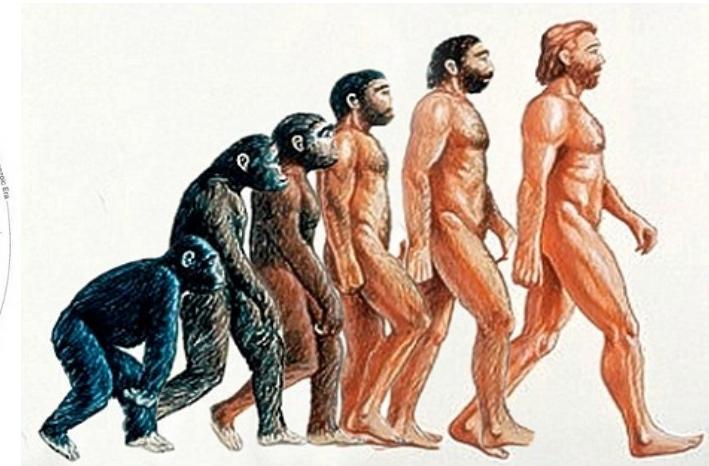
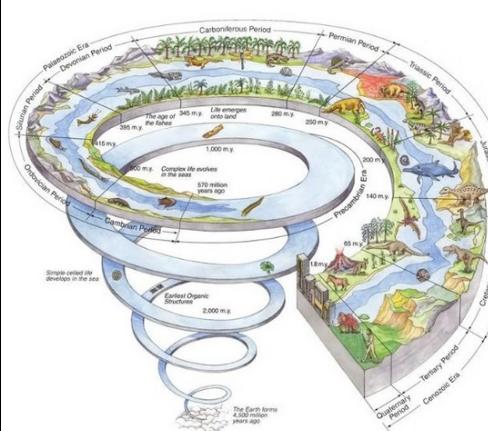
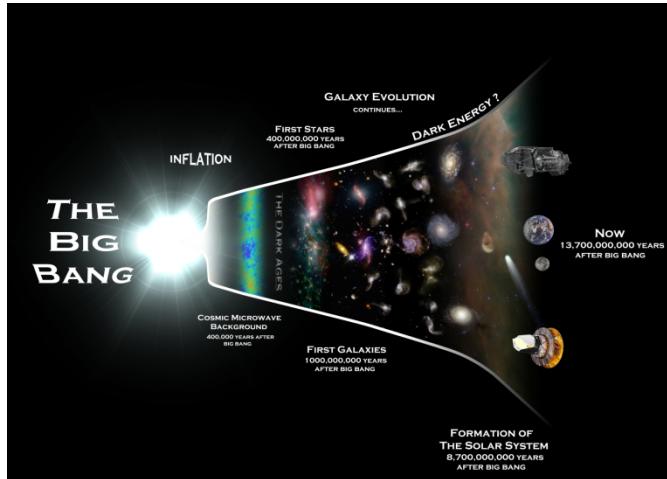


Evolution of the Universe

- **Where do we come from?** Parents, grandparents,...fish,...LUCA,...?. **Evolution.**
- Where does **the universe** come from? How did *it evolve* to become what it is today, a universe *able to support complex, intelligent life?*



Evolution of the Universe

- Some possibilities regarding **evolution** of the universe:

- Universe is **static** and **eternal** (no beginning or end)

- ✓ Articulated clearly by **Giordano Bruno** in 1584:

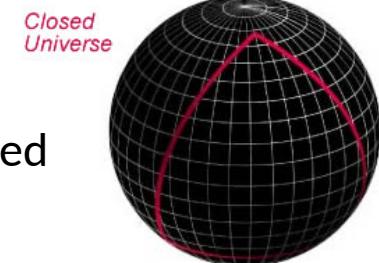
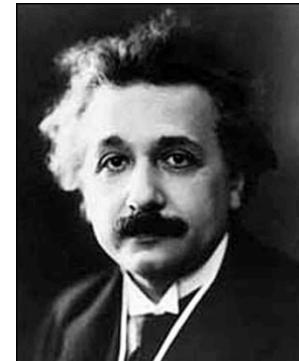
“The universe is then one, **infinite, immobile**.... It is not capable of comprehension and therefore is **endless and limitless**”.

- ✓ First to imagine an **infinite** universe **filled with stars**, each with their own **planets**, and **no centre** to the universe (“Copernican principle”)
 - ✓ Also wrote: other worlds “have no less virtue nor a nature different to that of our Earth” and, like Earth, “**contain animals and inhabitants**”



Evolution of the Universe

- Some possibilities regarding **evolution** of the universe:
 - Universe is **static** and **eternal** (no beginning or end)
 - ✓ **Cosmology** as a **science** began in the early 20th century with the advent of Einstein's **general theory of relativity**, a geometrical theory of space, time, and gravity (1915).
 - ✓ **1917: Einstein** applied his new theory to cosmology. Worried about imposing **ad hoc** boundary conditions at **infinity**, so postulated space is **finite** but **unbounded**: the 3D analogue of a 2D sphere.
 - ✓ Believed universe was **static** — dismayed that his theory predicted the universe must expand or contract — introduced his famous **cosmological constant** to force it to be static. (Was later realized model was **unstable**: small perturbation — **expand or contract**.)

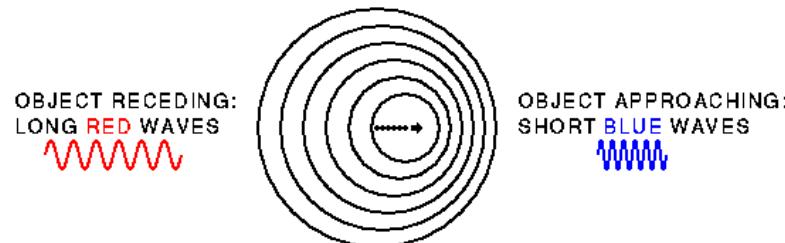


Evolution of the Universe

- Some possibilities regarding **evolution** of the universe:

- Universe is **dynamic**

- ✓ **1912: Vesto Slipher** measured the **redshift** of “spiral nebulae” and interpreted this redshift as a **Doppler shift**: the “spiral nebulae” were all moving away from us □ something **dynamic**



- ✓ But he didn't know their **extreme distance**—that the “spiral nebulae” were **separate galaxies outside of our own**, and so didn't fully appreciate the cosmic significance of this discovery.

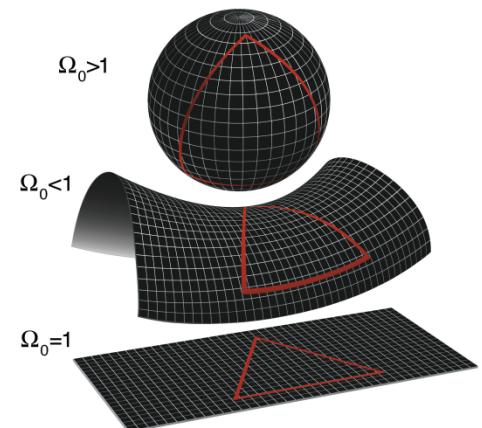
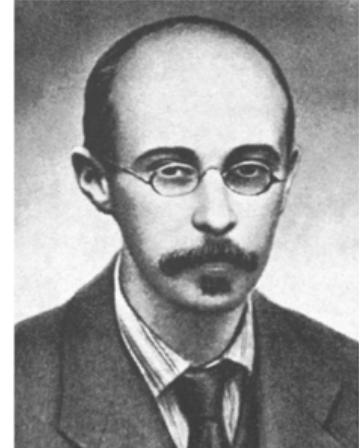
Evolution of the Universe

- Some possibilities regarding **evolution** of the universe:

- Universe is **dynamic**

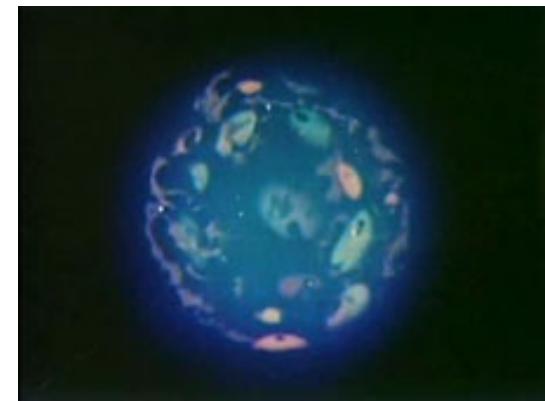
- ✓ **1924: Alexander Friedmann** fully understood the cosmological implications of Einstein's general relativity, including that space is **dynamic** (*necessarily expands or contracts*)

- ✓ ...and that space can have three types of **large-scale geometry**: **open** (negative curvature), **flat** (zero curvature), or **closed** (positive curvature—the case Einstein considered)



Evolution of the Universe

- Some possibilities regarding **evolution** of the universe:
 - Universe is **dynamic** and had a **beginning**
 - ✓ **1927: Georges Lemaître** (Catholic priest, astronomer, and physicist) independently derived Friedmann's solutions and, knowing about the **redshift** of the "spiral nebulae", **speculated that the universe began with the "explosion" of a "primeval atom"** (later called the **Big Bang**)—the moment of creation!
 - ✓ Apparently, his analysis hinted at the Hubble law (next slide) two years before Hubble, but published it in a scientific journal that was not widely read...

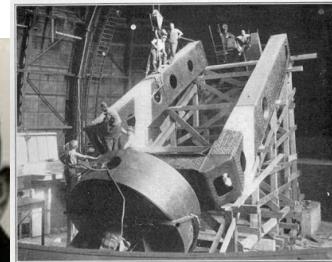


Evolution of the Universe

- Some possibilities regarding **evolution** of the universe:

- Universe is **dynamic** and had a **beginning**

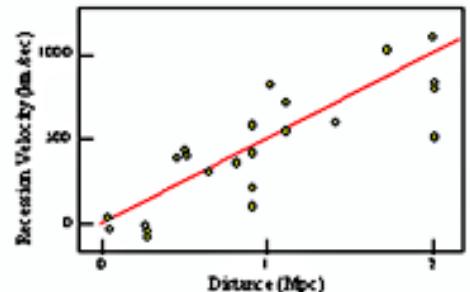
- ✓ **1929: Edwin Hubble** measured the **distances** to the receding “spiral nebulae” (using **Cepheid variable stars**) and discovered that they were **not** nebulae in our own galaxy, but are actually separate galaxies outside of our own. **A universe of galaxies!**



Mount
Wilson 100"
Hooker
Telescope

Hubble's Data (1929)

- ✓ Using redshift data he determined that **more distant** galaxies appear to be **receding faster** (Hubble's Law). **The “universe is expanding”!** This is most easily and naturally explained by Einstein's theory, which says that **space itself can expand**.

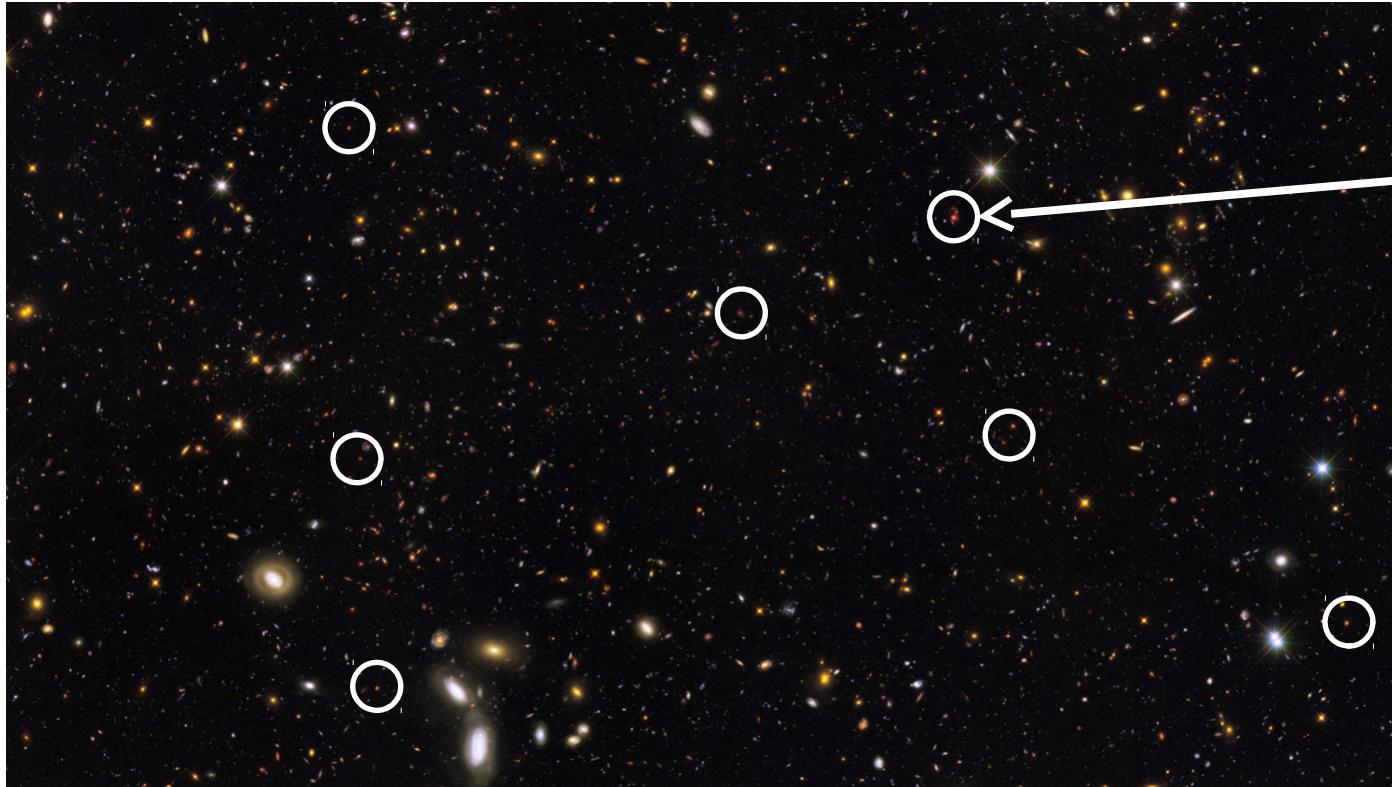


Evolution of the Universe—Expanding Space

Let's understand “**expanding space**”

Evolution of the Universe—Expanding Space

- **First:** What do we mean by **redshift**?

