

# Cosmology

- Carroll & Ostlie Chapter 29
- Sparke & Gallagher Chapter 8.2
- Ryden Chapter 2, 3, 4

The developing theory of the origin, evolution and fate of the universe.

Cosmology describes how matter is distributed at early times, and defines properties for those various components, which allows us to develop models for how the universe evolves.

**Cosmological Principle:** On average, over large scales, the universe is homogeneous and isotropic.

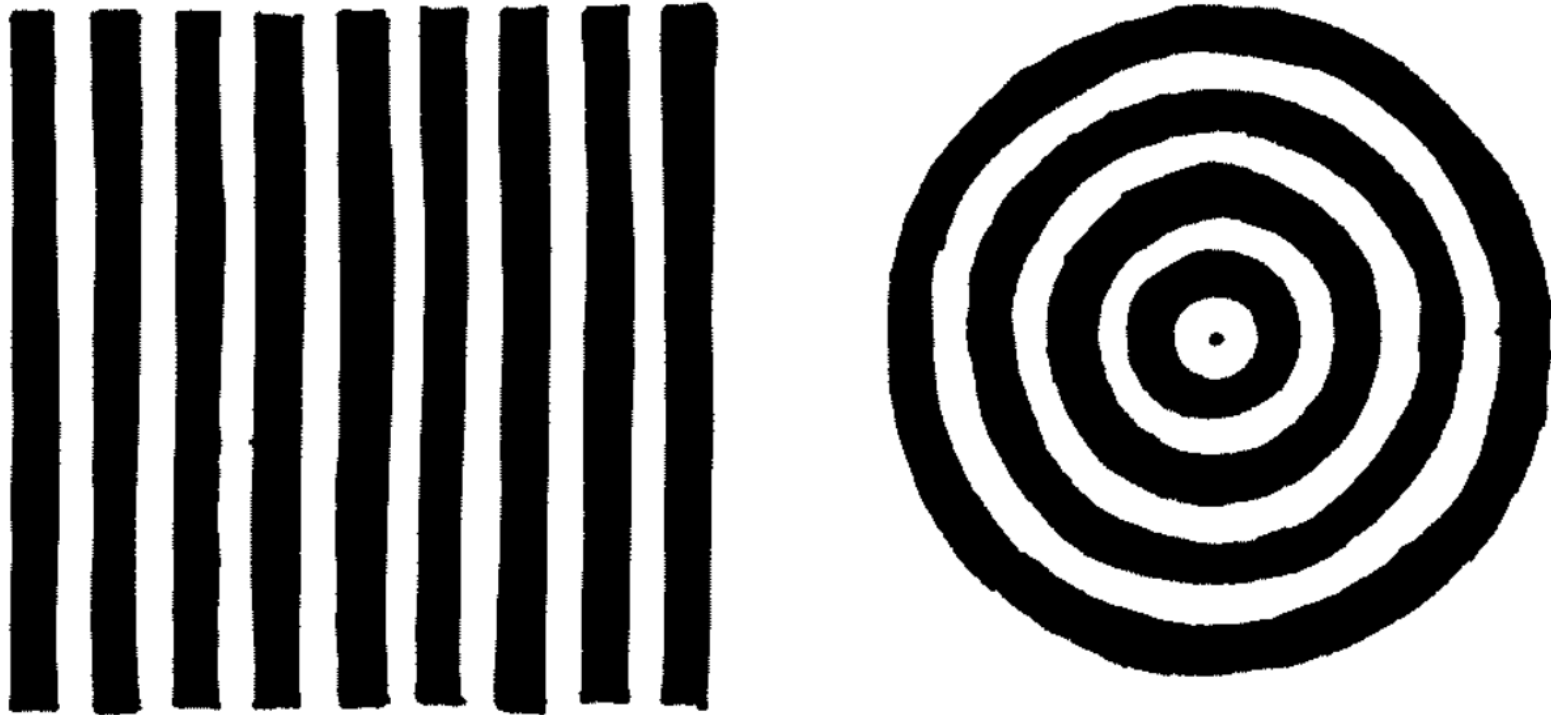
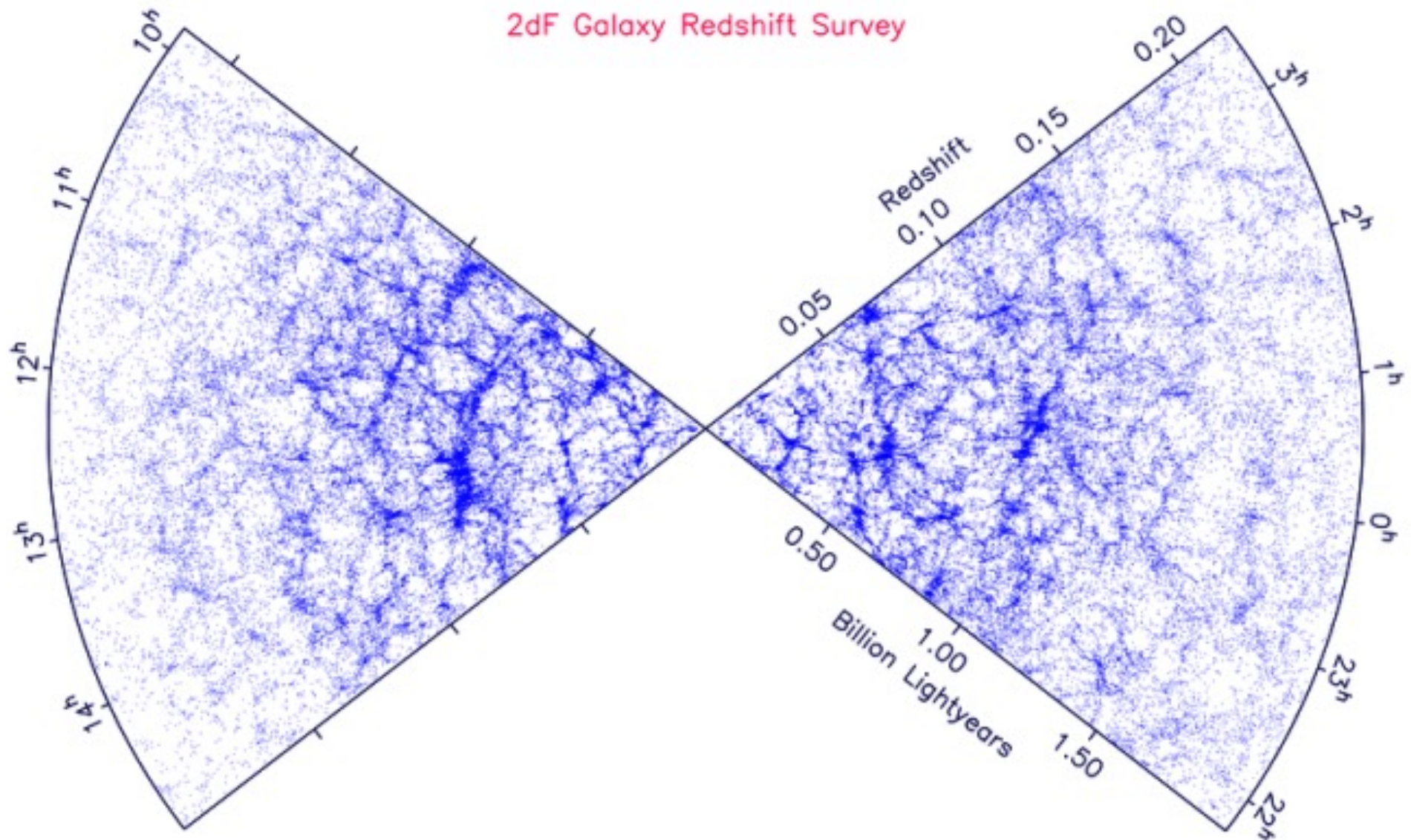


Figure 2.3: (a) A pattern which is anisotropic, but which is homogeneous on scales larger than the stripe width. (b) A pattern which is isotropic about the origin, but which is inhomogeneous.

**Cosmological Principle:** We are not located in a special location in the universe. Consequence is that either the universe is static, or it has purely radial motions.



