Three Distinctive Redshifts

- Redshift
  - the amount by which the 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

- Almost everybody in the public (including news papers, scientific magazines, books, etc.) confuses 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,** except for motion due to mutual gravitational attraction between galaxies. Space between galaxies is expanding.
  - It is the peculiar velocity that causes the Doppler redshift, not the expansion of the universe.
  - 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

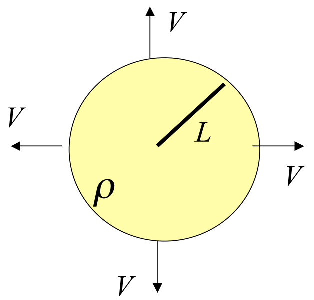
- Newspapers often say that “astronomers have discovered the most distant galaxy at 12 billion light years away”. What do they really mean?
  - As we have already learned, what astronomers measure is redshift. One has to use the measured redshift for calculating “how many years ago it was when light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

Expanding Cosmic Sphere Model

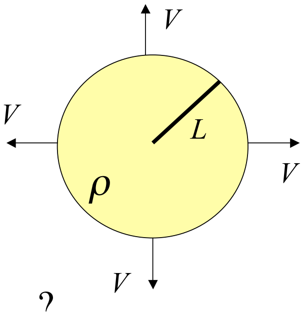
- Let’s pick a small spherical region (filled with matter) in the universe.
  - Radius: L
  - Mass: M
  - Density: ρ
  - Expansion Velocity: V



- Will this region expand forever?
  - It depends on the expansion velocity, V.

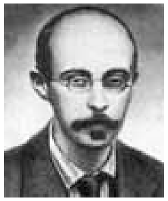
Escape Velocity

- Escape velocity is given by
  - $(V_{escape})^2=2GM/L$
    - The mass is $M=(4\pi G/3)\rho L^3$
  - $(V_{escape})^2= (8\pi G/3)\rho L^2$



- Is V larger or smaller than V_{escape}?
  - $V< V_{escape}$: the region will recollapse in the future
  - $V= V_{escape}$: the region will expand forever
  - $V> V_{escape}$: the region will expand forever

Friedmann Equation



- Let's write the expansion velocity using the escape velocity as follows:
  - $V^2 = (V_{escape})^2 + C$
  - The constant, "C", determines the fate of the region:
    - $C<0$: recollapse
    - $C=0$, $C>0$: expand forever
- Recalling the form of the escape velocity, one obtains the following "Friedmann equation":
  - $V^2 = (8\pi G/3)\rho L^2 + C$
  - The velocity-distance relation, $V=HL$, gives the most popular form of the Friedmann equation:
  - **$H^2 = (8\pi G/3)\rho + C/L^2$**
    - **This equation determines how the universe expands and what the fate of the universe is --- extremely important in cosmology!**

Acceleration

- In addition to the Friedmann equation,
  - **$H^2 = (8\pi G/3)\rho + C/L^2$**

  which describes the expansion velocity, there is the second equation which describes the **acceleration** of the expansion:
  - **$a = -(4\pi G/3)\rho L$**
    - Notice the negative sign in front: the presence of matter always ***decelerates*** (**$a<0$**) the expansion.
- Einstein did not like this.
  - Einstein wanted the universe to be static – neither expanding or contracting – however, this equation does not permit it.
  - He added the "cosmological constant", Λ, to this equation in order to cancel the effect of matter:
    - **$a = -(4\pi G/3)\rho L + \Lambda L/3 = 0$**
  - **This Λ is what Einstein called later "the biggest blunder".**
- More importantly, Λ can *accelerate* the expansion, unlike the ordinary matter.

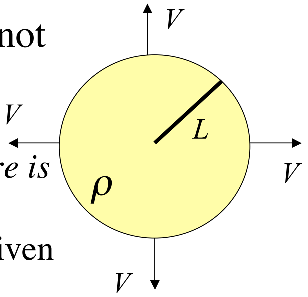
The fate of the universe

- We have now two fundamental cosmological equations:
  - **$H^2 = (8\pi G/3)\rho + C/L^2 + \Lambda/3$**
  - **$a = -(4\pi G/3)\rho L + \Lambda L/3$**
- These equations determine how the scale factor, R, changes with time. (remember $L=Rl$)
  - We have three quantities to specify
    - ρ, C, Λ
  - Here is the bottom line: we need to determine these quantities by observations.
    - These are called the "cosmological parameters" and determination of the cosmological parameters has been the most important task in cosmology as they determine the evolution of R in the past and in the future.

Where is relativity?

