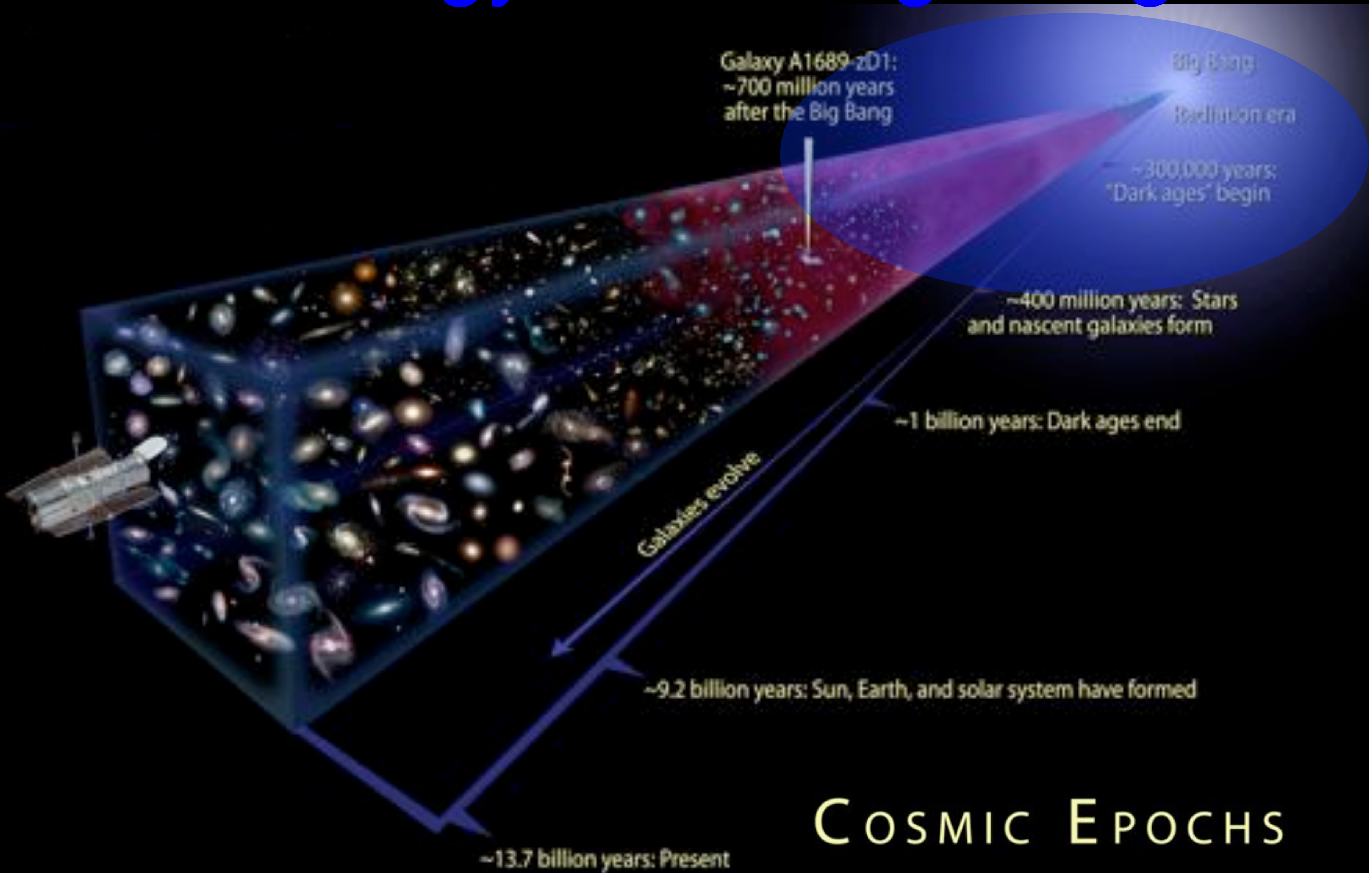
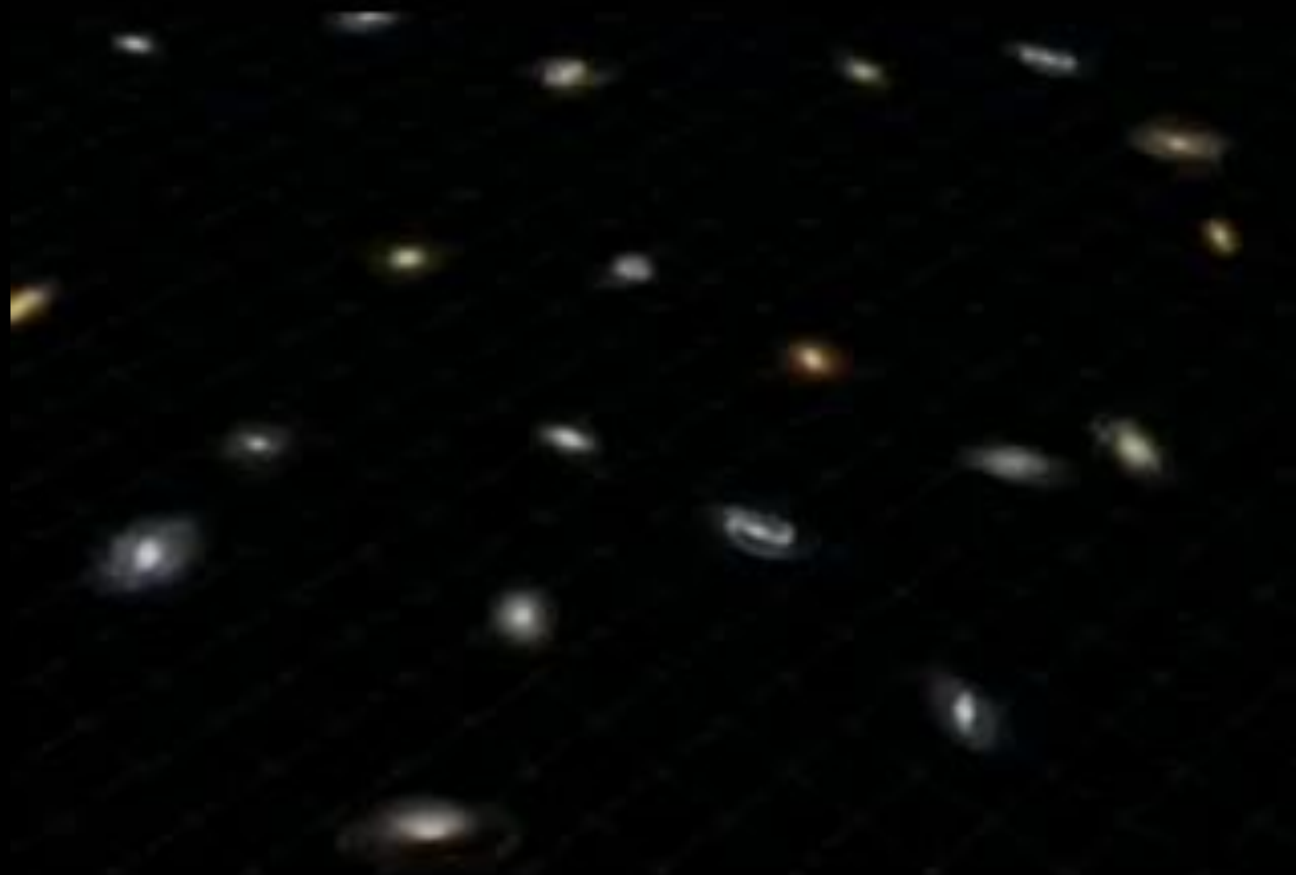
Cosmology – The Big Bang

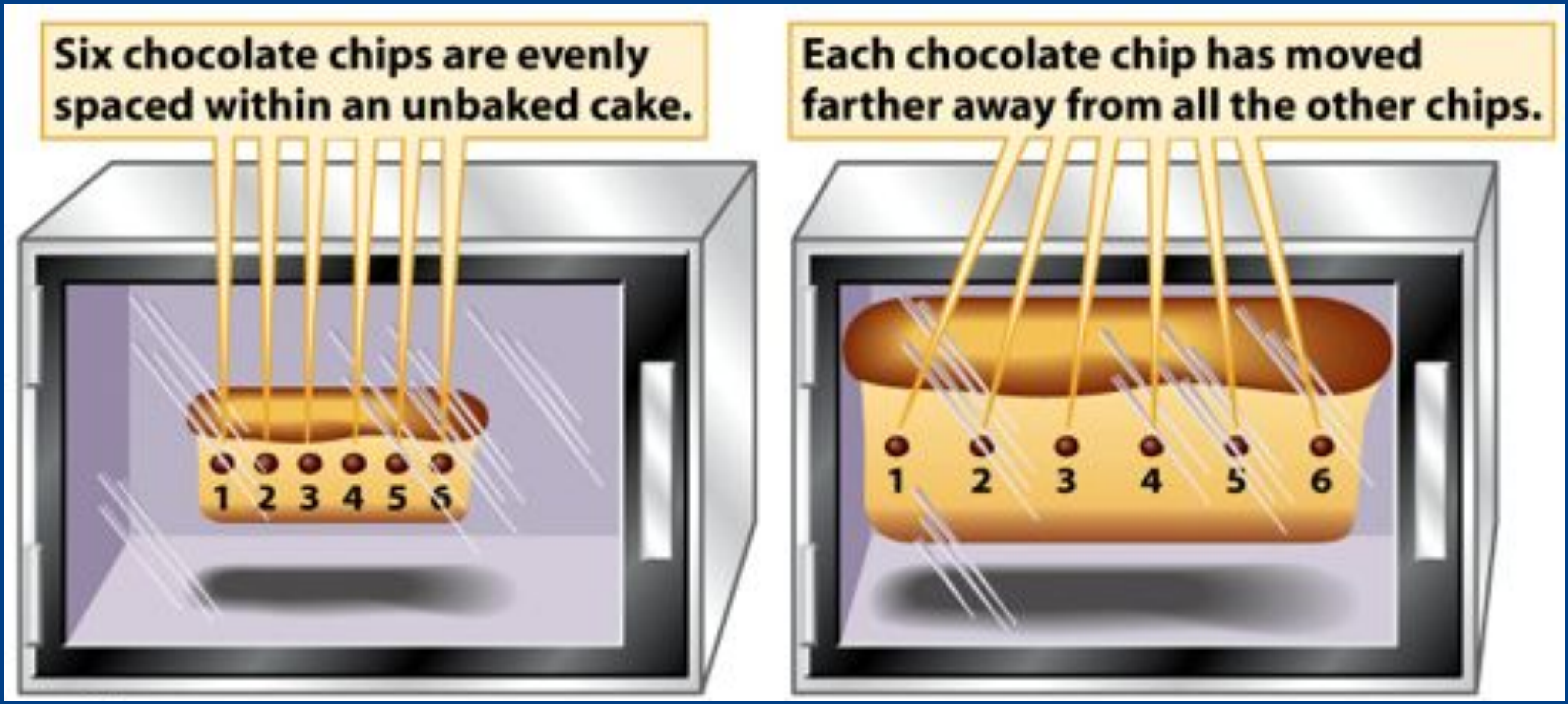


Hubble expansion



- Hubble seemed unaware of the implications for cosmology

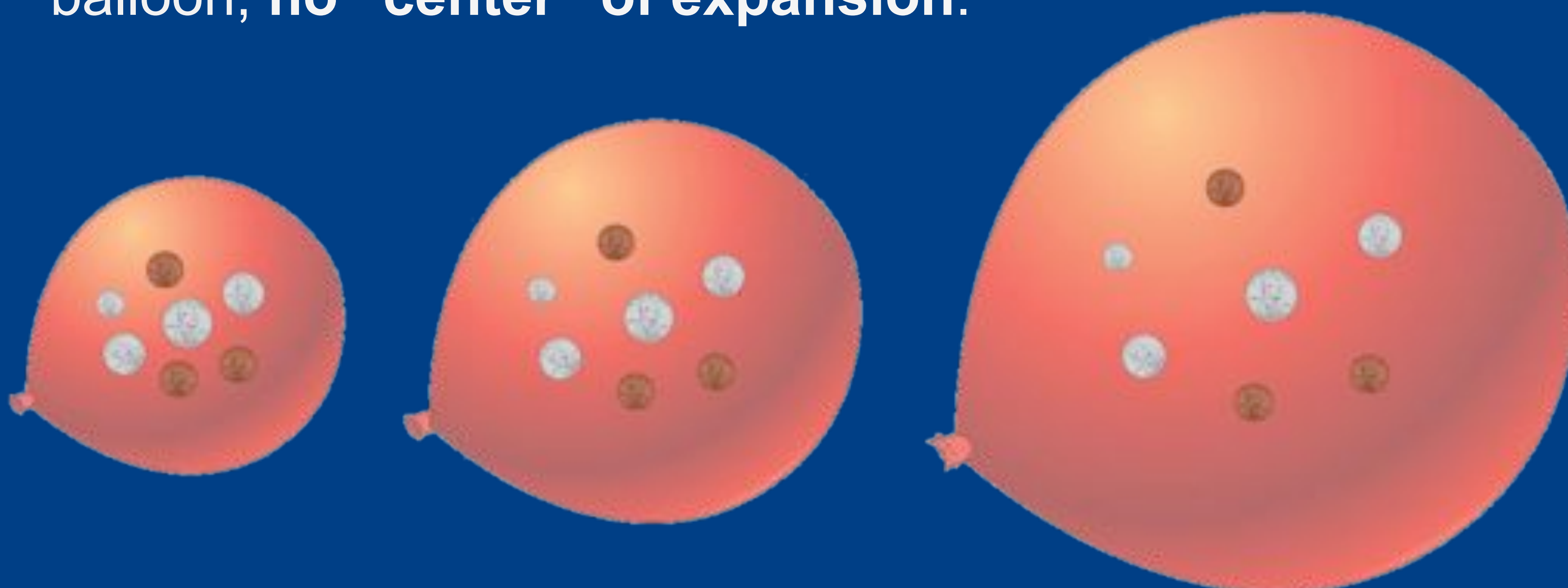
Hubble Law [AT 26.2]



no preferred centre to the expansion

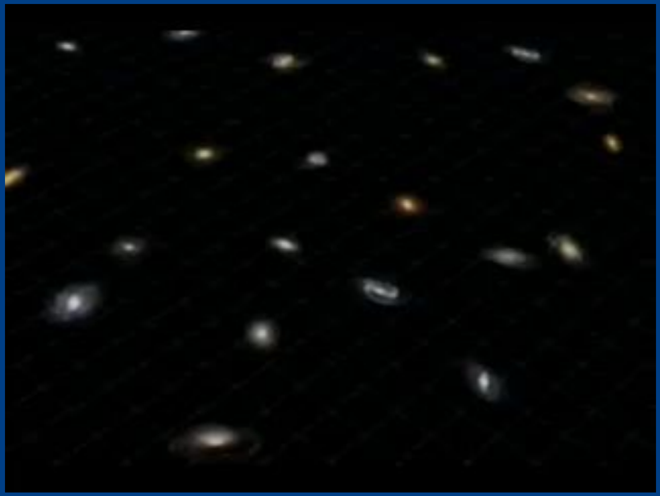
Hubble Law Urban Legend 0: We are the centre of the expansion

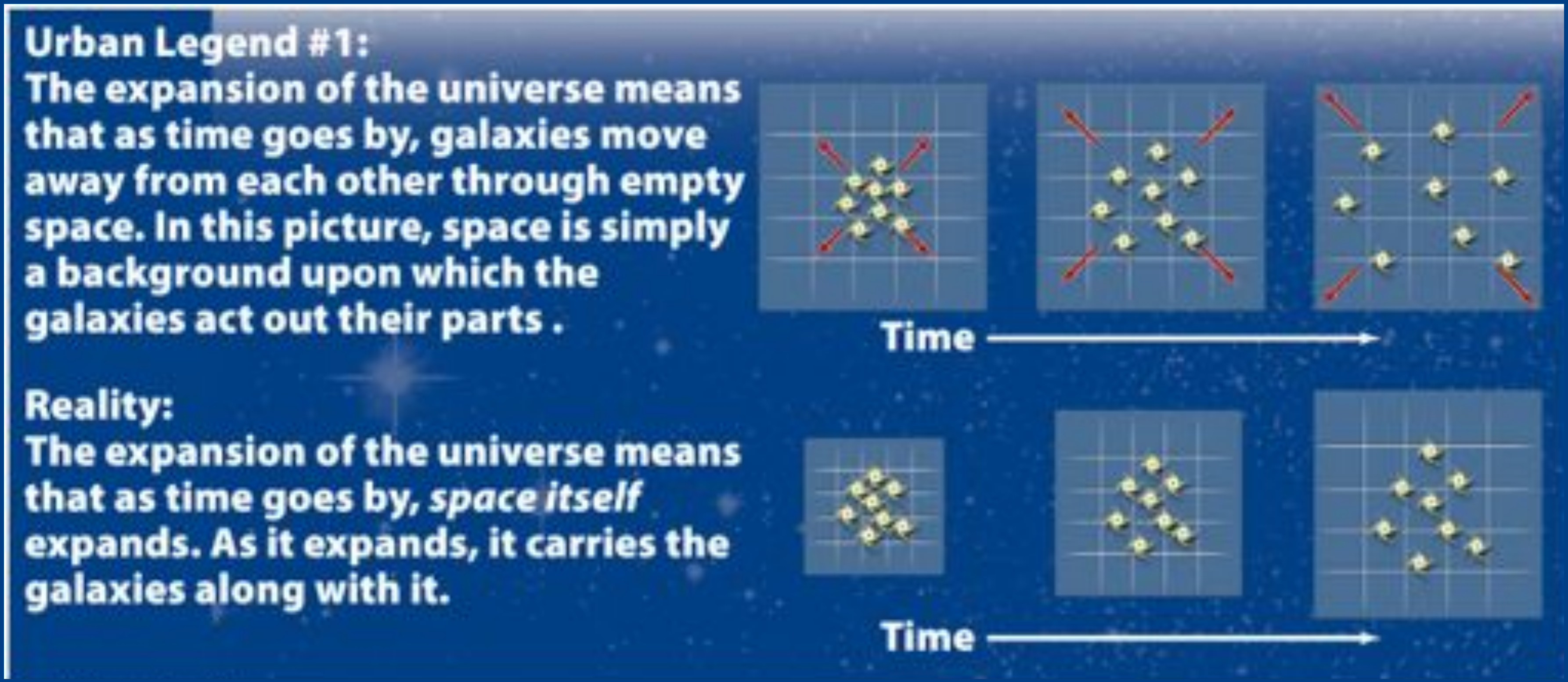
Reality: In two dimensions: imagine a balloon with coins stuck to it. As we blow up the balloon, the coins all move farther and farther apart. There is, on the surface of the balloon, **no “center” of expansion**.



