2011 Science with High-Power Lasers and
Pulsed Power Workshop
Santa Fe, NM

White Dwarfs on Z:
From Telescope to Laboratory and Back

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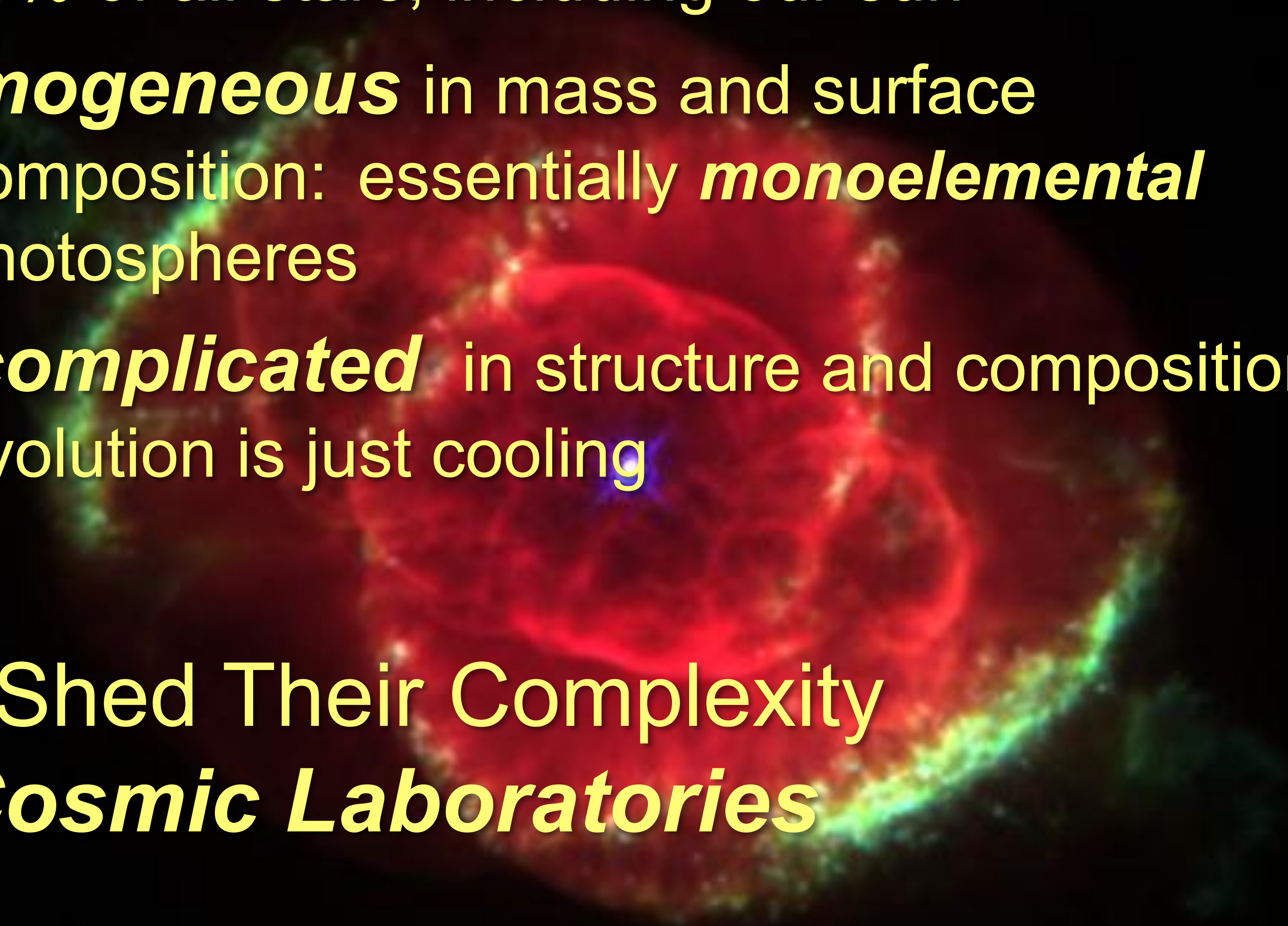
What Are White Dwarf Stars?

- ***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

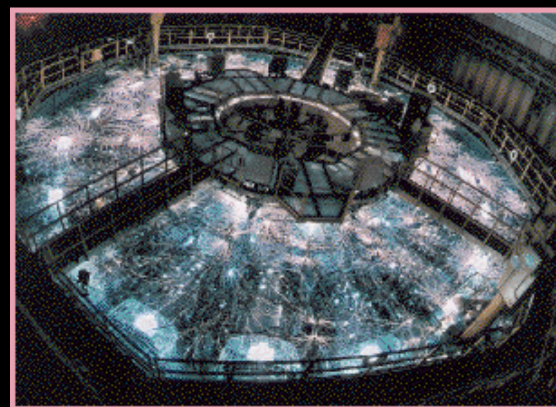
They Shed Their Complexity

➔ ***Cosmic Laboratories***



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



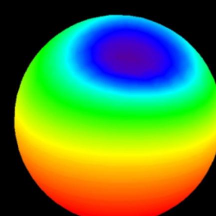
Measurements of lines at White
Dwarf photospheric conditions

Accurate Observed
Masses

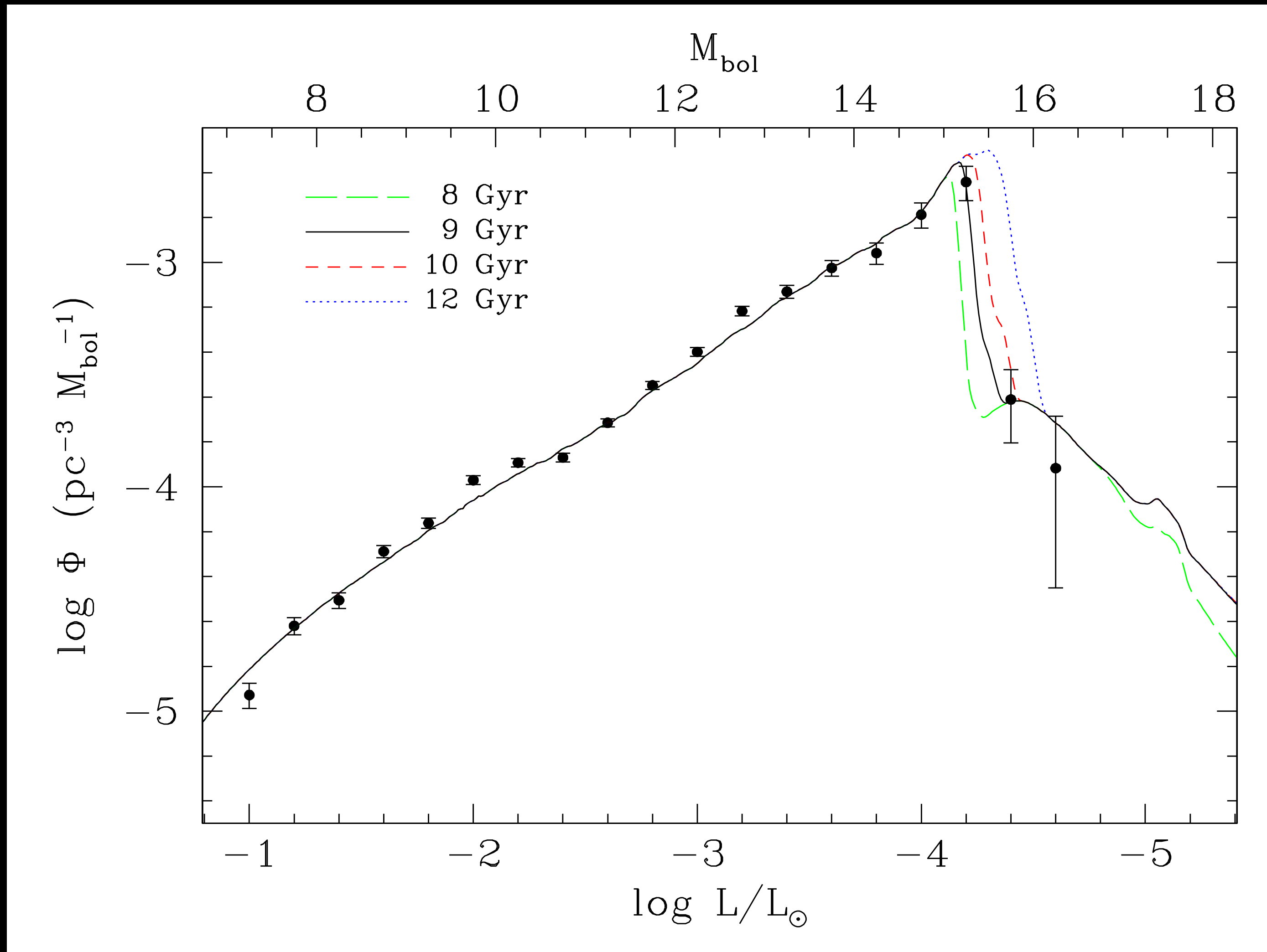
Cosmochronology

- Age of universe
- Age and history of the galaxy

Asteroseismology

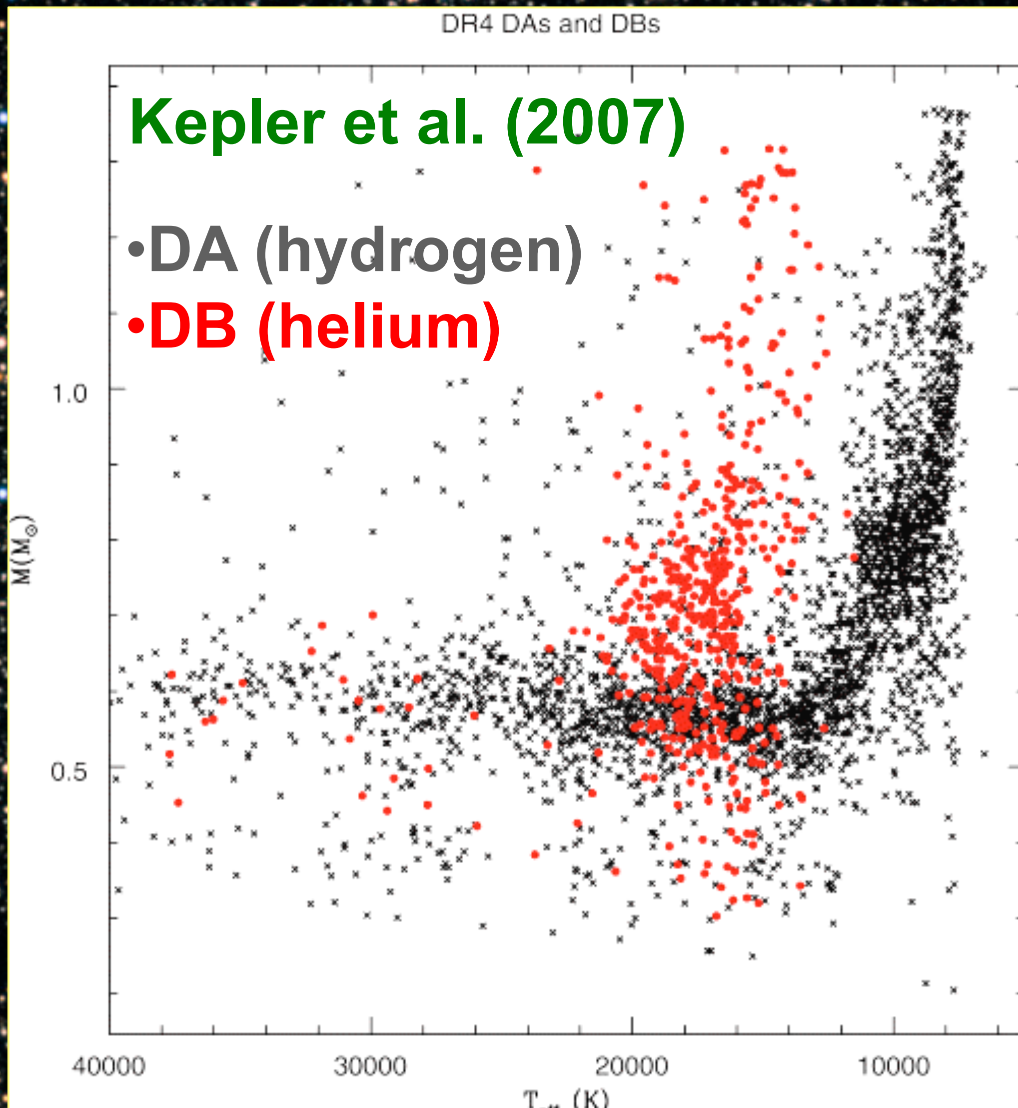


- Dark Matter & Dark Energy
- Snla Progenitors: DE
- Crystallization of Dense Coulomb Plasmas



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

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



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

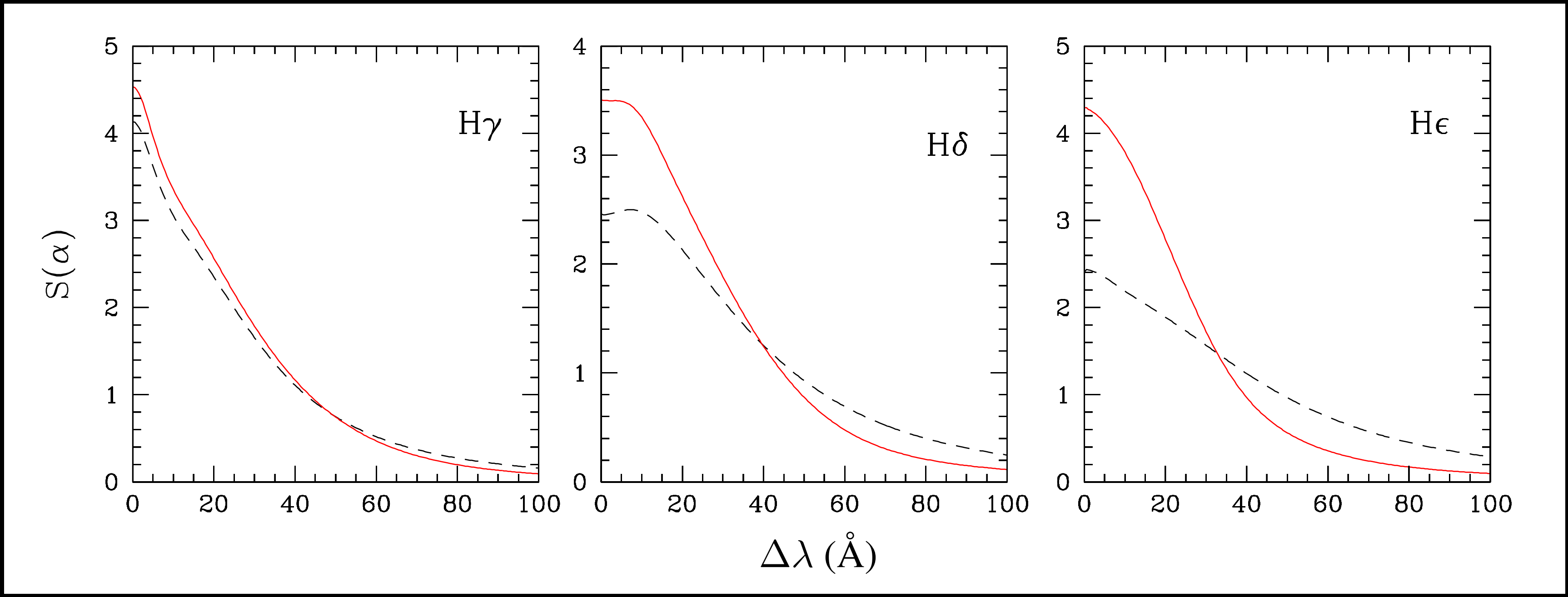
- For a sample of 449 non-binary thin disk normal DA WDs, Falcon et al. find

$$\langle M \rangle = 0.647 + 0.013 - 0.014\ M_{\odot}$$

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

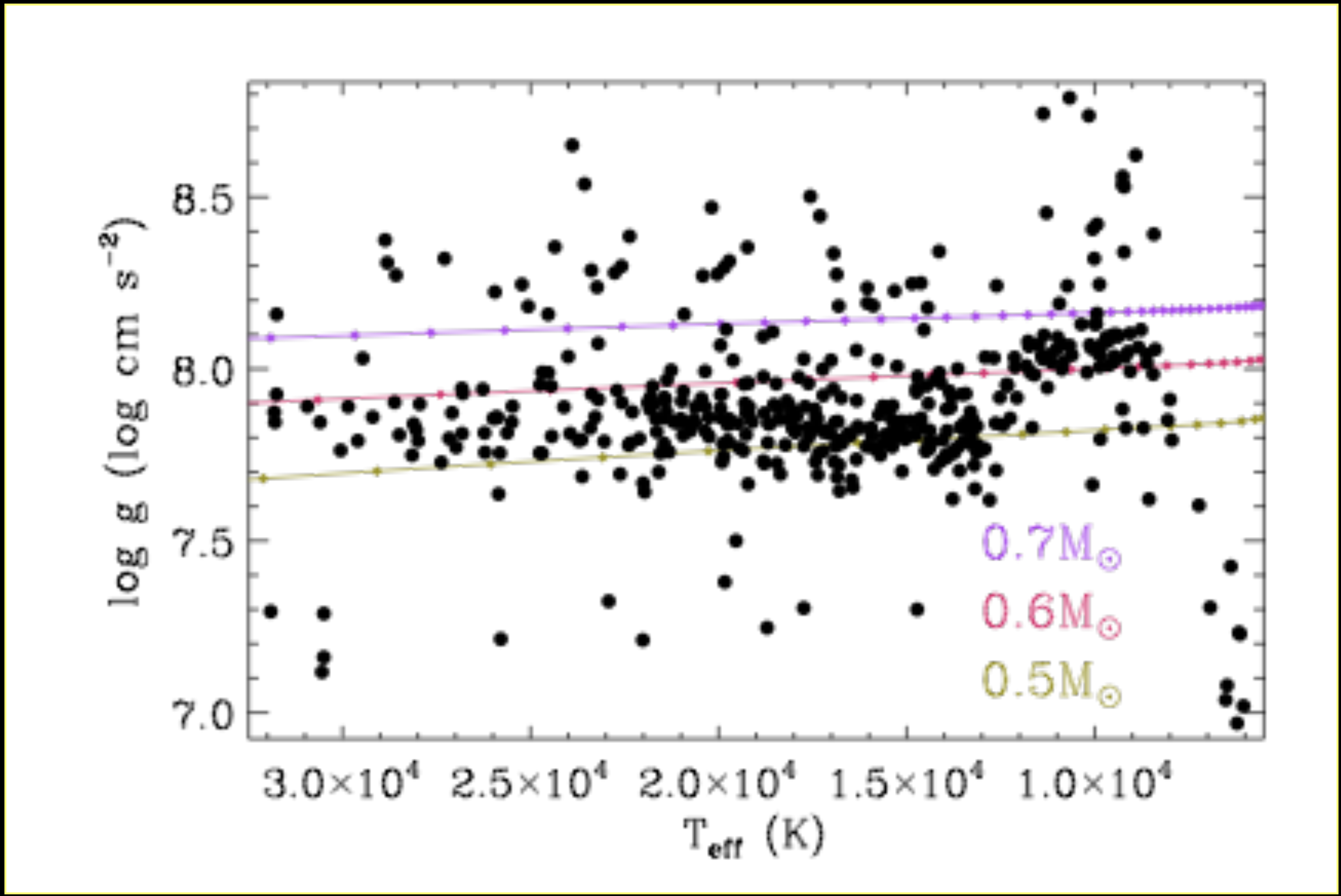
- Unlike spectroscopic surveys, do not find significant change in mean mass across T_{eff} split at 12000 K:

$$\Delta M = 0.046 +/- 0.053\ M_{\odot}$$



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!

Primary Near Term Science Goal:

- Measure relative line shapes for Hβ, Hγ, and Hδ at white dwarf photospheric conditions

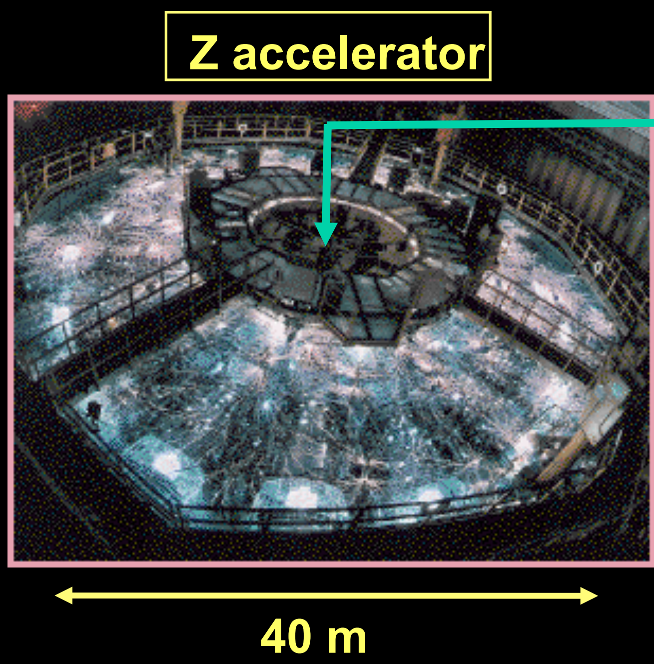
Approach:

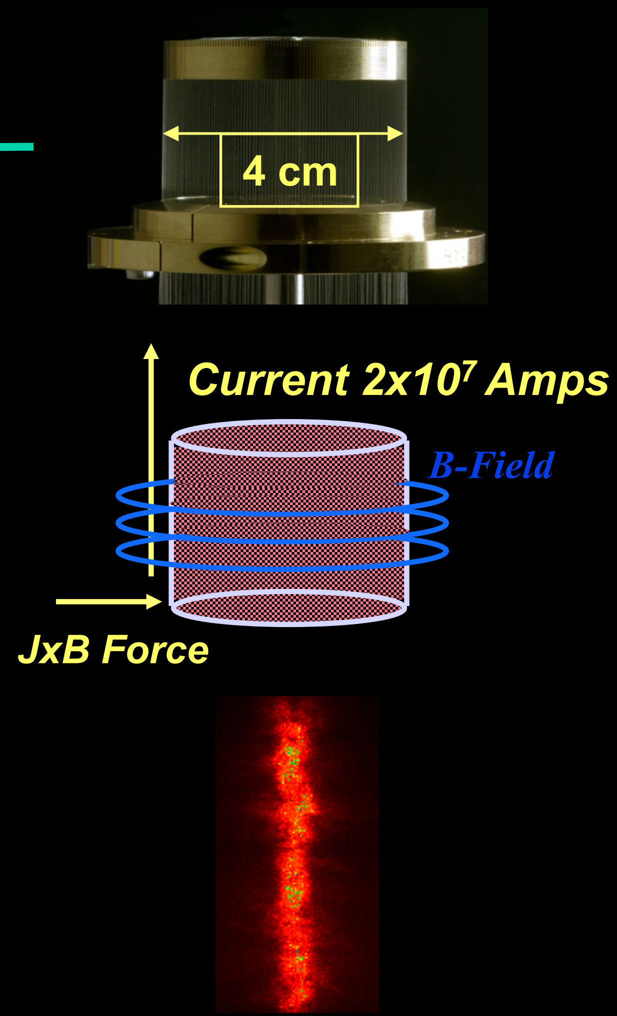
- Radiatively heat gas cells to conditions of

  T_e = 0.8-1.5 eV

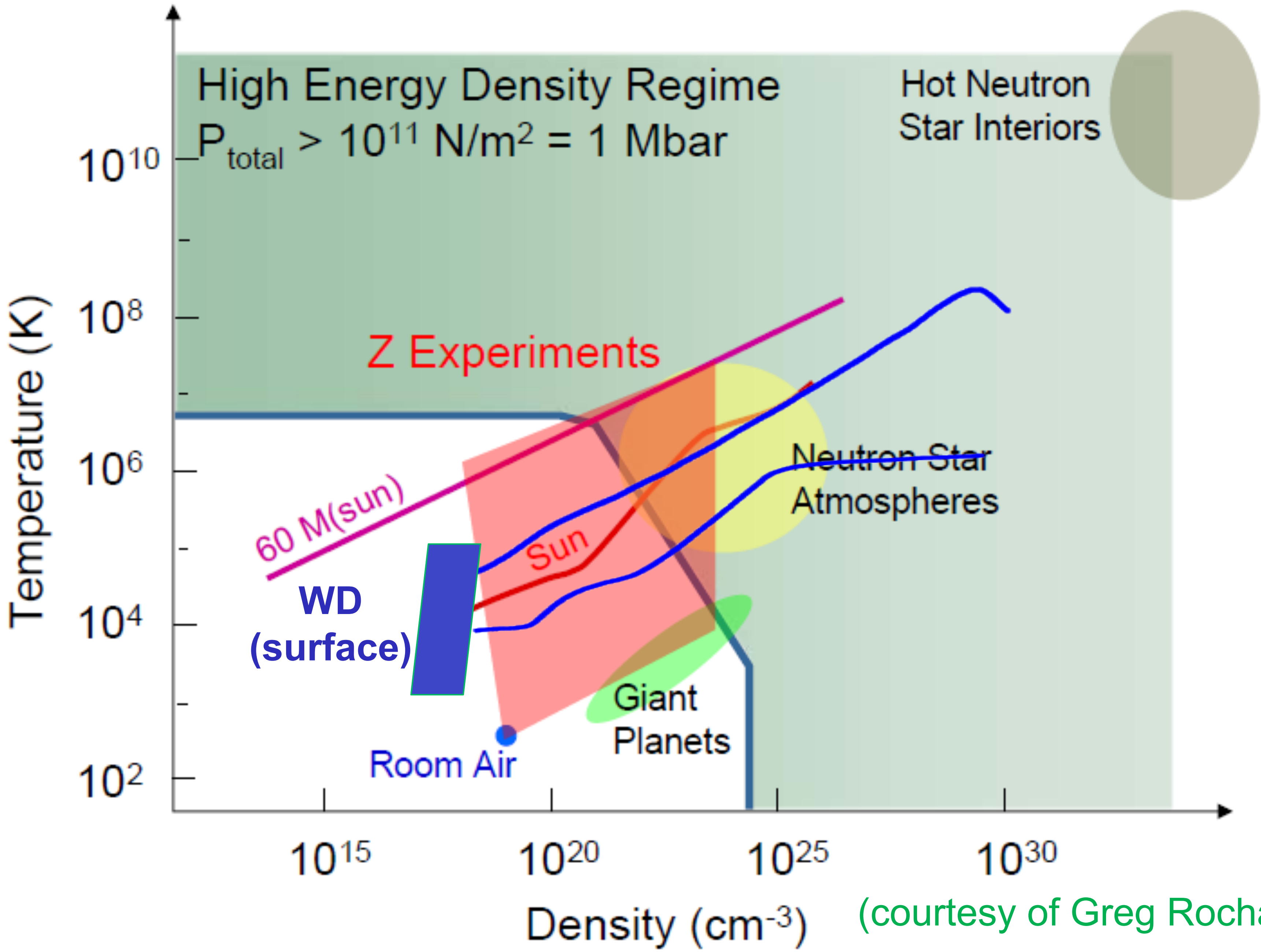
  ne = 1.e+16-1.e+18 atoms/cc

The 24 million Ampere current on Z provides access to new laboratory astrophysics regimes



