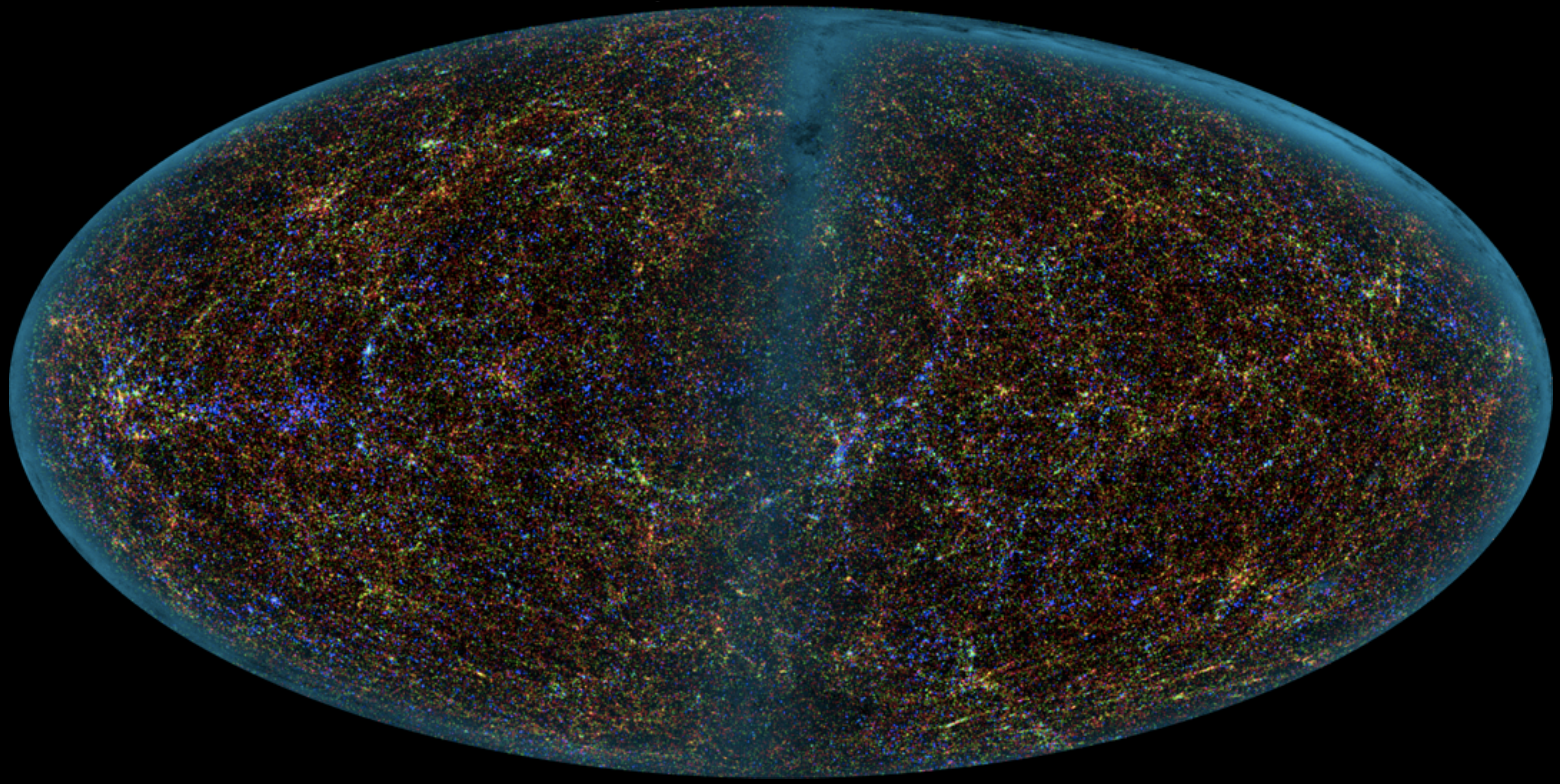
Cosmology

and Large Scale Structure



Today

Observational Tests

Tolman Test

Luminosity Distance-redshift

Angular Size Distance-redshift

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

- # 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 ***L***

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

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

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

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

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

- Luminosity-redshift relation

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

Example Standard Candles:

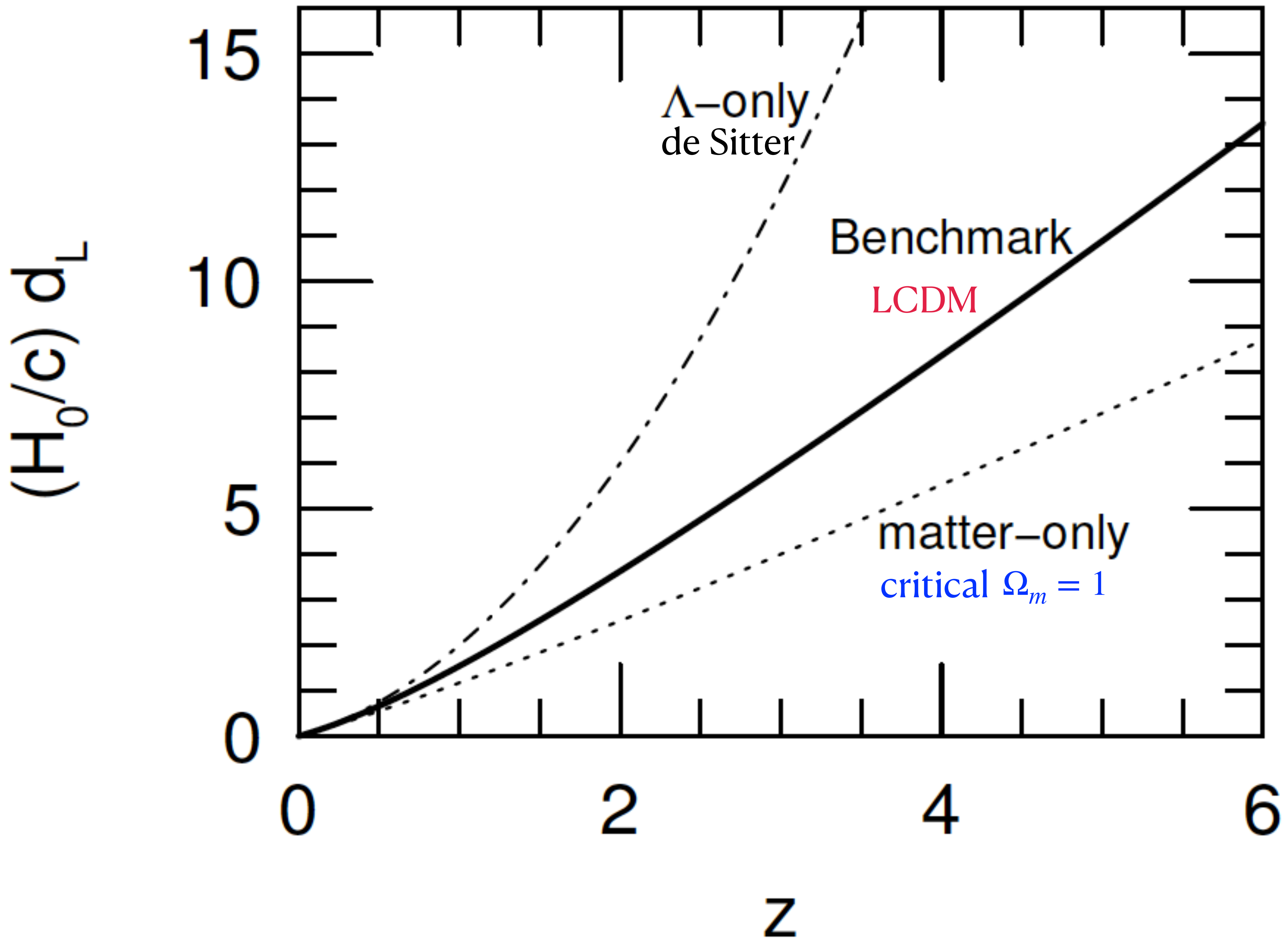
- Cepheids
- Tip of the Red Giant Branch
- Type Ia Supernovae

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

Luminosity Distance-redshift relations



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

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.

