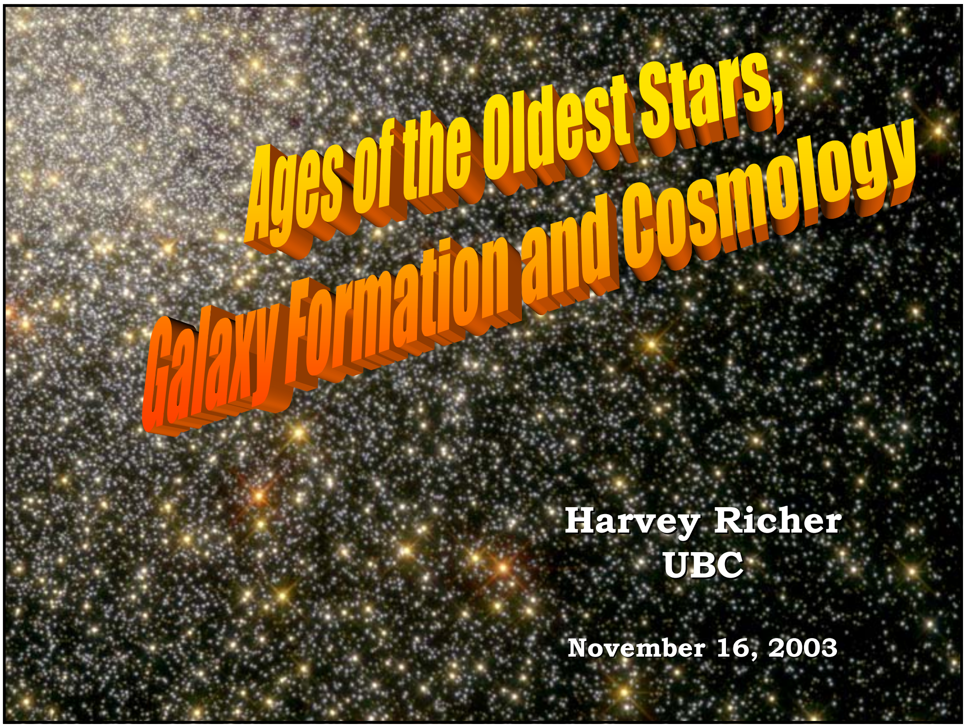
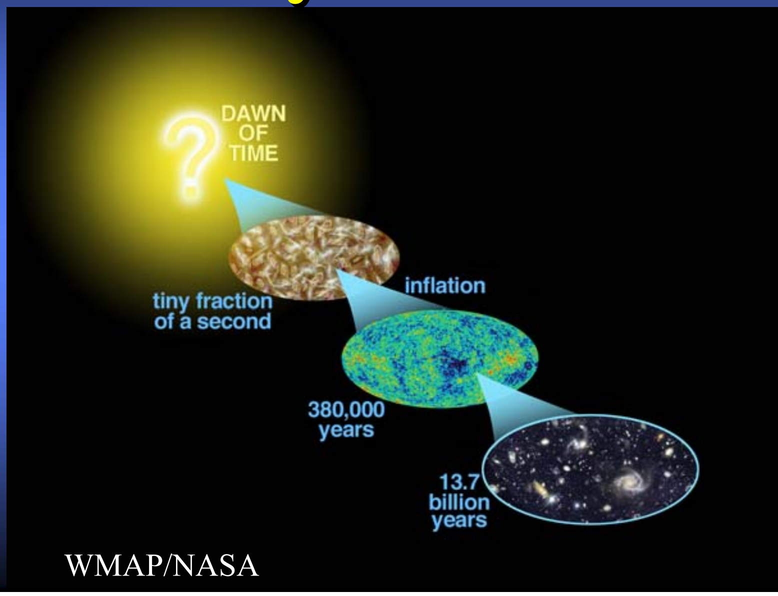


