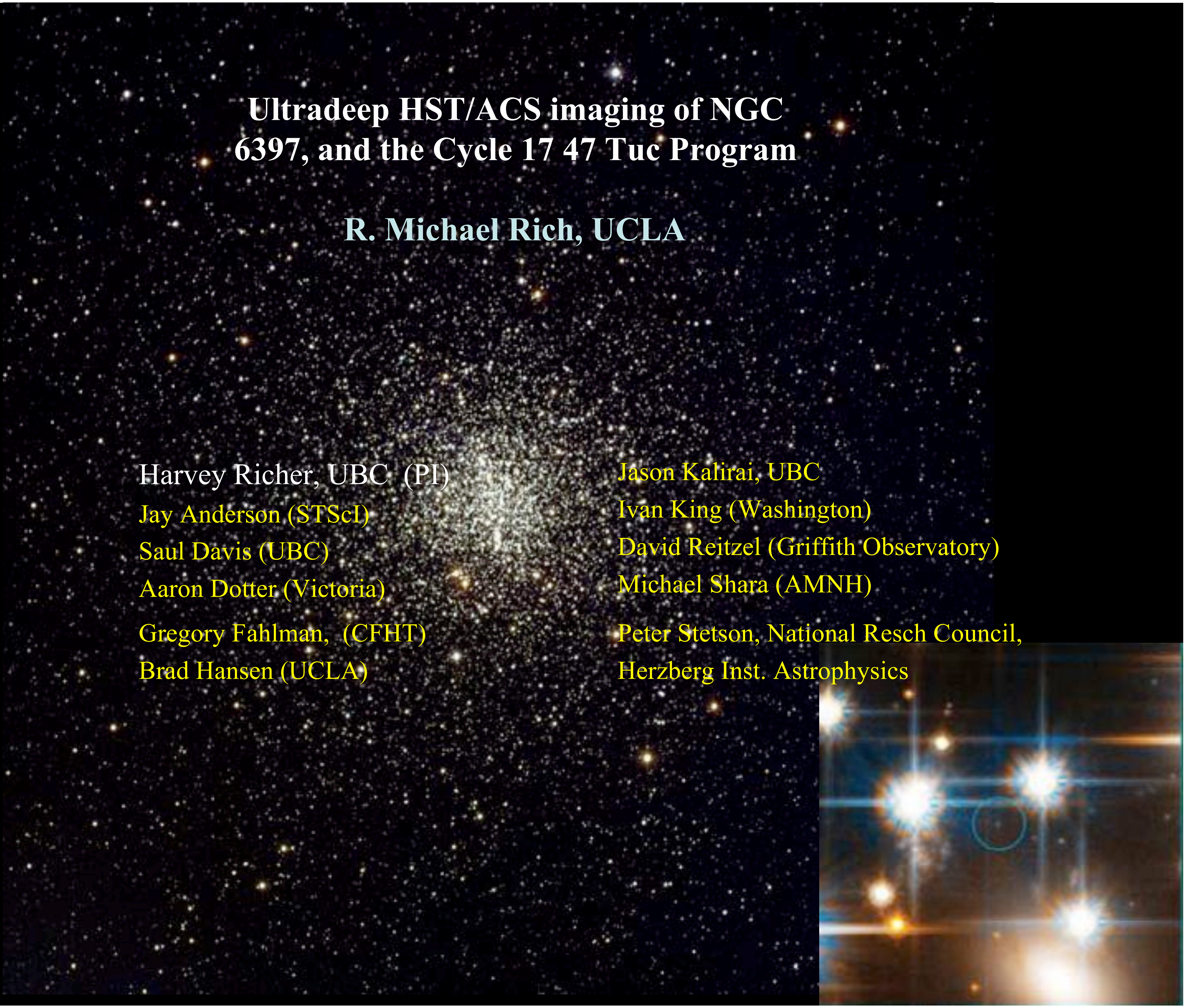


Ultradeep HST/ACS imaging of NGC 6397, and the Cycle 17 47 Tuc Program

R. Michael Rich, UCLA

Harvey Richer, UBC (PI)
Jay Anderson (STScI)
Saul Davis (UBC)
Aaron Dotter (Victoria)
Gregory Fahlman, (CFHT)
Brad Hansen (UCLA)

Jason Kalirai, UBC
Ivan King (Washington)
David Reitzel (Griffith Observatory)
Michael Shara (AMNH)
Peter Stetson, National Resch Council,
Herzberg Inst. Astrophysics

Motivation

Globular clusters are oldest dated systems

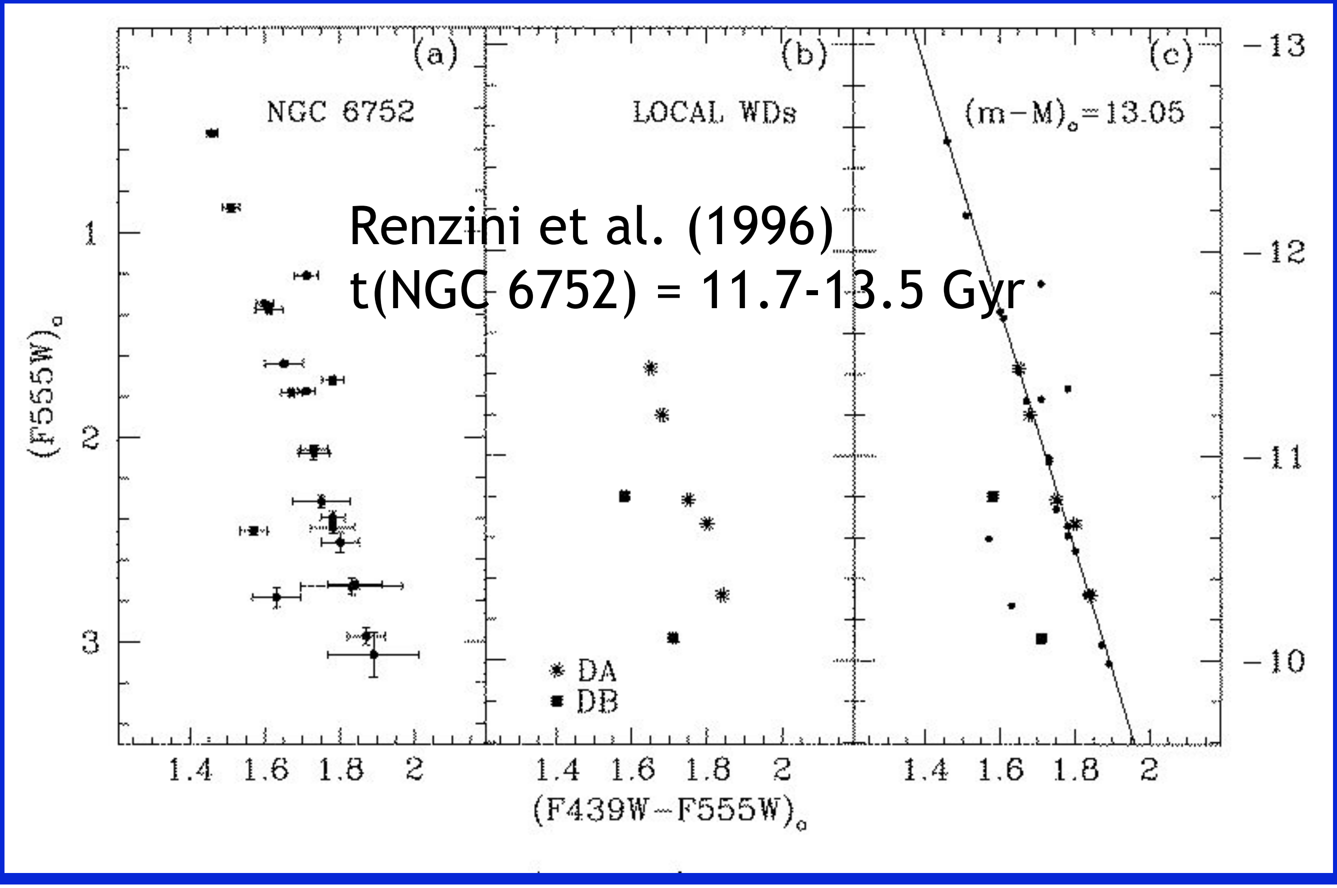
Main Sequence turnoff ages uncertain (distance, reddening, models)

HST capable of reaching the white dwarf cooling sequence in globular clusters

White dwarf cooling sequence gives independent age determination with different physics

Uncertainty in distance modulus leads to 25% uncertainty In derived age for globular clusters (Bolte & Hogan 1995)

In 1986, Renzini proposes an HST Key Project to measure distances to globular clusters using the white dwarf cooling sequence for DA (hydrogen atmosphere) white dwarfs in globular clusters.



Renzini et al. (1996)
t(NGC 6752) = 11.7-13.5 Gyr

Zoccali et al. (2001) find 47 Tuc $(M\text{-}m)_v$=13.27 +/- 0.14 using WD cooling sequence, but stellar Models + remaining distance uncertainties still give 13+/- 0.5 Gyr.

Helium diffusion in core could shorten lifetimes.

White dwarf luminosity function offers hope of independent age measurement.

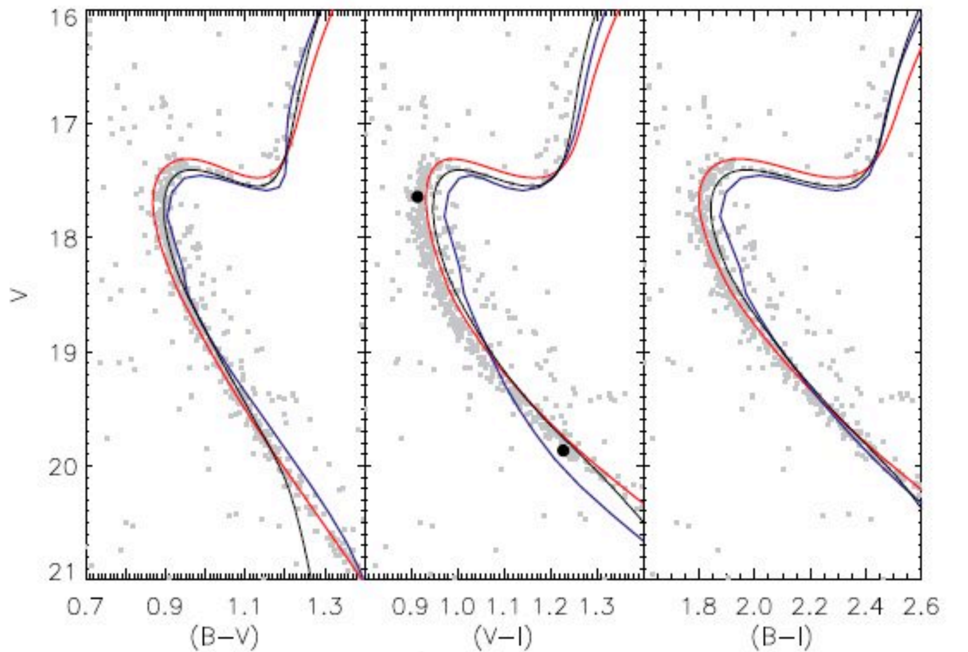


Fig. 18. Isochrones for ages 7.7 (VRSS, red), 8.2 (Y^2, blue), and 9.0Gyr (BaSTI, black) overplotted on the various CMDs of NGC 6791 (SBG03 photometry, plotted at light grey squares). In all plots we have adopted $E(B-V) = 0.15$ and $(m-M)_V = 13.46$ to transpose the isochrones to the observational plane (see Table 9). In the middle panel, the location of the primary and secondary component of V20 are shown as filled black circles. The models are the same as those used in Fig. 12. On black and white printers the models are hard to distinguish, but at the cluster turnoff the VRSS models are always the bluest and the Y^2 models always the reddest.

Zoccali et al. 2001

Grundahl et al. 2008: NGC 6791+eclipse binary 3 possible isochrone fits 7.7-9.2 Gyr - different models

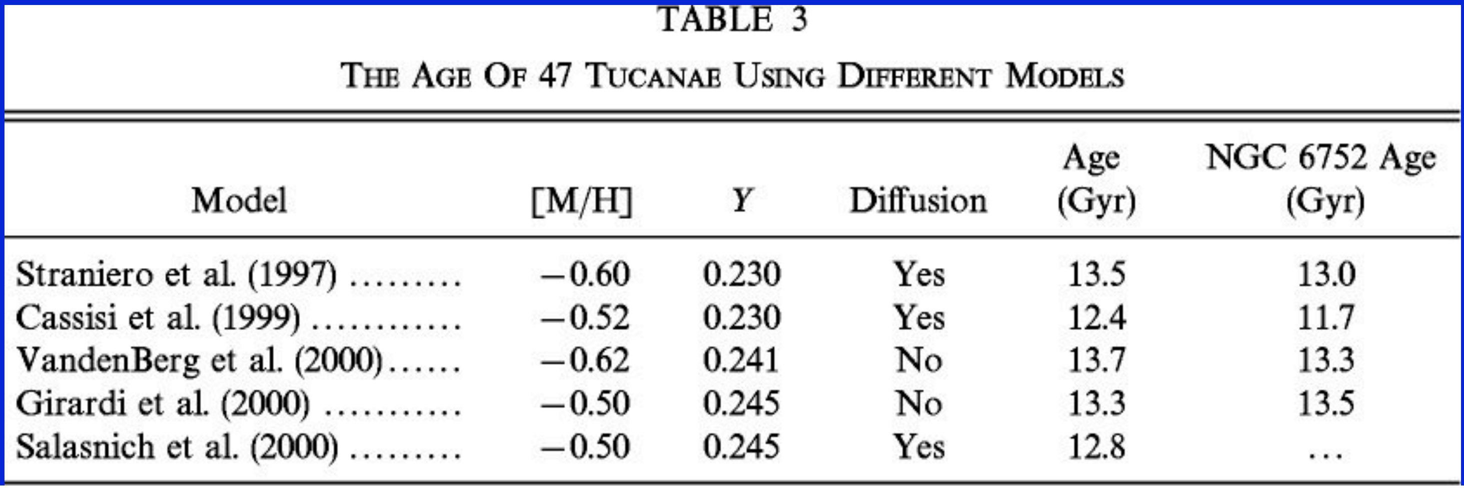
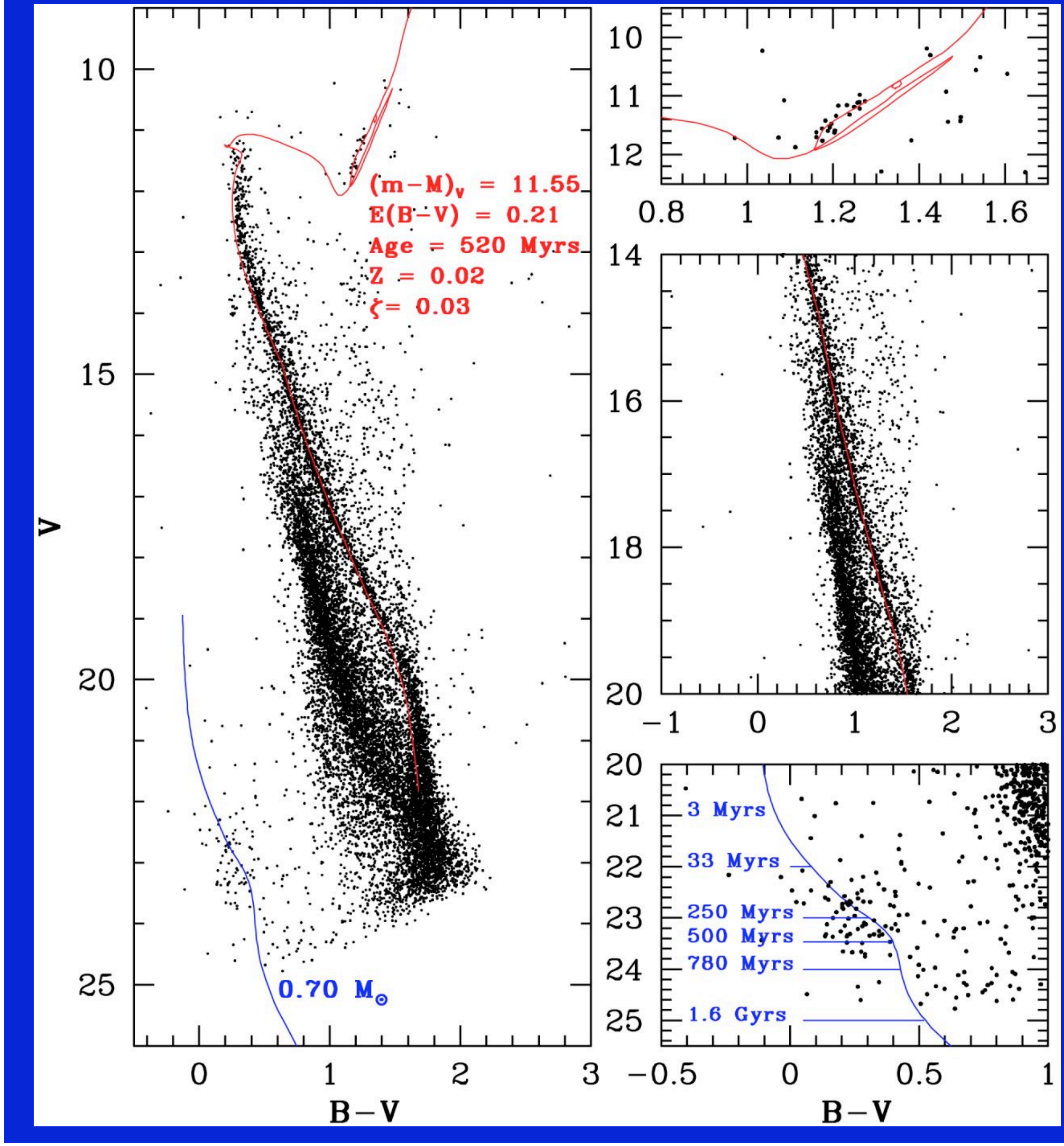


