Detection of a large population of white dwarfs in the direction of the Galactic bulge

SPACE TELESCOPE SCIENCE INSTITUTE
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CTIO 50 years, May 7, 2013

Summary

- **HST proposal and goals**
- Data set and data reduction
- PMs and cleaned bulge CMD
- EHBs and WD cooling sequence of the bulge
- Variables, binaries and exotic objects
- **Conclusions and future** goals

The project: detecting and measuring the masses of isolated black holes and neutron stars in the Galactic bulge

Stars with $M > 20\ M_\odot$ end their lives as black holes. There should be ~100 million of Black Holes (BHs) in the Galaxy.

A large fraction of them are expected to be isolated, because:

- ~30% start as single stars
- close binaries lead to merging during Supernova explosions
- very wide binaries produce single BHs due to orbital separation by the "kick velocity".

Yet, there has never been an unambiguous detection of an isolated black hole!

Microlensing is perhaps the only method capable of detecting solitary BHs

The SWEEPS low-reddening window

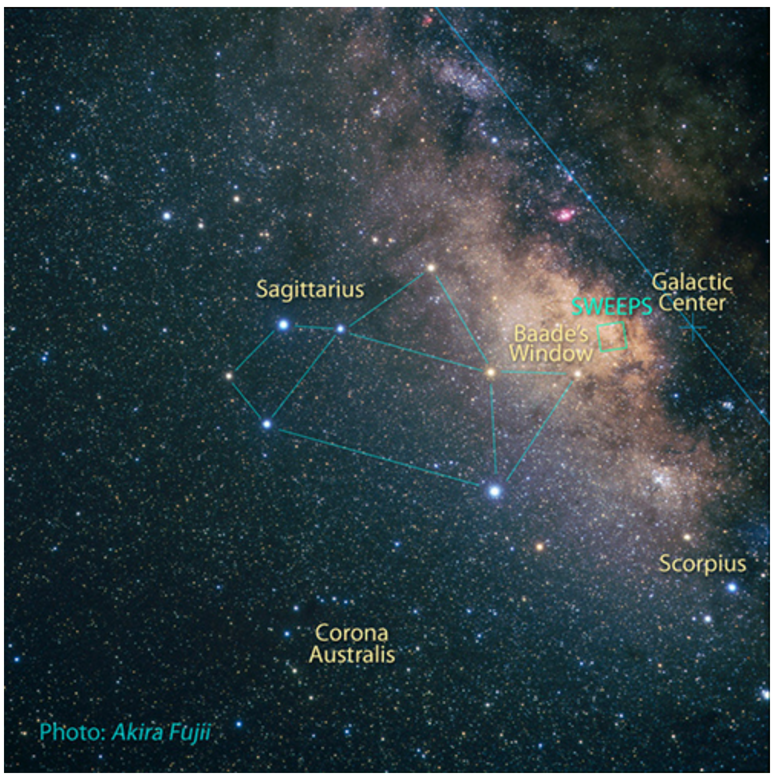
Sagittarius Window Eclipsing Extra-solar Planet Search (SWEEPS)

1 field observed already in 2004 with ACS time series photometry in F606W, F814W (1 week baseline)

Lead to the discovery of 16 candidate transiting extra-solar planets (Sahu et al. 2006)

RA = 17:58:43, DEC = -29:15:14, (l,b) = (1,-2.65)

E(B-V) ≈ 0.5 mag



Detecting and Measuring the Masses of Stellar Remnants

(HST Proposal GO-12586, 13057, PI: Sahu)

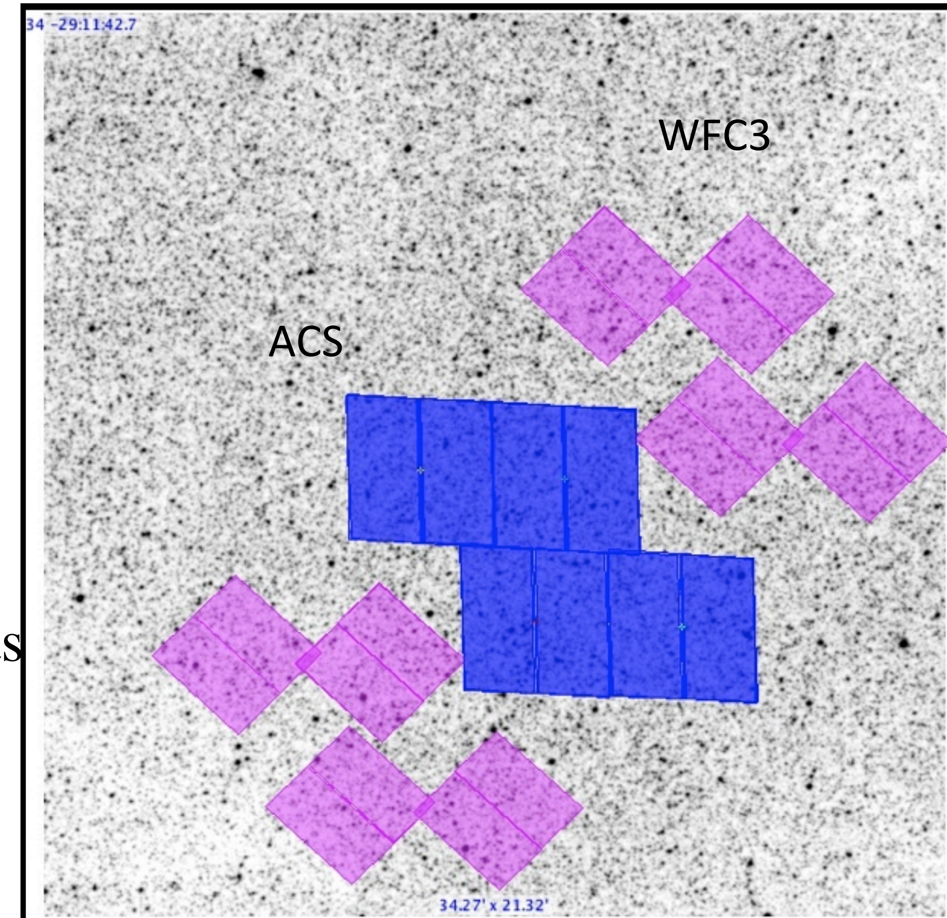
- Fields/ Targets

- 4 ACS, each with ~250,000 stars

- 8 WFC3/UVIS, each with ~120,000 stars

Total of ~ 2 million stars!

F606W, F814W



- Observing cadence

One visit every 2 weeks

8 months per year, for 3 years

Optimized for **long-duration events**

Should detect many microlensing events including some BHs and NSs.

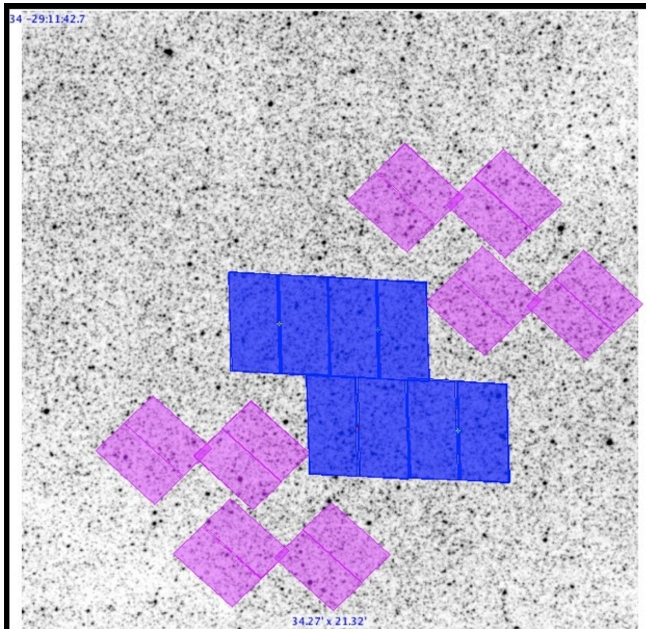
2nd year observations started Feb 14!

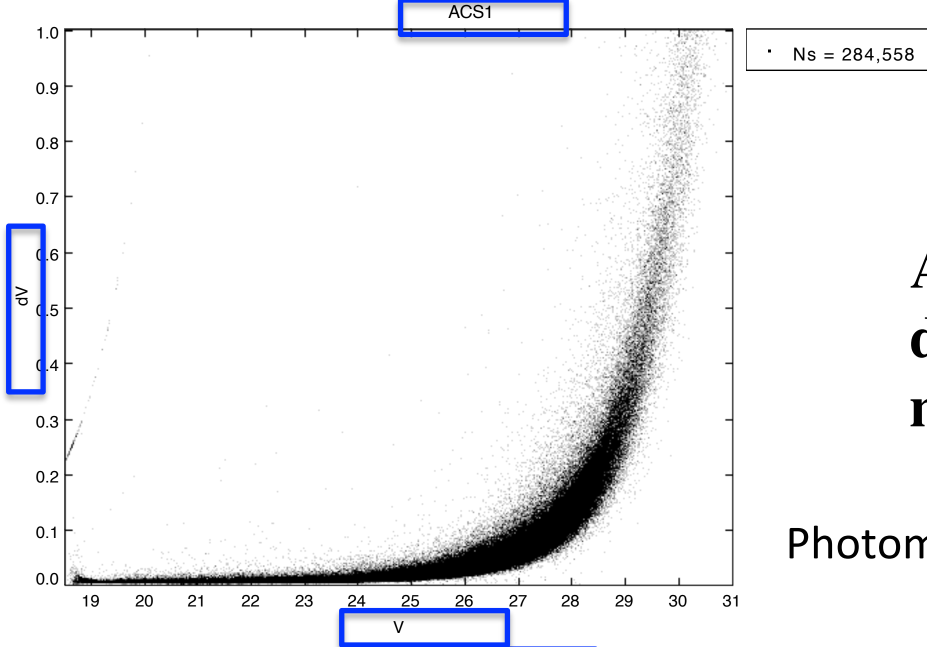
Data reduction

2 F606W and 2 F814W-band images per epoch**: total of 29 F606W and 30 F814W images in seven months baseline** (March-October 2012) plus one observation in October 2011 **for 4 ACS fields (~ 240 images)**

Routine **img2xym** for the first step Point-Spread Function (PSF) photometry on the individual images and routine **KS**2 for performing simultaneous PSF photometry on all the F606W-F814W images

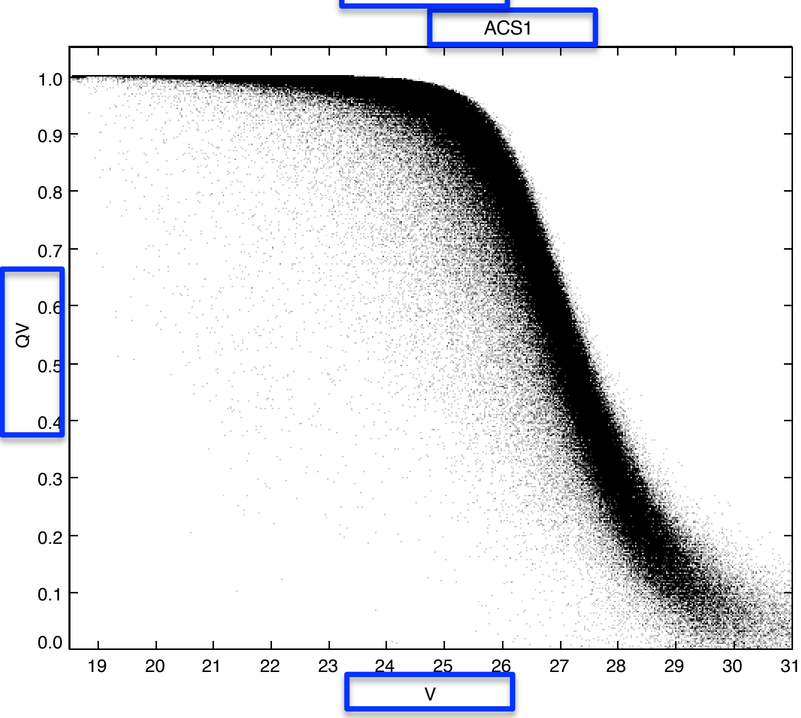
Four ACS fields reduced: ~ 250,000 stars per field -> Total of ~ 1 million stars down to V ~ 31 mag -> Deepest CMD in the direction of the bulge



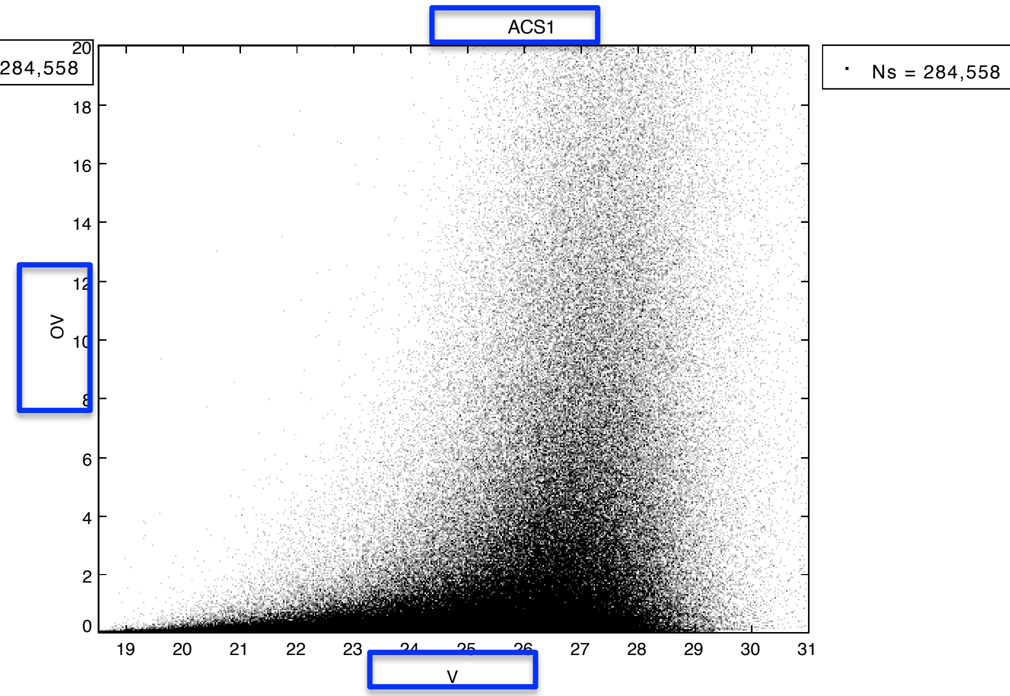


After selection -> ~ 700,000 stars down to V = 28.5 mag with σ(V) < 0.2 mag

Photometric accuracy (RMS of PSF fit)