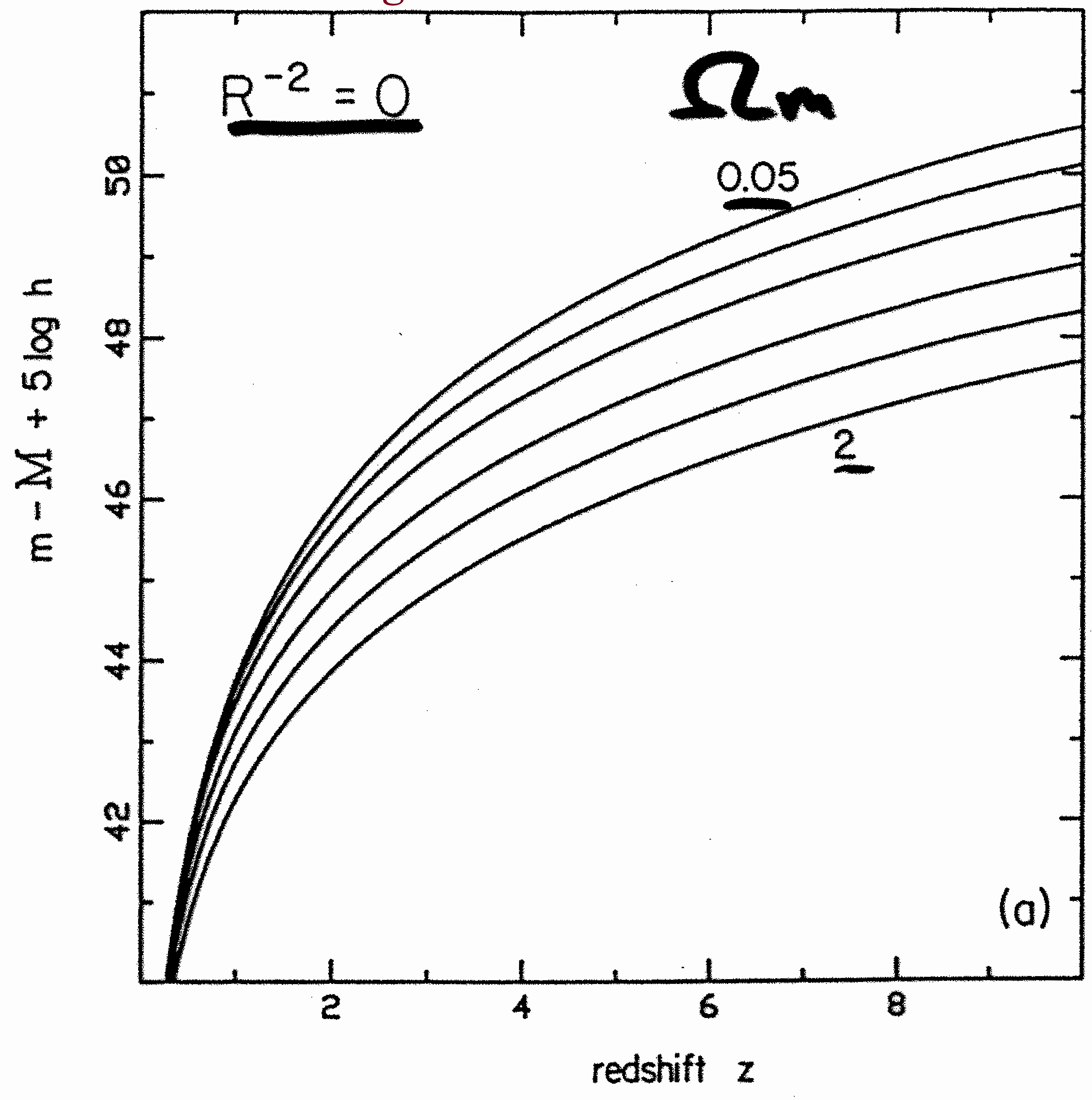
Ryden Fig. 6.2 (2nd ed)

• 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.

