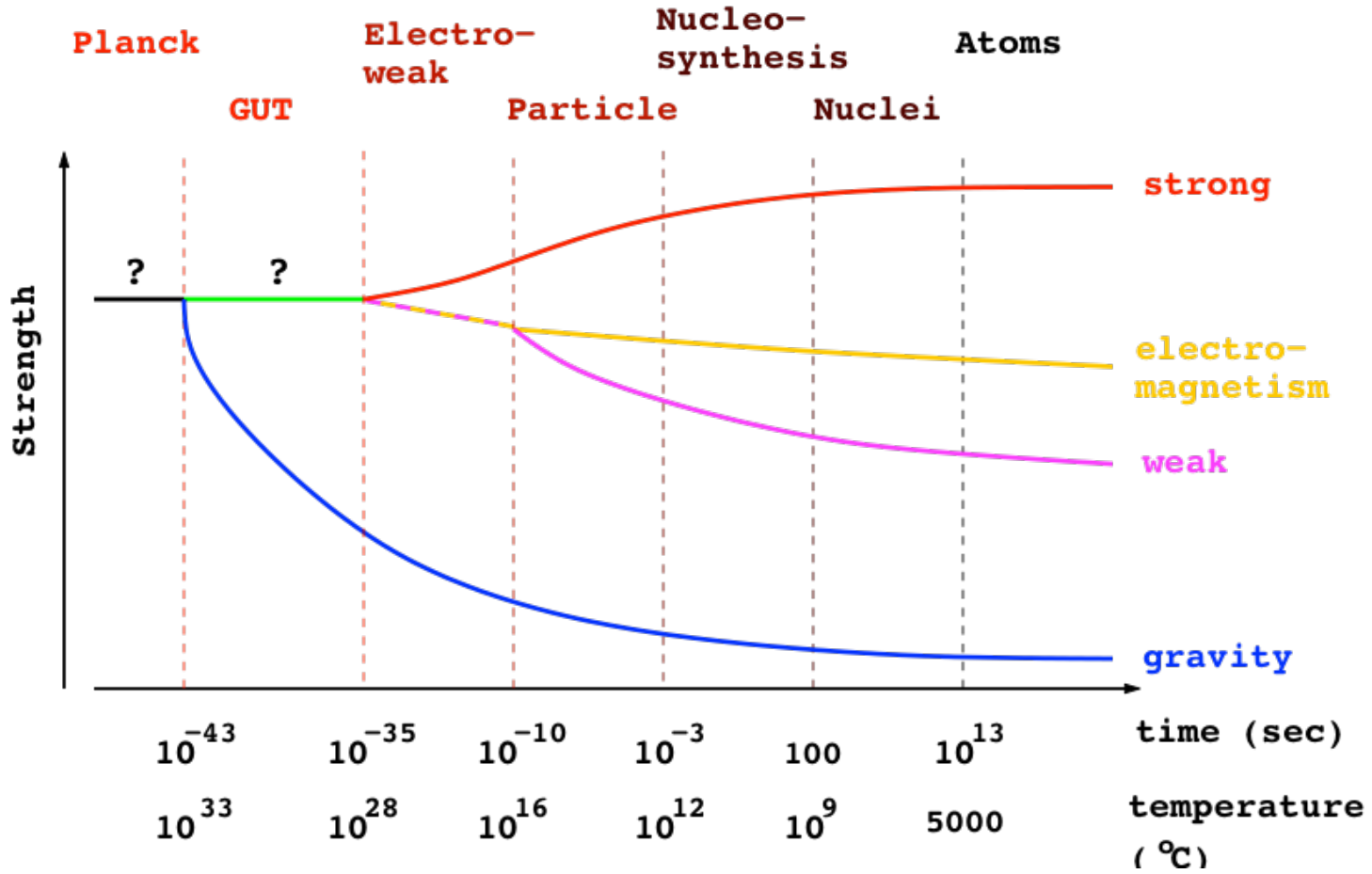
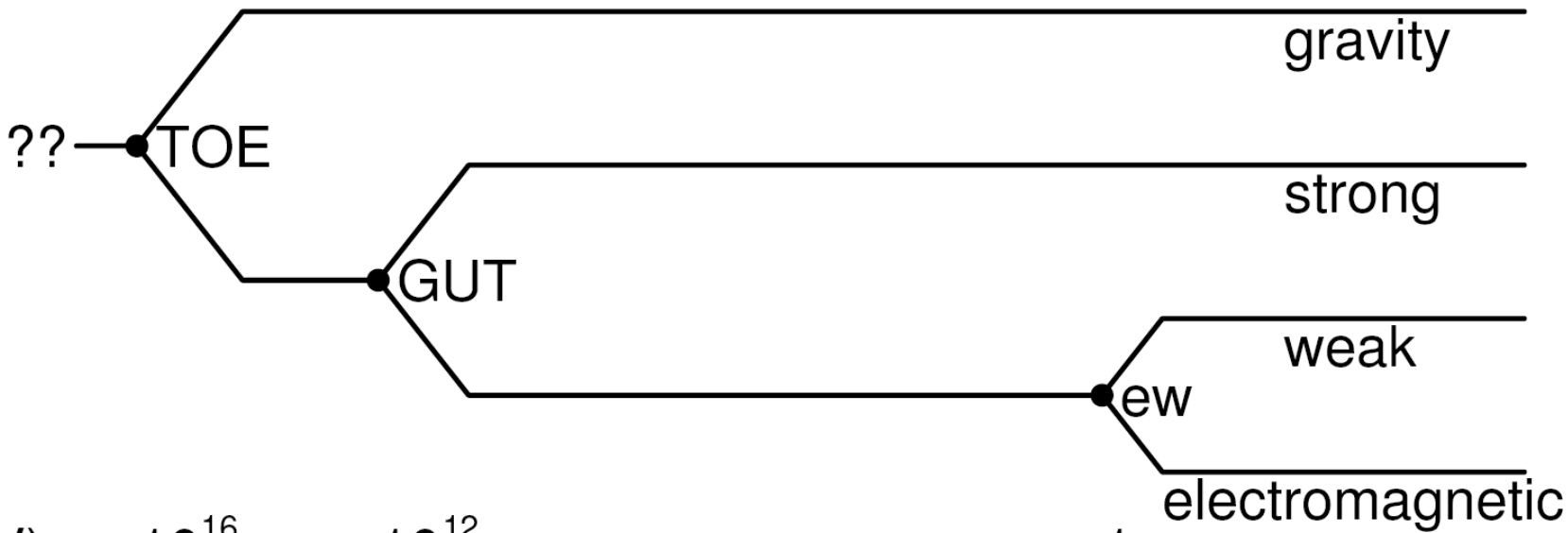
The Very Early Universe