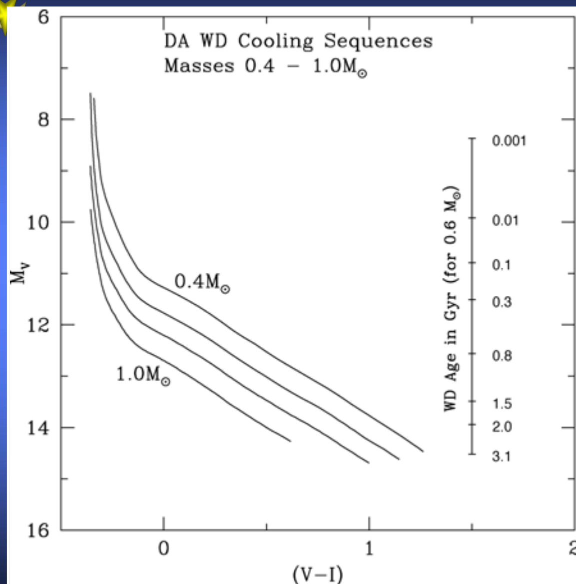
Outline

- WMAP and the Oldest Stars
- Prescription for a Precise White Dwarf Cooling Age of a Globular Cluster
- White Dwarfs and Ages
  Comparison with WMAP Age
  Formation of our Galaxy

Excessively Brief History of the Universe

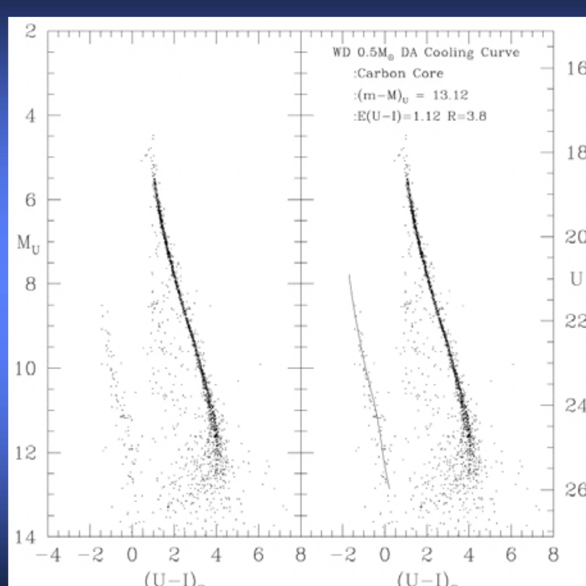


White Dwarf Models



WDs are
Good Clocks!

Models and Data

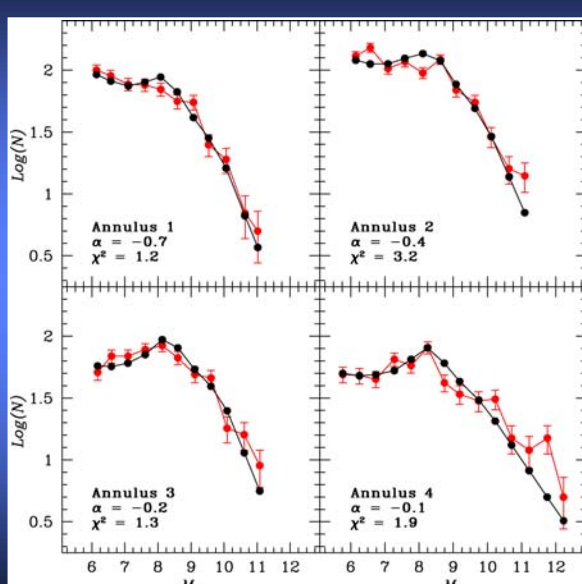


Richer et al 1997

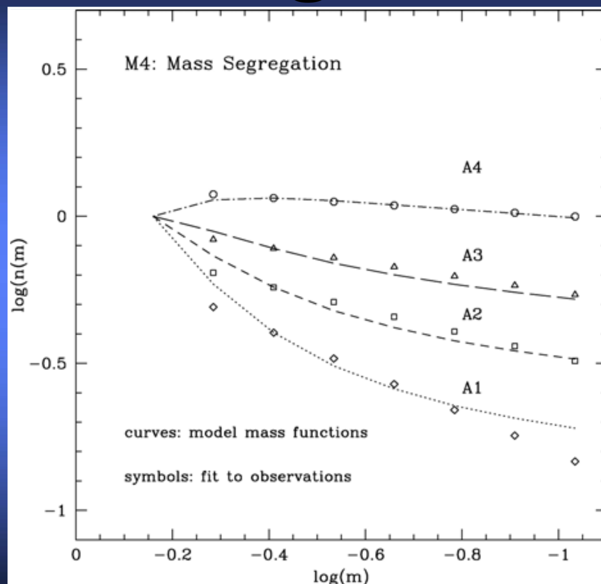
Prescription for a Precise WD Cooling Age

