

Lecture 35

The early Universe II:

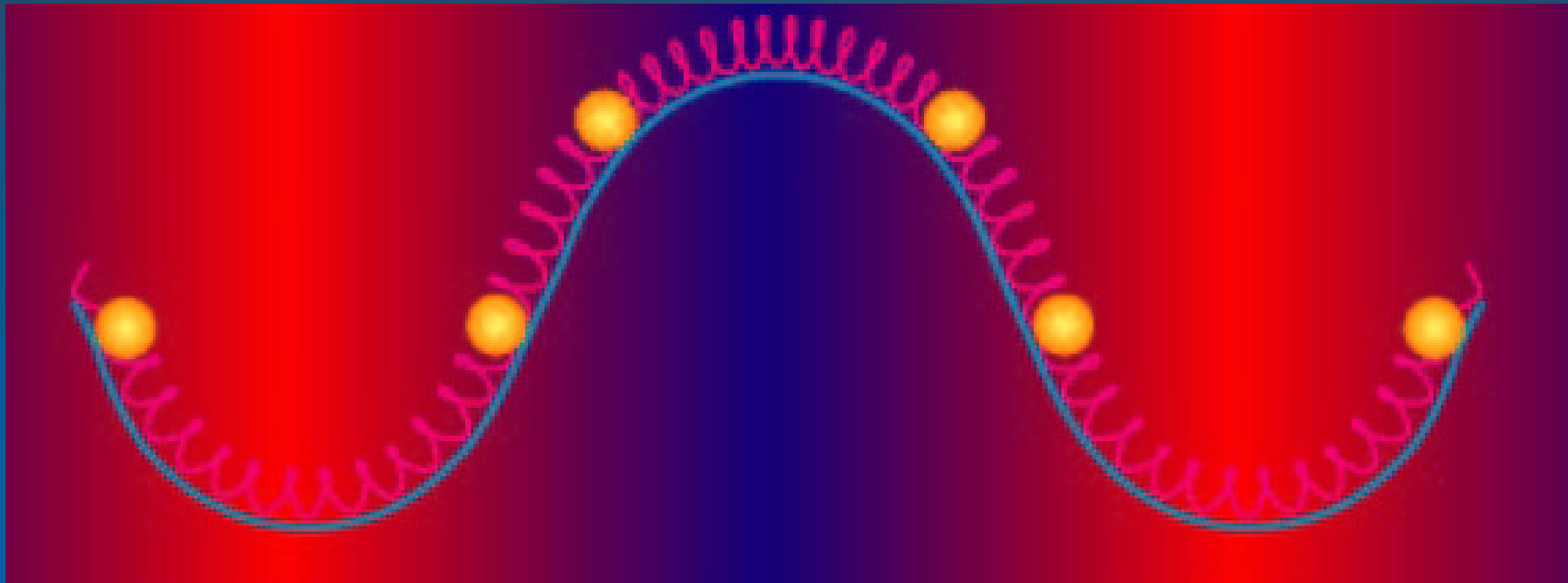
Astrophysics joins particle physics

General acceptance of the big bang model

- Until mid 60ies: big bang model very controversial, many alternative models
- After mid 60ies: little doubt on validity of the big bang model
- Four pillars on which the big bang theory is resting:
 - * Hubble's law \ddot{u}
 - * Cosmic microwave background radiation \ddot{u}
 - * **The origin of the elements**
 - * Structure formation in the universe