TABLE 3

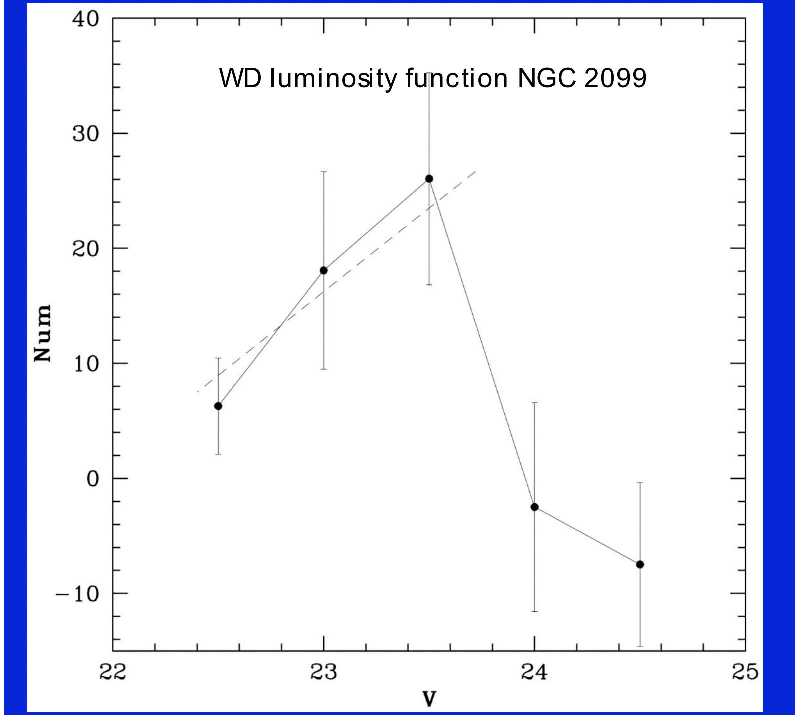
THE AGE OF 47 TUCANAE USING DIFFERENT MODELS

Model	[M/H]	Y	Diffusion	Age (Gyr)	NGC 6752 Age (Gyr)
Straniero et al. (1997)	−0.60	0.230	Yes	13.5	13.0
Cassisi et al. (1999)	−0.52	0.230	Yes	12.4	11.7
VandenBerg et al. (2000)......	−0.62	0.241	No	13.7	13.3
Girardi et al. (2000)	−0.50	0.245	No	13.3	13.5
Salasnich et al. (2000)	−0.50	0.245	Yes	12.8	...

White dwarf cooling method has been proven in open clusters (e.g. Kalirai et al. 2001) for NGC 2099. (also others)



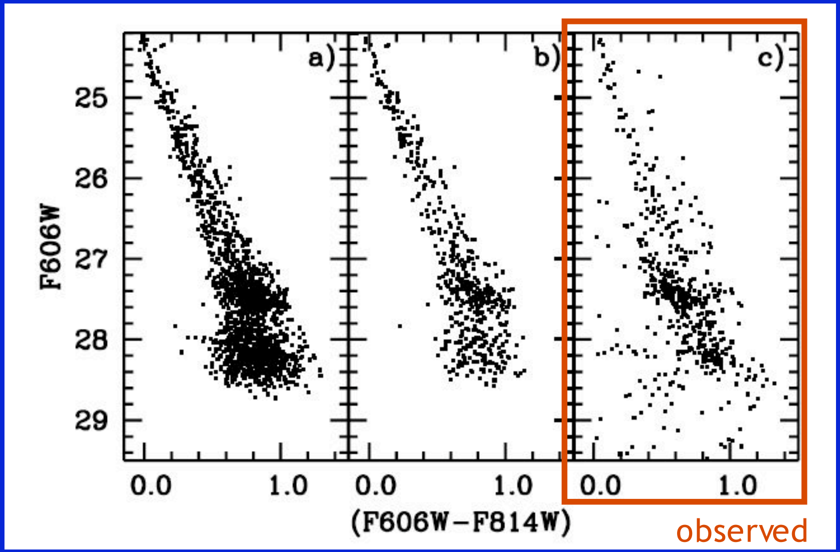
t(wd) = 566 Myr;
t(TO) = 520 Myr



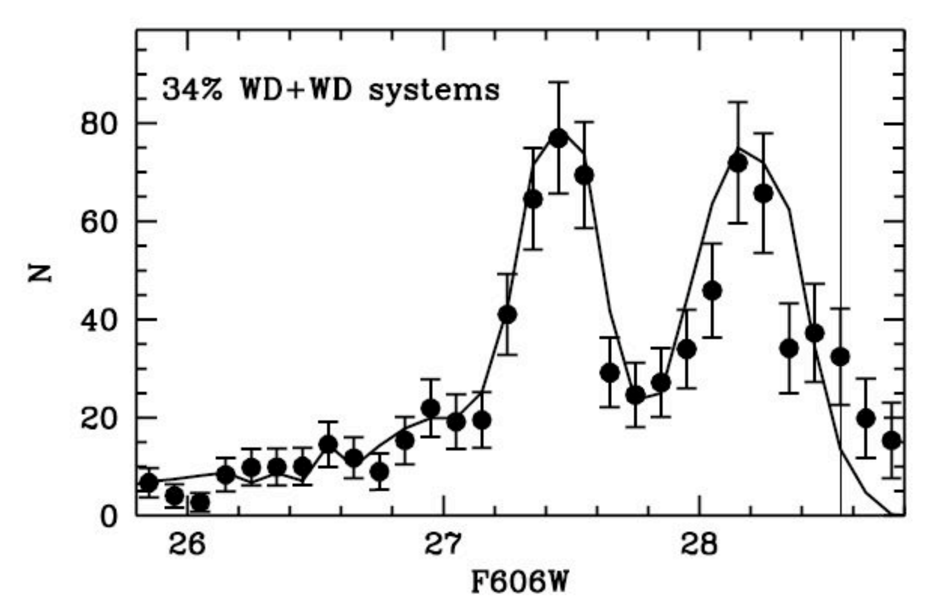
WD cooling sequences can have their own pitfalls…

Two NGC 6791 WD cooling sequence peaks are likely due to 50% WD-WD binaries

(Bedin et al. 2008)

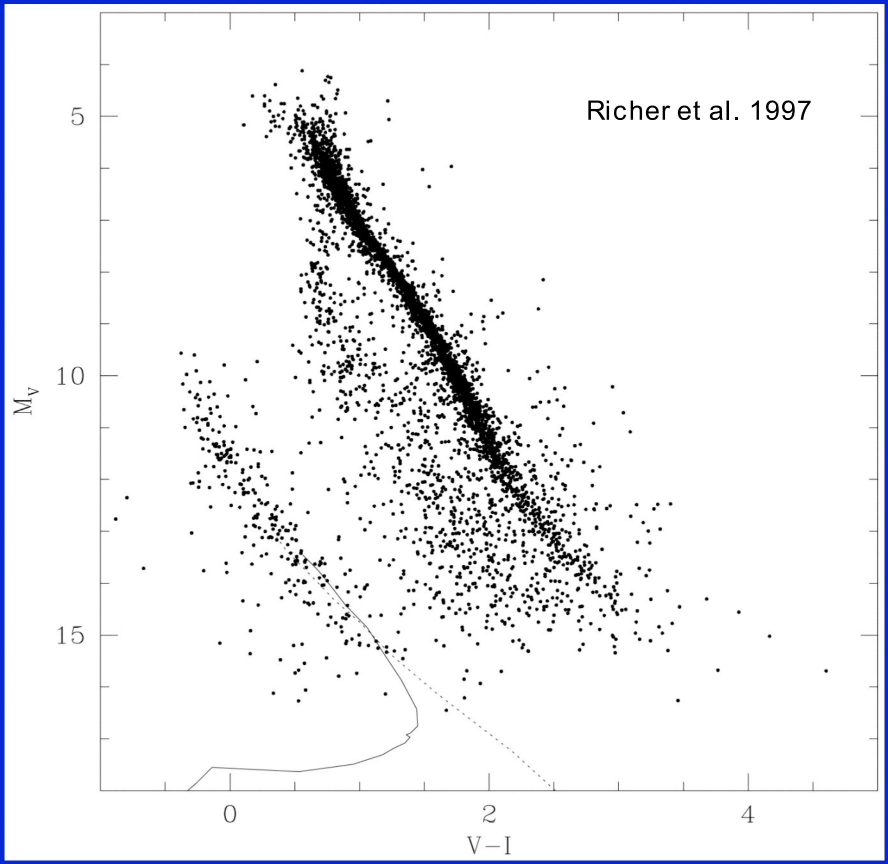


Not due to composition or mass loss history



Globular cluster white dwarfs are faint

Even for M4, end of WD cooling sequence appeared to be at V=32 or fainter… project judged to be impossible.

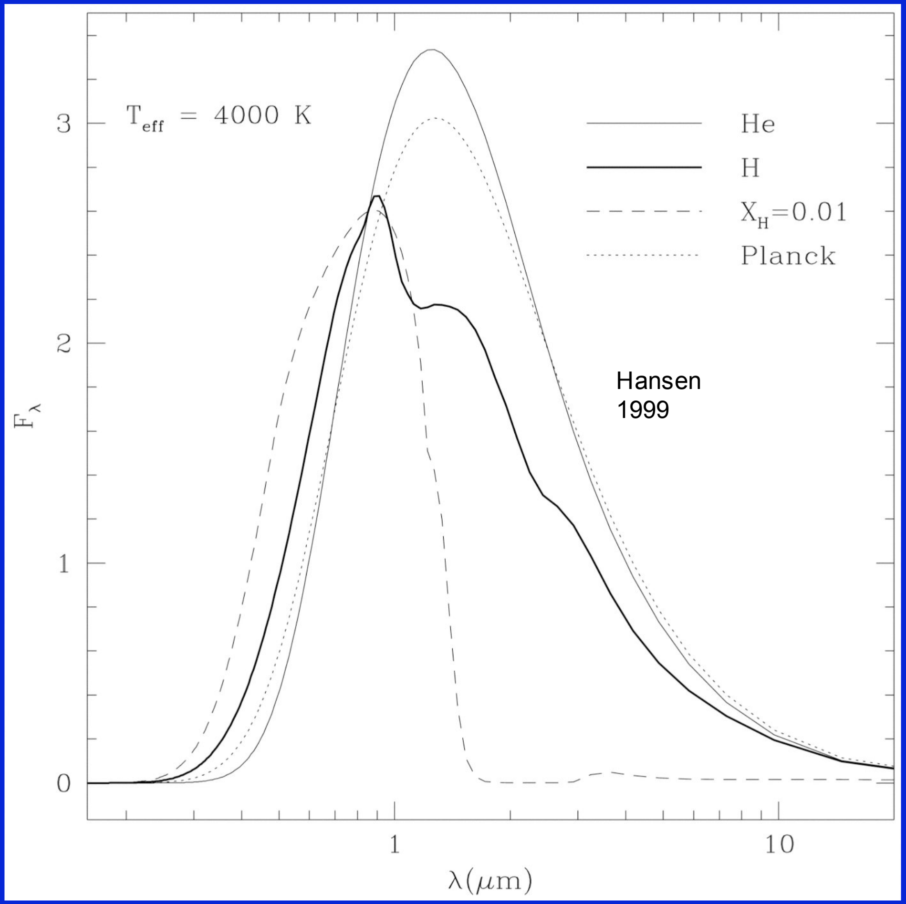


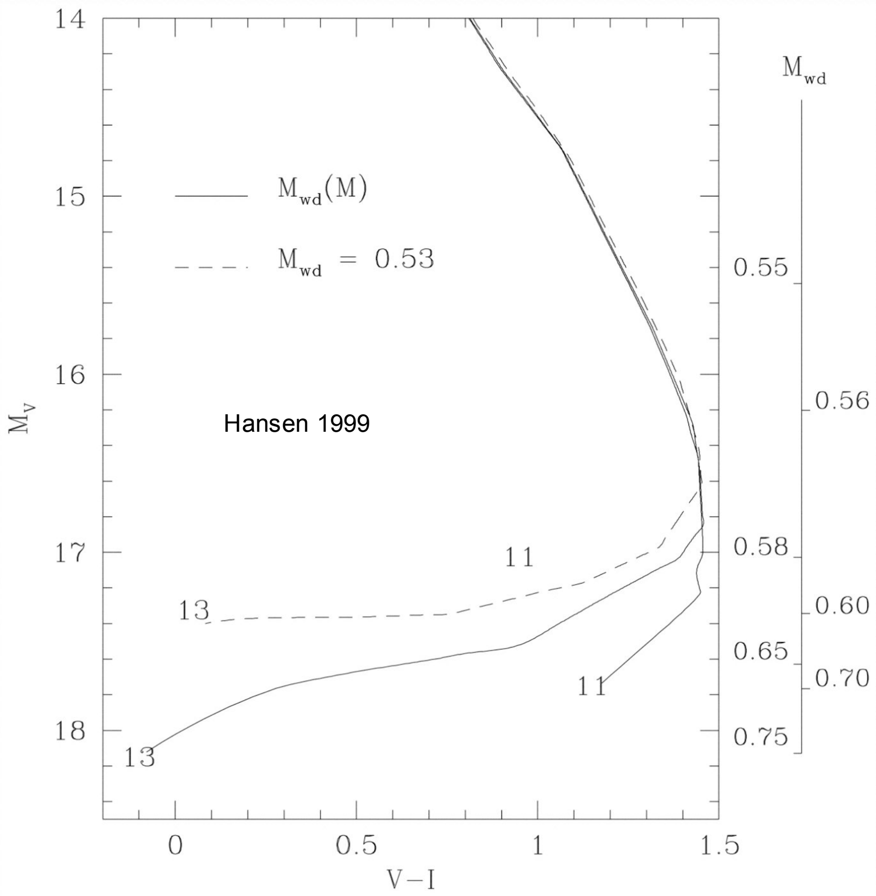
The CMD at left is based on data obtained over 31,500 sec in F555W and 5500 sec in F814W. CMD Reaches V=28, but not faint enough to reach the end of the cooling sequence.

A breakthrough comes with new WD cooling models by Hansen (1998).

Hansen (1998; 1999) realizes importance of H_2 molecular collision-induced absorption (CIA) opacity. Coolest WD become blue. Boundary condition (opacity in atmosphere) has drastic effect on internal structure and cooling.

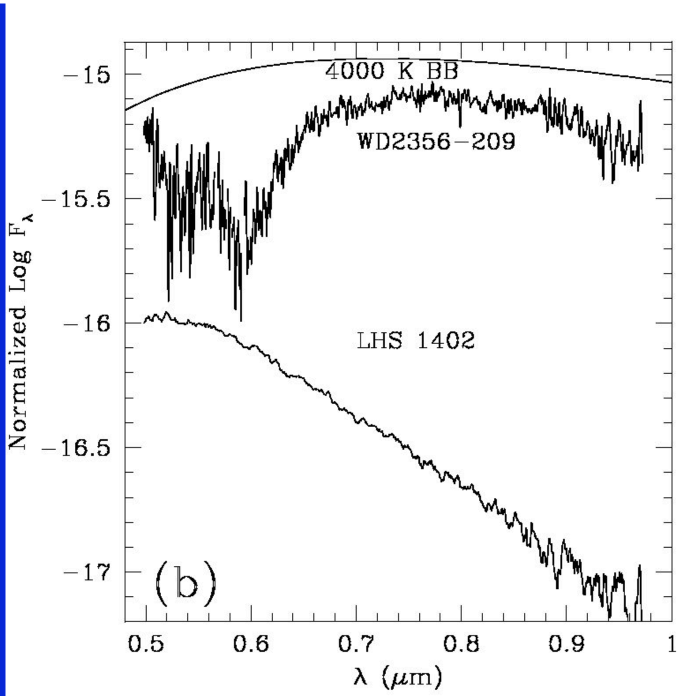
Coeval WD cooling sequences for 11 and 13 Gyr (solid lines) and cooling curve for 0.53 Msun WD (dashed lines). Right panel shows WD mass as a function of Mv for the 13 Gyr sequence.

