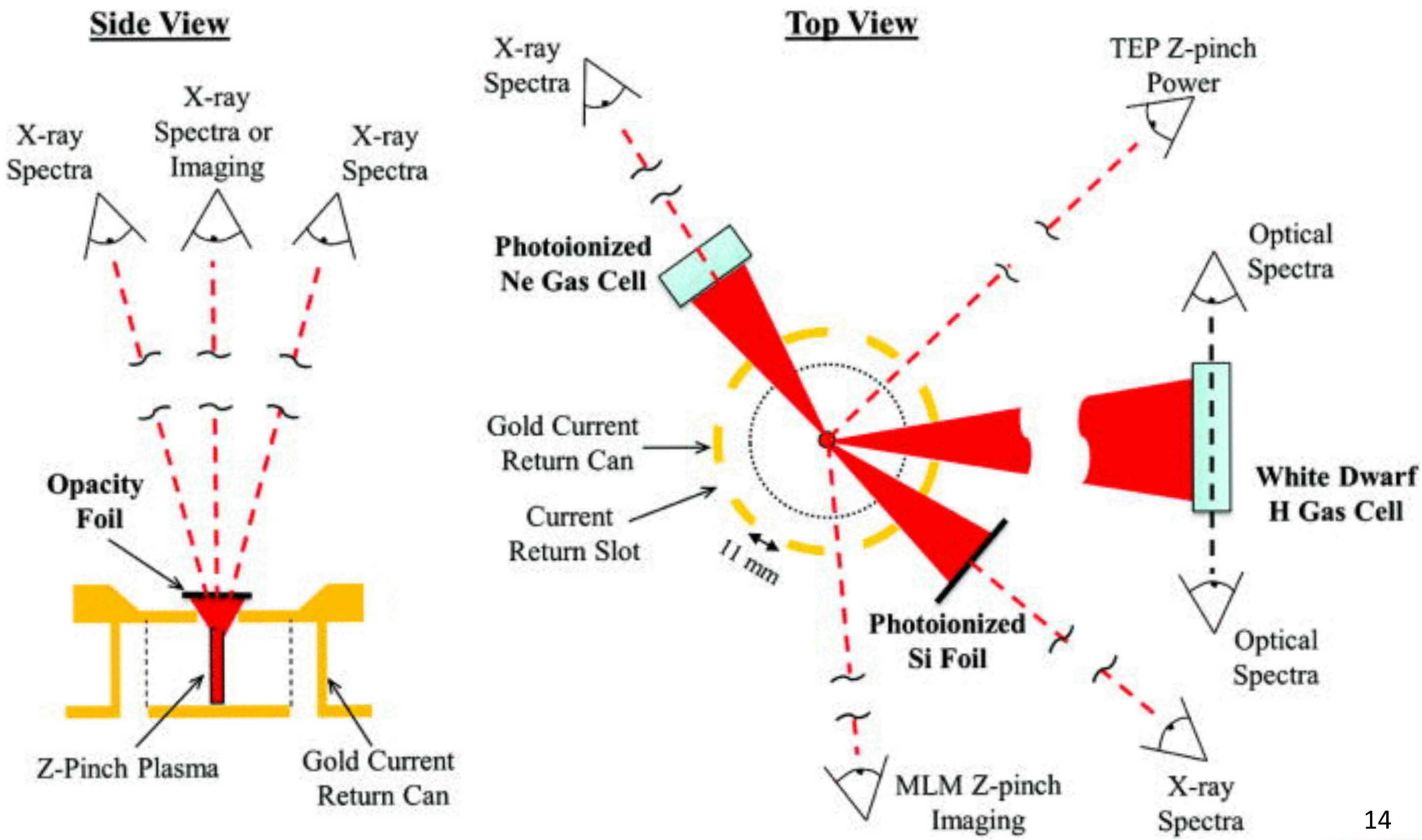
Z-pinch dynamic hohlraum as an x-ray source

- Pulsed power accelerator delivers ~26 MA to a wire array
  - ~1.6 MJ radial x-ray output
  - Peaks at ~220 TW
  - <4 ns FWHM



e.g., Sandford et al. (1999), *Phys. Rev. Lett.*, **83**, 5511; Bailey et al. (2006), *Phys. Plasmas*, **13**, 056301

X-ray source simultaneously drives multiple experiments



Rochau et al. (2014), *Phys. Plasmas*, **21**, 056308

X-ray source simultaneously drives multiple experiments

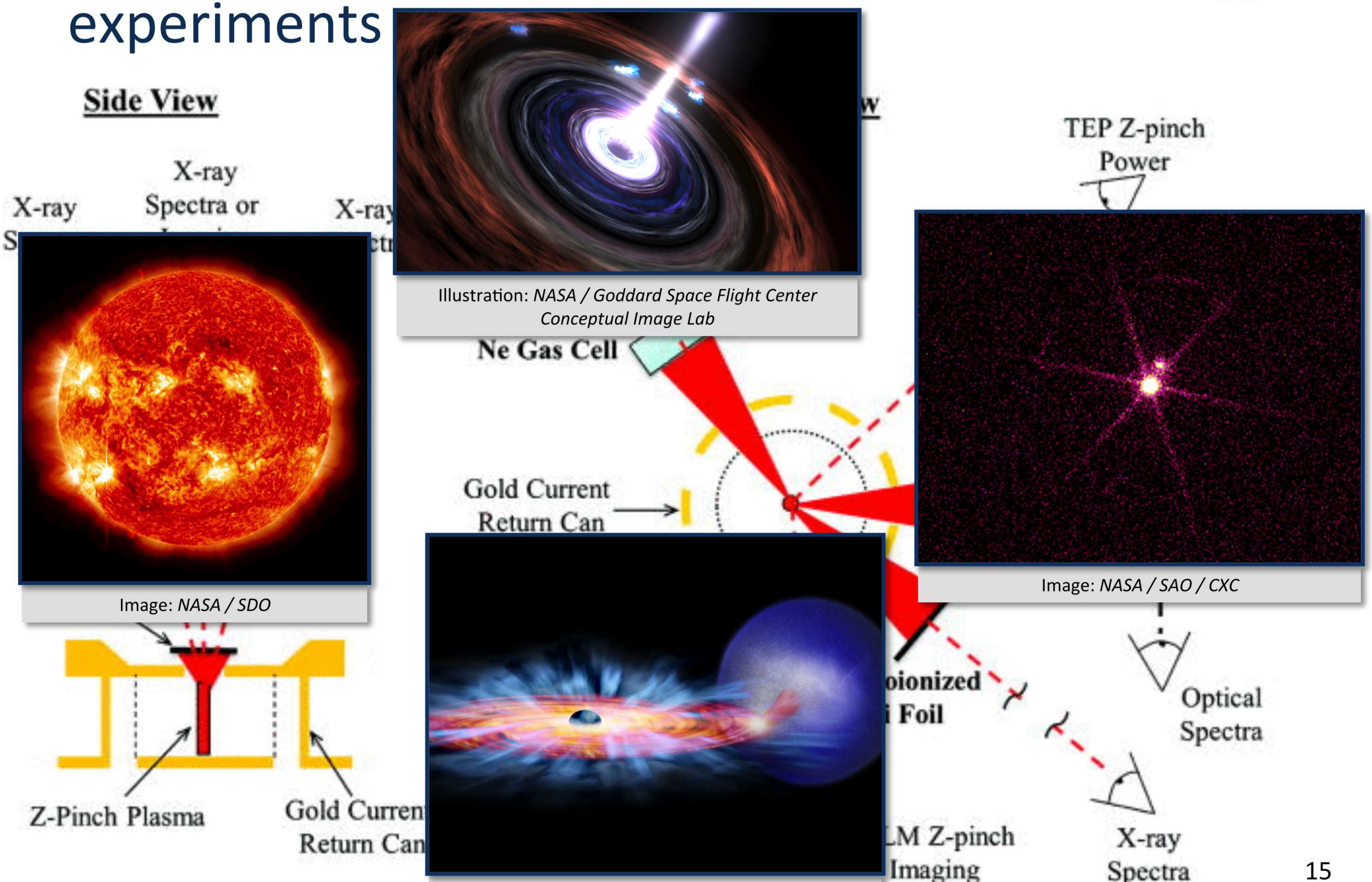


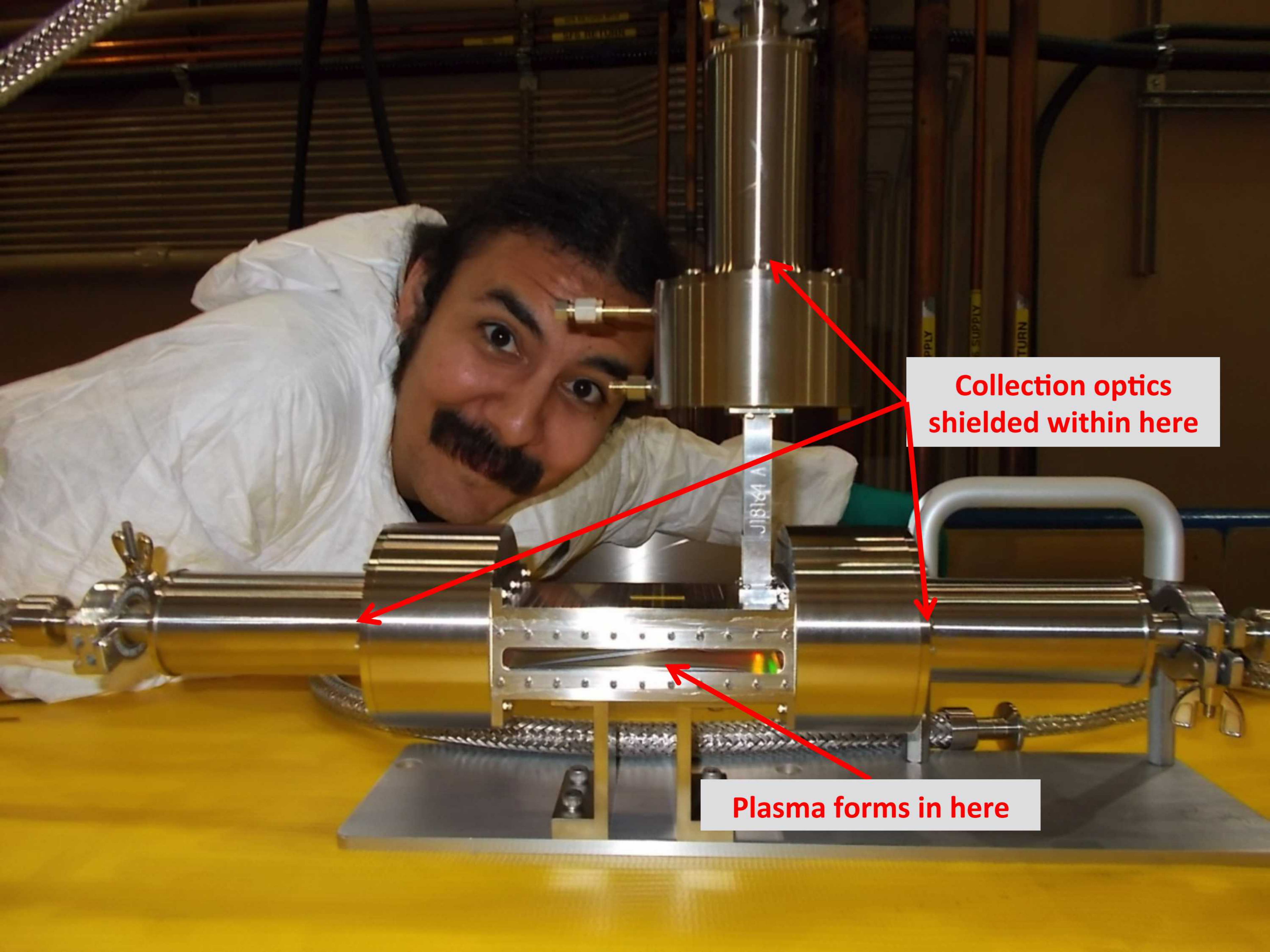
Illustration: *NASA / Goddard Space Flight Center Conceptual Image Lab*

