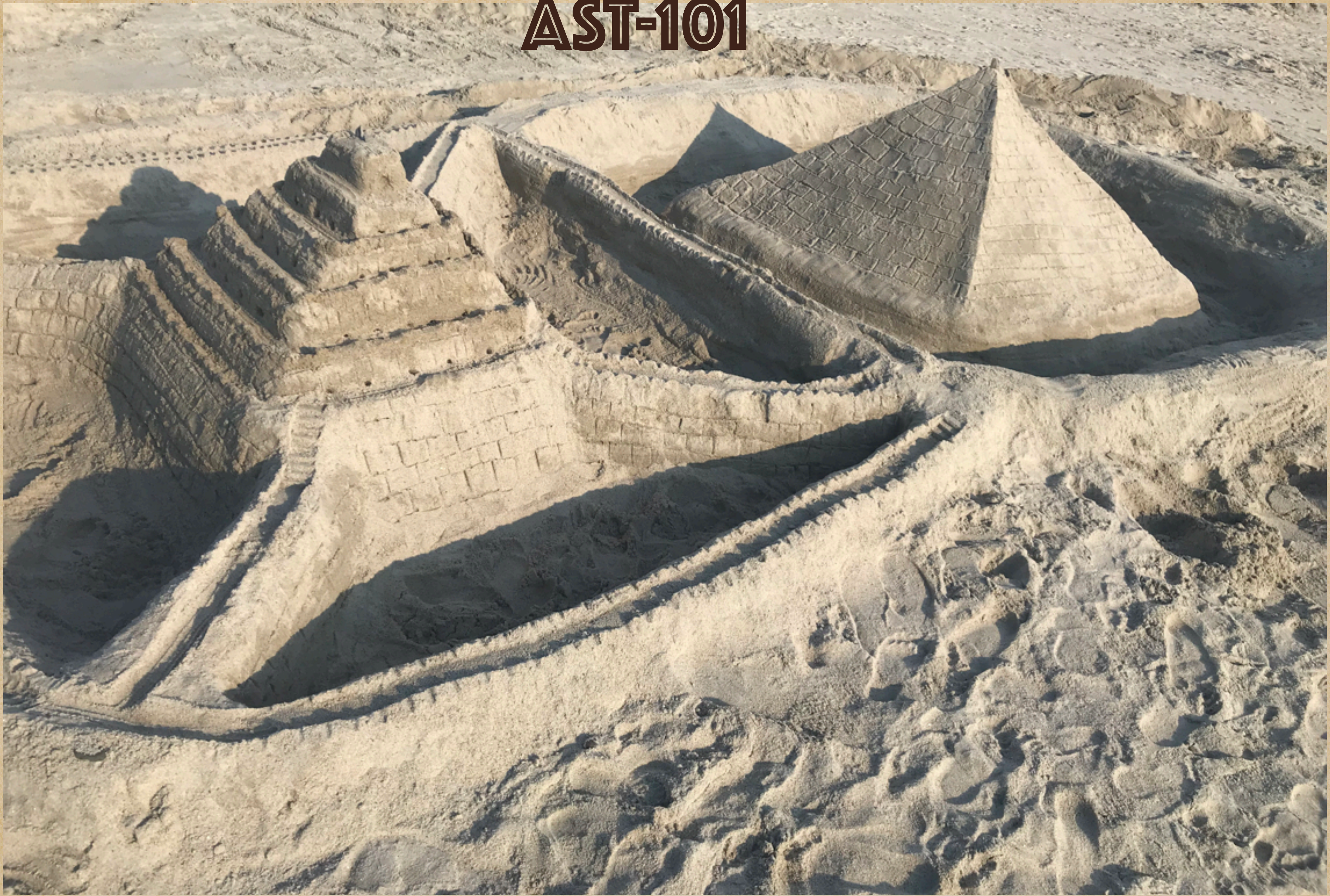
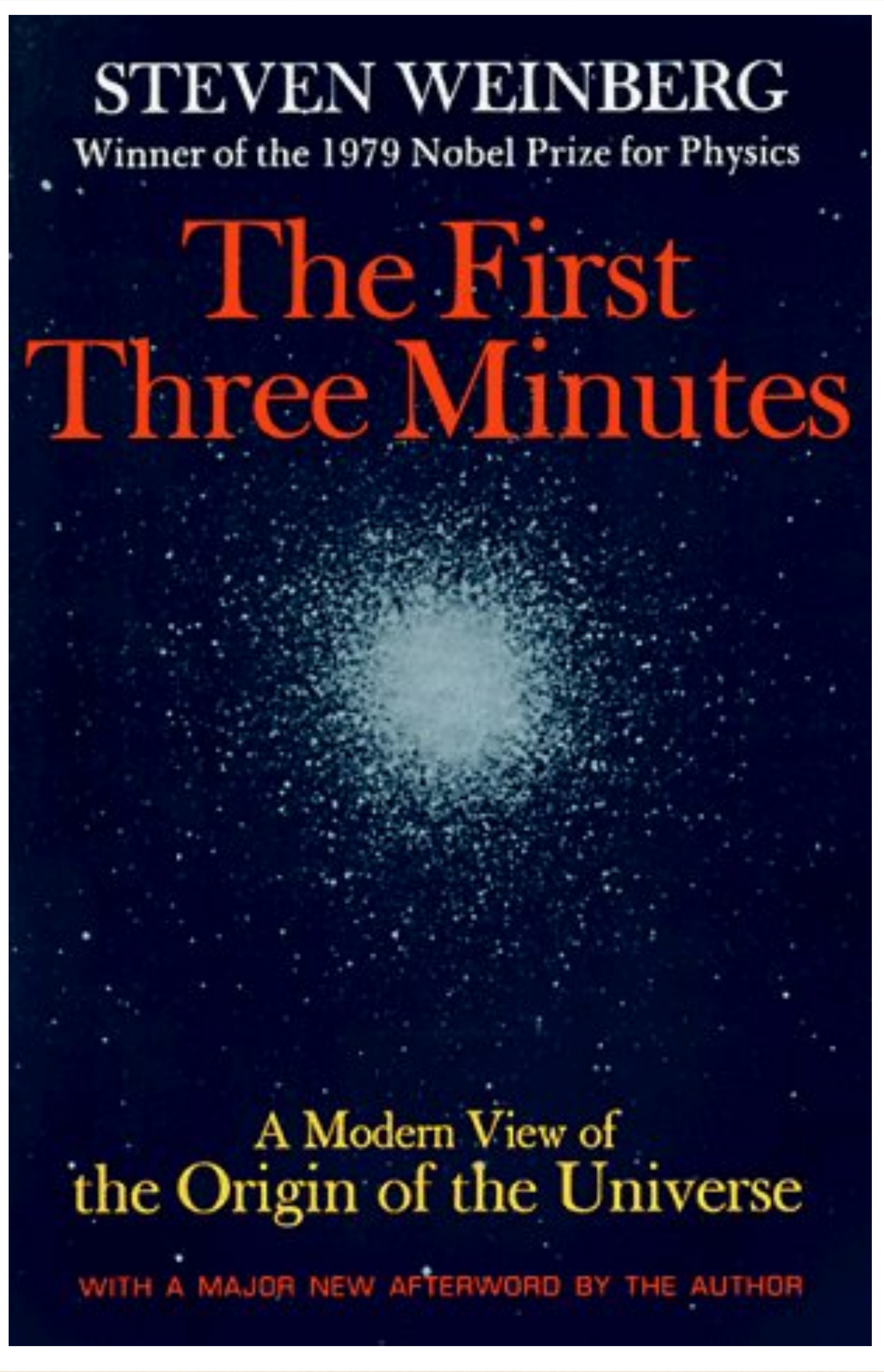


