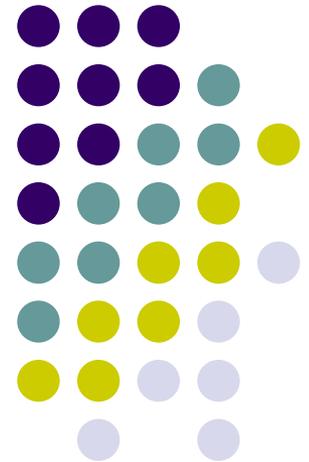
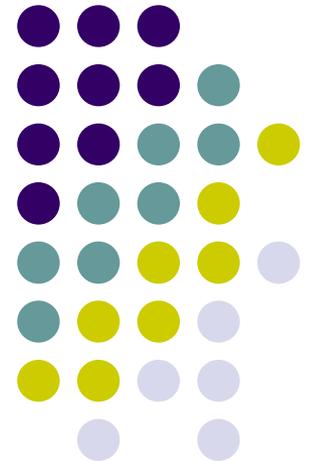


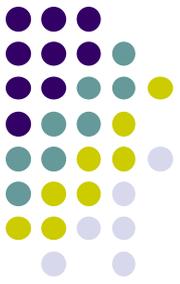
Early Universe II



Standard Cosmological Model

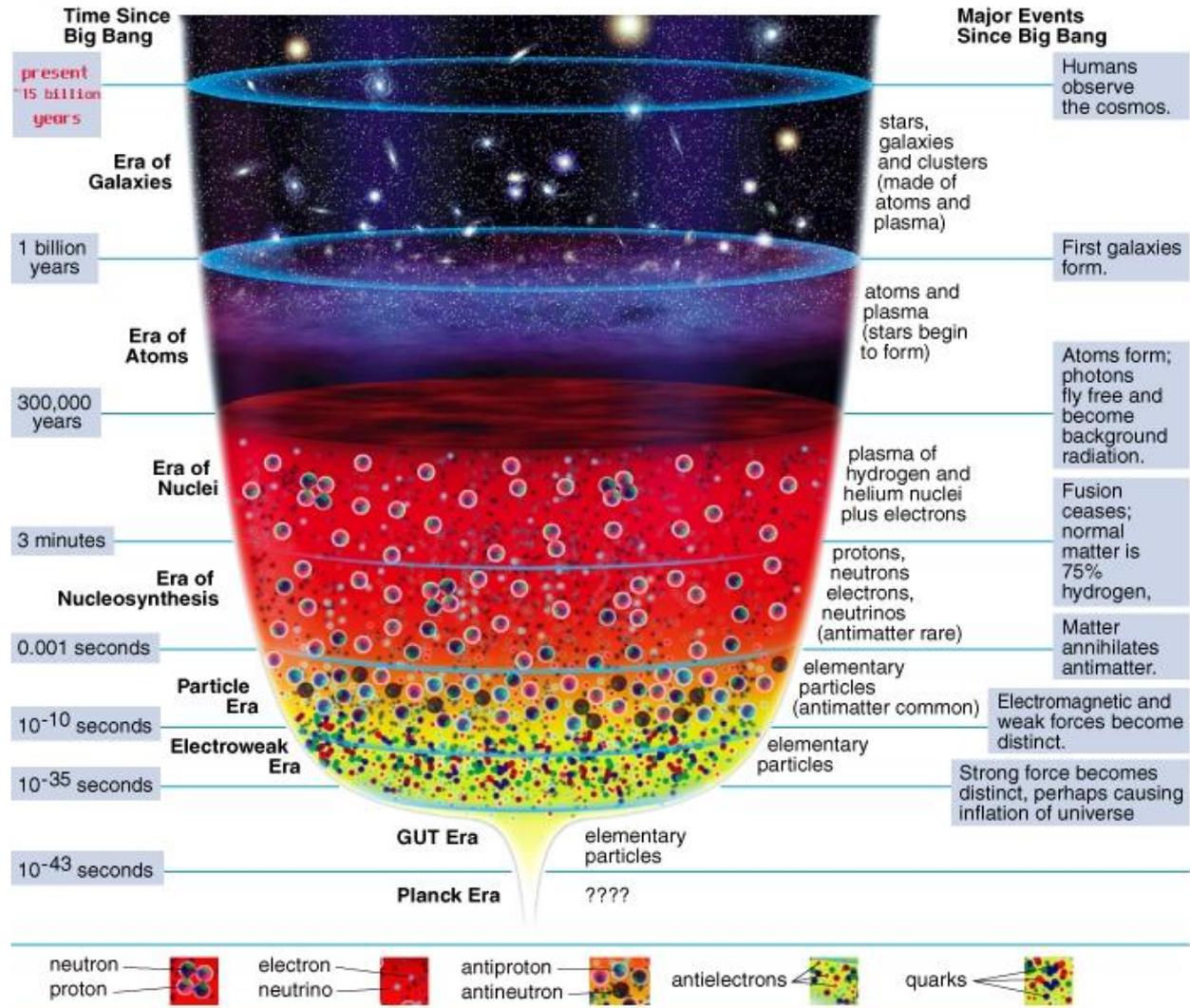


Standard Cosmological Model



- 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

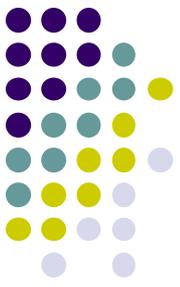


- ***Electroweak phase transition:*** 10^{15} K. Electromagnetic and weak forces separate.
- ***Still quark era:*** 10^{15} K to 10^{13} K. Strong + electromagnetic + weak + gravity forces. Quarks + electrons + neutrinos + photons.
- ***Hadron era:*** 10^{13} K to 10^{12} K. All four forces. Baryons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

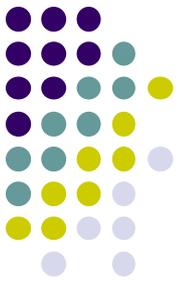
- The CMB was born during the electron-positron annihilation, when photons finally became the dominant source of energy in the universe. Thus, the CMB was born as gamma-rays, and during expansion of the universe it cooled down and passed through many kinds of electromagnetic radiation. Can you list which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