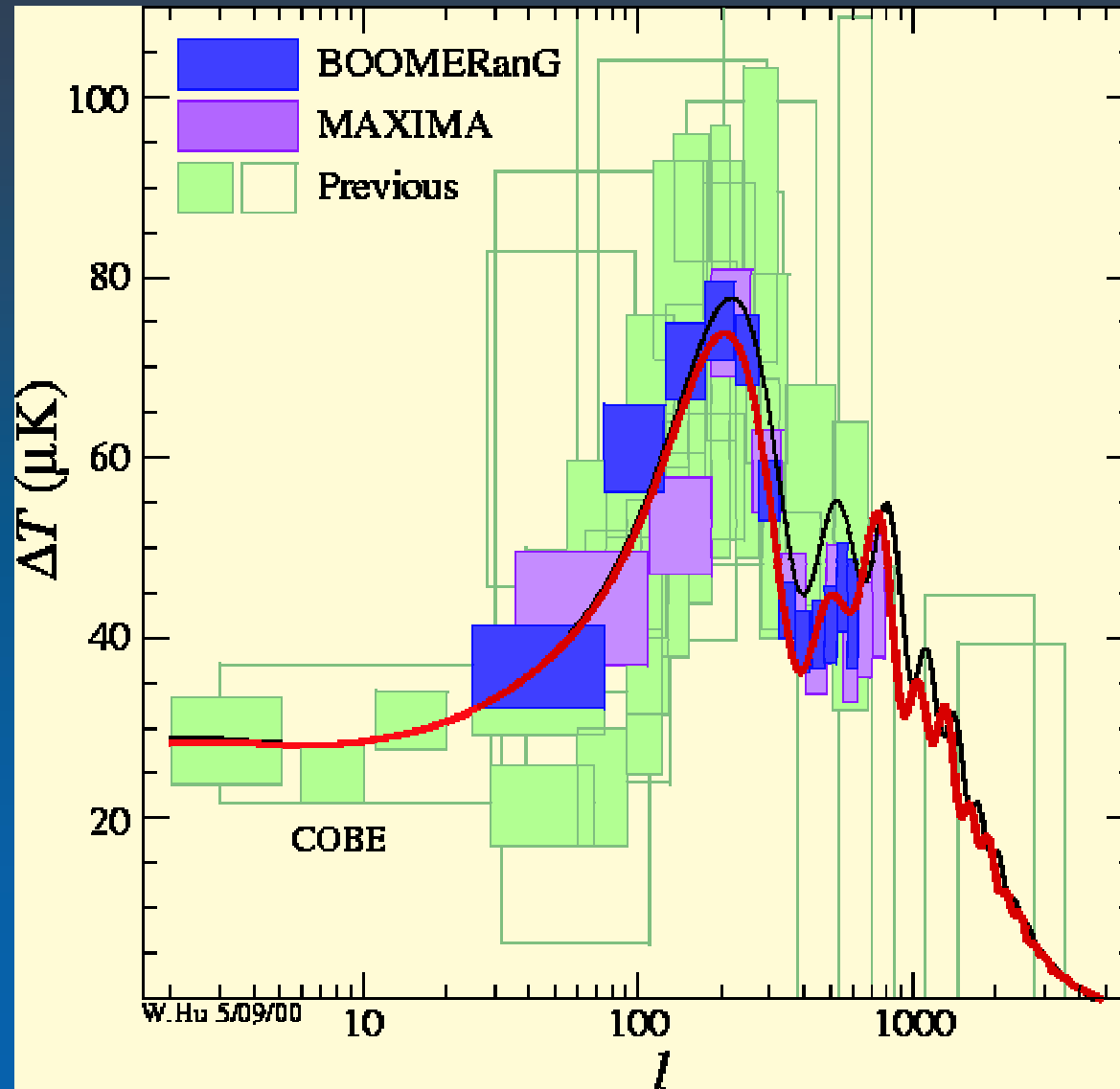
Can we see the sound of the universe ?