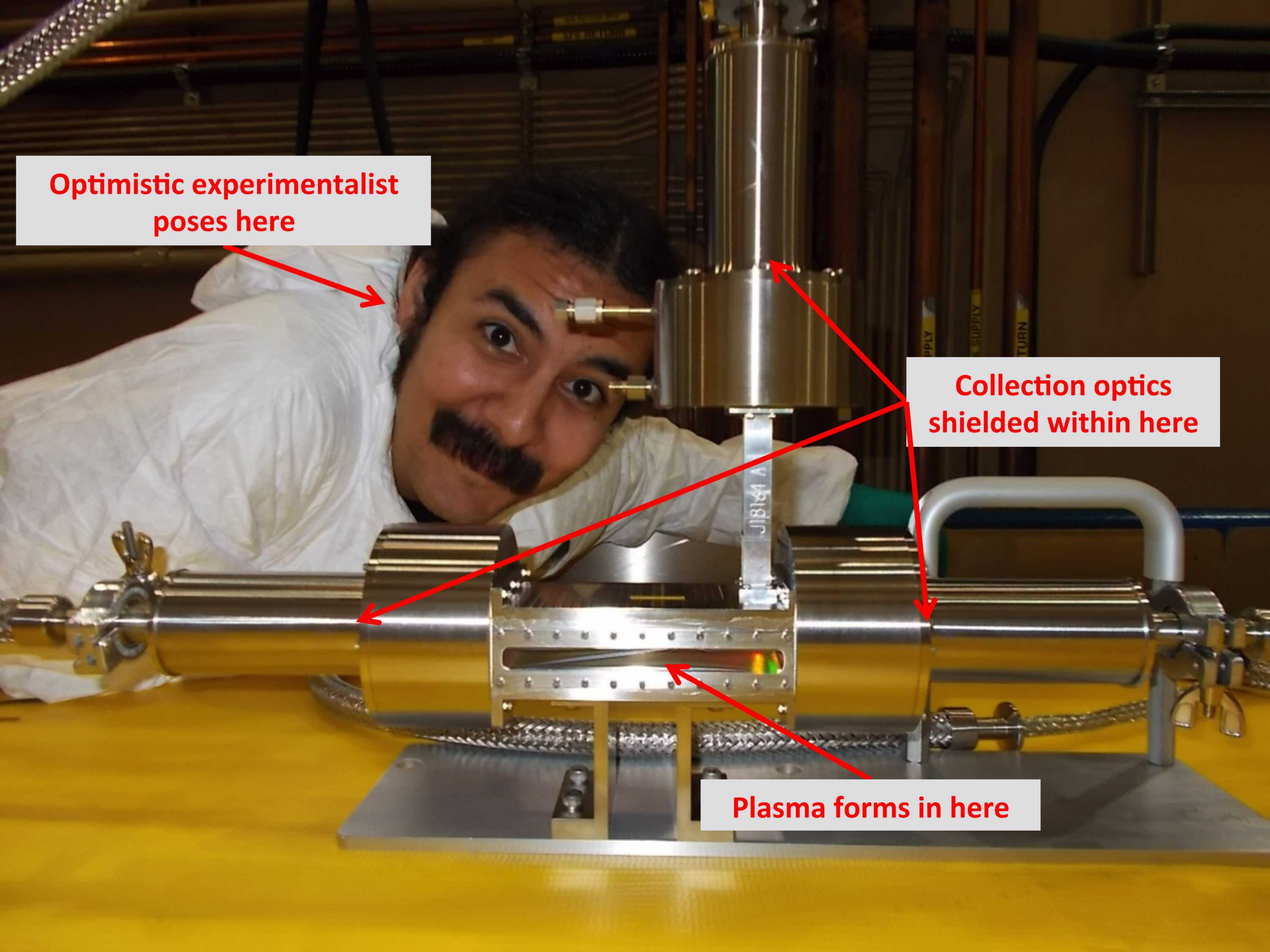
Image: *NASA / SDO*

Image: *NASA / SAO / CXC*

Illustration: *NASA / CXC / M. Weiss*

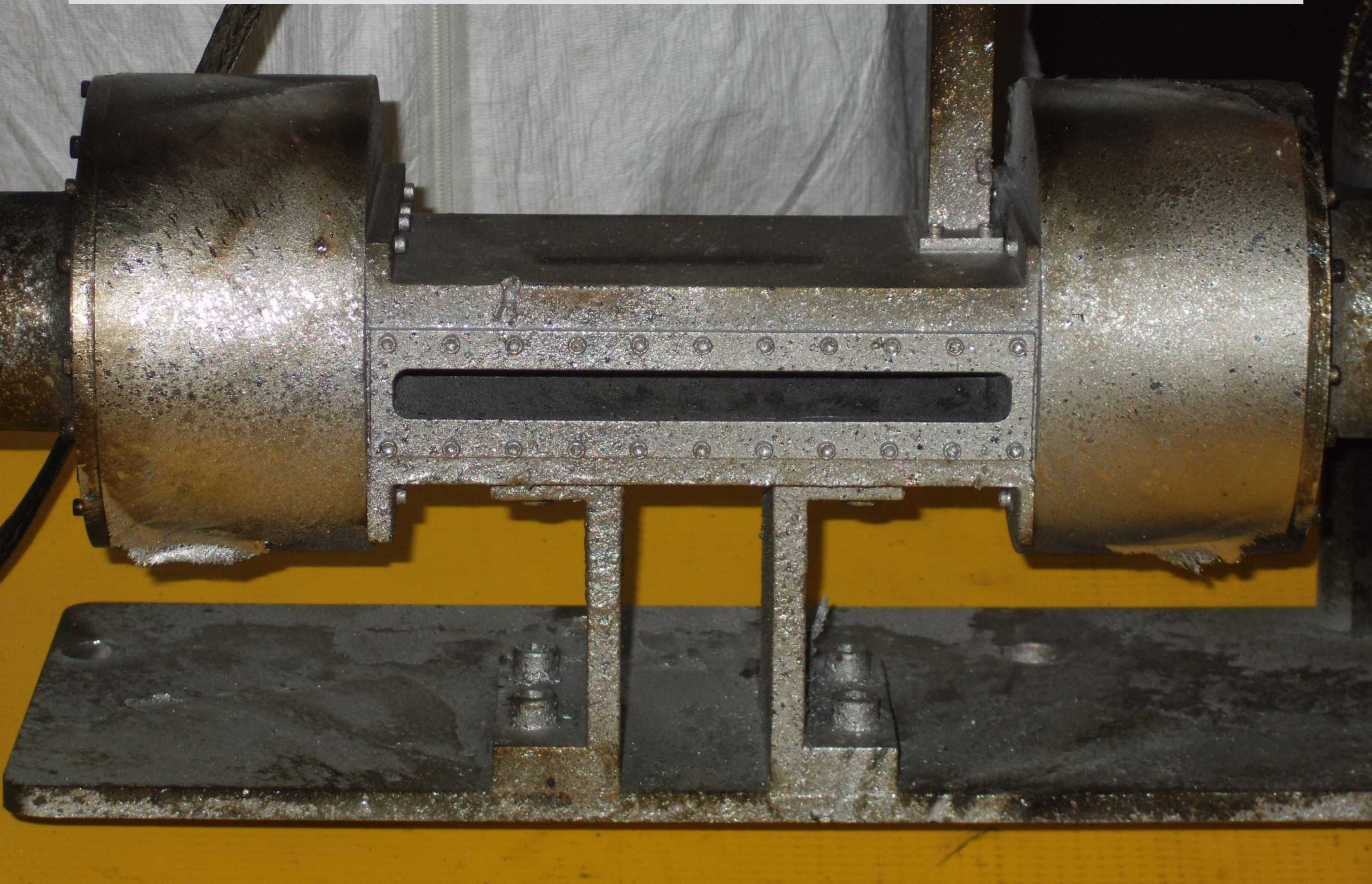

SF6 SUPPLY
SF6 SUPPLY
MARX RETURN


Collection optics
shielded within here
Plasma forms in here


Optimistic experimentalist poses here
Collection optics shielded within here
Plasma forms in here


