ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 15 • The very, very early Universe

10/26/2021

Exams & Doctor’s notes

- No need to bring doctor’s notes if you miss a lecture or need an extension on a quiz
- If you miss an exam, you do need to provide a doctor’s note

Recap

Participation: Recap #1

TurningPoint:
Which component dominates the Universe today?

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30 seconds

Participation: Recap #2

TurningPoint:
Which component dominated the Universe
at early times?

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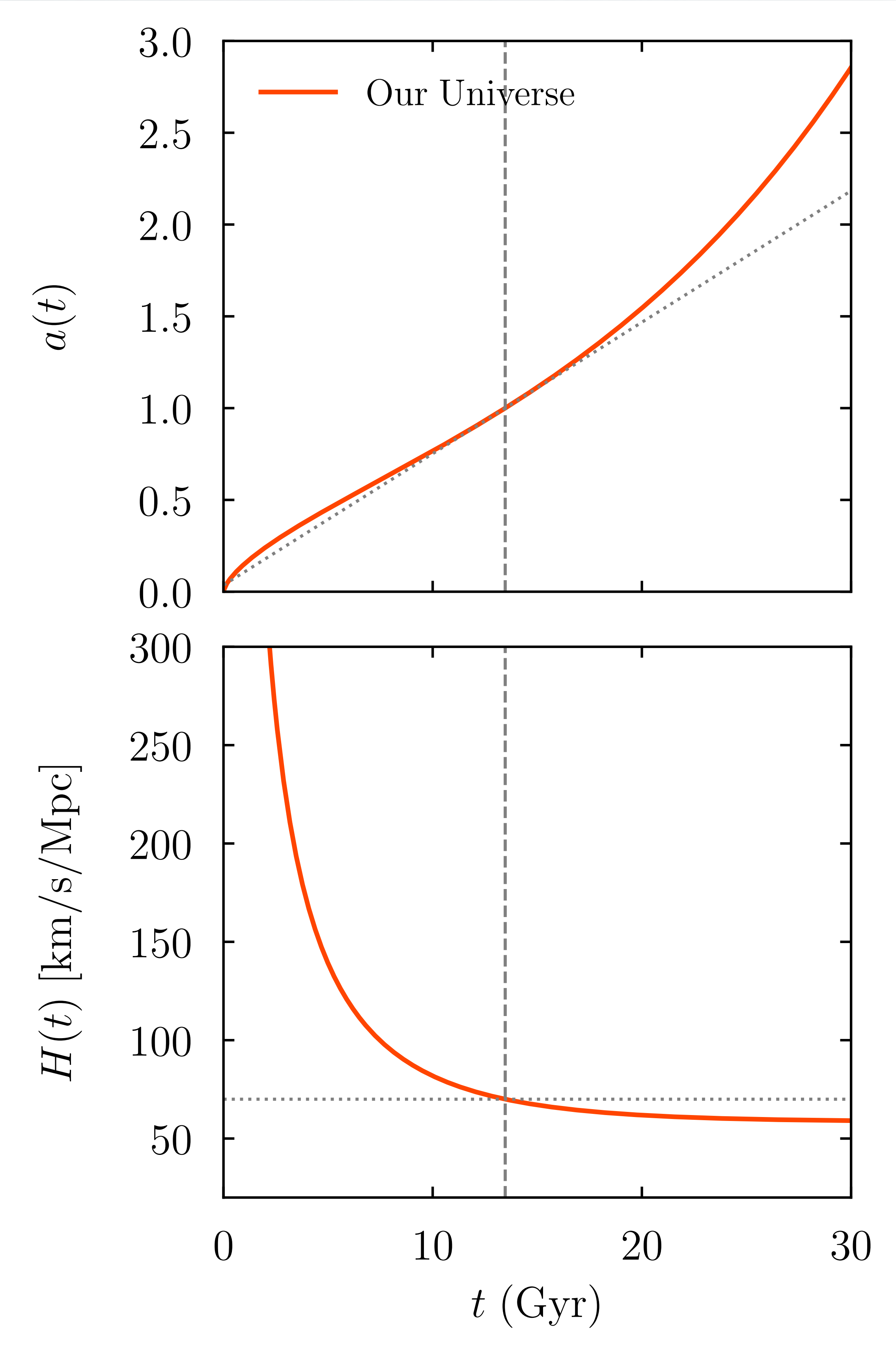
30 seconds

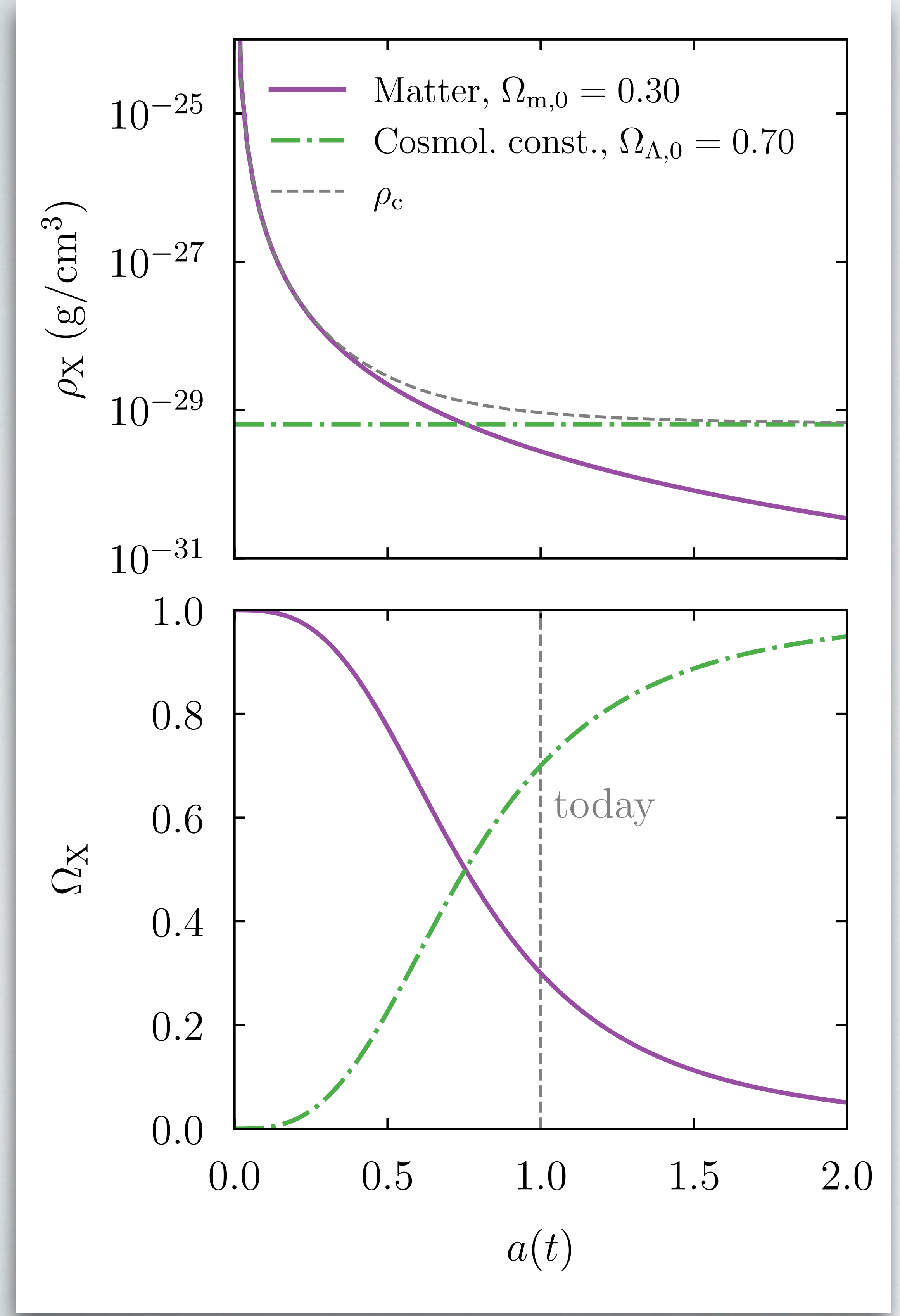
Our Universe



$$\Omega_{\mathrm{m},0} \approx 0.3$$
$$\Omega_{\Lambda,0} \approx 0.7$$
$$\Omega_{\mathrm{k},0} \approx 0$$
$$H_0 \approx 70 \text{ km/s/Mpc}$$

- **Flat** (as far as we can tell)
- Dominated by **dark energy** (since $t \approx 10$ Gyr)
- DE looks like **cosmological constant**
- Will undergo **accelerated expansion** forever (unless we're missing something)
- Hubble time is (coincidentally) quite close to true age of Universe

Understanding the Friedmann equation



$\Omega_{m,0} \approx 0.3$

$\Omega_{\Lambda,0} \approx 0.7$

$\Omega_{k,0} \approx 0$

$H_0 \approx 70$ km/s/Mpc

- Matter dominates in the beginning
- About 10 Gyr after the Big Bang ($a \approx 0.75$, $z \approx 0.3$) DE (the cosmological constant) becomes the dominant component
- DE will continue to become more dominant in the future

Early and late times

If there is any matter, there is an early time (a << 1) where matter dominates

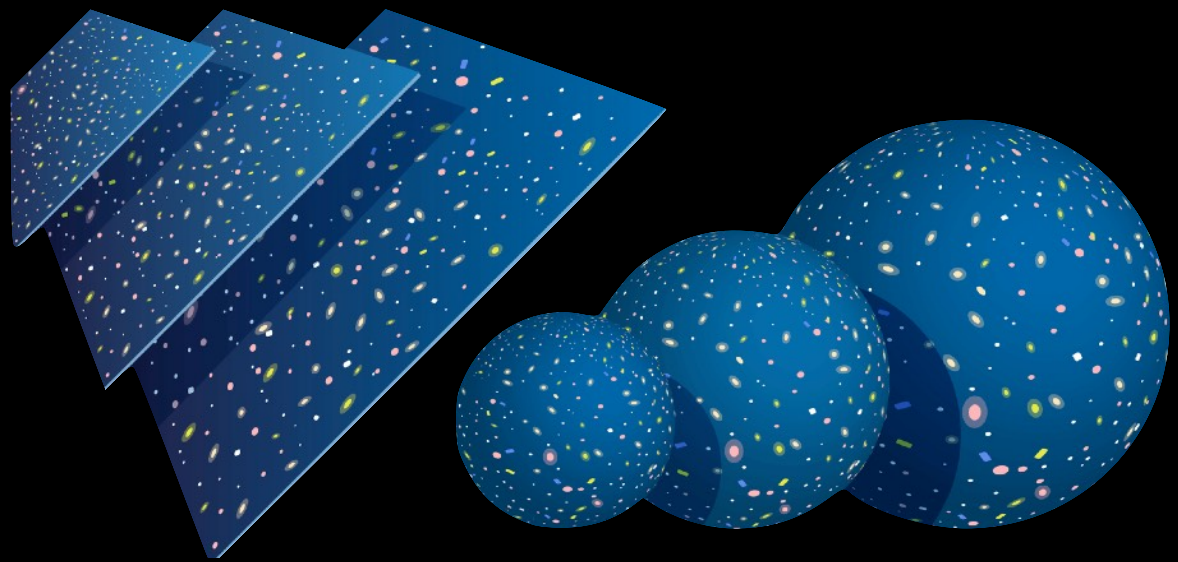
If there is any Λ and the Universe does not collapse, there is a late time (a >> 0) where Λ dominates

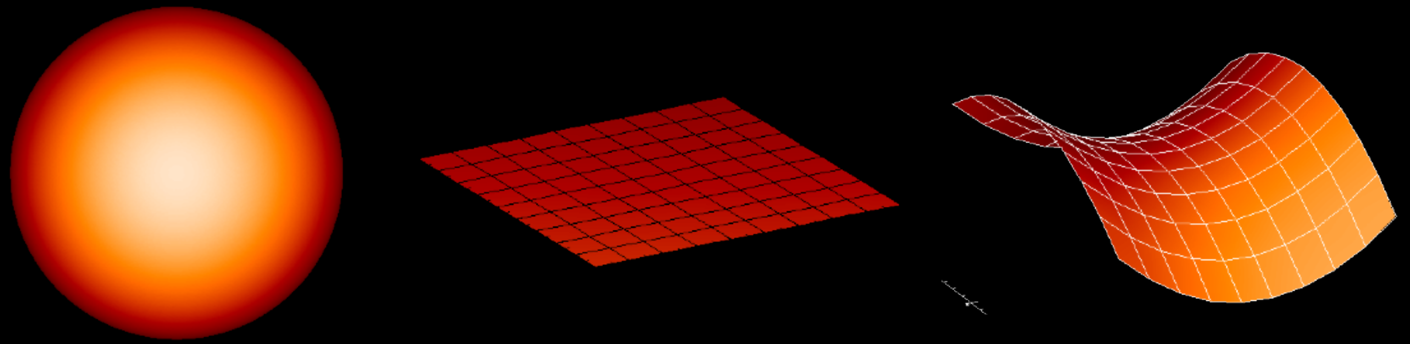
$$\left(\frac{H}{H_0}\right)^2 = \frac{\Omega_{m,0}}{a^3} + \frac{\Omega_{k,0}}{a^2} + \Omega_{\Lambda,0}$$

- In the **beginning**, the Universe behaves like a **flat matter-only** Universe (except for photons, which we have not included yet)
- At **late** times, the Universe **expands exponentially** if $\Lambda>0$

Is the Universe finite or infinite?

