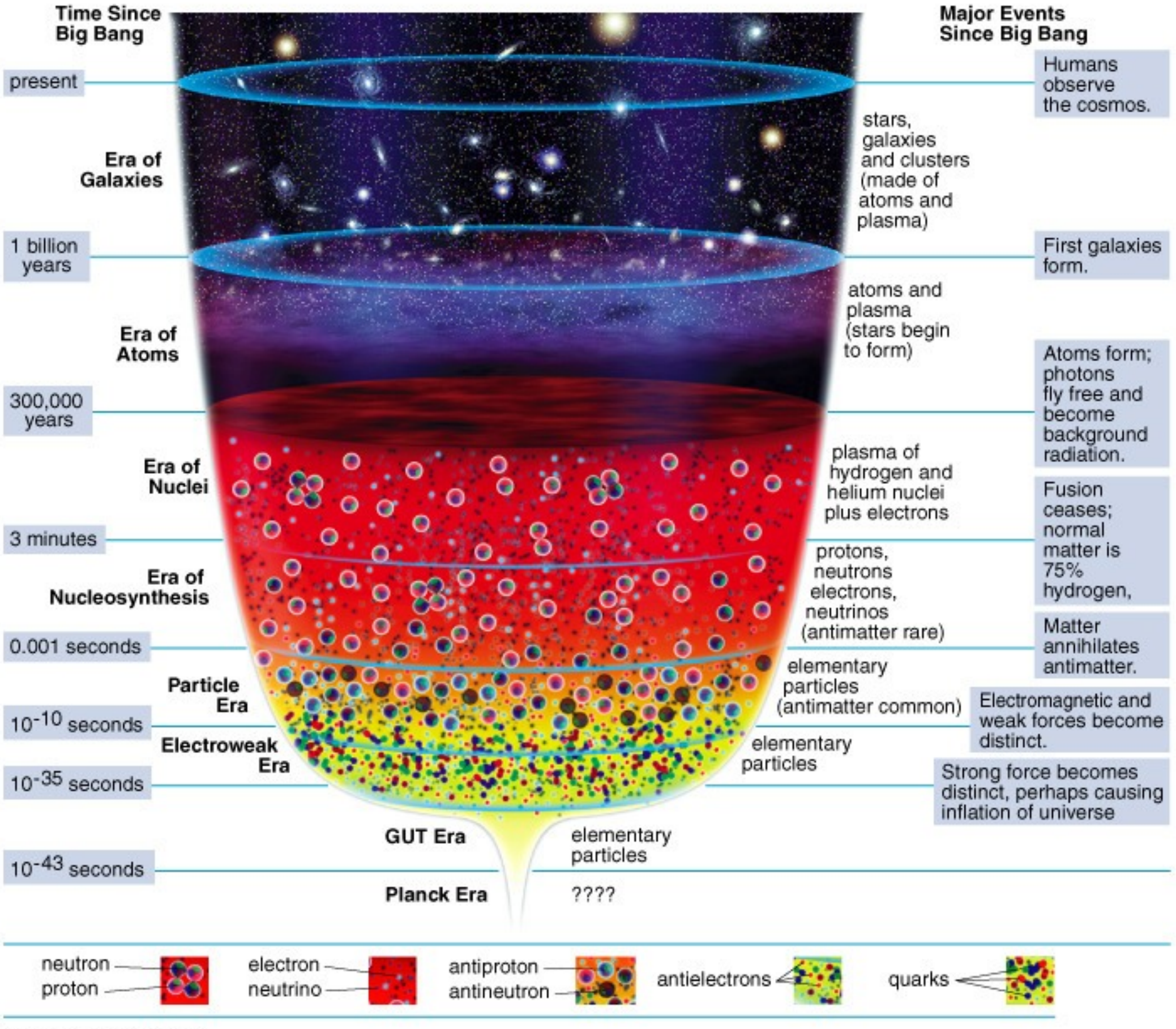
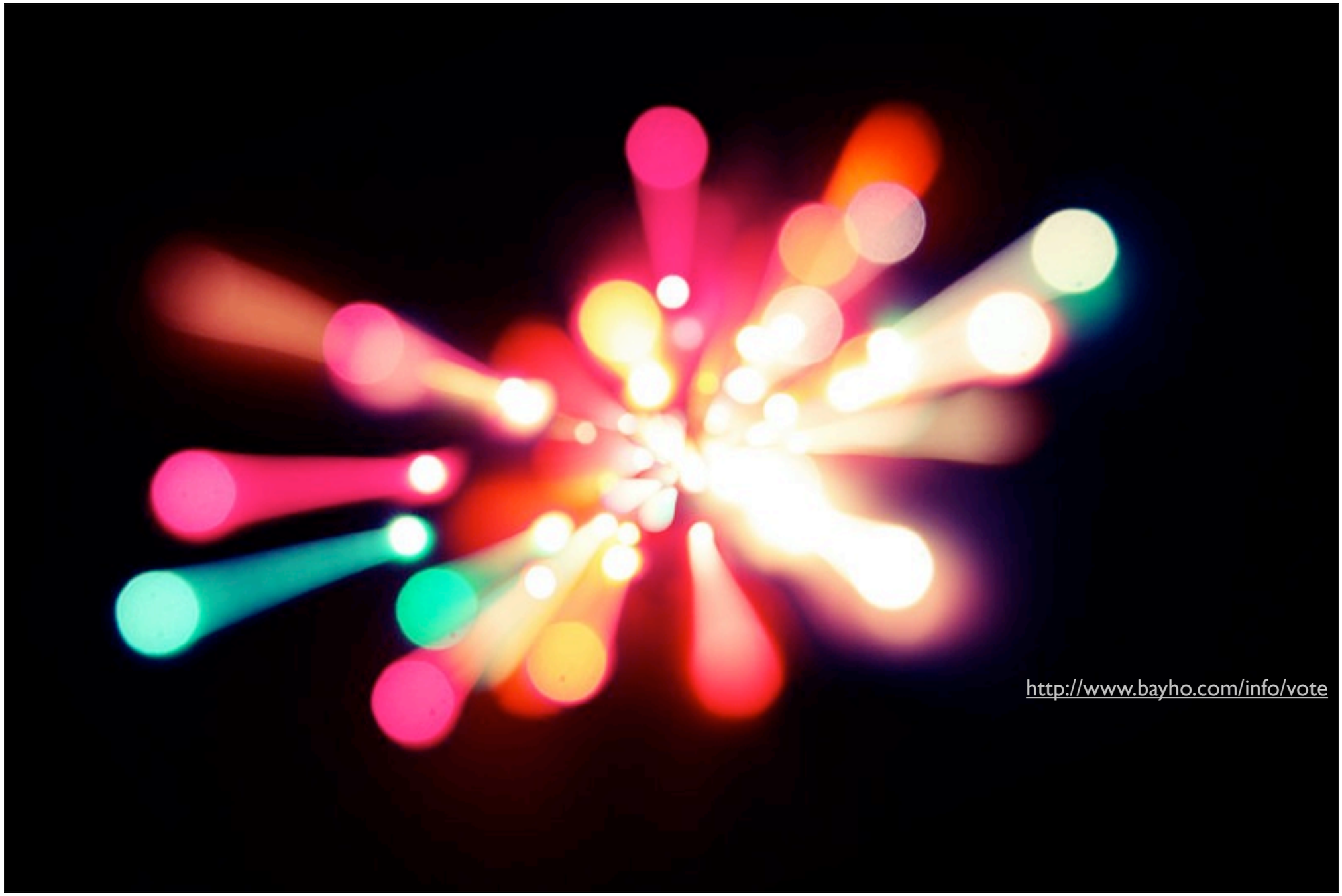

Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
Era of Galaxies
stars, galaxies and clusters (made of atoms and plasma)
1 billion years
First galaxies form.
Era of Atoms
atoms and plasma (stars begin to form)
300,000 years
Atoms form; photons fly free and become background radiation.
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
3 minutes
Fusion ceases; normal matter is 75% hydrogen,
Era of Nucleosynthesis
protons, neutrons electrons, neutrinos (antimatter rare)
0.001 seconds
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
10-10 seconds
Electroweak Era
Electromagnetic and weak forces become distinct.
elementary particles
10-35 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

The Hot Big Bang



universe @ the big bang was dense

assuming no inflation

at the Planck time (t ~ 10^{-43} sec)

- our visible universe was ~ 0.01 cm across (10^{30} smaller)
- but any observer only sees a tiny fraction of this (horizon ~ 10^{-33} cm)
- density of matter ~ 10^{63} g/cm^3

  -- nuclear density ~ 10^{14}g/cm^3

  -- not describable with current physics

  *-- no atom, nuclei, proton, neutron **persist**, not even quarks and leptons*

- but there is an even larger energy density than matter

universe @ the big bang was 'empty' of matter

(relatively speaking)

importantly, the early universe was hot

'hot' means high in temperature, but also means photons dominate the energy density (temperature in very massive stars so hot that most energy in the stars is in photons, not matter, we call it 'radiation dominated')

1) going back in time, photons 'blue-shifted' up in energy; while matter density $\propto a^{-3}$, photon energy density $\propto a^{-4}$, (# of photons conserved; # of photons/unit volume $\propto a^{-3}$; energy per photon $\propto a^{-1}$; so energy density of photon $\propto a^{-4}$)

radiation energy density >> matter energy density @ early times

2) energy density of a blackbody radiation $\propto T^4$, so $T \propto a^{-1}$

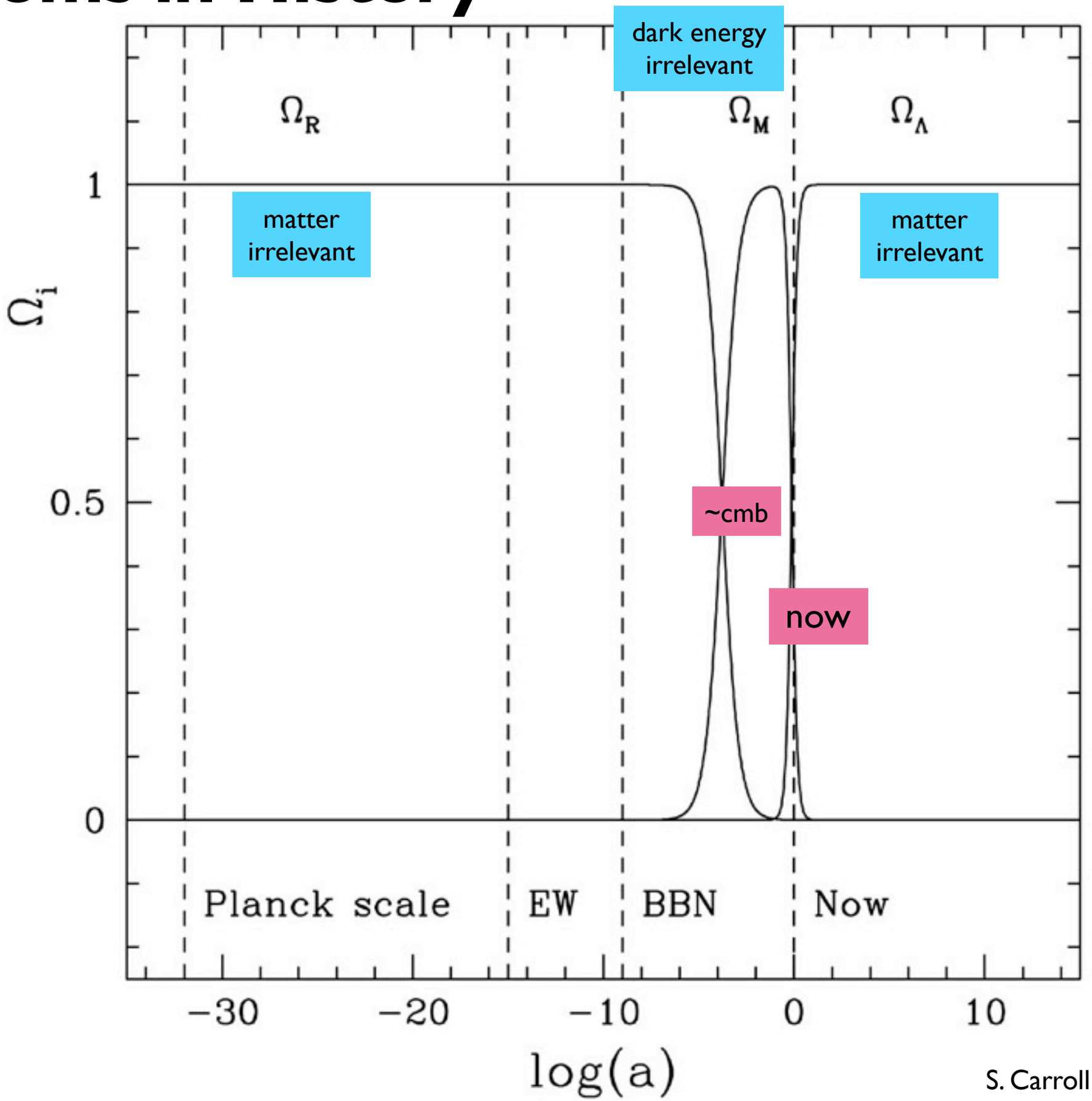
3) a higher blackbody temperature means a typical photon have higher energy: $E = h\nu \propto T$

Three Kingdoms in History

'In the beginning, there was light.'