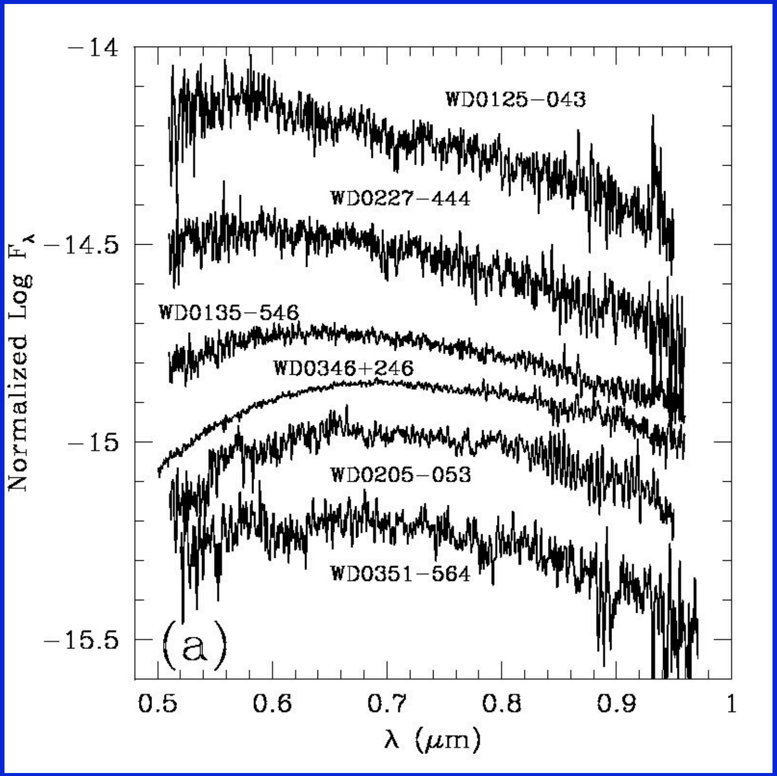


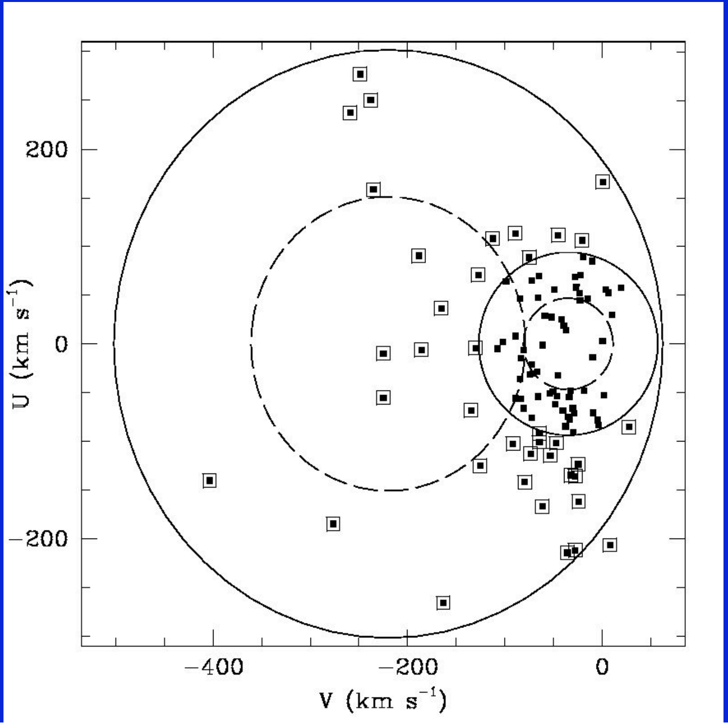


Cool white dwarfs have been claimed to comprise 1-7% of the halo dark matter (Oppenheimer et al. 2001; Nelson et al. 2002) but now considered unlikely (see e.g. Salim et al. 2004).

Spectra of cool white dwarfs hint strongly at existence of the H_2 molecular collision-induced absorption, but it is not proven beyond doubt.







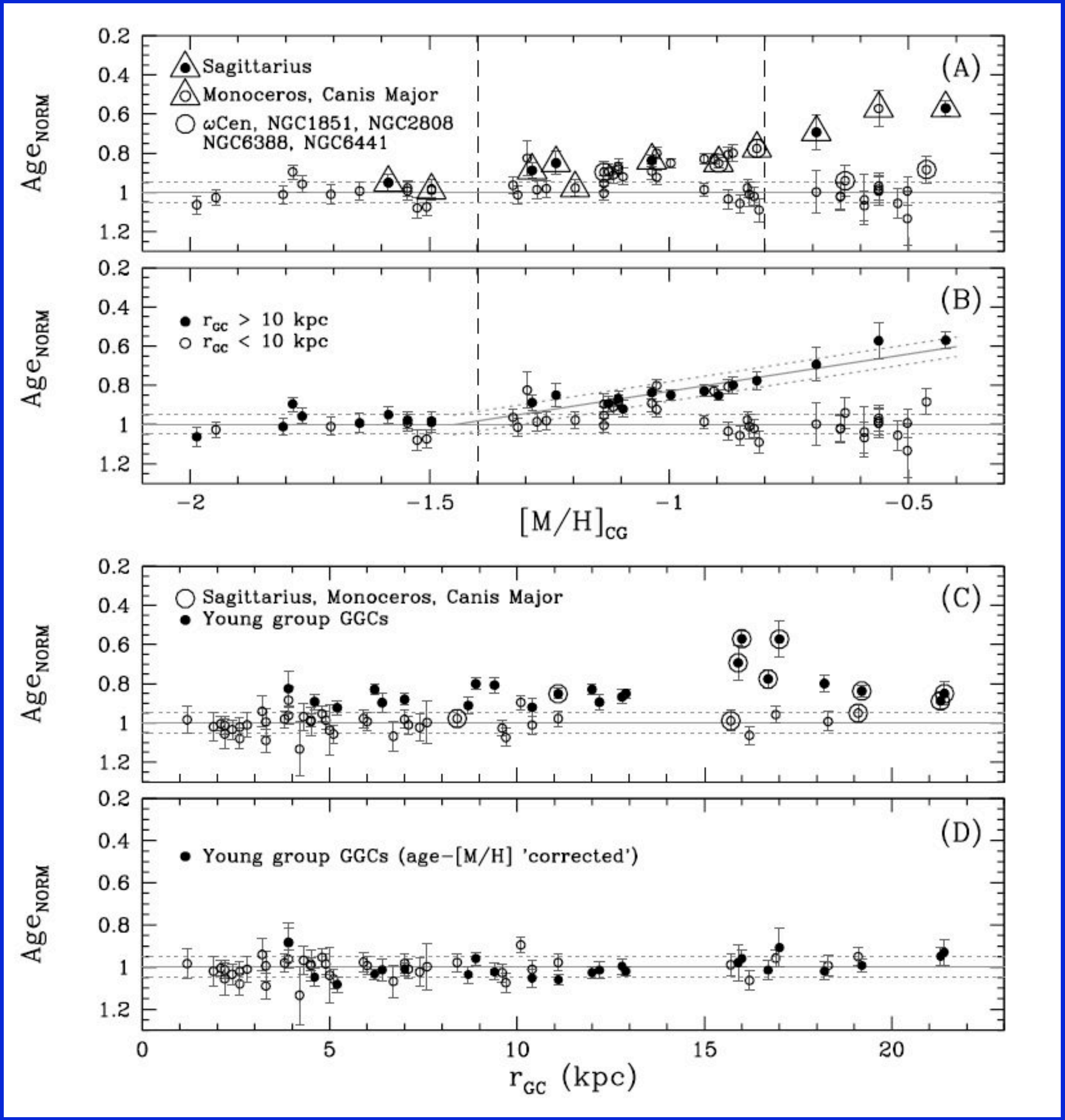
Globular Cluster Targets

Cluster	(m-M)_V	E(B-V)	M_V	[Fe/H]
M4	12.83	0.36	-7.20	-1.20
NGC 6397	12.36	0.18	-6.63	-1.95
47 Tuc	13.37	0.04	-9.42	-0.76

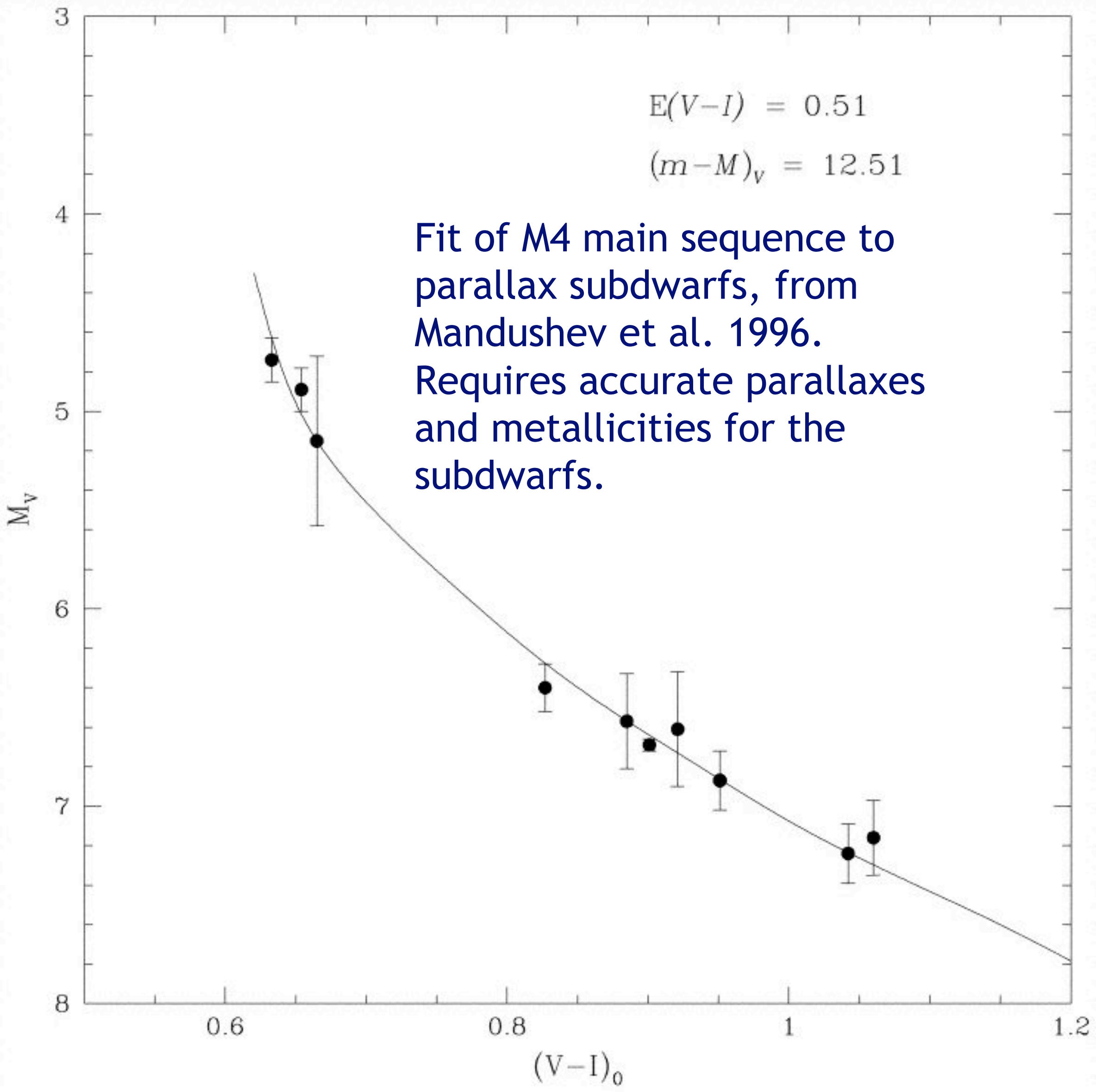
All 3 clusters ranked as “old halo” by the ACS cluster survey (Marin-French et al. 2008) based on MS/subgiant CMD relative comparison; 47 Tuc debatable

Table data: Harris 2003 Feb catalog

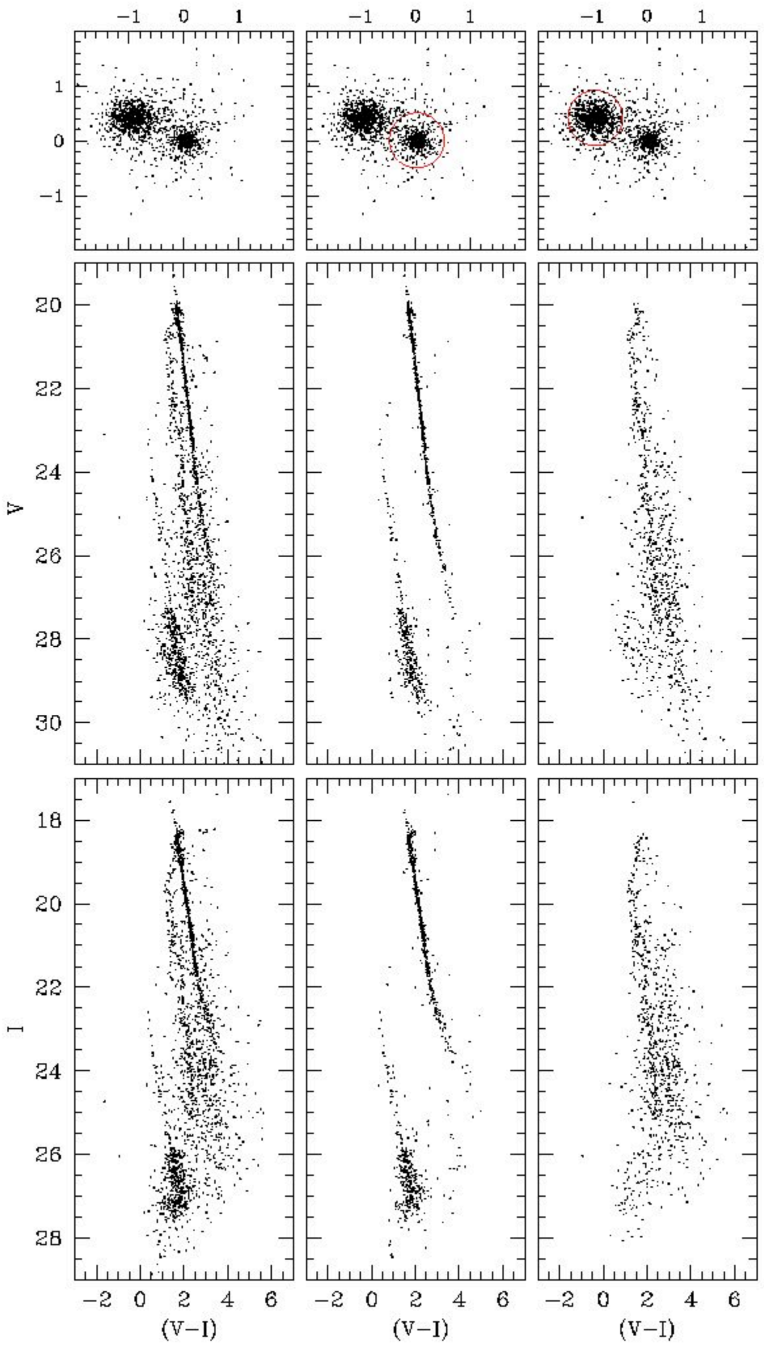
Old halo clusters have similar ages (Marin-French+08)



Traditional ages obtained first by distance determination, followed by age determination from fit of models to turnoff.



Fit of M4 main sequence to parallax subdwarfs, from Mandushev et al. 1996. Requires accurate parallaxes and metallicities for the subdwarfs.