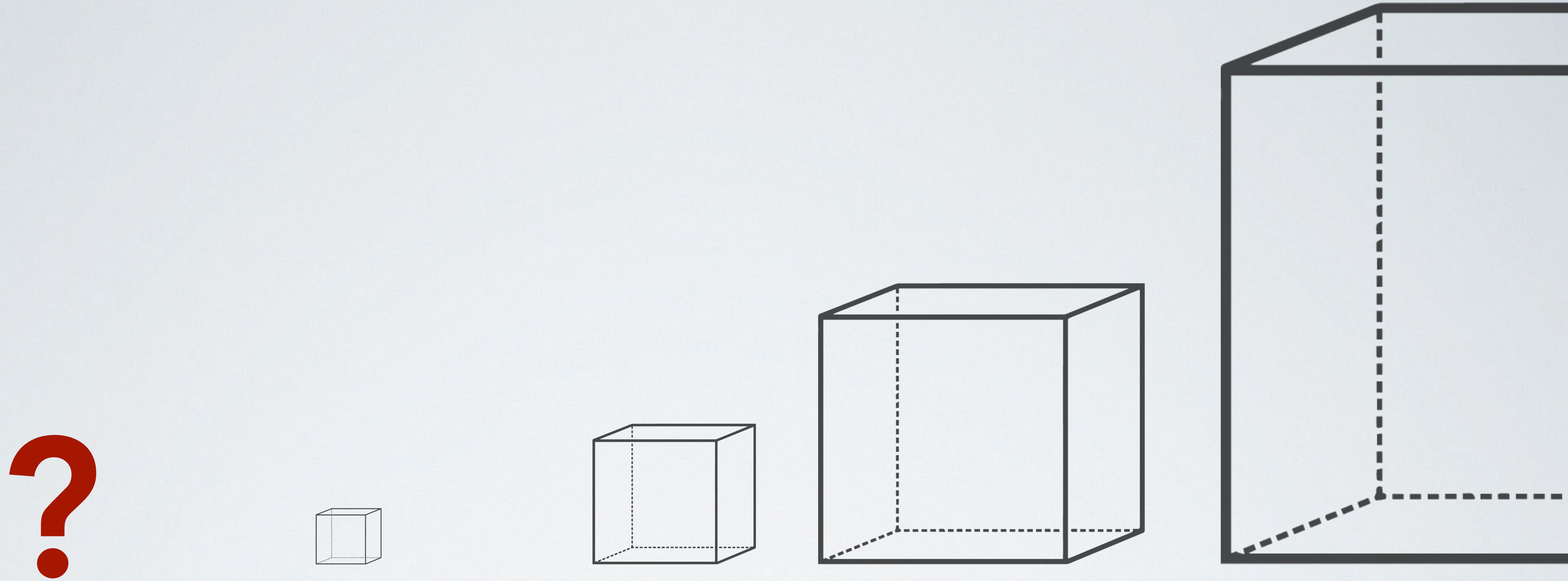
- If the Universe is **positively curved**, it is **finite**
- If the Universe is **flat or negatively curved**, it is probably **infinite**
- However, it could theoretically have a non-simple ("multiply connected") geometry, which could be finite
- We can only test flatness, homogeneity, and isotropy within the part of the Universe that we can see





Images: Quanta Magazine / Forbes

Connecting redshift and scale factor



$a = 0$ $\quad$ $a = 0.2$ $\quad$ $a = 0.5$ $\quad$ $a = 1$ $\quad$ $a = 2$

$z = \infty$ $\quad$ $z = 4$ $\quad$ $z = 1$ $\quad$ $z = 0$ $\quad$ $z = -0.5$

Big Bang ← today → future

Big questions

- As the scale factor goes to zero…
  - All matter must have been squeezed together very tightly
  - If crushed together at high enough density, galaxies, stars, etc could not have existed as we see them now
- Questions
  - How far back can we see?
  - What was the original content of the Universe?
  - What were the early conditions like?
  - What physical processes were important?
  - How did all of this result in the matter we see today?

Today

- The light-dominated Universe
- The hot Big Bang
- The very early Universe

Part 1: The light-dominated Universe

Participation: Oldest observation

TurningPoint:
How old (time since the Big Bang) is the oldest observation we have? (Universe is 13.8 Gyr old)

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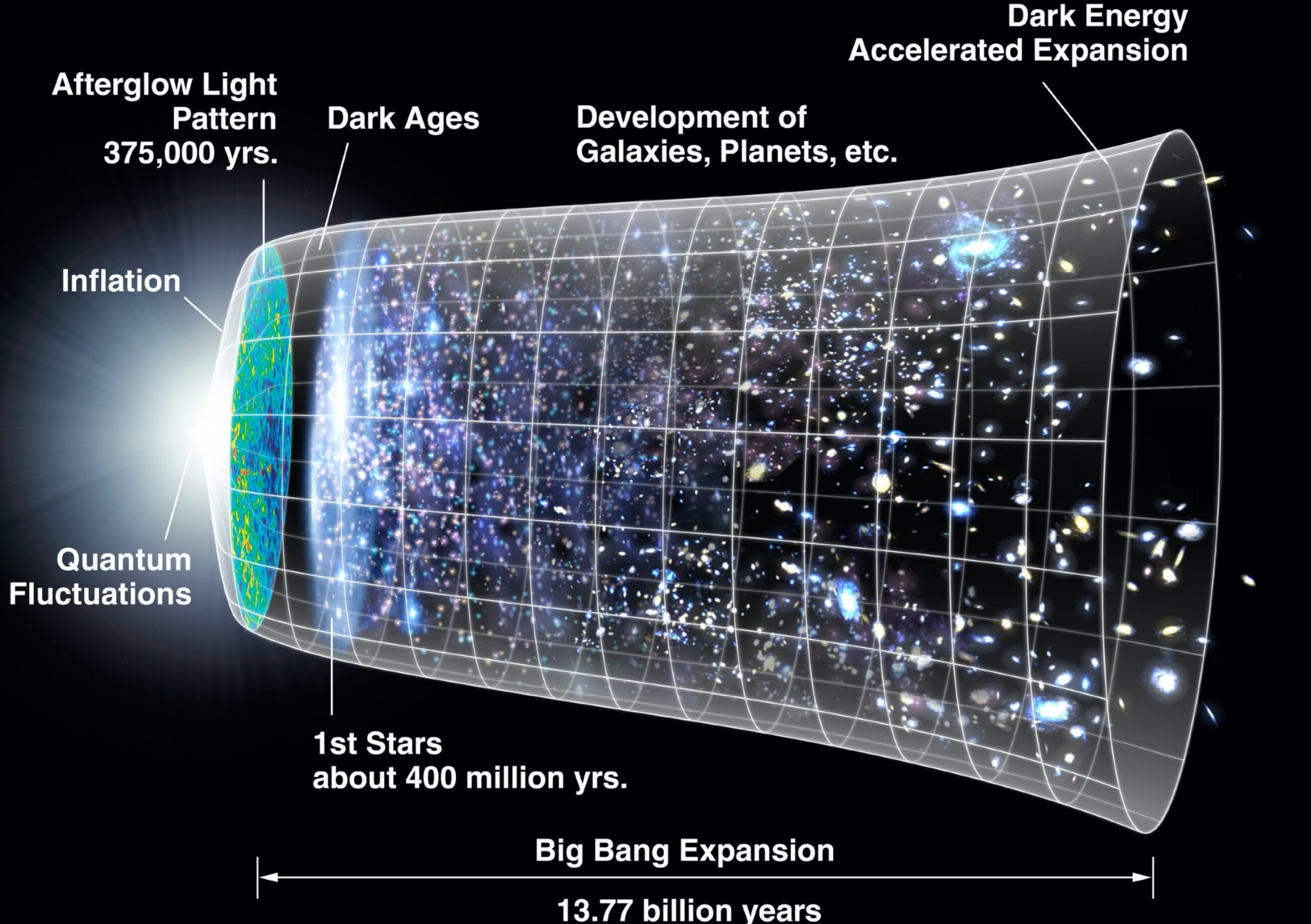
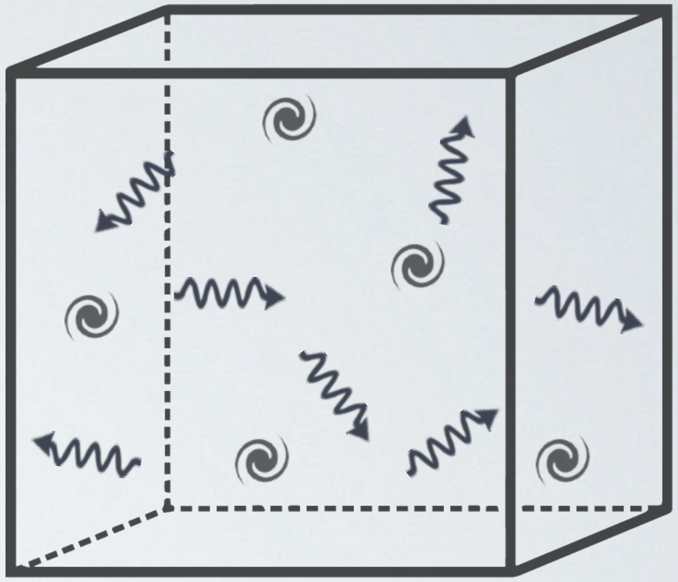
History of the Universe



