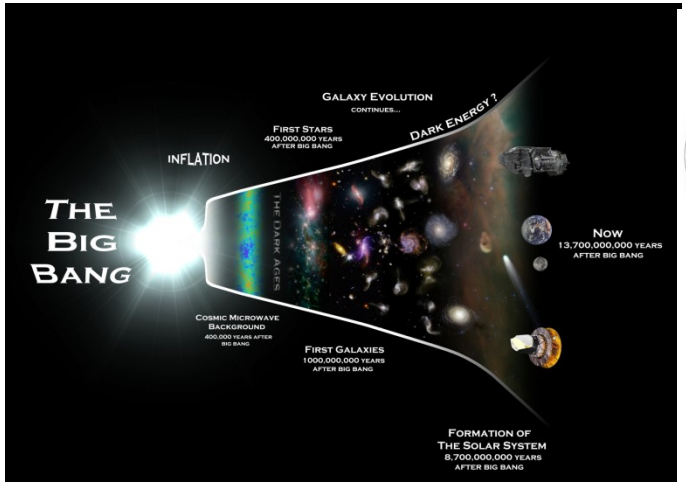
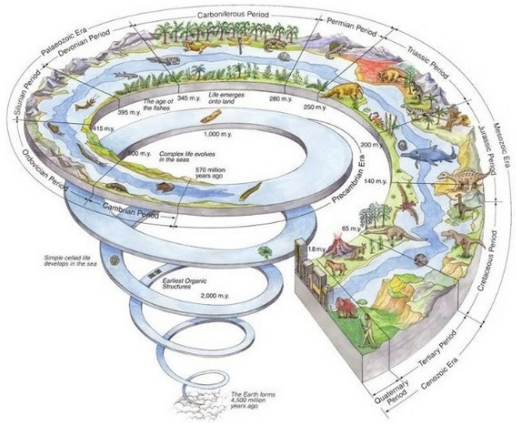
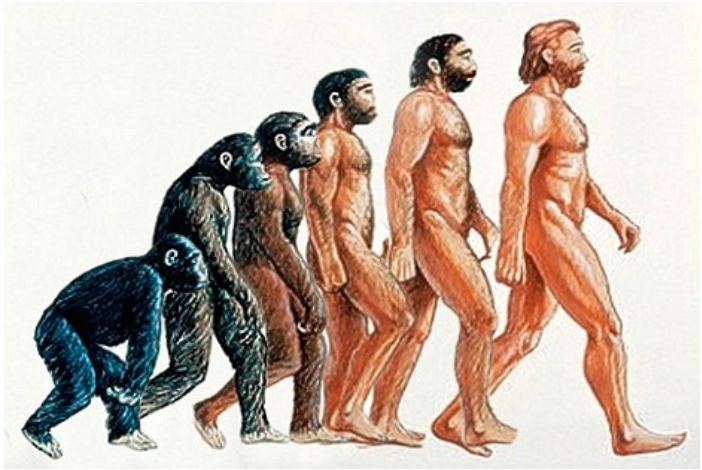
Evolution of the Universe

- **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

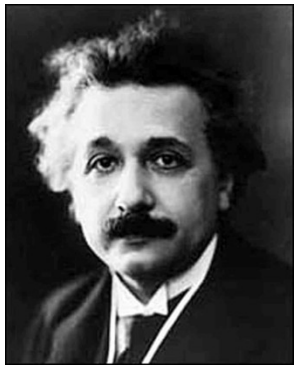
- Some possibilities regarding **evolution** of the universe:
  - Universe is **static** and **eternal** (no beginning or end)
    - ✓ Articulated clearly by **Giordano Bruno in 1584**:

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

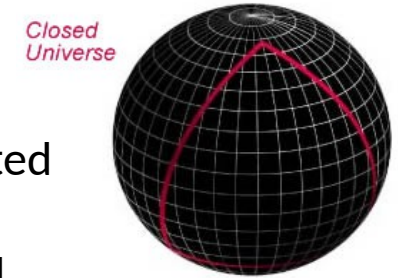
    - ✓ First to imagine an **infinite** universe **filled with stars**, each with their own **planets**, and **no centre** to the universe ("Copernican principle")
    - ✓ Also wrote: other worlds "have no less virtue nor a nature different to that of our Earth" and, like Earth, "**contain animals and inhabitants**"

Evolution of the Universe

- Some possibilities regarding **evolution** of the universe:
  - Universe is **static** and **eternal** (no beginning or end)

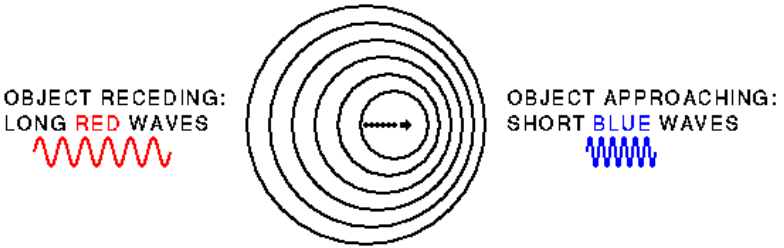


- ✓ **Cosmology** as a **science** began in the early 20th century with the advent of Einstein's **general theory or relativity**, a geometrical theory of space, time, and gravity (1915).
- ✓ **1917: Einstein** applied his new theory to cosmology. Worried about imposing **ad hoc** boundary conditions 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**.)

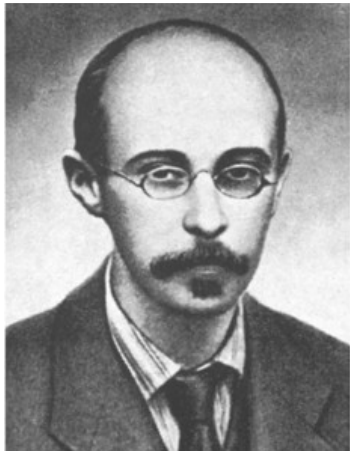
- Some possibilities regarding **evolution** of the universe:
  - Universe is **dynamic**
    - ✓ **1912: Vesto Slipher** measured the **redshift** of "spiral nebulae" and interpreted this redshift as a **Doppler shift**: the "spiral nebulae" were all moving away from us ⎵ something **dynamic**

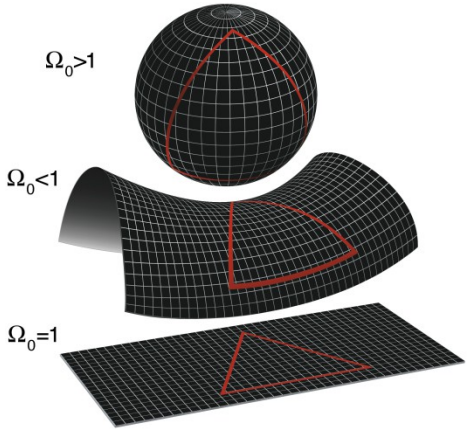


    - ✓ But he didn't know their **extreme distance**—that the "spiral nebulae" were **separate galaxies outside of our own**, and so didn't fully appreciate the cosmic significance of this discovery.

Evolution of the Universe

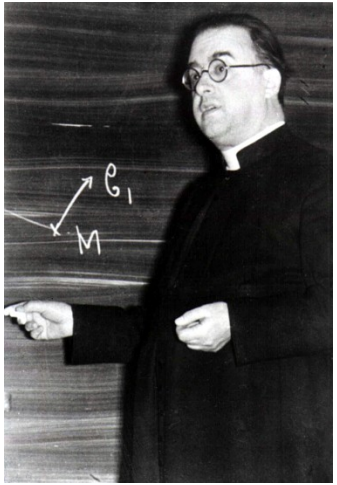
- Some possibilities regarding **evolution** of the universe:
  - Universe is **dynamic**
    - ✓ **1924: Alexander Friedmann** fully understood the cosmological implications of Einstein's general relativity, including that space is **dynamic** (*necessarily* **expands** or **contracts**)
    - ✓ …and that space can have three types of **large-scale geometry**: **open** (negative curvature), **flat** (zero curvature), or **closed** (positive curvature—the case Einstein considered)

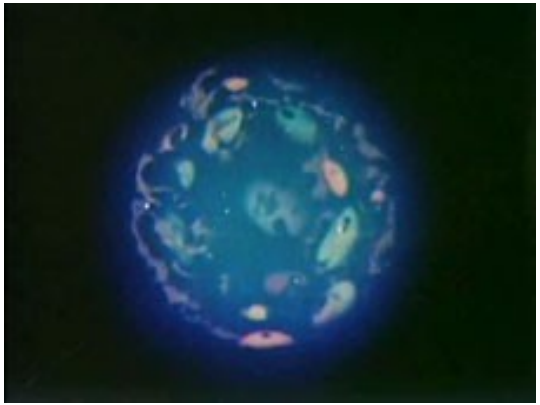




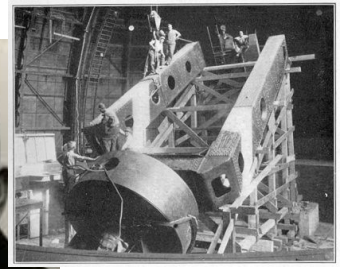
Evolution of the Universe

- Some possibilities regarding **evolution** of the universe:
  - Universe is **dynamic** and had a **beginning**
    - ✓ **1927: Georges Lemaitre** (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…



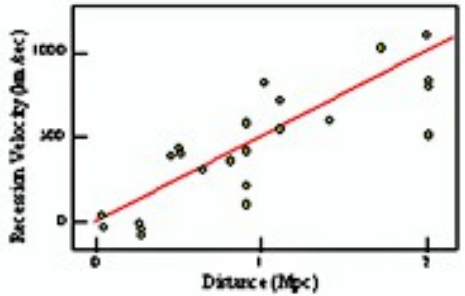


- Some possibilities regarding **evolution** of the universe:
  - Universe is **dynamic** and had a **beginning**
    - ✓ **1929: Edwin Hubble** measured the **distances** to the receding "spiral nebulae" (using **Cepheid variable stars**) and discovered that they were **not** nebulae in our own galaxy, but are actually separate galaxies outside of our own. **A universe of galaxies!**
    - ✓ 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**.



