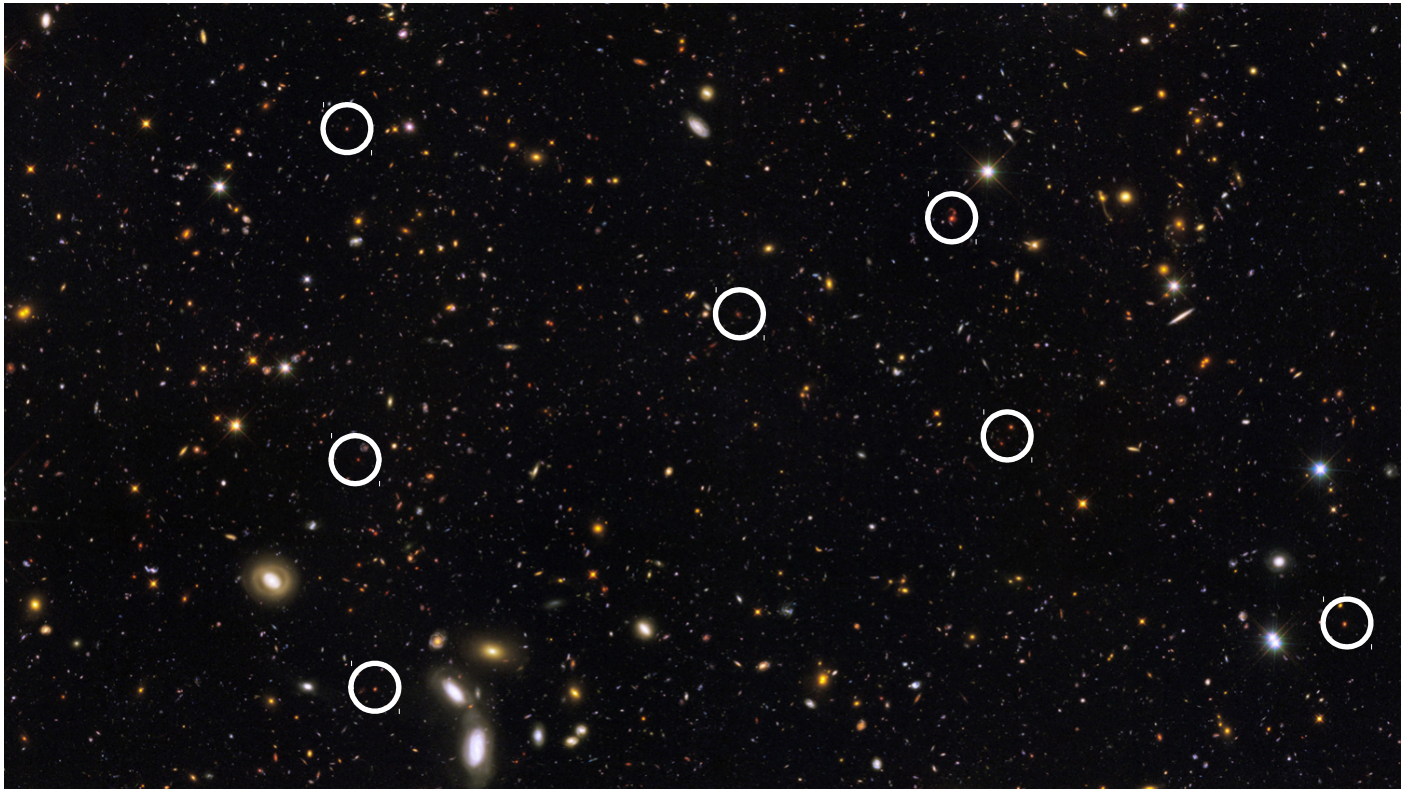
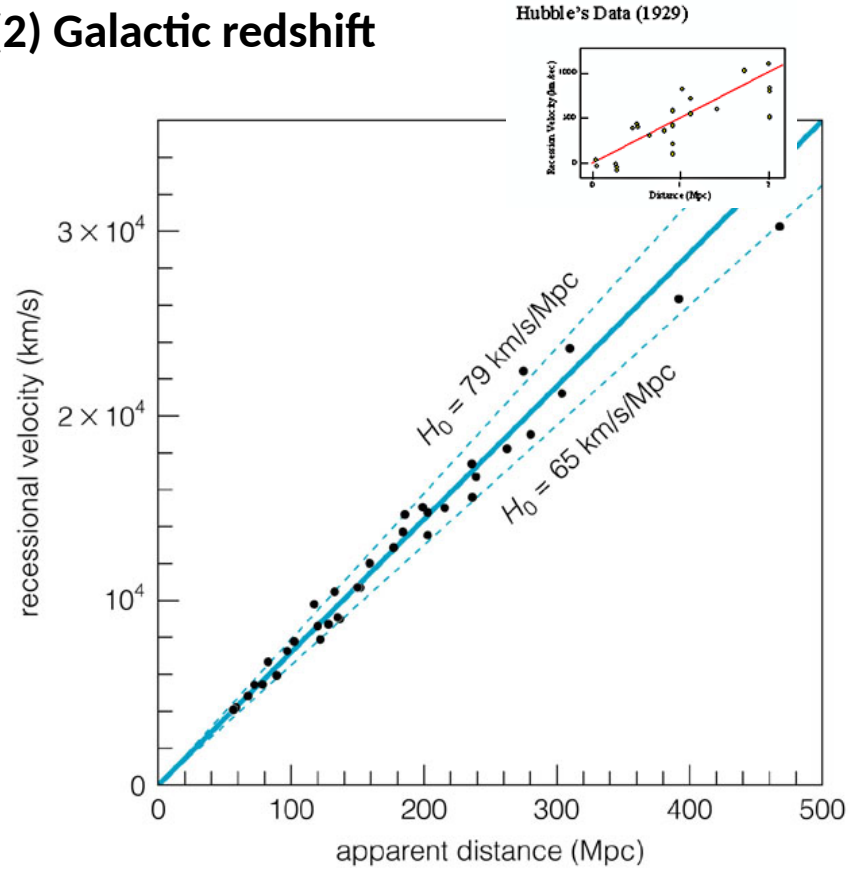
(2) Galactic redshift



Slipher
Friedmann
Lemaitre
Hubble
Einstein

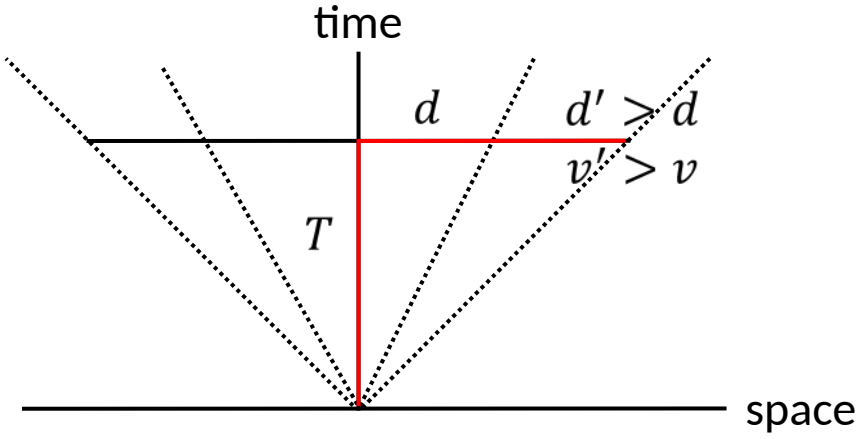
Most natural explanation is **expanding space** (Einstein's theory, which **also** explains many other things)

(2) Galactic redshift

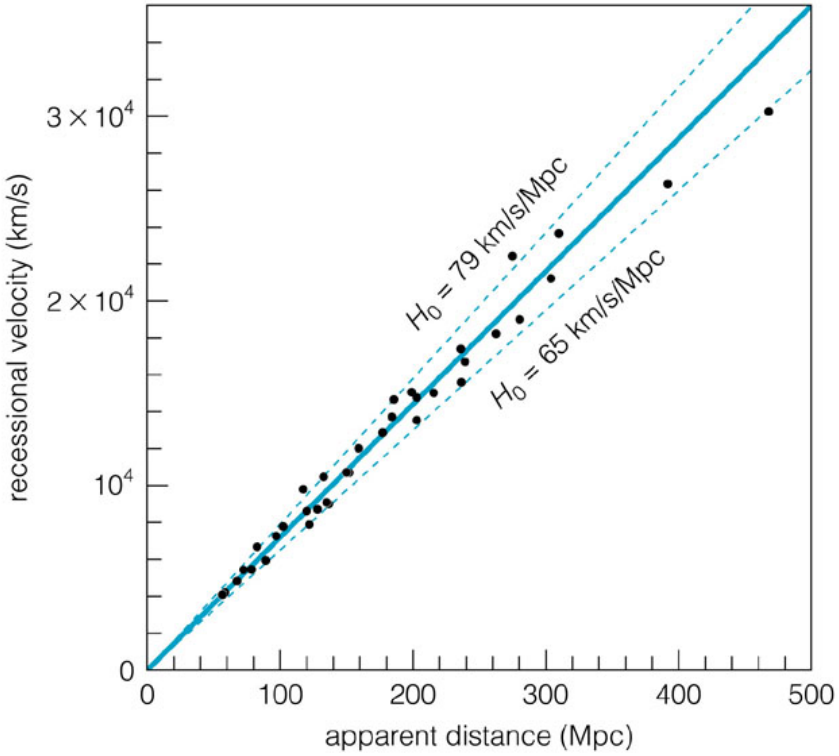


Rough estimate of the age of the universe:

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

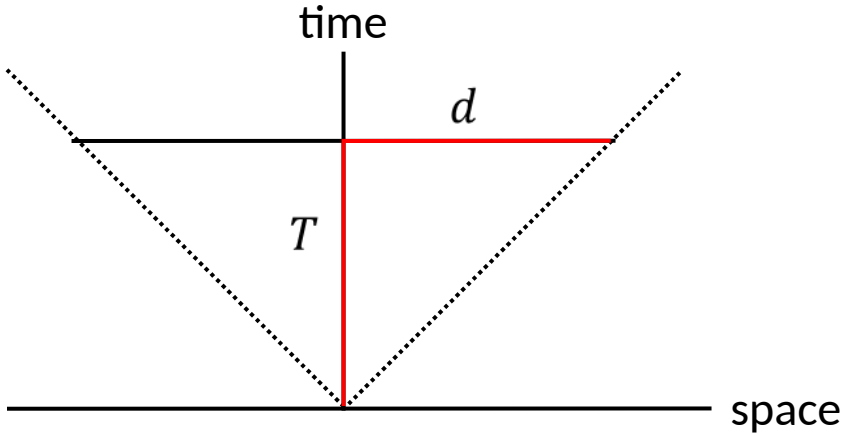


(2) Galactic redshift

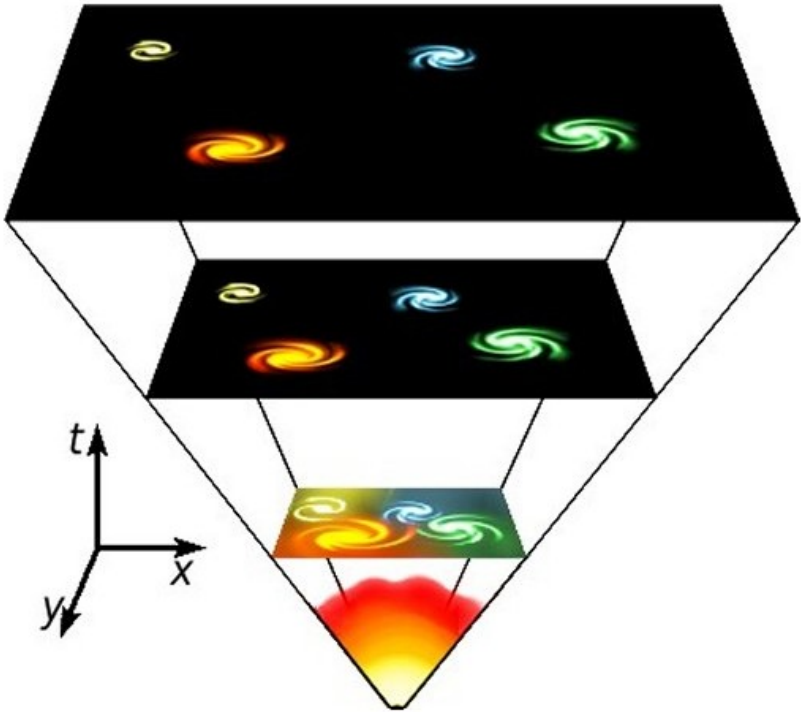


Best estimate of the age of the universe:

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



(2) Galactic redshift



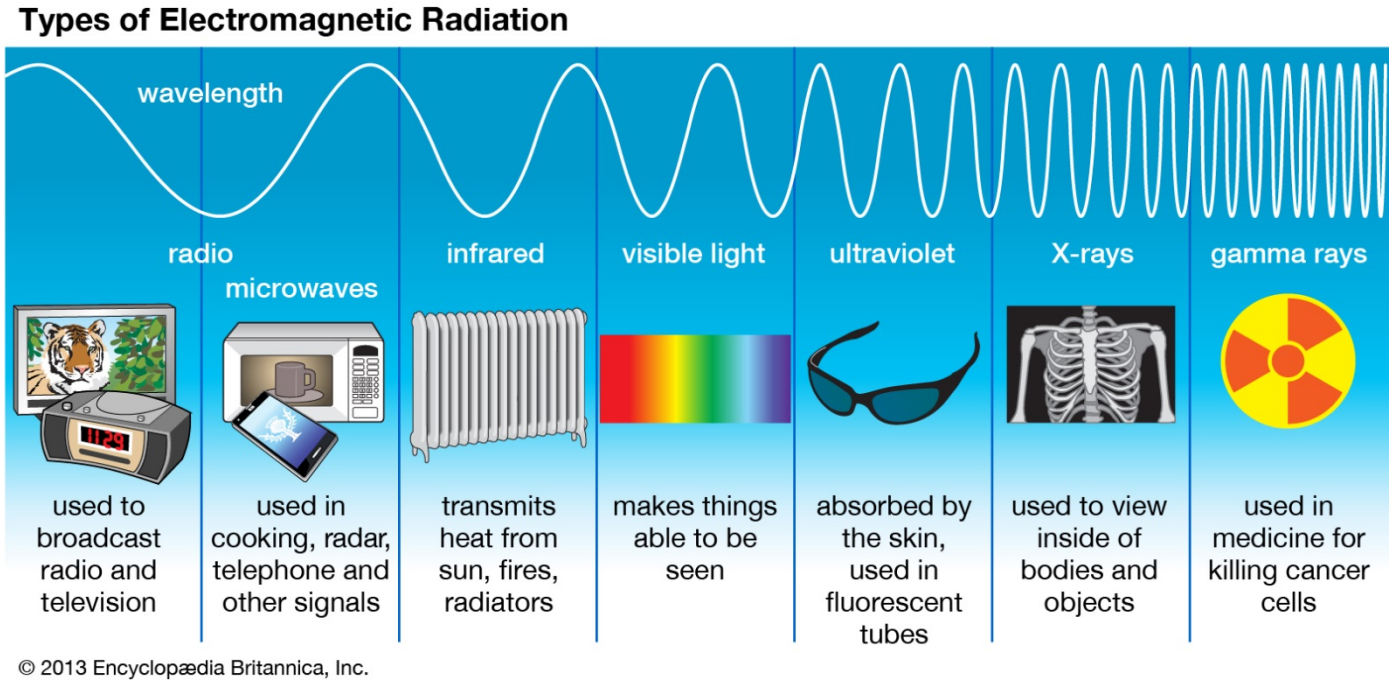
Expanding space means that, as we "run the movie" backwards, the **same** amount of matter occupied **smaller and smaller** volumes of space.

