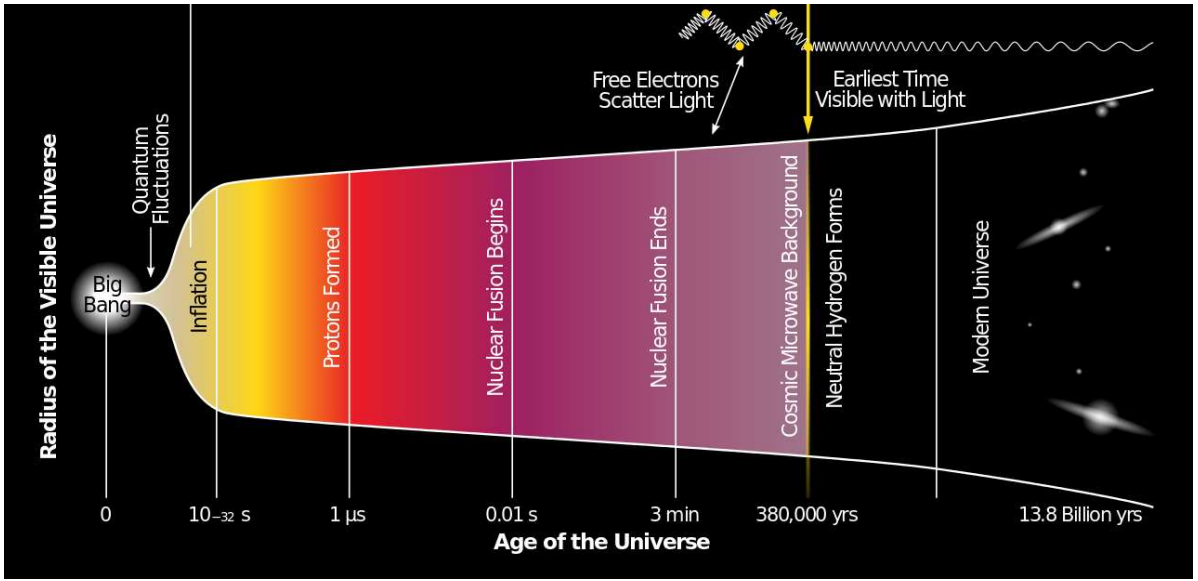
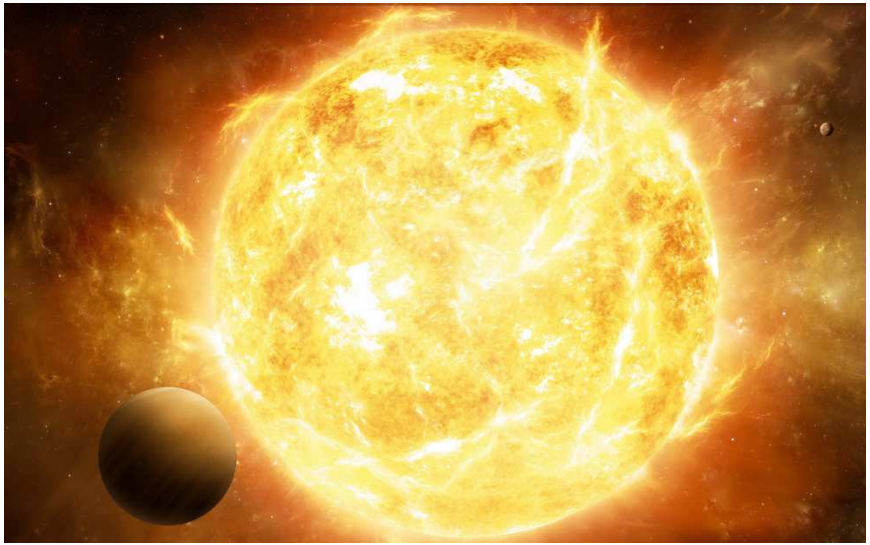
The Universe

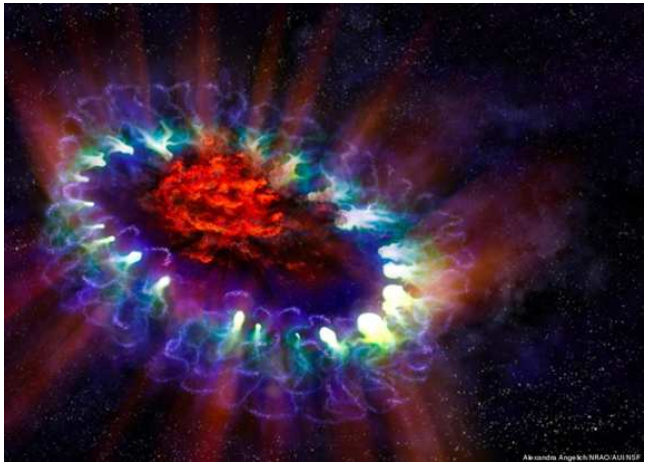
- **Life on Earth** is intimately connected with the **cosmos**:
  - **Big Bang nucleosynthesis** created the lightest atoms: mainly H (75%) & He (25%)



- **Life on Earth** is intimately connected with the **cosmos**:
  - **Thermonuclear fusion in stars** created the heavier elements up to iron, e.g., O, C, N, which (together with H) make up 98% of the mass of living organisms
    - Hydrogen (H) 59%
    - Oxygen (O) 24%
    - Carbon (C) 11%
    - Nitrogen (N) 4%
    - Others such as phosphorus (P) and sulphur (S) 2% combined
    - Also metals: Iron (Fe) needed for blood to carry oxygen; Magnesium (Mg) needed for plants to photosynthesize, etc.

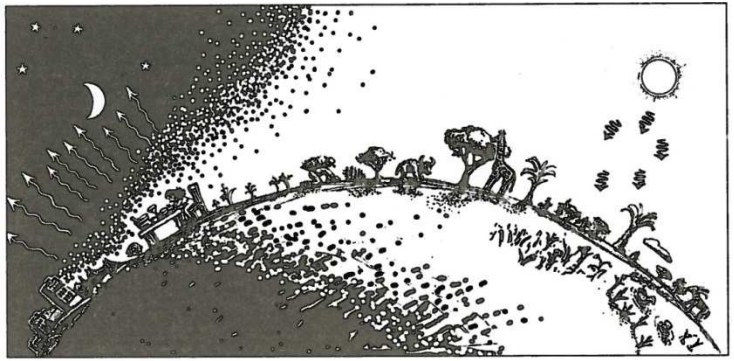


- **Life on Earth** is intimately connected with the **cosmos**:
  - **Stellar supernovae** created the elements **heavier than iron**, e.g., radioactive elements that heat the Earth's interior and help keep it geologically alive (necessary for life)



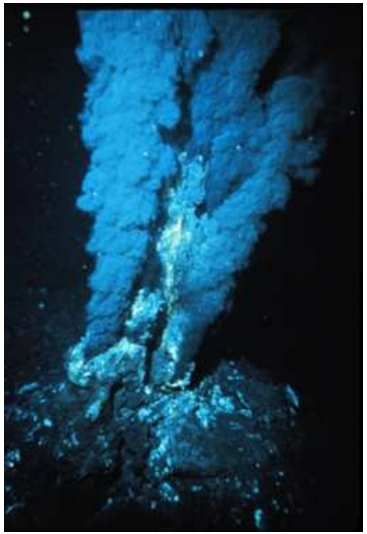
  - A significant fraction of the **organic molecules** on Earth were formed in **dusty interstellar clouds**, and eventually rained down on the Earth during the Late Heavy Bombardment

- **Life on Earth** is intimately connected with the **cosmos**:
  - But perhaps most crucially, the **universe** has provided ample sources of **free energy:**
    - ✓ The **Sun:**



  - **Low entropy** energy from the Sun is re-radiated into space as **high entropy** energy
  - The Earth is **exporting** much more entropy than it **receives**: this is the entropy **generated** by the maintenance of all the **low entropy (ordered) structures** on the Earth…like hurricanes, the water cycle, solar temperature gradients, and **life** itself

- **Life on Earth** is intimately connected with the **cosmos**:
  - But perhaps most crucially, the **universe** has provided ample sources of **free energy:**
    - ✓ The **Earth:**



  - chemical and thermal **disequilibrium**

- **Life on Earth** is intimately connected with the **cosmos**:
    - Life depends on the universe *itself* being “alive”:
      Disequilibrium, Dissipation, Gradients, Flows, etc.

- Thus, **big questions** we ask about **ourselves:**
  - Who are we? [What is the nature of life?]
  - Where do we come from? [How did life evolve?]
  - Why are we here? [Why is there life? What is its origin?]

Introduction

- …are **intimately connected** with big questions we ask about the **universe as a whole**:
    - What is the **nature** of the universe? [Size, composition, structure, role of gravity]
    - How did the universe **evolve**? [Expansion, cooling, gravitational clumping]
    - What is its **origin**? *Why something vs. nothing*? [Big Bang, inflation, other origin ideas]

Answering such questions about the universe may inform similar questions about ourselves…

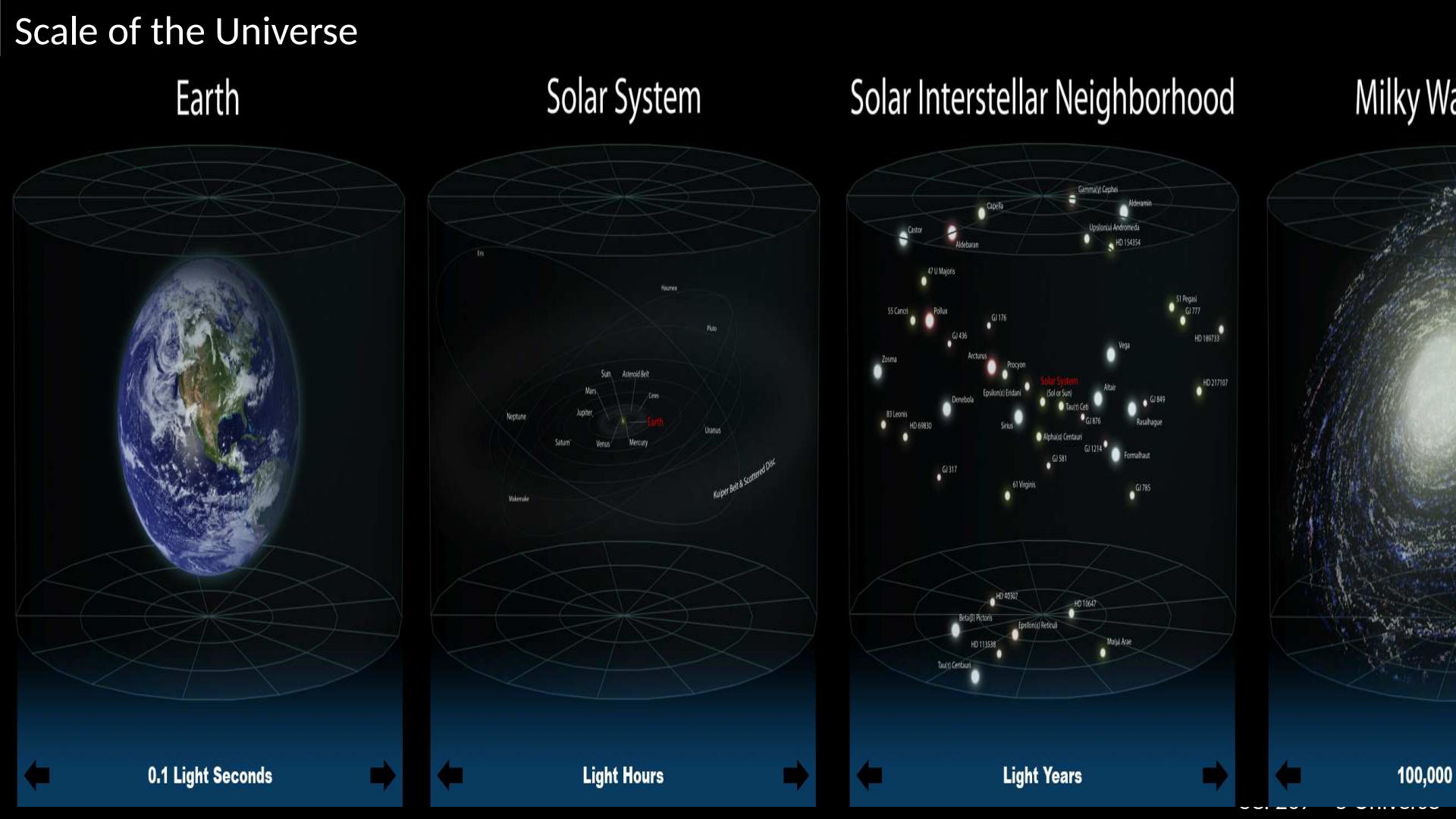
- In particular, we will address the crucial **free energy** question we asked earlier:
    - Why is the Sun a **hot spot** in an otherwise **cold sky**?
        - ✓ **Hot spot** part: What is the origin of the Sun's **free energy**? How can it be in such a relatively **low entropy** state?
        - ✓ We will trace the source of the Sun's free energy back through ever lower and lower entropy states of the universe, all the way back to the mysterious relatively very **low entropy** state of the universe at the **Big Bang**.

- In particular, we will address the crucial **free energy** question we asked earlier:
    - Why is the Sun a **hot spot** in an otherwise **cold sky**?
        - ✓ **Cold sky** part: Equivalently, why is it **dark at night**? We will see that the darkness of the night sky is intimately connected to the fact that our universe is not infinitely old, but of **finite age**—it had a **beginning**, that is *also* **deeply mysterious!**
- **Thus**: The fact that life exists at all is *intimately intertwined* with two of the greatest mysteries of the universe itself: *its* **origin**, in such a **low entropy** state.

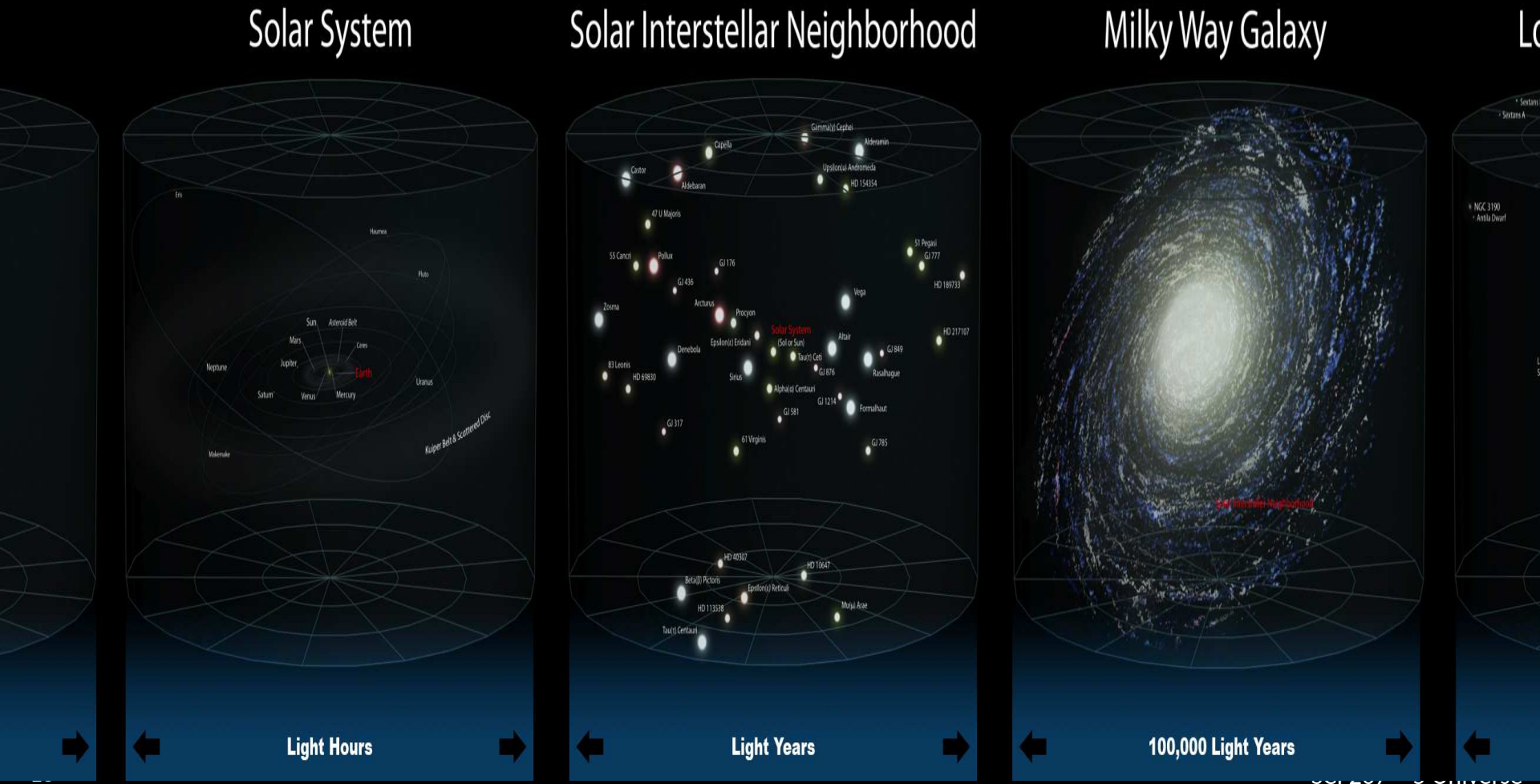
Scale of the Universe

Let’s first think about the **size** of the universe

Scale of the Universe



Scale of the Universe

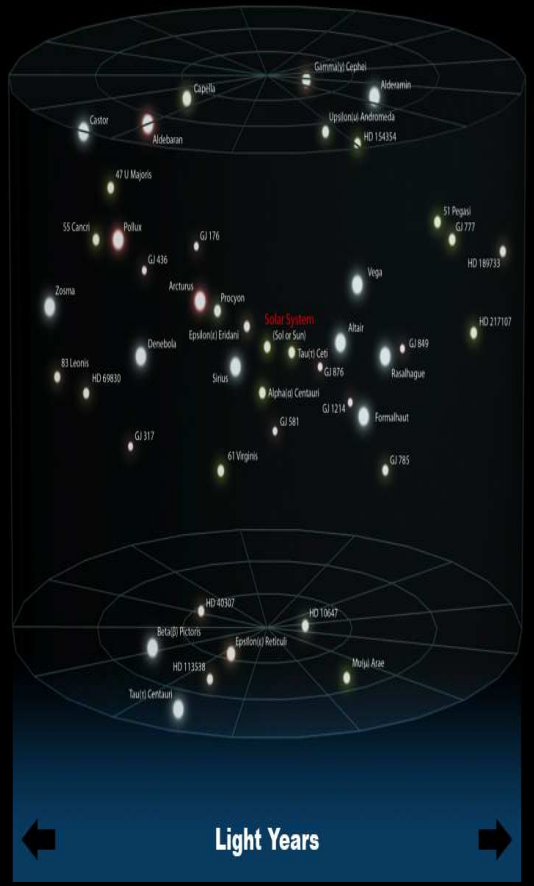


Scale of the Universe

ystem

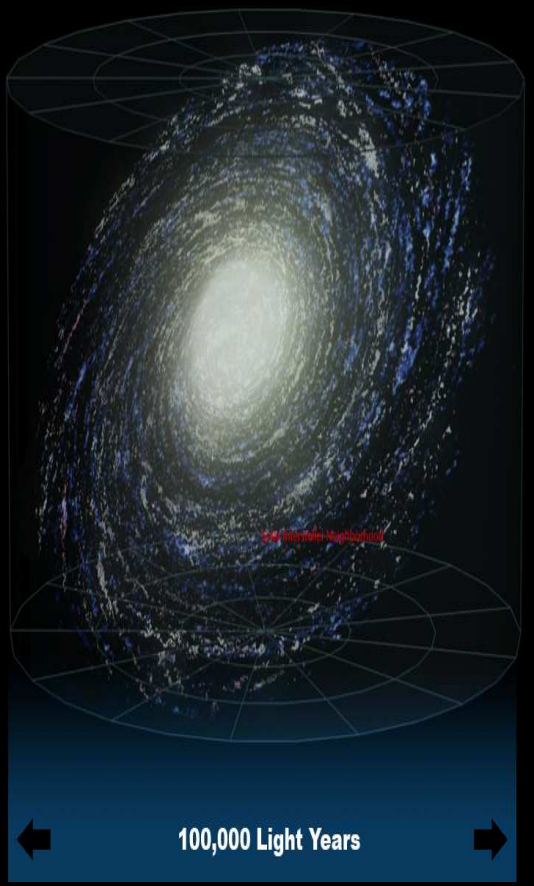
hours

Solar Interstellar Neighborhood



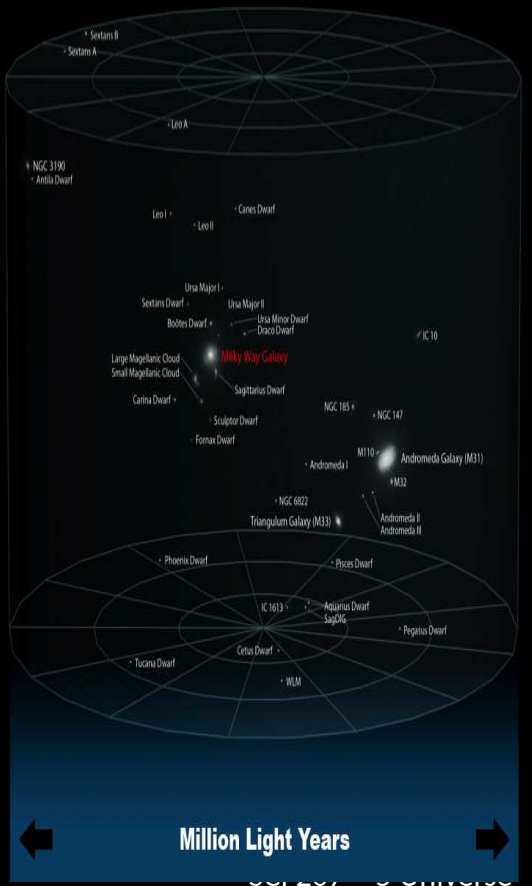
Light Years

Milky Way Galaxy



100,000 Light Years

Local Galactic Group



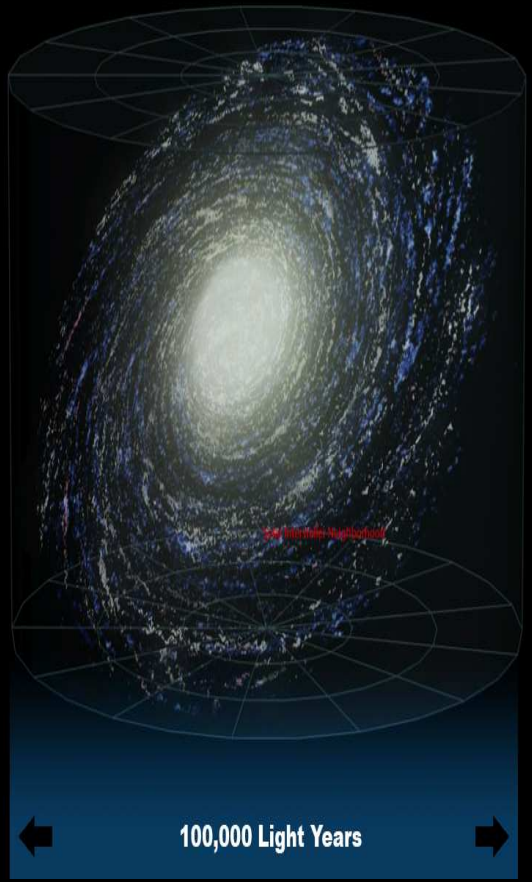
Million Light Years

Scale of the Universe

terstellar Neighborhood

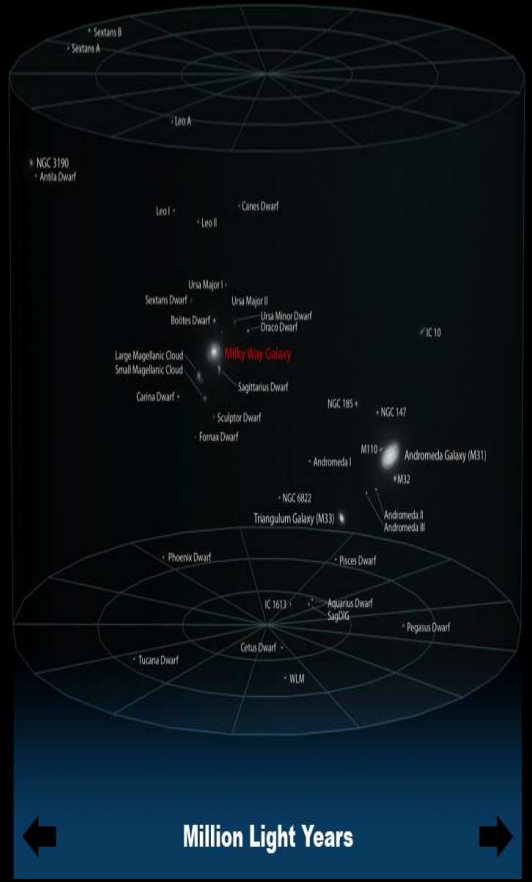
Light Years

Milky Way Galaxy



100,000 Light Years

Local Galactic Group

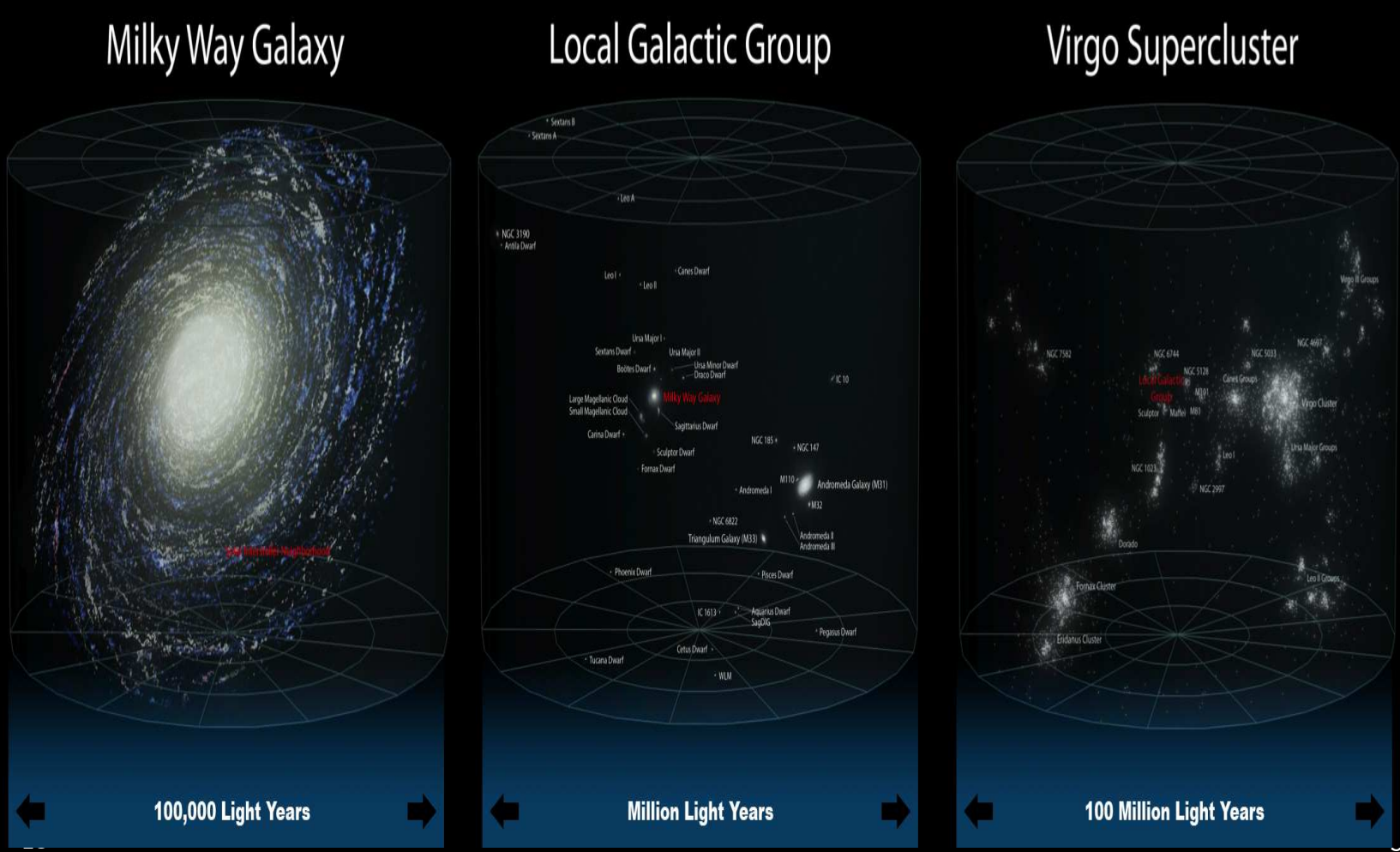


Million Light Years

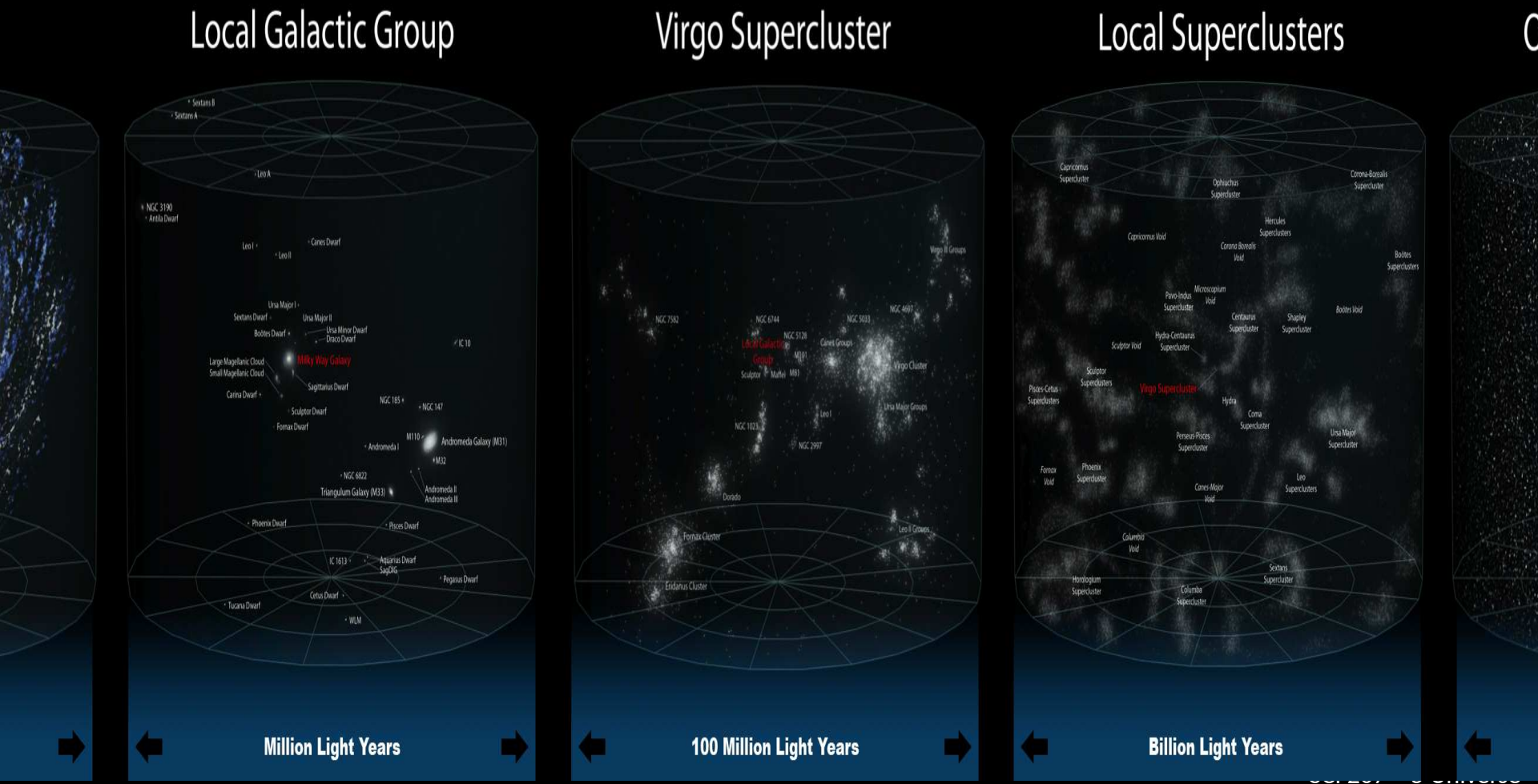
Virgo Supercluste

100 Million Light Years

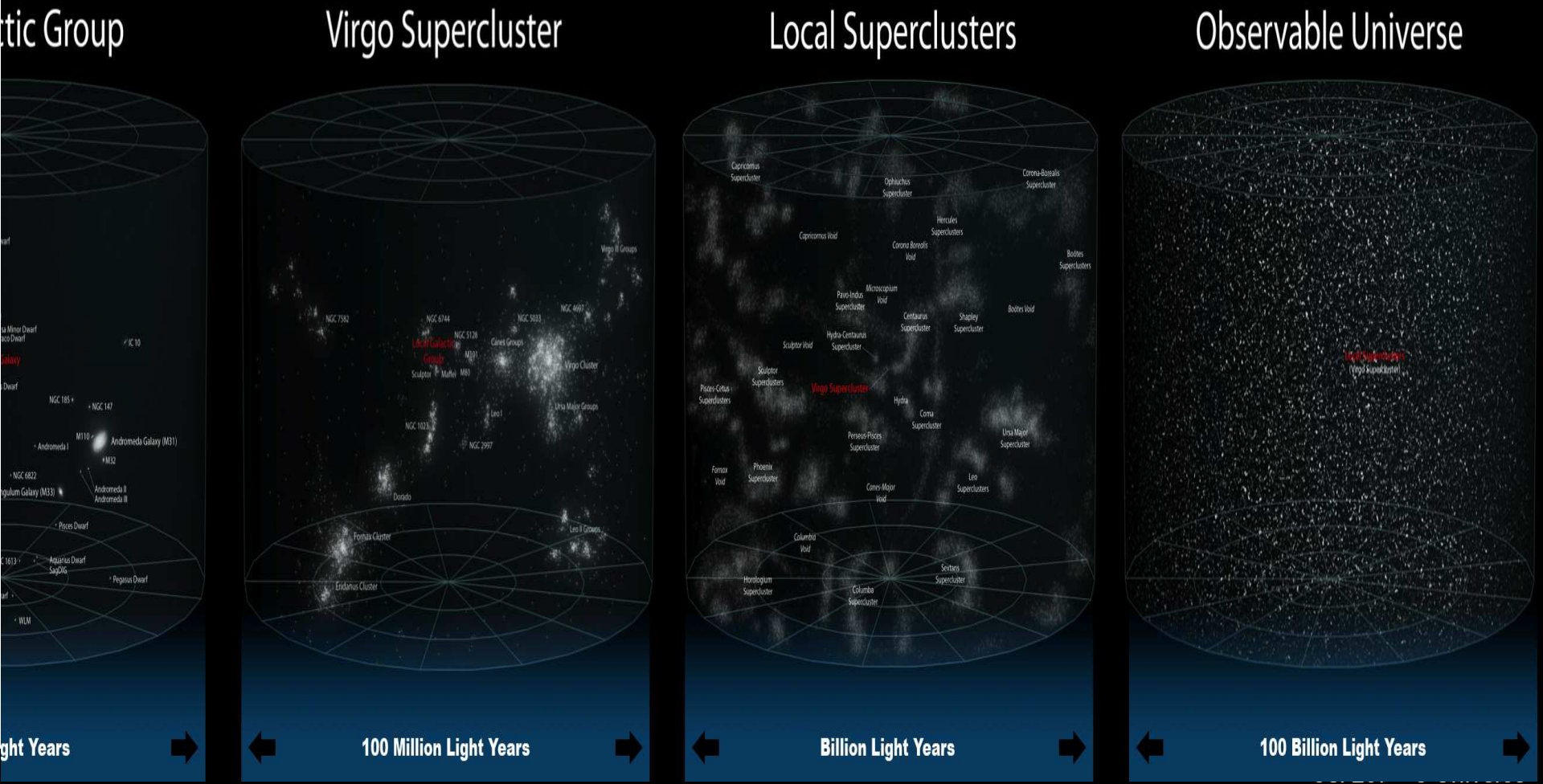
Scale of the Universe



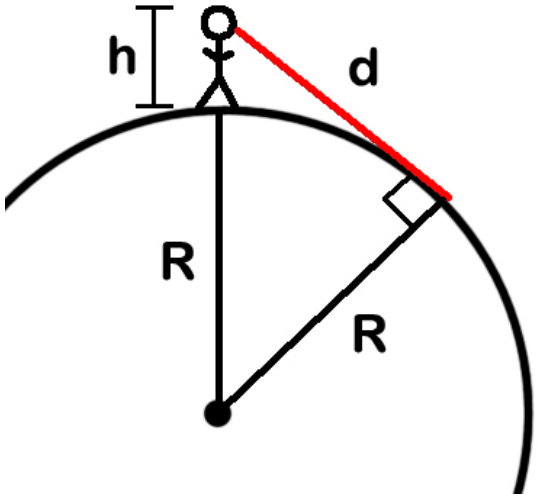
Scale of the Universe



Scale of the Universe



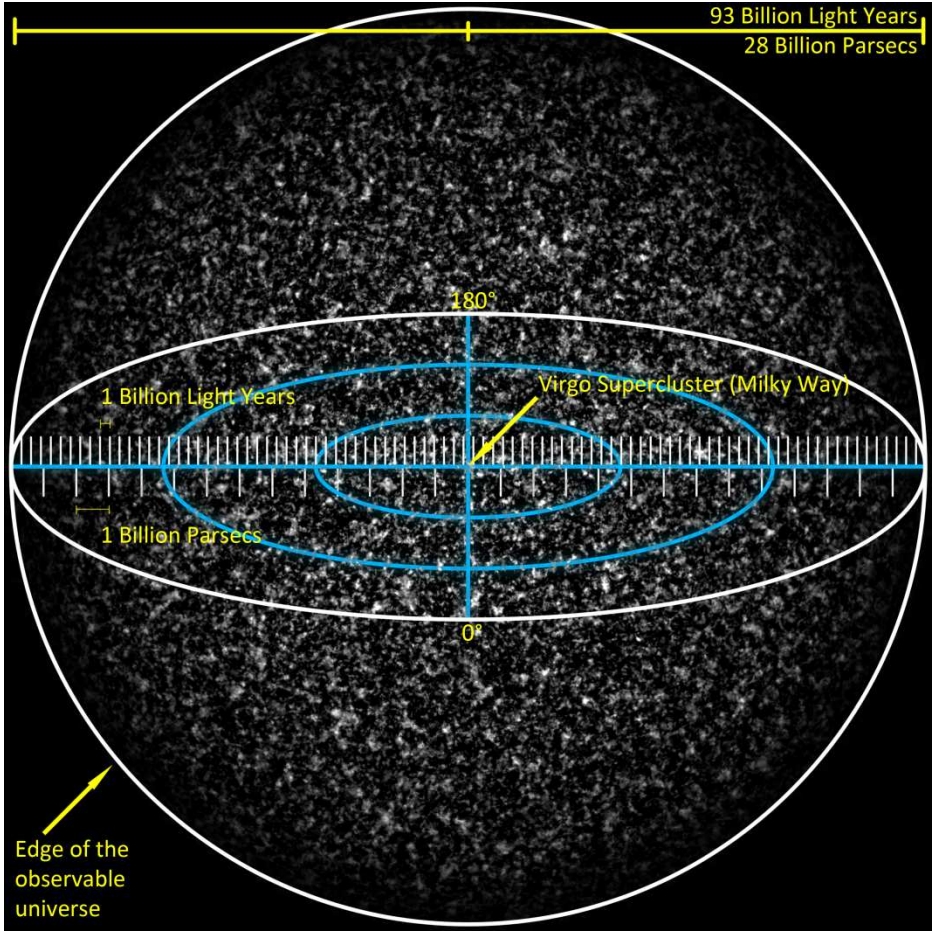
- **Observable Universe?**
  - We'll talk about this later. **Quick explanation** for now:
    - Because light moves at **finite speed**, *the farther out in space we look, the further back in time we see.*
    - Since the universe **had a beginning** (Big Bang), *we can't look further back in time than this, and thus farther out in space than this.*
    - The edge of the "observable universe" is called our **cosmological horizon**, much like a horizon on Earth: *there is certainly "stuff" beyond it, we just can't see it*!



- **Observable Universe?**

Question:

How big is the Solar System in this picture?



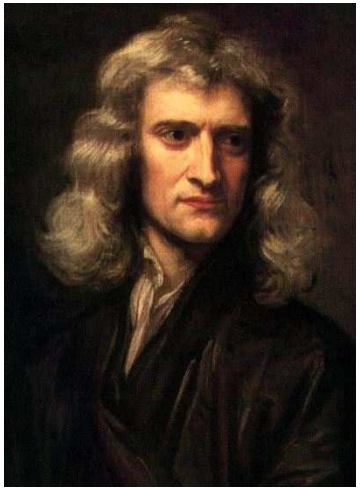
Mind Warp:

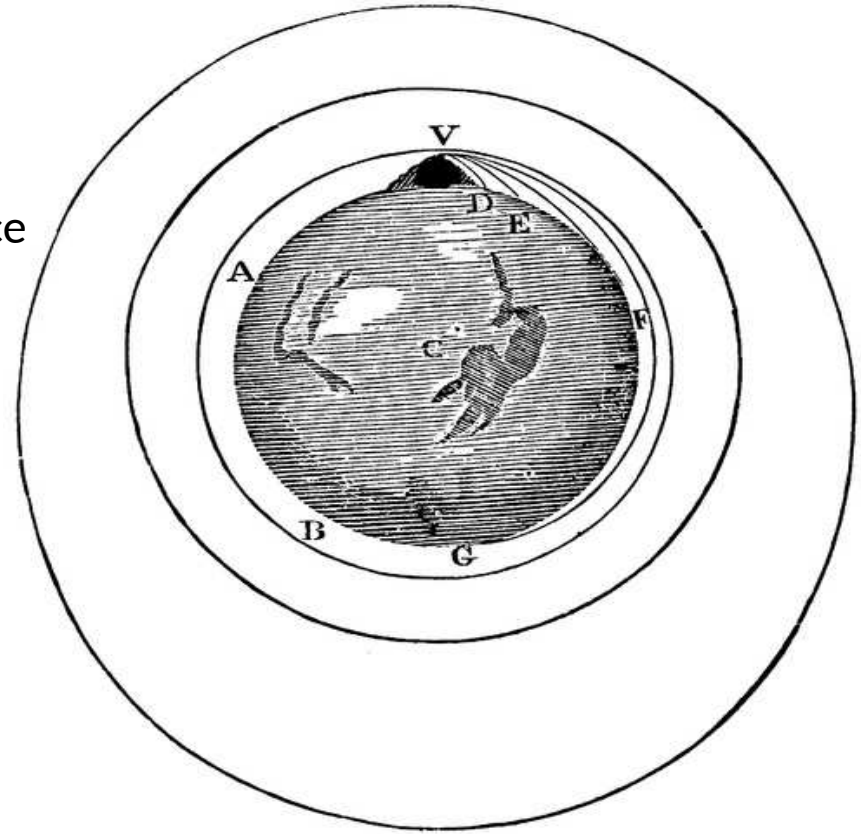
Universe is BIG

Scale of the Universe

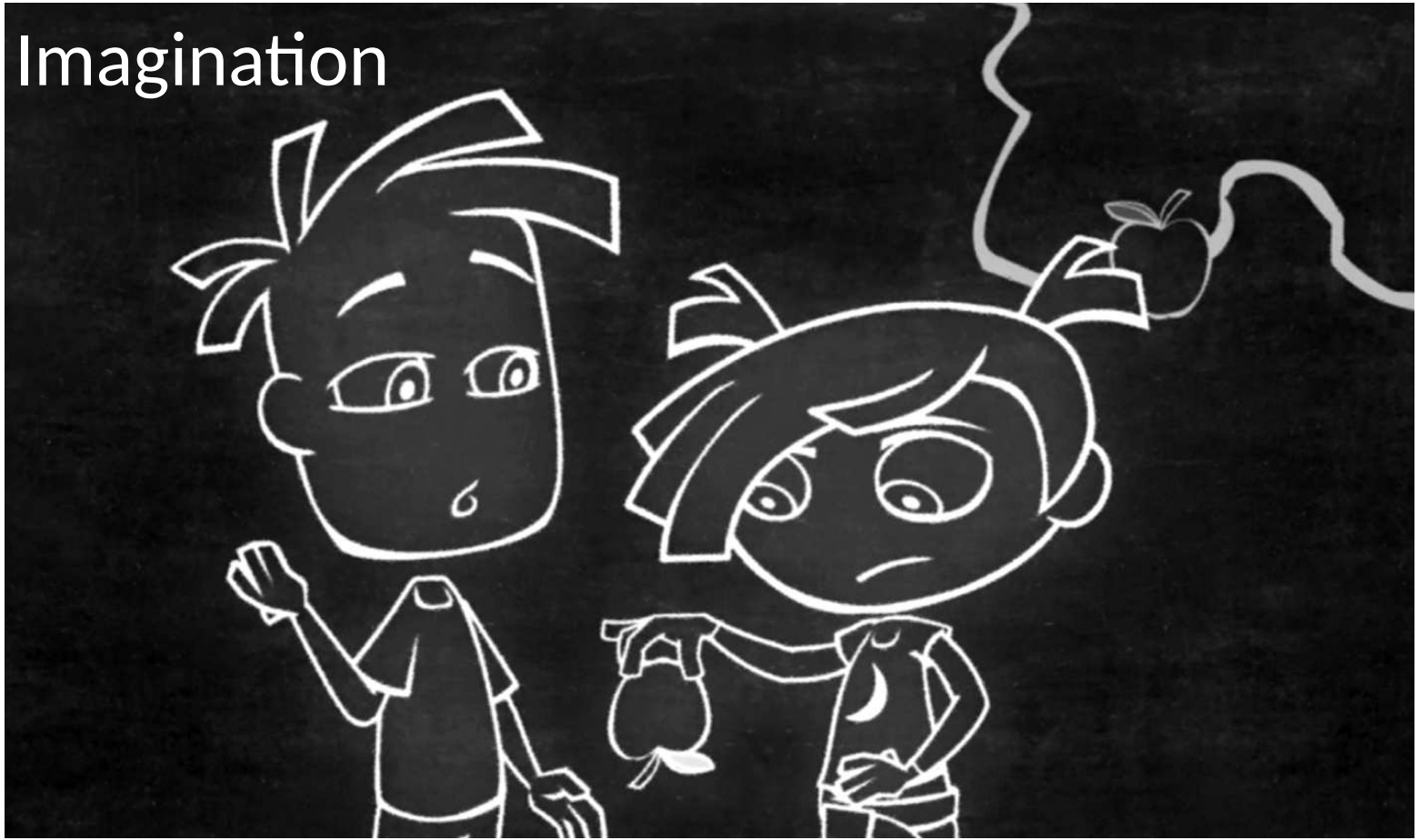
How big is the observable universe?

- **Isaac Newton:**
  - Imagined Earth's gravity **reaches to the Moon**, and figured out how the strength of gravity would need to diminish with distance to explain the Moon's orbit: **as inverse distance squared**

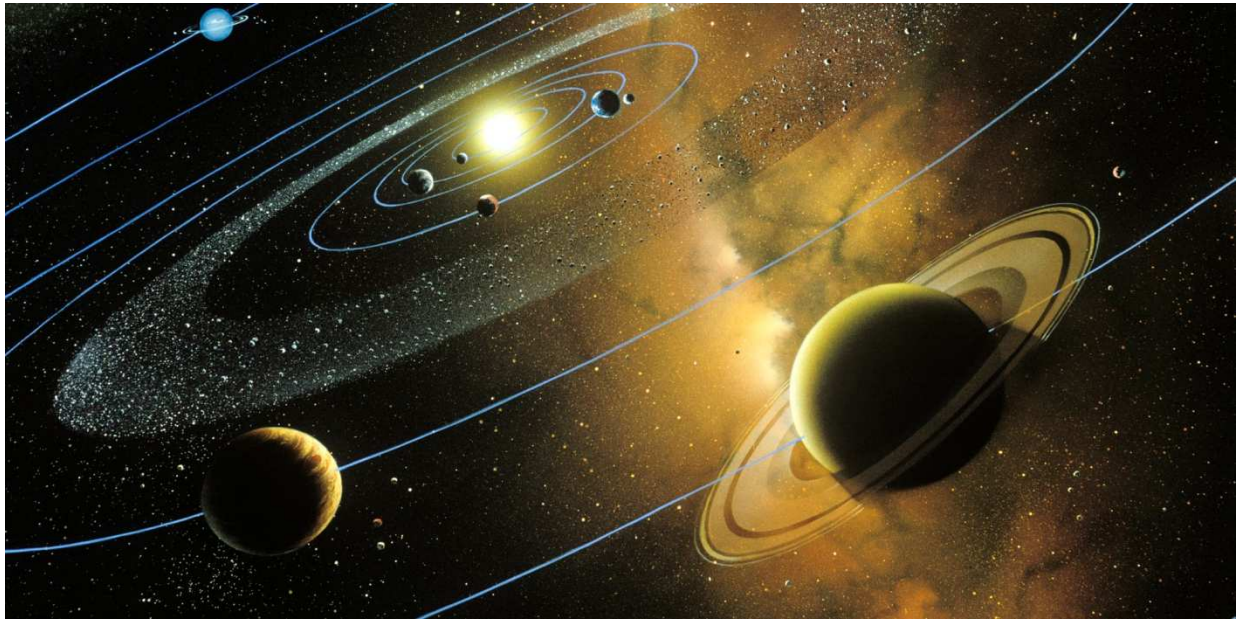




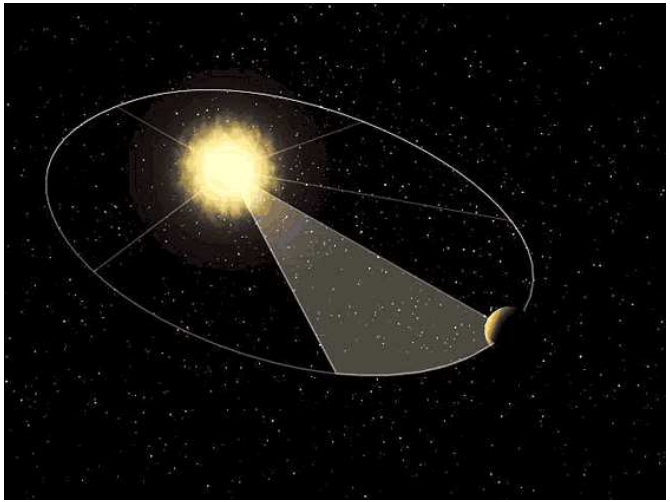
Newton's Imagination

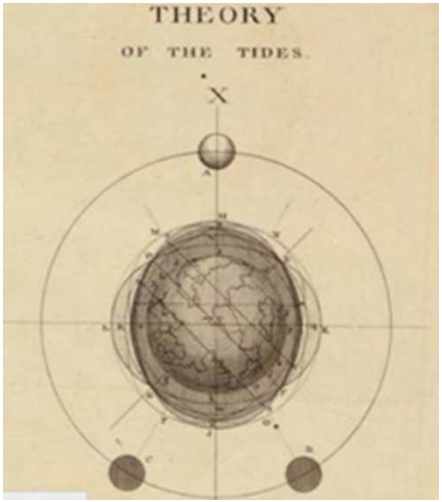


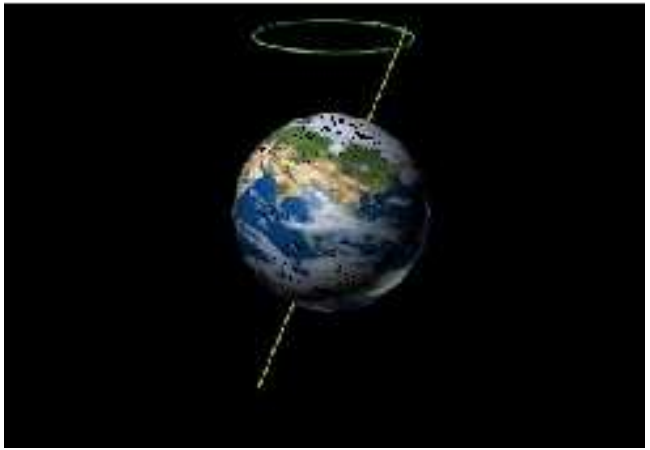
- **Isaac Newton:**
  - He then **extended** the idea to imagine the **Sun has gravity (*with inverse square force law*)**, which reaches **throughout the solar system** and controls the motions of the **planets**.



- **Isaac Newton:**
  - He showed how this **correctly explained** virtually all aspects of the hitherto mysterious **Solar System** (Kepler's laws of planetary motion, Earths tides, precession of the equinoxes, etc.)—a real *tour de force*. The *Principia* is "justly regarded as one of the **most important works in the history of science**".





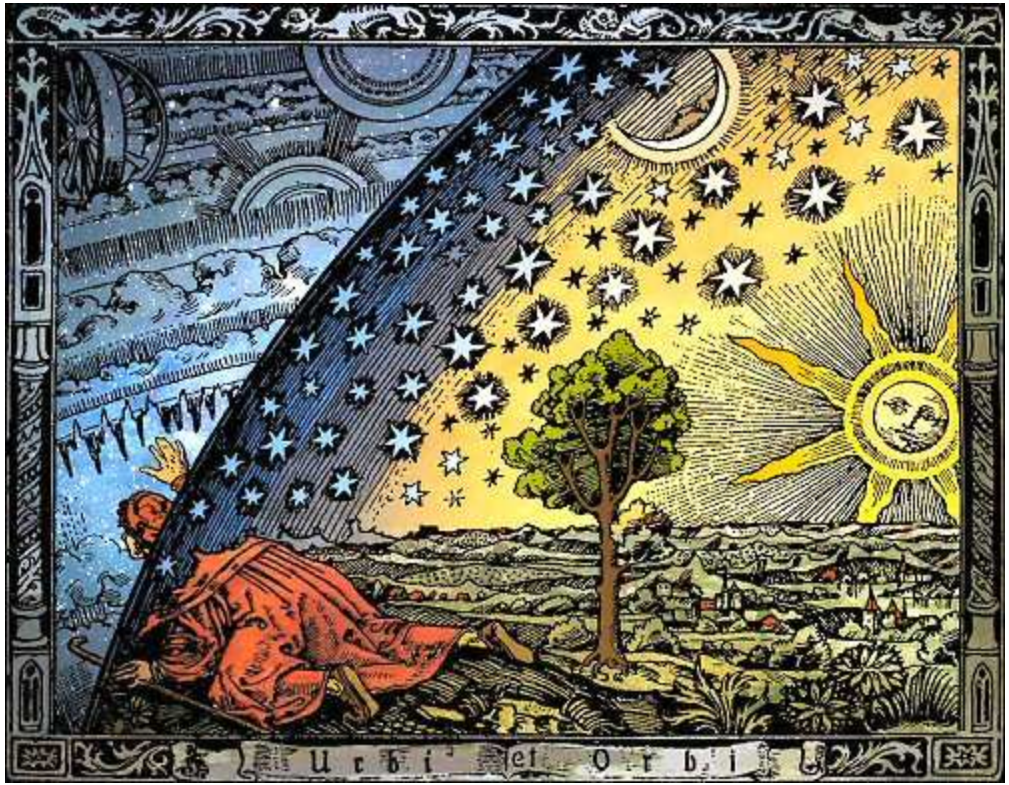


Role of Gravity

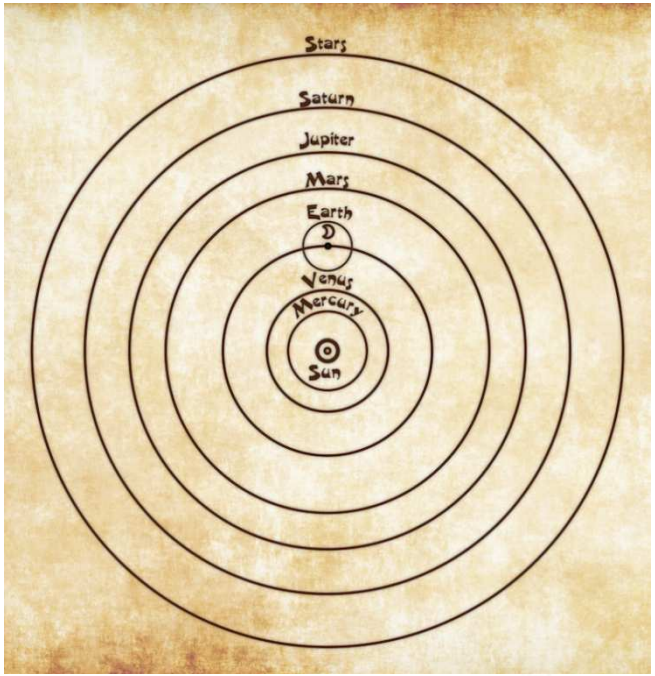
How did Newton explain the tides?

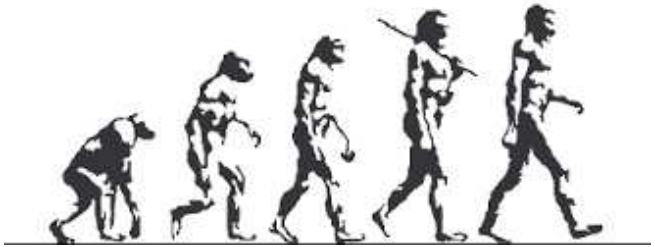
Role of Gravity

- **Isaac Newton:**
  - By showing that the planets orbit for the same reason an apple falls, Newton quite literally **unified the heavens and the Earth**.
  - He demolished the age-old separation between us and the cosmos, opening up a **whole universe of mysteries** for science to explore.

