UCLA IPAM Workshop I
Computational Challenges in Hot Dense Plasmas

Problems with Line Broadening and Opacities in White Dwarf Stars

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What Are White Dwarf Stars?

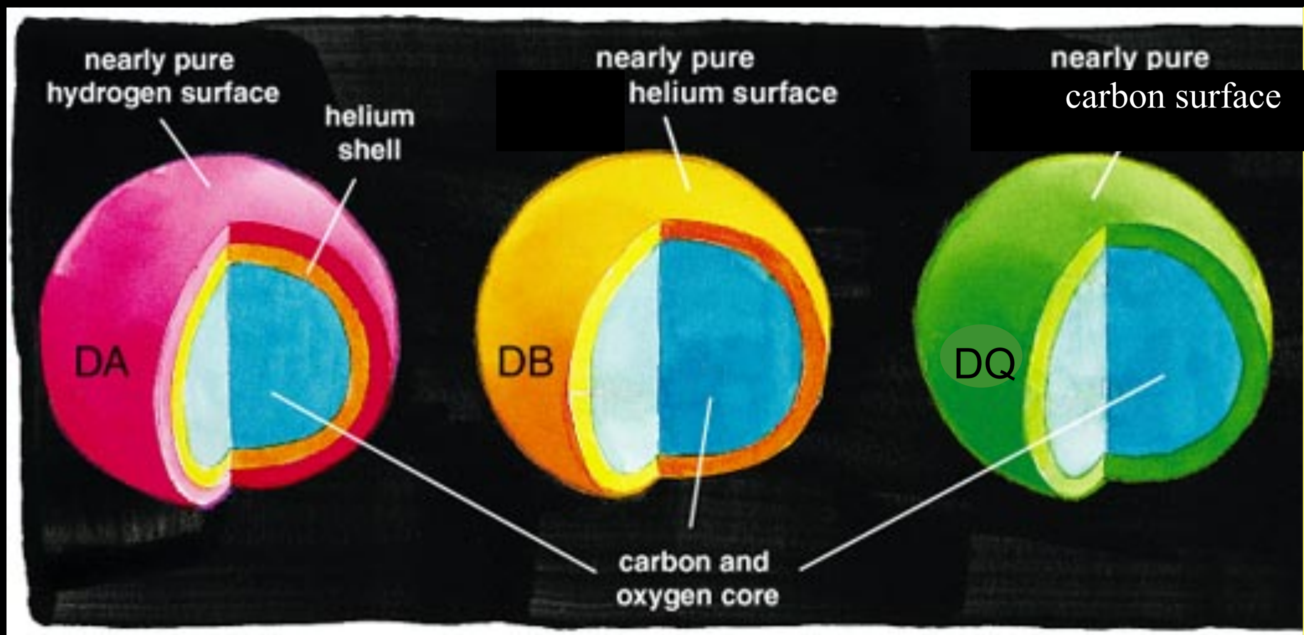
- ***Endpoint*** of evolution for most stars,
  98% of all stars, including our sun
- ***Homogeneous*** in mass and surface composition: essentially ***monoelemental*** photospheres
- ***Uncomplicated*** in structure and composition; evolution is just cooling

They Shed Their Complexity

→ ***Cosmic Laboratories***

Mono-elemental surface layers

H He C



Three White Dwarf Flavors

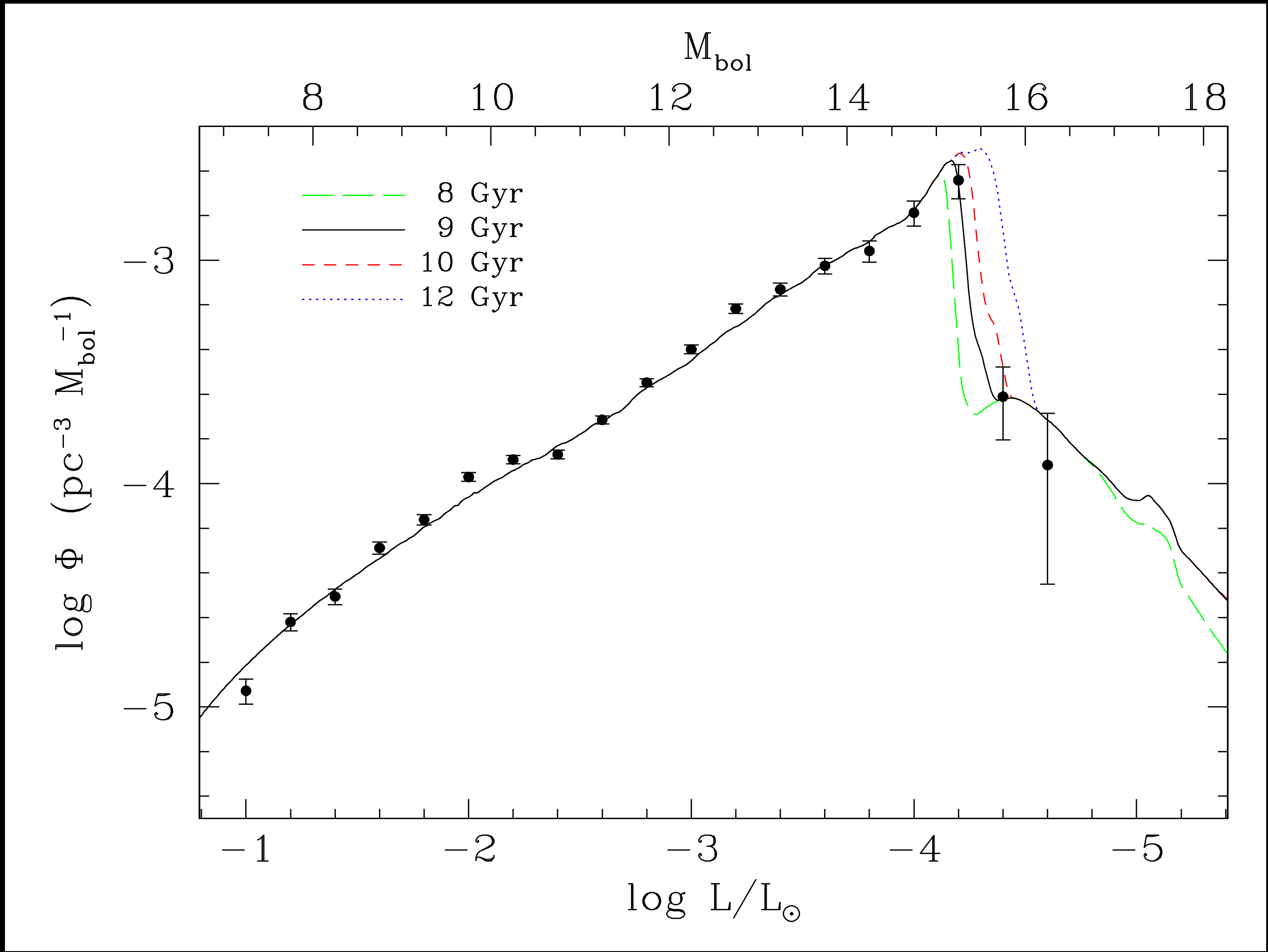
Why are they interesting?

- Representative (and personal)
  - Archeological history of star formation in our galaxy

    => White Dwarf ***Cosmochronology*****:** from ages of coolest white dwarf stars

- A way to find Solar Systems dynamically like ours

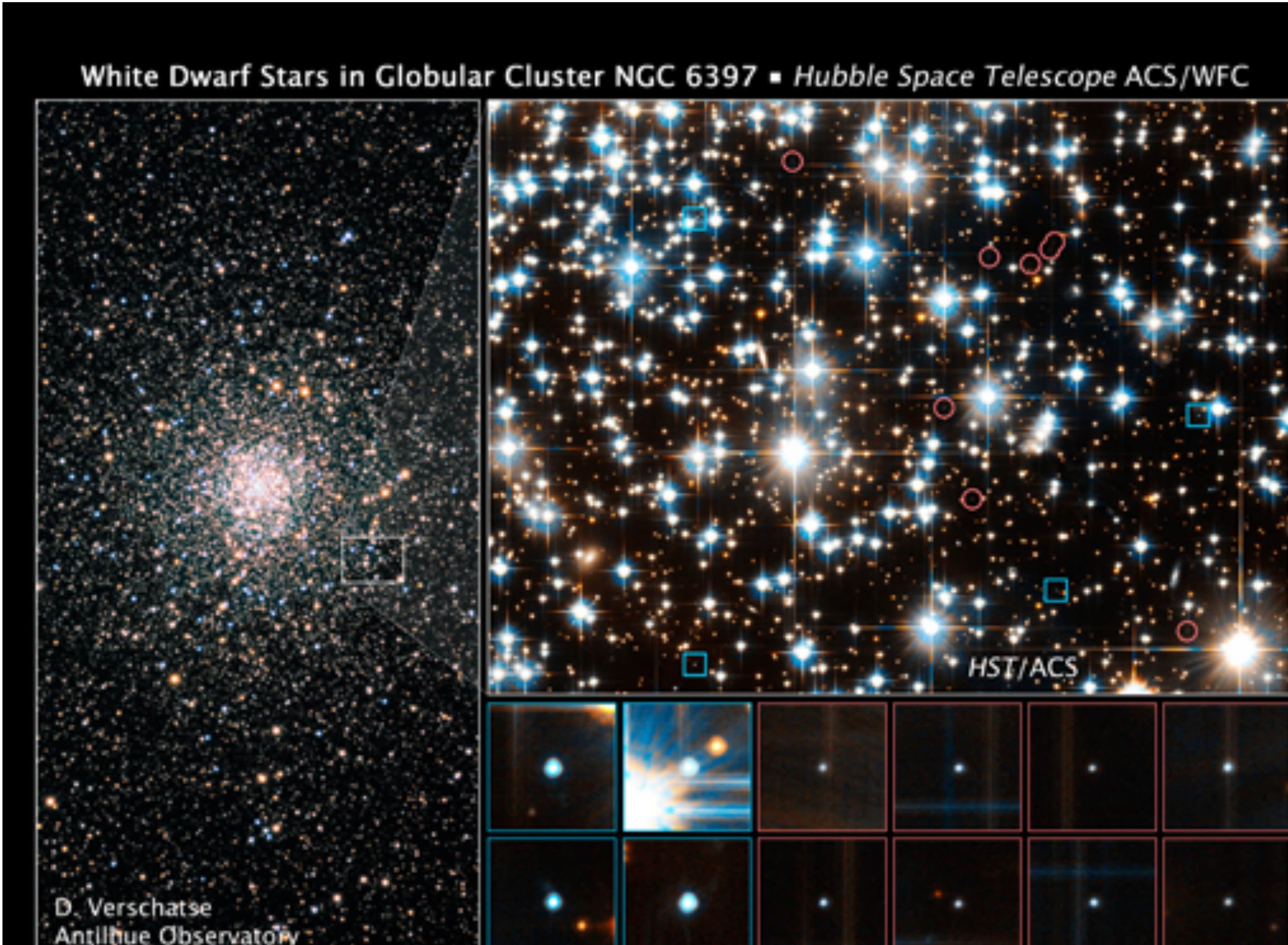
- Exploration of Extreme physics in interiors possible through Asteroseismology
  - Matter at extreme densities and temperatures gives us a chance to study important and exotic physical processes:
    - plasmon neutrinos test electro-weak theory at low-energies
    - turbulent energy transport in high gravity environments
    - dark matter in the form of axions and/or WIMPS
    - study EoS for hot dense matter and the physics of crystallization of a dense Coulomb plasma …

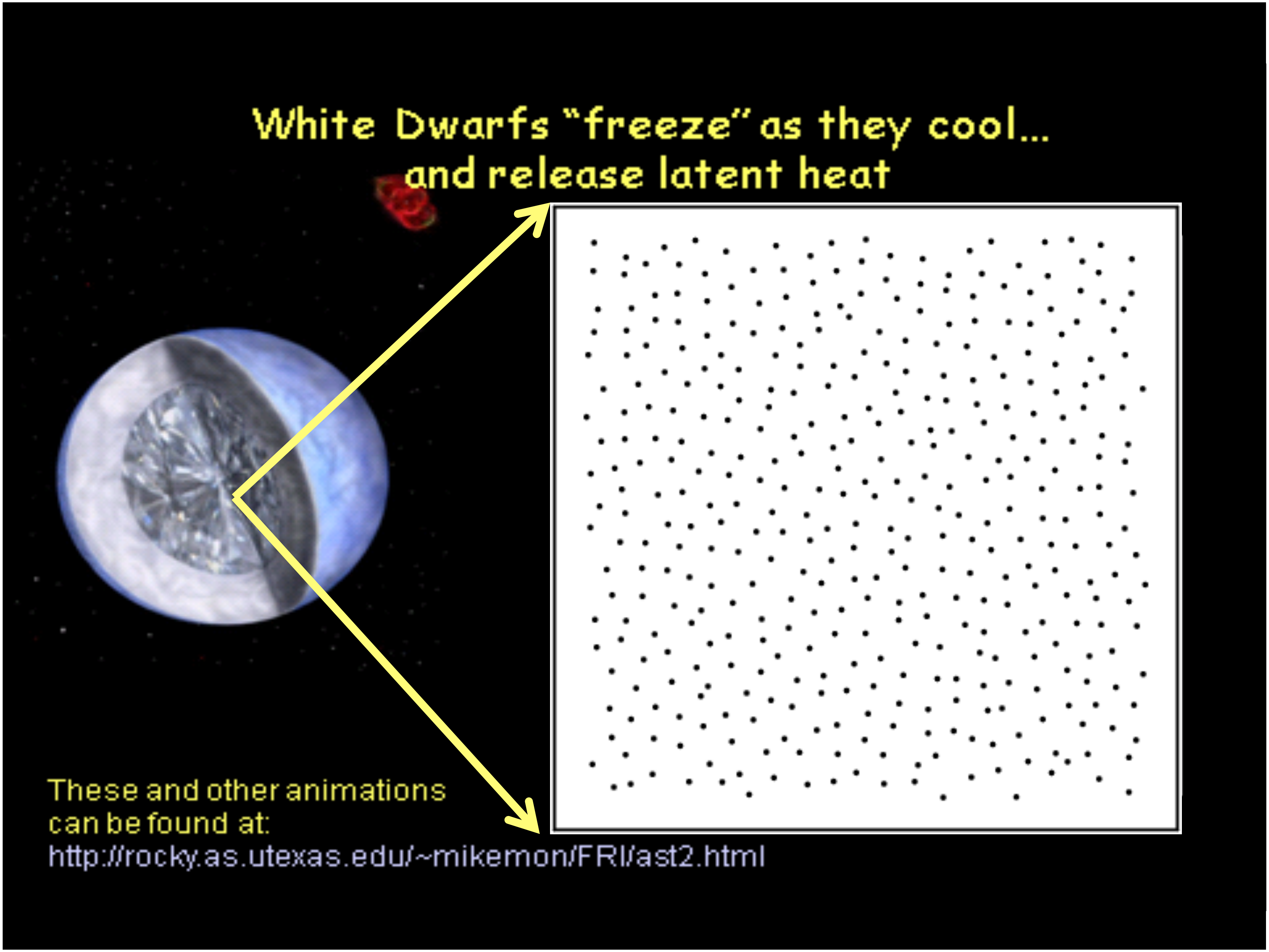


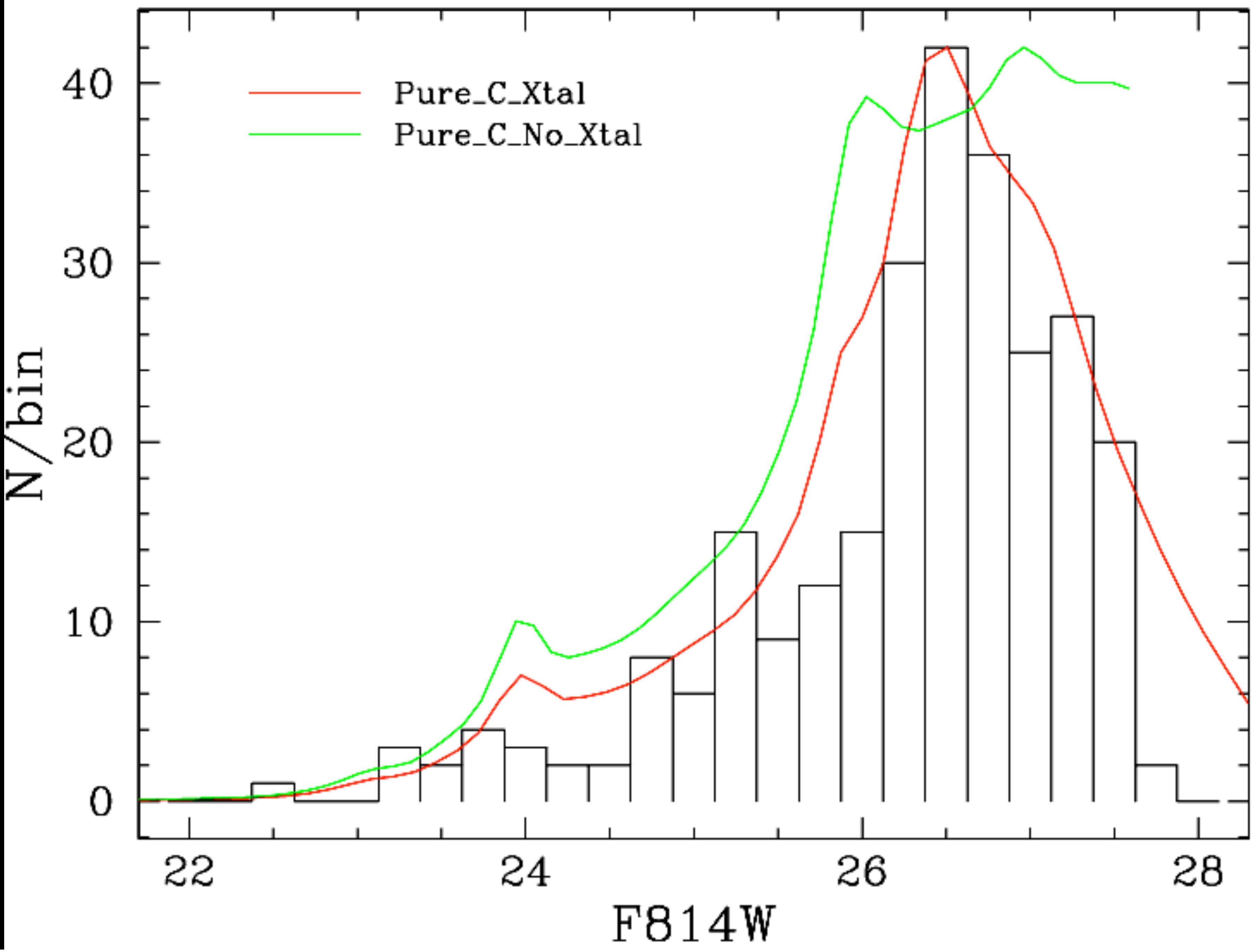
The observed space density of white dwarfs (points), with the theoretical white dwarf luminosity function (WDLF) as a function of intrinsic luminosity. The curves are theoretical models assuming a given age for star formation in our Galaxy.