Hubble Law Urban Legend 1

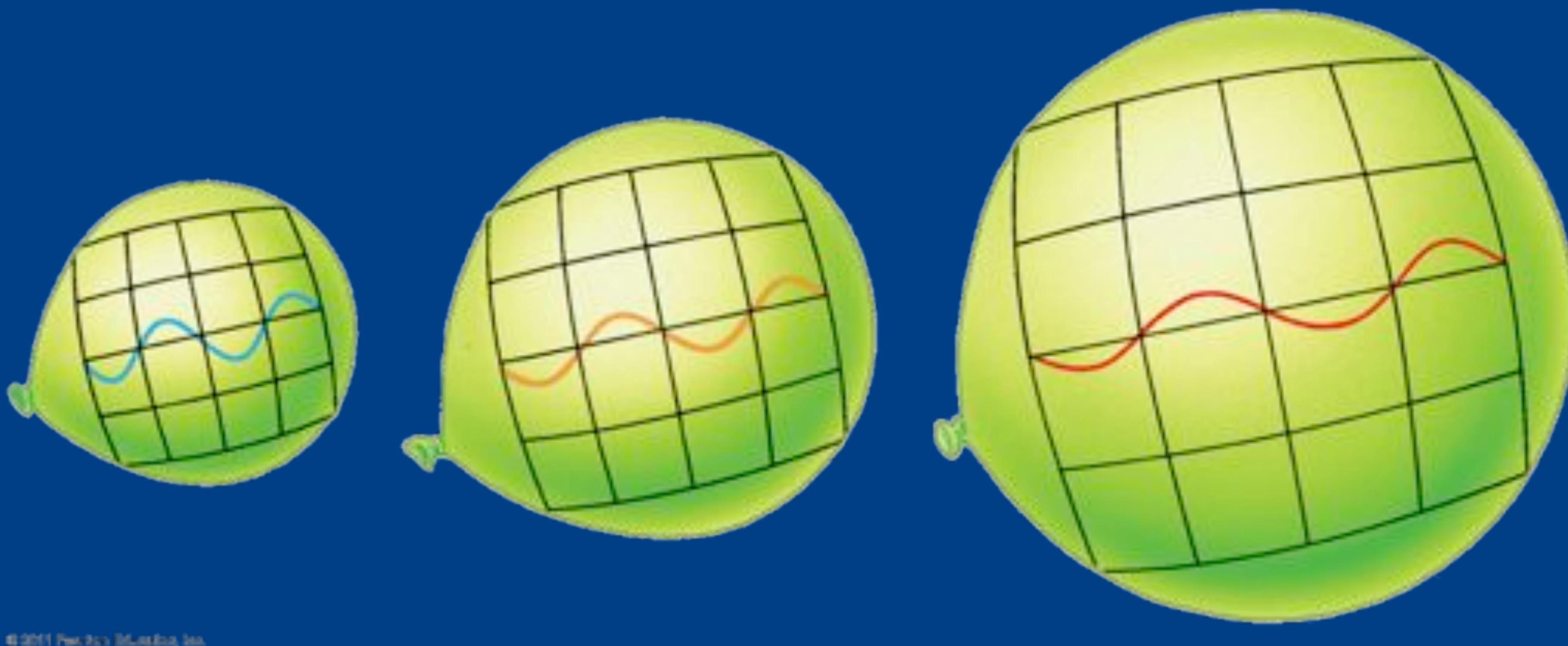
Hubble Law
Urban Legend 1



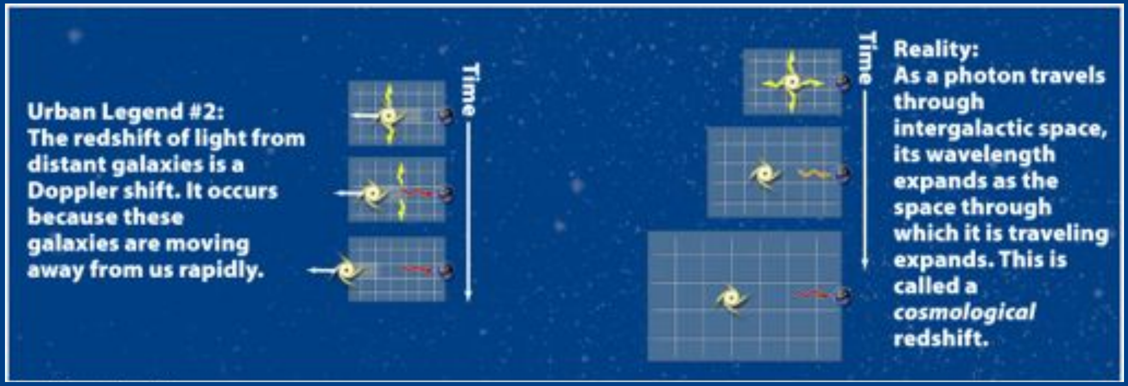


Hubble Law
Urban Legend 2

Hubble Law Urban Legend 2



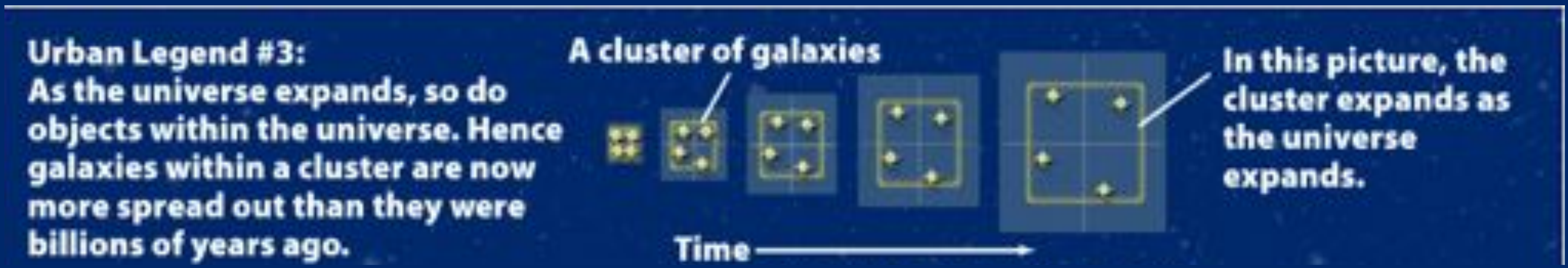
What's the diff?



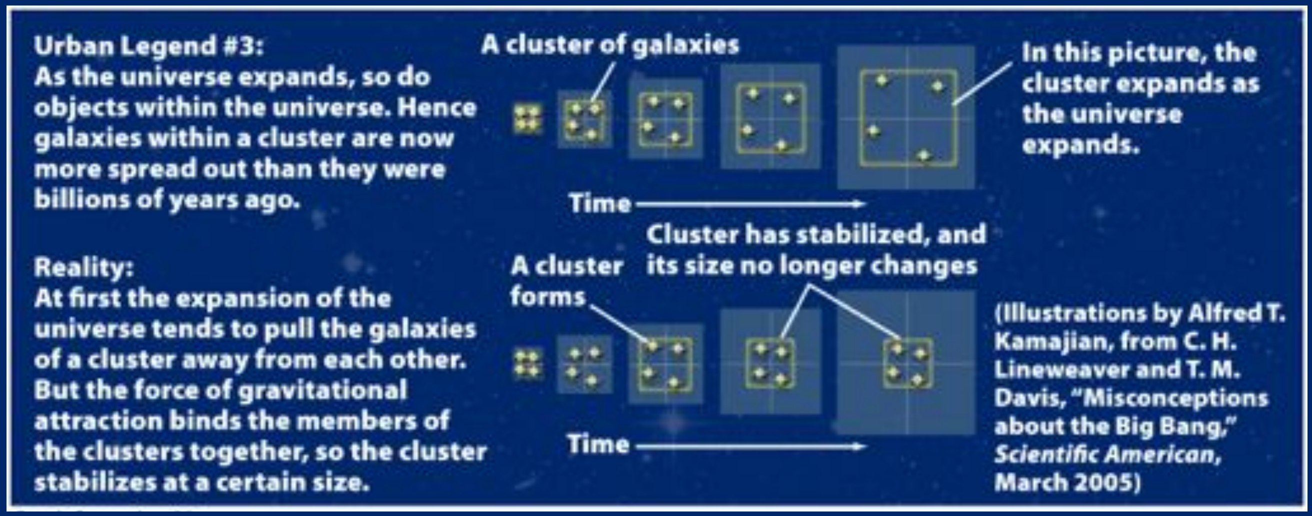
- Interpretation as a Doppler shift implies static space, but this is not the case.
- Interpretation of redshift as expansion of space gives you extra information!
  - Size of Universe at time wave emitted

[Note: there are still cases where the Doppler shift affects the cosmological redshift …]

Hubble Law Urban Legend 3



Hubble Law Urban Legend 3



- Size of earth, solar system, galaxy, most clusters of galaxies, etc is unchanging – not expanding with the universe

What is the cosmological redshift? [***best*** answer]

A. The Doppler shift of galaxies
B. The expansion of space
C. A relativistic mass induced redshift
D. B with a bit of A
E. Tired light

The moon's orbit around the earth is observed to be slowly expanding. Why?

A. Because of the expansion of the Universe.

B. Some other effect.

A wave of light is emitted by a distant galaxy. Some time later we observe it, and find that the observed wavelength is twice the wave-length that it was emitted at. What was the size of the Universe when the light was emitted?

A. Twice the present size
B. Half the present size
C. 200 x the present size
D. 1/200 of the present size
E. Need to know the Hubble constant to answer this

Hubble Law Summary

1. Hubble Law is the same from any point in the Universe. *There is no preferred centre to the expansion.*
   - This only works for a Hubble Law v=Hd, not other laws!
   - No matter where in the Universe we are, we will measure the same Hubble Law.

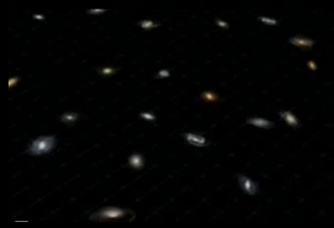
2. Space is expanding, no Doppler shift!