'life and prosperity in the middle kingdom.'

But at the end, darkness reigns...

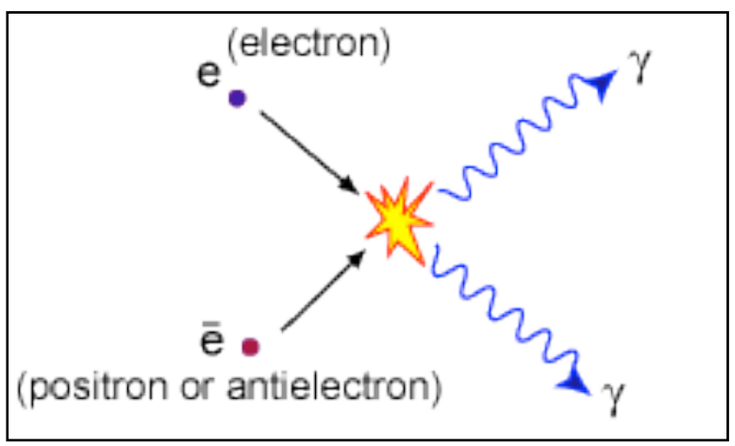


S. Carroll

4) photons are so energetic, they can produce pairs of heavy particles --- out of 'nothing'.

$E=Mc^2$

photons constantly undergo pair creation
Pair creation: 2 photons ===> matter + anti-matter particles



annihilation (reverse process of pair creation)

5) the matter-anti-matter particles quickly annihilate back to photons. a radiation soup bubbling with particles/anti-particles.

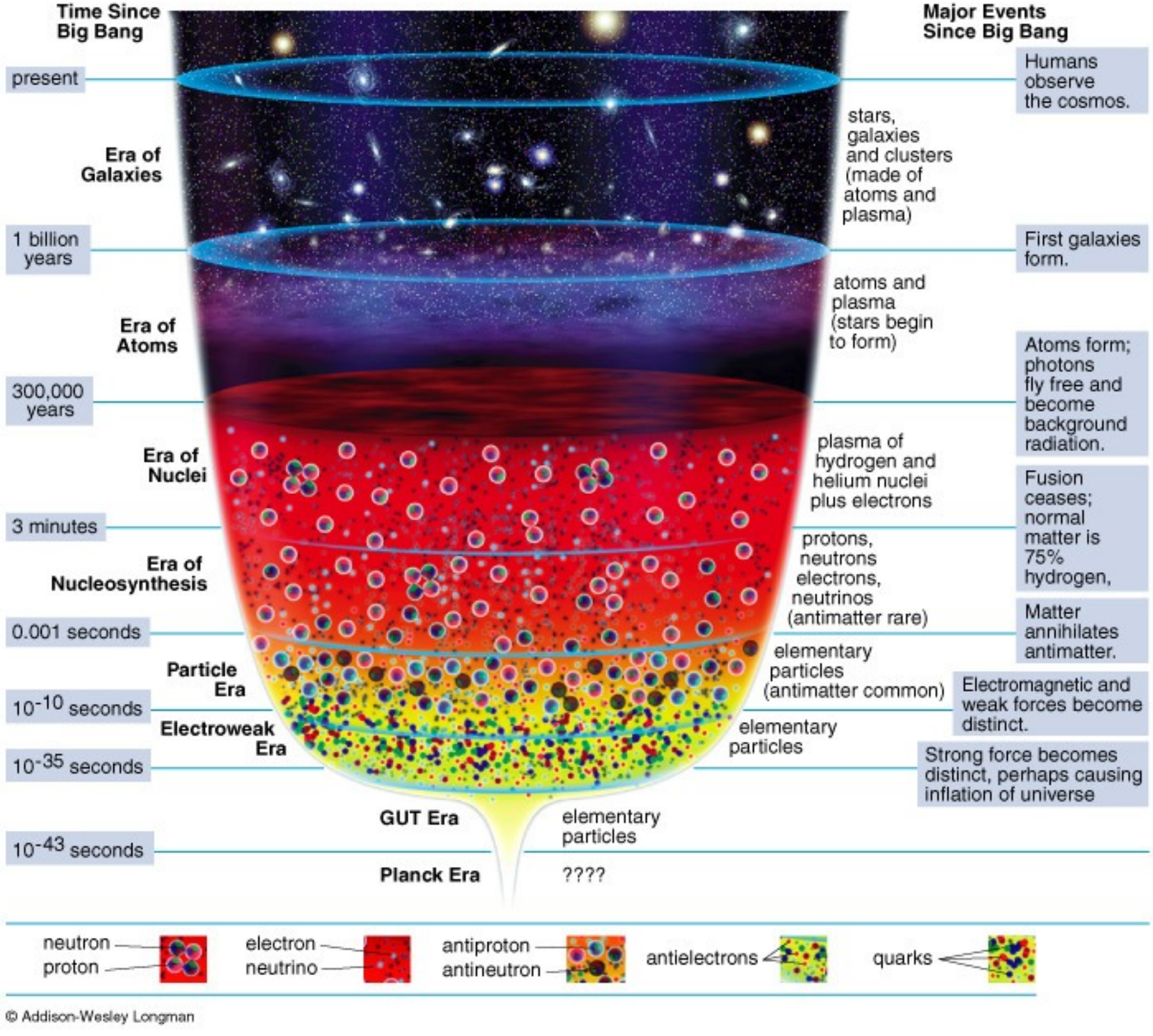
6) as the universe cools (why?), more and more limited in what particles can be pair-created. Earlier productions frozen-in.

