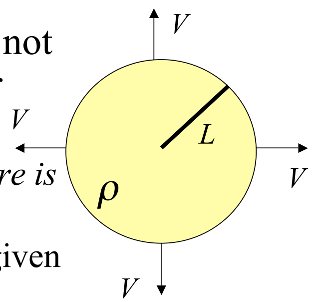
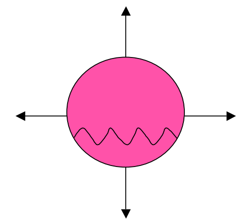
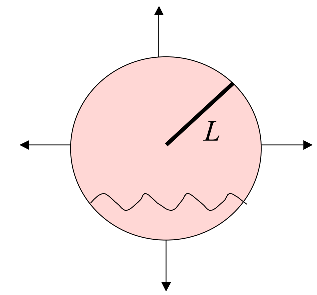
Expanding cosmic sphere



- 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

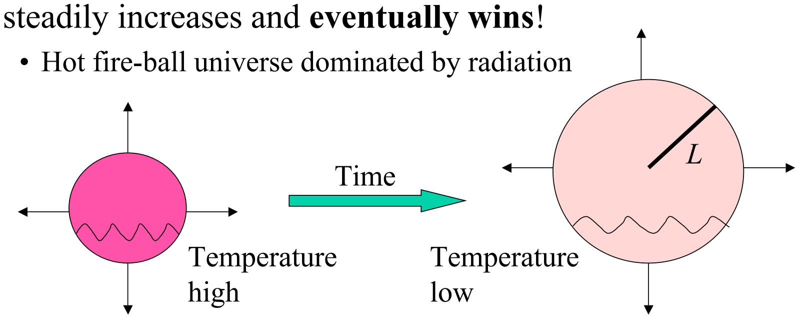




- Next, let's consider radiation (or light or photons)
  - Would energy of radiation also be conserved?
  - Radiation continues to lose its energy as the sphere expands, due to the *expansion redshift*!
    - Remember the expansion redshift stretches wavelength and energy of radiation is inversely proportional 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 consequence

- 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

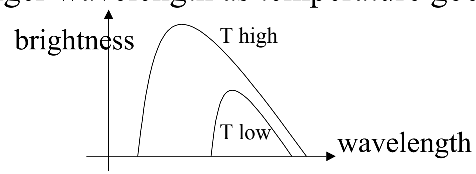


Cosmic Microwave Background

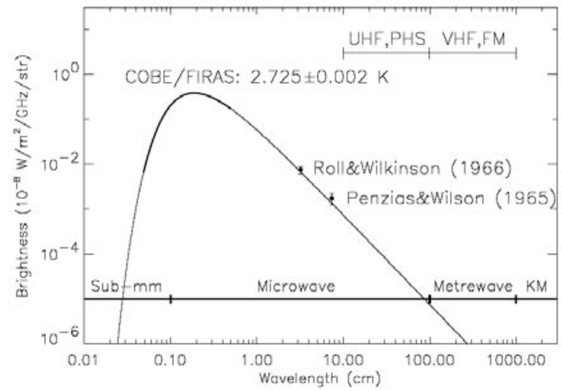
- In the past, when the energy was dominated by radiation, the universe was filled with hot radiation.
- Believe it or not, this radiation still fills the universe today!
- Why don't we see it by eyes at night then?
  - Why is the night sky dark?
  - Expansion explains it.
- Temperature of this radiation (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!!