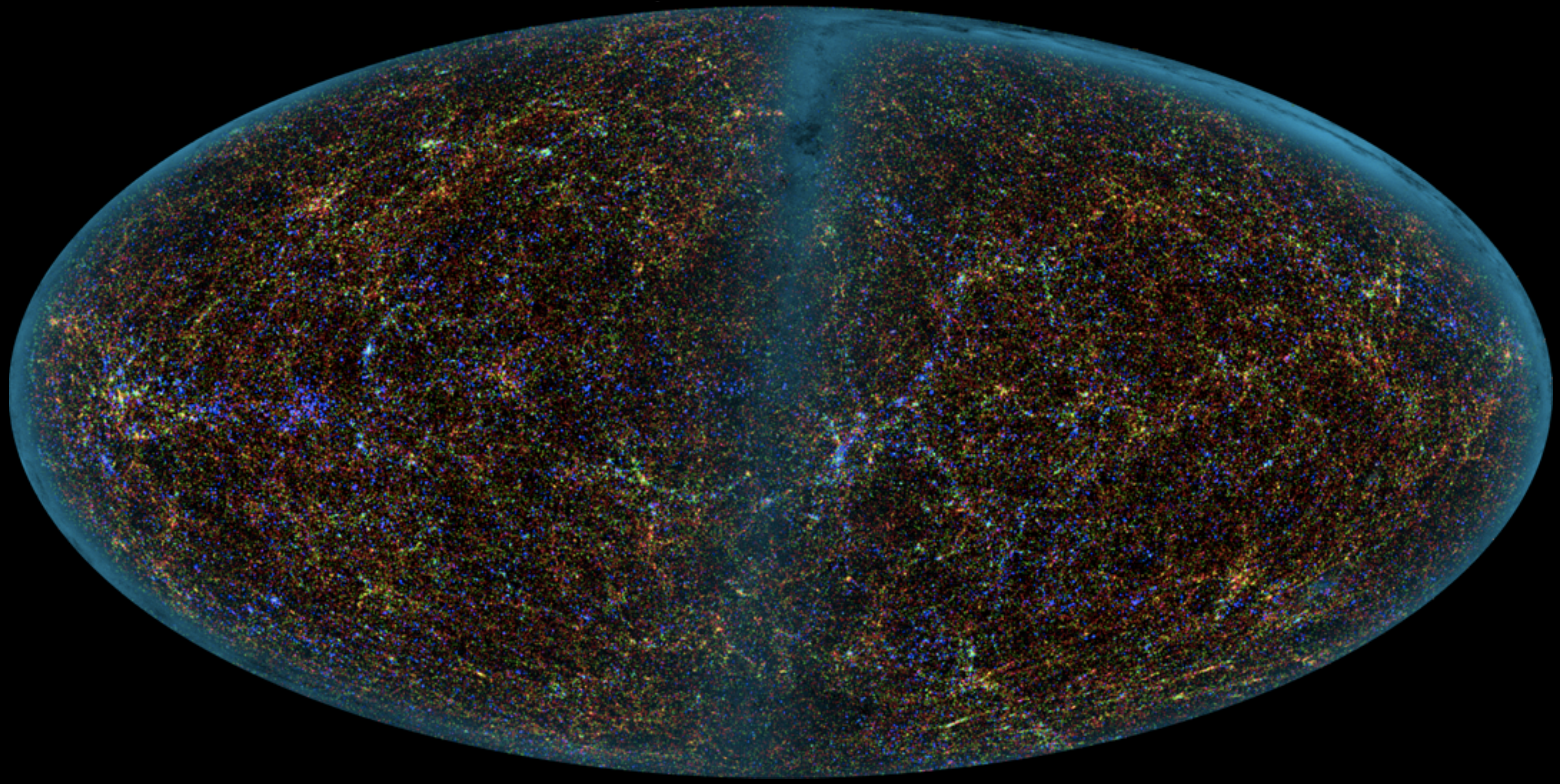
Cosmology
and Large Scale Structure



Today
Observational Tests

Tolman Test
Luminosity Distance-redshift
Angular Size Distance-redshift

homework 2 due Thu 9/22

Solutions from Felten & Isaacman (1986) Reviews of Modern Physics, **58**, 689

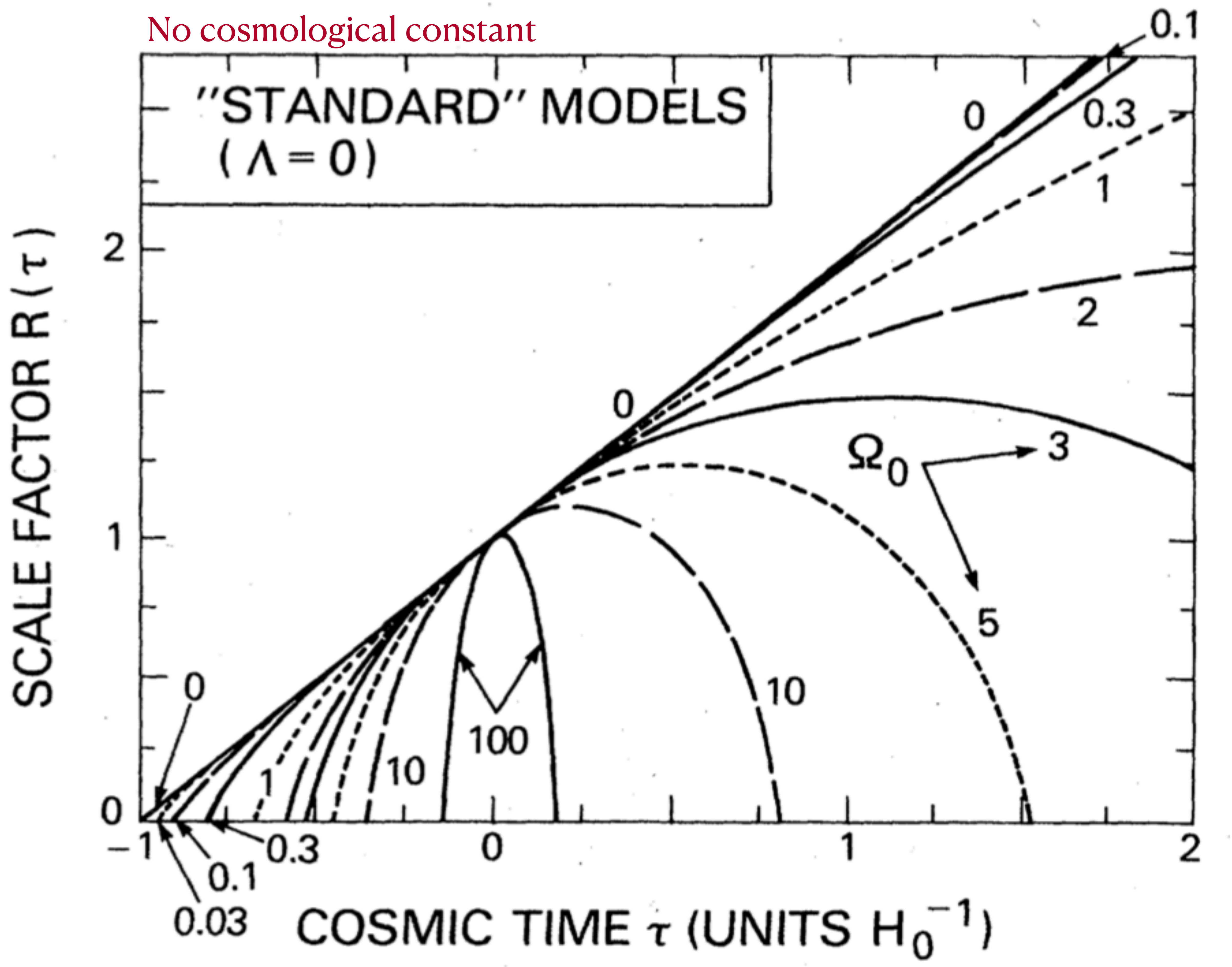


FIG. 3. "Standard" Friedmann models. The family of scale factors $R(\tau)$ for the "standard models" ($\Lambda=0$). The