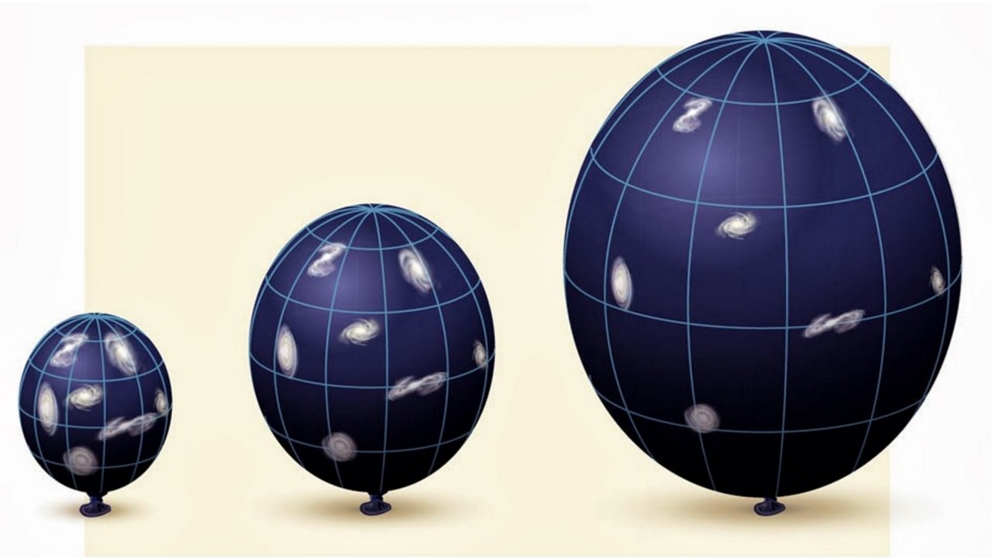
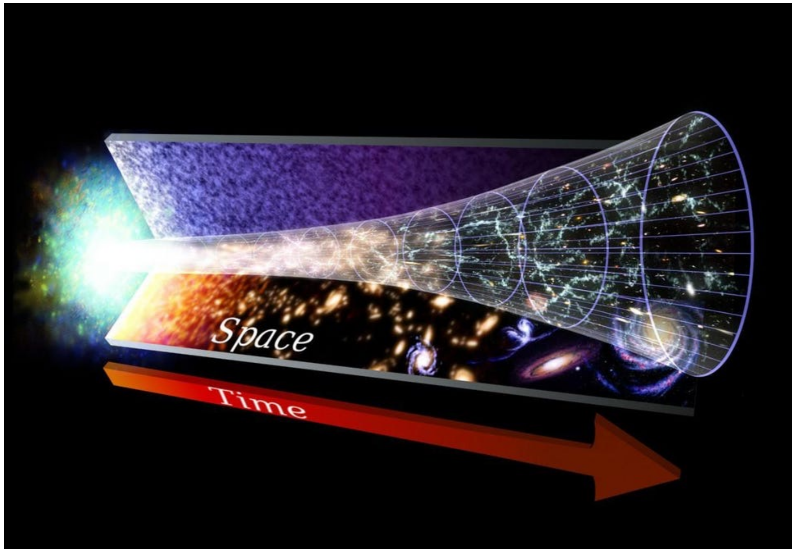
Honours Cosmology Week 1:

The Expanding Universe

This week we'll review the fundamental observational facts about the Universe which lead us to develop Big Bang Cosmology





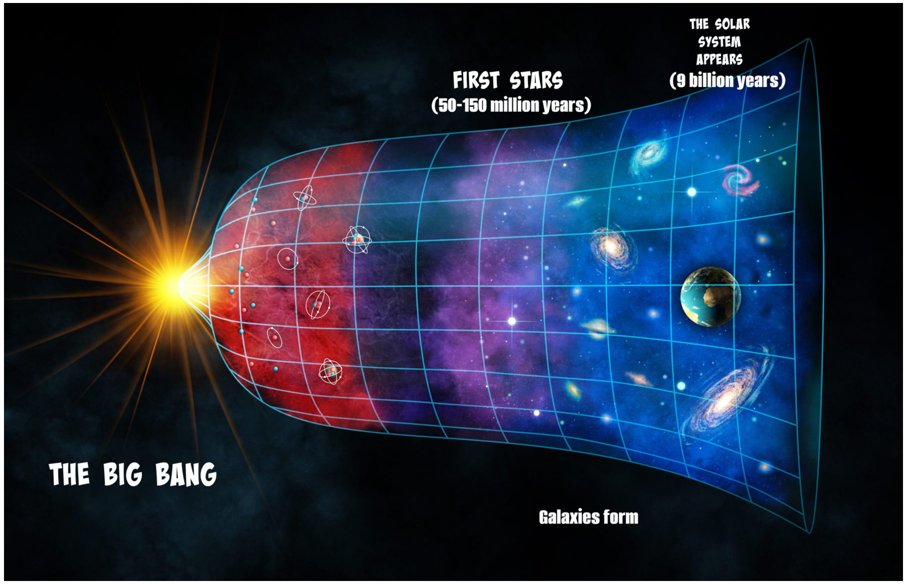
The Expanding Universe

At the end of this week you should be able to…

- … describe the **cosmological principle** and its implications
- … quantify universal cosmic expansion via the **cosmic scale factor**, **comoving coordinates** and the **redshifting of light**
- … understand the implications of **Hubble's Law**
- … describe the significance of the **Cosmic Microwave Background** radiation
- … express the concepts and misconceptions of **Big Bang cosmology**

Our place in the universe

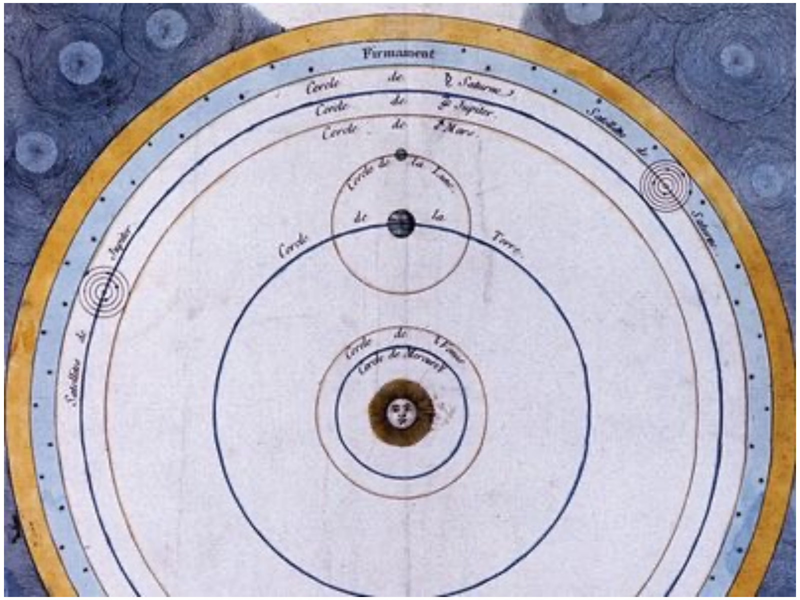
- In this module we will learn about the science of cosmology!
- *Cosmology is the study of the origin, evolution, contents and physics of the Universe as a whole*



