Astr 102: Introduction to Astronomy

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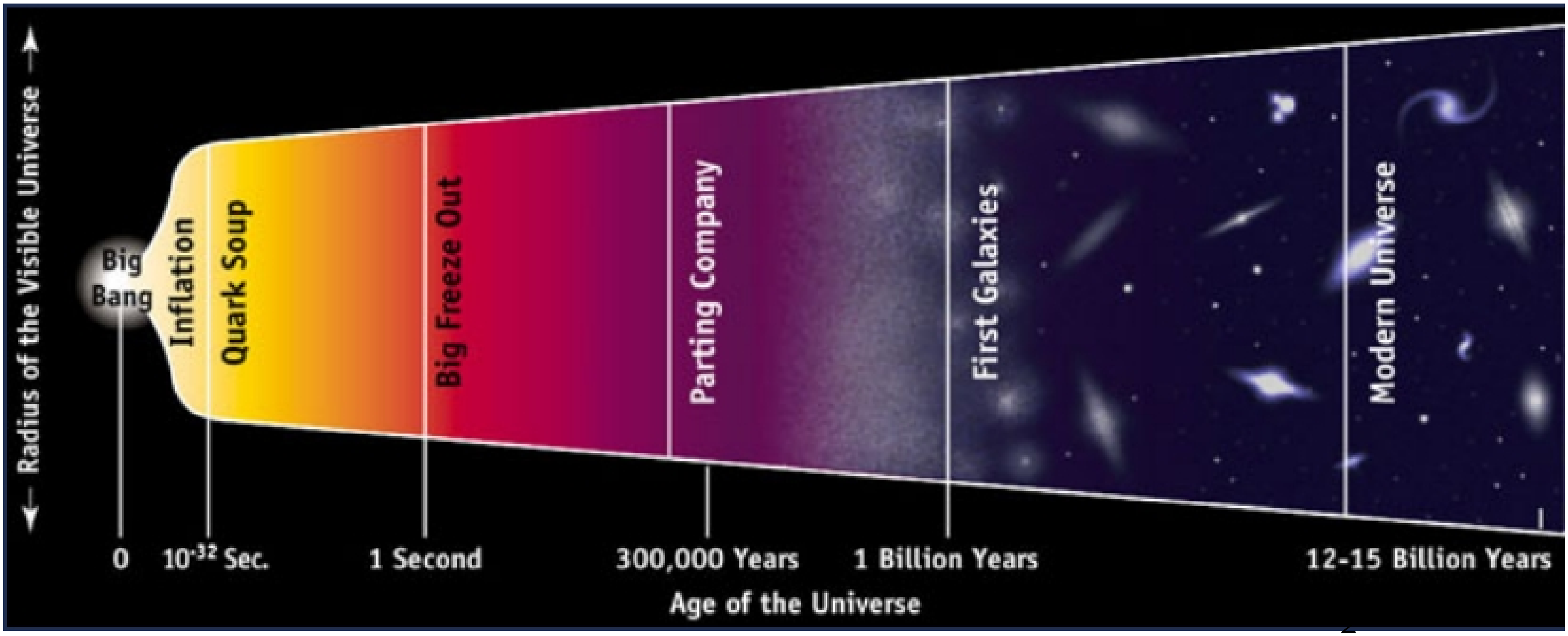
Lecture 18:

Early Universe and Inflation

Early Universe and Inflation

- A brief review of elementary particle physics
- The density and temperature in the early universe were much higher than today – some major phases when the matter was in significantly different forms than today
- Unresolved problems with the Big Bang theory
- Inflation



A brief review of elementary particle physics

- Baryonic (*barys* means heavy in Greek) matter: particles made of three quarks (quarks are fundamental spin 1/2 particles, their names are *up, down, strange, charm, bottom and top*), e.g. protons (uud) and neutrons (udd) are baryons with the largest contributions to Ω_b (NB *nucleosynthesis* is the generation of atomic nuclei from neutrons and protons).
- Baryons other than protons and neutrons do exist (e.g. lambda particle), but are not stable and do not contribute to baryonic Ω (they are called *hyperons*).
- Electrons are leptons (rather than baryons), but they **are** considered as contributors (though minor, *lepton* means light in Greek) to baryonic (aka *normal*) matter. Leptons also include muons and tau particles. Each lepton has a corresponding neutrino (and each lepton has an antilepton, which also has a corresponding antineutrino).

A brief review of elementary particle physics

- There are about 10^9–10^{10} photons per each baryon in the Universe (NB the most common particles in the universe are neutrinos, or perhaps axions). Neutrinos are **very** lightweight. For example, the current upper limit on the mass of electron neutrino is 1/1,000,000 of the electron mass (and the latter is only 1/2000 of the nucleon's mass).
- When particles turn into each other, in addition to dynamical quantities such as energy and momentum, quantities such as charge, baryon number and lepton numbers also need to be **conserved**. For example, this is allowed

$$n \rightarrow p + e^- + \overline{\nu}_e \tag{1}$$

but this is not (lepton number is not conserved)

$$n \rightarrow p + e^- + \nu_e \tag{2}$$

Non-baryonic matter

- The contribution to the mass of the Universe from these particles is **not** sufficient to account for all the gravitational forces observed in the Universe.
- This suggests that other matter, known as dark matter, also exists that must be in some other form which we call non-baryonic matter. Examples are neutralinos, axions, massive neutrinos, etc.