## We know the universe isn't static:

Vesto Slipher first discovered the Doppler shift in the spectra of galaxies, Hubble used this to prove the universe is expanding (1929)

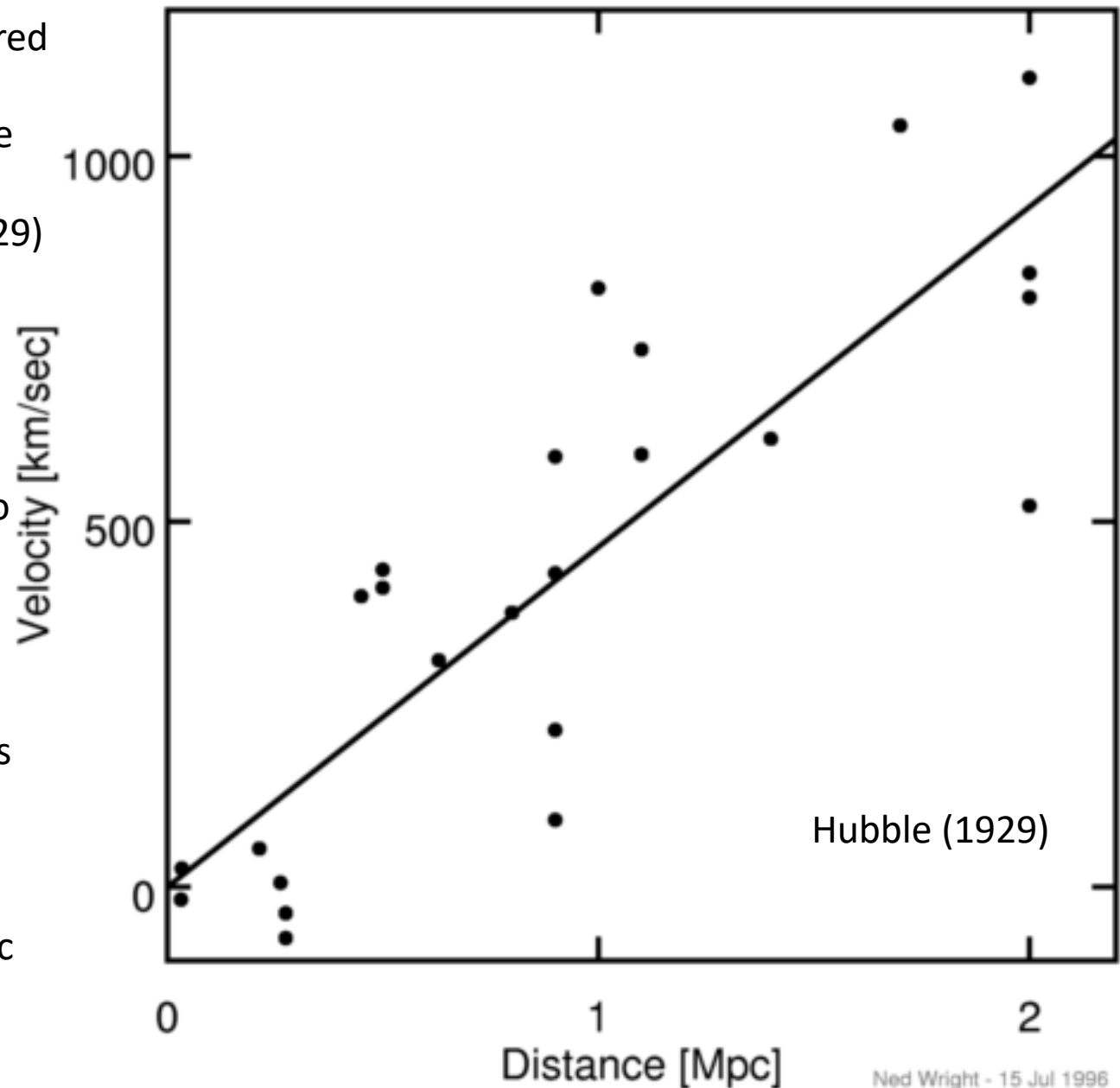
### Hubble's Law:

the *radial velocities* of galaxies are proportional to their distance.

$$V = H_0 r$$

The Hubble Constant ( $H_0$ ) is defined as the slope of the fitted line.

Here,  $H_0 = 464 \text{ km/sec/Mpc}$   
(Expansion Rate Today)



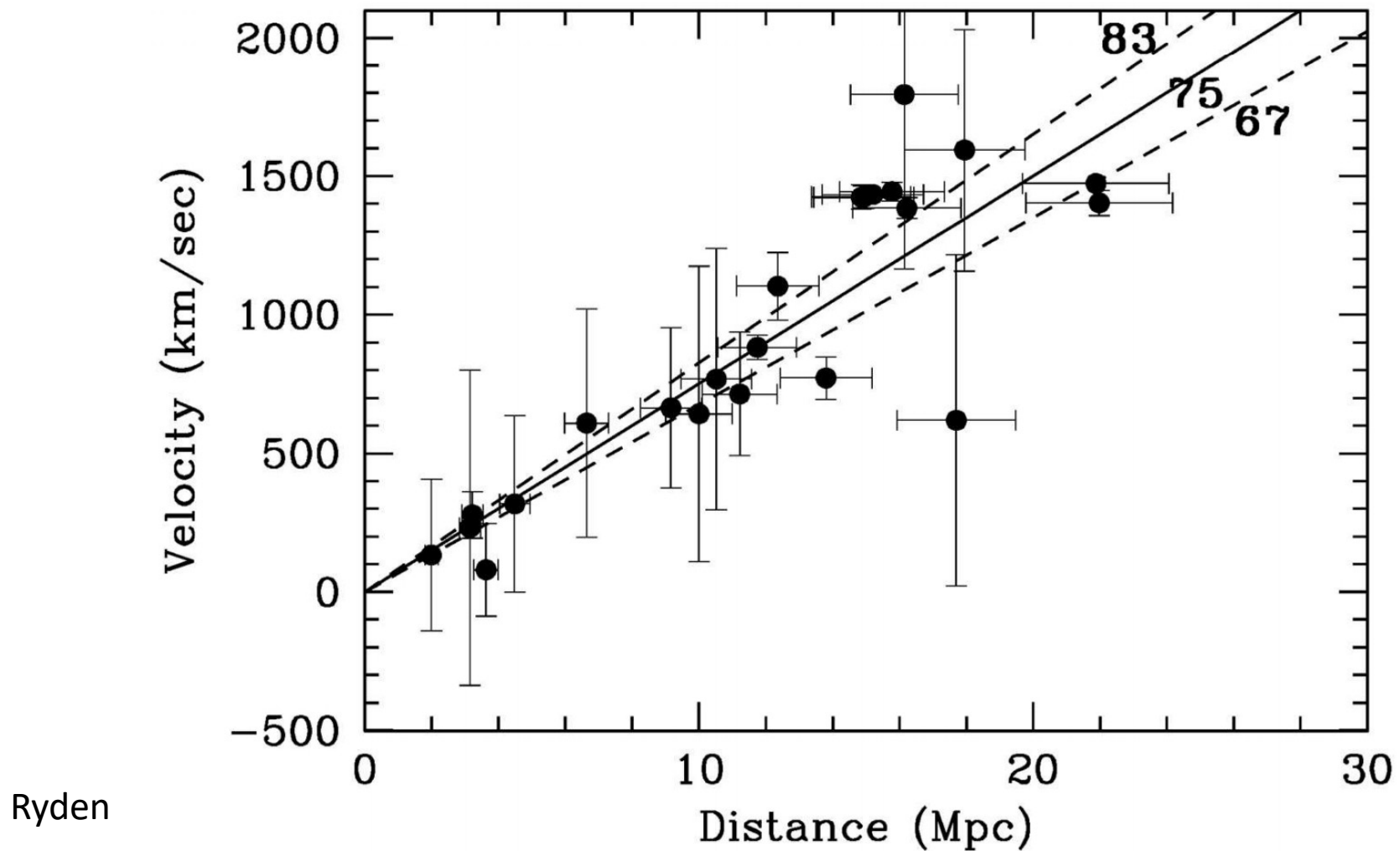
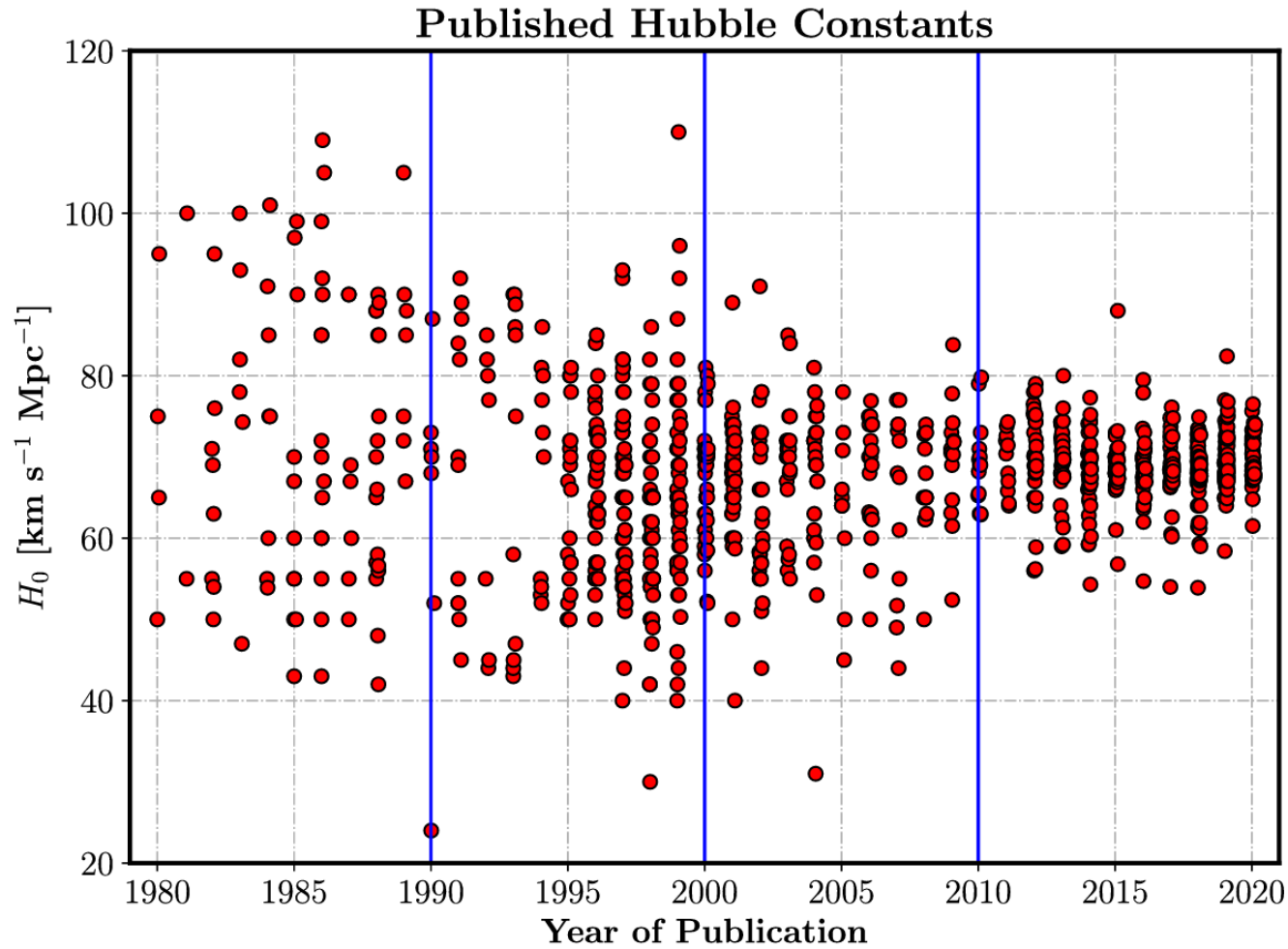