Physical Interactions in the Early Universe

As we get closer to $t \to 0$ and $T \to \infty$, we probe physical regimes in which different fundamental interactions dominate. Their strength is a function of energy, and at sufficiently high energies they become unified



The Grand Unification



E (TeV)	10^{16}	10^{12}	1
T (K)	10^{32}	10^{28}	10^{16}
t (sec)	10^{-43}	10^{-36}	10^{-12}

Each of the unifications (or, moving forward in time, spontaneous symmetry breakings) is effectively a phase transition in the early universe, as the dominant energy carriers change

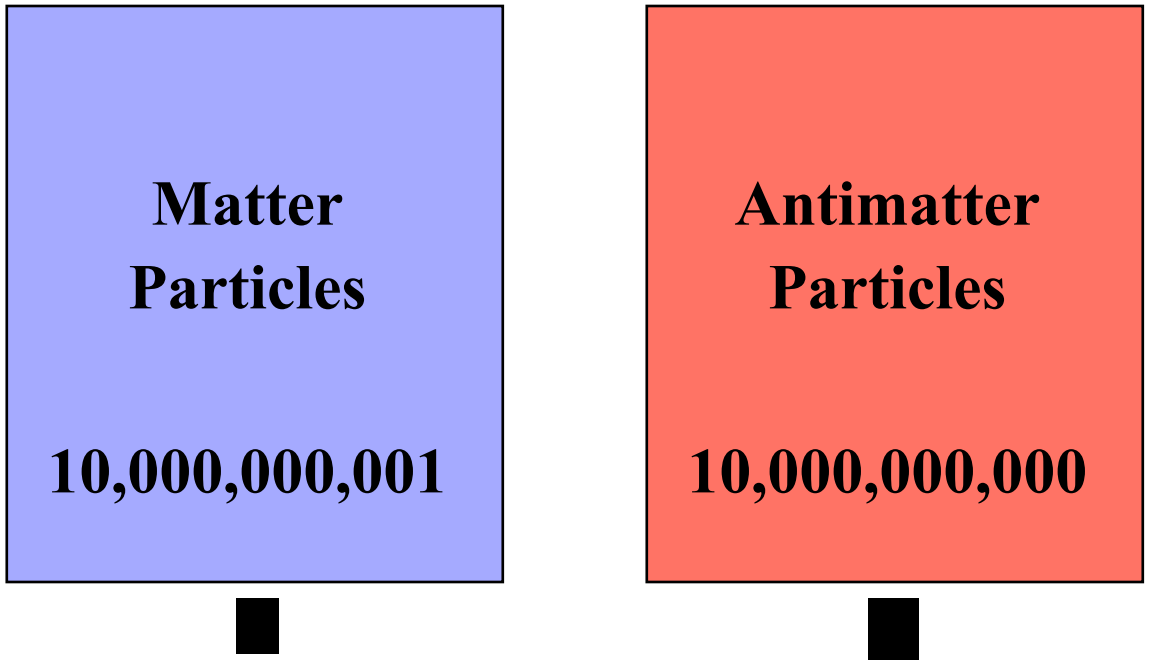
The Electroweak Era: up to 10^{-10} sec

- At $T \sim 10^{28}$ K, three distinct forces in the universe: Gravity, Strong, and **Electroweak:** unified Electromagnetism and Weak nuclear force
- At $T < 10^{15}$ K, Electromagnetism and Weak nuclear force split; this is the **Electroweak phase transition**
- Limit of what we can test in particle accelerators

The GUT Era: up to 10^{-35} sec

- At $T > 10^{29}$ K, electroweak force and strong nuclear force join to form the GUT (grand unified theory) interaction
- Relatively solid theoretical framework (but may be wrong), but not directly testable in experiments
- This **GUT phase transition** may be driving the Inflation (but there are other candidates)

Matter - Antimatter Asymmetry



They basically have all annihilated away
except a tiny difference between them

This process leads to the preponderance of photons over the leftover baryons today by the same factor …

Where does it come from?

