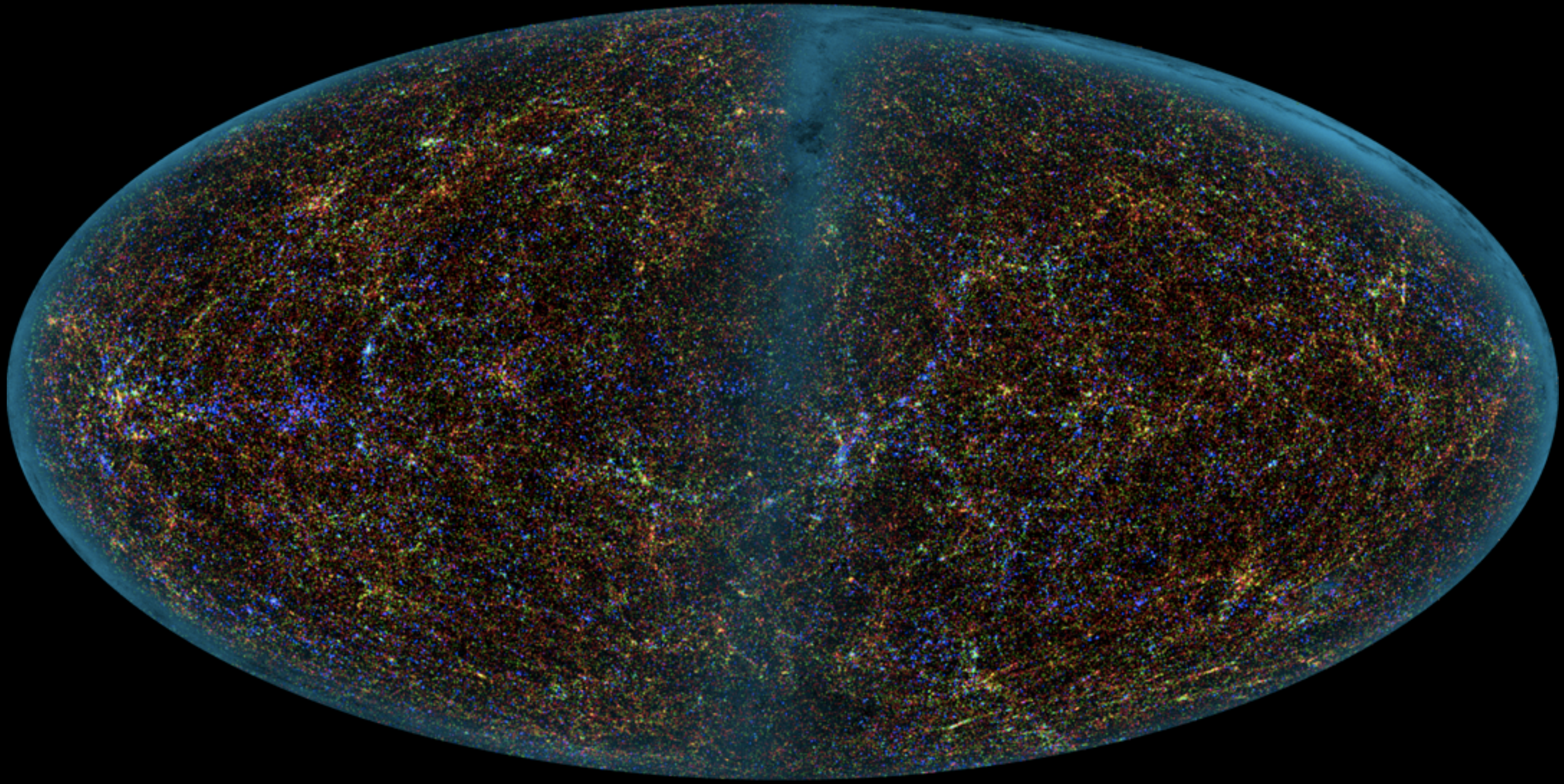
# Cosmology

## and Large Scale Structure



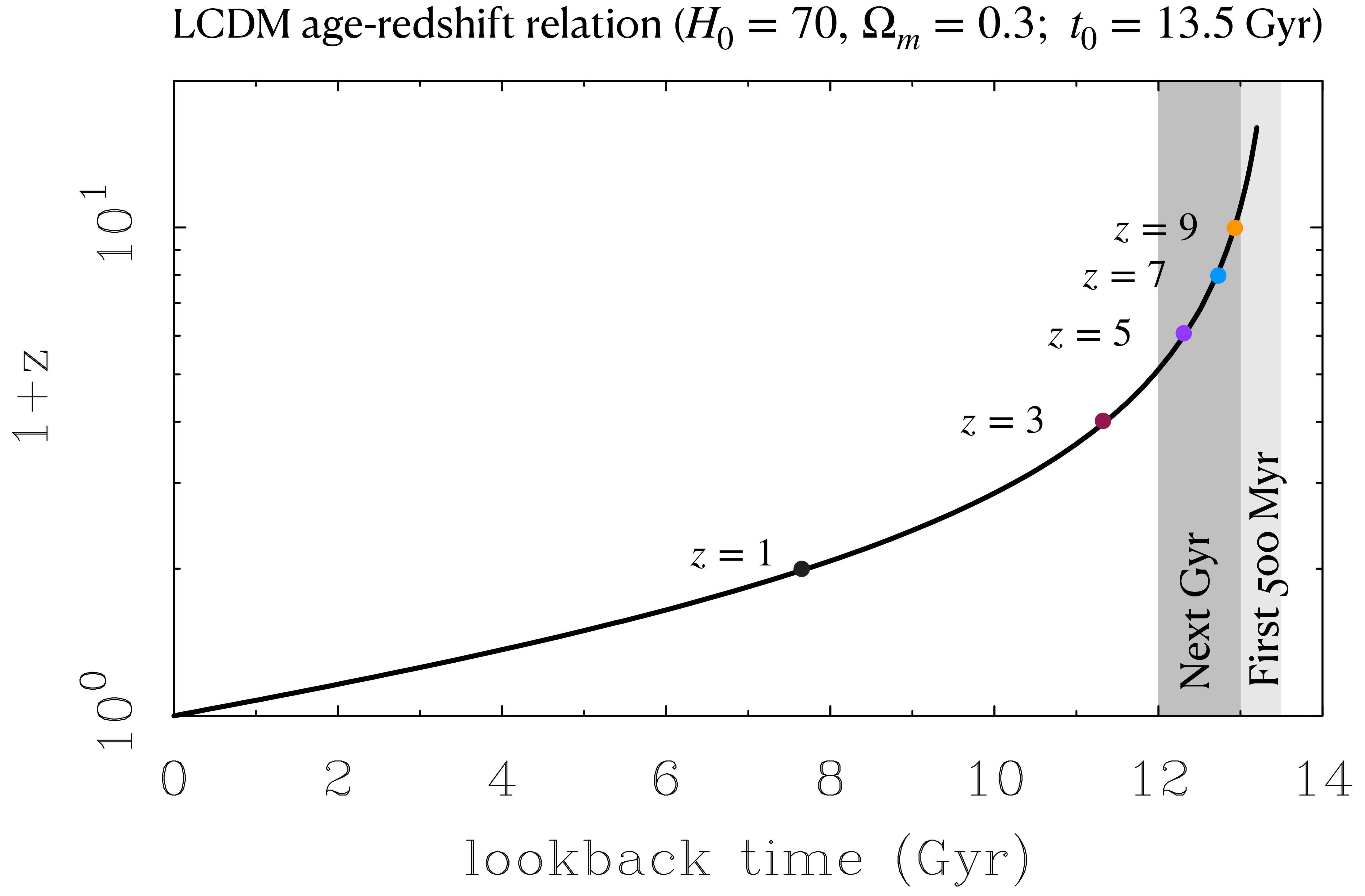
Today
Age constraints

*homework due*

10 October 2024

http://astroweb.case.edu/ssm/ASTR328/

- Age-redshift relation



LCDM age-redshift relation ($H_0 = 70$, $\Omega_m = 0.3$; $t_0 = 13.5$ Gyr)