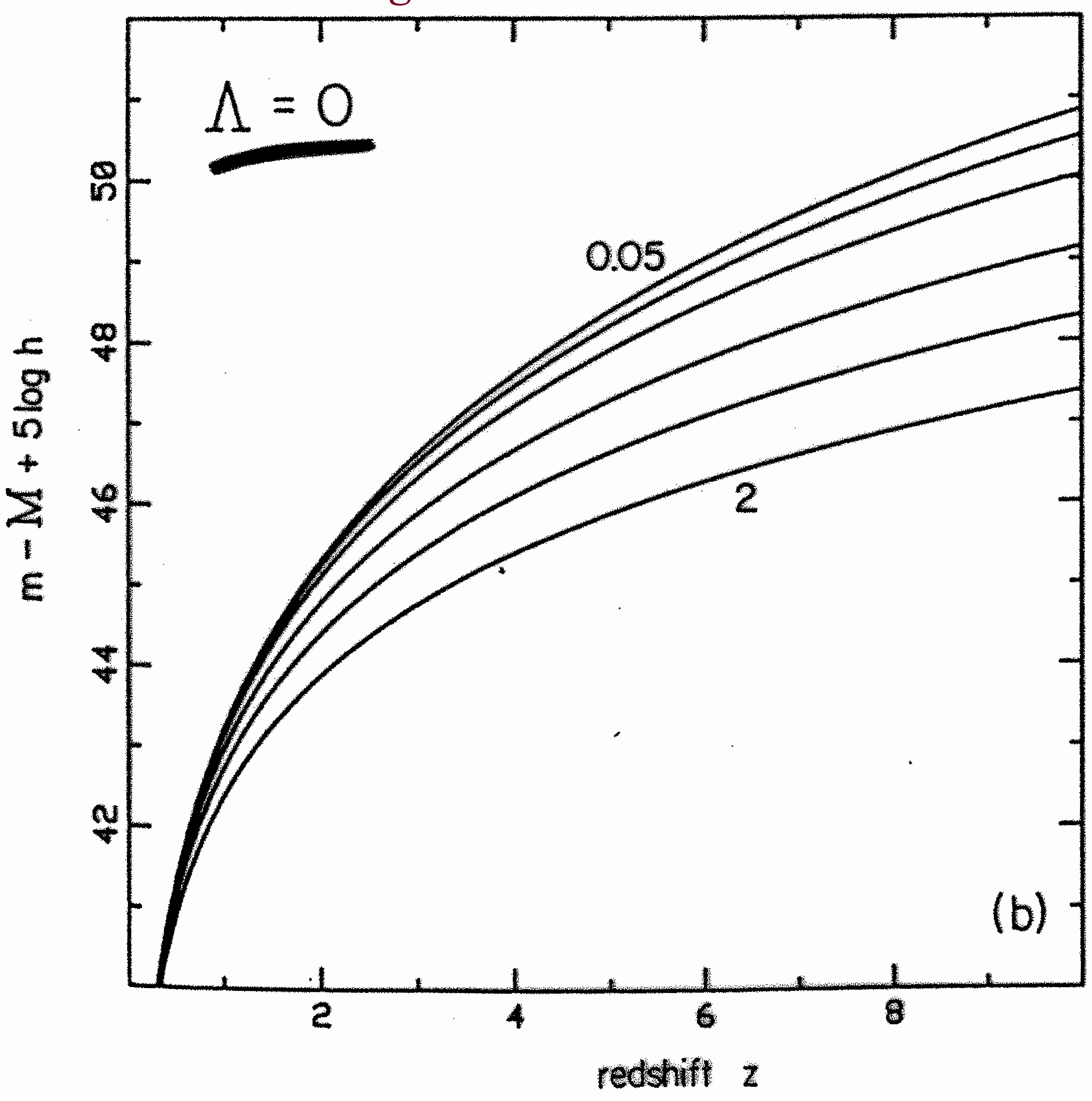
Flat cosmologies



distance modulus

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

Zero cosmological constant



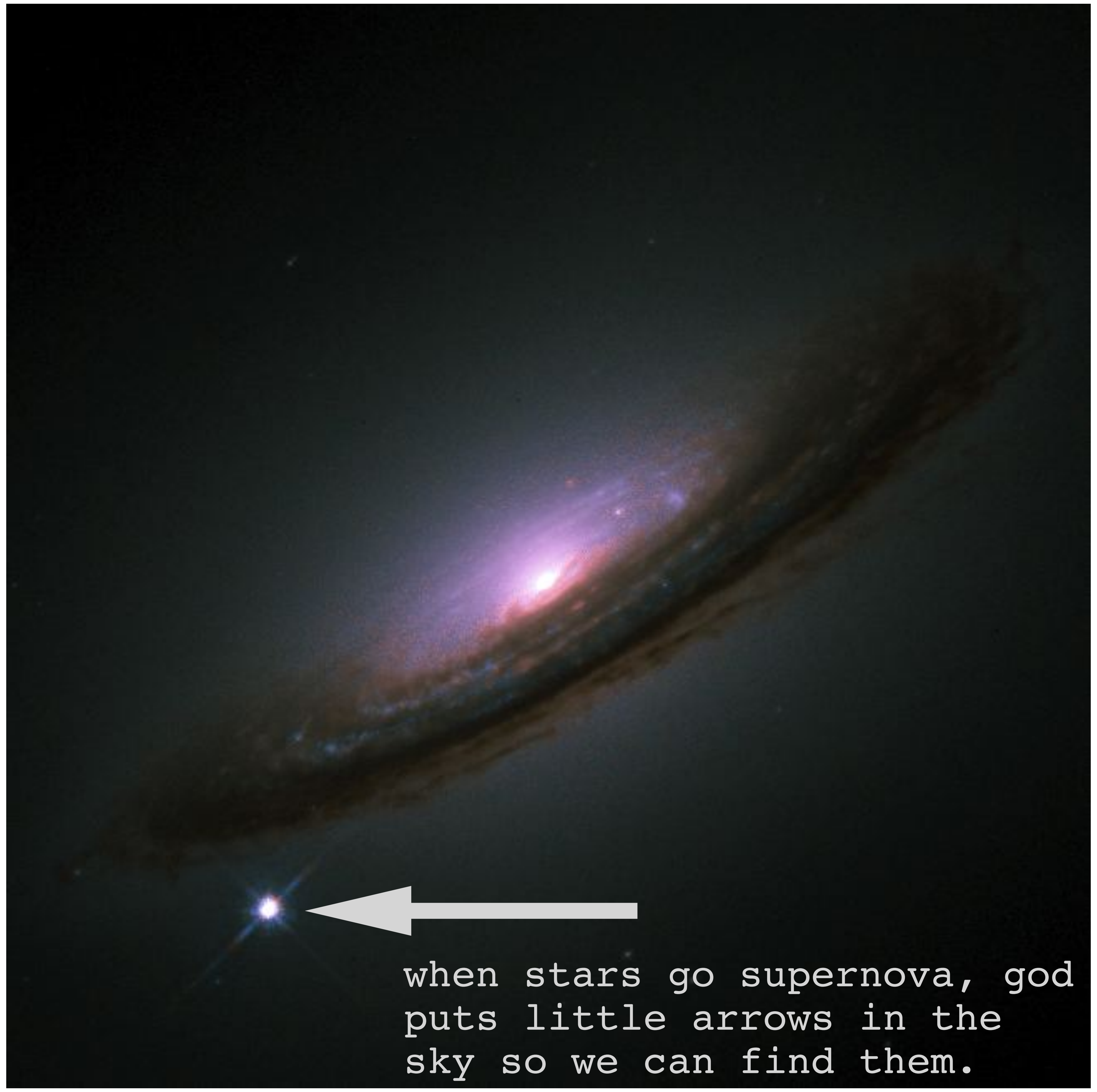
Peebles Fig. 13.6

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.



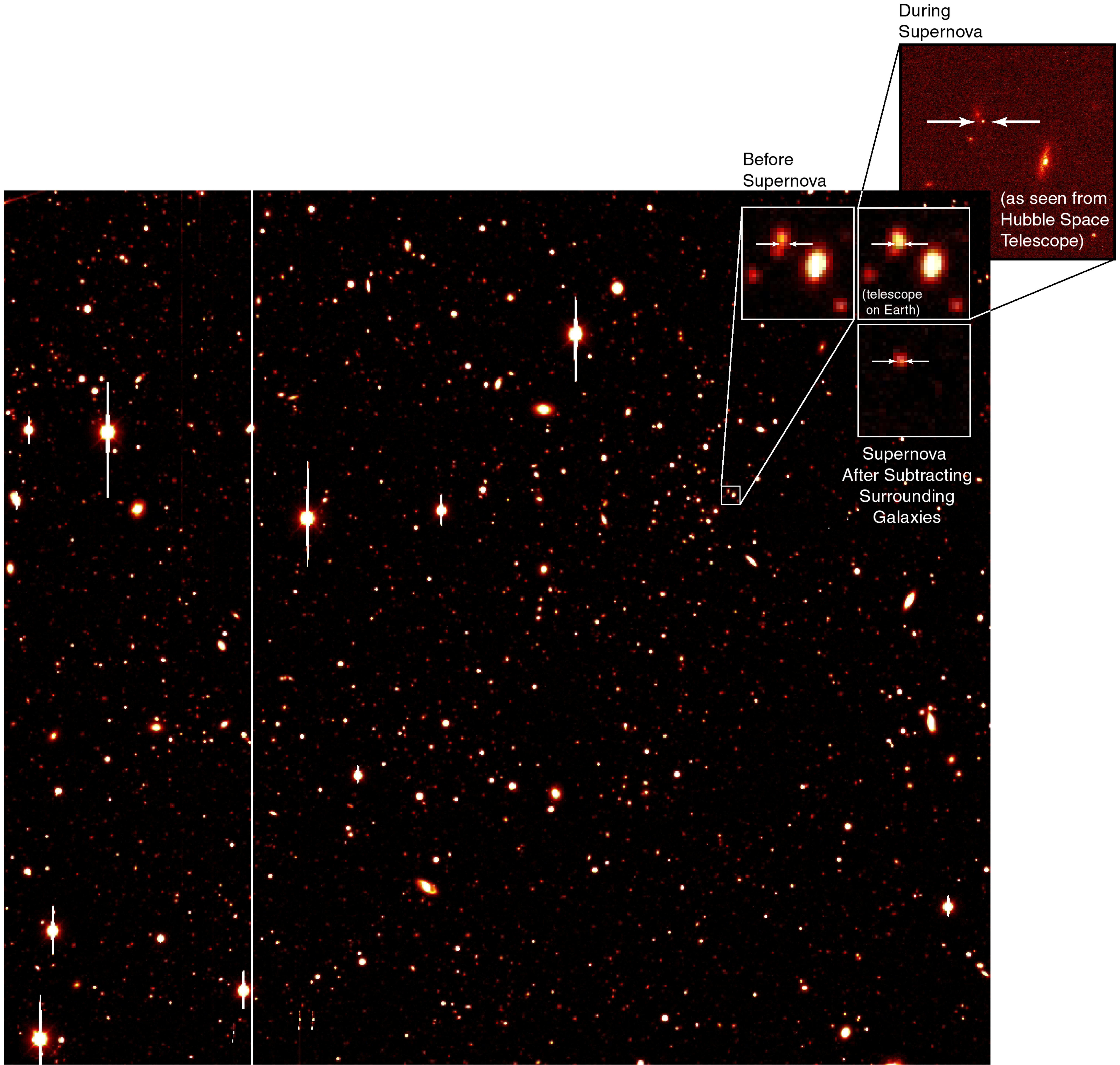
Example Standard Candle:

- 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

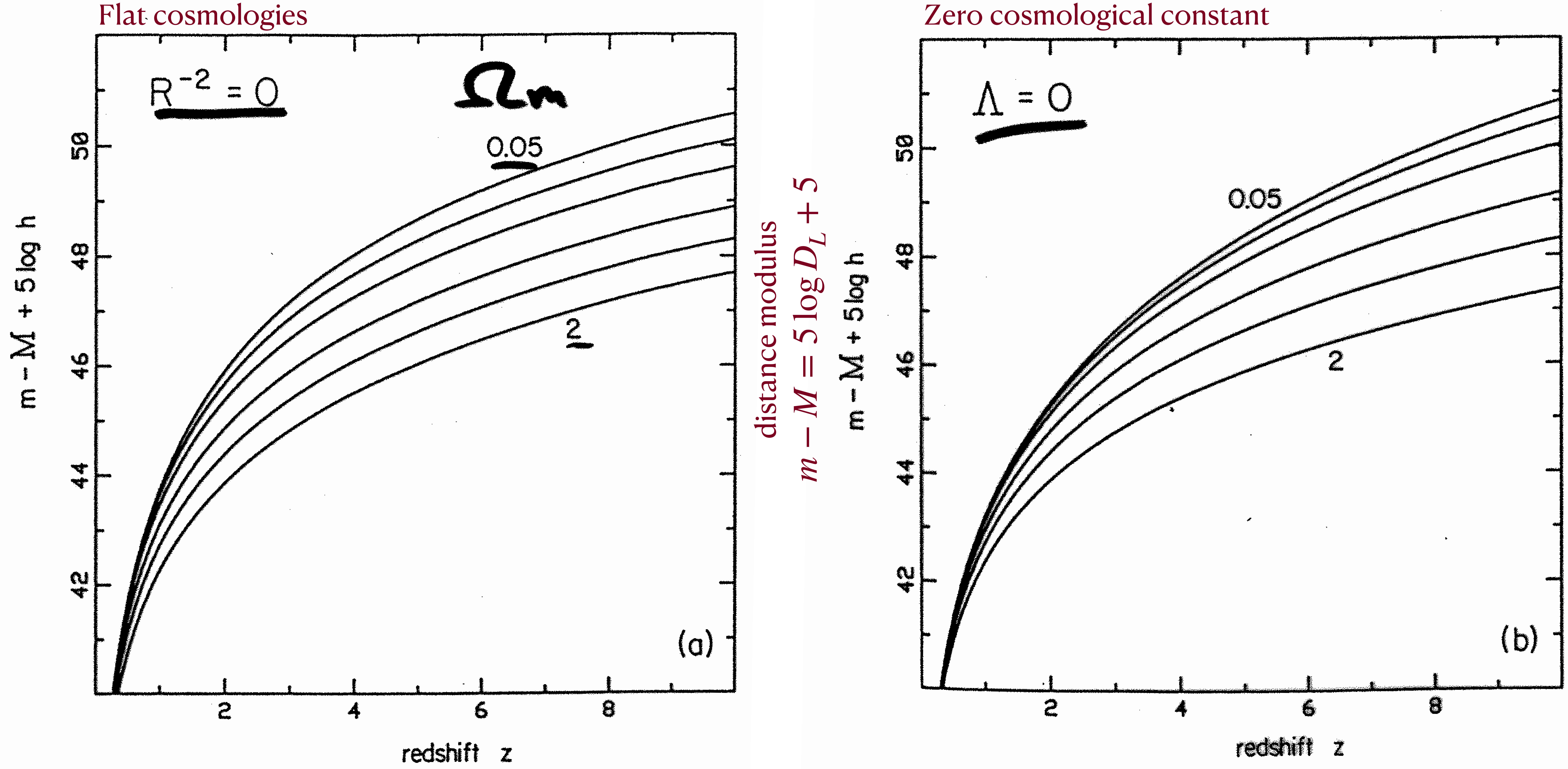
Perlmutter et al. (1998)



- 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.