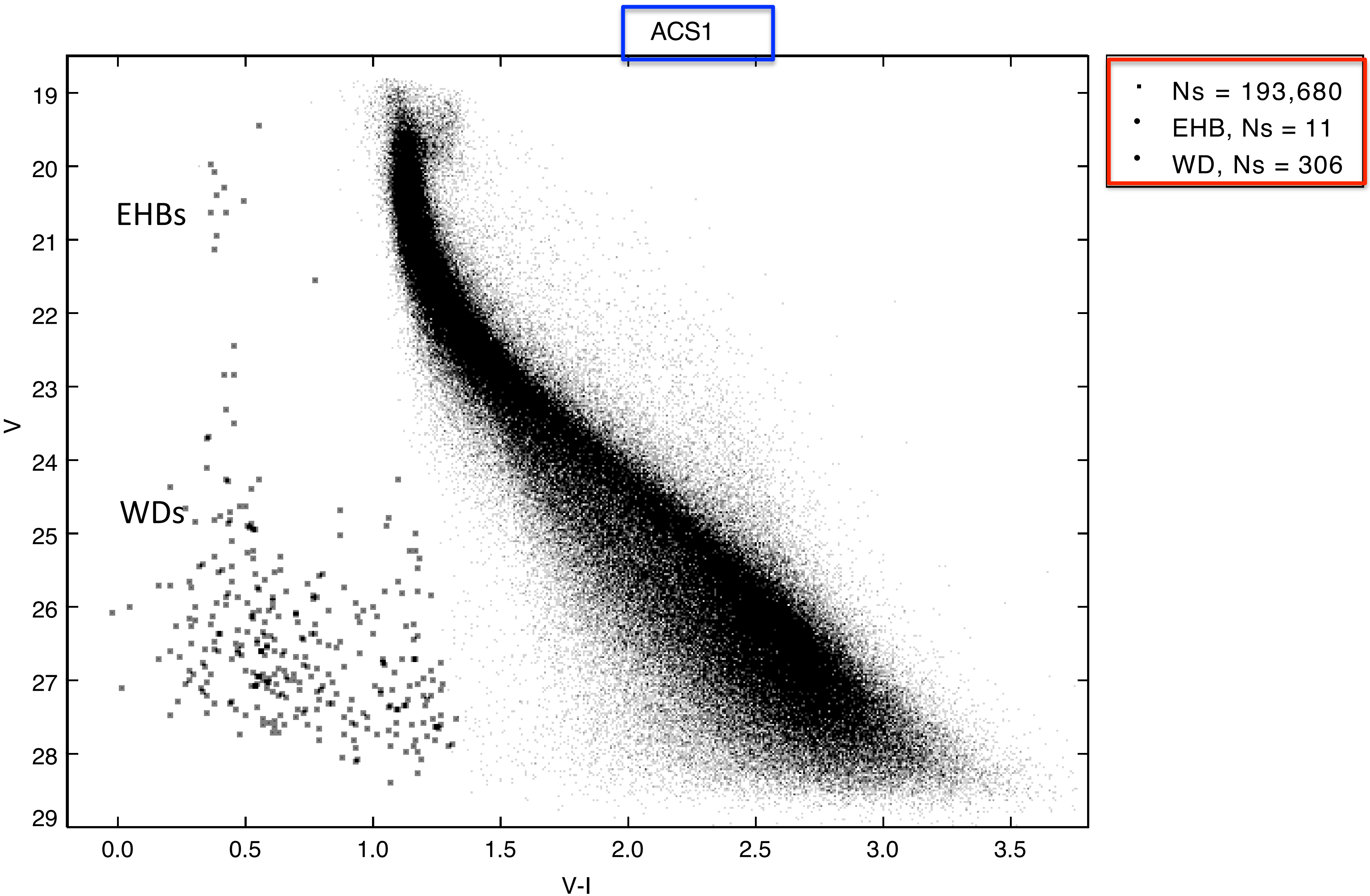


Similarity to the PSF

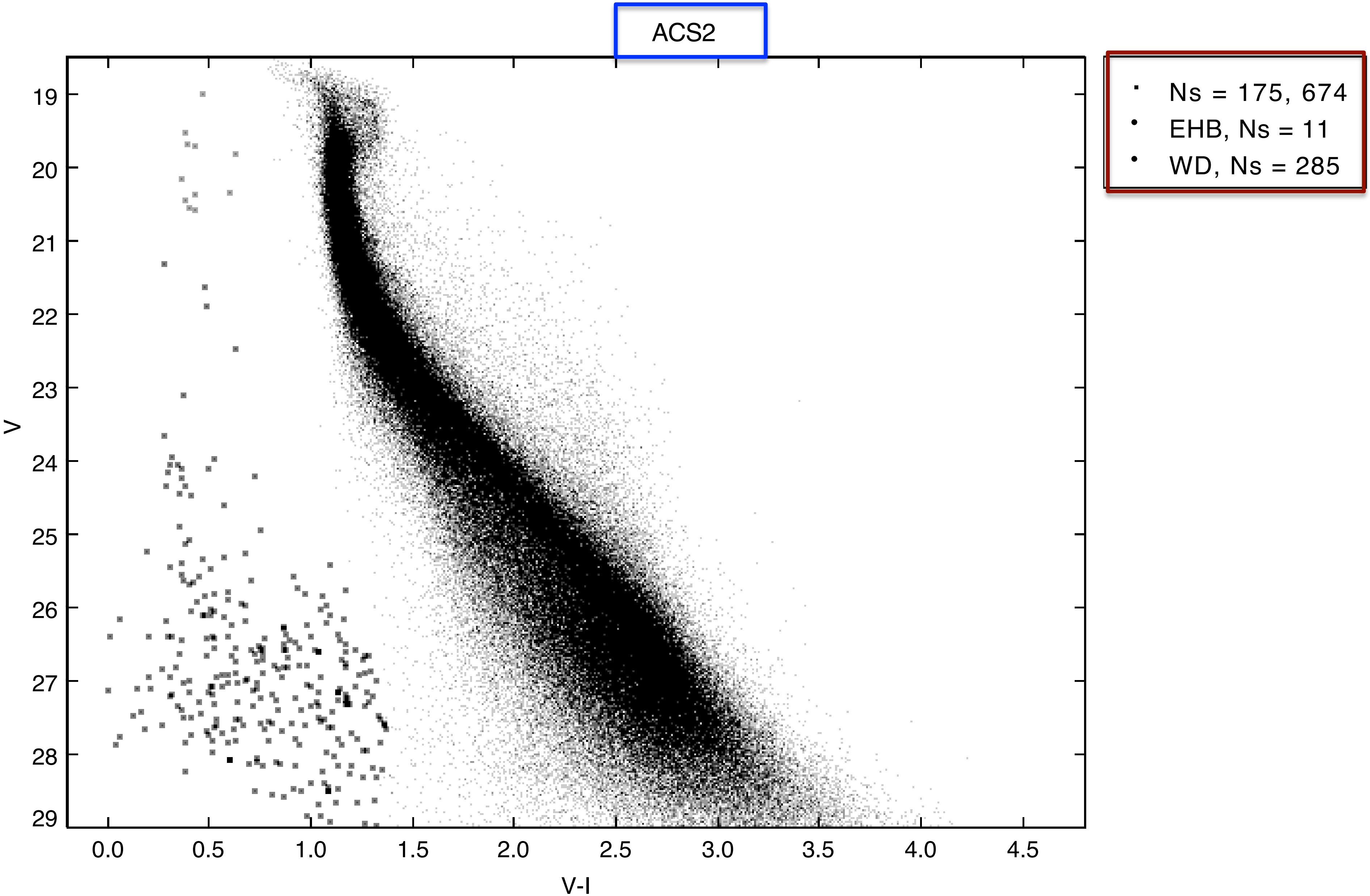


Percentage of contamination by neighbors

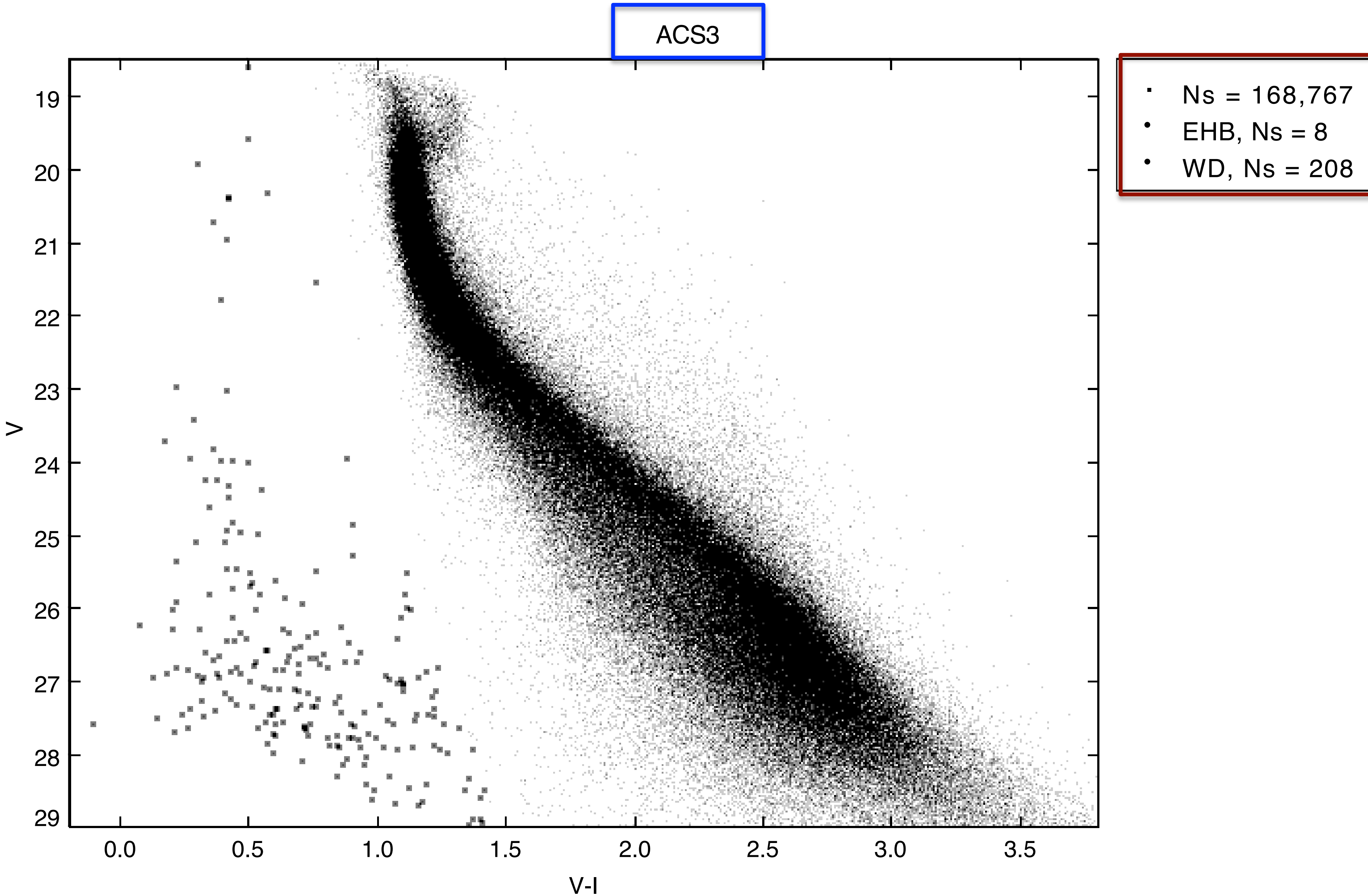
Color-Magnitude Diagrams of the four ACS fields



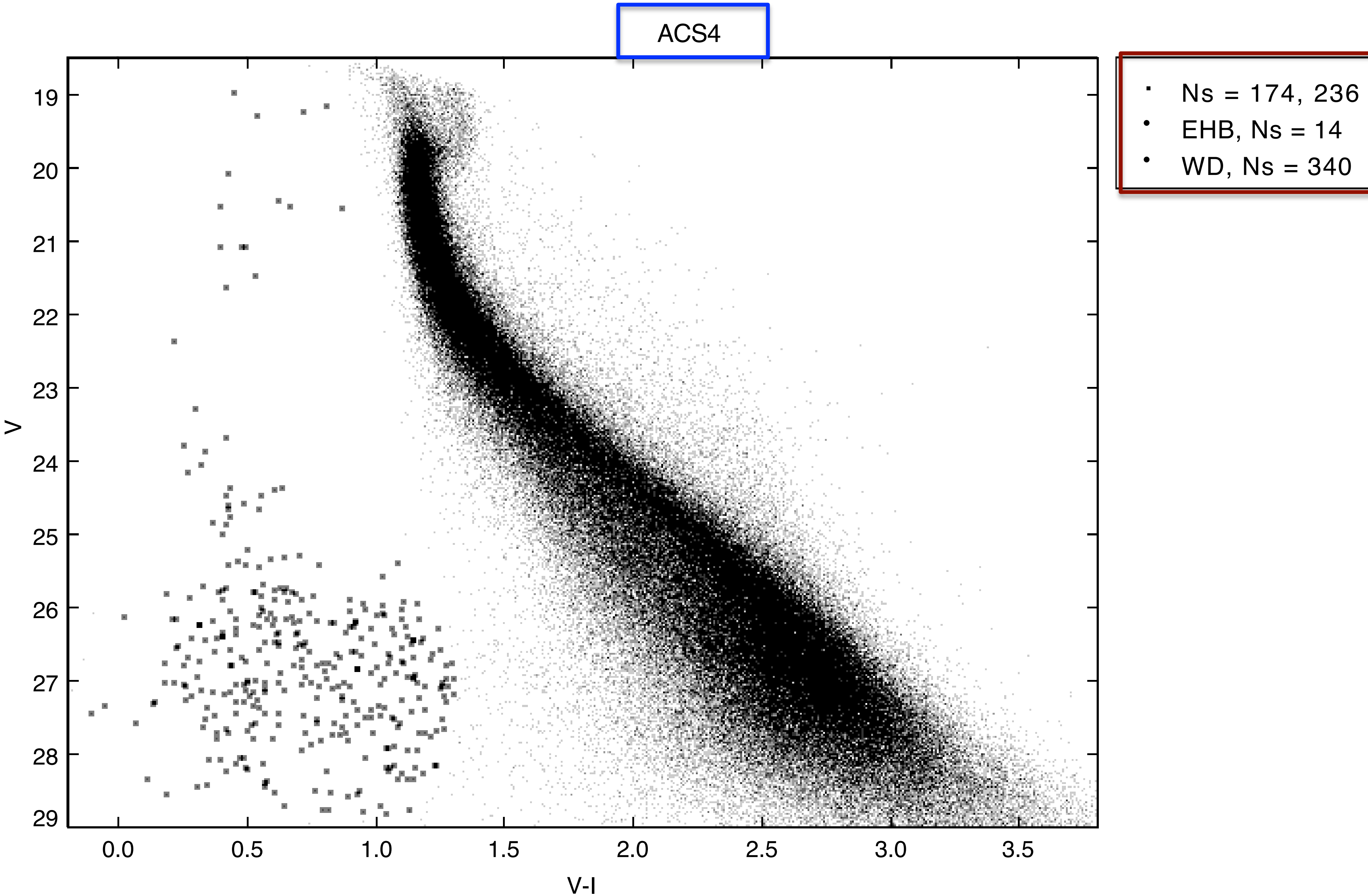
Color-Magnitude Diagrams of the four ACS fields



Color-Magnitude Diagrams of the four ACS fields

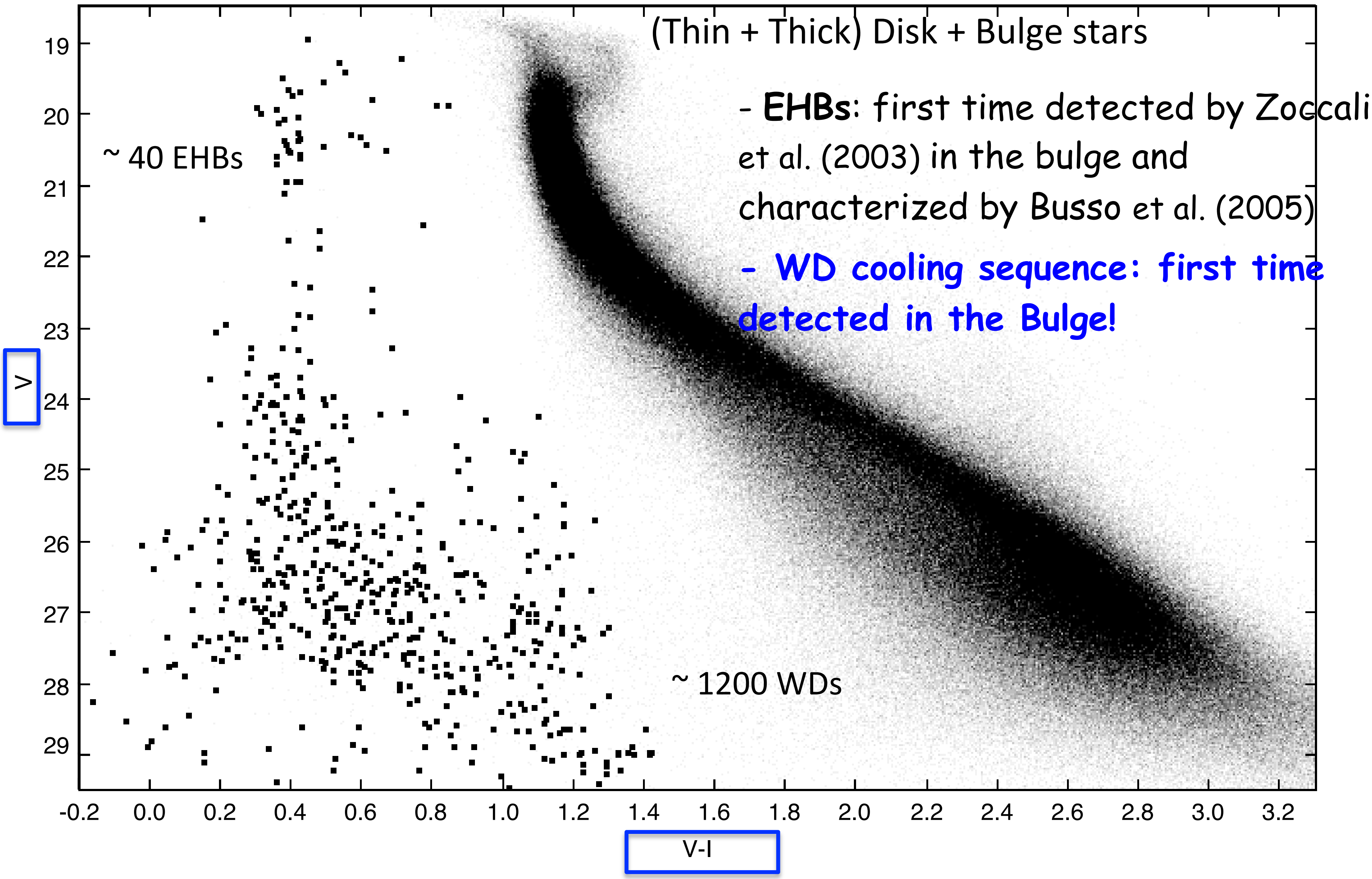


Color-Magnitude Diagrams of the four ACS fields



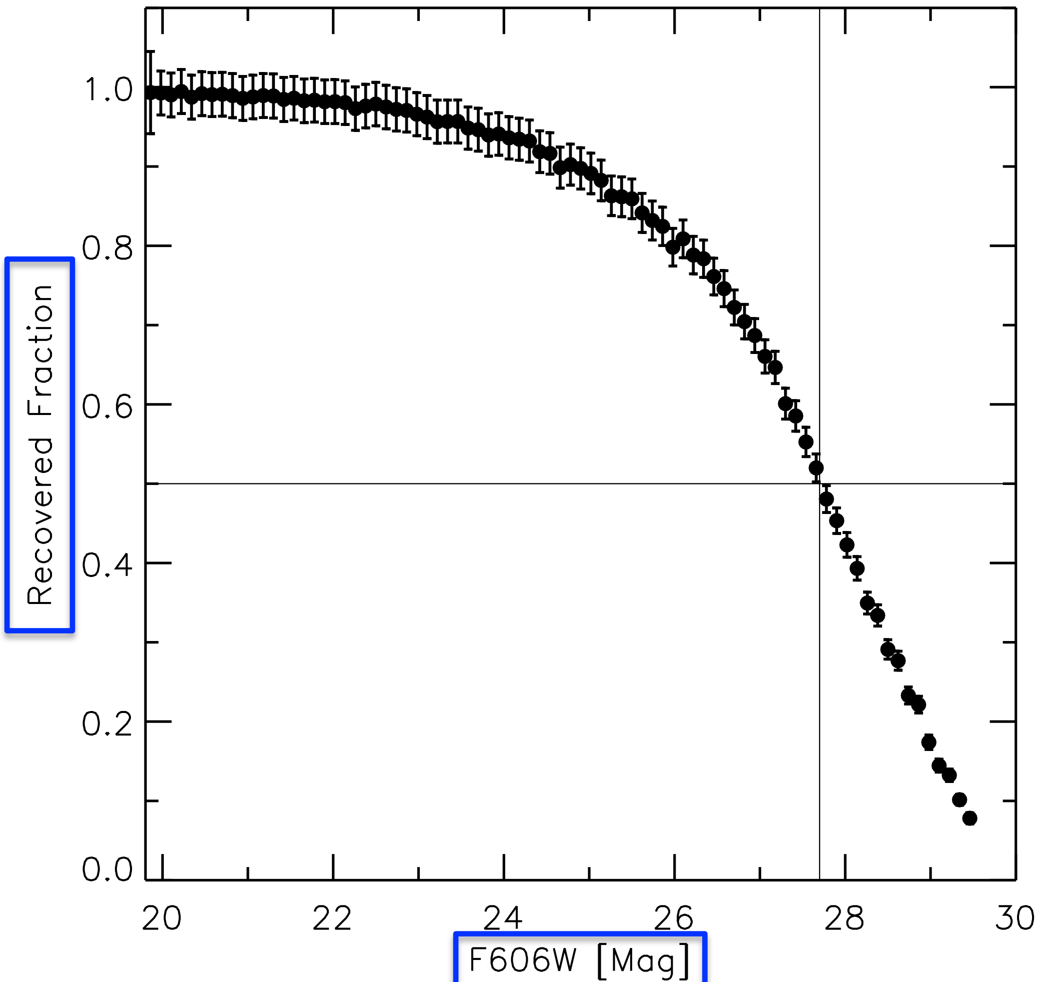
Composite CMD

ACS1 + ACS2 + ACS3 + ACS4: ~ 700,000 stars down to V = 28.5 mag!



Completeness along the MS

- ≈ 220,000 artificial MS stars randomly added to all F606W- and F814W-band images with input magnitudes in the range **19.9 < F606W < 29.5 mag**
- Stars measured with same software & techniques

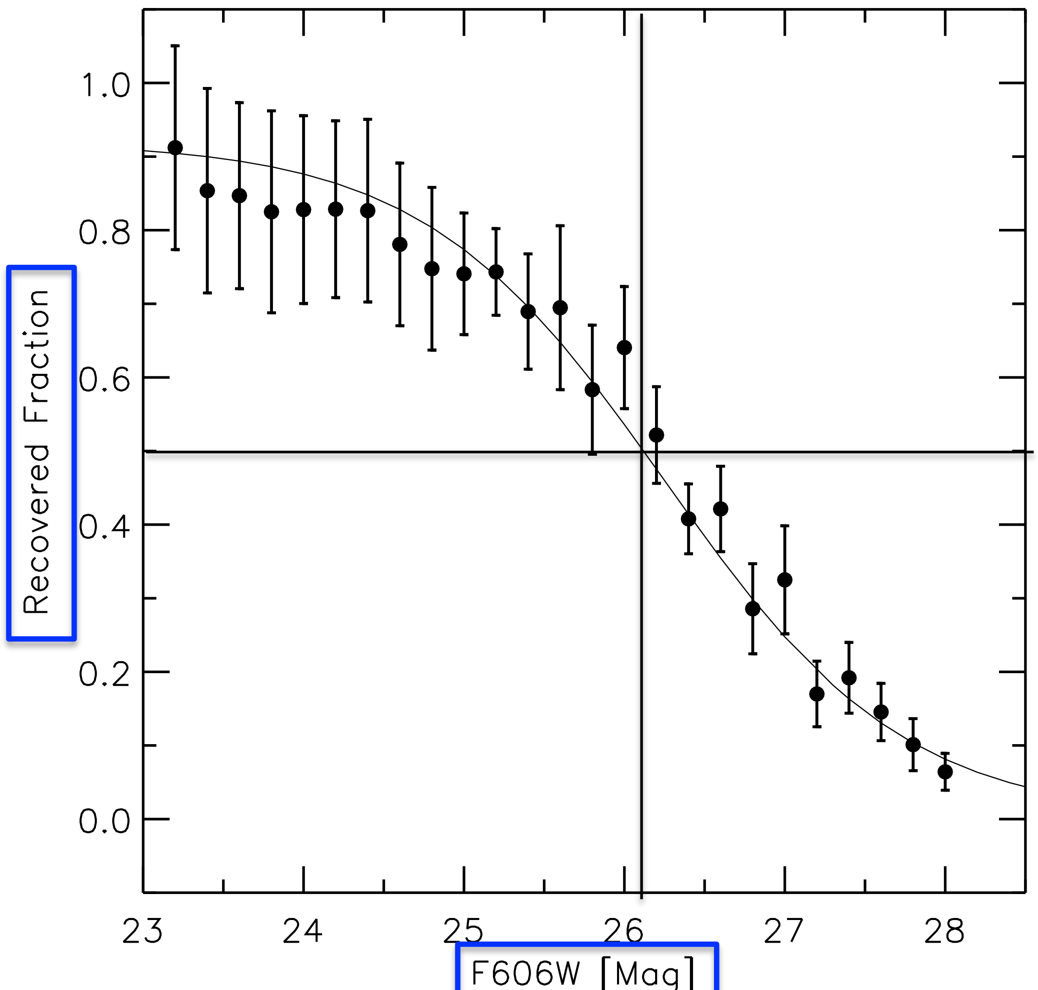


Recovered fraction:

