17th European White Dwarf Workshop
16-20 August, Tübingen

# White Dwarfs in NGC6397 & M4: Constraints onthe Physics of Crystallization

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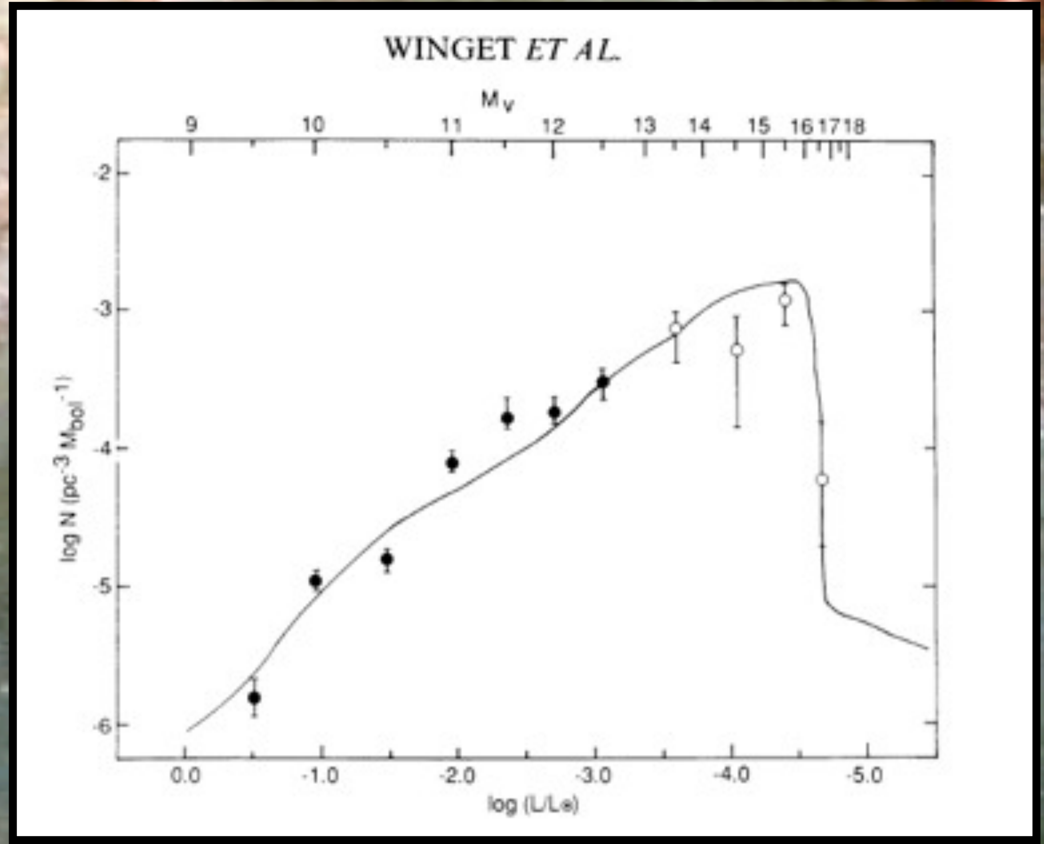
“One of the first tasks to be undertaken by the staff of the McDonald Observatory will be to investigate further the mysteries of the white dwarfs.”

-- May 5th, 1939

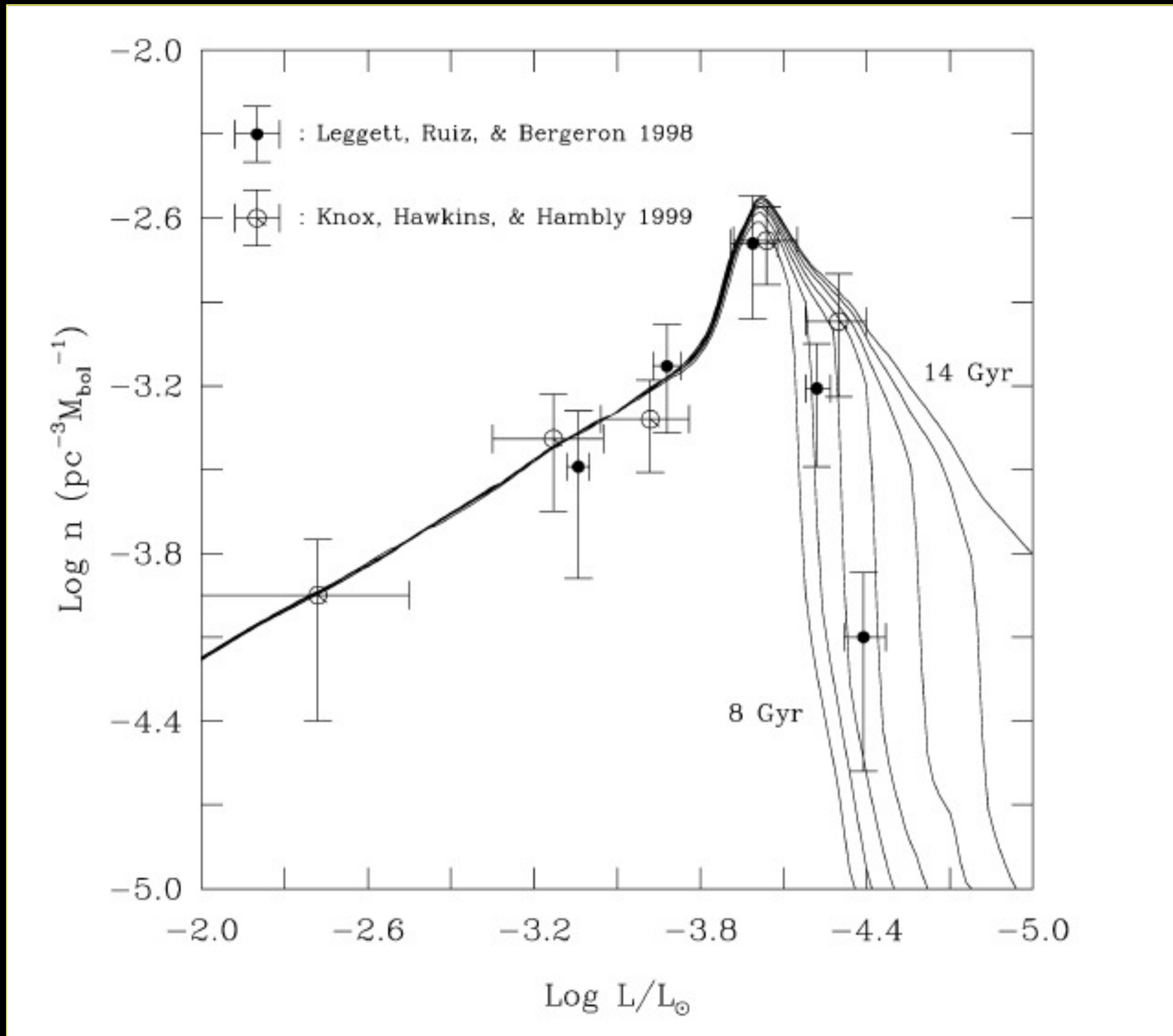
# *White Dwarf Cosmochronology*

- ***Winget, Hansen, Liebert, Van Horn, Fontaine, Nather, Kepler and Lamb* (1987)**

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



# The Disk Luminosity Function




Fontaine, Brassard & Bergeron (2001)

# Harris et al. (2006) Disk LF

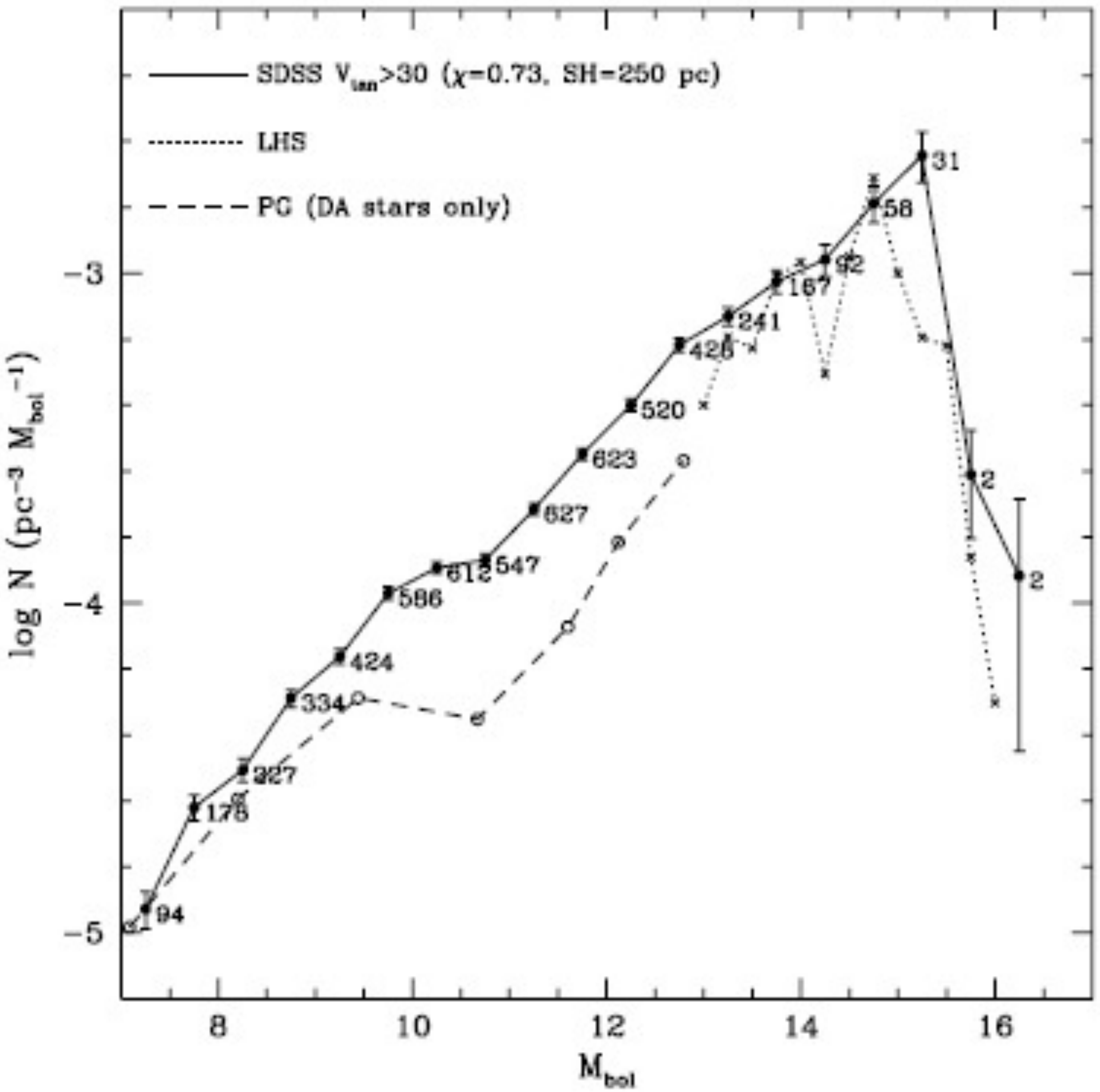
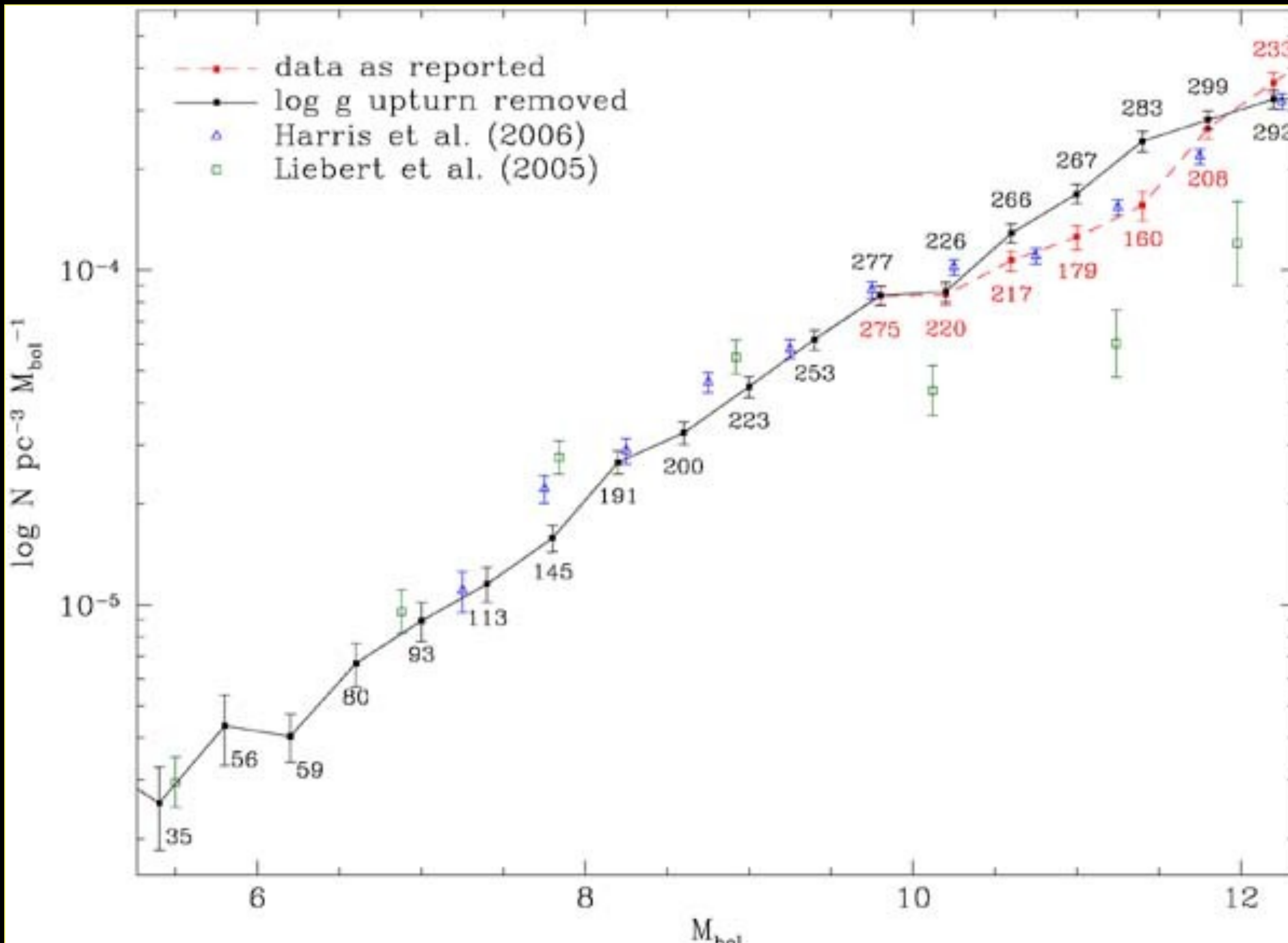
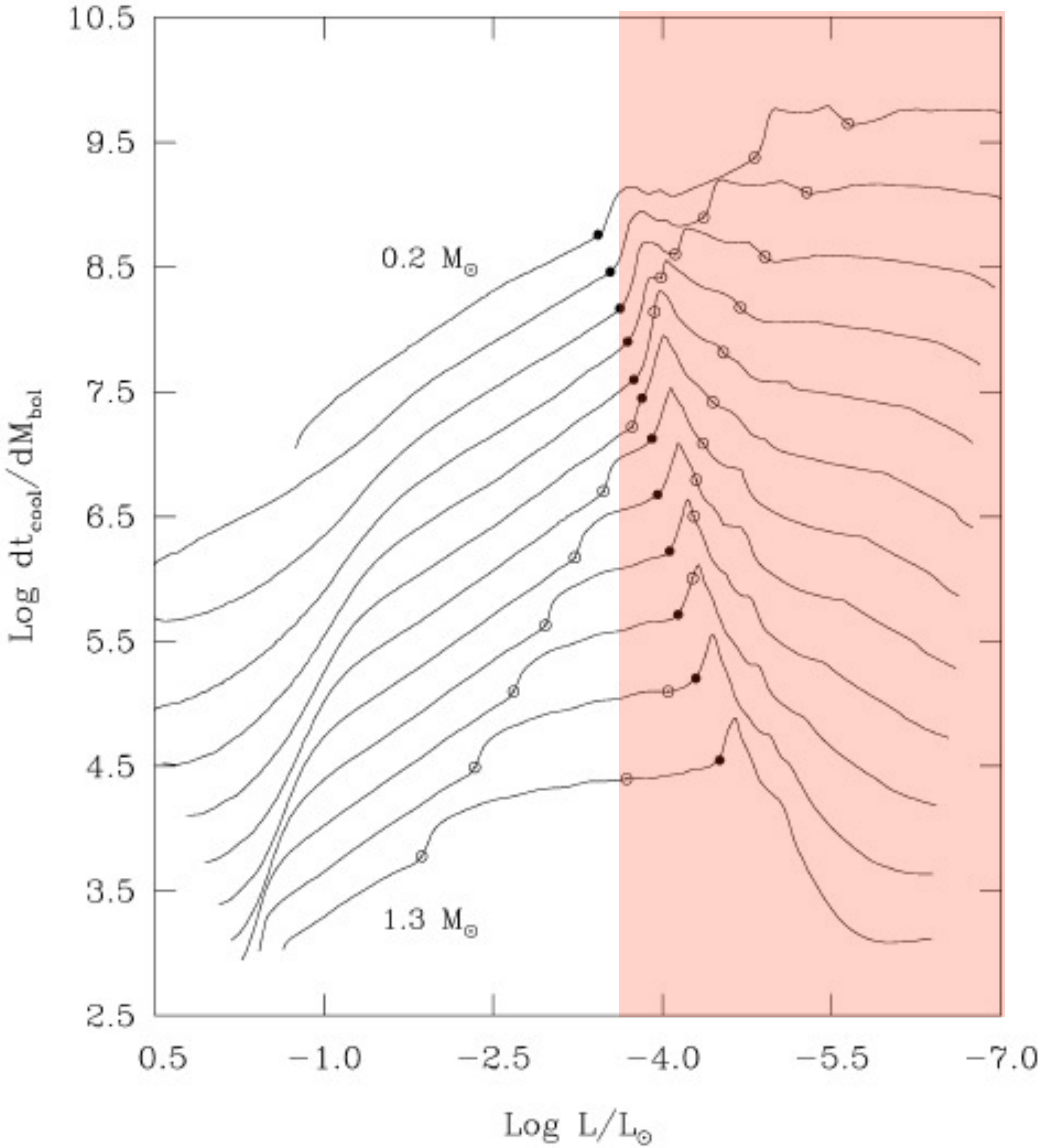



