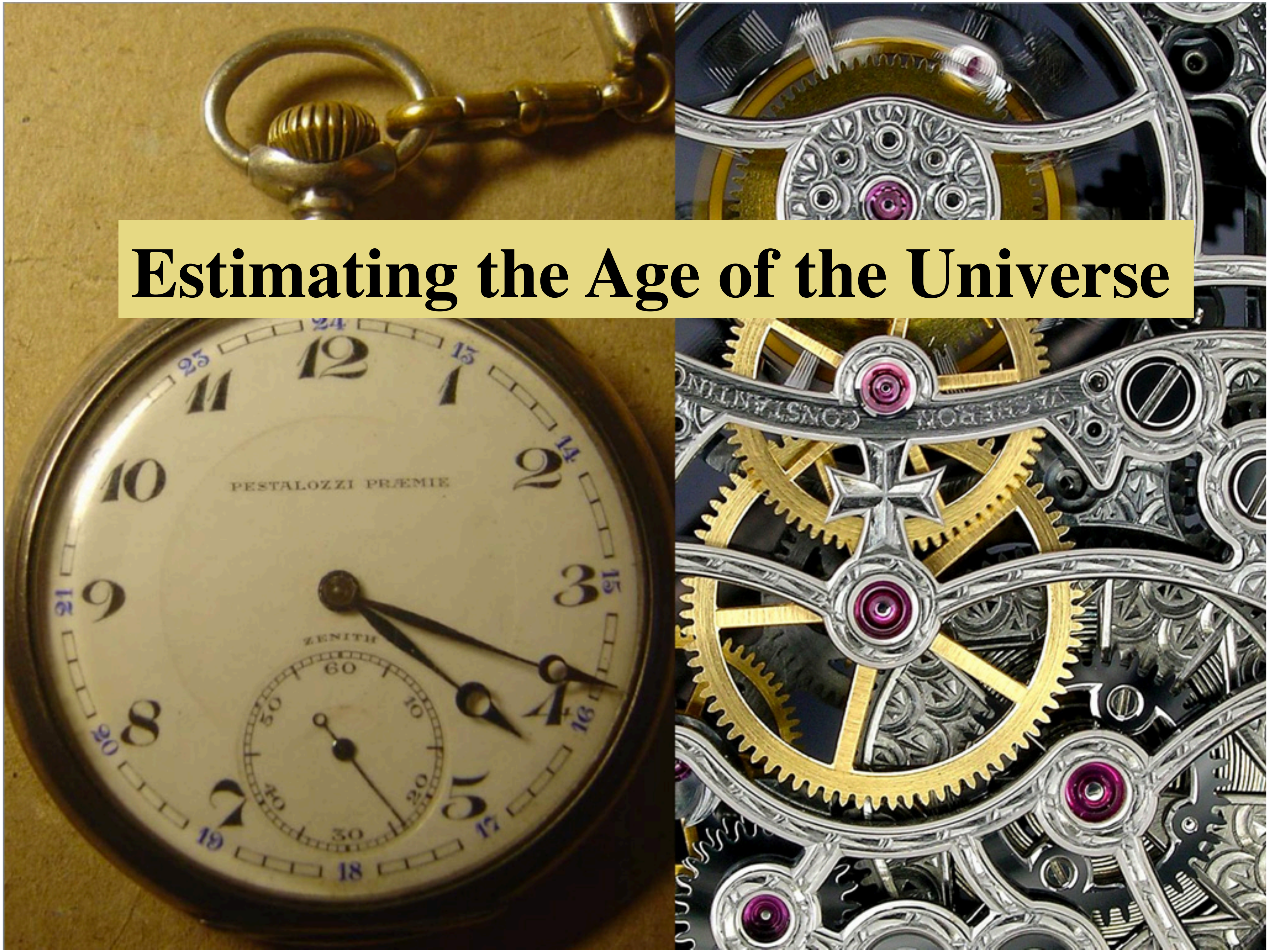
Estimating the Age of the Universe



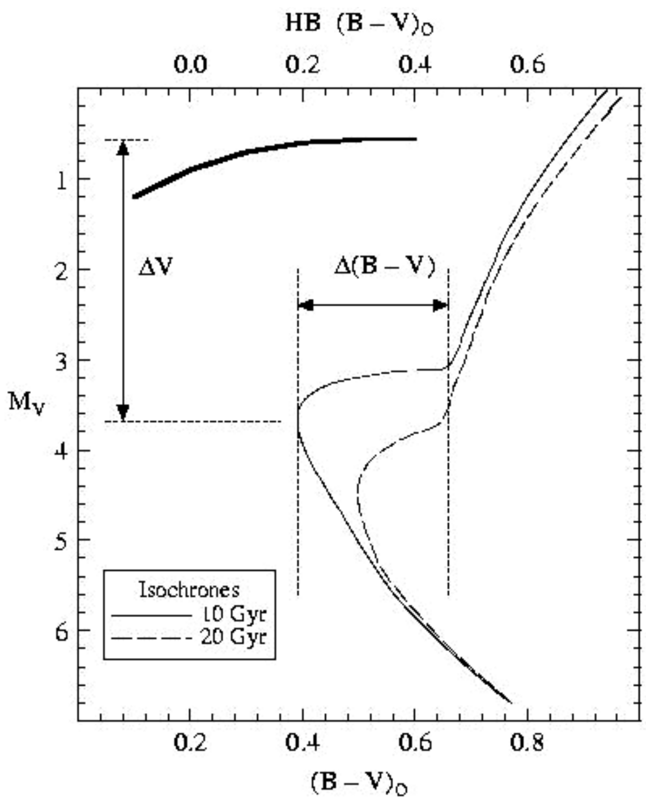
Measuring the Age of the Universe

- Related to the Hubble time $t_H = 1/H_0$, but the exact value depends on the cosmological parameters
- Could place a ***lower limit*** from the ages of astrophysical objects (pref. the oldest you can find), e.g.,
  - **Globular clusters** in our Galaxy; known to be very old. Need stellar evolution isochrones to fit to color-magnitude diagrams
  - **White dwarfs**, from their observed luminosity function, cooling theory, and assumed star formation rate
  - **Heavy elements**, produced in the first Supernovae; somewhat model-dependent
  - Age-dating **stellar populations** in distant galaxies; this is very tricky and requires modeling of stellar population evolution, with many uncertain parameters