50% at F606W ~ 27.7 mag

Completeness along the WD cooling sequence

- **≈ 6,000 artificial WD stars** randomly added to all F606W- and F814W-band images with input magnitudes in the range **23 < F606W < 31 mag**
- Stars measured with same software & techniques



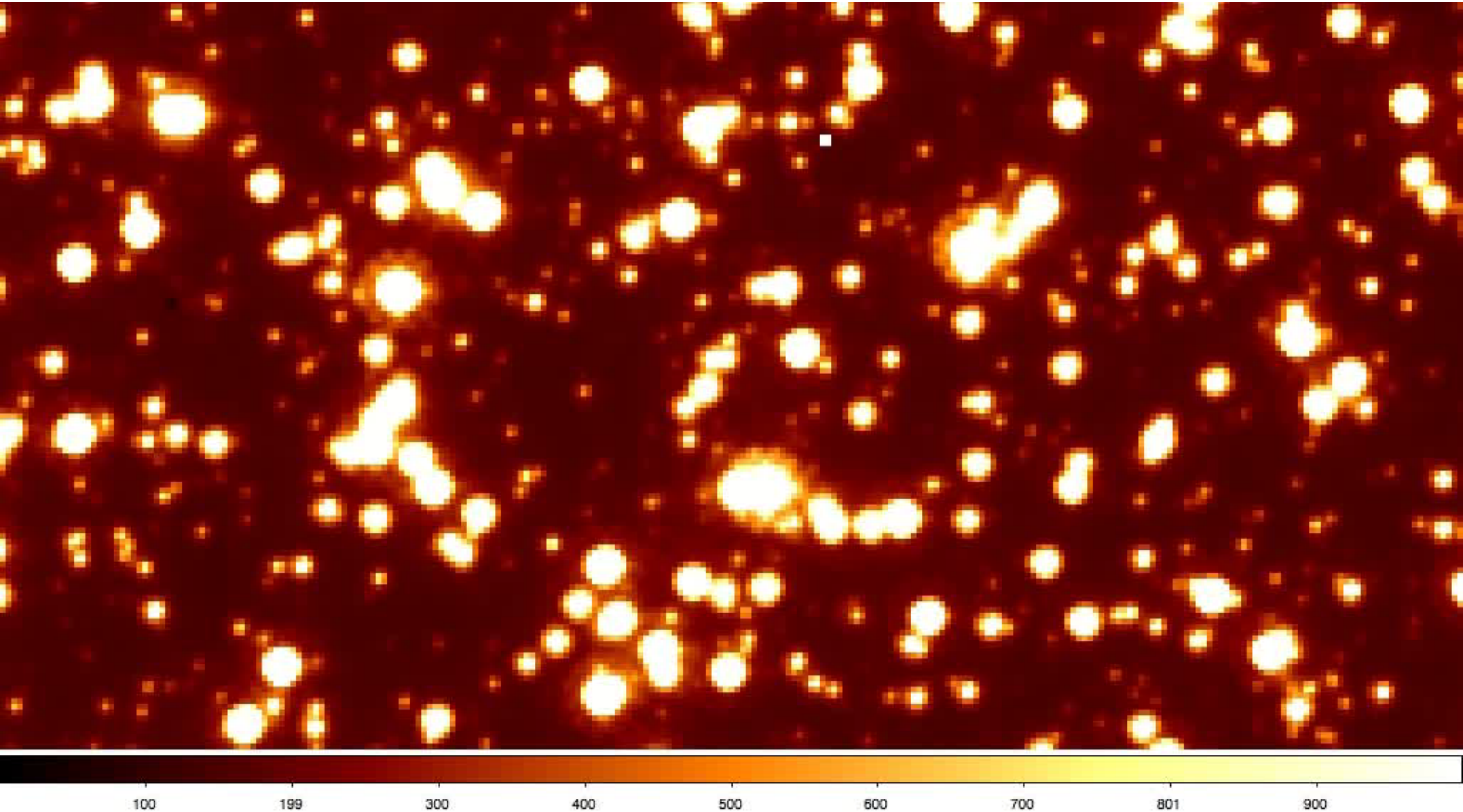
Recovered fraction:

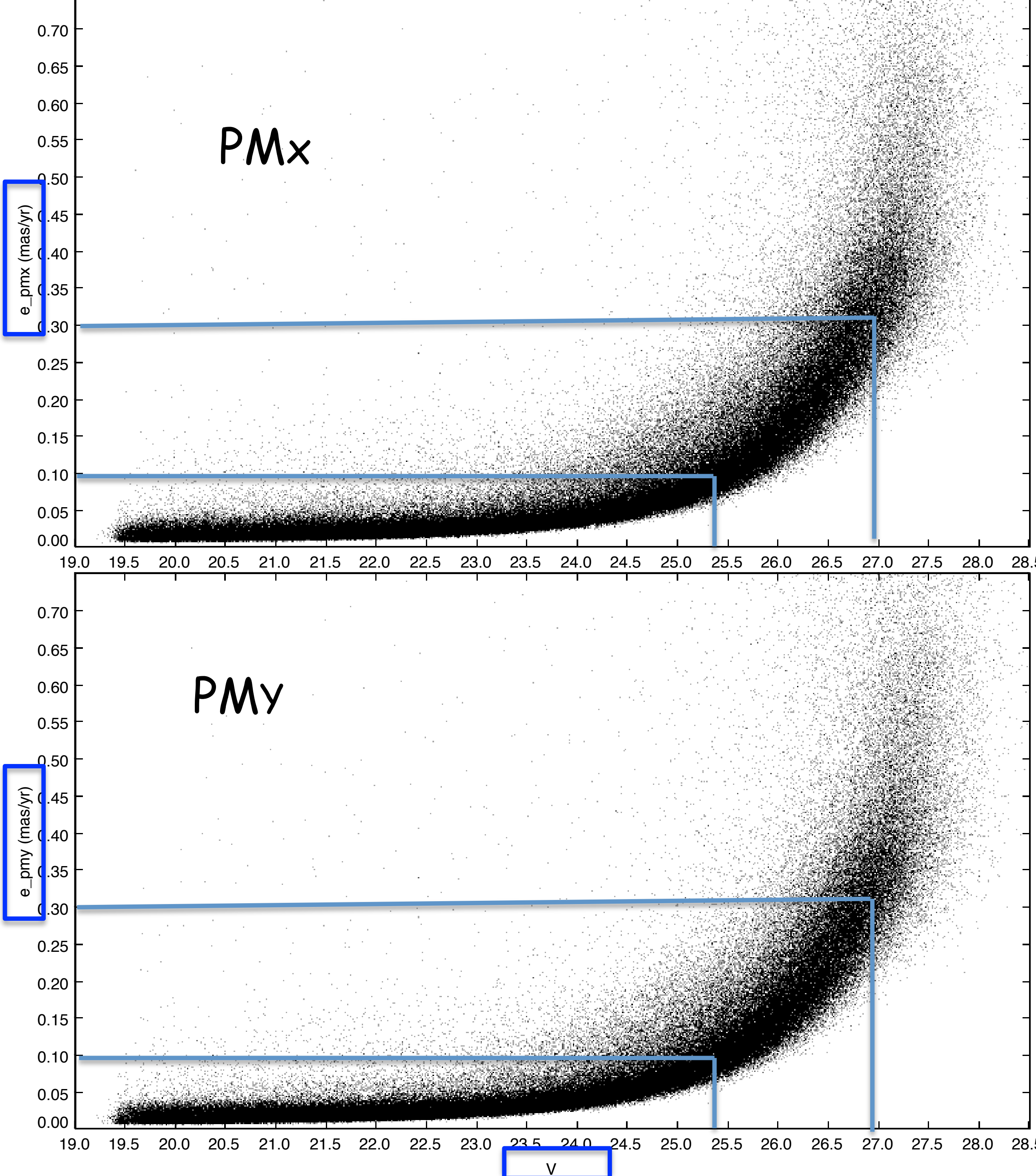
50% at F606W ~ 26 mag

Proper Motions for the SWEEPS field

Observations available in F606W, F814W-band for **2004** (Sahu et al. 2006, Clarkson et al. 2008) and in the F814W-band for **2006** and **2012**

Total of 8 years baseline!

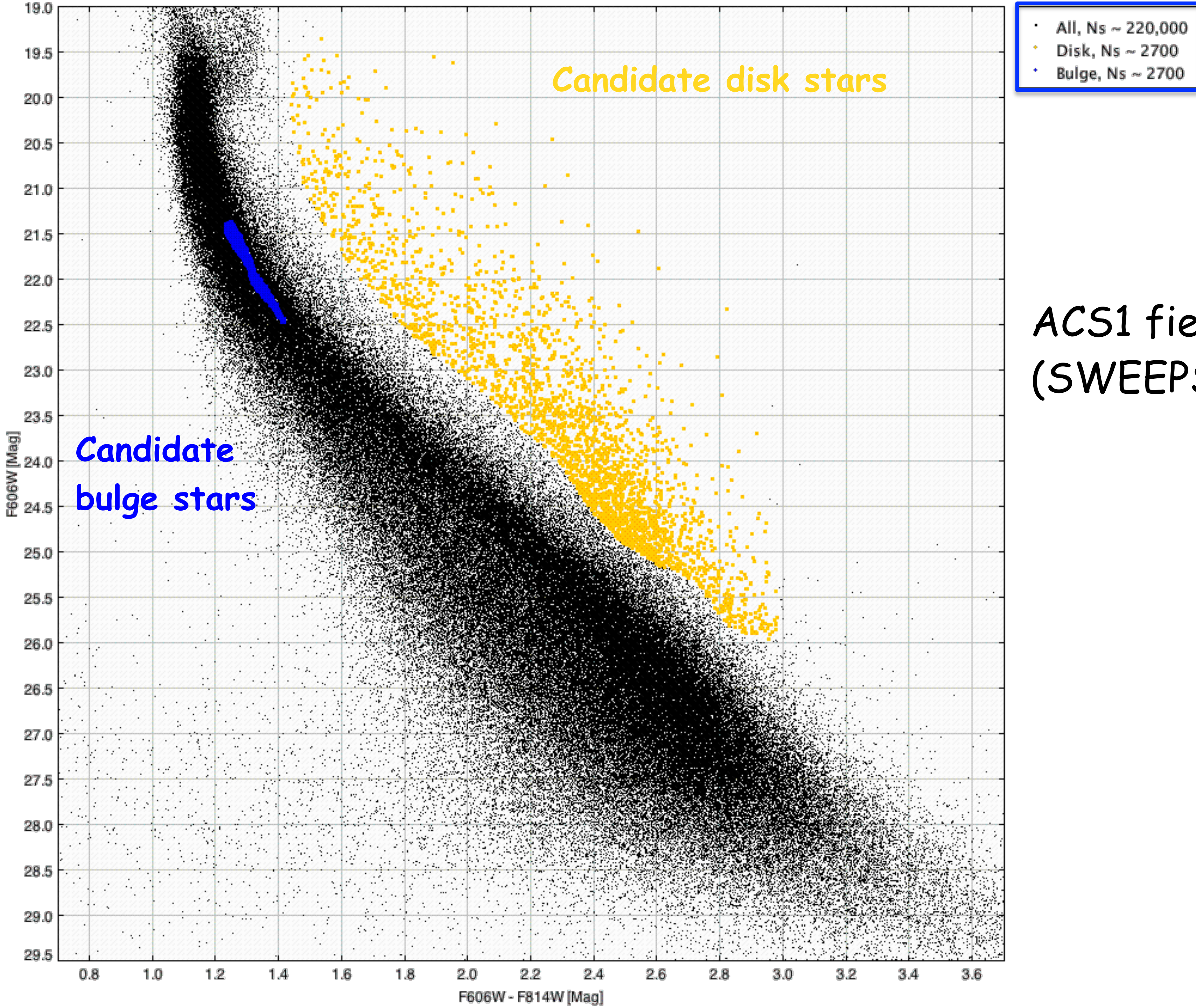




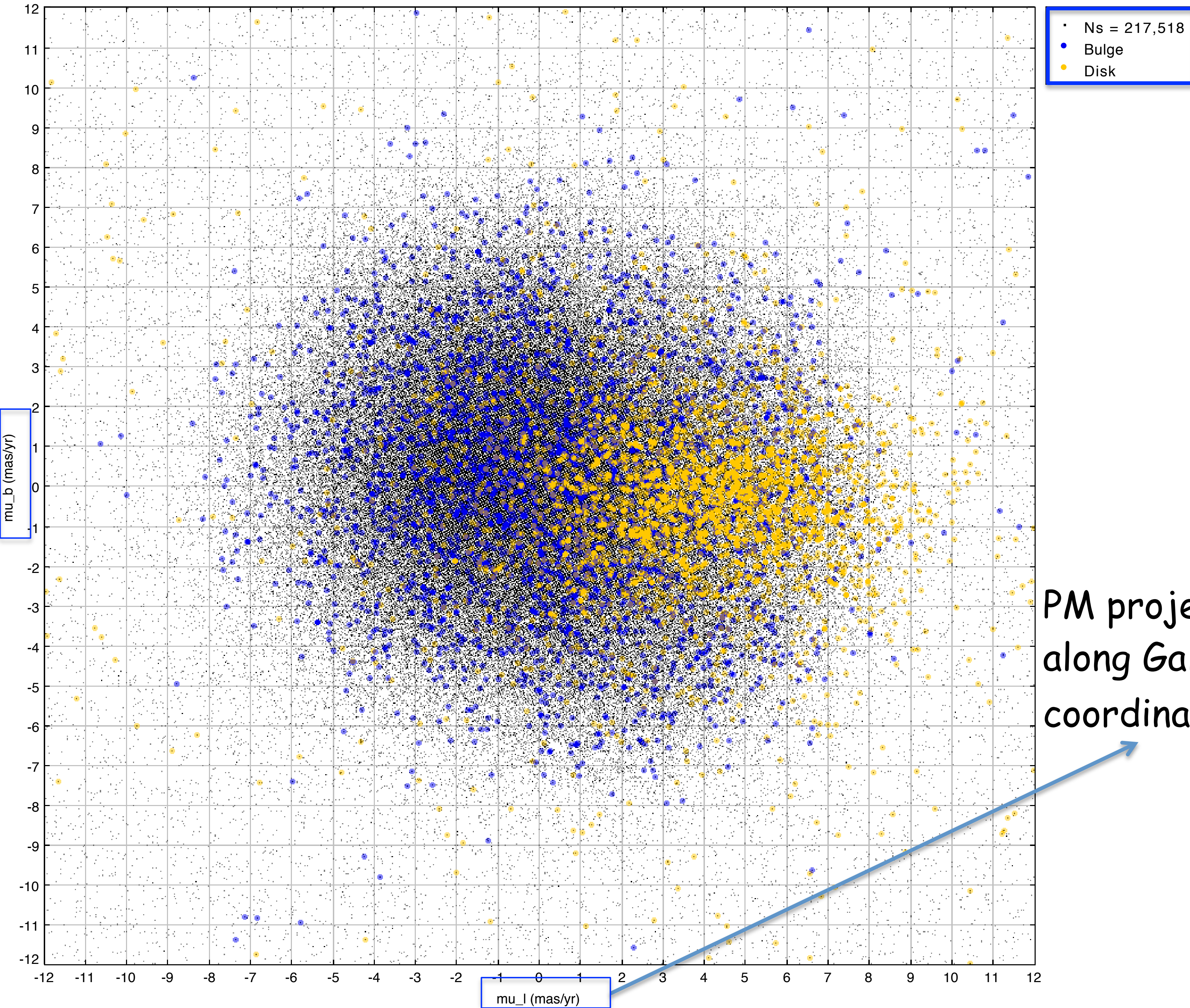
Proper motions for ~ 200,000 stars down to V ~ 28 mag

Proper motions accuracy: e_PMx (PMy) < 0.3 mas/yr at V ~ 27 mag and

e_PMx (e_PMy) < 0.1 mas/yr at V ≈ 25.5 mag

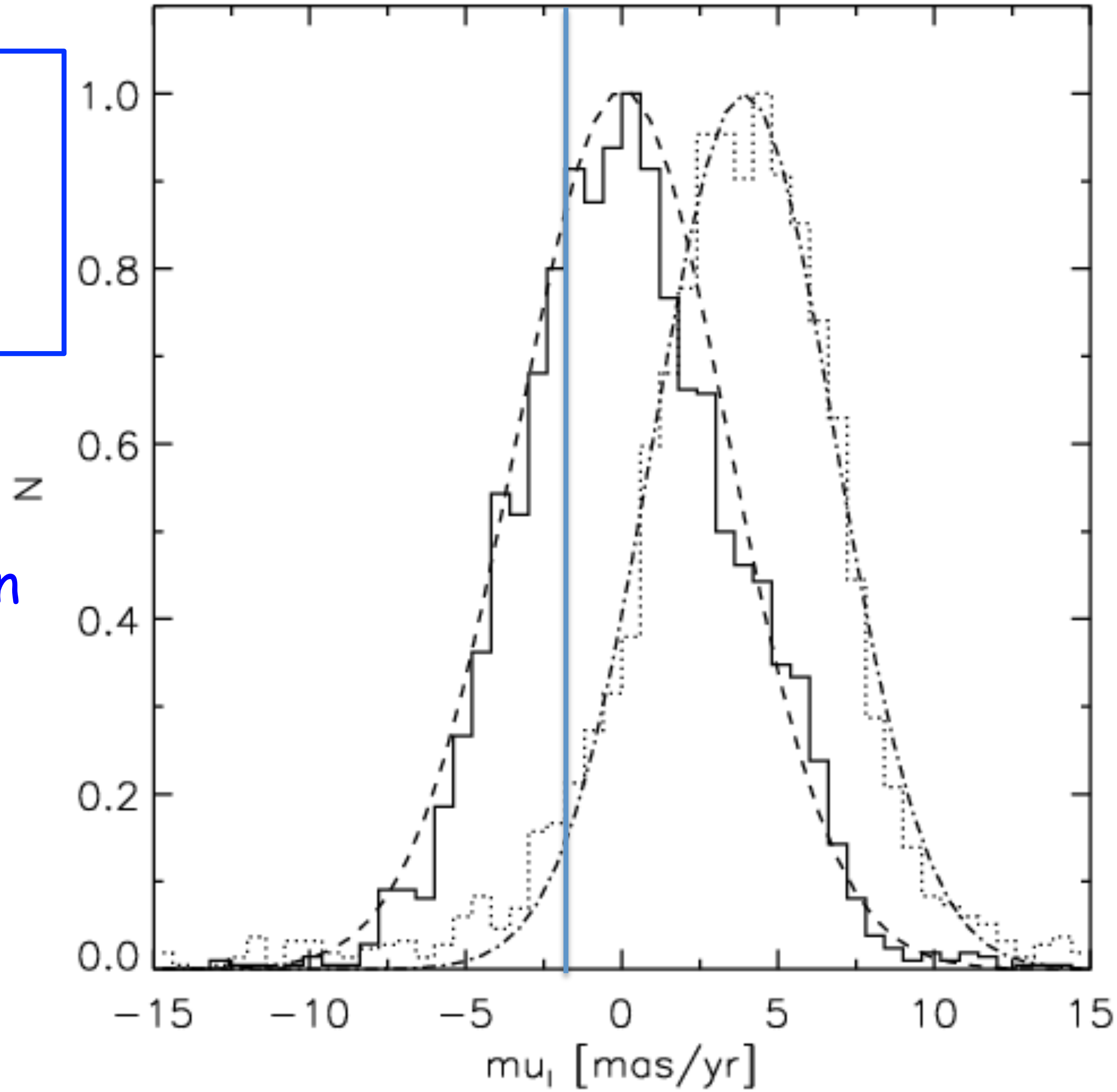


ACS1 field
(SWEEPS)



PM projected along Galactic coordinates

Cut at: -2 mas/yr:
selecting ~ 30% of bulge stars (Clarkson et al. (2008)