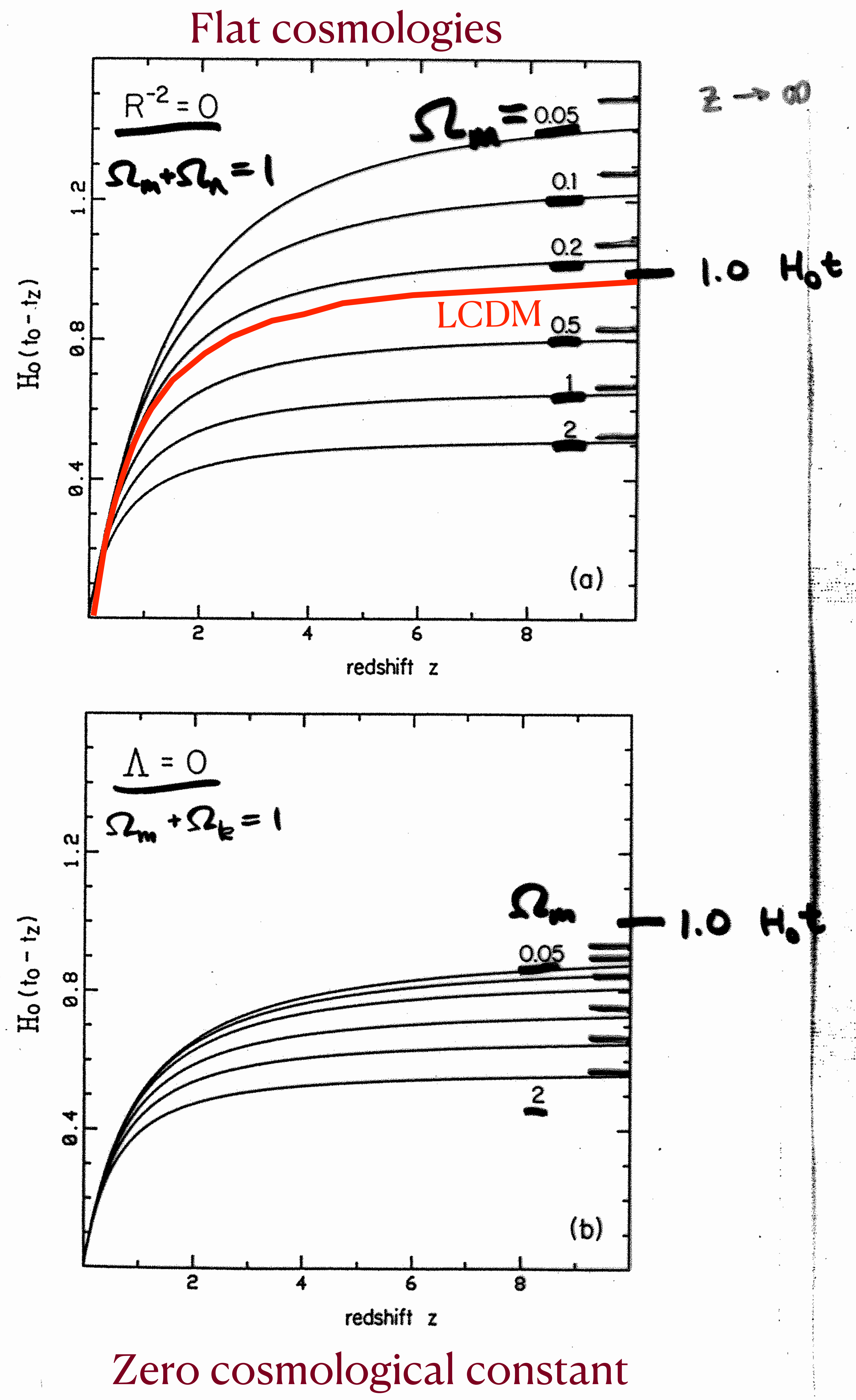


Figure 13.1. Lookback time as a function of redshift. The long dashes on the right-hand axis show the age $t_o$ of the universe computed from $z \to \infty$. In panel (a) space curvature is negligible, and in panel (b) the cosmological constant, Λ, is negligibly small. The curves are labeled by the density parameter, Ω.

| Time | Event |
|---|---|
| $t \sim 10^{-43}$ s | Planck scale (*speculative*) |
| $t \sim 10^{-38}$ s | GUT scale (*speculative*) |
| $t \sim 10^{-35}$ s | Inflation (*speculative*) |
| $t \sim 10^{-12}$ s | Standard Model forces emerge |
| $t \sim 10^{-8}$ s | WIMPs decouple (*speculative*) |
| $t \sim 10^{-5}$ s | quarks condense into baryons (*baryogenesis*) |
| $t \sim 10^{-4}$ s | proton-antiproton annihilation ends |
| $t \sim 1$ s | neutrinos decouple |
| $t \sim 4$ s | electron-positron annihilation ends |
| $t \sim 10^{2}$ s | Big Bang Nucleosynthesis |
| $t \sim 10^{5}$ yr | Matter-radiation equality |
| $t \sim 4 \times 10^{5}$ yr | Atoms form, CMB emerges |
| $t \sim 5 \times 10^{6}$ yr | Gas temperature decouples from radiation |
| $t \sim 10^{7}$ yr | Dark Ages |
| $t \sim 5 \times 10^{8}$ yr | Cosmic dawn (first stars) |
| $t \sim 10^{9}$ yr | Galaxies form |
| $t \sim 4 \times 10^{9}$ yr | Peak star formation |
| $t \sim 9 \times 10^{9}$ yr | Sun forms |
| $t \sim 13 \times 10^{9}$ yr | Multicellular life on earth |
| $t \sim 13.7 \times 10^{9}$ yr | You are now |

Decoupling means to fall out of thermal equilibrium - i.e., when it becomes impossible for the radiation field to spontaneously create particle-antiparticle pairs.

# Age of the Universe

- Oldest stars
  - Globular clusters
- White dwarfs
  - cooling curves & luminosity function
- Radioactive chronometers
  - Thorium/Europium ratio
- Interstellar dust grains
  - Oxygen isotope ratios

Expansion time scale set by the Hubble time $H_0^{-1}$.
What about the ages of observed objects?
The contents of the universe should not be older than the universe itself!

