Constraints and Measurements of the Equation of State from the White Dwarf Stars

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and

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Some Recommended Reading

Reviews:

- Fontaine, Brassard & Bergeron 2001, PASP 113:409
- Hansen & Liebert 2003, ARA&A 41:465
- Winget & Kepler 2008, ARA&A in press

New:

- Richer et al. 2008, AJ, 135, 2141
- Hansen et al. 2007, ApJ, 671,380
- Winget, Kepler, Campos, Montgomery, Girardi & Bergeron 2008 submitted to ApJL

Classic:

- Van Horn 1968, ApJ 151:227

OUTLINE

I. Astrophysical Context
   What are White Dwarf Stars—and why should I care? Exploring physics of matter under extreme conditions
II. Individual Stars: EoS from (spectroscopy, binary studies, and) asteroseismology
III. Ensembles of Stars: EoS from Luminosity Functions and Color-Magnitude Diagrams

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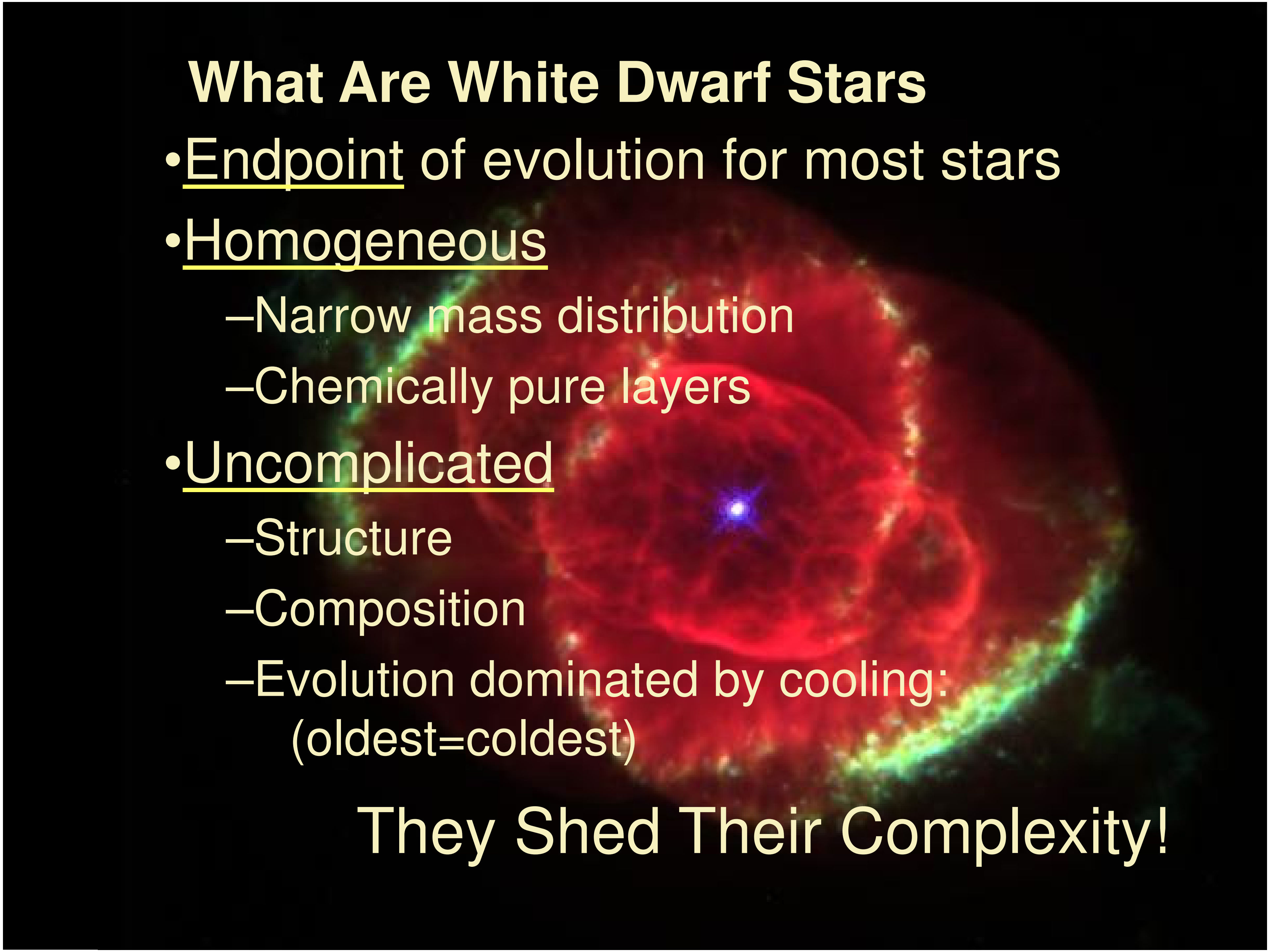
What Are White Dwarf Stars
•Endpoint of evolution for most stars
•Homogeneous
–Narrow mass distribution
–Chemically pure layers
•Uncomplicated
–Structure
–Composition
–Evolution dominated by cooling:
(oldest=coldest)
They Shed Their Complexity!

… and Why Should I Care?

- Representative (and personal)
  - 98% of all stars, including our sun, will become one
  - Archeological history of star formation in our galaxy
- A way to find Solar Systems dynamically like ours
- Exploration of Extreme physics
  - Matter at extreme densities and temperatures
    - 60% of the mass of the Sun compressed into star the size of the Earth
  - Chance to study important and exotic physical processes: plasmon neutrinos, internal crystallization

Most Importantly ….

- When we talk about white dwarf interiors, we are talking about neutron star crusts …

  Always remember, a neutron star is just a failed white dwarf, or for purposes of this meeting ….

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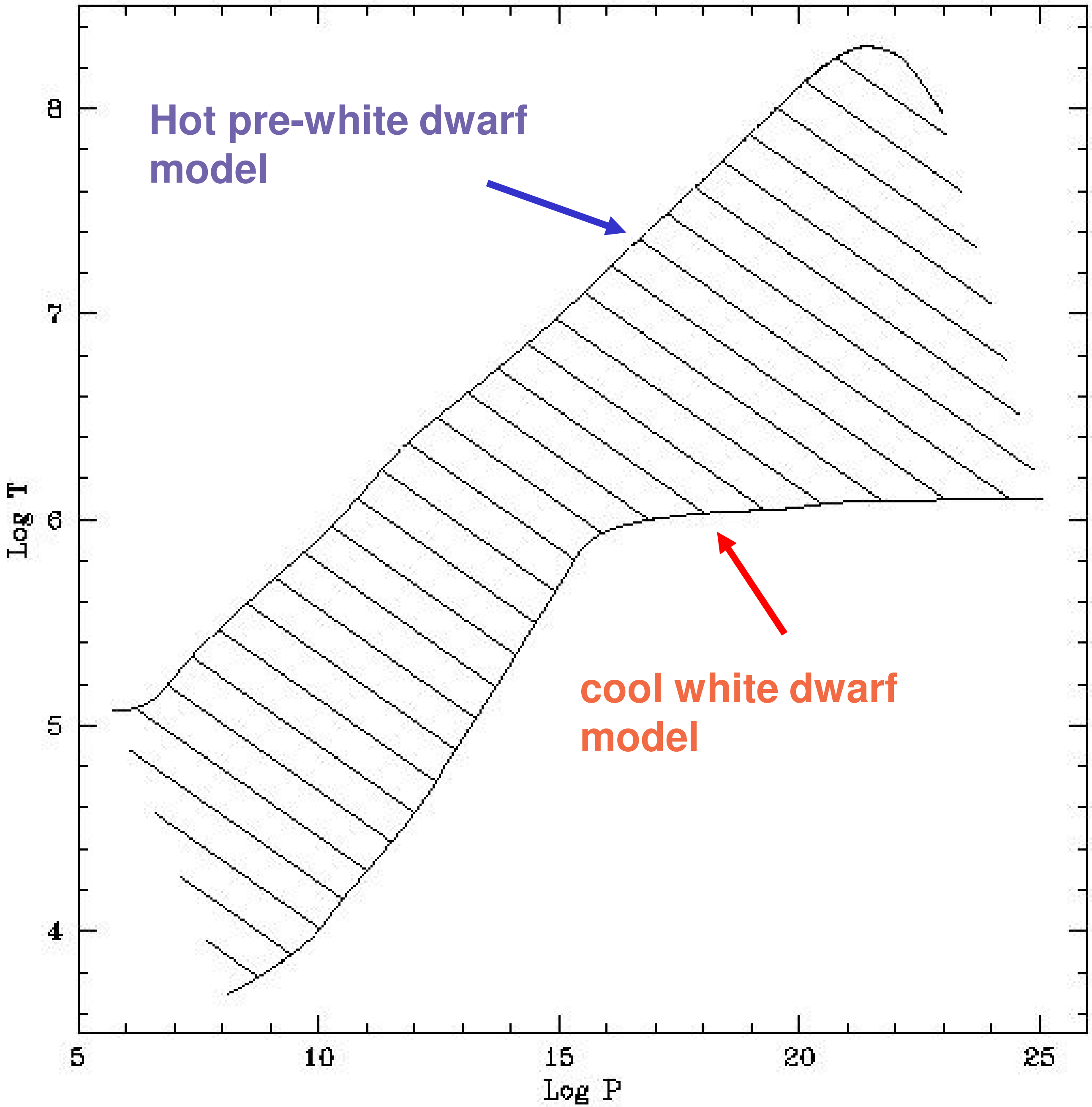
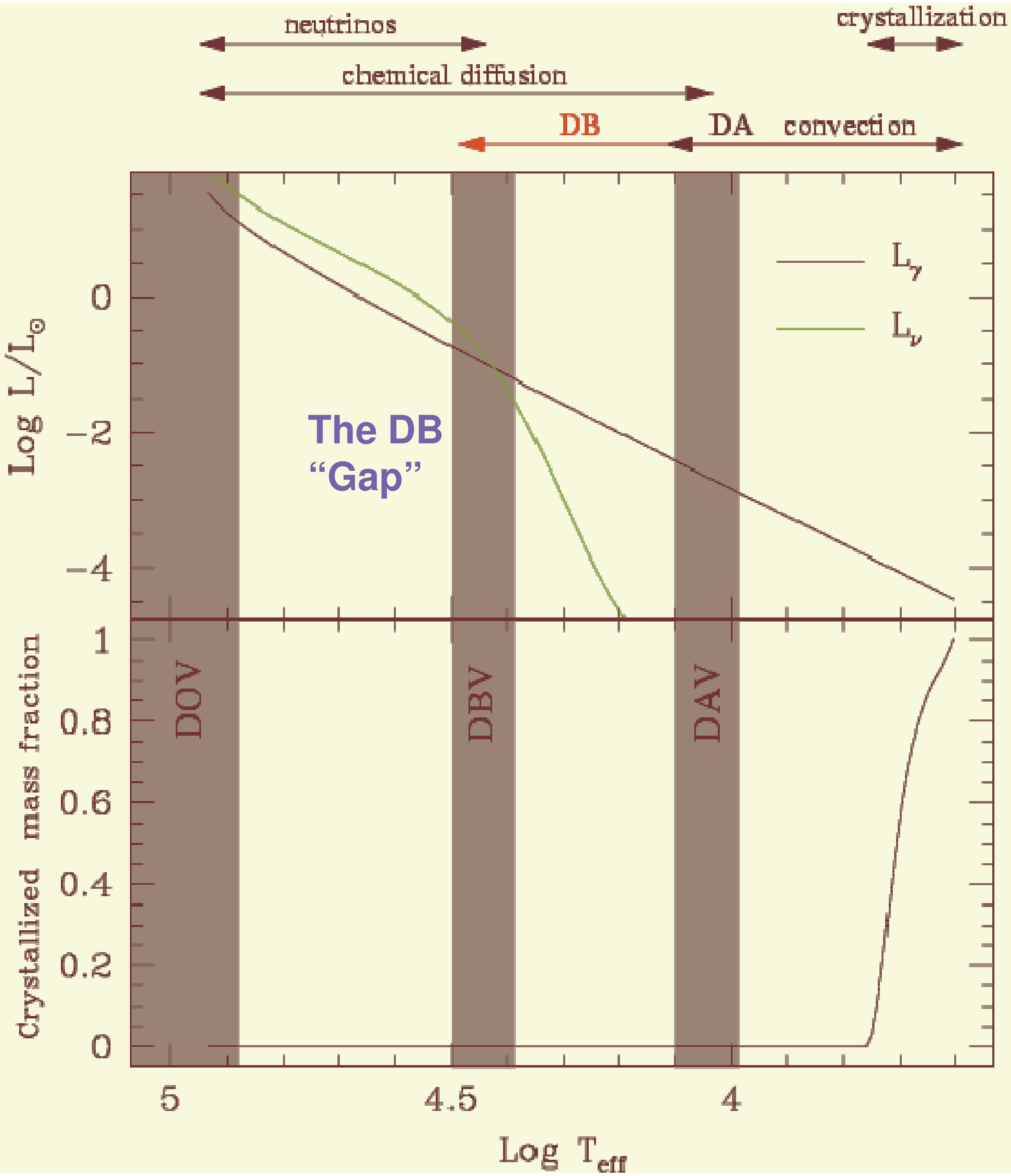


Hot pre-white dwarf model
cool white dwarf model
Log T
Log P
8
7
6
5
4
5
10
15
20
25

