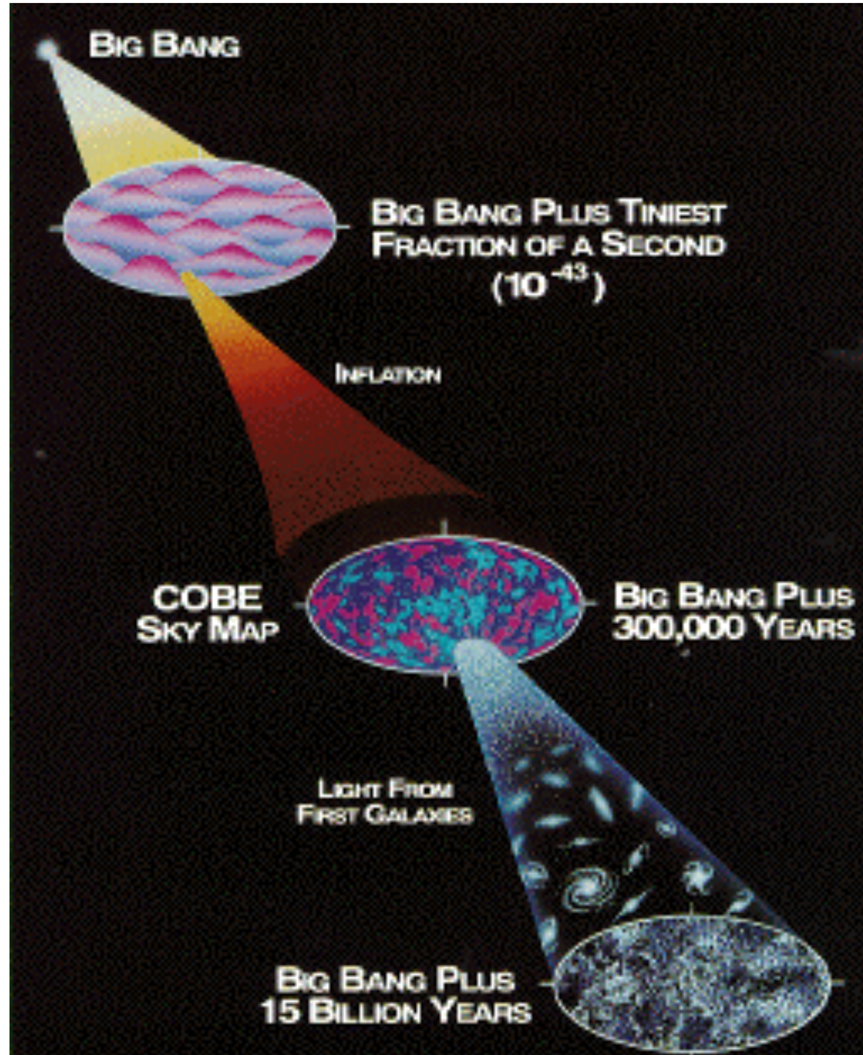
Astronomy 120

The Early Universe and the Big Bang

Class 24

Prof J. Kenney

June 28, 2018



Final Exam: Friday June 29 at 2-5pm in Watson A48

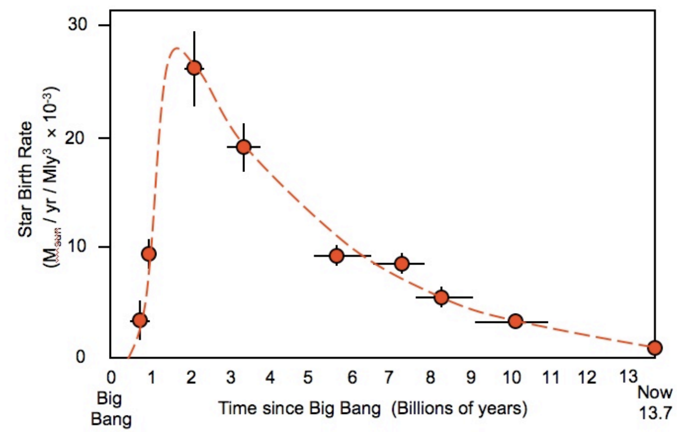
What the Final Exam will emphasize:

- Classroom lectures 10-24 (starting FRI June 8 thru the end of the semester)
- Homeworks #5 - #10
- Assigned Readings in Universe -- for lectures 10-24
- There is some overlap with the first exam. Topically, you are responsible for everything starting with the Milky Way Galaxy. While material from the first few weeks of the course will not be emphasized on the exam, you are responsible for knowing things from these first few weeks that become relevant for later material, e.g., Newton's Laws, properties of light, electromagnetic spectrum, blackbody radiation, atoms, HR diagram, mass-lifetime relation for stars.

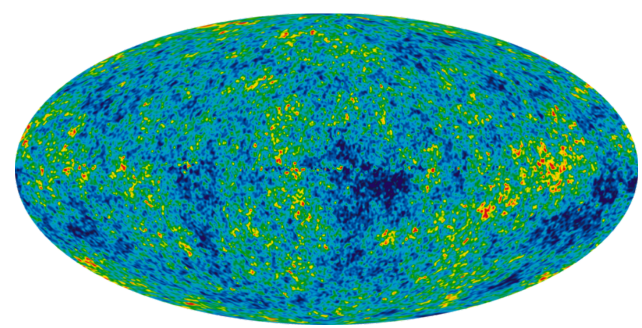
Try the Practice Exam! (on canvas & class website)

Evidence of evolving universe

- Universe now expanding
  (now, 13.7 Byr ABB)



- Star formation & quasar activity peak at z=2-4
  (1-4 Byr ABB)

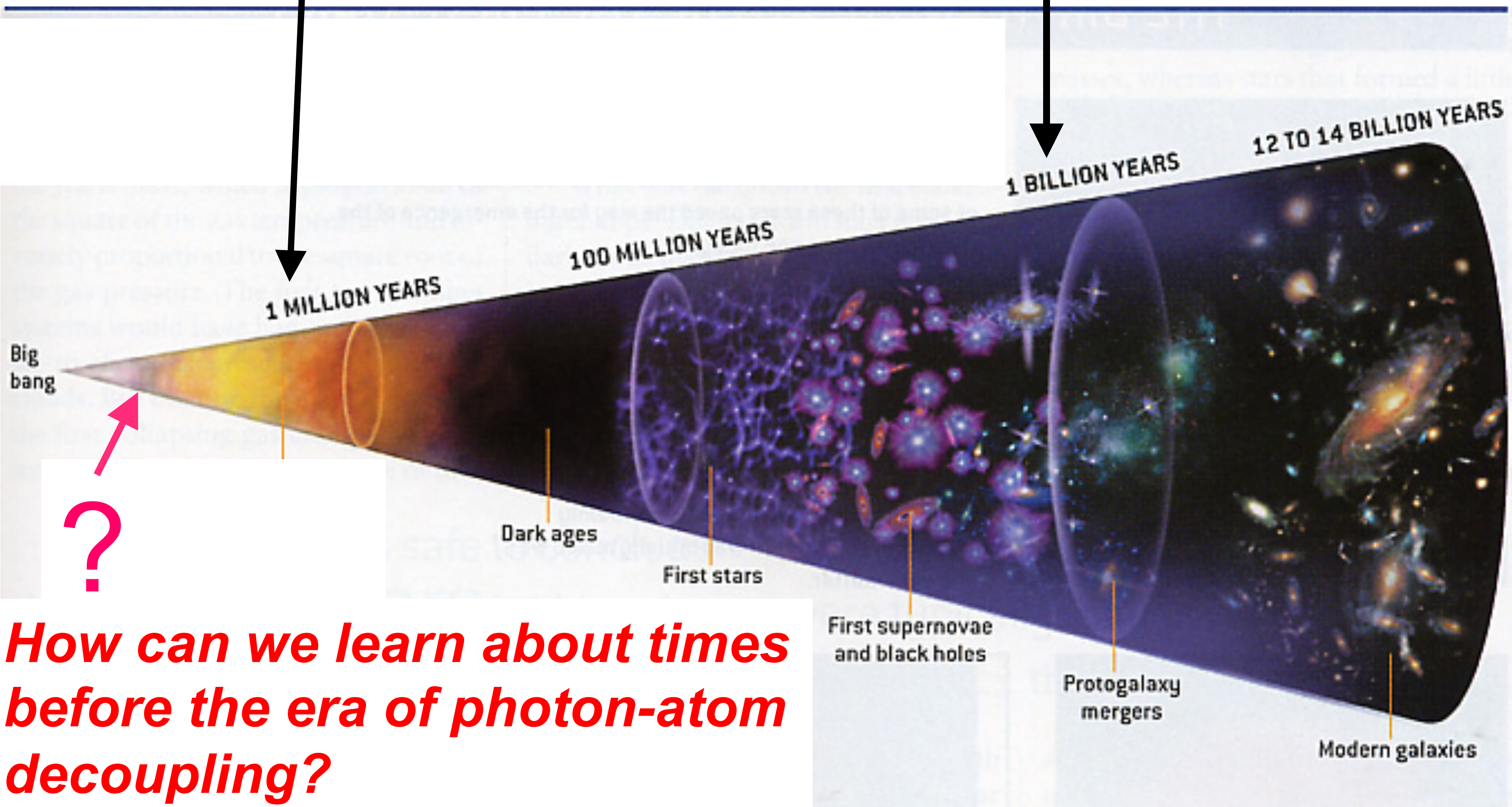


- CMB photons – evidence that universe was once 10^3x hotter & 10^9x denser, (380,000 yr ABB)

Do we have any evidence of earlier times in universe?

Emission of cosmic background radiation (380,000 yr ABB)

Era of Peak star, galaxy & black hole formation (1-4 Byr ABB)

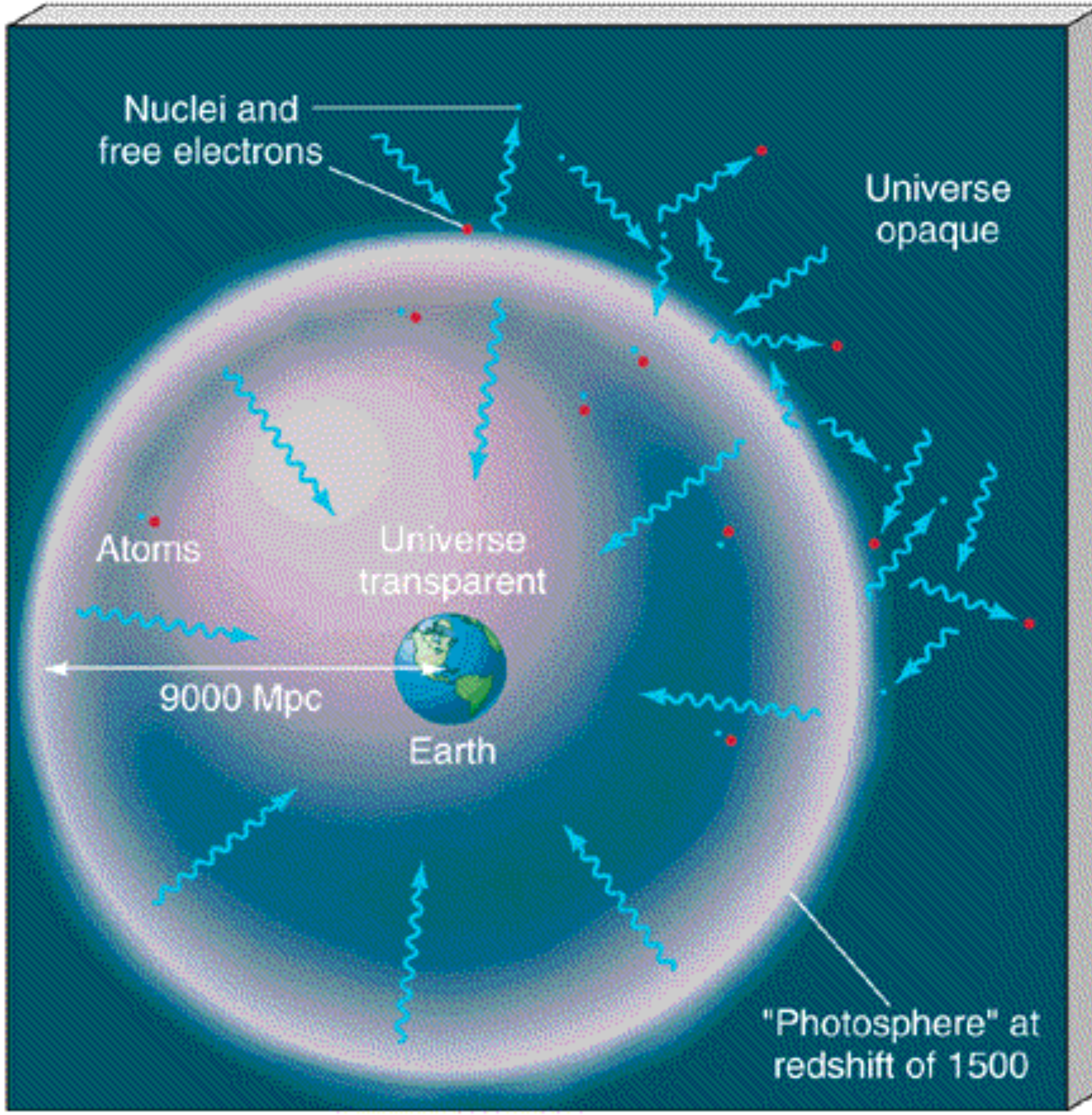


How can we learn about times before the era of photon-atom decoupling?