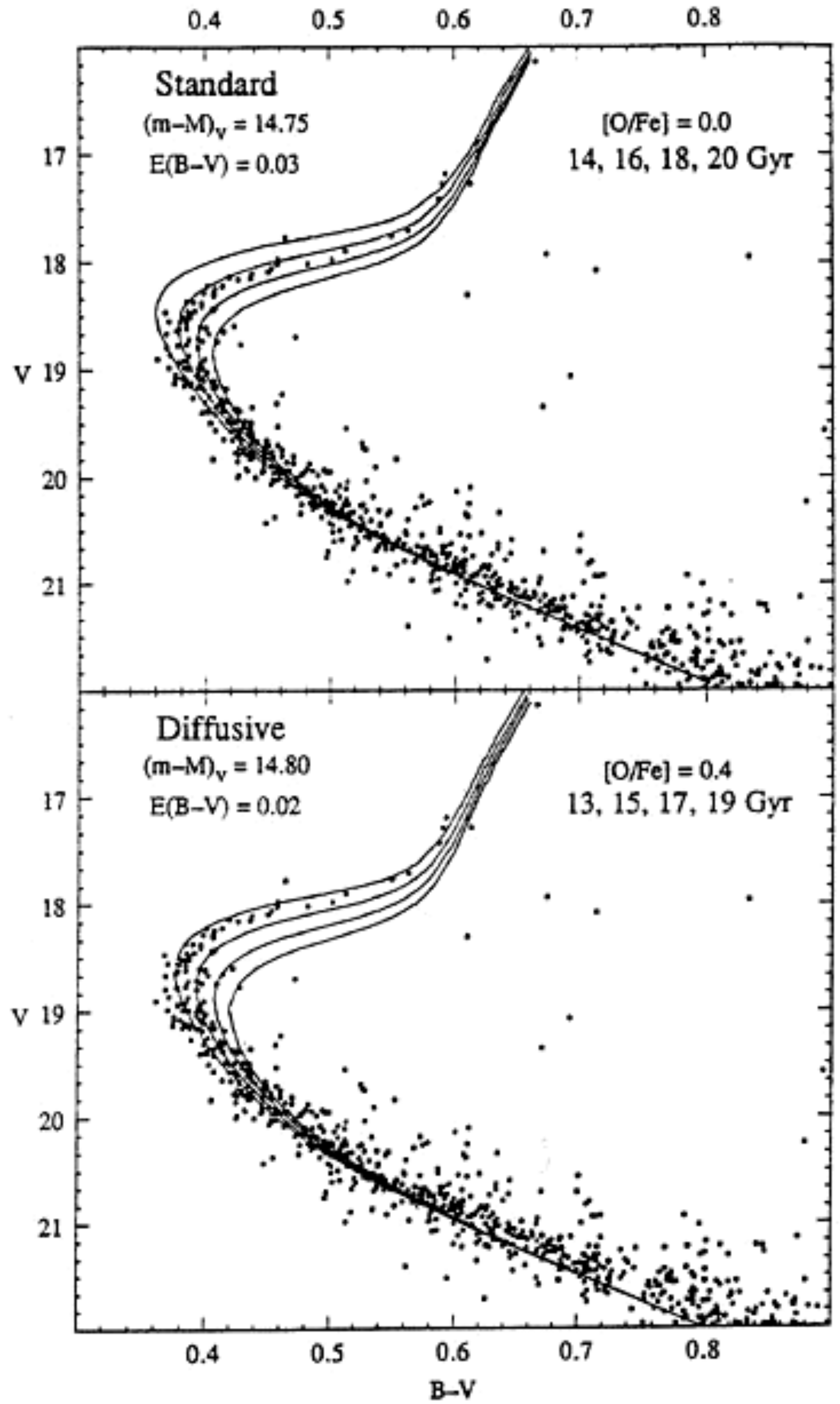
Ages of Globular Clusters

- We measure the age of a globular cluster by measuring the magnitude of the main sequence turnoff or the difference between that magnitude and the level of the horizontal branch, and comparing this to stellar evolutionary models of which estimate the surface temperature and luminosity of a stars as a function of time
- There are a fair number of uncertainties in these estimates, including errors in measuring the distances to the GCs and uncertainties in the isochrones used to derive ages (i.e., stellar evolution models)
- Inputs to stellar evolution models include: oxygen abundance [O/Fe], treatment of convection, He abundance, reaction rates of $^{14}N + p \rightarrow {}^{15}O + \gamma$, He diffusion, conversions from theoretical temperatures and luminosities to observed colors and magnitudes, and opacities; and especially ***distances***