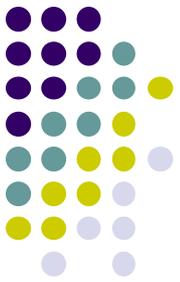


- This is known as the ***baryon problem***. Somehow the universe managed to create more matter than anti-matter. The process of creating more matter at the expense of anti-matter is called ***baryogenesis***.
- This excess is very small, one part in one billion, but it is enough to shape the universe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

Baryogenesis and Phase Transitions

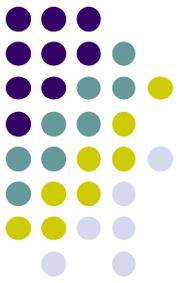


- The solution to the baryogenesis problem lies in the assumption of thermal equilibrium. If the universe was in thermal equilibrium all the time, there is no way there can be an excess of matter over anti-matter.
- Fortunately, there are two moments in the history of the universe when it was **not**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



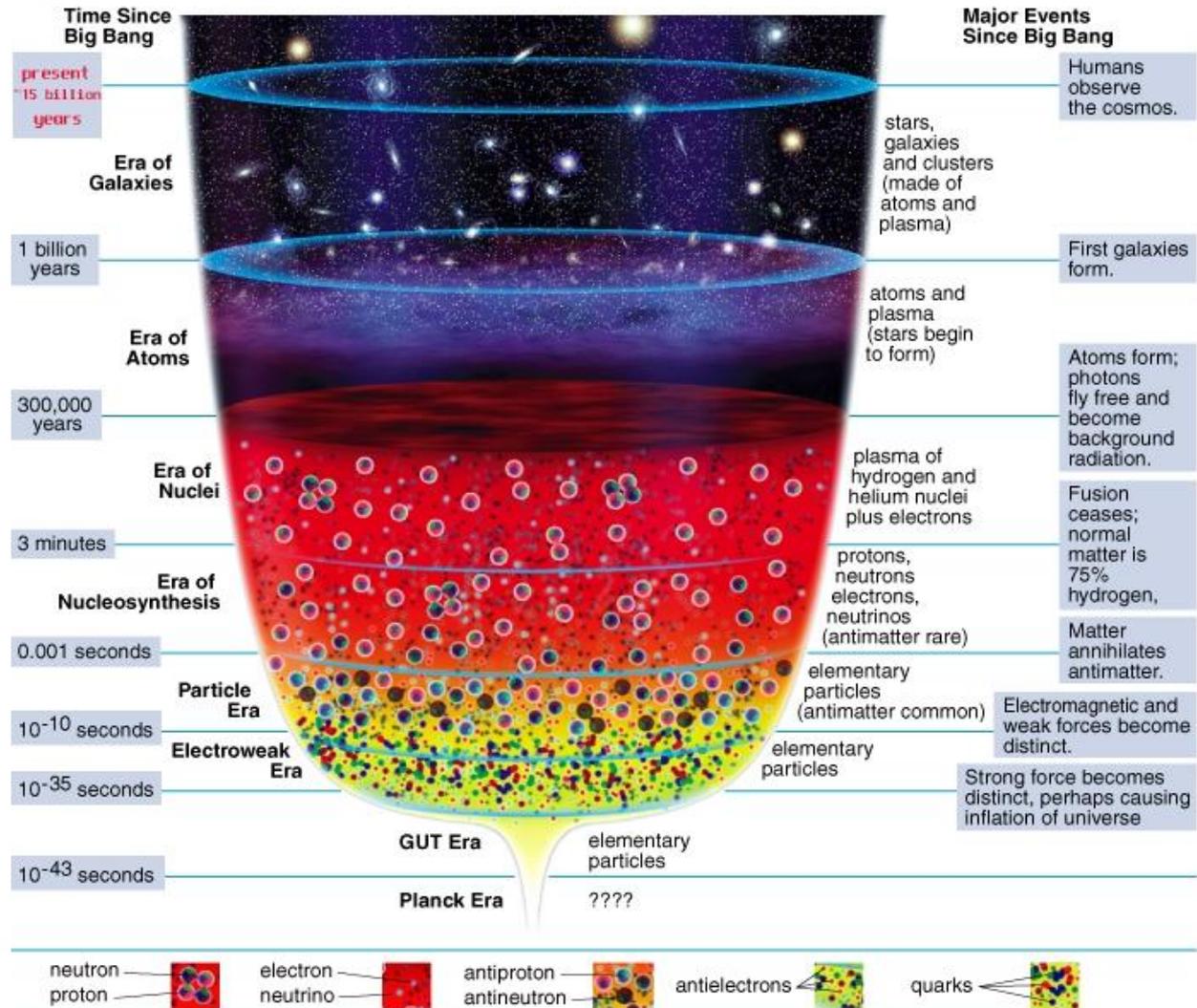
- Cosmologists think that during one of those two phase transitions the excess of matter was produced.
- The problem is baryogenesis is largely unsolved, we even do not know which of the two phase transitions was responsible for it.