Proper motion displacement in WF pixels (0.1 arcsec)

Left panel: All stellar objects

Middle Panel: Members of M4

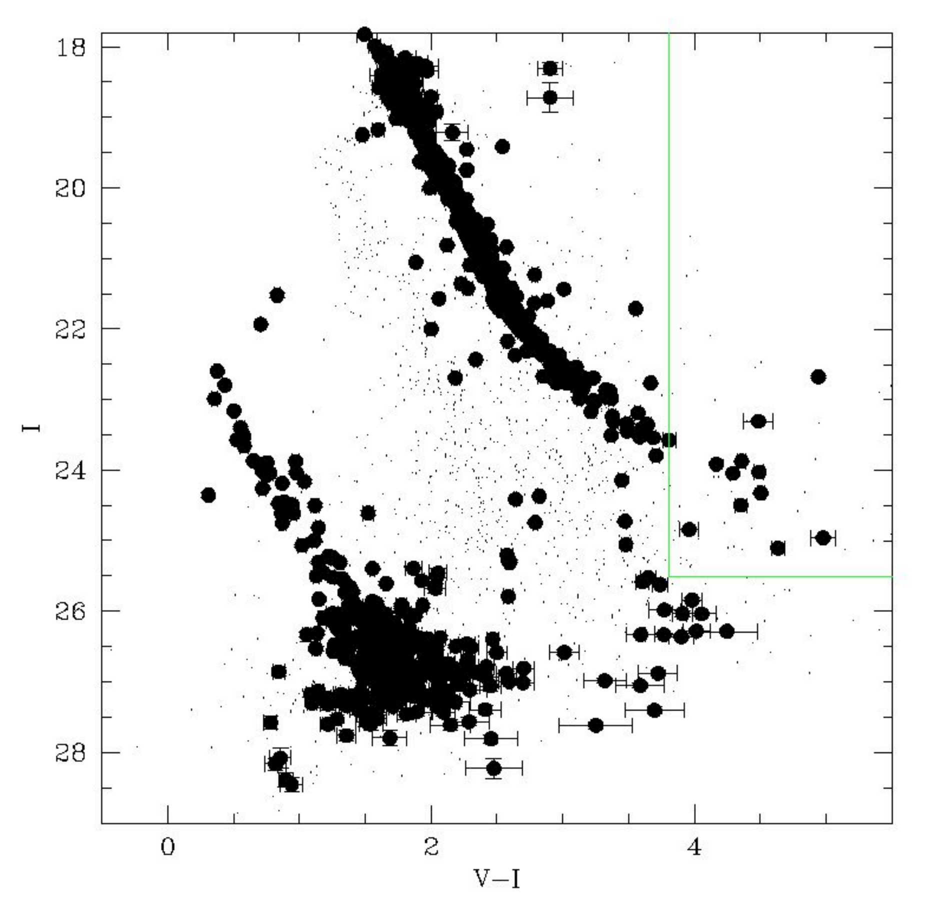
Right Panel: Field Stars

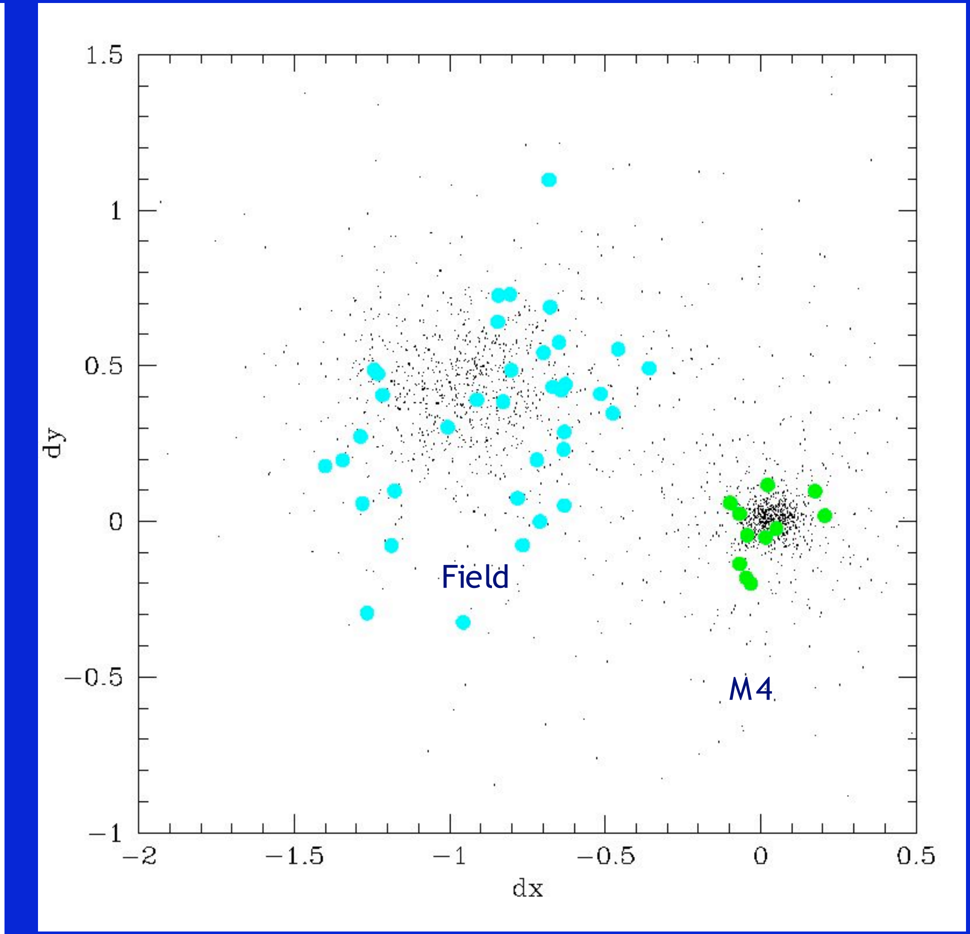
If field stars are halo population At tangent point (8.2 kpc) with sigma(v)=110 km/sec expect dispersion = 0.175 pix. Measure 0.277 pix. Likely “field” stars spread over wide distance or different populations.

Lower main sequence and Mass Function for M4
Richer et al. 2003

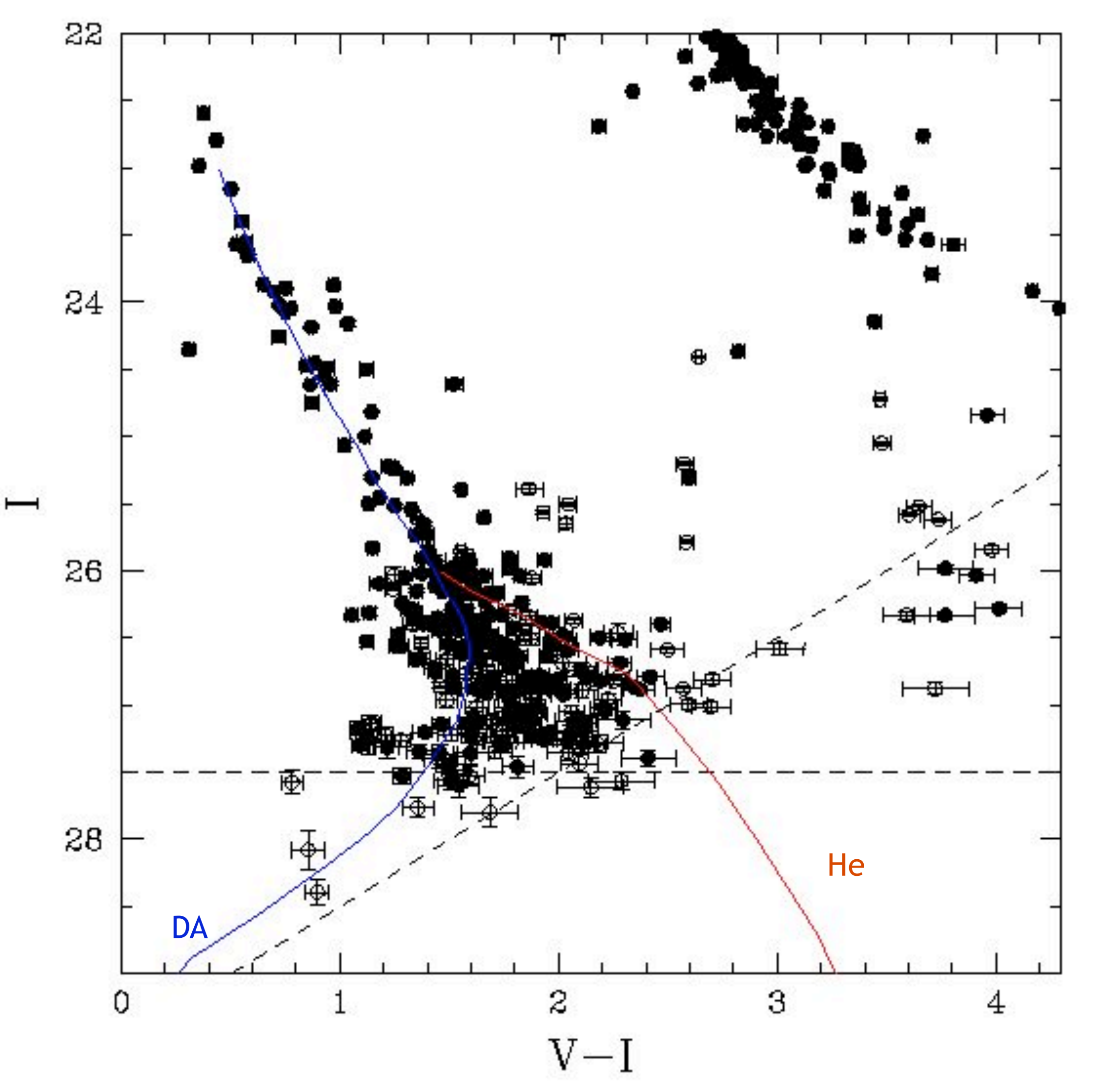
Left panel: solid points are proper-motion members of M4.
Light points: field stars

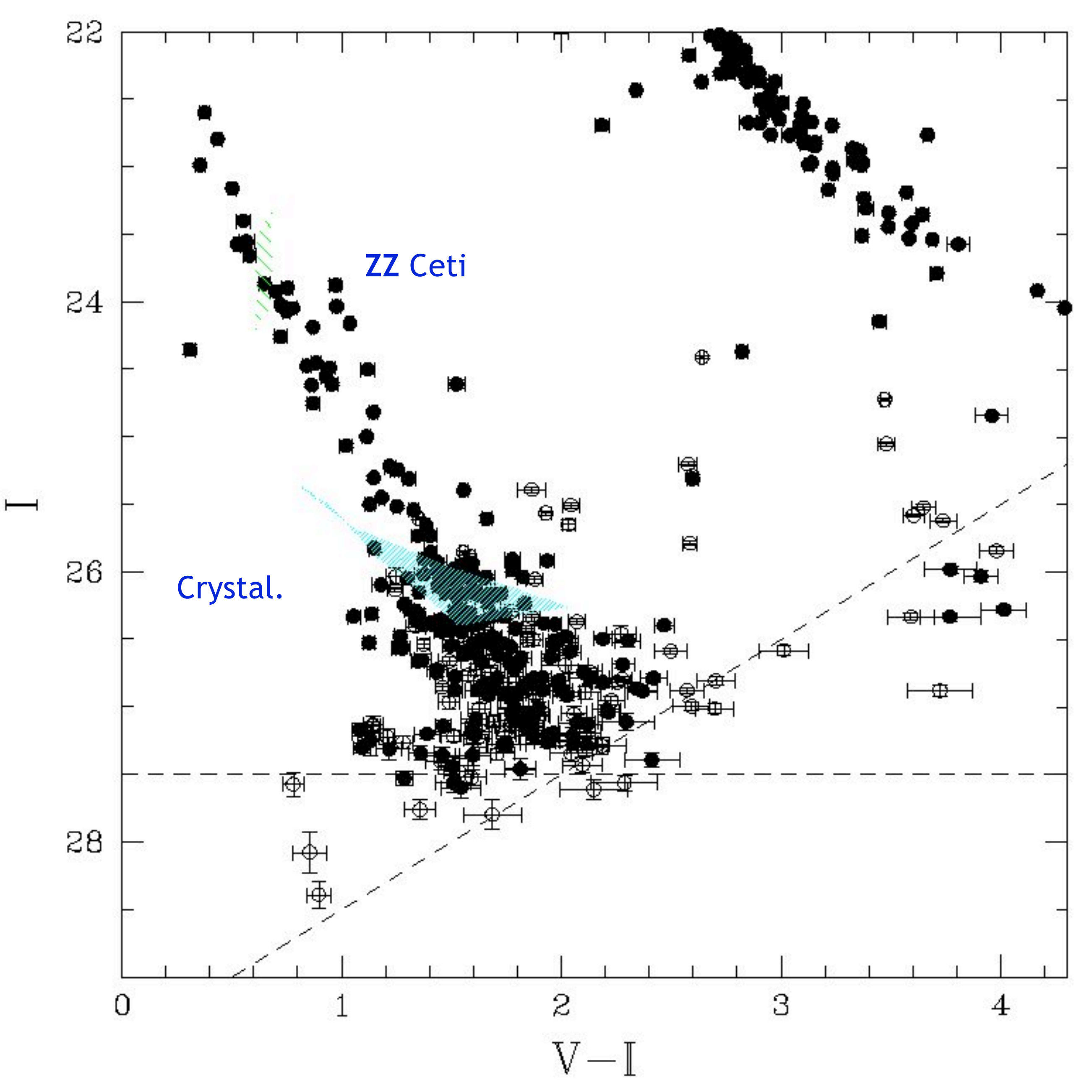
Right panel: The faintest M4 main sequence candidates are PM members.





The White Dwarf Cooling Sequence of M4
Hansen et al. 2004





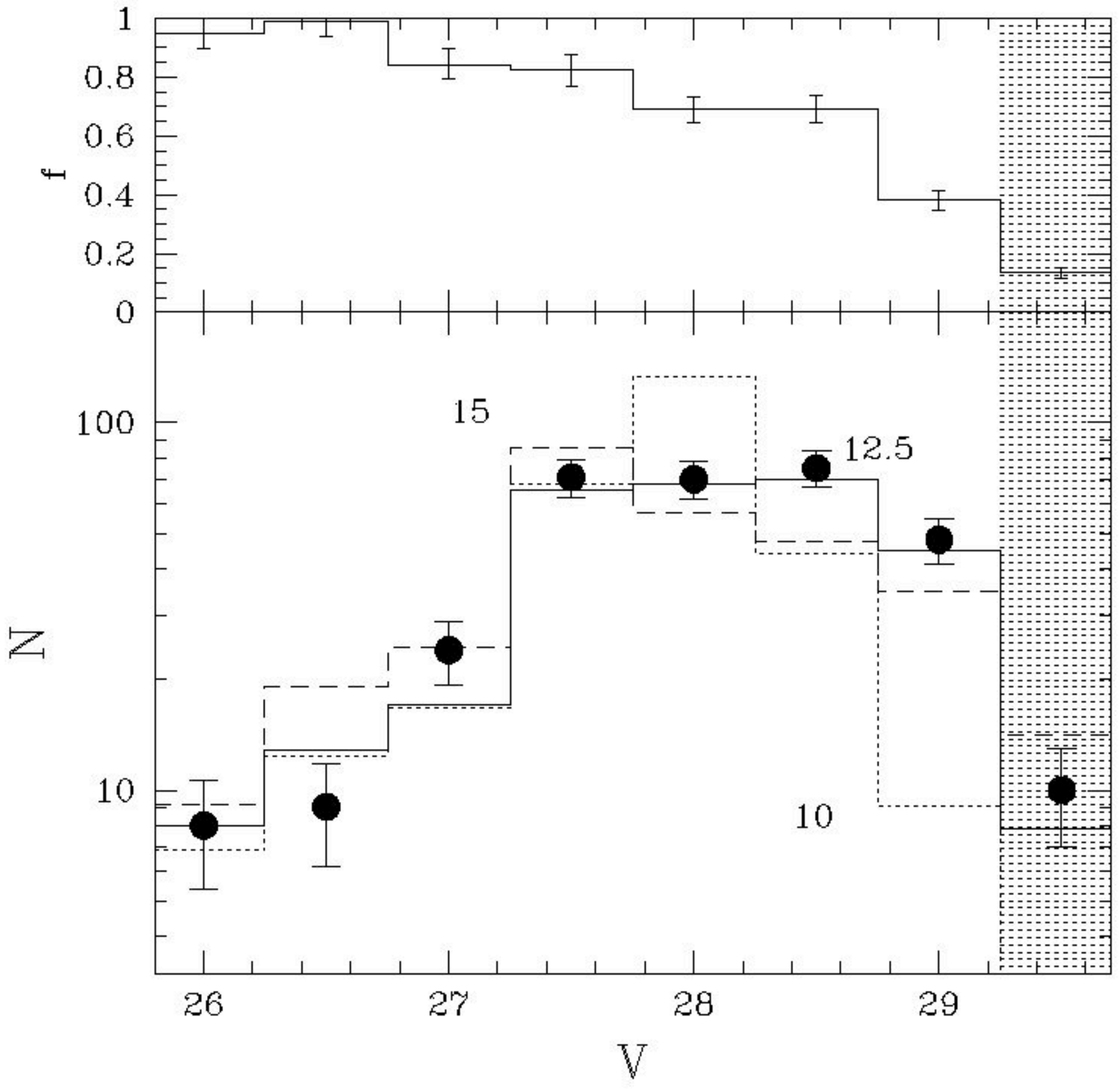
White dwarf cooling:

Radiation dominant source of cooling.

Bright part of curve (above ZZ Cet) model has conductive core and radiative envelope.

At ZZ Ceti region, T~10^4 K and envelope becomes convective.

Cooling slows dramatically when envelop completely convective and surface Teff couples to the whole star (convective envelope to conductive core).