Figure 2.5: A more modern version of Hubble's plot, showing  $cz$  versus distance. In this case, the galaxy distances have been determined using Cepheid variable stars as standard candles, as described in Chapter 6. (from Freedman, et al. 2001, ApJ, 553, 47)

## Freedman + 2021 ApJ 919



**Figure A1.** Plot of published  $H_0$  values since 1980. The data are courtesy of I. Steer (2021, private communication). These data provide an update of the John Huchra Hubble constant database originally maintained for the NASA HST Key Project on the extragalactic distance scale (Freedman et al. 2001). This figure further updates that shown in Steer (2020) with an additional 99 entries.

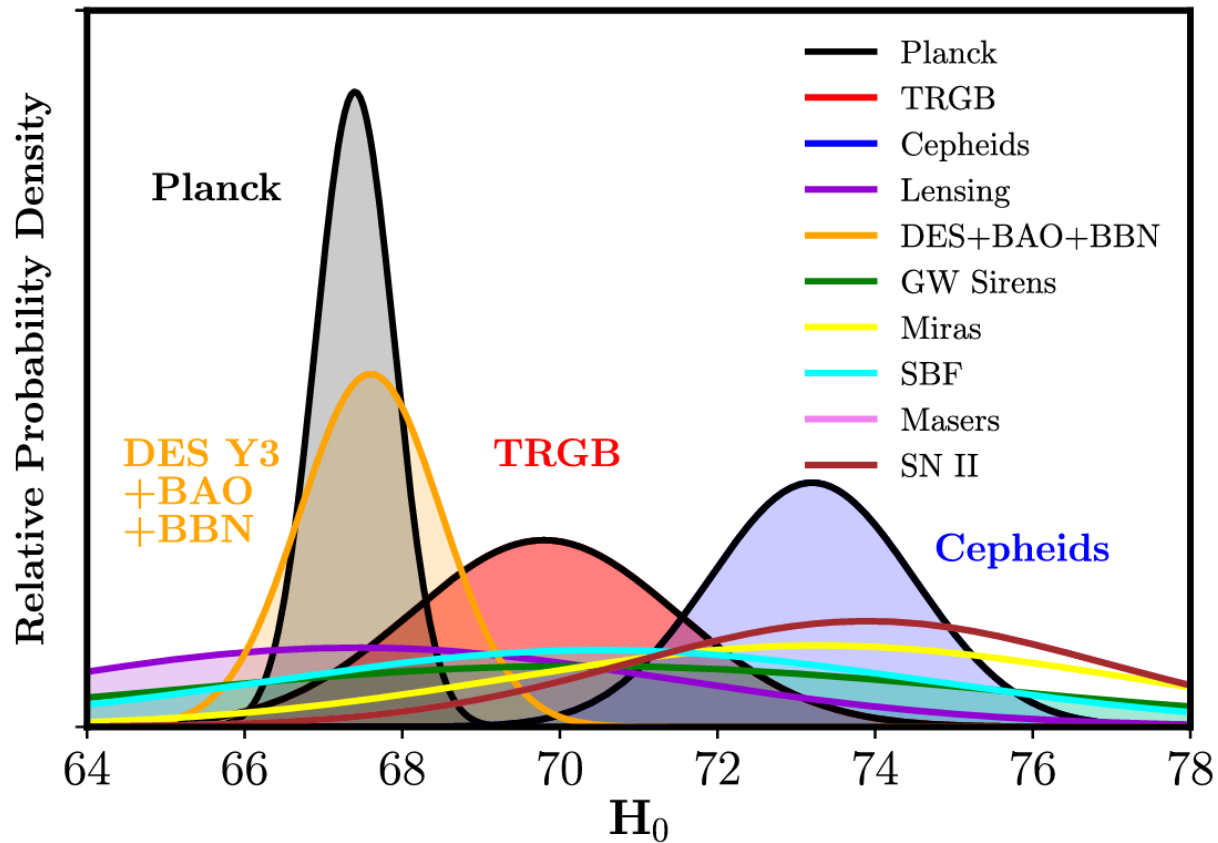
$$H_0 = 100 h \text{ km/s/Mpc}$$

$$h \sim 0.7 \text{ at present day (z=0)}$$

# Tension in $H_0$

Freedman + 2021 ApJ 919

## Recent Published $H_0$ Values



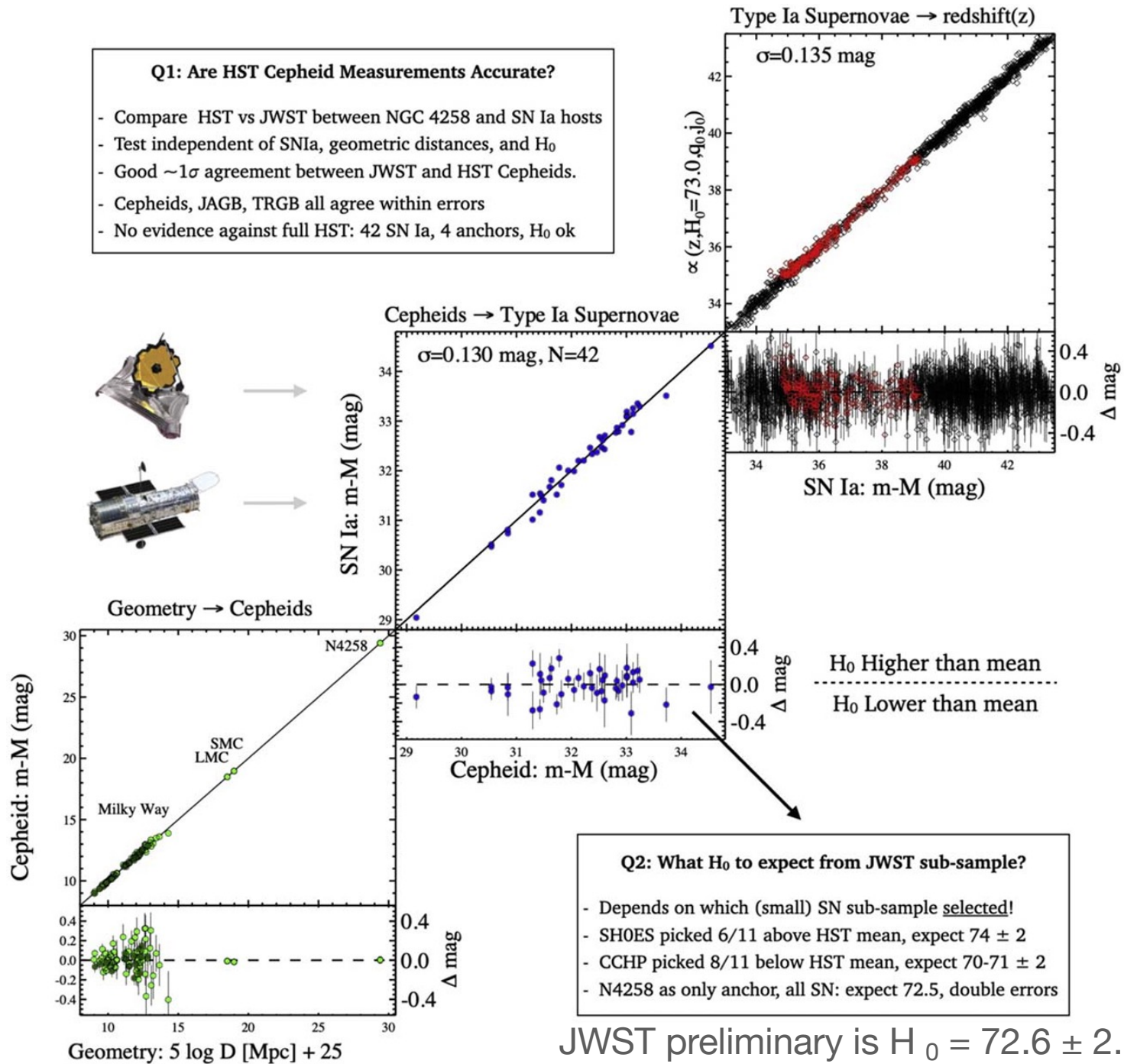