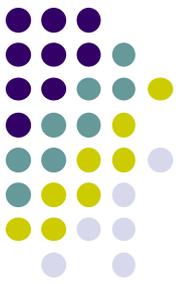
Nucleosynthesis



- 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).

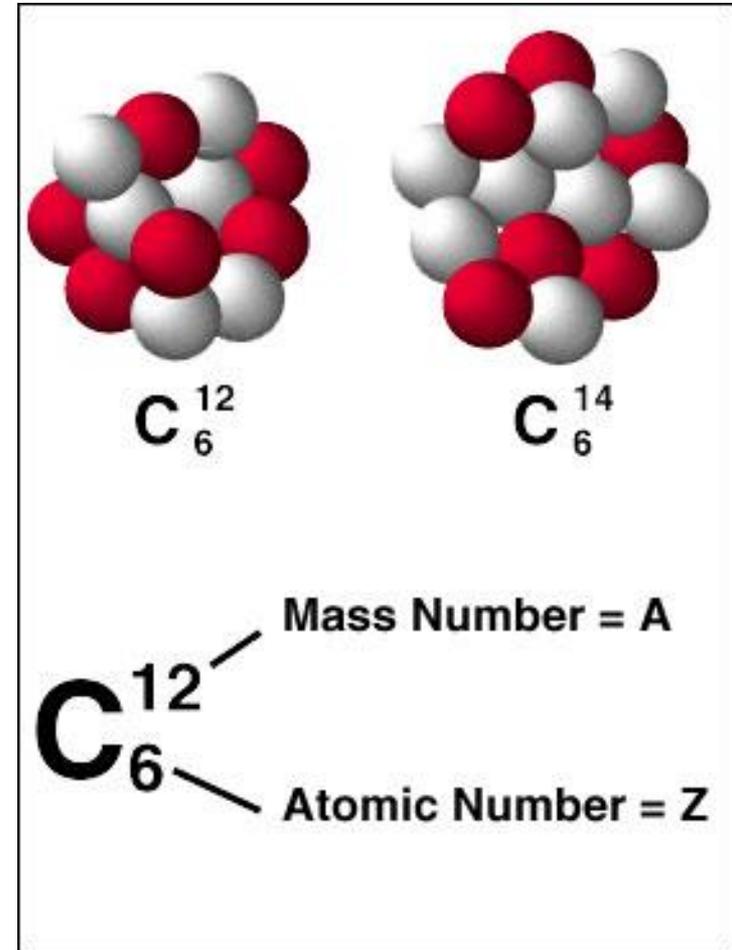
Nucleosynthesis





Layover: Chemical Elements

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



Periodic Table

Periodic Table of the Elements

																1 1IA 11A																	1 H Hydrogen 1.0079																	2 2IA 2A																																																																																																																																																																																																																																																															
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																19 K Potassium 39.0983																	20 Ca Calcium 40.078																	21 Sc Scandium 44.95591																	22 Ti Titanium 47.88																	23 V Vanadium 50.9415																	24 Cr Chromium 51.9961																	25 Mn Manganese 54.938																	26 Fe Iron 55.847																	27 Co Cobalt 58.9332																	28 Ni Nickel 58.6934																	29 Cu Copper 63.546																	30 Zn Zinc 65.39																	31 Ga Gallium 69.732																	32 Ge Germanium 72.64																	33 As Arsenic 74.92159																	34 Se Selenium 78.96																	35 Br Bromine 79.904																	36 Kr Krypton 83.80
																37 Rb Rubidium 85.4678																	38 Sr Strontium 87.62																	39 Y Yttrium 88.90585																	40 Zr Zirconium 91.224																	41 Nb Niobium 92.90638																	42 Mo Molybdenum 95.94																	43 Tc Technetium 98.9072																	44 Ru Ruthenium 101.07																	45 Rh Rhodium 102.9055																	46 Pd Palladium 106.42																	47 Ag Silver 107.8682																	48 Cd Cadmium 112.411																	49 In Indium 114.818																	50 Sn Tin 118.71																	51 Sb Antimony 121.760																	52 Te Tellurium 127.6																	53 I Iodine 126.90447																	54 Xe Xenon 131.29
																55 Cs Cesium 132.90543																	56 Ba Barium 137.327																	57-71 Lanthanide Series																	72 Hf Hafnium 178.49																	73 Ta Tantalum 180.9479																	74 W Tungsten 183.85																	75 Re Rhenium 186.207																	76 Os Osmium 190.23																	77 Ir Iridium 192.22																	78 Pt Platinum 195.08																	79 Au Gold 196.9665																	80 Hg Mercury 200.59																	81 Tl Thallium 204.3833																	82 Pb Lead 207.2																	83 Bi Bismuth 208.98037																	84 Po Polonium [209]																	85 At Astatine 208.9771																	86 Rn Radon 222.0176