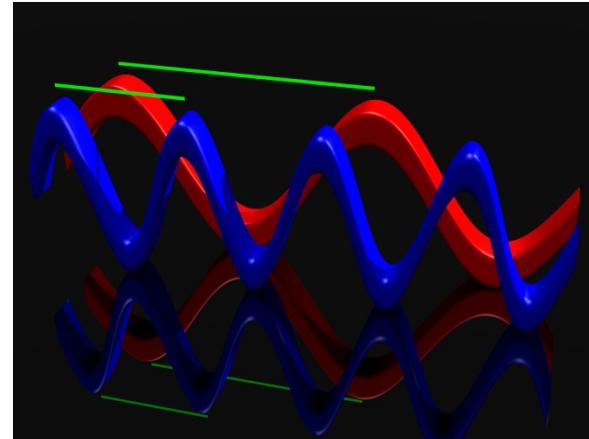
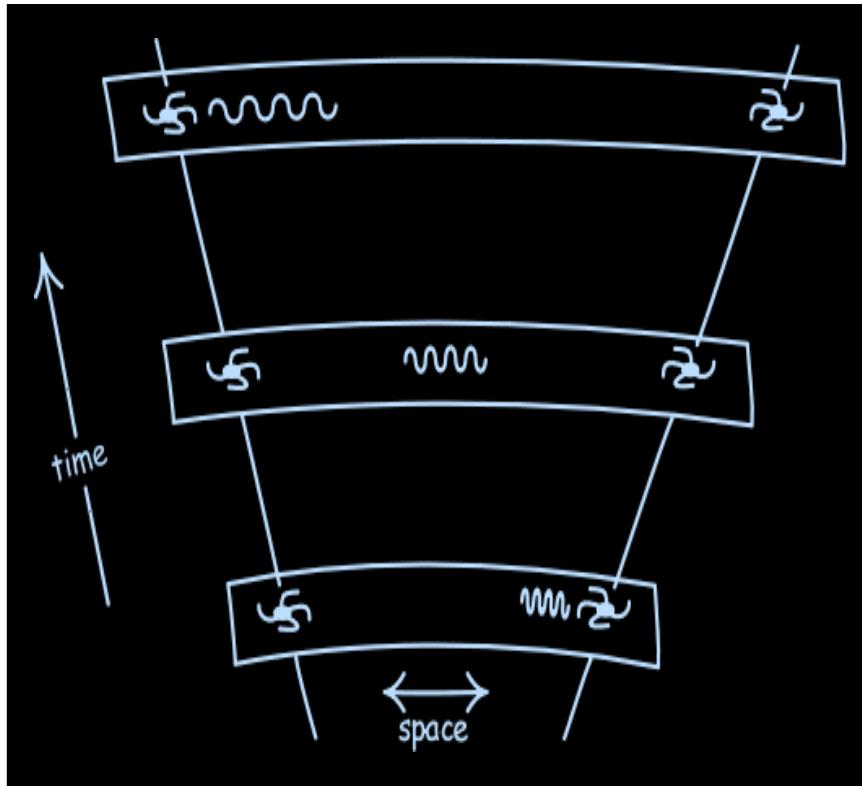


Many galaxies appear **unusually red** in colour

In fact, **more distant** galaxies appear **more deeply red**

Evolution of the Universe—Expanding Space

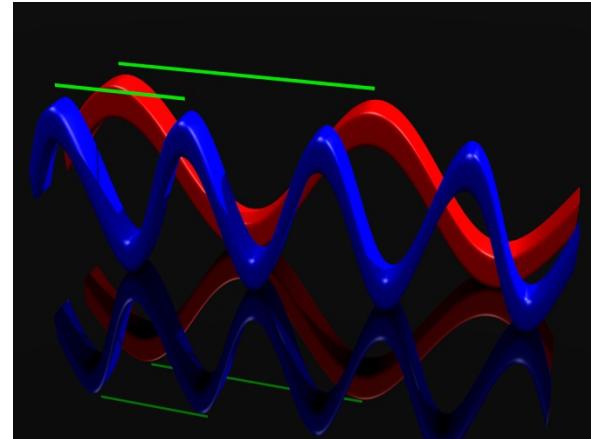
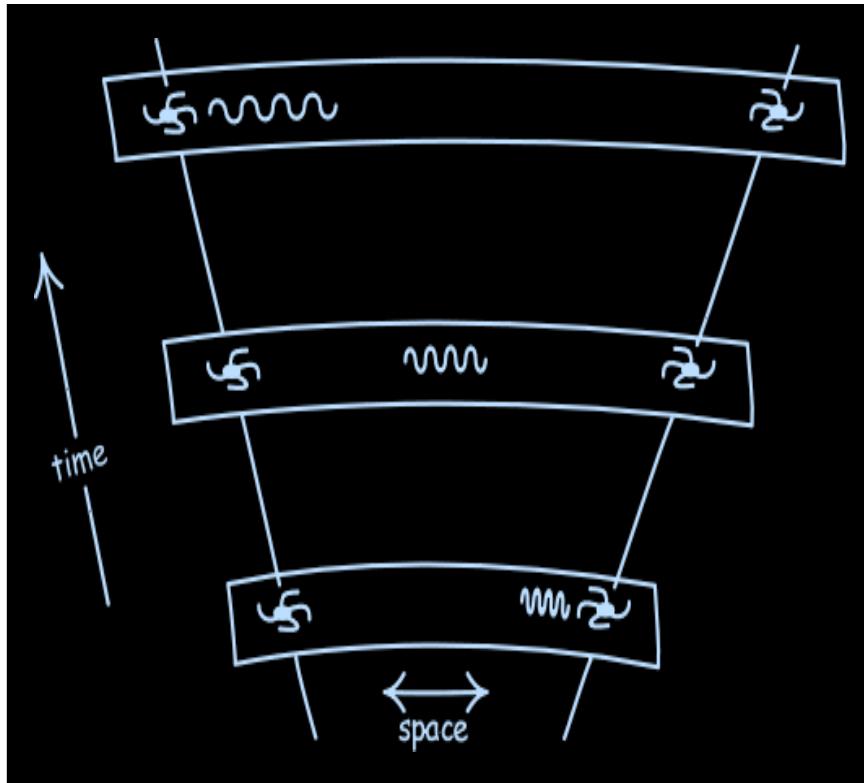
- Second: How can **expanding space** explain this **redshift**?



Light waves are **stretched to longer wavelengths** as they travel through **expanding space** (but not everything is stretched—more later!)

Evolution of the Universe—Expanding Space

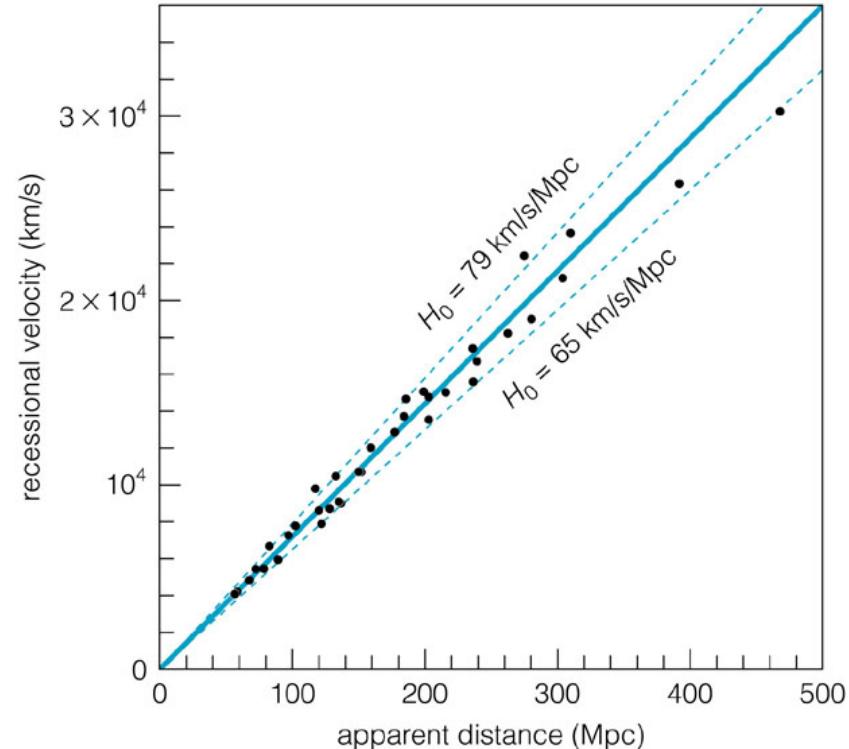
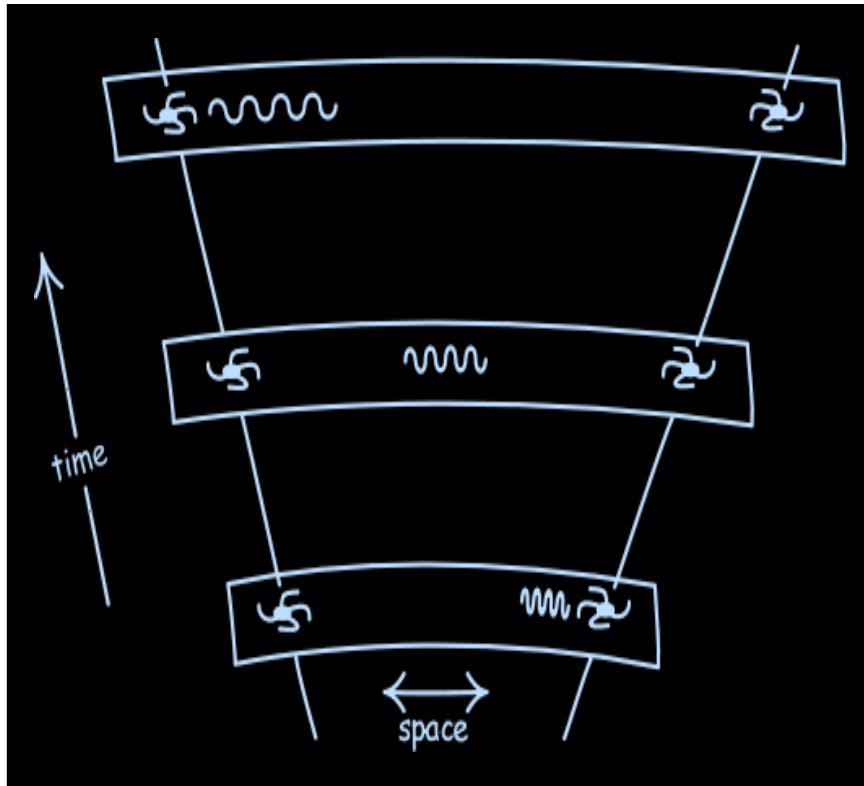
- Third: How can **expanding space** explain *increased* redshift with **increased distance**?



