First detection of the white dwarf cooling sequence of the Galactic bulge

Annalisa Calamida

K. Sahu, J. Anderson, S. Casertano, S. Cassisi,
M. Salaris, T. Brown, & more

SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA

RASPUTIN, October 14, 2014

White dwarfs are important for stellar population studies!

- White dwarfs (WDs) are the **endpoint of the vast majority of stars**: the Galactic population of WD remnants contains important information about the early history of the Milky Way

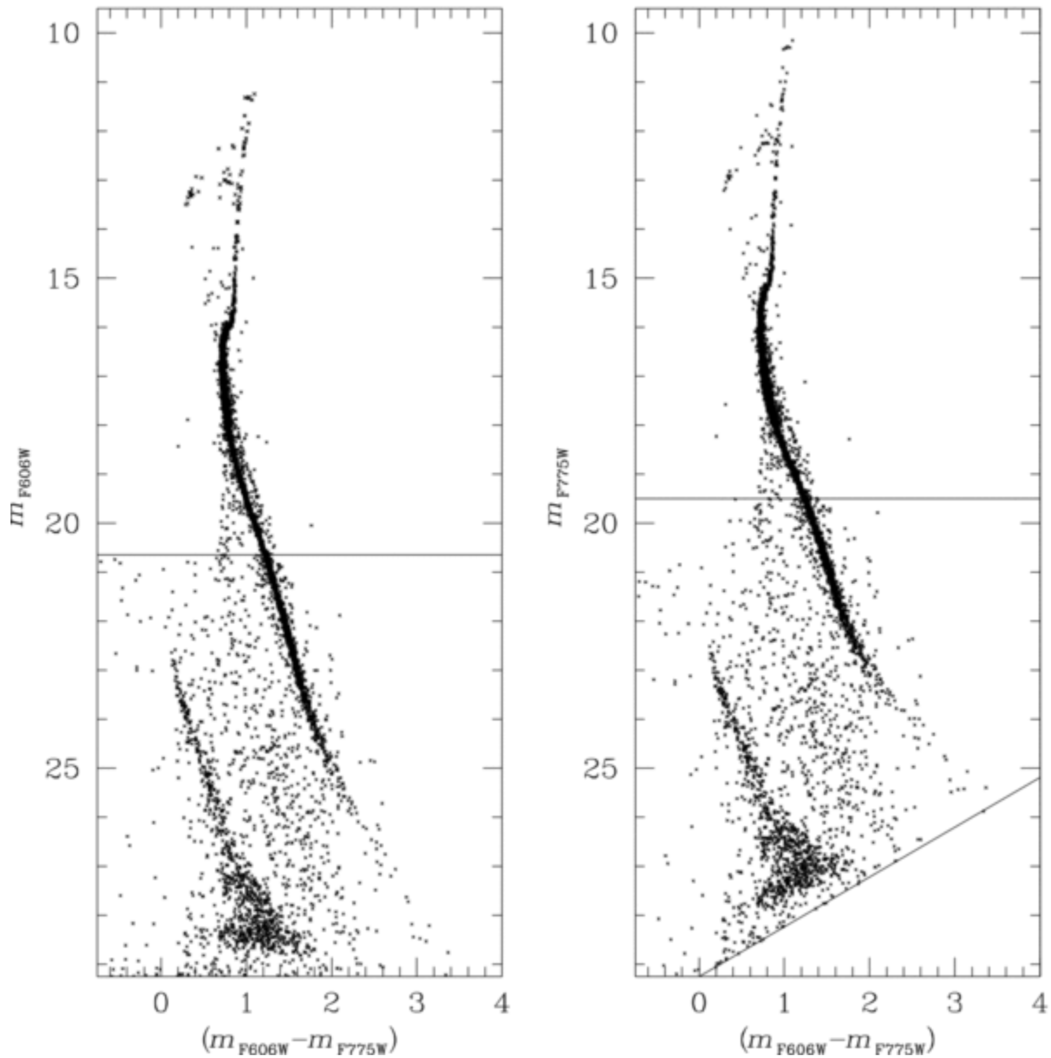
- They can be used as **age indicators**

- They can be used as **distance indicators**

Important to characterize WDs in the Galactic bulge: closest galaxy bulge we can observe

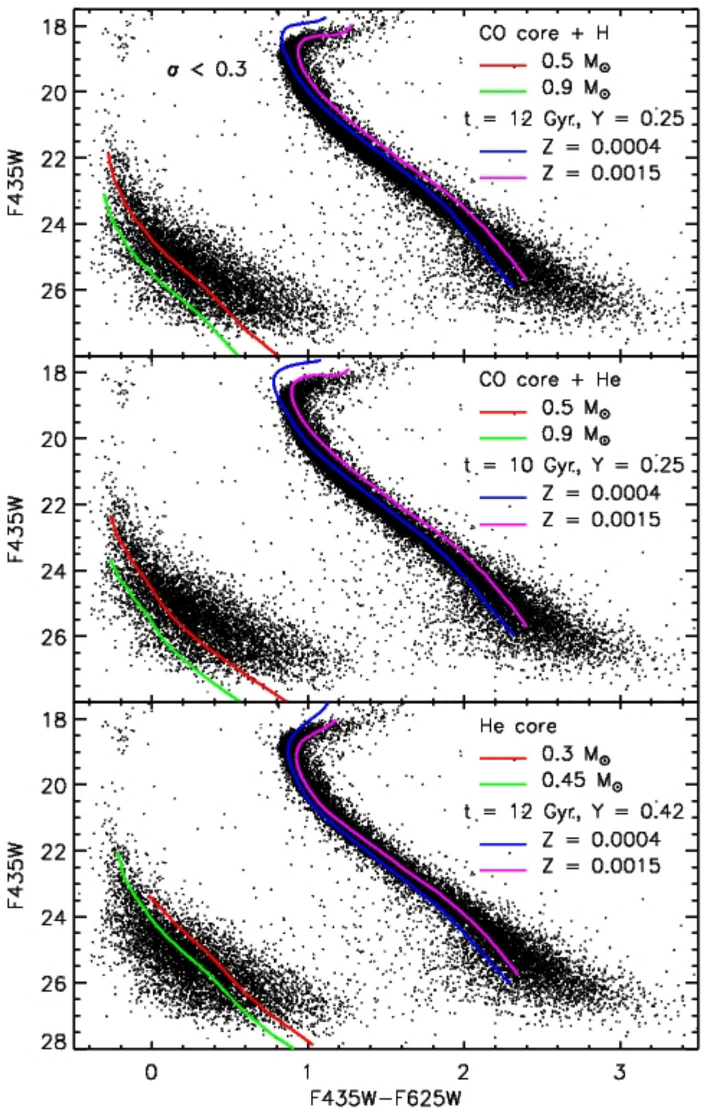
White dwarfs in clusters and the Galactic disk

Observed with HST in the closest GGCs ($\mu_0 < 13$ mag, such as M4 (Bedin et al. 2009)



White dwarfs in clusters and the Galactic disk

Calamida et al. (2008, ApJ, 673, L29)



In **ω Cen** evidence for the presence of He-core WDs from **broadening of the cooling sequence and number counts** -> In a Hubble time produced **in binary systems**

In the local disk 6% of WDs are less massive than ~0.4 M⊙ -> He-core WDs

Most He-core WDs in the disk are binaries (WDs, neutron stars, sdBs as companions, Marsh et al. 1995, Maxted et al. 2002)

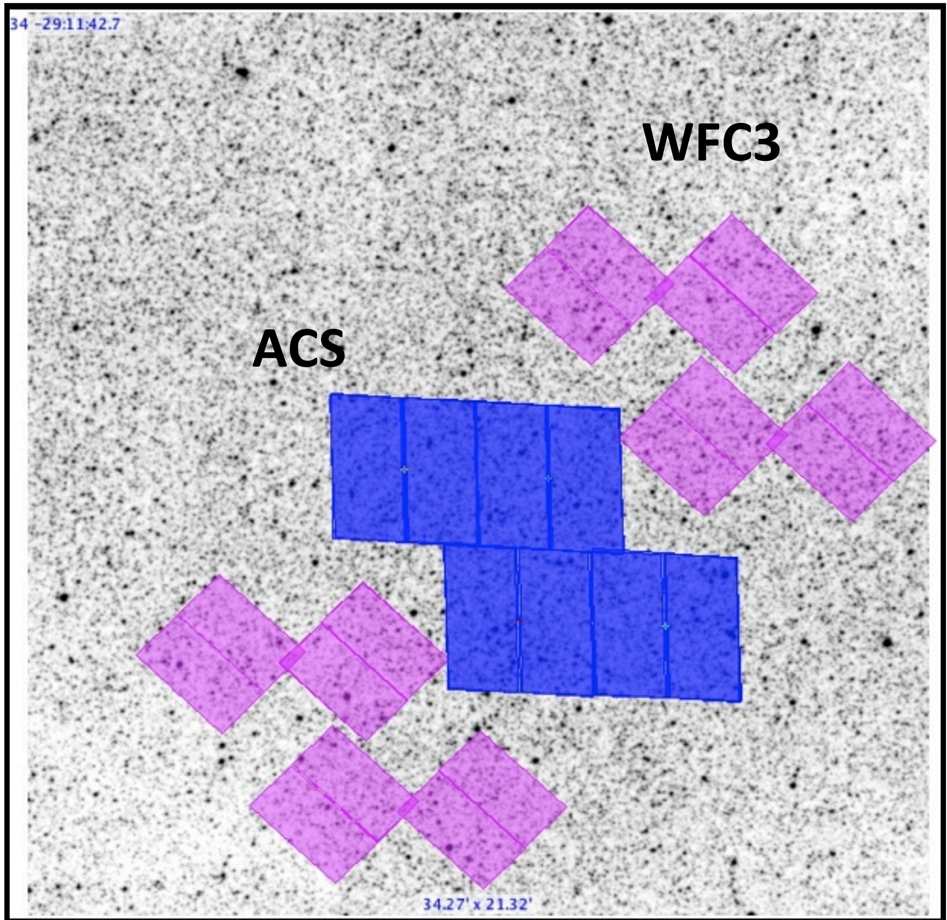
The SWEEPS low-reddening window

Sagittarius Window Eclipsing Extra-solar Planet Search (SWEEPS)

E(B-V) ≈ 0.5 mag

Detecting and Measuring the Masses of Stellar Remnants
(HST Proposal GO-12586, 13057, PI: Sahu)

F606W, F814W-band



(l,b) = (0, -2.65)

Observing cadence:

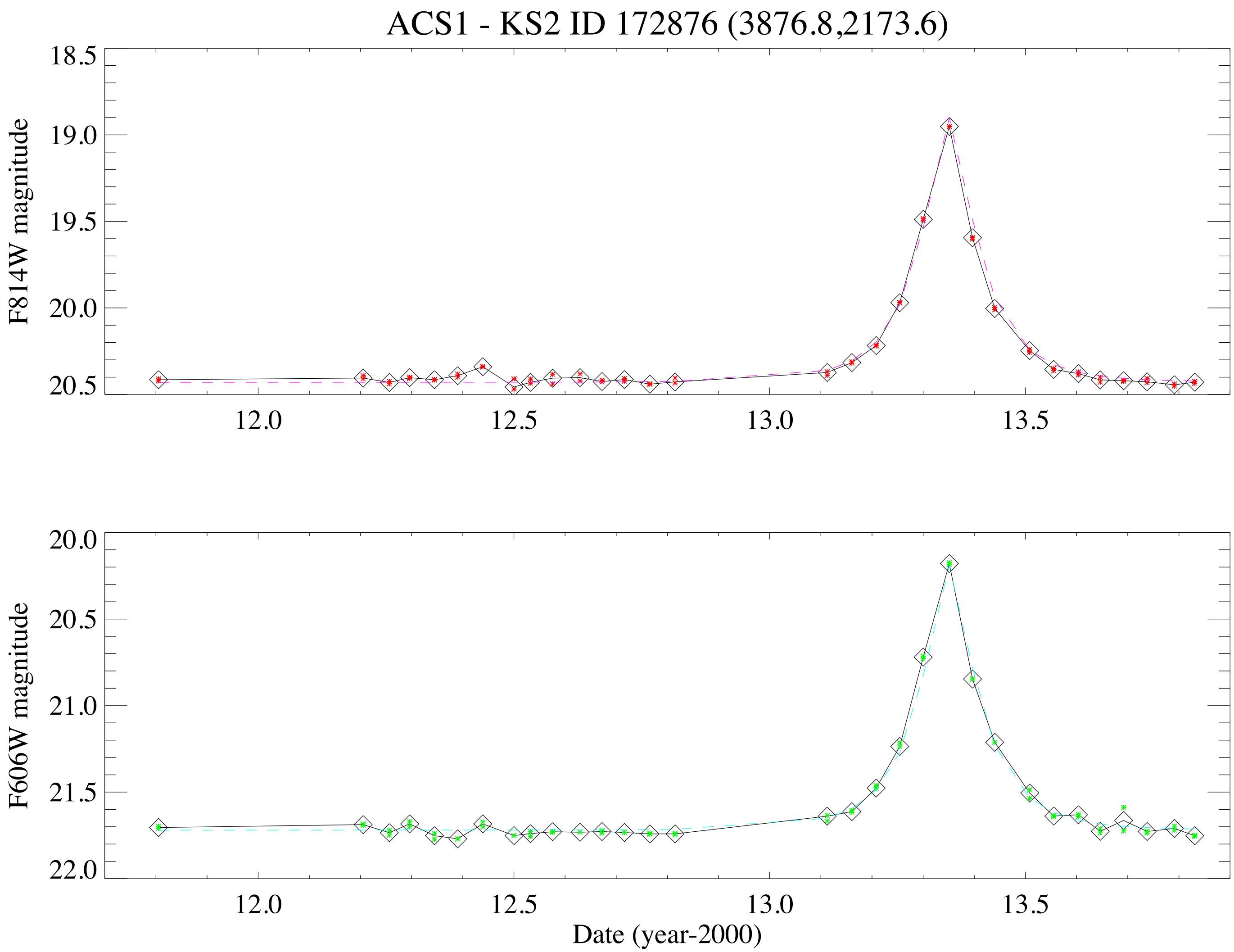
a visit every 2 weeks

8 months per year, for 3 years

Optimized for long-duration micro-lensing events

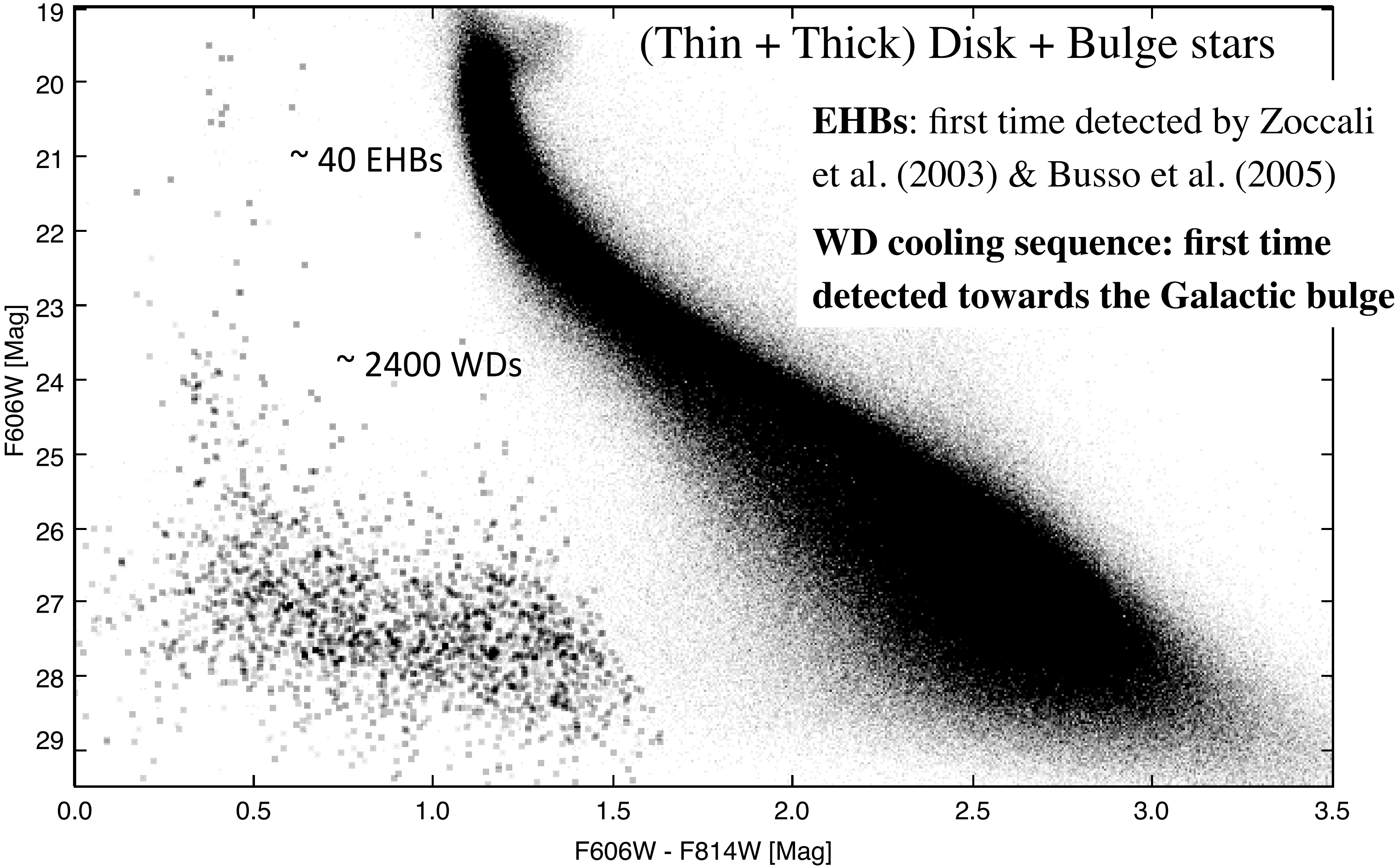
3rd year of observations just ended!!