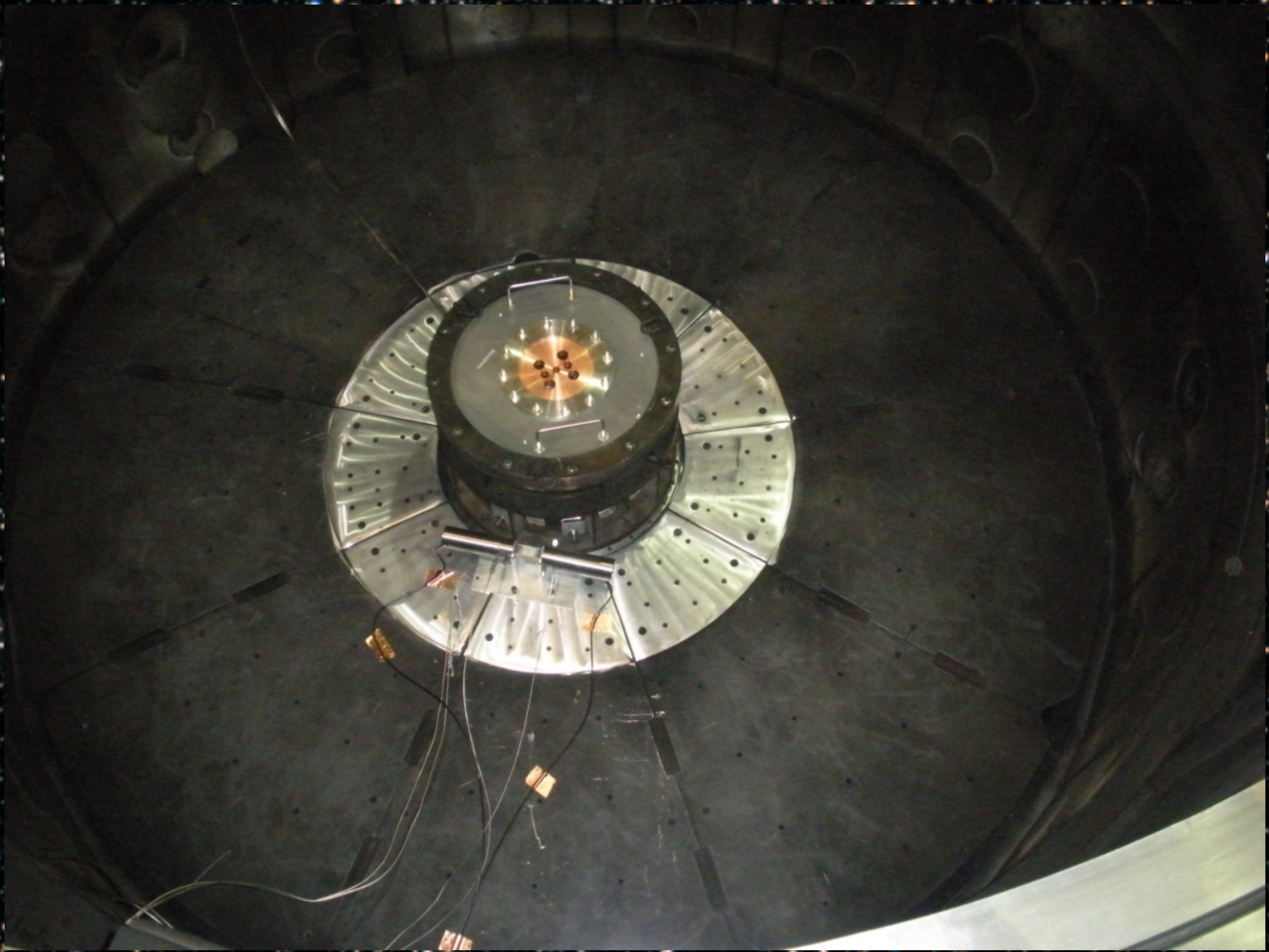


Z experiments use large magnetic fields or large x-ray flux to create extreme environments

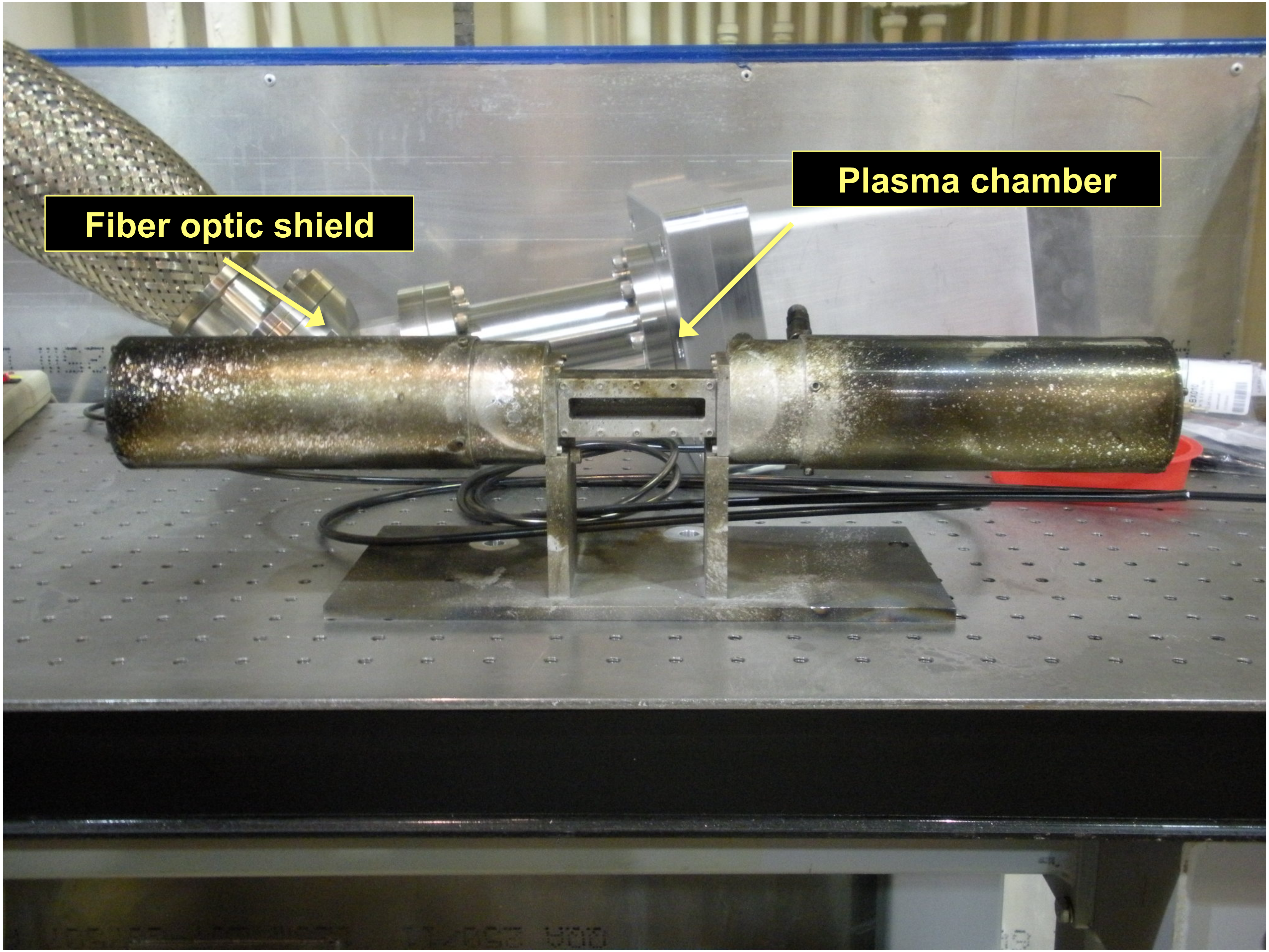


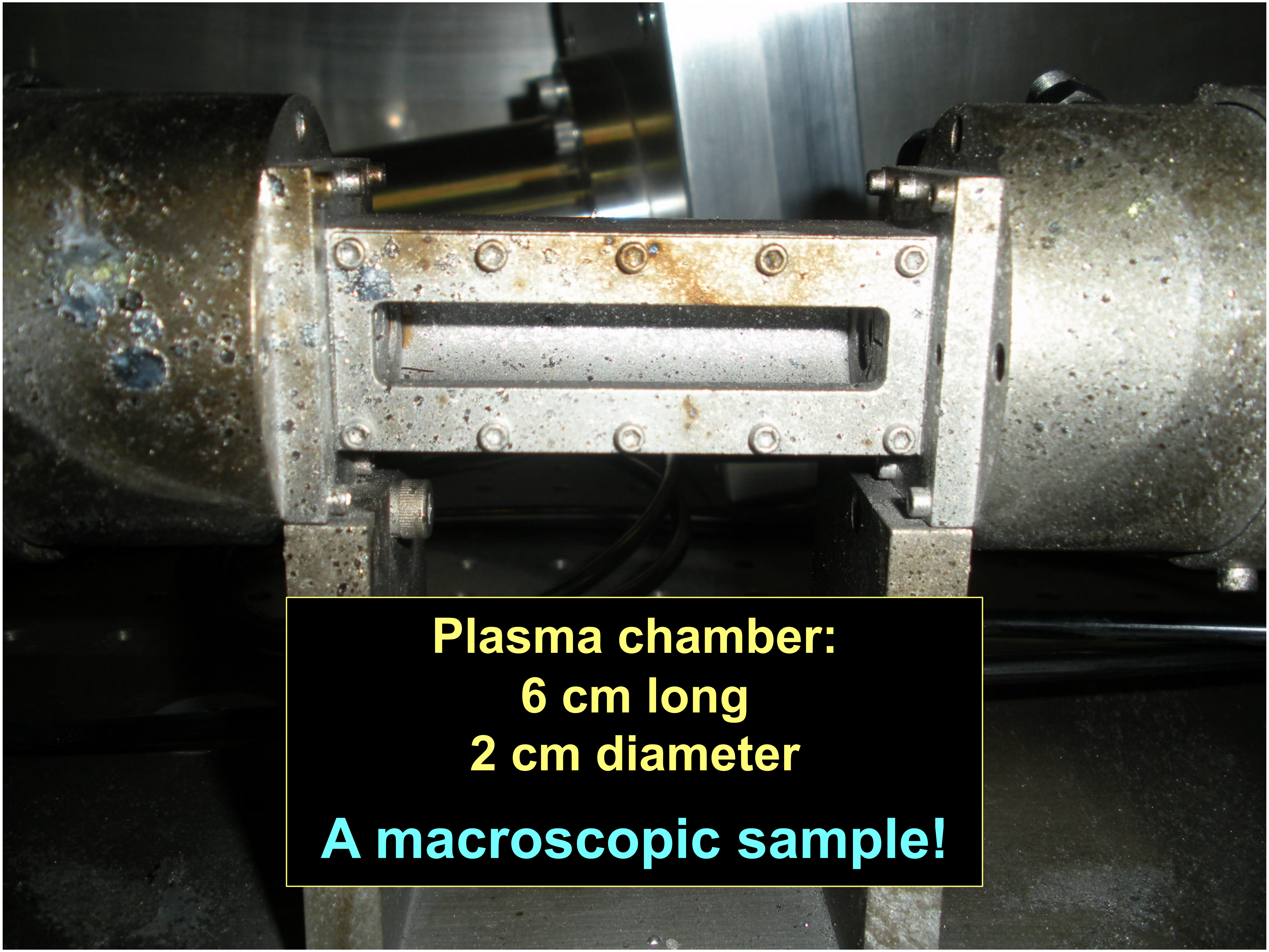
(courtesy of Greg Rochau)

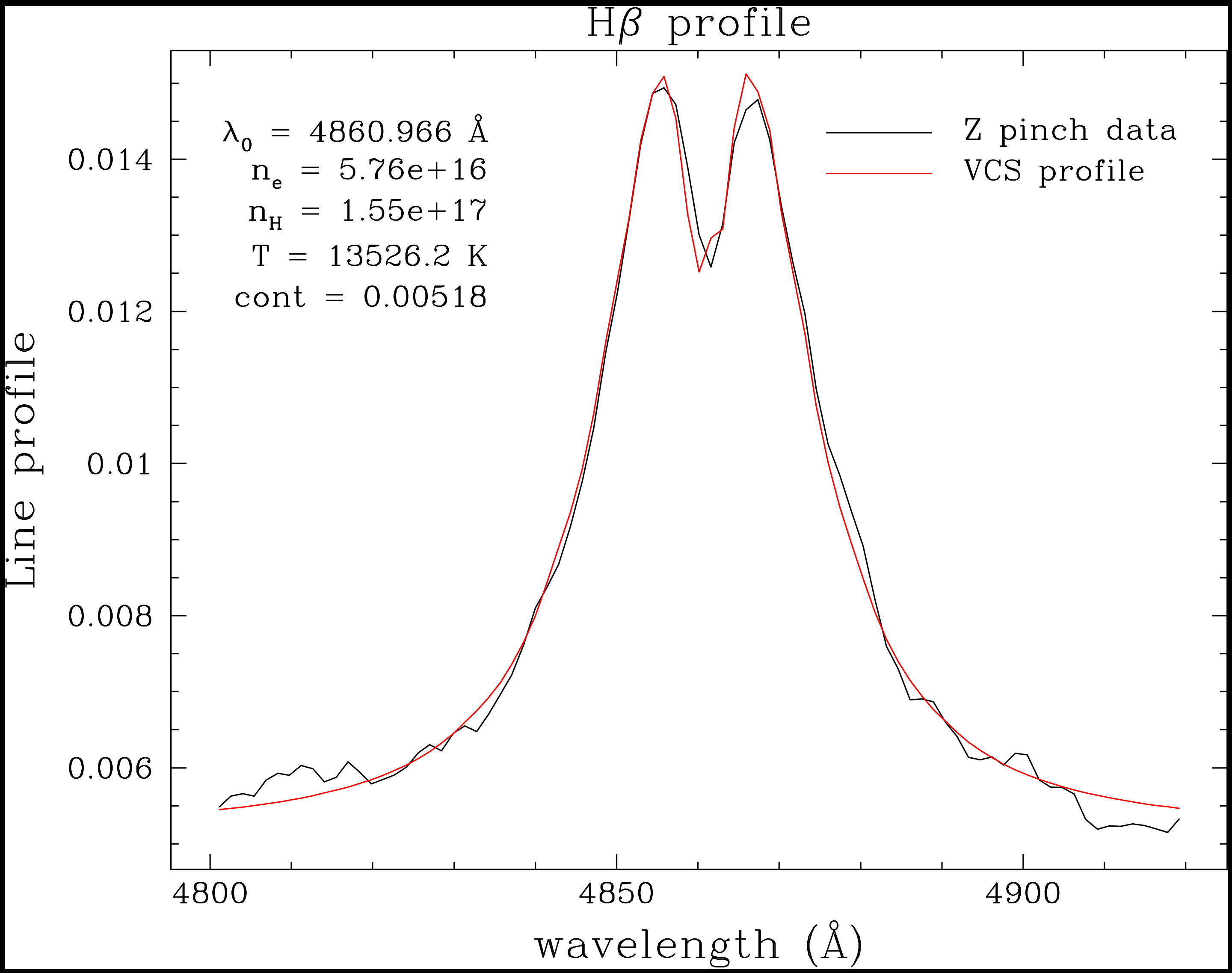
Measuring Line Profiles at White Dwarf Photospheric Conditions => Accurate Masses



Laboratory Setup


Fiber optic shield
Plasma chamber

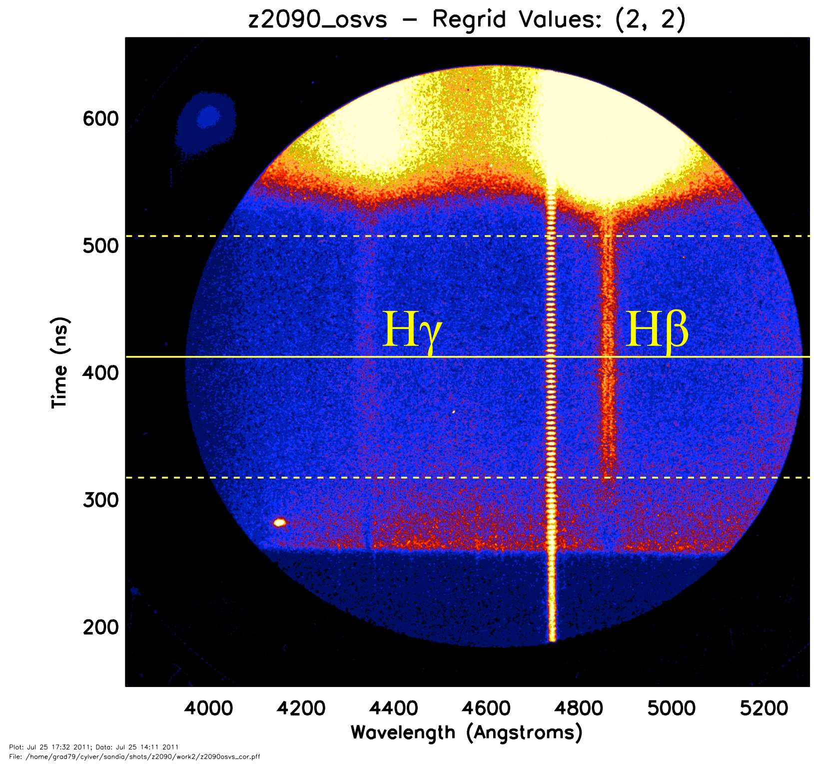

Plasma chamber:
6 cm long
2 cm diameter
A macroscopic sample!

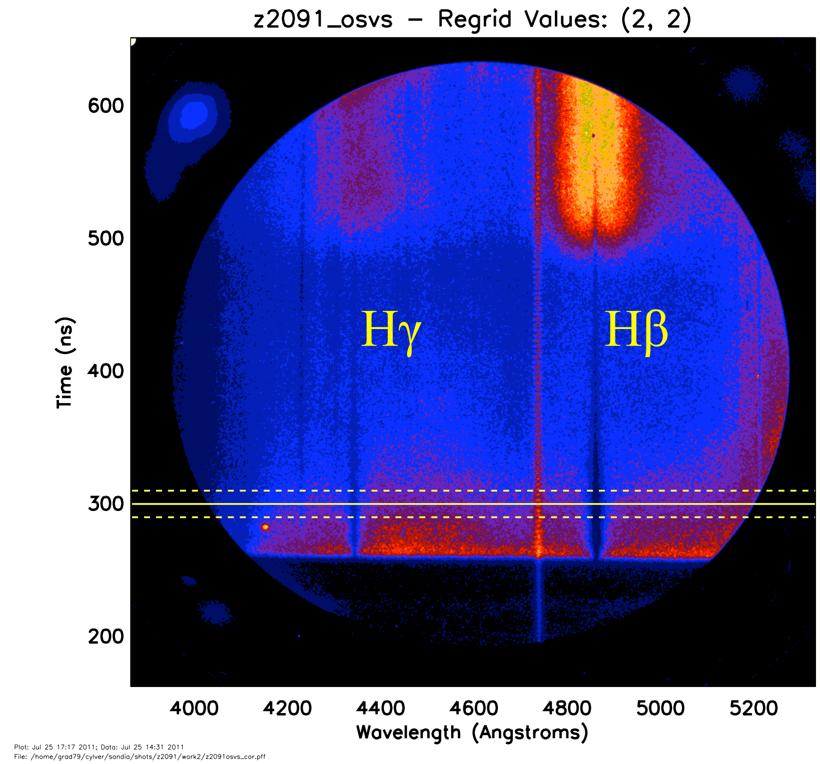


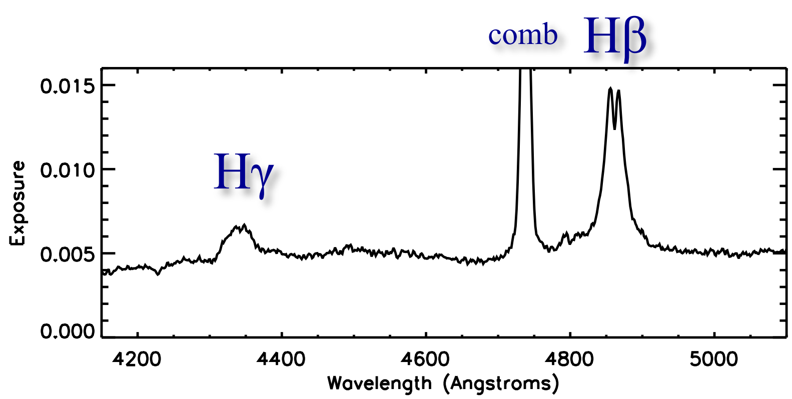
Comparison of the measured Hβ line profile from initial experiments on the Z machine (Z2090) to the Vidal-Cooper-Smith theory with n_e and T_e as free fitting parameters.

