

# Lecture 3: The Friedmann Equation

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January 28, 2018

## 1 The Robertson Walker metric

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- Saw in lecture 2 that an isotropic, homogeneous Universe can be fully described by just three numbers:  $\kappa$ ,  $R_0$ ,  $a(t)$ .
- $a(t)$  is particularly important: it tells us how the Universe expands and contracts over time.
- $a(t)$  also enables us to relate redshifts (which are easily measured) to distances (which are much more difficult to measure).
- However, let's first focus on curvature, described by  $\kappa$  and  $R_0$ .

### 1.1 What is curvature in the context of a universe?

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- Curvature in a universe would manifest itself in terms of the perceived sizes of distant objects.
- The *perceived* size of an object is the angular size it subtends.
- As such, it is convenient to think in terms of a triangle, with the object at one end, and the angular size at the other.
- In a flat universe, the angles of this triangle all add up to 180 degrees, and the object subtends the angle that we have come to expect for flat geometry.
- In a negatively curved universe, the interior angles of the triangle add up to less than 180 degrees, and the object subtends a *smaller* angle that we would expect. This would be witnessed as distant galaxies appearing disproportionately smaller than nearby ones.
- By contrast, in a positively curved universe, the interior angles of the triangle add up to more than 180 degrees, and the object subtends a *larger* angle that we would expect. This would be witnessed as distant galaxies appearing disproportionately larger than nearby ones.
- Such disproportionately large or small distant galaxies are not seen when we look to higher and higher distances (i.e., redshifts), so we can conclude that *if* the Universe is curved, then its radius of curvature,  $R_0$  is much larger than the size of the observable Universe.

## 2 Relating curvature to content

- General relativity tells us that a universe's curvature is dictated by its content (whether mass or energy, since they are one and the same thing in relativity).
- The *Field Equation* links the two - it tells spacetime ( $G_{\mu,\nu}$ ) how to curve in the presence of stress-energy ( $T_{\mu,\nu}$ ).
- Unfortunately, both  $G_{\mu,\nu}$  and  $T_{\mu,\nu}$  are  $4 \times 4$  tensors (i.e., matrices), and the equation as a whole represents ten non-linear second-order differential equations!
- Thus, in general, it can be extremely difficult to solve for  $G_{\mu,\nu}$ . **Slide 5**
- However, on large scales, we can make some sweeping simplifications.
- On very large scales, we can ignore the “clumpy” nature of the Universe and instead describe it as being filled with a uniform (i.e., homogeneous), isotropic gas or pressure  $P(t)$  and (energy) density  $\varepsilon(t)$ .
- In such a case, then  $T_{\mu,\nu}$  only depends on  $P(t)$  and  $\varepsilon(t)$ , and the metric is given by the Robertson Walker metric.
- Our goal, therefore, is simply to relate  $a(t)$ ,  $\kappa$ , and  $R_0$  to  $P(t)$  and  $\varepsilon(t)$ .

## 3 The Friedmann Equation

- To relate  $a(t)$ ,  $\kappa$ , and  $R_0$  to  $P(t)$  and  $\varepsilon(t)$ , we'll consider the gravitational influence of the aforementioned perfect gas.
- The full General Relativistic approach to this is beyond the scope of this course, so we'll instead consider the Newtonian equivalent, which gives a good sense of the physics involved.
- We'll start with considering a large sphere of the universe, containing a perfect gas with energy density  $\varepsilon(t)$ .
- Since spacetime itself is affected by energy density, the surface of this sphere will expand or contract according to the gravitational influence of the perfect gas.
- This expansion/contraction is given by Newton's law of gravitation:

$$\frac{d^2 R_s}{dt^2} = -\frac{GM_s}{R_s(t)^2} \quad (1)$$

- To solve this to get  $R_s(t)$  is a bit tricky, since  $R_s$  is a function of time, so we can't immediately put all  $R_s$  terms on side and all  $t$  terms on the other.
- So, we have to be a bit clever. First, we'll multiply both sides by  $\frac{dR_s}{dt}$ :

$$\frac{d^2 R_s}{dt^2} \frac{dR_s}{dt} = -\frac{GM_s}{R_s(t)^2} \frac{dR_s}{dt} \quad (2)$$

- How has that helped us to integrate this function to solve for  $R_s$ ?

- First, for the LHS of Eq. 2, consider the product rule:

$$\frac{d}{dx} \left( \frac{dy}{dx} \frac{dy}{dx} \right) = \frac{dy}{dx} \frac{d^2y}{dx^2} + \frac{dy}{dx} \frac{d^2y}{dx^2} = 2 \frac{dy}{dx} \frac{d^2y}{dx^2} \quad (3)$$

- By comparing the RHS of Eq. 3 to the LHS of Eq. 2, we can see that:

$$\int \frac{d^2R_s}{dt^2} \frac{dR_s}{dt} dt = \frac{1}{2} \frac{dR_s}{dt} \frac{dR_s}{dt} + C = \frac{1}{2} \left( \frac{dR_s}{dt} \right)^2 + C \quad (4)$$

- So now, Eq. 2 has become:

$$\frac{1}{2} \left( \frac{dR_s}{dt} \right)^2 + C = - \int \frac{GM_s}{R_s^2} \frac{dR_s}{dt} dt \quad (5)$$

where  $C$  is a constant of integration.

- For the RHS of Eq. 5, we consider the chain rule:

$$\frac{d \frac{GM_s}{R_s}}{dt} = \frac{d \frac{GM_s}{R_s}}{dR_s} \frac{dR_s}{dt} = - \frac{GM_s}{R_s^2} \frac{dR_s}{dt} \quad (6)$$

- Meaning:

$$- \int \frac{GM_s}{R_s^2} \frac{dR_s}{dt} dt = \int \frac{d \frac{GM_s}{R_s}}{dt} dt = \frac{GM_s}{R_s} + U \quad (7)$$

where  $U$  is a constant of integration, which we can combine with  $C$  to give:

$$\frac{1}{2} \left( \frac{dR_s}{dt} \right)^2 = \frac{GM_s}{R_s} + U \quad (8)$$

- Since the mass,  $M_s$ , within the sphere is constant (there's no net flow in or out of the sphere), we can say:

$$M_s = \frac{4}{3} \pi R_s(t)^3 \rho(t) \quad (9)$$

and we can also say that  $R_s = a(t)r_s$ , where  $a(t)$  is the scale factor and  $r$  is the radius of the sphere in spherical co-moving coordinates.

- Substituting for  $M_s$  and  $R_s$  (and since  $r_s$  is constant with time) gives:

$$\frac{1}{2} (r_s \dot{a})^2 = \frac{4}{3} \pi \frac{Ga(t)^3 r_s^3}{a(t)r_s} + U \quad (10)$$

- where  $\dot{a} = da/dt$ . When rearranged, this becomes:

$$\left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho(t) + \frac{2U}{r_s^2} \frac{1}{a(t)^2} \quad (11)$$

- which is the Newtonian form of the Friedmann Equation.

- By contrast, the full GR Friedmann equation is given by:

$$\left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \frac{\varepsilon(t)}{c^2} + \frac{\kappa c^2}{R_0^2} \frac{1}{a(t)^2} \quad (12)$$

- There are clear similarities between the two. Notice especially that mass density,  $\rho(t)$ , has become energy density,  $\varepsilon(t)/c^2$ , in the relativistic form of the Friedmann Equation. This is a direct result of the equivalence of mass and energy within relativity:  $E = mc^2$ .