DuPont
Tyvek

Gas cell littered with debris – the hardware remains from the other experiments

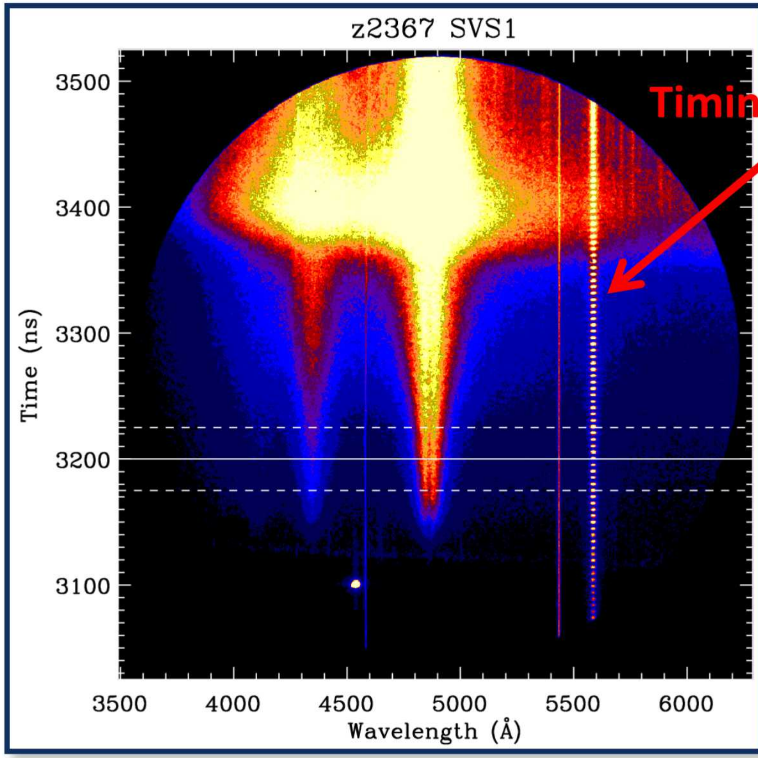


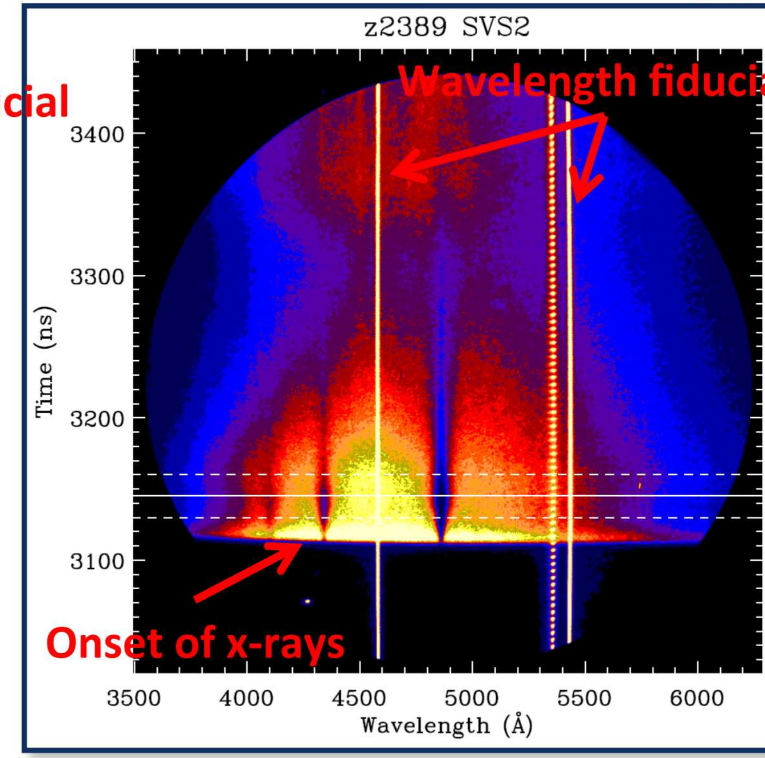
Sandia National Laboratories

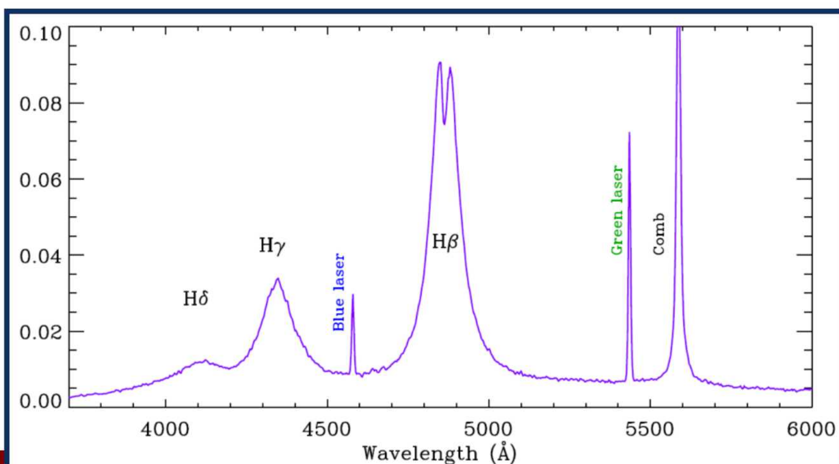
Emission

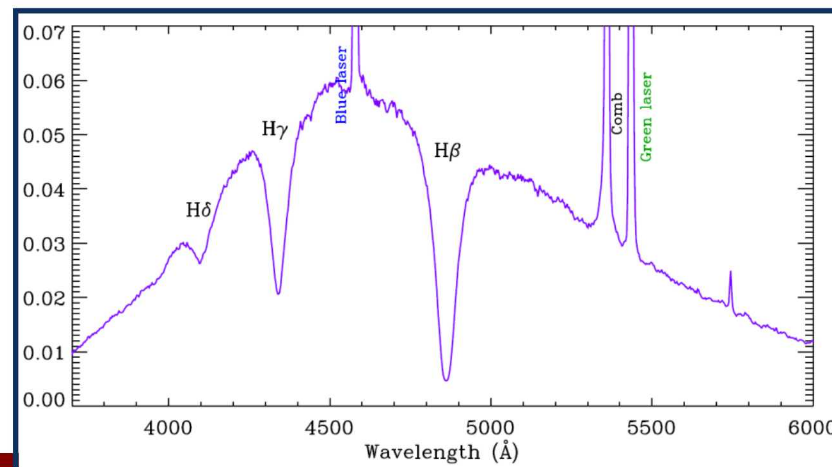
Absorption

Time

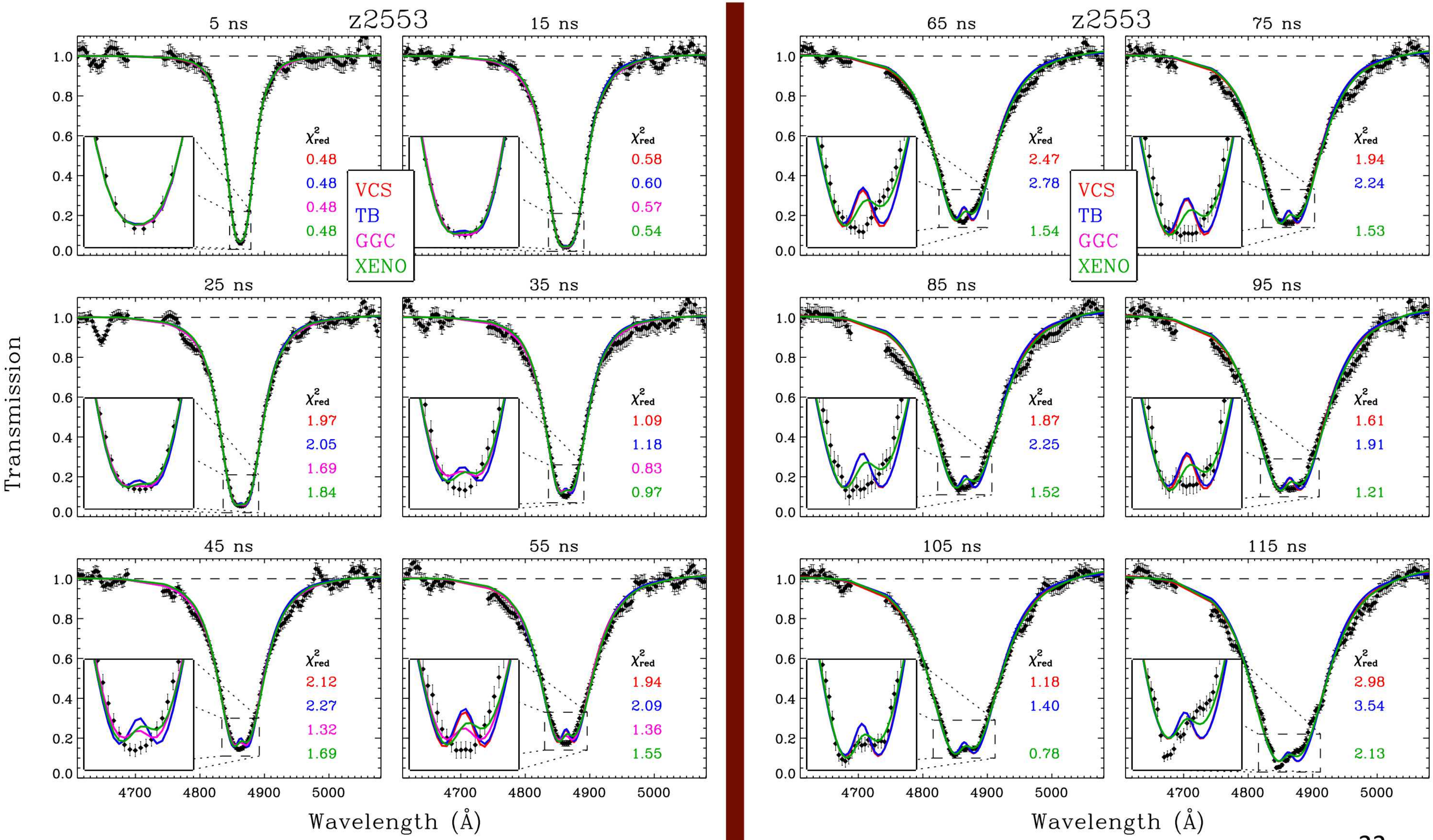








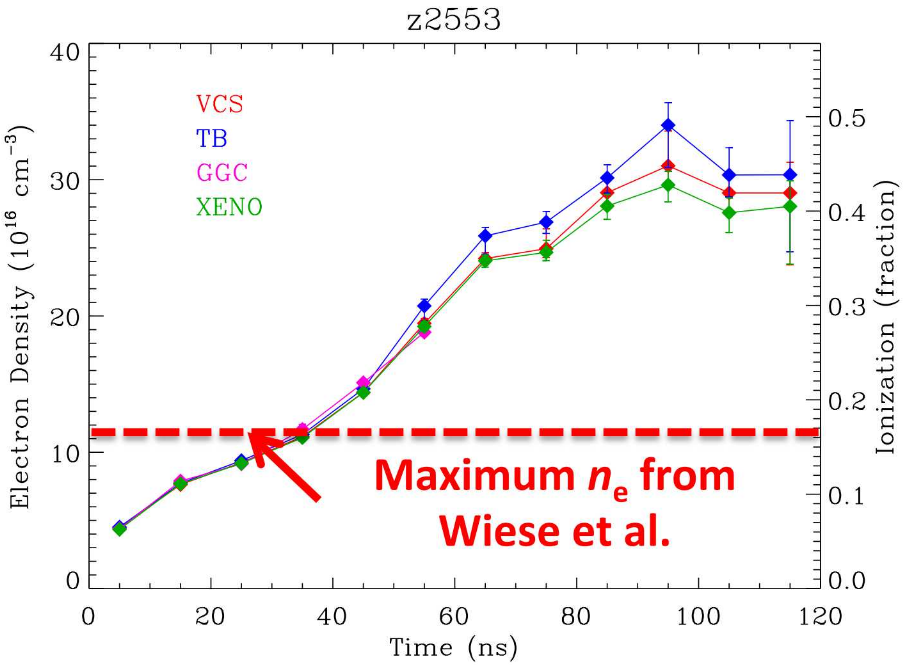
We measure and fit the Hβ transmission line throughout the duration of our experiment