3. Bound objects are not expanding!

Expansion of the Universe

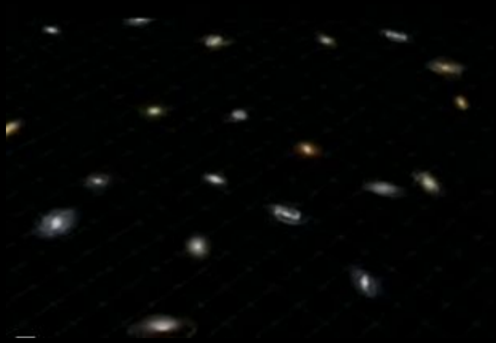
1 Gyr

Expansion of the Universe



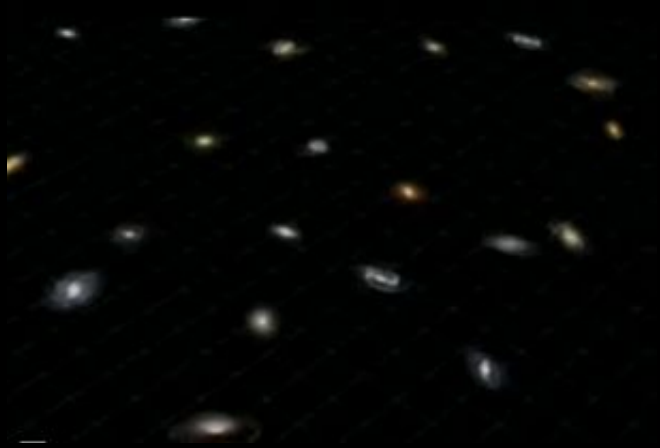
2 Gyr

Expansion of the Universe



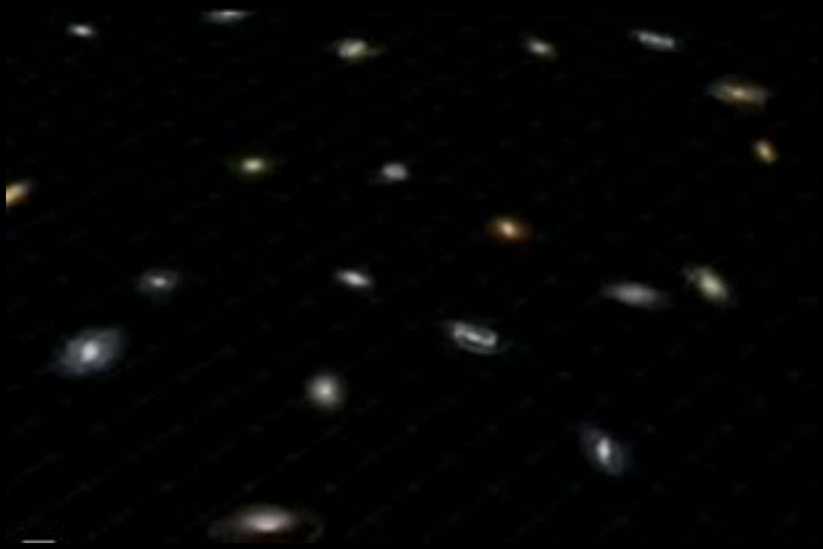
3 Gyr

Expansion of the Universe



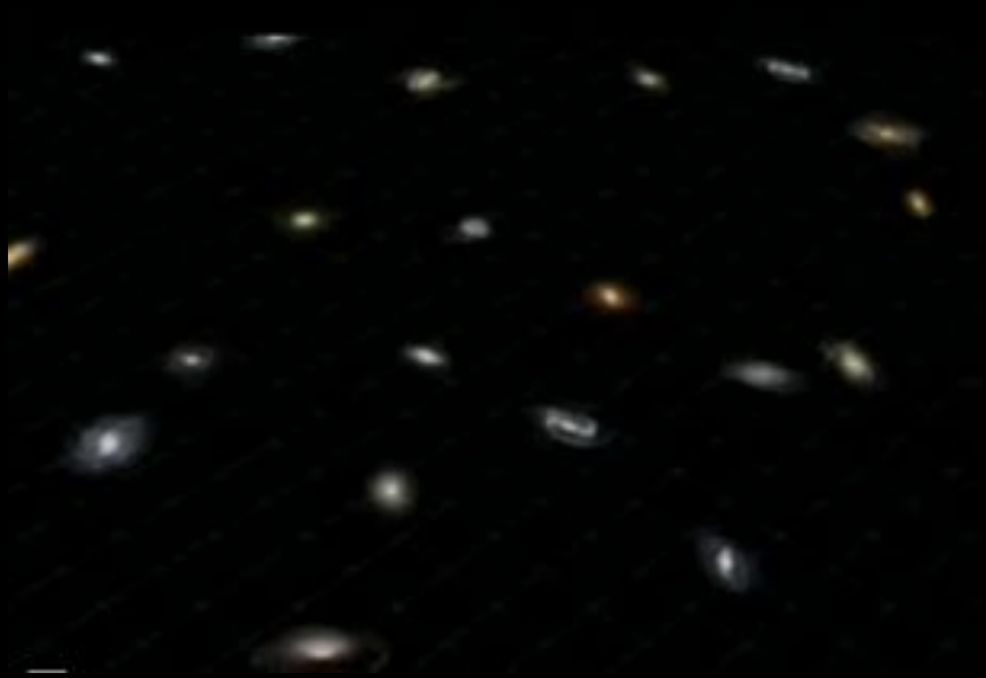
4 Gyr

Expansion of the Universe



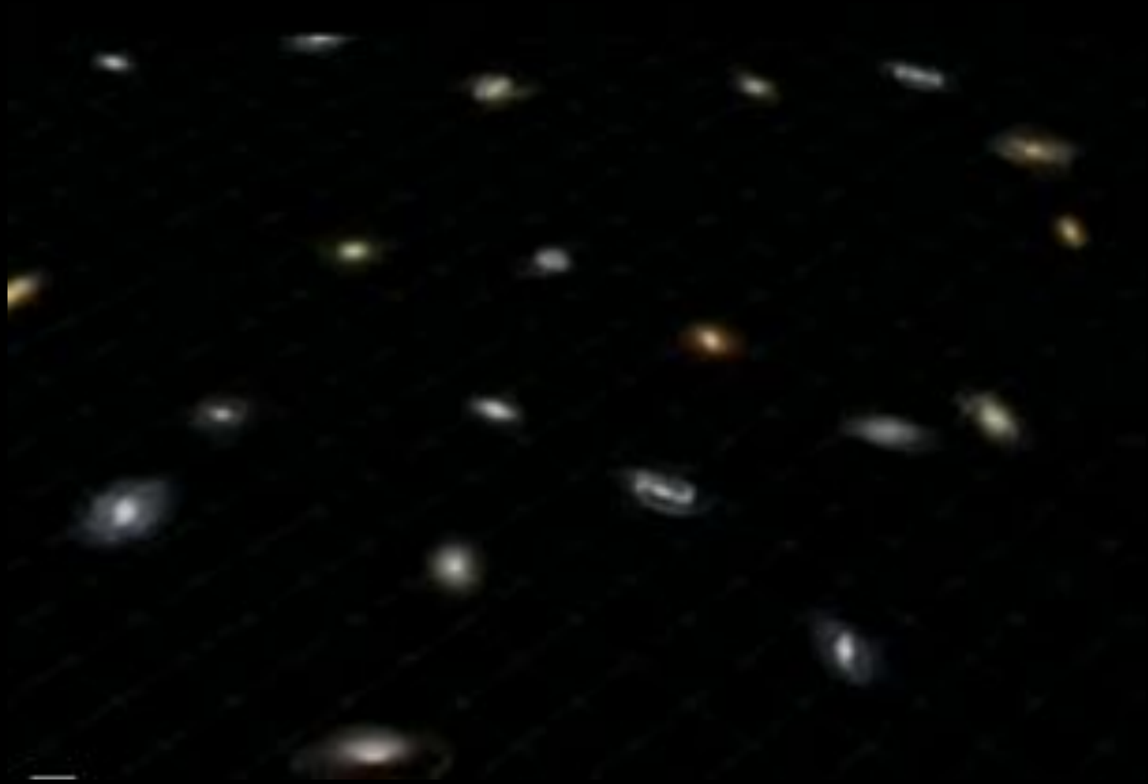
5 Gyr

Expansion of the Universe



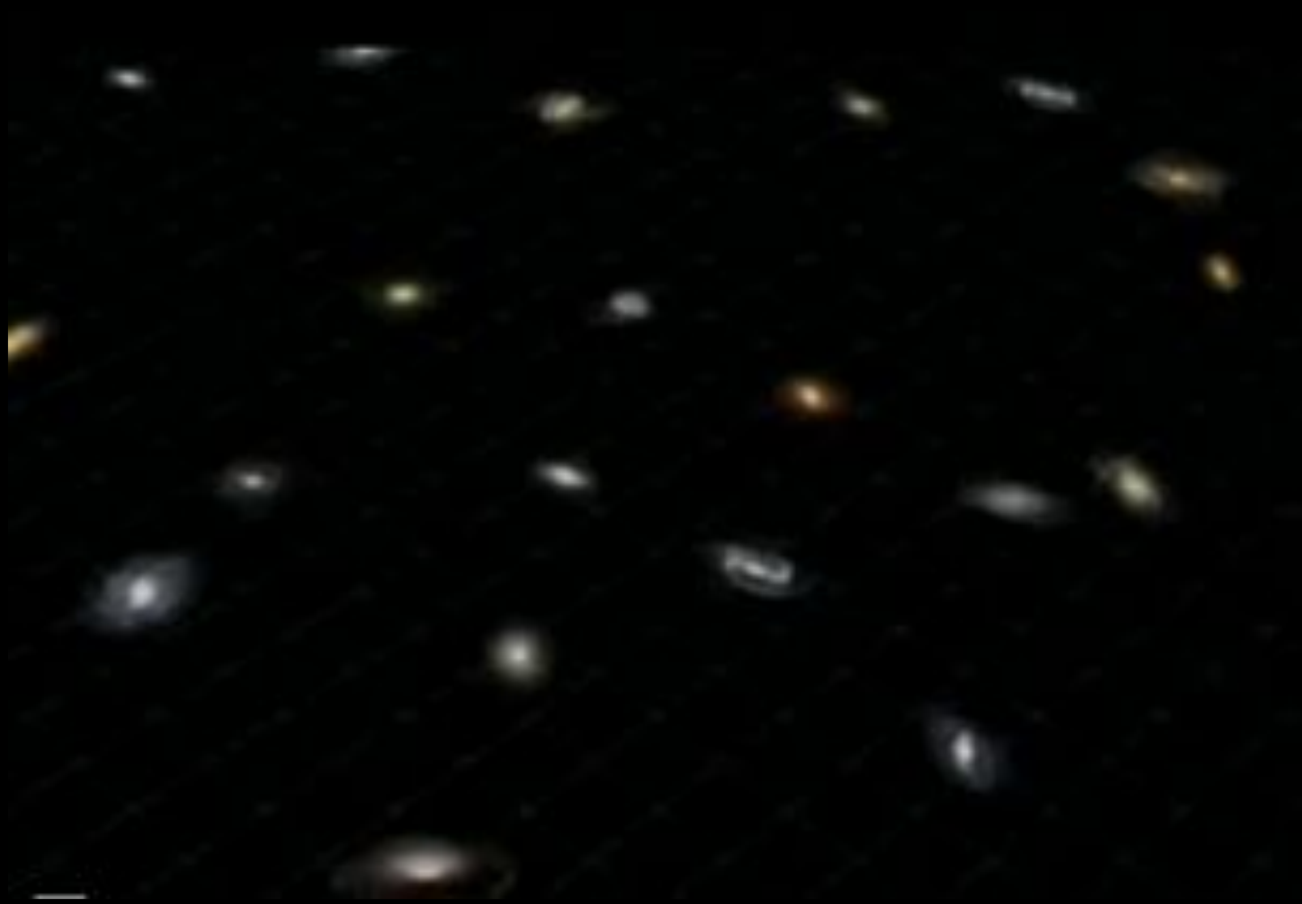
6 Gyr

Expansion of the Universe



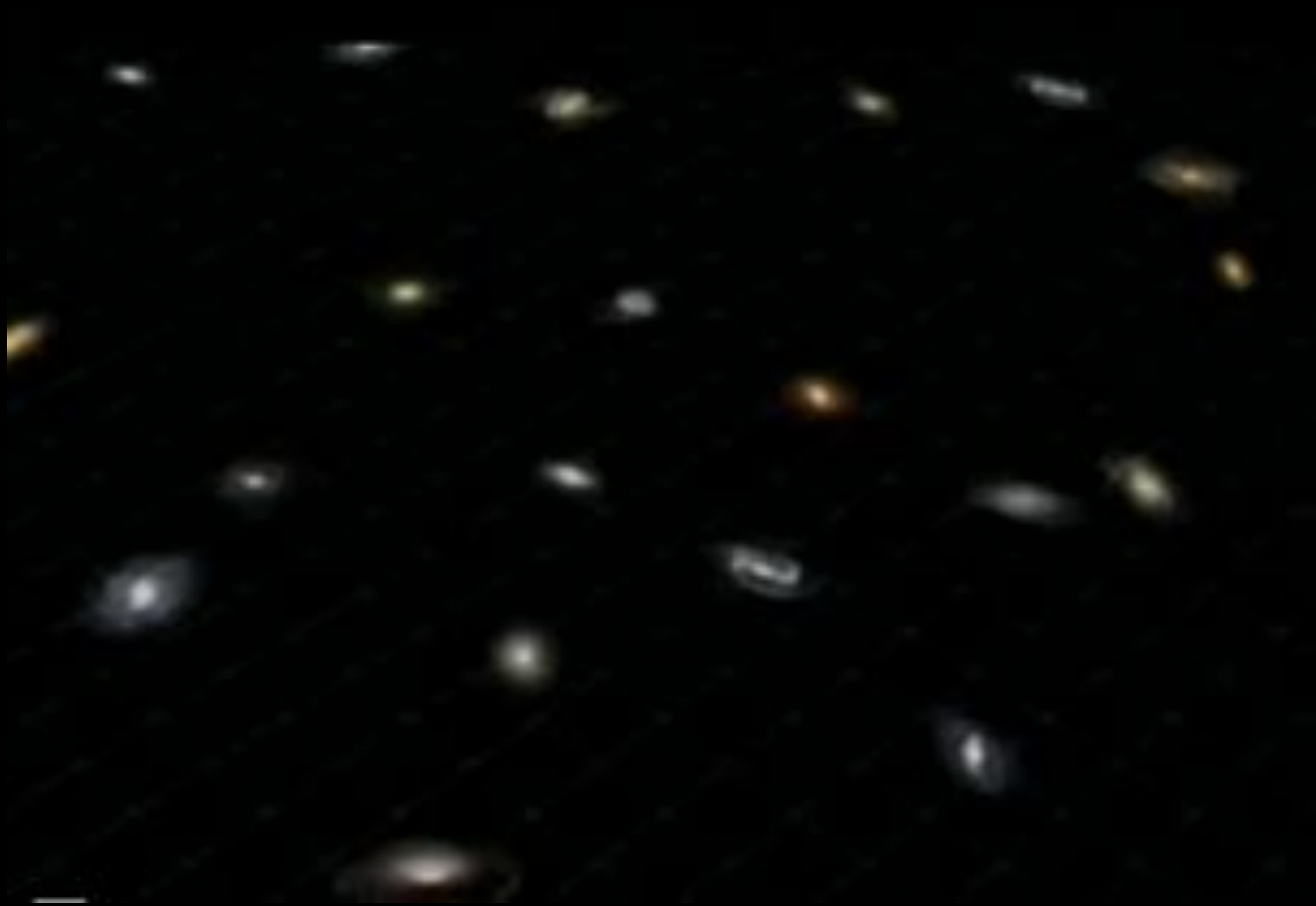
7 Gyr

Expansion of the Universe



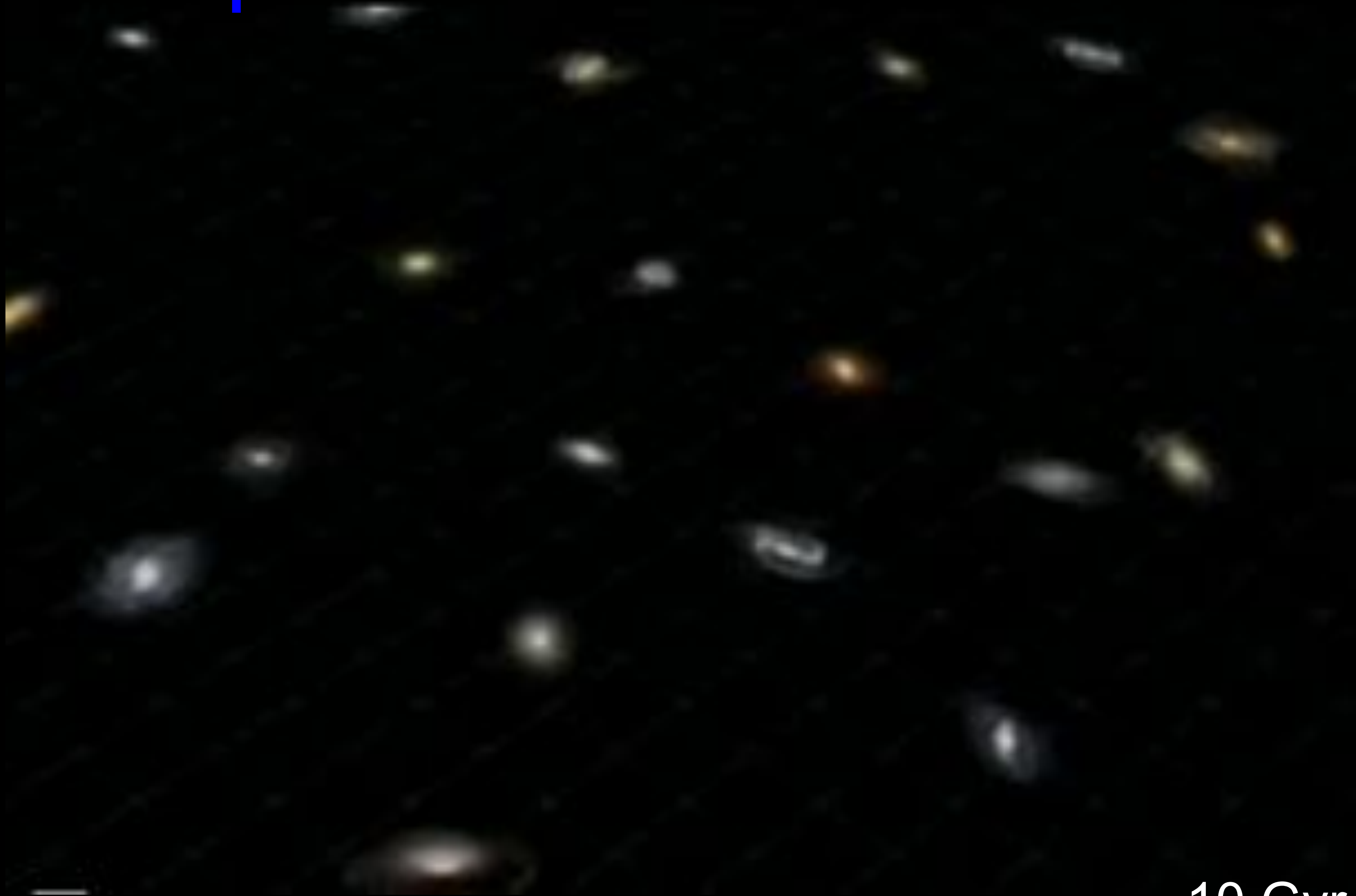
8 Gyr

Expansion of the Universe

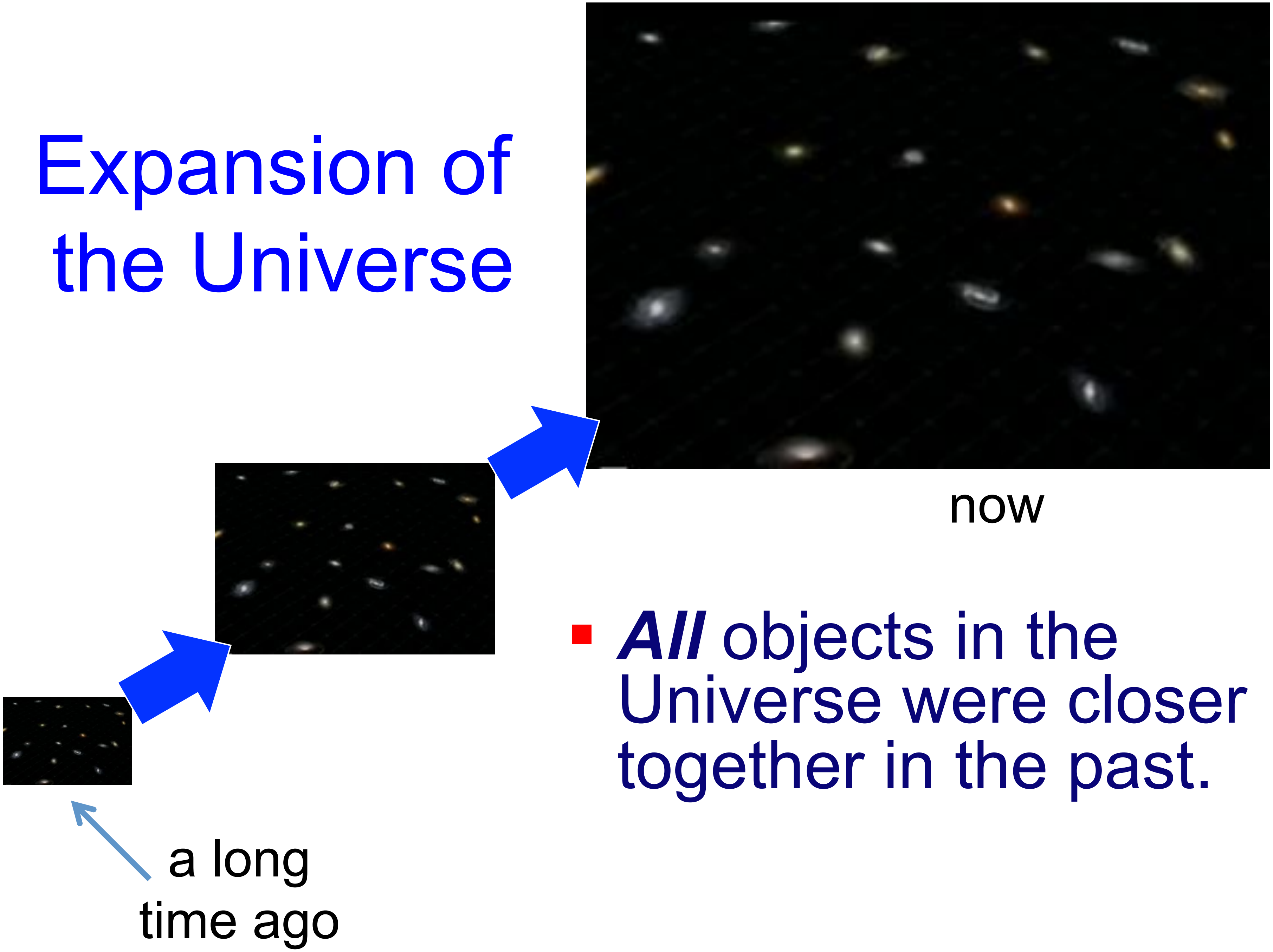


9 Gyr

Expansion of the Universe



Expansion of the Universe



- ***All*** objects in the Universe were closer together in the past.

Age of Universe

- At some time in the past, all matter was together at a single point.

The Big Bang

- So, where was the Big Bang?

Answer: It was everywhere!

Age of Universe

- Consider <u>any</u> 2 galaxies, relative velocity v and separation d – how long did it take the galaxies to get where they are today?
  - Let's assume H_0=100 km/s/Mpc for ease of calculation.
  - d=100 Mpc, v=10,000 km/s: t=…
  - d=200 Mpc, v=20,000 km/s: t=…   etc.

- Better: time = distance / velocity

  = distance / (H_0 x distance)

  = $1/H_0$

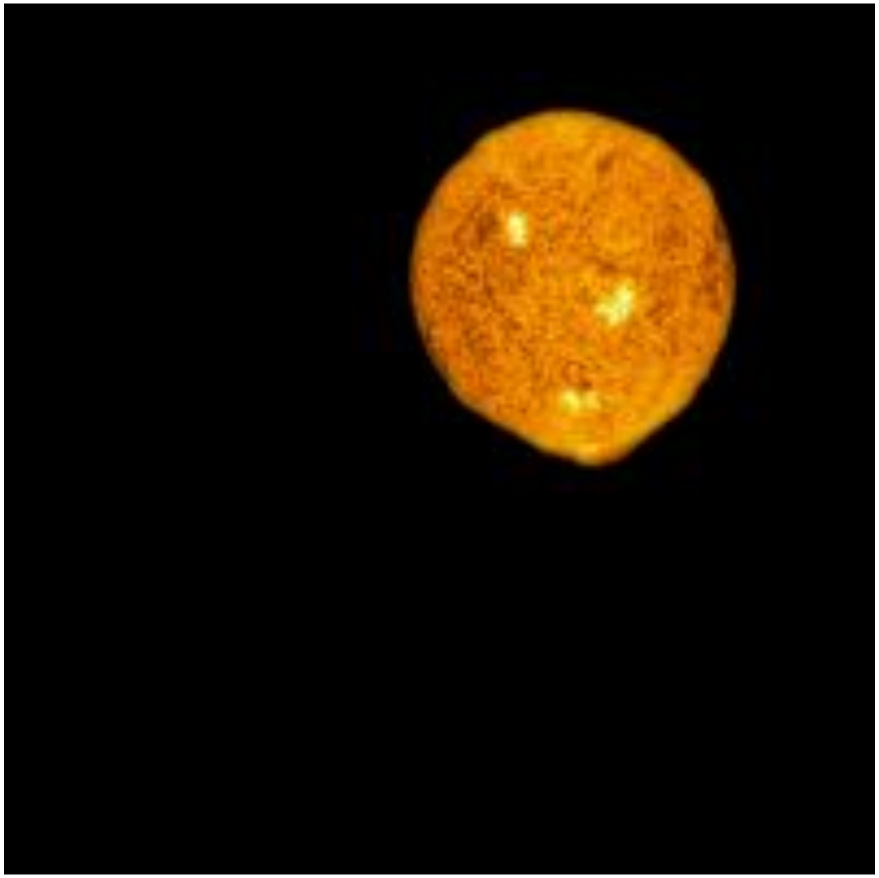
Age of Universe

- This is independent of which pair of objects is chosen! Therefore the age of the universe, *given a **pure** Hubble Law expansion*, is

$$t_0 = \frac{1}{H_0} = \frac{10^{12}\,\mathrm{yr}}{H_0 \text{ in km/s/Mpc}}$$

  - H_o=500 km/s/Mpc (Hubble) gives an expansion age …
  - H_o=70 km/s/Mpc (modern) gives an expansion age …
- Limitations …

Olbers Paradox (1823)

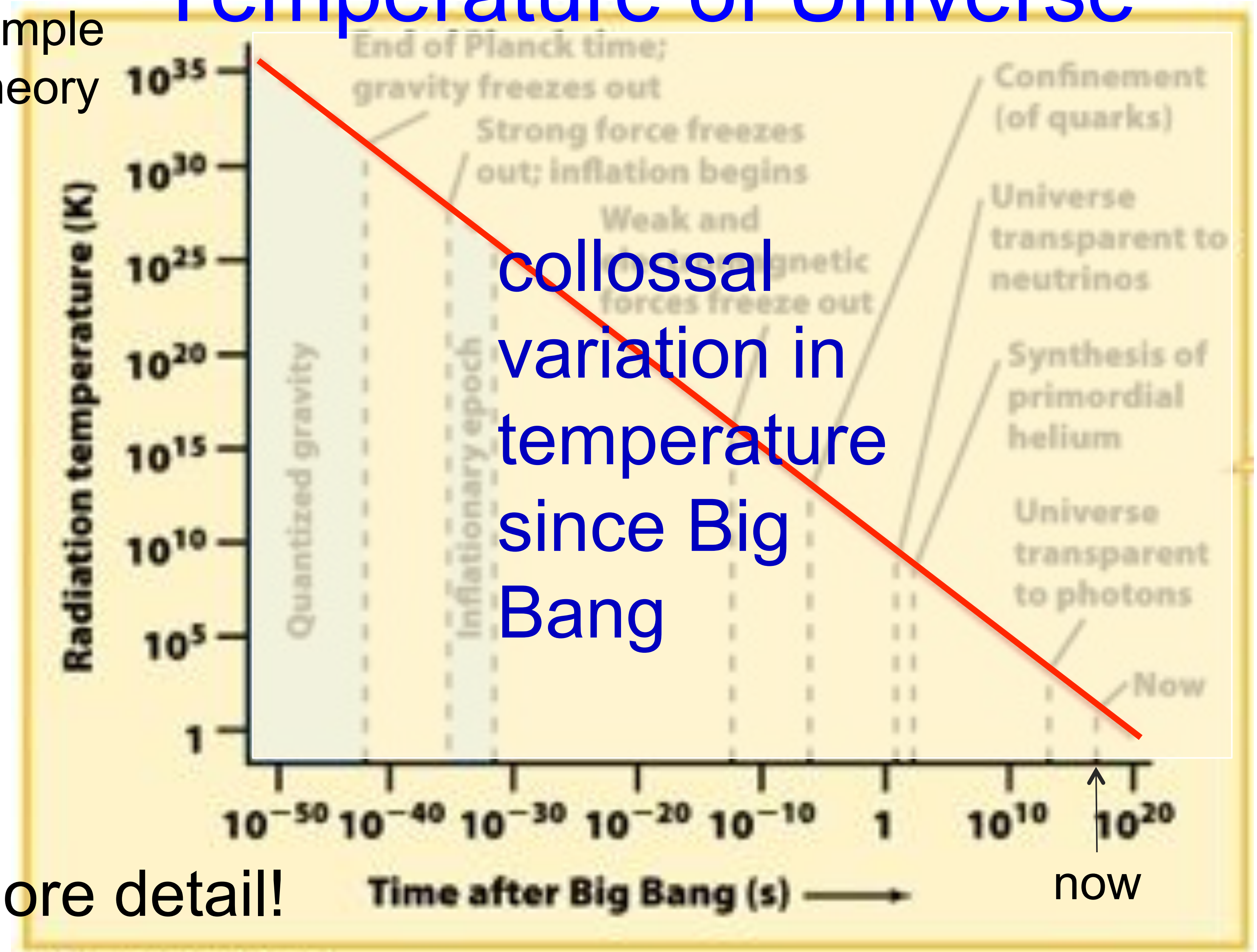


- Why is the sky dark?
  - The sky would have the surface brightness of the sun if the Universe were infinite.
  - Therefore …
- The Universe must be finite!
- Agrees with finite age to the expansion!

AT 27.2 part

from simple theory

Temperature of Universe



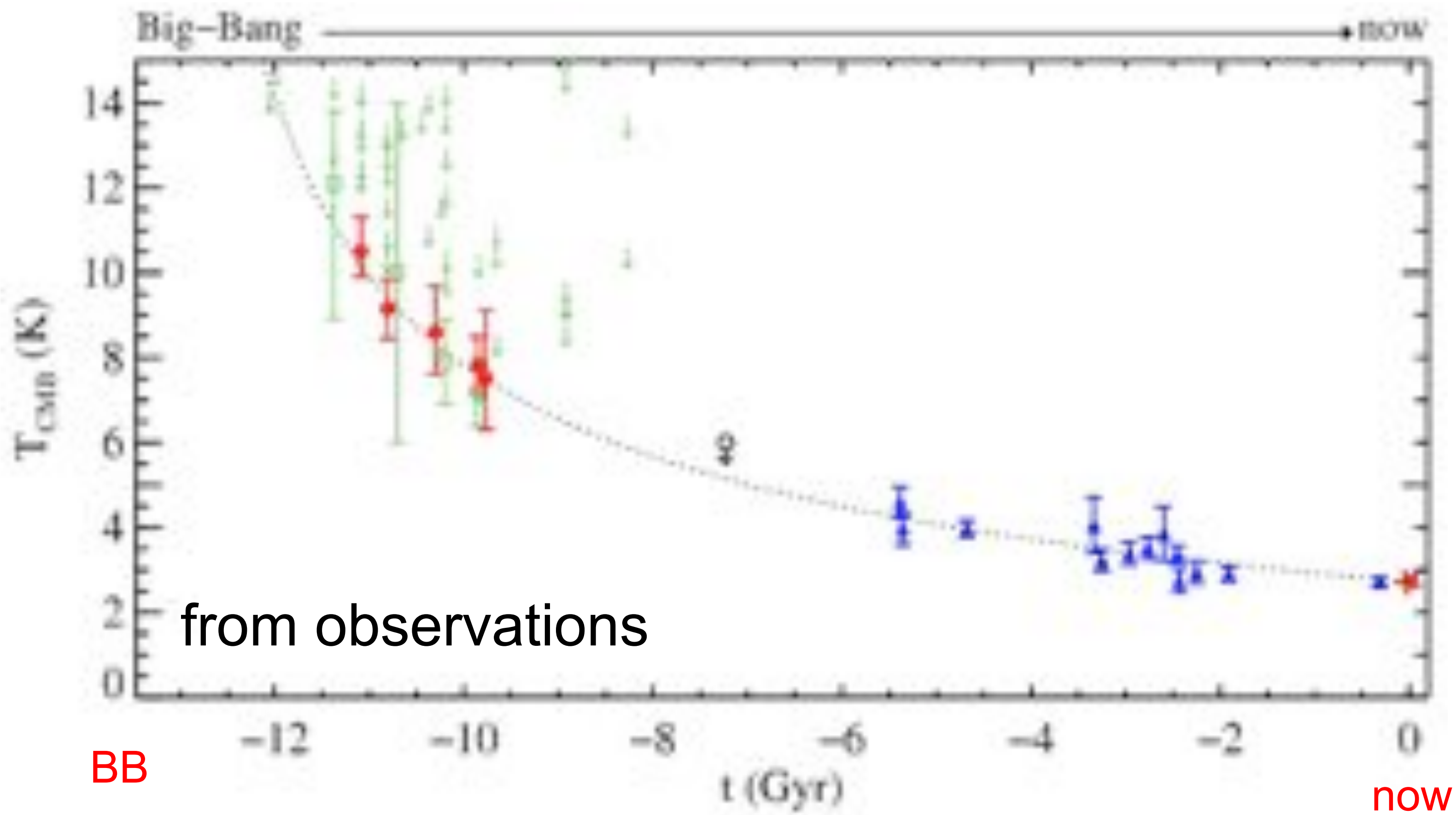
collossal variation in temperature since Big Bang

now

ignore detail!