Increased distance means light waves spend a **longer time** in the expanding space, thus stretching to **ever longer wavelengths** (ever more deeply red)

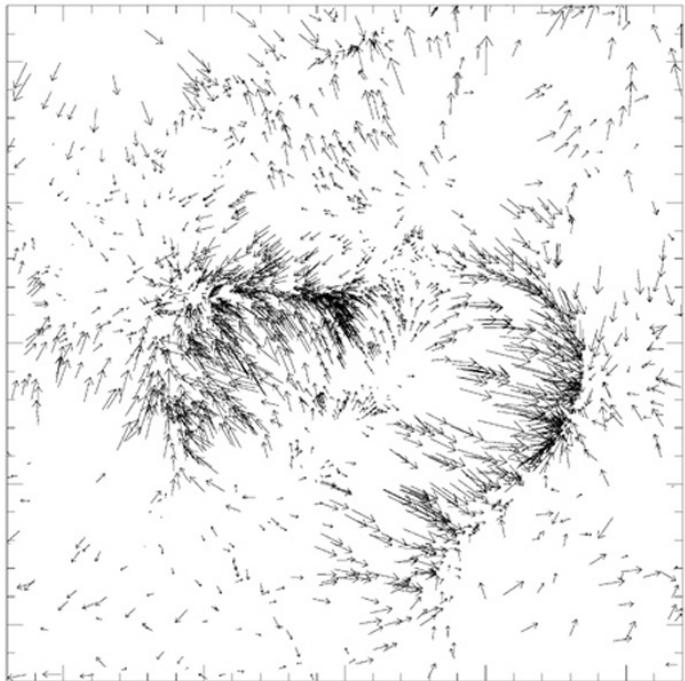
Evolution of the Universe—Expanding Space

- **Hubble's Law:** Apparent recessional velocity , (km/s) per Mpc

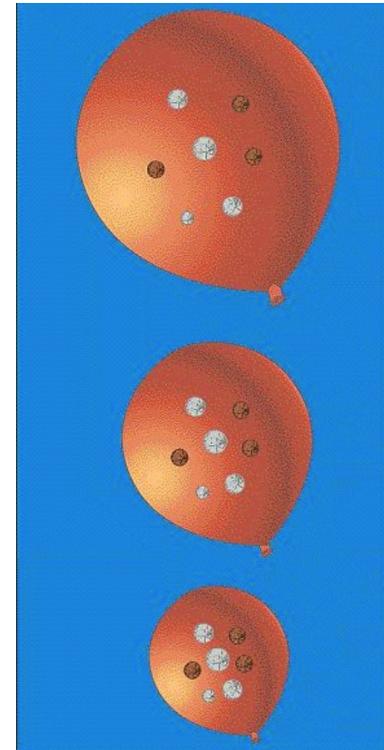
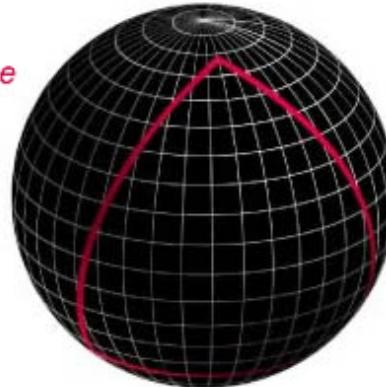


Evolution of the Universe—Expanding Space

- Except for small *peculiar velocities*, **galaxies don't move**. The space they are floating in simply expands, increasing the distance between them, like coins glued to an expanding balloon. (Also like the coins, galaxies themselves do **not** expand.)

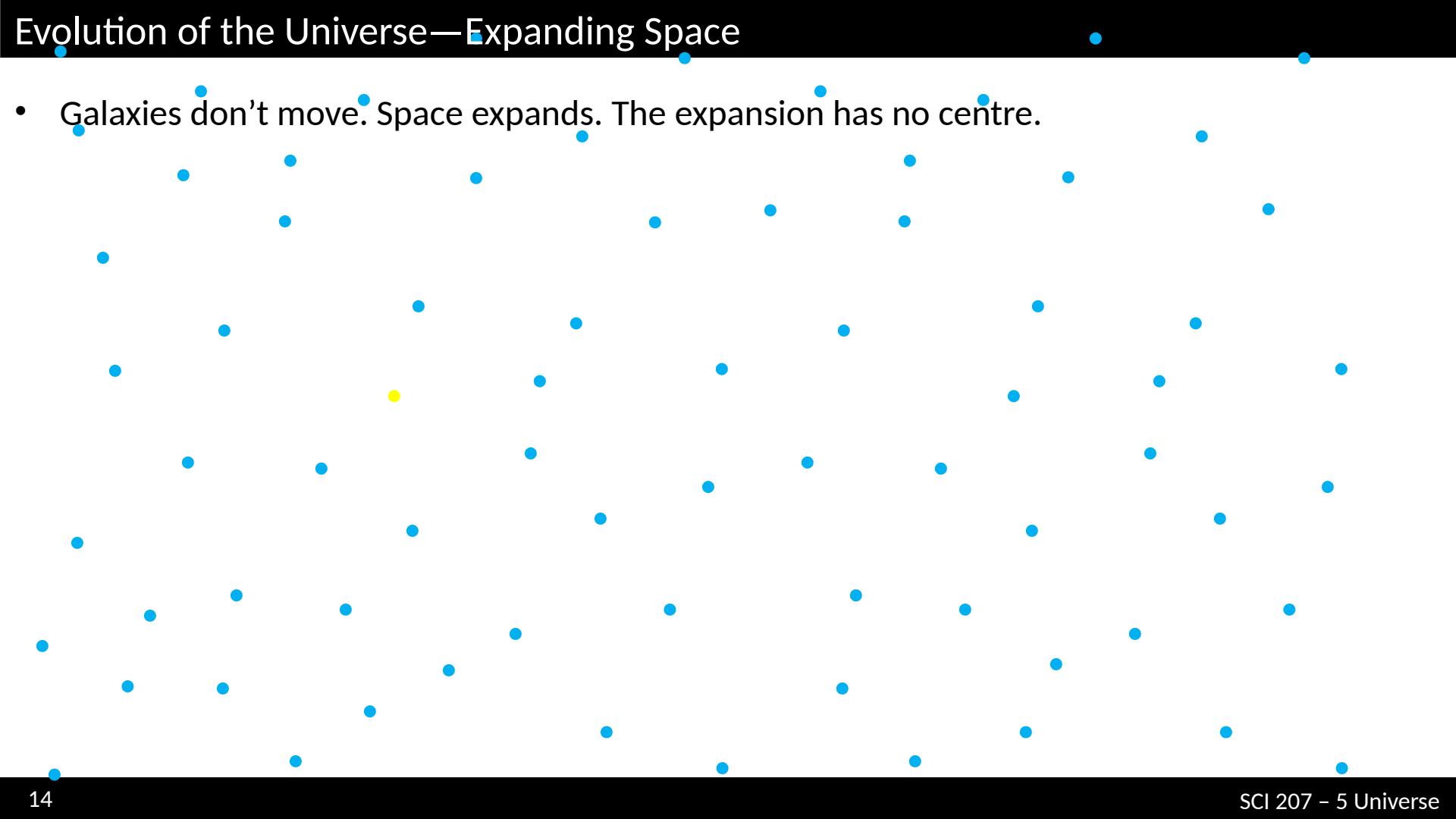


*Closed
Universe*



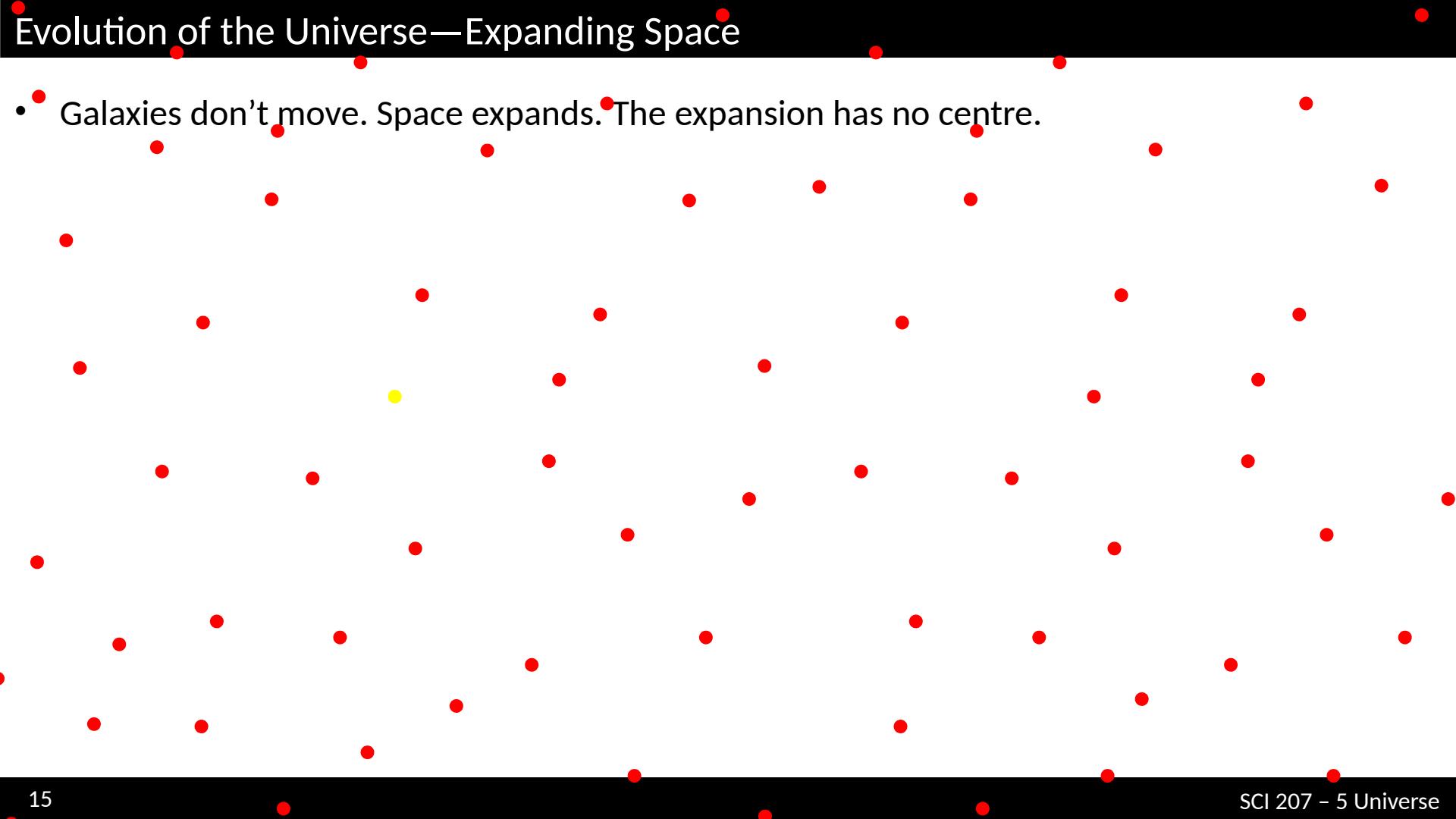
Evolution of the Universe—Expanding Space

- Galaxies don't move. Space expands. The expansion has no centre.