ACS observations of 1 OGLE microlensing event found in the SWEEPS field



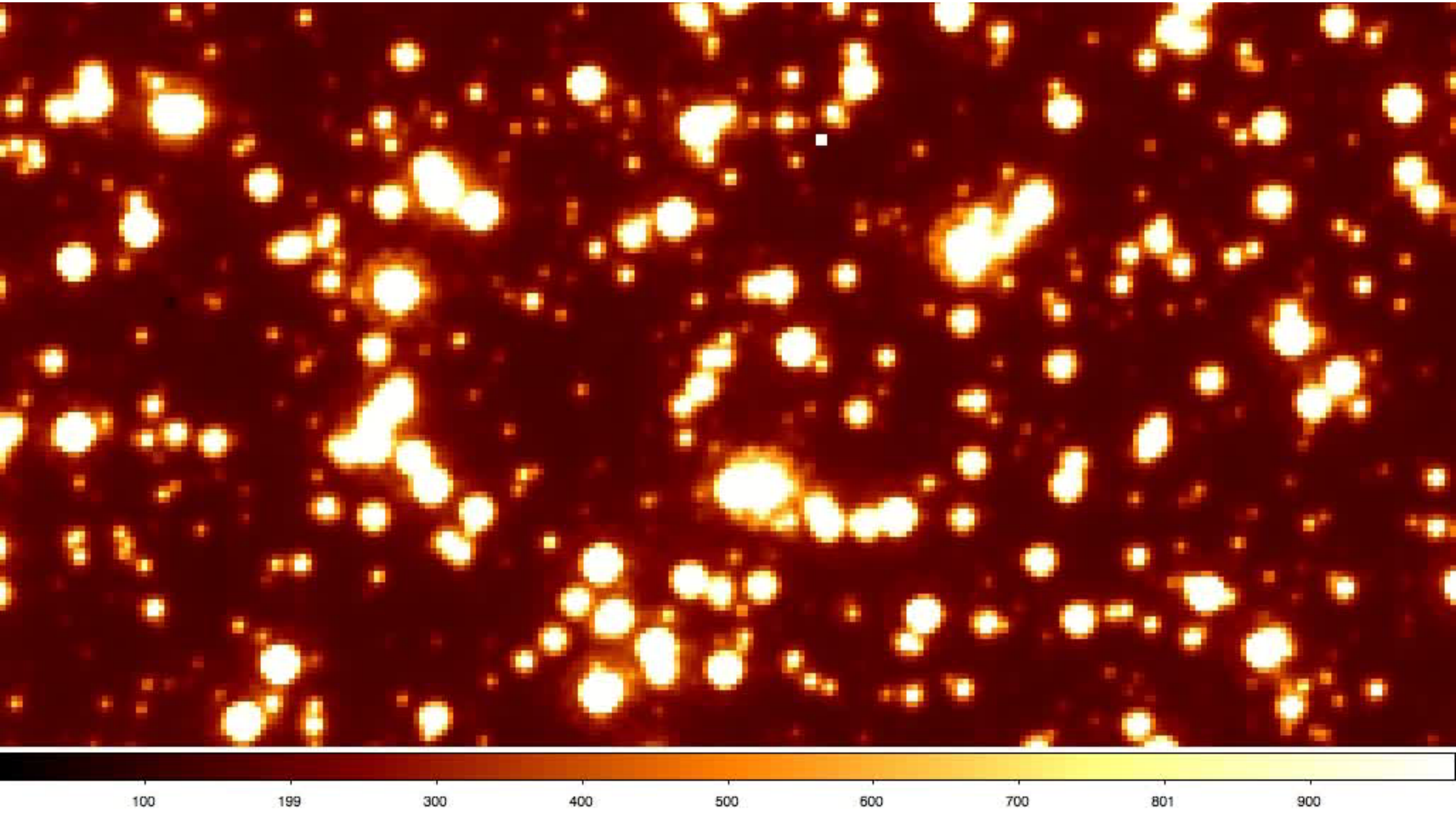
This data set is a goldmine for understanding the formation and evolution of the Galactic bulge

ACS1+ACS2+ACS3+ACS4: ~ 950,000 stars down to F606W ~ 30 mag!



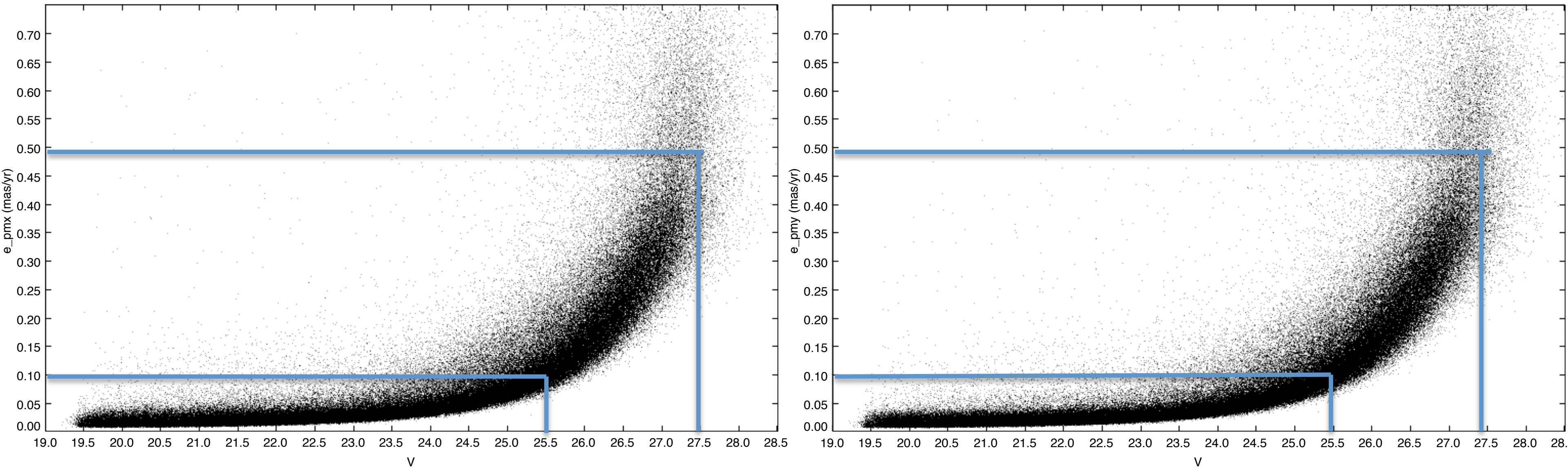
A clean bulge sample: proper motions

Observations available in **2004** (Sahu et al. 2006) and **2012-2013 for the SWEEPS field -> 9 year baseline**



Proper motions for the SWEEPS field

- Proper motions for ~ 200,000 stars down to F606W ~ 28 mag
- Proper motions accuracy: e_pmx(pmy) < 0.5 mas/yr (20 km/s) at F606W ~ 27.5 mag and **e_pmx(e_pmy) < 0.1 mas/yr (4 km/s) at F606W ≈ 25.5 mag**

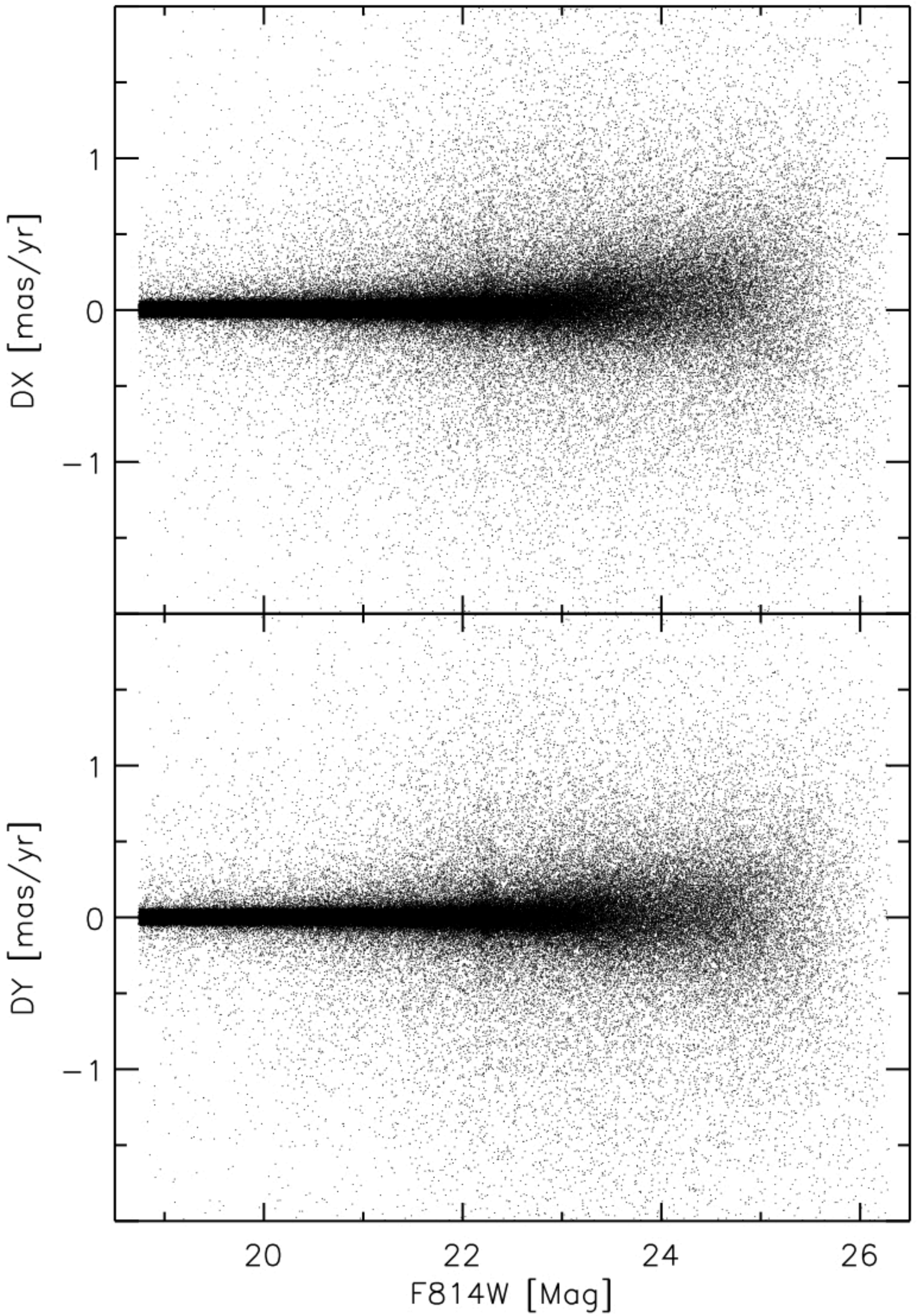


Artificial star tests

Completeness ~ 50% down to F606W ~ 28.2 mag and F814W ~ 25.3 mag

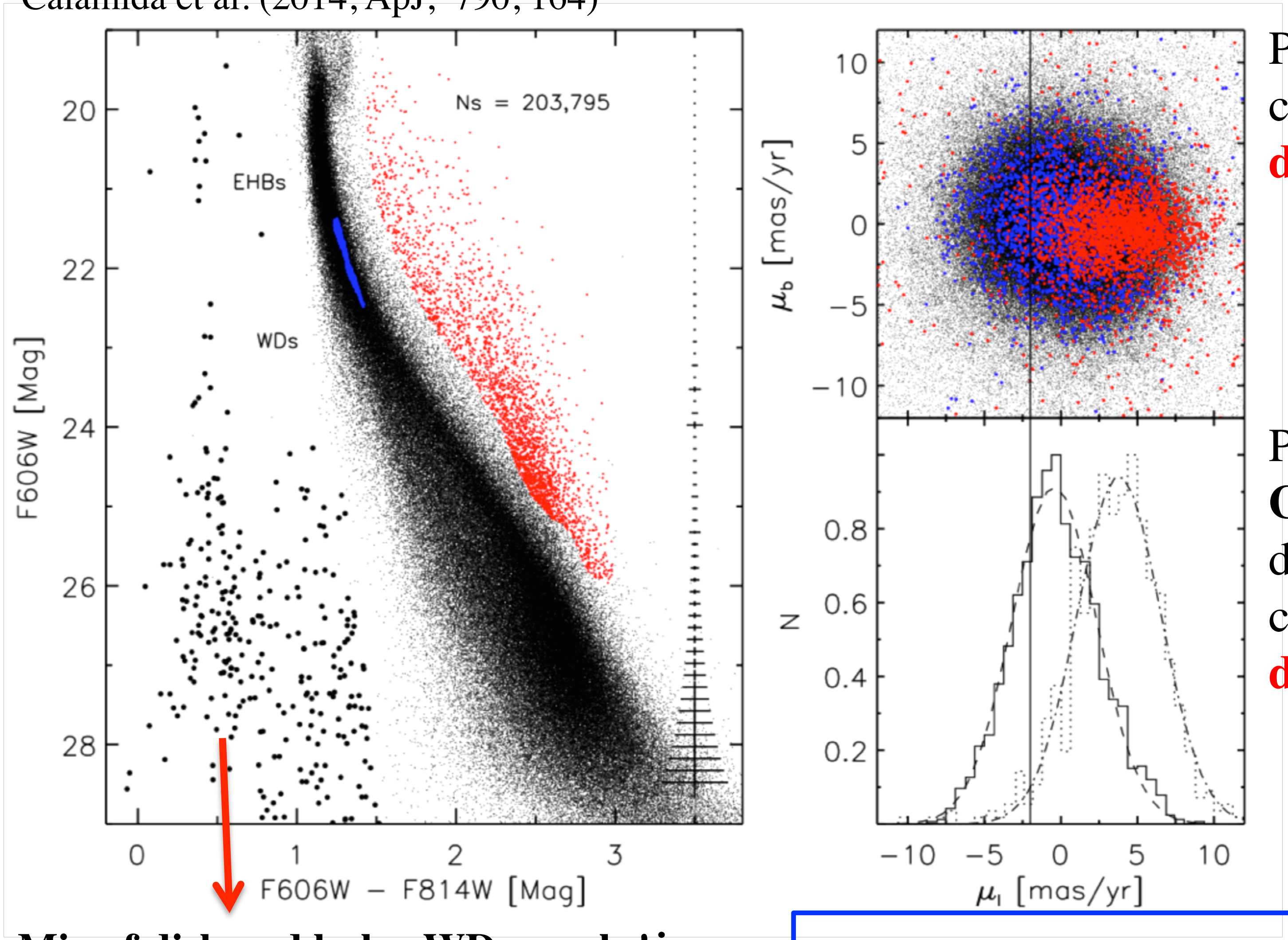
Proper motion accuracy: ~ 0.1 mas/yr at F606W ~ 28 mag and F814W ~ 25 mag

We can accurately separate bulge and disk stars down to F606W ~ 28 mag



Proper Motion selection for the SWEEPS field

Calamida et al. (2014, ApJ, 790, 164)



PM diagram with candidate **bulge** and **disk** stars marked.

PM histograms in the **Galactic longitude** direction for the candidate **bulge** and **disk** populations.