Various physical processes thought to occur in WDs as they cool



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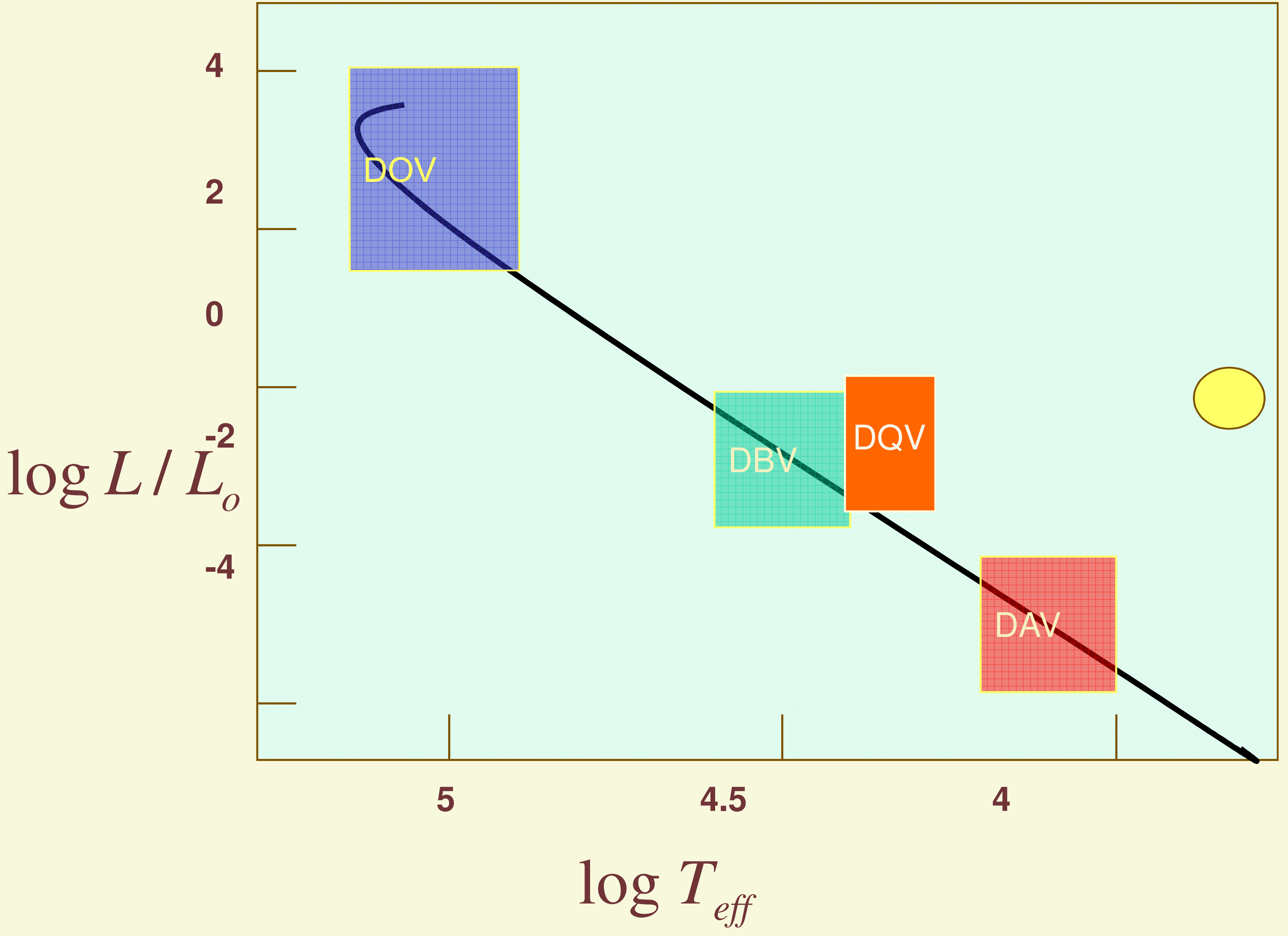
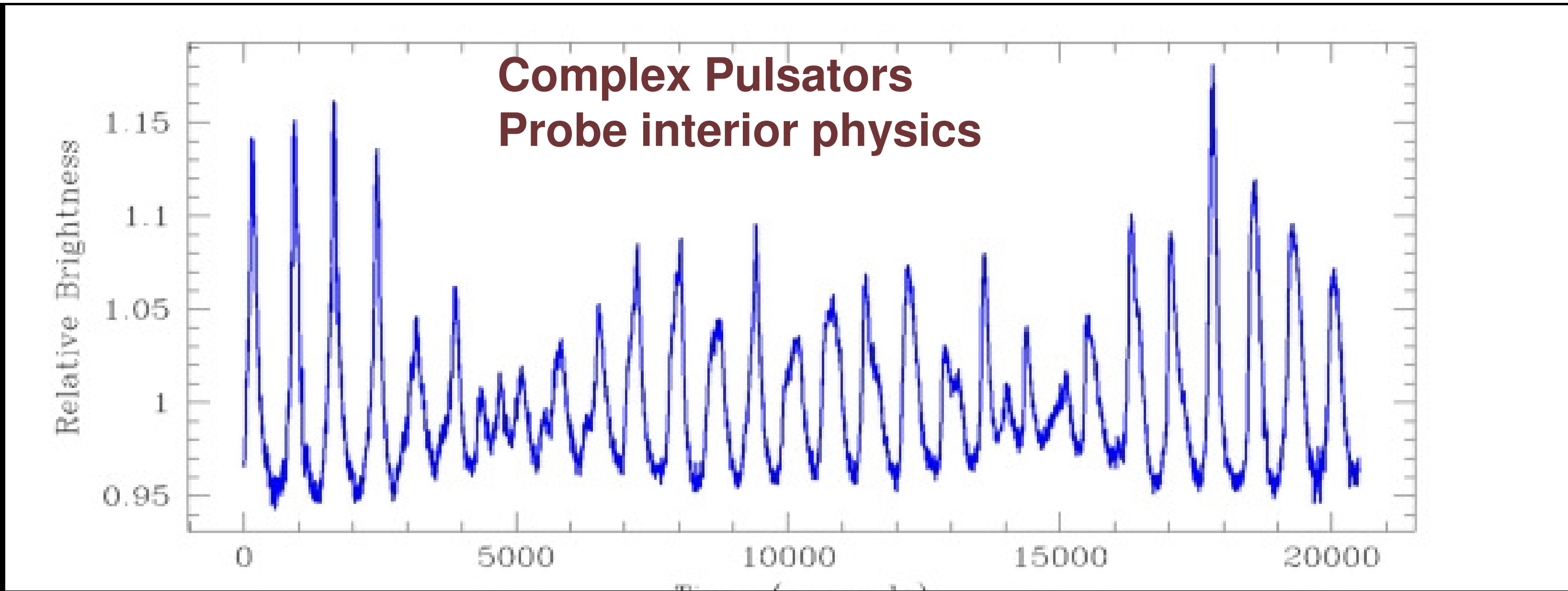
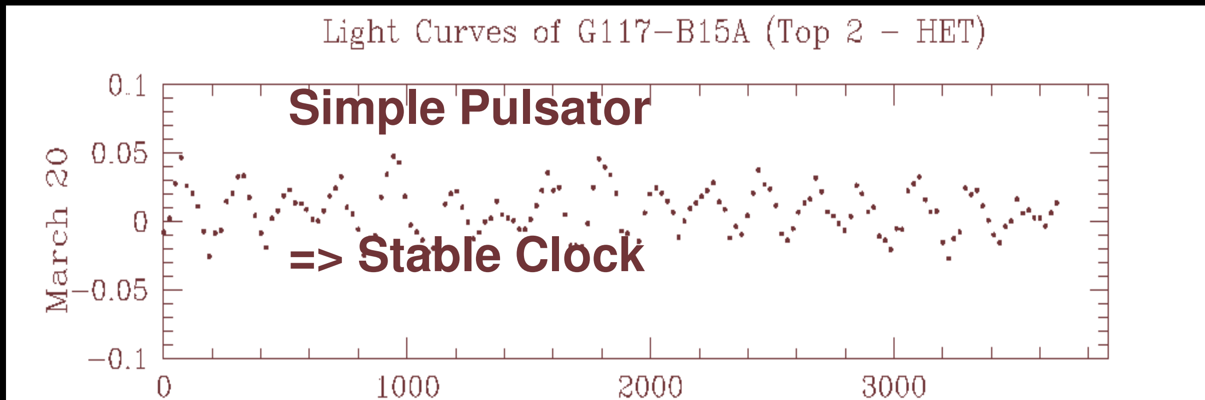

4
2
0
-2
-4
$\log L / L_o$
DOV
DBV
DQV
DAV
5
4.5
4
$\log T_{eff}$



<u>Asteroseismology</u>: Using normal modes of pulsating WDs to study extreme physics and time itself



Surface Brightness Variations 100-1,000 s

l = 2 modes

l = 3 modes

Nonradial Gravity Modes: g-modes

Quantum numbers l,m,n

Most commonly observed modes are *l* =1

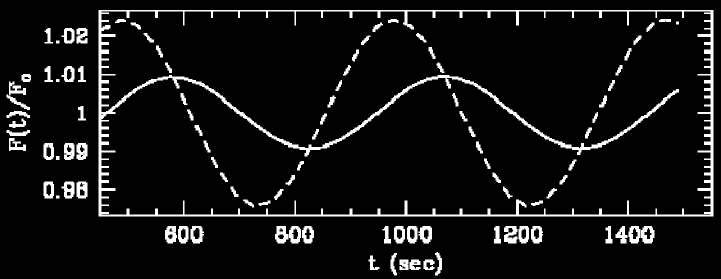
l = 1 modes

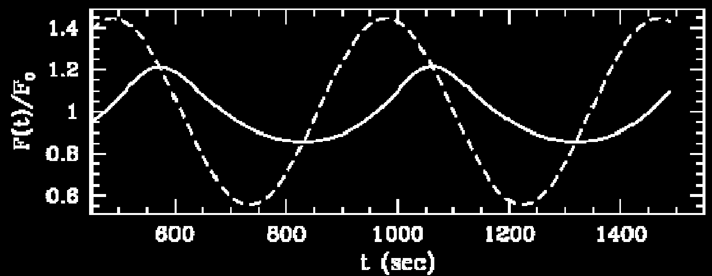
Non-radial Modes

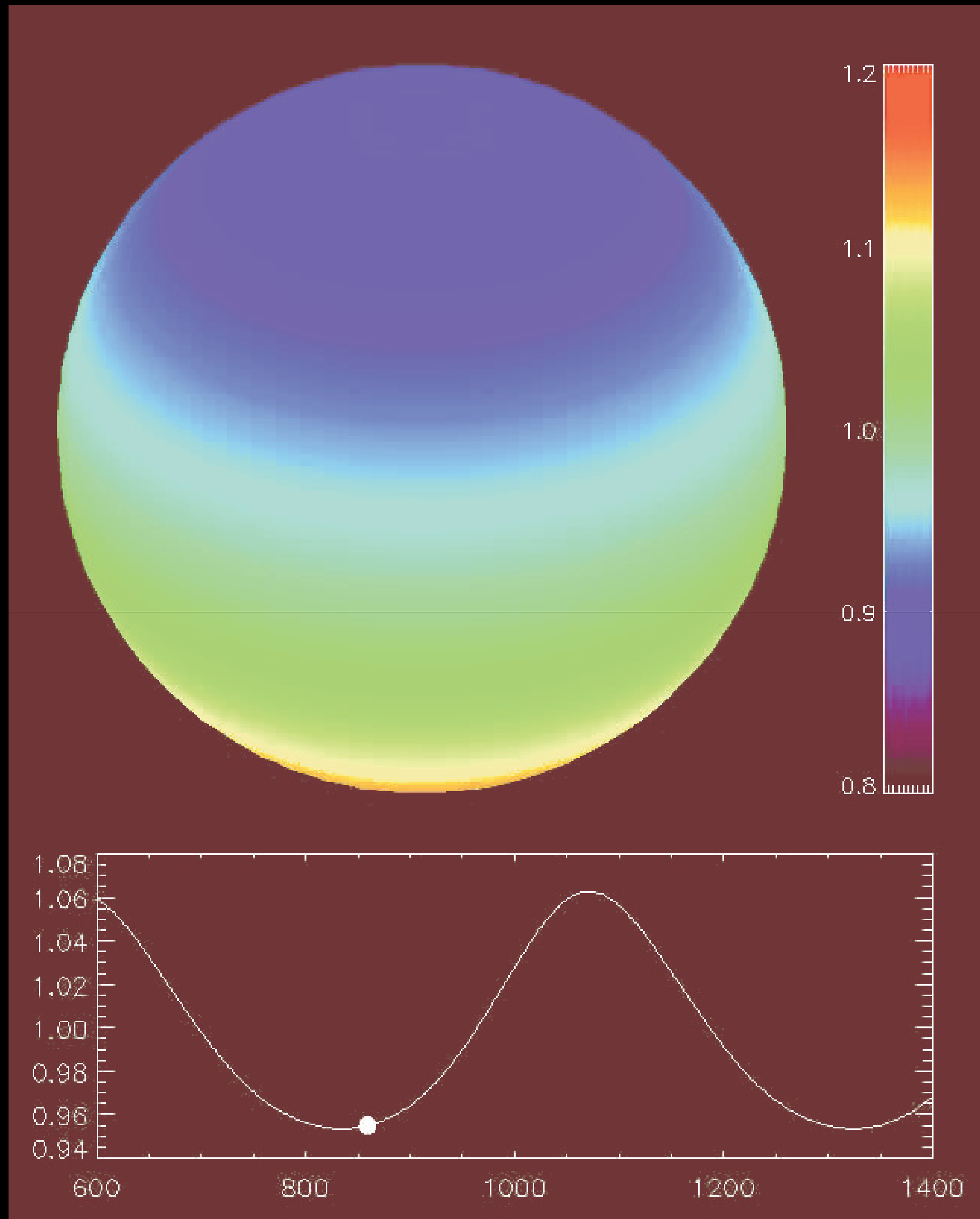
l=1,*m*=0

(standing wave)

$$F_b \propto \mathrm{Re}\{e^{i\omega t} Y_{10}\}$$





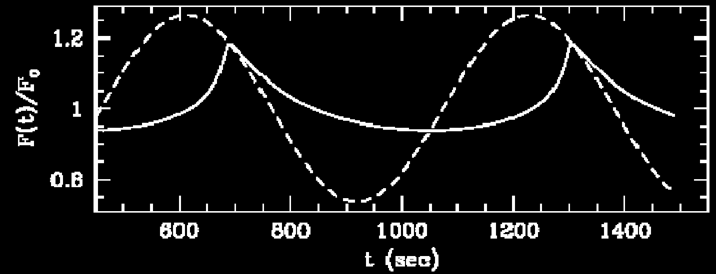


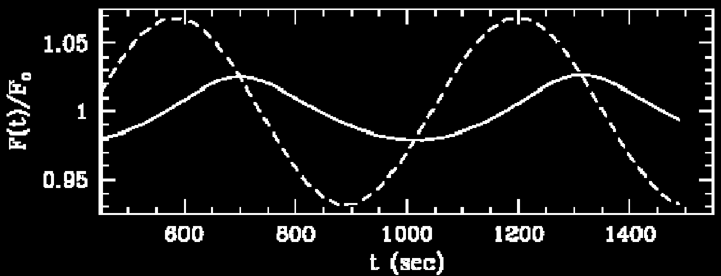
Non-radial Modes

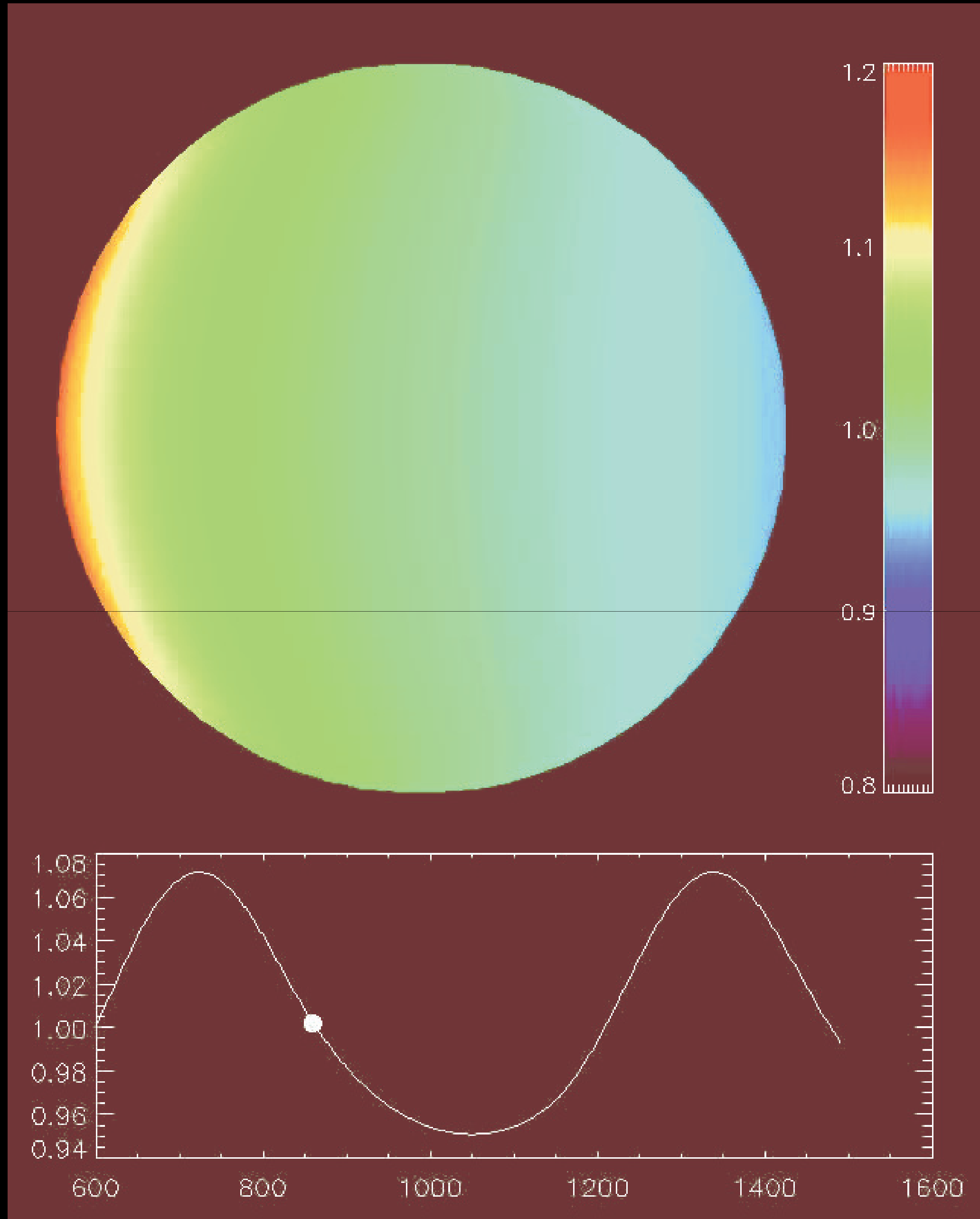
l=1,m=1

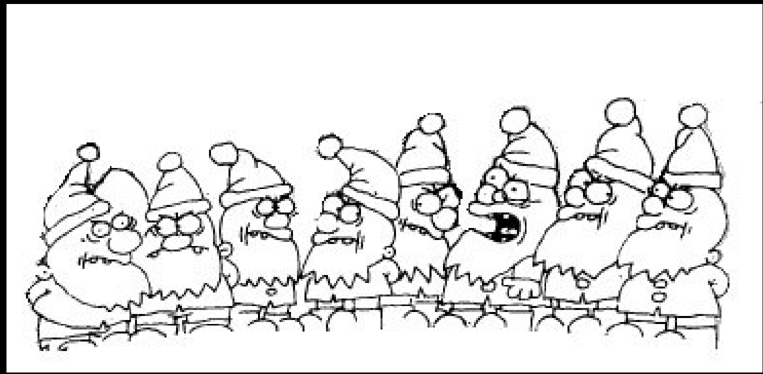
(travelling wave)

$$F_{\rm b} \propto {\rm Re}\{e^{i\omega t}Y_{11}\}$$









WANTED!