BIG BANG Cosmic Time NOW

How do we know about very early universe?

No photons from any times earlier than 380,000 yrs ABB can reach us



How do we know about very early universe?

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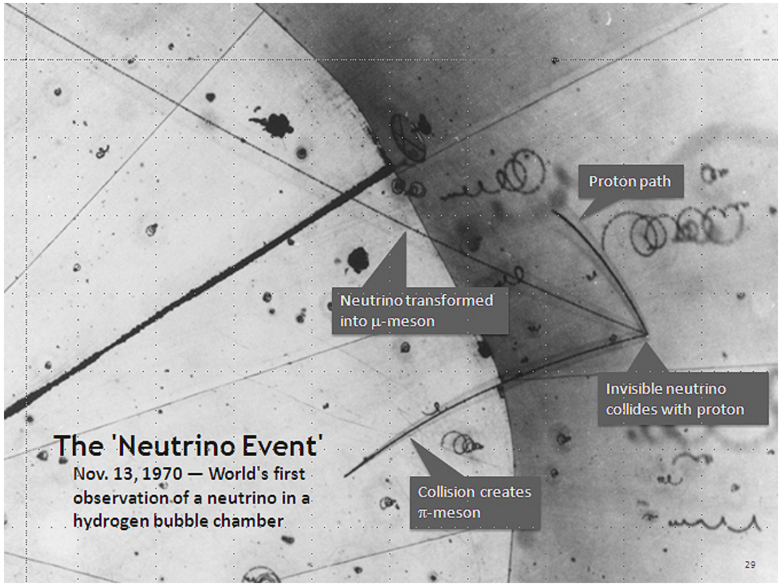
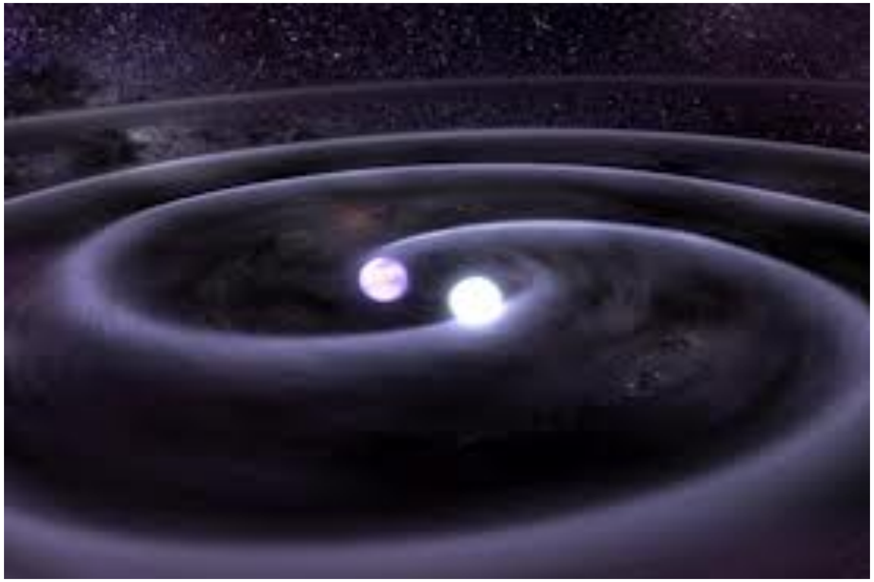
- Someday might be able to detect ***neutrinos*** or ***gravity waves*** from younger universe, but not yet





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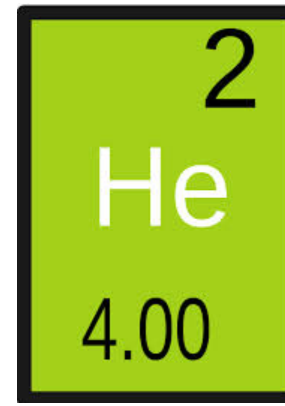
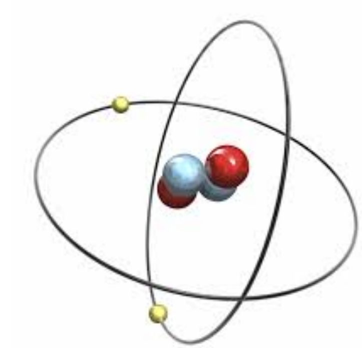
- Figure out what would have happened to cosmic photons and mass particles when universe was denser and cosmic photons had more energy – using known physics
- Seek evidence in present universe of very hot & dense early universe

the Mystery of Helium

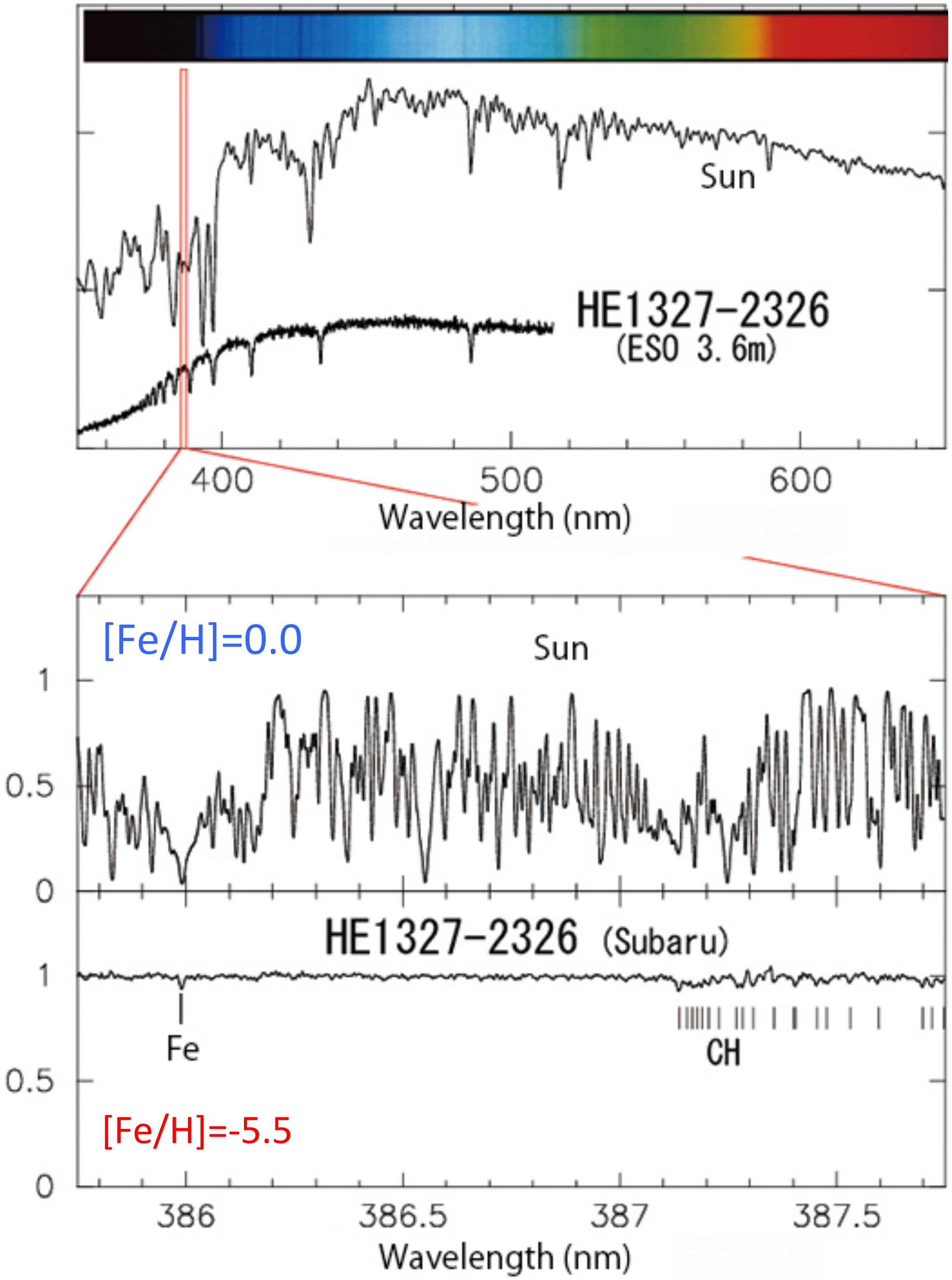
- Although stars certainly make Helium, they don’t make it in the right amounts and they don’t put it everywhere



- Elemental composition of universe:
  - H 74% by mass
  - He 25%
  - all else 1%



- Stars can’t make this much helium, but the early universe can!



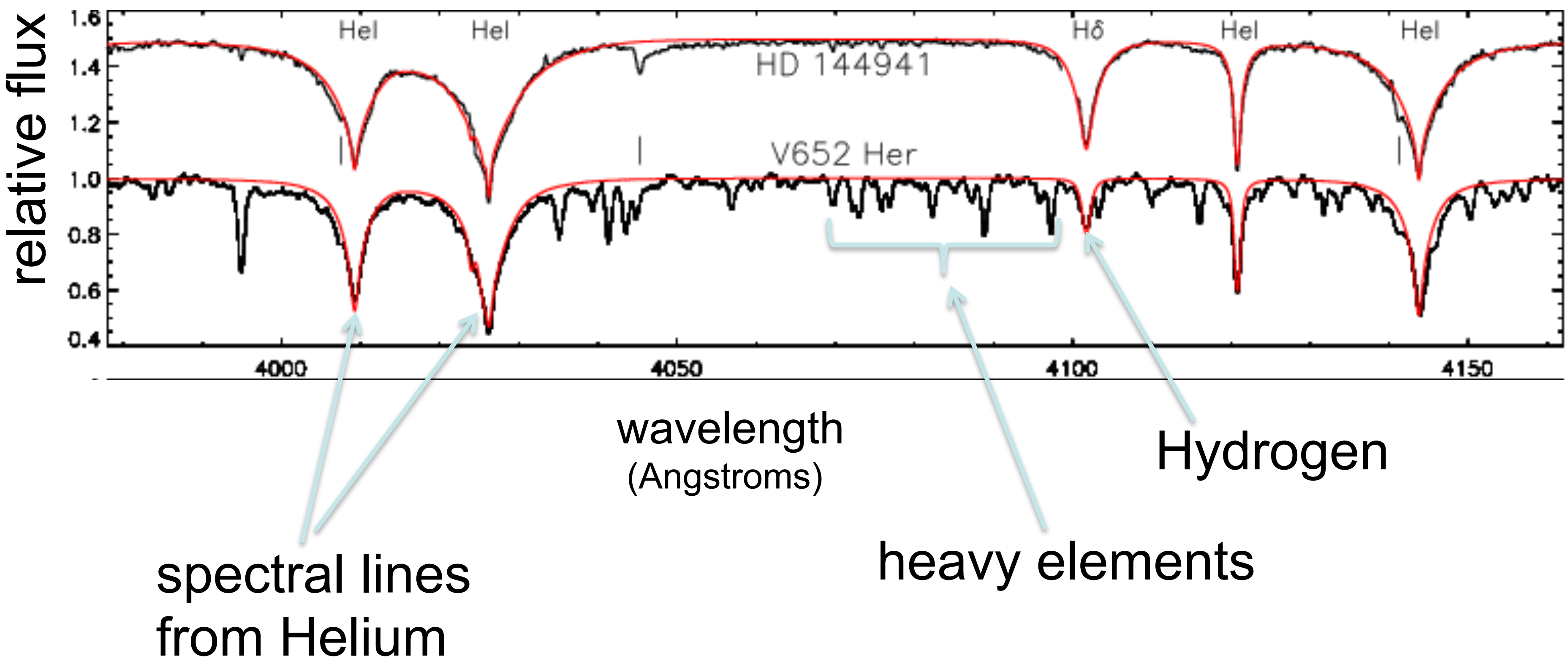
Spectra of Sun & extremely metal-poor star

"heavy" element content
1/300,000 x solar

mass fraction of "heavy" elements:
Sun: 2%
metal-poor star: 0.00001%

stars with very small amounts of elements heavier than Carbon still have large amounts of Helium!

spectra of metal-poor star & metal-rich star (like Sun)



range of Helium abundance in universe:
23-27% (very small range!)

range of “heavy element” (Carbon & heavier) abundance in universe:
0.00001% - 3% (very large range!)

even stars that contain almost no heavy elements still have lots of Helium!

So….