Cosmochronology

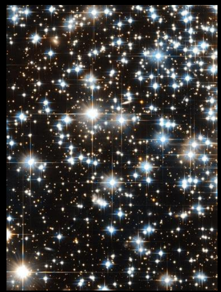
- Constrain Age of Universe
- *Measure* Age and History of the Components of the Galaxy
  - Thin disk
  - Open clusters
  - Thick disk
  - Halo
  - Globular clusters


White Dwarf Stars in Globular Cluster NGC 6397 ▪ Hubble Space Telescope ACS/WFC
HST/ACS
D. Verschatse
Antilhue Observatory


White Dwarfs "freeze" as they cool...
and release latent heat
These and other animations
can be found at:
http://rocky.as.utexas.edu/~mikemon/FRI/ast2.html


Pure_C_Xtal
Pure_C_No_Xtal
N/bin
F814W
0
10
20
30
40
22
24
26
28

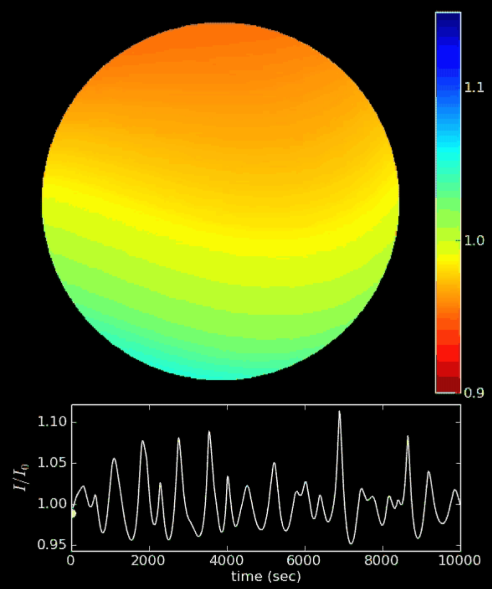
Conclusions from NGC 6397 and M4

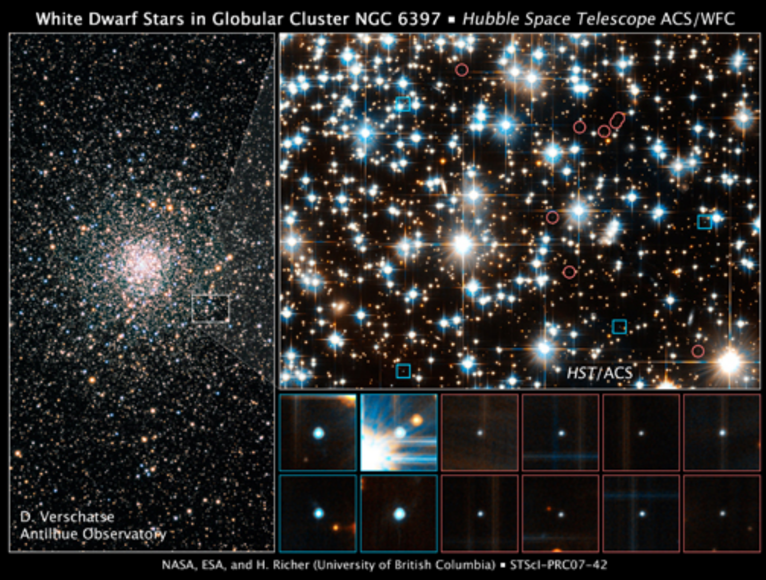


- Confirm that **crystallization** occurs in WDs
- Confirm that **Debye cooling** occurs in WDs
- We can ***measure*** the ***Gamma*** of crystallization
- Low metallicity clusters may not produce significant O in cores of some of the 0.5Msun stars (unlikely) … or the C/O mixture has
  $\Gamma_{xtal} = E_{coul}/kT = 230 - 260$
- We found the first empirical evidence that

  Van Horn’s 1968 prediction is correct:

  Crystallization is a first order phase transition!





Current techniques for studying white dwarf stars:

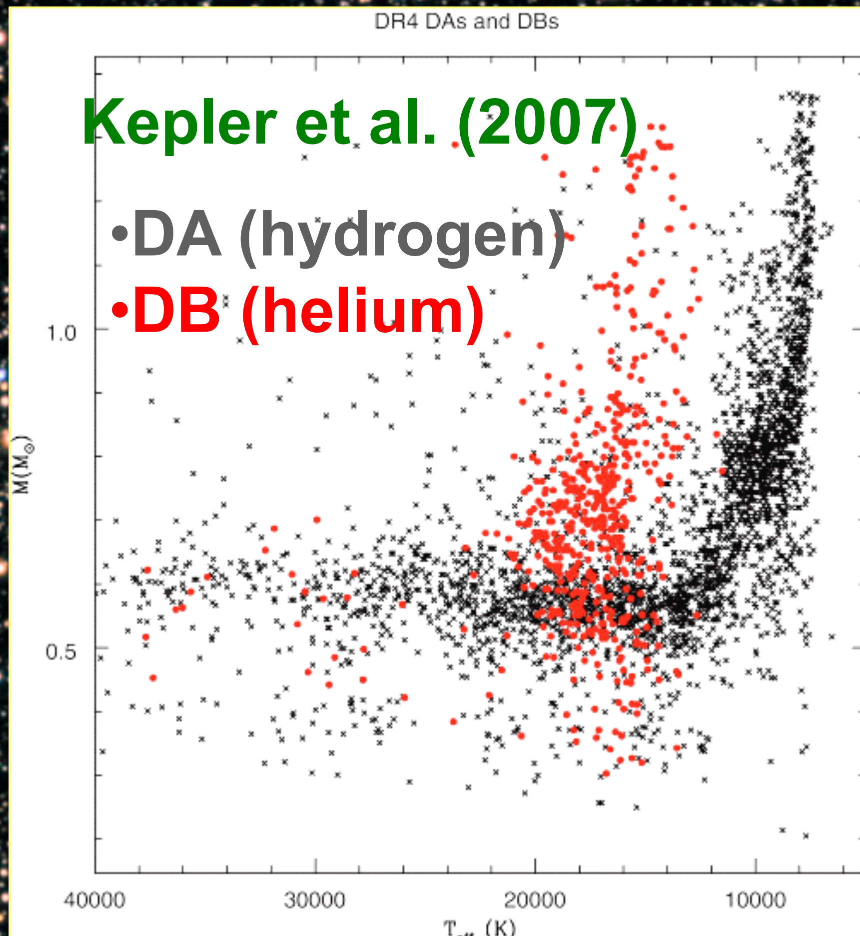
Precision Asteroseismology

Photometry

The Key: ***Spectroscopy***

=>Mass and Temperature

Spectral Fits Give Unreliable Masses for SDSS sample of 3358 DAs *and* DBs



Mean DA Mass from Gravitational Redshift => this isn't physical

Mean DA Mass From GR

- For a sample of 449 non-binary thin disk normal DA WDs, Falcon et al. find

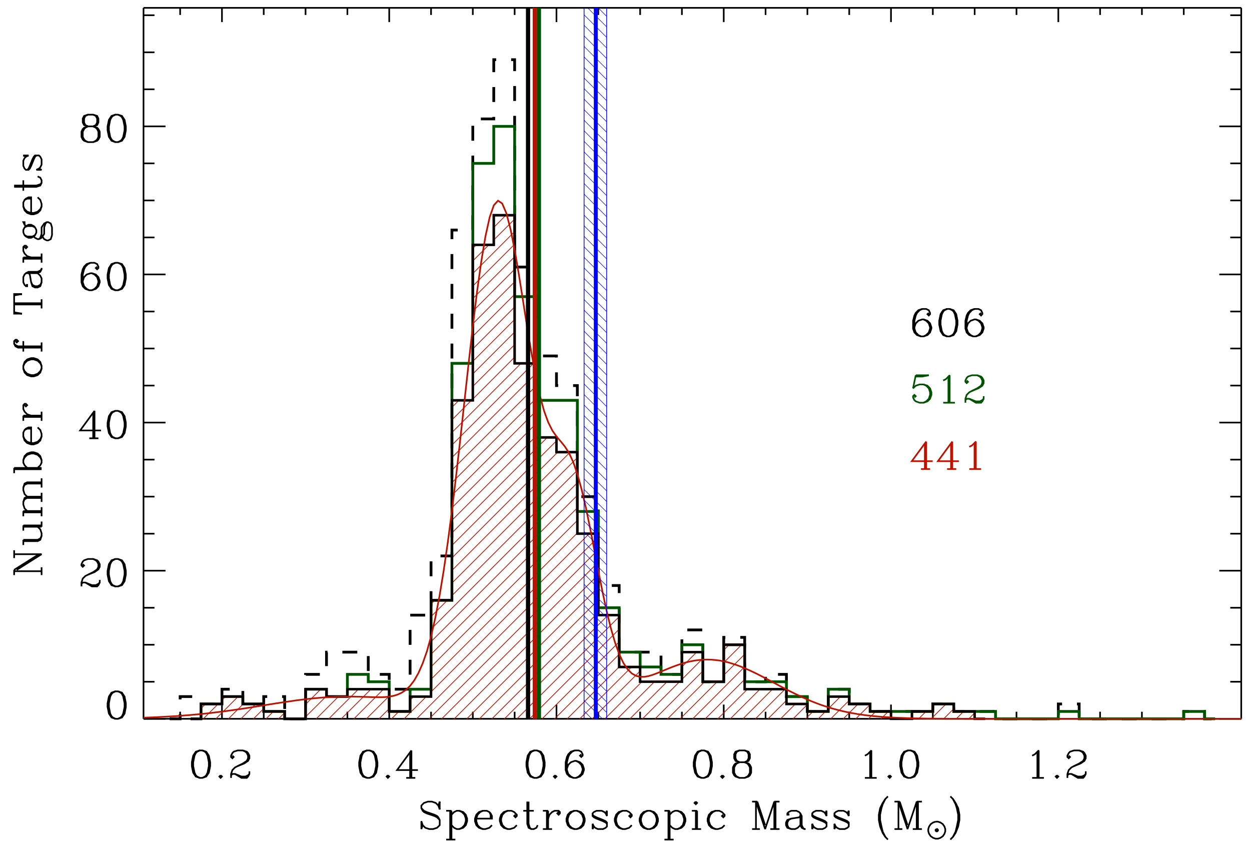
$$\langle M \rangle = 0.647\ M_\odot$$

  - Significantly higher than previous spectroscopic determinations except that of Tremblay & Bergeron (2009), which used improved Stark broadening calculations

- Unlike spectroscopic surveys, do not find significant change in mean mass across $T_{\rm eff}$ split at 12000 K:

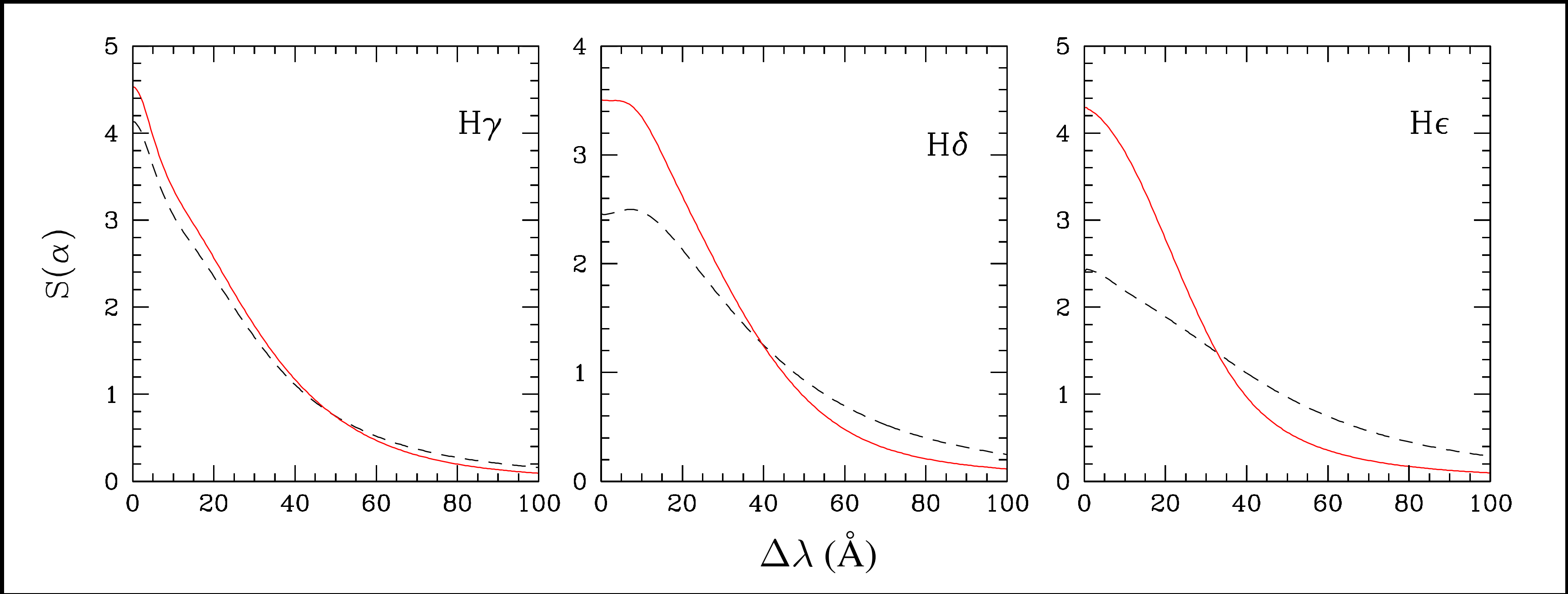
$$\Delta M = 0.046\ M_\odot$$

Mean DA Mass From GR



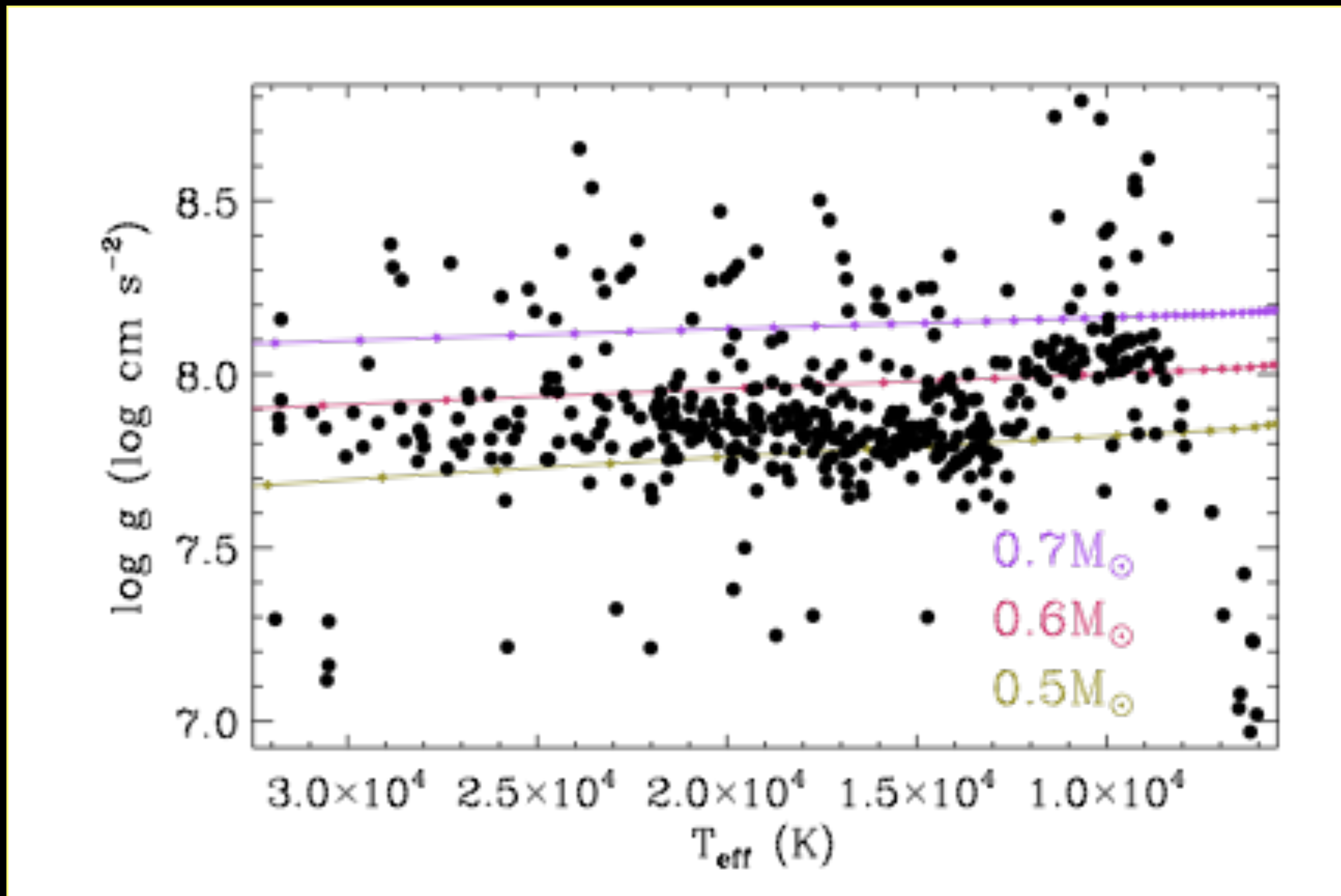
- (from Falcon et al. 2010a) Distributions of spectroscopic masses (histograms) gives significantly different mean values (orange, black, green vertical lines; $\sim 0.57\,M_\odot$) than that derived from gravitational redshift (blue, vertical line; $\sim 0.65\,M_\odot$).