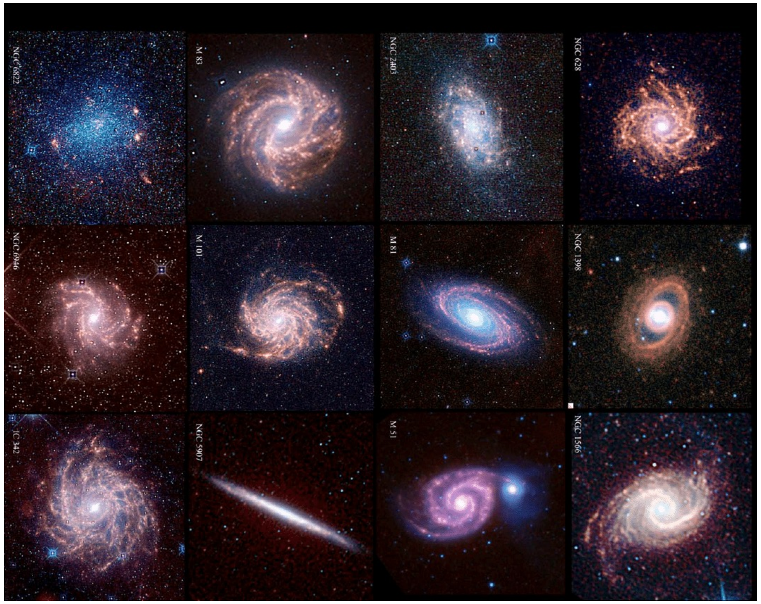
Our place in the universe

- Our view of the Universe has increasingly reflected the idea that *“we are not special”*

Copernicus’s model of the solar system placed the Sun at the centre, not the Earth



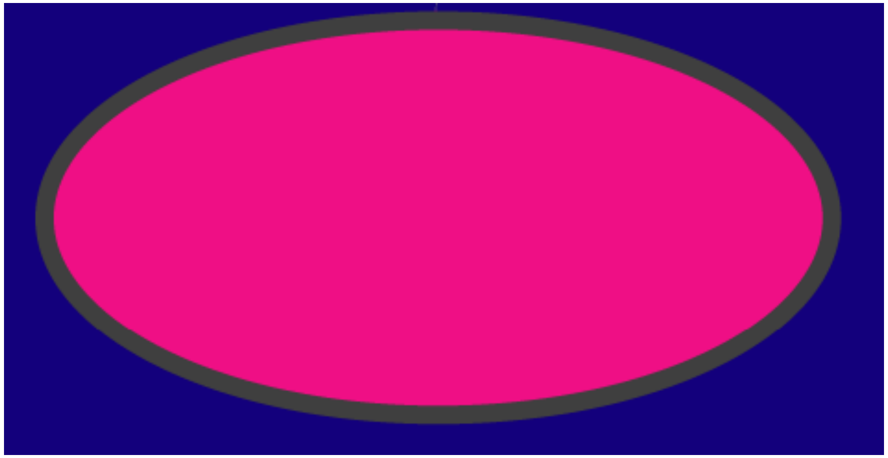
During the 20th century, we realized the existence of many galaxies external to our own



The cosmological principle

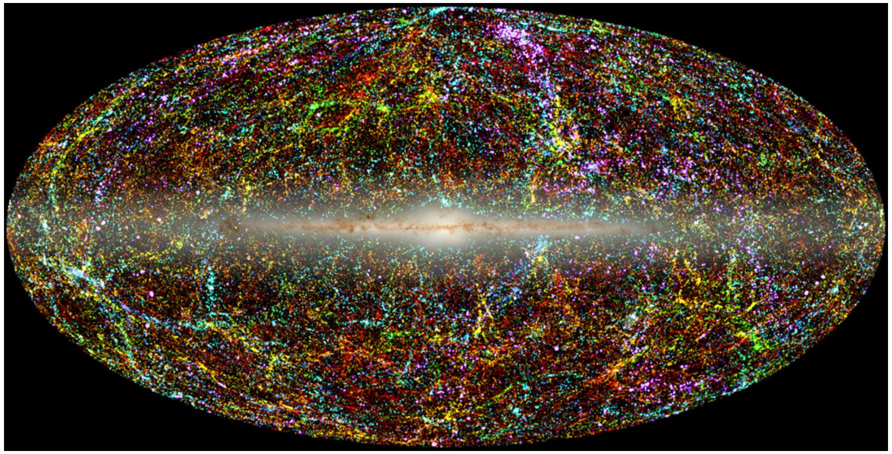
- We elevate the idea that "we are not special" into the *"cosmological principle"*: the Universe has the same general properties in every location and direction

This is our view of the Cosmic Microwave Background across the sky:



Its temperature is almost exactly $2.73\ \mathrm{K}$ in every direction!

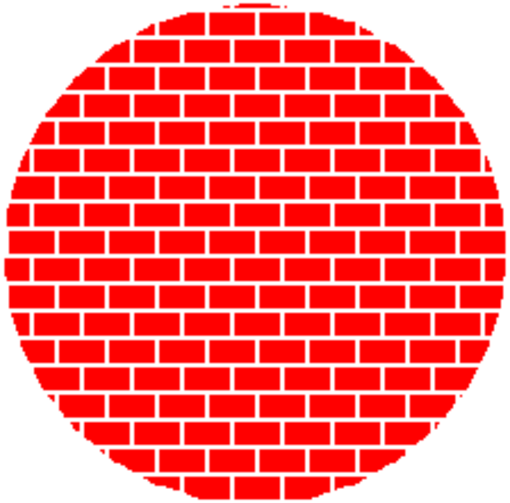
This is our view of the nearby distribution of galaxies around us:



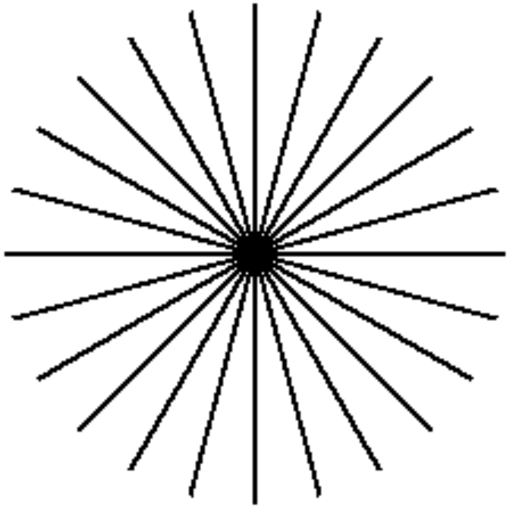
We can see some structure, but the "overall properties" are uniform

The cosmological principle

- **Homogeneity** means that the properties of the Universe are the *same in every location*
- **Isotropy** means that the properties of the Universe are the *same in every direction*



Homogeneous but not isotropic



Isotropic but not homogeneous

The cosmological principle

- **Why is this such a powerful assumption?**

- Due to homogeneity, observers on all galaxies must agree on consistent properties of the Universe

- Hence, any part of the Universe is representative of the whole – **homogeneous Universes can be studied locally**

- Due to homogeneity, observers on all galaxies measure the **same cosmic time** –for which the Universe itself acts as the synchronization agent

The expanding universe

- In 1912, Vesto Slipher made a critical observational breakthrough by measuring the *spectrum of light* from galaxies beyond the Milky Way

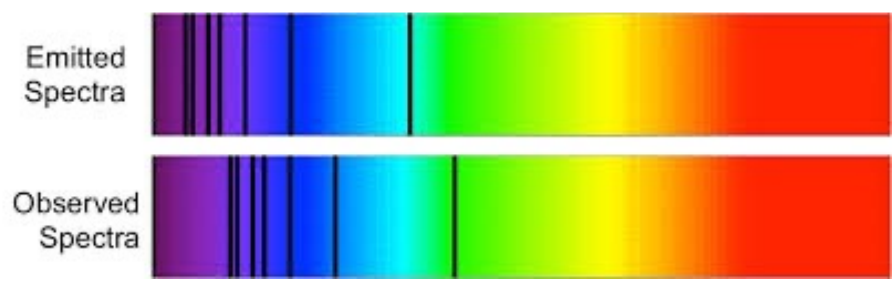
- He discovered that the light from almost all of these galaxies was ***redshifted*** by the Doppler effect

TABLE I.

Radial Velocities of Twenty-five Spiral Nebulæ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

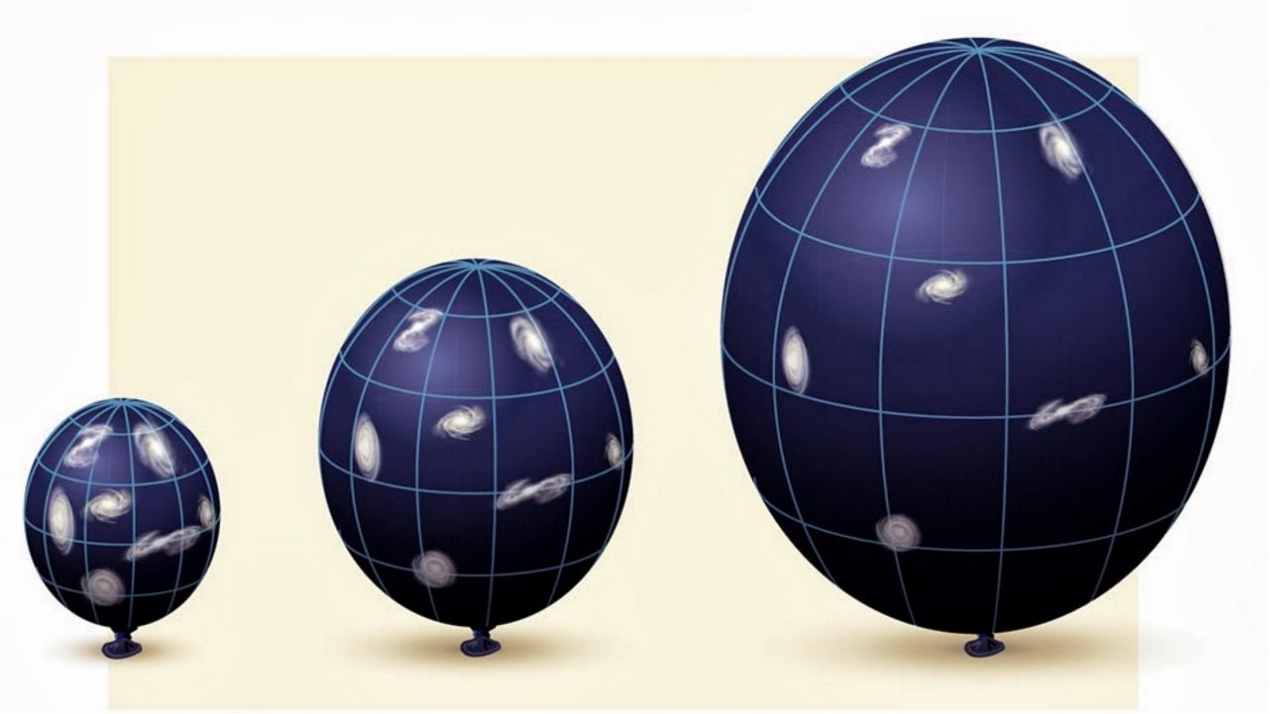
We know the "rest-frame" wavelengths corresponding to atomic transitions