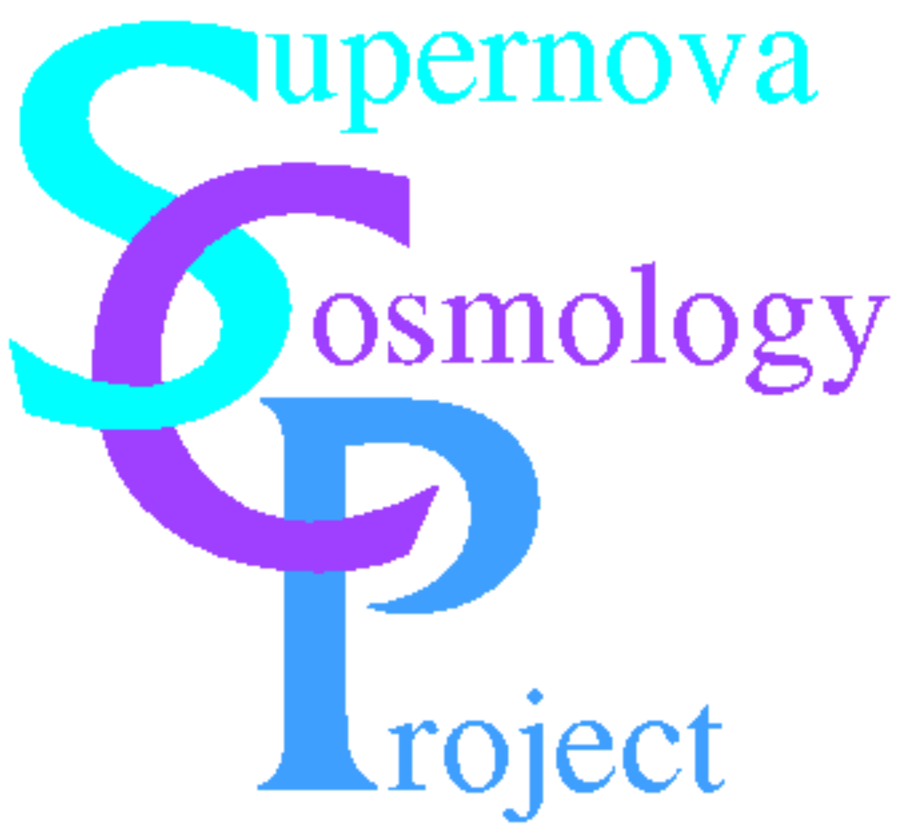


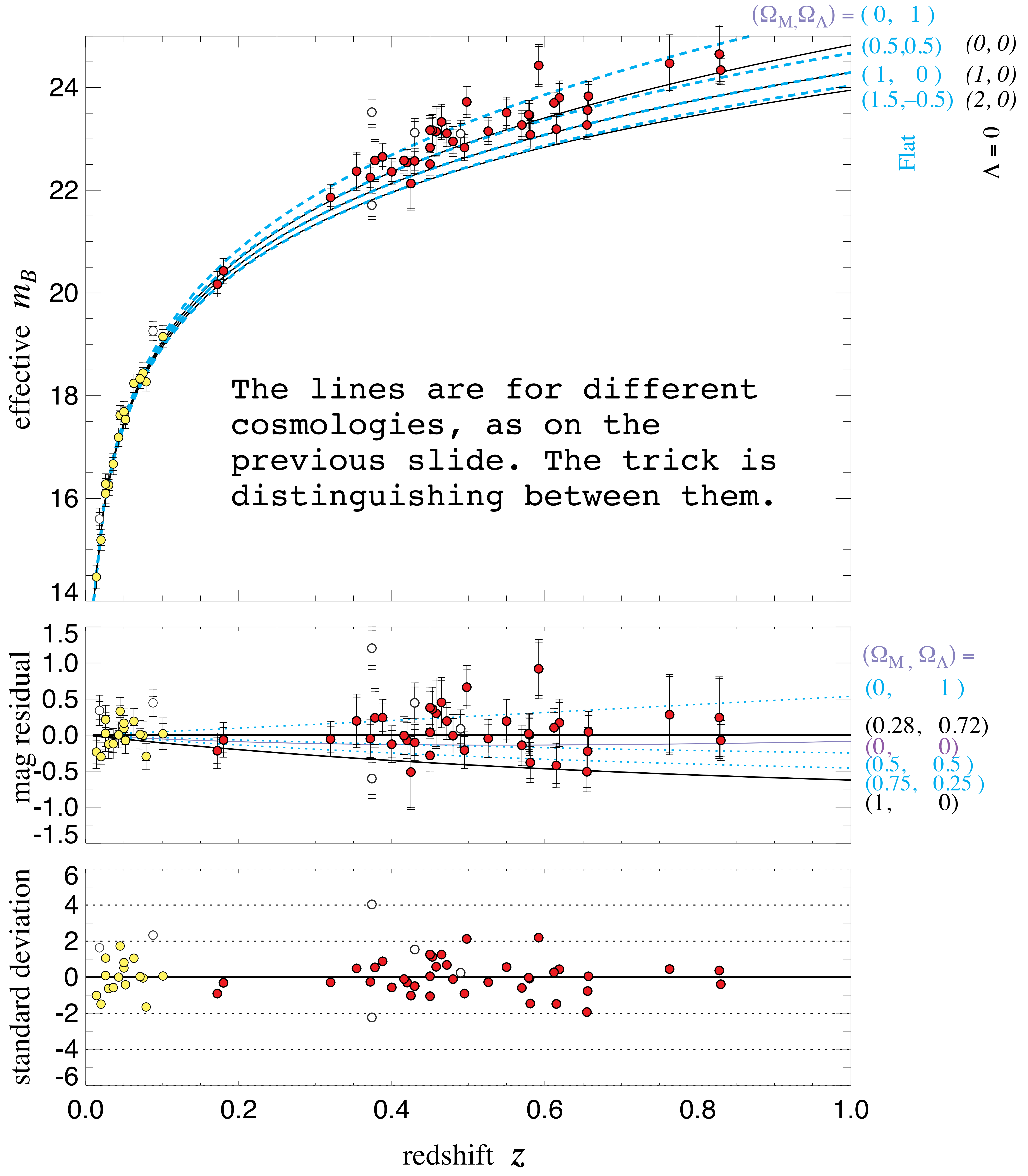
Peebles Fig. 13.6

- Luminosity-redshift relation

Hubble diagram
apparent magnitude vs. redshift
equivalent to distance modulus for standard candle
(M constant)

This example for Type Ia SN from the Supernova Cosmology Project
(won the Nobel Prize in Physics in 2011)



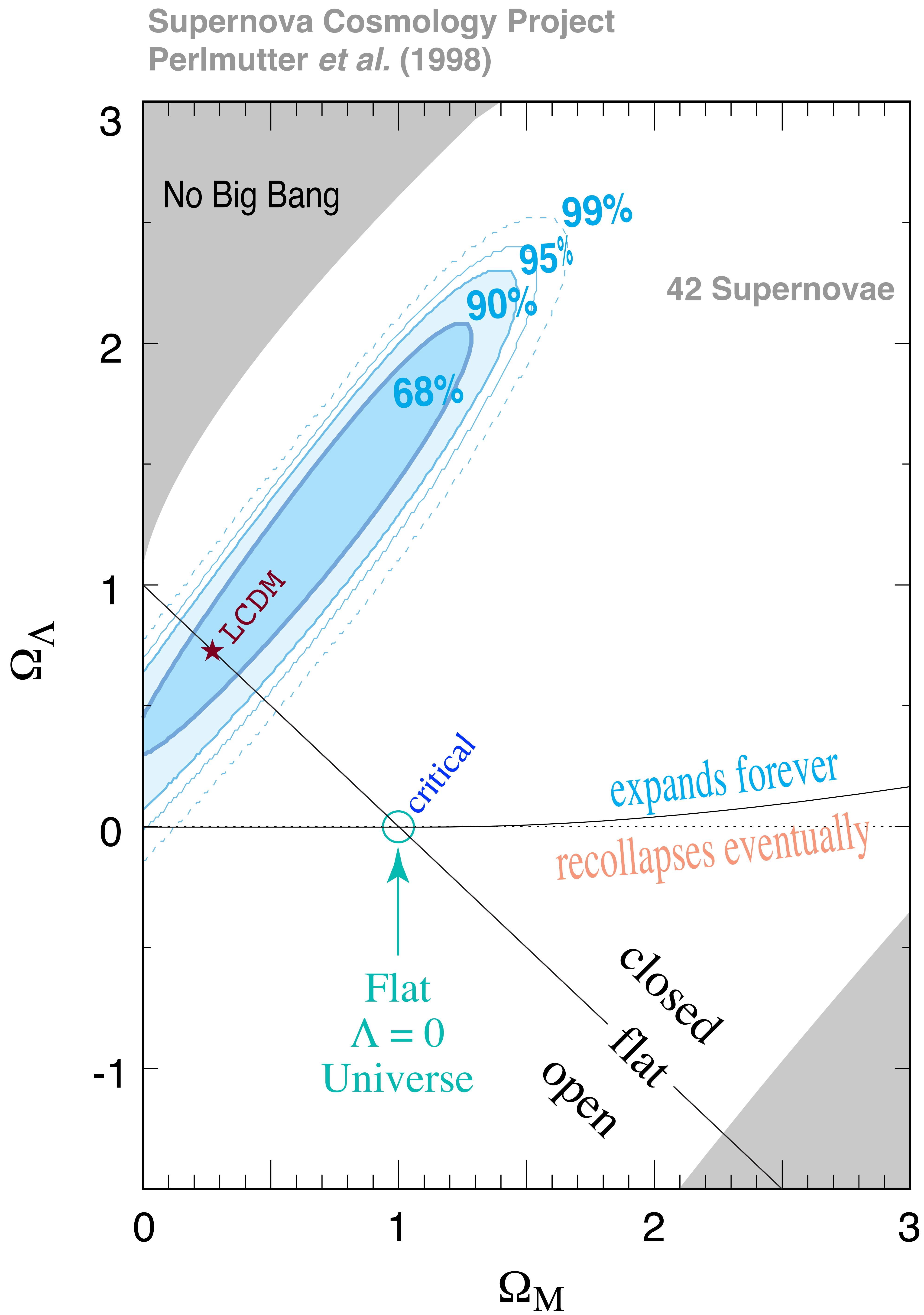


Perlmutter, *et al.* (1998)

- Luminosity-redshift relation

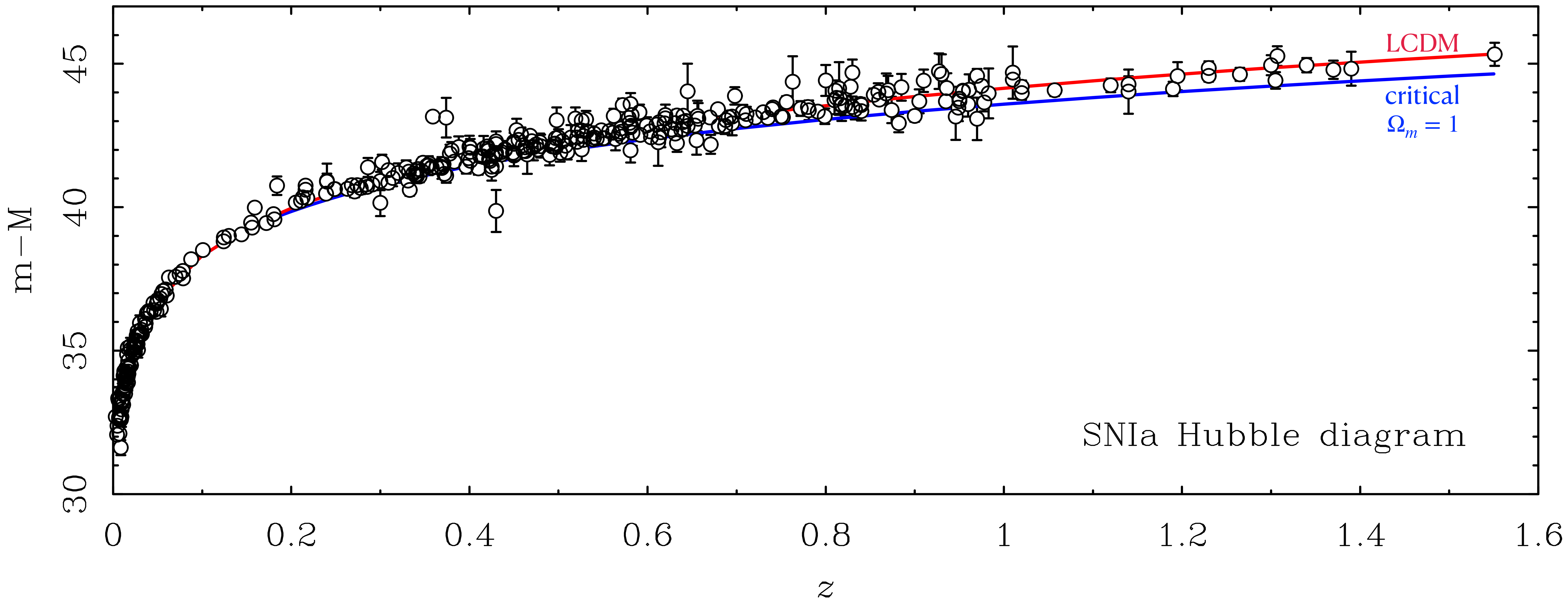
The Type Ia SN constraint practically excluded non-zero cosmological constant, but it did not provide a strong constraint on Ω_m and Ω_Λ individually.