The situation is much worse, as we pointed out for line profiles in the DB (Helium) WDs and the DQ (C/O) WDs (Dufour et al. 2009; Kowalski 2010). Here there are no gravitational redshift results to-date to



From Tremblay & Bergeron 2009: Theoretical hydrogen line profiles as a function of distance from the line center, Δλ. The plasma conditions assumed are T = 10,000 K and ne $=10^{17}$ cm^{-3}. The recent calculations of Tremblay & Bergeron are shown as the solid (red) lines and the previous Vidal-Cooper-Smith (VCS) calculations are shown as the dashed (black) lines.

The H white dwarfs (Koester et al.)

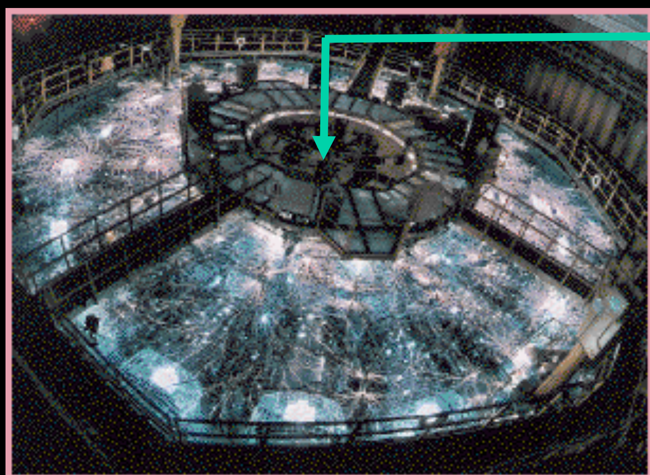


He WDs have the *same problem*, just higher T_{eff}

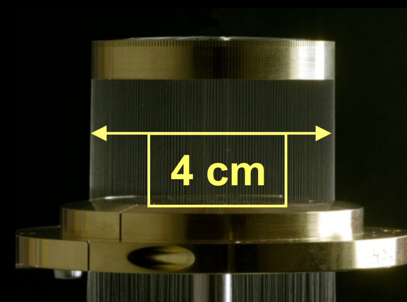
Carbon WDs are worse!

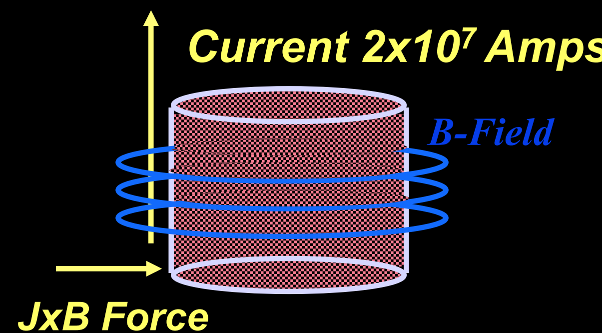
The 26 million Ampere current on Z provides access to new laboratory astrophysics regimes

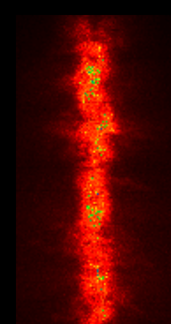
Z accelerator



40 m

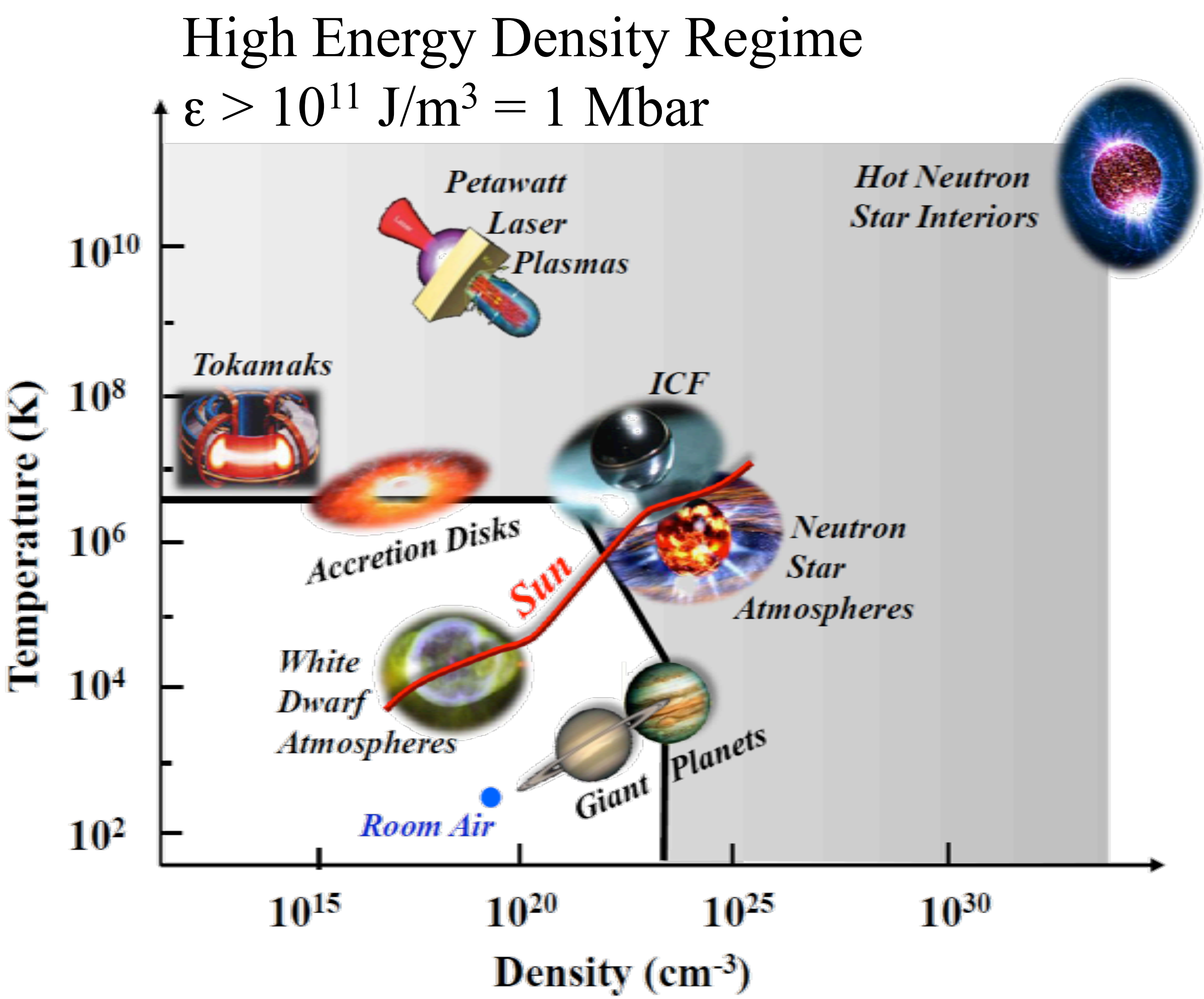




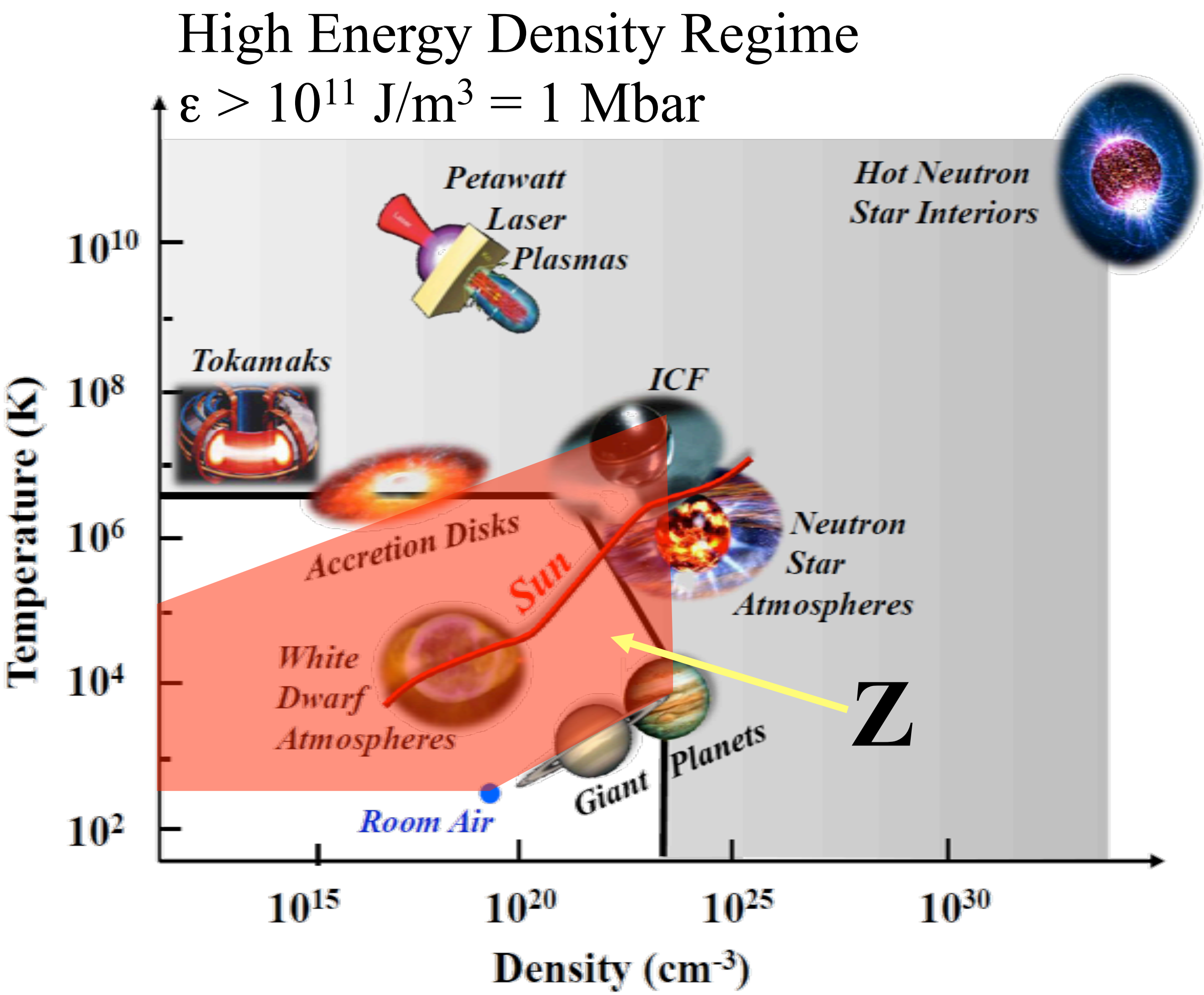


Z experiments use large magnetic fields or large x-ray flux to create extreme environments

Experiments on Z access a large region of the energy density phase-space



Experiments on Z access a large region of the energy density phase-space



Z Astrophysical Plasma Properties (ZAPP):

Experiment Purpose: Advance knowledge of four astrophysical plasmas: stellar interior opacities, spectral line broadening in White Dwarf photospheres, AGN warm absorbers, and plasmas surrounding accretion powered objects

Four Experiments carried out simultaneously on each shot:

1) Develop stellar interior opacity measurements
(w/Ohio State, LLNL, CEA, LANL)
2) Measure photo-ionized plasma kinetics
(w/ U. Nevada, LLNL, and Swarthmore)
3) Measure spectral line profiles for White Dwarf atmospheres
(w/ U. Texas, Weizmann Institute, & UCLA)
4) Measure self emission to examine Resonant Auger Destruction in black hole accretion disk plasmas (w/ LLNL, U. Nevada, Swarthmore)

Primary Near Term Science Goal of White Dwarf Photosphere Project:

- Measure relative line shapes

  for Hβ, Hγ, and Hδ at white dwarf photospheric/atmospheric conditions

Approach:

- Radiatively heat gas cells to conditions of

  $T_e = 11{,}400$ K ~ 1eV

  $n = 10^{16}$-10^{19} atoms/cc

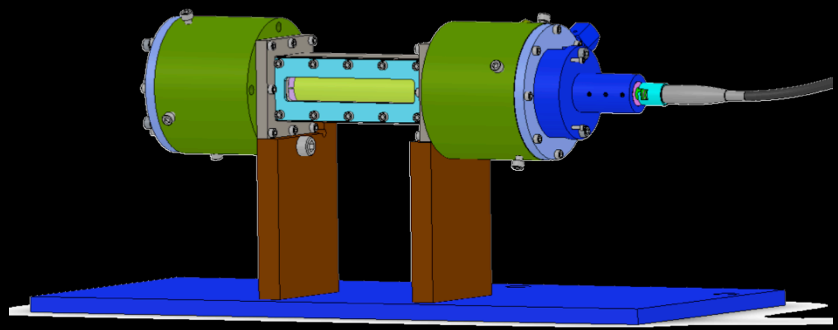
Measuring Hydrogen line-shapes

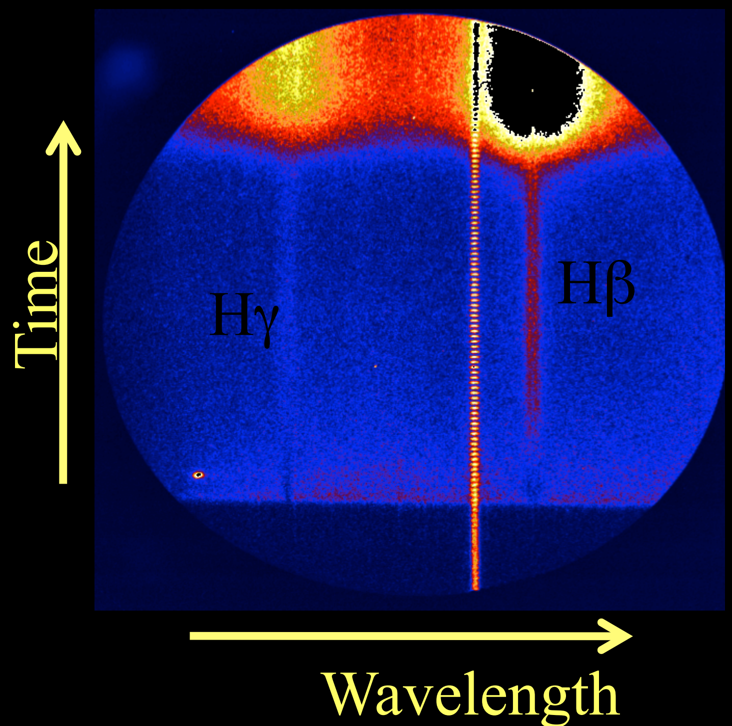
Relevant Diagnostics

• Streaked Visible Spectrometer

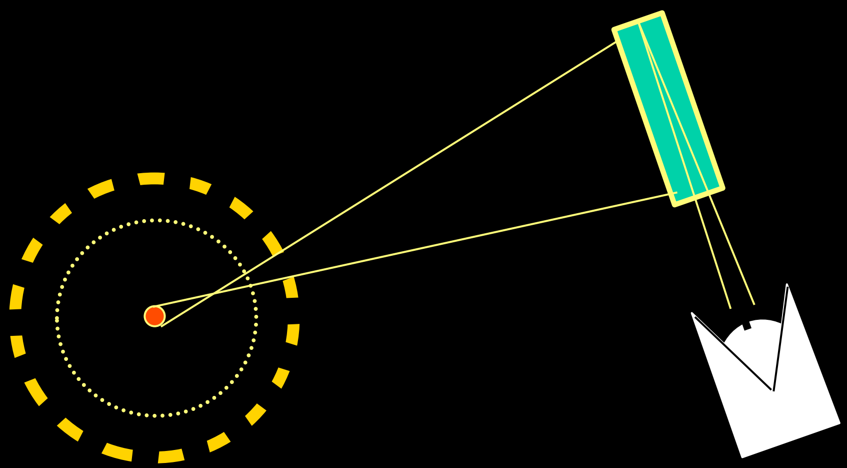
  • 2.3 – 3.0 eV

Fielded by UT students Ross Falcon, Thomas Gomez and Jennifer Ellis.





