# Early Universe II

# Standard Cosmological Model

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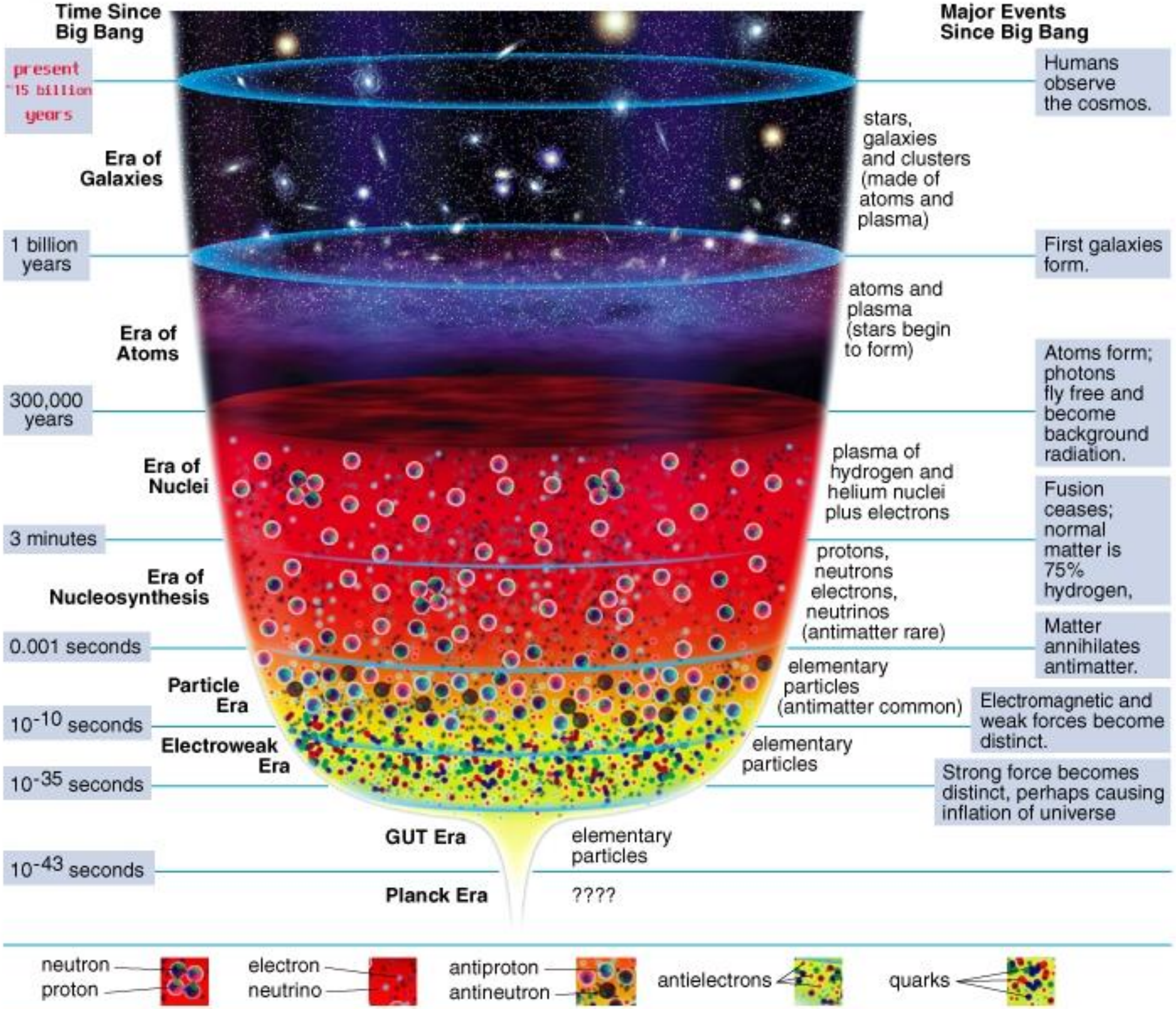
- The ”standard model” is the model of the universe based on the simplest description of nature and on known physical laws. (Forces are given in the order of decreasing strength. Particles are given in the order of decreasing contribution to the total matter-energy of the universe.)

# Standard Cosmological Model



# Standard Cosmological Model

- ***Planck epoch*****:** $10^{32}$ K. GUT and gravity forces separate.
- ***GUT era*****:** $10^{32}$ K to $10^{29}$ K. GUT + gravity forces. Zillions of particles, most of which are not detected yet.
- ***GUT phase transition*****:** $10^{15}$ K. Strong and electroweak forces separate.
- ***Quark era***: $10^{29}$ K to $10^{15}$ K. Strong + electroweak + gravity forces. Quarks + electrons + neutrinos + photons.

# Standard Cosmological Model

- ***Electroweak phase transition*: $10^{15}$ K.** Electromagnetic and weak forces separate.
- ***Still quark era*:** $10^{15}$ K to $10^{13}$ K. Strong + electromagnetic + weak + gravity forces. Quarks + electrons + neutrinos + photons.
- ***Hadron era***: $10^{13}$ K to $10^{12}$ K. All four forces. Baryons + mesons + electrons + neutrinos + photons.
- ***Hadron annihilation*:** $10^{12}$ K. Most of hadrons annihilate.

