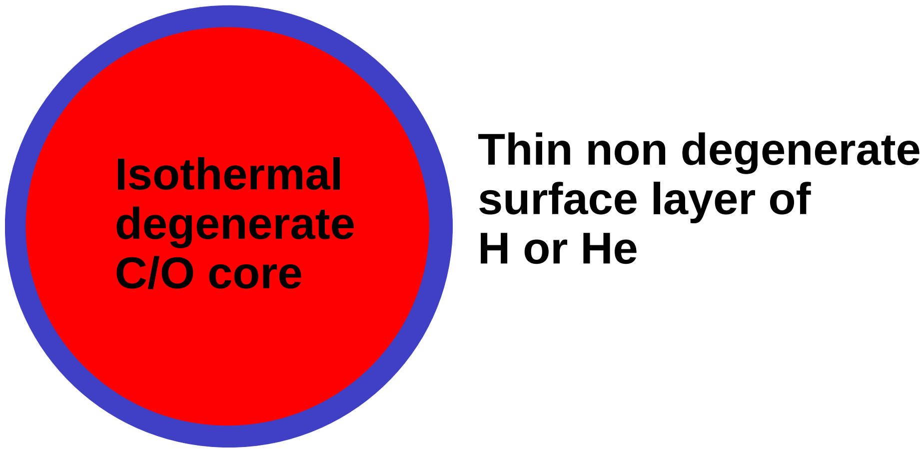
White dwarf cooling



Present temperature is determined by,

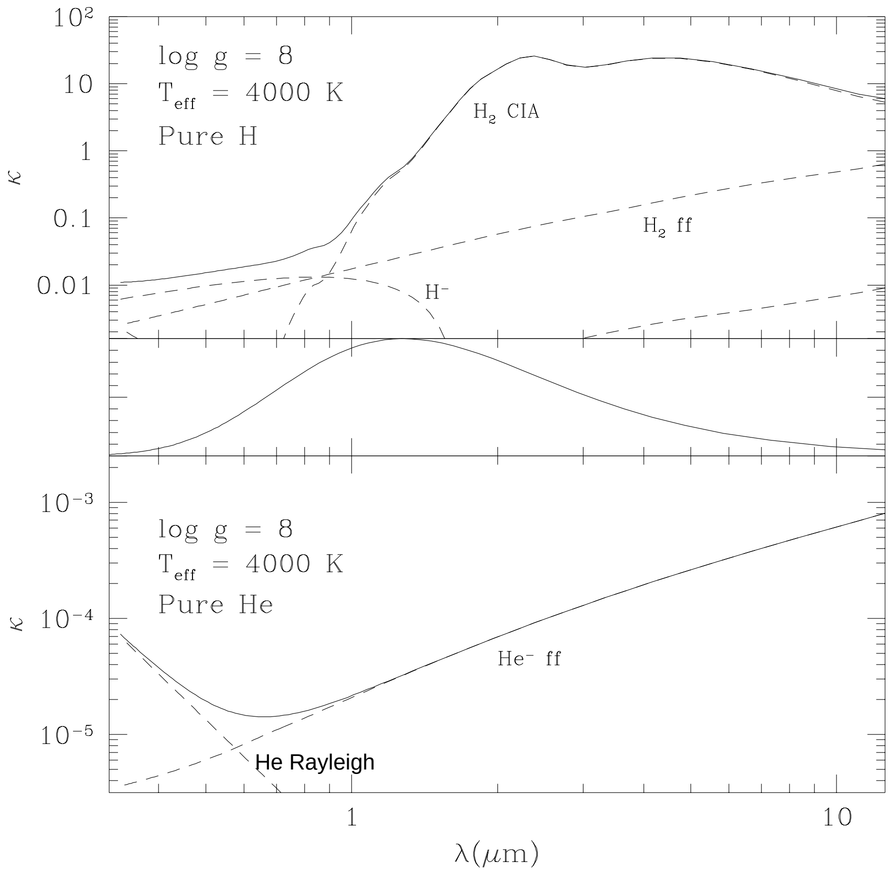
- The internal energy reservior in the degnerate core. Main complications:
  - (i) Possibility of crystallization.
  - (ii) Possibility of separation of the carbon and oxygen.
- The rate at which energy leaks out through the thermal blanket of the atmosphere. Depends upon the opacity, which will be dominated by molecules for the oldest white dwarfs with $T_e <$ 5000 K.