Globular Cluster Ages

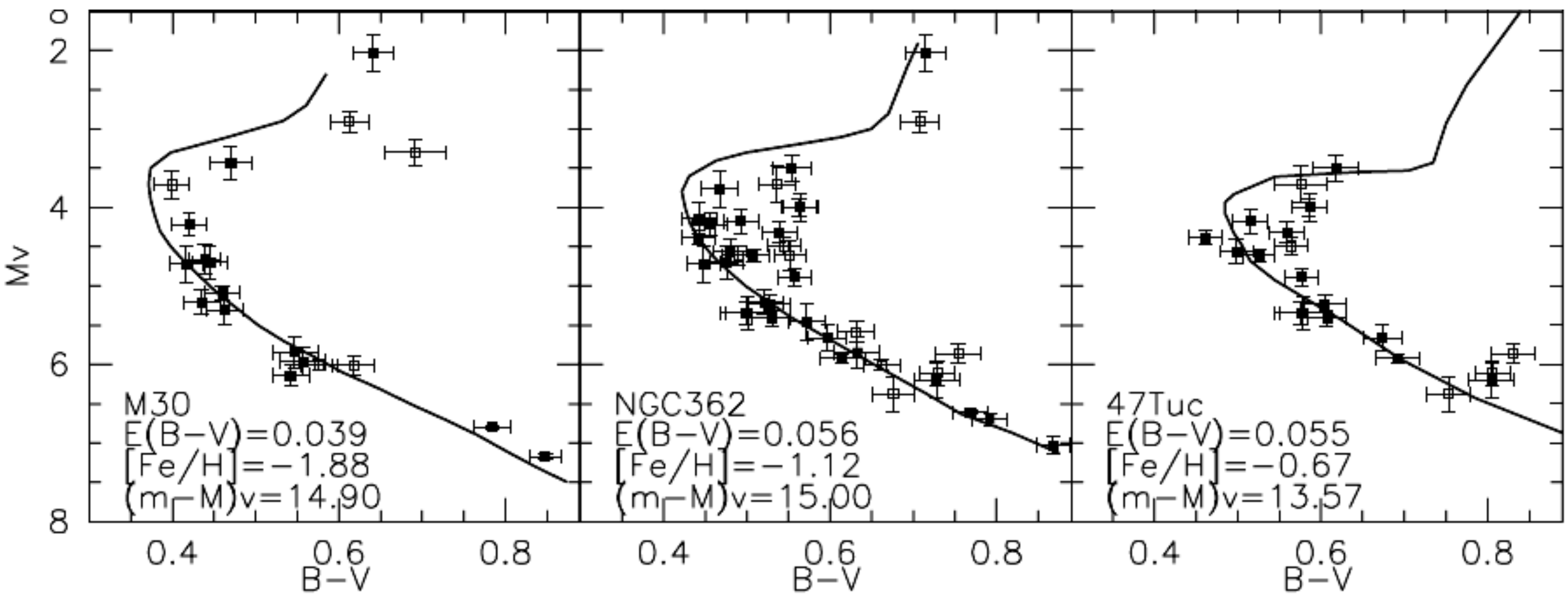


Schematic CMD and isochrones



Examples of actual model isochrones fits

Globular Cluster Ages From Hipparcos Calibrations of Their Main Sequences