Mix of disk and bulge WD population

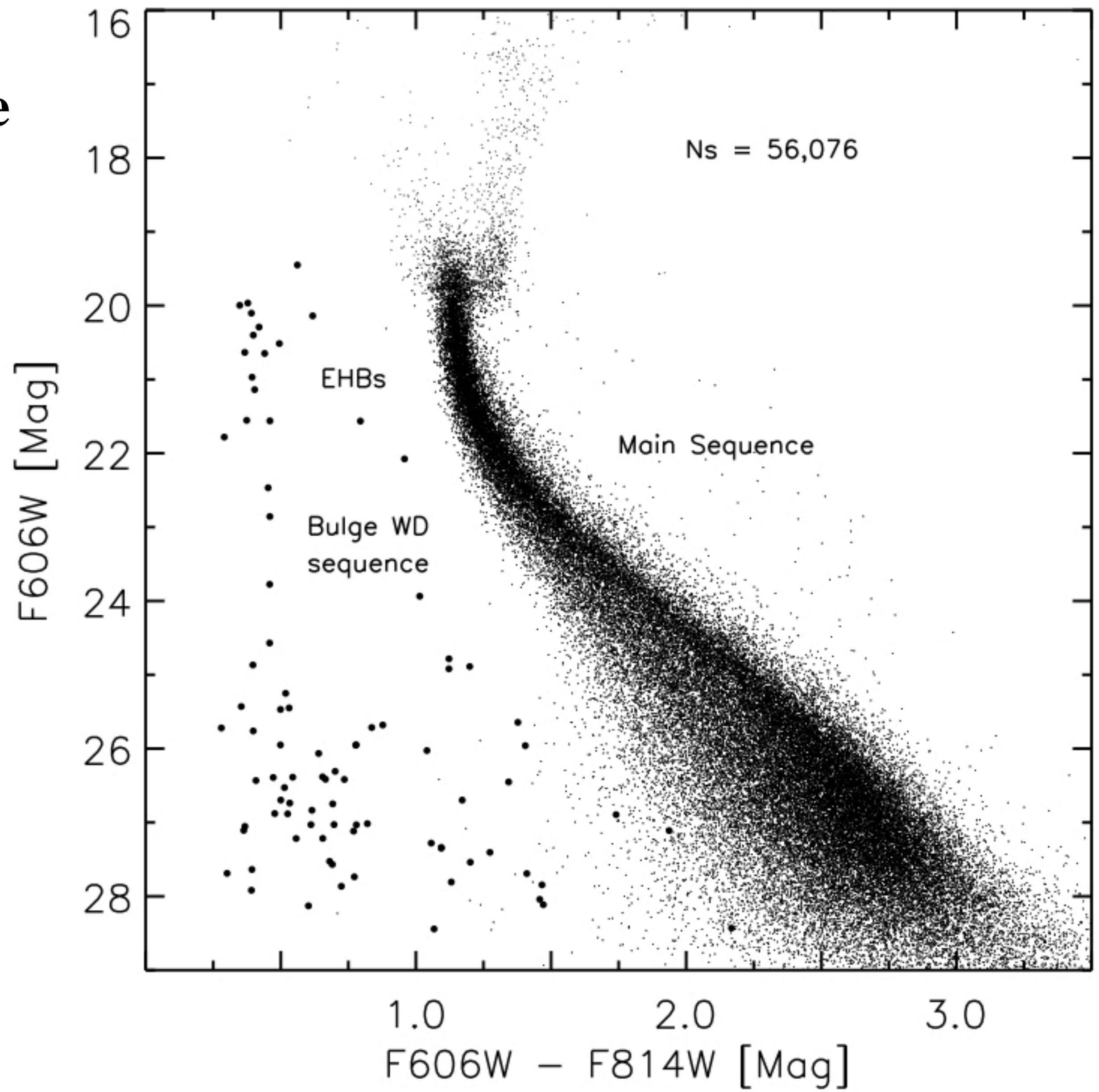
Cut at: μl < - 2 mas/yr: selecting **~30% of bulge stars** (Clarkson et al. 2008)

Residual disk contamination is ≤ 1%

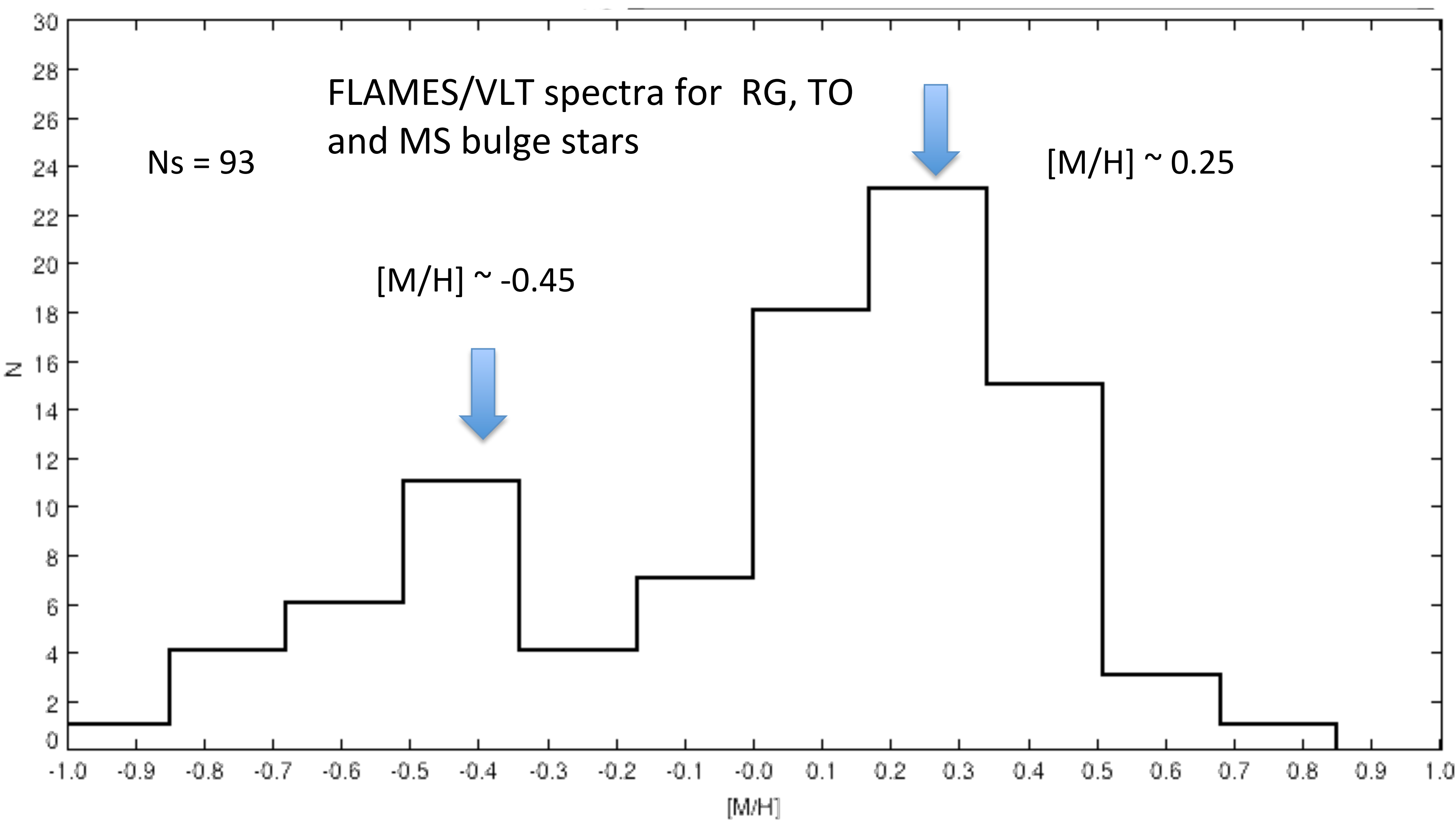
Proper Motion selected bulge CMD

Only 30% of bulge stars are shown

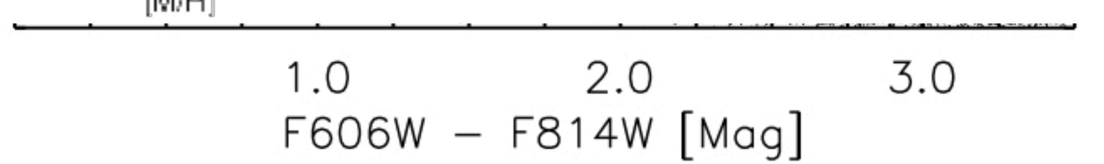
CMD selected in photometric accuracy



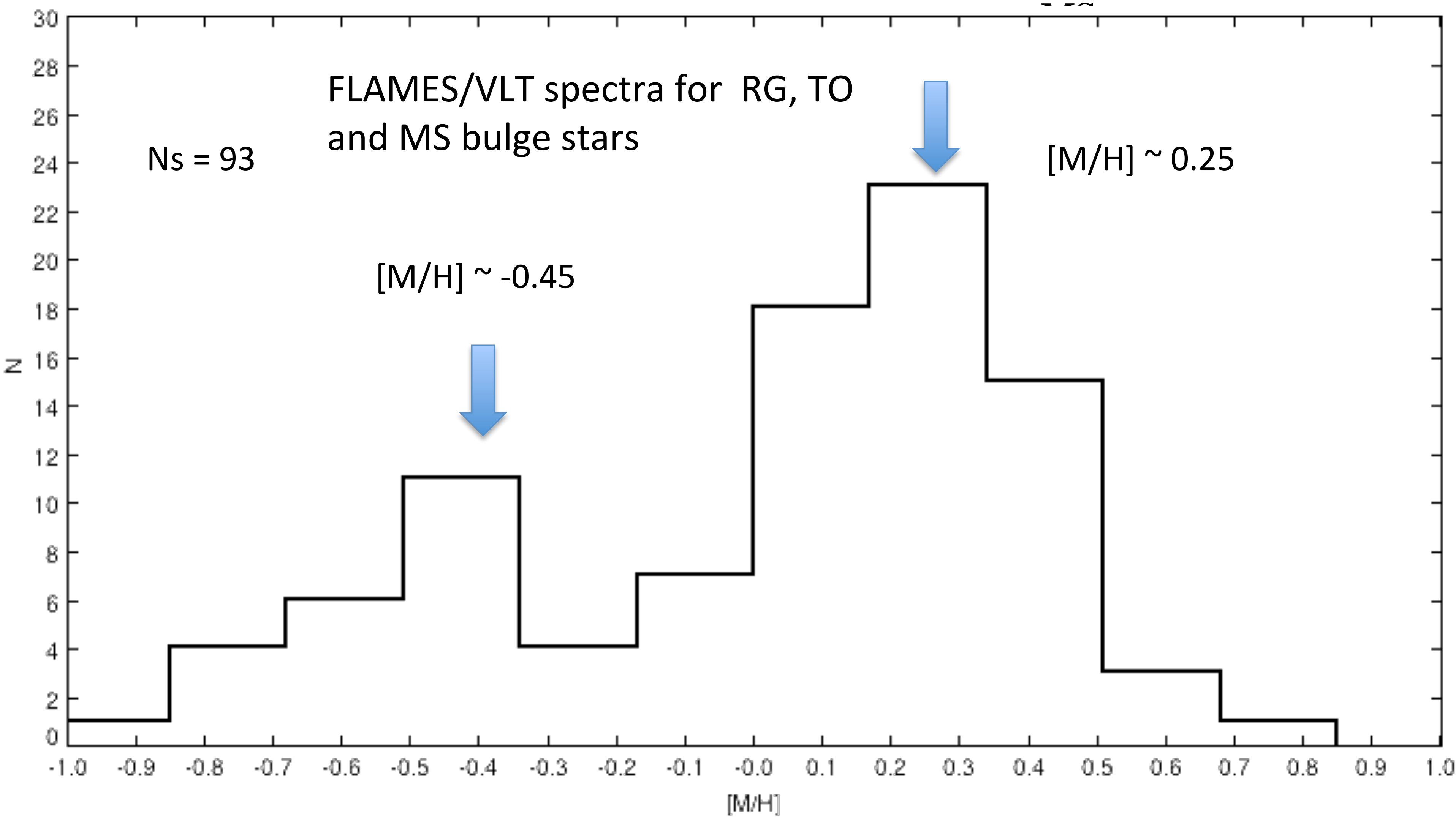
Proper Motion selected bulge CMD



- Binaries



PM-cleaned bulge CMD -> only 30% of bulge stars are selected - No disk contamination!



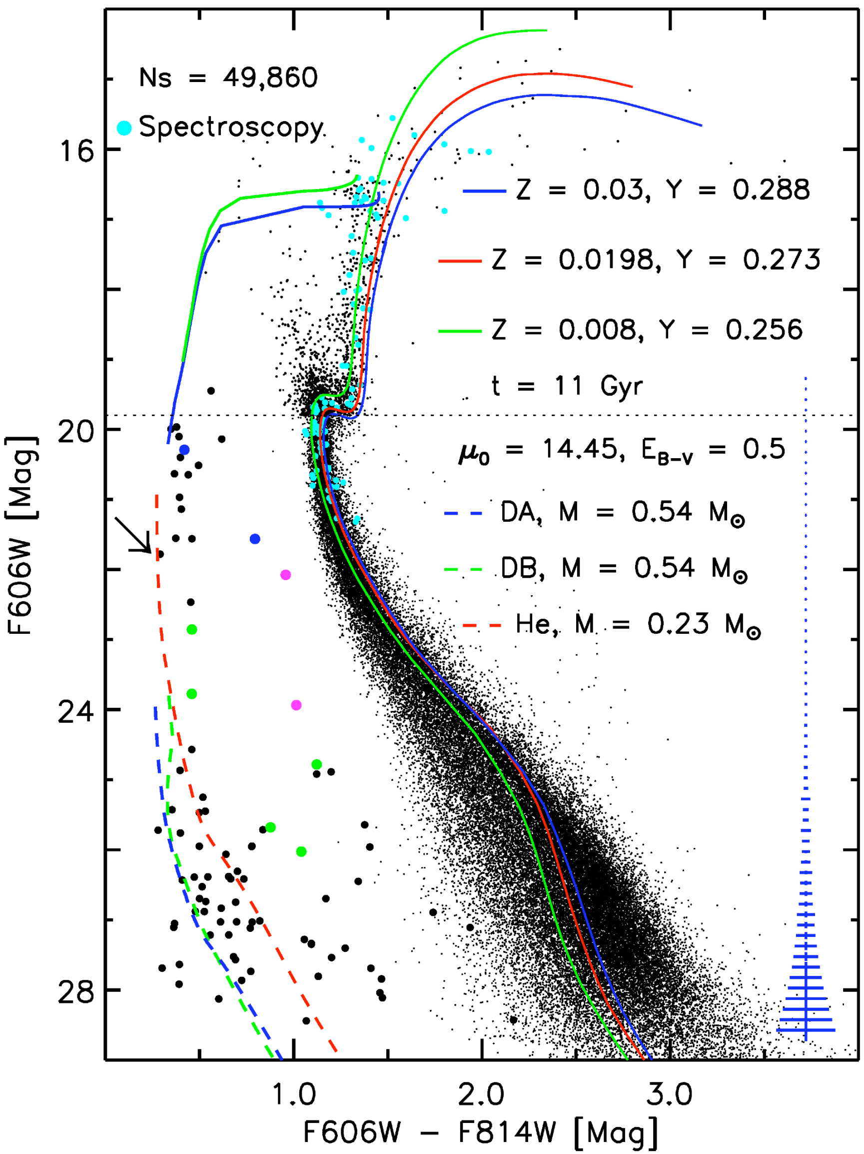
1.0 2.0 3.0

BASTI models F606W – F814W [Mag]

Calamida et al. (2014 ApJ, 790, 164)

PM-cleaned bulge CMD: only 30% of bulge stars are shown

Calamida et al. (2014, ApJ, 790, 164)



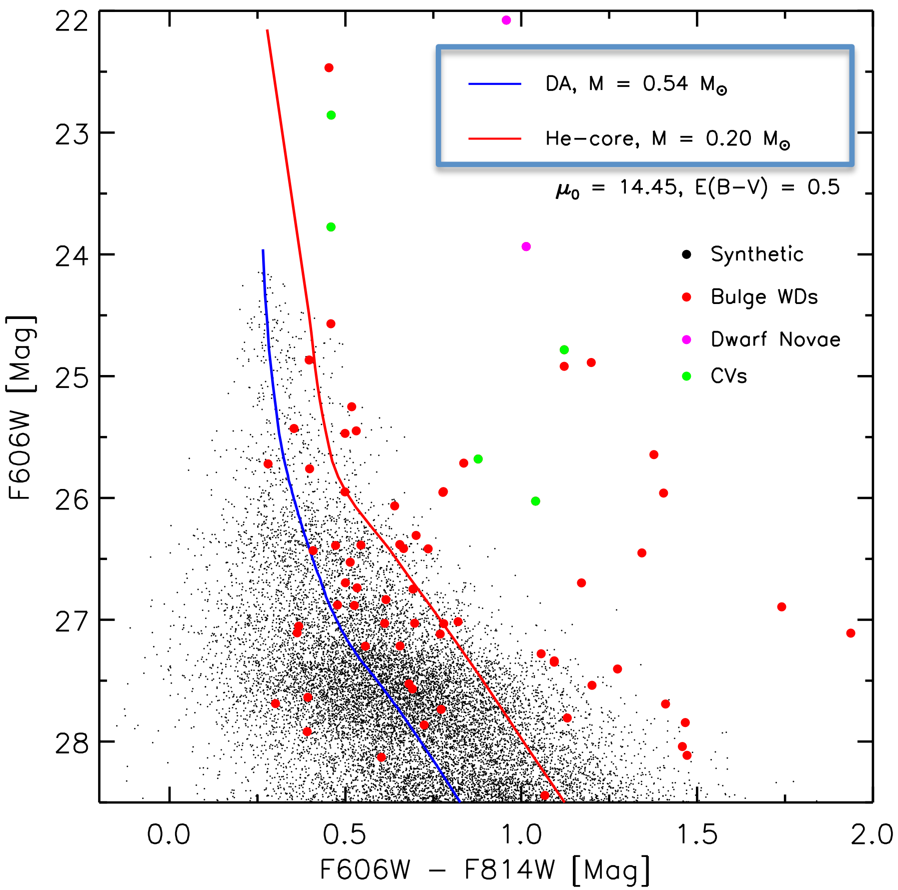
BASTI cooling tracks for **DA and DB CO-core WDs with M = 0.54 M⊙ (old stellar population,** turn-off mass ~ 0.95M⊙, t ~ 11 Gyr)

He-core track for 0.23 M⊙

WDs:

- Photometric errors
- Differential reddening
- Depth effects
- Binaries

Simulations



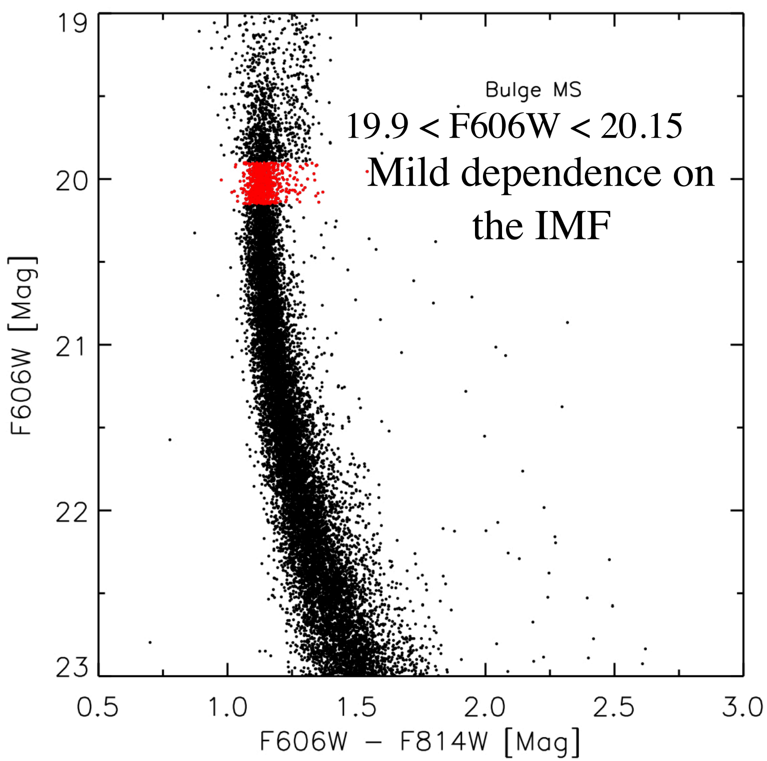
Calamida et al. (2014, ApJ, 790, 164)

- **Artificial star (AS) tests:** insert ~ 160,000 WDs in all images -> entire dataset reduced with the same technique
- **Synthetic WD cooling sequence for a population of CO-core WDs with 0.54 M⊙**
- **Differential reddening added**

Mass range?