																87 Fr Francium 223.0197																	88 Ra Radium 226.0254																	89-103 Actinide Series																	104 Rf Rutherfordium [261]																	105 Db Dubnium [262]																	106 Sg Seaborgium [266]																	107 Bh Bohrium [264]																	108 Hs Hassium [269]																	109 Mt Meitnerium [268]																	110 Ds Darmstadtium [269]																	111 Rg Roentgenium [272]																	112 Cn Copernicium [277]																	113 Uut Ununtrium unknown																	114 Uuq Ununquadium [289]																	115 Uup Ununpentium unknown																	116 Uuh Ununhexium [288]																	117 Uus Ununseptium unknown																	118 Uuo Ununoctium unknown
																57 La Lanthanum 138.9055																	58 Ce Cerium 140.115																	59 Pr Praseodymium 140.90765																	60 Nd Neodymium 144.24																	61 Pm Promethium 144.9127																	62 Sm Samarium 150.36																	63 Eu Europium 151.9655																	64 Gd Gadolinium 157.25																	65 Tb Terbium 158.92534																	66 Dy Dysprosium 162.50																	67 Ho Holmium 164.93032																	68 Er Erbium 167.26																	69 Tm Thulium 168.93421																	70 Yb Ytterbium 173.04																	71 Lu Lutetium 174.967																																																			
																89 Ac Actinium 227.0278																	90 Th Thorium 232.0381																	91 Pa Protactinium 231.03588																	92 U Uranium 238.0289																	93 Np Neptunium 237.0482																	94 Pu Plutonium 244.0642																	95 Am Americium 243.0614																	96 Cm Curium 247.0703																	97 Bk Berkelium 247.0703																	98 Cf Californium 251.0796																	99 Es Einsteinium [254]																	100 Fm Fermium 257.0951																	101 Md Mendelevium 258.1																	102 No Nobelium 259.1009																	103 Lr Lawrencium [262]																																																			
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Isotopes That Matter