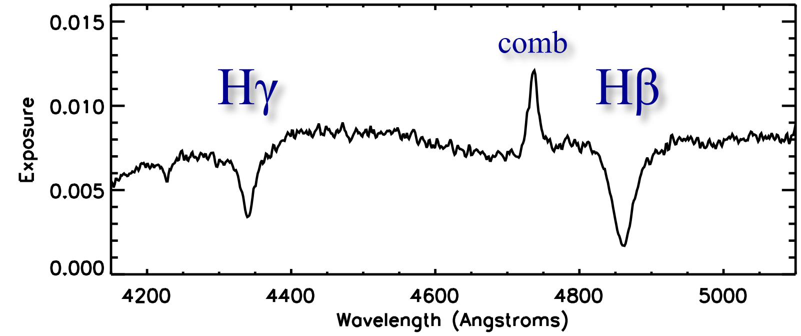
May 2010

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



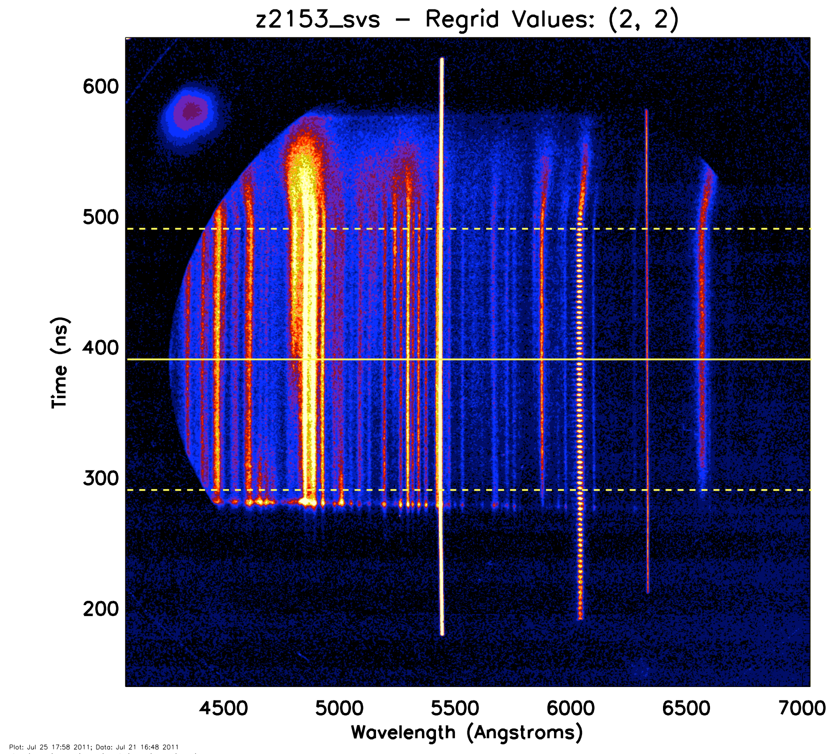


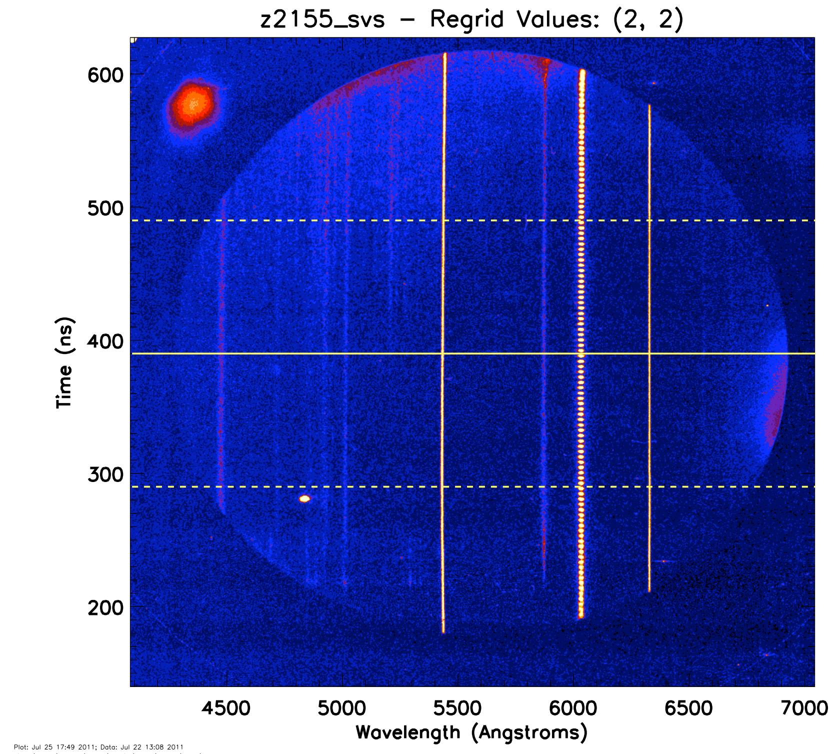


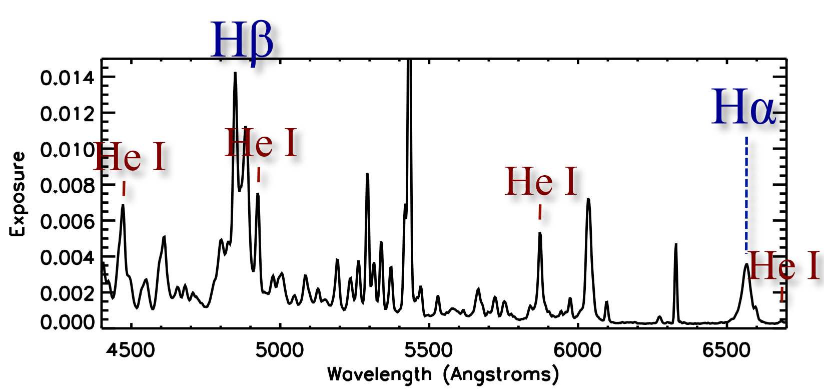


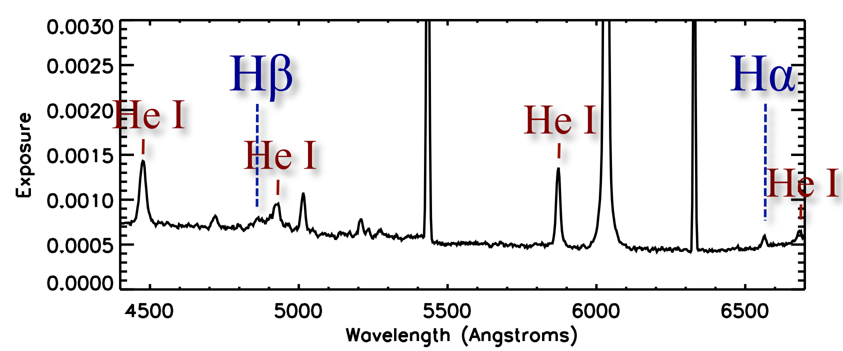
Jan 2011

- Observed helium lines; many contaminants
- First streak camera issues





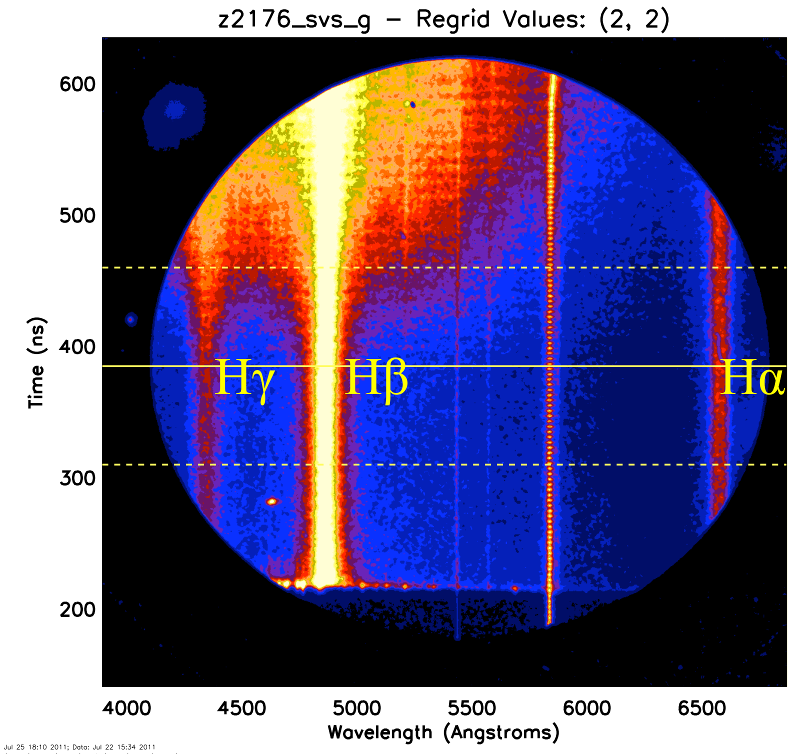


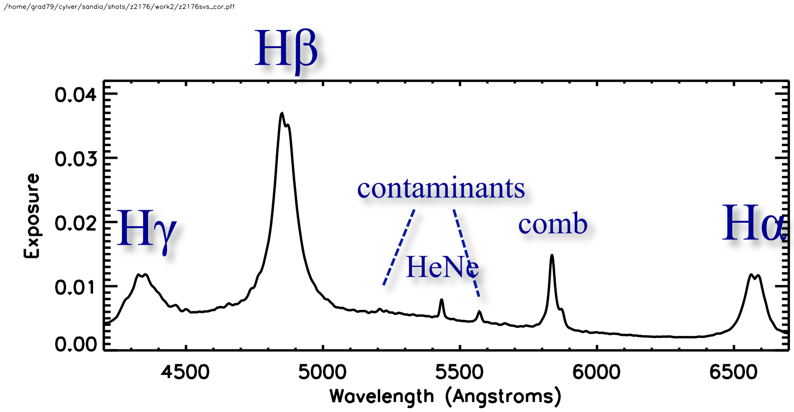


<u>Mar 2011</u>

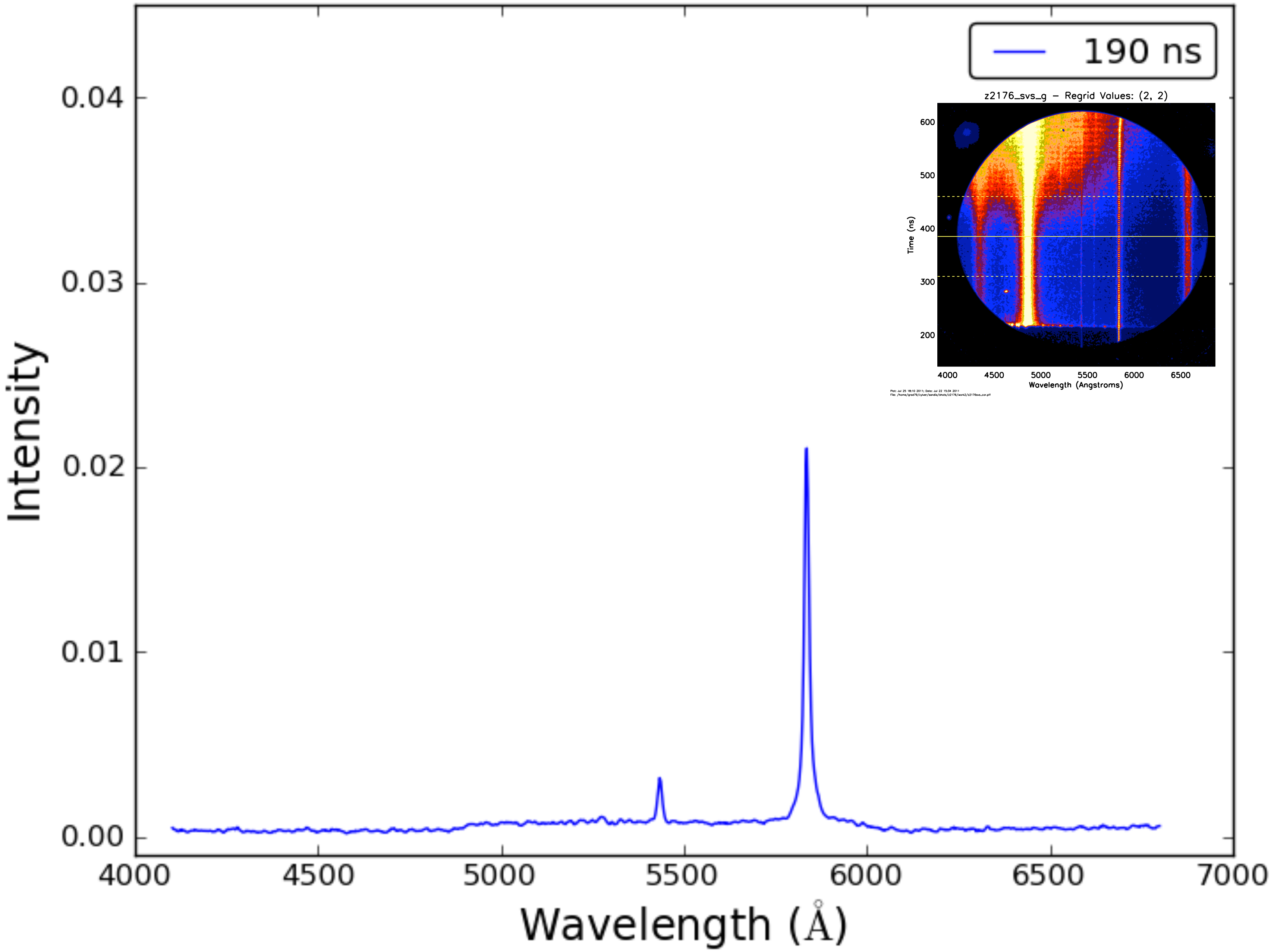
- Higher fill pressure (30 Torr)
- Broad lines
- Few contaminants
- Line profiles apparently affected by optical depth issues

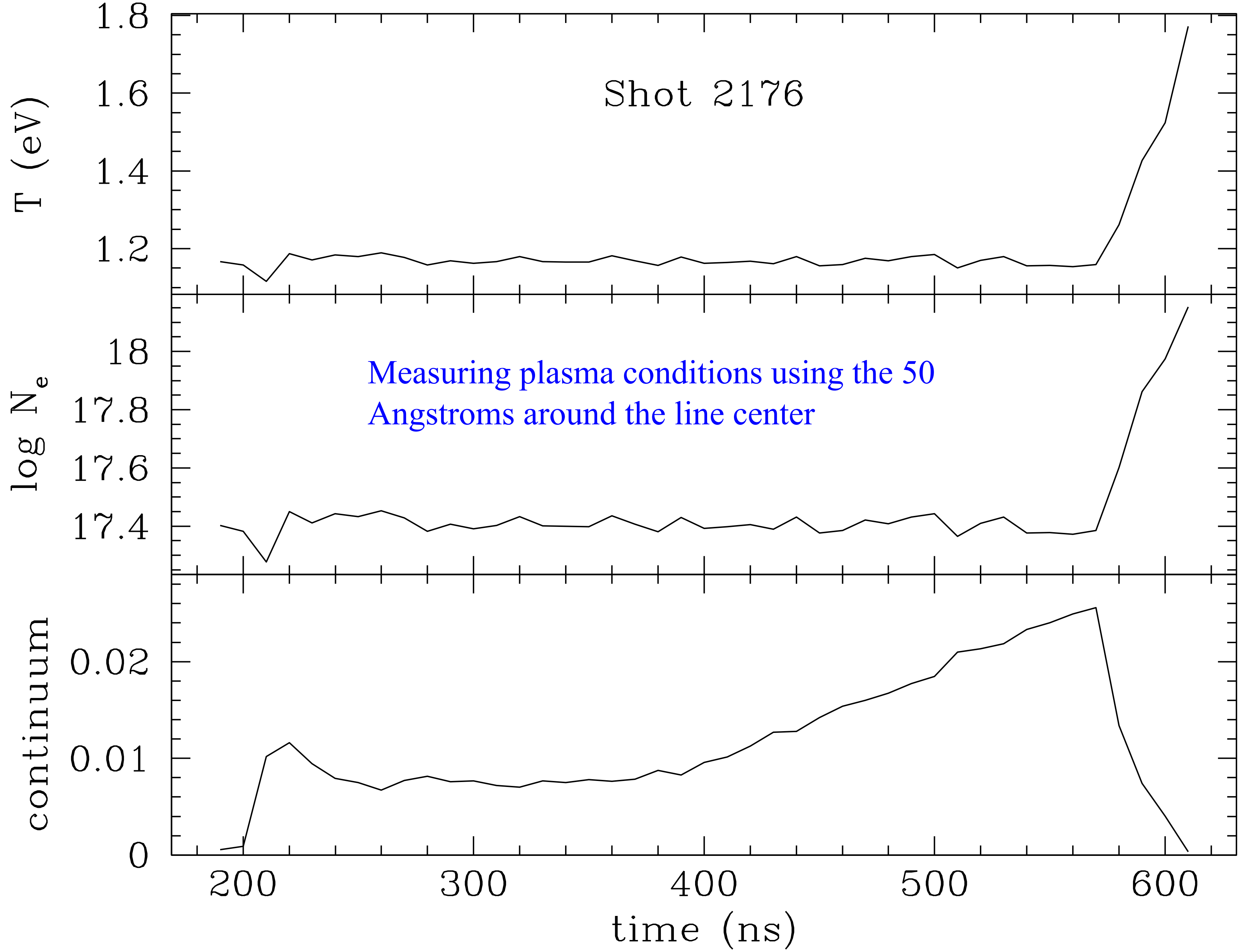
- Streak camera issues
  - Oscillations in intensity with time





Shot Z2176


190 ns
Intensity
0.00
0.01
0.02
0.03
0.04
4000
4500
5000
5500
6000
6500
7000
Wavelength (Å)
z2176_svs_g – Regrid Values: (2, 2)
Time (ns)
200
300
400
500
600
Wavelength (Angstroms)

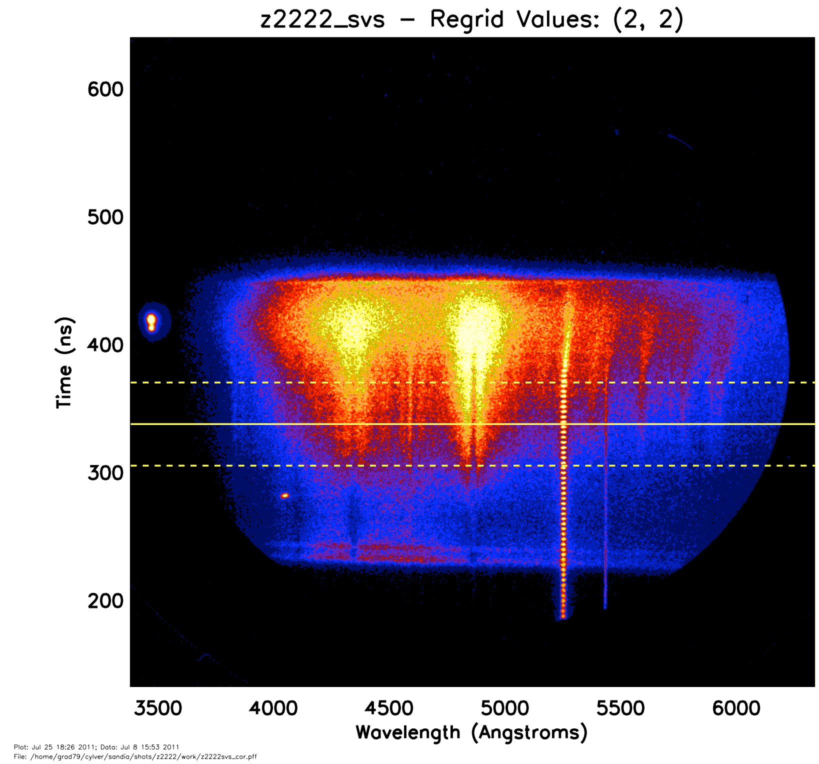

Shot 2176
T (eV)
1.2
1.4
1.6
1.8
log N_e
17.4
17.6
17.8
18
Measuring plasma conditions using the 50 Angstroms around the line center
continuum
0
0.01
0.02
200
300
400
500
600
time (ns)

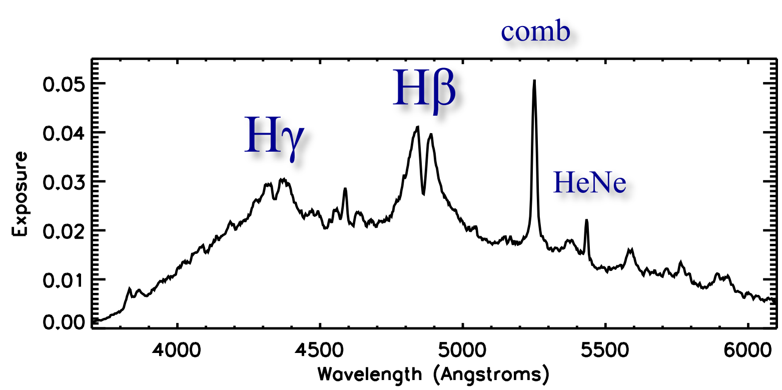
June 2011

- Higher fill pressure (30 torr)
- Broad lines
- Contaminants
- Distinct central dip in emission lines

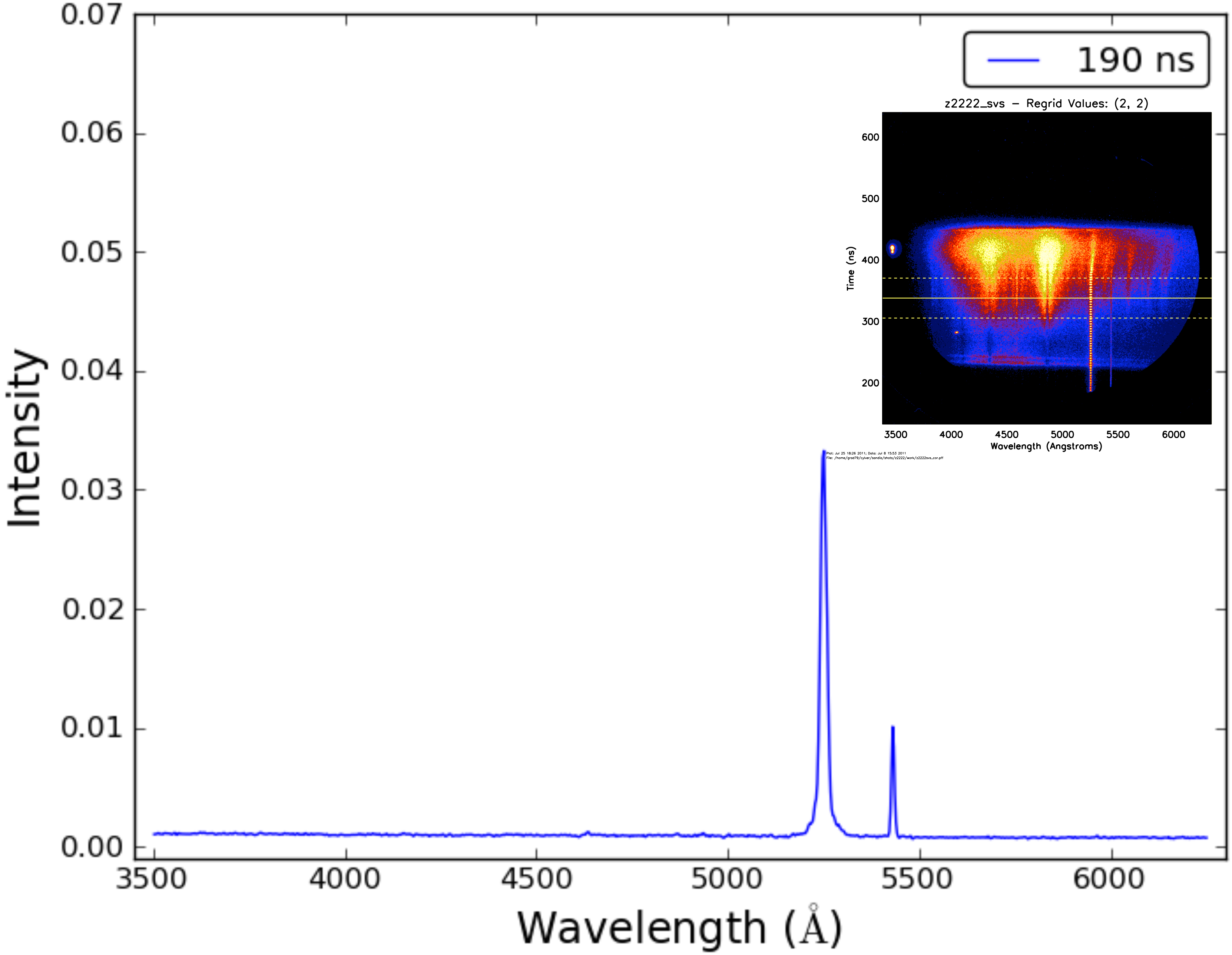
- Streak camera issues
  - Streak ending early
  - Oscillations

- 120mm hohlraum
- Modified blast shield

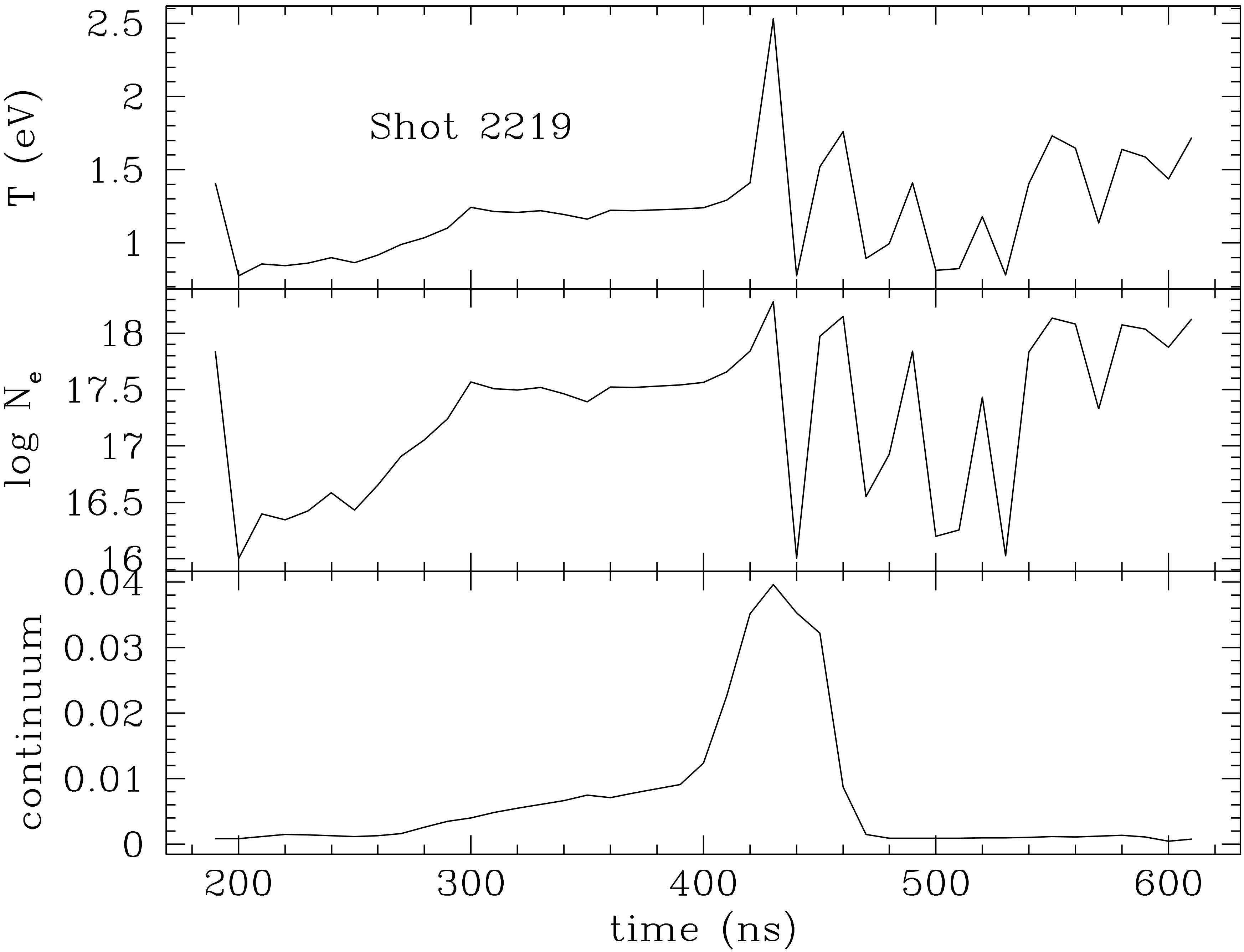




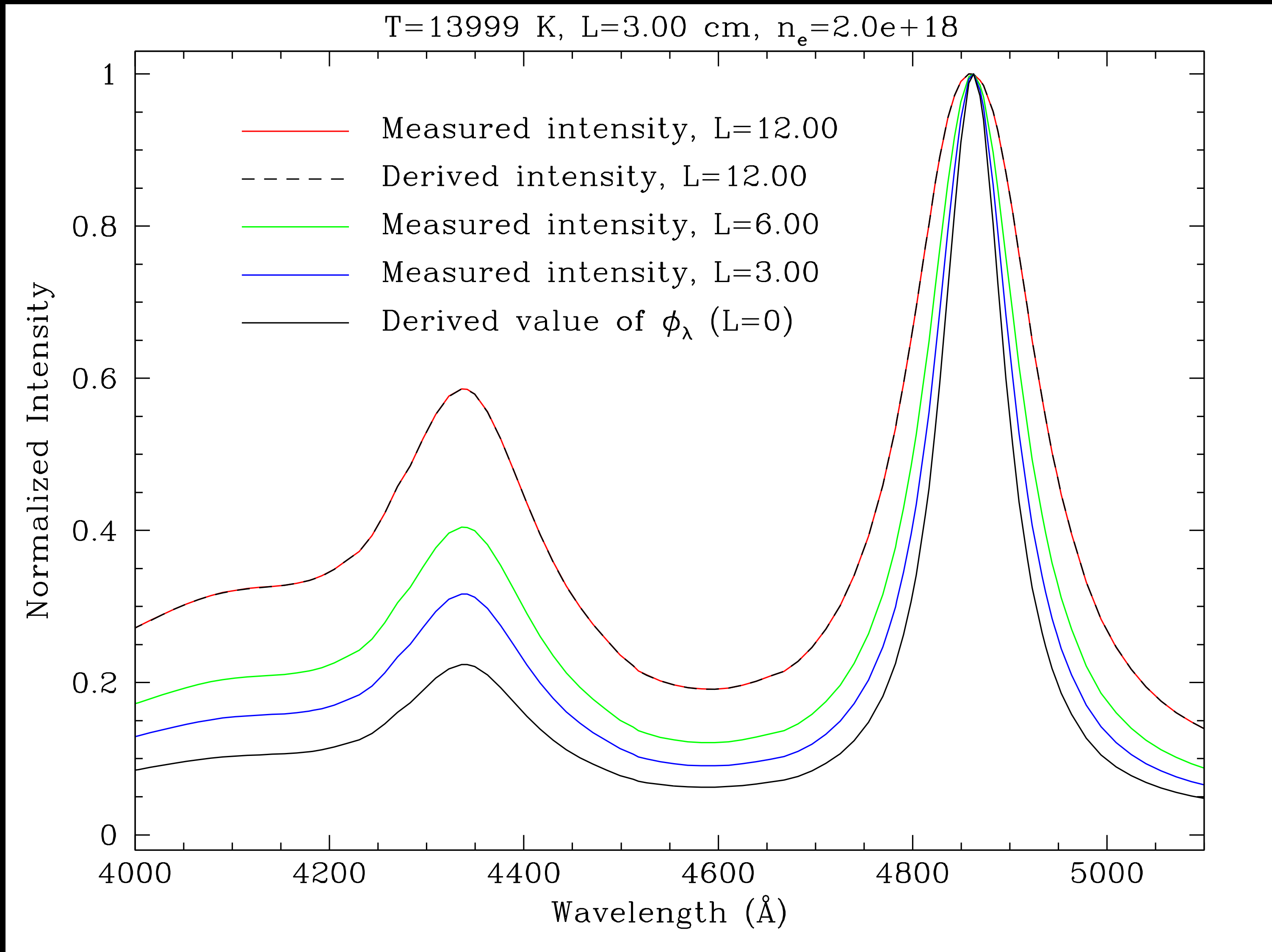
Shot Z2222



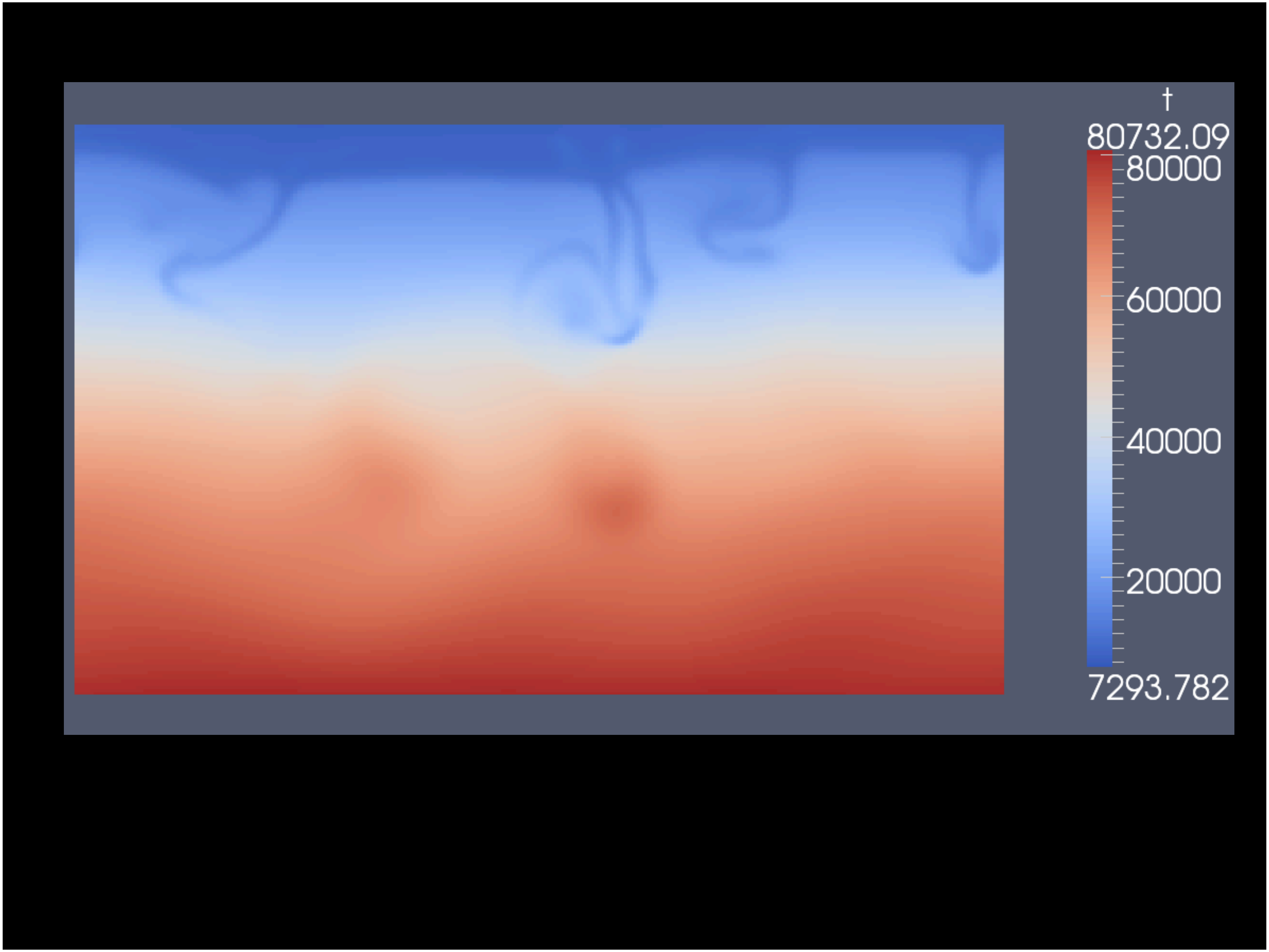
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Intensity
3500
4000
4500
5000
5500
6000
Wavelength (Å)
190 ns
z2222_svs – Regrid Values: (2, 2)
Time (ns)
600
500
400
300
200
Wavelength (Angstroms)



