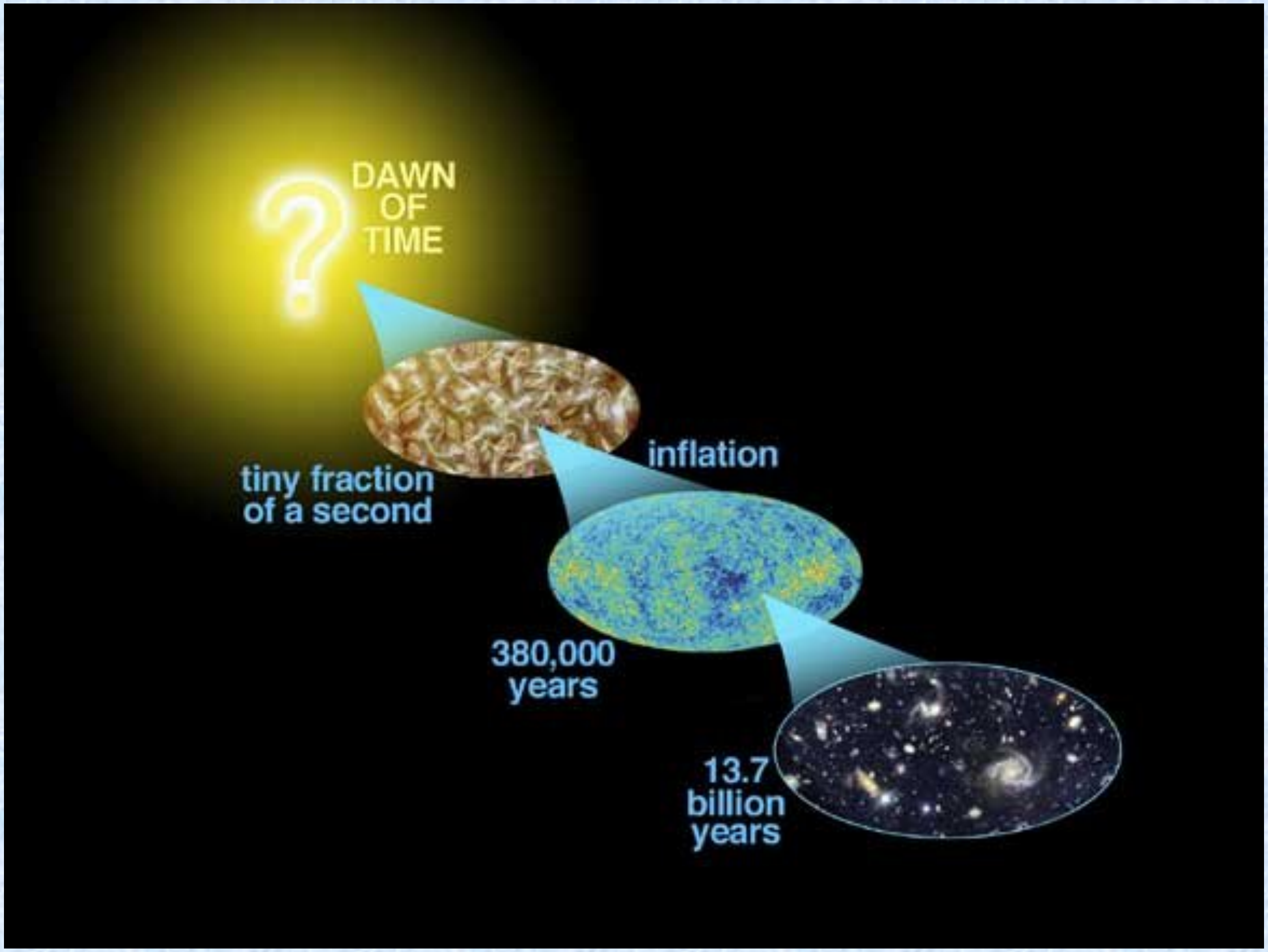
Astro-2: History of the Universe



Lecture 11; May 21 2013

Previously… on astro-2

- In an expanding universe the relationship between redshift and distance depends on the cosmological parameters (i.e. the geometry and expansion of the universe). Why?
- Every reliable standard candle or rod can provide you with an measurement of the cosmological parameters.
- The most popular at the moment are Supernovae Ia. They look dimmer than expected in the past indicating that the universe is accelerating
- This is the so called "Cosmic jerk"

Previously… on astro-2

- The volume of the universe as a function of redshift depends on the cosmological parameters, so can be used to do cosmography.
- Another approach is to measure the properties of the large scale structure of the universe and the abundance and evolution of density peaks (clusters). This is a sensitive measure of the matter density of the universe.
- These two approaches are useful but difficult to do in practice. It is important to have more than one method.

Previously… on astro-2

- CMB anisotropies are a snapshot of the universe at the last scattering surface at z~1000, when the universe was about 380,000 years old.
- Hot and cold spots in the CMB correspond to under and overdensities at that time.
- The angular distribution of CMB anisotropies conveys information about the content and geometry of the universe so that many parameters are known to a 10% or better.

