Quarknet Syracuse
Summer Institute
Lecture 1

Quarks and the Universe
The Cosmic Connection

Introduction

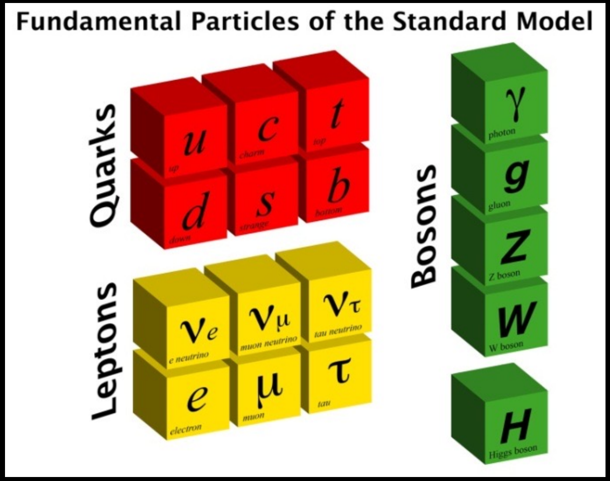
- "Laws" or theories used to describe nature
  - Driven by observation (measurement)
  - Postdictive & (hopefully) predictive

- Particle Physics
  - Aims to describe the most fundamental objects in nature and the force laws that govern their interactions.
  - Currently: Standard Model (SM)
    - 6 Quarks, 6 leptons, and force carriers (γ, gluon, $W^{\pm}$, Z)
    - Works very well, but certainly an effective theory

  - #1 Goal in Particle Physics: Expose & elucidate the most fundamental theory of matter…. and many reasons to believe the SM is not it !

  - 'New Physics' is any observation that is not in accord with the SM.

The sub-standard model !



Many key questions unanswered by SM

- Why 3 generations?
- Hierarchy problem?
- Explanation/origin of masses?
- Unification ?
- How does gravity fit in?
- Matter dominance over antimatter ?
- … + more

Many key question unanswered in Cosmology

- What is the dark matter in the Universe?
- What is the dark energy in the Universe?
- What caused inflation?
- ...+ more

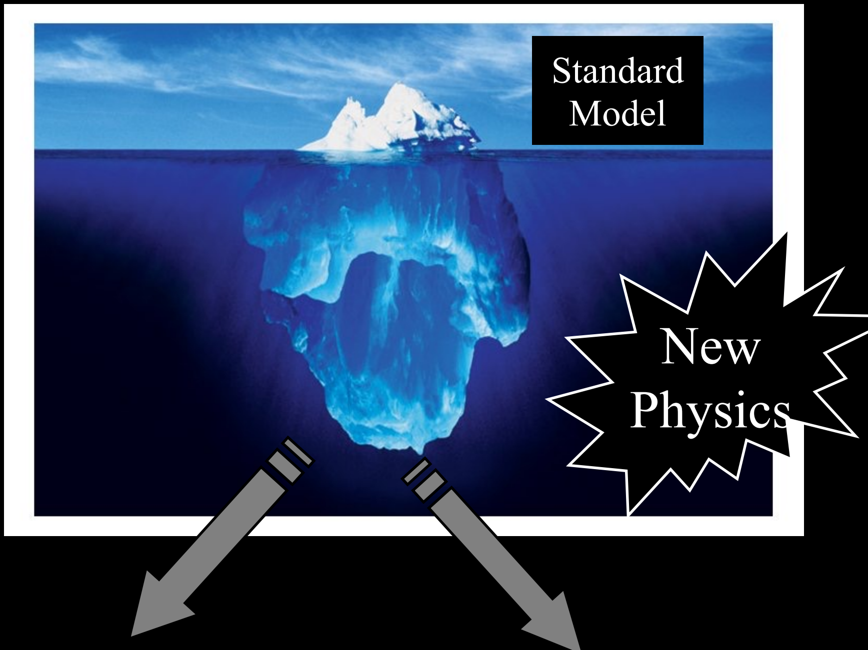
The Connection: Expected that whatever the "New Physics" is that addresses SM questions also provides a candidate particle that forms the Dark Matter in the Universe

This "new particle" ought to be observable in accelerator-based experiments

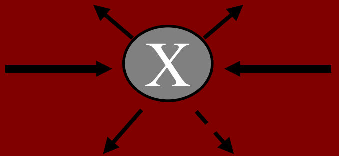
The Future of particle physics

- Higgs boson is a key piece of the Standard Model
  - Origin of mass in SM, yet to be discovered

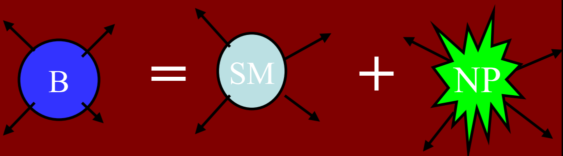
- But primary mission in HEP is to uncover and elucidate New Physics that will help answer the fundamental shortcomings of the Standard Model
  - more complete theory of matter



Direct Searches for New Particles (CMS & ATLAS)



Precision measurements & rare decays (B decays as an example)