- Main Sequence Models
- Main Sequence Mass Function*
- WD Initial-Final Mass Relation*
- WD Cooling Models*
- Superb Data*

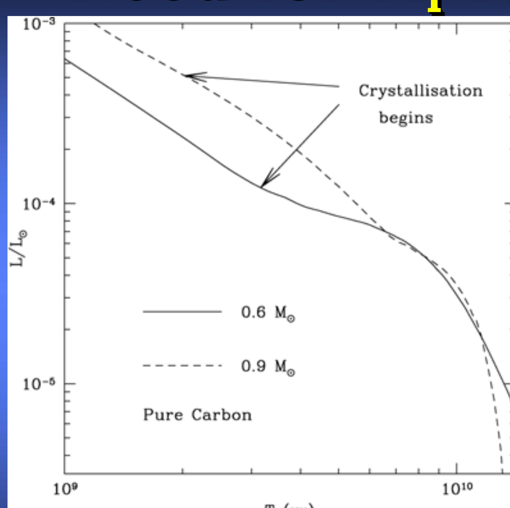
MFs with Radii



Modeling the MF

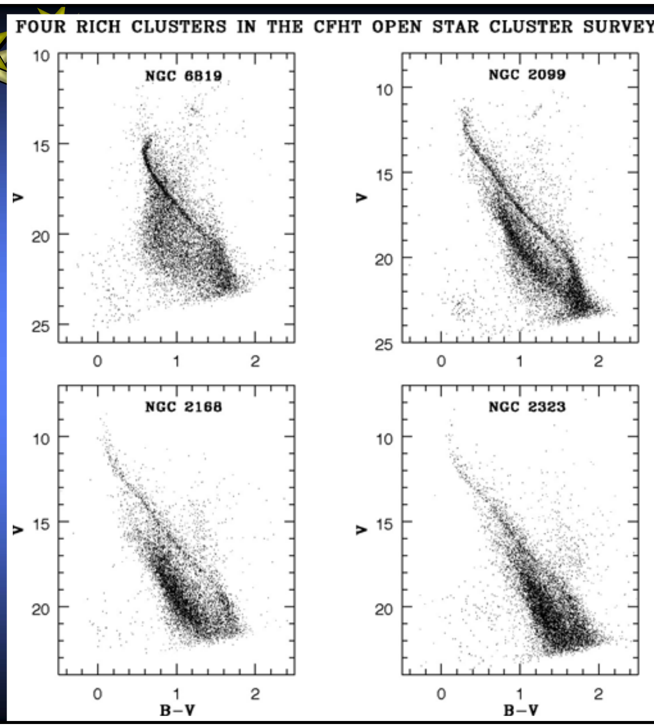


Need for M_i-M_f



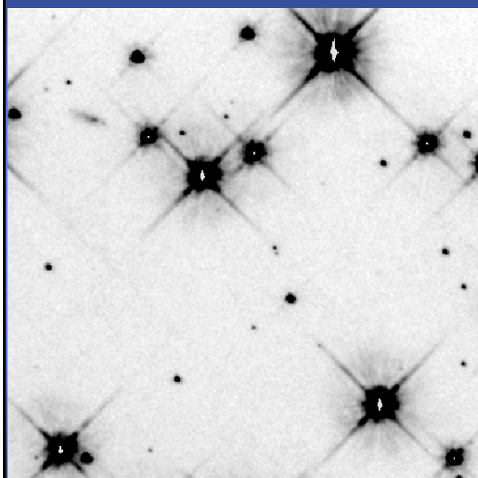
Hansen & Liebert 2004

- Massive WDs - more luminous early on - crystallize first cool more quickly
- Rate cooling flattens when molecules form-also latent heat released
- Cooling curves eventually cross