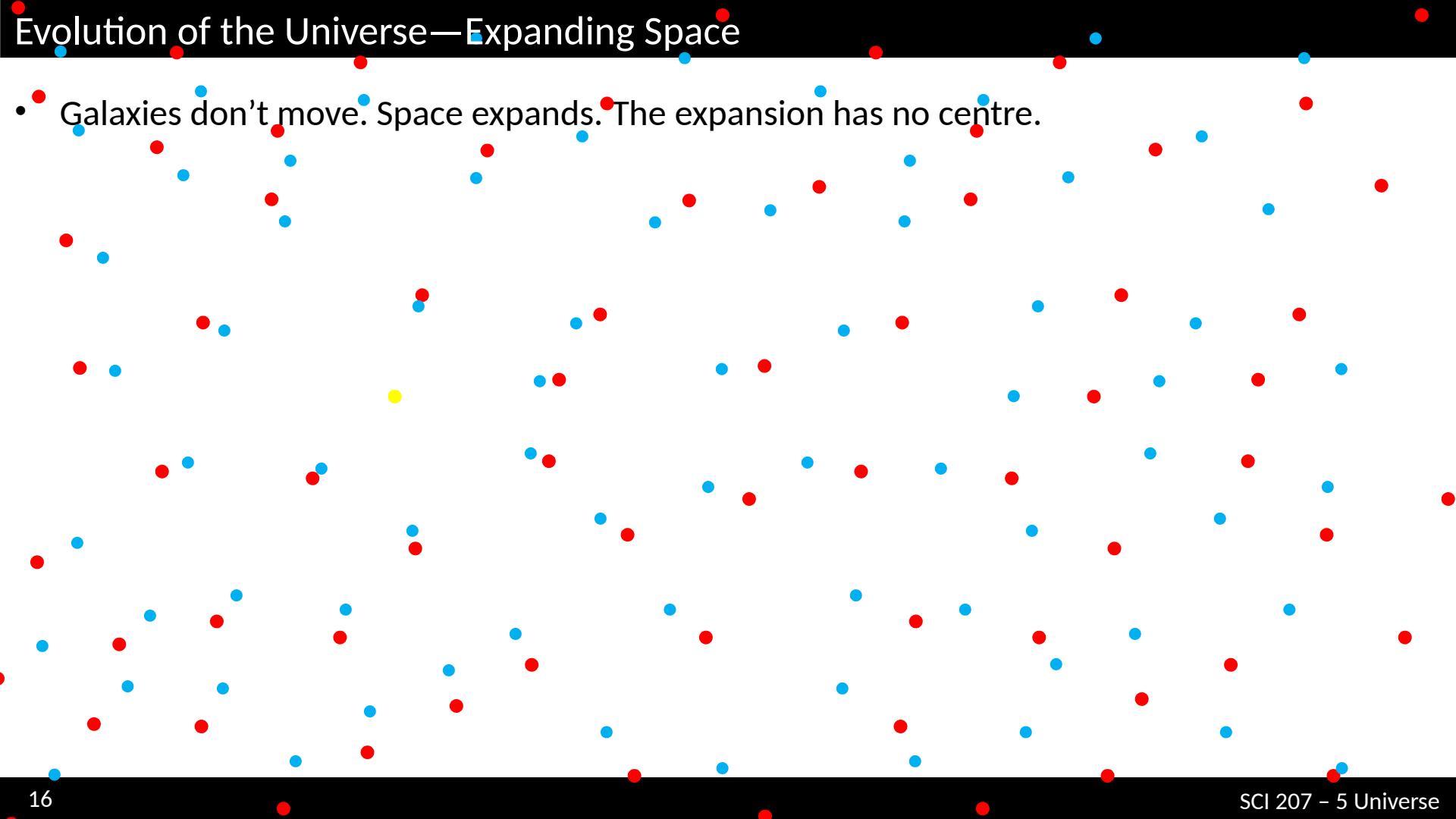
Evolution of the Universe—Expanding Space

- Galaxies don't move. Space expands. The expansion has no centre.



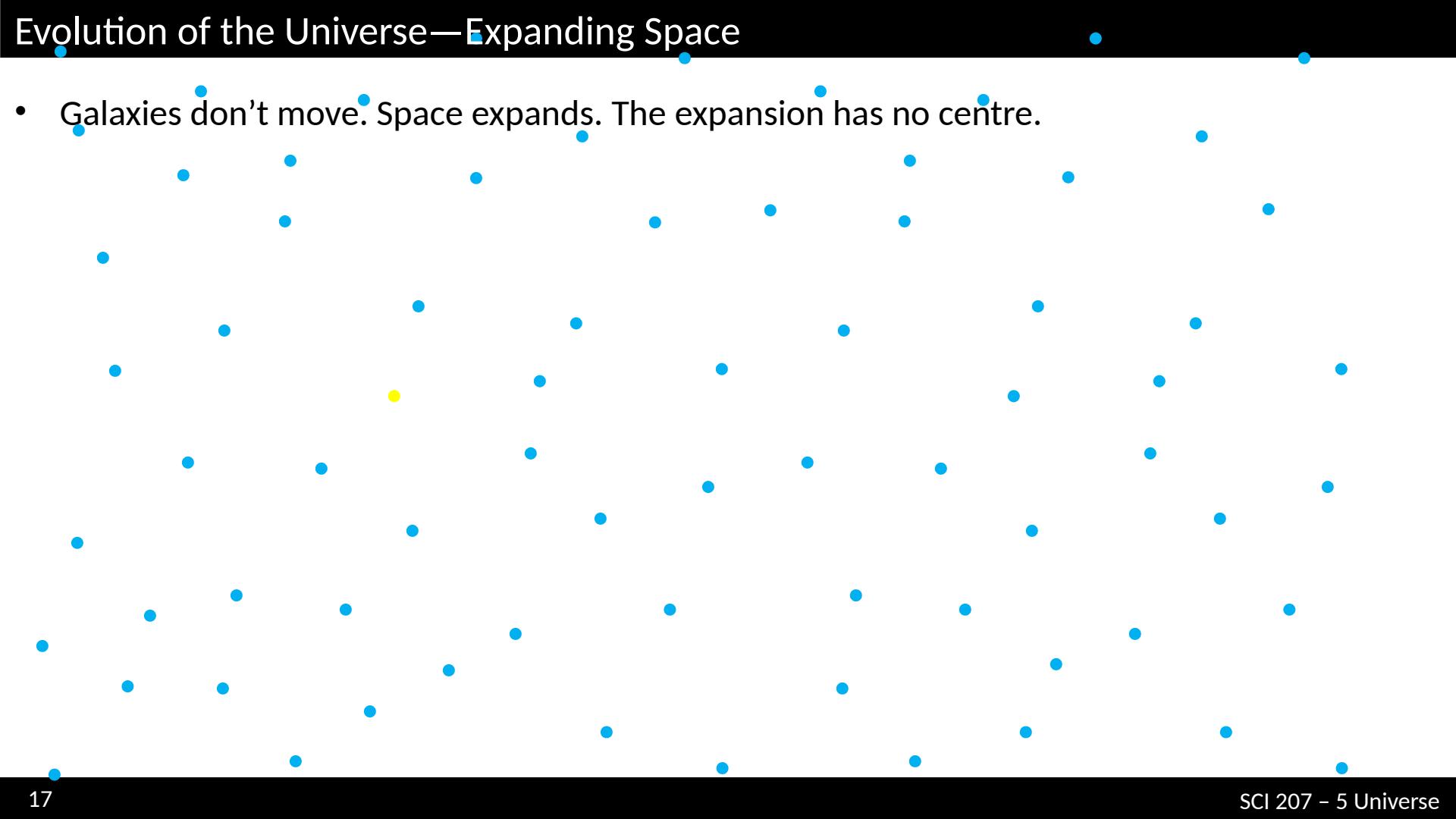
Evolution of the Universe—Expanding Space

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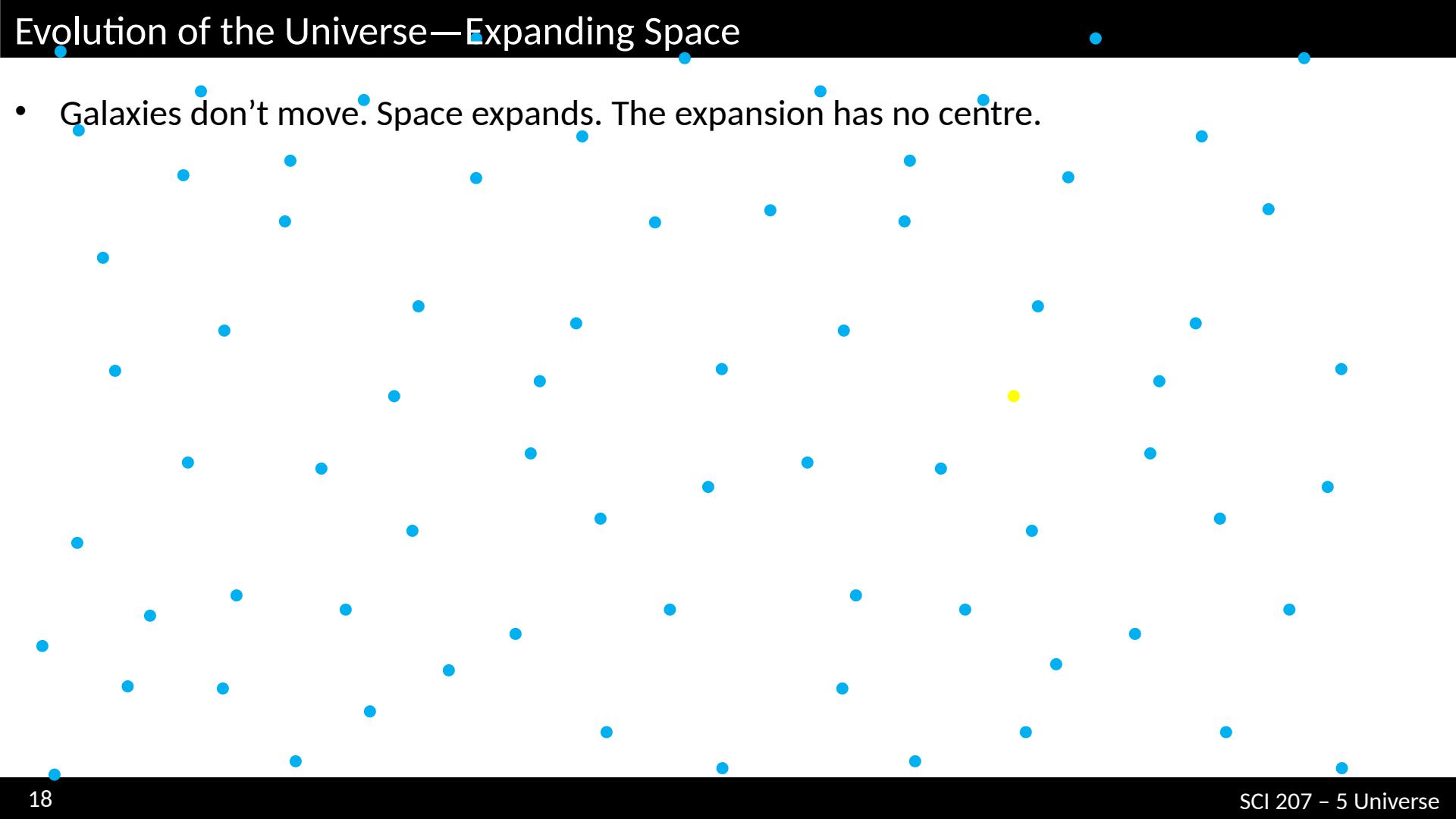
Evolution of the Universe—Expanding Space

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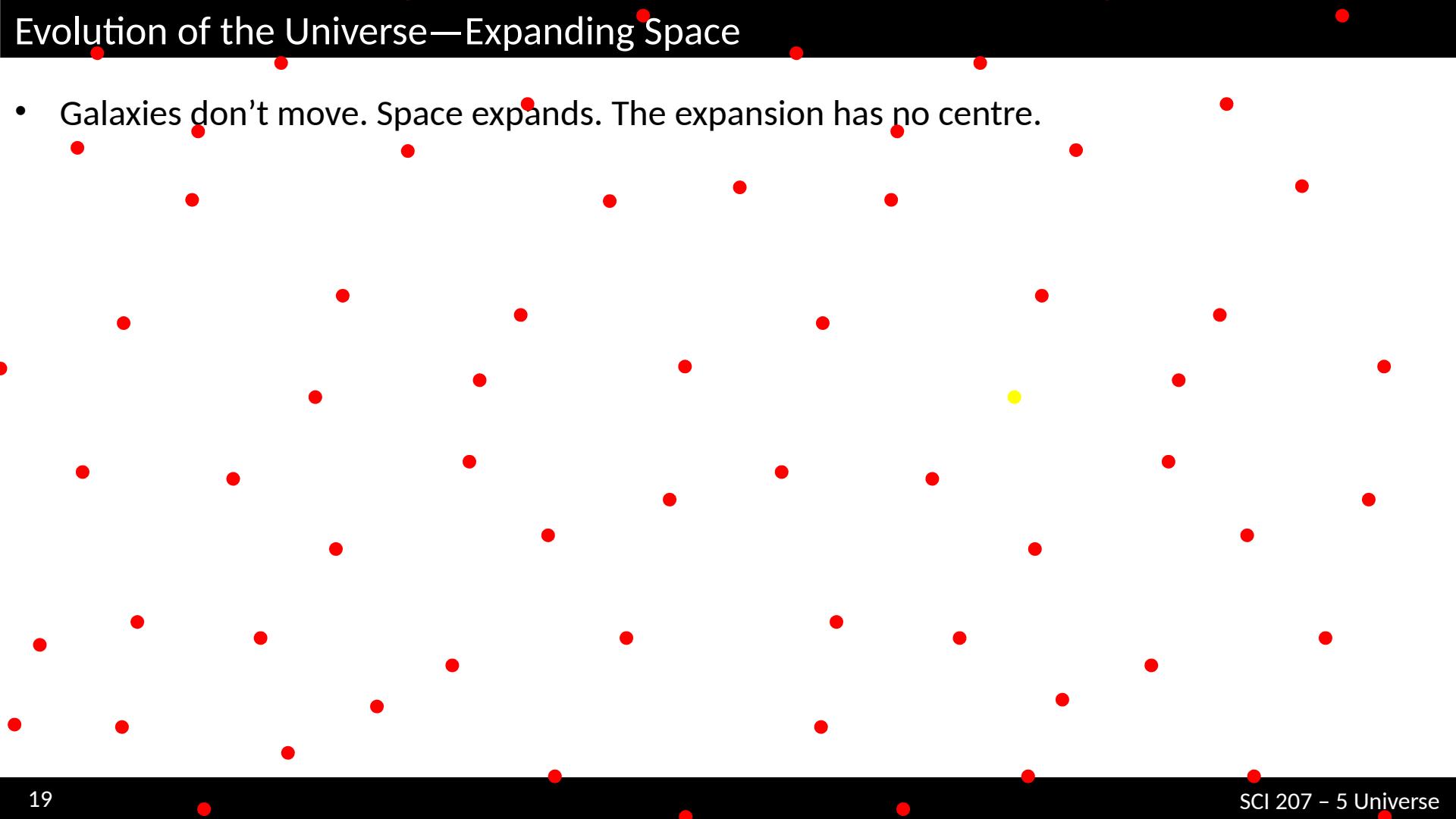
Evolution of the Universe—Expanding Space