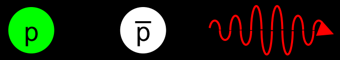


It All Began about 14.5 BYA

An
Explosion
of
Space-Time

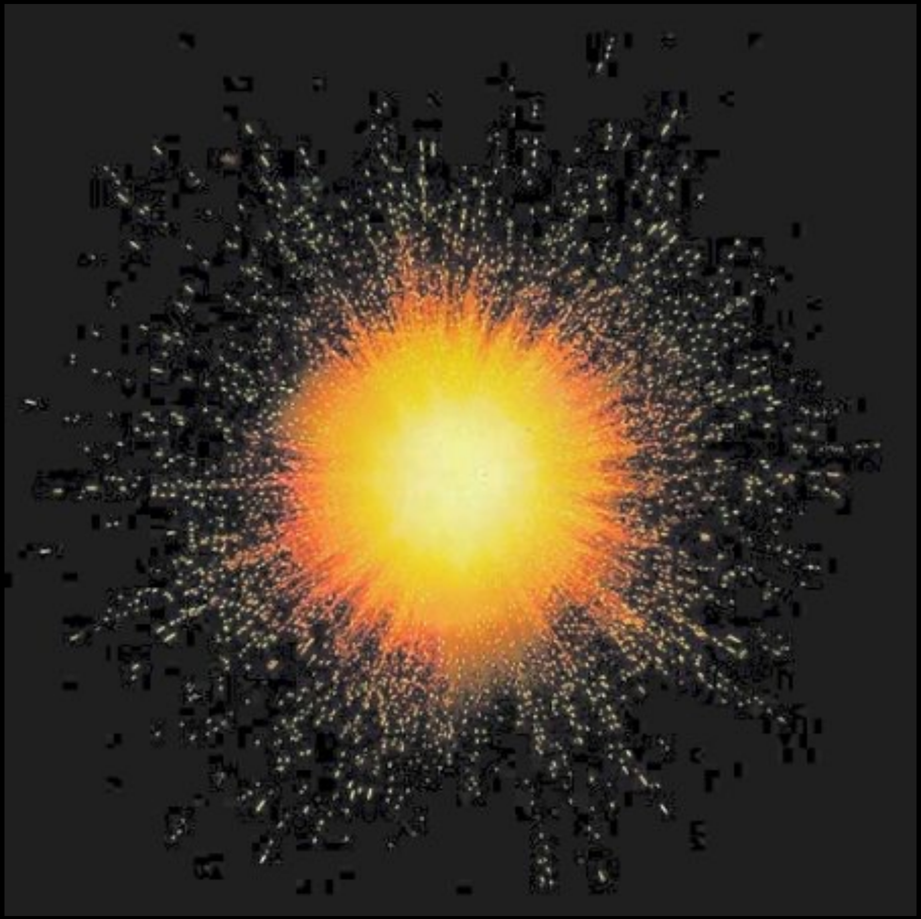
Tremendous
energy
released

Energy converted
into equal numbers
of particles, antiparticles
photons

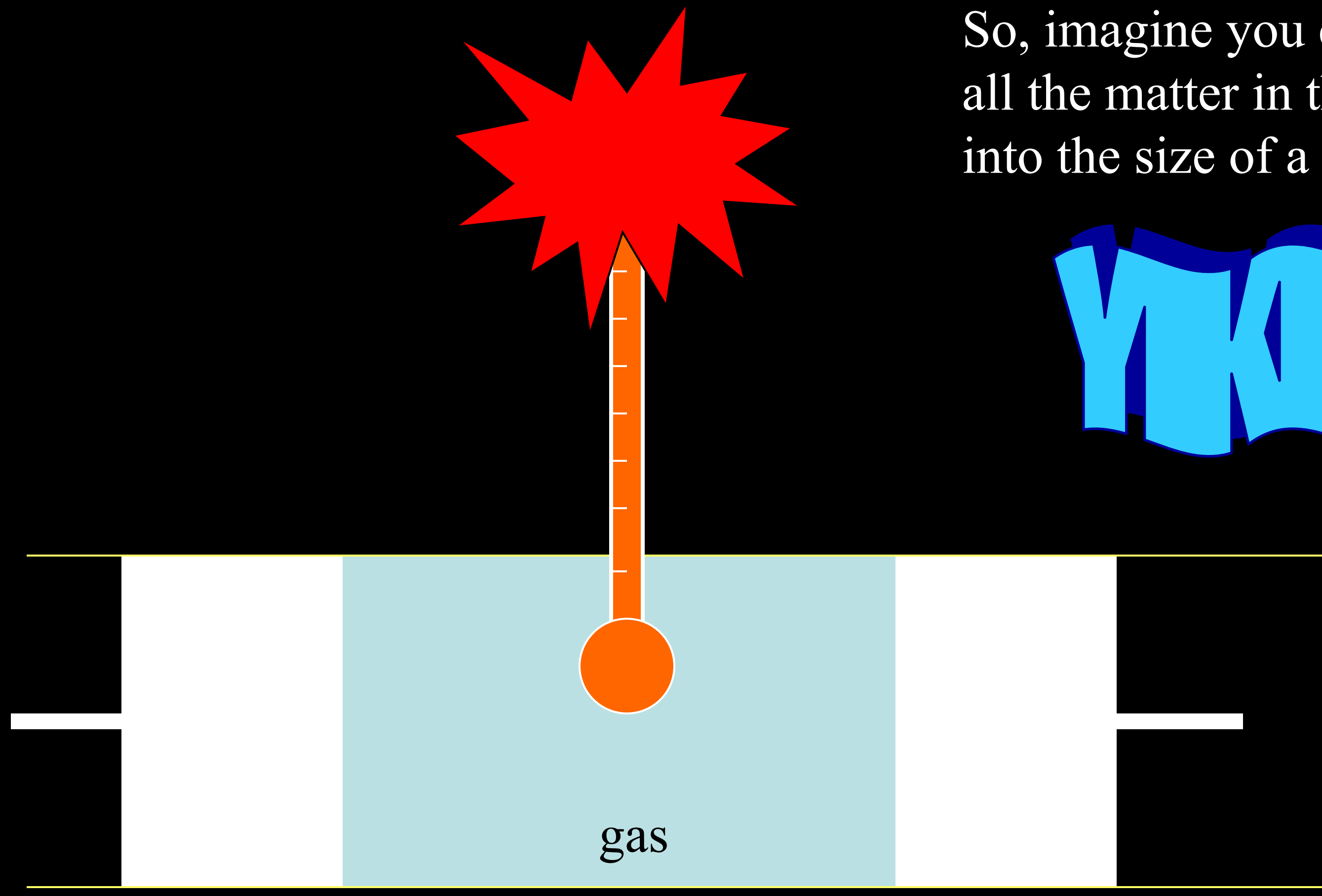


moving at very
high speed (temp)

Only most
fundamental
particles around.



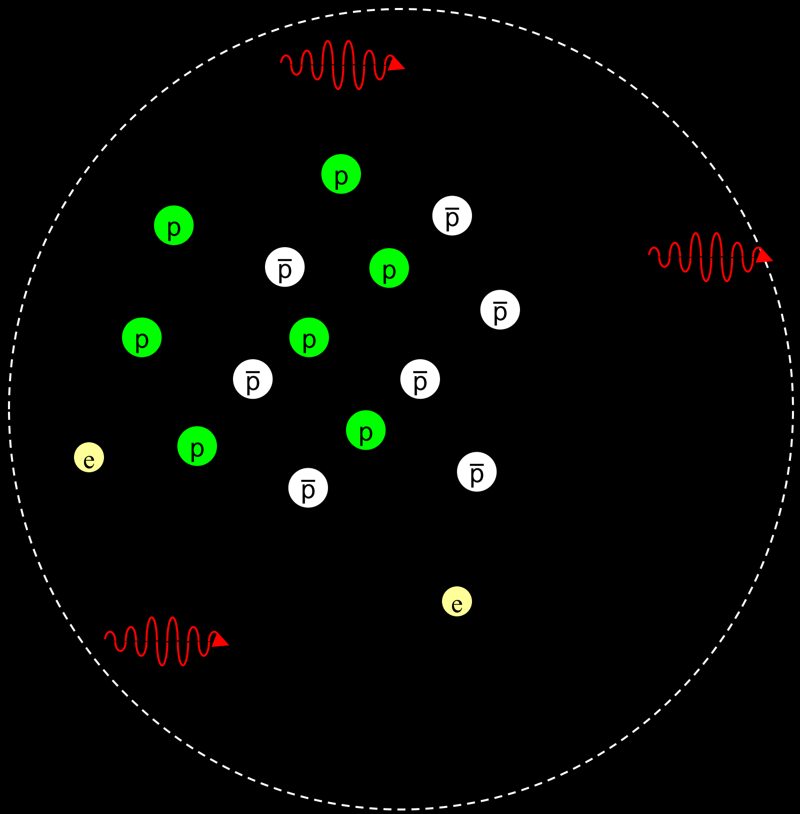
When gases are compressed they get HOT!