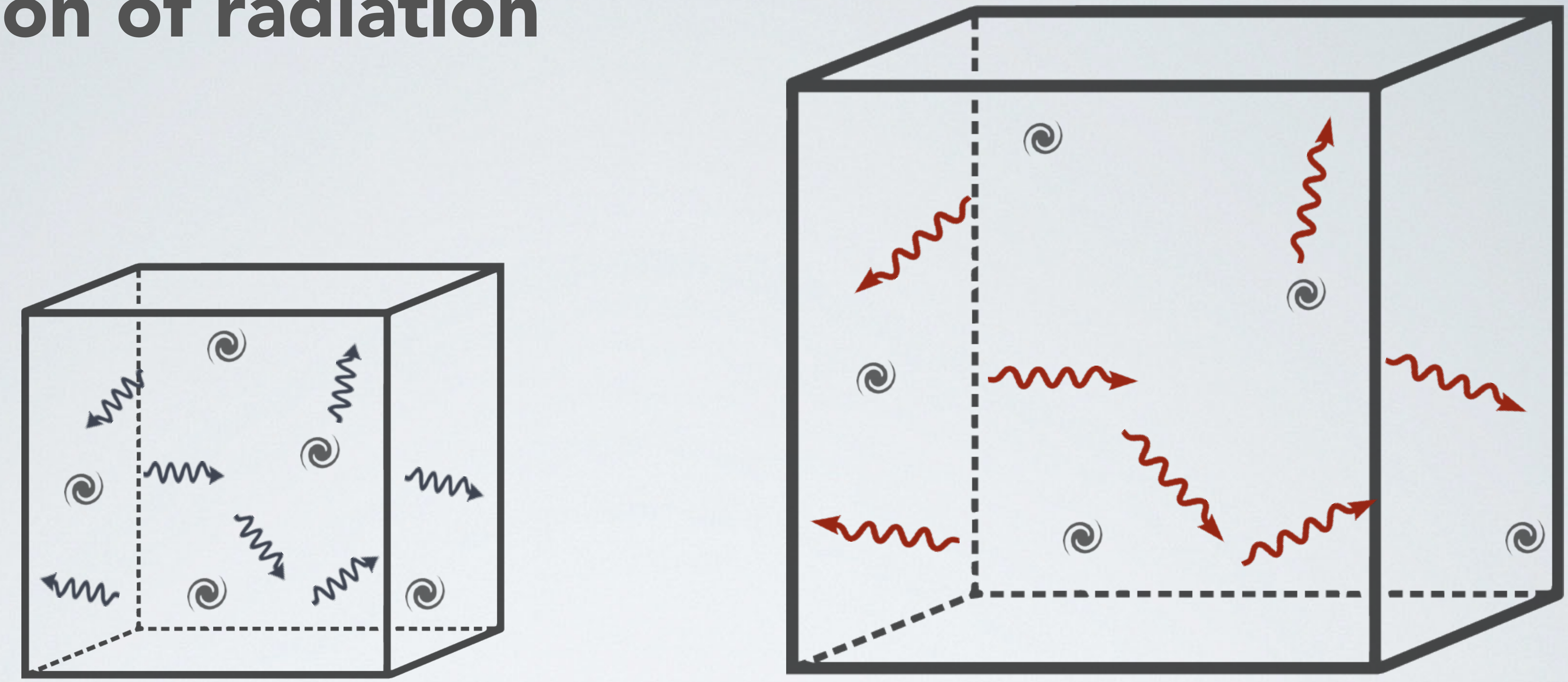
NASA / WMAP

The Cosmic Microwave Background (CMB)

- Space is filled with a nearly uniform, faint **radiation field**
- Discovered in the 1960's
- Range of wavelengths, with peak in **microwave** range
- Known as **Cosmic Microwave Background (CMB)**
- Present density is 411 photons/cm^3
- Emitted at $z \approx 1100$
- Will discuss CMB in detail next week



Evolution of radiation



- Density of matter decreases as 1/volume = $1/a^3$
- Density of photons decreases the same way, but photons are also **redshifted**
- Since photon energy is proportional to frequency:

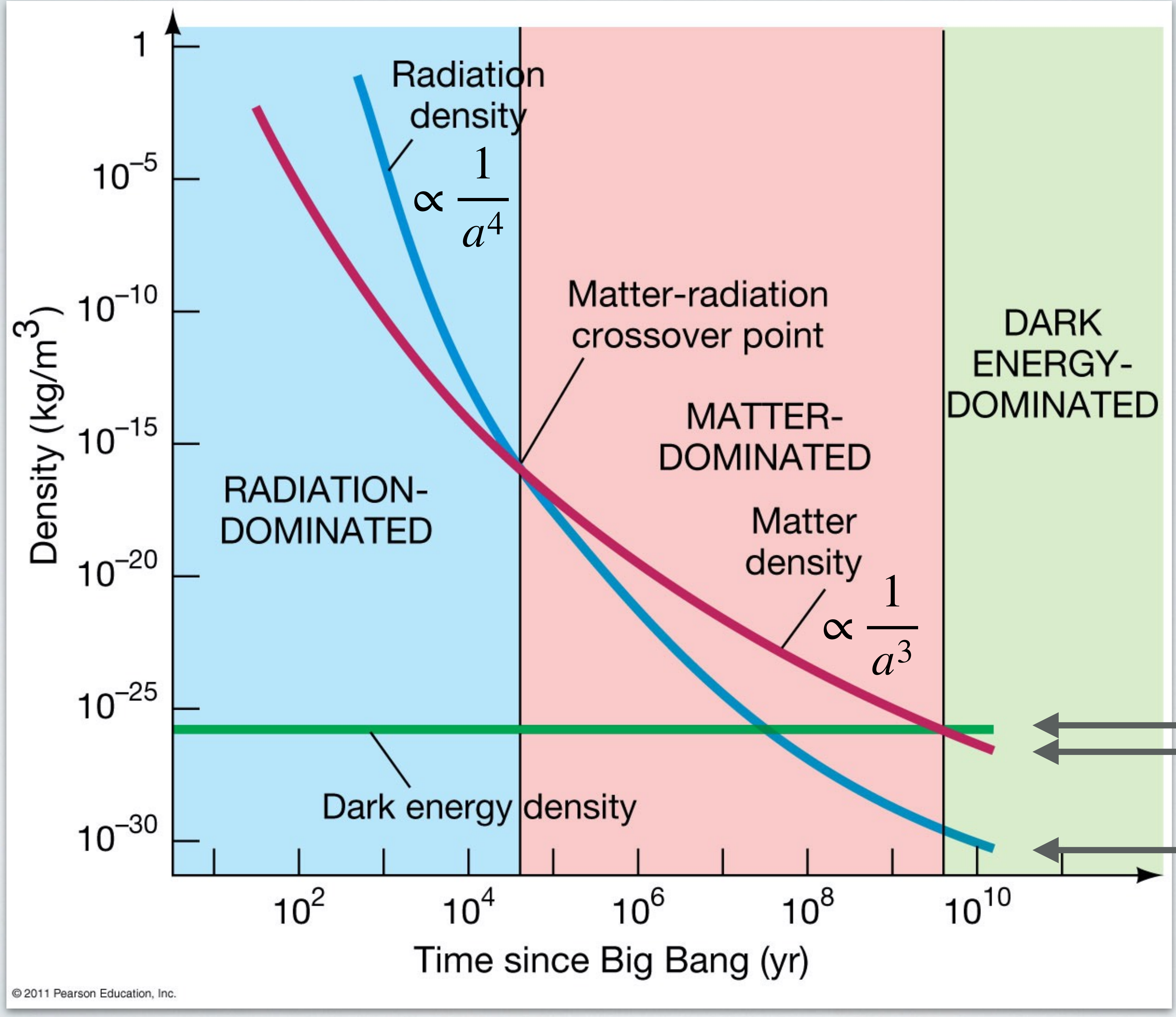
$$E = hf = \frac{hc}{\lambda} \implies E \propto \frac{1}{a}$$

- Thus, energy density of photons compared to today ($\rho_{r,0}$) goes down as $1/a^3 \times 1/a = 1/a^4$

$$\rho_m(t) = \frac{\rho_{m,0}}{a^3}$$

$$\rho_r(t) = \frac{\rho_{r,0}}{a^4}$$

What dominates the energy density?



Today:

$\approx 70\,\%$

$\approx 30\,\%$

$\approx 0.009\,\%$

University of Oregon / Pearson

Part 2: The hot Big Bang

Participation: What is temperature?

TurningPoint:
What physical quantity do we describe as temperature?

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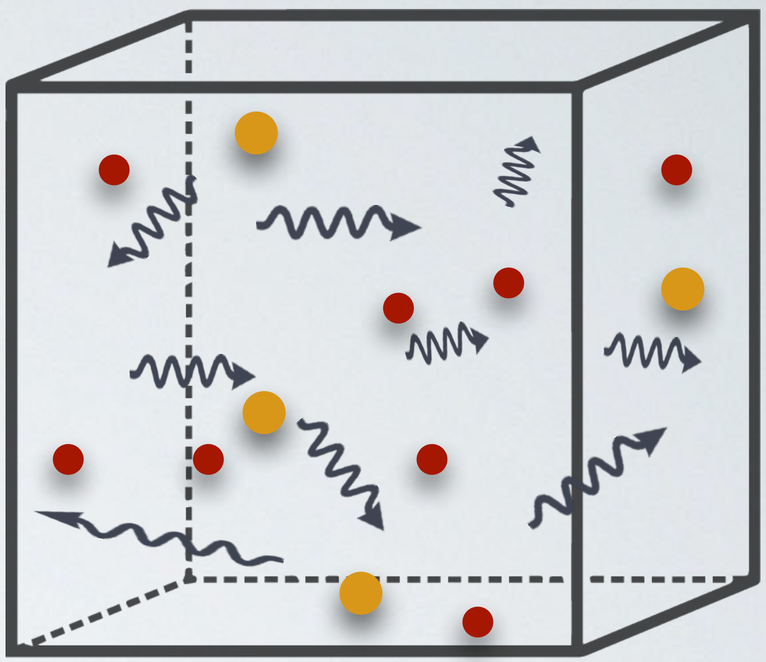
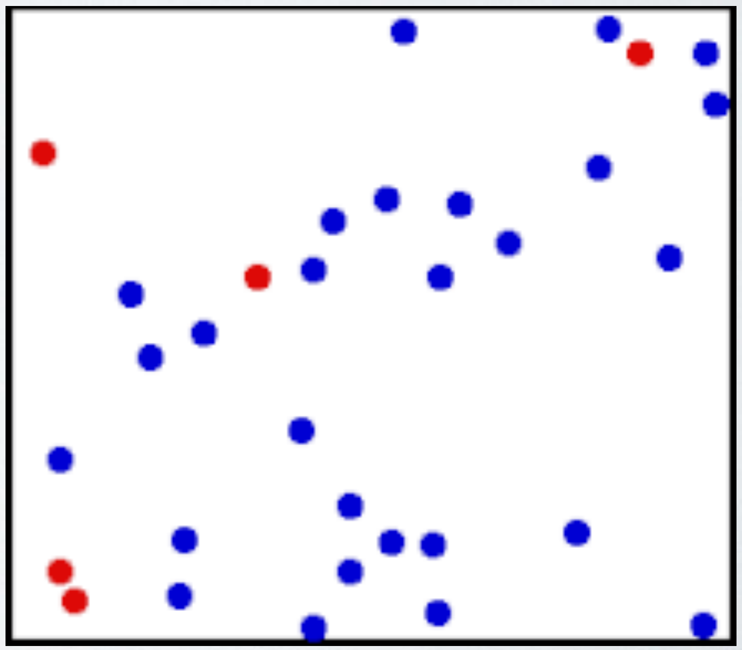
What is temperature?

- In the early Universe, photons and particles were in **thermal equilibrium**
- At a given temperature, each particle or photon has the **same average energy:**