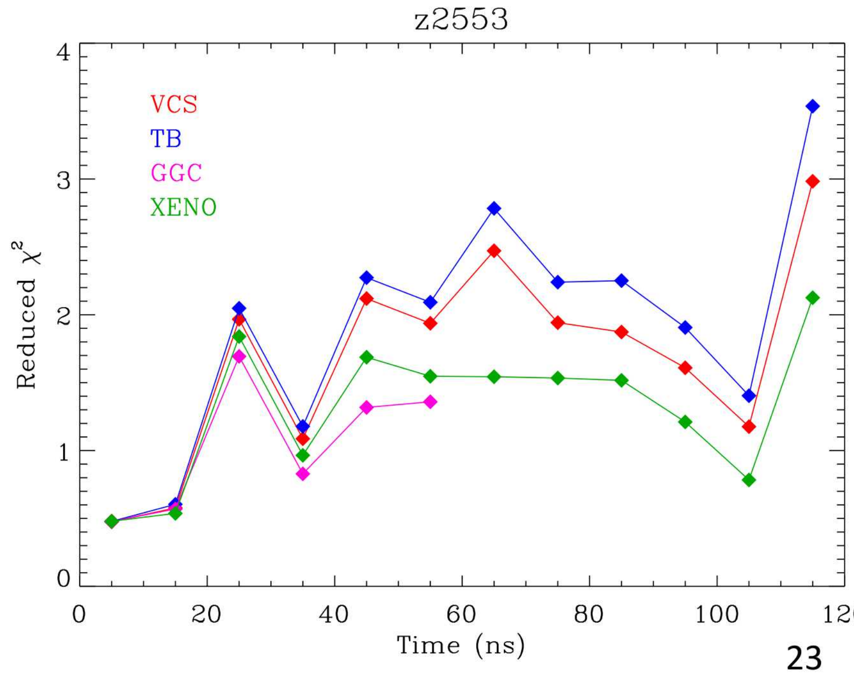


Falcon et al. (2015), *ApJ*, submitted

We span a range of electron densities

- Theoretical line profiles used in WD astronomy community (VCS, TB) do ***not*** fit as well as others
  - Computer-simulated calculations
  - i.e., Gigosos et al. (2003, GGC), Gomez et al. (Xenomorph)
- BUT, the inferred conditions ***agree***!
  - Analogous to surface gravity

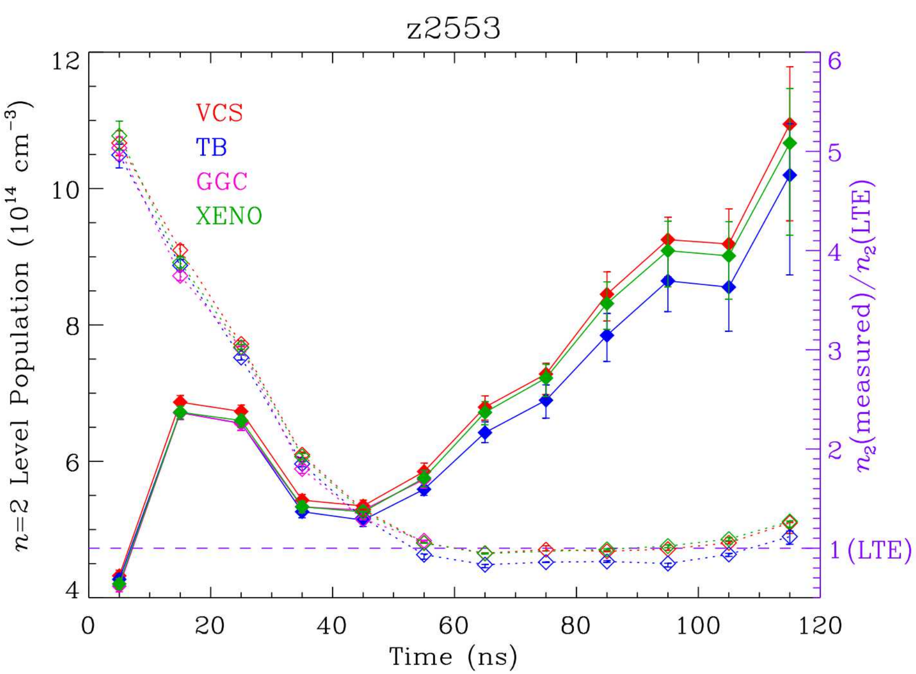


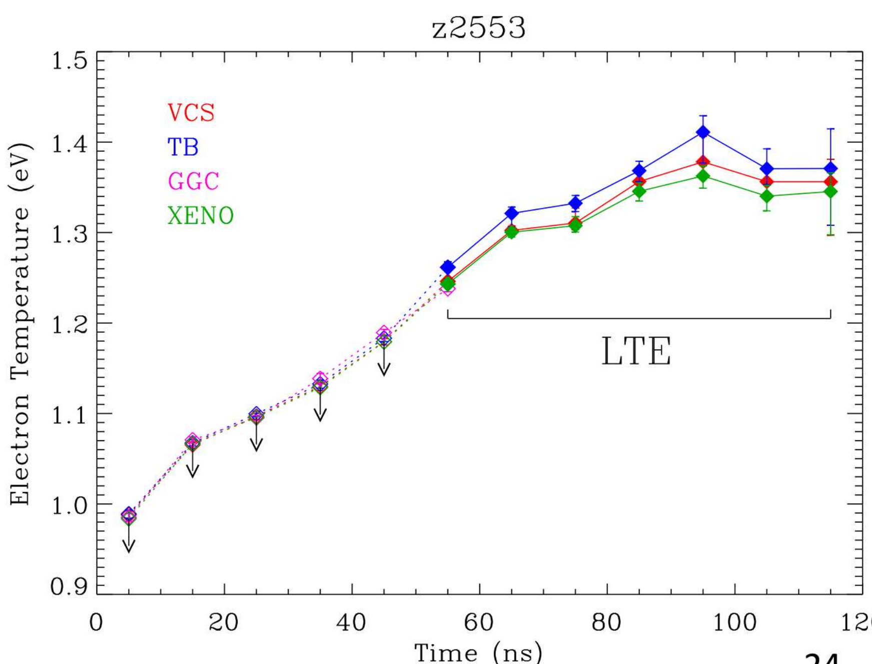


Falcon et al. (2015), *ApJ*, submitted

Our diagnosis continues

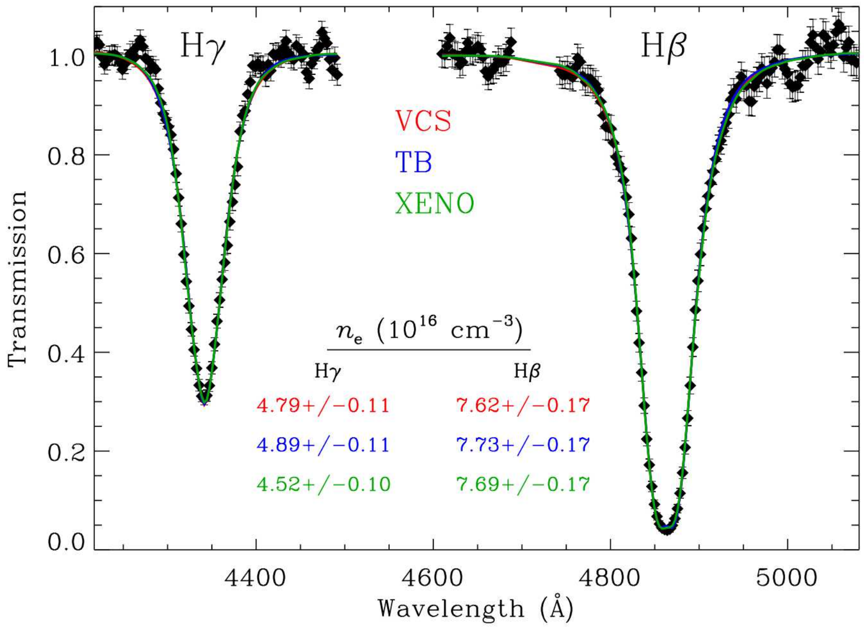
- Lower (n=2) level population, n_2, allows us to infer electron temperature, T_e
  - Measured line strength includes a measurement of occupation probabilities! (I'll come back to this)
- We witness our plasma relax into LTE



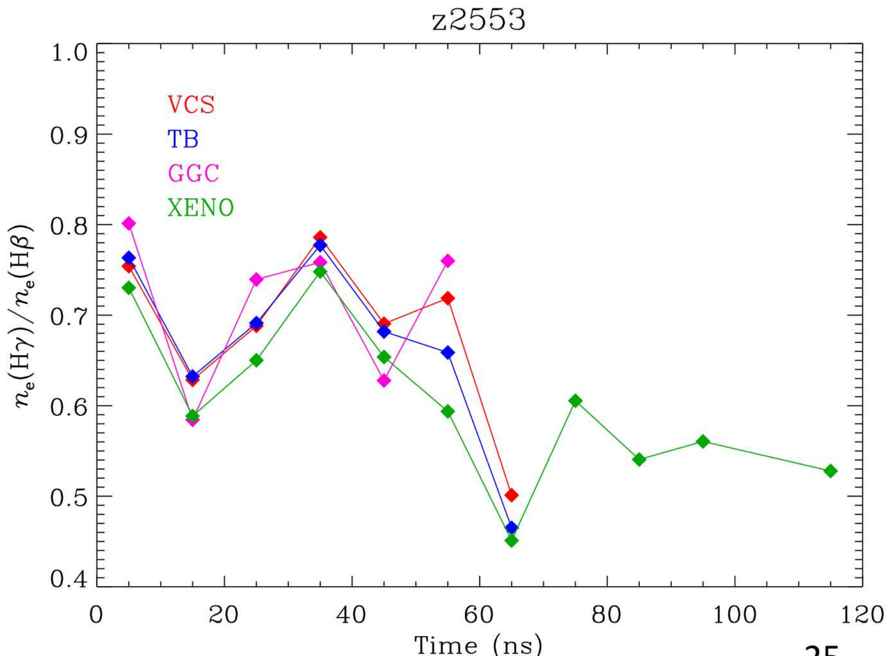


Falcon et al. (2015), *ApJ*, submitted

Our fits to Hβ and Hγ do not infer consistent plasma conditions



- Hγ systematically underestimates electron density, n_e, by 20—40 %
  - This implies Hγ profile is too wide



- Currently investigating possible systematic experimental uncertainties
  - Electron temperature
  - Gradients in plasma conditions