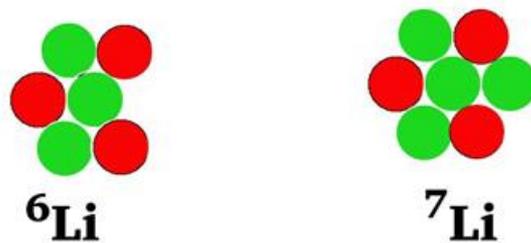
Hydrogen
1 proton



Helium
2 protons



Lithium
3 protons

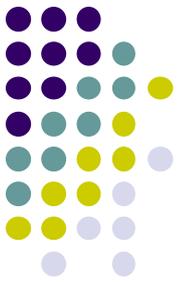


Big Bang Nucleosynthesis

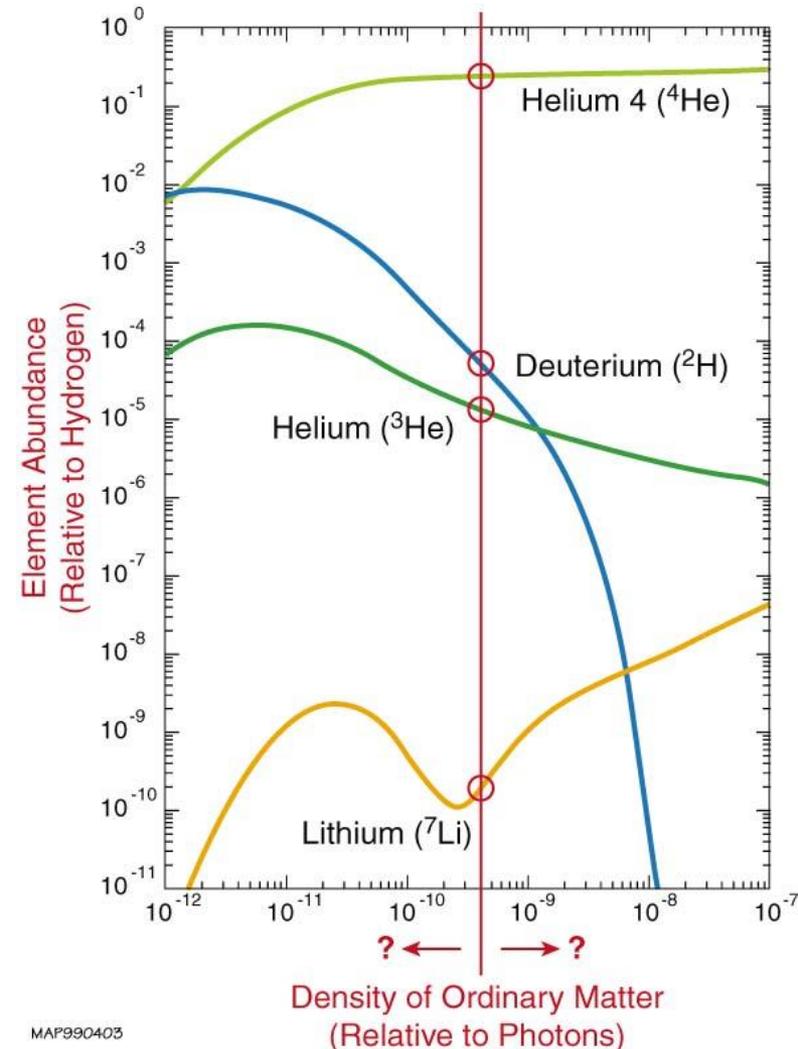


- Protons and neutrons combine to form D (^2H).
- Deuterium captures a proton and becomes ^3He ,
or
- Deuterium captures a neutron and becomes ^3H .
- ^3He captures a neutron to become ^4He (normal helium), or
- ^3H captures a proton to become ^4He .
- ^4He captures ^3H to become ^7Li , or
- ^4He captures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

Big Bang Nucleosynthesis



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

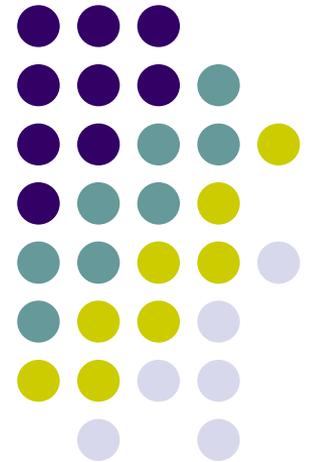




An Unexpected Side Result

- 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_ν 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



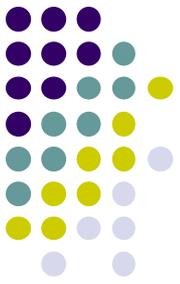
- A specific theory of Quantum Gravity that uses the idea of super-symmetry is called the *String Theory*.
- *Here is a very simplistic description of it:*
 - Elementary particles are actually not points but tiny (the size of Planck length) strings.
 - The multitude of various particles is explained 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

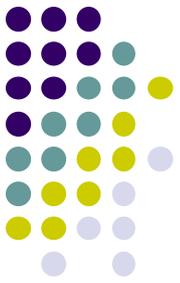
- An LSP is likely to be subject of the weak nuclear force.
- If it is, at present the density parameter for LSPs will be $\Omega_{\text{LSP}} \approx 0.3$.
- That means that LSP can be responsible for
 - A. Global warming
 - B. Solar flares
 - C. Dark matter
 - D. Dark energy



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...