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).

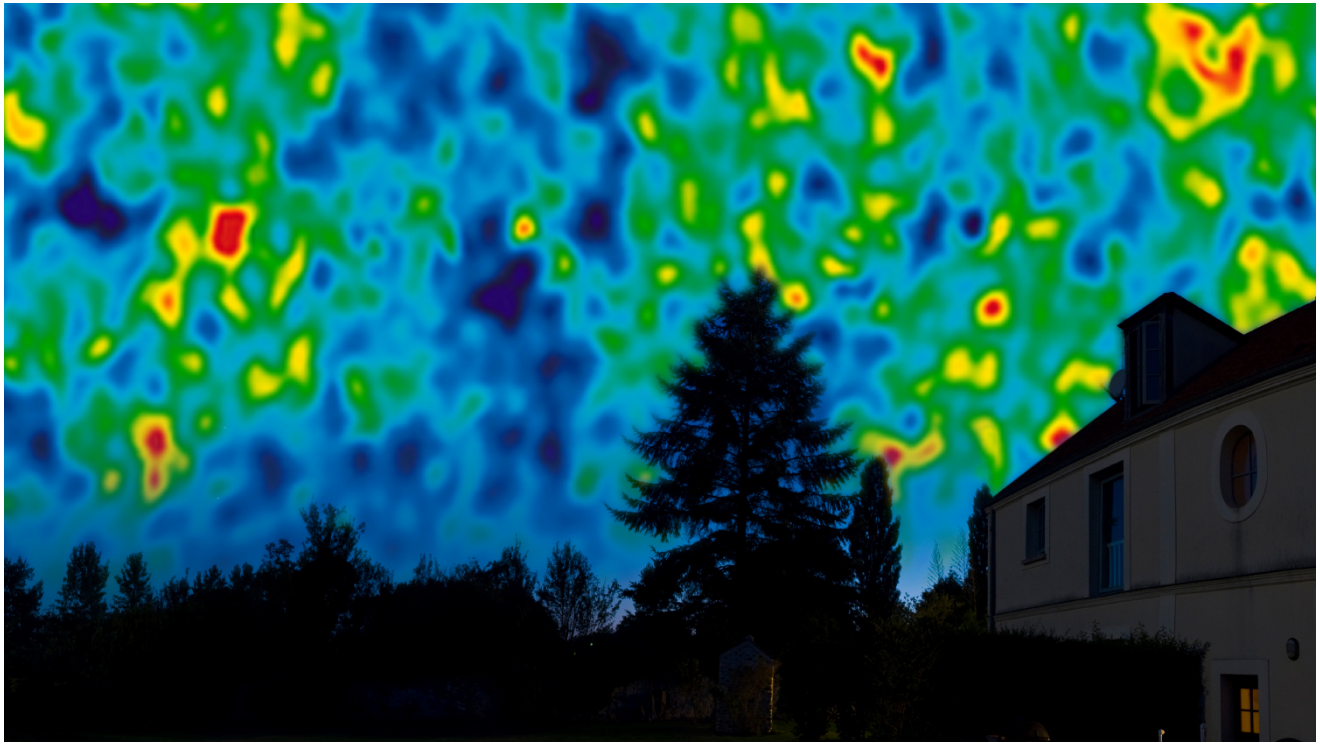
Do we have **evidence** for this? Yes! CMB…

(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



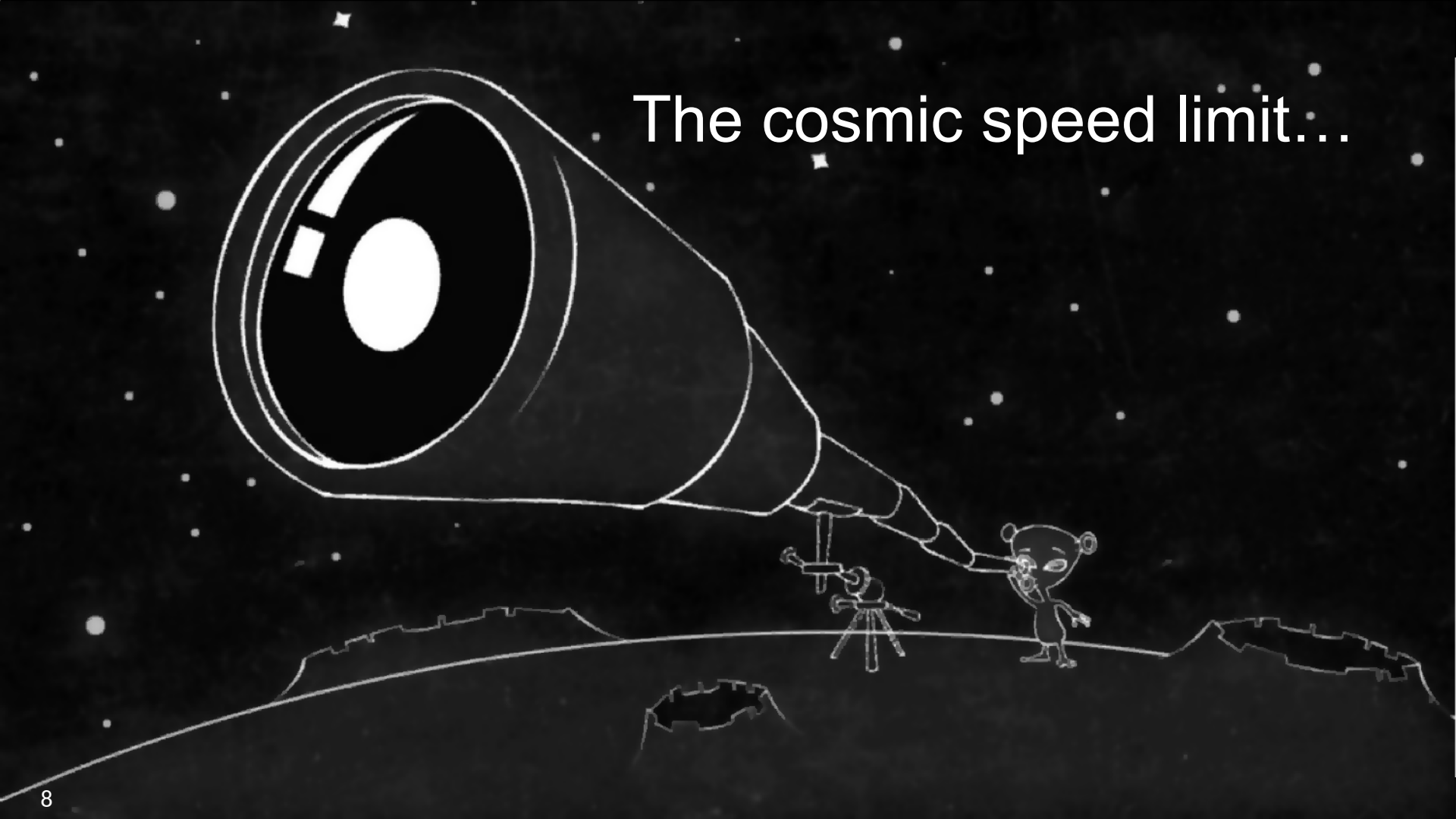
…the “afterglow” of the Big Bang

…the “smoking gun”

(3) Cosmic Microwave Background

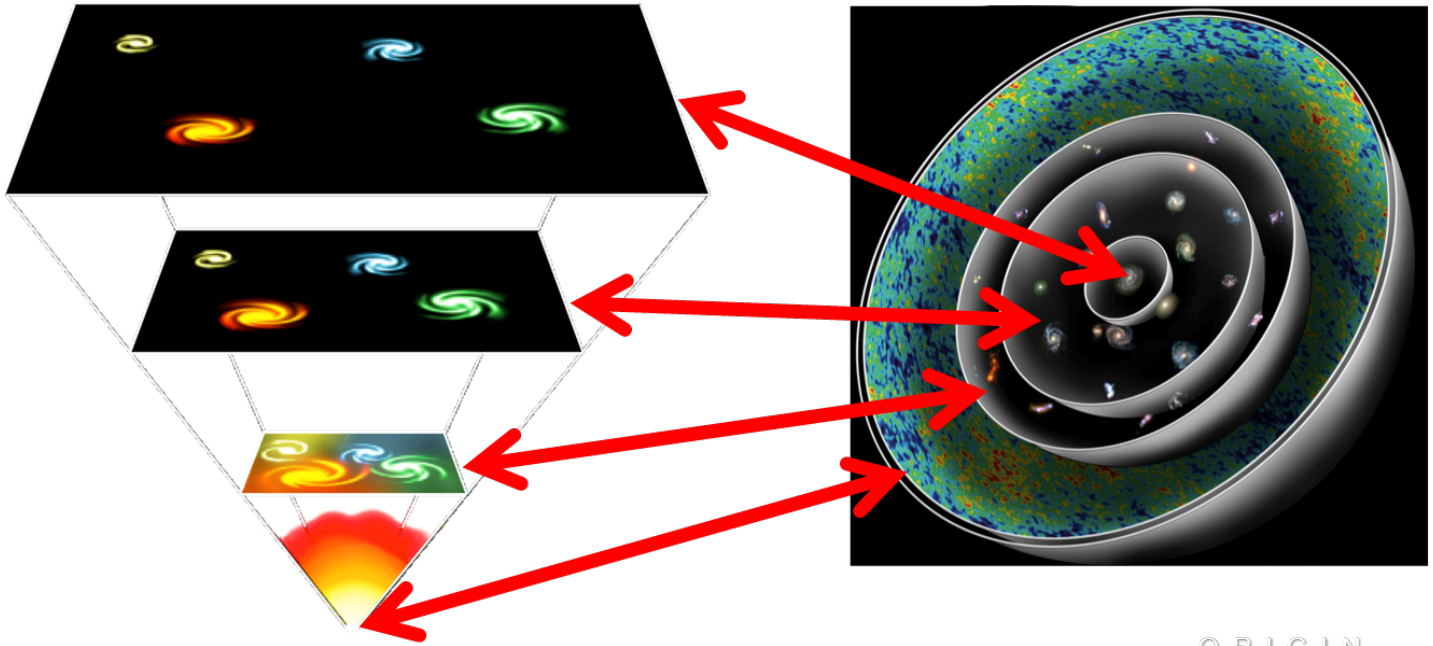
To understand what we're looking at, recall that light moves at a **finite speed**.

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


The cosmic speed limit…

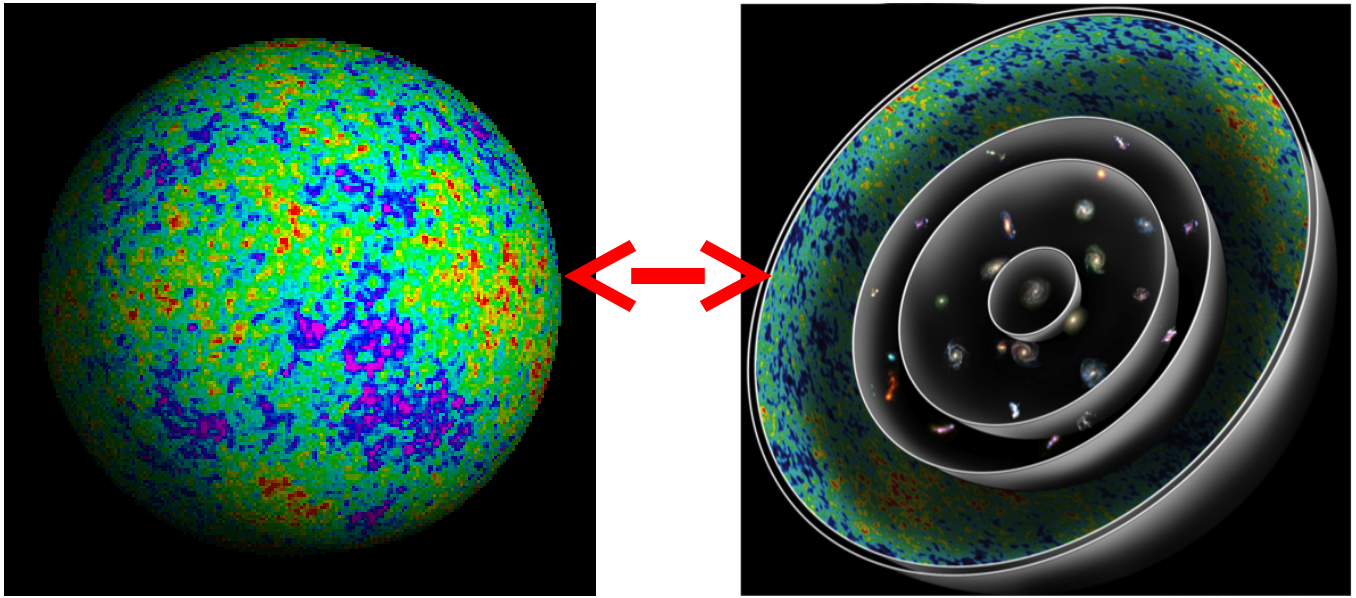
(3) Cosmic Microwave Background

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



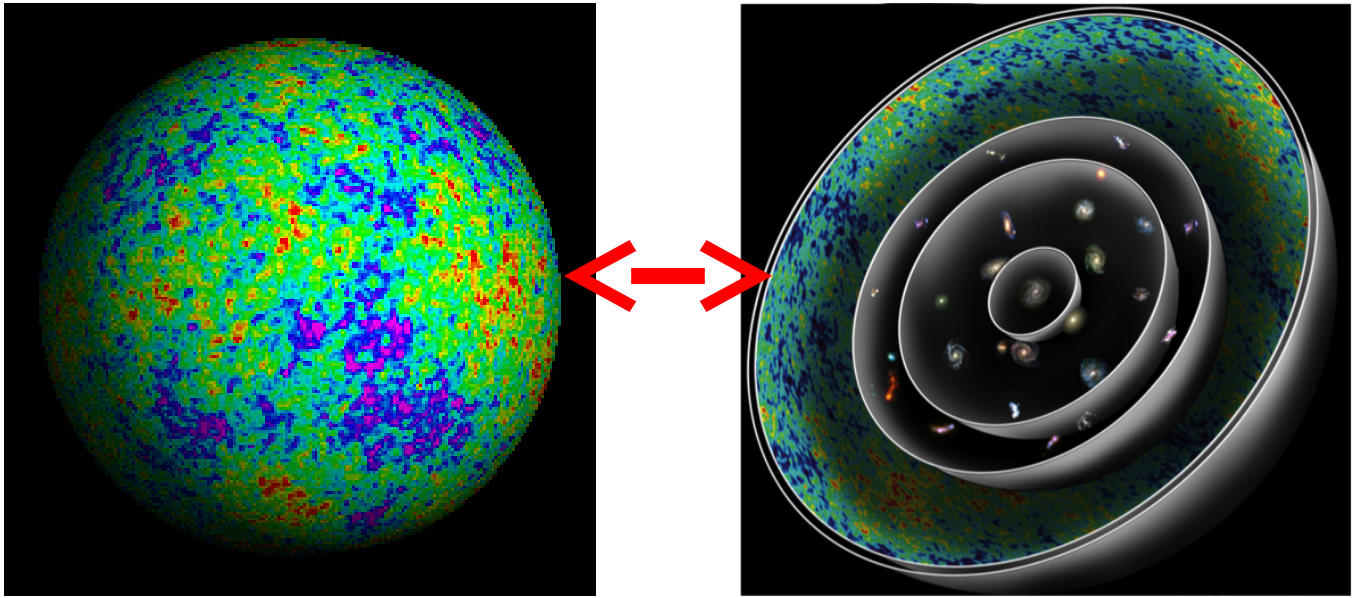
(3) Cosmic Microwave Background

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)!



