Arthur: You know, it’s at times like these, when I’m trapped in a Vogon airlock with a man from Betelgeuse, and about to die from asphyxiation in deep space that I really wished I’d listened to what my mother told me when I was young.

Ford: Why, what did she tell you?

Arthur: I don’t know, I didn’t listen.

The Hitchhiker’s Guide to the Galaxy

HW4 is due on Monday
Group Project due on Apr 26.
Quizzes 15, 16, & 17 still to do.

Total pre-last-test points posted by May 1
On blackboard (total points column at the end)
NOTE: blackboard's "%" and "Total points" at the top will be incorrect but your individual grades and point total column I'm adding at the bottom should be correct.

Total in-class points: 690
Lab points: 230
Total Points: 920
A: 920-824, B:823-732, C:731-639

We will NOT MEET during our final time. I will be available on **zoom** during test time **(Wednesday, May 8 11am-1pm)**, in case you wish to take the test in a 'live' setting.

Test 3 and the Comprehensive Final will be on blackboard.

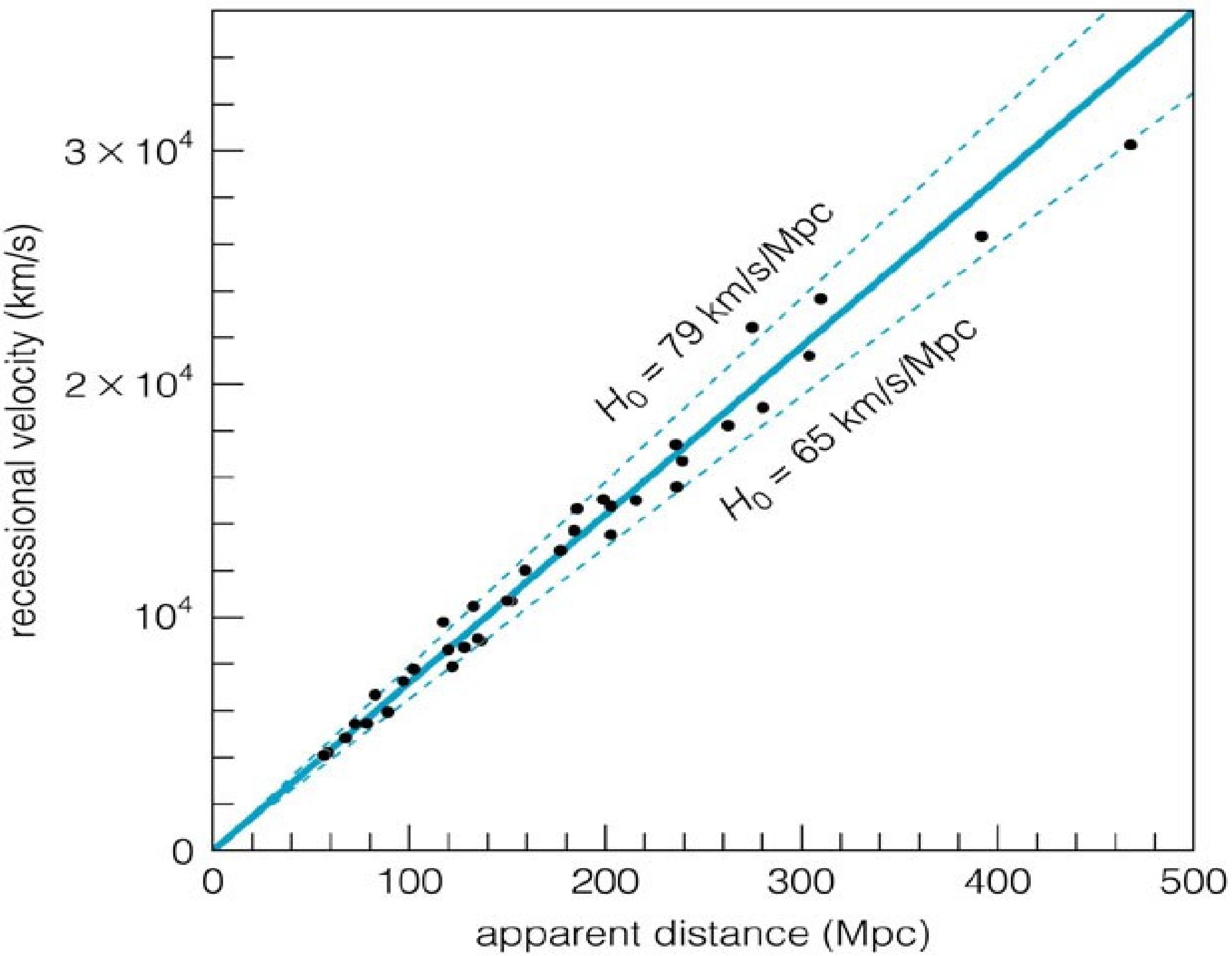
Tests will be timed: Test 3 has 60 minutes, CF has 120 minutes.

Tests will be available May 1 until May 8,1pm

Take Test 3 OR the Comprehensive Final, but not both.