Previously… on astro-2

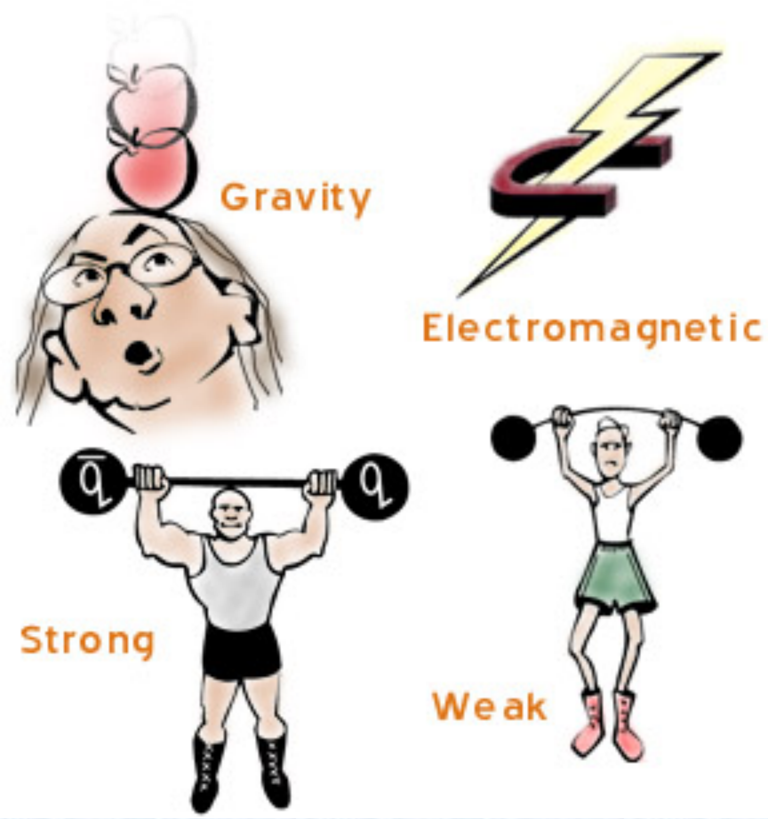
- In recent years different methods have reached an agreement over the numerical value of the cosmological parameters
- The currently preferred model is one dominated by dark energy. This is referred to as "concordance cosmology"
- It is great! Unless there is some poorly understood systematic effect at work..
- Depending on the properties of dark energy the universe could keep accelerating so fast to eventually push everything out of our horizon.

Today.. On Astro-2.

1. The early universe.
    1. Forces and unification
    2. Planck Time
2. Inflation
    1. False and true vacua
    2. Horizons and flatness problem

Forces and unification.

- In our current understanding of physics all interactions are due to 4 forces:
  1. Gravity
  2. Electromagnetic
  3. Strong Interactions
  4. Weak Interactions



Gravity

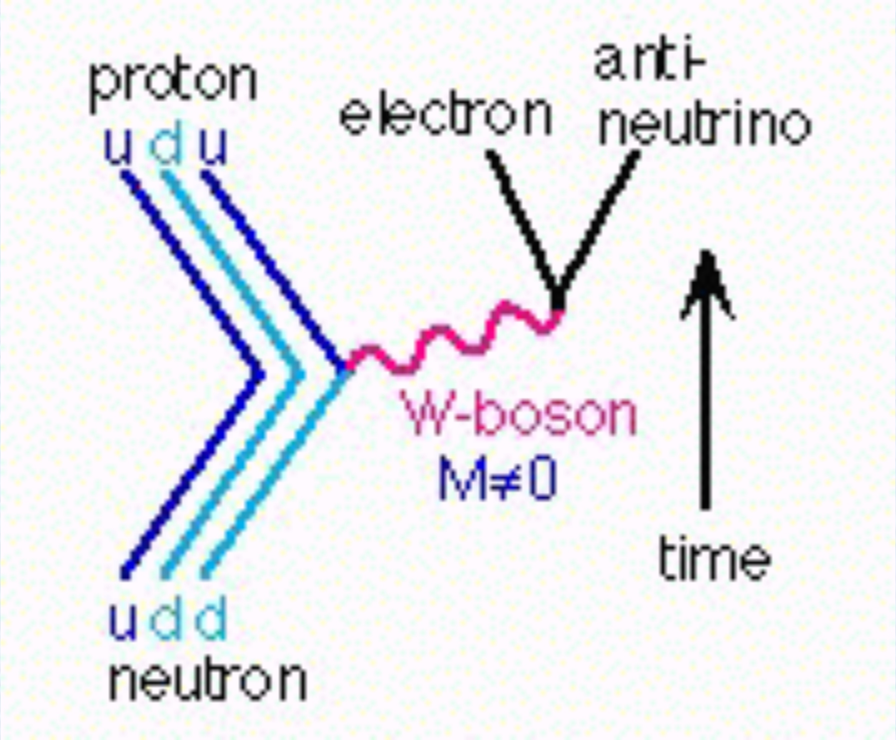
- Main properties:
  - Long range
  - Only attractive
  - Very weak force
  - Consider the ratio of the gravitational and electric attraction between a proton and an electron:
  - $FG = G\ m_p\ m_e / R^2$
  - $FEM = k\ Q^2 / R^2$
  - $FEM / FG = 10^{39}$!
  - Exchange boson: graviton
- Example of systems dominated by gravity?
  - Universe
  - Black hole

Electromagnetic force

- Main properties:
  - Long range
  - Attractive and repulsive
  - Much stronger than gravity but effectively "shielded over long distances"
  - Exchange Boson: photon
  - NB: E&M is unified description of electricity and magnetism
- Examples of systems:
  - Atoms (electrons and nuclei)
  - Electromagnetic waves: light, cell phone…

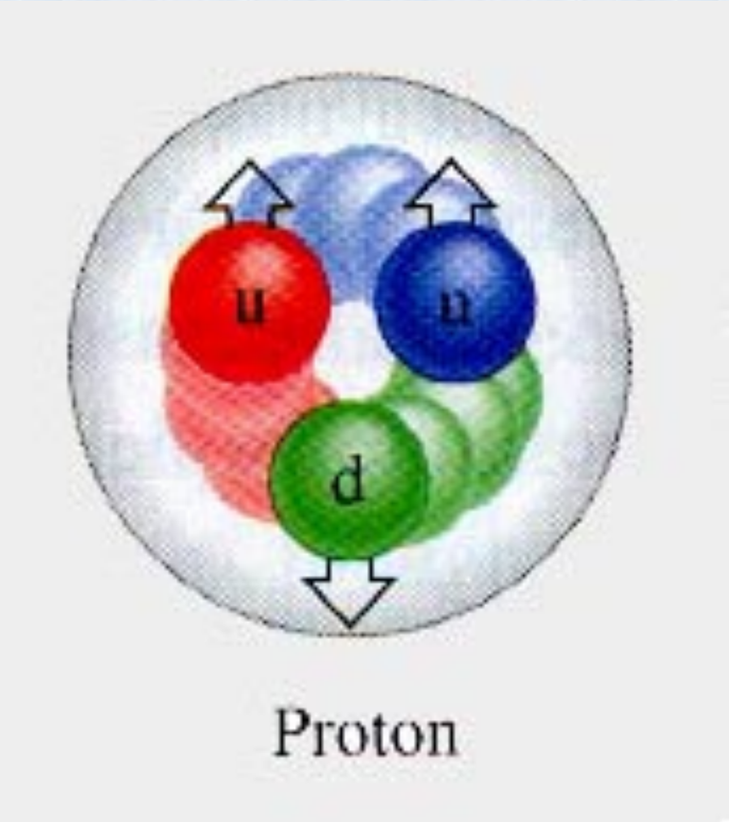
Weak force

- Main properties:
  - Short range
  - Responsible for change of flavor of quarks (e.g. neutron decaying into proton)
  - VERY WEAK!!
  - Exchange Boson: W+-, Z_0
- Examples of systems:
  - Neutrino interactions
  - Beta decays