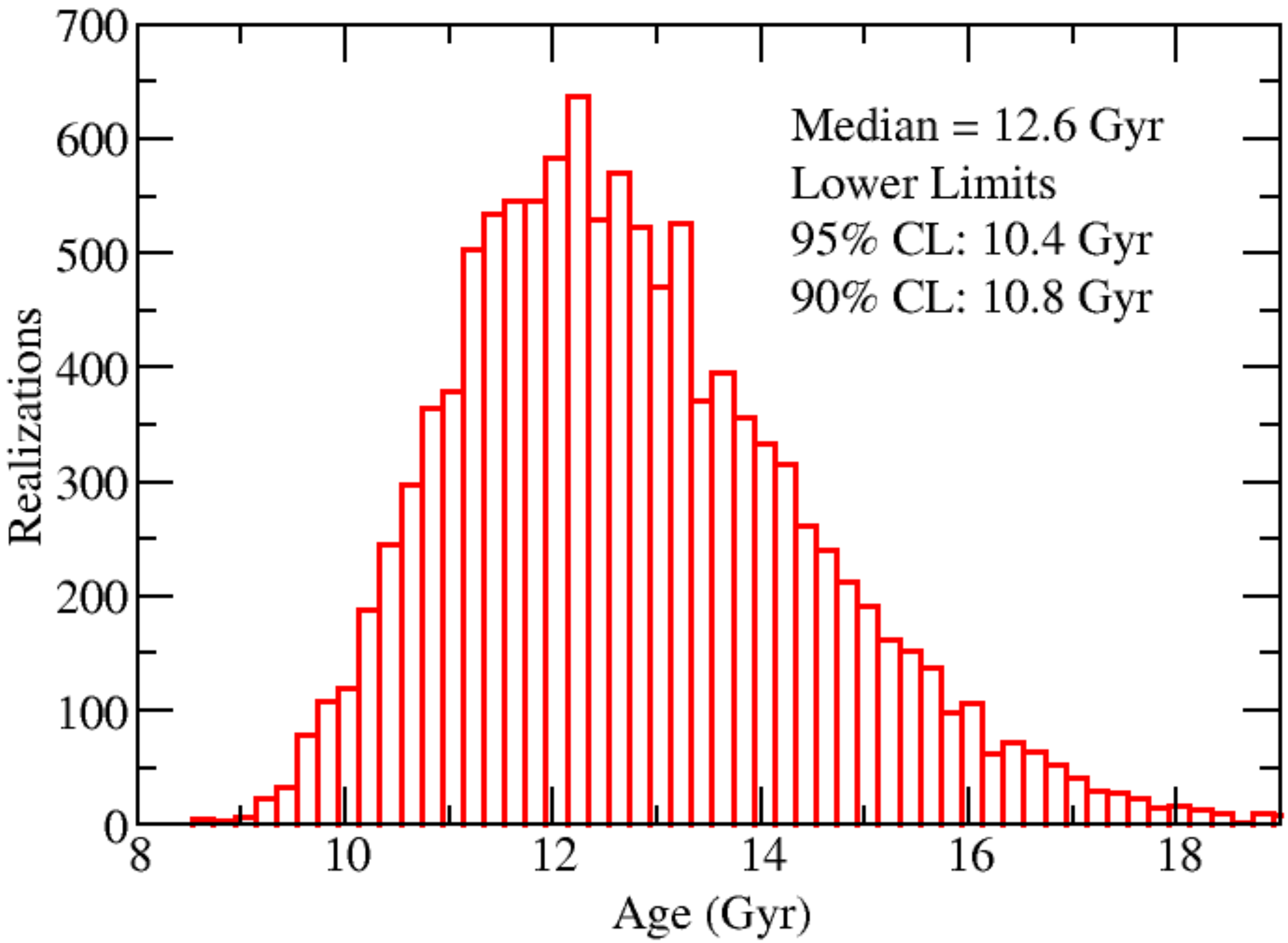
Examples of g.c. main sequence isochrone fits, for clusters of a different metallicity (Graton et al.)

The same group has published two slightly different estimates of the mean age of the oldest clusters:

$$\mathrm{Age} = 11.8^{+2.1}_{-2.5}\mathrm{Gyr}$$

$$\mathrm{Age} = 12.3^{+2.1}_{-2.5}\ \mathrm{Gyr}$$

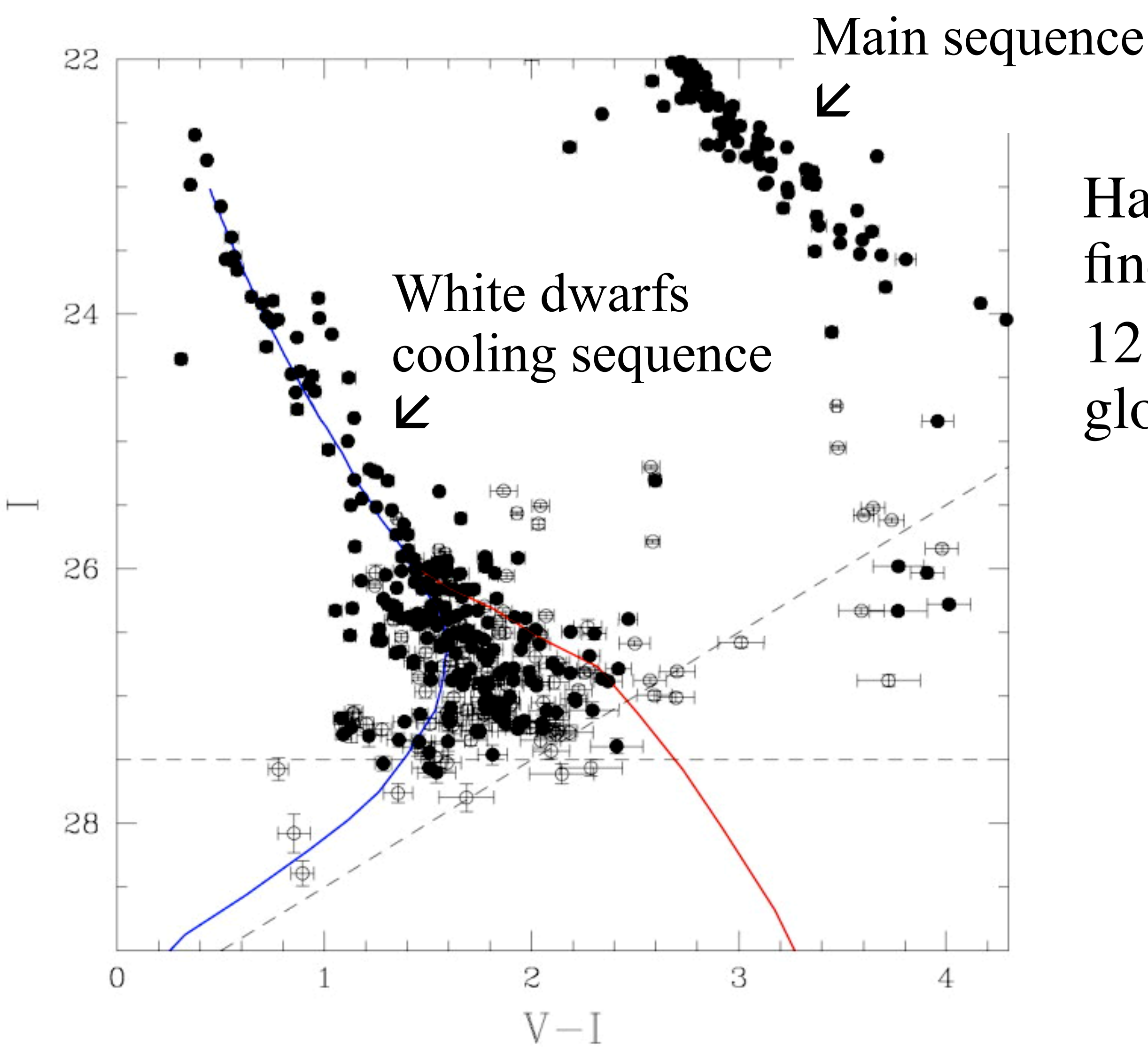
Range of possible GC ages (Chaboyer & Krauss 2003)



White Dwarf Cooling Curves

- White dwarfs are the end stage of stellar evolution for stars with initial masses < 8 $M_{\odot}$
- They are supported by electron degeneracy pressure (not fusion) and are slowly cooling and fading as they radiate
- We can use the luminosity of the faintest WDs in a cluster to estimate the cluster age by comparing the observed luminosities to theoretical cooling curves
- Theoretical curves are subject to uncertainties related to the core composition of white dwarfs, detailed radiative transfer calculations which are difficult at cool temperatures
- White dwarfs are faint so this is hard to do. Need deep HST observations
- Only been done for one globular cluster, consistent with the ages of GCs found from the main sequence turnoff luminosities, would be nice if there were more