free parameter, shown on the curves, is Ω_0. As shown by the τ intercepts, all models have ages ≤ 1 ($\leq H_0^{-1}$ yr).

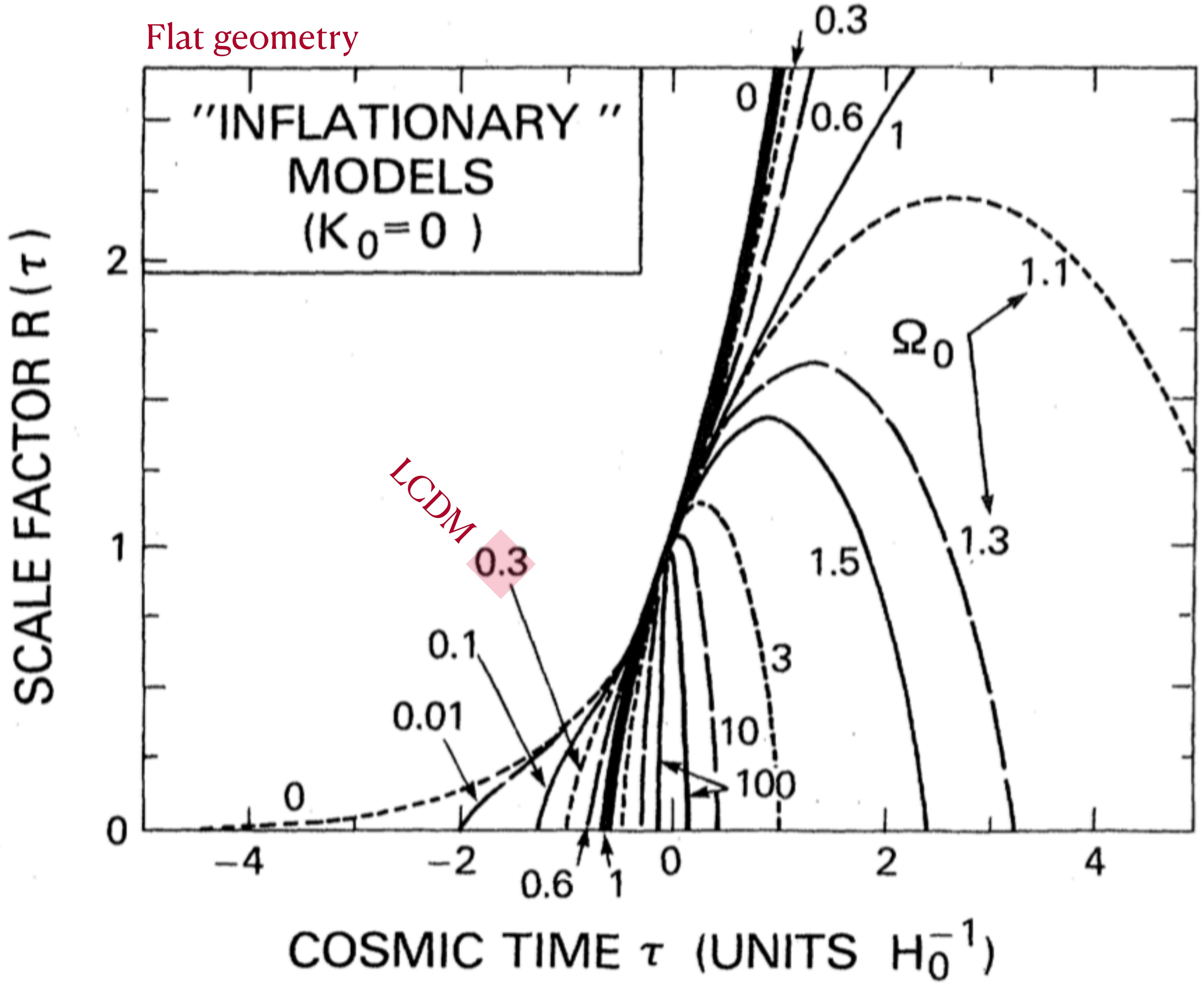


FIG. 2. "Inflationary" Friedmann models. The family of scale factors $R(\tau)$ for models satisfying the "inflationary constraint" (three-space curvature $K_0=0$). The free parameter, shown on the curves, is Ω_0. The cosmological constant Λ is determined from Ω_0 by Eq. (14).