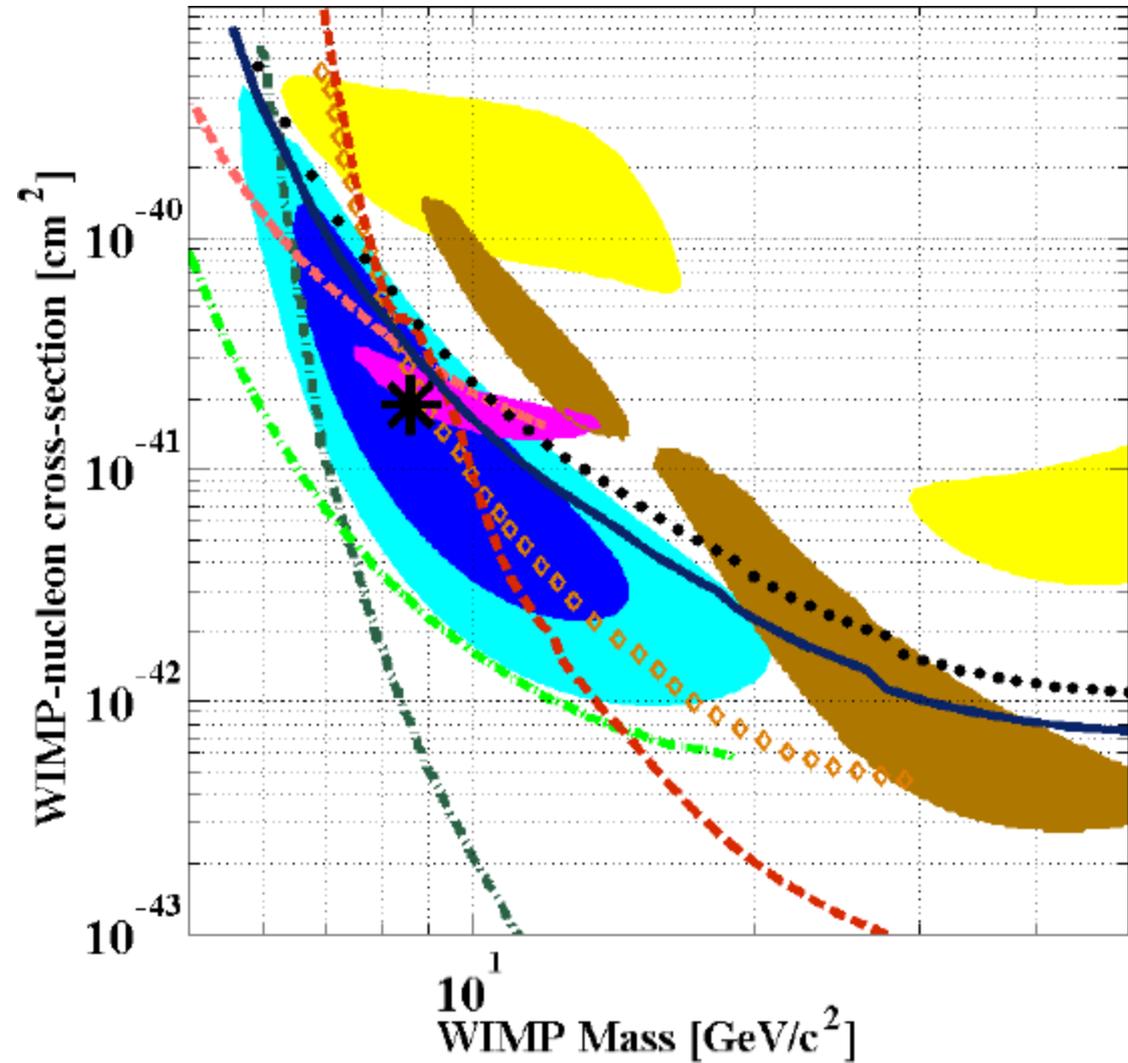
Search for Dark Matter

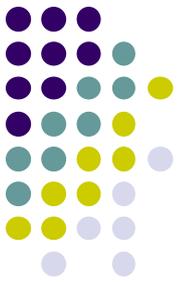
- DAMA (Italy): since ~2000 claimed a detection of “annual modulation”.
- CoGENT claimed a detection of Dark Matter in 2011.
- CRESST detected annual modulation in 2012.
- CDMS II announced the detection of 3 events in 2013.
- XENON 10 and XENON 100 claimed they ruled all of them out (XENON 10 is rumored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

Search for Dark Matter



- The battlefield as of Feb 2014.