We measure them to be shifted redder

The expanding universe

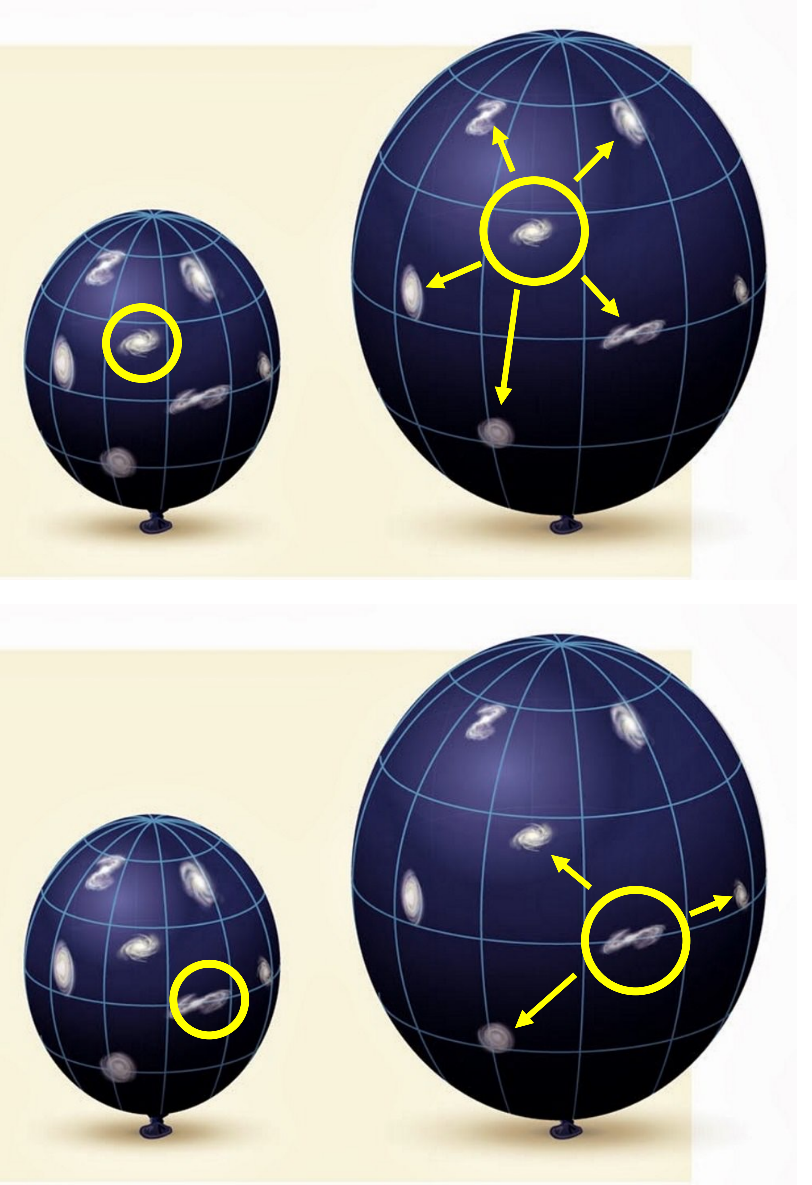
- Universal redshifting tells us *galaxies are luminous markers for the expansion of the universe!*



- If we "run the clock backwards", the universe gets denser. *The Big Bang model follows from this simple observation.*

The expanding universe

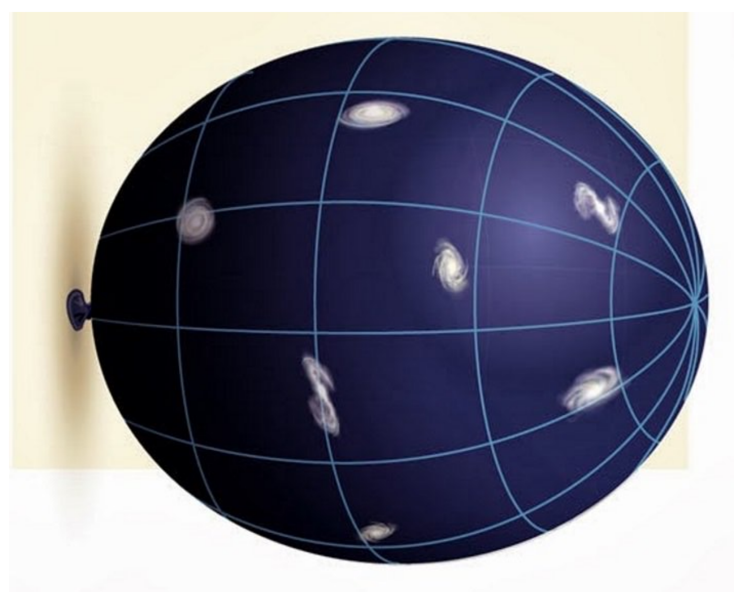
- “Universal recession” might suggest we’re at the centre of the universe
- However, the “we are not special” principle applies!
- The balloon analogy shows that *every observer perceives the same expansion* *(and thinks they are at the centre!)*



The expanding universe

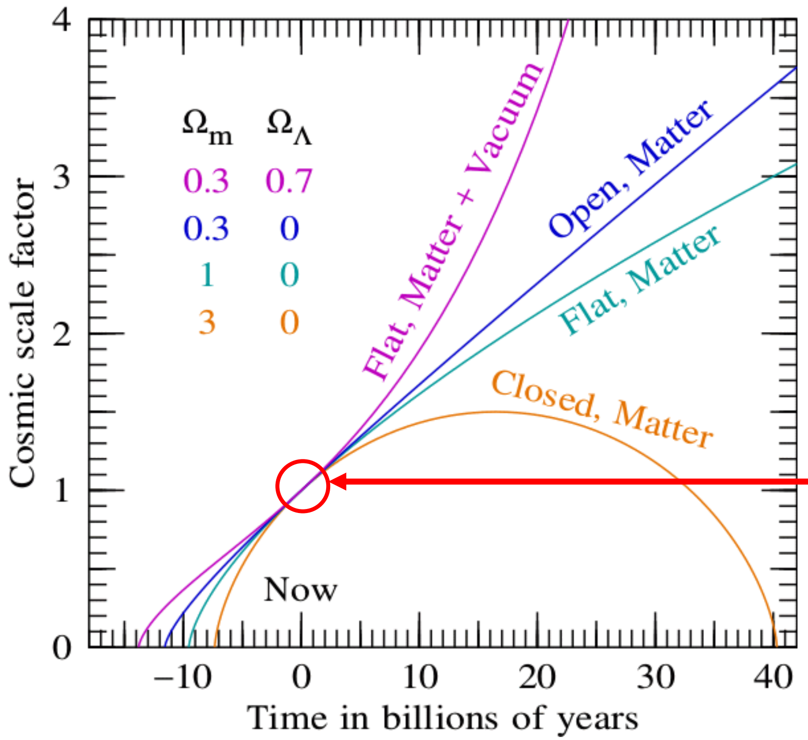
- *The Universe isn't expanding into anything*. The geometry of space-time is getting bigger, without reference to anything that sits outside

Imagine the Universe is the surface of the balloon: this defines a 2D space independently of anything external …



The cosmic scale factor

- We parameterise the expansion using the *cosmic scale factor* $a(t)$, which grows with the Universe
- The scale factor is normalised such that $a = 1$ today