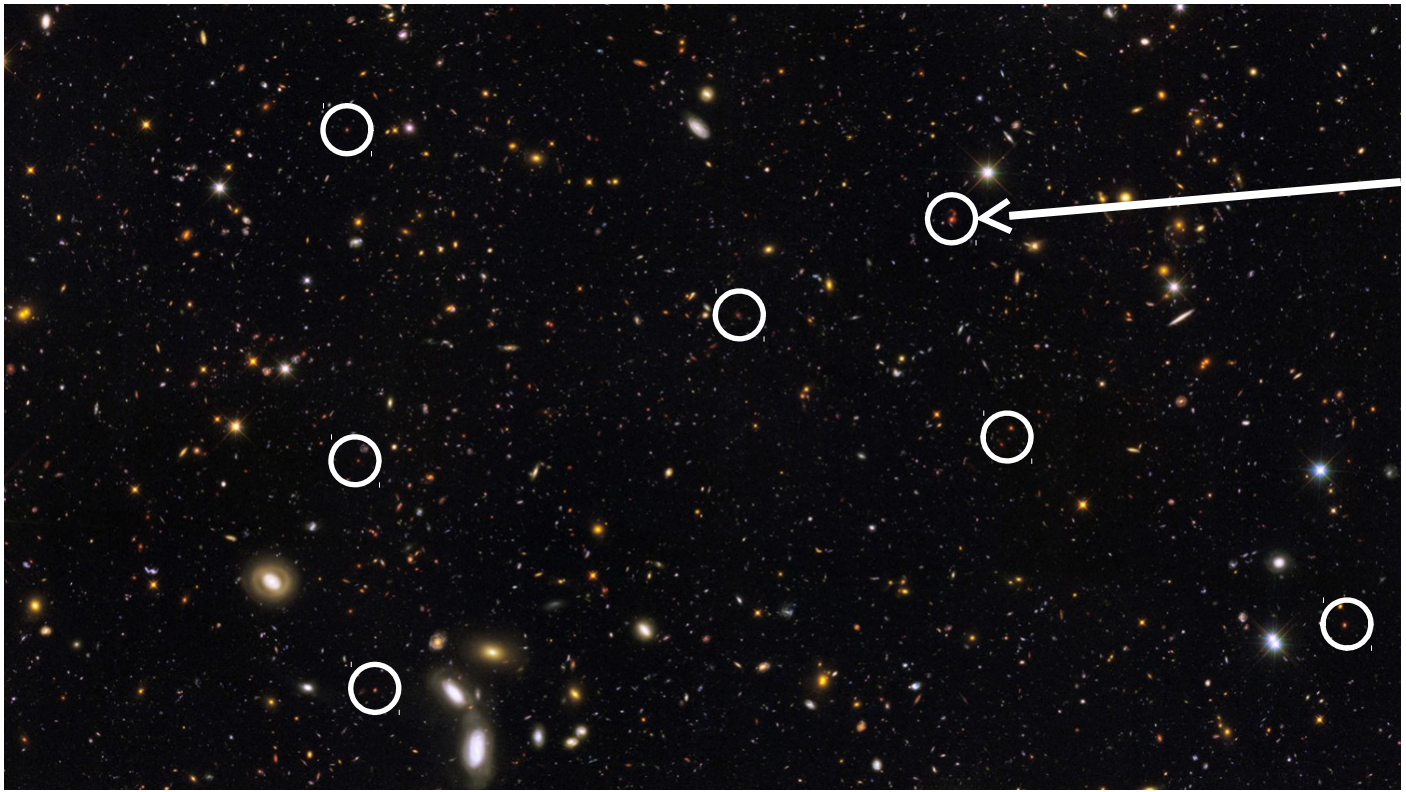
Mount Wilson 100" Hooker Telescope

Hubble's Data (1929)



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

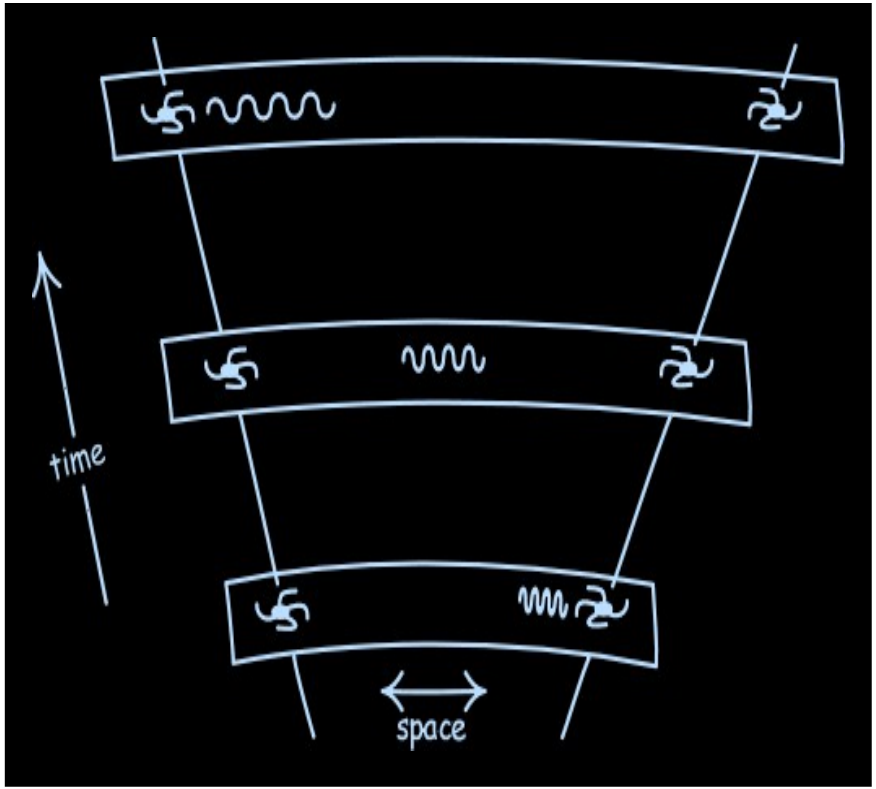
- **First:** What do we mean by **redshift**?

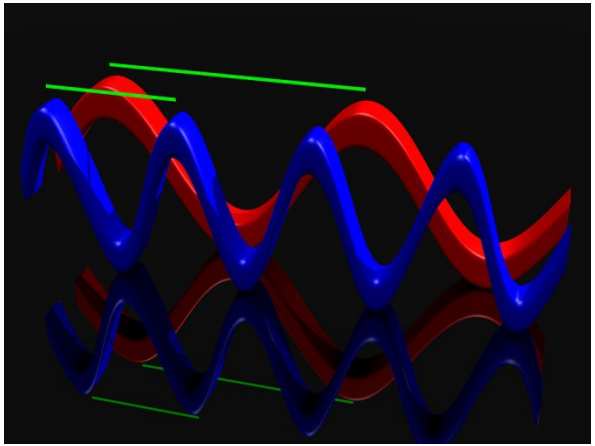


Many galaxies appear **unusually red** in colour

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

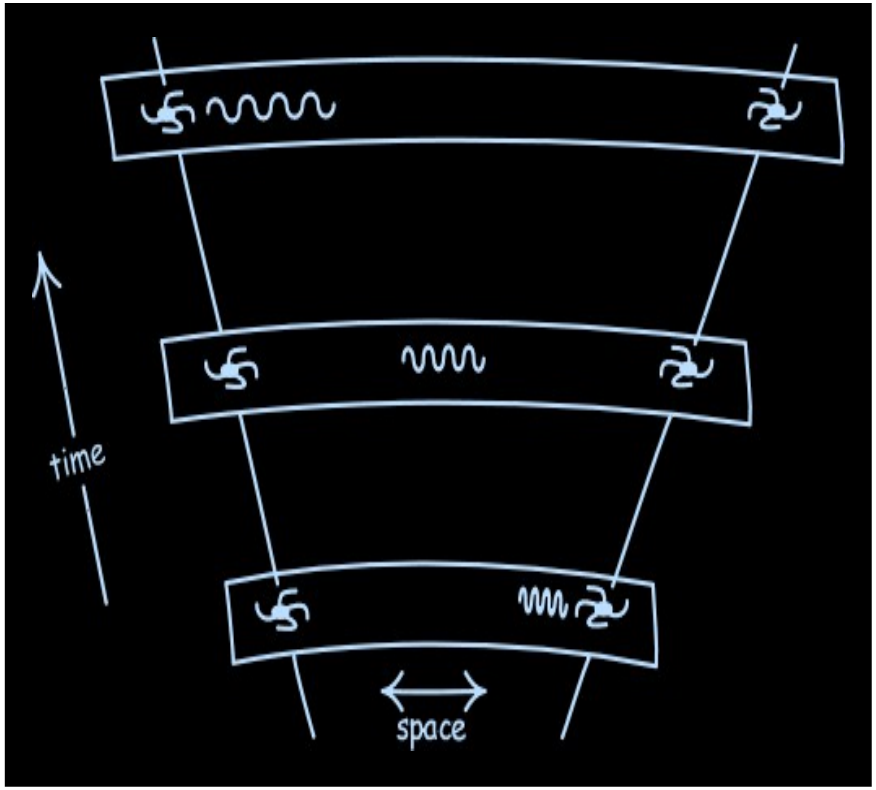
- **Second:** How can **expanding space** explain this **redshift**?

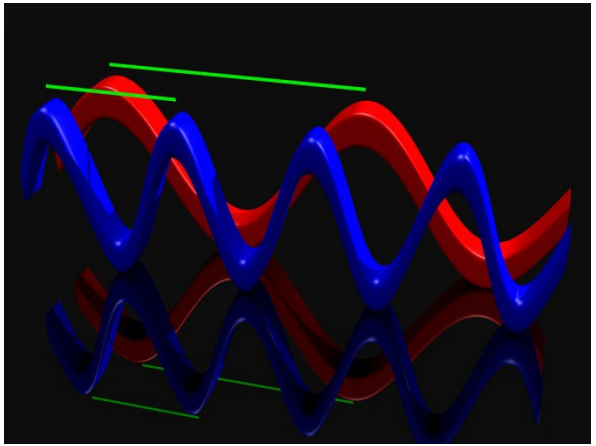




Light waves are **stretched** to **longer wavelengths** as they travel through **expanding** space (but not everything is stretched—more later!)