$$\langle E \rangle = \frac{3}{2} k_{\mathrm{B}} T$$

$$k_{\mathrm{B}} = 1.38 \times 10^{-16} \frac{\mathrm{erg}}{K}$$



- k_B is called the **Boltzmann constant**

Evolution of temperature

$$E_{\rm phot} \propto \frac{1}{a}$$

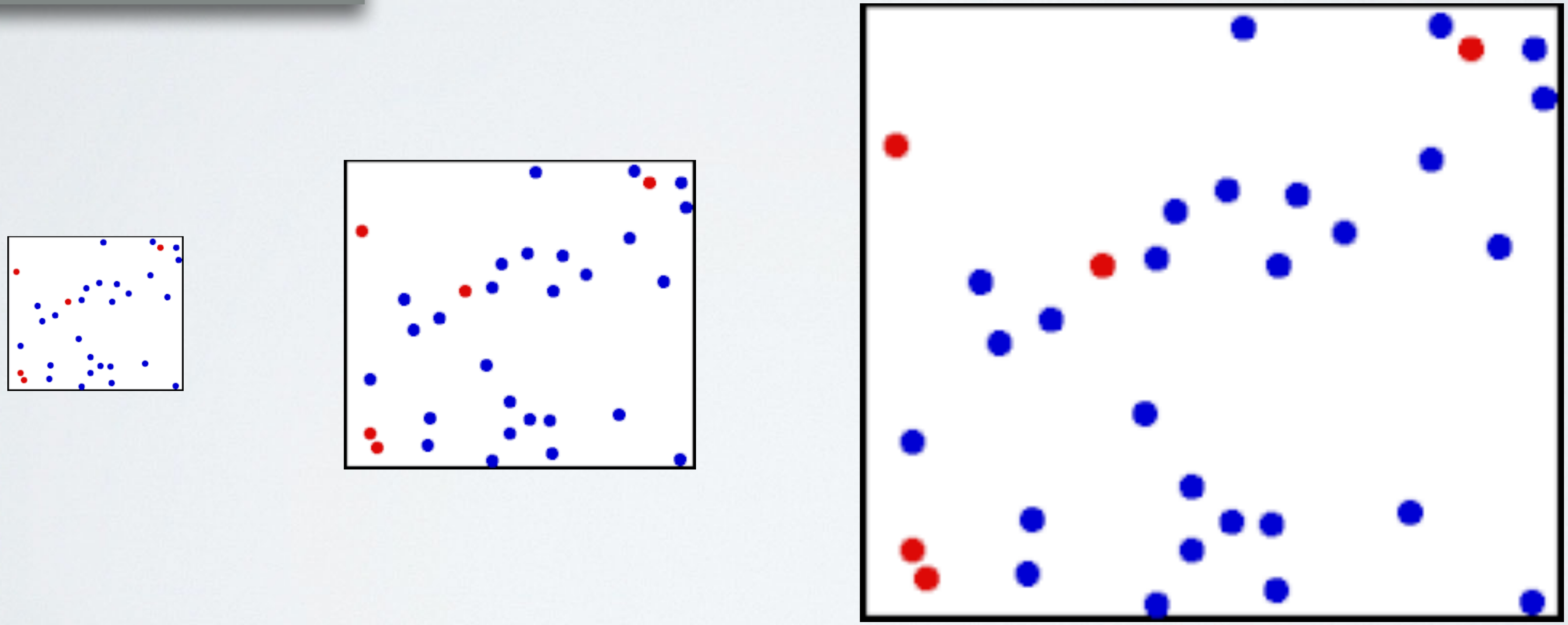
$$\langle E \rangle = \frac{3}{2} k_{\rm B} T$$

$$\Longrightarrow$$

$$T(t) = \frac{T_0}{a}$$

CMB photon temperature today:

$$T_0 = 2.725\ {\rm K}$$



Temperature and energy increase towards the Big Bang as 1/a

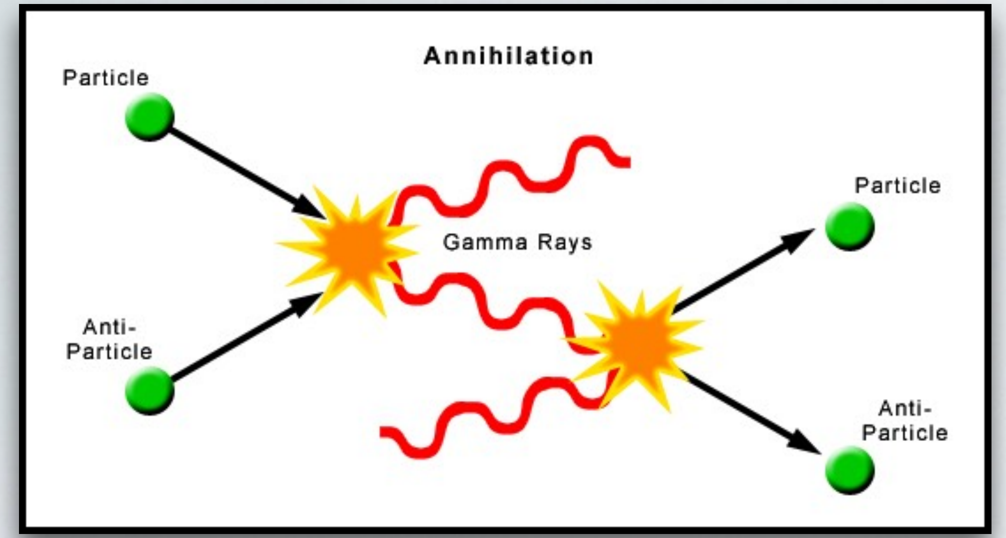
The hot Big Bang

- Lemaitre proposed Big Bang theory in 1927 (“primieval atom”)
- A hot early Universe was predicted in 1948 by George Gamow (with Alpher and Herman)
  - The idea: the universe started off very hot and cools as it expands
  - They predicted “relic radiation” with temperature of about 5K (close!)
  - Work not fully recognized until 1960s
- The **evolution of temperature** determines what happens
- In early Universe, temperature/energy was too high for electrons and nuclei to be bound as **atoms**
- In very early Universe, temperature/energy too high for protons and neutrons to remain bound as **nuclei**
- **No direct observations** to constrain theories

Lemaitre

Gamow

Matter-light conversion



- If photons have sufficient energy, they can create particle-antiparticle pairs
- Particles annihilate to create photons
- Thus, there is a temperature where photons can, on average, create a certain particle
- For example, protons with $m = 1.7 \times 10^{-24}$ g, $T_{\rm proton} \approx 10^{13}$K

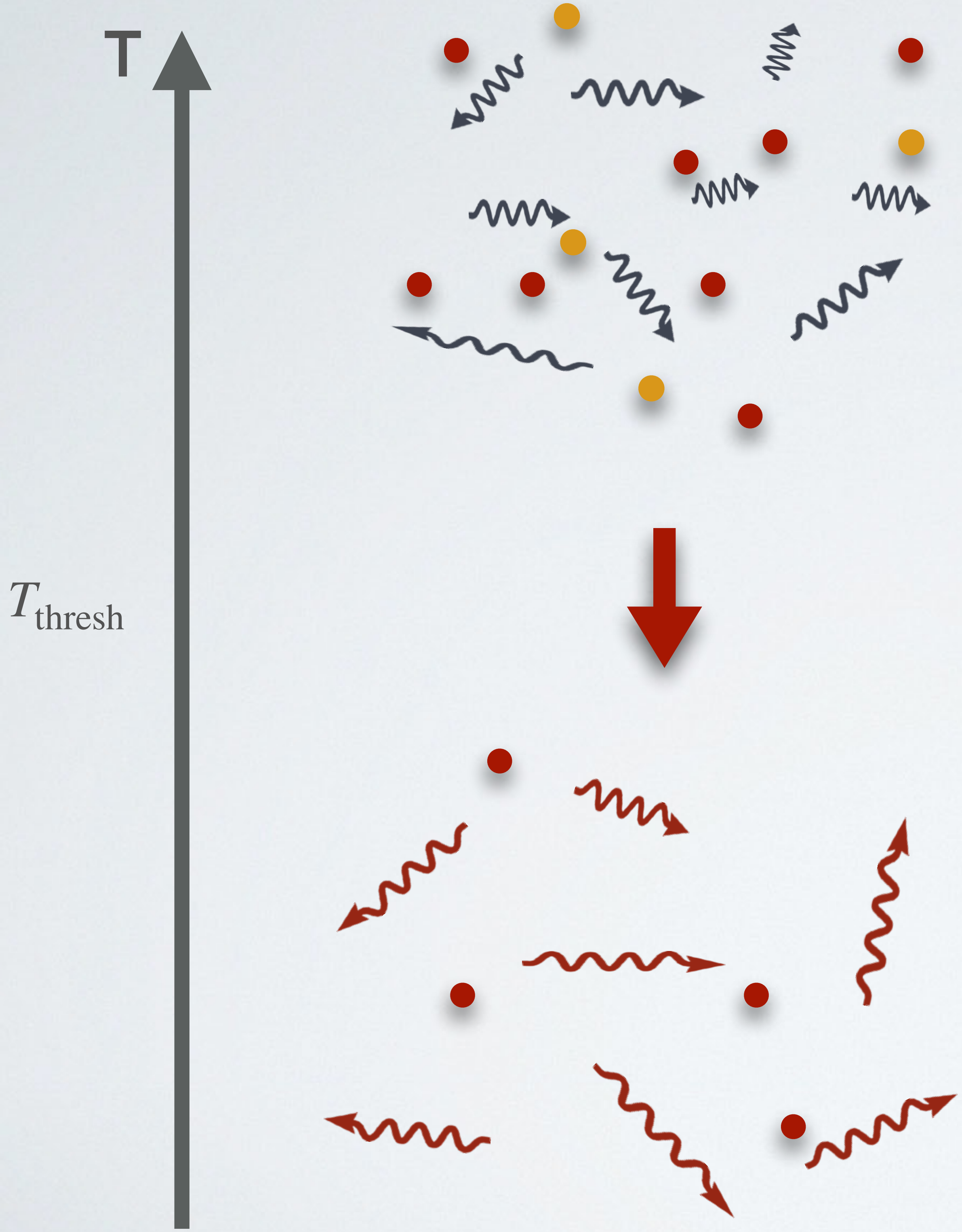
$$E = mc^2$$

$$\langle E \rangle = \frac{3}{2} k_{\rm B} T$$

$$\Longrightarrow$$

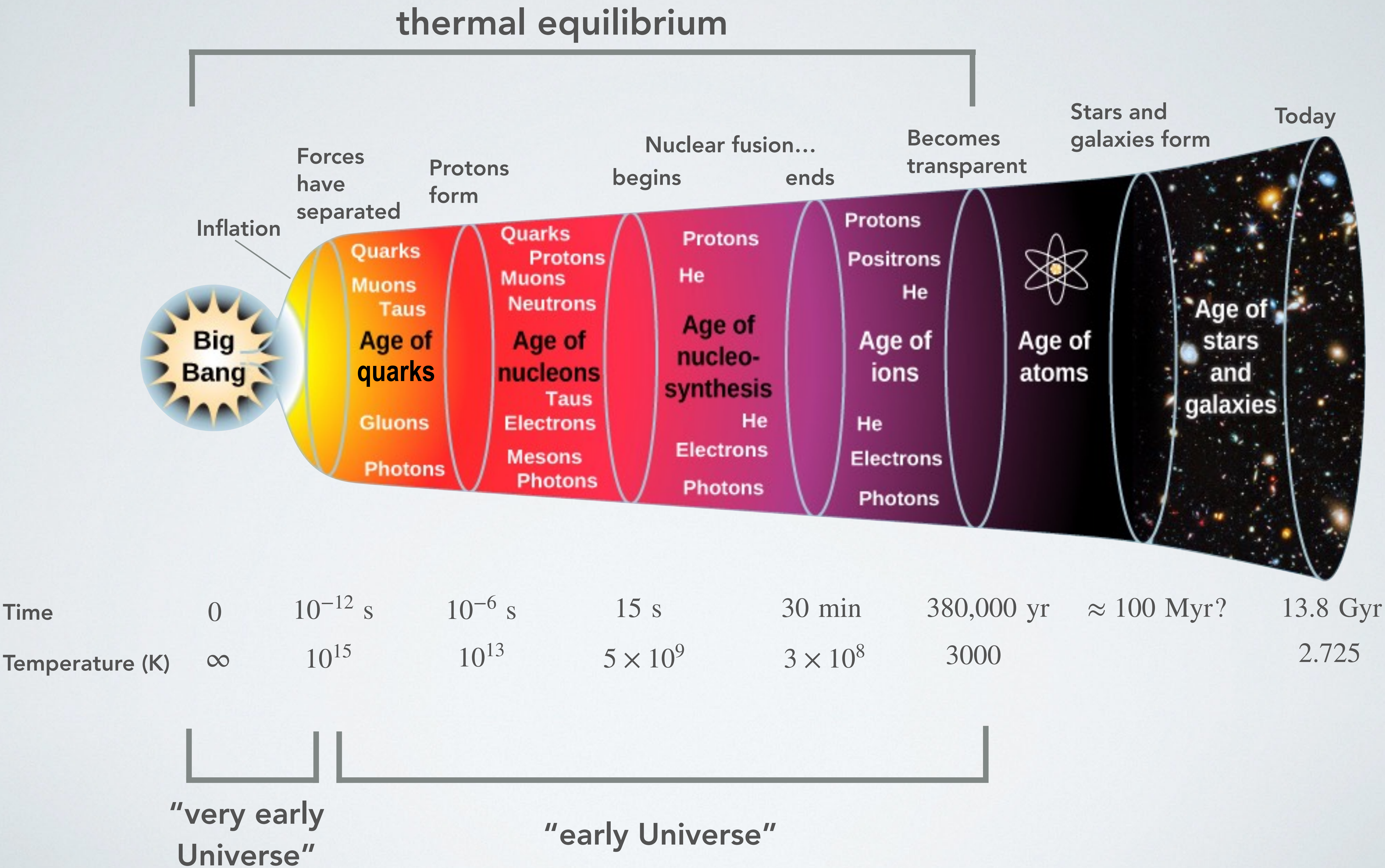
$$T_{\rm thresh} = \frac{2mc^2}{3k_{\rm B}}$$