Elementary particles in the early Universe:

Particle	Symbol	Mass (MeV)	Spin (h)	Charge (e)	Interaction
Quarks	u		1/2	2/3	G,W,E,S
	d			-1/3	
	c			2/3	
	s			-1/3	
	t			2/3	
	b			-1/3	
Leptons	ν_e	$< 3 \times 10^{-6}$	1/2	0	G,W
	e	0.511		-1	G,W,E
	ν_μ	< 0.19		0	G,W
	μ^-	105.66		-1	G,W,E
	ν_τ	< 18.2		0	G,W
	τ^-	1777		-1	G,W,E
Bosons	graviton	$< 10^{-36}$	2	0	G
	γ	$< 2 \times 10^{-22}$	1	0	G,E
	gluons		1	0	G,S
	$W^{\pm}$	8.04×10^4	1	-1	G,W,E
	Z^0	9.12×10^4	1	0	G,W

Early Universe: temperature vs. time

- As we run the cosmic time **backwards**, the density and temperature increase. The matter density (today $\Omega_m = 0.3$) increases as $(1+z)^3$, and the radiation density (today $\Omega_r = 5 \times 10^{-5}$) increases as $(1+z)^4$ (NB the lookback time connects time and redshift z). Therefore, despite being feeble today, the radiation used to be the dominant component in the universe.
- During the radiation-dominated era, the temperature T is equal to time t by

$$T \approx \sqrt{\frac{1\,\mathrm{sec}}{t}}\, 10^{10}\ \mathrm{K} \tag{3}$$

- This expression can be trusted for times after the Planck time

$$t_P = \sqrt{\frac{\hbar G}{c^5}} = 5.39 \times 10^{-44}\,\mathrm{s} \tag{4}$$

- For times earlier than that we cannot trust the physics we know, because we can't test it at implied extremely high energies/temperatures. But that's only one part in $\sim 10^{61}$ of the age of the universe, so we are not that bad...

Early Universe: radiation–matter equality

- Given Ω_r and Ω_m today, one would naively expect that the epoch of radiation–matter equality happens around $z \sim \Omega_m/\Omega_r \approx 10,000$. Recall that $R = 1/(1+z)$ and $T(t)R(t)$=const. Therefore, the radiation temperature is

$$T_r \approx 3\,(1+z)\,\mathrm{K} \tag{5}$$

  and thus for $z = 10,000$, we get $T_r = 30,000$ K.
- However, this is not the correct temperature for the radiation–matter equality. One needs to take into account that there are 10^9–10^{10} photons per each baryon, and hence even much lower temperature will have enough high energy photons ($E > 13.1$ eV) to ionize hydrogen. Using Planck function, we can find that already for $T = 3,000$ K, there are a fraction of $\sim 10^{-9}$ photons with $E > 13.1$ eV. Matter and radiation decouple when $T \sim 3,000$ K.
- This temperature corresponds to $z \sim 1000$, and represents the epoch observed today as the CMB.

Early Universe: the freezing of the N_n/N_p ratio

- After matter and radiation decouple, radiation evolves in an uneventful fashion, while matter collapses to make galaxies, stars, you and me.
- What was the state of matter at the time of decoupling?
- Let's start from the cosmic time equal to 10^{-4} sec. This corresponds to $z \approx 10^{12}$, and the temperature at that time was $T \approx 10^{12}$ K.
- The decay times of exotic particles are much shorter than 10^{-4} sec, and thus at that time all baryonic matter is in form of protons and neutrons. The universe also contains a mixture of photons and leptons (electrons, positrons, neutrinos, etc).
- At this temperature, the characteristic thermal energy of particles is

$$E_{kT} = \left(\frac{T}{10^{12}\,\mathrm{K}}\right) 86\,\mathrm{MeV} \tag{6}$$

- This is much higher energy than the proton-to-neutron mass difference of 1.3 MeV, and thus their numbers are practically equal (no nuclei exist!).

Early Universe: the freezing of the N_n/N_p ratio

- The equilibrium number ratio of neutrons and protons is given by the Boltzmann equation

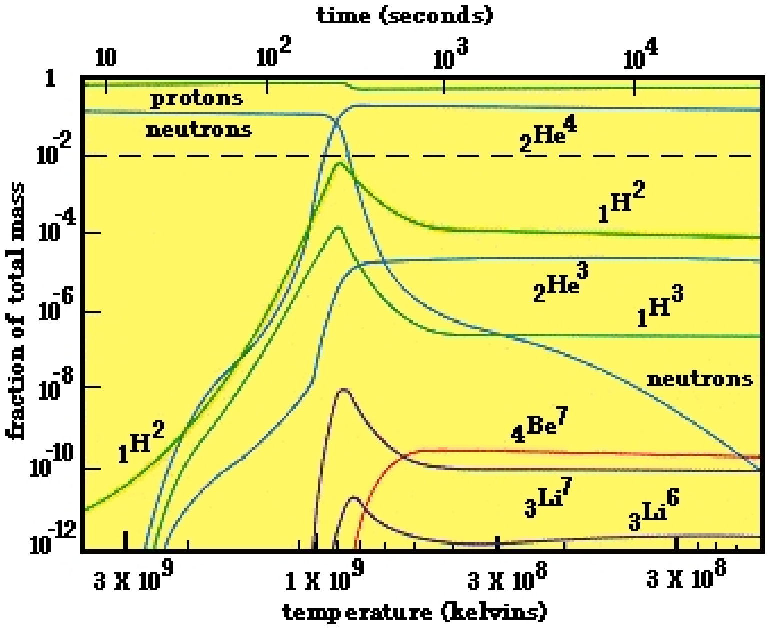
$$\frac{N_n}{N_p} = \mathrm{e}^{-\frac{(m_p - m_c)c^2}{kT}} \tag{7}$$