As shown in the problem, the exact initial conditions (ie $T(t = 0)$) don't matter – most of the time is spent at $T \sim T_{\mathrm{now}}$.

Hence, the coolest known white dwarf + cooling theory provides a clock for measuring the age of a stellar population (e.g. Winget et al., 1987, ApJ, 315, L77).

Observational appearance

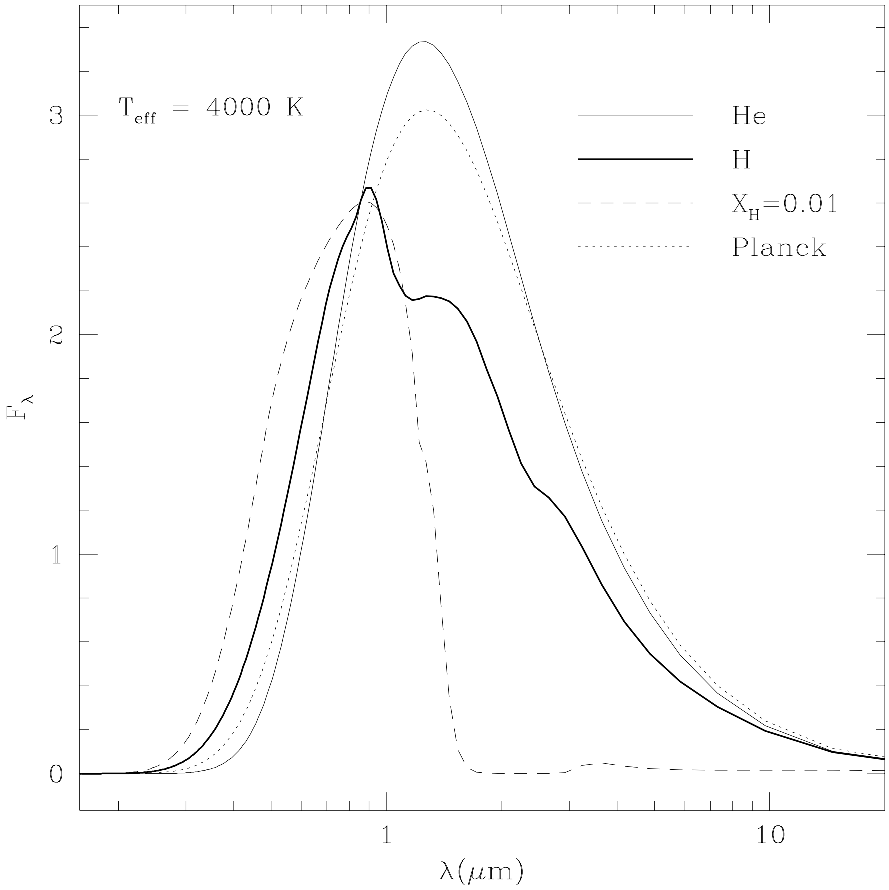
Molecular hydrogen produces a strongly frequency dependent opacity in the near-IR due to collisions exciting rotational / vibrational transitions.



(figure from Hansen, 1999, ApJ, 520, 680). At same T and P, opacity in a He atmosphere is much lower $\rightarrow$ photosphere will lie at higher pressure for He.

Expect all heavier elements to have settled out.