Incompleteness

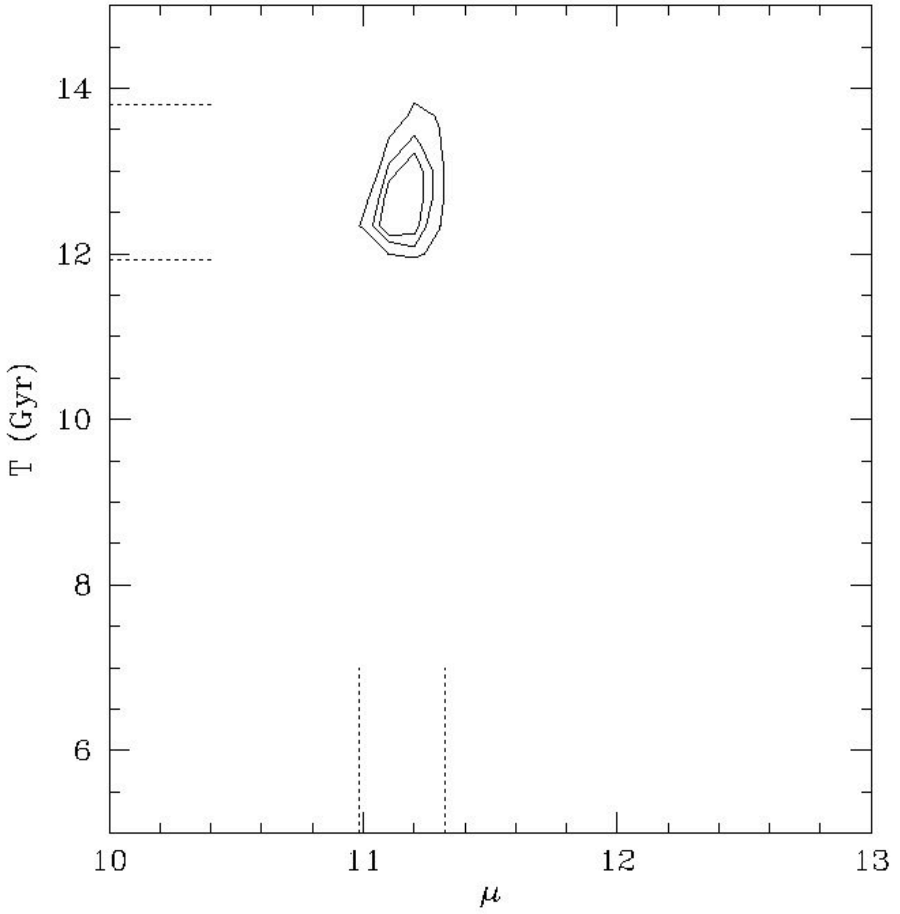
(Shaded region
not used in fit)

Theory convolved
with incompleteness
vs. data points;
age of models in Gyr.

(Hansen luminosity
functions)

Fixing f_H=0.75 and varying age and distance modulus instead:

T_age=12.9 +/- 0.9 Gyr   D=1.7 +/- 0.14 kpc (8%)



The distance modulus is in excellent agreement with Mandushev's subdwarf main sequence fitting constraint. BUT fitting the white dwarf LF gives an independent distance modulus estimate—a new technique in globular cluster distance determination.

NGC 6397

(126 orbits; ACS/HST 9 more orbits in Cycle 17

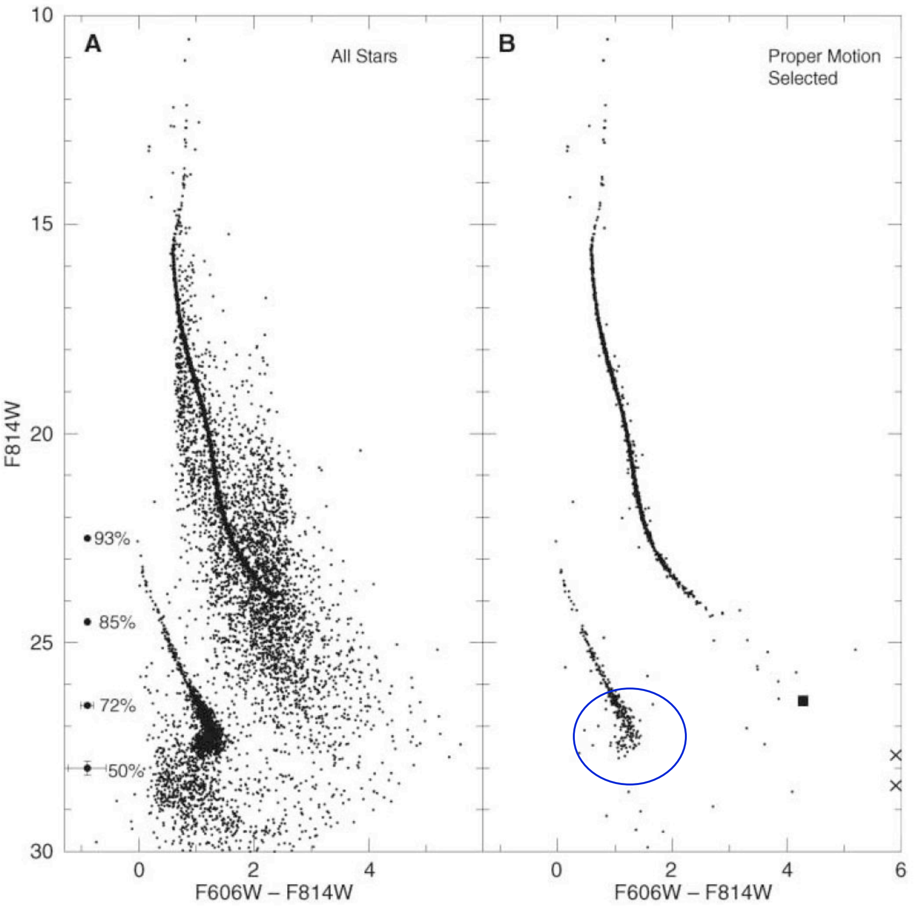
WD cooling age: Hansen et al. 2007

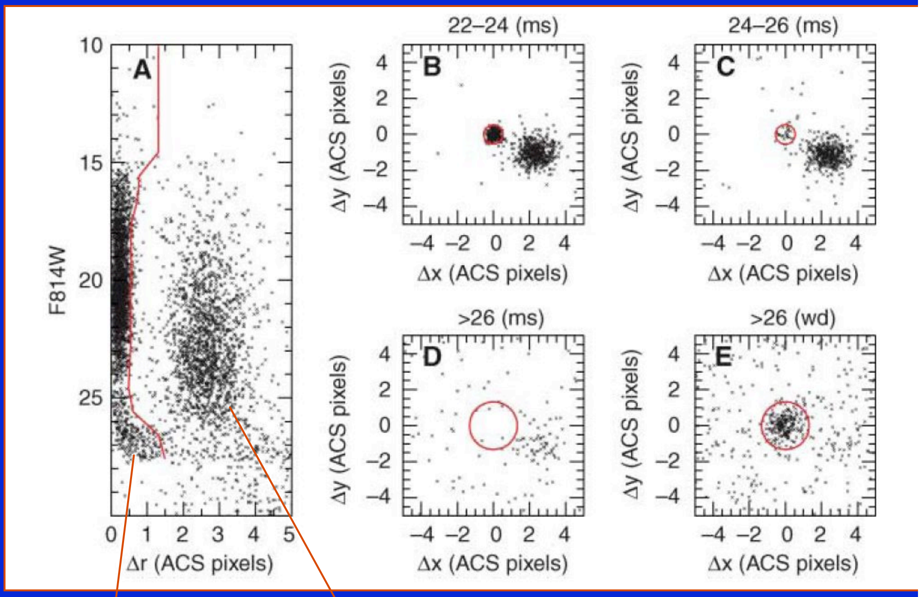
Data analysis: Anderson et al. 08

Dynamical models: Hurley et al. 08

CMD Richer et al. 08

Binary Fraction (1%) Davis et al. 08

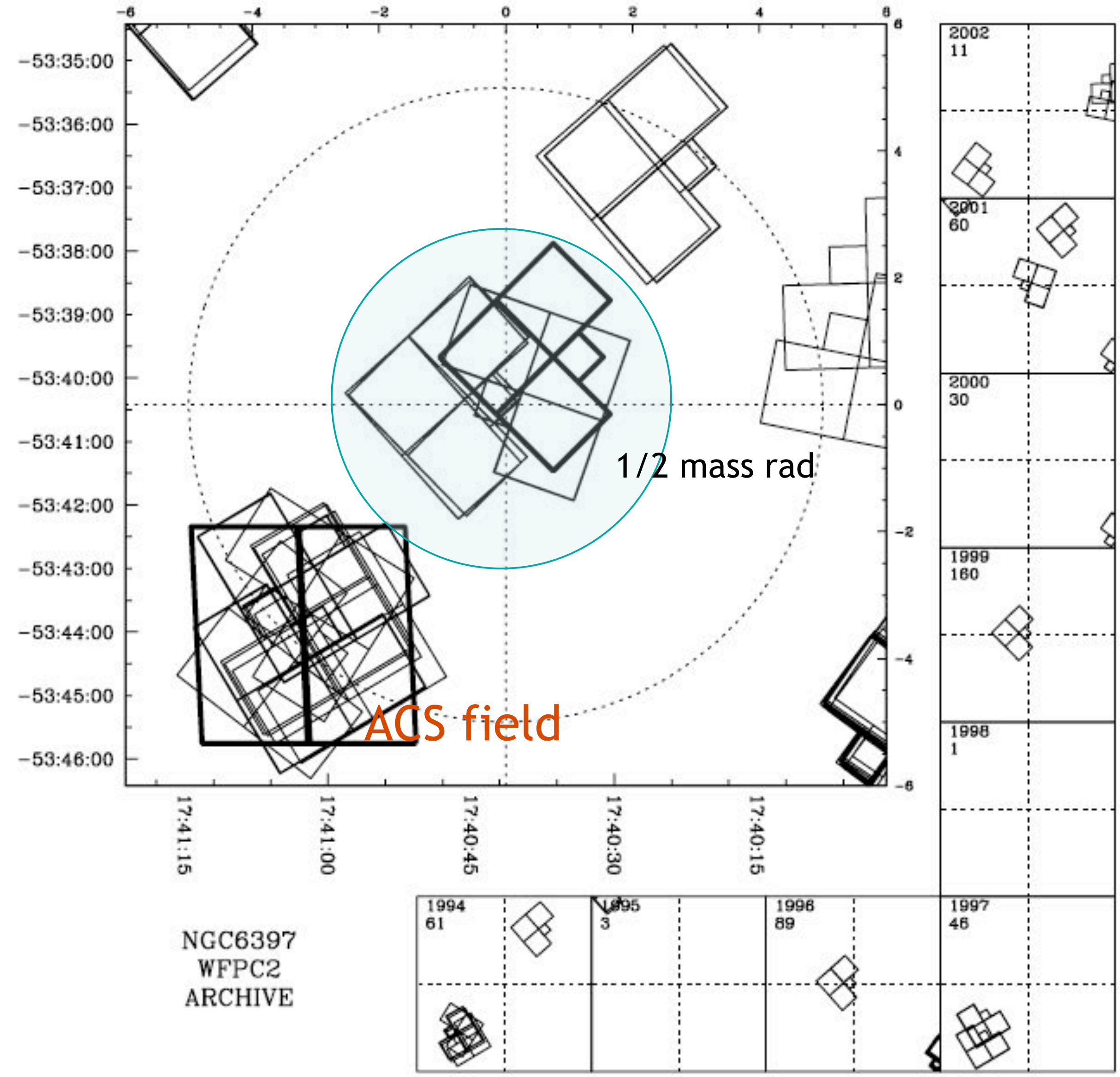




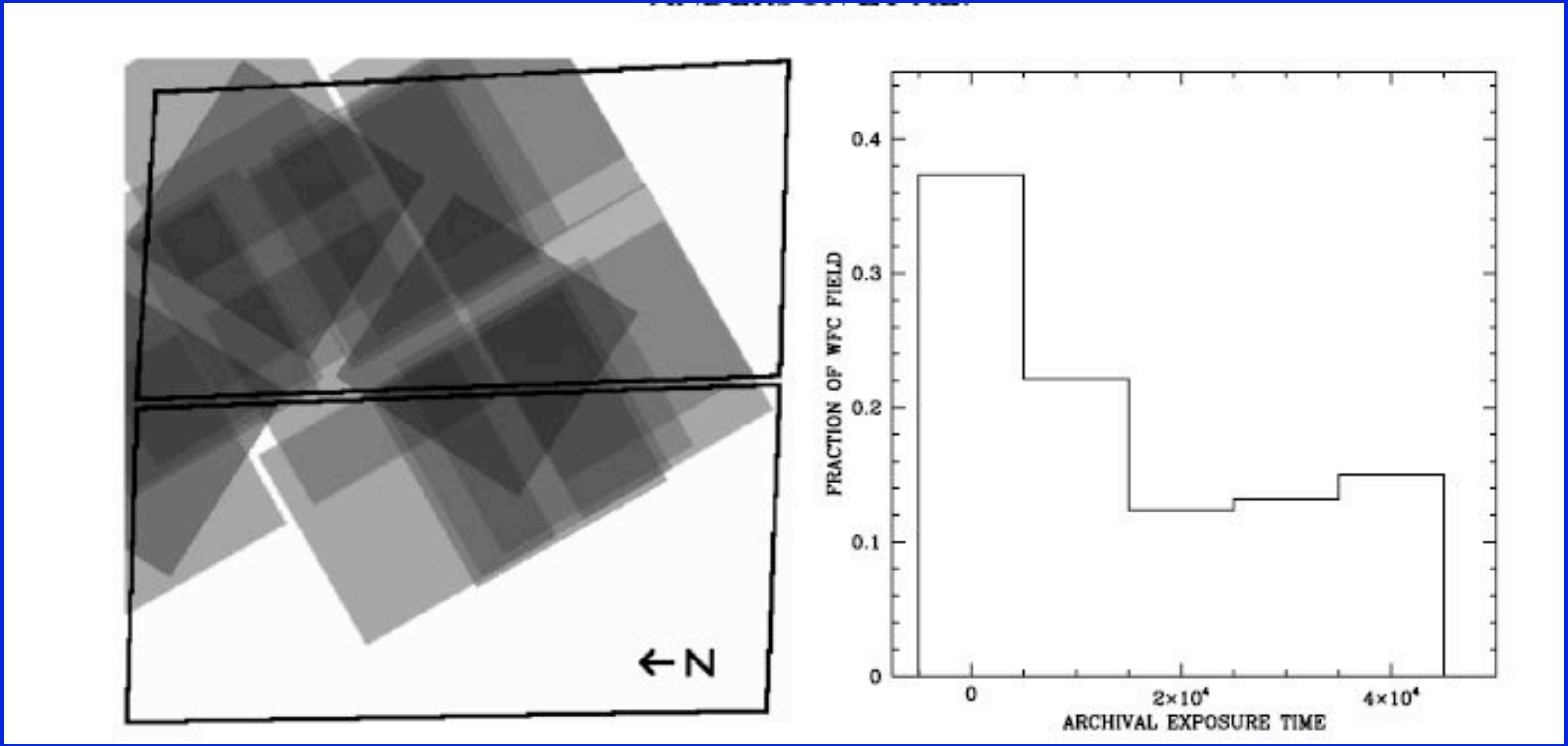
field

cluster

Richer et al. 2006
Science 313, 936


-6
-4
-2
0
2
4
6
−53:35:00
−53:36:00
−53:37:00
−53:38:00
−53:39:00
−53:40:00
−53:41:00
−53:42:00
−53:43:00
−53:44:00
−53:45:00
−53:46:00
17:41:15
17:41:00
17:40:45
17:40:30
17:40:15
1/2 mass rad
ACS field
NGC6397
WFPC2
ARCHIVE
2002
11
2001
60
2000
30
1999
160
1998
1
1994
61
1995
3
1996
89
1997
46

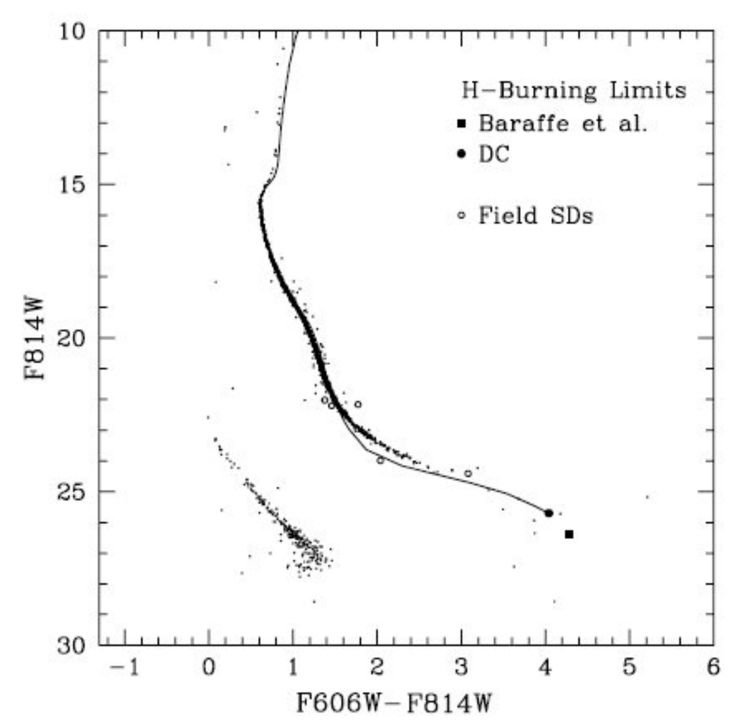
Patchy and incomplete first epoch coverage a problem