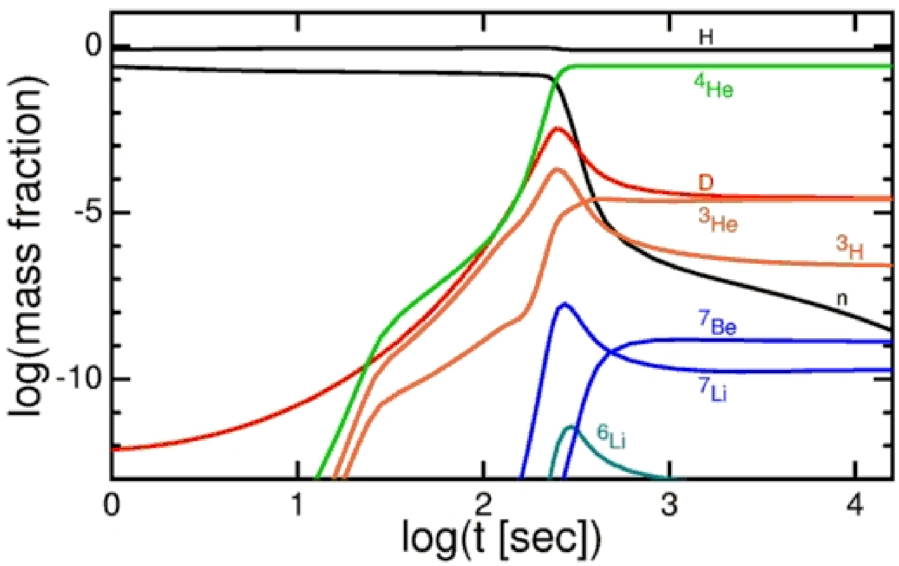
- The characteristic timescale for nuclear reactions that maintain this equilibrium is a strong function of temperature

$$\tau_{n \rightleftharpoons p} = \left(\frac{10^{10}\,\mathrm{K}}{T}\right)^5 10\,\mathrm{sec} \tag{8}$$

- For $T >> 10^{10}$ K, these reactions are much faster than the age of the universe (which is proportional to T^{-2}), but for $T << 10^{10}$ K they become very slow (with timescale much longer than the age of the universe)
- The result is that, as the temperature falls below $\sim 10^{10}$ K, the neutron to proton number ratio becomes "frozen" at $N_n/N_p \sim 0.15$. What's next?

The Formation of Light Elements





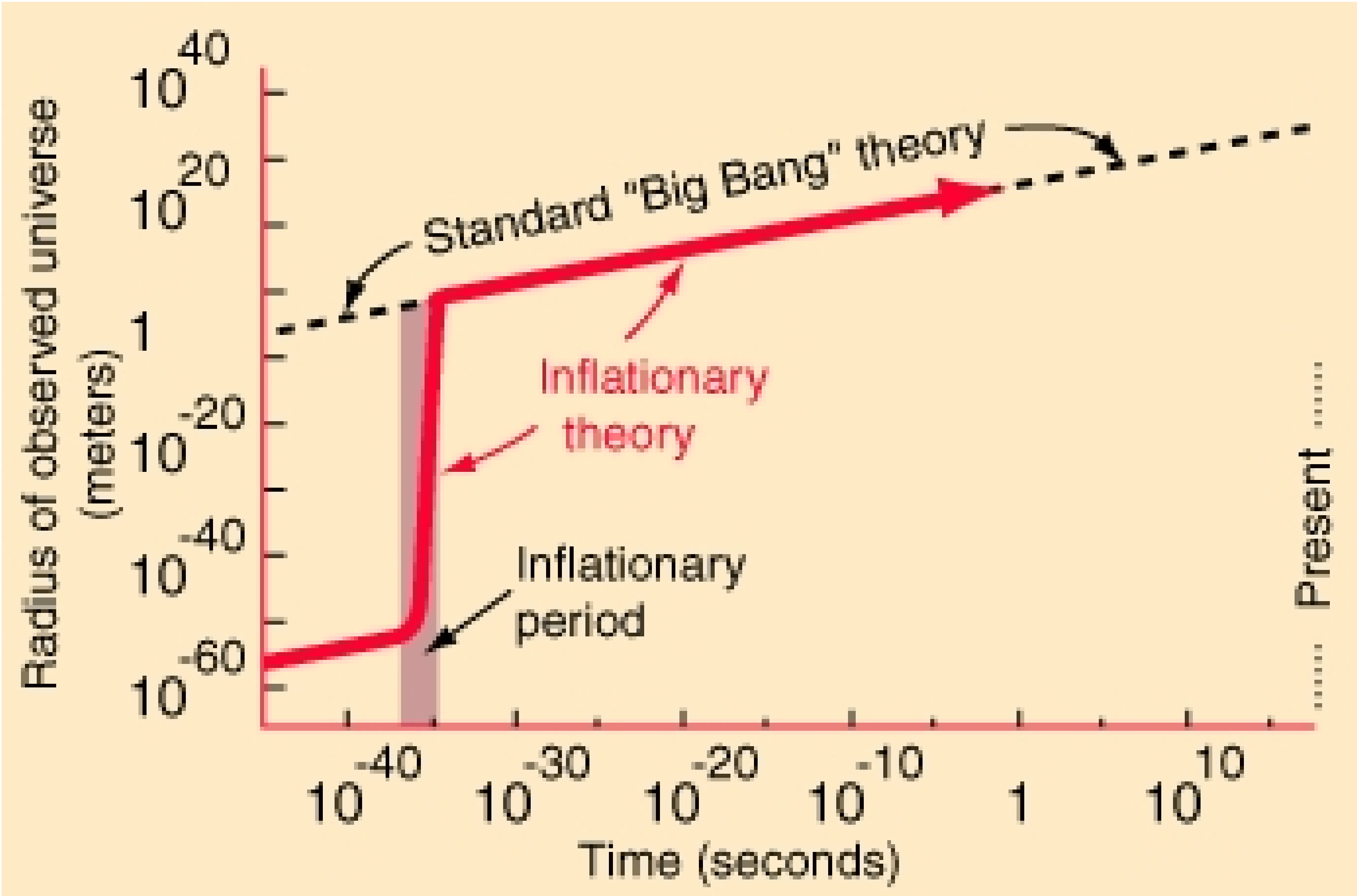
- At high temperatures only neutrons (13%) and protons (87%) exist.
- When nucleosynthesis began, roughly 10 sec after the Big Bang, all the neutrons were incorporated into He nuclei, while the leftover protons remained as hydrogen nuclei.
- After this first wave of nucleosynthesis was completed in about 3 minutes, the universe consisted of roughly 25% He and 75% H (by weight).
- The deuterium (H^2), He^3, He^4 and Li^7 abundances depend on a single parameter: the current density of ordinary matter made out of protons and neutrons: baryonic matter, or Ω_b.