FIG. 4.—LF derived in this paper. The number of stars used for each data point is indicated. Two results from the literature are shown for comparison: the dotted line at the faint end is taken from Leggett et al. (1998), based on the LHS catalog; the dashed line at the bright end is taken from Liebert et al. (2005), based on analysis of the PG survey, including DA WDs only.

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






Fontaine, Brassard & Bergeron (2001)

# What advantages do Globs have over the disk population?

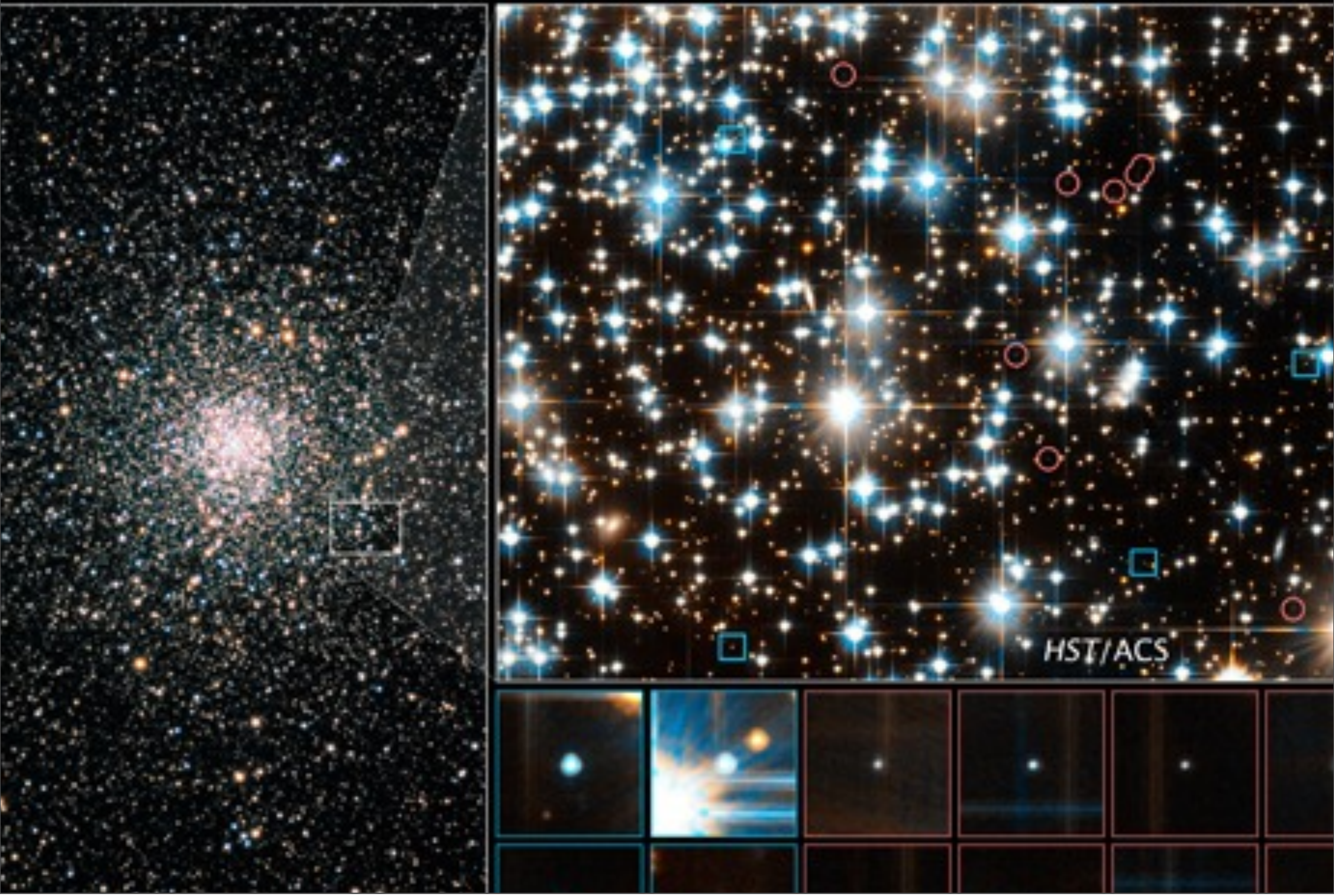
- The cooling sequences are "***pinned***" to the CMD by the main sequence and white dwarfs fitted together – sliding is not allowed.

- If we ignore the observational errors, the CMD location of a star uniquely determines its mass and radius: the ***mechanical properties*** of the white dwarf are determined independently of the thermal.

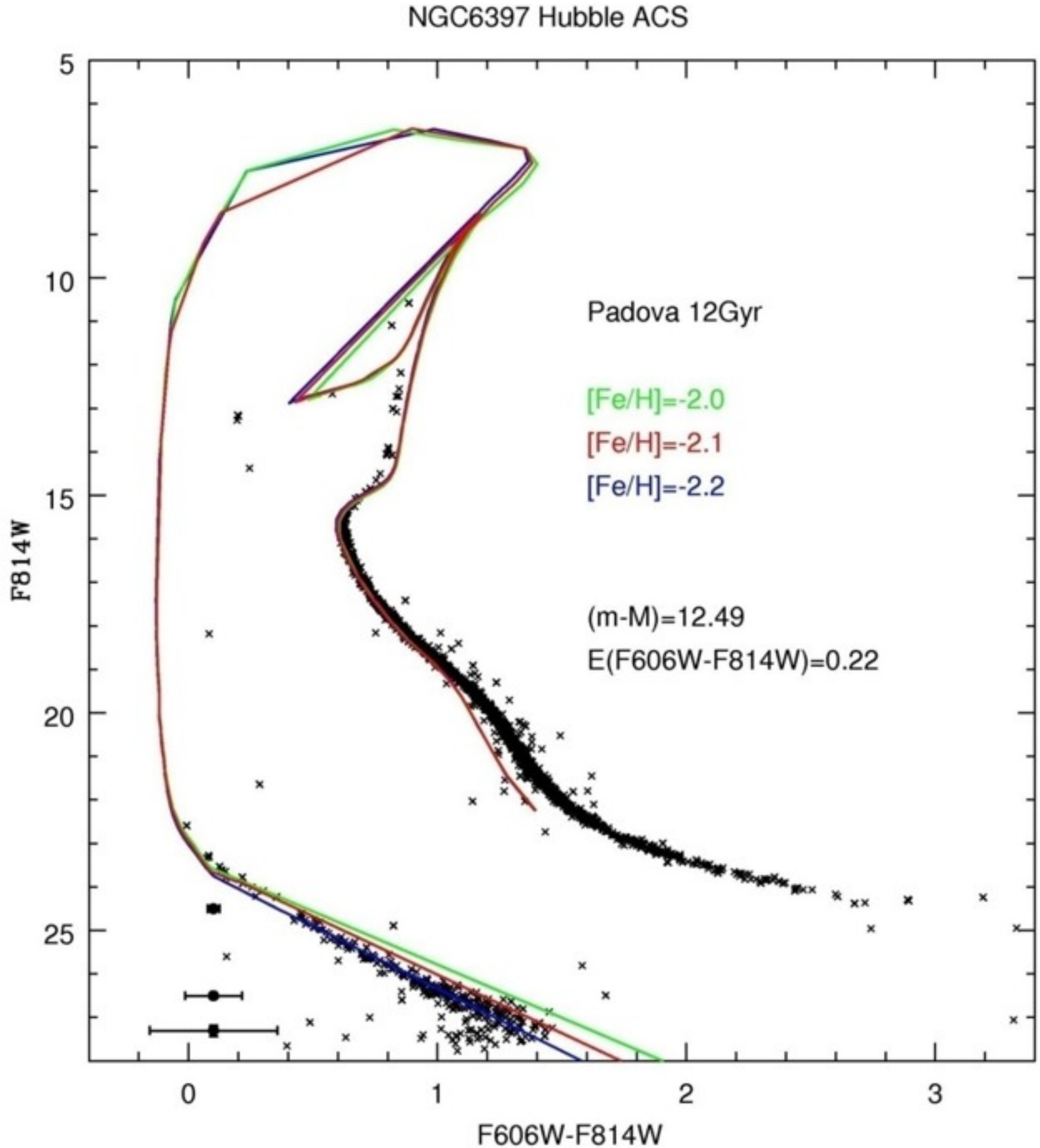
- The mass range is ***very narrow***.

- Ages provide some independent information …
  ***The terminus white dwarfs aren't as old as you think!***

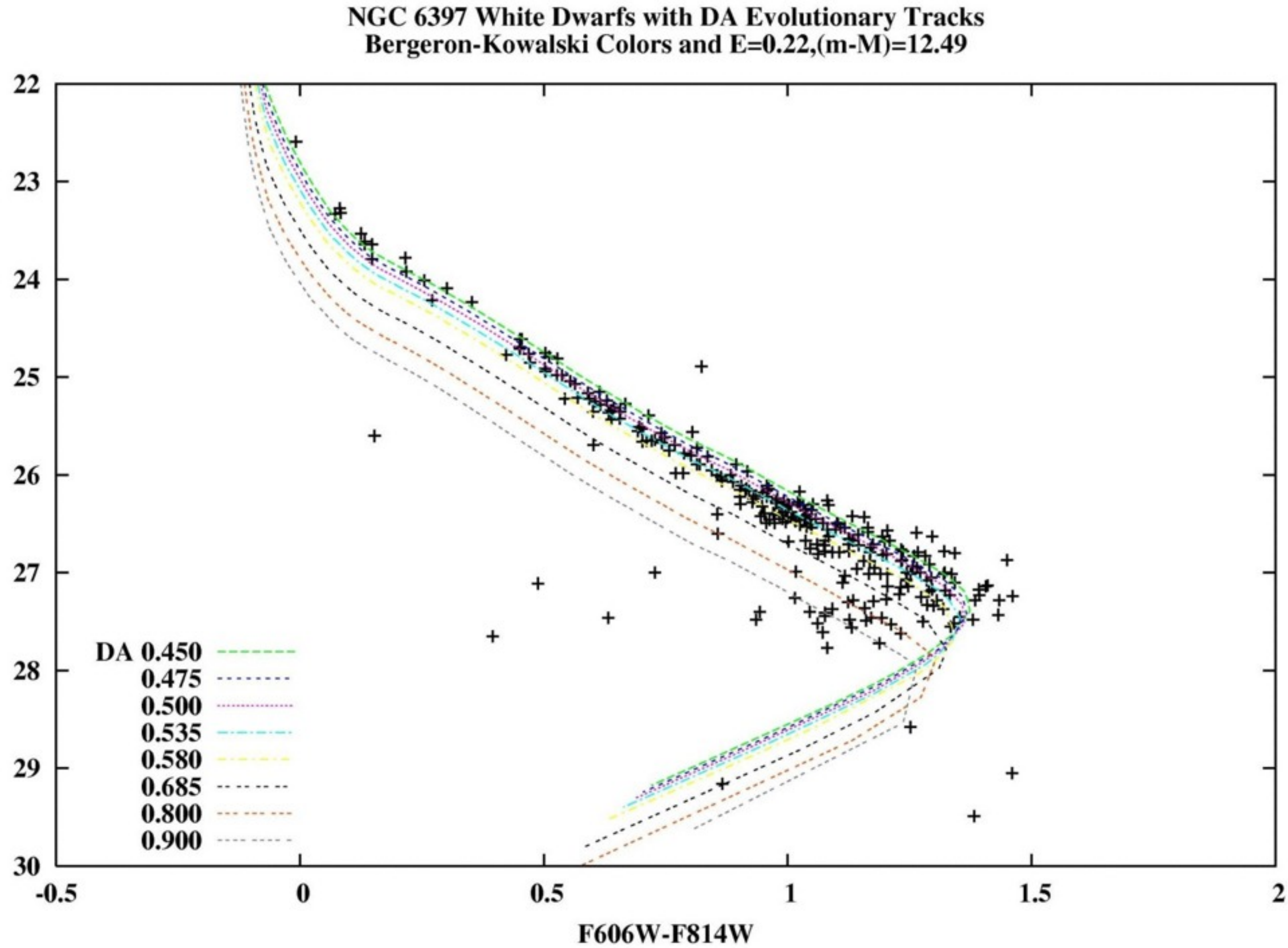
# White Dwarf Stars in Globular Cluster NGC 6397 ▪ *Hubble Space Telescope ACS/WF*