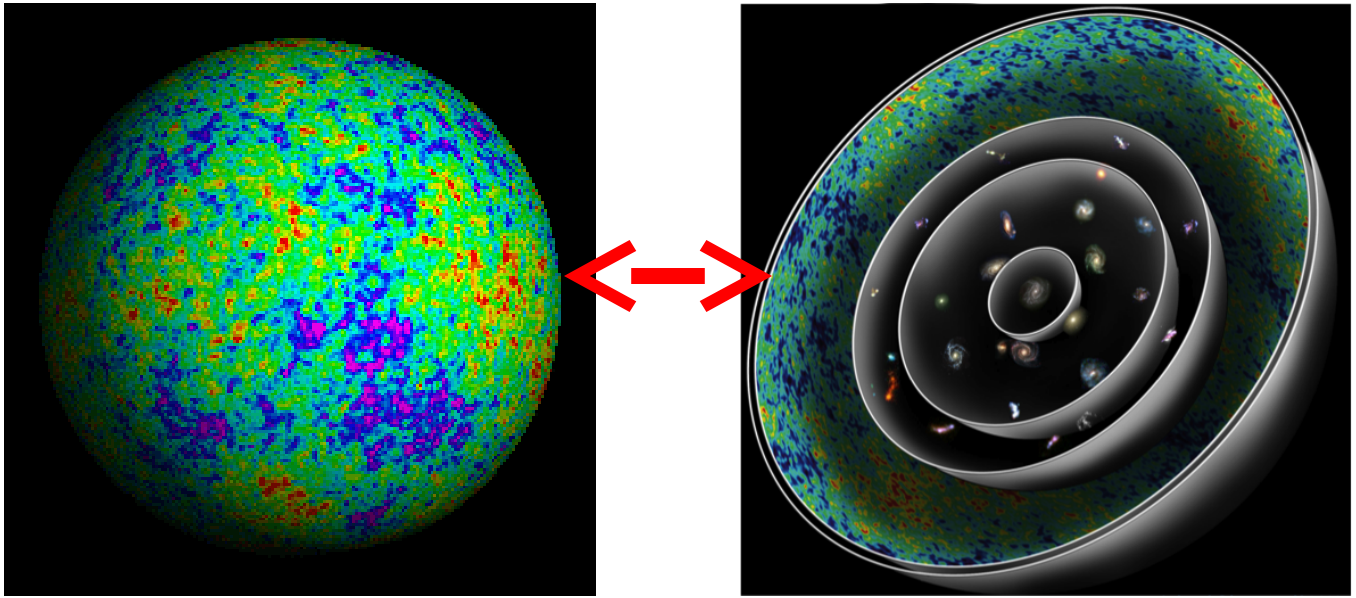
(3) Cosmic Microwave Background

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)



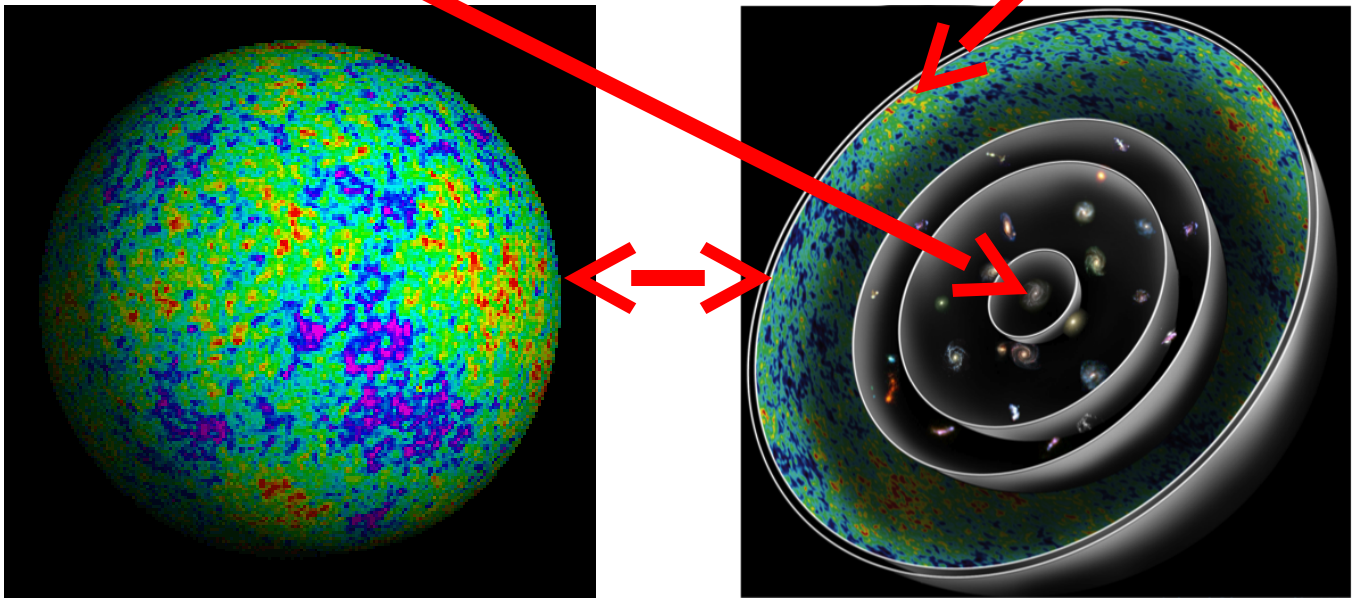
(3) Cosmic Microwave Background

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).



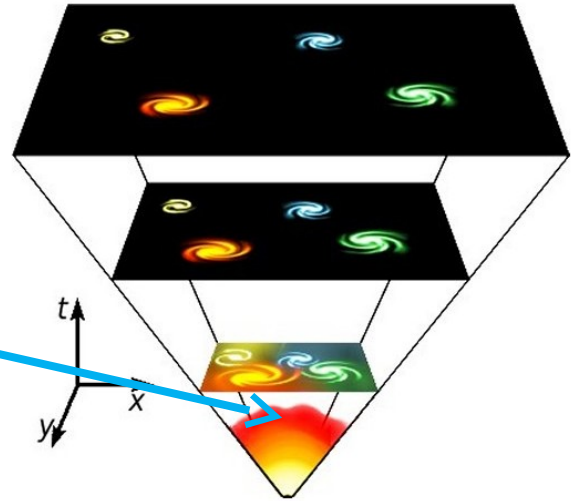
(3) Cosmic Microwave Background

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.



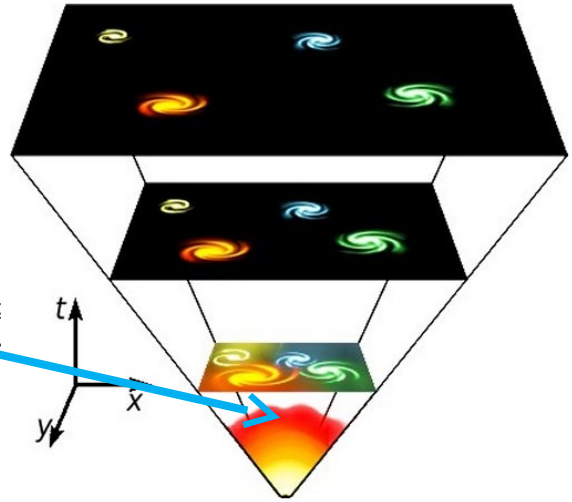
(3) Cosmic Microwave Background

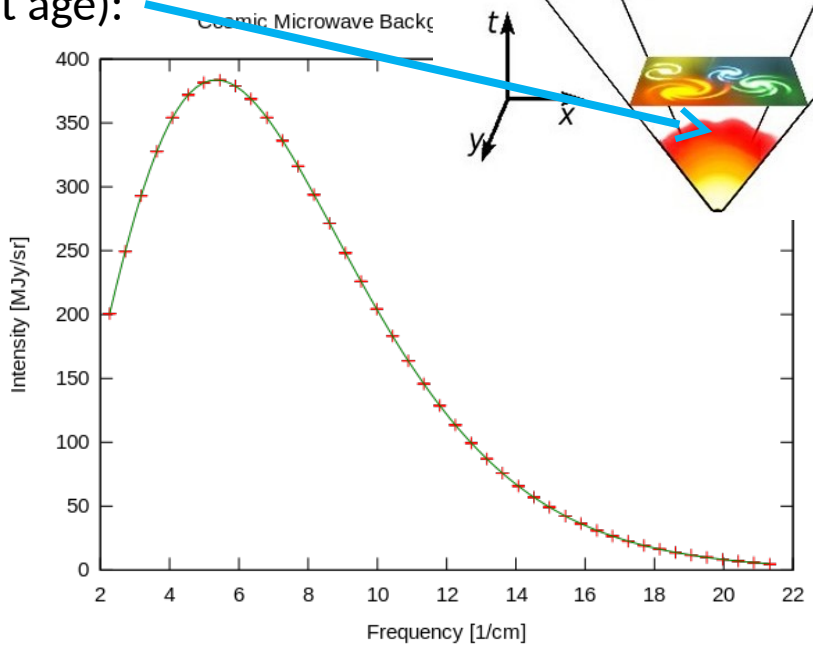
- What does this light that we are **bathed in** ("bath of thermal radiation") tell us? That when the universe was **380 thousand years old** (0.003% its present age):

  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

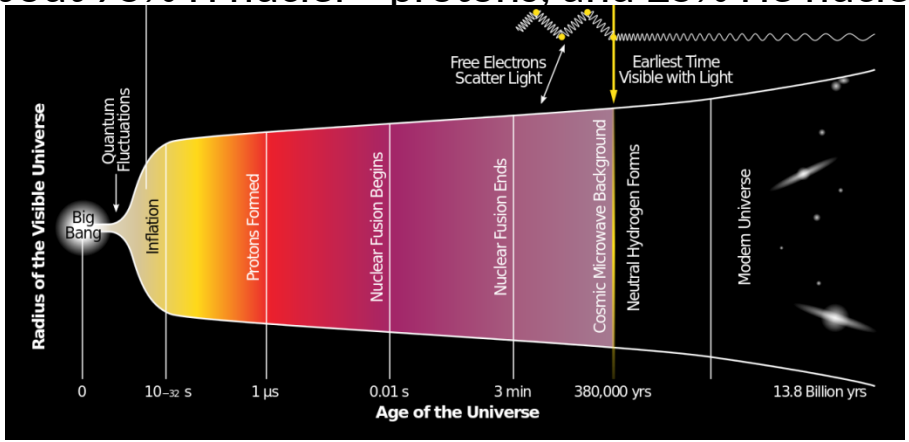
  A hot, dense beginning!





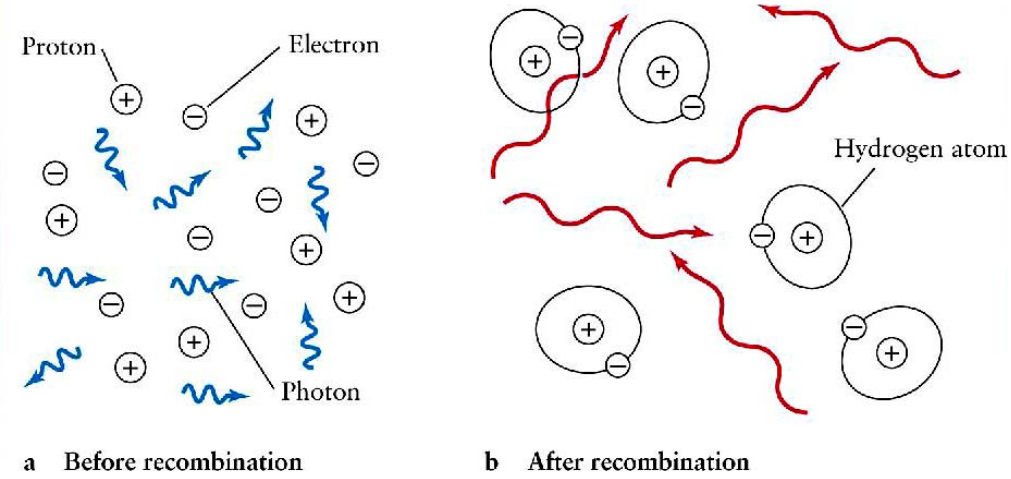
(3) Cosmic Microwave Background

- 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)



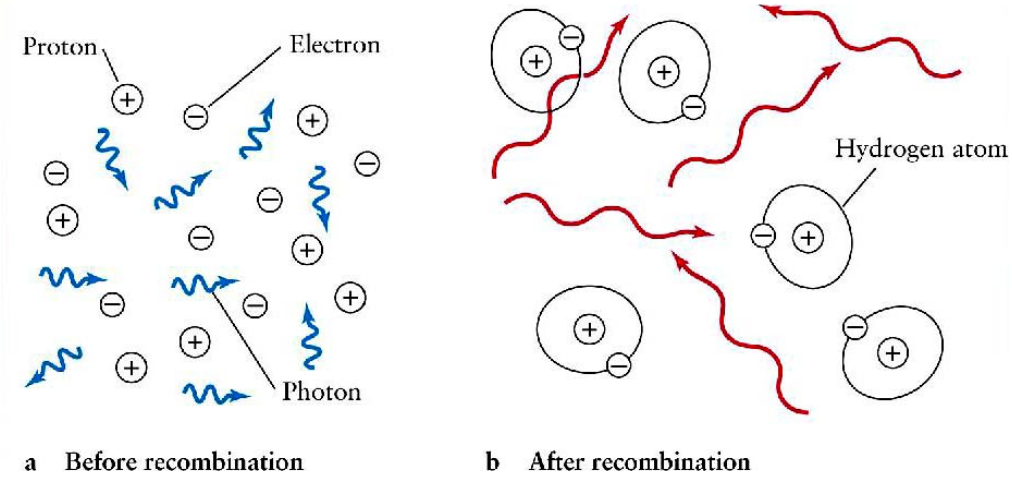
(3) Cosmic Microwave Background

- 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.