Temperature of Universe

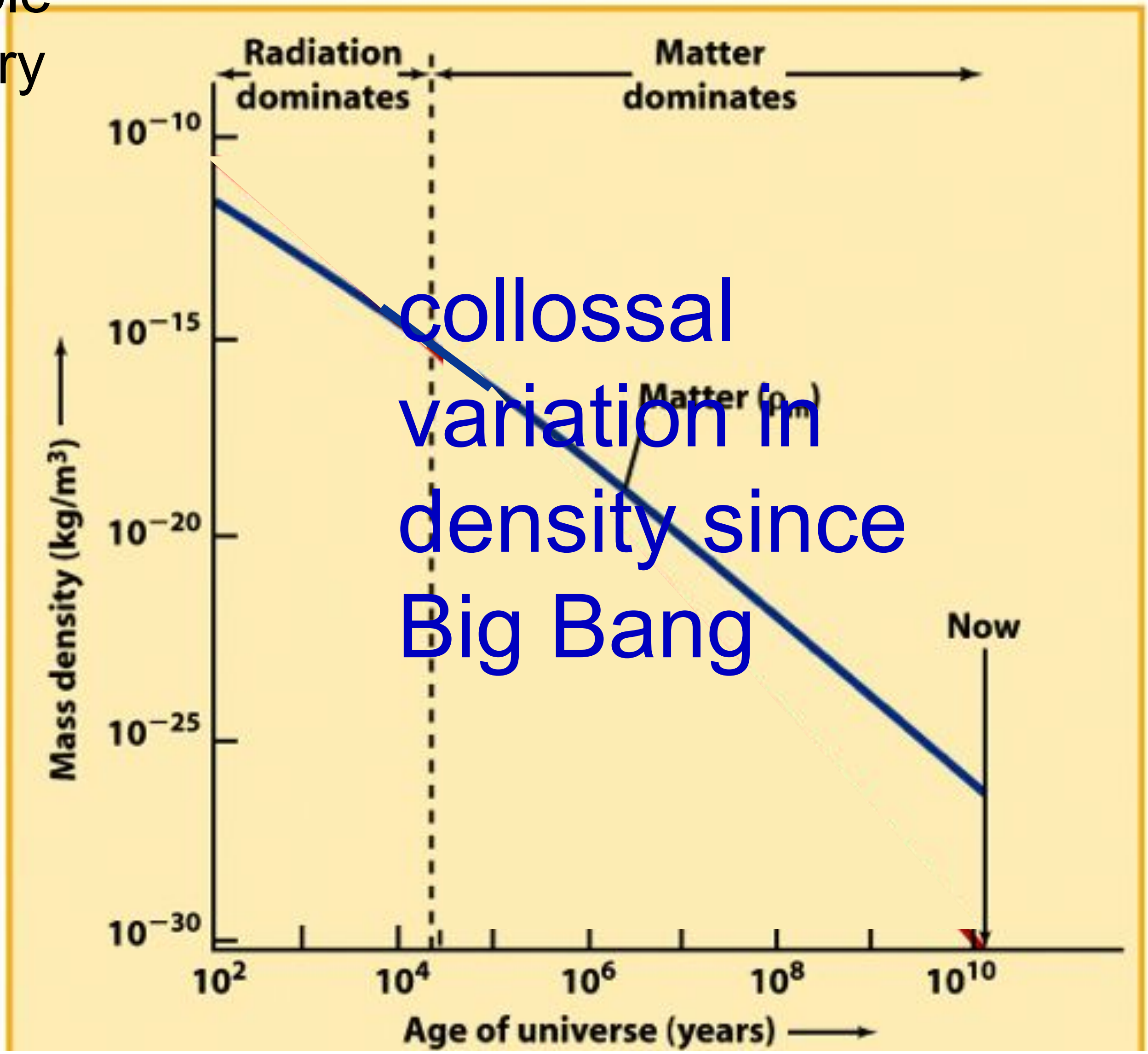
Q: what is mean by “temperature”?



- http://www.das.uchile.cl/das_ingles/new_temp_measurements.php

Density of Universe

from simple theory



collossal variation in density since Big Bang

Q: Why does it drop?

The Early Universe

- There must have been a very high density, and high temperature, phase early in the Universe:

The Hot, Dense Big Bang

- The Universe has been expanding, cooling, and becoming less dense since the initial big bang.

The Hot Big Bang

- Q: Is there independent observational evidence for a hot dense big bang?
- Yes, a lot. We'll consider three pieces of evidence:
    1. *Big Bang Nucleosynthesis*
    2. *Cosmic Microwave Background Radiation*
    3. *Inflation and the Horizon Problem*

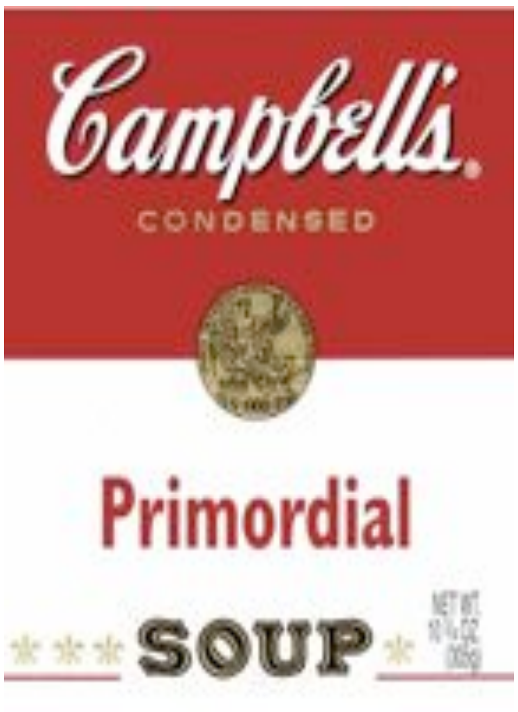
AT 27.3

Evidence for a Hot Big Bang

1. Big Bang Nucleosynthesis

Evidence for a Hot Big Bang
1. Big Bang Nucleosynthesis

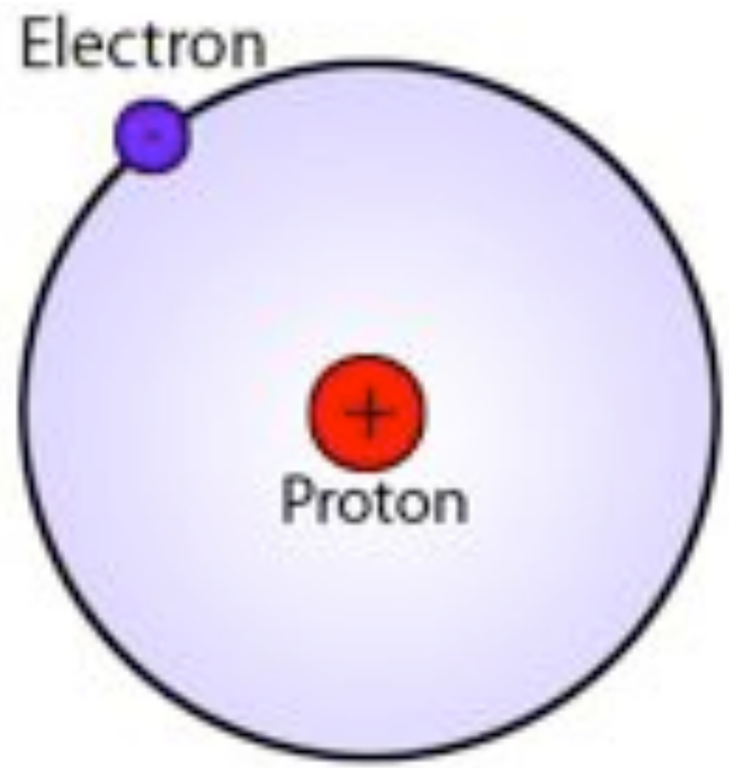
- Really early Universe (t <<< 1 sec) – what was it? Answer …



a primordial soup of quarks, gluons, bosons, radiation, dark matter …

$T >> 10^{10}$ K

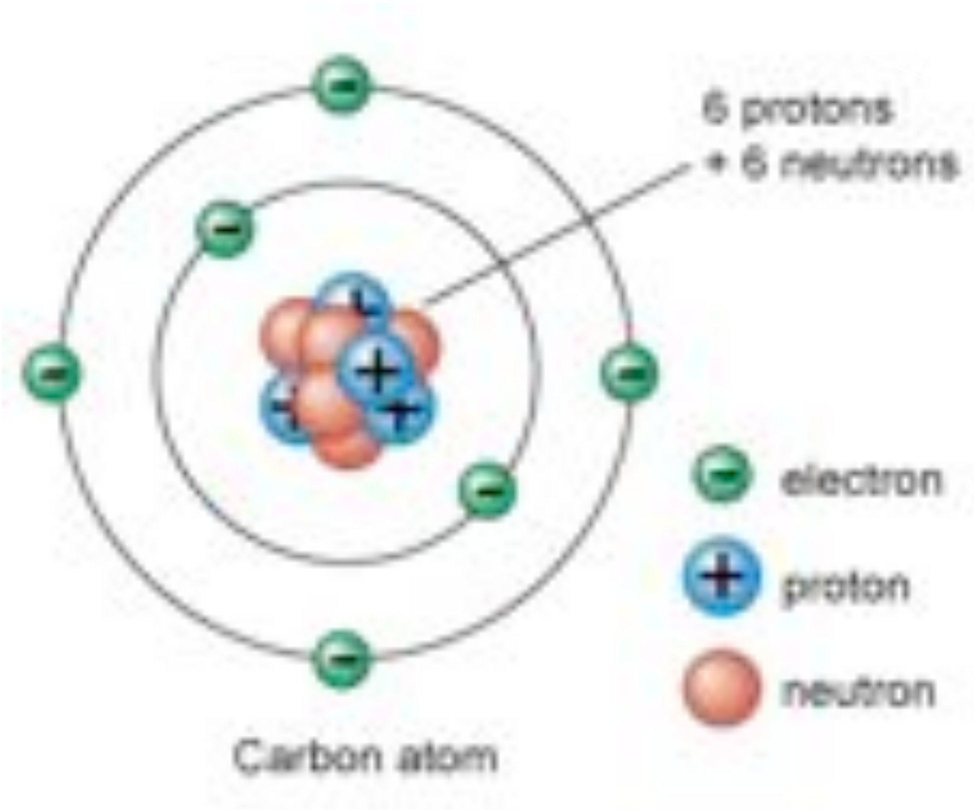
Atoms and Nuclei



Hydrogen atom:
Proton + electron

Nucleus on its own
stripped of electron:

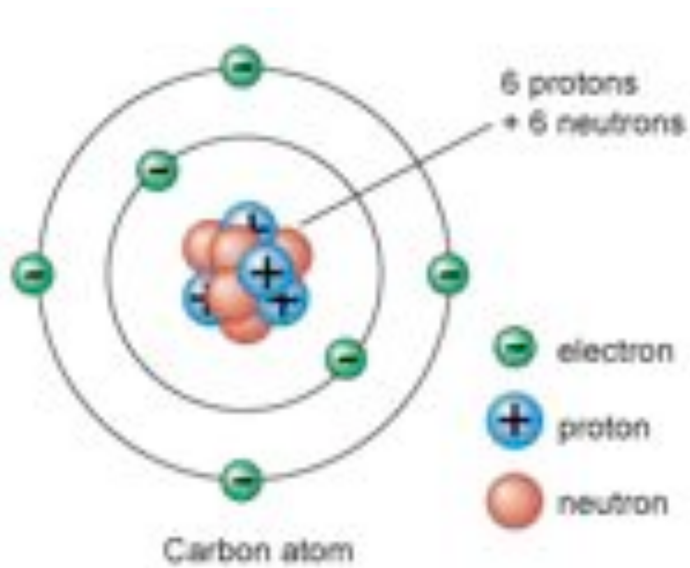
Atoms and Nuclei



Carbon atom:
6 protons
+ 6 neutrons
+ 6 electrons

nucleus on its own,
stripped of electrons:

Atoms and Nuclei



- electron is about 1/2000 mass of proton or neutron
- nucleus (10^{-14} m) is tiny compared to electron "orbits" (10^{-9} m) – atom is mostly empty space
- *Nucleus held together by the "strong force" – otherwise violent repulsion!*
- atomic weight = # of protons + # of neutrons
- atomic number = # of protons
- chemistry from electrons

Nuclear Reactions

AT 16.6

http://www.youtube.com/watch?v=pusKlK1L5To

Nuclear Reactions: E=mc²

- Einstein's (1905) famous equation:

$$E = mc^2$$

- In this equation, c is the speed of light, which is a very large number.
- A small amount of mass is the equivalent of a ***huge*** amount of energy
- This is how nuclear reactions produce energy, and this is where the energy from the sun comes from!

Example: suppose you destroy 1 gram of matter …

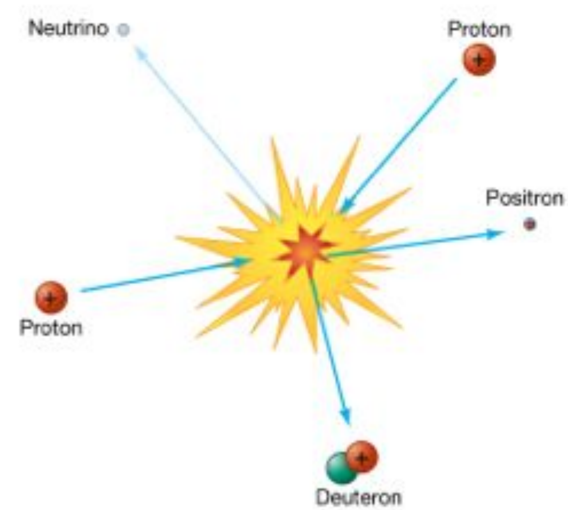

$\cancel{E=ma^2}$
$\cancel{E=mb^2}$
S. Harris

Nuclear Reactions

Nuclear fusion requires that like-charged nuclei get close enough to each other to fuse.

This can happen only if the temperature is extremely high—over a few million K.

Discuss: Why?



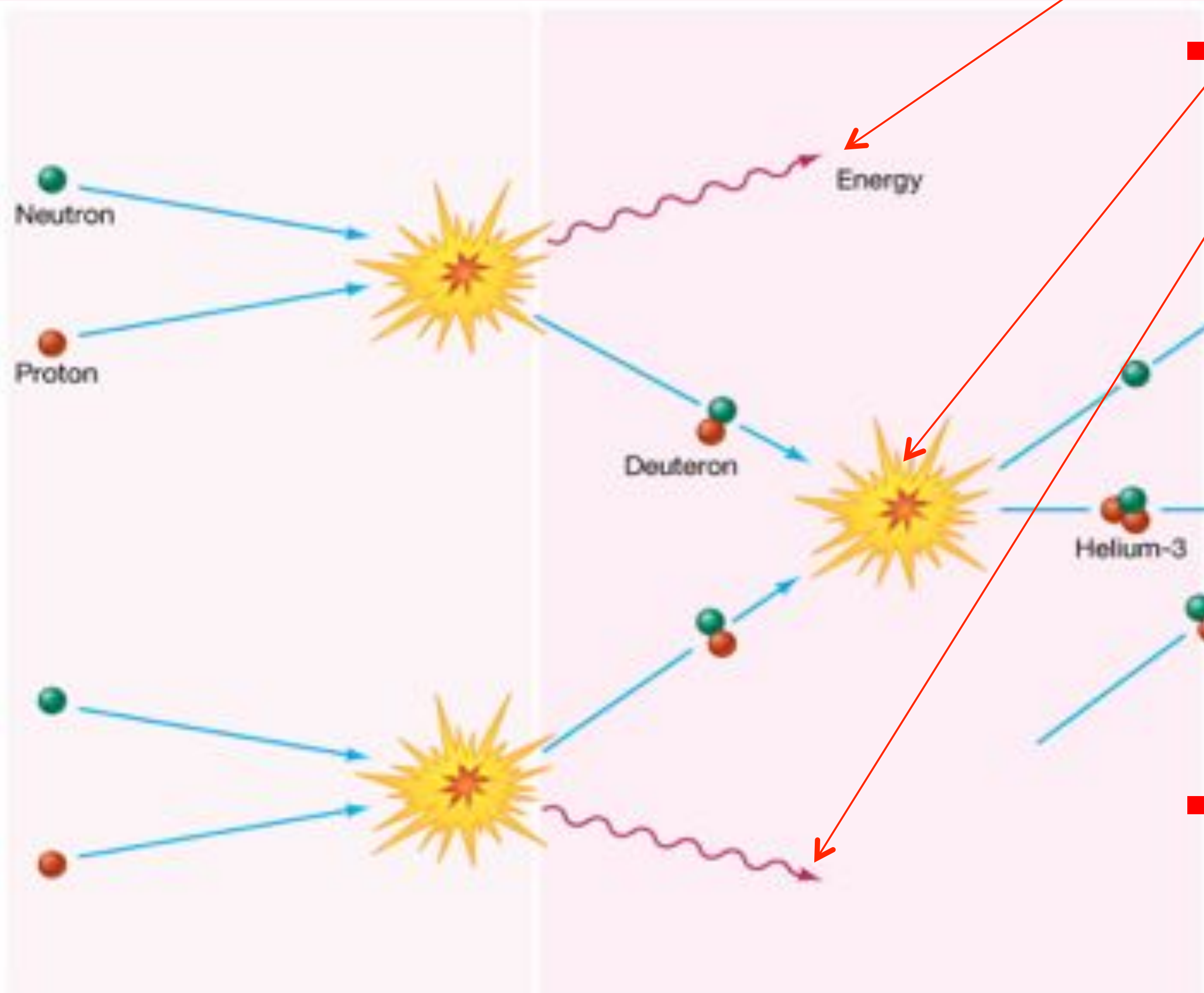
Big Bang Nucleosynthesis

- Fast forward from the Big Bang to t =1 sec after Big Bang:
  - mostly protons, neutrons, radiation, dark matter
  - $T \sim 10^9$ K and cooling
  - density ~ 1/1000th that of water and dropping

→ *nuclear reactions!*

Energy released – Later!

Big Bang Nucleosynthesis



- limited by number of neutrons
- nearly all neutrons get sucked into He formation

Net: 2 neutrons + 2 protons → a helium nucleus.

Big Bang Nucleosynthesis

- net result ~10% helium by number (25% by mass)
- **almost exactly as observed!**
- the rest H, trace amounts of D, Li …
- No other way to make this helium

Requires **The Hot, Dense Big Bang**

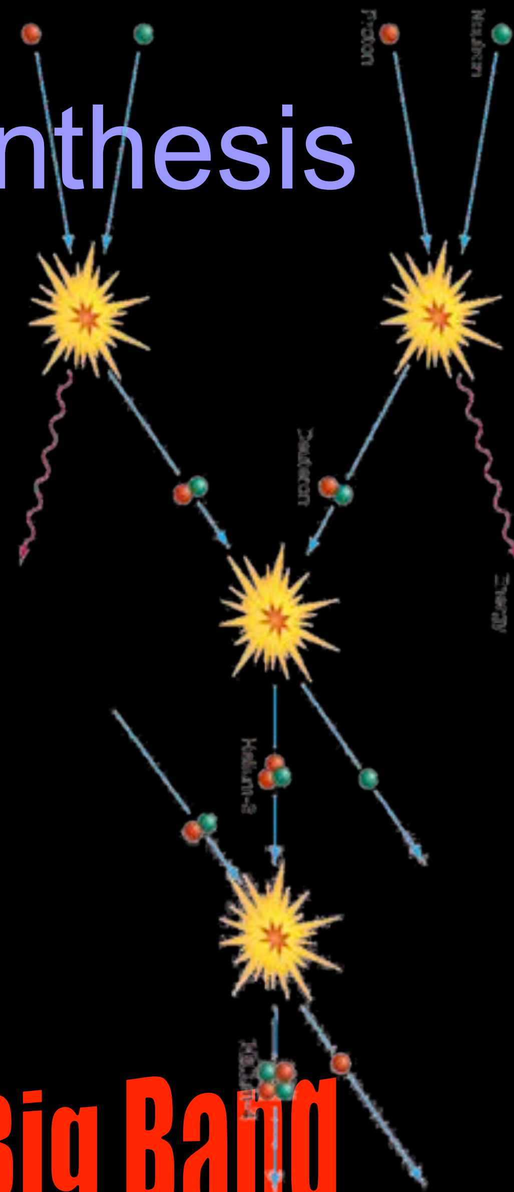
Big Bang Nucleosynthesis

- Q: why do the reactions stop there? Why not C, O, Fe etc as in the stars?

- Q: why no nuclear reactions at earlier times, when it was hotter and denser?

Big Bang Nucleosynthesis

1. Nuclear reactions fuse light elements early in the big bang
2. Exact agreement with observed abundances of light elements!



Requires **The Hot, Dense Big Bang**

Where does iron come from?

A. Nuclear reactions seconds to minutes after the Big Bang
B. Nuclear reactions thousands of years after the big bang
C. The Big Bang itself, at time=0
D. Exploding stars
E. Spontaneous generation from black holes

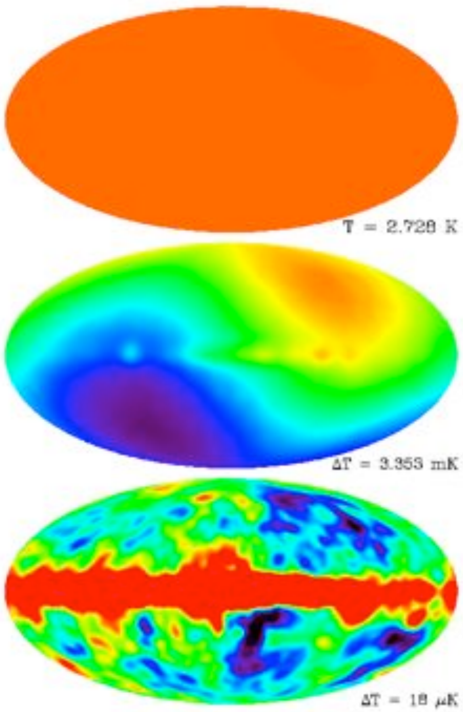
Why were there no nuclear reactions in the big bang before t=1 sec, when the Universe was hotter and denser?