**Figure 10.** Relative PDFs for several current methods for measuring  $H_0$ . The CMB, BAO, strong lensing, and TRGB methods currently yield lower values of  $H_0$ , while Cepheids yield the highest values. The uncertainties associated with  $H_0$  measurements from gravitational-wave sirens, strong lensing, Miras, masers, and SBF are currently significantly larger than the errors quoted for the TRGB and Cepheids. See text for details. (CMB: Planck Collaboration 2018; TRGB: this paper; Cepheids: [R21](#); lensing: Birrer et al. [2020](#); DES Y3 + BAO + BBN: DES Collaboration et al. [2021](#); GW sirens: Hotokezaka et al. [2019](#); Miras: Huang et al. [2018](#); SBF: Khetan et al. [2021](#); masers: Reid et al. [2019](#)).



Riess+2024

ApJ 977

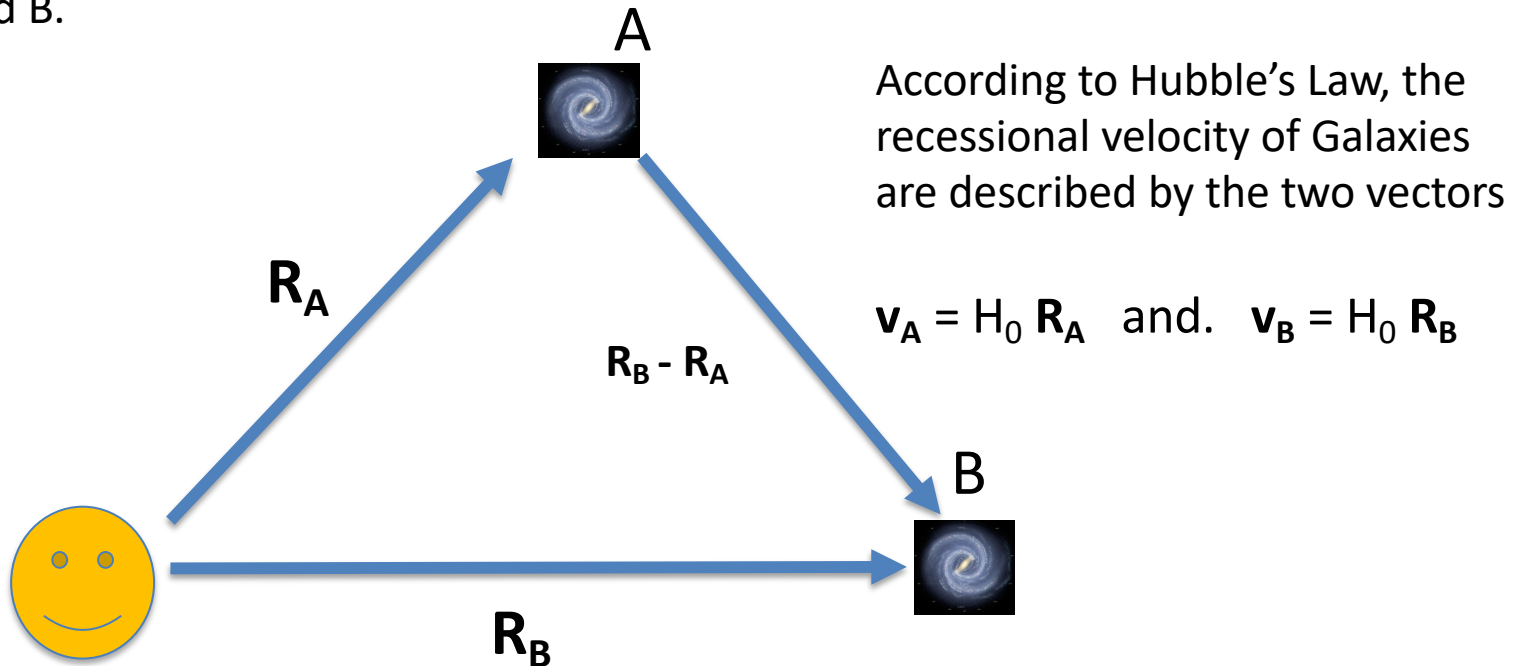
**JWST data for  
Cepheid  
Distances so  
far consistent  
with HST**





**The Cosmological Principle implies that:** the expansion of the universe appears the same to all observers at all locations.

Imagine an observer on Earth who is measuring the radial velocities of two other galaxies, called A and B.



The recessional velocity of Galaxy B as seen by an observer on Galaxy A is:

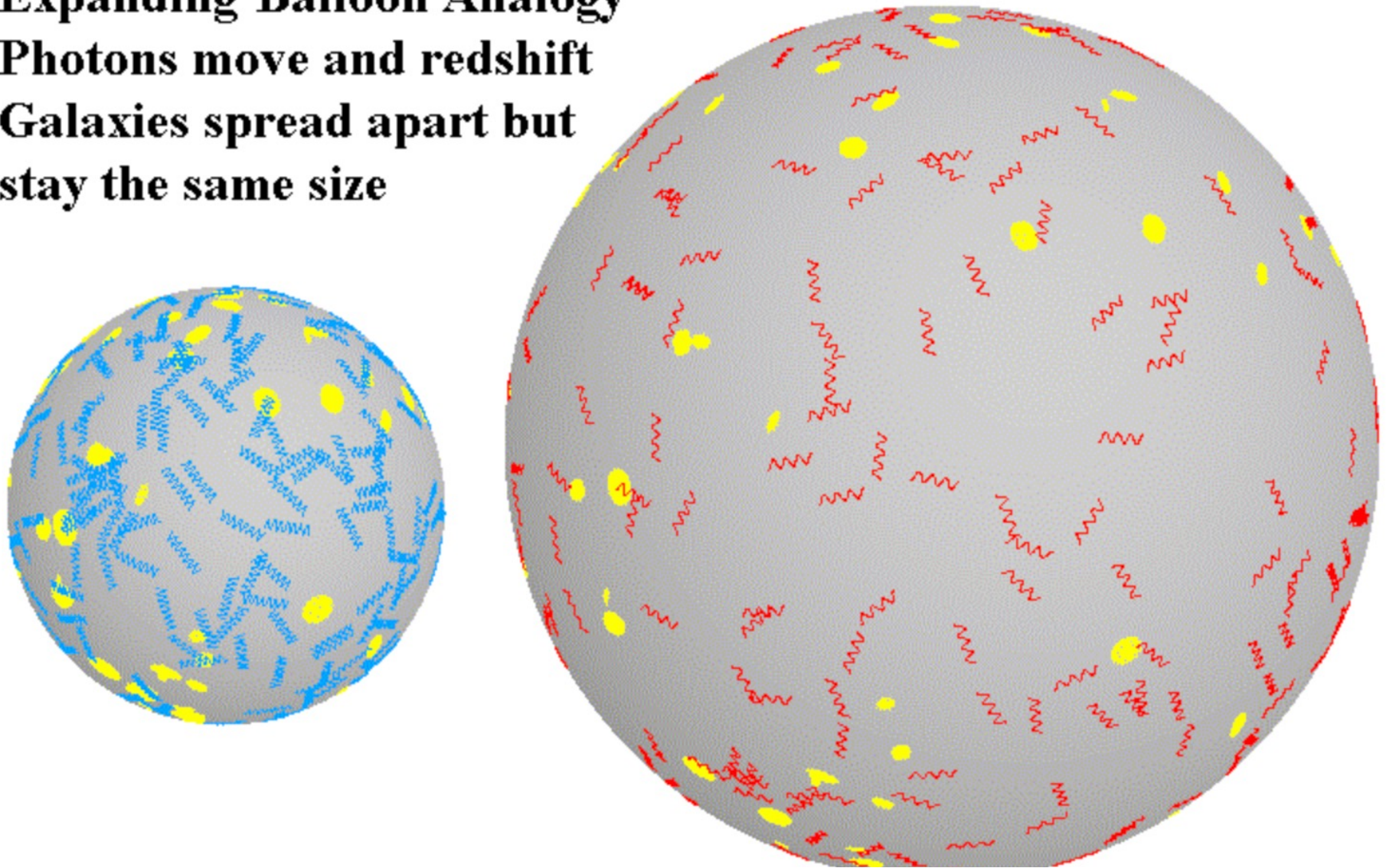
$$\mathbf{v}_B - \mathbf{v}_A = H_0 \mathbf{R}_B - H_0 \mathbf{R}_A = H_0 (\mathbf{R}_B - \mathbf{R}_A) \quad \text{This is the same Hubble Law!}$$

**Cosmological Principle:** the expansion of the universe appears the same to all observers at all locations.

## **Expanding Balloon Analogy**

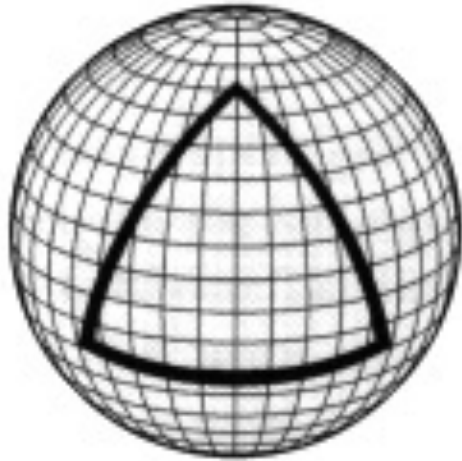
**Photons move and redshift**

**Galaxies spread apart but stay the same size**



**Metric:** A metric defines the distance between two points in space, accounting for topology.

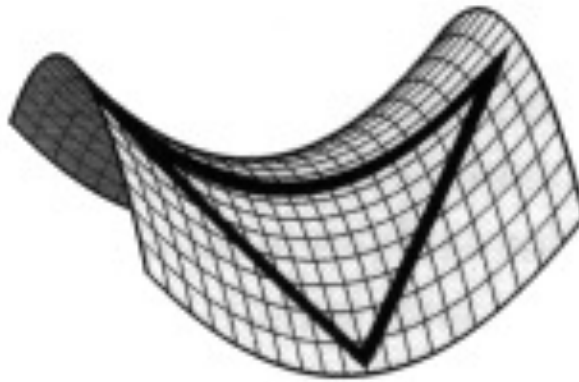
Consider three spatial geometries:



**Positive Curvature**

Closed Geometry

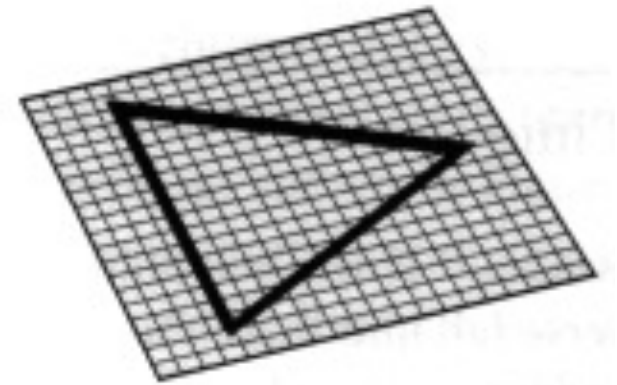
Angles  $> 180^\circ$



**Negative Curvature**

Open Geometry

Angles  $< 180^\circ$



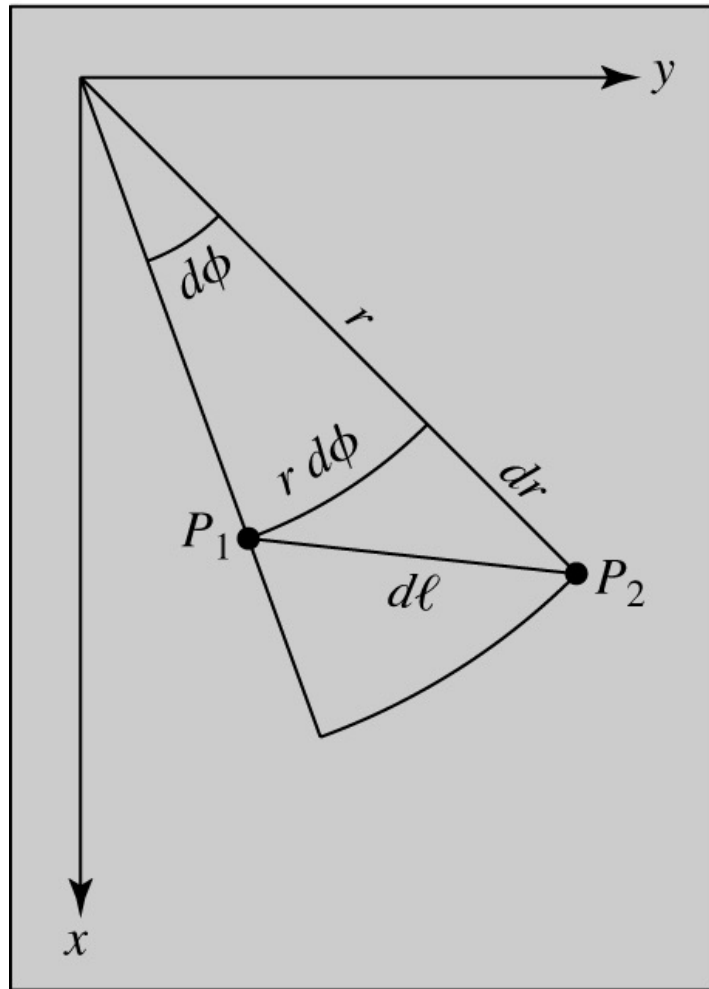
**Flat Curvature**

Flat Geometry

Angles  $= 180^\circ$

Computing distances depends strongly on the assumed geometry of space.