Solutions from Felten & Isaacman (1986) Reviews of Modern Physics, **58**, 689

Can in principle have solutions in which there was no Big Bang in the past, depending on the value of Lambda.

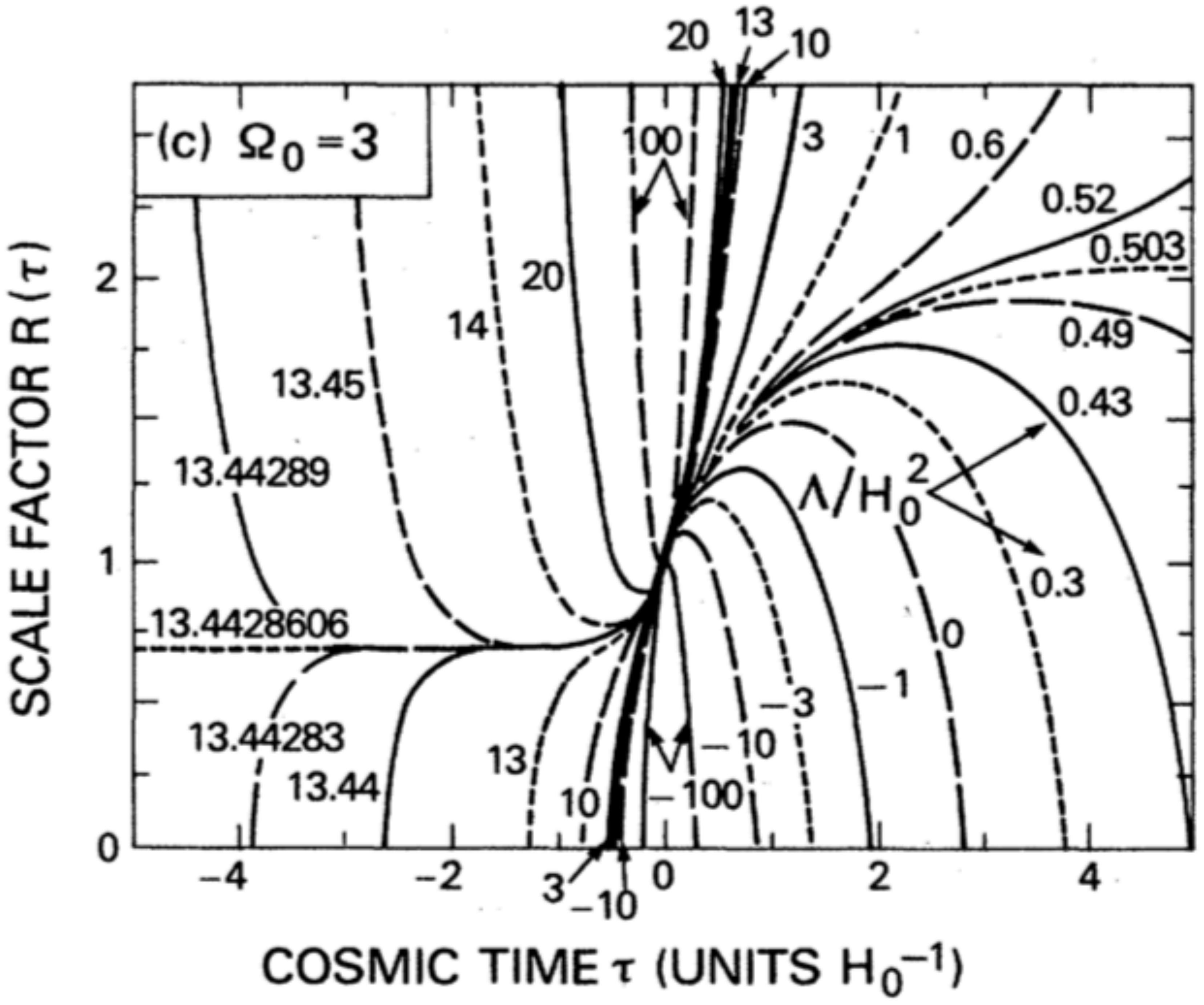


FIG. 1. Solutions of the Friedmann equation. Three families of scale factors $R(\tau)$ for Friedmann (zero-pressure) universes, with three fixed values of the present density parameter Ω_0: (a) $\Omega_0=0.1$; (b) $\Omega_0=1$; (c) $\Omega_0=3$. The free parameter, shown on the curves, is the cosmological constant Λ in units of H_0^2, where H_0 is the present Hubble parameter. The time τ is measured in units of the Hubble time H_0^{-1} and is taken $=0$ at present. The scale factor $R(\tau)$ is normalized to unity at present: $R_0=1$. For further discussion see the text.

Observational Tests

Five Classic Tests

• Luminosity-redshift relation	$D_L - z$	Standard Candle
• Angular size-redshift relation	$D_A - z$	Standard Rod
• Number-redshift relation	$N(z)$	Source counts with redshift
• Number-magnitude relation	$N(m)$	Source counts with magnitude
• Tolman test	$\Sigma(z)$	Surface brightness not distance independent in Robertson-Walker geometry

Other tests are possible. E.g., one could in principle make an age-redshift test - if one could confidently measure ages of objects at cosmic distances.