The Cosmic Baryogenesis

- The conditions required for the creation of more matter than anti-matter were first derived by A. Sakharov in 1967:
  1. **Baryon number violation**
     - Otherwise have same no. of particles and antiparticles
     - Never been observed
     - Predicted to occur in several GUT theories
  2. **C and CP violation**
     - Parity of antiparticles is opposite to that of particles
     - CP violation discovered in 1964 (Cronin and Fitch)
  3. **Departure from non-thermal equilibrium**
     - Otherwise all reactions go both ways
     - Provided by the expansion of the universe
- Now believed to be the mechanism responsible for the matter - antimatter asymmetry

Planck Units

Proposed in 1899 by M. Planck, as the "natural" system of units based on the physical constants:

Name	Dimension	Expression	Approx. SI equivalent measure
Planck time	Time (T)	$t_P = \frac{l_P}{c} = \sqrt{\frac{\hbar G}{c^5}}$	5.39121×10^{-44} s
Planck length	Length (L)	$l_P = \sqrt{\frac{\hbar G}{c^3}}$	1.61624×10^{-35} m
Planck mass	Mass (M)	$m_P = \sqrt{\frac{\hbar c}{G}}$	2.17645×10^{-8} kg
Planck charge	Electric charge (Q)	$q_P = \sqrt{\hbar c 4\pi\epsilon_0}$	$1.8755459 \times 10^{-18}$ C
Planck temperature	Temperature (Θ)	$T_P = \frac{m_P c^2}{k} = \sqrt{\frac{\hbar c^5}{G k^2}}$	1.41679×10^{32} K

They may be indicative of the physical parameters and conditions at the era when gravity is unified with other forces … assuming that ***G***, ***c***, and ***h*** do not change … and that there are no other equally fundamental constants

"Derived" Planck Units

Name	Dimension	Expression	Approx. SI equivalent measure
Planck energy	Energy (ML^2T^{-2})	$E_P = m_P c^2 = \sqrt{\frac{\hbar c^5}{G}}$	1.9561×10^9 J
Planck force	Force (MLT^{-2})	$F_P = \frac{E_P}{l_P} = \frac{c^4}{G}$	1.21027×10^{44} N
Planck power	Power (ML^2T^{-3})	$P_P = \frac{E_P}{t_P} = \frac{c^5}{G}$	3.62831×10^{52} W
Planck density	Density (ML^{-3})	$\rho_P = \frac{m_P}{l_P^3} = \frac{c^5}{\hbar G^2}$	5.15500×10^{96} kg/m^3
Planck angular frequency	Frequency (T^{-1})	$\omega_P = \frac{1}{t_P} = \sqrt{\frac{c^5}{\hbar G}}$	1.85487×10^{43} s^{-1}
Planck pressure	Pressure ($ML^{-1}T^{-2}$)	$p_P = \frac{F_P}{l_P^2} = \frac{c^7}{\hbar G^2}$	4.63309×10^{113} Pa
Planck current	Electric current (QT^{-1})	$I_P = \frac{q_P}{t_P} = \sqrt{\frac{c^6 4\pi\epsilon_0}{G}}$	3.4789×10^{25} A
Planck voltage	Voltage ($ML^2T^{-2}Q^{-1}$)	$V_P = \frac{E_P}{q_P} = \sqrt{\frac{c^4}{G4\pi\epsilon_0}}$	1.04295×10^{27} V
Planck impedance	Resistance ($ML^2T^{-1}Q^{-2}$)	$Z_P = \frac{V_P}{I_P} = \frac{1}{4\pi\epsilon_0 c} = \frac{Z_0}{4\pi}$	2.99792458×10^1 Ω

Towards the Planck Era

"Infinity, and Beyond…"

- Probably gravity unified with the other forces - so we need a theory of Quantum Gravity
  - Characteristic time ~ Planck Time ~ 10^{-43} sec after the Big Bang
  - Size of the universe then ~ Planck Length
- *Highly Speculative* theories include
  - **M-theory** particles are excitations on high dimensional membranes (D-branes). This has taken over from(and includes)
  - **String Theory**, where particles are different vibrations of one type of strings

open string  closed string 

  - **Ekpyrotic cosmology, String Landscape, …**
- The future of fundamental physics?

Next:
The Contents of the Universe