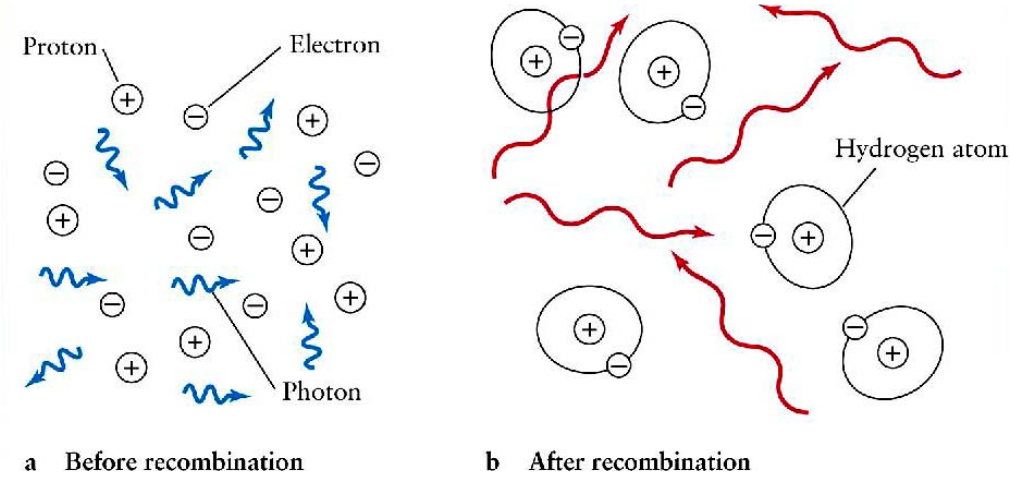
(3) Cosmic Microwave Background

- 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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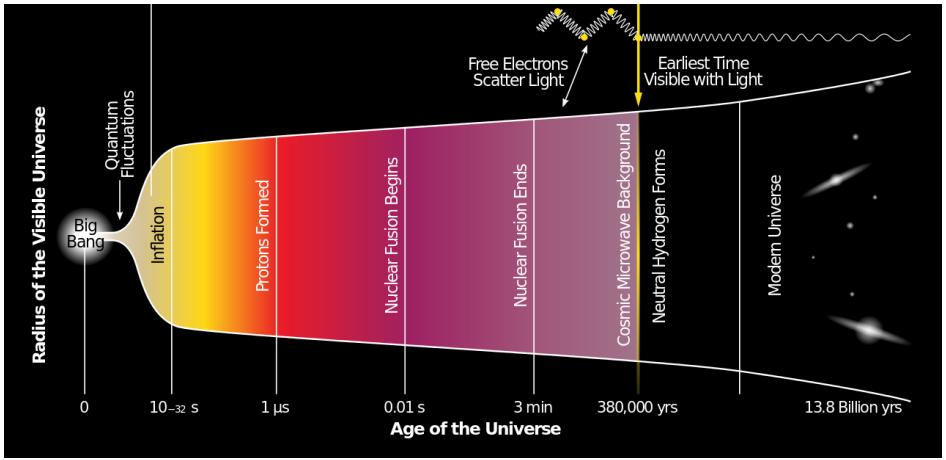
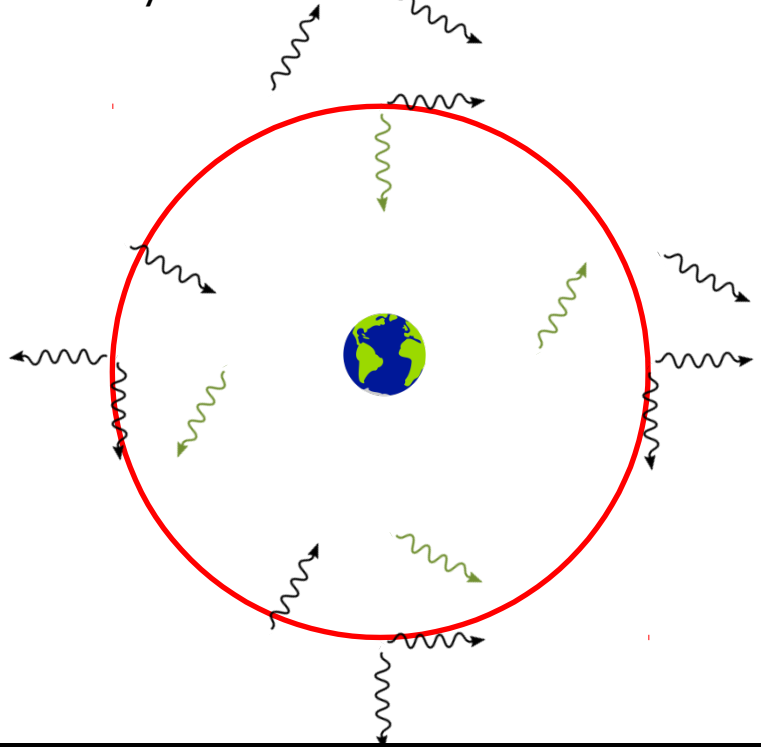


(3) Cosmic Microwave Background

- Why does this make sense?



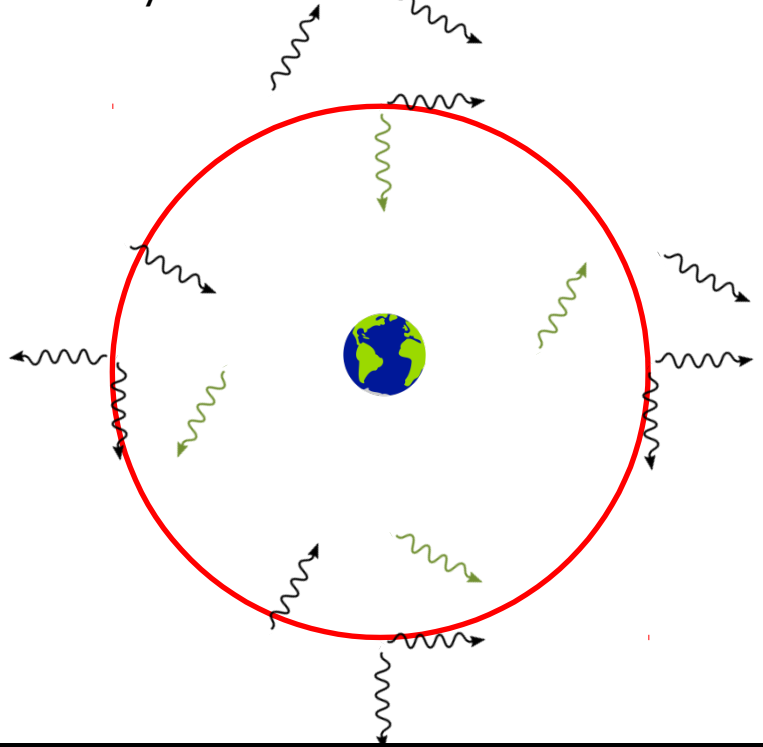
The green photons, that **last scattered** off an electron **long ago** and **far away**, then travelled for 13.8 billion years through transparent space to reach Earth **now.**

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**.

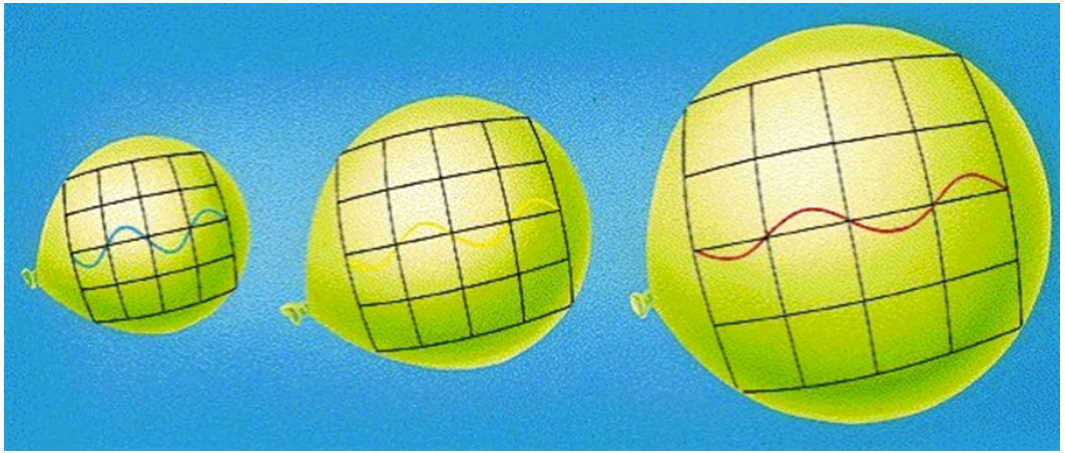
From Earth's perspective, we see photons arriving from **every direction in the sky**, originating long ago from a giant spherical surface that is *almost* at the edge of our observable universe, called ***surface of last scattering***.

(3) Cosmic Microwave Background

- Why does this make sense?



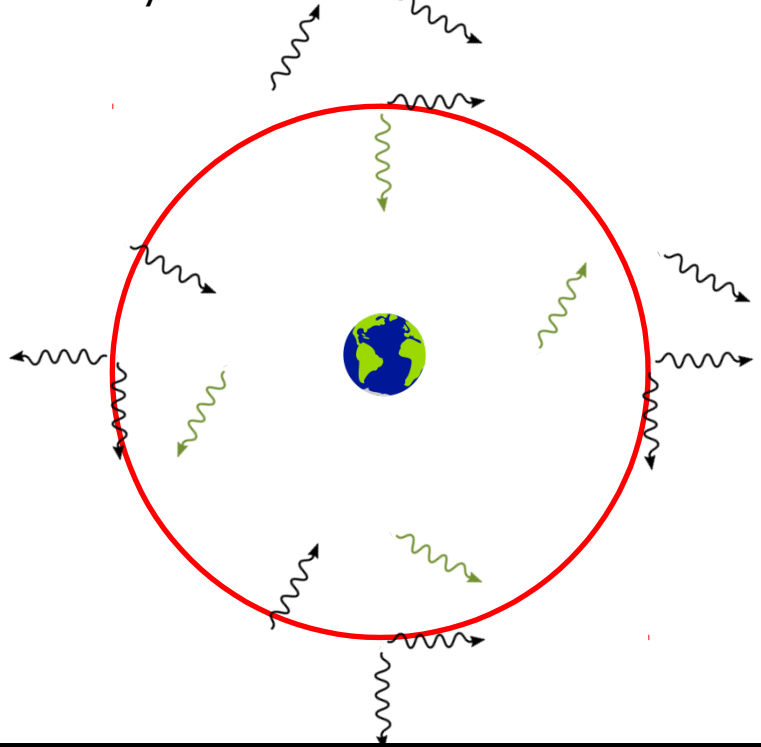
But remember, space continued to **expand** over those 13.8 billion years while those photons were in flight.



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

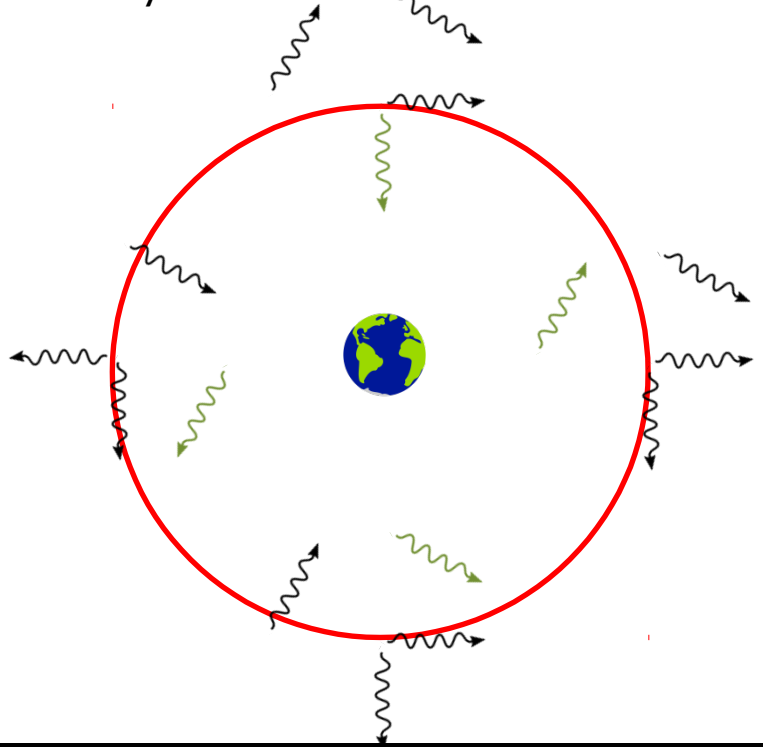
corresponds to **hot** photons at about **3000 K**

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

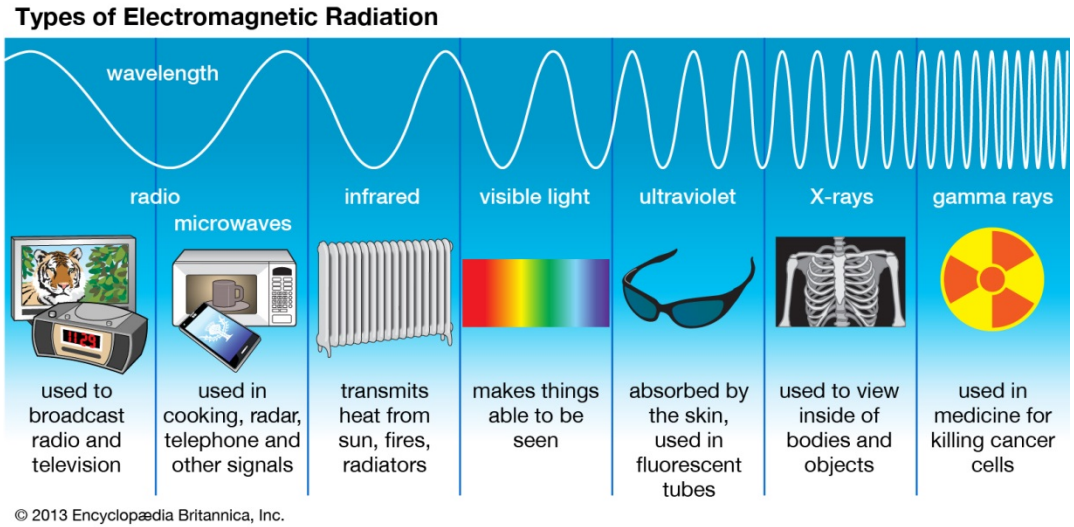
Space has **expanded** by a factor of since the light from the surface of last scattering was emitted, a mere **380 thousand years** after the Big Bang!