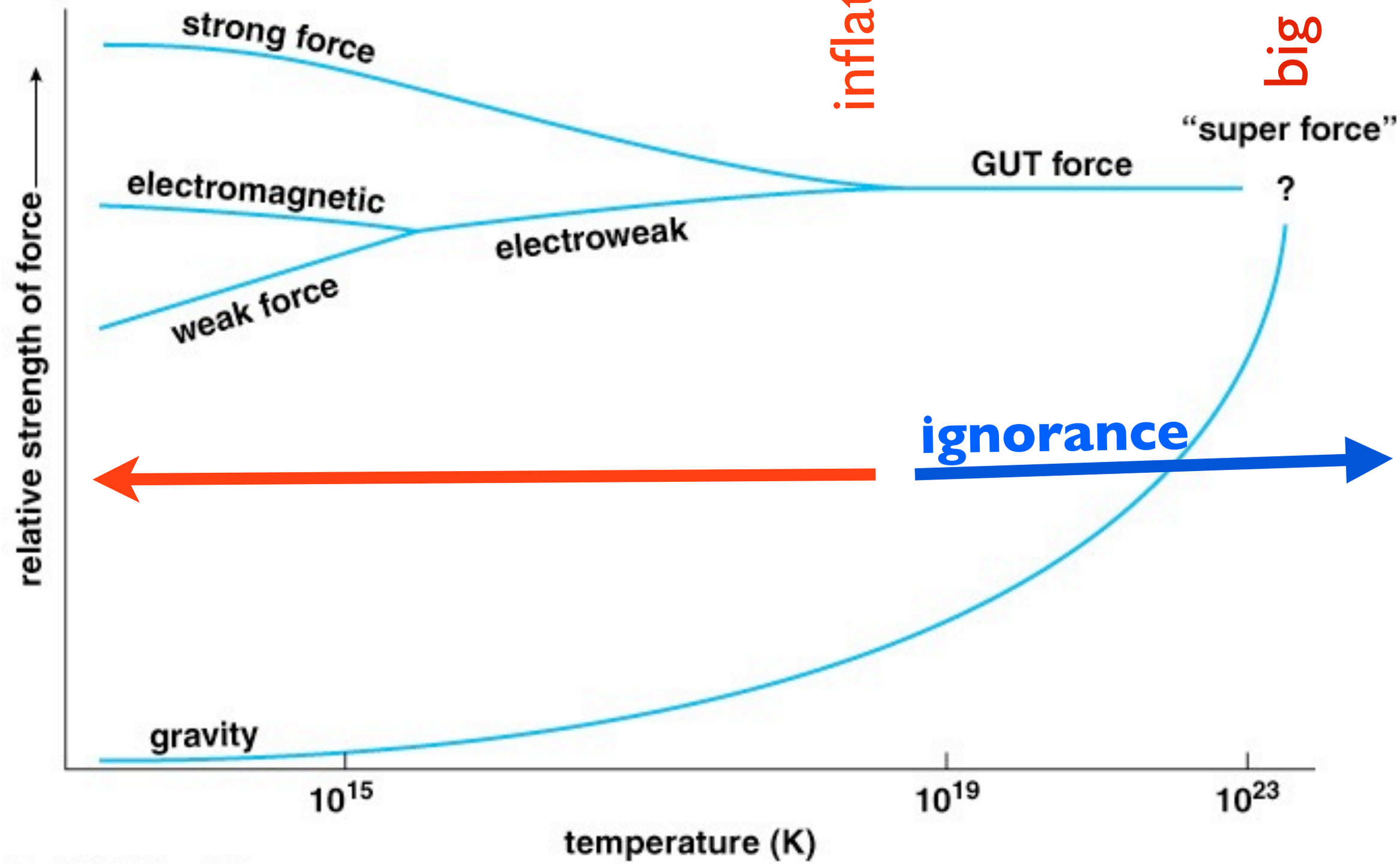
7) the early universe was separated into different epochs based on what particles can be pair-created. Many properties of our universe were determined here.

Photon "fog" at CMB (~300,000 yrs), how do we know what happened before that?

Safe physics

Unsafe physics





No quarks till strong force separates.
Temperature too high for confinement.

Quark Epoch

inflation

big bang

strong force

electromagnetic

weak force

electroweak

GUT force

"super force"

?

