The Planck Era:
Disconnected Islands in Space

Not yet enough time to make contact

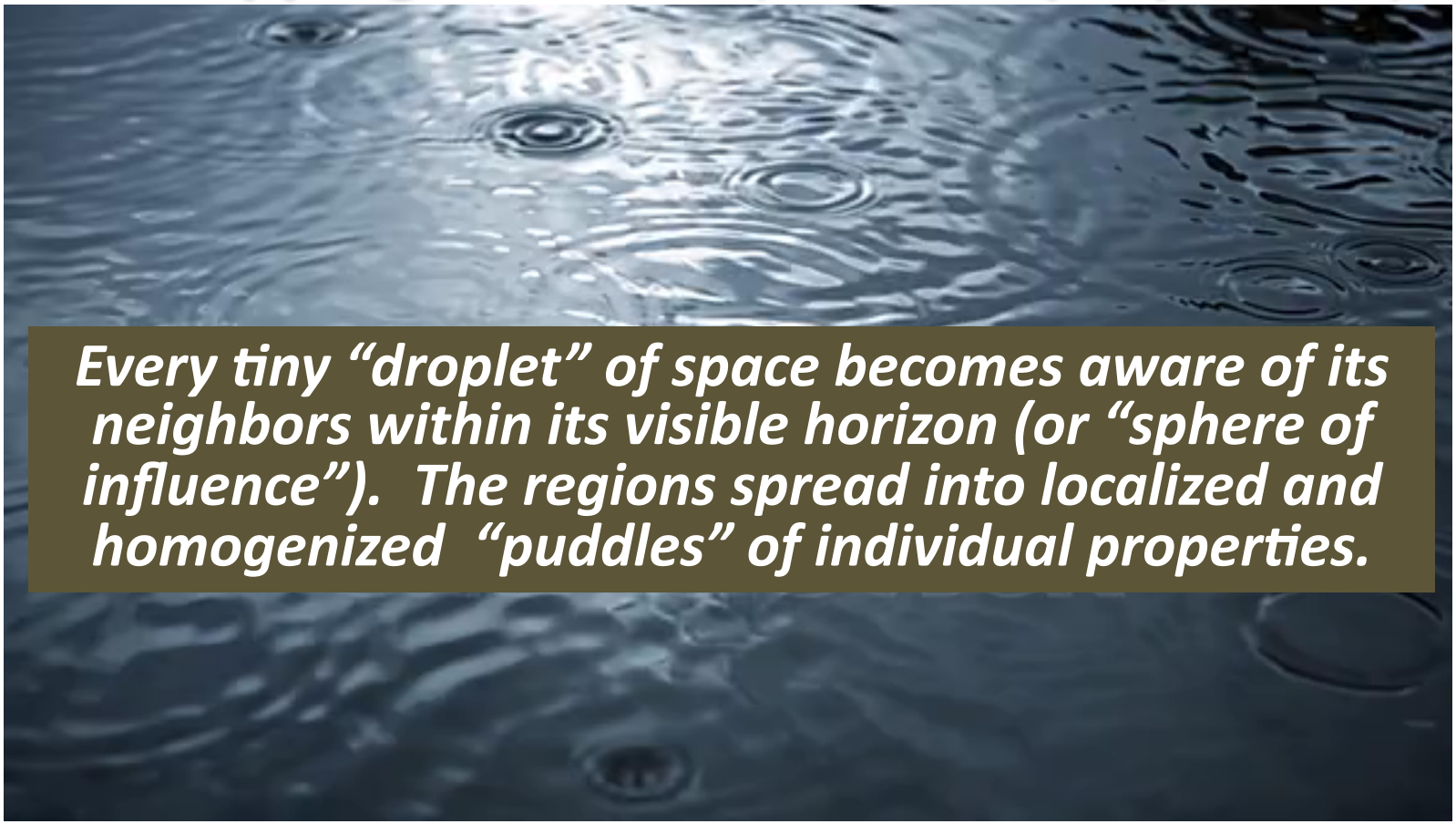
The Post-Planck Era

Discovering Others

End of "Planck Era"
$T \approx 10^{+31}$ K

Second: The Post-Planck Era

Overlapping Horizons (realms of influence)



Better analogy: *spreading waves from a handful of gravel dropped suddenly into water*

https://www.shutterstock.com/video/clip-3762701-water-drop-ripple-shooting-high-speed-camera

End of "Planck Era"
$T \approx 10^{+31}$ K

Strong forces cause rapid homogenization within local regions of space of size = the light travel time across them)

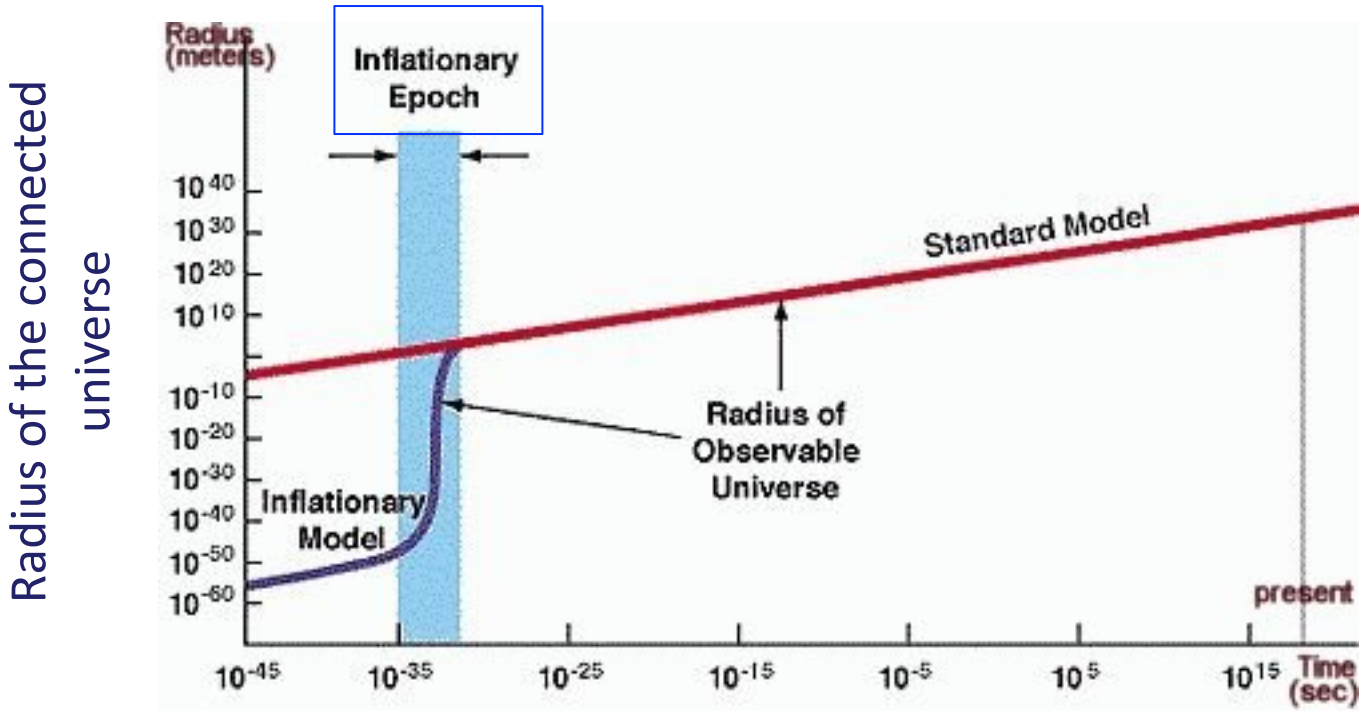
Then comes Cosmic Inflation!

Connected space abruptly expands by $\approx 10^{50}$!!!