DEAD

(Stars)

OR

ALIVE

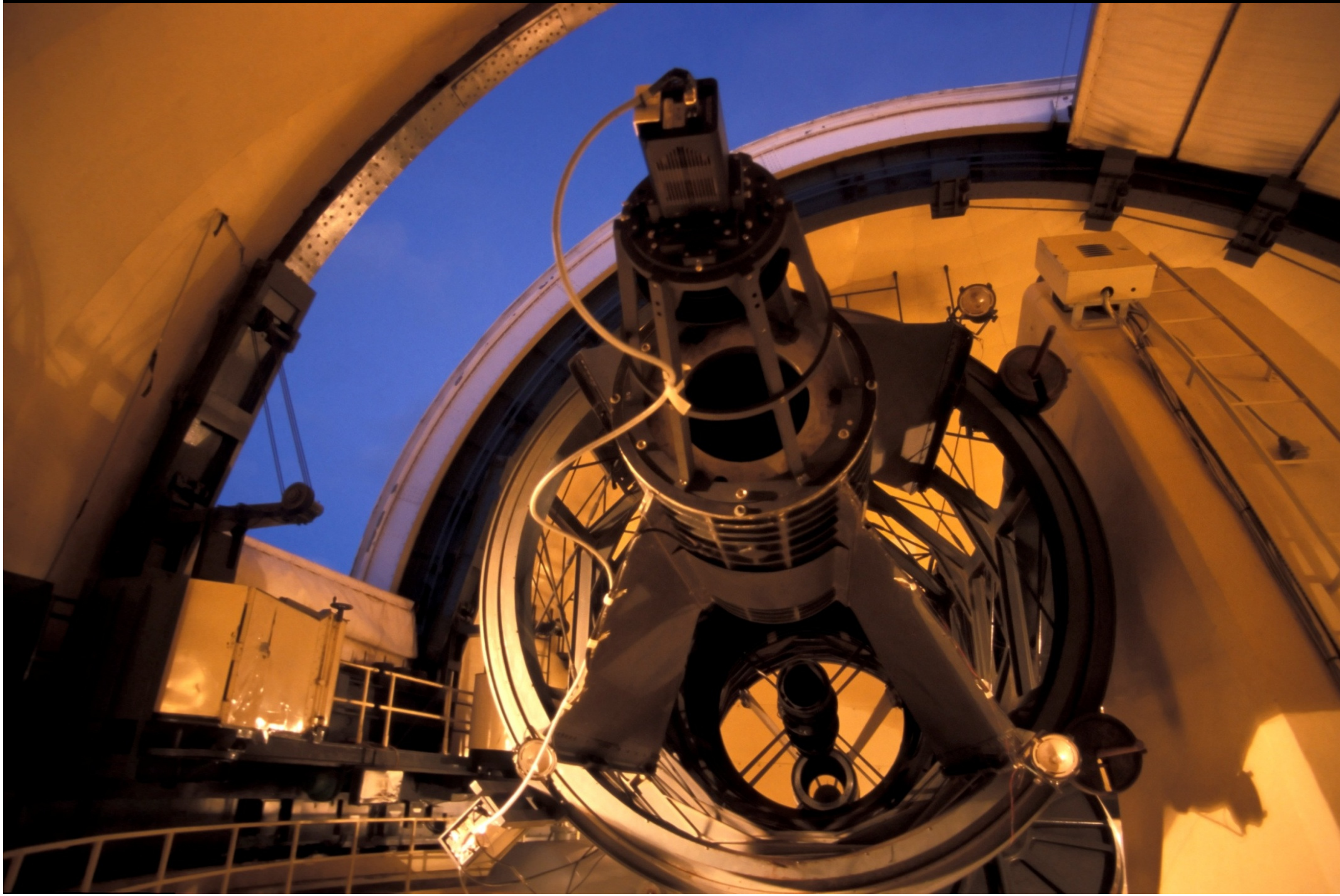
(Planets)

A substantially larger sample

of angry pulsating white dwarf stars,

last seen at APO, headed east to McDonald…

The Competitive Edge …



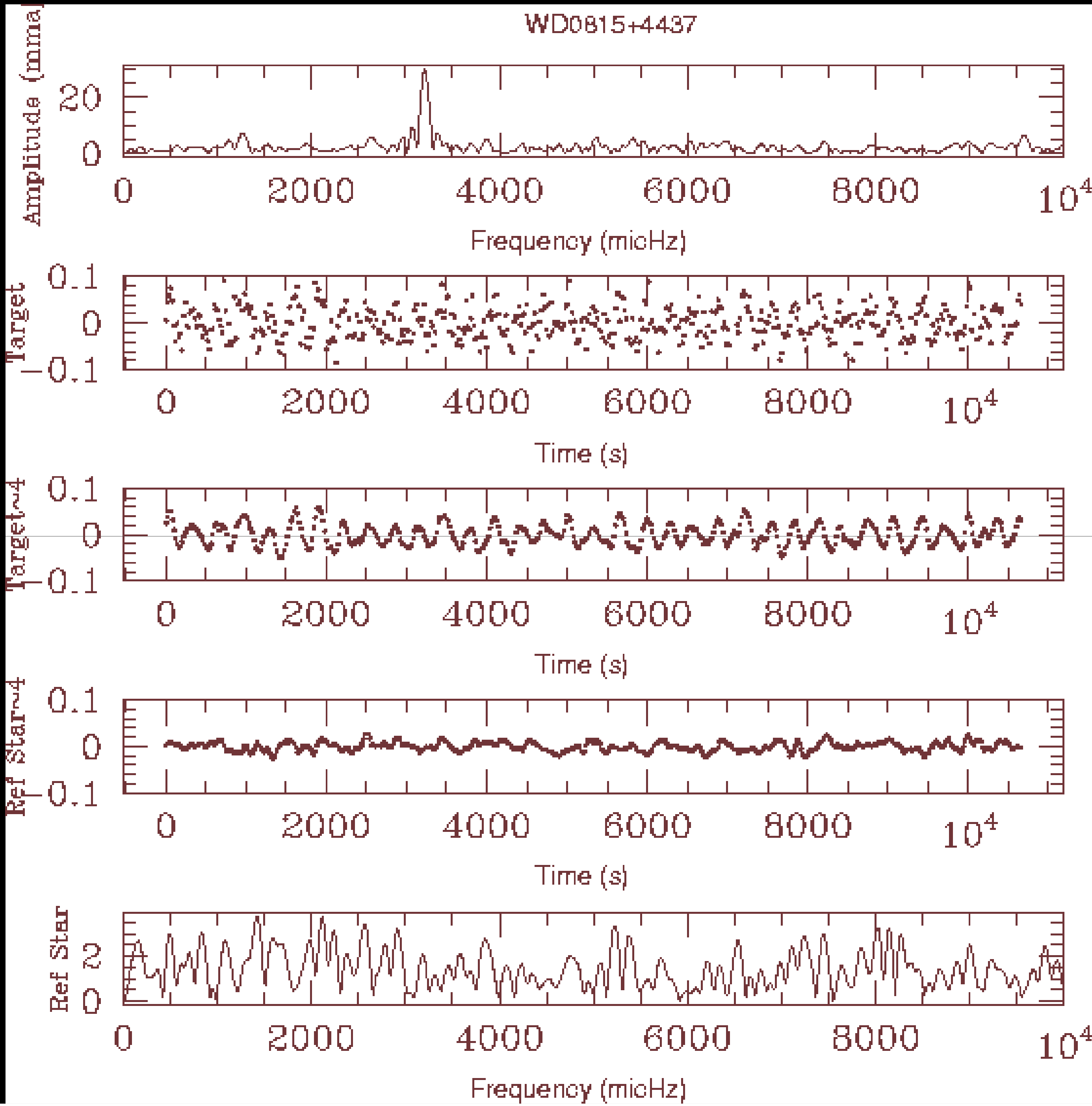
u’=19.6

g’=19.3

Argos:

15 => 150 DAVs

600 more to come …



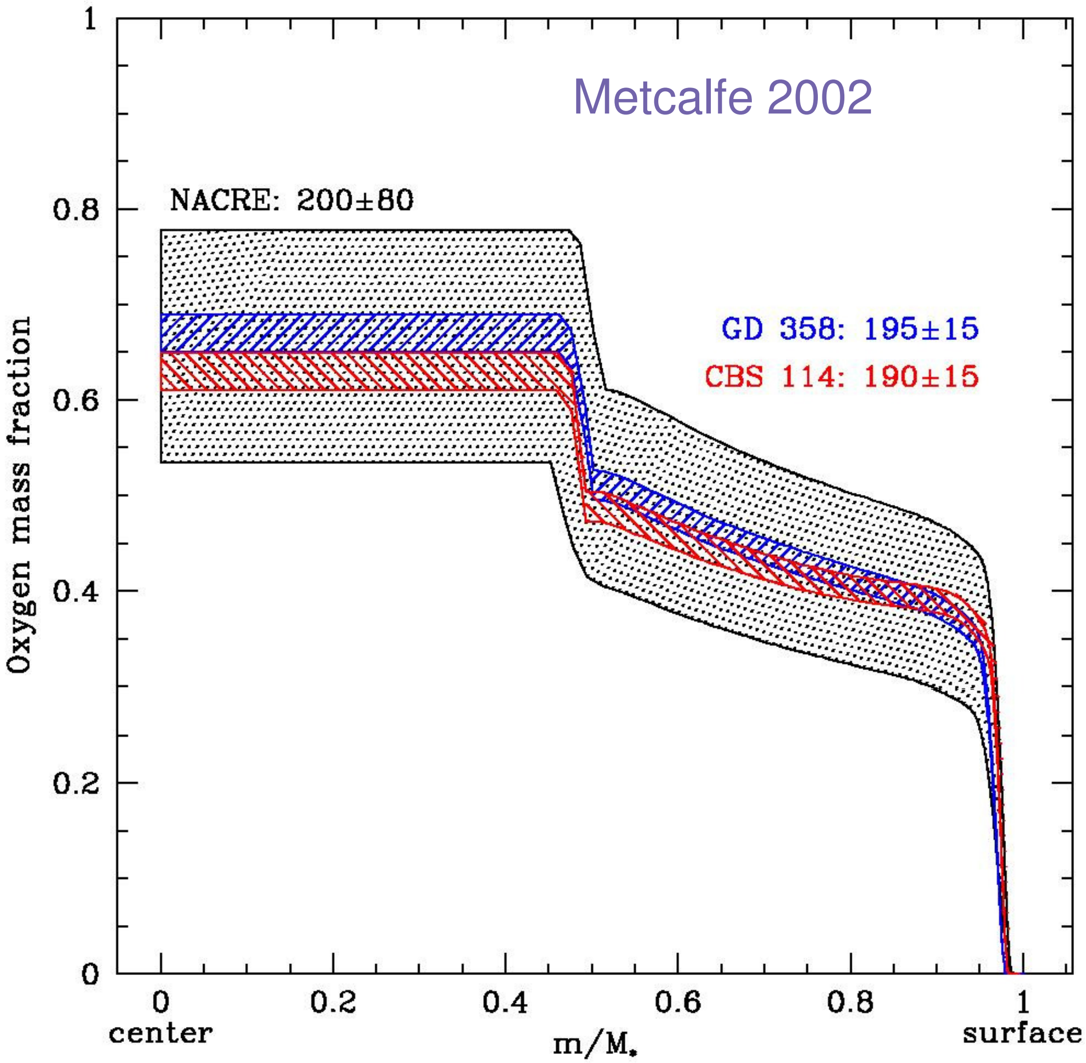
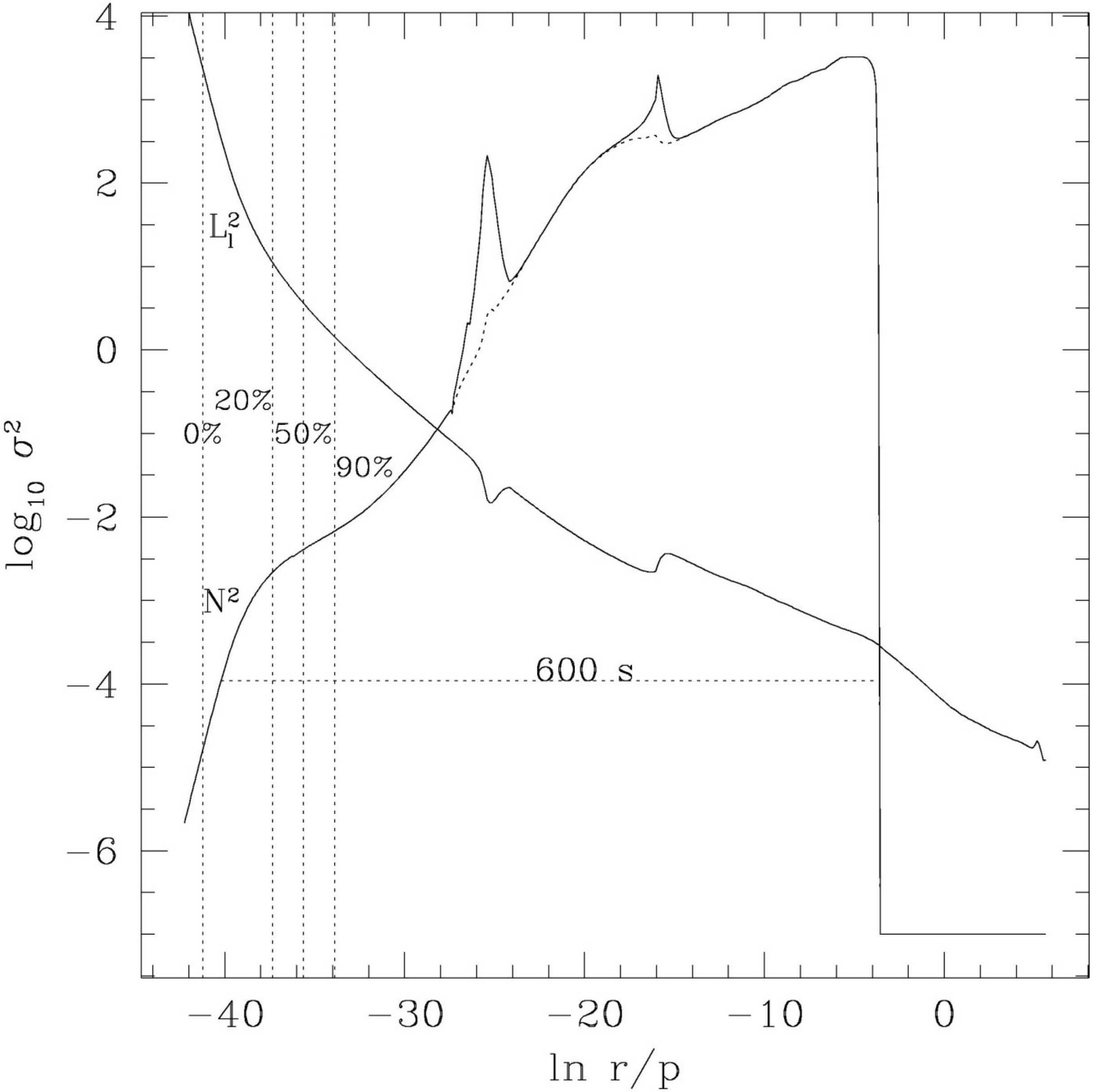
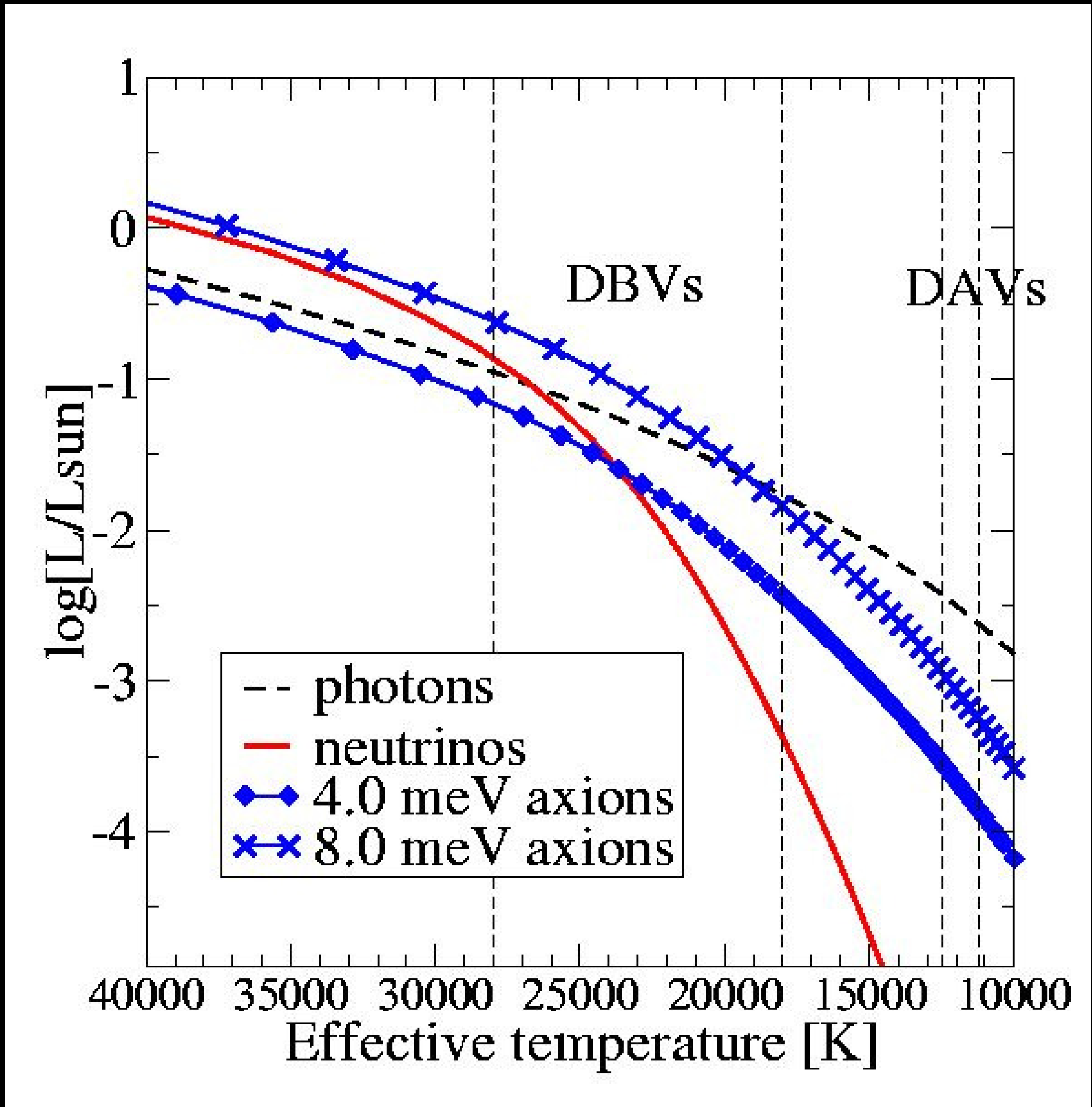


Fig. 2. The $\pm 1\sigma$ range of theoretical internal chemical profiles for a 0.65 $M_{\odot}$ white dwarf model using the NACRE rate for the $^{12}C(\alpha,\gamma)^{16}O$ reaction (Angulo et al., 1999, shaded area), along with profiles scaled to the optimal central oxygen mass fraction derived for GD 358 (upper hashed area) and CBS 114 (lower hashed area) with the corresponding values for the $^{12}C(\alpha,\gamma)^{16}O$ rate.