# Standard Cosmological Model

- ***Lepton era***: $10^{12}$ K to $10^{10}$ K. Electrons + neutrinos + photons + baryons.
- ***Electron-positron annihilation***: $10^{10}$ K. Most of electron - positron pairs annihilate.
- ***Radiation era:*** $10^{10}$ K to $10^{4}$ K. Photons + neutrinos + baryons.
- ***Matter era*****:** $10^{4}$ K to 5 K. Baryons + photons + neutrinos.
- ***Dark Energy era*****:** 5 K to 2.73 K (and beyond). Dark Energy + baryons + photons + neutrinos.

# The Birth of the CMB

- The CMB was born during the electron-positron annihilation, when photons finally became the dominant source of energy in the universe. Thus, the CMB was born as gamma-rays, and during expansion of the universe it cooled down and passed through many kinds of electromagnetic radiation. Can you list which ones?

# Baryogenesis

- The universe around us consists mostly of matter. Anti-matter (anti-protons, anti-neutrons, positrons) is very rare.
- In Big Bang theory particles and antiparticles exist in equal numbers in the thermal equilibrium of the early universe. Then they annihilate by pairs, and at the end there are equal numbers of particles and anti-particles. Thus, the universe should be filled with the same amount of matter as anti-matter.

# Baryogenesis

- This is know as the ***baryon problem***. Somehow the universe managed to create more matter than anti-matter. The process of creating more matter at the expense of anti-matter is called ***baryogenesis***.
- This excess is very small, one part in one billion, but it is enough to shape the universe as it is.

# Baryogenesis and Phase Transitions

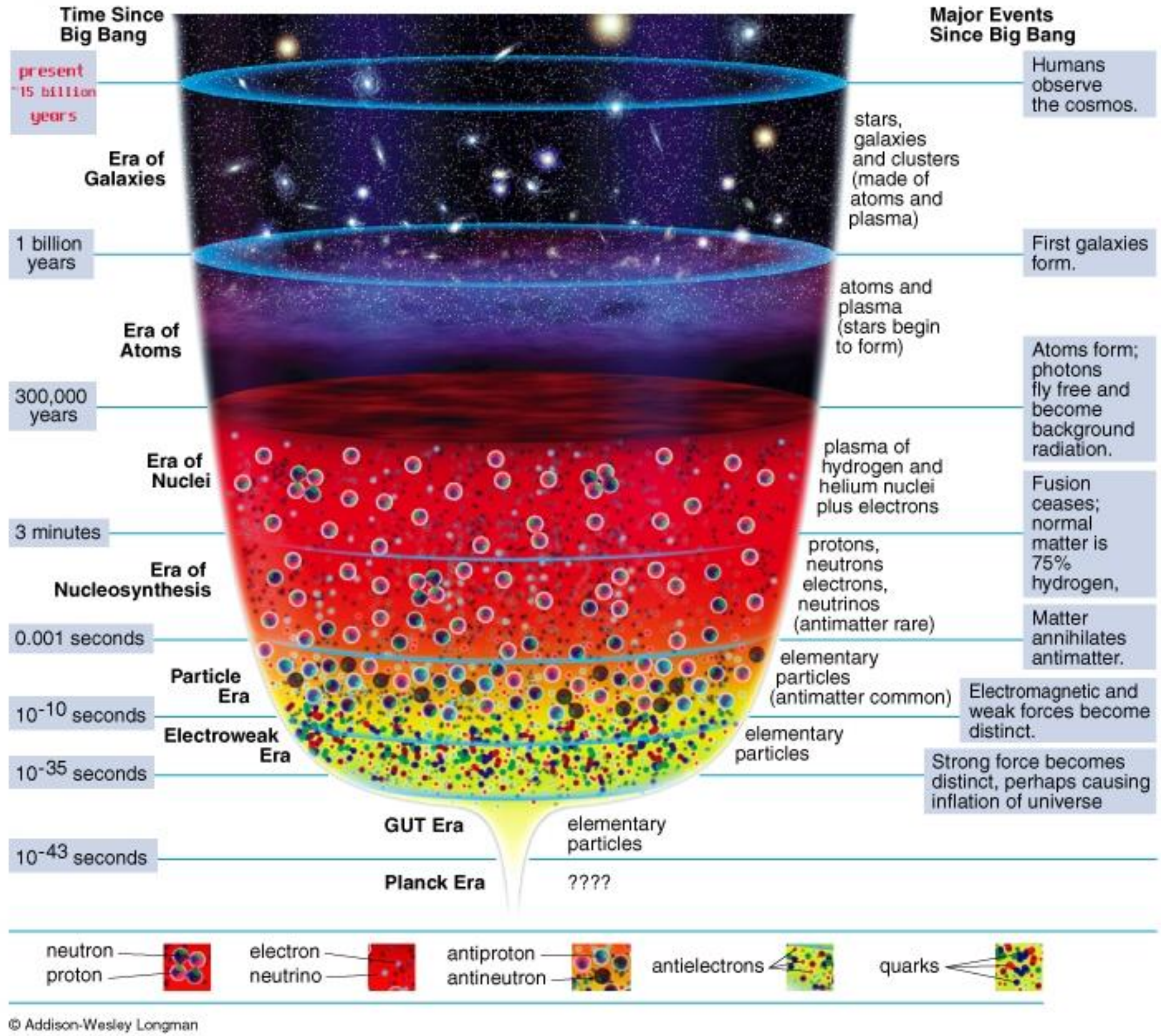
- The solution to the baryogenesis problem lies in the assumption of thermal equilibrium. If the universe was in thermal equilibrium all the time, there is no way there can be an excess of matter over anti-matter.
- Fortunately, there are two moments in the history of the universe when it was **not** in thermal equilibrium: during GUT and electroweak phase transitions. A phase transition is a non-equilibrium process.