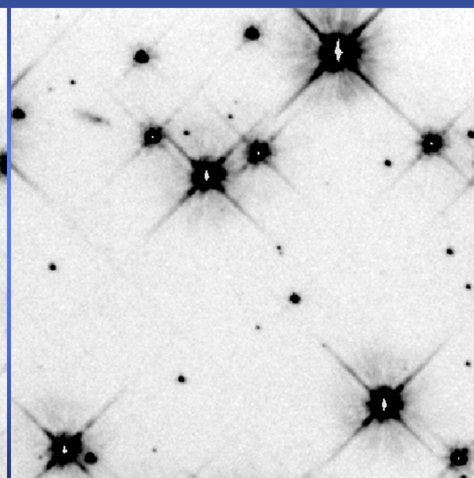


WD Initial-Final Mass Relation

M4 Images Over 6 Years

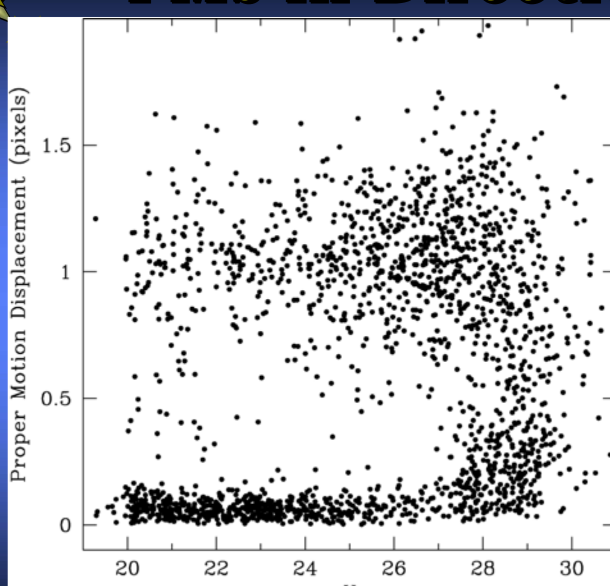


F555W (1995)



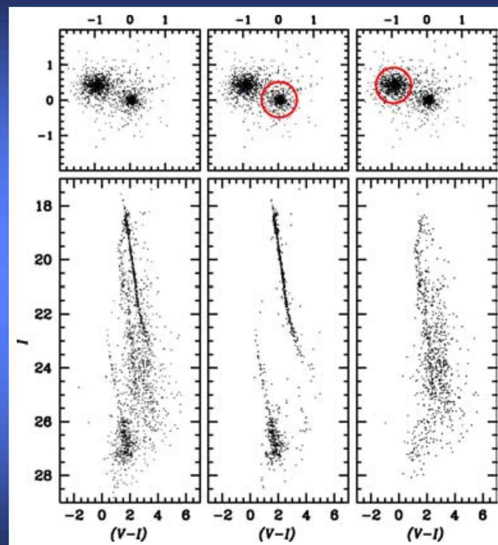
F555W (1995)