- Age-redshift relation

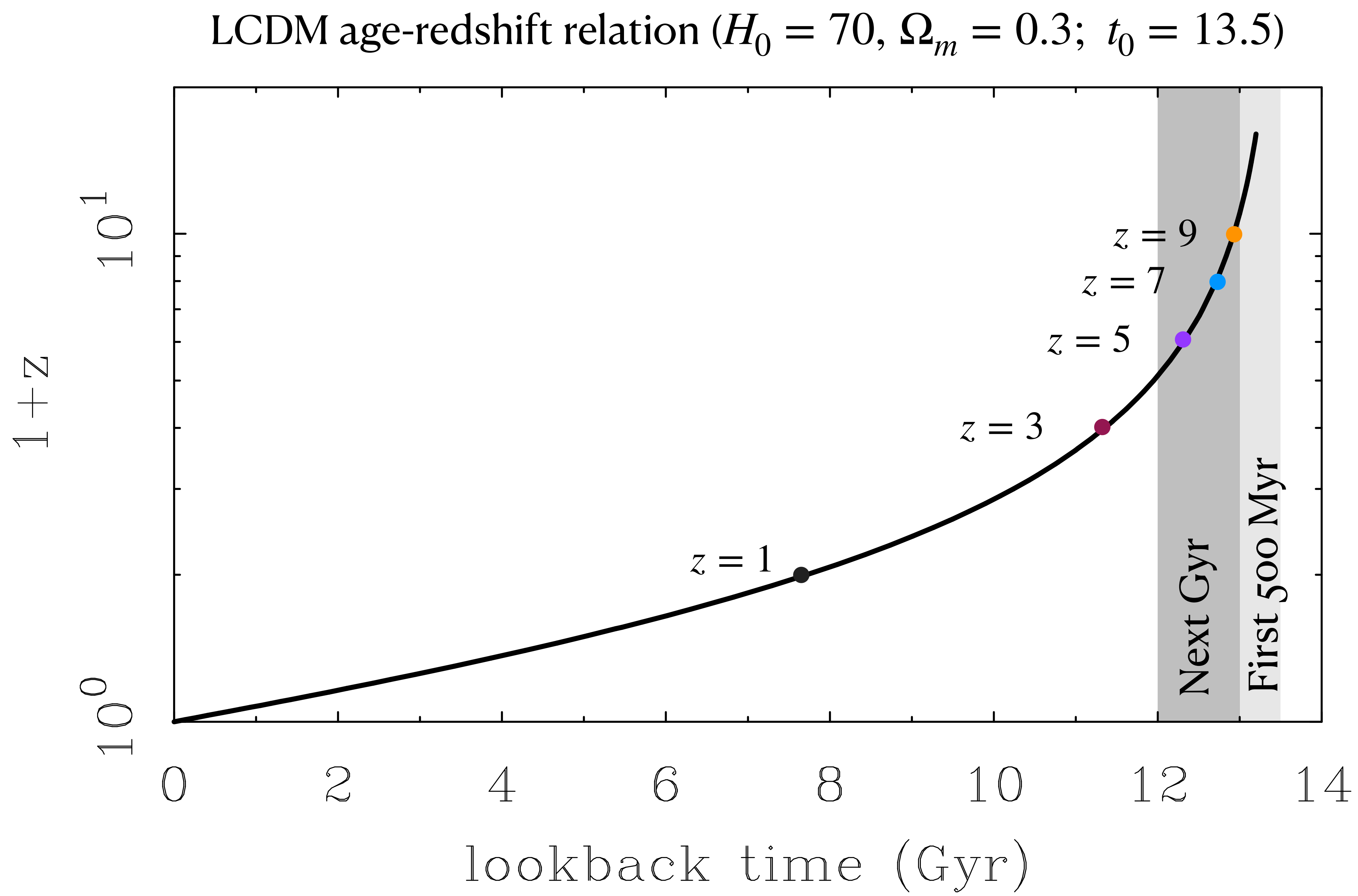
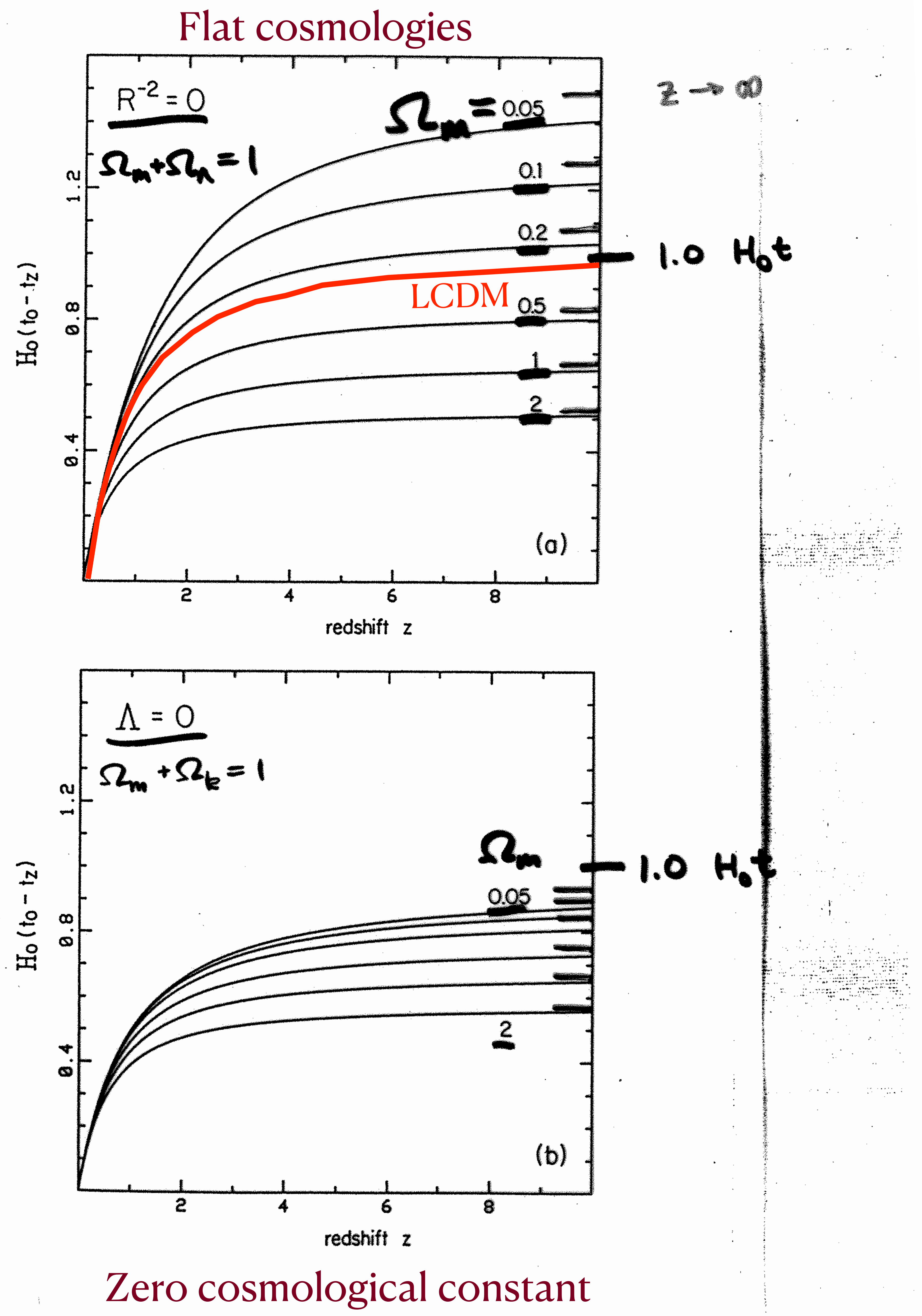


Figure 13.1. Lookback time as a function of redshift. The long dashes on the right-hand axis show the age t_o of the universe computed from $z \to \infty$. In panel (a) space curvature is negligible, and in panel (b) the cosmological constant, Λ, is negligibly small. The curves are labeled by the density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



- Tolman Test

Also referred to as $(1+z)^4$ dimming.