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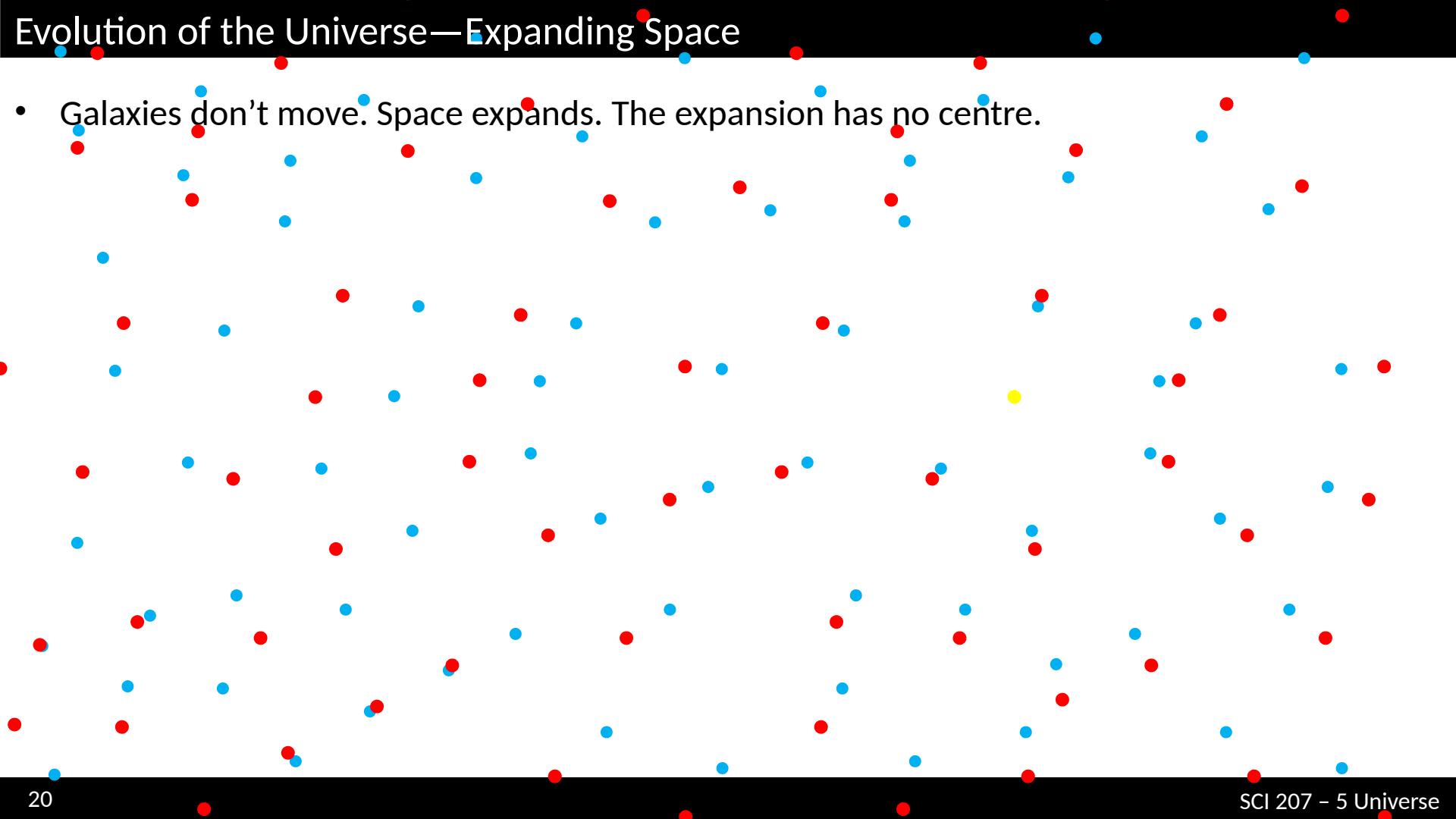
Evolution of the Universe—Expanding Space

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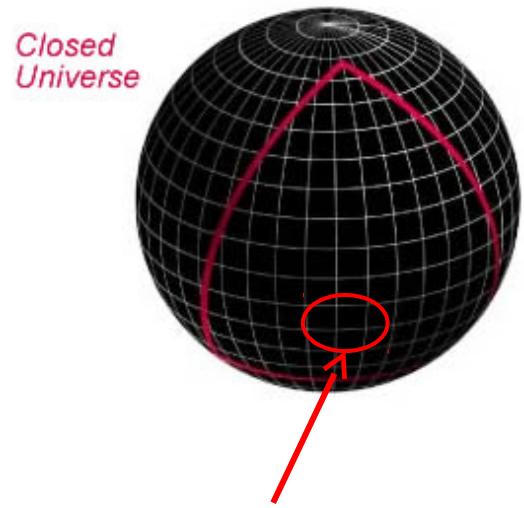
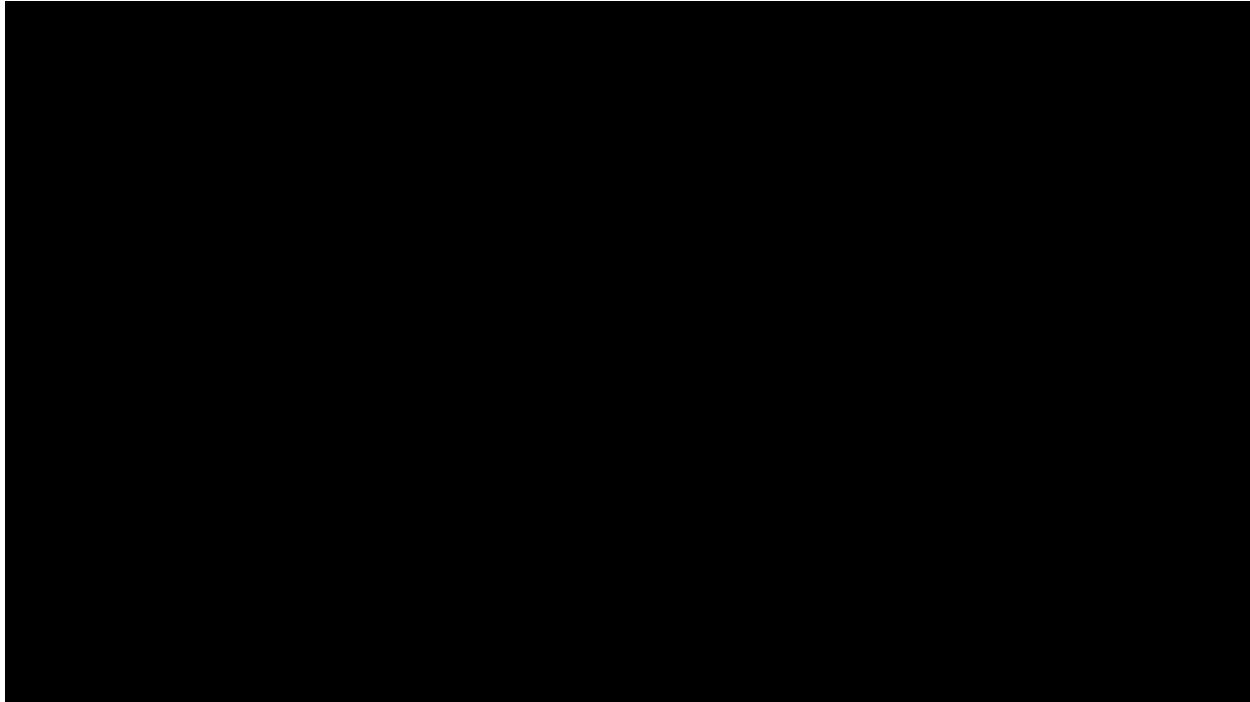
Evolution of the Universe—Expanding Space

- Galaxies don't move. Space expands. The expansion has no centre.



Evolution of the Universe—Expanding Space

There is no centre of the expansion. No preferred point (Copernican principle).



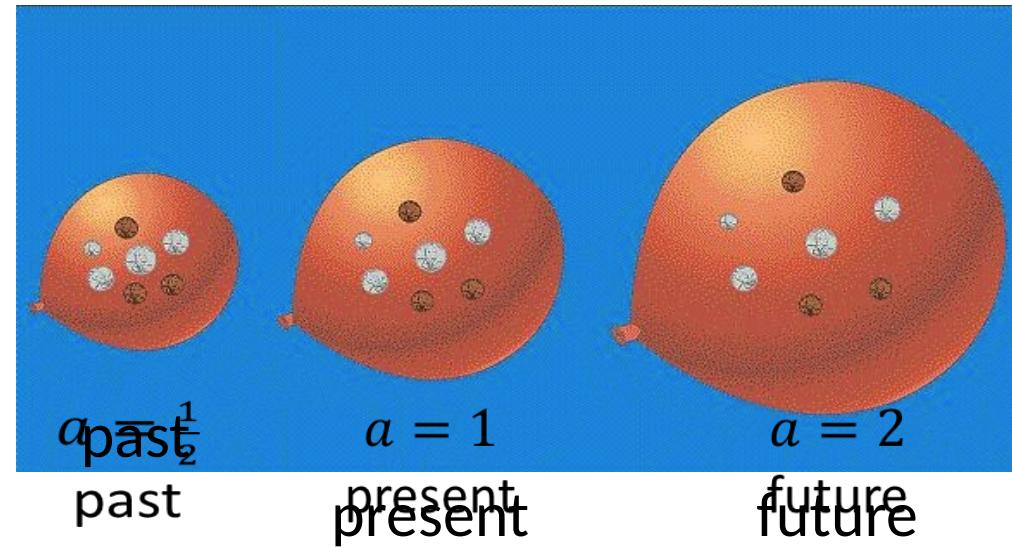
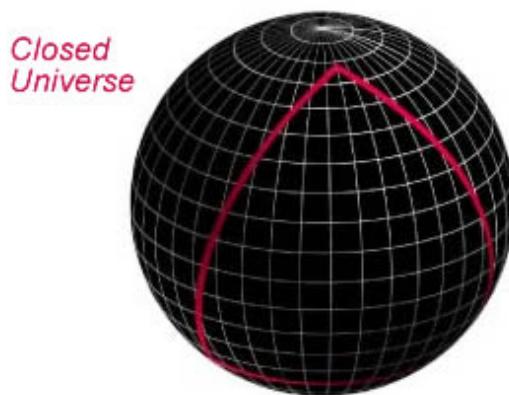
Observable Universe

Evolution of the Universe—Expanding Space

Old Hubble Law (galaxies moving away from us):