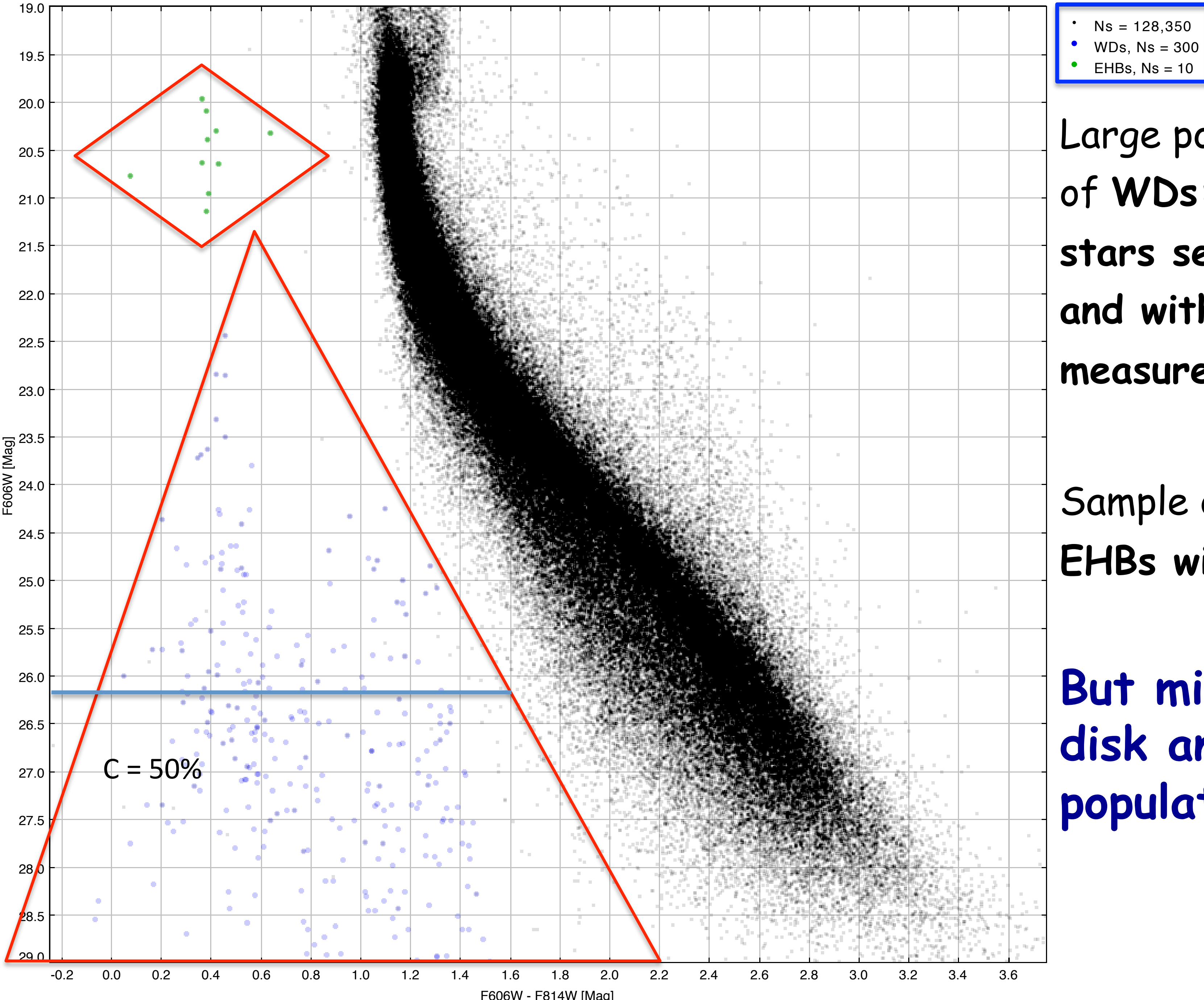


Residual contamination of the sample by disk stars: ~ 1%

Disk: mu_l = **3.91 ± 0.05 mas/yr**

Bulge: mu_l = **0.02 ± 0.07 mas/yr**

ACS1 – SWEEPS field



Large population of **WDs: 300 stars selected and with PM measurements**

Sample of **10 EHBs with PM**

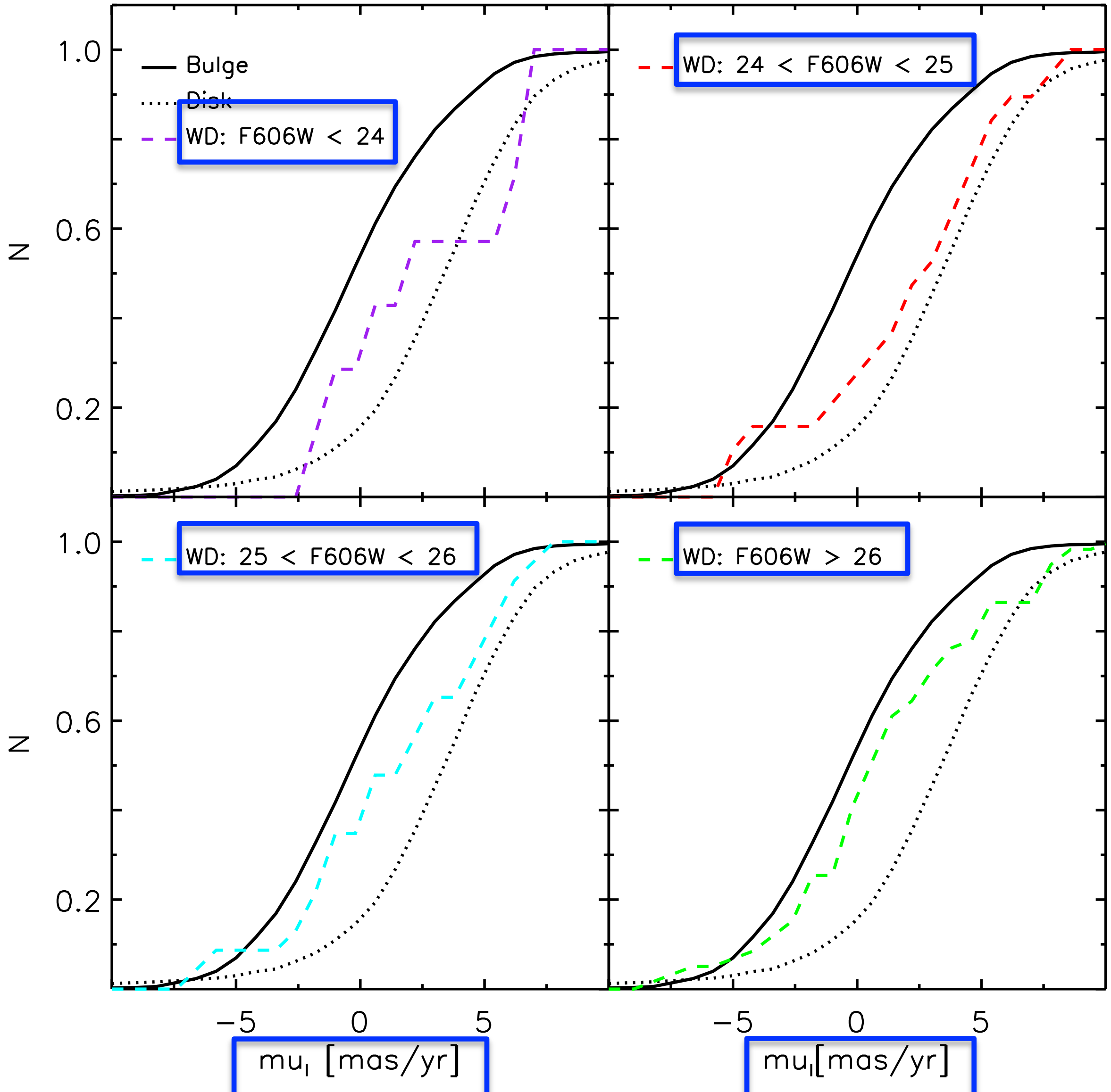
But mix of disk and bulge population!!

WDs with PM measurements (bulge + disk population)

Cumulative distributions in μl (mas/yr)   **Bulge & Disk stars + WDs**

Disk-like

Bulge-like



Apply same PM cut

applied to MS sample:

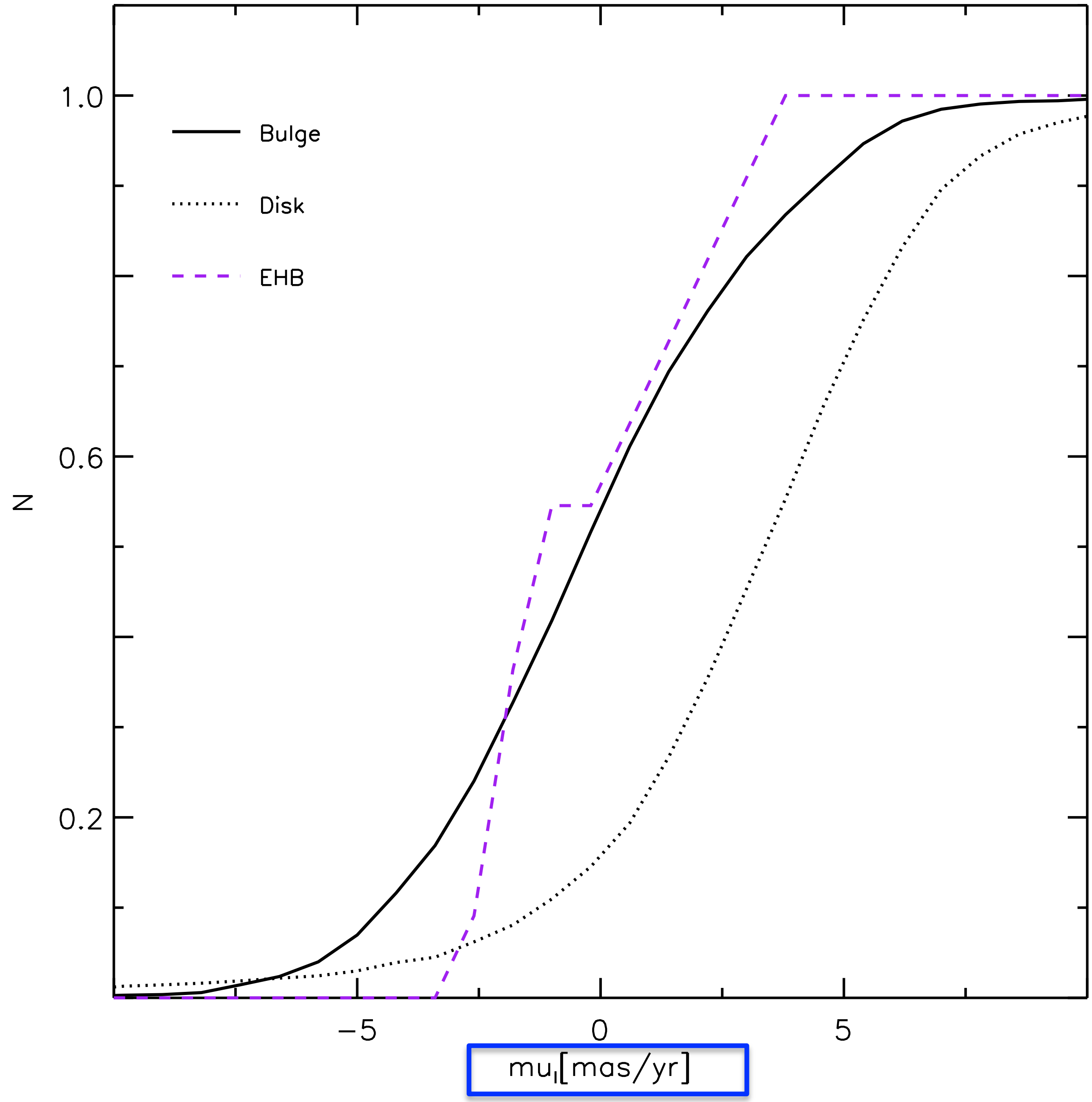
μl < -2 mas/yr:

Sample of 170 WDs

10 EHBs with PM measurements in the SWEEPS field

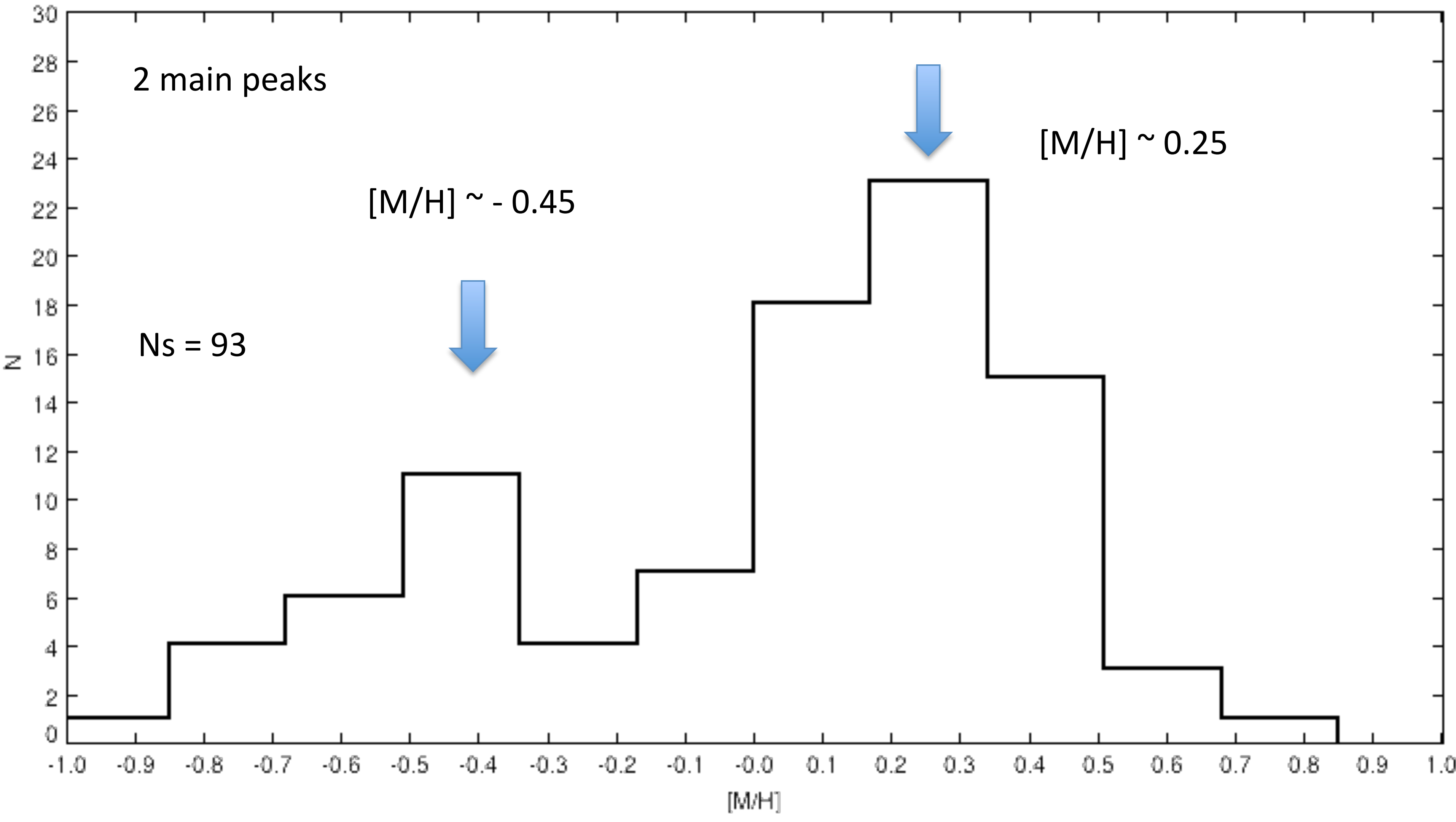
Bulge like!

Include ALL!
Sample of 10 EHBs



Medium-resolution spectroscopy

FLAMES/VLT (ESO) spectra for a sample of 93 red-giant, Turn-Off and main-sequence bulge stars in the **SWEEPS field**



61,166 candidate bulge stars selected for μl < -2 mas/yr

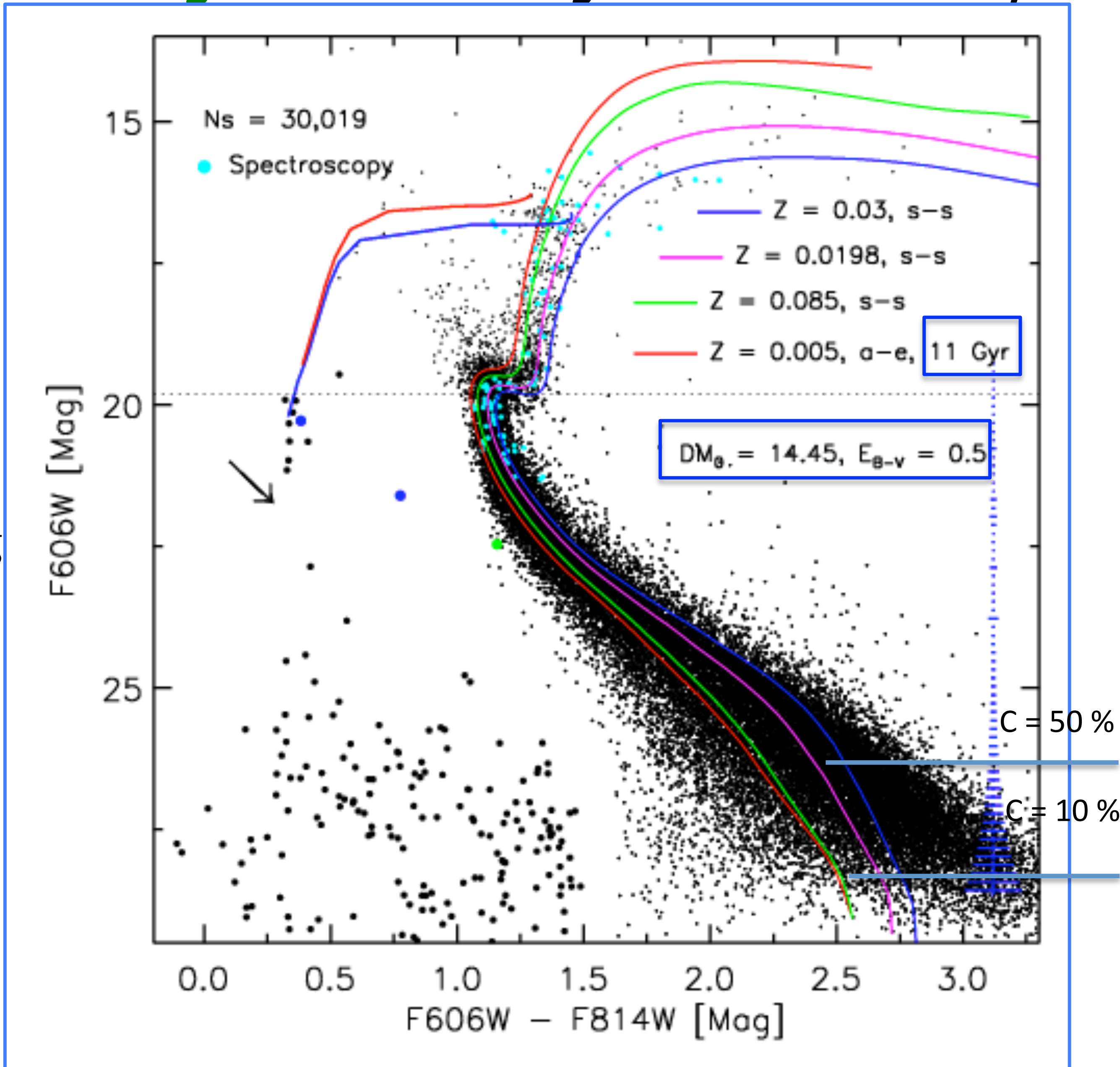
Dartmouth Stellar Evolutionary Database

BASTI ZAHBs

- **Metallicity spread**
- Photometric errors
- Differential reddening
- Binaries
- Depth effects