Shot 2219
T (eV)
2.5
2
1.5
1
log N_e
18
17.5
17
16.5
16
continuum
0.04
0.03
0.02
0.01
0
200
300
400
500
600
time (ns)



T=13999 K, L=3.00 cm, n_e=2.0e+18
Measured intensity, L=12.00
Derived intensity, L=12.00
Measured intensity, L=6.00
Measured intensity, L=3.00
Derived value of ϕ_λ (L=0)
Normalized Intensity
Wavelength (Å)
0
0.2
0.4
0.6
0.8
1
4000
4200
4400
4600
4800
5000


t
80732.09
80000
60000
40000
20000
7293.782

This Dynamic Field

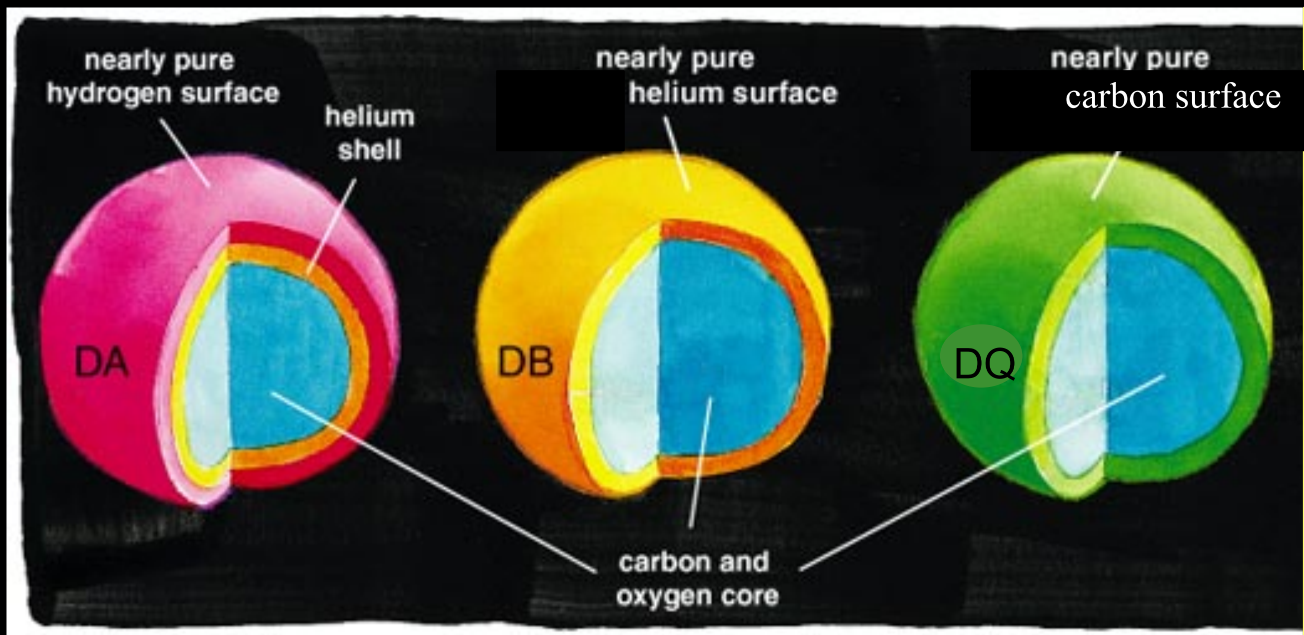
- Multiple new competing theories for line shapes

- 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

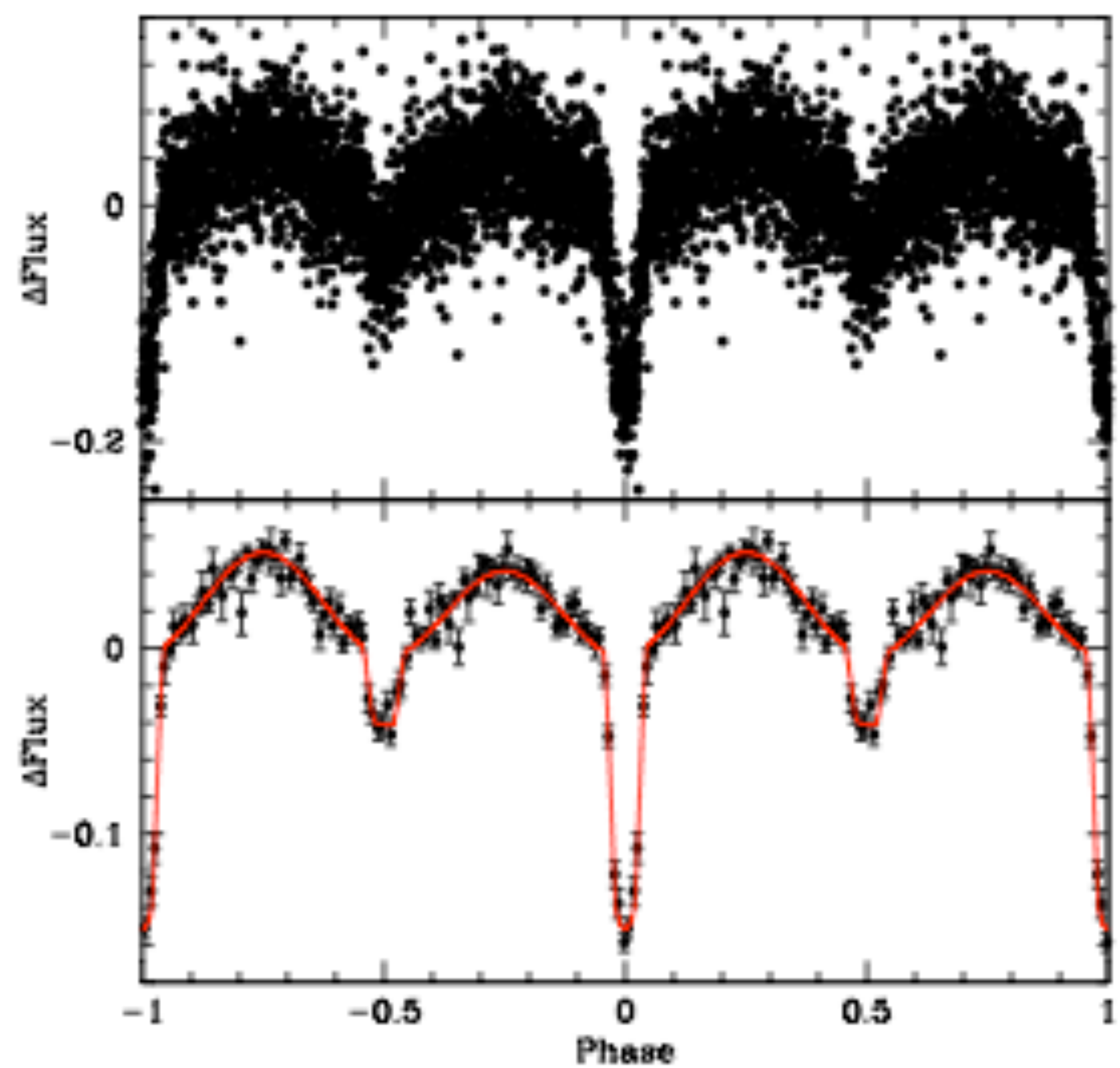
The Opportunity of Ultra-Low Mass White Dwarf Stars

- 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

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.
- The change in orbital period will provide a fundamental test of Einstein's General Relativity.
- In 1-2 years we can measure this change at the McDonald Observatory.



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

Epilogue: The Human Equation
Towards a formula for innovation

- Building a team: SNL scientists, University faculty, research scientists, postdocs, graduate and undergraduate students

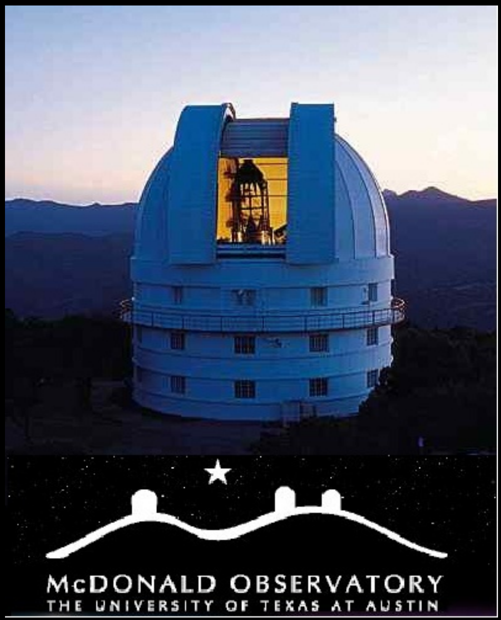
- Critical skill sets and personalities

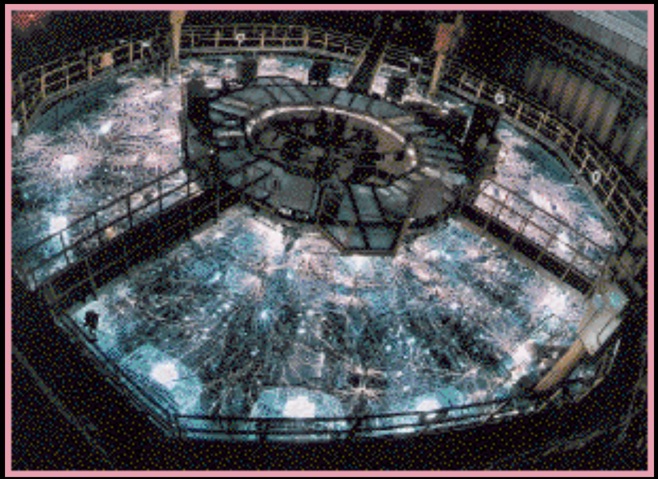
- Layered mentoring

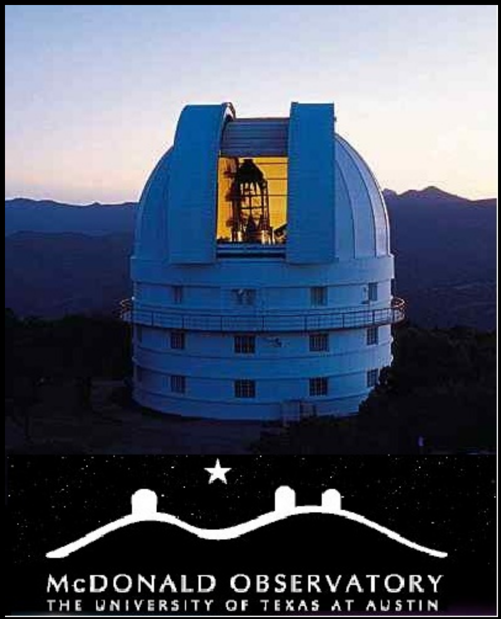
- The value of boots on the ground

2011 Science with High-Power Lasers and Pulsed Power
28 July 2011

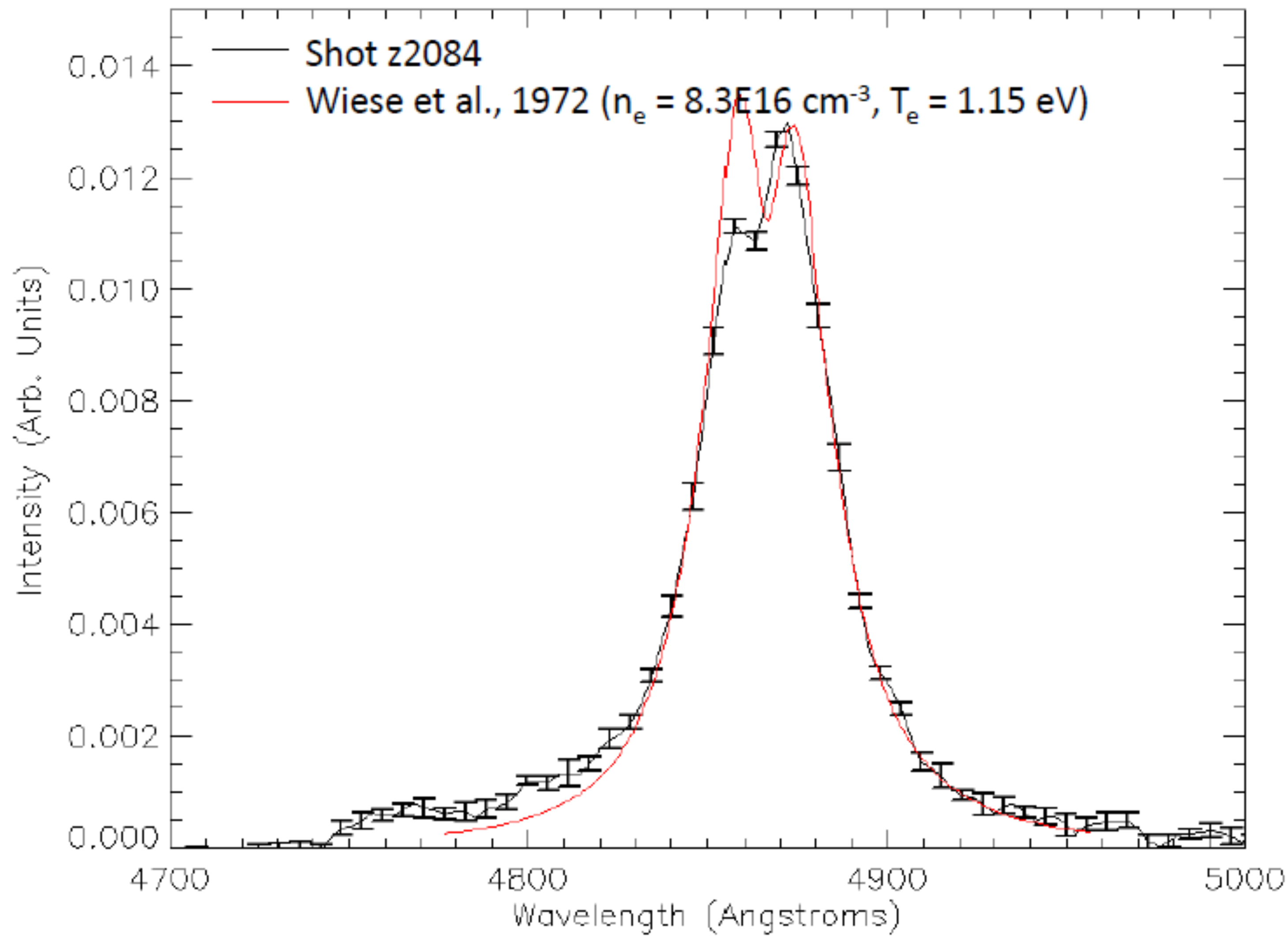
Thanks!

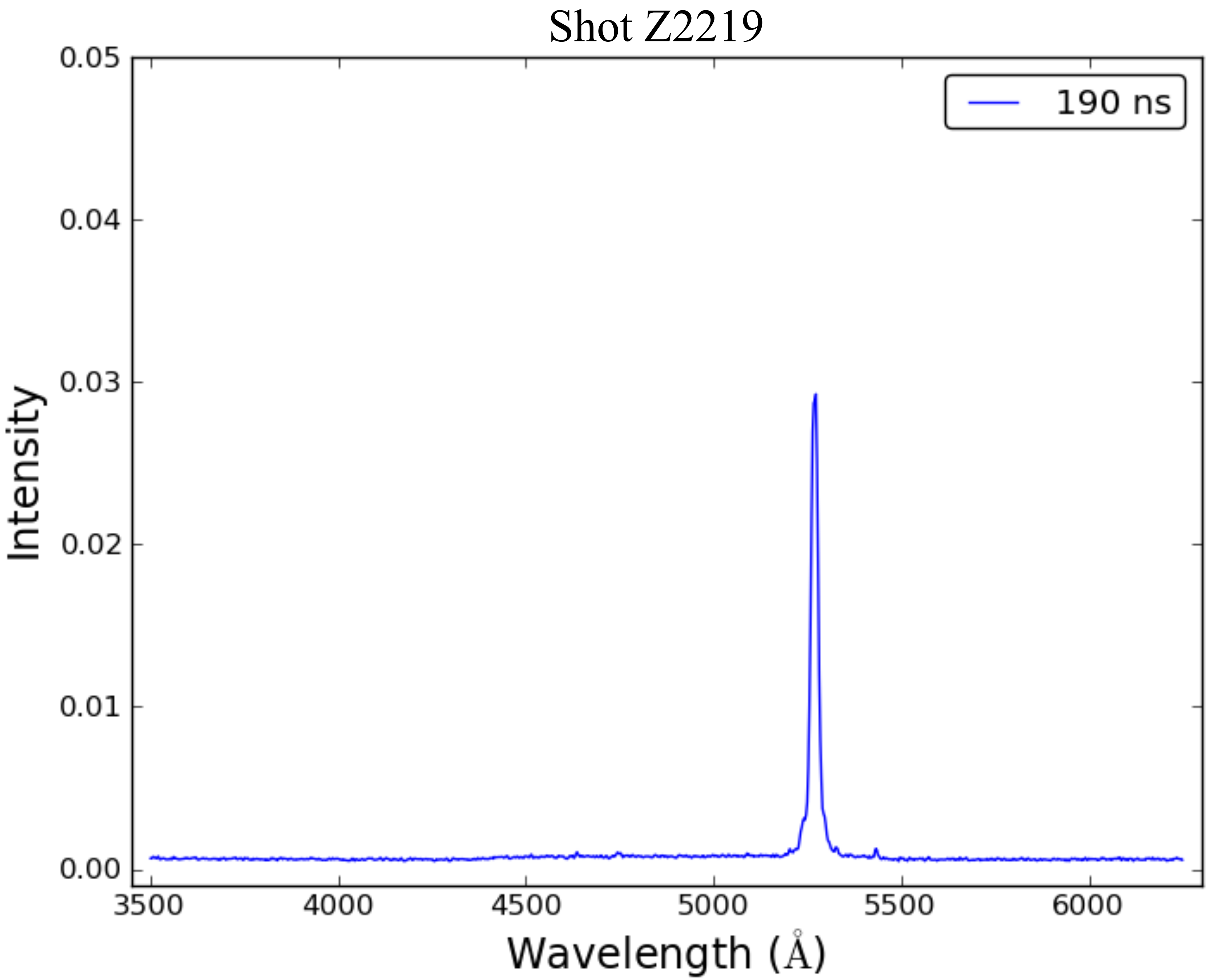


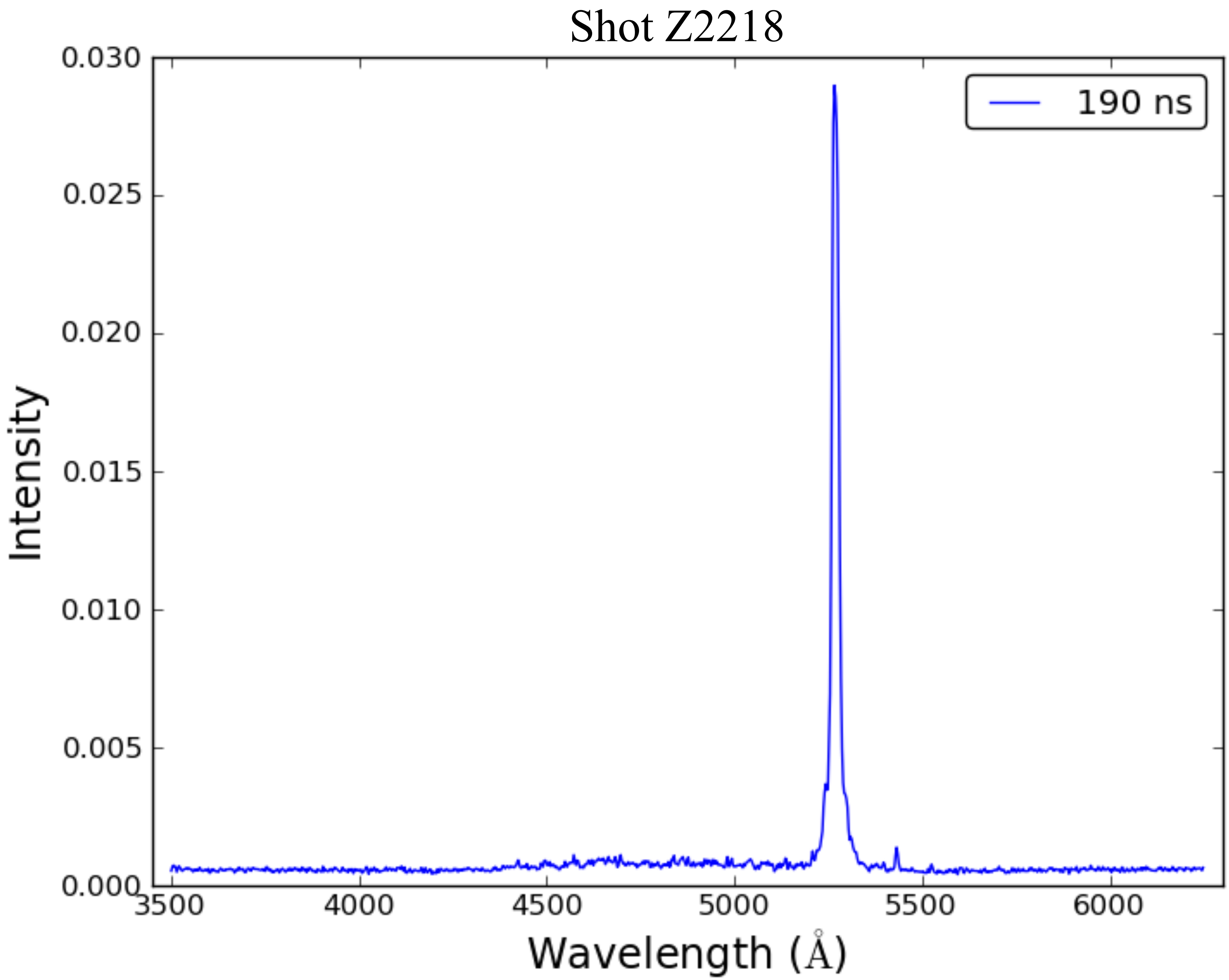




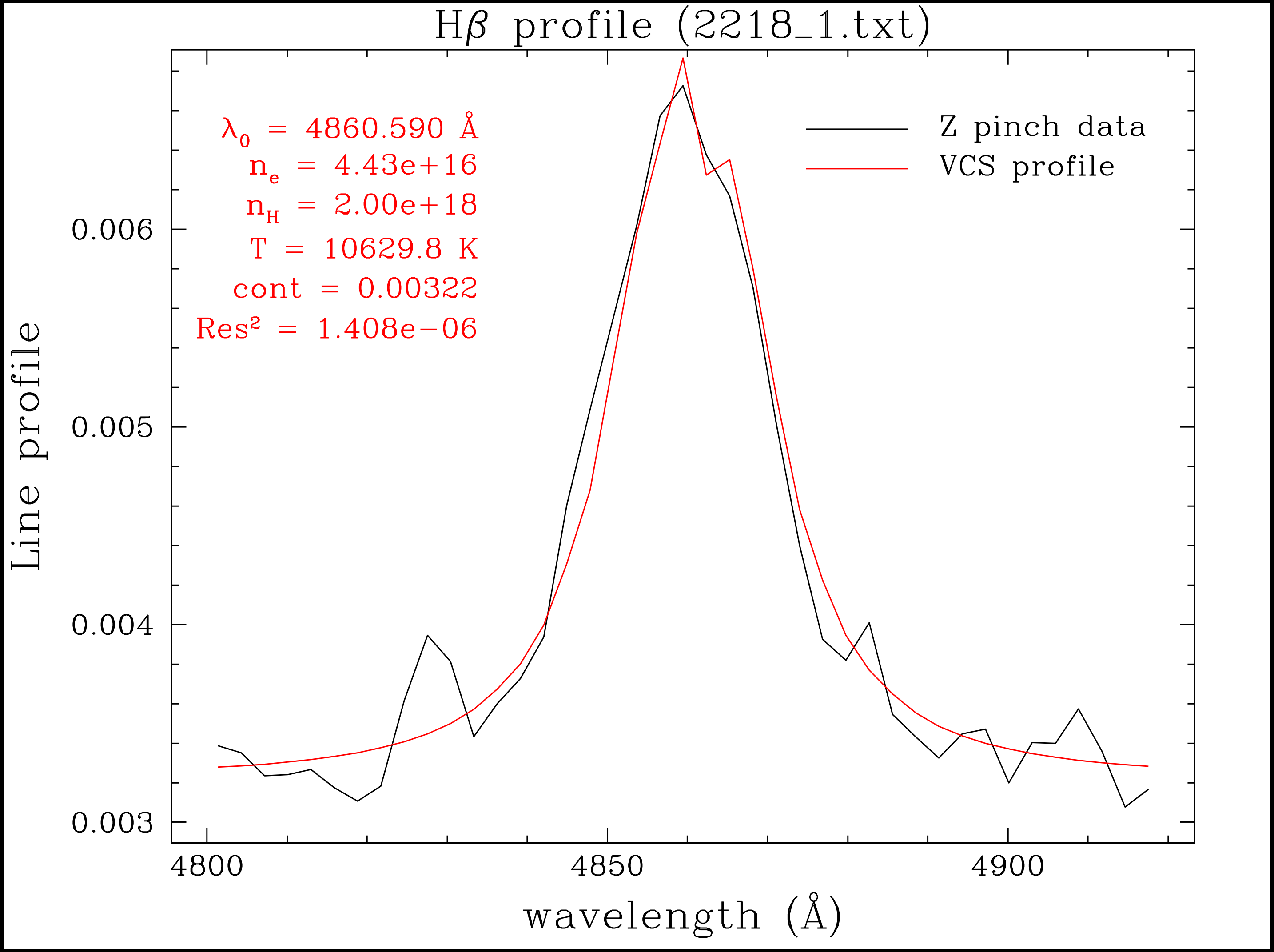
Shot z2084 H-beta line profile averaged over 80 ns centered about a time 140 ns after the peak of the z-pinch