# Metric: 2D Flat Geometry



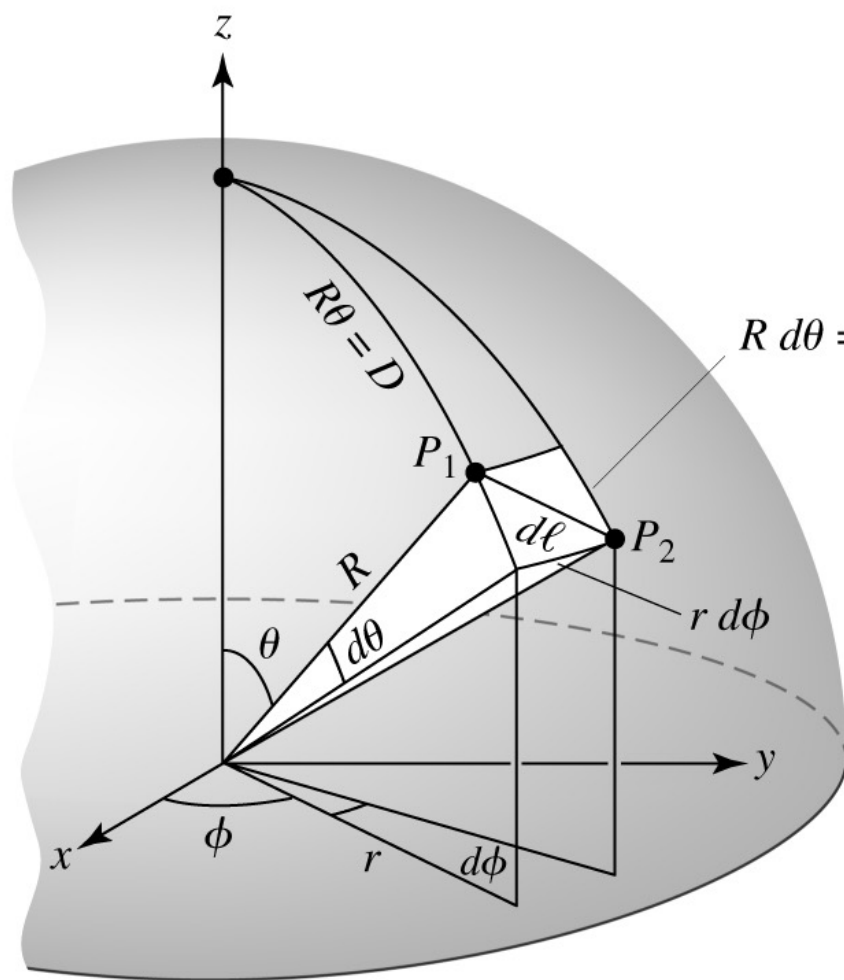
Consider a distance element  $d\ell$  connecting two points in space,  $P_1$  and  $P_2$ .

In Polar coordinates:

$$d\ell^2 = dr^2 + r^2 d\phi^2$$

(a) Carroll & Ostlie Figure 29.18

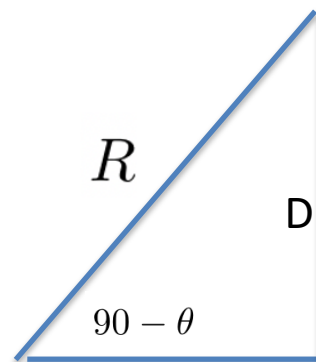
# 2D Curved Geometry



(b)

Carroll & Ostlie Figure 29.18  
 $d\ell$  as measured for the surface of a spherical shell

$$d\ell^2 = R^2 d\theta^2 + r^2 d\phi^2$$



$$R^2 = D^2 + r^2$$

$$D = \sqrt{R^2 - r^2}$$

$$r = R \sin \theta, \text{ so } dr = R \cos \theta d\theta$$

$$R d\theta = \frac{dr}{\cos \theta}$$

$$\cos \theta = D/R$$

$$R d\theta = \frac{R dr}{\sqrt{R^2 - r^2}} = \frac{dr}{\sqrt{1 - r^2/R^2}}$$

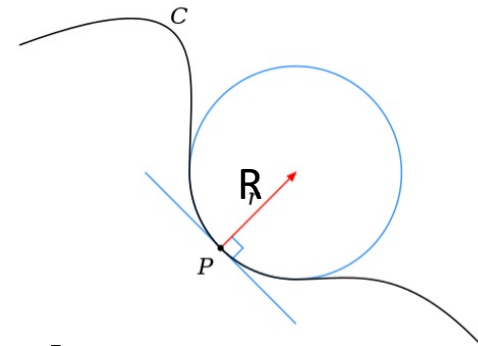
$$d\ell^2 = \left( \frac{dr}{\sqrt{1 - r^2/R^2}} \right)^2 + (r d\phi)^2$$

(polar coordinates)

Curvature  $K = 1/R^2$

Positive Curvature:  $K = 1$   
Negative Curvature :  $K = -1$   
Flat Curvature :  $K = 0$

$$d\ell^2 = \left( \frac{dr}{\sqrt{1 - r^2 K}} \right)^2 + (rd\phi)^2$$



## Metric: 3D Curved Geometry

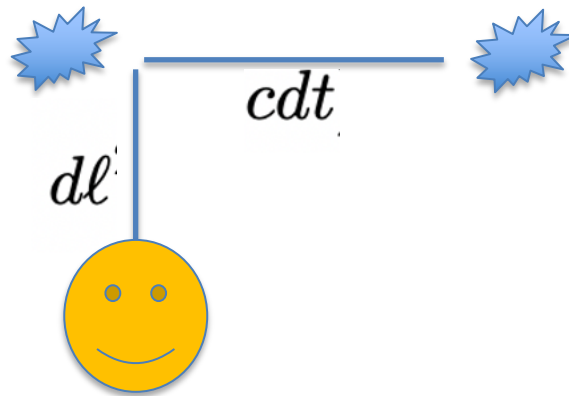
Switch from Polar to Spherical Coordinates:  $r = \sqrt{x^2 + y^2 + z^2}$

$$d\ell^2 = \left( \frac{dr}{\sqrt{1 - r^2 K}} \right)^2 + (rd\theta)^2 + (r\sin\theta d\phi)^2$$



# Space Time

Consider two events that occur at the same location, but at two different points in time.



Space-time Interval:

$$ds^2 = (cdt)^2 - d\ell^2 = (cdt)^2 - \left[ \left( \frac{dr}{\sqrt{1 - r^2 K}} \right)^2 + (rd\theta)^2 + (r \sin\theta d\phi)^2 \right]$$

If  $K = 0$  (flat) this is called the Minkowski Metric

In an expanding universe,  $d\ell$  will change during the period of time between when light is emitted from an object and time we observe it. So we need to account for time in  $d\ell$ .

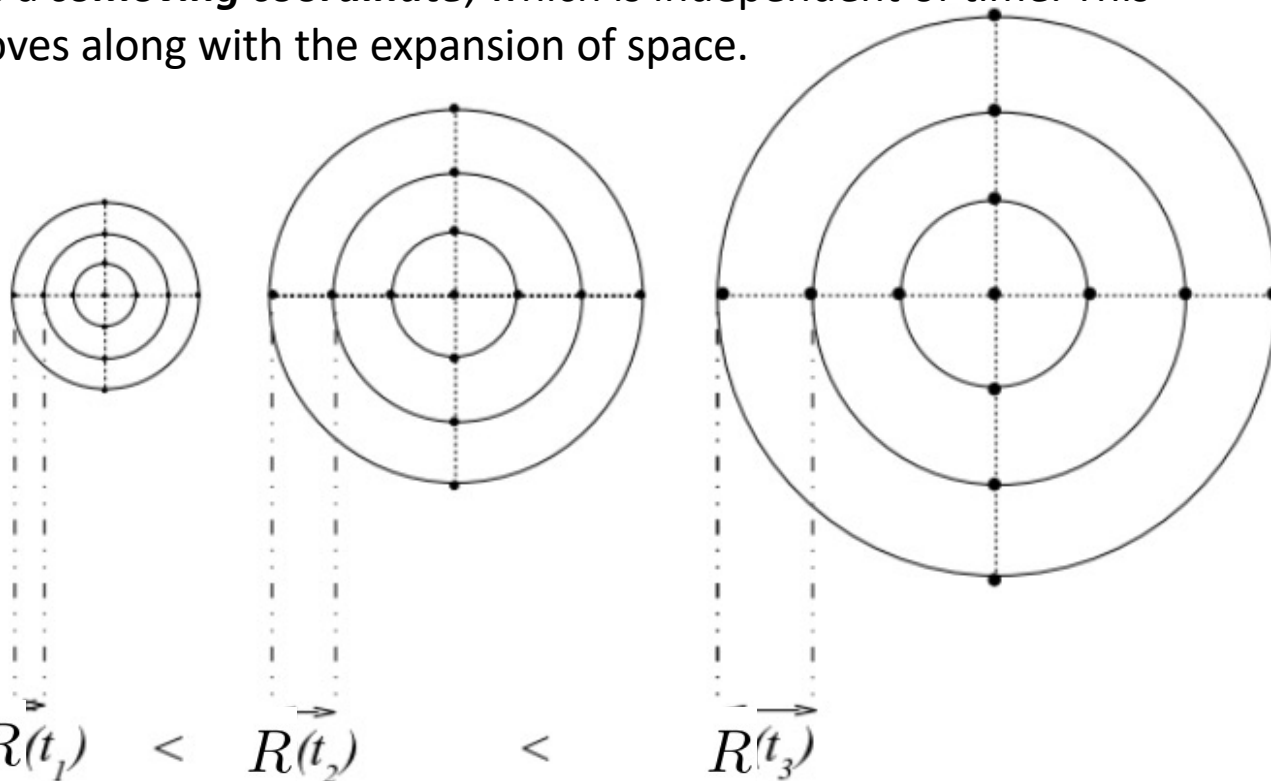
# Scale Factor

Let's define our radial distance element in terms of the expansion of the universe.

$$r = R(t)u$$

Where  $R(t)$  is the **scale factor**, which defines the rate of expansion at any point in time.  
[NOTE: in Ryden the scale factor is written as  $a(t)$ ]

And  $u$  is referred to as a **comoving coordinate**, which is independent of time. This coordinate system moves along with the expansion of space.