Nearby objects separate v > c; soar beyond their mutual observable horizons and lose all contact

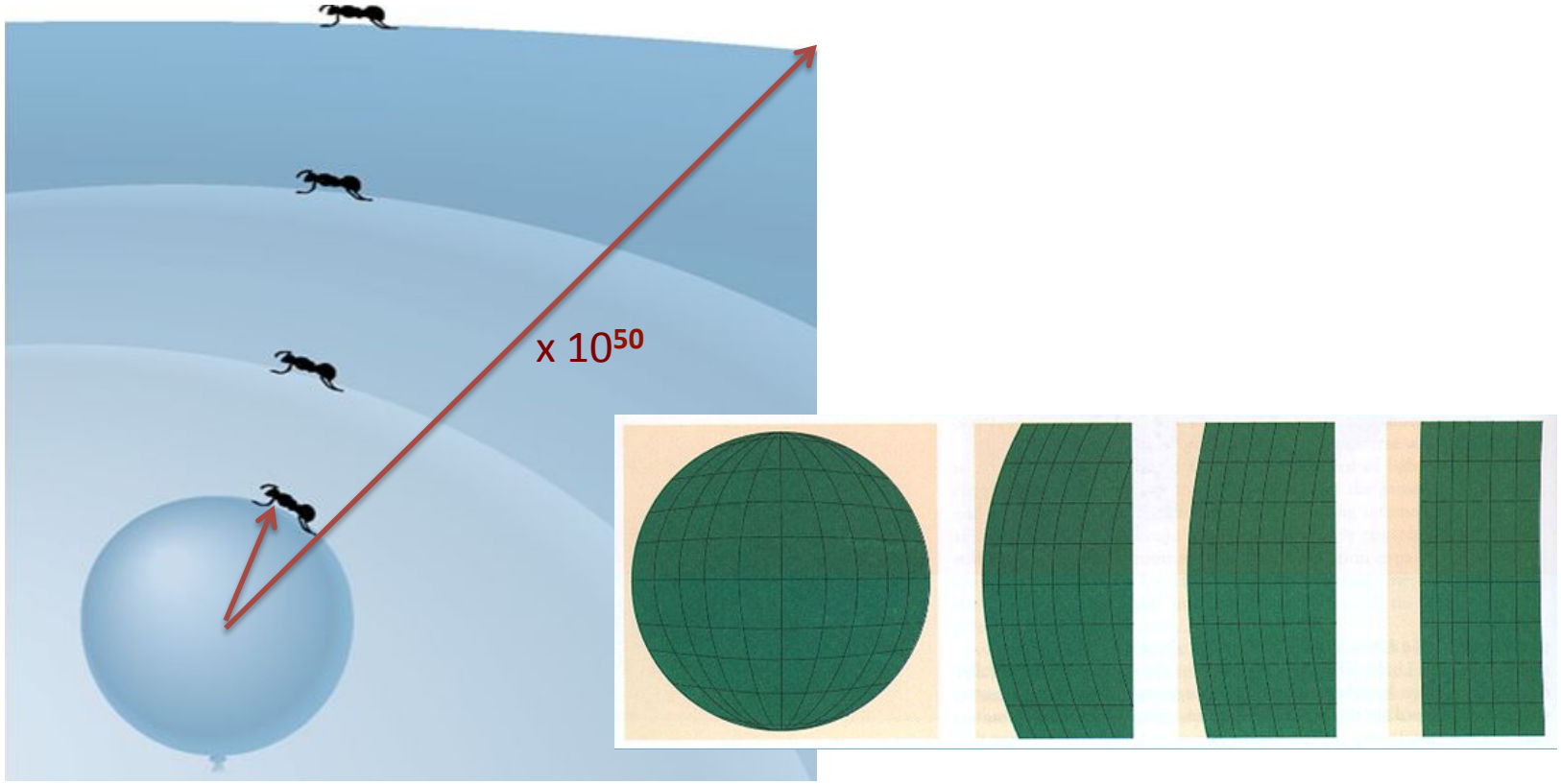
Third: Cosmic "Inflation"

Connected space abruptly expands by ≈10^{50} !!!



- Space expands everywhere by ≈10^{50}@ $t_{ABB} \approx 10^{-35}$ secs
- Objects once in close contact become very widely separated
  - **Separations the width of a proton, 10^{-18} km, grew to 10^{32} km = 10^{19} l.y. = 10^{9} x present horizon! IMPRESSIVE!**
    - **Our original horizon = 10–35 sec x speed of light**

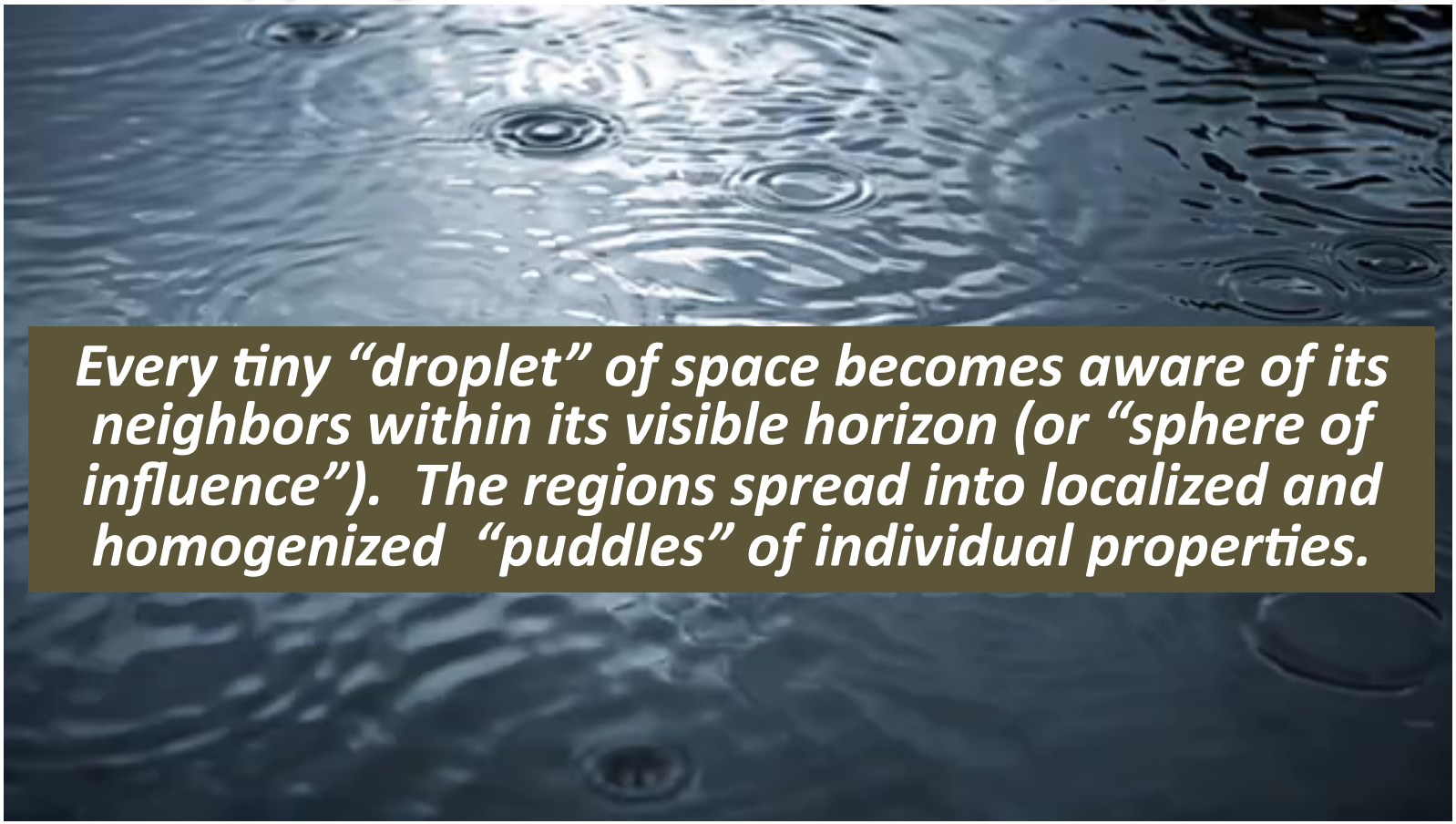
Then comes Cosmic Inflation! Space flattens.



Even if space wasn't flat before horizon, inflation makes space appear flat for some time afterwards (including now) (the "radius of curvature" increases by ≈10^{50}!)

Second: The Post-Planck Era

Overlapping Horizons (realms of influence)



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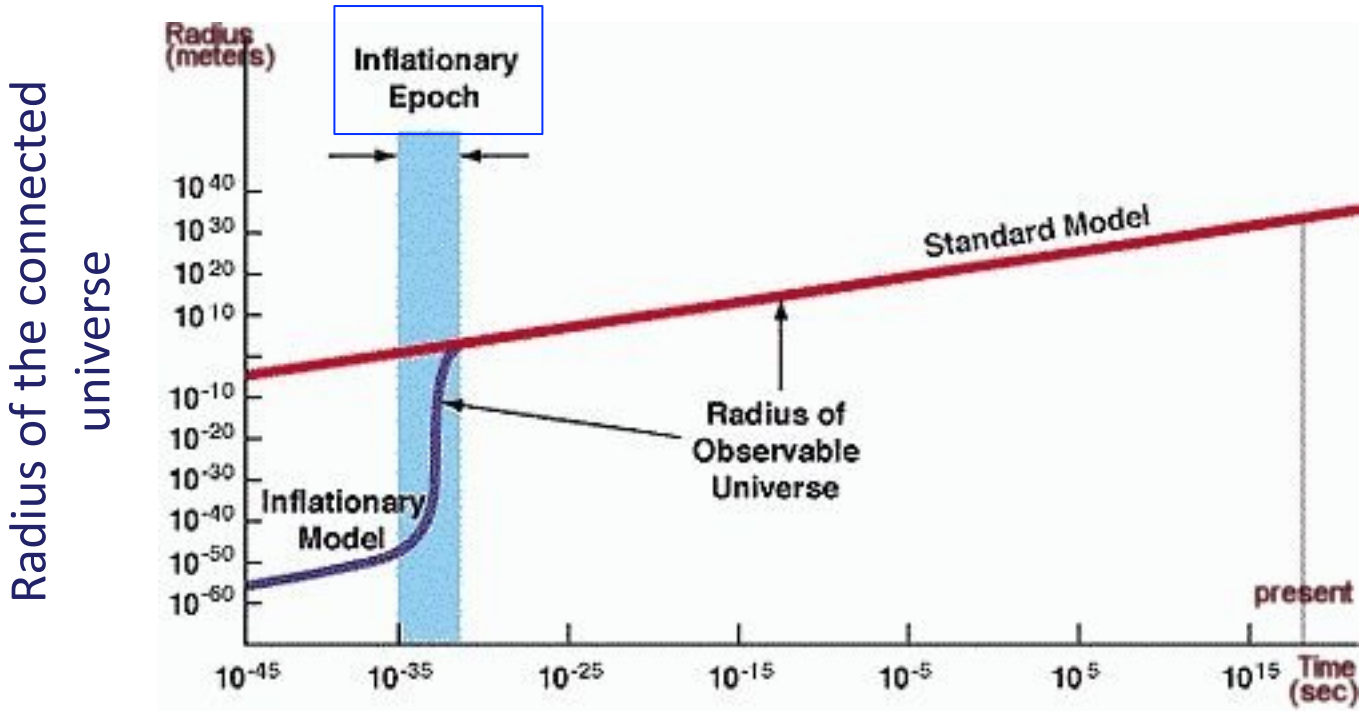