A. Nuclear reactions happen faster when the temperature is cooler
B. Nuclear reactions happen faster when the density is lower
C. There were no protons or neutrons to react prior to 1 sec after the BB
D. There were reactions – it's just that energetic photons split apart the products of the reactions as soon as they were created.

Evidence for a Hot Big Bang
2. *Cosmic Microwave Background "Radiation"*

AT 26.7, 27.6

light



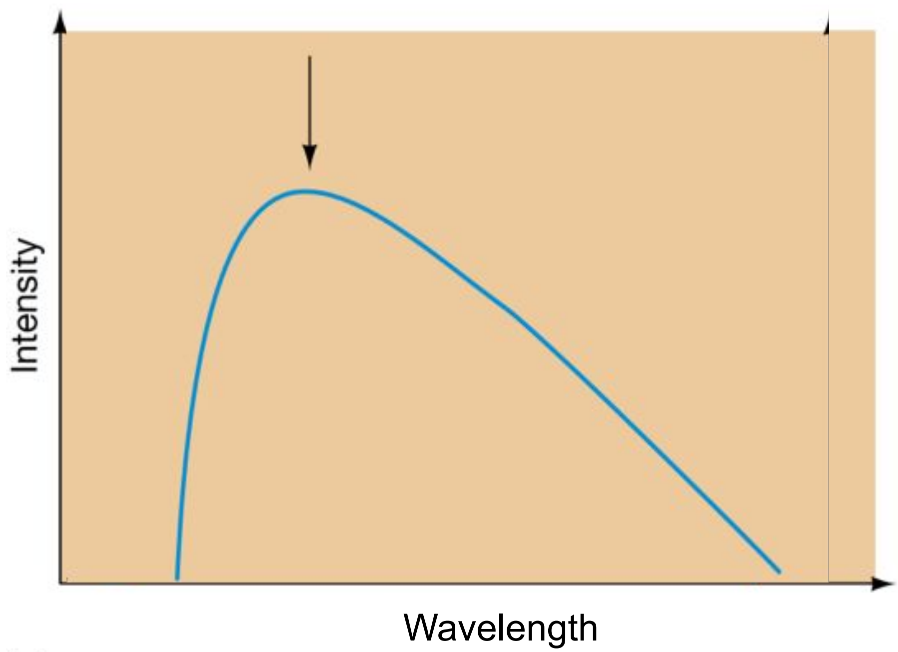
- First we need to talk a bit more about light, in particular **"black body radiation"** [AT 3.4]

http://www.youtube.com/watch?v=B7pACq_xWyw http://www.youtube.com/watch?v=RIV6IEu5CBk

Blackbody (Thermal) Radiation

AT 3.4

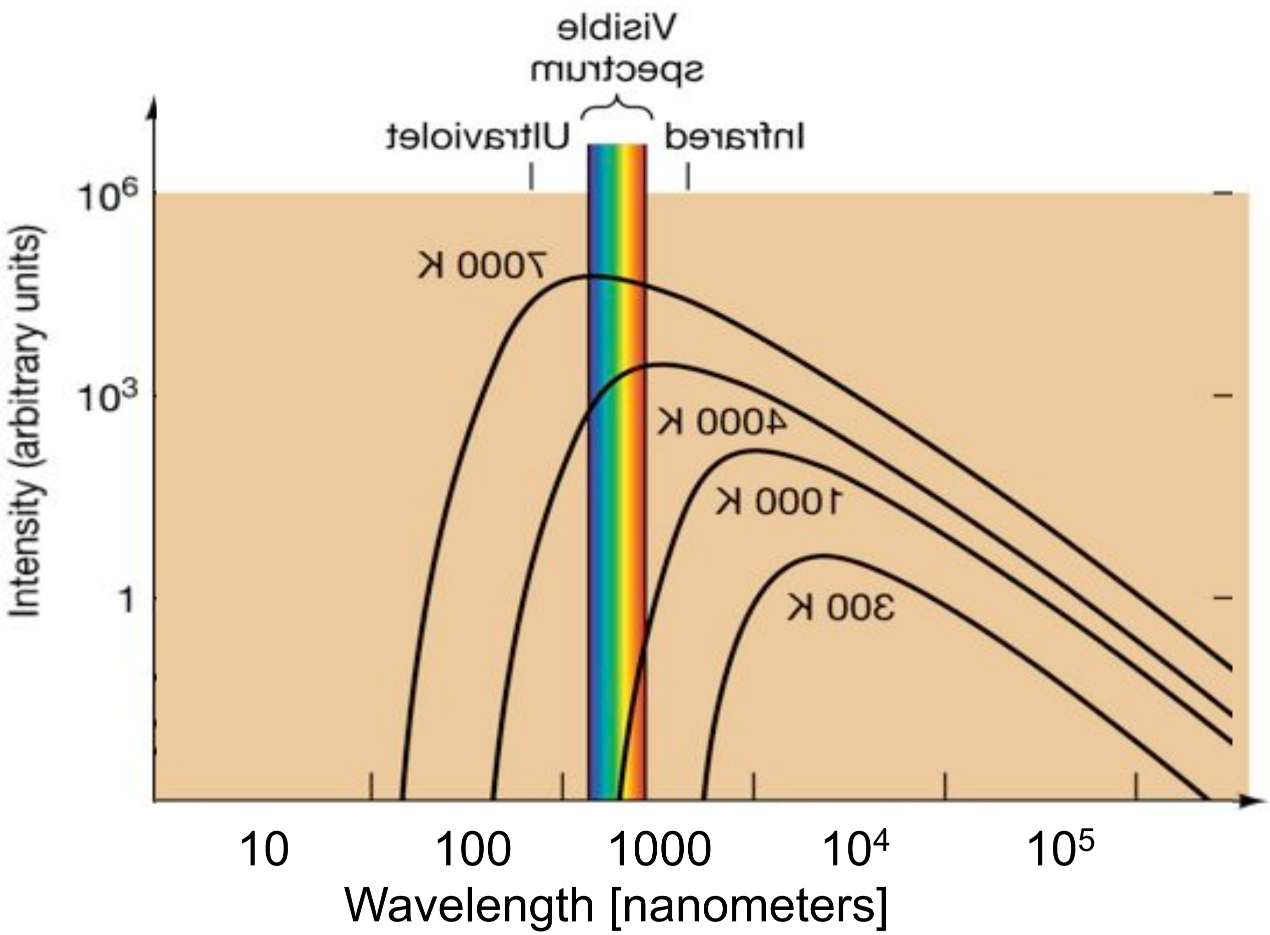
Blackbody spectrum: All objects not at absolute zero emit continuous radiation. Radiation emitted by an object depends “primarily” on its temperature.



Observed by many 1800s, theory Max Planck 1900

Blackbody Radiation Laws

- Wien's Law: Peak wave-length is inversely proportional to temperature



Blackbody Radiation Laws

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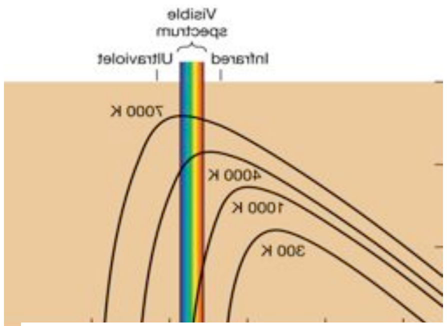


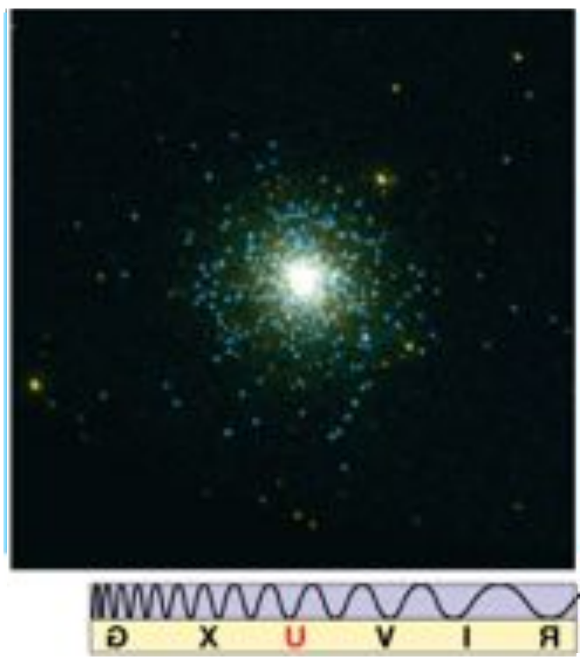
Wavelength [nanometers]

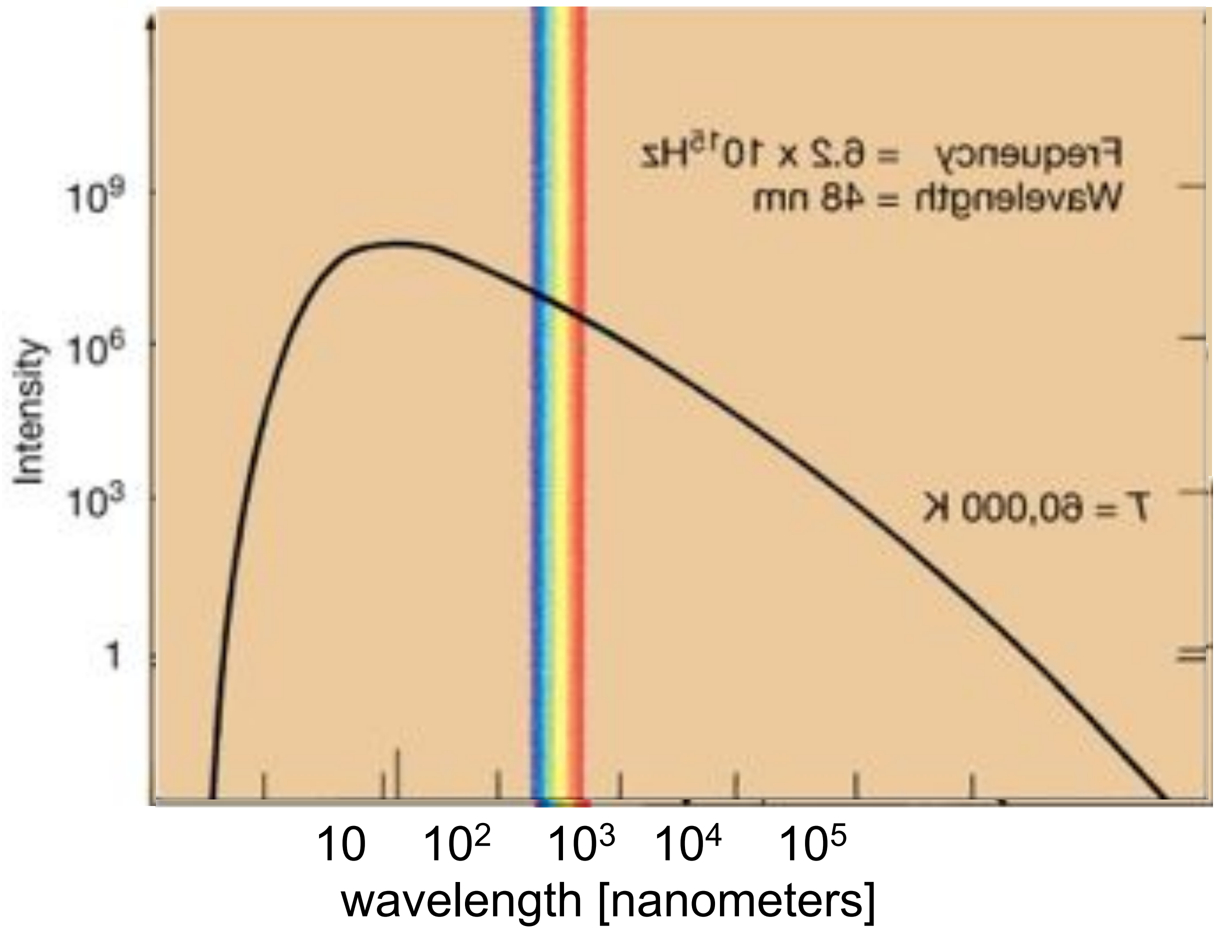
$$\lambda_{max} = \frac{0.003}{T} \text{ metres}$$

Wavelength of peak

Temperature In K

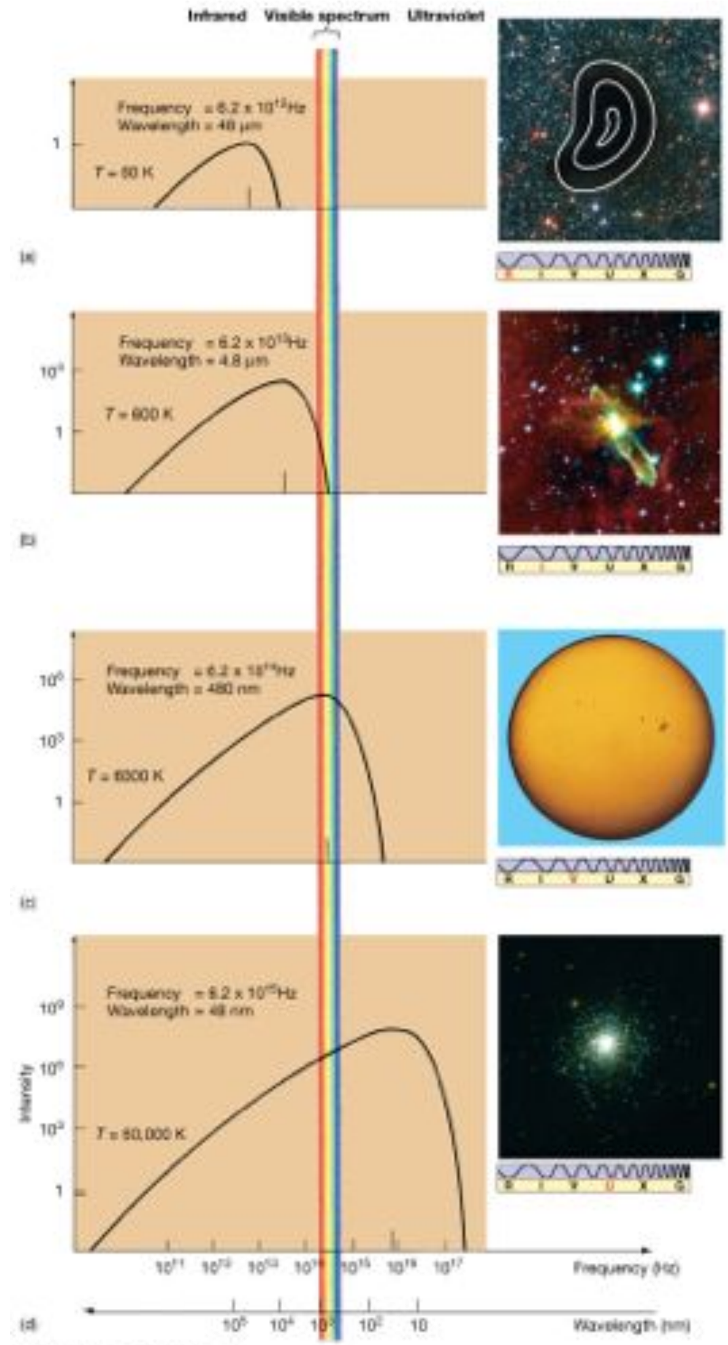
Blackbody Radiation Laws





Blackbody Radiation Laws

- Stefan-Boltzmann Law: Total energy emitted is proportional to fourth power of temperature (note height of curves).



Blackbody Radiation Laws

Stefan-Boltzmann Law: Total energy emitted per unit area is proportional to fourth power of temperature.

$$\underbrace{F}_{\text{Energy per unit area}} = \underbrace{\sigma}_{\text{Constant}} \underbrace{T^{4}}_{\text{Temperature to the fourth power}}.$$

Blackbody Radiation Laws

Stefan-Boltzmann Law:

$$F = \sigma T^4.$$

Energy per unit area

Constant

Temperature to the fourth power

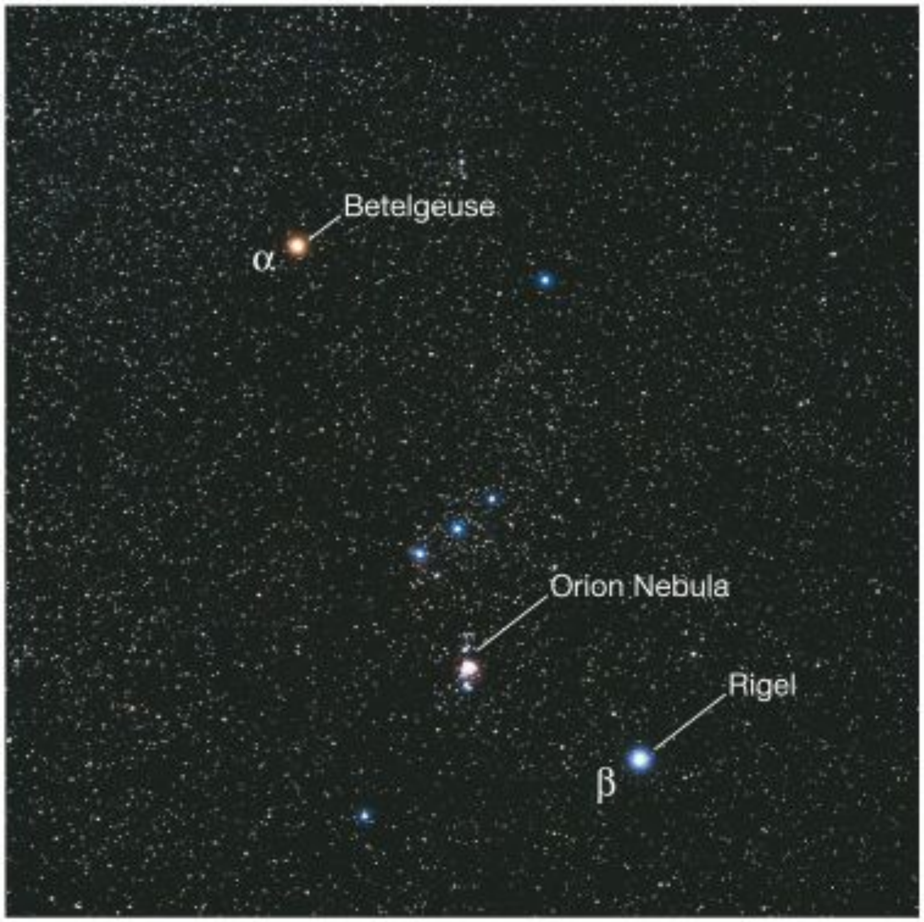
Two stars the same size: one has a temperature of 6000 K, the other 12000 K. How much power does the hot one emit compared to the cool one?

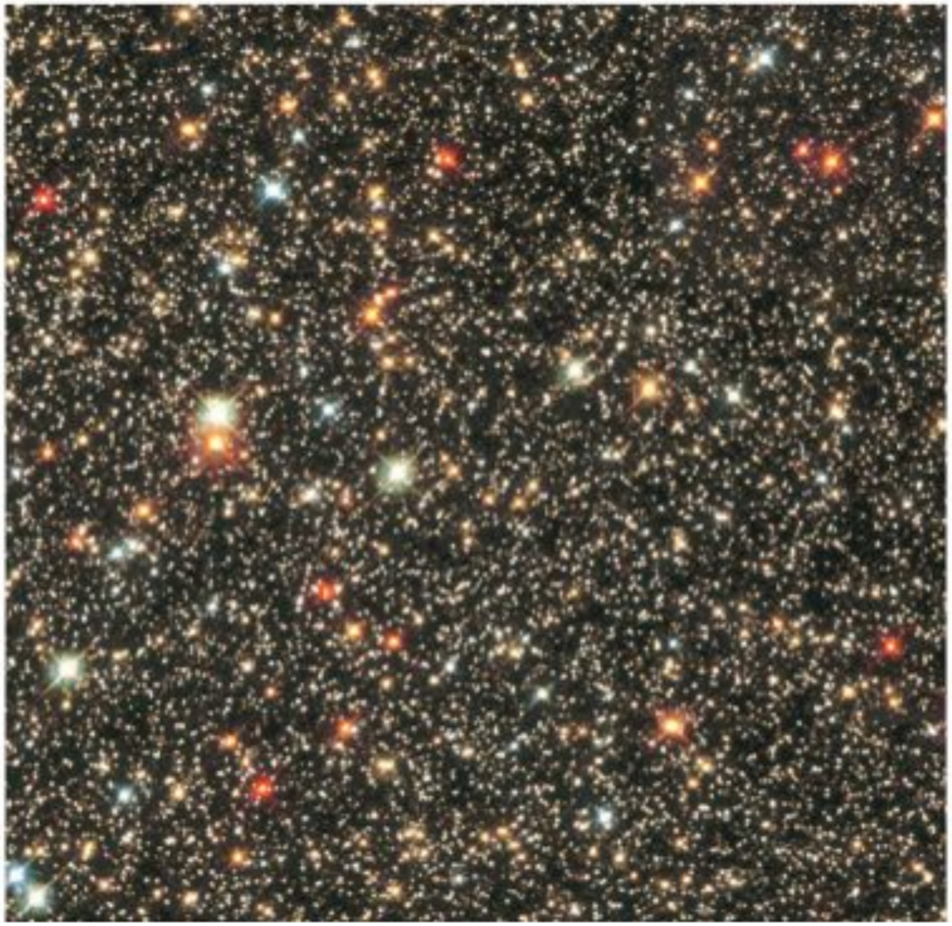
Q: why "the same size"?