Asteroseismology of Crystallizing Stars



Sources of energy loss in WDs



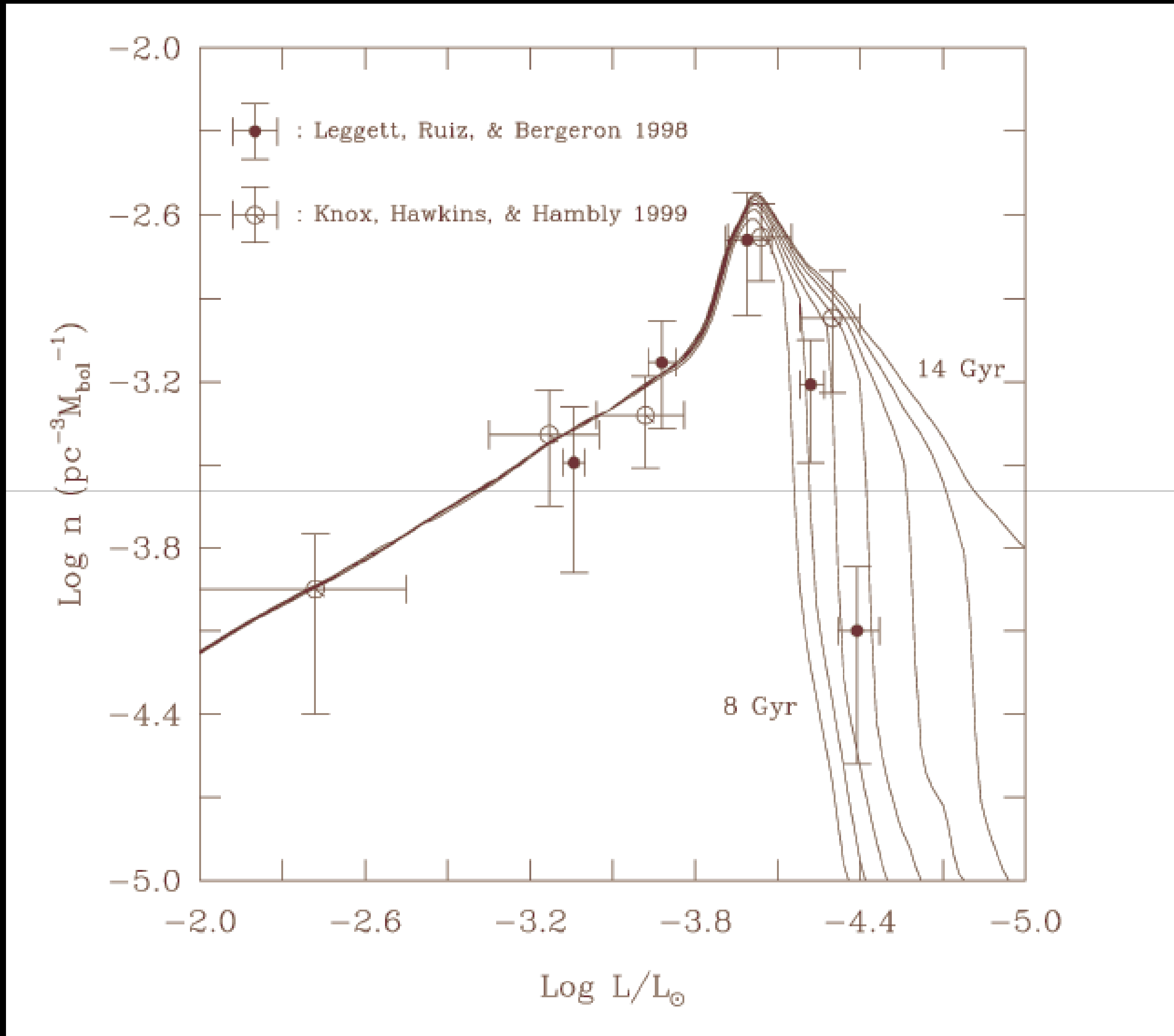
Are Effects of Plasmon Neutrinos or Axions Measurable Using the Techniques of Asteroseismology?

- **Observations: finding the coolest white dwarf stars**
  - **Thin disk**
  - **Open clusters**
  - **Thick disk**
  - **Halo**
  - **Globular clusters**

Calculate the ages of the coolest white dwarf stars: White Dwarf Cosmochronology

- Critical theoretical uncertainties for dating the coolest WDs
  - Outer layers
    - Convection and degeneracy control throttle
  - Deep interiors
    - Neutrino emission in the hot stars
    - Crystallization and phase separation in coolest
- Compare with observed distribution, and repeat the cycle… and also…

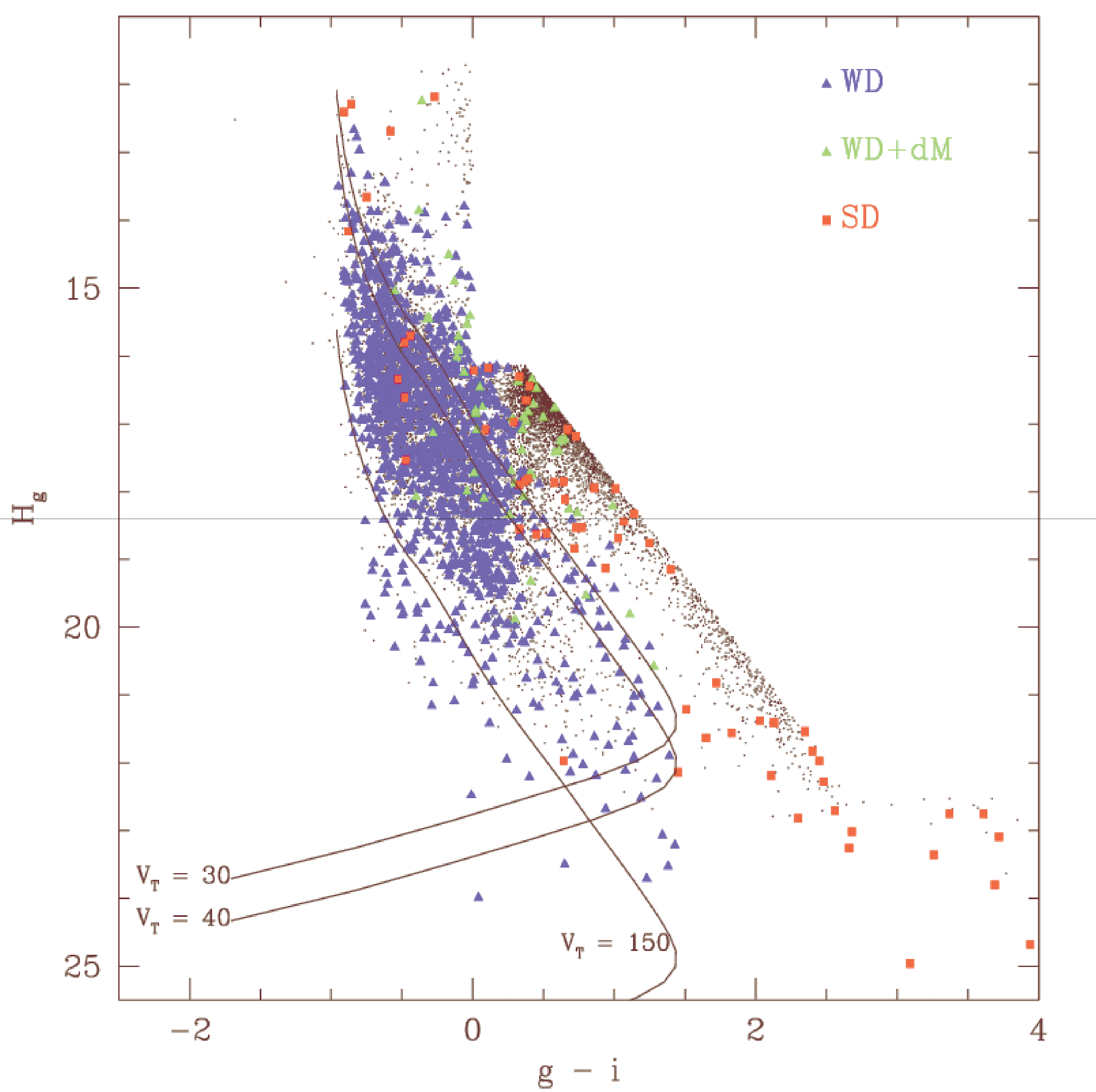
The Disk Luminosity Function

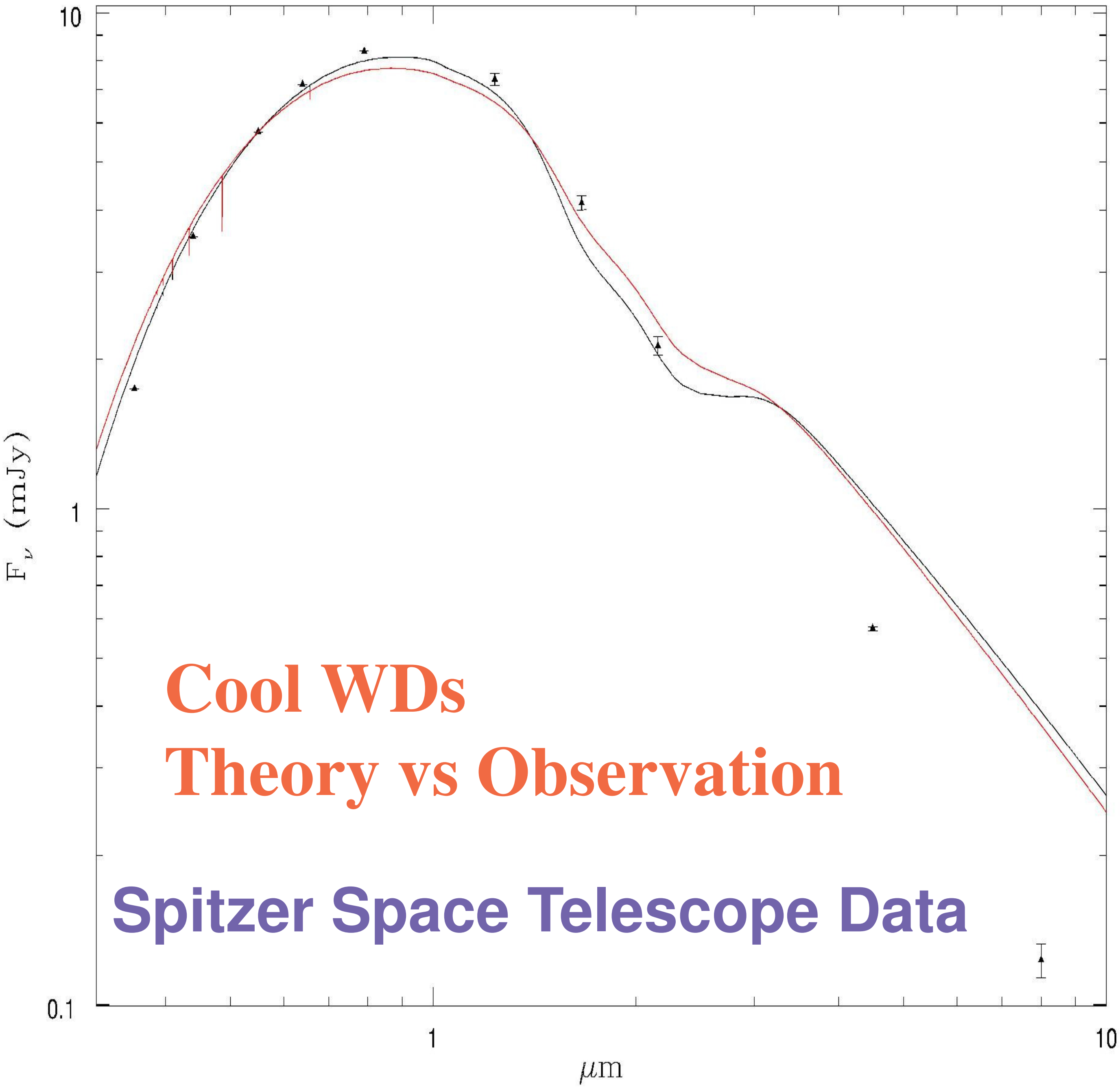


Fontaine, Brassard, & Bergeron (2001)

shows the lower left portion of

Figure to test color blindness




Cool WDs
Theory vs Observation
Spitzer Space Telescope Data
F_ν (mJy)
μm
10
1
0.1
1
10

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

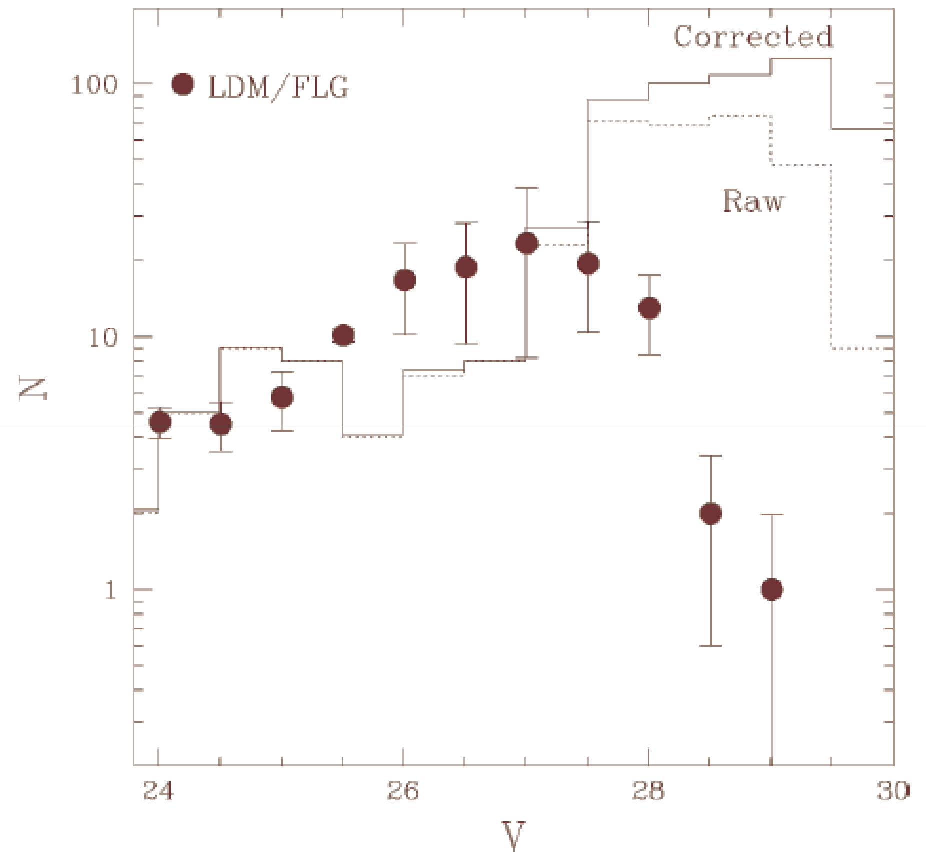


Figure 9 The solid histogram shows the luminosity function for the WDs in M4, corrected for incompleteness. The dashed histogram shows the raw counts. The solid points indicate the disk LF from Leggett, Ruiz & Bergeron (1998), with a V-band distance modulus of $\mu_V = 12.51$ for M4 applied. The vertical 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)

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White Dwarf Stars in Clusters

- Explore white dwarf cooling ages as compared to main sequence isochrone ages
- Open clusters help in establishing constraints on disk age
- Older open clusters sample critical physics of white dwarf cooling

White Dwarf Stars in Clusters

- Explore white dwarf cooling ages as compared to main sequence isochrone ages
- Open clusters help in establishing constraints on disk age
- Older open clusters sample critical physics of white dwarf cooling
- Globular Clusters: Finally, we can isolate masses and explore the physics!