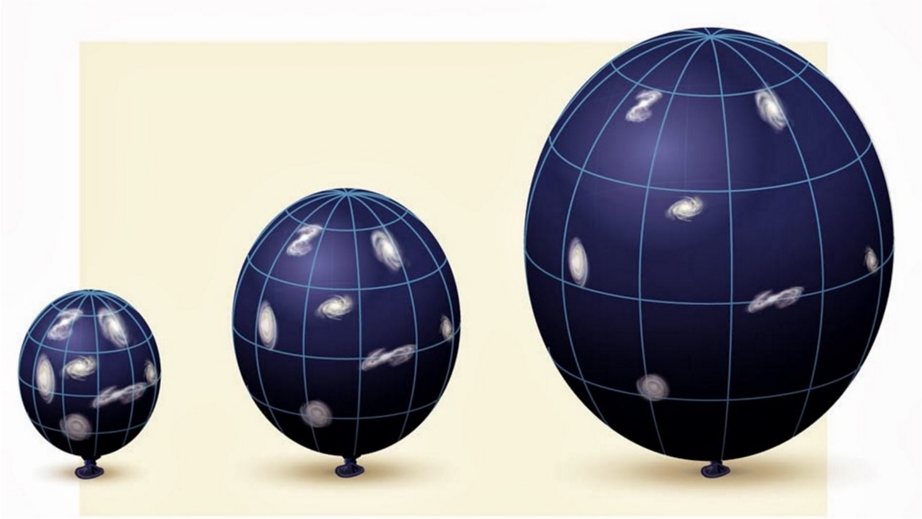


We'll learn more about these different models in future weeks

Notice that all the models cross $a = 1$ at the current time (which is marked as $t = 0$ in this plot)

Comoving coordinates

- We create a *comoving coordinate system* which expands with the Universe like the grid on the balloon:



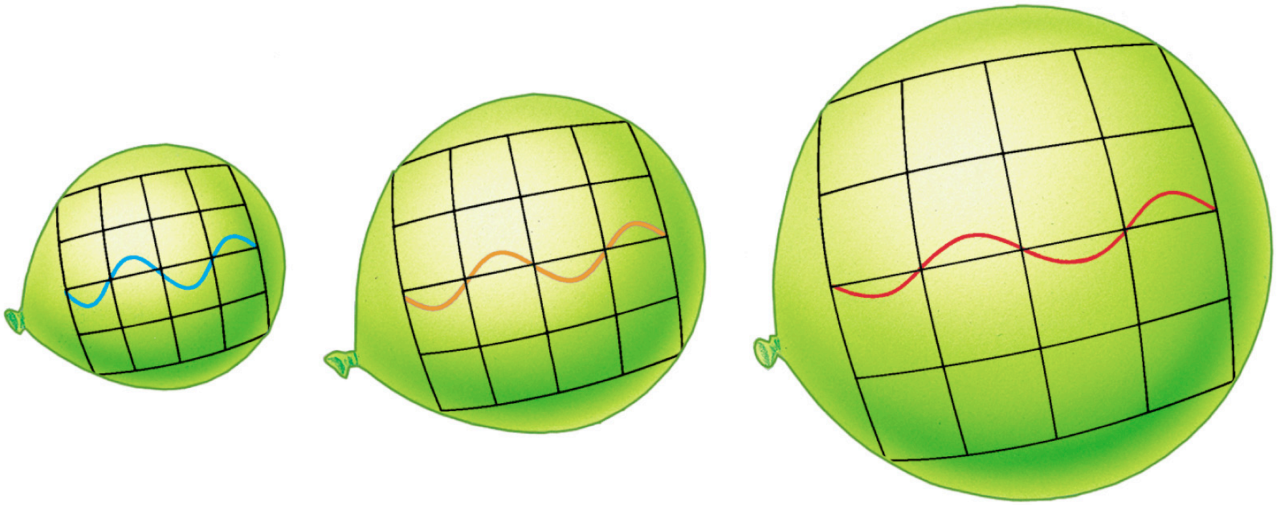
We can calculate real physical distances from the comoving distances using the equation:

$$r_{\text{physical}}(t) = a(t)\, r_{\text{comoving}}$$

- The comoving coordinates of galaxies expanding with the Universe do not change, but their distances increase with time

Redshifting

- Wavelength of light travelling in expanding space increases, $\lambda \propto a(t)$



We're using the "balloon analogy" to describe this for now, but later we'll show the connection with relativity

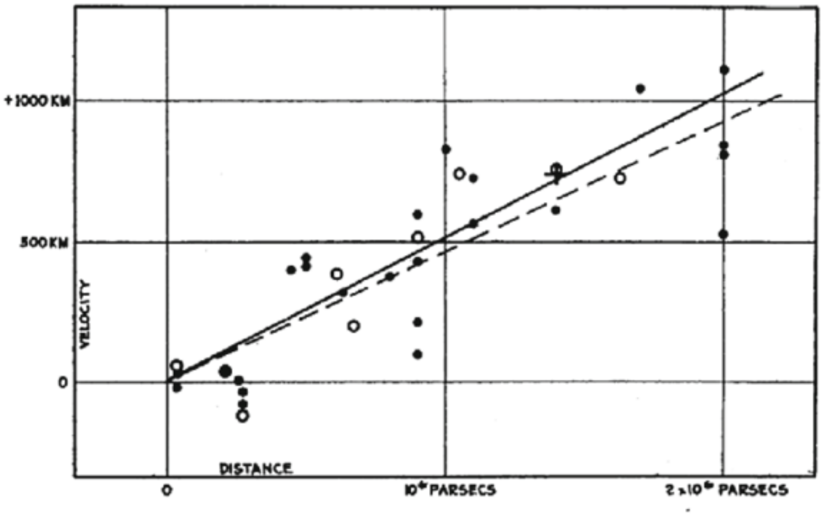
- Redshift is defined by: $z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} - 1$

- Hence, since $a_{\text{observed}} = 1$, we find: $a_{\text{emitted}} = \frac{1}{1+z}$