The Problems with the Big Bang Theory

- The Big Bang is a scientific theory and thus it is constantly subjected to critical re-examination in the context of new observations and theoretical results. **No scientist** thinks that the Big Bang theory **must** be correct! Indeed, there are some problems with the picture that we discussed so far:
- Why is the CMB so smooth (fluctuations are only one part in $\sim 10^{-5}$)? How did causaly disconnected photons know what should be their temperature? The horizon problem.
- Why is the universe (so nearly) flat? Unless it is **exactly flat**, we have a fine-tuning problem. The flatness problem.
- Why is the universe made of matter, rather than of antimatter? What caused this asymmetry? The matter-antimatter asymmetry problem.
- Why are there so many photons in the universe?
- What physical process produced the initial fluctuations in the density of matter?
- How can we begin to understand these problems?

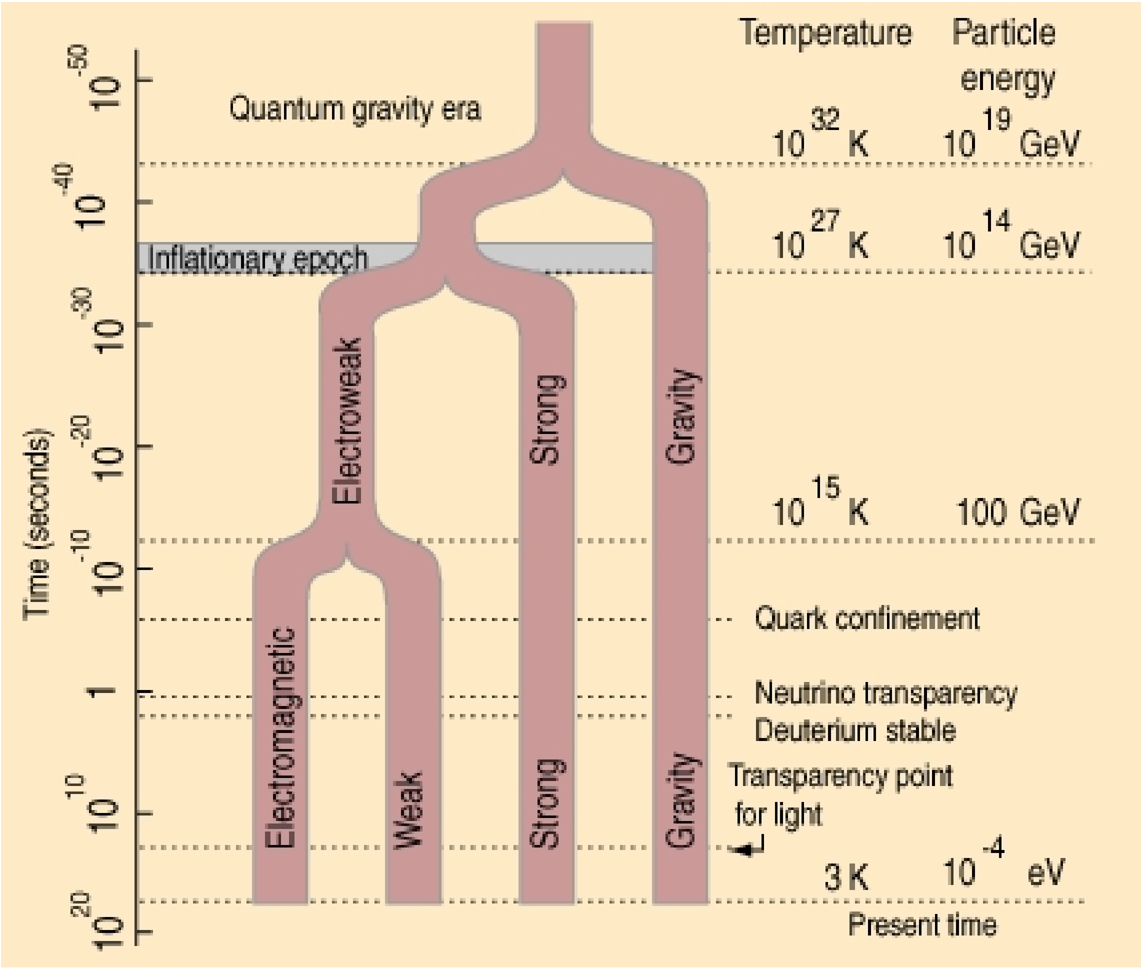
The Inflation Theory

- The inflation theory links important ideas in modern physics, such as symmetry breaking and phase transitions, to cosmology.
- Inflation theory is based on the presence of vacuum energy: particles and antiparticles forming out of nothing and then re-combining (Alan Guth, the proposer of this theory, called this "the ultimate free lunch").
- The theory **assumes** a period of extremely rapid (exponential) expansion of the universe about 10^{-35} seconds after the Big Bang, during which time the energy density of the universe was dominated by a cosmological constant term. This caused very strong acceleration lasting for about 10^{-32} seconds, during which the universe increased its size scale by about a factor of 10^{50}!
- Then the universe settled down into the big bang evolution that we have discussed prior to this point.


Radius of observed universe (meters)
10^{40}
10^{20}
1
10^{-20}
10^{-40}
10^{-60}
Standard "Big Bang" theory
Inflationary theory
Inflationary period
Present
10^{-40}
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
Time (seconds)

The Inflation Theory

- This fast "inflationary" expansion, much faster than assumed in the standard big bang models, is a consequence of the nuclear force breaking away from the weak and electromagnetic forces, that it was unified with at higher temperatures, in what is called a phase transition.