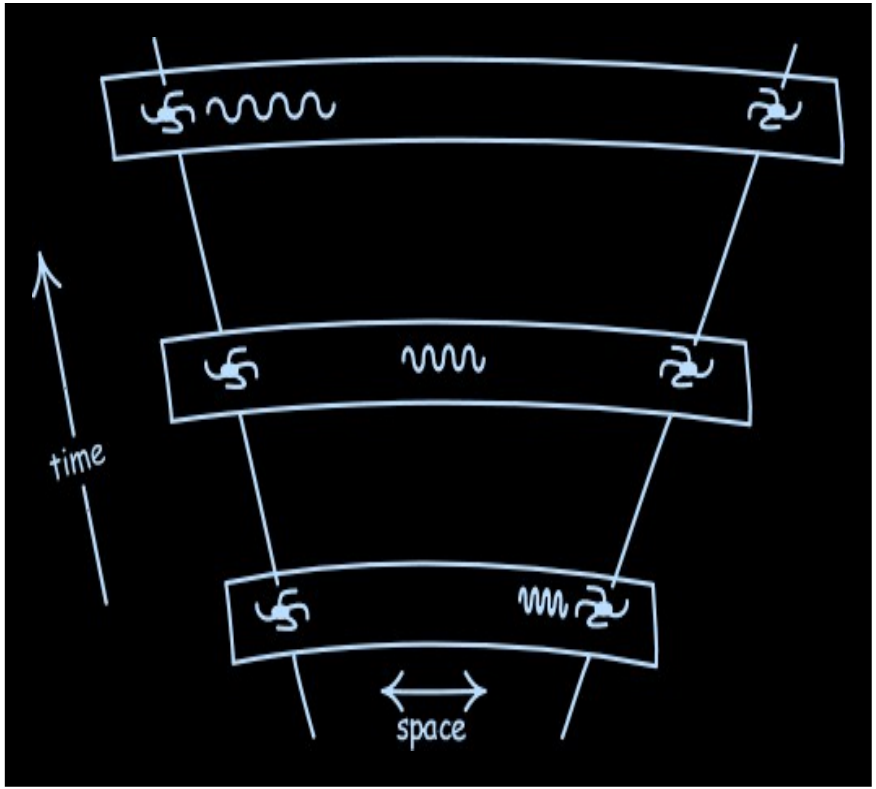
- **Third:** How can **expanding space** explain ***increased*** redshift with **increased** distance?

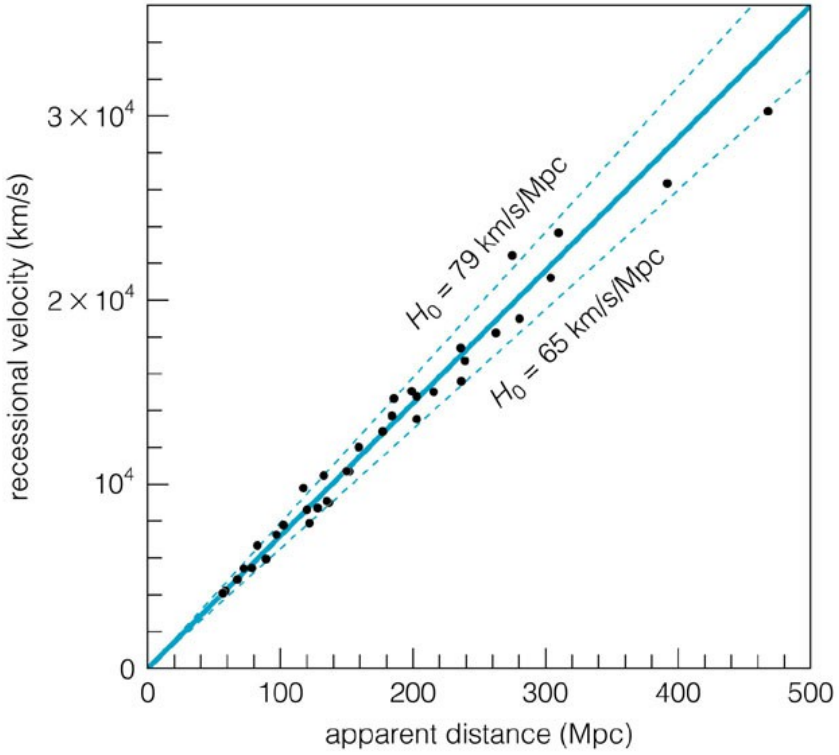




Increased distance means light waves spend a **longer time** in the expanding space, thus stretching to **ever longer wavelengths** (ever more deeply red)

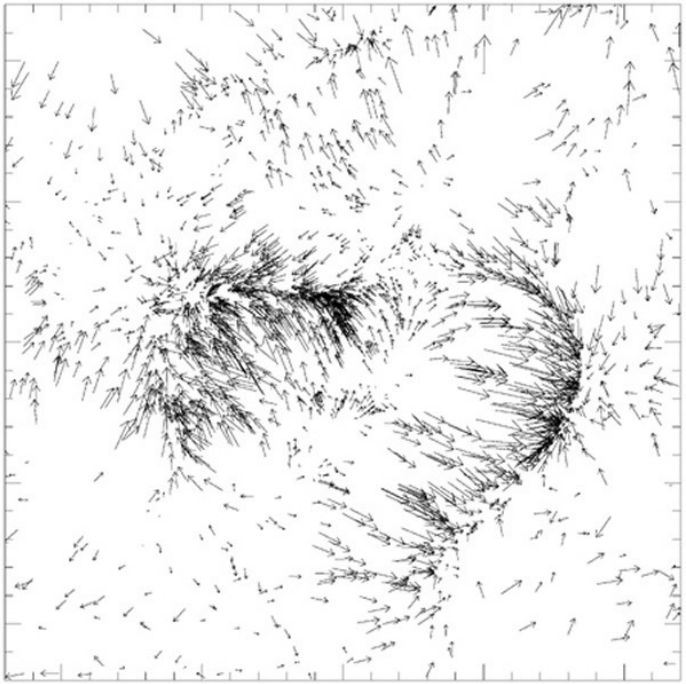
- **Hubble's Law:** Apparent recessional velocity $v = H_0 d$, $H_0 \approx 70$ (km/s) per Mpc

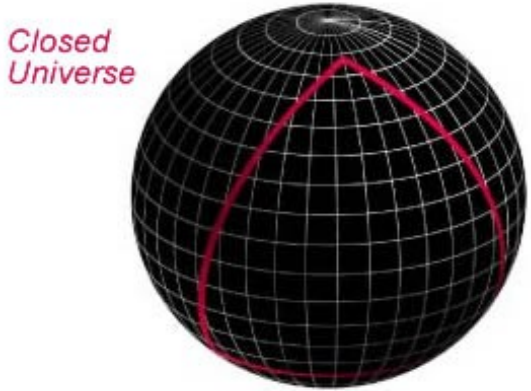


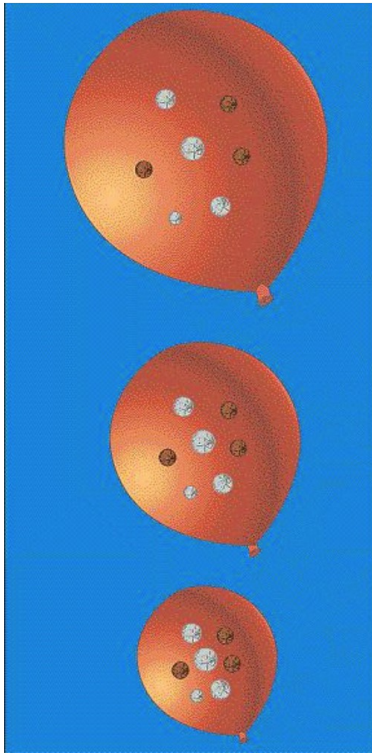


Evolution of the Universe—Expanding Space

- 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.)