- Cosmologists think that during one of those two phase transitions the excess of matter was produced.
- The problem is baryogenesis is largely unsolved, we even do not know which of the two phase transitions was responsible for it.

# Nucleosynthesis

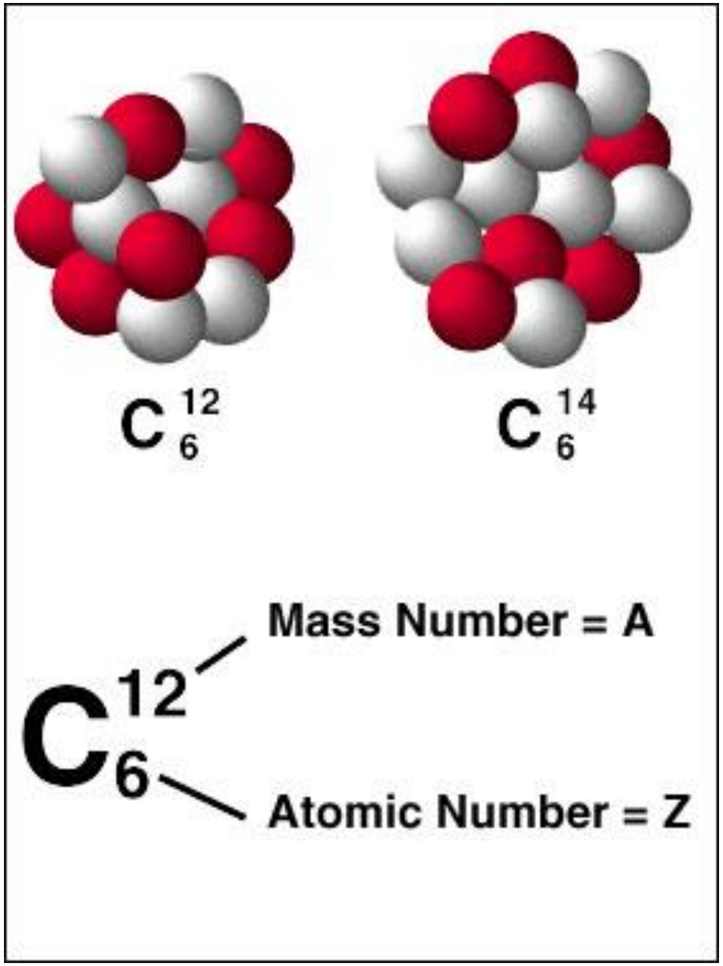
- Shortly after electron - positron pairs annihilated at $10^{10}$ K (the universe is about 1 second old), helium and trace amounts of other *isotopes* were synthesized (the universe is about 100 seconds old).