A fraction of He-core WDs (M < 0.45 M⊙ -> binary origin)

Star counts ← → Theoretical lifetimes

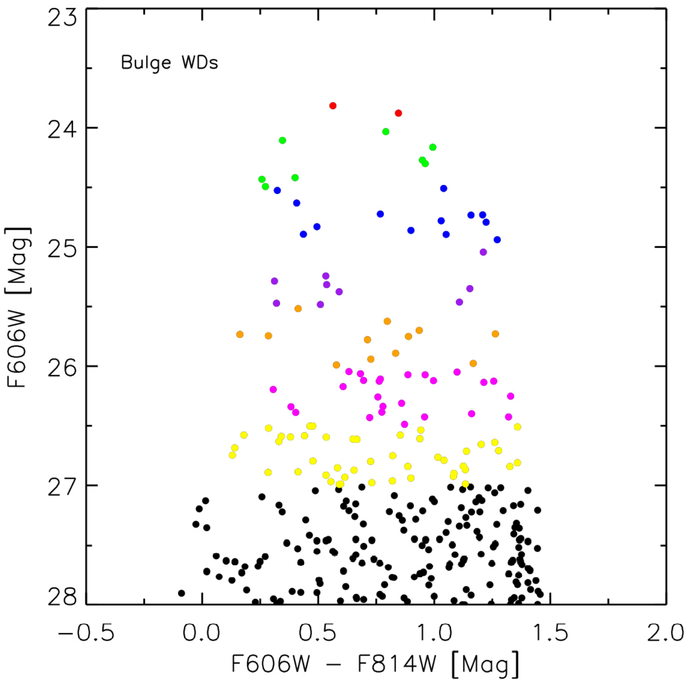


WD counts for F606W ≤ 27 mag, corrected for completeness, compared to **MS counts across the TO region** where the mass is almost constant

If all WDs are CO-core, the observed number of WDs compared to MS stars is larger than the expected number by at least a factor of 2.

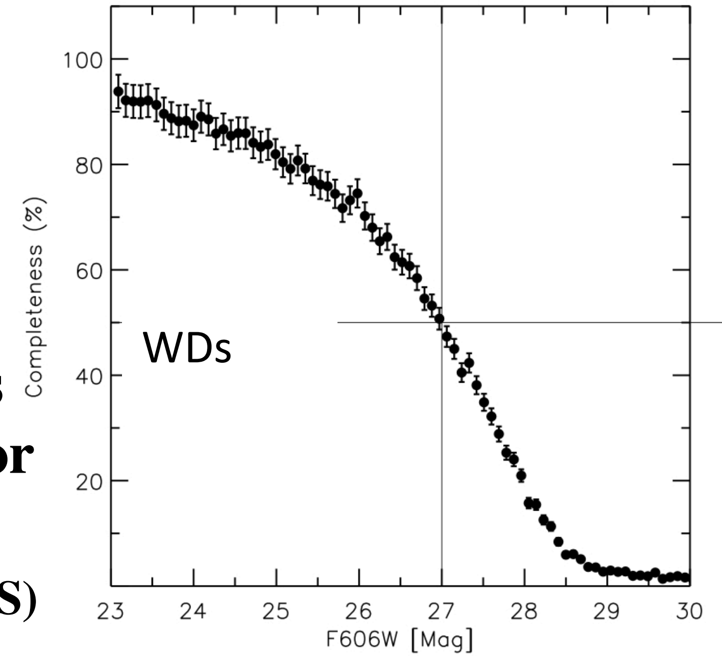
If ~ 30-40% of WDs are 0.4 M⊙ He-core, the observed WDs are consistent with what is predicted by theoretical lifetimes.

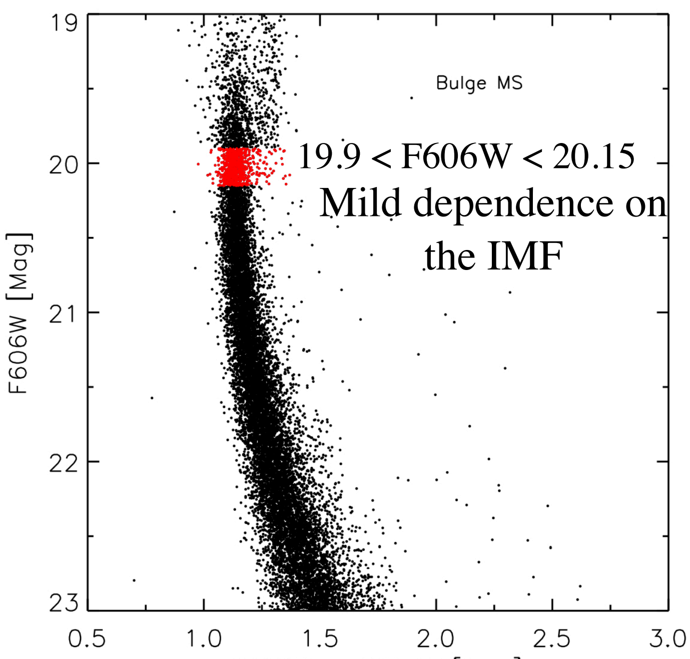
Star counts ← → Theoretical lifetimes



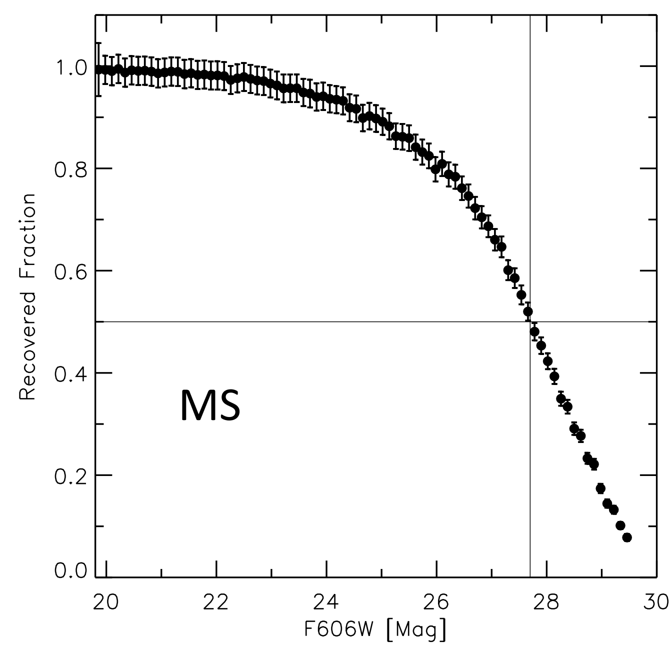
Star counts corrected for completeness

N(WDs) /N(MS) is more than a factor of 2 larger than t(WD_CO-core)/t(MS)

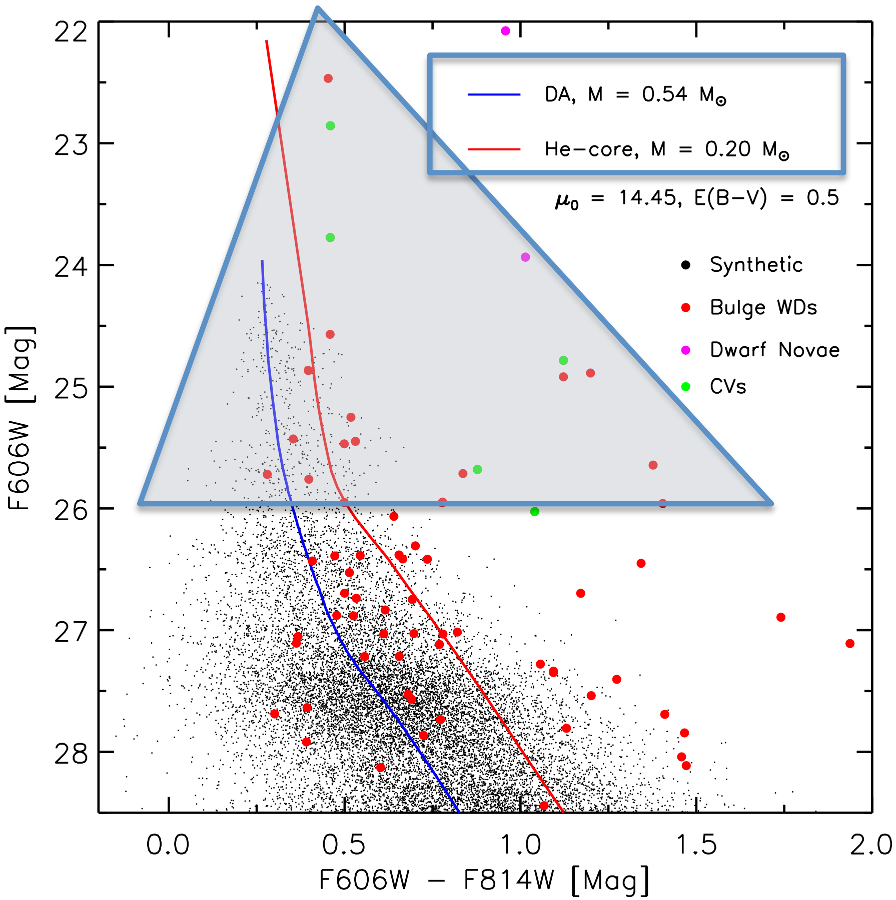




The agreement between theory and observations improves if we assume the **presence of ~30-40% 0.4 M⊙ He-core WDs in the bulge.**



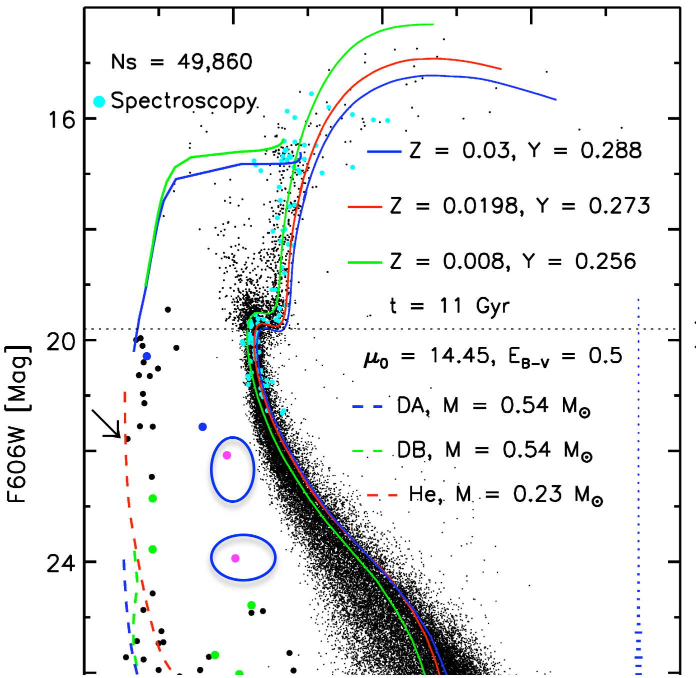
Simulations

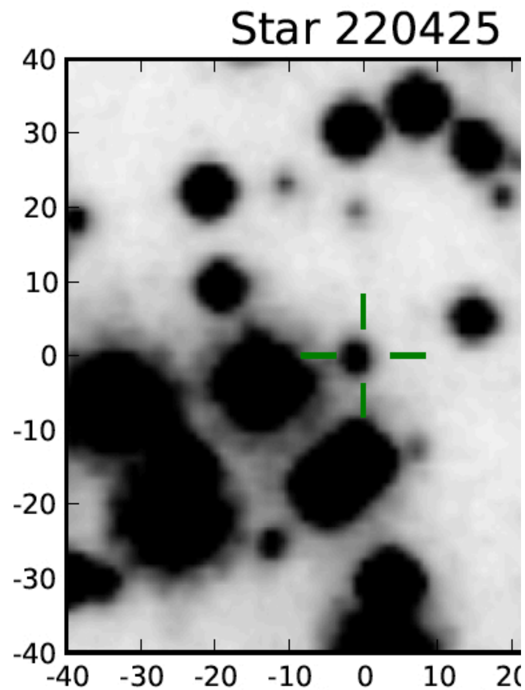


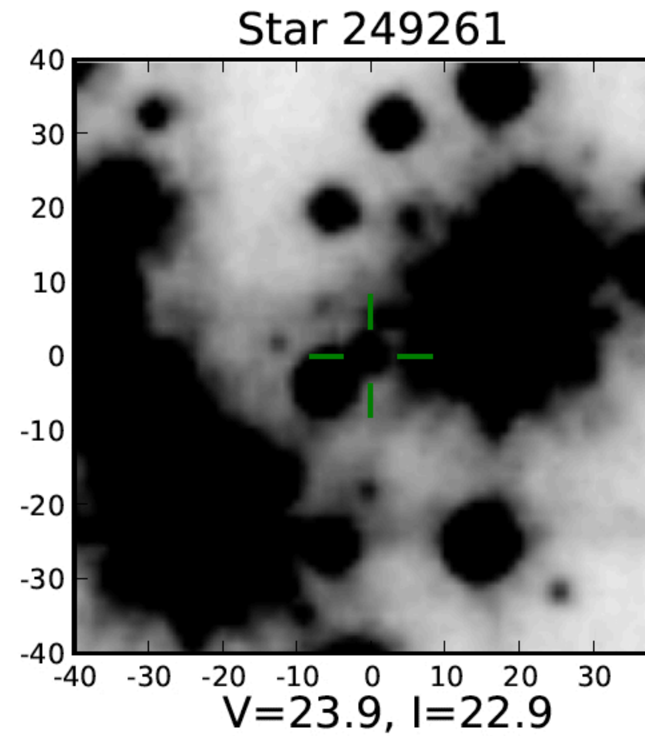
- **Reddest WDs cannot be explained as He-core WDs**
- **WD + MS binaries?**

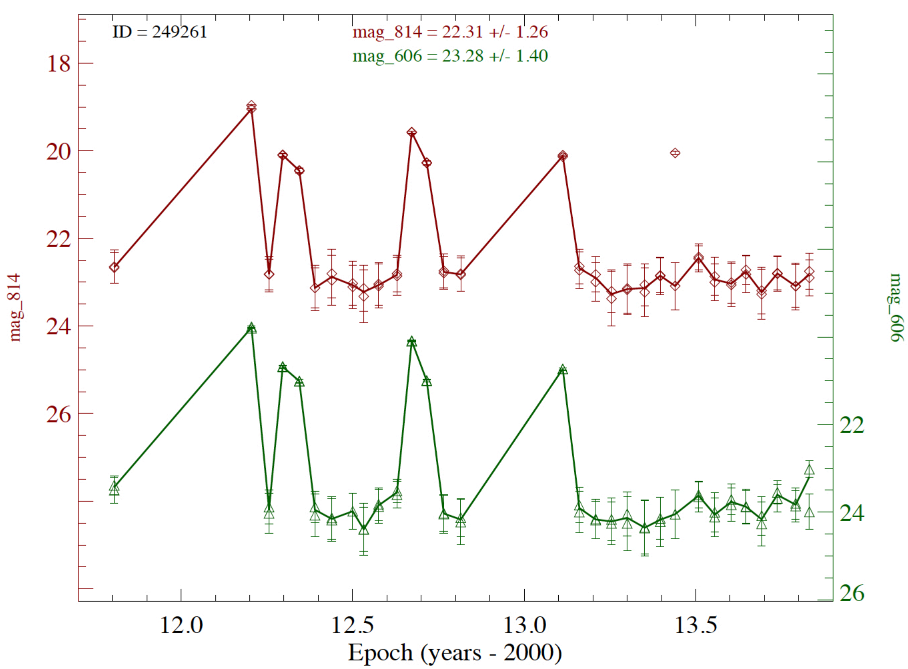
Check the variability of brightest WDs

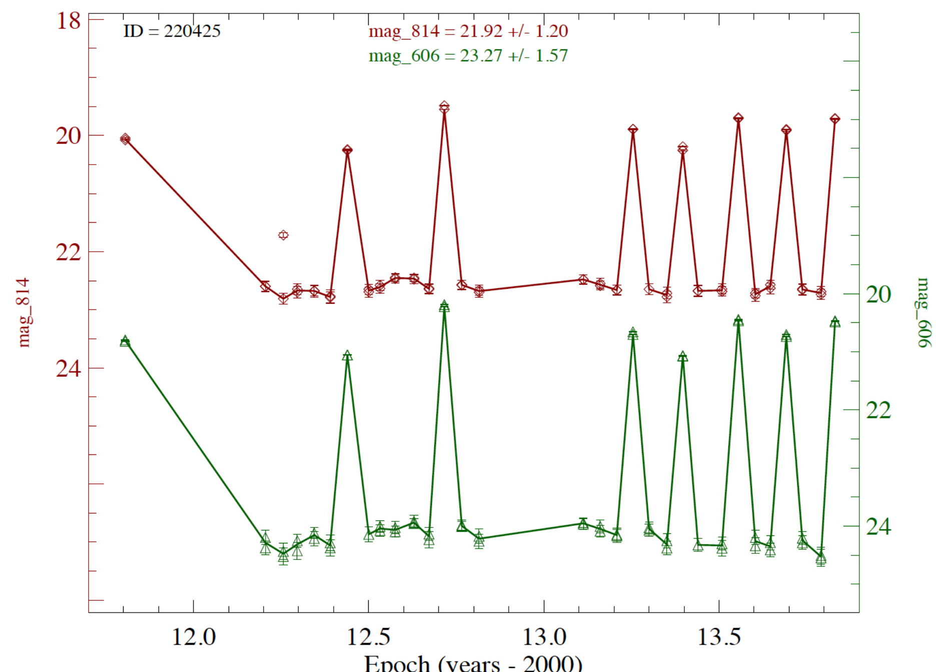
Two candidate dwarf novae!