- Compressed gas heats up

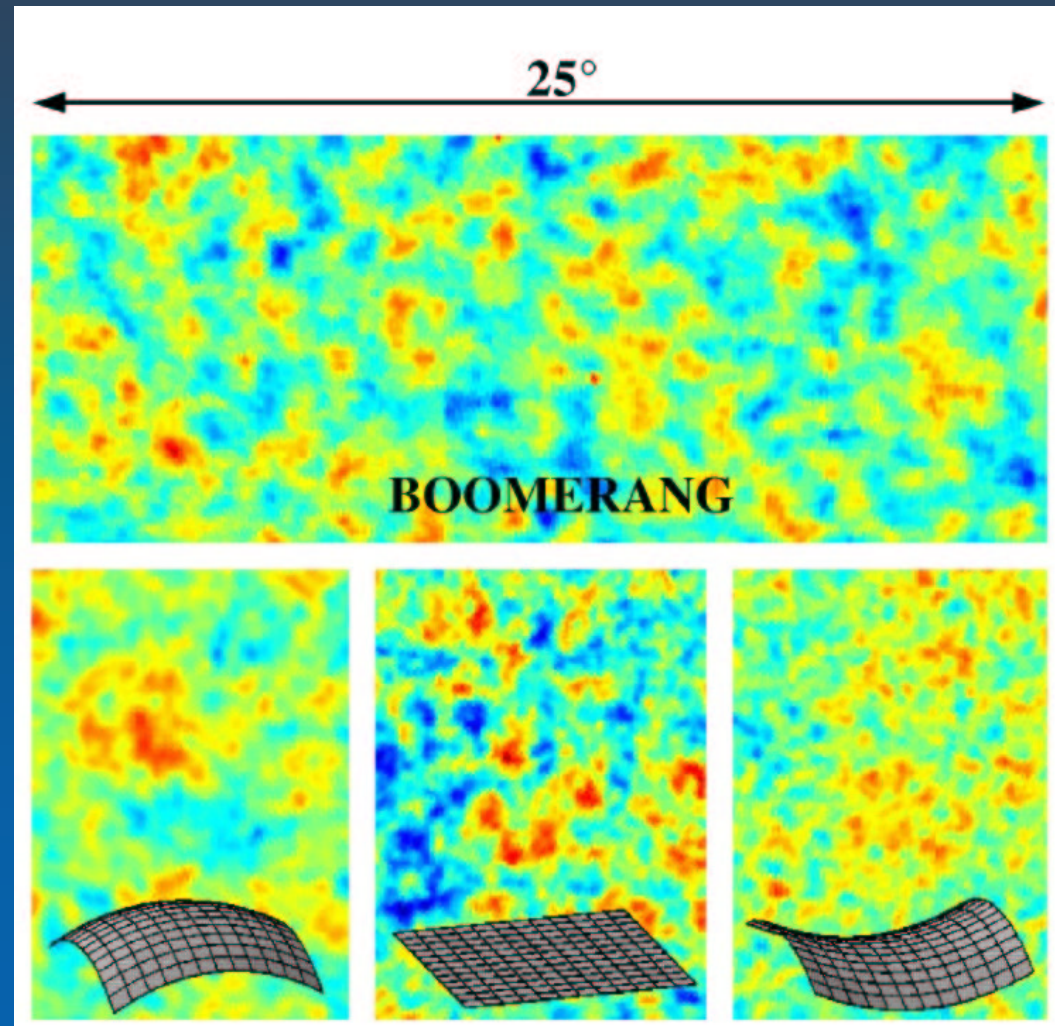


⇒ temperature fluctuations

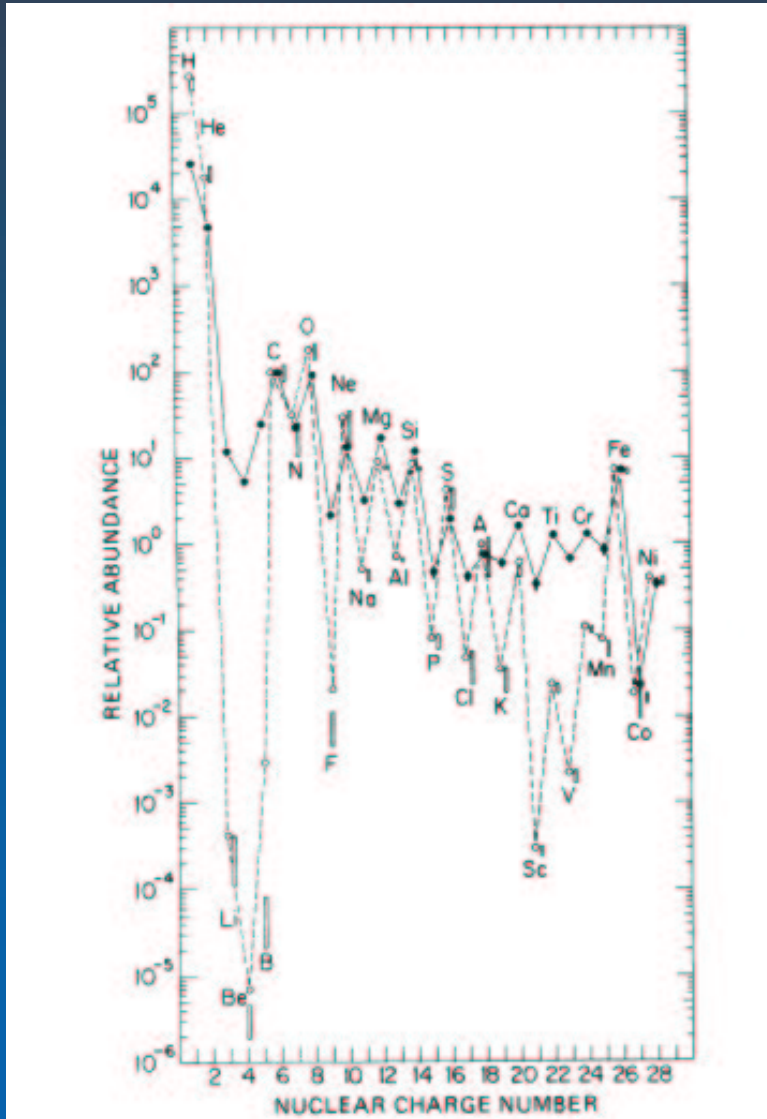
The Music of the Universe



Measuring the Curvature of the Universe Using the CMB



Abundance of elements



- Hydrogen and helium most abundant
- gap around Li, Be, B

The structure of matter

Periodic Table of the Elements

1 H																	2 He		
3 Li	Be											B	C	N	O	F	Ne		
11 Na	Mg	III B	IV B	V B	VI B	VII B	— VII —					IB	IB	Al	Si	P	S	Cl	Ar
19 K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
37 Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe		
55 Cs	Ba	* La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn		
87 Fr	Ra	+ Ac	Rf	Ha	106	107	108	109	110	111	112								

Naming conventions of new elements

* Lanthanide Series

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
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+ Actinide Series

90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr
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Nomenclature