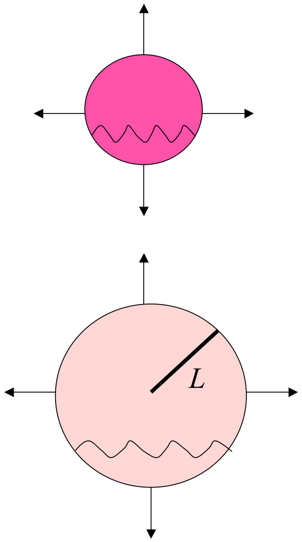
- The derivations of the Friemann equation so far did not use relativity – it was totally Newtonian.
- Where is relativity?
  - In Newtonian picture, it is not clear what C really means or what determines *C*.
  - In relativistic picture, *C* is actually related to the geometry of space:
    - $C<0$: spherical geometry
    - $C=0$: flat geometry
    - $C>0$: hyperbolic geometry
  - In other words, the geometry of the universe determines the fate of the universe!!
    - Spherical geometry: recollapse
    - Flat or hyperbolic geometry: expand forever

Expanding Cosmic Sphere



- Matter inside of the sphere does not go outside of the sphere. (Matter doesn't escape)
  - Therefore, *mass inside of the sphere is conserved.*
  - Energy of matter in the sphere is given by Einstein's relation: **$E=Mc^2$**
  - So, energy of matter is also conserved.
- Since mass energy is conserved, **energy density decreases as $1/L^3$** as the sphere expands.

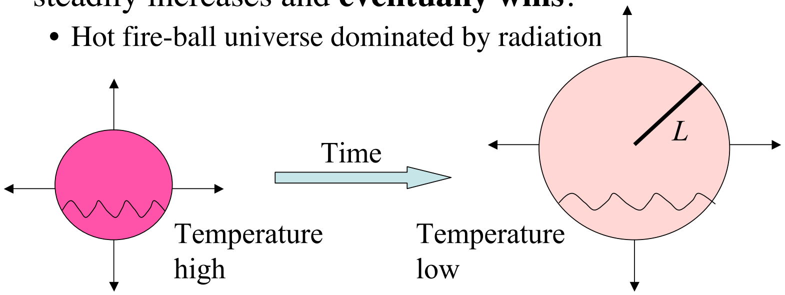
Radiation in the sphere



- Next, let's consider radiation (or light or photons)
  - Would energy of radiation also be conserved?
  - Radiation continues to lose its energy as the sphere expands, due to the *expansion redshift*!
    - Remember the expansion redshift stretches wavelength and energy of radiation is inversely proportional to wavelength.
  - Energy of radiation decreases as 1/L → temperature goes down as 1/L
- Since energy goes as 1/L, **energy density decreases as $1/L^4$** as the sphere expands.

Important consequences

- Energy of matter is constant.
- Energy of radiation decreases as 1/L.
- Currently, the matter energy dominates over the radiation energy, but…
  - As we go back in time, the radiation energy steadily increases and **eventually wins**!
    - Hot fire-ball universe dominated by radiation

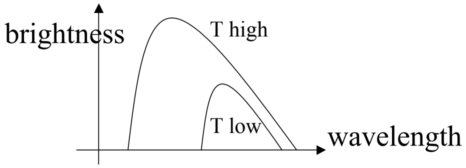


Cosmic Microwave Background

- In the past, when the energy was dominated by radiation, the universe was filled with hot radiation.
- This radiation still fills the universe today.
- Why don't we see it by eyes at night then?
- Temperature of this radiation (called the cosmic microwave background radiation) has gone down so much that we don't see it.
  - Temperature is only 2.73 degrees above absolute zero. (2.73 K)
  - Compare this extremely low temperature with temperature of the surface of the Sun: 5800K
  - When the size of the universe was about 1/2000 of the present size, temperature of the universe was about the same as that of the Sun.

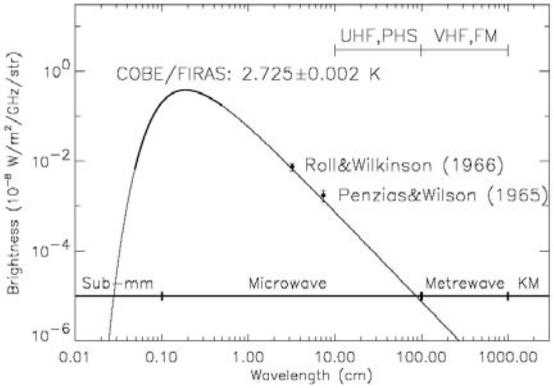
Spectrum of CMB

- The cosmic microwave background (CMB) has a ***black-body*** spectrum.
  - Stars also have a nearly black-body spectrum
  - CMB has a perfect black-body: the most beautiful black-body in the universe
- A black-body spectrum is determined by temperature only.
  - There is a peak in a black-body spectrum which shifts to longer wavelength as temperature goes down.



- The spectrum of CMB has a peak at 1.1mm.
- Let's compare it with…

– Microwave oven:	12cm
– Cellular phone:	20cm
– UHF Television:	39-64cm
– FM radio:	3m
– AM radio:	300m



You can "see" CMB by TV (not by cable TV of course!), and you can "hear" CMB by cell phone!!