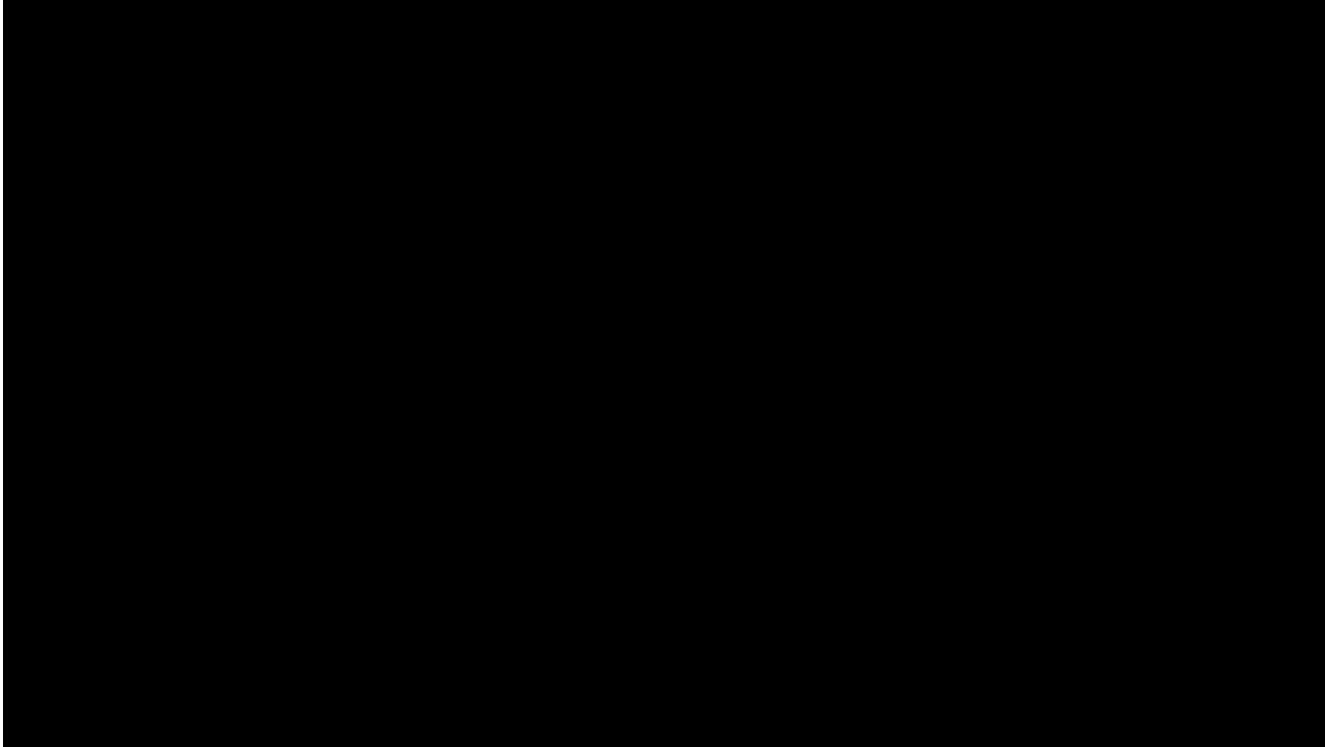
New Hubble Law (galaxies don't move; **space expands**):

where **scale factor** of space the size of space relative to the present



Evolution of the Universe—Expanding Space

Why don't **galaxies** (and other things) expand as **space** expands?

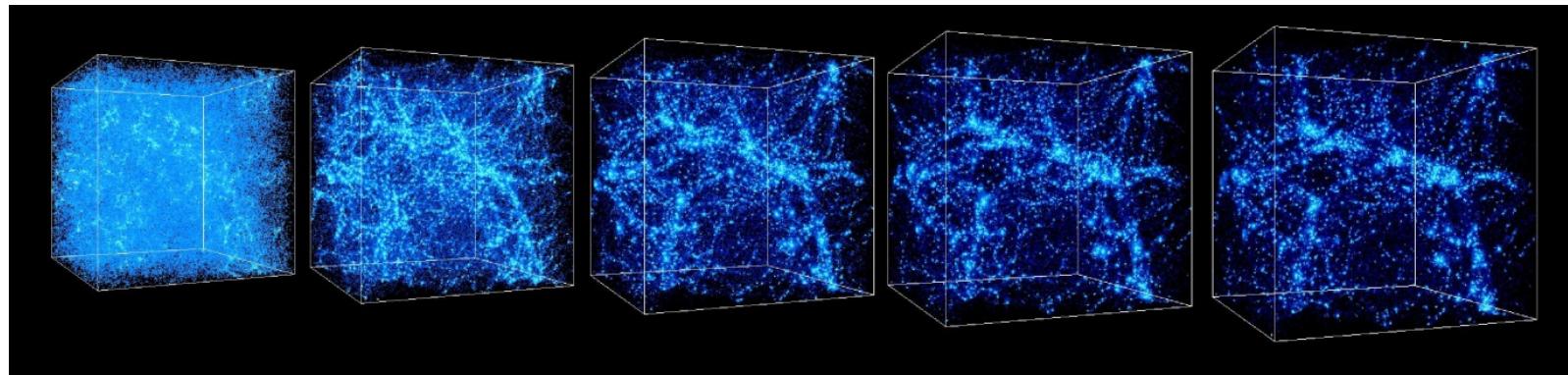


Evolution of the Universe—Expanding Space

Important: All of space has always been uniformly filled with matter and radiation.

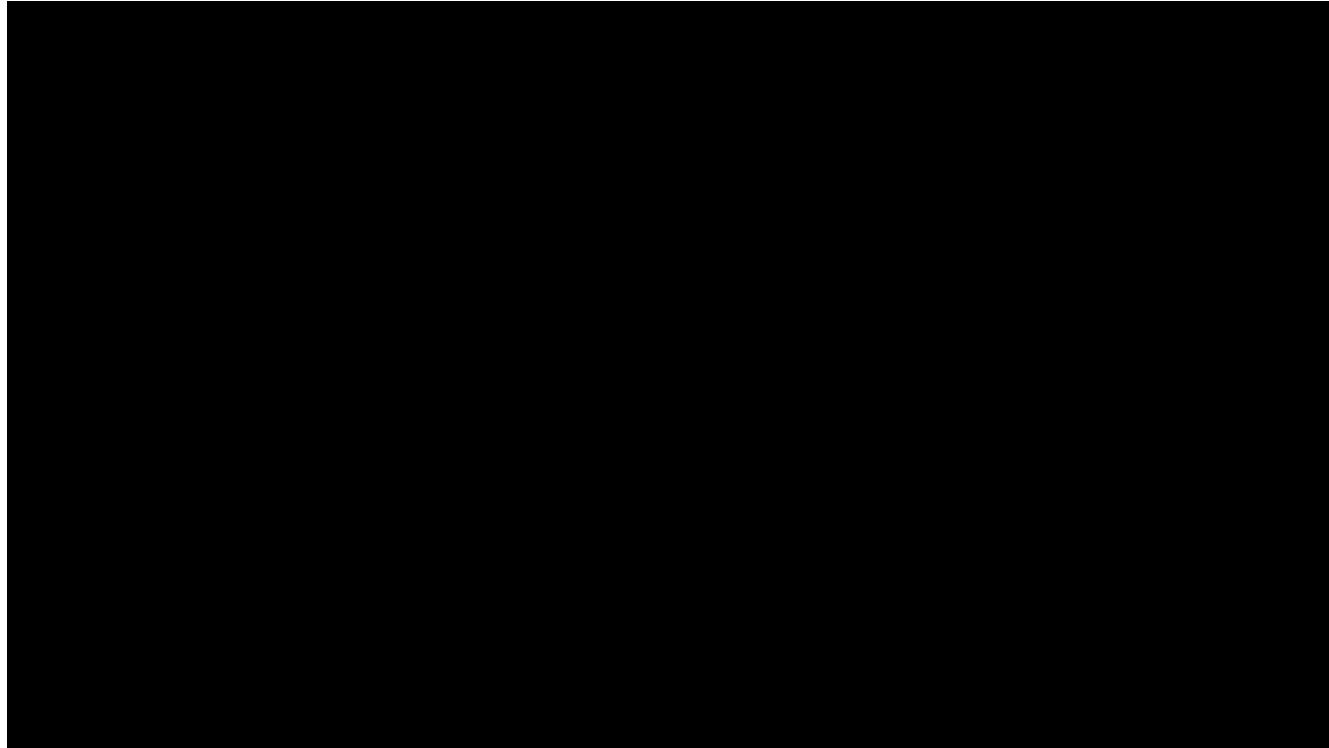
(Since the early universe there has been much **gravitational clumping** into stars & galaxies, but on **average**, over big enough scales, it's **still uniform**)

The Big Bang was **not** a dense point of stuff that exploded into an otherwise empty space. Stuff was dense **everywhere**, and space expanded **everywhere**, diluting the stuff **everywhere**. Also, the observable universe is just a small part of all of space. The size of “all of space” is not known.



Evolution of the Universe—Expanding Space

Big Bang = Everywhere Stretch

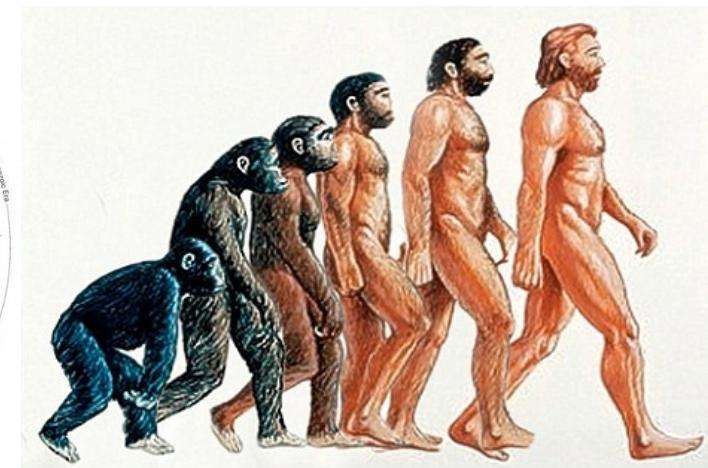
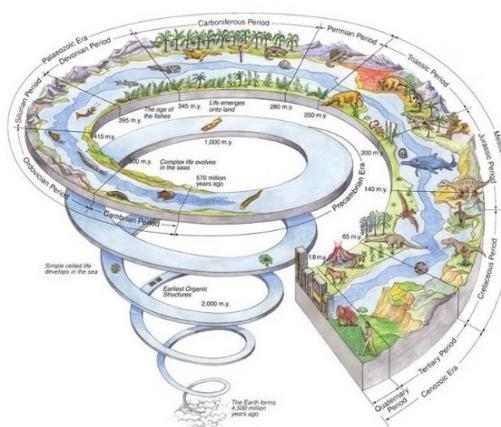
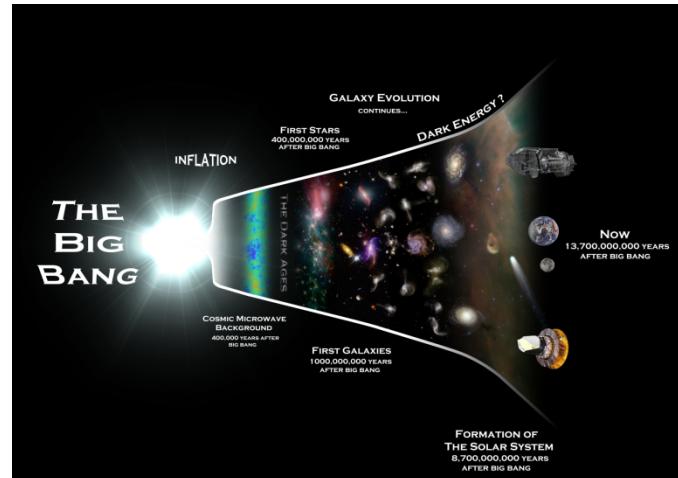


Beginning of the Universe

- The questions:

- Where we come from? [How did life evolve?]
- Where does the universe come from? [How did it evolve?]