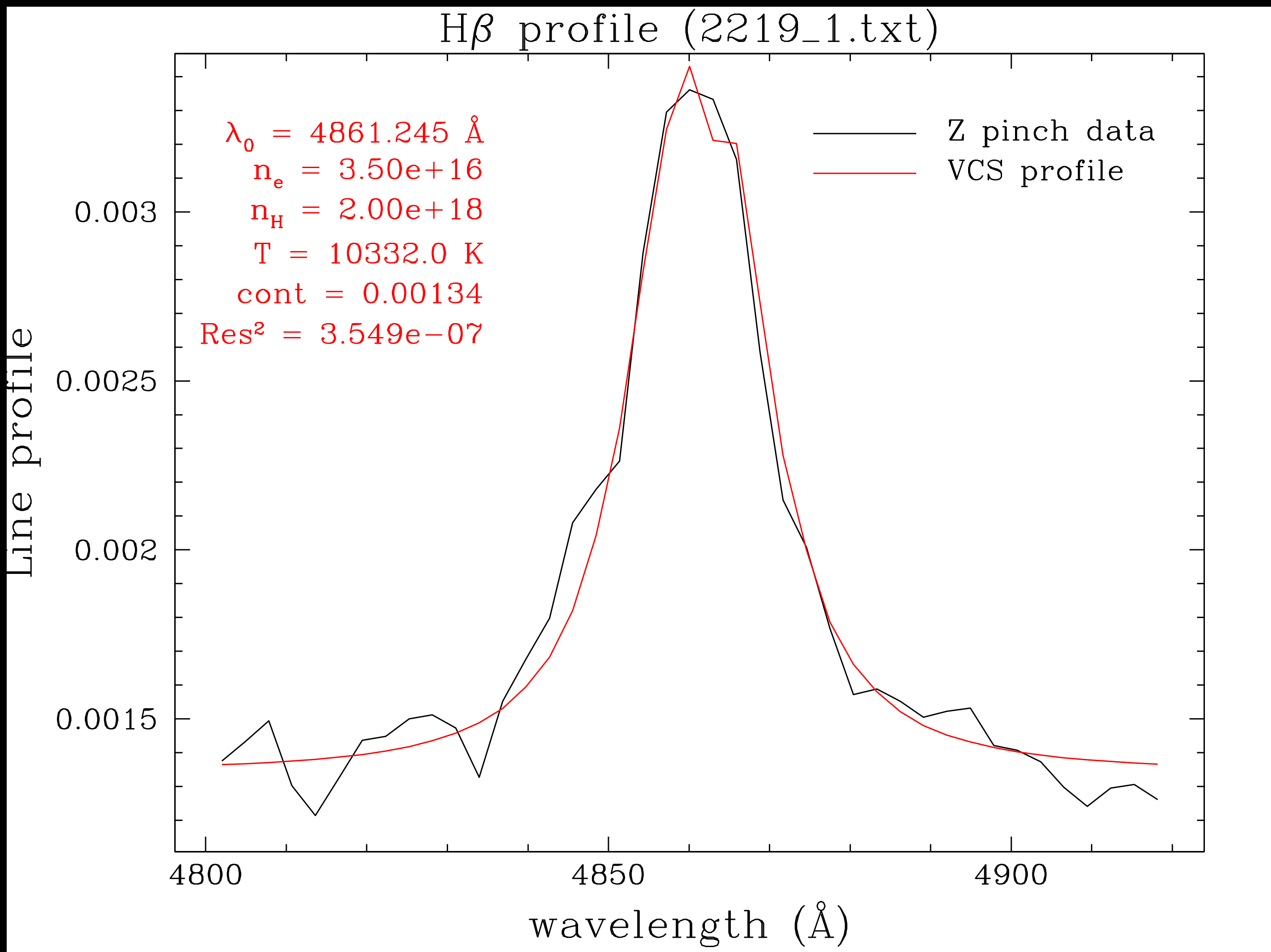

Shot Z2219
190 ns
Intensity
0.05
0.04
0.03
0.02
0.01
0.00
3500
4000
4500
5000
5500
6000
Wavelength (Å)



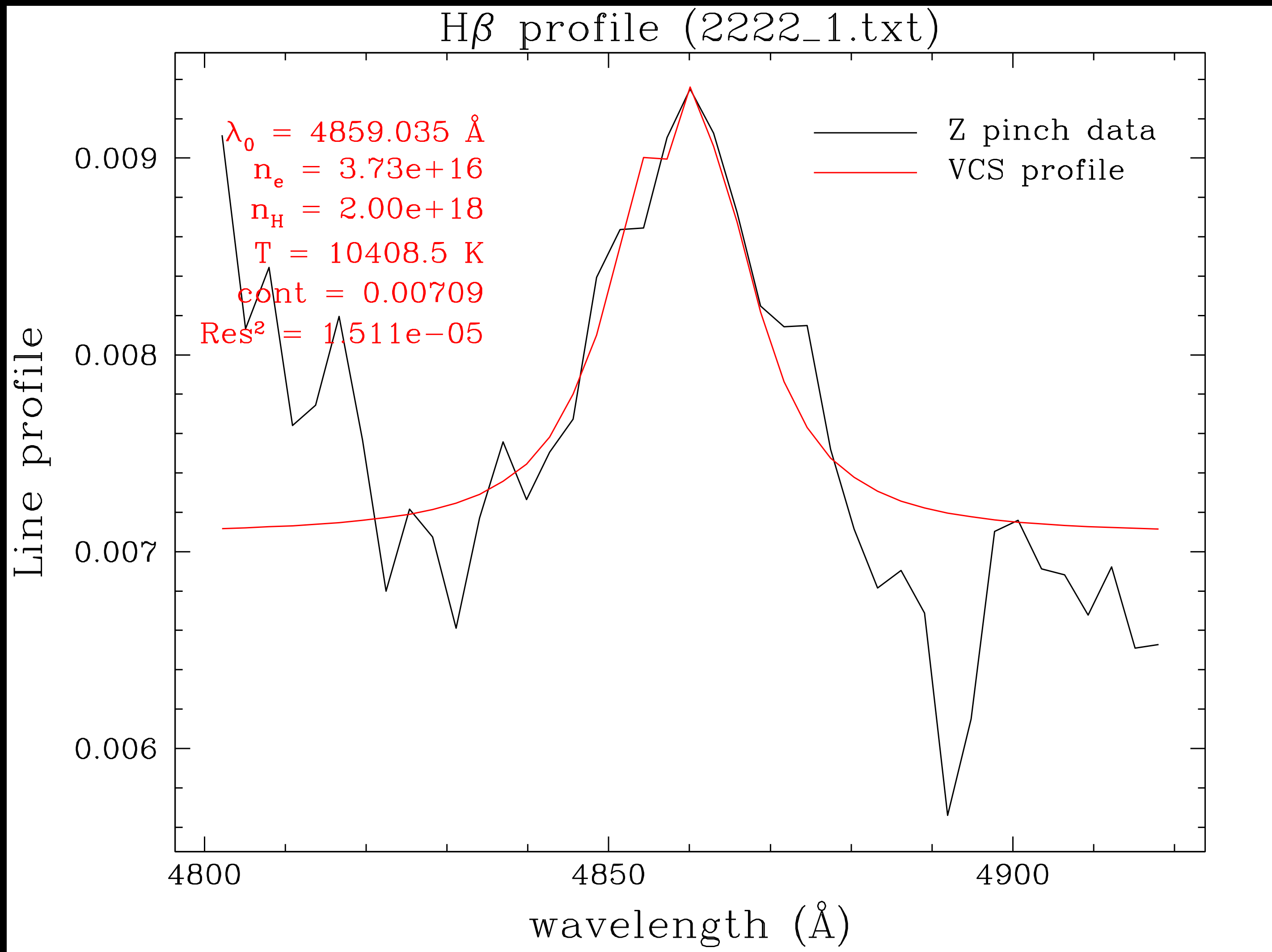
Shot Z2218
190 ns
Intensity
0.030
0.025
0.020
0.015
0.010
0.005
0.000
3500
4000
4500
5000
5500
6000
Wavelength (Å)



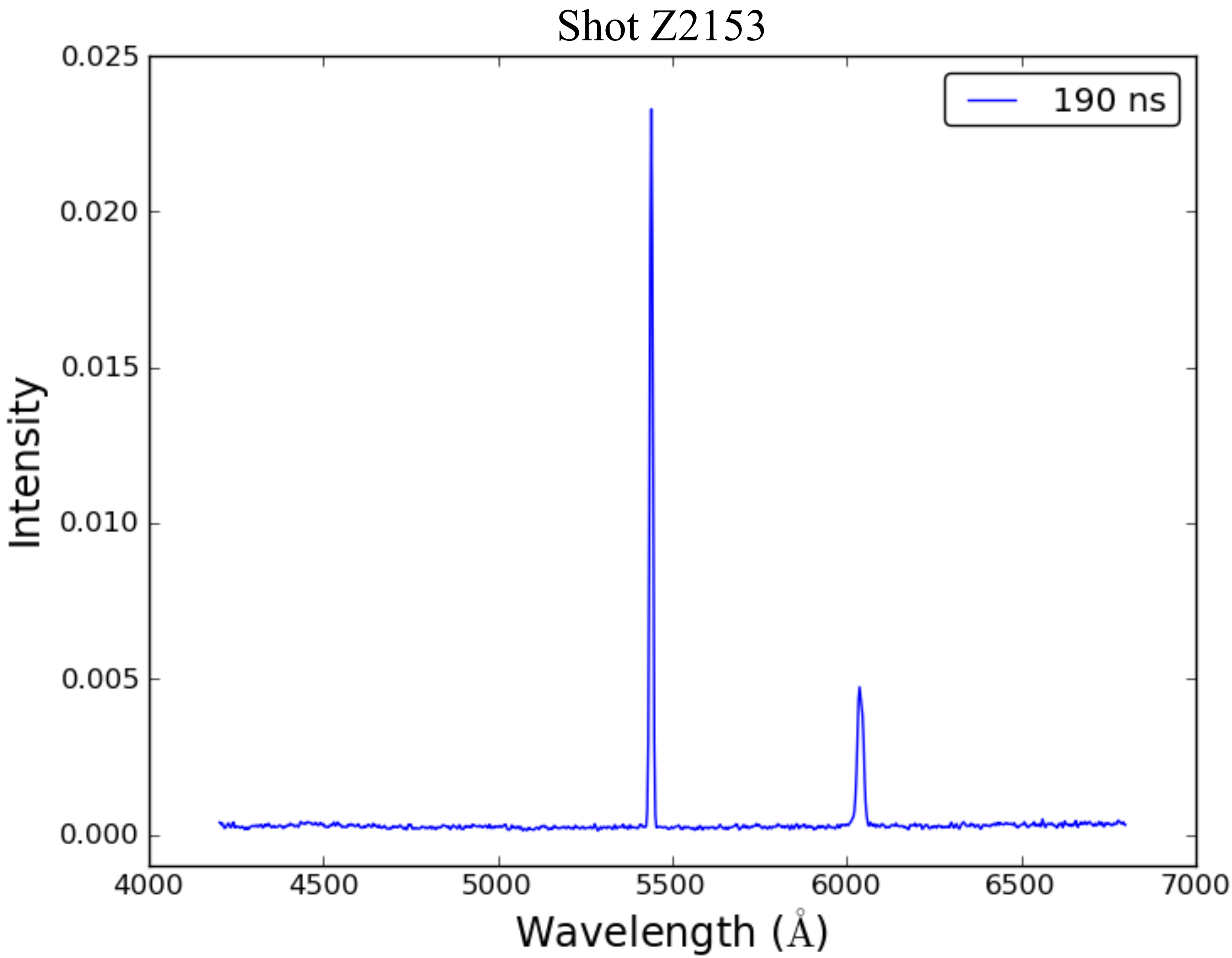
Hβ profile (2218_1.txt)
λ0 = 4860.590 Å
ne = 4.43e+16
nH = 2.00e+18
T = 10629.8 K
cont = 0.00322
Res² = 1.408e−06
Z pinch data
VCS profile
Line profile
0.006
0.005
0.004
0.003
4800
4850
4900
wavelength (Å)

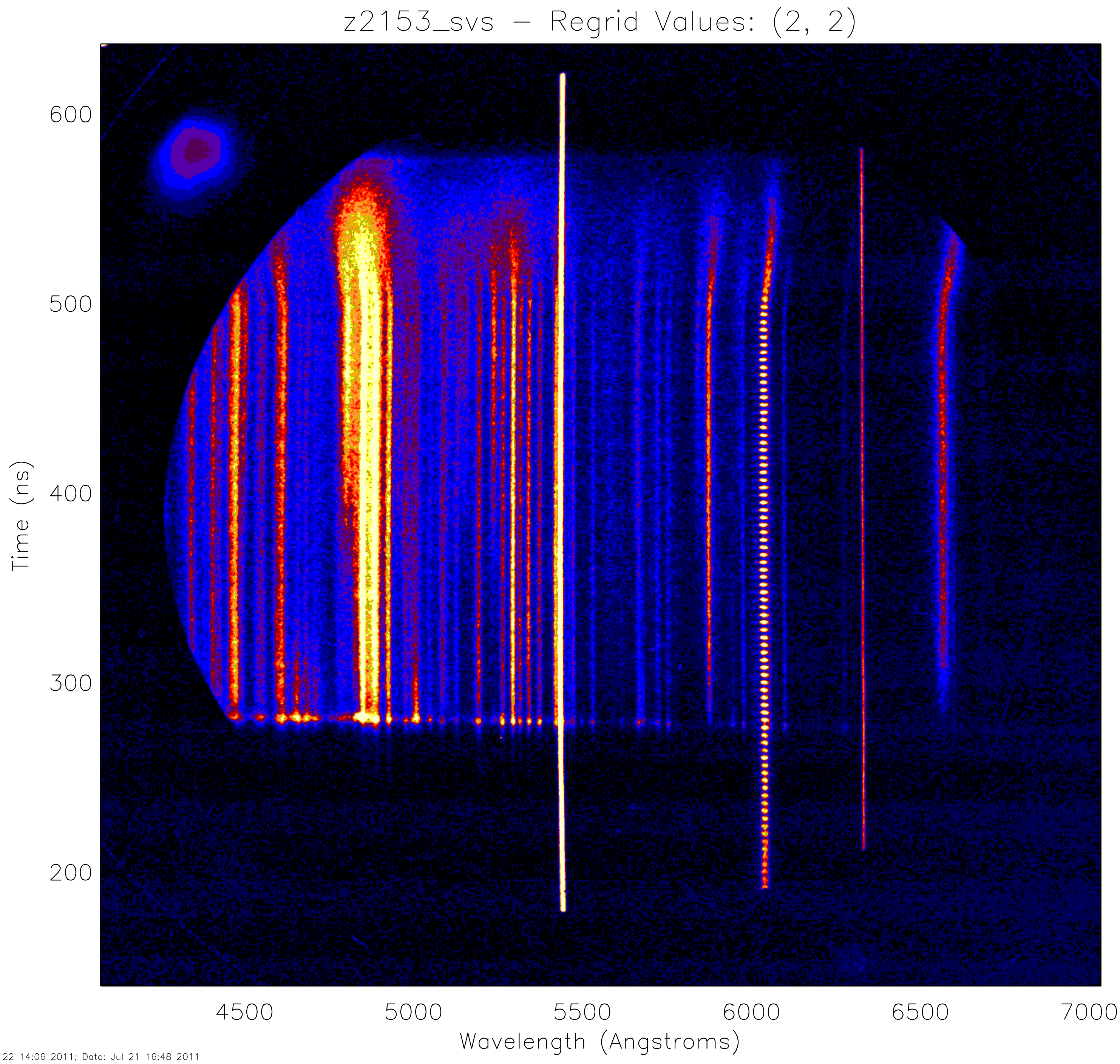


Hβ profile (2219_1.txt)
λ0 = 4861.245 Å
ne = 3.50e+16
nH = 2.00e+18
T = 10332.0 K
cont = 0.00134
Res² = 3.549e−07
Z pinch data
VCS profile
0.003
0.0025
0.002
0.0015
Line profile
4800
4850
4900
wavelength (Å)



Hβ profile (2222_1.txt)
λ0 = 4859.035 Å
ne = 3.73e+16
nH = 2.00e+18
T = 10408.5 K
cont = 0.00709
Res² = 1.511e−05
Z pinch data
VCS profile
Line profile
0.006
0.007
0.008
0.009
4800
4850
4900
wavelength (Å)


Shot Z2153
190 ns
Intensity
0.025
0.020
0.015
0.010
0.005
0.000
4000
4500
5000
5500
6000
6500
7000
Wavelength (Å)



Plot: Jul 22 14:06 2011; Data: Jul 21 16:48 2011
File: /home/grad79/cylver/sandia/shots/z2153/work/z2153svs_cor.pff

… and this is why they are interesting!

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

    => White Dwarf ***Cosmochronology***

- A way to find Solar Systems dynamically like ours

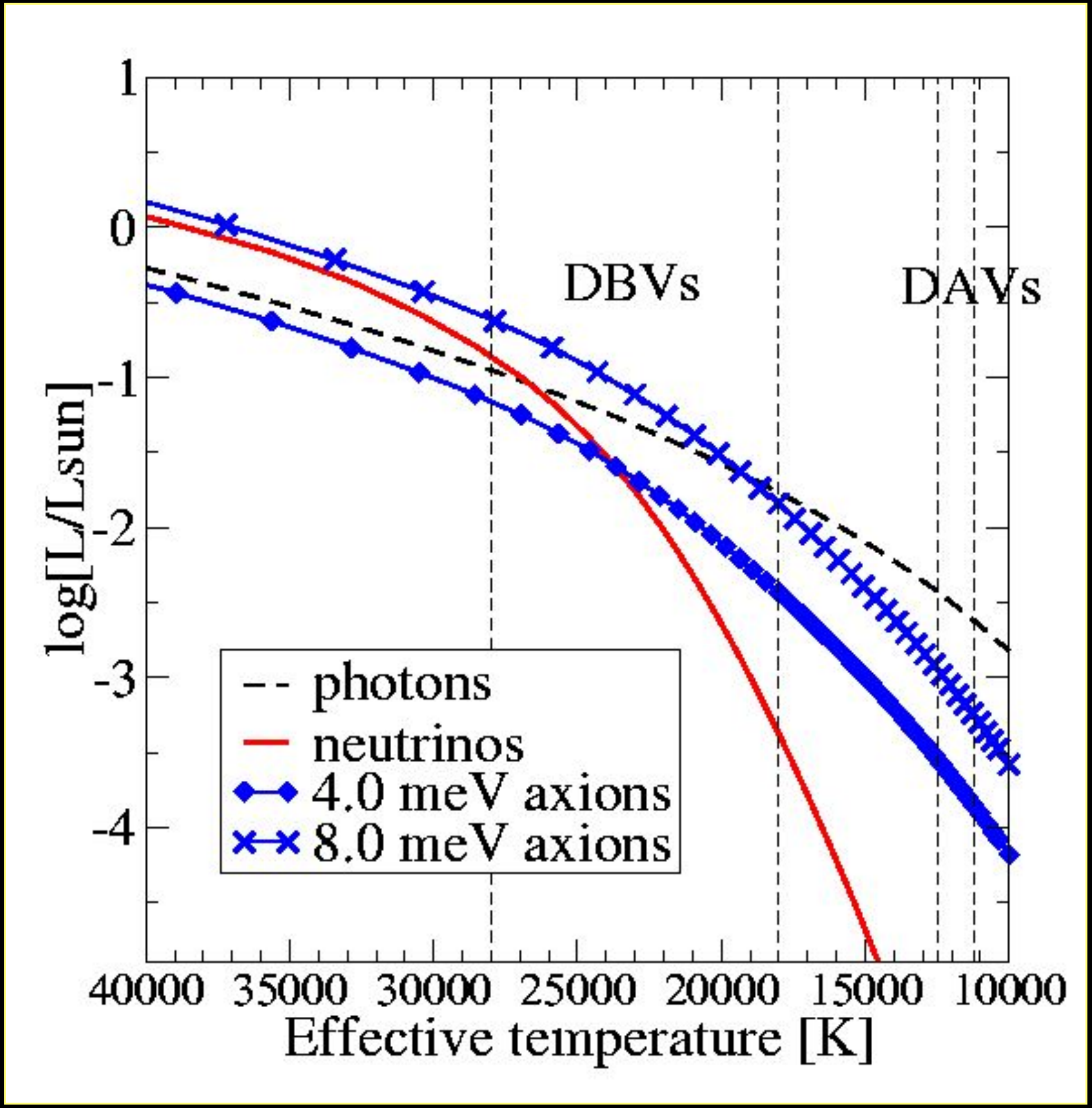
- Exploration of Extreme physics in interiors through Asteroseismology
  - Matter at extreme densities and temperatures gives us
    - Chance to study important and exotic physical processes:
    - plasmon neutrinos, search for
    - dark matter in the form of axions or, alternatively, WIMPS
    - study the physics of crystallization …

Whirlpool Galaxy • M51

Cosmochronology

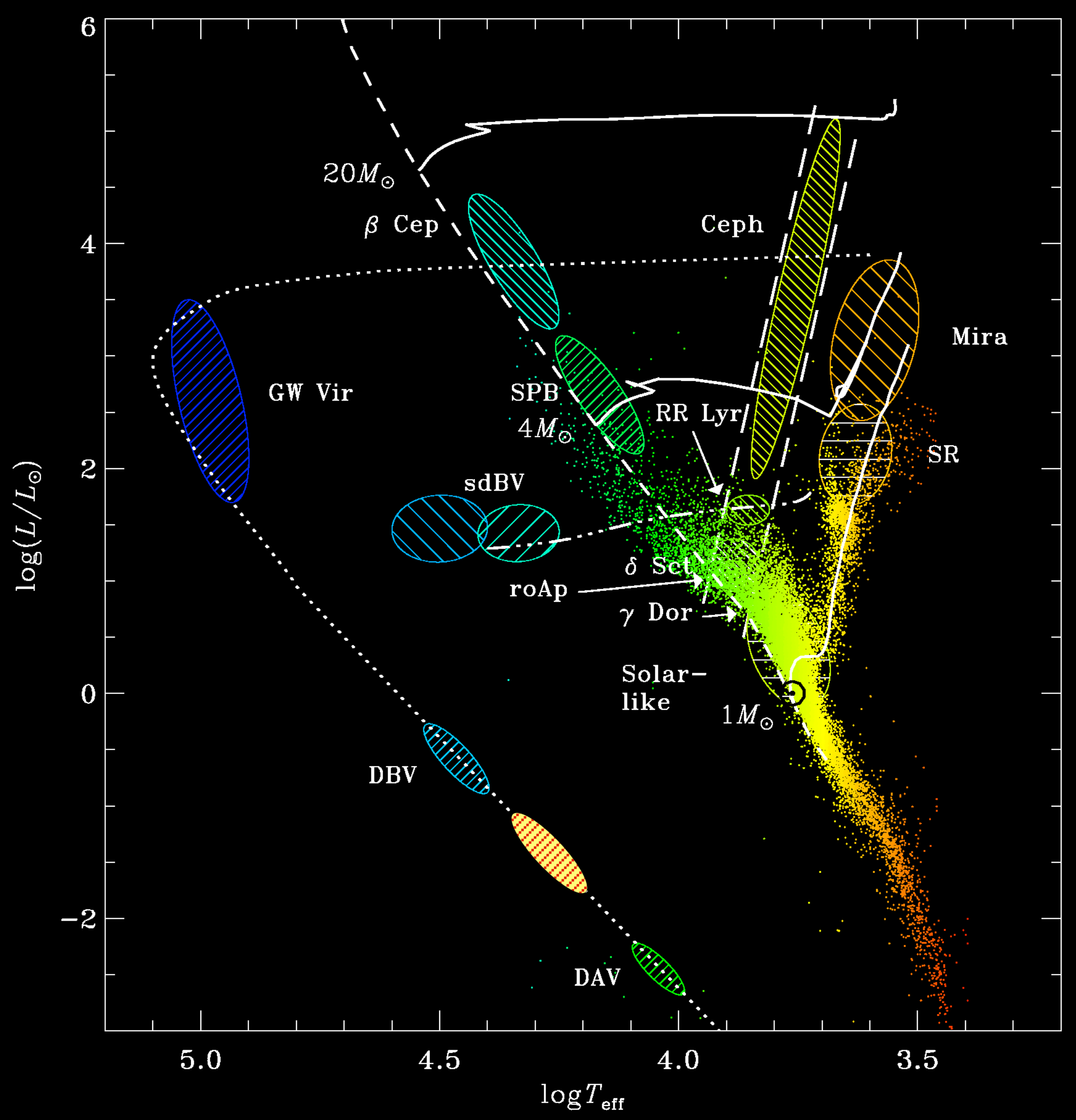
- Constrain Age of Universe
- *Measure* Age and History of the Components of the Galaxy
  - Thin disk
  - Open clusters
  - Thick disk
  - Halo
  - Globular clusters

Sources of energy loss in WDs

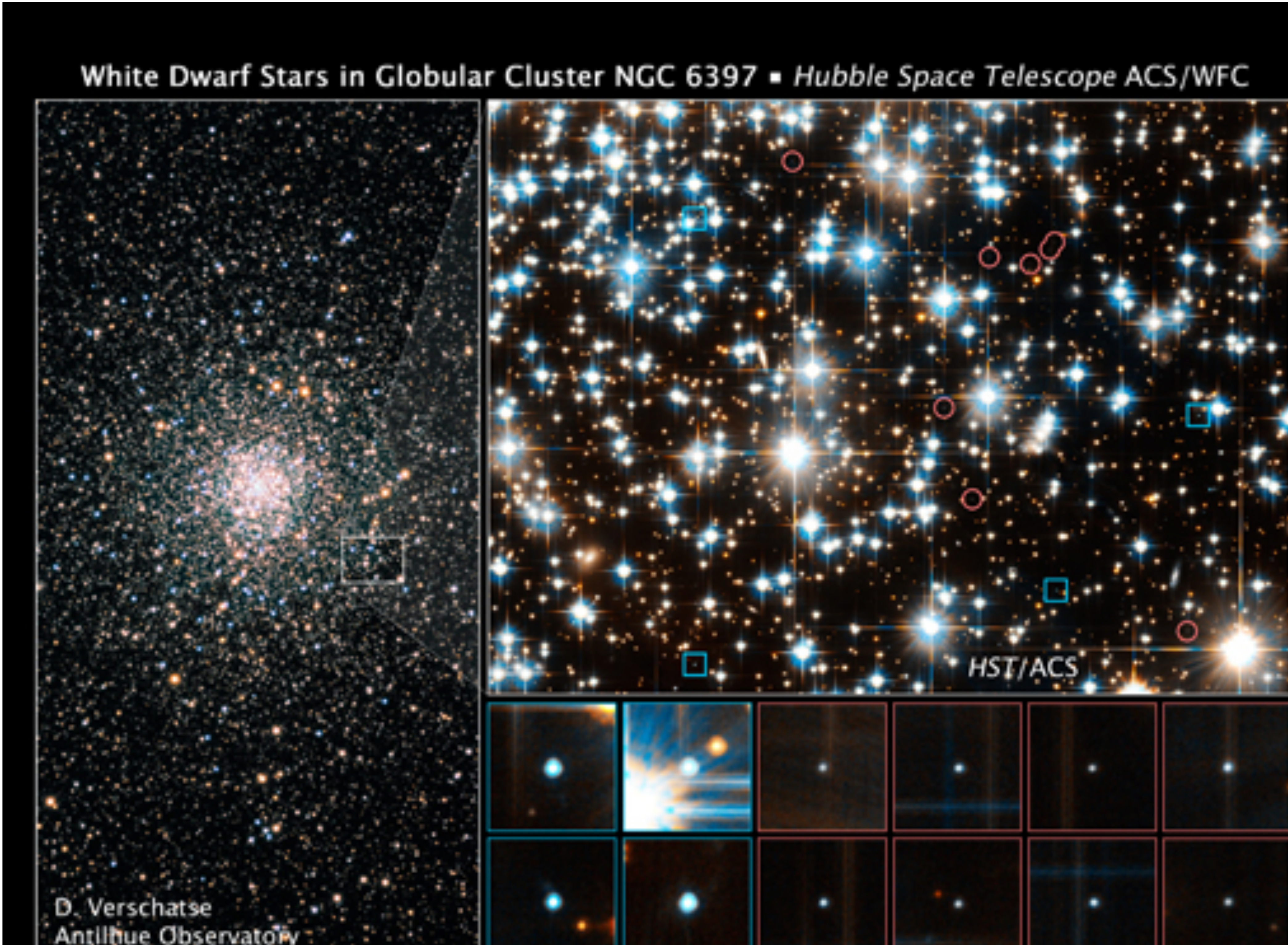


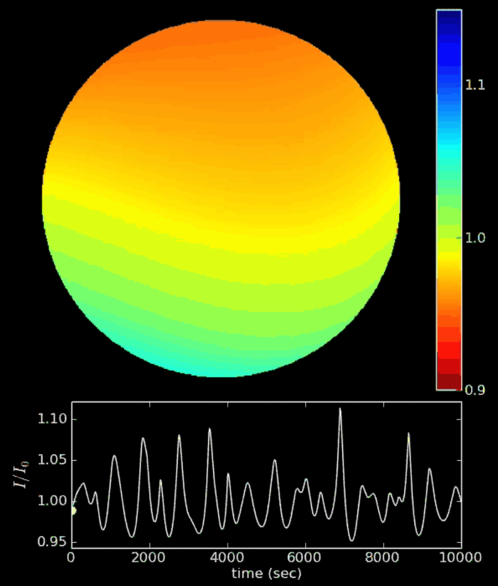
Are Effects of <u>Plasmon Neutrinos</u> or <u>Axions</u> Measurable Using the Techniques of Asteroseismology?