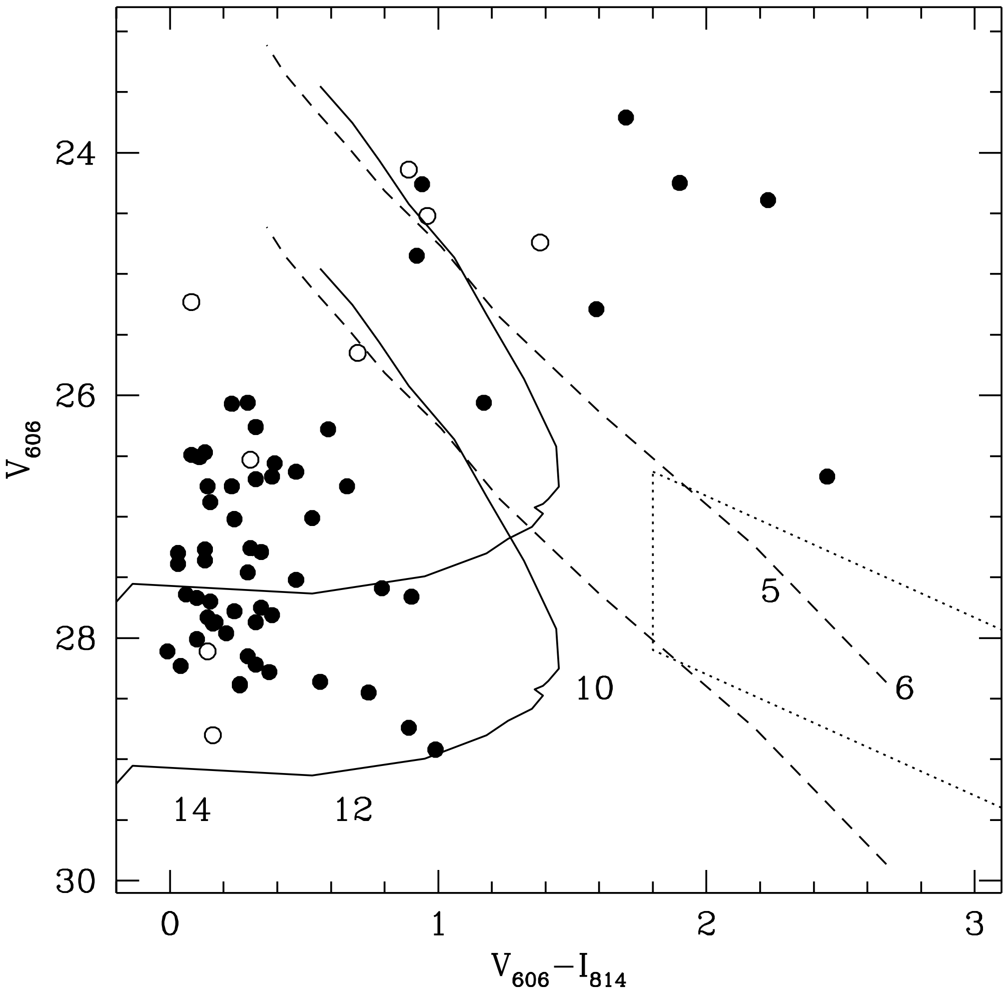
Frequency-dependence of the opacity $\rightarrow$ large departures from blackbody spectra for H atmosphere WDs at low effective temperature.



$\rightarrow$ a cooling WD with a hydrogen atmosphere can become bluer as it cools.

Also more flux escaping in the visible, so easier to detect in optical wavebands.