Intriguing trend seen in spectroscopic fits to observed WD spectra

Sandia National Laboratories

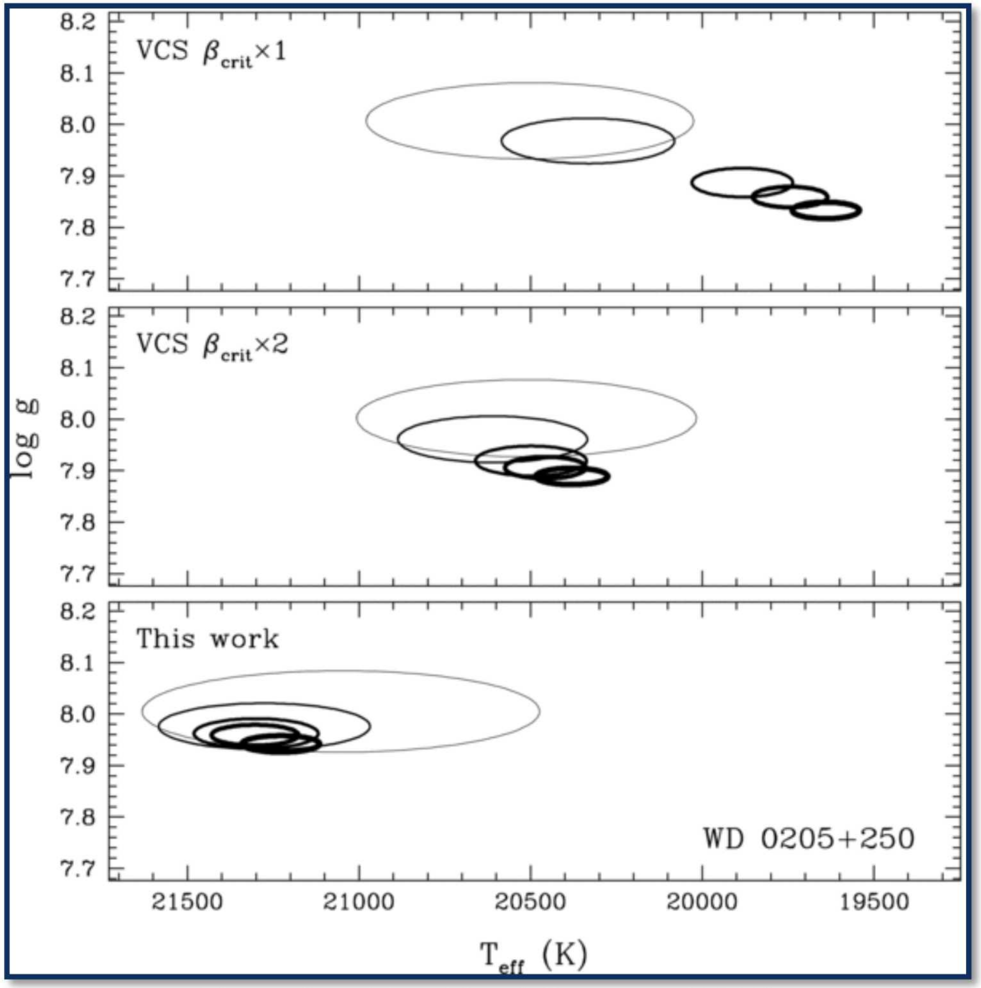


Figure from Tremblay & Bergeron (2009)

- 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

Our data provide new, unique measurements of occupation probabilities

- We measure transmission lines:

Opacity

$$T = e^{-\kappa L}$$

Length of plasma

Our data provide new, unique measurements of occupation probabilities

- We measure transmission lines:

Opacity

$$T = e^{-\kappa L}$$

Length of plasma

- Neglecting the instrumental convolution, we recover the line strength

$$-\kappa L = \ln(T)$$

Our data provide new, unique measurements of occupation probabilities

- We measure transmission lines:

Opacity

$$T = e^{-\kappa L}$$

Length of plasma

- Neglecting the instrumental convolution, we recover the line strength

$$-\kappa L = \ln(T)$$

- Compare relative line strengths of Hγ and Hβ:

Lower-level population (*because we measure in absorption*)

$$\frac{\kappa^{H\gamma} L}{\kappa^{H\beta} L} = \frac{n_2 f_{2\to5} w_5(n_e)\varphi^{H\gamma}}{n_2 f_{2\to4} w_4(n_e)\varphi^{H\beta}}$$

Normalized line shape

Our data provide new, unique measurements of occupation probabilities

- We measure transmission lines:

Opacity

$$T = e^{-\kappa L}$$

Length of plasma

- Neglecting the instrumental convolution, we recover the line strength

$$-\kappa L = \ln(T)$$

- Compare relative line strengths of Hγ and Hβ:

Lower-level population (*because we measure in absorption*)

$$\frac{\kappa^{H\gamma} L}{\kappa^{H\beta} L} = \frac{\cancel{n_2} f_{2\to 5} w_5(n_e) \cancel{\varphi^{H\gamma}}}{\cancel{n_2} f_{2\to 4} w_4(n_e) \cancel{\varphi^{H\beta}}}$$

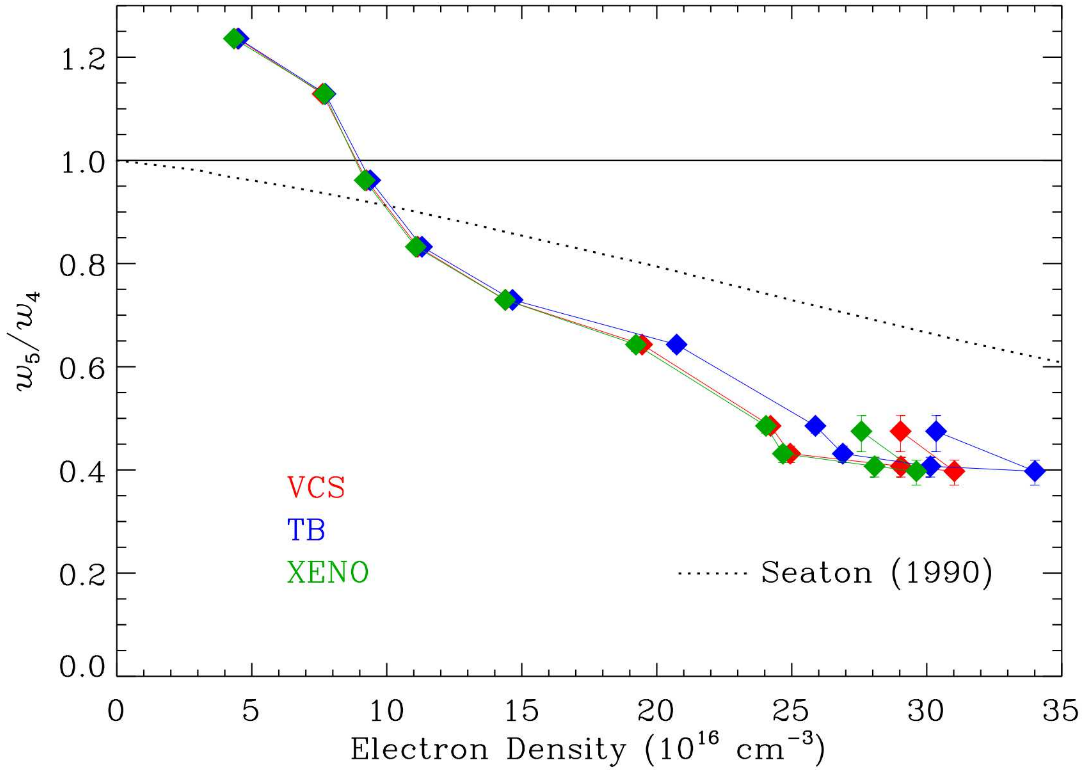
Normalized line shape

- Using measured oscillator strengths (Baker 2008), we are left with ratio of occupation probabilities, w_u!

Our data provide new, unique measurements of occupation probabilities

- Measured curve falls off with n_e more steeply than predicted by Seaton (1990)?

- Values >1 are not physical
  - I suspect artifact of instrumental broadening
  - Currently investigating



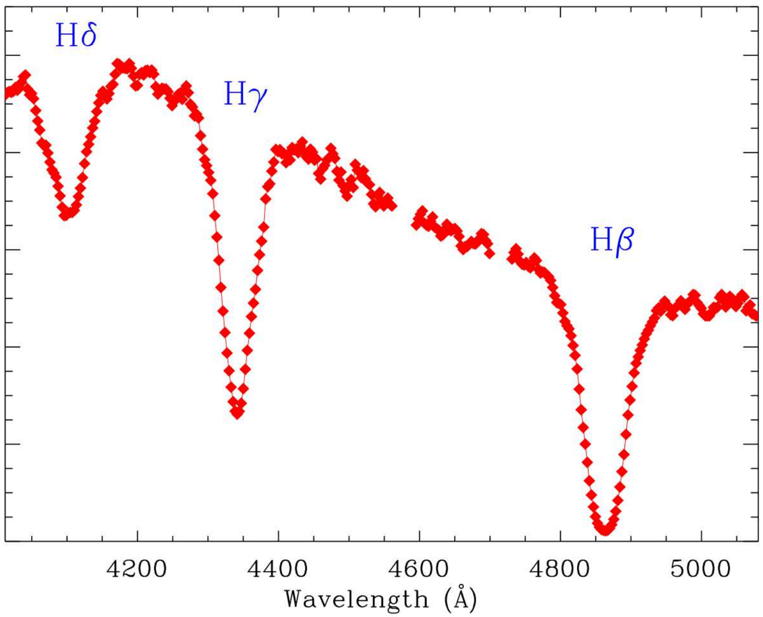
Falcon et al. (2015), in preparation

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

- [place holder for preliminary figures of SVS data from shots z2736, z2740 and z2785]
- [these will show line-outs of molecular/atomic carbon spectral features obtained using the White Dwarf Photosphere Experiment (WDPE) gas cell]

Summary: Our experimental platform has matured, produces important results, and continues to develop

- Theoretical line *shapes* used by white dwarf astronomers are valid for Hβ
  - Higher-order lines (Hγ) seem to infer underestimated n_e
  - True for all theories
- We also measure line *strengths* (occupation probabilities)
  - Preliminary measurement lower than expected by theory
- We are now exploring other compositions, such as carbon



From my hydrogen gas cell and me, thank you!

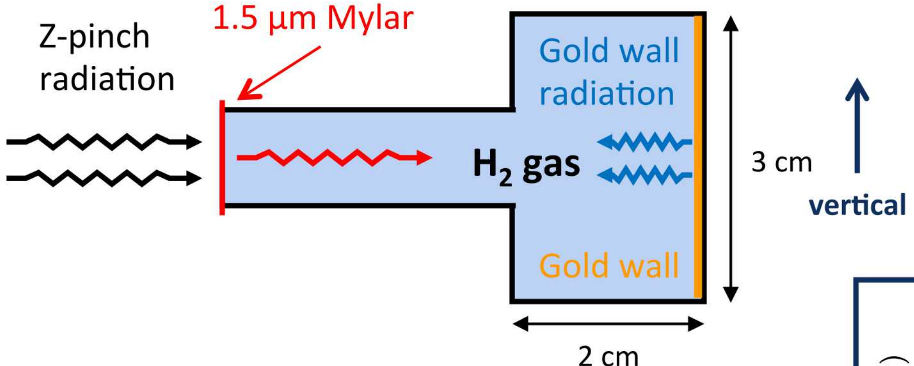
Additional details…

What does such an experiment require?