Expanding Universe

As we look farther away from us, galaxies are moving away from us faster.



Math Example

$D = v/H_o$ using $H_o = 73.8$ km/s/Mpc

What is D if v=112,000 km/s?

Example

$D = v/H_o$ using $H_o = 73.8$ km/s/Mpc

What is D if v=112,000 km/s?

D = 112000/73.8 = 1518 Mpc.

Look Closer

What if we switch it a little bit?

H_o=1/s or 1/time:

1/ H_o= time.

What does this time mean?

It is the age of the Universe!

About 14 billion years.

Age of the Universe!

About 14 billion years.

The Big Bang Theory

All that we know as our Universe came from a single point.

In the beginning....

The Big Bang was an expansion from a quantum singularity. What does that mean?

It means the Universe came into existence from 1 point, whose size is too small to be described.

The next beginning...

At 10^{-43} seconds, we can begin our discussion. This is not long after the Big Bang, but not the beginning

0.000000000000000000000000000000000000000001

After 10^{-43} seconds

Gravity separates from the other 3 forces (electromagnetic, weak nuclear, strong nuclear).

The density of the Universe was 10^{94} g/cc (estimated)

At 10^{-35} seconds

The temperature is 10^{27}K!

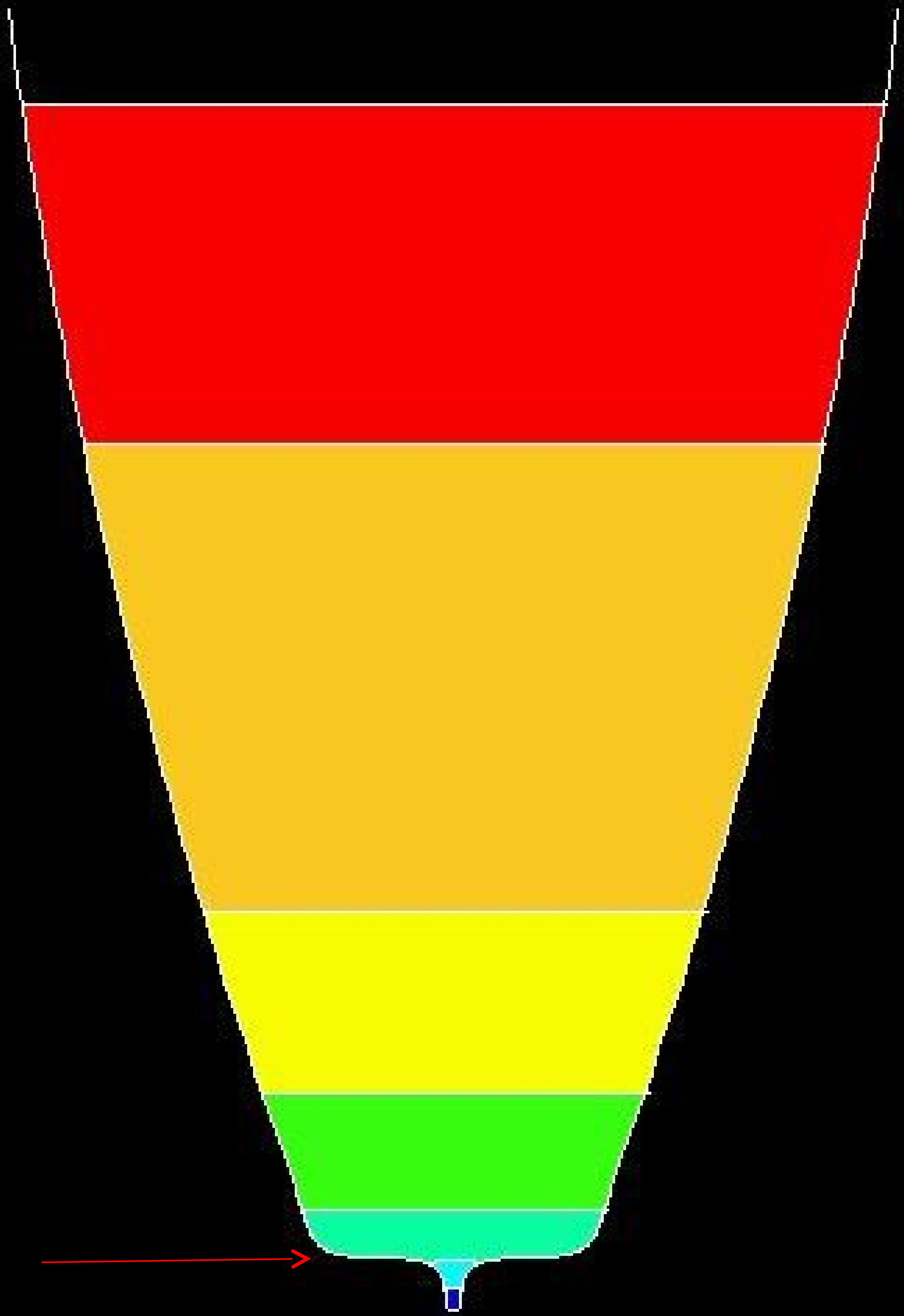
Inflation

The Universe expanded exponentially at a rate much faster than the speed of light.