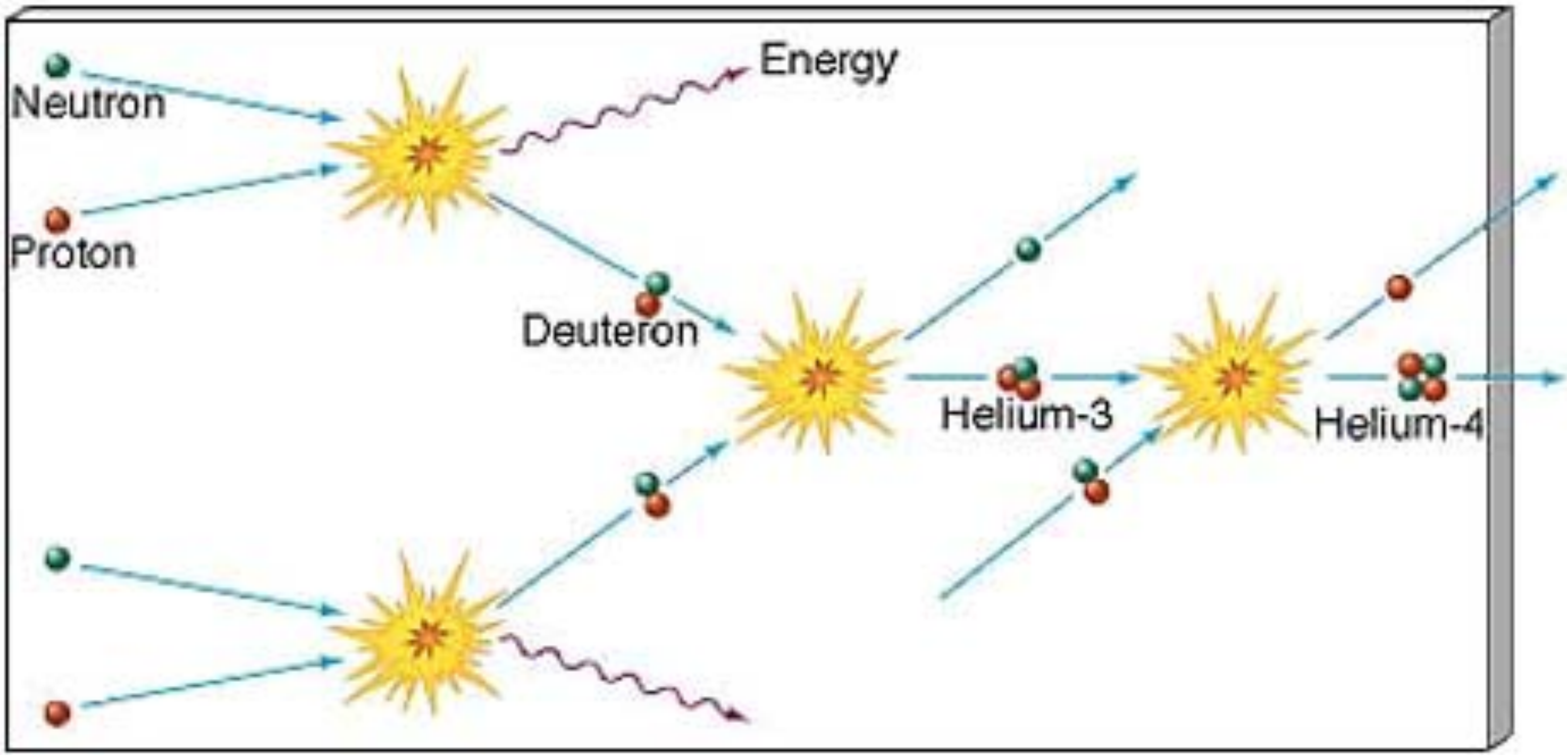
- most of the helium in the universe was made before the first stars!

- need nuclear reactions to make Helium (not required for Hydrogen)

- when did these nuclear reactions occur?

Origin of light elements

At t_{ABB}=1-5 min, T ~ 10^9 K which is hot enough for nuclear fusion to occur



fusion is one of main processes in early universe

How is this different from proton-proton chain that occurs in stars?

Main nuclear reactions in first few minutes of Big Bang

$p + e^- \longleftrightarrow n + \nu$

$n + e^+ \longleftrightarrow p + \bar{\nu}$

<1 sec

$n \longrightarrow p + e^- + \bar{\nu}$ 1-100 sec

$p + n \longleftrightarrow d + \gamma$ 100-300 sec

$d + n \longrightarrow H^3 + \gamma$

$H^3 + p \longrightarrow He^4 + \gamma$

$d + p \longrightarrow He^3 + \gamma$

$He^3 + n \longrightarrow He^4 + \gamma$

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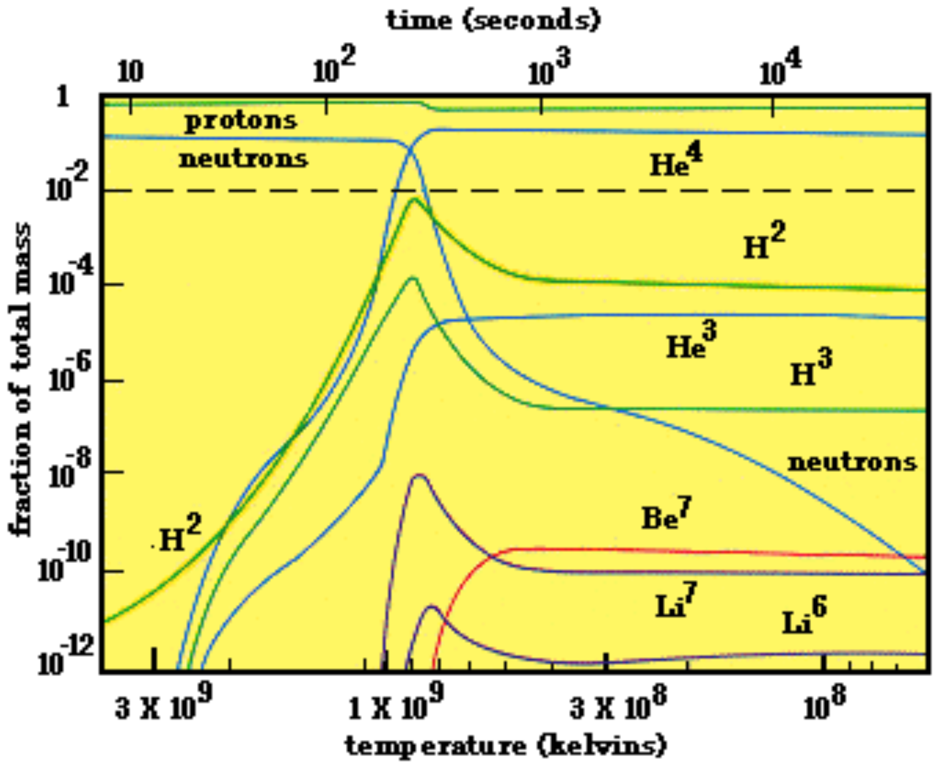


Reaction products for $\Omega_B = 0.04$

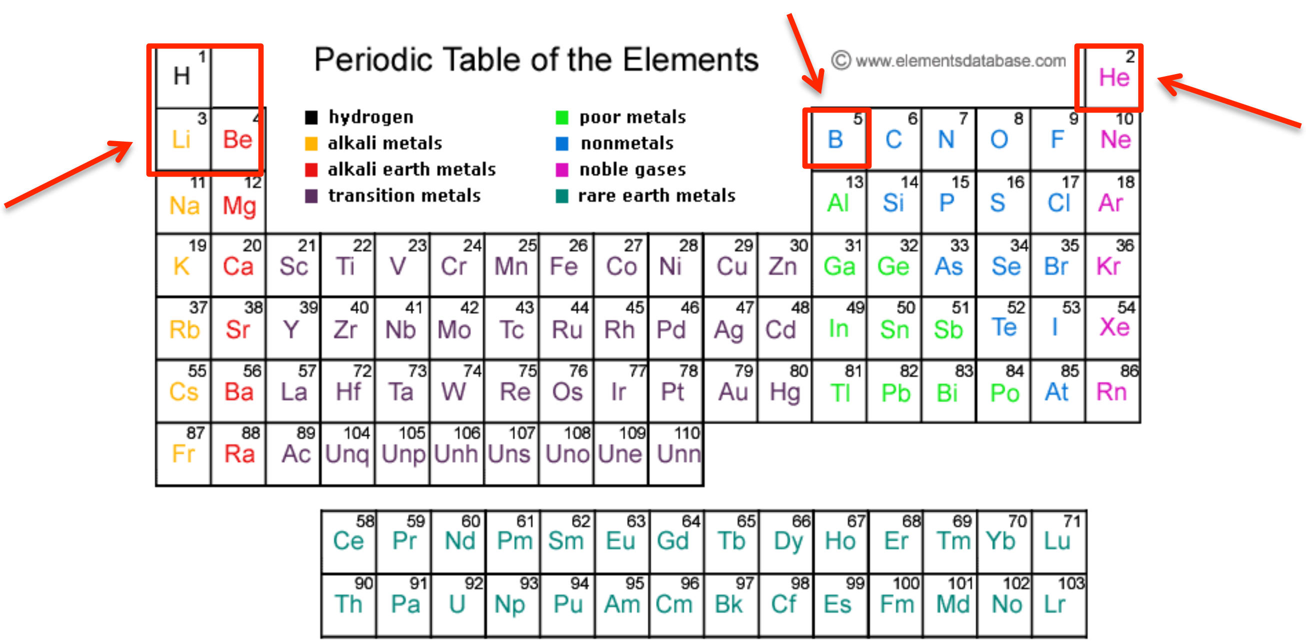
Origin of light elements

Most of the light elements were made in first few minutes after Big Bang, not in stars

At t_{ABB}=1-5 min, T ~ 10^9 K which is hot enough for nuclear fusion to occur

Protons (H nuclei) undergo fusion to form:

^{2}H, He, Li, Be, B (elements with 1,2,3,4,5 protons)



Stars can make Lithium in nuclear reactions but most stars actually DESTROY lithium. Why?

A. It gets fused into other elements

B. No energy is released by the fusion of lithium

C. Lots of energy is released by the fusion of lithium

D. Lithium reacts chemically to make molecules

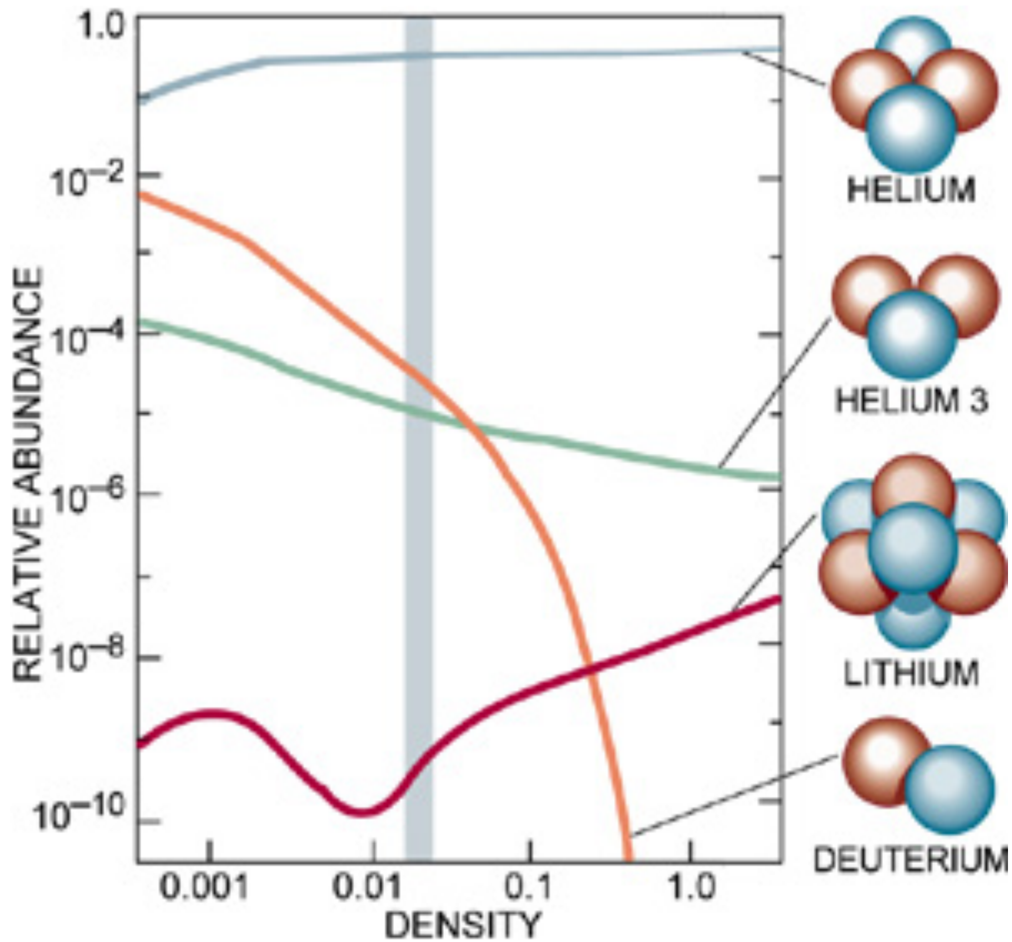
E. Stars hate lithium

How are conditions in the early universe different from those in the cores of stars (so that more light elements are formed in the early universe)?