Assume  $\Delta u = 1$

Physical distance:

$R(t_1)$

<

$R(t_2)$

<

$R(t_3)$

Comoving distance:

1

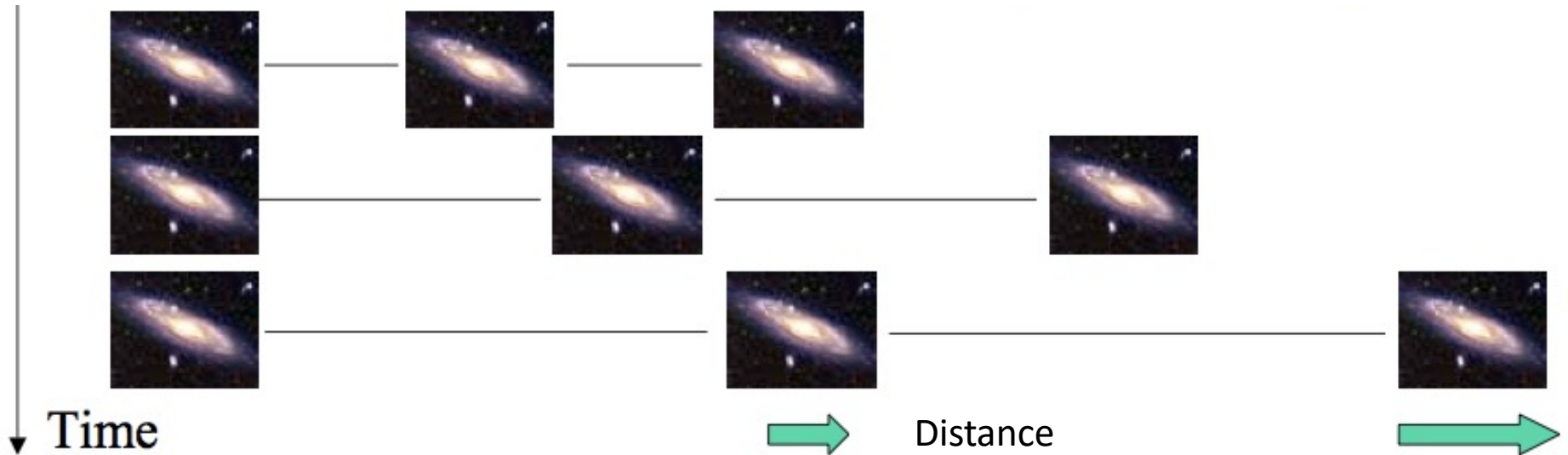
=

1

=

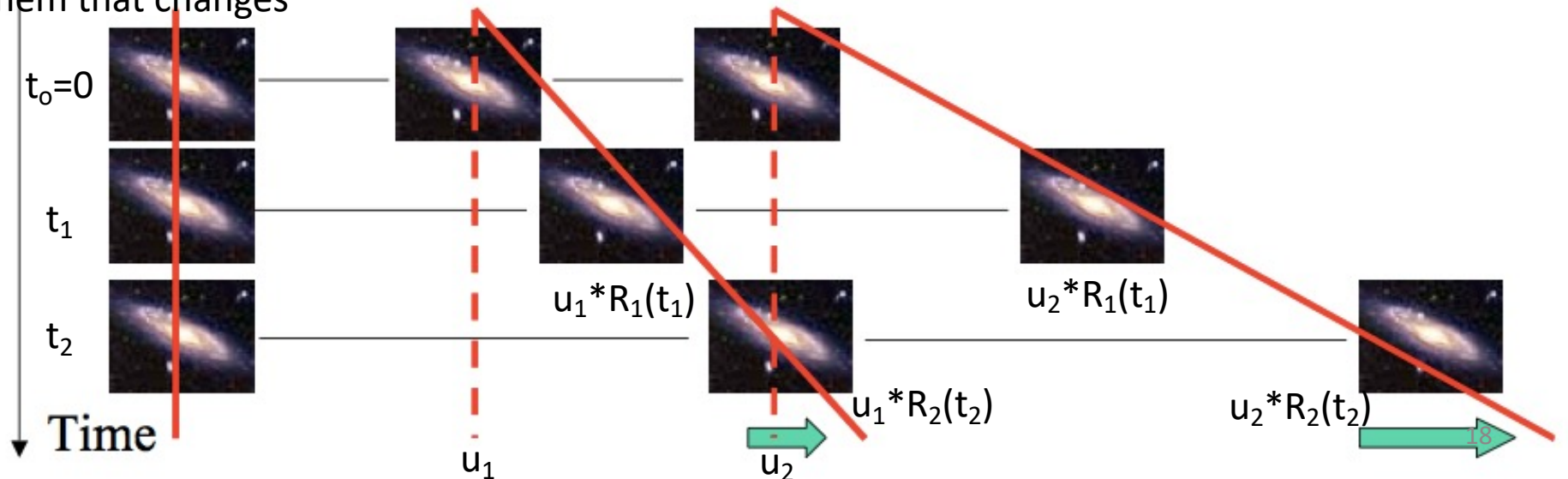
1

We observe galaxies receding from us



**Comoving coordinates:** Galaxies are not moving.

Galaxies remain at the same position in comoving coordinates – it is the space between them that changes



# Robertson-Walker Metric

3D Curved metric  $ds^2 = (cdt)^2 - d\ell^2 = (cdt)^2 - \left[ \left( \frac{dr}{\sqrt{1 - r^2 K}} \right)^2 + (rd\theta)^2 + (r\sin\theta d\phi)^2 \right]$

Replacing  $r$  with  $R(t)u$

$$ds^2 = (cdt)^2 - R(t)^2 \underbrace{\left[ \left( \frac{du}{\sqrt{1 - u^2 K}} \right)^2 + (ud\theta)^2 + (u\sin\theta d\phi)^2 \right]}_{d\ell^2}$$

**Proper Distance** ( $ds^2 = d\ell^2$ ): distance between two events that occur at the same time ( $dt=0$ ). I.e. the distance that would be measured by a ruler at the time they are observed.

This metric is used to measure the interval between two events in a curved ( $K$ ), variably expanding ( $R(t)$ ) space time.

# Proper Time

Light rays travel paths with  $ds^2 = 0$ , called null geodesics.  $c^2 dt^2 = d\ell^2$

Light rays travel on radial paths, where  $(\theta = 0, \phi = 0)$   $c dt = R(t) \frac{du}{\sqrt{1 - Ku^2}}$

Consider a photon that leaves its source at comoving coordinate  $u_e$  at time  $t_e$  and reaches us at  $t_0, u_0$ . Integrate both sides of the above equation.

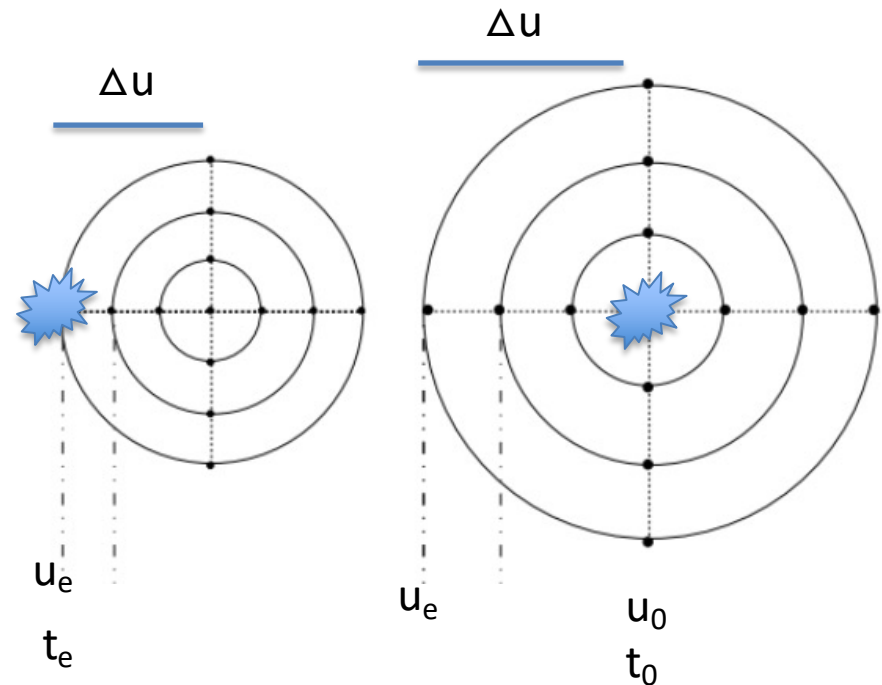
$$c \int_{t_e}^{t_0} \frac{dt}{R(t)} = \int_{u_e}^{u_0} \frac{du}{\sqrt{1 - ku^2}}$$

Comoving distance

Consider another photon leaving at a later time  $t_e + \Delta t_e$ . It arrives at  $t_0 + \Delta t_0$ .