Fitting the MS

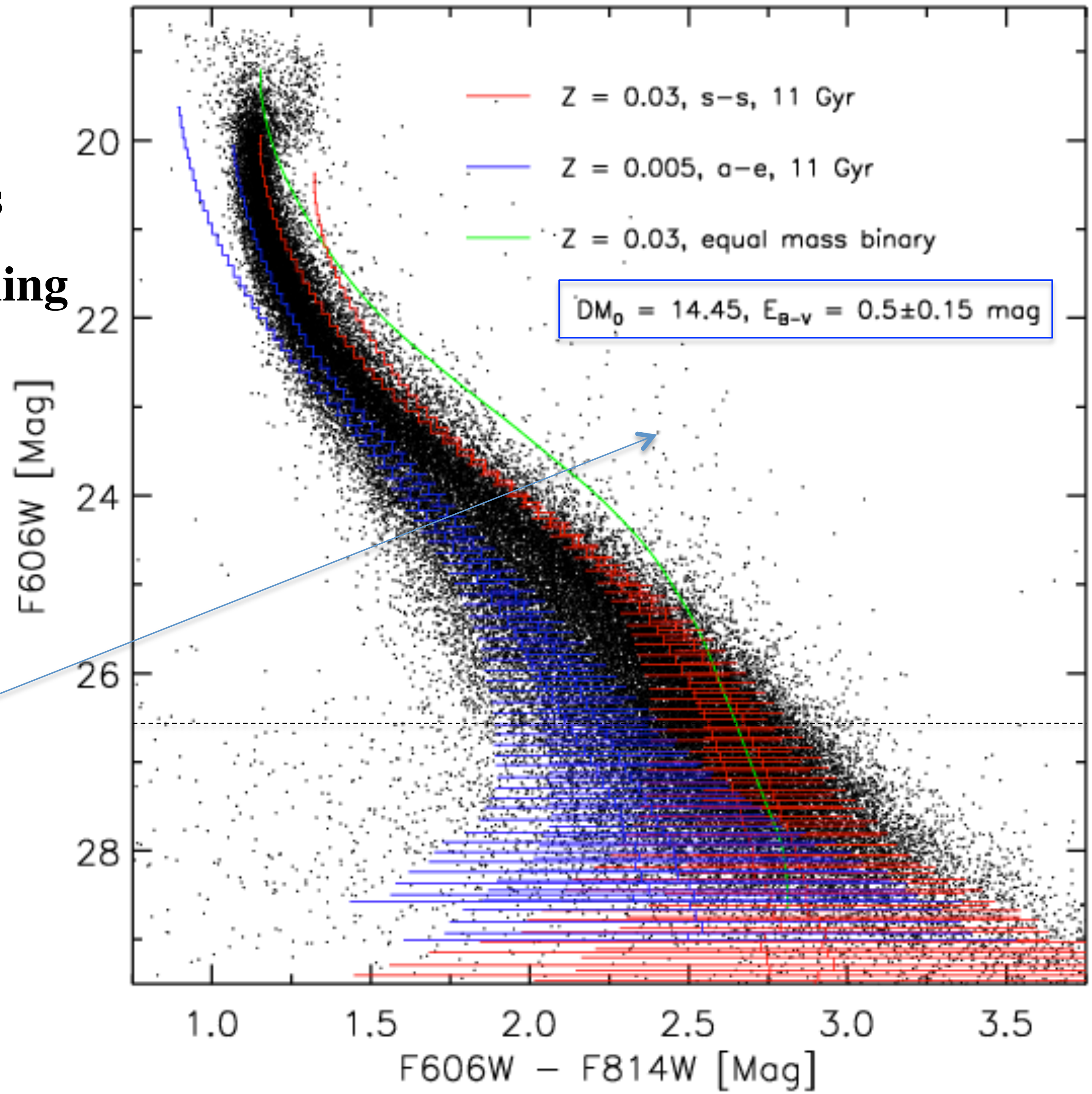
Bulge selected stars only



From the artificial star test

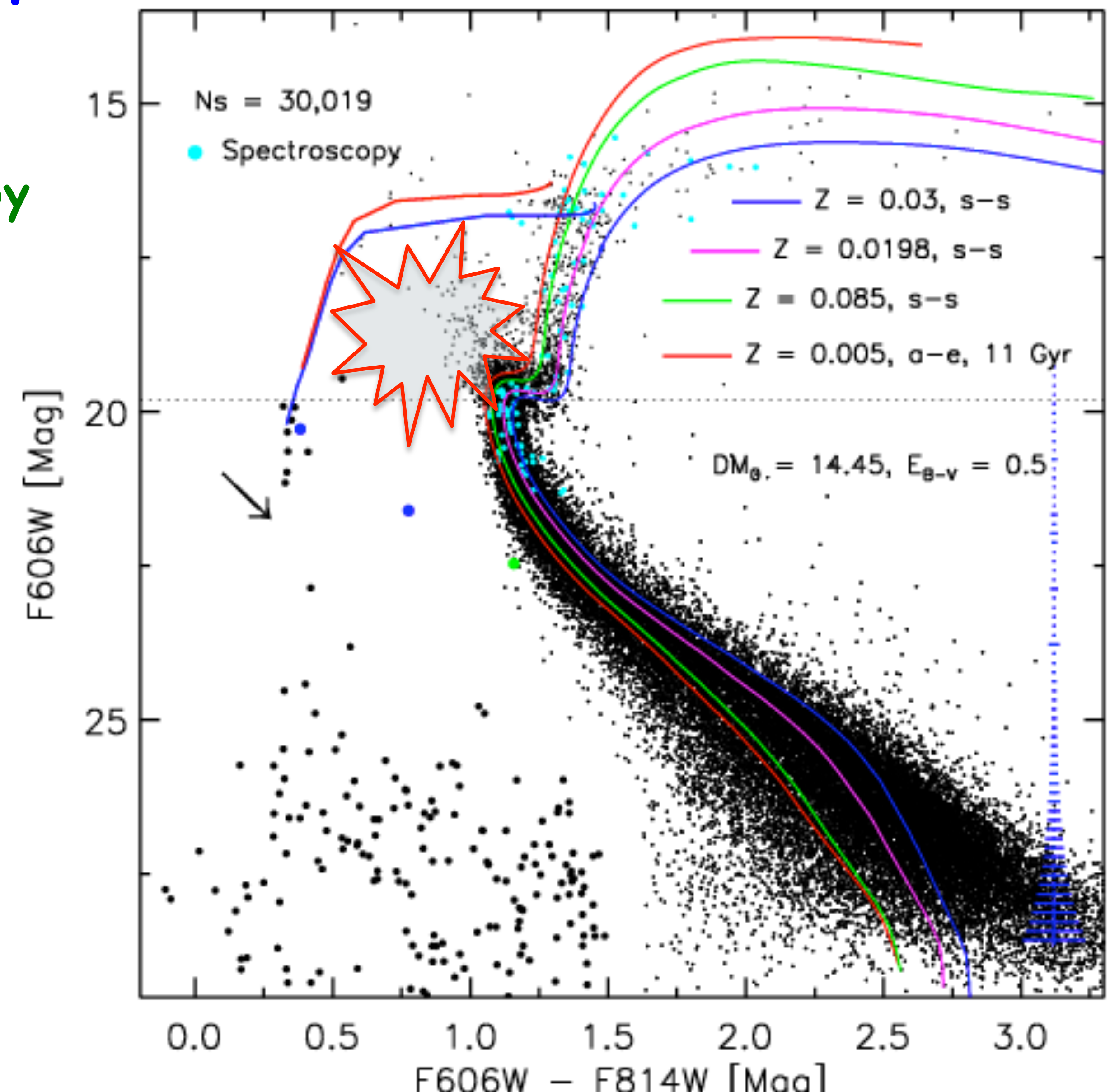
- **Metallicity spread**
- **Photometric errors**
- **Differential reddening**
- **Binaries**
- Depth effects

Residual disk contamination (1%)



Age spread ≤ 2 Gyr

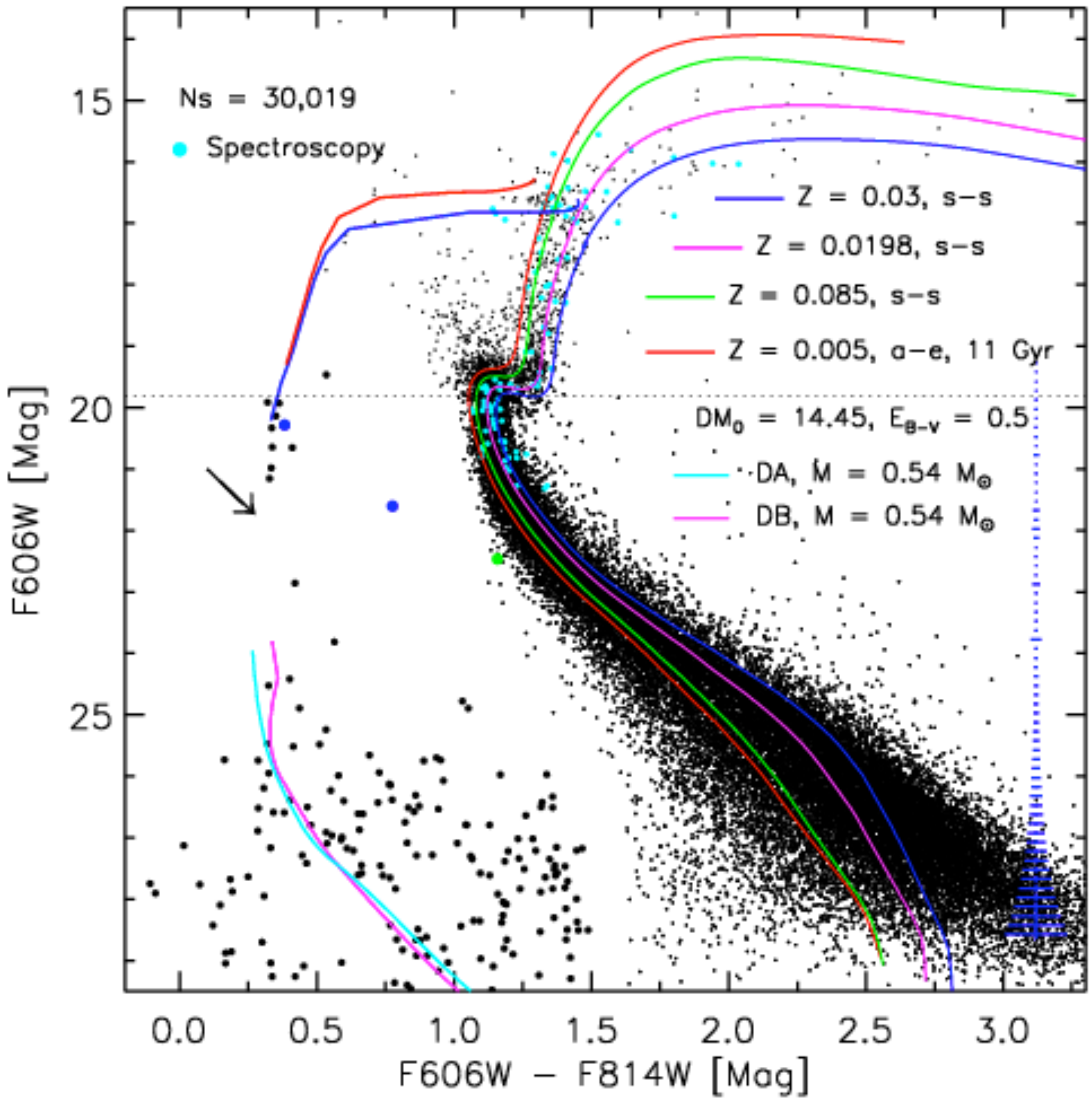
BSS (first detected by Clarkson et al. 2011)



First detection of a WD cooling sequence in the Bulge!!

Bulge selected stars only

Sample of **170 cleaned bulge WDs**
(μl < -2 mas/yr)