Stellar Temperatures

AT 17.3

The color of a star is indicative of its temperature. Red stars are relatively cool, whereas blue ones are hotter.





AT 26.7, 27.6

Evidence for Hot Big Bang

2. Cosmic Microwave Background "Radiation"

light

2. Cosmic Microwave Background "Radiation"

AT 26.7, 27.6

- Large microwave low noise "horn", early 1960's – reflection off Echo satellites

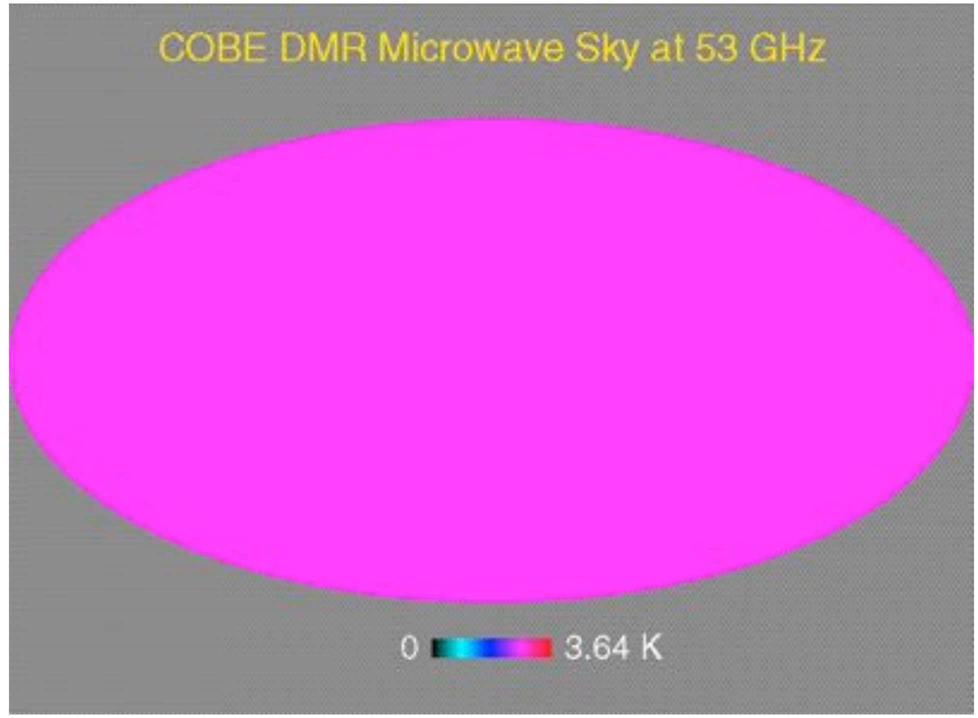
http://en.wikipedia.org/wiki/Discovery_of_cosmic_microwave_background_radiation

2. CBR

Cosmic background radiation

- Very low noise sensitive amplifiers
- Found an intense source of low energy (microwave) ***light*** filling the sky
- Interpreted as the relic radiation of the Big Bang
- Penzias and Wilson 1964 (Nobel 1978)

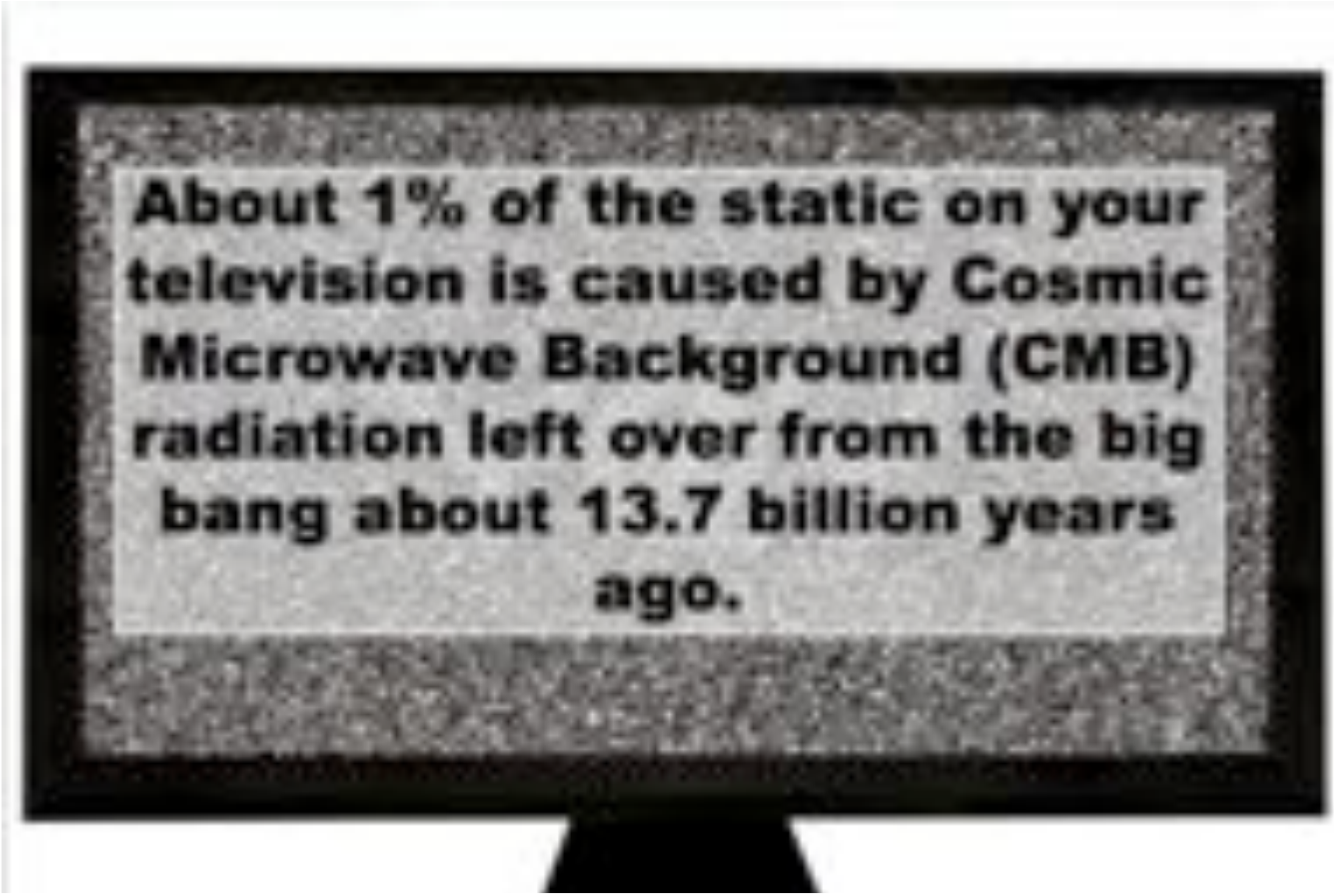
CBR



- one billion photons for every particle of matter in the Universe!
- isotropic (same in all directions), constant

almost

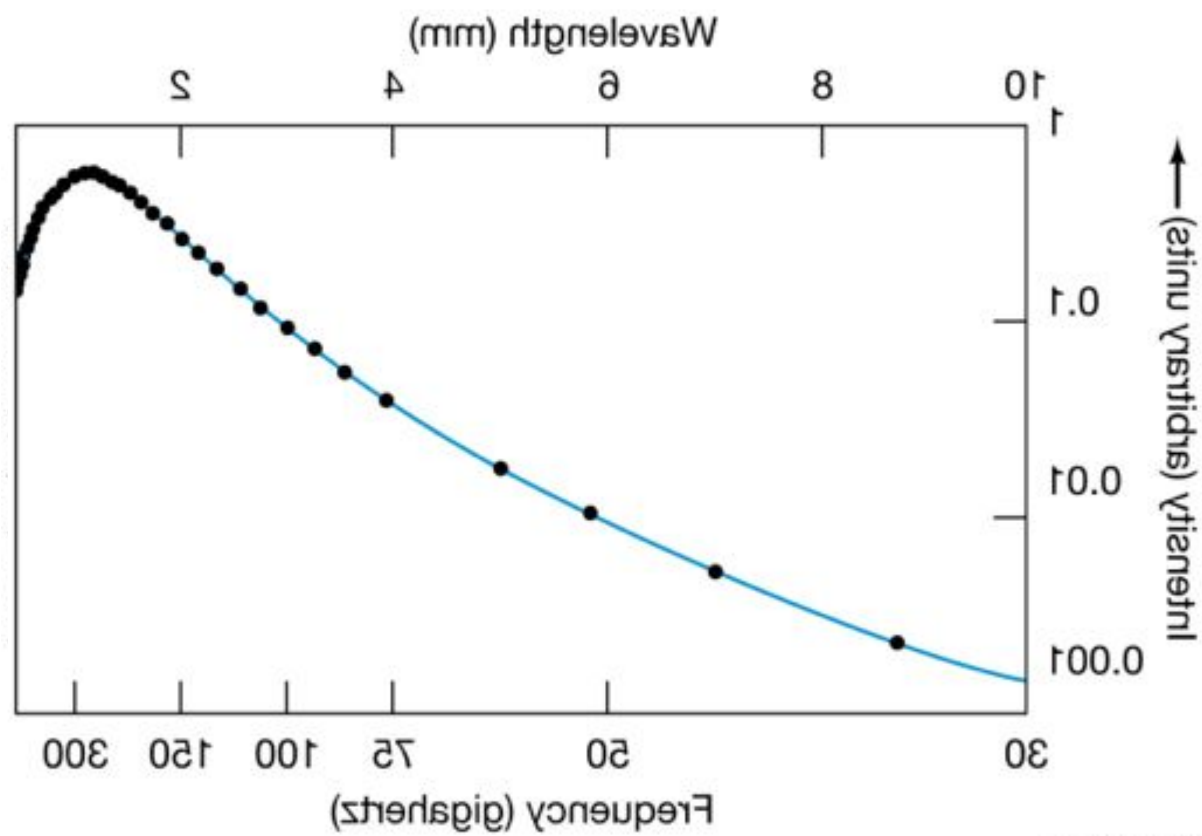
Cosmological Principle - "Universe is homogeneous and isotropic" [will come back to]


About 1% of the static on your television is caused by Cosmic Microwave Background (CMB) radiation left over from the big bang about 13.7 billion years ago.

Cosmic Background Radiation

Since then, the cosmic background spectrum has been measured with exquisite accuracy – e.g. COBE:

Why satellite?

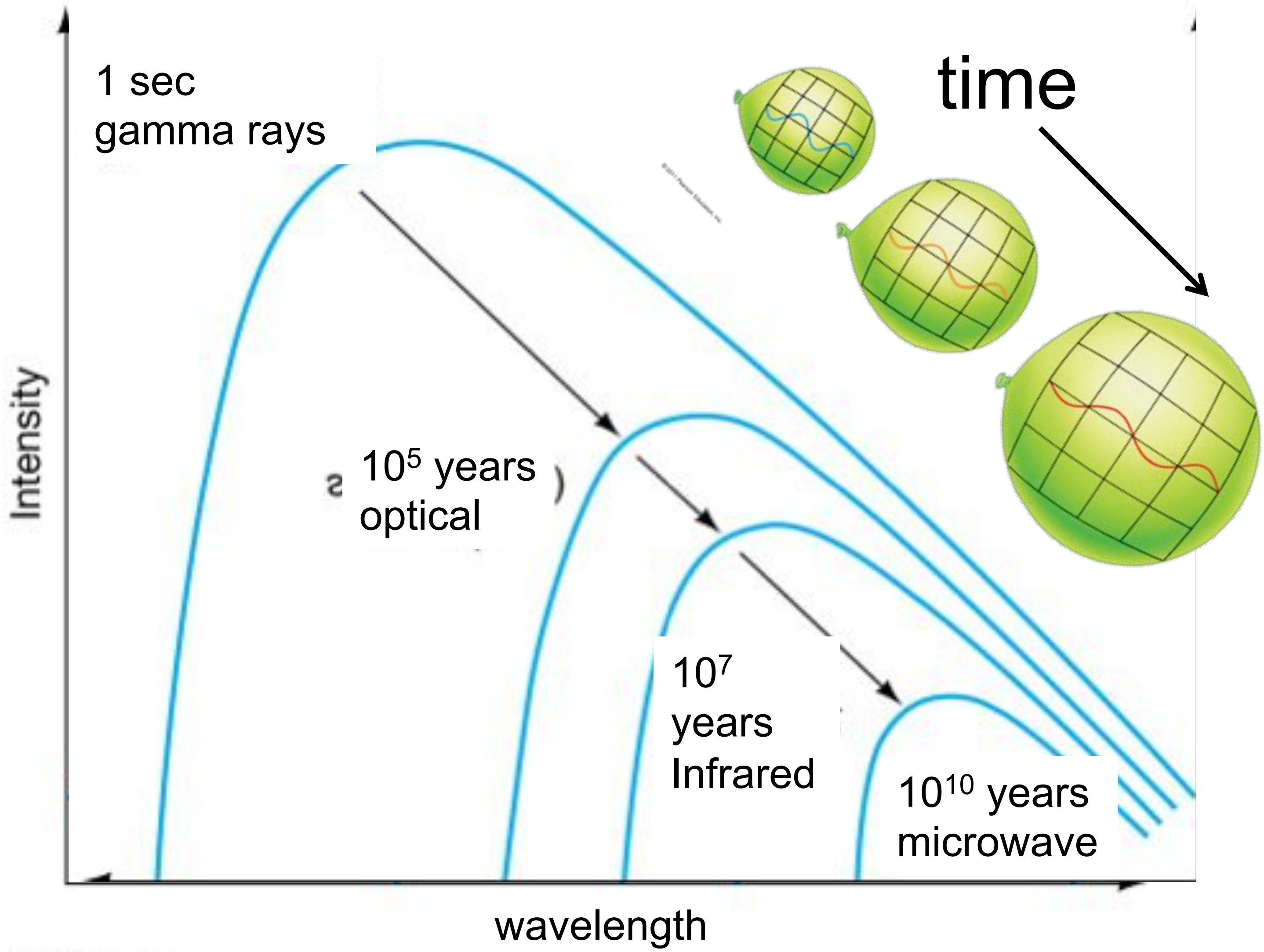


Cosmic Background Radiation

What is it?

- Ans: “relic” light from the Big Bang! Predicted by George Gamow c. 1950
- The Universe was hot and dense in the past → blackbody radiation that we observe today.
- But why is the light in the radio or microwave if it was emitted by a very hot blackbody?

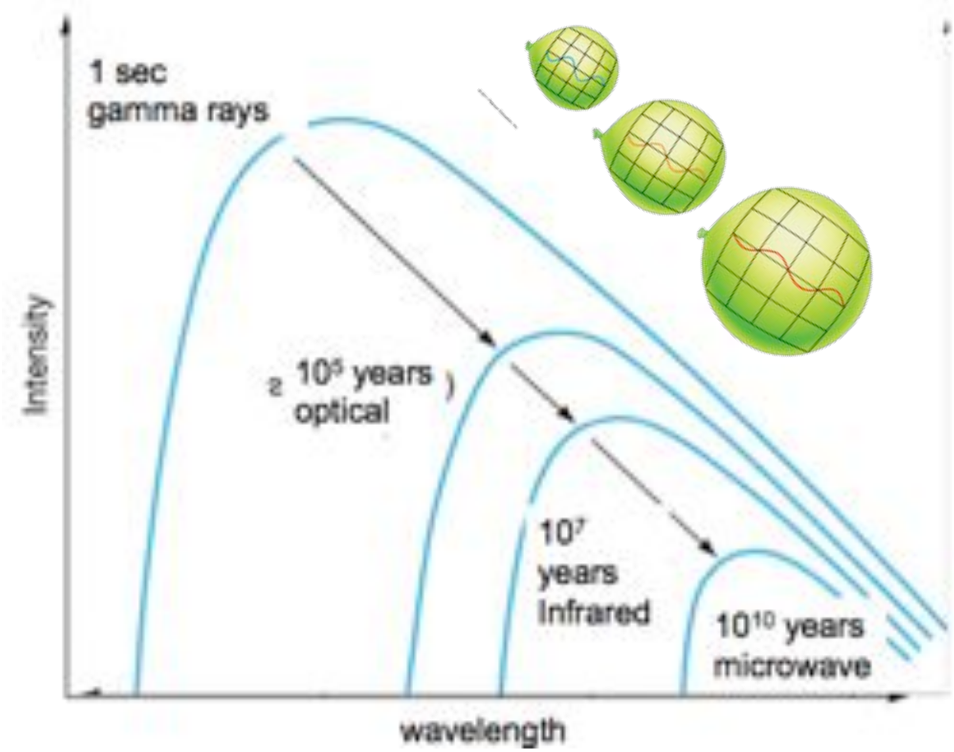
Cosmic Background Radiation



Text says that photons were generated 1 sec after BB – this is not correct!

Cosmic Background Radiation

- photons were created shortly after Big Bang
- $T \gg 10^{10}$ K, time << 1s
- gamma rays
- expansion of the universe has redshifted wave-lengths so that now they are in the radio spectrum, with a blackbody curve corresponding to about 3 K



Proof that early Universe was hot and dense.

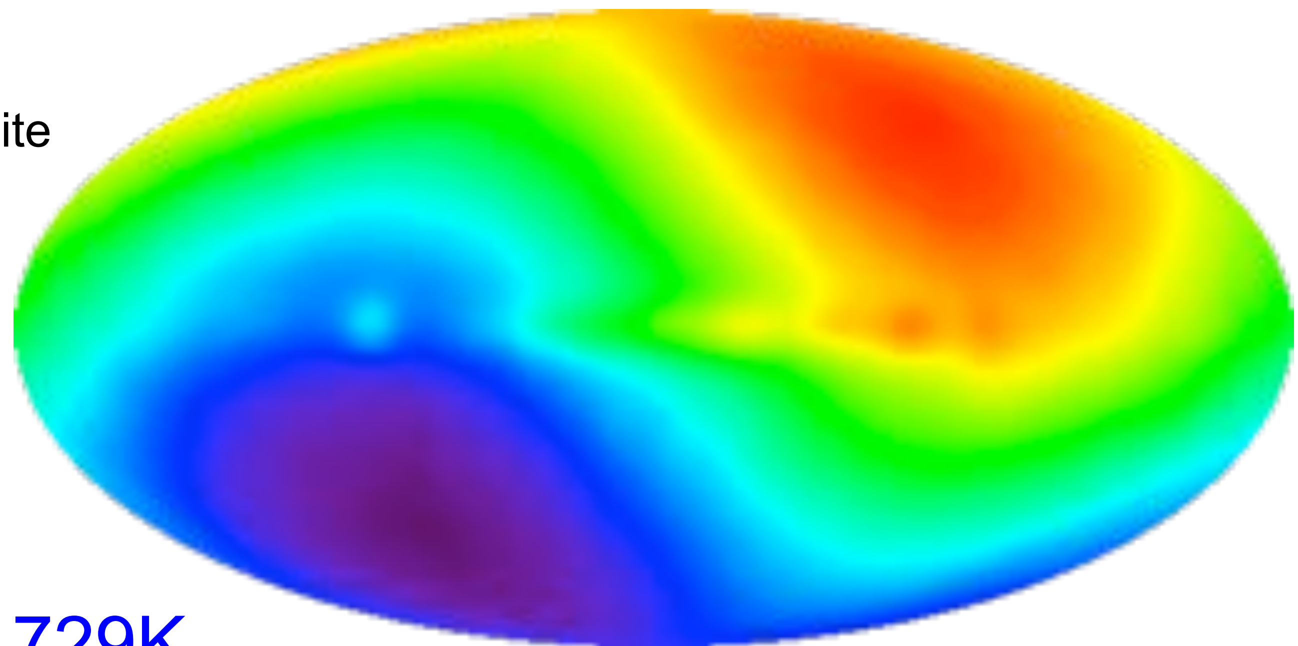
Entire sky

Smooth part
removed

Cosmic Background Radiation

- not quite uniform – distinct low level pattern (one thousandth of total signal)

COBE satellite
all-sky view

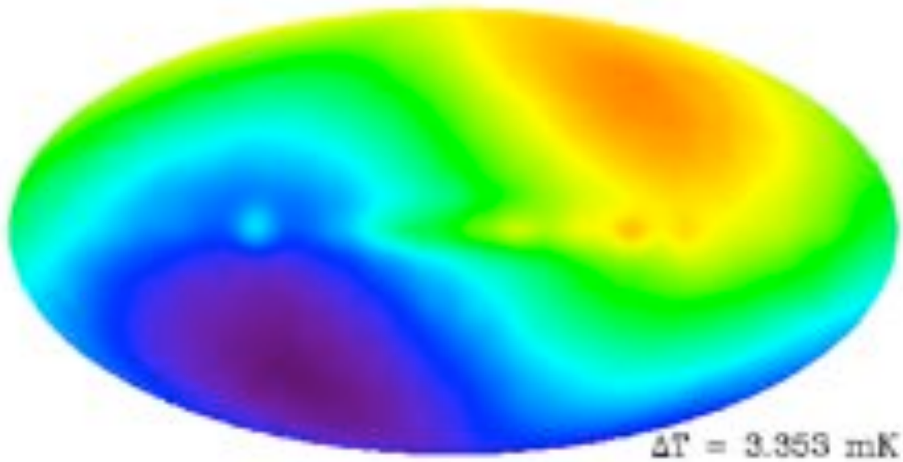


blue = 2.729K
red = 2.721K

Why?

