White Dwarfs in Globular Clusters

(1) Deep exposures for "normal" white dwarfs → constraints on ages / mass functions

(2) low mass white dwarfs in cluster cores → dynamics

(1) → M_4 : Richer PI (1995, 1997, 2002)

H.B. Richer et al (1995) ApJ 451, L17
" (1997) ApJ 484, 741
(2002) ApJ 574, L151
B. Hansen et al (2002) ApJ 574, L155

(2) → NGC 6397: Cool, Grindlay & Collaborators

A.M. Cool et al (1998) ApJ 508, L75
J.M. Taylor et al (2001) ApJ 553, L169
P.D. Edmonds et al (1999) ApJ 516, 250
J.E. Grindlay et al (2001) ApJ 563, L53

Hansen, Kalogera & Rasio (2003) ApJ 586, ?
/astro-ph/0206035

M4 white dwarf cooling sequence

Cluster members selected by proper motion displacement.

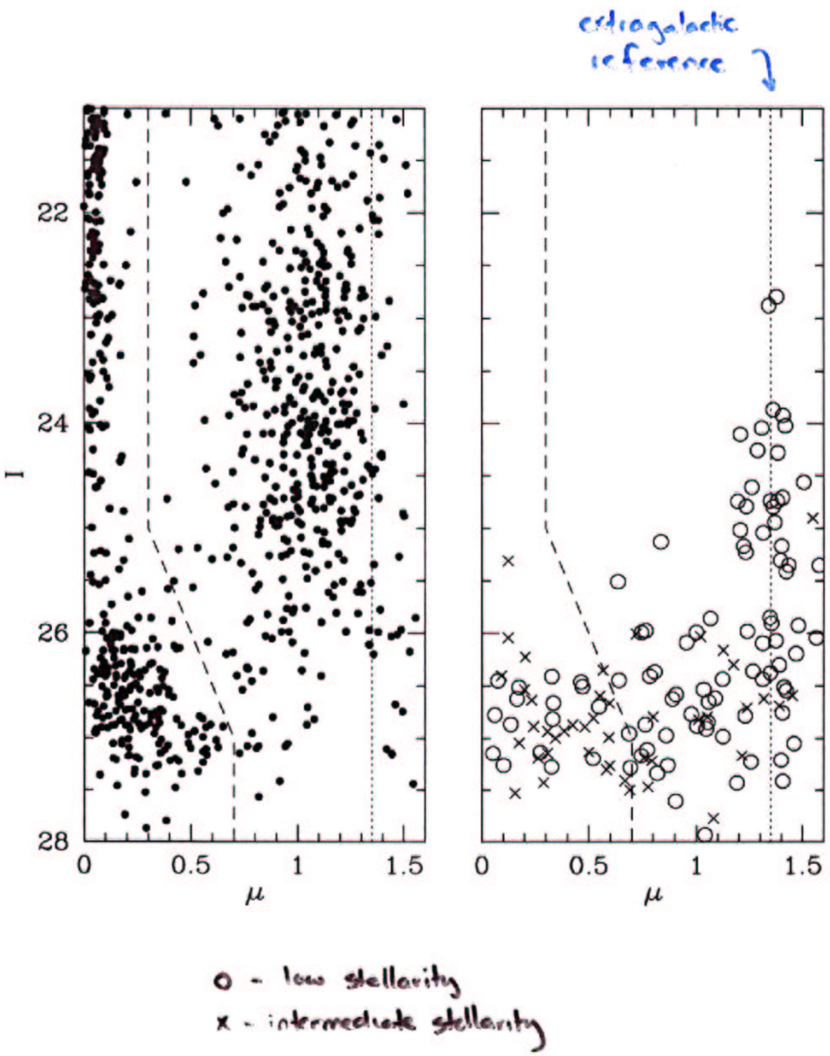
- centroiding gets worse as a function of magnitude
  - ⇒ pm cut should be magnitude dependent