Tracks in color-magnitude diagram,

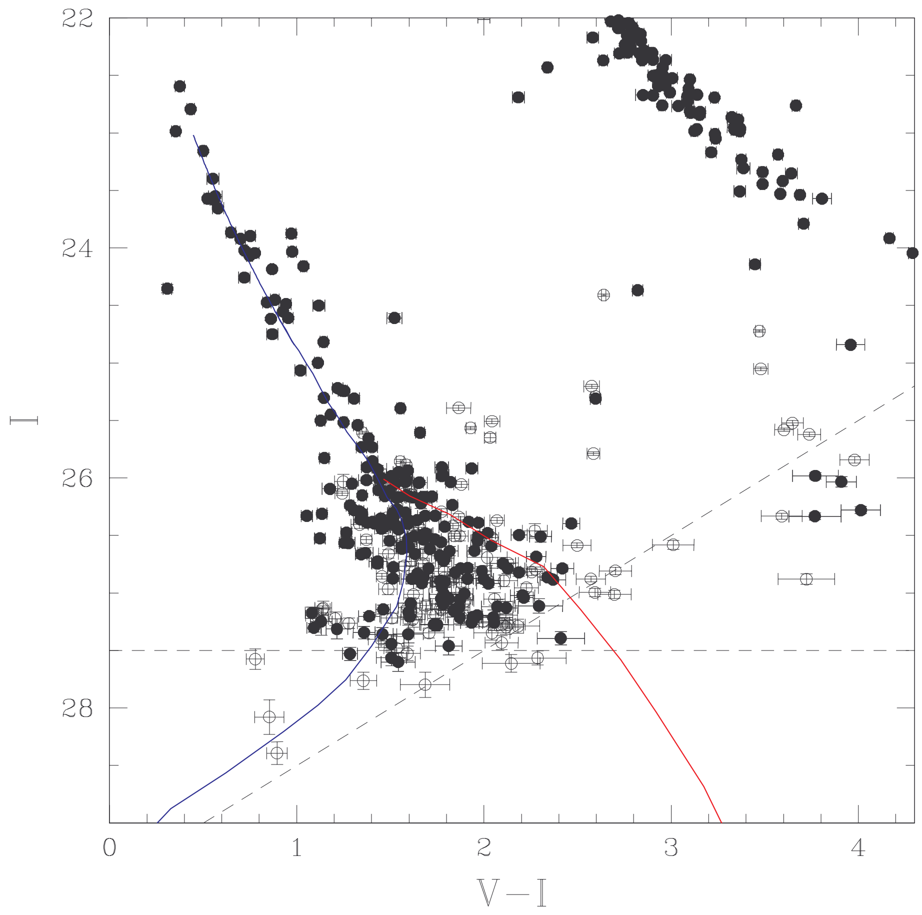


...at an assumed distance 1 kpc or 2 kpc. Note:

- He atmosphere WDs are predicted to be unobservably faint at 10 Gyr.
- H atmosphere WDs may be observable at modest distances in the halo or in globular clusters at these ages.