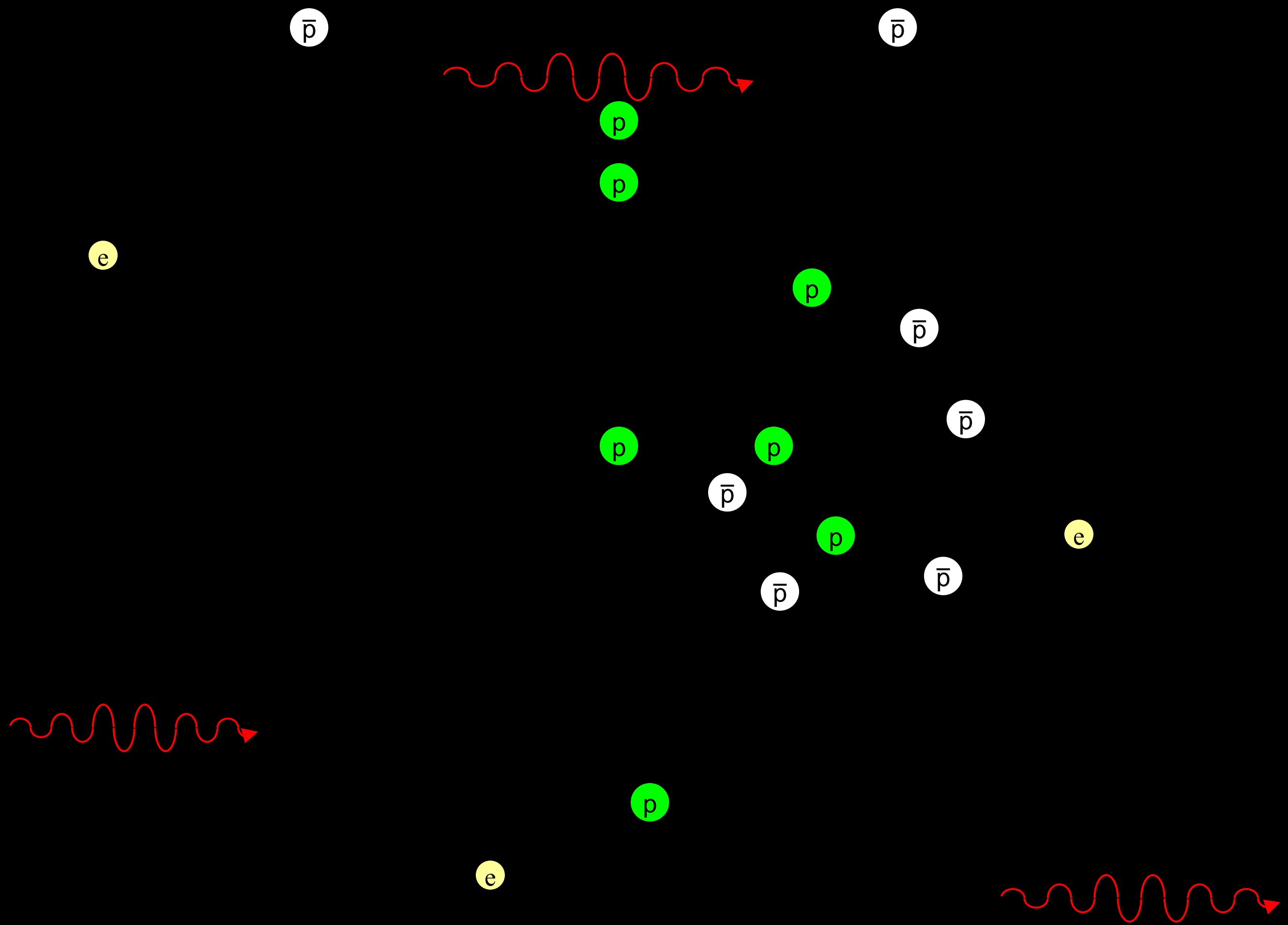
So, imagine you compress all the matter in the Universe into the size of a baseball!