PMs in Direction M4

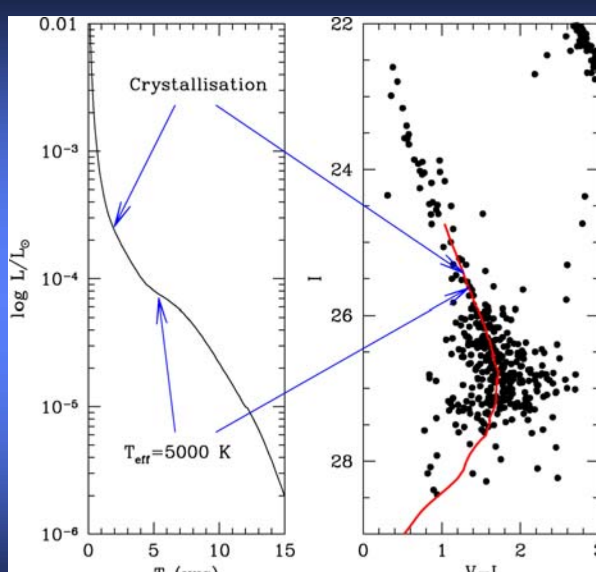


- Lower is M4
- Upper is Field
- Clean separation to V > 29

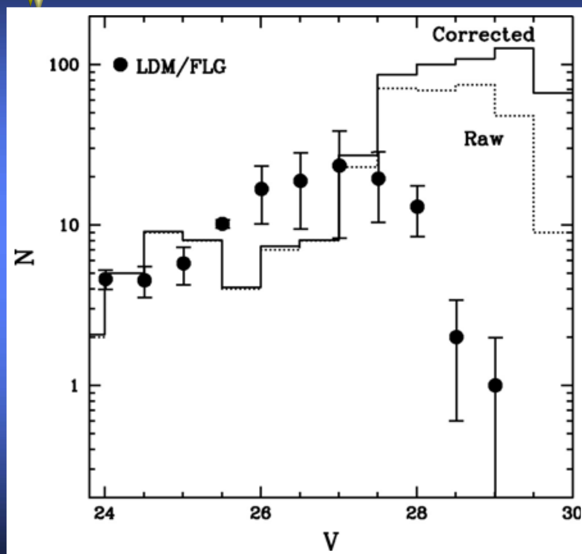
Messier 4 CMD



Richer et al. 2002

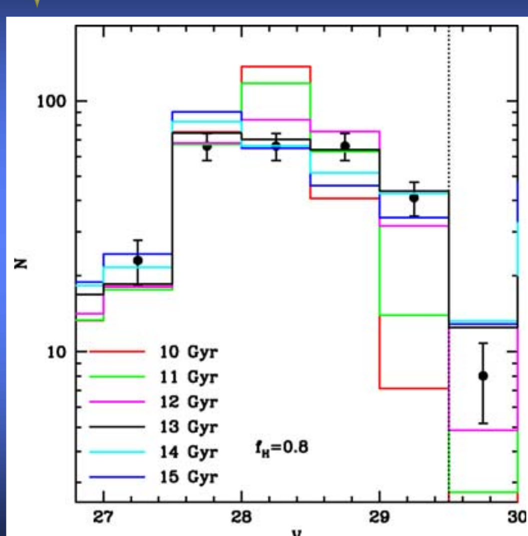


WD Luminosity Functions



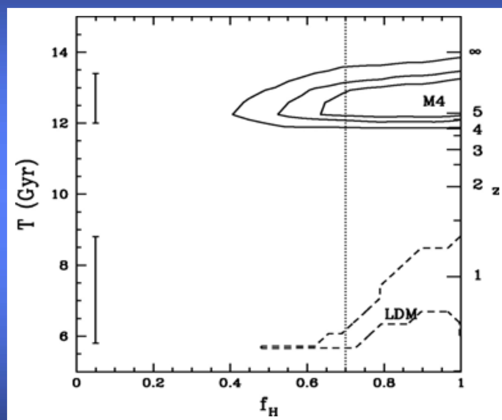
- Dots = disk
- Line = M4 (halo)
- M4 LF has fainter WDs
- M4 older than Galactic disk

WD Cooling Age of M4



- Derived Age 12.7 +/-0.35 Gyr (1σ – statistical only)
- Systematic errors? To come.