The Universe underwent a "phase change" (like water to ice) that caused the inflation.

Universe exists as quarks

0.00000000000000000000000000000000001

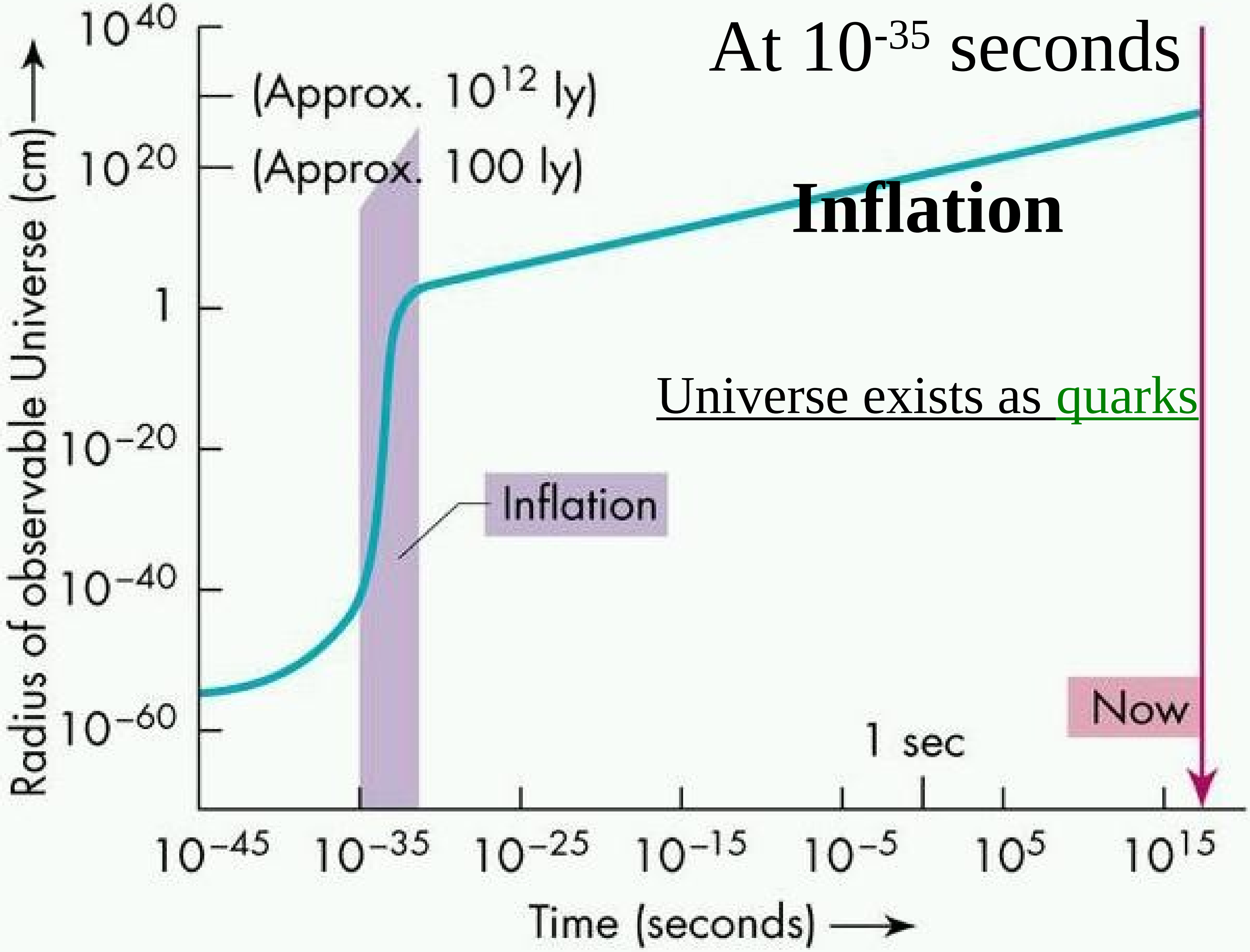


Inflation. Universe expands like crazy!

