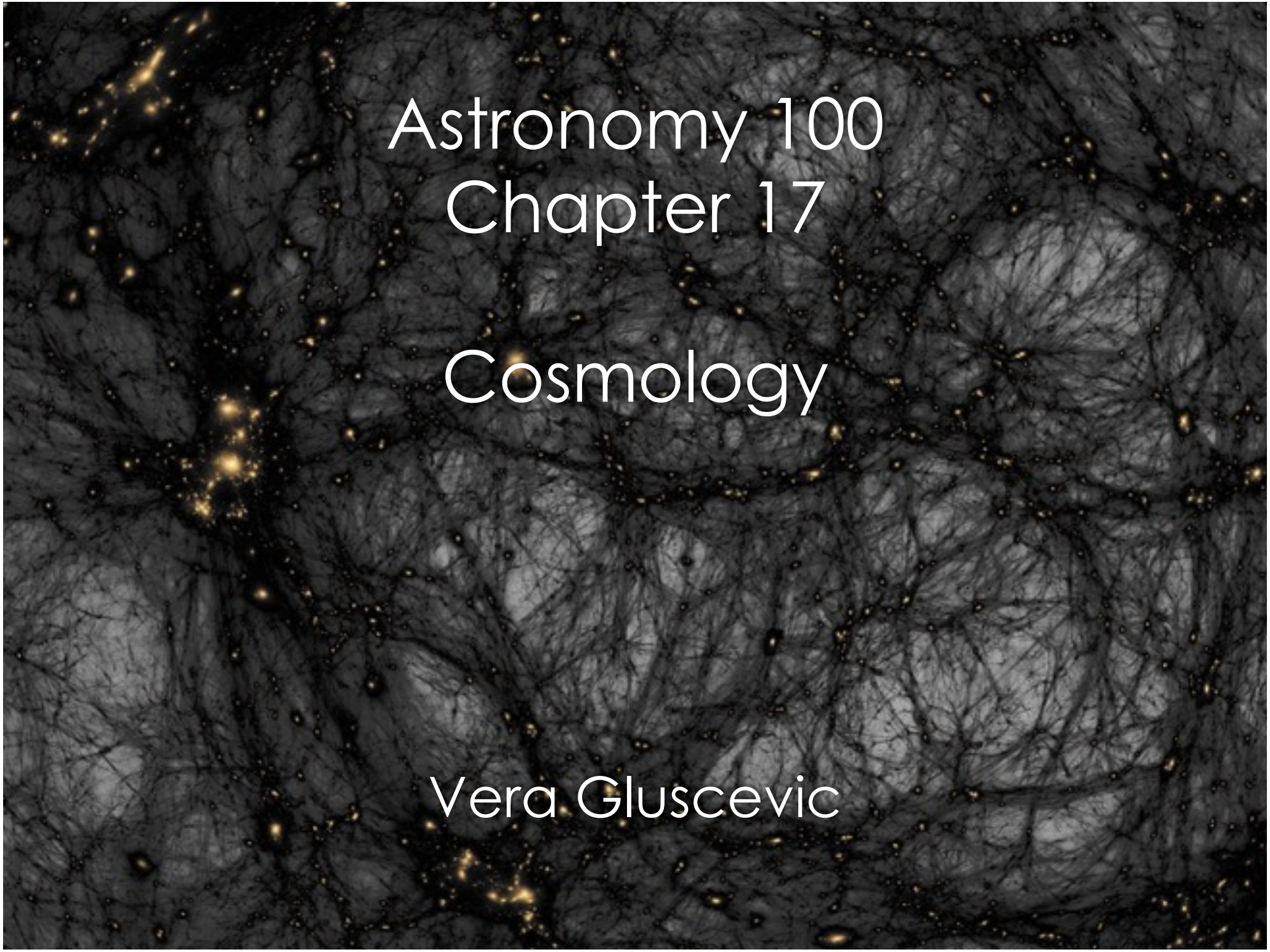


Astronomy 100
Chapter 17

Cosmology

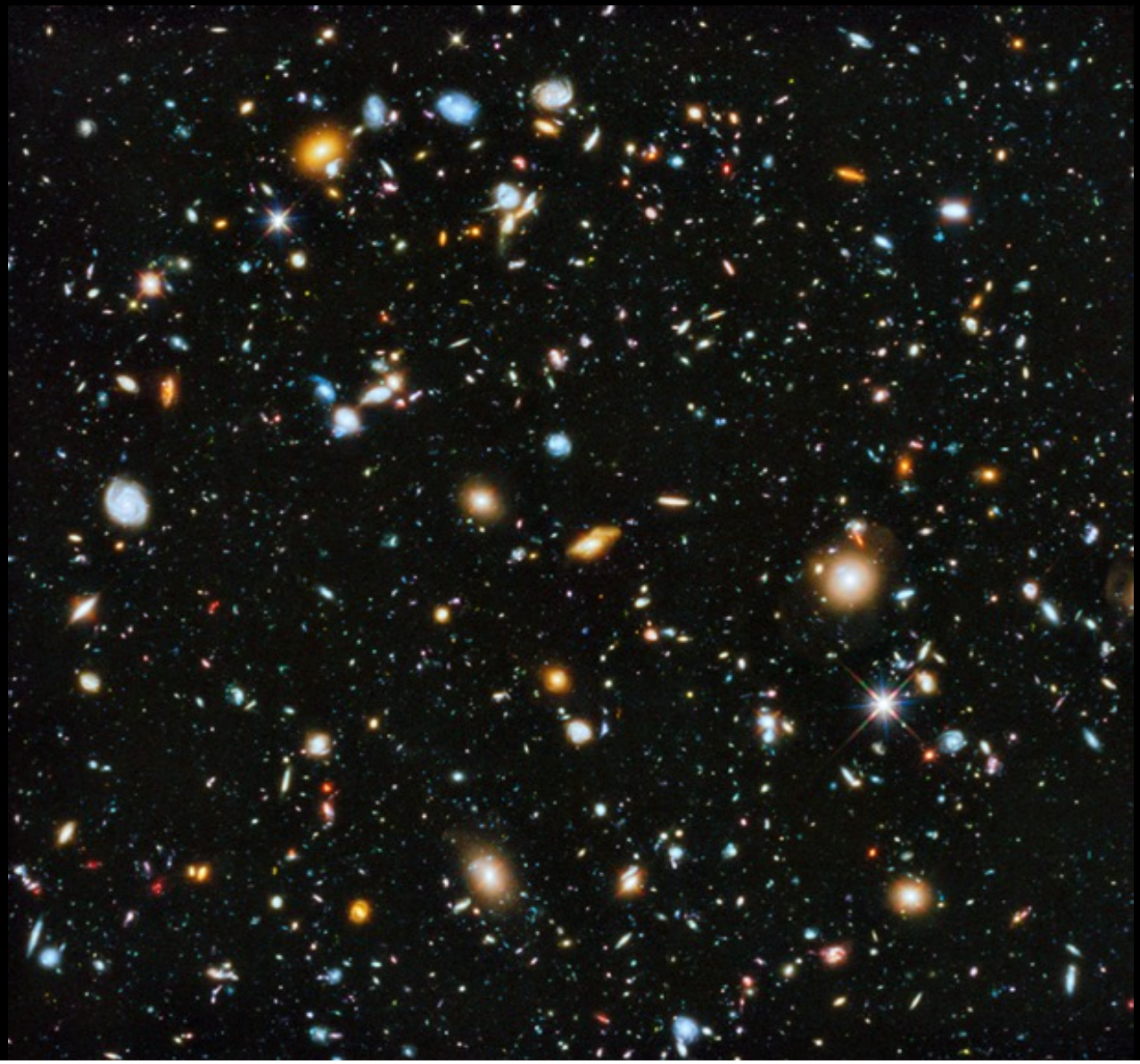
Vera Gluscevic

Let's zoom out more…

- **Local cluster of galaxies:** Virgo cluster shown here has about 1000 galaxies, with a total mass of about a quadrillion solar masses.
- Clusters are the biggest gravitationally bound structures in the Universe today.
- Between them is mostly empty space (vacuum).

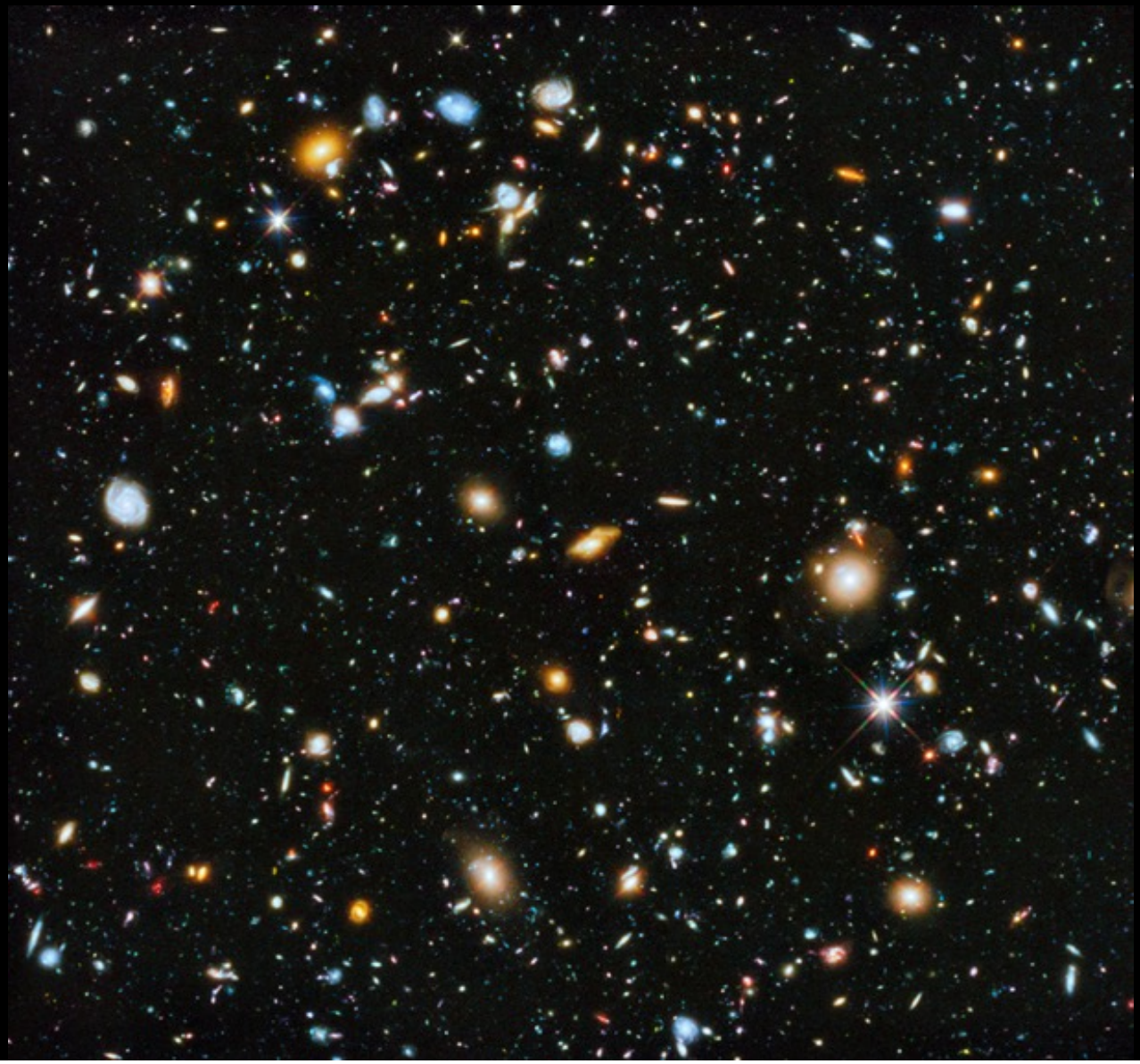
The Universe today:

Cold, ionized, sprinkled with galaxies, expanding faster and faster.



We live in a dark Universe.

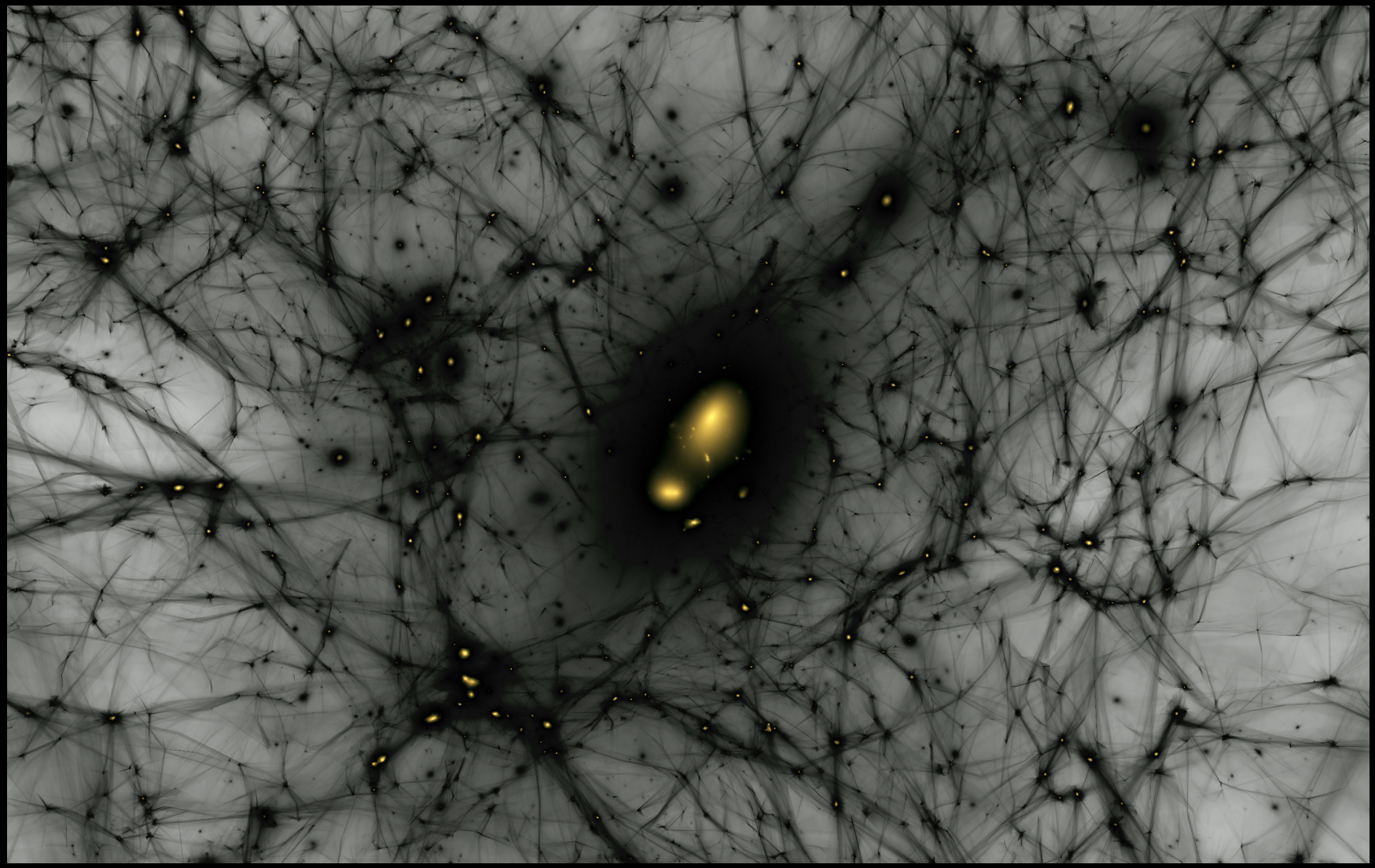
Normal matter accounts for less than 5% of its content.



If all the matter in our Universe emitted light...

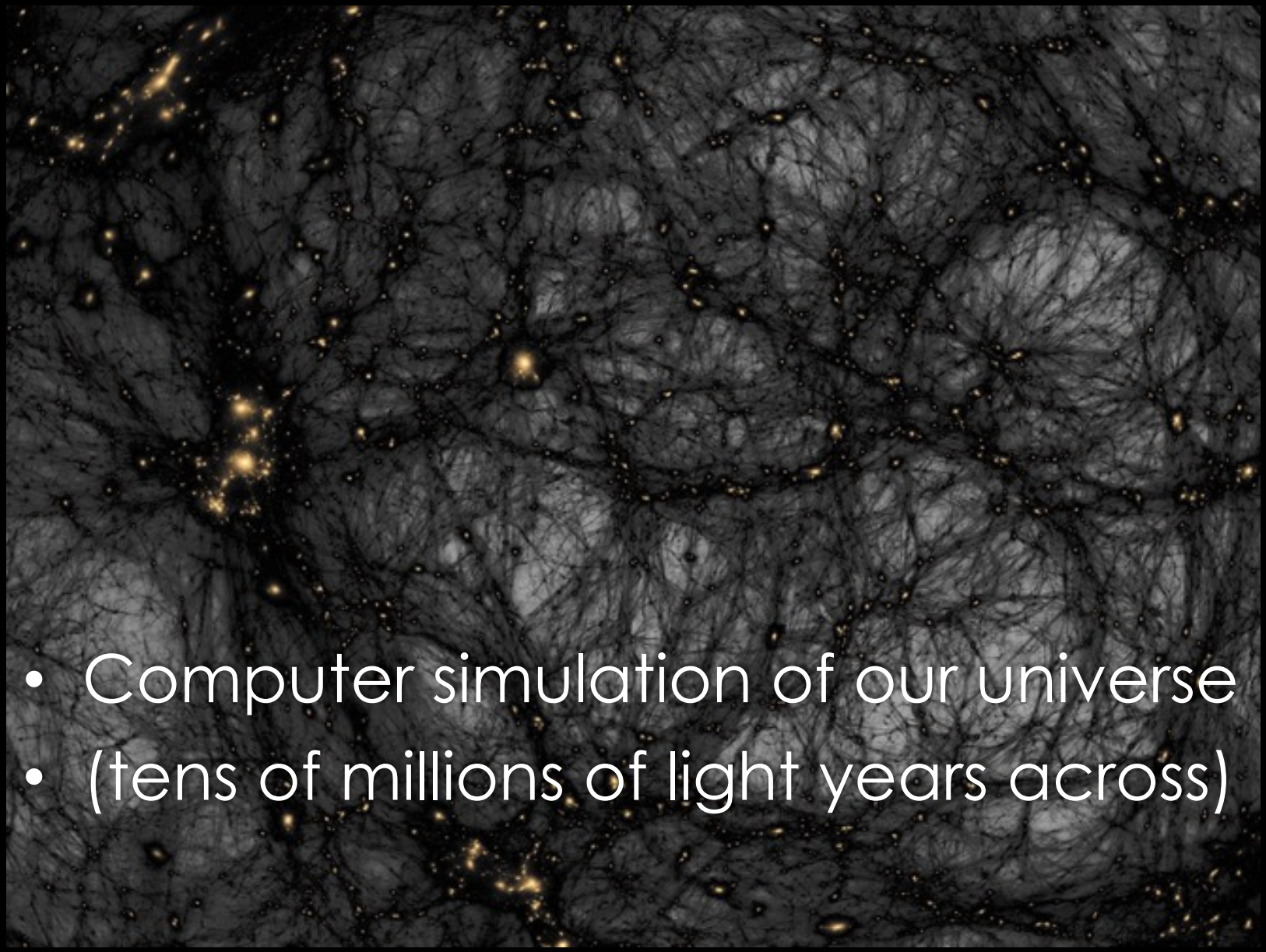
Simulation by Nadler, Mao, Kaehler:
https://www.youtube.com/watch?v=c8xDQlt4pYA

If all the matter in our Universe emitted light...