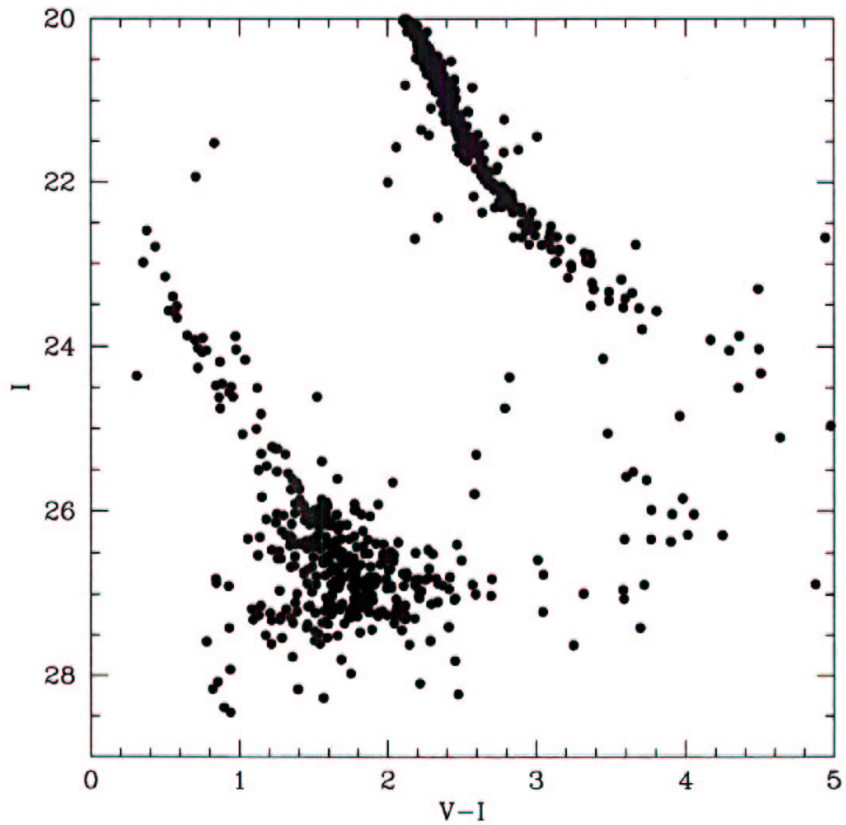
→ 383 white dwarfs @ V < 29

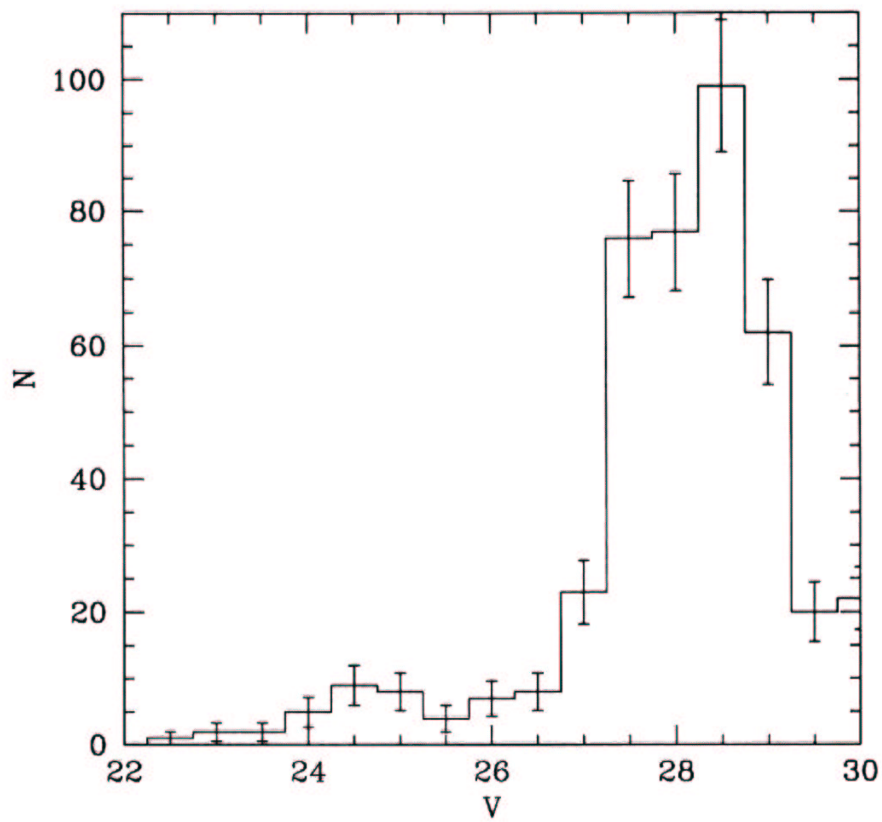
- → sharply peaked white dwarf luminosity function

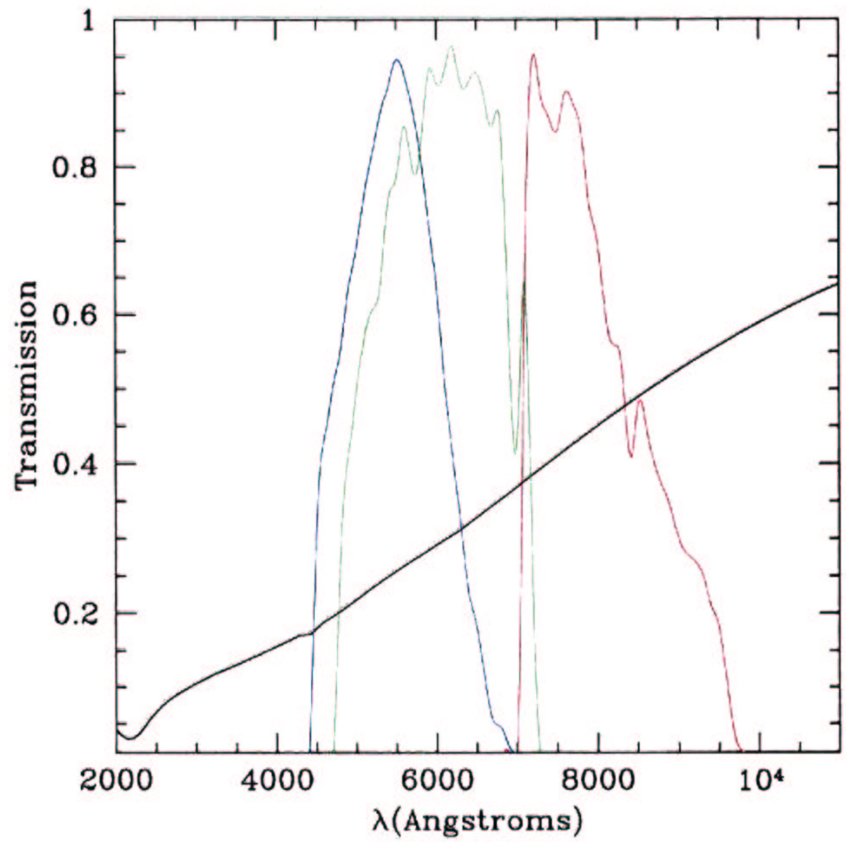
→ to determine an age we need to compare to theoretical cooling models