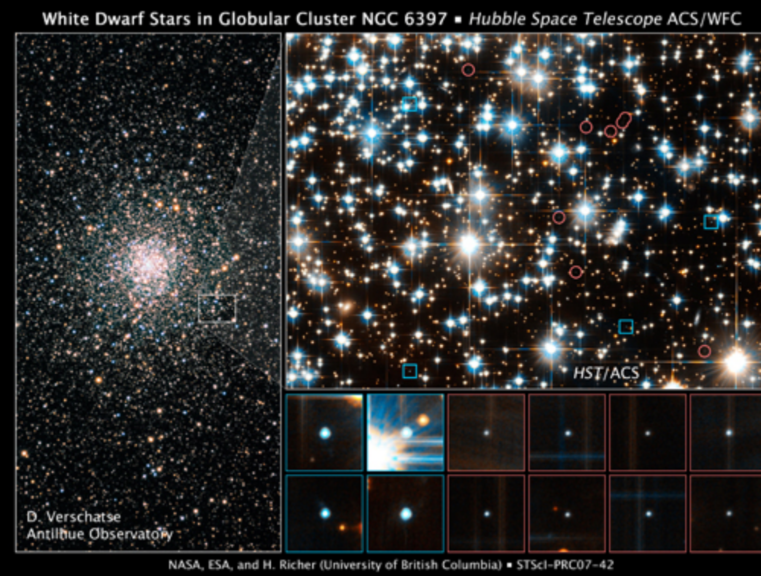
The first new class of pulsating white dwarf found in the last 25 years!



Montgomery et al. (2008)


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





Current techniques for studying white dwarf stars:

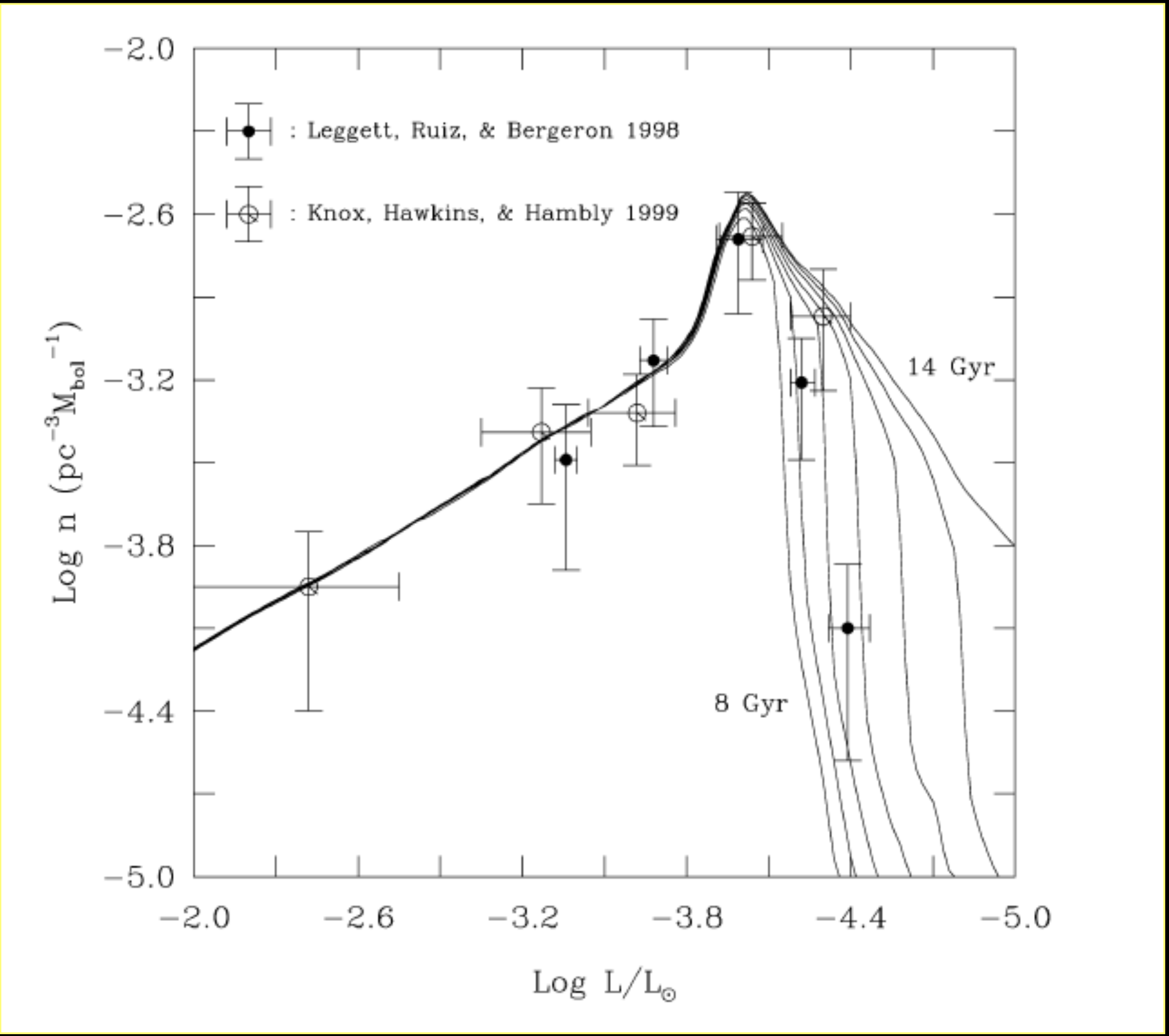
(Precision) Asteroseismology

Photometry

The Key: ***Spectroscopy***

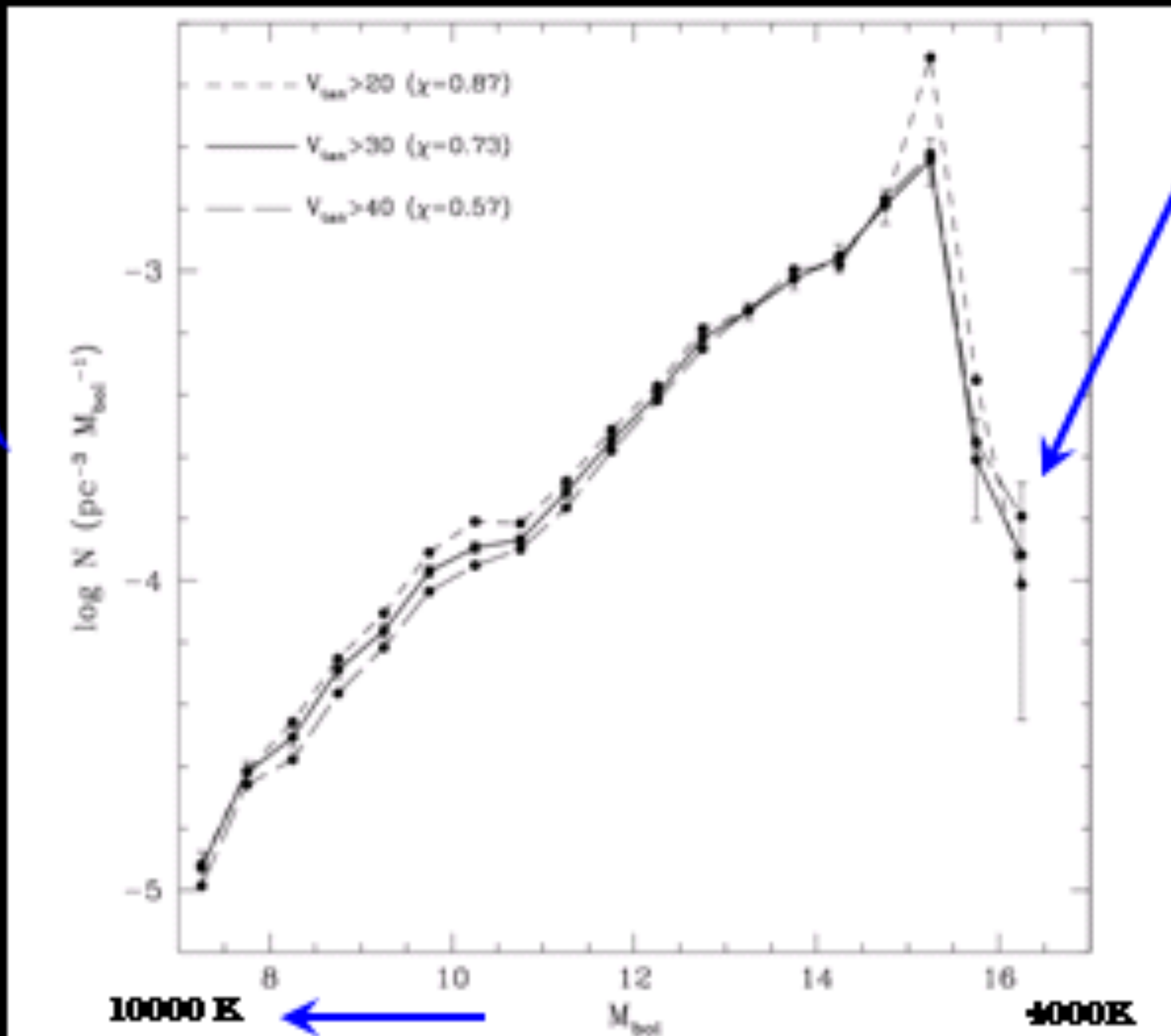
=>Mass and Temperature

The Disk Luminosity Function



Fontaine, Brassard & Bergeron (2001)

The age of the Galaxy...



9.5 ± 1.0

Billion years old

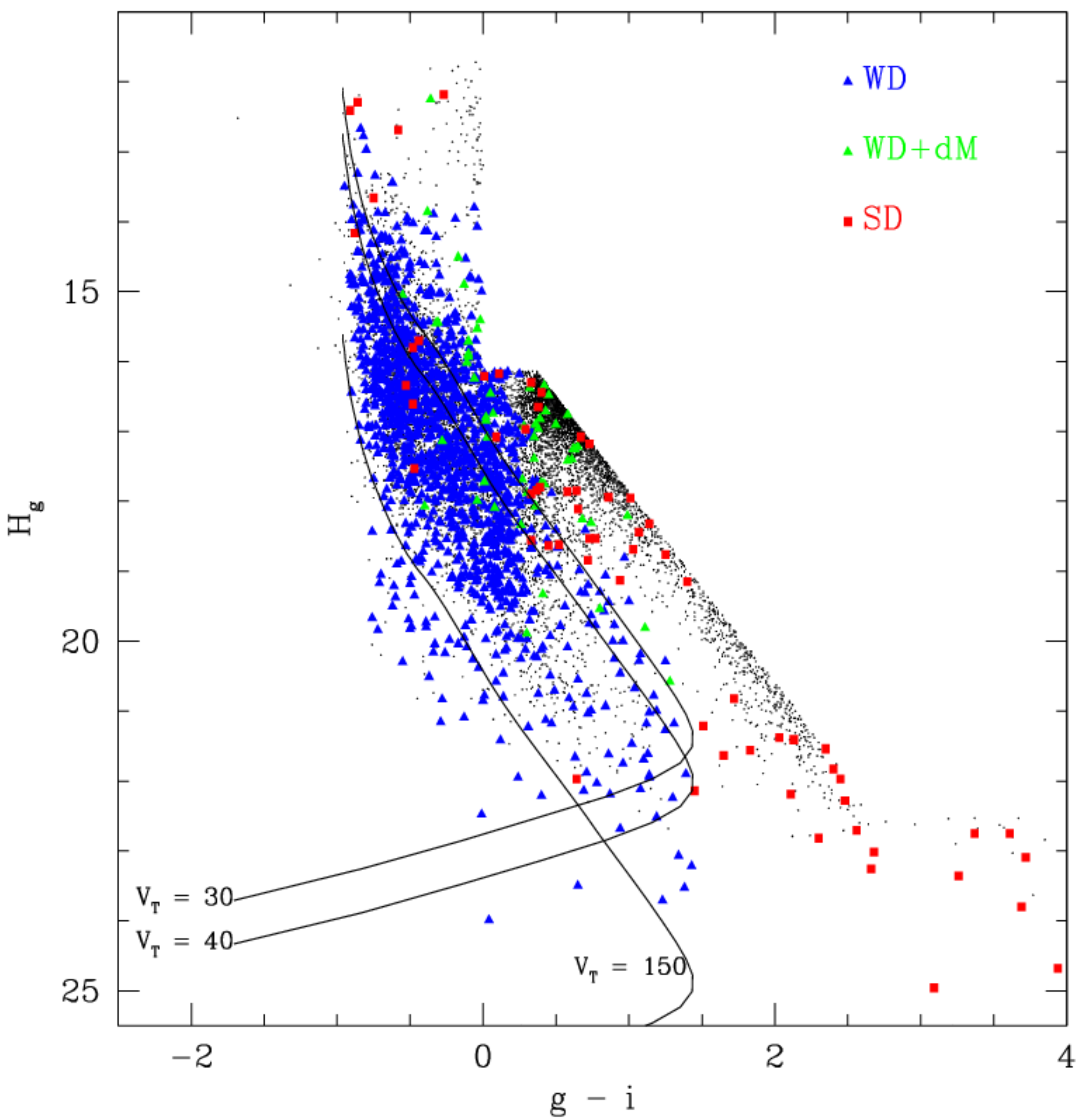
Luminosity

(∝ T^4)

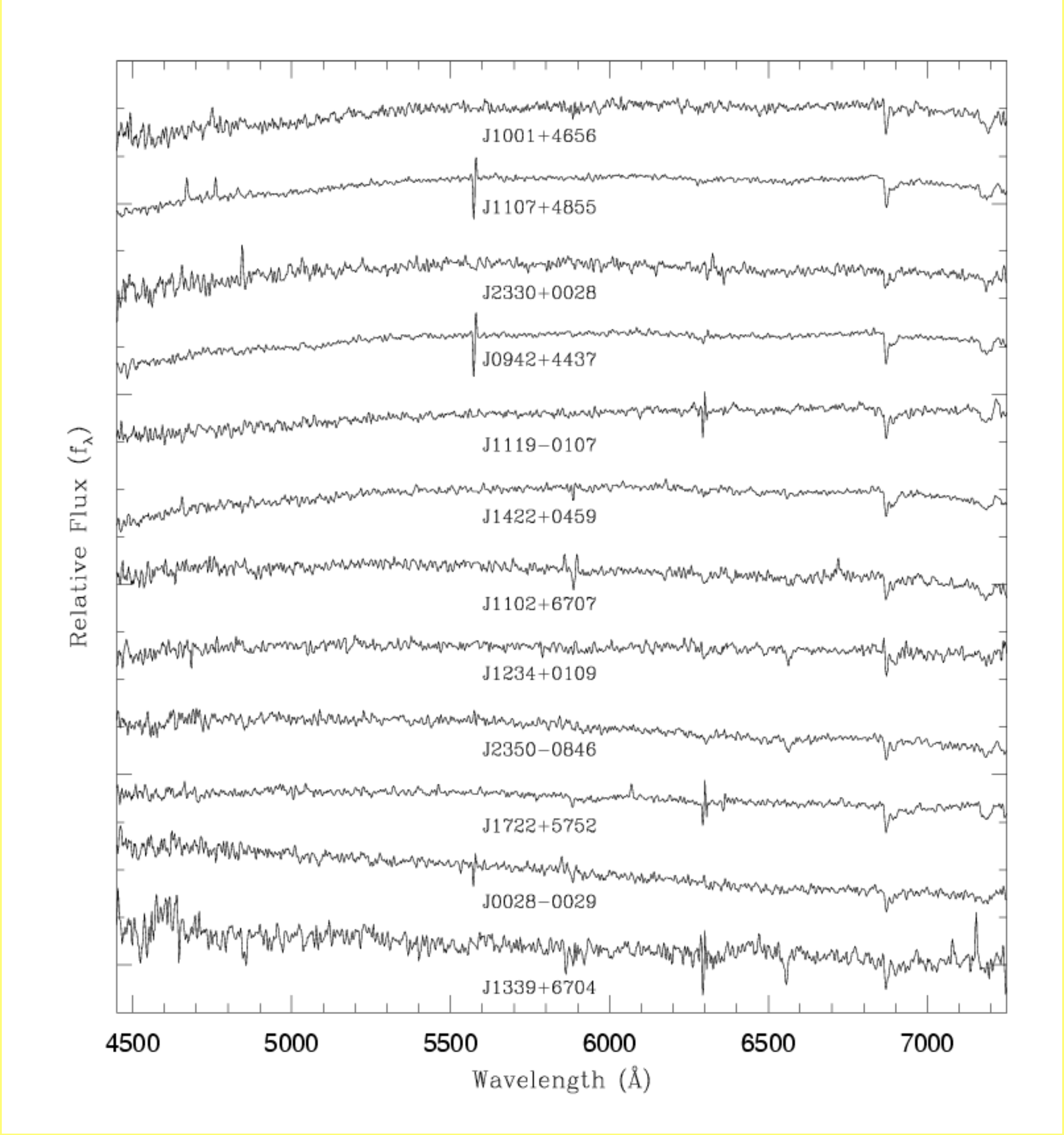
Harris et al (2006)

original paper by Don Winget et al. (1987)

Going after the cool WDs: Mukremin Kilic ….



HET Spectra of Cool White Dwarf Stars



The Disk vs M4: Globular clusters are older than the disk…

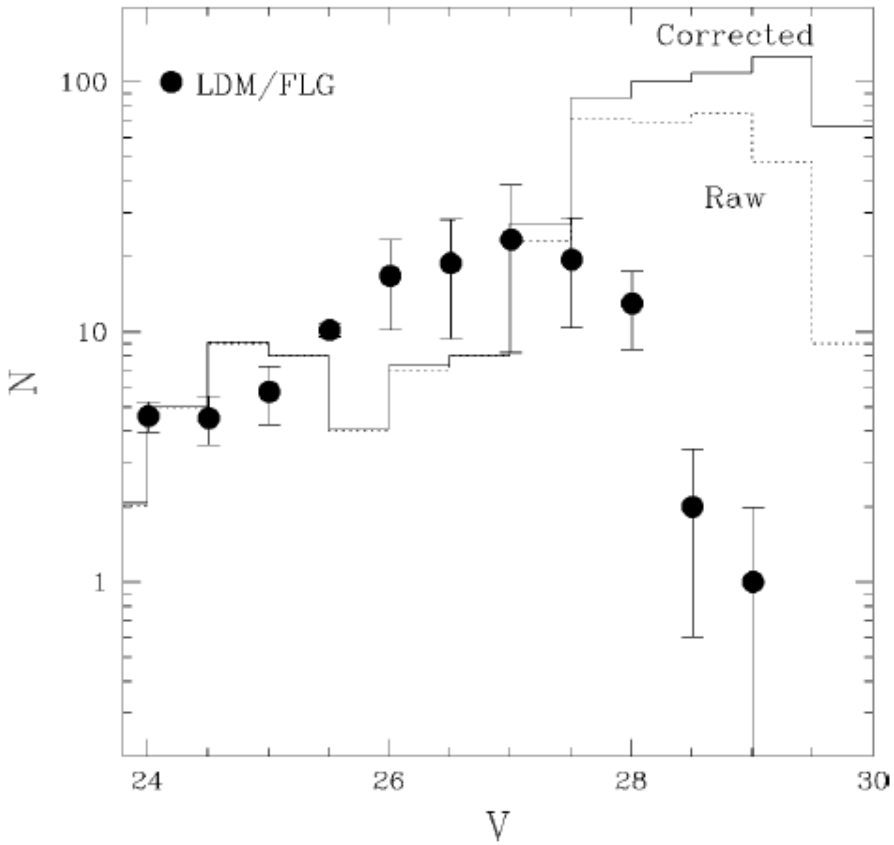
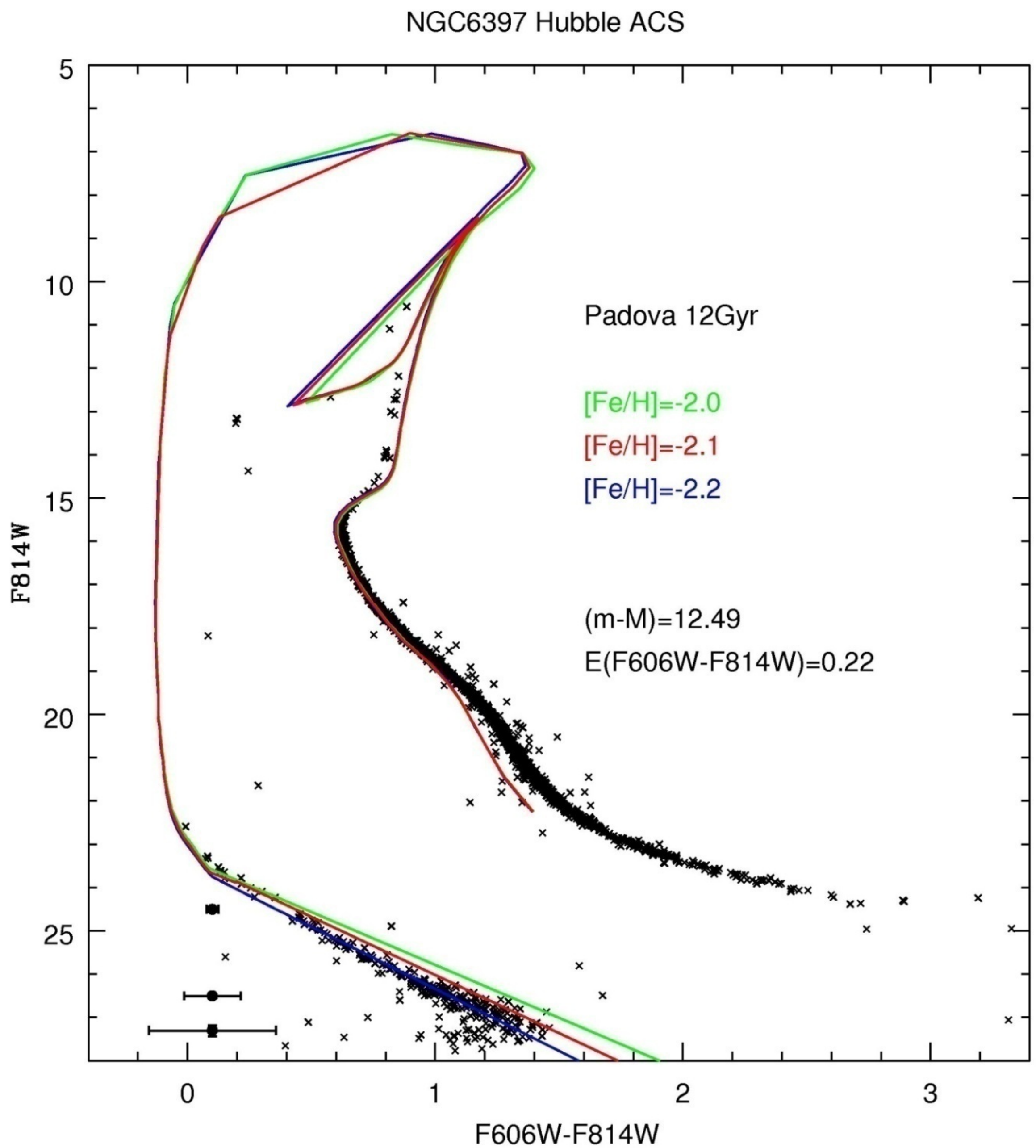


Figure 9 The solid histogram shows the luminosity function for the WDs in M4, corrected for incompleteness. The dashed histogram shows the raw counts. The solid points indicate the disk LF from Leggett, Ruiz & Bergeron (1998), with a V-band distance modulus of $\mu_V = 12.51$ for M4 applied. The vertical normalization is arbitrary—the comparison is designed to demonstrate that the M4 luminosity function extends beyond the turnover in the disk LF, a clear indication that M4 is older than the galactic disk.

Hansen & Liebert (2003)

But the white dwarfs are not!