YIKES

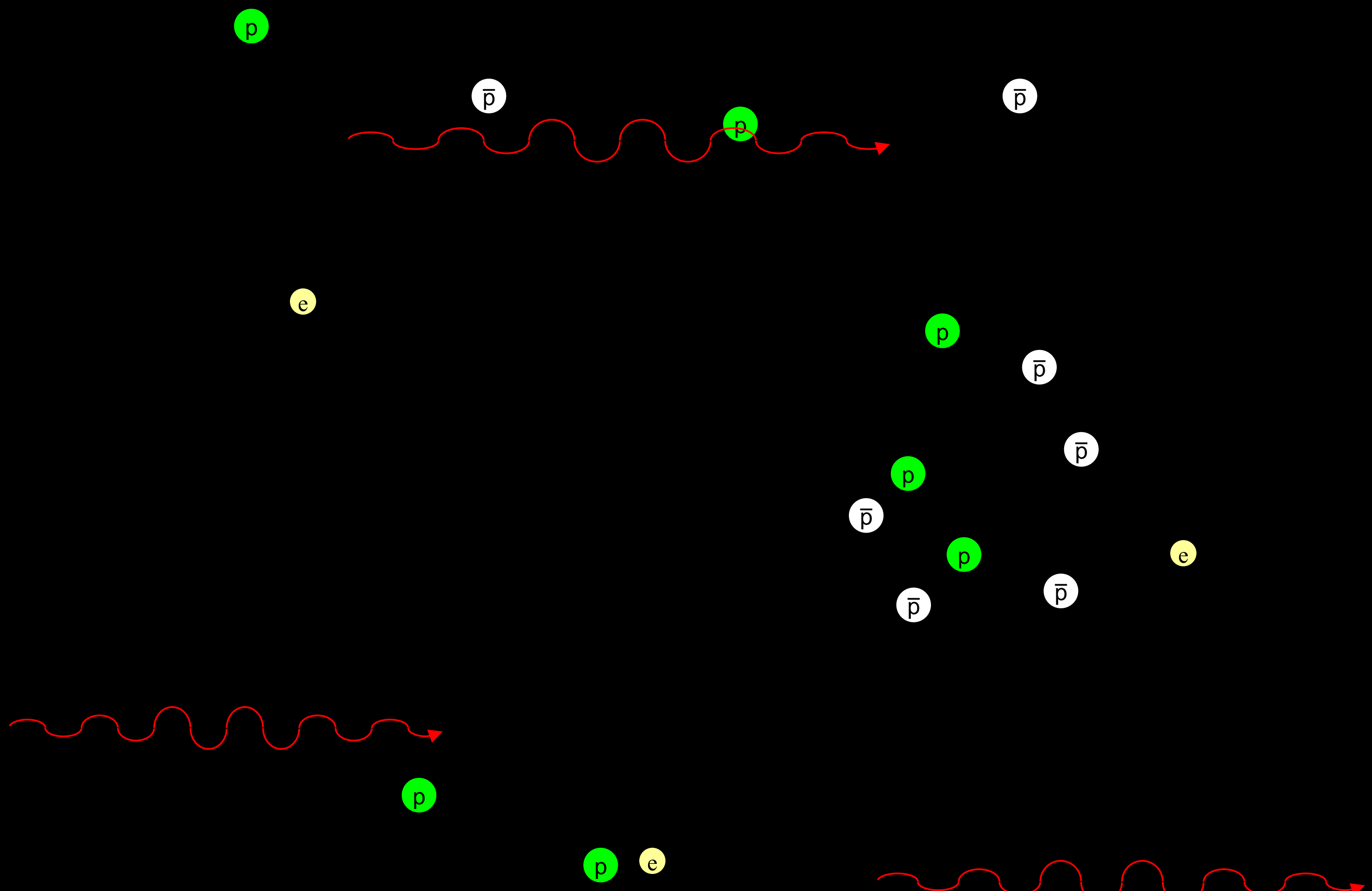
It All Began about 14.5 BYA



But as the Universe Expanded, it Cooled

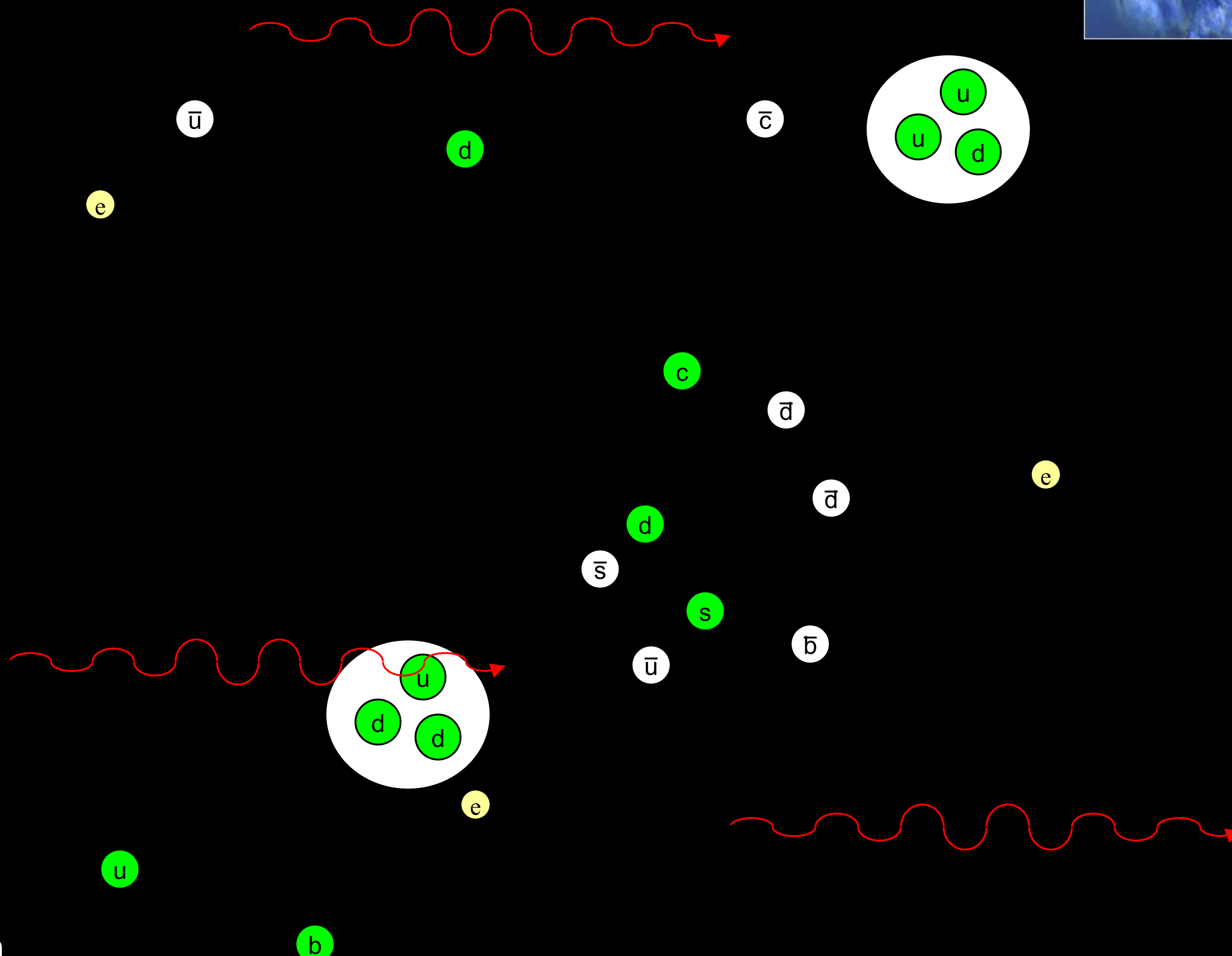


And Cooled …



Until

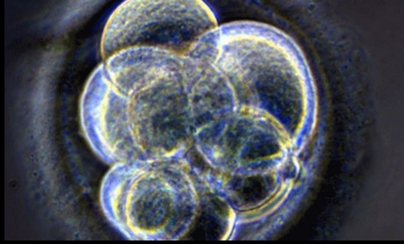
Protons and neutrons began to form



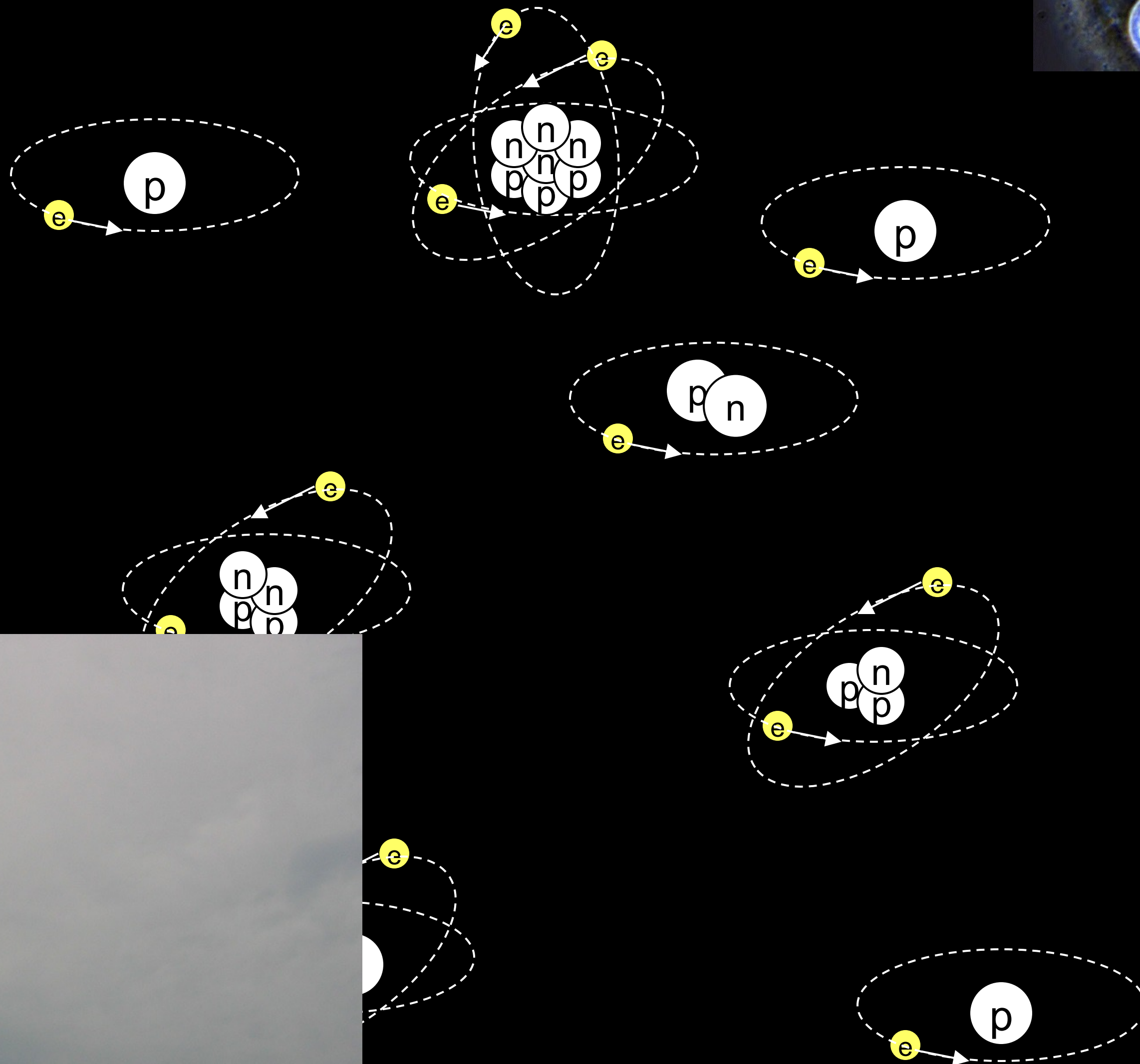
All of this happened within the first second after the Big Bang

Over the next ~300,000 yrs, protons & neutrons will combine to form light nuclei (H, He, D, Li)