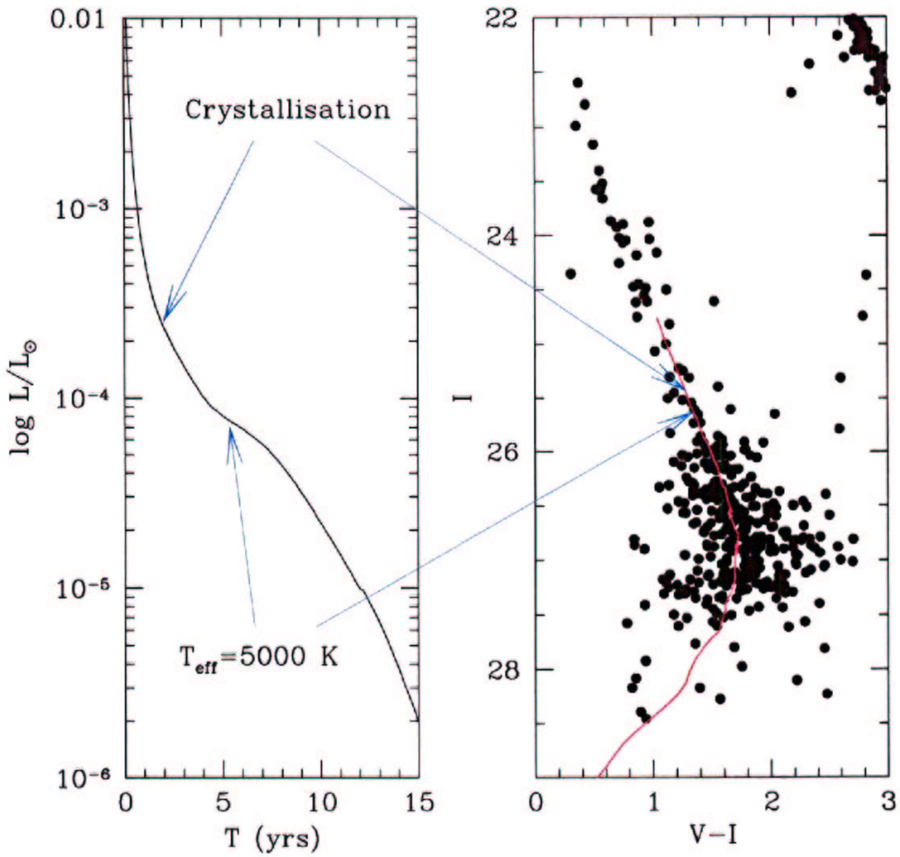
- → it is worth noting this process is actually <u>easier</u> here than for the field sample, because $1/V_{max}$ weightings cause problems @ low bin occupation