Surface brightness dimming

No surface brightness dimming in Euclidean geometry

$$\Sigma \sim \frac{f}{\theta^2} \sim \frac{D^{-2}}{D^{-2}} \sim \text{constant}$$

Lots of surface brightness dimming in Robertson-Walker geometry

$$\Sigma \sim \frac{f}{\theta^2} \sim \frac{D_L^{-2}}{D_A^{-2}} \sim \frac{D_p^{-2}(1+z)^{-2}}{D_p^{-2}(1+z)^2} \sim (1+z)^{-4}$$

Surface brightness dims as a strong function of redshift!

The Tolman test is a sanity check:
it does not distinguish between FLRW models: the same amount of dimming occurs in all.

In practice, it is hard to distinguish from evolutionary effects.

- Luminosity-redshift relation

Ideal case:
a **Standard Candle**
an object of constant, known luminosity $\boldsymbol{L}$

Measuring redshift-distance pairs D_L, z measures cosmology through H_0, q_0

$$a(t) \approx 1 + H_0(t - t_0) - \frac{1}{2}q_0 H_0^2 (t - t_0)^2 + \dots$$

Then its apparent brightness is simply dimmed by its distance
as a consequence of the inverse square law in the appropriate geometry.

flux & luminosity

$$f = \frac{L}{4\pi D_L^2}$$

Luminosity distance

$$D_L = (1 + z) D_p$$

apparent & absolute magnitude

$$m - M = 5 \log D_L + 25$$

in practice, also have to worry about line of sight extinction A

$$m - M = 5 \log D_L + 25 + A$$

as a source can be dimmed by obscuration as well as remoteness

The line of sight extinction A that corrects the distance modulus

$$m - M = 5 \log D_L + 25 + A$$

has been well mapped in the Milky Way

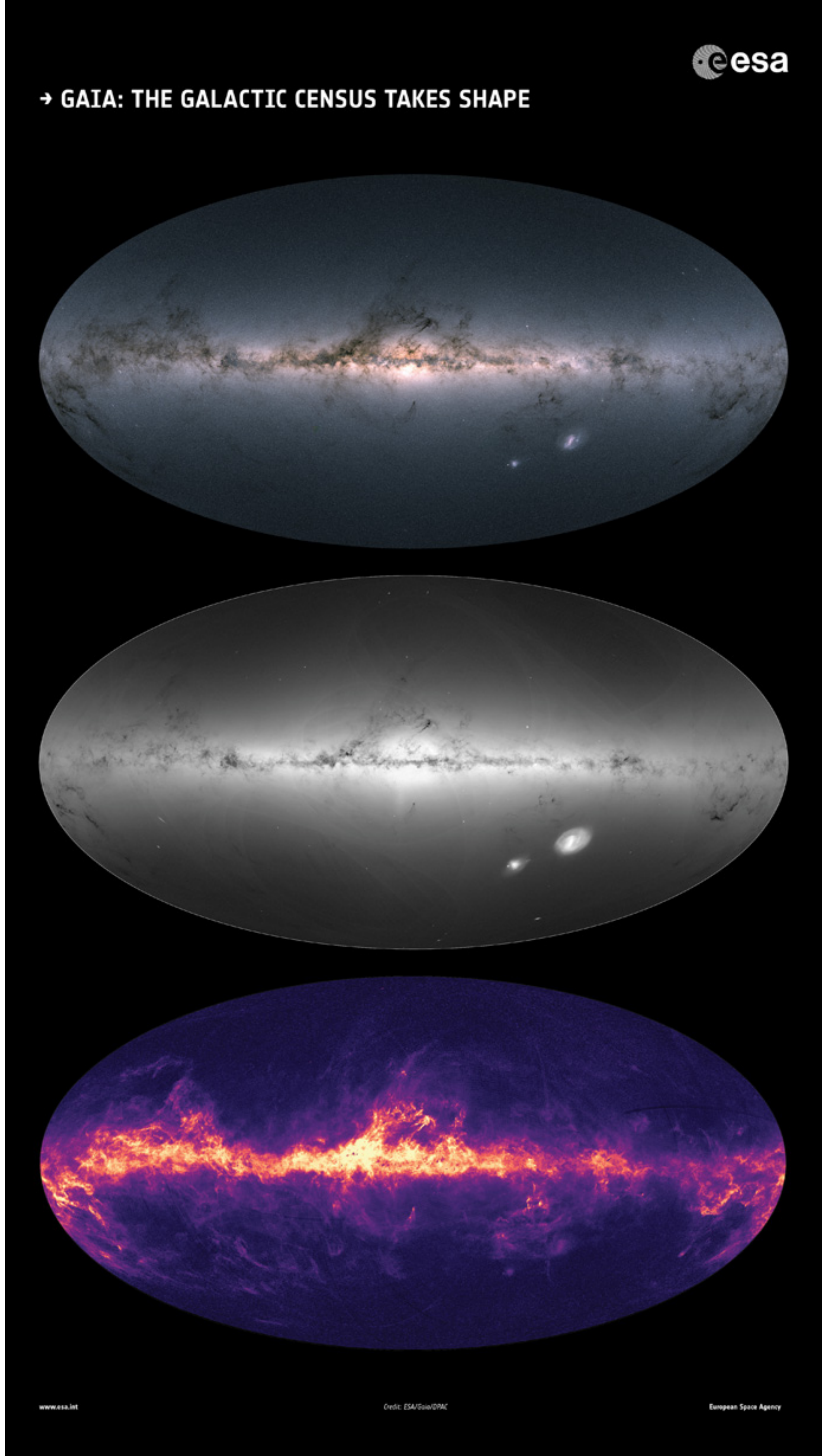
There are reasonably well calibrated maps of $A(\ell, b)$ where ℓ b are Galactic longitude and latitude. You can look up the line-of sight extinction with resources like NED.