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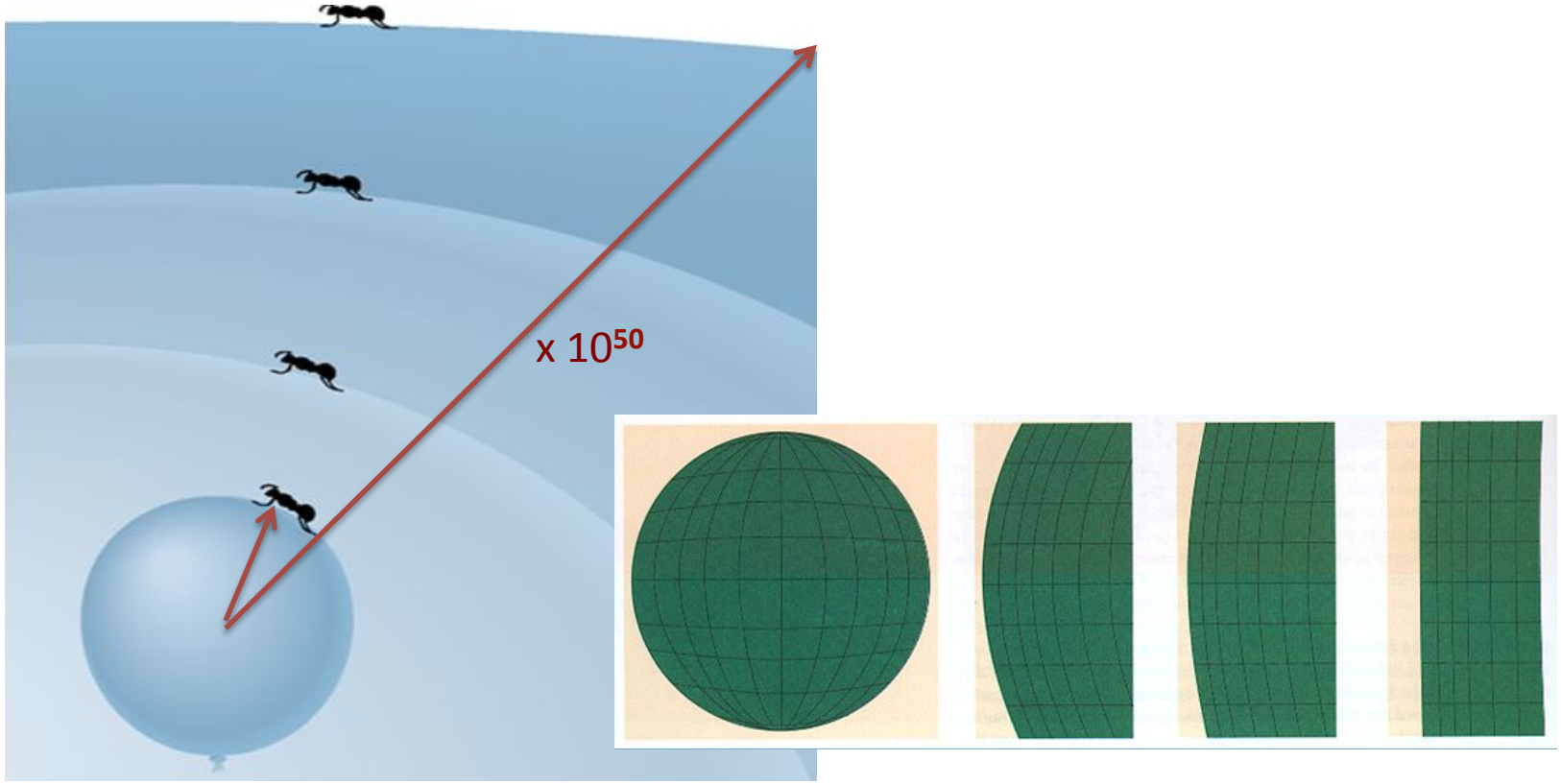
Cosmic Inflation flattens space



Even if space wasn't flat before horizon, inflation makes space appear flat for some time afterwards (including now) (the "radius of curvature" increases by ≈10^{50}!)

- Space expands everywhere by $\approx 10^{50}$ @ $t_{ABB} \approx 10^{-34}$ secs
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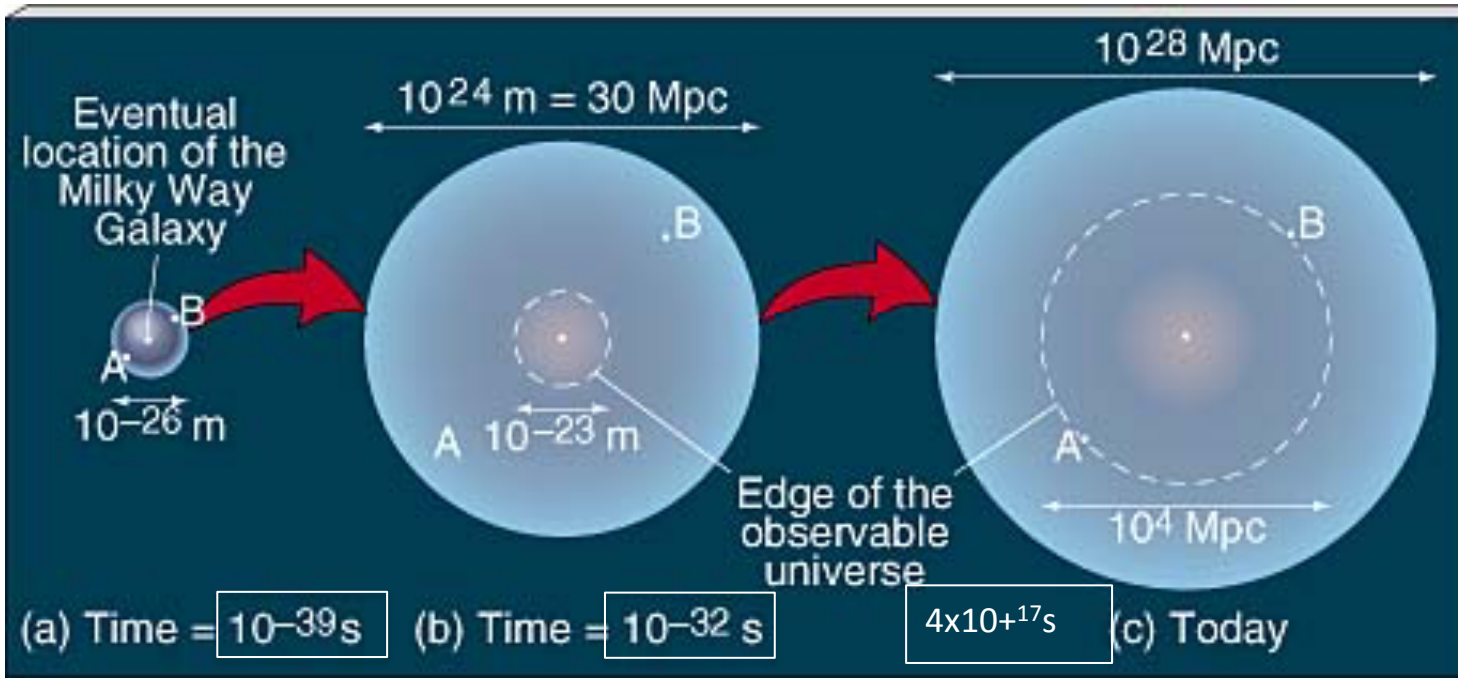
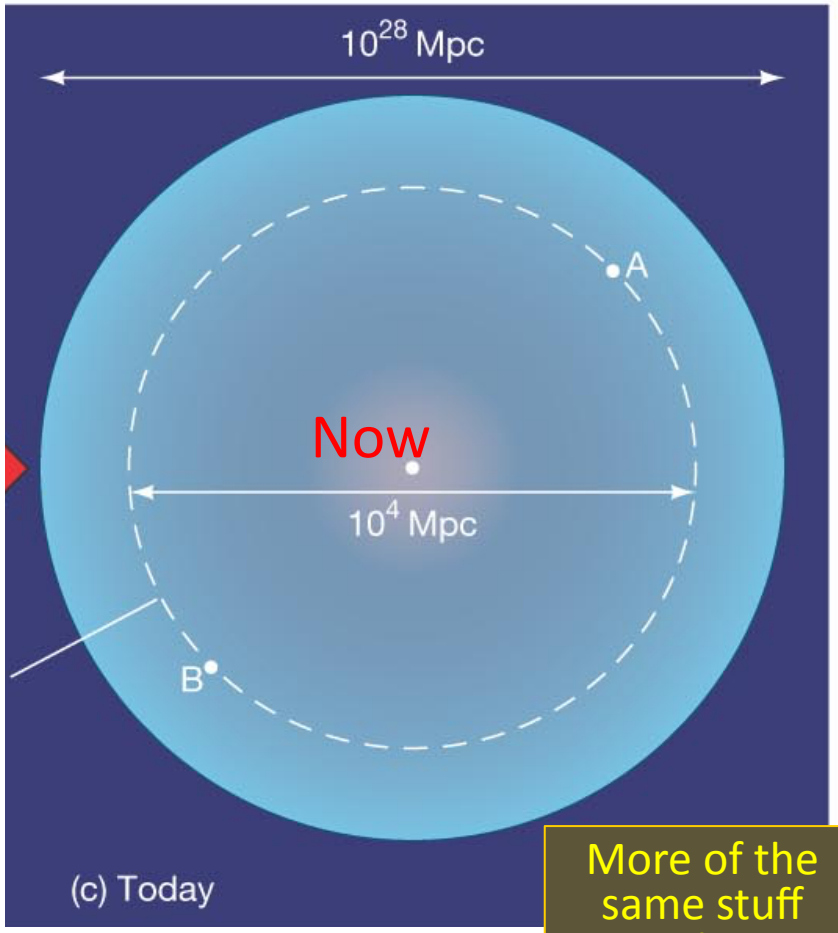
all regions maintain their initial "genetic inheritance"- physical properties, forces, & processes