Simulation by Nadler, Mao, Kaehler:
https://www.youtube.com/watch?v=c8xDQlt4pYA

Most of this is NOT normal matter…



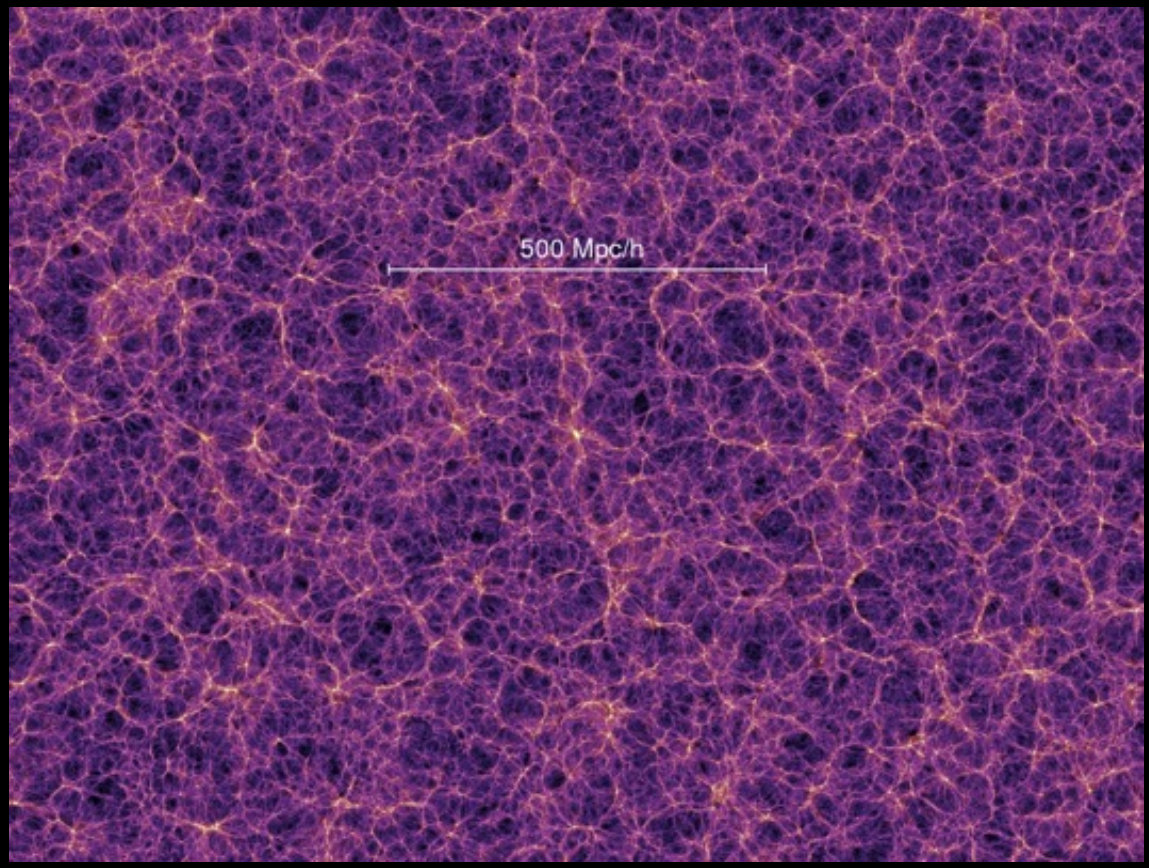
- Computer simulation of our universe
- (tens of millions of light years across)

What is the Universe made of?

Credit: A. Peter

Let's zoom out the most…

Large scale structure of the Universe (billion light years across).



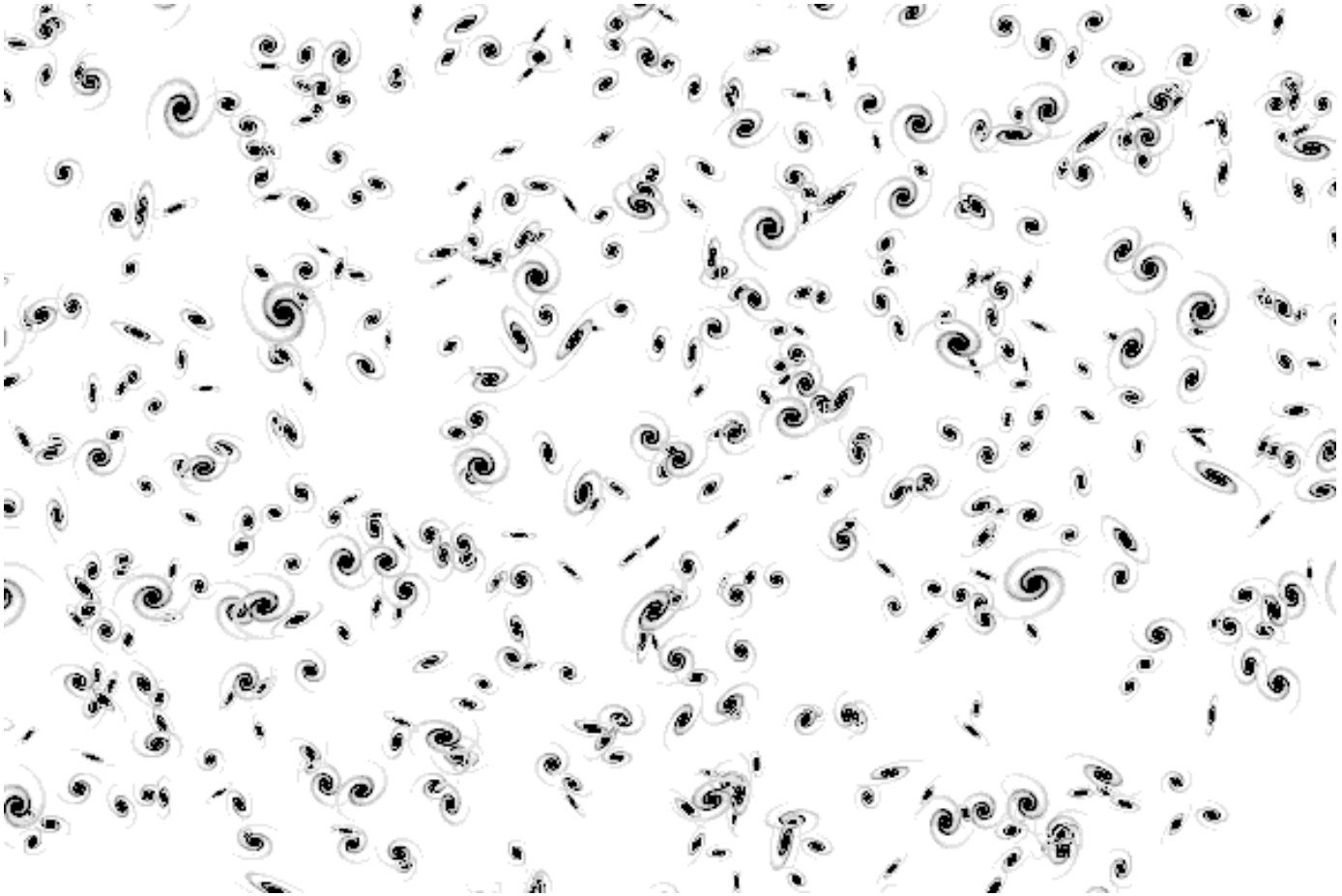
- Maps from "galaxy surveys" reveal that our universe is uniform on large scales (shown is a computer simulation that matches observations).
- Visible are superclusters of galaxies in the knots and filaments, with voids in between them.

Modern Cosmology

= study of the physical universe (Greek kosmos=order)

Cosmological principle

= Universe is homogeneous and isotropic.



Cosmological principle

= Universe is homogeneous and isotropic.

Cosmological principle

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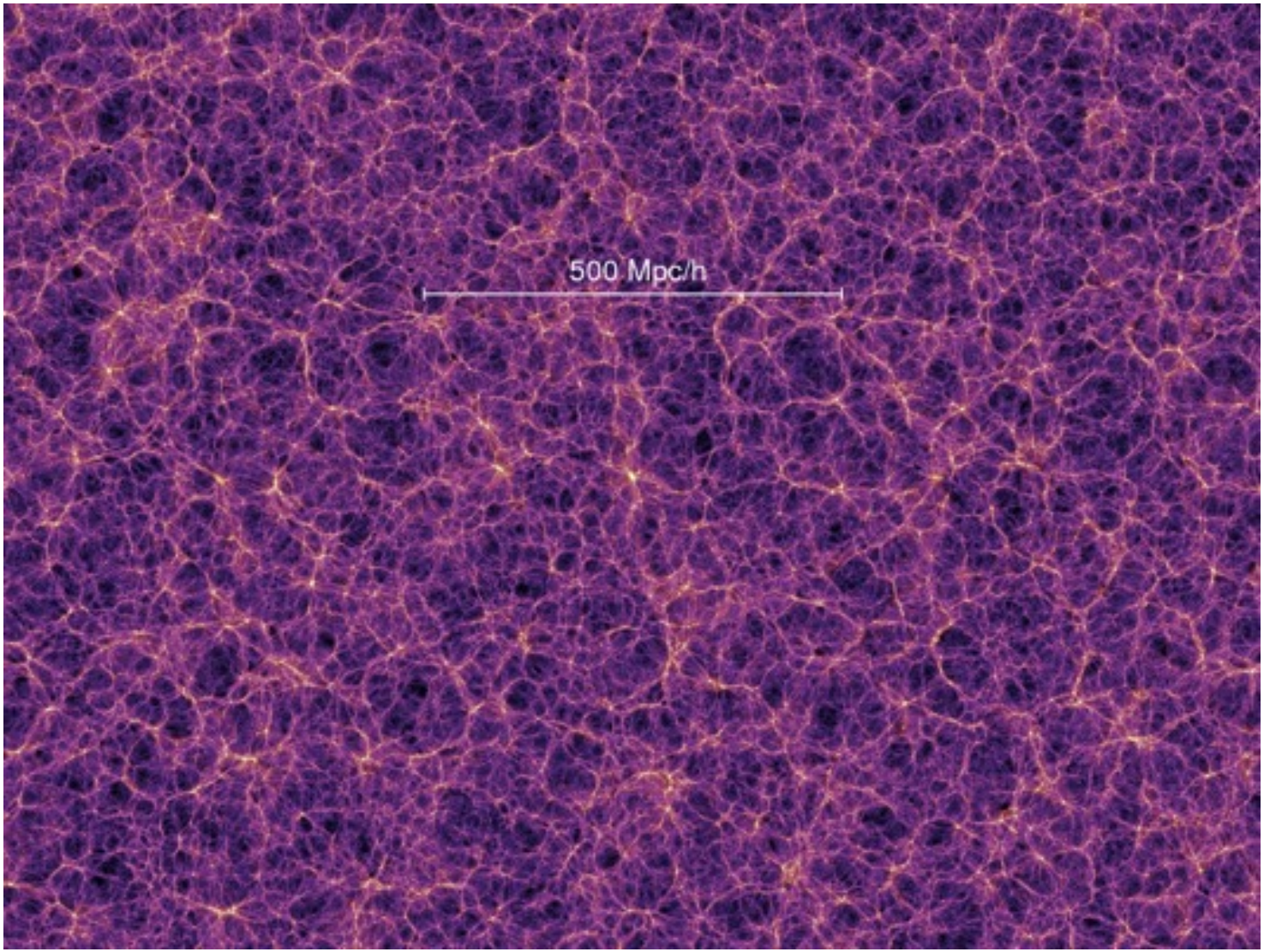
Cosmological principle

= Universe is homogeneous and isotropic



The speed limit and time travel

Nothing travels faster than light => when looking at farther away objects, we are looking farther back in time!

Images from ~3 million years ago…

Navaneeth Unnikrishnan of Kerala, India, created this wonderful stacked image of the Andromeda galaxy with images taken in 2014.

In the beginning...

Expansion of the Universe

The Universe is expanding!

- 1925: Lemaitre finds out about the expansion using Slipher's data.
- 1927: Hubble finds the same, using the Cepheids.

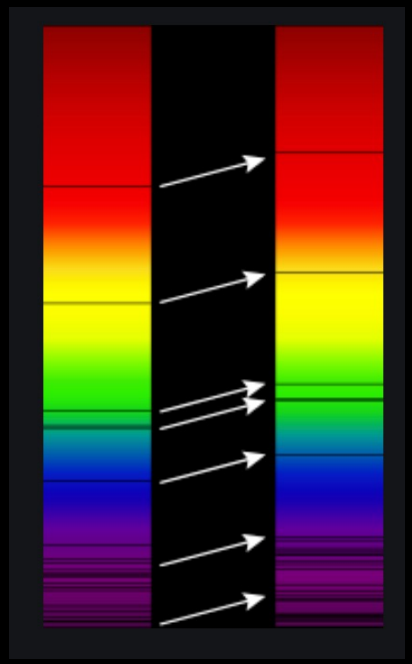
Hubble's Law

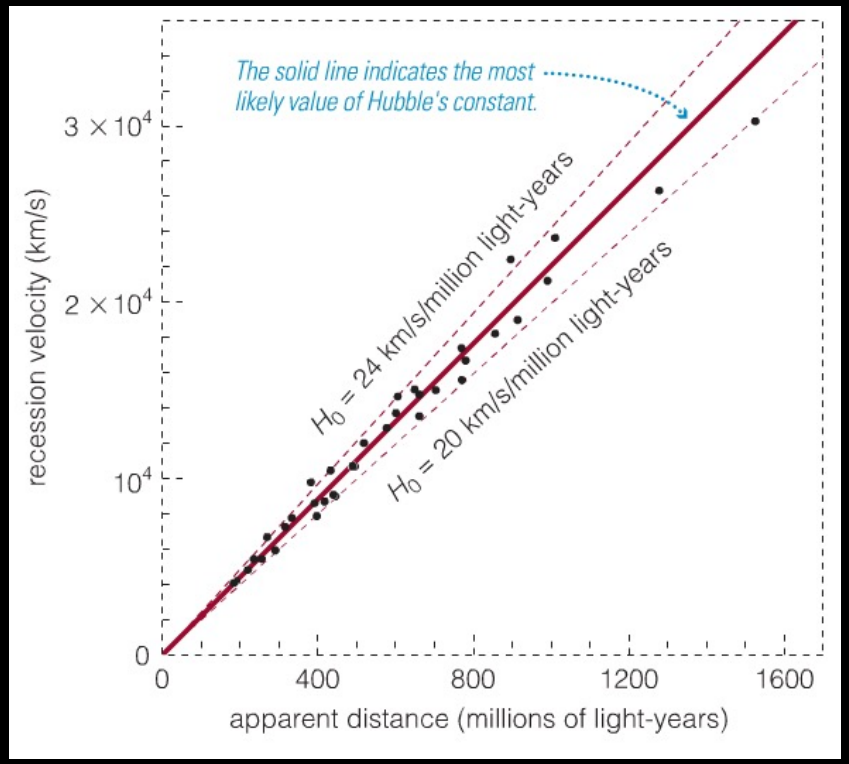
The more distant the galaxy, the higher its redshift, and the faster it is moving away from us:

velocity = H_0 x distance

H_0 = Hubble's constant = 70 km/sec/Mpc

How do you get Hubble's Law from data??