Hubble's Law

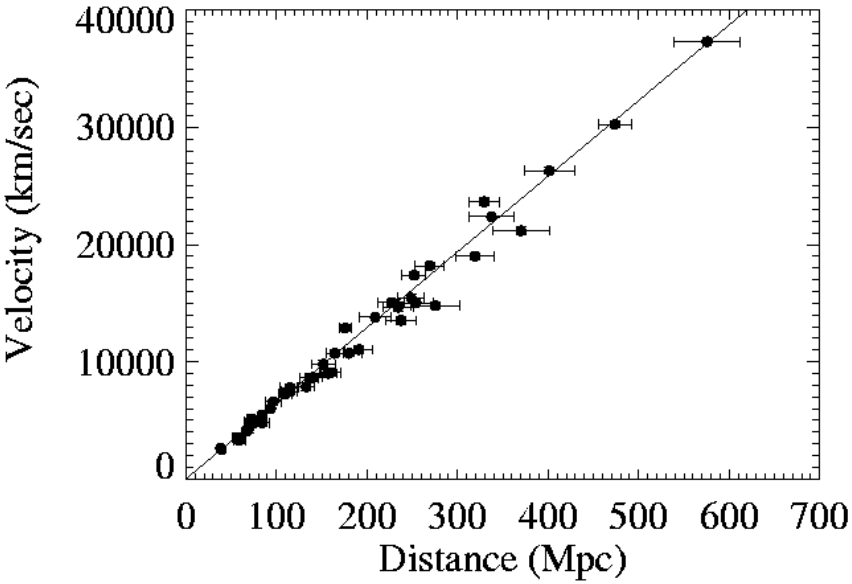
- In the 1920s, Hubble added more information to the recession velocities by estimating distances to galaxies
- A distance-velocity correlation was discovered!

Hubble's original plot was very noisy!



Velocity-Distance Relation among Extra-Galactic Nebulae.

Here is a more modern dataset:



Hubble's Law

- This correlation is known as Hubble's Law:

Recession velocity → $v = H_0\, D$ ← Distance

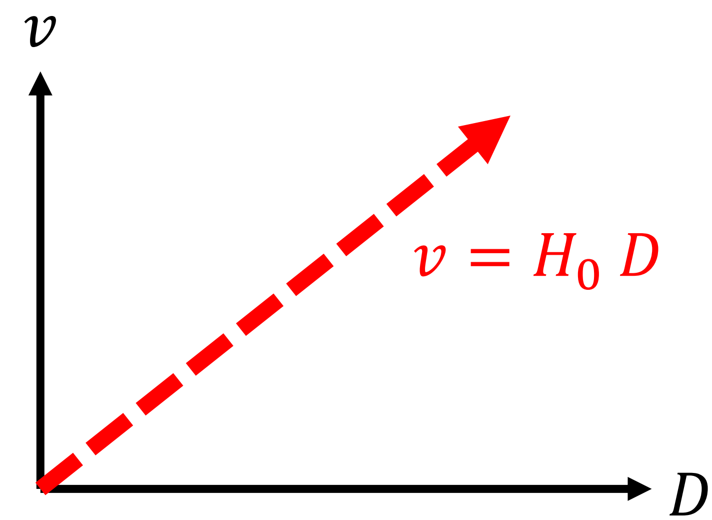
- H_0 is Hubble's constant, although note that it slowly changes in value as the Universe ages!

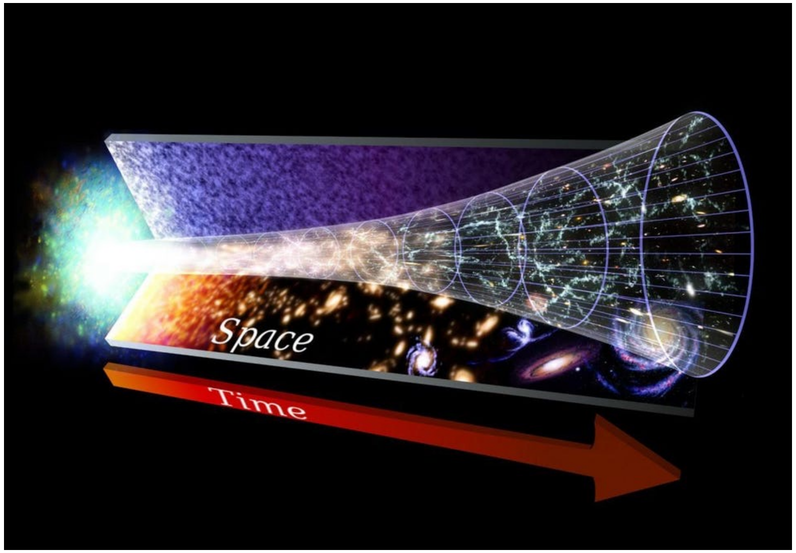
- Astronomers have measured $H_0 \approx 70\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

- The units of $\mathrm{km\ s^{-1}\ Mpc^{-1}}$ seem strange (since the dimensions are time^{-1}), but it makes sense from Hubble's Law if v is measured in $\mathrm{km\ s^{-1}}$ and D in Mpc (Megaparsecs). *Please see the formula sheet for useful values in other units.*

Hubble's Law

- It seems there is no obstacle to recession velocity growing faster than the speed of light, $v > c$!
- However, v is measuring the relative velocity of two distant points between which no information is transferred, so faster-than-light travel is not involved
- The interpretation is also changed by General Relativity, as we'll discuss later





Hubble's Law

- We can derive Hubble's law using our definition of comoving coordinates from the previous slide:

$$r_{\text{physical}}(t) = a(t)\, r_{\text{comoving}}$$

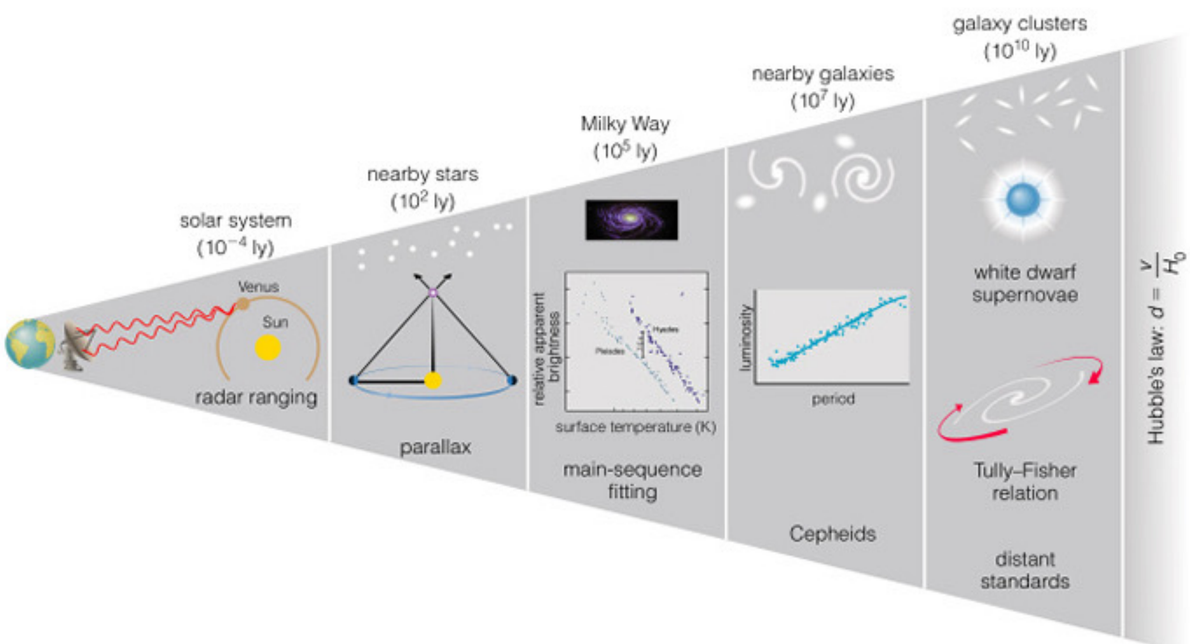
$$\rightarrow \frac{dr_{\text{physical}}}{dt} = \dot{a}\, r_{\text{comoving}} = \frac{\dot{a}}{a}\, r_{\text{physical}}$$