Then…at about 300,000 yrs

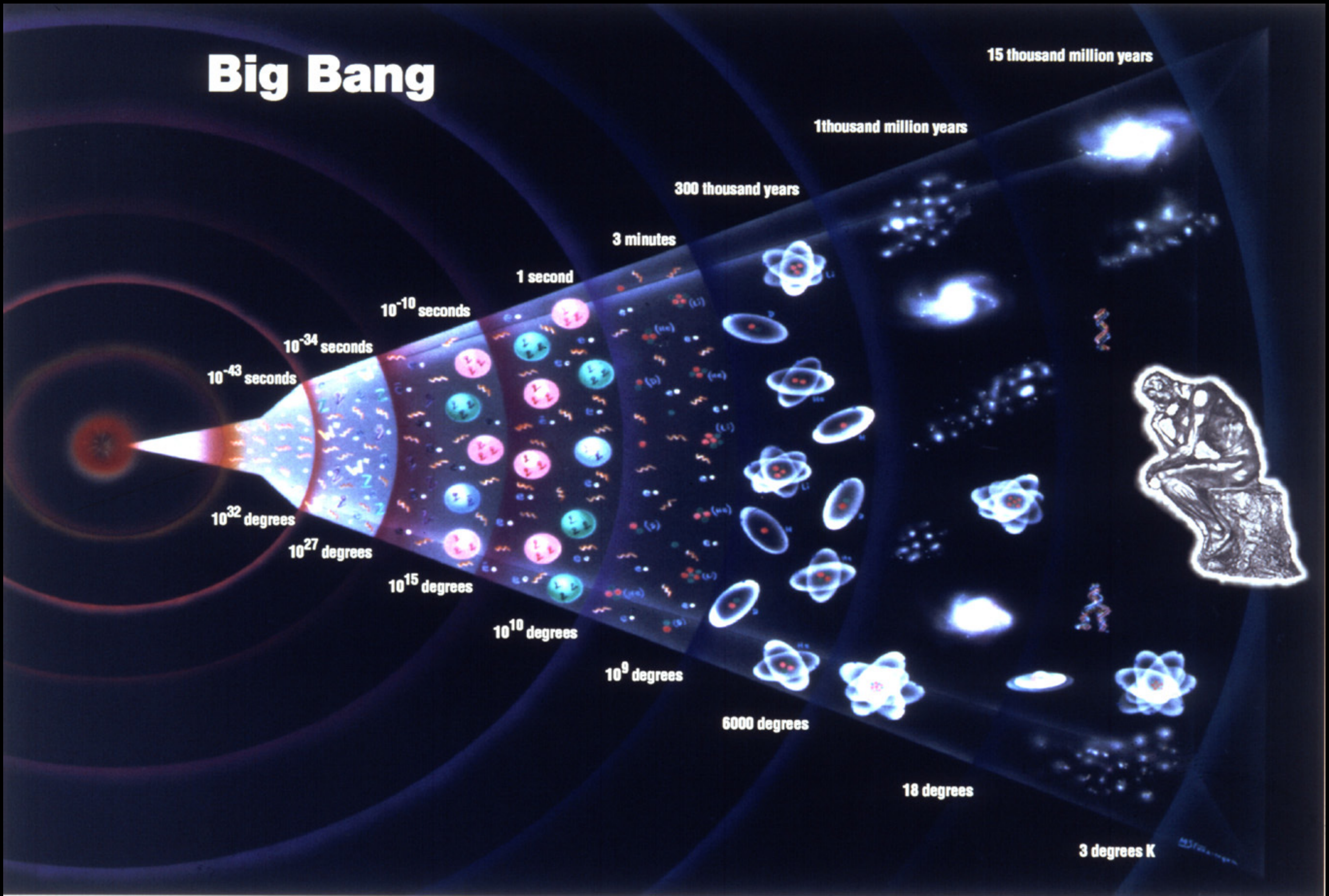


Electrons combine with light nuclei to form neutral atoms

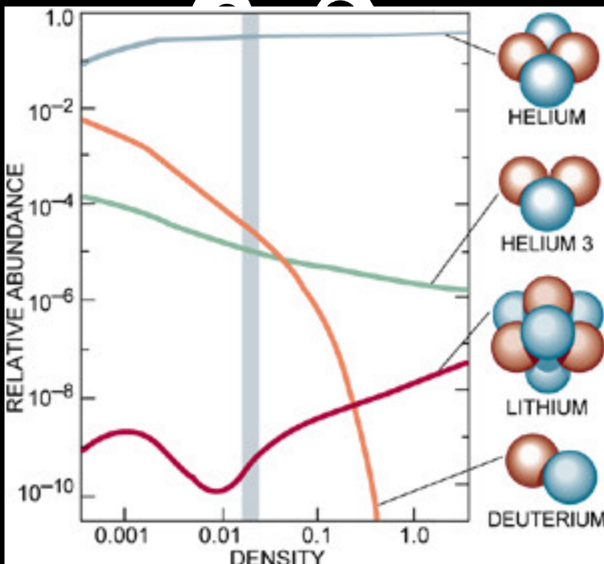


Then, Gravity took hold!

14.5 Billion Years of Evolution

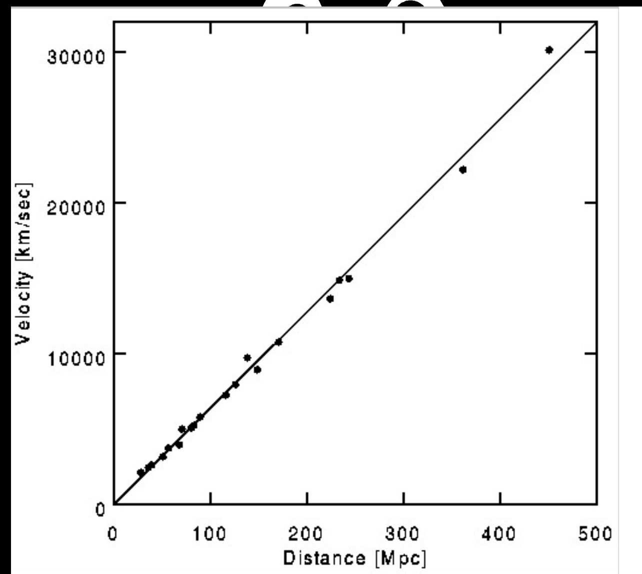


3 Pillars of Big Bang Theory



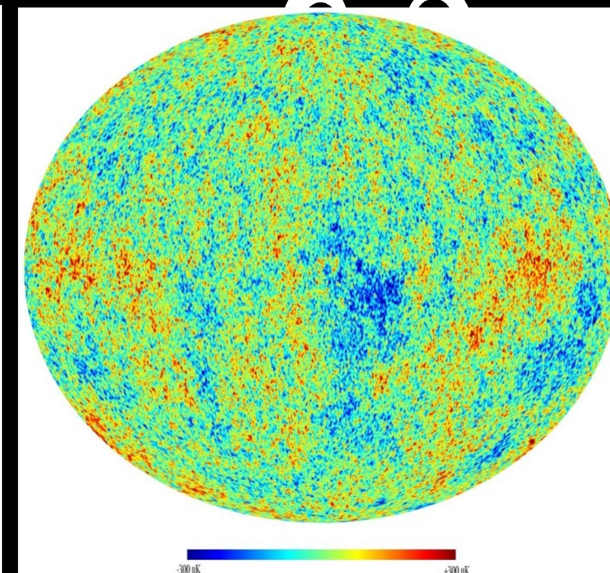
Big Bang
Nucleosynthesis

Explains the abundances
of the light elements
in the Universe



Hubble
Expansion

All objects receding
from each other at a
speed which is proportional
to their distance