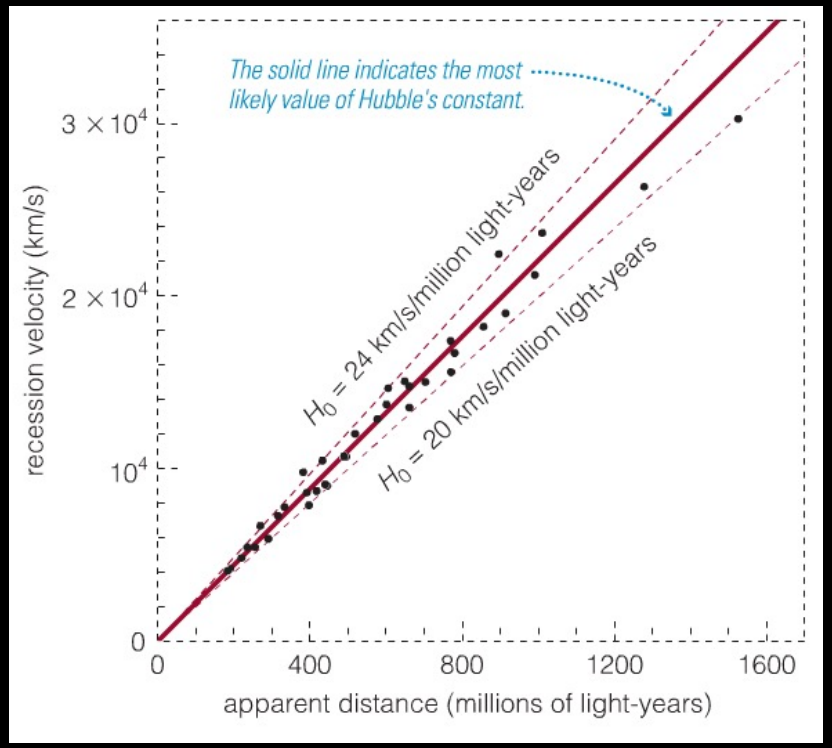


Measuring distances using **Hubble's Law**

- Hubble's observations showed that the more distant the galaxy, the higher its redshift, and the faster it was moving away from us.
- Relationship of velocity and distance to a galaxy:

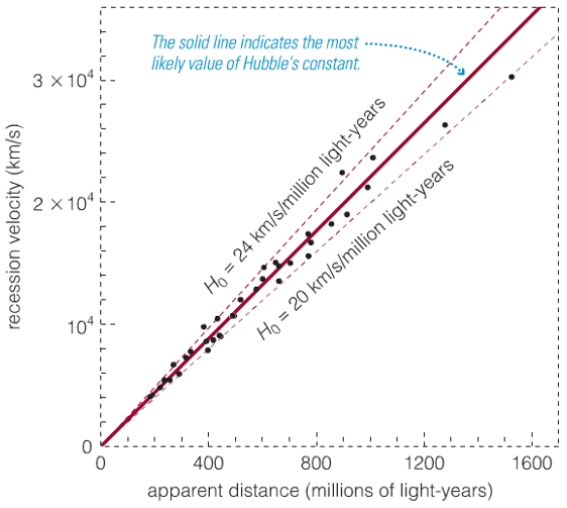
velocity = H_0 x distance

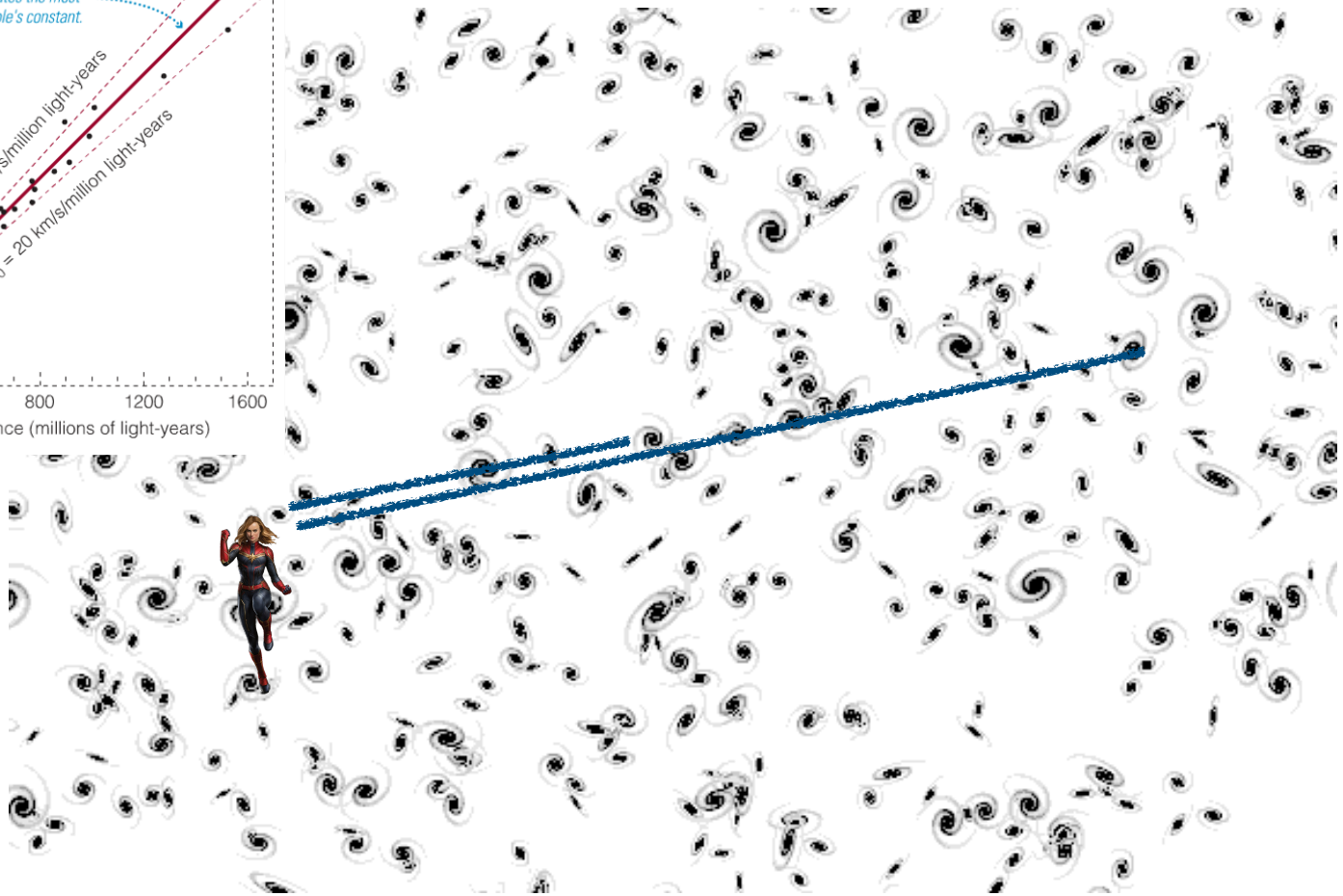
H_0 = Hubble's constant
= 70 km/sec/Mpc



Hubble's Law

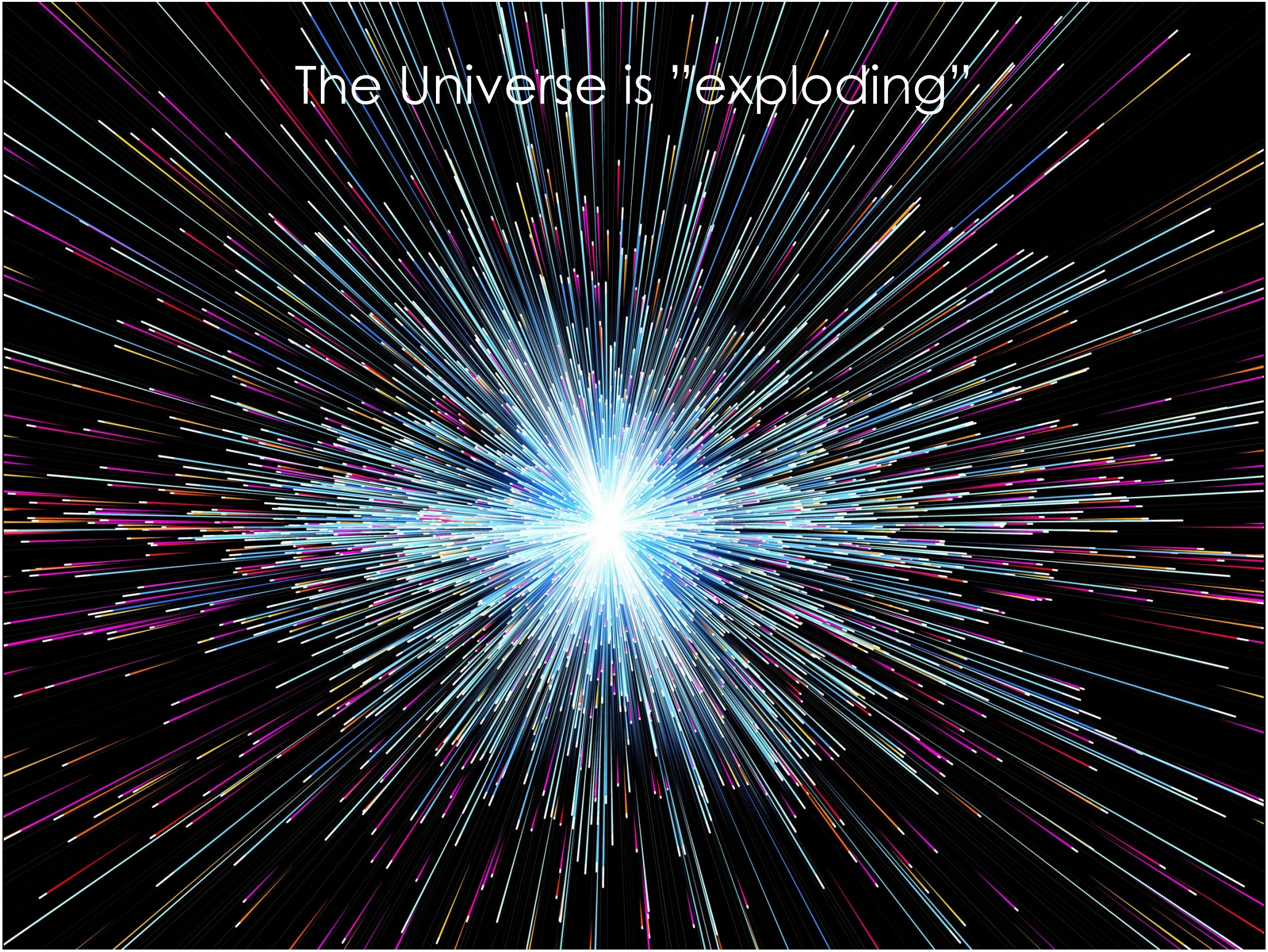
Distant galaxies move away faster, the farther away they are, picking up about 70km/sec for every 3 million light years.





The evolving Universe

Our Universe has no boundary, but it has a beginning: it is about **13.7 billion years old**.


The Universe is ”exploding”

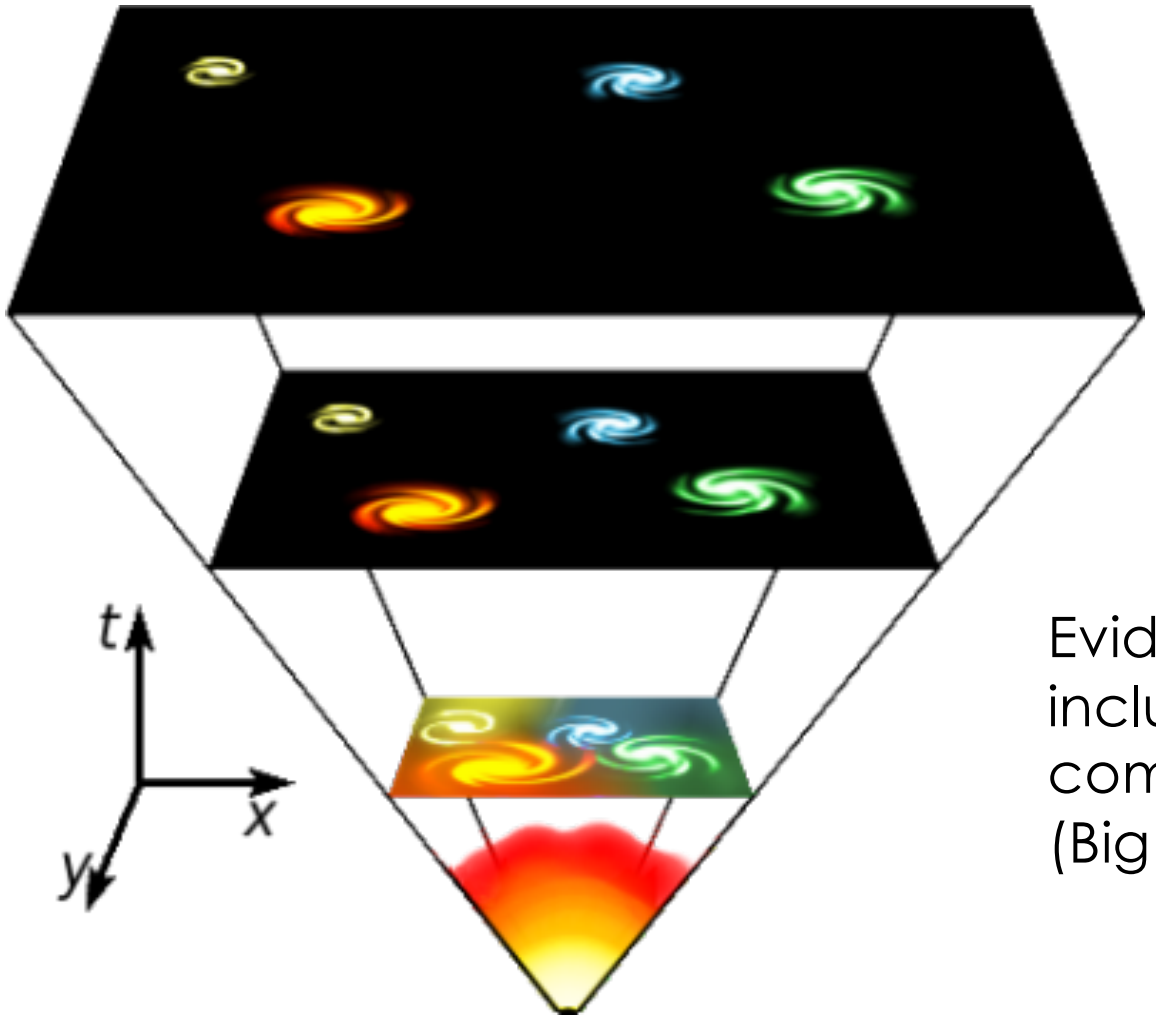
question for you

If the Universe is expanding, how come Andromeda is NOT moving away from us?

A. It's just a random fluke.
B. It's because Andromeda is moving in the opposite direction from the Milky Way, due to the expansion.
C. It's because Milky Way is stationary, so some galaxies are moving towards us.
D. It's because gravitational pull between us and Andromeda is too strong.

The Hot Big Bang

the Universe started smaller than a particle and expanded to 100 billion light years today.



Evidence for a hot Big Bang includes: CMB, expansion, composition of the Universe (Big Bang nucleosynthesis).

question for you

If we observe three different galaxies, which one appears to be moving the fastest?

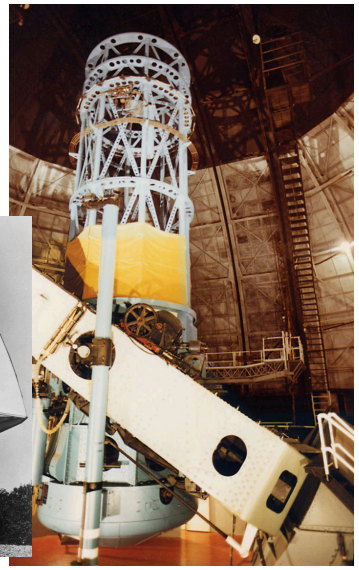
A. Galaxy A 1 billion light years away
B. Galaxy B 2 billion light years away
C. Galaxy C 3 billion light years away
D. All of them appear to move the same speed

The evolving universe

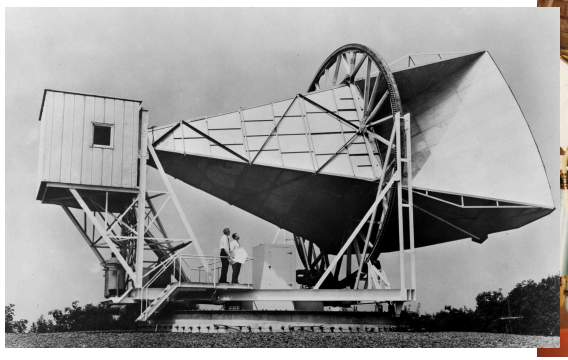
1) 1920's, Lemaitre and Hubble:

The Universe is expanding!

100", Mt Wilson



Bell Labs, NJ



2) 1960's, Penzias and Wilson:

The Universe was hot+dense!

3) 1990's, Reiss, Schmidt, Perlmutter, et al:

The Universe is accelerating!

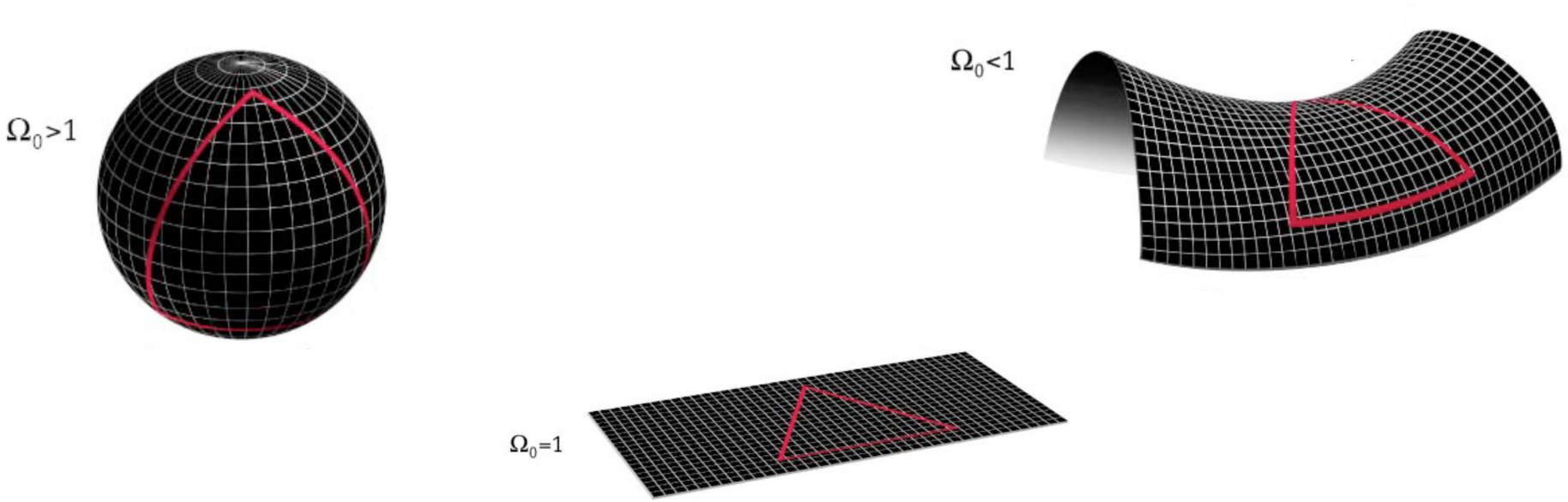
CTIO, Chile

The Density and Geometry of the Universe

- **General relativity: expansion (H0) and shape of the Universe depend on its density and what it is made of.**
- Density of matter needed to reverse the expansion of a Universe filled with only matter is called **critical density**.
- Critical density of universe is **10^{-29} grams per cubic centimeter** (less than 1 proton per cubic m).

