The age of the universe

- The age of the universe
  - Time elapsed from the birth of the universe (R=0) to the present epoch (R=$R_{present}$).
  - Therefore, it depends on how R changes with time.
- The latest determination = **13.7 billion years**
  - This estimate was made possible by knowing the expansion of the universe accurately.

Deceleration and Acceleration

- Time evolution of R is classified as follows.
  - Constant speed expansion
  - Decelerating expansion
  - Accelerating expansion
- The latest observations suggest that the expansion was
  - accelerating in the very early universe,
  - then decelerating until recently, and
  - accelerating again at present.

Three Redshifts

- Redshift – wavelength of light is stretched
  - c.f., Blueshift – wavelength of light is squeezed
- Doppler Redshift
  - Wavelength is stretched by relative motion
  - z = (relative velocity)/c
    - This formula is correct only when velocity is much smaller than c
- Gravitational Redshift
  - Wavelength is stretched by strong gravity
  - z = (1/2)[(escape velocity)/c]^2
    - This formula is correct only when velocity is much smaller than c
- Expansion Redshift
  - Wavelength is stretched by expansion of space
  - z = (scale factor at reception)/(scale factor at emission) – 1

Pitfall

- Many people confuse the "expansion redshift" with the "Doppler redshift". They are different!
  - Confusion may arise from the use of the term, "recession velocity".
  - However, **galaxies are not moving in comoving coordinates!** Space between galaxies is expanding.
  - On the other hand, peculiar velocity causes the Doppler redshift.
  - Keep in mind the difference.
    - Observed velocity of a galaxy
      = recession velocity : due to expansion of space
      + peculiar velocity : due to galaxy's motion

…light-years away

- Newspapers often say that "astronomers have discovered the most distant galaxy at 12 billion light years away". What do they really mean?
  - As we have already learned, what astronomers measure is redshift. One has to use the measured redshift for calculating "how many years ago it was when light was emitted".

Redshift	**How many billion years ago**
0.01	0.14
0.1	1.3
0.5	5.0
1	7.7
2	10.2
3	11.4
4	12.0
5	12.3
10	13.0
100	13.4

To do this conversion, we have to know how *R* has changed with time.