(3) Cosmic Microwave Background

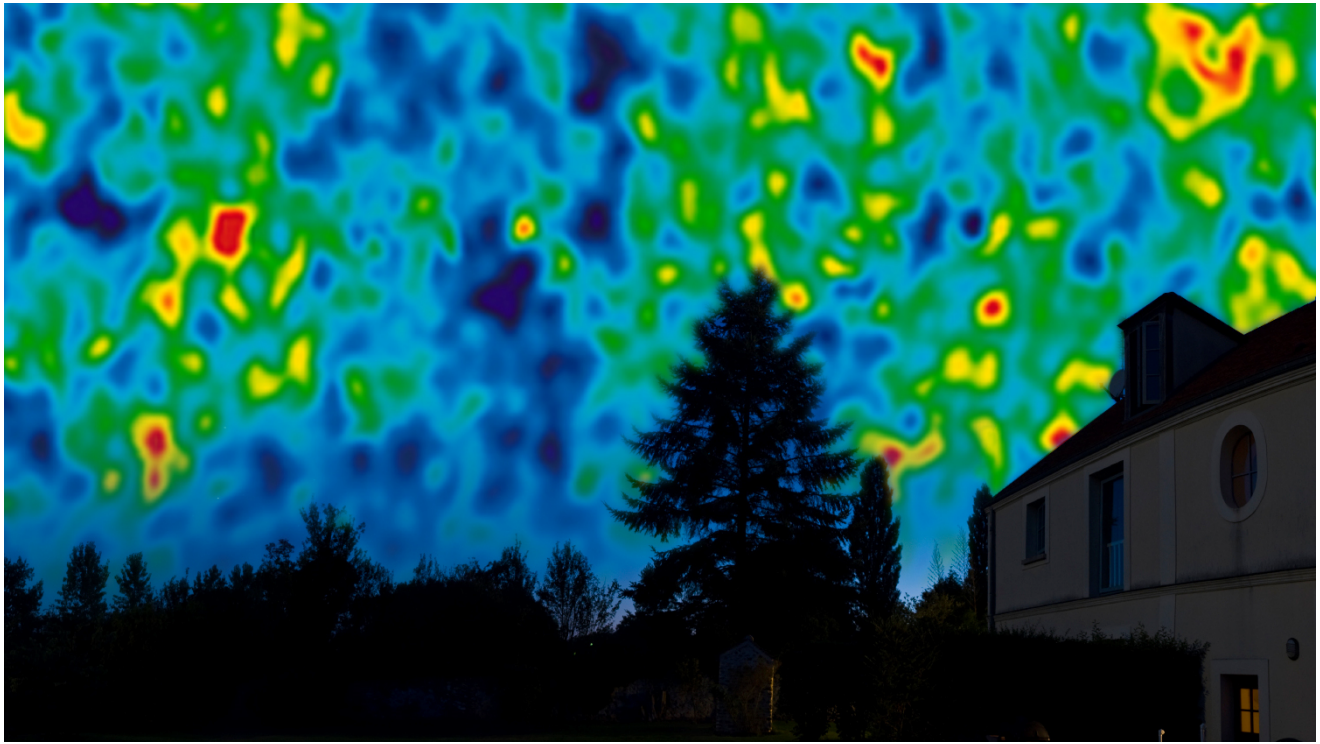
- Why does this make sense?



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

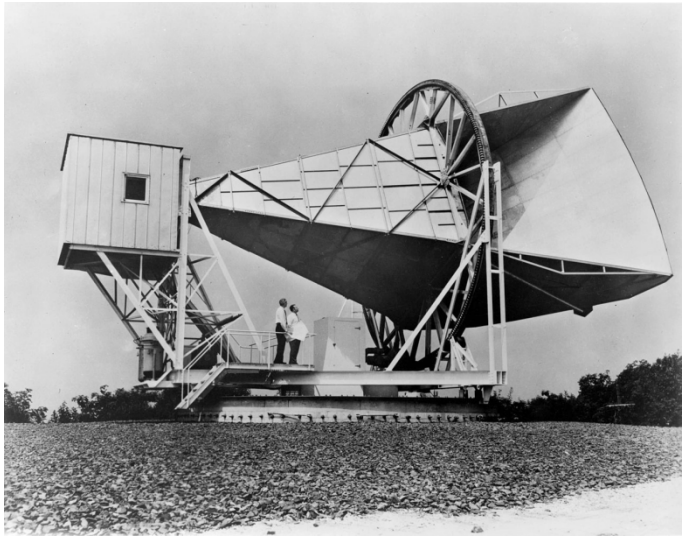


(3) Cosmic Microwave Background



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**.

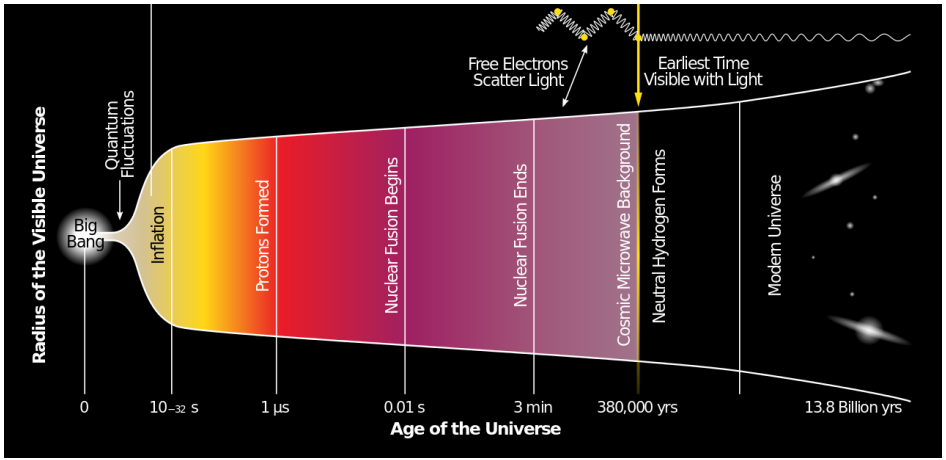
- At the same time, Dicke and colleagues were building an antenna to measure CMB…“**Boys, we’ve been scooped**”.

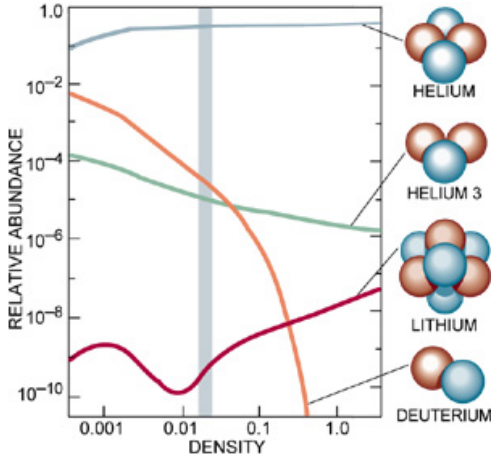
- **1978:** Penzias and Wilson get the **Nobel Prize in Physics**.

(3) Cosmic Microwave Background

(4) Abundances of the Light Elements

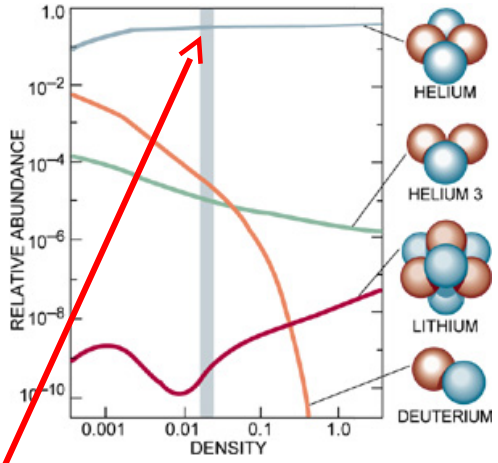
- By about **1 second** after the Big Bang, the universe contains **protons and neutrons**, but they are **too hot** (moving too fast) to fuse (be bound) into **heavier nuclei**.
- Between about **3 minutes and 20 minutes** the universe is cool enough for fusion: p + n ⎵ D (deuterium), D + D ⎵ helium-4,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





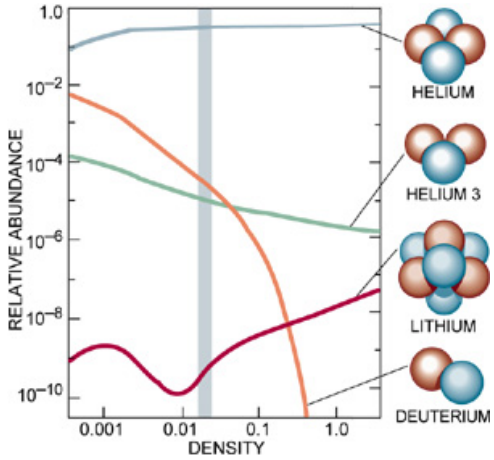
(4) Abundances of the Light Elements

- 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

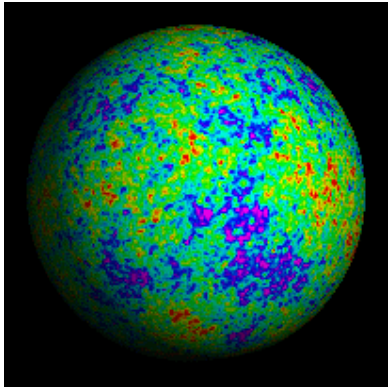


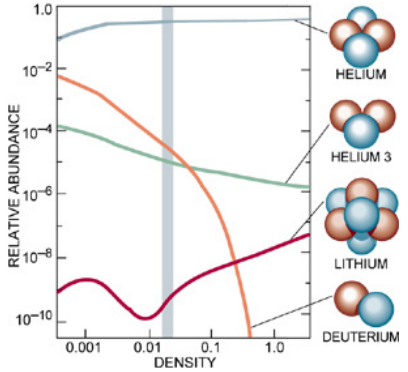
- Using particle physics again, we can **predict the abundances** of the other light elements, relative to hydrogen (see graph)
- **Key point:** Predicted abundances depend very sensitively on the **density of baryons** (p & n) during nucleosynthesis.
- **Agreement** between **predicted and observed** 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





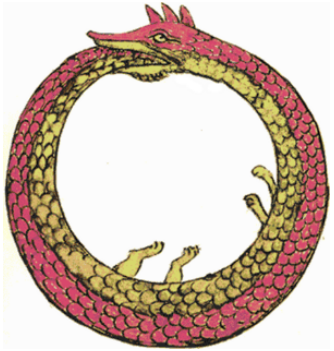
- Such detailed agreement between theory and observation leaves virtually **no doubt** that **13.8 billion years** ago the universe was in a **hot, dense state,** which then **expanded** and **cooled**.
  - CMB data takes us back to **380,000 years** after BB (and indirectly, much further back…)
  - 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

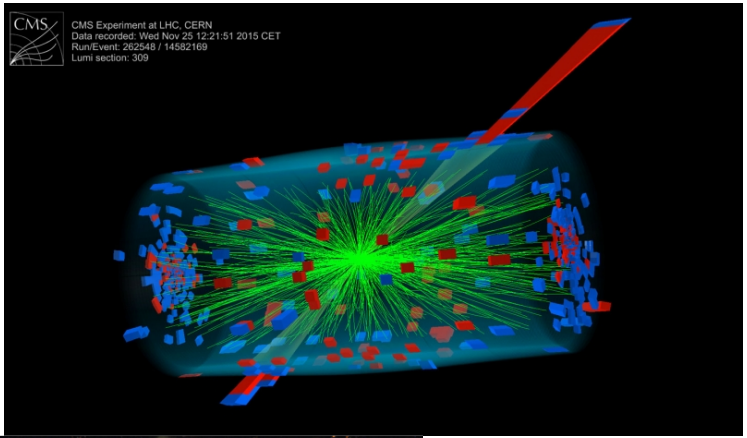
Summary:

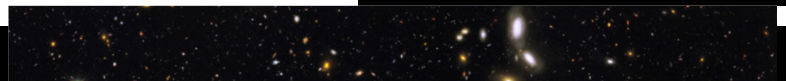
The mystery of origins has been pushed back to the blink of an eye after the Big Bang!

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

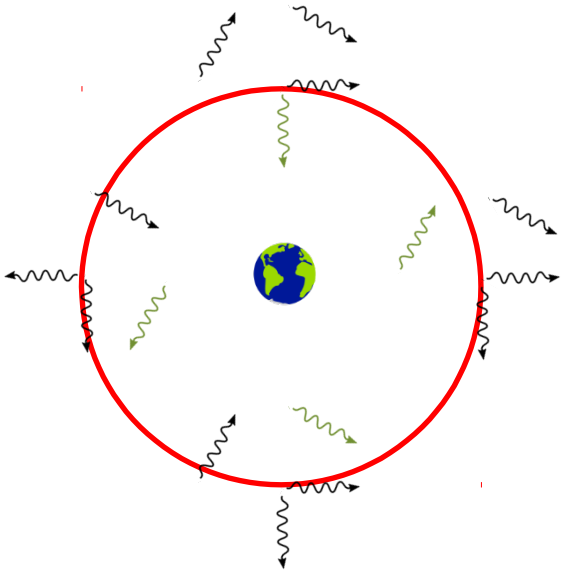
The growing connections between **macro**scopic and **micro**scopic physics is particularly exciting.

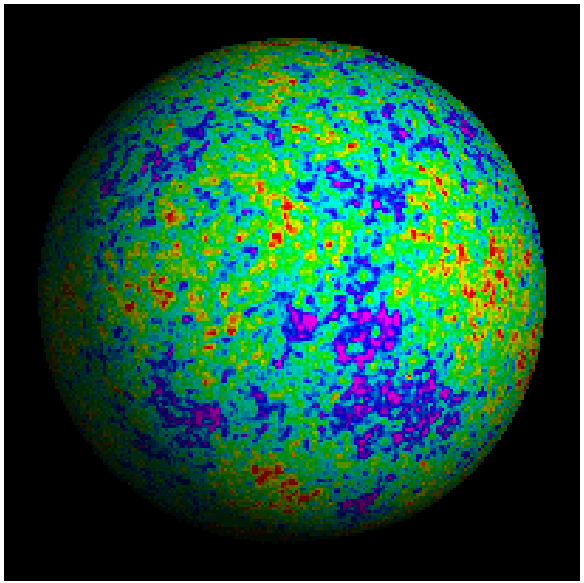


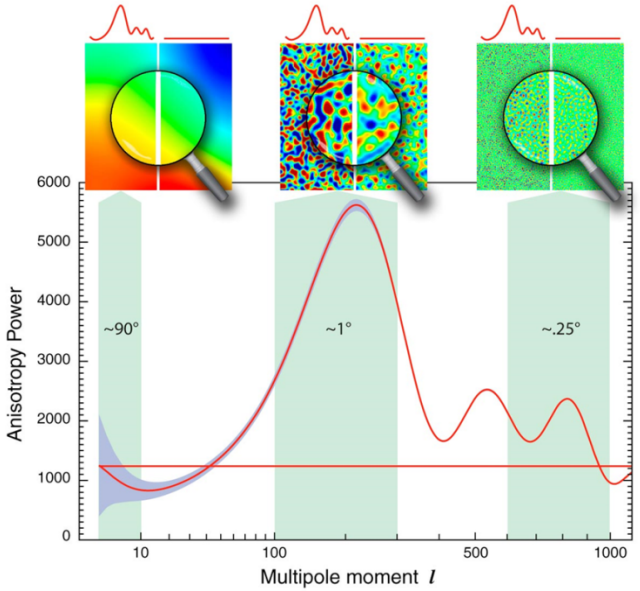




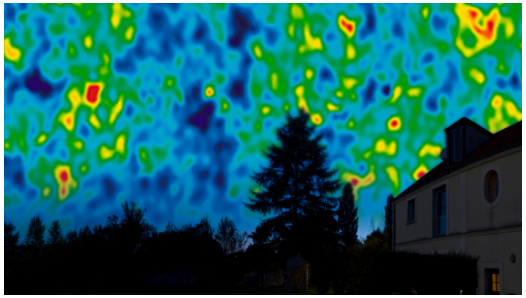
The CMB is **not perfectly uniform** over the sky. It has **tiny fluctuations (~1:100,000)** which indicate that the **temperature** & **density** of matter in the early universe **varied slightly from place to place**: hotter and less dense in some places, colder and more dense in others.