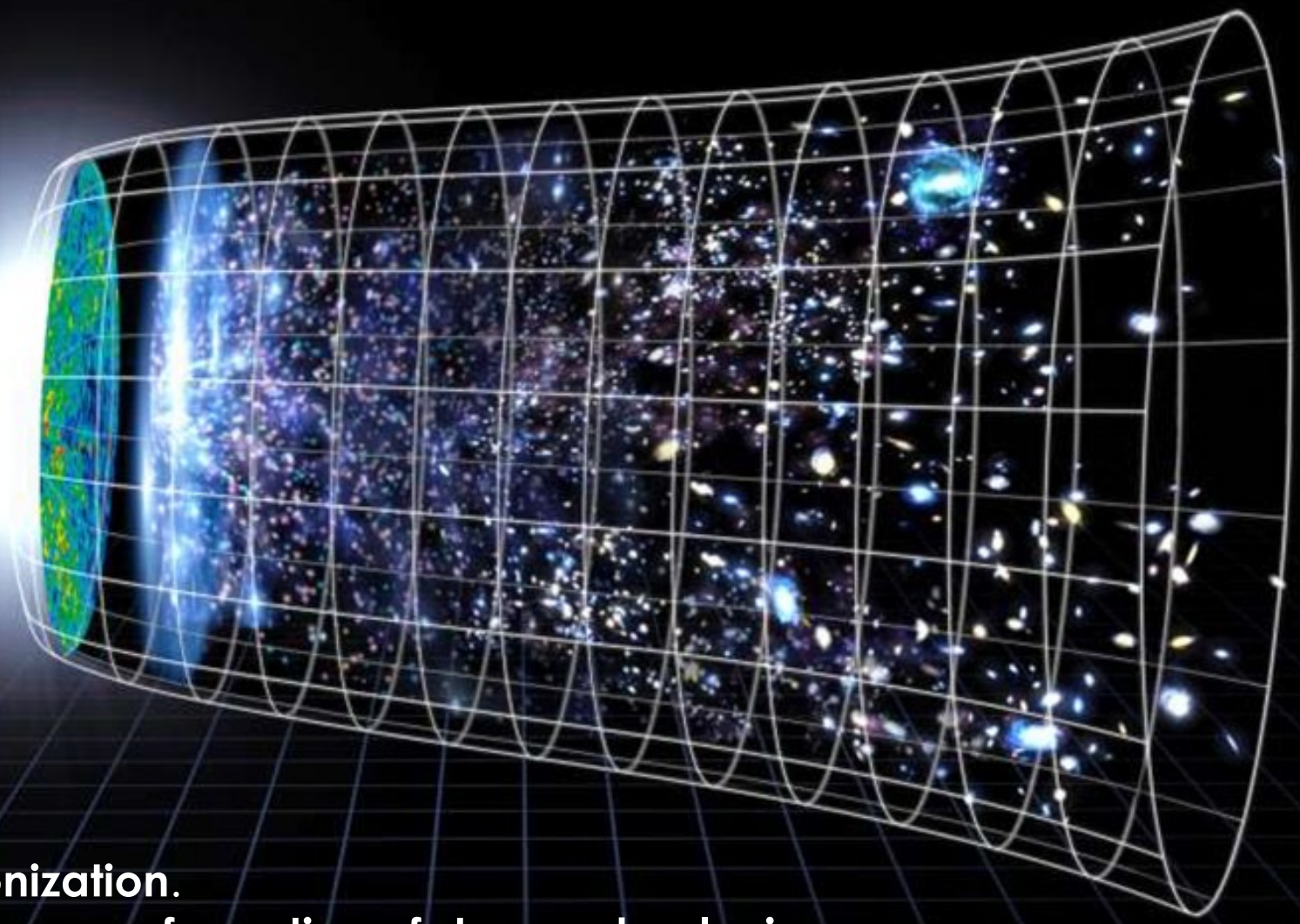
Density and geometry of the Universe are related.

- **Closed Universe:** density exceeds critical density, all paths eventually meet.
- **Open Universe:** density is less than the critical density, all paths grow apart.
- **Flat Universe:** density is exactly the same as critical, parallel lines do not intersect. This is the kind of Universe we live in.



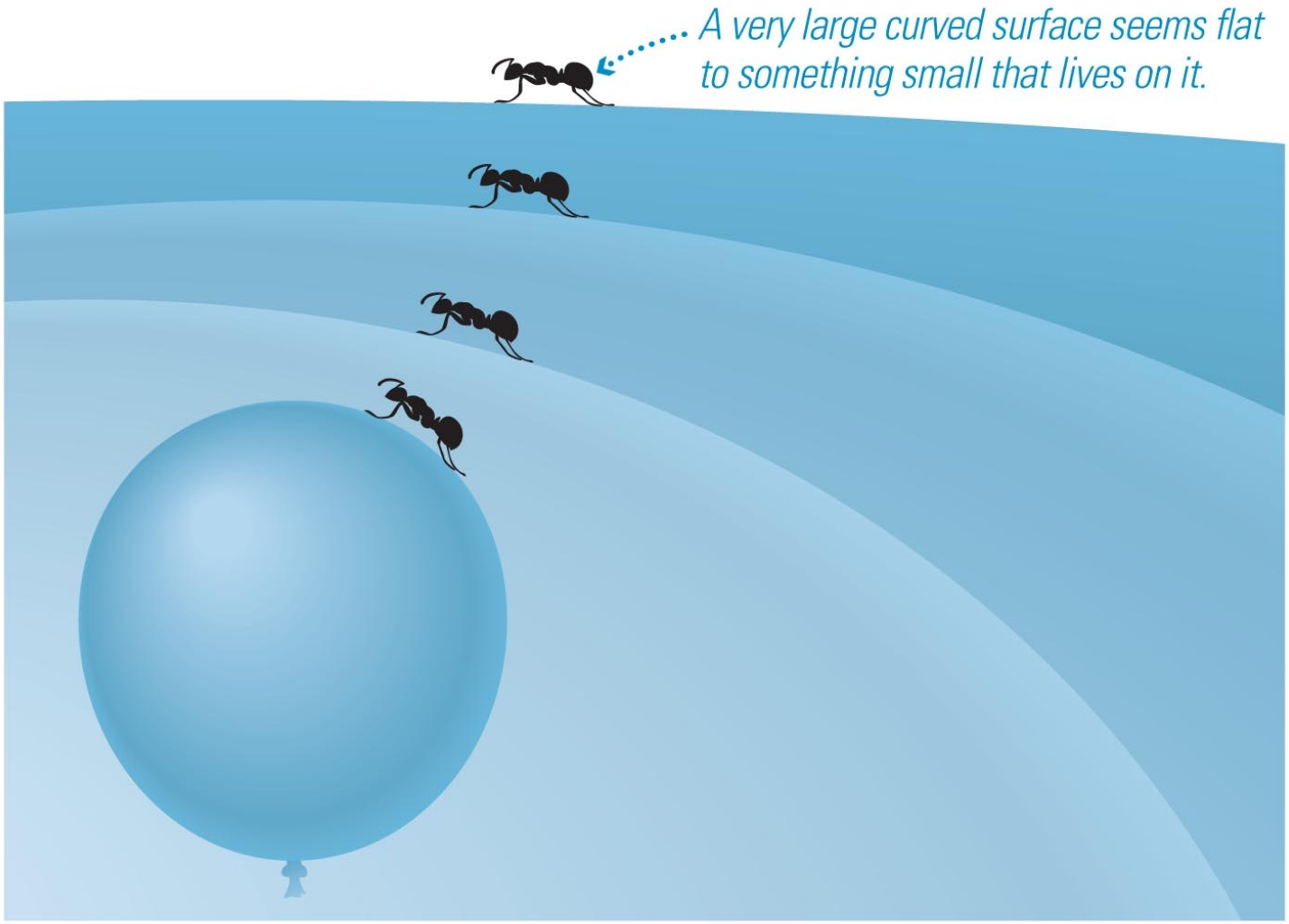
Evolution of the Universe

History of the Universe



- ✓ Later: **Reionization**.
- ✓ @0.5 billion years: **formation of stars and galaxies**.
- ✓ @400,000 years: **Recombination**.
- ✓ First few mins: **nucleosynthesis**.
- ✓ First fraction of a second: **cosmic inflation.**

@ the first fraction of a second after the Big Bang:
Cosmic Inflation makes the Universe flat by inflating it,
and seeds structure from quantum fluctuations**.**



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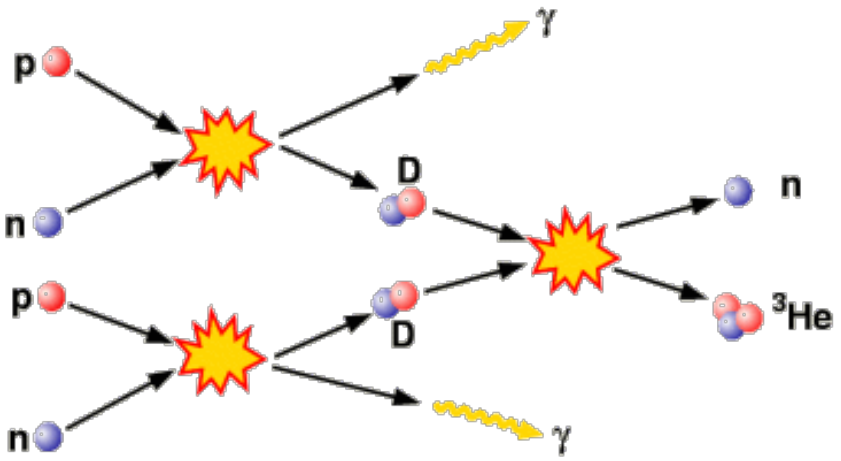
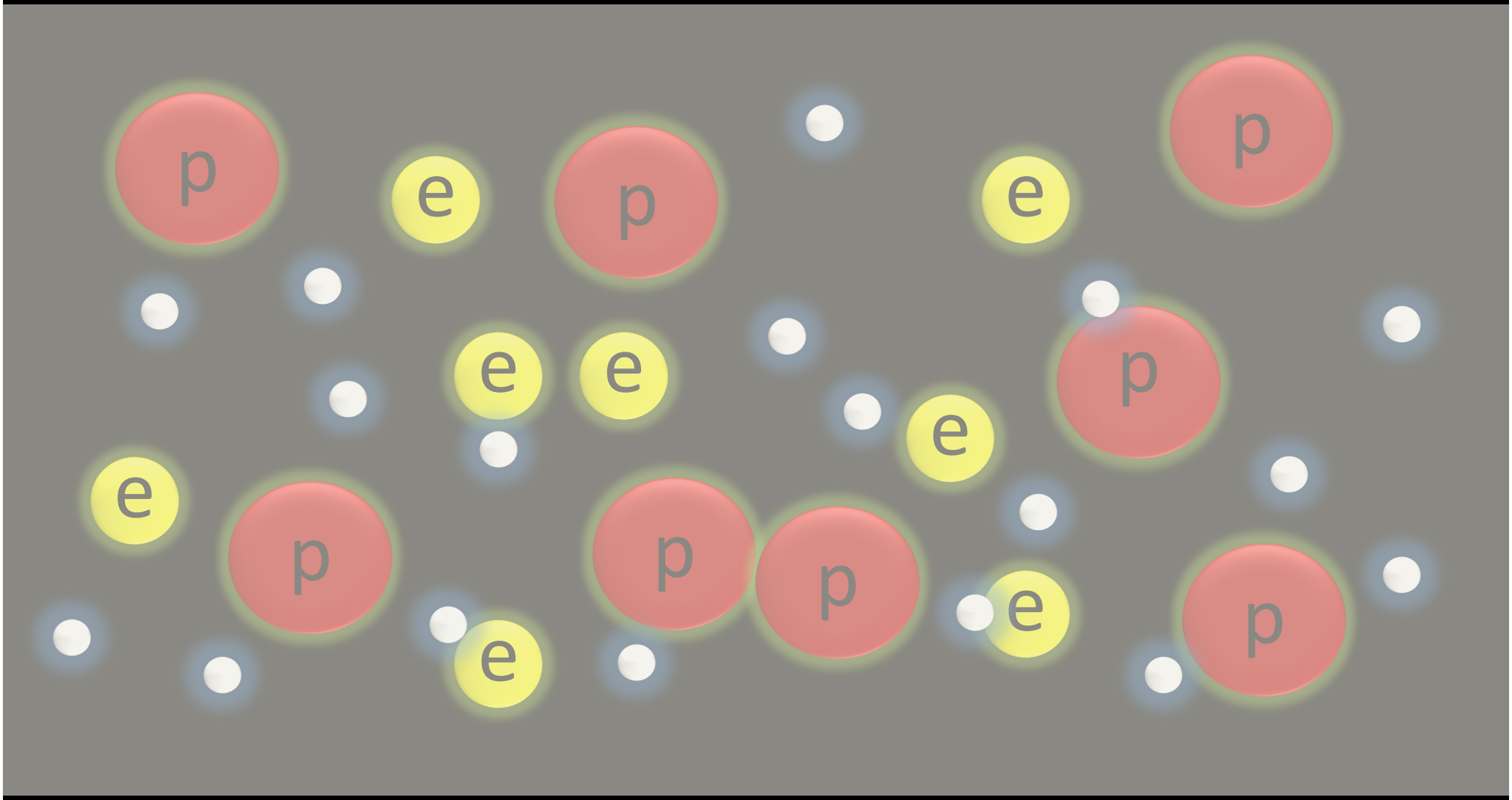
@ the first few minutes after the Big Bang:
Big Bang Nucleosynthesis

- Started 0.001 s after the Big Bang.
- **After a few minutes**, fusion has ceased:
  - Temperature was 10^9 degrees.
  - 75% of matter was now hydrogen, and 25% helium.
- Everywhere we look in the Universe, we see this composition, as evidence that the Big Bang nucleosynthesis occurred as predicted by theory.

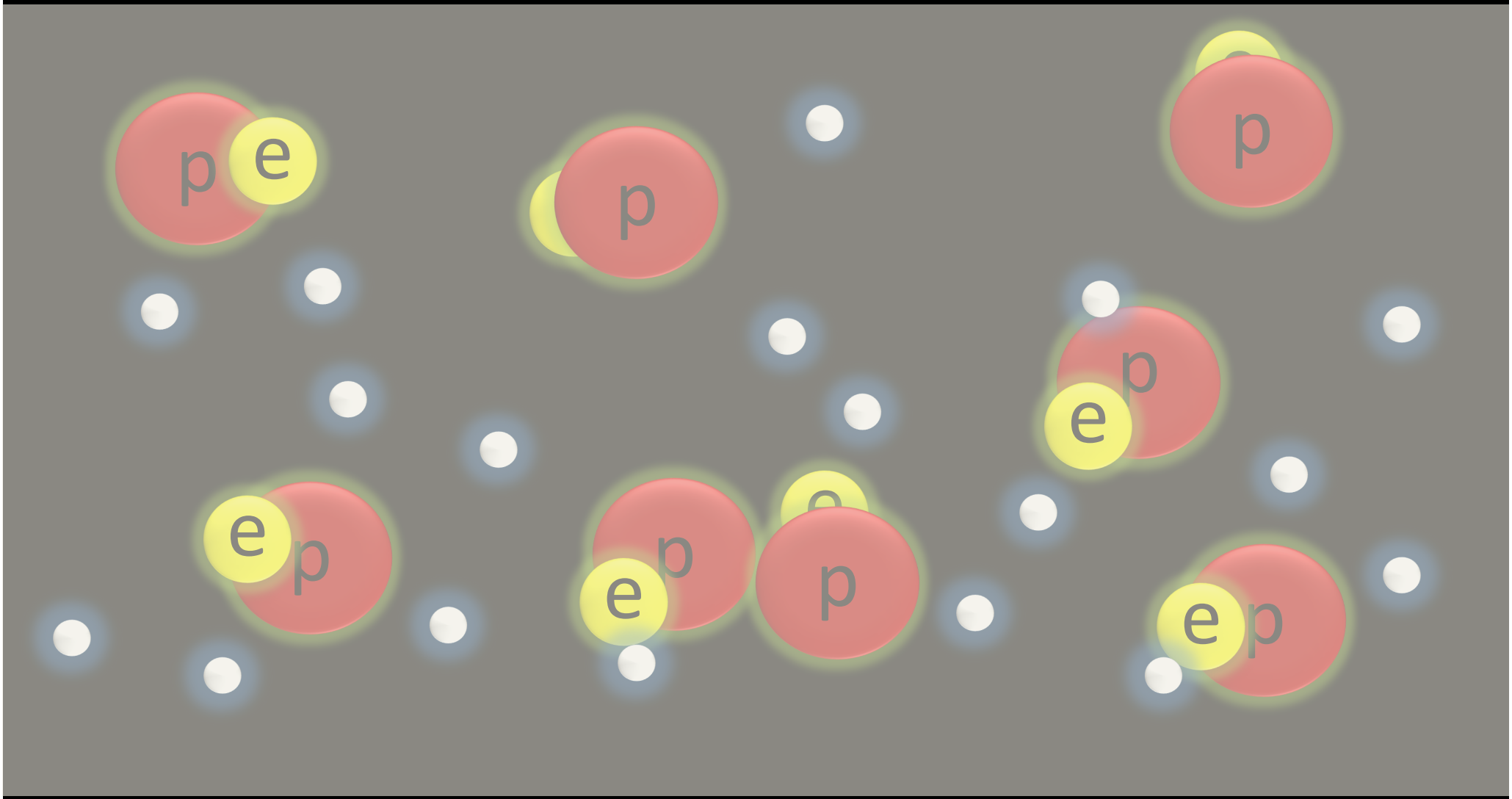


@ 400 000 years after the Big Bang…



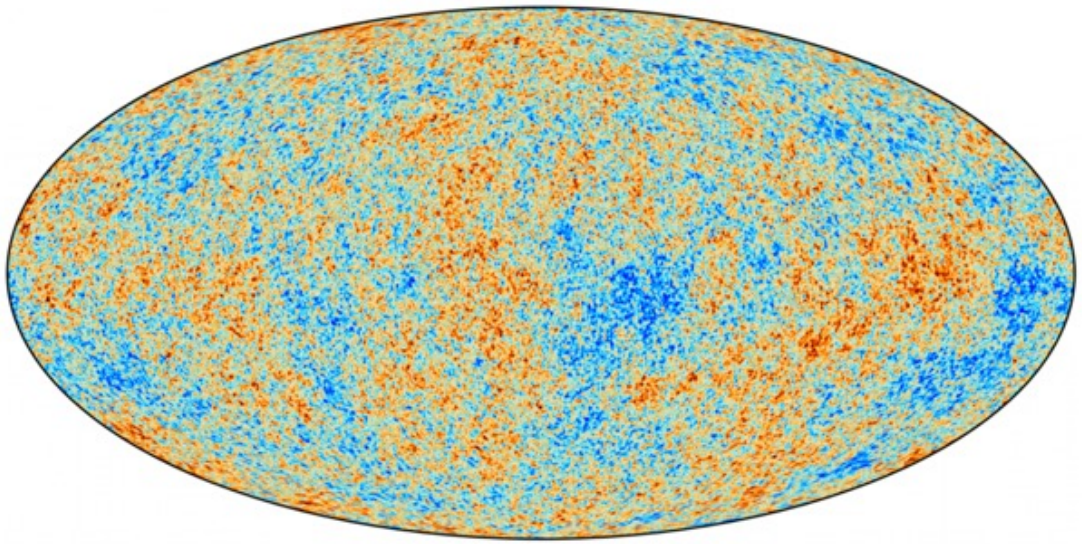
"soup" of particles+ radiation @ 3000 degrees

Cosmic Recombination

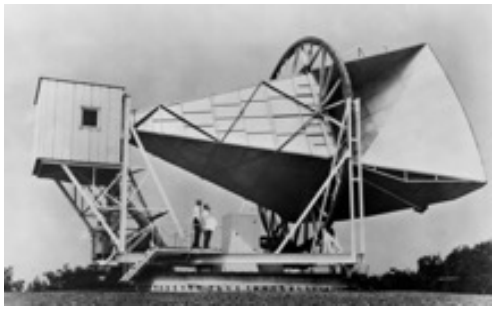


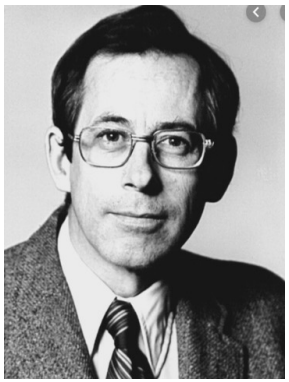
Cosmic Microwave Background Radiation (CMB)

- Heat from the Big Bang, now @ 2.73 K (predicted by Peebles).
- CMB streamed since cosmic recombination and is now stretched to radio frequencies, due to the expansion of the Universe.
- It is extremely uniform, with variations no bigger than 1 part in 100 000.