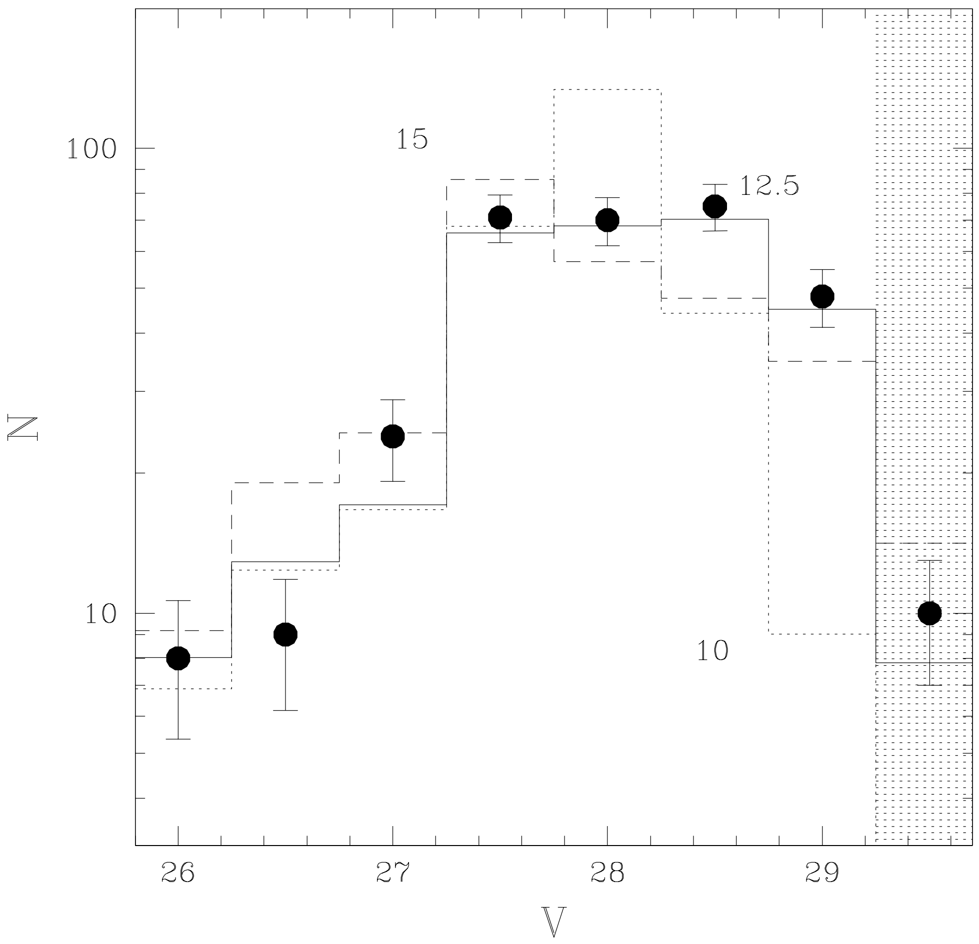
White dwarf sequence in M4

Deep HST observation of the globular cluster M4 over several epochs (Hansen et al., 2002, ApJ, 574, L155).



- Faintest objects ∼ 2.5 mag fainter than peak of local WD luminosity function → older population.
- Sharp peak in numbers at $V \sim 27$ – indicative of a burst of star formation in the cluster.

Age estimate from cooling models:

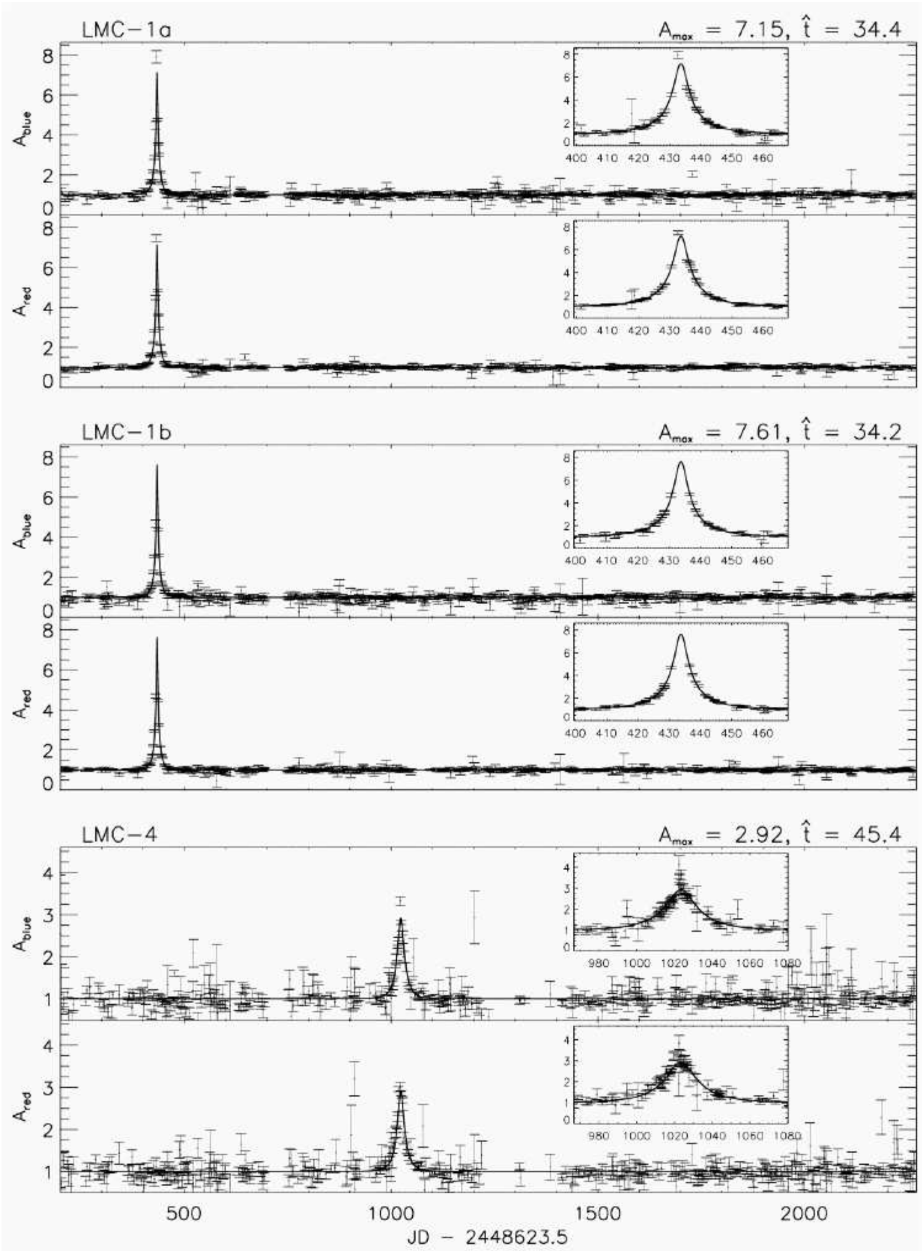


Consistent with a cluster age (including the main sequence lifetime) of 12.7 ± 0.7 Gyr (with 2σ errors).

Consistent with ages estimated for globular clusters using location of main sequence turnoff, but older by at least 3 Gyr than the disk dated using identical WD models.

A baryonic component to the Galactic halo?

MACHO experiment observed ~ 15 microlensing events towards the LMC (monitoring 12×10^6 stars for 6 yr).



Microlensing timescale is (Paczynski 1986),

$$t_0 = \frac{R_0}{v}$$

where R_0 is the Einstein ring radius and v is the lens velocity.

$$R_0 = \frac{2}{c}\sqrt{\frac{GMD_lD_{ls}}{D_s}}$$

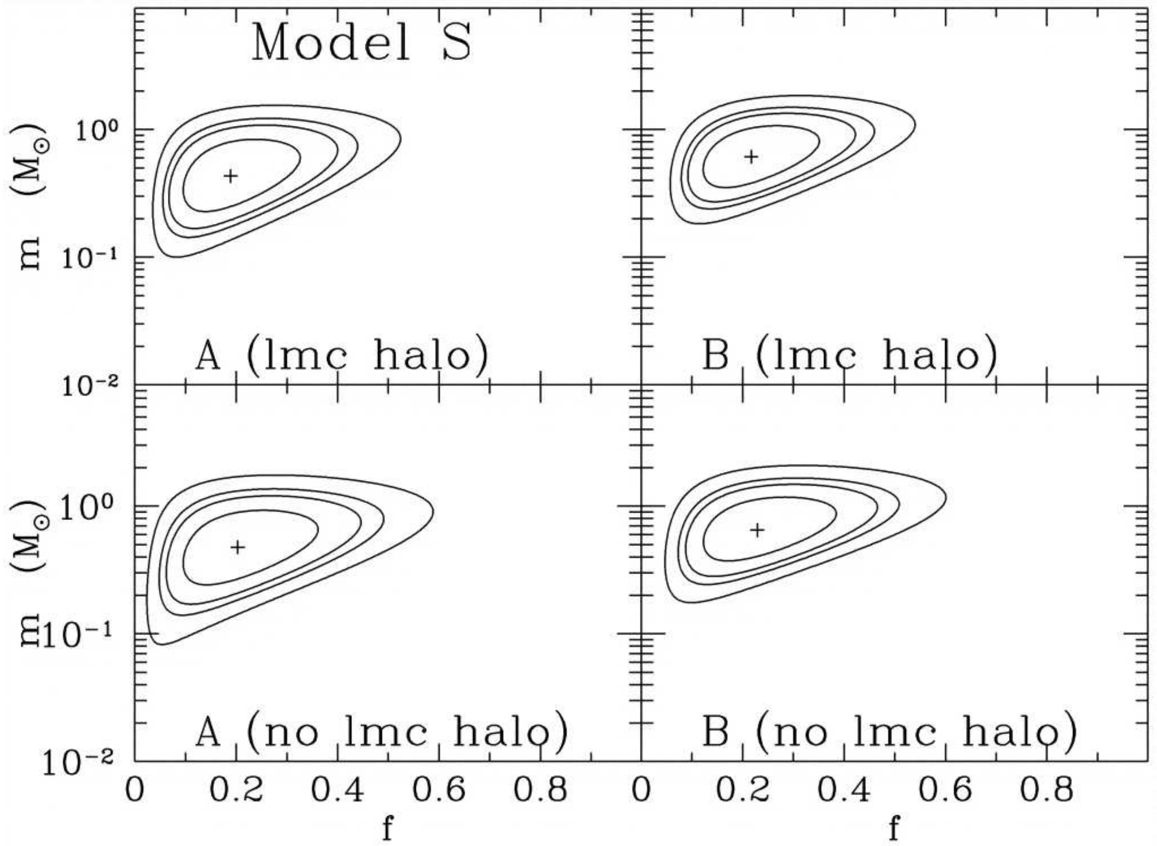
where D_l is the distance to the lens, D_s the distance to the source, and D_{ls} the lens-source distance.