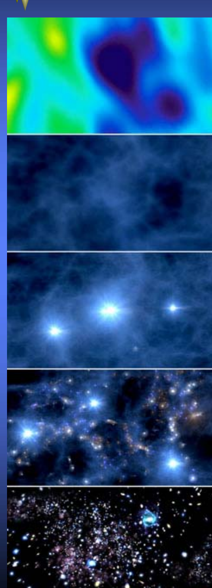
Ages, Cosmology and Galaxy Formation



- M4 (halo) age 12.7±0.35 Gyr
- Disk age 7.5±1.0 Gyr
- WMAP Age = 13.7±0.2 Gyr

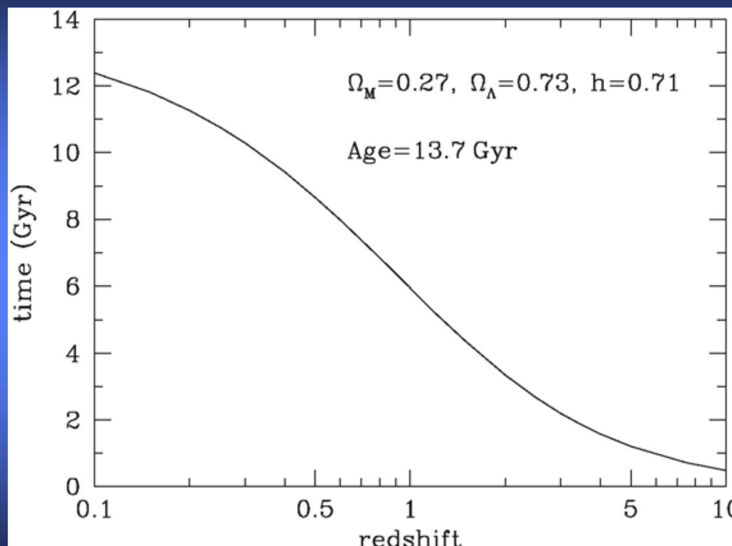
Hansen et al. 2002

Old Stars and WMAP

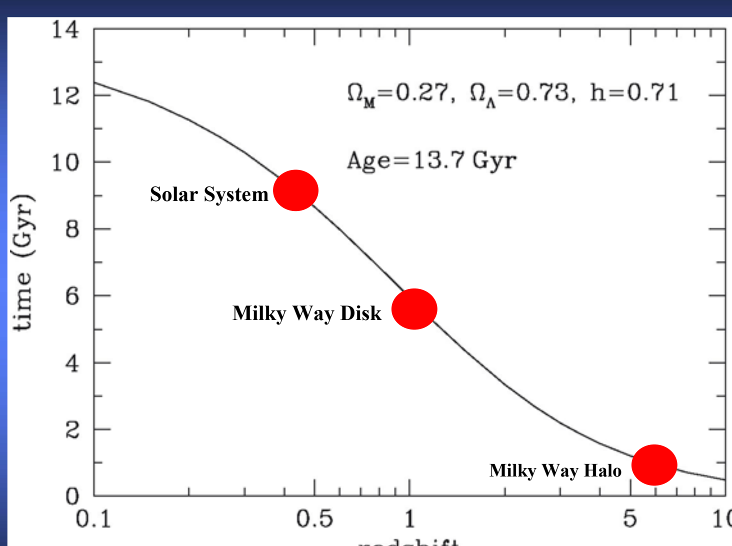


- Decoupling 13.7 Gyr
- Structure begins forming 13.7 Gyr
- First Stars? - reionization 13.5 Gyr (z=15-20)
- Globulars form - 12.7 Gyr (z=6)
- The Universe Today

