

## IV. Cosmology

### ▶ Lookback time

- Farther away = seeing farther back in time
- Questions about galaxy evolution (ellipticals, spirals, etc.)
- $c = 1$  light-year / year

### ▶ A Uniform Expansion

- Same expansion rate everywhere
- Models : paperclips on rubberband, pennies on balloon, the Universe...

### ▶ Expansion timescale

- The “Hubble Time”  $t_H$
- How old the expansion would be *if the expansion rate had always been constant.*

- $$\frac{\Delta d}{d} = \frac{\Delta t}{t_H}$$

## IV. Cosmology (continued)

### ▶ Cosmological redshift

- Wavelengths of light stretch at the same rate as the expansion of the Universe.

- $z = \frac{\Delta d}{d} \quad 1+z = \frac{\text{Size Now}}{\text{Size then}}$

### ▶ The expansion equation

- $z = \frac{d}{c t_H} \quad \text{our } t_H = 13.8 \text{ Gyr}$

### ▶ Evidence for Dark Matter

- Galaxy Rotation Curves
- Galaxy cluster random motions
- Most of the matter offset from the luminous matter as measured in the Bullet Cluster with “weak lensing”

## IV. Cosmology (continued)

### ▶ Measuring Distances

- Cosmic Distance Ladder
- Parallax
- Standard Candle : Cepheid Variable
- Standard Candle : Type Ia Supernova

### ▶ The Hubble Diagram

- Plot of size (measured by redshift) vs. time (measured by distance/lookback time/brightness of standard candle)
- Where is  $t_H$
- Accelerating vs. decelerating, age of Universe vs.  $t_H$ , etc.

## IV. Cosmology (continued)

### ▶ Constituents of the Universe

- Dark Energy (70%) : drives acceleration
- Dark Matter (25%) : holds galaxies, clusters together, has normal gravity
- Normal Matter : makes up stars, dust, gas, us, everything we can directly see

### ▶ Evidence for the Big Bang

- Expansion / Cosmological Redshift
- Cosmic Microwave Background
- Ratios of the light elements

### ▶ Calculating expansion history

- General Relativity + (reasonable, tested) assumption of homogeneous & isotropic
- 3 parameters:  $t_H$  (today's expansion rate),  $\Omega_M$  (matter density),  $\Omega_\Lambda$  (dark energy density)

*(Drumroll please...)*

The Age of the Universe:

**13.7 ± 0.2 billion years**

...but what is that since?

...clips from a movie:

*From Here to Infinity:  
How Will the Universe Die?*

Prof. Knop, helping  
to discover the  
acceleration of the  
Universe.



(Shown as part of the BBC "Horizon" series in 1999.)