relative strength of force

'standard' physics

ignorance

gravity

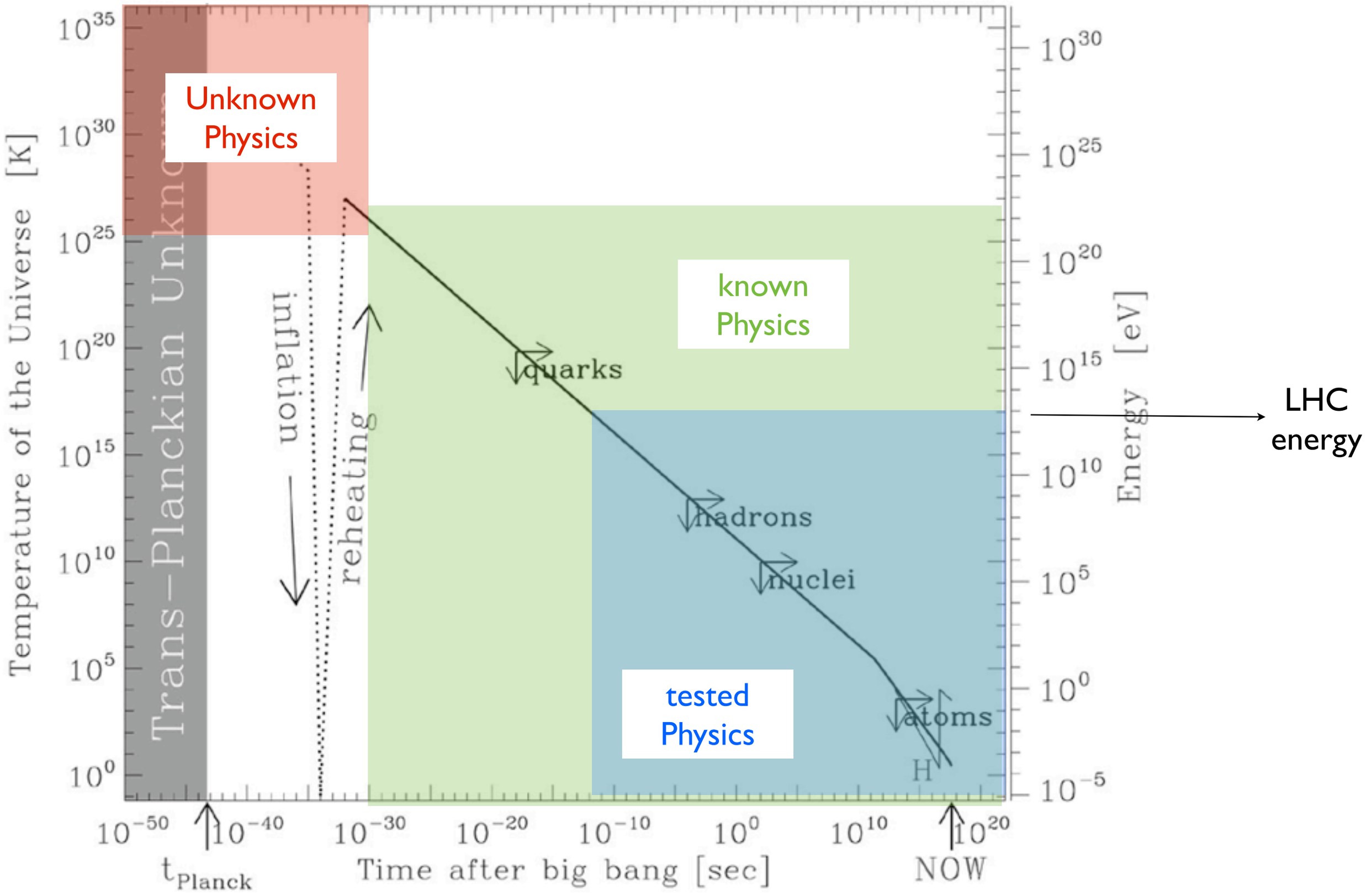
10^{15}

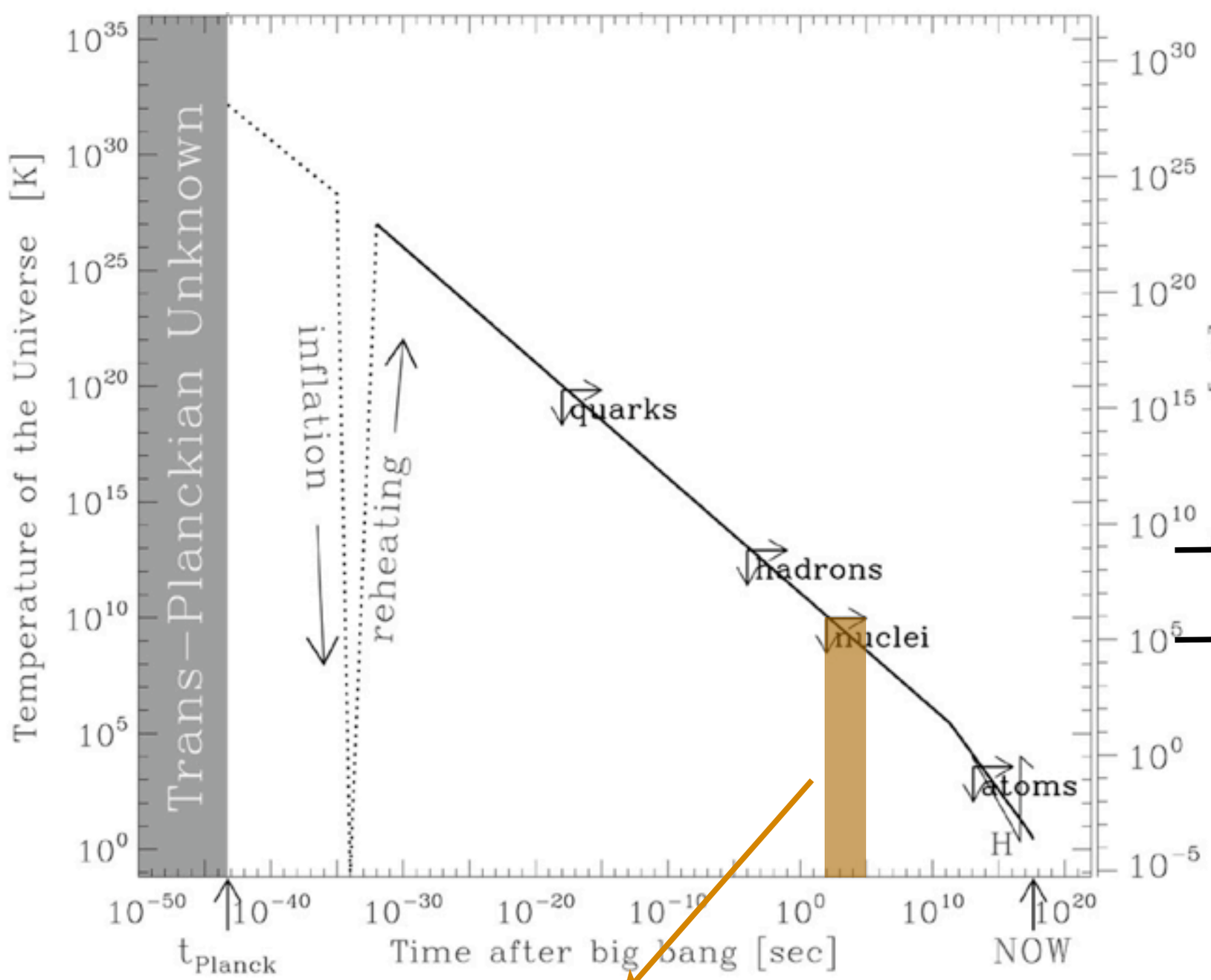
10^{19}

10^{23}

temperature (K)

When photon mean energy drops below mc^2 pair creation/annihilation freezes out -- era of particles