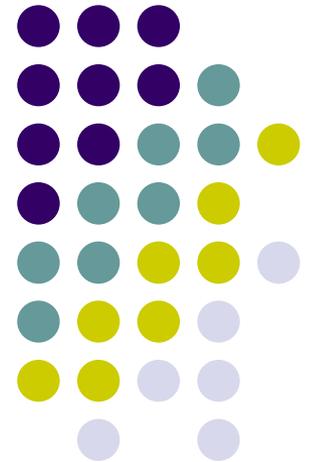




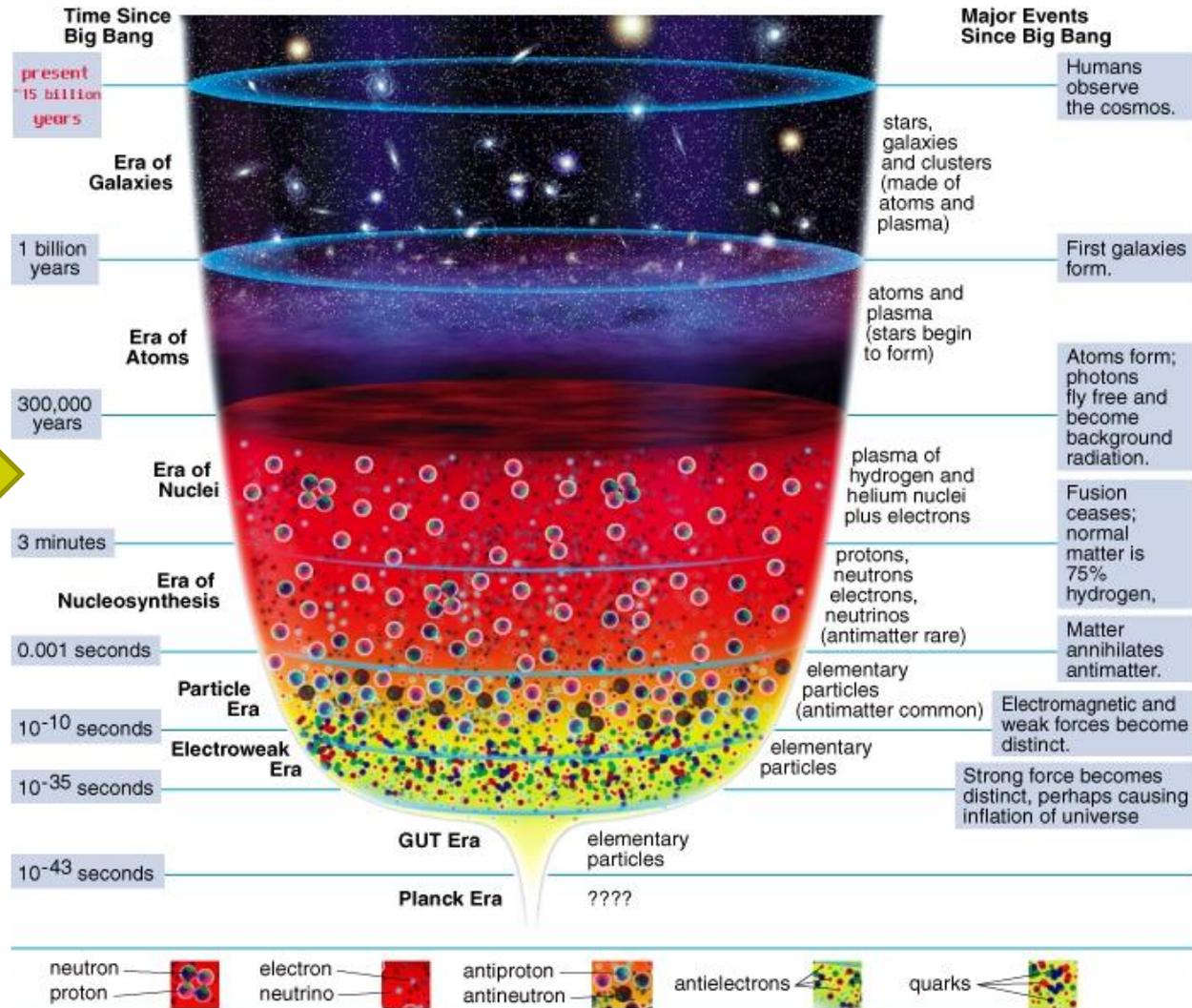
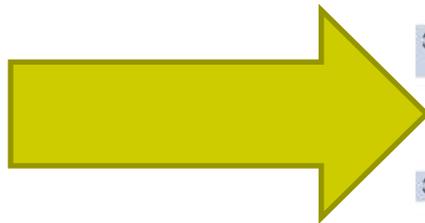
Search for Dark Matter

- All detection claims converge on the WIMP mass of about 10 GeV ($m_p = 0.938\text{GeV}$).
- 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

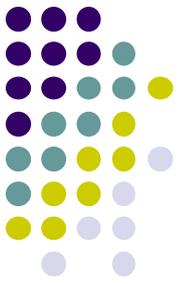
- Thus, when we see a CMB photon coming straight into our ``eyes'', we see it coming from the moment of last collision with the free electron. This moment and place in the universe is called *the surface of last scattering*. It was at the moment of recombination, at $z=1200$.