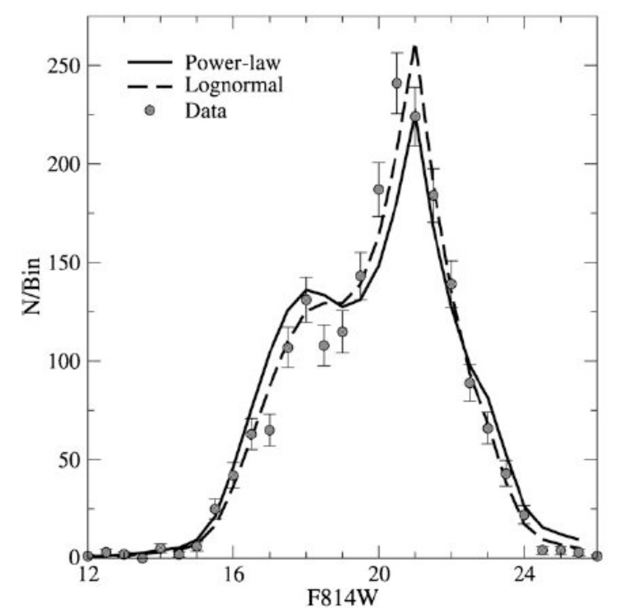


Shaded areas are WFPC2 fields

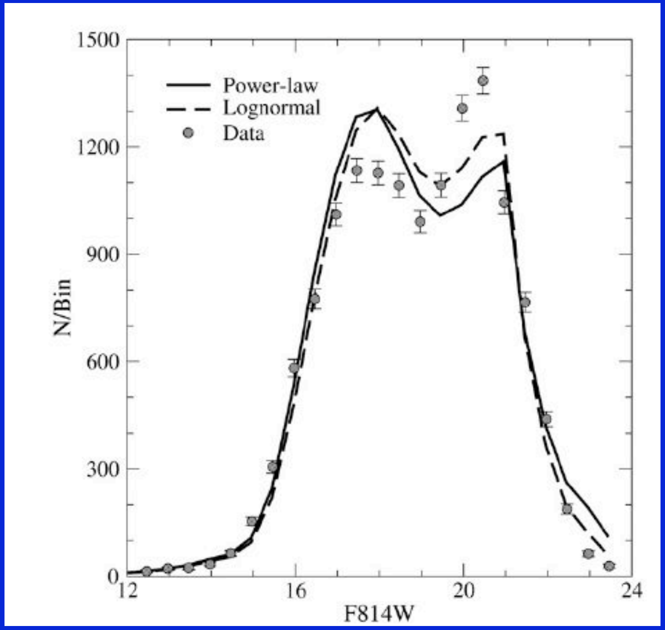
NGC 6397 deep CMD, mass segregation

Richer et al. 2008



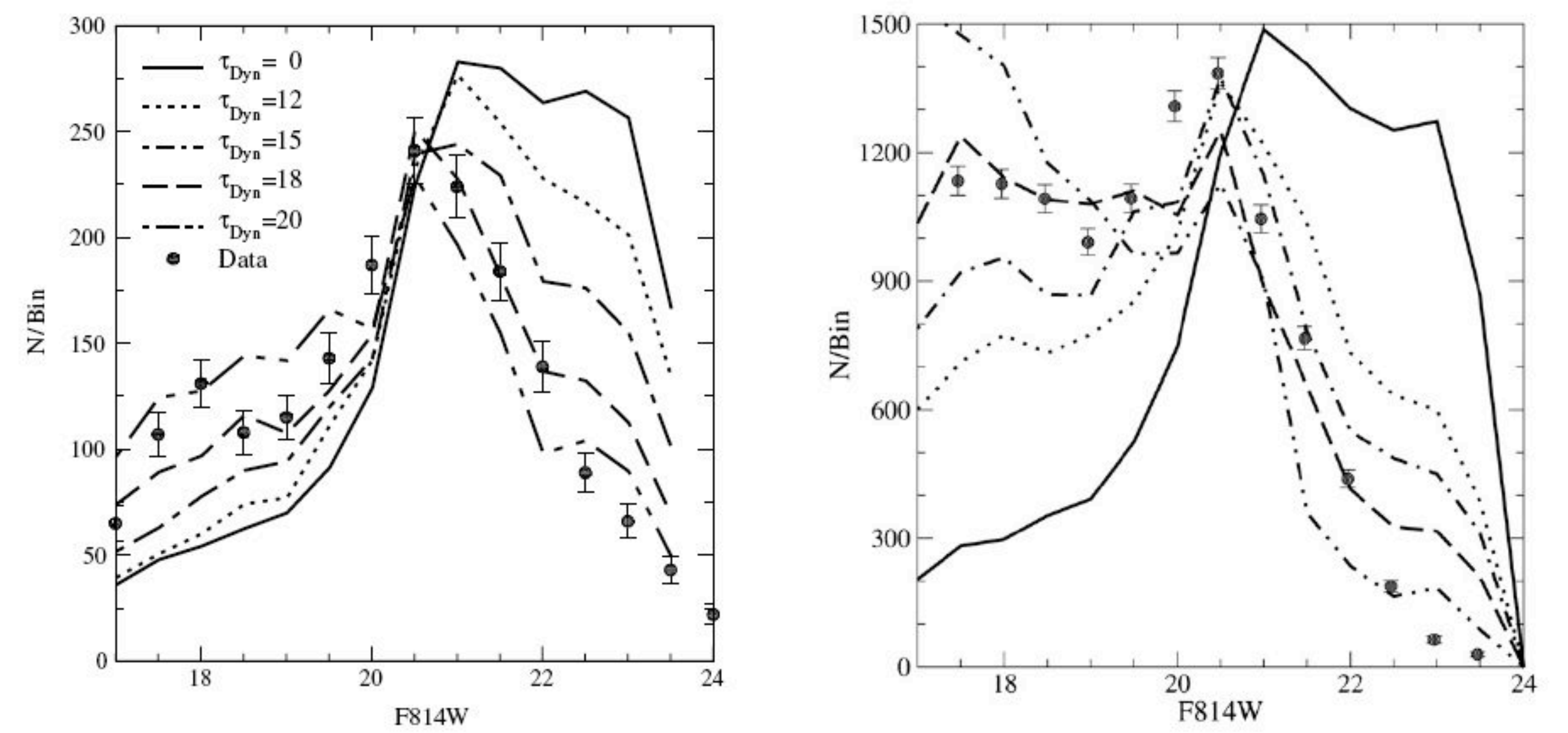


Outer field

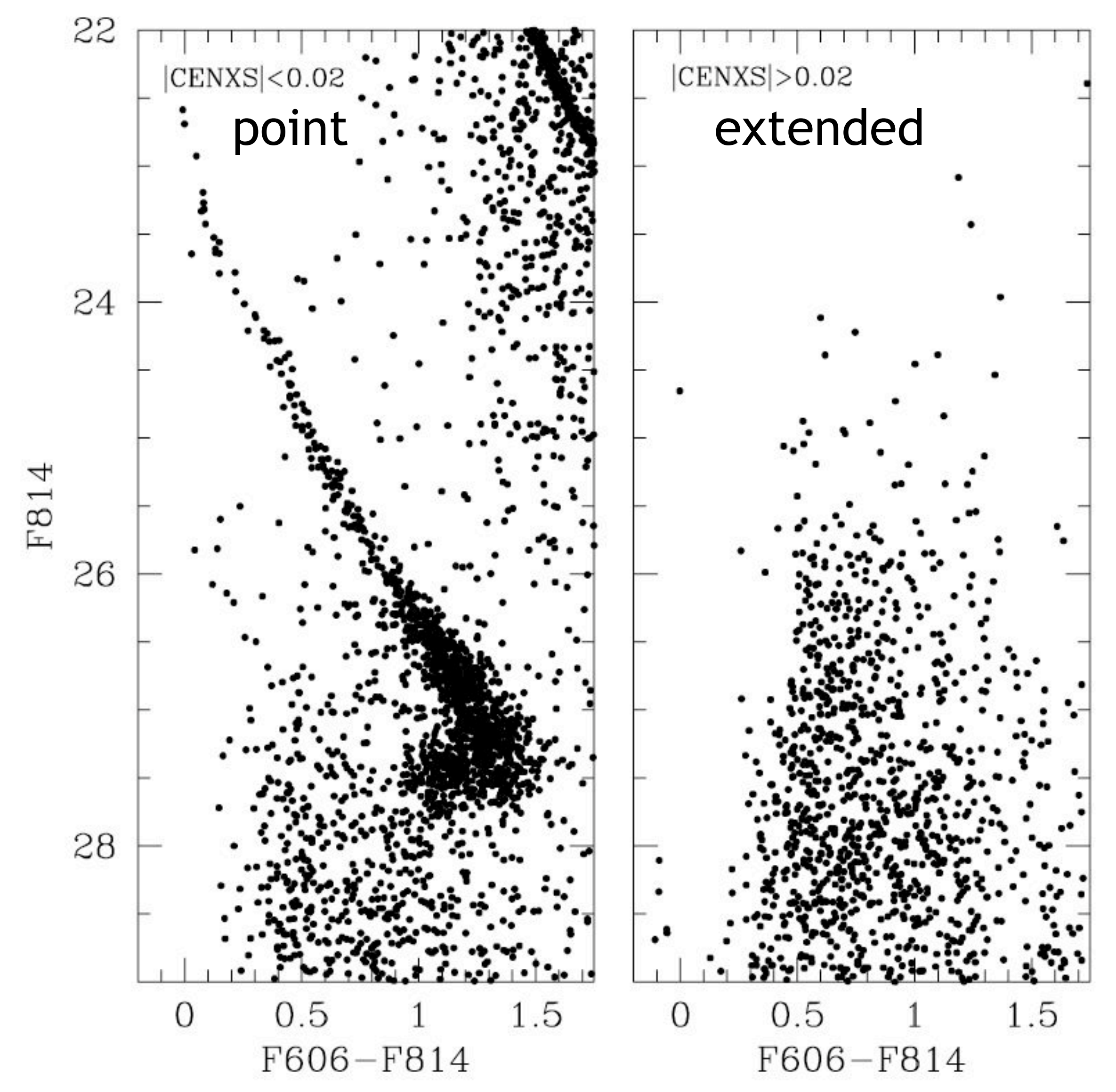


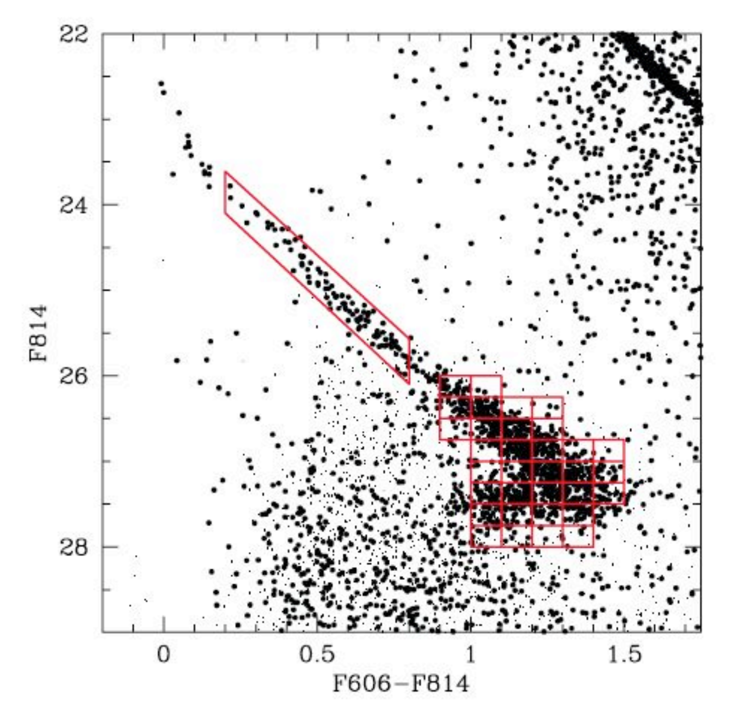
core

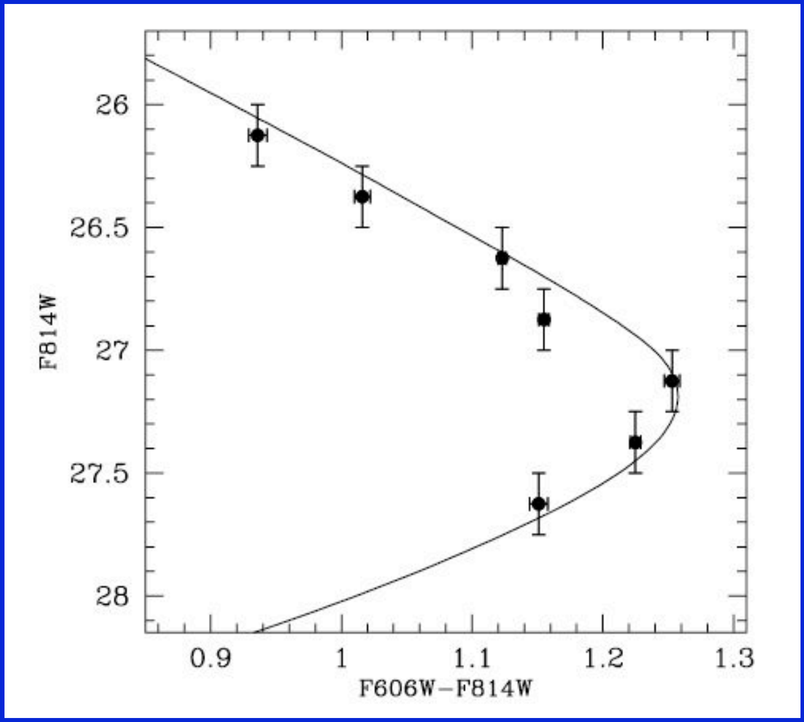
Comparison- dynamical models and LF



WD cooling sequence for NGC 6397- Hansen et al. 2007

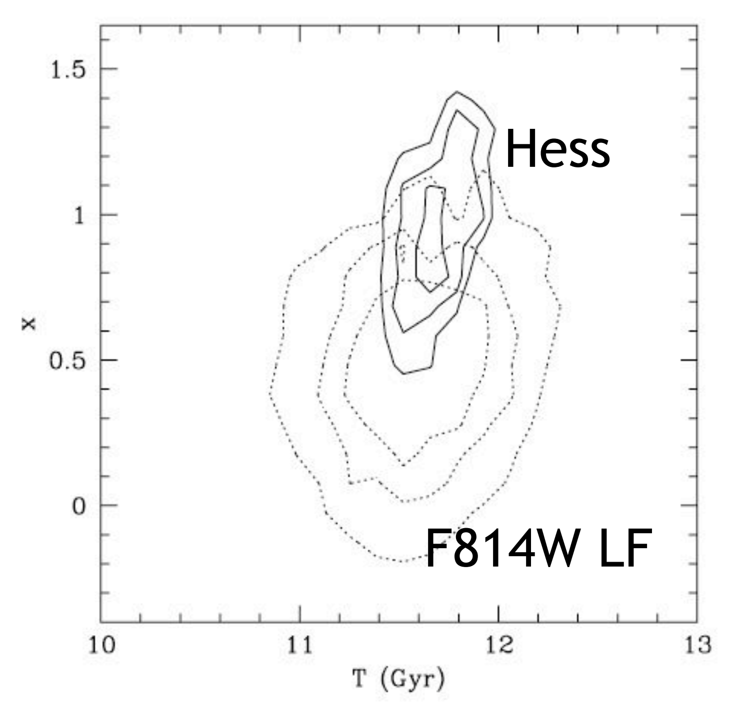




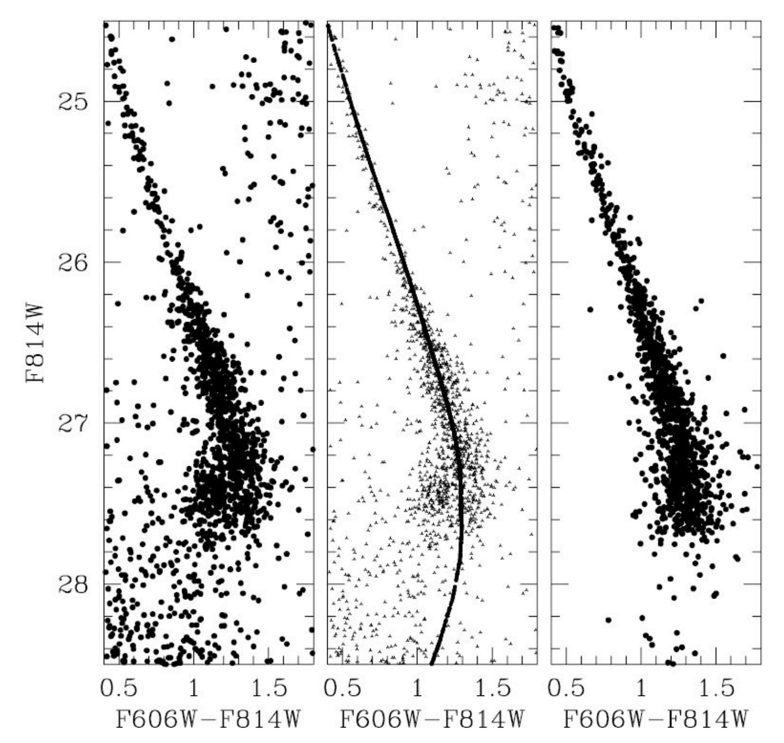


Solid line: Bergeron 0.5Mo Model, + redden, modulus

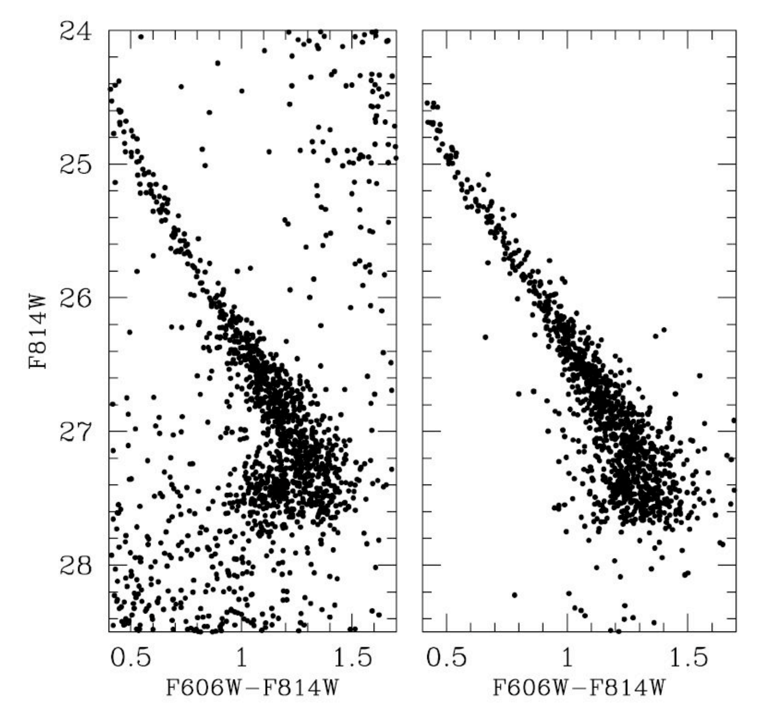
11.7 +/- 0.3 Gyr
X=0.95



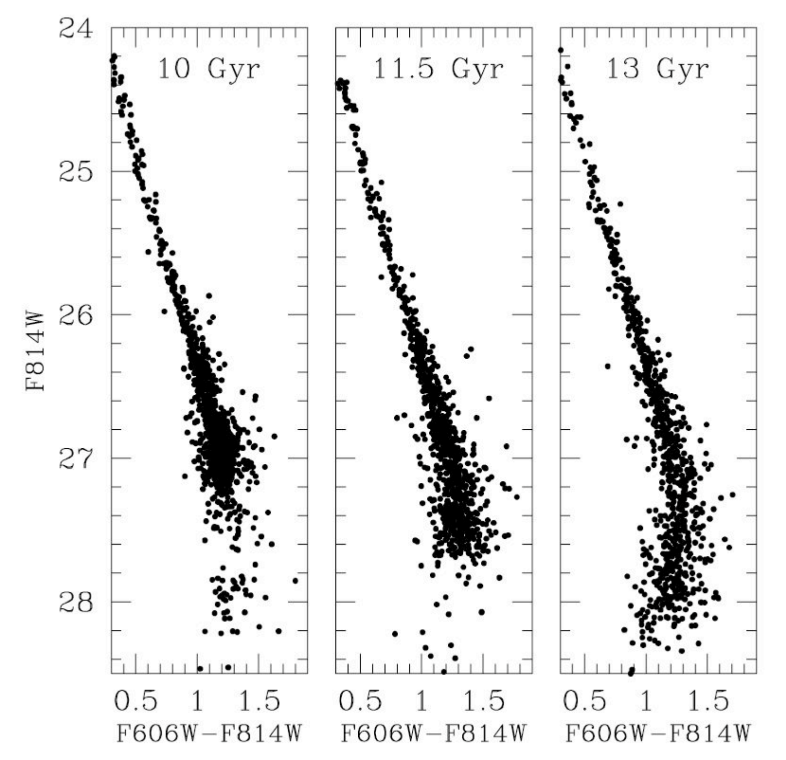
Bergeron’s cooling model



Cleaning via extended source rejection



N6397 model CMDs



Hansen et al. 2007

11.46 Gyr fit

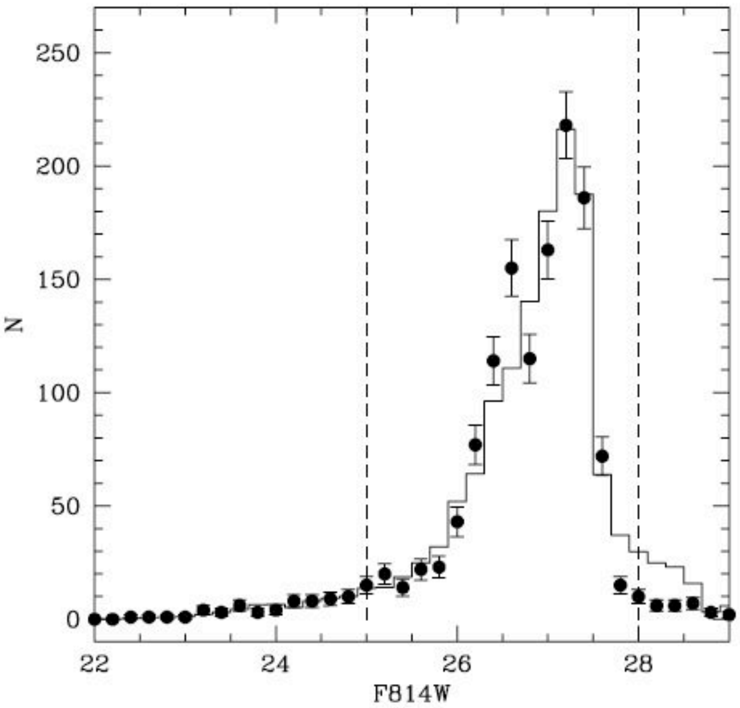


FIG. 16.—Model luminosity function shown is for an age of 11.46 Gyr.

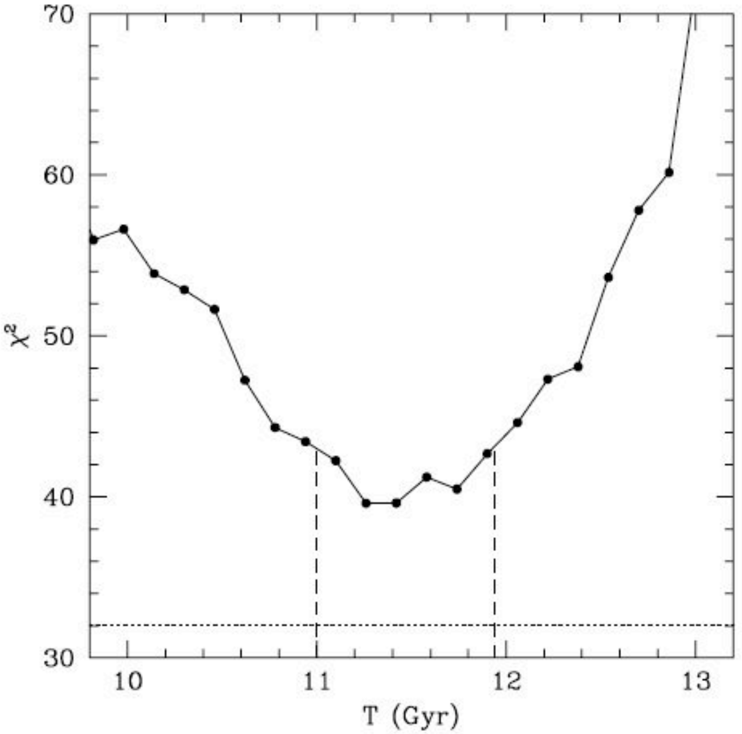
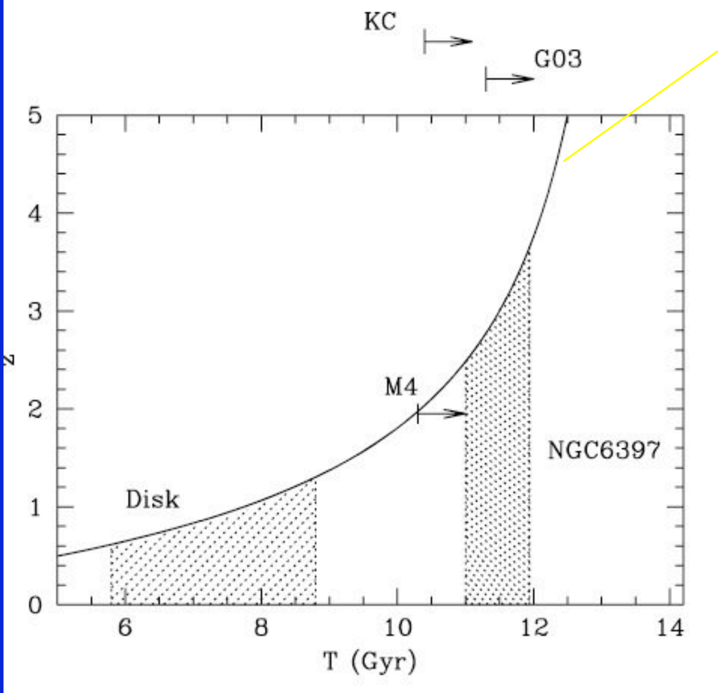
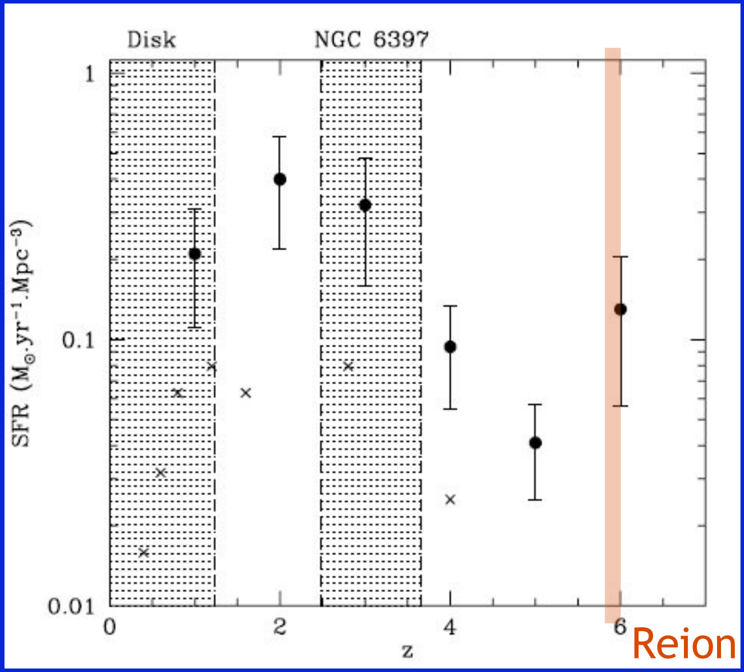


FIG. 17.—The χ^2 curve vs. cluster age, marginalized over all other parameters for the metal-poor main-sequence models (both those of Dotter & Chaboyer and those of Hurley et al. 2000). The dashed lines indicate the 2 σ age range and the horizontal dotted line corresponds to $\chi^2 = 1$ per degree of freedom.