1Gev

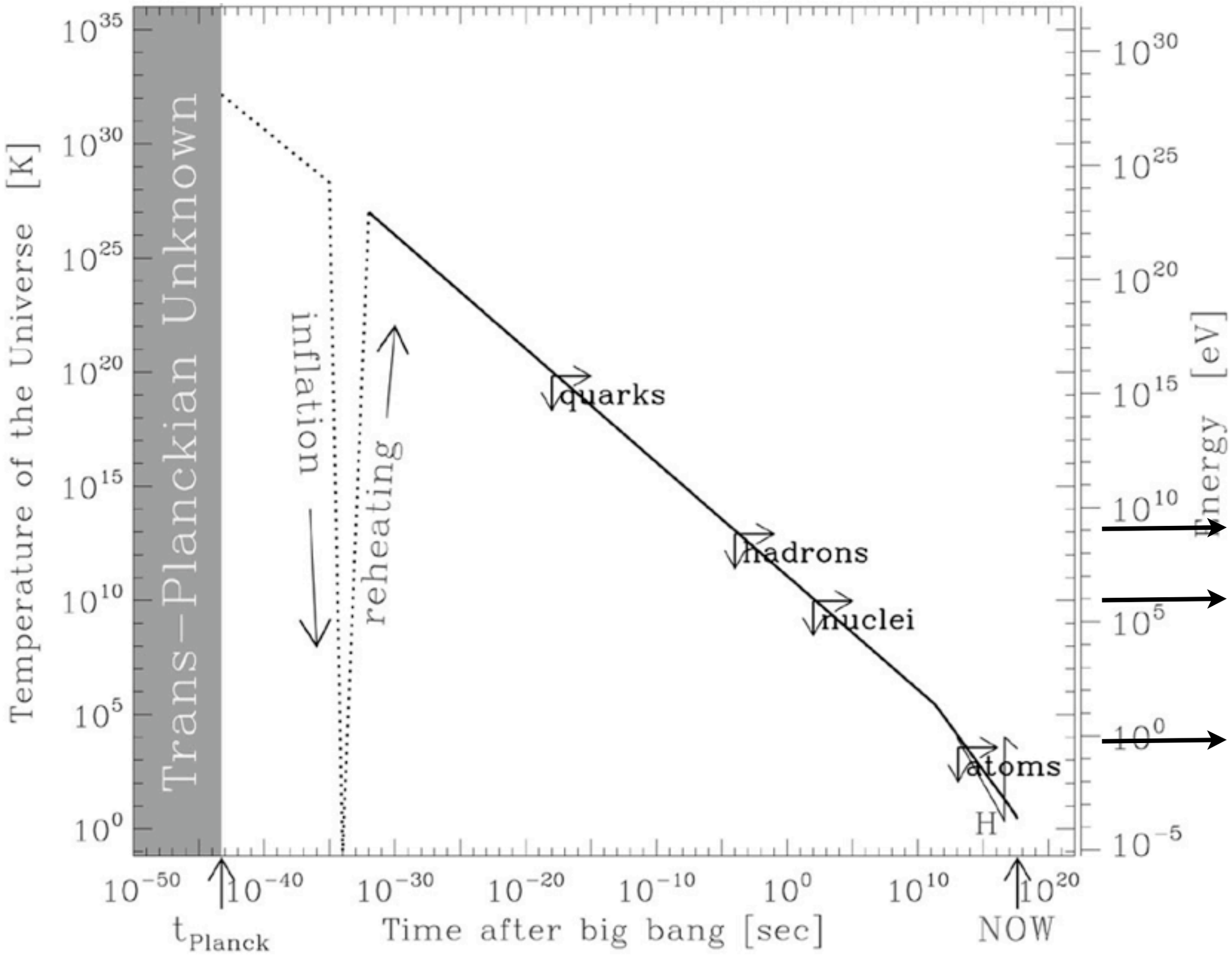
$m_{proton}\ c^2$

nuclear binding energy, ~ 1Mev

the ERA of NUCLEOSYNTHESIS

- before 1 sec (post BB), nuclei formed and broken apart continuously. The universe is one big nuclear reactor (going nowhere)
- by 1 sec, 1 Mev temperature reached. Nuclei can survive afterwards.
- all 'primordial' nuclei made in 3 minutes.

When photon mean energy drops below ~10 ev,
electrons bound to nuclei --- era of atoms (300,000 yrs post BB)



$m_{proton}\ c^2$

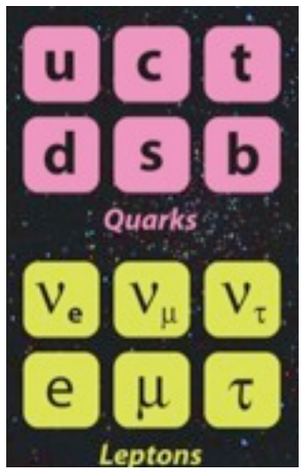
nuclear binding energy, ~ 1Mev

electron binding energy to nuclei ~ 1ev, CMB

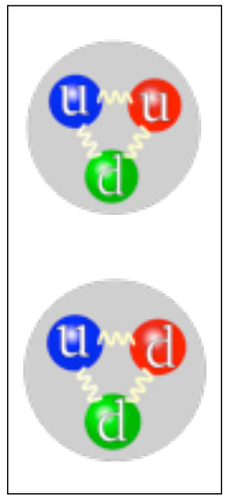
early universe

In the beginning, there is light.

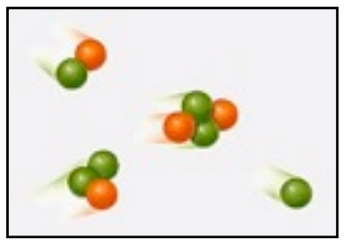
particles
~10^{-10} sec



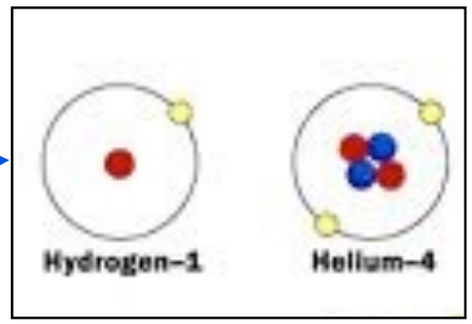
proton & neutron
0.001 sec



nuclei
3 min.



atom
300,000 yrs



accelerators

Two big events that allow 'us' to happen

1) "**baryon asymmetry**"

during the particle era, particles/anti-particles continuously produced and annihilated, until the universe cools to a point.

somehow, miraculously, there is a slight over-production of particles (1/10^9); this explains all the matter today in the universe