Timescale $t_0 \propto \sqrt{M}/v$ does not specify mass uniquely. Events seen towards LMC could be,

- Compact objects in the halo of the Galaxy.
- Stars in the LMC itself.

Detailed model of the LMC / Milky Way required to try and distinguish between these possibilities.

Alcock et al. (2000) favor the halo interpretation, and obtain constraints on the mass of the lenses and the the fraction of the halo mass they represent:



Preferred mass is $\approx 0.5\ M_\odot$ – white dwarfs from a pre-galactic epoch of star formation?

Claims that a population of halo white dwarfs have been detected locally remain controversial (Oppenheimer et al 2001).

Indirect constraints

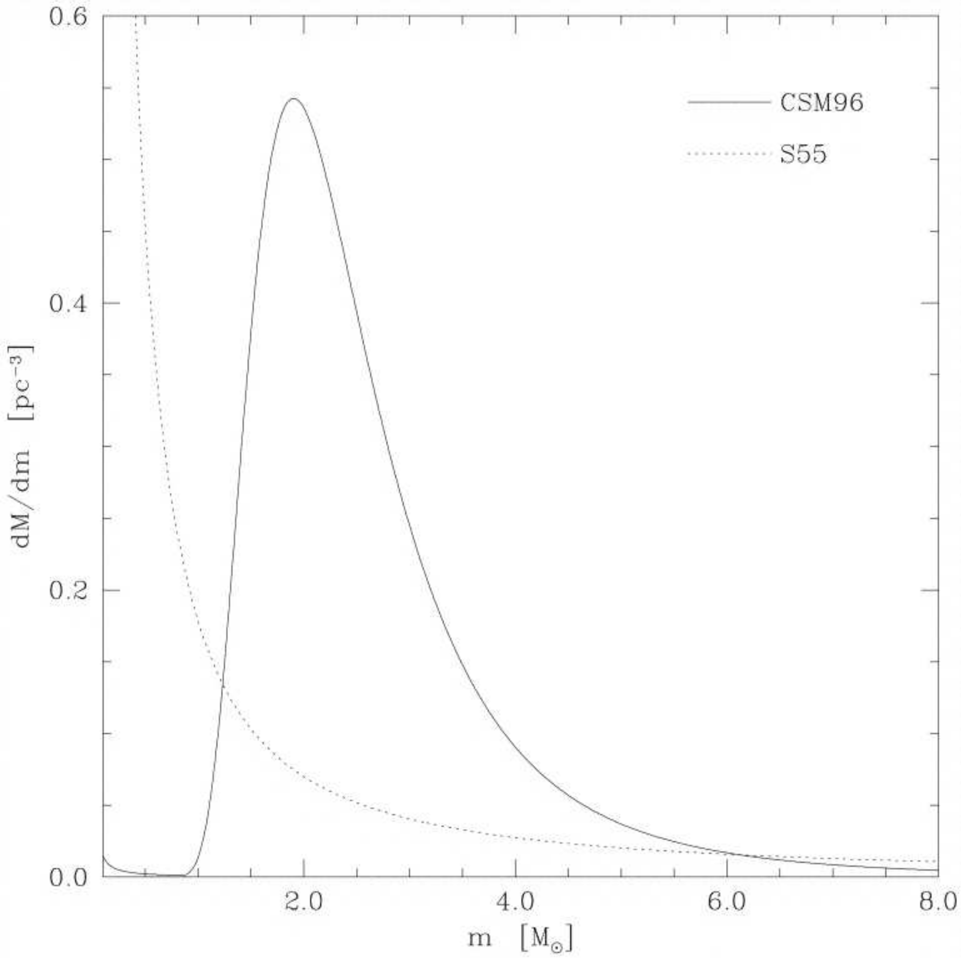
If the MACHO detections are white dwarfs, implies a large population of halo stars at early epochs. Can place constraints on this from,

- Lack of faint stars in the Galactic halo $\rightarrow$ initial IMF cannot have been rich in low mass stars that would still be on the main sequence today.
- Halo light in external galaxies.
- Chemical enrichment arguments.