Comparing Theoretical models: new(er) opacities, interior EOS and atmospheric boundary conditions

Hansen & Liebert (2003)

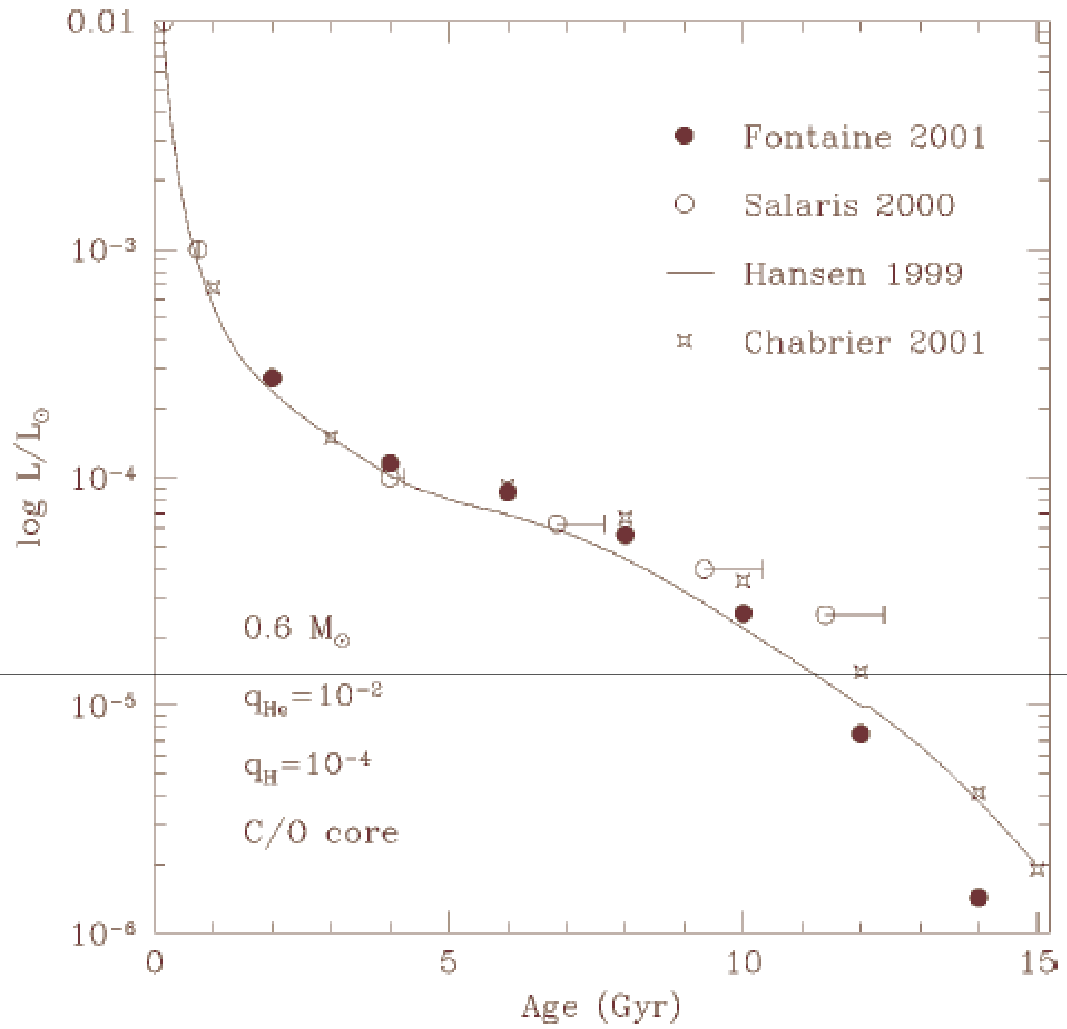
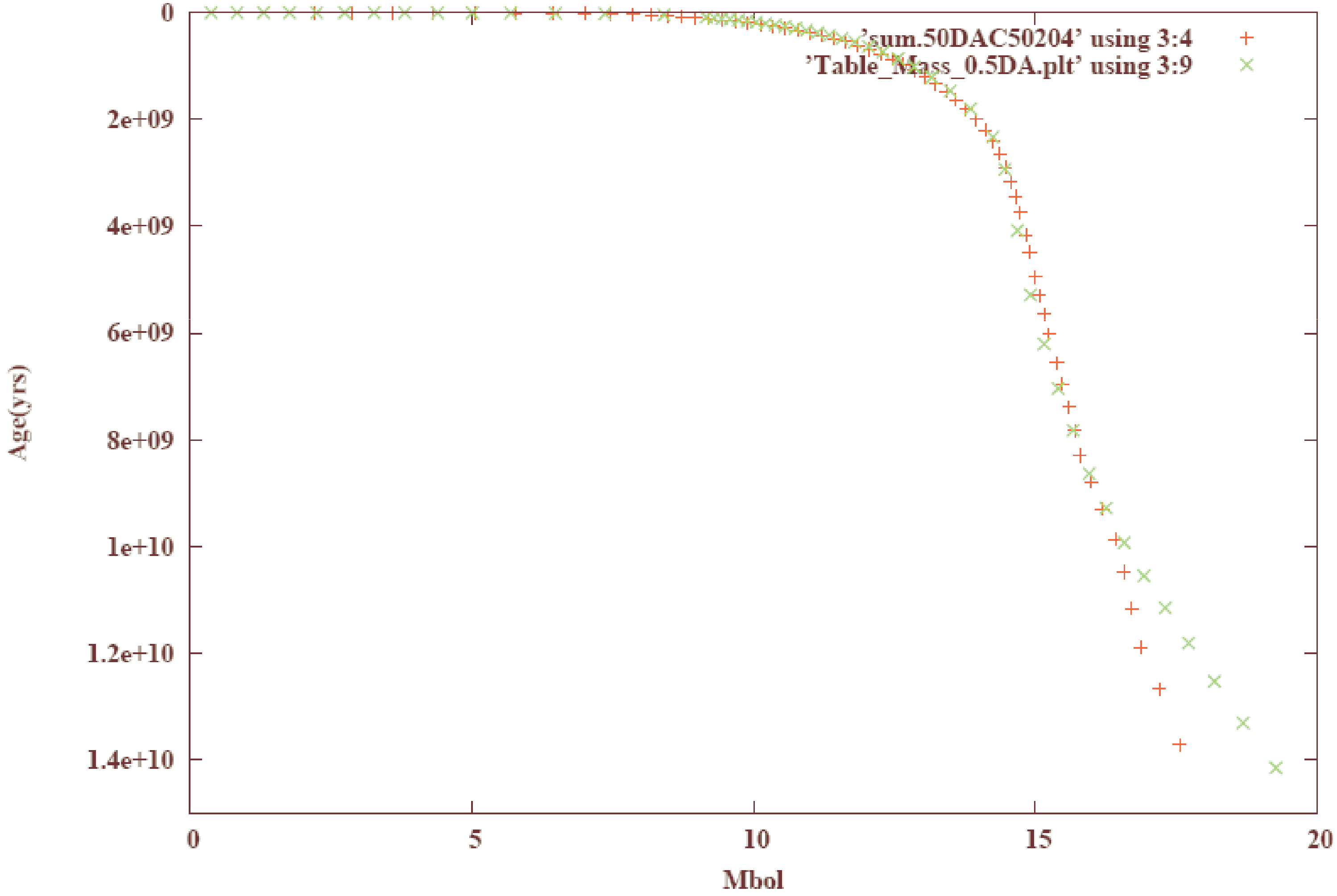
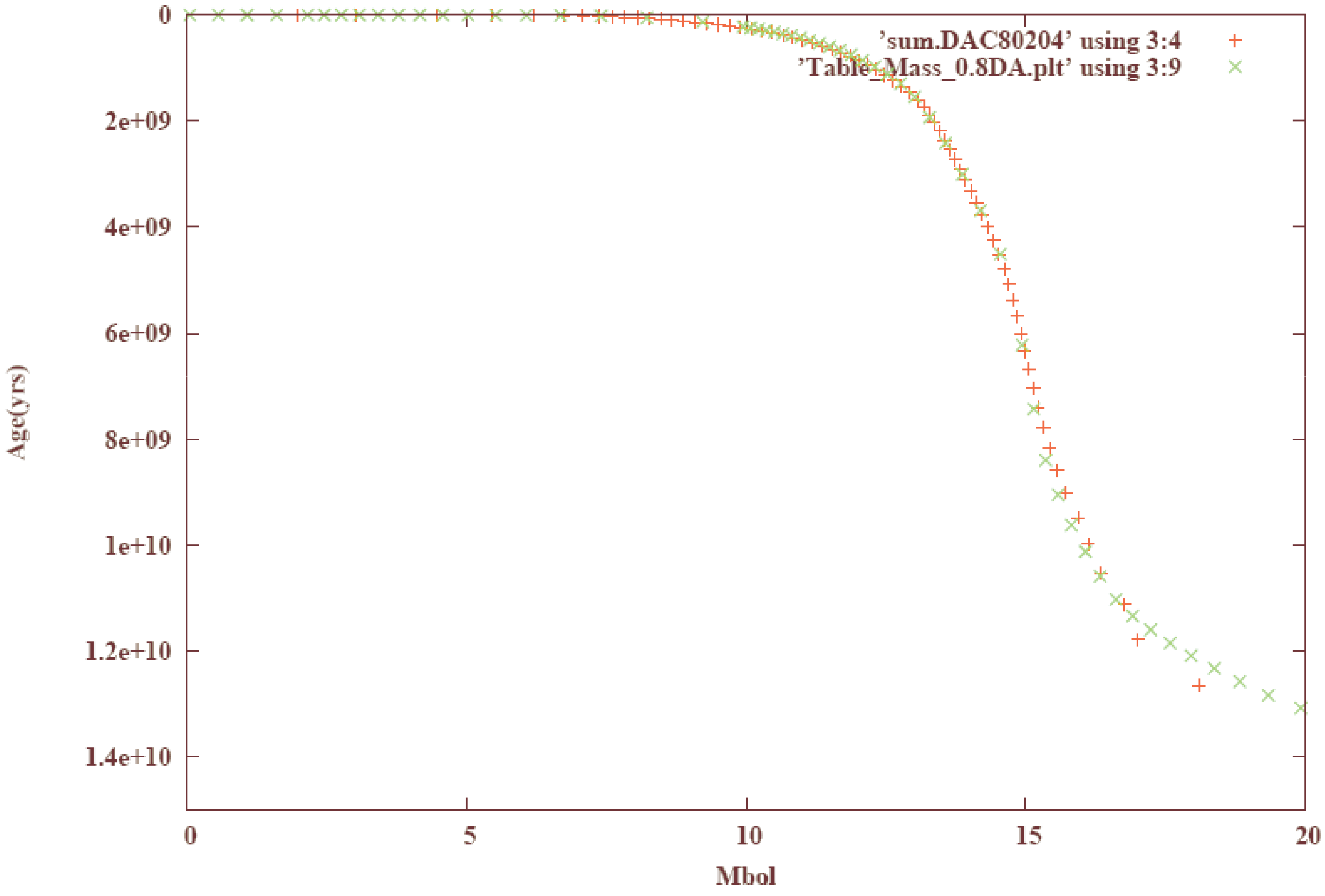


Figure 18 The solid curve shows the cooling of a 0.6 $M_\odot$ model from Hansen (1999). The open points are from Salaris et al. (2000), for a 0.61 $M_\odot$, fully consistent model. The filled points are from Fontaine et al. (2001). The open stars points are from Chabrier et al. (2001), which, while still not a fully self-consistent code, at least uses $L - T_c$ relations based on nongray atmosphere models, and so should be more accurate than previous calculations in this vein. The extensions of the Salaris points indicate the extra delay in the cooling if they take into account the release of separation energy upon crystallization.

Fontaine 2001 models and Winget et al. 2008 models 0.5 Msun



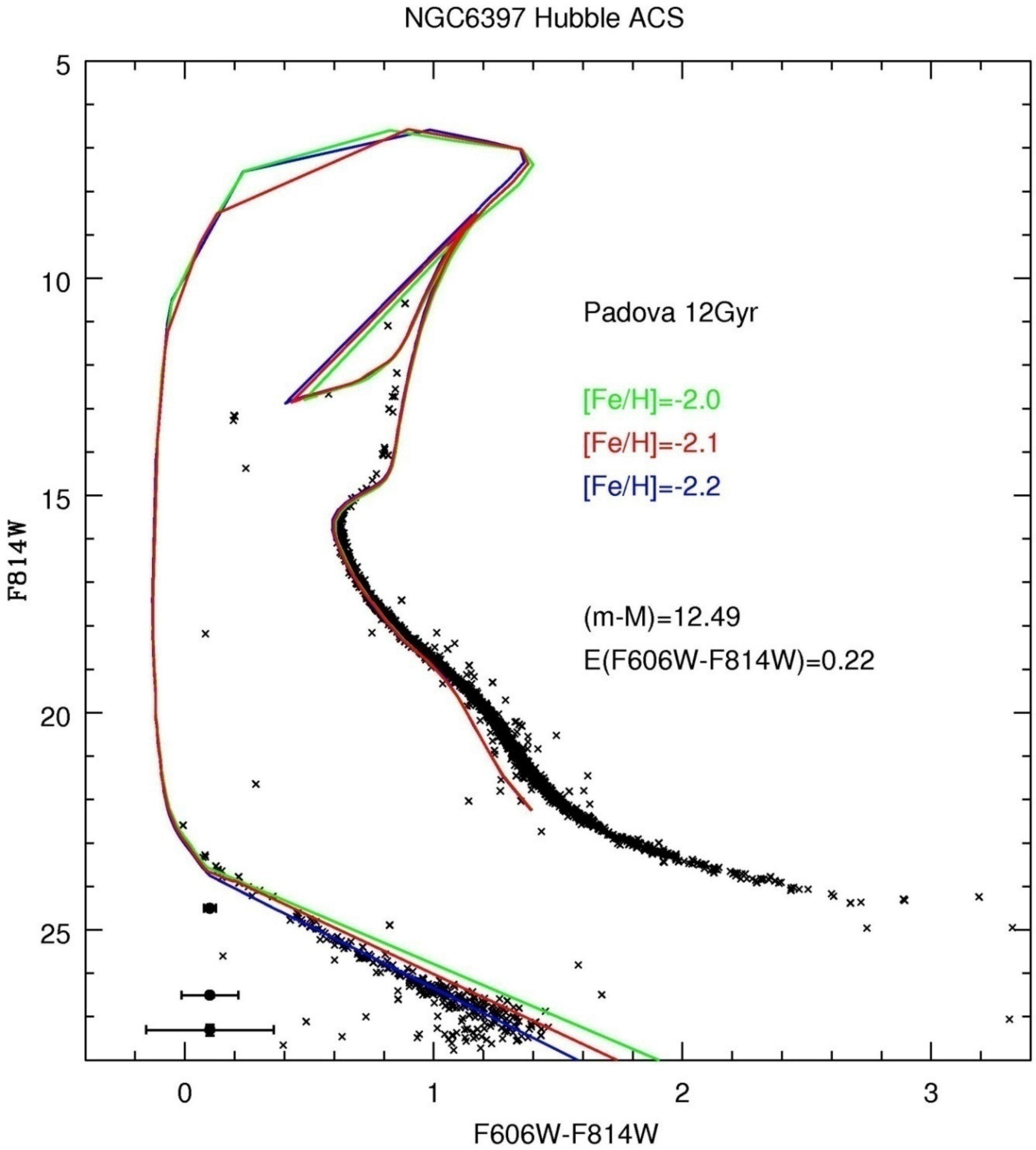
Fontaine 2001 models and Winget et al. 2008 models
0.8 Msun