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

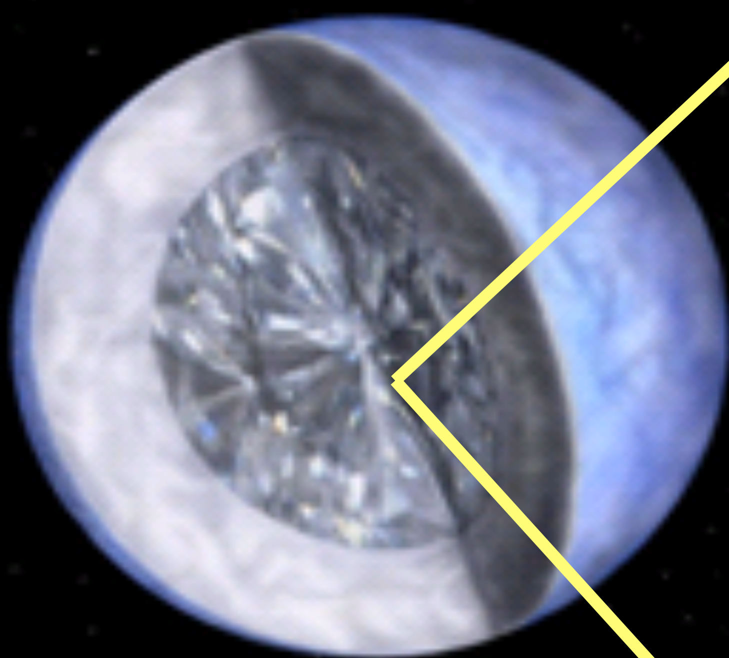


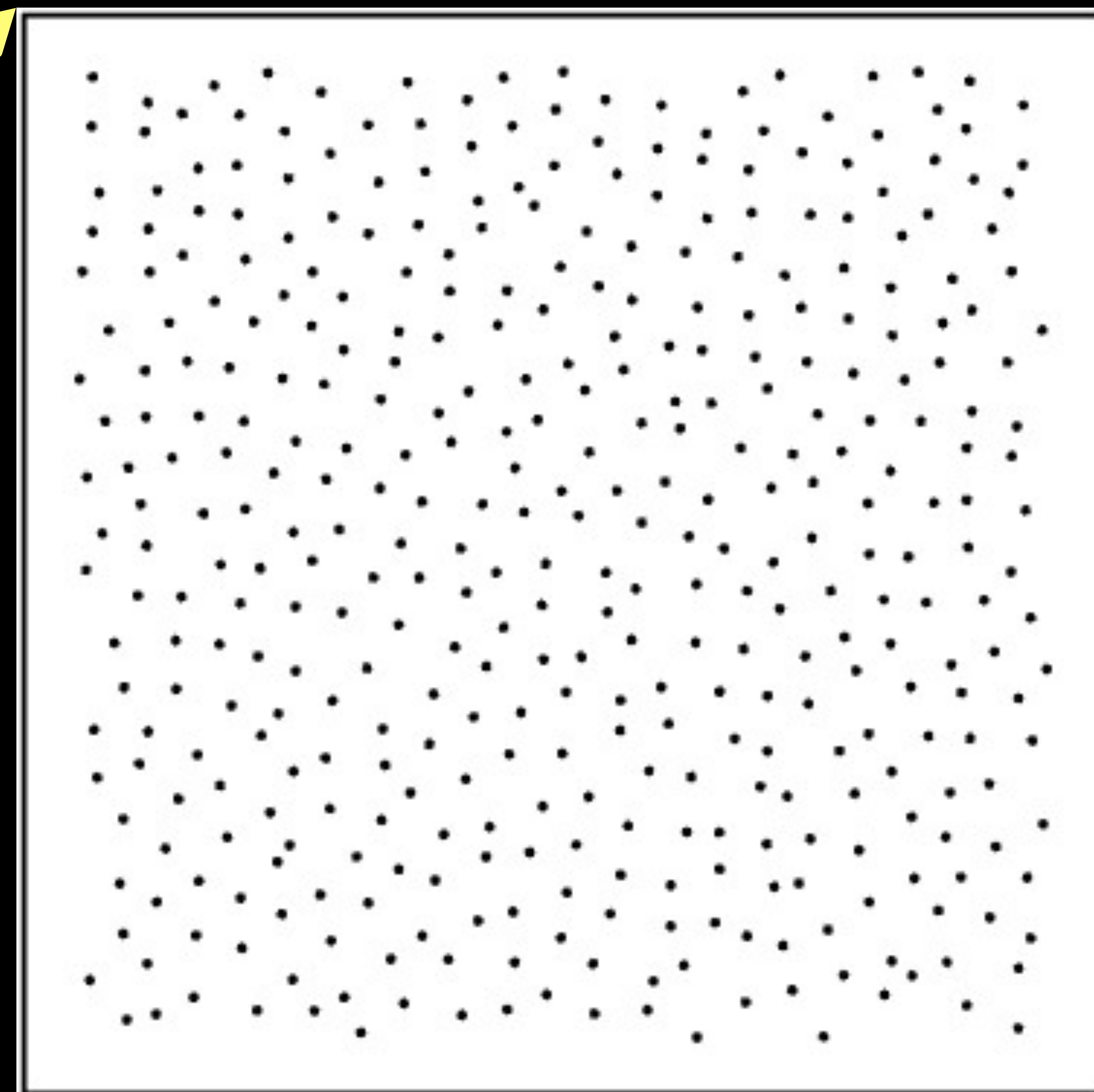

Data: proper motion screened sample from **Richer et al. 2008, AJ, 135,2131**



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

# 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

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

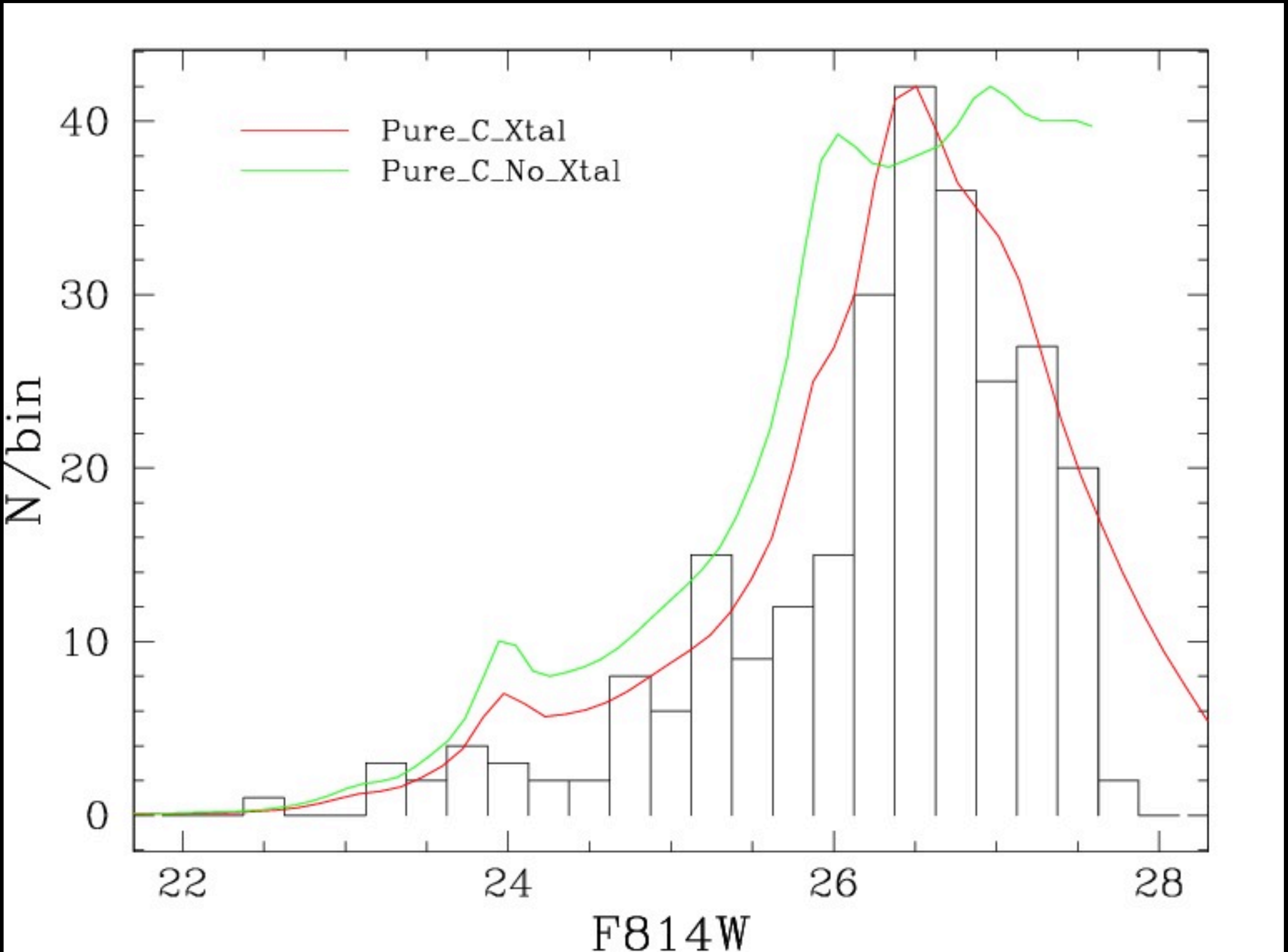
What is the value of Gamma at and near the "clump" in the observed CMD, or equivalently, the value of Gamma at and before (rise) the peak of the Luminosity Function?

log rho = 6.32 log T = 6.40

… nearly independent of composition!

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

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


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

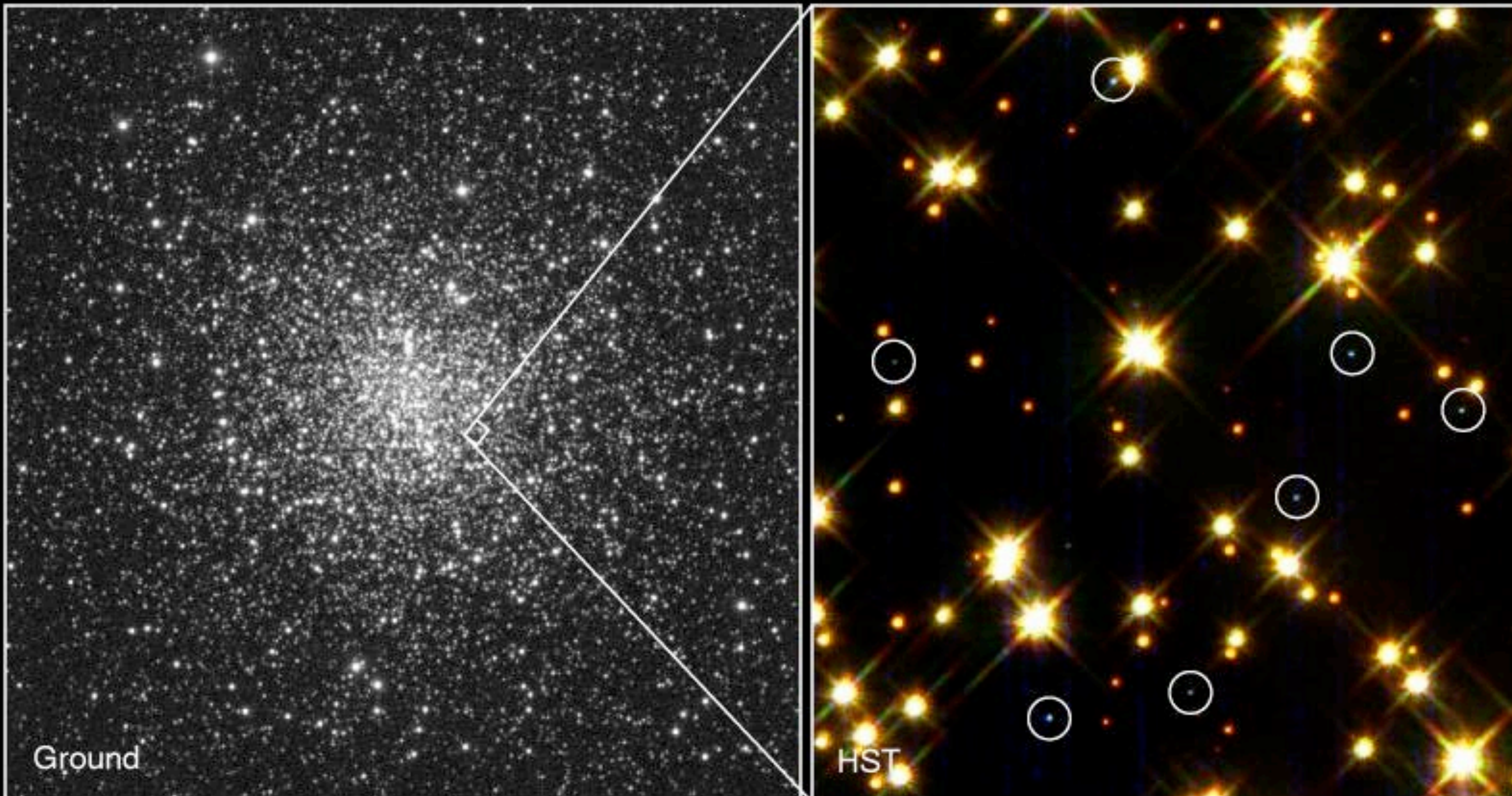
# Ratio of Coulomb Energy to Ion Thermal Energy

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

**What is the expected value of Gamma at crystallization?**

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

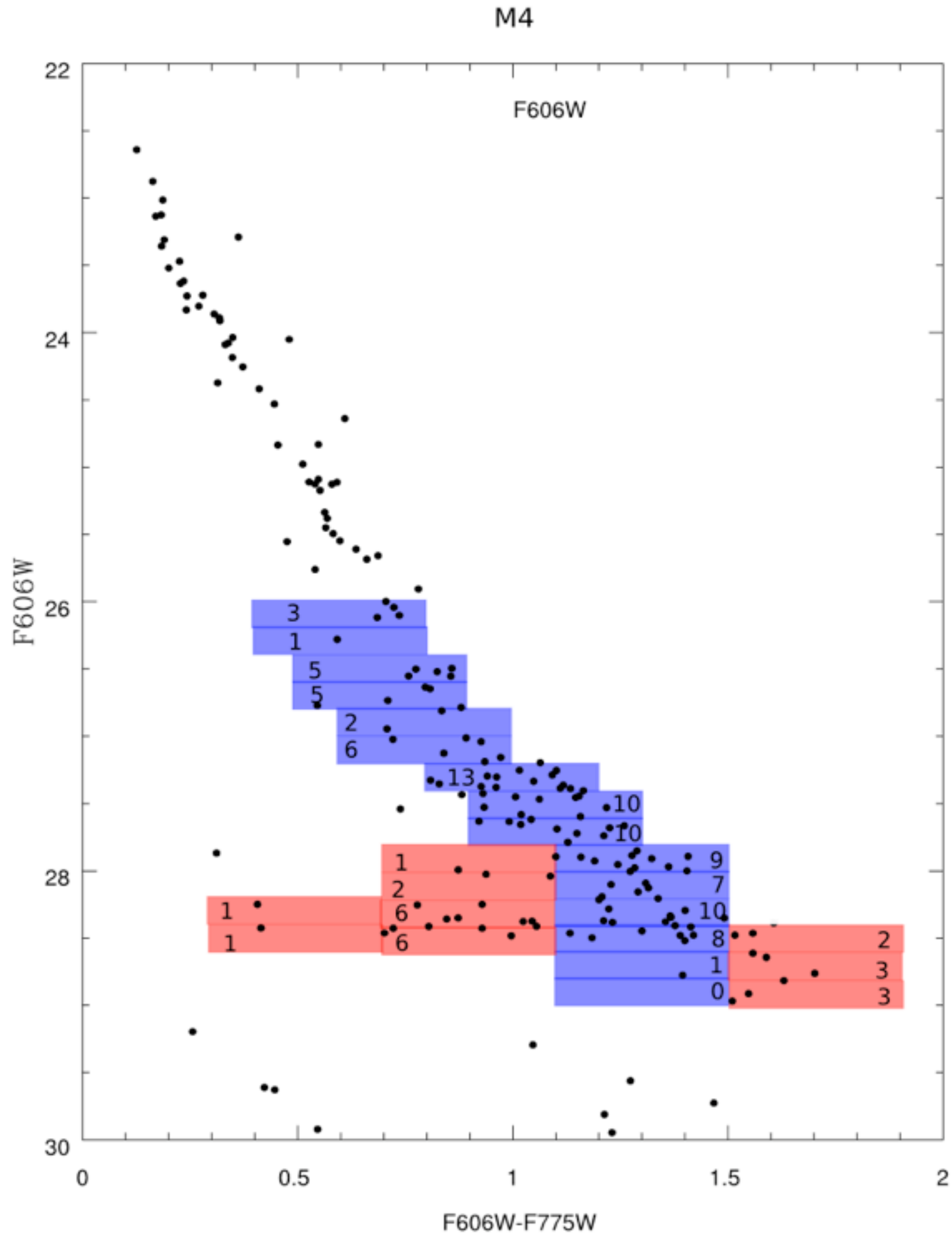
- **(MIX) = 230 - 260** (Horowitz, Berry & Brown 2007)
- This is at the ***frontier*** of (brute force) molecular dynamics we eagerly await the upcoming work by **Hugh DeWitt** and collaborators!