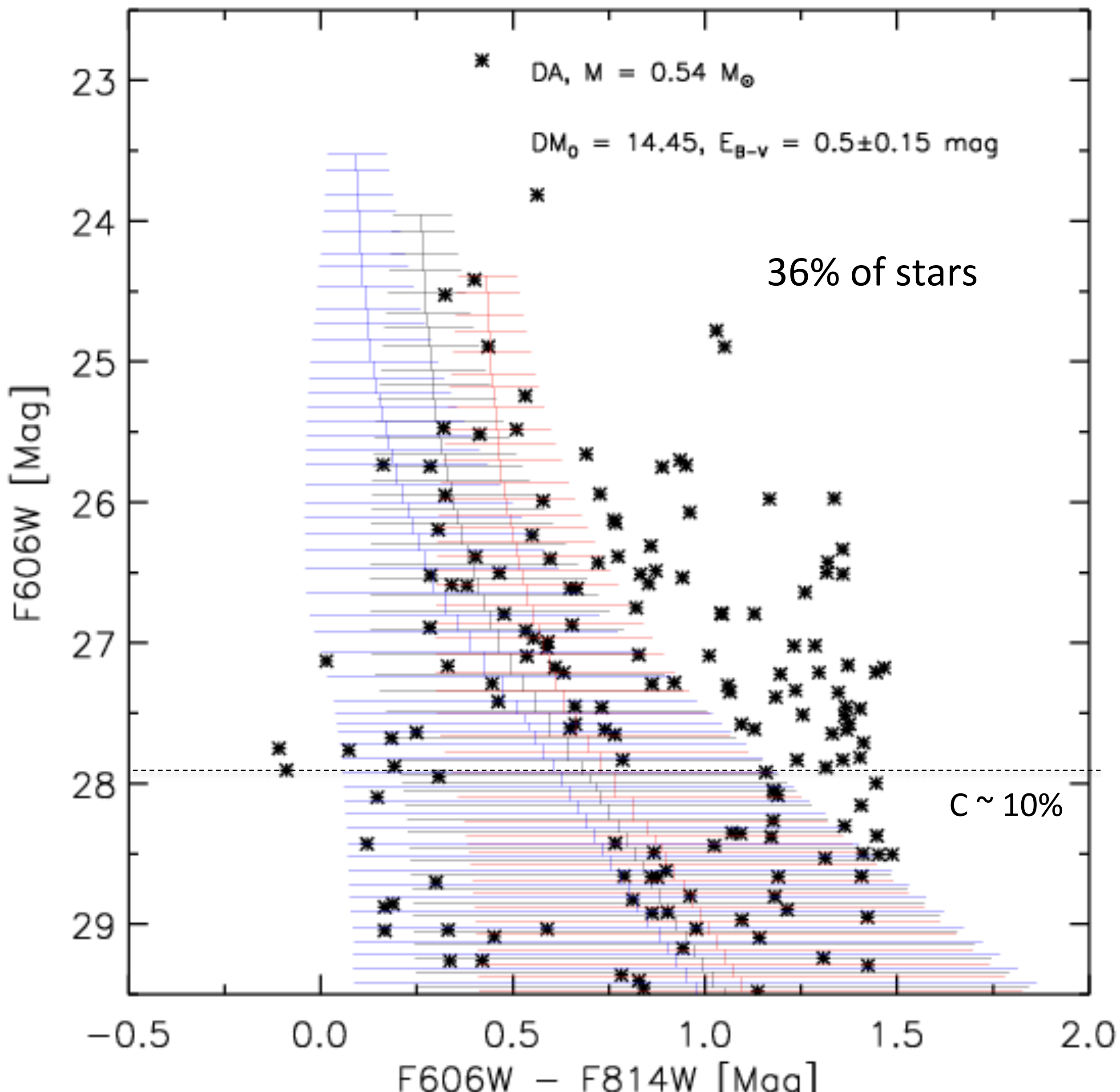


BASTI cooling tracks for **DA and DB CO-core WDs**

From the artificial star test

- **Photometric errors**
- **Differential reddening**

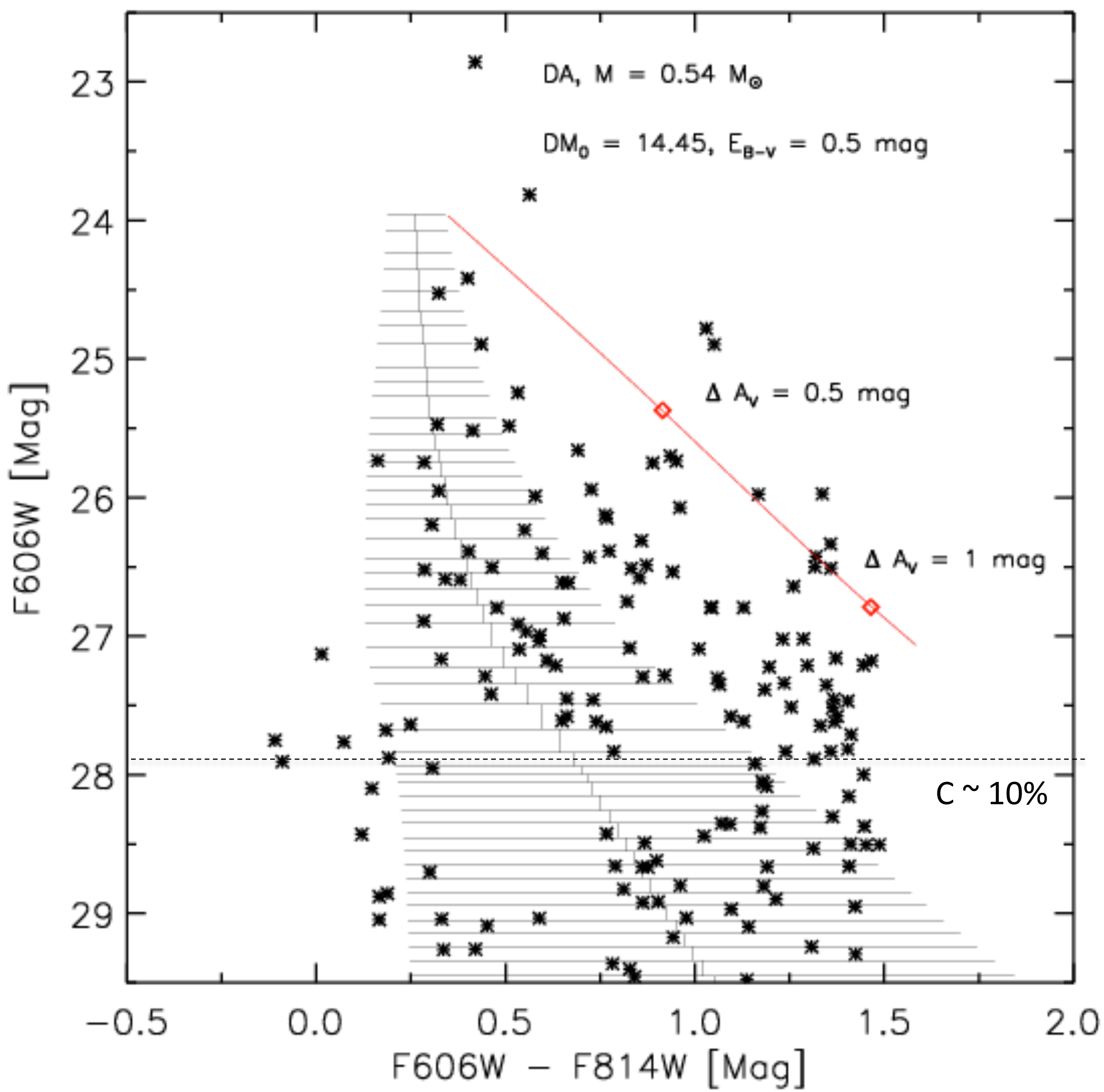
Assume mass spread



From the artificial star test

- **Photometric errors**
- **Differential reddening**

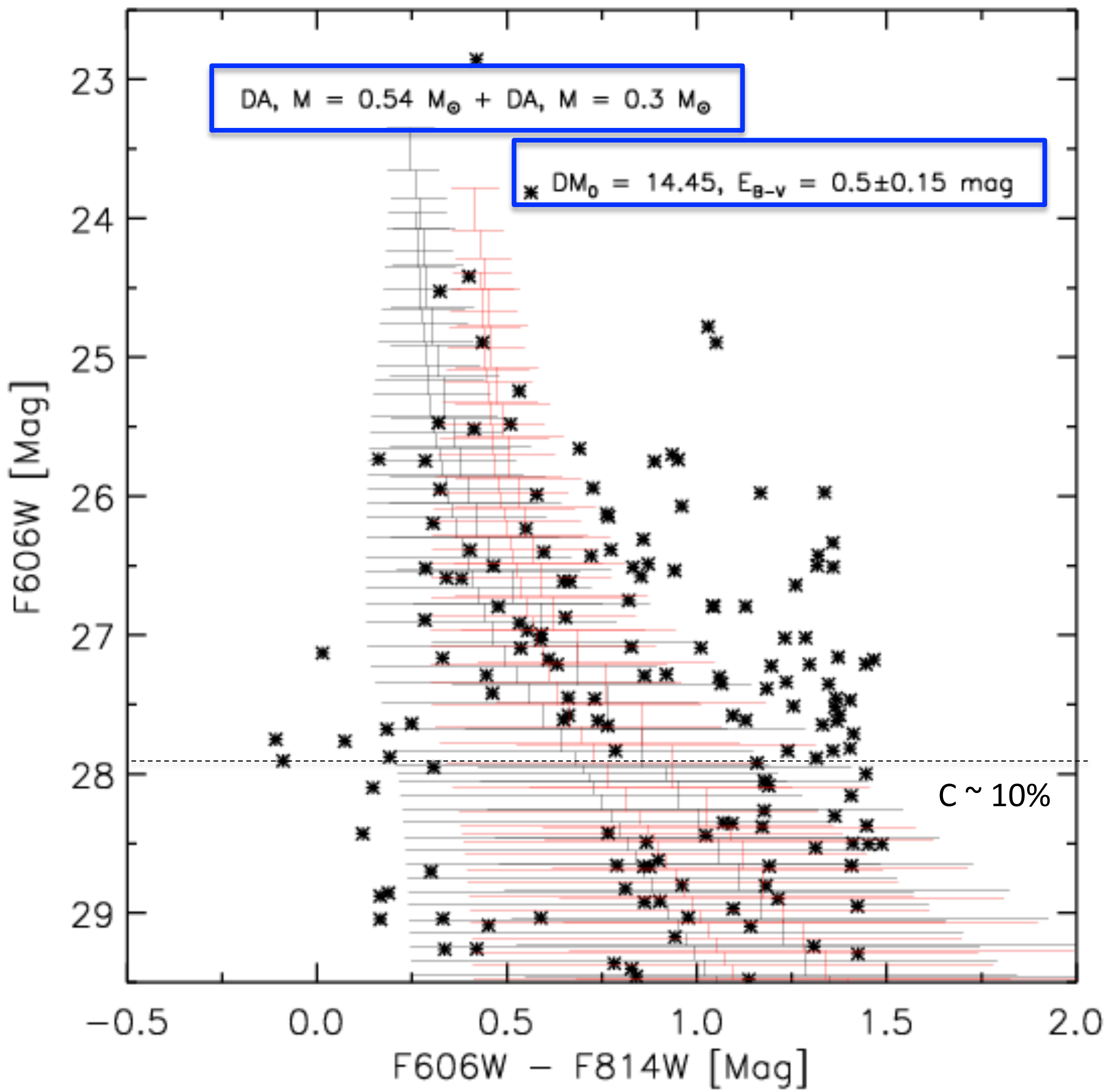
Assume mass spread



From the artificial star test

Assume mass spread

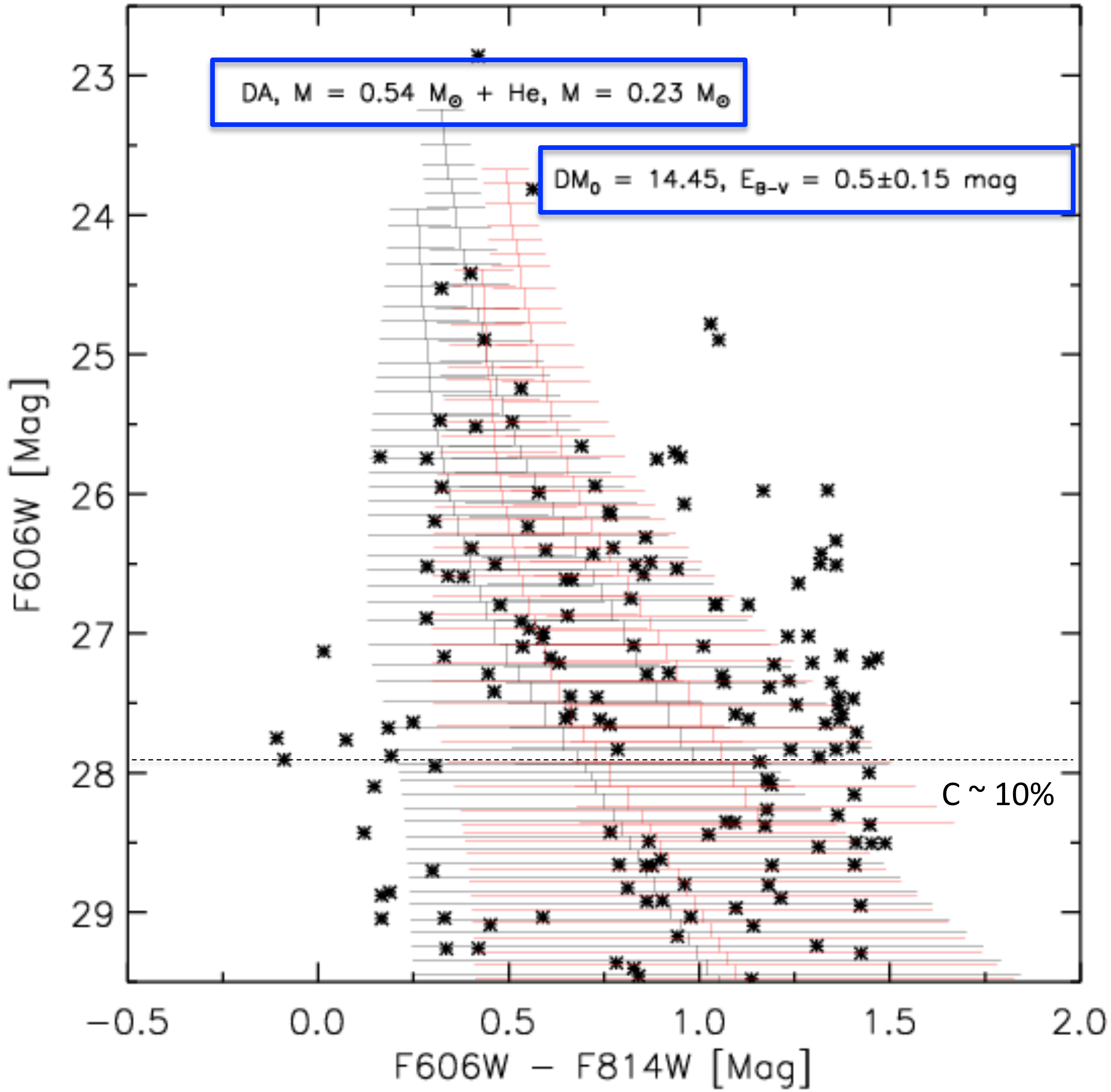
1 - DA CO-core WD with M = 0.3 M⊙



From the artificial star test

2 – He-core WD with M = 0.23 M⊙

In an Hubble time: binary origin



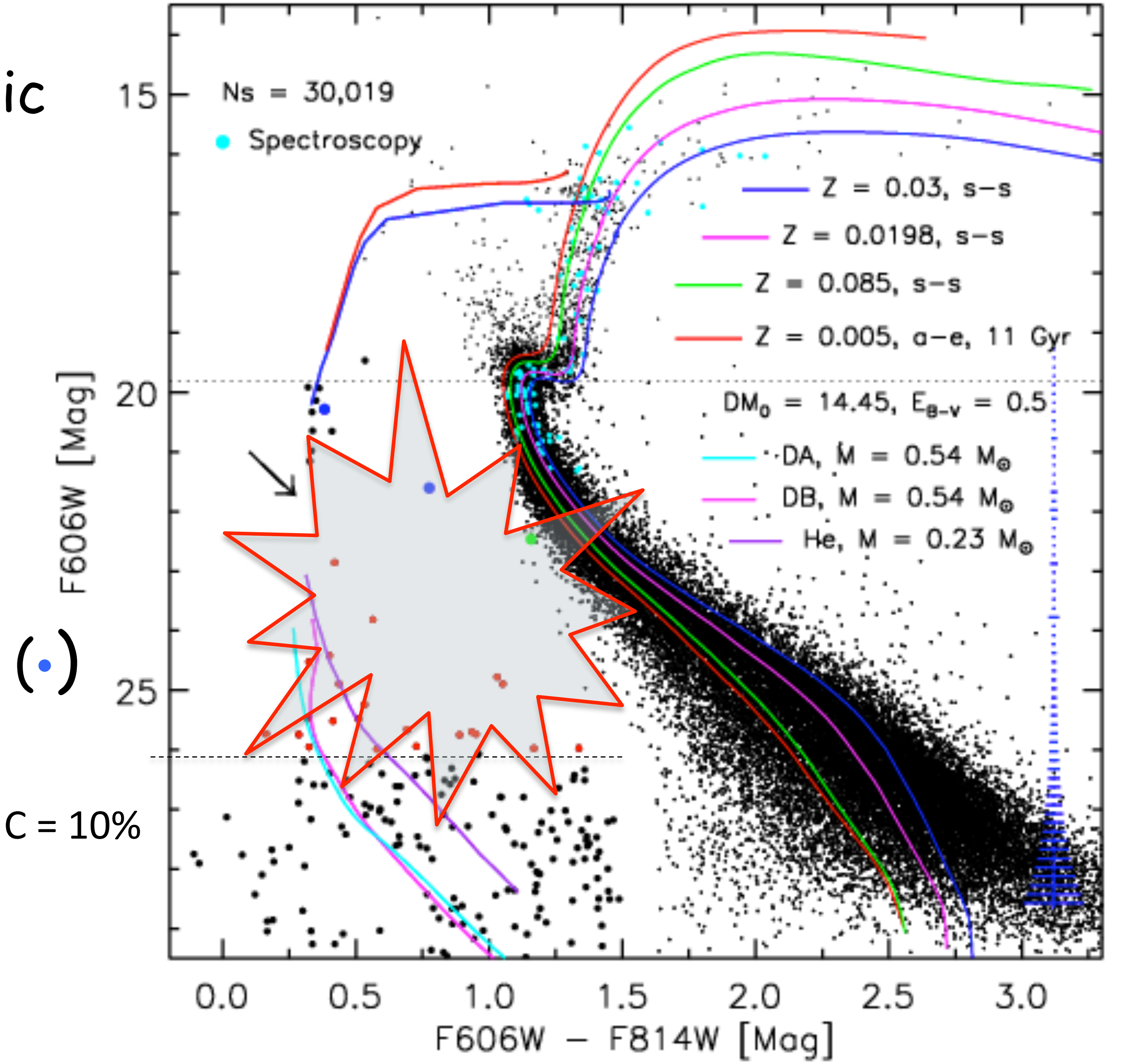
Checking the variability of the brightest WDs

Redder WDs:

candidate Cataclysmic Variables (CVs)

1 Dwarf Nova candidate! (•)

1 system showing ellipsoidal variations (•)

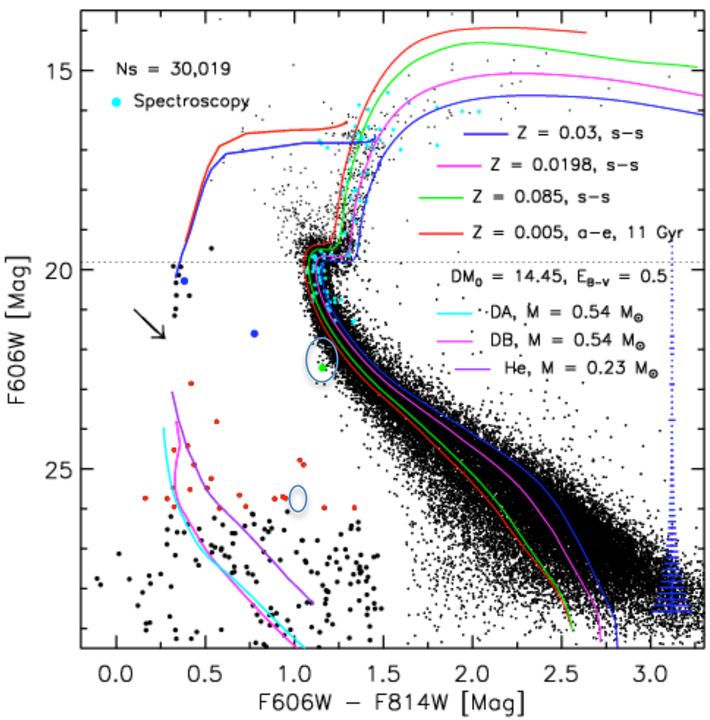


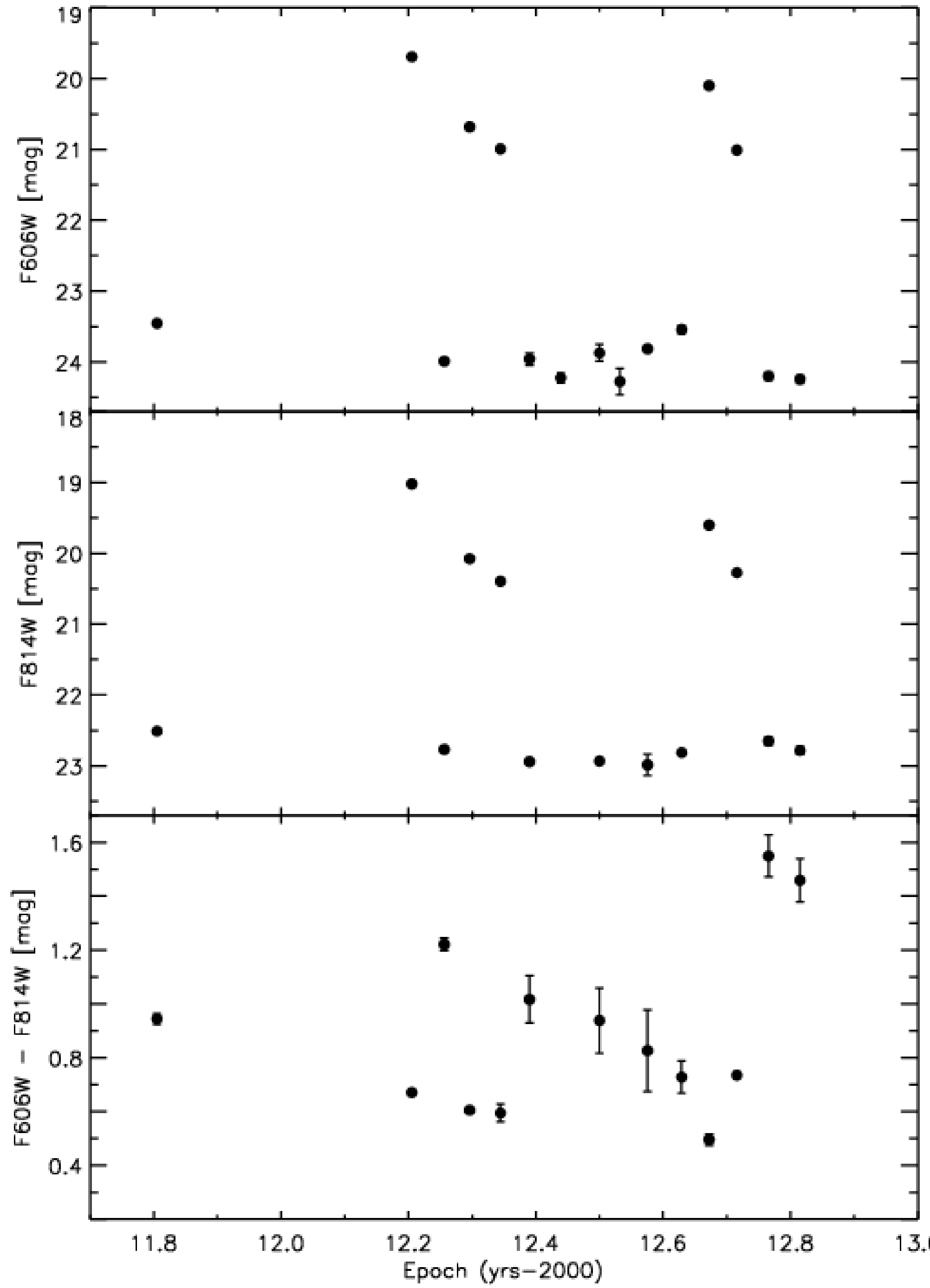
The candidate dwarf nova

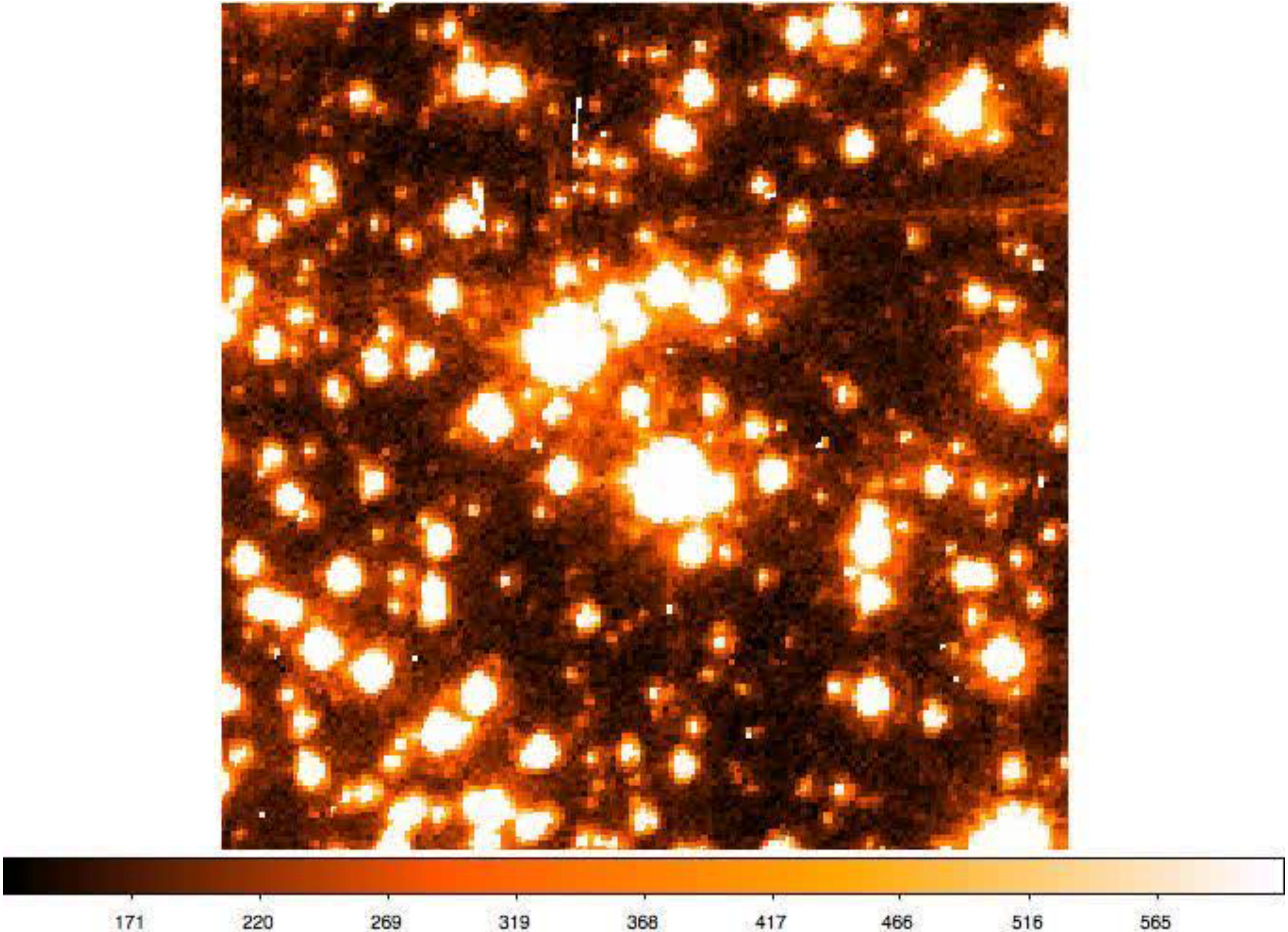
$\langle F606W \rangle = 22.46 \pm 0.24$ mag