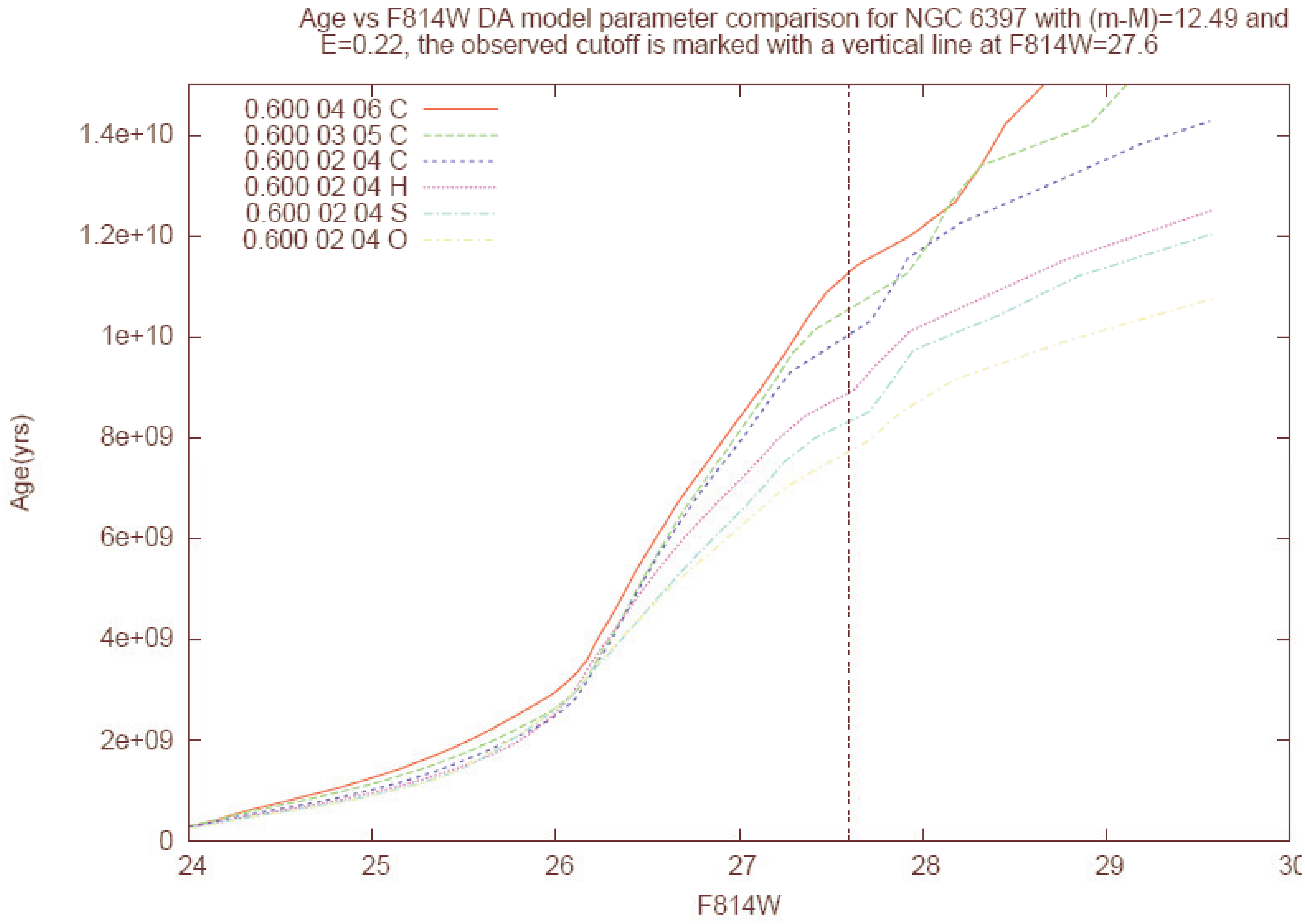
Conclusions from model comparisons

- Mass – radius is consistent for all groups
  - **EoS improvements** (Chabrier et al. 2000 over Lamb & Van Horn 1975 for interiors and Saumon Chabrier & Van Horn 1993 over Fontaine , Graboske & Van Horn 1977 for the envelope) do not produce (presently) observable differences in the models.
  - Improved **atmospheric surface boundary** condition is not as important as has been claimed in the literature … it produces no observable differences until bolometric luminosities below the largest magnitude globular cluster stars

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

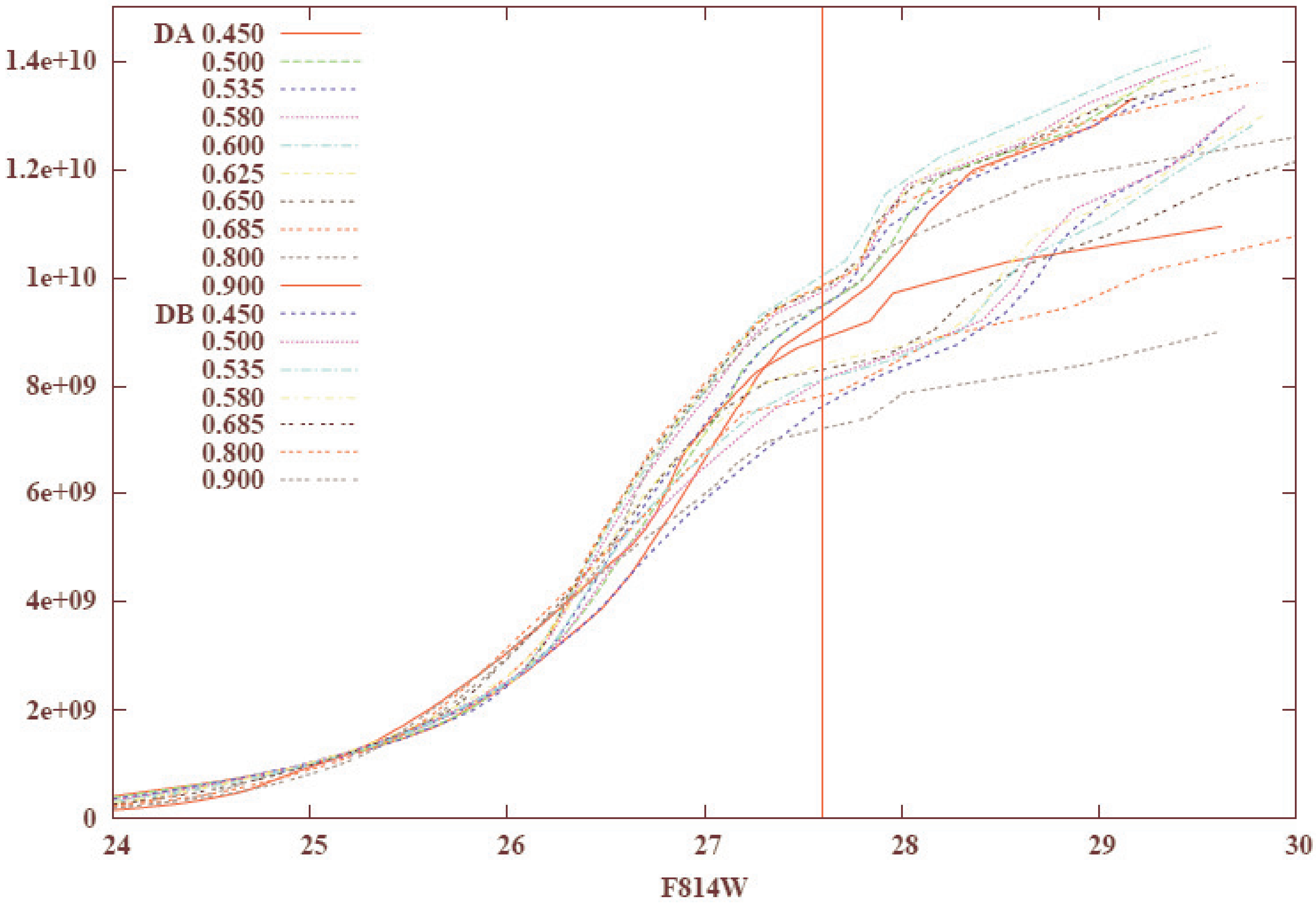


Data: proper motion screened sample from **Richer et al. 2008, AJ, 135,2131**



Age vs F814W DA model parameter comparison for NGC 6397 with (m-M)=12.49 and E=0.22, the observed cutoff is marked with a vertical line at F814W=27.6
0.600 04 06 C
0.600 03 05 C
0.600 02 04 C
0.600 02 04 H
0.600 02 04 S
0.600 02 04 O
1.4e+10
1.2e+10
1e+10
8e+09
6e+09
4e+09
2e+09
0
Age(yrs)
24
25
26
27
28
29
F814W

DA DB c-core model age as a function of F814W magnitude for a range of masses for NGC 6397 with (m-M)=12.49 and E=0.22, the observed white dwarf cutoff at 27.6 is indicated by a vertical line.



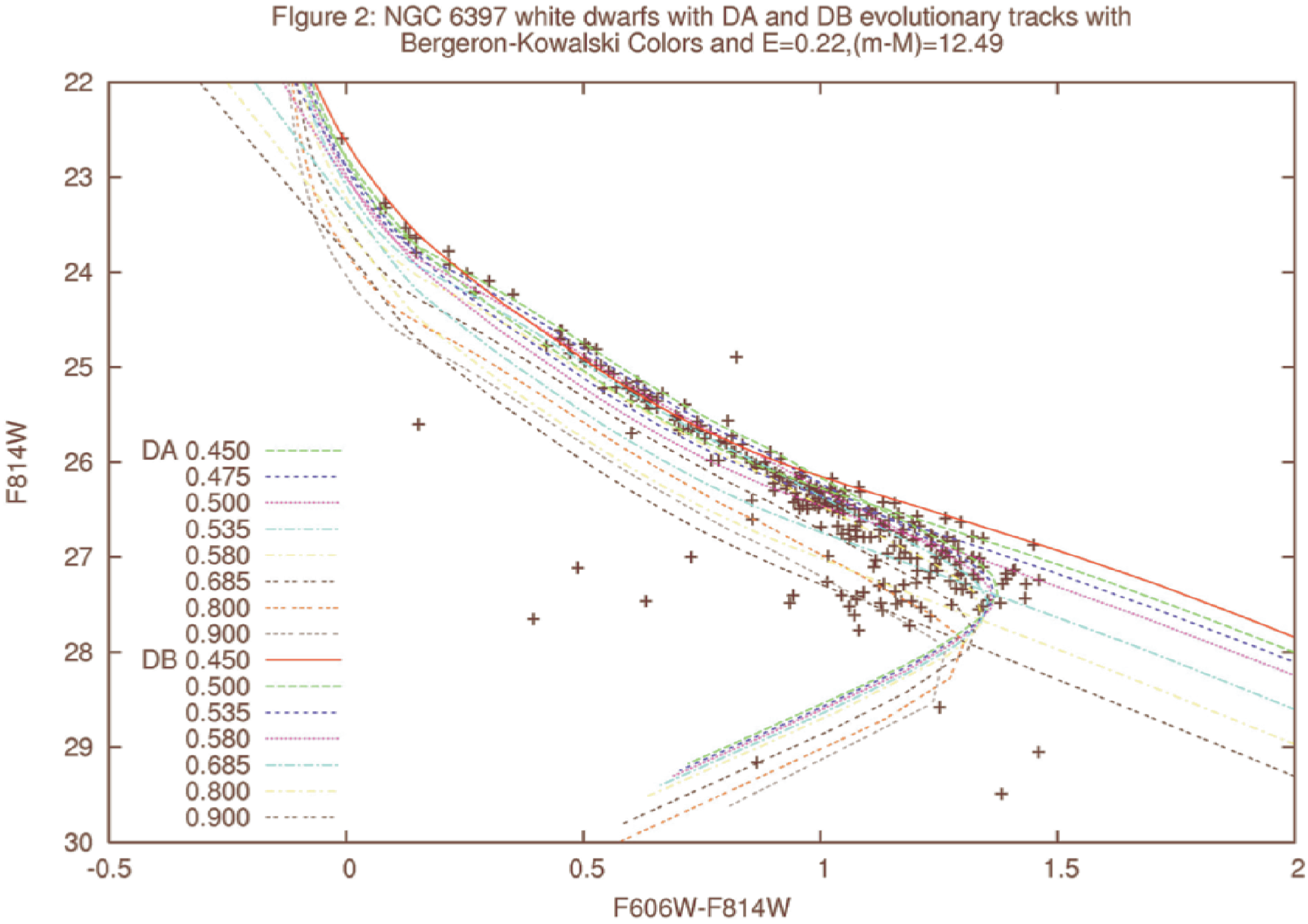
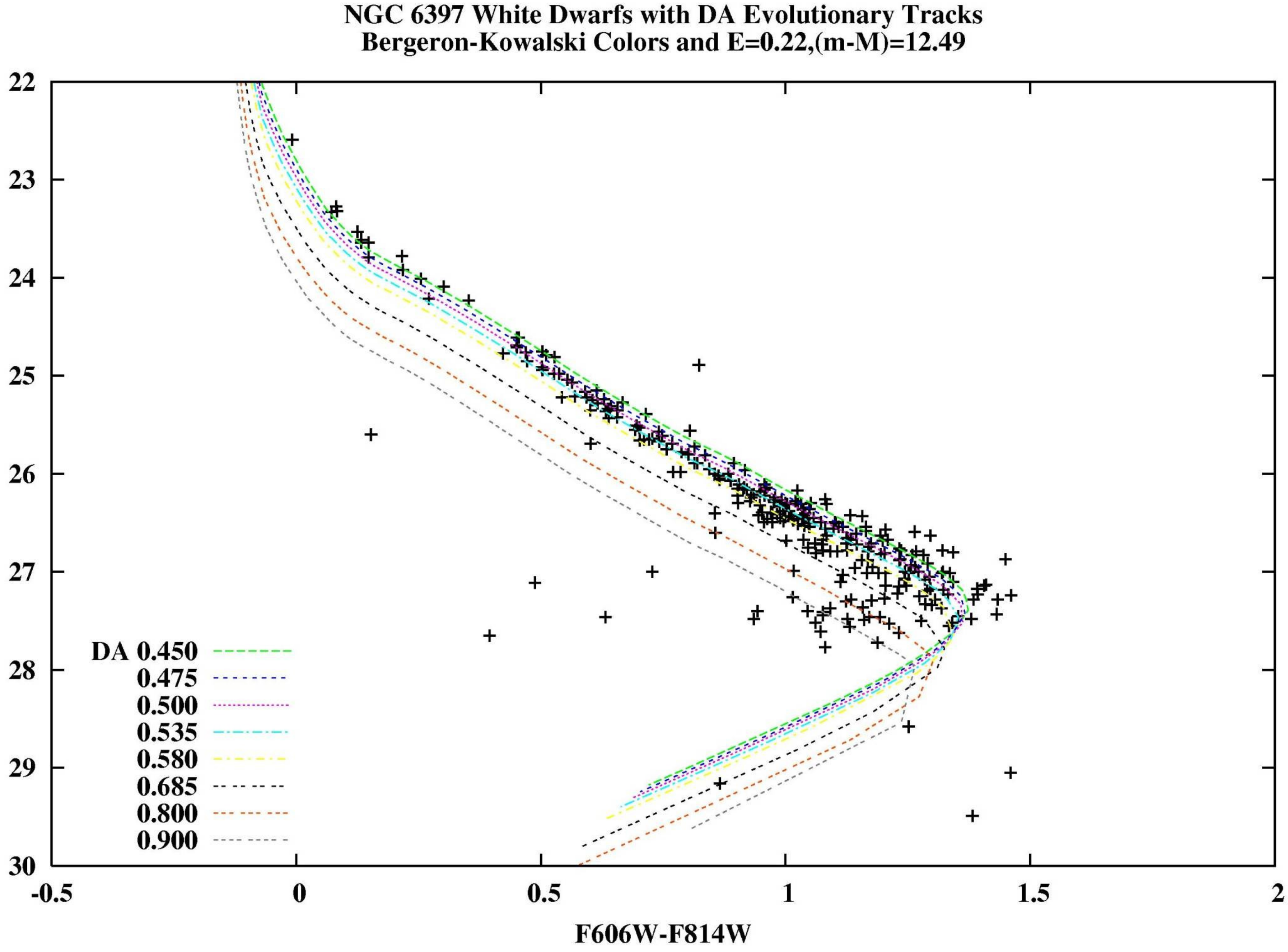
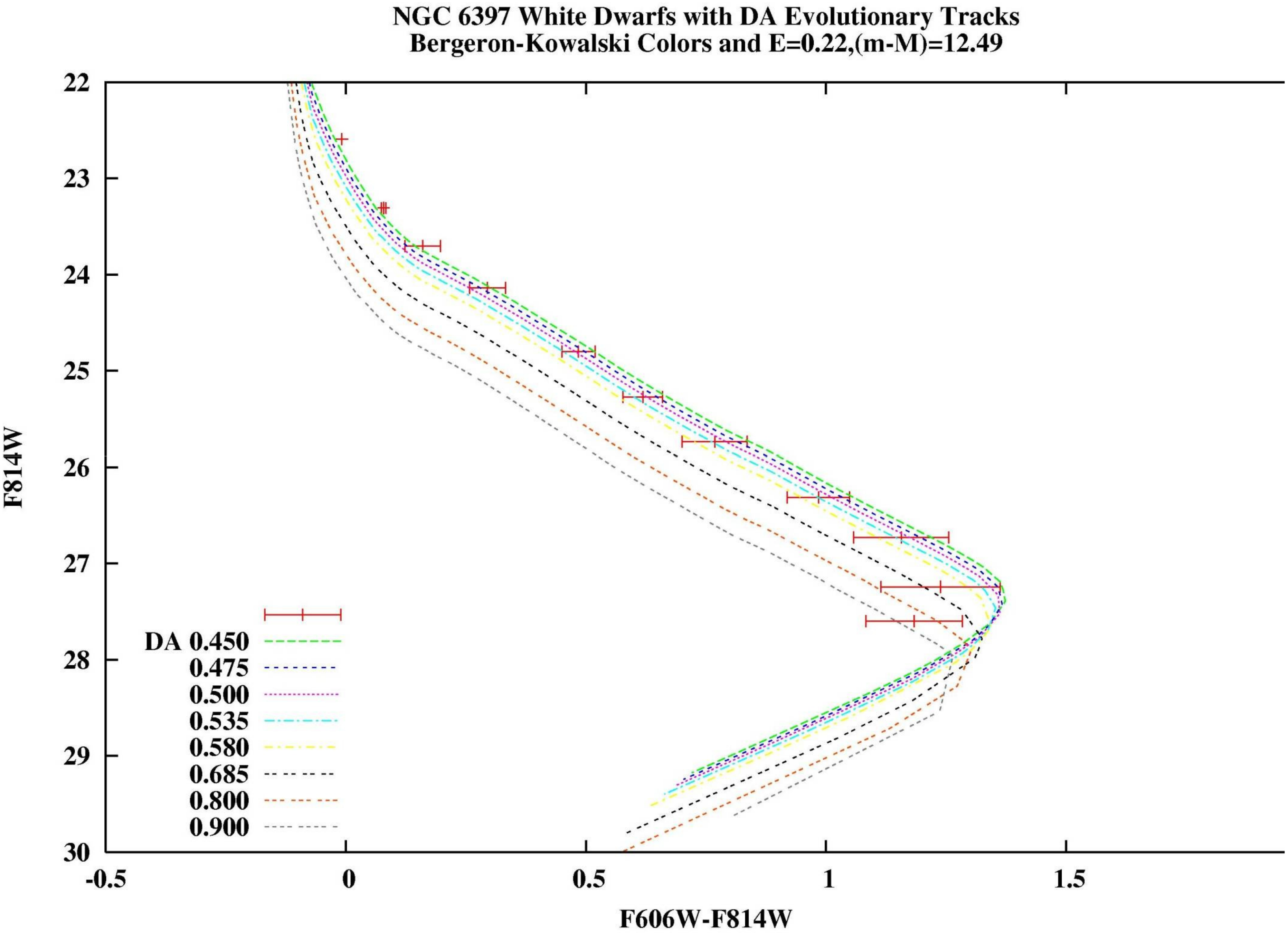
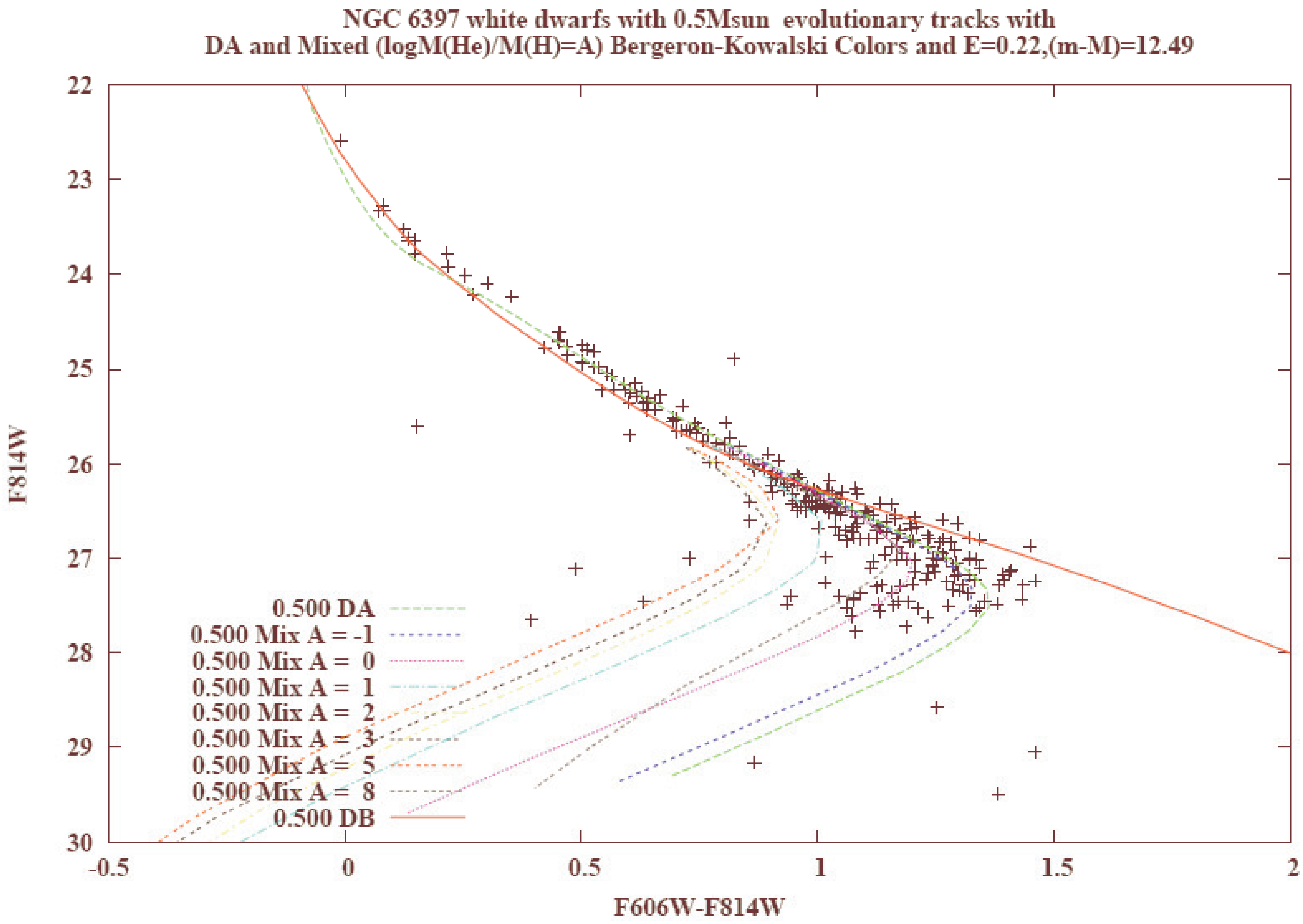