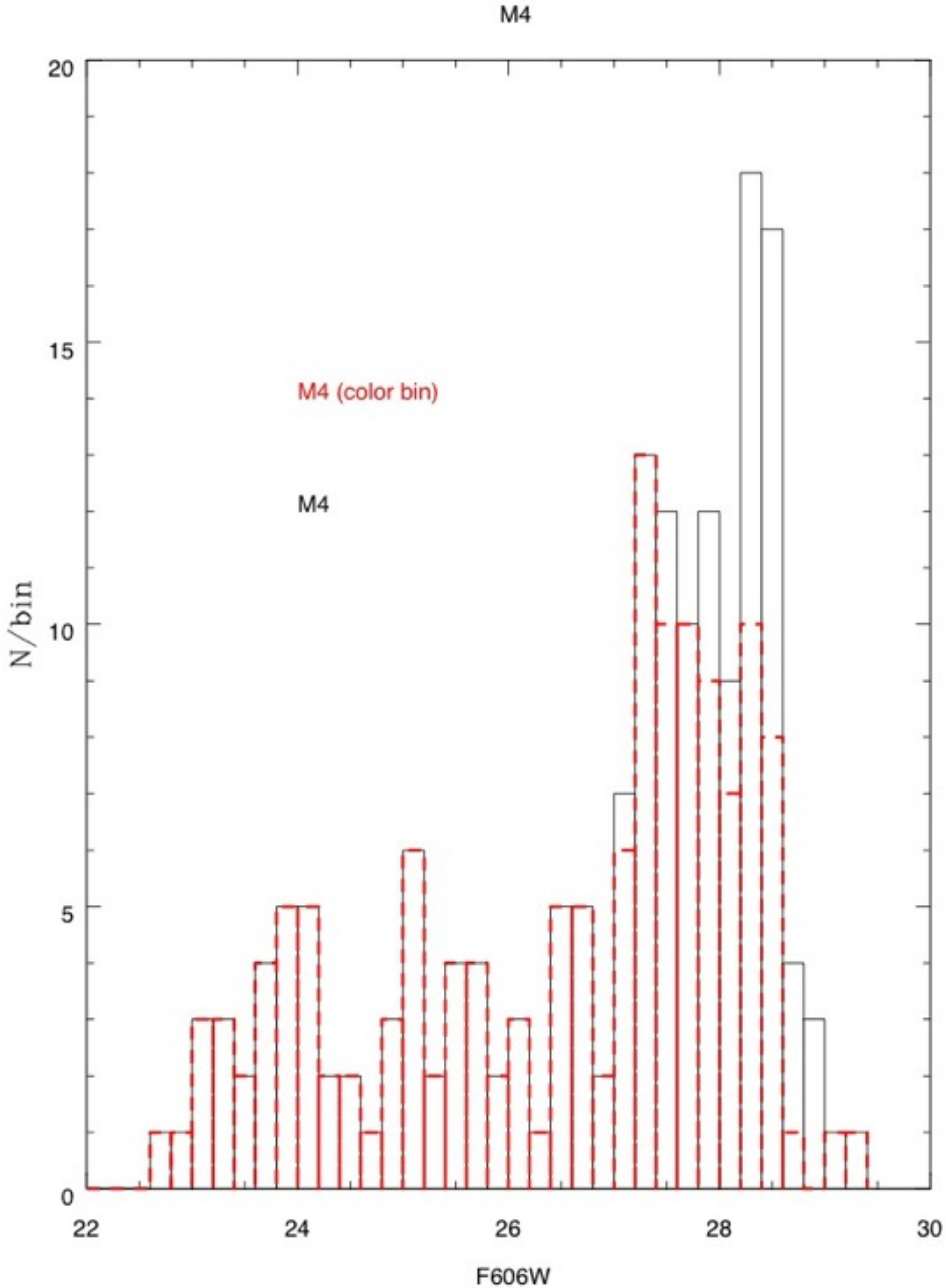

**White Dwarf Stars in M4**

HST • WFPC2

**PRC95-32 • ST ScI OPO • August 28, 1995 • H. Bond (ST ScI), NASA**

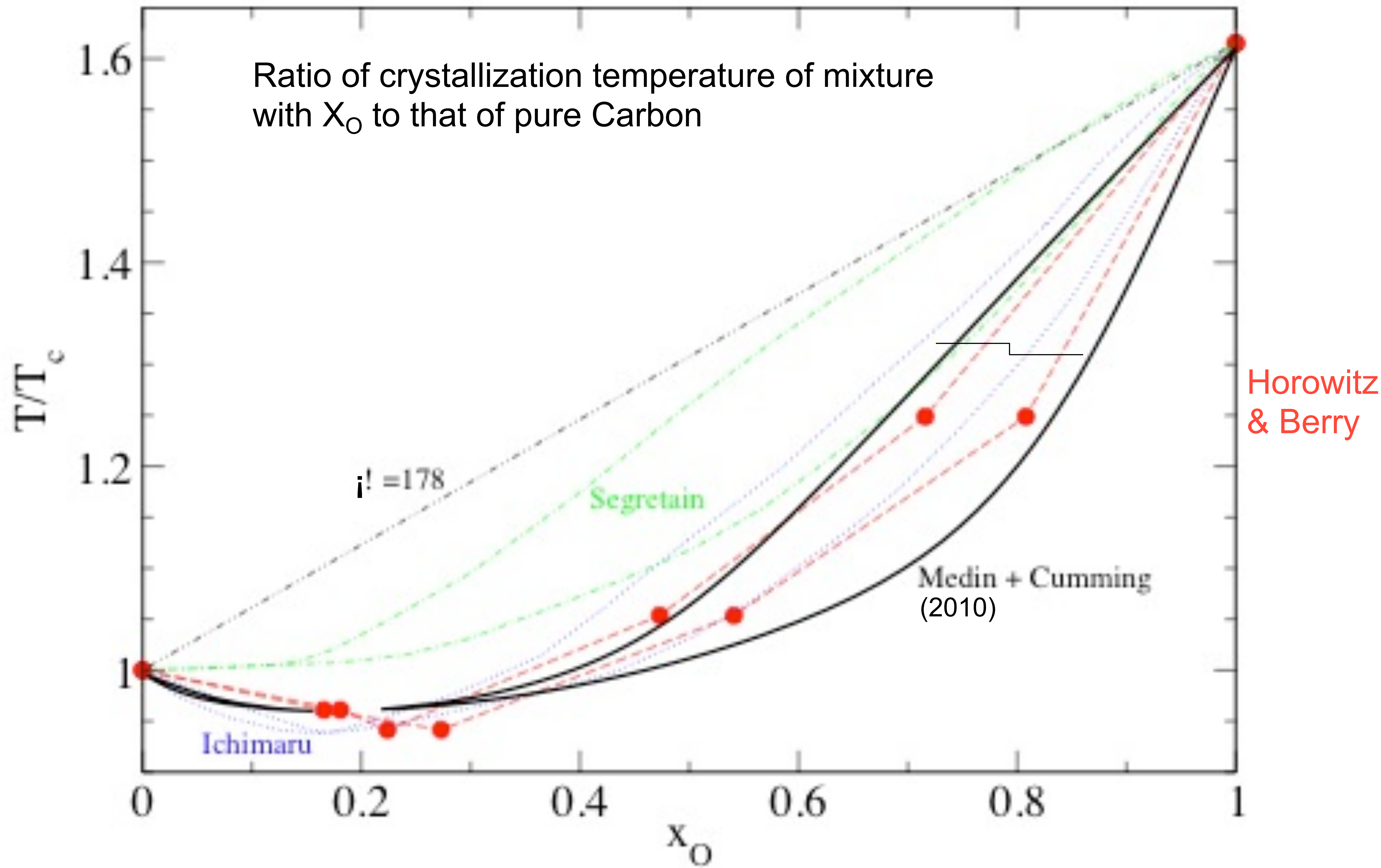



# M4 Color Magnitude Diagram



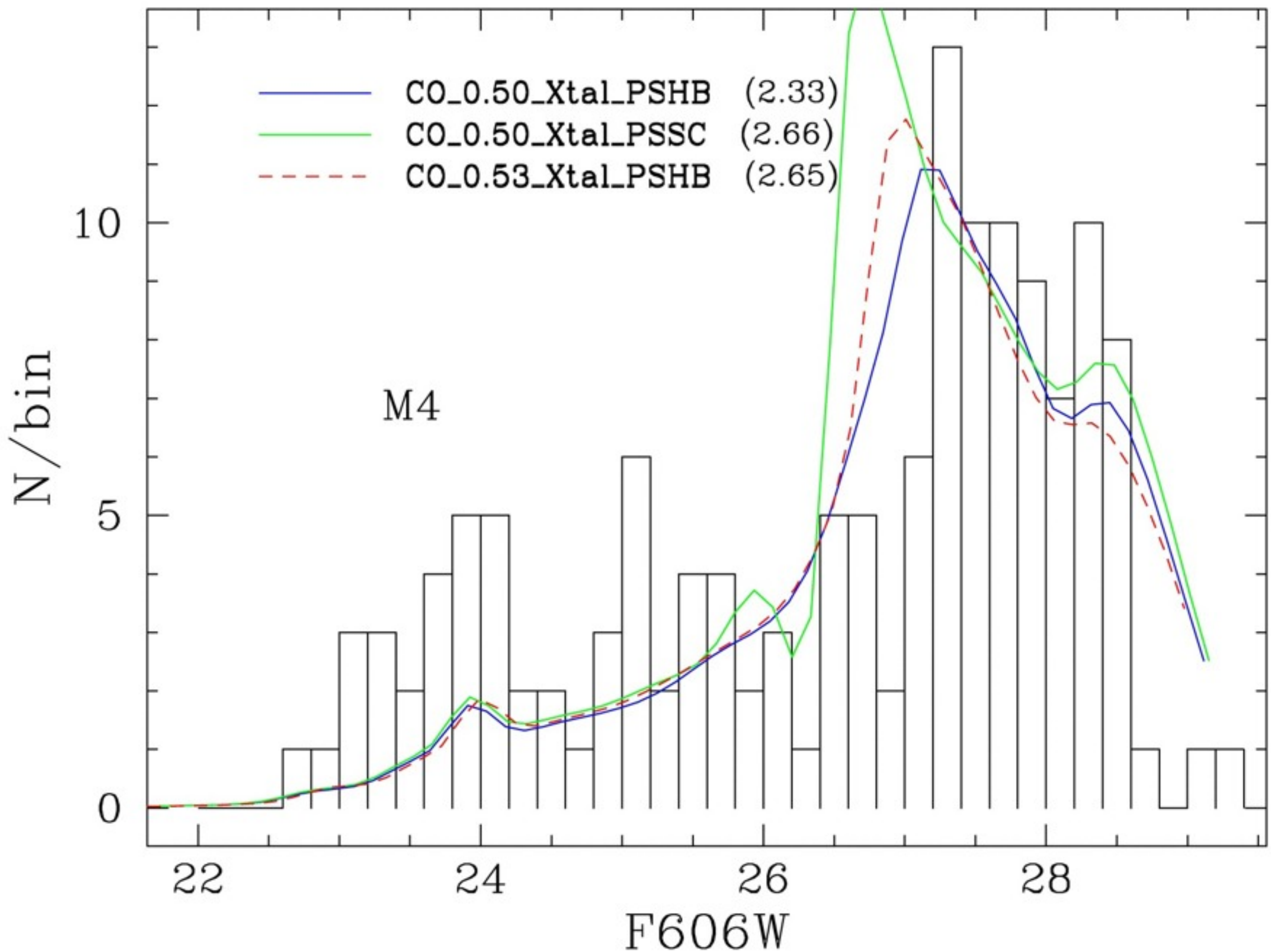
M4
M4 (color bin)
M4
N/bin
F606W
0
5
10
15
20
22
24
26
28
30

Phase Diagram of Horowitz and Berry (2010, in press)

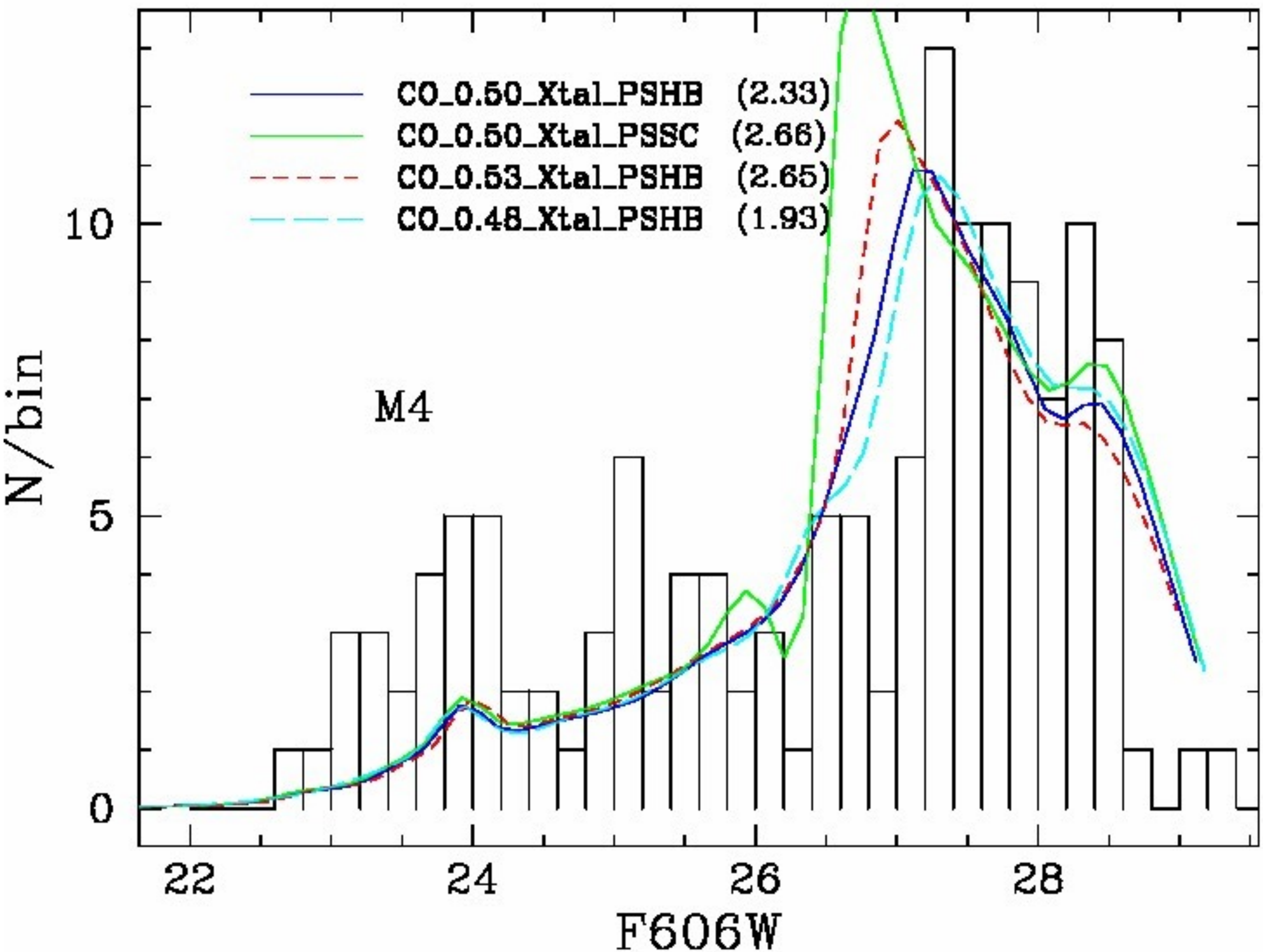



pure Carbon

pure Oxygen



CO_0.50_Xtal_PSHB (2.33)
CO_0.50_Xtal_PSSC (2.66)
CO_0.53_Xtal_PSHB (2.65)
M4
N/bin
F606W
0
5
10
22
24
26
28