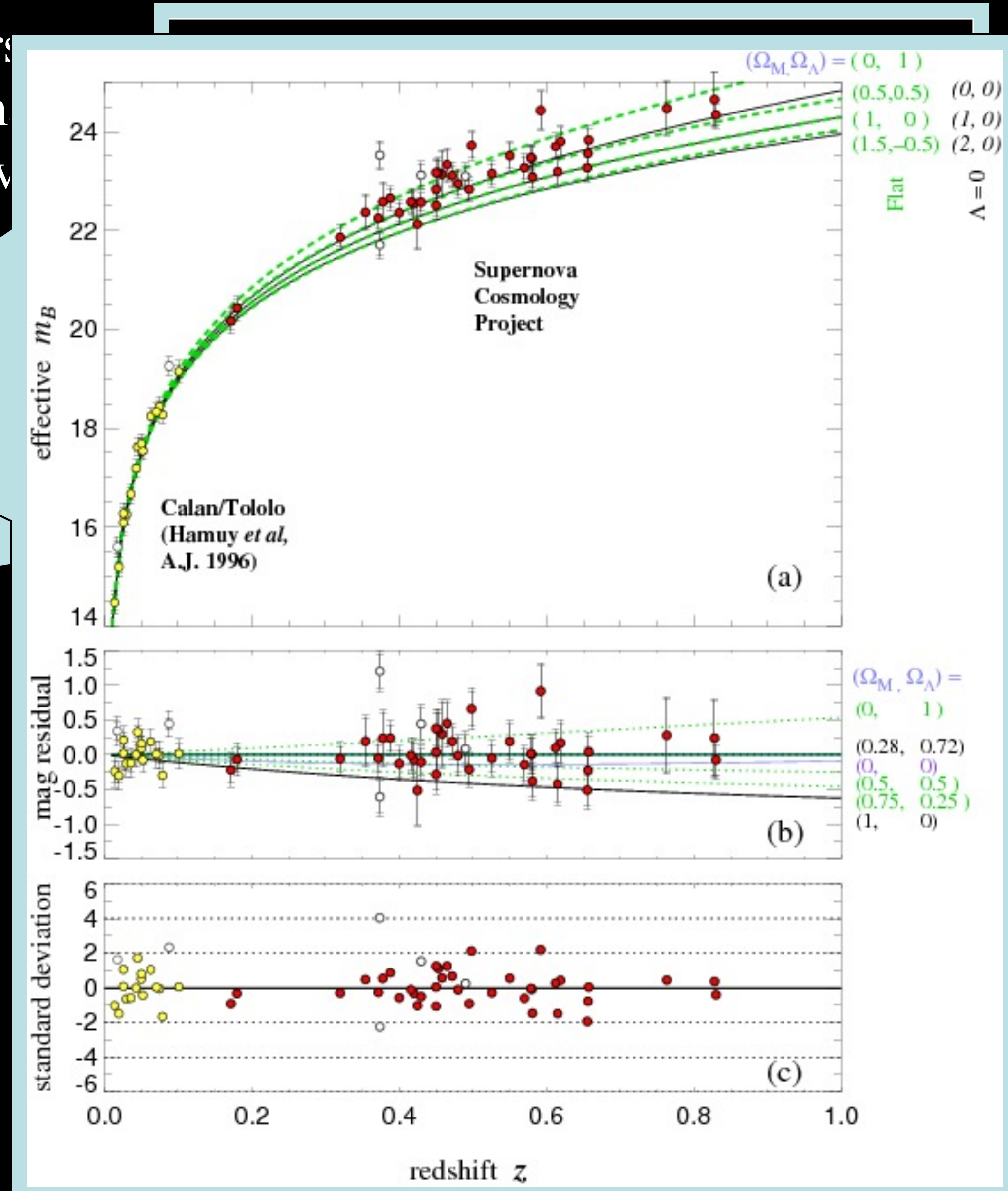


CMB
(Cosmic Microwave Background)

"Microwave" photons left
over from the BB permeate
the visible Universe.
Temp. uniform to ~0.00001 ^{o}C

But mysteries remain

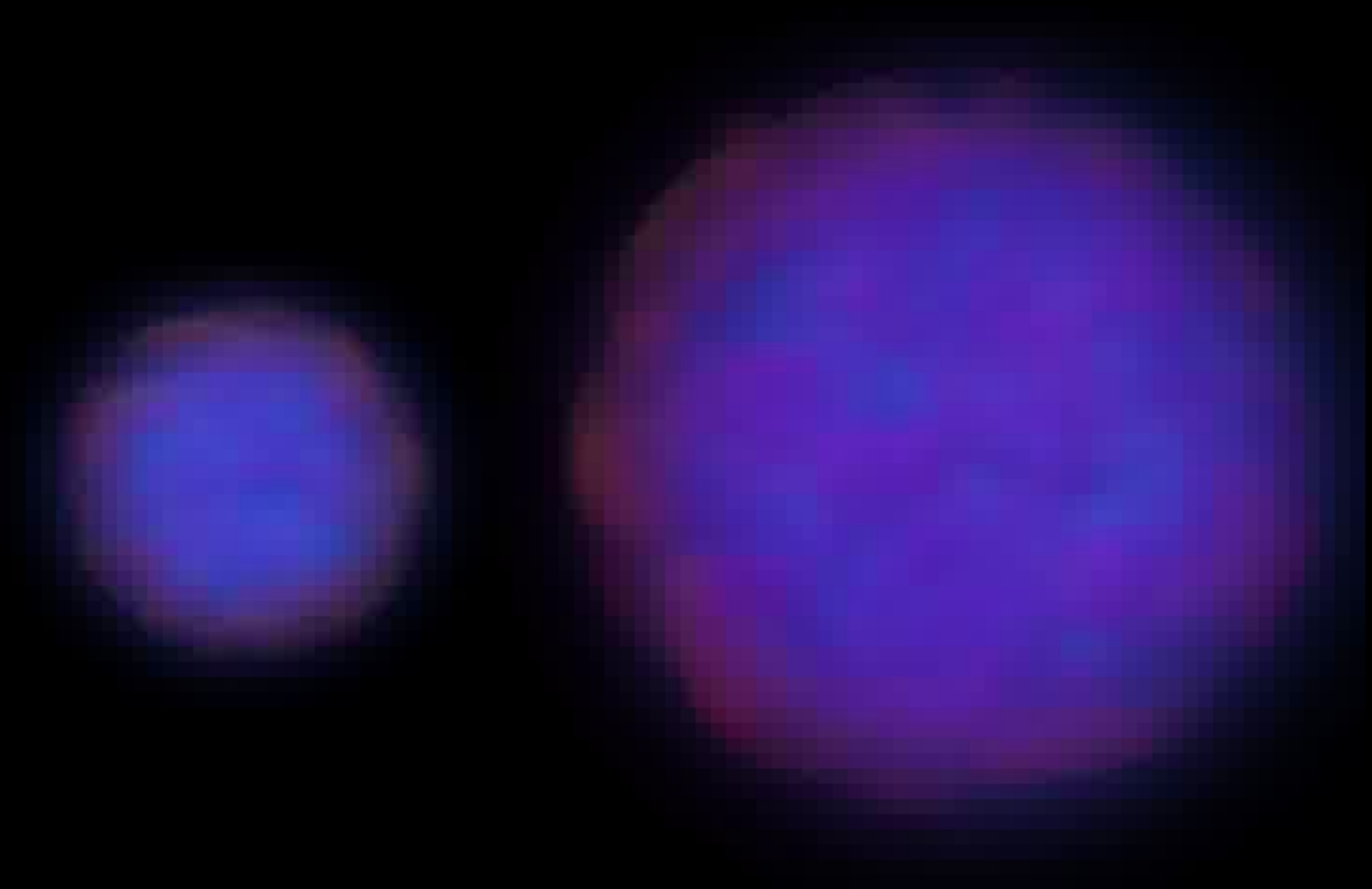
Many observations of galaxies, clusters
Type 1 Supernovae, CMB, Gravitation
lensing, etc all point to a mystical Univ



All the “visible” stuff only constitutes about 4% of the energy budget of the observable Universe.

- ❑ 6X more dark matter than ordinary matter???
- ❑ Dark energy permeating all space
  → Causing Universe to *accelerate*

Dark Matter & the Bullet cluster



Some mysteries from Cosmology

1) What is the dark matter?
   - It is not ordinary matter (cannot be seen optically)

2) What is the dark energy
   - Fate of the Universe?

3) What happened to all the antimatter?
   - It was produced in equal abundance in the Big Bang, yet today there is none left… whew!