NGC 6397 appears to form after reionization epoch

Need better 3-sigma upper limit





KC=Krauss& Chaboyer 2003 halo
G03= Gratton (03) age NGC 6397

SF histories: Filled HUDF SF (Thompson +06)
X = HDF SF (Madau+96)

Shading=2-sigma limits **upper limit** very important

Cycle 17: 47 Tuc= NGC 104
(121 orbits awarded)

- WD cooling age for a metal rich globular cluster
- 47 Tuc may be a disk/thick disk cluster
- Turnoff age of 47 Tuc very similar to old metal rich clusters, Galactic bulge (constrain bulge age)
- But 47 Tuc may be ~2.6 Gyr < old halo
- 47 Tuc most luminous cluster, msec pulsars in core, etc.
- Complete WD LF studies spanning [Fe/H] from -2 to -0.7

Cycle 17: NGC 6397 (9 orbits)

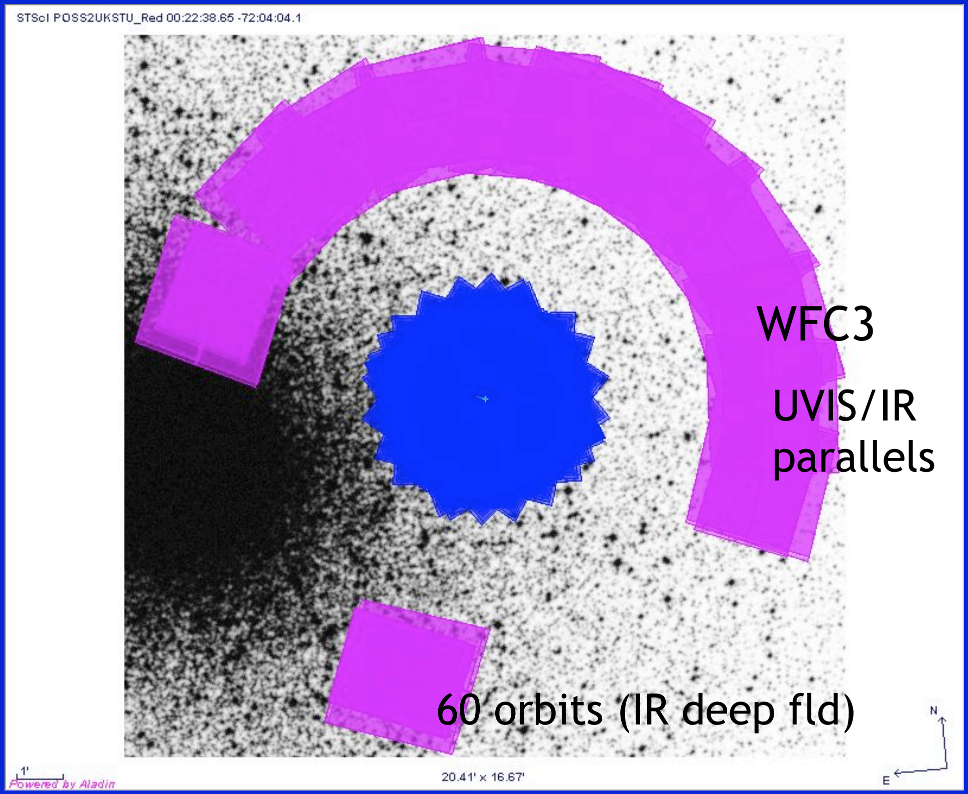
New 9 orbit image at same position as earlier 126 orbit pointing (deep proper motion separation).

- Clearly define blue hook, faint end of WD LF
- Potential to constrain detailed SF history

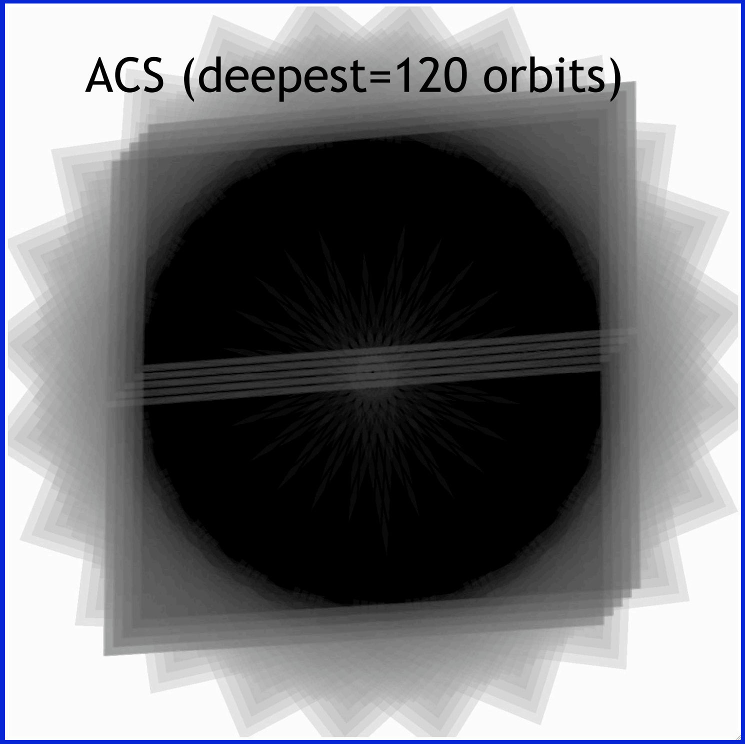
Cycle 17 Planned Observations (120 orbits)

One orient for 60 orbits > IR deep field (paired with earlier WFPC2 data). Upper arc gives the LF from the core to the outskirts (with binary fractions) for dynamical studies. Time divided between F606W and F814W.