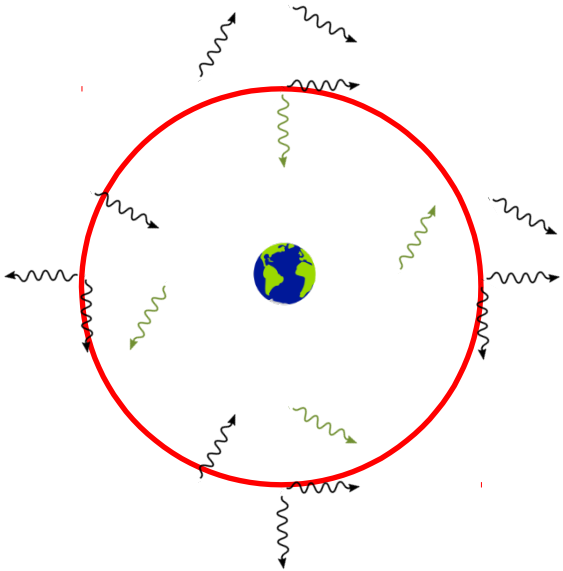


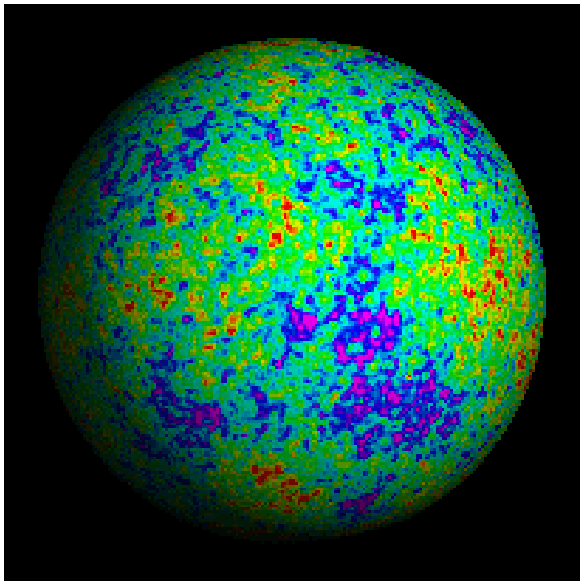


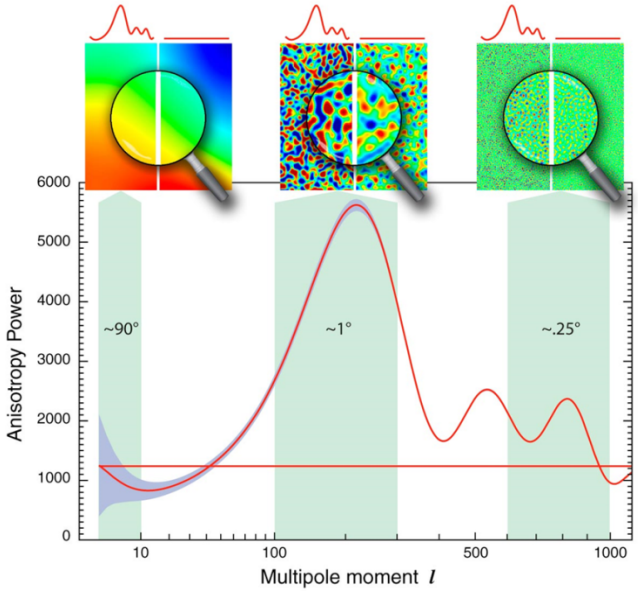


The **average angular size** of the **most intense** fluctuations is about **1 degree** on the sky (about twice the angular size of the Moon or Sun). **Why?**

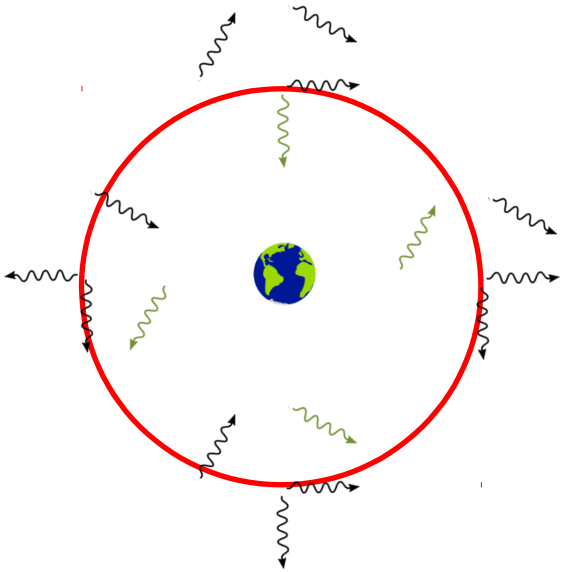


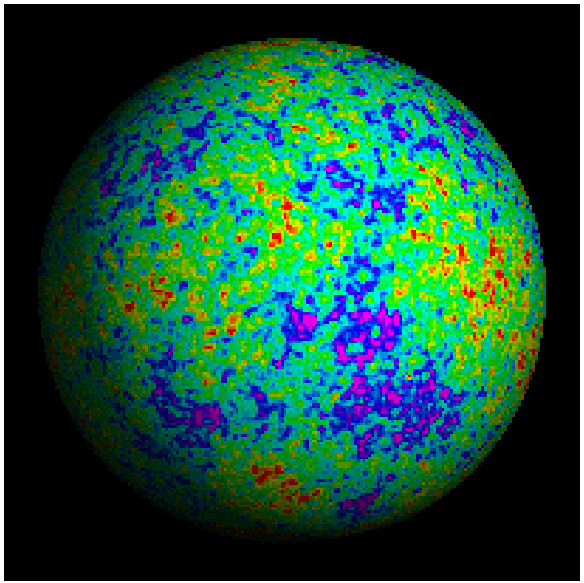


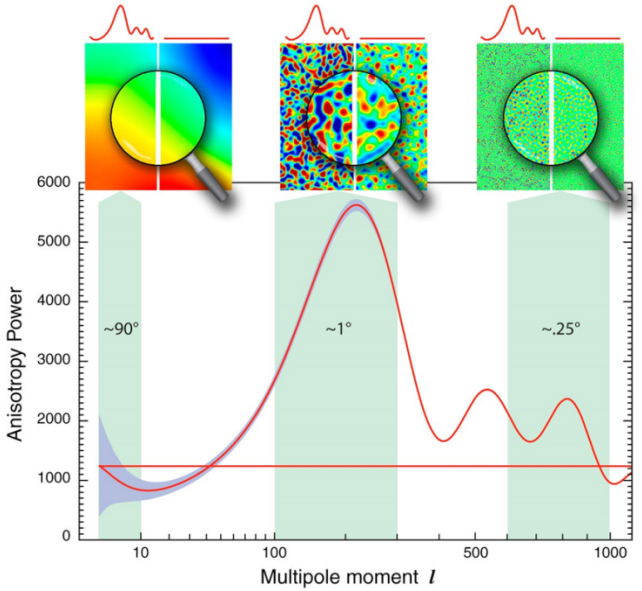




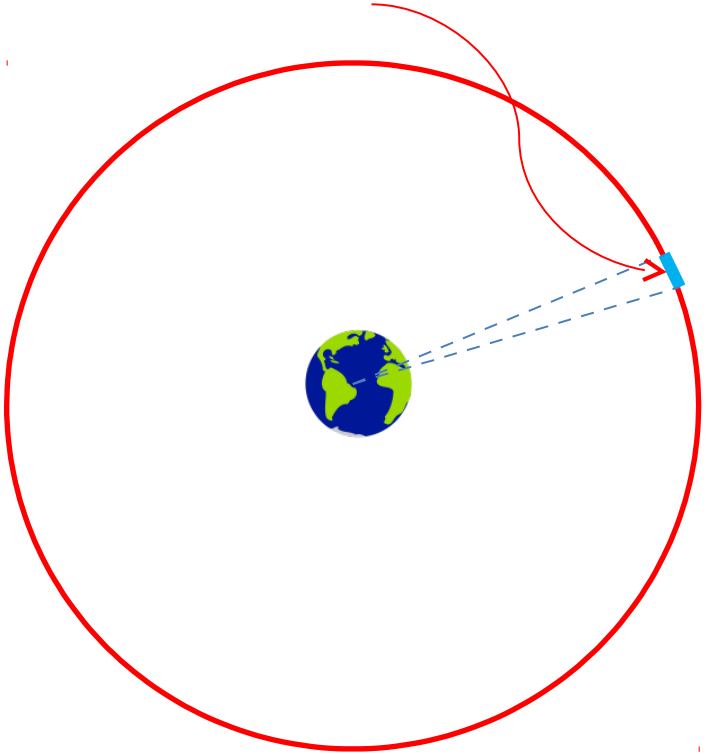
Rough Argument: At **380,000 years** after the Big Bang, light would have had a chance to travel only about **380,000 light years** in any direction, or a sphere of about 2 x 380,000 = **760,000 light years** in diameter. Thus, the largest "blobs" of matter that could have the **same temperature** (different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



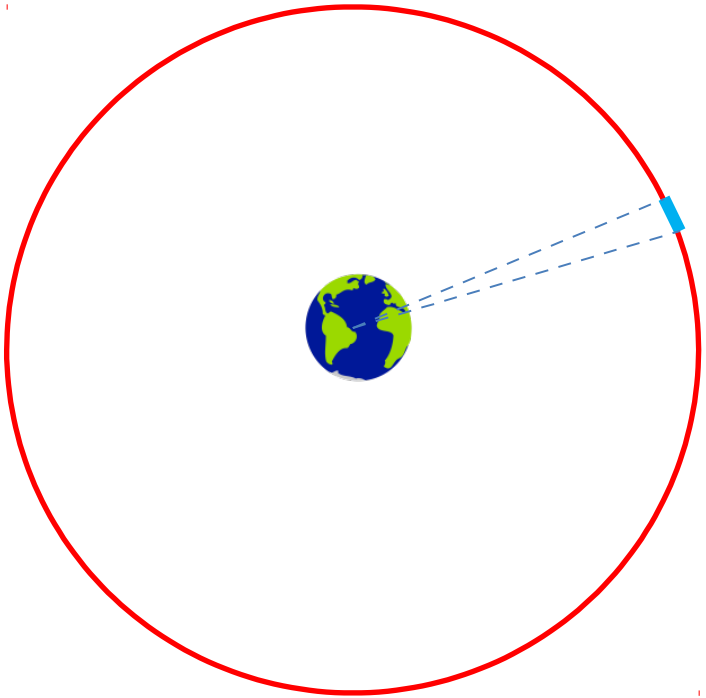
The *current* **radius** of the surface of last scattering (observable universe) is about **46 billion light years**

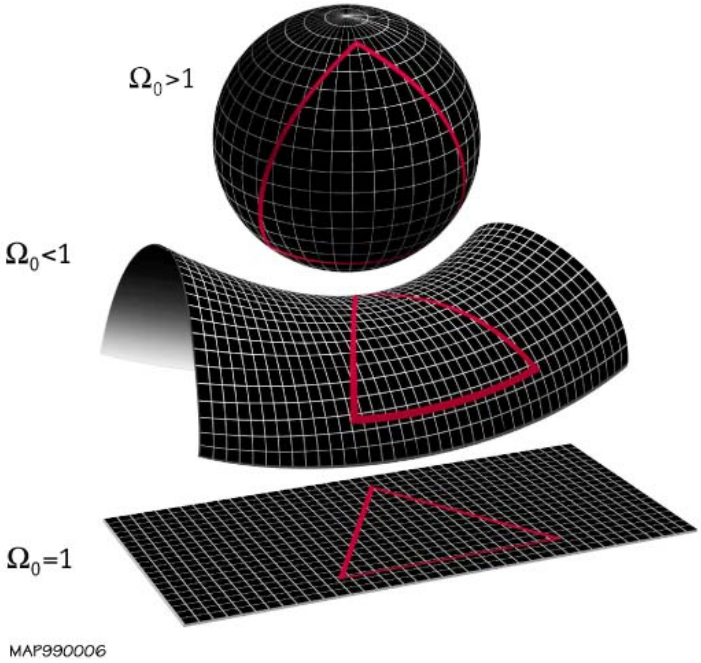
But space was about **1100 times smaller** at the time of last scattering, so the **circumference** of the red circle **at that time** was about 2π x 46 billion ly / 1100 = **260 million ly**.

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

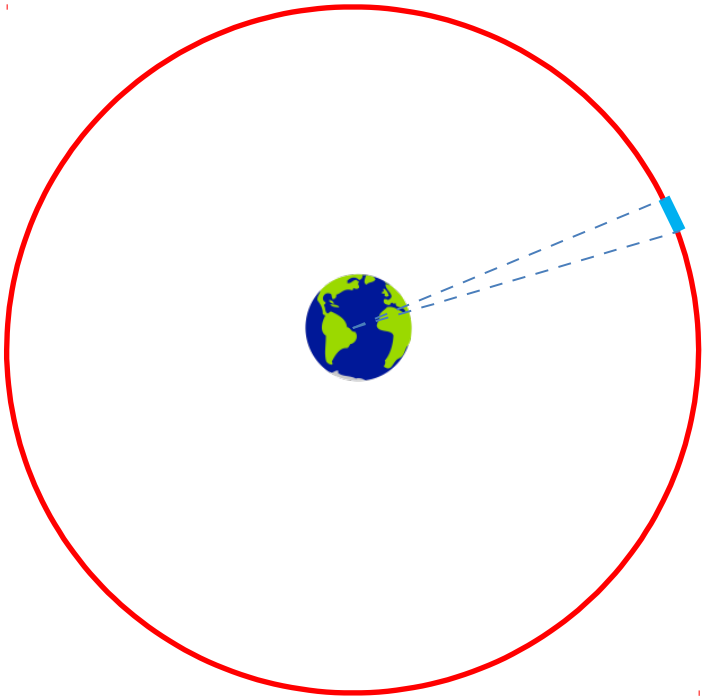
So this make sense!