# Age of the Universe

- Oldest stars
  - Globular clusters

$\langle t_{GC} \rangle = 17 \pm 2$ Gyr (Chaboyer et al 1992)

Globular cluster ages are an ancient and venerable constraint. Were important in encouraging belief in Sandage's $H_0 = 50$ in preference to de Vaucouleurs's $H_0 = 100\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$.

Then the Hipparcos satellite changed the local distance scale:

$\langle t_{GC} \rangle = 11.5 \pm 1.3$ Gyr (Chaboyer et al 1998)

Estimates continue to be refined:

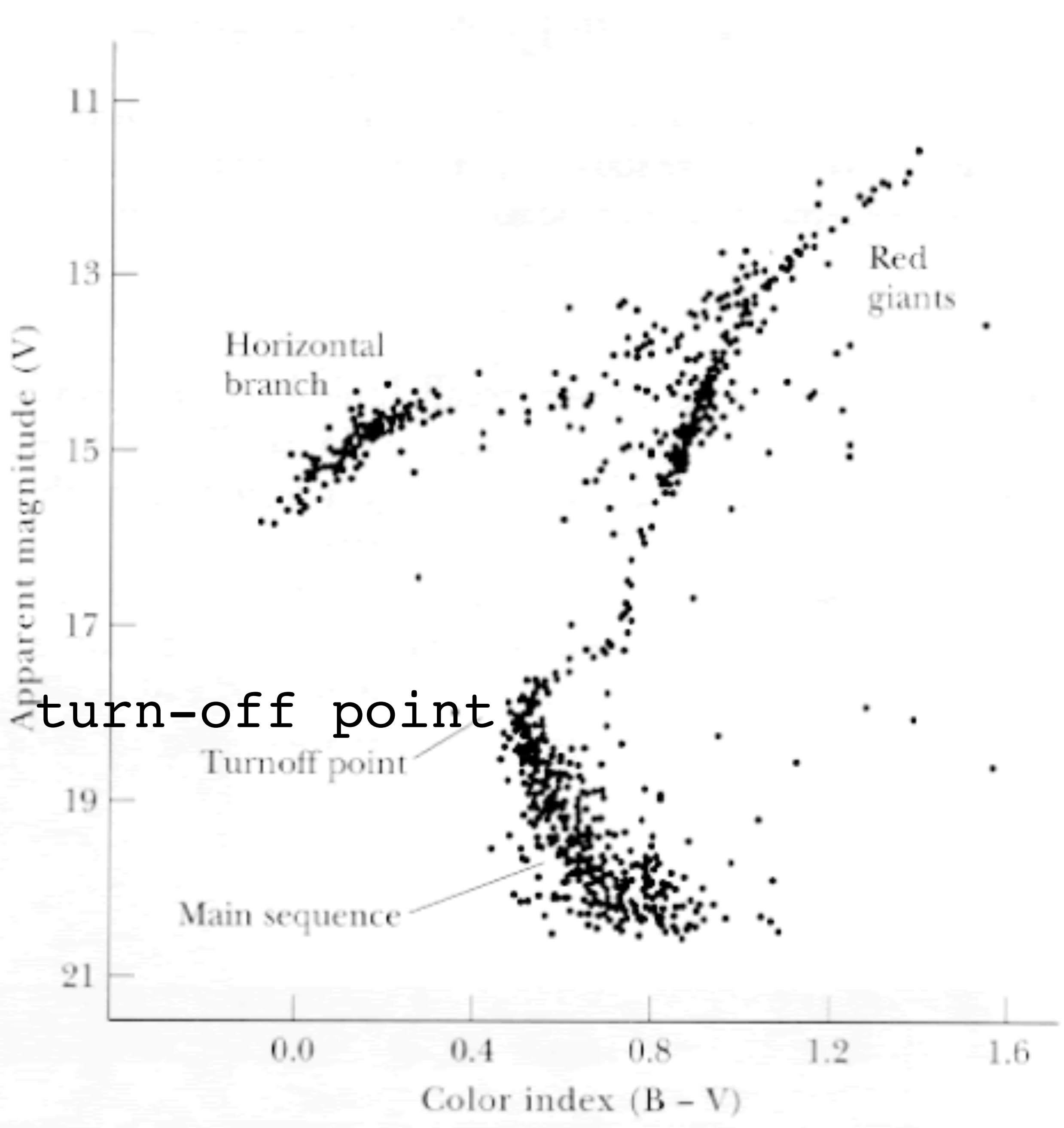
$\langle t_{GC} \rangle = 13.32 \pm 0.1$ (stat) $\pm\ 0.5$ (sys) Gyr (Valcin et al 2020)