At 10^{-35} seconds

Inflation

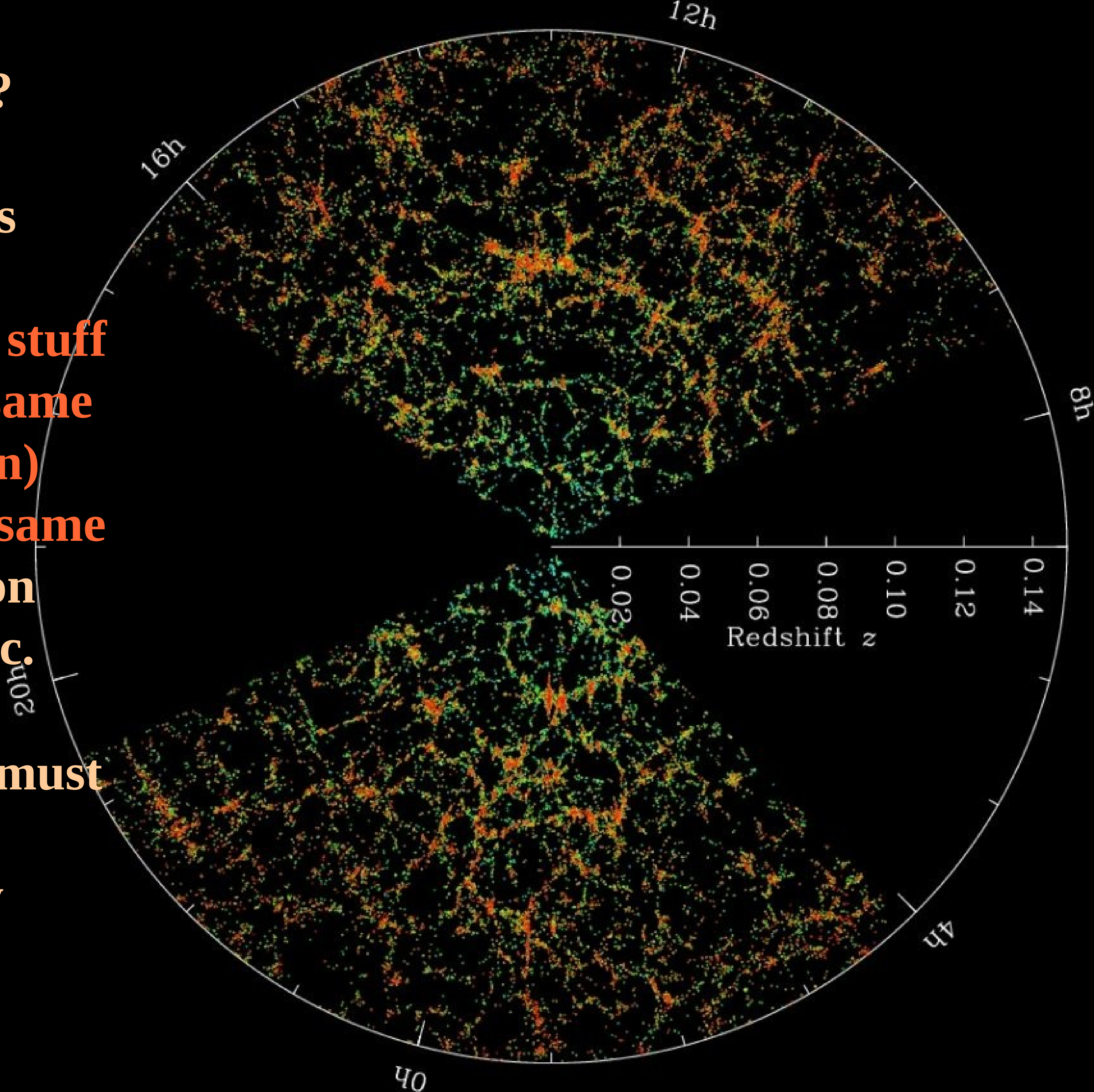
Universe exists as quarks



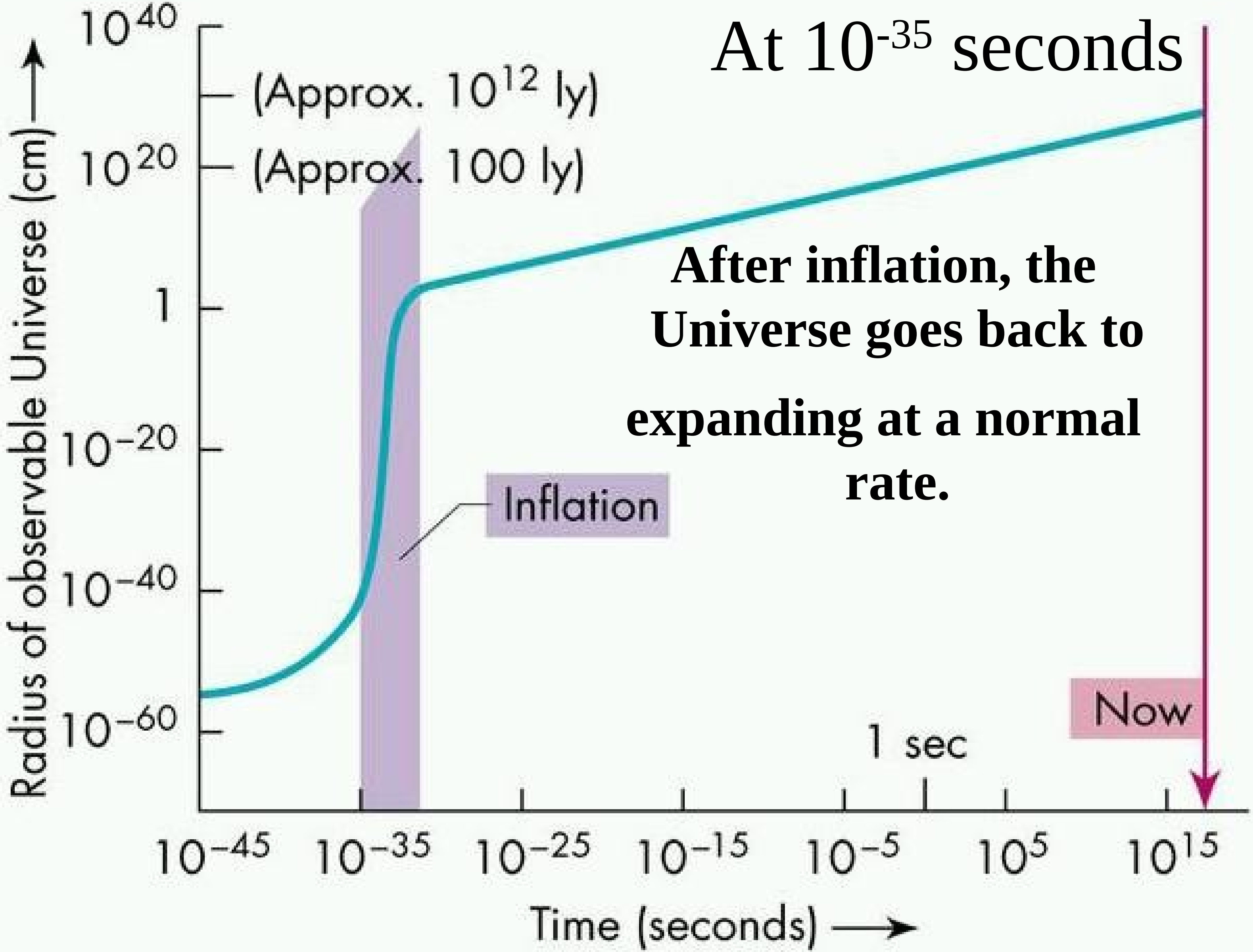
Why Inflation?