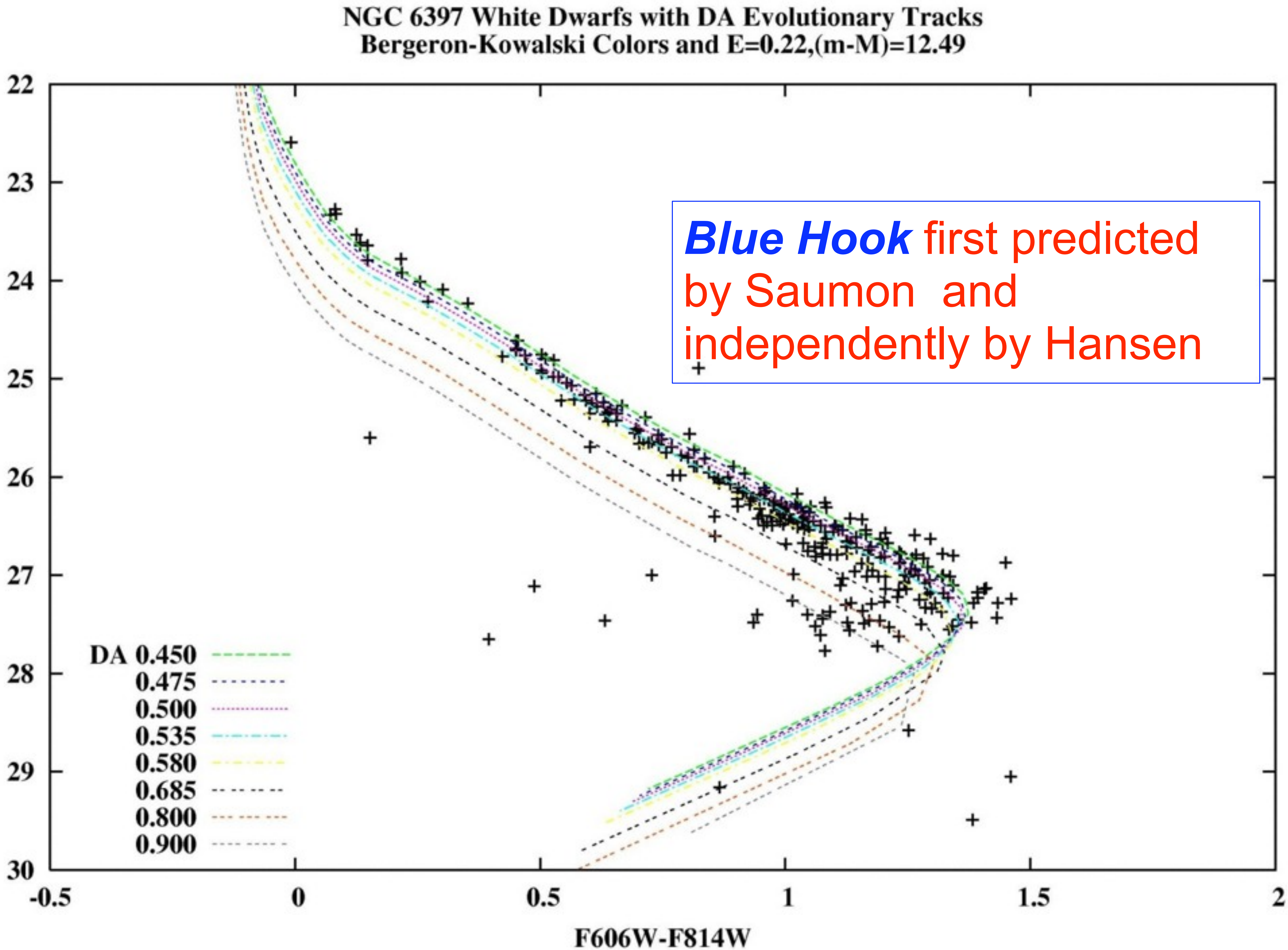


CO_0.50_Xtal_PSHB (2.33)
CO_0.50_Xtal_PSSC (2.66)
CO_0.53_Xtal_PSHB (2.65)
CO_0.48_Xtal_PSHB (1.93)
M4
N/bin
0
5
10
22
24
26
28
F606W

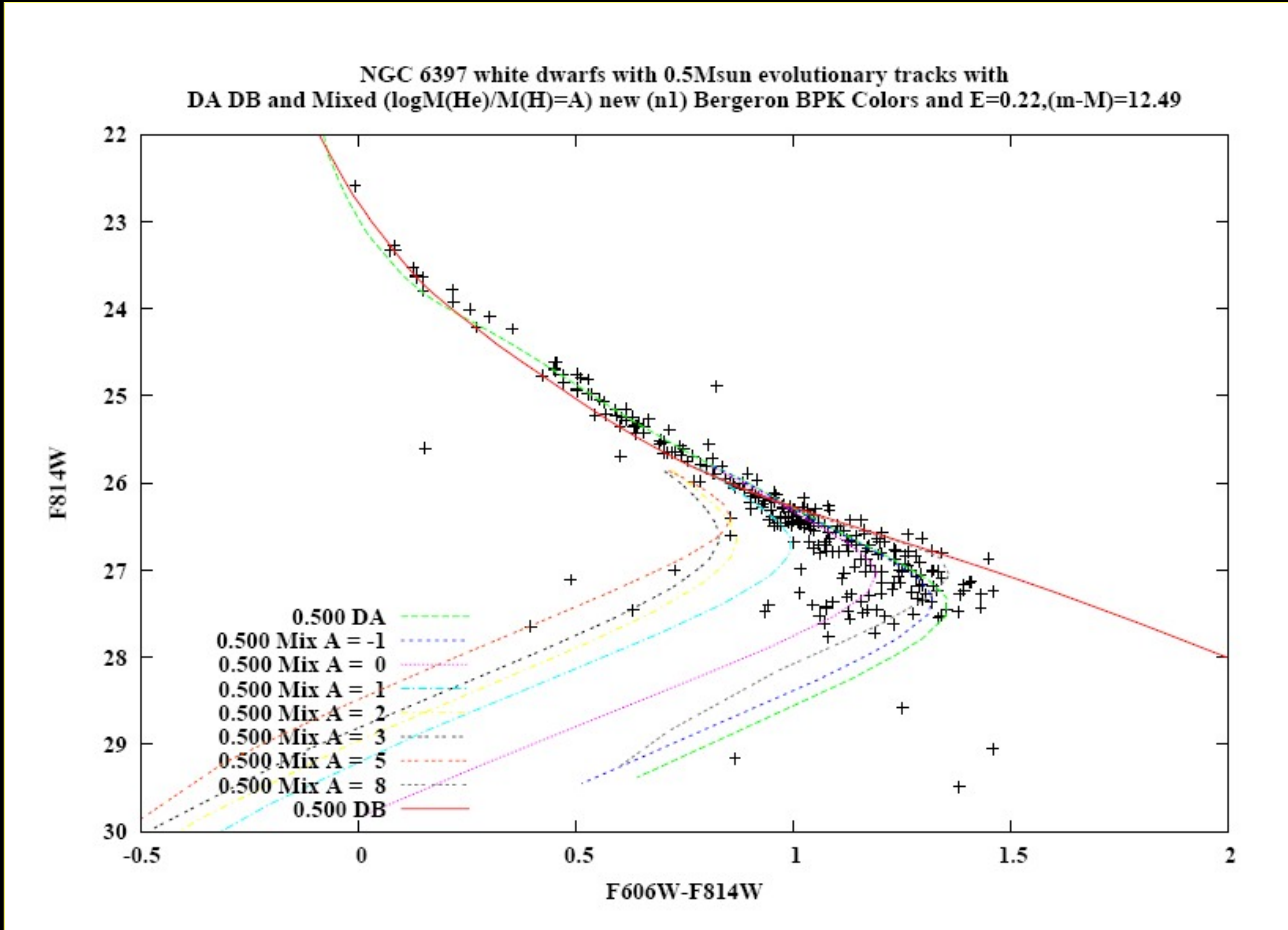
# Conclusions from NGC 6397 & M4

- 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!***



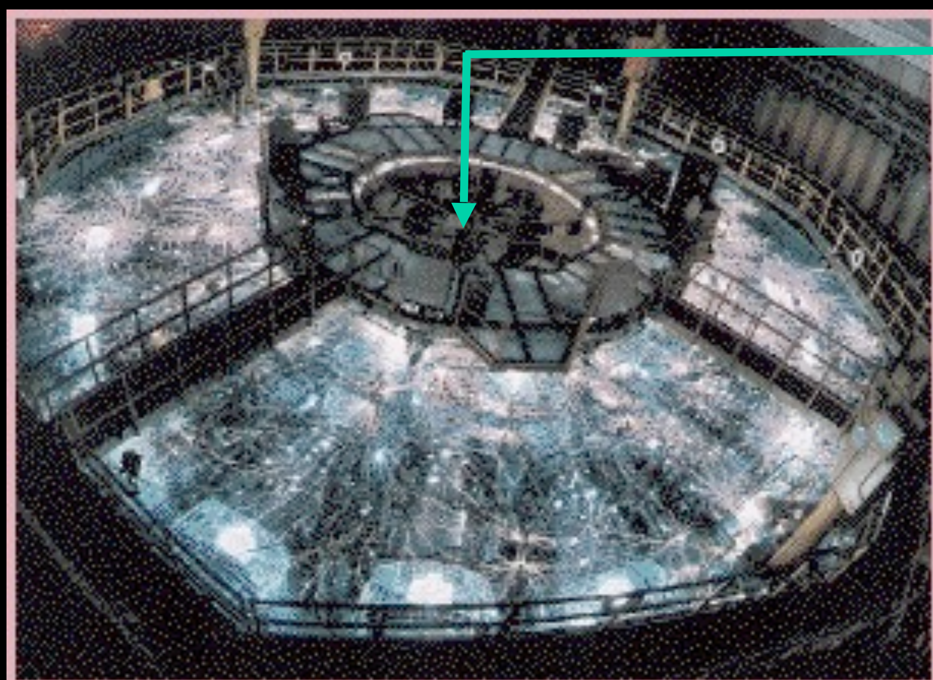

Oops … the CIA hook is in the wrong place!



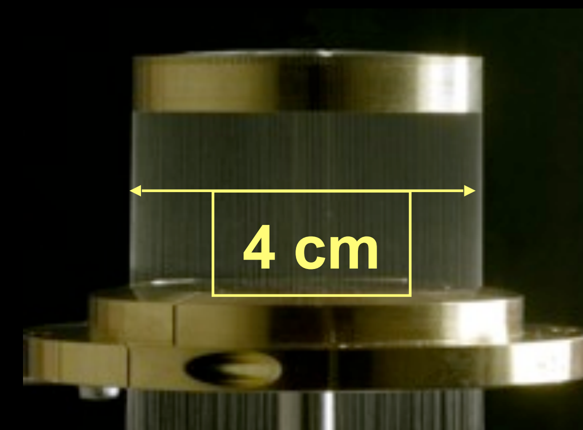

Pierre Bergeron to the rescue: adding He seems to solve our problem, but is this physical? We can go to the laboratory to tell!

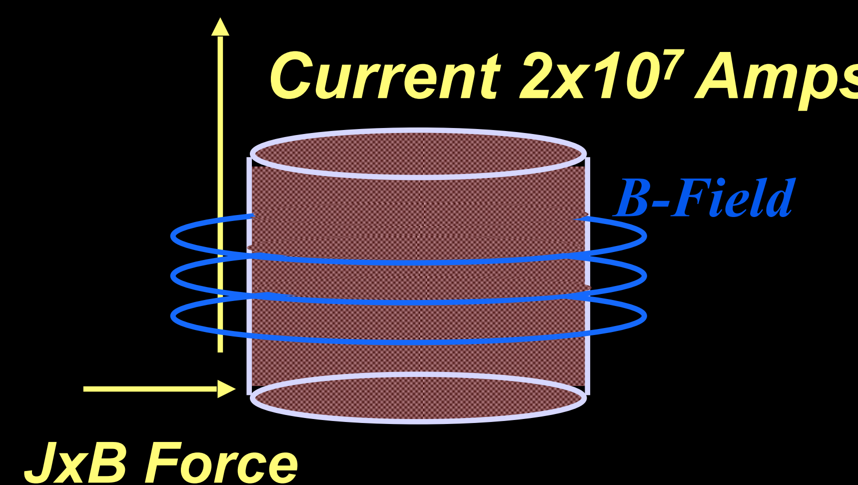
# The 24 million Ampere current on Z provides access to new laboratory astrophysics regimes