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



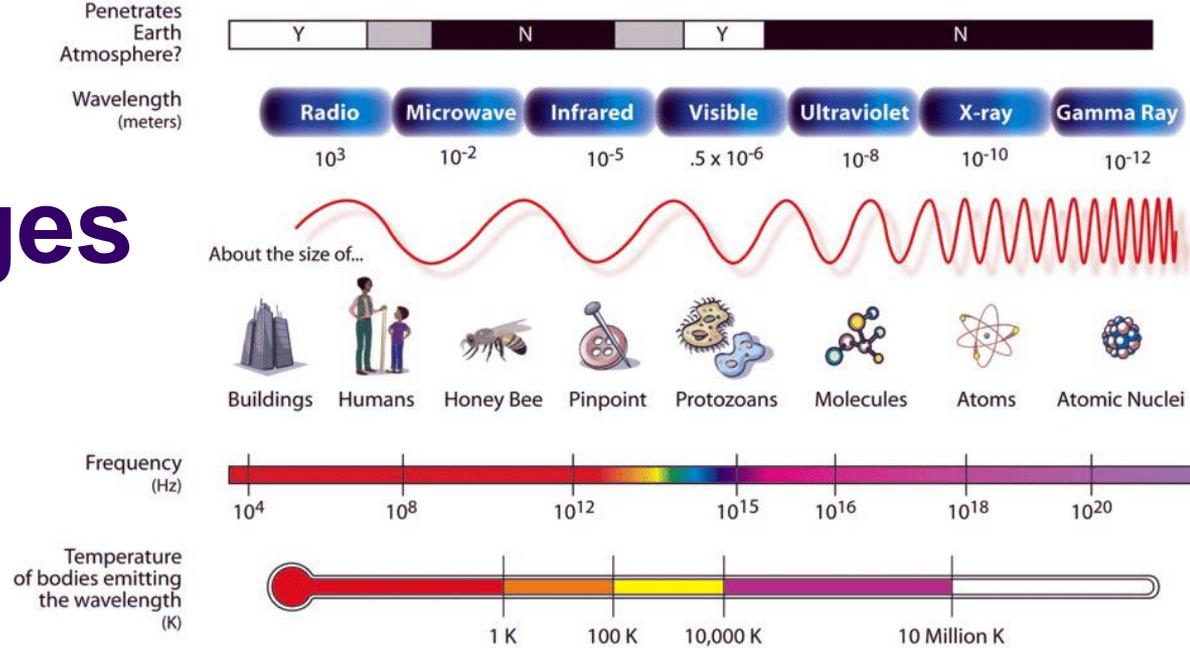
- The fact that the CMB spectrum is an equilibrium black body spectrum to one part in 100,000 means that during the epoch between nucleosynthesis and recombination ...
- Can you guess what happened then?

The Dark Ages



- As CMB cools down, it moves through 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 $\sim 3,000\text{K}$.
- 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

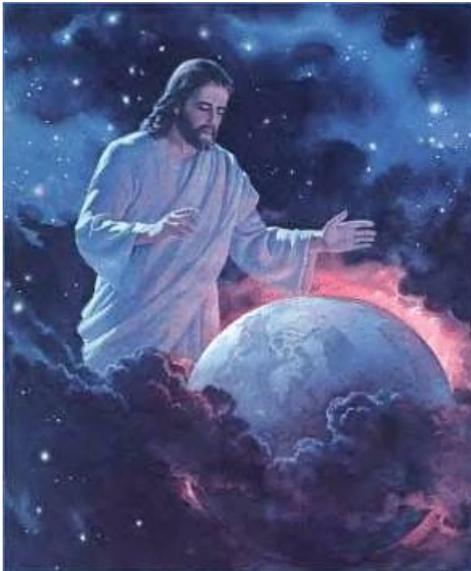


- After the first stars formed, they began emitting light. But at the same time they also emitted ultra-violet (UV) radiation. UV radiation is capable of kicking out electrons from atoms, thus ionizing them. When about 10% of all stars present in the universe formed, they produced enough UV radiation 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...