A. different temperatures
B. different densities
C. gravity stronger in cores of stars
D. same conditions but existing for different lengths of time
E. inflation affects the nuclear reactions in the early universe
F. different anti-boson shielding factors

The Relative number of light elements tells us:

the DENSITY of baryonic (normal) matter *at the time when the universe was hot enough to fuse nuclei*



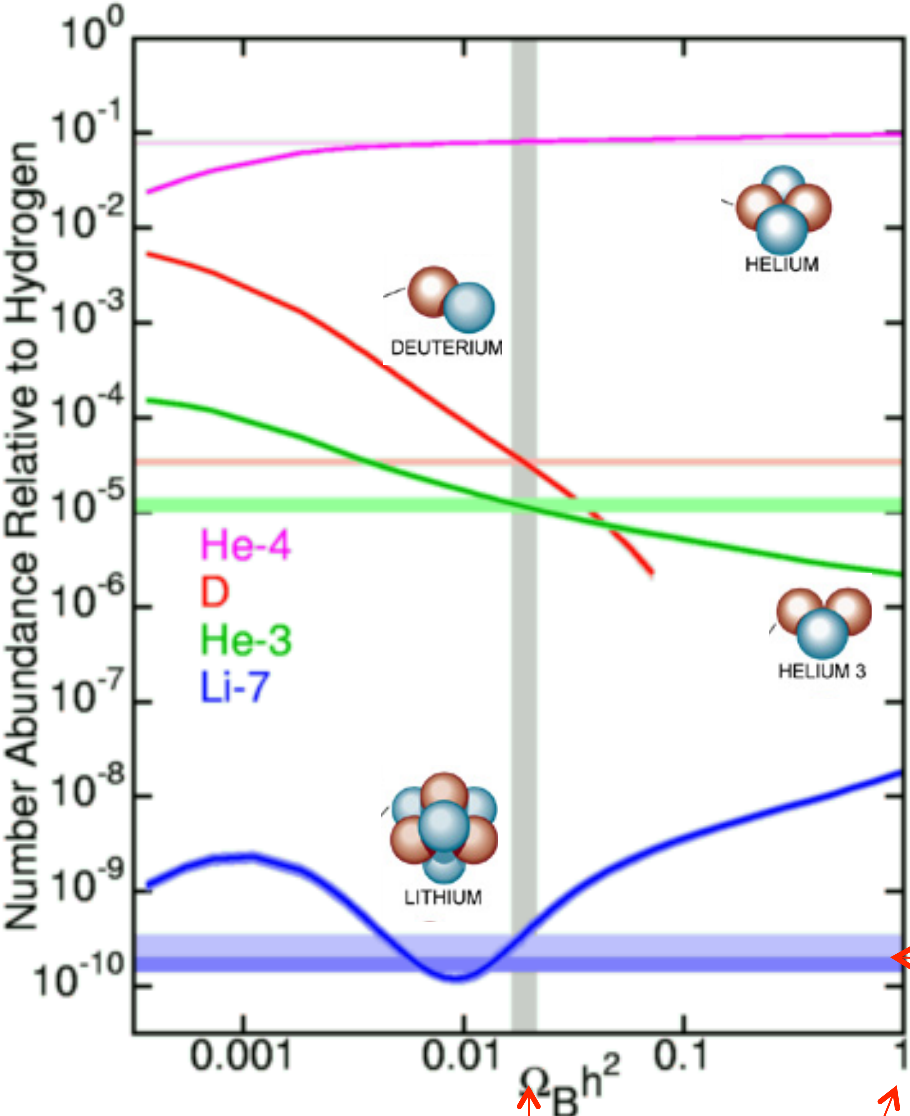
Abundance of light elements vs. density

WHY?

Higher density -> more collisions -> more nuclear reactions -> more total "heavier" light elements

Some elements become *less abundant* with higher density or longer exposure to extreme conditions, since those elements burn into heavier elements

Abundance of light elements vs. density



Big Bang nucleosynthesis

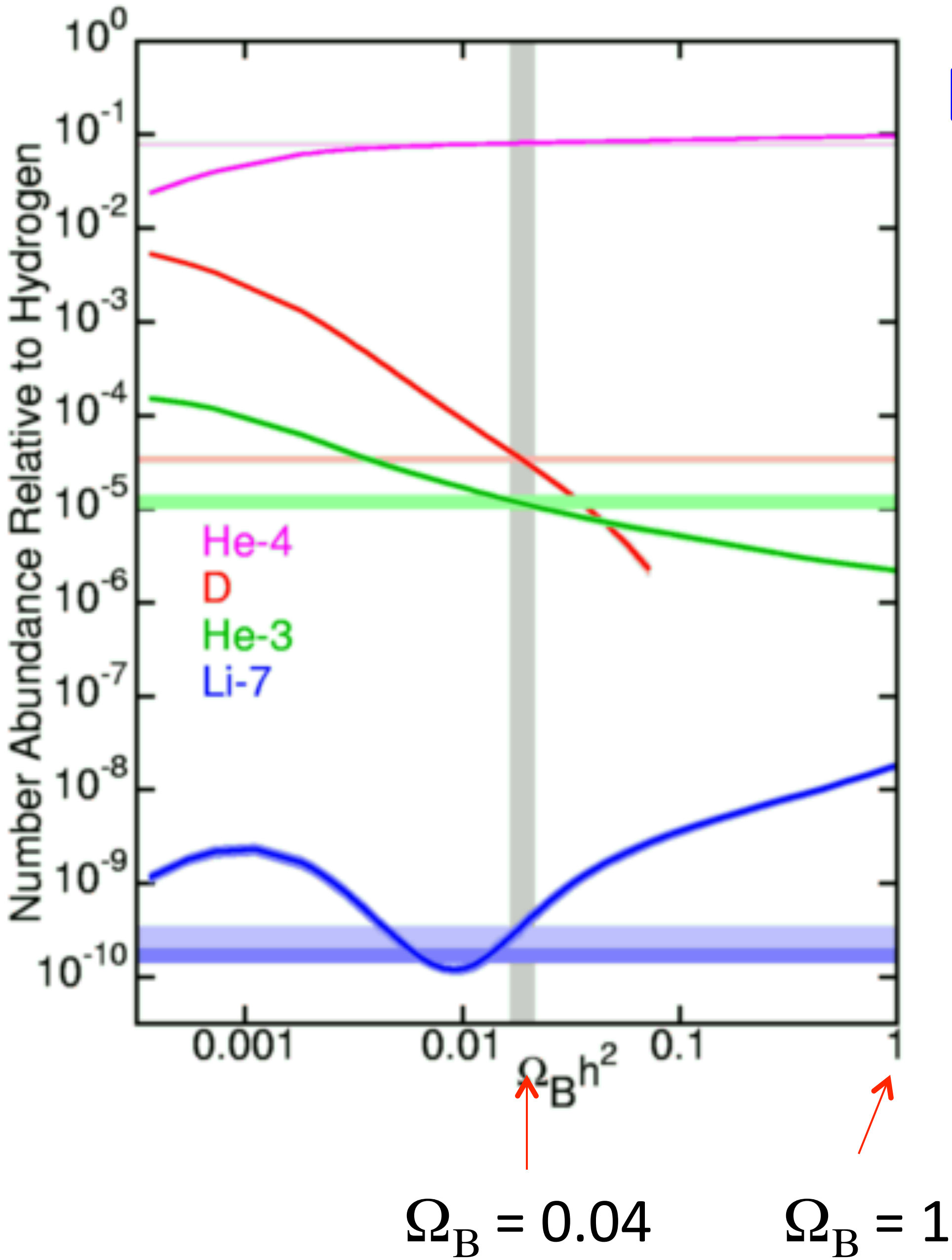
Predicted abundance from BB nucleosynthesis

Measured abundance

$\Omega_B = 0.04$

$\Omega_B = 1$

Abundance of light elements vs. density



Big Bang nucleosynthesis

The relative abundances of the light elements (H,He,Li,Be,B) are consistent with conditions expected in Big Bang

AND…

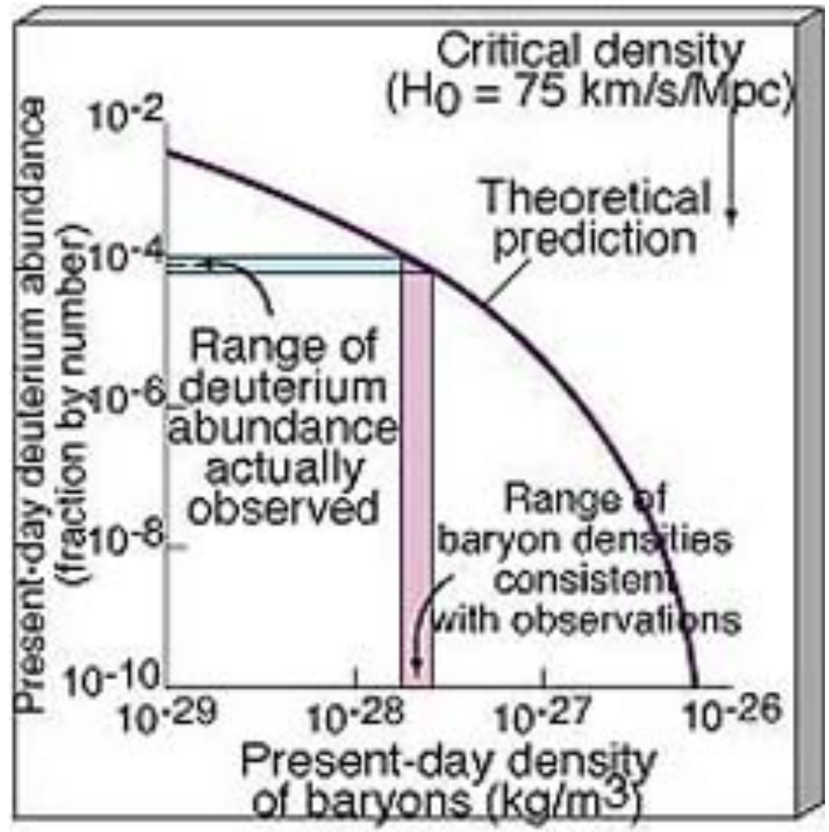
Provide strong evidence on the density of baryons in the universe, relative to the total mass-energy density of the universe ($\Omega_B = 0.04$)

Abundances of light elements

→Density of baryons a few minutes after big bang is 4% of the critical density

i.e. $\Omega_{baryon} = 0.04$

Deuterium (^2H) abundance vs density

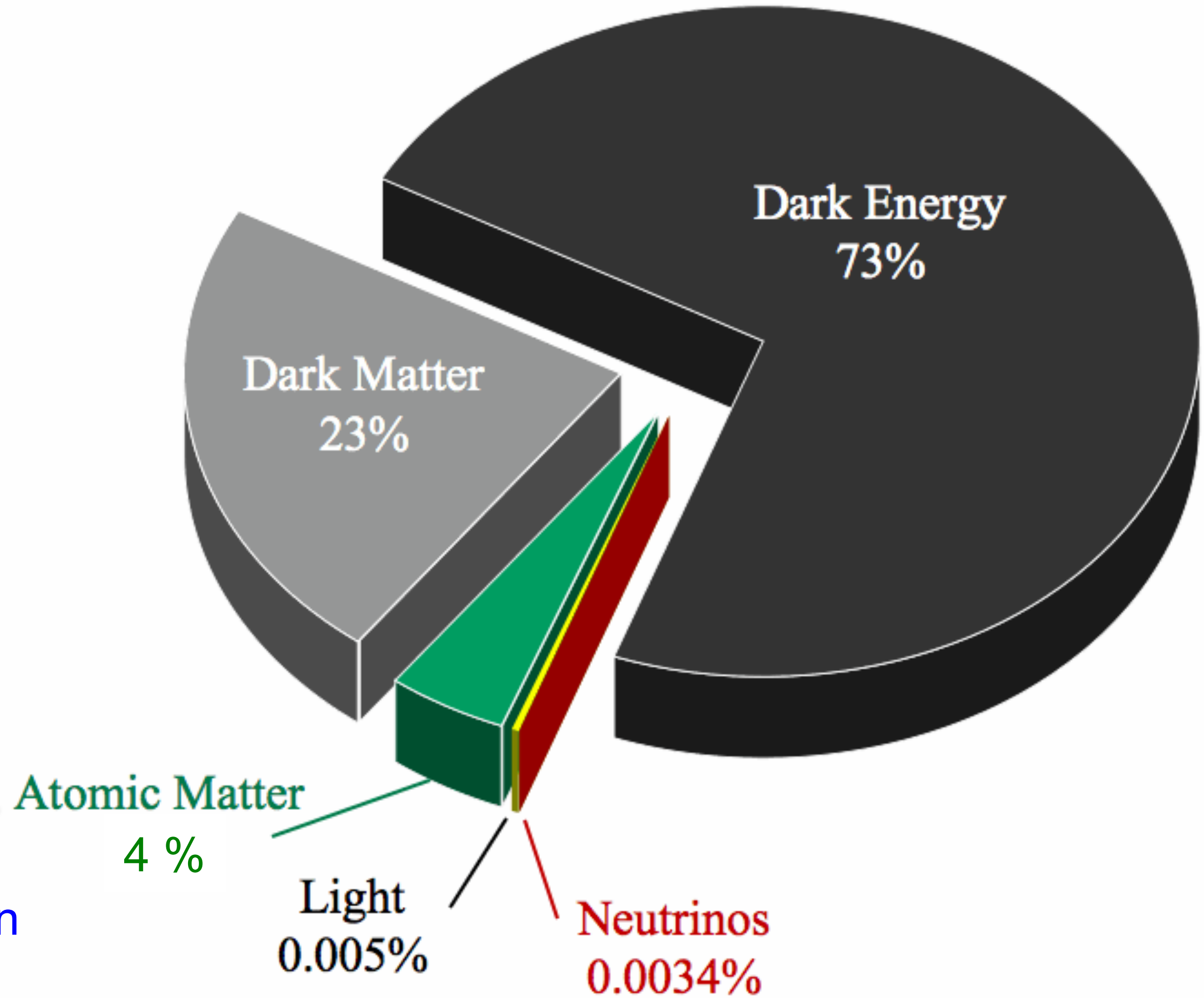


→Since $\Omega_m = \Omega_{baryon} + \Omega_{DM} = 0.27$

this implies $\Omega_{DM} = 0.23$

this is how we know dark matter is not hidden forms of atoms!