Figure 2: NGC 6397 white dwarfs with DA and DB evolutionary tracks with
Bergeron-Kowalski Colors and E=0.22,(m-M)=12.49
F814W
F606W-F814W
22
23
24
25
26
27
28
29
30
-0.5
0
0.5
1
1.5
2
DA 0.450
0.475
0.500
0.535
0.580
0.685
0.800
0.900
DB 0.450
0.500
0.535
0.580
0.685
0.800
0.900

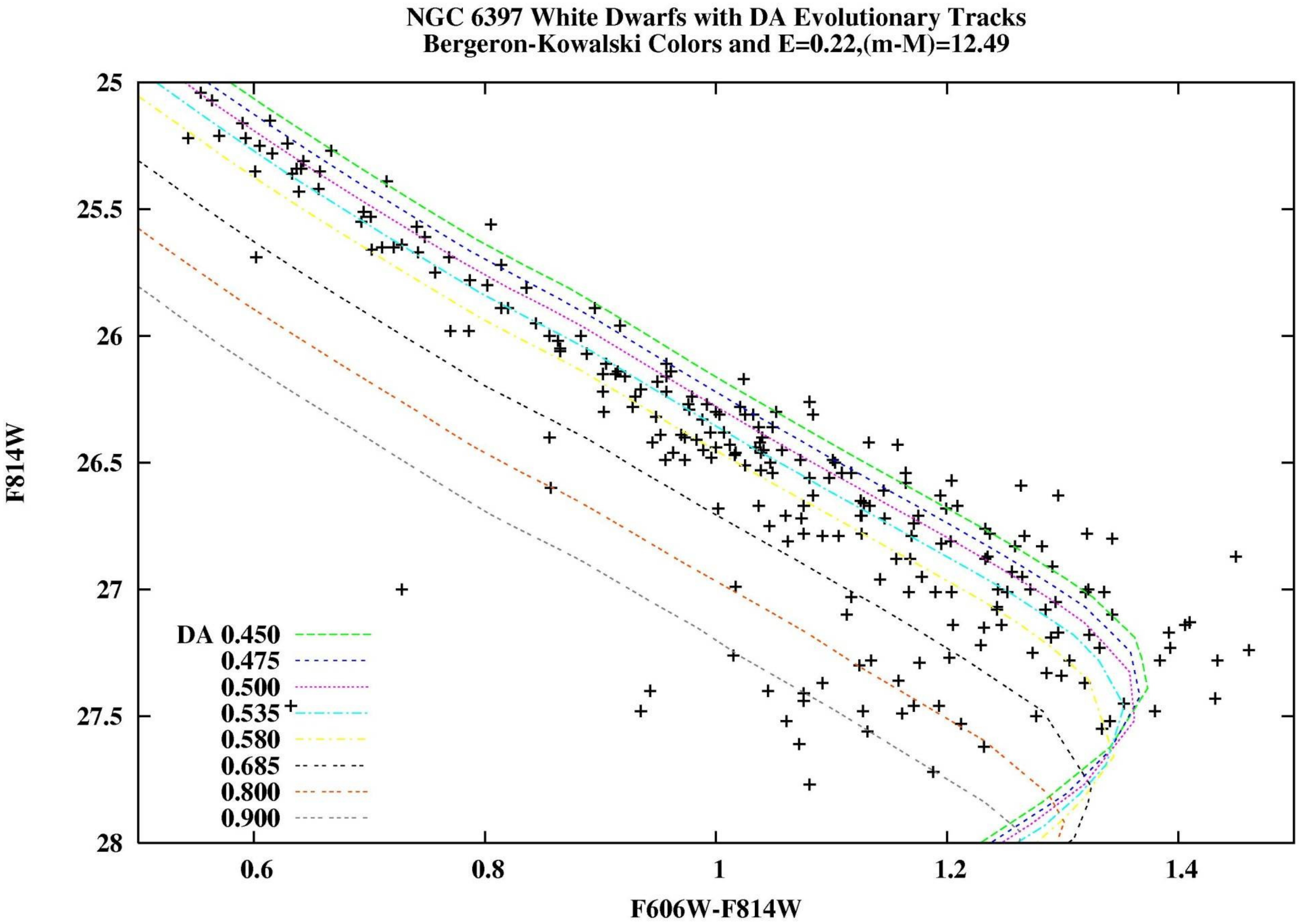


NGC 6397 White Dwarfs with DA Evolutionary Tracks
Bergeron-Kowalski Colors and E=0.22,(m-M)=12.49
22
23
24
25
26
27
28
29
30
-0.5
0
0.5
1
1.5
2
F606W-F814W
DA 0.450
0.475
0.500
0.535
0.580
0.685
0.800
0.900

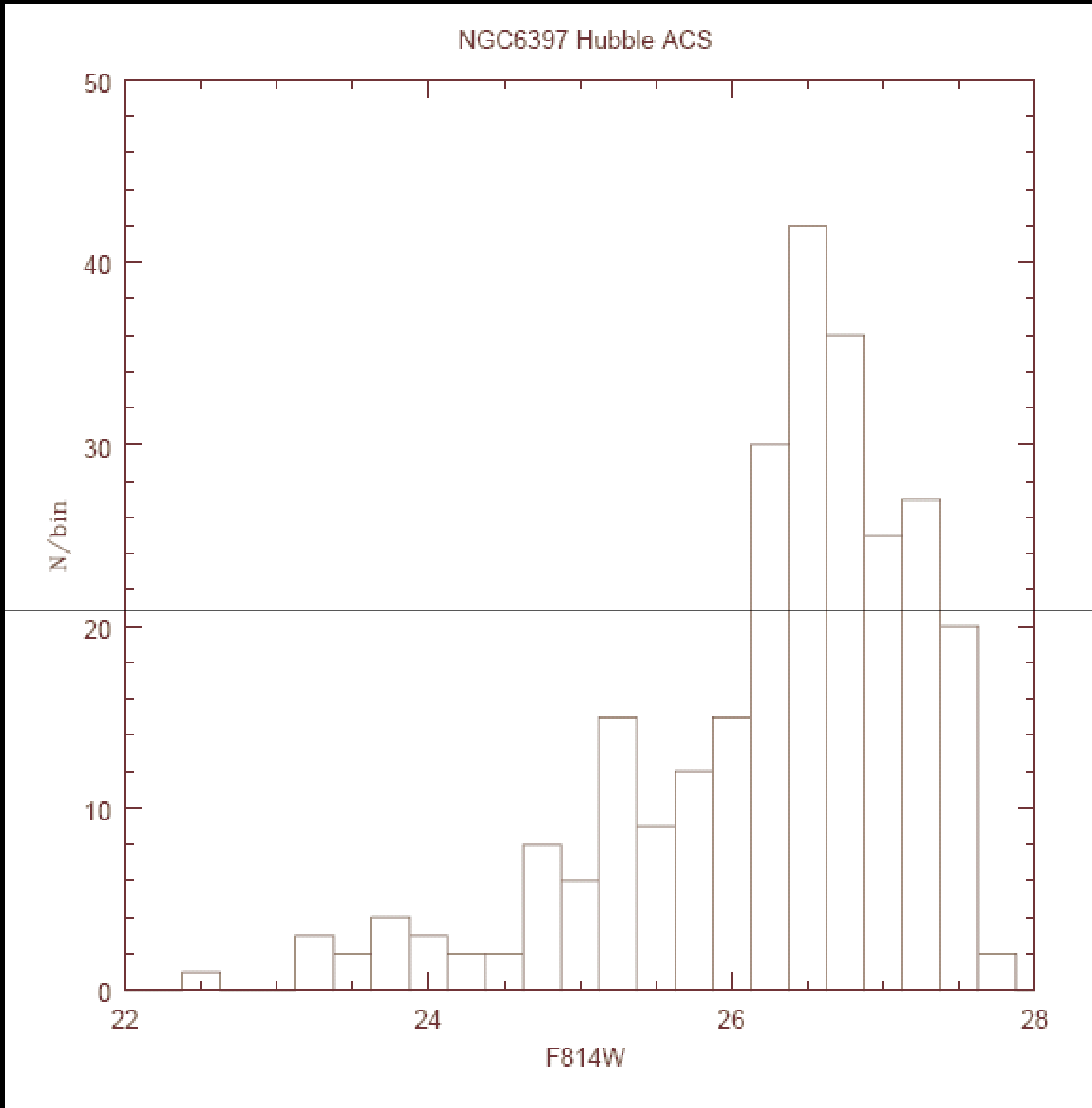

NGC 6397 White Dwarfs with DA Evolutionary Tracks
Bergeron-Kowalski Colors and E=0.22,(m-M)=12.49
F814W
F606W-F814W
22
23
24
25
26
27
28
29
30
-0.5
0
0.5
1
1.5
DA 0.450
0.475
0.500
0.535
0.580
0.685
0.800
0.900



NGC 6397 white dwarfs with 0.5Msun evolutionary tracks with
DA and Mixed (logM(He)/M(H)=A) Bergeron-Kowalski Colors and E=0.22,(m-M)=12.49
F814W
F606W-F814W
22
23
24
25
26
27
28
29
30
-0.5
0
0.5
1
1.5
2
0.500 DA
0.500 Mix A = -1
0.500 Mix A = 0
0.500 Mix A = 1
0.500 Mix A = 2
0.500 Mix A = 3
0.500 Mix A = 5
0.500 Mix A = 8
0.500 DB