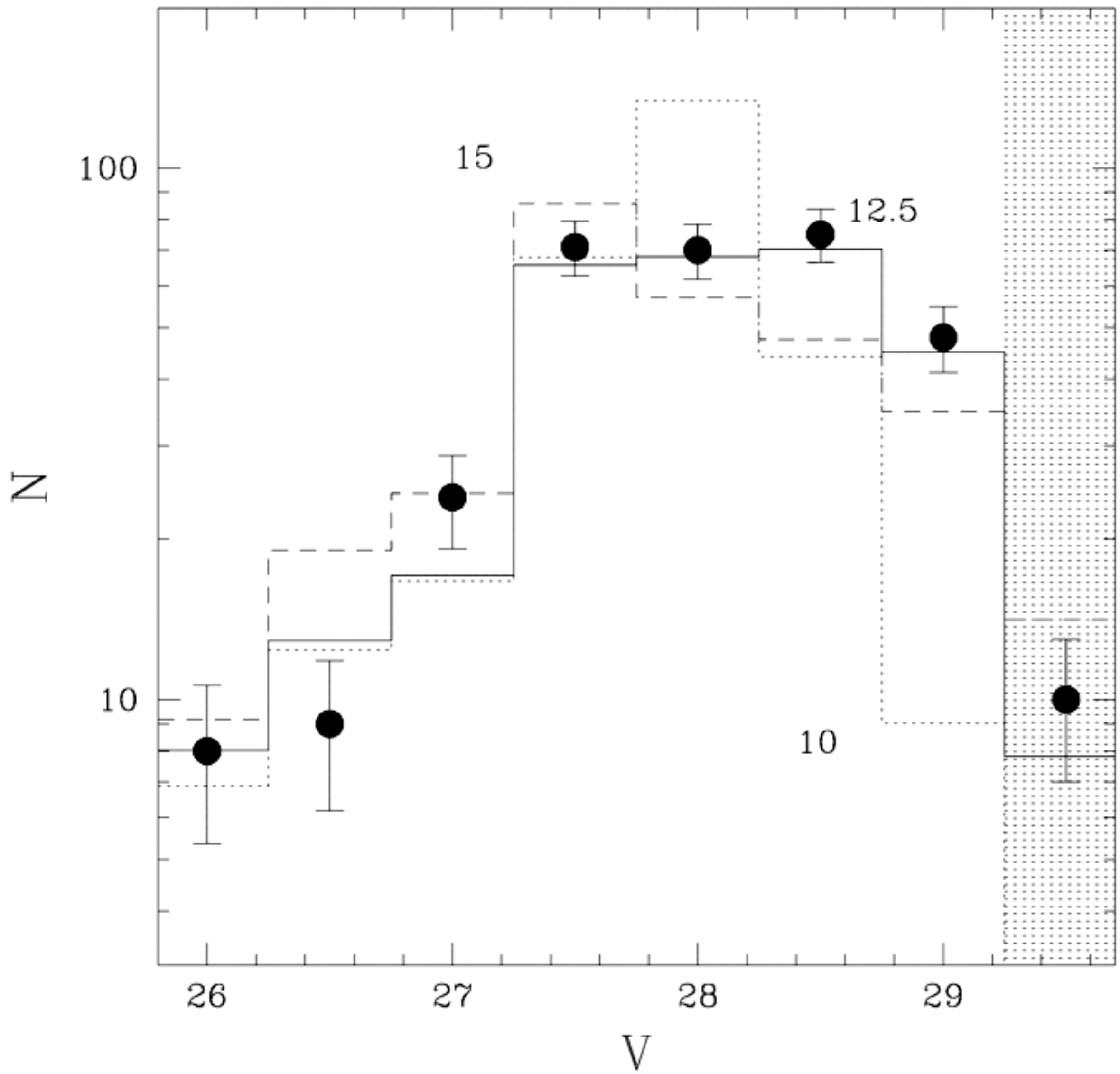
An Example: White Dwarf Sequence of M4



Hansen *et al*. (2002) find an age of 12.7 ± 0.7 Gyr for the globular cluster M4

Blue = hydrogen atmosphere models
Red = helium atmosphere models for a 0.6 $M_{\odot}$ WD

An Example: WD Luminosity Function of M4



Observed WD luminosity function compared to theoretical predictions for various ages from Hansen *et al.* (2002)

Nucleocosmochronology

- Can use the radioactive decay of elements to age date the oldest stars in the galaxy
- Has been done with ^{232}Th (half-life = 14 Gyr) and ^{238}U (half-life = 4.5 Gyr) and other elements
- Measuring the ratio of various elements provides an estimate of the age of the universe given theoretical predictions of the initial abundance ratio
- This is difficult because Th and U have weak spectral lines so this can only be done with stars with enhanced Th and U (requires large surveys for metal-poor stars) and unknown theoretical predictions for the production of r-process (rapid neutron capture) elements

Nucleocosmochronology:

An Example Isotope Ratios and Ages for a Single Star

CHRONOMETRIC AGE ESTIMATES FOR BD +17°3248

Chronometer Pair	Predicted	Observed	Age (Gyr)	Solar[a]	Lower Limit (Gyr)
Th/Eu	0.507	0.309	10.0	0.4615	8.2
Th/Ir	0.0909	0.03113	21.7	0.0646	14.8
Th/Pt	0.0234	0.0141	10.3	0.0323	16.8
Th/U	1.805	7.413	≥13.4	2.32	11.0
U/Ir	0.05036	0.0045	≥15.5	0.0369	13.5
U/Pt	0.013	0.0019	≥12.4	0.01846	14.6

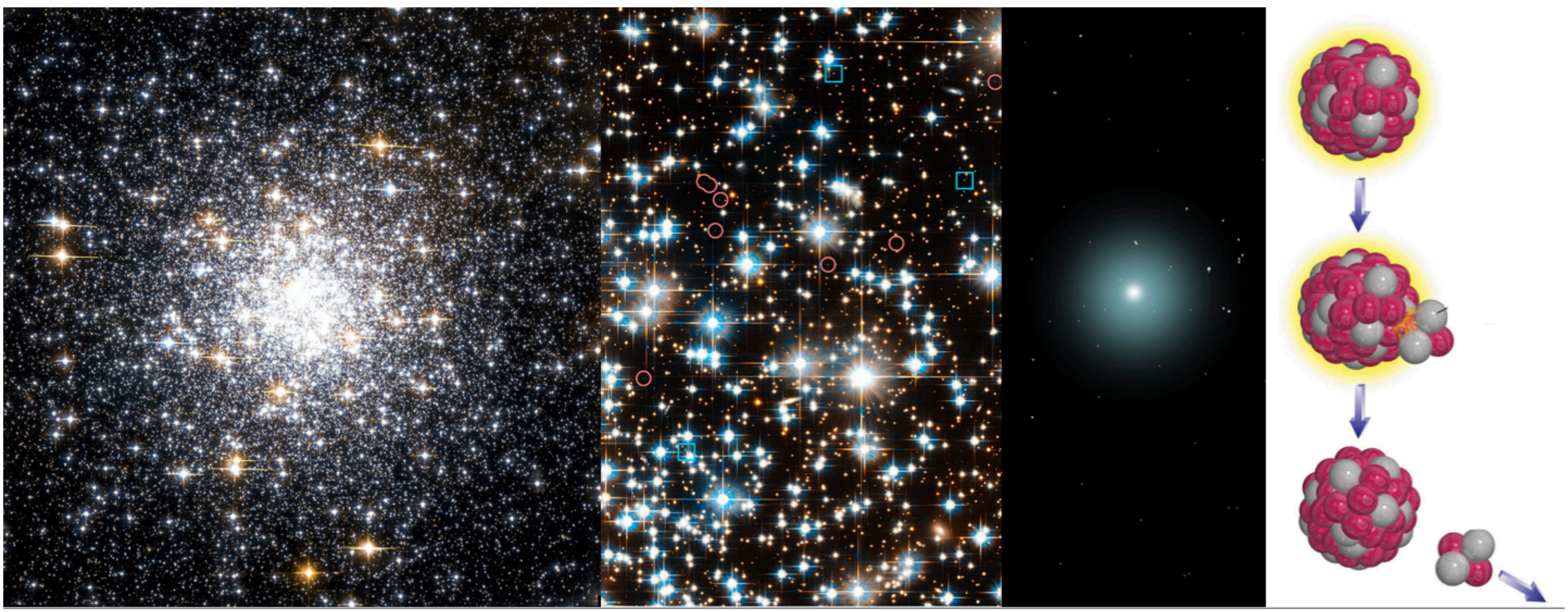
[a] From Burris et al. 2001.

(from Cowan *et al.* 2002)

Mean = 13.8 +/- 4, but note the spread!

The Age of the Universe

- Several different methods (different physics, different measurements) agree that the lower limit to the age of the universe is ~ 12 – 13 Gyr
- This is in an excellent agreement with the age determined form the cosmological tests (~ 13.7 Gyr)



Next:
Tests for the Expansion of the Universe