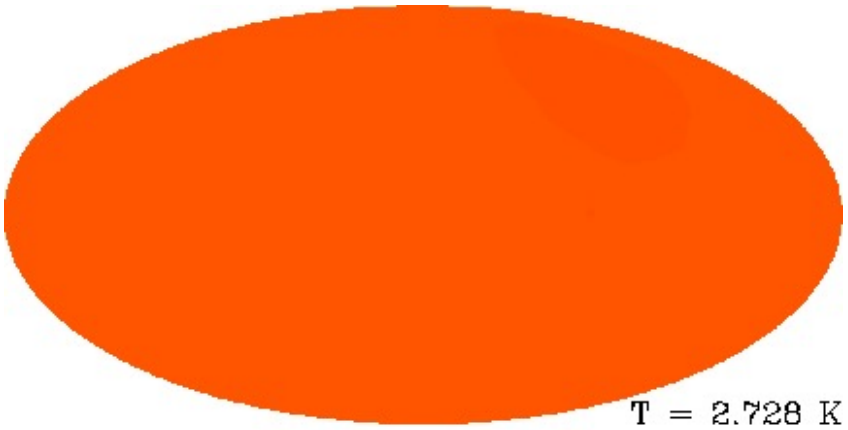


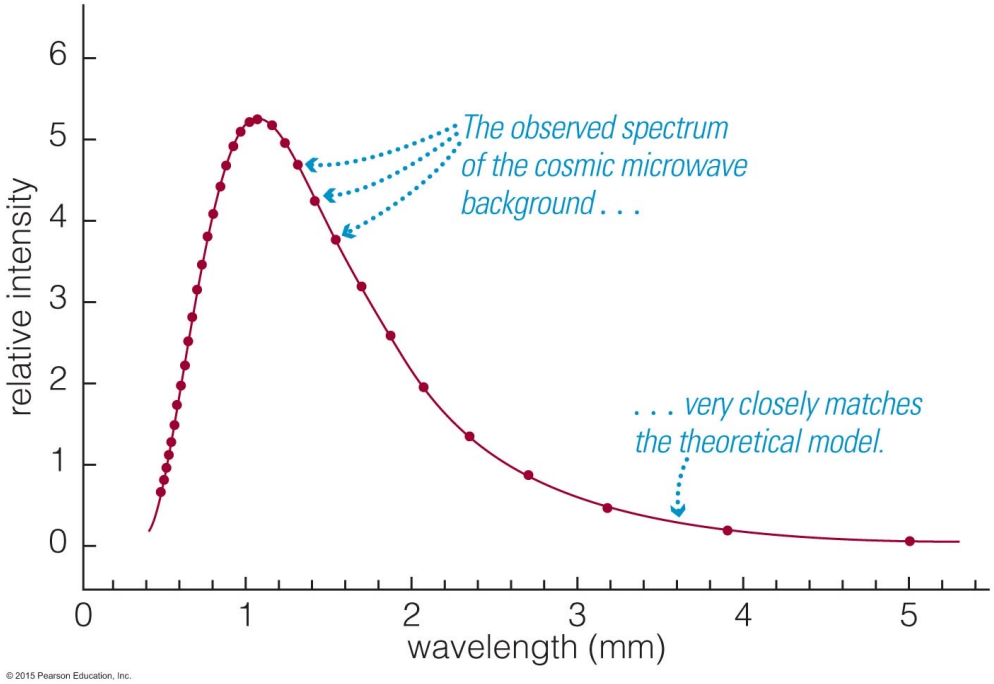
Map of the CMB from the Planck satellite.





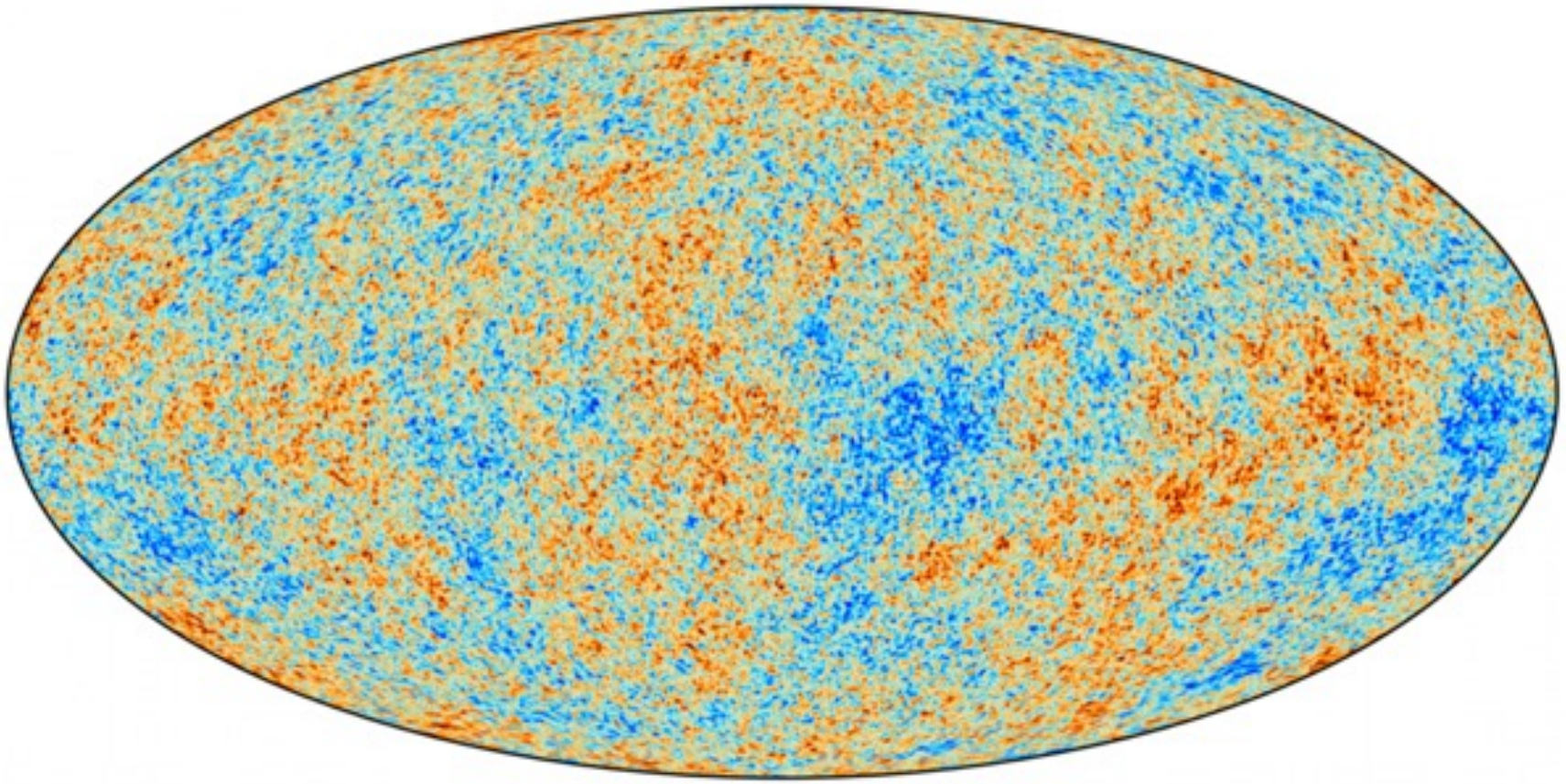
Cosmic Microwave Background Radiation (CMB)





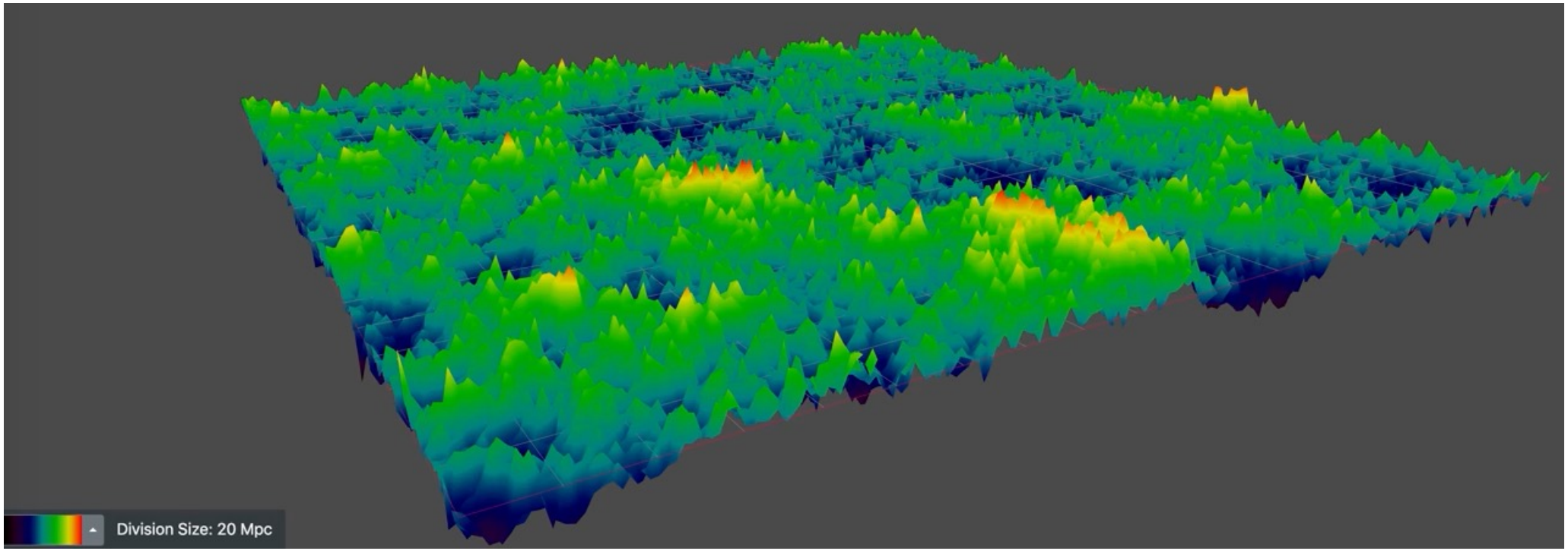
CMB is almost perfectly uniform across the sky (to within 1 part in 100,000), and has a **blackbody spectrum**, whose temperature is **2.73 K**. The CMB is heat left over from the Big Bang.

Cosmic Microwave Background Radiation (CMB): you can see the first seeds of structure!



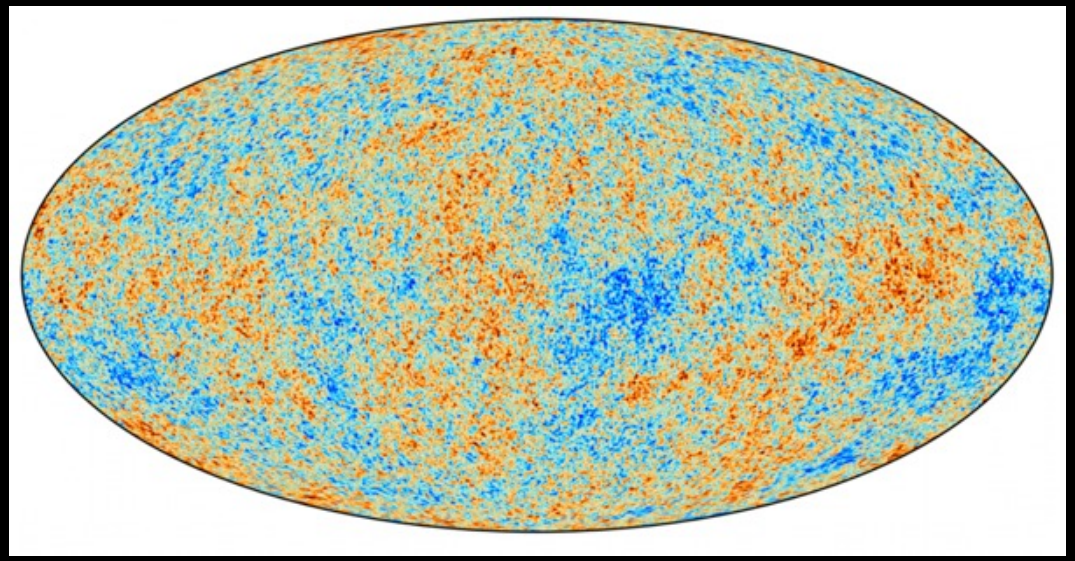
Map of the sky from the Planck satellite shows the CMB, the leftover heat from the Big Bang.

Acoustic oscillations (waves) in early universe



@380 000 years after the Big Bang:
Recombination occurs and **Cosmic Dark Ages** begin

CMB temperature fluctuations carry information about the age, composition, expansion history, and physics that governs particles in the Universe.



Cosmic history

- ✓ Later: **Reionization**.
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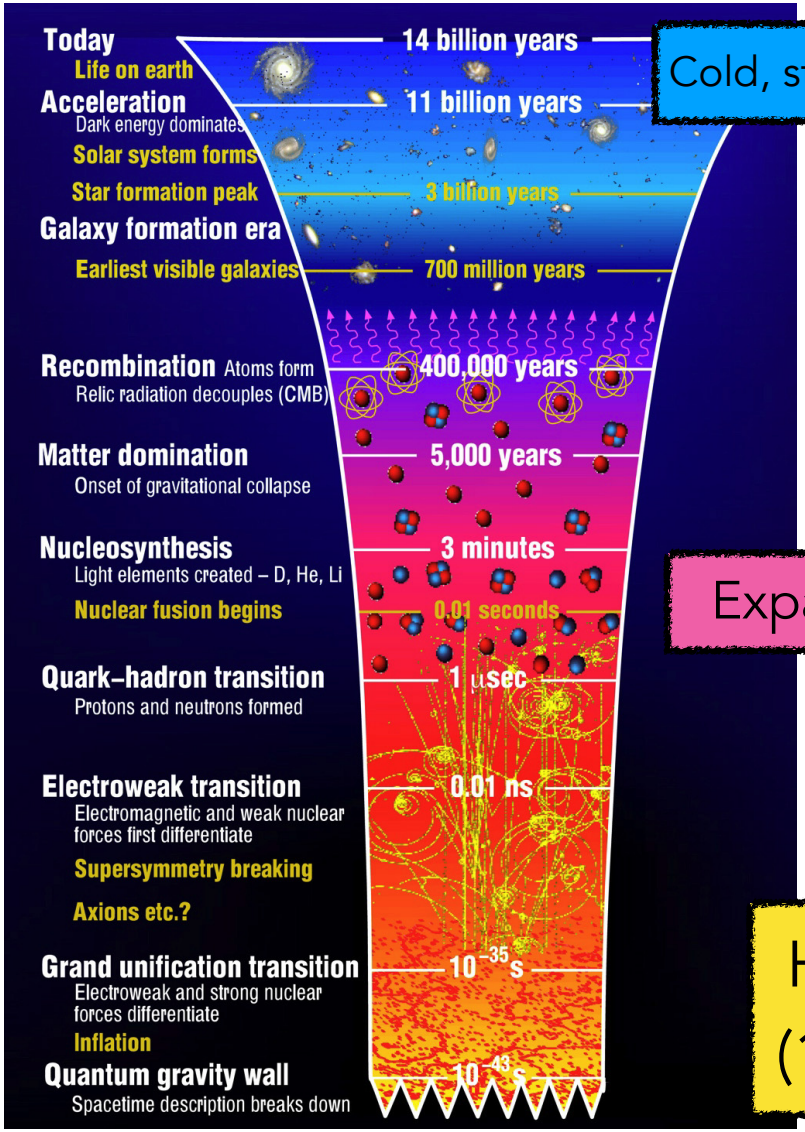


Cold, structured, accelerating

Expanding + cooling

Hot Big Bang
(13.7 Gyr ago)

http://www.ctc.cam.ac.uk/outreach/origins/big_bang_three.php

The Illustris simulation of galaxy formation

@0.5 billion years after the Big Bang:
The era of stars begins and **reionization** occurs

- From the small clumps of matter, over half a billion years, through gravitational collapse and mergers, galaxies form.
- The first stars begin to turn on in young galaxies.
- The photons from the stars eventually **reionize** the intergalactic medium.