- Z: number of protons
- A: number of nucleons (protons and neutrons)
- N: number of neutrons (=A-Z)
- X: name of the element

Transforming hydrogen into helium

- Hot big bang: neutrons and protons
- Use a multi step procedure:
 - * $p + n \rightarrow {}^2\text{H}$
 - * $p + {}^2\text{H} \rightarrow {}^3\text{He}$
 - * $n + {}^2\text{H} \rightarrow {}^3\text{H}$
 - * ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2 p$
- some side reactions:
 - * ${}^3\text{He} + {}^3\text{H} \rightarrow {}^7\text{Li}$
 - * ${}^3\text{He} + {}^3\text{He} \rightarrow {}^7\text{Be}$

Mass gap/stability gap at $A=5$ and 8

- Reaction chain:



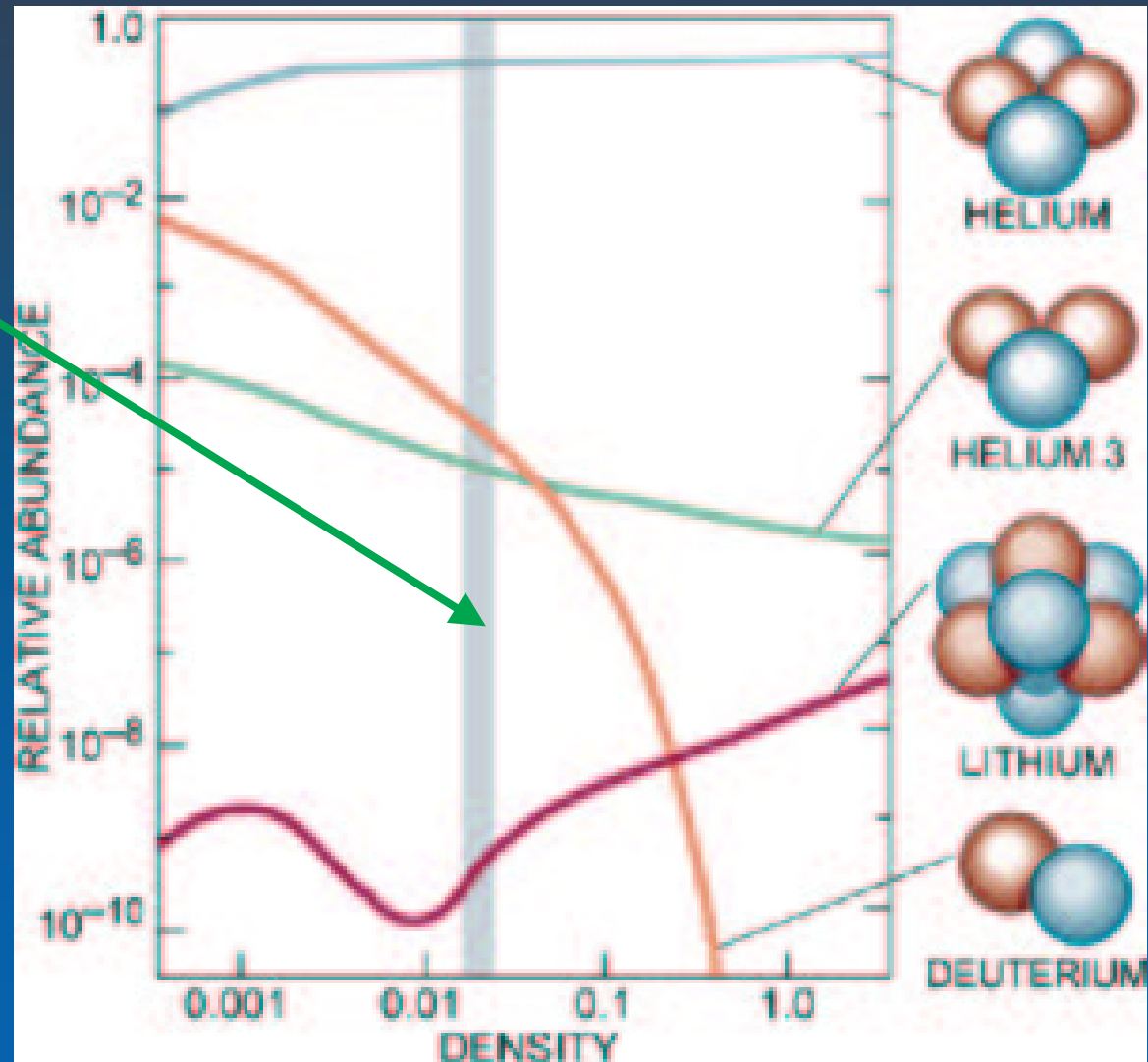
- so-called 3-body reaction
- in order to have 3-body reactions, high particle densities are required
 - * densities are not high enough in the big-bang
 - * but they are in the center of evolved stars
- **Conclusion: big bang synthesizes elements up to ${}^7\text{Li}$. Higher elements are formed in stars**