...hinge critically on whether or not there was a beginning



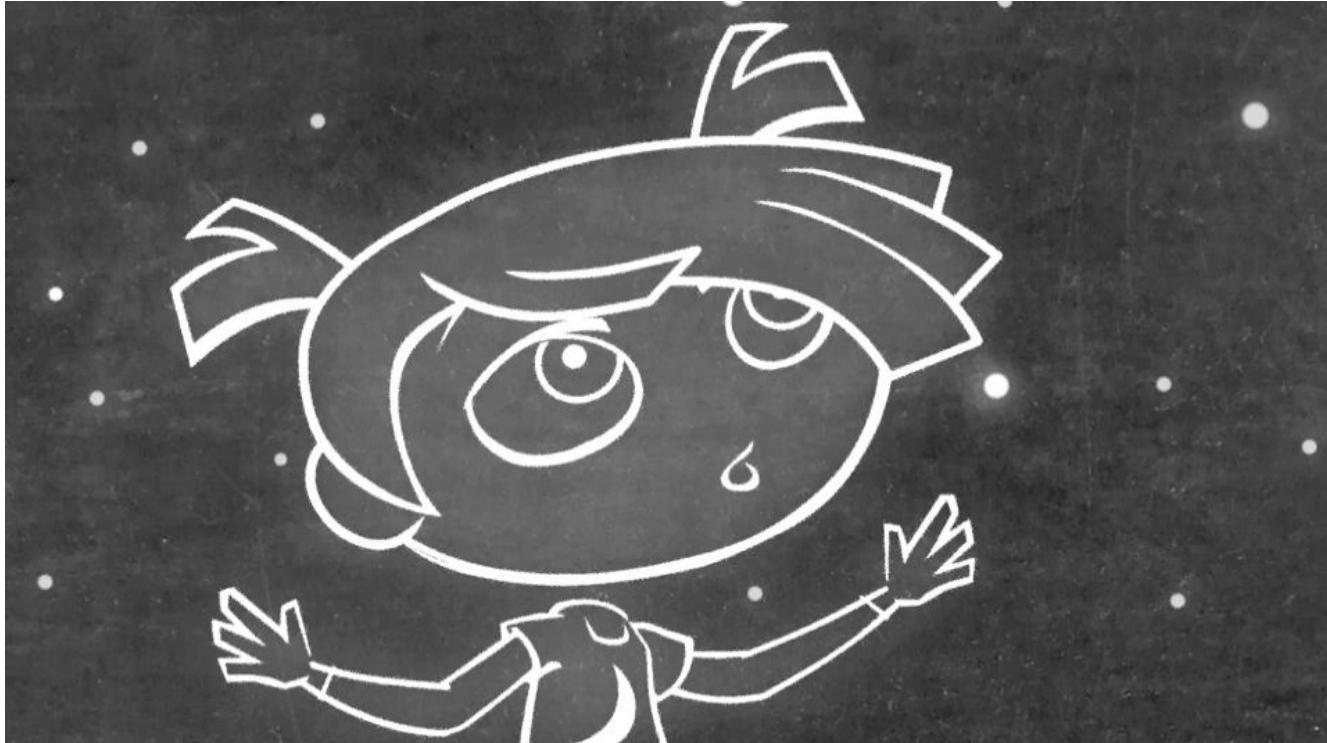
Beginning of the Universe

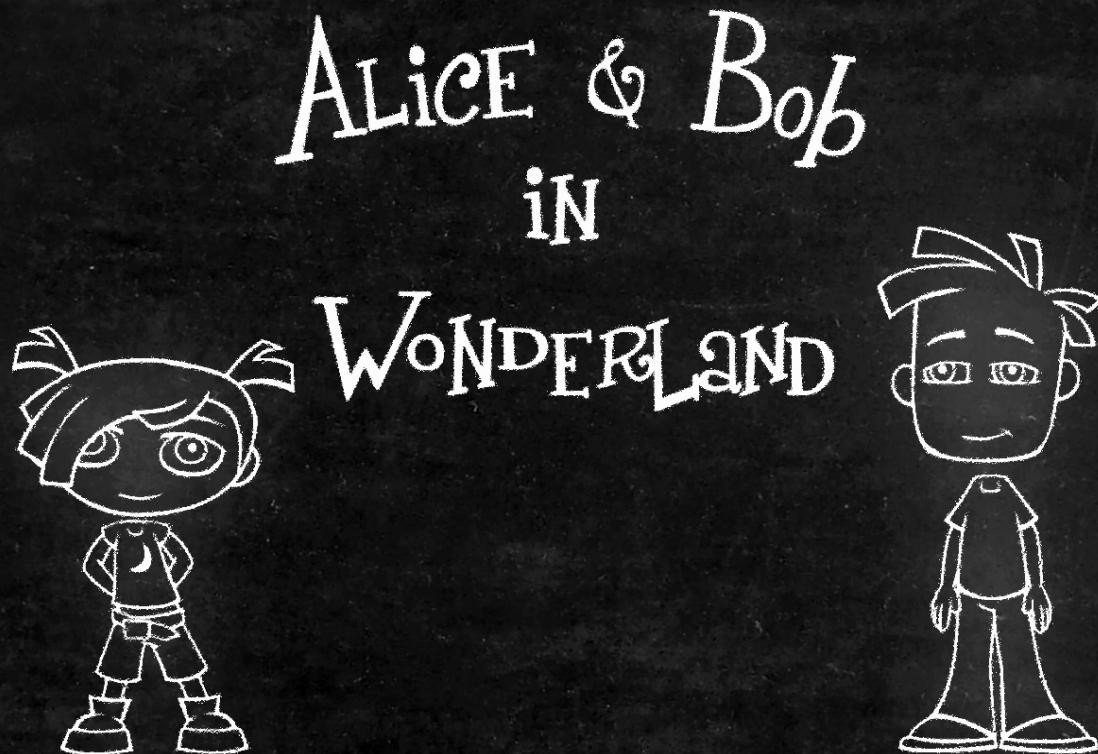
- Remarkably, evidence that there **was** a beginning has been staring us in the face since the dawn of human consciousness, in the form of the **darkness of the night sky**.



Evidence for the Big Bang

(1) Sky is dark at night





Evidence for the Big Bang

(1) Sky is dark at night

- Go back to **Giordano Bruno (1584)**:

“The universe is then one, **infinite, immobile**.... It is not capable of comprehension and therefore is **endless and limitless**”.

- ...and make the following **simple assumptions**:

- Universe is **static**
- Universe is **infinitely big**
- Stars (or today, galaxies of stars) are evenly scattered throughout (**Copernican Principle**)
- Universe is **infinitely old**



Evidence for the Big Bang

(1) Sky is dark at night

- Logical consequence:

Every line of sight would hit a star



Evidence for the Big Bang

(1) Sky is dark at night

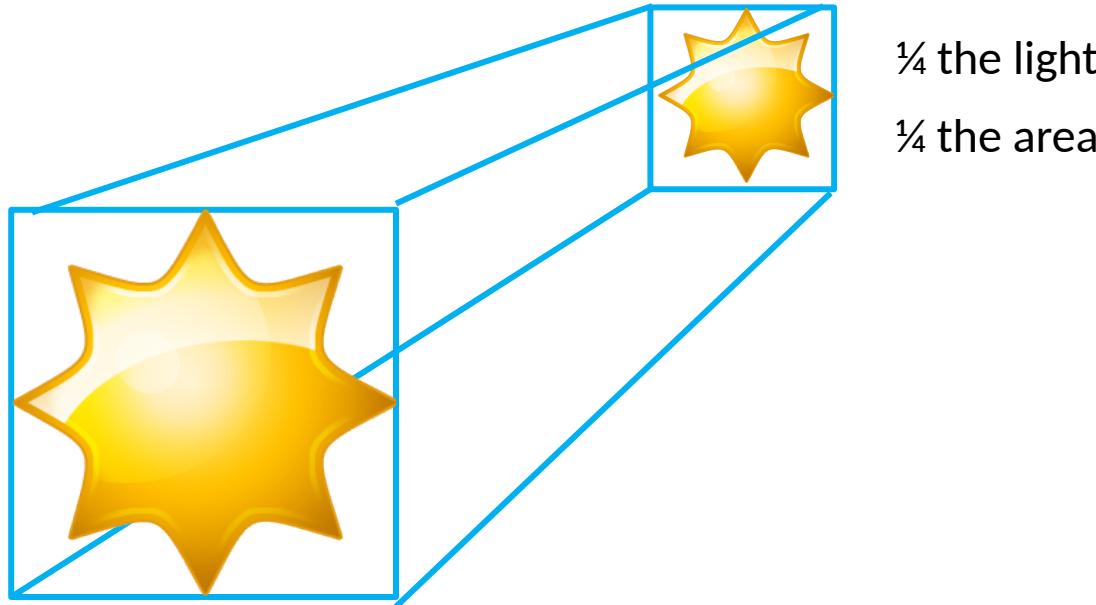
- Logical consequence:

Every point in the sky would be bright like the Sun!

Evidence for the Big Bang

(1) Sky is dark at night

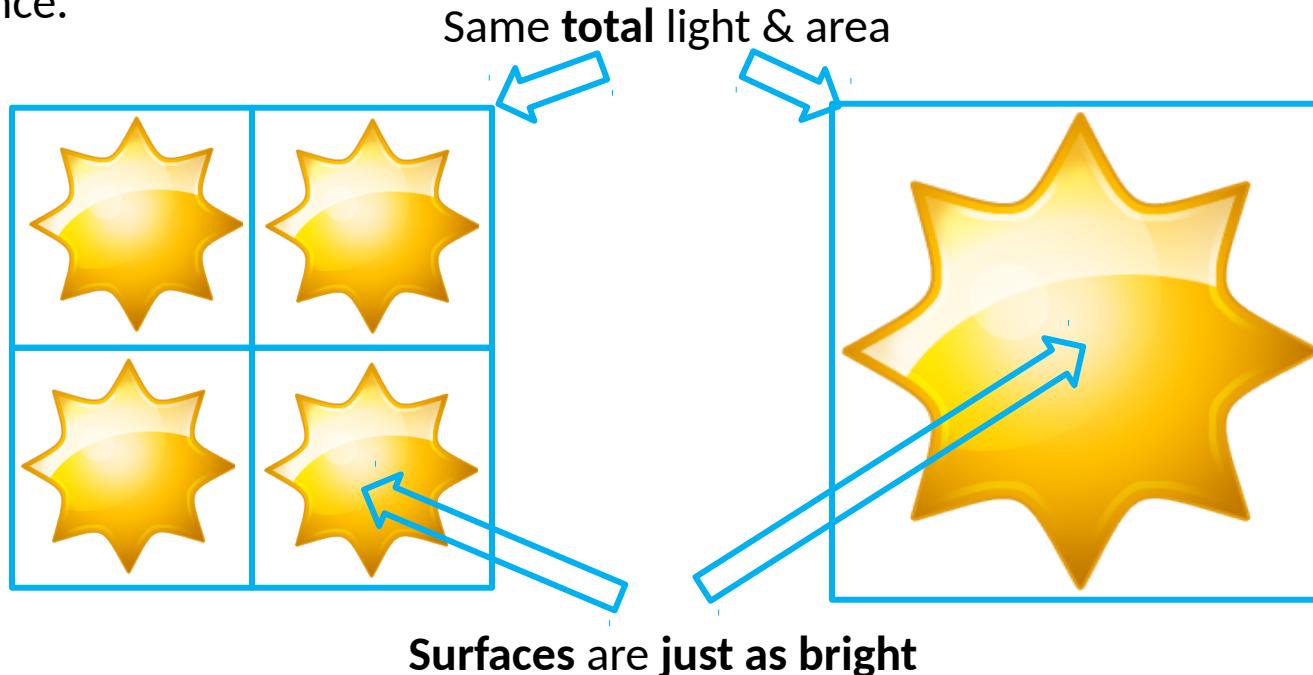
- **But wait:** Aren't far away stars dimmer? Yes, but their **surface brightness** is independent of their distance.



Evidence for the Big Bang

(1) Sky is dark at night

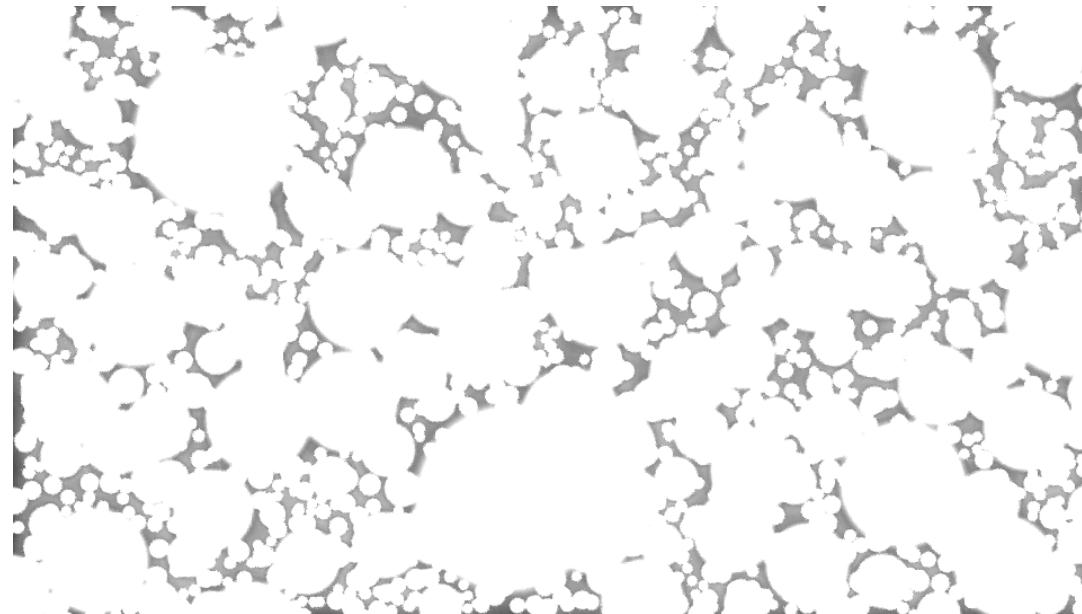
- **But wait:** Aren't far away stars dimmer? Yes, but their **surface brightness** is independent of their distance.