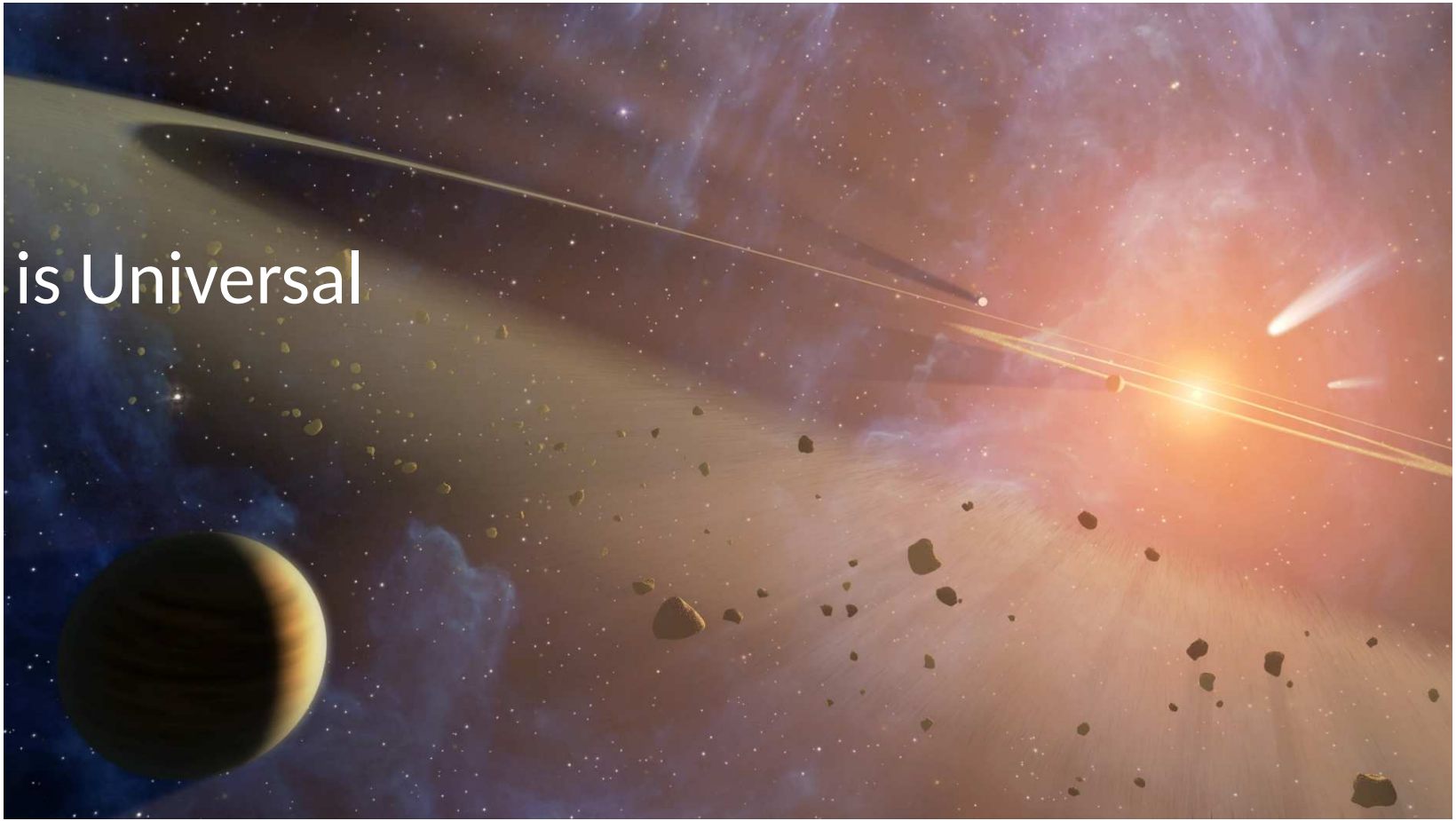


- **Isaac Newton:**
  - Together with Galileo's **observations**, Newton provided the crucial **theoretical** support that eventually convinced everyone that **Copernicus was right**: The Earth (and so also "Man") are **not** at the center of the universe.
  - This had a profound impact on how we understand our **place in the universe**, rivalled only by Darwin's **theory of evolution**: two of the greatest "mind warps" of all time.

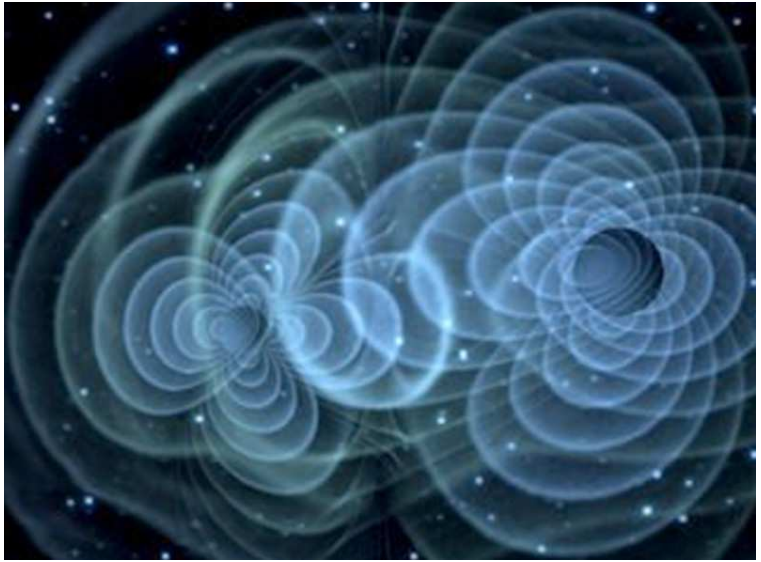




Gravity is Universal

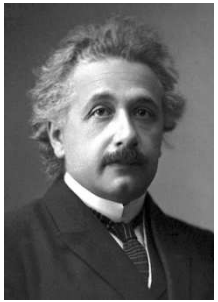


Role of Gravity

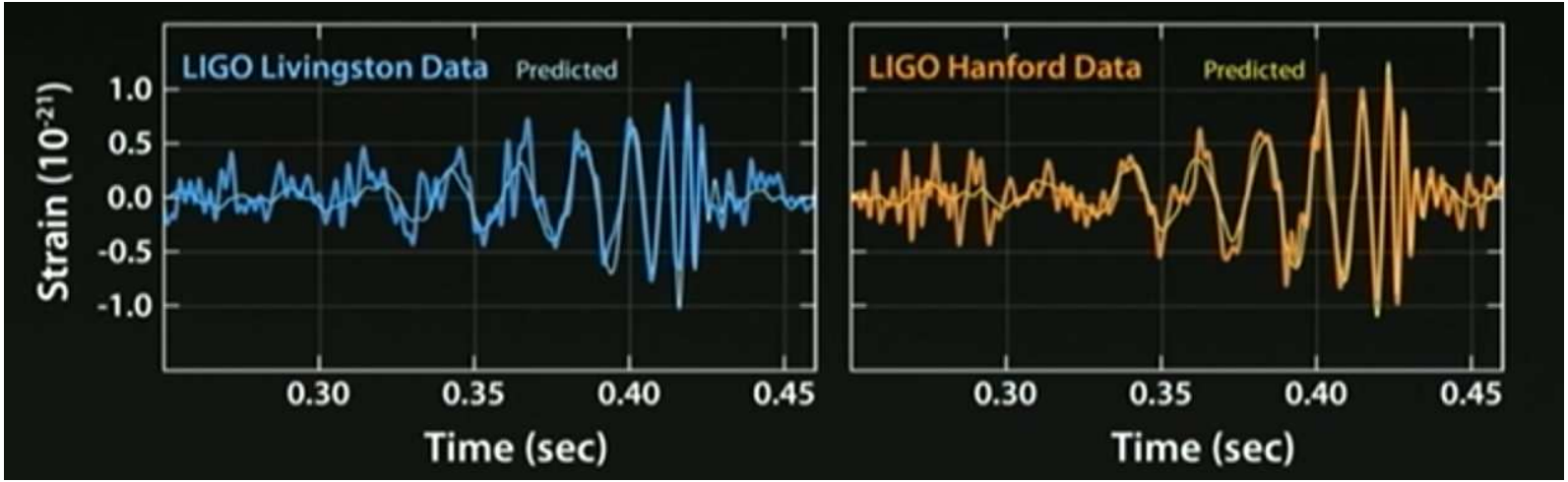


LIGO (Laser Interferometer Gravitational-Wave Observatory)

4 km length



Role of Gravity

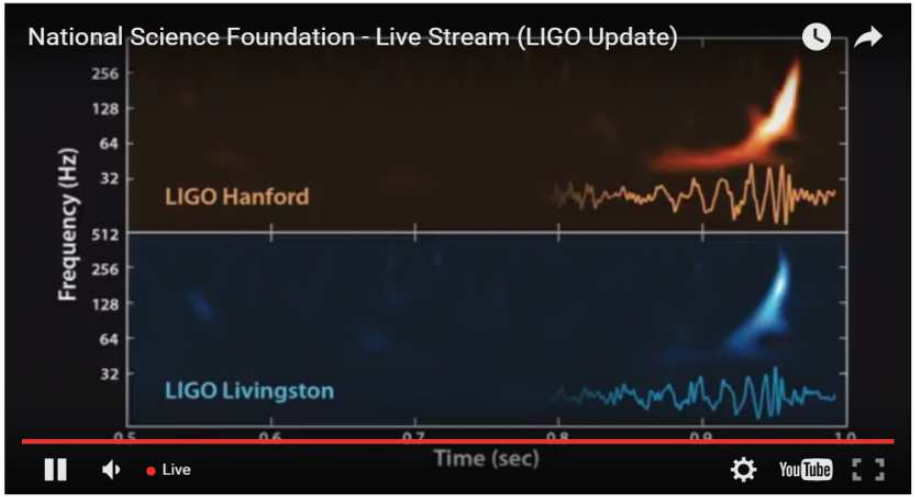


Strain = 10^{-21} ⎵ 1/1000 times size of proton (!)

Inspiral signal (“chirp”) lasted about 7 ms

Repeated in two independent detectors

Role of Gravity



Merger of two black holes about 1 billion light years away

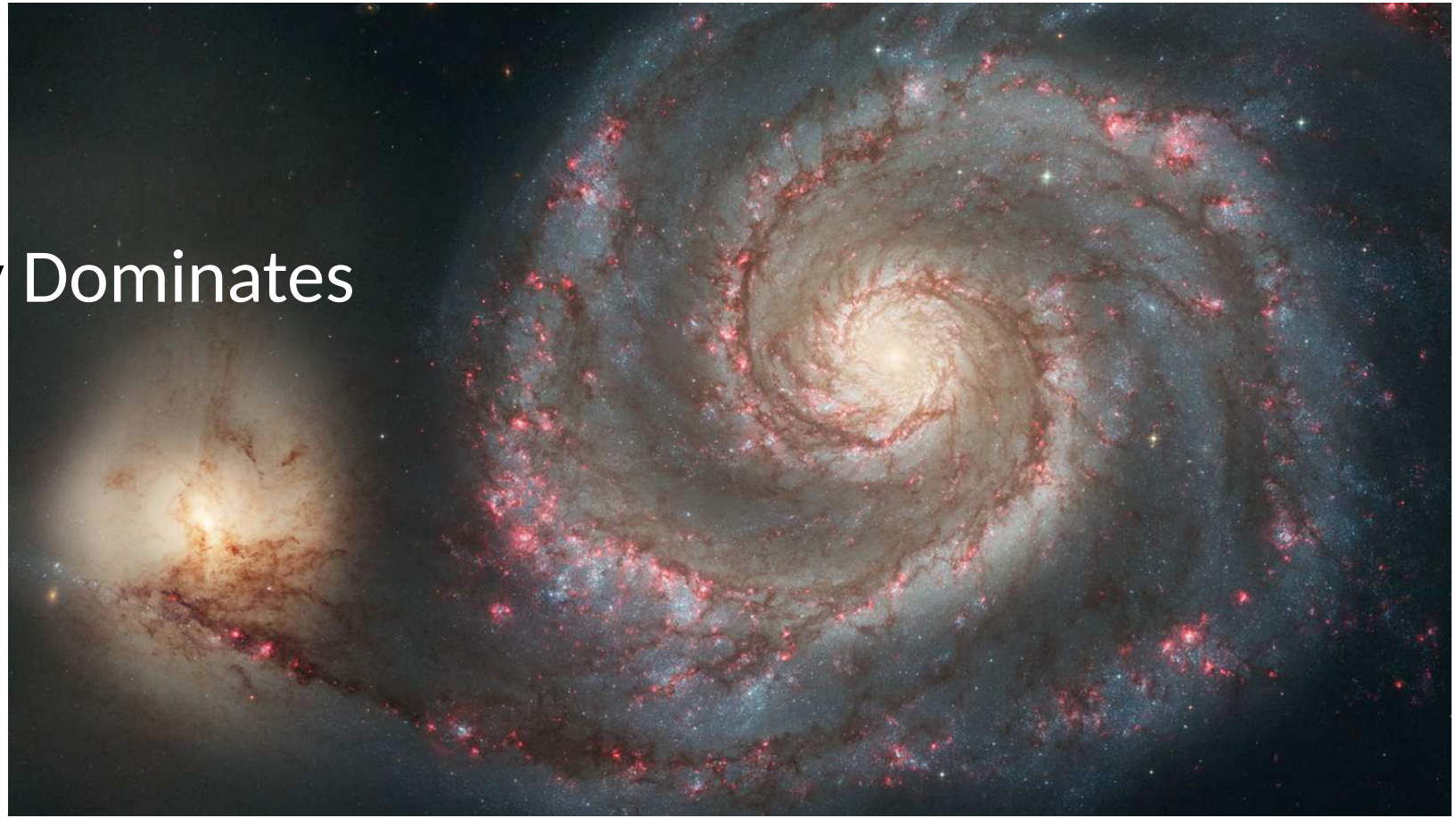
3 solar masses worth of energy converted to gravitational wave energy

Opens entirely new window on the universe: “hear” instead of just “see”!

Role of Gravity

- **Gravity** is also the **dominant force** on large scales (planets, galaxies, cosmos):
    - The **strong** and **weak** nuclear interactions are **short-range** forces. They act only between particles separated by nuclear distances, e.g., inside the nucleus of atoms.
    - **Electromagnetism** is a relatively **strong**, **long-range** force, but it tends to **cancel out** over large distance because there is an **equal amount** of **positively** and **negatively** charged particles in the universe: strong electrostatic attraction tends to bring these together and **neutralize** them (e.g., atoms are normally electrically neutral).
    - Gravity is a relatively **weak**, **long-range** force, but it tends to **add up** on large scales because **all particles have positive mass** (no negative mass particles to cancel the effects of the positive mass particles). E.g.: The Earth has a gravitational field, but virtually no net electrostatic field.

Gravity Dominates



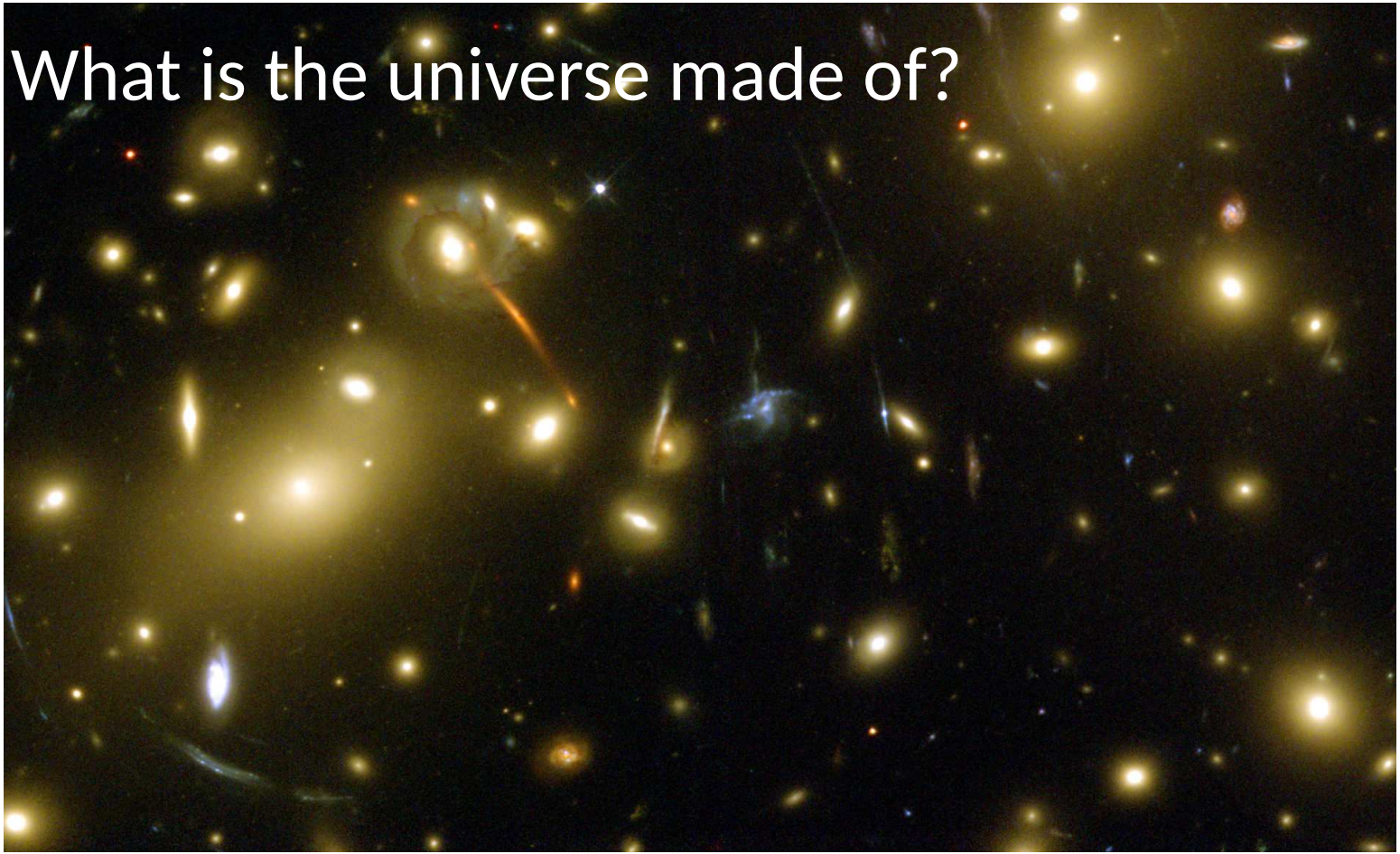
Role of Gravity

- Even though gravity is the most **familiar** force we experience, it is the most **mysterious**:
    - It is **not a "force"** like the others (strong, weak, and electromagnetic). As Einstein discovered, it is ***geometry***: the "curvature of spacetime".
    - It is the only "force" **not yet understood** in the context of the **quantum** nature of the universe. Finding a unified theory of **quantum gravity** is the "holy grail" of theoretical physics.
    - Both the **energy** and **entropy** of the gravitational field are poorly understood, despite the importance of these concepts to fully understanding the **evolution** of the universe (in particular, how this evolution resulted in the "**right conditions**" for life) and constructing a theory of **quantum gravity.**

Role of Gravity

What is Gravity?

Question: What is the universe made of?



Composition & Structure

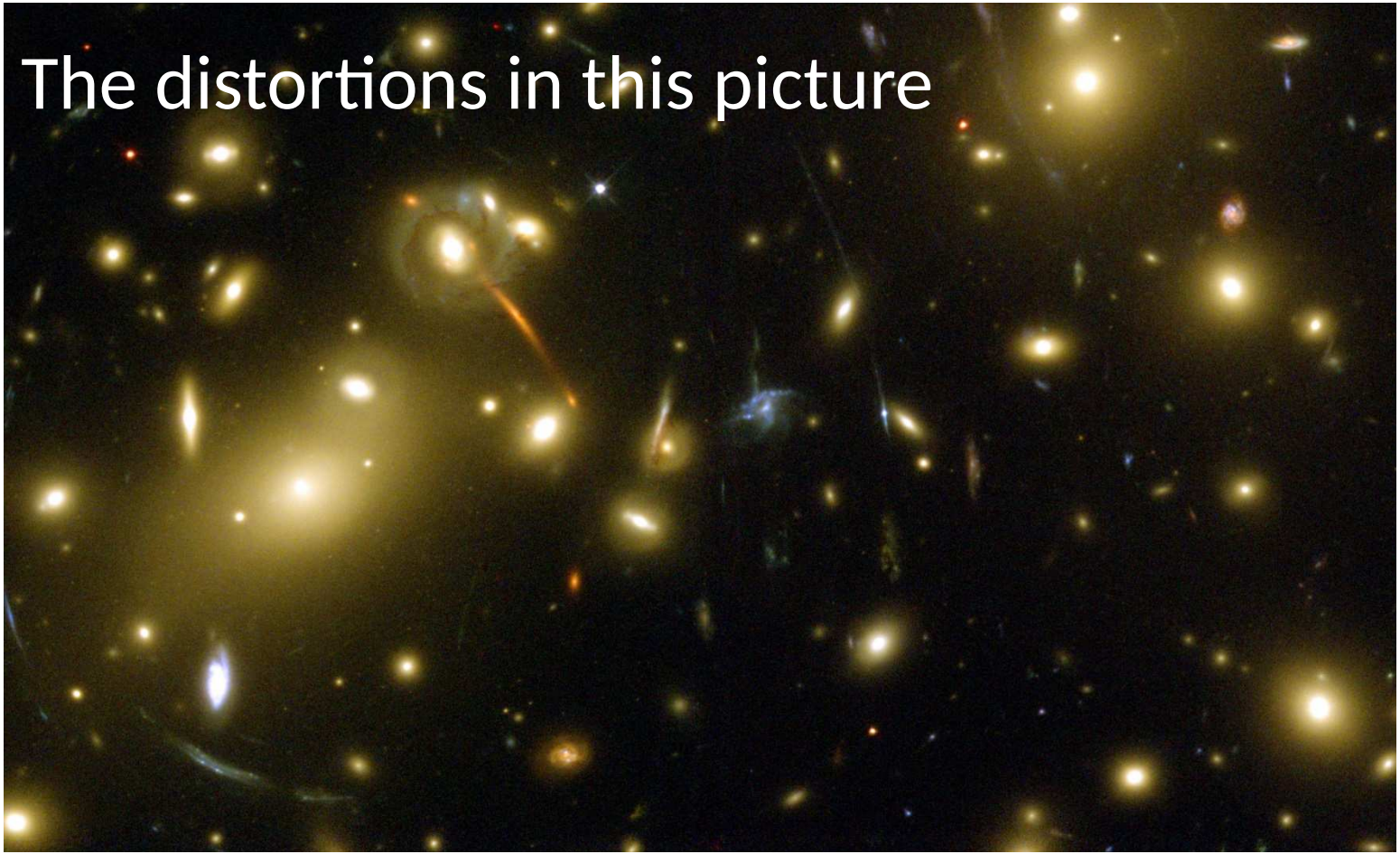
- Taking pictures of the universe in many wavelengths of light

  …and analysing them in the context of a wealth of understanding about astronomy, physics, and astrophysics (light, gravity, stellar models, behaviour of gasses, etc.)

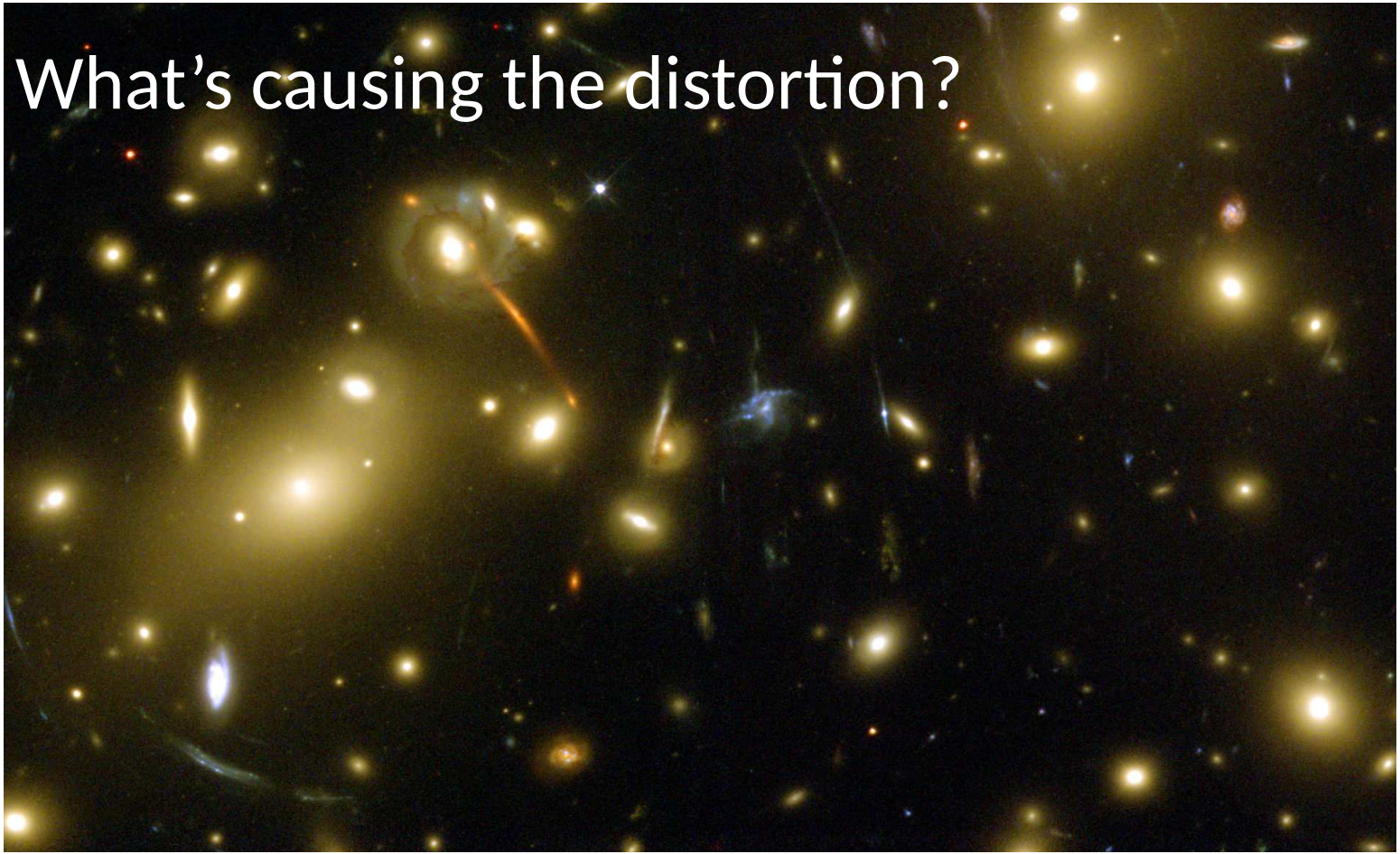
  …tells us the universe contains a lot of **stars**, **gas**, and **dust**, composed of:

  - 74% hydrogen
  - 24% helium
  - 2% heavier elements (“dust”)

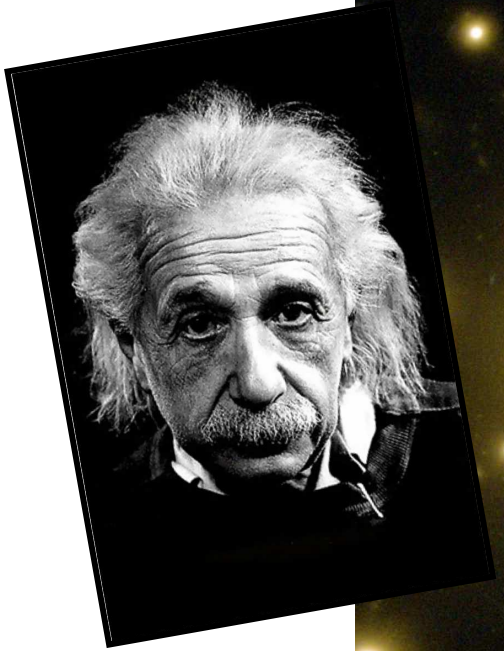
Hence: The distortions in this picture



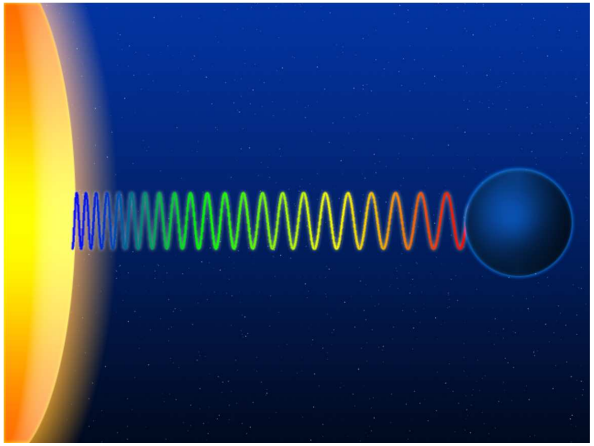
But wait: What's causing the distortion?

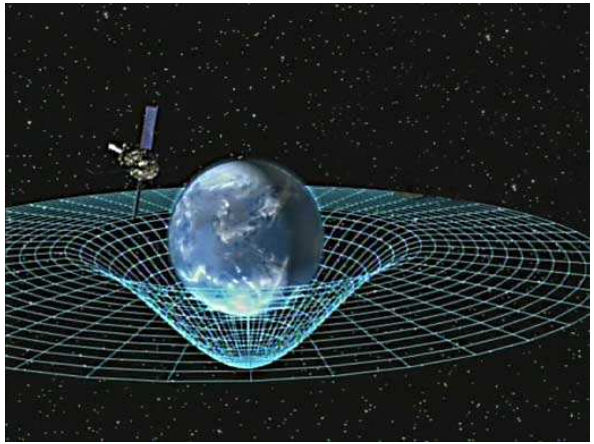


Einstein: Gravity bends light!



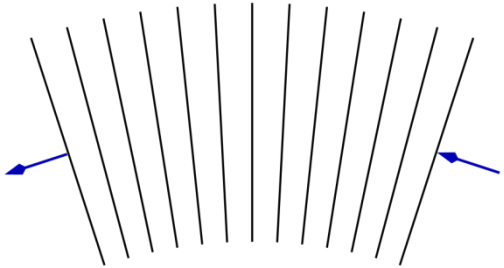
- Mass-energy **warps** space and time (actually, **spacetime**)
  - **Time slows down** closer to massive objects
  - Massive objects have **extra space** in their vicinity

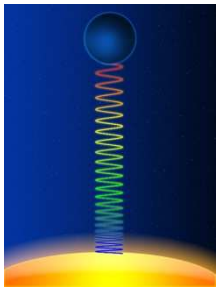




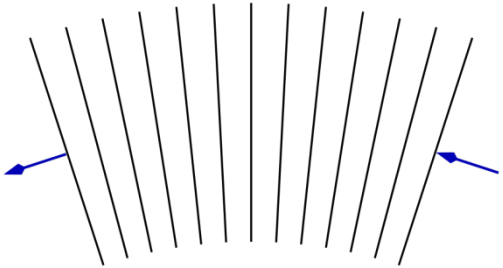
3D and 2D representations of extra space

- Mass-energy **warps** space and time (actually, **spacetime**)
  - The **local** speed of light is always c.
  - During 1 second, the part of a light wave-front farther from a mass can move a certain distance at speed c.
  - But because of **time warping**, when 1 second elapses farther out, **less** than 1 second elapses closer in.
  - Thus, the part of the light wave-front closer in, also **locally** moving at speed c, but for **less** time, can move a **lesser distance**, causing the wave-fronts to tilt, and the light ray to "bend" as it travels.

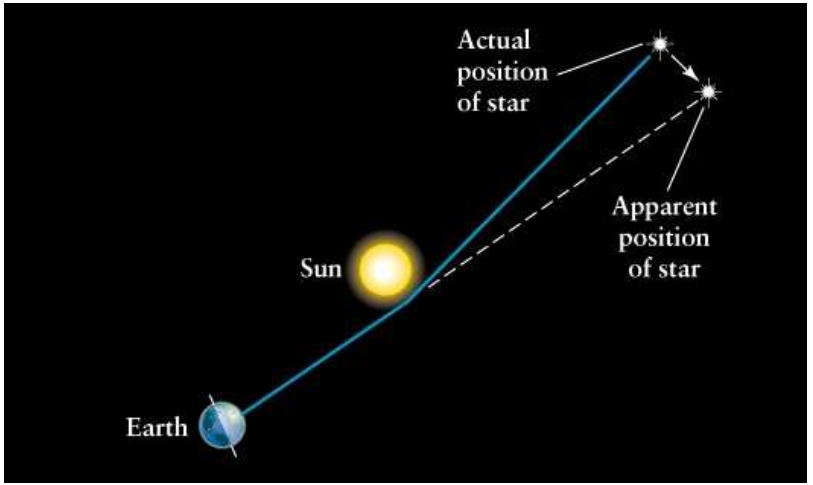


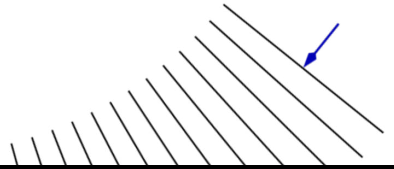


- Mass-energy **warps** space and time (actually, **spacetime**)
  - The **local** speed of light is always .
  - During 1 second, the part of a light wave-front farther from a mass can move a certain distance at speed .
  - But because of **space warping**, that distance appears **smaller** in this picture when it is closer in.
  - This also causes the wave-fronts to tilt, and the light ray to “bend” as it travels.
  - For light, the two effects (time warp and space warp) contribute equal amounts to the “bending”

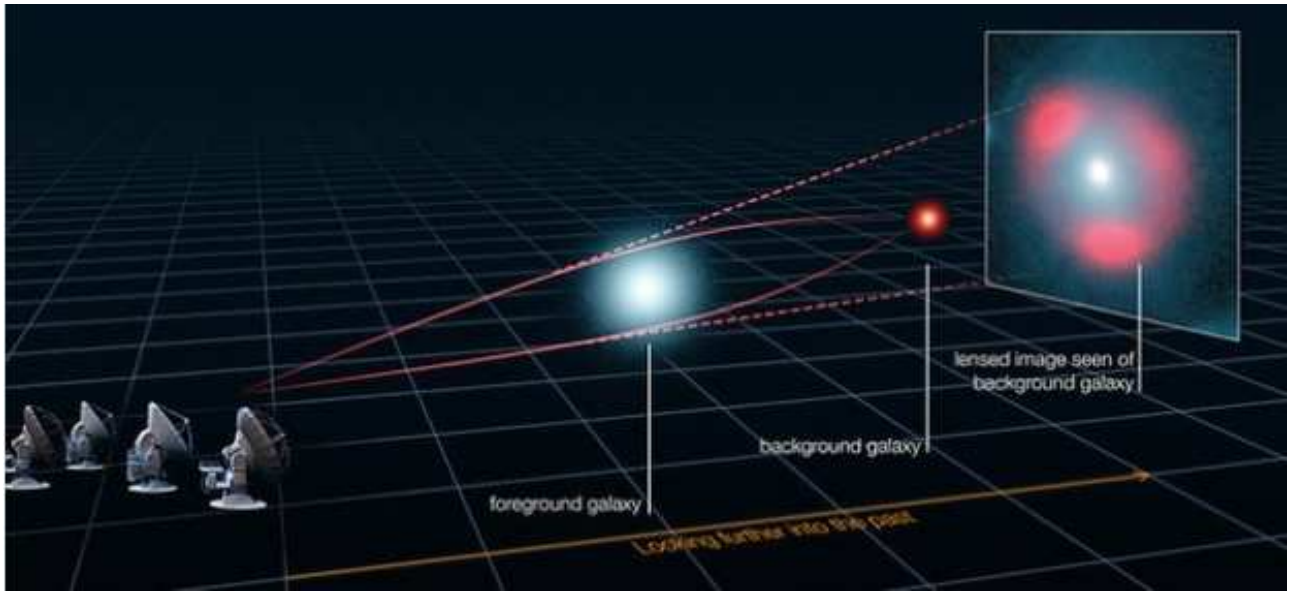


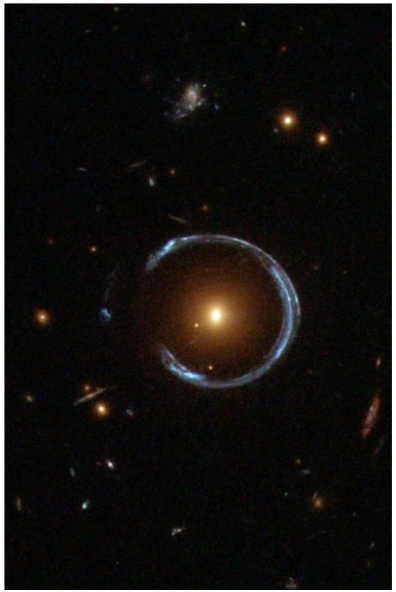
- Mass-energy **warps** space and time (actually, **spacetime**)
  - "Bend" is not the right word: **Locally**, light always moves in a **straight line** at **speed c**, and it is spacetime that is bent.
  - When moving from one region of flat spacetime to another, through a region of warped spacetime, a light ray will emerge moving in a different direction **relative** to its original direction.
  - This distorts the view of objects seen through the warped region—called a ***gravitational lens.*** But in popular science we just say "gravity bends light".

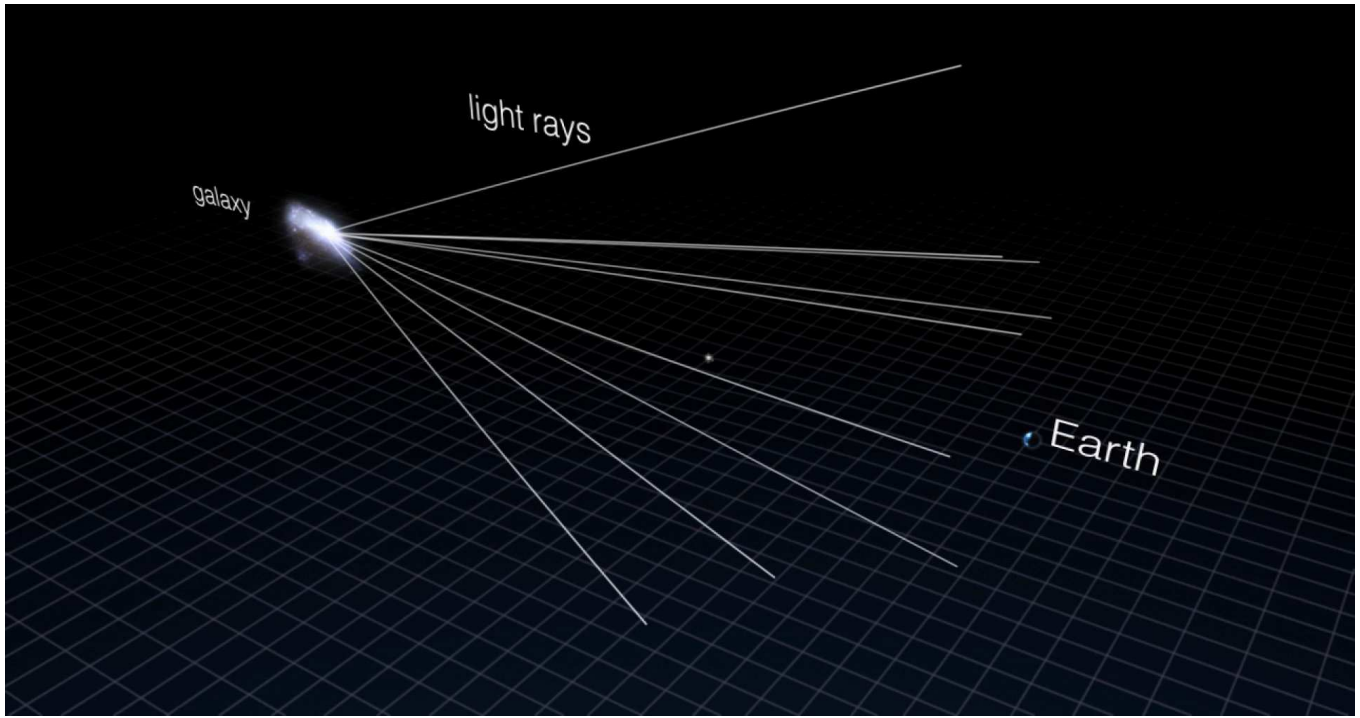




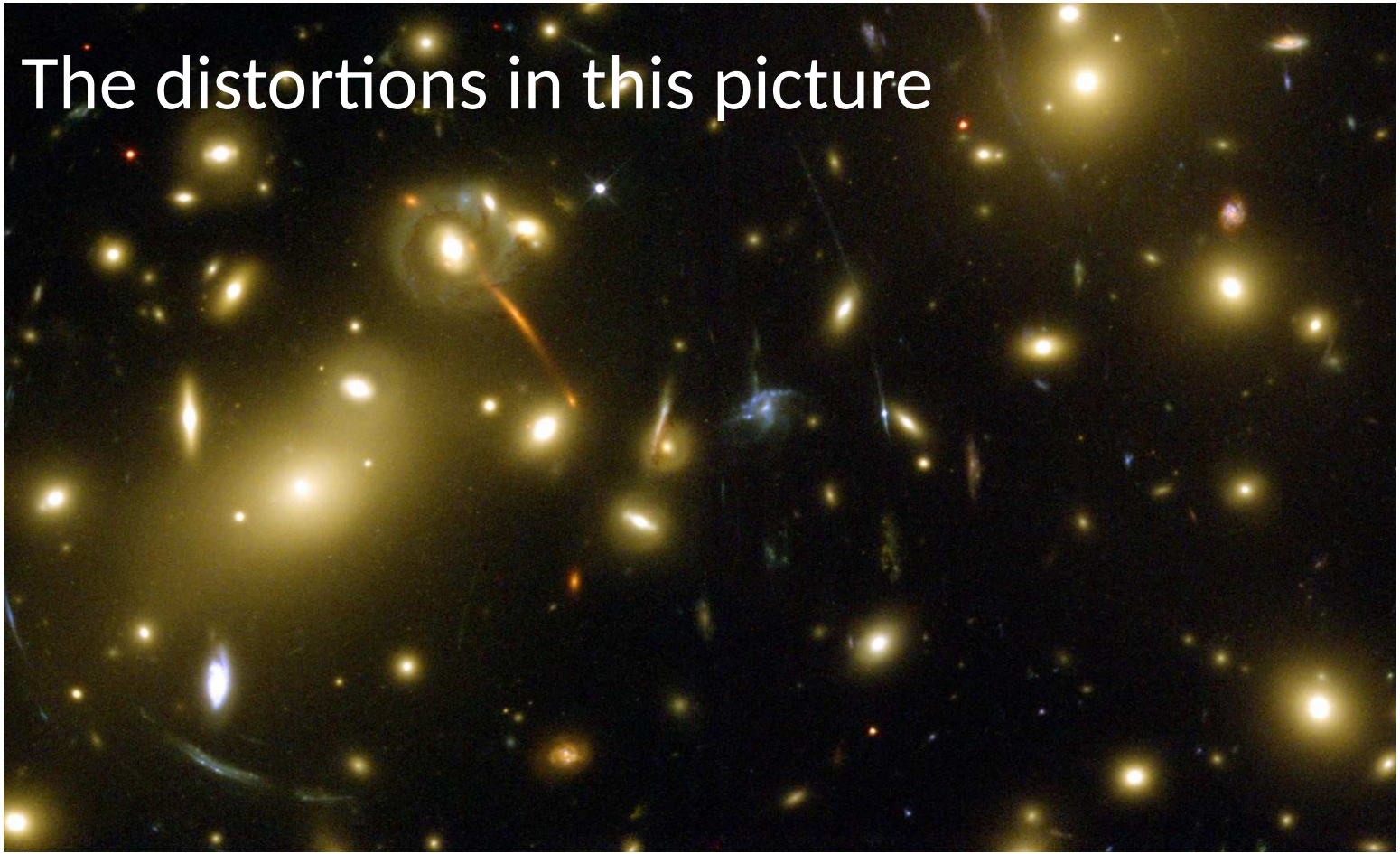
- **Any** form of mass-energy can create a gravitational lens: planets, stars, black holes, galaxies, clusters of galaxies, gas between galaxies, etc., as well as any **invisible** forms of mass. Gravity is **universal**: it measure **all mass**, visible or not.
- **All** these gravitational lenses distort the images of further away objects.



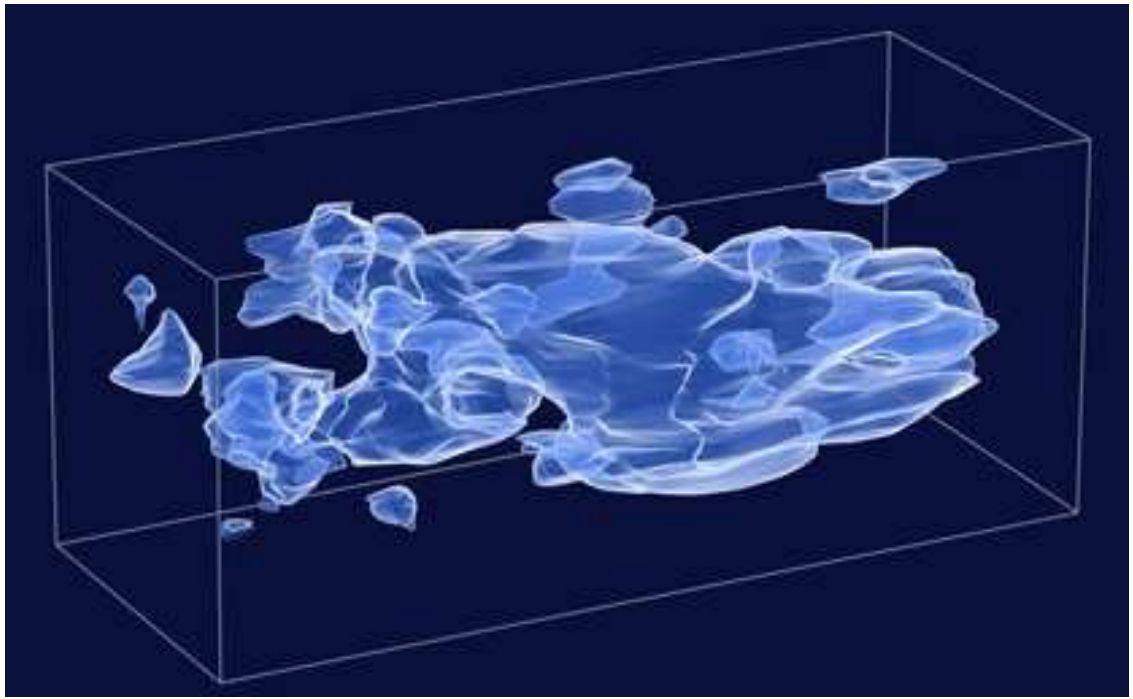



light rays
galaxy
Earth

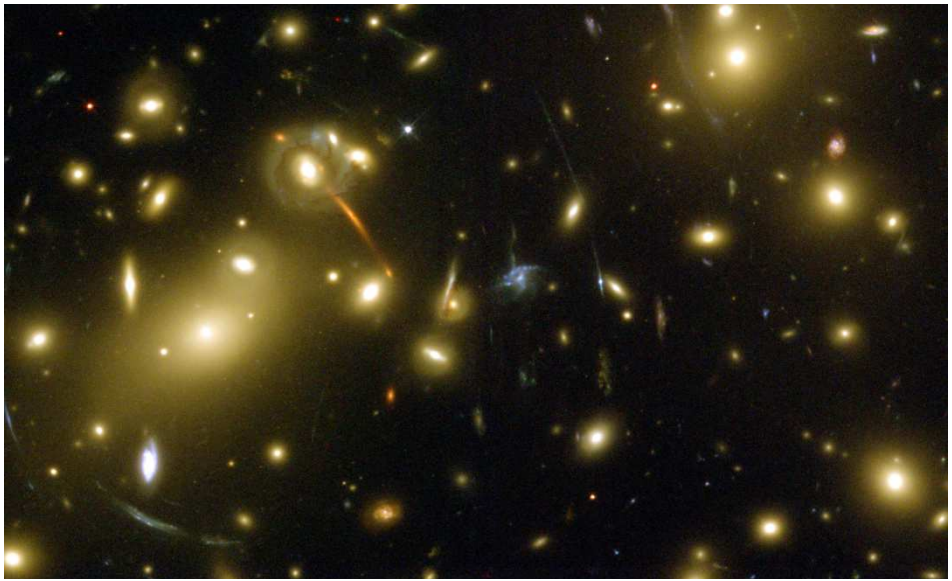
Hence: The distortions in this picture



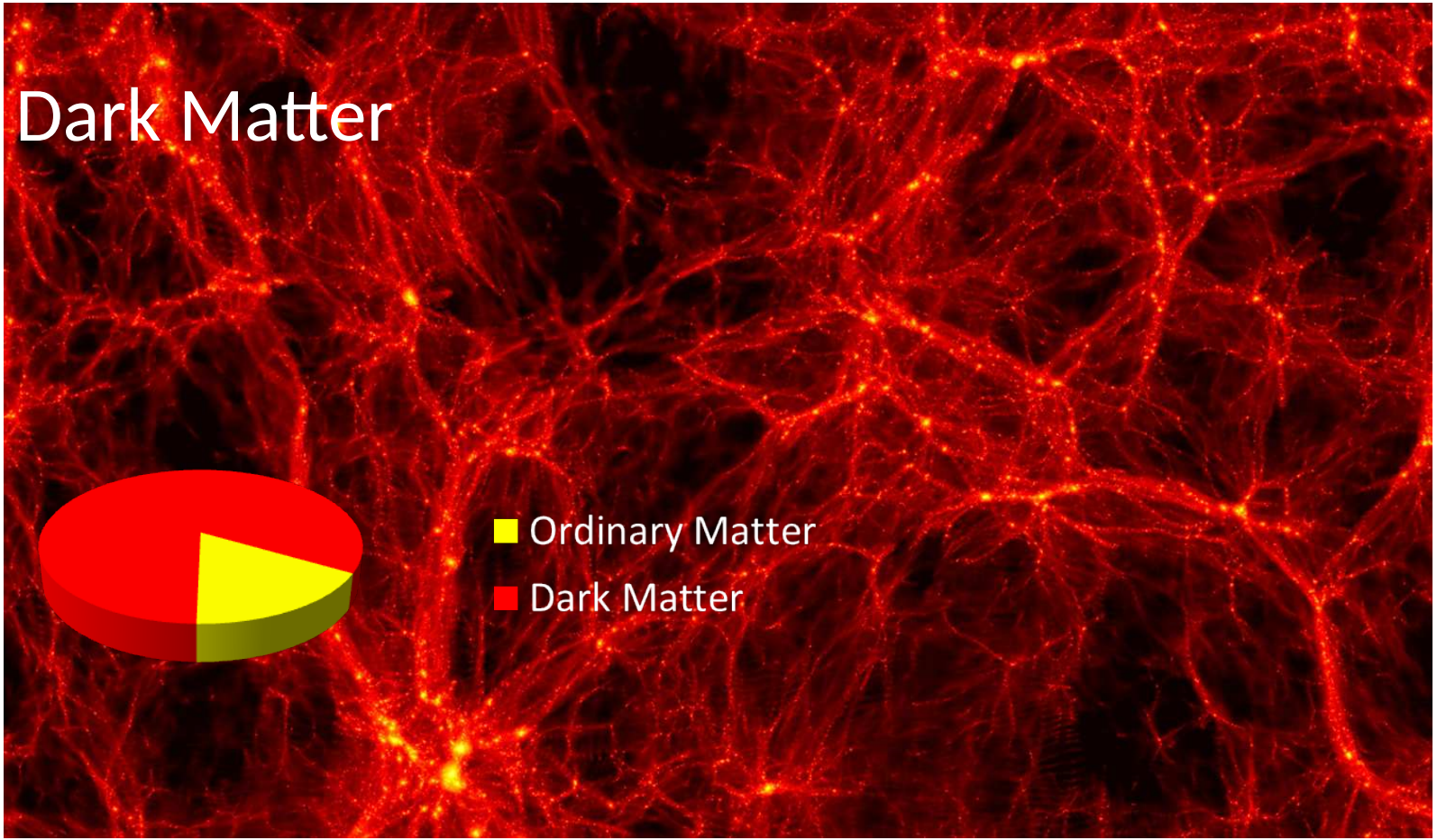
- By measuring the distortions in detail, physicists can construct a detailed 3D map of **all** the mass-energy in a given region of space, **seen and unseen**.



- **Surprise!**
  - All the mass that can be **seen** (or reasonably inferred), is **not nearly enough** to cause the amount of gravitational lensing that is observed.
  - Any typical picture like this contains:
    - ✓ 15% ordinary matter (stars, gas, dust, i.e., atoms)
    - ✓ 85% ***dark matter***
  - If the dark matter in space could be made visible, it would look like this…

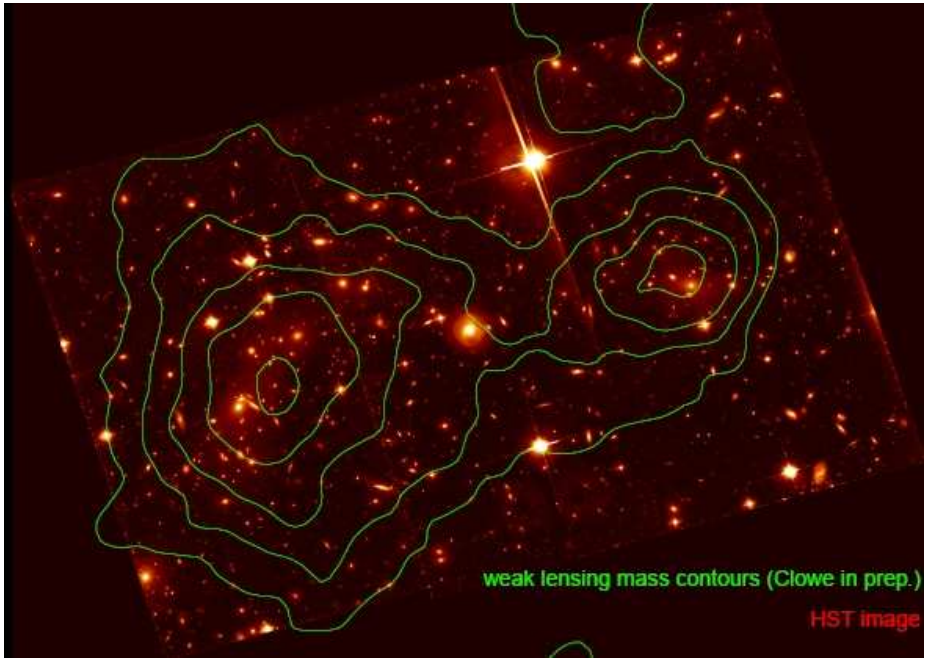


Mystery: Dark Matter



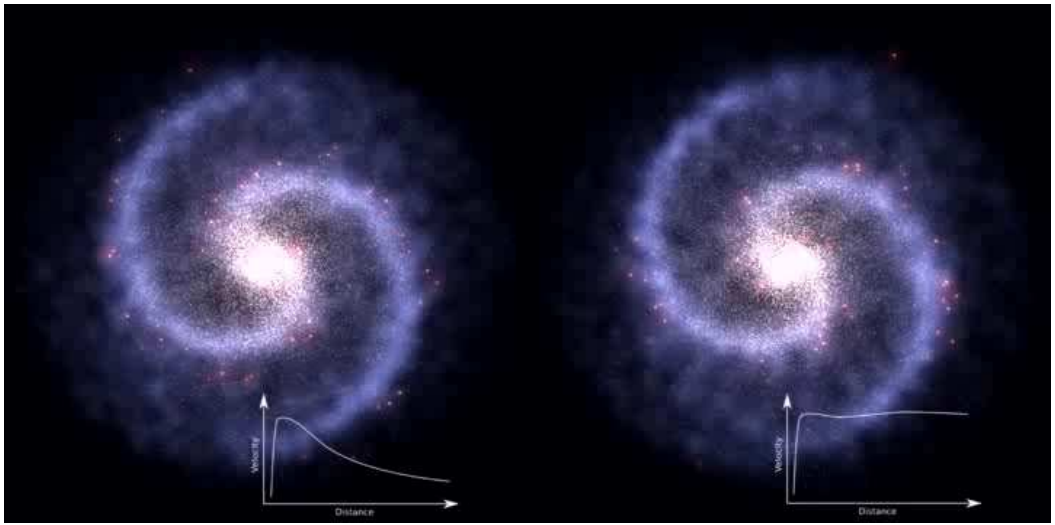
- Basic properties:
  - Dark matter is called “dark” because it appears to **emit no light** of its own. Nor does dark matter appear to **reflect** or **absorb** light. Thus it is **transparent**.
  - The existence and properties of dark matter are **inferred** from its **gravitational effects** on things we **can** see.
  - Dark matter has not been detected **directly**, making it one of the **greatest mysteries** of our times. Currently a worldwide race for first direct detection!

- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
  - **Gravitational lensing**



- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
  - **Galaxy rotation curves** (Vera Rubin)

Solar System Analogy

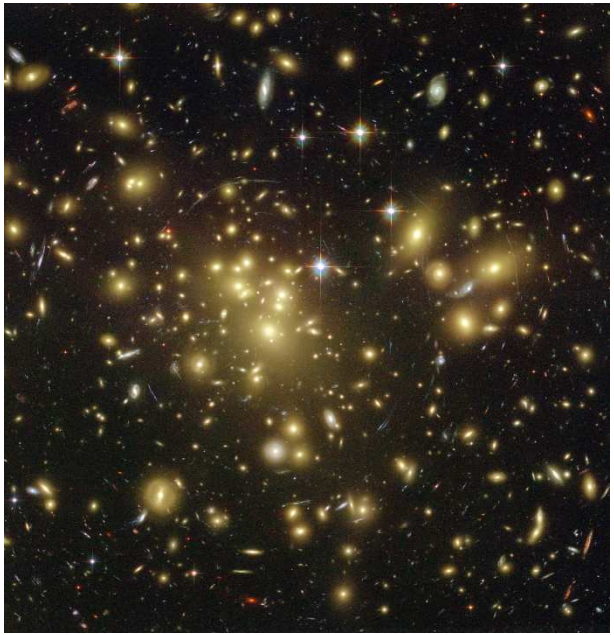


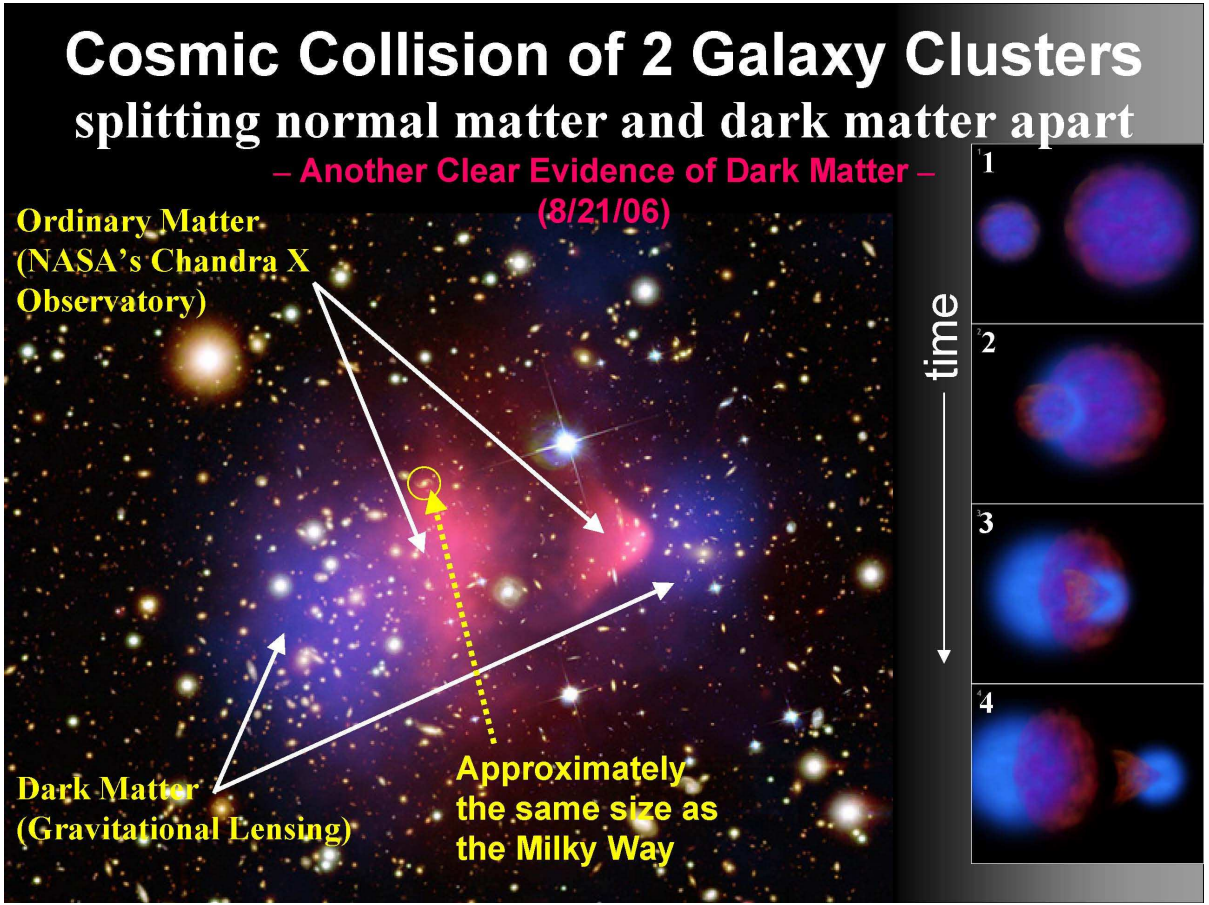
Expected

Observed

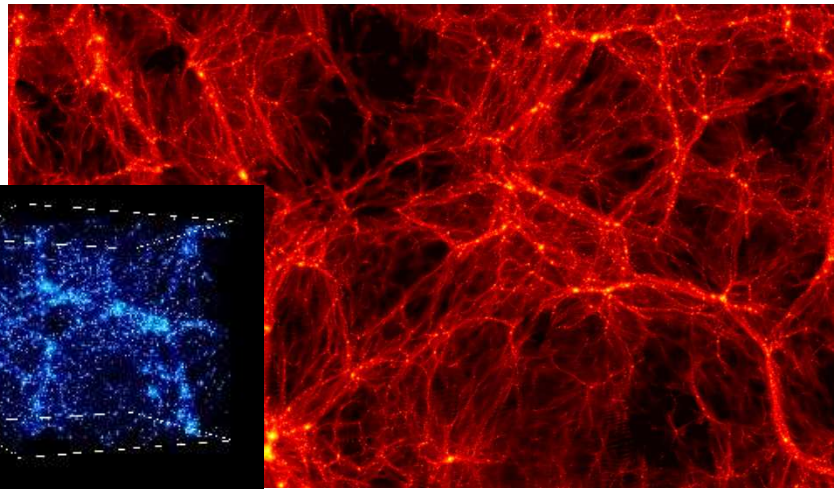
- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
    - **Galaxy rotation curves** (Vera Rubin)

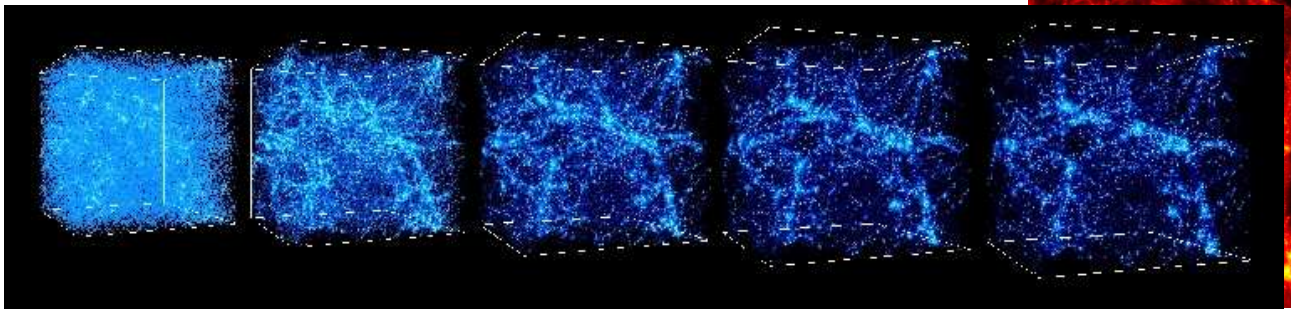
- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
  - **Anomalies in galaxy clusters**
  - **Mass** measured three **independent** ways:
    - ✓ Orbital velocities of individual galaxies
    - ✓ X-rays emitted by hot gas between galaxies (assuming pressure/gravity balance)
    - ✓ Gravitational lensing of background galaxies




Cosmic Collision of 2 Galaxy Clusters
splitting normal matter and dark matter apart
– Another Clear Evidence of Dark Matter –
(8/21/06)
Ordinary Matter
(NASA's Chandra X
Observatory)
Dark Matter
(Gravitational Lensing)
Approximately
the same size as
the Milky Way
time
1
2
3
4

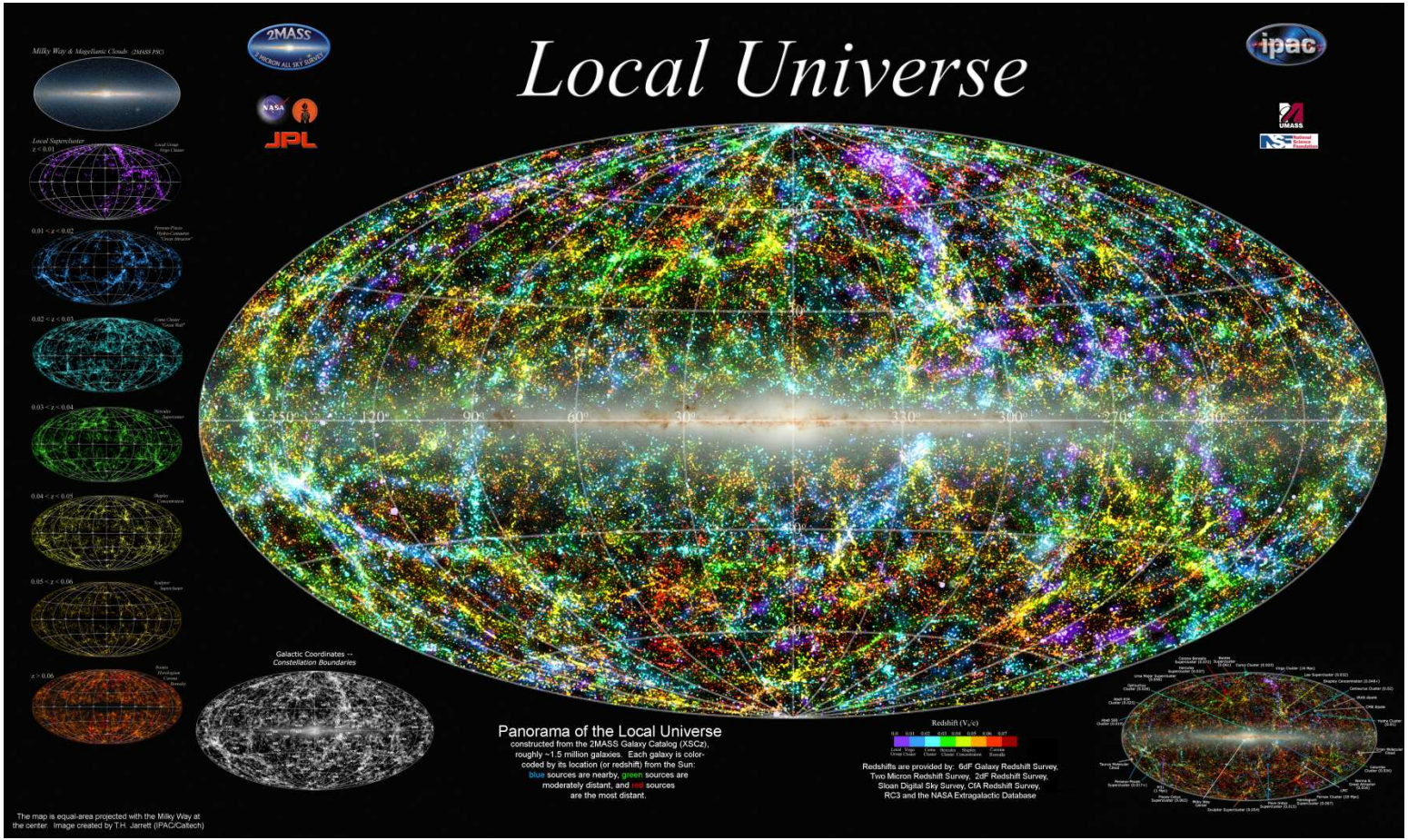
- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
  - **Large scale structure formation**



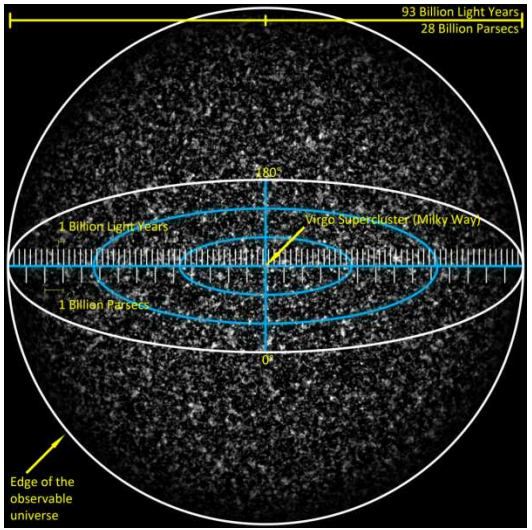


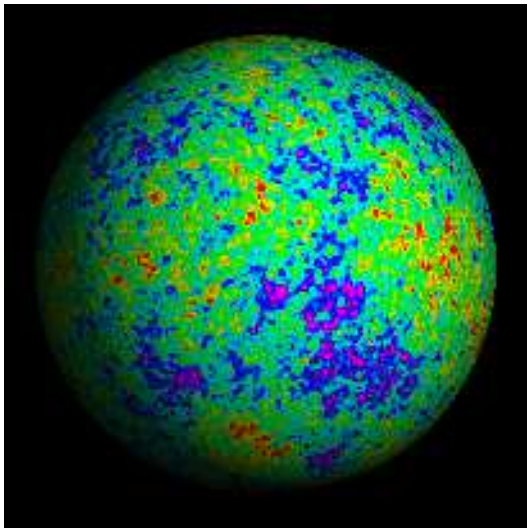
Computer simulation of **evolution of universe** showing gravitational clumping of **dark matter**. Clumped dark matter attracts ordinary matter (H and He gas), facilitating gravitational collapse into stars ⏤ stars gravitationally collapse into galaxies ⏤ galaxies gravitationally collapse into clusters of galaxies (large scale structure of the universe). *Without dark matter, it's hard to understand how the large scale structure we see could have evolved*.

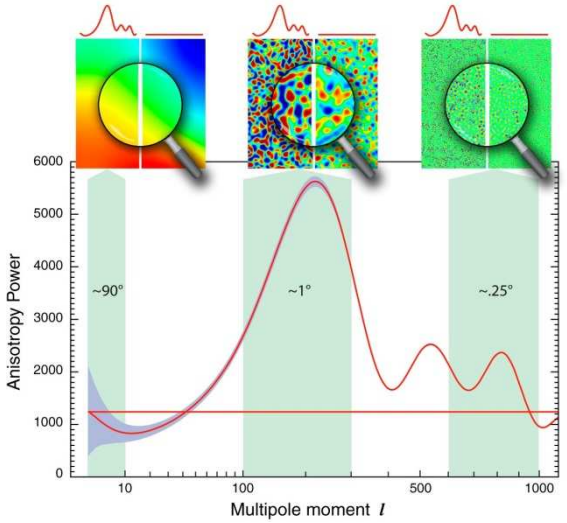
Composition & Structure—Dark Matter



- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
  - **Cosmic microwave background**
  - The “afterglow of the Big Bang” contains evidence about the amount of dark matter there should be in the universe (“twenty-sigma detection”!). Discuss this more later…

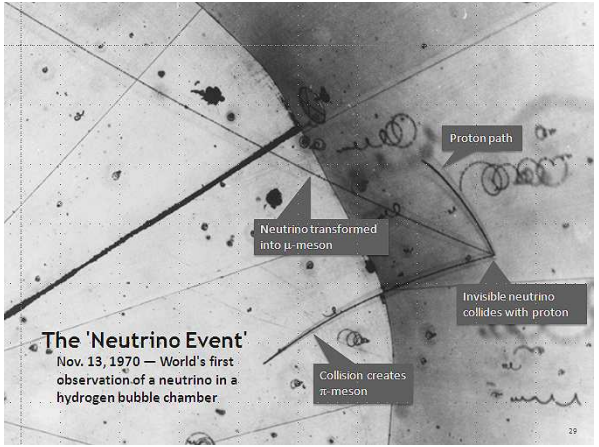






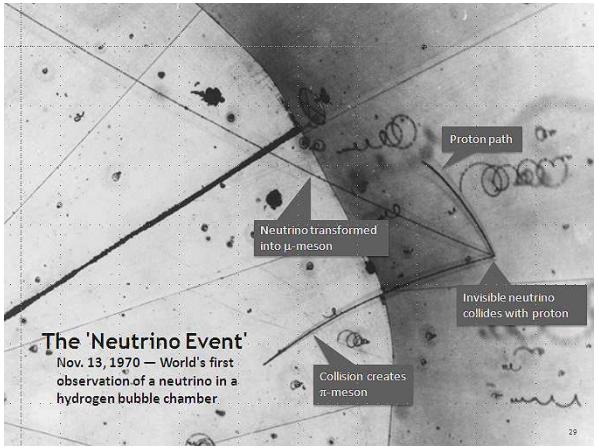
- Strong general consensus: Dark matter is really present. **But what is it?**
  - **Baryonic** dark matter?
    - ✓ ***Baryons*** are mainly **protons and neutrons** making up **ordinary matter** (atoms)
    - ✓ Big Bang nucleosynthesis **limits the amount of ordinary matter** (more later…)
    - ✓ Of this ordinary matter, only about 20% is luminous; **80% is dark**
    - ✓ **Examples** of **dark ordinary matter**: black holes, other dark & dense remnants of dead stars, brown dwarfs, planets, warm or cold gas (most of it)
    - ✓ But in total, the amount of dark ordinary matter is **far short** of what is needed. Most of the dark matter must be ***nonbaryonic*** (not protons & neutrons)

- Strong general consensus: Dark matter is really present.
  But what is it?
  - **Nonbaryonic** dark matter. Two possibilities:
  - **Hot** (fast-moving)
    - ✓ Example: **Neutrinos**.
      - **Second most abundant** particle in the universe (after the photon)
      - More than a **billion** neutrinos for every proton created by the Big Bang
      - Interact only though **gravity** and **weak nuclear force** → hard to detect
      - **Problem:** $m_\nu \ll m_e$: Total mass of neutrinos < 1% total dark matter mass



What is a Neutrino?

- Strong general consensus: Dark matter is really present.
  But what is it?



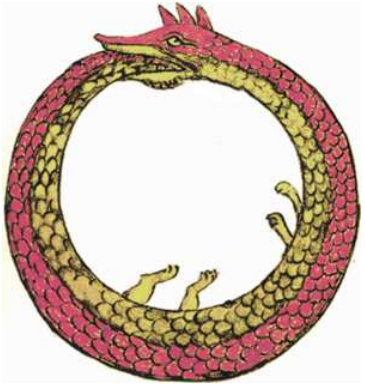
  - **Nonbaryonic** dark matter. Two possibilities:

  - **Hot** (fast-moving)

    - ✓ Example: **Neutrinos**.
      - ➢ **Second most abundant** particle in the universe (after the photon)
      - ➢ More than a **billion** neutrinos for every proton created by the Big Bang
      - ➢ Interact only though **gravity** and **weak nuclear force** ⎵ hard to detect
      - ➢ **Problem:** : Total mass of neutrinos < 1% total dark matter mass

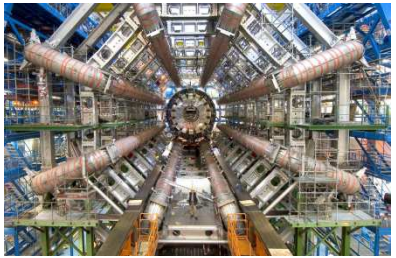
    - ✓ **Bigger Problem:** Hot dark matter particles **don't gravitationally clump** well, in a way that could explain the large scale structure we observe.

- Strong general consensus: Dark matter is really present. **But what is it?**
  - **Nonbaryonic** dark matter. Two possibilities :
  - **Cold** (slow-moving)
    - ✓ **WIMPs**: Weakly Interacting Massive Particles (like neutrino, but heavier)
    - ✓ **Axions**: Hypothetical particle invented to explain the "strong CP problem in QCD"
    - ✓ And others; this gets deep into particle physics. **Amazing**: *the strong new interplay between particle physics (physics of the **very small**) and cosmology (physics of the **very large**)*



- Strong general consensus: Dark matter is really present. **But what is it?**
  - **Current consensus view** is that dark matter is primarily composed of a mysterious new type of **subatomic particle** that is **slow-moving (cold)**
  - **Other ideas:**
    - ✓ **Alternative theories of gravity:** dark matter reveals itself gravitationally; maybe we just have gravity wrong, and there is no dark matter!
    - ✓ **Matter in extra dimensions**, that interacts only gravitationally with matter in our universe?
    - ✓ **Primordial defects** in the topology of quantum fields, which contain energy and therefor gravitate?
    - ✓ **Etc.** Very active area of physics. Symmetry Magazine article.

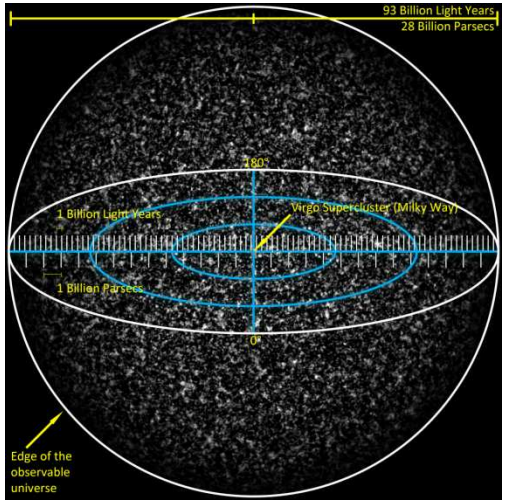
- **Searching** for dark matter particles:
  - **Direct** detection:
    - ✓ Detect naturally-occurring dark matter particles in labs deep underground (to reduce background cosmic rays), e.g., SNOLAB
    - ✓ Generate & detect dark matter particles in accelerators (LHC)

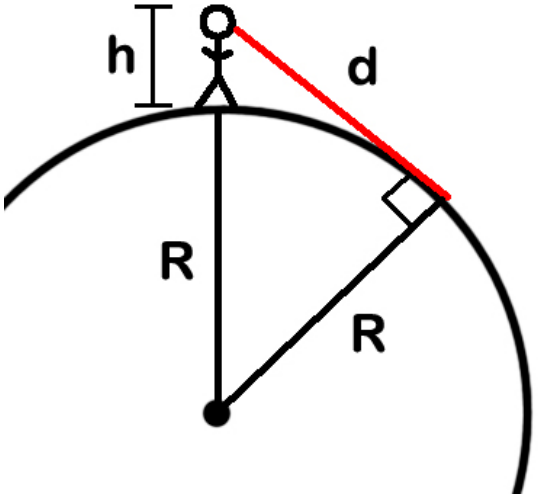


  - **Indirect** detection:
    - ✓ Dark matter annihilation or decay can produce gamma rays or particle-antiparticle pairs. Excess gamma rays or antimatter from regions of high dark matter density might provide indirect evidence.

  - **No conclusive evidence** so far…

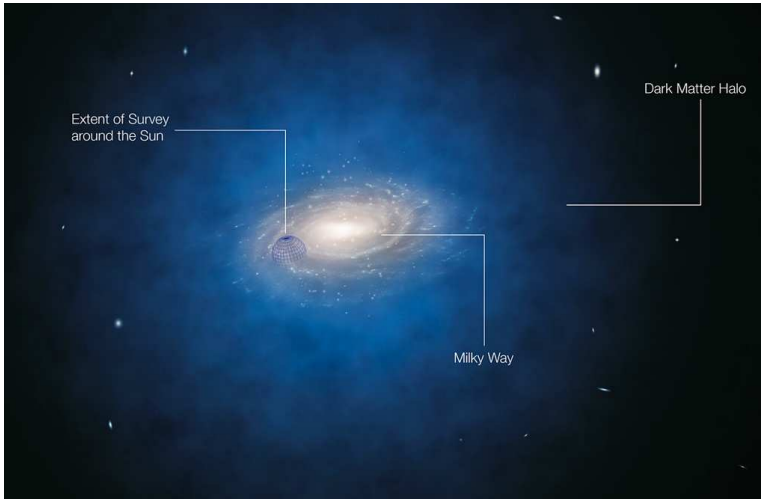
- Summary:
  - The **observable** universe is **big**: about **46 billion light-years** in radius. It almost certainly extends **beyond our cosmological horizon**, how far no one knows. Estimates range from at least 100s of times larger than the observable universe (by measure of **flatness**…) to at least of times larger than the observable universe (by **inflation theory**).

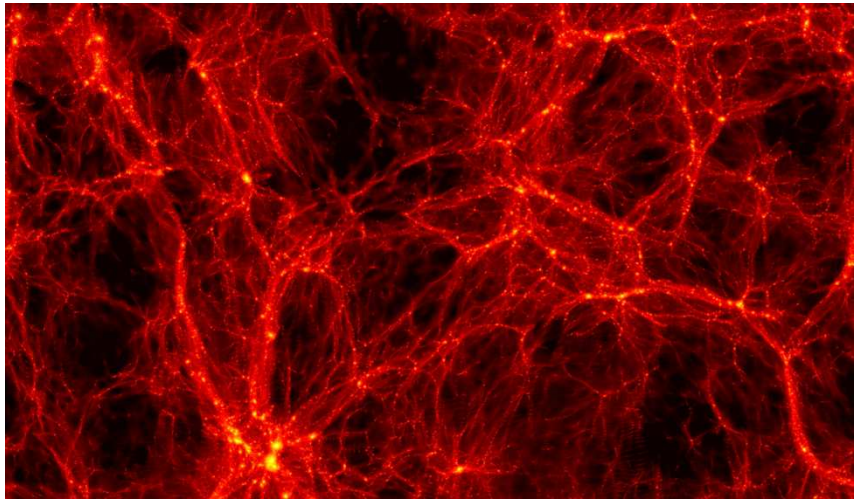




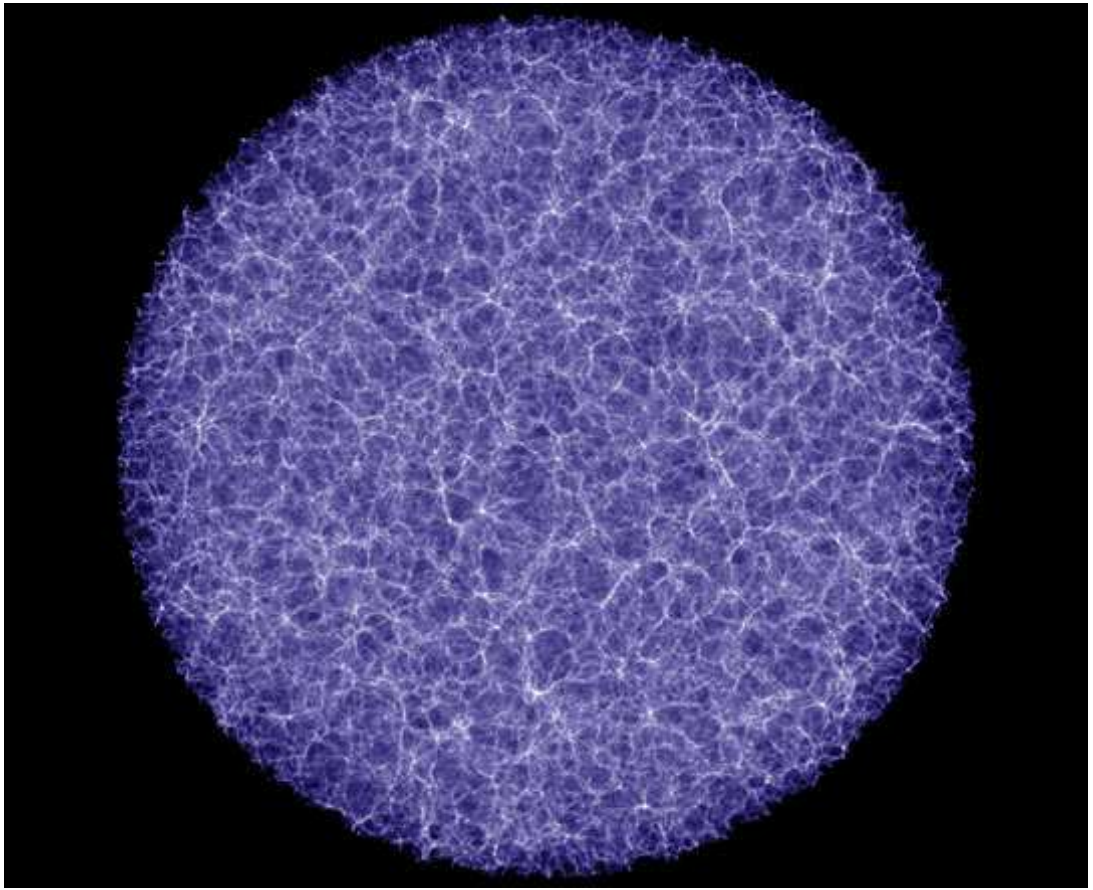
- Summary:
    - **15%** of the matter in it is **ordinary (baryonic) matter** in the form of stars, gas, and dust. There are **several hundred billion** galaxies in the observable universe, many (like our own Milky Way galaxy) having **several hundred billion** stars or more and a central **supermassive black hole** (more later…).

- Summary:
  - **85%** of the matter in it is invisible **nonbaryonic dark matter**, inferred to exist by its **gravitational effect** on stuff we *can* see. No one knows what it is, but **best guess** is a new type of subatomic particle that is slow-moving (cold). It is one of the **greatest mysteries** of our times, with a worldwide race to unravel it…

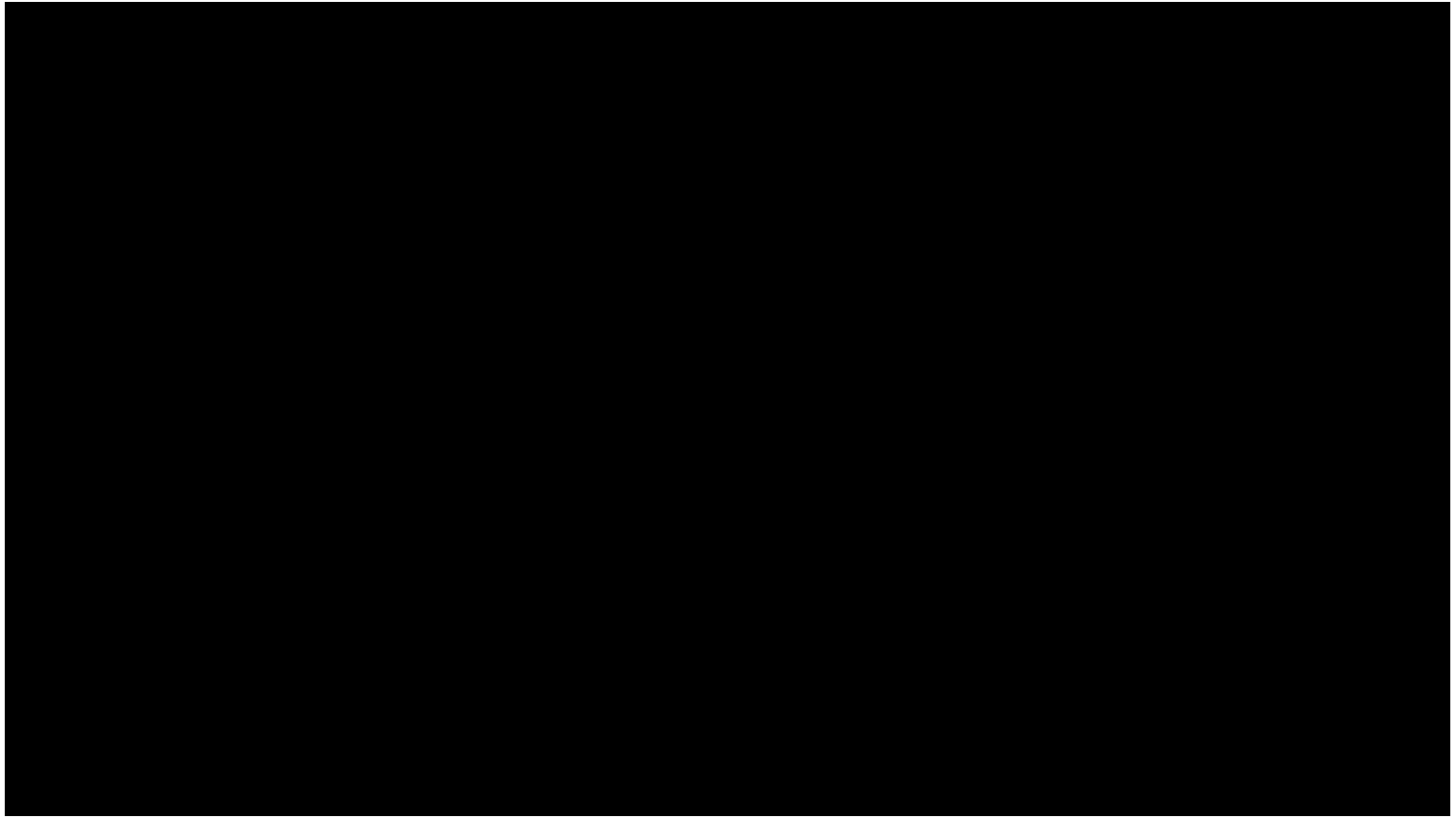




- Summary:
  - This matter has **structure on all scales**: people, planets, solar systems, galaxies, galaxy clusters and galaxy superclusters (and voids).
  - **Dark matter** forms the **backbone** of this structure, onto which ordinary matter gravitationally collapsed.
  - Averaged over very large distances, this matter (ordinary & dark) fills all of space **almost perfectly uniformly**.



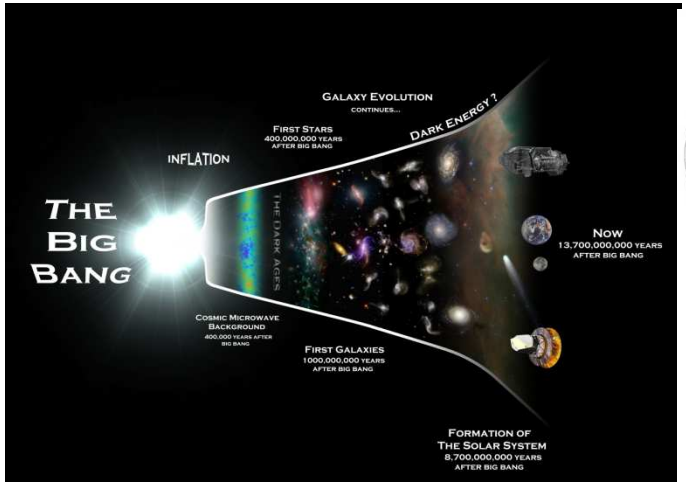
- Summary:
  - Observable universe on **logarithmic scale**, with the Solar System at the center, inner & outer planets, Kuiper belt, Oort cloud, Alpha Centauri, Perseus Arm, Milky Way galaxy, Andromeda galaxy, nearby galaxies, Cosmic Web, Cosmic microwave background radiation, near the edge of the observable universe. (Wikipedia)

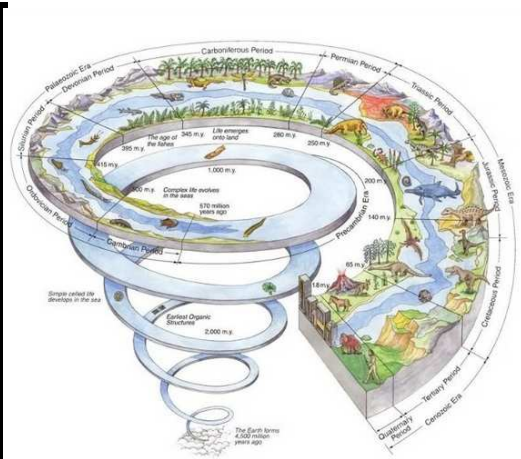


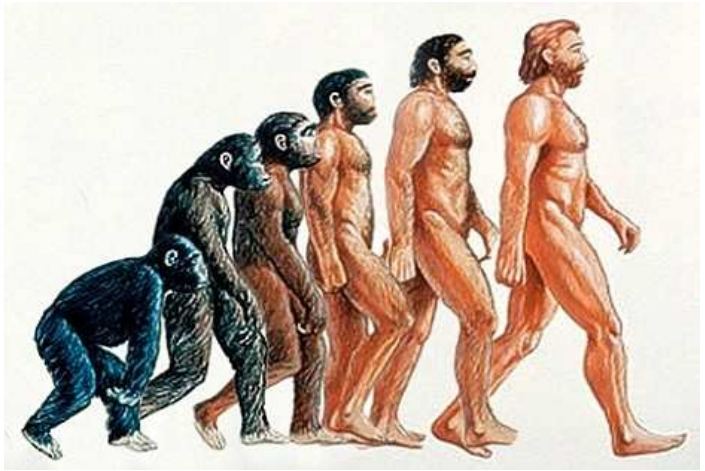
Evolution of the Universe

- **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

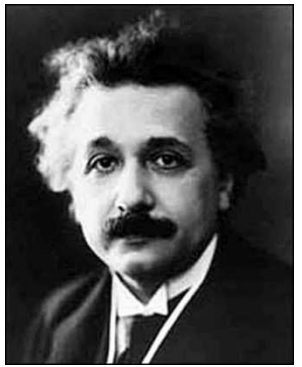
- Some possibilities regarding **evolution** of the universe:
  - Universe is **static** and **eternal** (no beginning or end)
    - ✓ Articulated clearly by **Giordano Bruno in 1584**:

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

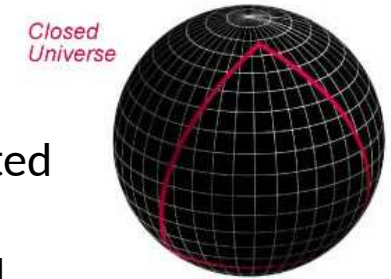
    - ✓ First to imagine an **infinite** universe **filled with stars**, each with their own **planets**, and **no centre** to the universe ("Copernican principle")
    - ✓ Also wrote: other worlds "have no less virtue nor a nature different to that of our Earth" and, like Earth, "**contain animals and inhabitants**"

Evolution of the Universe

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

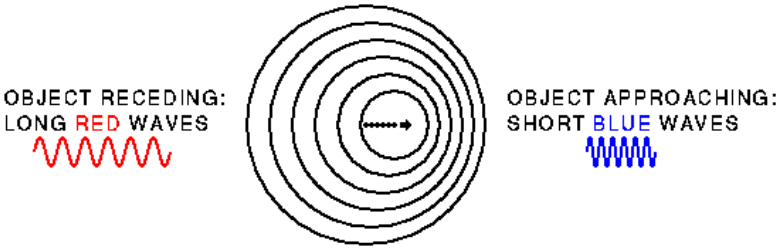


    - ✓ **Cosmology** as a **science** began in the early 20th century with the advent of Einstein's **general theory or relativity**, a geometrical theory of space, time, and gravity (1915).
    - ✓ **1917: Einstein** applied his new theory to cosmology. Worried about imposing **ad hoc** boundary conditions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

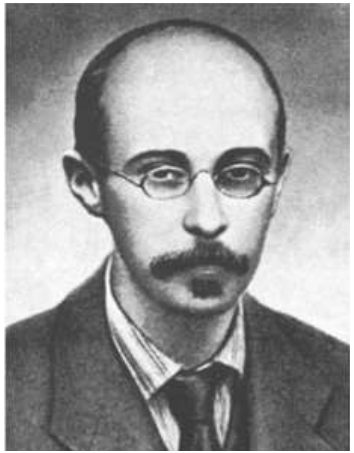
- Some possibilities regarding **evolution** of the universe:
  - Universe is **dynamic**
    - ✓ **1912: Vesto Slipher** measured the **redshift** of "spiral nebulae" and interpreted this redshift as a **Doppler shift**: the "spiral nebulae" were all moving away from us ⎵ something **dynamic**

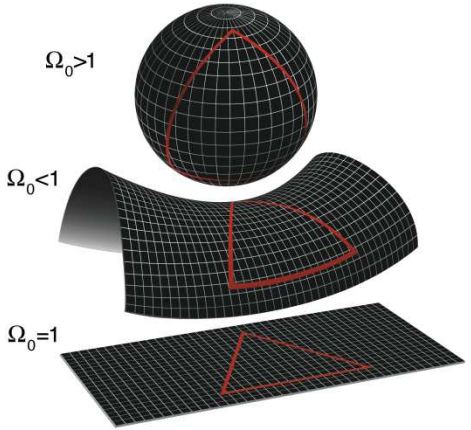


    - ✓ But he didn't know their **extreme distance**—that the "spiral nebulae" were **separate galaxies outside of our own**, and so didn't fully appreciate the cosmic significance of this discovery.

Evolution of the Universe

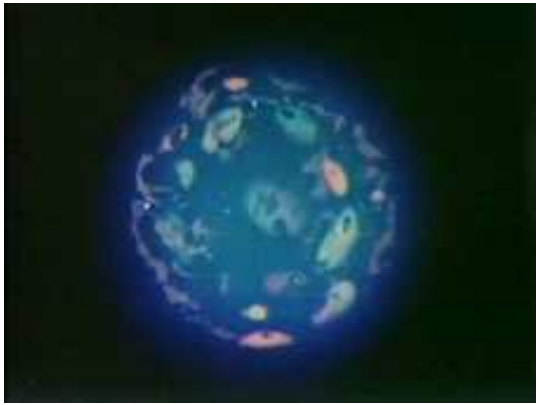
- Some possibilities regarding **evolution** of the universe:
  - Universe is **dynamic**
    - ✓ **1924: Alexander Friedmann** fully understood the cosmological implications of Einstein's general relativity, including that space is **dynamic** (*necessarily* **expands** or **contracts**)
    - ✓ …and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



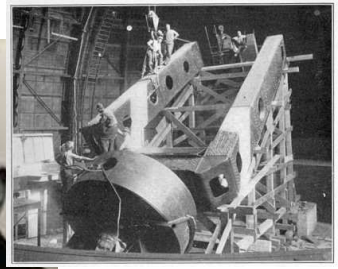


Evolution of the Universe

- 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…

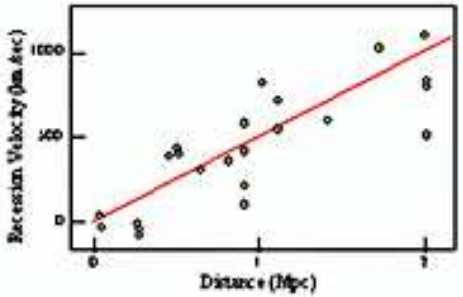


- Some possibilities regarding **evolution** of the universe:
  - Universe is **dynamic** and had a **beginning**
    - ✓ **1929: Edwin Hubble** measured the **distances** to the receding "spiral nebulae" (using **Cepheid variable stars**) and discovered that they were **not** nebulae in our own galaxy,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

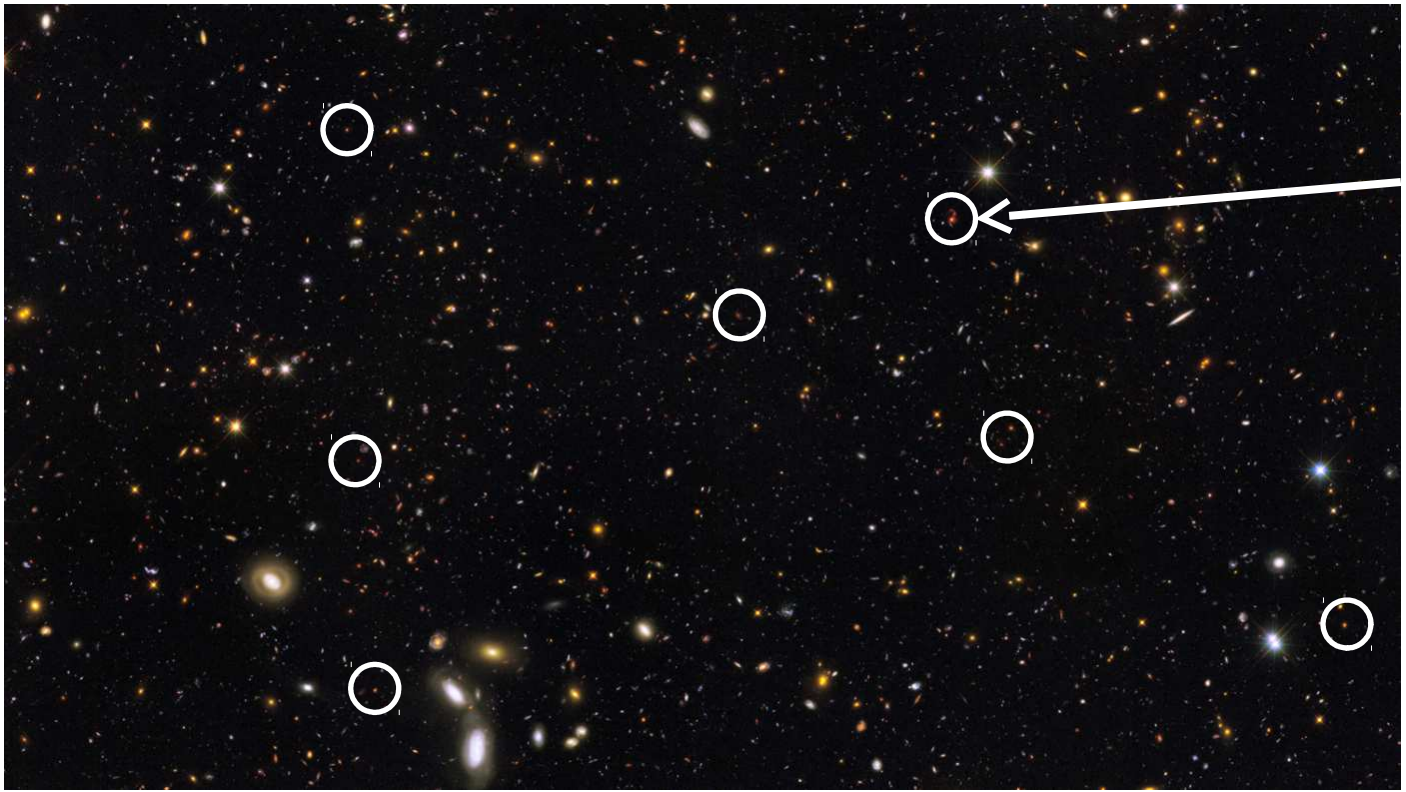
Hubble's Data (1929)



Evolution of the Universe—Expanding Space

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

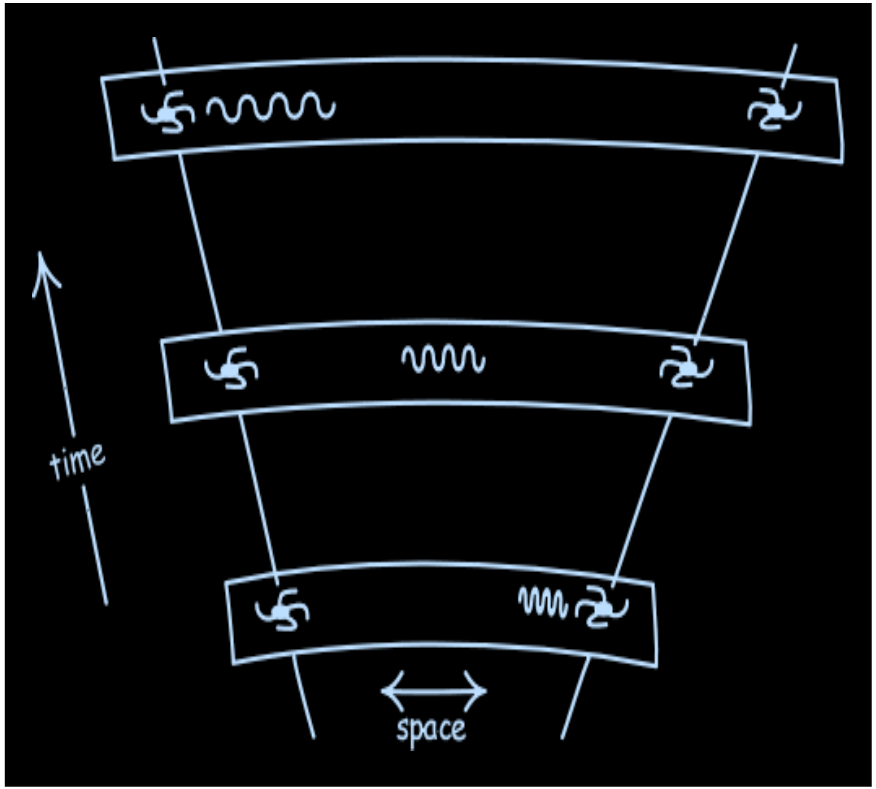
- **First:** What do we mean by **redshift**?

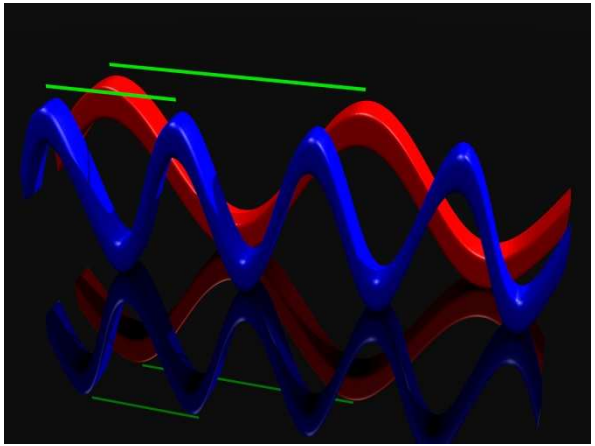


Many galaxies appear **unusually red** in colour

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

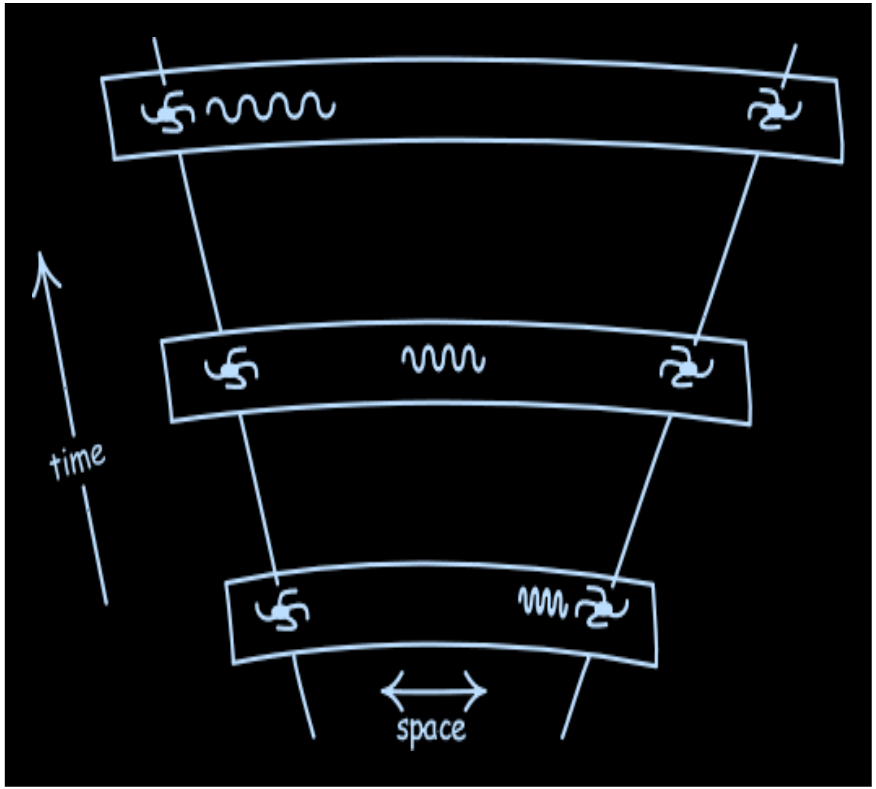
- **Second:** How can **expanding space** explain this **redshift**?

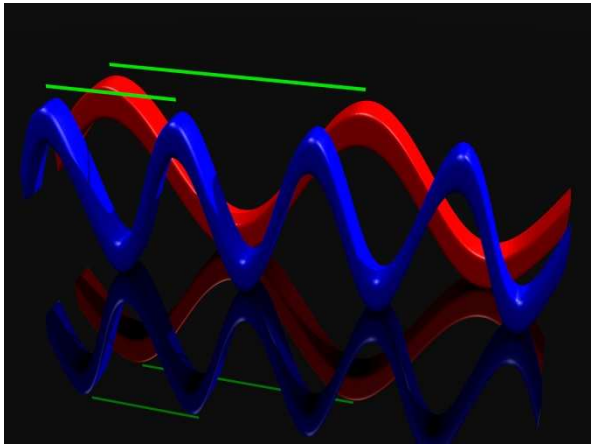




Light waves are **stretched** to **longer wavelengths** as they travel through **expanding** space (but not everything is stretched—more later!)

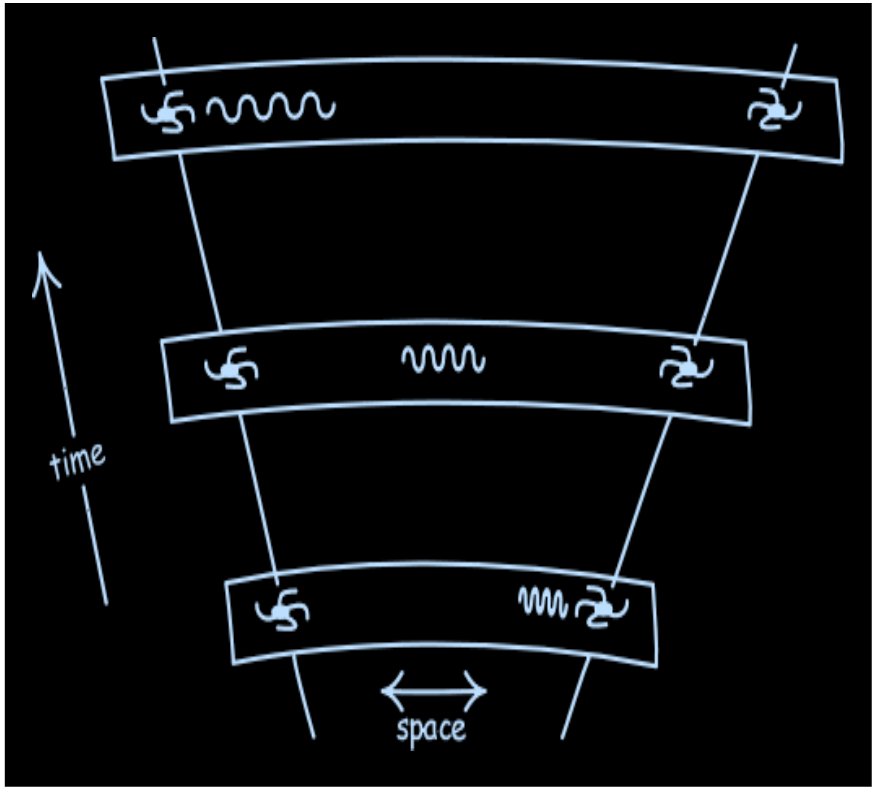
- **Third:** How can **expanding space** explain ***increased*** redshift with **increased** distance?

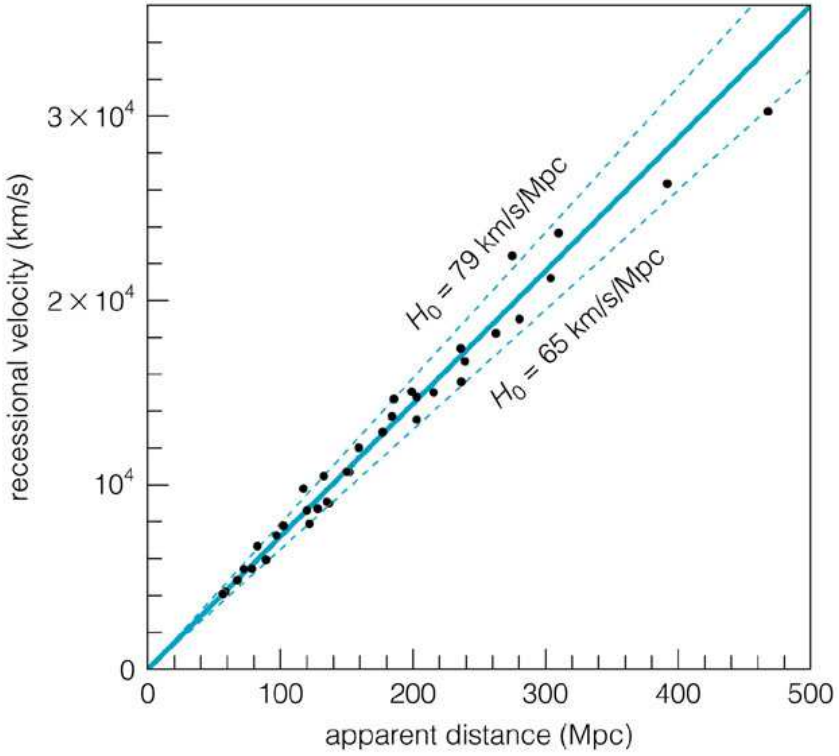




Increased distance means light waves spend a **longer time** in the expanding space, thus stretching to **ever longer wavelengths** (ever more deeply red)

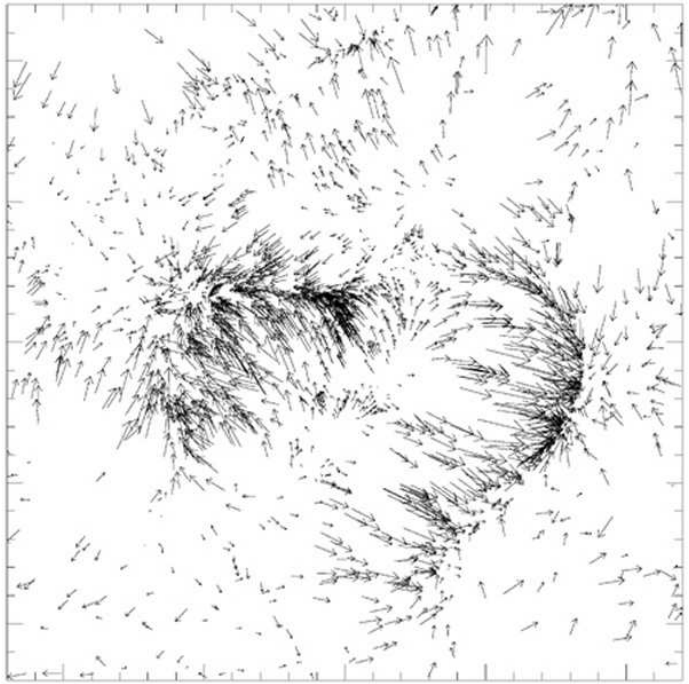
- **Hubble's Law:** Apparent recessional velocity , (km/s) per Mpc

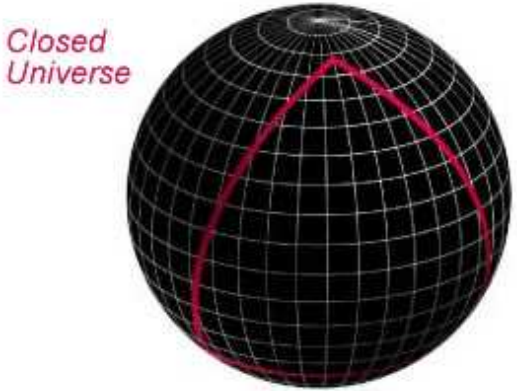


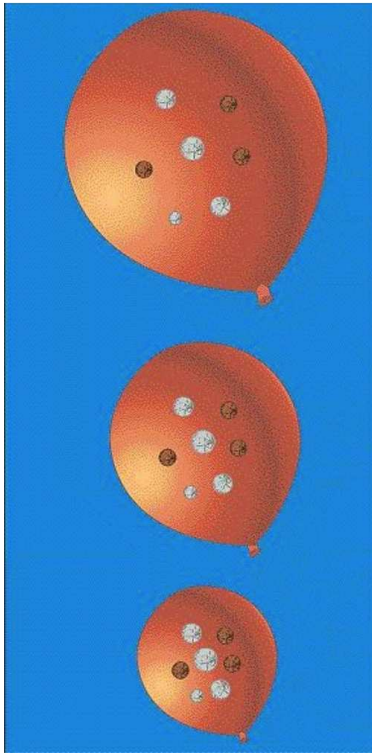


Evolution of the Universe—Expanding Space

- 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.)