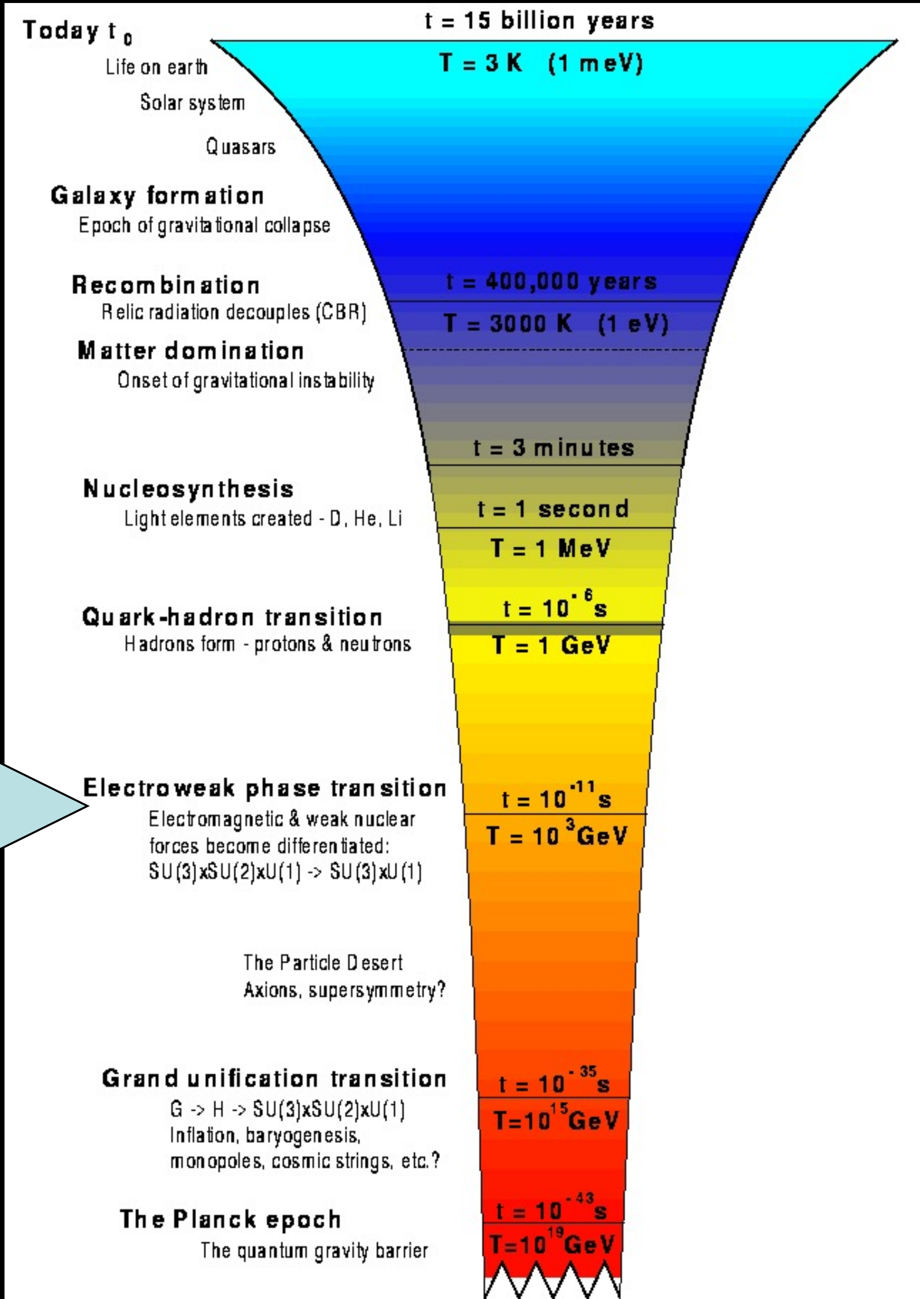
4) What were the Laws of Nature ~10^{-30} sec after the Big Bang (T~10^{30} C) ?
   - Presumably something different than what we see today at -270 C

Turns out, we can probe (1), (3) and (4) in controlled experiments on Earth!

Game Plan

- Particles right after Big Bang had enormous energy
- Can we reproduce these energies in the lab (at particle accelerators) ?
  - –Not quite, but can get close!
  - – How close?

Energy = 10^{12} eV
time = 10^{-11} s

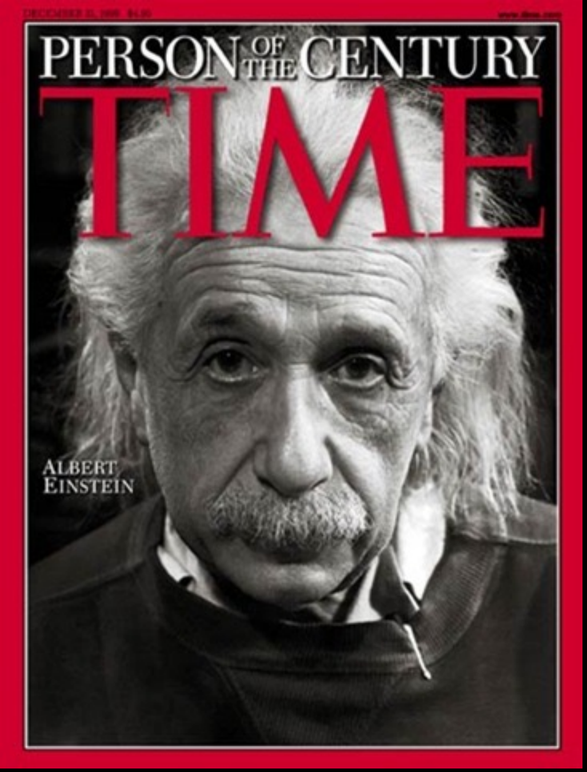


What laws of nature are in affect at this energy?

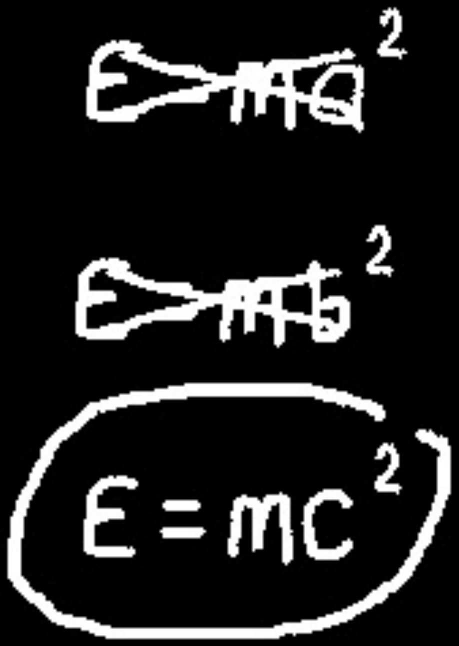
Two Key Points about high energy particle accelerators

1) Higher energy allows us to produce more massive particles
   - ❑ New particles → need a theory to explain them

2) Increasing energy is like turning up the magnification on a microscope
   - ❑ Higher energy → see deeper into structure of matter!



Energy & Mass



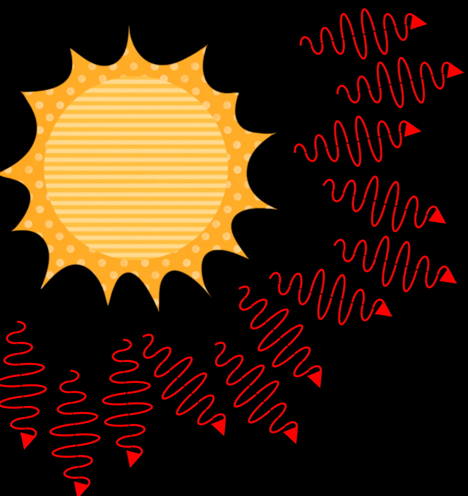
Mass can be converted into Energy

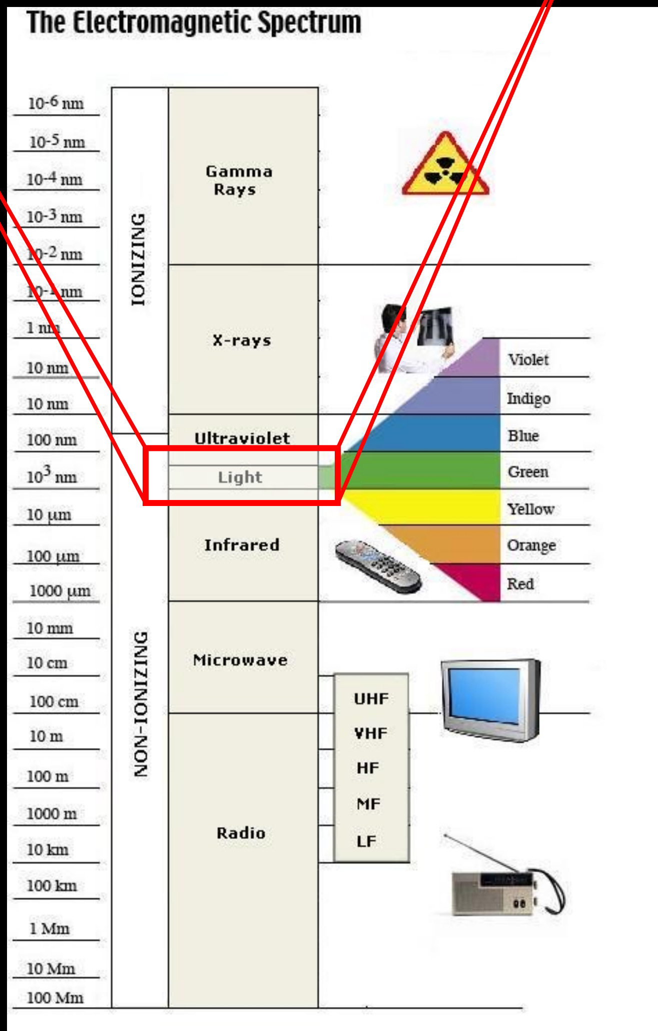
Energy can be converted into Mass

Energy and Resolving Power

Human eye sensitive to visible light

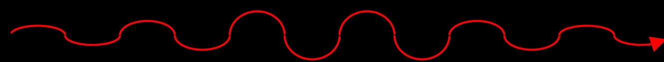
Limits what we can see to ~10^{-7} m



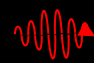


What if you want to see something smaller?