# Nucleosynthesis

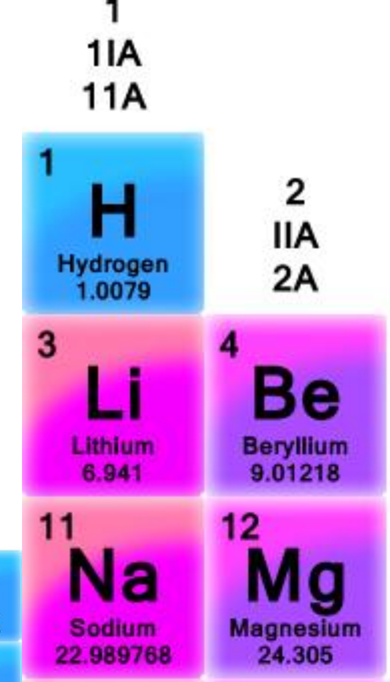


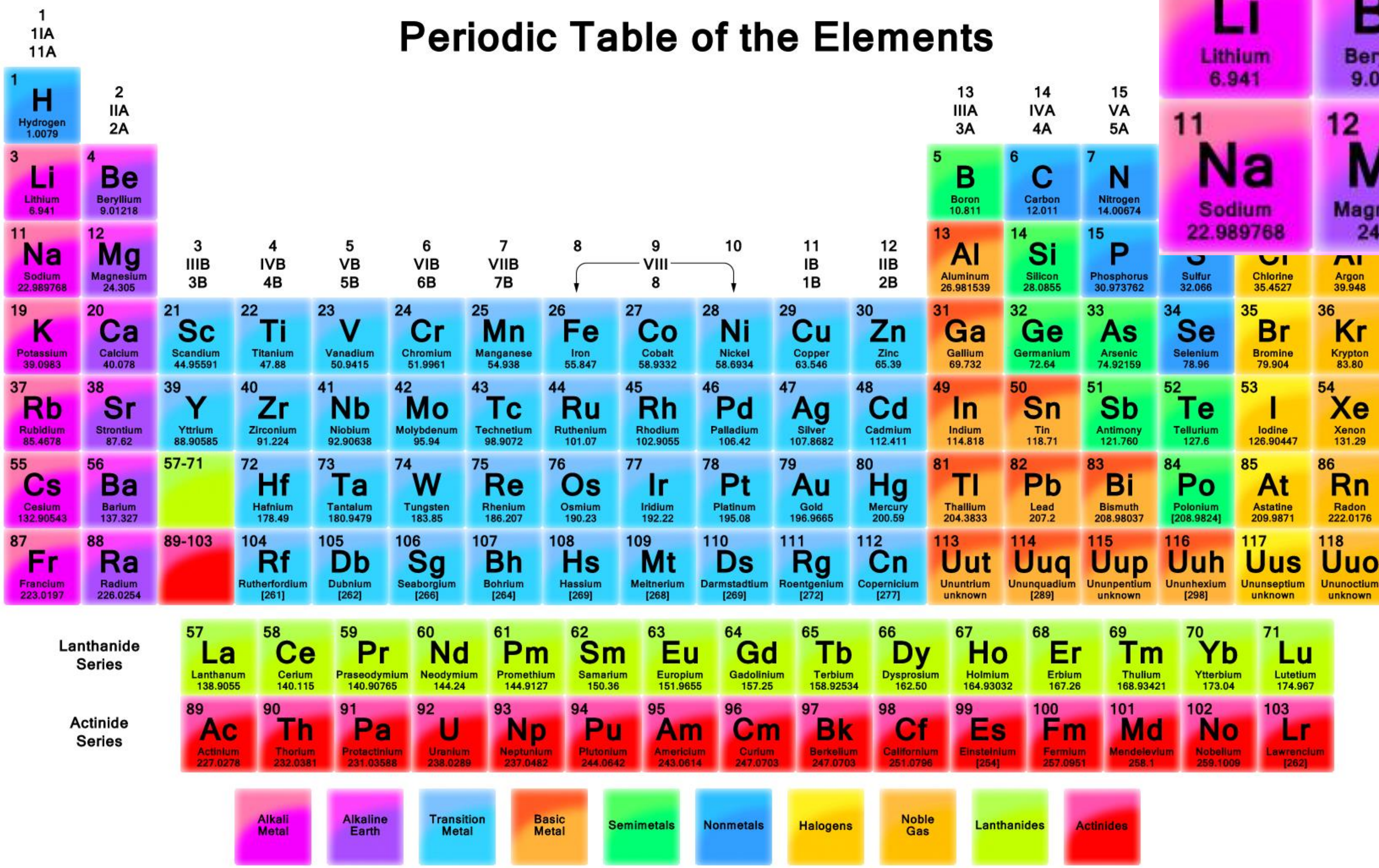
# Layover: Chemical Elements

- Number of protons = chemical element
- Number of neutrons can vary – different ***isotopes***
- Atomic mass = $N_n + N_p$
- Proton mass: 938.3 MeV/$c^2$
- Neutron mass: 939.6 MeV/$c^2$
- Electron mass: 0.511 MeV/$c^2$