Evidence for the Big Bang

(1) Sky is dark at night

- **But wait:** Aren't far away stars dimmer? Yes, but their **surface brightness** is independent of their distance.



Evidence for the Big Bang

(1) Sky is dark at night

- Thus, at least one of these assumptions is **wrong**:
 - Universe is **static**
 - Universe is **infinitely big**
 - Stars (or today, galaxies of stars) are evenly scattered throughout (**Copernican Principle**)
 - Universe is **infinitely old**

Which one(s)?

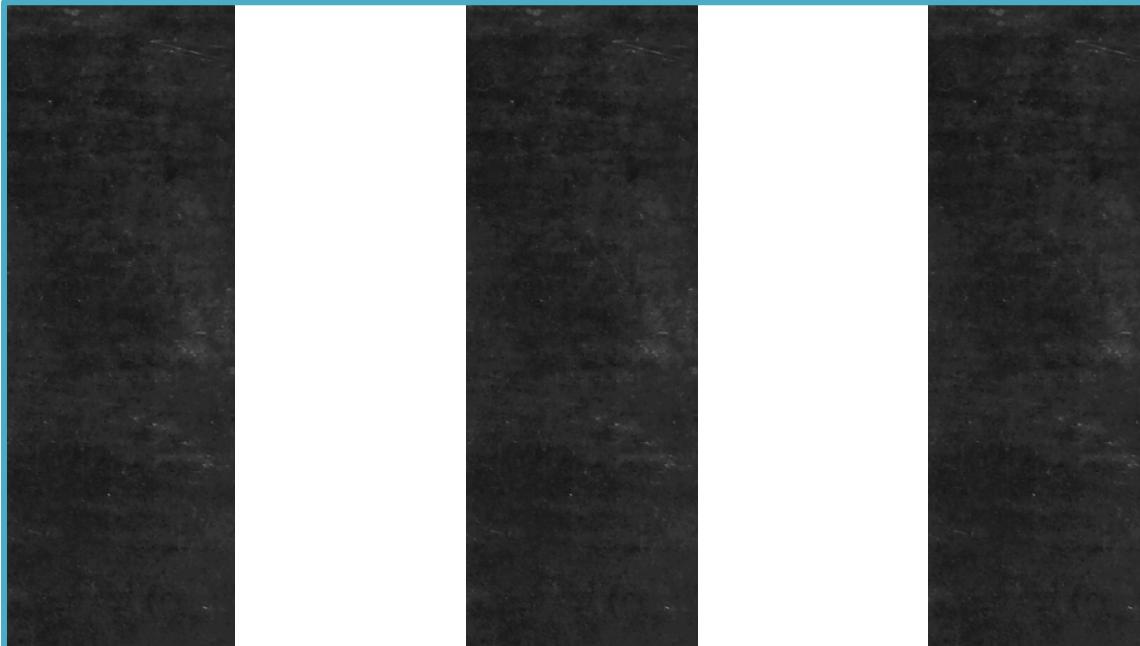
Most likely (?) to be wrong: Universe is **infinitely old?** Universe is **static?**

- Darkness of night sky strongly suggests universe is **dynamic** and had a **beginning**
(these are related: *an expanding universe implies a beginning*)

Evidence for the Big Bang

(1) Sky is dark at night

- Our Cosmic Horizon (case of *static* universe with **finite age**)



Evidence for the Big Bang

(1) Sky is dark at night

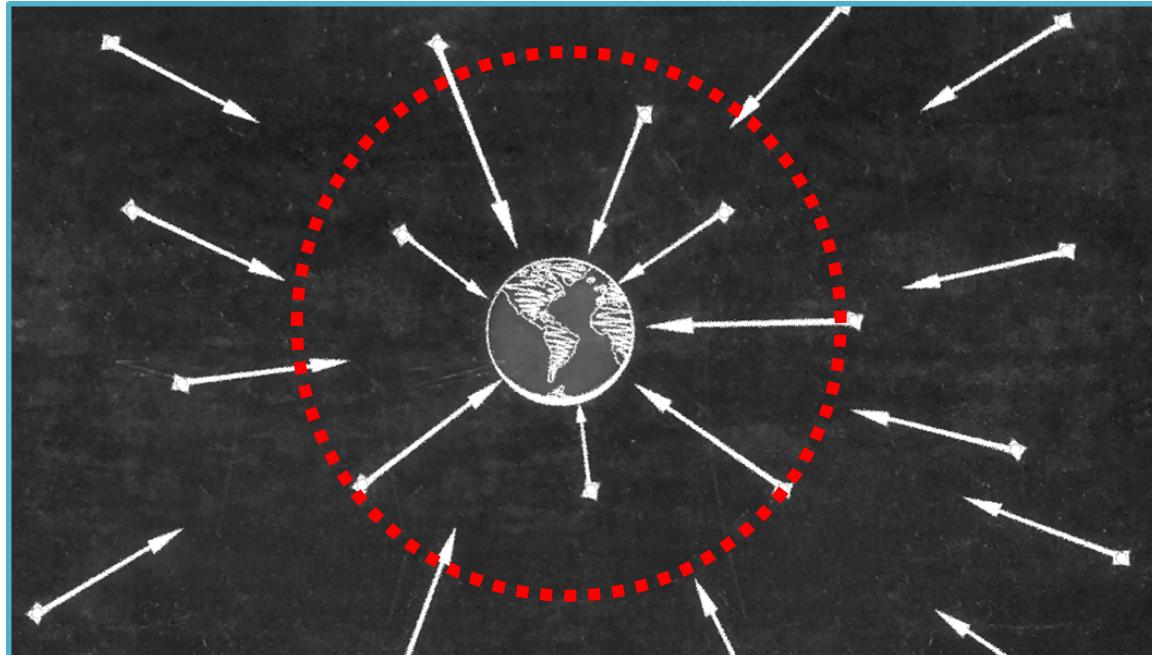
- Our Cosmic Horizon (case of *static* universe with **finite age**)



Evidence for the Big Bang

(1) Sky is dark at night

- Our Cosmic Horizon (case of *static* universe with **finite age**)



Evidence for the Big Bang

(1) Sky is dark at night

- Notes on assumptions:

It's stars all the way out

(Actually, can **replace stars** with
galaxies and same argument
applies)



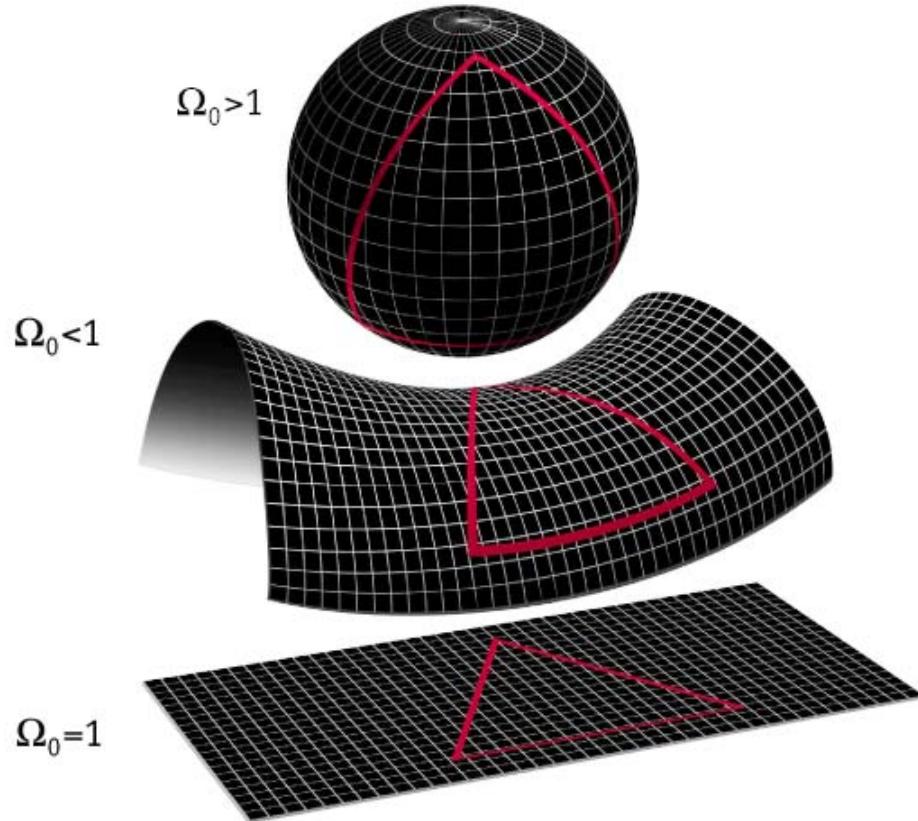
Evidence for the Big Bang

(1) Sky is dark at night

- Notes on assumptions:

Space is flat

(Actually, **it is**, on a cosmic scale;
know this from CMB...more later)



MAP990006

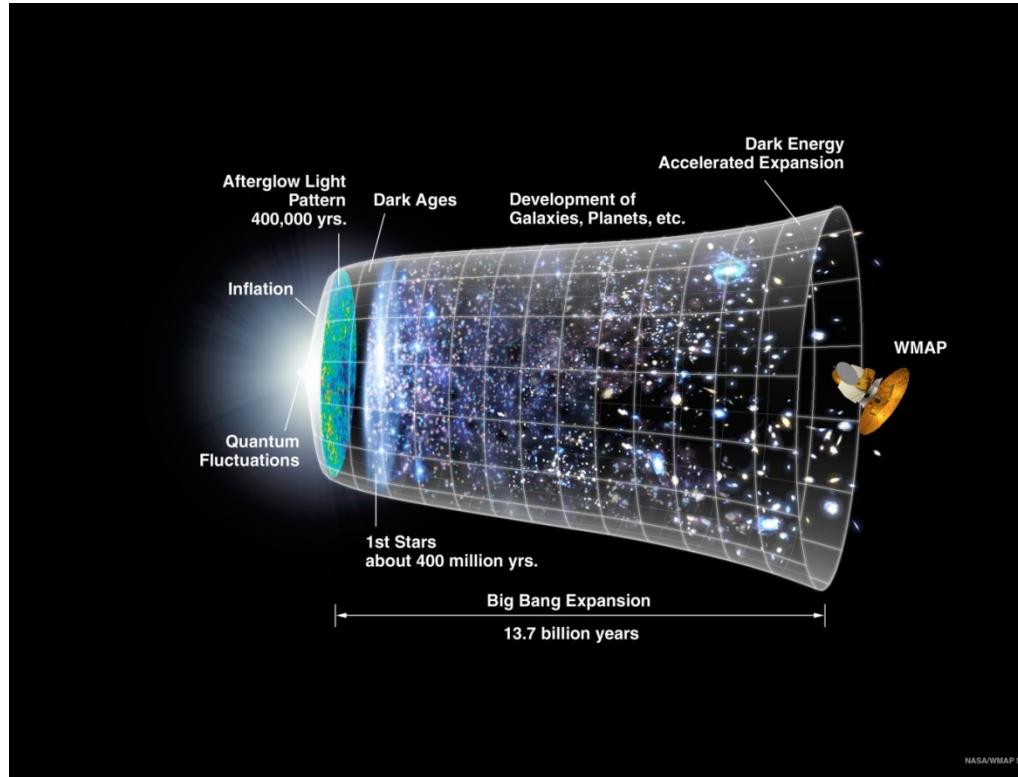
Evidence for the Big Bang

(1) Sky is dark at night

- Notes on assumptions:

The universe is static

(Actually, it's **expanding**. This causes **dimming** of very distant objects associated with **redshift**. **Both the redshift and the finite age** are important to the darkness of the night sky.)



Evidence for the Big Bang

(1) Sky is dark at night