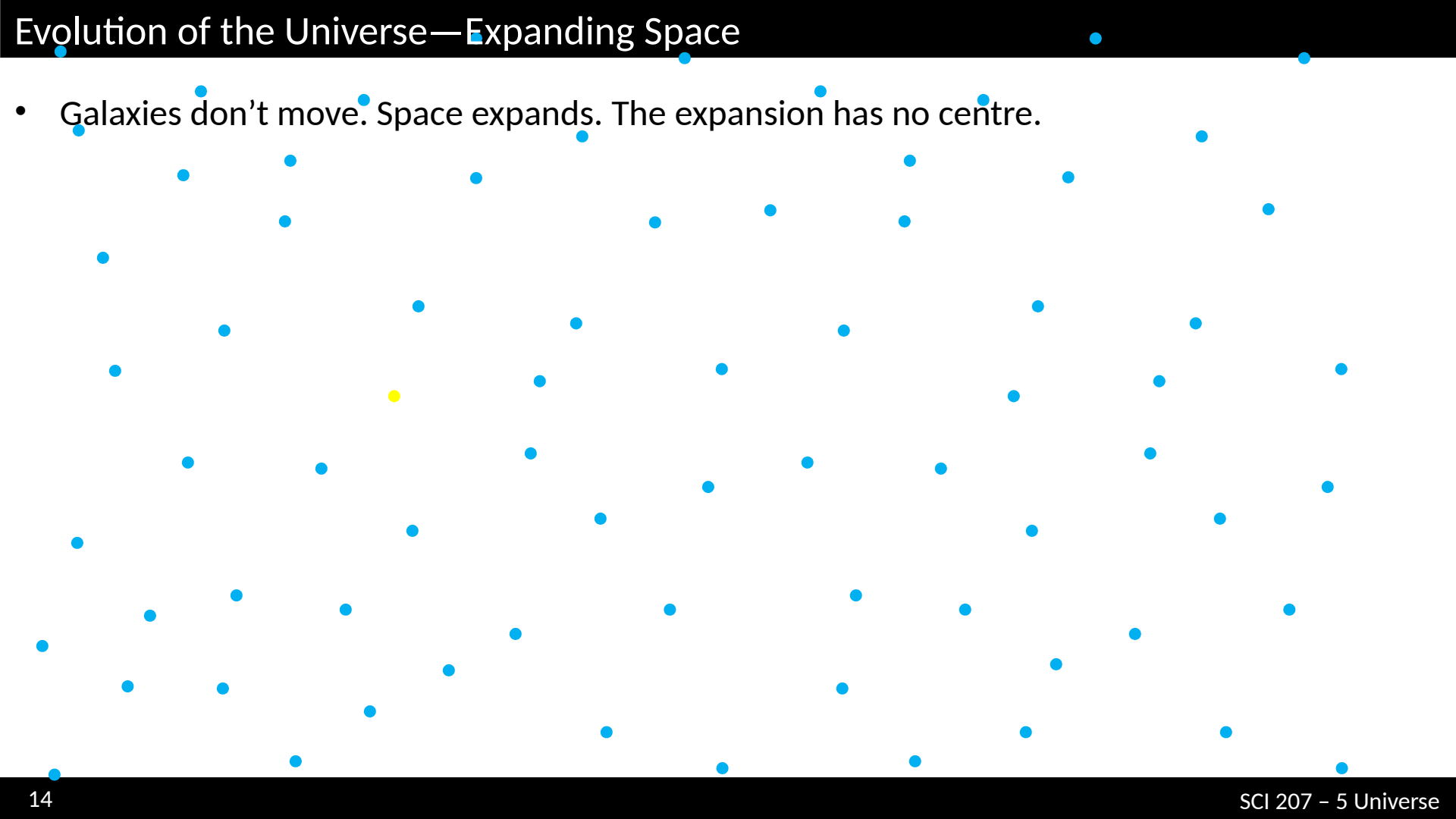






Evolution of the Universe—Expanding Space

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



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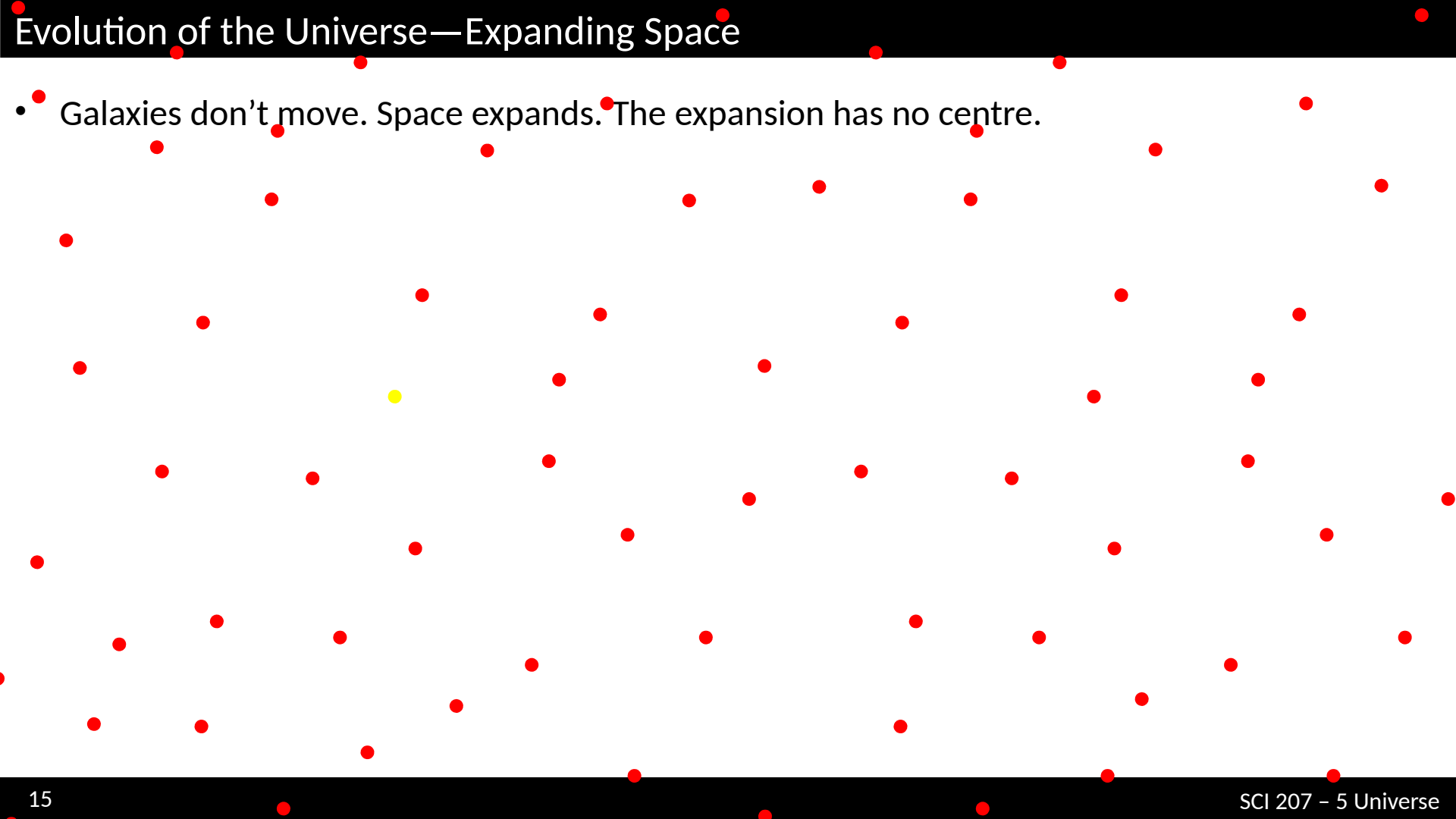

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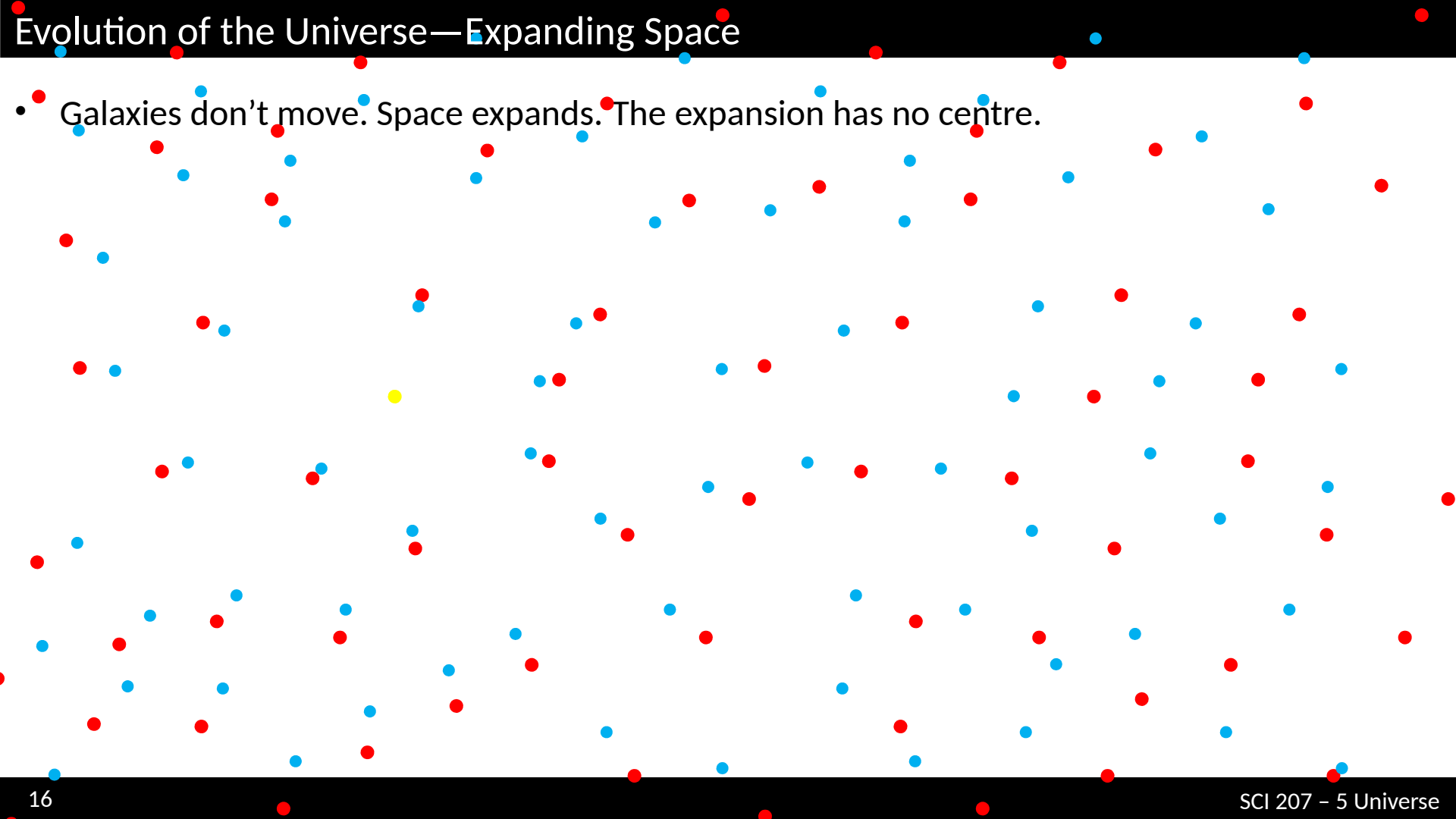

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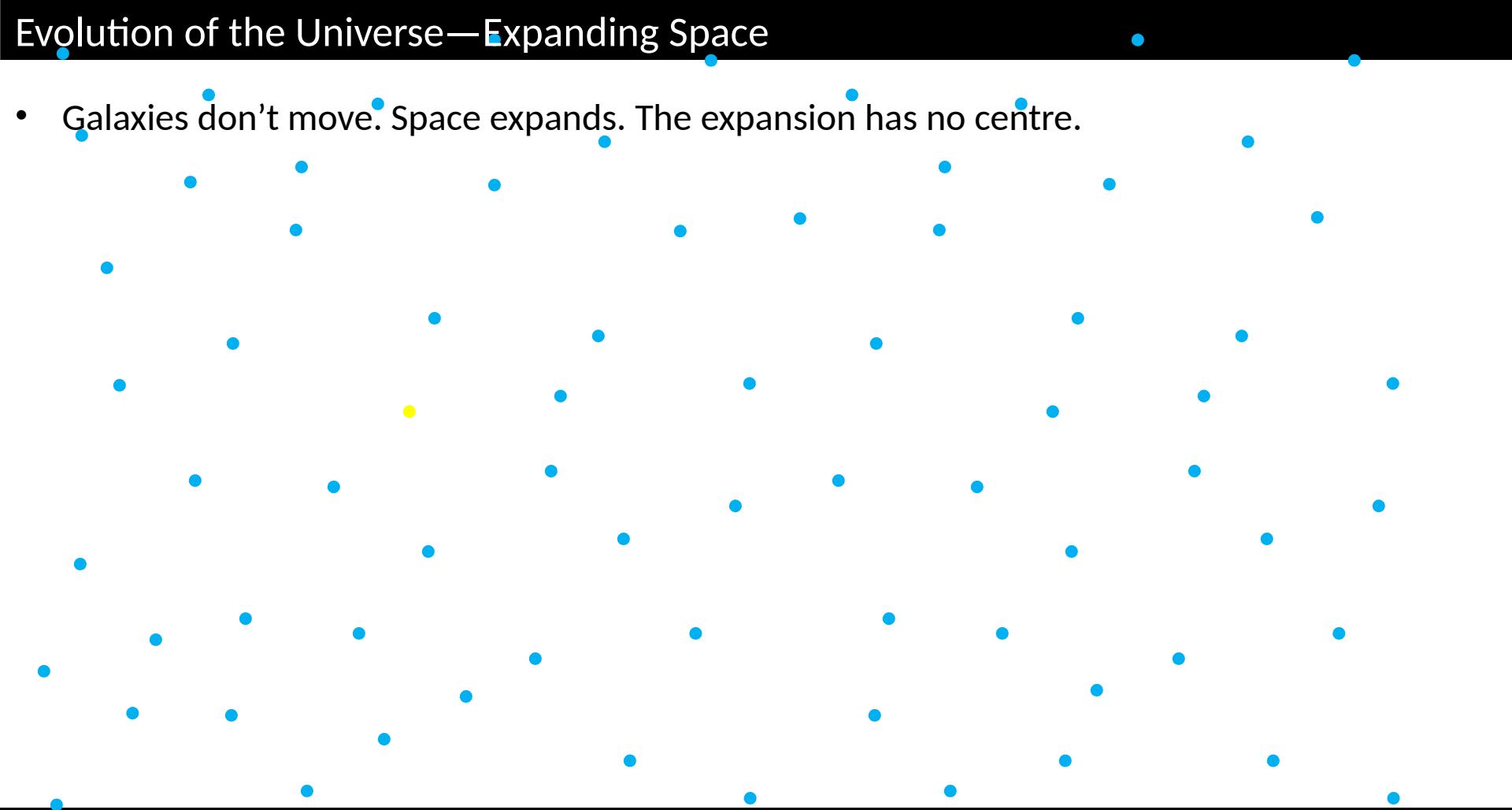