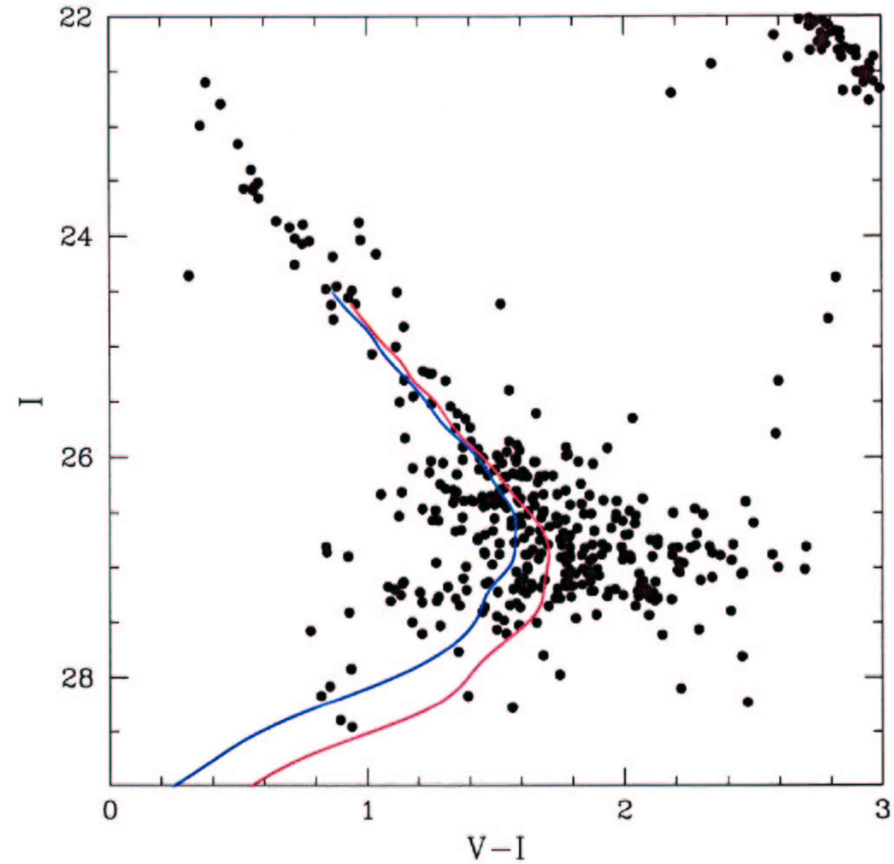

extragalactic
reference
22
24
26
28
I
0
0.5
1
1.5
μ
o - low stellarity
x - intermediate stellarity