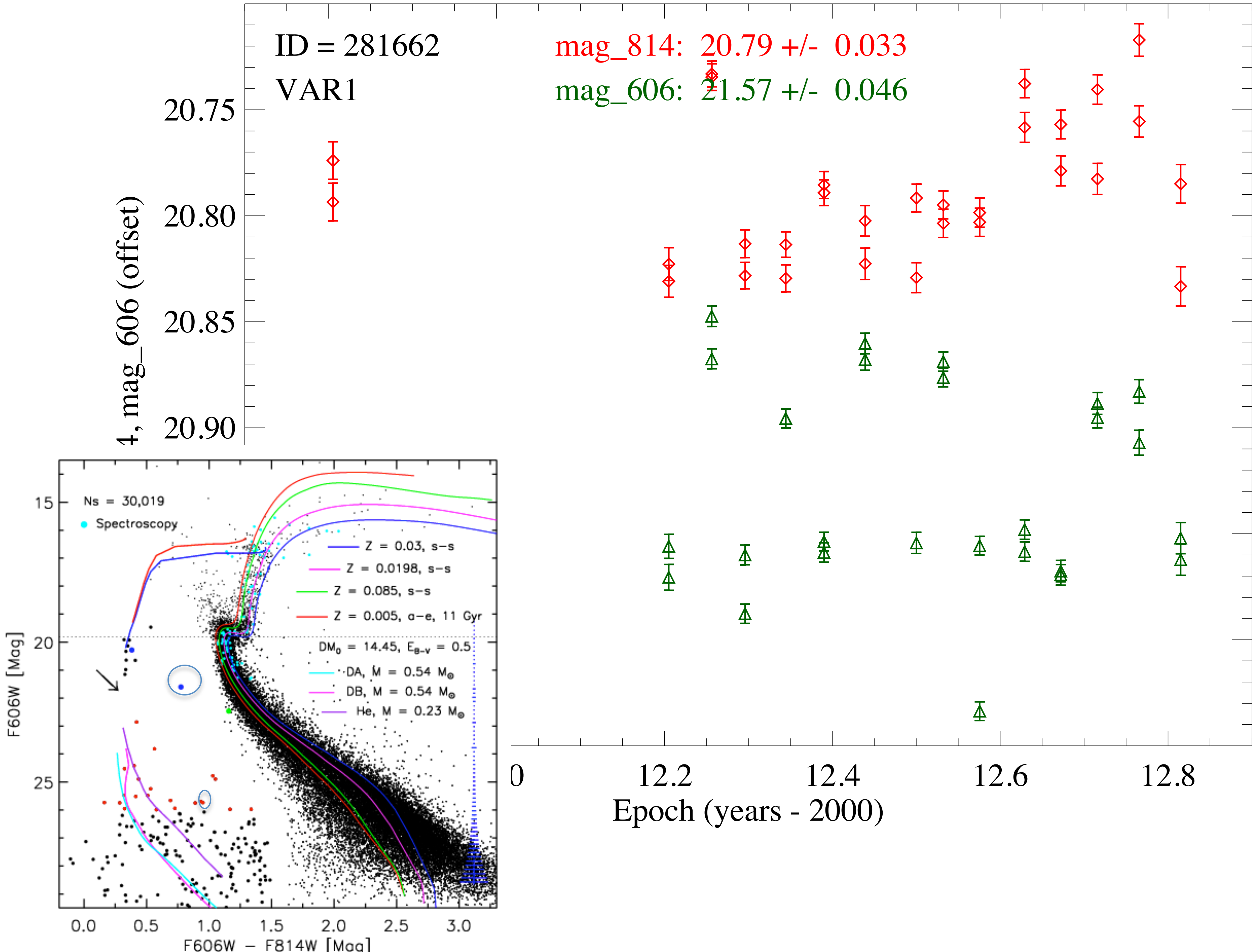
$\langle F814W \rangle = 21.30 \pm 0.22$ mag

$\langle F606W - F814W \rangle = 1.16 \pm 0.32$ mag






171
220
269
319
368
417
466
516
565


ID = 281662
VAR1
mag_814: 20.79 +/- 0.033
mag_606: 21.57 +/- 0.046
20.75
20.80
20.85
20.90
4, mag_606 (offset)
0
12.2
12.4
12.6
12.8
Epoch (years - 2000)
Ns = 30,019
Spectroscopy
Z = 0.03, s-s
Z = 0.0198, s-s
Z = 0.085, s-s
Z = 0.005, a-e, 11 Gyr
DM0 = 14.45, EB-V = 0.5
DA, M = 0.54 M⊙
DB, M = 0.54 M⊙
He, M = 0.23 M⊙
15
20
25
F606W [Mag]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
F606W − F814W [Mag]

Differential Image photometry from Sahu 2004 data set for the SWEEPS field (1 week baseline)

Ellipsoidal variable

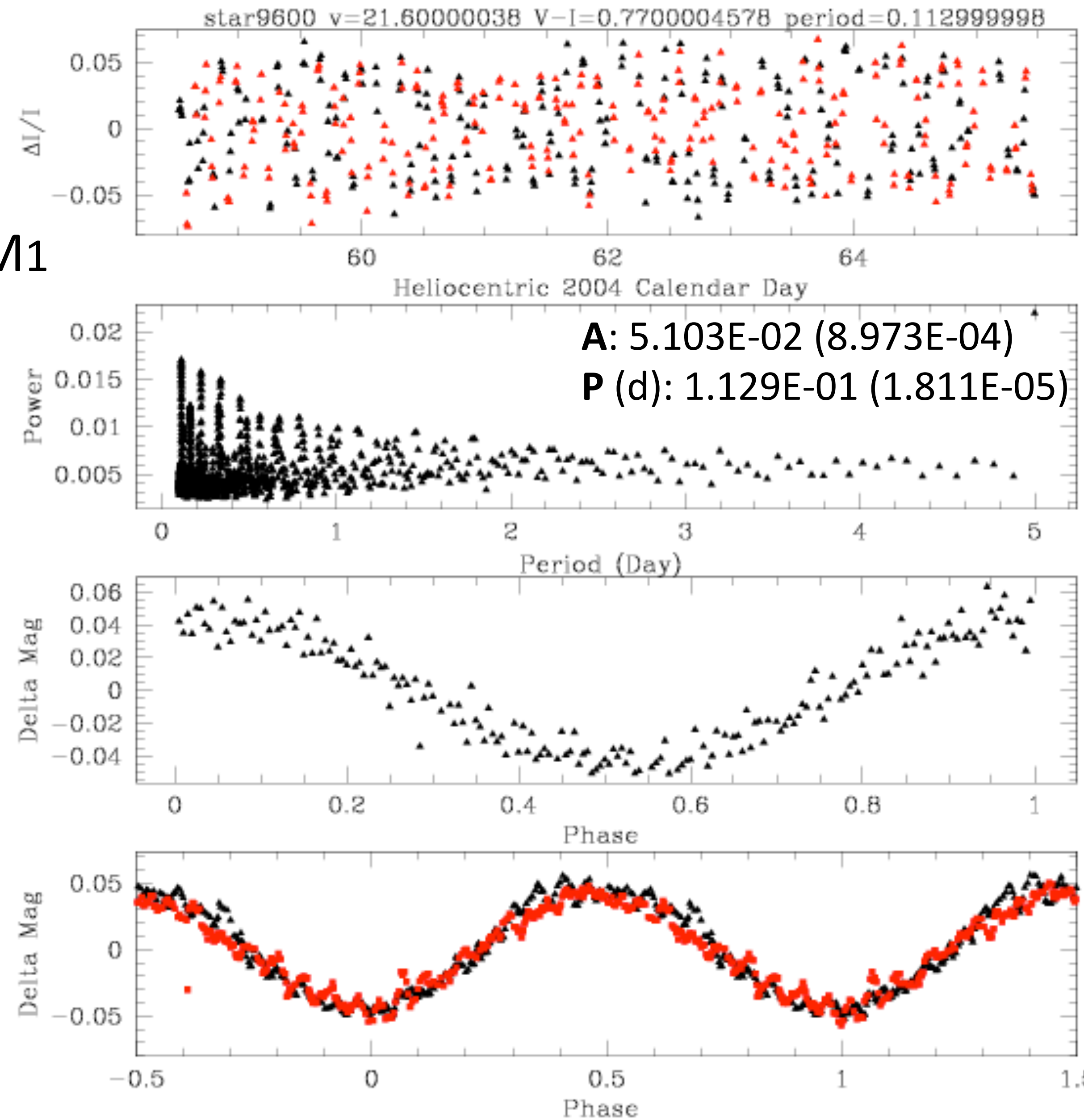
$M_2 \approx A/1.5 \times (a/R_1)^3 \times M_1$

A = amplitude, **M_1 and R_1** = mass and radius of the primary, ***a*** = semi-major axis