**BUT The comoving distance is the same!**

$$c \int_{t_e + \Delta t_e}^{t_0 + \Delta t_0} \frac{dt}{R(t)} = \boxed{\int_{t_e}^{t_0} \frac{dt}{R(t)}} c$$




The equation in the red box is called the **Proper Time**: the time delay between two events that occur over the same comoving distance

# Redshift

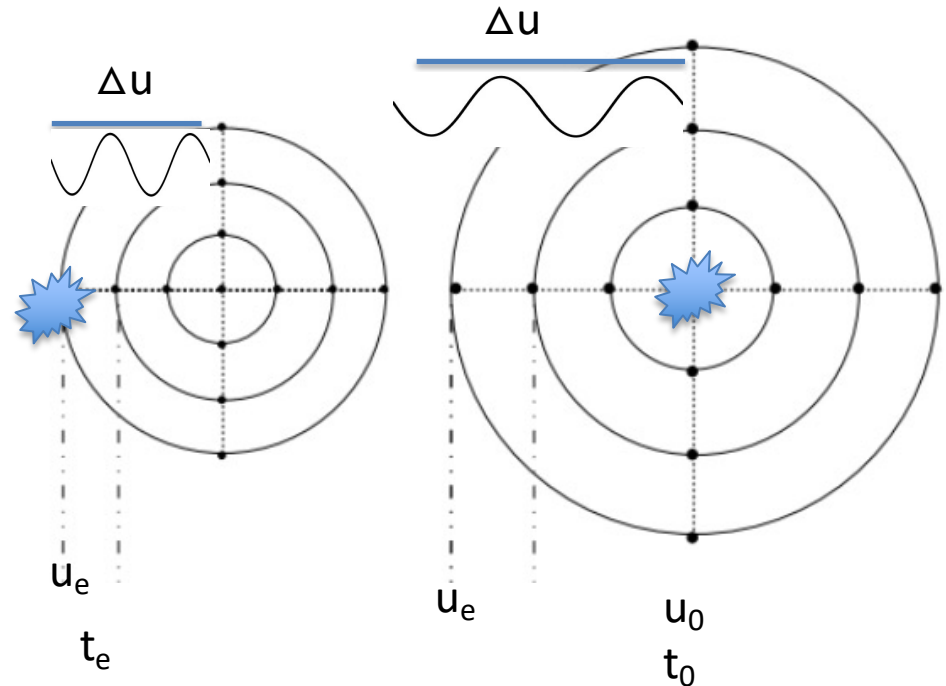
$$\int_{t_e + \Delta t_e}^{t_0 + \Delta t_0} \frac{dt}{R(t)} = \int_{t_e}^{t_0} \frac{dt}{R(t)}$$

This means that  $\frac{\Delta t_e}{R(t_e)} = \frac{\Delta t_0}{R(t_0)}$

At Emission:  $\Delta t_e$



$\lambda_e = c \Delta t_e$



This photon is received with wavelength:  $\lambda_0 = c \Delta t_0 = c \Delta t_e R(t_0) / R(t_e)$

The wavelength increases by the ratio of the scale factor.

$$1 + z = \frac{\lambda_{obs}}{\lambda_e} = \frac{R(t_0)}{R(t_e)} = \frac{1}{R(t_e)}$$

Where we define  $R(t_0) = 1$

$$R(t) = \frac{1}{1 + z}$$

Dimensionless scale factor



# Hubble Parameter

Hubble Law (local):  $v_r = H_0 r$

Distance to galaxy in terms of comoving coordinates:  $r = R(t)u$

The velocity  $v_r$  is then  $\frac{dr}{dt} = \frac{dR}{dt}u$  where  $u$  is constant in time.

$$v_r = \dot{R}u = \frac{\dot{R}}{R}r$$

Where  $u$  was replaced with  $r/R$

$$H(t) = \frac{\dot{R}}{R}$$

Time evolving Hubble Parameter

So the Hubble Parameter is the fractional rate of expansion of the universe.  
It tells you about the rate at which the scale factor is increasing over time.

# The time evolution of the scale factor

Consider a homogeneous spherical density distribution of radius  $r(t)$  that is expanding uniformly.

The rate at which the sphere can expand is limited by the mass and energy within it.

The expansion will be halted by gravity. We need to determine the expansion rate needed to counteract gravity.

$$\frac{d^2 r}{dt^2} = -\frac{GM(< r)}{r^2} = -\frac{4\pi G}{3}\rho(t)r$$

Changing to comoving units,  $r = R(t)u$

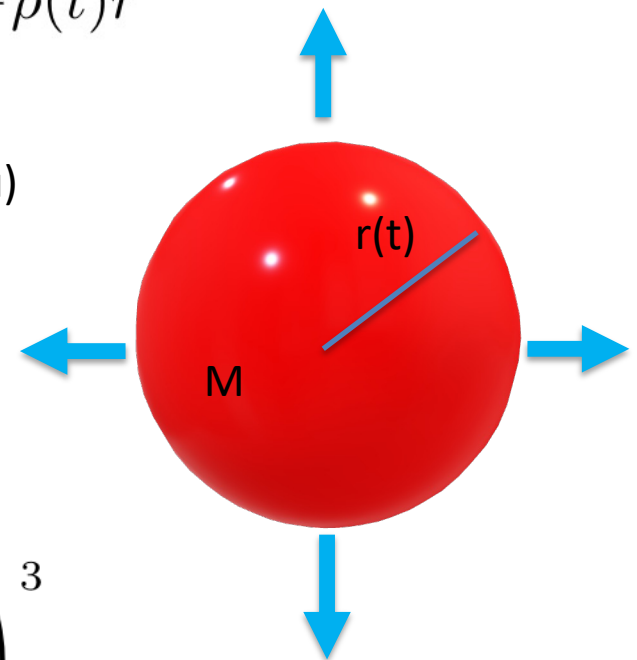
$$\frac{d^2 r}{dt^2} = \ddot{R}(t) = -\frac{4\pi G}{3}\rho(t)R(t) \quad (\text{divide out } u)$$

The mass is constant, but the volume is growing

$$M = 4/3\pi\rho_o R_o^3 = 4/3\pi\rho R^3$$

So the density can be written as:

$$\rho(t) = \rho_o \left( \frac{R_o}{R(t)} \right)^3$$



Combine the acceleration equation with the density equation

$$\ddot{R}(t) = -\frac{4\pi G}{3}\rho(t)R(t) = -\frac{4\pi G}{3}\frac{\rho_o R_o^3}{R^2(t)}$$

Multiply both sides by  $dR/dt$

$$\frac{1}{2}\frac{d}{dt}[\dot{R}^2(t)] = \dot{R}(t)\ddot{R}(t) = -\frac{4\pi G}{3}\frac{\rho_o R_o^3}{R^2(t)}\dot{R}(t)$$

Integrate both sides over  $t$

$$\dot{R}^2(t) = \frac{8\pi G}{3}\rho_o\frac{R_o^3}{R} + C \quad \text{where } C = -Kc^2$$

Putting back  $\rho(t) = \rho_o\left(\frac{R_o}{R(t)}\right)^3$

## First Friedmann Equation

$$\dot{R}^2(t) = \frac{8\pi G}{3}\rho(t)R^2(t) - Kc^2$$

# First Friedmann Equation & Density

## First Friedmann Equation

$$\dot{R}^2(t) = \frac{8\pi G}{3} \rho(t) R^2(t) - K c^2$$

Total Mass Density = Mass + Radiation + Cosmological Constant (Dark Energy)  
 $\rho(t)$   $(\rho_m + \rho_{rad} + \rho_\Lambda)$

Modifying so that Density refers to *Energy Density*, ( $E = mc^2$ ) :  
rho =>  $\epsilon$  energy density[mass + radiation + dark energy]/ $c^2$

$$\dot{R}^2(t) = \frac{8\pi G}{3c^2} \epsilon(t) R^2(t) - K c^2$$