"God's-eye view of space



Before	After	Now
Rapid Inflation	(Super Expansion)	Slower Inflation (Normal Expansion)

Dark Energy will eventually hide all galaxies

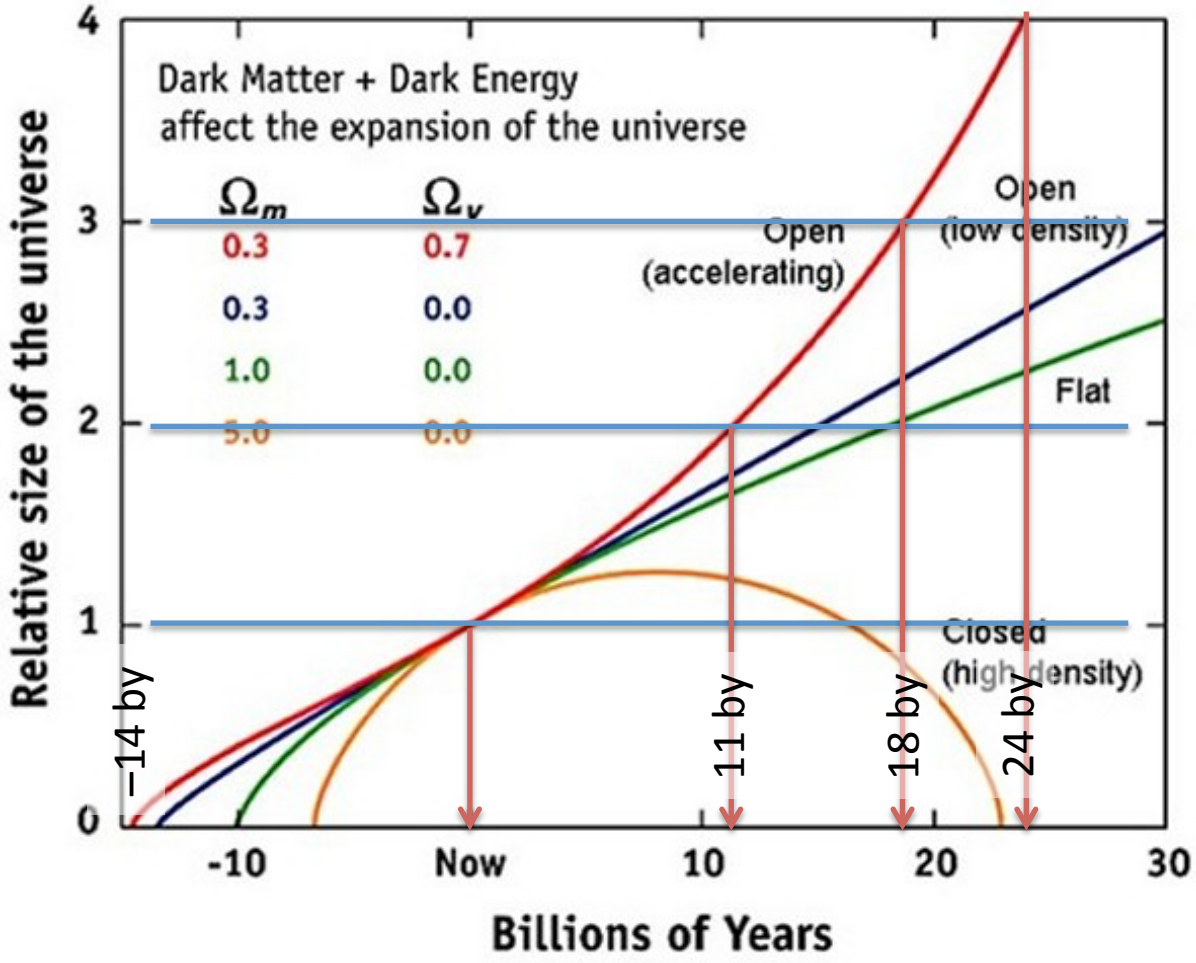


The Universe will soon start to re-expand faster than the visible horizon grows (1 l.y. per year).

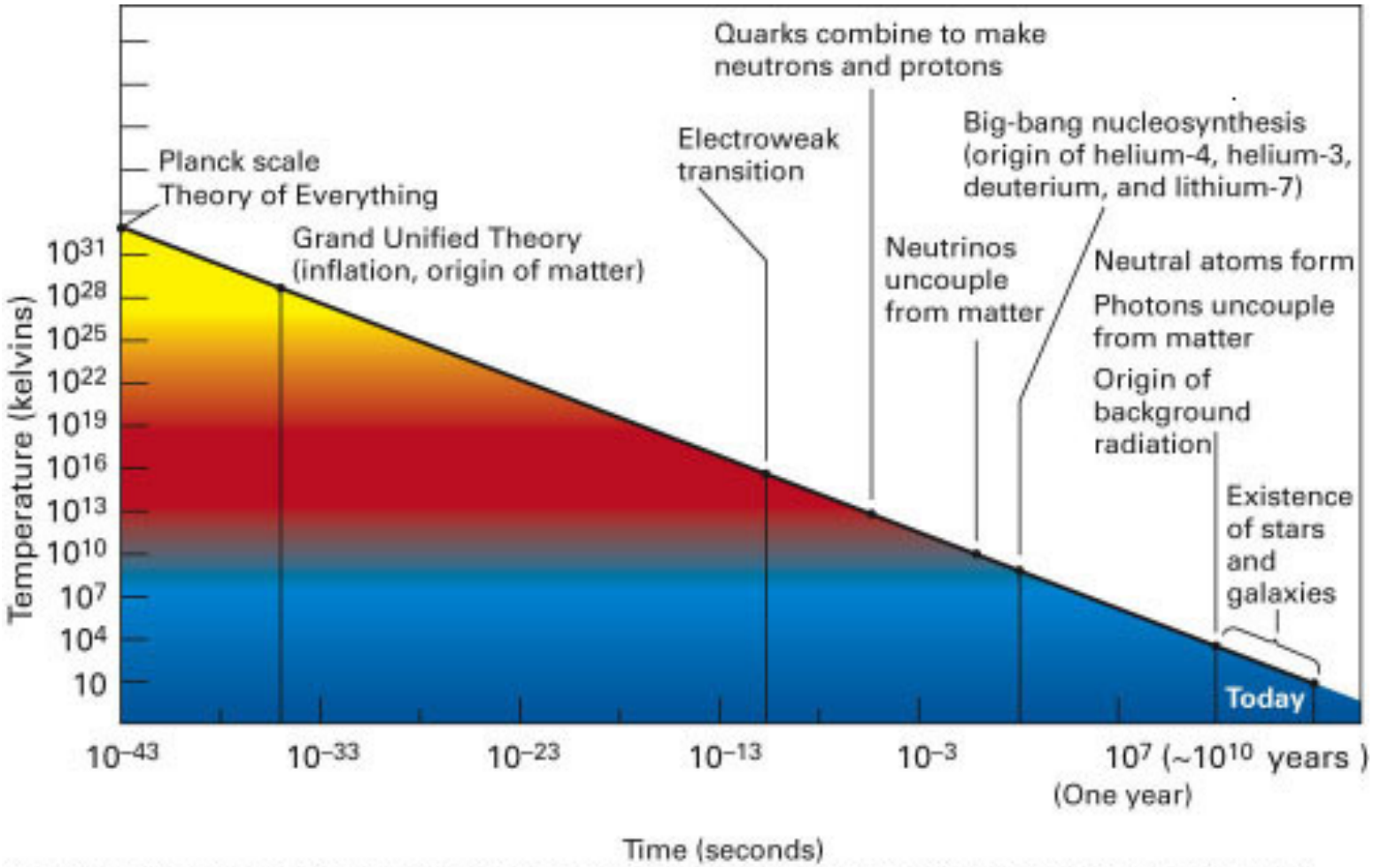
Objects we can see now will eventually recede faster than the speed of light.

