Horizons in the Universe

- The horizon divides all events in the spacetime diagram into two regions.
- Two horizons
  - Particle horizon ("world-line horizon")
    - Divides the events into "visible" and "invisible" ones from one particular observer's point of view **at a given moment**.
    - The particle horizon exists when there is the beginning.
      - Space-time diagram is useful for understanding this.
    - The particle horizon grows over time.
  - Event horizon
    - Divides the events into the ones that are visible at some time or other and **those that are never visible at any time** from particular observer's point of view.
    - The event horizon exists when there is an end.
    - The event horizon does not change over time

Horizon and Recession Velocity

- Would the velocity-distance relation, V=HL, define the event horizon?
  - No, because H changes over time. The objects that were once outside L=c/H would come inside L=c/H later, as H decreases with time.
- The particle horizon does not always coincide with L=c/H either.
  - When the universe is matter dominated, the particle horizon is given by 2c/H.
  - The particle horizon coincides with c/H only when the universe is radiation dominated.
- The particle horizon is not given by ct.
  - The particle horizon = 3ct during the matter era.
  - The particle horizon = 2ct during the radiation era.
- The age of the present universe is 13.7 billion years. How many light-years would the particle horizon size be?

The Horizon Problem

- Why do galaxies look alike?
- Why is the cosmic microwave background so isotropic?
- Because the particle horizon grows over time, the particle horizon was smaller in the past.
  - Some of the galaxies we see today might not have had a chance to communicate each other in the past.
    - Why do they look so similar?
  - When the cosmic microwave background radiation was emitted, there was no chance for photons in one place to propagate to the other at more than 1 million light years away.
    - Why is the CMB so isotropic?

Four Problems in the Big-bang theory

- Horizon Problem
  - Why do galaxies look alike?
  - Why is the CMB so isotropic?
- Flatness Problem
  - Why is the geometry of the observable universe so flat?
    - In fact, the Friedmann equation tells us that it is very unnatural to have a flat universe.
- Monopole Problem
  - Why is there no monopole in the universe?
    - The grand unified theories predict that there should be as many monopoles as photons today. (North and south monopoles would be created in pairs in the very early universe.)
- The origin of galaxies
  - Where did the irregularities come from?

- Accelerated expansion in the early universe solves all the problems (Alan Guth, 1981)
  - Very rapid expansion that occurred when the universe was only 10^{-36} seconds old.
  - Inflation lasted from age 10^{-36} seconds to 10^{-34} seconds, and the size of the universe increased by an enormous factor.
- What caused inflation?
  - Dark energy in the early universe (c.f., dark energy at late times)
- Horizon Problem Solved
  - Observable universe is only a tiny fraction of inflated patch
- Flatness Problem Solved
  - The pre-existing curvature is stretched out by inflation
- Monopole Problem Solved
  - The abundance is diluted to negligible amount
- The origin of galaxies
  - Quantum mechanical fluctuations

Reheating of the Universe

- During inflation, temperature of the universe rapidly drops down to essentially zero.
- How did the universe become hot again?
- Dark energy (at early times) decays into heat, which heats up the universe back to a very high temperature.
  - Reheating of the universe
- Then, the ordinary big-bang model describes the subsequent evolution of the universe.