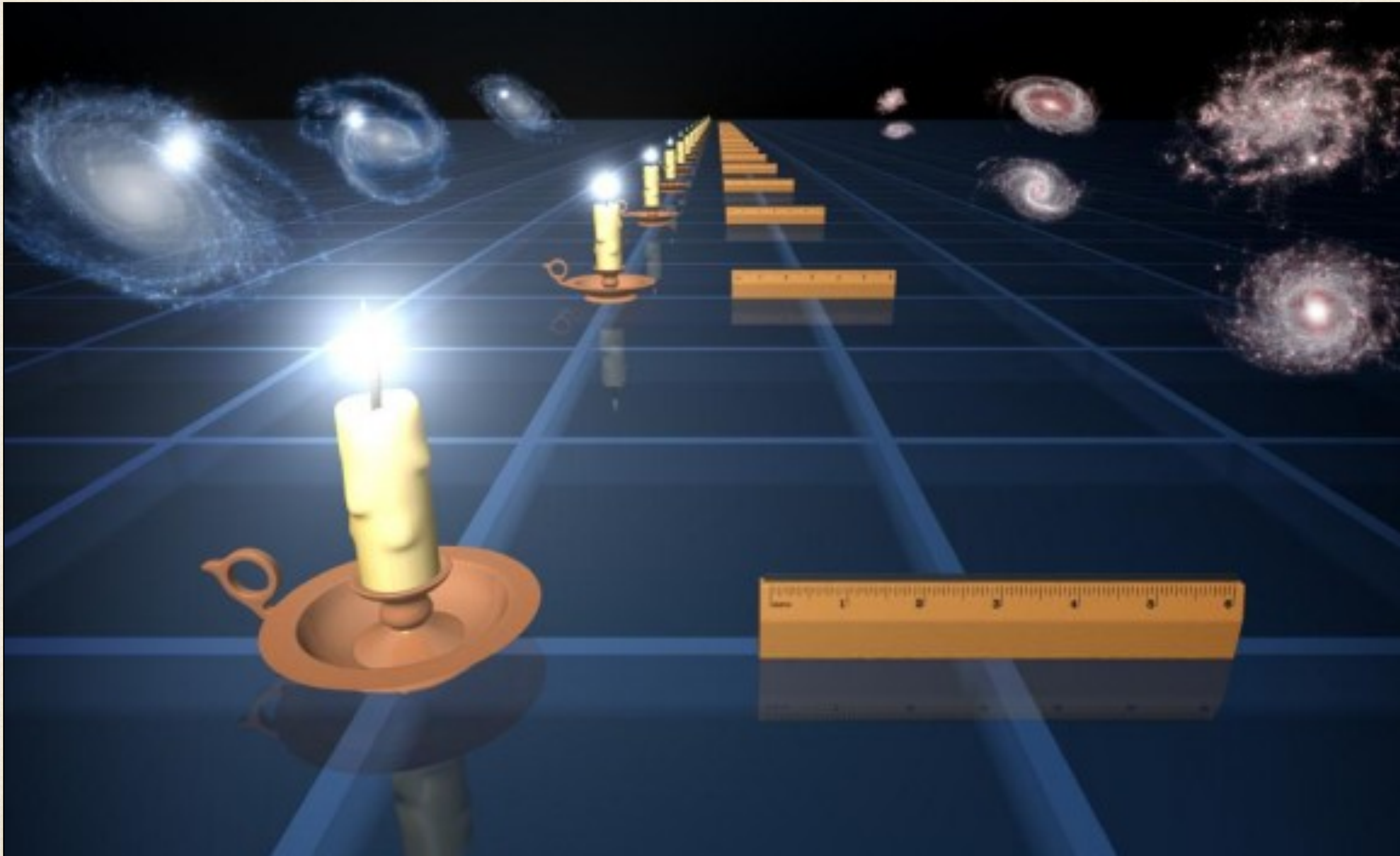
Hubble's law and the expanding Universe

Luis Anchordoqui

Recommended Textbook



Distance in Cosmology



Scales in the Universe: our Cosmic Address

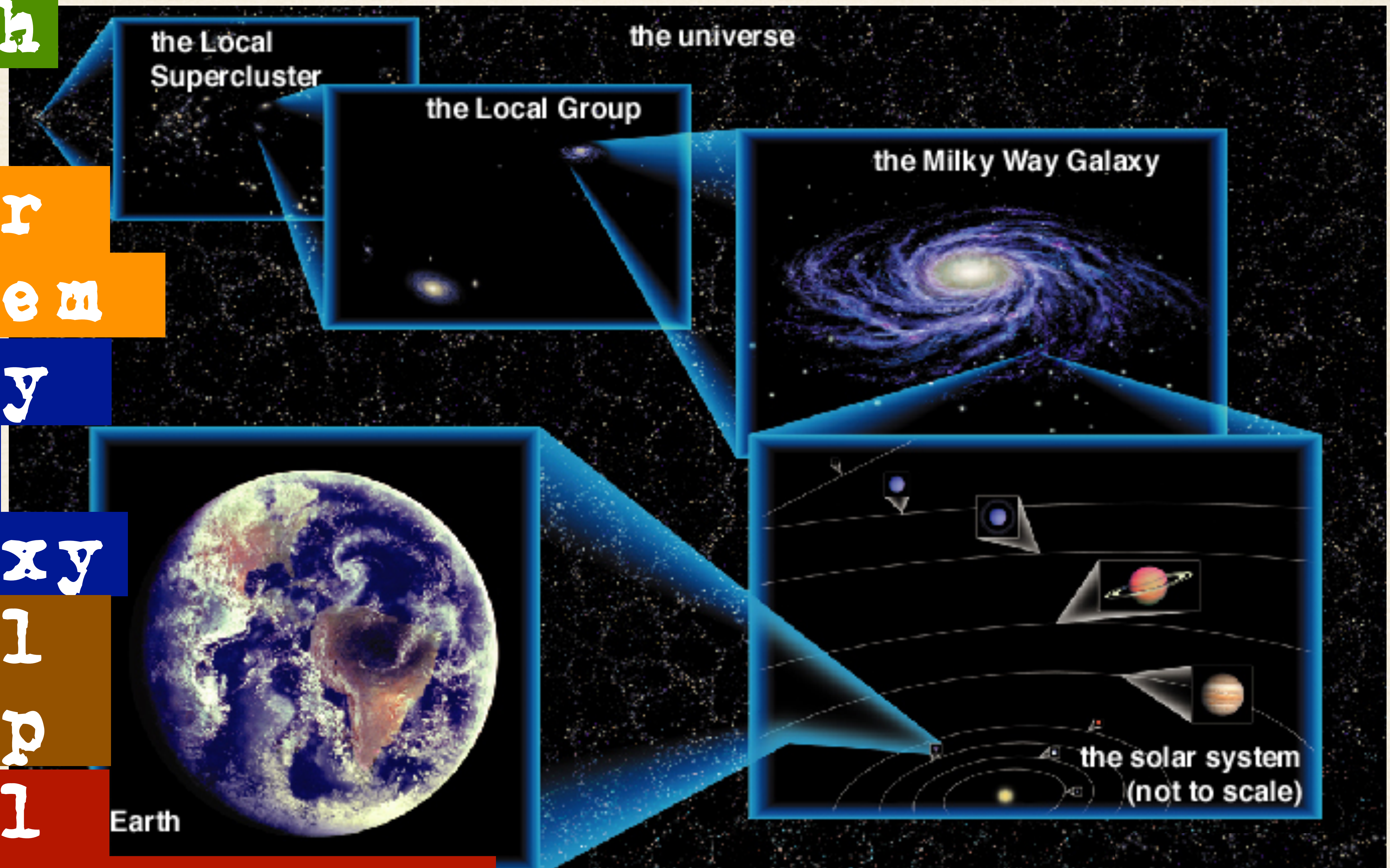
Earth

Sun/ Solar System

Milky Way Galaxy

Local Group

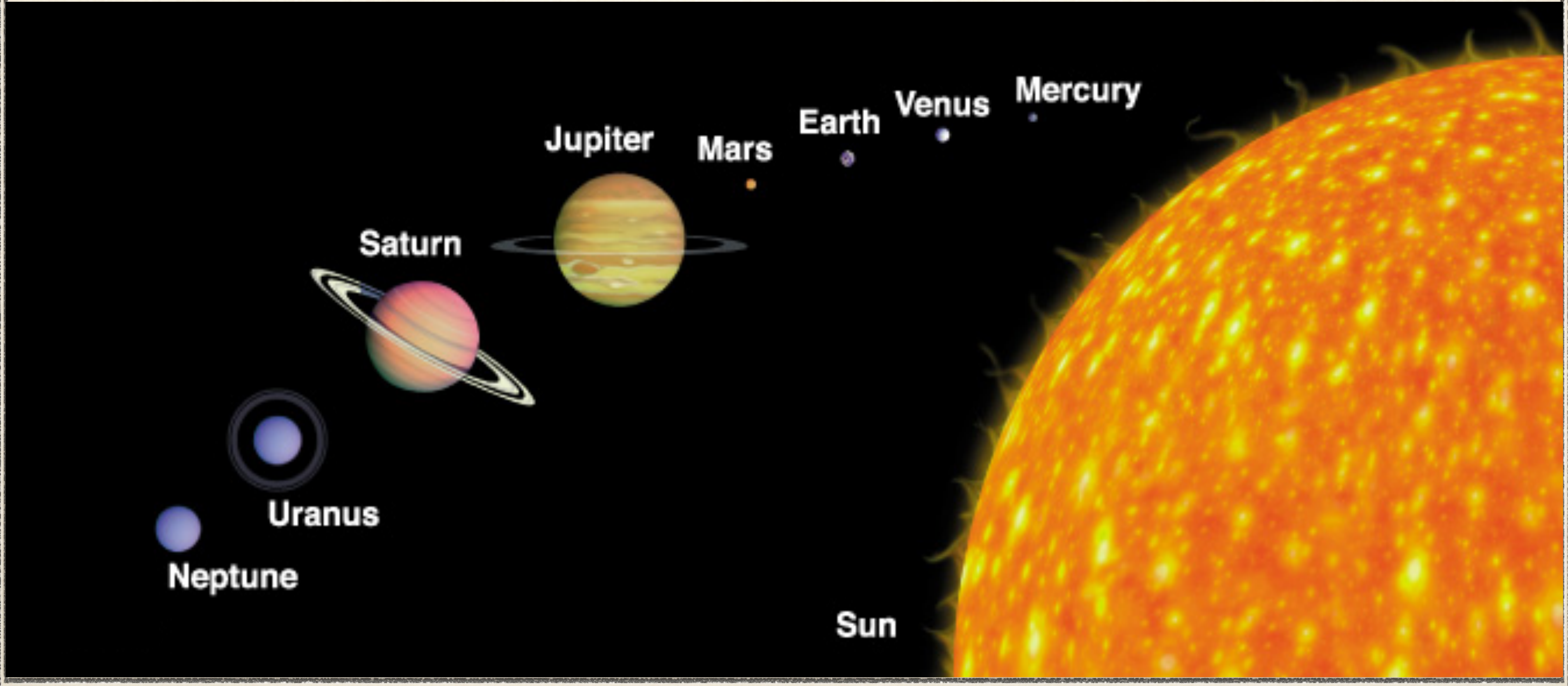
Local Supercluster



Scale models of the Universe

Scale Sun as a grapefruit

(1:10,000,000,000)



New Scale for the Galaxy:

Stars are microscopic - located a few mm apart

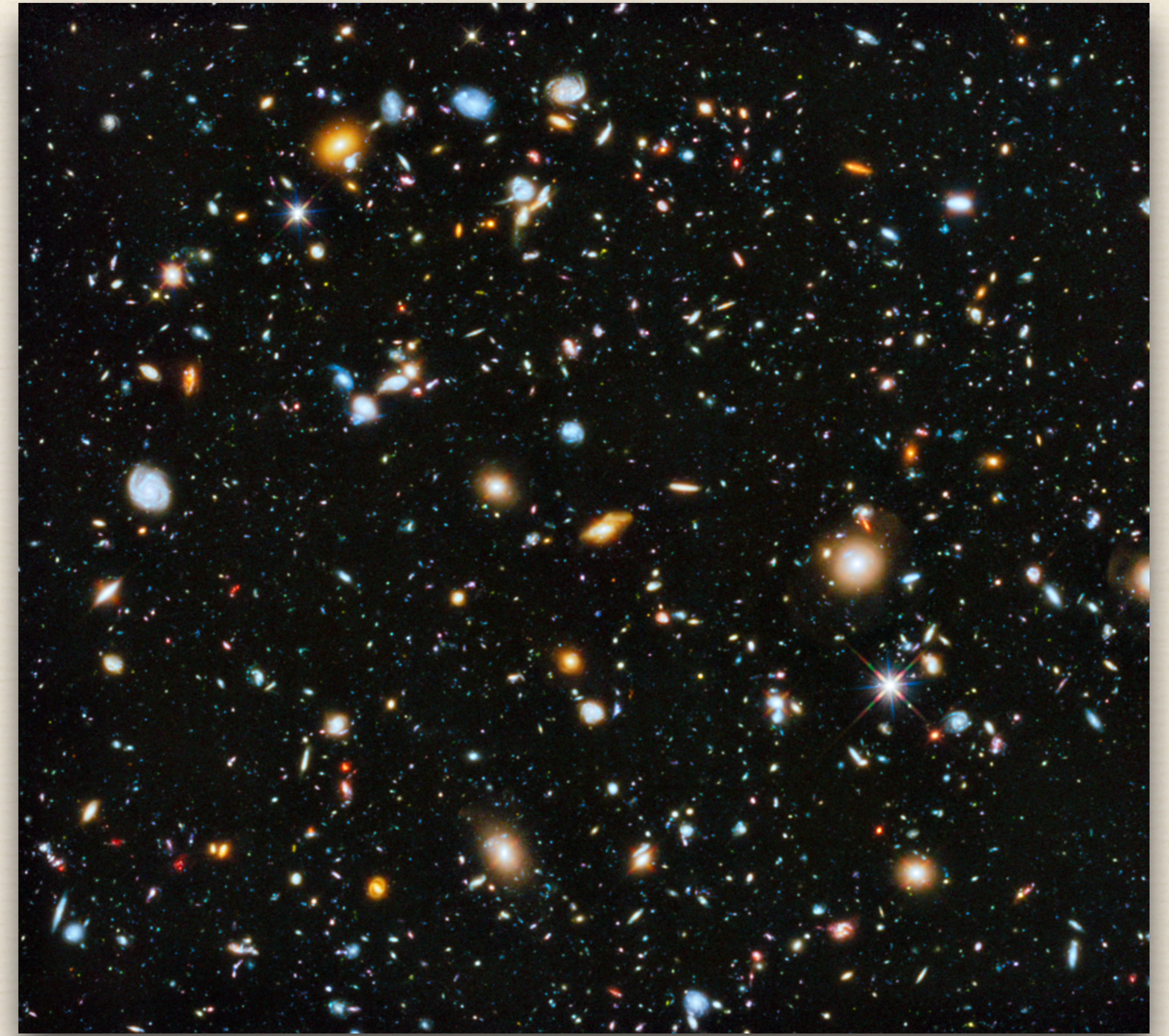
Milky Way galaxy is 100 meters in diameter, contains 100,000,000,000s (100s of billions) of stars

1 to 10^{19} scale - MW=100 m

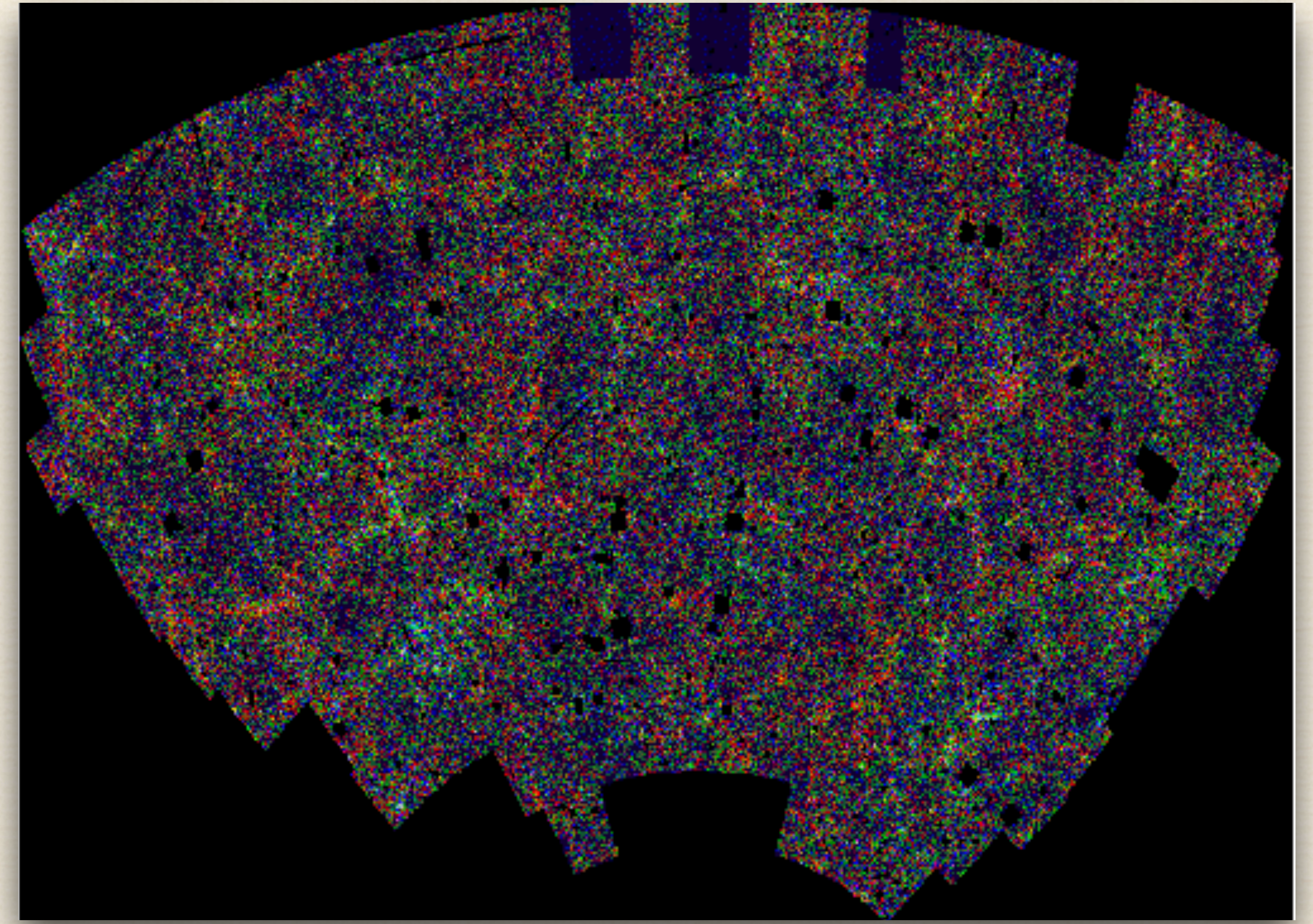
Solar system: dot ~20 meters away from center

Yet Another Scale for Everything Else

- Galaxies are 10" paper plates
- Milky Way and nearest neighbor Andromeda) are 5 meters apart
- Galaxy groups and clusters contain 10s to 1000s of galaxies



Superclusters 50 meters across
(size of buildings in our scale model)
are the largest structures we see



In this image, each dot is an entire galaxy

Which of these are the most likely?

A. Two planets colliding

B. Two stars colliding

C. Two galaxies colliding

D. None of the above… theres too much space!

Which of these are the most likely?

A. Two planets colliding

B. Two stars colliding

C. Two galaxies colliding

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Milky way and Andromeda Galaxy in local group predicted to collide in about 4 billions years

Why are collisions between galaxies more likely than between stars within a galaxy?

A. Galaxies are much larger than stars

B. Galaxies travel through space much faster than stars

C. Relative to their sizes, galaxies are closer together than stars

D. Galaxies have higher redshifts than stars

Why are collisions between galaxies more likely than between stars within a galaxy?