Mass-energy budget of present universe



In galaxies 1%
Not in galaxies 3%
(probably hot gas between galaxies)

Evidence of evolving universe

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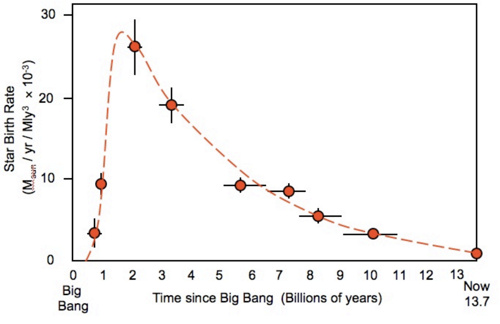
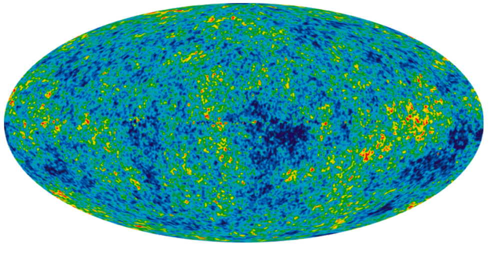
  (now, 13.7 Byr ABB)



- Star formation & quasar activity peak at z=2-4 (1-4 Byr ABB)



- CMB photons – evidence that universe was once 10^3x hotter, 10^9x denser
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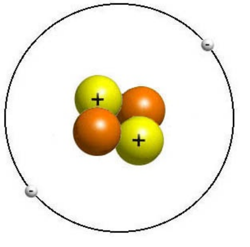
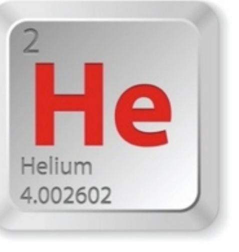




- Ratios of light elements – evidence universe was 10^9x hotter, 10^{27}x denser
  (3 minutes ABB)

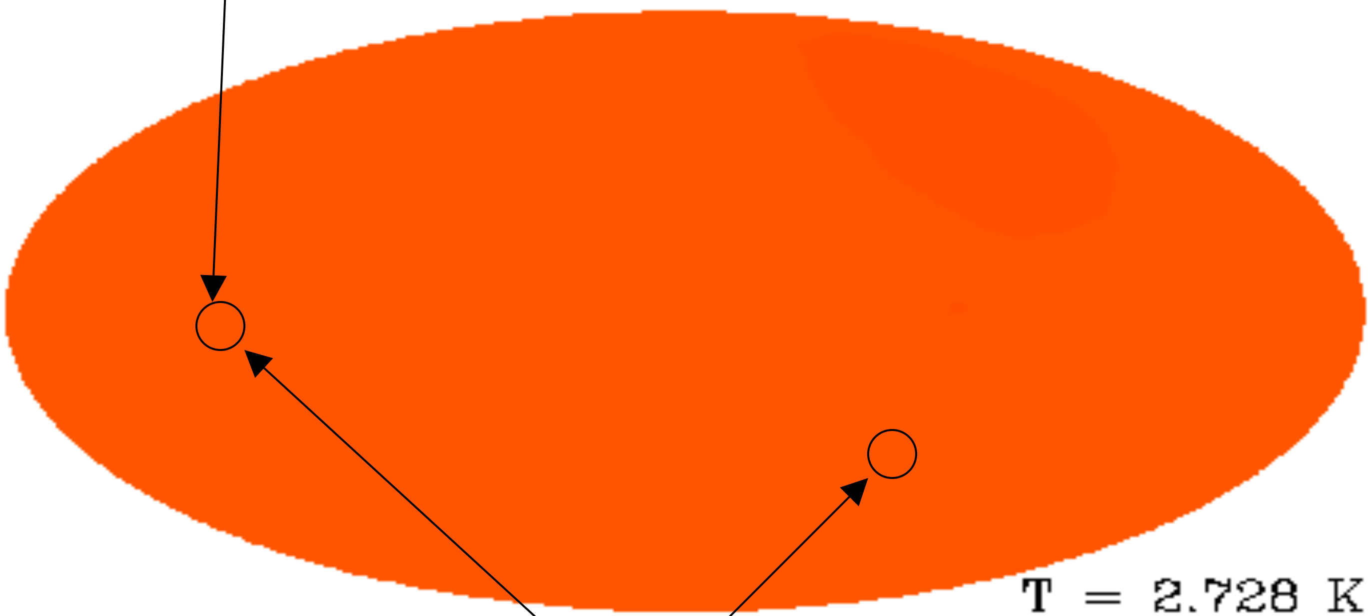
we have evidence of events in the universe even earlier than primordial nucleosynthesis!

Map of Cosmic Background Radiation over whole sky

Map of Cosmic Background Radiation over whole sky

Remarkably smooth over whole sky!

Largest region you would think is *causally connected*
= size of Cosmic Light Horizon = 380,000 LY

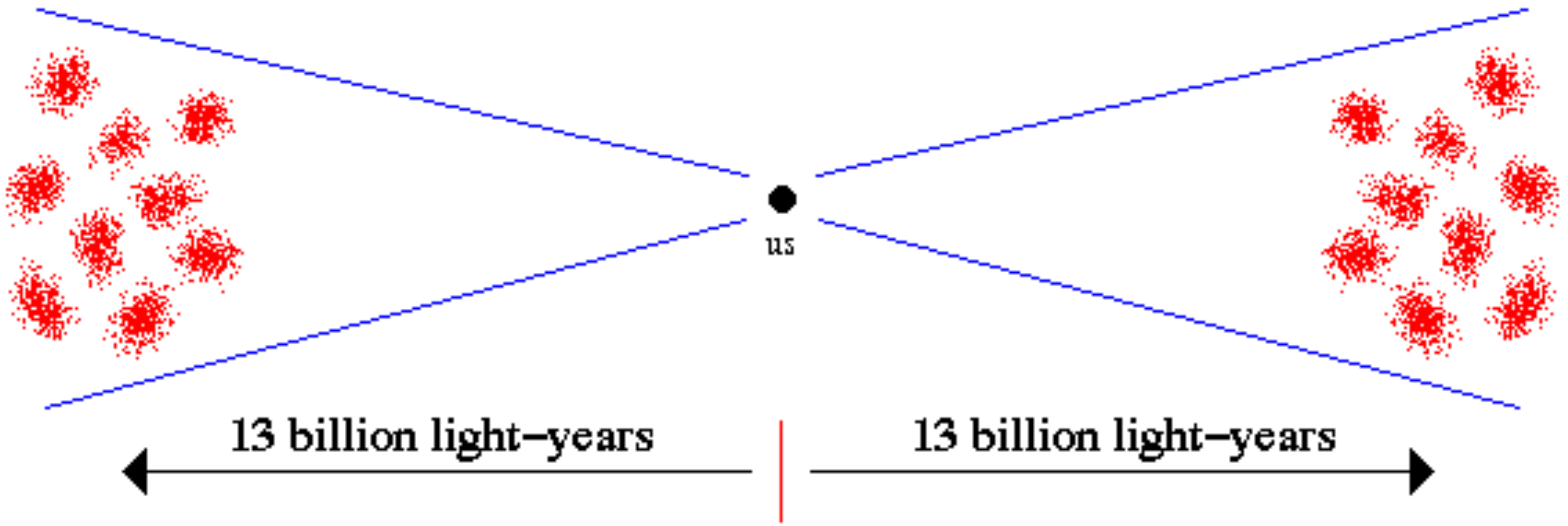


Yet distant regions are very nearly the same temperature T=2.728K

Places need to be in causal contact with one another to reach thermal equilibrium (same temperature)

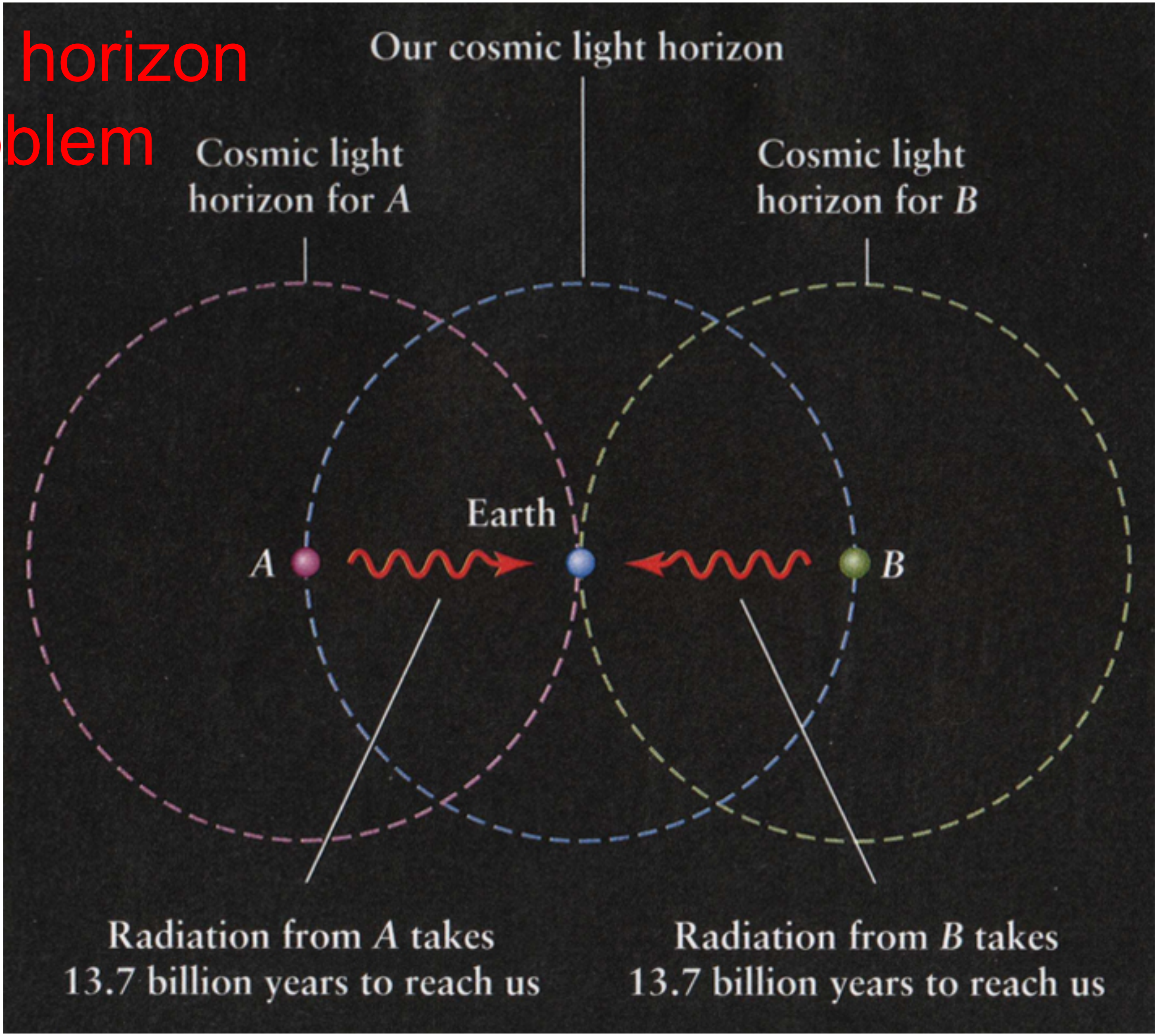
Horizon problem

the number and size of density fluctuations on both sides of the sky are similar, yet they are separated by a distance that is greater than the speed of light times the age of the Universe, i.e. they should have no knowledge of each other by special relativity



at some time in the early Universe, all parts of spacetime were causally connected, this must have happened after the spactime foam era, and before the time where thermalization of matter occurred.

the horizon problem



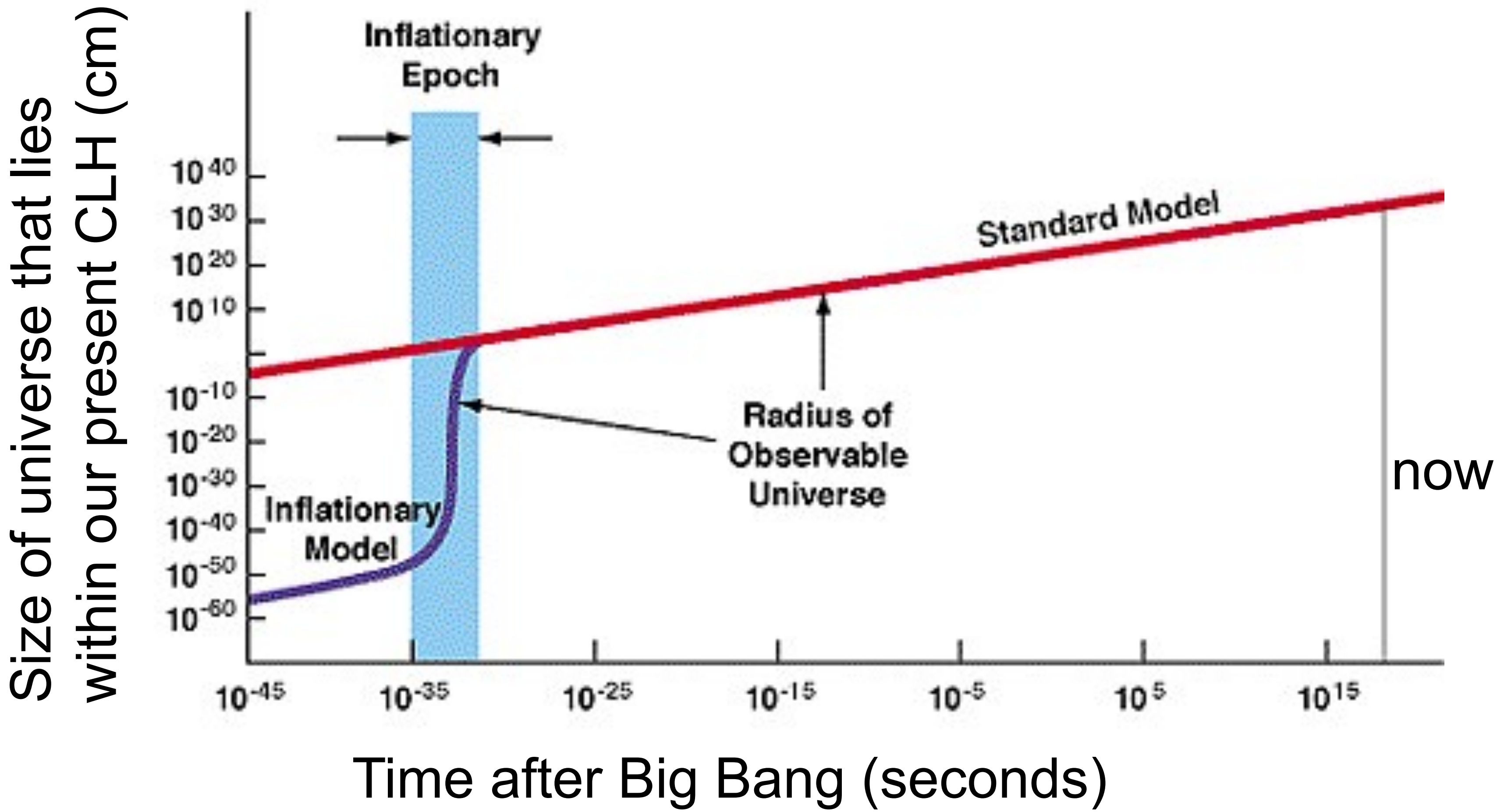
A and B are outside each other's CLH, so they can't have been in causal contact (unless faster than light travel is invoked)

Why do opposite sides of the universe have the same temperature, even though they seem too far apart for light (and heat) to have traveled from one side to the other in the age of the universe?