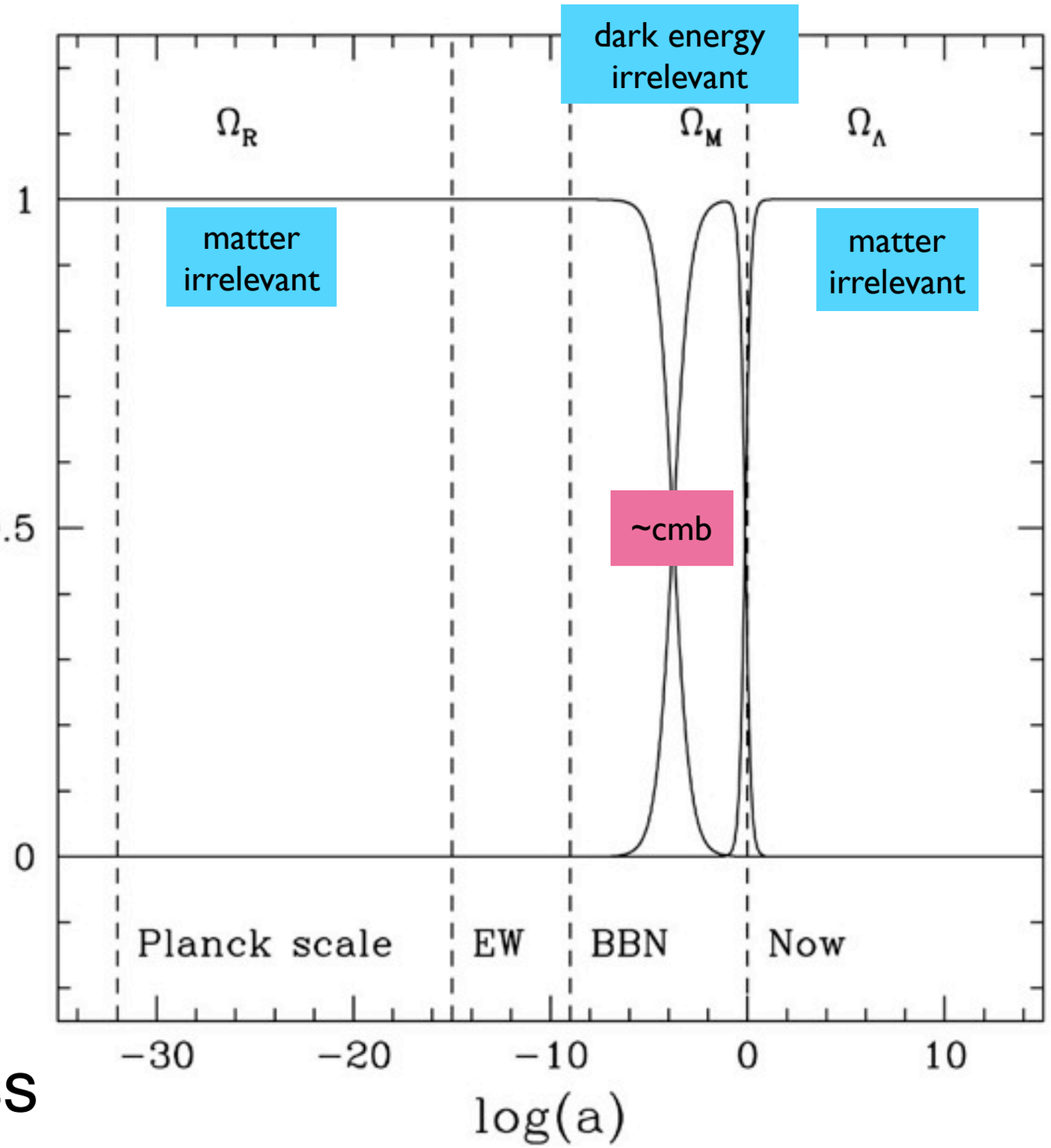
exotic physics in GUT Era? inflation? other parts of universe may be anti-matter?

other examples of asymmetry:

people 90% right-handed;
all amino acid on Earth left-handed

baryon asymmetry

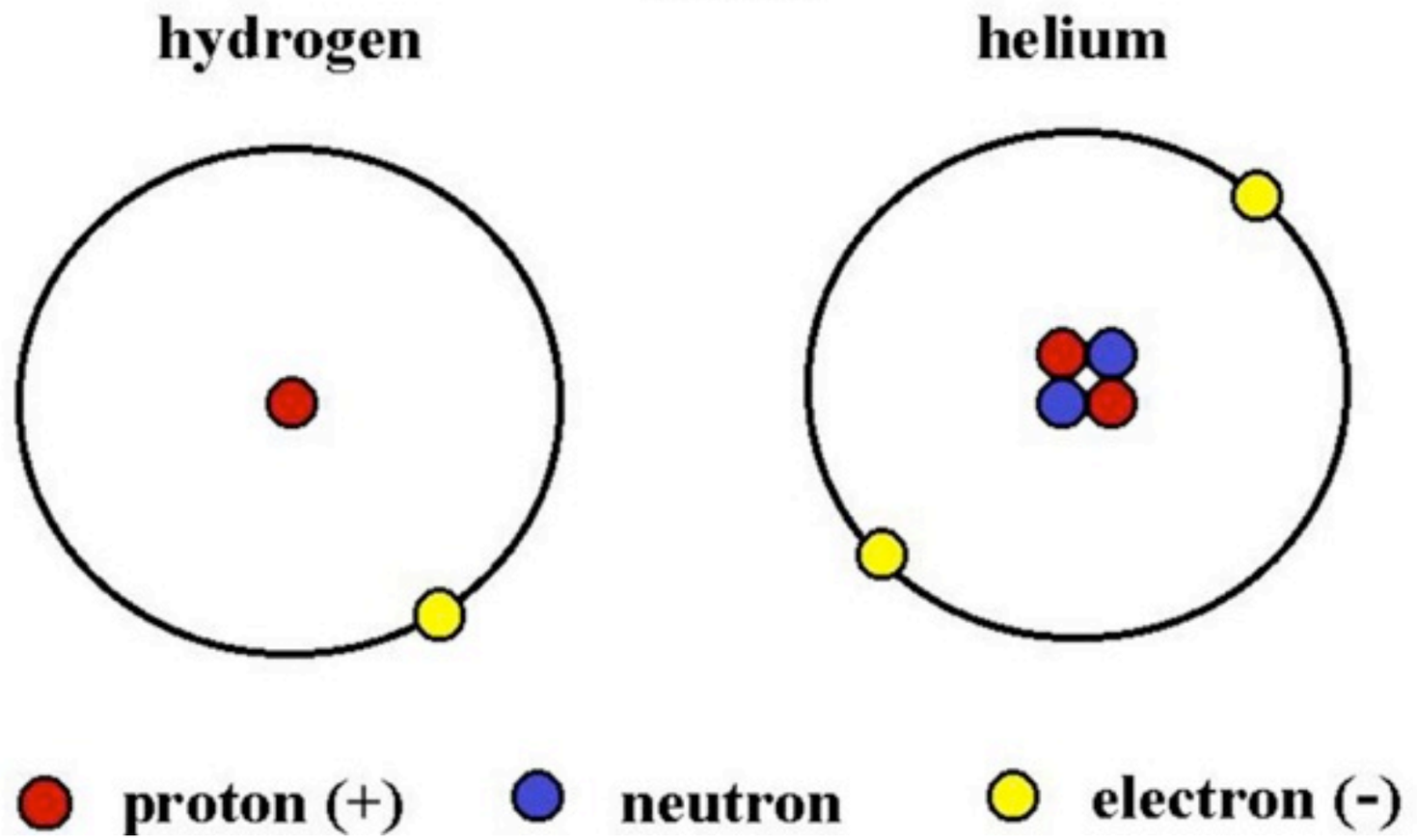
- pair creation yields equal matter/anti-matter (e-, e+, quark, anti-quark...)
- rapid annihilation back to photons
- both photon energy and density decreases with time
- @1 milli-second, one excess baryon for every 10^9 photons