H Gas Cell



Measuring Hydrogen line-shapes

Relevant Diagnostics

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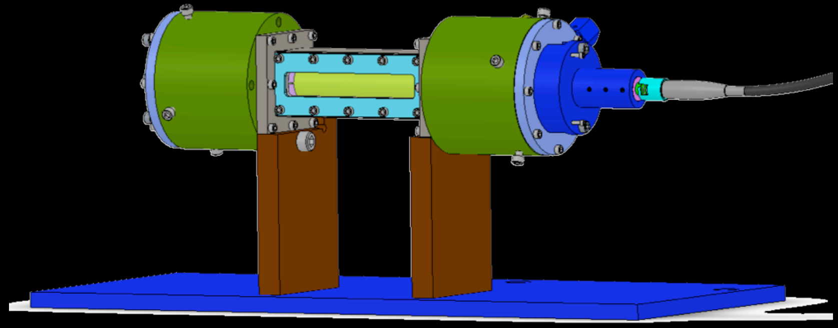
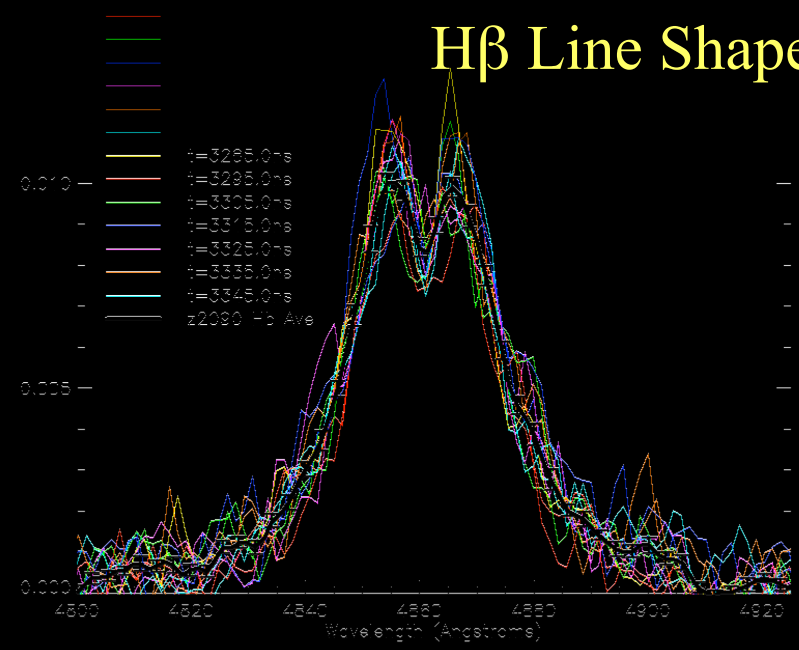
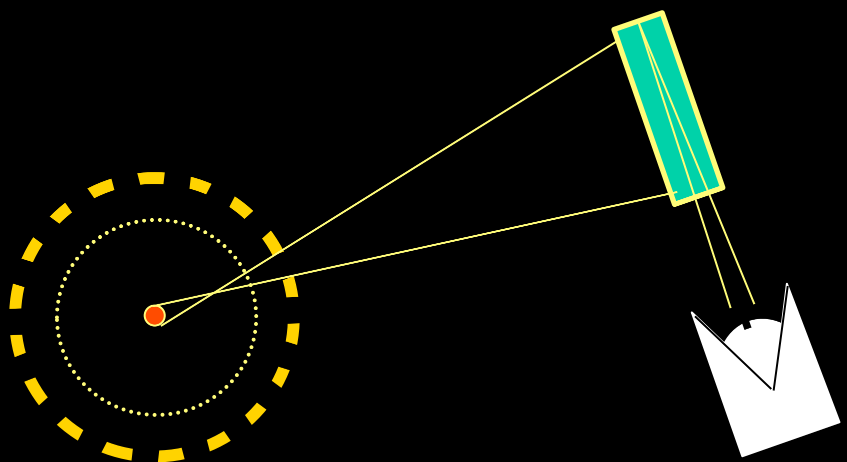


Fielded by UT students Ross Falcon, Jennifer Ellis, and Thomas Gomez

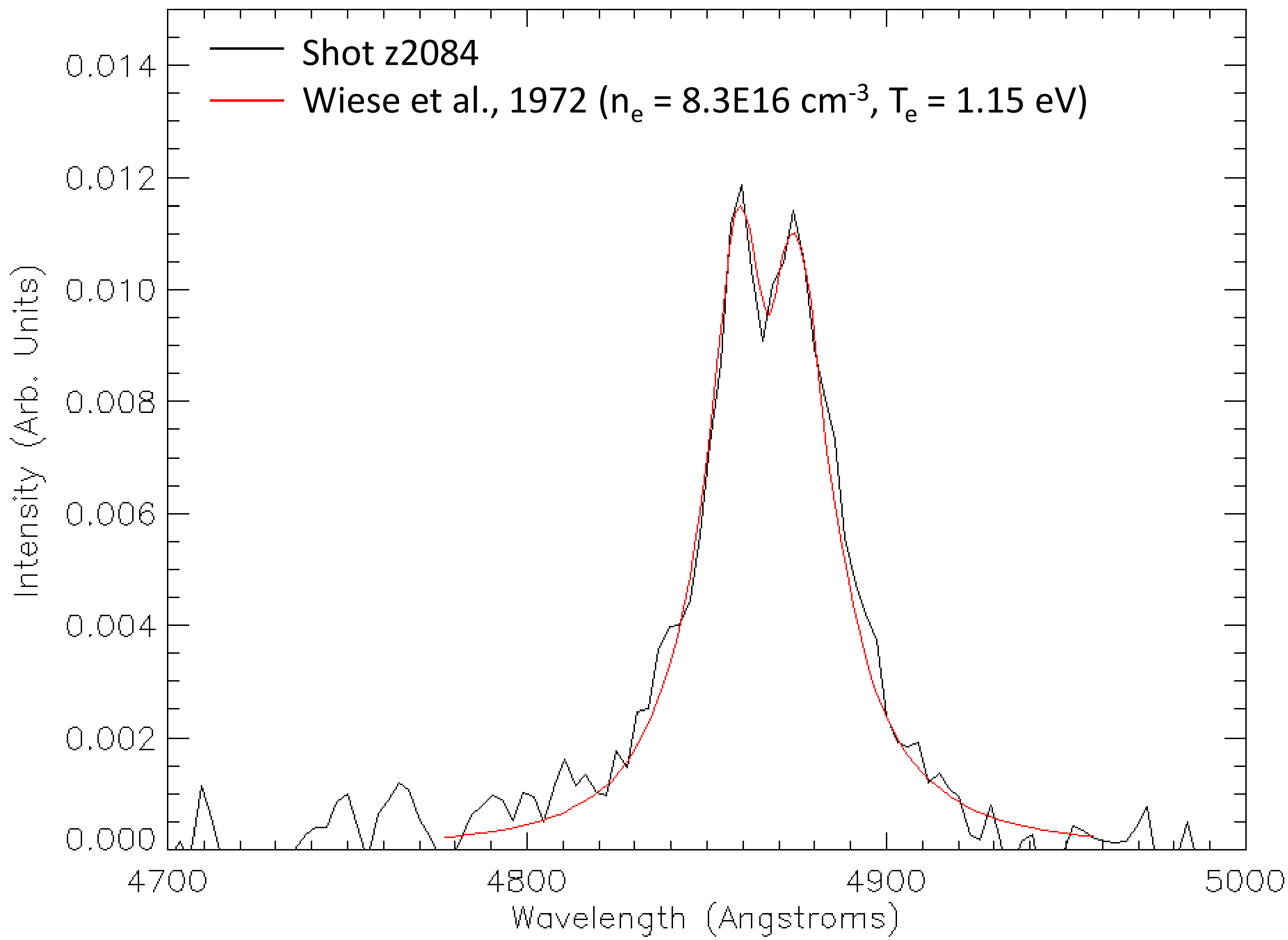
Hβ Line Shape

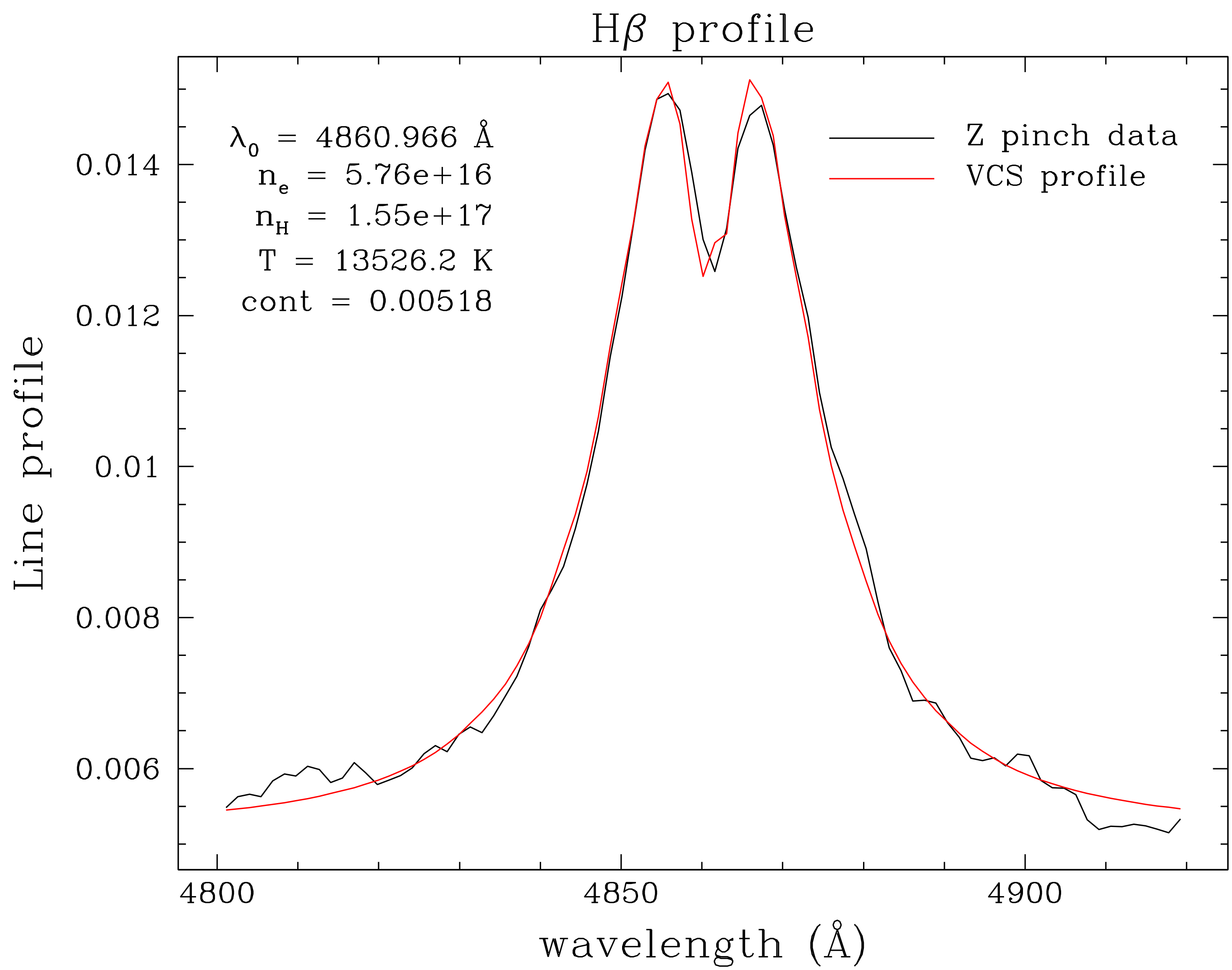


H Gas Cell

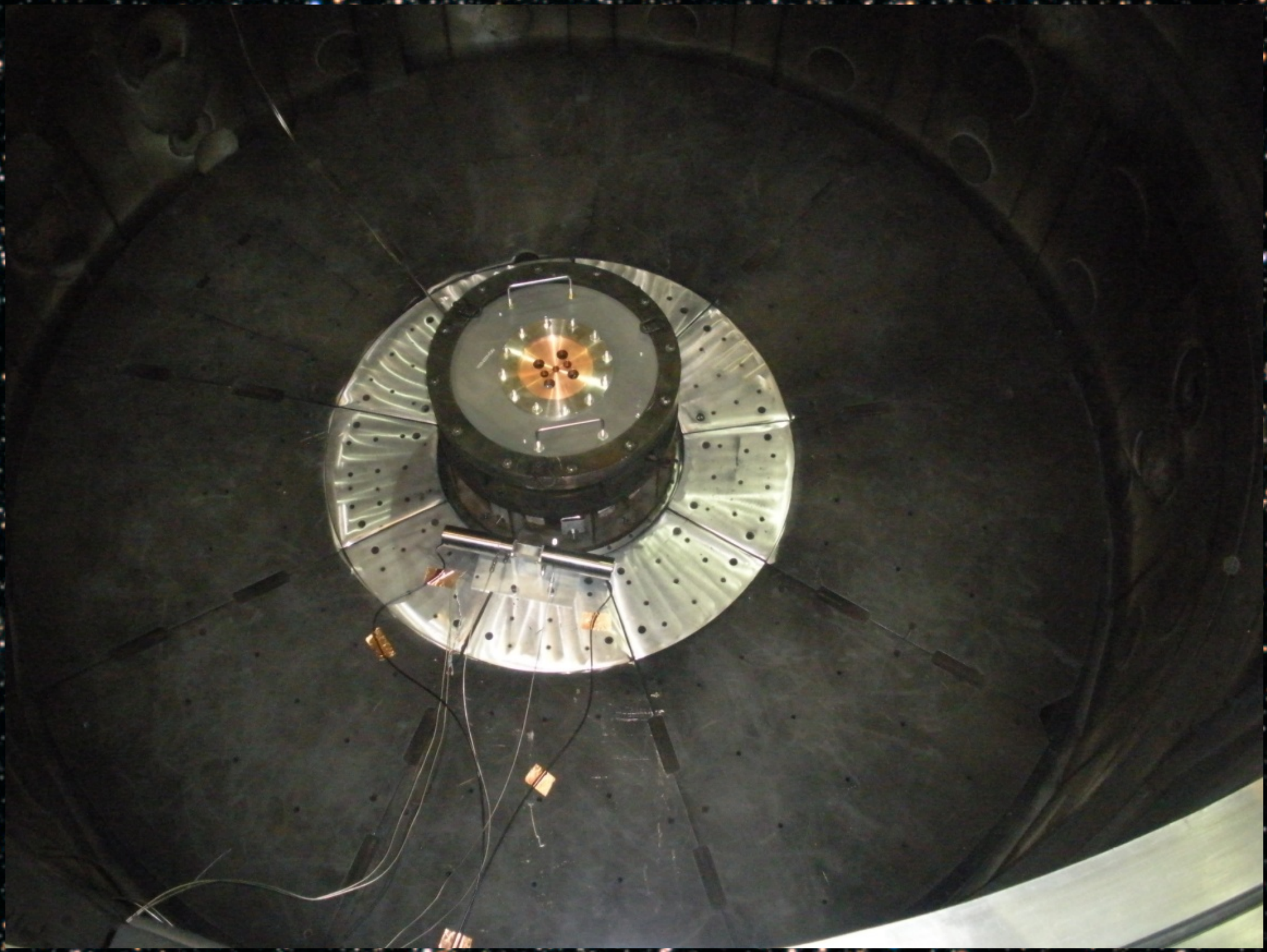


Shot z2084 H-beta line profile averaged over 10 ns centered about a time 80 ns after the peak of the z-pinch

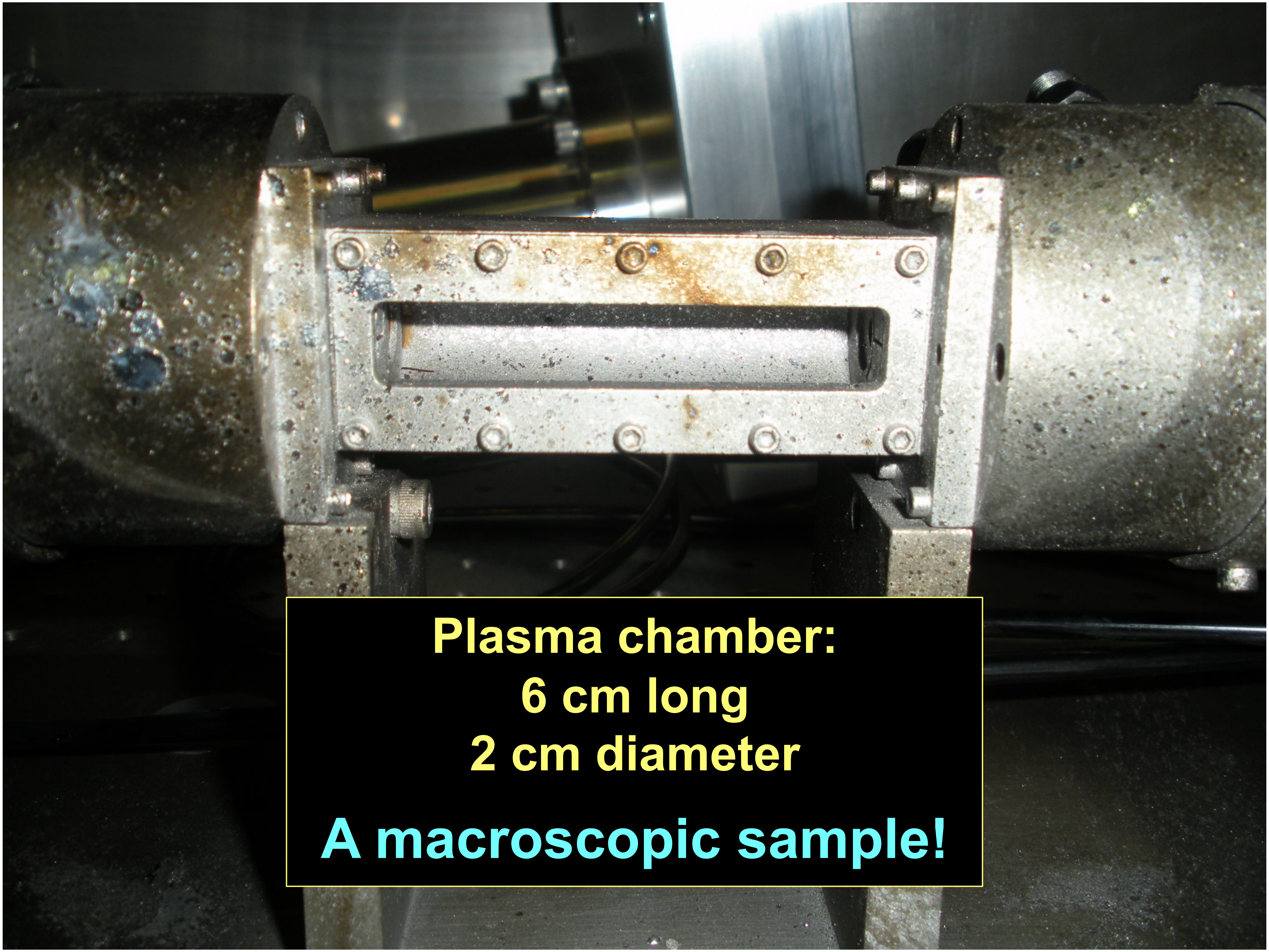



Hβ profile
λ0 = 4860.966 Å
ne = 5.76e+16
nH = 1.55e+17
T = 13526.2 K
cont = 0.00518
Z pinch data
VCS profile
0.014
0.012
0.01
0.008
0.006
Line profile
4800
4850
4900
wavelength (Å)