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Measuring cosmic distances

- Most useful measure is based on the speed of light = 300,000 km/sec

- Light-year = the distance light travels in a year = ~ 10 trillion kilometers = 10^{16} m

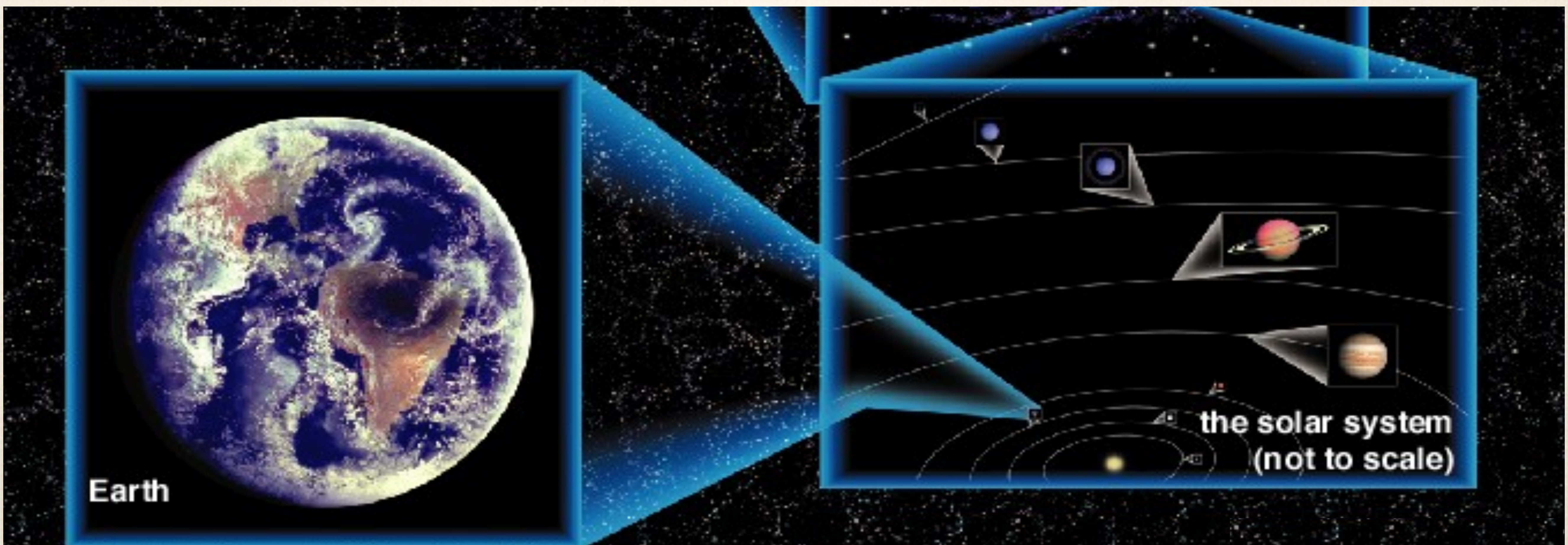
- Like saying I live 30 min from Stony Brook

- Constant speed for light traveling in space

- Nothing travels faster through space

Measuring distances with light

- Earth-Moon = 1.5 light-seconds
- Earth-Sun (a.k.a. astronomical unit, or AU) = 8 light-minutes
- Solar system = light-hours



Nearest stars = several light-years

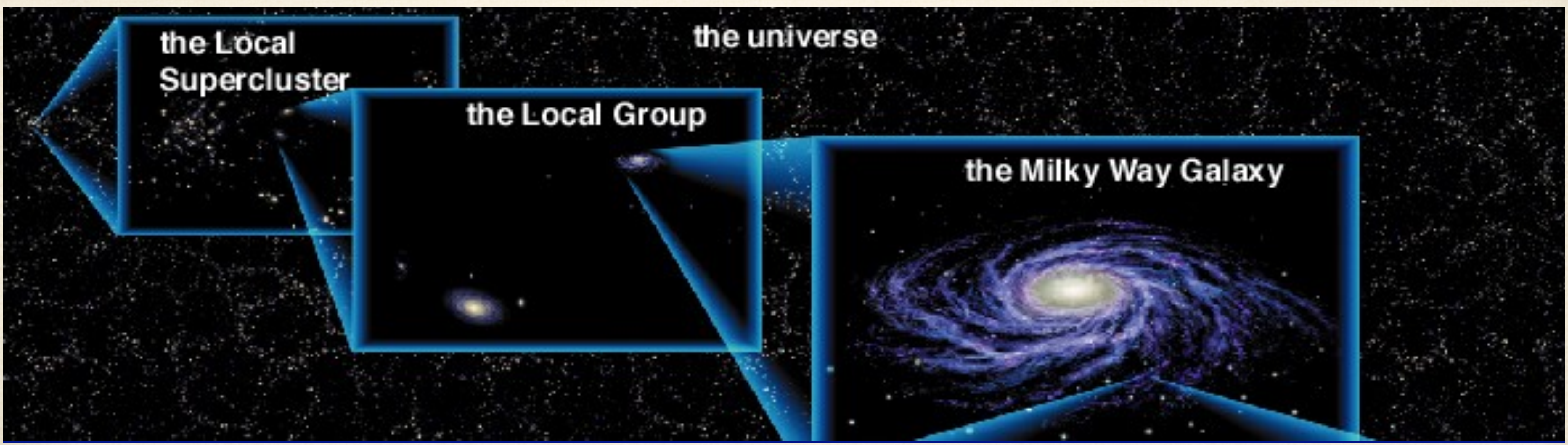
Milky Way= 100,000 light-years = 10^5 ly

Galactic Center is 28,000 light-years away

Local group = several million light-years =10^6 ly

Observable universe = 46 billion light-years

= 4.6×10^{10} ly



A radio message from outer space arrived today which was sent from planet Buff on the day you were born. The friendly aliens sending you the birthday message live:

A.- In the Solar System

B.- From a close-by star in the Milky Way

C.- In Andromeda, the nearest major galaxy

D.- In a galaxy outside the local group

Answer B:

You are probably between 10 and 90 years old Objects at distances between 10 and 90 light-years away from us are relatively close-by stars in the Milky Way

The solar system is light-hours in size

The Local group is millions of light-years in size

Over astronomical distances, even light takes a lot of time (from a humans perspective!) to travel between the stars

This means that what we SEE in the distant universe is light that has traveled a long time.

Our image of the universe is a delayed image

In looking out into space, we are looking back in time!

Look Back Time

What we SEE is always delayed by the speed of light

In the classroom, our view of each other is only about 10^{-5} seconds old, so we barely notice (10^{-5} sec = 0.00001 sec)

Satellite communications - noticeable delays

The image of the Sun is _______ old?

Analogy: what we hear is delayed by the speed of sound - more familiar in our everyday lives (e.g. lightening-thunder delay)

When studying the Universe, it is impossible to separate space and time

The image of a galaxy spreads across 100,000 years of time

Try to think of what we SEE NOW as different from what may EXIST now

Last night we saw a bright supernova explode in the Andromeda galaxy (the other big galaxy in the local group)

The remnants from such explosions disperse in about 10,000 years

A.- The supernova remnant still exists now, and we will watch it disperse over the next 10,000 Earth years

B.- In reality, the supernova remnant has already dispersed, but we will watch it disperse over the next 10,000 Earth years

C.- The image of the supernova dispersing will not reach us for another 2 million years

D.- We will never see the supernova remnant because it has already dispersed

Answer B:

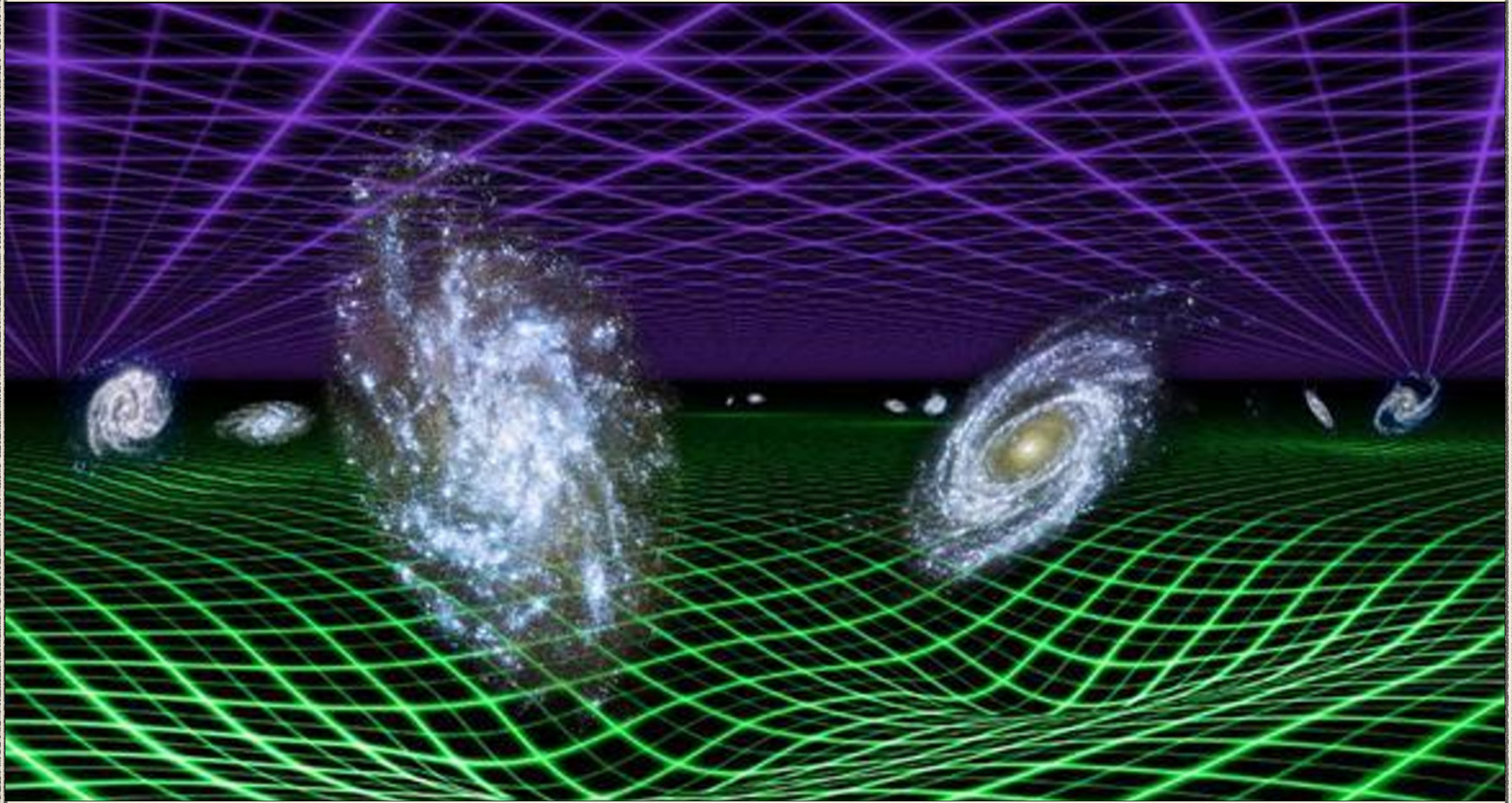
This galaxy is millions of light-years away from us

The light left the galaxy millions of years ago and only arrived yesterday

In the intervening time, the supernova remnant has dispersed and no longer exists today

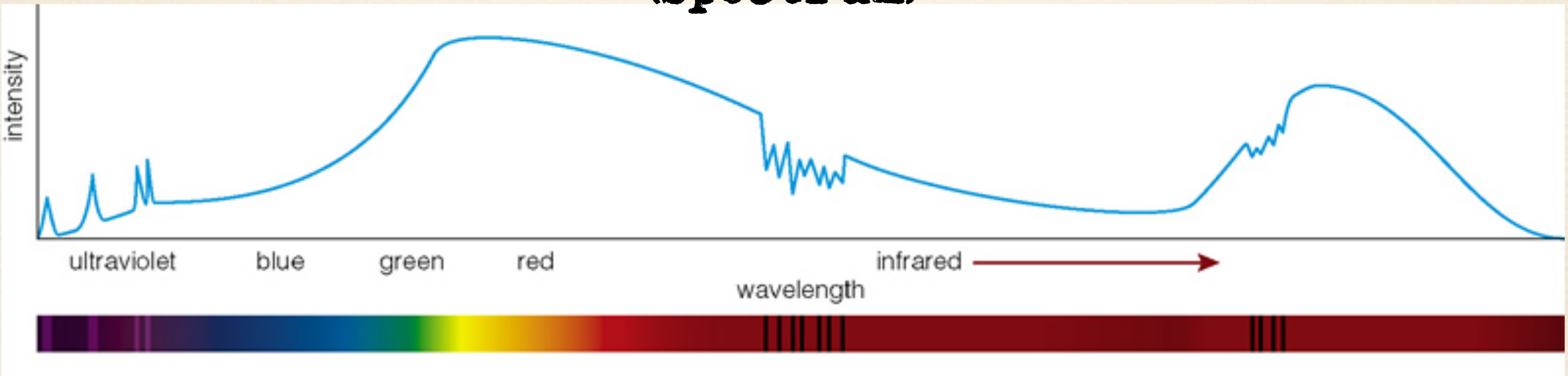
But the light that left on the day after the explosion will arrive here today and we can see that

The Expanding Universe
Introduction to Cosmology



Light as Information Bearer through its interaction with matter

We can separate light into its different wavelengths (spectrum)



By studying the spectrum of an object, we can learn its:

Composition

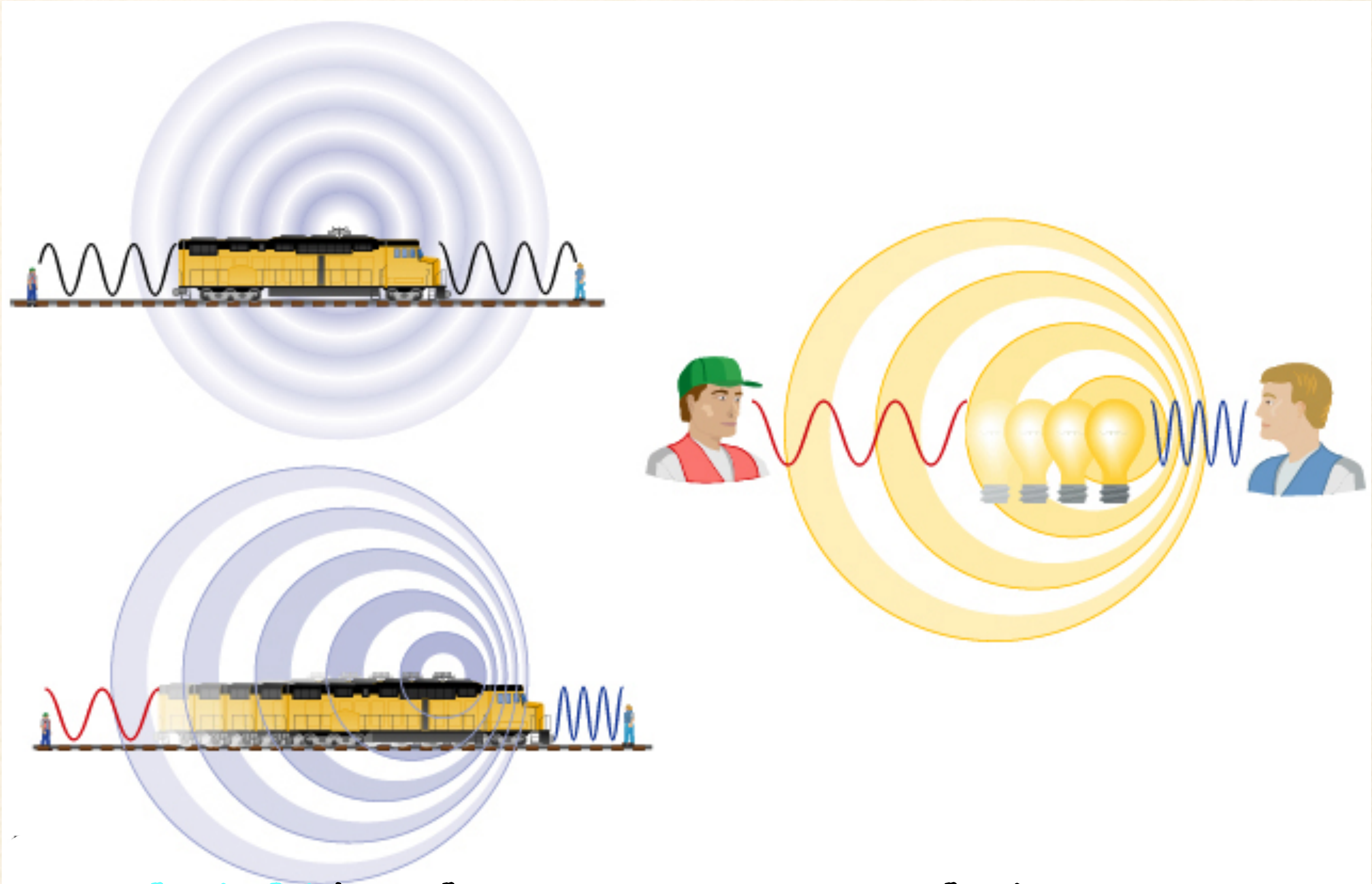
Temperature

Velocity

Measuring velocities without a stopwatch: the Doppler Shift

Familiar shift in pitch of SOUND:

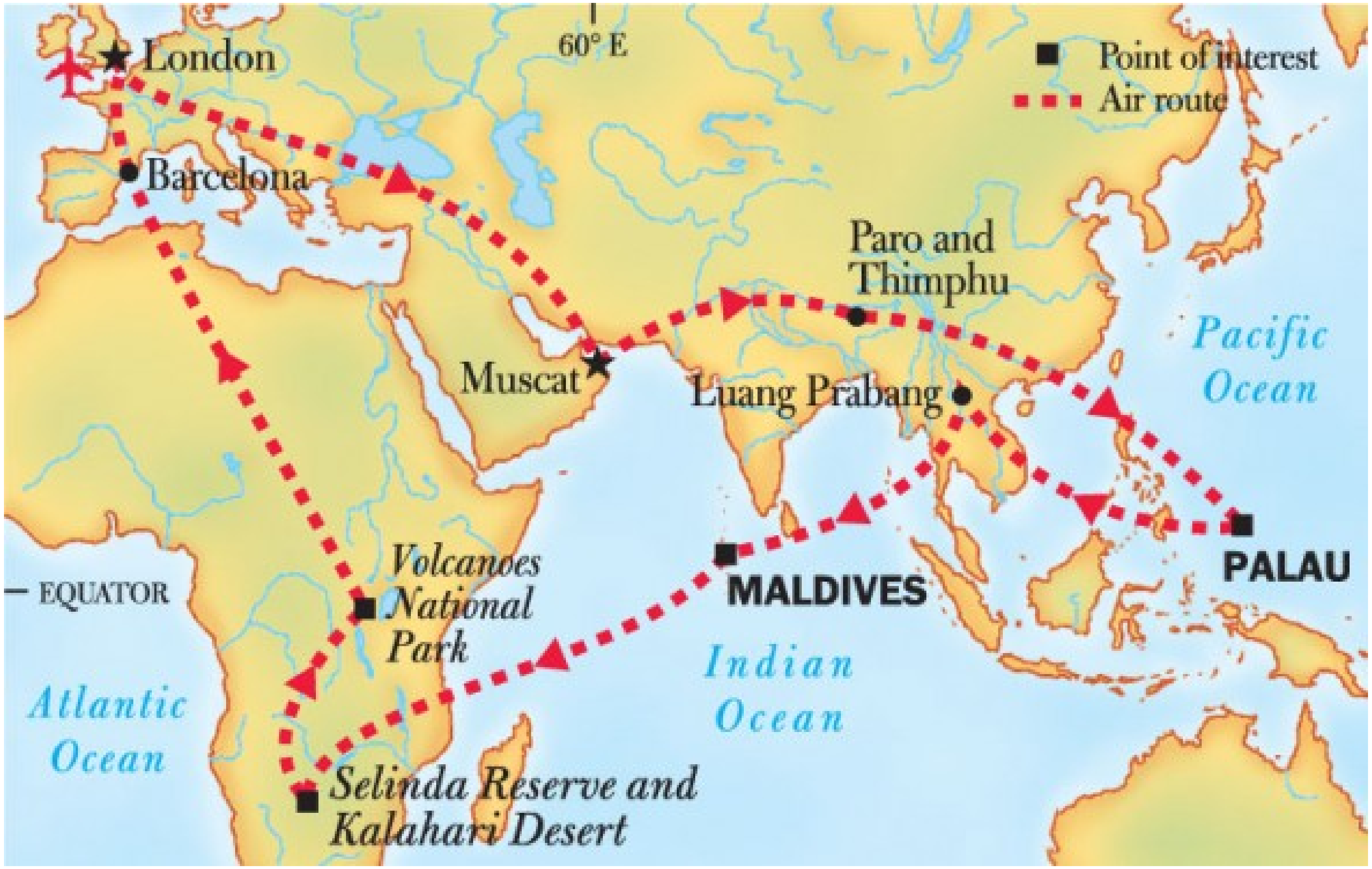
higher when approaching, lower when receding



Similar shift in frequency of light:

higher frequency (blueshift) when approaching, lower frequency (redshift) when receding

- Weinberg's analogy



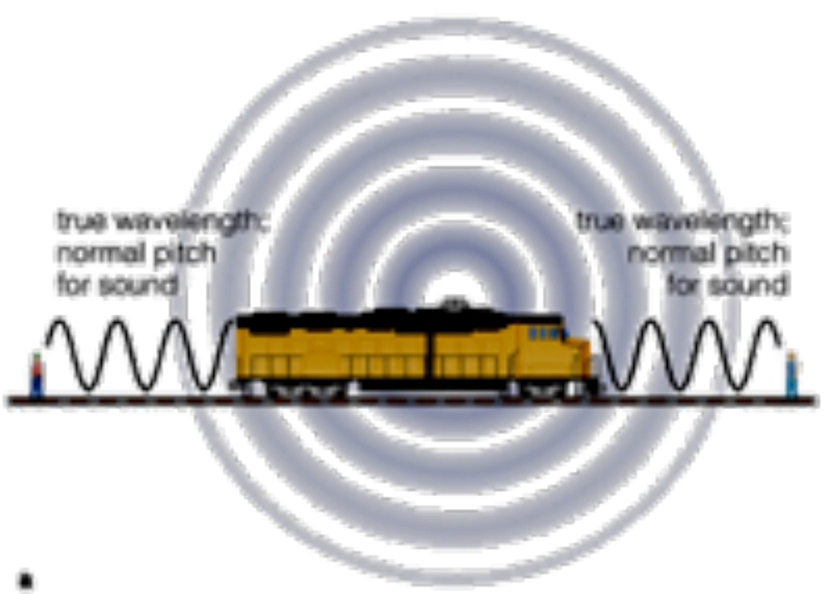
- *Doppler effect* ☞ change in observed frequency of source due to relative motion between source and receiver
- Relative motion that affects observed frequency is only motion in line-of-sight between source and receiver

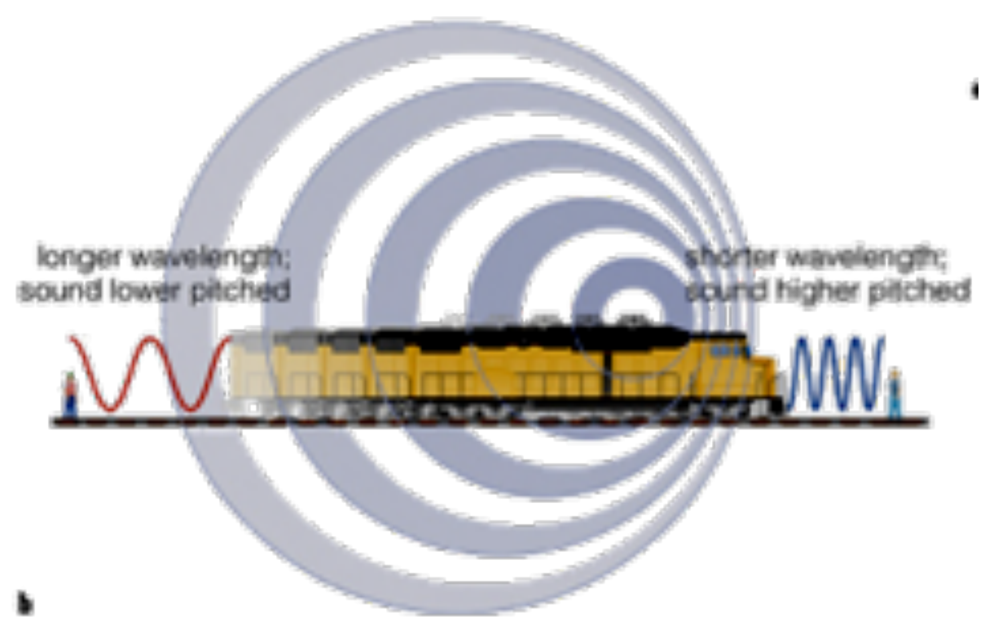
- When we observe sound wave from source at rest
  time between arrival wave crests at our instruments
  is same as time between crests as they leave source

- If source is moving toward us
  time between arrivals of wave crests is decreased
  because each successive crest has shorter distance to go

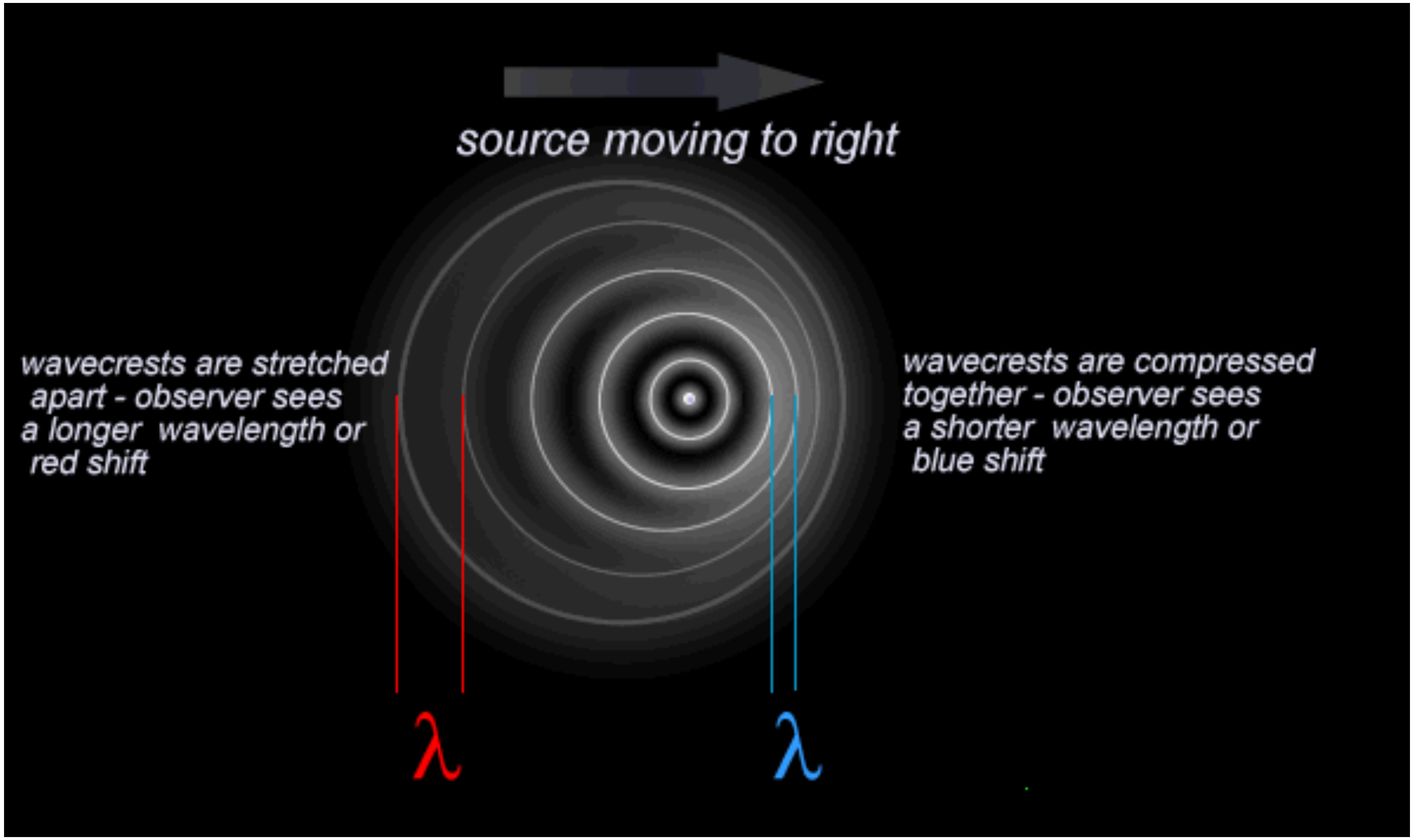
- Time between crests ☞ wavelength divided by speed of wave

- A wave sent out by source moving towards us
  will appear to have shorter wavelength than if source were at rest





Doppler Effect



*** Sound waves**

*** Electromagnetic waves**

*** Any kind of wave**

Shift in wavelength (simplest form):

$\Delta\lambda/\lambda = V/c$

V = velocity of emitting object

c = velocity of light or velocity of sound

But … motion is not the only cause of wavelength shifts!