Threshold temperature

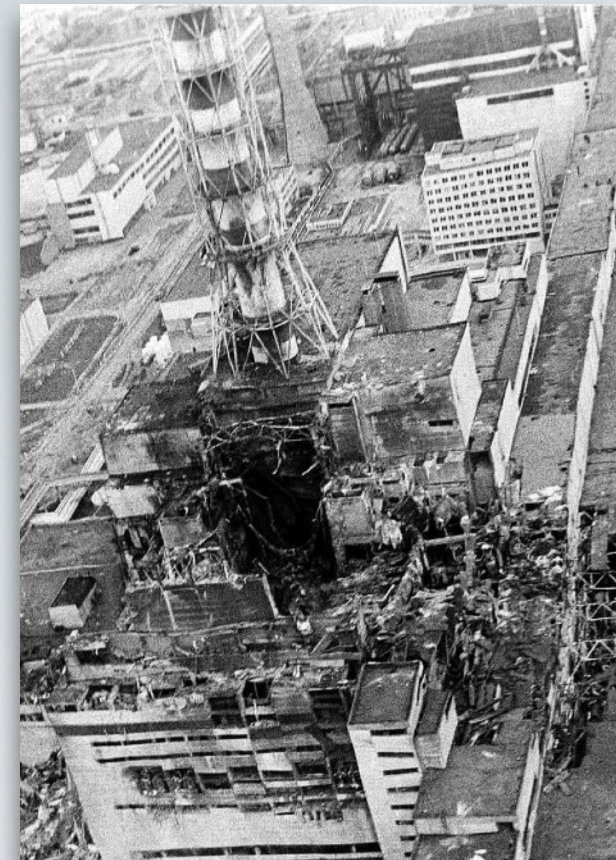


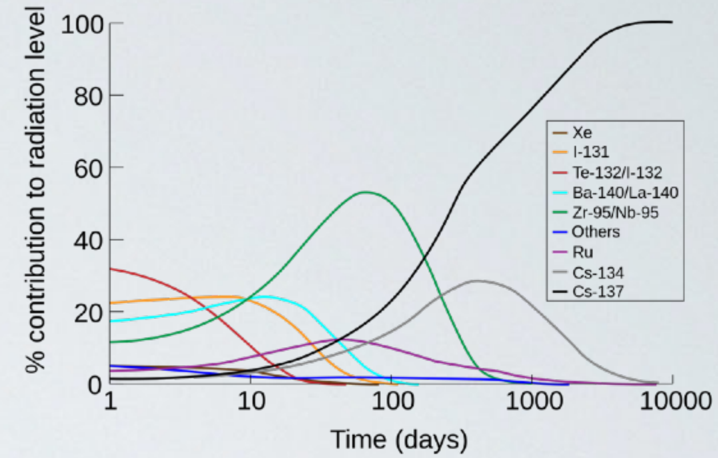
- **Above** the threshold temperature, **creation/destruction** of particles and anti-particles in equilibrium
- Below threshold temperature, particles and antiparticles have annihilated
- Residual particles left over
- May still be in **thermal equilibrium**, but photons not energetic enough to create pairs any more

History of the Universe



Logarithmic time scales: Chernobyl



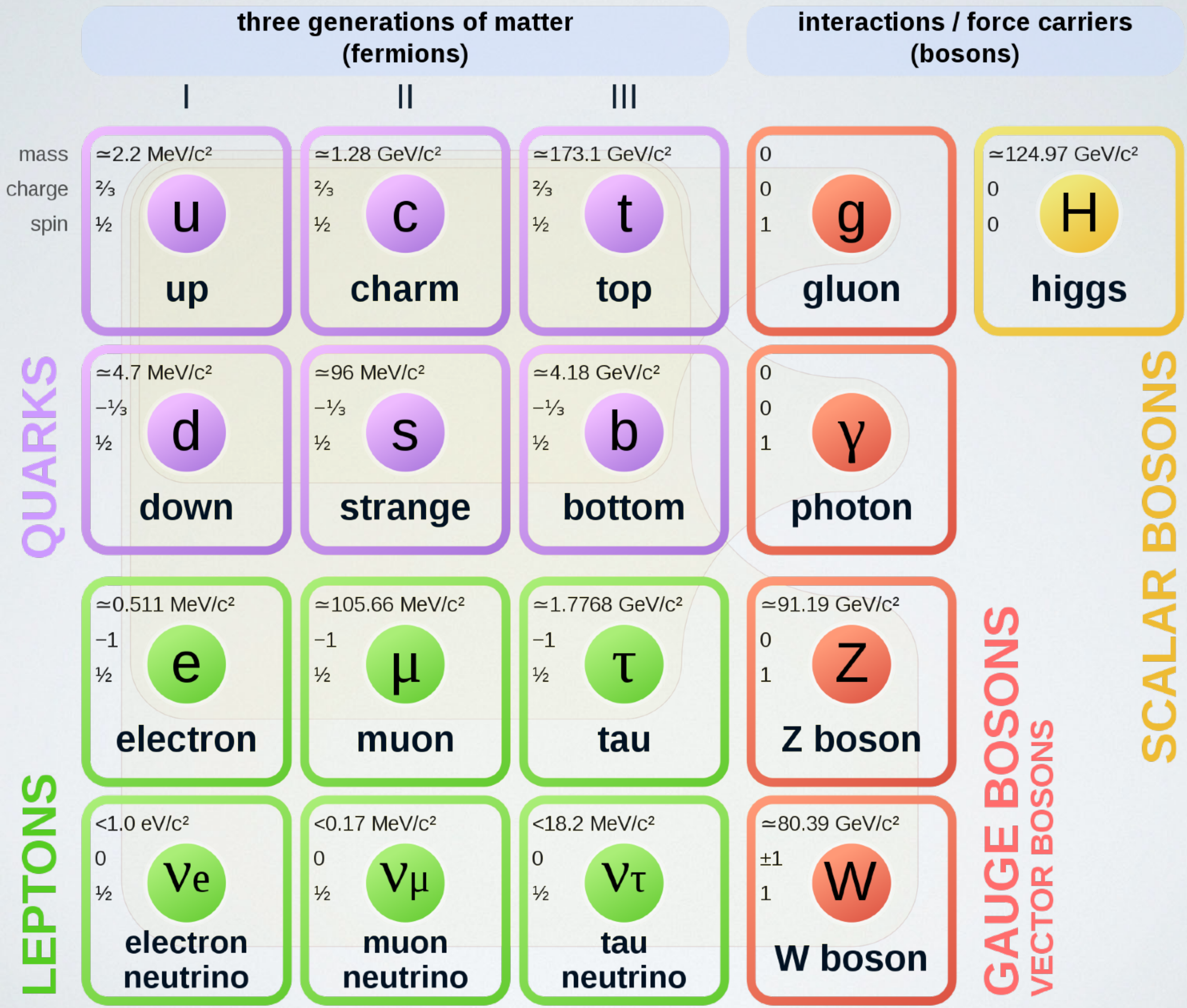


	explosion	evacuation	reactor shield	^{137}Caesium half-life
Timescale	$\approx 1\ s$	36 hr	8 months	30 years
Seconds	1	10^5	10^7	10^9

Images from Wikipedia / HBO show

Part 3: The very early Universe

Standard model of elementary particles



Participation: Fundamental Forces

TurningPoint:
Which is not a fundamental force?

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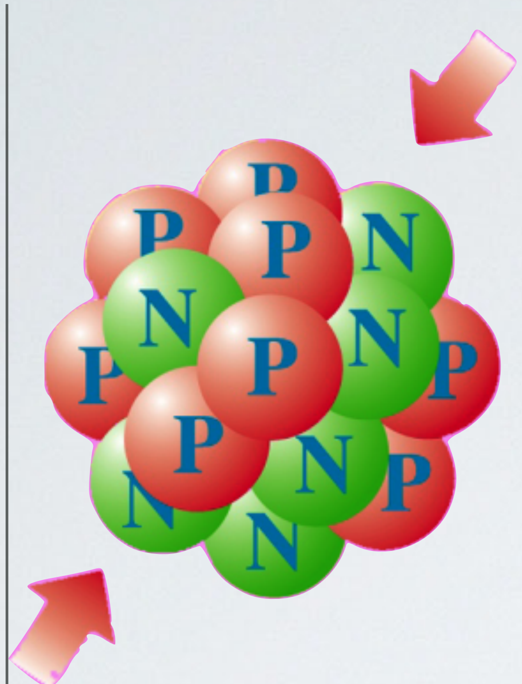
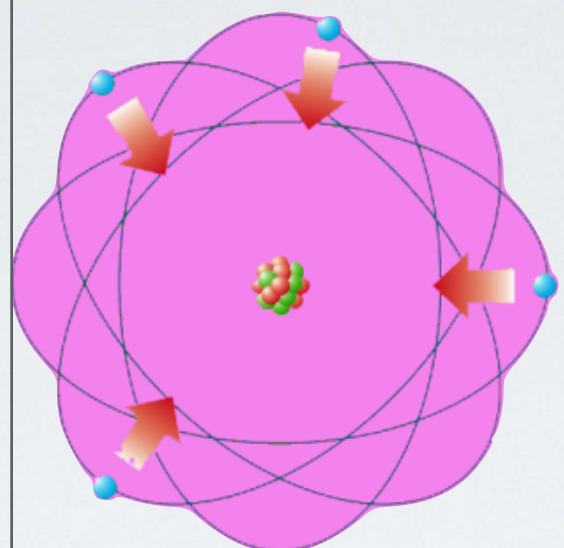
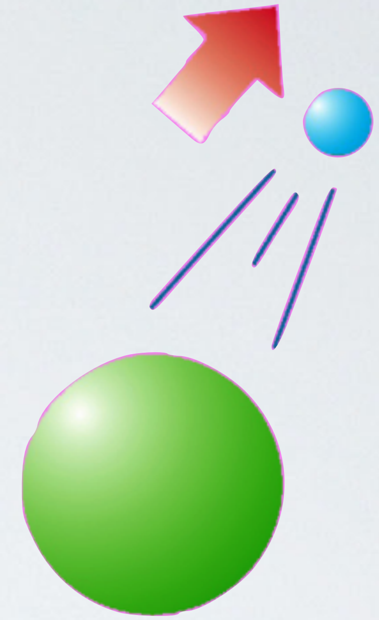
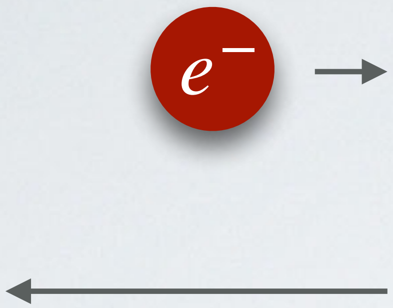
Fundamental forces

Force	 **Strong Interaction**	 **Electro-magnetism**	 **Weak Interaction**	 **Gravitation**
Strength	1	$\approx 10^{-2}$	$\approx 10^{-6}$	$\approx 10^{-38}$
Mediator particle	gluon	photon	W/Z bosons	graviton?
Examples	• Binds quarks into protons, neutrons etc • Holds nuclei together	• Electric and magnetic fields • Light	• Neutron decay	• Gravity • Graviton has not yet been detected