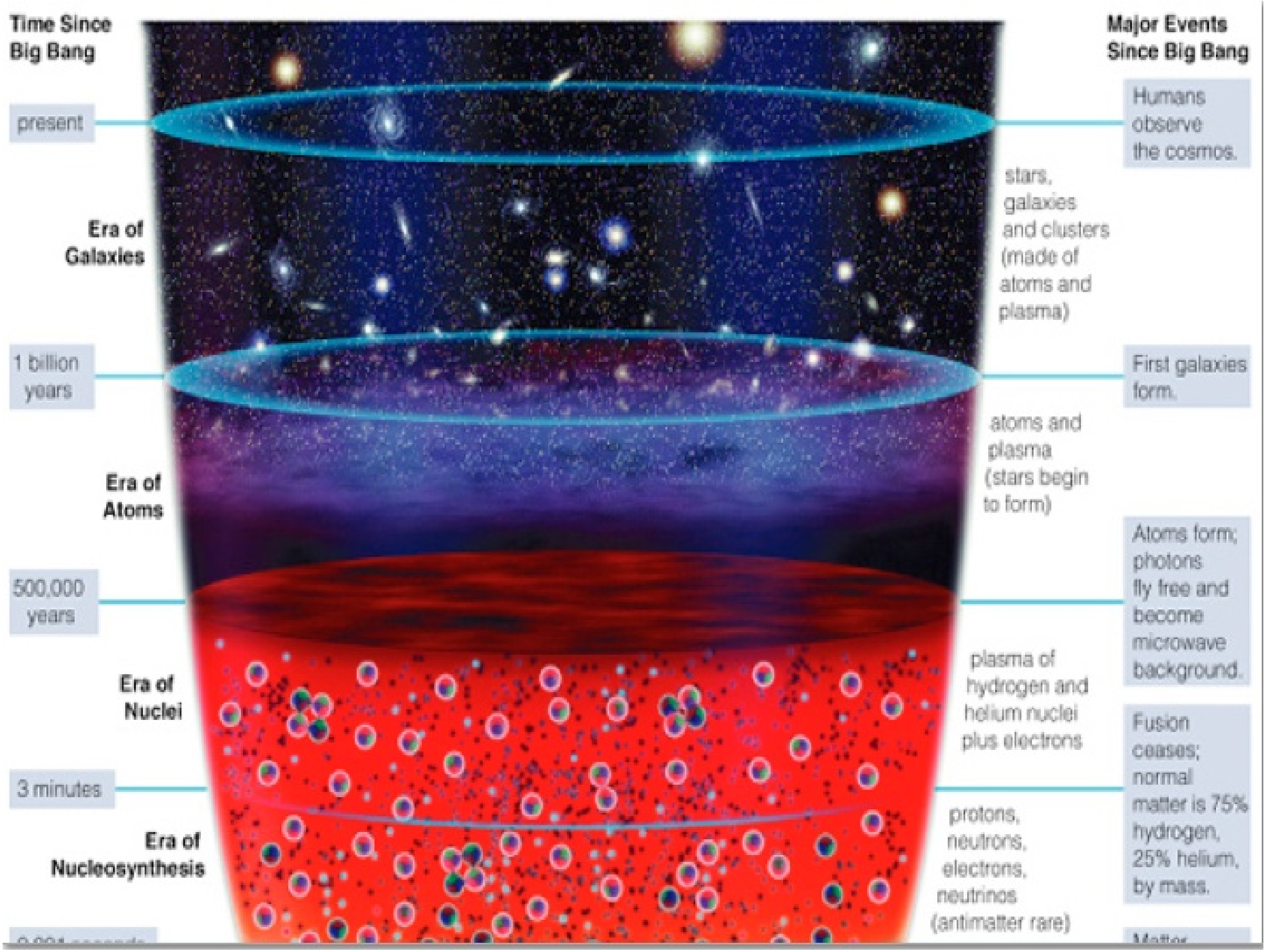


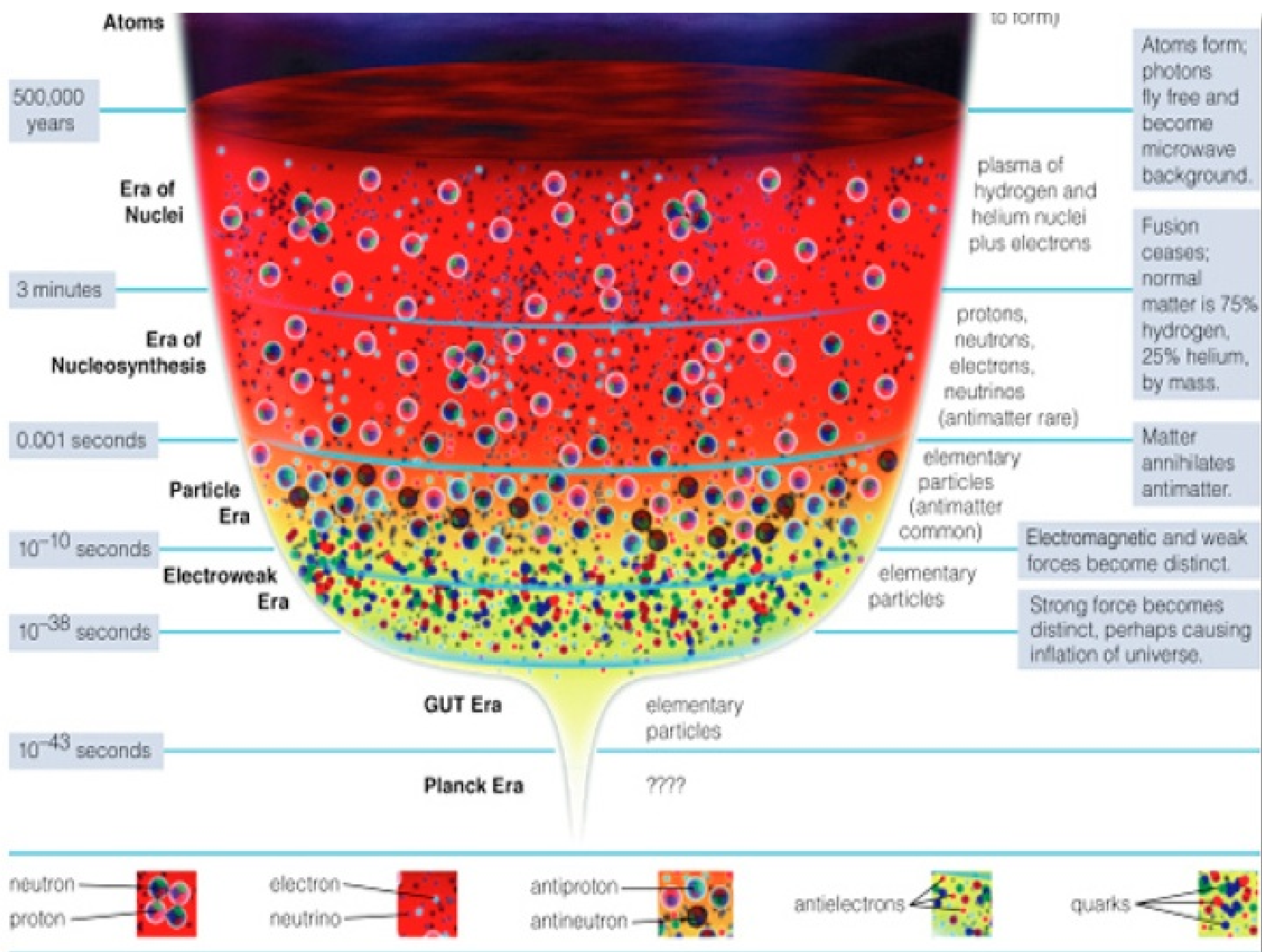
The Inflation Theory

- This fast "inflationary" expansion, much faster than assumed in the standard big bang models, is a consequence of the nuclear force breaking away from the weak and electromagnetic forces, that it was unified with at higher temperatures, in what is called a phase transition.
- The fast expansion simultaneously solves the horizon and flatness problems. The tremendous expansion means that regions that we see widely separated in the sky now at the horizon were much closer together before inflation and thus could have been in causal contact.
- This cosmological constant term, due to vacuum energy, later decayed to produce the matter and radiation that fill the universe today.
- Bonus: the inflation is capable of producing small density fluctuations that can later in the history of the Universe provide the seeds to cause matter to begin to clump together to form the galaxies and other observed structure.