Photon A has a wavelength of 1000nm and Photon B has a wavelength of 400nm

Whether the following statements about these photons are TRUE or FALSE

A.- Photon A is more energetic than Photon B

B.- Photon A is redder than Photon B

C.- Photon A has a greater frequency than Photon B

D.- Photon B is moving faster than Photon A

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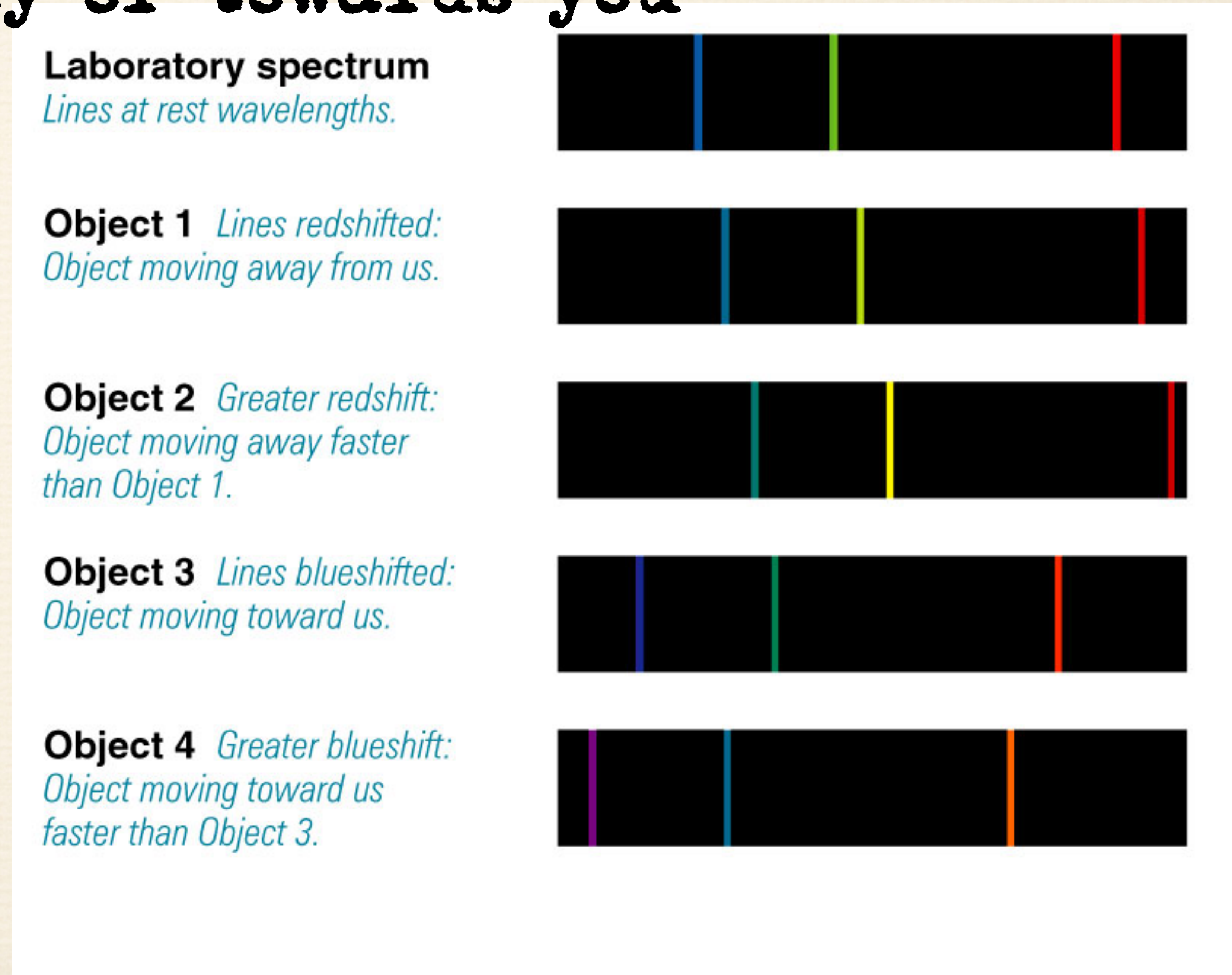
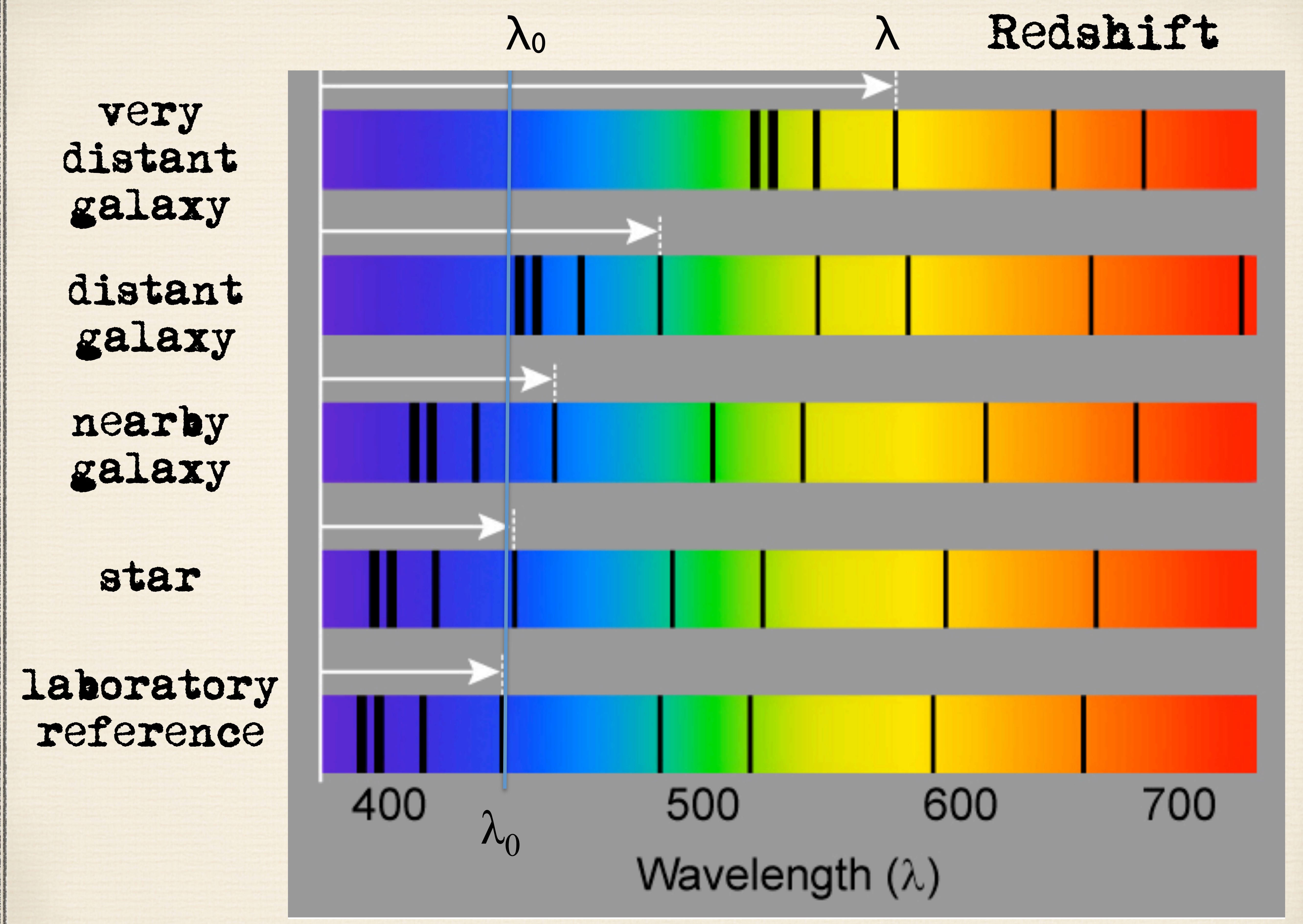
Most easily used with absorption or emission lines where you know the zero-velocity (rest) wavelengths

Then, measure redshift or blueshift to get the velocity away or towards you





λ_0
λ
Redshift
very distant galaxy
distant galaxy
nearby galaxy
star
laboratory reference
400
500
600
700
λ_0
Wavelength (λ)

The Cosmological Principle

The universe looks about the same no matter where you are within it

Matter is evenly distributed on very large scales in the universe

No center & no edges

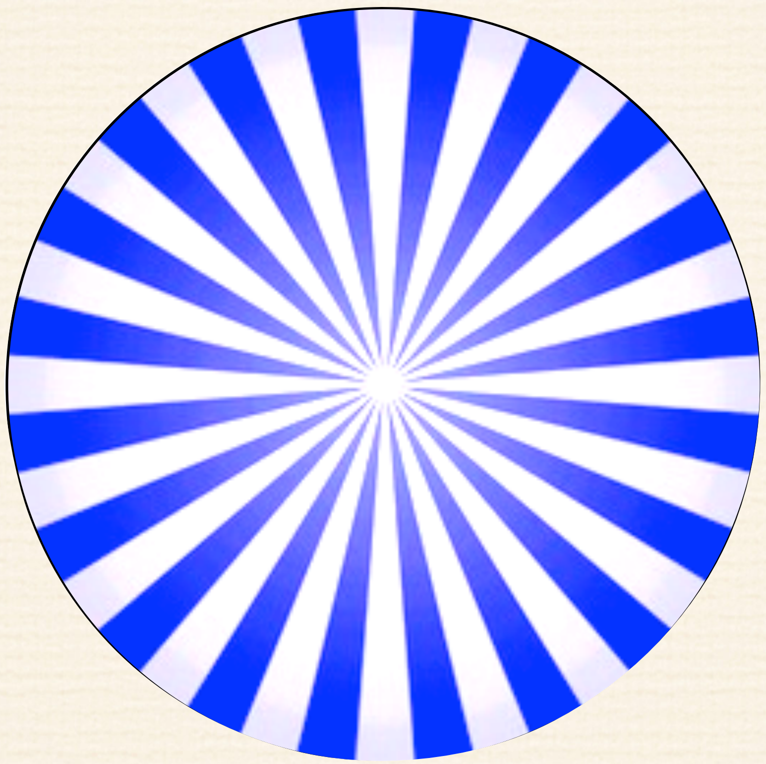
Not proven but consistent with all observations to date

Homogeneity and Isotropy!

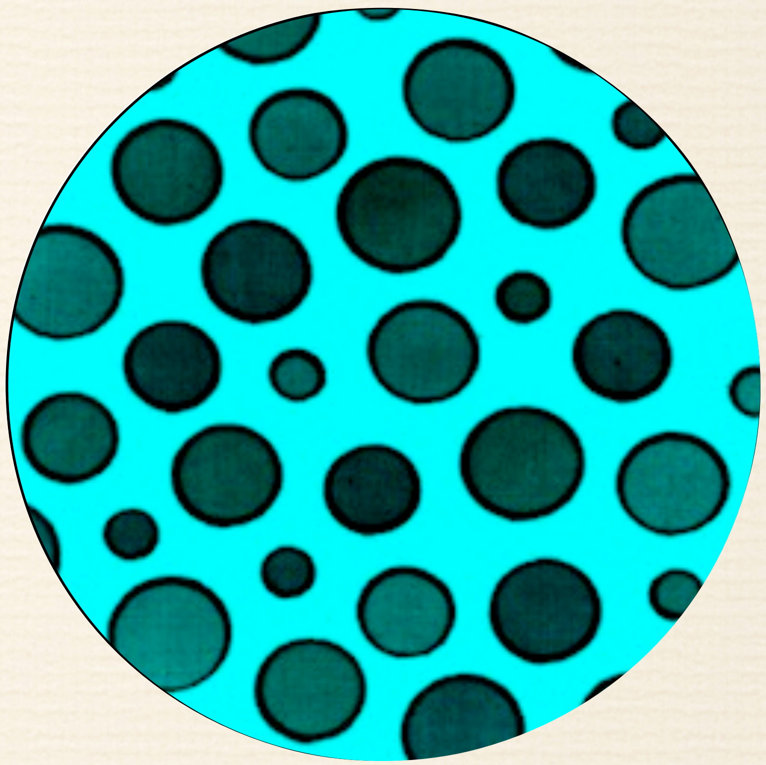
(in space, but not in time)!

Homogeneous but not Isotropic

Isotropic but not Homogeneous



Isotropic and Homogeneous



This simplifies the modeling, since only the radial coordinate matters, and the density of any mass/energy component is the same everywhere at a given time !

The Cosmological Principle

Relativistic cosmology uses some symmetry assumptions or principles in order to make the problem of solving the universe viable

The Cosmological Principle states that

At each epoch, the universe is the same at all locations and in all directions, except for local irregularities

Therefore, globally the Universe is assumed to be homogeneous and isotropic at any given time; and its dynamics should be the same everywhere

Note: the Perfect Cosmological Principle states that the Universe appears the same at all times and it is unchanging - it is also homogeneous in time - this is the basis of the Steady State model

No matter which direction we look, we see galaxies moving away from us

Therefore, we must be at the center of the expansion

A.- True

B.- False

No matter which direction we look, we see galaxies moving away from us

Therefore, we must be at the center of the expansion

A.- True

B.- False

Your friend leaves your house

She later calls you on her cell phone, saying that she's been driving at 60 mph (miles per hour) directly away from you the whole time and is now 60 miles away

Without looking at your watch, can you tell how long has she been gone?

A.- Yes,30minutes

B.- Yes, 60 minutes

C.- Yes, 120 minutes

D.- No, not enough information to tell

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Discovery of the Expanding Universe

Based on an early work byVesto Melvin Slipher ->

< - Edwin Hubble discovered that galaxies recede from us with a velocity that is proportional to the distance

The ***Hubble's law***:

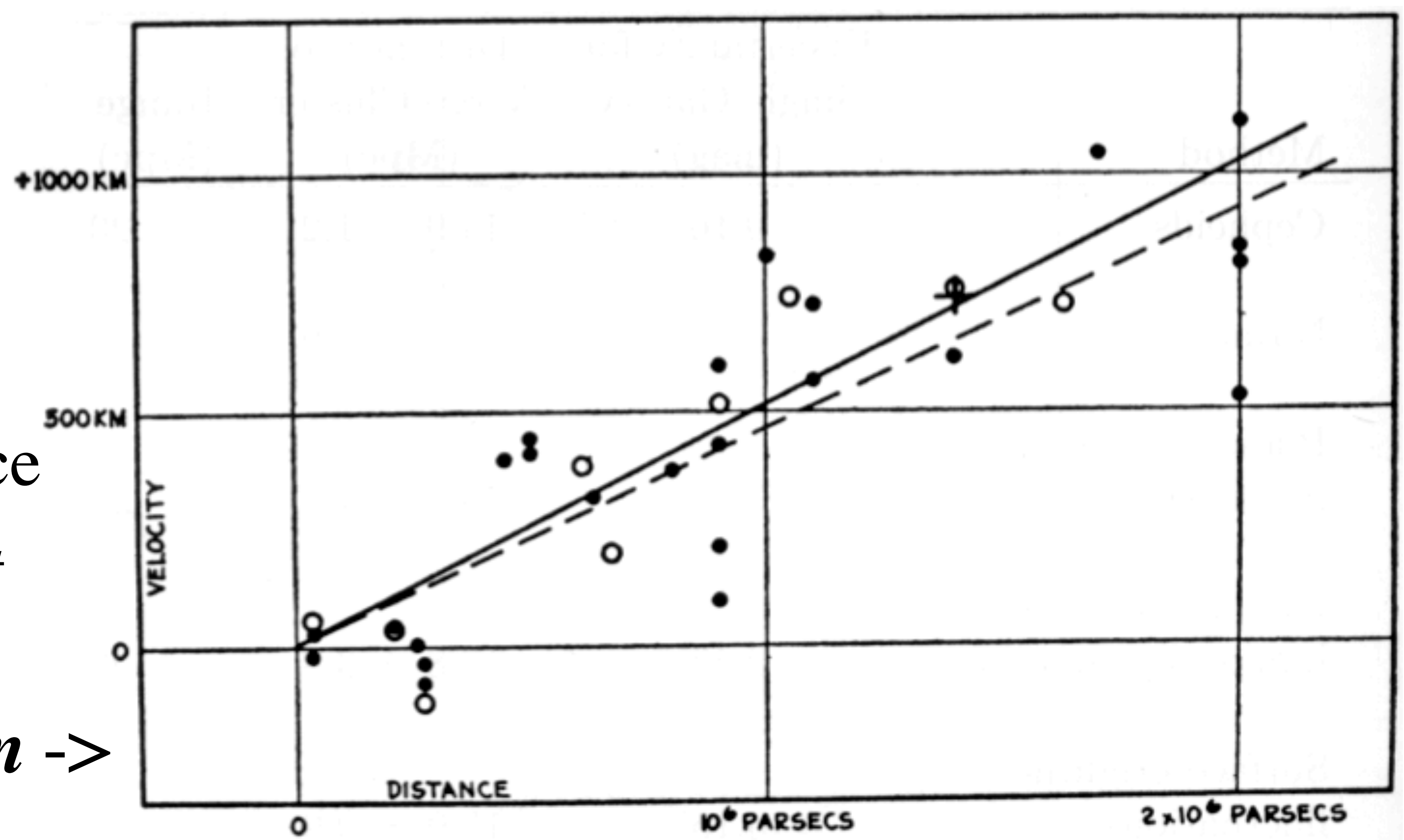
$$V = H\ D$$

Velocity

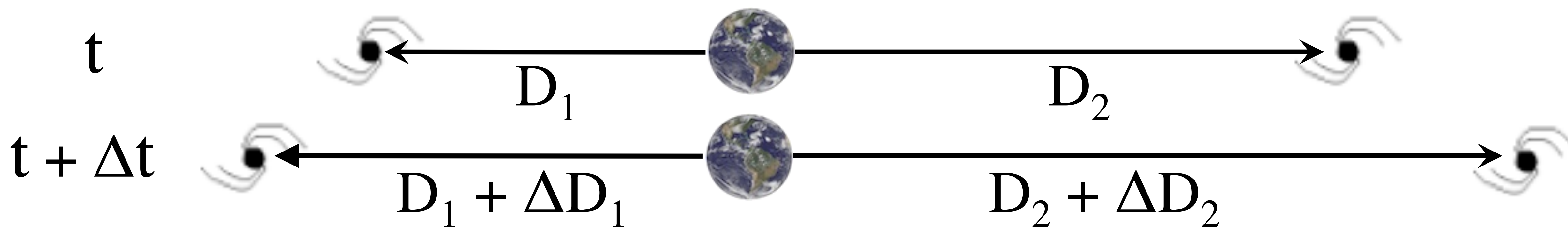
Distance

Hubble's constant

The ***Hubble diagram*** ->

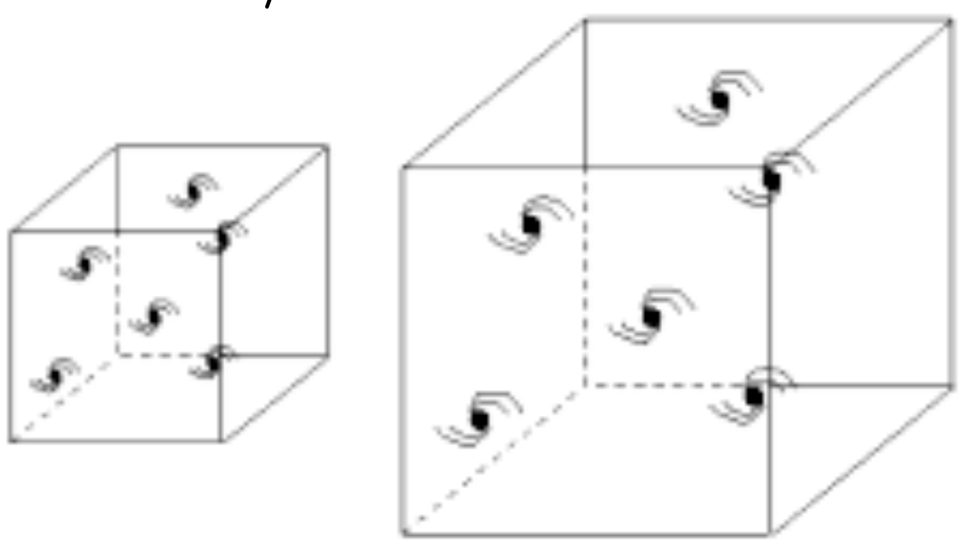


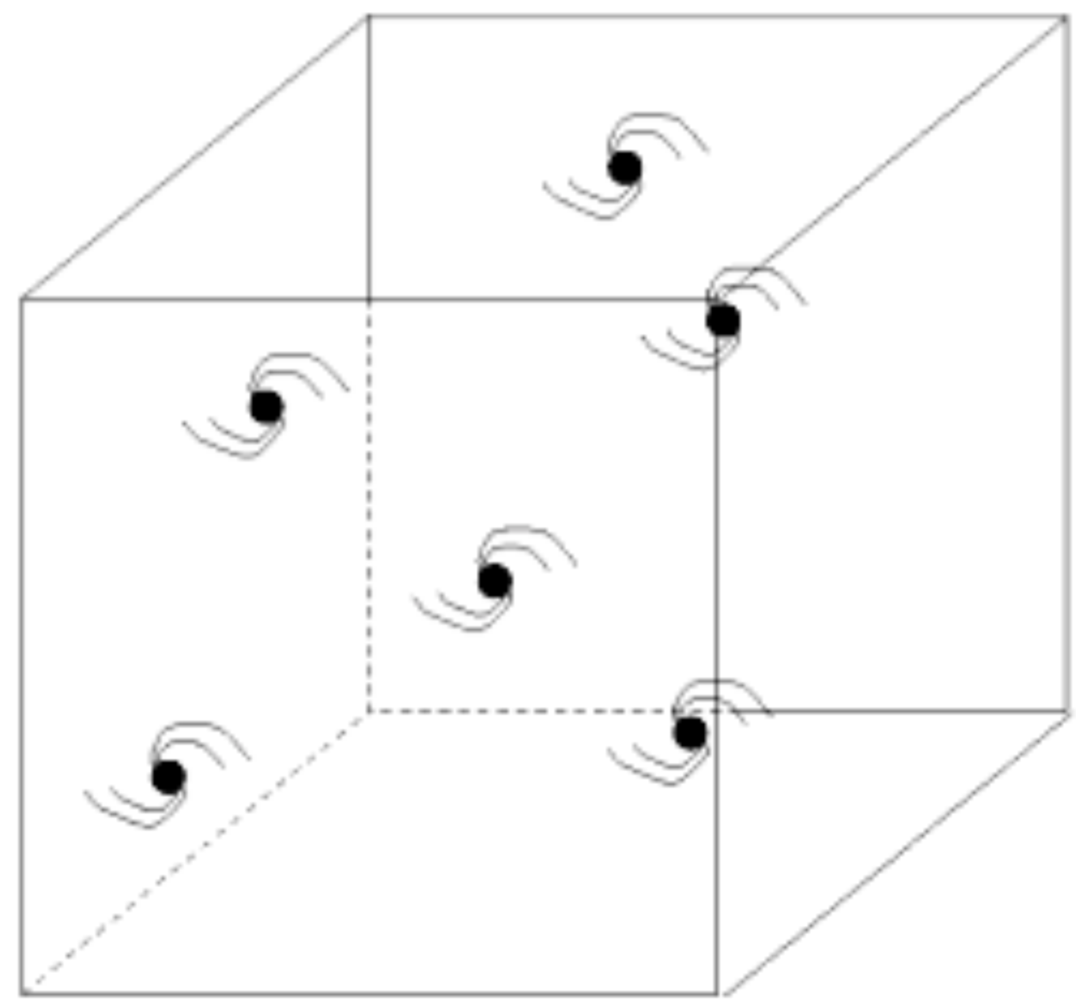
Expansion of the Universe



$$\Delta D \propto D$$

$$V = \Delta D/\Delta t \propto D$$





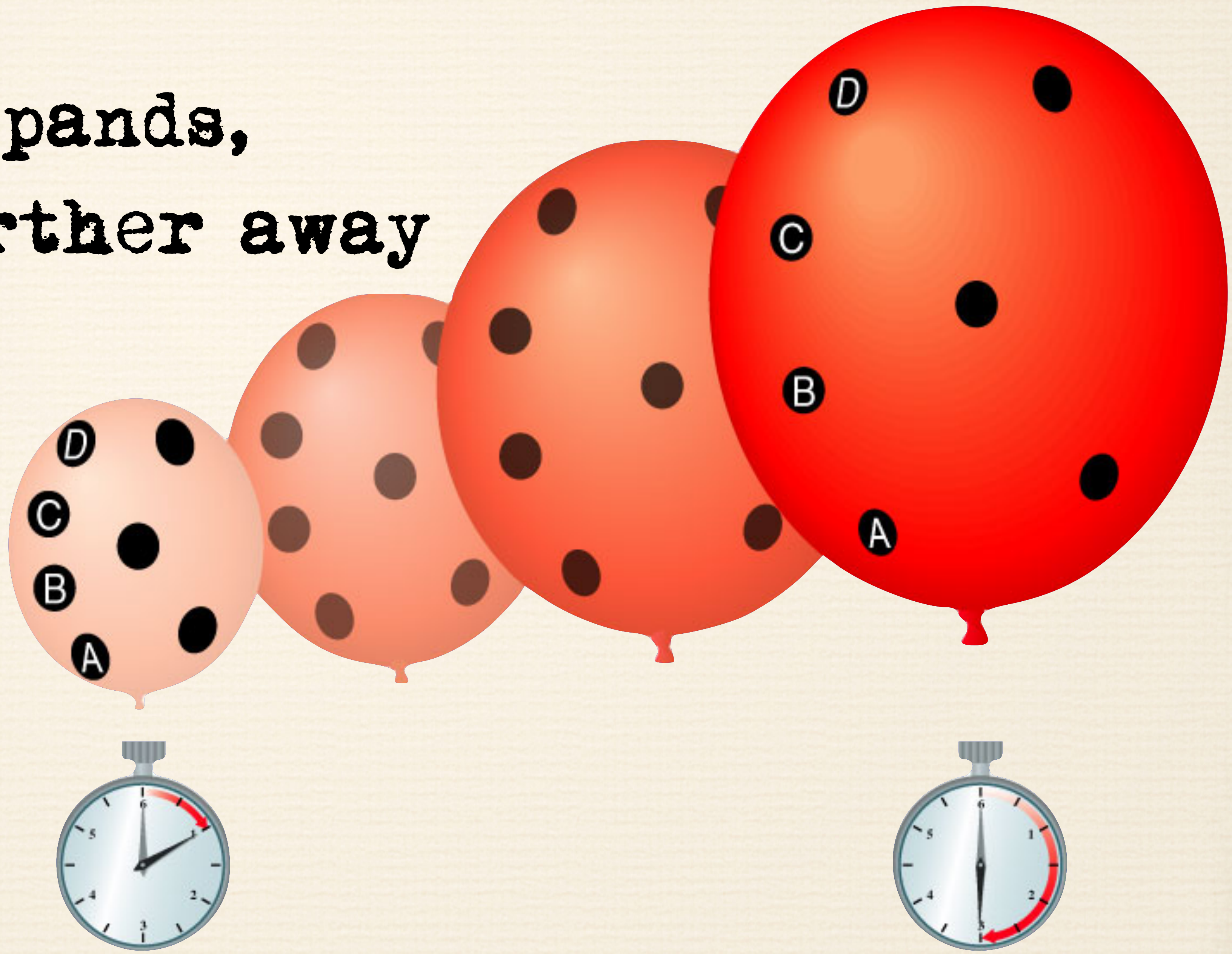
The ***space itself expands***, and carries galaxies apart

In a homogeneous, isotropic universe, there is no preferred center

Balloon analogy for expanding universe

Each dot on the balloon can be thought of as a galaxy

As the balloon expands, galaxies move farther away from each other



Expansion Relative to What? Comoving and Proper Coordinates

There are fundamentally two kinds of coordinates in a GR cosmology:

- ***Comoving coordinates*** = expand with the universe

  Examples:

  – Unbound systems, e.g., any two distant galaxies

  – Wavelengths of massless quanta, e.g., photons

- ***Proper coordinates*** = stay fixed, space expands relative to them. Examples:

  – Sizes of atoms, molecules, solid bodies

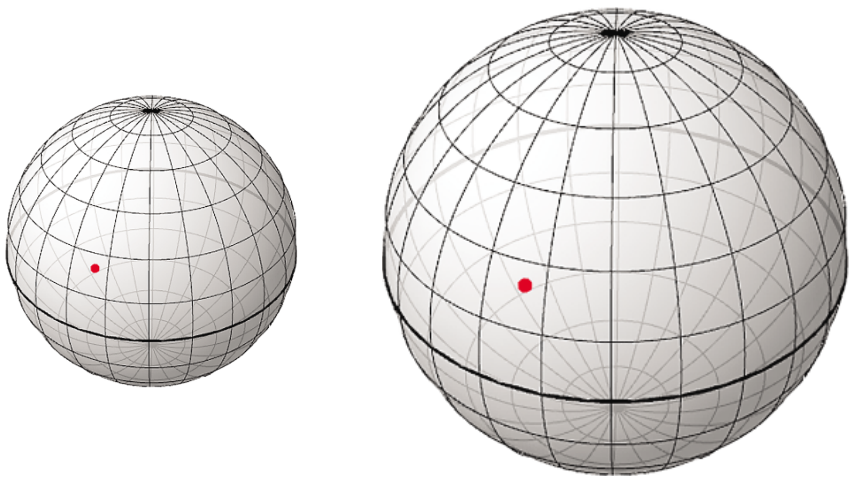
  – Gravitationally bound systems, e.g., Solar system, stars, galaxies …

Expansion into What?