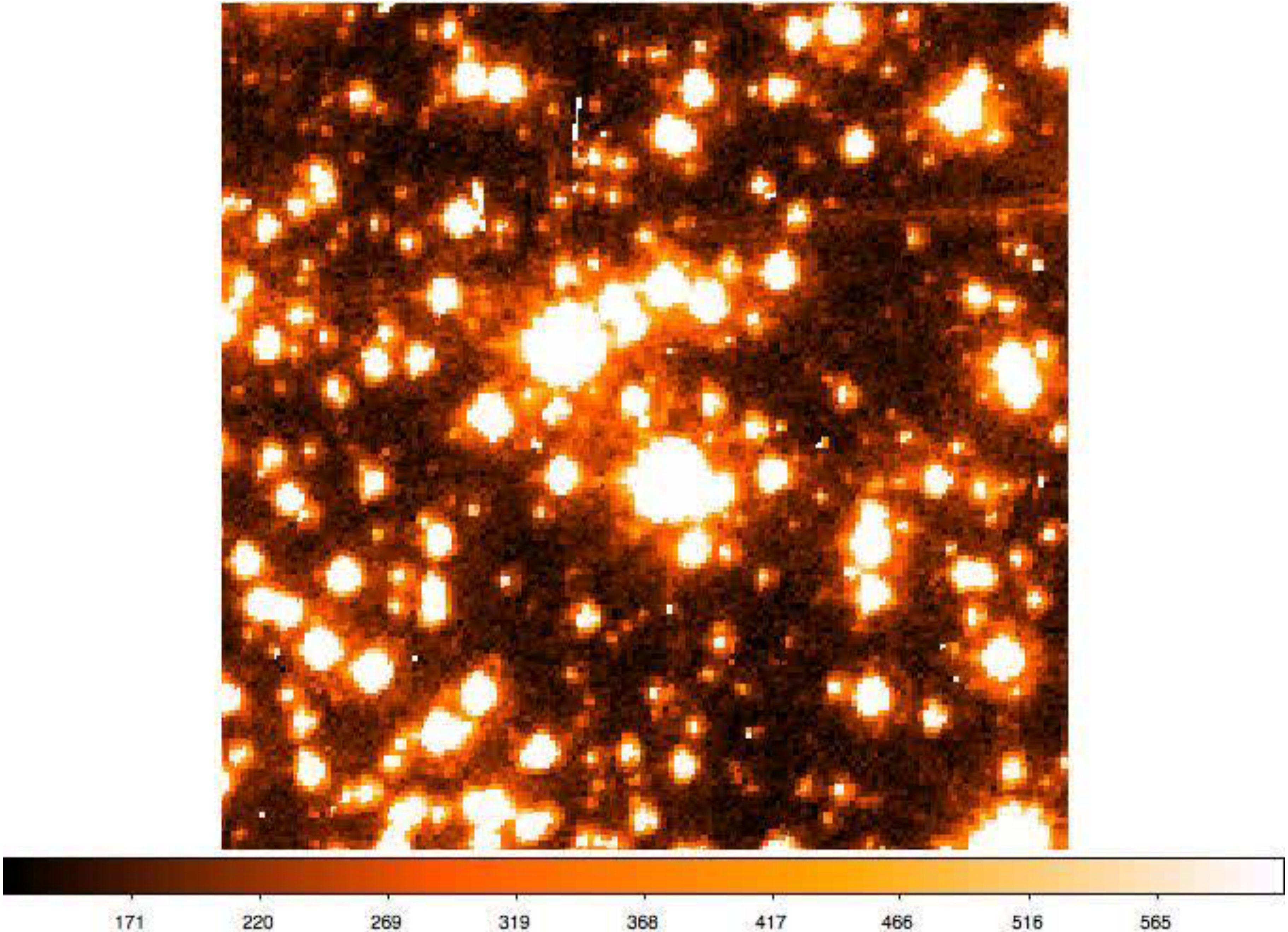




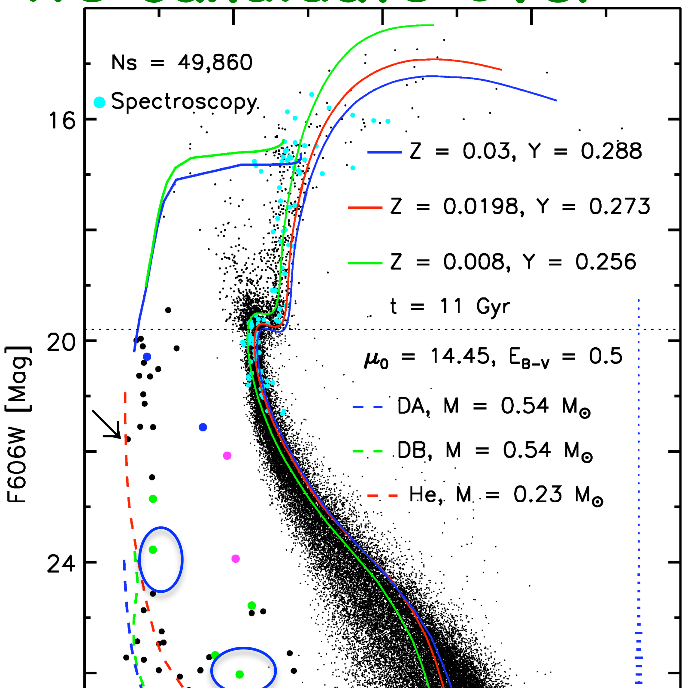


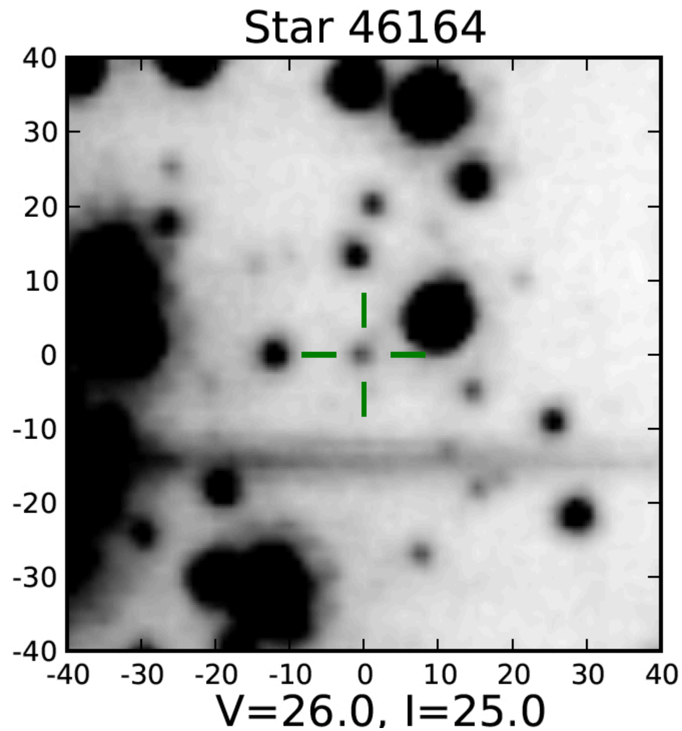


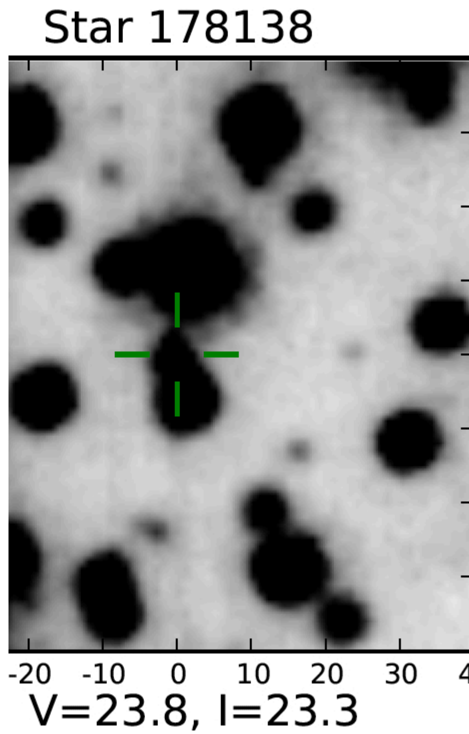


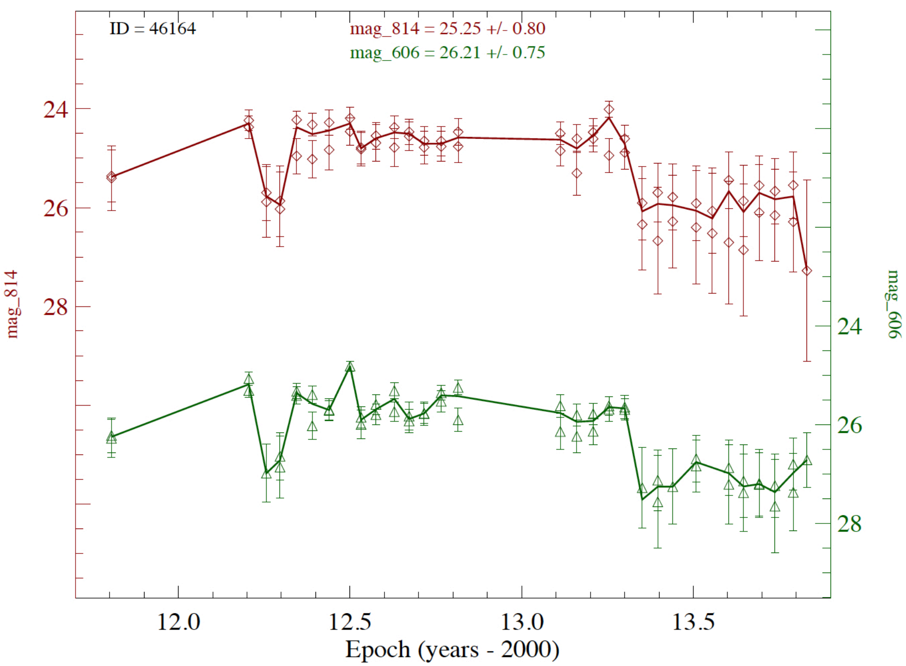

171
220
269
319
368
417
466
516
565

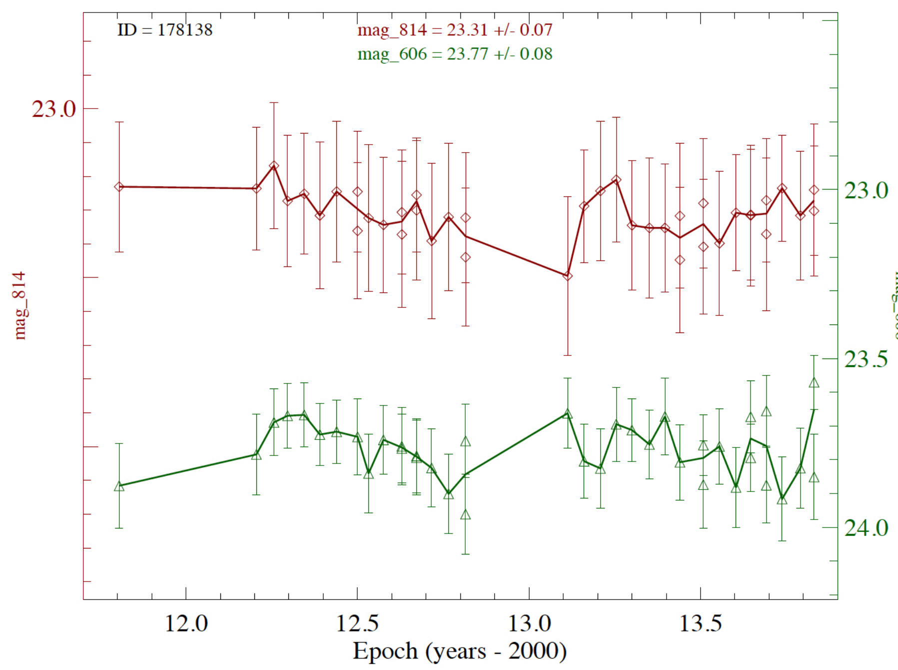
Five candidate CVs!





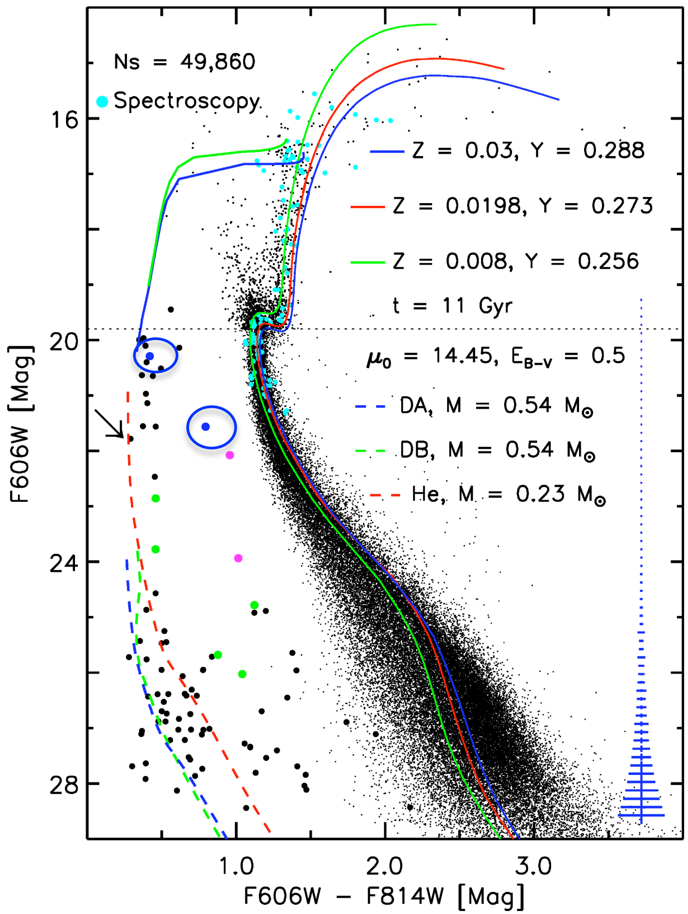






Differential Image photometry from Sahu 2004 data set (1 week baseline)

Two ellipsoidal variables!