Measuring Line Profiles at White Dwarf Photospheric Conditions => Accurate Masses

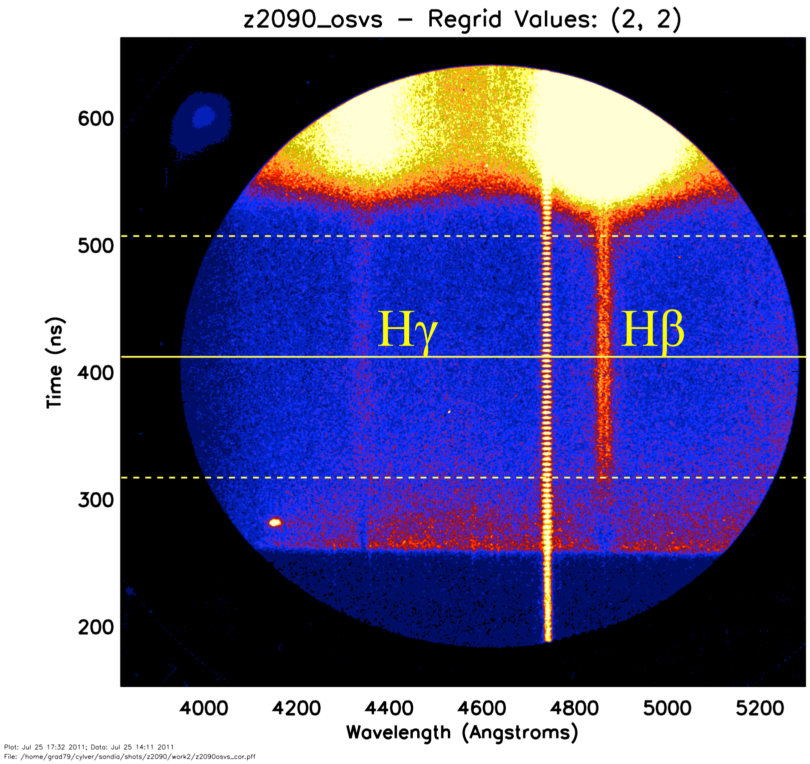


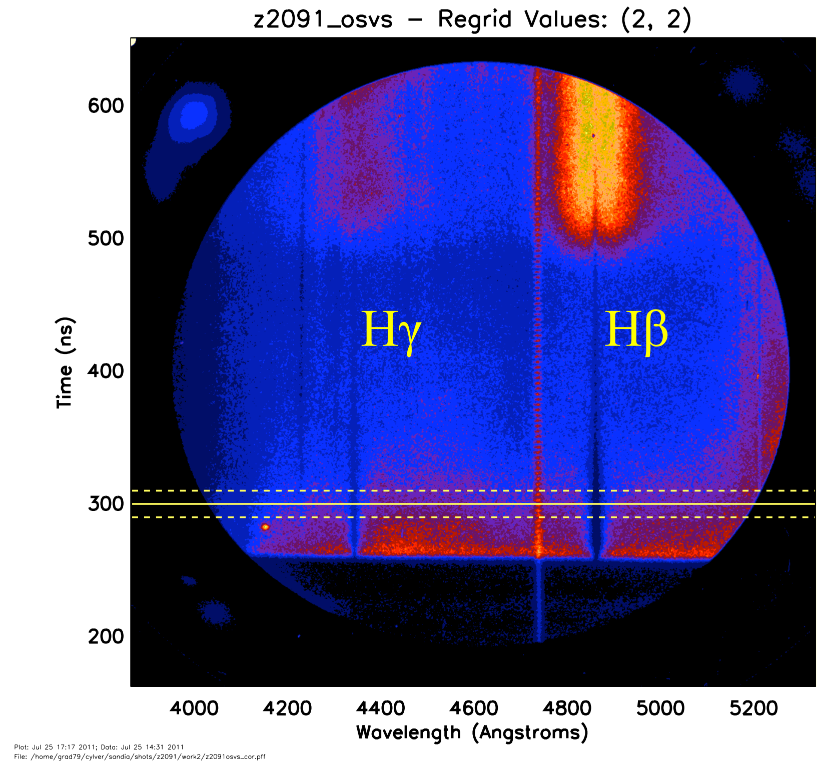
Laboratory Setup

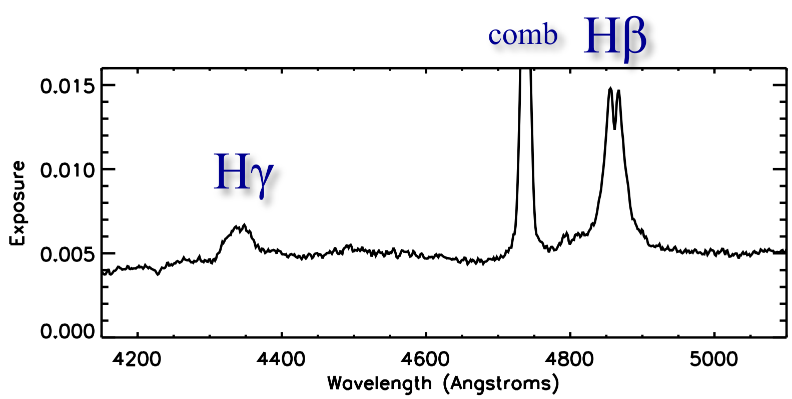

Plasma chamber:
6 cm long
2 cm diameter
A macroscopic sample!

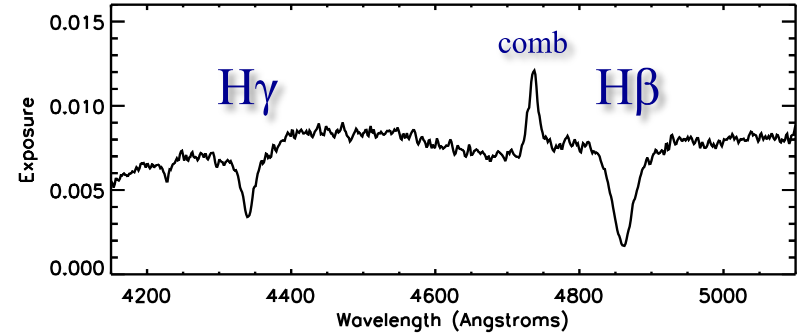
May 2010

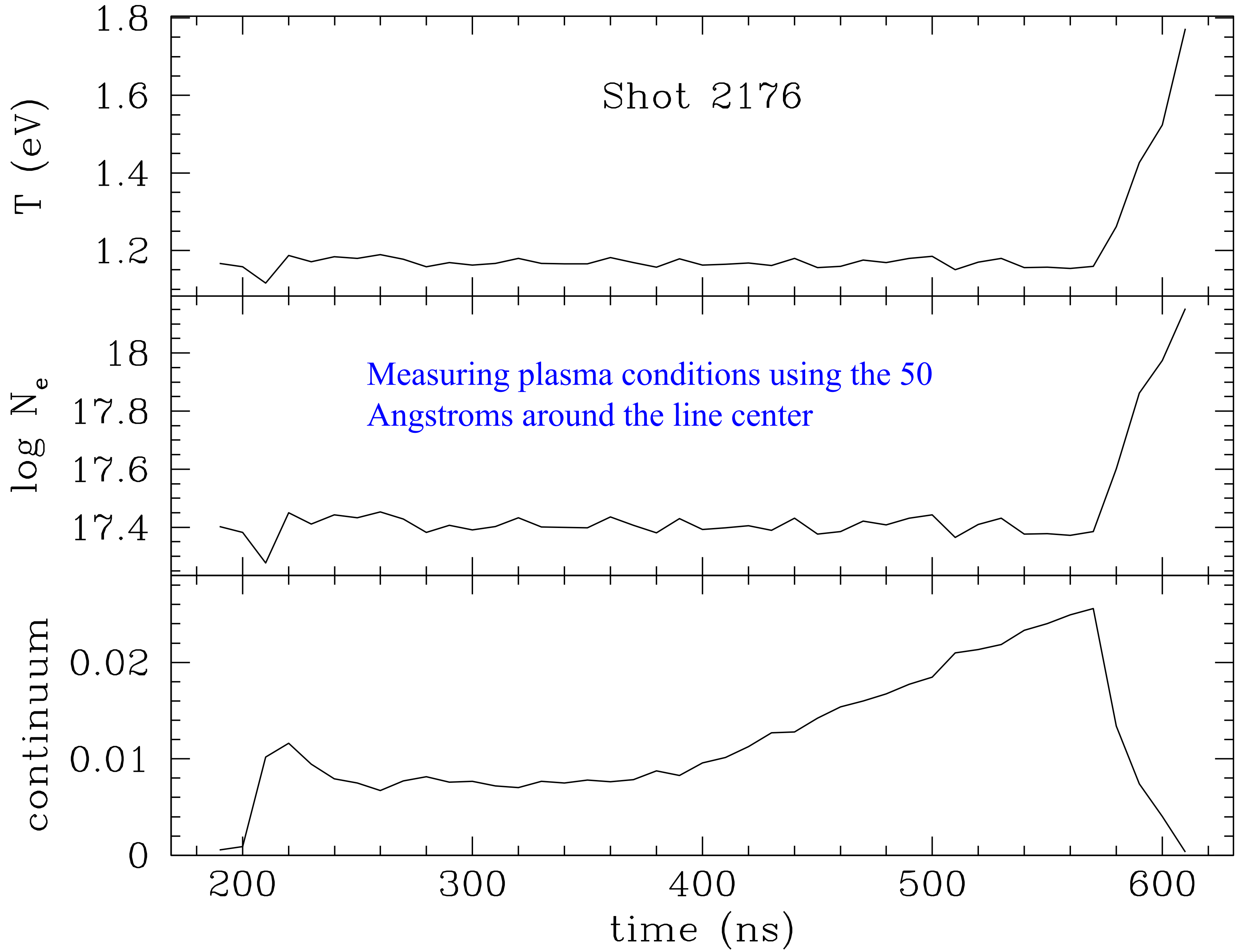
- Acquired data in emission and absorption
- Great signal in absorption; MCP gain at 125 V less





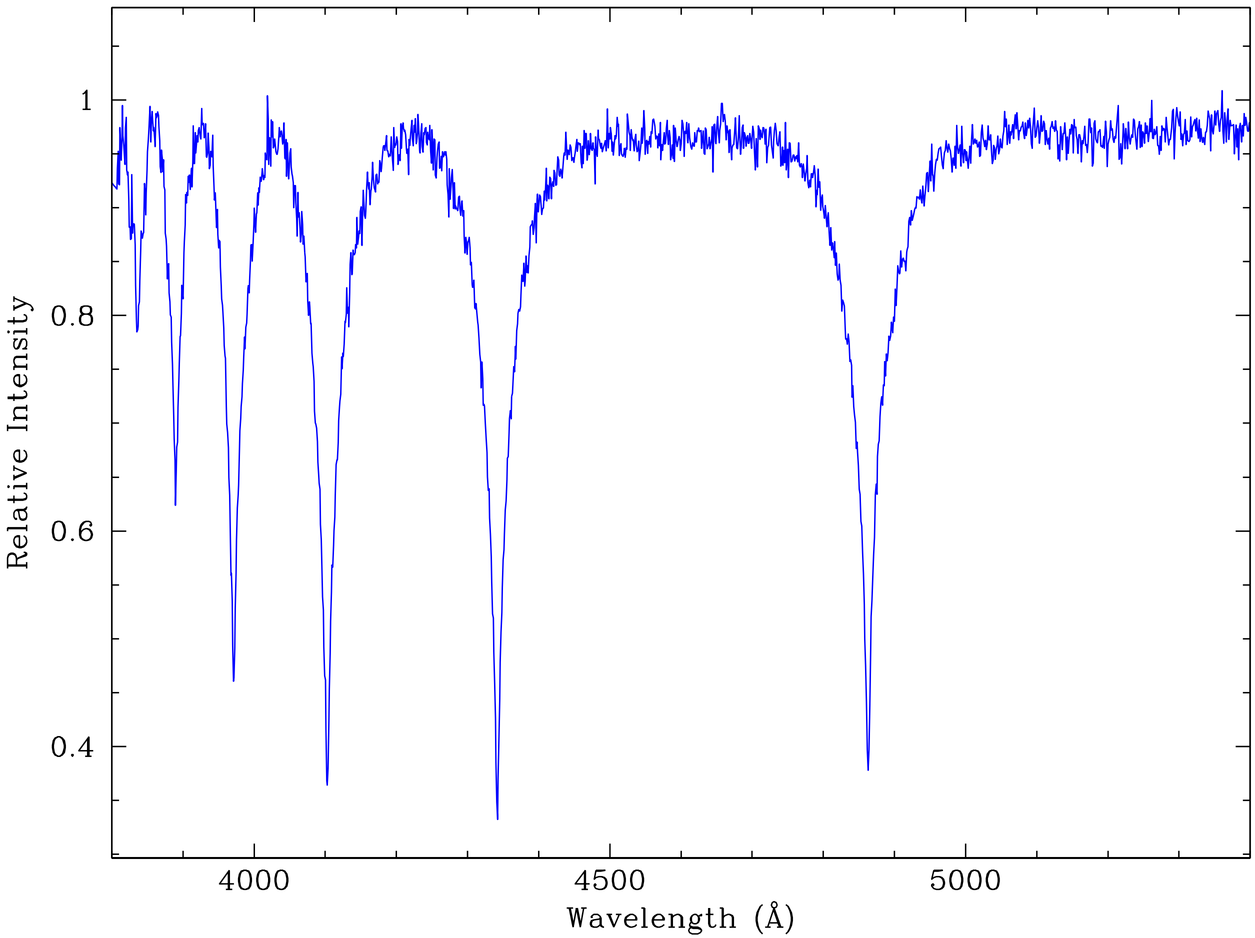





Shot 2176
Measuring plasma conditions using the 50 Angstroms around the line center
T (eV)
1.2
1.4
1.6
1.8
log N_e
17.4
17.6
17.8
18
continuum
0
0.01
0.02
200
300
400
500
600
time (ns)