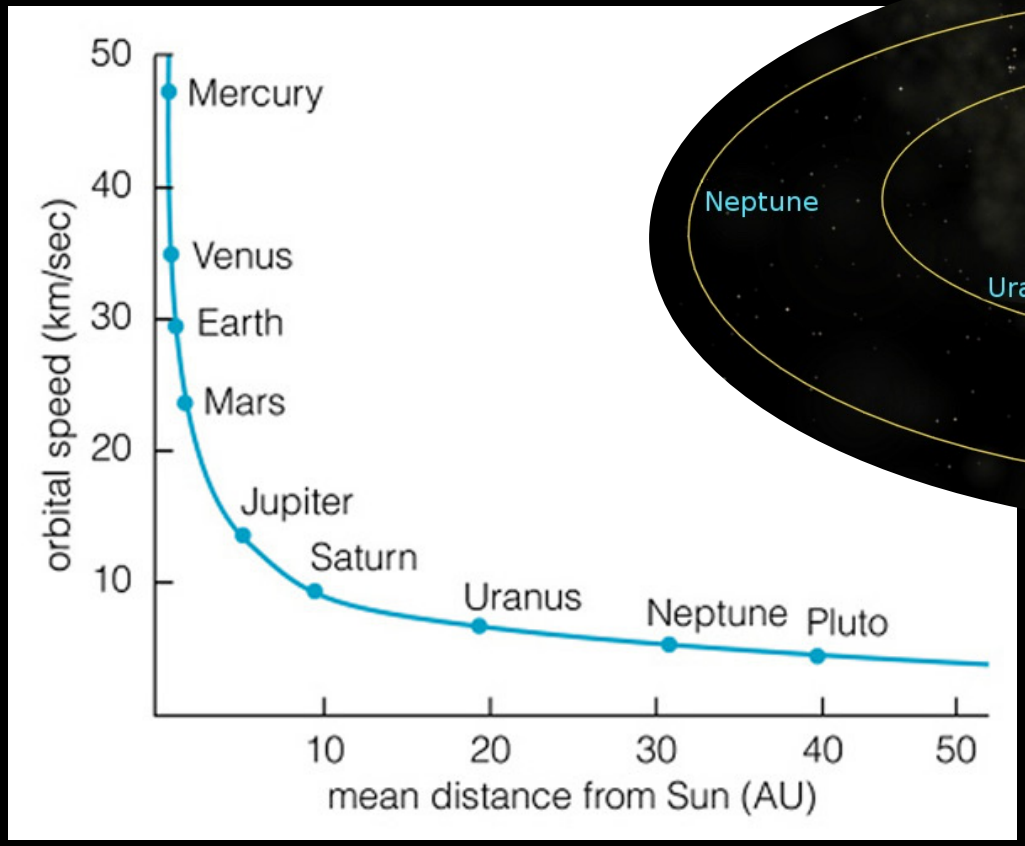
Dark matter

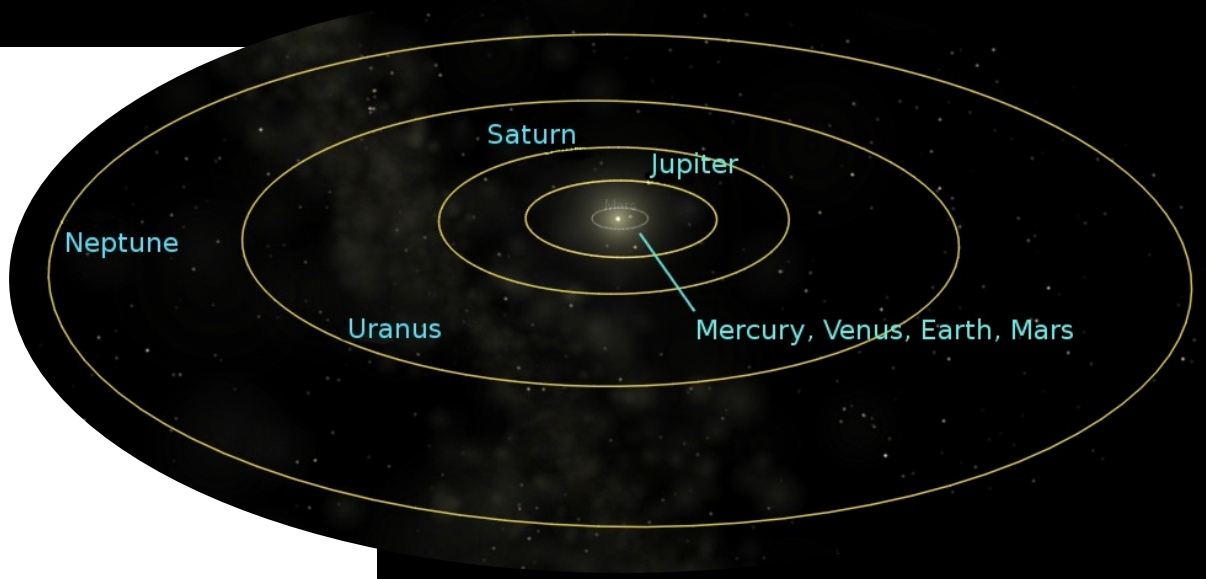
How do we know?

- Overall, 85% of matter in the universe is **dark matter**.
- 1970's: Vera Rubin: In most galaxies, a **dark matter halo** extends far out, beyond where stars are, and outweighs the galactic disk by a factor of 10.

Example #1:

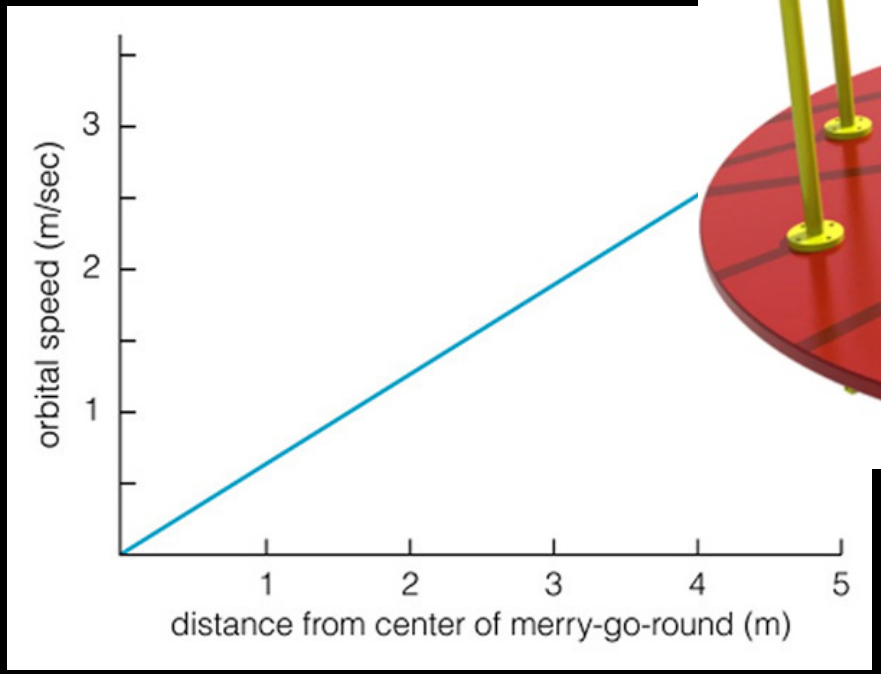
- In the Solar System, planets closest to the Sun orbit much faster, because the mass of the Solar System is concentrated at the center.

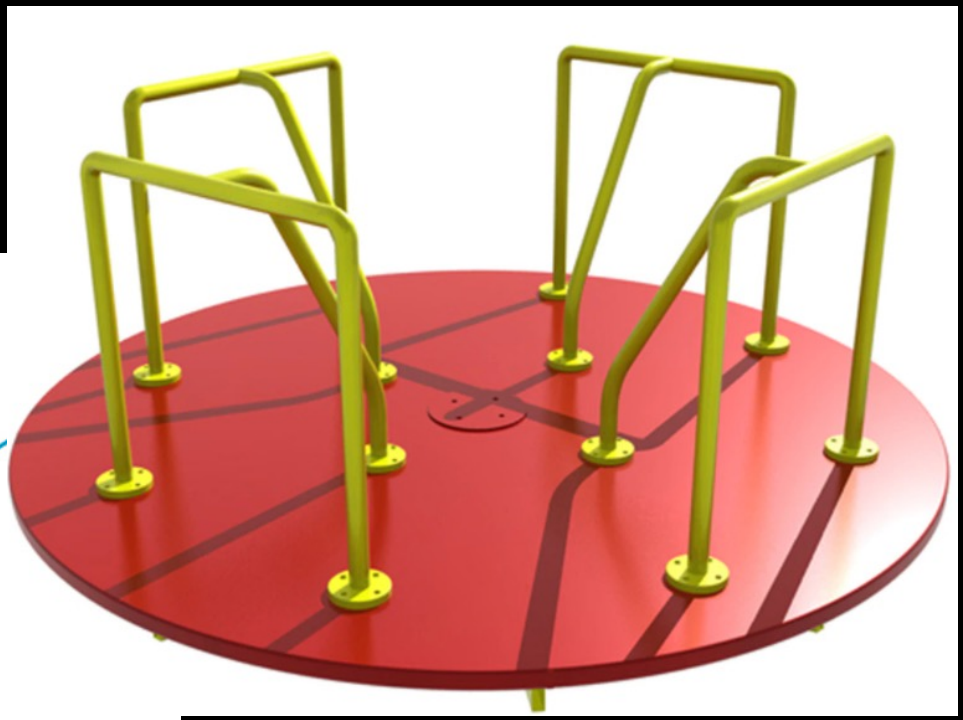




Example #2:

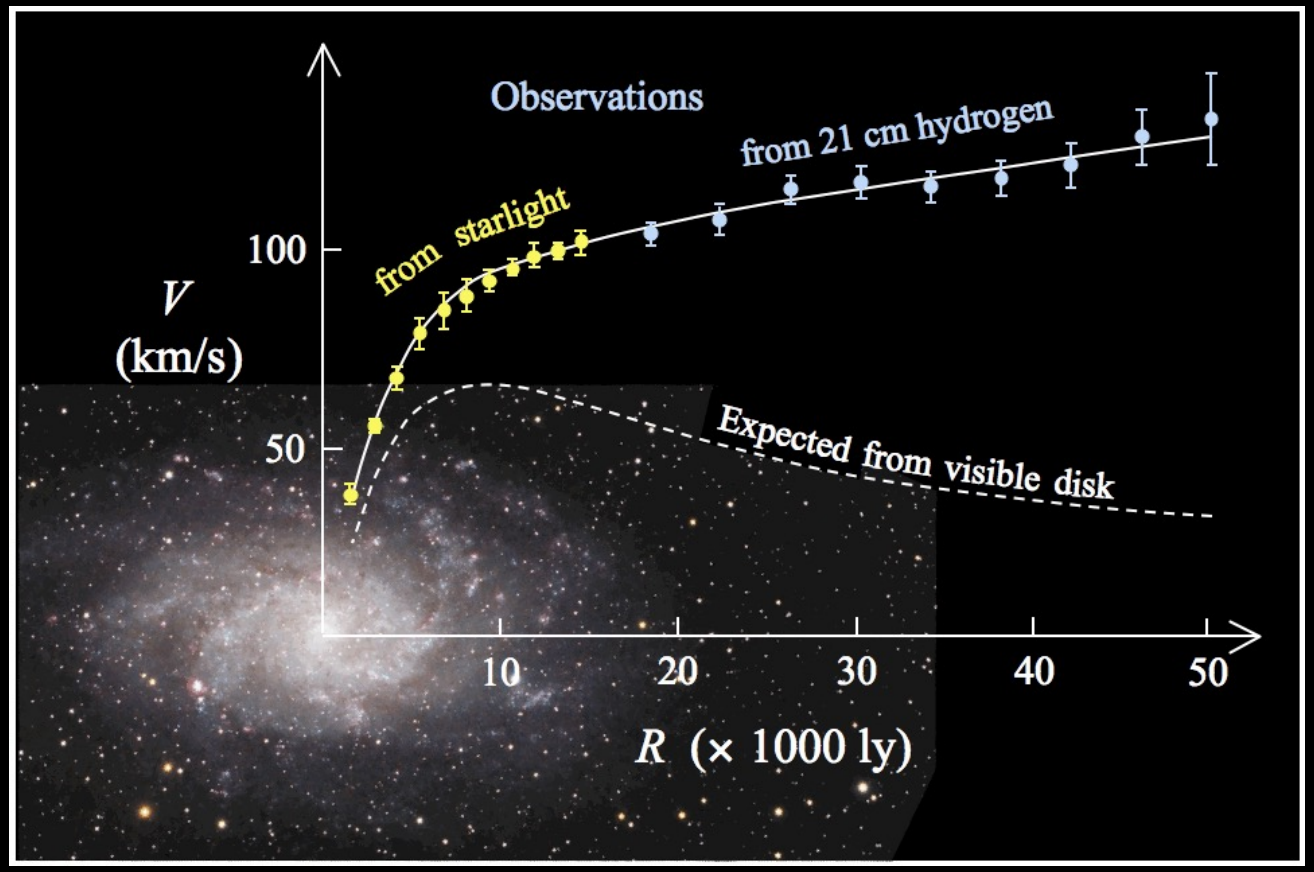
- In a merry-go-round, objects near the outer edge travel at higher speeds than objects near the center.





Galaxies spin too fast!

1970's: Vera Rubin: Most galaxies have **flat rotation curve => halos of galaxies are mostly made of dark matter.**



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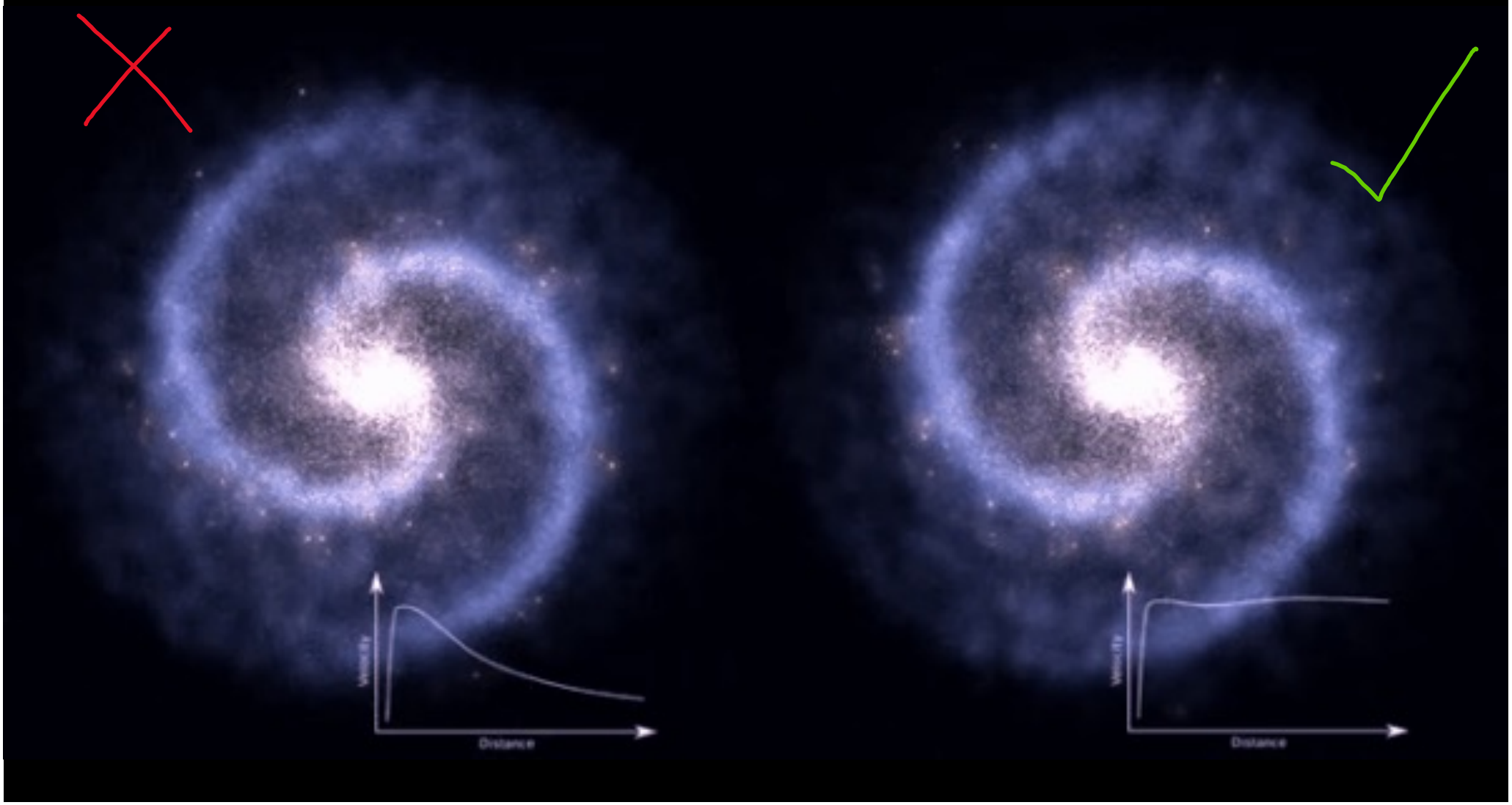
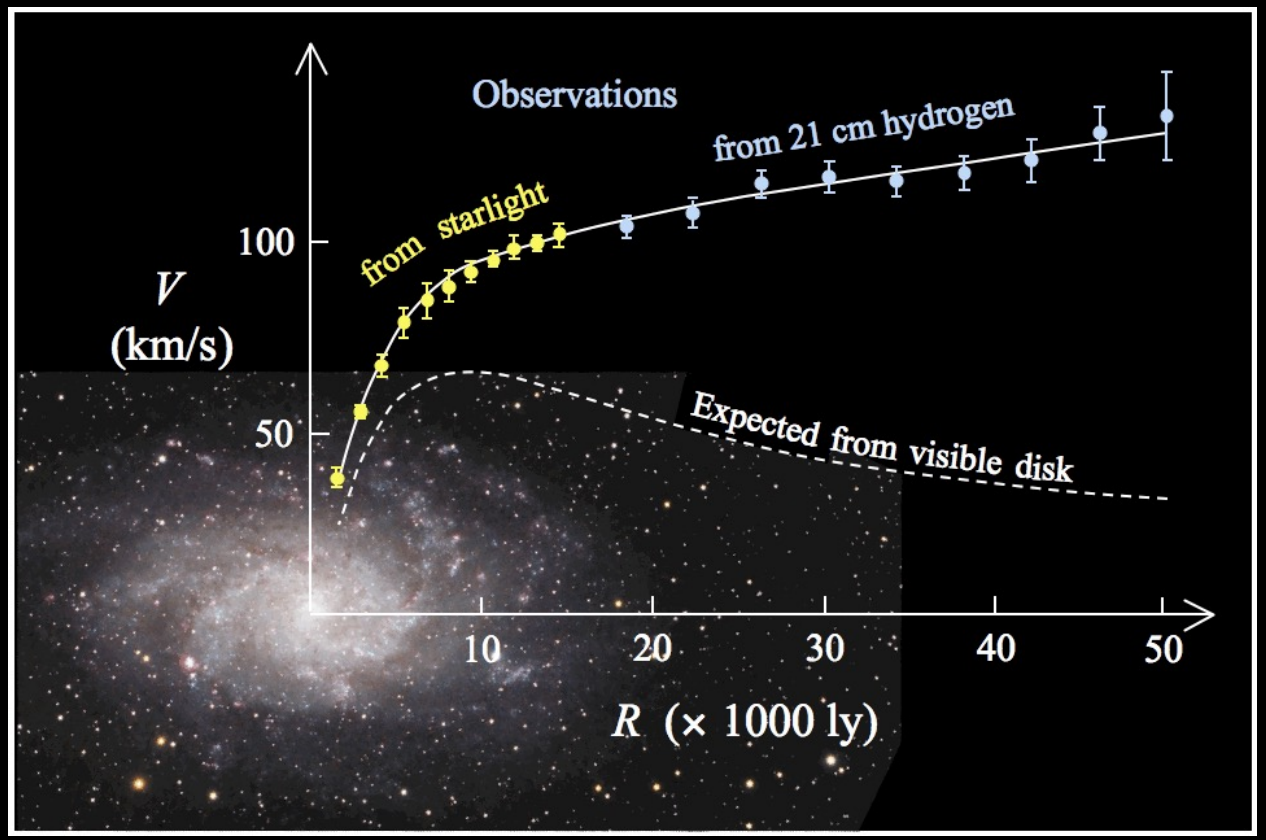
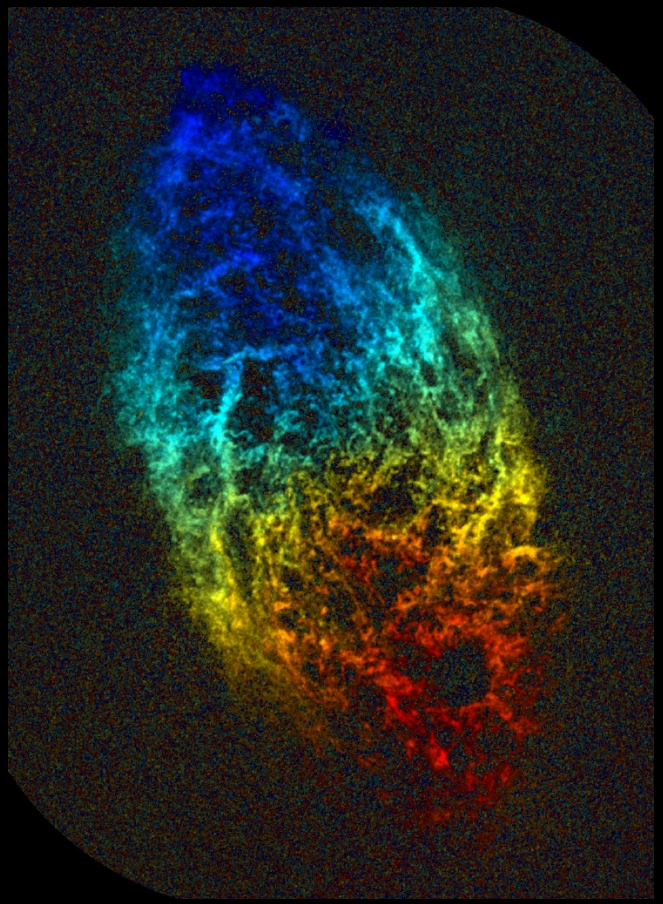