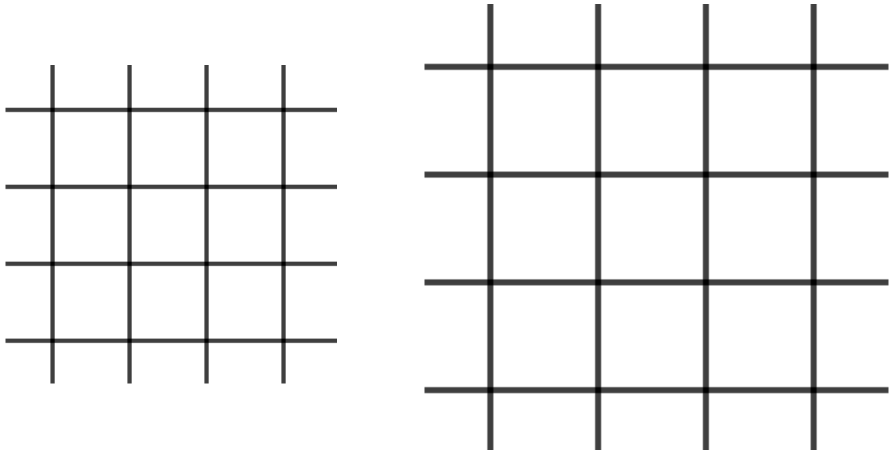
Into itself. There is nothing “outside” the universe

(Let’s ignore the multiverse hypothesis for now)

A positive curvature universe is like the surface of a sphere, but in one extra dimension. Its volume is finite, but changes with the expansion of space



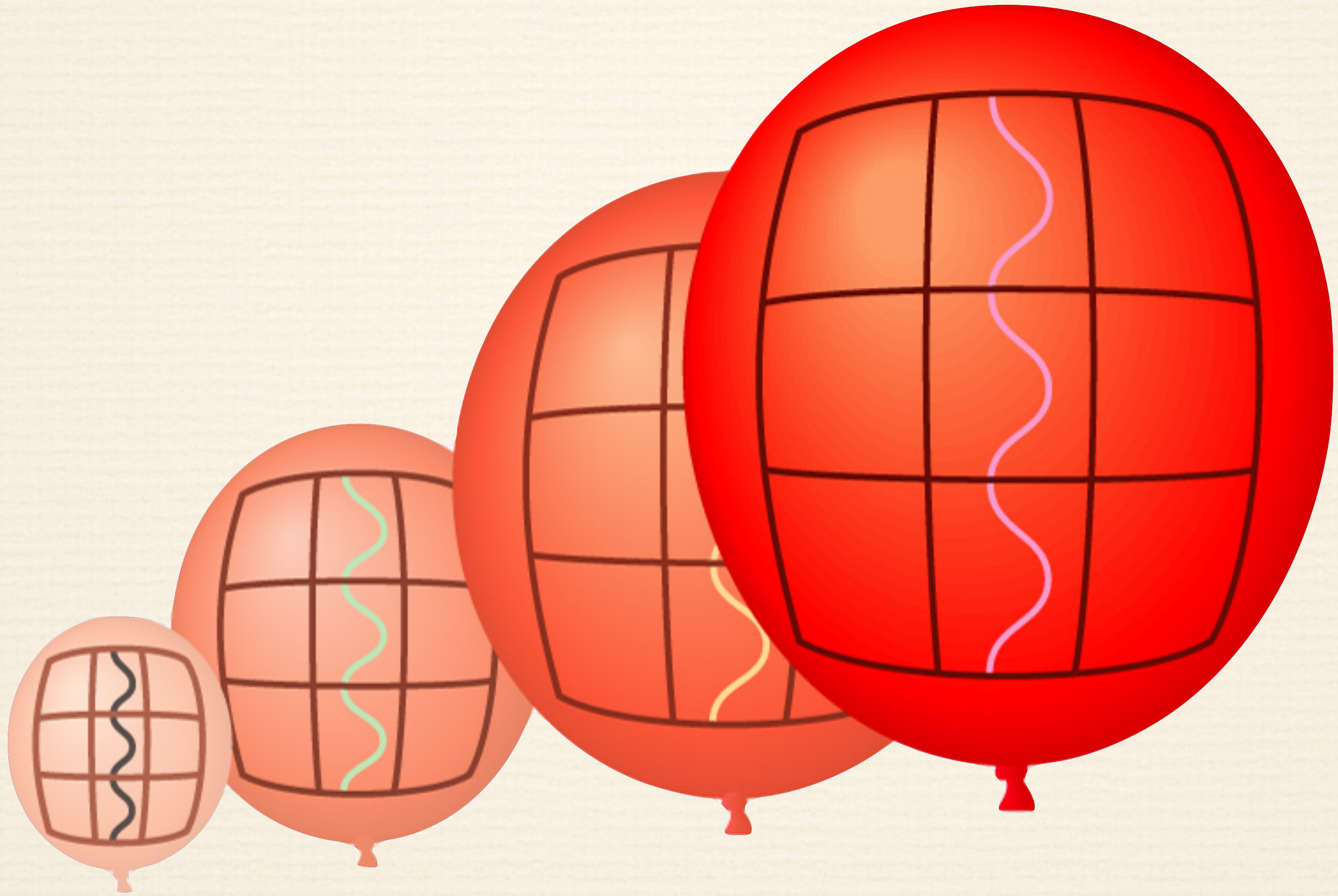
A flat or a negative curvature universe is infinite in all directions; the comoving coordinate grid stretches relative to the proper coordinates



In either case, there is no “edge”, and there is no center

(homogeneity and isotropy)

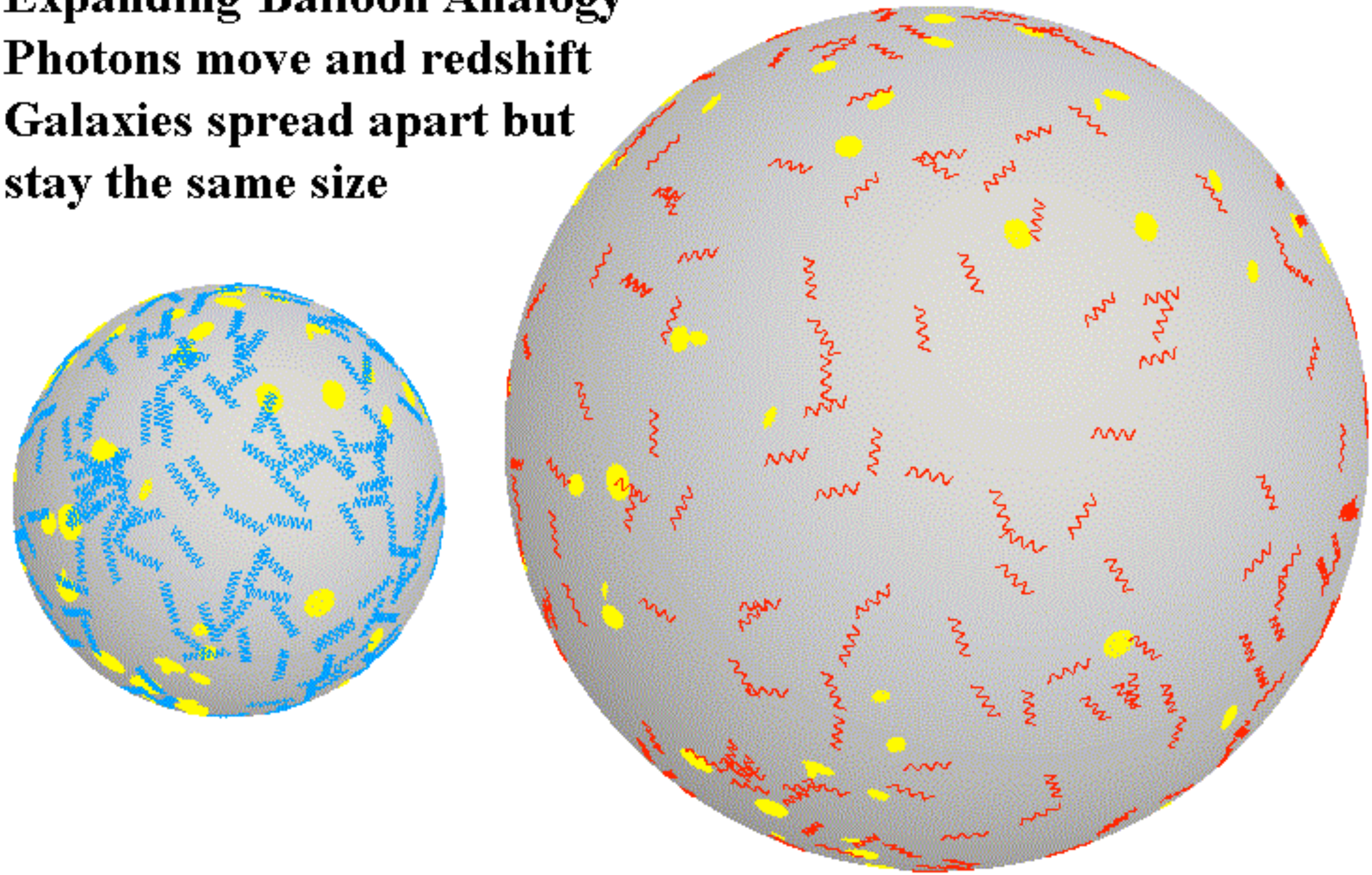
Since the universe is expanding, light traveling through the universe feels the stretch as it travels



Cosmological Redshift

The Cosmological Redshift

Expanding Balloon Analogy
Photons move and redshift
Galaxies spread apart but stay the same size



Redshift as Doppler Shift

We define **doppler redshift** to be the shift in spectral lines due to motion:

$$z = \frac{\Delta\lambda}{\lambda}$$

which, in the case of **v<<c** reduces to the familiar

$$z = \frac{v}{c}$$

The **cosmological redshift** is something different, although we are often sloppy and refer to it in the same terms of the doppler redshift. The cosmological redshift is actually due to the **expansion of space** itself.

Cosmological Redshift

A more correct approach is to note that the wavelengths of photons expand with the universe:

$$\frac{R(t_0)}{R(t_e)} = \frac{\lambda_0}{\lambda_e}$$

Where *R(t)* is a separation between any two comoving points

Or, by our definition of redshift:

$$z = \frac{\Delta\lambda}{\lambda}$$

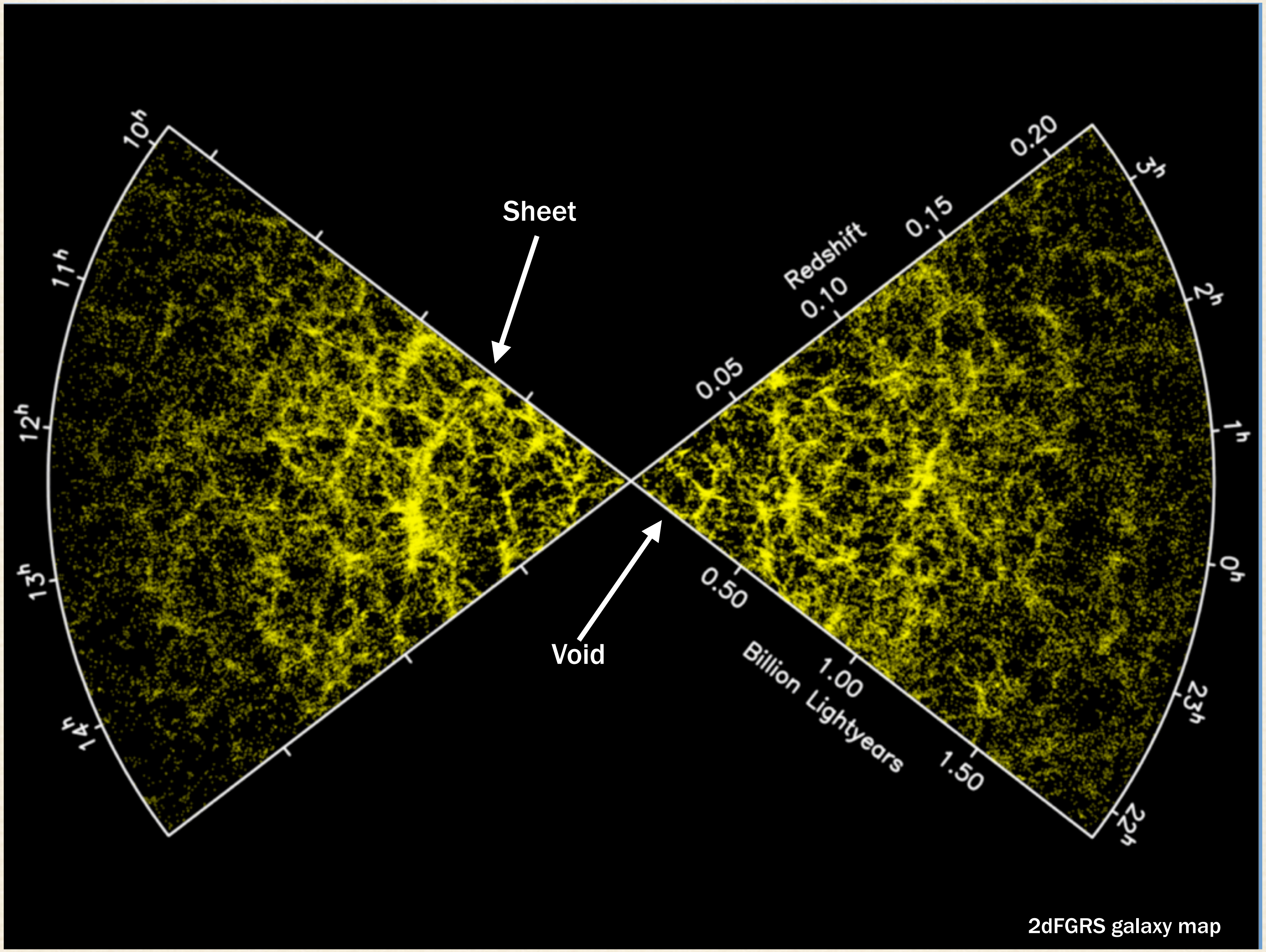
We get:

$$\boxed{\frac{R(t_0)}{R(t_e)} = (1+z)}$$

Thus, by measuring redshifts, we measure directly how much has the universe expanded since then

The two approaches are actually equivalent

Structure in the Distribution of Galaxies and Galaxy Clusters



What is Hubble's Law?

A.- An equation giving the maximum luminosity for a white dwarf supernova

B.- The relationship between the period and luminosity of a Cepheid variable star

C.- A law stating that more distant galaxies move away from us faster than closer ones

D.- The idea that there are more galaxies outside our own and that the universe contains immense numbers of these island universes

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What does the expansion of the universe most accurately mean?

A.- Galaxies are moving apart through space

B.- Space itself is expanding

C.- Everything is expanding, including the earth, our bodies, etc

D.- The Milky Way is at the center of the universe and all other galaxies are expanding away from us

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Galaxy A has a radial velocity of 1000 km/s while Galaxy B has a velocity of 4000 km/s. According to Hubble's law, which of the following statements are TRUE?