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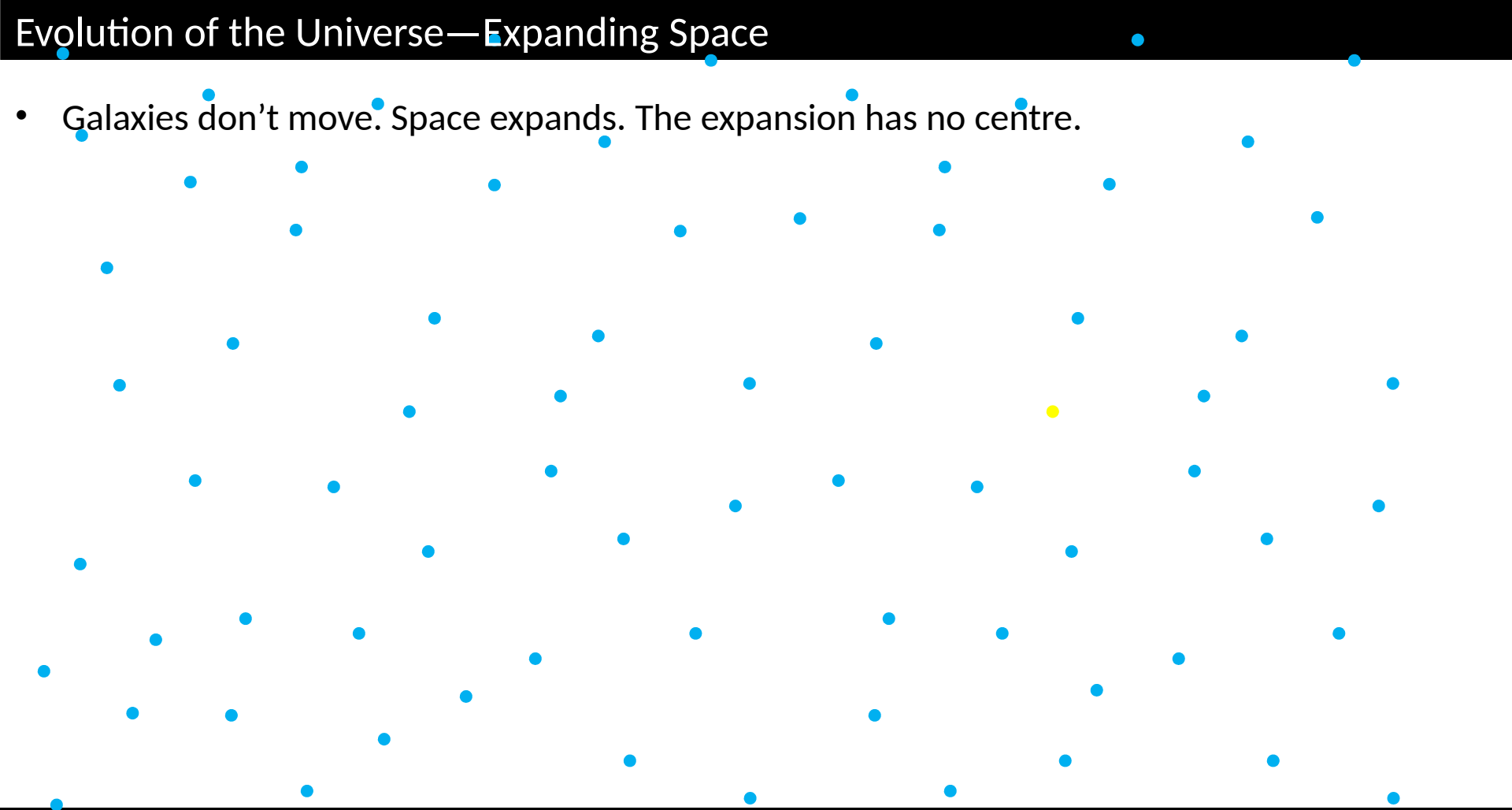

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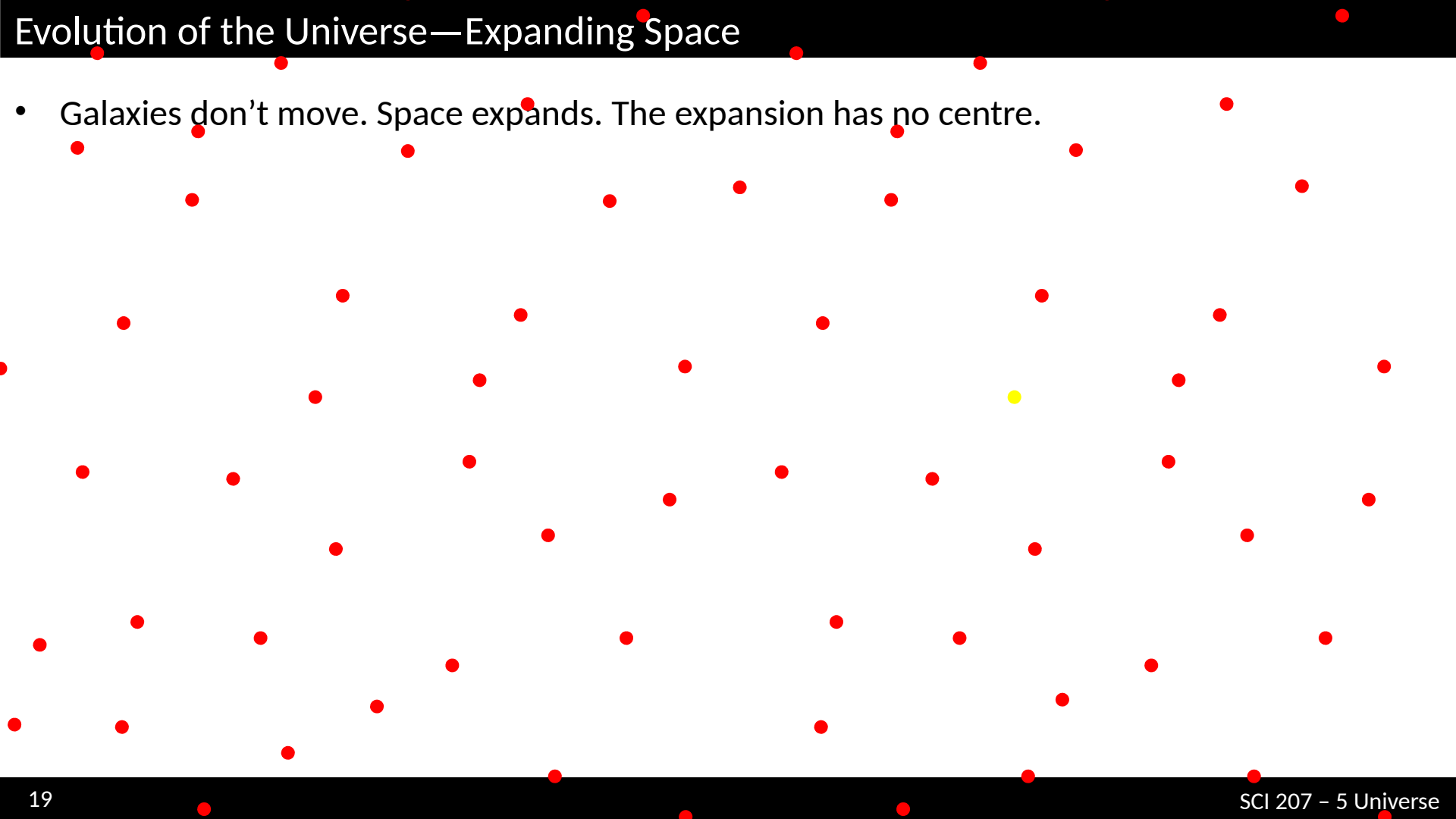