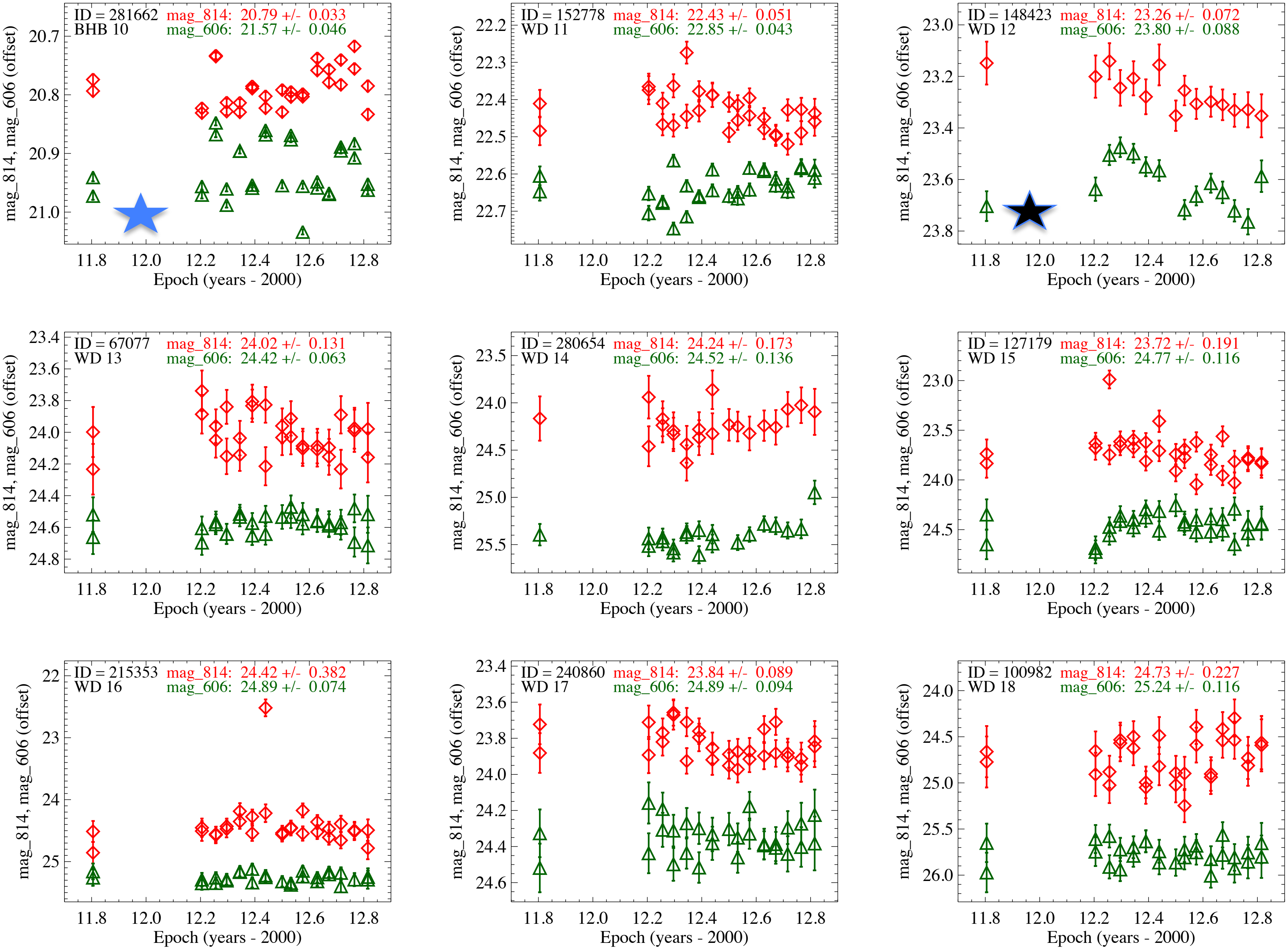
If M_1 (MS) = 0.6 $M_\odot$

a = 0.07 AU

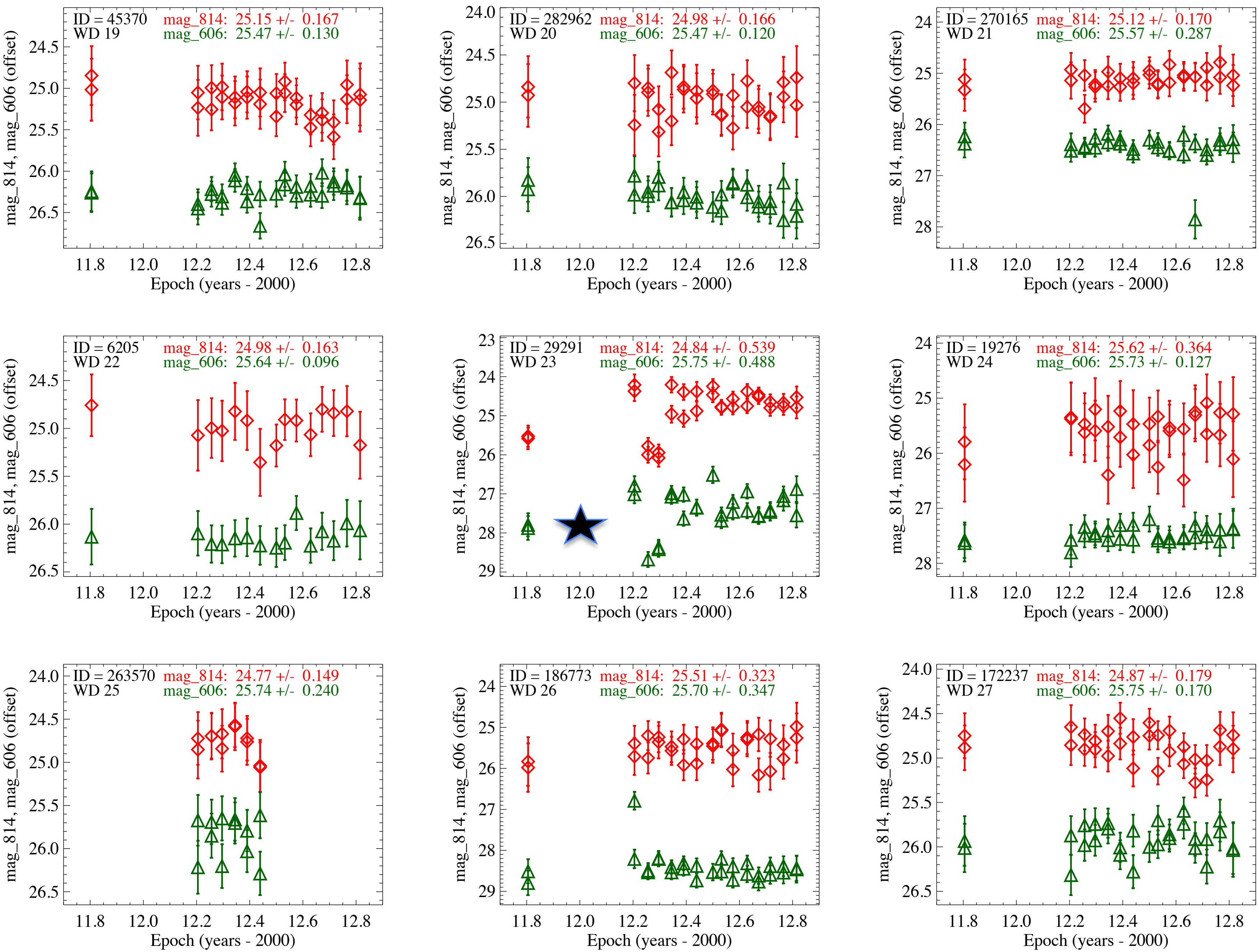
M_2 (WD) = 0.4 $M_\odot$



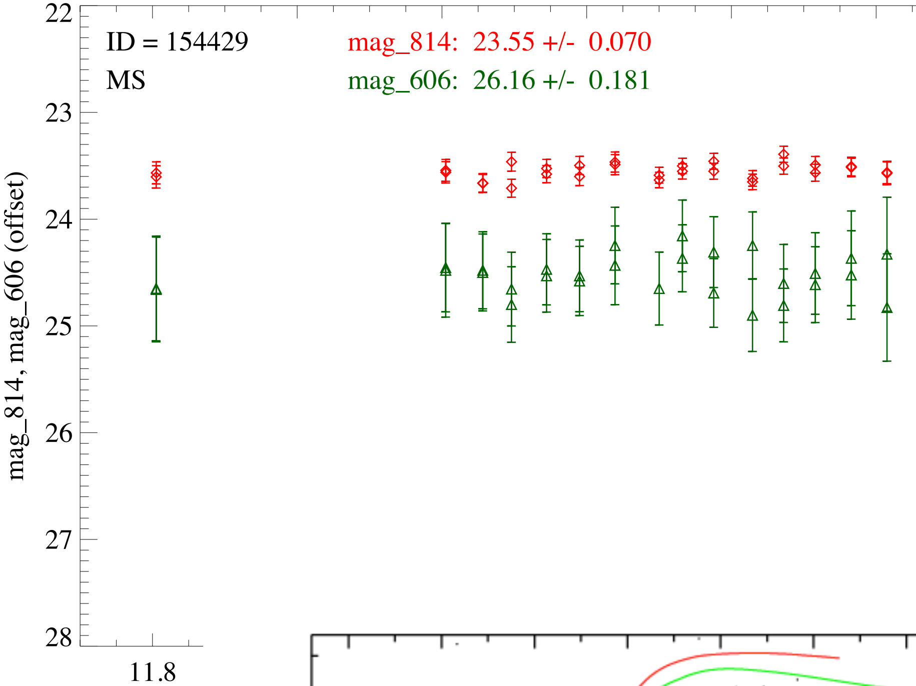
Preliminary analysis



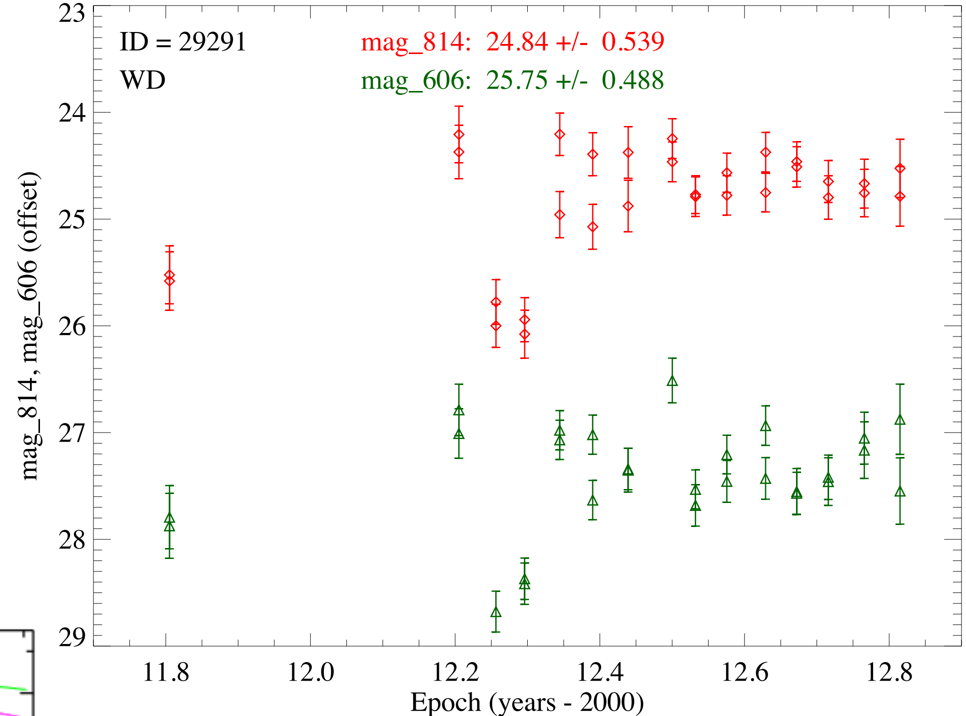
Preliminary analysis

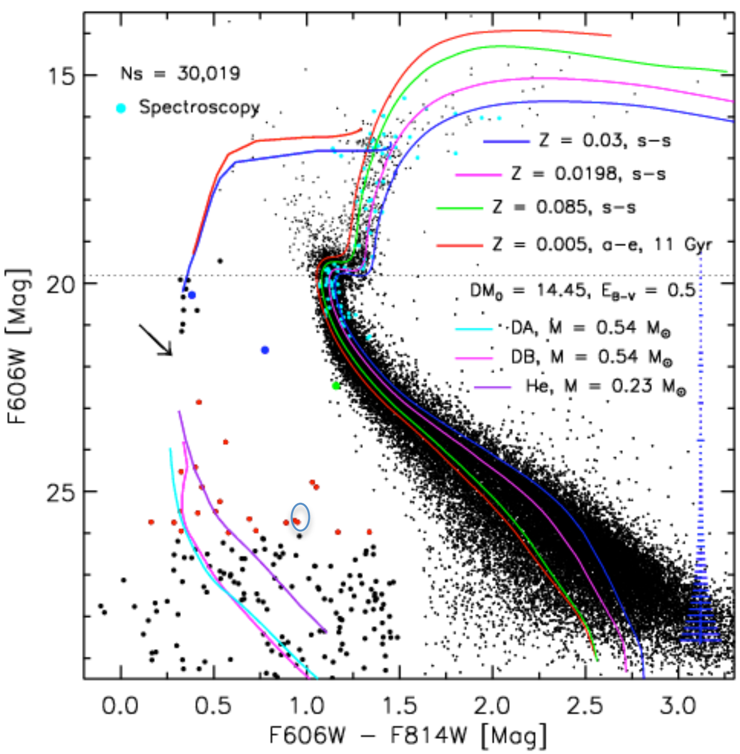


Constant MS star



Candidate variable WD

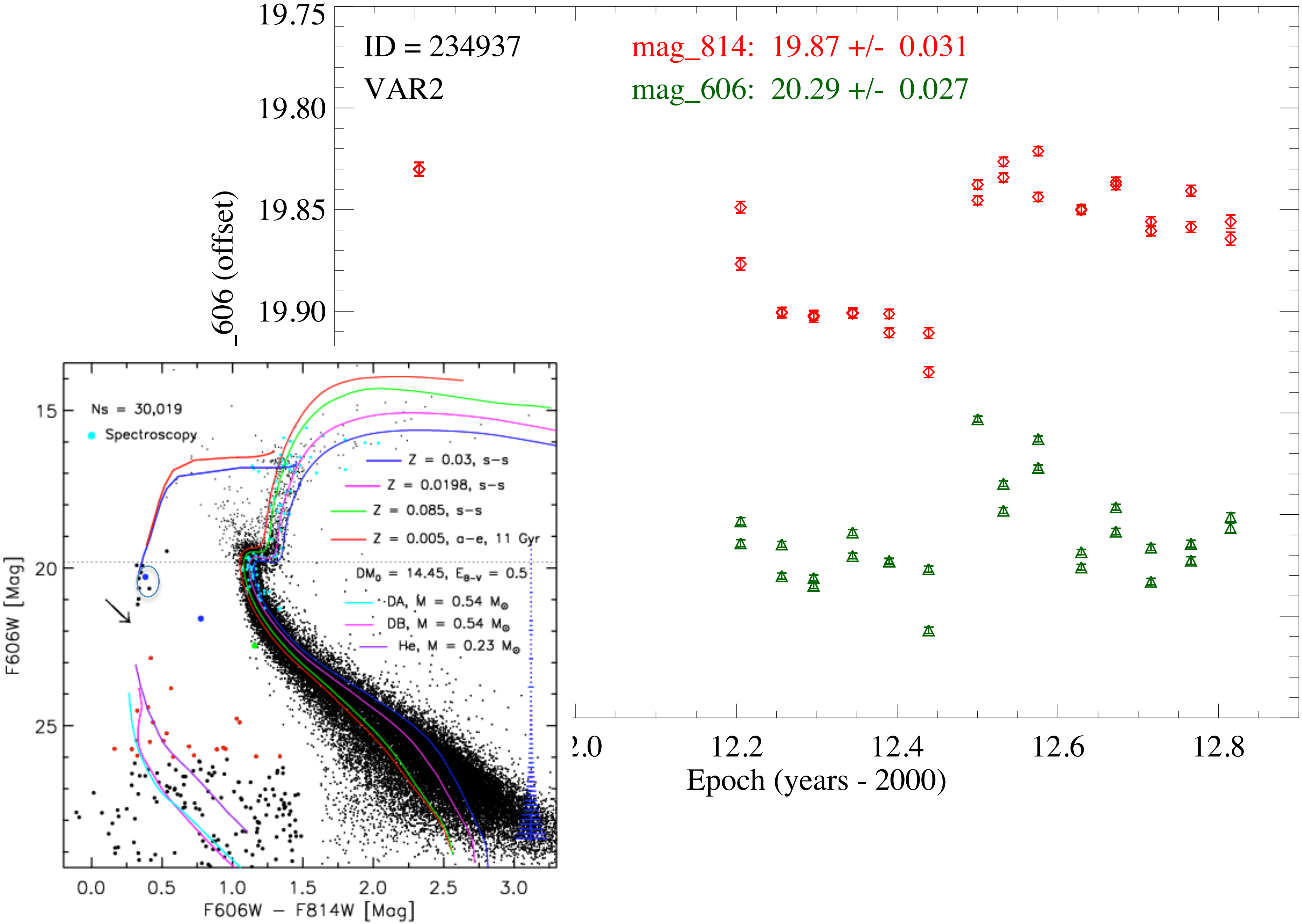




Eclipse of 1.5 mag

But period > 14 days!

Ellipsoidal variable on the EHB

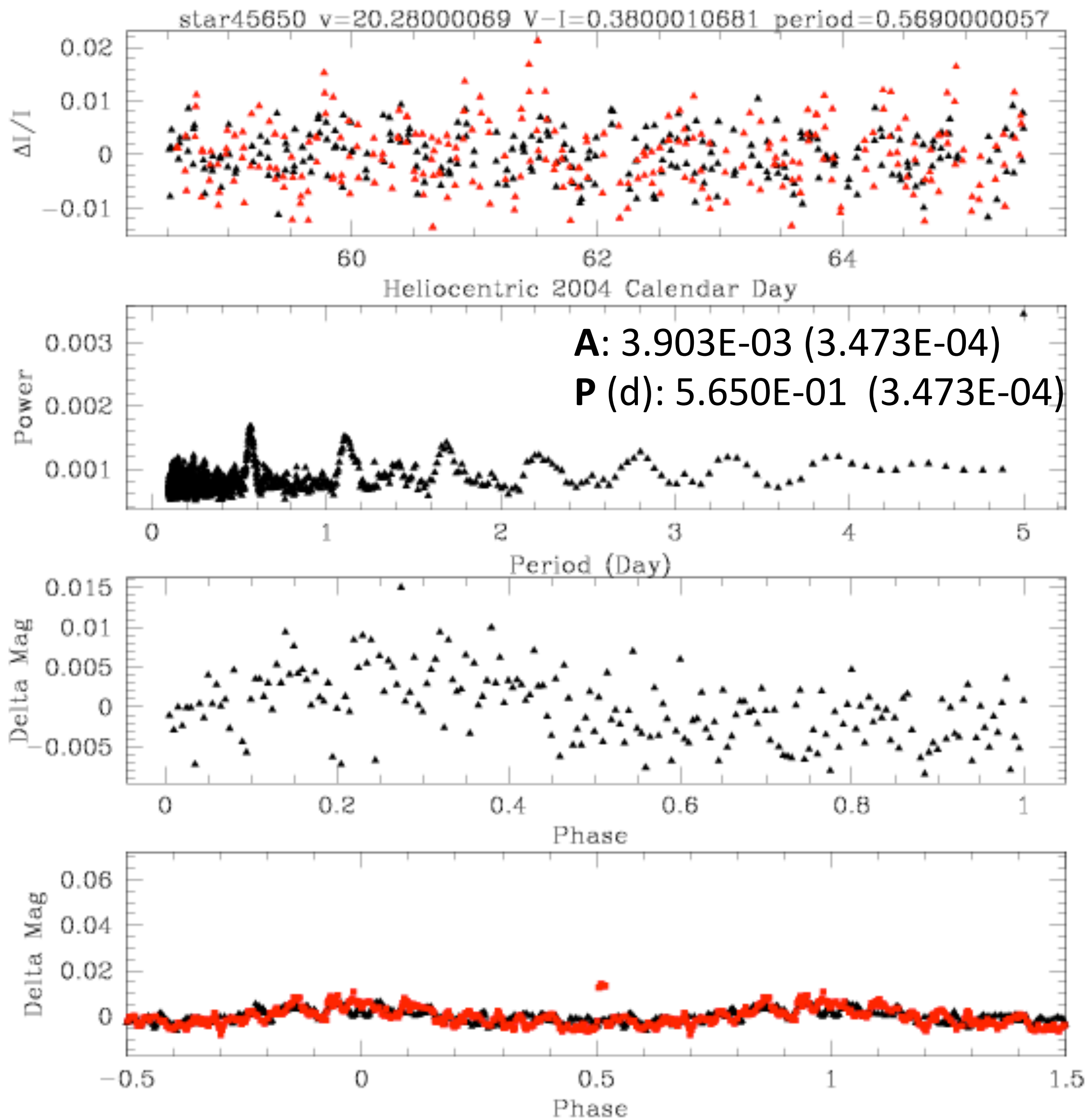


Differential Image photometry from Sahu 2004 data set for the SWEEPS field (1 week baseline)

M_1 (EHB) = 0.5 $M_\odot$

a = 0.017 – 0.024 AU

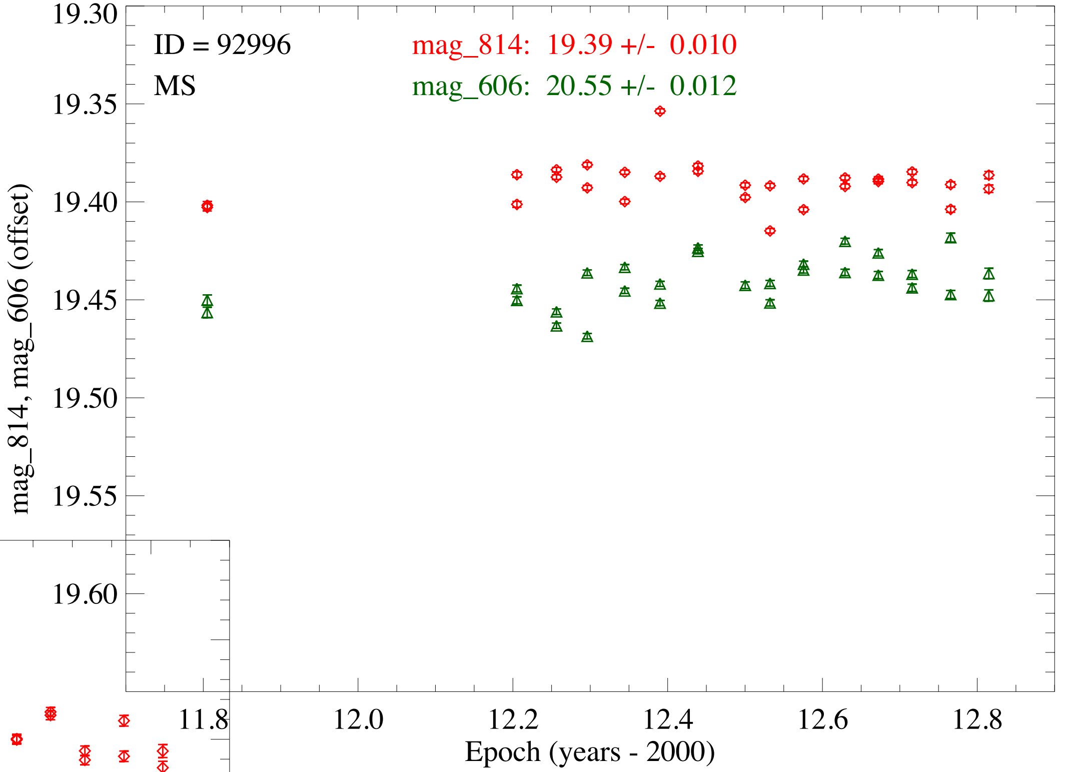
M_2 (?) = 3.6 – 8 $M_\odot$



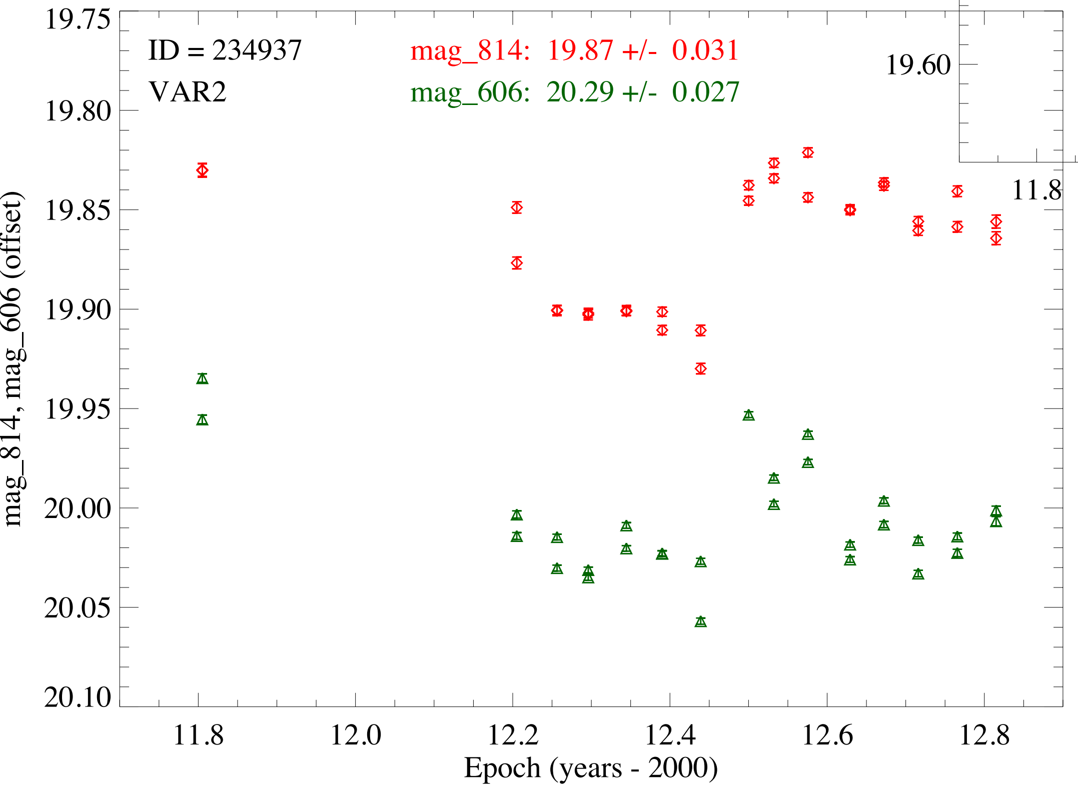
Candidate Black hole companion -> need radial velocity measurements to confirm

Checking the variability of the EHBs

Constant MS star

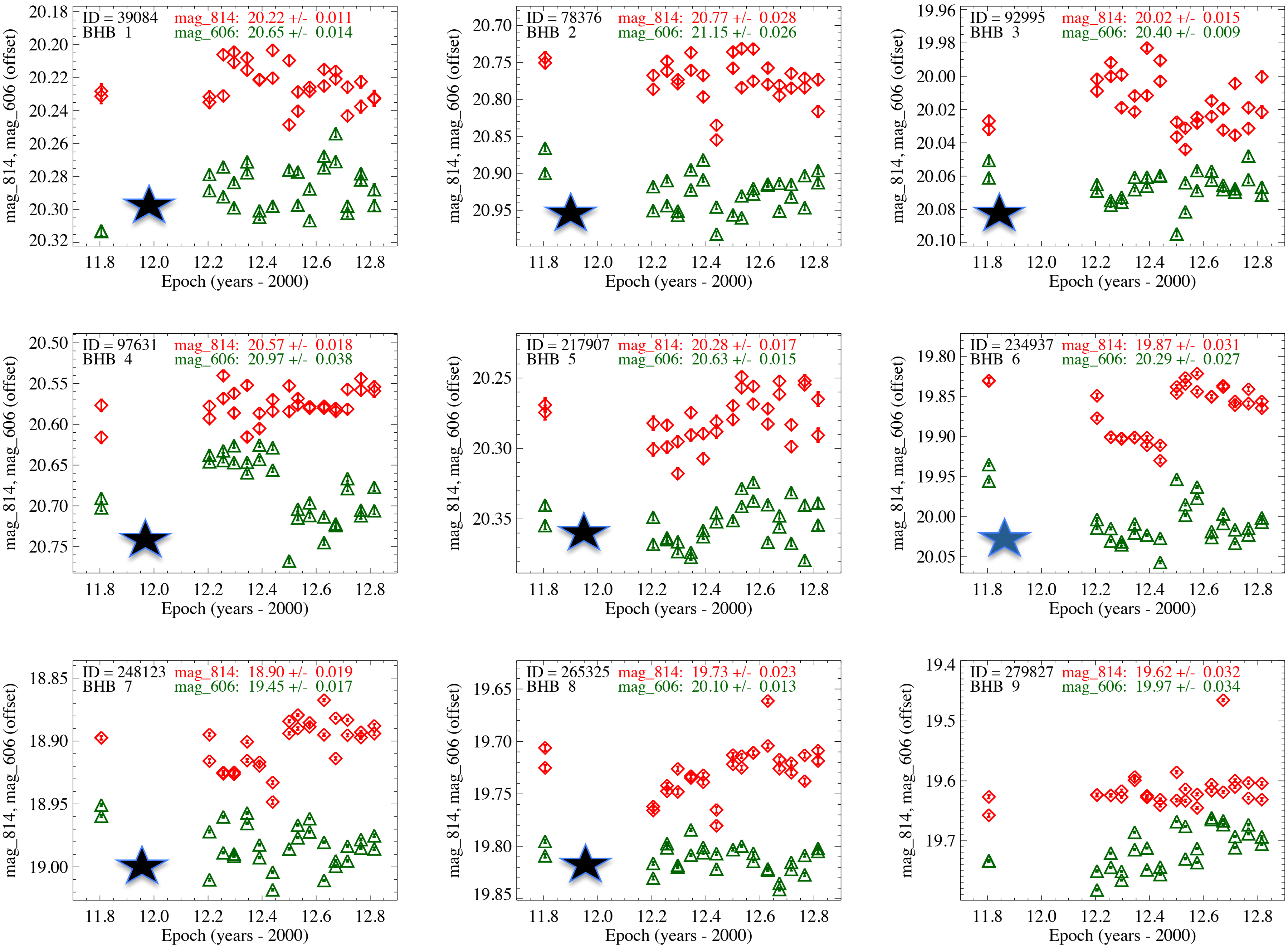


Maxted et al. (2001): ≈ 100% field **sub-dwarf B stars** seem to be in **binary systems**



EHB ellipsoidal variable

Checking the variability of the EHBs



Conclusions

- ✓ **Deepest CMD in the bulge direction:** ~ 1 million stars down to F606W ~ 31 mag. **Proper motions for ~ 160,000 stars down to F606W ~ 27 mag with accuracy e_PMx,e_PMy < 0.3 mas/yr**
- ✓ PM cleaned bulge CMD: **~ 61,000 bulge members in 1 ACS field (3'x3'), including 170 WDs and 10 EHBs**
- ✓ From medium-resolution spectroscopy of RG,TO and MS stars, and isochrones fitting, **age spread ≤2 Gyr**
- ✓ Up to 1/3 of WDs are low-mass WDs -> **candidate He-core WDs -> binary origin: 1 WD-MS compact system (P ≈ 0.23 d), 2 candidate CVs (1 with eclipse), 1 dwarf nova** (need radial velocities, UV deep HST photometry to confirm)
- ✓ **1 EHB-Degenerate compact system (P ≈ 1 d) -> candidate BH companion (M = 3.6 – 8 M⊙)** (only 2 confirmed such systems in the field, Geier et al. 2008) > need radial velocities
- ✓ **Almost all EHBs seem to show variability:** binaries? Similar origin of field sdBs?

This data set is a goldmine for understanding the formation and evolution of the Galactic bulge

- ✓ **Adding the 8 WFC3 fields, we will double the data set: more than 2,000,000 stars ->** PMs for all the 12 (ACS+WFC3) fields with a baseline of 3 years
- ✓ **Constrain the bulge initial mass function down to M ~ 0.1 M⊙ (V ~ 30 mag)**
- ✓ The sample of PM cleaned bulge EHBs & WDs will increase of a factor of 8-> **- constrain the nature of the bulge EHBs & WDs through star counts, - constrain the binary fraction in the bulge**
- ✓ **Constrain the fraction of mass hidden in isolated (gravitational micro-lensing) and binary NSs and BHs**
- ✓ **For the brightest stars we will be able to estimate parallaxes:**
  - constrain the age of disk and bulge WDs
  - better constrain the age of the Galactic bulge