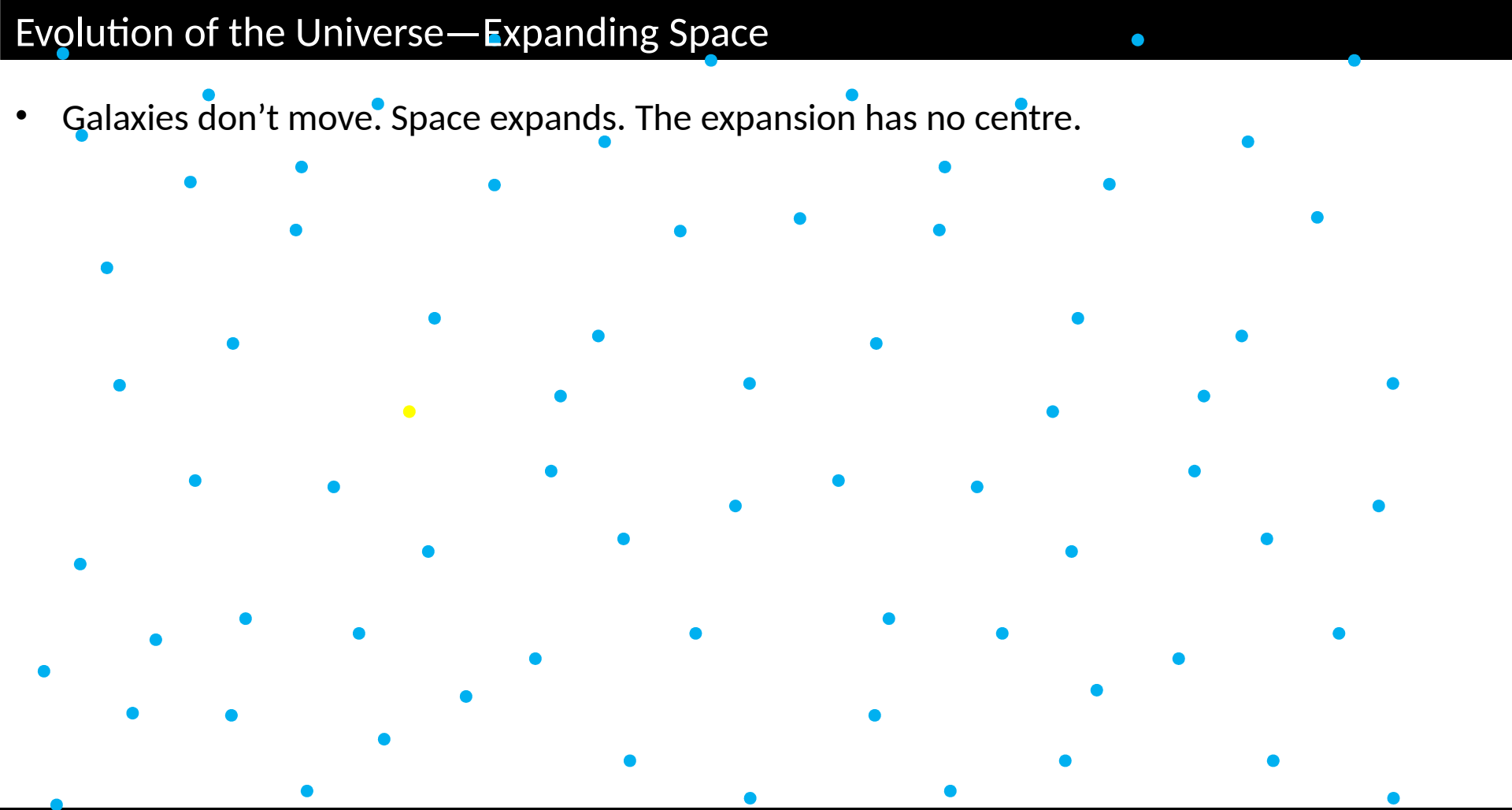






Evolution of the Universe—Expanding Space

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



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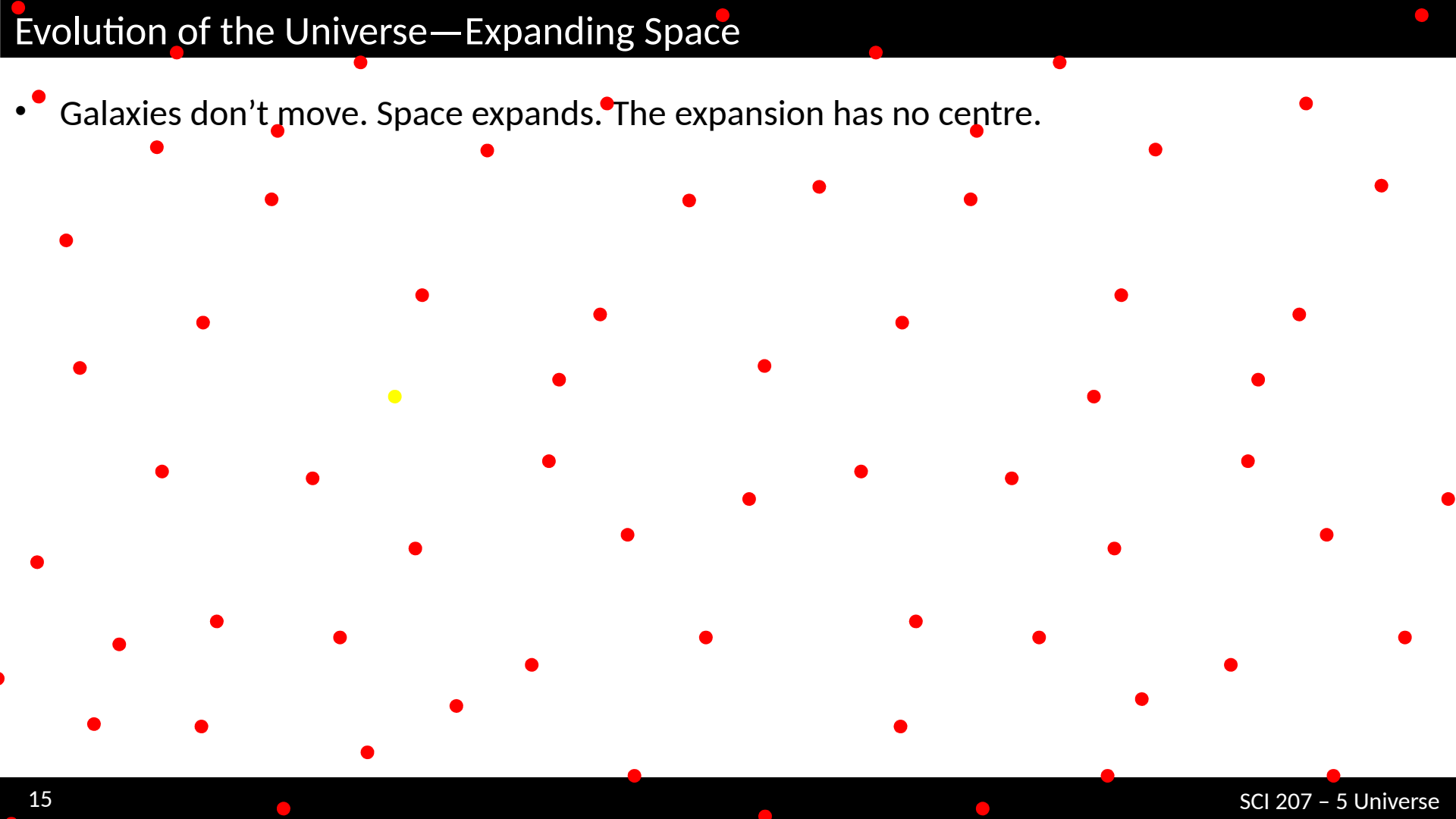

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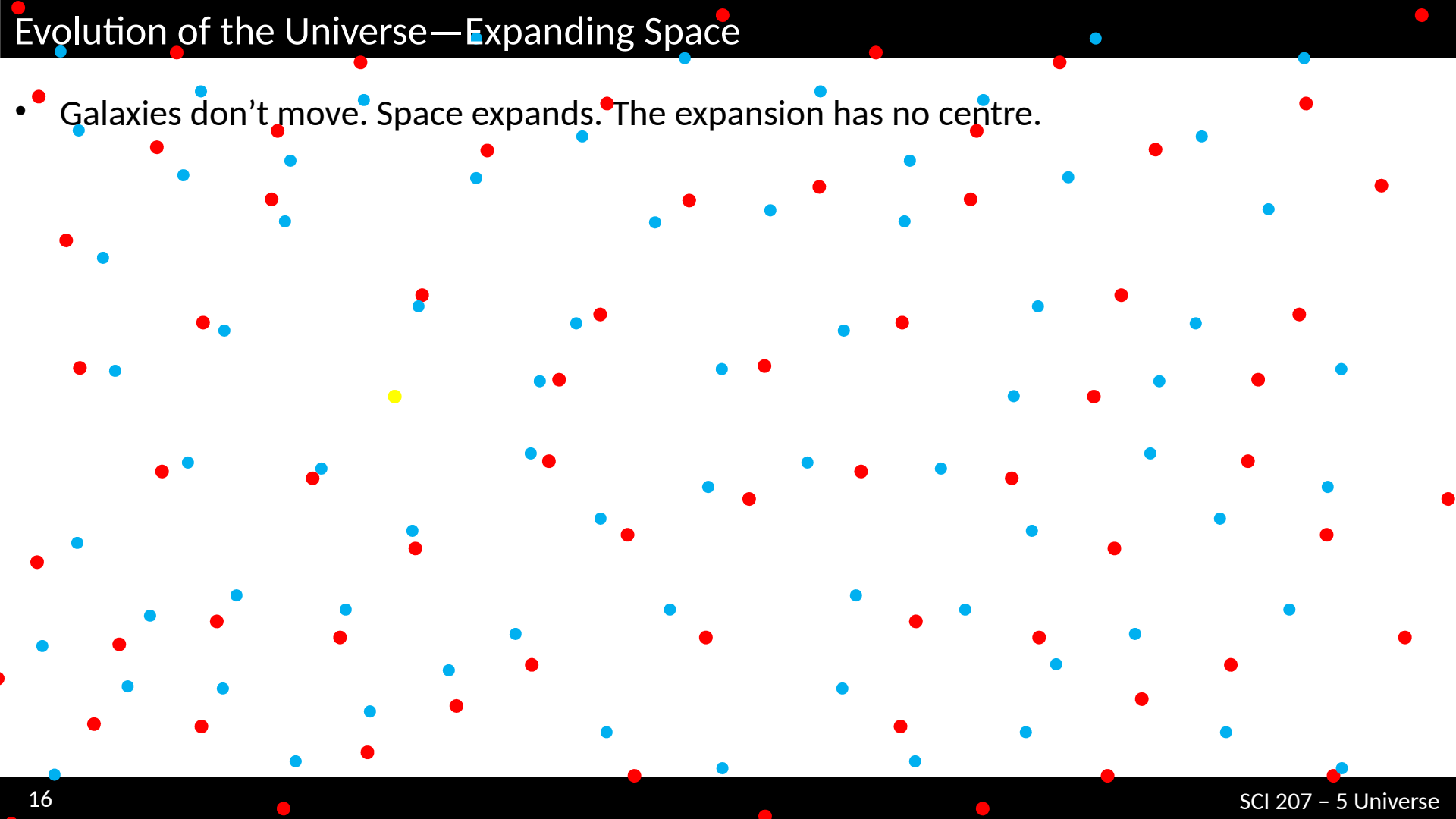

Evolution of the Universe—Expanding Space

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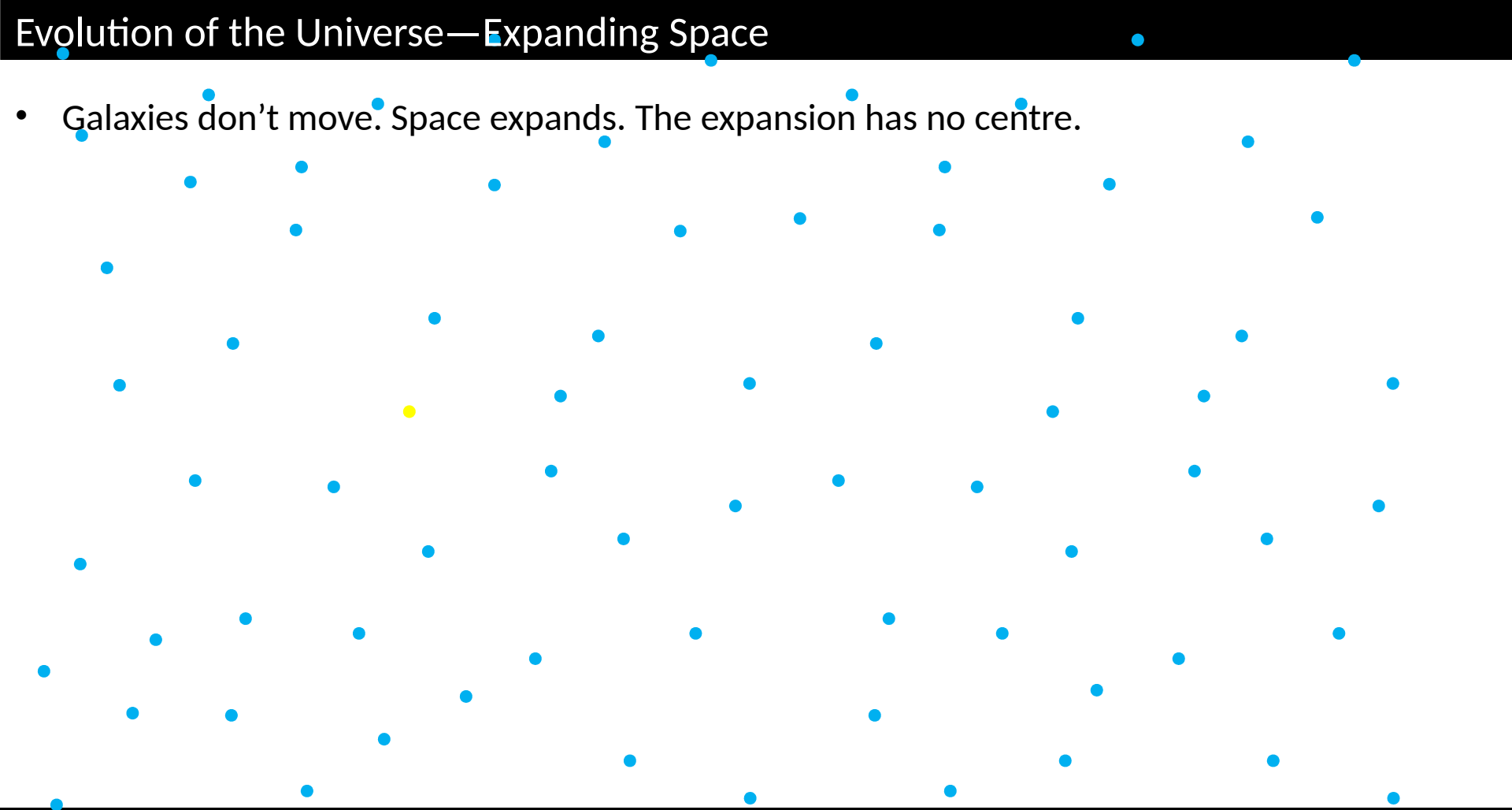

Evolution of the Universe—Expanding Space

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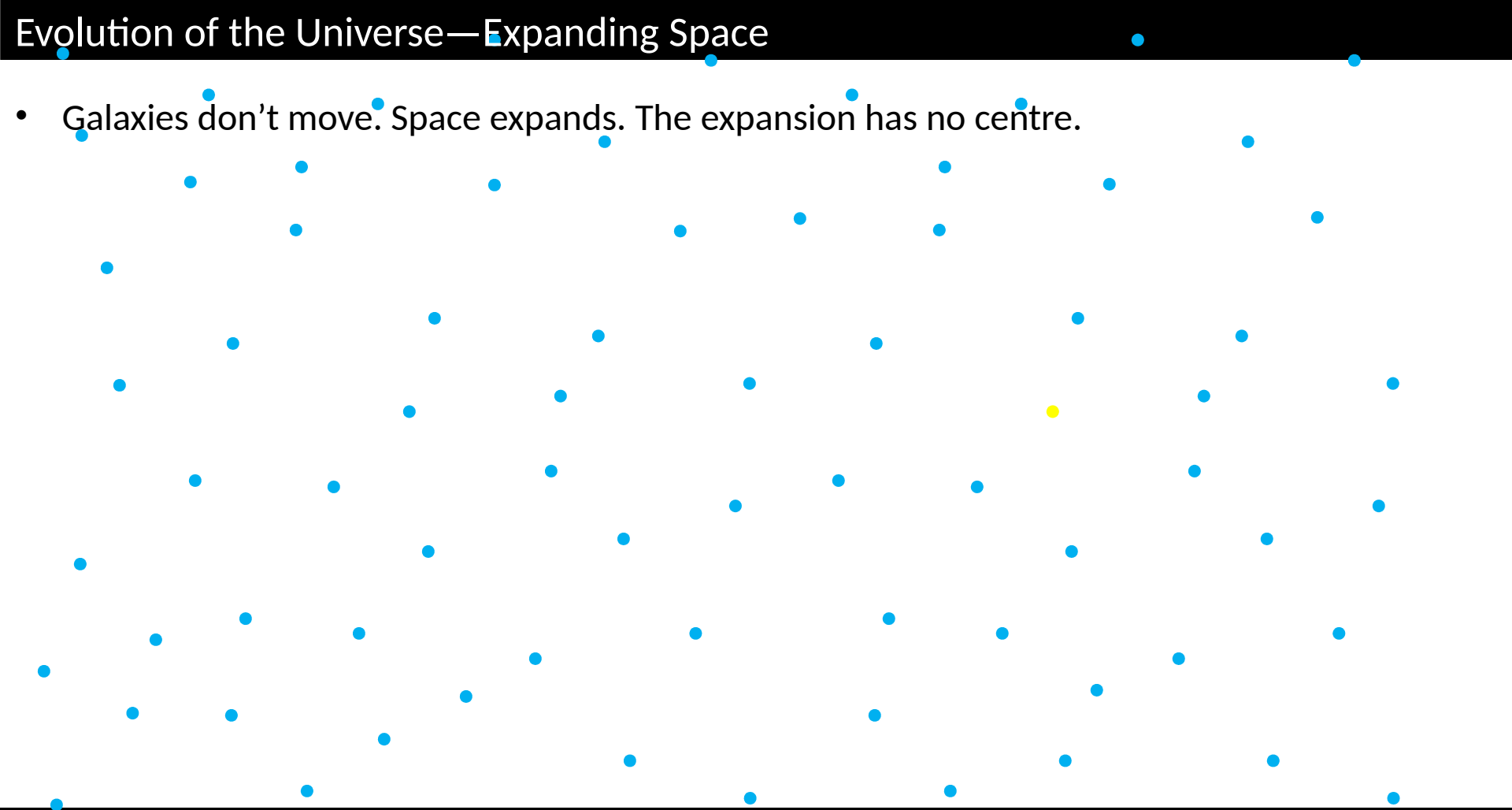

Evolution of the Universe—Expanding Space

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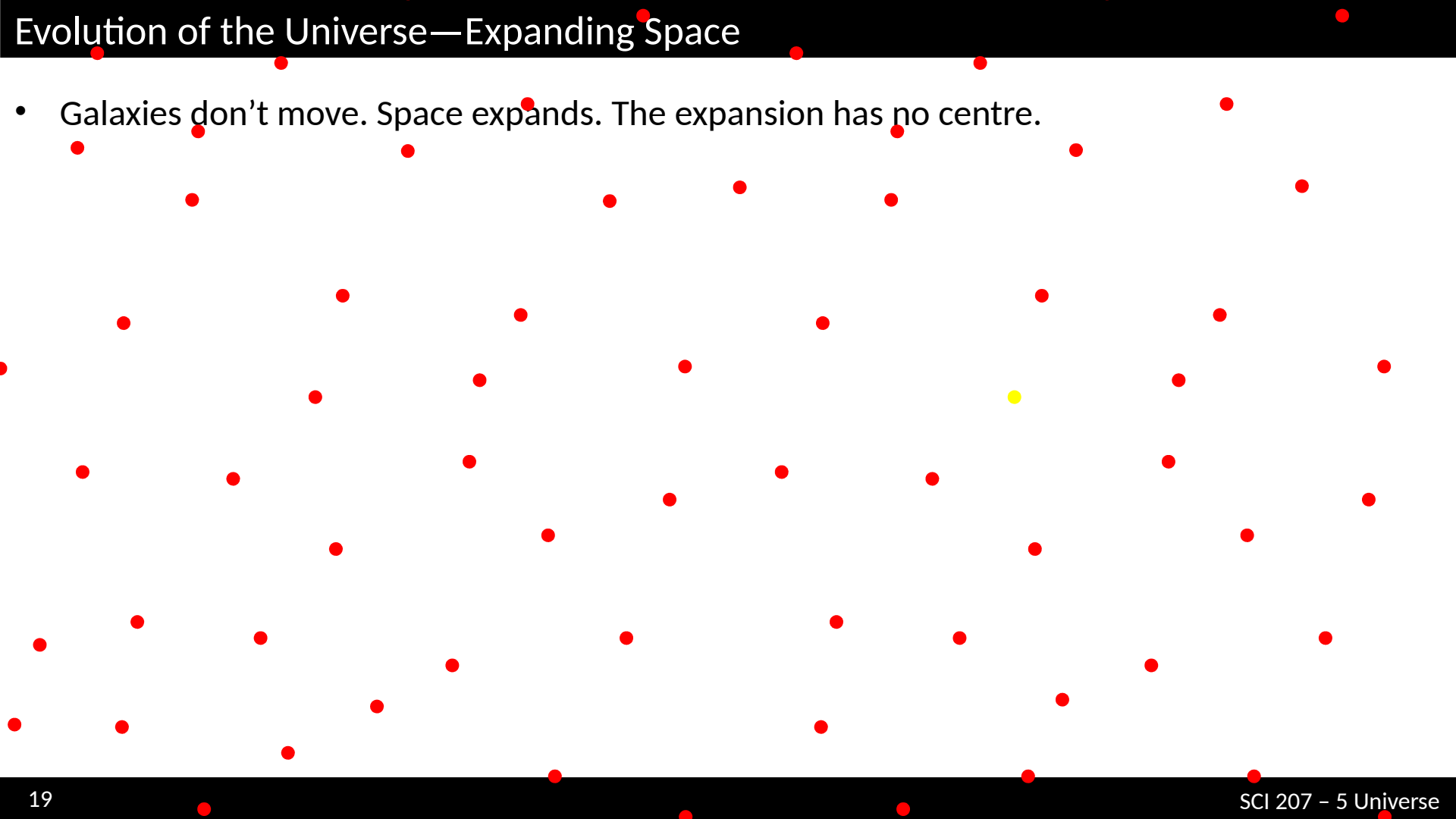

Evolution of the Universe—Expanding Space

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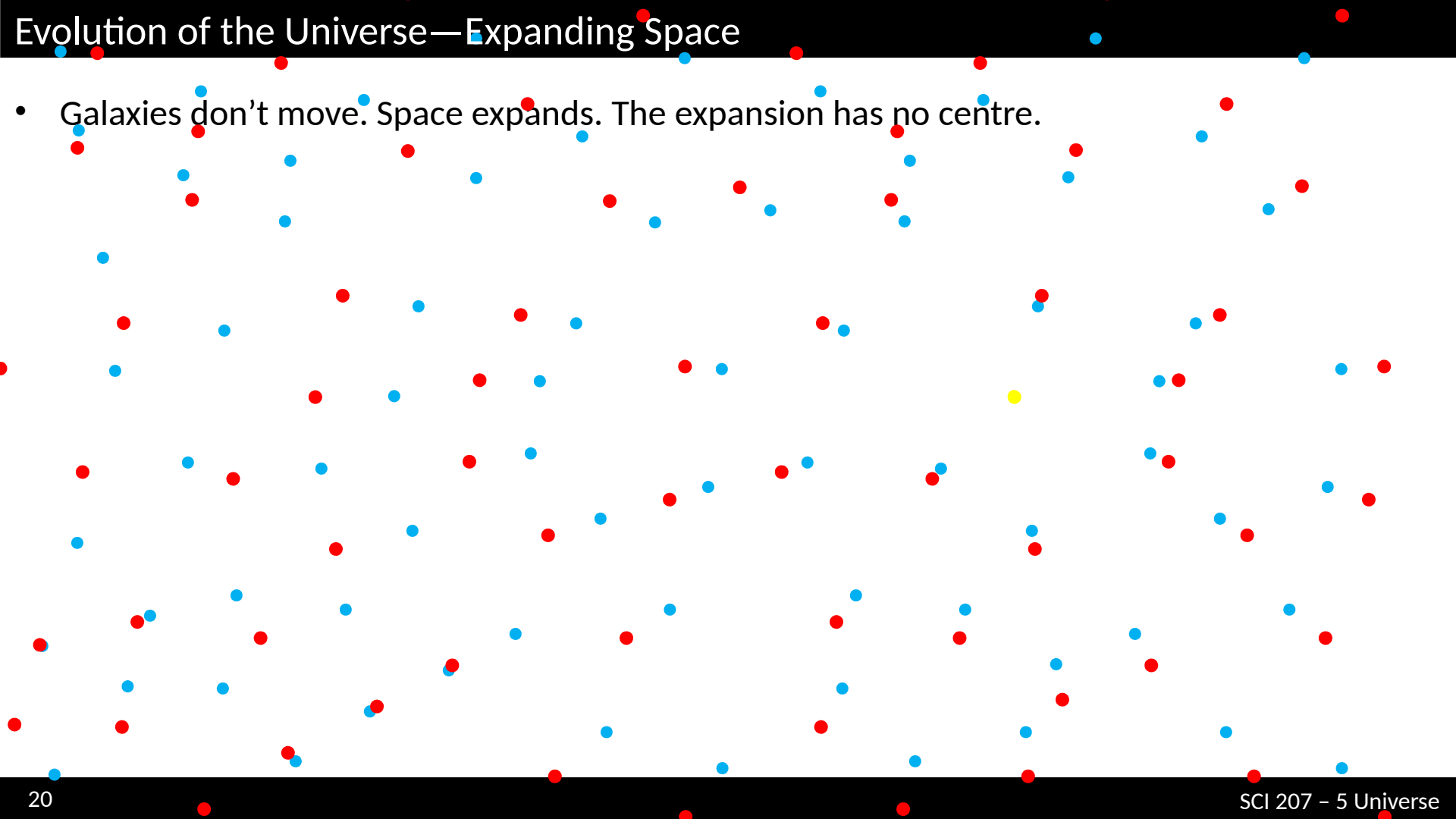
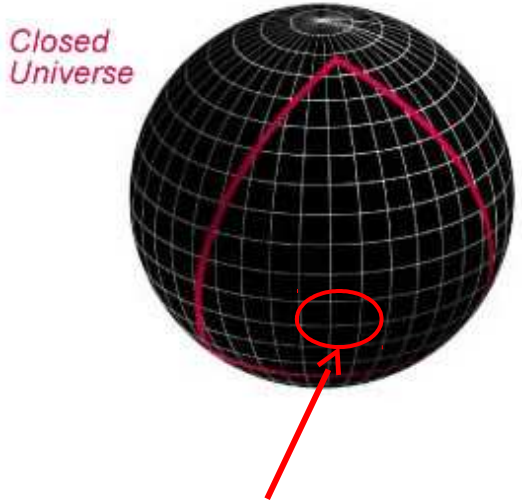


Evolution of the Universe—Expanding Space

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



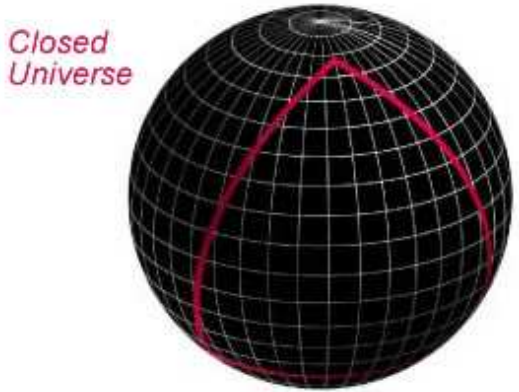
Observable Universe

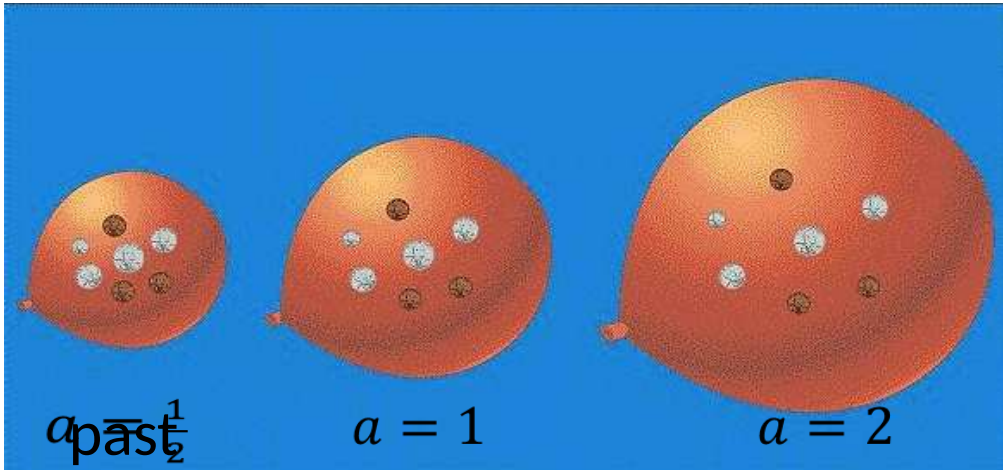
Evolution of the Universe—Expanding Space

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

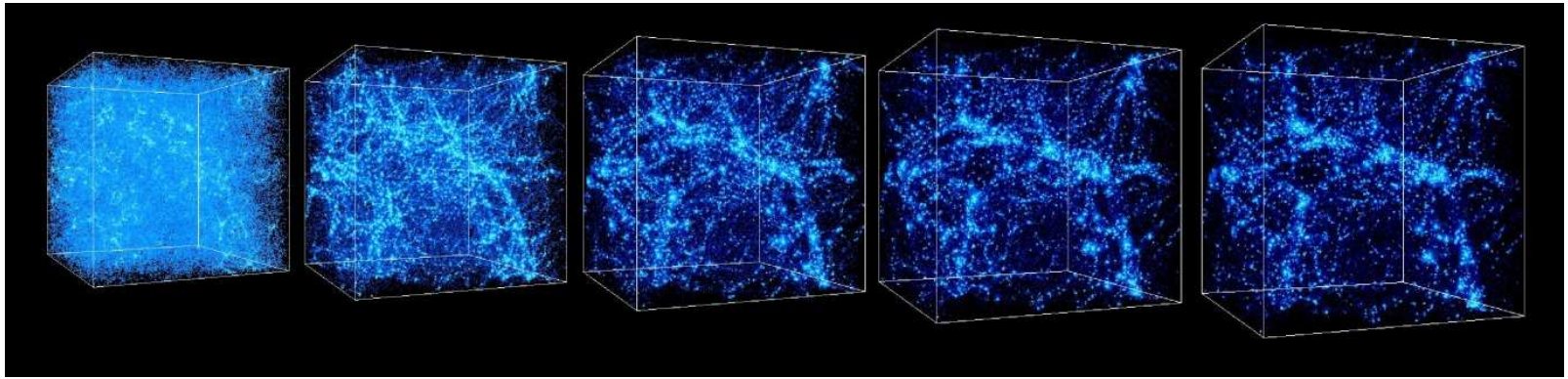
Why don’t **galaxies** (and other things) expand as **space** expands?

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.



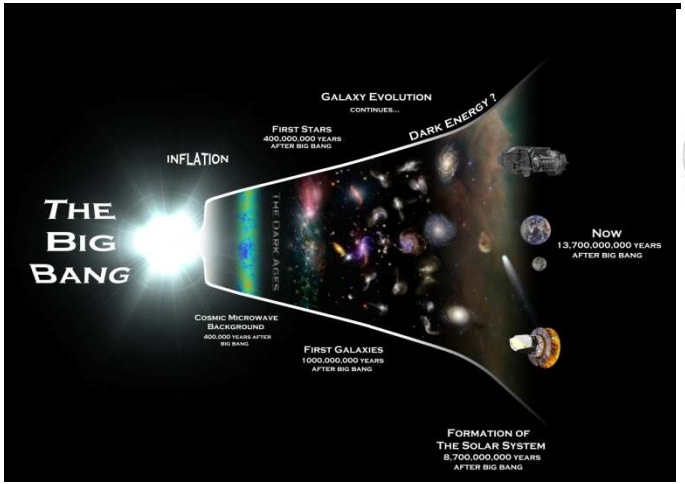
Evolution of the Universe—Expanding Space

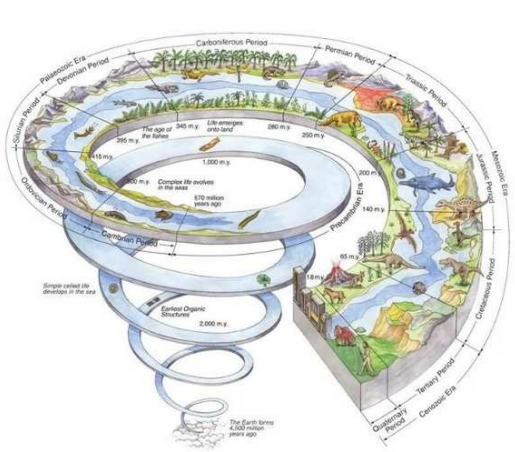
Big Bang = Everywhere Stretch

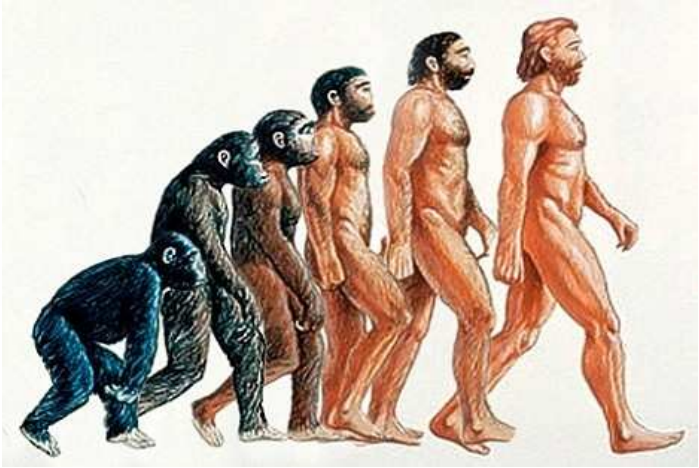
Beginning of the Universe

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



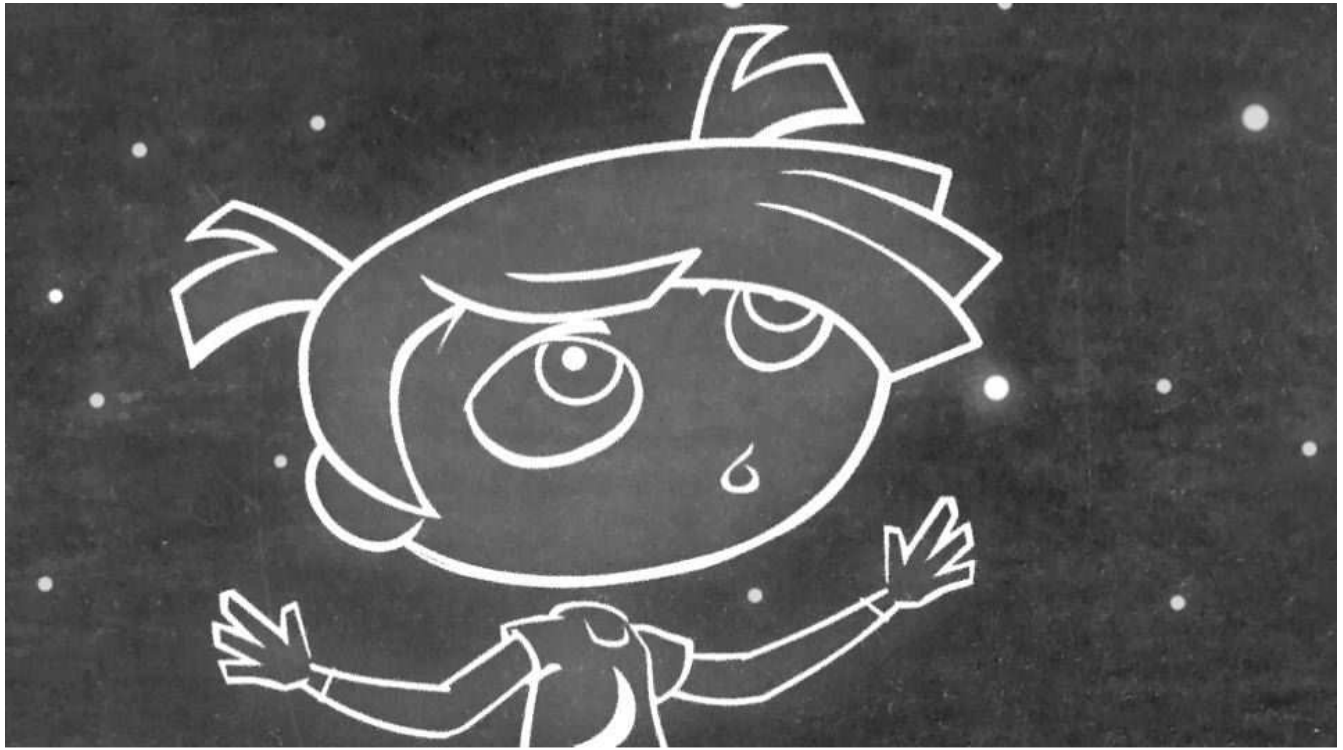


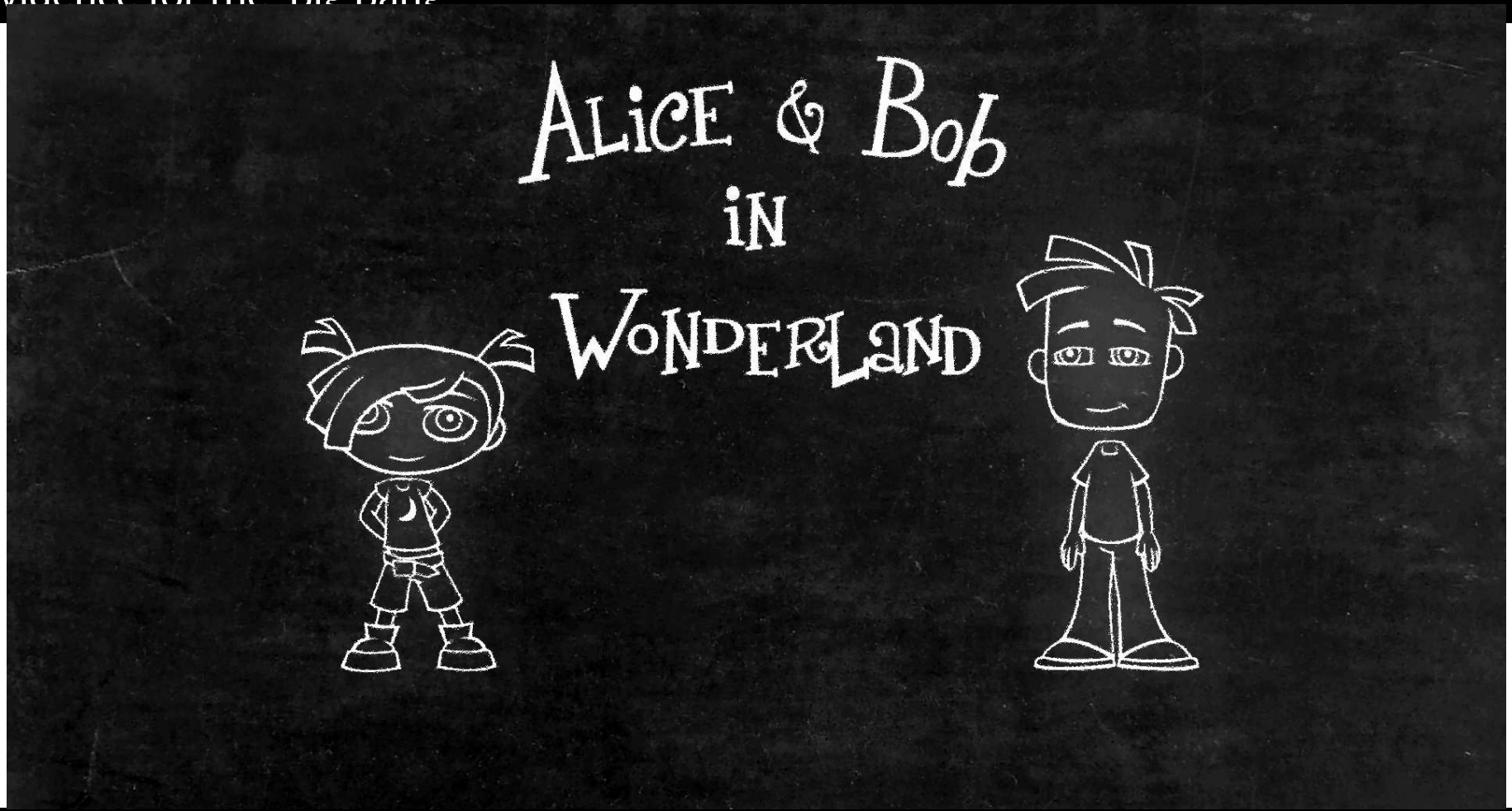


Beginning of the Universe

- 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



- 
Alice & Bob
in
Wonderland

(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

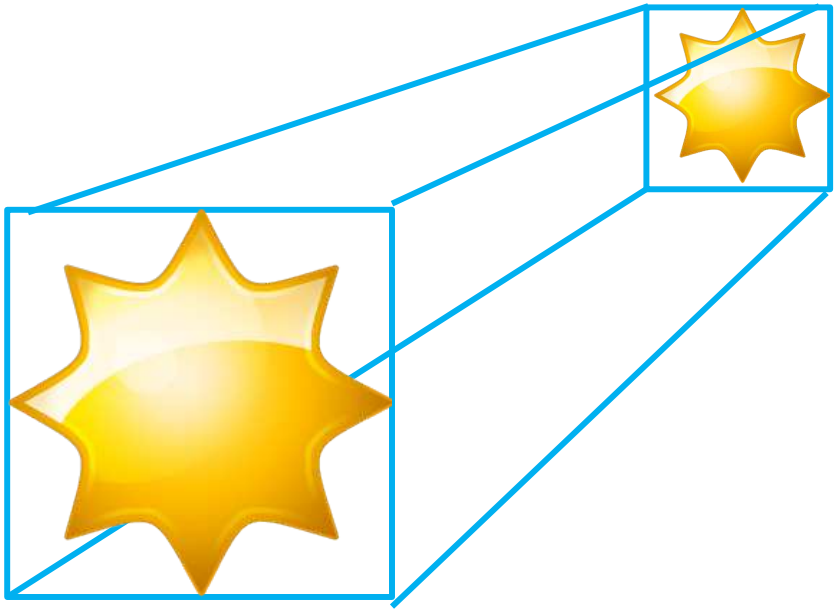
(1) Sky is dark at night

- 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.



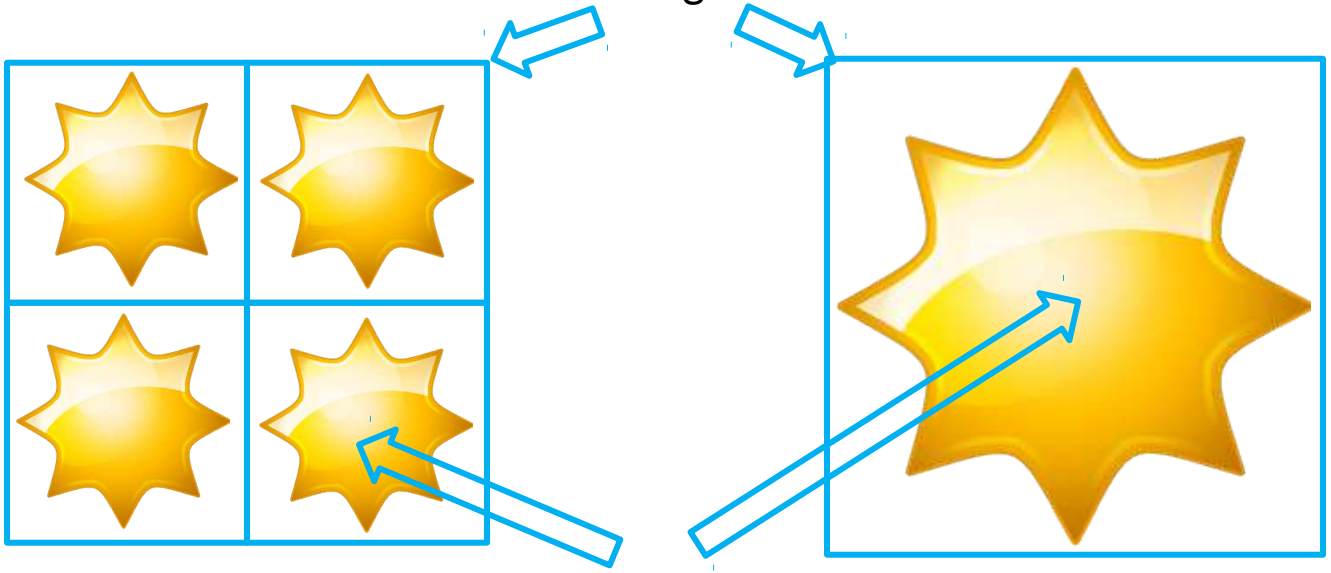
¼ the light

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.

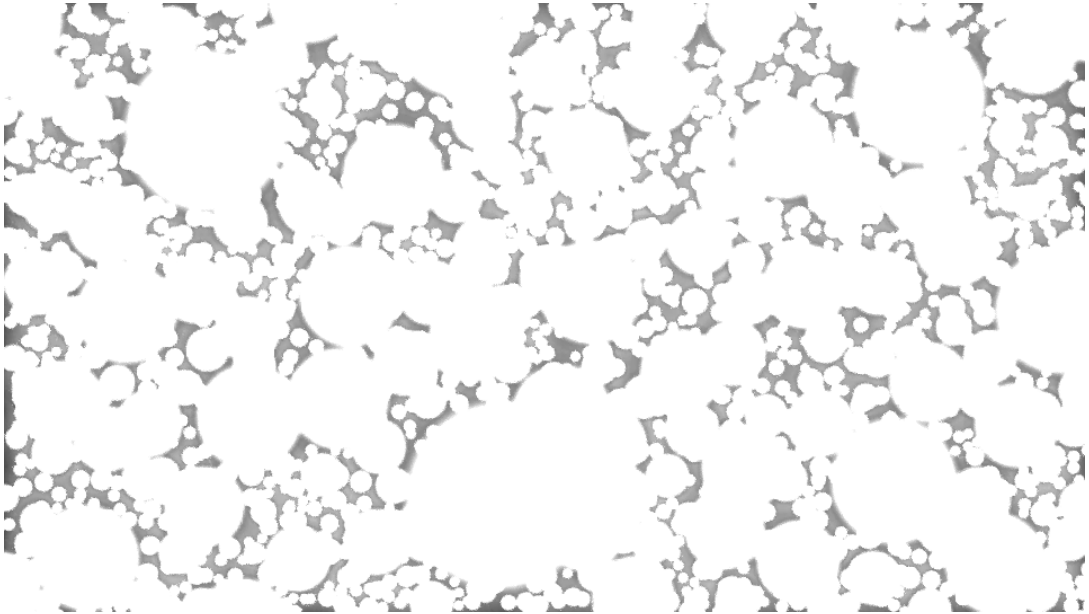
Same **total** light & area



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**

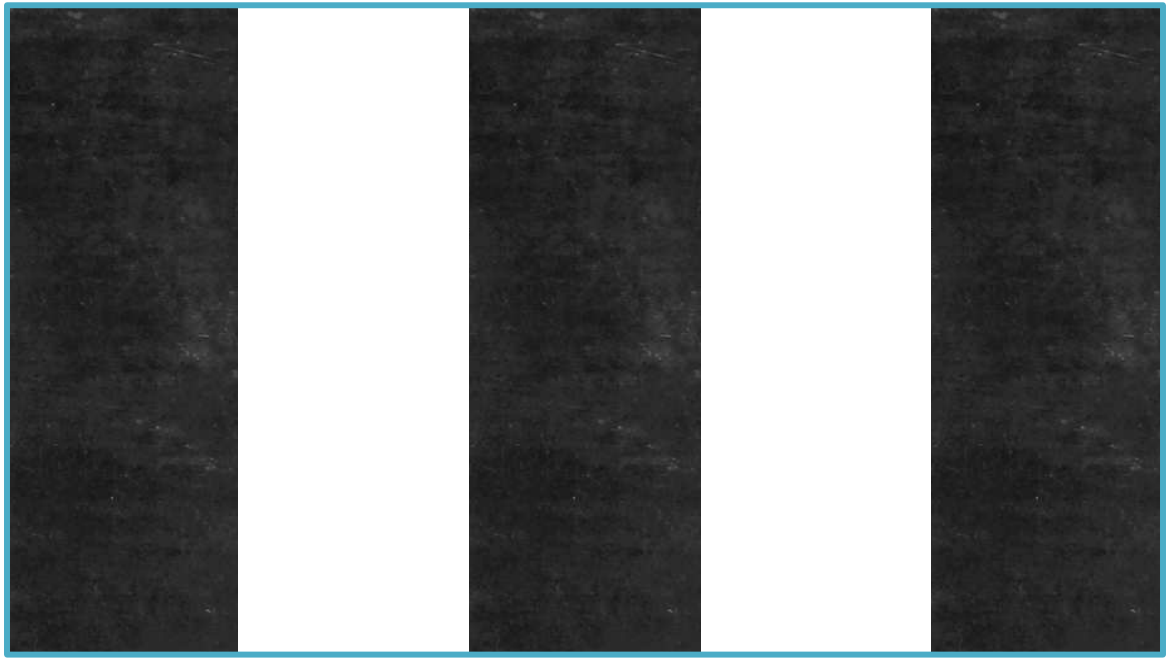
Which one(s)?

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

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(1) Sky is dark at night

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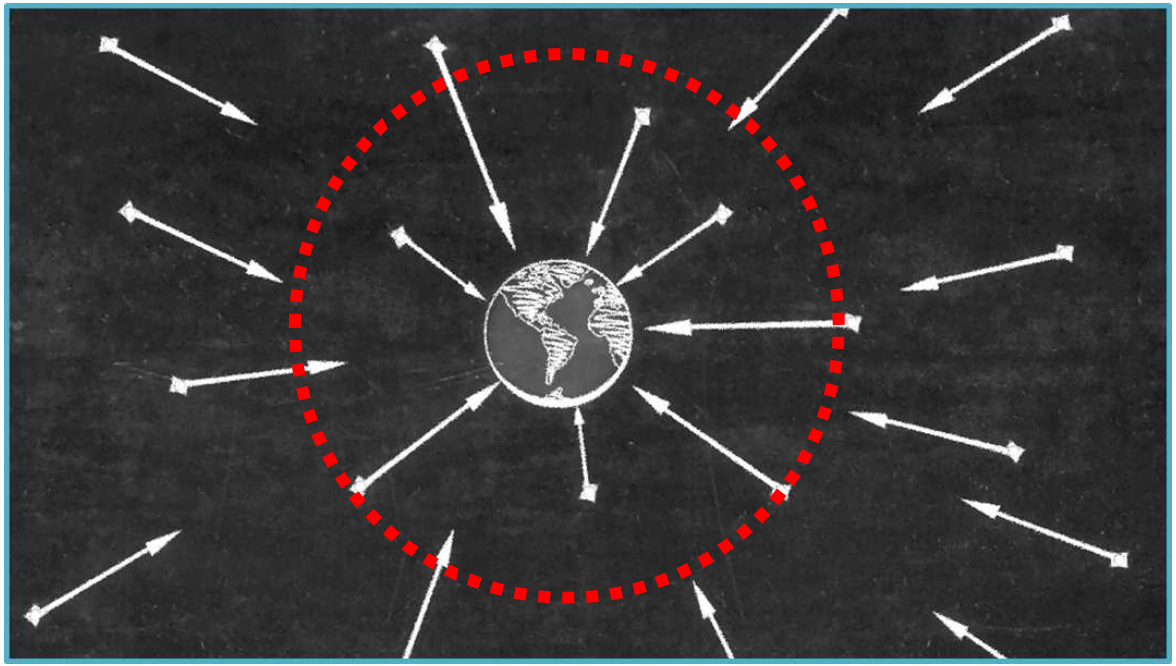
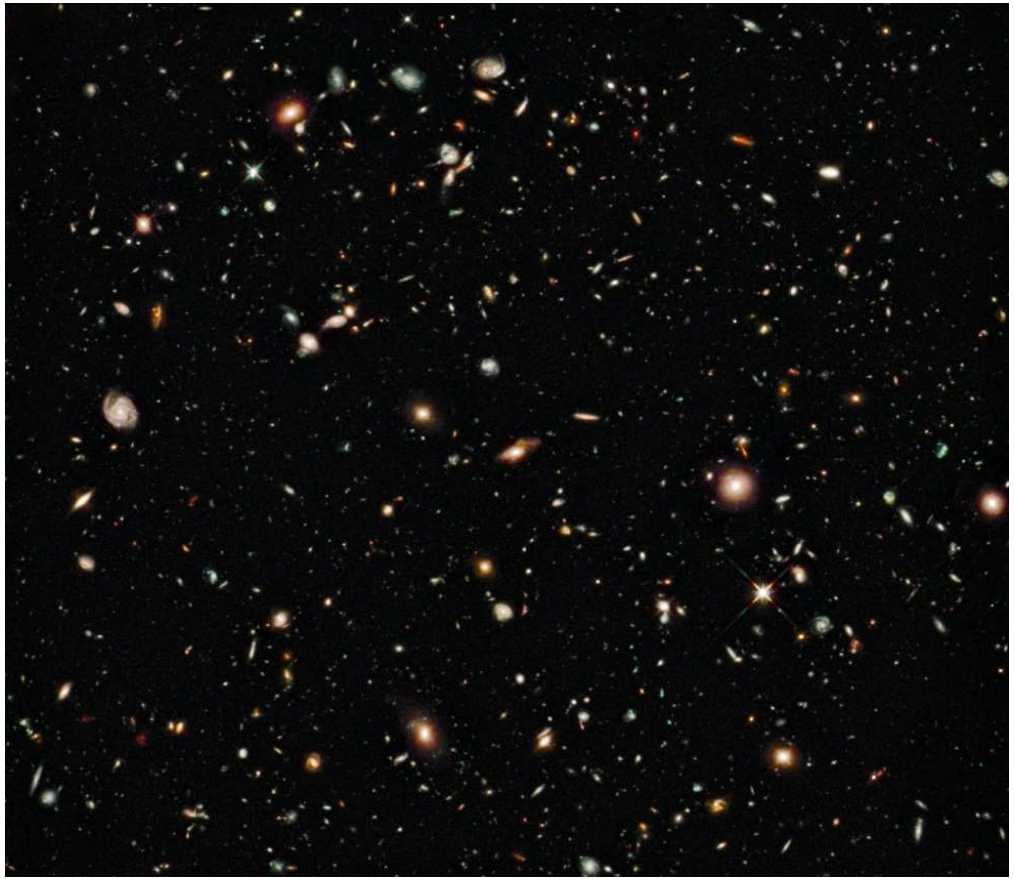


(1) Sky is dark at night

- Notes on assumptions:

  It's *stars* all the way out

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

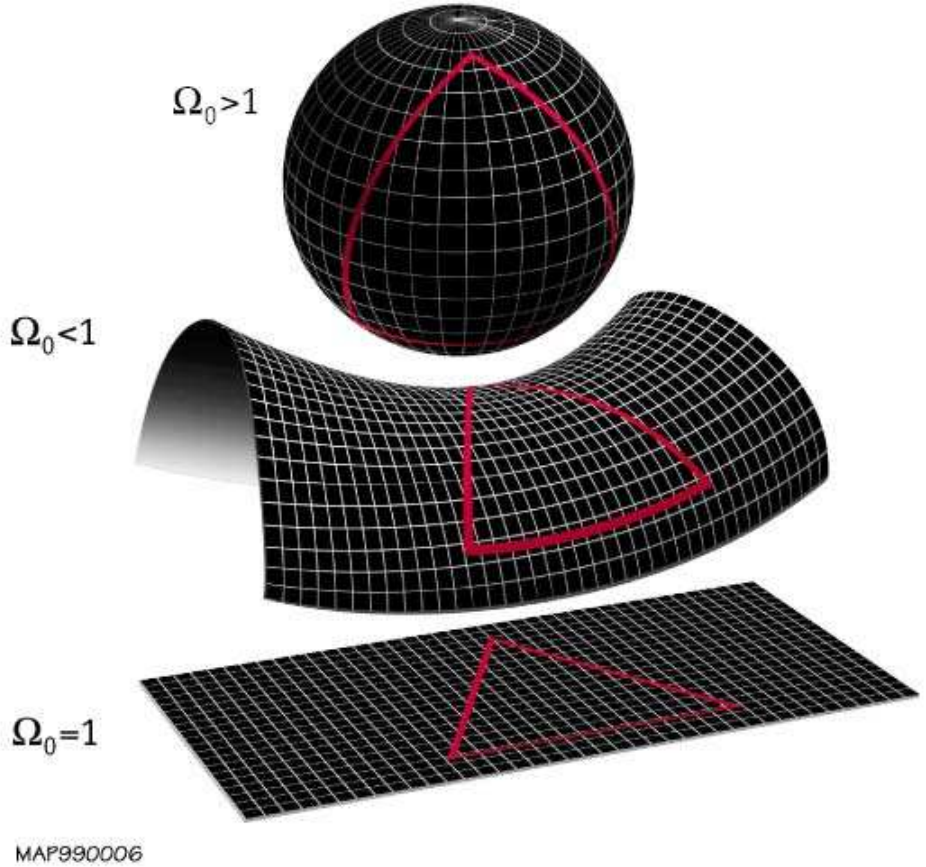


(1) Sky is dark at night

- Notes on assumptions:

  Space is *flat*

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

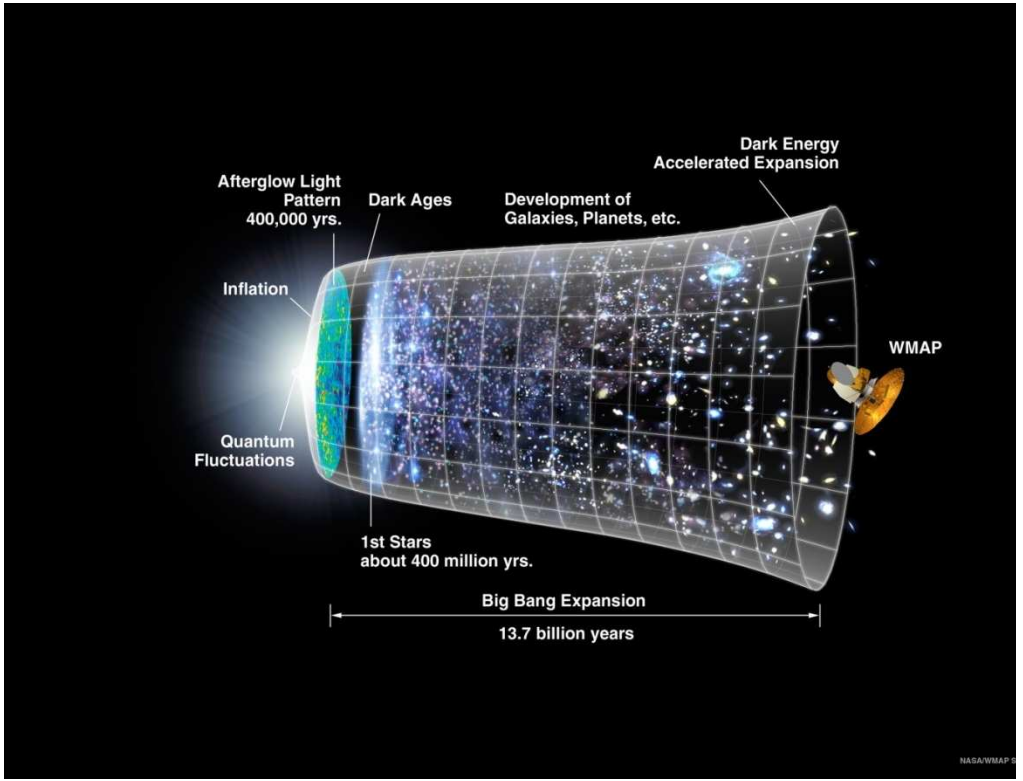


(1) Sky is dark at night

- Notes on assumptions:

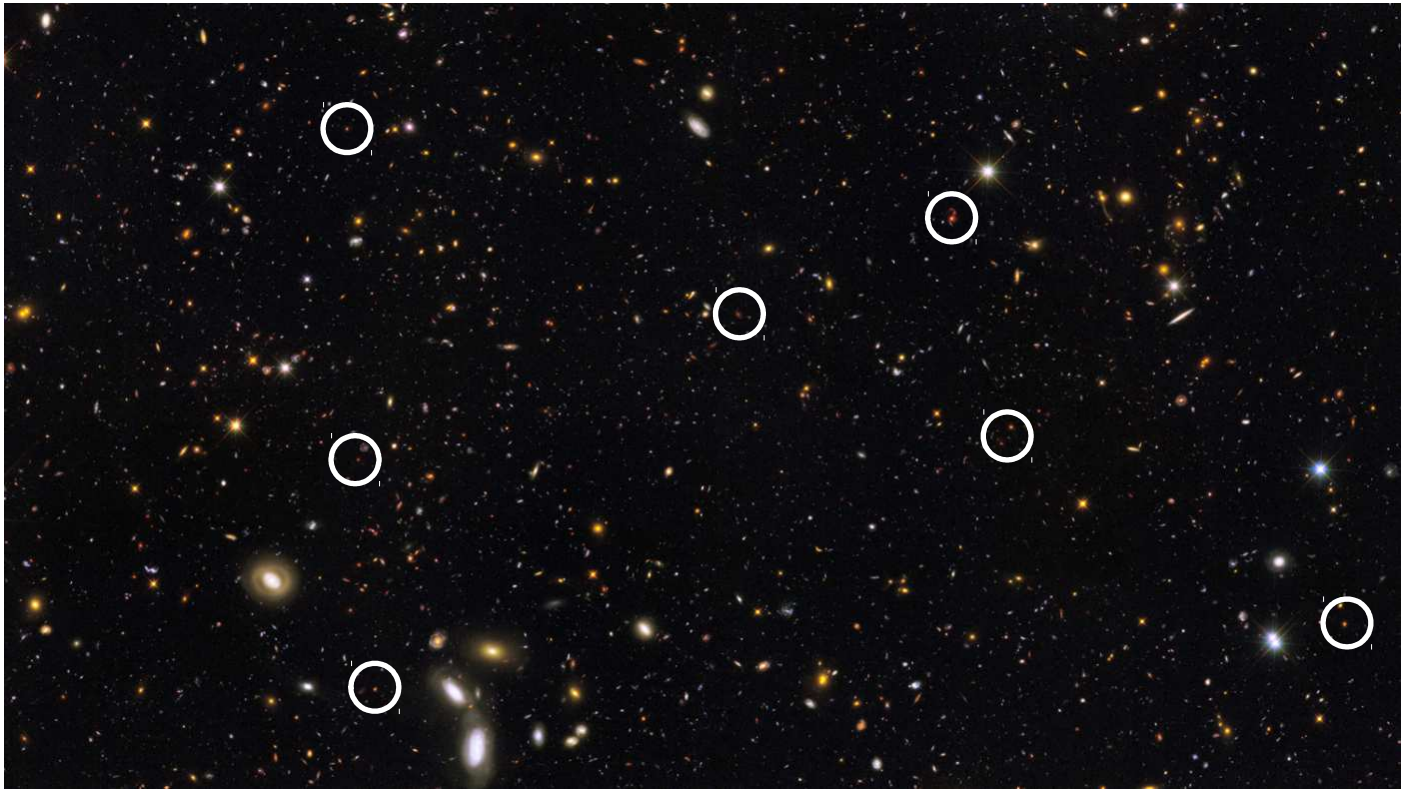
  The universe is *static*

  (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

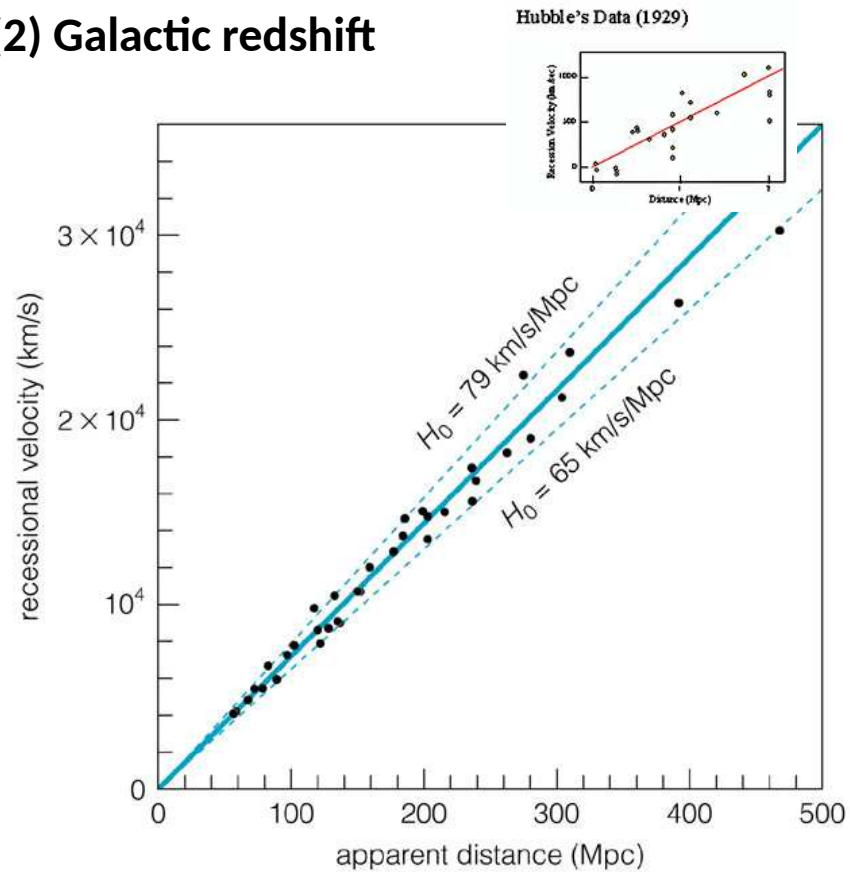
(2) Galactic redshift



Slipher
Friedmann
Lemaitre
Hubble
Einstein

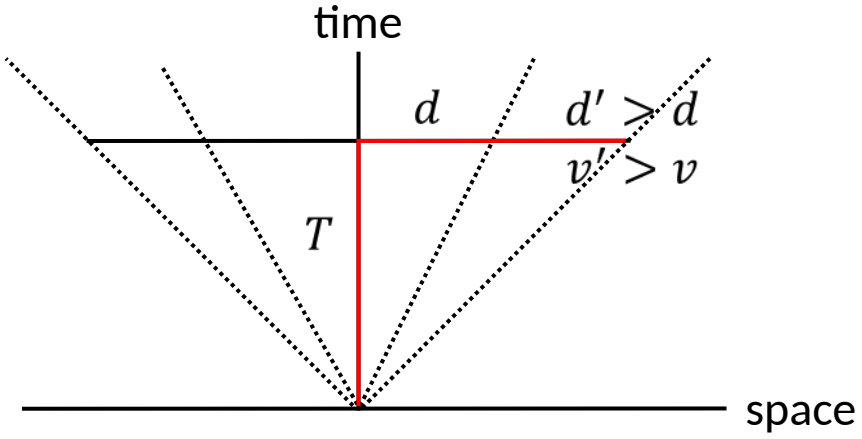
Most natural explanation is **expanding space** (Einstein's theory, which **also** explains many other things)

(2) Galactic redshift

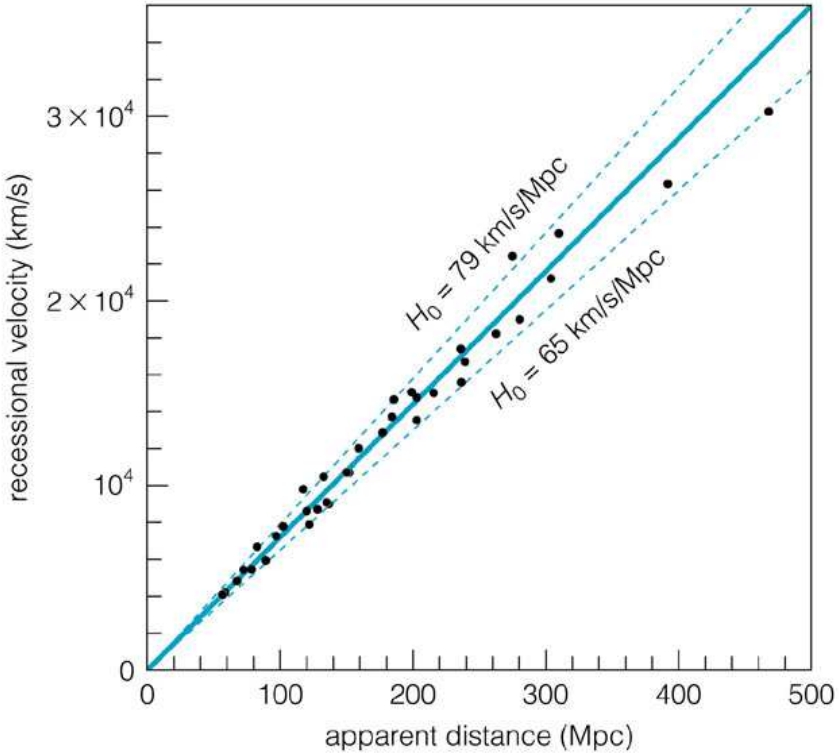


Rough estimate of the age of the universe:

$$T = \frac{d}{v} = \frac{d}{H_0 d} = \frac{1}{H_0} \approx 13 \text{ billion years}$$

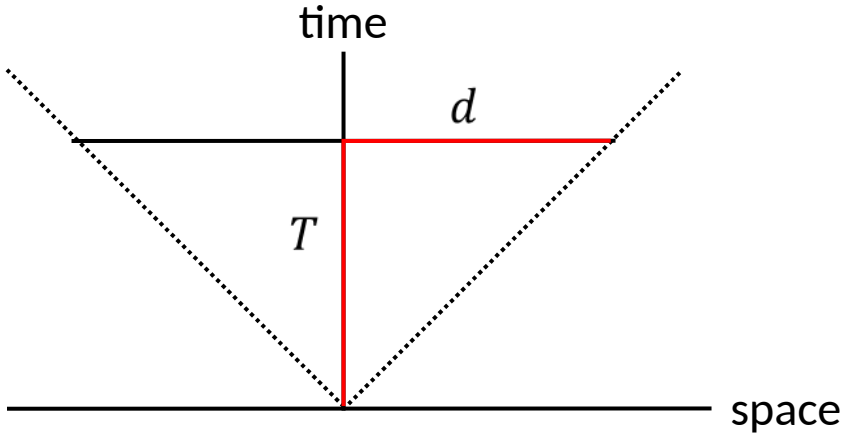


(2) Galactic redshift

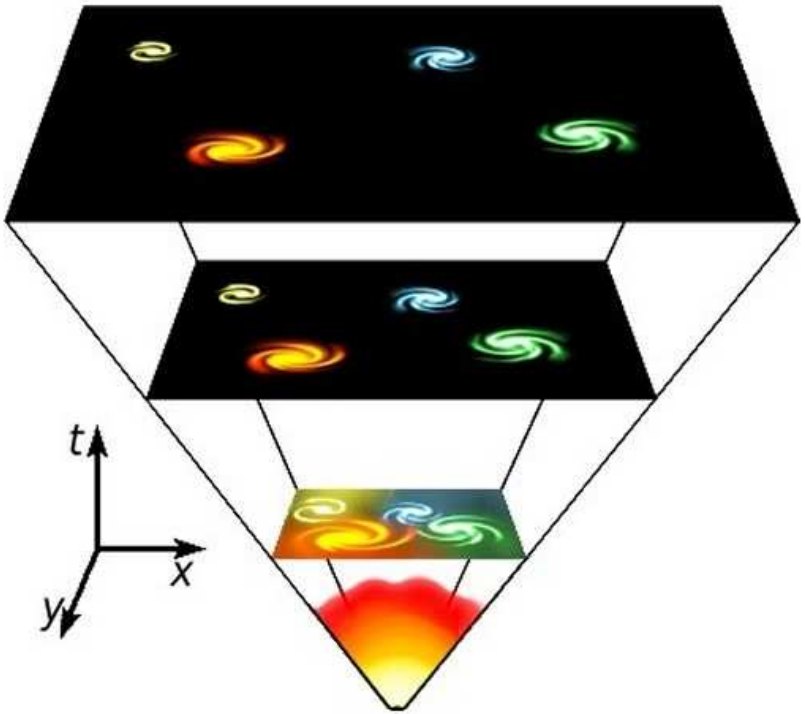


Best estimate of the age of the universe:

Based on "ΛCDM model" and all available data:
$T = 13.799 \pm 0.021$ billion years



(2) Galactic redshift



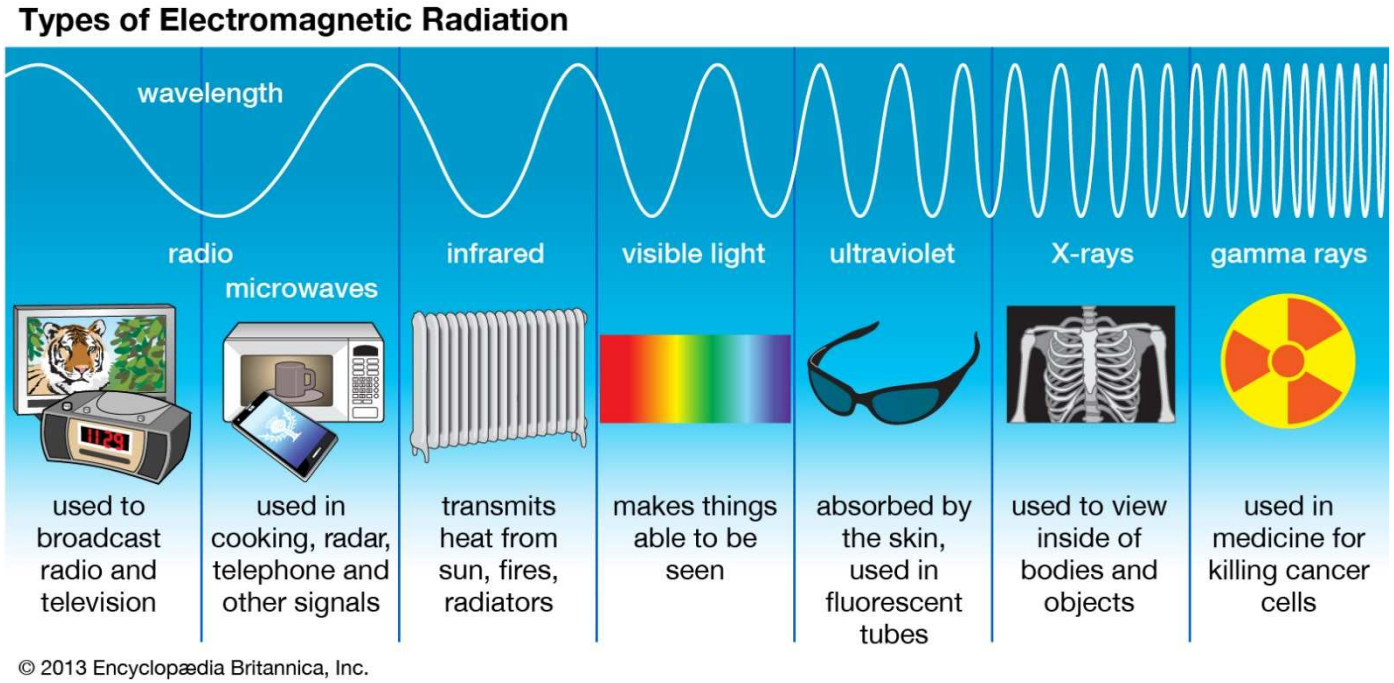
Expanding space means that, as we "run the movie" backwards, the **same** amount of matter occupied **smaller and smaller** volumes of space.

The further back in time we go, the **more dense** and **compressed** the matter would have been. When a gas is compressed, it **heats up**.

Prediction: the universe must have started in a very **dense, hot** state (*everywhere* in space).

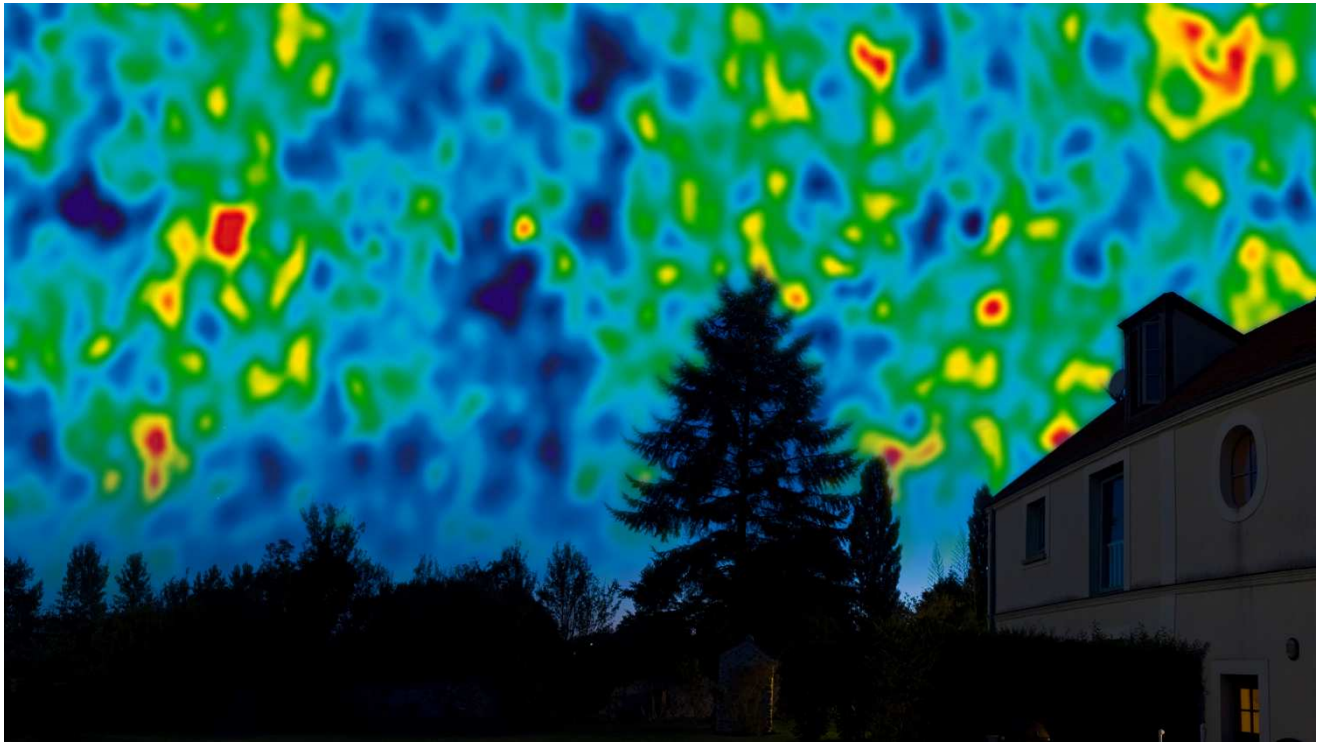
Do we have **evidence** for this? Yes! CMB…

(3) Cosmic Microwave Background



If you looked at the sky in the **microwave** (instead of visible) band of the electromagnetic spectrum, this is what you would see ▭

(3) Cosmic Microwave Background



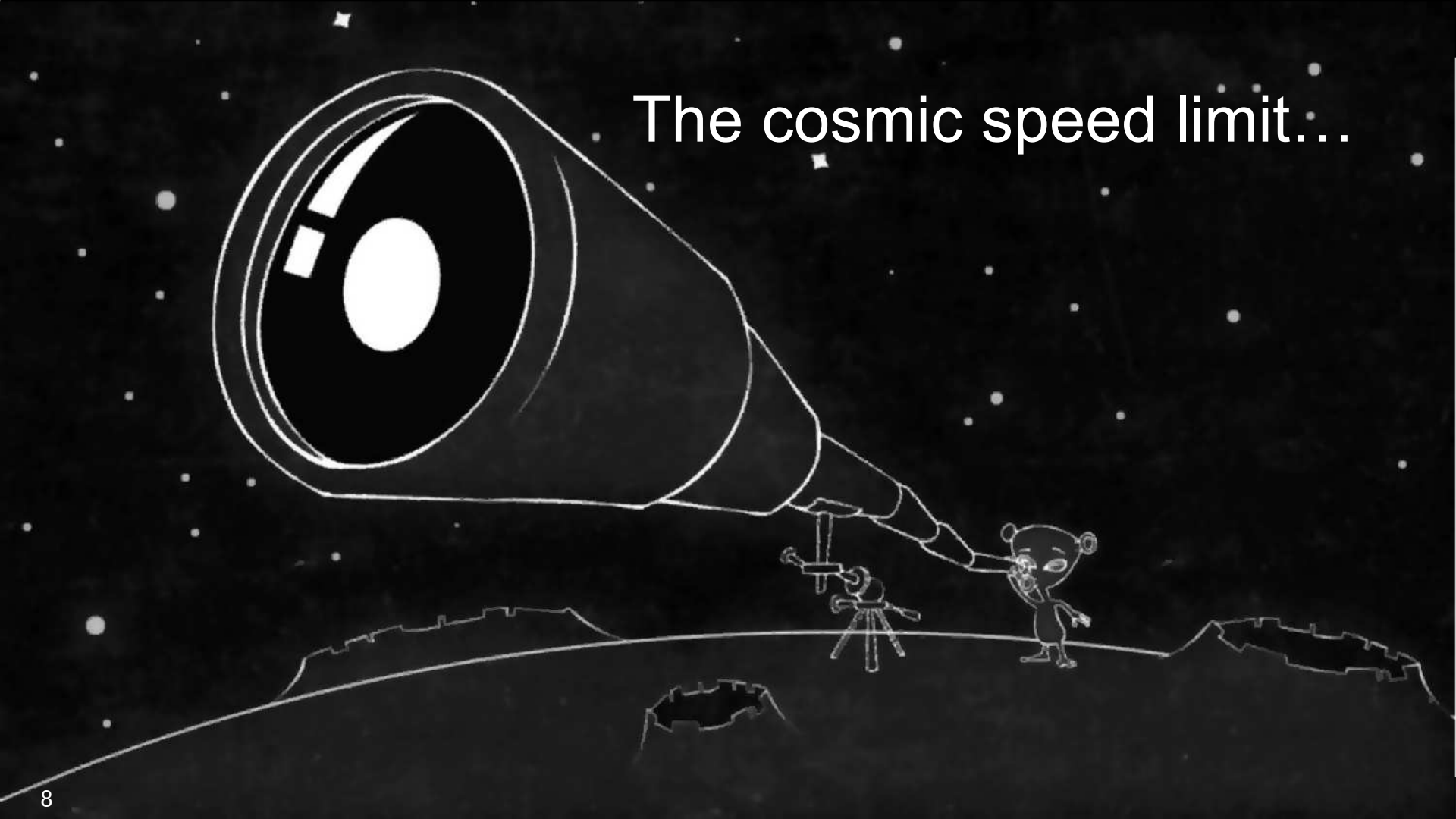
…the “afterglow” of the Big Bang

…the “smoking gun”

(3) Cosmic Microwave Background

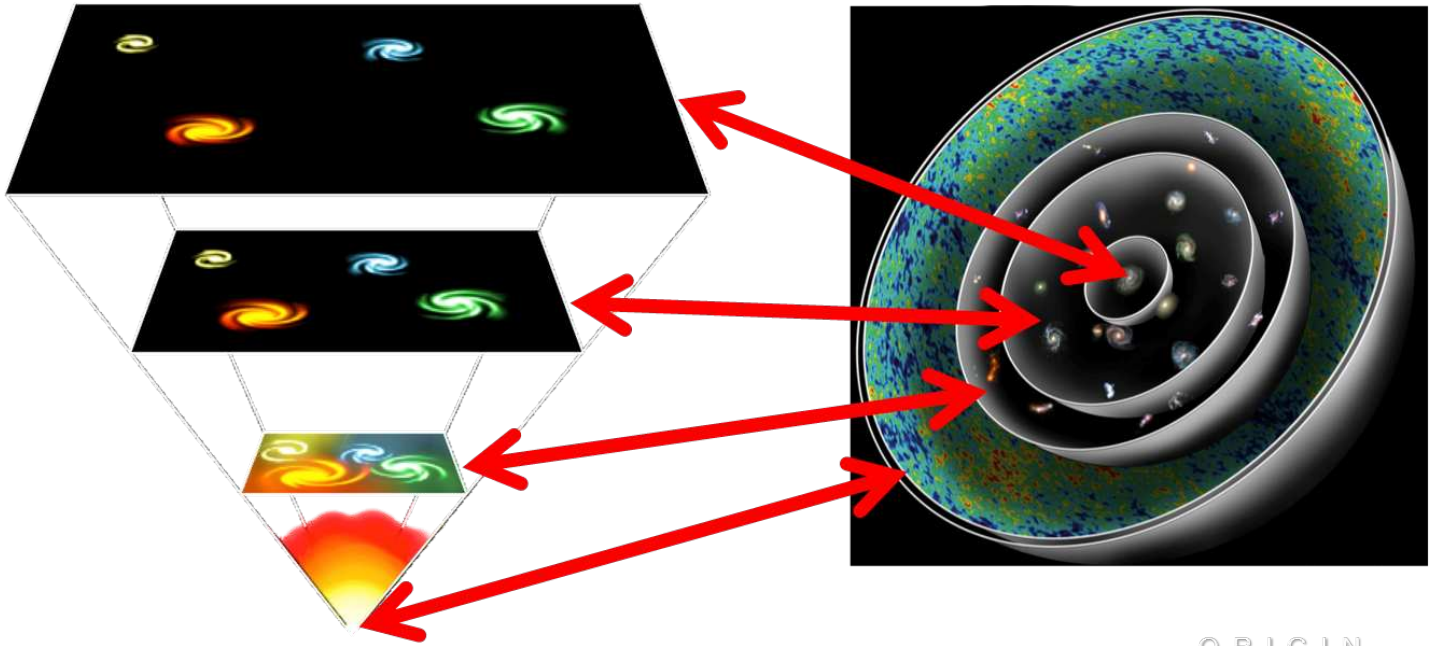
To understand what we're looking at, recall that light moves at a **finite speed**.

So as we look **farther out into space**, we are also looking **further back in time**.


The cosmic speed limit…

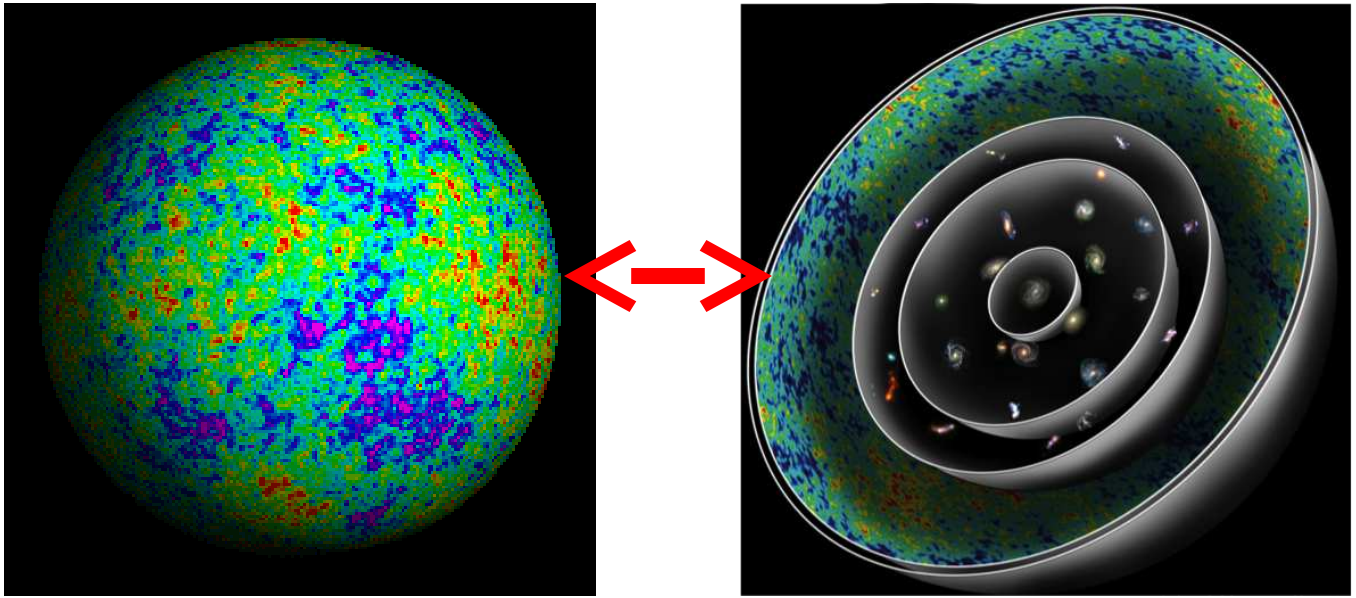
(3) Cosmic Microwave Background

Question: Can we look far enough out into **space** to see back in **time** to the fiery beginning?



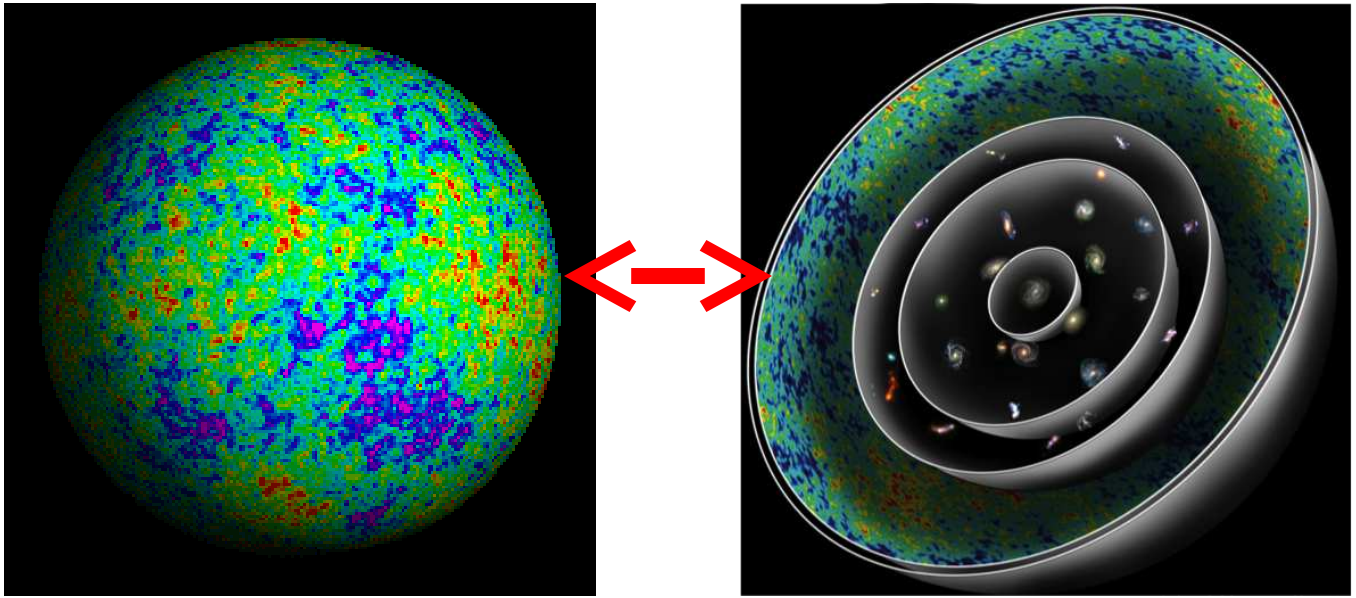
(3) Cosmic Microwave Background

Answer: Almost! We can see light that was emitted from matter located at **almost** the edge of the observable universe, a mere **380 thousand** years after the Big Bang (0.003% its present age)!



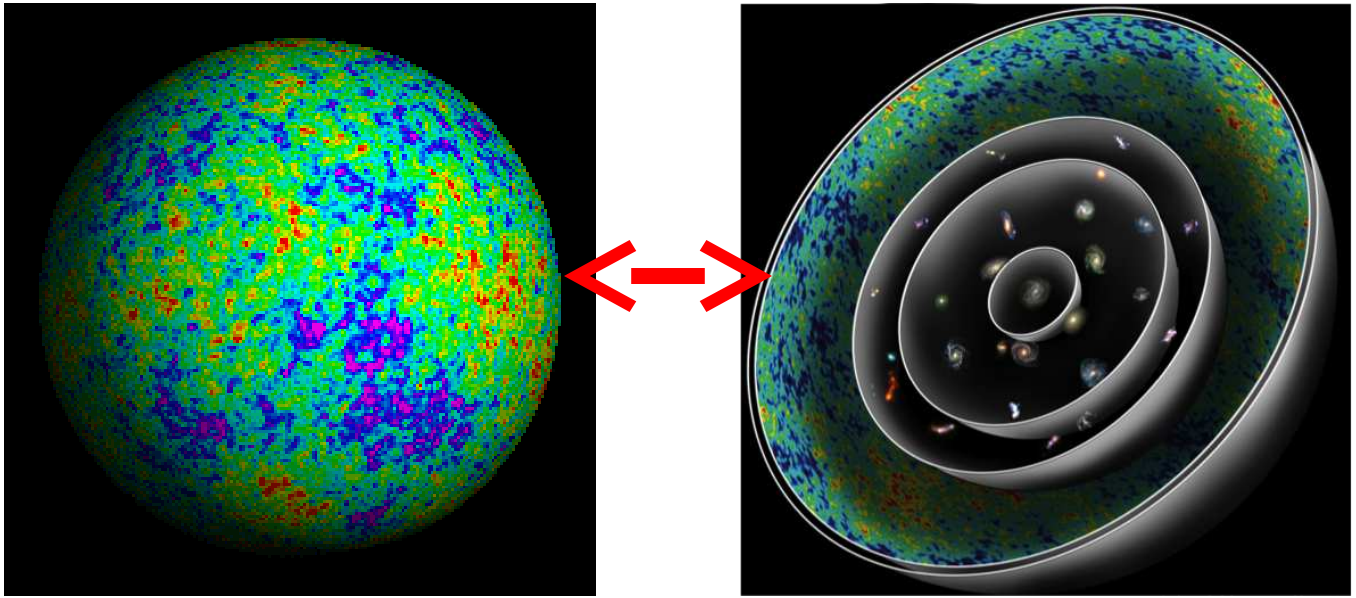
(3) Cosmic Microwave Background

This “glow” is coming from all directions in the sky, with **almost perfectly uniform intensity**, with **extremely tiny fluctuations** of about **1 part in 100,000** (indicated by the colours)



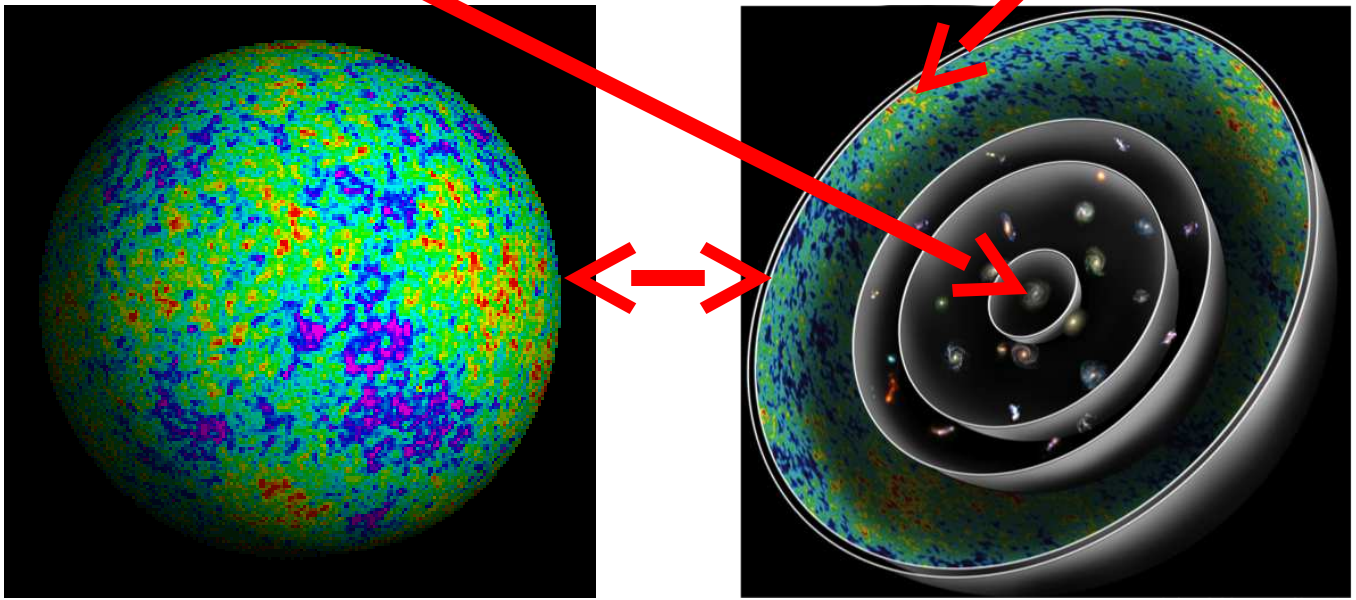
(3) Cosmic Microwave Background

This light was emitted **long ago** and **far away**, and has been travelling towards us ever since. It has covered a **cosmic distance** (radius of observable universe) in a **cosmic time** (age of universe).



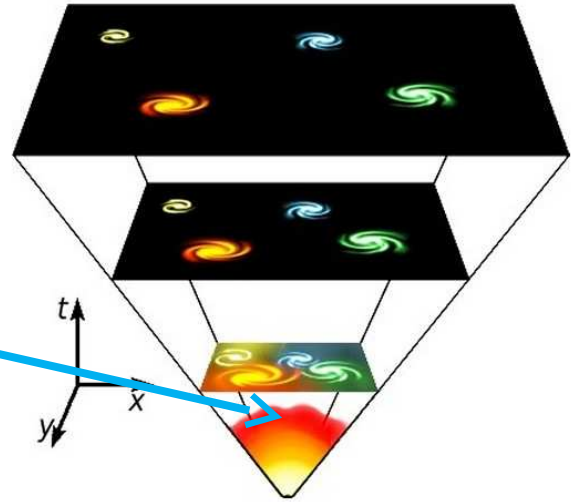
(3) Cosmic Microwave Background

The light that was **here** (at our location) at the beginning is now **there** (edge of ***our*** observable universe), and is part of the CMB seen by aliens **there, now**.



(3) Cosmic Microwave Background

- What does this light that we are **bathed in** (“bath of thermal radiation”) tell us? That when the universe was **380 thousand years old** (0.003% its present age):
    - **All of space** was filled with matter (the ordinary matter being mainly H and He gas) and radiation (light) with **almost perfectly uniform density**.
    - This matter and radiation was in **thermal equilibrium** at **almost perfectly uniform temperature** everywhere in space: about **3000 K** (“red hot”), about the temperature of the surface of a red dwarf star.



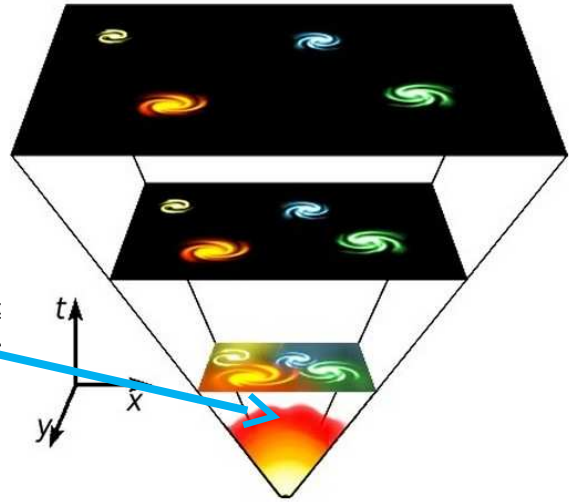
(3) Cosmic Microwave Background

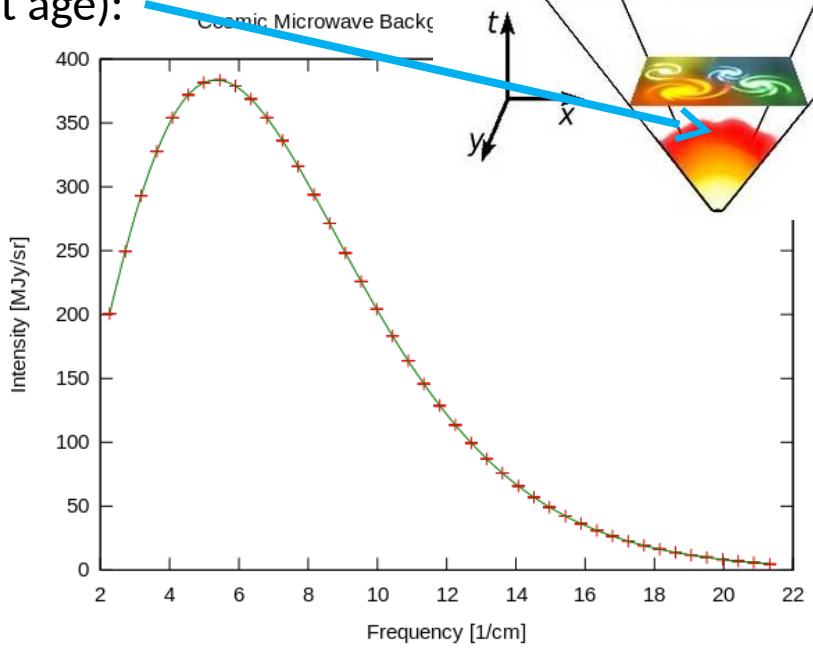
- What does this light that we are **bathed in** ("bath of thermal radiation") tell us? That when the universe was **380 thousand years old** (0.003% its present age):

It is the most perfect source of pure thermal "**blackbody radiation**" ever observed

The **agreement** between **theory** & **observation** is so exact that error bars are not visible in this graph

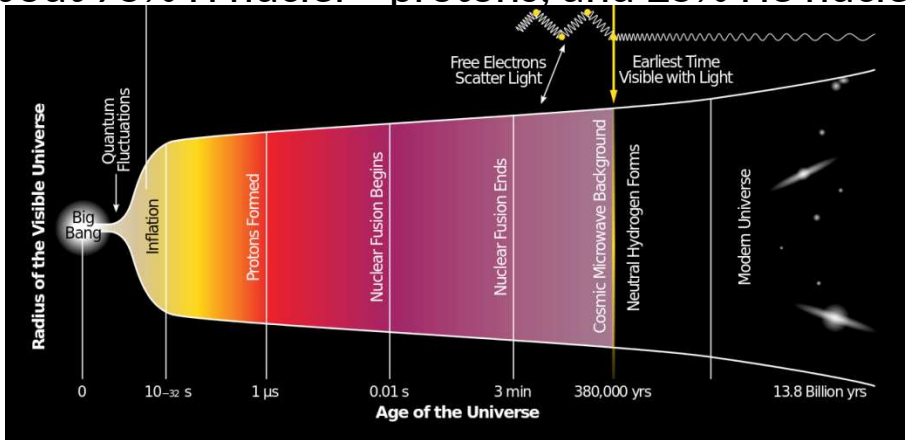
A hot, dense beginning!





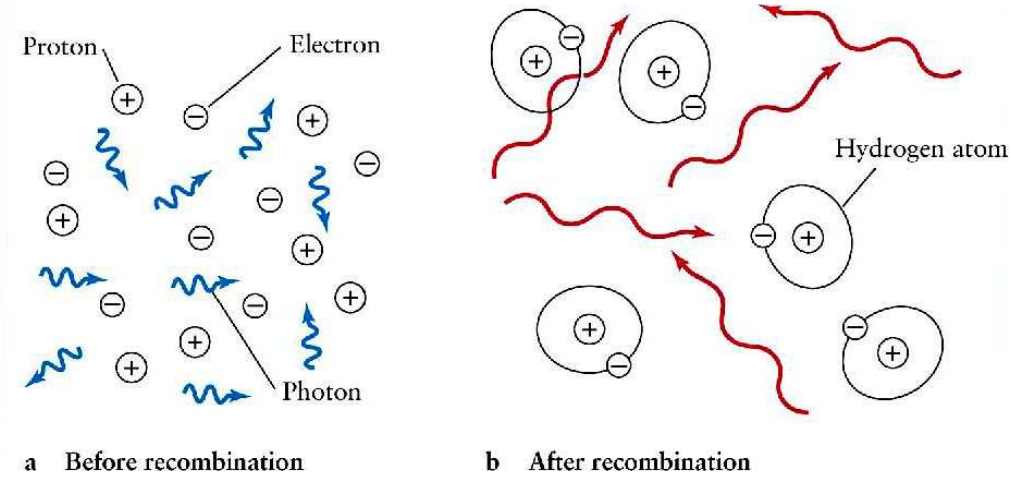
(3) Cosmic Microwave Background

- Why does this make sense?
    - If the Big Bang really happened, simple physics (**Big Bang nucleosynthesis**—more later…) tells us that about **20 minutes** after the Big Bang **all of space** was filled, **almost perfectly uniformly**, with a very hot *plasma* of interacting photons (light), electrons, and atomic nuclei (about 75% H nuclei—protons, and 25% He nuclei—alpha particles)



(3) Cosmic Microwave Background

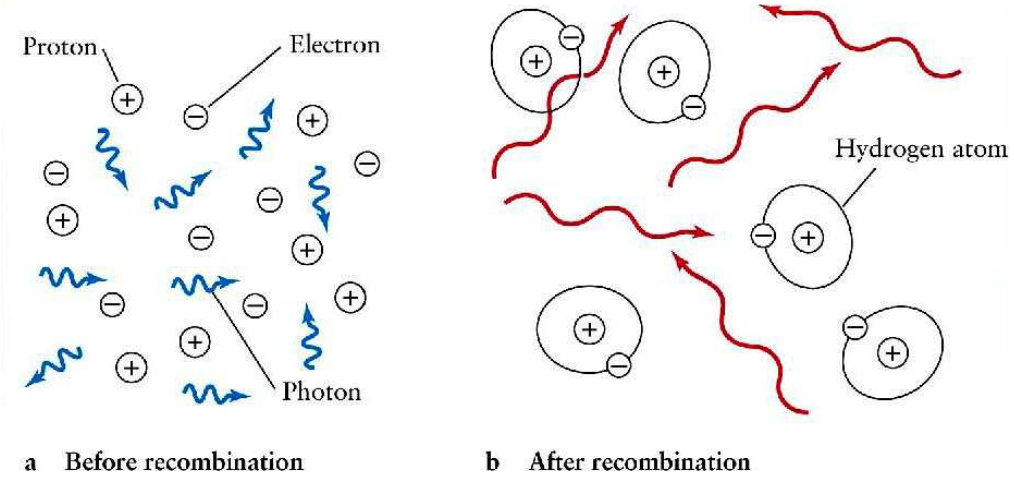
- Why does this make sense?
    - The electrons and protons were initially **too hot to form neutral H atoms** (their thermal energy was greater than the ionization energy of H). Light (photons) could not travel very far before being **scattered by free electrons**. The plasma was **opaque**, like fog.



a Before recombination b After recombination

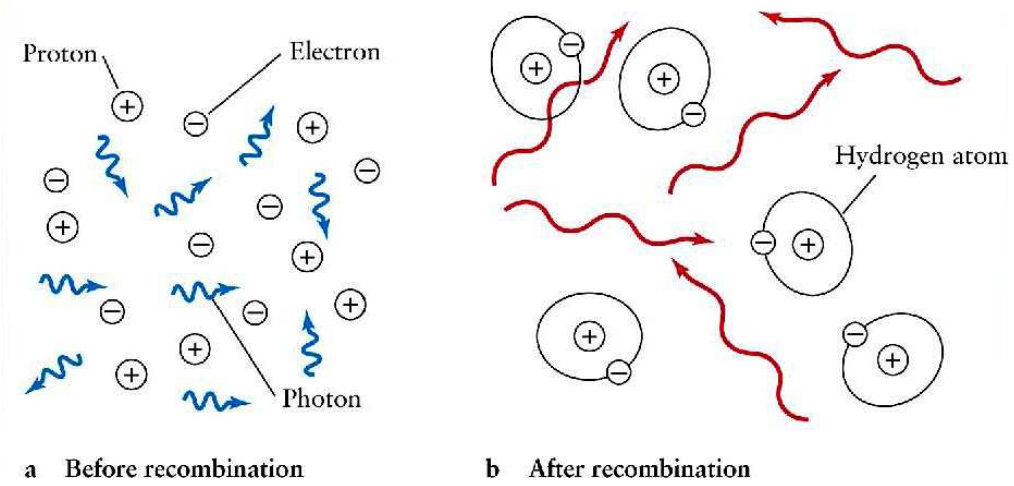
(3) Cosmic Microwave Background

- Why does this make sense?
    - As space continued to **expand**, the plasma continued to **cool** until the kinetic energy of the particles was low enough for electrons to be **captured** by protons and form **neutral H atoms** (and similarly, neutral He atoms). **Neutral** atoms **do not** scatter photons.



(3) Cosmic Microwave Background

- Why does this make sense?
    - Suddenly, and for the first time, light could **move freely** through space: the matter and radiation had "**decoupled**." The matter in the universe became **transparent**. **All of space** was filled with freely-moving radiation (photons) at a temperature of **about 3000 K**.



(3) Cosmic Microwave Background

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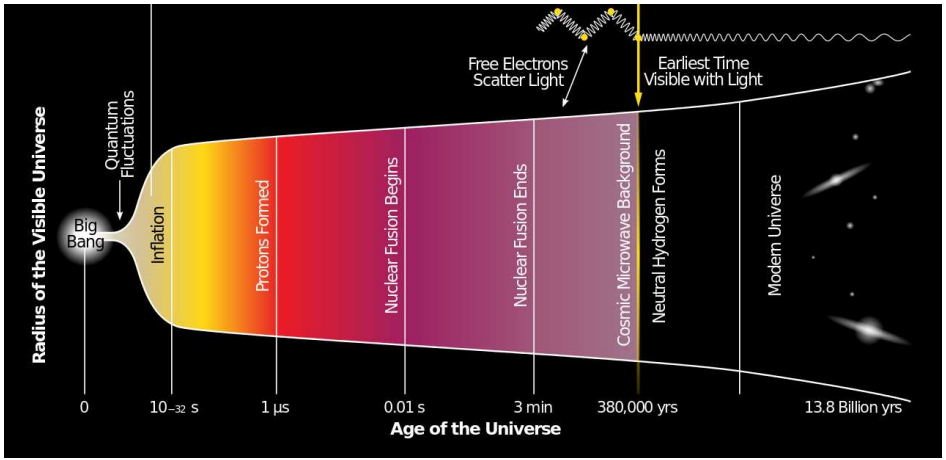
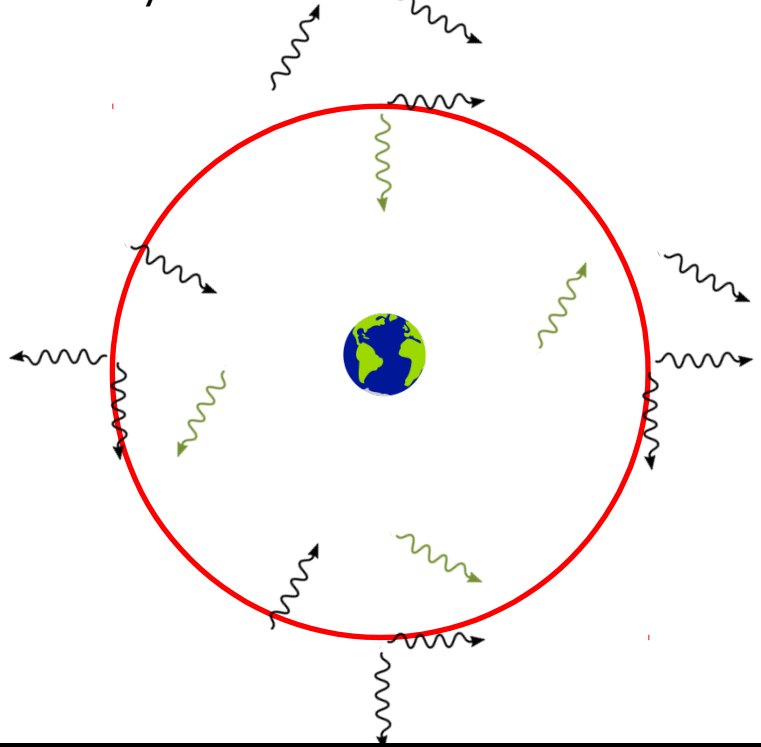


(3) Cosmic Microwave Background

- Why does this make sense?



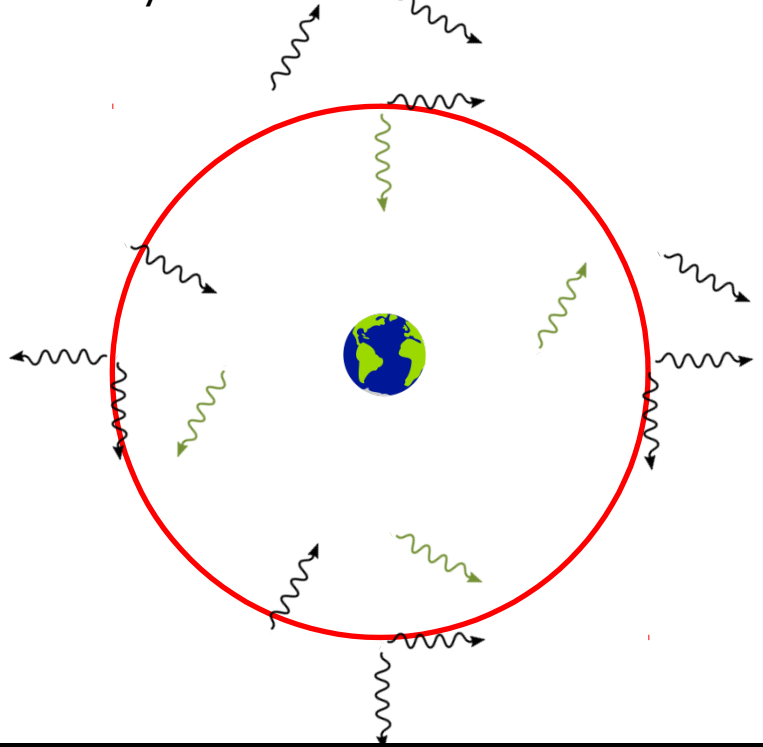
The green photons, that **last scattered** off an electron **long ago** and **far away**, then travelled for 13.8 billion years through transparent space to reach Earth **now.**

The **black** photons went off in other directions, never reaching Earth. The photons that were near the **Earth's** location **13.8 billion years ago** have long since travelled elsewhere. Space is **still uniformly filled** with these photons, **everywhere**, and moving in **all directions**.

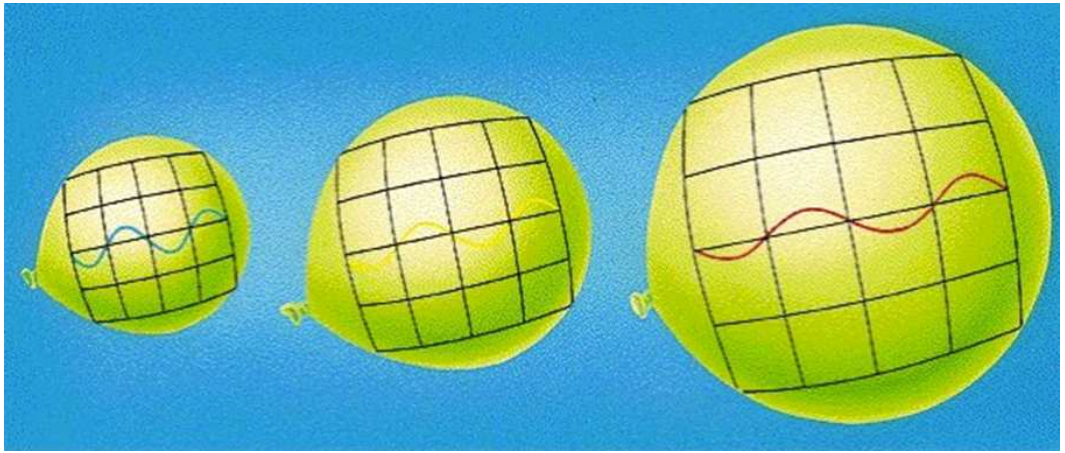
From Earth's perspective, we see photons arriving from **every direction in the sky**, originating long ago from a giant spherical surface that is *almost* at the edge of our observable universe, called ***surface of last scattering***.

(3) Cosmic Microwave Background

- Why does this make sense?



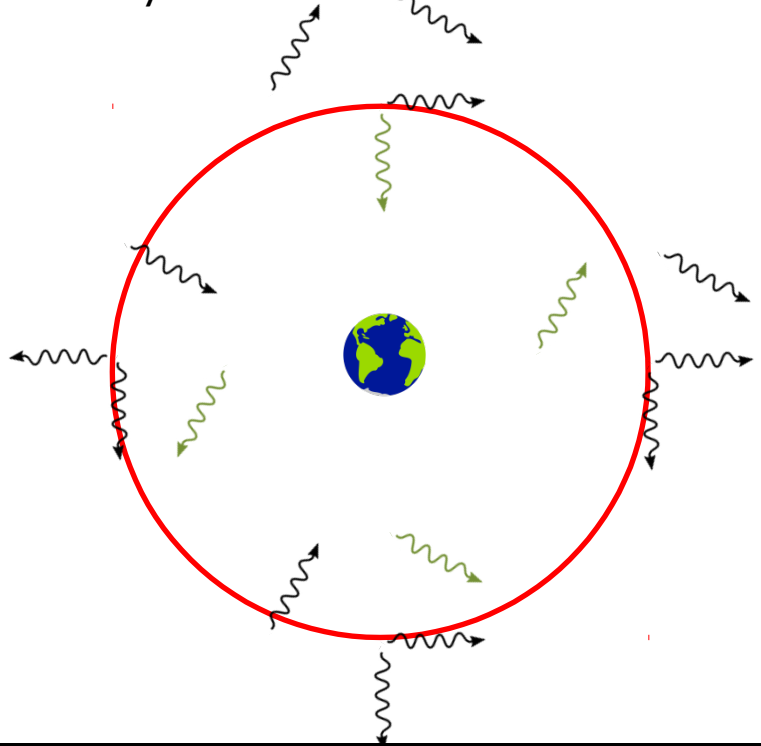
But remember, space continued to **expand** over those 13.8 billion years while those photons were in flight.



The expansion **stretched** the wavelength of the photons

(3) Cosmic Microwave Background

- Why does this make sense?



But remember, space continued to **expand** over those 13.8 billion years while those photons were in flight.

Redshift

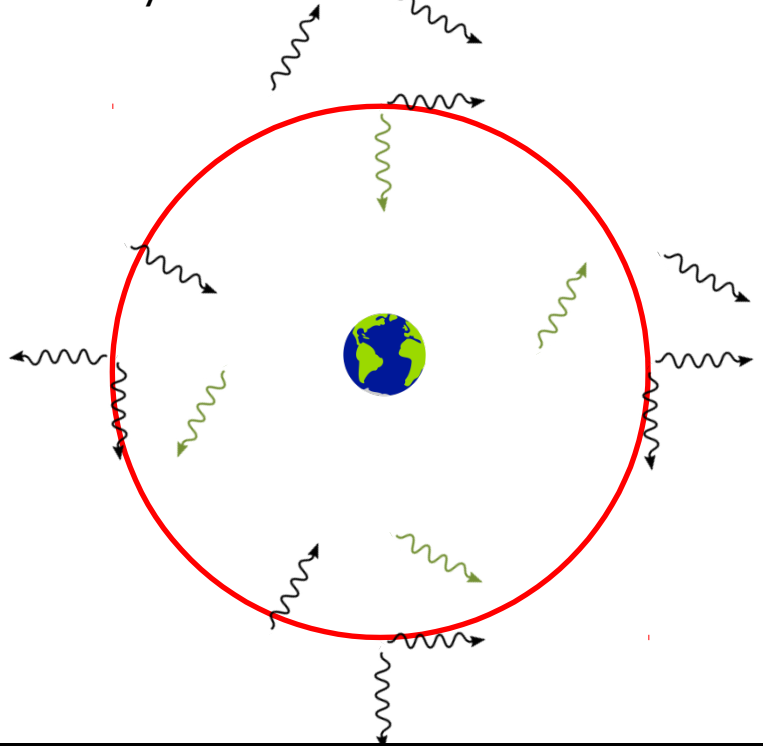
corresponds to **hot** photons at about **3000 K**

corresponds to **cold** photons at **2.73 K**

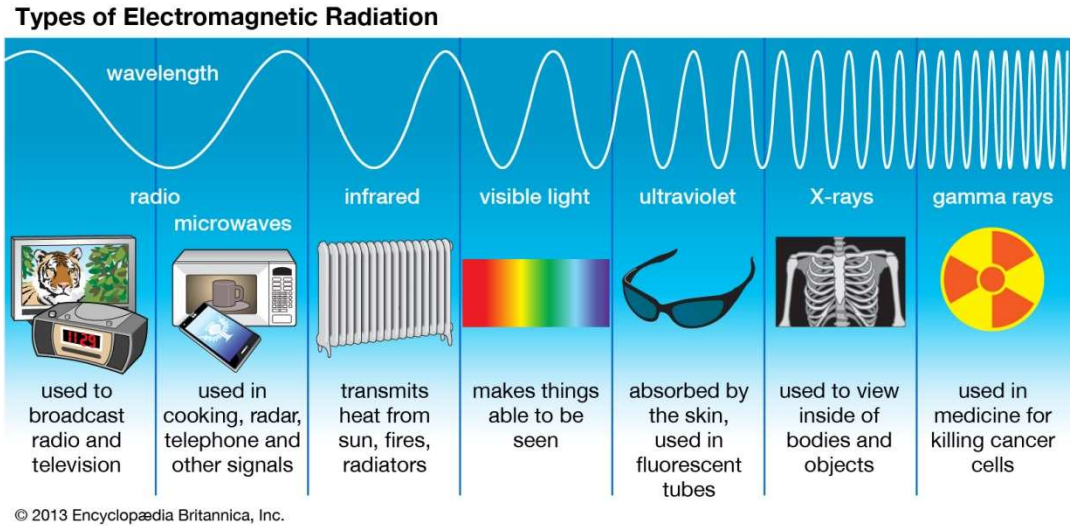
Space has **expanded** by a factor of since the light from the surface of last scattering was emitted, a mere **380 thousand years** after the Big Bang!