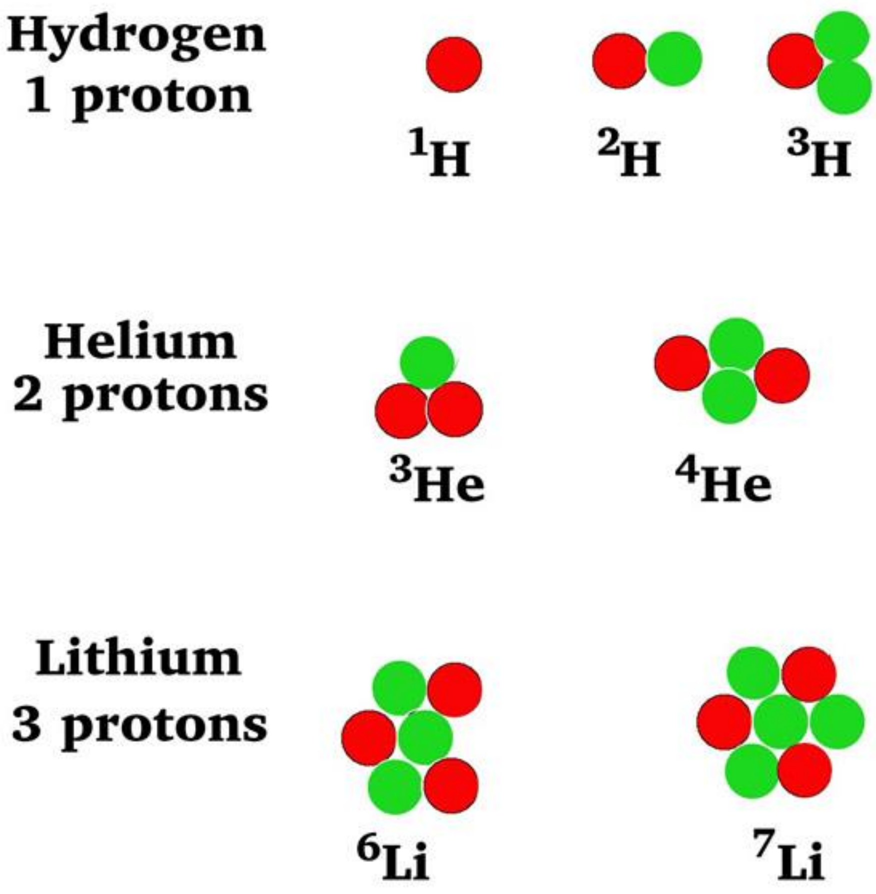


# Periodic Table



# Isotopes That Matter

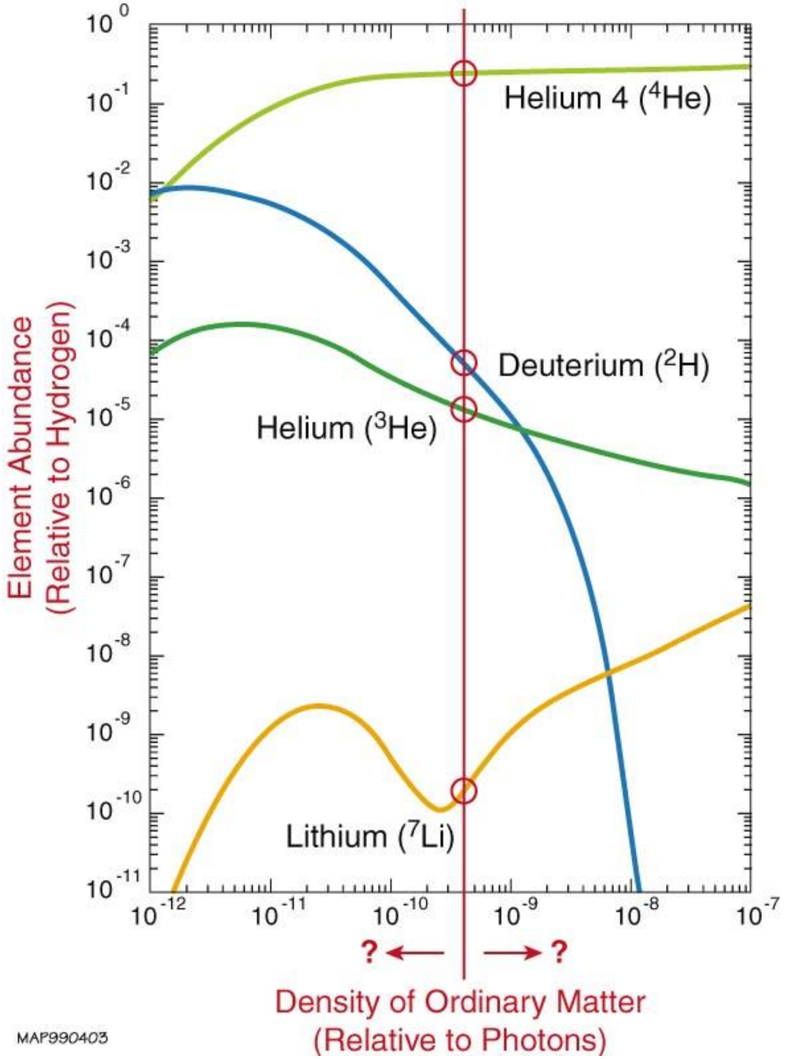


# Big Bang Nucleosynthesis

- Protons and neutrons combine to form D ($^{2}H$).
- Deuterium captures a proton and becomes $^{3}He$, or
- Deuterium captures a neutron and becomes $^{3}H$.
- $^{3}He$ captures a neutron to become $^{4}He$ (normal helium), or
- $^{3}H$ captures a proton to become $^{4}He$.
- $^{4}He$ captures $^{3}H$ to become $^{7}Li$, or
- $^{4}He$ captures $^{3}He$ and emits one electron to become $^{7}Li$.

# Big Bang Nucleosynthesis

- Abundances of light elements have been measured, they are all consistent with the same value of the density of baryons.



# An Unexpected Side Result

- It turns out that the precise amount of helium produced depends on how many different neutrino species exist. The modern particle physics predicts that there should be three different neutrino species in the universe.
- Using the Big Bang nucleosynthesis, we can measure this number: $2.5 < N_\nu < 3.5$.
- Can $N_\nu$ be non-integer?

# WIMP Dark Matter

# Super-symmetry

- A concept of symmetry proved itself very powerful in particle physics so far.
- Based on that concept, an idea of *super-symmetry* (SUSY) has been proposed: every elementary particle has a super-symmetric partner: a boson has a fermion, a fermion has a boson.
- A quark's partner is called *squark*, a neutrino partner *sneutrino*, etc.

# String Theory

- A specific theory of Quantum Gravity that uses the idea of super-symmetry is called the *String Theory.*
- *Here is a very simplistic description of it:*
  - Elementary particles are actually not points but tiny (the size of Planck length) strings.
  - The multitude of various particles is explained by different excitations of the same string.
  - Space-time is woven out of graviton strings the same way as a cloth is woven out of threads.

# String Theory

- For the math to work out, the dimension of space-time should be not 4 but at least 11 (or 26, or 27).
- The extra dimensions then must be *compactified* (i.e. not extend beyond the Planck length).
- I.e. we are all 10-dimensional, just are very thin in 7 out of 10 dimensions (does not mean we don’t need to exercise).
- The simplest formulation of the String Theory is in mild conflict with LHC measurements.