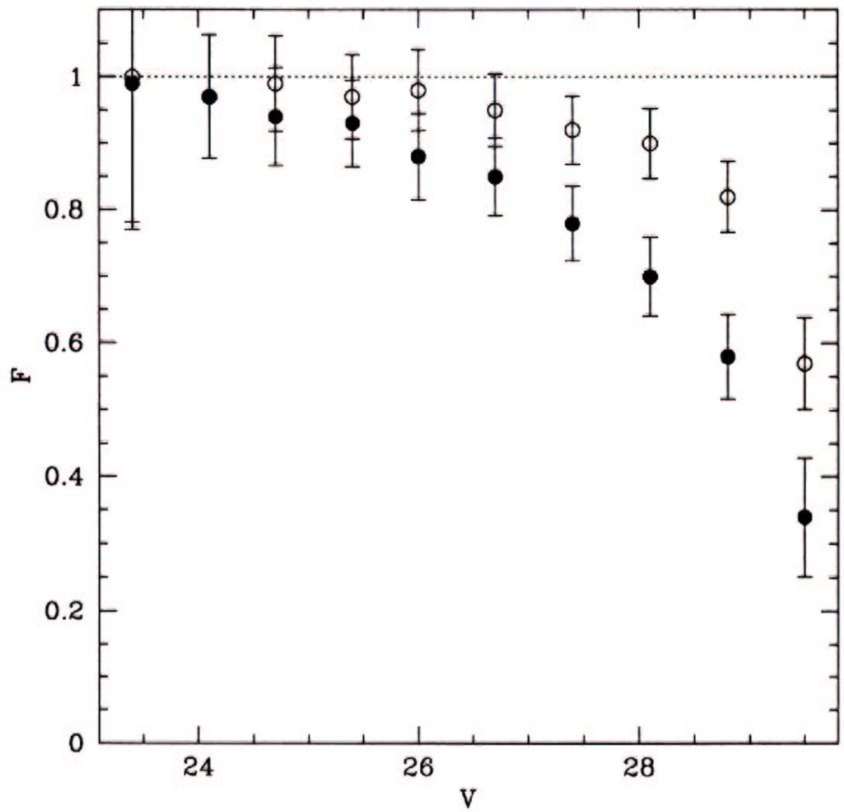

20
22
24
26
28
I
0
1
2
3
4
5
V−I

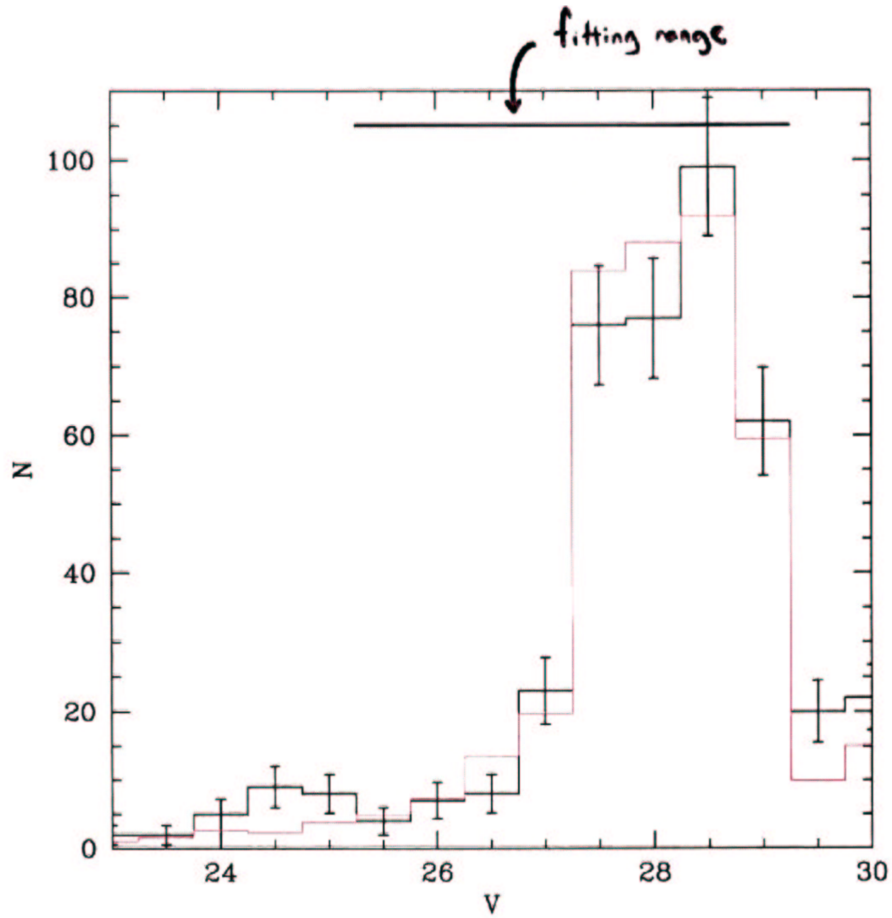

N
V
0
20
40
60
80
100
22
24
26
28
30


Transmission
λ(Angstroms)
0.2
0.4
0.6
0.8
1
2000
4000
6000
8000
10⁴


Crystallisation
Teff=5000 K
log L/L⊙
T (yrs)
V−I
I


V−I
I


1
0.8
0.6
0.4
0.2
0
F
24
26
28
V


fitting range
100
80
60
40
20
0
N
24
26
28
30
V

12.5 Gyr fit

Theoretical Luminosity functions

Ingredients:

- Cooling models
- MS → WD mass relation
- IMF & stellar models

⇒ extinction model & distance for M4

∃ some degeneracies between distance, extinction & mass (radius)

The sharp jump in the LF is caused by the change in the atmosphere boundary condition as the photospheric material becomes neutral & molecular

Age discrimination comes about because cooling is a function of mass in the core crystalline regime → couples the various ingredients above

Folding our cooling models through the incompleteness corrections, we may compare to the observations:

Default:

Cooling models from Hansen (1999) ApJ 520, 680

MS-WD relation from Wood (1992) ApJ 386, 539

mass-age from Hurley et al (2000) MNRAS 315, 543

Distance & extinction from Richer et al (1997) ApJ 484, 741

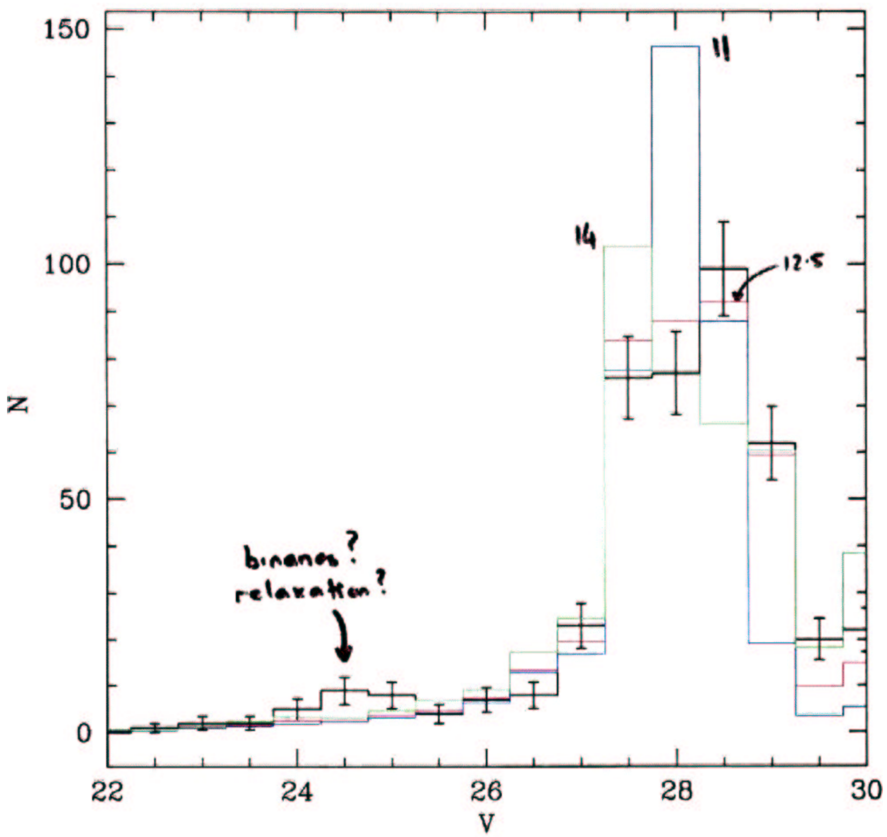
$x = 0.05$ from Richer et al (2002) ApJ 574, L151