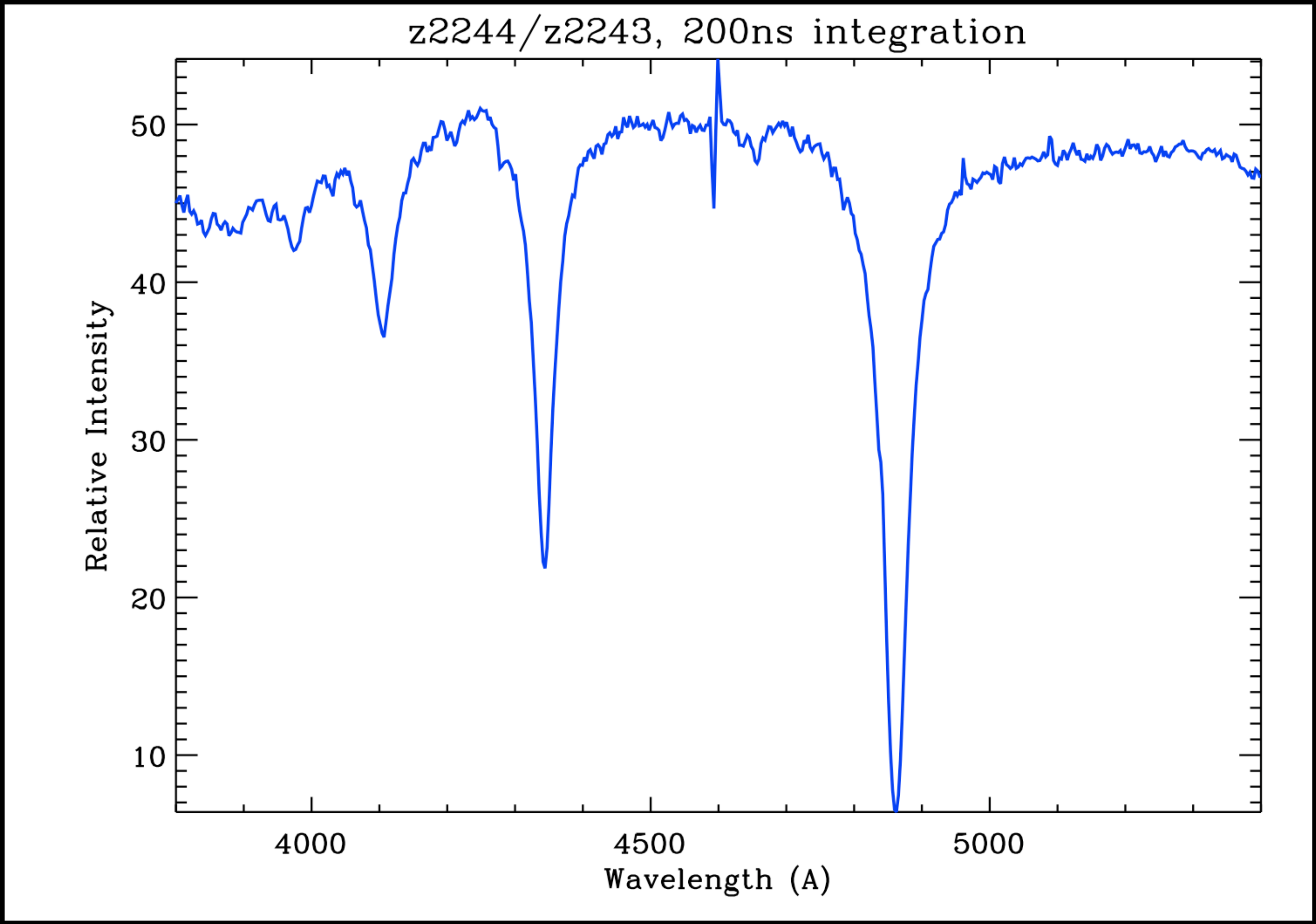
ory

“Typical” WD Spectrum

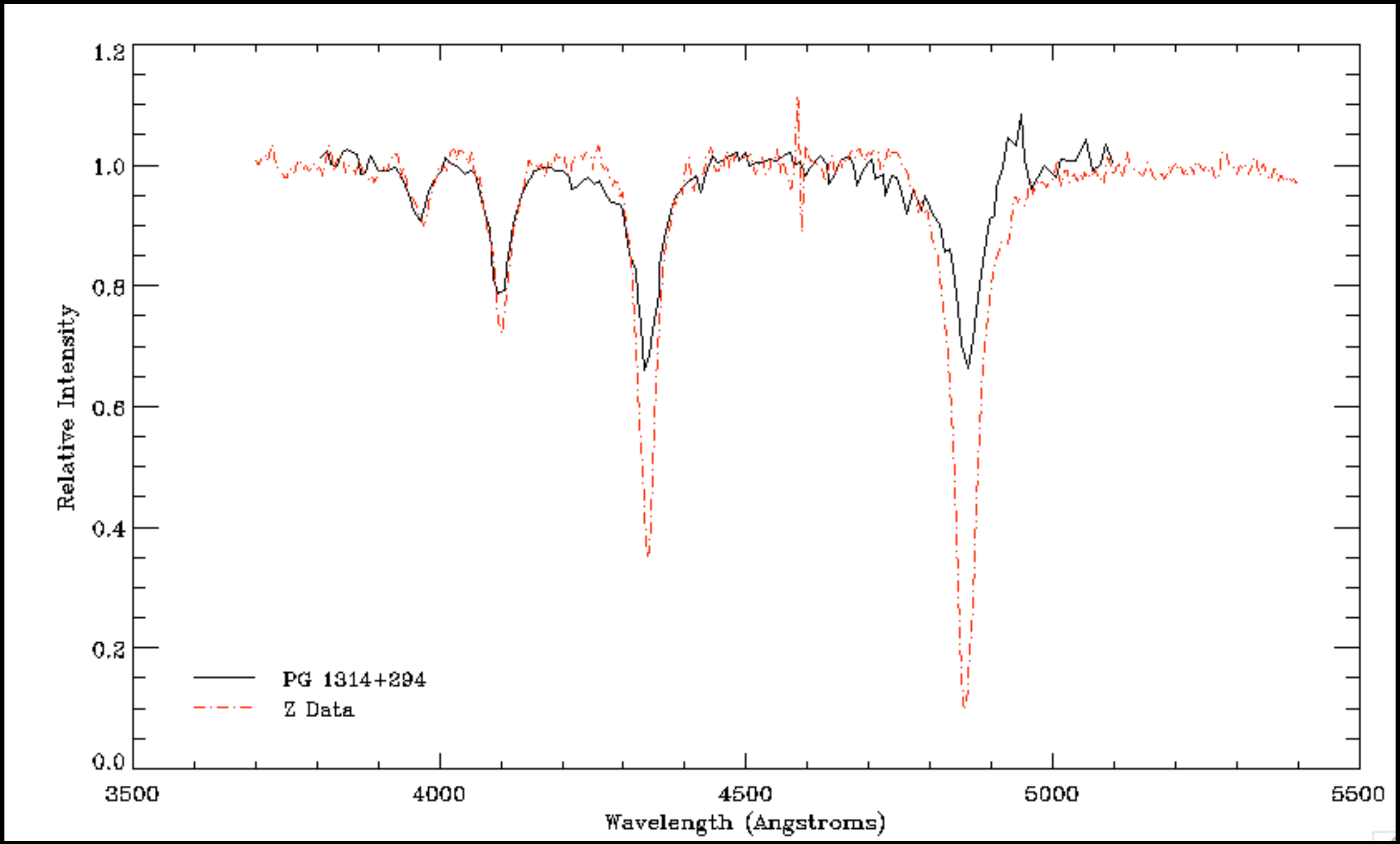


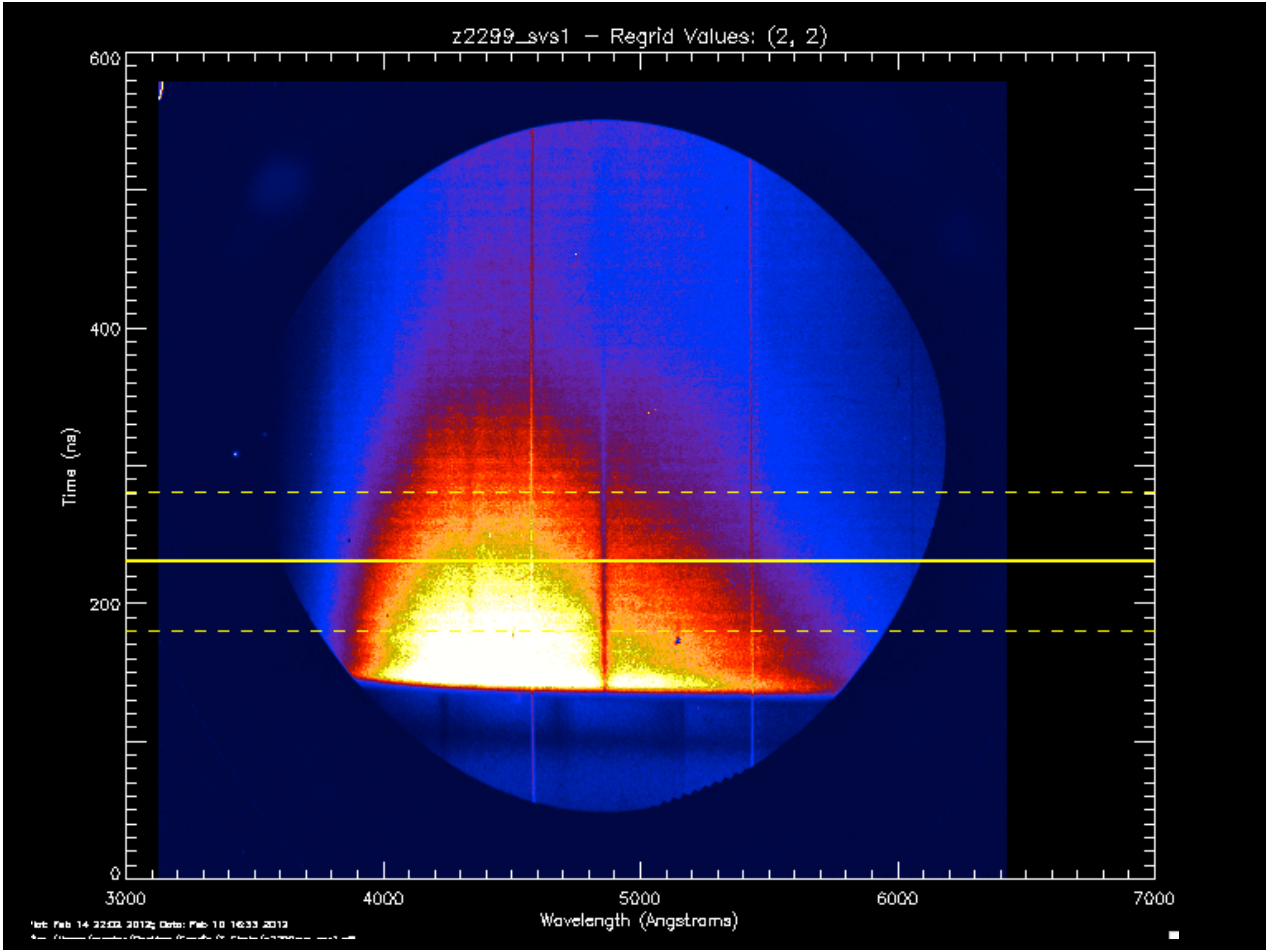
f a 200 ns integration from streaked data that clearly shows Hβ

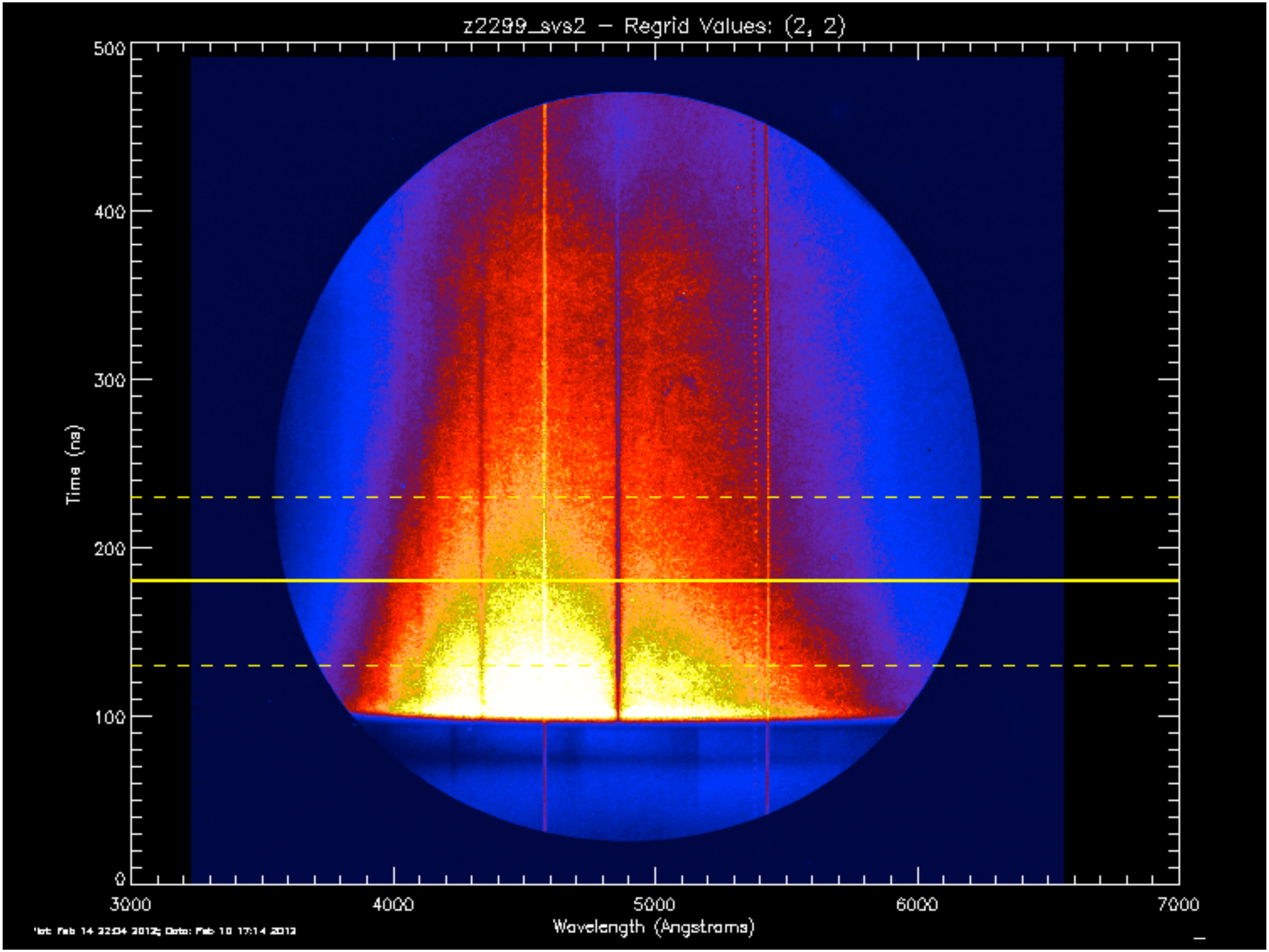
August 2011: A Spectrum from a White Dwarf Plasma in the Lab