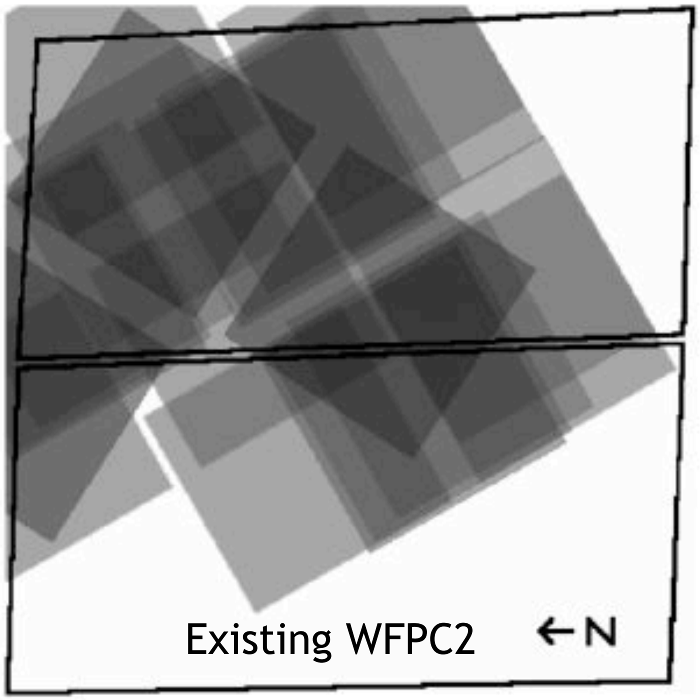
Rosette improves CTE measurement, photometry

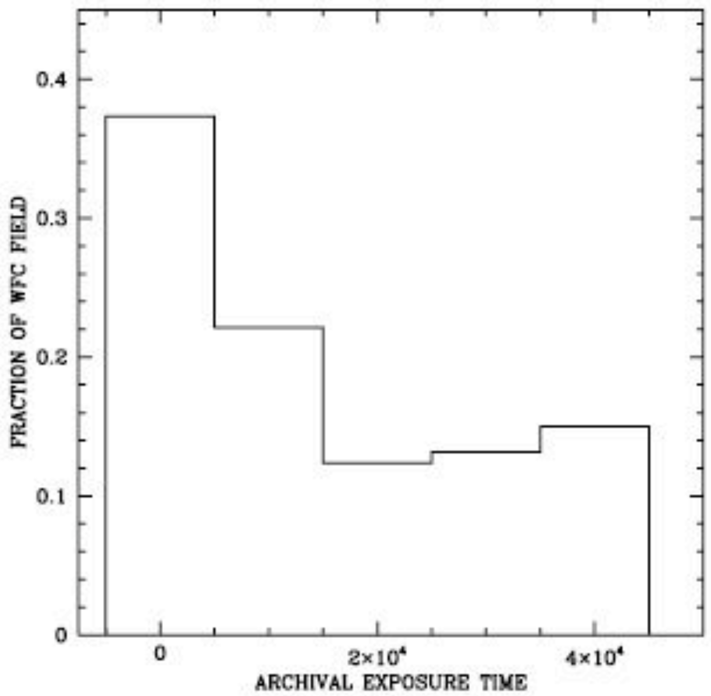


Courtesy J. Anderson, D. Reitzel



NGC 6397 field has 126 orbits, but first epoch exposures cover <60% of field

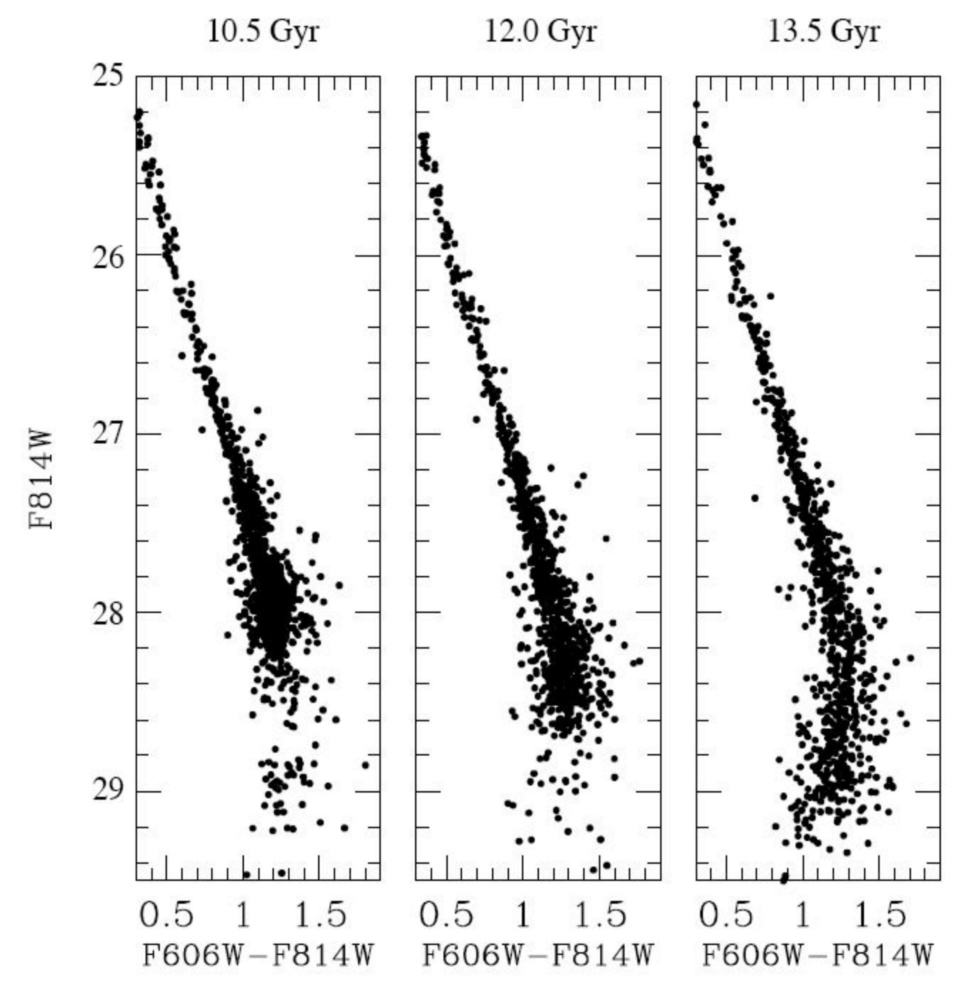




A Cycle 17 9 orbit exposure is approved to exactly superpose the earlier deep imagery, enabling PM separation to the faintest possible levels.

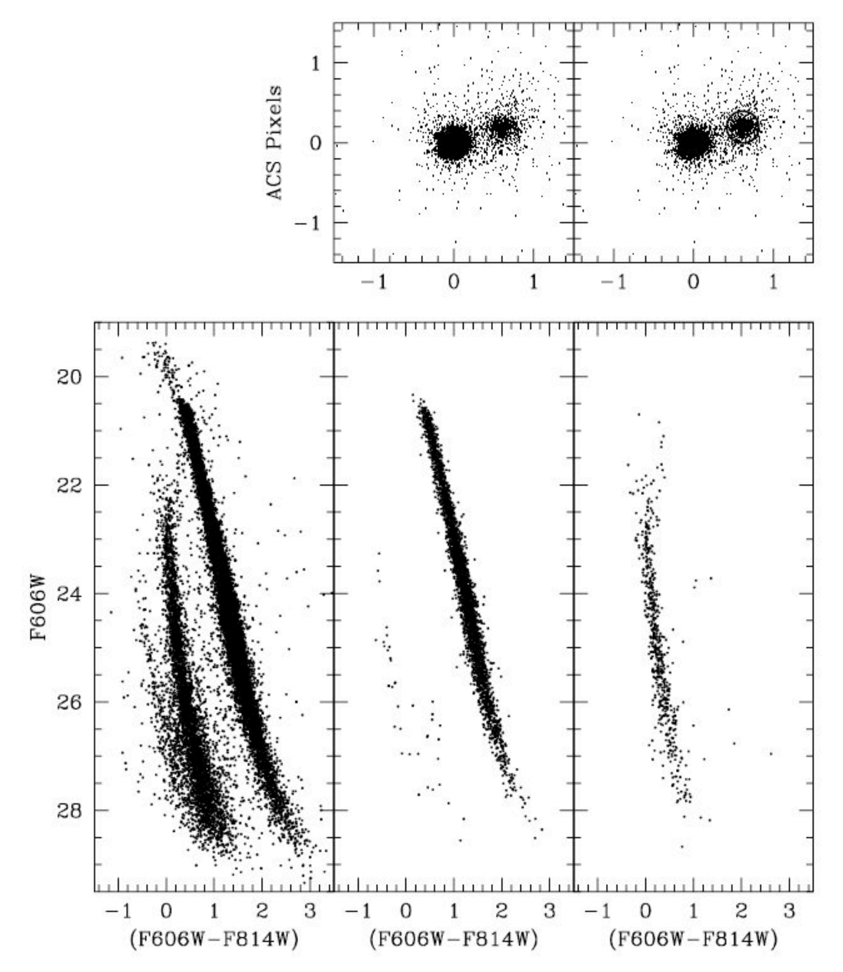
Anderson et al. 2008

47 Tuc WD cooling sequence for 3 ages



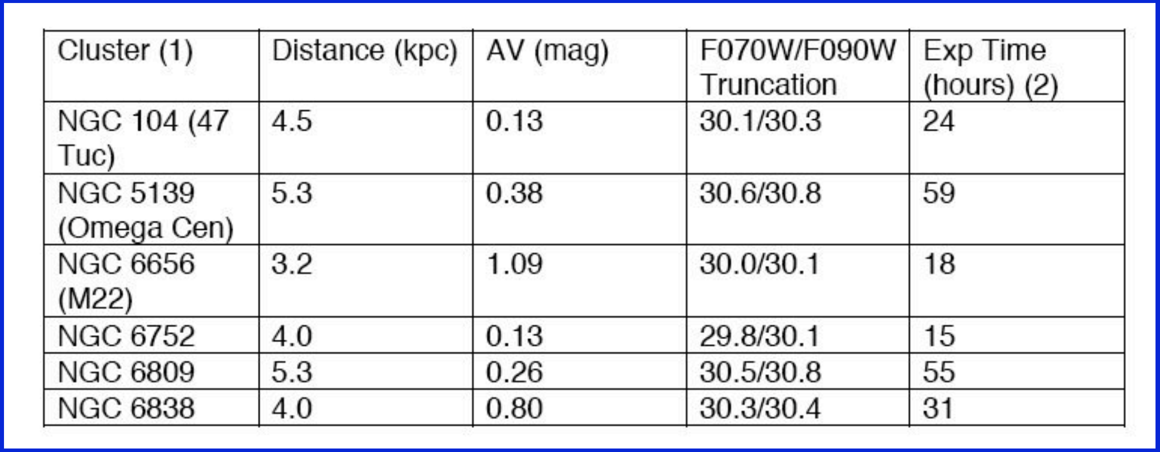
Courtesy B. Hansen

Preliminary 47 Tuc reductions (UBC)

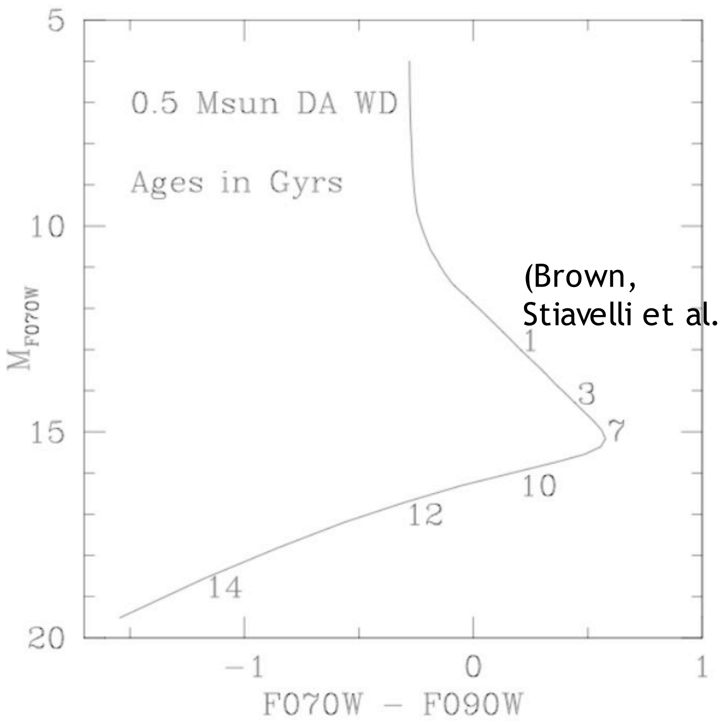


47 Tuc MS+WD SMC

Future with JWST (H. Richer)



Cluster (1)	Distance (kpc)	AV (mag)	F070W/F090W Truncation	Exp Time (hours) (2)
NGC 104 (47 Tuc)	4.5	0.13	30.1/30.3	24
NGC 5139 (Omega Cen)	5.3	0.38	30.6/30.8	59
NGC 6656 (M22)	3.2	1.09	30.0/30.1	18
NGC 6752	4.0	0.13	29.8/30.1	15
NGC 6809	5.3	0.26	30.5/30.8	55
NGC 6838	4.0	0.80	30.3/30.4	31



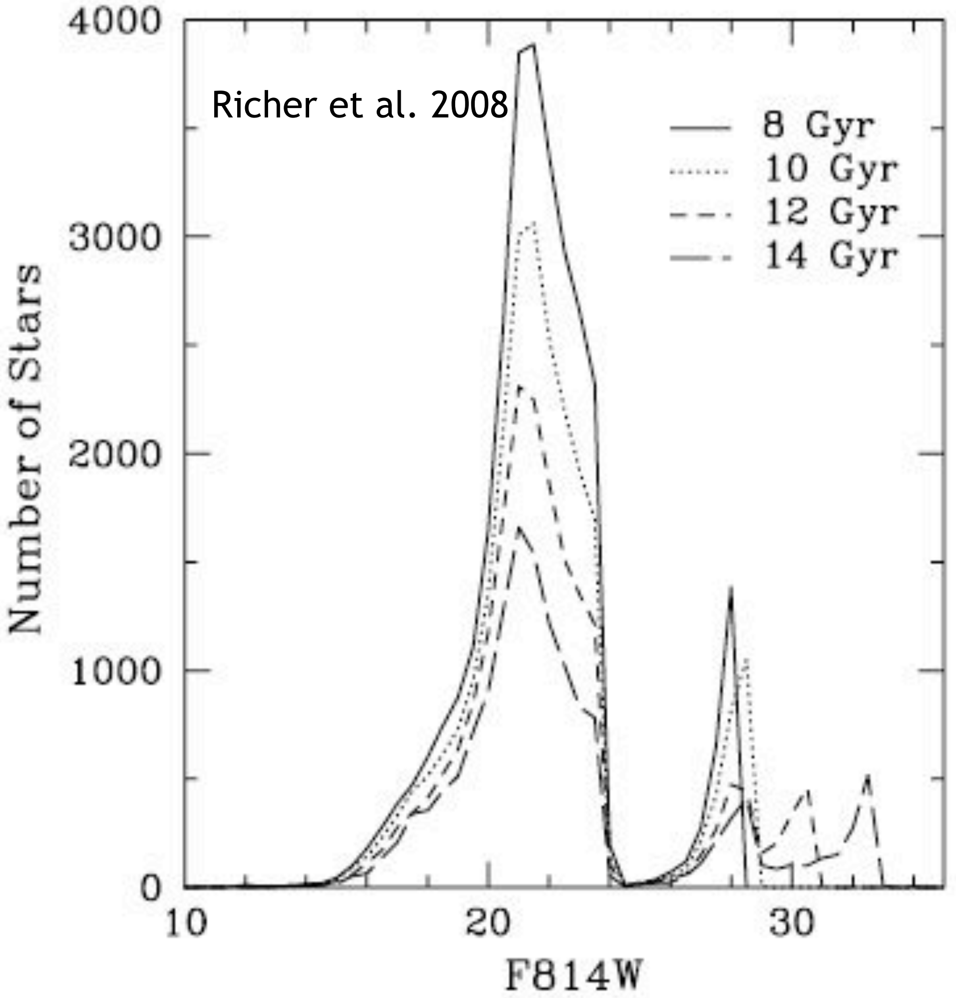
(Brown, Stiavelli et al.

Figure 8. The WD cooling sequence in the JWST filters F070W and F090W. This sequence is for a hydrogen-rich WD with a mass of 0.5 $M_\odot$ and was calculated by P. Bergeron.

JWST to have some “optical” capability, at 7000, 9000A.

Strehl will be relatively poor, but 6.5m aperture may overcome this.

HST-like spatial resolution + large aperture, better sensitivity, makes possible major programs in this area.



Richer et al. 2008

Figure 12. Simulated LFs at various ages in our field of NGC 6397. This is an example of a LF that JWST could potentially produce with a very deep exposure in this cluster and with a second epoch for PM cleaning. Images in only a single color would be required, thus substantially reducing observing time.