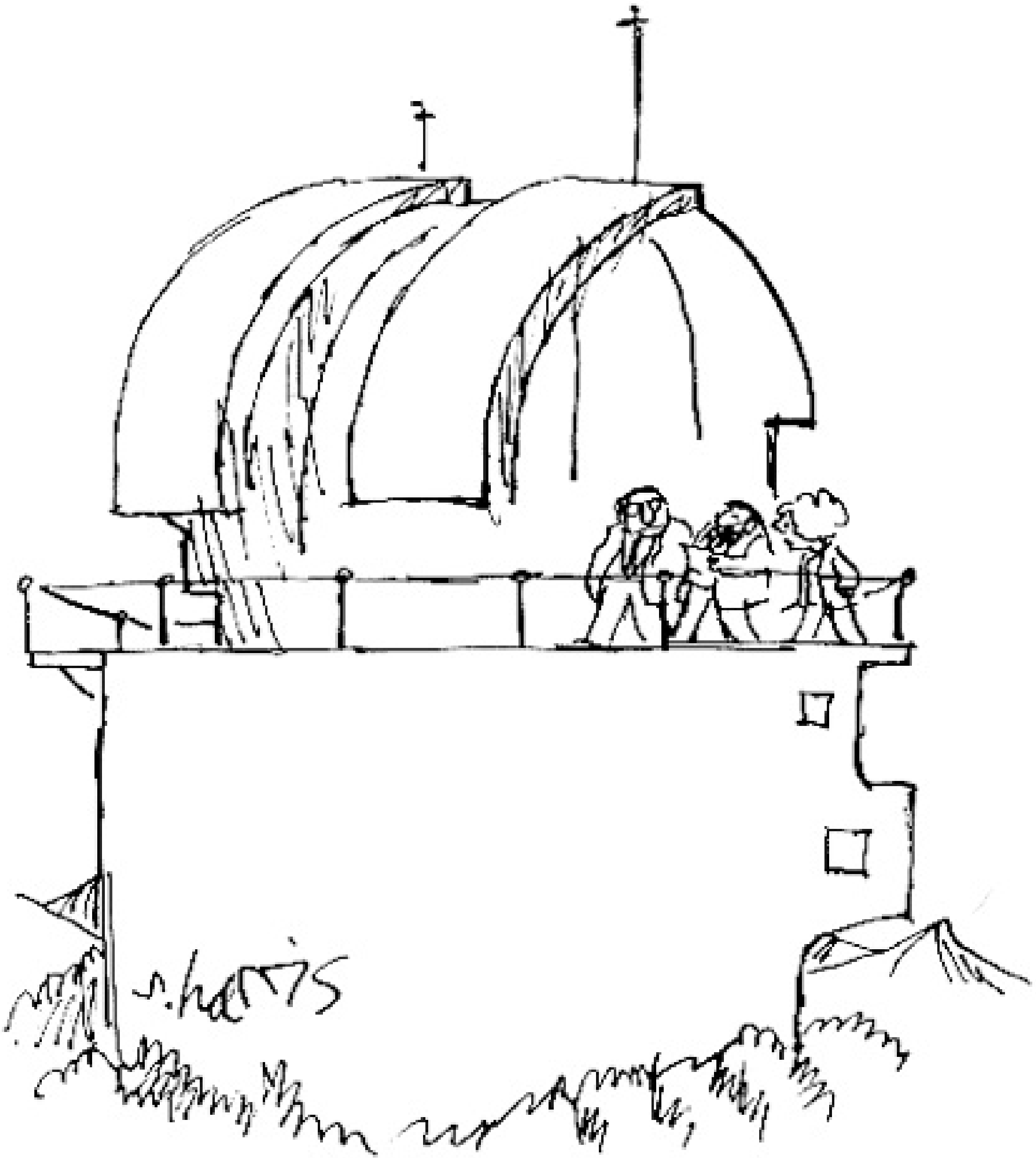
Predictions of the inflation theory

- One of the basic tenants of science is that theories must have predictions that can be tested:
- The density of the universe is close to the critical density, and thus the geometry of the universe is flat.
- The fluctuations in the primordial density in the early universe had the same amplitude on all physical scales.
- There should be, on average, equal numbers of hot and cold spots in the fluctuations of the cosmic microwave background temperature.
- WMAP has recently tested these predictions and they seem to hold up.
- Nevertheless, there are unsolved theoretical problems within the inflation theory, and this is an active area of research. Most cosmologists today believe inflation to be correct at least in its outlines, but further investigation is definitely required to establish whether this is indeed so.


Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
Era of Galaxies