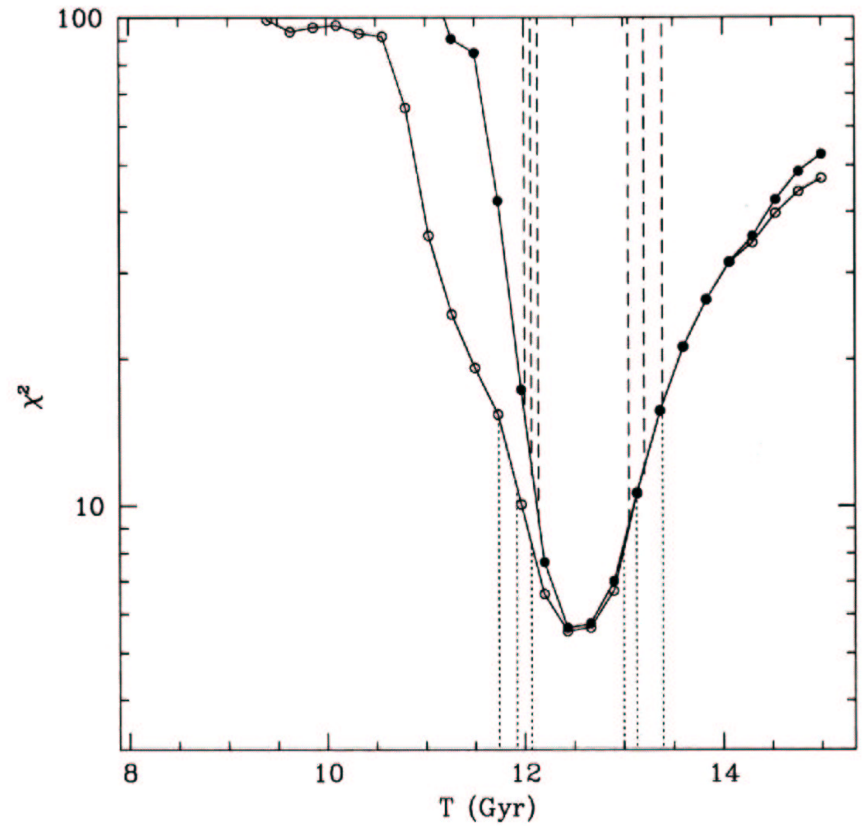
Pure H atmospheres – cf Hansen et al (2002) ApJ 574, L155

⇒ 3σ age range 12 Gyr – 13.4 Gyr

If we move the magnitude cutoff up by 0.5 mags

⇒ 3σ age range 11.7 – 13.4 Gyr


150
100
50
0
N
22
24
26
28
30
V
11
14
12.5
binaries?
relaxation?


100
10
χ^2
8
10
12
14
T (Gyr)

Given such excellent fits, we can try to constrain other parameters

eg. let the distance float

⇒ 36 $\mu = 11.18 \pm 0.1$ mags

& no significant age variation

let the mass function float

⇒ 36 $x < 0.4$ ← WD region only

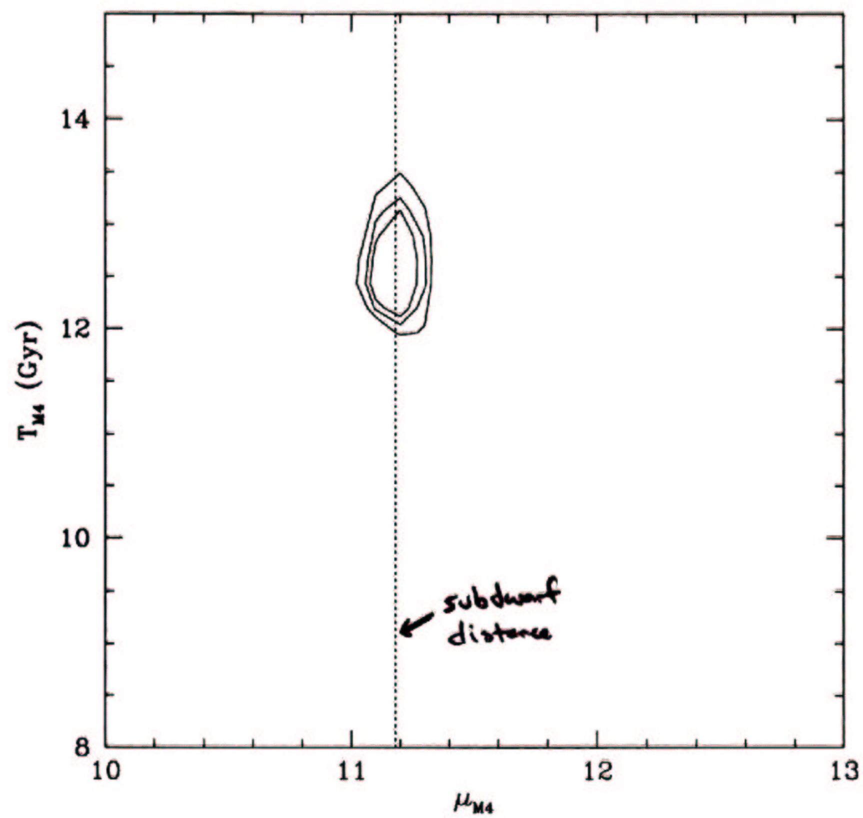
We can also use global constraints by comparing N_{WD} (383) to N_{MS} (585)