# LSP

- If every normal particle has a super-symmetric partner, one of them is the lightest – Lightest Super-symmetric Partner, or LSP.
- Other super-symmetric particles can decay into LSP, but it cannot decay into anything (conservation of “super-symmetric charge”).
- Hence, LSP must be stable.
- It still annihilates as other particles, hence there should be some of that stuff left at present.

# WIMP Miracle

- An LSP is likely to be subject of the weak nuclear force.
- If it is, at present the density parameter for LSPs will be $\Omega_{\mathrm{LSP}} \approx 0.3$.
- That means that LSP can be responsible for
  A. Global warming
  B. Solar flares
  C. Dark matter
  D. Dark energy

# WIMP Miracle

- Such a particle is often generically called “Weakly Interacting Massive Particle” (WIMP). Here “weakly” means “with weak nuclear force”, not “meekly”.
- The fact that particle physics predicts that WIMP should be as abundant as Dark Matter is called “WIMP miracle”.
- Such coincidences are rarely by chance.

# Search for Dark Matter

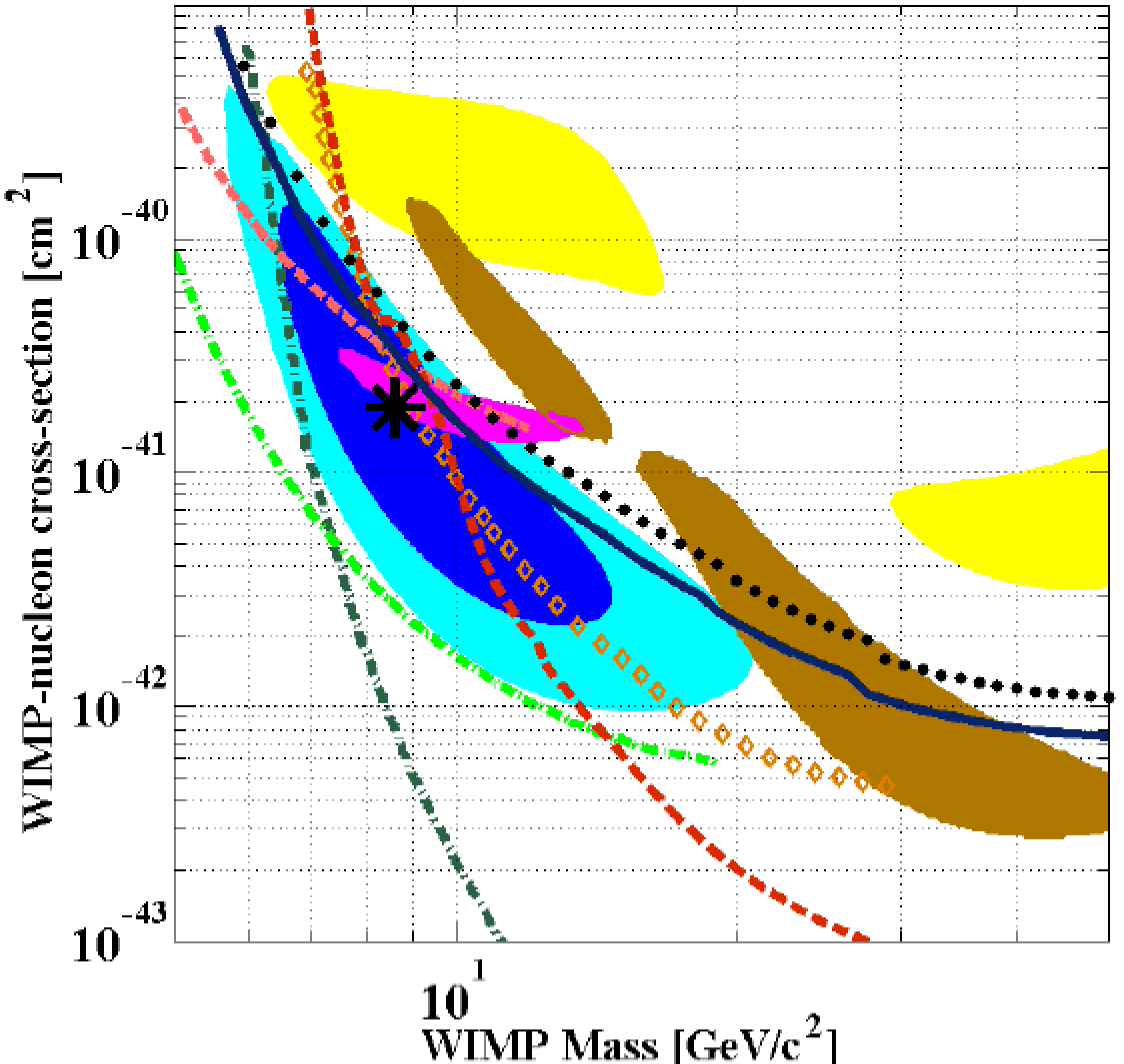
- Both the “WIMP Miracle” and the appeal for super-symmetry makes WIMPs the primary candidate for Dark Matter.
- Numerous experiments are being conducted right now to detect a WIMP particle in the lab.
- The whole field starts looking more and more like an adventure story…

# Search for Dark Matter

- DAMA (Italy): since ~2000 claimed a detection of "annual modulation".
- CoGENT claimed a detection of Dark Matter in 2011.
- CRESST detected annual modulation in 2012.
- CDMS II announced the detection of 3 events in 2013.
- XENON 10 and XENON 100 claimed they ruled all of them out (XENON 10 is rumored to be about to retract its claim).