The most distant objects will vanish first. But the exponential rate of the expansion (if it persists) will eventually assure that all galaxies beyond the local group will vanish!

Inflation: Pairs separate faster than light travels and "go past each others' visible horizon"

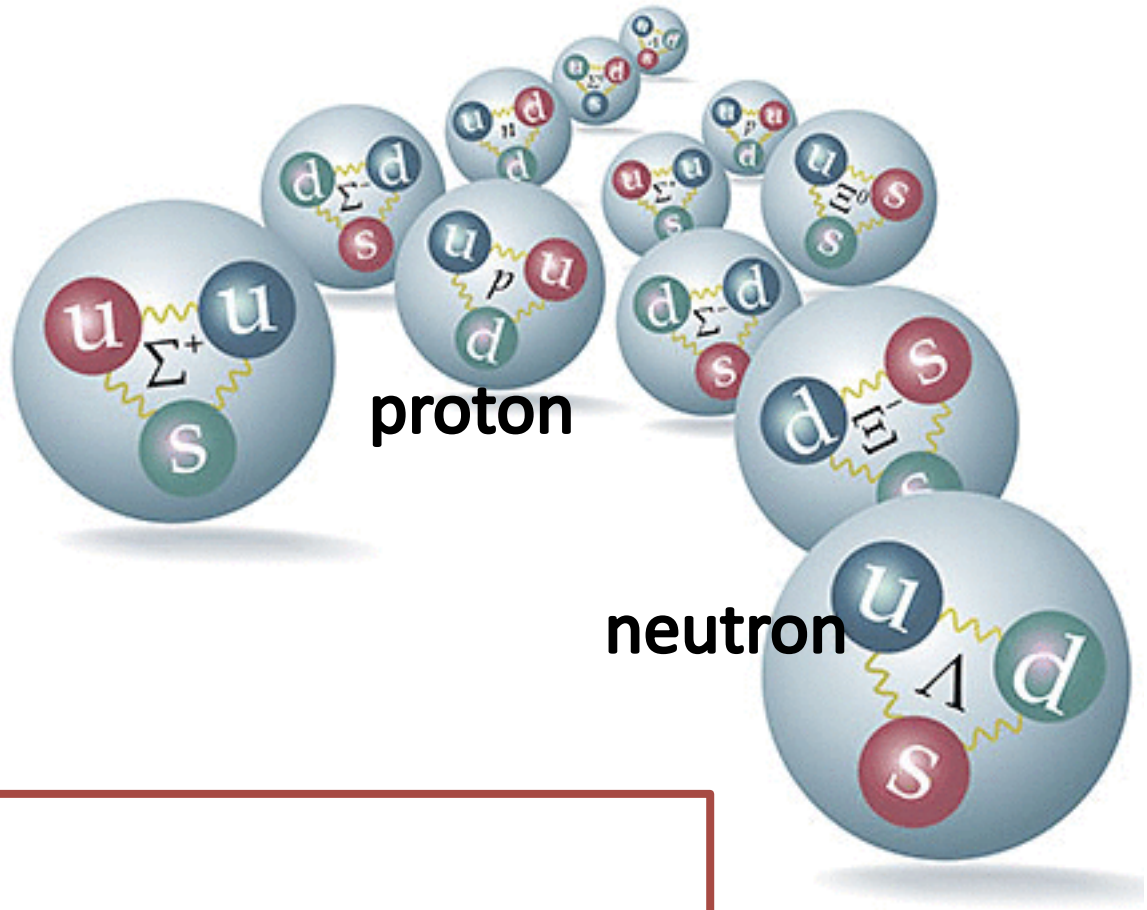


Now what?


Quarks combine to make neutrons and protons
Electroweak transition
Big-bang nucleosynthesis (origin of helium-4, helium-3, deuterium, and lithium-7)
Planck scale
Theory of Everything
Grand Unified Theory (inflation, origin of matter)
Neutrinos uncouple from matter
Neutral atoms form
Photons uncouple from matter
Origin of background radiation
Existence of stars and galaxies
Today
Temperature (kelvins)
10^{31}
10^{28}
10^{25}
10^{22}
10^{19}
10^{16}
10^{13}
10^{10}
10^{7}
10^{4}
10
10^{-43}
10^{-33}
10^{-23}
10^{-13}
10^{-3}
10^{7} (~10^{10} years)
(One year)
Time (seconds)

Post Inflation (10^{-35} to 10^{-9} s)

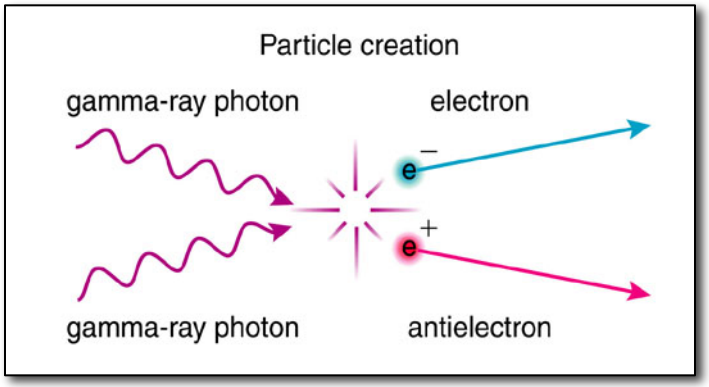
Quarks form, then make baryons, etc.



Main events:
Forces divide
Quarks appear when the strong force materializes
Leptons (and antiparticles) appear when the weak force materializes

Familiar nuclear particles (protons and neutrons and antiparticles) continuously form and are destroyed by their antiparticles

Particle/Antiparticle Creation & Annihilation



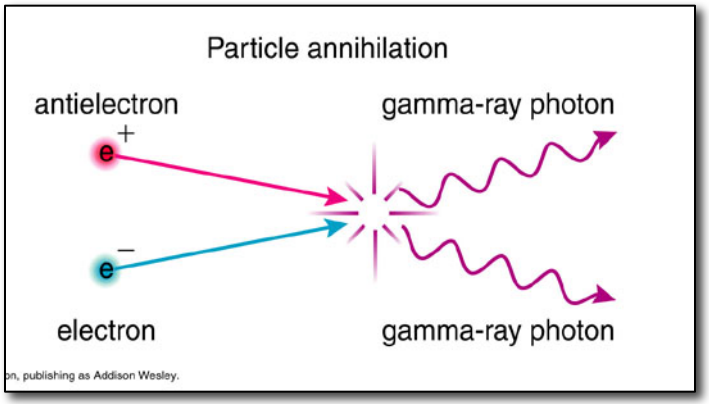
pair creation

2 photons of sufficient energy "create" a particle-antiparticle pair:

$2\ \gamma\ (h\nu > 2m_pc^2) \rightarrow p,p'$ pair

AND

requires 2 photons of sufficient total energy*



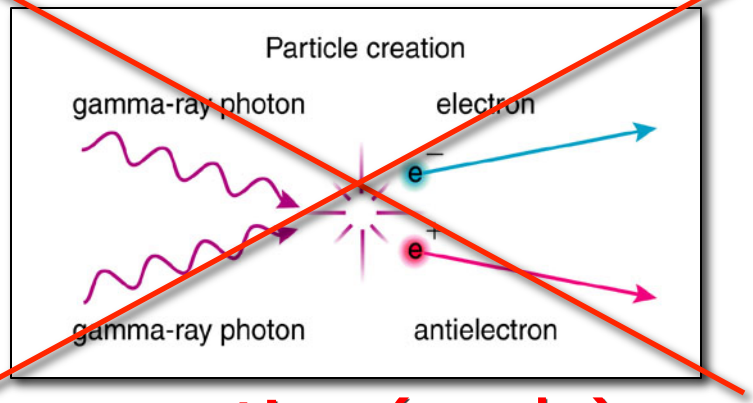
pair annihilation

A particle-antiparticle pair annihilate to make a photon pair:

$2\ \gamma\ (h\nu > 2m_pc^2) \leftarrow p,p'$ pair

* Why not just one photon? Because charge, spin, and other properties of the reactants must be conserved (as well as energy)

~~Creation &~~ Annihilation
time 1-10 sec, T ≈ 10^{12} K



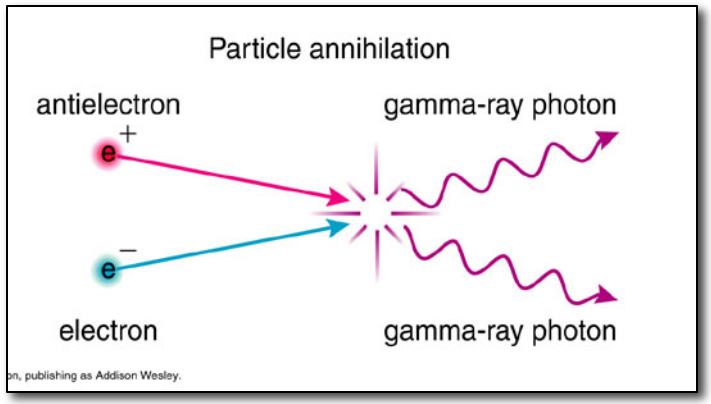
creation(ends)

IN!

2 photons of sufficient energy can't "create" a particle-antiparticle pair:

$2\ \gamma\ (h\nu > 2m_pc^2) \rightarrow p,p'$ pair

~~AND~~



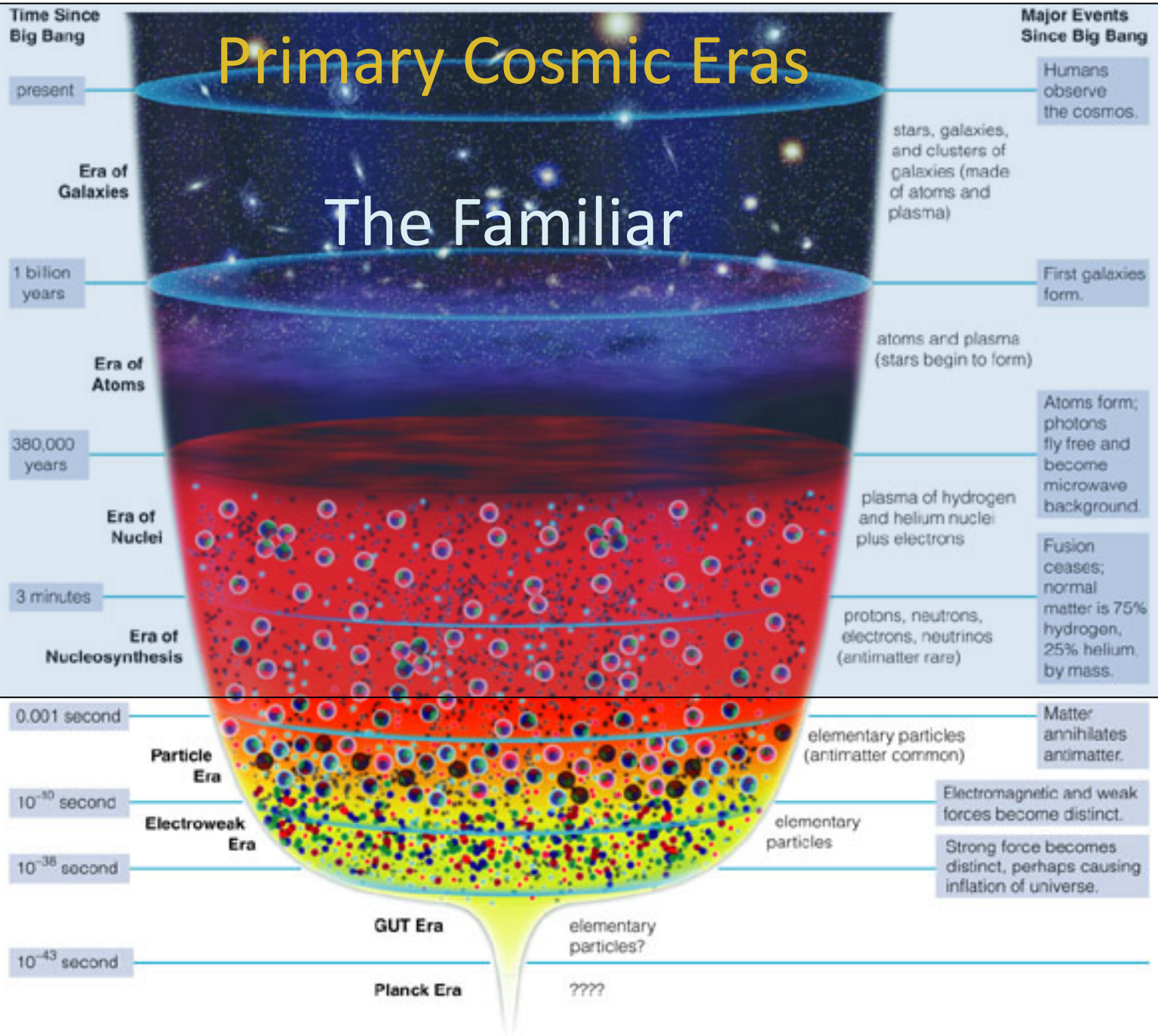
A particle-antiparticle pair annihilate to make a photon pair:

$2\ \gamma\ (h\nu > 2m_pc^2) \leftarrow p,p'$ pair

annihilation (continues)

Primary Cosmic Eras

The Familiar

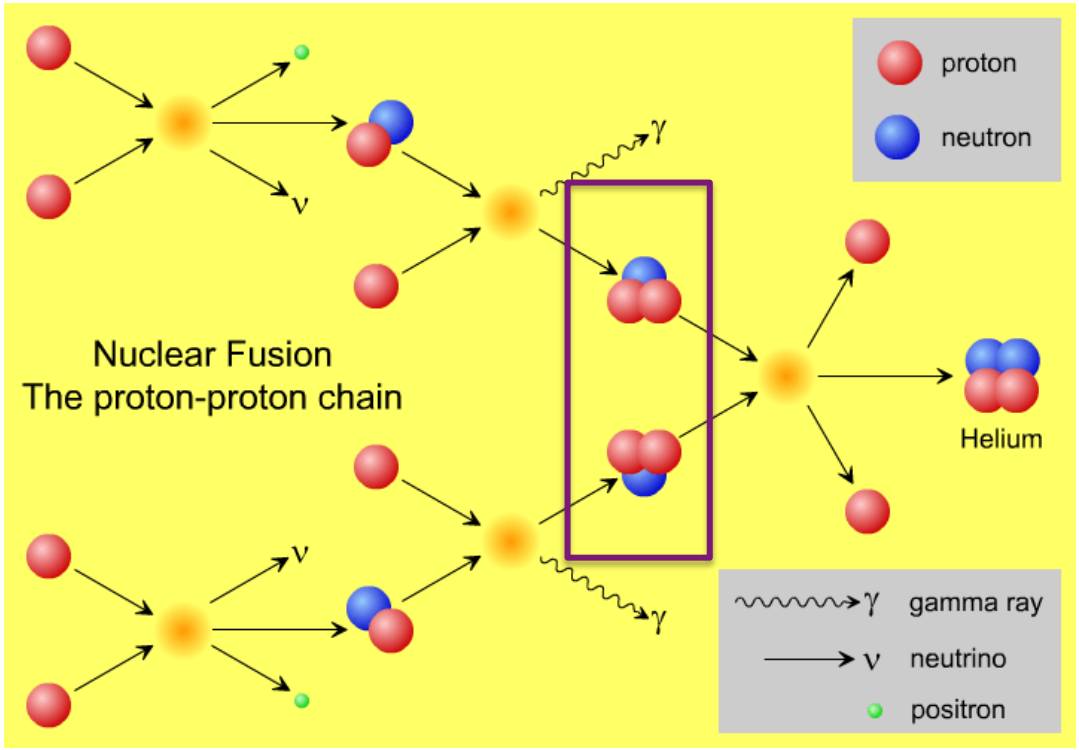


"Nucleosynthesis" < 10^2 s
T ≈ 10^9 K

Nuclear burning produces stable lighter nuclei:

2 protons + 2 neutrons -> Helium

plus really tiny amounts of 2H, 3He, Li, Be. But no C, N, O...