Primordial nucleosynthesis

Consistent with
abundance
of H, He and Li

Result:

- abundance of H, He and Li is consistent
- but: $\Omega_b \sim 0.04$



Can we understand why 25% He?

- Before the universe cooled sufficiently to allow nucleons to assemble into helium, the neutron to proton ratio was 1:7
- ${}^4\text{He}$: equal number of protons and neutrons
- Assume that all neutrons grab a proton to form a ${}^4\text{He}$. The left over protons form hydrogen.

Can we understand why 25% He?

- Abundance of hydrogen

$$X_H = \frac{n - 2 * n_n}{n} = \frac{n_p - n_n}{n_p + n_n} = \frac{1 - n_n / n_p}{1 + n_n / n_p} = \frac{6/7}{8/7} = 0.75$$

- Abundance of helium: $1 - 0.75 = 0.25$
- but why is $n_n / n_p = 1/7$?

The four forces of nature

- Gravity
 - * weak, long ranged
- electromagnetism
 - * intermediate, long ranged
- strong nuclear force
 - * strong, short ranged
- weak nuclear force
 - * weak, short ranged

The weak nuclear force

- Free neutrons decay into protons



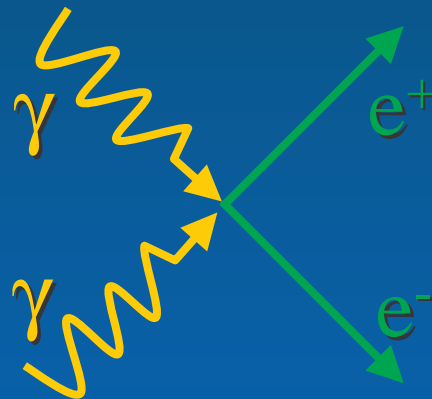
- n : neutron
 - p⁺ : proton
 - e⁻ : electron
 - ν : neutrino
 - half life time: 10 min
- } Baryons ⊂ Hadrons
- } Leptons

What happened when the universe was even younger?

- Recall special relativity: $E=mc^2$
- If the thermal energy exceeds twice the rest mass energy of a particle, particle-antiparticle pairs can be created
⇒ **Pair creation**
- **Matter:** protons, neutrons, electrons, neutrinos
- **Antimatter:** antiprotons, antineutrons, positrons, antineutrino

Pair creation

- Antiparticle: same mass as particle, but opposite charge.
- Antimatter has positive mass !!!!!