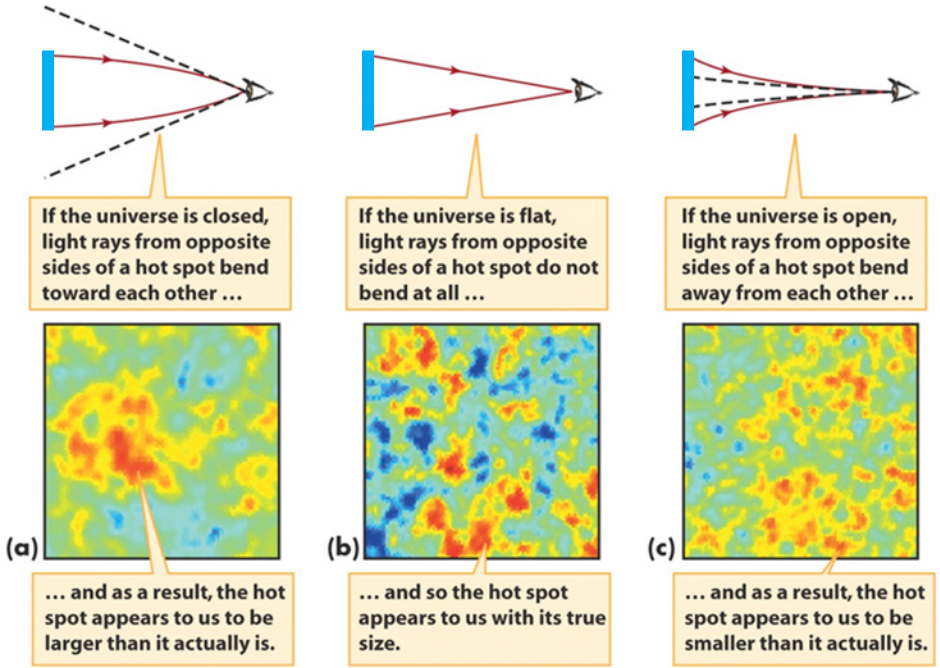
But Wait: In making this calculation we **assumed** that space (**on cosmic scales**) is **flat.** Einstein's theory says it could be **flat**, **positively** curved (a 3D sphere), or **negatively** curved (a 3D saddle).





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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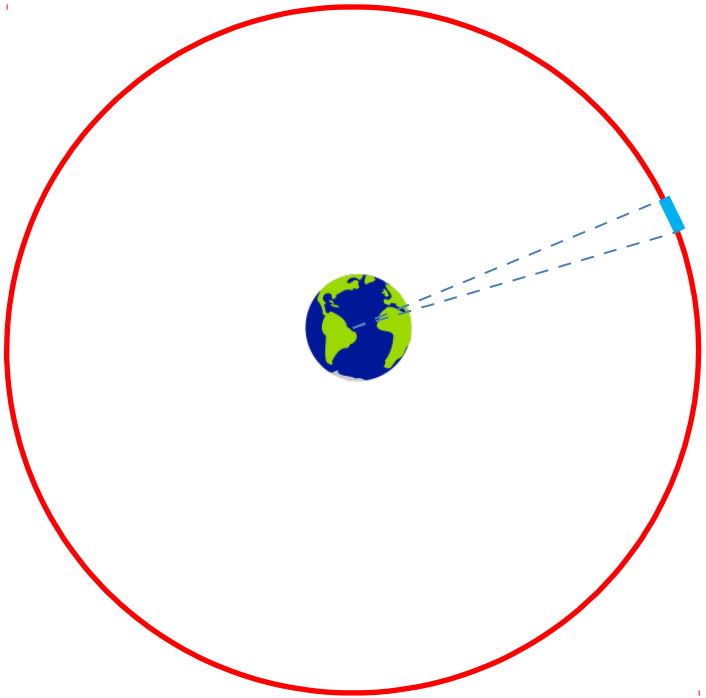

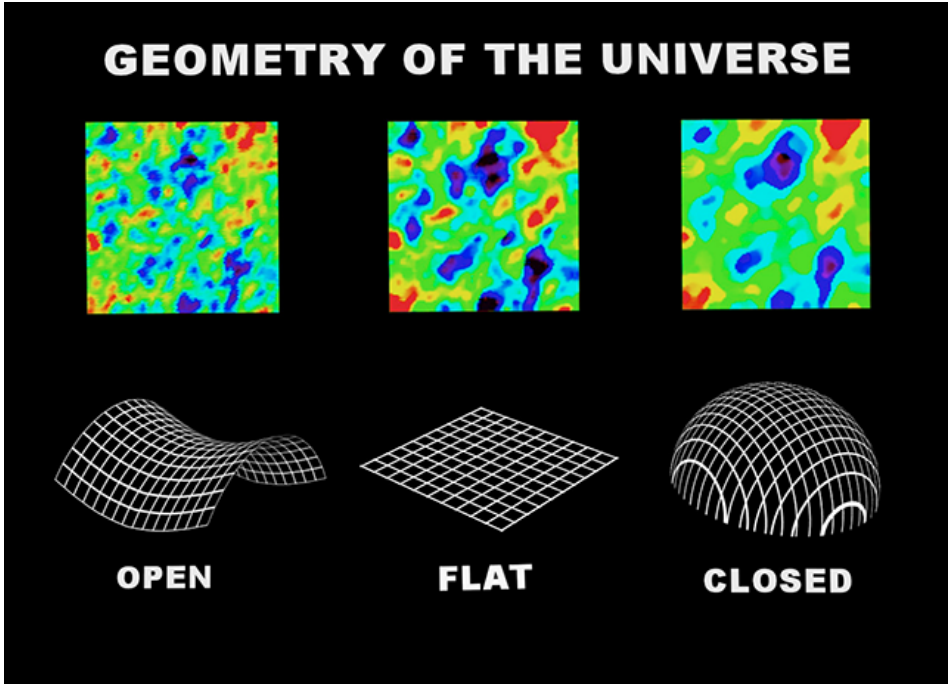

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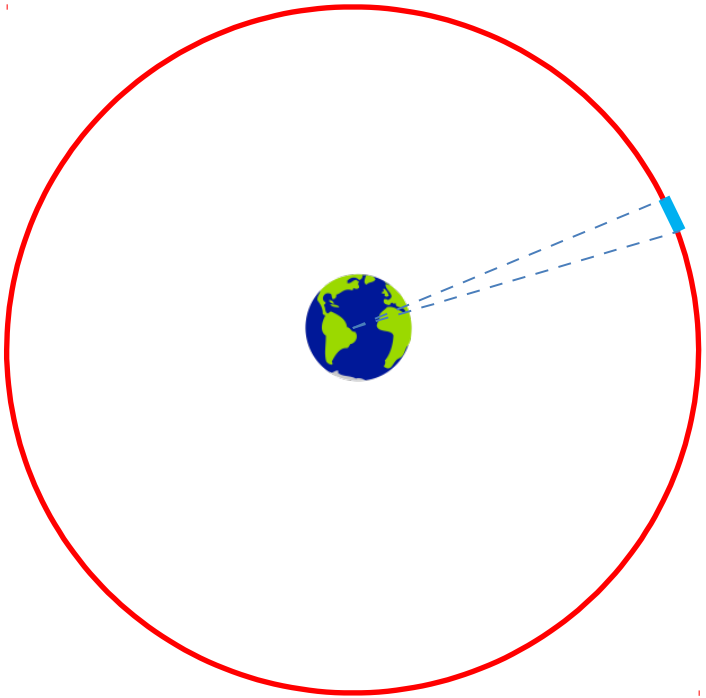
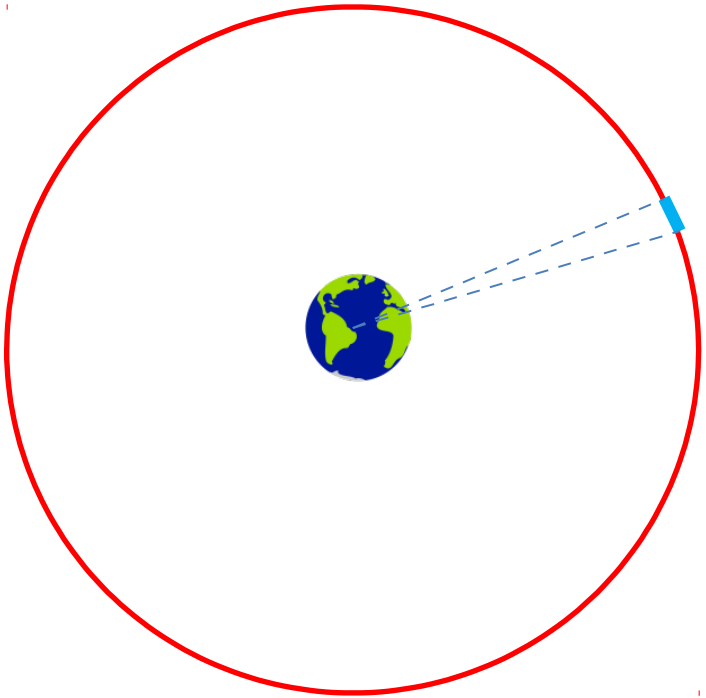
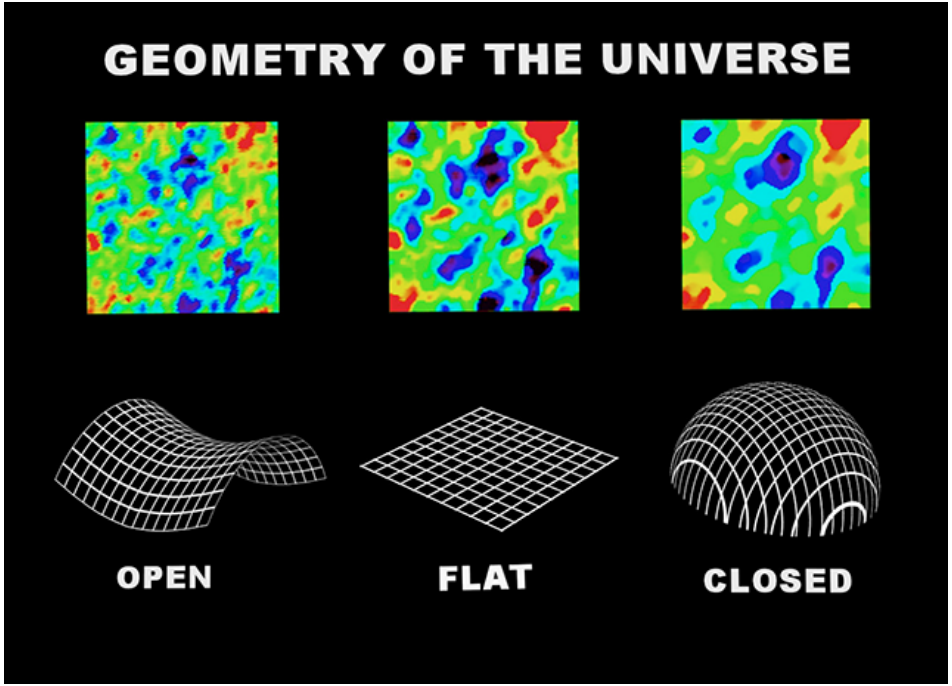


The angular size of the blobs we see is consistent with the observable universe being **FLAT** on the **cosmic scale** (or very nearly so).





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**.

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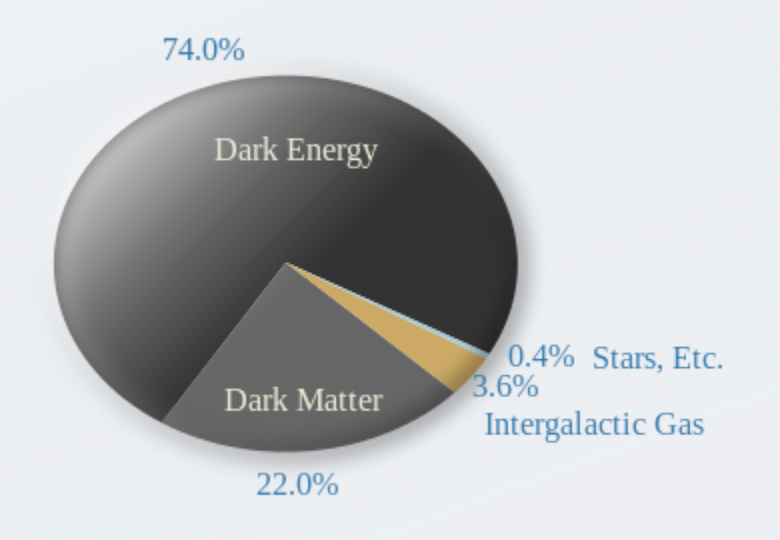
This missing mass-energy is called **DARK ENERGY**



Mystery of Dark Energy

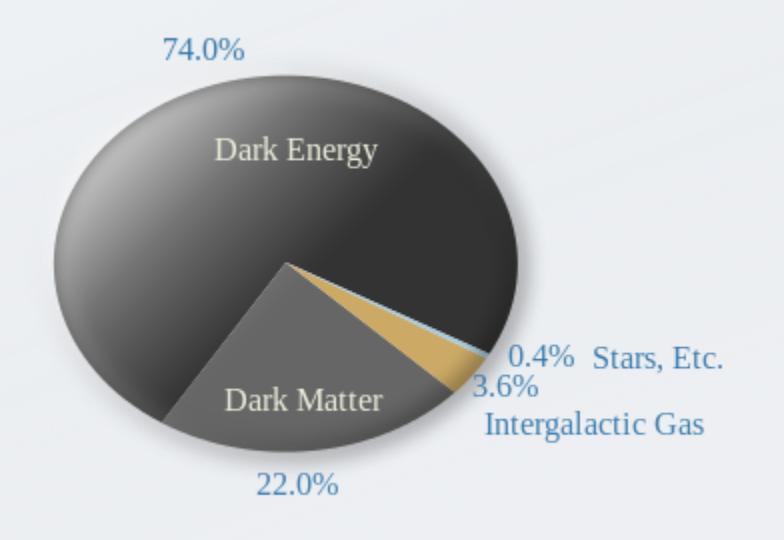
So what? Einstein's theory says that a **FLAT** universe requires a certain **critical density of total mass-energy**. Less ⊔ OPEN; more ⊔ CLOSED. We seem to at **critical density**.

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**.

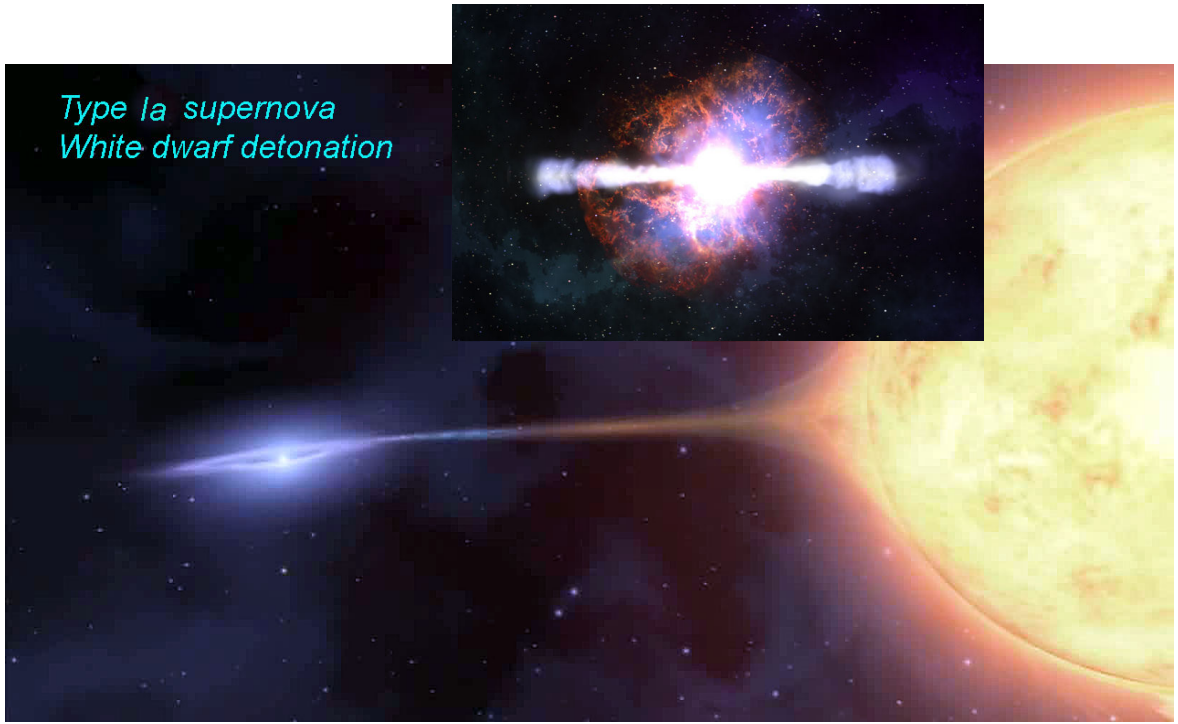


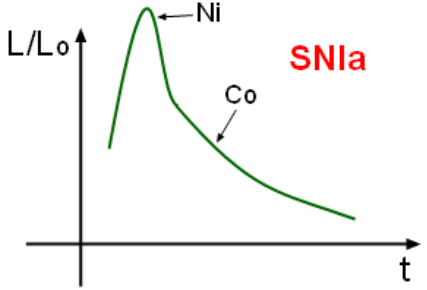
But extraordinary claims (**74% dark energy**) require extraordinary proof.