Galaxy Extinctions for NGC 3109

View References in ADS (2) — 1 of 1 (1 - 102 of 102)

Bandpass (char)	Central Wavelength (um) (double)	The Galactic extinction (Mag) (double)	Refcode of the publications (char)
Landolt U	0.35	0.289	2011ApJ...737..103S
Landolt B	0.43	0.242	2011ApJ...737..103S
Landolt V	0.54	0.183	2011ApJ...737..103S
Landolt R	0.64	0.145	2011ApJ...737..103S
Landolt I	0.80	0.100	2011ApJ...737..103S
CTIO U	0.37	0.274	2011ApJ...737..103S
CTIO B	0.43	0.243	2011ApJ...737..103S
CTIO V	0.55	0.179	2011ApJ...737..103S
CTIO R	0.65	0.141	2011ApJ...737..103S
CTIO I	0.80	0.101	2011ApJ...737..103S
UKIRT J	1.25	0.047	2011ApJ...737..103S
UKIRT H	1.66	0.030	2011ApJ...737..103S
UKIRT K	2.19	0.020	2011ApJ...737..103S

This is only the dust in our own Galaxy. There can be additional dust in other galaxies, which is often hard to estimate, but in principle $A = A_{Gal} + A_{exgal}$.



Gaia

Brightness

Star counts

Dust (Zone of Avoidance)

- Luminosity-redshift relation

Ideal case:
a **Standard Candle**
an object of constant, known luminosity ***L***

Example Standard Candles:

- Cepheids
- Tip of the Red Giant Branch
- Type Ia Supernovae

None of these Standard Candles are really standard, but they are standardizable — e.g., the Cepheid period-luminosity relation allows one to measure a distance-independent quantity (the period) as a proxy for the distance-dependent luminosity.

Then the trick is in the calibration.

• Luminosity-redshift relation

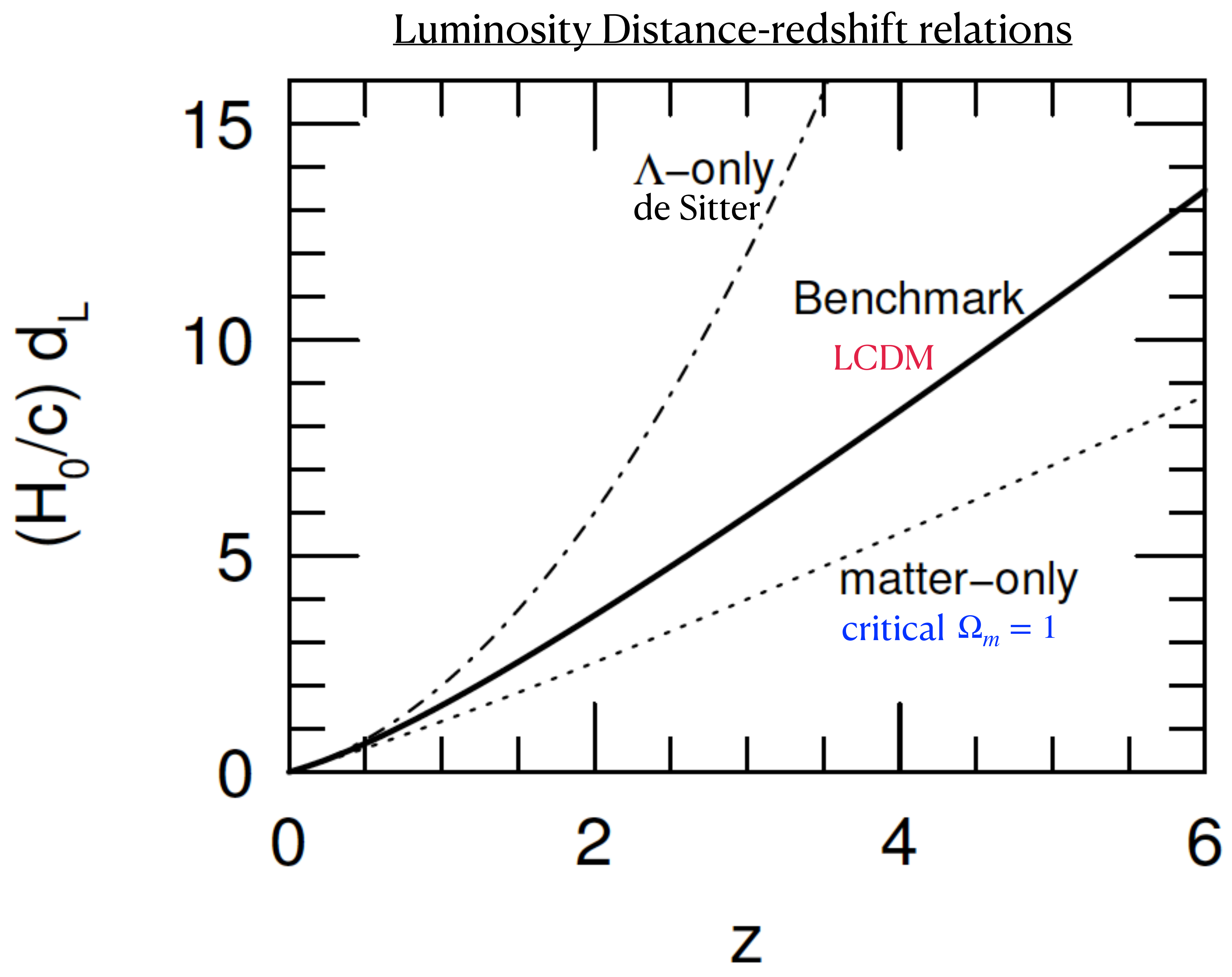


Figure 7.2: The luminosity distance of a standard candle with observed redshift z. The bold solid line gives the result for the Benchmark Model, the dot-dash line for a flat, lambda-only universe, and the dotted line for a flat, matter-only universe.

Note that the luminosity distance can easily exceed the Hubble length.