Measuring galactic rotation curves

A Doppler shift "map" of the 21cm line of hydrogen in the Triangulum Galaxy (M33) leads to its rotation curve.





question for you

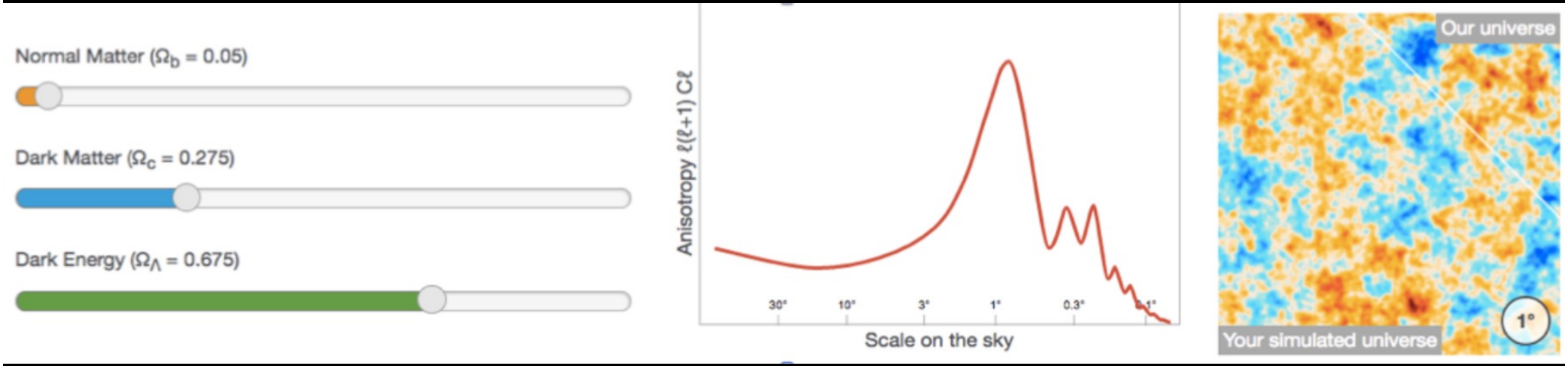
Do you believe that there is dark matter?

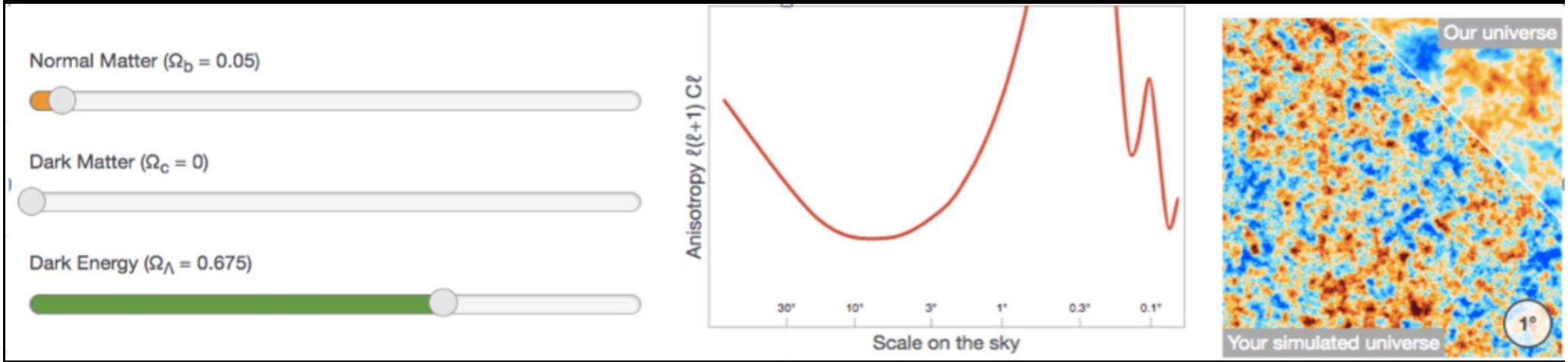
Evidence 2: Gravitational lensing

Most of the mass of galaxy clusters is NOT always where most of the stars and gas are… like in the Bullet Cluster below. Blue=where dark matter is, and pink=x-ray emission from hot gas.

Evidence 3: CMB

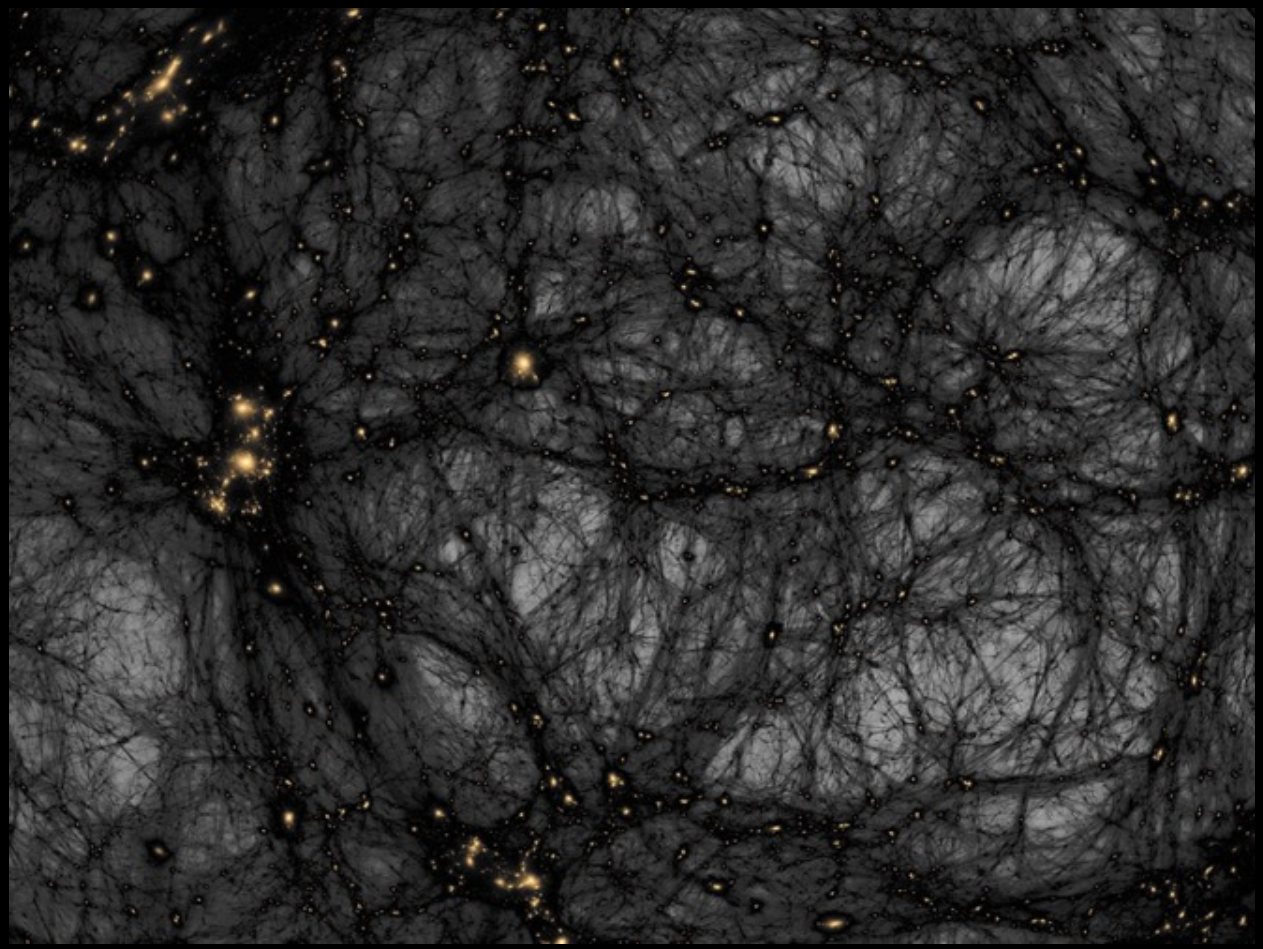
Without dark matter, the pitch, the amplitude, and the color of the CMB would be totally wrong!





Evidence 4: Large scale structure

Without dark matter, there would be no structure as we know it. It holds together the scaffolding of the Universe.



question for you

What about now?

Dark matter: what do we know?

It's not a lot of things
(~~hot~~, ~~interacting much~~, ~~decaying much,~~…)

It could be a lot of things
(WIMPs, WIMP-likes, axions, sterile neutrinos,...)

How does it interact?

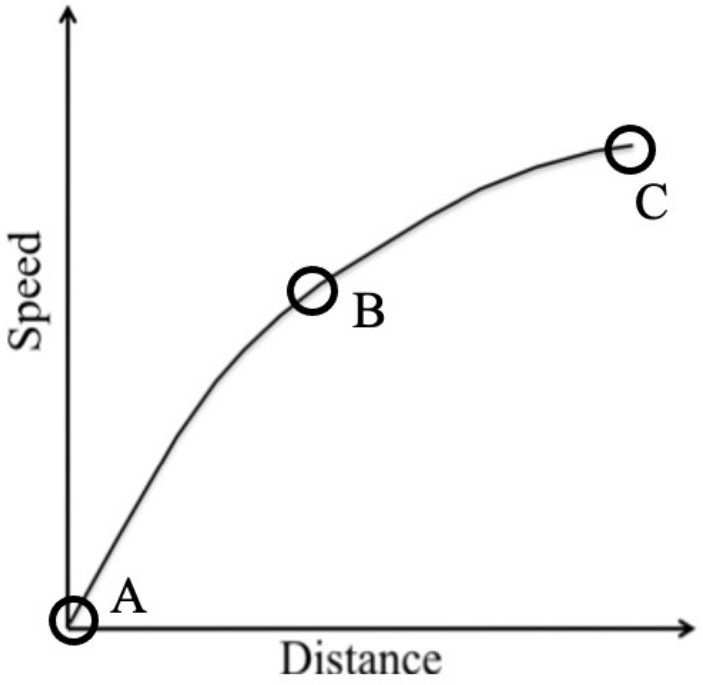
question for you

C 1. Which point on the graph, A, B or C, corresponds with a time when the universe was younger?

A 2. Which point on the graph, A, B, or C, corresponds with the fastest expansion rate?

3. The universe represented by this graph is:

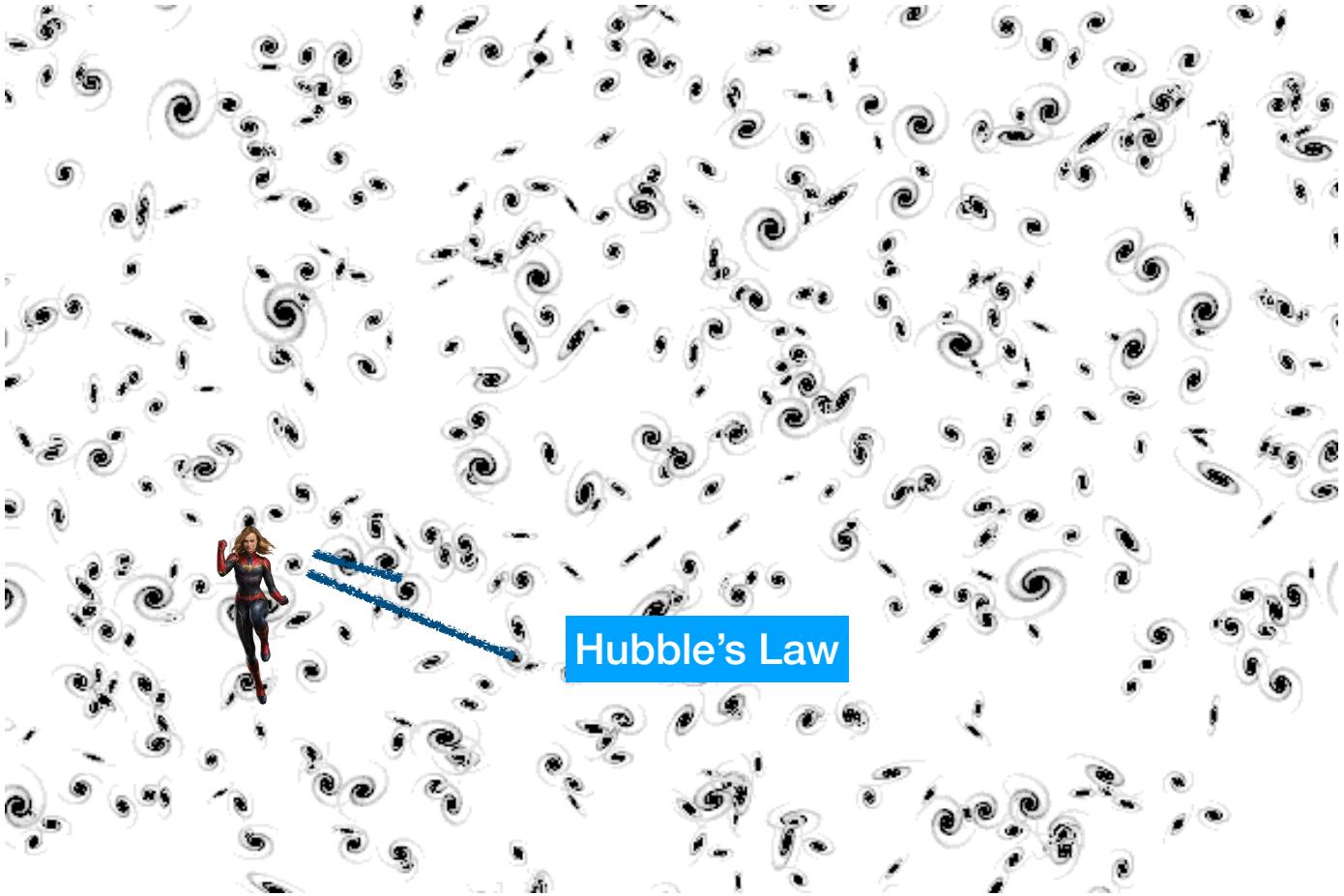
A. accelerating
B. decelerating
C. expanding at a constant rate
D. not expanding



Dark energy

The Universe is also accelerating!