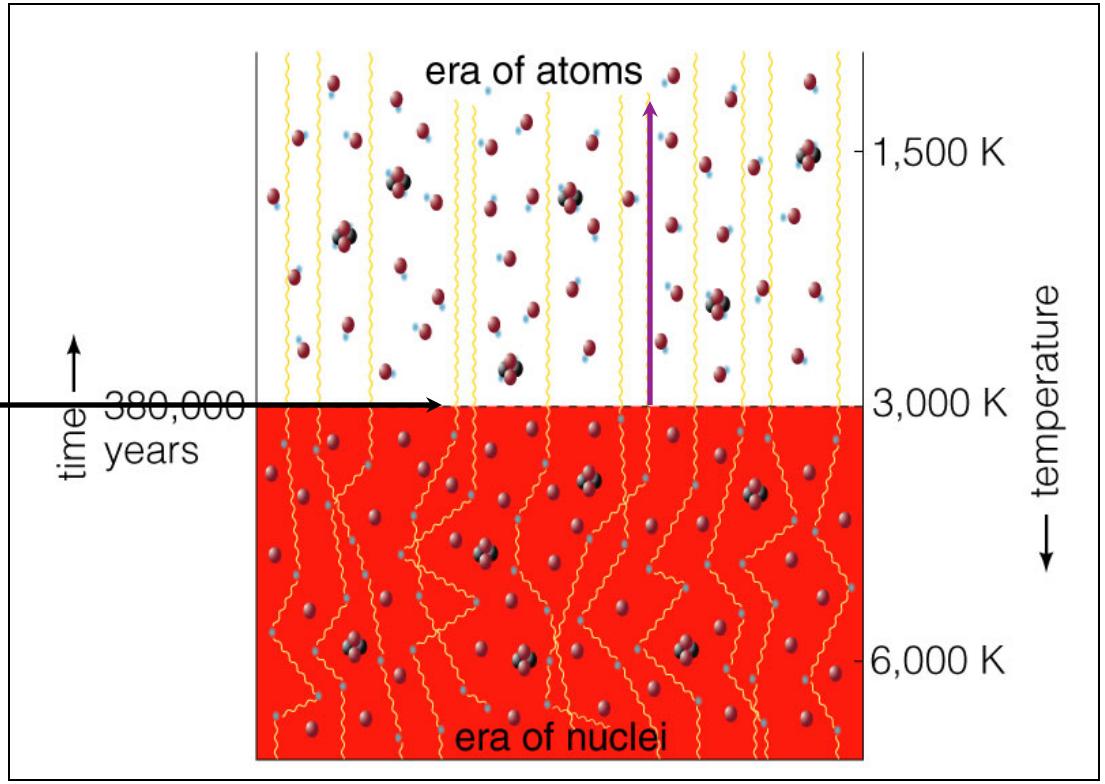


At the start of the first minute

- Density and temperature still dropping
  - Universe is still hotter than core of Sun
- Dense matter and radiation ($\Omega \approx \Omega_{\mathbf{rad}}$)
- (All) antimatter and (most) matter have annihilated
- Formation/destruction of deuterium and helium:
  Free protons, electrons & neutrons collide and start to fuse into heavier nuclei (^{2}H, ^{3}He, etc).
  At first, collisions destroy these nuclei as fast as they form.
  After ~ 3 mins no longer enough energy to overcome the repulsive force between ^{3}He particles in the reaction
- Photons lose energy as the Universe expands.
- Matter, not radiation, now dominates the cosmic energy budget.

Opaque to Transparent

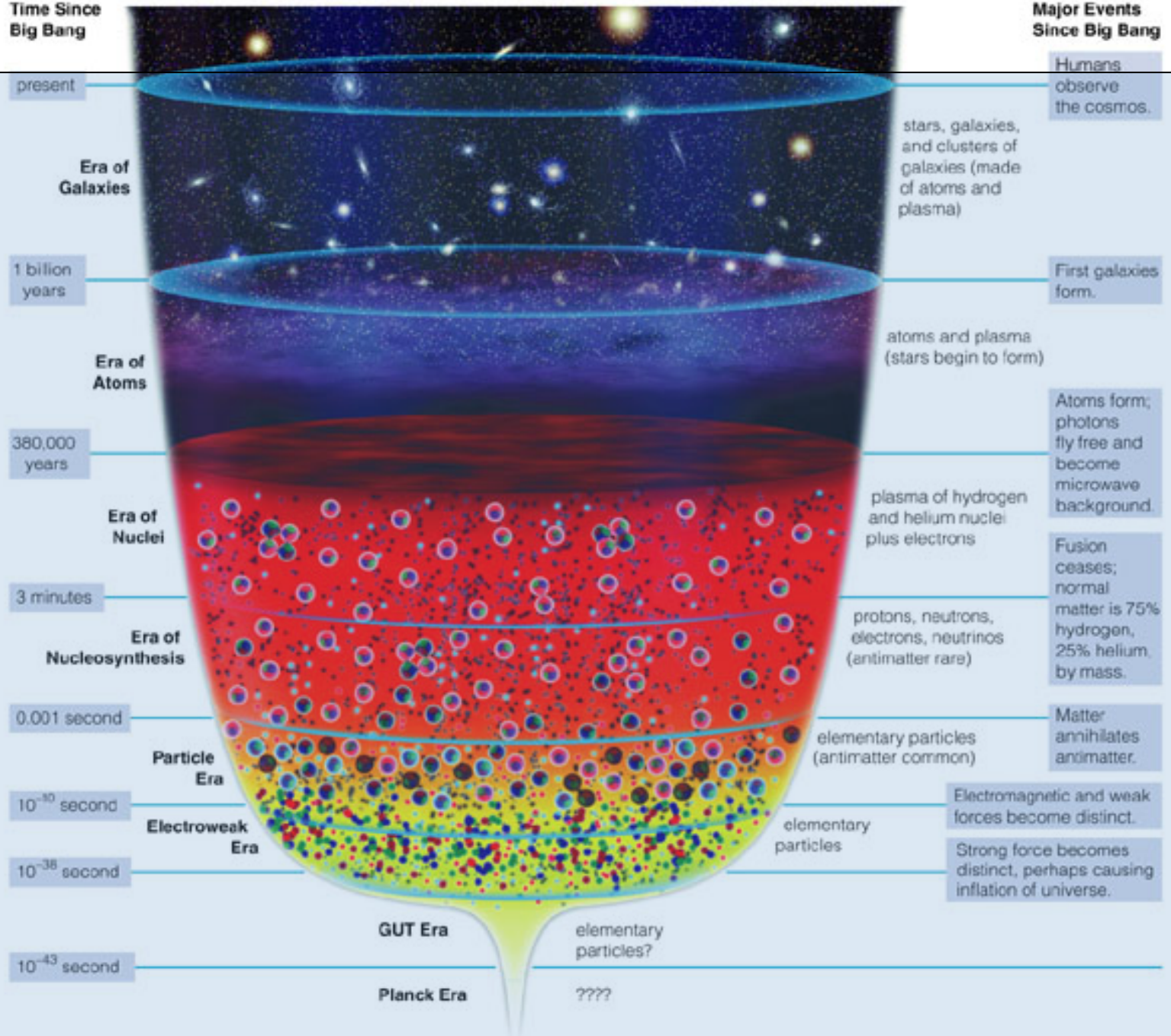
- After the temperature drops below 3000K the **nuclei and electrons combine to form neutral atoms**
- Opaque ➔ transparent.
- The dense "fog" vanishes.