Evolution of the Universe—Expanding Space

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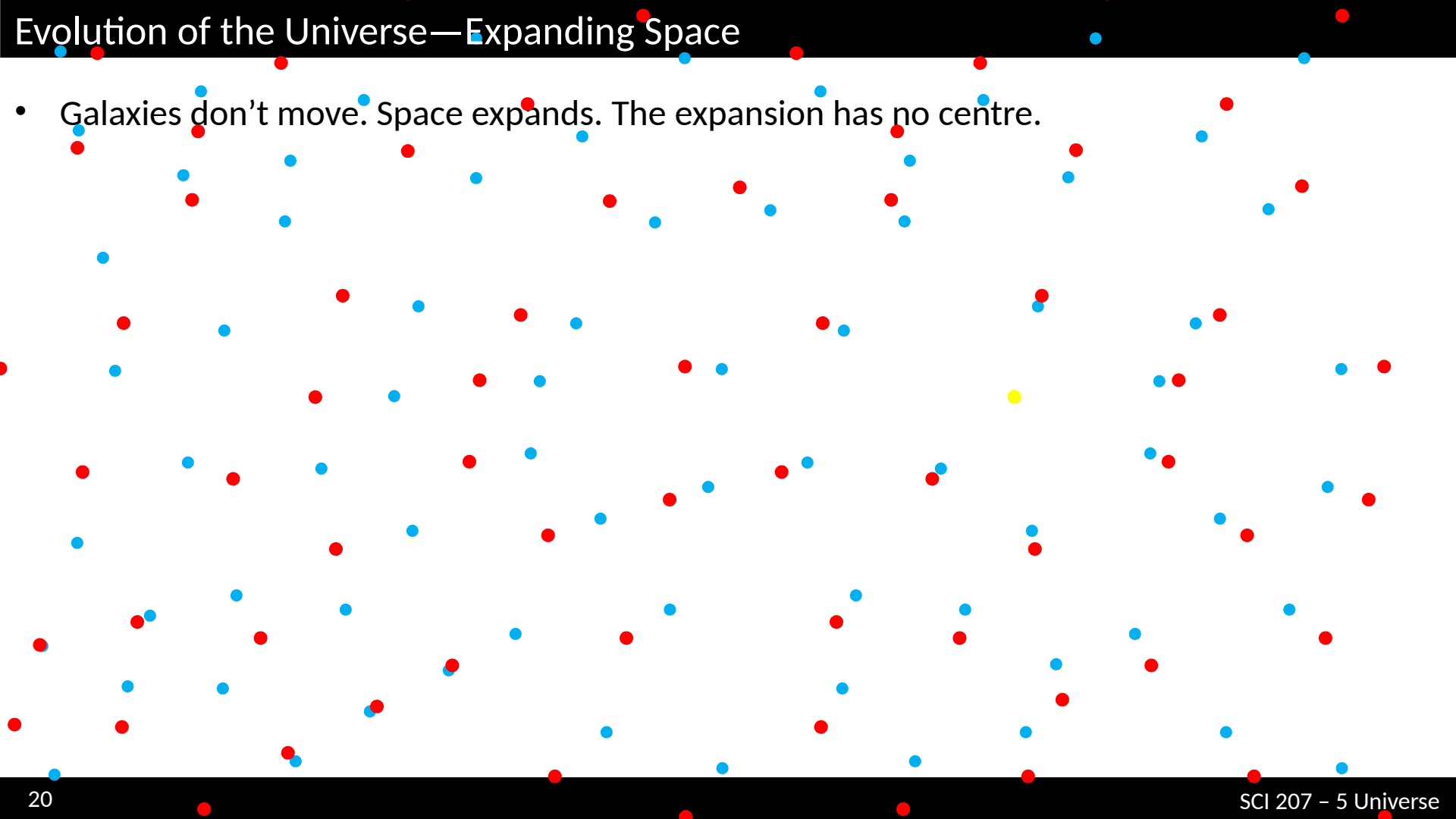
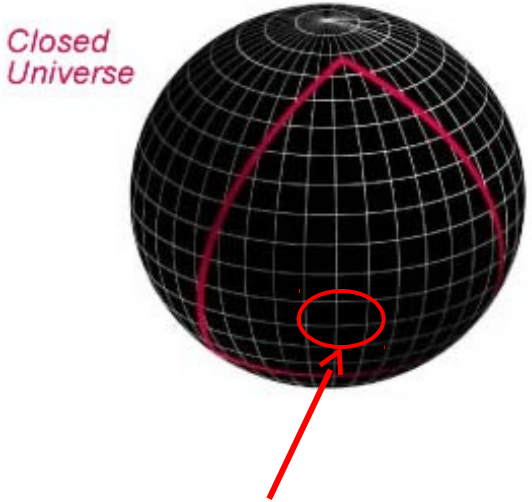


Evolution of the Universe—Expanding Space

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



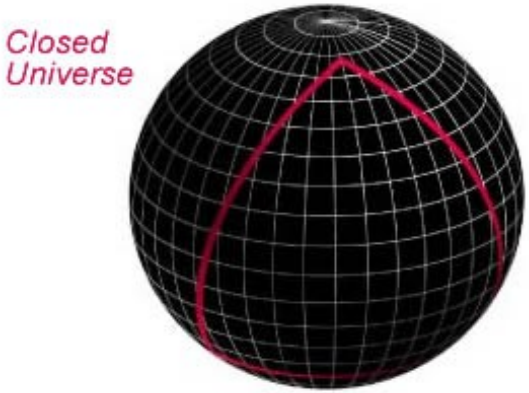
Observable Universe

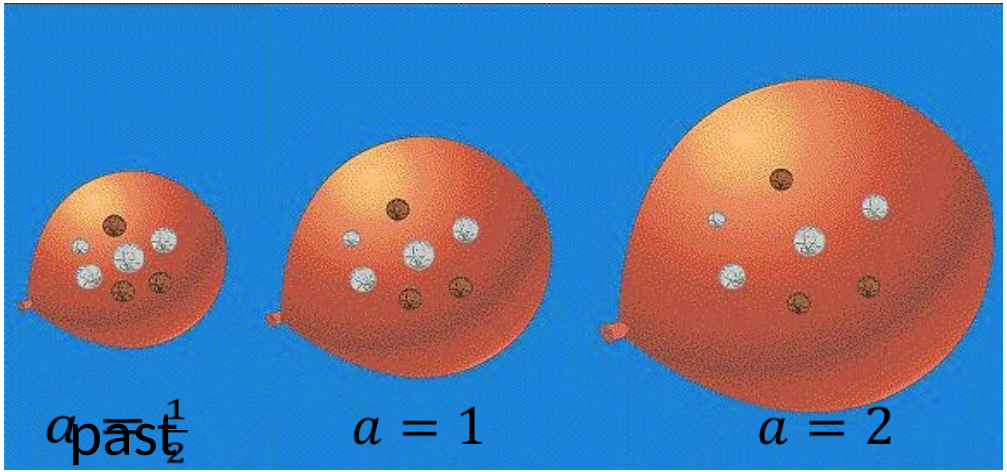
Evolution of the Universe—Expanding Space

Old Hubble Law (galaxies **moving away** from us): $v = H_0 d$

New Hubble Law (galaxies don't move; **space expands**): $H(t) = \dot{a}(t)/a(t)$

where $a(t)$ = **scale factor** of space = the size of space relative to the present





Evolution of the Universe—Expanding Space

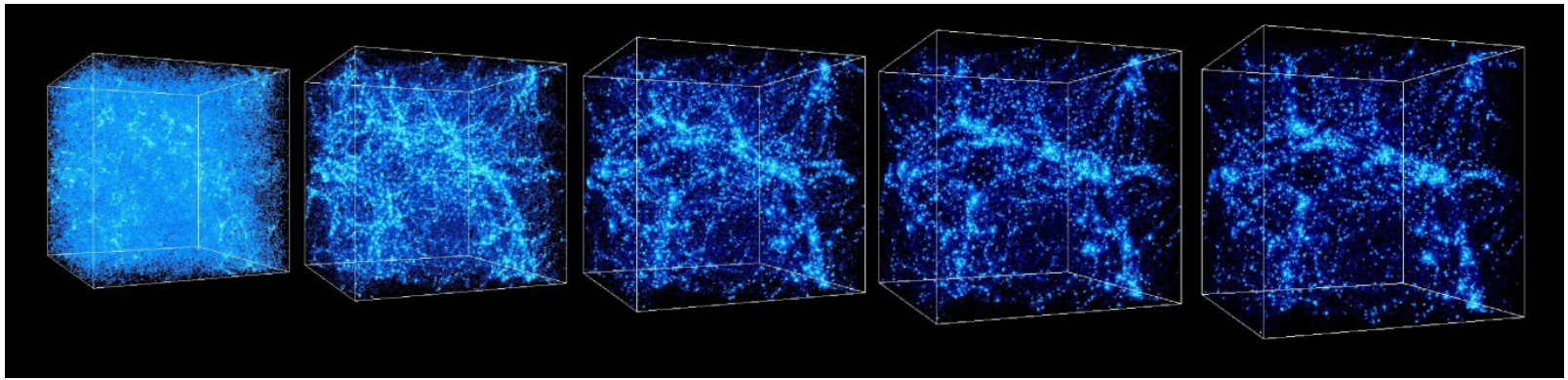
Why don’t **galaxies** (and other things) expand as **space** expands?

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.