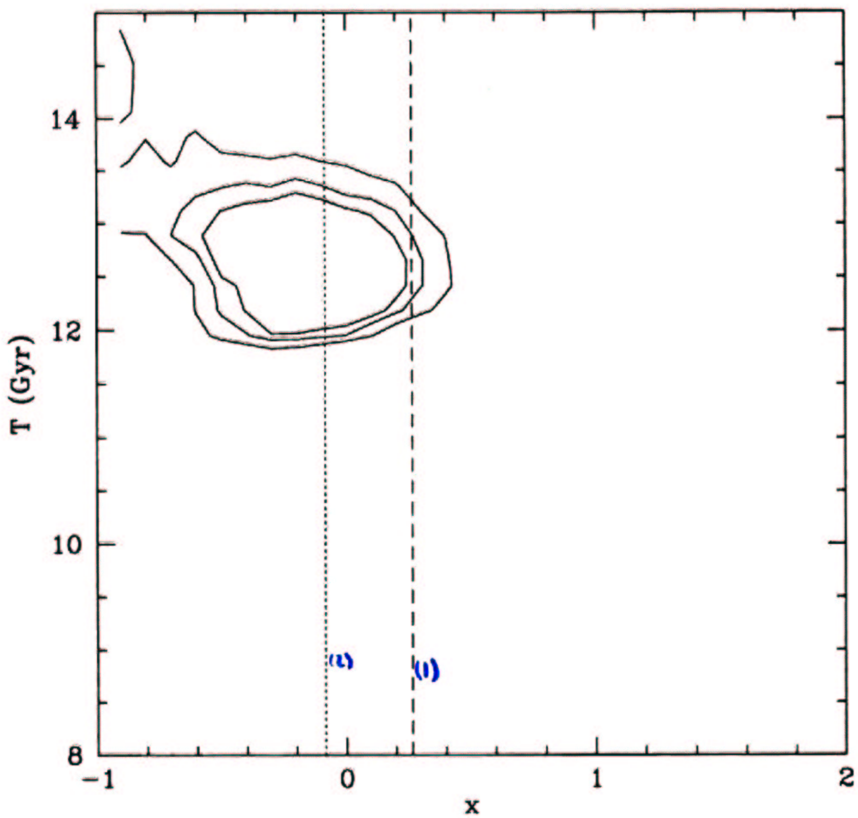
(1) $\frac{N_{WD}}{N_{MS}} = \frac{8^{-x} - 0.8^{-x}}{0.53^{-x} - 0.086^{-x}} = 0.666$ ⇒ $x = 0.26$