The Universe is homogeneous (made of same stuff and looks the same in any direction) and isotropic (same temperature) on scales >200Mpc.

This property must have been generated very early on.



At 10^{-35} seconds



After inflation, the Universe goes back to expanding at a normal rate.

Quiz 15: Why is inflation important for the big bang theory?

A) To make the Universe homogeneous and isotropic.

B) So aliens could exist.

C) To keep the Universe expanding.

D) To keep scientists busy.

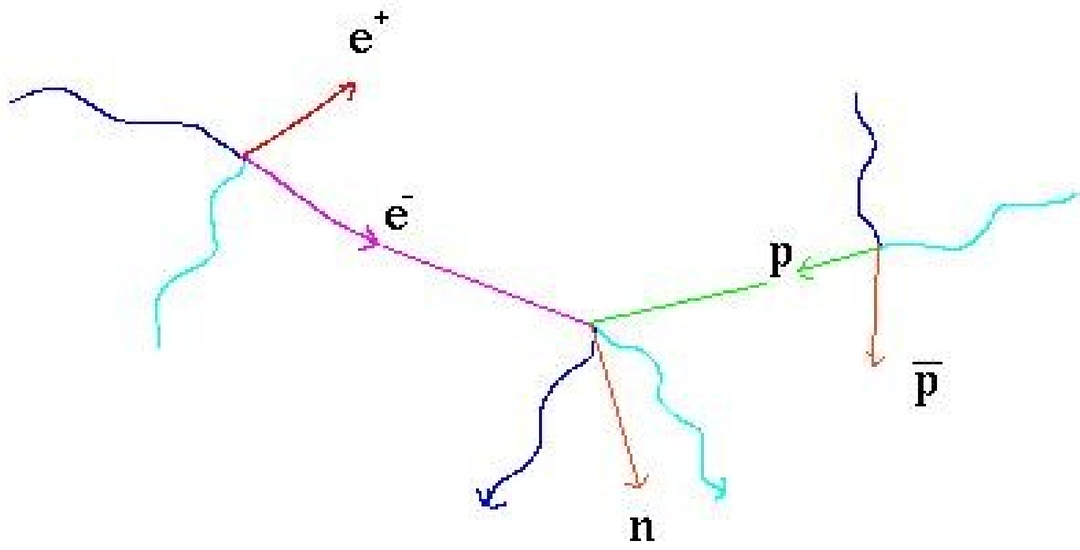
At 10^{-11} seconds

The remaining forces separate.

Now quarks can form protons, neutrons, neutrinos, electrons (normal stuff), and their antimatter partners.

Particles are created and annihilated almost immediately.

0.00000000001 seconds



2 photons meet and make an electron/positron pair.

Elsewhere, 2 photons meet and make a proton/anti-proton pair.

The electron and proton meet and make a neutron and photons.

$E=mc^2$, matter and energy (photons) can switch back and forth under the right conditions.

At 10^{-6} seconds

The Universe has made all the protons (H) and neutrons it can. This is also called 'freezing out'

Photons can still make electrons and positrons.

0.000001

At 1 second

Electrons and positrons freeze out. Again, there's a huge annihilation as the matter and antimatter destroy each other, leaving behind only a small excess of matter.

Deuterium (1p 1n) can begin to form- but is easily broken apart. The deuterium bottleneck (important!).