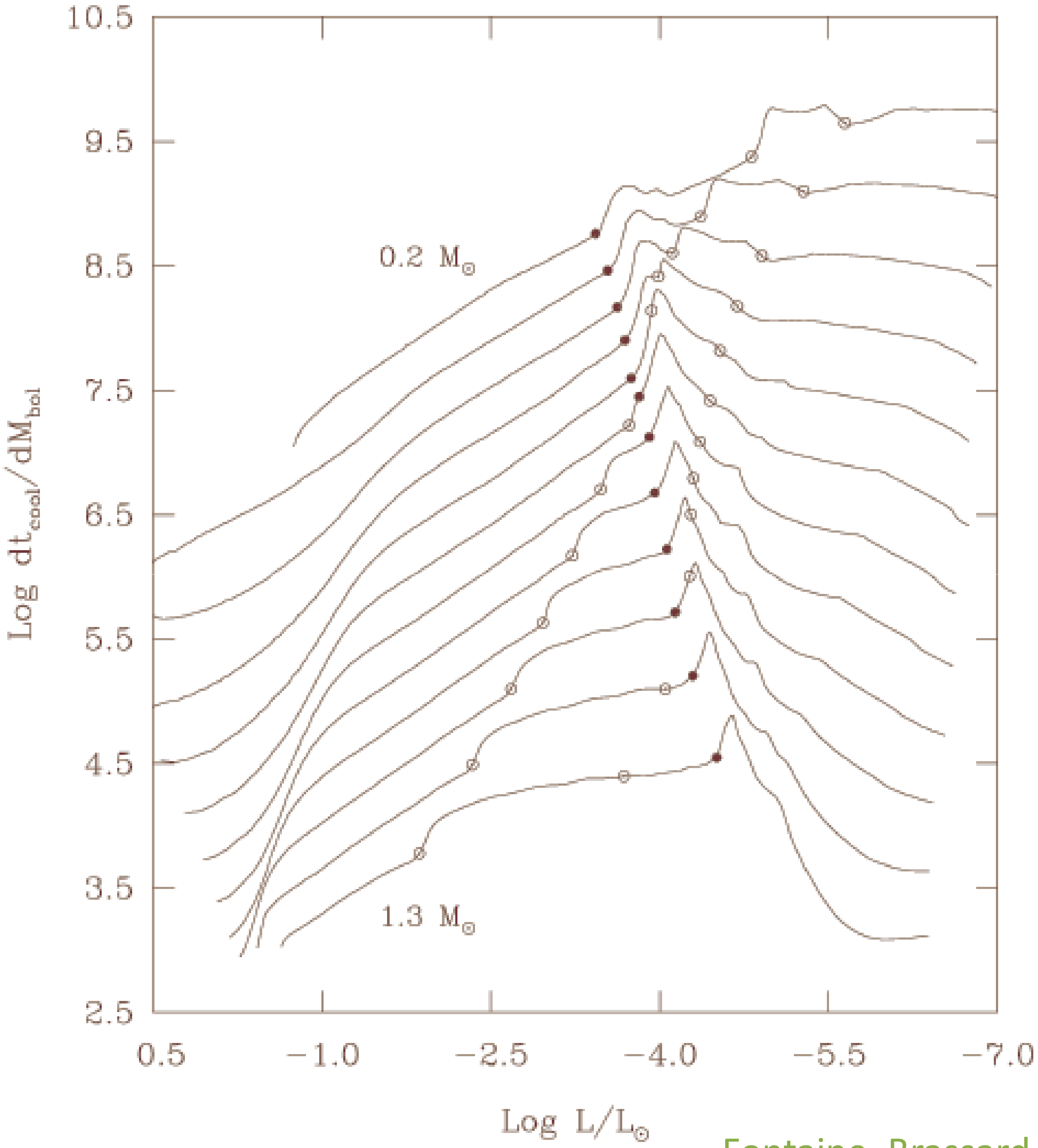
This diagram (and previous ones) determines
the low-mass limit for WDs at the “clump”= 0.5 Msun



Luminosity Function for NGC 6397 proper motion screened WD sample

What **physics** might be relevant near the peak of theLuminosity Function (the “clump” in the CMD)?

- **Convective Coupling**: The surface convection zone reaches the degeneracy boundary, reducing the insulation of the envelope
- **Crystallization**: Ions crystallize with attendant latent heat and phase separation expected from theory



Fontaine, Brassard & Bergeron (2001)

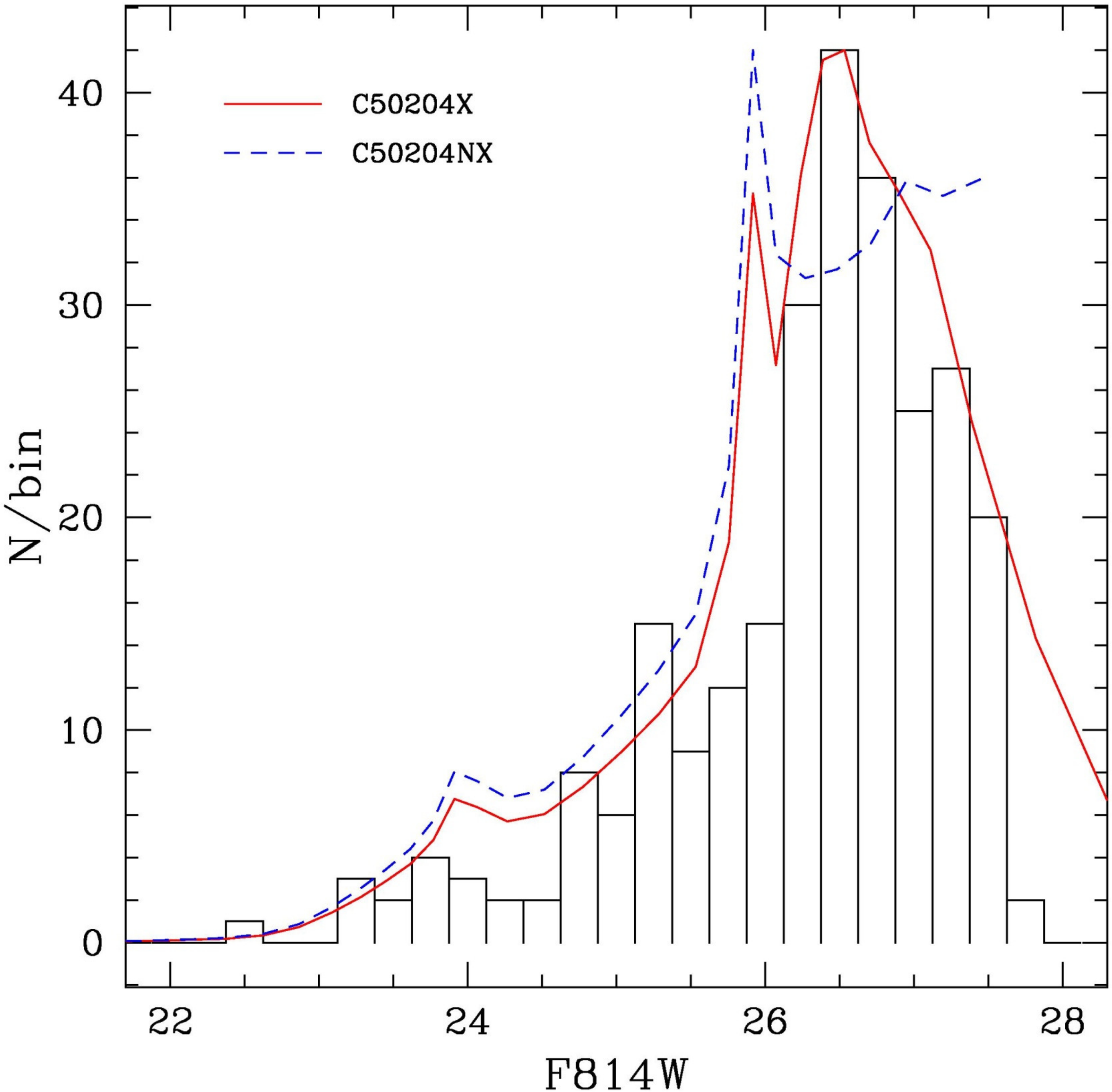
Ratio of Coulomb Energy to Ion Thermal Energy

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

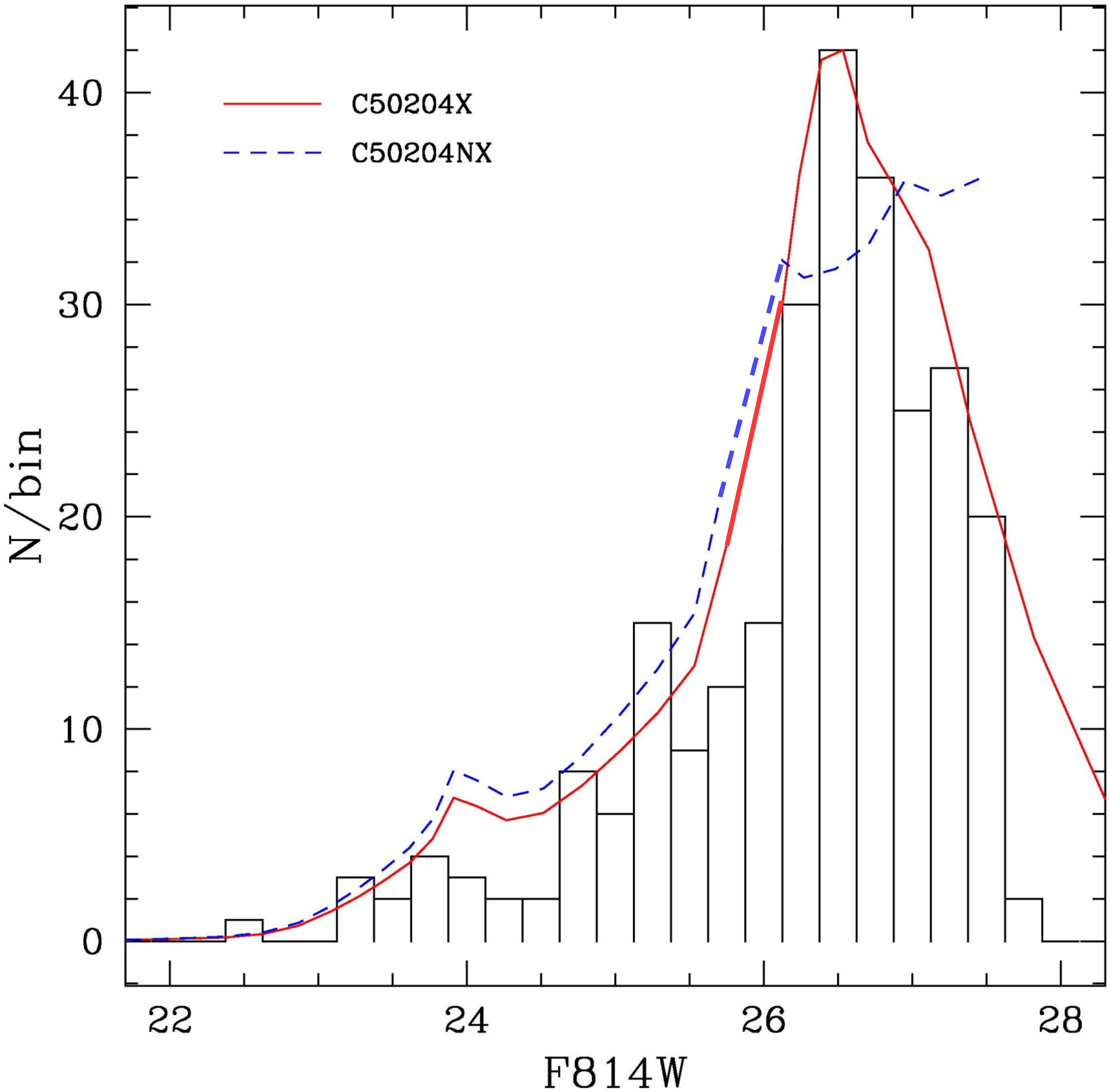
What is the value of Gamma at and near the "clump" in the observed CMD, or equivalently, the value of Gamma at the peak of the Luminosity Function?

Γ(peak) = 194 (carbon) = 313 (oxygen)

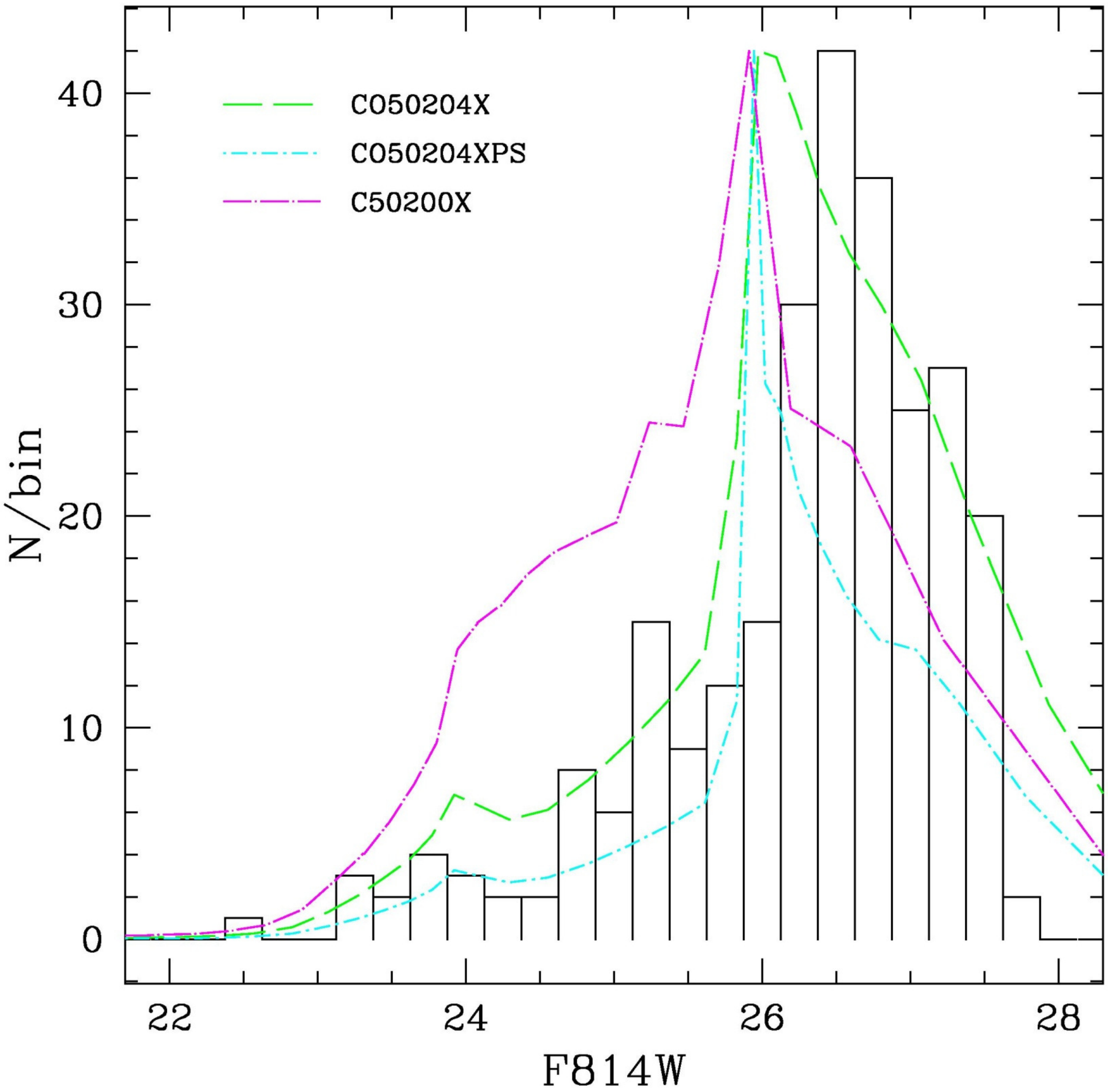
Γ(rise) = 182 (carbon) = 291 (oxygen)



C50204X
C50204NX
N/bin
F814W
0
10
20
30
40
22
24
26
28



C50204X
C50204NX
N/bin
0
10
20
30
40
22
24
26
28
F814W



C050204X
C050204XPS
C50200X
N/bin
F814W
0
10
20
30
40
22
24
26
28

Conclusions from NGC 6397

- Confirm that **crystallization occurs**
- Confirm that **Debye cooling occurs**
- We can ***measure*** **the** Γ for crystallization
- We find the first empirical evidence that

  Van Horn's 1968 prediction is correct:

  Crystallization is a first order phase transition
- Low metallicity clusters may not produce significant O in cores of some of the 0.5Msun stars …
- **He mixing** combined with CIA opacities explains the mysterious "blue hook."

Observational and theoretical futures for EoS constraints and other physics from white dwarfs

- More fields for NGC 6397 and other globular clusters
- More clusters: globular and rich, old, open clusters different white dwarf and masses and Z, C/O = C/O(Z)?
- SDSS => enormous increase in the disk and halo white dwarfs
- SDSS => more asteroseismology of high (near Chandra mass) and (He-core) low mass white dwarf stars
- Measurements of evolutionary changes allows study of particle physics aspects and general thermal properties

Observational and theoretical futures for EoS constraints and other physics (cont'd)

- Measurements of evolutionary changes allows study of particle physics aspects and general thermal properties
- Bayesian analysis of data with different classes of theoretical models for these large observational samples
- New opacity calculations for warm and cool white dwarfs
- Your list goes here ….

McDONALD OBSERVATORY
THE UNIVERSITY OF TEXAS AT AUSTIN

Some Recommended Reading (reprise)

Reviews:

- Fontaine, Brassard & Bergeron 2001, PASP 113:409
- Hansen & Liebert 2003, ARA&A 41:465
- Winget & Kepler 2008, ARA&A in press

New:

- Richer et al. 2008, AJ, 135, 2141
- Hansen et al. 2007, ApJ, 671,380
- Winget, Kepler, Campos, Montgomery, Girardi & Bergeron 2008 submitted to ApJL

Classic:

- Van Horn 1968, ApJ 151:227

The End

Thank you