$t_{\mathrm{M92}} = 13.80 \pm 0.75$ Gyr (Ying et al 2023)

# Age of the Universe

- Oldest stars
    - Globular clusters

To first order, the age can be estimated from the luminosity of the main sequence turn-off point. It is this luminosity dependence that makes the age dependent on distance.



main sequence turn-off point

# Age of the Universe

- Oldest stars
  - Globular clusters

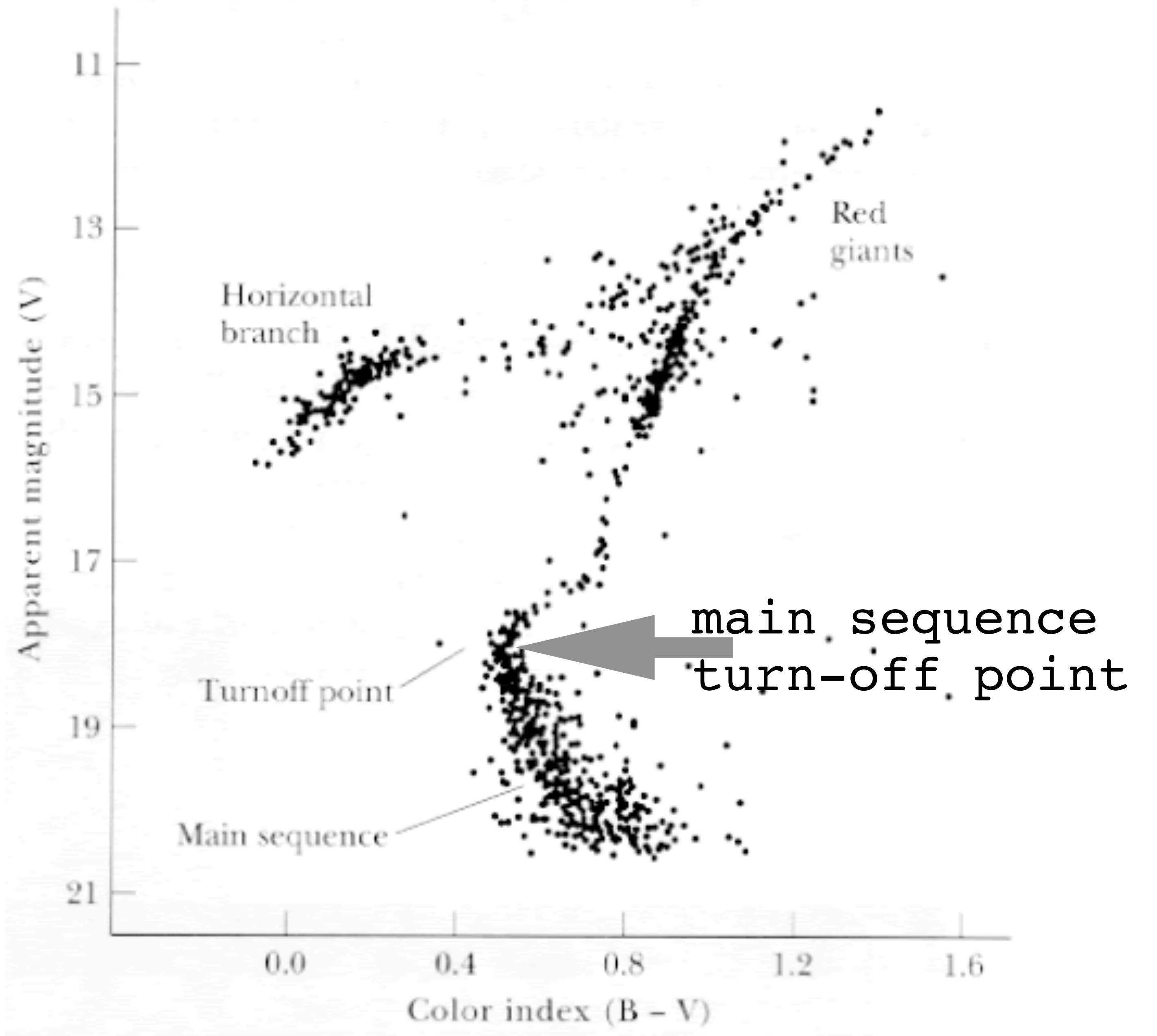
To first order, the age can be estimated from the luminosity of the main sequence turn-off point. It follows simply from the available energy supply (the hydrogen mass in core) and the rate of energy use (the luminosity).

$$E_{\mathrm{MS}} = f_{core}\, \epsilon_H\, M_*\, c^2$$

| | | |
|---|---|---|
| where | $f_{core}$ | is the mass fraction in the star's core (~12%) |
| | $\epsilon_H$ | is the conversion efficiency of fusion (0.7%) |
| | $M_*$ | is the mass of the star. |

$$t_{\mathrm{TO}} = \frac{E_{\mathrm{MS}}}{L_{\mathrm{TO}}}$$

where $L_{\mathrm{MS}}$ is the luminosity of a star at the main sequence turn off point.
This depends on the distance through $L = 4\pi d^2 F$ where $F$ is the observed flux.