Strong force

- Main properties:
  - Short range
  - Holds quarks (and nuclei) together
  - VERY STRONG!!! (keeps protons together even though they have the same electric charge)
  - Exchange Boson: gluons
- Examples of systems:
  - Nuclei of atoms



Four forces, or one?

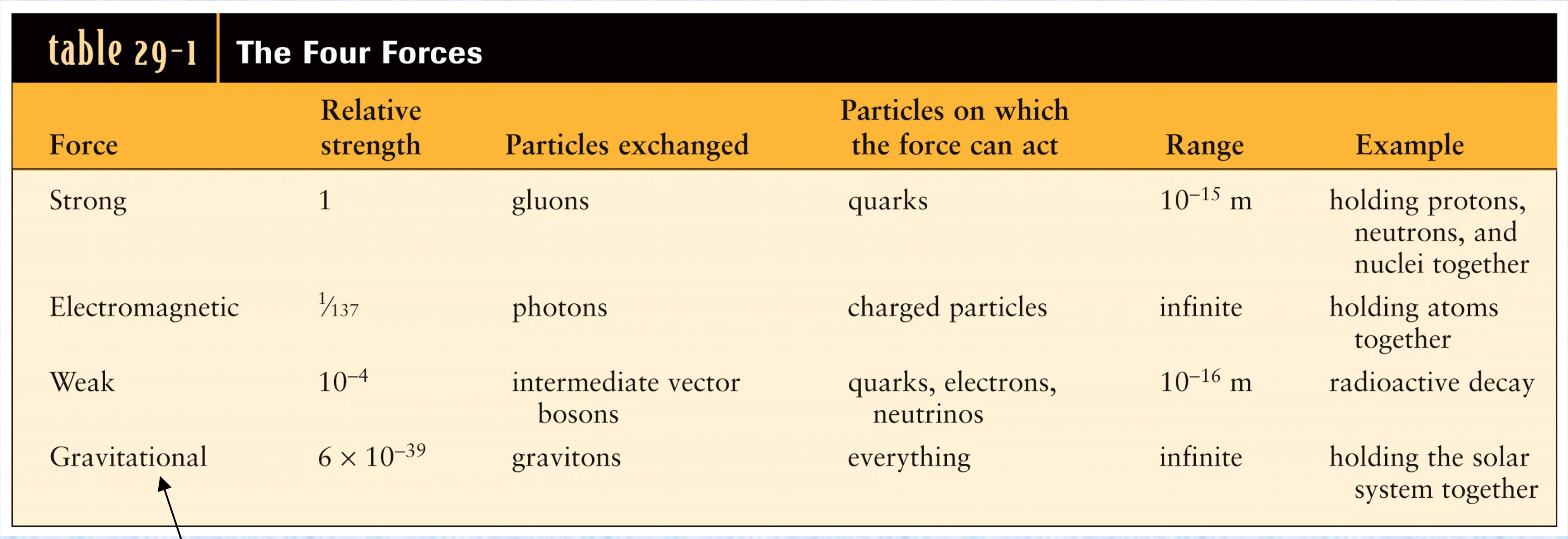


table 29-1 **The Four Forces**

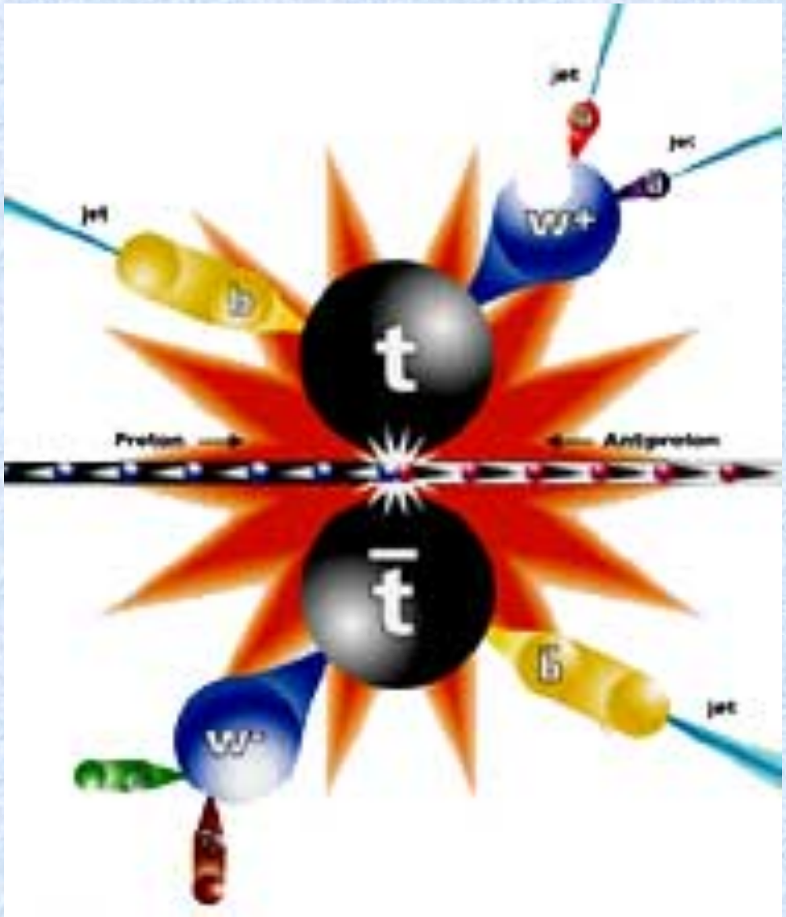
Force	Relative strength	Particles exchanged	Particles on which the force can act	Range	Example
Strong	1	gluons	quarks	10^{-15} m	holding protons, neutrons, and nuclei together
Electromagnetic	$\frac{1}{137}$	photons	charged particles	infinite	holding atoms together
Weak	10^{-4}	intermediate vector bosons	quarks, electrons, neutrinos	10^{-16} m	radioactive decay
Gravitational	6×10^{-39}	gravitons	everything	infinite	holding the solar system together