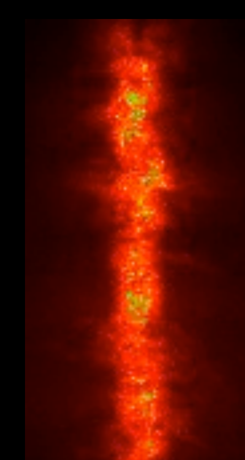
Z accelerator



40 m

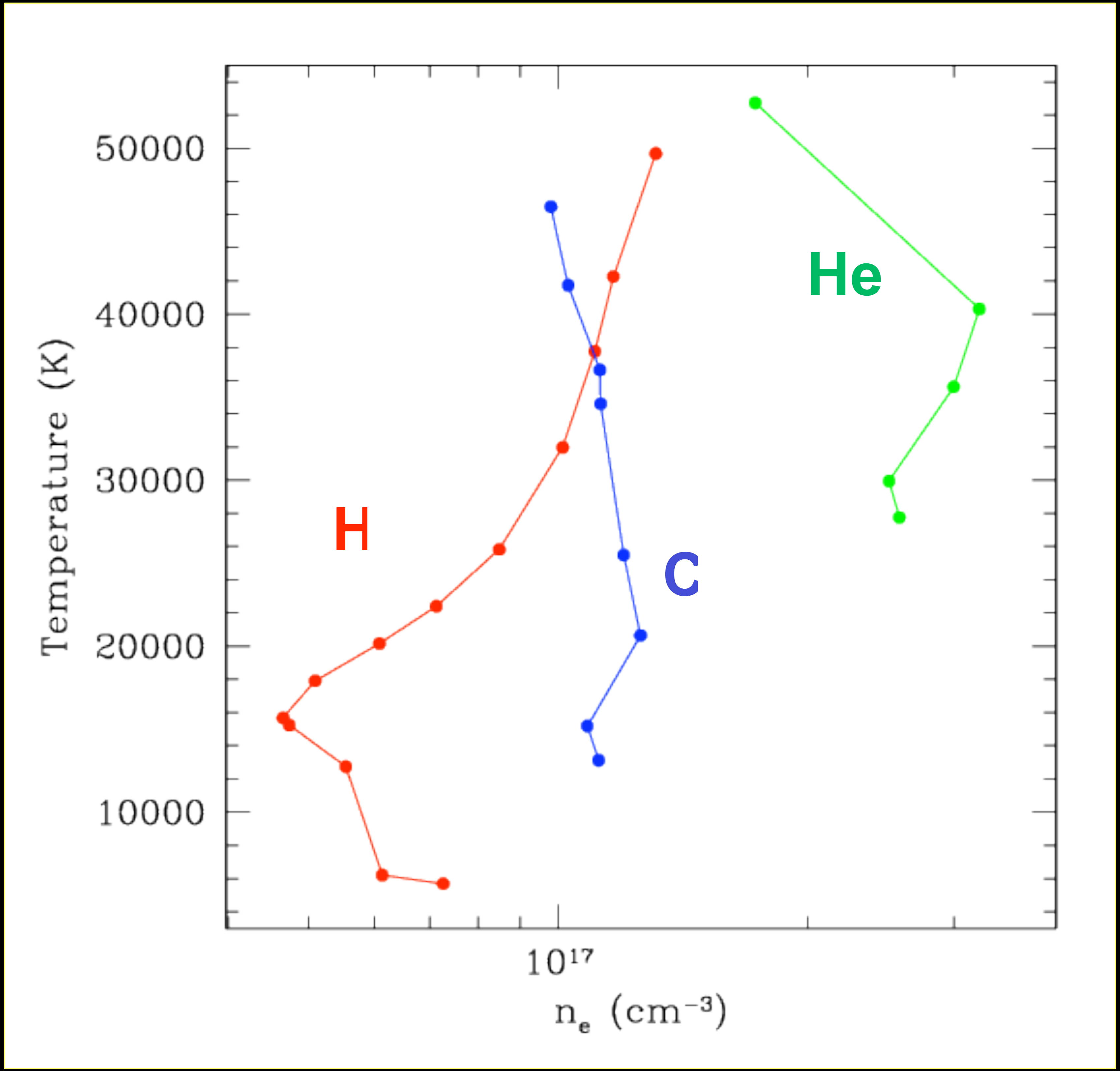


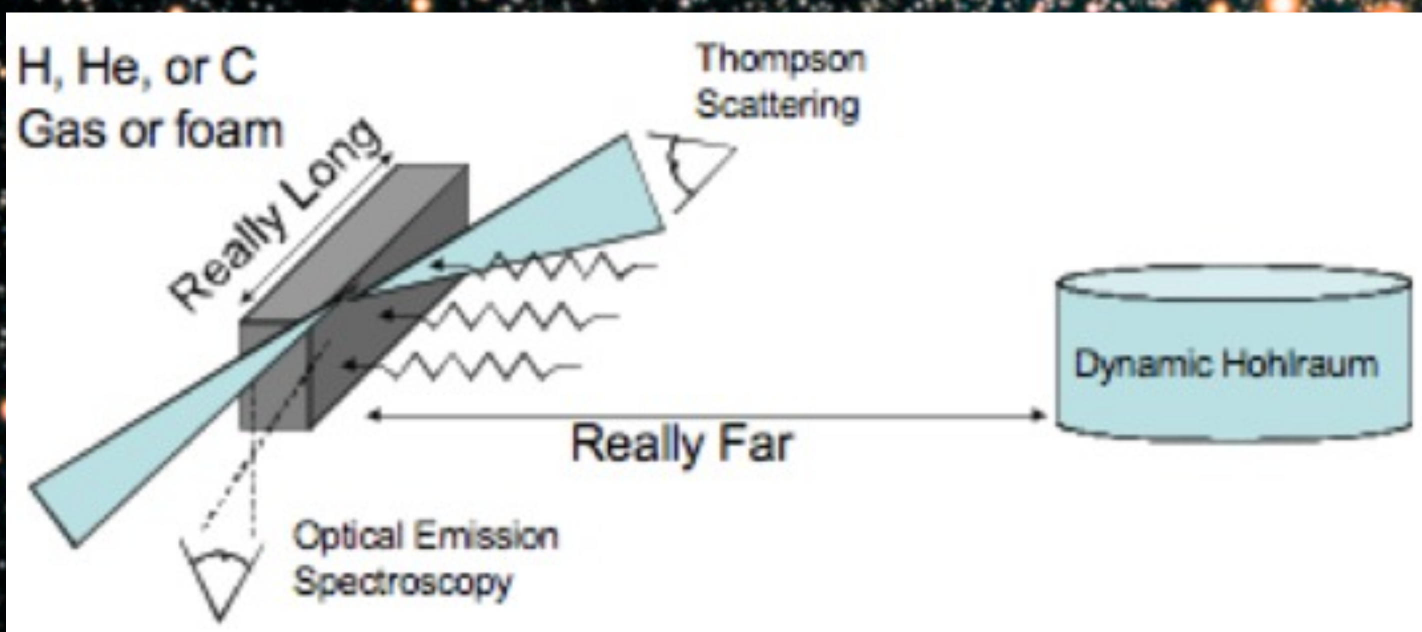



**Z experiments use large magnetic fields or large x-ray flux to create extreme environments**

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

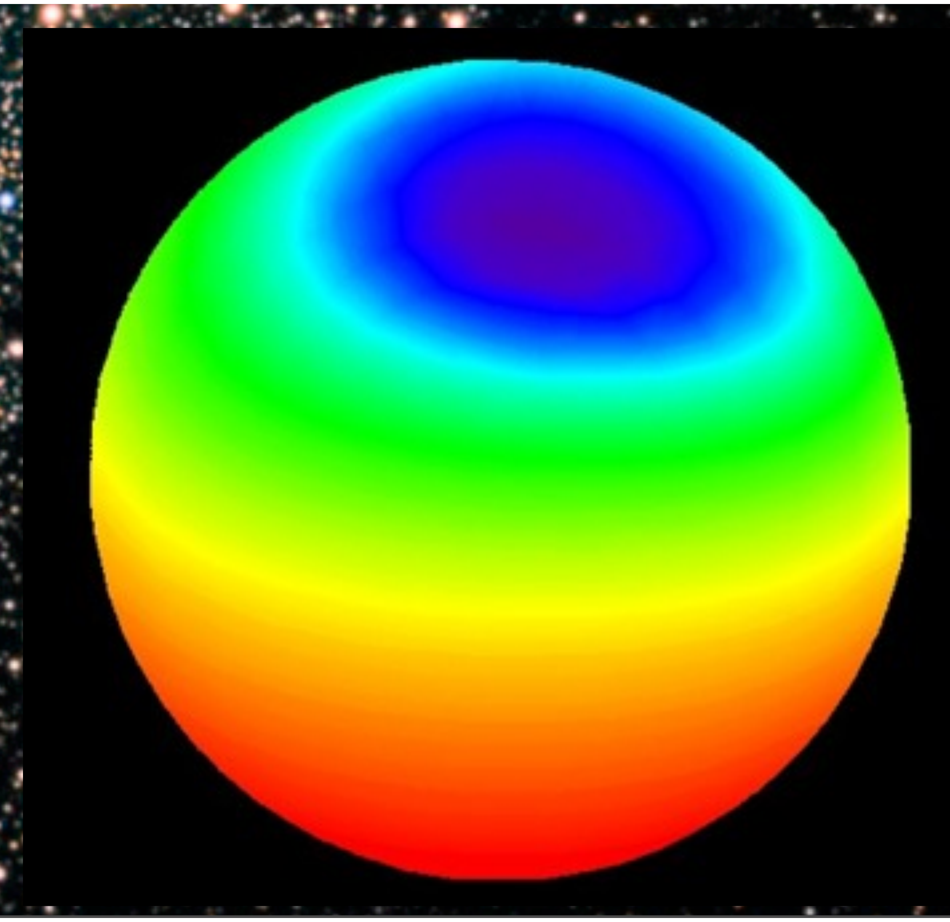


# Measuring Line Profiles at White Dwarf Photospheric Conditions => Accurate Masses




Laboratory Setup

Astrophysical Laboratory



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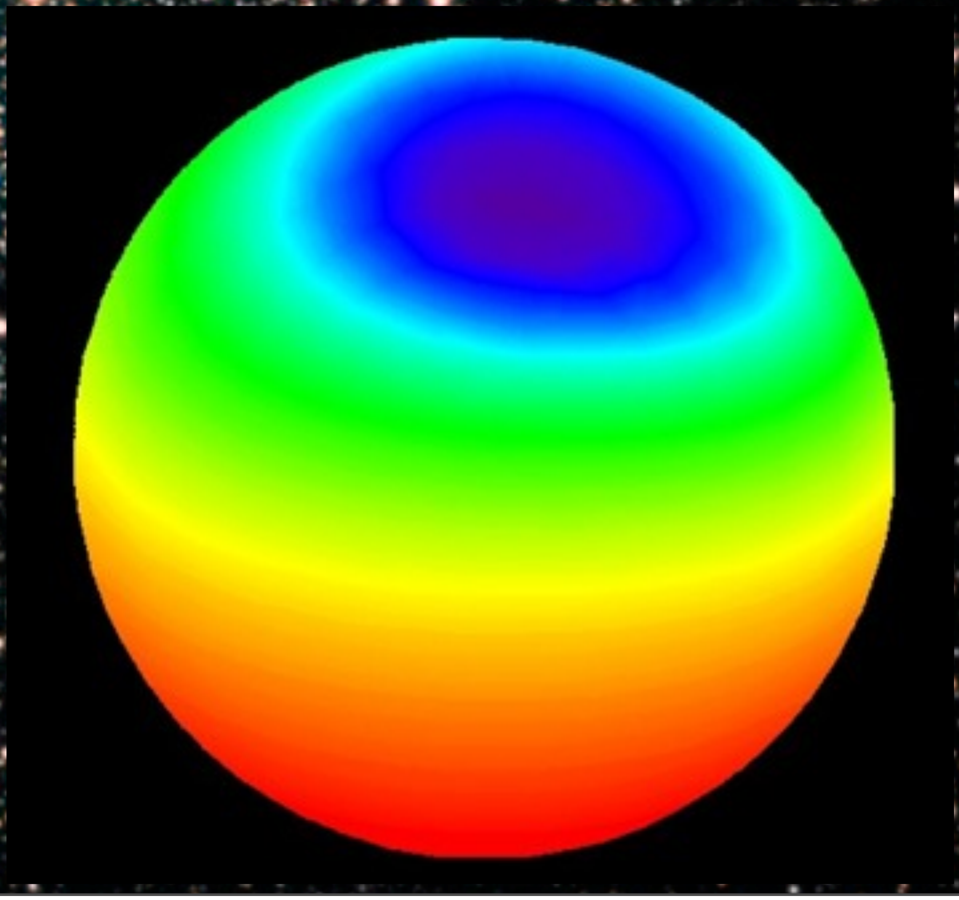
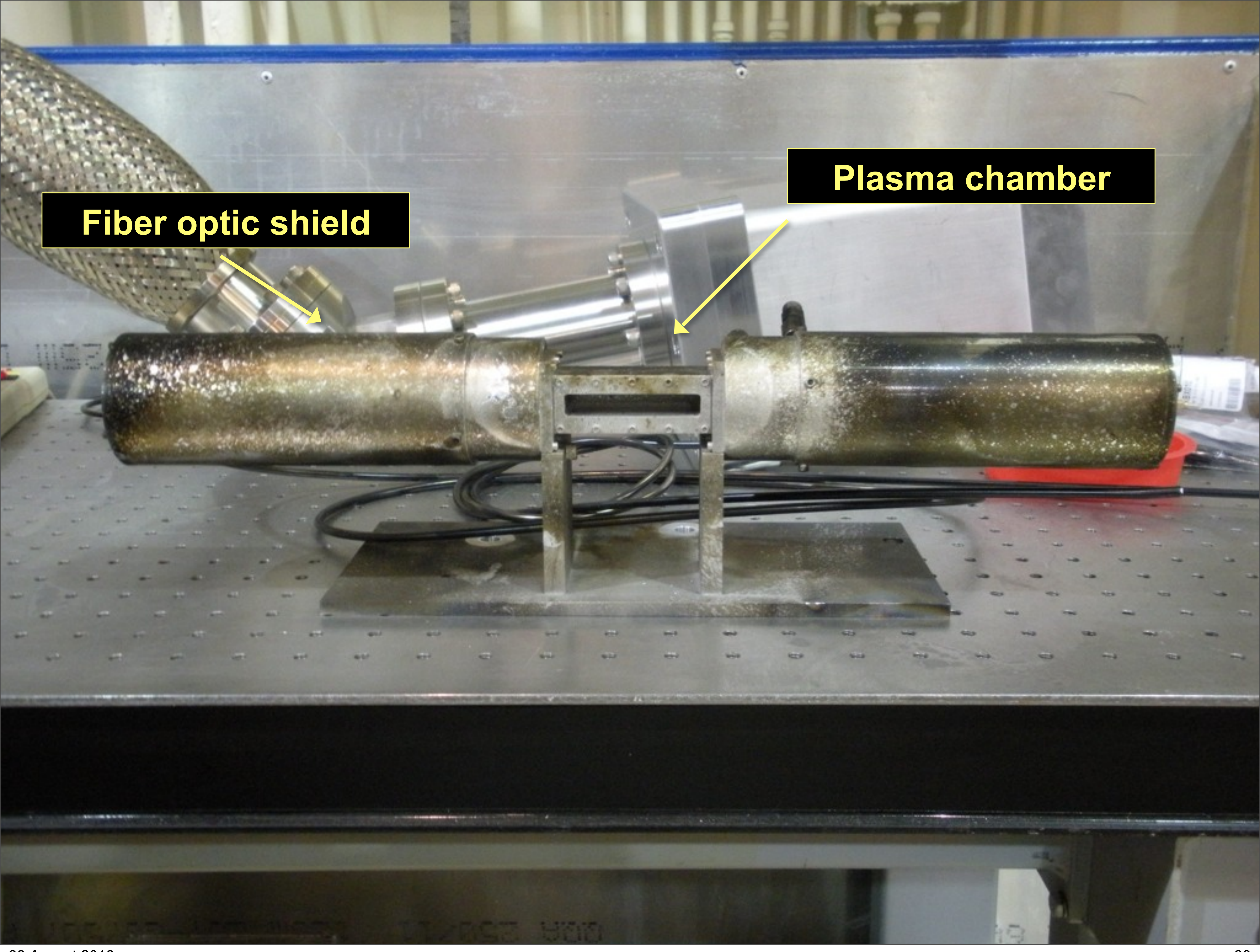
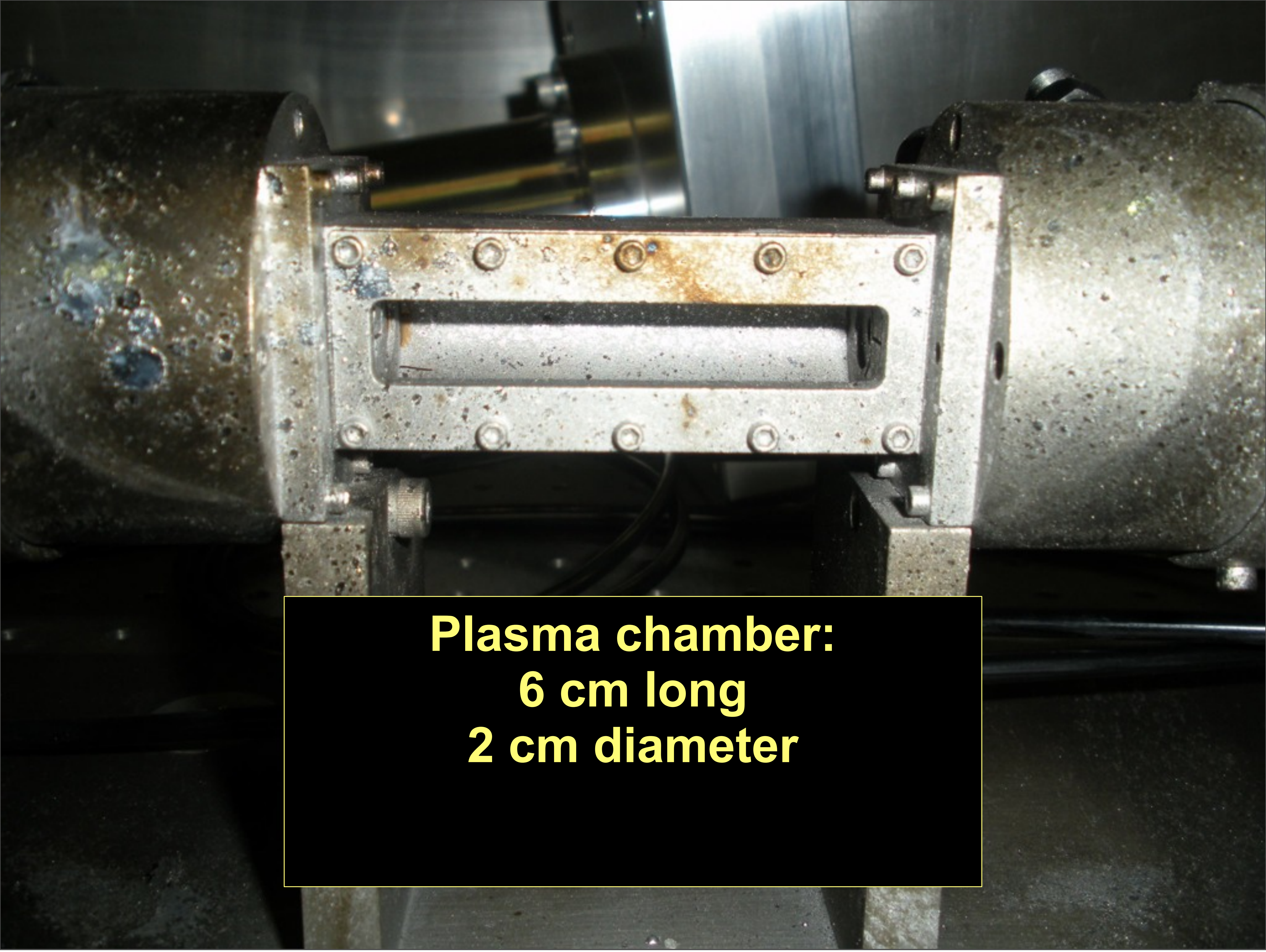
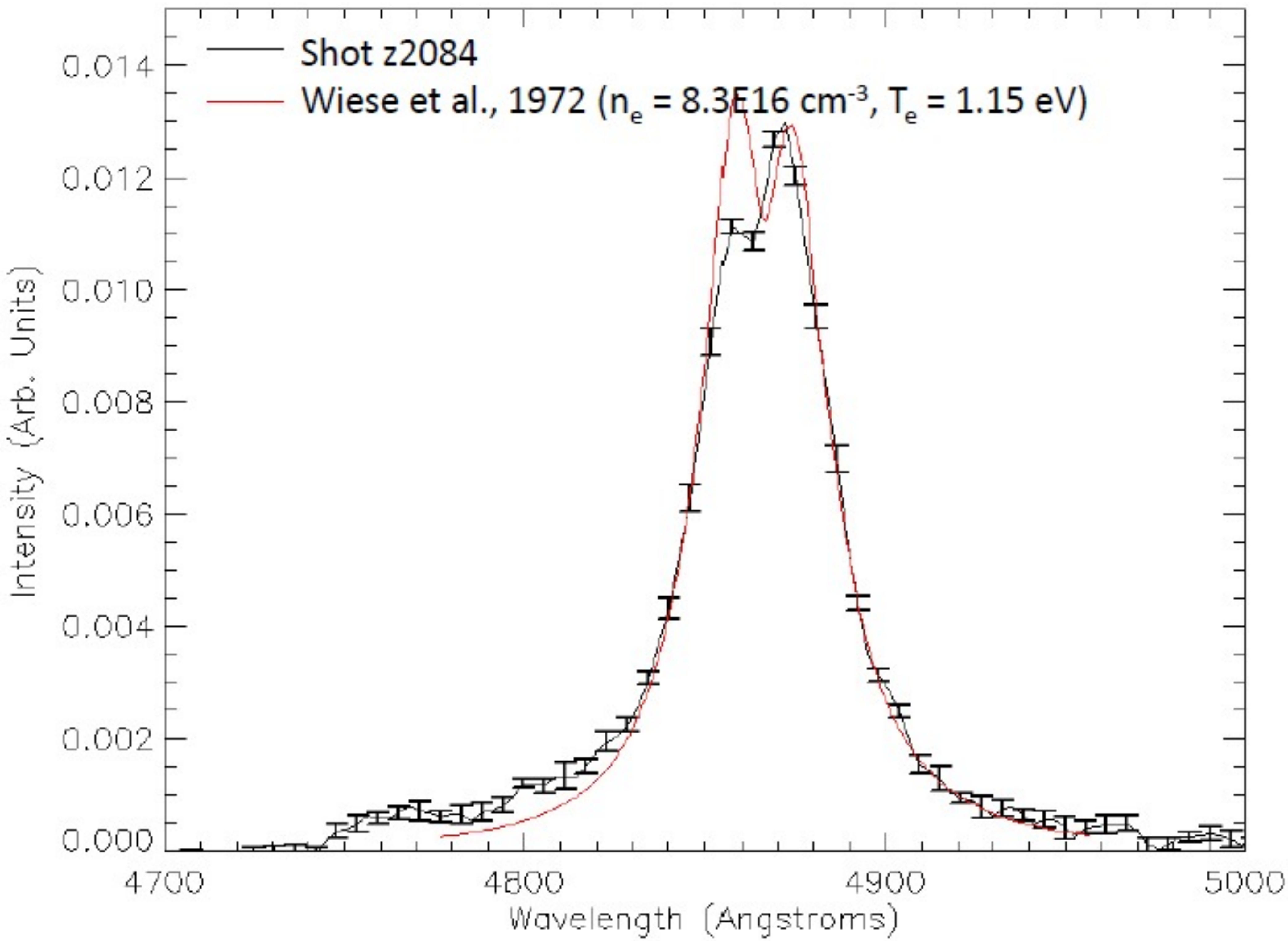