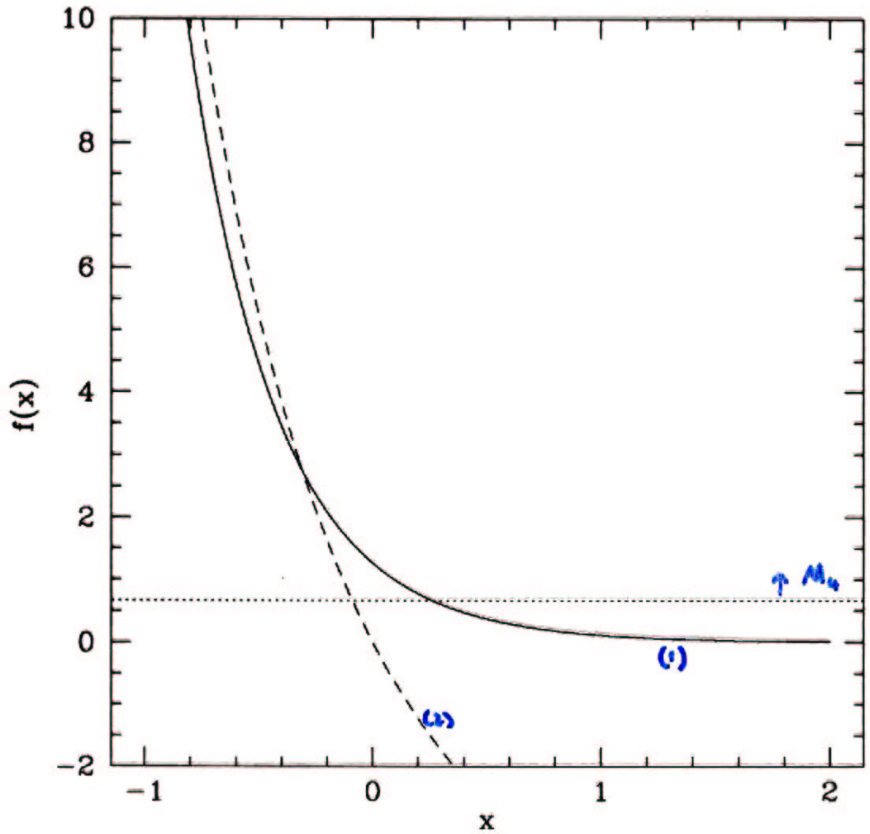
↗ global x

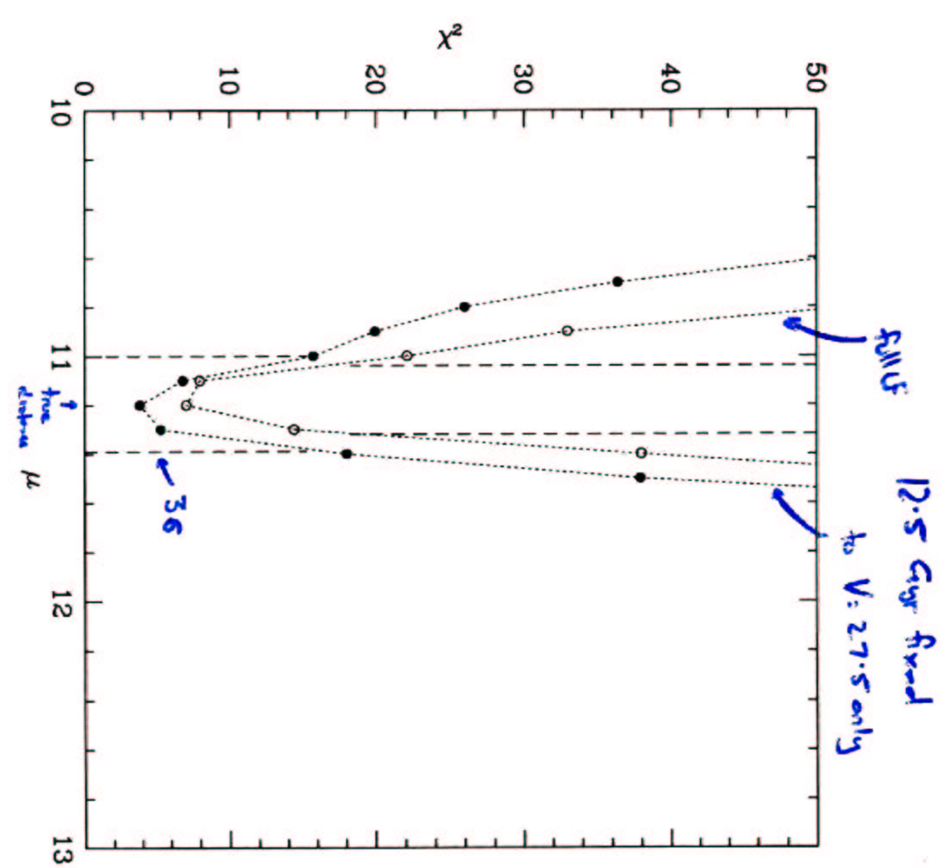
(2) $\frac{N_{WD}}{N_{MS}} = 3.031 \left[6.4^{-x} - 0.64^{-x} \right]$ ⇒ $x = -0.085$

↗ assumes $x = -0.25$ for MS & continuity across the turnoff




14
12
10
8
T (Gyr)
−1
0
1
2
x
(2)
(1)


10
8
6
4
2
0
−2
f(x)
−1
0
1
2
x
(1)
(2)



WDLF jump as distance indicator

We can also constrain the burst nature of the cluster's provenance.

Assume $p(t_{offset}) = \frac{1}{t_0} e^{-t/t_0}$

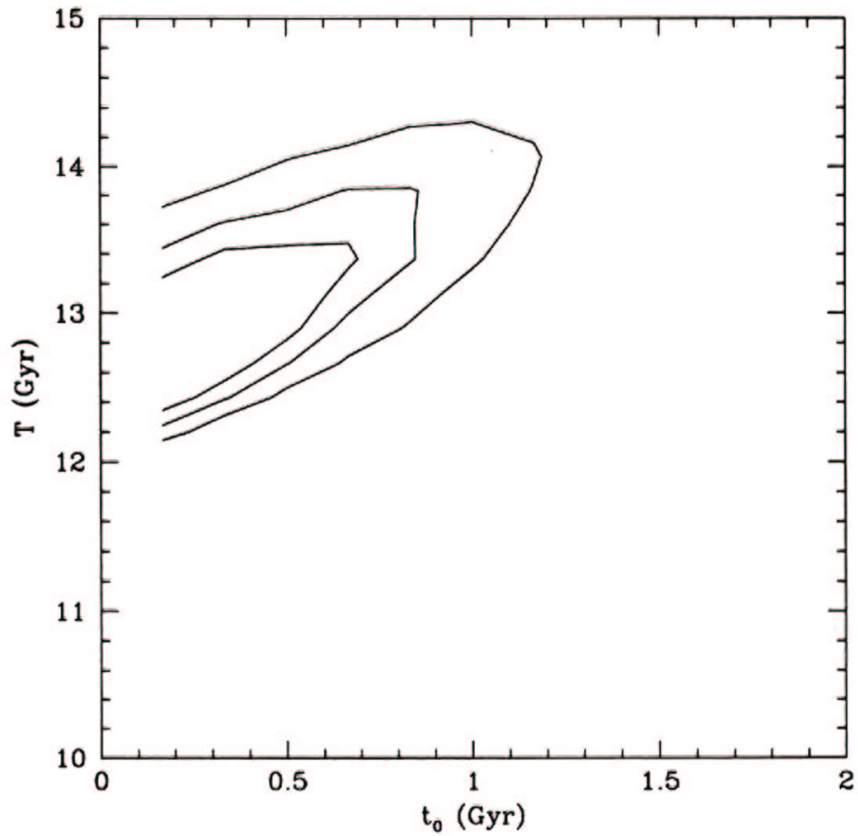
⇒ 3σ limit $t_0 < 1.2$ Gyr (assuming $x = 0.05$, $\mu = 11.18$)

Systematic errors from cooling models:

Default models use C/O cores, with profiles from Hernanz et al (1994)

→ Some variation is to be expected

→ upper mass limit likely to change more than the lower one.


15
14
13
12
11
10
T (Gyr)
0
0.5
1
1.5
2
t0 (Gyr)