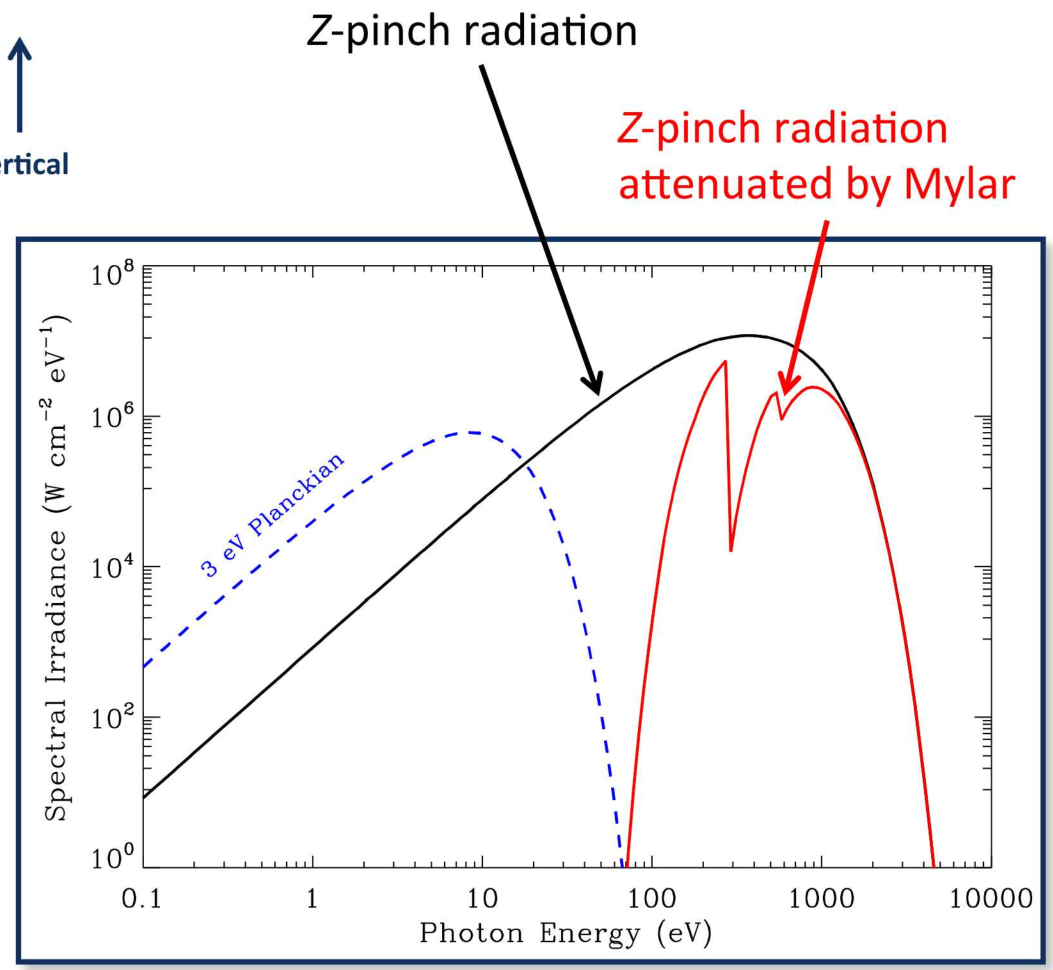
- Relevant plasma conditions
  - Composition
  - Electron density
  - Temperature
- Large plasma
  - Observe long line of sight to achieve optical depths
  - Stationary or non-dynamic; steady
  - Homogeneous (minimal gradients in plasma conditions)
- Measure multiple Balmer lines

Gold-wall radiation photoionizes plasma

Cross-section of Gas Cell

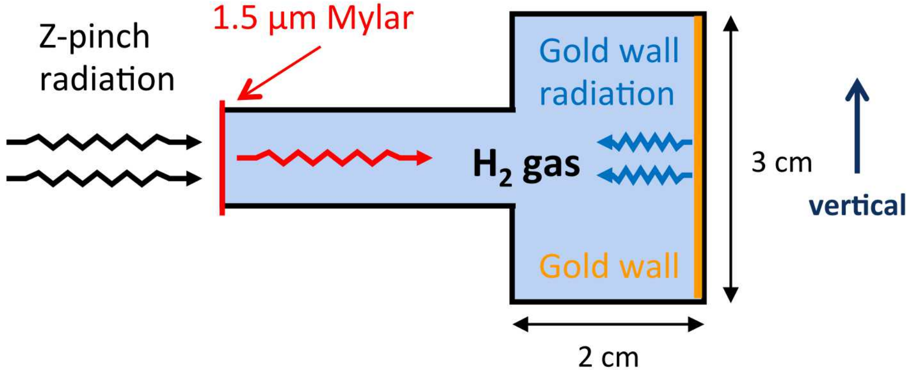


- Mylar blocks lower-energy photons
- Gold absorbs x-rays
  - Re-emits photons that couple well with hydrogen

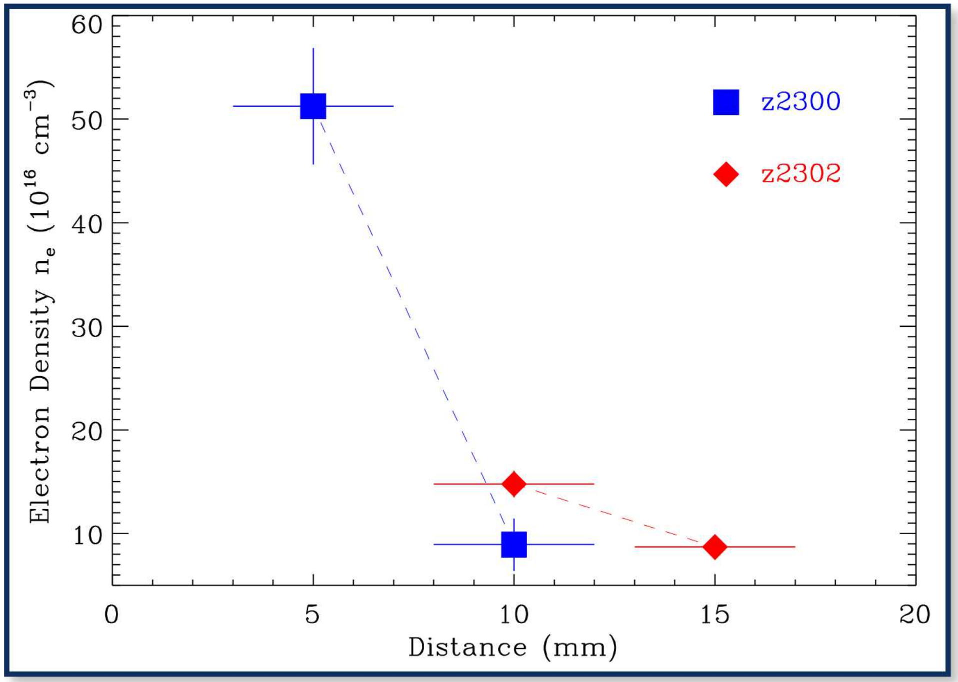


Radiation-driven plasma allows for a range of conditions

Cross-section of Gas Cell

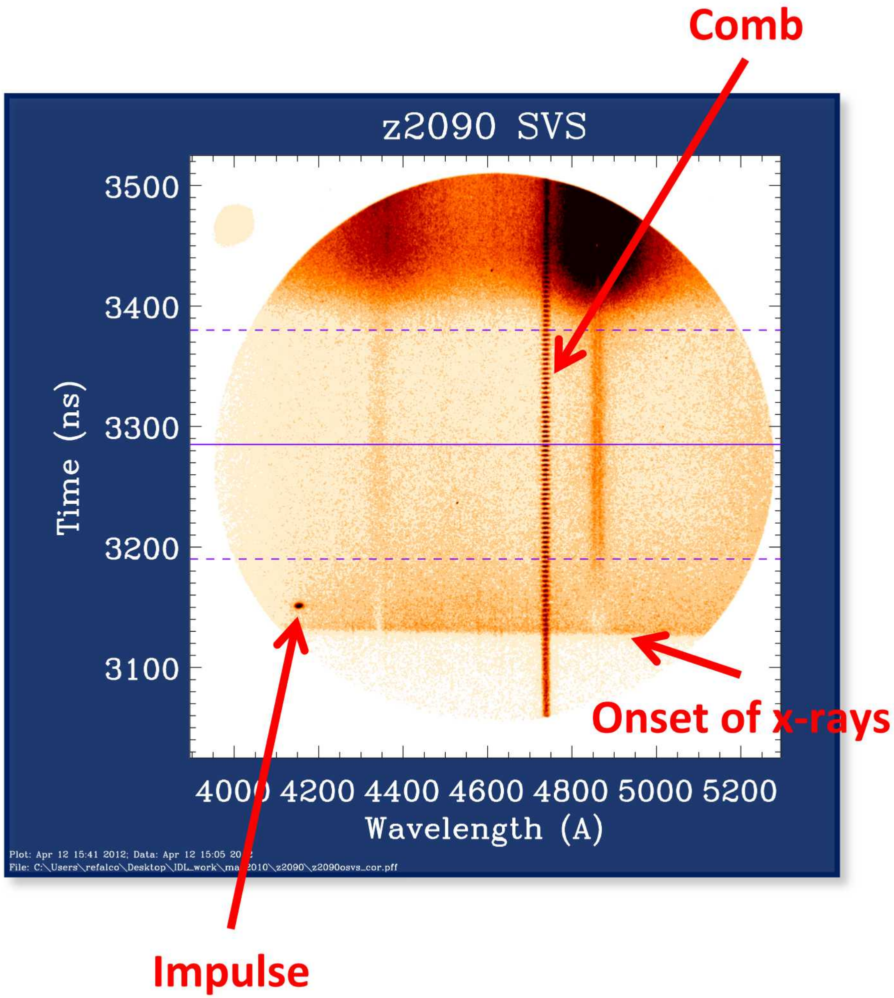


- Distance from gold wall ↑, ionization ↓
  - Plasma heating dominated by gold wall
- Falls off more steeply for higher gas fill pressures