2) nucleosynthesis

During the nucleosynthesis era, the universe contains 1 neutron for every 7 protons:

1) neutrons slightly more massive
2) free neutrons decay (half life ~ 15 minutes)



Eventually all neutrons end up in helium, this determines the primordial helium abundances: ? H nuclei for every 1 He nuclei

or: ~ 76% H, 24% He by mass (as well as some light elements like Li, Be...)

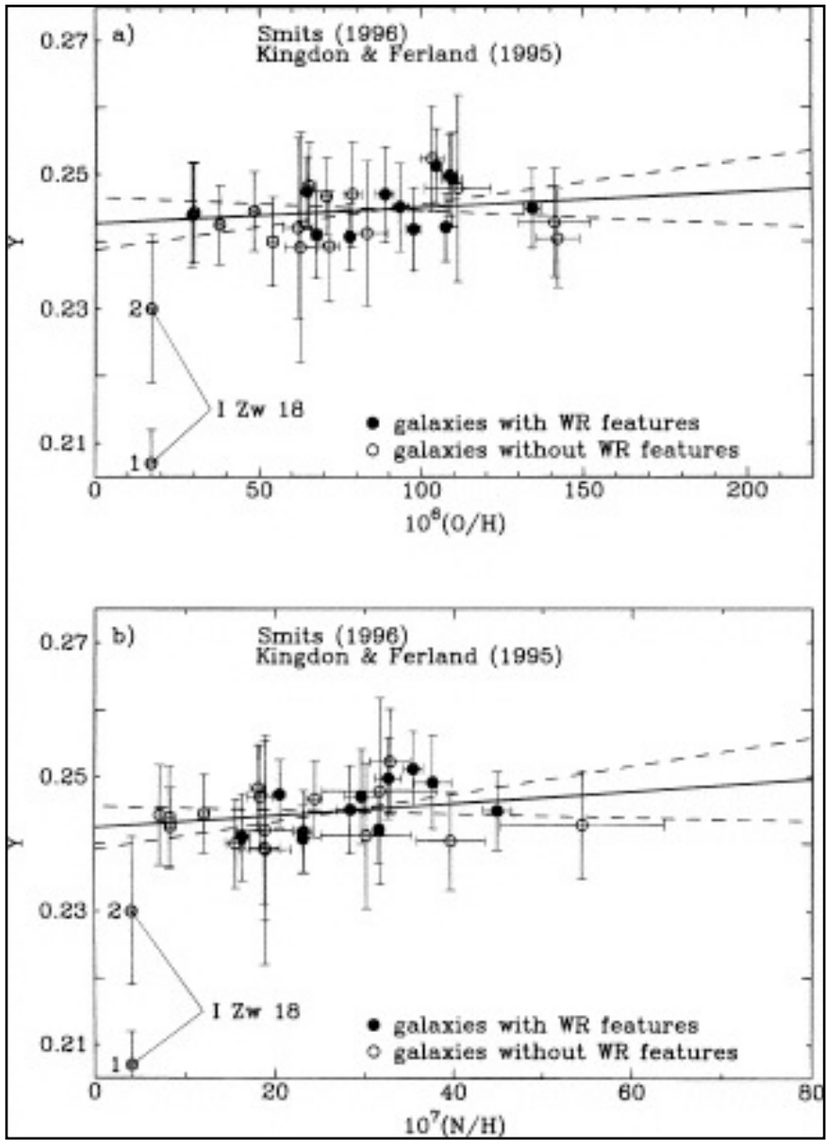
Big bang theory predicts:
@ 3 minutes, proton: neutron ~ 7:1
or, primordial abundance H 76%, He 24% (by mass)

elemental abundances by mass:

Sun:
71% H, 27% He, rest 'metal'
Jupiter:
~76% H, ~ 22% He
Earth:
hardly any H & He

dwarf galaxies with 'pristine' gas:
76% H, 24% He

==> a 'primordial' abundance of
~76% H, ~24% He



observed helium abundances in un-processed regions in the universe

the success in predicting the primordial H/He abundances is considered a great success of the hot big bang theory.

The first Three Minutes

ignorance

- **PLANCK ERA**: before the Planck time. Uncertainty Principle indicates huge energy fluctuations, as well as space/time changes (space-time foam).

  GUT ERA (grand unified theories): GUT force combines the strong force with the electroweak force (the combination of weak and electromagnetic force). **INFLATION**.

- **ELECTROWEAK ERA**: electromagnetic and weak forces were still united. Conditions achieved in particle accelerator in 1983.

- **PARTICLE ERA**: particles and anti-particles created and destroyed continuously in the hot bath, until the universe cools to a point. **Asymmetry of matter/anti-matter** 1/10^9. This slight excess explains all the matter in the universe.

- **NUCLEOSYNTHESIS ERA**: nuclei (proton + neutron) formed and broken apart continuously. The universe is one big nuclear reactor. The end of this era sets the chemical composition of the universe: 76% H + 24% He

Universe after the first 3 minutes -- in a nutshell

- **ERA of NUCLEI**: Electrons continuously bound into a nucleus or be dissociated by a photon. Foggy path for photons. As universe cools to ~ 3000K, photons no longer destroy atoms and free to travel **--CMB**. Can never look beyond CMB using photons.

- **ERA of ATOMS**: first structures getting ready to form, the "**cosmic dark ages**". Lasting from z ~ 1100 to z at least 8.4 (highest redshift galaxy known). Need infrared observations. New generations of telescopes (JWST -- Hubble Space Telescopes's successor, Herschel and ALMA) are designed to detect the first structure.

- **ERA of GALAXIES**: structures form following primordial fluctuations (imprinted on cmb). Large and small galaxies, first stars.... generations of stars burn nuclear fuels, generating the chemical elements useful for Earth and Life...