LCDM depended on the inclusion of other information, like independent measures of the mass density and the assumption of a flat geometry.



- Luminosity-redshift relation

<u>Type Ia SN Hubble diagram</u>
(more recent data)



- Angular size-redshift relation

Ideal case:
a **Standard Rod**
an object of constant, known size ℓ

angular extent & size

$$\theta = \frac{\ell}{D_A}$$

Angular size distance

$$D_A = \frac{D_p}{(1+z)}$$

Note that

$$D_A = \frac{D_L}{(1+z)^2}$$

ANGULAR-DIAMETER DISTANCE 137

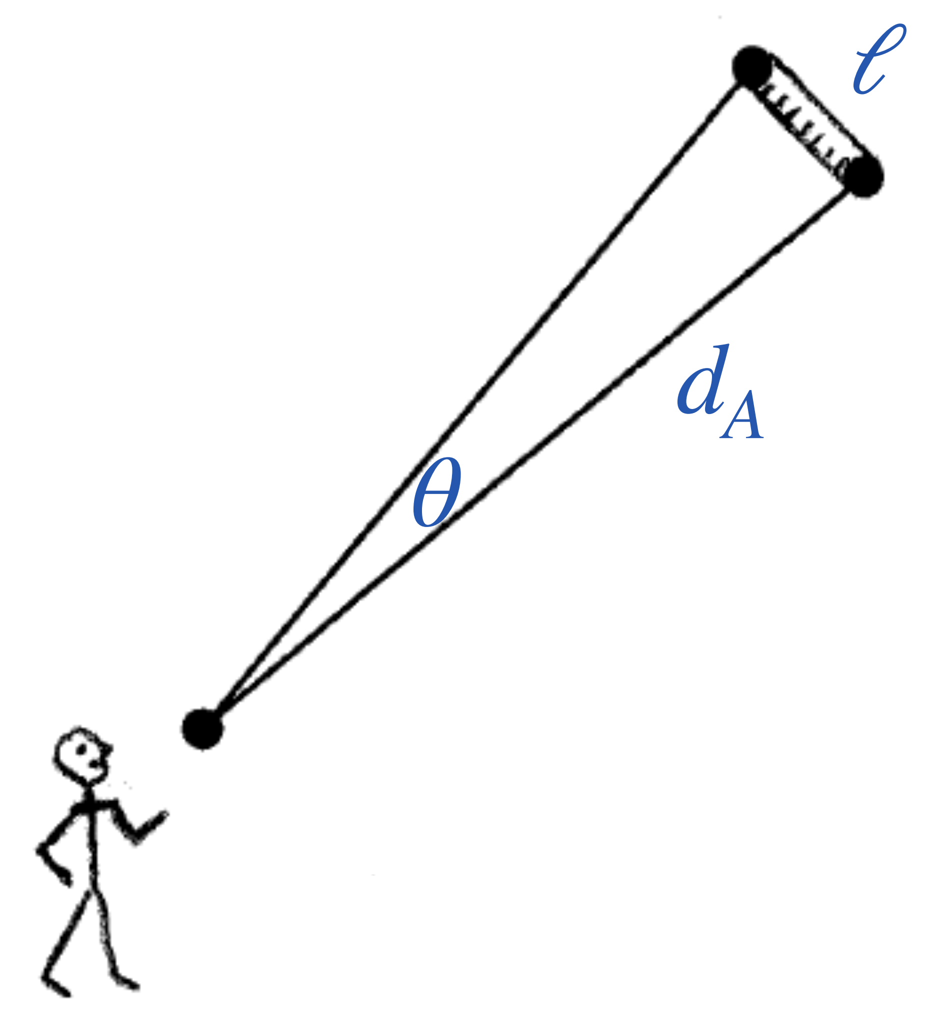
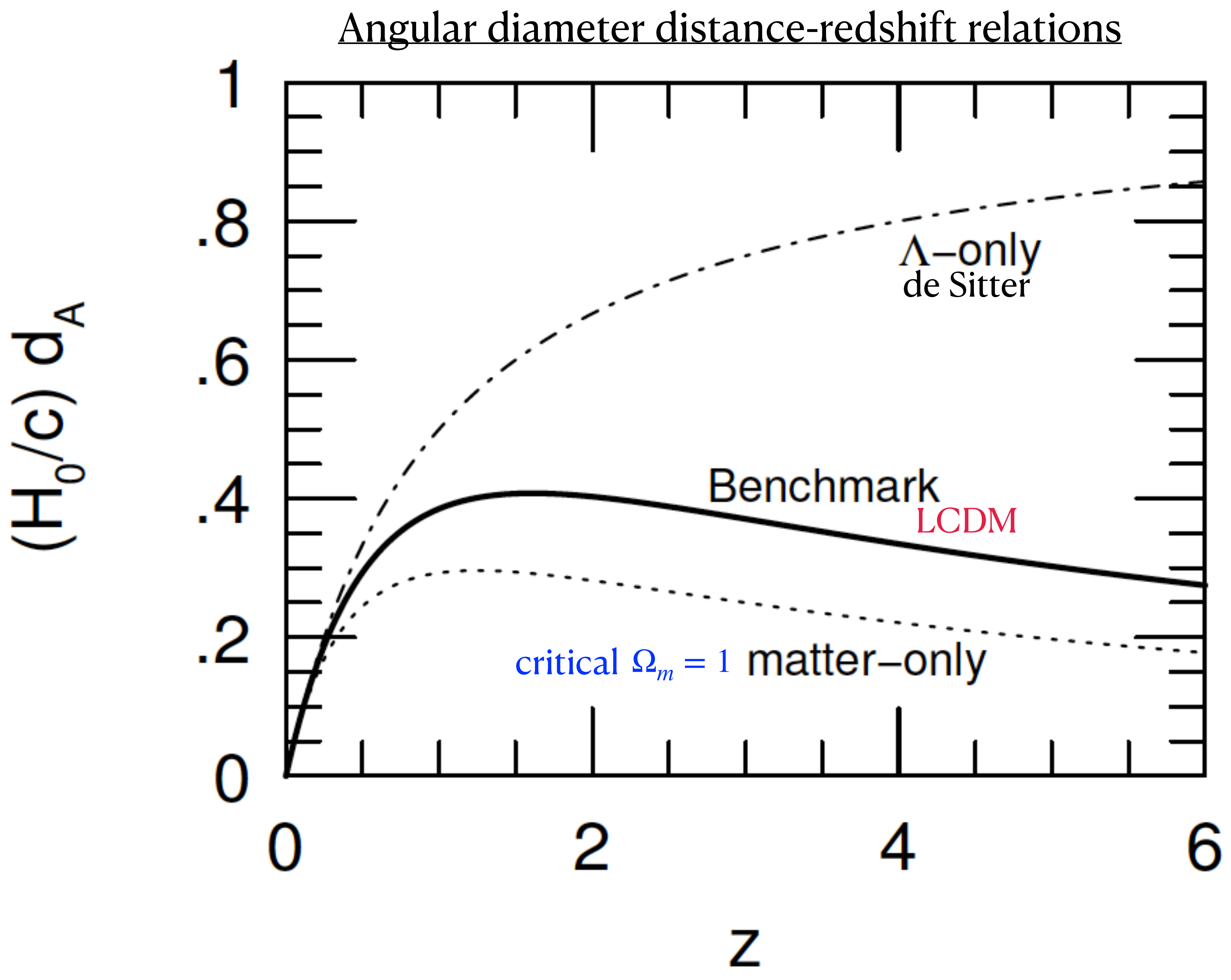


Figure 7.3: An observer at the origin observes a standard yardstick, of known proper length ℓ, at comoving coordinate distance r.