Entire sky

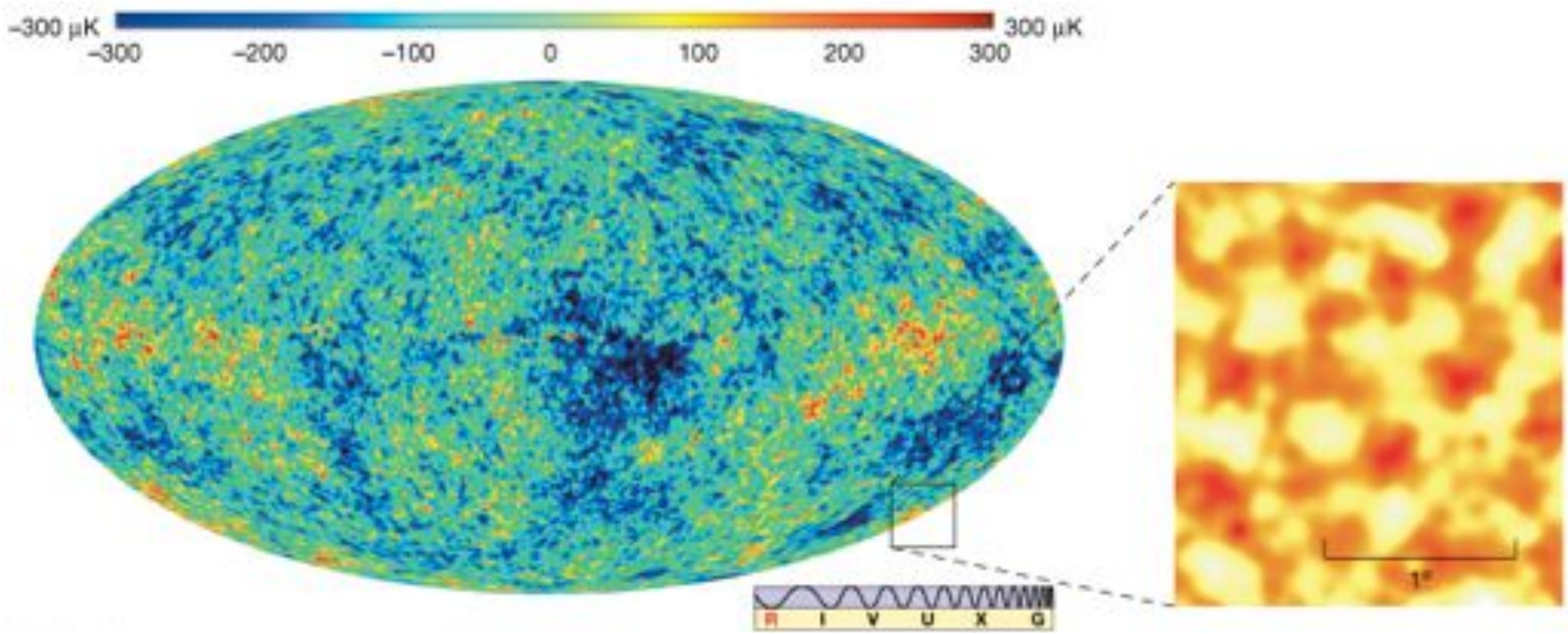
Smooth part removed



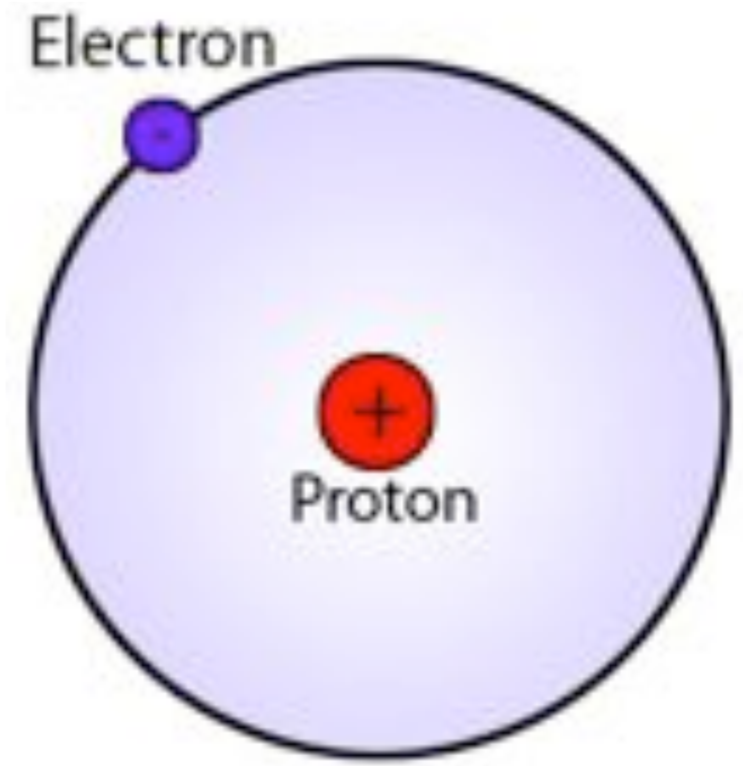
Smooth variation removed

Cosmic Structure and the Background Radiation

This is a much higher-precision map of the cosmic background radiation – WMAP satellite, after effects of (previous slide) removed.



Atoms and Ions

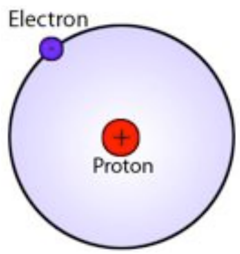


Hydrogen atom:
Proton + electron

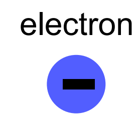
Nucleus on its own
stripped of electron

Discussion: under what conditions do you find hydrogen atoms stripped of their electrons?

Atoms and Ions



Discussion question: under what conditions do you find hydrogen atoms stripped of their electrons?



A. Very dense and compressed
B. Very low density, expanded

C. Very hot
D. Very cool
E. None of the above

The gas is said to be "ionized" when atoms are stripped of some of their electrons. The stripped atoms are called "ions".

CBR: Time 100,000 yr after BB

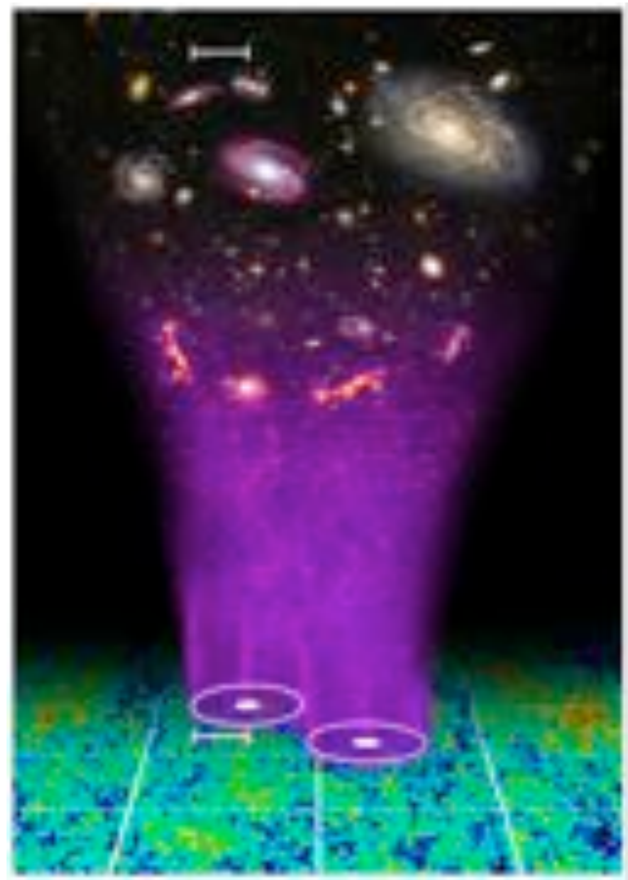
- Temperature 10,000 K ±
- Universe “radiation dominated”
- Most (90%) matter is hydrogen
  - How do we know this?
- (Nearly) all H atoms are ionized
  - sea of electrons and protons
- Free electrons absorb like crazy!

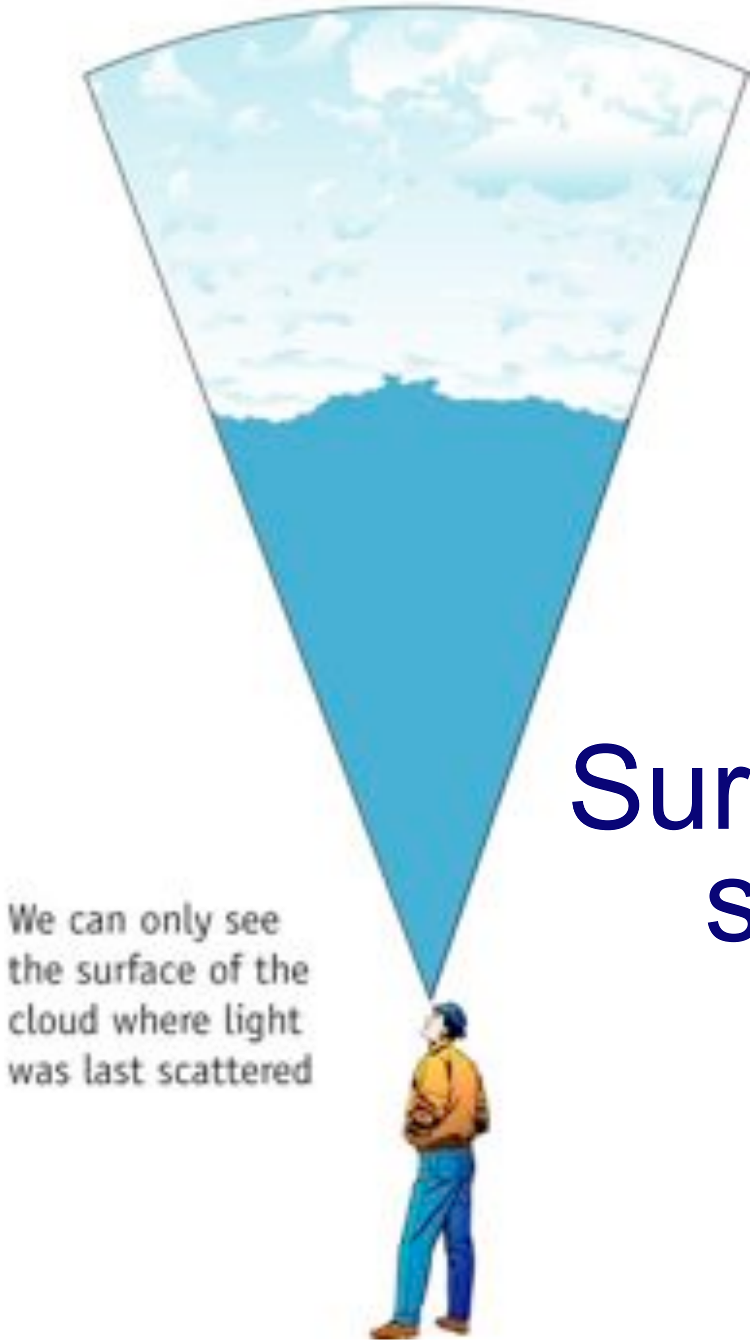
Cosmic Background Radiation

300,000 0 Years after big bang

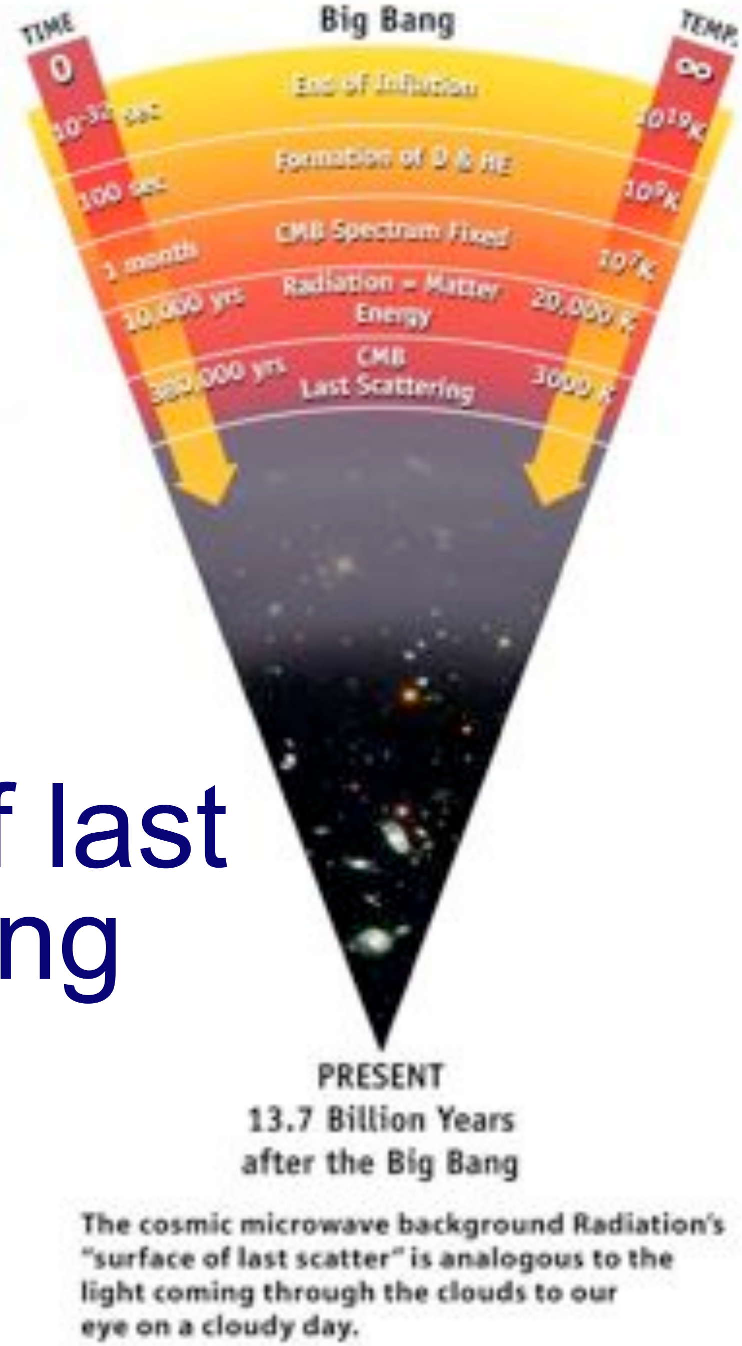
Cosmic Background Radiation

- Universe was a fog until ~400,000 yr after big bang (T~3000K)
- Cleared over 10 yr
  - Protons and electrons formed atoms of H, no electrons left to absorb
- photons we see trace that “surface”
  - tells us about blobs of gas that eventually become galaxies

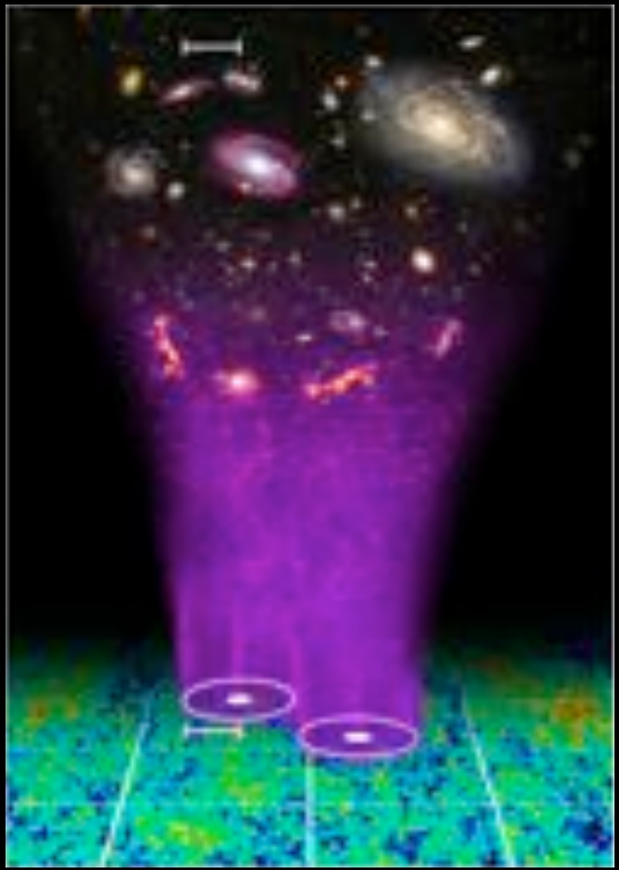




Surface of last scattering



Cosmic Background Radiation

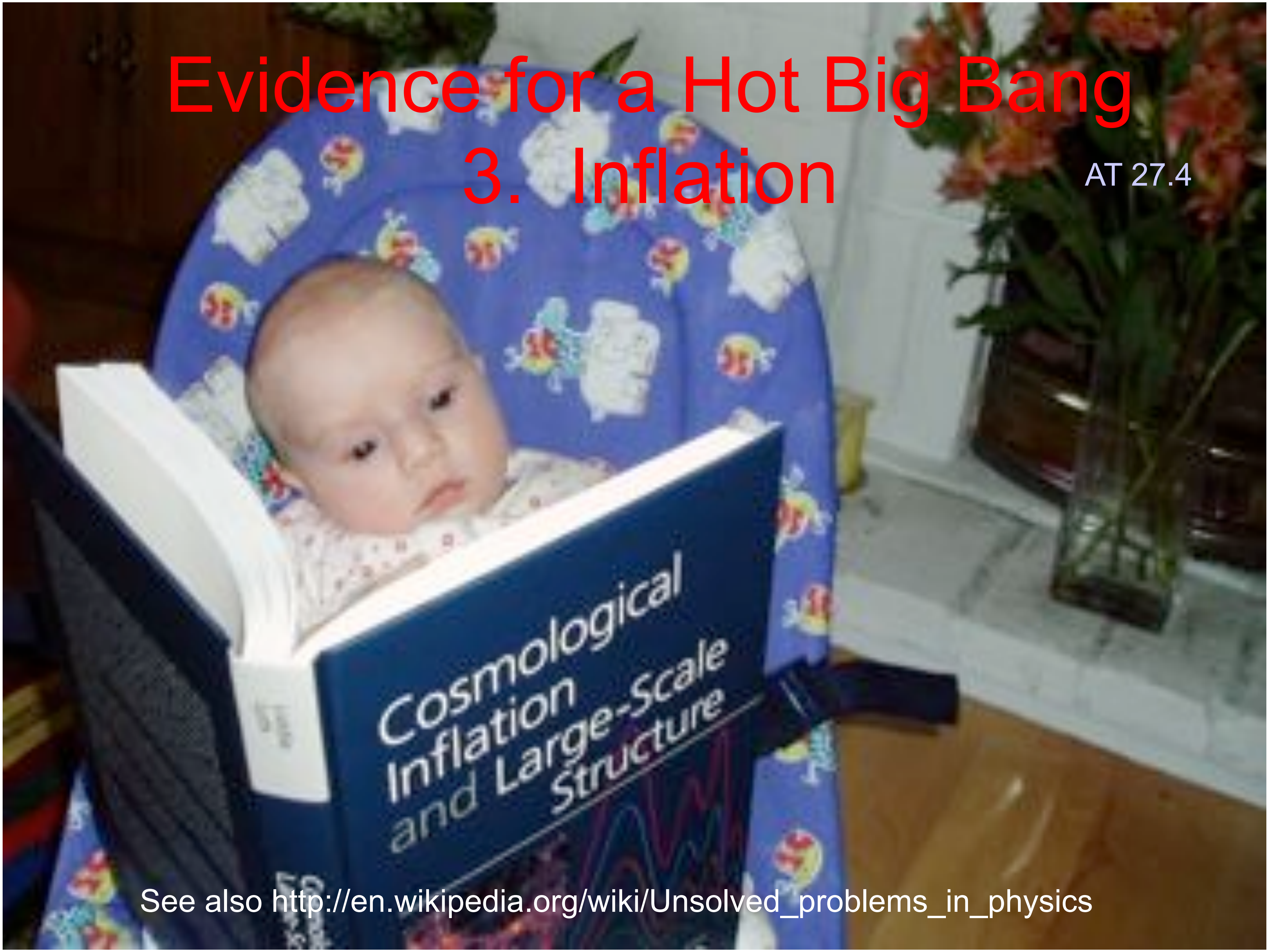


- Most important point: existence of background radiation

requires The Hot, Dense Big Bang

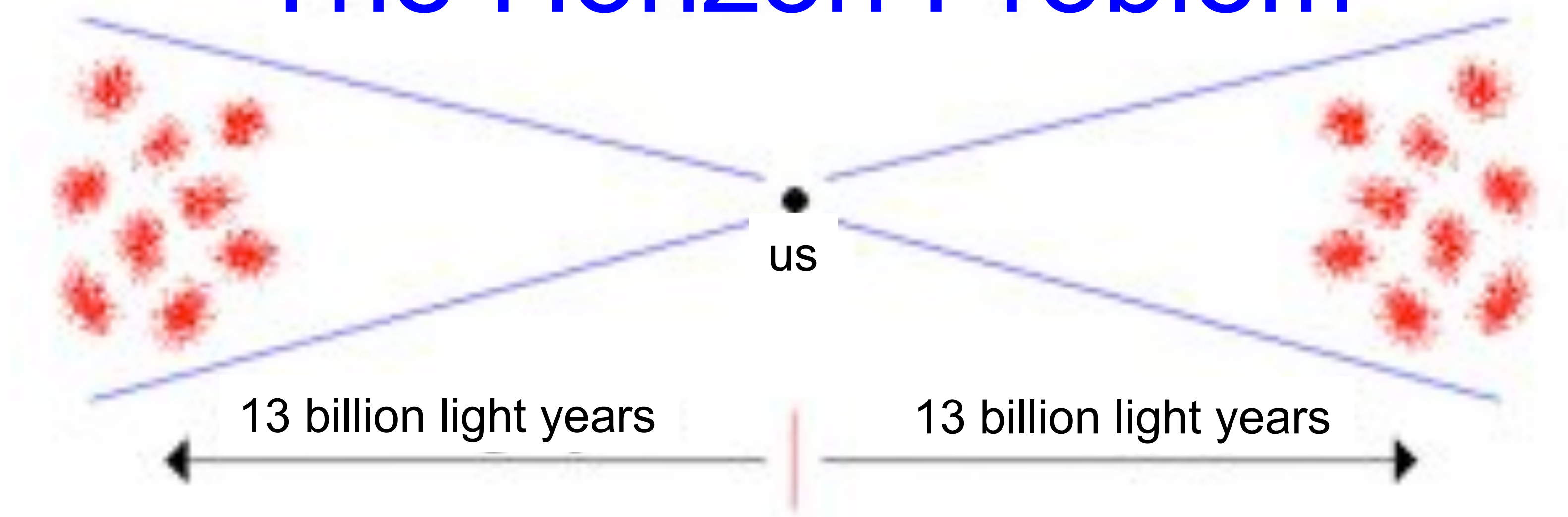
Evidence for a Hot Big Bang
3. Inflation