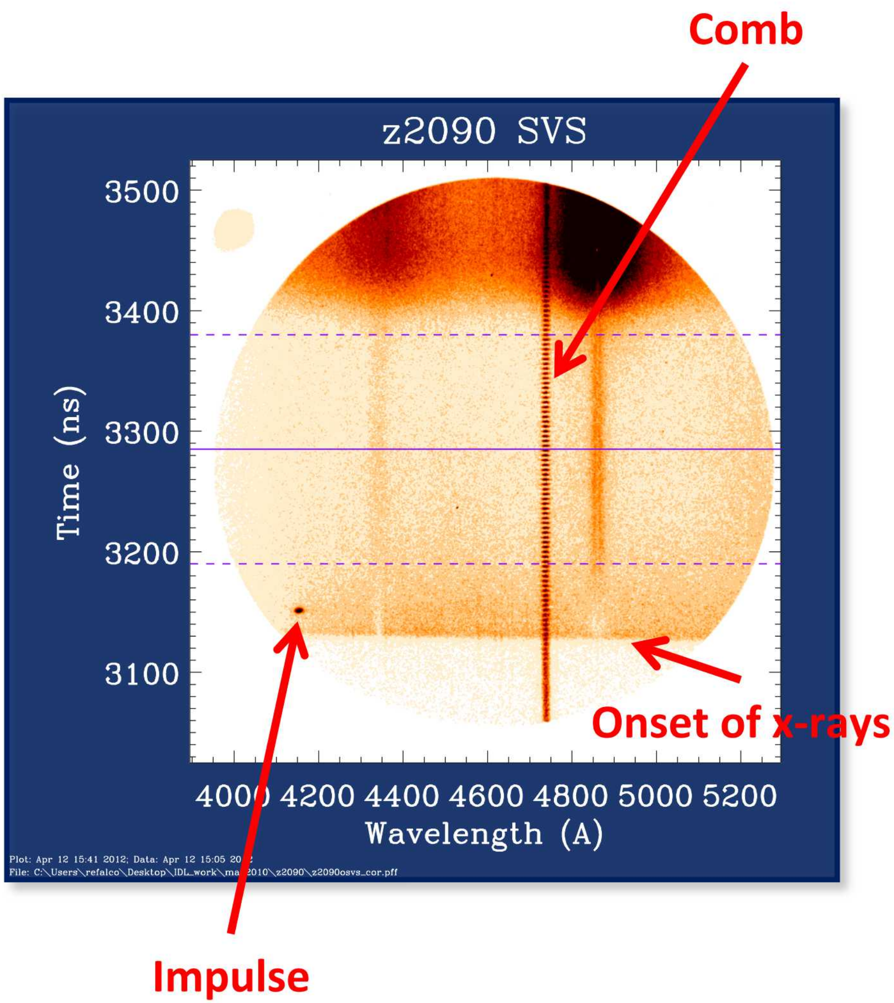


Falcon et al. (2013), *High Energy Density Phys.*, **9**, 82

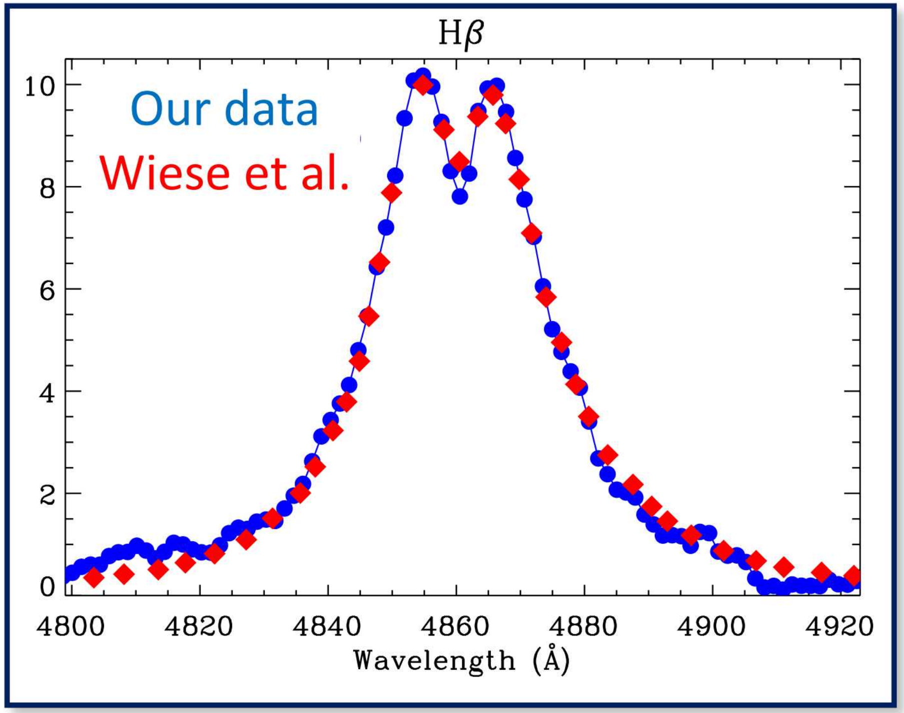
Time-resolved optical spectroscopy shows that our plasma is steady in time



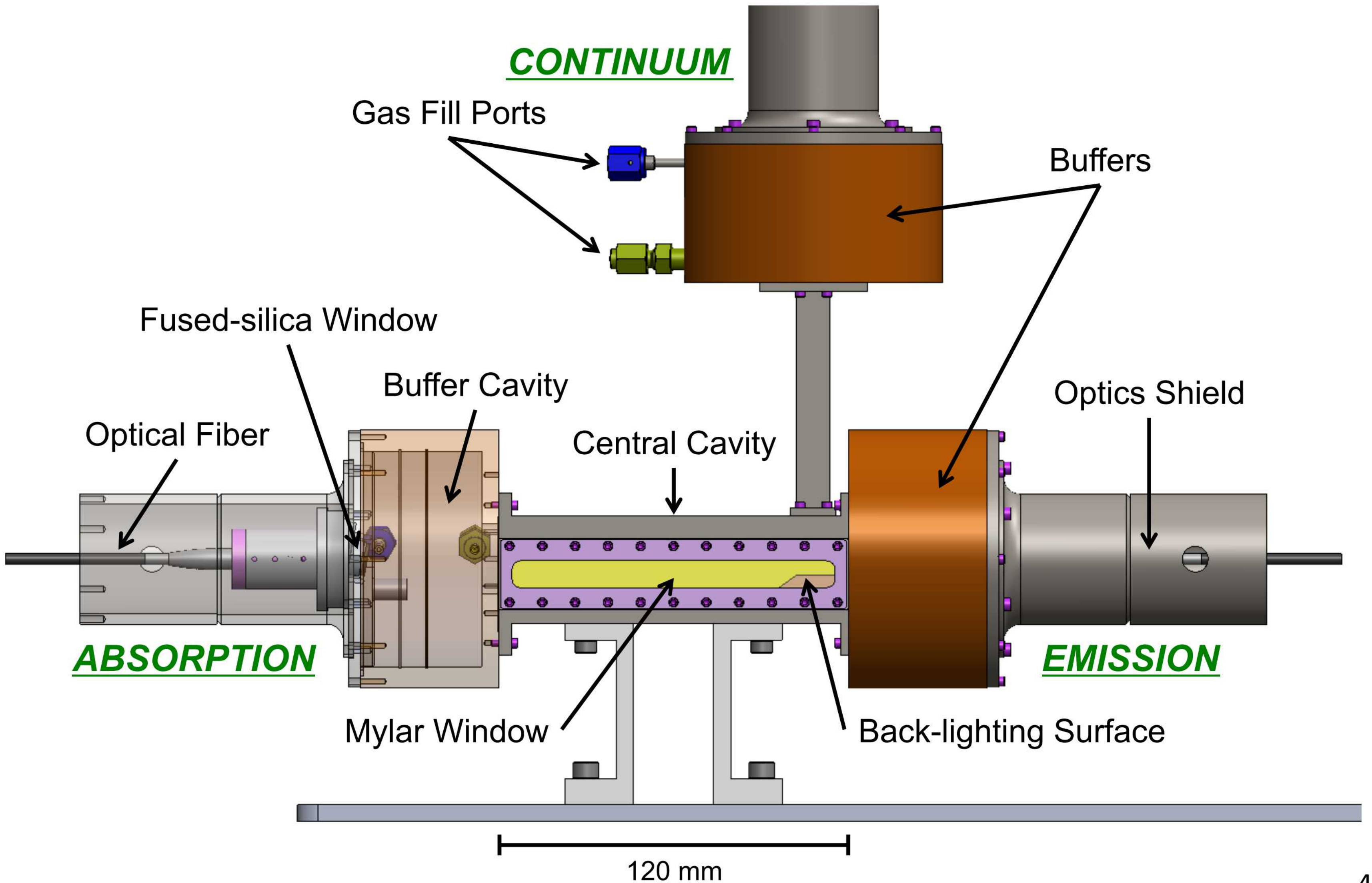
Hβ-emission-line agreement with Wiese et al. shows we achieve desired conditions