$$\rightarrow v_{\text{recession}} = H\, D$$

- The Hubble constant can hence be related to the scale factor by $H = \frac{\dot{a}}{a}$, showing its evolution with time

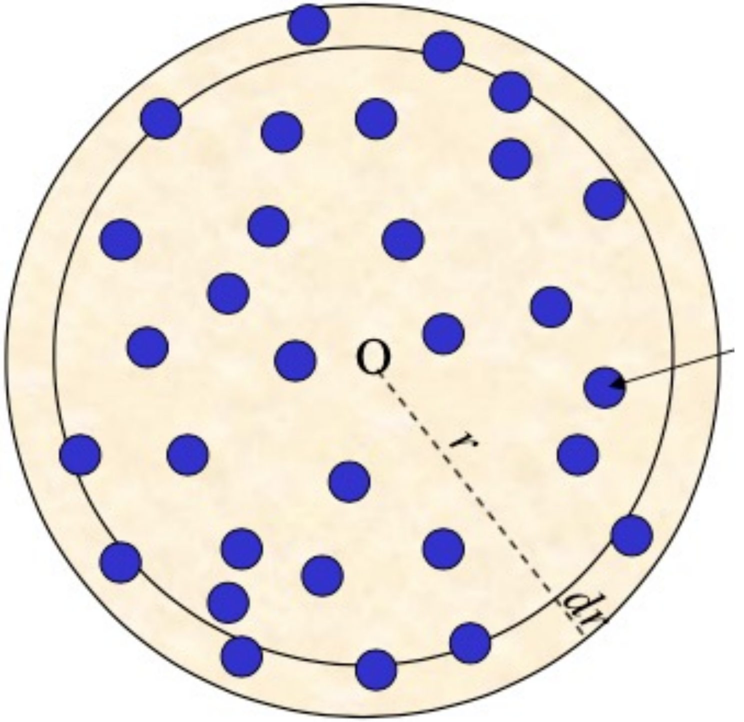
A sense of scale

- Distance to Sun $= 1\ \mathrm{AU} = 1.5\times10^{11}\ \mathrm{m}$
- Distance to stars $\approx 1\ \mathrm{pc} = 3.1\times10^{16}\ \mathrm{m} = 3.26\ \mathrm{ly}$
- Distance to galaxies $\approx 1\ \mathrm{Mpc} = 3.1\times10^{22}\ \mathrm{m}$
- Size of observable Universe $\approx 10\ \mathrm{Gpc}$



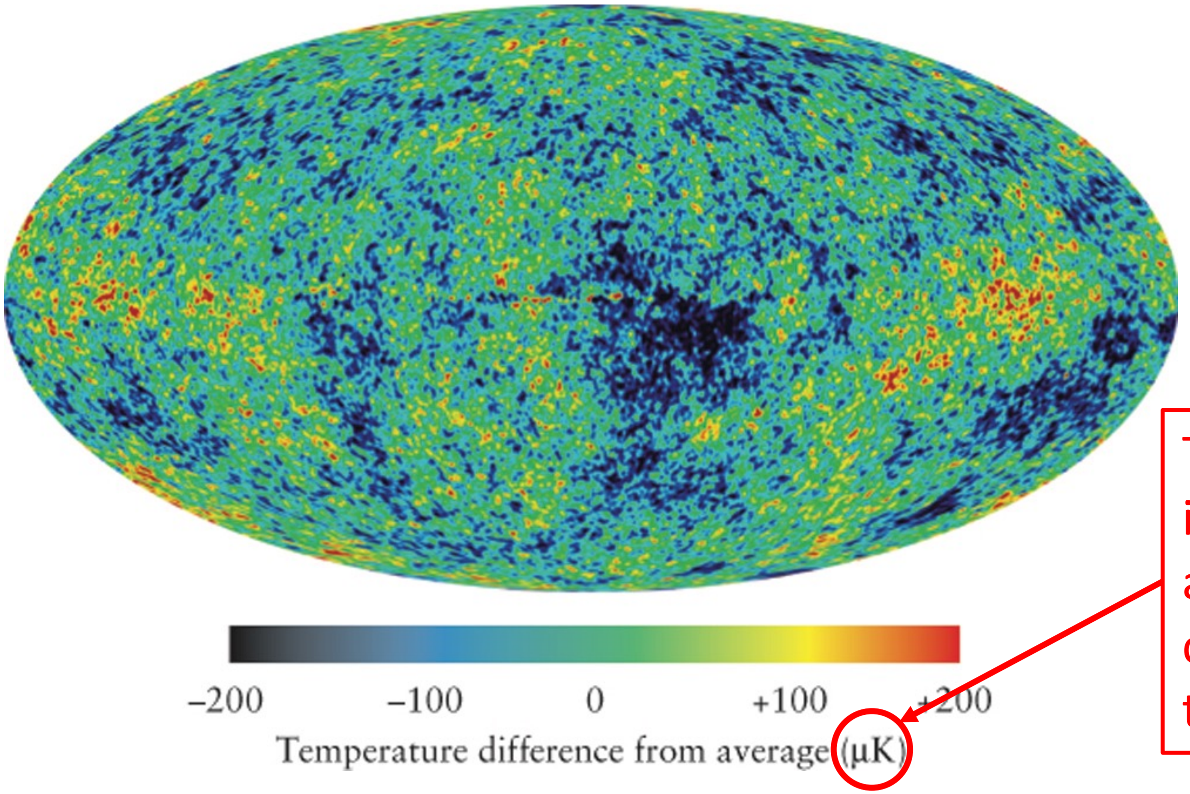
Olber's paradox

- Olber's paradox poses a simple question: why is the sky dark at night?
- e.g. total flux from sources with luminosity L and number density n over radius r is:
$$\int \frac{L}{4\pi r^2} \cdot n \cdot 4\pi r^2 dr \rightarrow \infty$$
- Resolutions include the finite age/extent of the Universe and the redshifting of light



Cosmic microwave background

- Actually the sky is not dark: everywhere we look, we see the faint glow of the *cosmic microwave background (CMB) radiation* (with temperature $2.73\ \mathrm{K}$)



These ripples in temperature are very tiny compared to the average!