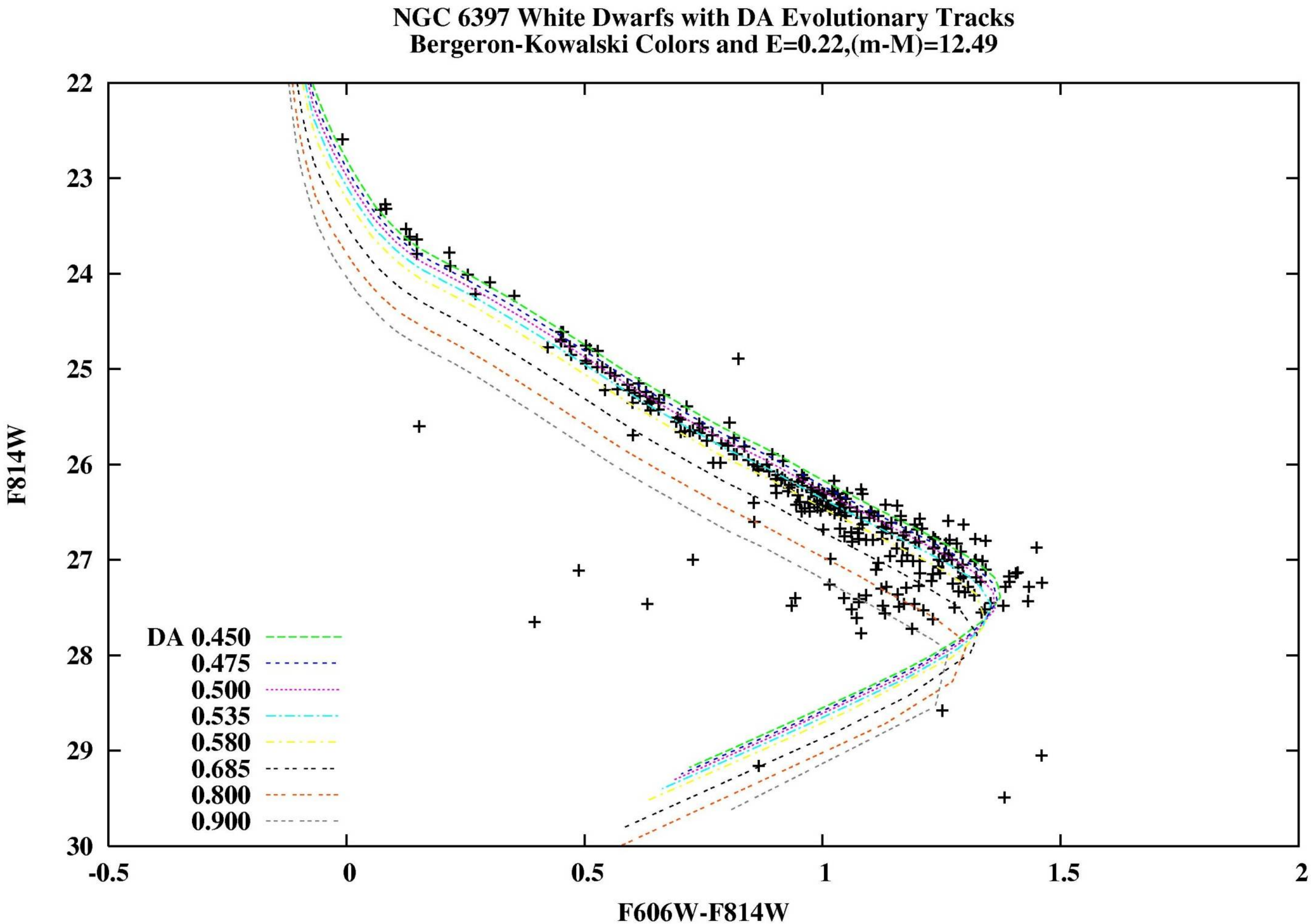
Fixing the WD evolutionary tracks in the CMD by simultaneously fitting the main sequence and the WDs gives Z, (m-M) and E



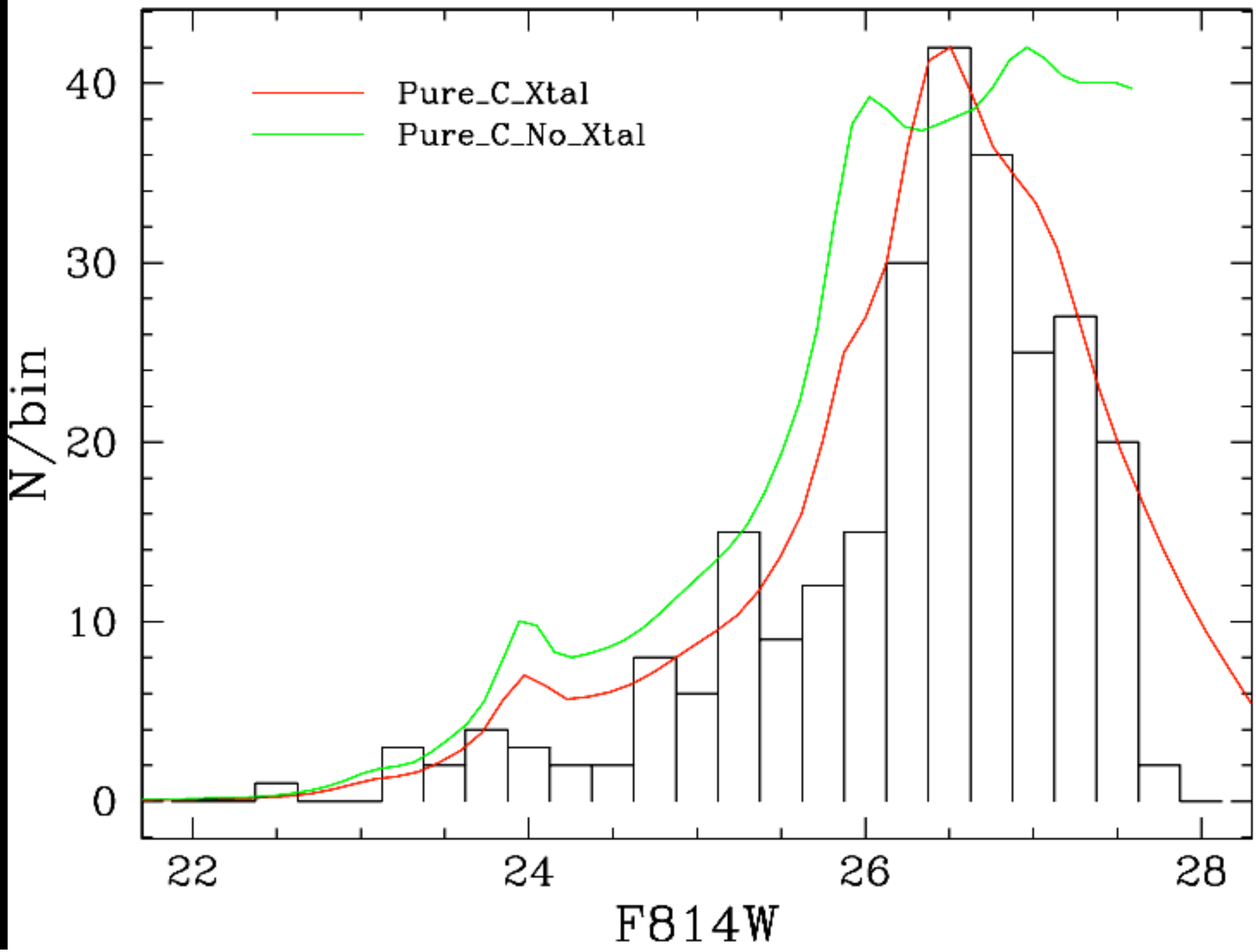
Data: proper motion screened sample from **Richer et al. 2008, AJ, 135,2131**

What advantages do Globs have over the disk population?

- The cooling sequences are "***pinned***" to the CMD by the main sequence and white dwarfs fitted together – sliding is not allowed.
- If we ignore the observational errors, the CMD location of a star uniquely determines its mass and radius: setting the ***mechanical properties*** of the white dwarf determined independently of the thermal.
- The mass range is ***very narrow***.
- Ages provide some independent information …
The terminus white dwarfs aren't as old as you think!

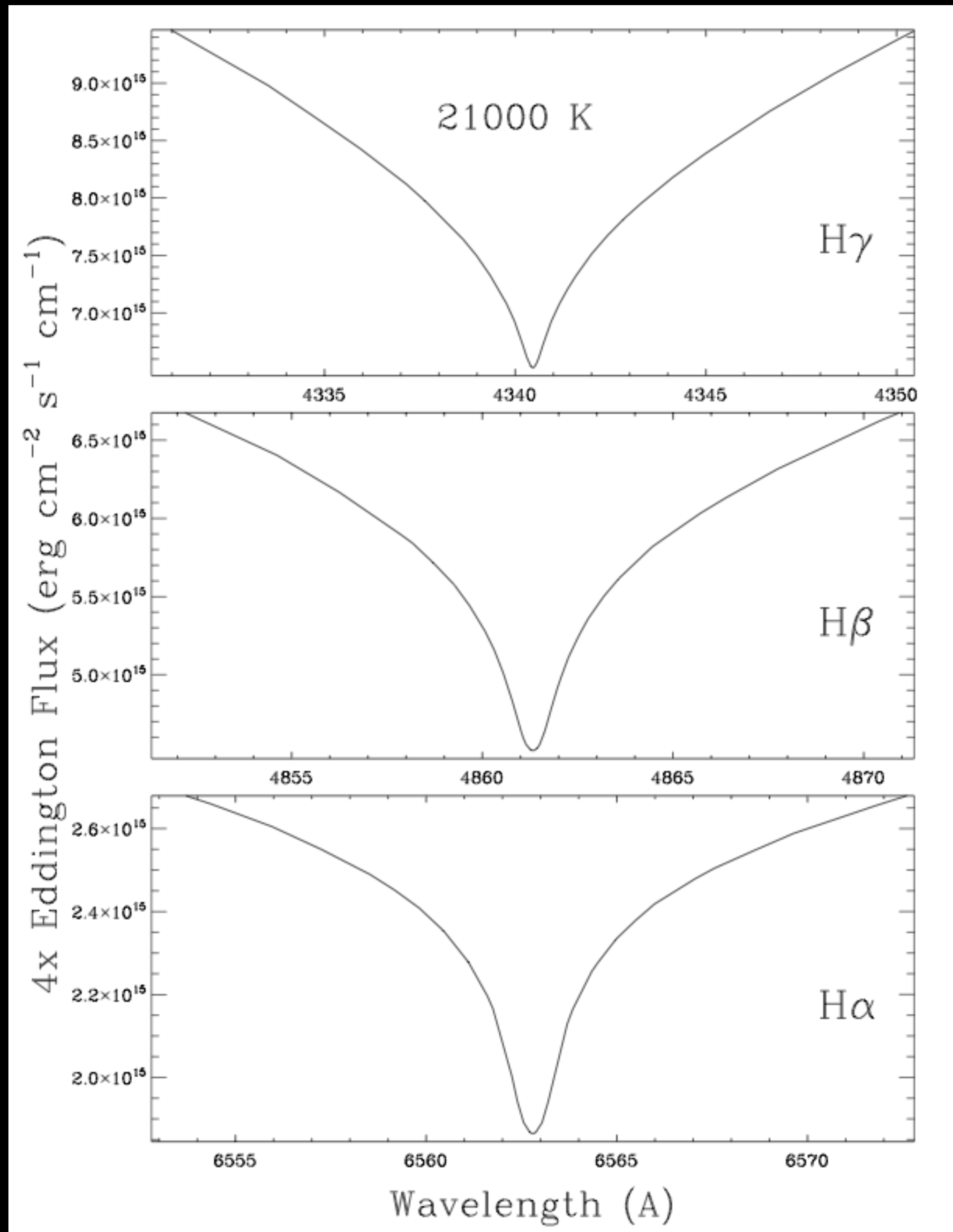


NGC 6397 White Dwarfs with DA Evolutionary Tracks
Bergeron-Kowalski Colors and E=0.22,(m-M)=12.49
F814W
F606W-F814W
DA 0.450
0.475
0.500
0.535
0.580
0.685
0.800
0.900
22
23
24
25
26
27
28
29
30
-0.5
0
0.5
1
1.5
2

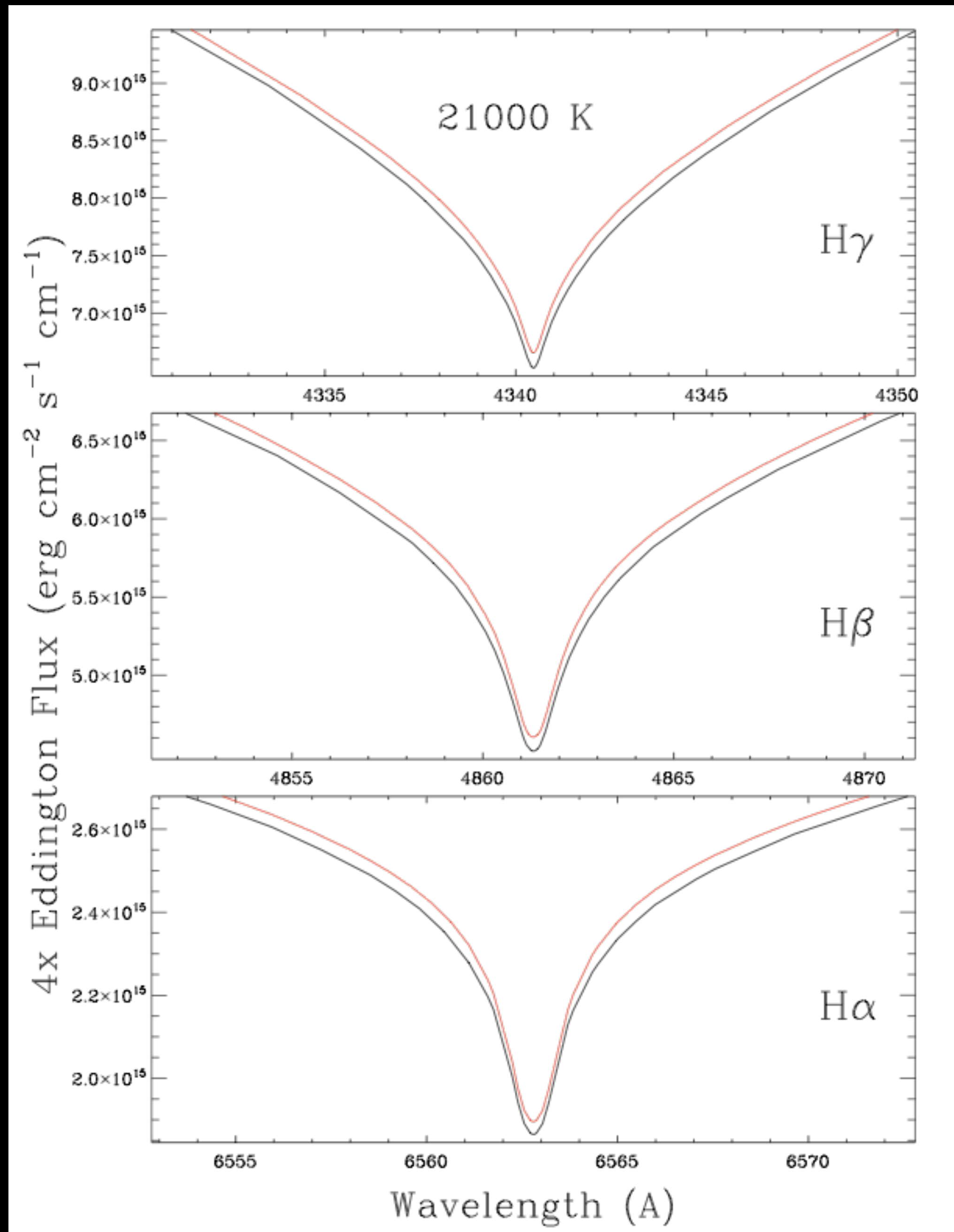


Pure_C_Xtal
Pure_C_No_Xtal
N/bin
0
10
20
30
40
22
24
26
28
F814W

d
09



21000 K
Hγ
Hβ
Hα
4x Eddington Flux (erg cm^{-2} s^{-1} cm^{-1})
Wavelength (A)
9.0×10^{15}
8.5×10^{15}
8.0×10^{15}
7.5×10^{15}
7.0×10^{15}
4335
4340
4345
4350
6.5×10^{15}
6.0×10^{15}
5.5×10^{15}
5.0×10^{15}
4855
4860
4865
4870
2.6×10^{15}
2.4×10^{15}
2.2×10^{15}
2.0×10^{15}
6555
6560
6565
6570



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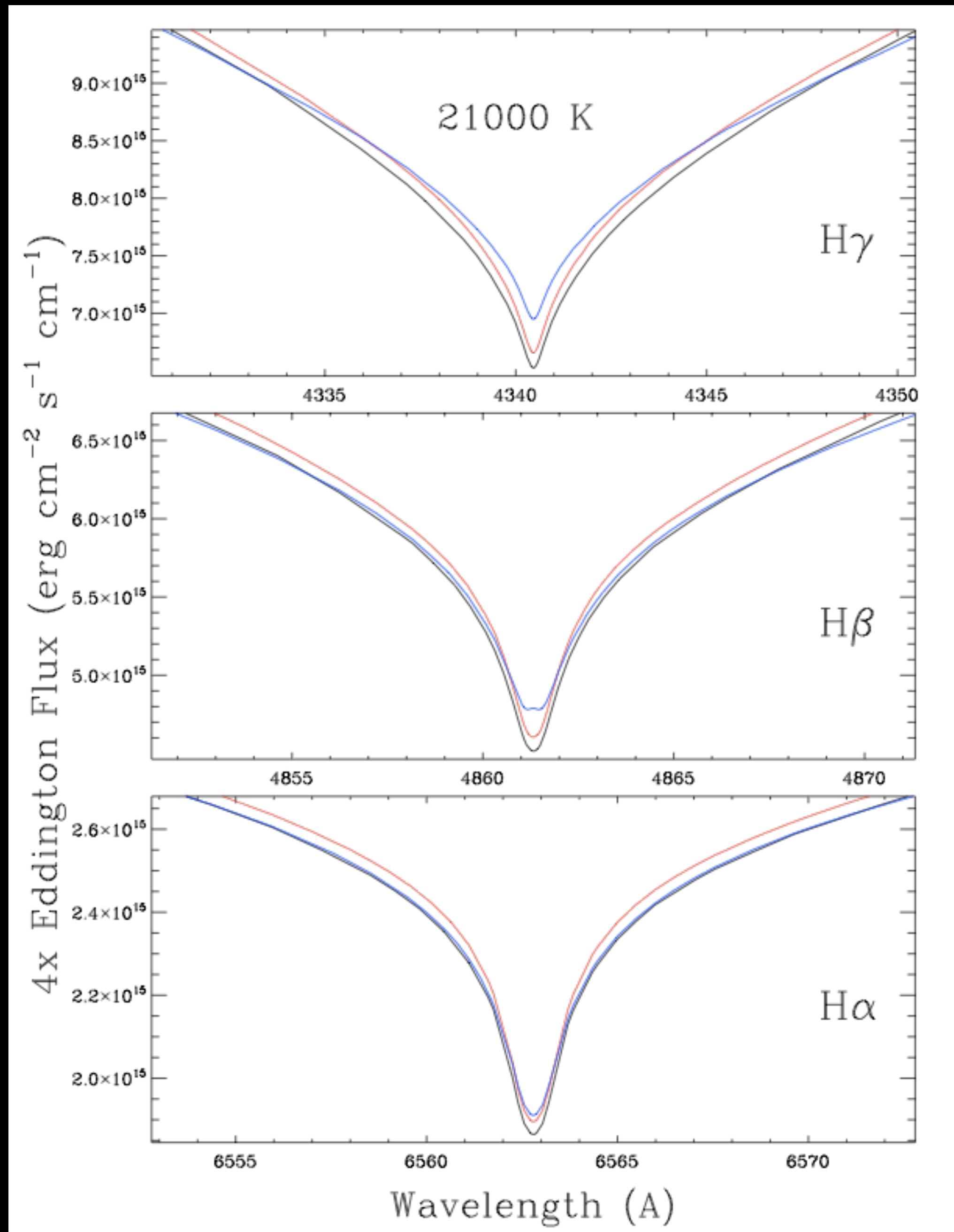
21000 K
Hγ
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Hα
4x Eddington Flux (erg cm^-2 s^-1 cm^-1)
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2.6×10^15
2.4×10^15
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6555
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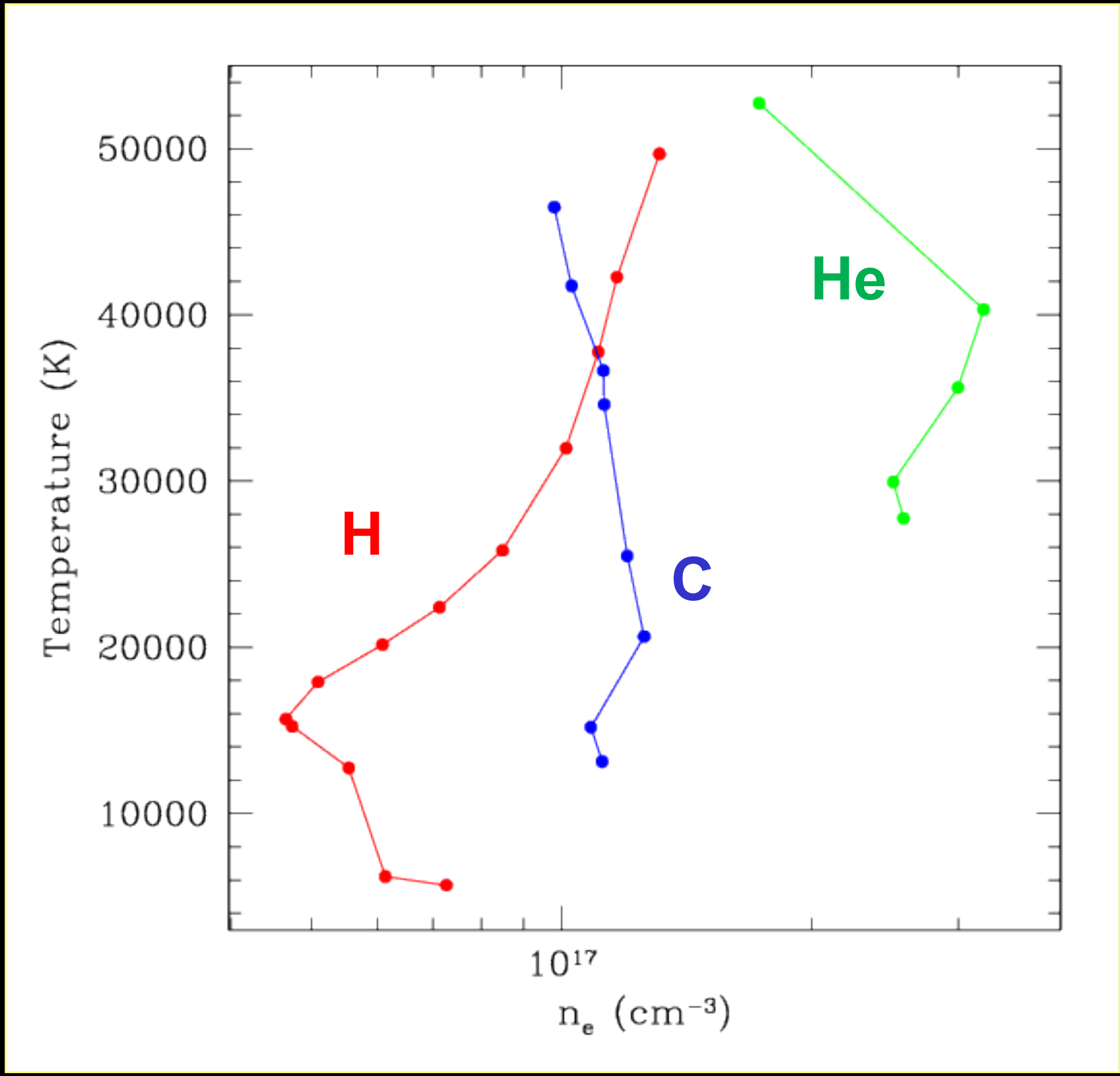
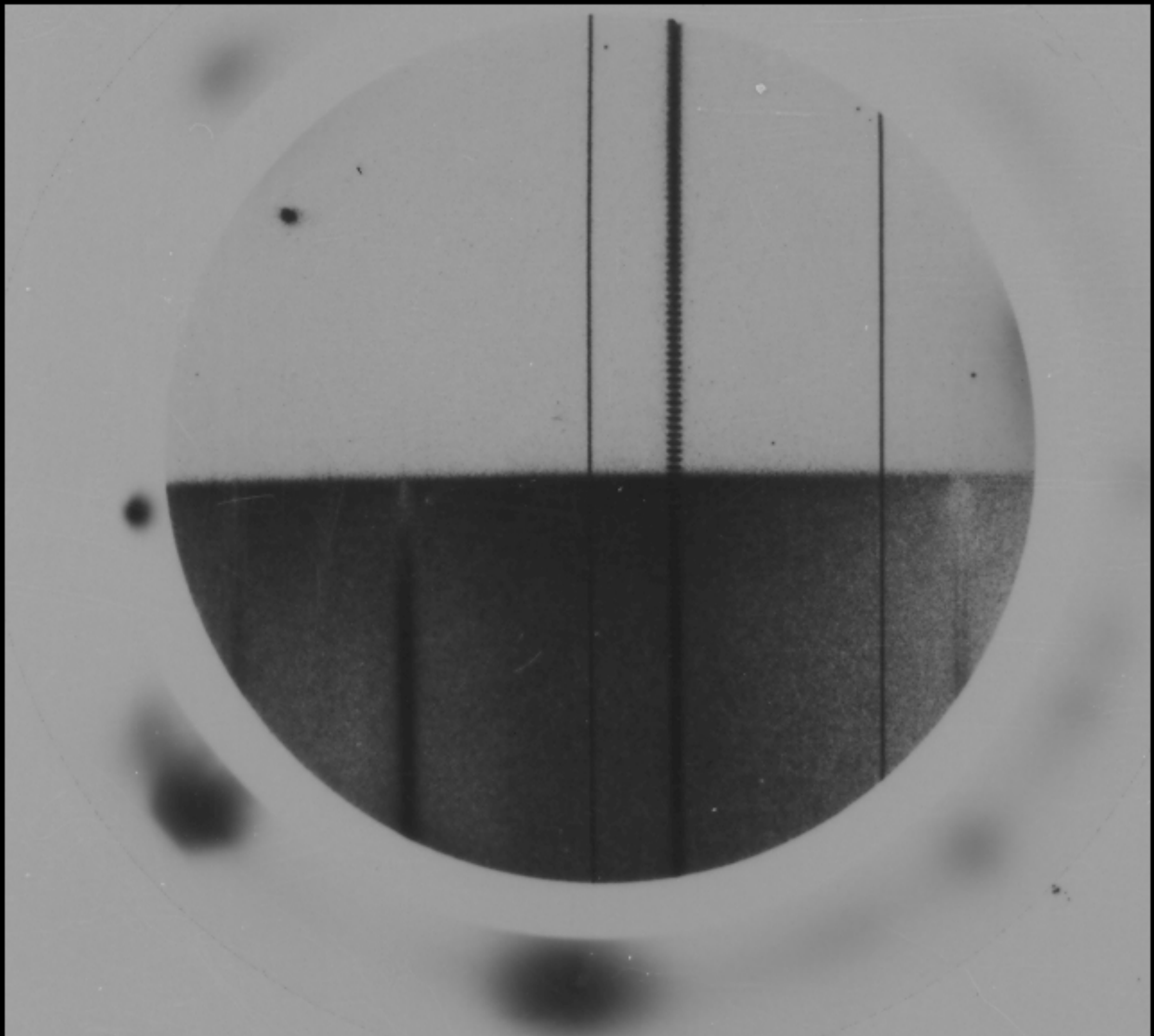
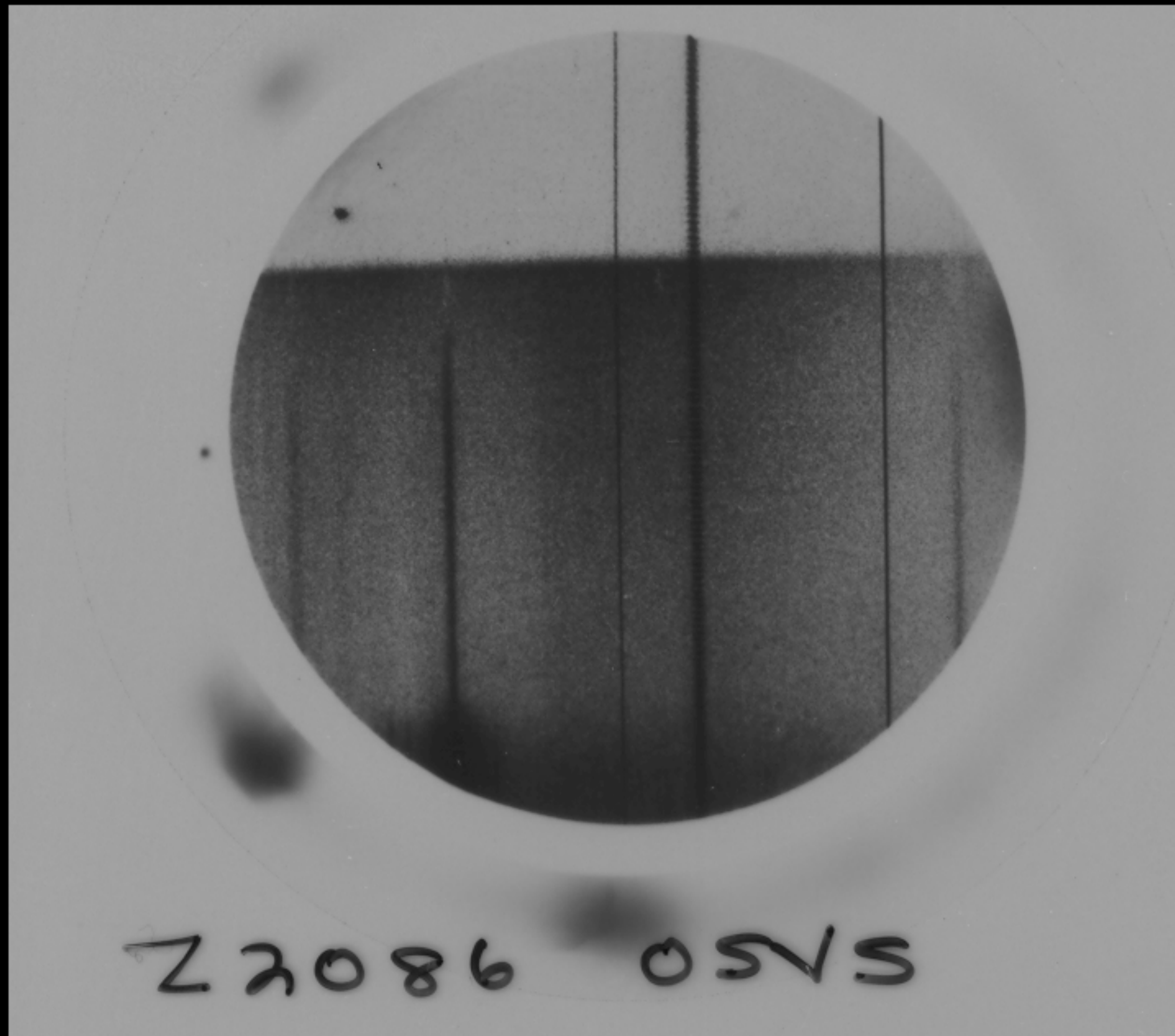
6565
6570