# Search for Dark Matter

- The battlefield as of Feb 2014.

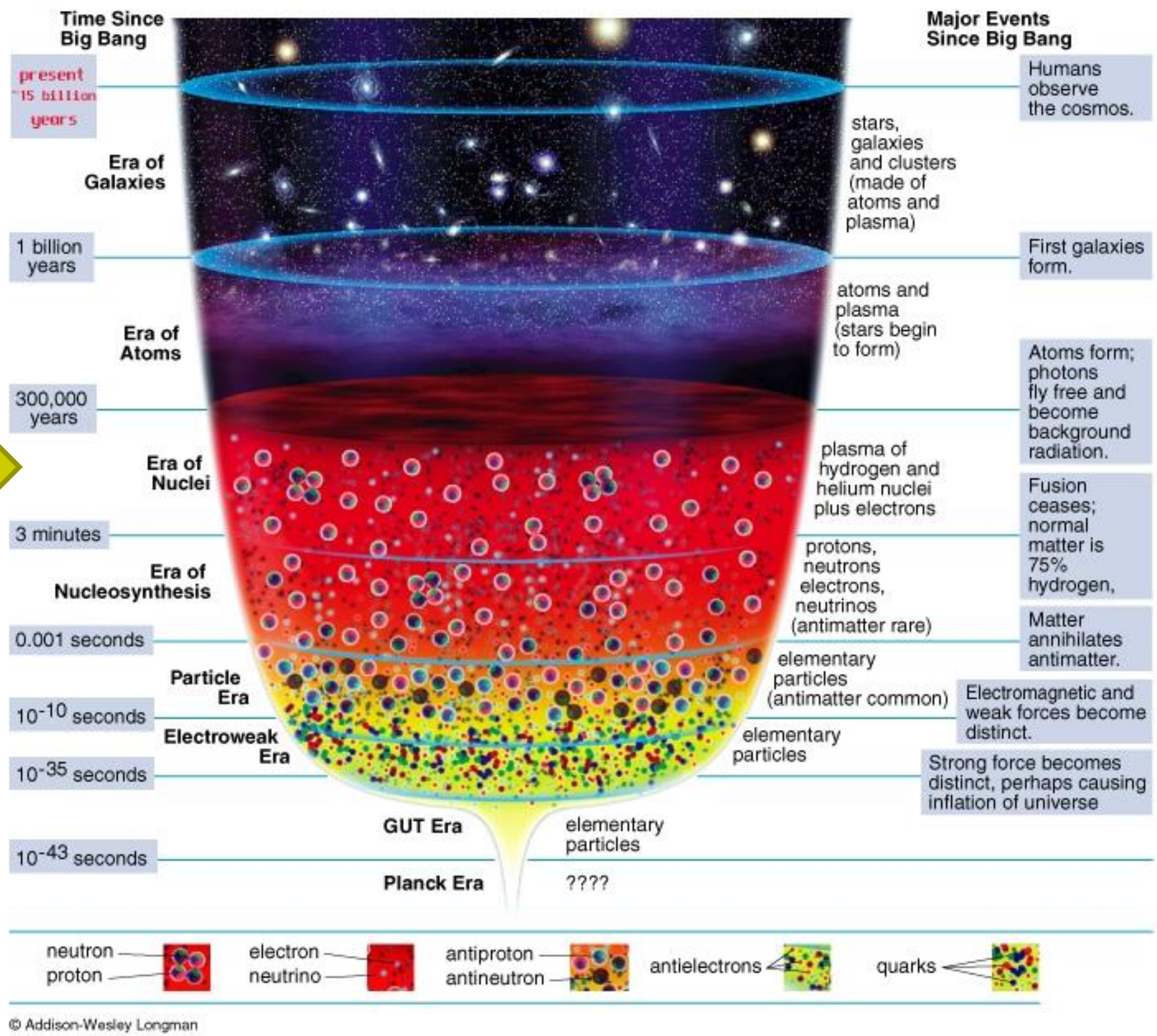


# Search for Dark Matter

- All detection claims converge on the WIMP mass of about 10 GeV ($m_p = 0.938\mathrm{GeV}$).
- There are several other indirect pieces of evidence pointing to the same value.
- The race may be entering the last round, so stay tuned.

# Back To History of the Universe

# Recombination



# Recombination

- After an electron - positron annihilation and nucleosynthesis, the universe is filled with photons, neutrinos, atomic nuclei and electrons (one electron for each proton, to ensure electric neutrality). It is still so hot, that no atoms can form.
- The universe keeps expanding and cooling until the temperature drops to about 3000 degrees Kelvin, which occurs at redshift $z \approx 3000/2.73 = 1200$ .

# Recombination

- At this temperature (3000 K) the universe is cold enough for atoms to exist. So, quickly electrons combine with atomic nuclei to form atoms. This process is called ***recombination***.
- Before recombination, while the gas was ionized, free electrons collided with the CMB photons quite often. This kind of collisions is called ***scattering***. Then suddenly, when all free electrons jumped into atoms, CMB photons had nothing to collide with. They just flew in straight lines after that.