Free neutrons begin to decay (turn) into protons.

At 100 seconds

Nucleosynthesis begins.

The temperature drops below 3 billion K.

The Universe is a fusion reactor!- first making deuterium (1p 1n) then ^{3}He, ^{4}He, and finally ^{7}Li (most of which breaks apart as it's very fragile)

At 3 minutes

Nucleosynthesis is over.

The Universe is now 75% free protons (H),

24% ^{4}He and 1% ^{3}He and Li.

Still far too hot for electrons to combine with protons or nuclei, so the Universe is a bath of foggy light.

180

At 3 minutes

Nucleosynthesis is over.

The Universe is now 75% free protons (H),

24% ^{4}He and 1% ^{3}He and Li.

Sound familiar? 0% 'metals' is what Pop. III stars would have.

After a busy 3 minutes, the Universe does very little for a long, long time.

The Universe exists as particles and photons in a plasma, which is like being inside a star.

With time, the Universe continues to expand, cooling from a blue-hot plasma down to a red-hot plasma.

At 300,000 years

Recombination

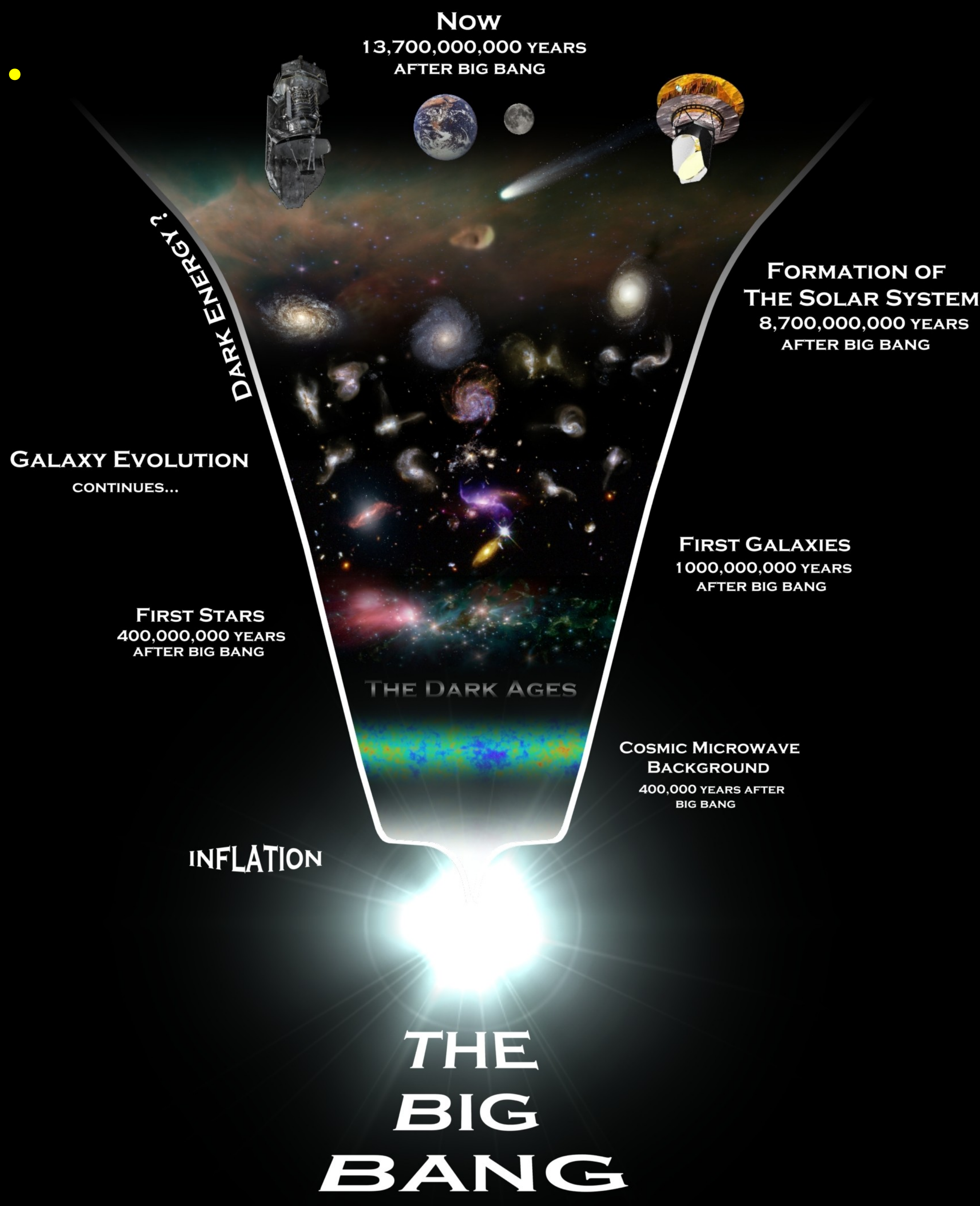
Electrons and protons can finally combine. The temperature of the Universe is 3,000 K (4900^oF).

Light can now travel freely and the Universe becomes transparent.

