

# General Relativity (I)

homework for week 15

due: week 18

1. [time-evolving universe] 60%

Consider the following example of an evolving Universe which is spatially **homogeneous** and **isotropic** at all cosmological times  $t$ :

$$ds^2 = -dt^2 + a(t)(dr^2 + r^2 d\Omega^2), \quad (1)$$

where  $a(t)$  is called the scale factor. Eqn (1) is a **comoving coordinate** as there is no  $g_{ti}$  terms and  $g_{tt}$  is independent of the spatial coordinates.

Representing  $(0, 1, 2, 3) = (t, r, \theta, \phi)$ , the non-vanishing Christoffel symbols are:

$$\begin{aligned} \Gamma_{11}^0 &= a\dot{a} & \Gamma_{22}^0 &= a\dot{a}r^2 & \Gamma_{33}^0 &= a\dot{a}r^2\sin^2\theta \\ \Gamma_{01}^1 &= \Gamma_{02}^2 = \Gamma_{03}^3 = \frac{\dot{a}}{a} & \Gamma_{22}^1 &= -r & \Gamma_{33}^1 &= -r\sin^2\theta \\ \Gamma_{12}^2 &= \Gamma_{13}^3 = \frac{1}{r} & \Gamma_{33}^2 &= -\sin\theta\cos\theta & \Gamma_{23}^3 &= \cot\theta \end{aligned}$$

(a) The (ideal) fluid at rest in co moving coordinates can be described by  $T_{\beta}^{\alpha} = \text{diag}(-\rho, p, p, p)$ . By the 00-term of EFE, show that  $R_{00} = T_{00} - \frac{1}{2}g_{00}T$  reduces to the so-called **acceleration equation** or the *second* Friedmann equation:

$$\boxed{\frac{\ddot{a}}{a} = -\frac{4\pi}{3}(\rho + 3p)} \quad (2)$$

(b) Show that  $g_{0\mu}T_{;\nu}^{\mu\nu} = 0$  reduces to the so-called **fluid equation**;

$$\boxed{\frac{\dot{\rho}}{\rho} = -3(1 + \omega)\frac{\dot{a}}{a}} \quad (3)$$

with the help of the equation of state:

$$p = \omega\rho, \quad (4)$$

where  $\omega = 0$  for matter and  $\omega = 1/3$  for radiation.

(c) Using Eqn (2) and (3) to obtain the *first* **Friedmann equation**:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}\rho \quad (5)$$

[hint: eqn (5) can be inferred from  $\frac{d}{dt}(\dot{a}^2) = \frac{d}{dt}\left(\frac{8\pi}{3}\rho a^2\right)$ ]

2. [evolution in the Friedmann models] 40%:

Eqn (1) is actually one possible realization of the **Robertson-Walker metric**

$$ds^2 = -dt^2 + a(t)\left(\frac{1}{1 - \kappa r}dr^2 + r^2 d\Omega^2\right), \quad (6)$$

where  $\kappa = (1, 0, -1)$  describes different 3D geometry. For cases of nonvanishing  $\kappa$ , both Eqn. (2) and (3) will remain the same, while the Friedmann equation including the  $\kappa$  contribution becomes

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}\rho - \frac{\kappa}{a^2} . \quad (7)$$

Technically, we need to derived the above equation directly from the EFE.

(a) Eqn (3) implies the energy density evolution as a function of the scale factor. Show that

$$\rho(a) \propto a^{-3(1+\omega)} .$$

From the relation we can inferred that the Universe is dominated by the radiation (or matter) energy density when  $a$  is sufficiently small (or large).

(b) Show that the second term in Eqn (7) is negligible when  $a$  is sufficiently small.

(c) For cases of either  $k = 0$  or  $a$  is sufficiently small, show that Eqn (7) implies

$$a(t) \propto t^{2/3(1+\omega)} .$$

(d) Our current cosmological observations is consistent with a flat Universe ( $\kappa = 0$ ). With  $\kappa = 0$ , show that the energy density evolution of radiation  $\rho_\gamma(t)$  in the **radiation dominated** epoch follows  $\rho_\gamma(t) \propto t^a$ , and the energy density evolution of matter  $\rho_m(t)$  in the **matter dominated** epoch follows  $\rho_m(t) \propto t^b$ , with  $a = b = -2$ .