# Recombination

- Thus, when we see a CMB photon coming straight into our ``eyes'', we see it coming from the moment of last collision with the free electron. This moment and place in the universe is called ***the surface of last scattering***. It was at the moment of recombination, at $z$=1200.

# Between Nucleosynthesis and Recombination

- Surprisingly, we know pretty well what happened after nucleosynthesis but before recombination, much better than what happened after recombination!
- The reason for that is that the CMB spectrum is very fragile during that era. Any physical process that produces or consumes energy will leave easily identifiable features in the CMB spectrum.

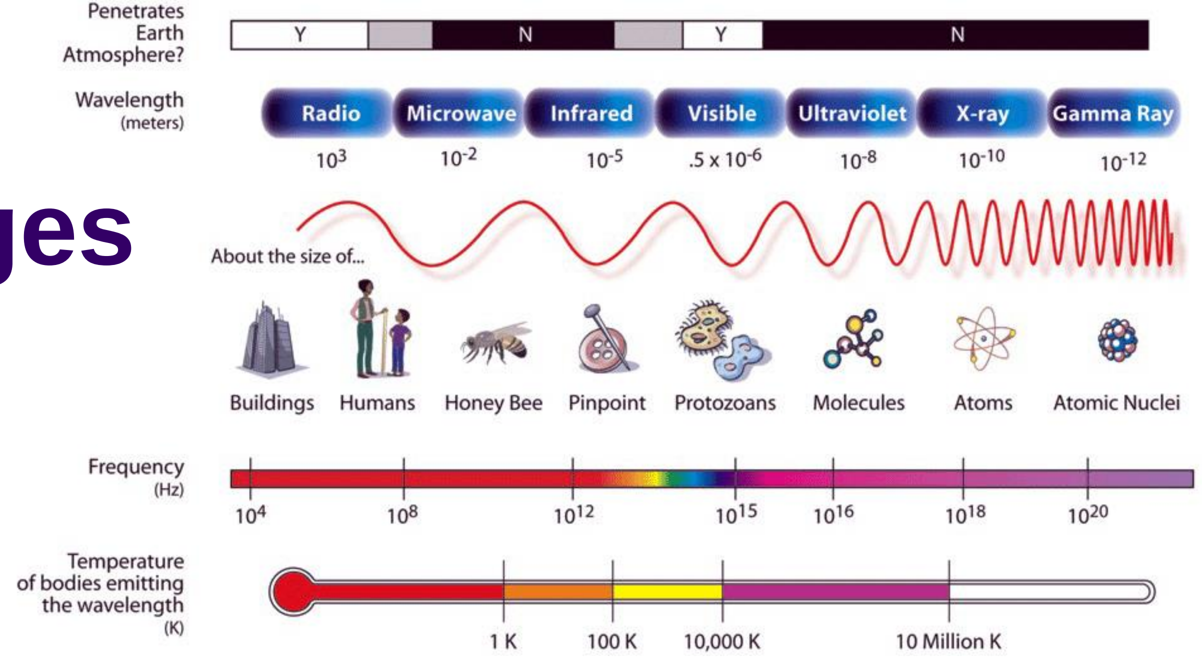
# Between Nucleosynthesis and Recombination

- The fact that the CMP spectrum is an equilibrium black body spectrum to one part in 100,000 means that during the epoch between nucleosynthesis and recombination ...
- Can you guess what happened then?

# The Dark Ages

- As CMB cools down, it moves trough different kinds of electromagnetic radiation. Thus, at some moment it was visible light. The whole universe then was as bright as the surface of the Sun. As it cooled down further, it shifted into infrared, which we can not see, and the universe became completely dark to human eyes. This time often called the ***dark ages***.

# The Dark Ages



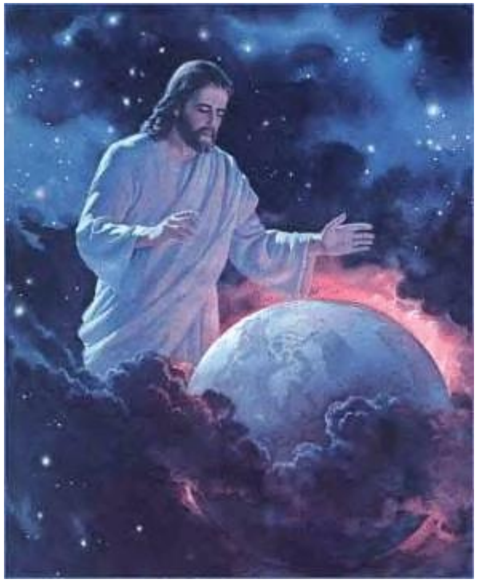

- Visible light is emitted by bodies heated to ~3,000K.
- Hence, the Dark Ages started shortly after recombination, at $z \sim 3000\text{K}/2.73\text{K} \approx 1100$.
- This is *not* a coincidence, BTW.

# The End of the Dark Ages

- After the first stars formed, they began emitting light. But at the same time they also emitted ultra-violet (UV) radiation. UV radiation is capable of kicking out electrons from atoms, thus ionizing them. When about 10% of all stars present in the universe formed, they produced enough UV radiation to ionize the whole universe.
- This process is called ***reionization*** - the universe became ionized again - and is identified with the end of the dark ages.

# You Have a Choice:

God's View



Mortal's View

# How It All Happens…