- Angular size-redshift relation



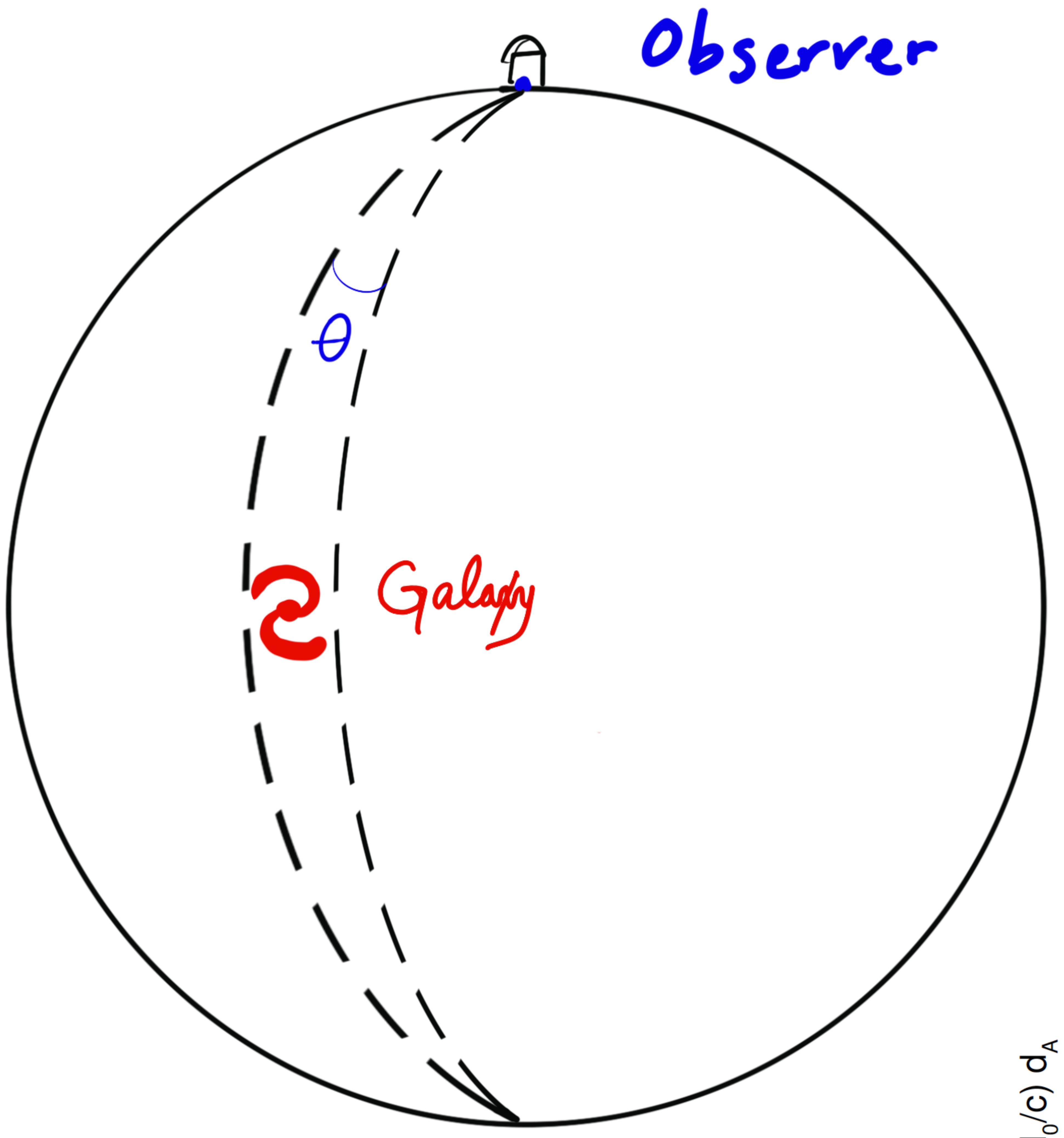
Note that the angular diameter distance never exceeds the Hubble length.

Sometimes has a maximum!

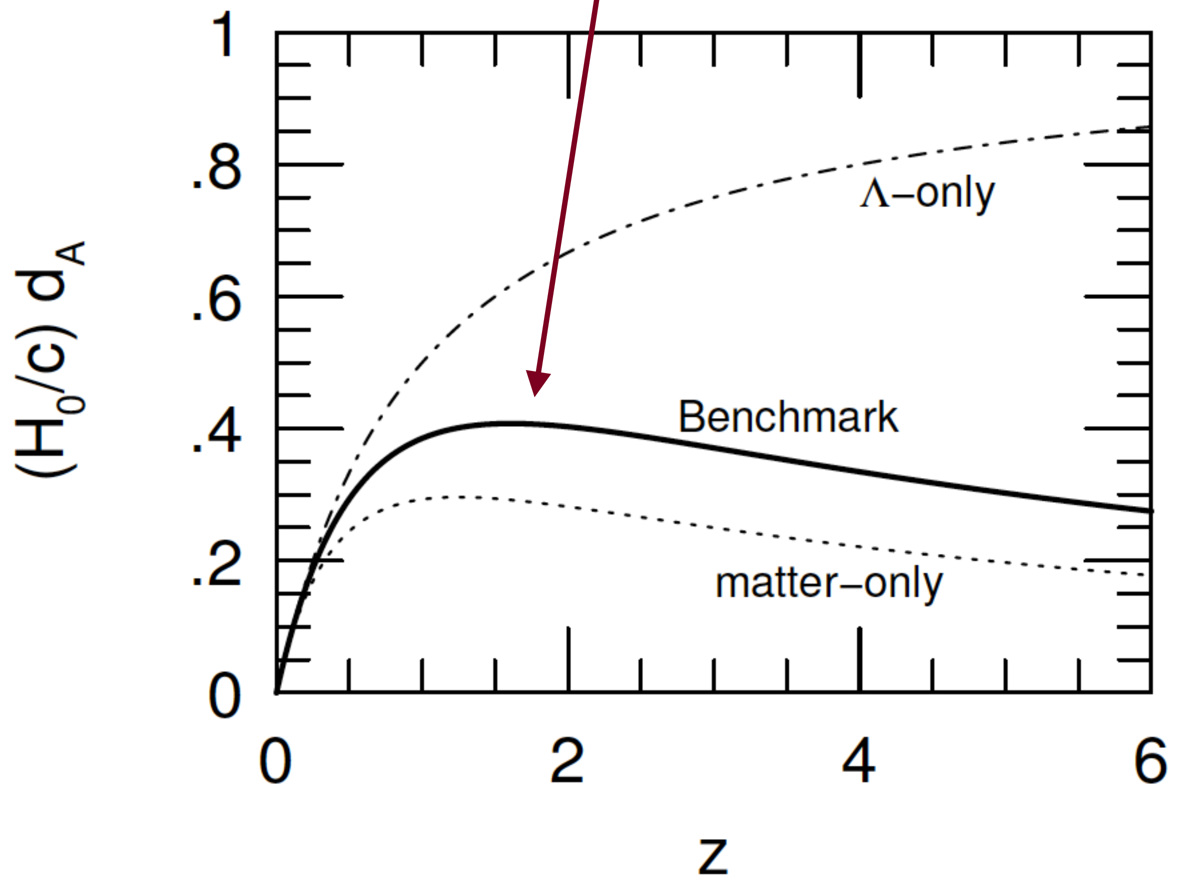
Figure 7.4: The angular-diameter distance for a standard yardstick with observed redshift z. The bold solid line gives the result for the Benchmark Model, the dot-dash line for a flat, lambda-only universe, and the dotted line for a flat, matter-only universe.

Ryden Fig. 6.4 (2nd ed)

Angular size can have a minimum in non-Euclidean geometries because of the divergence of light rays. Beyond the distance corresponding to this minimum size, objects start to look bigger again!