stars, galaxies and clusters (made of atoms and plasma)
1 billion years
First galaxies form.
Era of Atoms
atoms and plasma (stars begin to form)
500,000 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)



to form)
Atoms
500,000 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 seconds
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
10^{-10} seconds
Electromagnetic and weak forces become distinct.
Electroweak Era
elementary particles
10^{-38} seconds
Strong force becomes distinct, perhaps causing inflation of universe.
GUT Era
elementary particles
10^{-43} seconds
Planck Era
????
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks



"We now know all the extraordinary changes the universe went through in it's first second. After that, unfortunately, it turns out to be very monotonous."

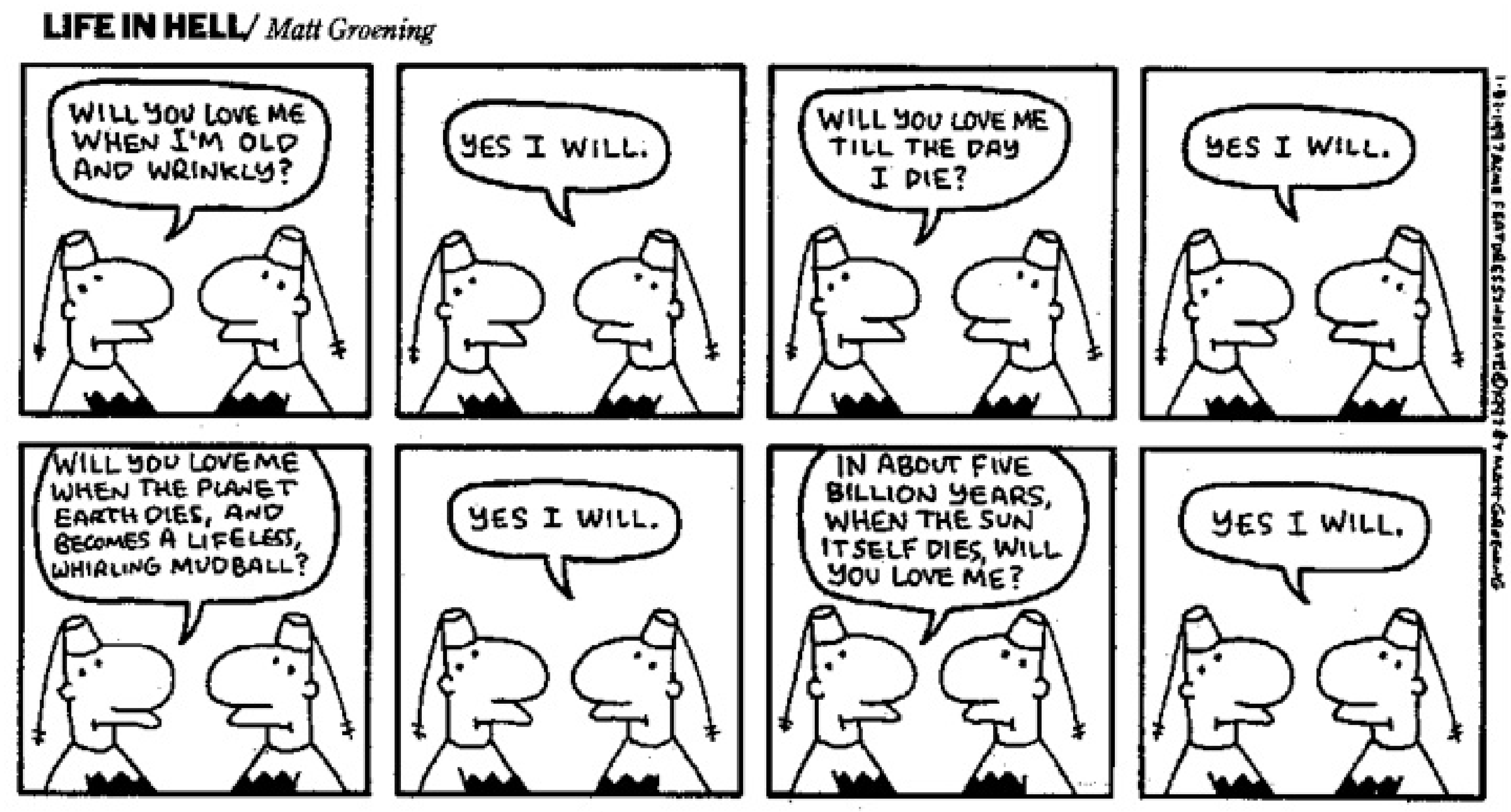
"We now know all the extraordinary changes the universe went through in it's first second. After that, unfortunately, it turns out to be very monotonous."