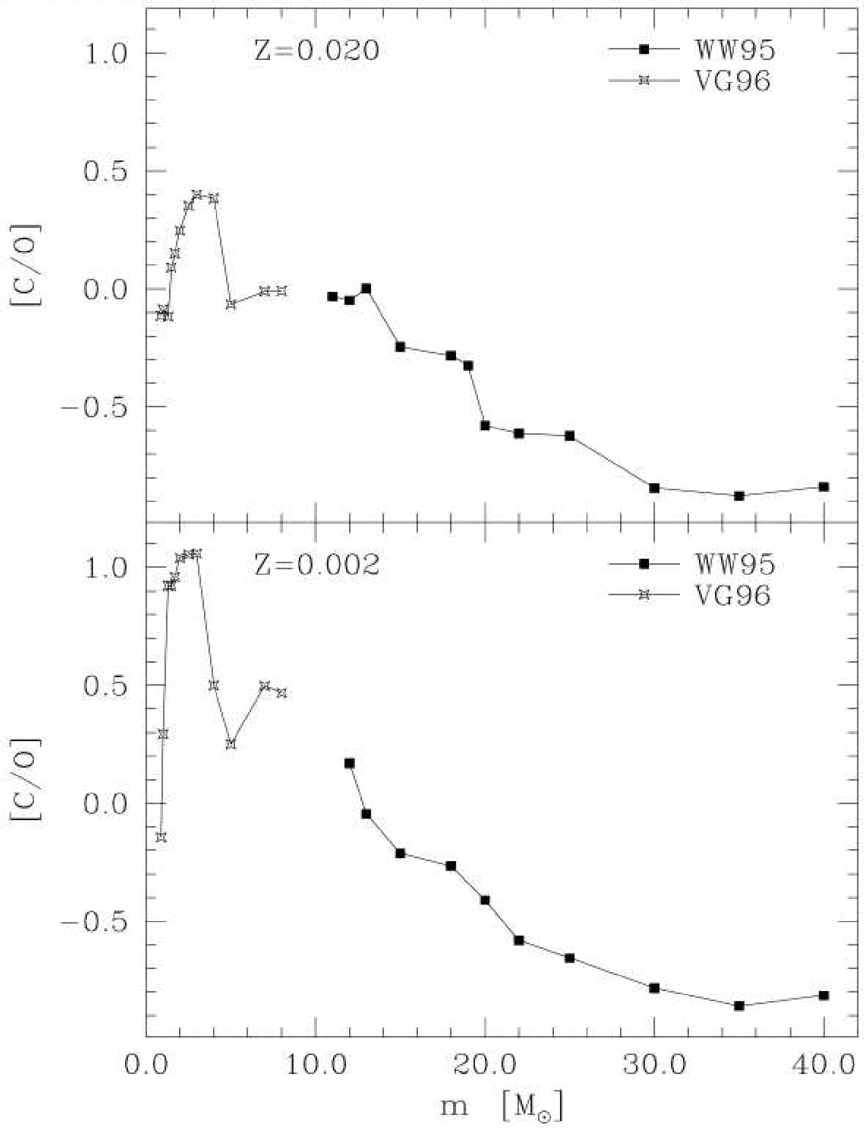
Enrichment argument (eg Gibson & Mould 1997):

- An ordinary IMF produces too high an abundance of heavy elements.
- An IMF chosen to maximise the production of white dwarfs produces a ratio of carbon to oxygen inconsistent with the abundances of halo dwarfs.

eg Assume an IMF peaked at $2M_{\odot}$,



This gives a predicted yield,



Compared to an observed value [C/O] = -0.5. Possible caveats,

- $Z = 0$ stars are different.
- Excess metals are blown away in a (Galactic) wind.