Introduction

Cosmology: Study of the universe: structure and evolution on large scale.

- Gravity is the dominant force (though EM is stronger, large-scale objects are neutral)

GR: governs the evolution of the universe

Newtonian limit: at scales smaller than horizon, Newtonian gravity becomes excellent approximation.

Expansion of the Universe only calls for redefinition of momentum and coordinates.

Units

<table>
<thead>
<tr>
<th>Objects</th>
<th>Mass (g)</th>
<th>Size (radius)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>$1M_\odot = 2 \times 10^{33}$</td>
<td>$7 \times 10^{10}$</td>
</tr>
<tr>
<td>Galaxy</td>
<td>$\sim 10^{11} M_\odot = 2 \times 10^{44}$</td>
<td>$\sim 10$ kpc $= 3 \times 10^{22}$</td>
</tr>
<tr>
<td>Cluster</td>
<td>$\sim 10^{14} M_\odot = 2 \times 10^{47}$</td>
<td>few Mpc $= 10^{25}$</td>
</tr>
<tr>
<td>Universe</td>
<td>$\sim \text{Sect} \times \text{Horizon} = 8 \times 10^{55}$</td>
<td>Horizon $= 3000$ Mpc $= 10^{28}$</td>
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$\text{pc}$: distance where star has a period of 1 arc sec.
- The mass distribution is close to homogeneous and isotropic on large scales (on avg.)

- The universe is expanding, mean velocity between objects:
  \[ V_{\text{H}0} r = H_0 r \]
  \[ H_0 = 100 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1} \]

- Dynamics of expanding Universe obeys GR
  (local physics is same everywhere and at all times)

- The universe expanded from a hot dense state where energy was dominated by radiation
Homogeneity & Isotropy

Homogeneity: invariance under translations
Isotropy: invariance under rotations

in the empty Universe

Obviously, if these do not hold exactly, but statistically (we shall come back to this later in the course)

- How do time enter into the picture?

We cannot say that in some particular time slice since this is observer dependent. The time slice we mean is that of comoving observers:

- locally at rest and \( \dot{a} = 0 \) (with respect to nearby matter)
- moves with the expansion of the Univ
- measures zero momentum density at their location

- comoving are inertial obs, but not the other way around, since a boost generates velocity w.r.t local matter.

So: Universe is homogeneous:

Comov obs. see inv. under translations rotations

- Isotropic w.r.t. 2 points \( \Rightarrow \) Homogeneous
- Example of Homogeneous but Anisotropic

Cosmological Principle: The Universe is homogeneous and isotropic

Cannot be true at small scale, we mean in average sense, over scales much larger than typical structures.
Expansion of the Universe

Hubble obs (using cepheids w/HST) to get distances:

\[ H_0 = 500 \text{ km s}^{-1} \text{ Mpc}^{-1} \rightarrow \text{ age} \approx 2.6 \text{ yr} \quad \text{(in conflict)} \]

Wrong because of 2 different kinds of cepheids (+ P-L relation) and different H0 regions:

\[ H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad \text{(HST key project)} \]

(Show SNI diagram)

Note that \( \bar{v} \propto \bar{r} \) is compatible with Cosmological PPle, since \( \bar{v}_i - \bar{v}_c \propto \bar{r}_i - \bar{r}_c \)