For LCDM, the minimum angular size occurs around $z \approx 1.6$ at $D_A \approx 1.75$ Gpc



- # Angular size-redshift relation

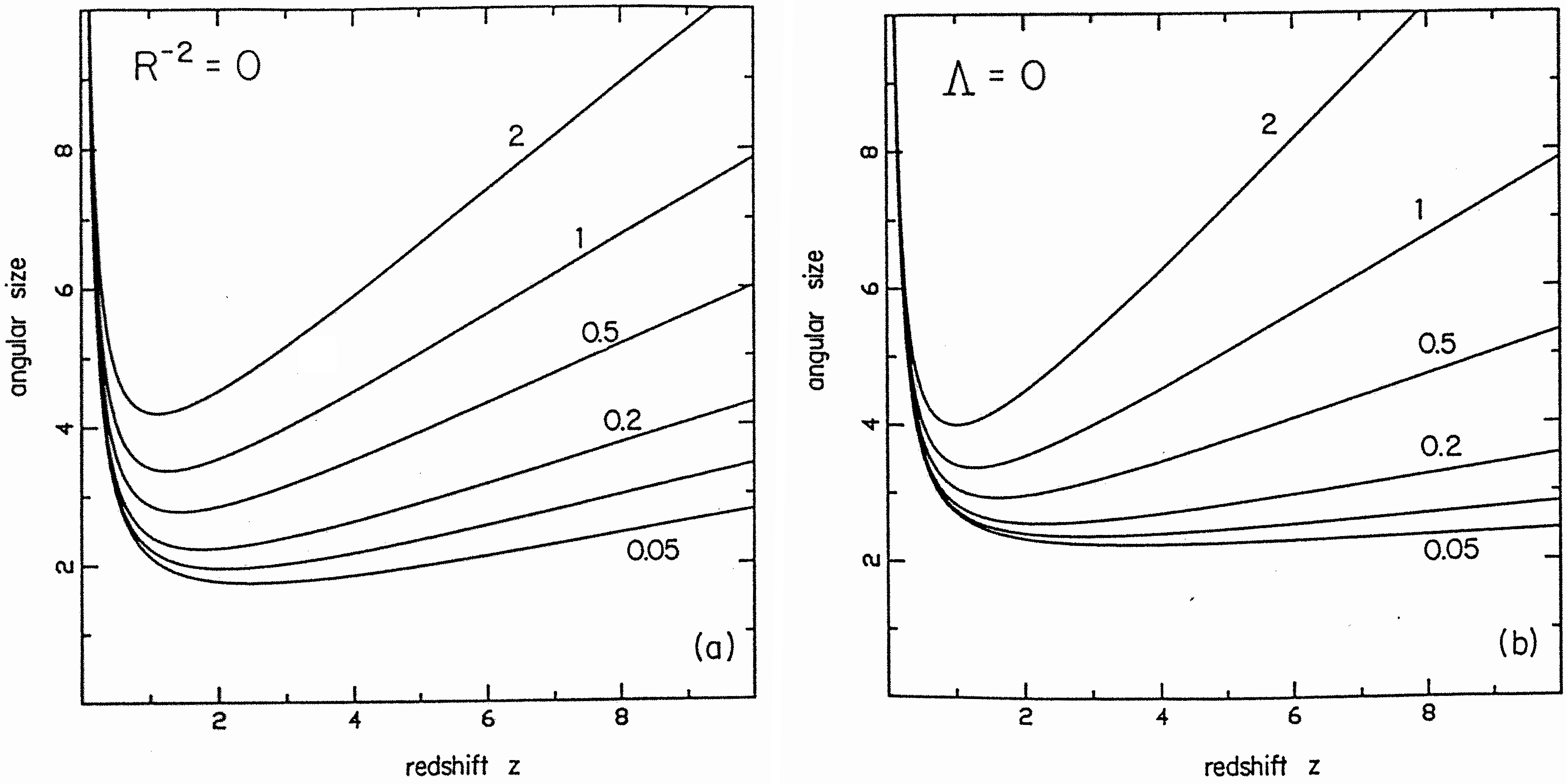
Peebles Fig. 13.5

<u>Angular Size-redshift relations</u>

Flat cosmologies

Zero cosmological constant

Figure 13.5. Angular size as a function of redshift. The vertical axis is the factor $F_\theta = (1+z)/H_o a_o r(z)$ in equation (13.47). The parameters are arranged as in figure 13.1.



Initially objects decline in angular size with increasing distance, but this trend reverses at high redshift in the Robertson-Walker geometry!

- Angular size-redshift relation

L.I. Gurvits et al.: The “angular size – redshift” relation f

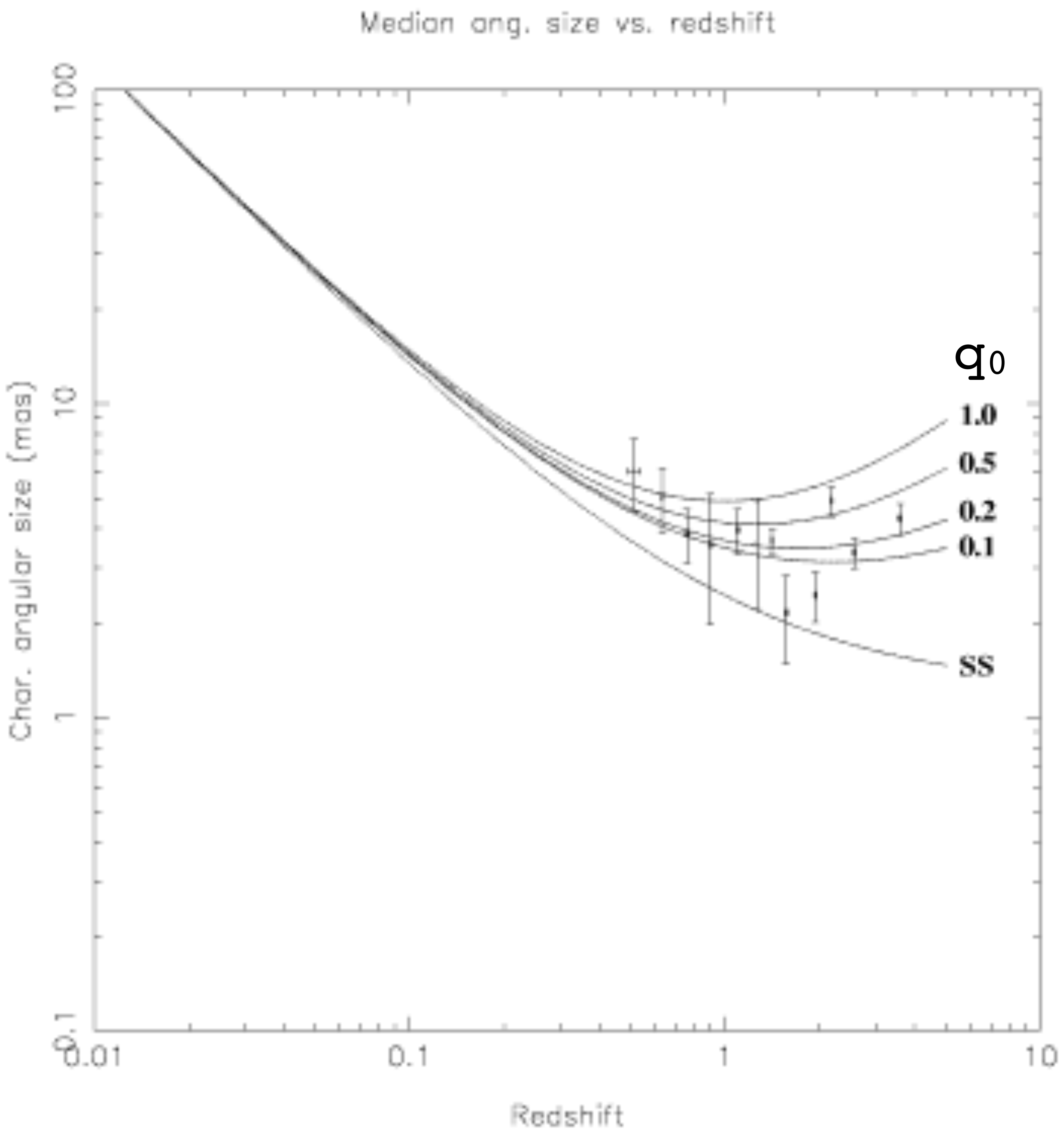


Fig. 10. Median angular size versus redshift for 145 sources (binned into 12 bins, 12–13 sources per bin) with $-0.38 \leq \alpha \leq 0.18$ and $L \geq 10^{26}$ W/Hz. The solid lines correspond to the linear size parameter $lh = 22.7$ pc, the Steady-state model (SS) and models of a homogeneous, isotropic Universe with $\Lambda = 0$ and various shown values of $q_{\circ}$. None of the solid lines represents the best fit.

Gurvits et al. (1999)
Fig. 10

angular sizes of compact radio sources

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