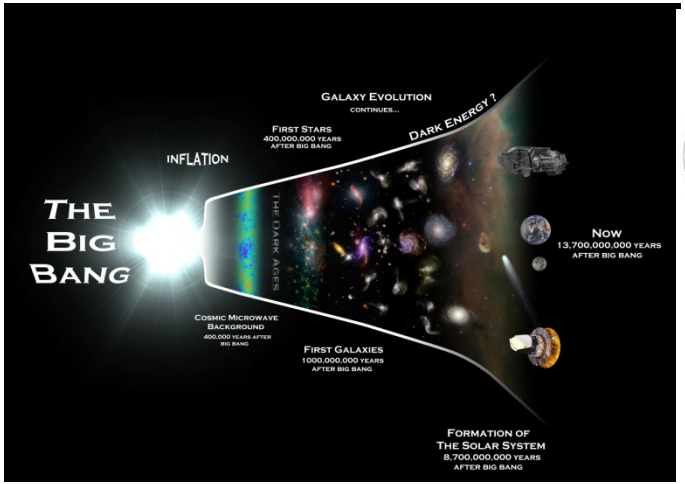


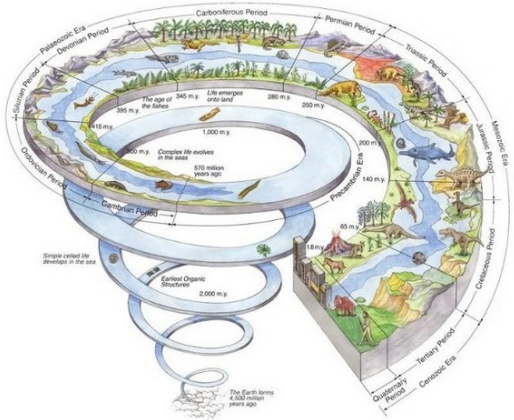
Big Bang = Everywhere Stretch

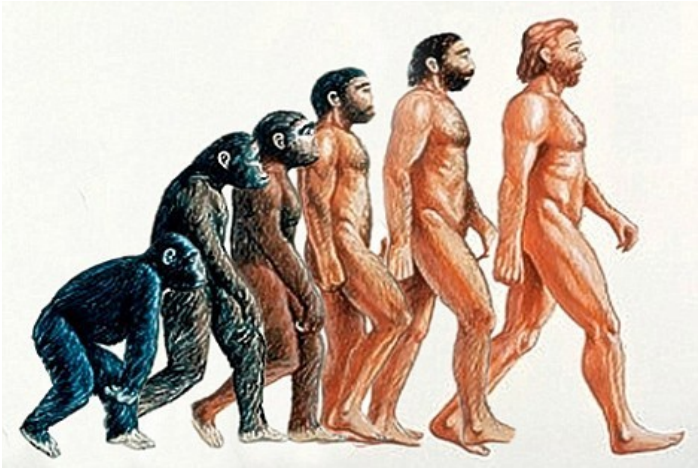
Beginning of the Universe

- 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 **<u>beginning</u>**



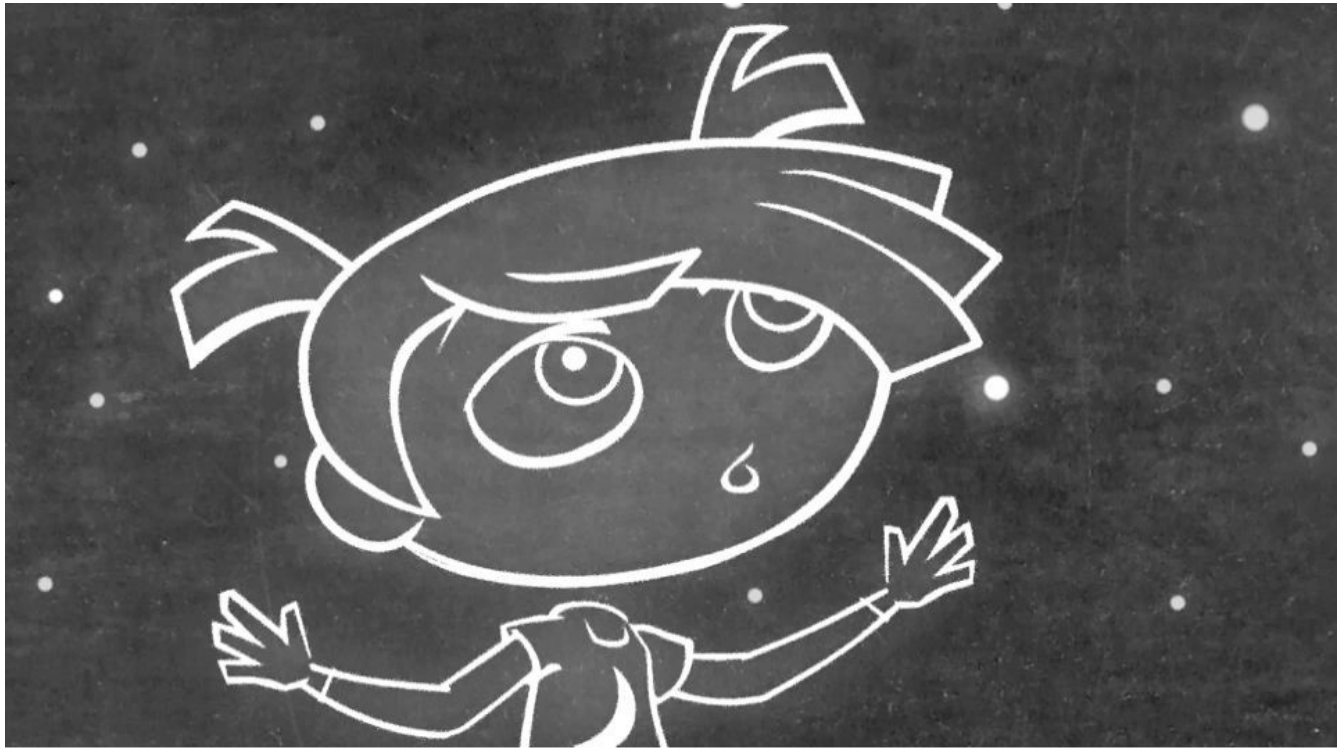




Beginning of the Universe

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

(1) Sky is dark at night



(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**

(1) Sky is dark at night

(•) Logical consequence:

Every line of sight would hit a star

Evidence for the Big Bang

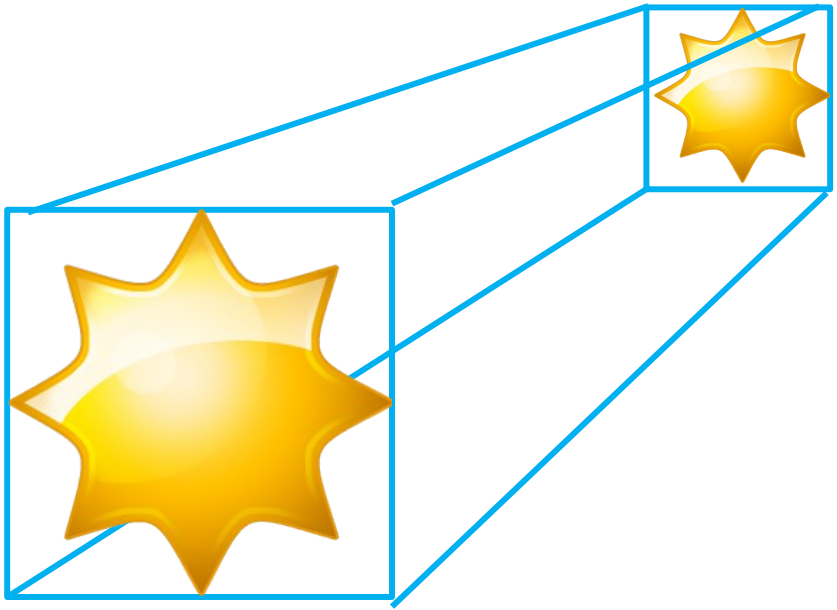
(1) Sky is dark at night

(•) Logical consequence:

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

(1) Sky is dark at night

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



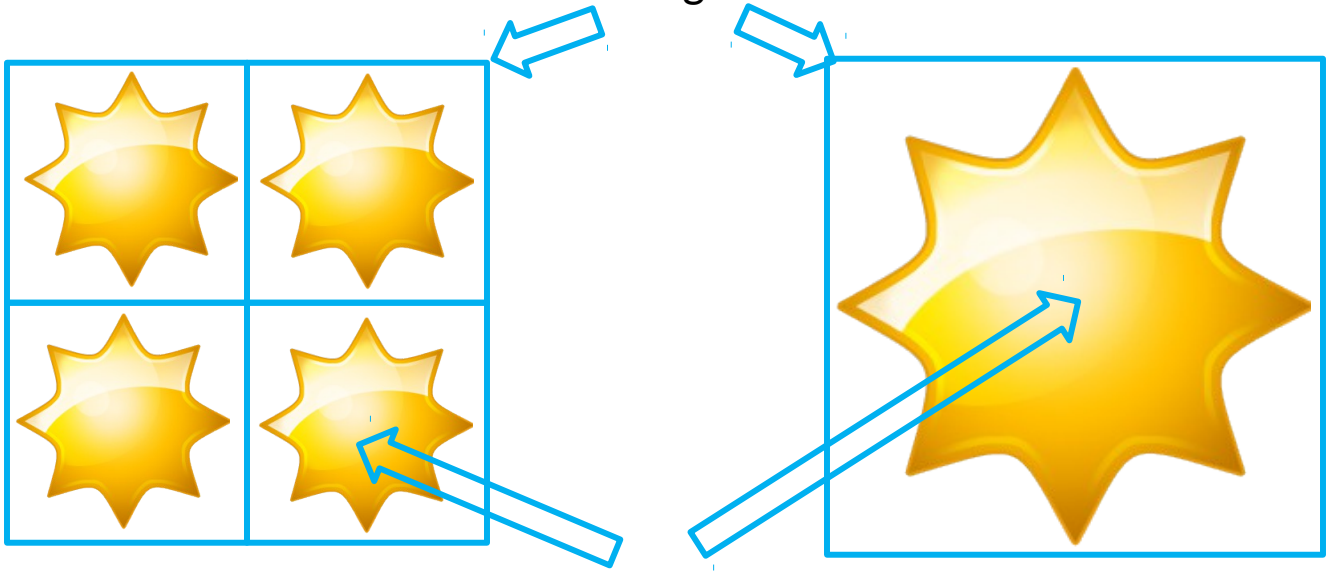
¼ the light

¼ the area

(1) Sky is dark at night

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

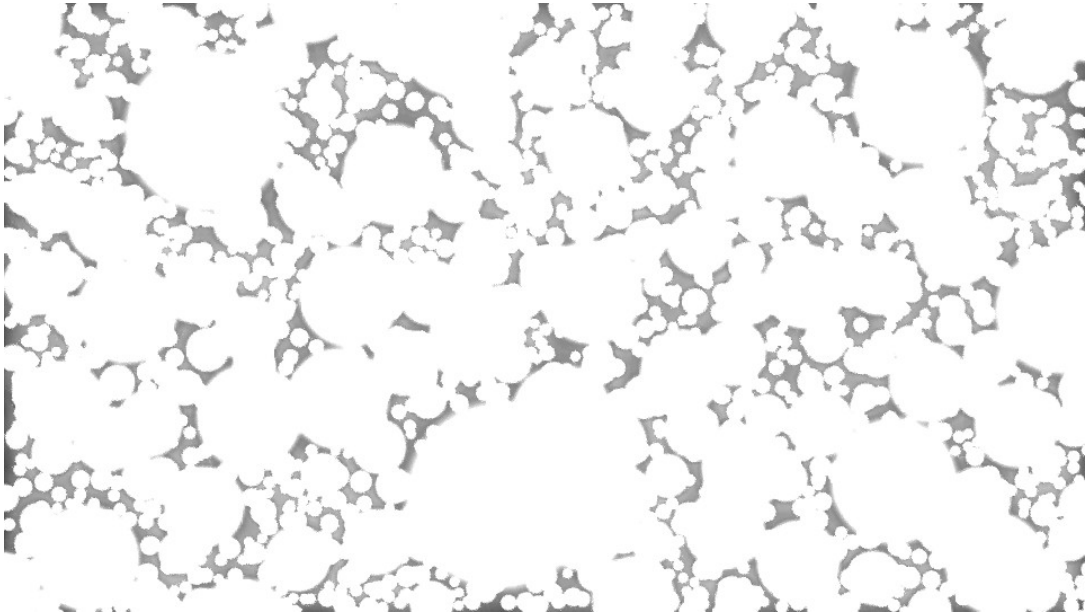
Same **total** light & area



Surfaces are **just as bright**

(1) Sky is dark at night

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



(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**

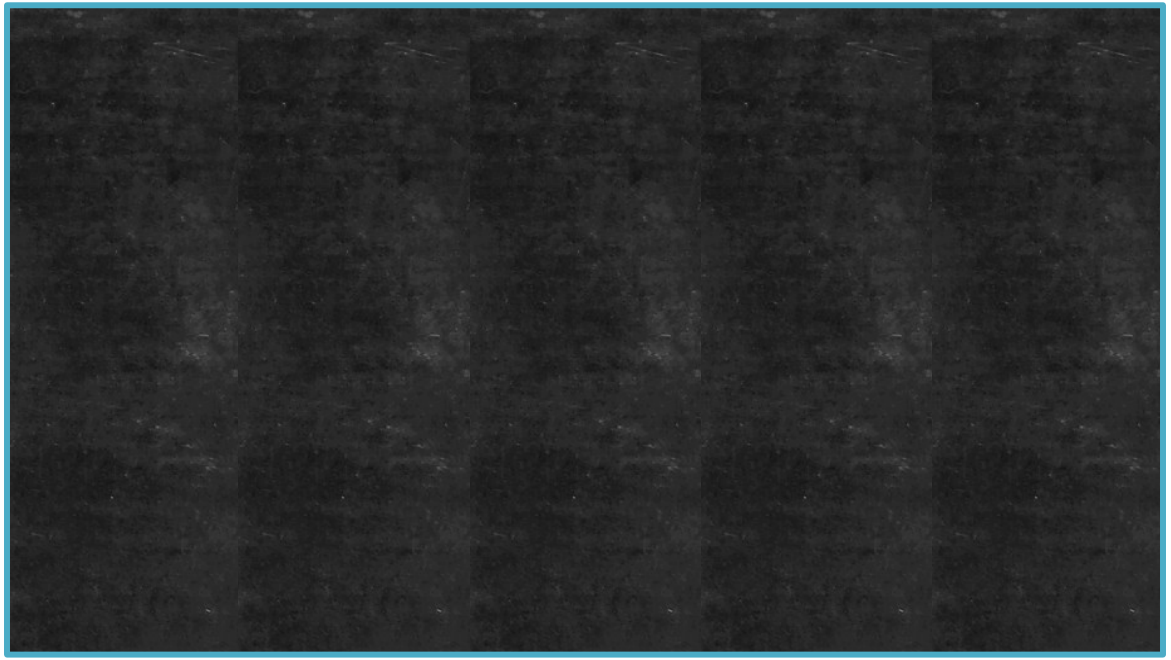
Which one(s)?

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*)

(1) Sky is dark at night

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

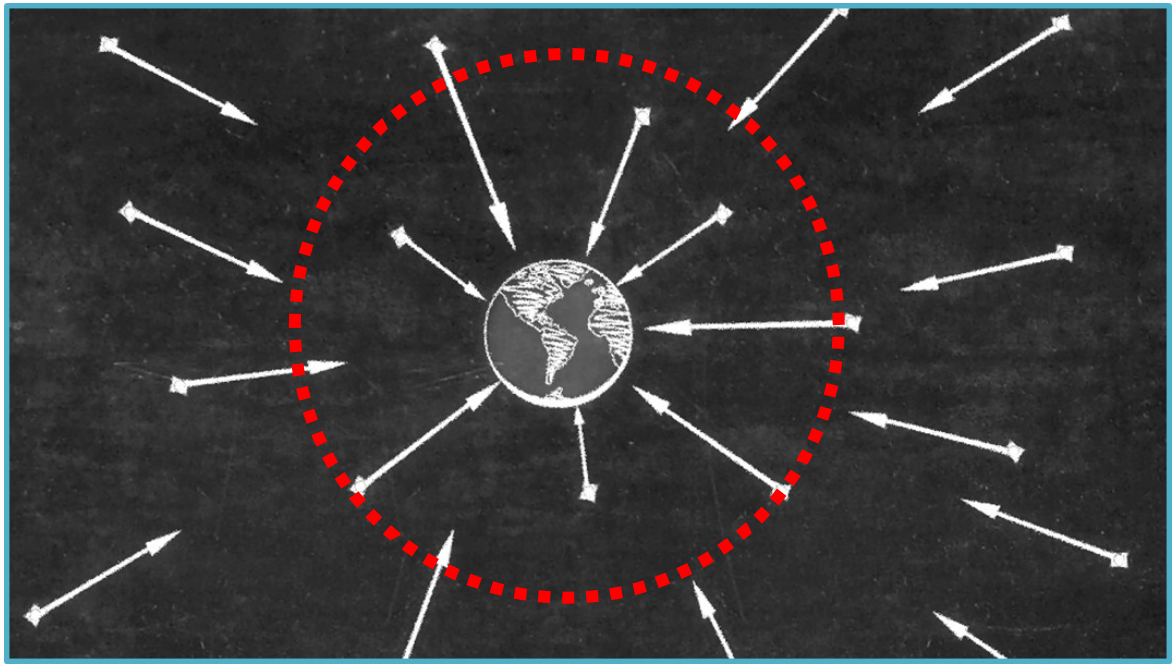


(1) Sky is dark at night

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

(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

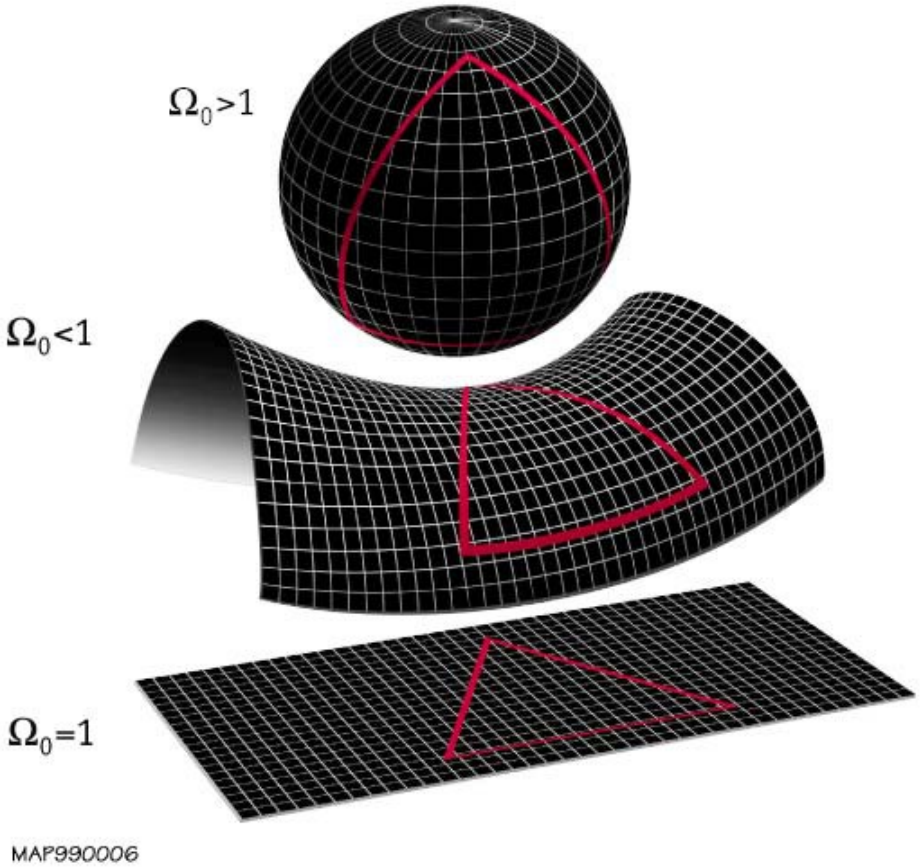
(Actually, can **replace stars** with **galaxies** and same argument applies)

(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)

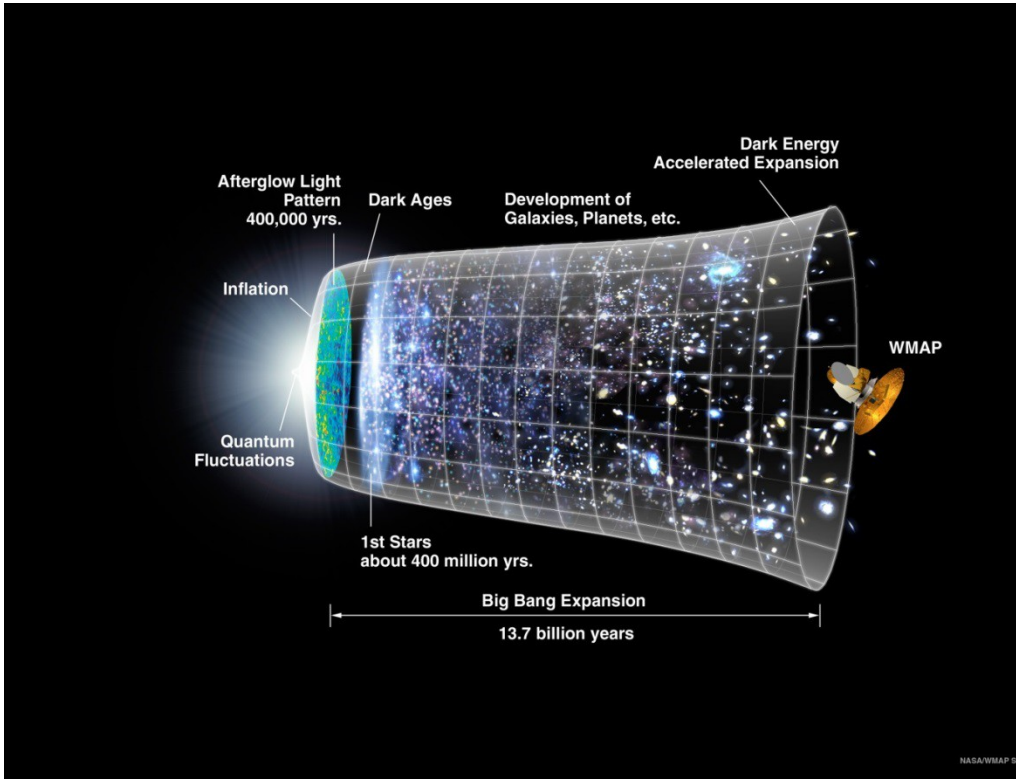


(1) Sky is dark at night

(•) 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.)



(1) Sky is dark at night