(3) Cosmic Microwave Background

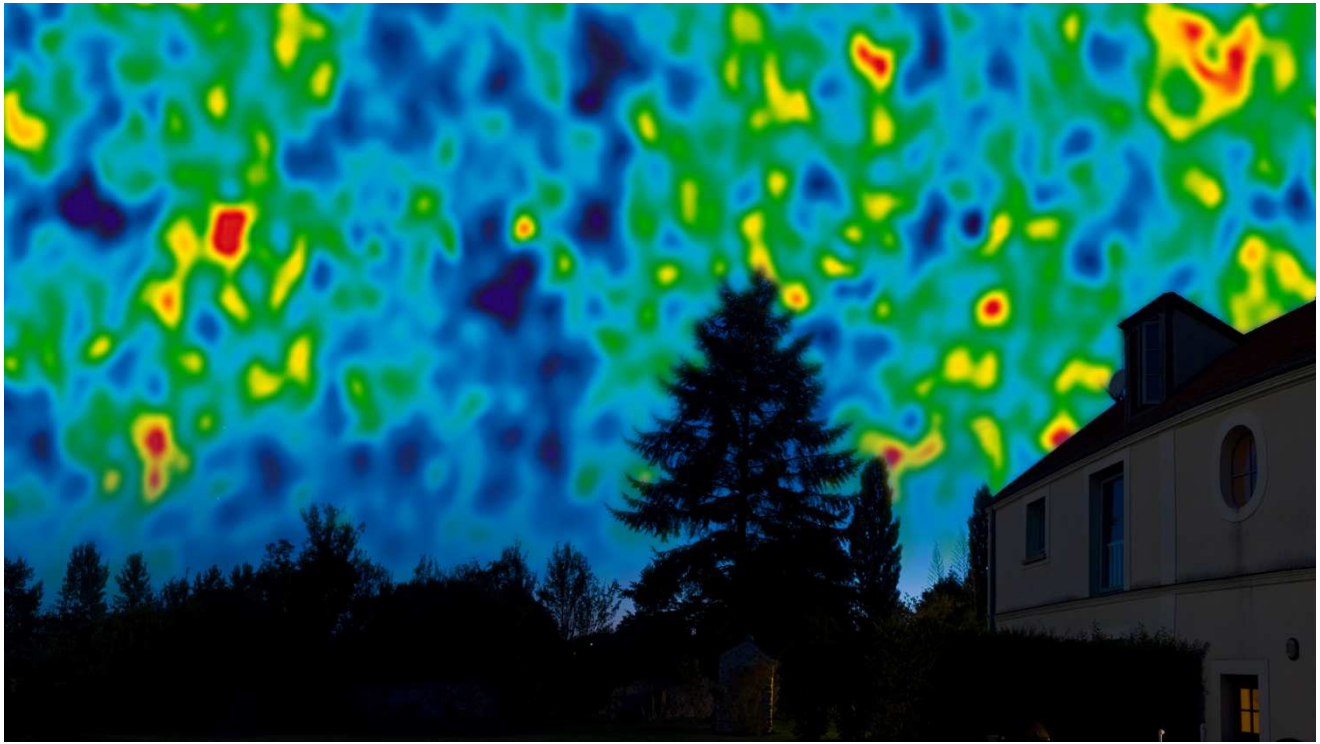
- Why does this make sense?



At present, the whole universe is bathed in thermal microwaves, hence: **Cosmic Microwave Background**.



(3) Cosmic Microwave Background



Observation of the CMB in 1964 ruled out Fred Hoyle's competing "**Steady State**" model of the universe (eternal expansion of space with continuous creation of matter), and gave **strong support** for the "**finite age**, **hot Big Bang**" model.

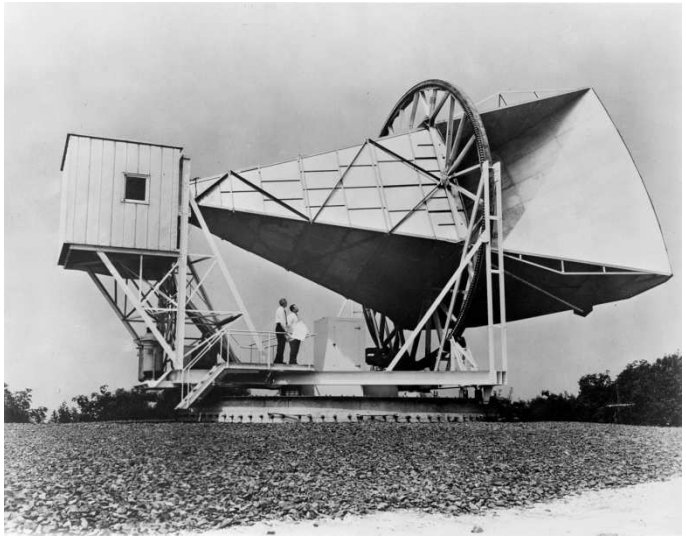
(3) Cosmic Microwave Background

- **1948:** Physicists **Ralph Alpher** and **Robert Herman** first predict the CMB (later, independently predicted by **Robert Dicke** and others).

- **1964:** Radio astronomers **Arno Penzias** and **Robert Wilson** accidentally measure the CMB. They detected a faint, steady, mysterious “noise” coming from all directions on the sky, originating **outside our galaxy**.

- At the same time, Dicke and colleagues were building an antenna to measure CMB…“**Boys, we’ve been scooped**”.

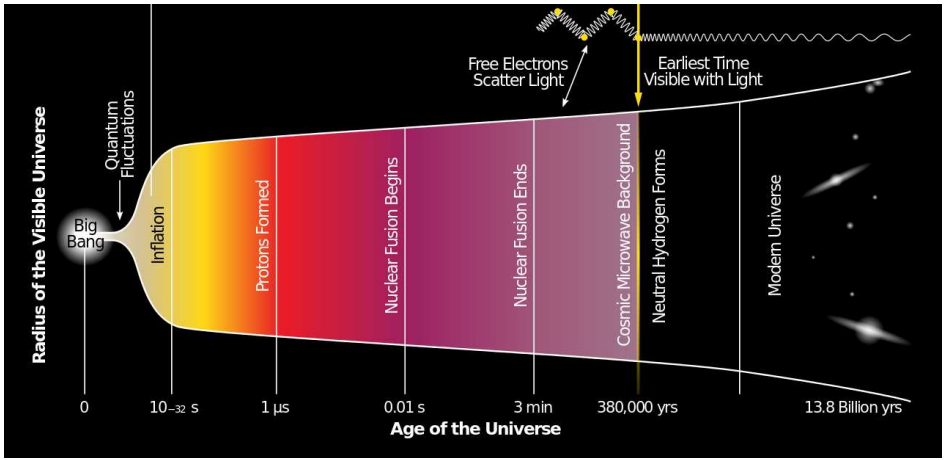
- **1978:** Penzias and Wilson get the **Nobel Prize in Physics**.

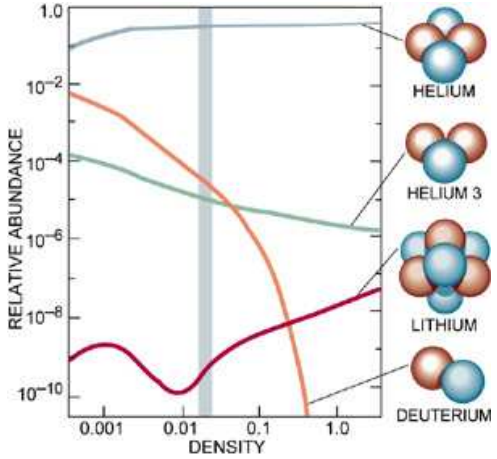


(3) Cosmic Microwave Background

(4) Abundances of the Light Elements

- By about **1 second** after the Big Bang, the universe contains **protons and neutrons**, but they are **too hot** (moving too fast) to fuse (be bound) into **heavier nuclei**.
- Between about **3 minutes and 20 minutes** the universe is cool enough for fusion: p + n ⎵ D (deuterium), D + D ⎵ helium-4, plus trace amounts of helium-3 (tritium) and lithium.
- **After 20 minutes** temperature & density too low to sustain fusion ⎵ no heavier elements.





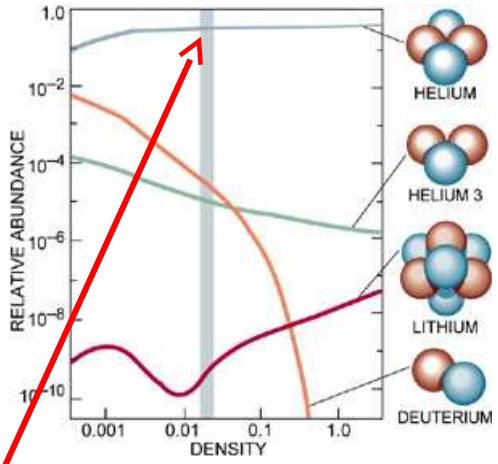
(4) Abundances of the Light Elements

- From basic particle physics, we known that the **p:n ratio must have been 7:1 during nucleosynthesis**.

- Notice that virtually all of the n's end up in helium-4 (there are n's in deuterium, helium-3, and lithium, but there are only trace amounts of these nuclei).

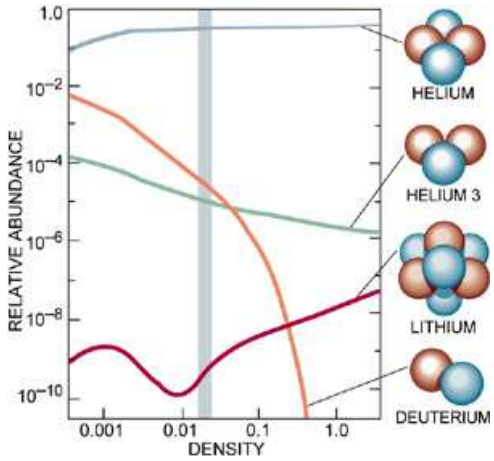
- Thus, for every He (which has 2 n's) there should be 7 x 2 = 14 p's. Two p's in He leaves 14 – 2 = 12 p's in H.

- The mass of 12 H is about the mass of 12/4 = 3 He. So **by mass**, there should be **three times as much hydrogen as helium**, which is *exactly* what is observed: 75% H, 25% He



pppp = 4 H
pppp = 4 H
pppp = 4 H
ppnn = 1 He

(4) Abundances of the Light Elements

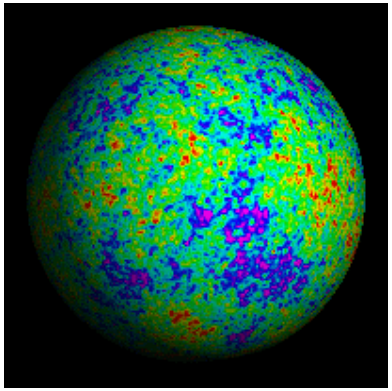


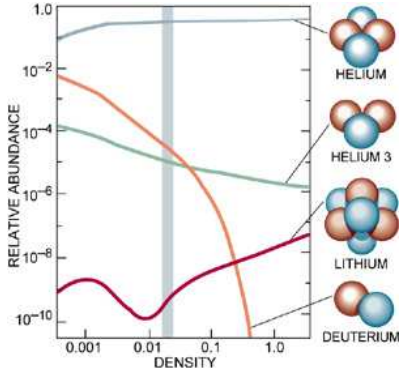
- Using particle physics again, we can **predict the abundances** of the other light elements, relative to hydrogen (see graph)
- **Key point:** Predicted abundances depend very sensitively on the **density of baryons** (p & n) during nucleosynthesis.
- **Agreement** between **predicted and observed** abundances (**grey bar**) tells us the amount of ordinary matter in the universe: **atoms can make up about 4% of total mass-energy** ("total" includes dark matter *and dark energy*; more later…)
- This is one of the strongest pieces of evidence that the **majority of dark matter** is **nonbaryonic (not ordinary atoms).**

Evidence for the Big Bang

Summary:

- **Evidence for the Big Bang includes**:
  - Darkness of the night sky
  - Galaxy redshift
  - Cosmic microwave background
  - Abundances of the light elements





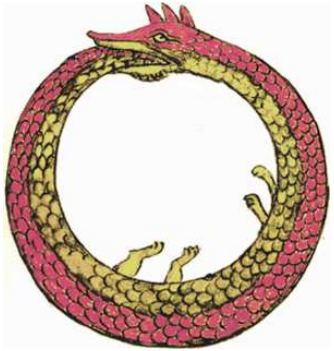
- Such detailed agreement between theory and observation leaves virtually **no doubt** that **13.8 billion years** ago the universe was in a **hot, dense state,** which then **expanded** and **cooled**.
  - CMB data takes us back to **380,000 years** after BB (and indirectly, much further back…)
  - Abundances of light elements takes us back to **a few minutes** after BB
  - Particle collider experiments (e.g., LHC) probe the state of matter **millionths of a second** after BB (**quark-gluon plasma**), at temperatures of **trillions** of K

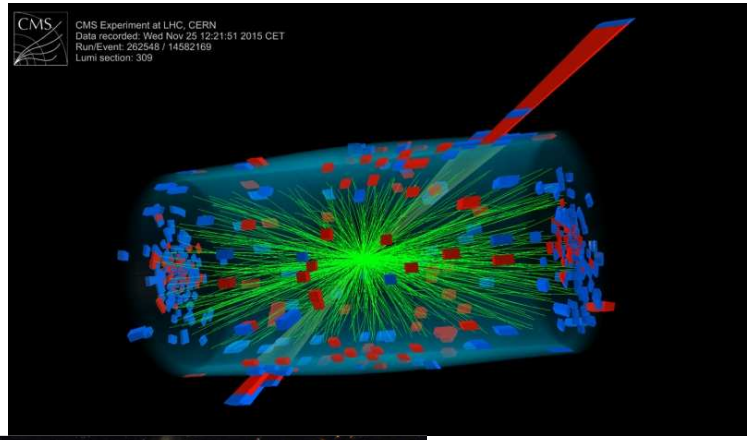
Summary:

The mystery of origins has been pushed back to the blink of an eye after the Big Bang!

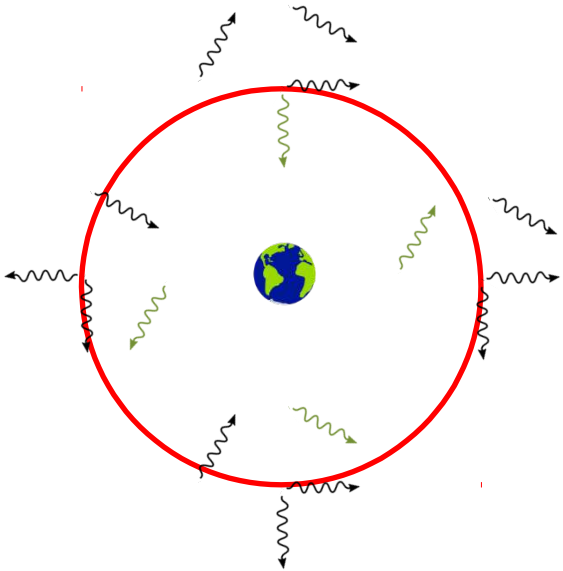
The physics of the early universe is an extremely active area of research.

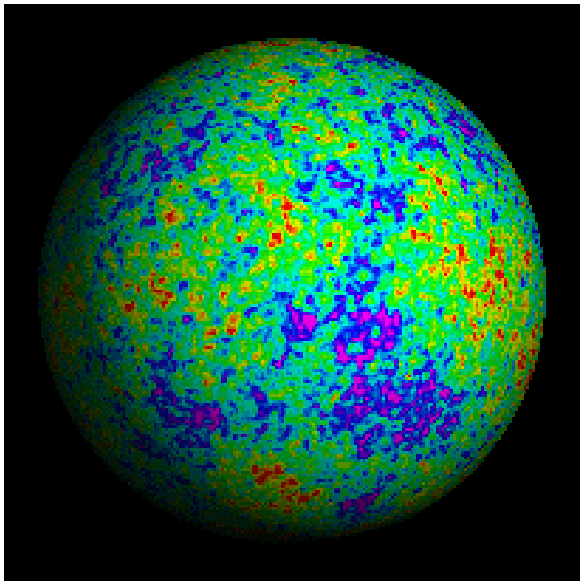
The growing connections between **macro**scopic and **micro**scopic physics is particularly exciting.

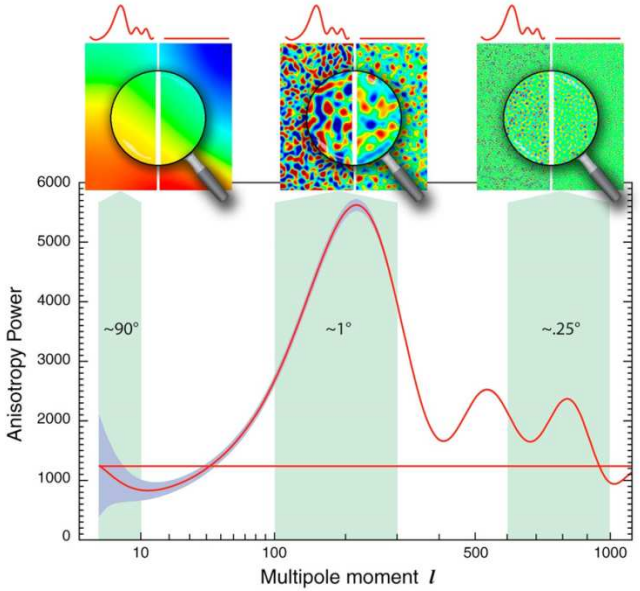




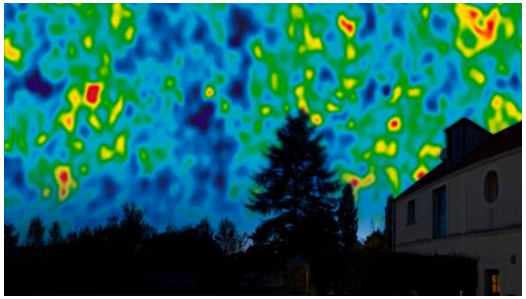
The CMB is **not perfectly uniform** over the sky. It has **tiny fluctuations (~1:100,000)** which indicate that the **temperature** & **density** of matter in the early universe **varied slightly from place to place**: hotter and less dense in some places, colder and more dense in others.

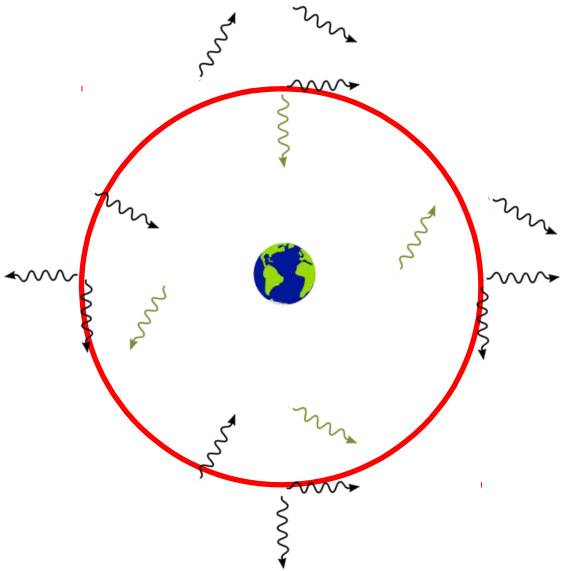


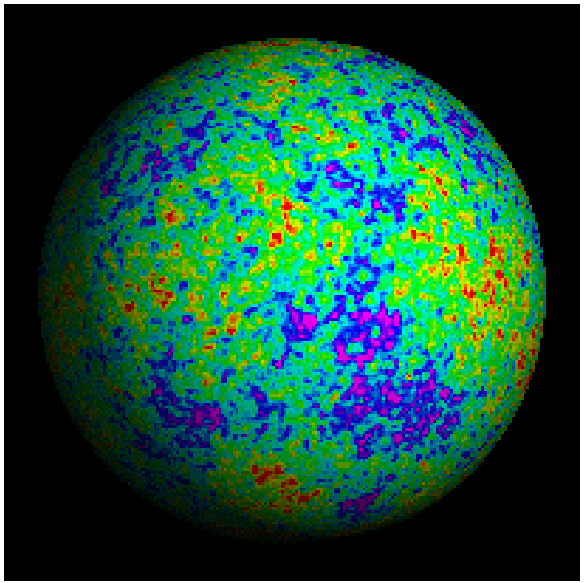


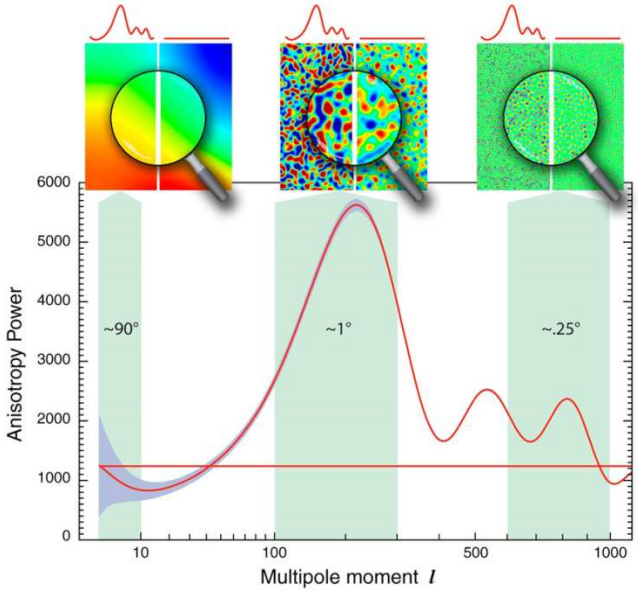


The **average angular size** of the **most intense** fluctuations is about **1 degree** on the sky (about twice the angular size of the Moon or Sun). **Why?**

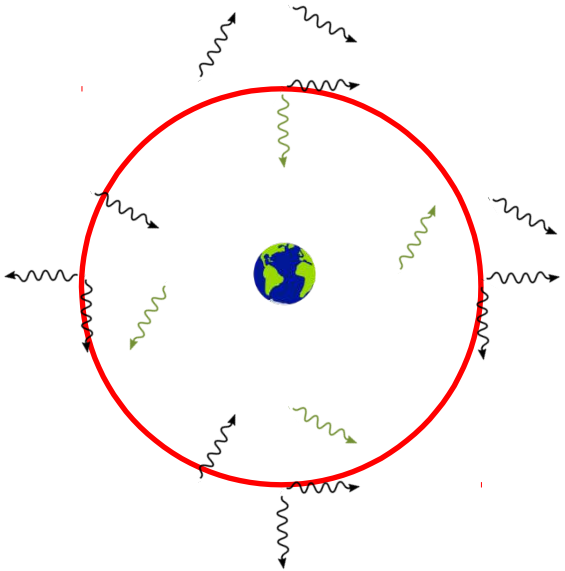


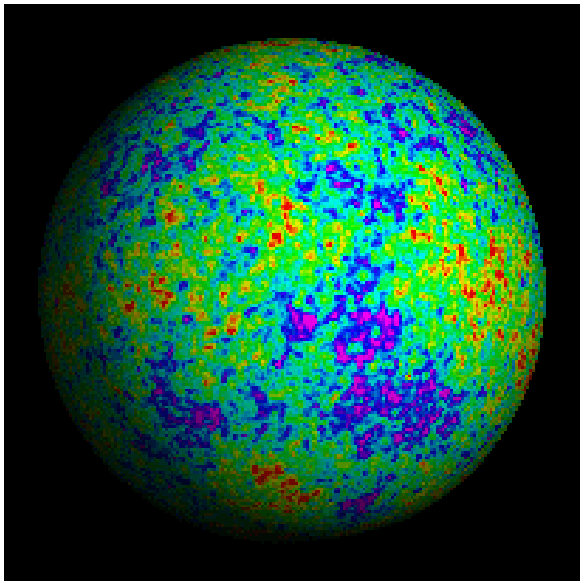


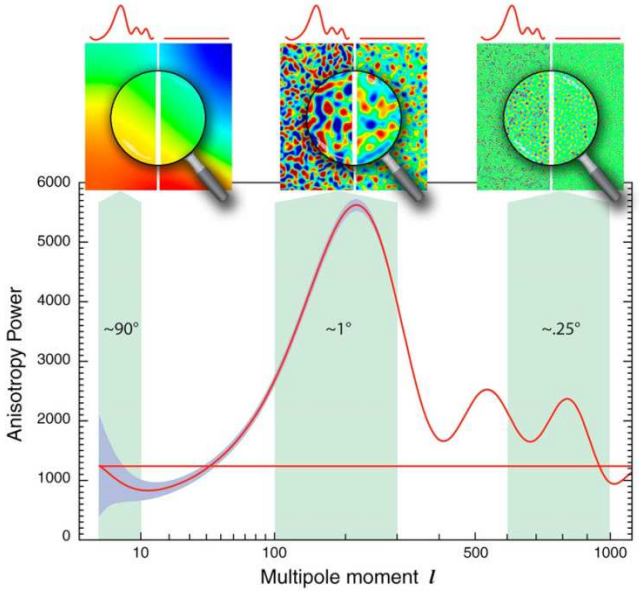




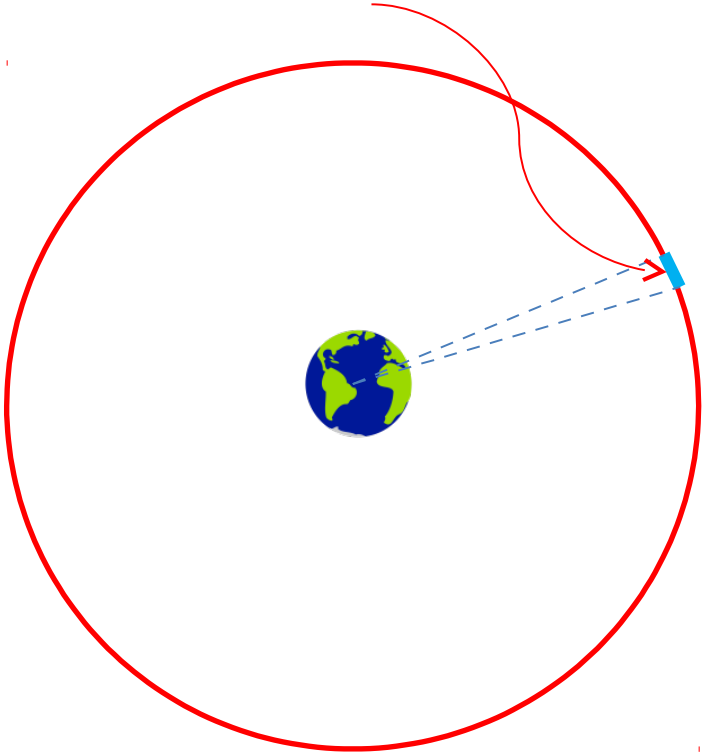
Rough Argument: At **380,000 years** after the Big Bang, light would have had a chance to travel only about **380,000 light years** in any direction, or a sphere of about 2 x 380,000 = **760,000 light years** in diameter. Thus, the largest "blobs" of matter that could have the **same temperature** (different parts of the gas in **thermal equilibrium**), hot or cold, would be about this size.







Rough Argument: These "blobs" give a **standard ruler** (a structure of **known size**), on the surface of last scattering:



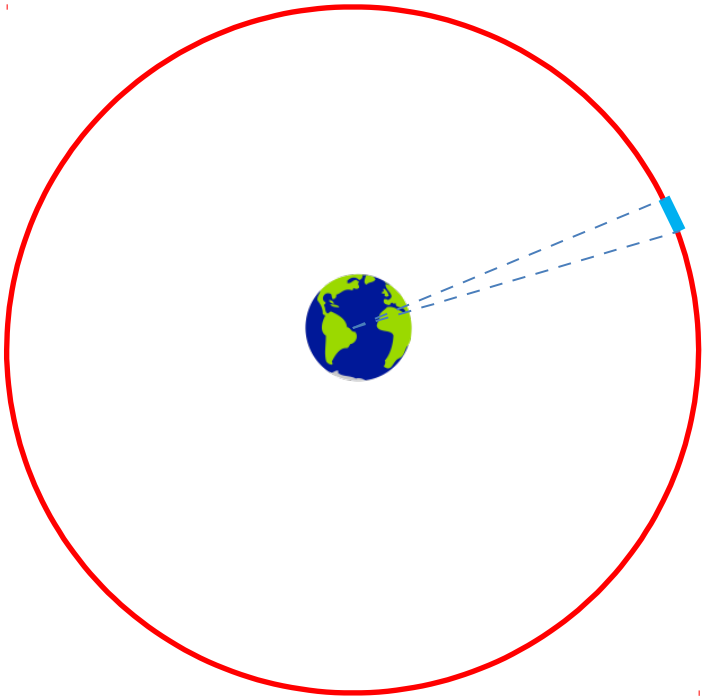
The *current* **radius** of the surface of last scattering (observable universe) is about **46 billion light years**

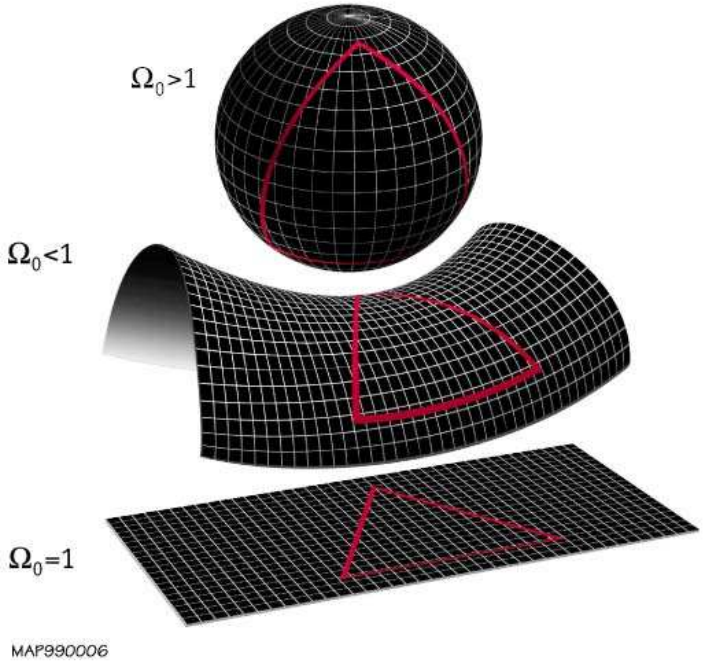
But space was about **1100 times smaller** at the time of last scattering, so the **circumference** of the red circle **at that time** was about 2π x 46 billion ly / 1100 = **260 million ly**.

So the angular size of the blob should be about (760 thousand ly) / (260 million ly) x 360° = 1°

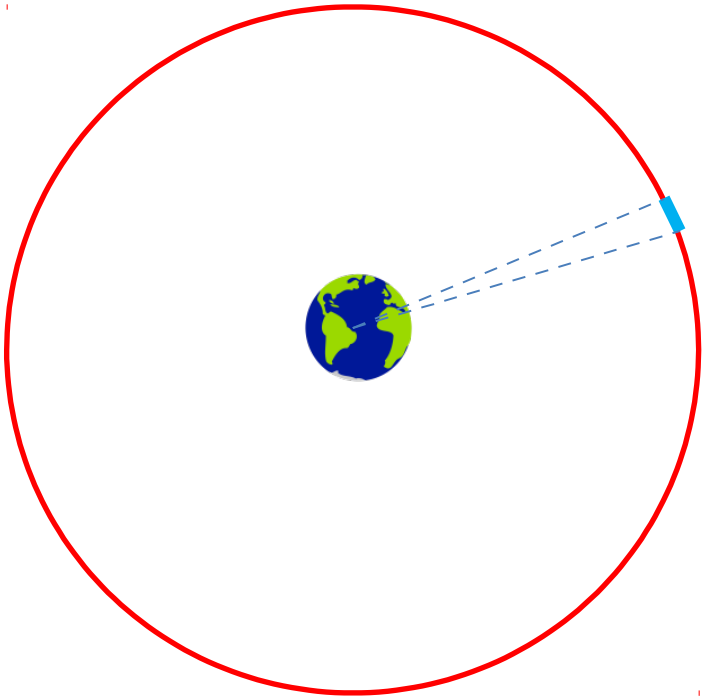
So this make sense!

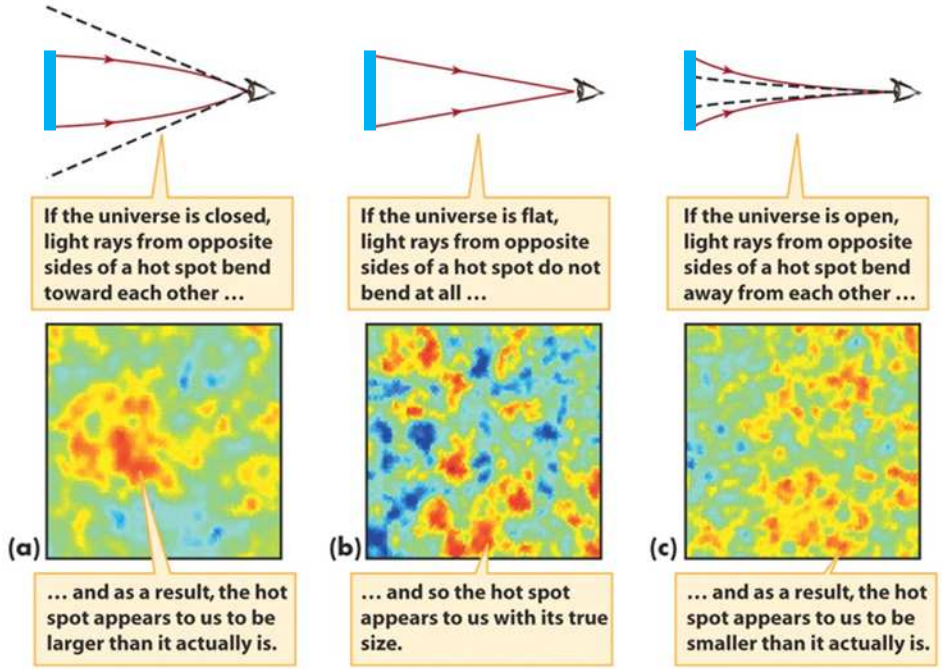
But Wait: In making this calculation we **assumed** that space (**on cosmic scales**) is **flat.** Einstein's theory says it could be **flat**, **positively** curved (a 3D sphere), or **negatively** curved (a 3D saddle).





Positive or negative **curvature of space** would **distort** the angular size of these blobs, like a cosmic-sized gravitational lens. **Positive** curvature would **magnify**, **negative** would **shrink**.





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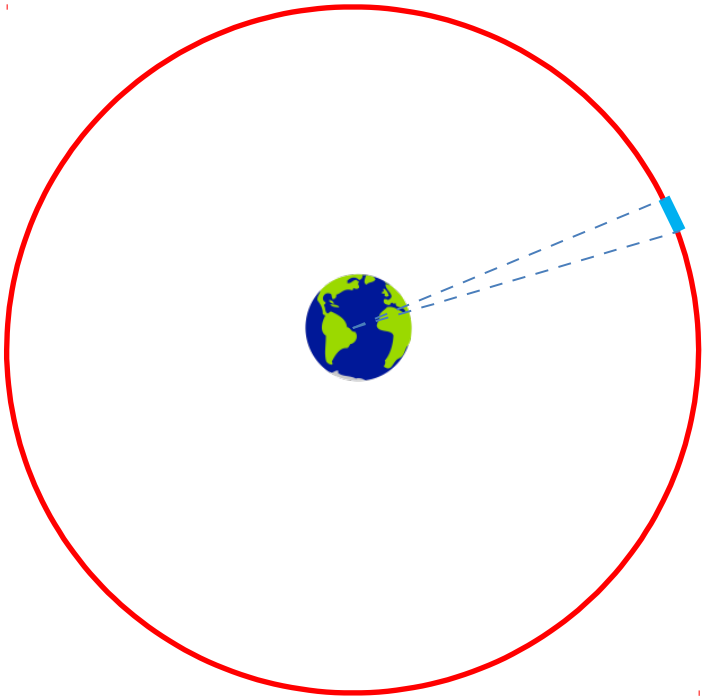

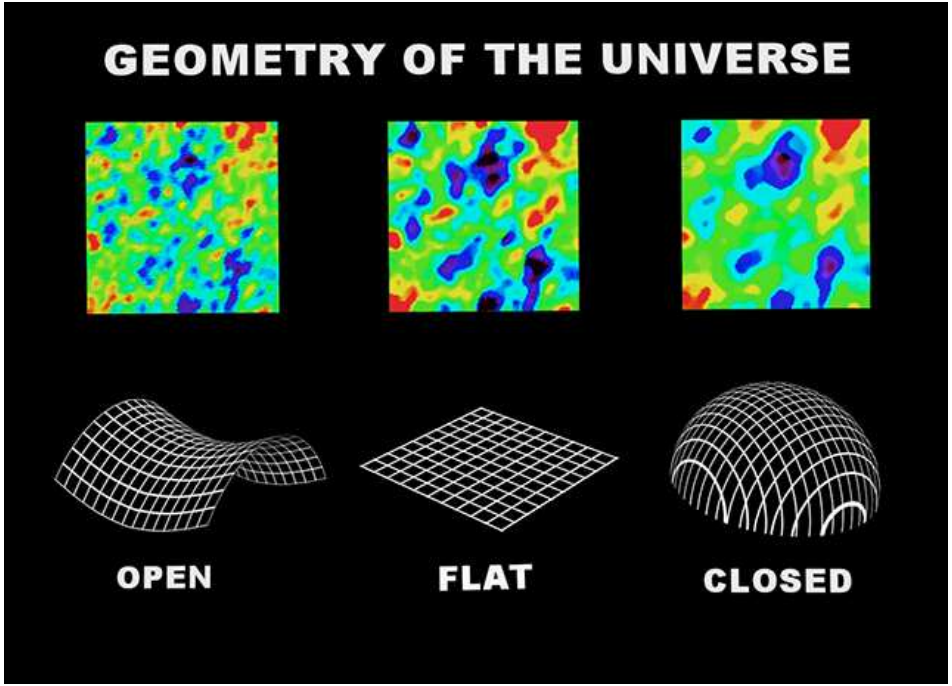

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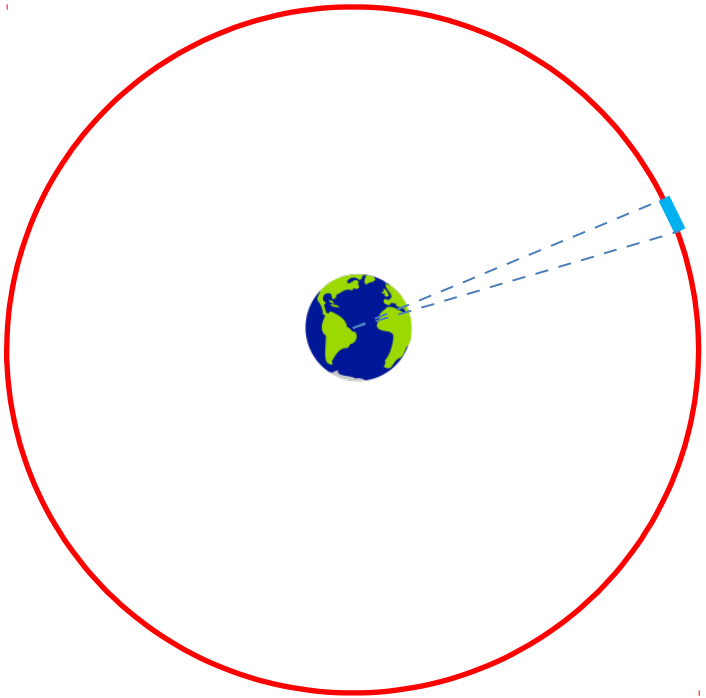
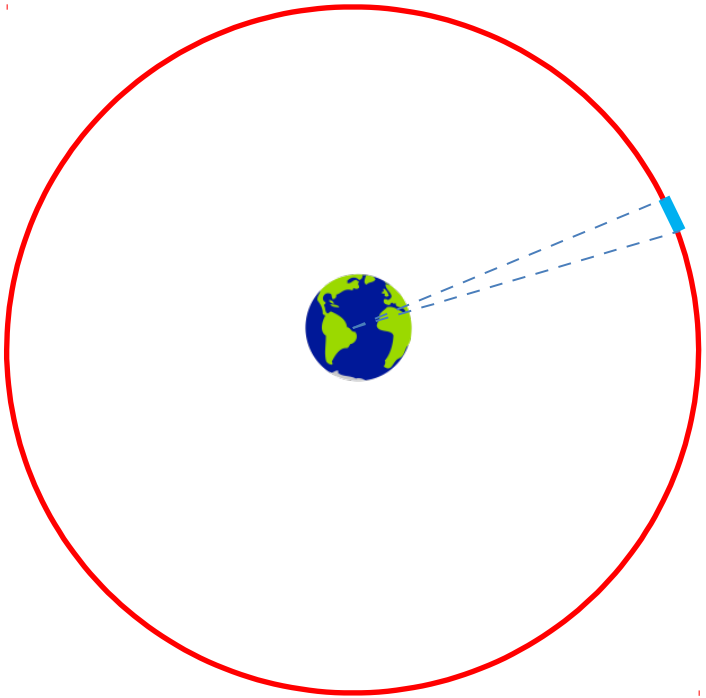
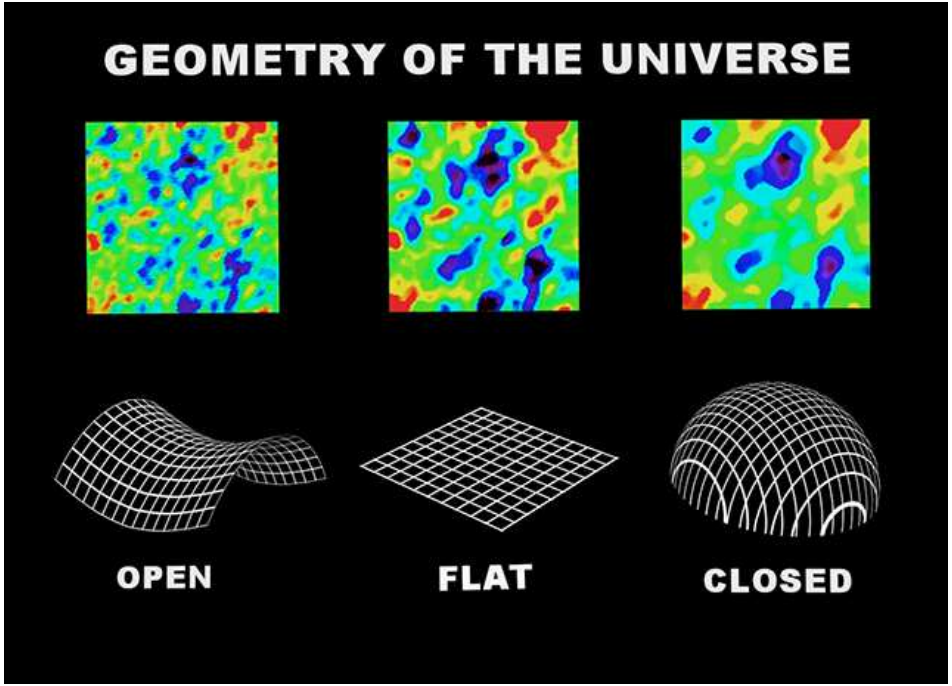


The angular size of the blobs we see is consistent with the observable universe being **FLAT** on the **cosmic scale** (or very nearly so).





So what? Einstein's theory says that a **FLAT** universe requires a certain **critical density of total mass-energy**. Less → OPEN; more → CLOSED. We seem to be at **critical density**.

This critical density is **presently** equivalent to about **5 hydrogen atoms per cubic meter** of space.

Problem:

Ordinary matter (stars, gas, and dust) ≈ 0.2 H per cubic meter

Dark matter (nonbaryonic) ≈ 1.1 H per cubic meter (about 5 x ordinary matter)

Total matter (ordinary + dark) ≈ 1.3 H per cubic meter

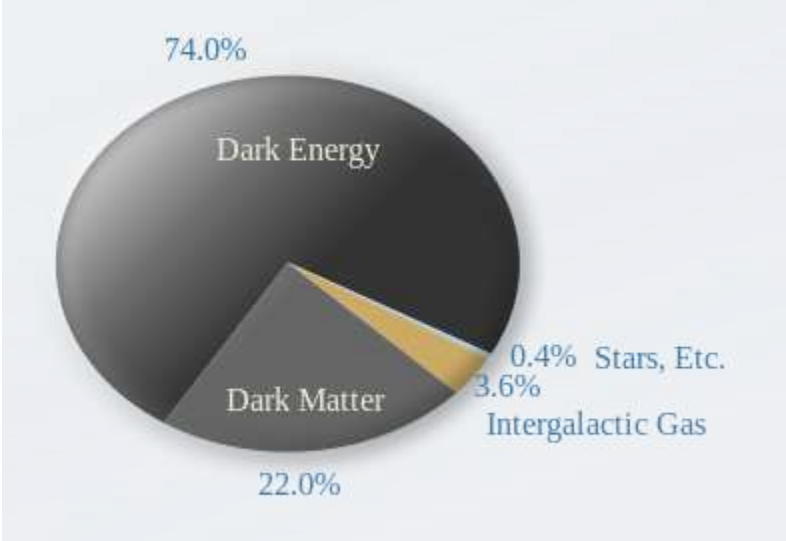
Thus, to make space flat, we're **missing ≈ 5 – 1.3 = 3.7 atoms per cubic meter** of mass-energy! This is about **74% of the total mass-energy budget of the universe!**

Mystery of Dark Energy

So what? Einstein's theory says that a **FLAT** universe requires a certain **critical density of total mass-energy**. Less ⊔ OPEN; more ⊔ CLOSED. We seem to at **critical density**.

This critical density is **presently** equivalent to about **5 hydrogen atoms per cubic meter** of space.

This missing mass-energy is called **DARK ENERGY**



Mystery of Dark Energy

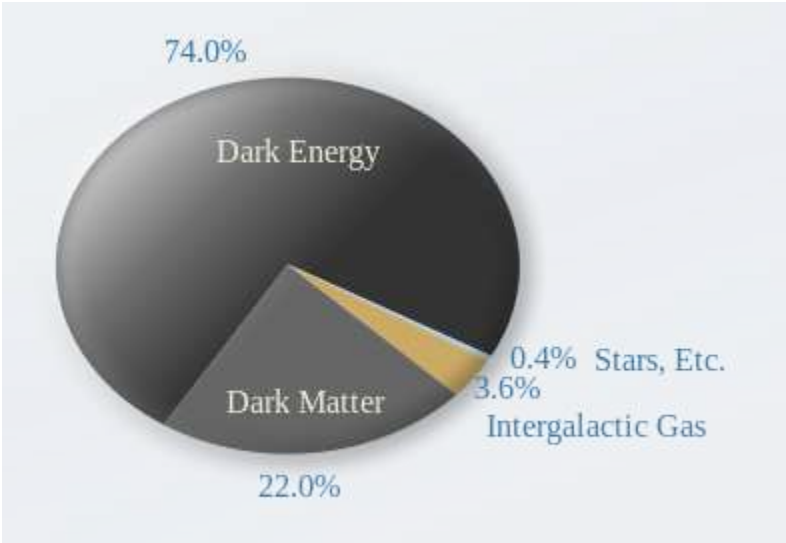
So what? Einstein's theory says that a **FLAT** universe requires a certain **critical density of total mass-energy**. Less ⊔ OPEN; more ⊔ CLOSED. We seem to at **critical density**.

This critical density is **presently** equivalent to about **5 hydrogen atoms per cubic meter** of space.

So not only do we have the mystery of **DARK MATTER** (**22%** of the stuff in the universe)…

…we how have the new mystery of **DARK ENERGY** (**74%** of the stuff in the universe)

A whopping **96%** of the stuff making up the total mass-energy in the universe is **utterly mysterious**.

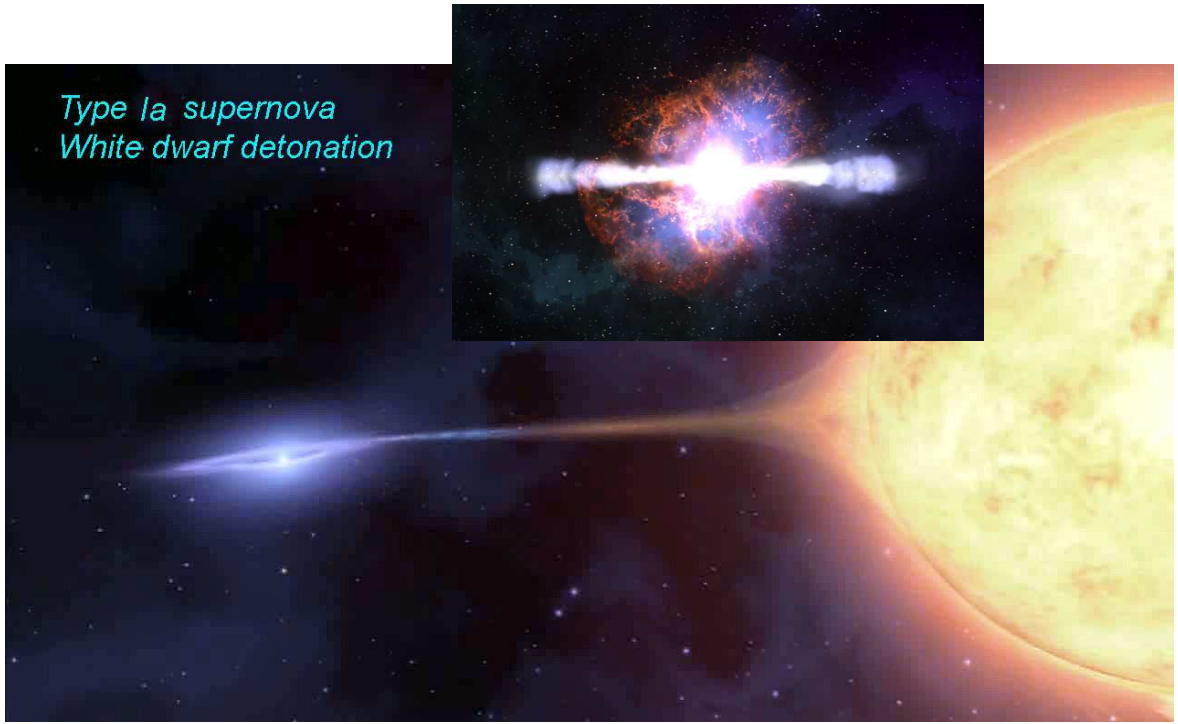


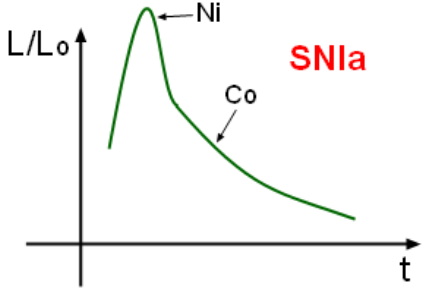
But extraordinary claims (**74% dark energy**) require extraordinary proof.

Is there any **independent evidence** for **dark energy**?

Yes: The **accelerated expansion** of the universe!

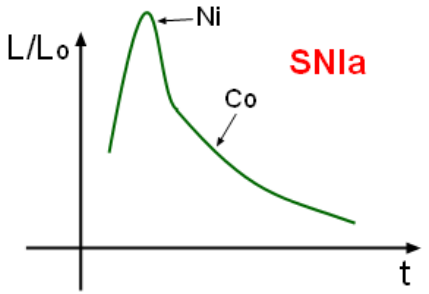
In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

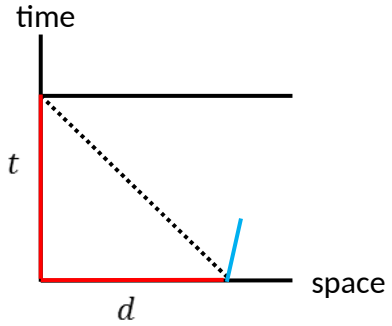




In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

- A Type Ia Supernova is a **standard candle** (object of known **intrinsic brightness**)
- Roughly speaking, measuring its **apparent brightness** tells us its **distance** (more precisely, its *luminosity distance*), and thus (indirectly, see next slide) the **time** in cosmic history when the light was emitted
- Measuring the **redshift** of its spectral lines tells us its **recessional velocity**, or the **rate at which space was expanding** *at that time* (more precisely, the factor by which space has expanded since the light was emitted)

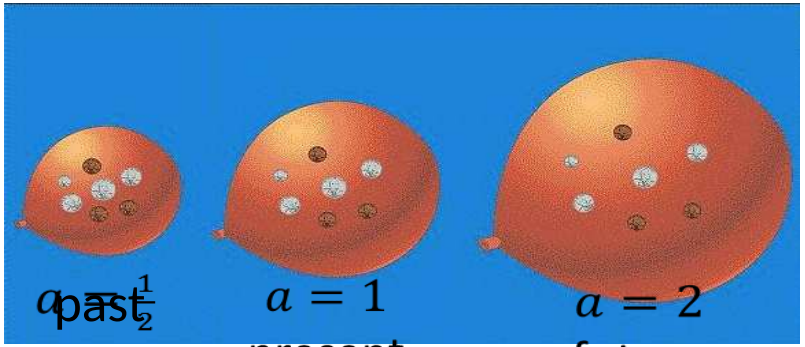


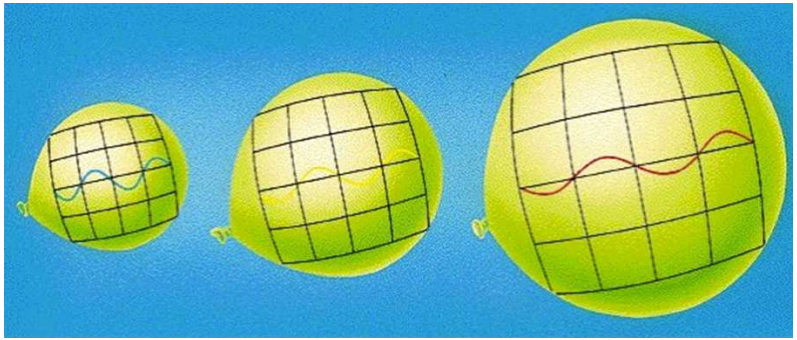


Mystery of Dark Energy

In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

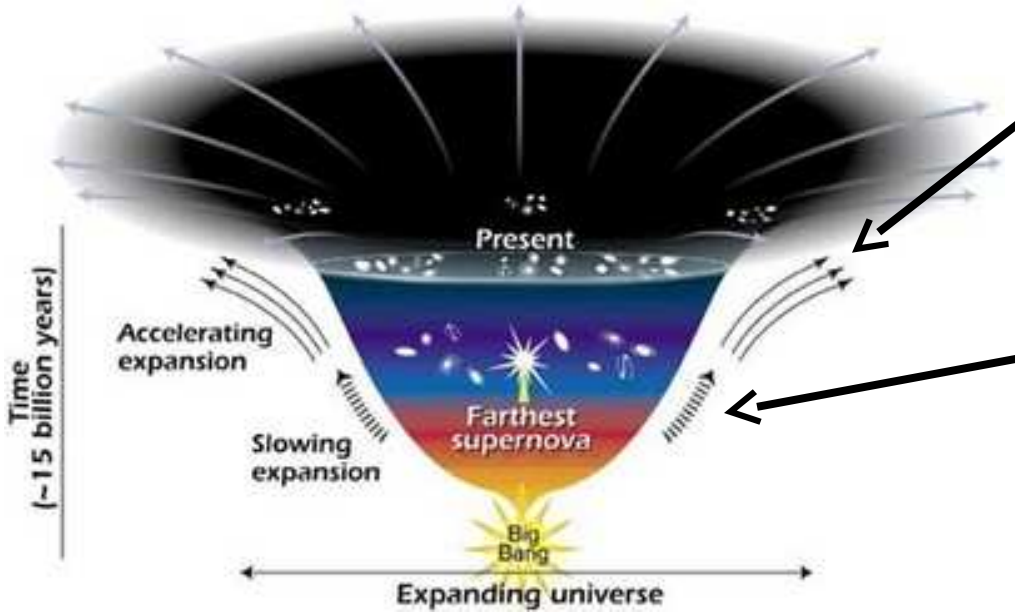
- This data (**apparent brightness & redshift**), input into the mathematics of Einstein's cosmological model of the universe, gives $a(t)$.
- Recall: $H(t) = \dot{a}(t)/a(t)$, $a(t) =$ **scale factor** of space $=$ the size of space relative to now.





In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

- **Surprise!** The rate at which space is expanding has "recently" started to **speed up!**



Unexpected:
"something" is **speeding up** the expansion: increases with time **more quickly**; in calculus language:

Expected:
attractive gravitational force between ordinary matter **slows down** the expansion: increases with time **more slowly**

Mystery of Dark Energy

In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

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Mystery of Dark Energy

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Note: The mathematics in the next few slides is **optional** content. You will NOT be tested on it!