Not quantized

Force unification

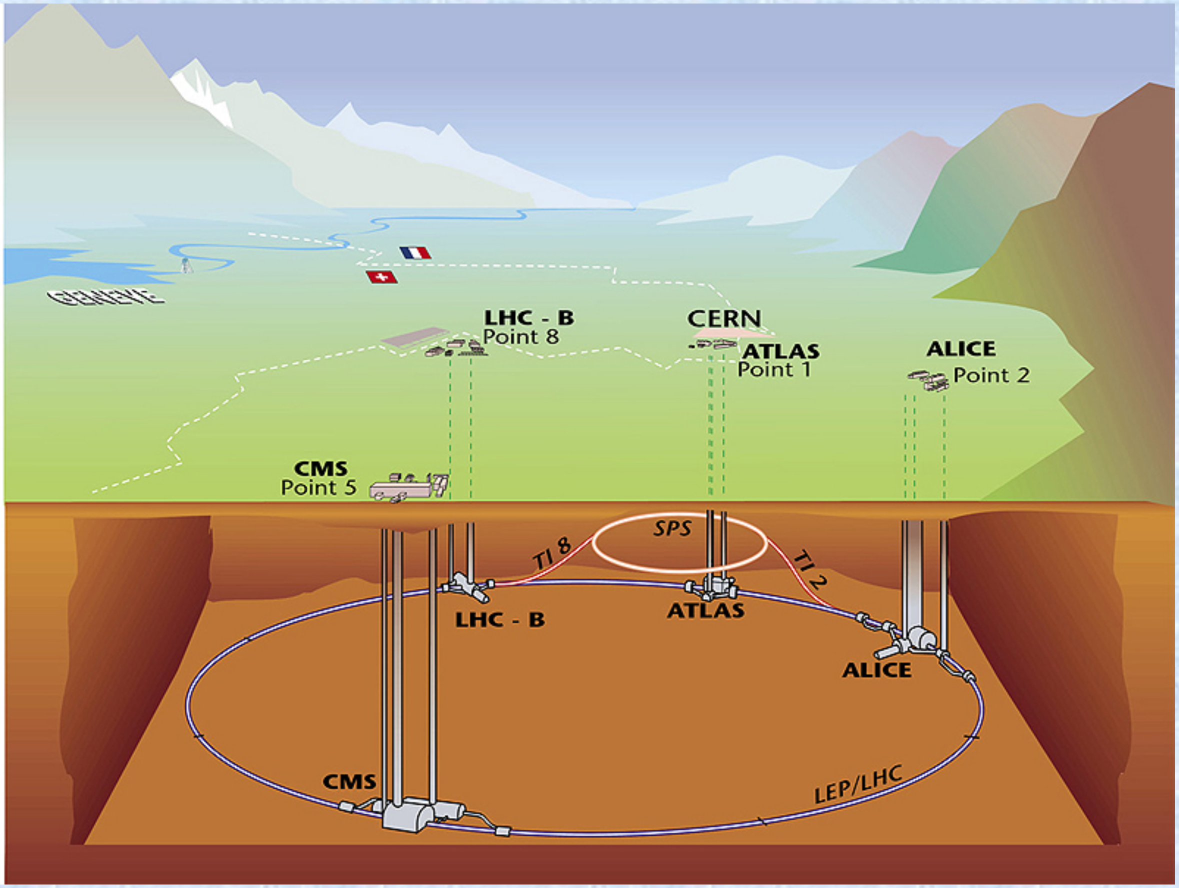
- Physics is reductionist, i.e. wants to explain complexity with simple laws
- One of the major goals is to find a unified description of all forces (called supergrand unified theories). The four forces are just manifestations of what is called “spontaneous symmetry breaking” at low energies
- So far, physicist have successfully unified weak and electromagnetic interactions (electroweak interaction), confirmed experimentally
- Strong forces are also predicted to be indistinguishable from electroweak interactions at VERY high energies. This is called grand unified theory.
- The dream is to unify gravity as well. It is a matter of energy