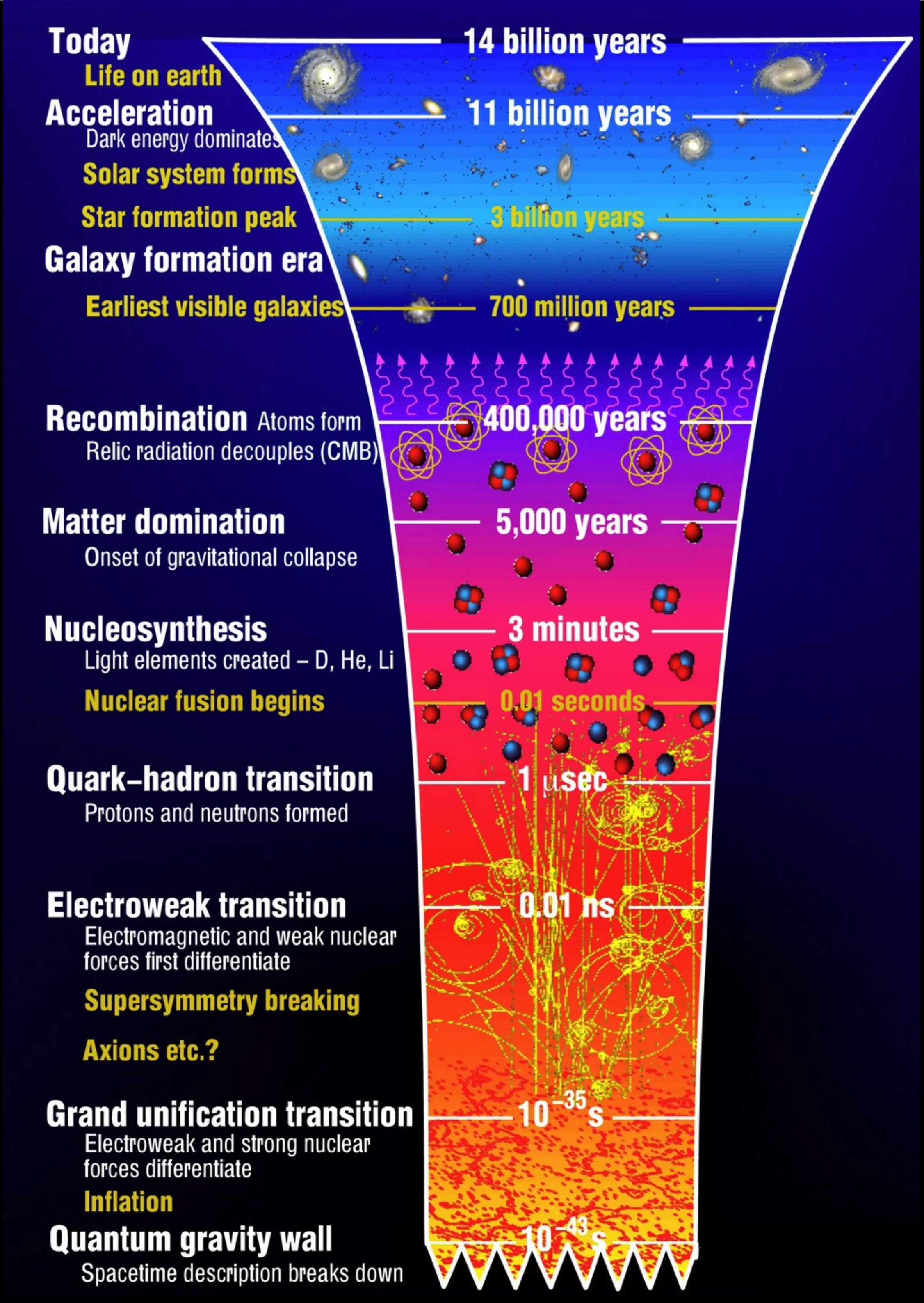
9000000000000 seconds

This is the end of the Big Bang Theory

Since then...



After that time, stars and galaxies began forming and so on.



Another graphic depicting the big bang with some descriptive text.

For reference

Gravity first: Universe is made of only energy.