Mystery of Dark Energy

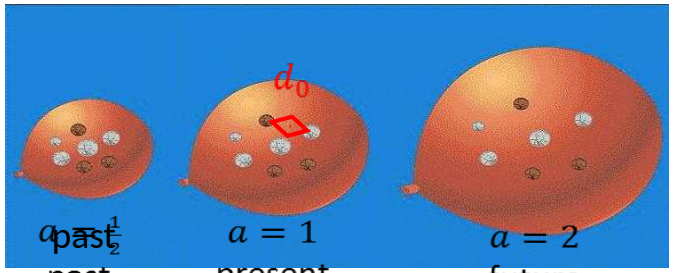
In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

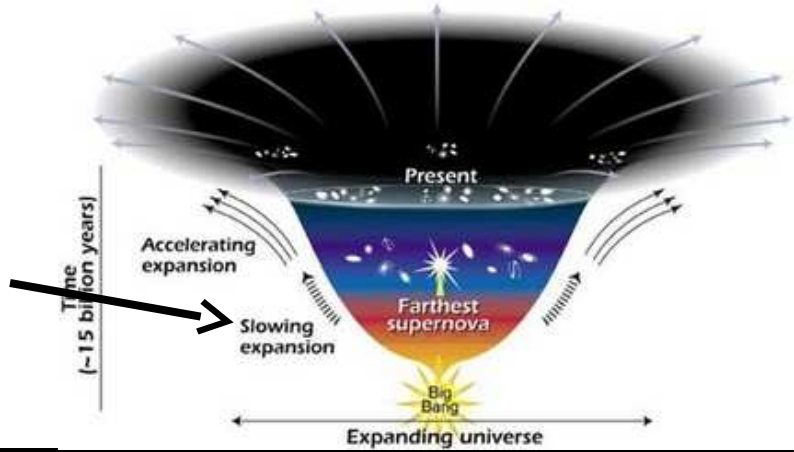
- Hubble Law: $v = Hd = \left(\frac{\dot{a}}{a}\right)(ad_0) = \dot{a}d_0$
- Observe: $\dot{v} > 0 \rightarrow \ddot{a} > 0$
- Friedmann: $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$

ρ = density, p = pressure

For ordinary or dark matter (this) is **positive** and causes the expansion of space to **decelerate** ()

However, it **decreases** as space expands (matter





Mystery of Dark Energy

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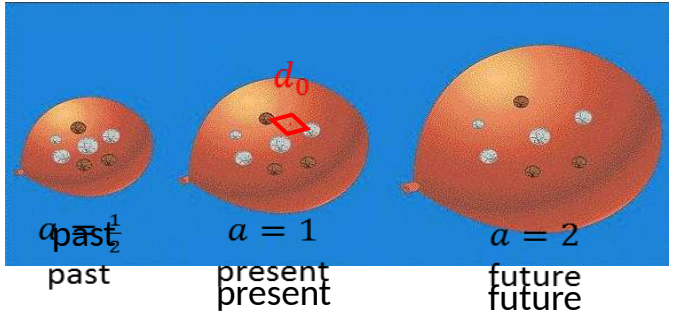
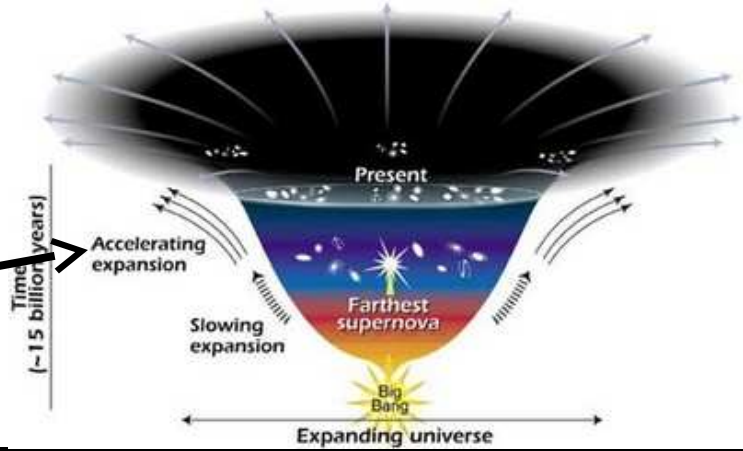
ρ = density, p = pressure

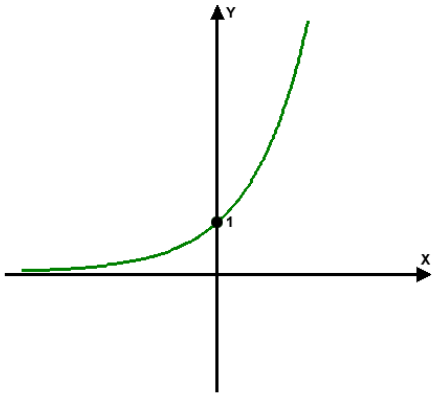
Λ = Einstein's **cosmological constant**. Eventually it **dominates** and, with $\Lambda > 0$, causes the expansion of space to **accelerate** ($\ddot{a} > 0$)





In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

- Friedmann: $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$
- In an era where Λ dominates (as we are approaching): $\frac{\ddot{a}}{a} = \frac{\Lambda c^2}{3}$



- Solution: $a(t) \propto e^{t/T}$, where $T = \frac{1}{c}\sqrt{\frac{3}{\Lambda}}$ = time for space to expand in size by $e = 2.718\ldots$

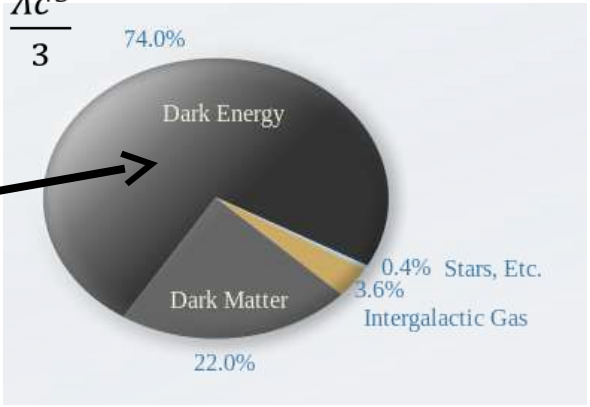
  Small Λ → long time (slow expansion), large Λ → short time (fast expansion)

In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

- Friedmann: $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$
- Alternatively, we set $\Lambda = 0$ and introduce a new kind of "stuff" (*dark energy*) that has **positive** constant density (and energy) and **negative** constant pressure: $p_{DE} = -c^2\rho_{DE}$:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho_{DE} + \frac{3p_{DE}}{c^2}\right) = -\frac{4\pi G}{3}(\rho_{DE} - 3\rho_{DE}) = +\frac{8\pi G}{3}\rho_{DE} = \frac{\Lambda c^3}{3}$$

- ρ_{DE} is the 74% of mass-energy appearing in this pie chart



In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

- Also, Friedmann (flat): $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho = \frac{8\pi G}{3}(\rho_{ord} + \rho_{DM} + \rho_{DE})$
- Hubble Law: $v = Hd = \left(\frac{\dot{a}}{a}\right)(ad_0) = \dot{a}d_0$

decrease (dilute) constant

- H is **decreasing** with time, but d is **increasing faster** so that v is **increasing** ($\dot{v} = \ddot{a}d_0 > 0$)

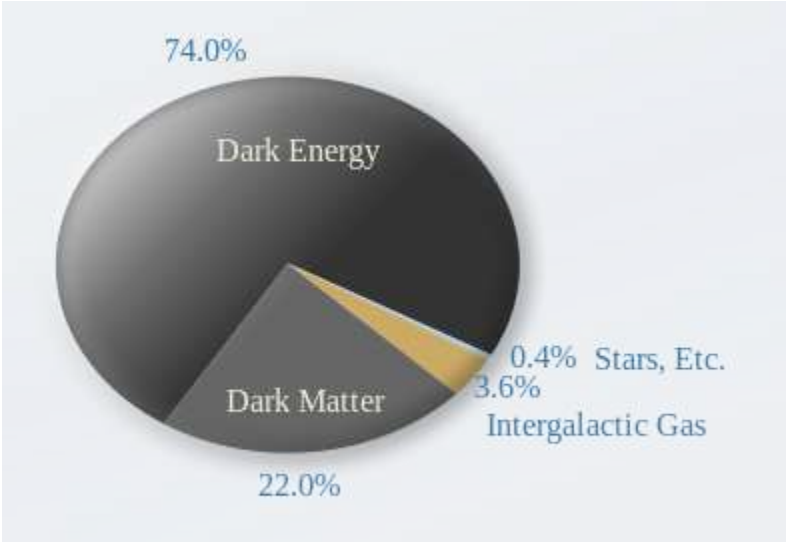
…that's a quick introduction to the basic mathematics underlying modern cosmology.

In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

- **Summary:**
  - Space is **expanding** [the scale factor $a(t)$ is increasing]: Galaxies appear to be moving away from us. They also appear to be moving away from everyone else—no "centre"!
  - Since Hubble's observation, it was *assumed* that the expansion rate would be **slowing down** due to gravitational attraction between all the matter (ordinary and dark).
  - Type Ia Supernovae observations (dimmer than expected, so further away), confirmed by other observations since then (details of the CMB & evolution of large scale structure) showed the **opposite**: the expansion rate is **increasing**: Galaxies appear to be moving away from us **ever faster**.

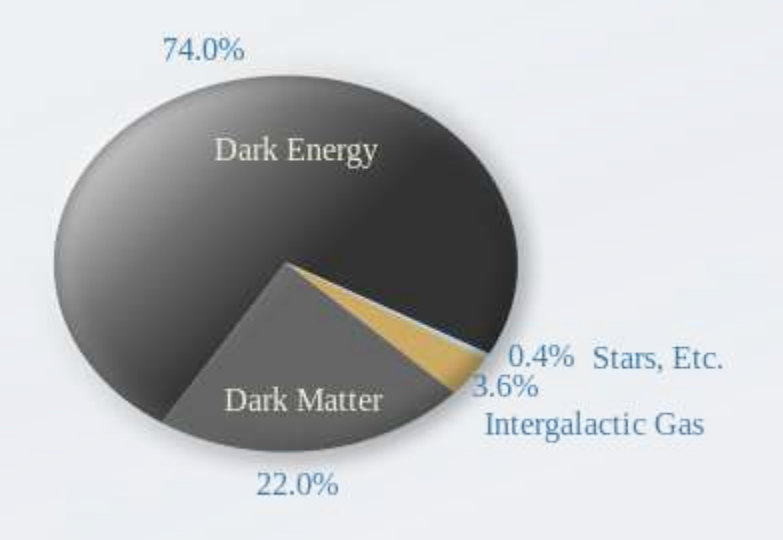
In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

- **Summary:**
  - This requires a **positive cosmological constant**, or equivalently, some weird "stuff" (*dark energy*) with **positive density** () and **negative pressure** ().
  - **Punch line:** The amount of mass density () required to **explain the accelerated expansion** is exactly the amount of **missing mass-energy** required to explain the CMB observation that **space is flat**, or nearly (on cosmological scale)!



In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

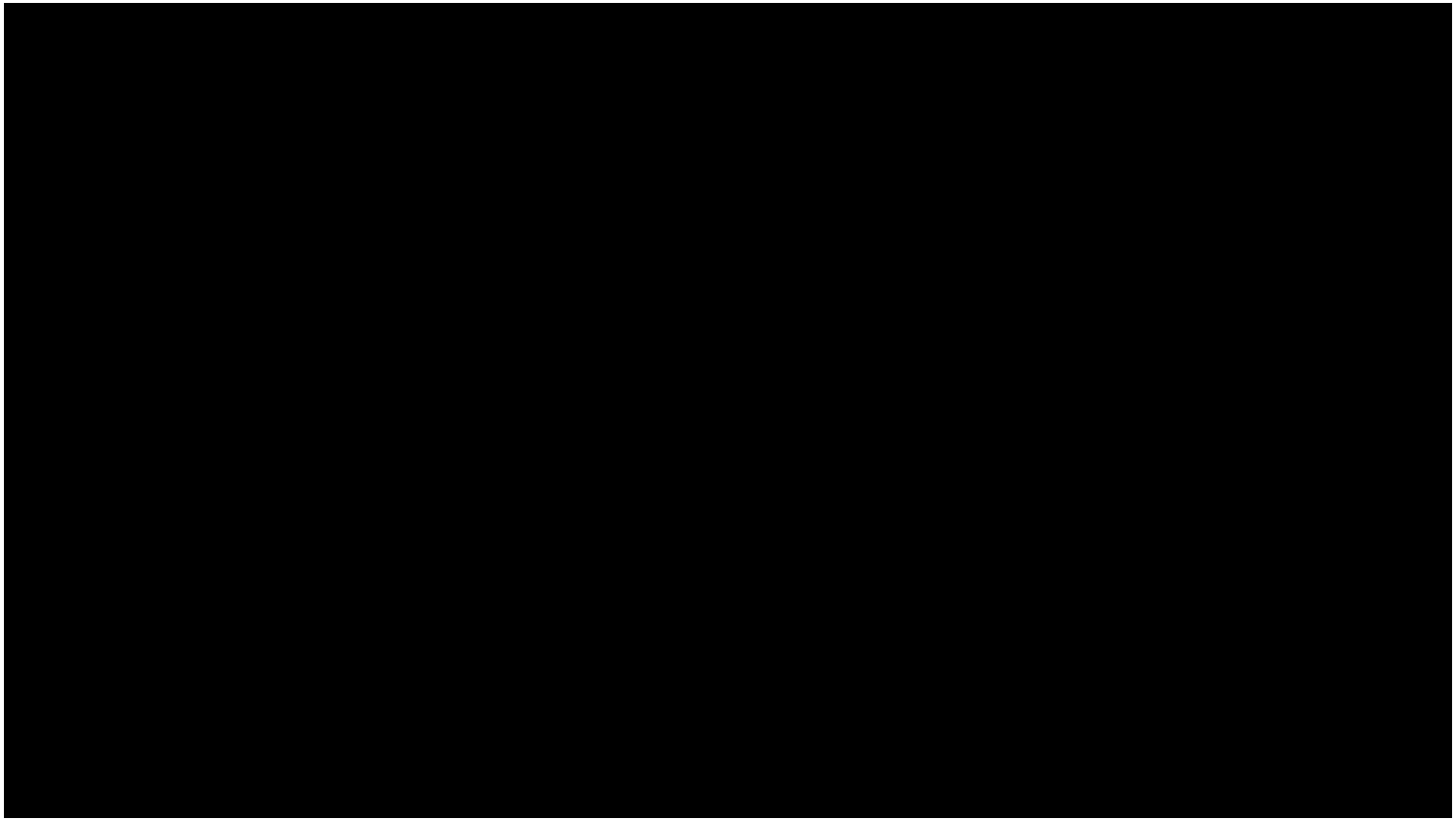
- **Summary:**
  - Recall:
  - ✓ Total **matter** (ordinary and dark) ≈ 1.3 H per cubic meter. Need ≈ 5 H per cubic meter to explain **flat space**.
  - ✓ Thus, missing ≈ 3.7 H per cubic meter. The ρ_{DE} required to explain the accelerated expansion is **exactly equivalent to this**!
  - ✓ **Suddenly, the universe made sense!**



In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

- **Summary:**
  - Thus, despite how "radical" the idea was, it was accepted **very quickly**. The 2011 Nobel Prize in Physics was awarded jointly to two supernovae research groups led by:
    - ✓ Saul Perlmutter (Supernova Cosmology Project—USA)
    - ✓ Brian Schmidt & Adam Riess (High-z Supernova Search Team—Australia)

Mystery of Dark Energy



So What?

Mystery of Dark Energy

- The actual value of the cosmological constant turns out to be relatively **small** (more later…) and **positive**. Based on $\frac{\ddot{a}}{a} = \frac{\Lambda c^3}{3}$ (when Λ dominates), this has profound implications for our existence:

  - If Λ were **much larger** than it is (anything remotely close to its predicted value…more later), the universe would have expanded so fast that galaxies, stars, or even atoms could not have formed ⌴ **no life**.

  - If Λ were much larger & **negative**, the universe would have collapsed too soon for life to have evolved ⌴ **no life**.

  - Λ is relatively "**fine tuned**" to allow for the existence of life. Thus, the **question of our existence** is intimately tied to why Λ has the value it does. **Where does it come from?**

Mystery of Dark Energy

- So, what is dark energy?
    - **It is dark:** Or invisible/transparent—we cannot see it. It doesn't appear to interact with matter or radiation (light) at all. (We can "see" **dark matter** by its gravitational interaction with visible matter; not so for **dark energy**.)
    - **It is smoothly distributed:** It does not fall into galaxies or clusters (gravitationally clump), or it would affect the dynamics of those objects (like dark matter does).
    - **It is persistent:** It's density appears to remain constant even as space expands. It **doesn't dilute** (get less dense) like ordinary and dark matter does, when space expands.
    - In short: Dark energy is **not matter**. Unlike matter, it appears to have no dynamics, and does not dilute as space expands. **It is something else.** Hence the name: *dark energy*.

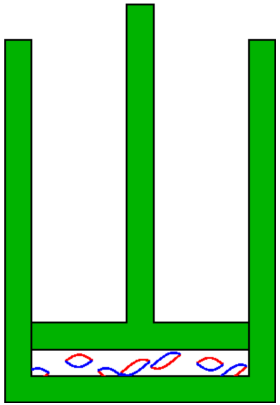
Mystery of Dark Energy

- So, what is dark energy?
  - **Best guess:** Dark energy is "**vacuum energy**":
    - ✓ Observations indicate the dark energy is at least *approximately* uniform and persistent, but is *consistent* with being **perfectly** uniform and persistent
    - ✓ Assuming this is so, that's the definition of **vacuum energy**: an energy associated with space *itself*: space **empty of all matter,** i.e., **vacuum**.
    - ✓ But a vacuum energy means that *if we double the amount of space, we double the amount of vacuum energy*.

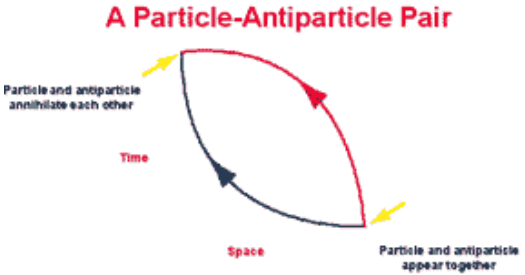
- So, what is dark energy?
  - **But wait!** Doesn't this violate *conservation of total energy*?
    - ✓ **Unknown**. Remember, Einstein's theory of space, time and gravity threw a "monkey wrench" into our understanding of "energy". We don't yet properly understand how to include **gravitational energy**, so we don't really know if **total** energy is conserved or not, especially on the cosmological scale.
    - ✓ Certainly, energy of matter **alone** (ignoring gravity) is **not** always conserved. **Example:** The number of CMB photons is fixed, but as space expands, they get stretched to lower-energy photons, so matter (light) energy is lost. **However**, the matter still obeys what's called the "**energy-momentum conservation**" equation (), which includes the effects of the expanding space in the "". Energy loss of photons is a **clear prediction of general relativity**, that has been verified.

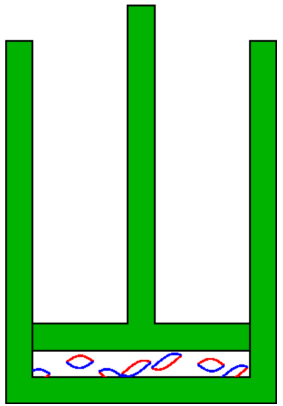
- So, what is dark energy?
  - **But wait!** Doesn't this violate *conservation of total energy*?
    - ✓ It can be argued that the *decreasing CMB photon energy* is **no weirder** than the *increasing dark energy*. Both happen because, in general relativity, spacetime *itself* is **dynamical**, and participates in how things evolve over time. See the article by Sean Carroll.
    - ✓ On the other hand, physicists sometimes talk about changes in **negative gravitational energy** compensating for changes in **positive matter/radiation energy**, but this is not completely understood. Rough arguments are even made that the total **negative** gravitational energy in the universe plus the total **positive** matter/radiation energy add up to simply **zero**. If true, the total energy of the universe **is** conserved, and **adds up to exactly nothing**! (We'll come back to this…)

- So, what is dark energy?
  - **But wait!** Doesn't this violate *conservation of total energy*?
    - ✓ Imagine a cylinder filled with a gas at **negative pressure** (analogous to the negative pressure of dark energy). This will tend to pull in the piston. If we do work to pull it out, we **add positive energy** to the gas, like stretching an elastic band (analogous to more dark energy appearing as space expands).
    - ✓ So **increasing dark energy** & **negative dark pressure** work together to make sense. But what's pulling the piston out? Like , "just the math" of Einstein's theory, : *Negative* pressure drives *positive* accelerated expansion! It seems weird only because we don't have day-to-day experience with it.

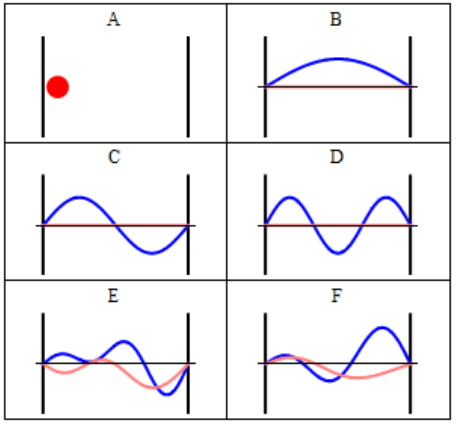


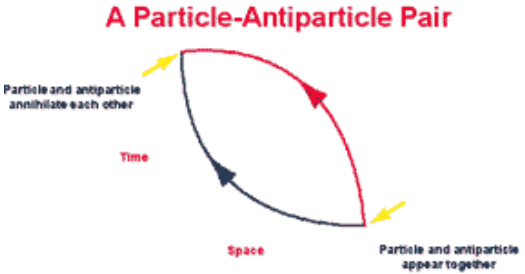
- So, what is dark energy?
  - Vacuum energy? **How can empty space have energy?**
    - ✓ Before physicists discovered **quantum mechanics** (more later…) we would have said that the vacuum is *empty*.
    - ✓ But the quantum nature of the universe says that the vacuum is *teeming with activity* in the form of **spontaneous creation and annihilation** of "virtual particle-antiparticle pairs", called *quantum vacuum fluctuations*.
    - ✓ This does **NOT violate conservation of energy**; it just means the vacuum has energy that is greater than zero.



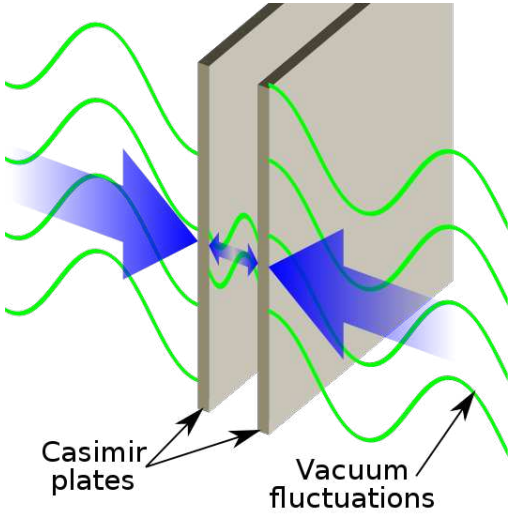


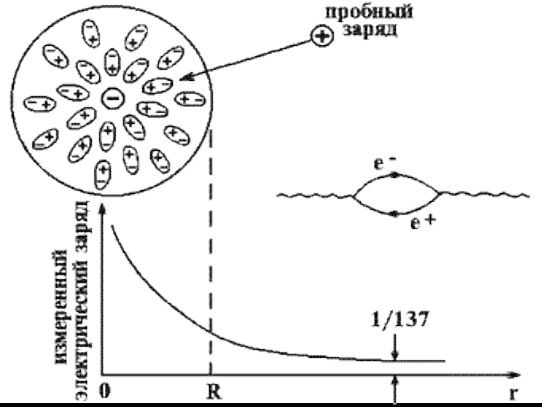
- So, what is dark energy?
  - Vacuum energy? **How can empty space have energy?**
    - ✓ **Example:** Particle in one-dimensional box of length L. A is the classical behaviour; B-F are examples of the particle behaving like a wave (quantum behaviour).
    - ✓ **Heisenberg Uncertainty Principle** (quantum) says: and so: ▭
    - ✓ The momentum of the particle is **uncertain**: it **cannot have a certain value**, e.g., zero. Thus, it **cannot have zero energy**. The lowest possible energy is > 0.
    - ✓ Same is true for **fields**: **spontaneous creation and annihilation** of "virtual particle-antiparticle pairs"





- So, what is dark energy?
  - Vacuum energy? **How can empty space have energy?**
    - ✓ This weird consequence of the quantum nature of our universe can be **accurately observed in the lab**:
      - ➢ Casimir effect
      - ➢ Lamb shift
      - ➢ Anomalous magnetic dipole moment of the electron (most accurately predicted and experimentally confirmed quantity **ever**)
    - ✓ Also responsible for **Hawking radiation** (more later…)





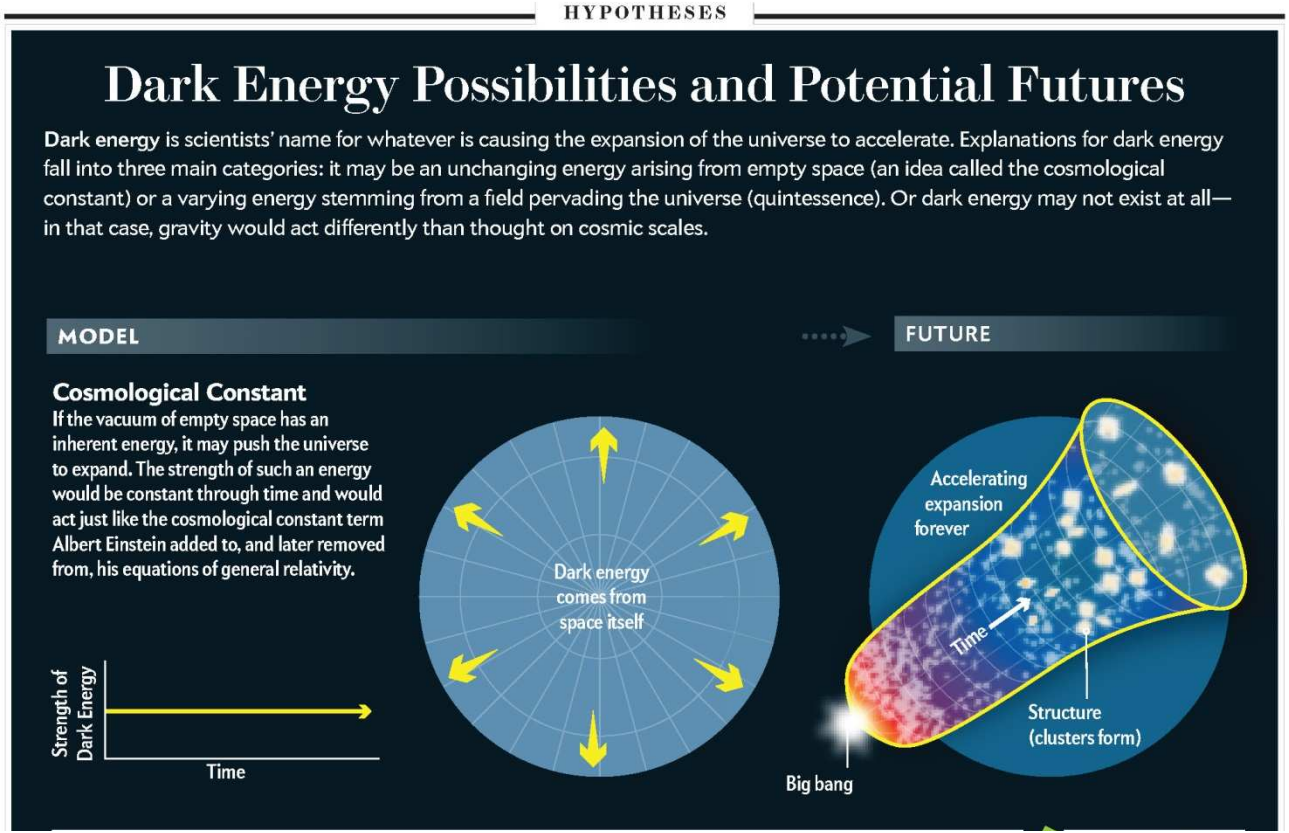
- So, what is dark energy?
  - **Can such vacuum energy be the dark energy?**
    - ✓ The vacuum energy of quantum fields has **exactly the right form** to be the cosmological constant, or dark energy: it has contant > 0 and .
    - ✓ **Problem:** Physicists estimate .
      This is the **MOST WRONG** prediction in the history of science!
    - ✓ This is called the "**cosmological constant problem**": What is the origin of this discrepancy? Why is the cosmological constant so many orders of magnitude **smaller than we expect**? If it's that small, then why is it not just **zero**?

- So, what is dark energy?
  - **Can such vacuum energy be the dark energy?**
    - ✓ But is it ***really*** a problem?
    - ✓ Maybe is simply **not a valid prediction**. It accounts for **quantum** effects, but **ignores gravity**, and so should not be expected to have anything to do with the real world.

[is calculated assuming the virtual particles responsible for vacuum energy **do not gravitate** (curve spacetime). But , together with general relativity, tells us they **must**. Ignoring gravity, the vacuum energy can be made to be ***anything***; usually, it's made to be just **zero**…which then doesn't explain the observed Λ.]

- So, what is dark energy?
  - **Can such vacuum energy be the dark energy?**
    - ✓ But is it ***really*** a problem?
    - ✓ In order to get a **valid prediction**, we need a deeper understanding of the universe that properly incorporates *both* its **quantum** and **gravitational** nature. We need a **theory of quantum gravity**, or more generally, a "**theory of everything**".
    - ✓ So: understanding the observed value of Λ, and thus **our existence**, is intimately linked to a **theory of everything** (more later…).

- So, what is dark energy?



Despite its uncertain origin, vacuum energy / cosmological constant is the **leading candidate** for what dark energy might be.

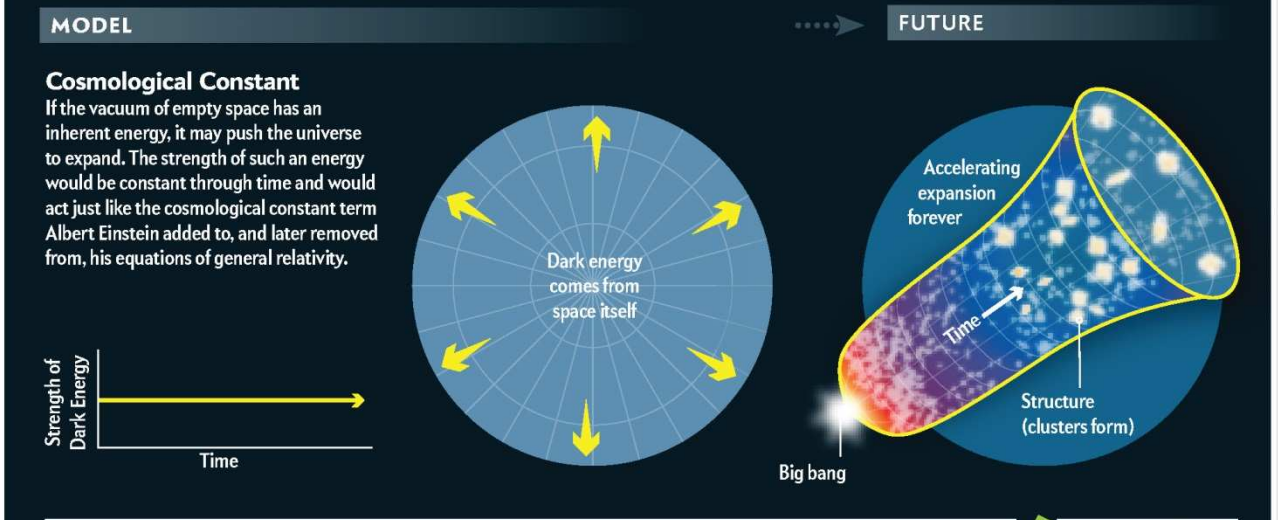
If so, the expansion of space will continue to accelerate; after a **trillion years**, our observable universe will contain essentially just the **Milky Way and Andromeda**; more distant galaxies will be "receding faster than ".

- So, what is dark energy?

HYPOTHESES

Dark Energy Possibilities and Potential Futures

Dark energy is scientists' name for whatever is causing the expansion of the universe to accelerate. Explanations for dark energy fall into three main categories: it may be an unchanging energy arising from empty space (an idea called the cosmological constant) or a varying energy stemming from a field pervading the universe (quintessence). Or dark energy may not exist at all—in that case, gravity would act differently than thought on cosmic scales.



Ultimate fate of the universe would be a "Big Freeze"—essentially "**heat death**":

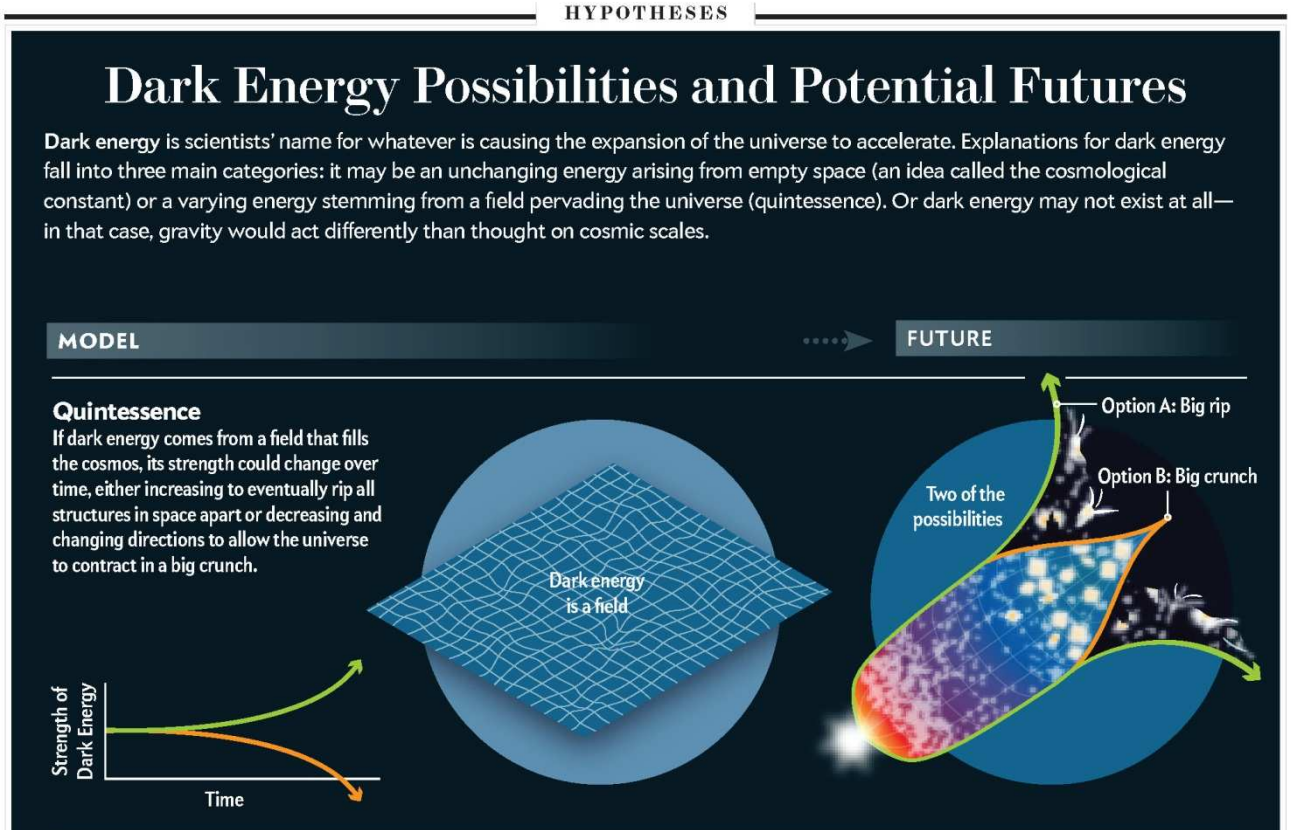
In 1-100 trillion years, **gas to fuel stars** will be exhausted → universe will grow dark.

Most matter will coalesce into BHs (by 10^{40} years), which will **evaporate** in Hawking radiation (by 10^{100} years) → **redshift** to zero.

(More complicated than this…research on your own.)

- So, what is dark energy?
  - Another possible answer: **Dark Energy = Quintessence**
    - ✓ Maybe dark energy is a **dynamical field**, like the electromagnetic field, except **unlike** the electromagnetic field, it does **not** arise from localized sources, and pervades all of space **uniformly** (or almost uniformly).
    - ✓ Named after the **fifth classical element** (beyond earth, fire, water, and air). It was believed to fill all space in the "heavens"; what the gods breathed.
    - ✓ "**Dynamical**" means it can **change with time**, thus changing the rate at which the expansion of space is accelerating. Its strength could change over cosmic time, both into the past and into the future. However, any hypothesized dynamics of such a quintessence field is **purely speculative** at this stage.

- So, what is dark energy?



If dark energy is quintessence the fate of the universe depends on its (unknown) dynamics.

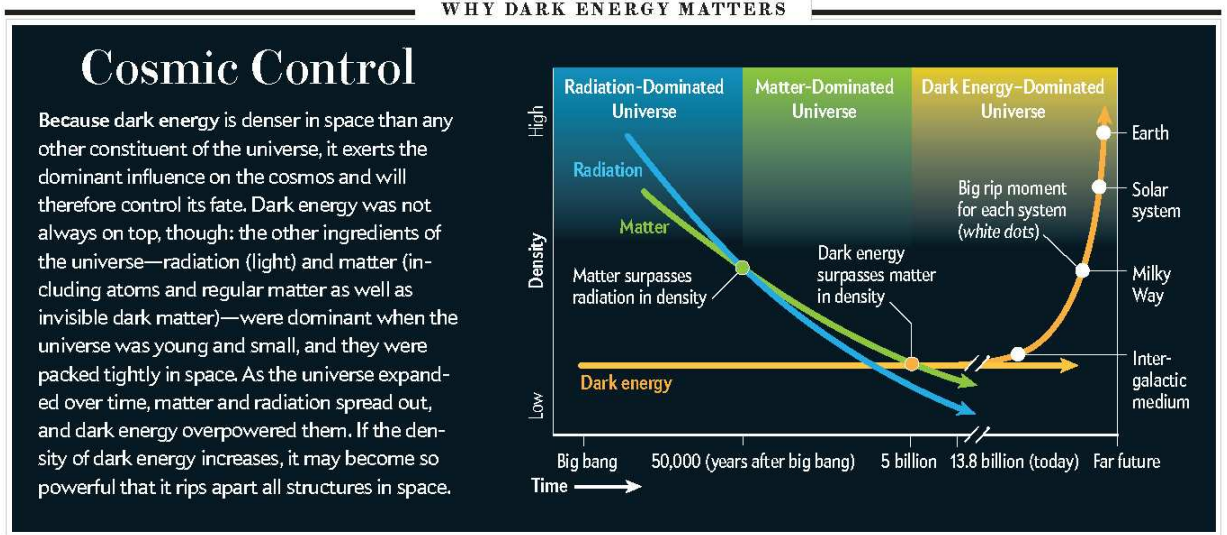
If its strength **decreases** and eventually changes direction ▭ "Big Crunch".

If its strength **increases** enough ▭ "Big Rip".

So the nature of dark energy (cosmological constant or quintessence) is important because it **controls the ultimate fate of the universe.**

The universe was originally dominated by **radiation** (light), then later **matter** (dark & ordinary), and now **dark energy**. The first two **dilute as space expands** (radiation started bigger, but **dilutes faster** than matter); presently, the (at least roughly constant) **dark energy** is left to **dominate**.

If dark energy is **quintessence**, in the "**Big Rip**" scenario, the accelerated expansion of space can be so large that it rips apart first galaxy clusters, then galaxies, then solar systems, then planets, people, atoms, atomic nuclei, etc… (!)

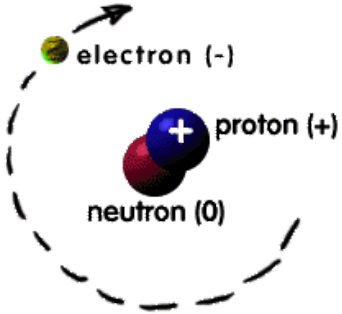


How?

Imagine electron and proton **at rest**, and **turn off** electrostatic attraction. A small, **constant** (accelerated expansion of space) would cause the space between them to expand, faster and faster. Like galaxies, they are **not accelerating**, and there is **no force** between them, but they are accelerating ***relative*** to each other, ***as if*** they are experiencing a very weak "repulsive force".

Now turn on the electrostatic attraction, and add to it this very weak ***effective*** "repulsive force". **Net** effect is a **slightly weaker** attractive force, and hence a **slightly larger** atom (if you put in the numbers, larger by 1 part in)

A small, ***constant*** Λ produces a small, ***constant*** increase in the size of atoms.
Atoms (and people) are **NOT** getting bigger and bigger as space expands!

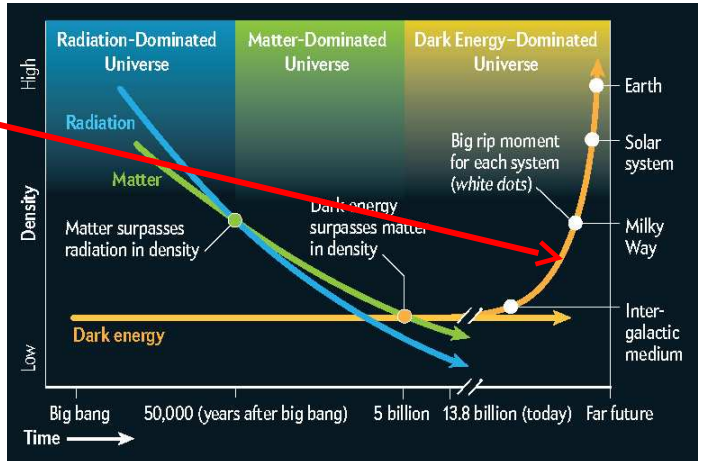


Challenge for physics students: If r_0 is the Bohr radius, then a small, constant Λ will increase r_0 to $(1+\epsilon)r_0$, where ($\lambda = \frac{\hbar}{mc}$ = Compton wavelength):

$$\frac{\epsilon}{r_0} = \frac{1}{3}\frac{\Lambda}{\lambda^2/{r_0}^4} \sim 10^{-68}$$

How?

However, if Λ were to ***increase*** with time (not constant), by ***many orders of magnitude*** (Big Rip scenario), then yes, atoms and people would get bigger with time. First galaxy clusters, then galaxies, then solar systems, then planets, people, atoms, atomic nuclei, etc., would get **ripped to shreds**, everywhere, simultaneously.



A small, ***constant*** produces a small, ***constant*** increase in the size of atoms.
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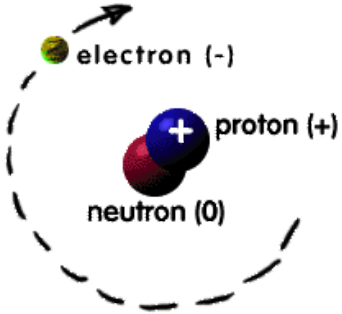
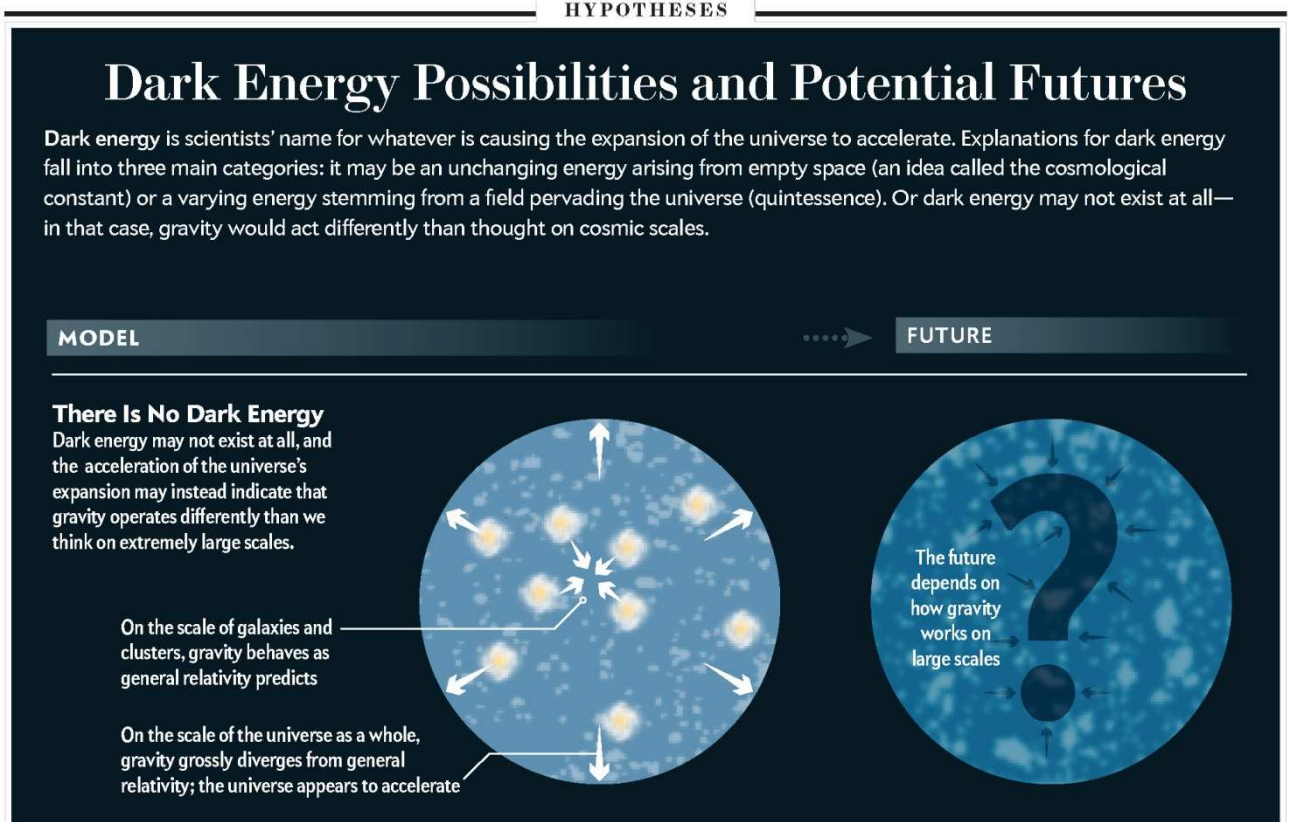
Challenge for physics students: If is the Bohr radius, then a small, constant will increase to , where (Compton wavelength):



- So, what is dark energy?
  - Another possible answer: **There is no dark energy; it's just gravity**
    - ✓ The expansion of space is **certainly accelerating**: getting faster and faster. Two **completely independent** lines of evidence point to the same thing: Type 1a supernovae measurements, discussed earlier, and rate of galaxy clustering.
    - ✓ But just as there may be no **dark matter**—the observations might instead be explained by a **modified theory of gravity**, maybe there is no **dark energy**—the observed accelerated expansion might instead be explained by modifying our understanding of gravity on the scale of galaxy clusters and larger.
    - ✓ While possible, and currently an active area of research, this is **not** the currently favoured hypothesis.

- So, what is dark energy?



If there is no dark energy, and it's just gravity behaving in an unexpected way at very large scales, then the fate of the universe is **completely unknown**.

"All bets are off," until we discover this new, deeper theory of gravity…

Mystery of Dark Energy

- So, what is dark energy?
  - **No one knows**, but very active research continues.
  - **Main question:** Is the dark energy density really **constant**, or has it **changed** over cosmic time?
  - **New projects** (research on your own):
    - ✓ Dark Energy Survey (DES), begun in 2013
    - ✓ Large Synoptic Survey Telescope (2021?)
    - ✓ Wide-Field Infrared Survey Telescope (mid 2020s?)
    - ✓ ESA's Euclid space mission (2020?)
    - ✓ Etc…
- Dark energy is a **major unsolved mystery** of **huge importance** in the **"bigger picture"**…

Two Profound Properties of the CMB

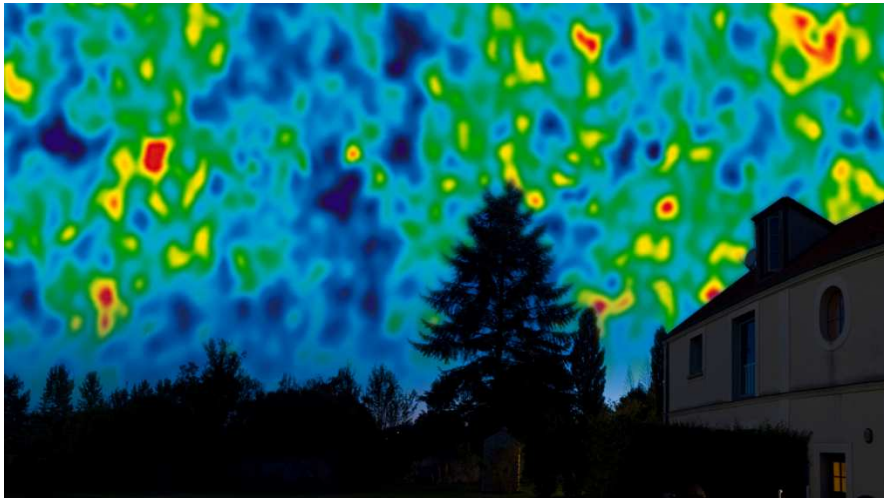
Let’s return to the CMB, and try to unravel its profound implications for our ultimate origin

Two Profound Properties of the CMB

- While the CMB provides **strong evidence** for a **hot, dense beginning** (afterglow of the BB) it raises two **deep mysteries**, which provide **profound clues** to our **ultimate origin**:
  - Why is the temperature of the CMB **almost perfectly uniform**?
  - Why is it **not** perfectly uniform? What is the origin of the **tiny temperature fluctuations**?

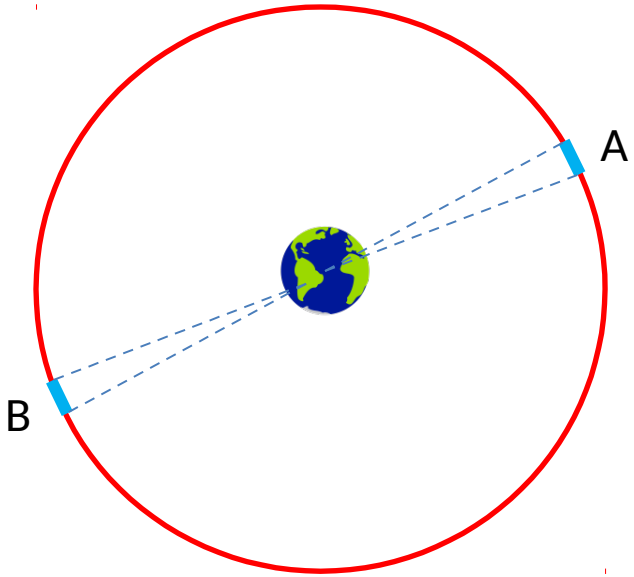
Average temperature $= 2.7260 \pm 0.0013$ K

Temperature **fluctuations** $\approx$ 1 part in 100,000



Two Profound Properties of the CMB

- Why is the temperature of the CMB **almost perfectly uniform**?
  - By exactly the **same rough argument** we gave before, the angular size of the "blobs" (regions that have the same temperature) should be about **1° on the sky**.



Shown are two blobs of gas, A & B, seen in opposite directions on the sky (light coming from long ago, far away). In the 380,000 years since the BB, the gas in each blob (**separately**) would have had time to **thermalize** (come to the same temp), say: T_A & T_B.

In principle, however, T_A & T_B could be **very different** temperatures. But in fact, they differ by only **1 part in 100,000**. We need to explain this! This is called the **horizon problem**.

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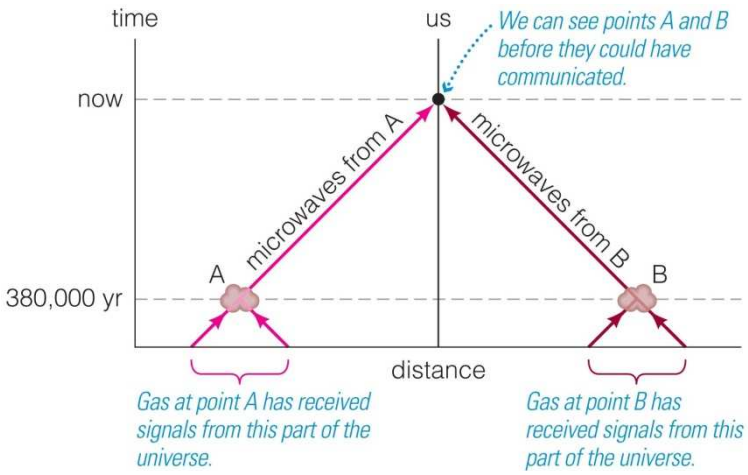

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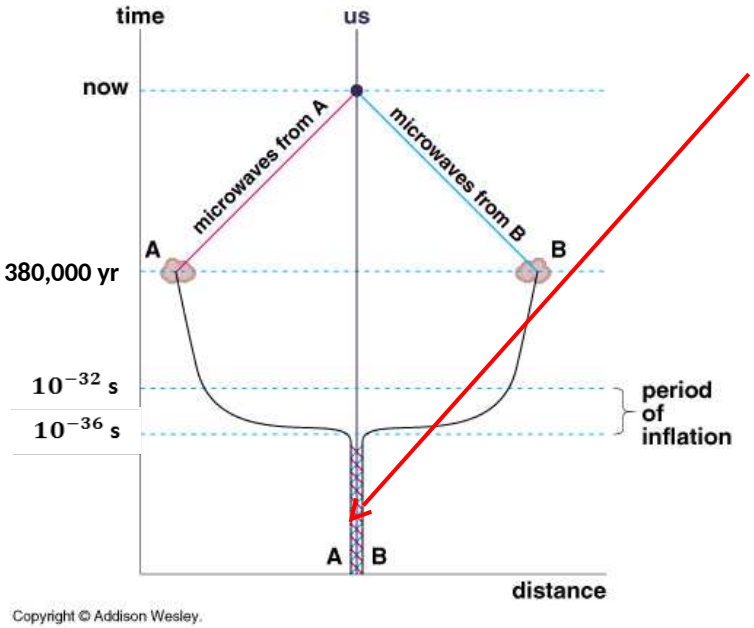
Two Profound Properties of the CMB

- Why is the temperature of the CMB **almost perfectly uniform**?
  - Current widely adopted hypothesis: **Cosmic Inflation** (Alan Guth, 1980)



In the early universe ($t < 10^{-36}$ seconds), the space in the current observable universe was **very tiny**, **much smaller** than the nucleus of an atom.

Although 10^{-36} seconds is a **very small time**, this region was **so tiny** that any "stuff" in it, that would eventually give rise to all the matter and radiation in the observable universe today, had **plenty of time to thermalize**. It was in **perfect thermal equilibrium**.

Two Profound Properties of the CMB

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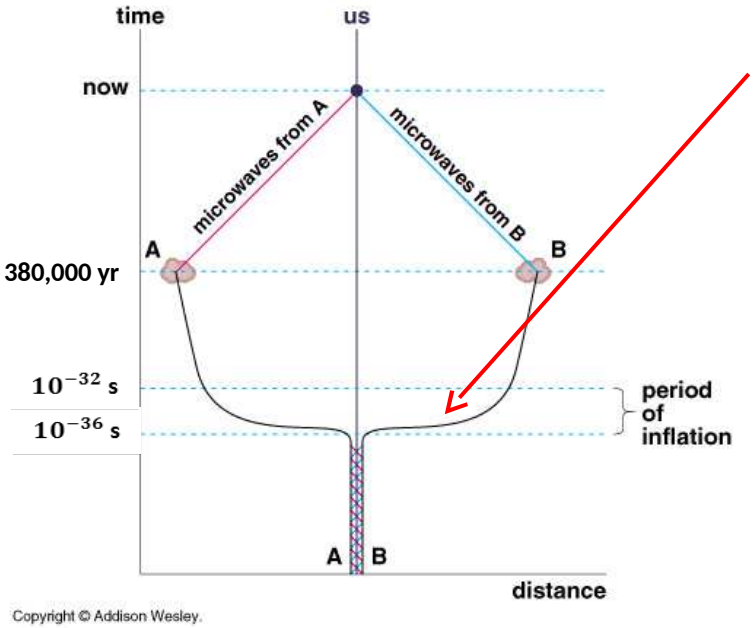

Then came a very short period of **extremely** rapid accelerated expansion, called **inflation**.

In roughly seconds, space expanded in size by an **enormous factor** (e.g., to pick a number), to something, say, the size of a marble.

How? E.g., just simple Einstein/Friedmann: , where is value of the cosmological "constant" during this inflationary period.

Two Profound Properties of the CMB

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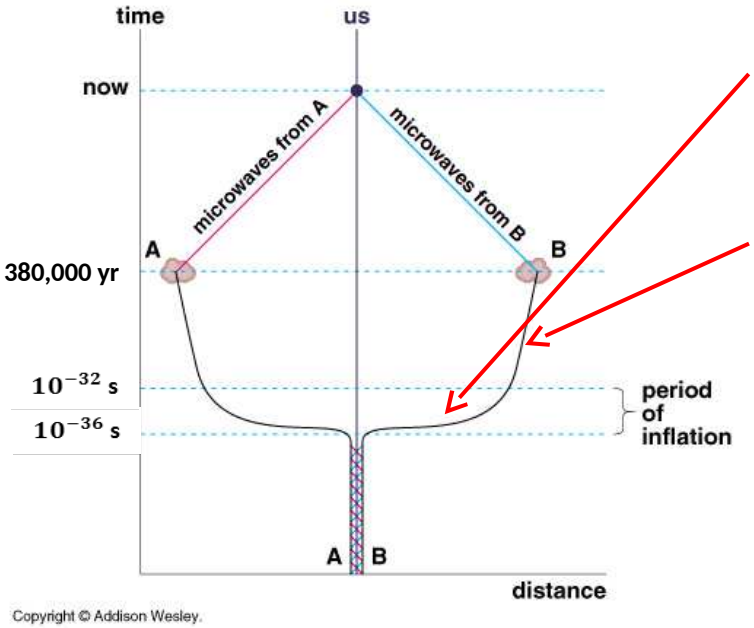

would have been **huge**, corresponding to an **extremely high** vacuum energy density.

Then inflation (somehow) “turned off”, and the universe continued to expand normally, with the present-day, very much smaller, cosmological constant.

Two Profound Properties of the CMB

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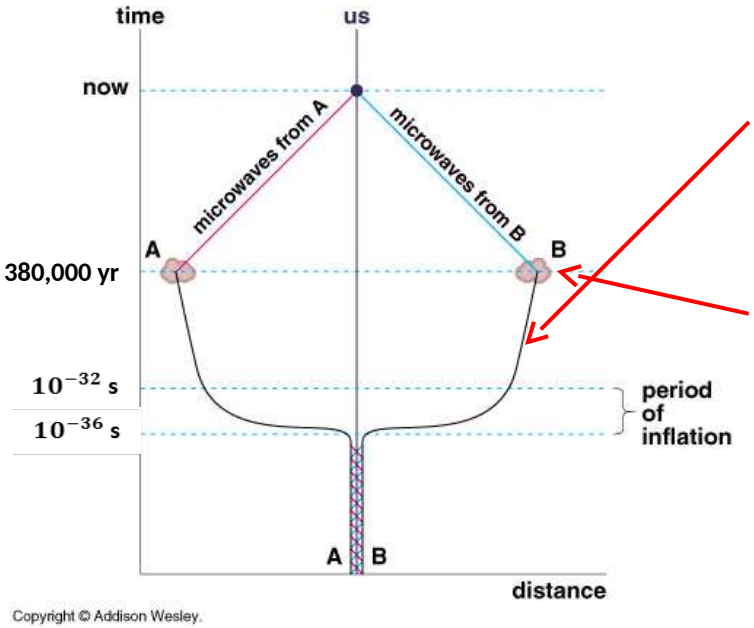

So what? All of the "stuff" in the normally-expanding "marble of space" would have been in perfect thermal equilibrium.

When the marble had expanded to the size of the observable universe at 380,000 years (1100 times smaller than it is today), all of the hot gas in it would have been in **perfect thermal equilibrium**: $T_A = T_B$.

The CMB would have been **perfectly uniform**.