Energy is the name of the game…



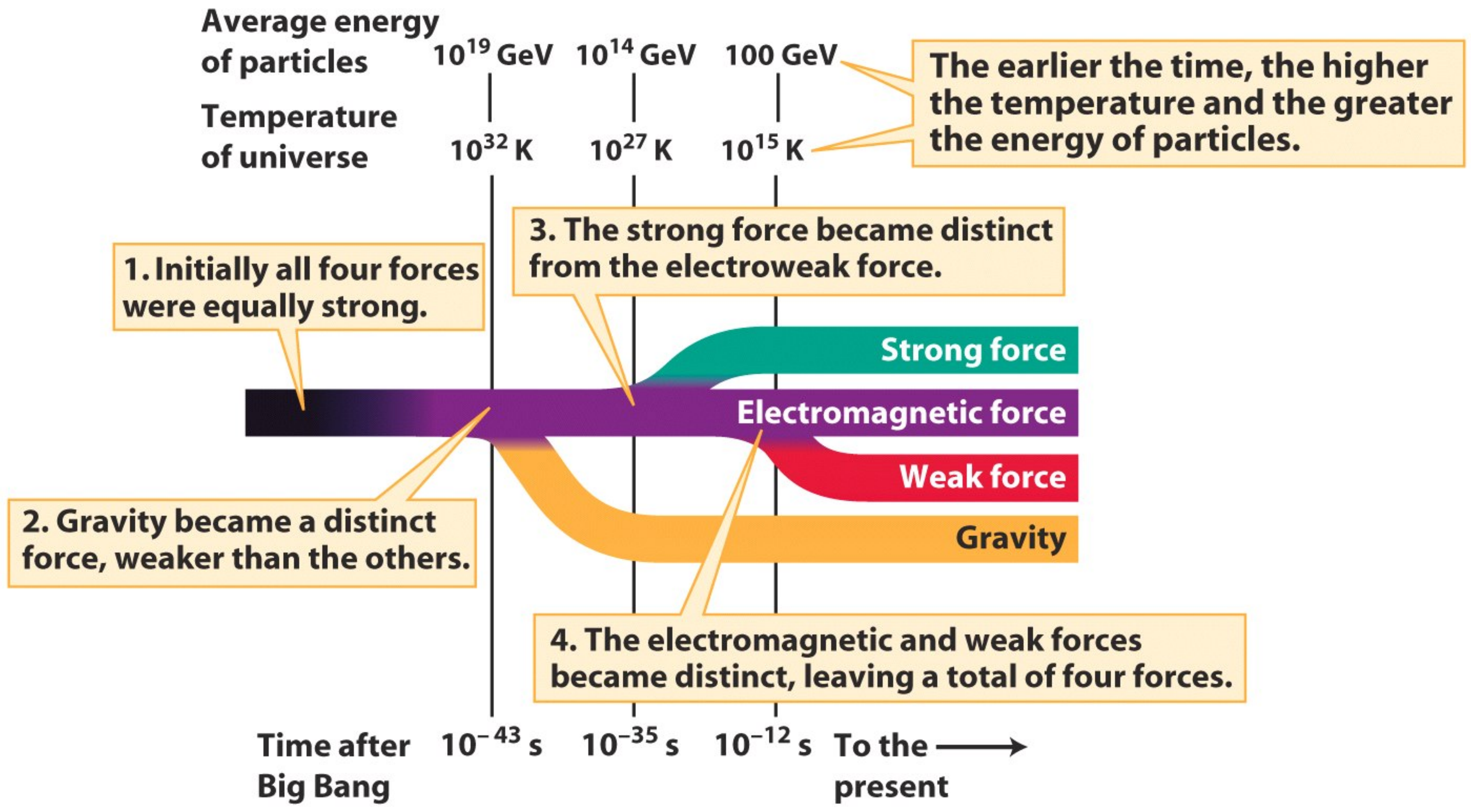
Weak and EM interactions unify at 100 Gev. Strong above 10^{14} Gev

On Earth: particle accelerators



LHC (Large Hadron Collider) is the most powerful accelerator.
Starting soon will accelerate protons to 7 TeV = 7,000 GeV

The universe is the most powerful accelerator!!



The earlier the time, the higher the temperature and the greater the energy of particles.

1. Initially all four forces were equally strong.

2. Gravity became a distinct force, weaker than the others.

3. The strong force became distinct from the electroweak force.

4. The electromagnetic and weak forces became distinct, leaving a total of four forces.

Plank Time ~ $t_p=\surd Gh/c5=1.35e\text{-}43\mathrm{s}$

The very early Universe. Summary

- The four fundamental interactions are?
- Strong, weak, electromagnetic and gravity.
- We think they are unified at high energies, like those in the very early universe
- Before Planck time (which is?) energies were so high that a unified theory of all forces (including gravity) is required but we do not know how to do that.
- So our description can only begin from Planck time
- After that, as the universe expanded “cooled” the various forces froze out via spontaneous symmetry breaking