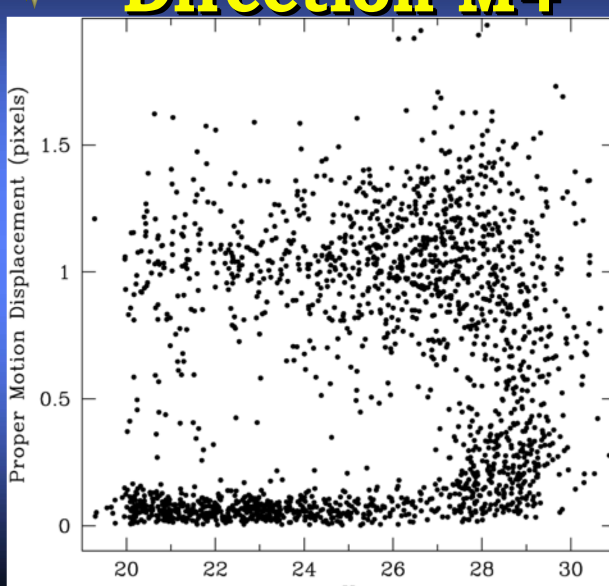
Time vs redshift in ΛCDM



Some Events in Universe

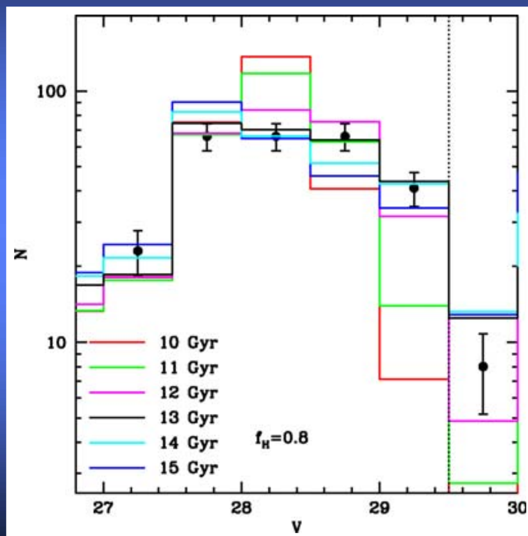


Proper Motions in Direction M4



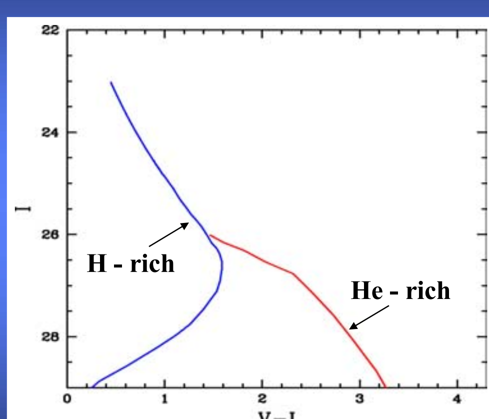
- Lower is M4
- Upper is Field
- Clean separation to V > 29

WD Cooling Age of M4



- Derived Age 12.7 +/-0.35 Gyr (1σ – statistical only)
- Systematic errors may add ~1 Gyr to error

Cooling Curves Old WDs



- Hook to the blue diagnostic old H-rich WDs
- Hook never observed in any stellar sample
- He WDs no hook

Stars – Basic Ideas

- For normal stars (Sun) $t_{dynamical} = \frac{R}{v_{free-fall}} \cong 40 \; minutes$
- By contrast $t_{thermal} = \frac{GM^2}{RL} \cong 3 \times 10^7 \; years$
- Therefore, normal stars are very close to hydrostatic equilibrium $\frac{dP}{dr} = -\frac{\rho G M(r)}{r^2}$
- Normal stars $b = b^{\text{[illegible]}} + b^{\text{[illegible]}}$
- White dwarfs $P = P_{degenerate \; electrons}$

Degeneracy Pressure

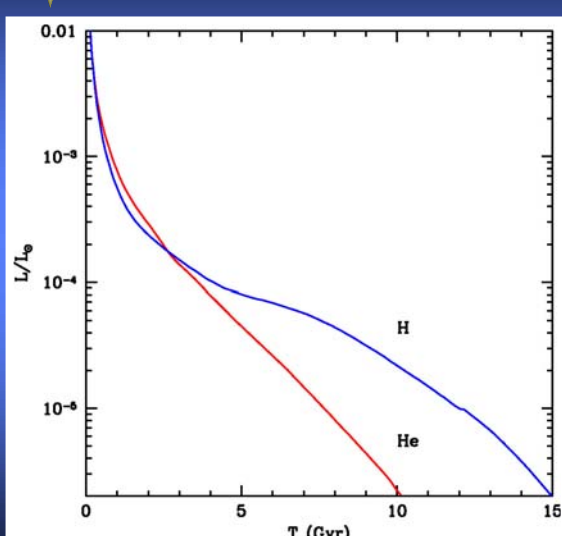
- When matter is compressed, the Uncertainty Principle $\Delta p \cdot \Delta x \cong \hbar$ comes into play
- There is zero point energy $E_{\deg} = \frac{p^2}{2m} \cong \frac{\hbar^2}{2m\Delta x^2}$
- With $P_{\deg} = \frac{E_{\deg}}{V}$ we derive $P_{\deg} \propto \rho^{5/3}$
- This leads to $M = \left(\frac{\hbar^2}{m_e m_p^{5/3} G} \right) R^{-3}$
- More massive stars are smaller, for 1 solar mass $R \cong 6 \times 10^3 \, km \;\; (Earth)$

Cooling of white dwarfs

- Heat content of core $C_V = \frac{3}{2}\left(\frac{n_i k}{\rho}\right)$
- Luminosity of the core $L_C = MC_V \frac{dT}{dt}$
- This leads to $T \propto t^{-2/5}$