- Why is the temperature of the CMB **almost perfectly uniform**?
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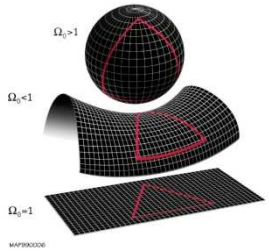
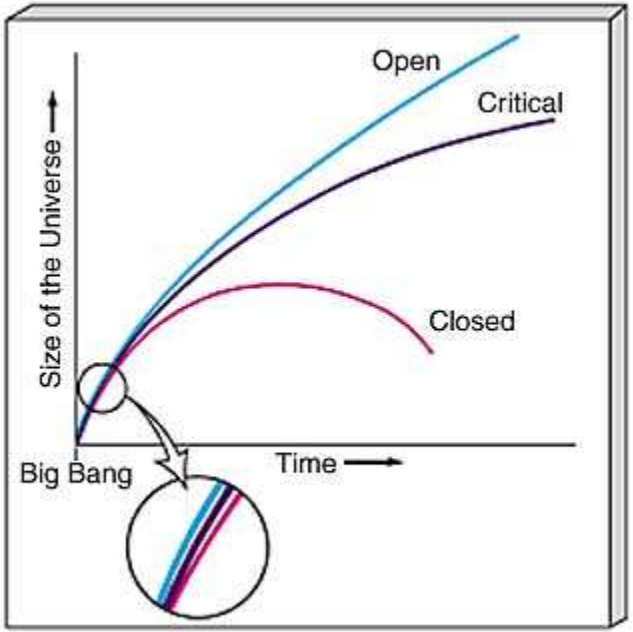




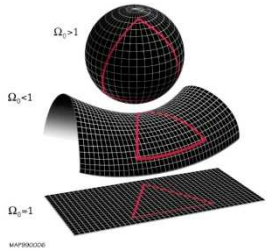
Aside: Inflation also solves the **flatness problem**:

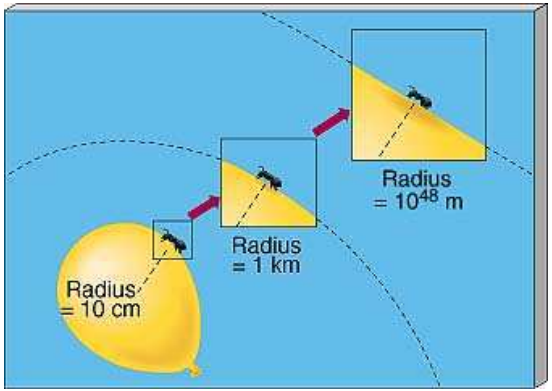
CMB observations tell us that space (on the cosmic scale) is **almost perfectly flat** (critical density ≈ 1)

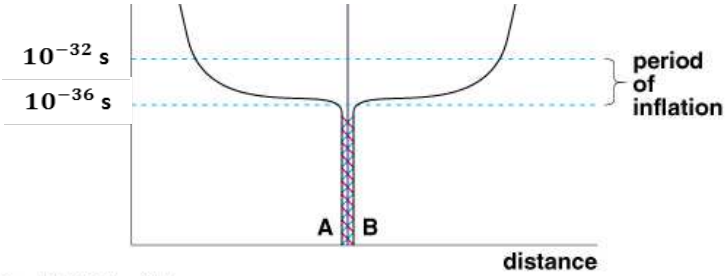
Problem: A universe that starts off close to, but not exactly on, the critical curve soon deviates greatly from it, so if the universe is **close to critical now**, it must have been **extremely close to critical** in the past.

This is a **severe** "fine-tuning" problem!

- Why is the temperature of the CMB **almost perfectly uniform**?
  - Current widely adopted hypothesis: **Cosmic Inflation** (Alan Guth, 1980)







Aside: Inflation also solves the **flatness problem**:

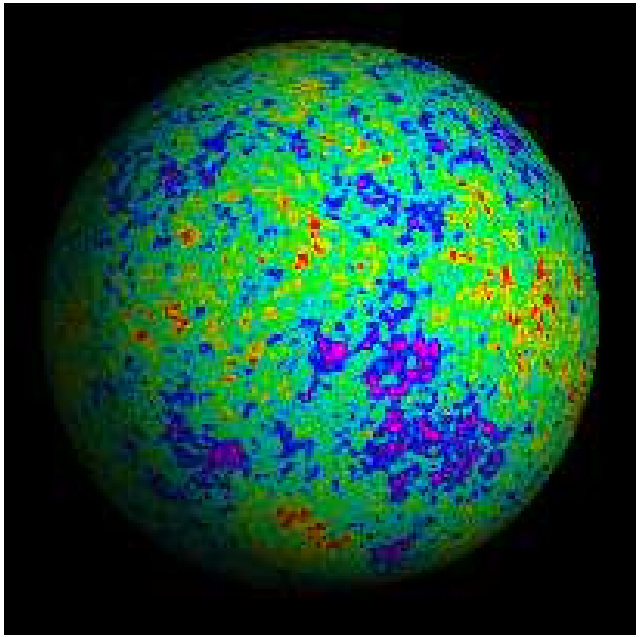
Before inflation started, space could have had **any random curvature**.

But inflation allows the entire observable universe to come from a **extremely tiny patch** of that space, which is **extremely** flat.

…flat enough that even after cosmic time, space is still almost perfectly flat. Problem solved!

Two Profound Properties of the CMB

- Why is the temperature of the CMB **almost perfectly uniform**?
  - Current widely adopted hypothesis: **Cosmic Inflation** (Alan Guth, 1980)



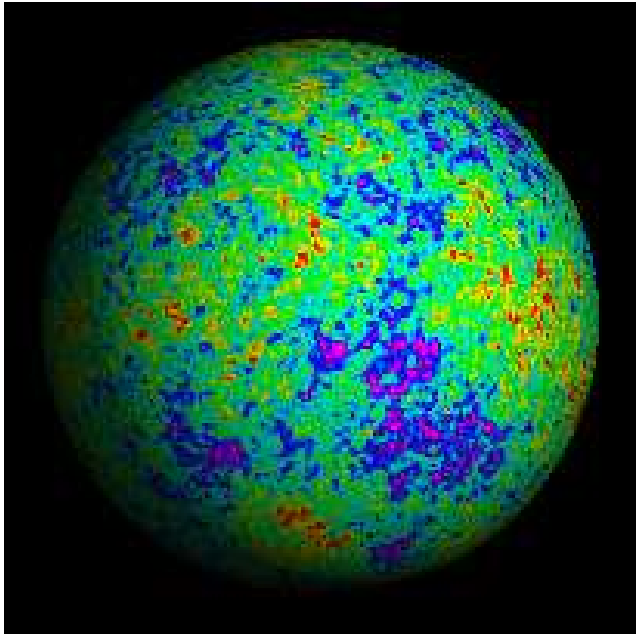
Back to the CMB:

We discussed how inflation would have made the CMB **perfectly uniform**. Virtually **zero** fluctuations in temperature. All of the hot gas at time 380,000 years would have been in **perfect thermal equilibrium**.

Problem: **Perfectly** uniform is not what we see. We see only **almost** perfectly uniform. Fluctuations of 1 part in 100,000.

Two Profound Properties of the CMB

- Why is the temperature of the CMB **not** perfectly uniform?
  - Current widely adopted hypothesis: **Cosmic Inflation** (Alan Guth, 1980)



This leads to the **second** profound property of the CMB: Why is it **not** perfectly uniform? What is the origin of the **tiny temperature fluctuations**?

Two Profound Properties of the CMB

- Why is the temperature of the CMB **not** perfectly uniform?
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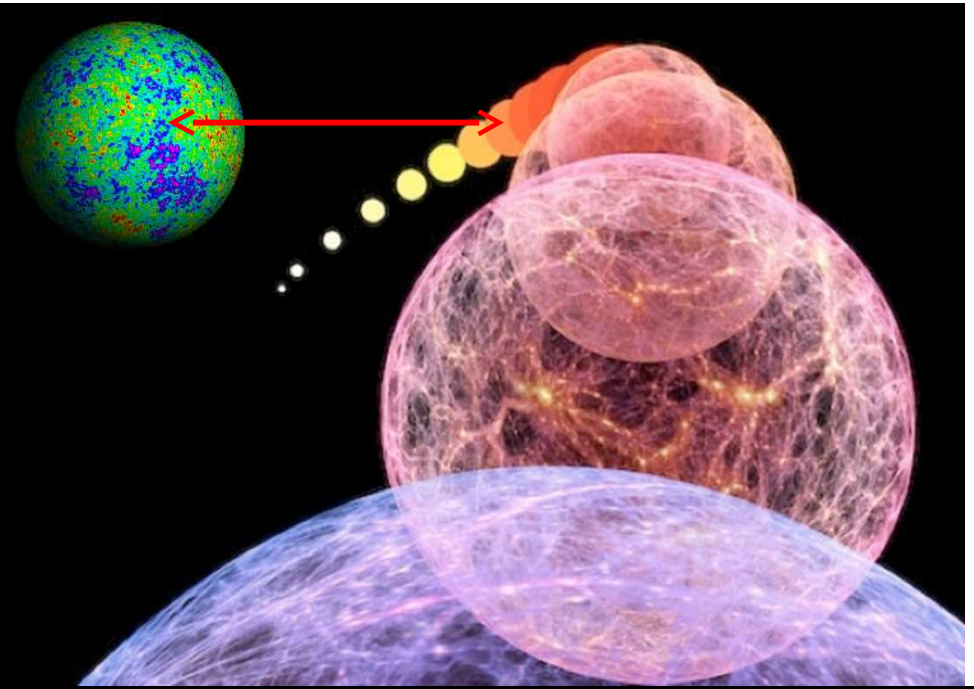

Why do we care? It is precisely these **tiny** temperature (and density) fluctuations in the hot gas in the universe at time 380,000 years that were the **"seeds" of gravitational clumping** that gave rise to all of the structure in the present universe: stars, galaxies, clusters of galaxies…**and us**.

Without these fluctuations, all of the matter (ordinary and dark) would have just expanded uniformly as space expanded. NO STRUCTURE would have formed ⎵ **no life**.

Two Profound Properties of the CMB

- Why is the temperature of the CMB **not** perfectly uniform?
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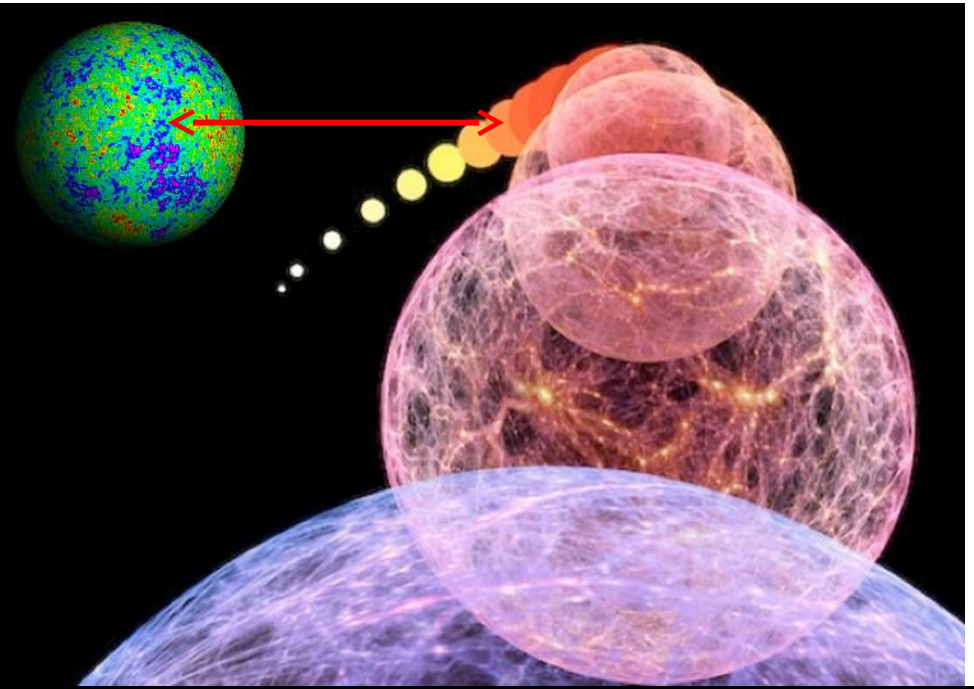
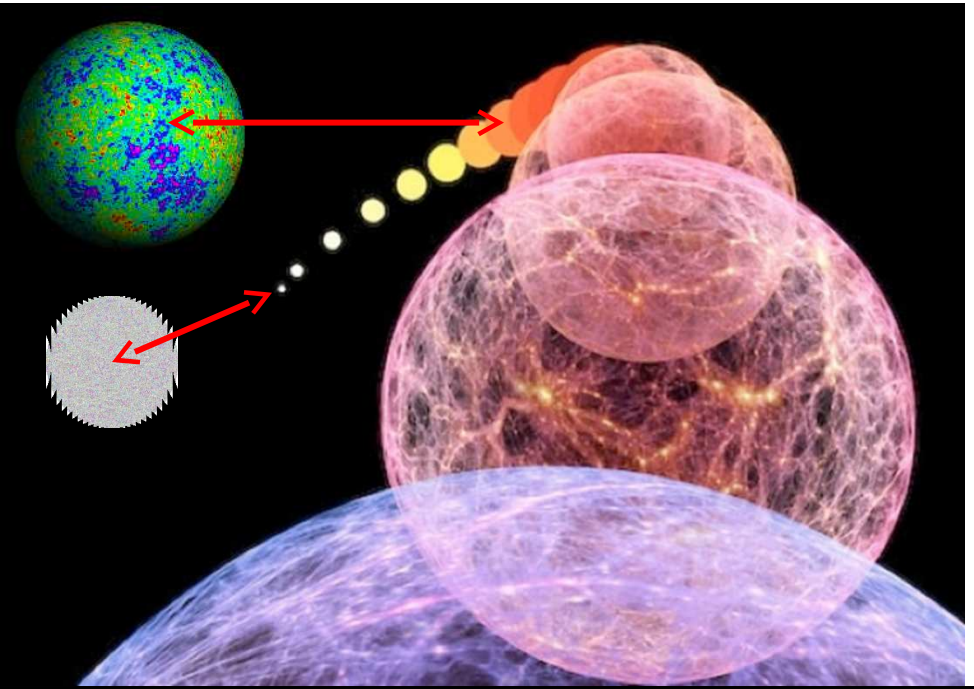


So explaining the origin of these tiny (1 part in a 100,000) fluctuations is also answering the question "**Where do we come from**", at a very deep and profound level…

Two Profound Properties of the CMB

- Why is the temperature of the CMB **not** perfectly uniform?
  - Current widely adopted hypothesis: **Cosmic Inflation** (Alan Guth, 1980)



Basic Idea:

Before inflation, the bit of space that would eventually expand into our observable universe was **very tiny**, say 10^{-43} m across.

On this tiny scale, the vacuum would have been filled with **quantum fluctuations**: incessant spontaneous creation and annihilation of virtual particle-antiparticle pairs.

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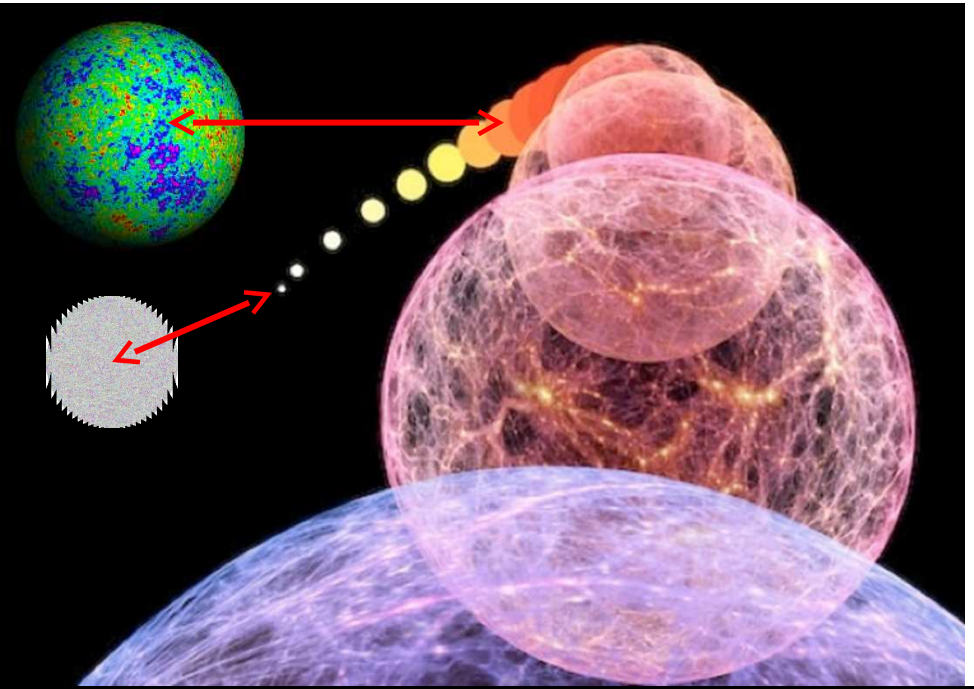

Basic Idea:

Normally, quantum fluctuations are **submicroscopic**. But inflation theory predicts that the **extremely rapid expansion** of space from some 10^{-43} m across to about the size of a marble would have similarly expanded these **submicroscopic** quantum fluctuations to **macroscopic** size, much like expanding space stretches the wavelength of a photon.

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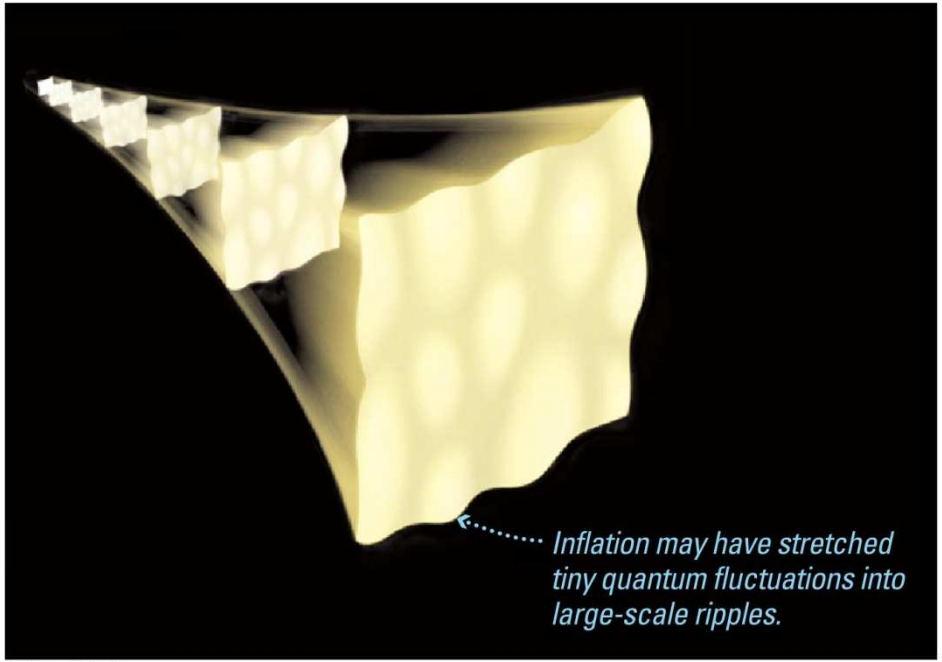

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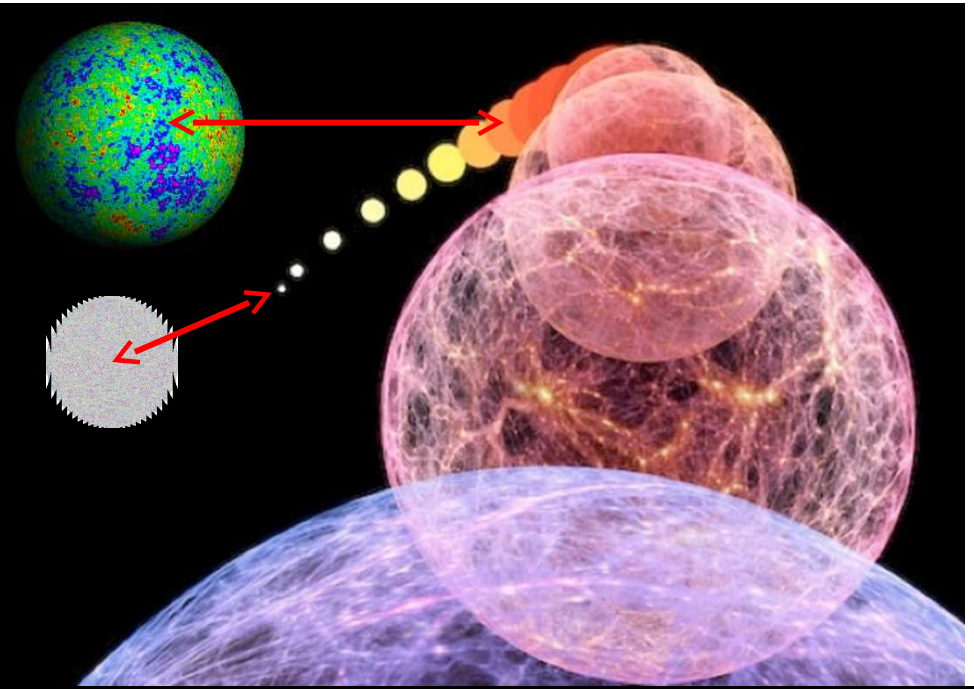

Basic Idea:

By the end of inflation, the **expanded quantum fluctuations** would have left an **imprint** on the **density and temperature fluctuations** in the stuff in the **marble-sized** observable universe.

Over the next 380,000 years, these density and temperature fluctuations **continued to expand** in size, until they became the **cosmic sized fluctuations** we observe in the CMB.

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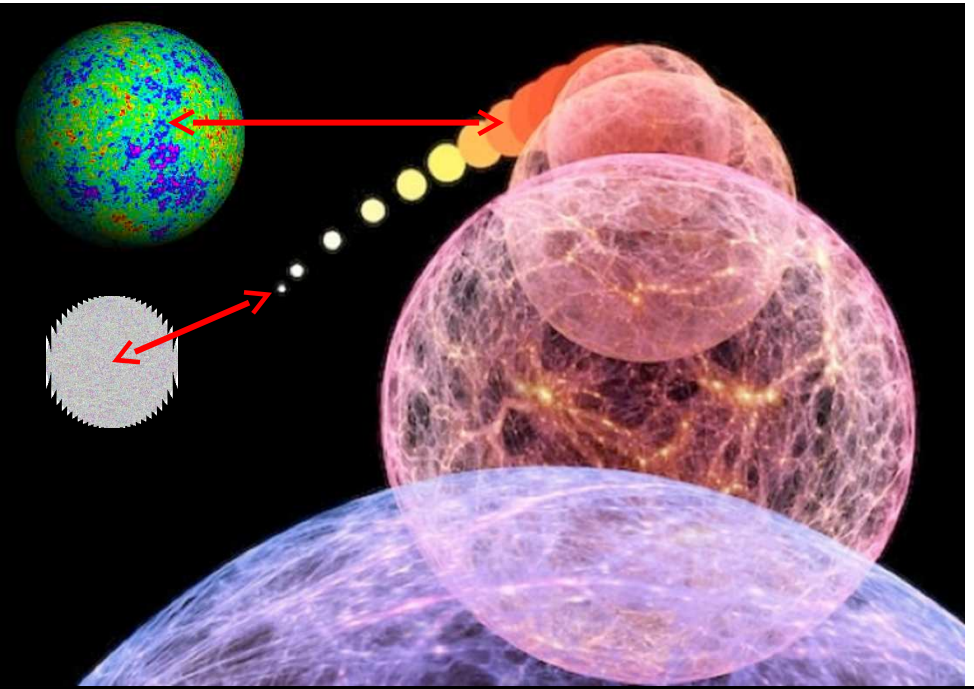

Basic Idea:

These then became the **"seeds" of gravitational clumping** that gave rise to all of the structure in the present universe: stars, galaxies, clusters of galaxies…**and us**.

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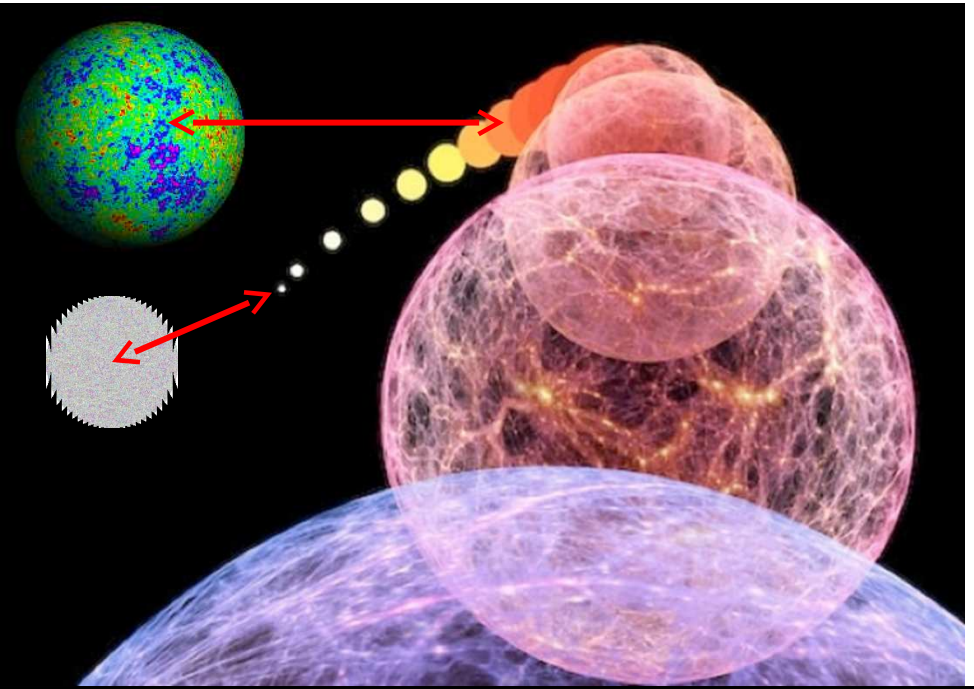

Basic Idea:

…and these seeds were of **just the right amplitude**: if the fluctuations were even just **half** the amplitude, they would have been too weak for galaxies and clusters to form.

…and these seeds were of **just the right type: same** amplitude across **different** sizes. E.g., bigger amplitude at smaller sizes ⎵ lots of black holes; at larger sizes ⎵ huge aggregates of matter pulling everything in

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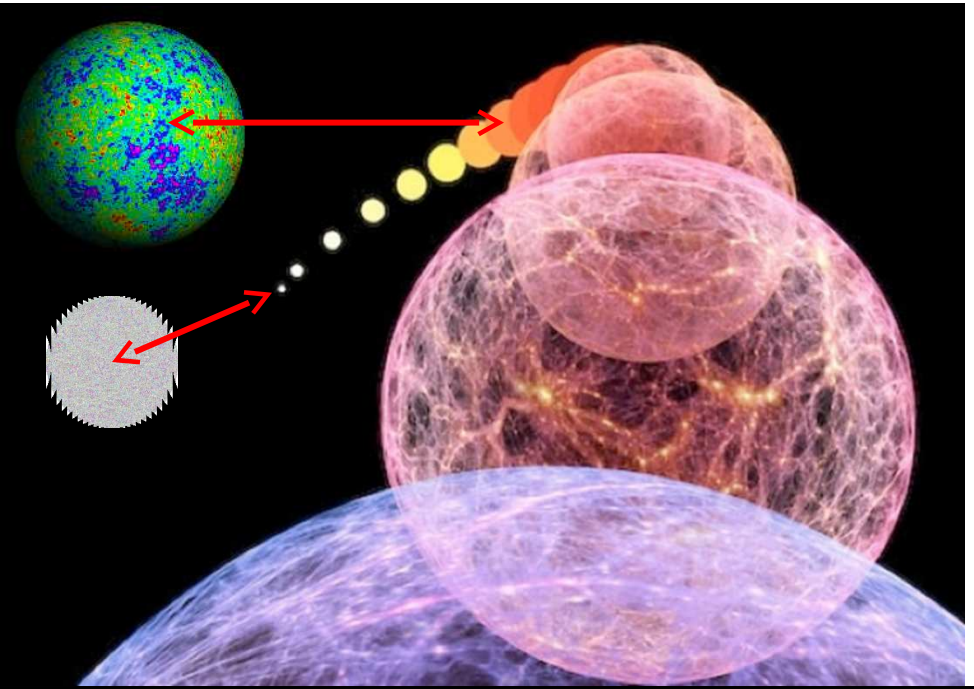


Basic Idea:

Notwithstanding many deep questions that remain, in broad brush strokes, **inflation + quantum** can actually **explain** all this!

Right or not, we are actually coming up with **plausible "origins stories"**, like RNA World, but now all the way back at 10^{-32} seconds after the Big Bang!

Two Profound Properties of the CMB

So what?

Two Profound Properties of the CMB

Old story: We are stardust…

New story: We are quantum fluctuations…

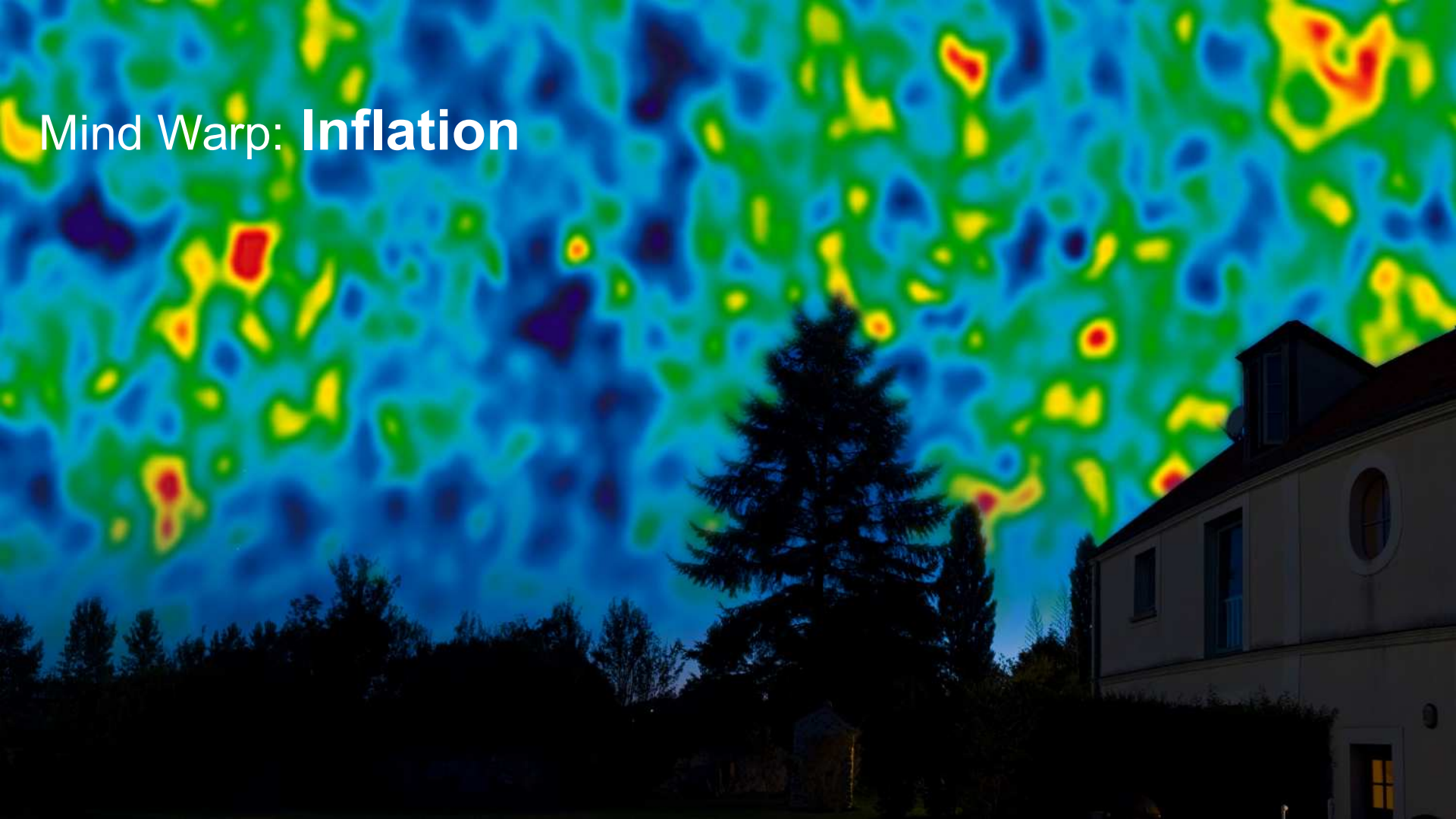
All of the structure in the universe today originated in **quantum fluctuations** that existed a tiny fraction of a second after the Big Bang in a region of space much smaller than an atomic nucleus.

During **inflation**, these **microscopic** quantum fluctuations were almost instantly expanded to **macroscopic** size, which we can now see **imprinted on the Cosmic Microwave Background**.

If these 1:100,000 density fluctuations weren't there (or were even just a bit smaller, say less than half the size), the matter (dark and ordinary) would have **diluted *before gravitationally clumping***: no stars, no galaxies, **no life**.

The **quantum nature of the universe [and Einstein's gravity]** is **paramount to our existence**.

Our quantum origins are **written in the sky**!

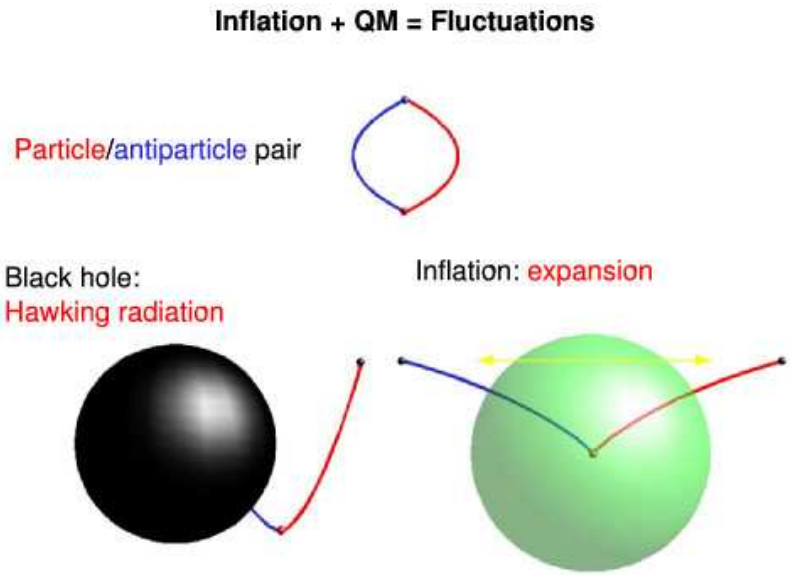

Mind Warp: **Inflation**

Let’s go even deeper…

Origins

- One of the deepest questions of all is: **Why is there something rather than nothing?**
- Of course, **no one knows**, but here are two intriguing ideas to contemplate:
  - QUANTUM: **Spontaneous creation and annihilation**.
  - GRAVITY: **Space itself is dynamical, and gravitational energy is negative**
- Let's try to put these together…

- One of the deepest questions of all is: **Why is there something rather than nothing?**



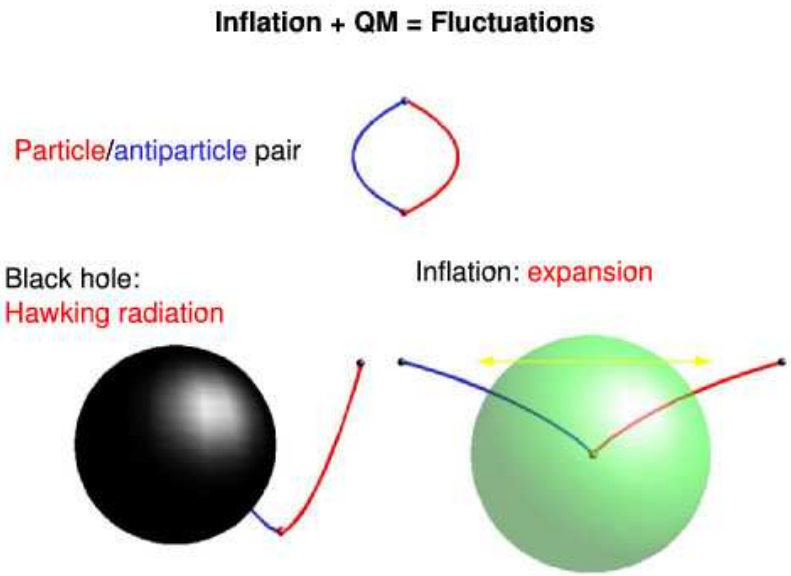
Spontaneous creation & annihilation:

Normally, **virtual** particles spontaneously appear and disappear too fast to become **real** particles.

But near a **black hole** (Einstein gravity), one can fall into the BH so that the other cannot “find” it to annihilate with, and so becomes a **real** particle.

Similarly, during **inflation** (also Einstein gravity), the pair is quickly separated and cannot “find” each other to annihilate with, so **both** become **real** particles.

- One of the deepest questions of all is: **Why is there something rather than nothing?**



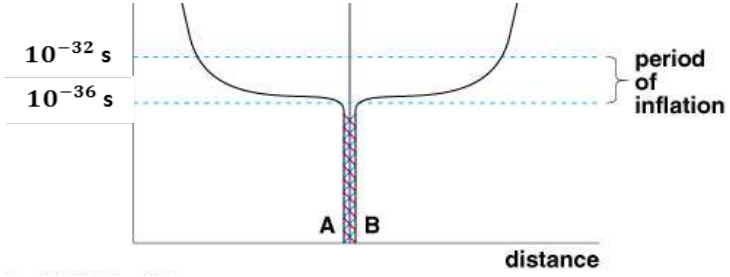
It *appears* as if we are "**getting something from nothing**"

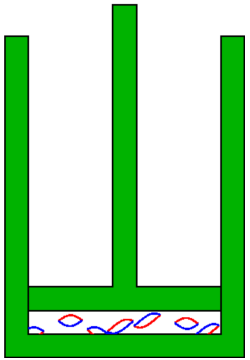
But **not really**:

In the **BH case**, the BH loses the same amount of energy as the created real particle has.

In the **inflation case**, we need some kind of energy to drive inflation; ***where does that come from***?

- One of the deepest questions of all is: **Why is there something rather than nothing?**



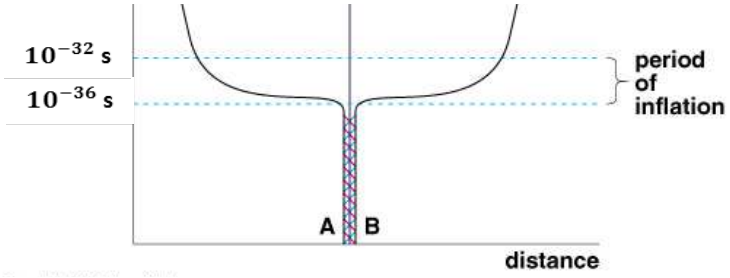


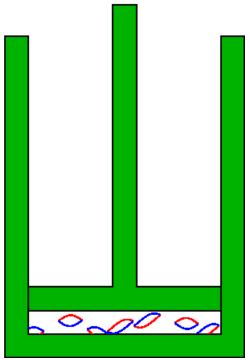
Recall: Inflation requires a very large cosmological constant, or equivalently, a **very high vacuum energy density** (energy per unit volume). [Technically: "inflaton field" potential energy density.]

But the volume of the space when inflation begins, that will eventually become the observable universe, is **exceedingly tiny** (<< atomic nucleus).

(Large energy per unit volume) x (Exceedingly tiny volume) can be a **relatively small** amount of total energy, e.g., the energy equivalent of a 1 g mass.

- One of the deepest questions of all is: **Why is there something rather than nothing?**

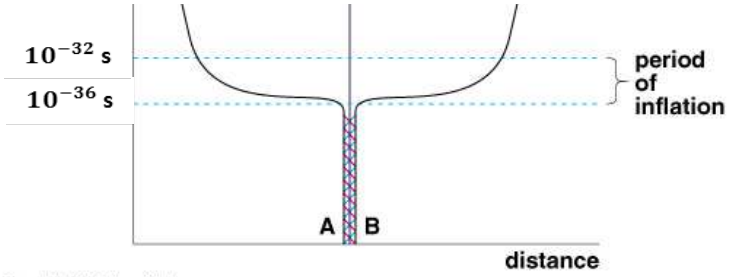


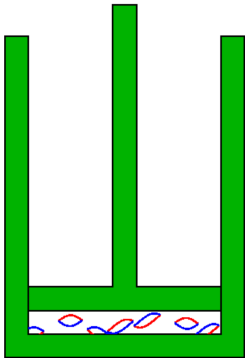


Recall: During inflation, the **negative pressure** of this vacuum energy *drives* the accelerated expansion of space ("pulls up on the piston"), just through the "magical" math of Einstein's theory.

Every cubic meter of **space** created, creates **more vacuum energy**. When inflation stops, **all this vacuum energy** (technically: inflaton field potential energy) **decays into particles (matter & antimatter)** and fills the universe with Standard Model particles (photons, electrons, quarks, etc.)!

- One of the deepest questions of all is: **Why is there something rather than nothing?**



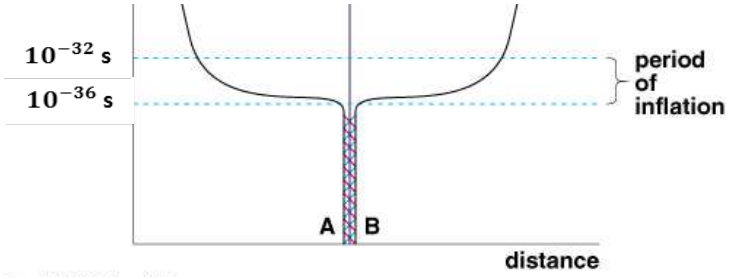


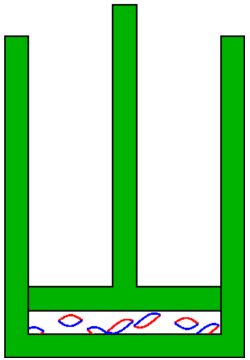
So: *Are* we getting something from nothing?!
Maybe, but maybe not:

The vacuum energy **creates spacetime curvature** (even if space is flat, its dynamical expansion means space*time* is curved), i.e., a **gravitational field**.

Bringing in the idea that this gravitational field might have "**negative energy**", it **may** be that this **growing negative** gravitational energy (as the expansion continues) balances the **growing positive** vacuum energy contained in the ever larger space. (**Speculation!**)

- One of the deepest questions of all is: **Why is there something rather than nothing?**



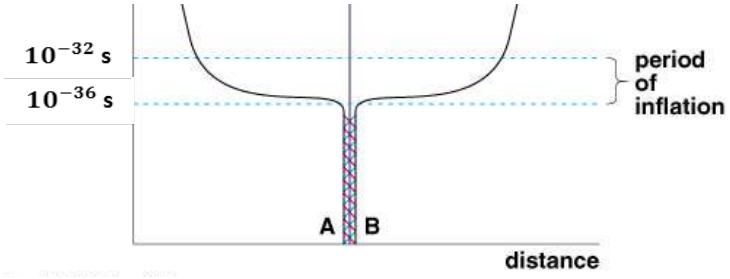


If so, the **total** energy—matter plus gravitational—**remains constant** (conserved) and very small (e.g., 1 g worth), and could even be **exactly zero.**

Thus, we may not be getting **something** from nothing, but **nothing** from nothing.

If the total energy in the universe is exactly zero, the universe is just an interesting way of writing "0", e.g., 0 = 2 + (–2) !

- One of the deepest questions of all is: **Why is there something rather than nothing?**



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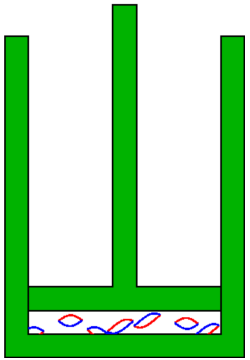
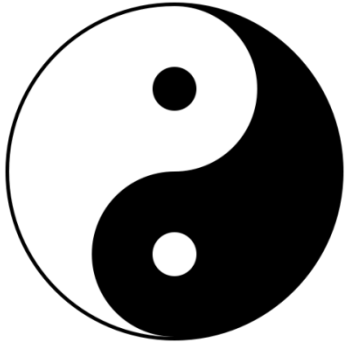


Like **Yin and Yang**:
Complementary opposites (positive and negative energy) "give rise to each other as they interrelate to one another…"
—Wikipedia



- One of the deepest questions of all is: **Why is there something rather than nothing?**

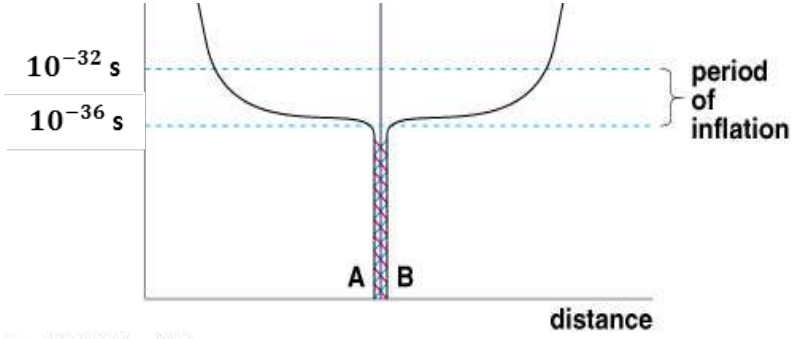
Either way **(nothing from nothing** or **something from nothing),** it's a **remarkable story…**

Quote from Alan Guth, inventor of the cosmic inflation idea:
"This borrowing of energy from the gravitational field gives the inflationary paradigm an entirely different perspective from the classical Big Bang theory, in which all the particles in the Universe (or at least their precursors) were assumed to be in place from the start. Inflation provides a mechanism by which the entire Universe can develop from just a few ounces of primordial matter. Inflation is radically at odds with the old dictum of Democritus and Lucretius, "Nothing can be created from nothing" If inflation is right, everything can be created from nothing, or at least from very little. If inflation is right, the Universe can properly be called **the ultimate free lunch**."

Popular science article: Why is there something rather than nothing (BBC)

So what?

- Before inflation began, space may have had “stuff” in it: Standard Model particles, exotic particles, etc. Then something happened that **triggered** inflation: perhaps the energy released when the strong and electroweak forces “**froze out**” of the GUT force, like energy released when water freezes?

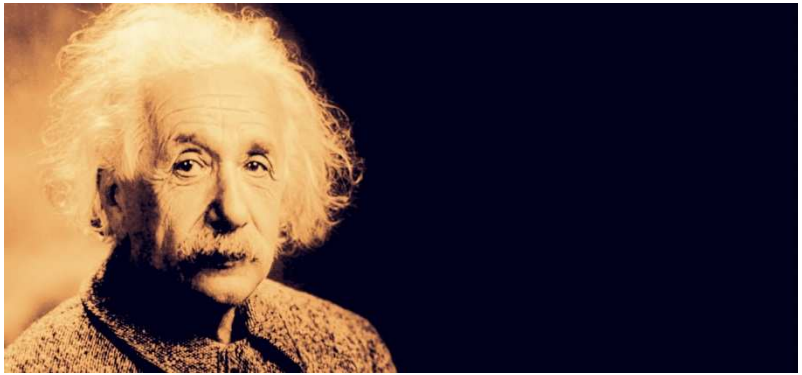


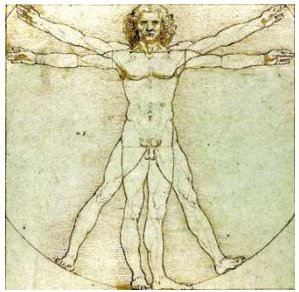
- But the expansion of space during inflation was **so extreme** that any pre-existing “stuff” would have been **diluted to virtually zero density**. Space would have been **almost perfectly empty** of everything **except the uniform “inflaton vacuum energy”**. The amount of this energy, in the tiny region of space that would become our observable universe, was **small before inflation began**, but grew large as space became large (“**ultimate free lunch**”).

Origins

- As mentioned earlier, at the end of inflation, during what's called "reheating", this "inflaton vacuum energy" then **decayed into the Standard Model particles** (photons, electrons, quarks, etc.) that fill the universe today, and that **eventually became us**.

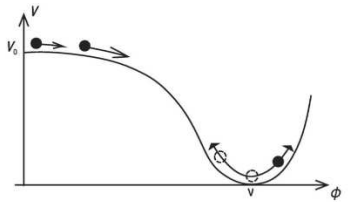
- If inflation is right, we exist as a direct result of the weird effect that **persistent** quantum vacuum energy (pressure = – energy density) has on expanding space, according to Einstein's ideas about spacetime and gravity.





- Did inflation really happen?
  - It explains the surprising **homogeneity** of the observable universe: the matter, at any given time in cosmic history, is, on average, almost perfectly uniformly distributed (**density** and **temperature**). Relatedly, it accounts for the observed **flatness** and **absence of magnetic monopoles**.
  - It also explains the origin of the **large-scale structure** of the universe: microscopic quantum fluctuations, magnified to cosmic size, became the **seeds** for the gravitational collapse into the structures we see today. It predicts the peak CMB fluctuations of **one degree** on the sky (due to flatness), and is consistent with its amplitude (**1:100,000**).
  - Technically detailed prediction: CMB is a “nearly-scale-invariant Gaussian random field”. The “nearly” part predicts a “spectral index” between 0.92 and 0.98. CMB measurements show 0.963 ± 0.012. This is considered an important confirmation.

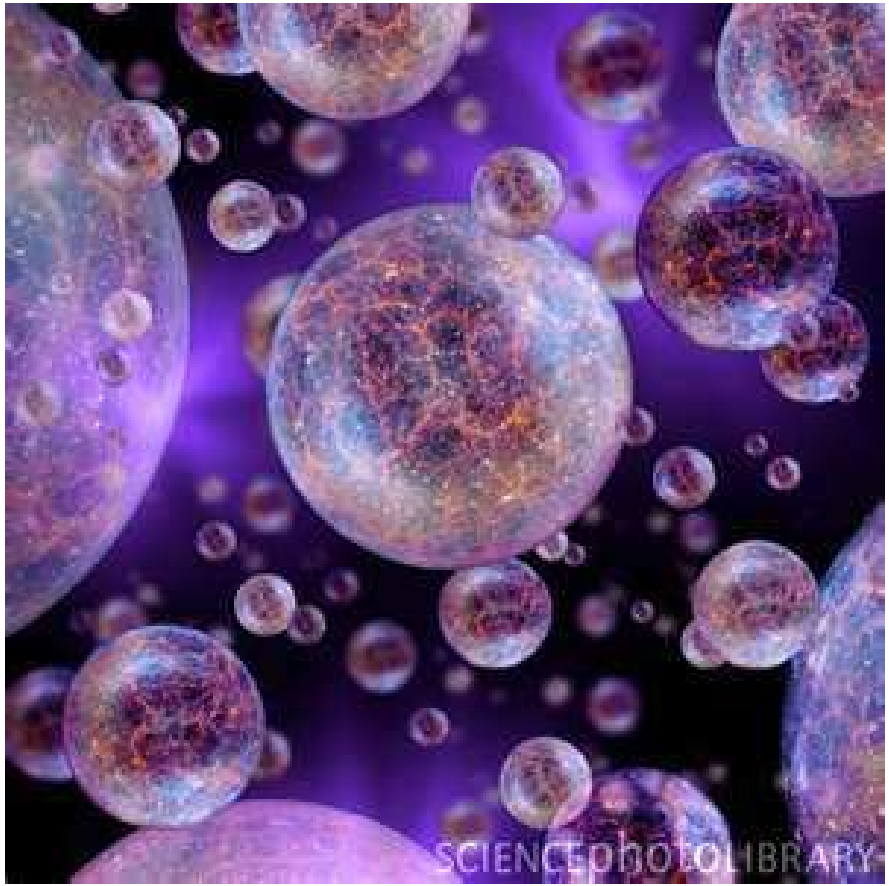
- While there is some evidence supporting inflation (and none against it), and it is a **widely pursued** hypothesis, with many variants (e.g., eternal inflation), it is also **widely criticized**:
  - The "**inflaton field**" that drove inflation does not correspond to any know physical field (no concrete connection with particle physics; **yet**, at least. Inflaton = Higgs?...)
  - The theory has **ad hoc elements**, that can be adjusted to fit a wide range of data...



  - The **initial conditions** for inflation itself may be just as "**fine tuned**" as the initial conditions (very flat universe) inflation tries to explain (e.g., exceptionally low entropy)...

- While inflation (1980+) has provided one plausible "origins" model (like "RNA World" in origin of life), it is still fraught with mysteries, and is almost certainly not the final word!

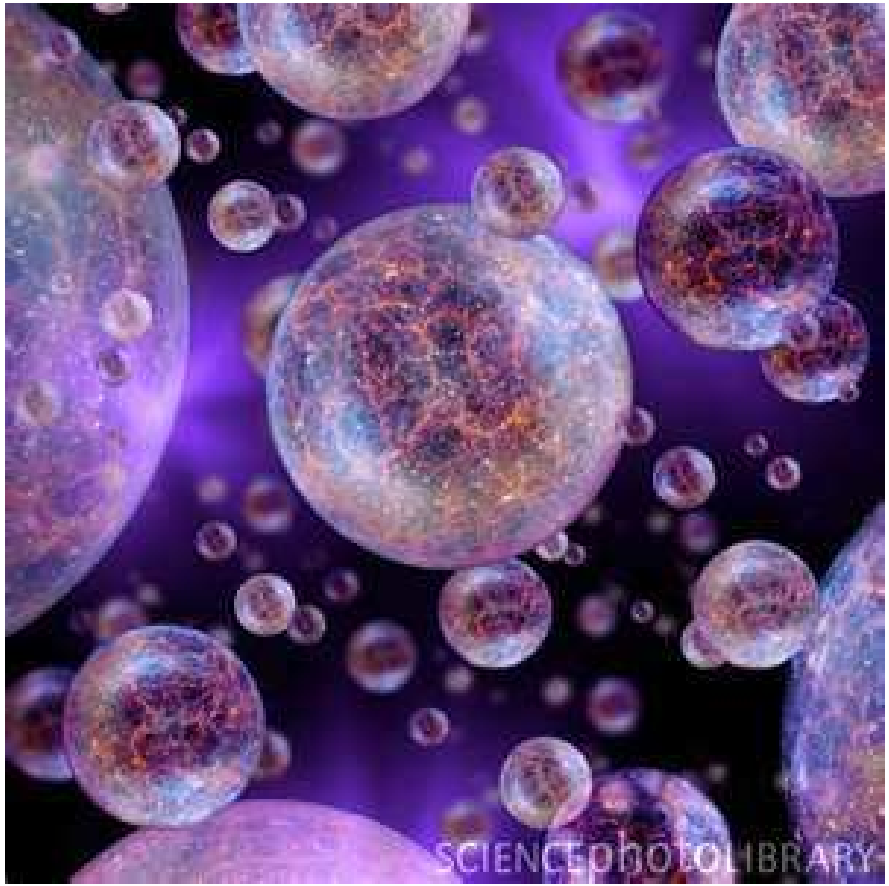
- There are **other origins hypotheses** being pursued (research these on your own):
  - Within **classical gravity**, e.g., Roger Penrose's **Conformal Cyclic Cosmology**, popularized in his book *Cycles of Time: An Extraordinary New View of the Universe*; focus on **entropy** (video interview with Roger Penrose)…but also strongly criticized, e.g., by Sean Carroll.
  - Within **quantum gravity**, e.g., **Loop Quantum Gravity** can "soften" the classical Big Bang singularity and push back to a universe that existed *before* the Big Bang (video interview with Abhay Ashtekar), i.e., a general resurgence of the "**Big Bounce**" idea.
  - Within **Superstring Theory**, inspired by extra dimensions, D-branes, etc., e.g., the **cyclic model** of Turok & Steinhardt. Video presentation by Paul Steinhardt (includes **general critique of eternal inflation, multiverse**, etc. & **tests** through cosmic gravitational waves)
- Early universe cosmology is a **very active** area of physics. There is great interest in understanding **where we come from**, and **where we're going**!



Eternal Inflation & Multiverse

Imagine that space is **infinite** and **eternal**. Assuming inflation can occur at all, it may occur at **different rates** in **different places**, and **shut off** after different amounts of time.

All of space could be **eternally inflating**, and ***randomly*** shutting off in "pockets" ␣ bubble universes. These universes may have very different, ***randomly*** determined properties (physical constants **including** Λ, number of dimensions, etc.). **Some may support life**, but most probably not.



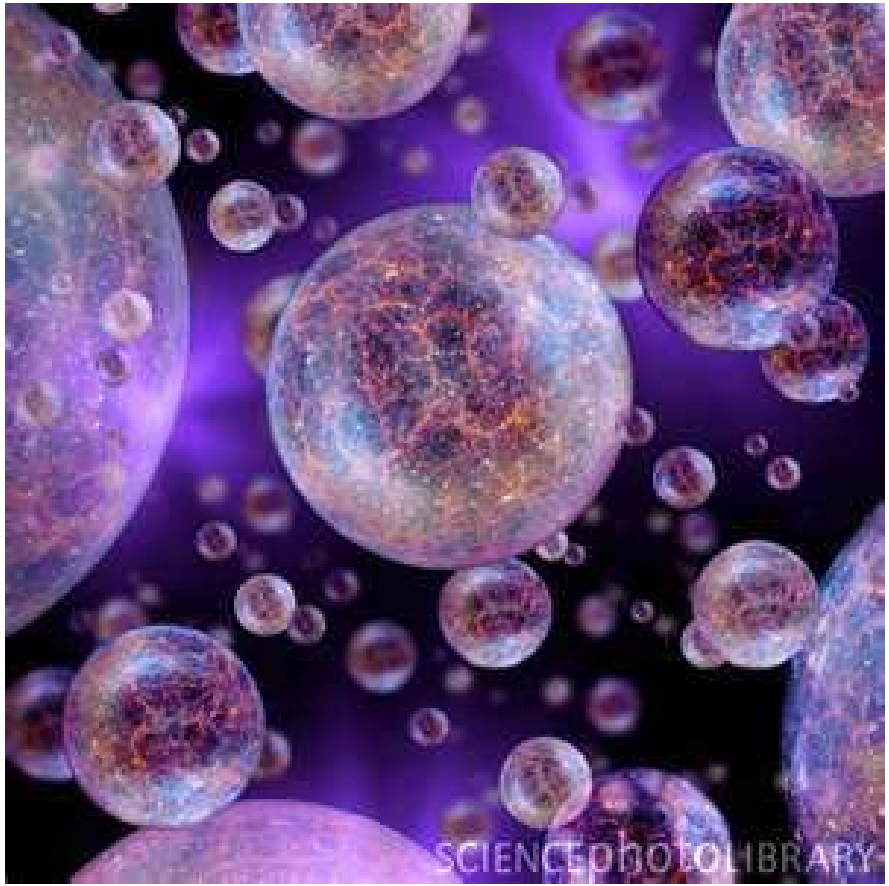
Eternal Inflation & Multiverse

Are we just **one bubble** in such a multiverse?

Is this the “explanation” for the cosmological constant problem (and other “**fine tuning**” problems)?

Do we just happen to live in a bubble where Λ is small (and the other physical constants are “just right”) for **existence of complex life**?

Do we really have to resort to such “**anthropic reasoning**”? Is this the **end of science**?



Or do we just need to work harder…maybe a **theory of everything** will explain more?

A Brief History of the Universe…