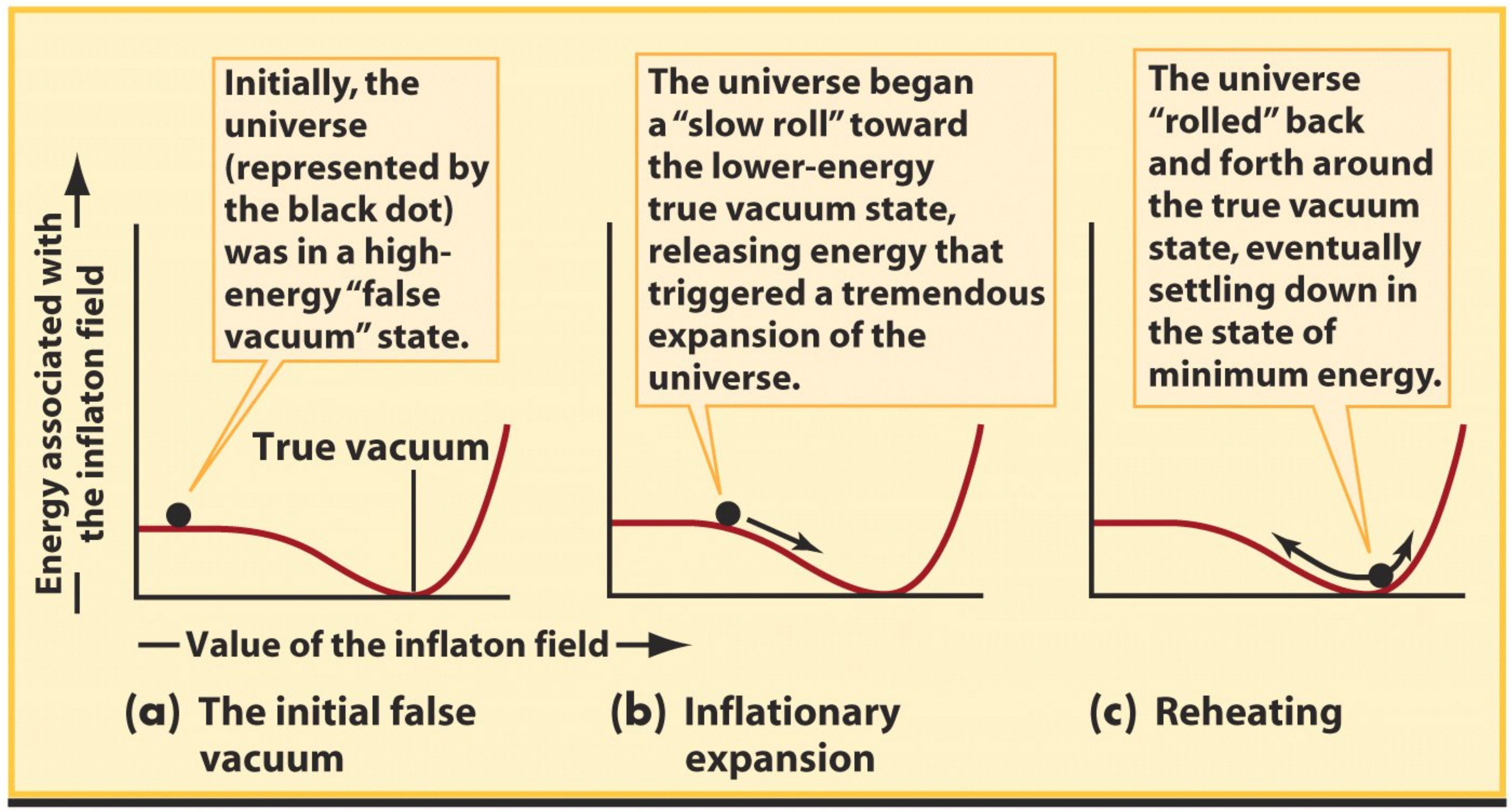
Inflation. True and false vacua

- At about ~10^{-36} s after the Big Bang symmetry broke and strong and electroweak forces separated.
- A quantity called the inflaton field (similar to the Earth's magnetic field in some sense) found itself in a position of false vacuum, i.e. in a state that looked like a minimum but was not a minimum of energy

Inflation. The inflaton rolls down

- The inflaton wants to roll down to its true vacuum, i.e. the energy minimum
- While you roll down you release energy (the guy in the ball is speeding up!) by transforming potential energy into kinetic energy

Inflation. The inflaton rolls down



(a) The initial false vacuum

(b) Inflationary expansion

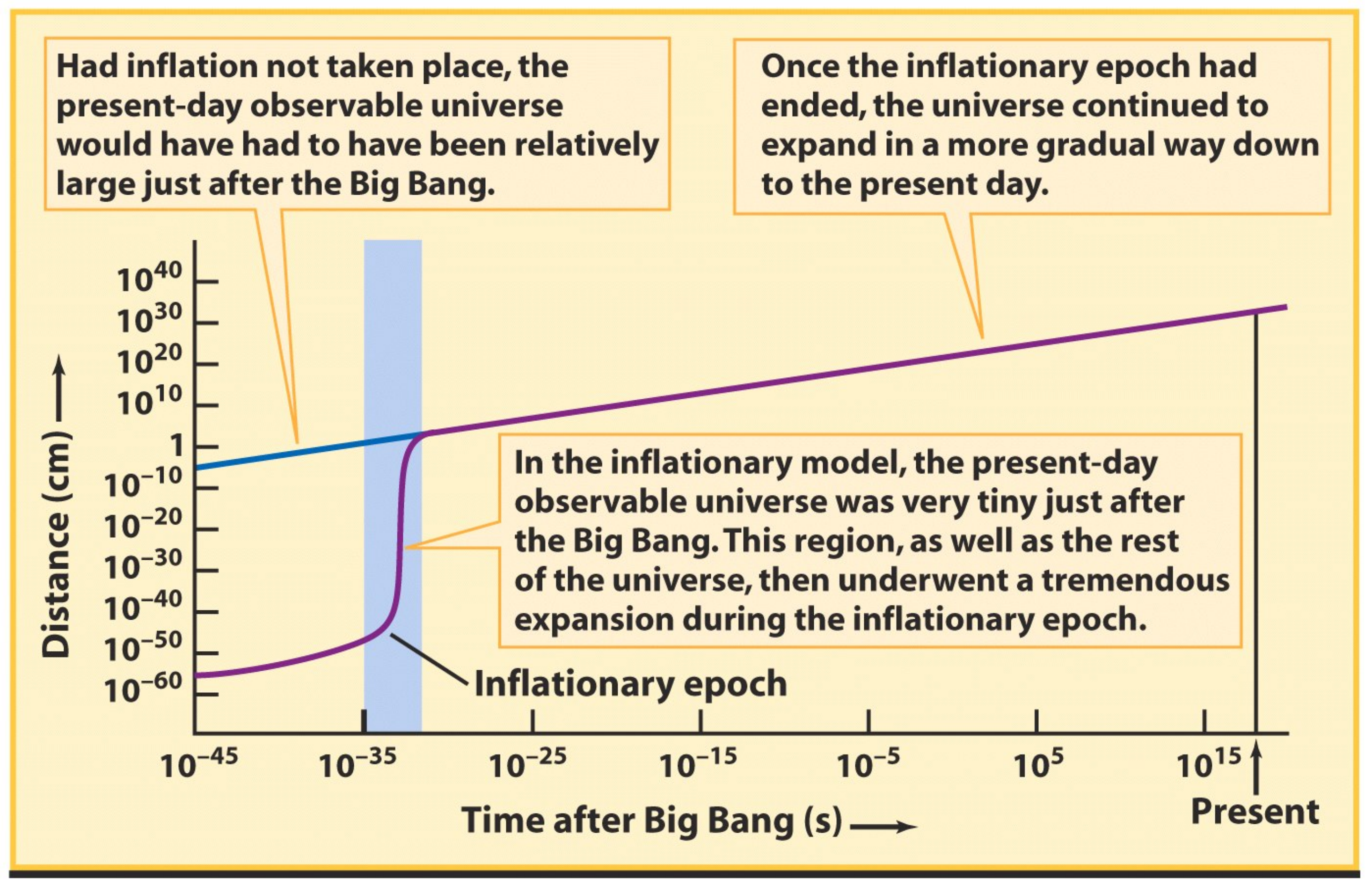
(c) Reheating

The same thing happens for the inflaton!

As the inflaton rolls down the universe expands very fast (inflates)!