Fiber optic shield
Plasma chamber



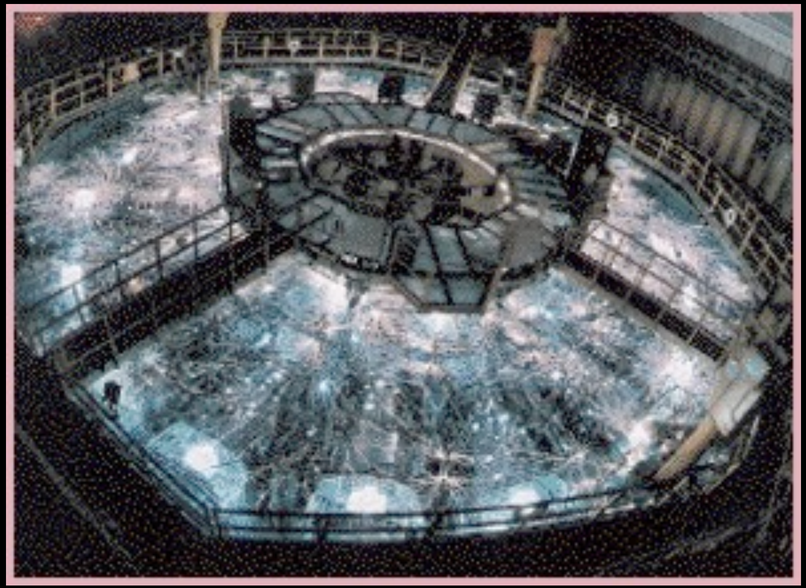
**Plasma chamber:**
**6 cm long**
**2 cm diameter**

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



# 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



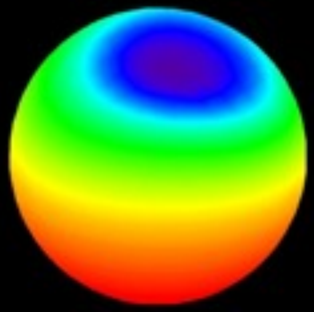
Measurements of lines at White Dwarf photospheric conditions

Accurate Observed Masses

Cosmochronology

- Age of universe
- Age and history of the galaxy

Asteroseismology

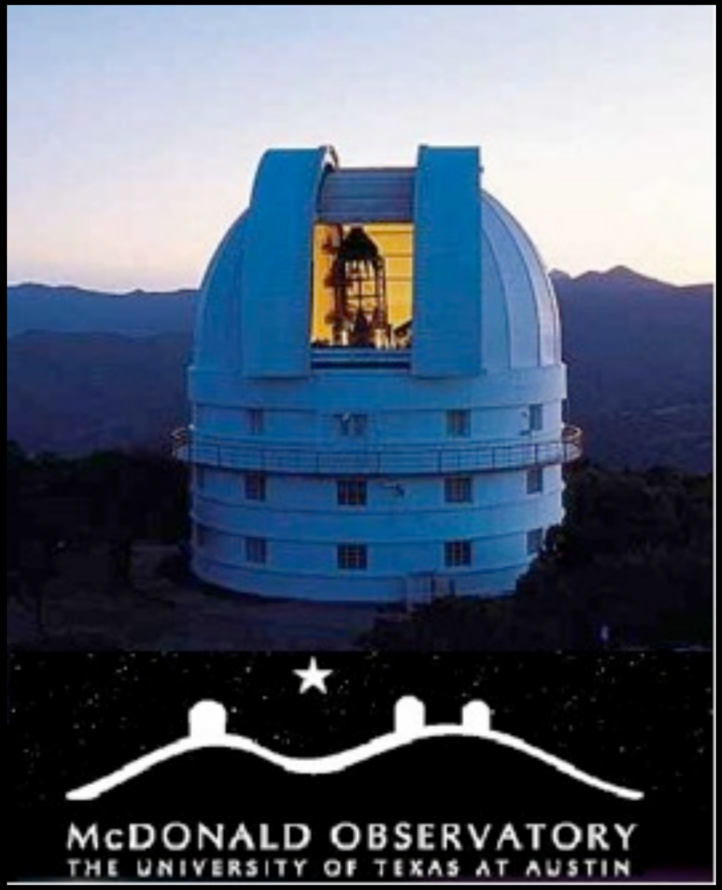


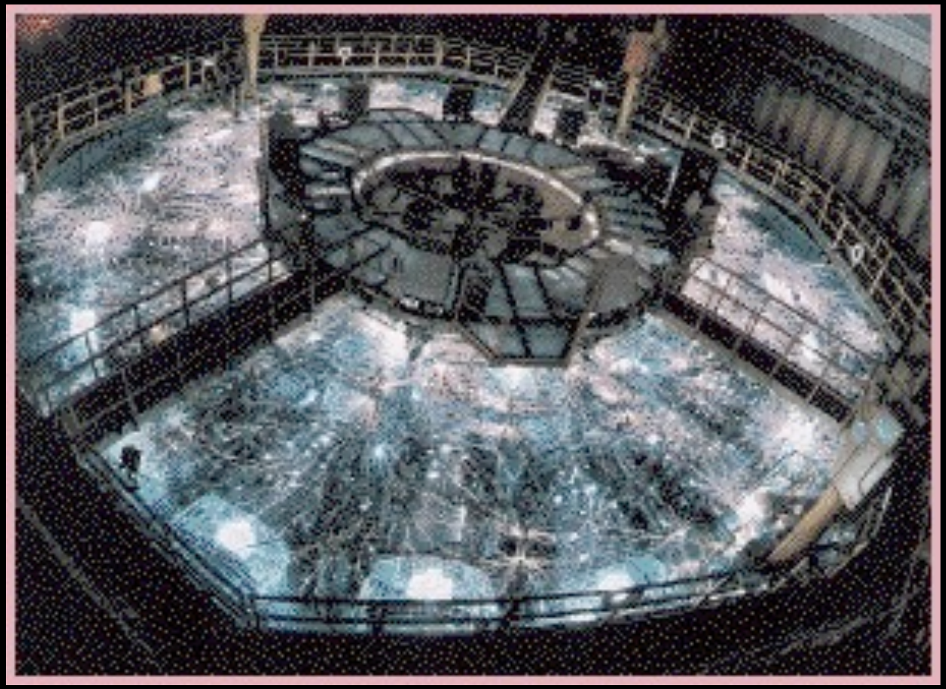
- Dark Matter & Dark Energy
- Snla Progenitors: DE
- Crystallization of Dense Coulomb Plasmas

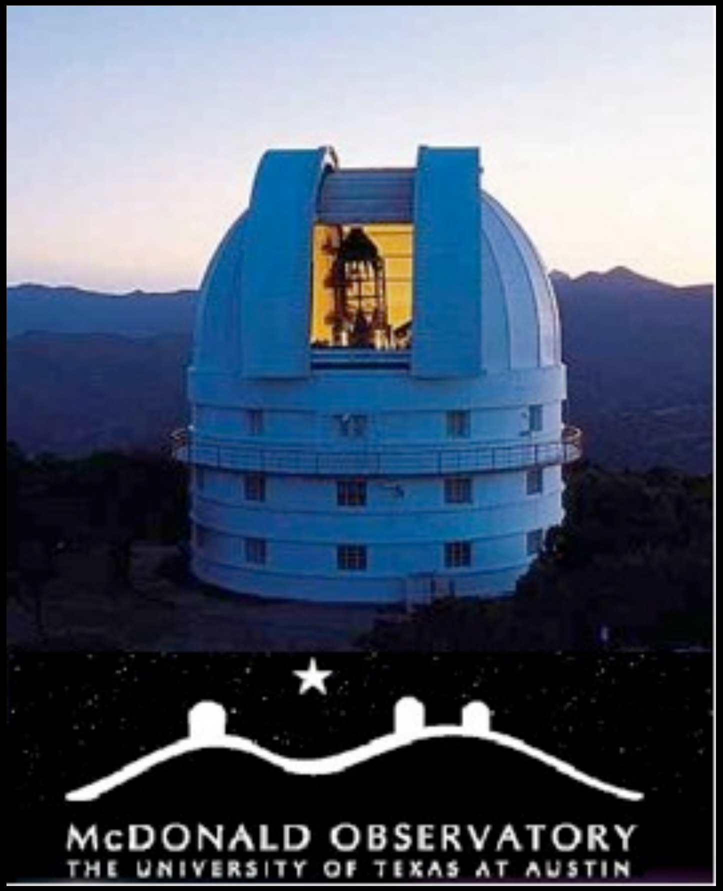
# 17th European Workshop on White Dwarfs
# 16-20 August,Tübingen

Please see posters by Ross Falcon: lab WDs
J.J. Hermes: planet search status!

***Vielen Dank!***

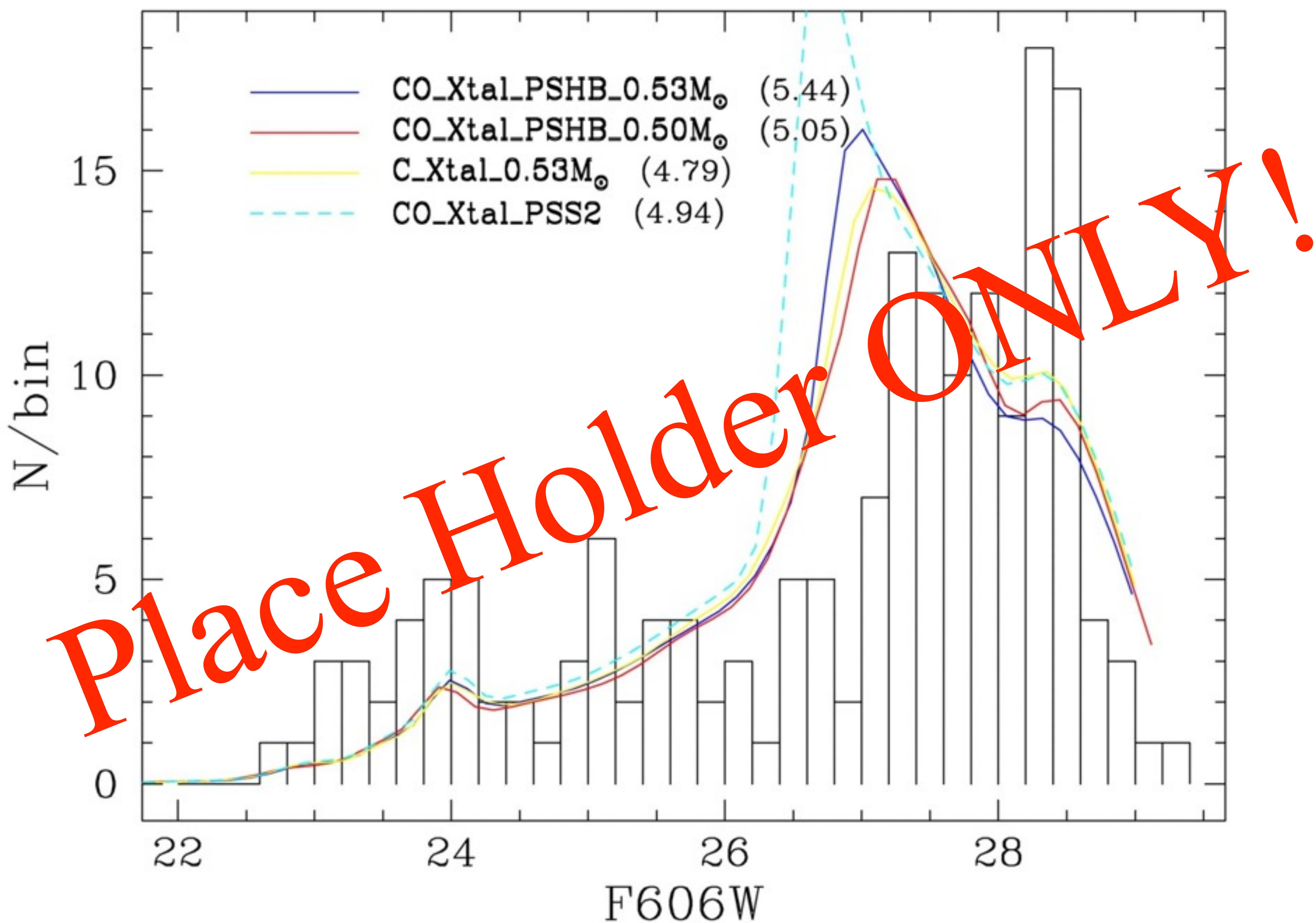




Please see posters by Ross Falcon: lab WDs
J.J. Hermes: planet search status!