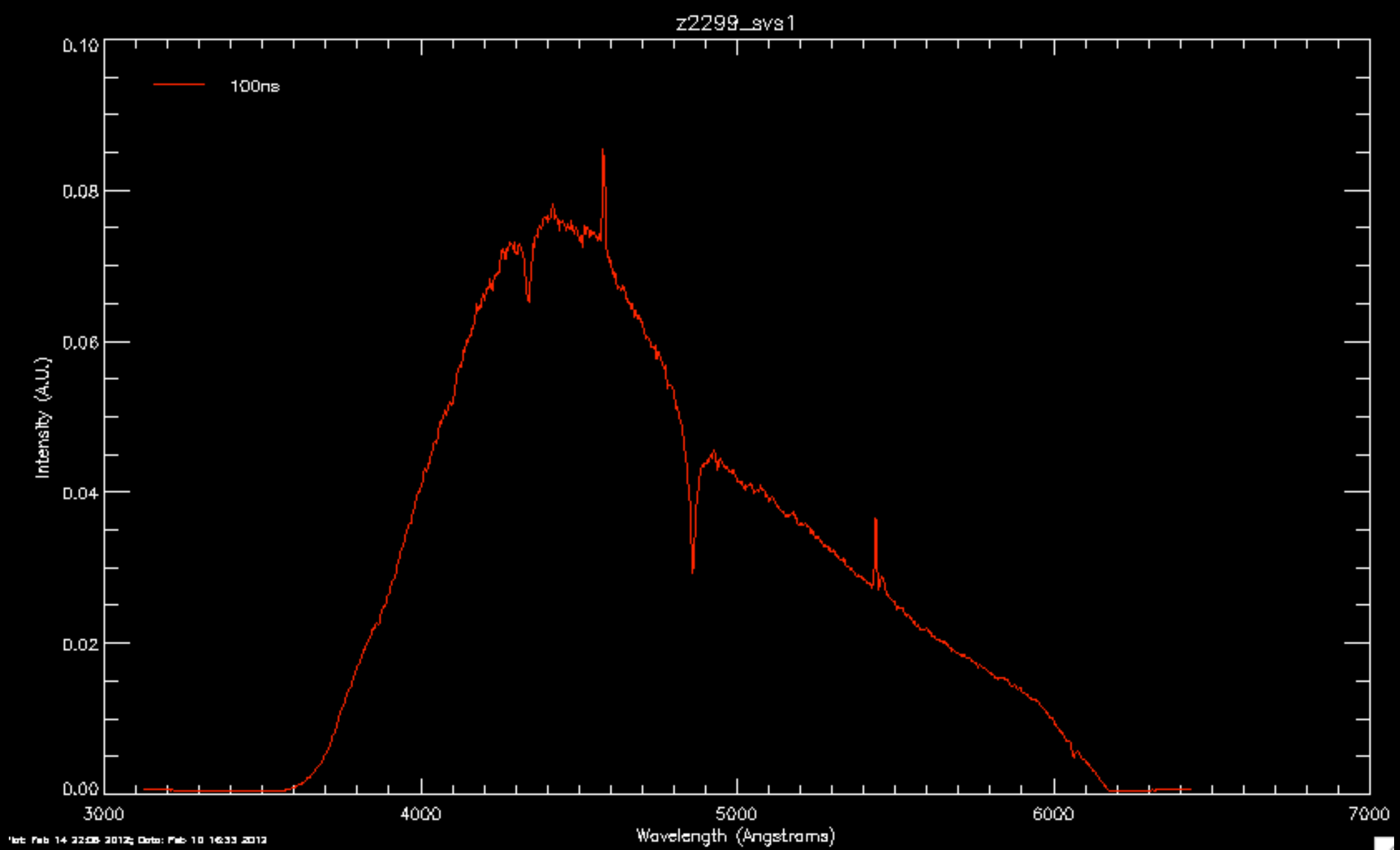
Lab WD plasma
vs
Observed WD



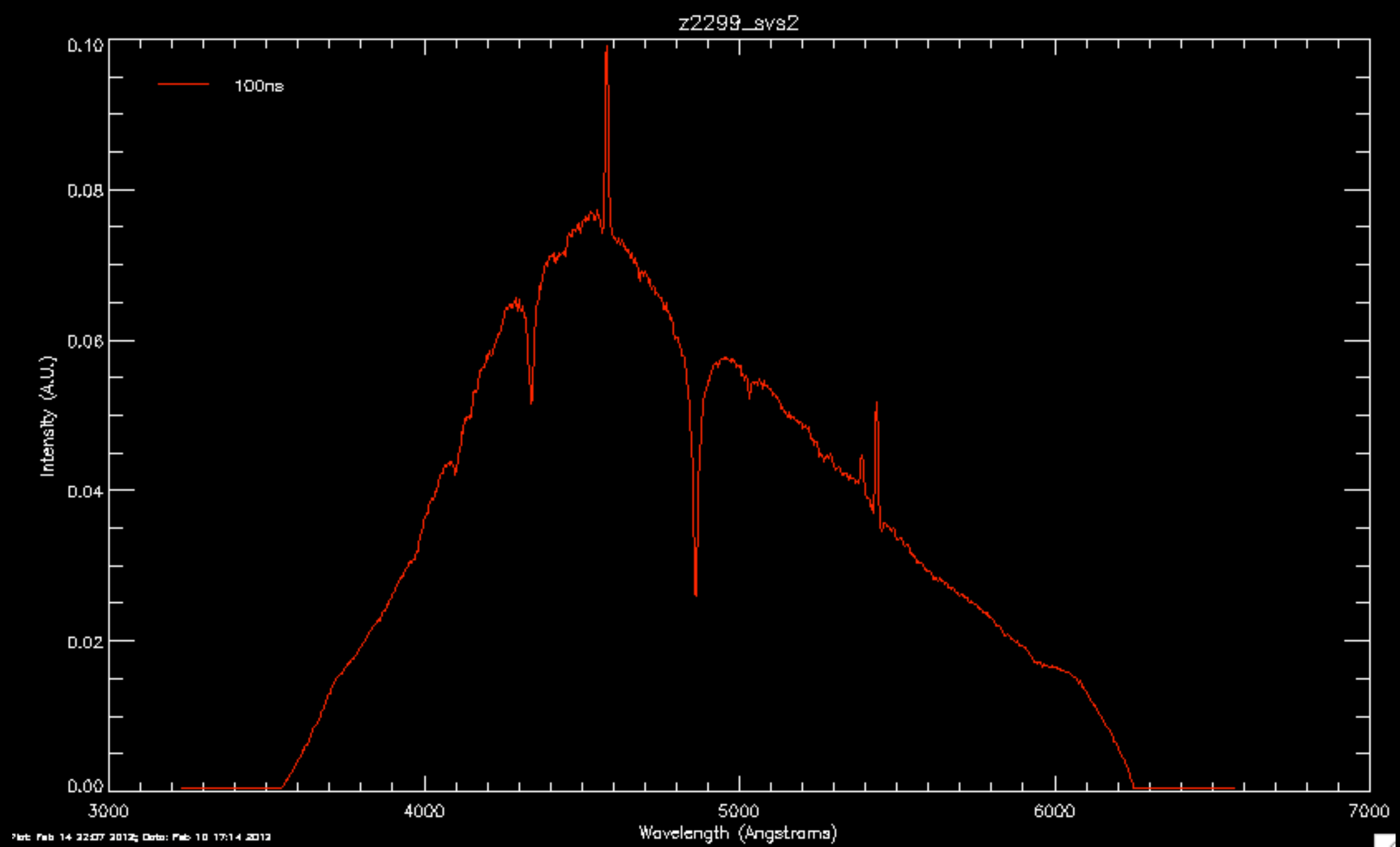

z2299_svs1 – Regrid Values: (2, 2)
Time (ns)
600
400
200
0
3000
4000
5000
6000
7000
Wavelength (Angstroms)

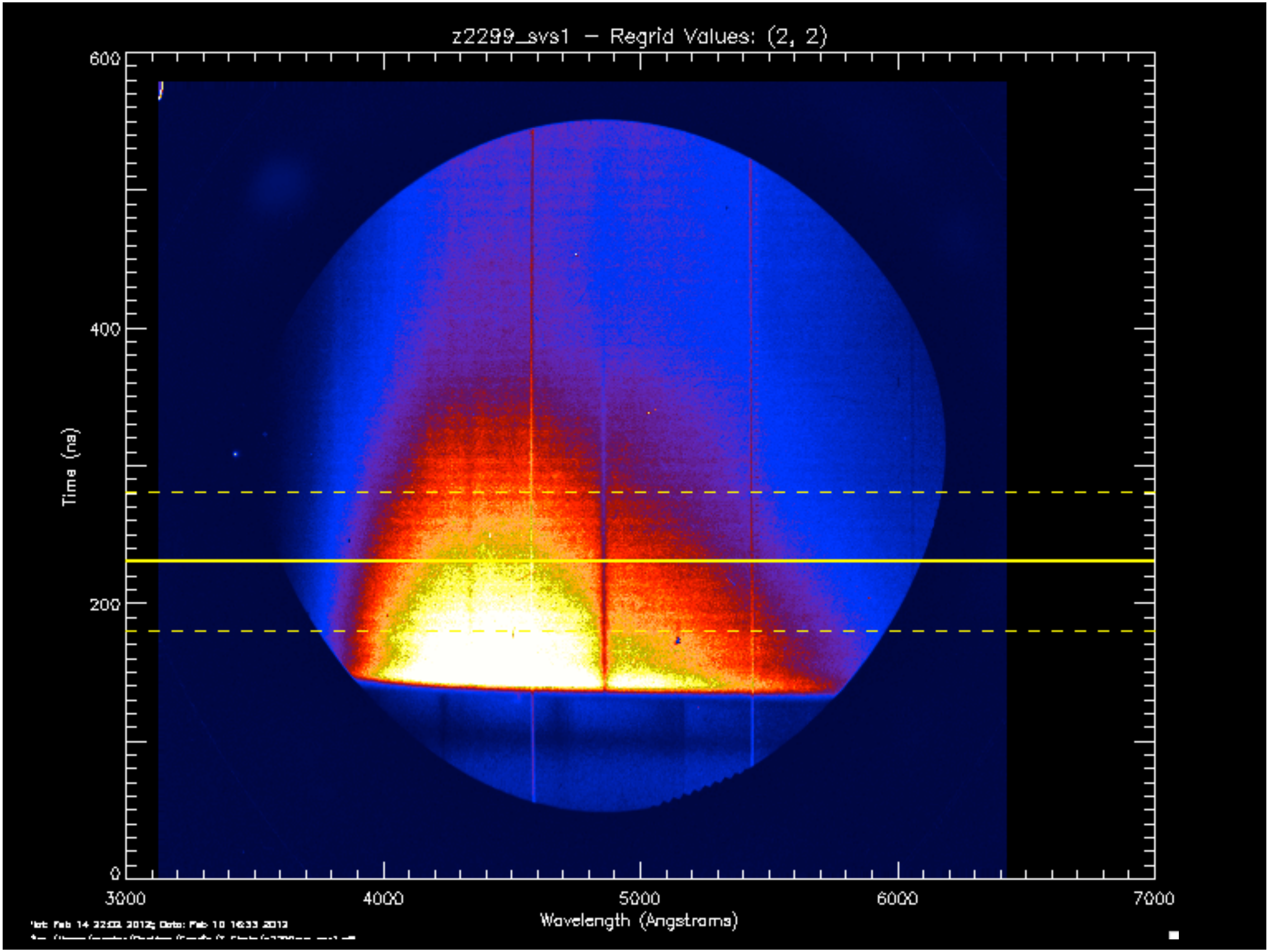

z2299_svs2 – Regrid Values: (2, 2)
Time (ns)
500
400
300
200
100
0
3000
4000
5000
6000
7000
Wavelength (Angstroms)
Plot: Feb 14 22:04 2012; Data: Feb 10 17:14 2012

3.5 cm plasma path length

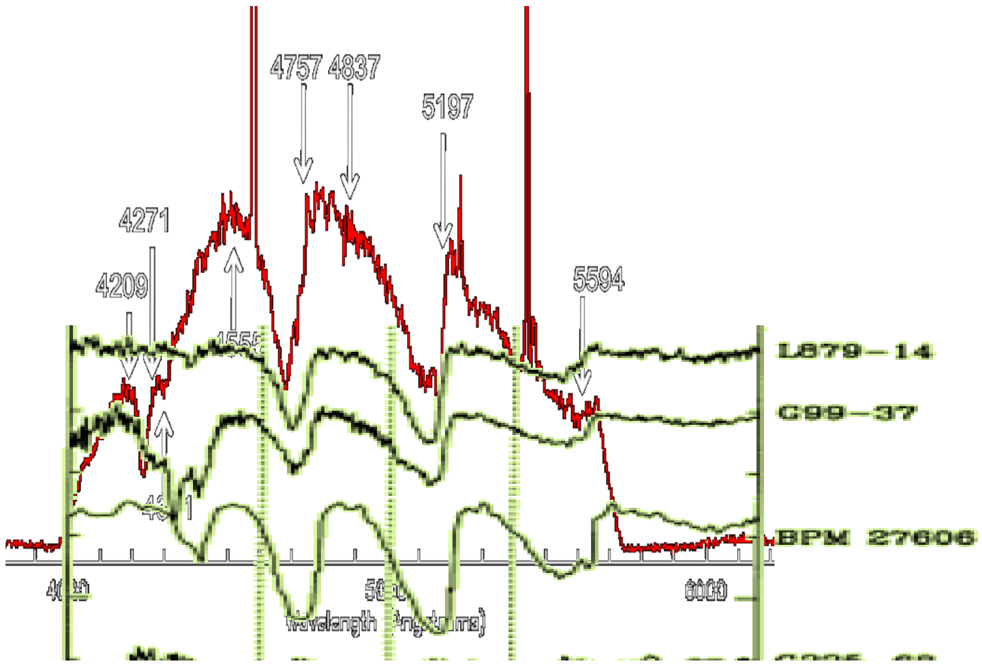


6.5 cm plasma path length




z2299_svs1 – Regrid Values: (2, 2)
Time (ns)
Wavelength (Angstroms)
600
400
200
0
3000
4000
5000
6000
7000

Cool DQ White dwarfs

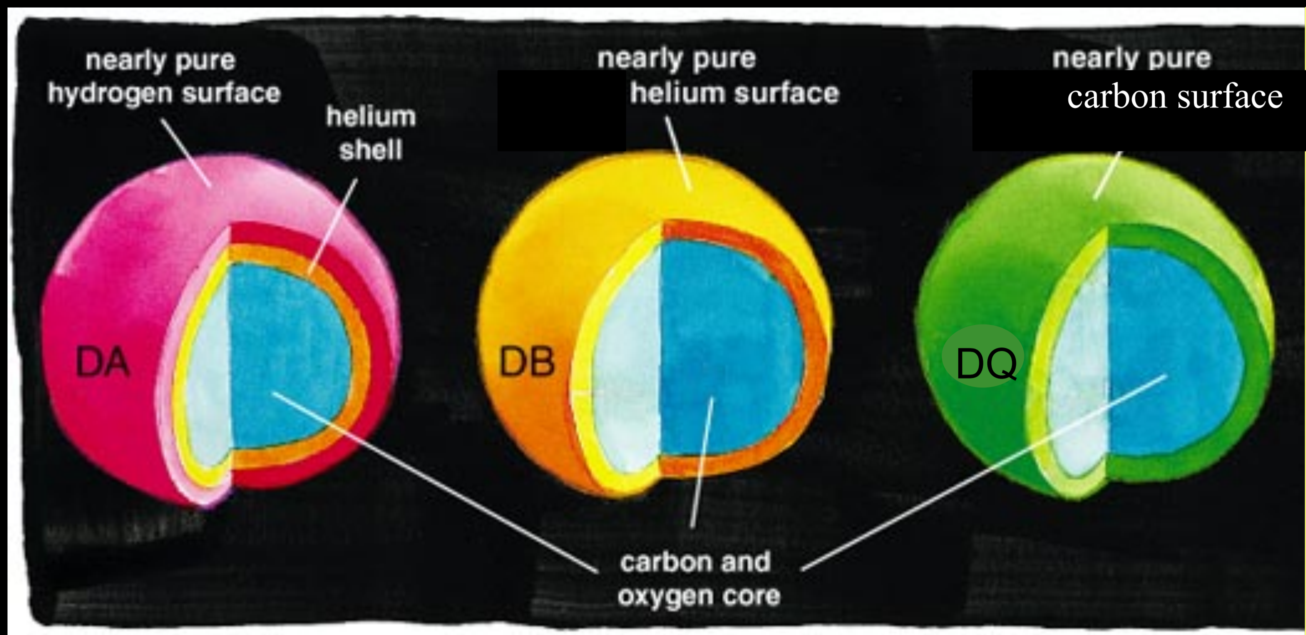


This Dynamic Field

- White Dwarf photospheric plasmas in the lab in *absorption* and *emission*
- Multiple ***new*** competing theories for line shapes—significant *disagreements* for H!
- Within 2-3 years test to see which, if any, is most accurate or best with dual purposes:
  - Improve astrophysics--small changes have large effects!
  - Improve line-broadening theory
- Use new discoveries to advance the field…

Mono-elemental surface layers

H He C



Three White Dwarf Flavors

The Opportunity of Newly Discovered Extremely Low Mass (ELM) White Dwarf Stars

•New binaries

•Eclipsing binaries

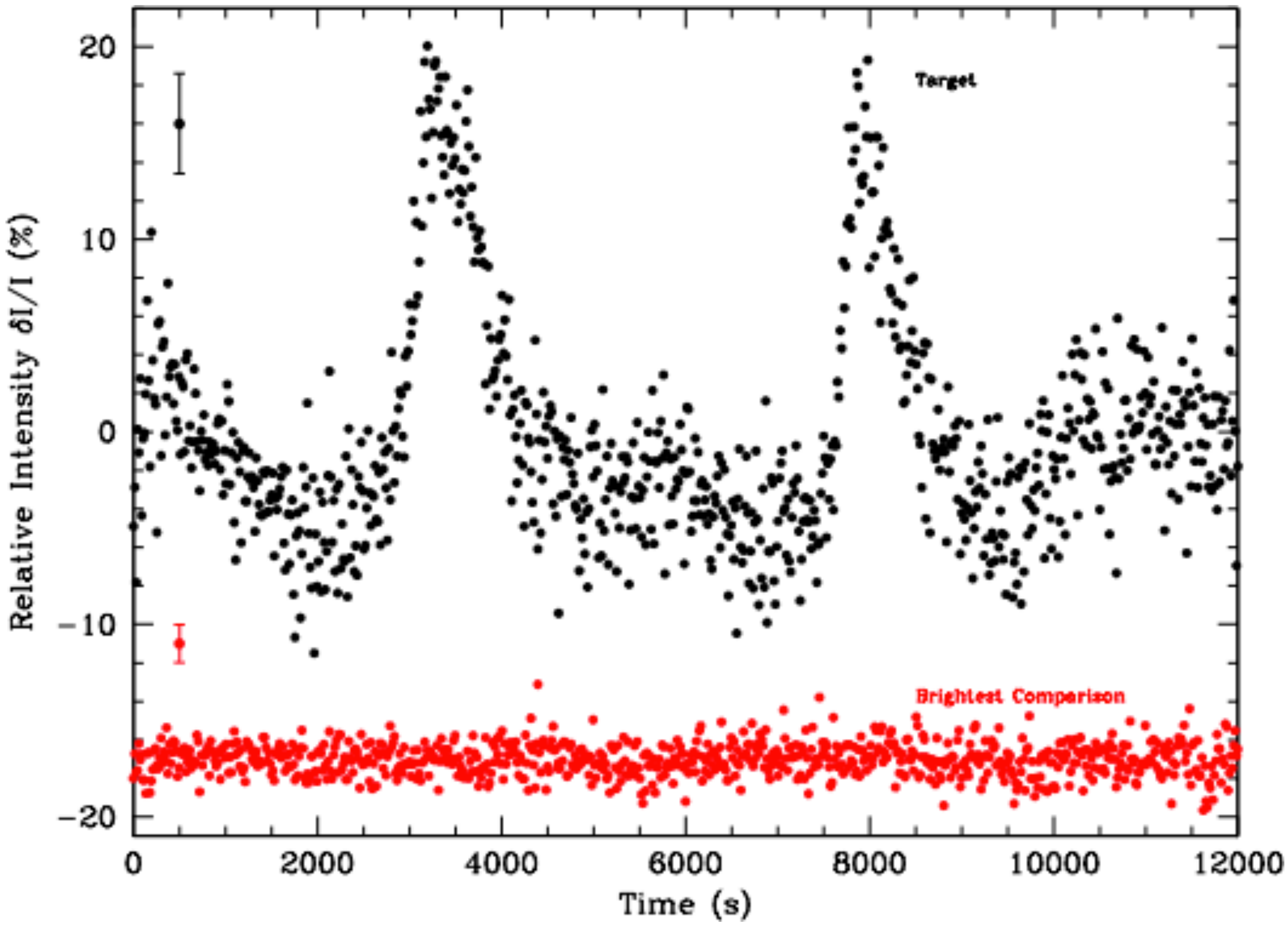
•Gravities more than 10 times lower than normal mass white dwarf stars: gives a significant dynamic range in masses