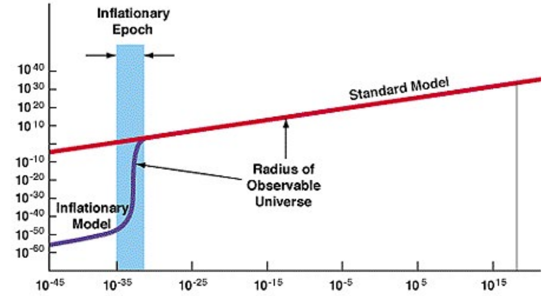
A. heat could travel much faster in the early universe, allowing them to exchange heat while the universe was young
B. because of the curvature of space, very distant regions are actually the same point
C. the big bang started in one place so everything was initially at the same temperature
D. they were originally close together but then a superfast expansion carried them far apart

Inflation model

A brief period of superfast expansion (space expanding > c) is hypothesized to occur in 1st fraction of a second after the BB



Inflation model:



Universe expanded by factor of ~10^{50} in 10^{-32} seconds

Expansion of space much faster than speed of light

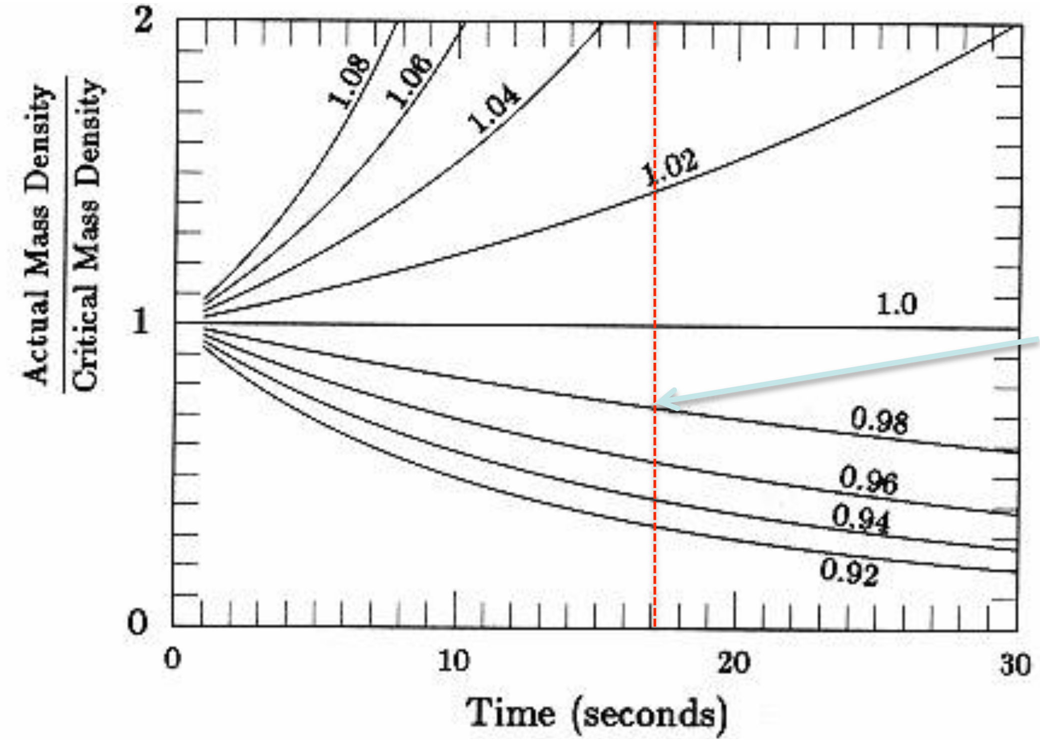
Regions which are now very far apart and no longer in causal contact *were in causal contact before inflation*

Inflation pushed these regions really far apart, so now they are no longer in causal contact

Sounds nuts BUT this can resolve:
1. Horizon problem (CMB temp is amazingly uniform)
2. Flatness problem (it is hard to maintain Ω_o=1)

Observable Universe is close to flat $\Omega_o = 1.00 \pm 0.01$

Flatness problem: *Why does universe now appear so flat?*



Ω_0 value which starts at 0.98 at t=0 decreases to 0.70 by $t=10^{17}$ sec = 10^{10} yrs (now)

$\Omega_o = \rho_o/\rho_{crit}$ is not constant over time.

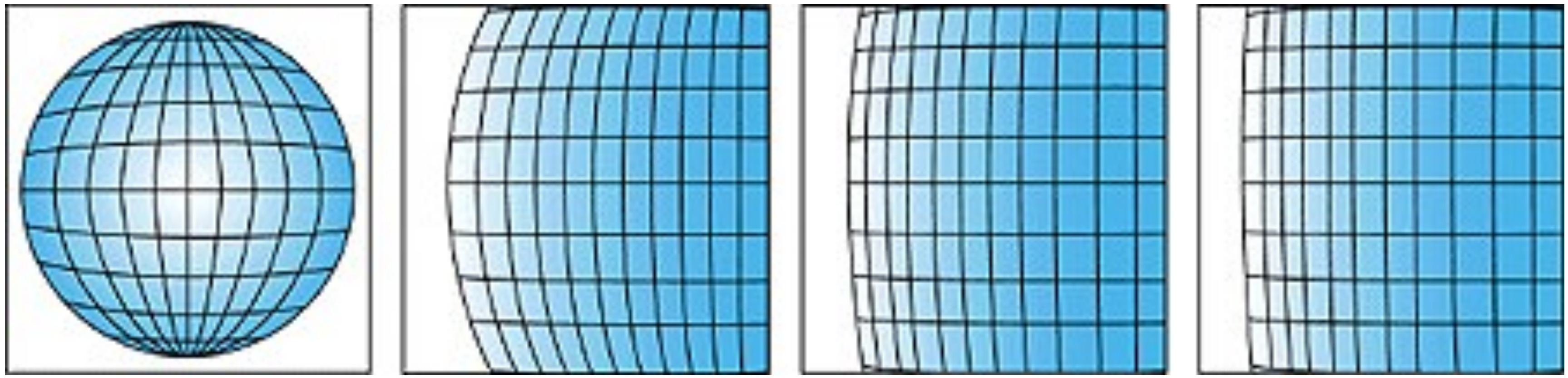
If it starts out being a little different from 1.00,

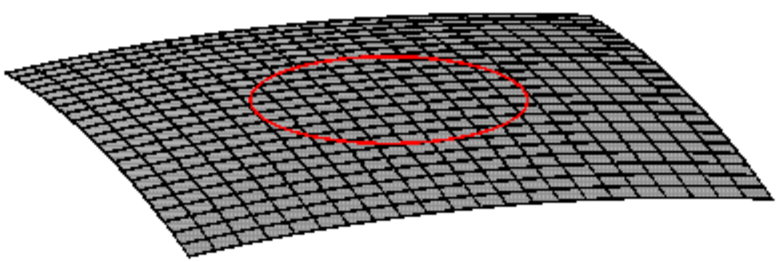
it rapidly evolves to be very different than 1.00.

WHY? $\boldsymbol{\rho_{crit} = 3\, H_o^2/8\pi G}$ **doesn't change as much as** $\boldsymbol{\rho_o}$

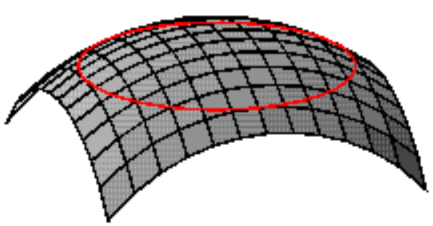
if expansion rate were contant, H_o is constant but densities drop

Spatial curvature evolves like this during inflation:



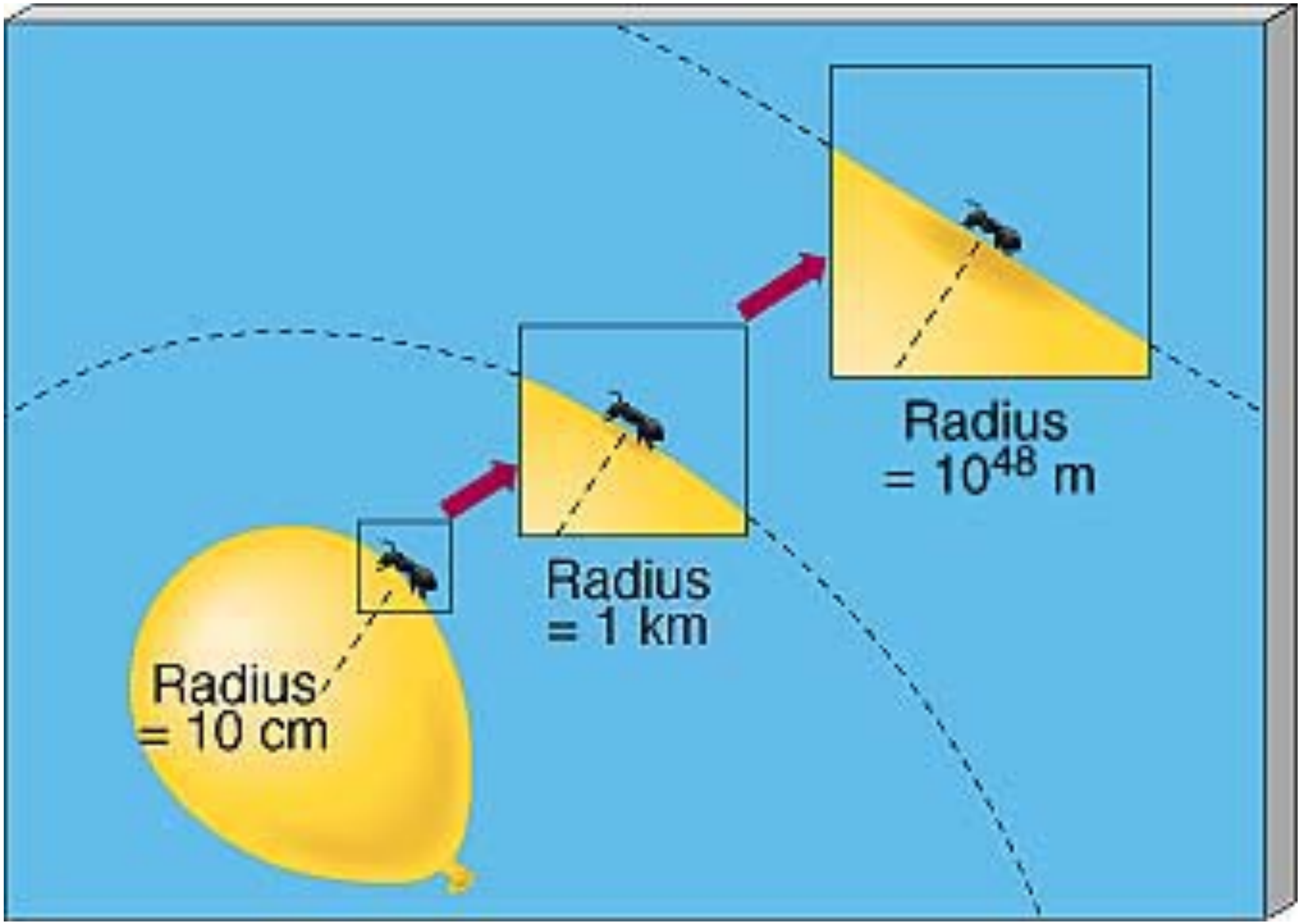


Curvature of space within cosmic light horizon ***with inflation***

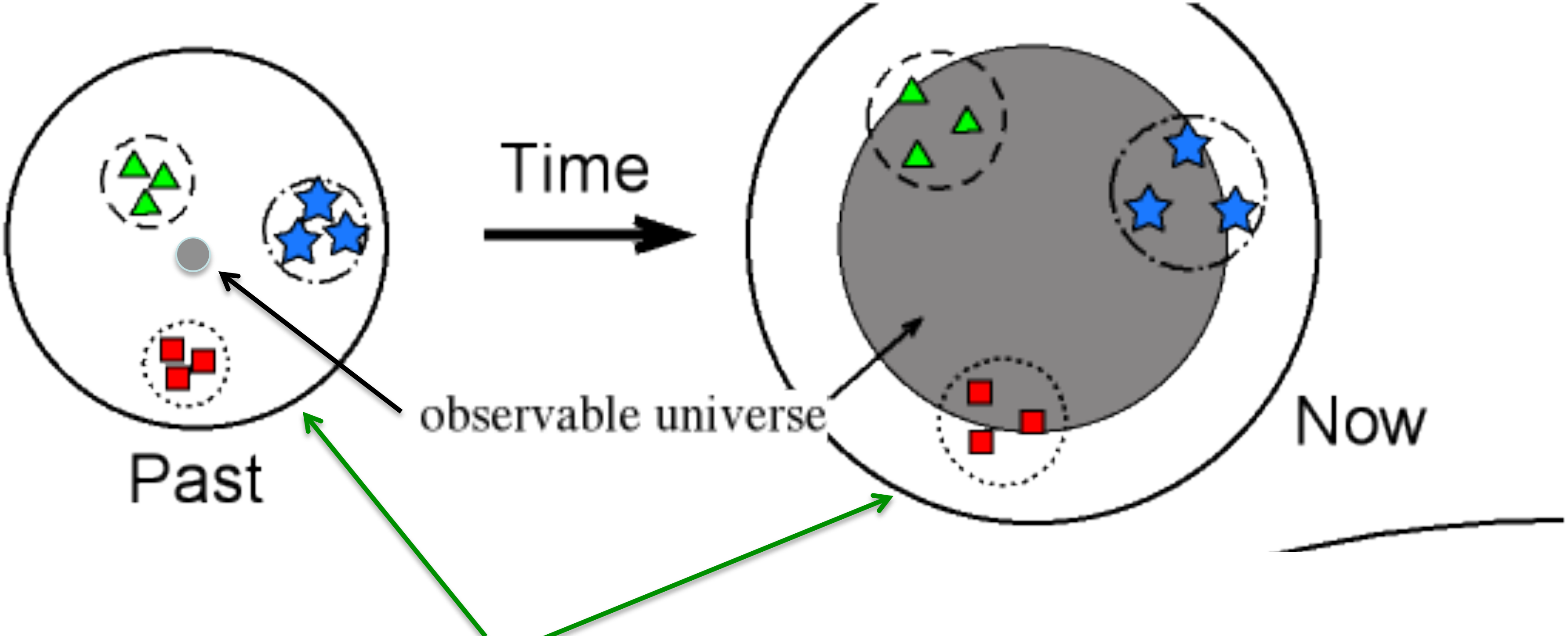


Curvature of space within cosmic light horizon ***without inflation***

Inflation makes the observable universe nearly flat

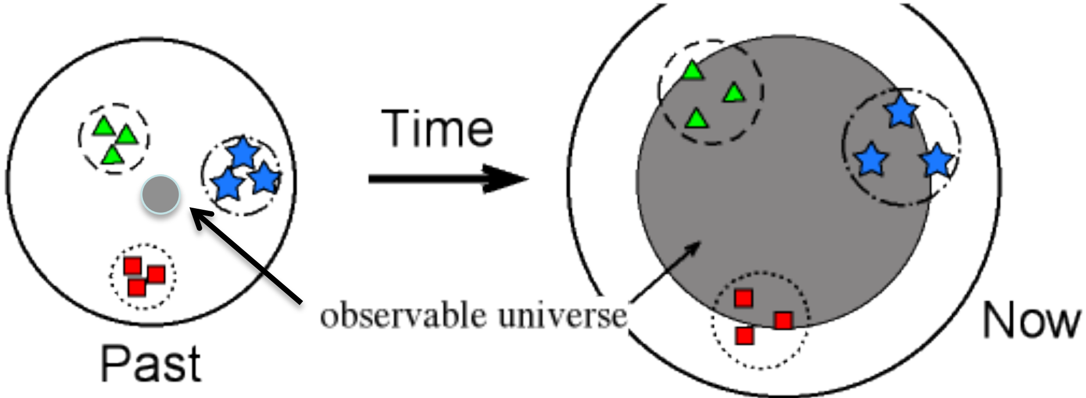


NO inflation: observable universe (shaded) includes parts that are different from each other

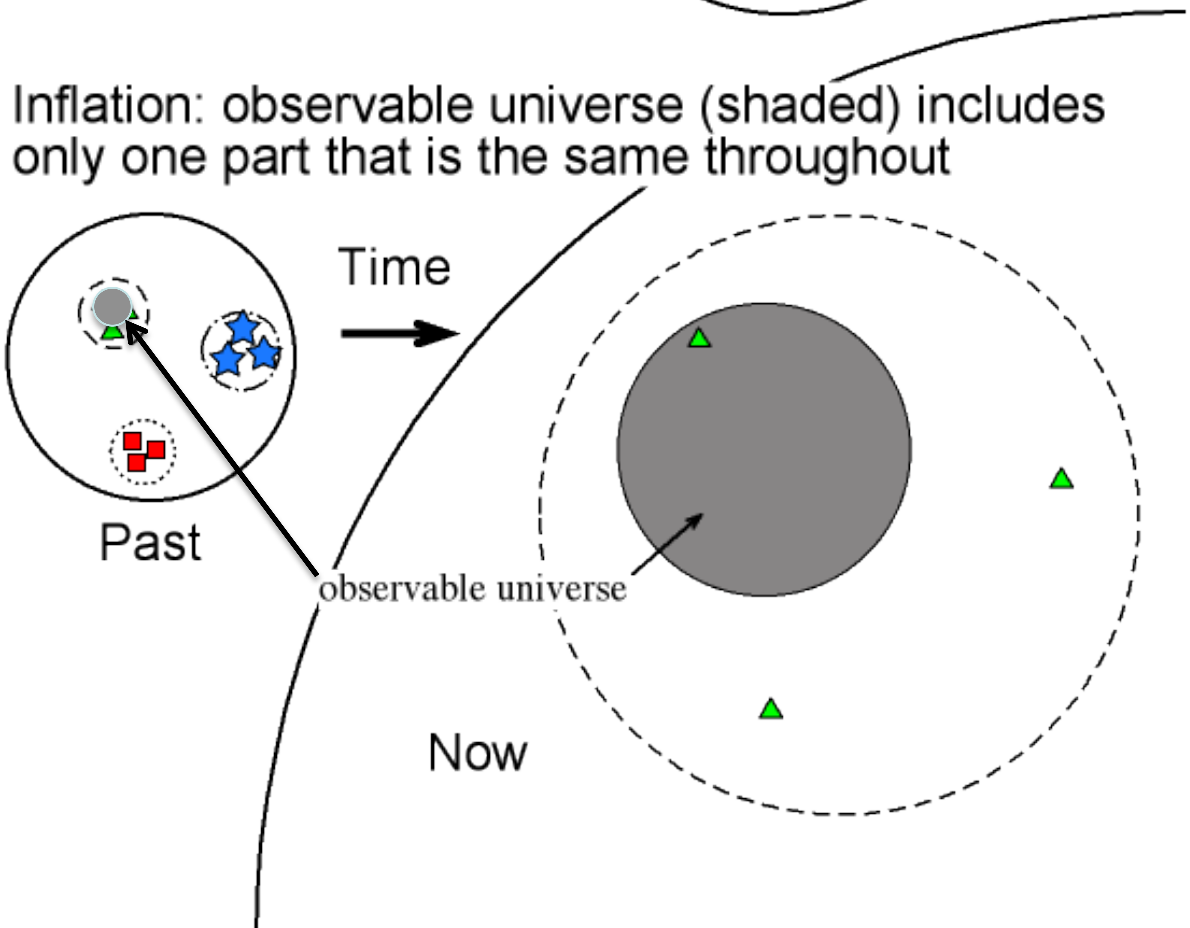


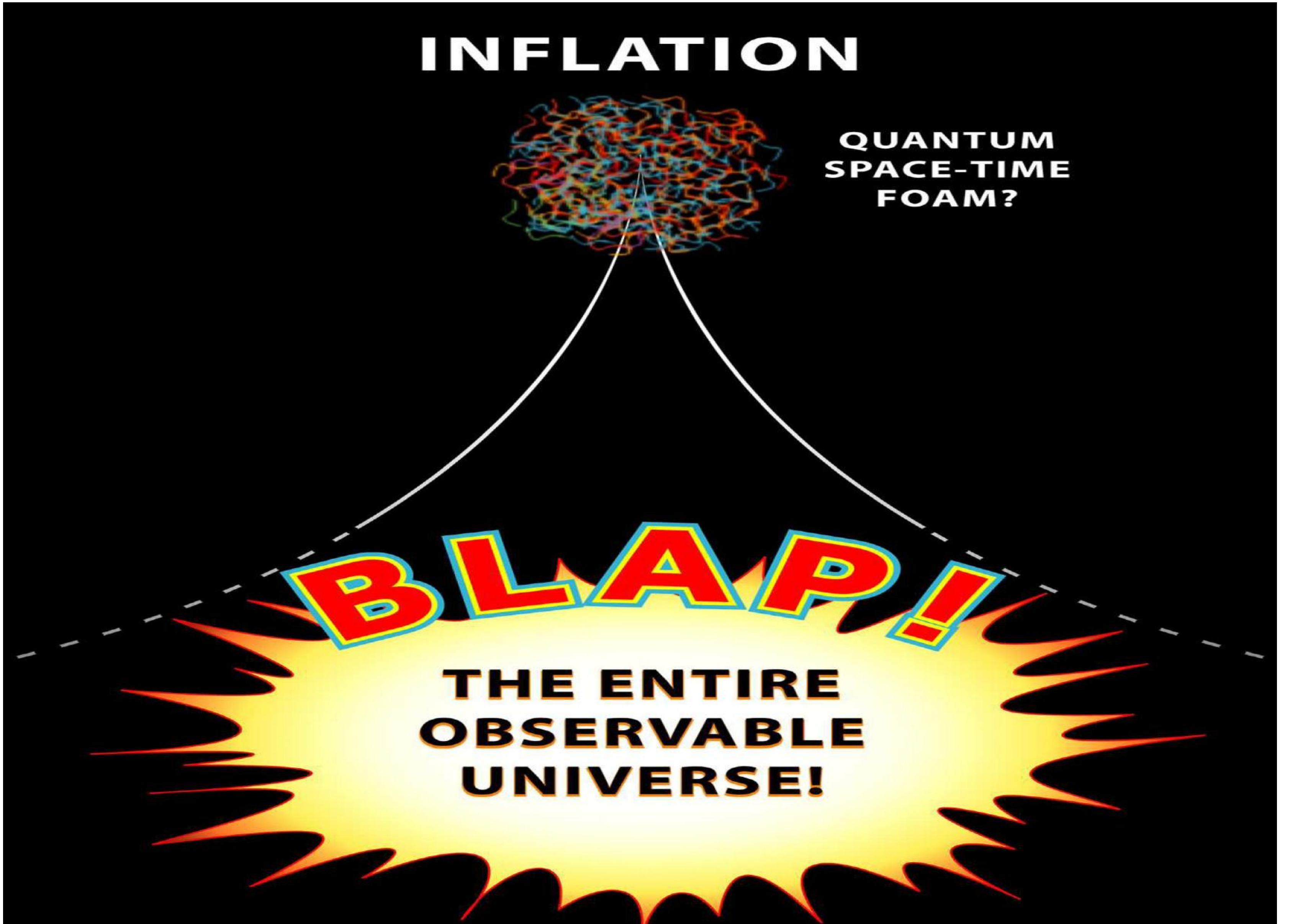
region of universe containing 3 different blobs