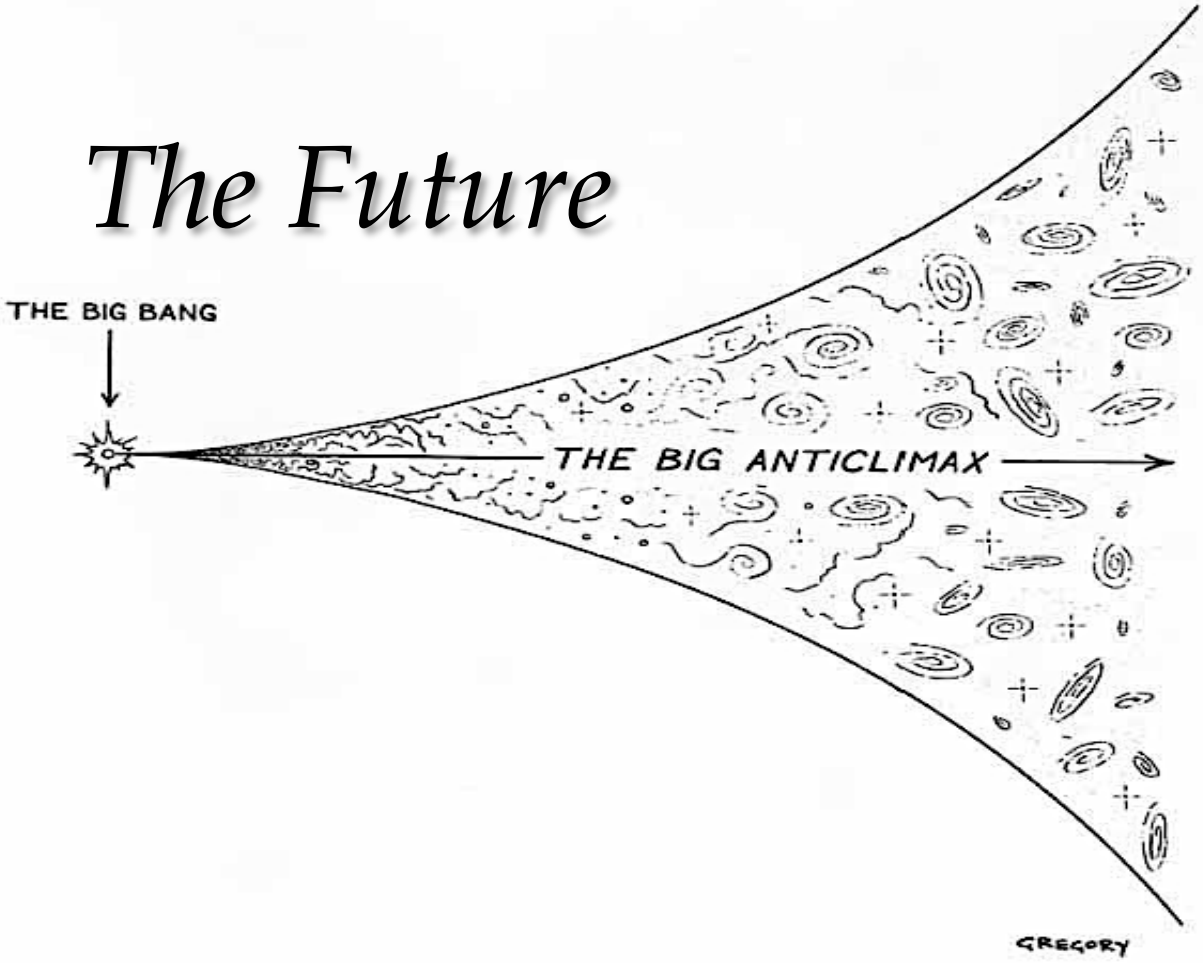
Photons travel unimpeded from their source through space. The fog clears.

Clusters, Galaxies, Stars, Planets

$T \approx 10^3$ to 2.73 K


Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
Era of Galaxies
stars, galaxies, and clusters of galaxies (made of atoms and plasma)
1 billion years
First galaxies form.
Era of Atoms
atoms and plasma (stars begin to form)
380,000 years
Atoms form; photons fly free and become microwave background.
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
3 minutes
Fusion ceases; normal matter is 75% hydrogen, 25% helium by mass.
Era of Nucleosynthesis
protons, neutrons, electrons, neutrinos (antimatter rare)
0.001 second
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
10^{-10} second
Electromagnetic and weak forces become distinct.
Electroweak Era
elementary particles
10^{-38} second
Strong force becomes distinct, perhaps causing inflation of universe.
GUT Era
elementary particles?
10^{-43} second
Planck Era
????

The Future

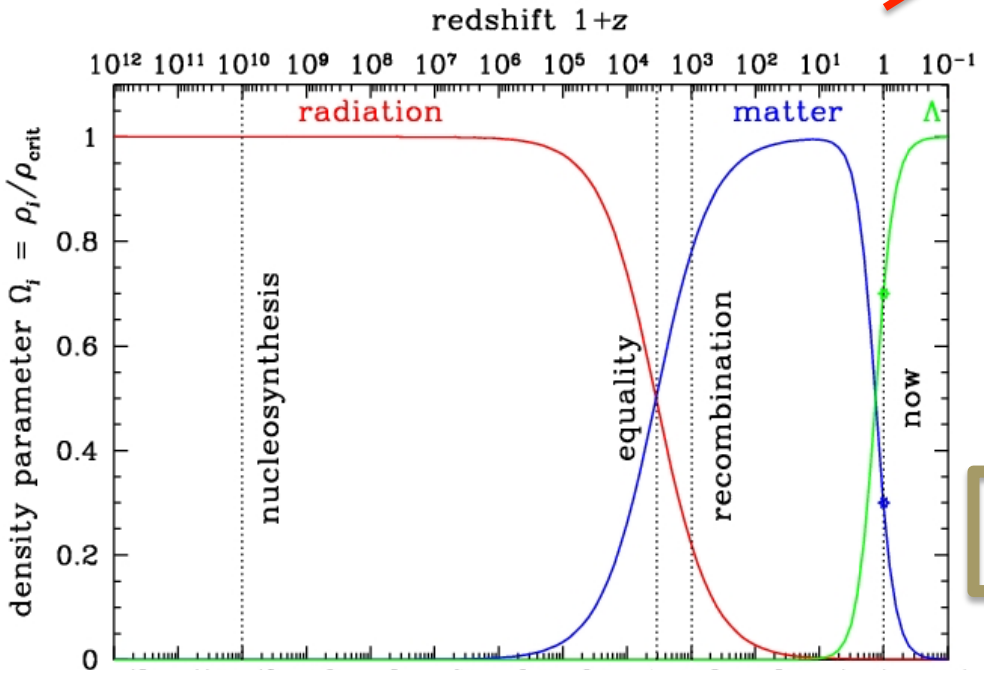


Dark Energy in Our Universe
($\Omega_{\text{mass-energy}} > 0$)

Before long mass will lose all of its cosmic influence

Attraction **contraction** — Repulsion **expansion**

$$acceleration = -GM / r^2 + \Lambda \cdot r / 3$$



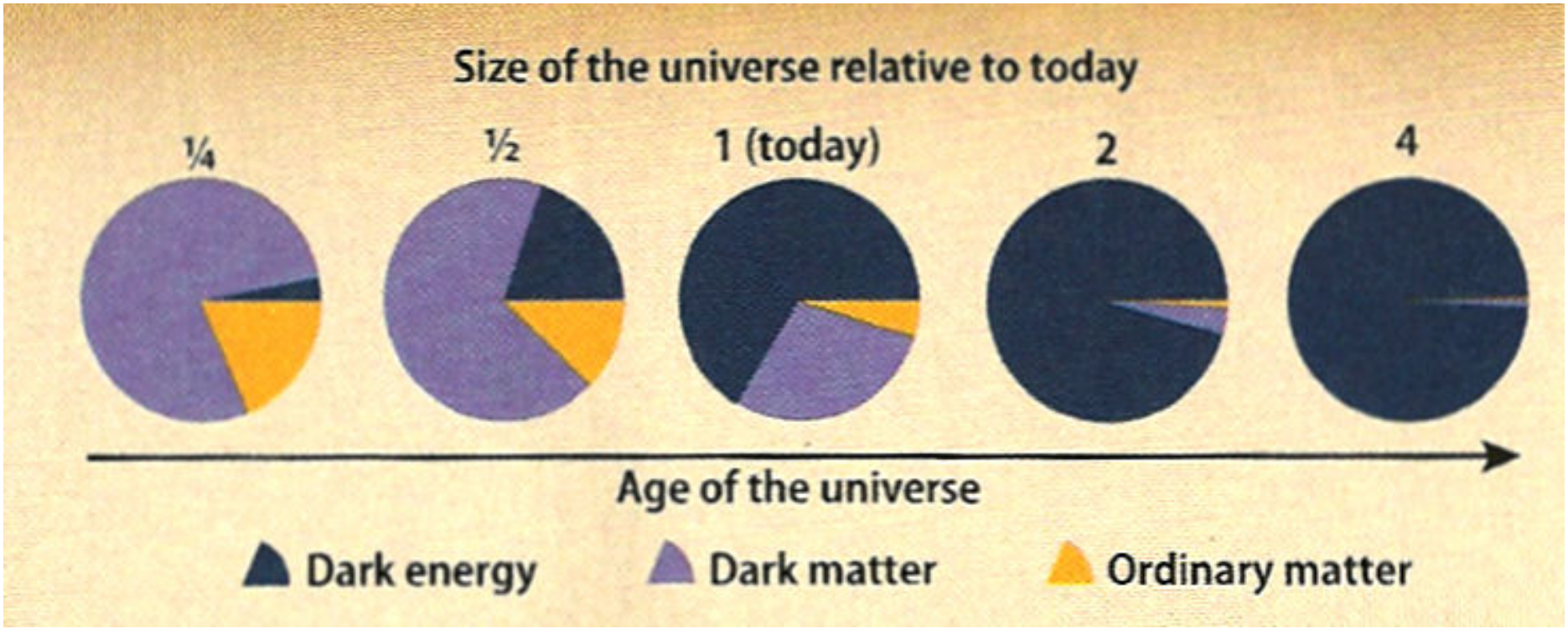
The expansion "runs away" as r increases a few billion years from now.

Once this happens the size scale of the Universe will increase exponentially:

$$separation \propto \exp\left[(\Lambda / 3)^{1/2}\, t\right]$$

Long-term Cosmic Outcomes

What do you expect?



Dark Energy Will Rule!

Before long mass will play an insignificant role in restraining the acceleration of space.