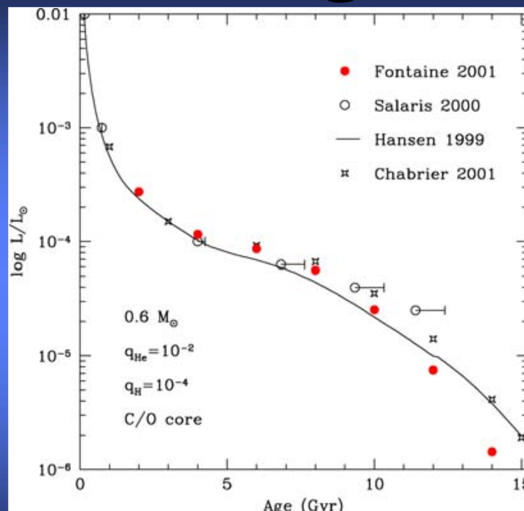
  or $L \propto t^{-7/5}$
- White dwarfs cool with time - a clock!

Cooling Rate WDs



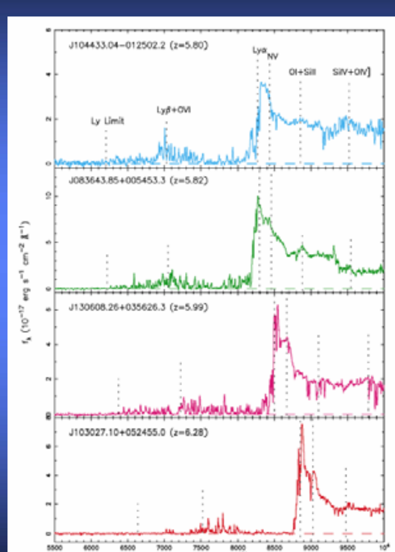
- He WDs cool rapidly
- H WDs cool slowly
- After ~10 Gyr do not expect to see He WDs
- In field 70% H

WD Cooling Models



Hansen & Liebert 2004

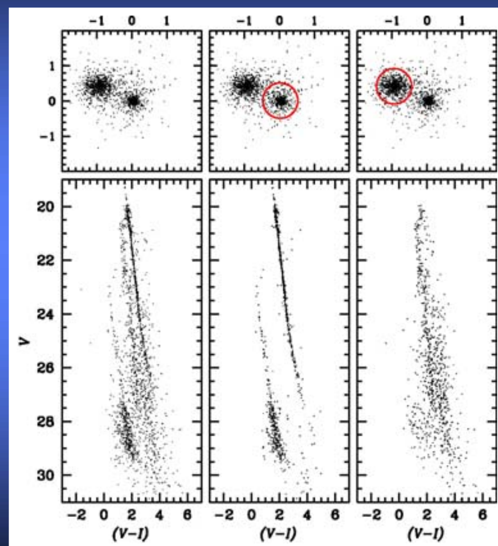
High z QSO Spectra



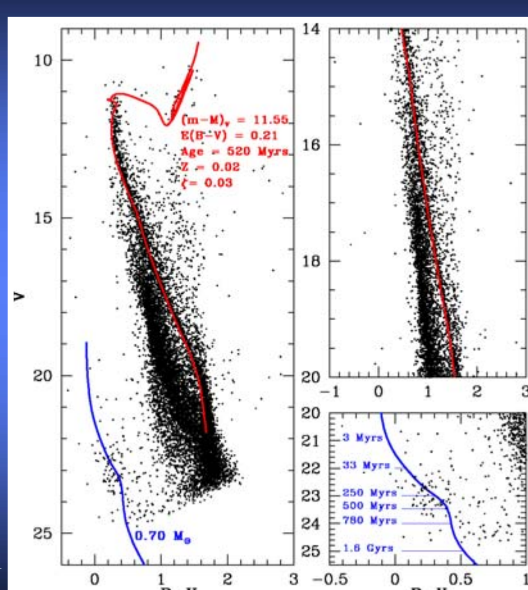
Becker et al. 2001

- Gunn-Peterson trough near z~6
- Suggests approaching reionization z~6 (cf with WMAP z=15-20)
- Early star formation and reionization are complex

M4 CMD



CMDs for NGC 2099



Kalirai et al. 2001