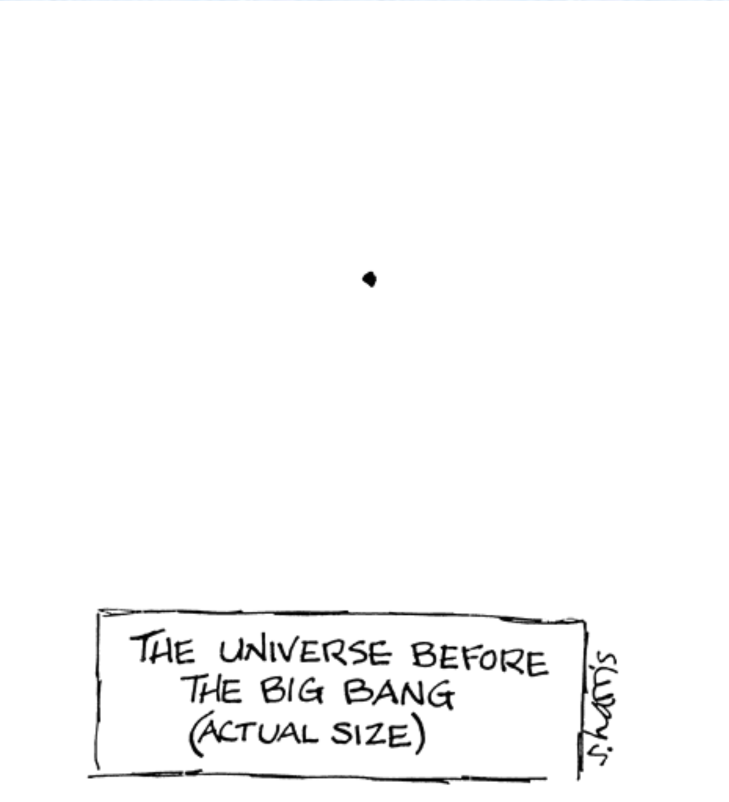
- As the universe rolls down it releases huge amounts of energy that make it expand dramatically
- This period is called inflation
- The size of the universe grows exponentially as $a \sim e^{Ht}$ where H is the "Hubble constant" at that time.
- In just 10^{-32} s the universe expands by a factor of 10^{50}

Inflation. The universe expands fast!



The period of ultra-rapid expansion means that our present day horizon was tiny before inflation. There could be a lot of “bubbles”!

Inflation. Faster than the horizons!



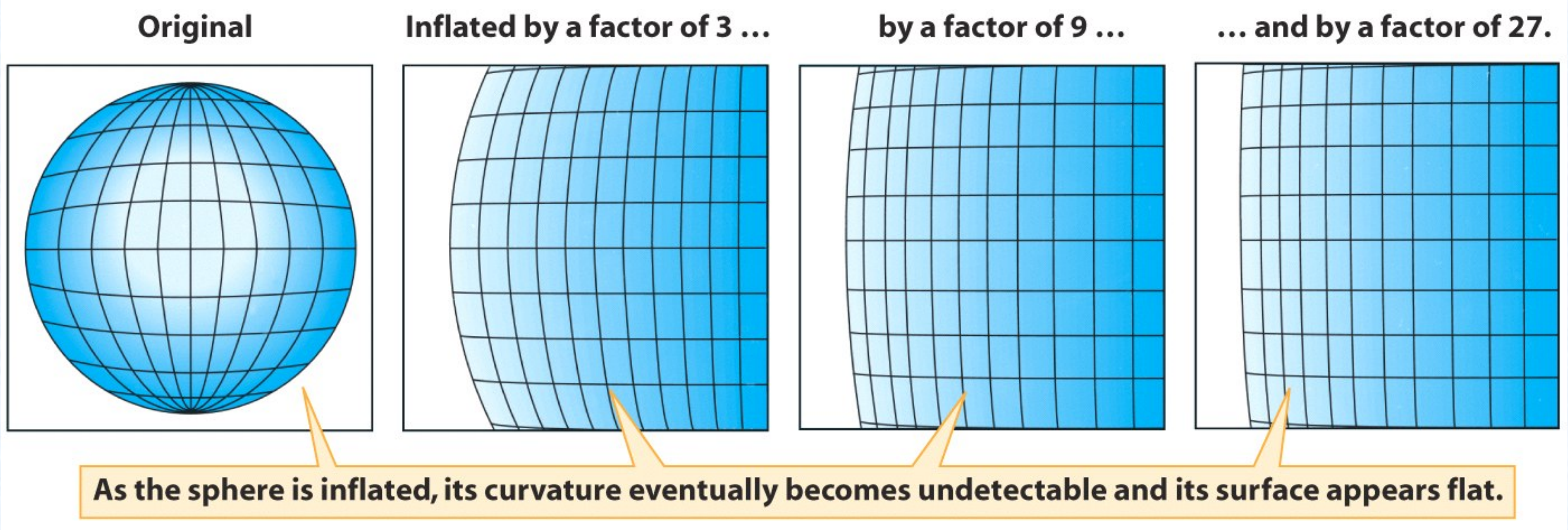
This is very important!!!

Before inflation the universe was small enough to have been in causal contact. This solves the horizon problem of classic Big Bang!

Inflation. What happens to the temperature?

- Inflation expands space so much that the temperature of the universe cools down to about 3K at the end of inflation
- Is this good?
- No, it' s way too cold
- But at the end of this phase transition there is a bunch of latent heat released by the inflaton field that heats it back to the right temperature, about 10^{27} K
- It' s similar to boiling water that it doesn' t change temperature while it evaporates…

Inflation. A prediction



As space inflates the universe becomes flatter. Inflation predicts that the universe should be close to “flat” at present time.

Inflation. A prediction

Pretty much like a basketball court… the players don’t realize it is curved because the radius of curvature of the Earth is so big!!

Inflation. Observations of flatness agree with the prediction!!!