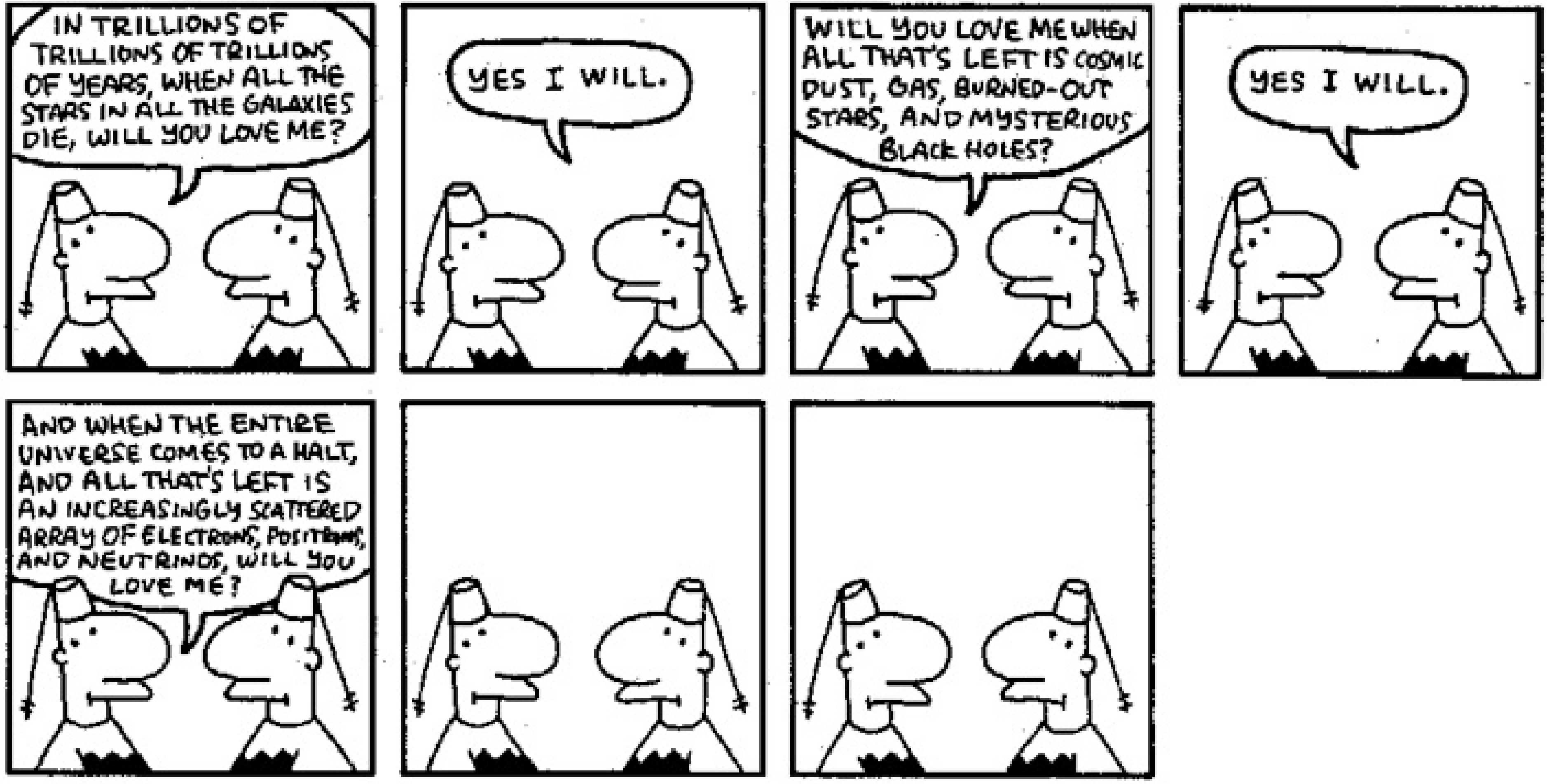
What about the future?

If we apply the physics we know, then:

- Galaxies turn all available gas into stars ($< 10^{14}$ years)
- All stars eventually die, and turn into white dwarfs, neutron stars, or black holes (10^{15}-10^{37} years)
- After about 10^{30} years, protons start to decay! Stars and planets start dissolving...
- By 10^{40} years, all protons are gone.
- Most remaining mass is in black holes (10^{37}-10^{100} years
- By 10^{100} years, all black holes will have evaporated. The Universe will consist of nothing but a soup of photons, neutrinos, positrons, and electrons

Of course, these speculations may not be correct: we are extrapolating from the current age of 10^{10} years to 10^{100} years – and we still don't know what dark matter and dark energy are...


LIFE IN HELL/ Matt Groening
WILL YOU LOVE ME WHEN I'M OLD AND WRINKLY?
YES I WILL.
WILL YOU LOVE ME TILL THE DAY I DIE?
YES I WILL.
WILL YOU LOVE ME WHEN THE PLANET EARTH DIES, AND BECOMES A LIFELESS, WHIRLING MUDBALL?
YES I WILL.
IN ABOUT FIVE BILLION YEARS, WHEN THE SUN ITSELF DIES, WILL YOU LOVE ME?
YES I WILL.


IN TRILLIONS OF TRILLIONS OF TRILLIONS OF YEARS, WHEN ALL THE STARS IN ALL THE GALAXIES DIE, WILL YOU LOVE ME?
YES I WILL.
WILL YOU LOVE ME WHEN ALL THAT'S LEFT IS COSMIC DUST, GAS, BURNED-OUT STARS, AND MYSTERIOUS BLACK HOLES?
YES I WILL.
AND WHEN THE ENTIRE UNIVERSE COMES TO A HALT, AND ALL THAT'S LEFT IS AN INCREASINGLY SCATTERED ARRAY OF ELECTRONS, POSITRONS, AND NEUTRINOS, WILL YOU LOVE ME?