1990s: Reiss and Perlmutter:
observations of Type Ia Supernovae



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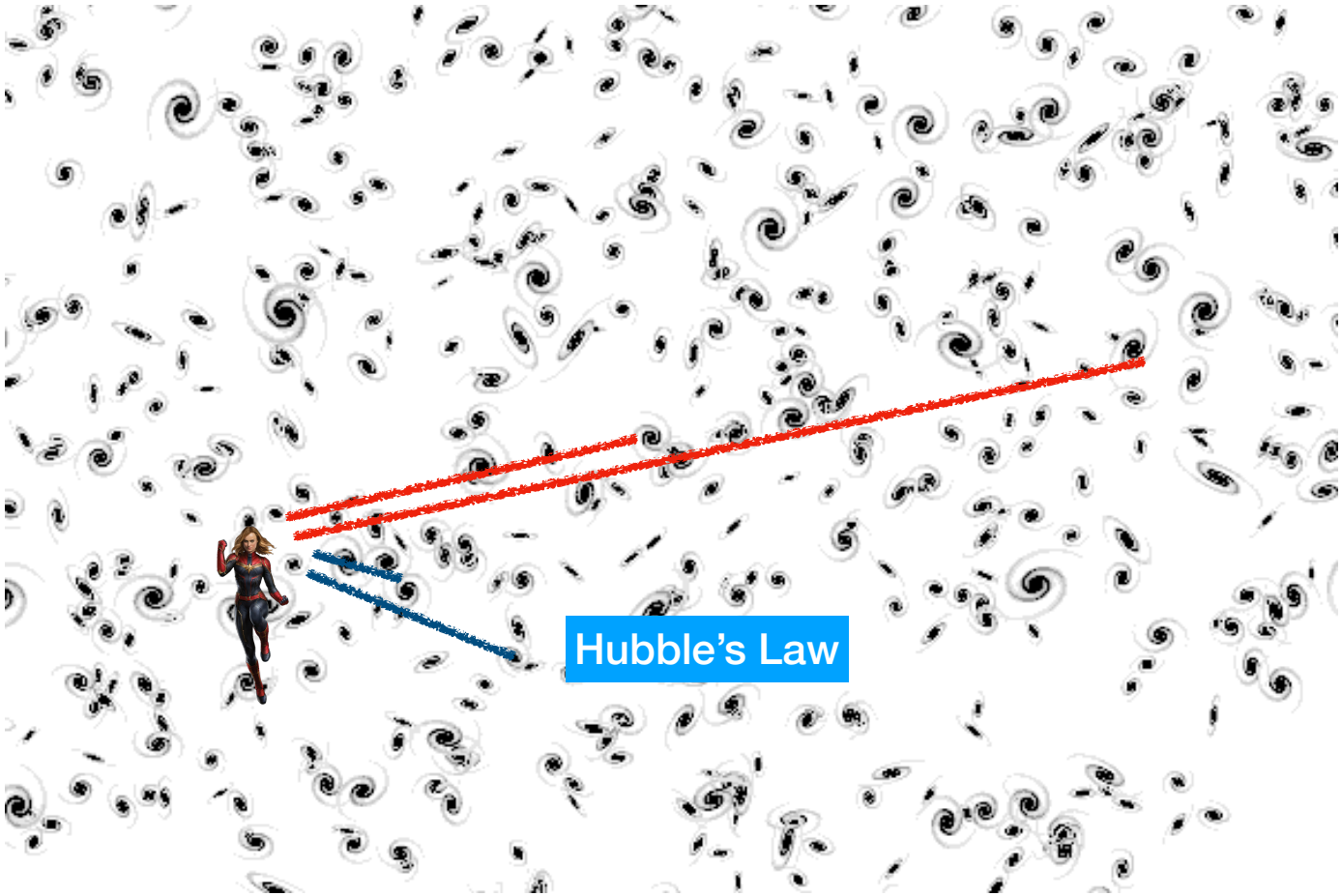
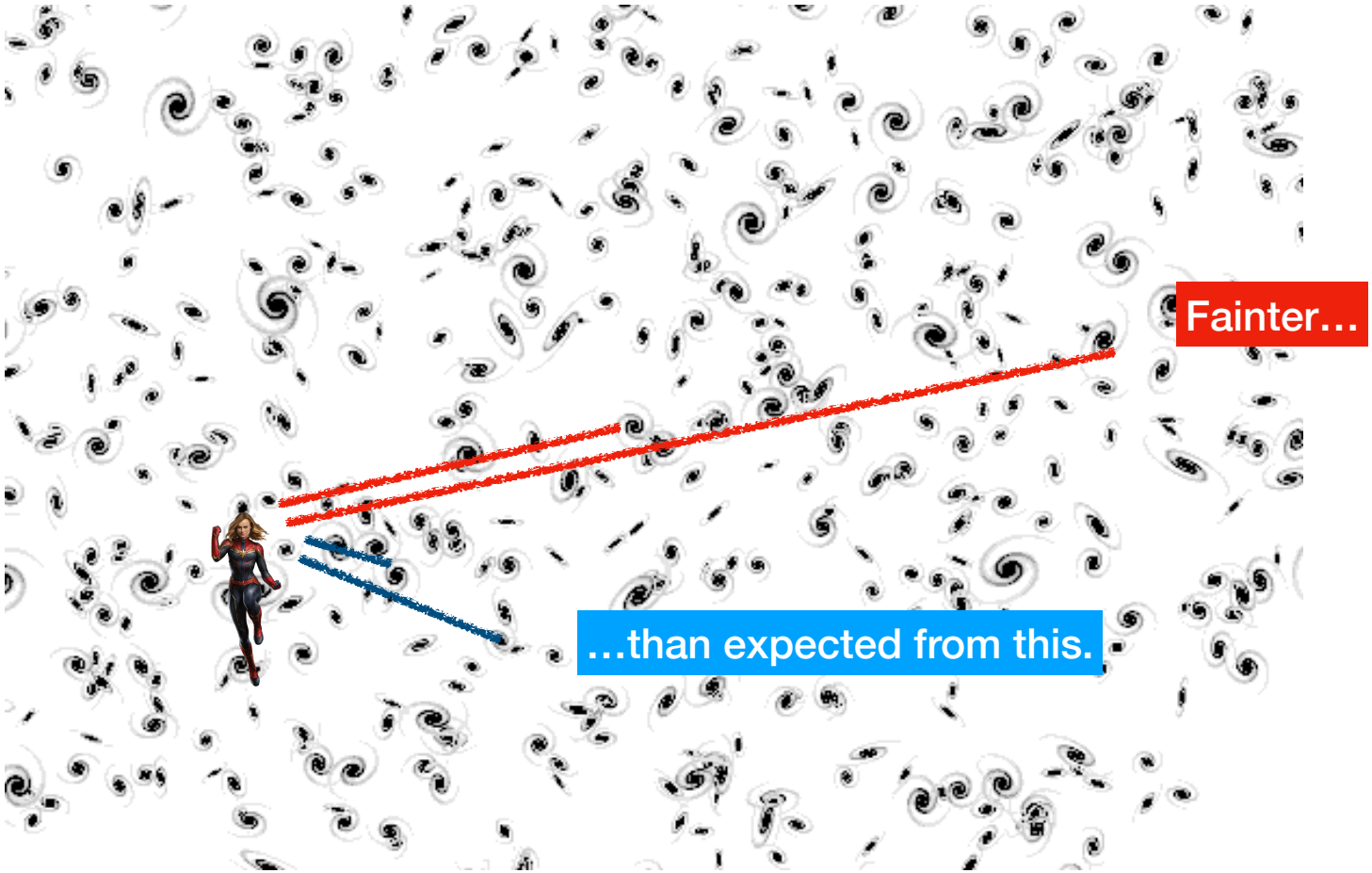


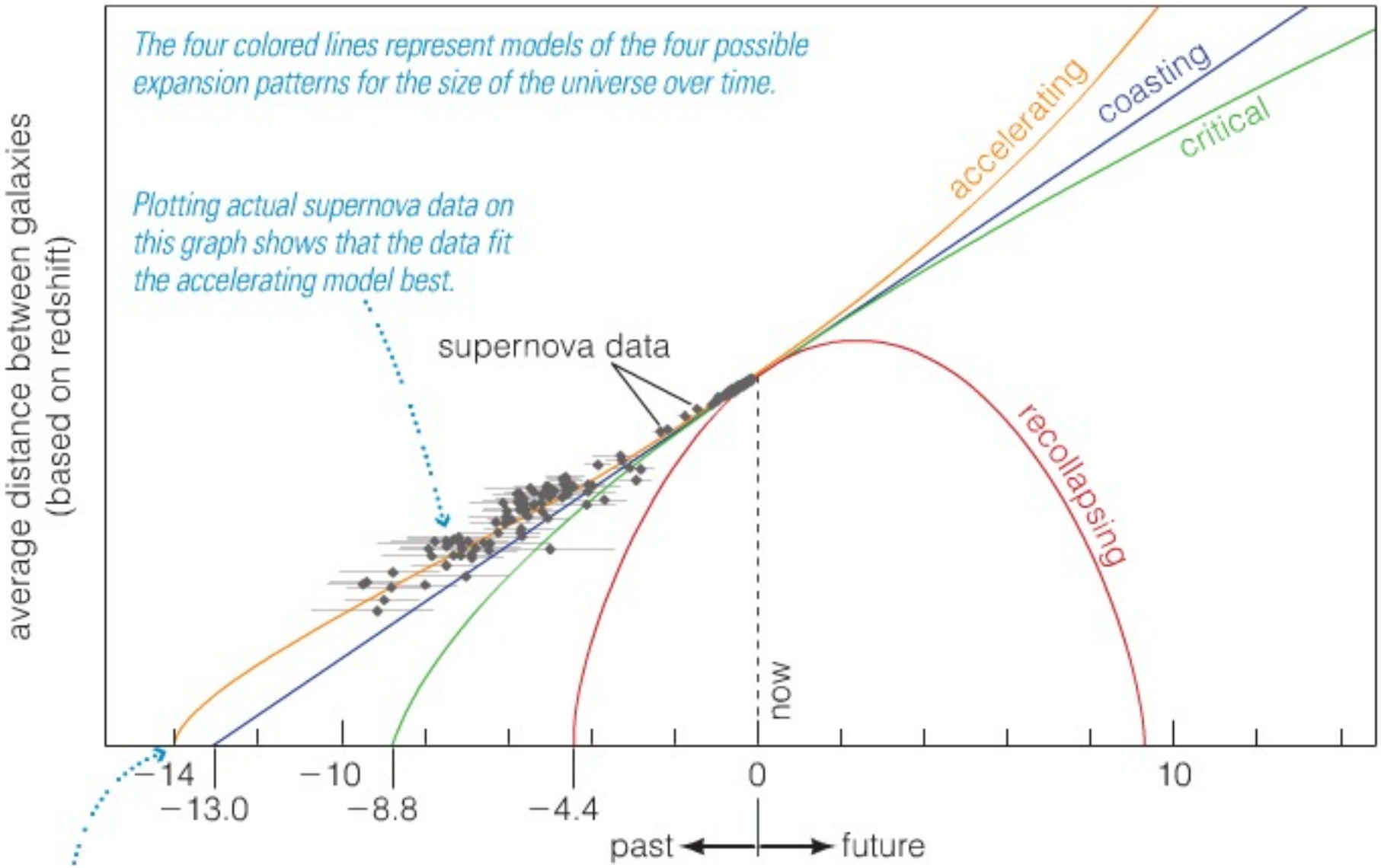
The Universe is also accelerating!

1990s: Reiss and Perlmutter:

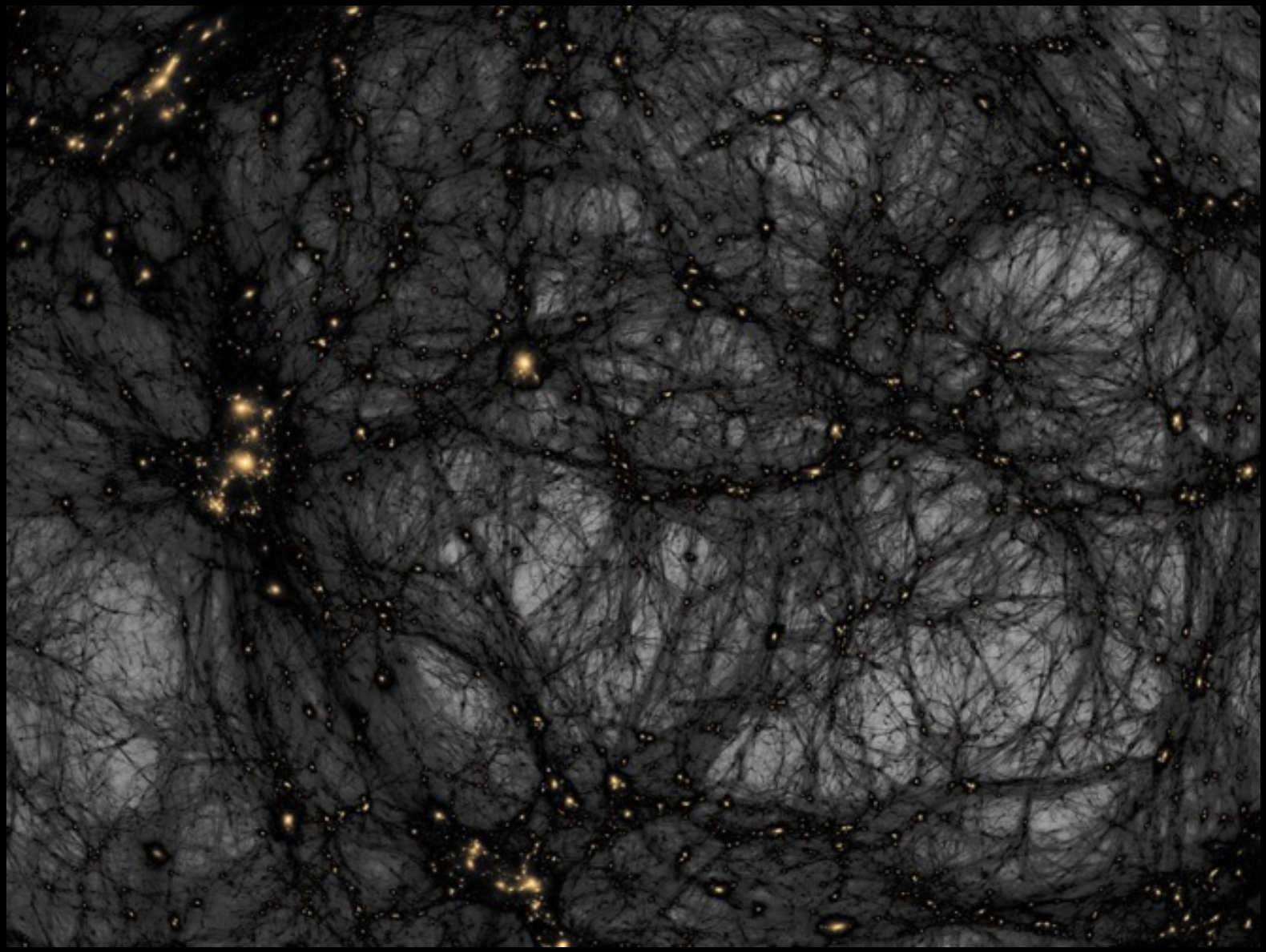
Supernovae Type Ia appear systematically fainter than expected, given the redshifts of their galaxies, indicating that they are farther away.

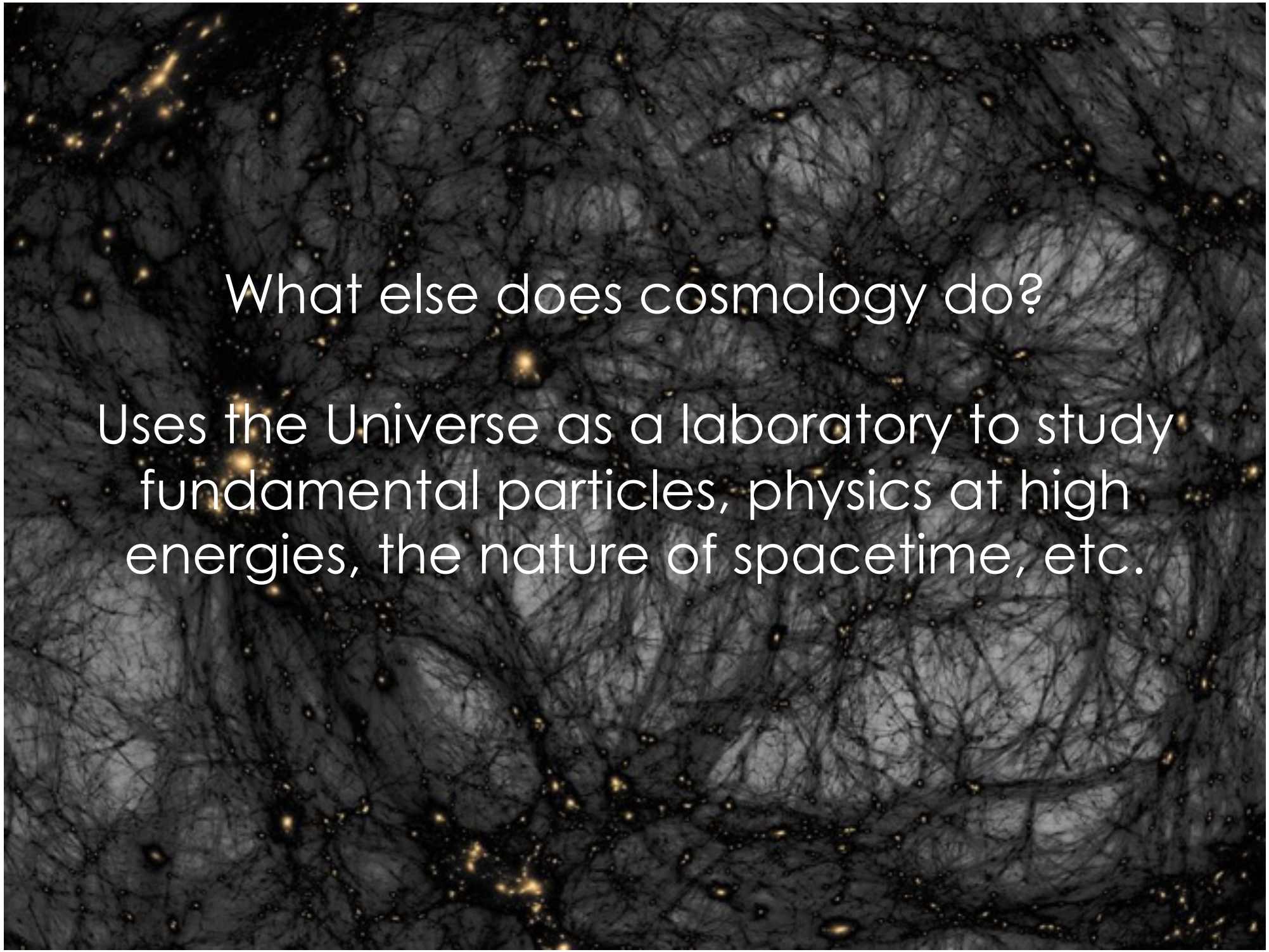


White Dwarf Supernovae give evidence for Dark Energy



Dark energy or a Cosmological Constant must make up ~70% of the Universe.




What else does cosmology do?
Uses the Universe as a laboratory to study fundamental particles, physics at high energies, the nature of spacetime, etc.

What did we learn in Chapter 17?

- Galaxy rotation curves indicate the presence of a dark matter halo 10x more massive than the visible mass / energy.
- Evidence for dark matter:
  - Rotation of Galaxies
  - The filamentary structure of the observable universe.
  - Gravitational lensing
  - Structure in the cosmic microwave background
- The faster an object is traveling away from us, the more redshifted its spectrum becomes.

What did we learn in Chapter 17?

- The cosmological principle states that the Universe is homogeneous and isotropic.
- Hubble discovered that all galaxies outside the Local Group were moving away from us, and the farther away the galaxy, the faster it was moving. This became quantified as Hubble's law.
- Key evidence for the Big Bang:
  - The expansion of the Universe
  - The Cosmic Microwave Background (CMB).
  - The 75% hydrogen and 25% helium composition of the Universe.
- The shape and temperature of the CMB gives us the age of the Universe very accurately.
- "Clumps" in the CMB are the precursors of galaxies.

What did we learn in Chapter 17?

- Measurements of the expansion of the Universe indicate that the rate of expansion is increasing. This increase is attributed to dark energy.
- White dwarf supernovae indicate that we live in an accelerating universe in which galaxies are moving apart faster and faster.