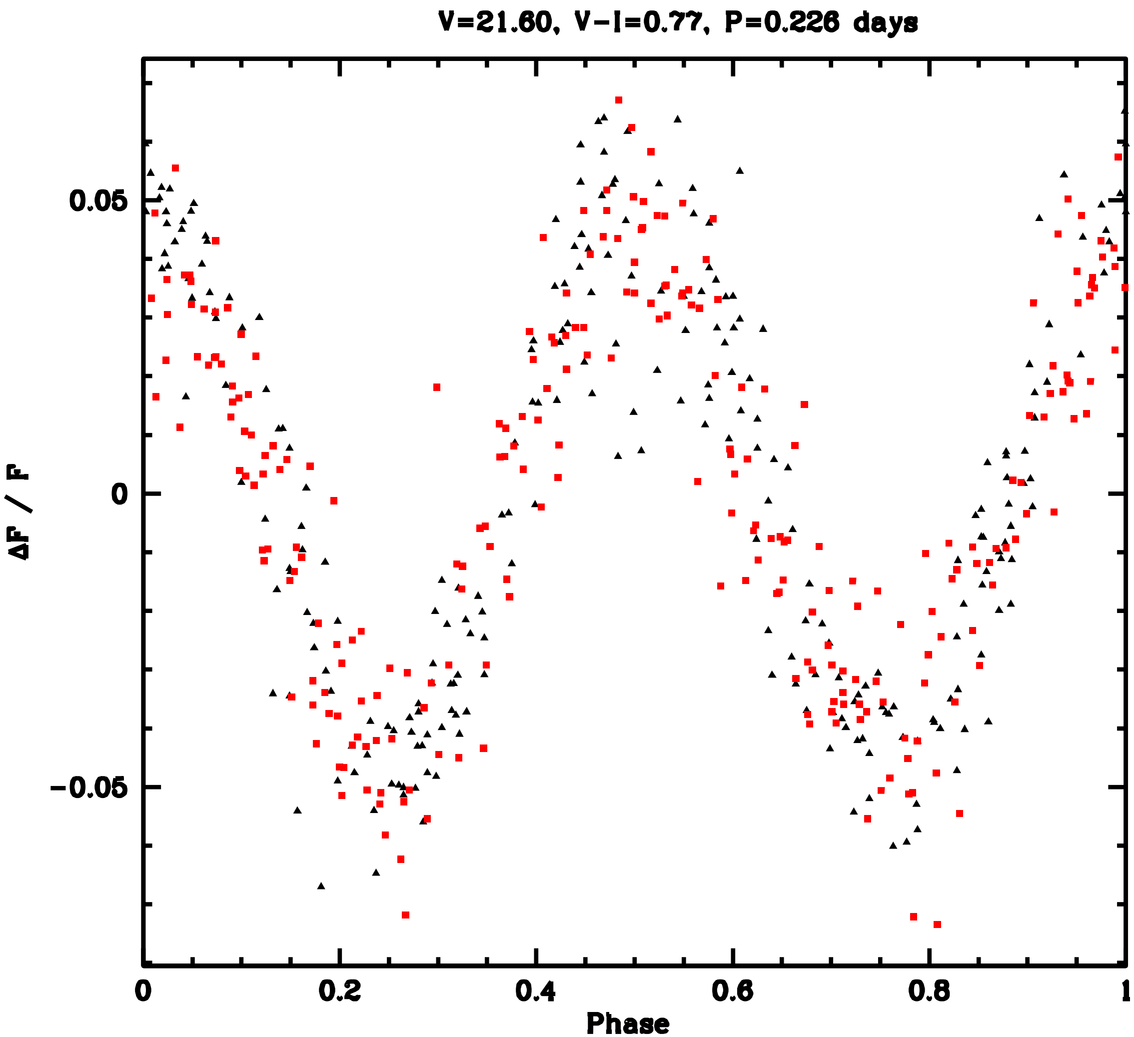
If M1 (MS) ~ 0.6 M⊙

a ~ 0.007 AU

M2 (WD) ~ 0.4 M⊙

A: 5.103E-02 (8.973E-04)

P (d): 1.129E-01 (1.811E-05)



Calamida et al. (2014, ApJ, 790, 164)

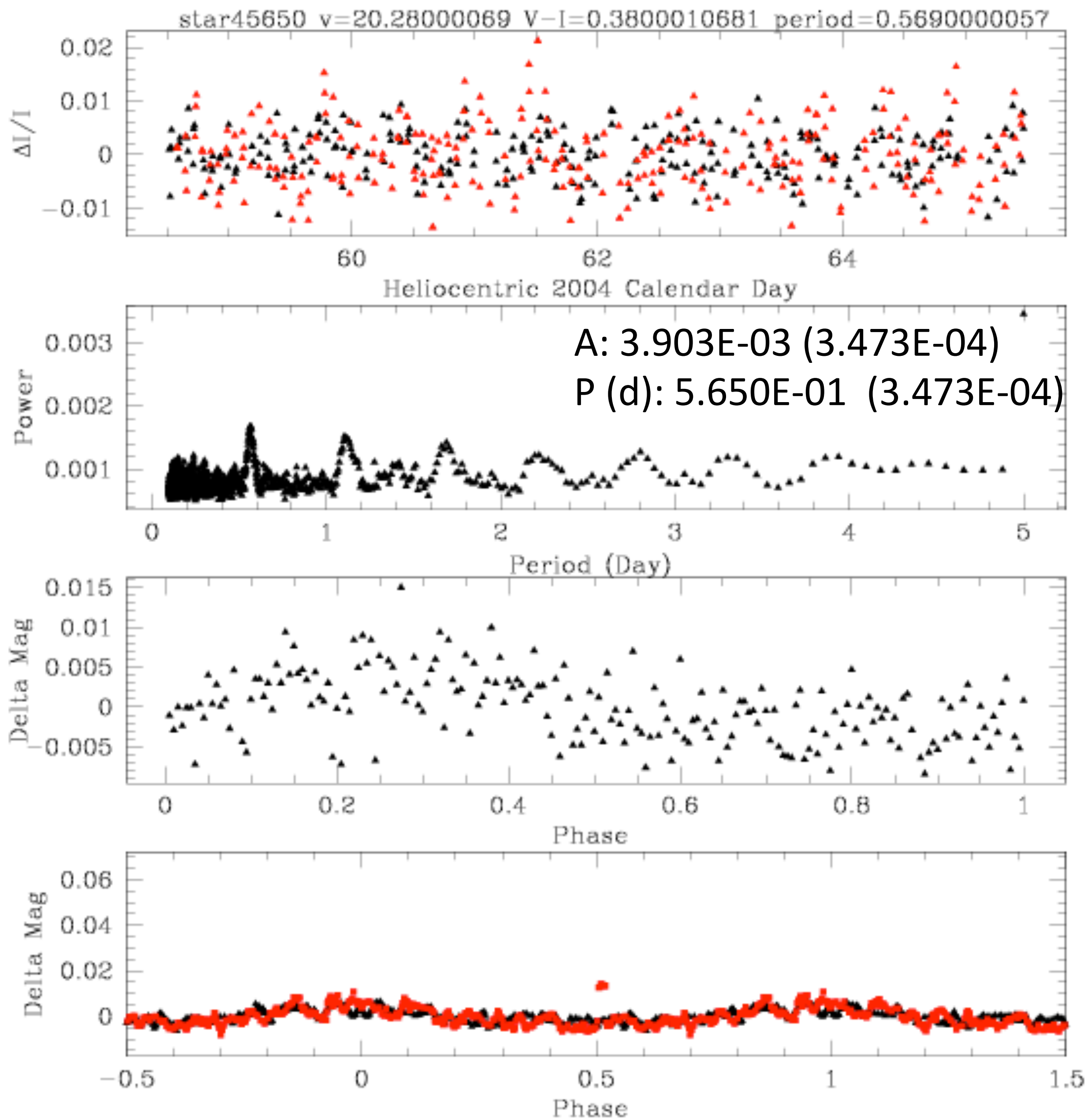
Differential Image photometry from Sahu 2004 data set for the SWEEPS field (1 week baseline)

M1 (EHB) = 0.5 M⊙

a = 0.017 – 0.024 Au

M2 (?) = 3.6 – 8 M⊙

Candidate Black hole companion -> need radial velocity measurements to confirm **(Gemini approved proposal GS-2014A-Q86)**

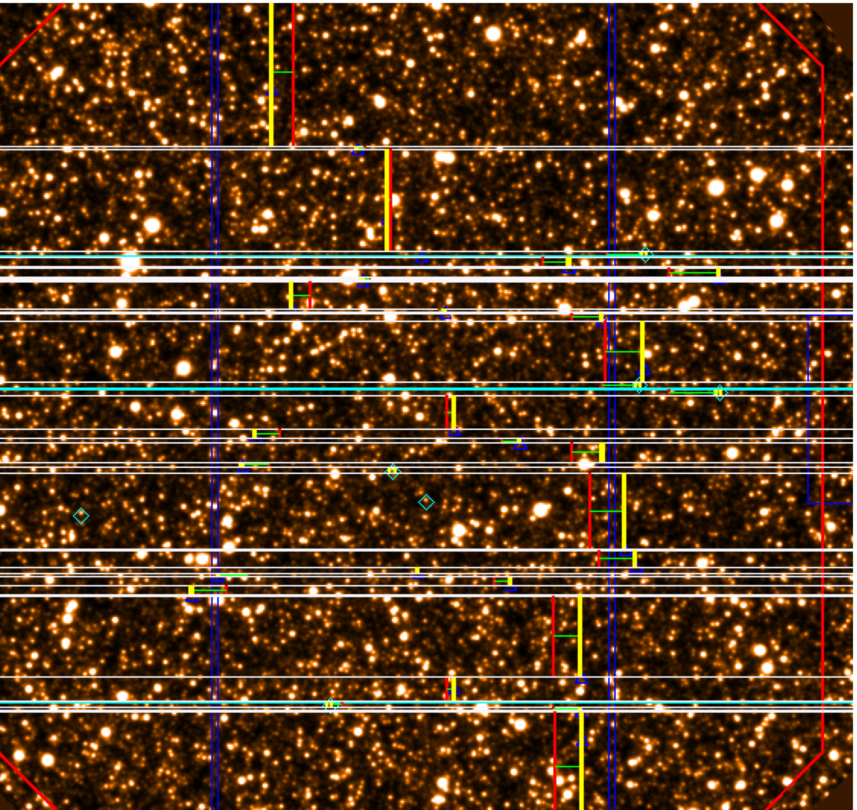


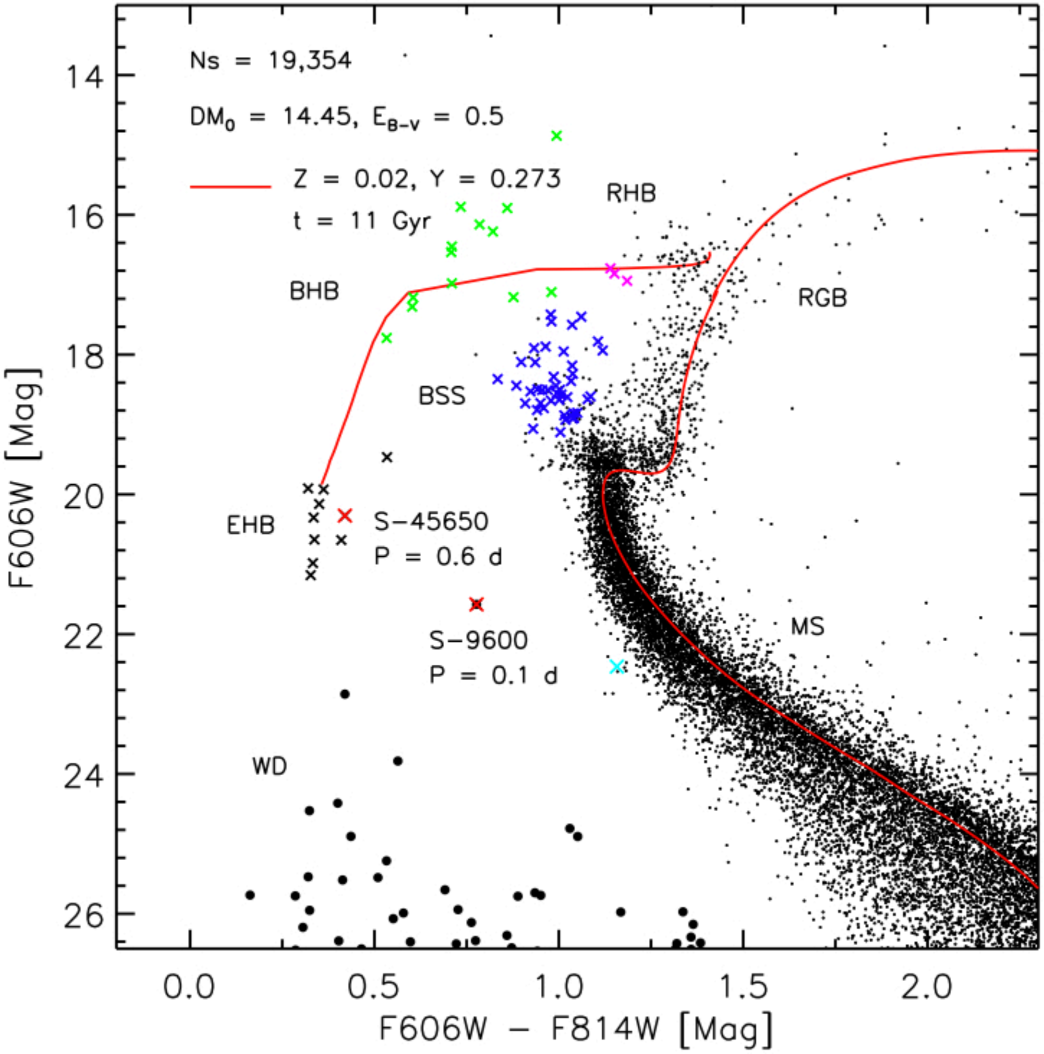
Gemini - GMOS-S multi-object spectroscopy