A. Galaxy B is farther away than Galaxy A

B. Galaxy B is rotating faster than Galaxy A

C. Galaxy A will collide with Galaxy B

D. Galaxy A is farther away than Galaxy B

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Why is the Night Sky Dark?

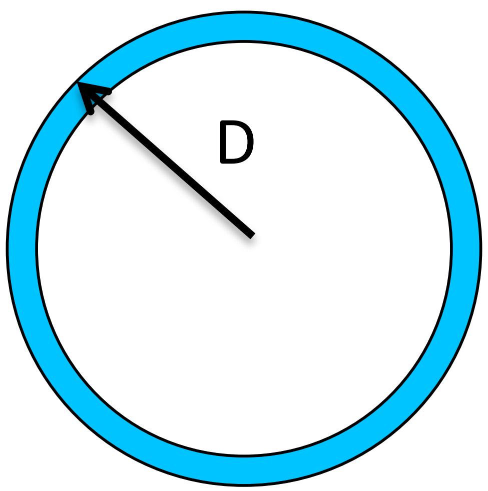
- On a moonless night: night sky < 10^{-6} daytime brightness
- *'It takes a genius to realize that the relative weakness of starlight is of great cosmological significance and such a person was Johannes Kepler'*

  (E.R. Harrison, Cosmology)
- Possible answers:
  1. Kepler 1610: universe not infinite
  2. Olbers 1823: universe infinite but starlight is absorbed by intervening material
  3. Poe 1848: '… by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all.'
  4. 20^{th} century: redshifts make distant objects dim at a given wavelength: Hubble law
- Who is correct? Poe
- Because:
  (1) the speed of light is finite ($3x10^5$ km/s)
  (2) the universe has finite age (and stars didn't exist until > 100 Myr after the BB)

Poe: Stars have a finite age and a finite power
thereby implying that each star has a finite impact on a sky's light field density

Olber's "paradox"

Consider a universe made up of stars that have the same luminosity L_* = their wattage (joules/s or erg/s)



Shell with radius D, thickness ΔD

Volume of shell
$\Delta V = 4\pi D^2 \Delta D$

n_* = number density of stars (e.g. 1 per cubic pc)

- The flux of radiation from a single star is
- $F_* = L_* / 4\pi D^2$
- The flux from all the stars in the shell is
- $F_D = F_* n_* \Delta V$
- $= (L_* / 4\pi D^2)\, n_*\, 4\pi D^2 \Delta D$
- $= n_* L_* \Delta D$
- If we sum over all distances out to some maximum D_{max} we get an integral

sum over all distances:
$L_* n_* \Delta D \rightarrow dD L_* n_*$

$$F = \int_0^{D_{\max}} dD\, L_* n_*$$

$$F \rightarrow \infty \quad \text{as} \quad D_{\max} \rightarrow \infty$$

Hubble Space Telescope was designed to accurately measure the Hubble constant

High resolution images to find faint Cepheid variable stars in very distant galaxies

SUMMARY

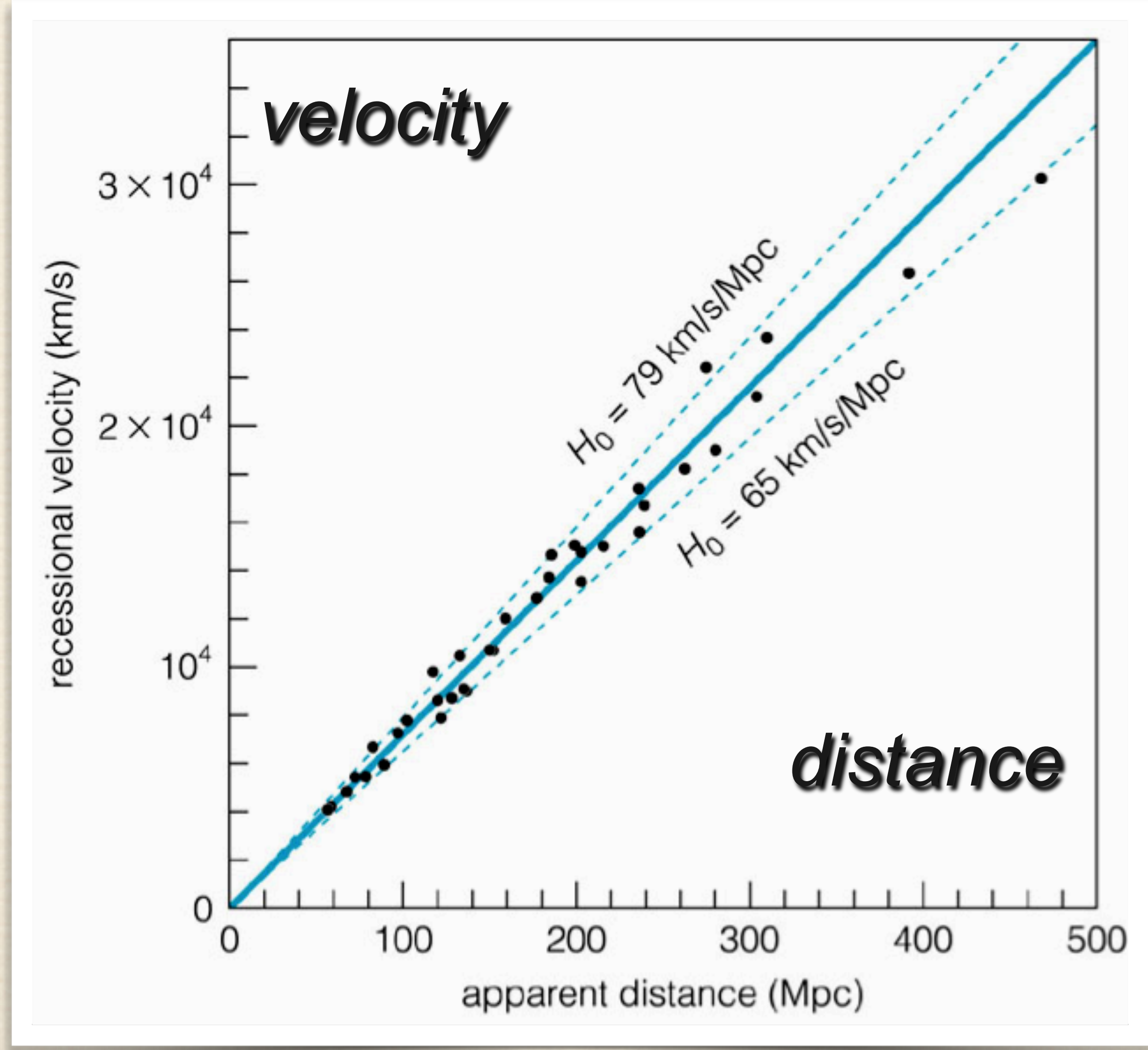
Hubble's Law

$v = H_0 \times d$

Velocity of Recession (Doplpler Shift) (km/sec)

Hubble's Constant (km/sec/Mpc)

Distance (Mpc)



Best current values for expansion

H_0 = 71 +/- 4 km/s/Mpc

Expansion and the Age of the Universe

IF the universe has been expanding at the same speed always:

Distance = velocity × time ☛ time = distance/velocity

Hubble's Law: $v = H_0 \times D$ ☛ H_0 = velocity/distance

Time (Age) = $1 / H_0$

For 71 km/sec/Mpc: Age ~ 13.7 billion years

For larger H_0, shorter time

For smaller H_0, longer time

A Better Way To Image the Expanding Universe

NOT like an explosion of galaxies THROUGH space from a center place

The space BETWEEN galaxies is expanding, carrying the galaxies away from each other

- Why don't galaxies themselves expand? Gravity!

Is this anywhere near correct?

- Age of the solar system ~ 4.6 billion years
- Age of the oldest star clusters ~ 13 billion years
- General agreement, but well revisit the assumption of constant expansion soon..

QUERY 23

Assume that a typical galaxy contains 100 billion stars, and that there is one galaxy per cubic megaparsec, on average

How many galaxies are within a Hubble distance, c/H_0 = 4300 Mpc, of us?

How many stars are within a Hubble distance of us?

QUERY 23

The volume of space within a Hubble distance of us constitutes a sphere of radius $r = c/H_0$

Thus, its volume will be

$$V = \frac{4\pi}{3} r^3 = \frac{4\pi}{3}\left(\frac{c}{H_0}\right)^3 = \frac{4\pi}{3}(4300\,\mathrm{Mpc})^3 = 3.33 \times 10^{11}\,\mathrm{Mpc}^3$$

With one galaxy per cubic megaparsec, the total number of galaxies will be

$$N_{\mathrm{gal}} = 3.33 \times 10^{11}\,\mathrm{Mpc}^3 \left(\frac{1\,\mathrm{galaxy}}{1\,\mathrm{Mpc}^3}\right) = 3.33 \times 10^{11}\,\mathrm{galaxies}$$

Thus, there are roughly 300 billion galaxies within a Hubble distance of us, which is larger than the number of stars whithin our own galaxy

The total number of stars whithin a Hubble distance of us will be

$$N_{\mathrm{star}} = 3.33 \times 10^{11}\,\mathrm{galaxies}\left(\frac{10^{11}\,\mathrm{stars}}{1\,\mathrm{galaxy}}\right) = 3.33 \times 10^{22}\,\mathrm{stars}$$

QUERY 24

The Sahara has an area of $A = 9,000,000\ km^2$

The average depth of sand in the Sahara is $d = 10\ m$

What is the total volume of sand in the Sahara, expressed in cubic meters?

If an average grain of sand has a volume of $1\ mm^3$, how many grains of sand are in the Sahara?

Is the number of grains of sand in the Sahara greater than or less than the number of stars within a Hubble distance of us?

QUERY 24

The area of the Sahara, expressed in square meters, is

$$A = 9 \times 10^6\,\mathrm{km}^2 \left(\frac{1000\,\mathrm{m}}{1\,\mathrm{km}}\right)^2 = 9 \times 10^{12}\,\mathrm{m}^2$$

The total volume of the sand is its area times its depth:

$$V = A \times d = (9 \times 10^{12}\,\mathrm{m}^2)(10\,\mathrm{m}) = 9 \times 10^{13}\,\mathrm{m}^3$$

The volume of a single grain of sand, expressed in cubic meters, is

$$V_{\text{grain}} = 1\,\mathrm{mm}^3 \left(\frac{1\,\mathrm{m}}{1000\,\mathrm{mm}}\right)^3 = 10^{-9}\,\mathrm{m}^3$$

The total number of grains of sand is the total volume divided by the volume of a single grain:

$$N_{\text{grain}} = \frac{V}{V_{\text{grain}}} = \frac{9 \times 10^{13}\,\mathrm{m}^3}{10^{-9}\,\mathrm{m}^3} = 9 \times 10^{22}$$

QUERY 25

If every star within a Hubble distance of us were as massive as the Sun and were made entirely of hydrogen, how many hydrogen atoms would be within a Hubble distance of us?

Dividing this number of atoms by the volume of space within a Hubble distance of us, show how many hydrogen atoms there would be, on average, per cubic meter of the visible universe.

$[\text{Hint}: M_\odot = 1.99 \times 10^{33}\text{g and } m_\text{H} = 1.66 \times 10^{-24}\text{g}]$

QUERY 25

The number of stars within a Hubble distance of us is $N_{star} = 3.33 \times 10^{22}$

If each star were a blob of hydrogen equal in mass to the Sun, the number of hydrogen atoms per star would be $N_H = 1.176 \times 10^{57}$

Multiplying these two numbers together, we find that the total number of hydrogen atoms within a Hubble distance would be

$$\boxed{N = N_{\text{stars}} \times N_{\text{H}} = (3.33 \times 10^{22})(1.176 \times 10^{57}) = 3.92 \times 10^{79}}$$

QUERY 25

Yes, that's a Lot of hydrogen atoms
However, they are dsitributed over a large volume

The volume within a Hubble distance of us is

$$V = 3.33 \times 10^{11}\,\mathrm{Mpc}^3 \left(\frac{3.1 \times 10^{19}\,\mathrm{km}}{1\,\mathrm{Mpc}}\right)^3 \left(\frac{1000\,\mathrm{m}}{1\,\mathrm{km}}\right)^3 = 9.9 \times 10^{78}\,\mathrm{m}^3$$

Now we have the fun of dividing one hyper-gargantuan number by another to find the average number of hydrogen atoms per cubic meter:

$$\frac{N}{V} = \frac{3.92 \times 10^{79}}{9.9 \times 10^{78}\,\mathrm{m}^3} = 4\,\mathrm{m}^{-3}$$

QUERY 26

A distant galaxy is observed to have a redshift $V/c = 0.1$, where V is the recession velocity of the galaxy, and c is the speed of light

(i) What is the recession velocity of the galaxy in units of km/s?

(ii) Using the Hubble expansion formula calculate the distance to the galaxy in units of ly?

(iii) How long ago was the light we are now seeing from the galaxy emitted?

QUERY 26

(i) The recession velocity is

$$V = 0.1c = 0.1 \times 3 \times 10^5 \text{ km/s} = 30{,}000 \text{ km/s}$$

(ii) $d = V/H_0 = 1,339$ million light years

(iii) The light we are seeing today was emitted 1, 339 million years ago

QUERY 27

The Whirlpool Galaxy is at a distance d = 7.1 Mpc from us

Using Hubble's law, what do you expect the radial velocity V of the Whirlpool Galaxy to be?

What do you expect the redshift z of the Whirlpool Galaxy to be?

When hydrogen is at rest, it produces an emission line with a wavelength λ_0 = 656.281 nanometers; what wavelength λ would you measure for the corresponding emission line from hydrogen in the Whirlpool Galaxy?

QUERY 27

The radial velocity v is given by Hubble's law:

$$\boxed{v = H_0 d = 70 \text{ km/s/Mpc} \times 7.1 \text{ Mpc} = 497 \text{ km/s}}$$

The redshift z = $(\lambda - \lambda_0) / \lambda_0$ is equal to the radial velocity divided by the speed of light:

$$\boxed{z = \frac{v}{c} = \frac{497 \text{ km/s}}{300,000 \text{ km/s}} = 0.00166}$$

The wavelength λ is given by the relation

$$\boxed{z = \frac{\lambda - \lambda_0}{\lambda_0}}$$

which can be rearranged to give

$$\boxed{\lambda = z\lambda_0 + \lambda_0}$$

Therefore, the observed wavelength λ will be

$$\boxed{\lambda = (1 + z)\lambda_0 = 1.00166 \times 656.281 \text{ nm} \quad = 657.368 \text{ nm}}$$