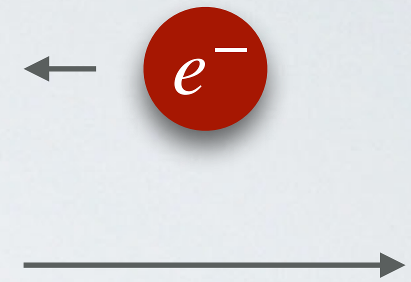
emedicalprep.com

Electrostatic force vs. gravity



$$F_g = \frac{Gm_e^2}{r^2}$$

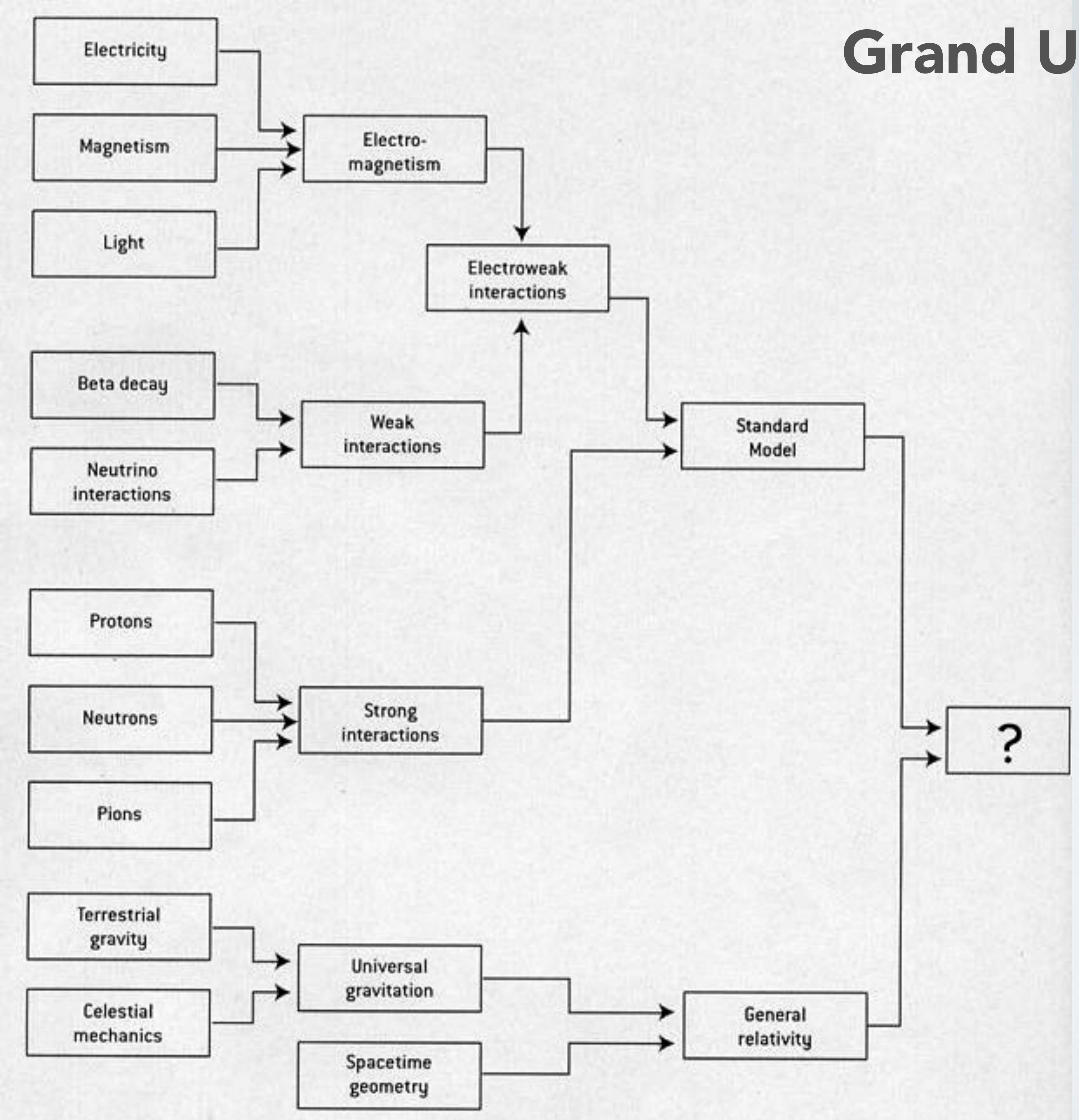
$$F_e = \frac{k_e q^2}{r^2}$$



$$\frac{F_e}{F_g} = 4 \times 10^{42}$$

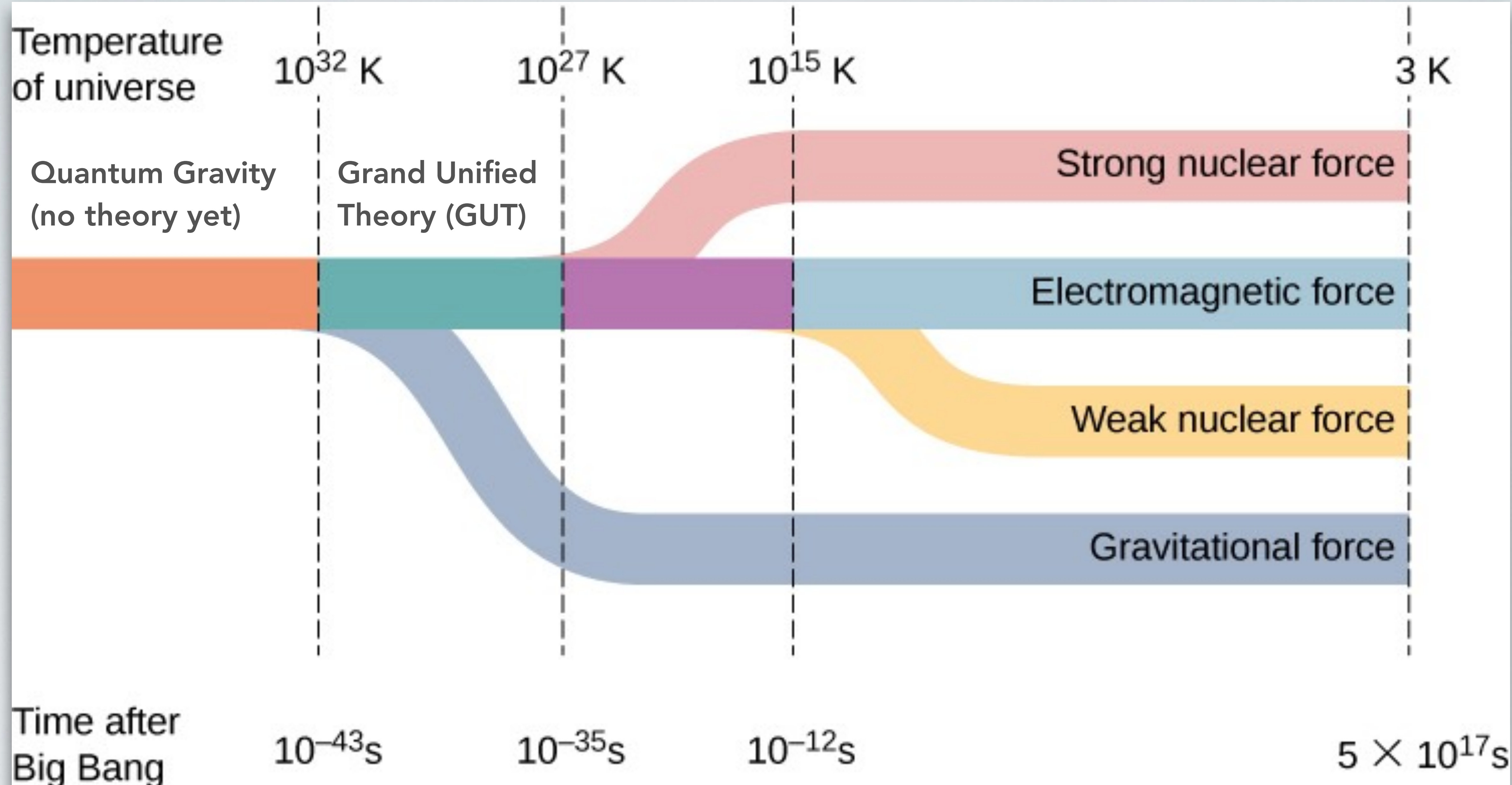
- Gravity is attracting two electrons (with mass m_e)
- Electrostatic force is repelling them (with charge q_e)
- Both fall of as $1/r^2$ with distance
- The electrostatic force is much, much stronger!