Cosmic microwave background

- *The CMB constitutes a direct observation of the "primeval fireball" predicted by the Big Bang*
- The CMB captures the moment when atoms first formed in the Universe (temperature $\sim 3000\ K$)
- Since the temperature of radiation scales as $T \propto 1/a$, the CMB was produced at scale factor $a \sim 0.001$ ($t \sim 300{,}000$ yrs)
- The temperature of the CMB is very uniform, implying that opposite sides of the sky had to be in causal connection
- The CMB contains small temperature fluctuations $\frac{\Delta T}{T} \sim 10^{-5}$ that grow under gravity into the galaxies we see today

The Big Bang

It's misleading to picture the Big Bang like this…

The Big Bang model does not say that the Universe started with a "Bang" and in fact says nothing about the moment $t = 0$.

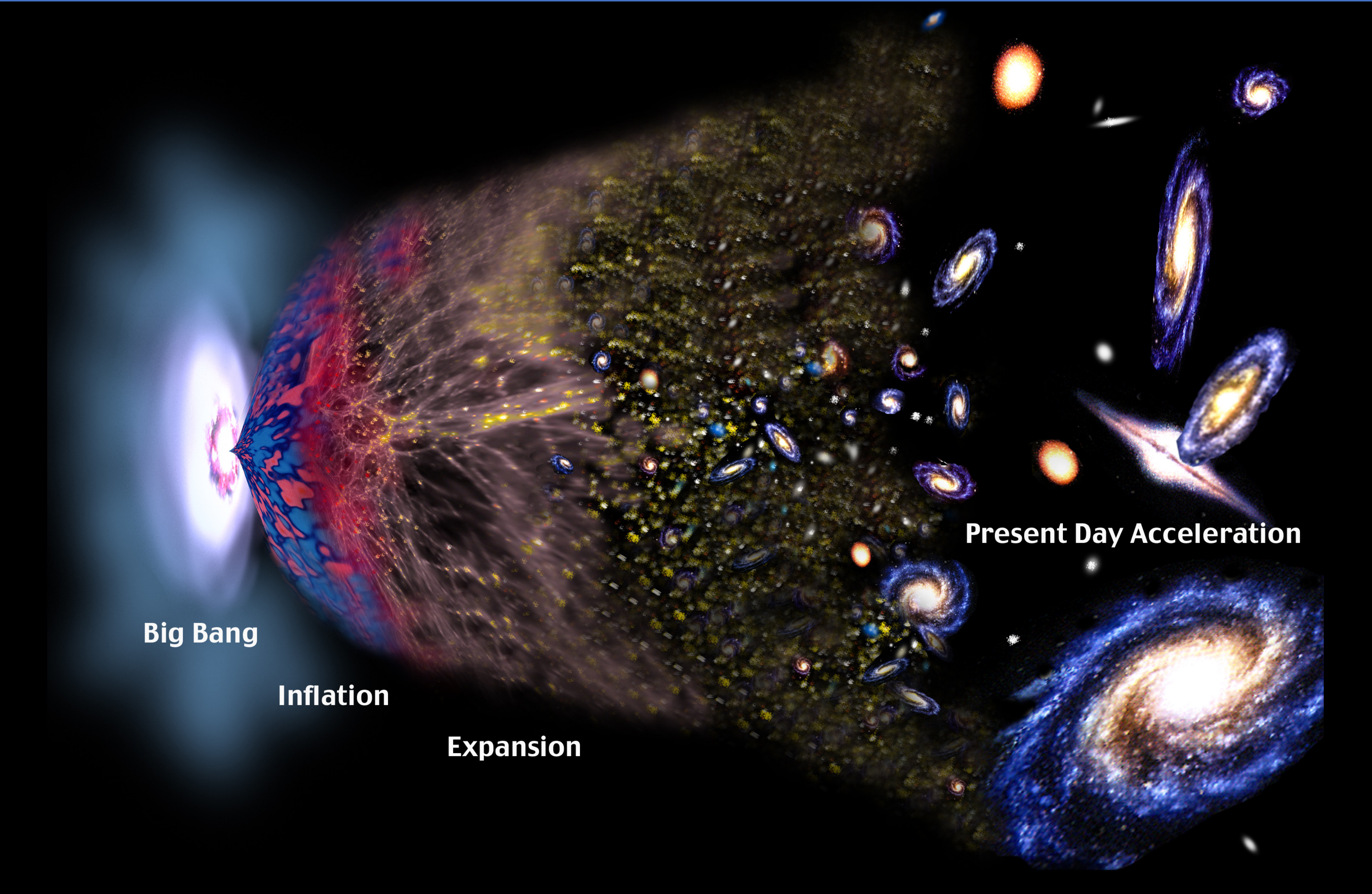
The Big Bang is not a point in space, but a point in time. It happens everywhere in space, so everything doesn't need to be at the origin.

What can we say about the Big Bang?

The Big Bang postulates that there was a time in the past when the Universe was so hot that matter, atoms and nuclei melted

The Big Bang model allows us to calculate what happened in this expanding fireball. Particle physics theory allows us to do so at $t \sim 10^{-12}$ s

The Big Bang



Key take-aways

- The **cosmological principle** of homogeneity and isotropy creates a remarkably accurate model of the Universe in which its fundamental properties may be studied by local observers
- The **Big Bang Model** describes the fireball of the hot, early Universe in which nuclei and atoms formed
- The first key pillar is the **expanding Universe**, creating the redshifting of light and measured using Hubble's Law
- The second key pillar is the **Cosmic Microwave Background**, the faint glow of radiation travelling from the early Universe
- The expanding Universe may be quantified by the **cosmic scale factor** which dilates a comoving coordinate grid