AT 27.4



See also http://en.wikipedia.org/wiki/Unsolved_problems_in_physics

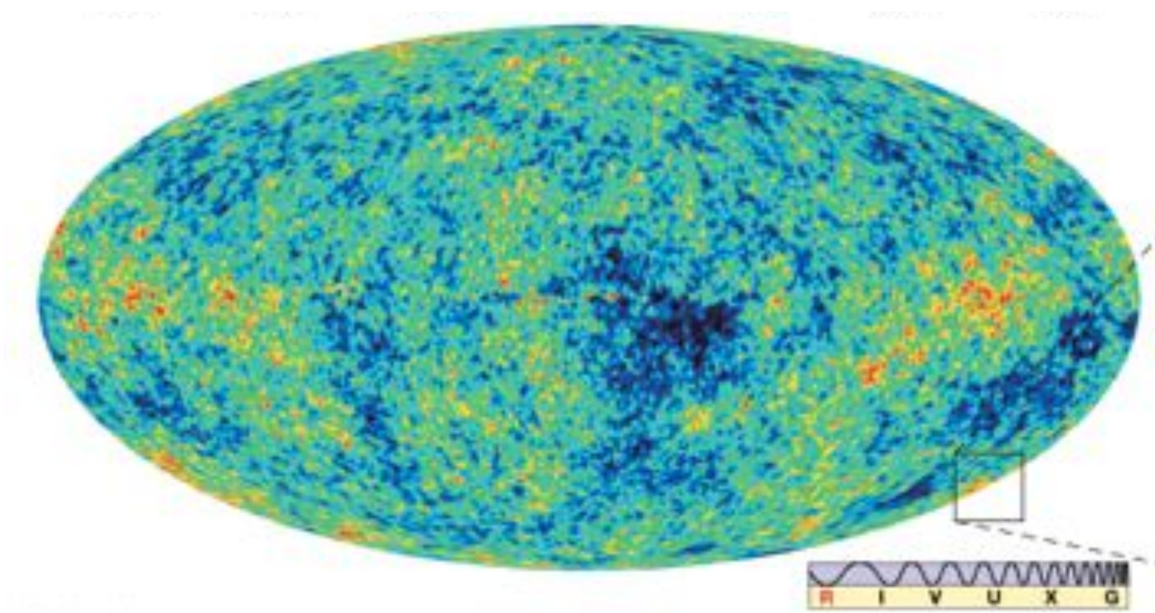
The Horizon Problem



- The Universe on one side of us can't communicate with the Universe on the other side!
- Yet, from our viewpoint they look the same! (T, density, …). How did they know about each other?

See also http://en.wikipedia.org/wiki/Unsolved_problems_in_physics

The Horizon Problem



- Yet, from our viewpoint they look the same! (T, density, …). How did they know about each other?

See also http://en.wikipedia.org/wiki/Unsolved_problems_in_physics

The Horizon Problem

- Wikipedia: so beautifully put!

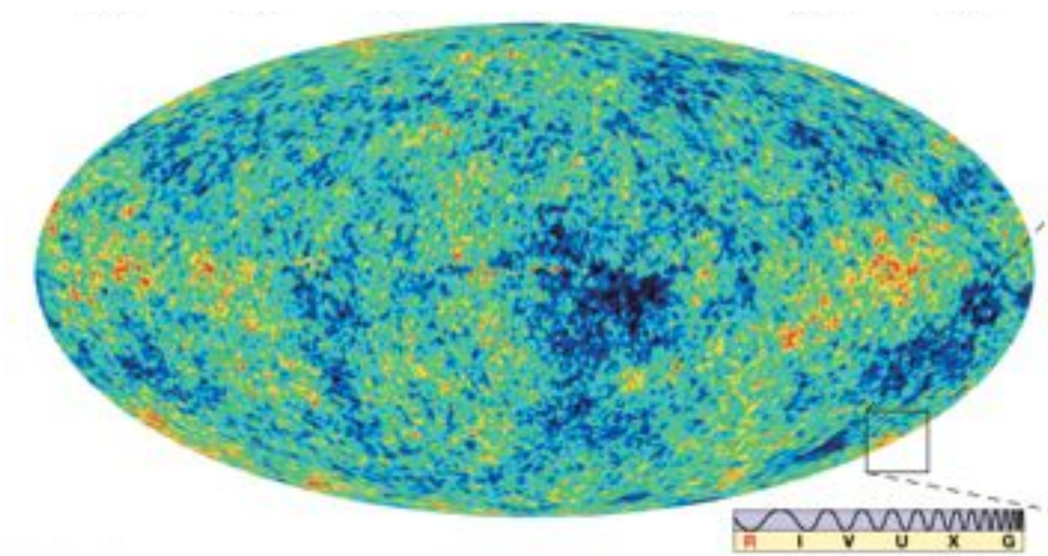
“The observable universe is one *causally-connected patch* of a much larger unobservable universe; there are parts of the universe which cannot communicate with us yet. These parts of the universe are outside what we call our current “cosmological horizon”. In the standard hot big bang model, without inflation, the cosmological horizon moves out, bringing new regions into view. As we see these regions for the first time, they look no different from any other region of space we have already seen: they have a background radiation which is at nearly exactly the same temperature as the background radiation of other regions, and their “space-time curvature” is evolving lock-step with ours. This presents a mystery: how did these new regions know what temperature and curvature (and other properties) they were supposed to have? They couldn't have learned it by getting signals, because they were not in communication with our patch of the Universe before

Two ways of looking at horizon

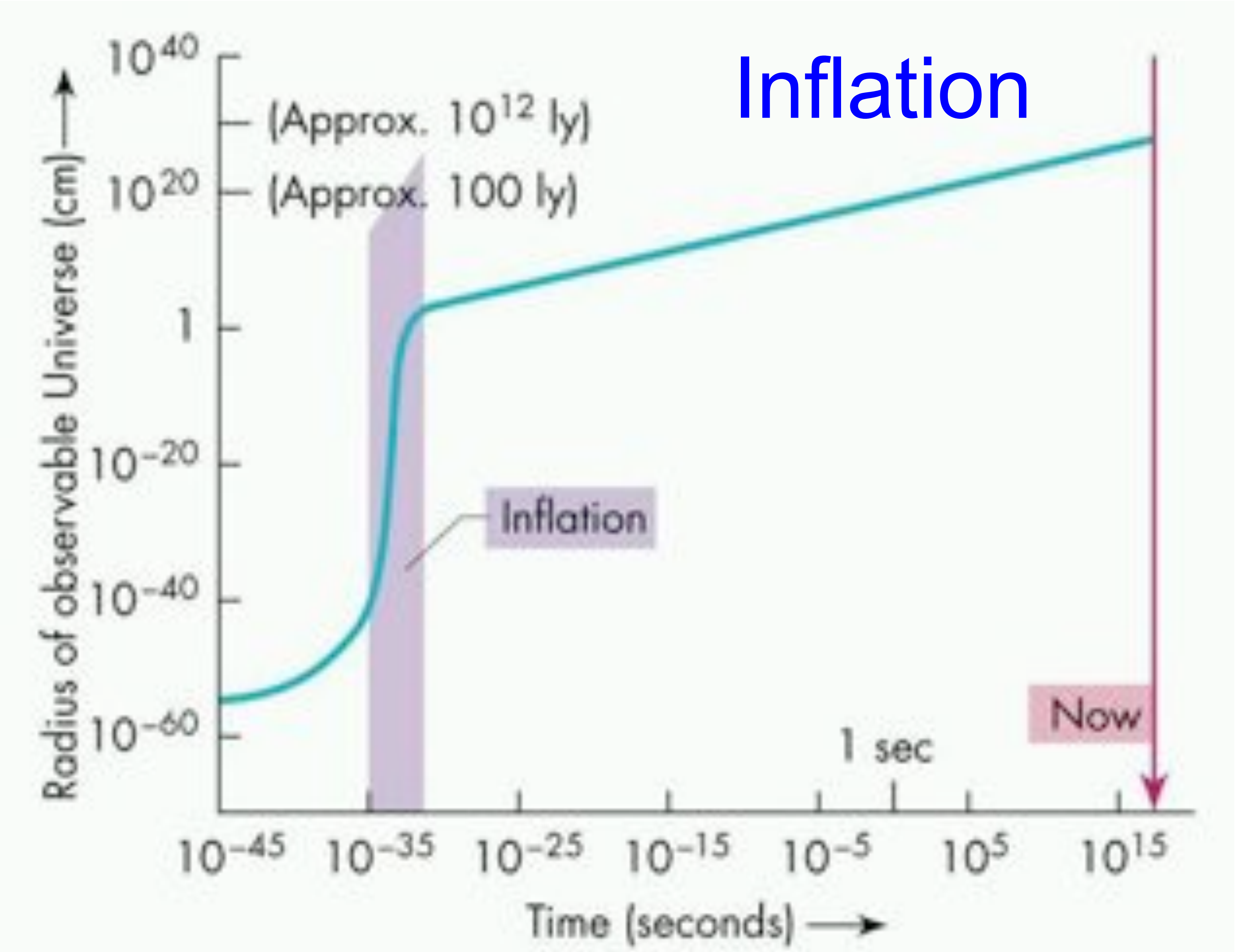
1. Horizon for an observer at CBR "surface of last scattering" is 400,000 l.y.. Universe has expanded by 1000x since then. Therefore that horizon is 0.4 billion l.y. now. But our horizon is 13.7 billion light years!

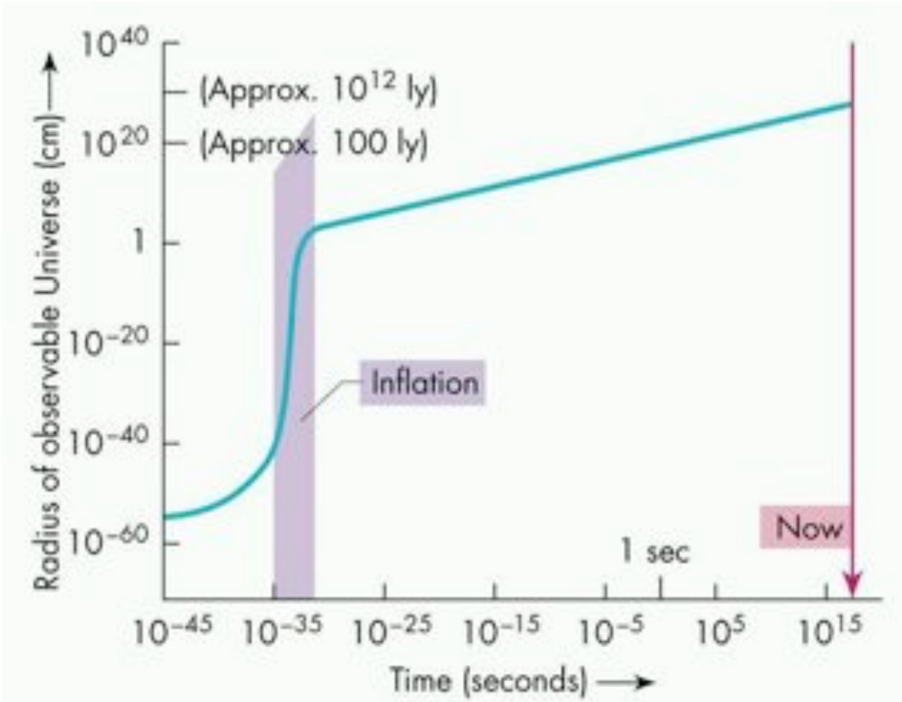
Two ways of looking at horizon

2. A detailed calculation shows that 400,000 l.y. at z=1000 corresponds to an angle of a mere 2 degrees!



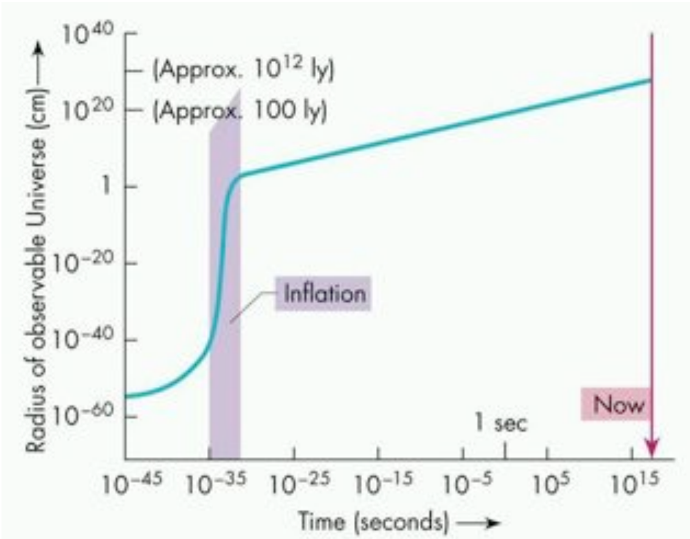
Inflation


10^{40}
(Approx. 10^{12} ly)
10^{20}
(Approx. 100 ly)
1
10^{-20}
10^{-40}
10^{-60}
Radius of observable Universe (cm)
Inflation
Now
1 sec
10^{-45}
10^{-35}
10^{-25}
10^{-15}
10^{-5}
10^{5}
10^{15}
Time (seconds)



Inflation

- Early Universe, 10^{-36} s to 10^{-32} s
- "Physical processes" drive a period of crazy exponential expansion
- Universe expands by a factor of $>10^{30}$!

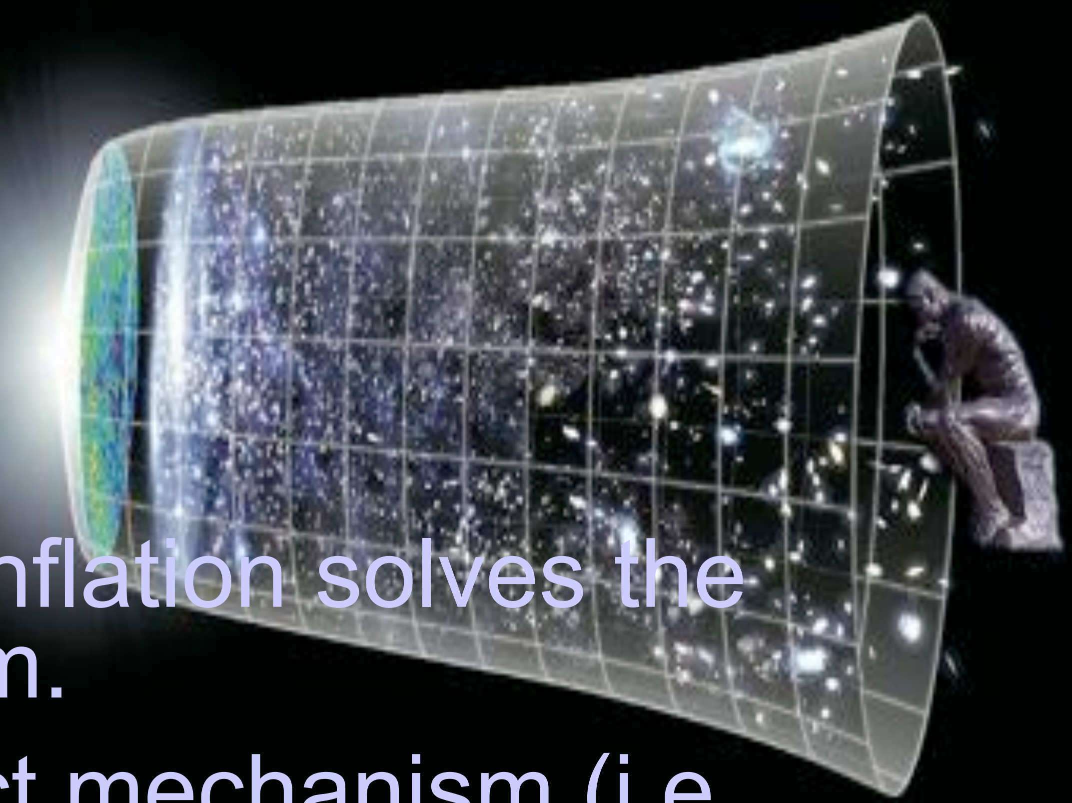


Inflation

Imagine a small patch in causal contact before the epoch of inflation.

- Now inflate the patch by 10^{30} times.
- Most parts of the patch are no longer in contact [can't be seen by a single observer].
- But they derive from the same patch of pre-inflationary space and so have the same properties!

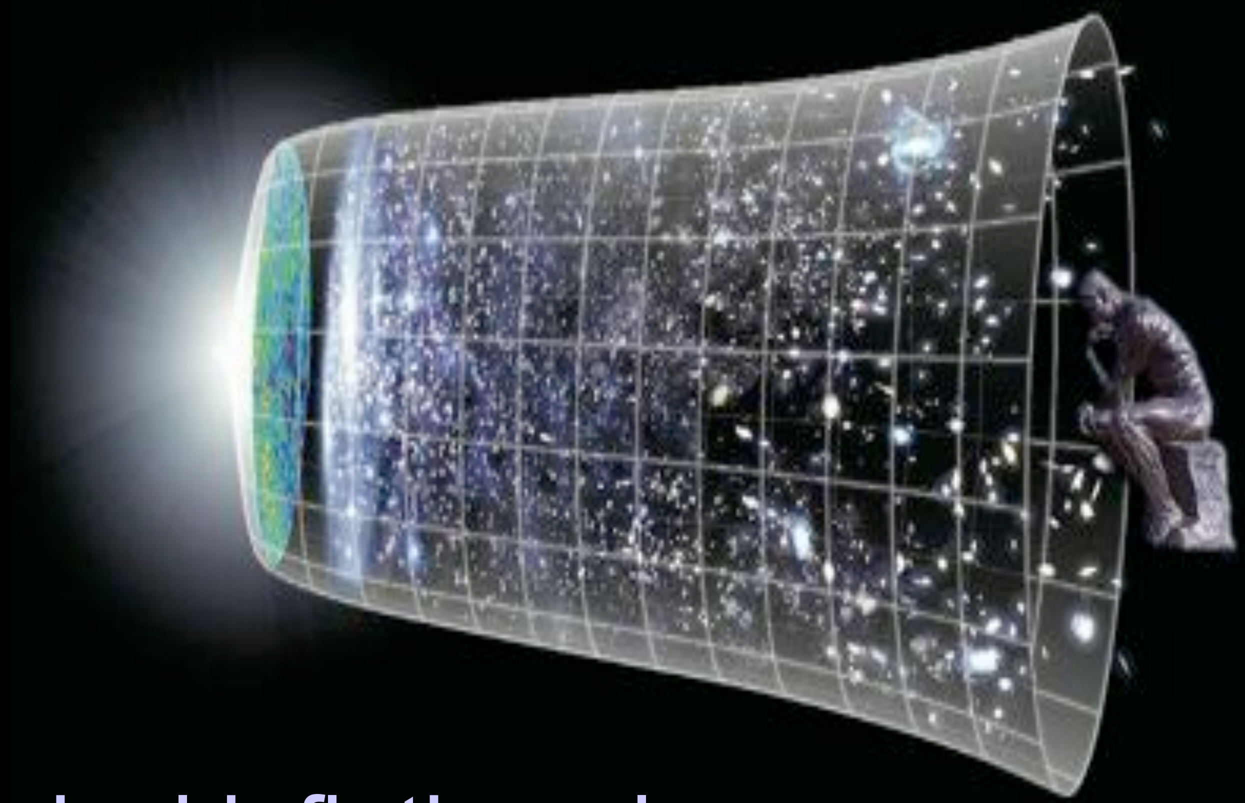
Inflation Summary



- Cosmological inflation solves the horizon problem.
- But … the exact mechanism (i.e. source of energy) that drives the inflation is not known!

Inflation requires **The Hot, Dense Big Bang**

Inflation



- Cosmological inflation also solves something called the “flatness problem” (which we’ll come to later).