Photospheric White Dwarf Temperatures and Densities for log g = 8 (cgs)

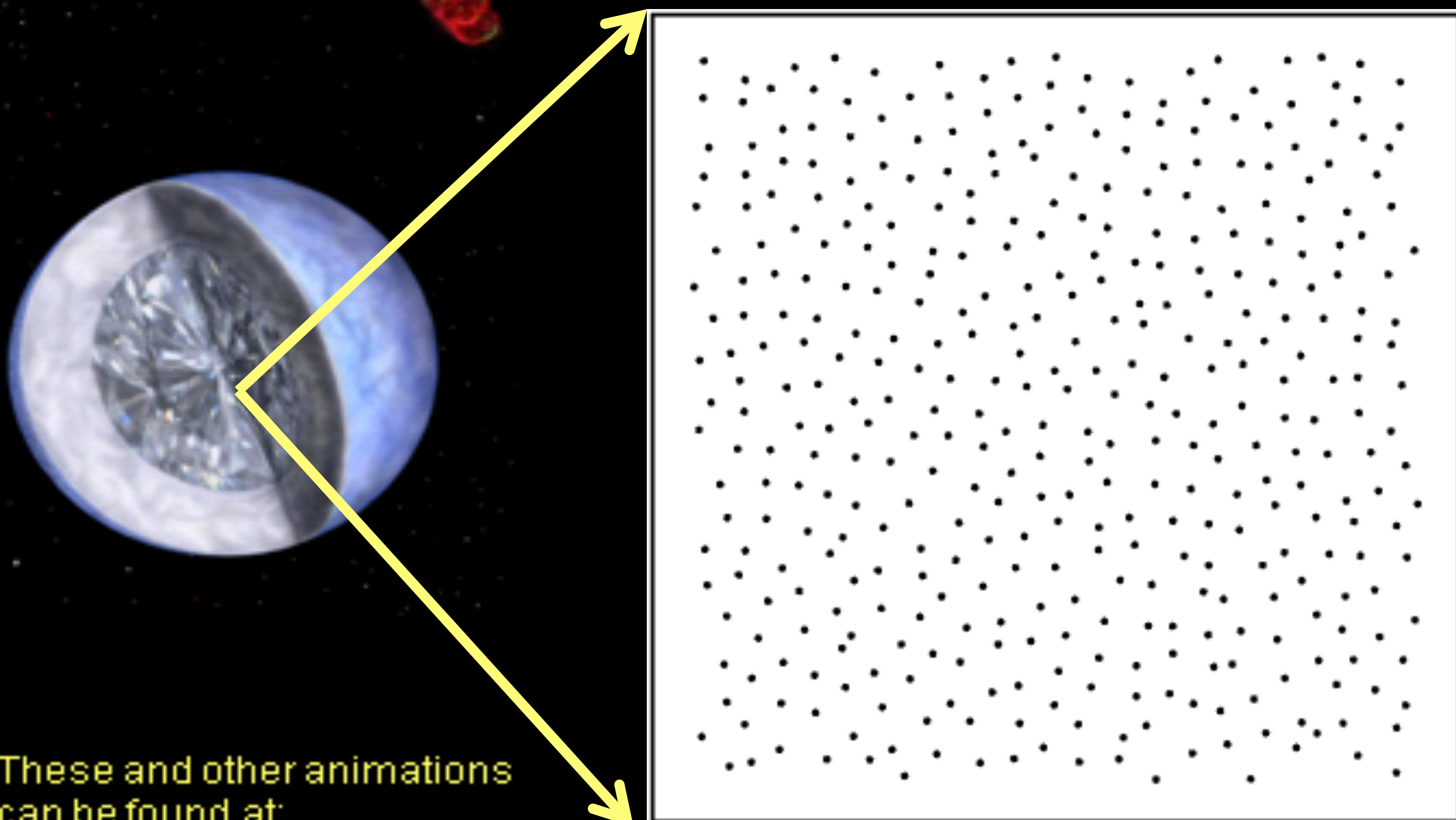




Z2084 OSVS


Z2086 05VS

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

Ratio of Coulomb Energy to Ion Thermal Energy

$$\Gamma = \frac{1}{kT}\frac{(Ze)^2}{R} = 2.692 \times 10^{-3} Z^2 N_i^{1/3} T^{-1}$$

What is the expected value of Gamma at crystallization?

(OCP) = 176 (see, most especially, the work by **DeWitt** et al. 2001, also Potekhin & Chabrier 2000, and Horowitz, Berry & Brown 2007)

(MIX)= 230 - 260 (Horowitz, Berry & Brown 2007)

This is at the ***frontier*** of (brute force) molecular dynamics;
We eagerly await the upcoming work by **Hugh DeWitt** and collaborators!

Ratio of Coulomb Energy to Ion Thermal Energy

$$\Gamma = \frac{1}{kT}\frac{(Ze)^2}{R} = 2.692 \times 10^{-3} Z^2 N_i^{1/3} T^{-1}$$

What is the value of Gamma at and near the "clump" in the observed CMD, or equivalently, the value of Gamma at and before (rise) the peak of the Luminosity Function?

log rho = 6.32 log T = 6.40

… nearly independent of composition!

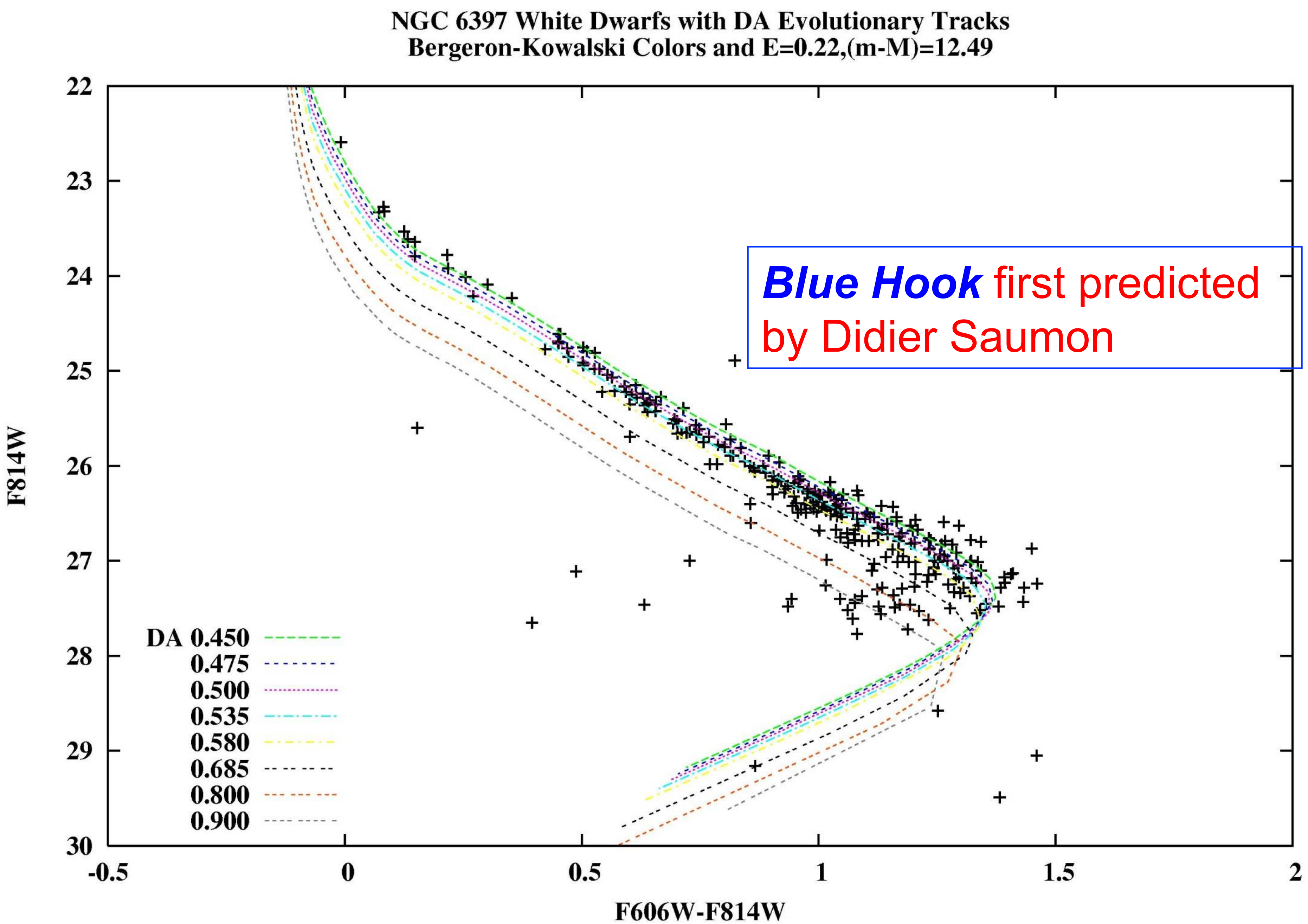
(peak) = 194 (carbon) = 313 (oxygen)

(rise) = 182 (carbon) = 291 (oxygen)

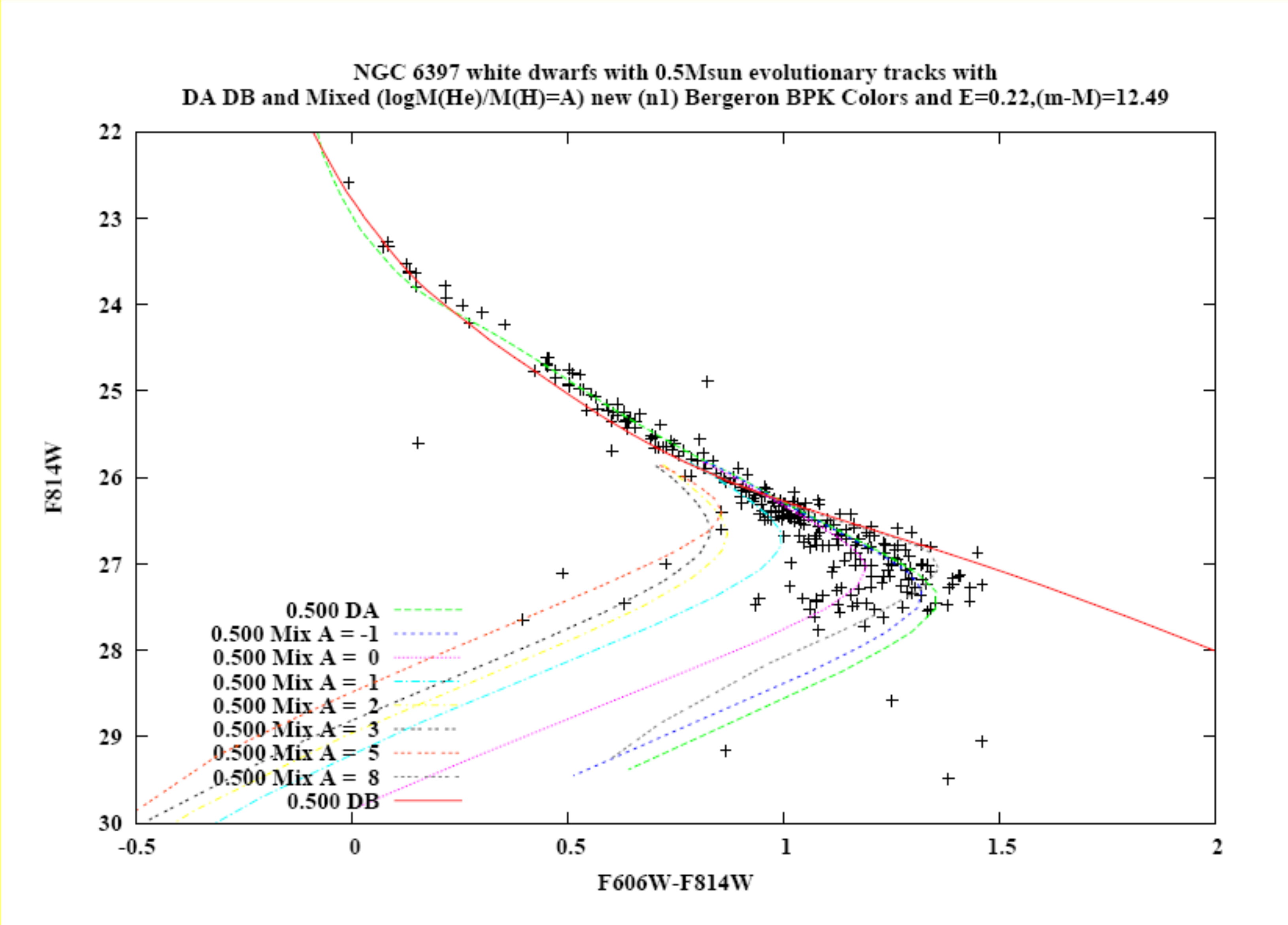
Conclusions from NGC 6397

- Confirm that **crystallization occurs**
- Confirm that **Debye cooling occurs**
- We can ***measure*** the ***Gamma*** of crystallization
- Low metallicity clusters may not produce significant O in cores of some of the 0.5Msun stars … or the C/O mixture has

  ***Gamma* = 230 - 260**
- We find the first empirical evidence that Van Horn's 1968 prediction is correct: ***Crystallization is a first order phase transition!***

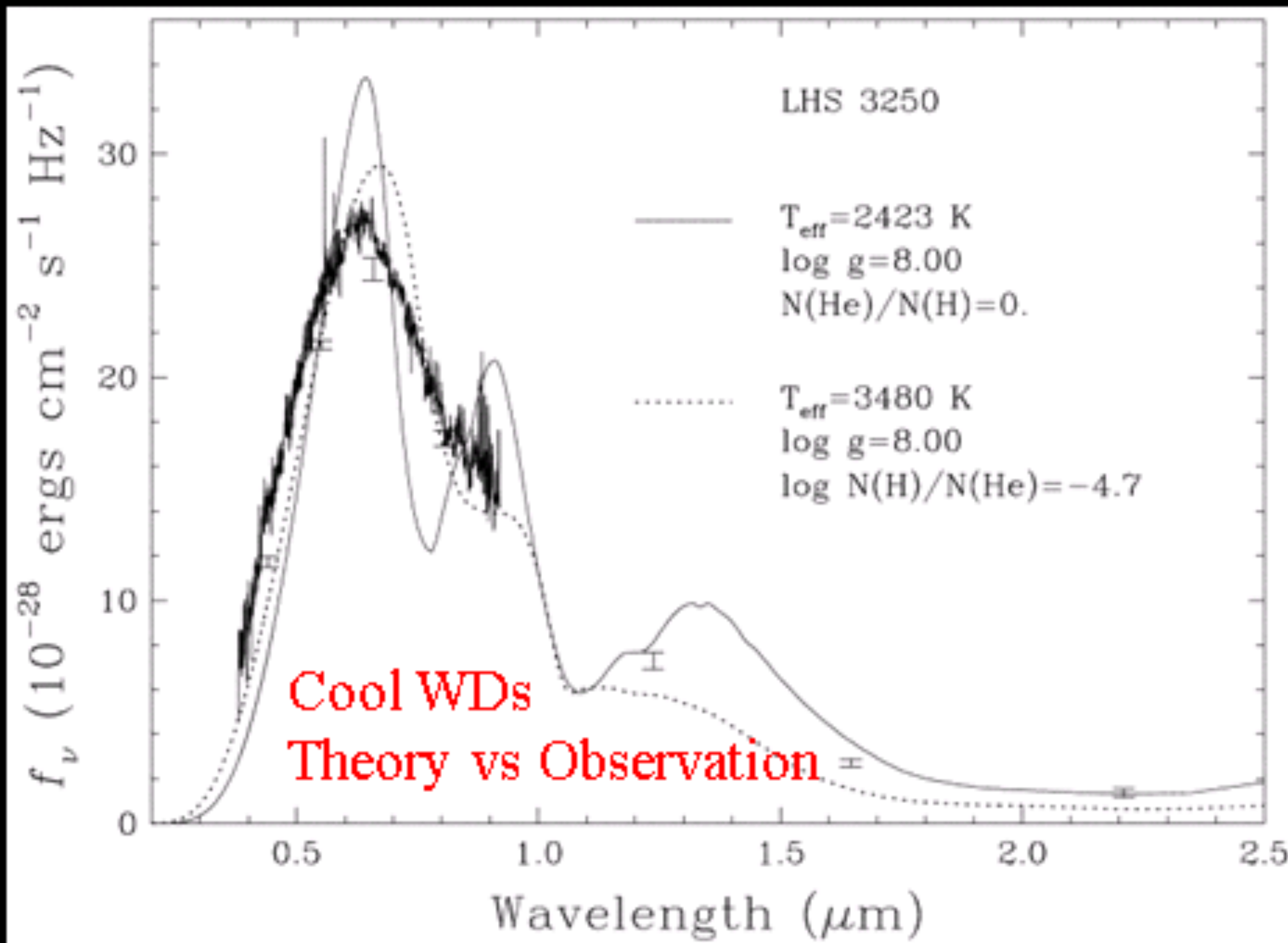


Oops … the CIA hook is in the wrong place!



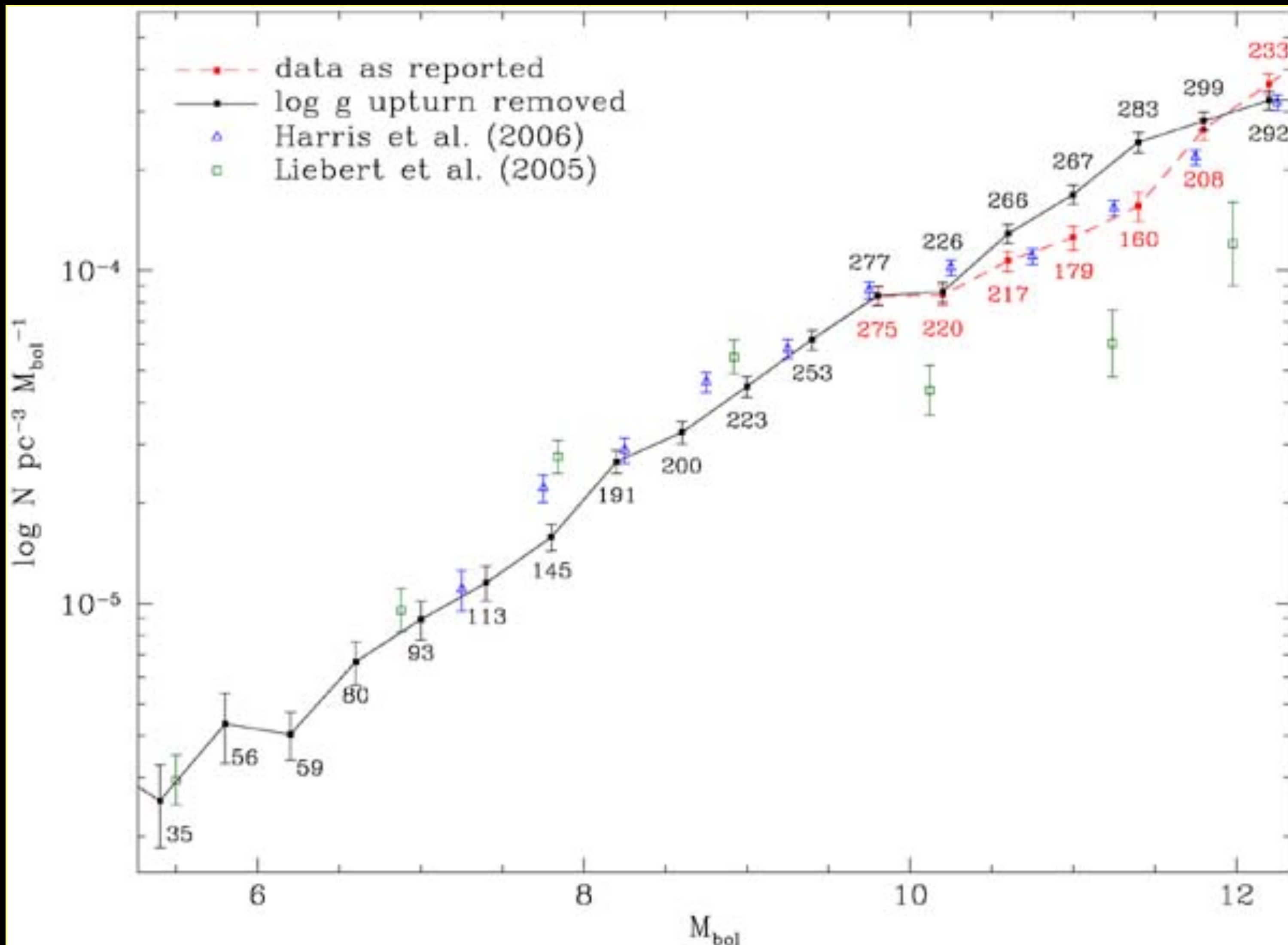
Adding He seems to solve our problem, but is this physical?
We can go to the laboratory to tell!

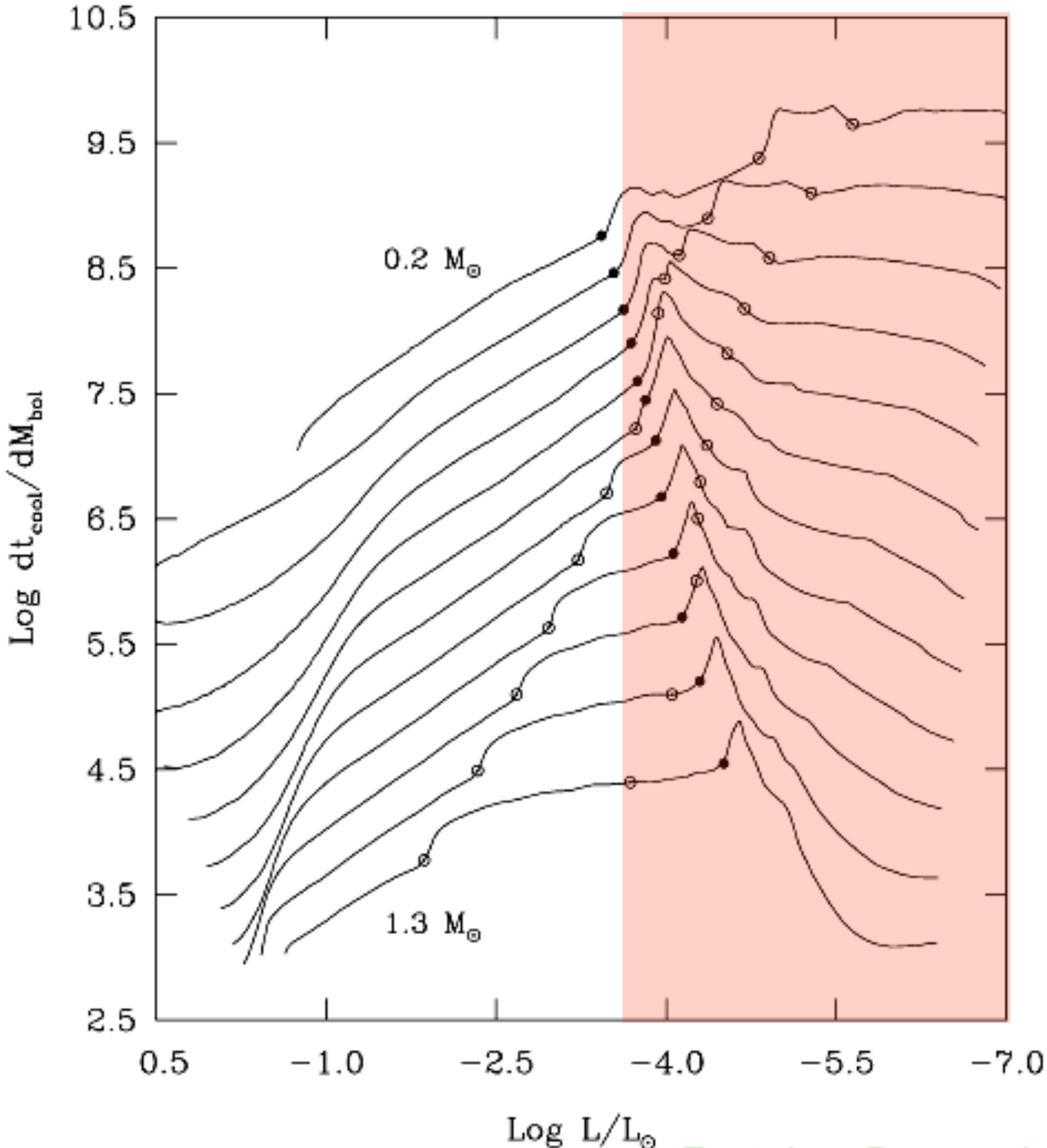
The coolest white dwarf stars are badly fit …



Temperature difference => age difference of ***several Gyr***

DeGennaro et al. (2008) Disk LF
3358 new SDSS WDs (with spectra)

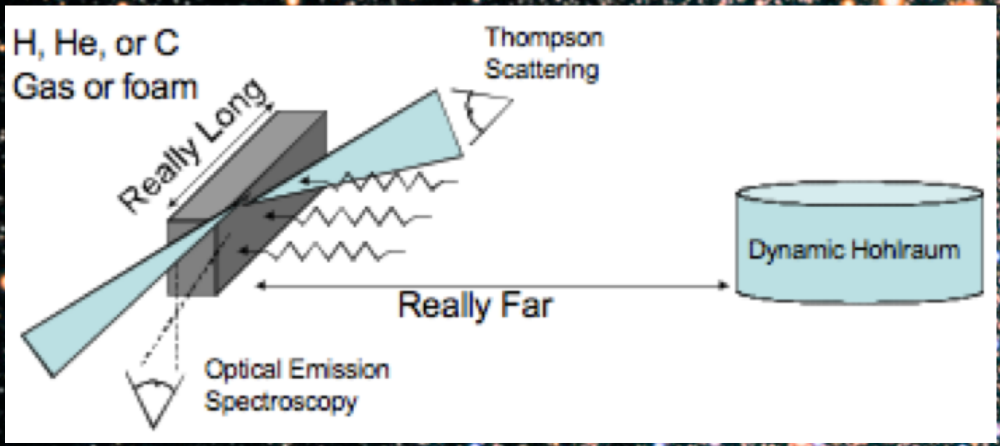




Fontaine, Brassard & Bergeron (2001)

FIG. 5.—Evolutionary paths (*solid curves*) of 12 (M = 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, and 1.3 $M_\odot$, *from top to bottom*) of our template

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



Laboratory Setup

Astrophysical Laboratory