Grand Unification



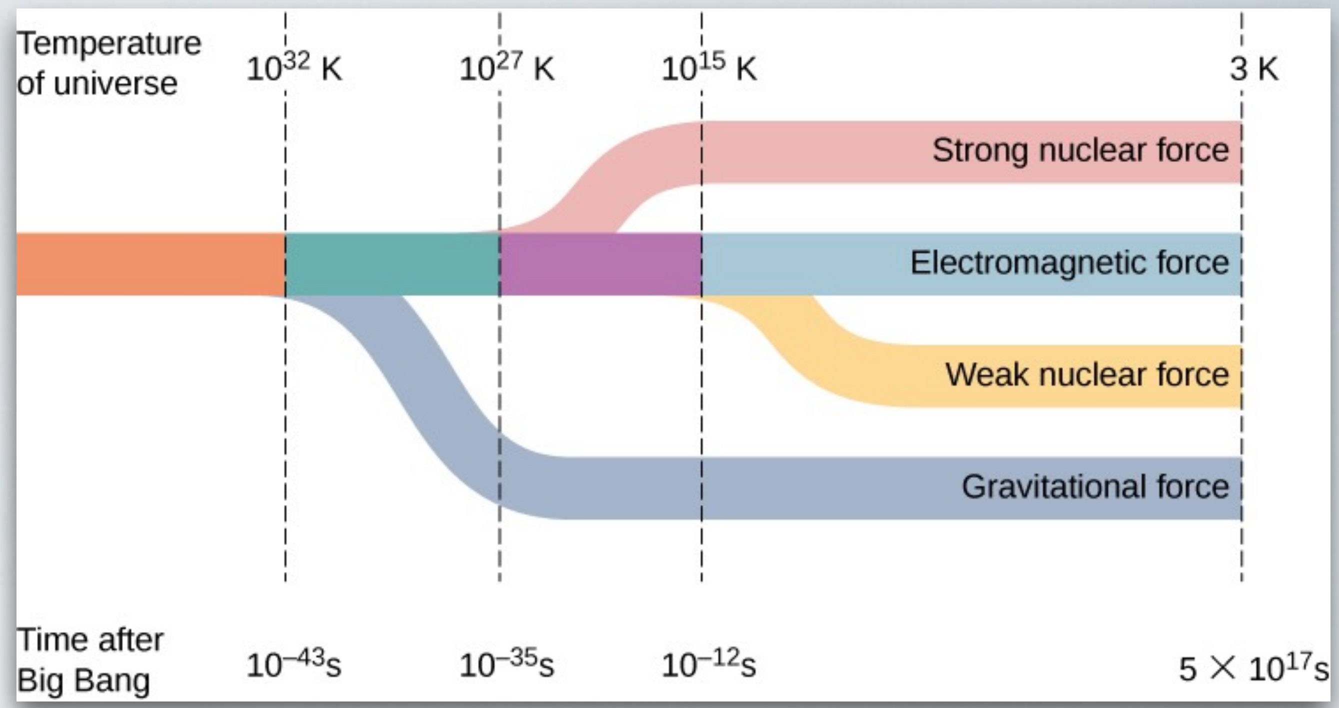
universe-review.ca

Four fundamental forces



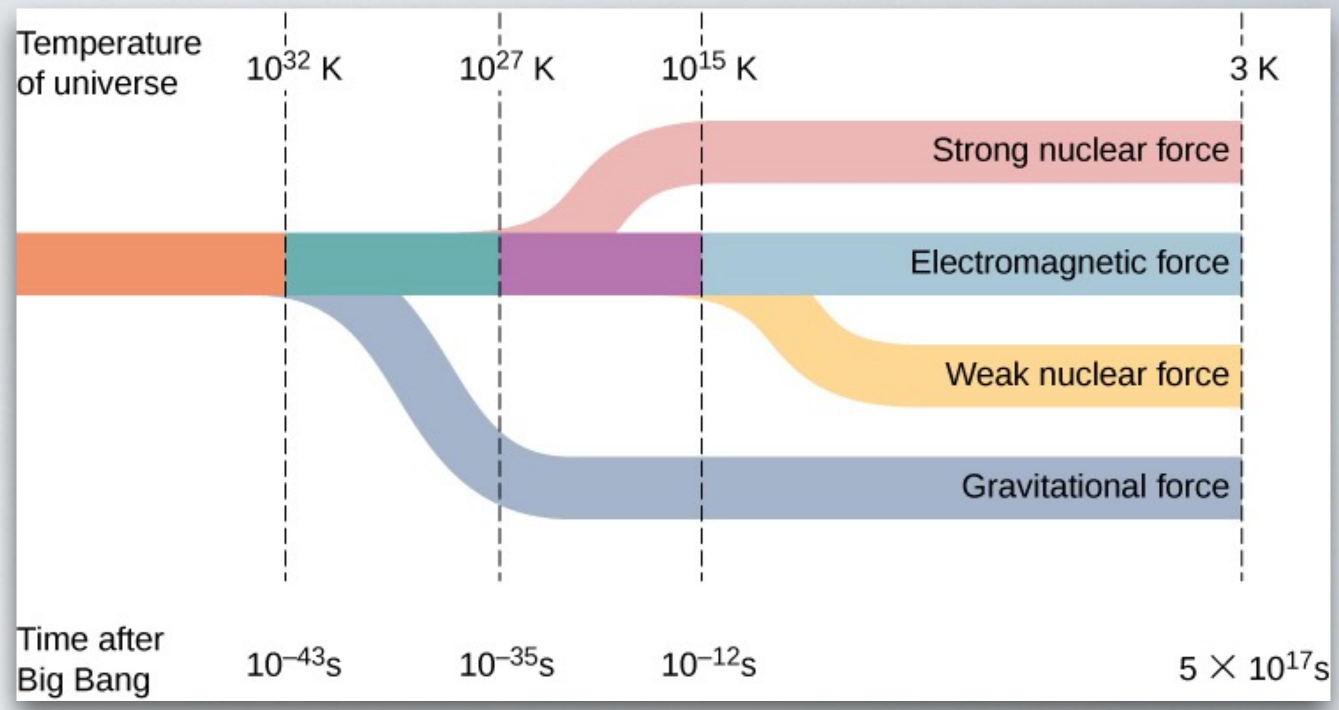
- In very early Universe, all forces were of roughly equal strength, or "unified"
- As universe cooled down, they started to "decouple" from each other

The Planck Epoch



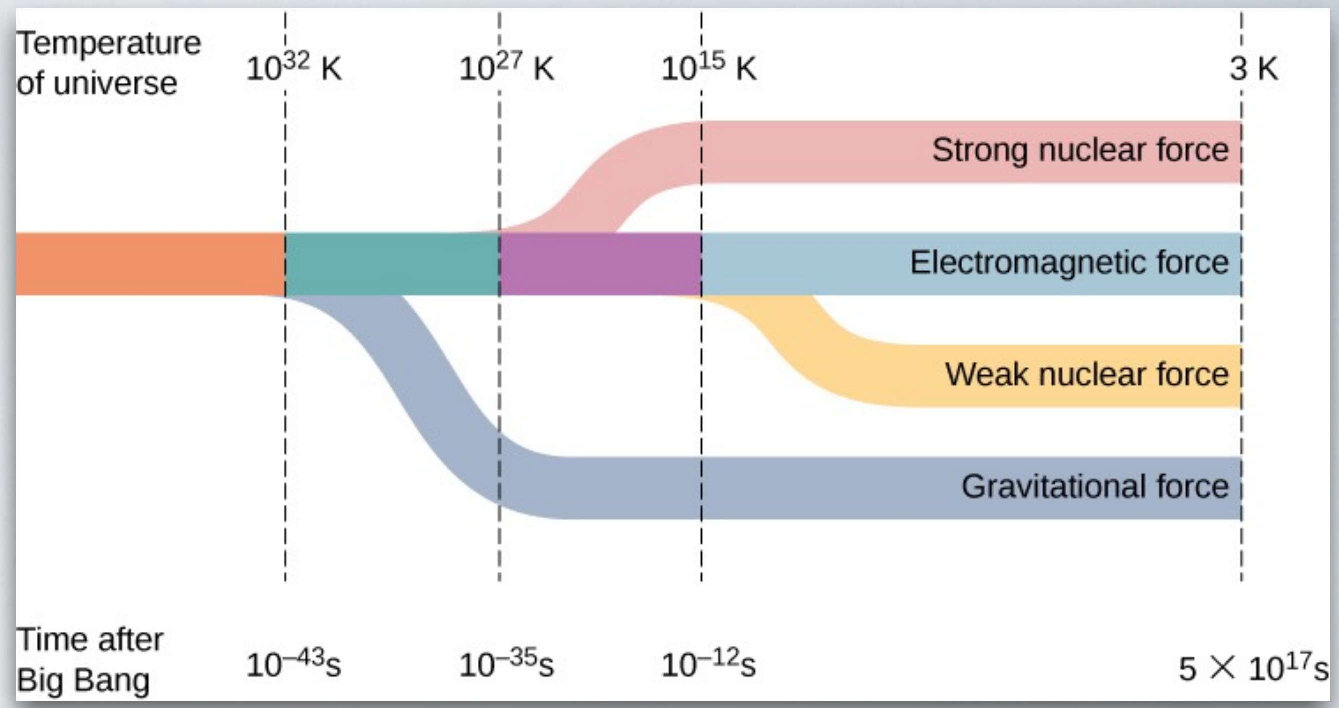
- Big Bang happens at t = 0
- The **Planck Epoch** ($t < 10^{-43}$s)
  - All fundamental forces are **unified**, including gravity
  - We have **no working theory** for the physics during this epoch (quantum gravity)
- End of the Planck Epoch ($t = 10^{-43}$s)
  - **Gravity decouples** from other forces, General Relativity starts to describe gravity
  - Gravitons cease their interactions with other particles and start freely moving through space
  - A background of gravitational waves is produced (but almost completely redshifted away by the present day)

The Unified Epoch

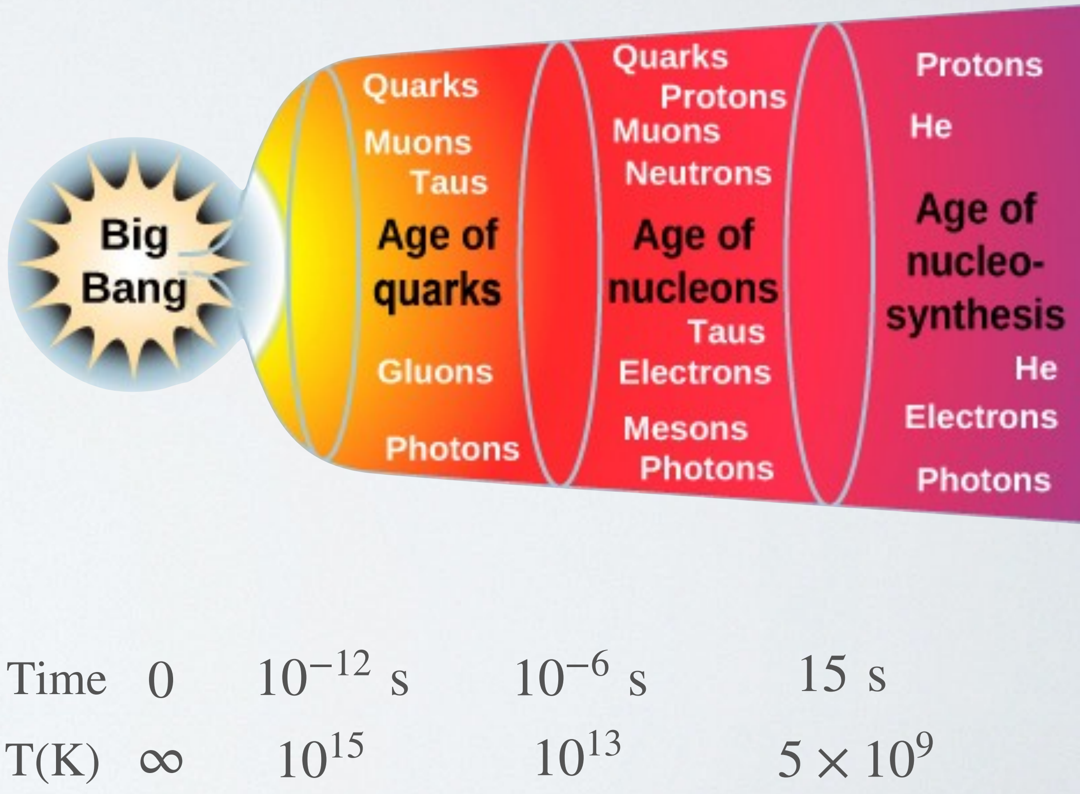


- Lasts from t = 10^{-43} s to 10^{-35} s
- **Two forces** operate:
  - Gravity (described by GR)
  - All other forces (described by GUTs): Strong, Weak, Electromagnetic
- During unified epoch (~10^{-37}s), Universe is believed to have undergone a period of **exponential expansion called "inflation"**
  - Size of universe expanded by factor 10^{100} to 10^{1000}
  - Will discuss inflation later in the course
- At end of epoch, GUT force splits into Strong and Electroweak force

The Electroweak Epoch

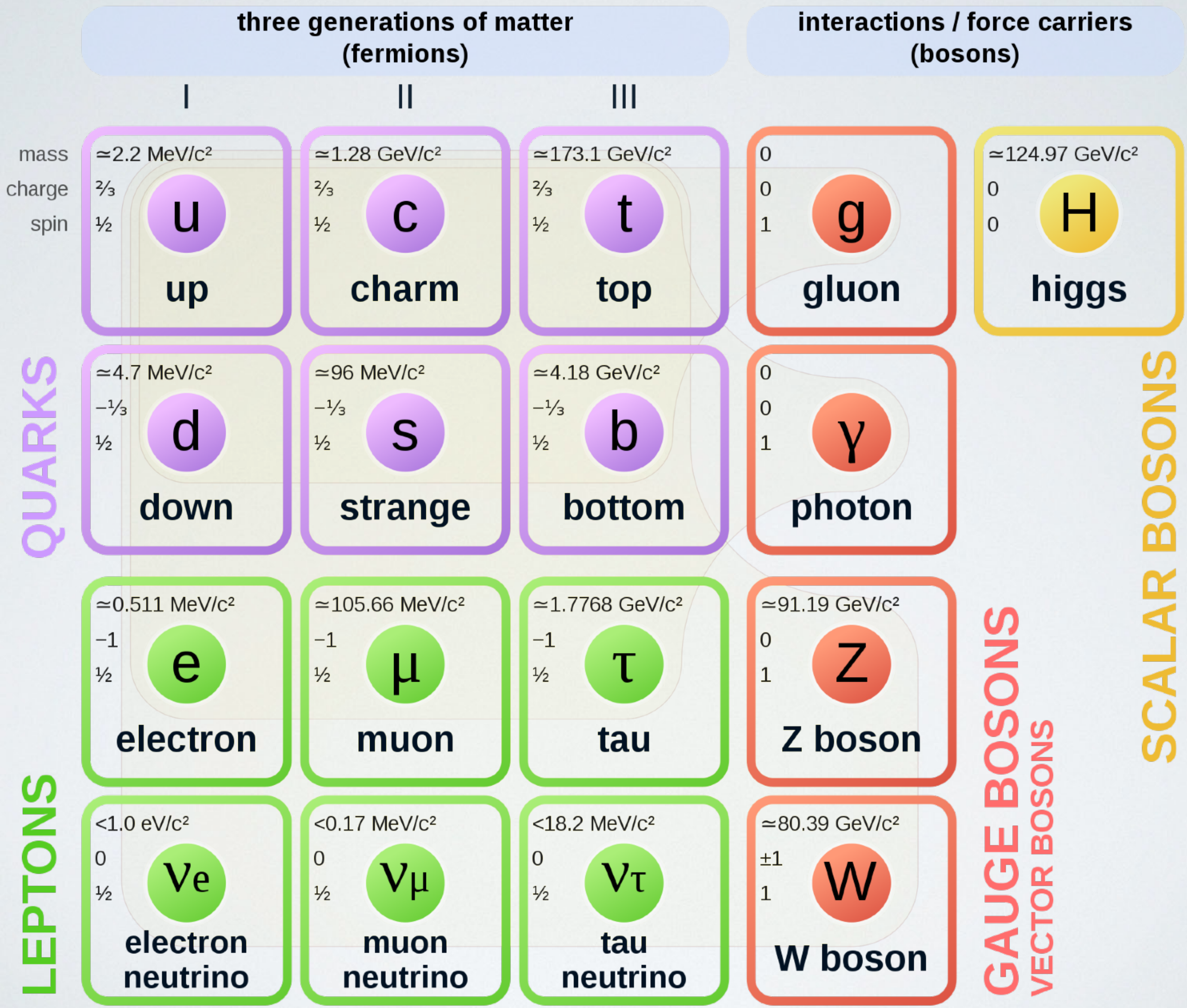


- Lasts from t = 10^{-35} s to 10^{-12} s
- **Three forces** operate:
  - Gravity (described by GR)
  - Strong (nuclear) force
  - Electroweak force
- Ends when weak and electromagnetic force separate
- At end of "very early Universe", we have arrived at "normal" physics
- Still, the temperature is so high that there are no atoms or even nuclei