# Age of the Universe

- Oldest stars
  - Globular clusters

Stellar luminosity, and hence the main sequence lifetime, is a strong function of stellar mass.

To first order, the age can be estimated from the luminosity of the main sequence turn-off point. It follows simply from the available energy supply (the hydrogen mass in core) and the rate of energy use (the luminosity).

$$E_{\rm MS} = f_{core}\, \epsilon_H\, M_*\, c^2$$

$$t_{\rm TO} = \frac{E_{\rm MS}}{L_{\rm TO}}$$

where $L_{\rm MS}$ is the luminosity of a star at the main sequence turn off point.
This depends on the distance through $L = 4\pi d^2 F$ where $F$ is the observed flux.

$$L \sim M^a$$

in solar units
with

$$a = 3.5 - 4$$

the exponent is mass dependent;
that $a > 1$ means that more
massive stars burn out faster.

$t_{\rm TO}$

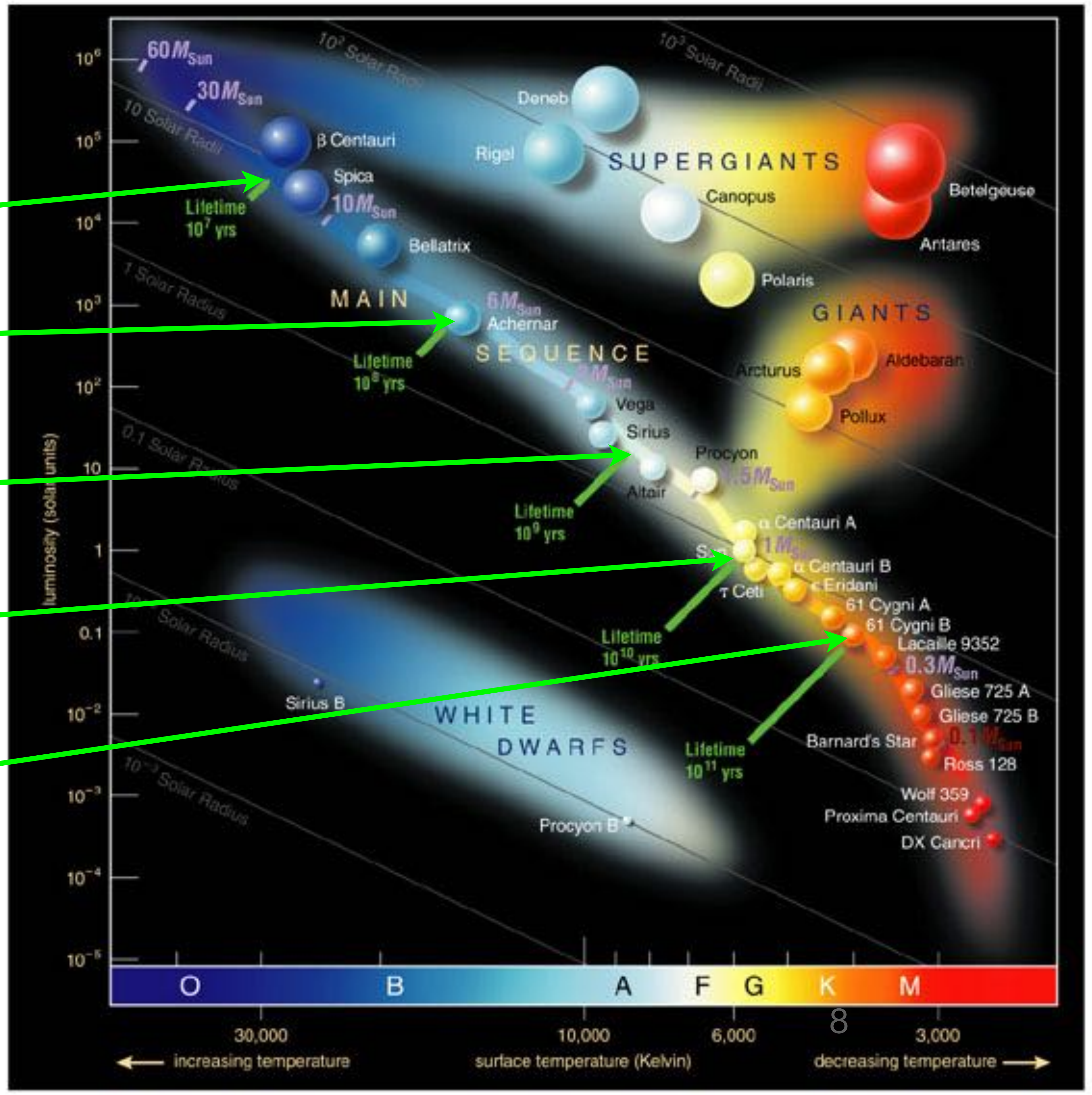
$10^7$yr

$10^8$yr

$10^9$yr

$10^{10}$yr

$10^{11}$yr



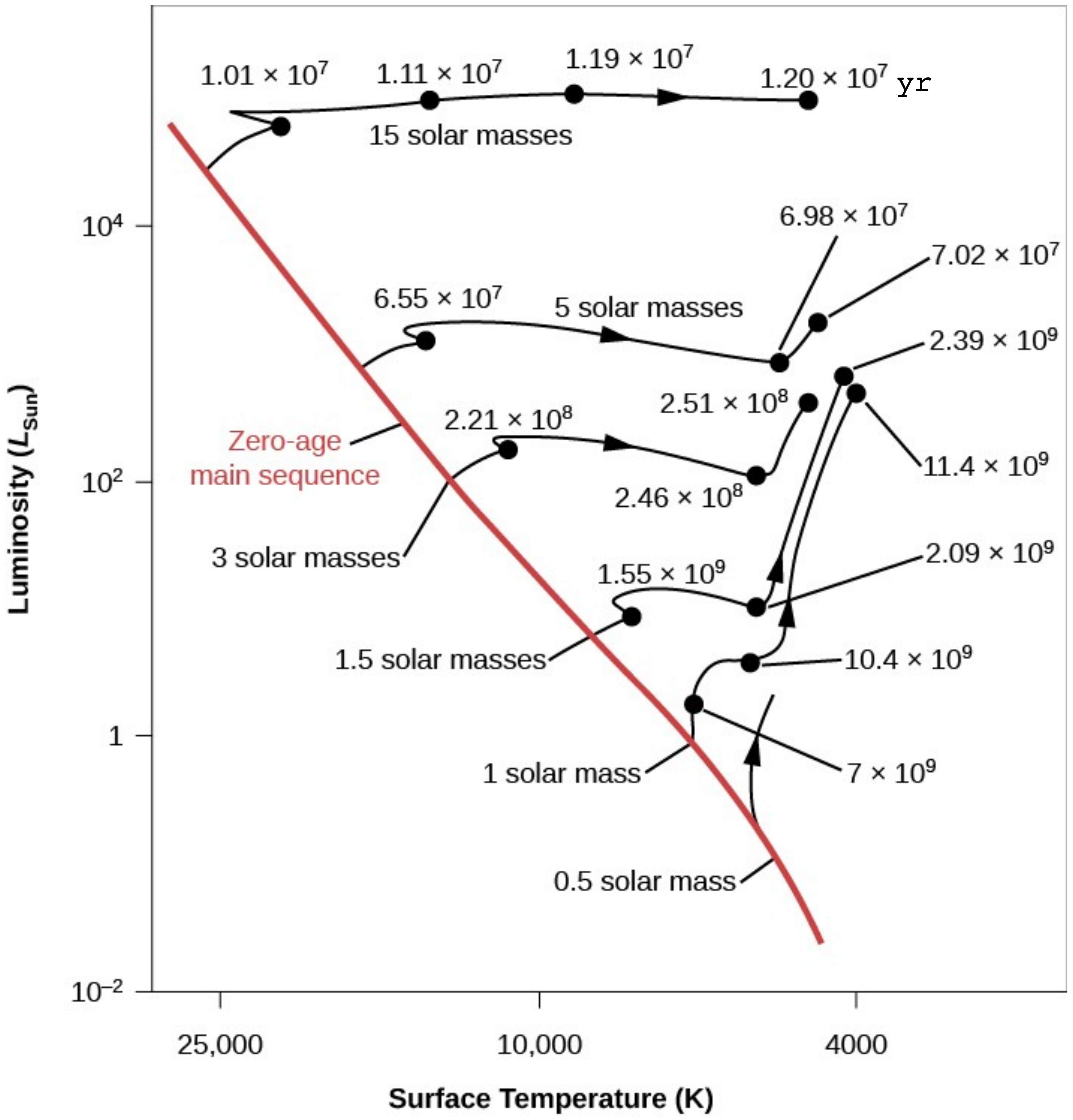
# Age of the Universe

- Oldest stars
  - Globular clusters

More accurately, one can build models of stellar evolution that track the changes in a star's luminosity and surface temperature/color as a function of time.

One then fits these evolutionary tracks to HR diagrams.

Evolutionary tracks for stars of various masses



# Age of the Universe

- Oldest stars
  - Globular clusters

More accurately, one can build models of stellar evolution that track the changes in a star's luminosity and surface temperature/color as a function of time.