B600 grating, t_{exp} ~ 1200s

Expected radial velocities ~ 100-500 km/s

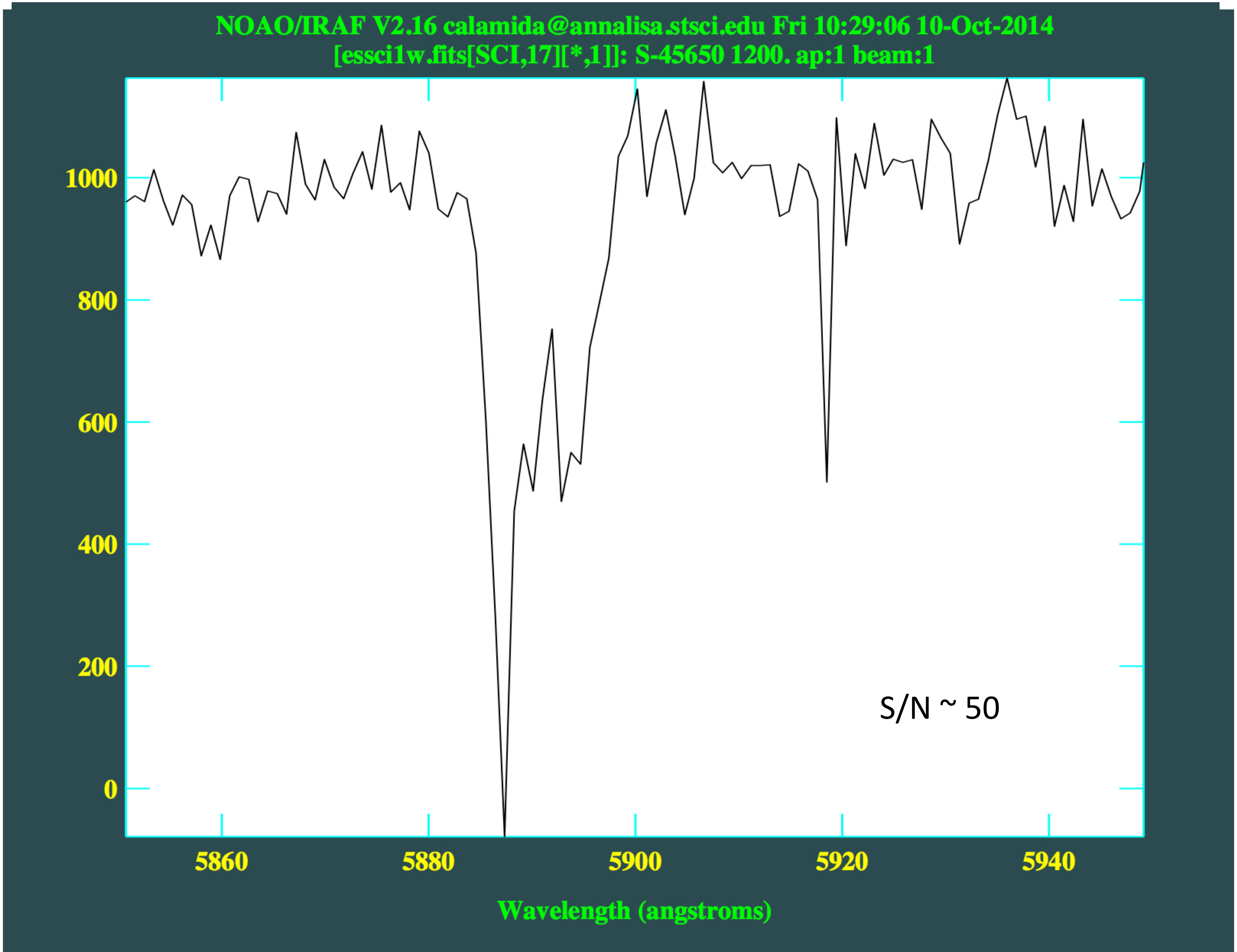
Periods: 0.1 – 10 days





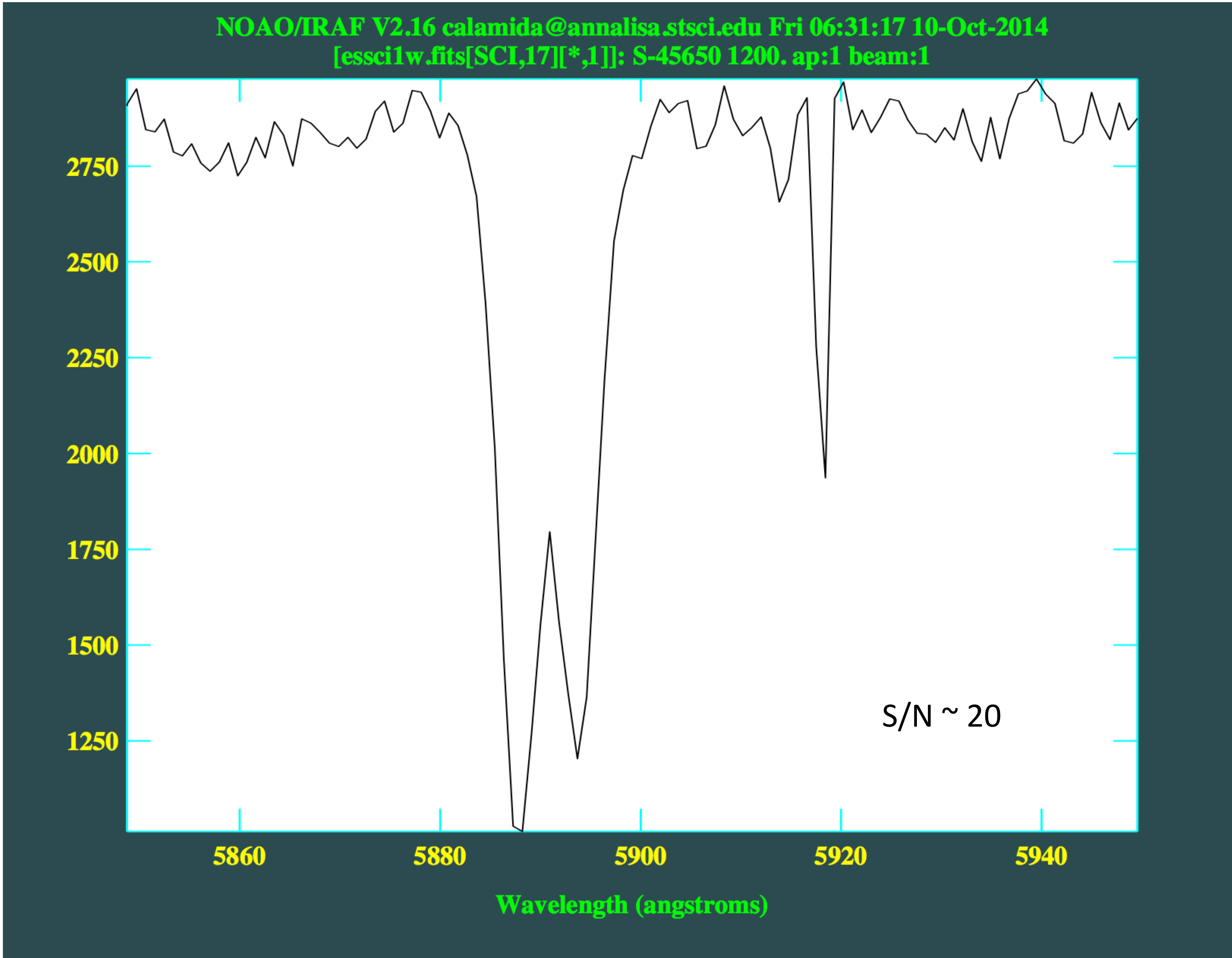
Ellipsoidal variable

Gemini - GMOS-S

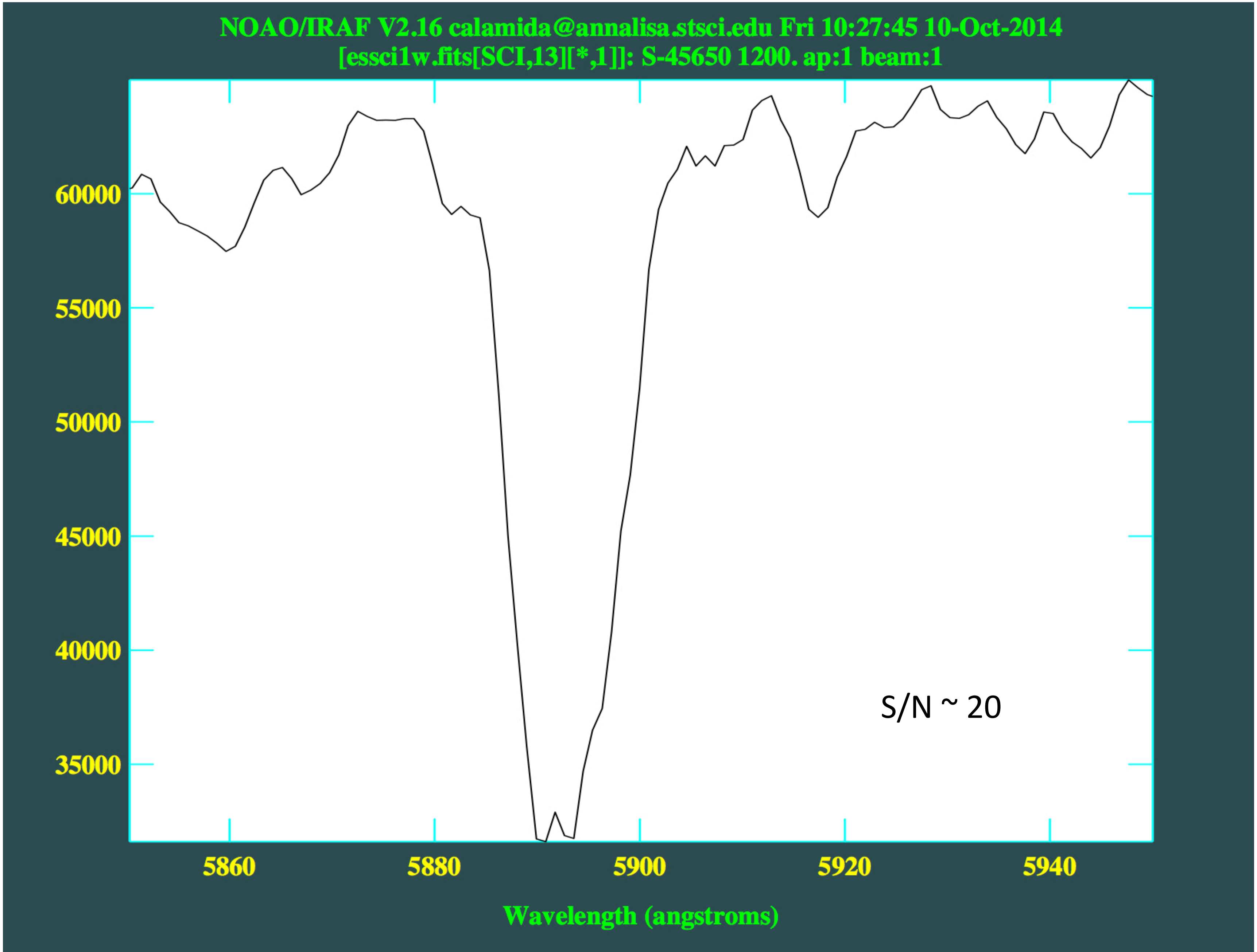


Dwarf nova

Gemini - GMOS-S



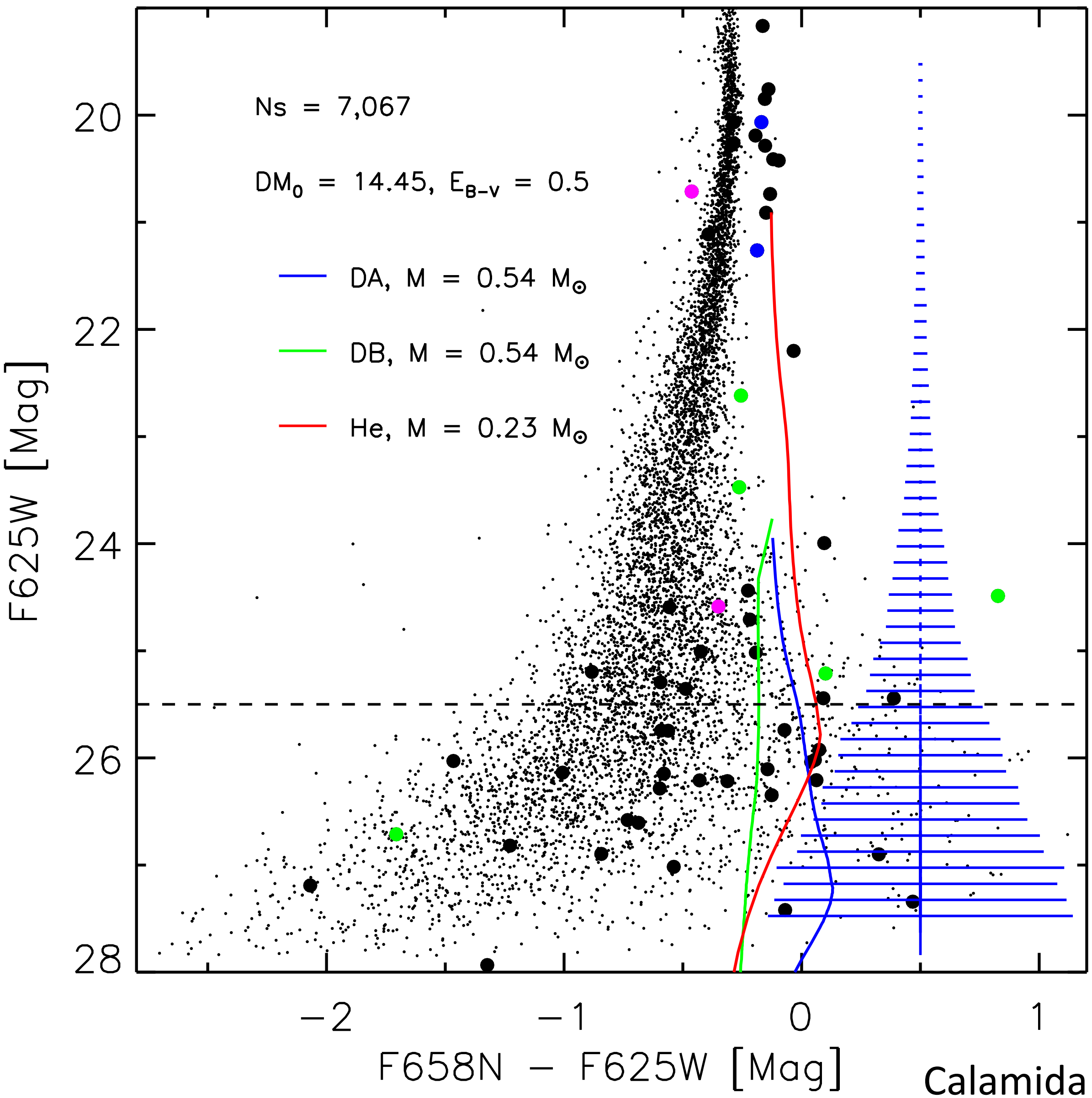
Dwarf nova



NOAO/IRAF V2.16 calamida@annalisa.stsci.edu Fri 10:27:45 10-Oct-2014
[essci1w.fits[SCI,13][*,1]]: S-45650 1200. ap:1 beam:1
60000
55000
50000
45000
40000
35000
5860
5880
5900
5920
5940
Wavelength (angstroms)
S/N ~ 20

Hα and R-band photometry

~30% of WDs, including the DN, are showing Hα excess, Hα-R ≤ -0.3



F625W ≤ 25.5 mag

- Dwarf novae
- CVs
- Ellipsoidal Variables

Calamida et al. (2014, ApJ, 790, 164)

Preliminary results for bulge IMF

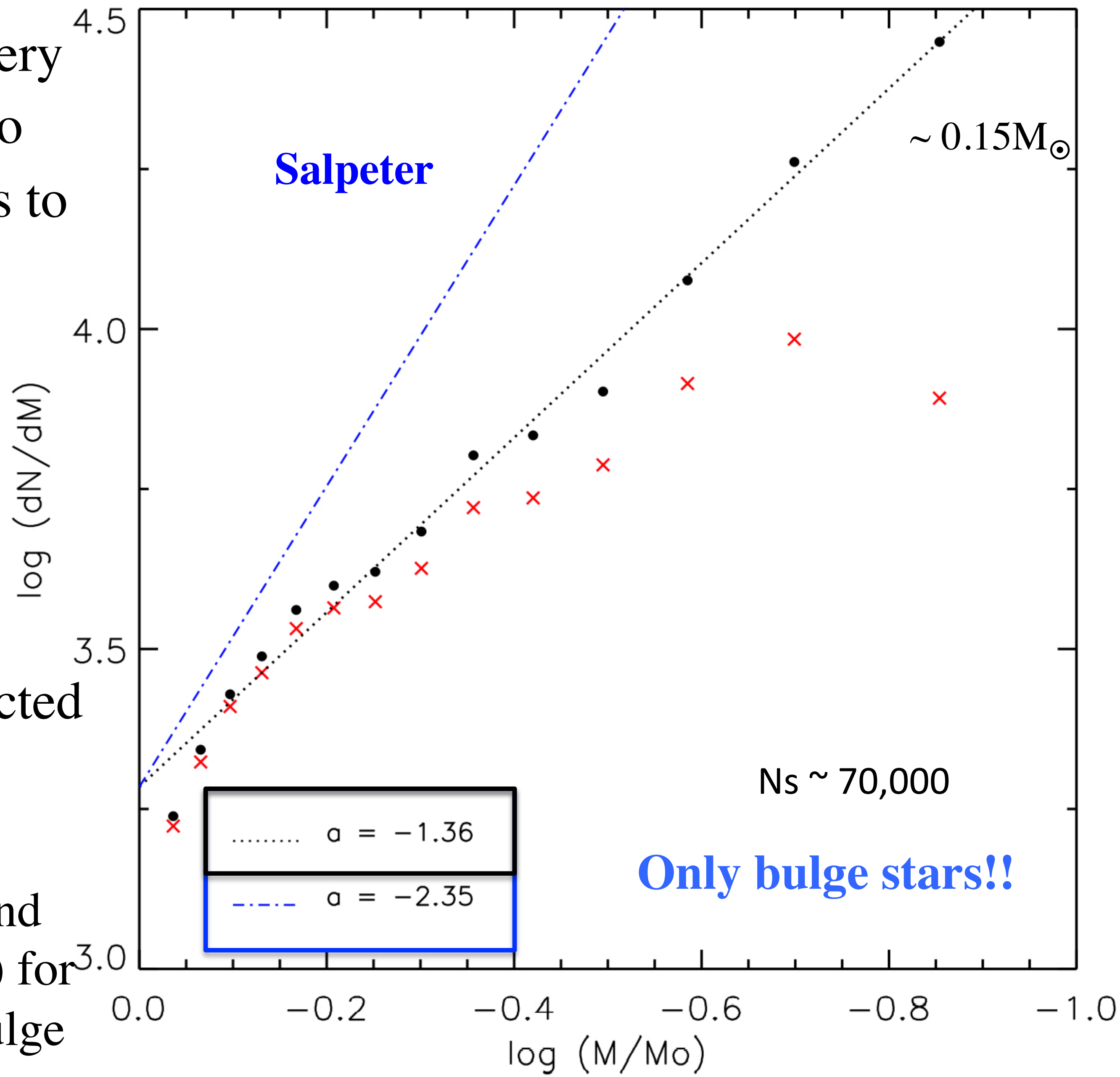
BASTI models for very low mass stars used to transform magnitudes to masses.

DM_0 = 14.48 mag

E(B-V) = 0.5 mag

× Observations

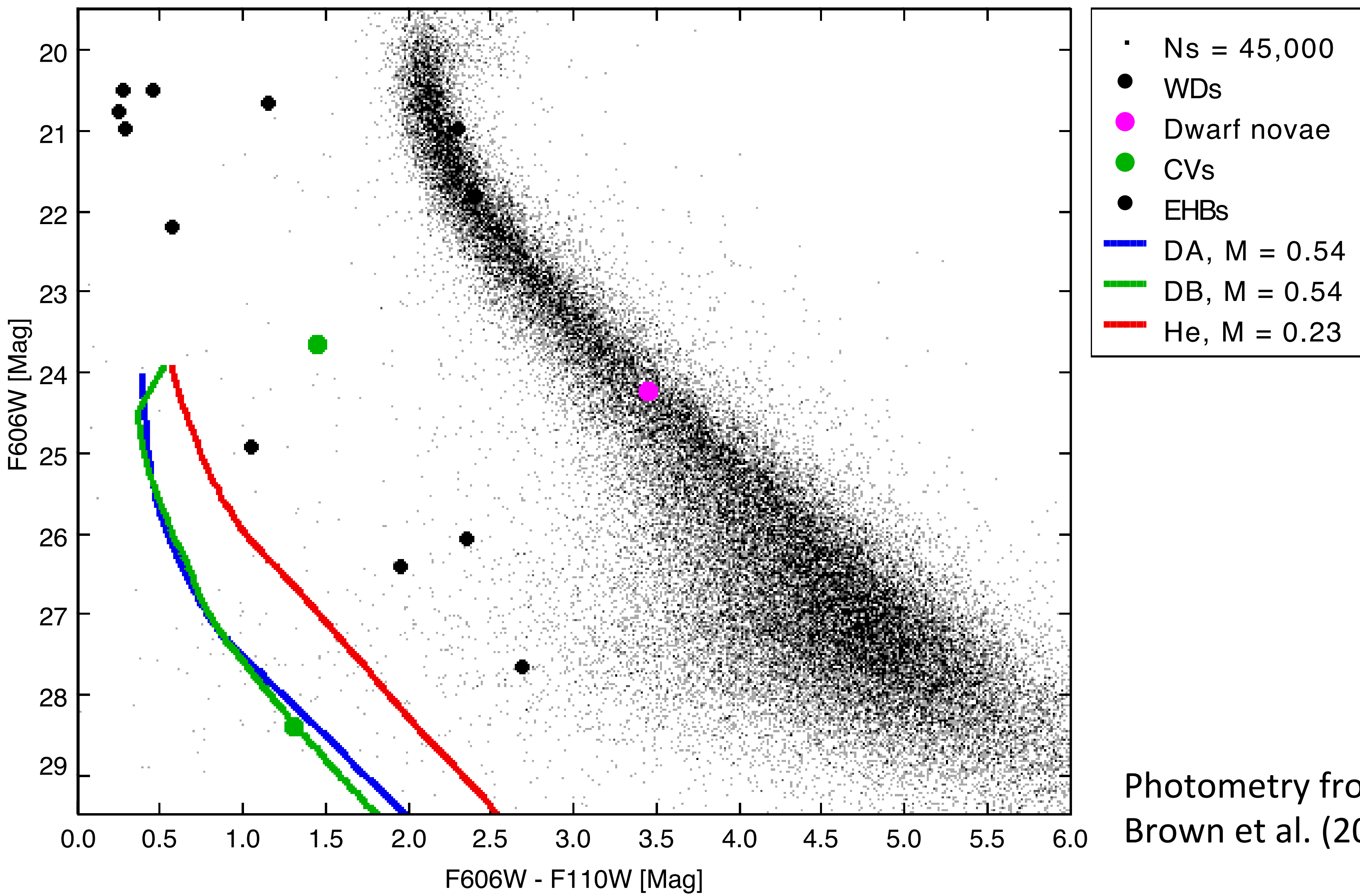
• Completeness corrected



In agreement with Zoccali et al. (2000) and Holtzman et al. (1998) for other regions of the bulge