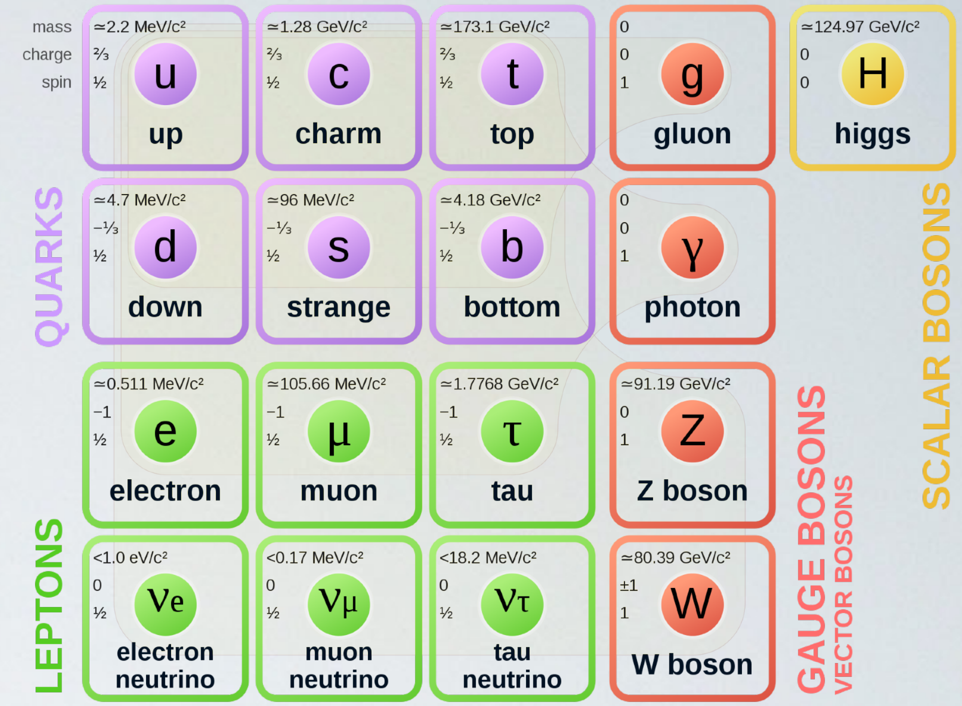


Part 4: The (slightly less) early Universe

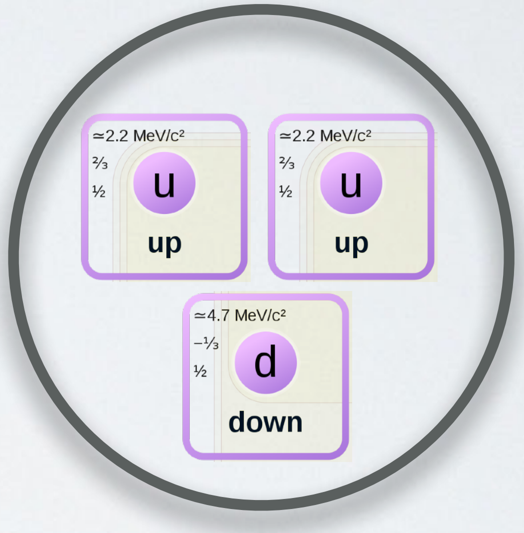
Standard model of elementary particles



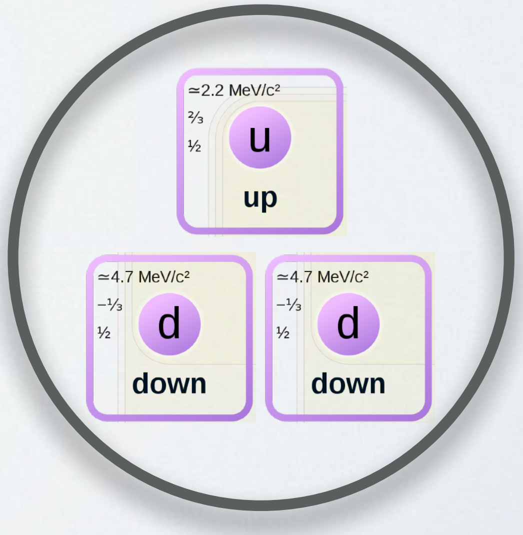
Particles



- Particles created/annihilated in the very early Universe were more than the ordinary types of particles abundant today (protons, neutrons, electrons, photons, neutrinos)
- More exotic particles are observed today only as products of collisions in high-energy accelerators
- Two types of particles: fermions and bosons
  - Primary duty of **fermions** is to make up **matter**
  - Primary duty of **bosons** is to mediate **forces**
- **Fermions** include:
  - Particles made from quarks, called **hadrons**
    - **Baryons** are made of 3 quarks (e.g. proton, neutron)
    - **Mesons** are made of 2 quarks (e.g. pion)
  - Particles not made from quarks, called **leptons**
    - Electrons, muons, tauons
    - Neutrinos
- Hadrons are generally more massive than leptons

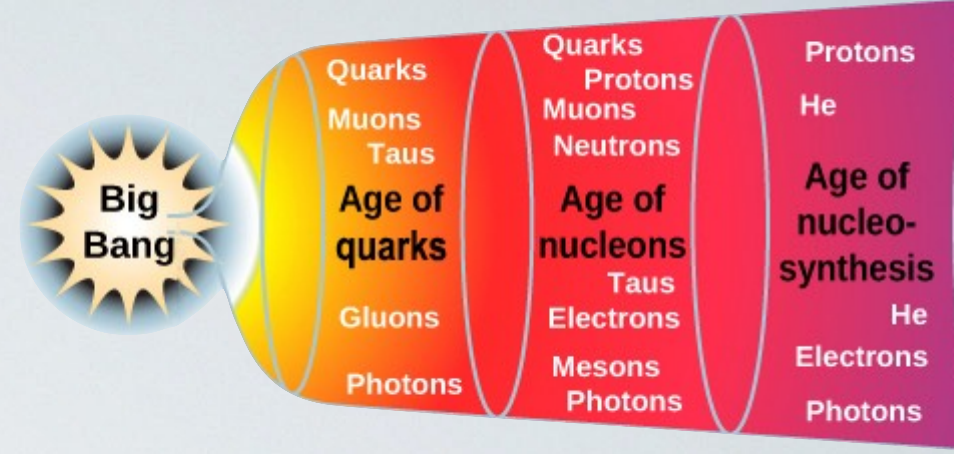


proton



neutron

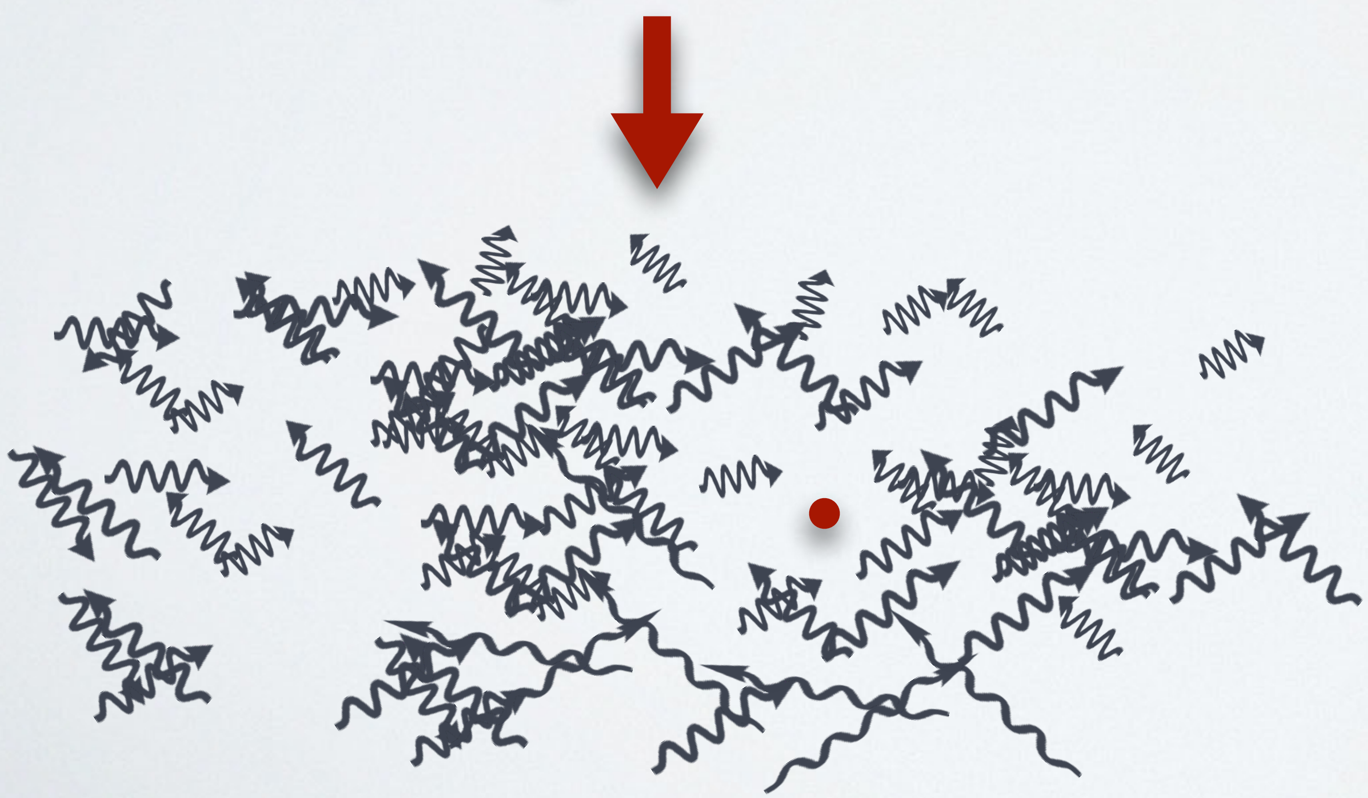
Quark Epoch



Time	0	10^{-12} s	10^{-6} s	15 s
T(K)	∞	10^{15}	10^{13}	5×10^{9}

- Lasts from 10^{-12} s to 10^{-6} s
- Universe consists of soup of
    - Quarks
    - Gluons
    - W/Z bosons
    - Photons
    - Leptons
    - More exotic particles
- Quark epoch ends when **quarks** pull themselves together into **hadrons** (mesons and baryons)
- **Baryogenesis**
    - Slight asymmetry between particles & antiparticles
    - Get more matter than antimatter by 1 part in a billion
    - This produces all the matter we have today!

Matter-antimatter asymmetry



Get one particle and about 1 billion photons!

Take-aways

- **Radiation** was the dominant component for most of the evolution of the early Universe

- Radiation and matter were in **thermal equilibrium**, where particles can be freely created and destroyed if the **temperature** is above the **threshold** for their mass

- The **four fundamental forces** (strong, electromagnetic, weak, gravity) were initially **unified** and then separated

Next time…

We'll talk about:

- How the elements were created

Assignments

- Post-lecture quiz (by tomorrow night)

Reading:

- H&H Chapter 12