Inflation: Still only energy

Quarks form

Protons/neutrons freeze out

Electrons freeze out: deuterium bottleneck

Nucleosynthesis begins

Nucleosynthesis ends H+He

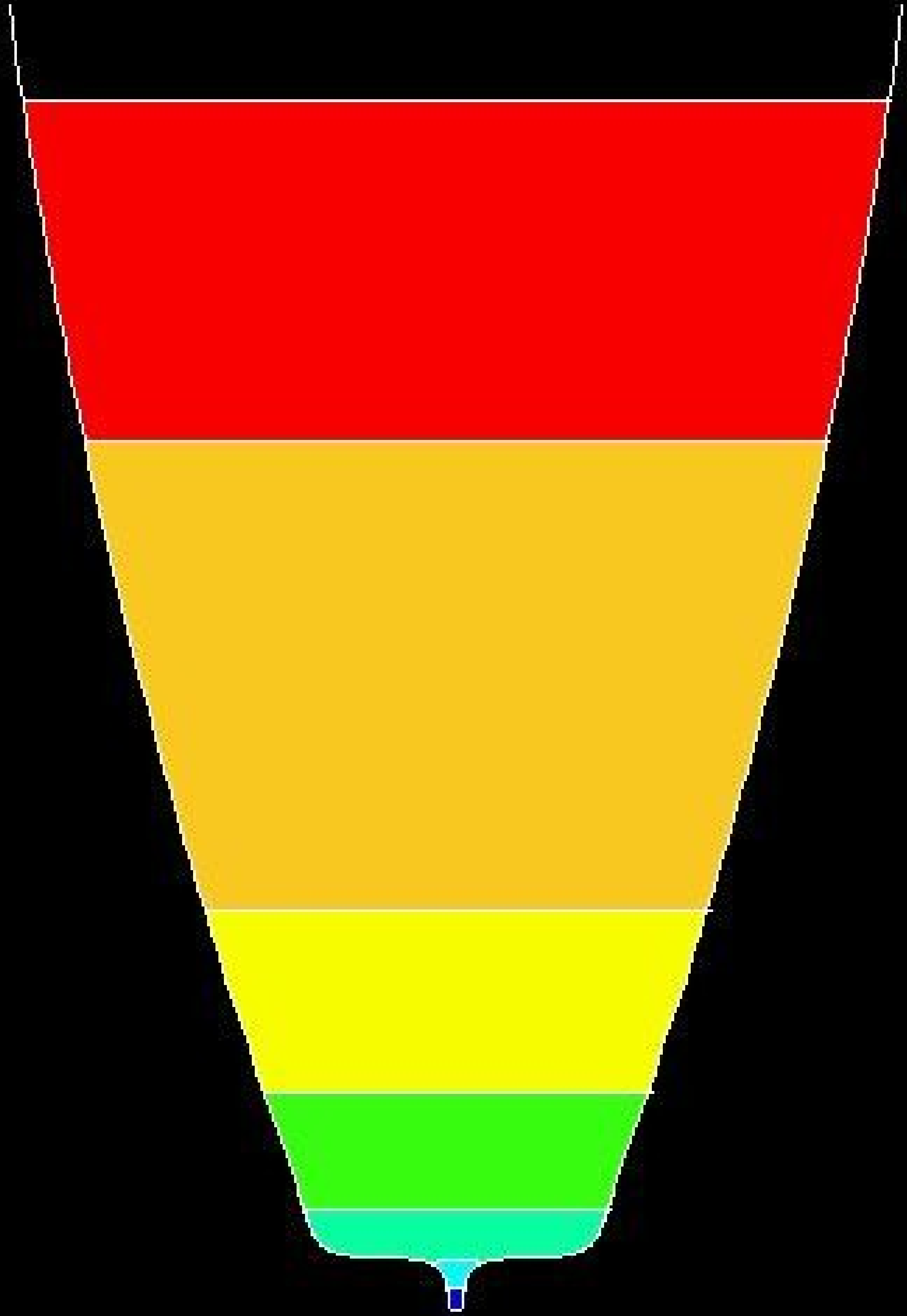
Recombination: CMB

Stars form

Galaxies form

Our solar system forms

Humans evolve to question where the Universe came from.



Take-aways

*Our Universe began as an incredibly dense, bunch of energy, too hot for matter to exist

* Freaky expansion occurred early on to make our Universe *homogeneous and isotropic*.

* heavier particles (protons & neutrons) ‘froze’ out of the energy first, then the lighter ones (electrons)

*The Universe was hot enough to be a nuclear furnace, but deuterium prevented it early on. Then this furnace produced He (~23%).

*The Universe became too cool to produce any particles or do fusion, but still very hot.

*After ~300,000 years, the Universe cooled to become the dark skies we know now. Big Bang Theory ends here!

*Eventually stars, galaxies, planets, and people formed.

The scientific principle

Now that we have discussed the theory, it is time to determine what the Big Bang theory predicts.

Big Bang predictions #1

Expanding Universe
(bit of a circular argument, but it is a prediction that comes out of the theory)

Big Bang predictions #2

Nucleosynthesis:

Pop I stars have 1-2% 'metals'

Pop II stars have 0<metals< 0.1%

So Pop III stars should have 0% metals.

(The current record holder, SMSS J0313-6708, has 0.00000002% 'metals' and is still considered Pop II)

Big Bang predictions #2

Under the assumption that the Universe once only consisted of H (protons), where do the other elements come from?

Nuclear fusion requires hot, dense environments. There are only 2 ways to produce the large amount (24%) of helium we see today:

1) in stars

2) the Universe itself had to be hot and dense enough to do this.

Big Bang predictions #2

Nucleosynthesis:

If stars did it, there would be a lot more heavier elements, like carbon and oxygen.

1) Planetary nebulae put back elements up to Pb

2) Supernova remnants put back all elements.

Big Bang predictions #2

Nucleosynthesis:

We know that the Universe is neither hot nor dense enough to produce helium today.

At some time in the past it must have been hotter and denser than it is today.