- The inverse process is called annihilation

Examples

- $T > 10^{10}$ K: creation/annihilation of electron-positron pairs
- $T > 10^{13}$ K: creation/annihilation of proton-antiproton pairs

A common theme ...

- For each reaction there is a temperature T_c :
 - * For temperature larger than T_c , there is a continuous transformation between photons into particle-antiparticle pairs and vice versa
 - * This state is called **thermal equilibrium**
 - * If the temperature drops below the threshold temperature T_c , pair creation **freezes out**, remaining pairs annihilate.



The History of the Universe

Matter era

- The energy of matter is nowadays ~ 10000 times higher than that of radiation
- but temperature rises like $(1+z)$
- $2.7\text{K} < T < 10000\text{K}$: matter era
- dominate particles (in order of decreasing contribution):
 - * baryons, photons, neutrinos
- dominant forces:
 - * gravity

Radiation era

- As the temperature exceeds $\sim 10000\text{K}$, radiation starts dominating
- $10000\text{K} < T < 10^{10}\text{K}$: radiation era
- dominate particles (in order of decreasing contribution):
 - * photons, neutrinos, baryons
- dominant forces:
 - * electromagnetism, gravity

Electron-positron annihilation

- As the temperature exceeds $\sim 10^{10}\text{K}$, creation of electron-positron pairs
 - * $T > 10^{10}\text{K}$: equilibrium between electron-positron pair creation and annihilation
 - * $T < 10^{10}\text{K}$: freeze-out. Remaining pairs annihilate

Lepton era

- $10^{10}\text{K} < T < 10^{12}\text{K}$
- dominate particles (in order of decreasing contribution):
 - * electrons, positrons, photons, neutrinos, antineutrinos, baryons
- dominant forces:
 - * electromagnetism, weak nuclear, gravity

Hadron annihilation

- As the temperature exceeds $\sim 10^{12}\text{K}$, creation of hadron-antihadron pairs (e.g. proton-antiproton)
 - * $T > 10^{12}\text{K}$: equilibrium between hadron pair creation and annihilation
 - * $T < 10^{12}\text{K}$: freeze-out. Remaining pairs annihilate

Hadron era

- $10^{12}\text{K} < T < 10^{13}\text{K}$
- dominate particles (in order of decreasing contribution):
 - * baryons+antiparticles, mesons+antiparticles, electrons, positrons, photons, neutrinos, antineutrinos
- dominant forces:
 - * electromagnetism, strong nuclear, weak nuclear, gravity

Still quark era

- $10^{13}\text{K} < T < 10^{15}\text{K}$
- hadrons (baryons, mesons) break into quarks
- dominate particles (in order of decreasing contribution):
 - * quarks, antiquarks, electrons, positrons, photons, neutrinos, antineutrinos
- dominant forces:
 - * electromagnetism, strong nuclear, weak nuclear, gravity

Electroweak phase transition

- As the temperature exceeds $\sim 10^{15}\text{K}$, electromagnetism and weak nuclear force join to form the electroweak force
 - * $T > 10^{15}\text{K}$: electroweak force
 - * $T < 10^{15}\text{K}$: electromagnetism, weak nuclear force
- Limit of what we can test in particle accelerators.
- Nobel prizes 1979 (theory) and 1984 (experiment)

Quark era

- $10^{15}\text{K} < T < 10^{29}\text{K}$
- dominate particles (in order of decreasing contribution):
 - * quarks, antiquarks, electrons, positrons, photons, neutrinos, antineutrinos
- dominant forces:
 - * electroweak, strong nuclear, gravity

GUT phase transition

- As the temperature exceeds $\sim 10^{29}\text{K}$, electroweak force and strong nuclear force join to form the GUT (grand unified theories)
 - * $T > 10^{29}\text{K}$: GUT
 - * $T < 10^{29}\text{K}$: electroweak force, strong nuclear force
- relatively solid theoretical framework (but may be wrong), but pretty much no constraint by experiments

GUT era

- $10^{29}\text{K} < T < 10^{32}\text{K}$
- dominate particles (in order of decreasing contribution:
 - * Zillions of particles, most of them not detected yet
- dominant forces:
 - * GUT, gravity

Planck epoch

- $T > 10^{32}\text{K}$ unification of GUT and gravity
- Particles:
 - * ???
- Forces:
 - * TOE (theory of everything)
- The last frontier ...