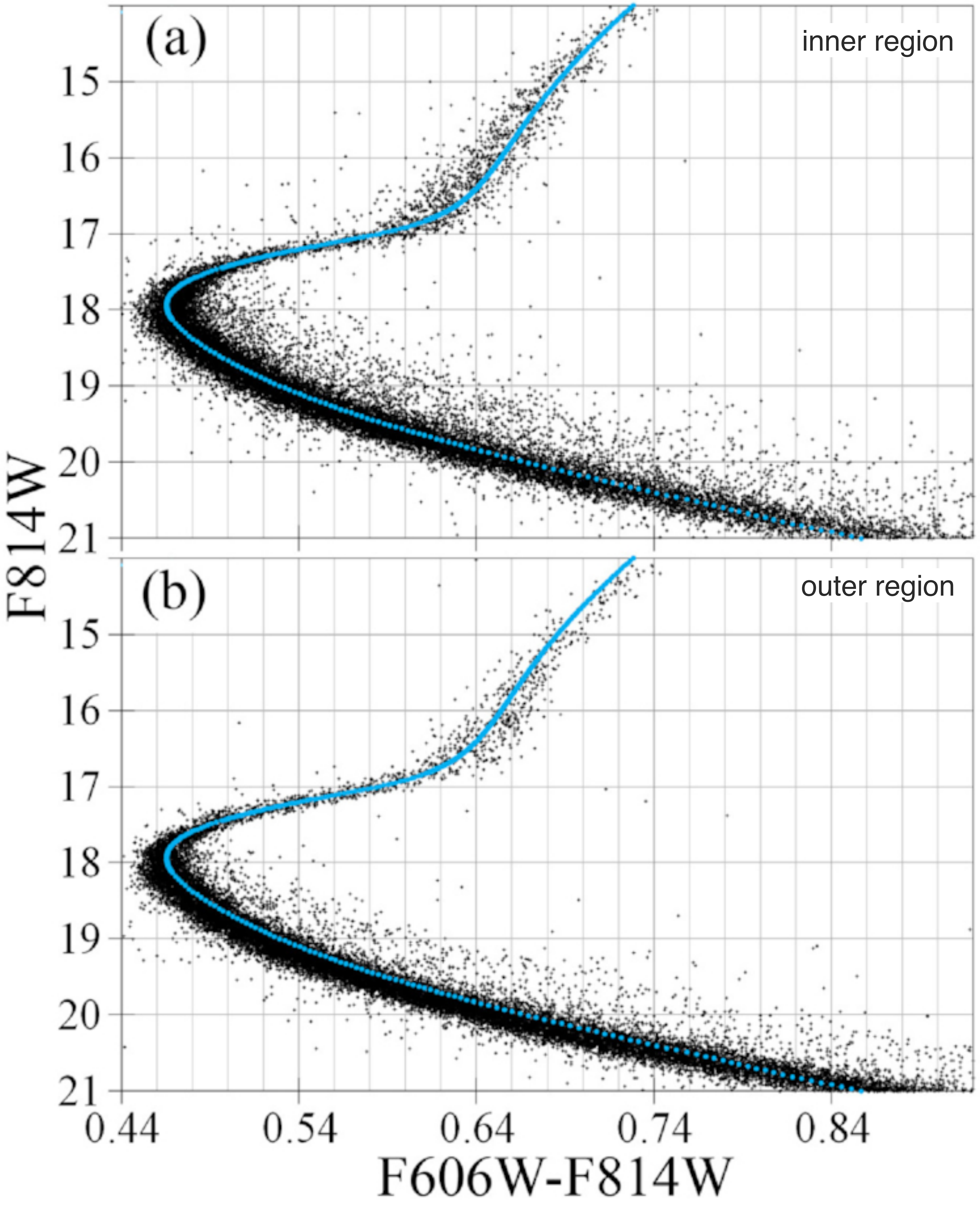
One then fits these evolutionary tracks to HR diagrams.
The physics is well understood, but the details of the models do matter, as does the composition ([Fe/H], [$\alpha$/Fe]) of the stars.

"the derived ages are different for the different models/isochrones, e.g. in the optical range from 12.3 ± 0.7 Gyr for He-α-enhanced DSEP to 14.4 ± 0.7 Gyr for MIST."
(Gontcharov et al. 2020)

Bottom line:
**We never see stars with ages *clearly* exceeding ~14 Gyr.**

Gontcharov et al. (2020)

Best fitting isochrone for globular cluster NGC 6205



*F*606*W* – *F*814*W* versus *F*814*W* CMD of NGC 6205 based on the *HST* ACS data for (a) 25 231 stars within and (b) 24 958 stars outside the 1.14 arcmin radius from the cluster's centre. The best-fitting IAC-BaSTI isochrone is shown by the curve as a reference.