Preliminary results from NIR photometry

~ 10% of WDs showing NIR excess. 1 dwarf nova showing extreme NIR excess



Photometry from Brown et al. (2010)

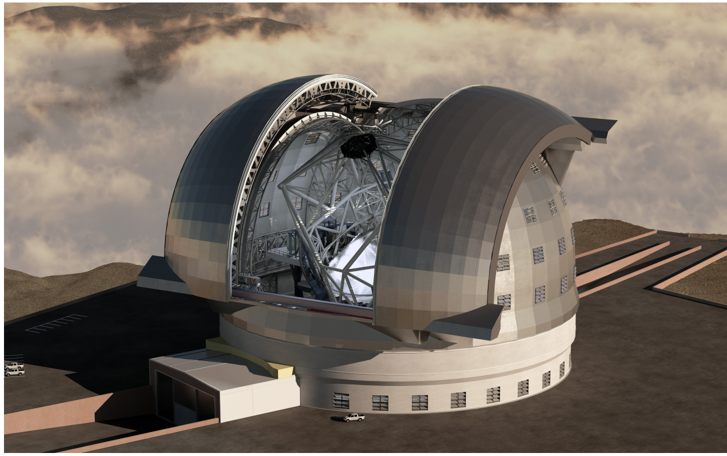
Conclusions

- ✓ **We report the first detection of the WD cooling sequence in the Galactic bulge (see Calamida et al. (2014b, ApJ, 790, 164)**
- ✓ **Up to ~30-40% of the WDs are low-mass He-core WDs with a binary origin**
- ✓ **Among the WDs are 1 ellipsoidal variable (WD-MS compact system, P < 1d), 5 candidate CVs, 2 confirmed dwarf novae (GMOS-S-GEMINI rad.vel obs taken in May)**
- ✓ **Constraining the bulge initial mass function down to M ~ 0.15 $M_\odot$ (V ~ 28.5 mag)**

More is coming →

JWST & E-ELT

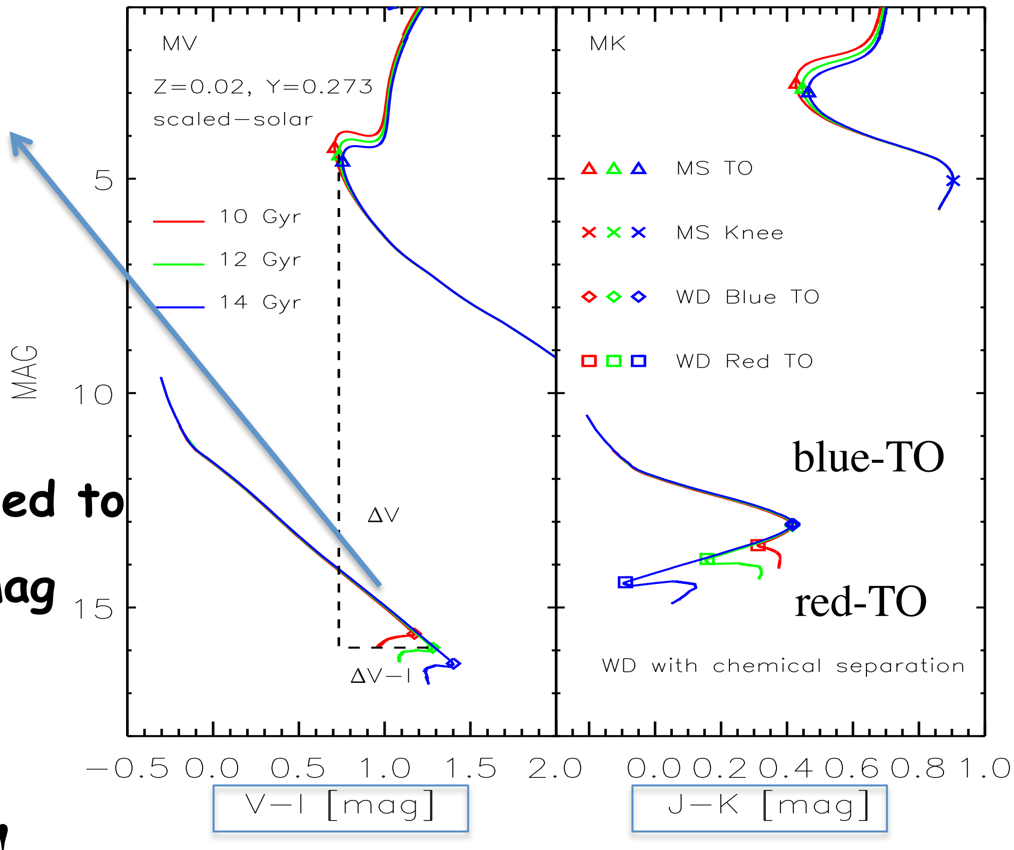
Validation for different physics between MS & WDs



Observed in the optical ONLY in the closest GGCs, such as M4 with HST

For the Galactic bulge, need to reach V ~ 32 mag with S/N ~ 10

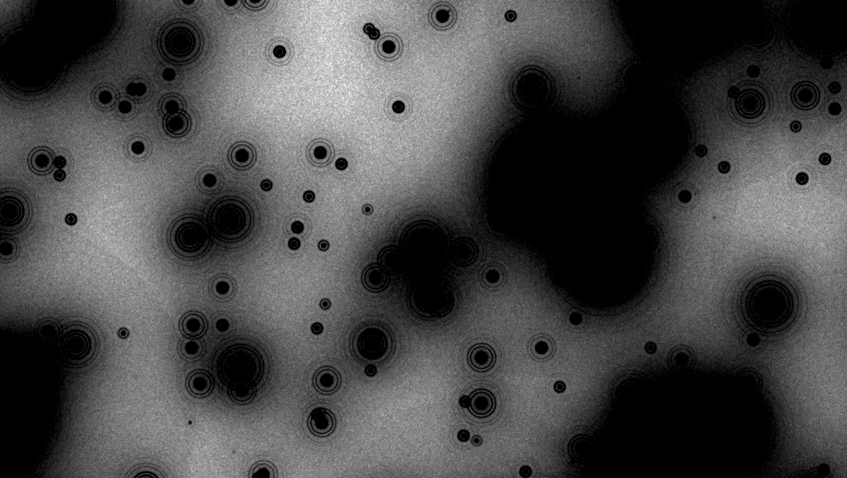
NIR: less than 10 WDs observed in the Galactic bulge with HST -> **blue-TO need to reach K ~ 28 mag, red-TO K ~ 29 mag**

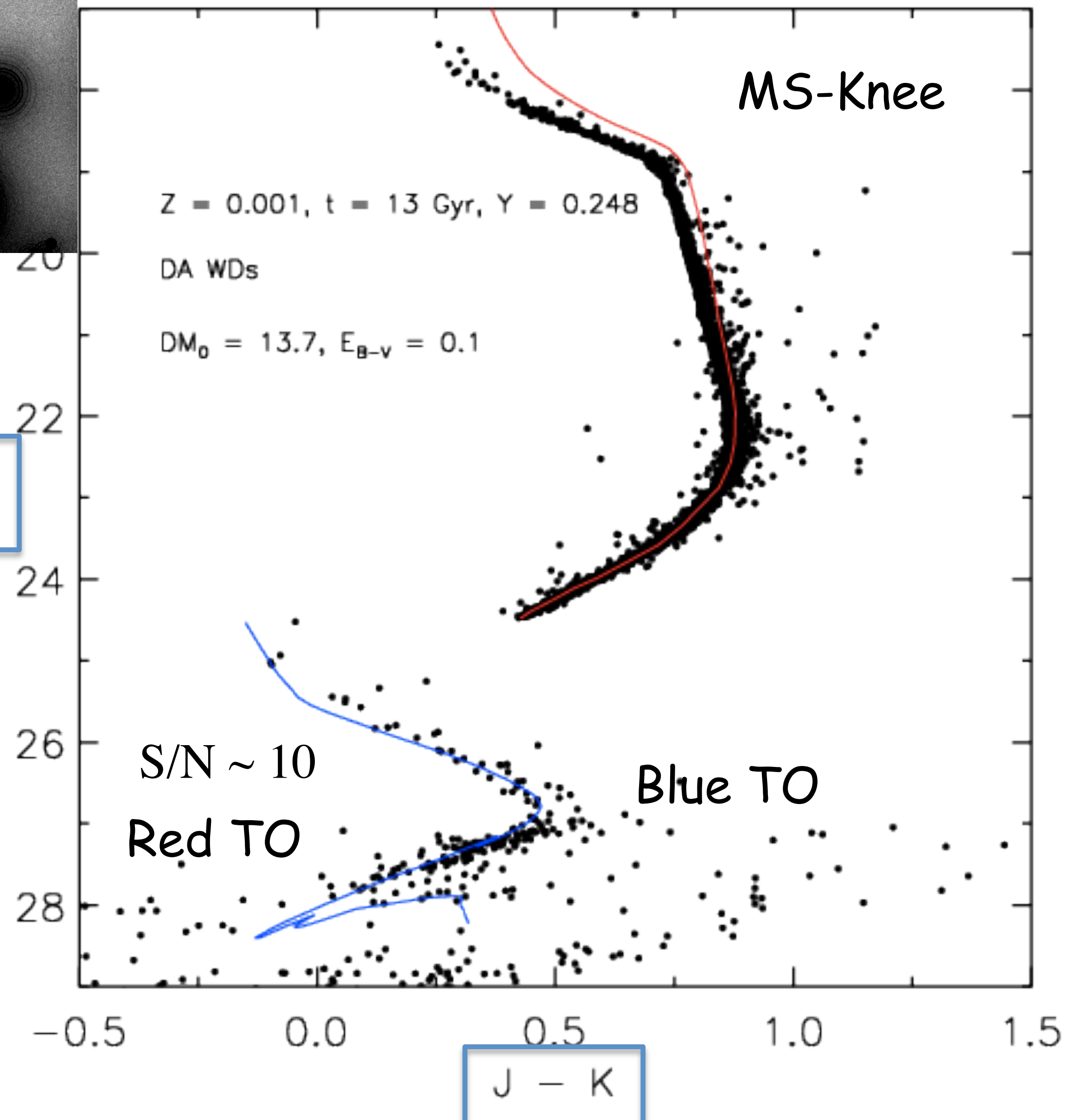


Feasible with JWST & E-ELT!

Bono et al. (2013)

E-ELT simulations





Crowding & dynamical range are an issue

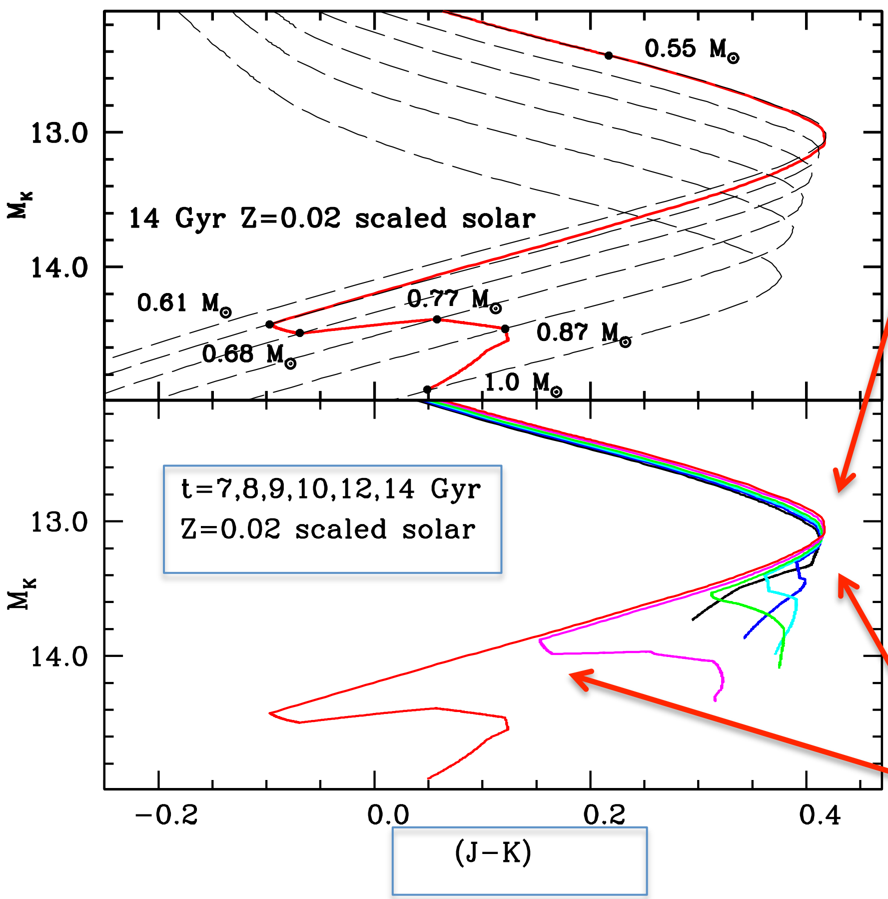
ω Cen like population

Future….

- ✓ With the 8 WFC3 fields, we will double the data set: more than 2,000,000 stars! PMs for all the 12 fields with a baseline of 3 years
- ✓ More statistics to constrain WD properties
- ✓ Constrain the fraction of mass hidden in isolated and binary NSs and BHs (gravitational microlensing)

Theory of WD cooling sequences

Cooling tracks: 0.55 - 1 Mo



DA WDs

Bono et al. (2013)

Blue TO caused by CIA

Independent of age

Independent of metallcity

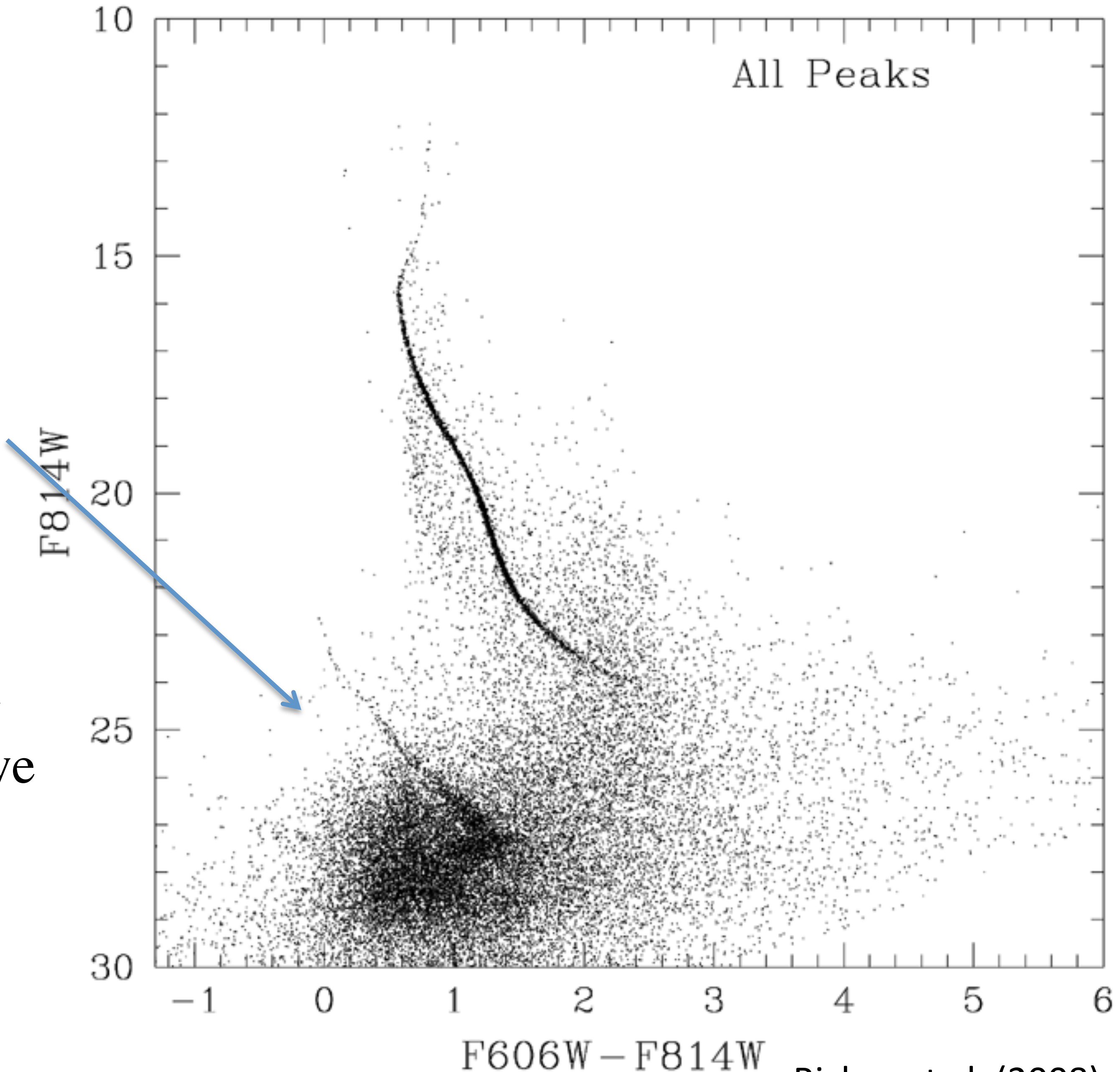
Distance Indicator

Red TO caused by the pile up of WDs in mass

In GGCs

Faint blue galaxies, PSF artifacts

We cannot see faint galaxies through the Galactic bulge but we need to clean the CMD for PSF artifacts



Richer et al. (2008)