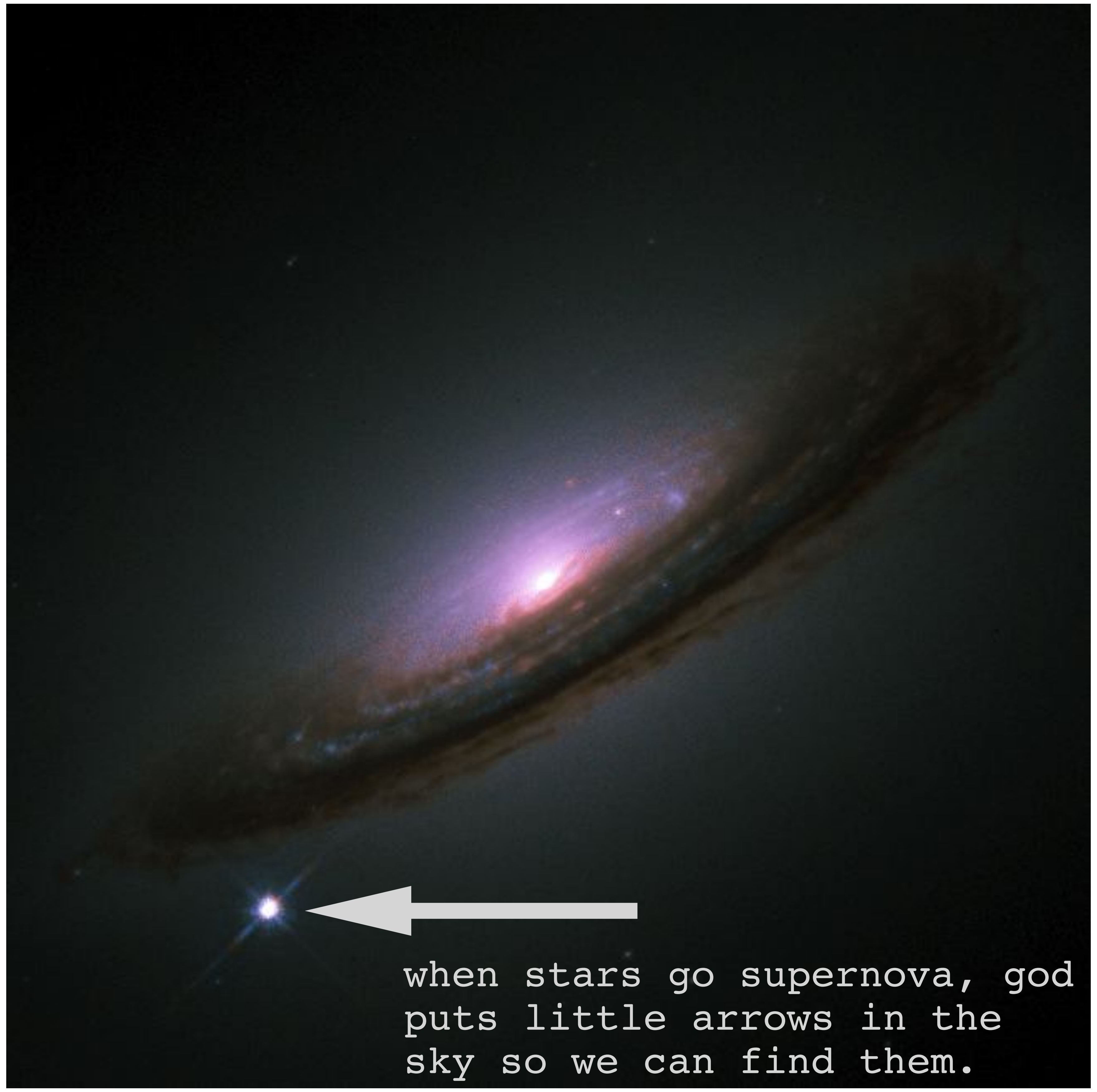
Ryden Fig. 6.2 (2nd ed)

Example Standard Candle:

- Type Ia Supernovae

Exploding white dwarf.

When a mass accretion event pushes a white dwarf over the Chandrasekhar limit (1.4 $M_\odot$), the sudden compression results in the fusion of carbon & oxygen, detonating the remnant in its entirety.



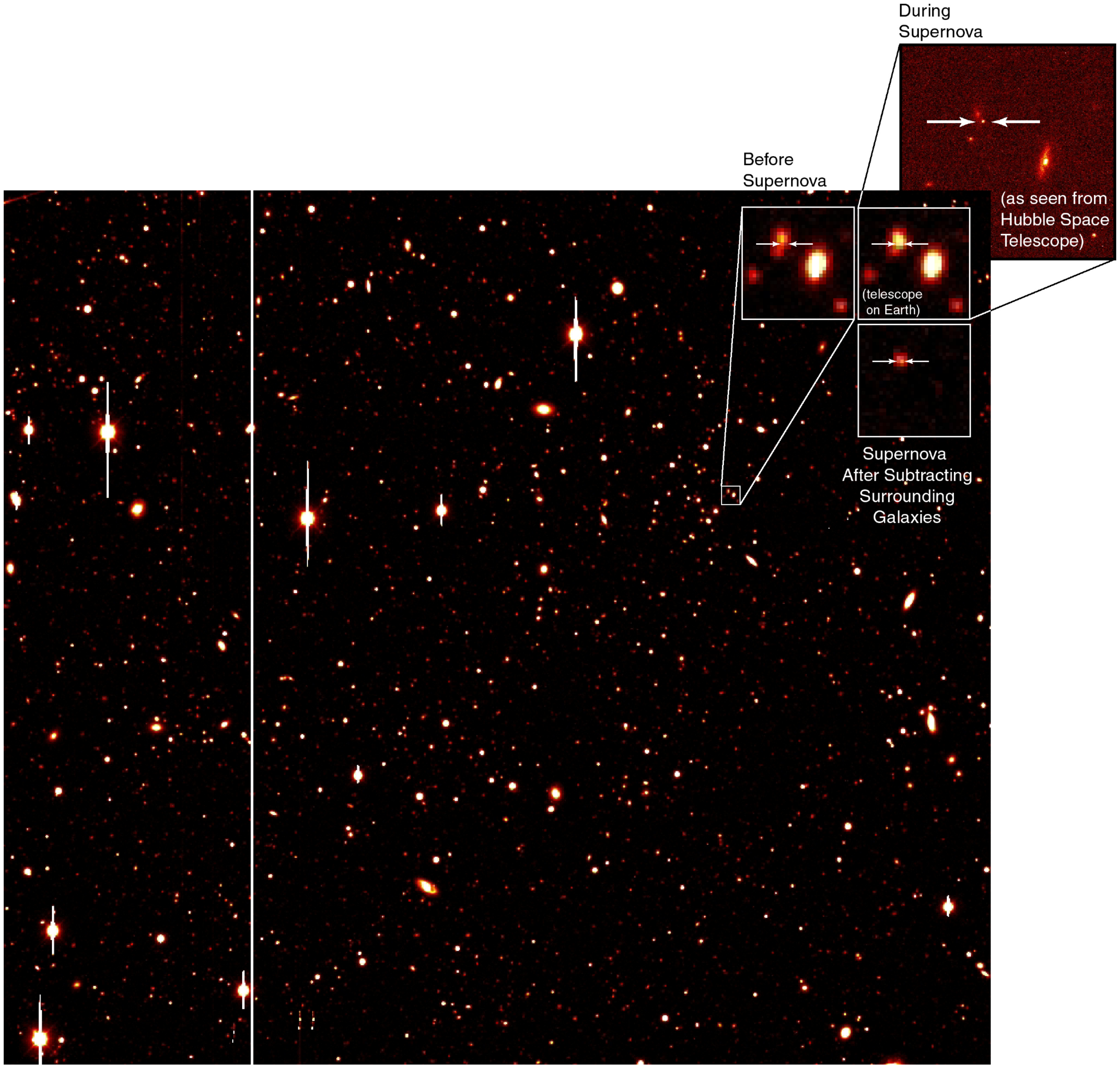
Example Standard Candle:

- Type Ia Supernovae

Survey wide swath of sky, imaging repeatedly over many nights, looking for change. If you look at enough galaxies, you'll see SN go off.

Supernova Cosmology Project

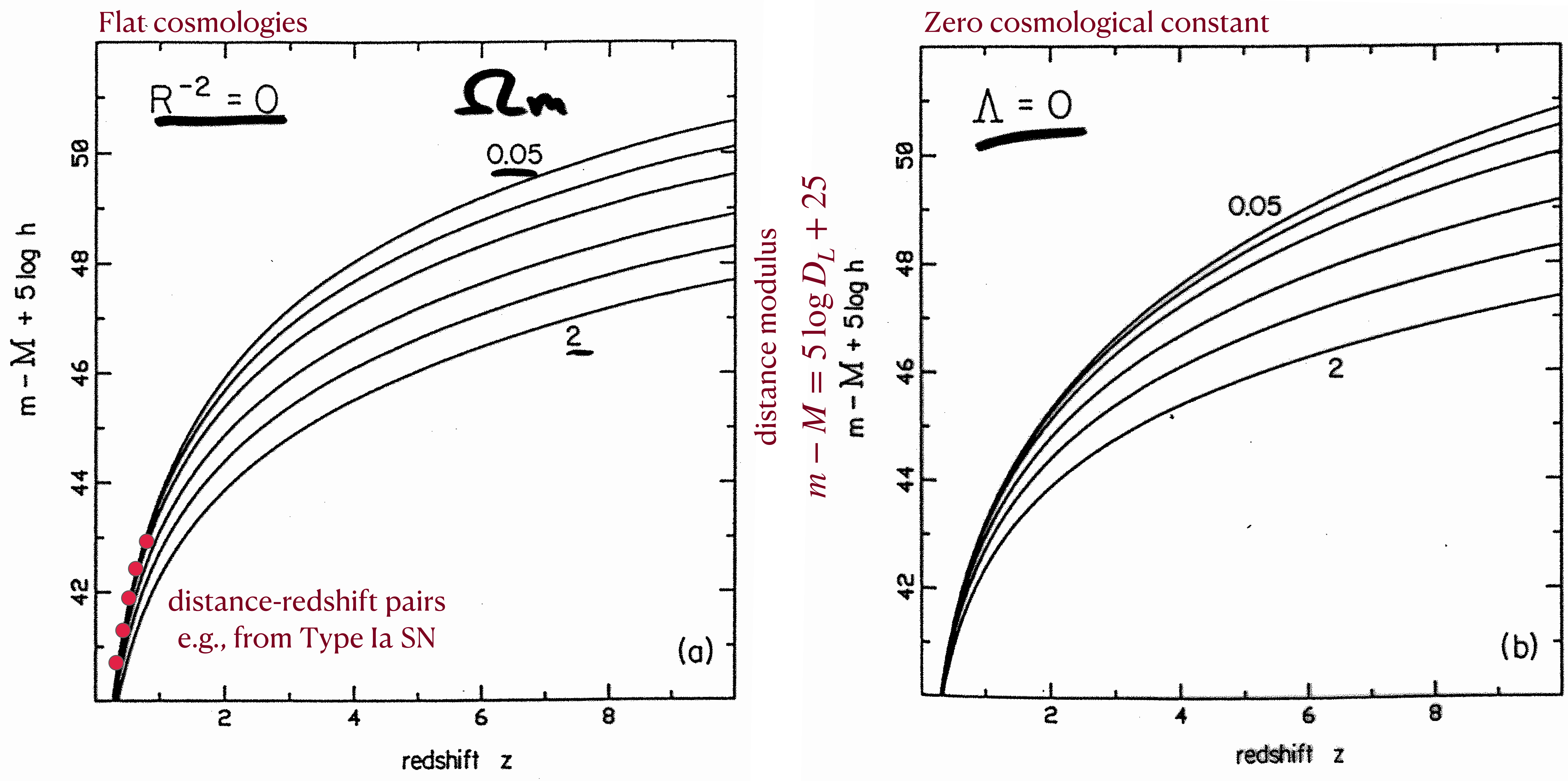
Perlmutter et al. (1998)



- Luminosity-redshift relation

Luminosity Distance-redshift relations

Figure 13.6. Bolometric distance modulus $m - M + 5\log h$ as a function of redshift. The parameters are arranged as in figure 13.1.



Peebles Fig. 13.6