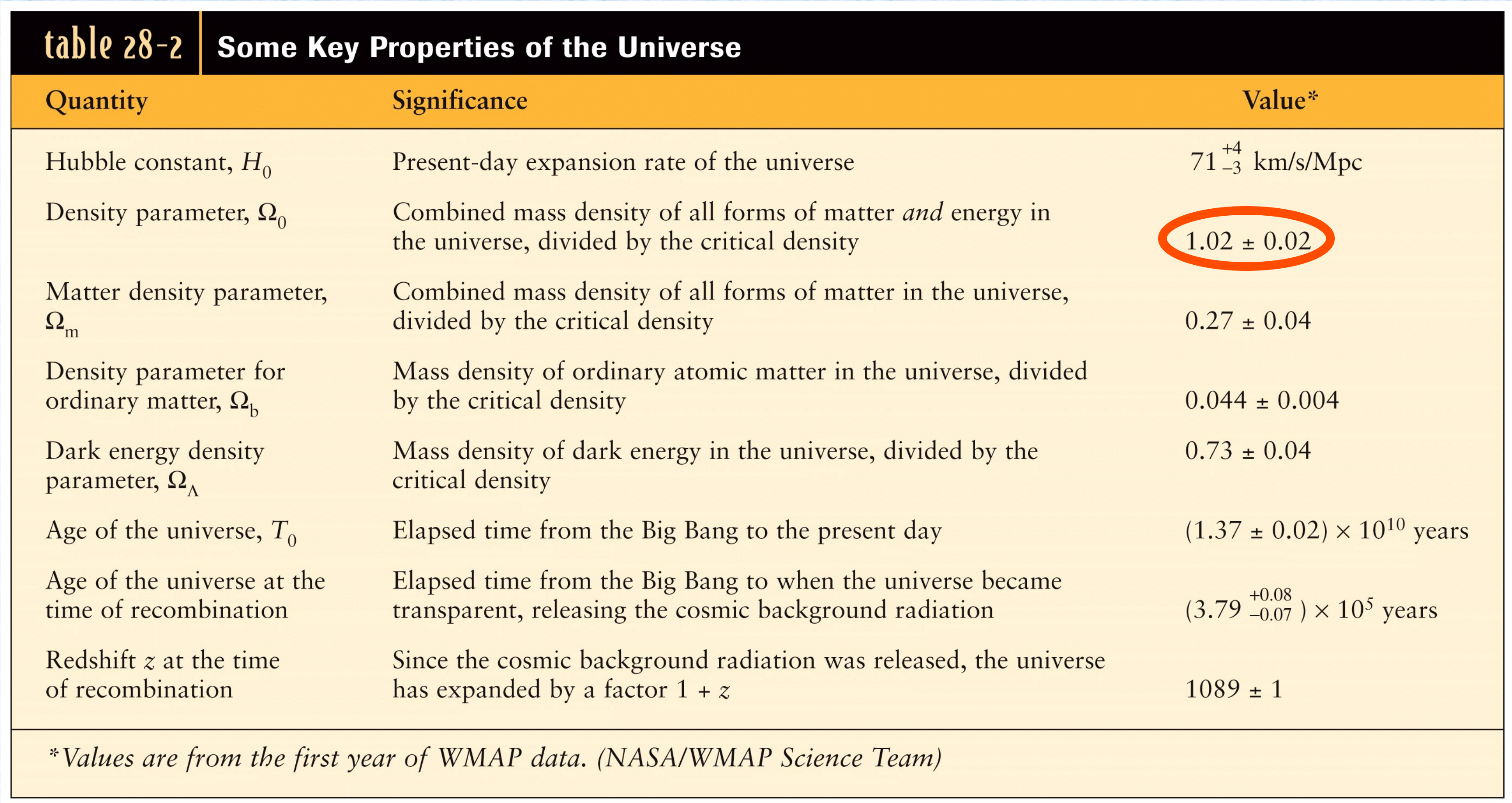


table 28-2 Some Key Properties of the Universe

Quantity	Significance	Value*
Hubble constant, H_0	Present-day expansion rate of the universe	71^{+4}_{-3} km/s/Mpc
Density parameter, Ω_0	Combined mass density of all forms of matter *and* energy in the universe, divided by the critical density	1.02 ± 0.02
Matter density parameter, Ω_m	Combined mass density of all forms of matter in the universe, divided by the critical density	0.27 ± 0.04
Density parameter for ordinary matter, Ω_b	Mass density of ordinary atomic matter in the universe, divided by the critical density	0.044 ± 0.004
Dark energy density parameter, Ω_Λ	Mass density of dark energy in the universe, divided by the critical density	0.73 ± 0.04
Age of the universe, T_0	Elapsed time from the Big Bang to the present day	$(1.37 \pm 0.02) \times 10^{10}$ years
Age of the universe at the time of recombination	Elapsed time from the Big Bang to when the universe became transparent, releasing the cosmic background radiation	$(3.79^{+0.08}_{-0.07}) \times 10^5$ years
Redshift z at the time of recombination	Since the cosmic background radiation was released, the universe has expanded by a factor $1 + z$	1089 ± 1

**Values are from the first year of WMAP data. (NASA/WMAP Science Team)*

Other tests of inflation

- Inflationary models can predict the amount of polarization of the CMB (see Universe)
- Inflationary models predict fossil gravitational waves, like the CMB but for gravitons.
- Precision measurements of polarization in the CMB and of gravitational wave background can test the theory.
- Polarization measurements of the CMB are currently starting to become interesting (ESA mission Planck first results just came out; no polarization yet)
- For fossil gravitational waves… we' ll have to wait..

Inflation. Summary

- In the last twenty year the classic Big Bang model has evolved to include a period of inflation
- During inflation, as a result of a phase transition of a field called inflaton, space expanded dramatically so that our entire horizon was once in causal connection
- Did anything move faster than light? Is this violating some fundamental law of physics?
- NO!
- Inflation gives a “natural” explanation for fundamental questions such as the horizon problem
- Inflation predicts that space is flat, in agreement with observations
- Other observable properties (at least in theory!) of inflationary models are polarization of the CMB and fossil gravitational waves

Inflation. Discussion

- Why did people come up with the idea of inflation?
- Is inflation a good scientific theory?
- Is it as good a scientific theory as classic big bang?

The End

See you on thursday