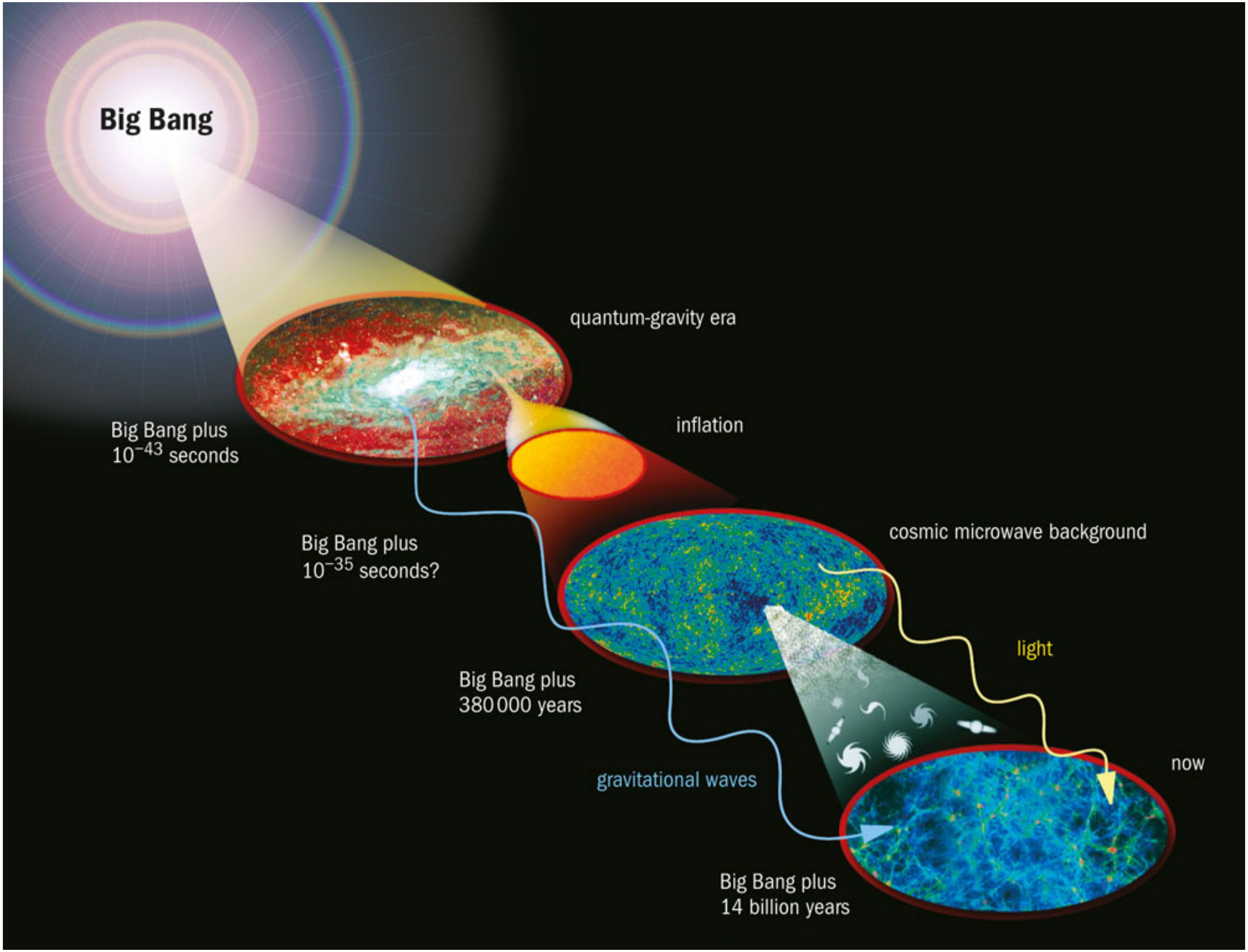
NO inflation: observable universe (shaded) includes parts that are different from each other



Inflation: observable universe (shaded) includes only one part that is the same throughout




INFLATION
QUANTUM SPACE-TIME FOAM?
BLAP!
THE ENTIRE OBSERVABLE UNIVERSE!



Big Bang
quantum-gravity era
Big Bang plus
10−43 seconds
inflation
Big Bang plus
10−35 seconds?
cosmic microwave background
light
Big Bang plus
380 000 years
gravitational waves
now
Big Bang plus
14 billion years

What is The “Big Bang”

- Standard cosmological model for “beginning” of space, time, energy & matter
- “Big bang theory describes how our universe is evolving, not how it began” J. Peebles
- Not a highly specific account of early evolutionary history of universe, but a broad idea under which more specific theories fall

Evidence for Big Bang

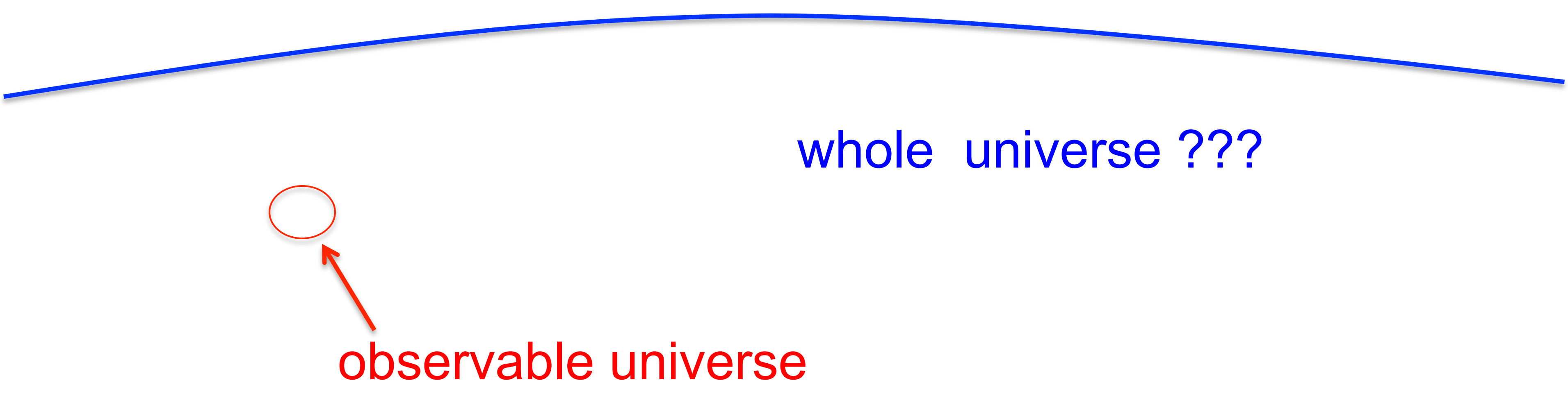
- Expansion of universe
- Cosmic microwave background
- Abundances of light elements

Big Bang – what it isn't, what it is

- Not an explosion of matter and energy into pre-existing space
- But an explosion of STEM (Space Time Energy Matter)
- All STEM were bound up in primordial, high density universe
- Spacetime, as well as matter and energy, are expanding

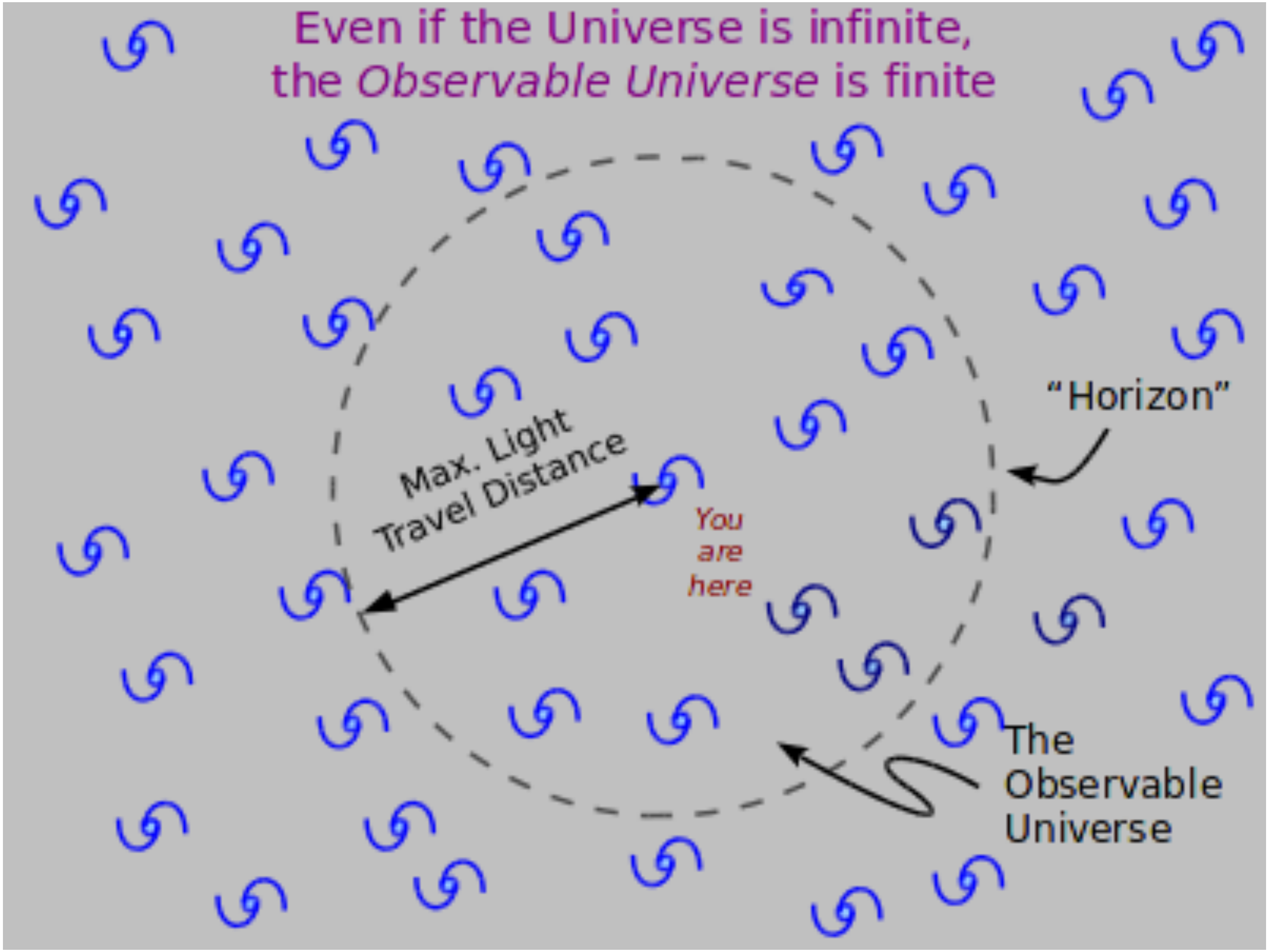
Questions I cannot answer!

How large is the universe?




Are there more than 1 universes?
Is there a “multiverse”?

Is The Universe Infinite or Finite?



Even if the Universe is infinite,
the *Observable Universe* is finite
"Horizon"
Max. Light
Travel Distance
You
are
here
The
Observable
Universe

What existed before the Big Bang?

What caused the Big Bang?

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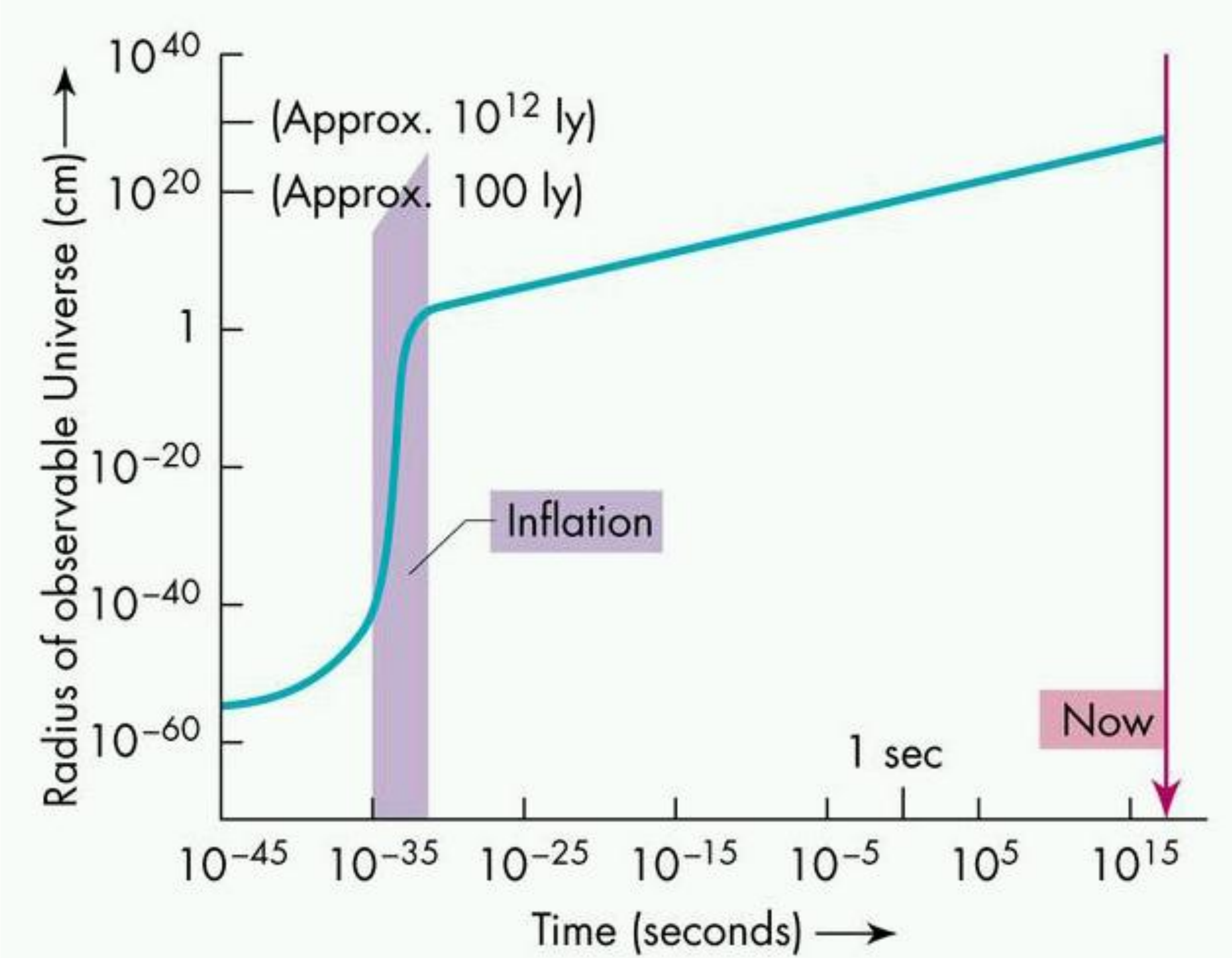

10^{40}
(Approx. 10^{12} ly)
10^{20}
(Approx. 100 ly)
1
10^{-20}
10^{-40}
10^{-60}
Radius of observable Universe (cm) ⟶
Inflation
Now
1 sec
10^{-45}
10^{-35}
10^{-25}
10^{-15}
10^{-5}
10^{5}
10^{15}
Time (seconds) ⟶