n_e = 5.7e16 cm^{-3}

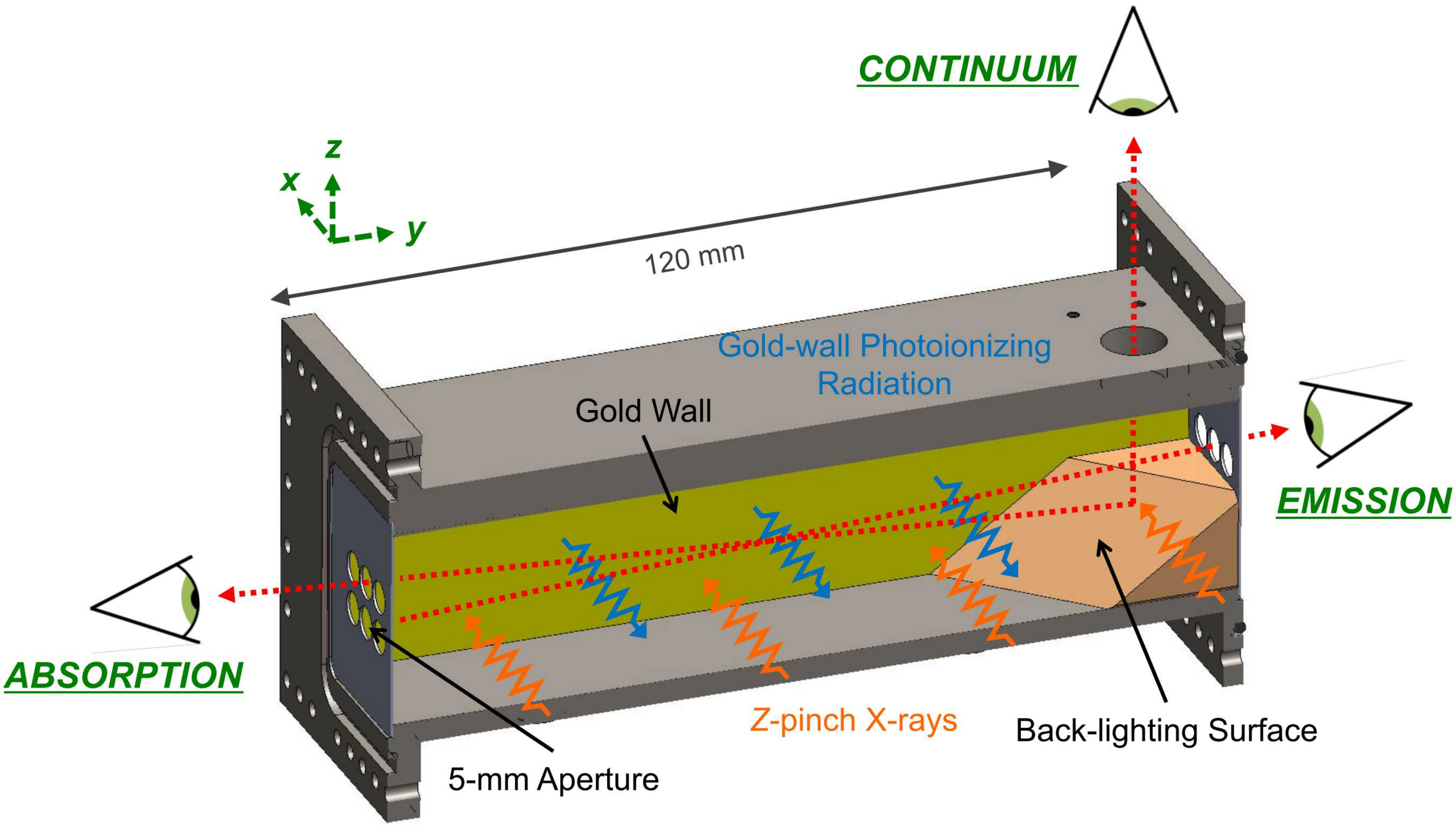


Observe plasma along 3 lines of sight



Falcon et al. (2015), *ApJ*, submitted

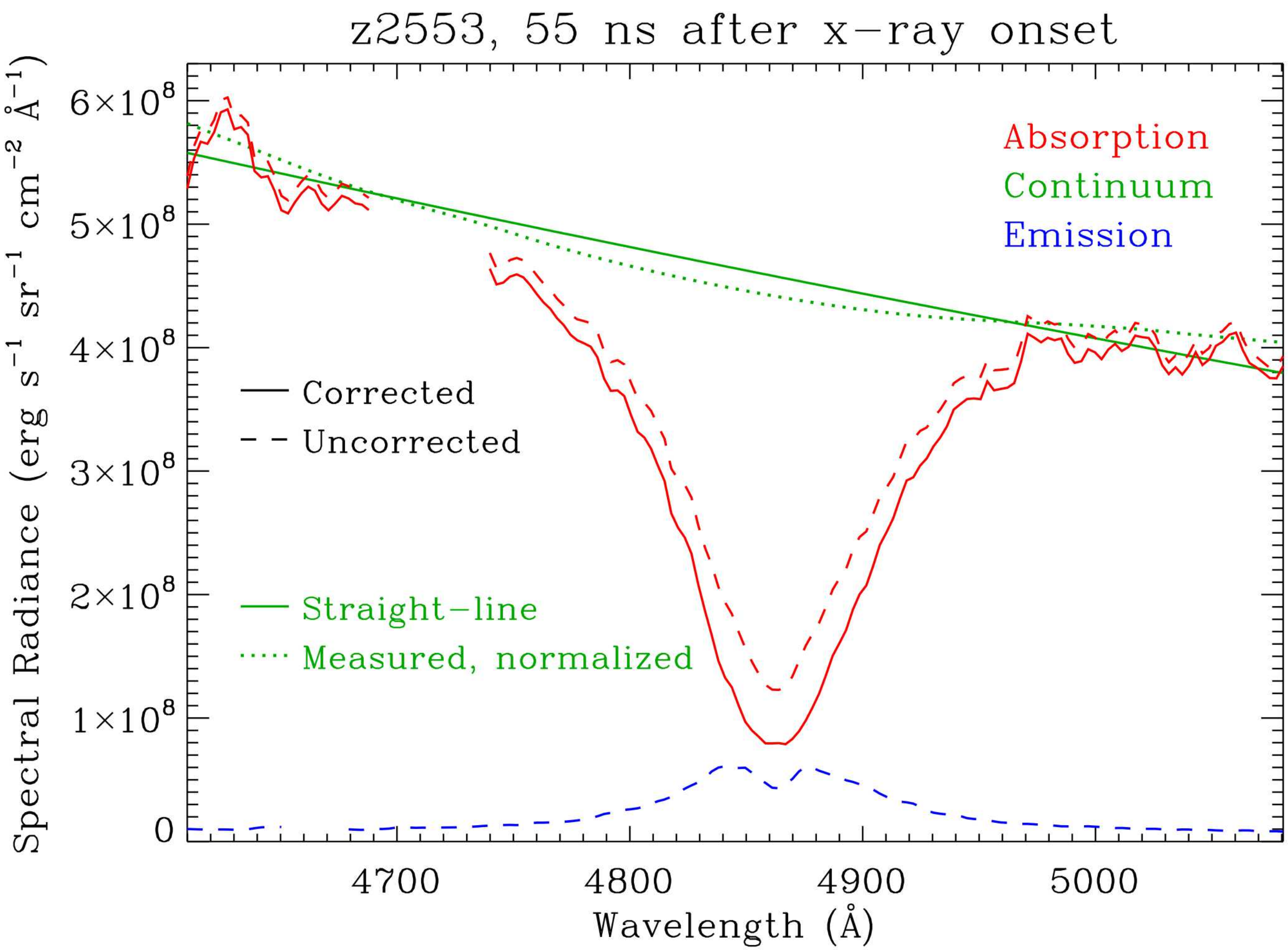
Observe plasma along 3 lines of sight



Falcon et al. (2015), *ApJ*, submitted

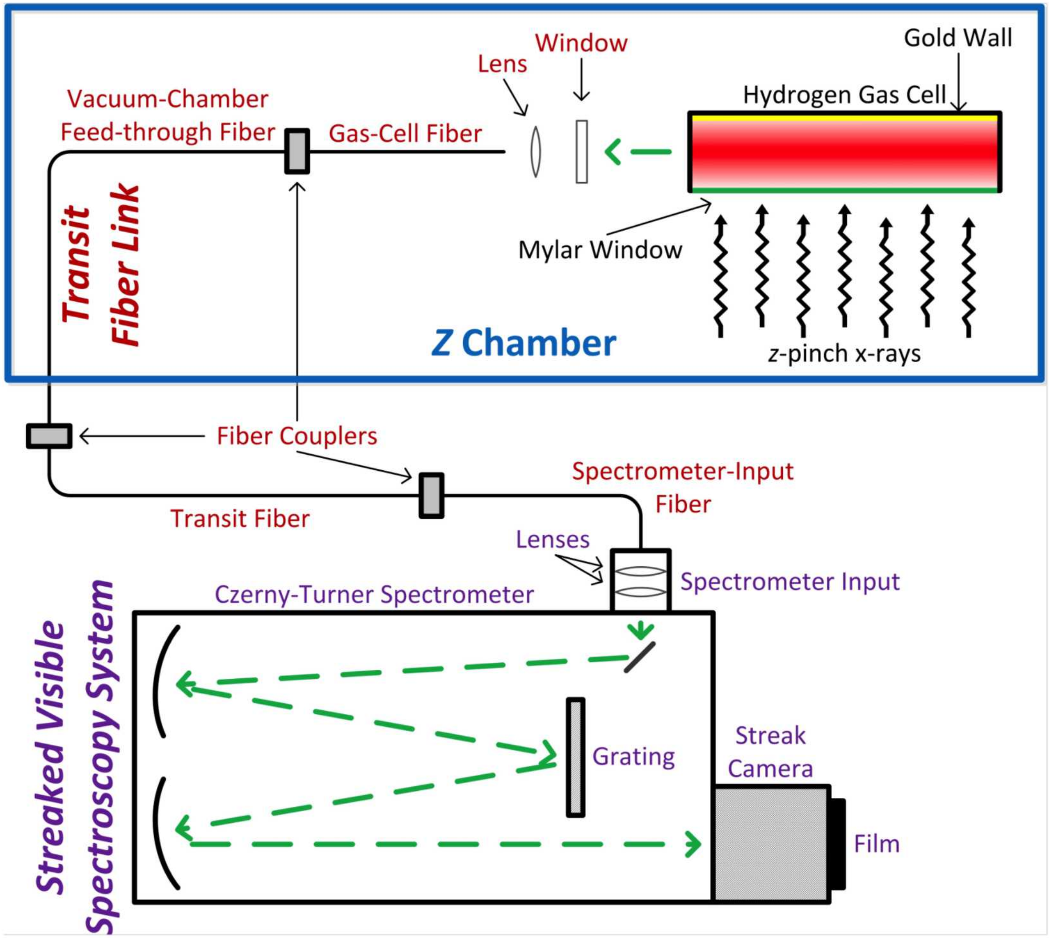
Observe plasma along 3 lines of sight

Noise ~ 3%
S/N ~ 33



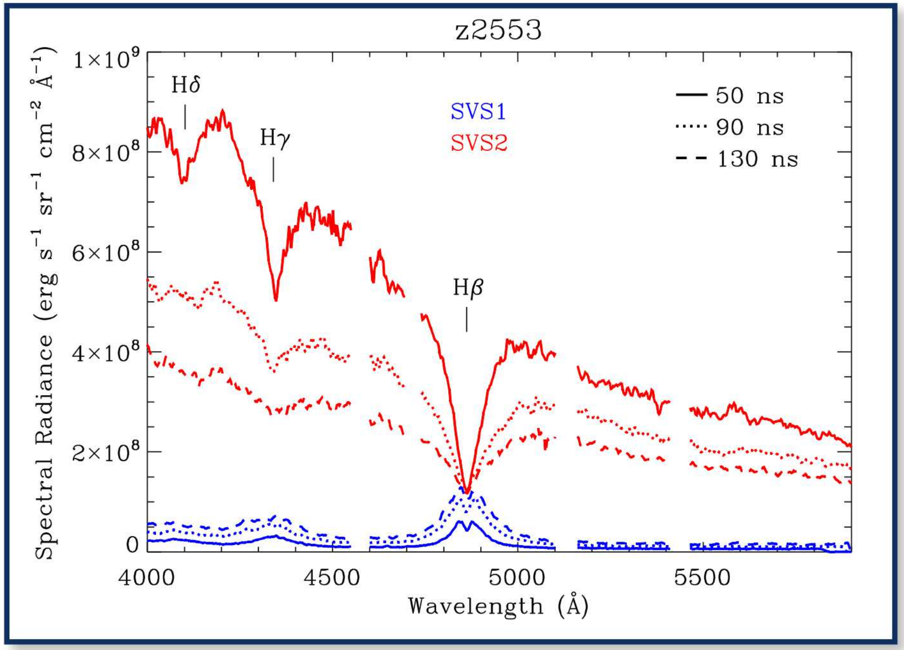
Falcon et al. (2015), *ApJ*, submitted

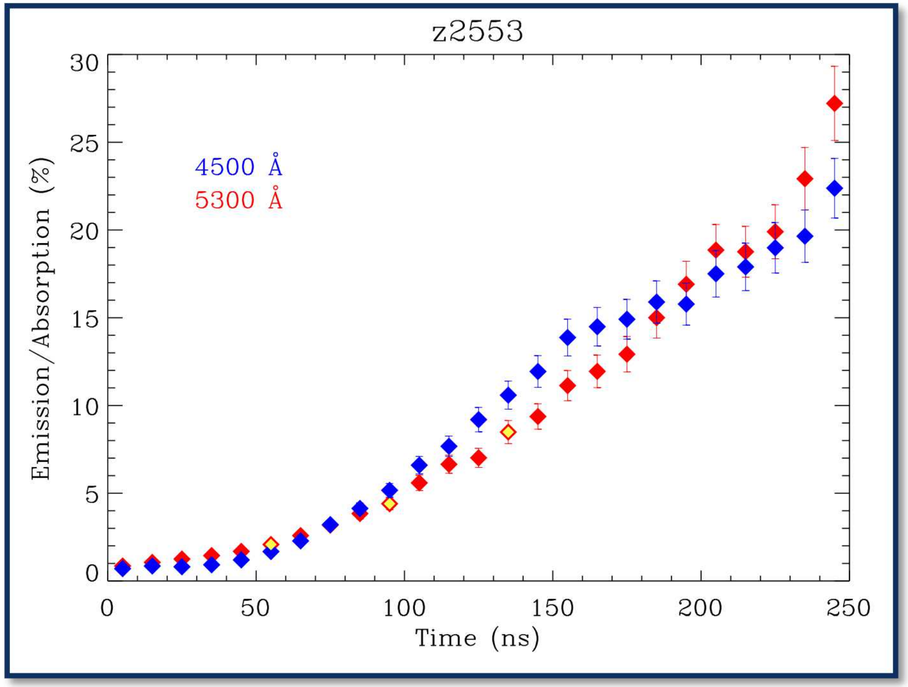
Combining data from multiple spectrometer systems requires calibrations



- 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 back-lighter cools





- Most significant for Hβ line