# M4 White Dwarfs



# 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 all previous spectroscopic determinations except that of **Tremblay & Bergeron (2009)** which used improved Stark broadening calculations

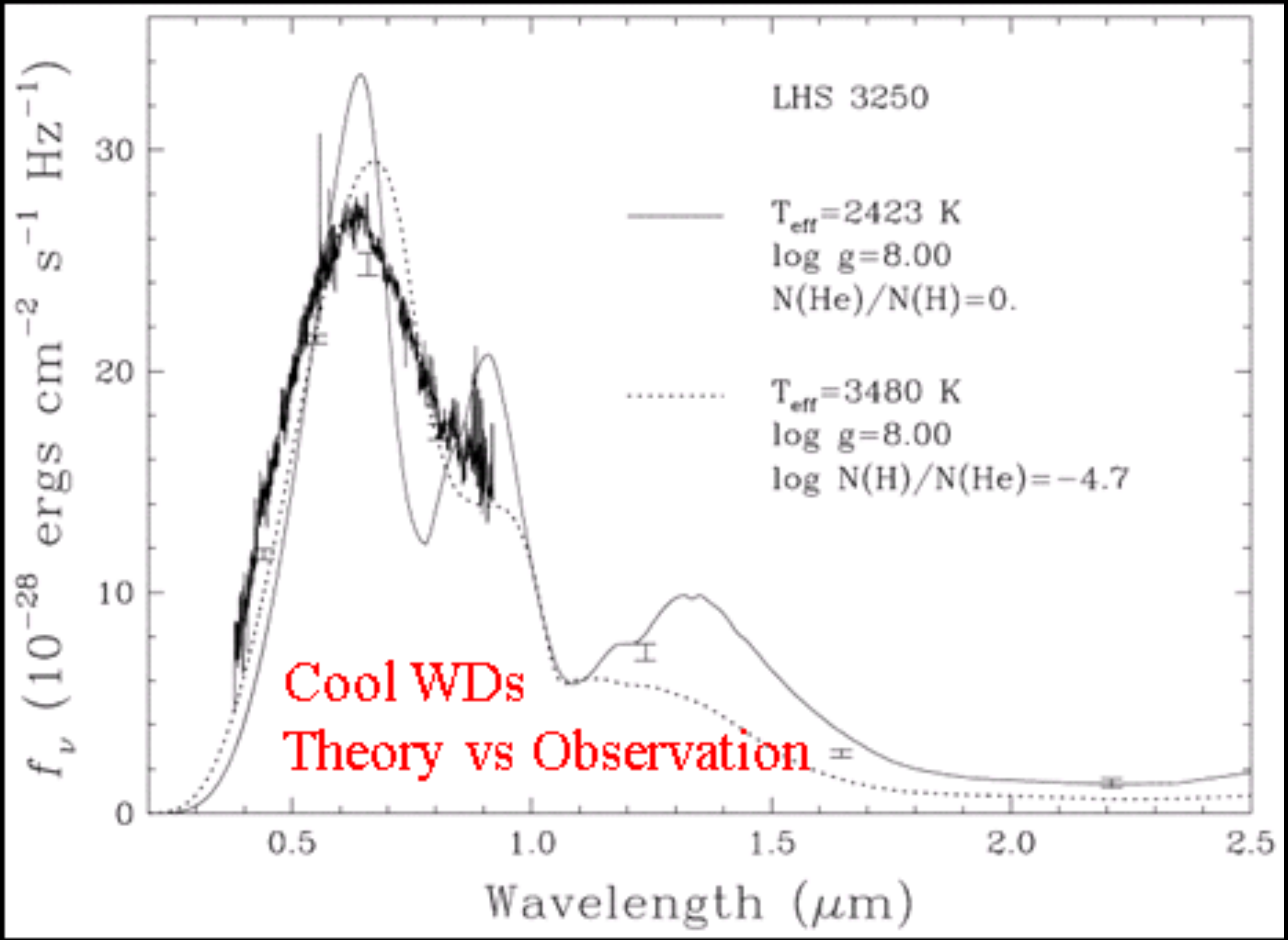
- Unlike spectroscopic surveys, do not find significant change in mean mass across $T_{eff}$ split at 12000 K:

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

  - Need more cool WDs to decrease error bars and get more stringent result
    - HET proposal in prep
  - ***Rule out*** change in mass seen in SPY (Koester et al. 2009) and SDSS samples (Kepler et al. 2007):

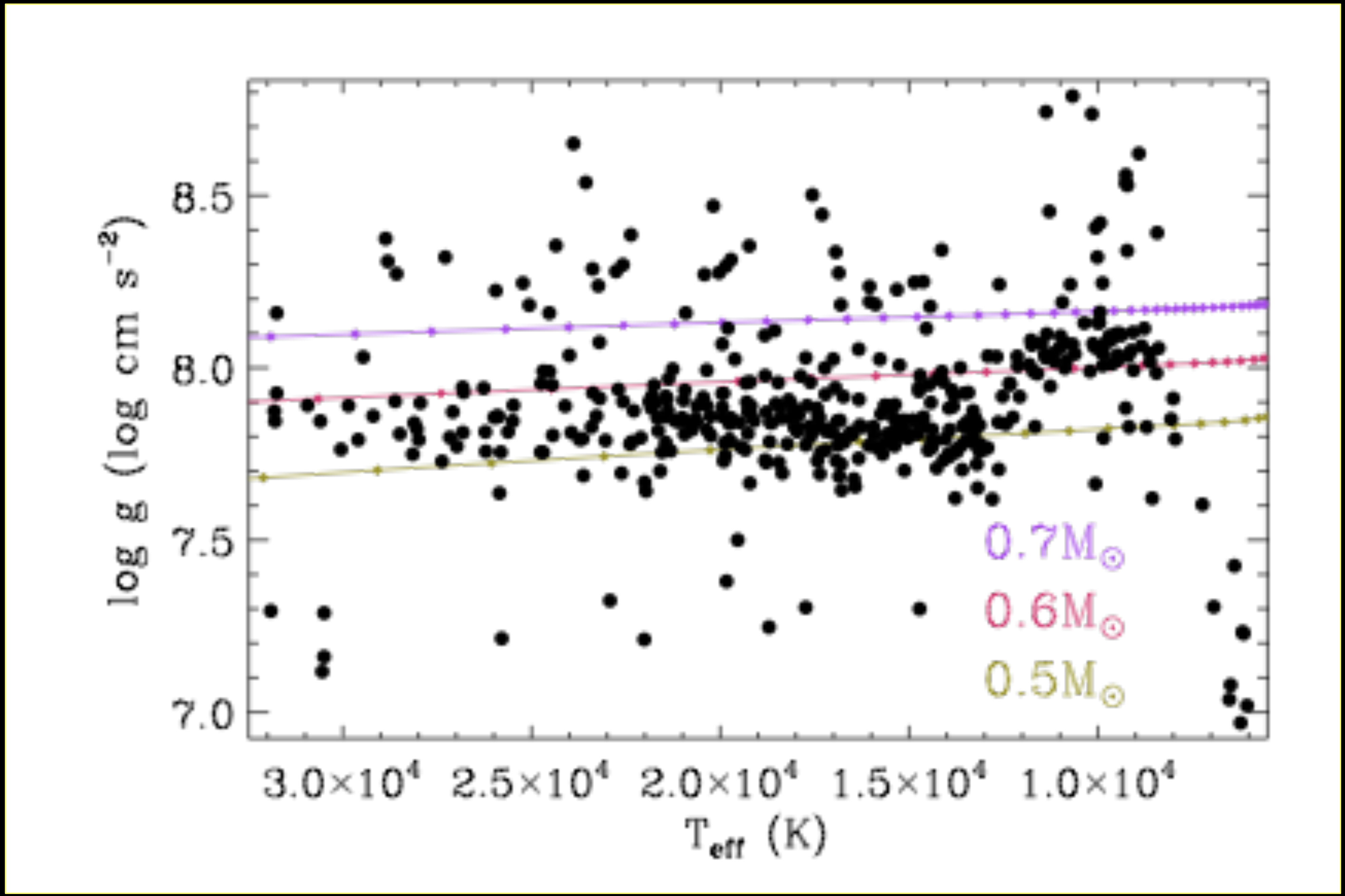
  $$\Delta M = 0.102 +/- 0.01 \text{ and } 0.196 +/- 0.021\ M_\odot$$

# The coolest white dwarf stars are badly fit …




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

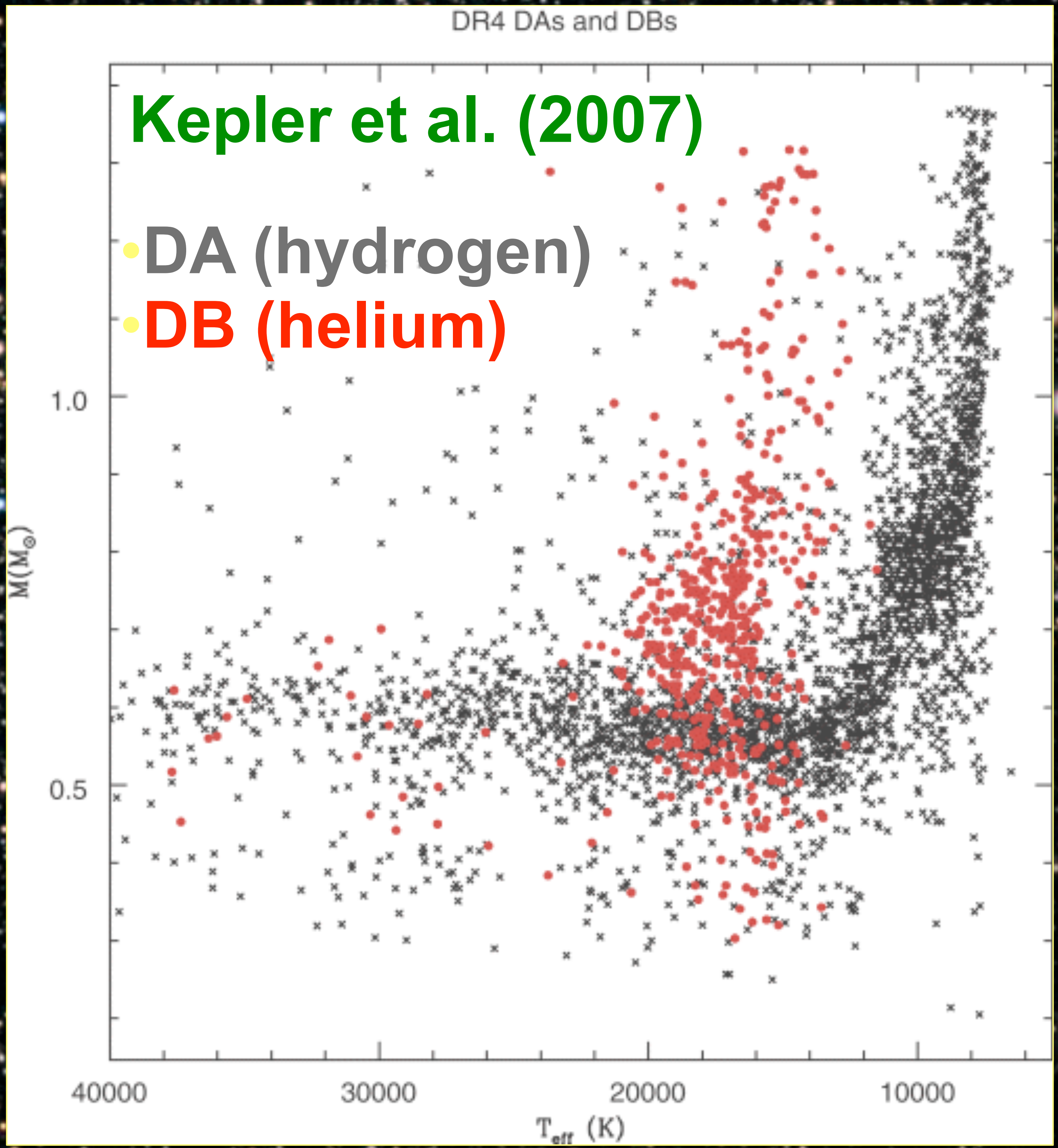
# The H white dwarfs (Koester et al. 2009)

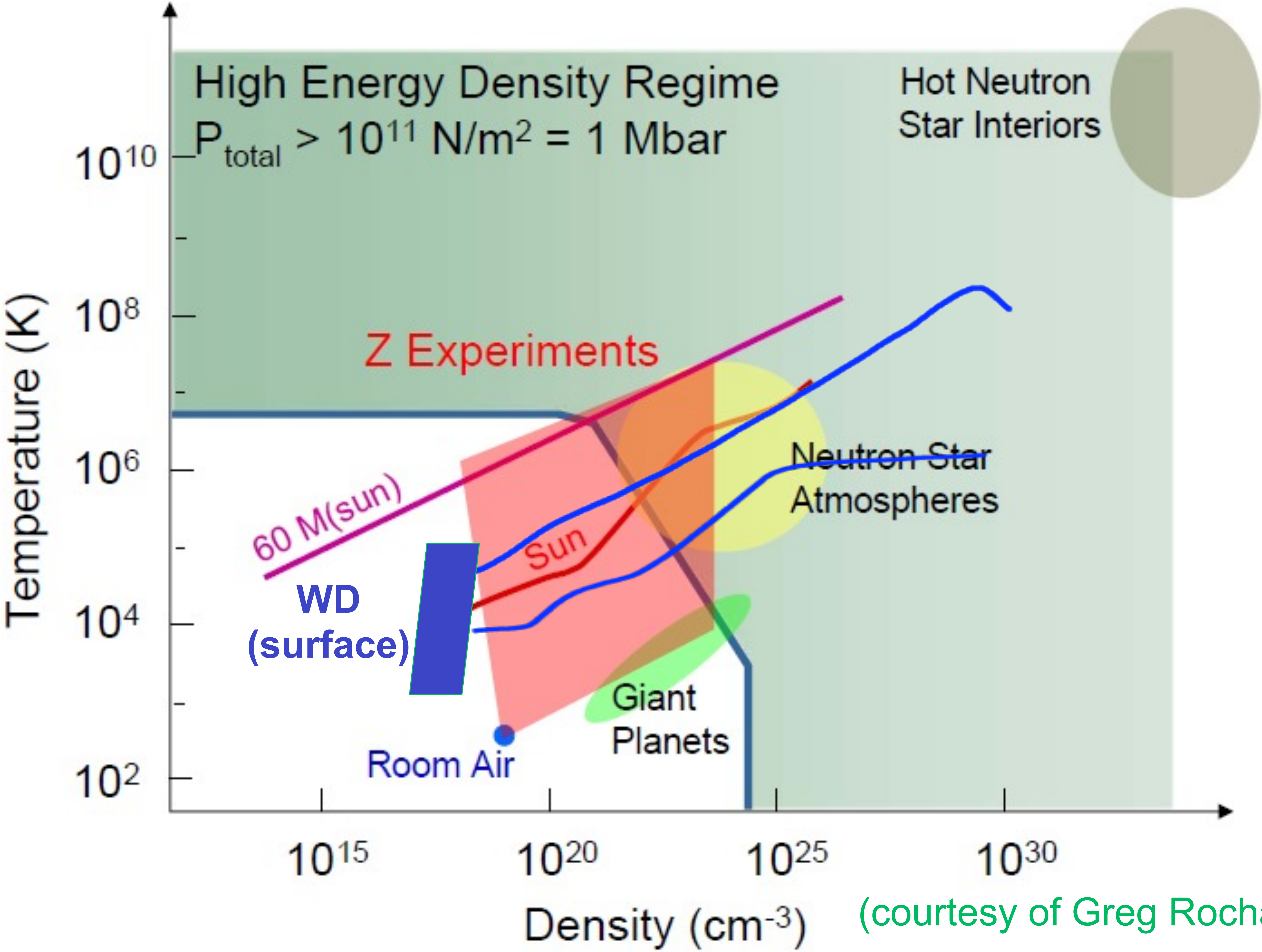



He WDs have the *same problem*, just higher $T_{\mathrm{eff}}$

Carbon WDs are worse!

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






(courtesy of Greg Rochau)