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

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

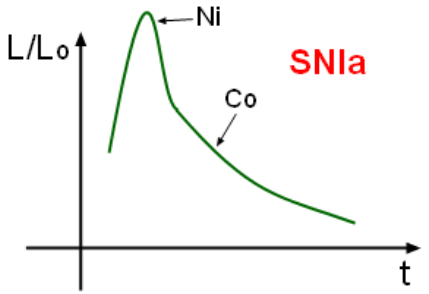
In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

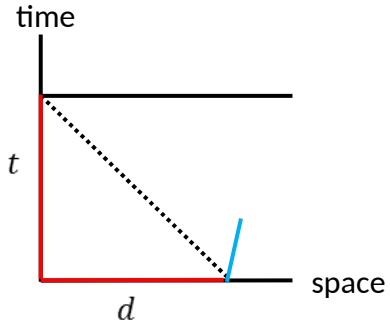




In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

- 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)

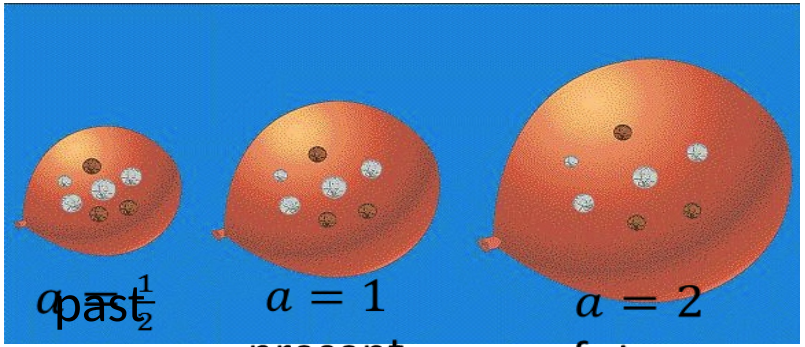


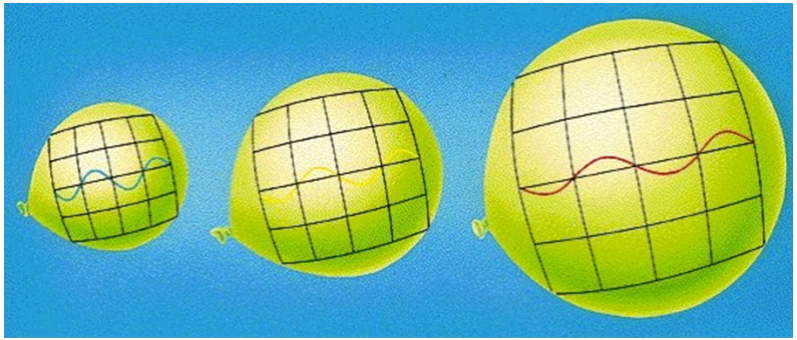


Mystery of Dark Energy

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**:

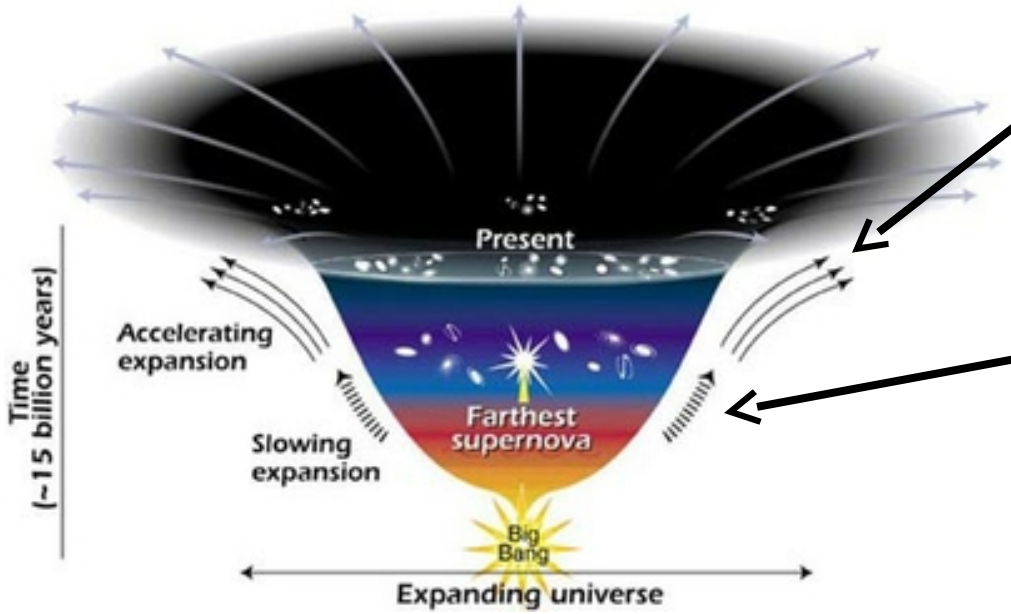
- This data (**apparent brightness & redshift**), input into the mathematics of Einstein's cosmological model of the universe, gives $a(t)$.
- Recall: $H(t) = \dot{a}(t)/a(t)$, $a(t) =$ **scale factor** of space $=$ the size of space relative to now.





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

Mystery of Dark Energy

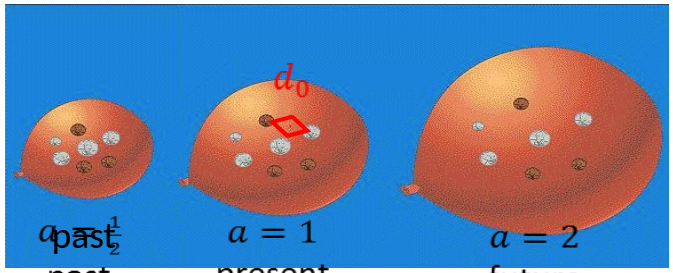
In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

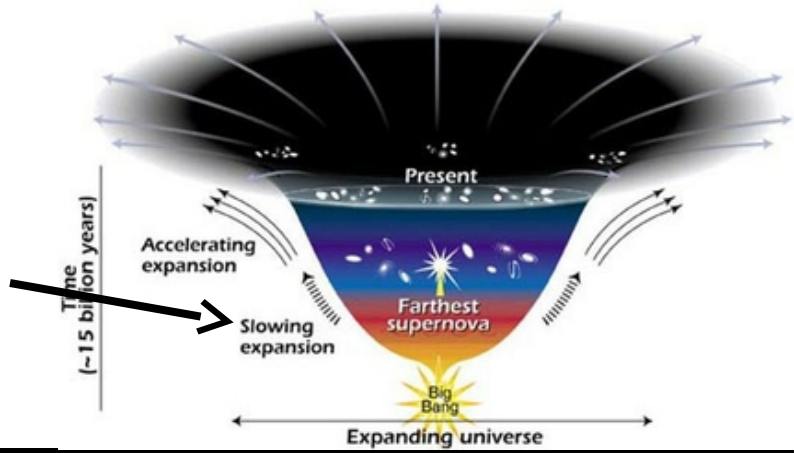
- Hubble Law: $v = Hd = \left(\frac{\dot{a}}{a}\right)(ad_0) = \dot{a}d_0$
- Observe: $\dot{v} > 0 \rightarrow \ddot{a} > 0$
- Friedmann: $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$

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





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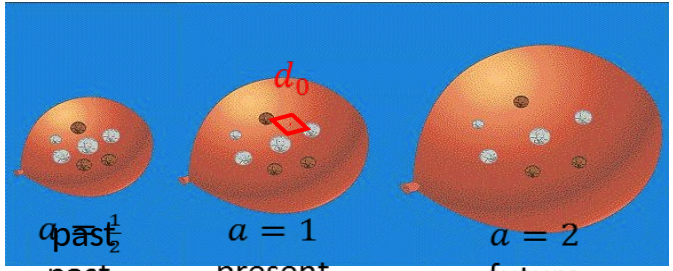
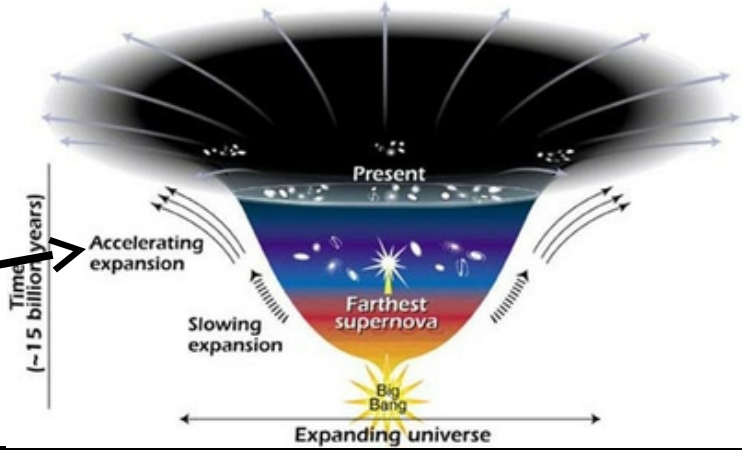
ρ = density, p = pressure

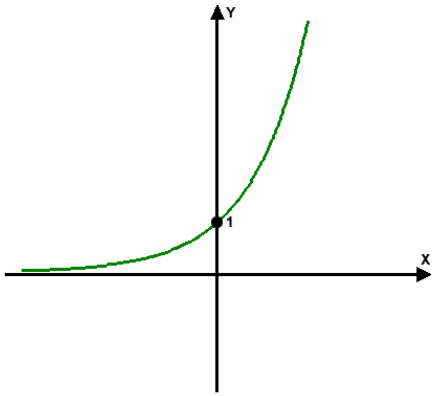
Λ = Einstein's **cosmological constant**. Eventually it **dominates** and, with $\Lambda > 0$, causes the expansion of space to **accelerate** ($\ddot{a} > 0$)





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)

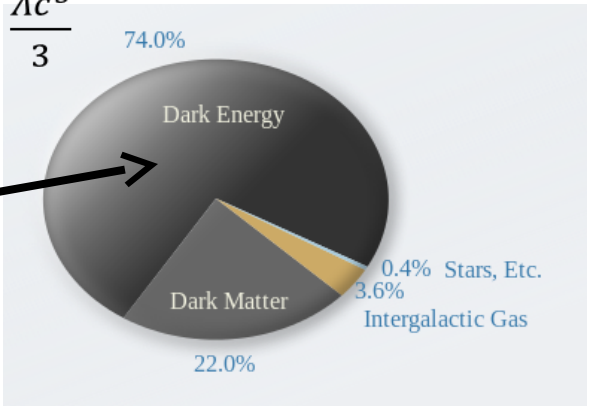
In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

- 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** ($\dot{v} = \ddot{a}d_0 > 0$)

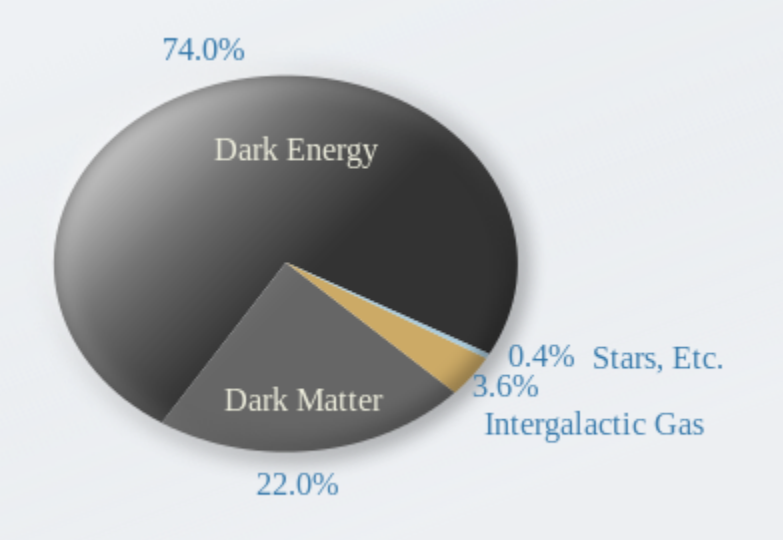
…that's a quick introduction to the basic mathematics underlying modern cosmology.

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**.

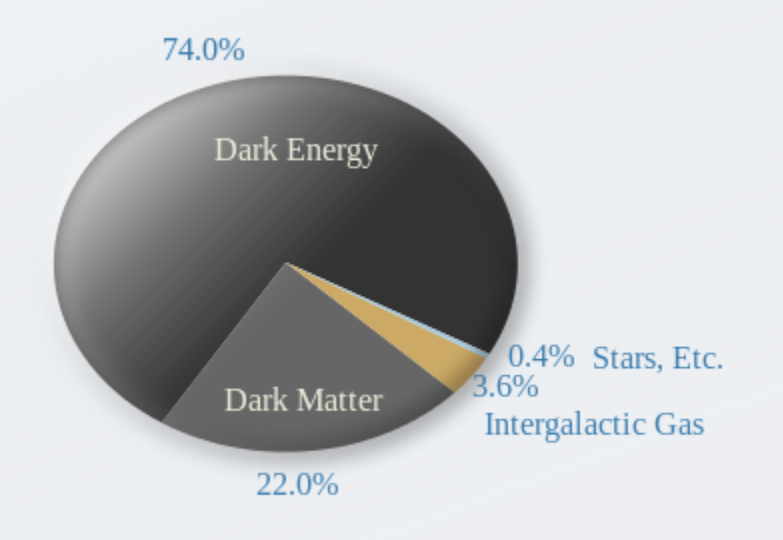
In **1998**, observations were made of the **expansion rate** of space at **different times** in cosmic history, based on observations of distant **Type Ia Supernovae**:

- **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