•Boundary conditions for comparing with stellar evolution codes

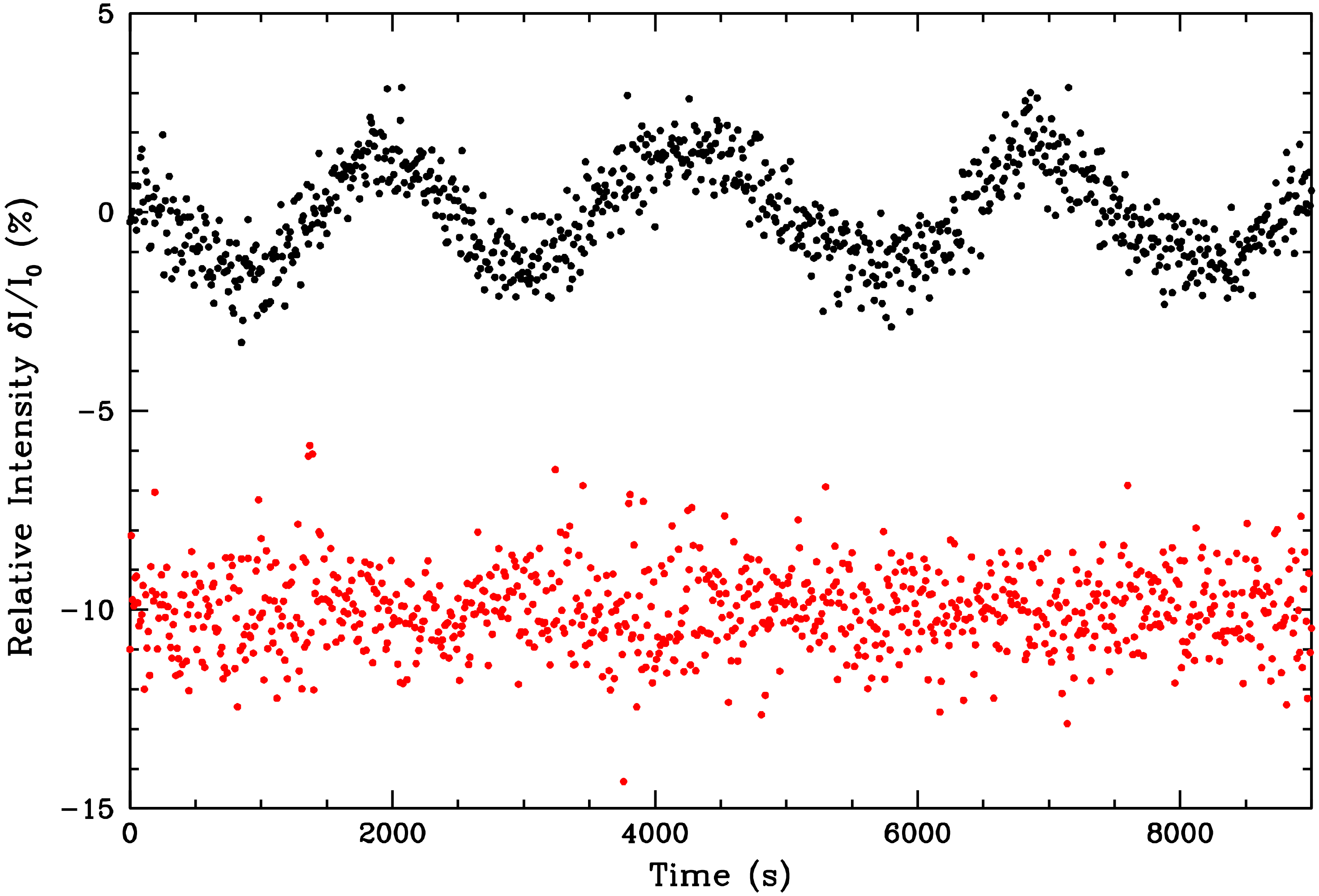
•Accurate comparison points for lab measurements at low electron densities

•A chance to study core He EoS, role of residual time-dependent nuclear burning

JJ Hermes' new ELM Pulsator: ELMV1

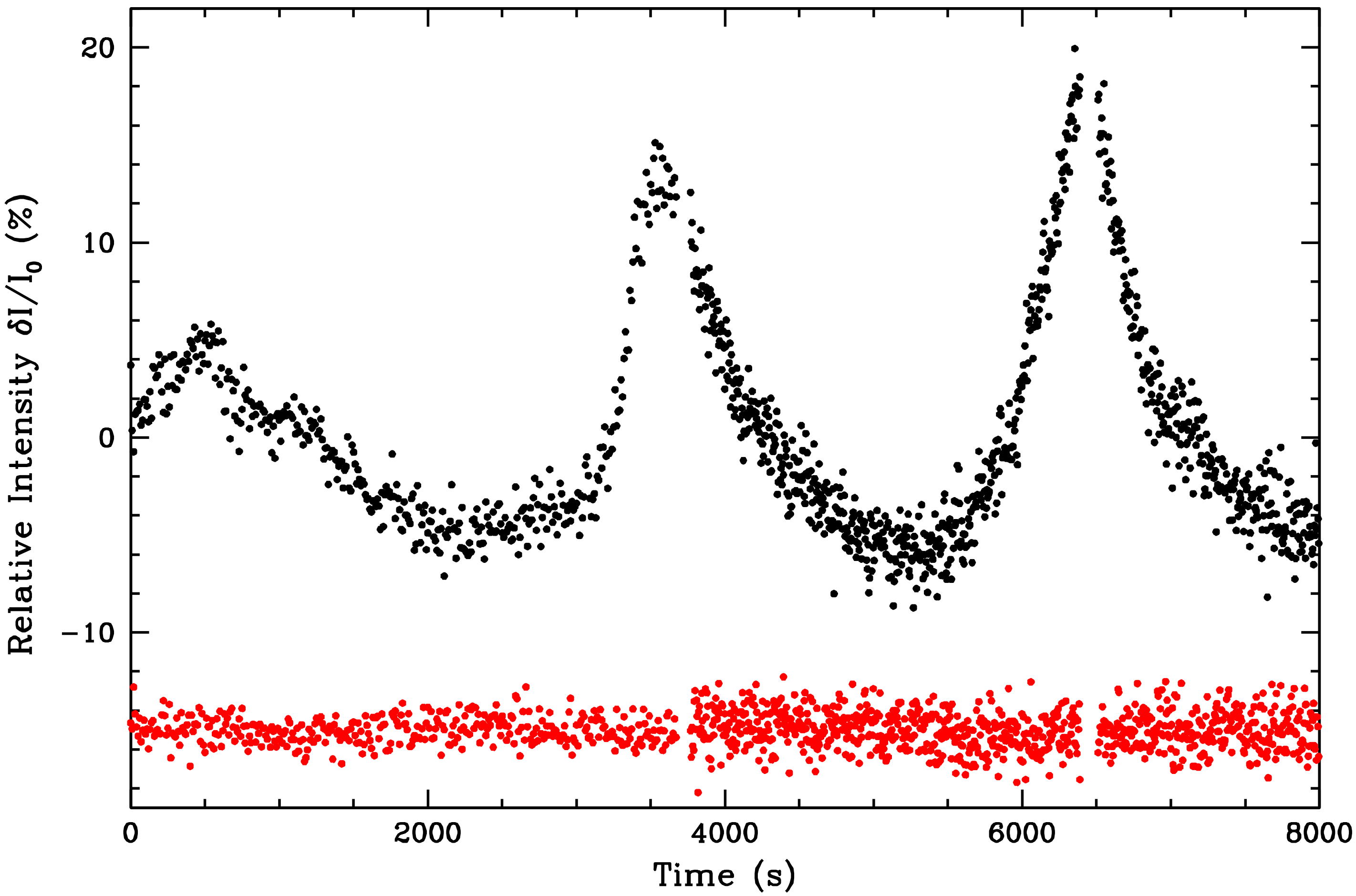


ELMV2



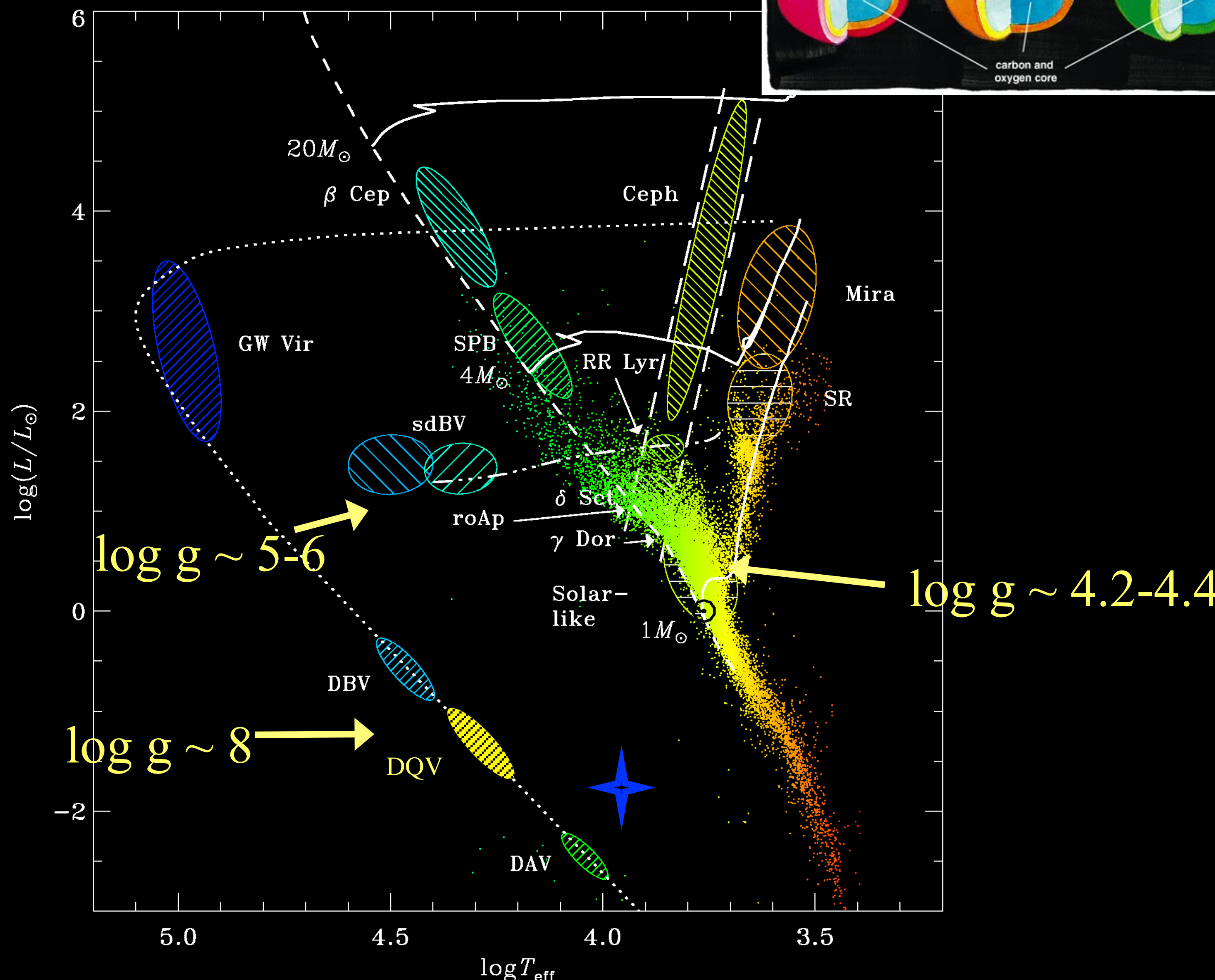
Relative Intensity $\delta I/I_0$ (%)
Time (s)
5
0
−5
−10
−15
0
2000
4000
6000
8000

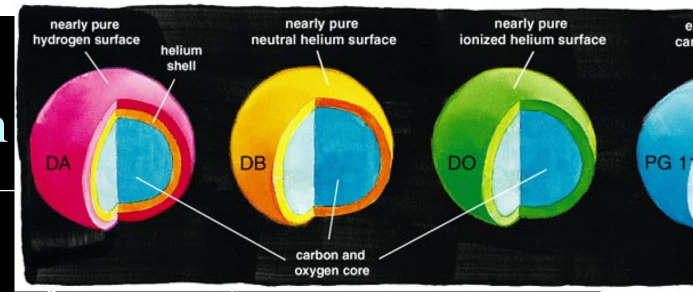
ELMV3



20
10
0
−10
0
2000
4000
6000
8000
Time (s)
Relative Intensity $\delta I/I_0$ (%)

The Pulsational H-R Diagram

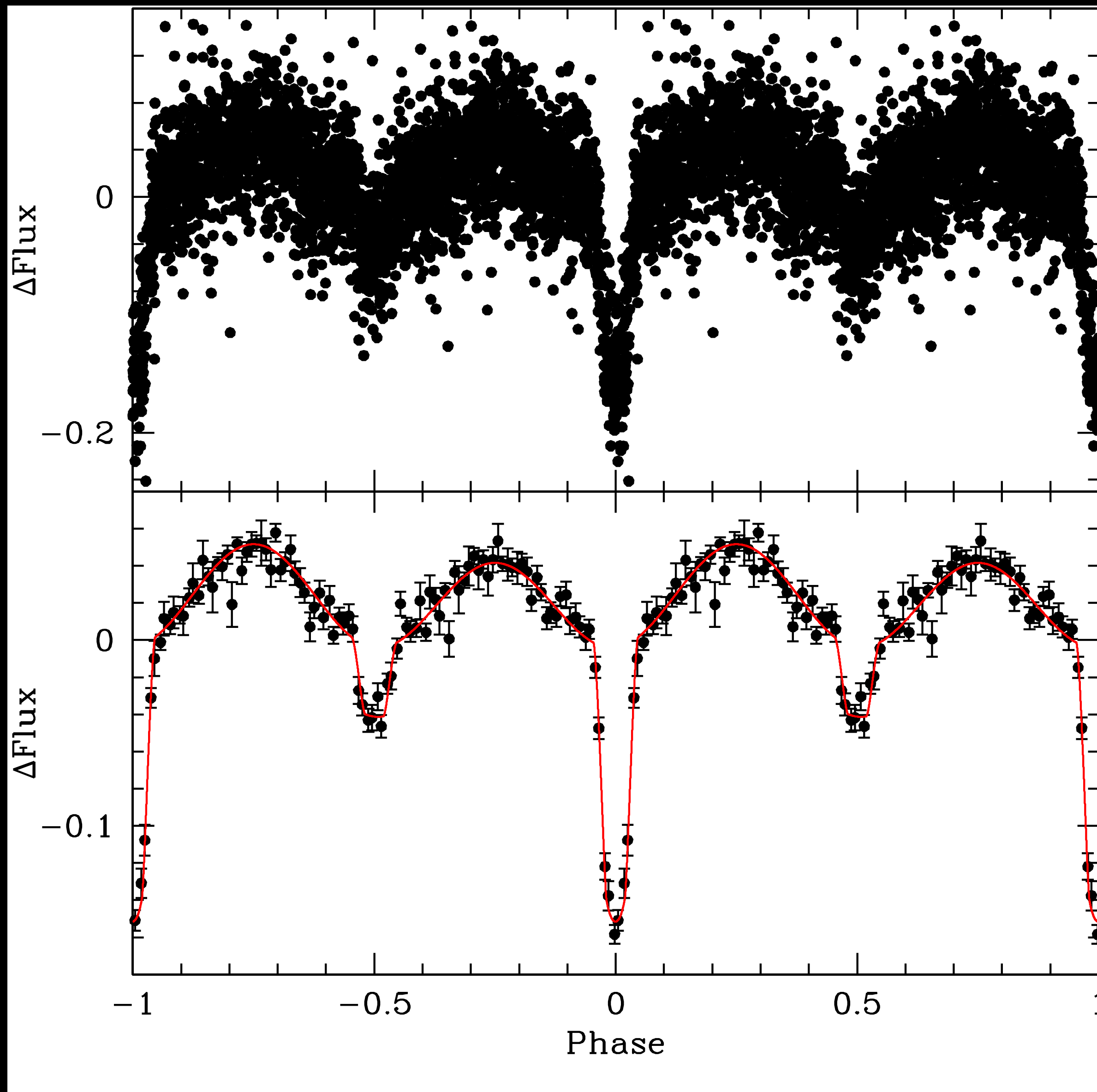




Shortest Period WD Binary Discovered

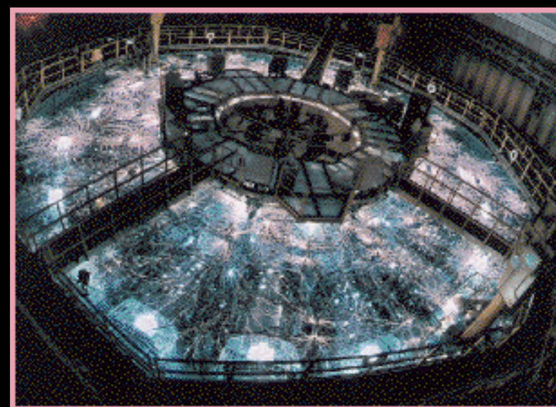
http://mcdonaldobservatory.org/news/releases/2011/0713.html

- The White Dwarfs are orbiting around each other at a very rapid speed - 1,315 km/s
- The orbit should be shrinking rapidly so the WDs should come in contact due to loss of energy through gravitational wave radiation.
- We expect this to happen in less than 1 million years.
- In 1-2 years we can measure this change at the McDonald Observatory.
- The change in orbital period, coupled with direct gravity wave measurements will provide a fundamental test of Einstein's General Relativity. This object should have a high signal to noise and be easily detected with LISA or ELISA.



From: A 12 Minute Orbital Period Detached Eclipsing Binary (Brown, Mukremin, Hermes, Winget et al., 2011)

Q: How do we improve our understanding of white dwarf photospheres?
A: By going from telescope to laboratory and back again…



Spectra give unphysical masses

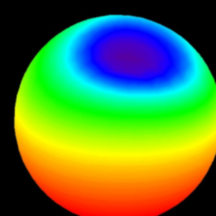
Measurements of lines at White Dwarf photospheric conditions

Accurate Observed Masses

Cosmochronology

- **Age of universe**
- **Age and history of the galaxy**

Asteroseismology



- **Dark Matter & Dark Energy**
- **SnIa Progenitors: DE**
- **EoS of C/O/He**
- **Crystallization of Dense Coulomb Plasmas**

Video from Aug 19 shot on Z

Z

A painting by Leah Flippen

Dedicated to the memory of two mentors and friends:

Carl J. Hansen and Francois Wesemael

Thanks!