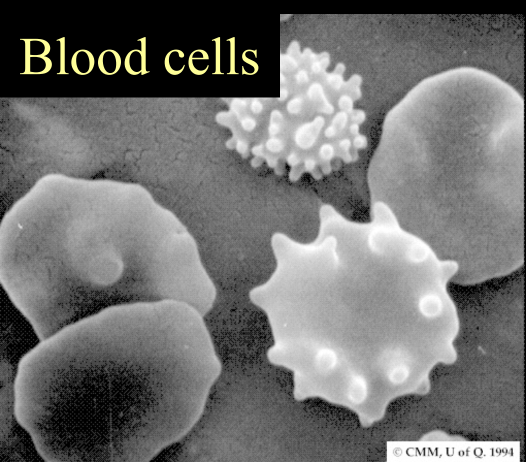
Electron microscope: electrons act as “waves”. Their “wavelength” is much shorter though. Finer wavelength → better resolving power!



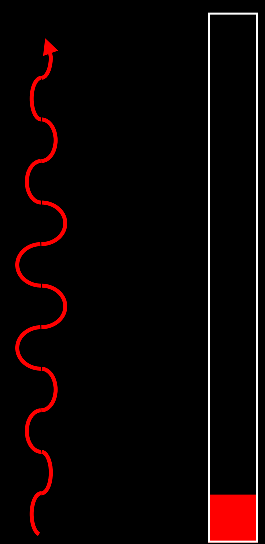
Light waves



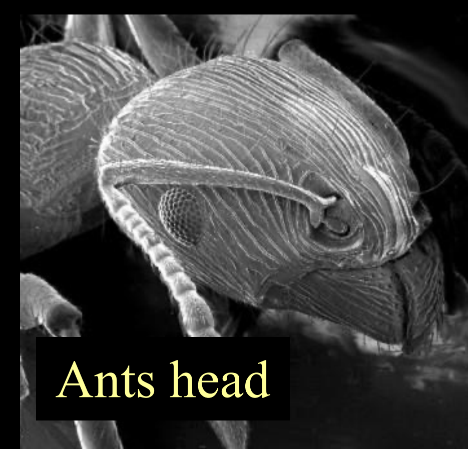
Electron waves



Better resolution requires
smaller wavelength wave
→ higher energy

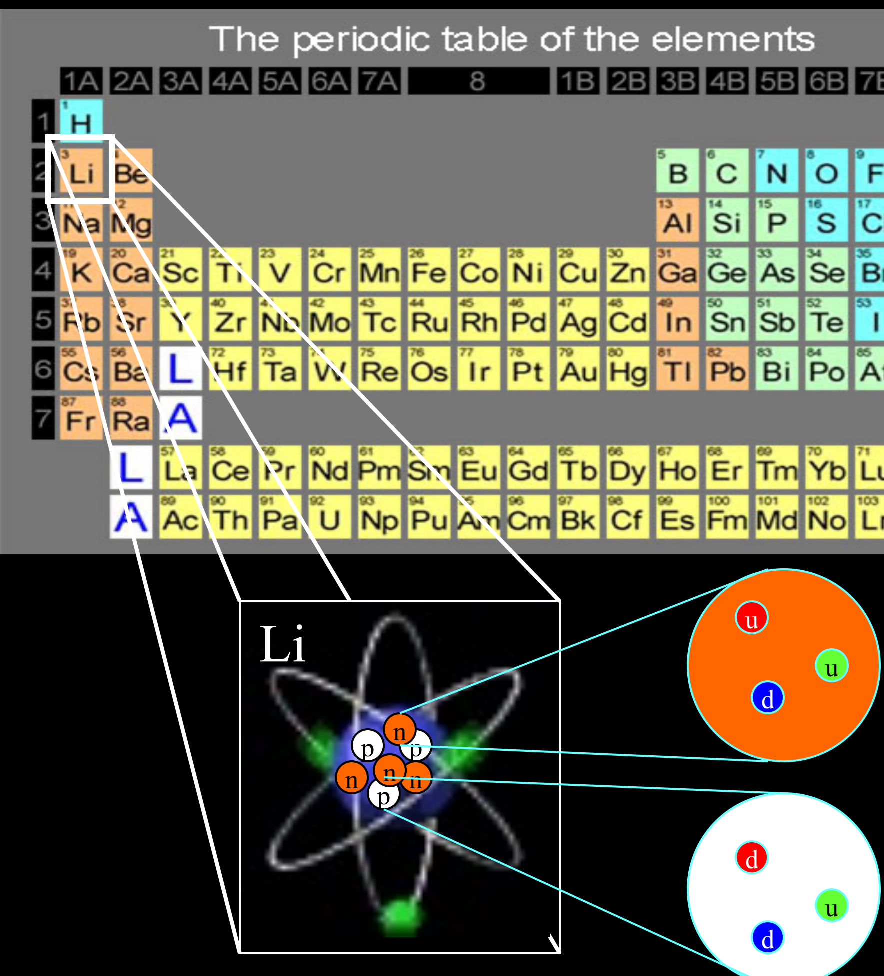


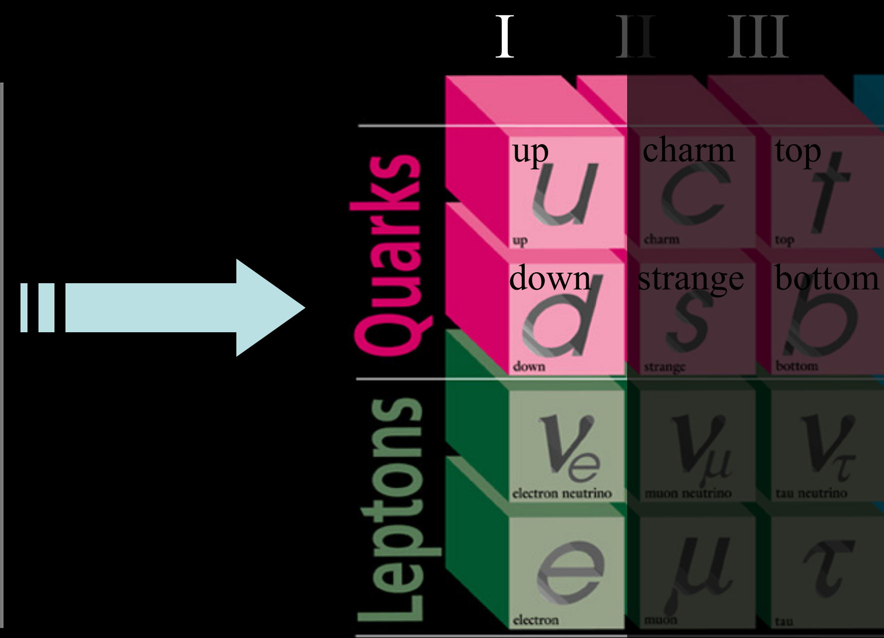
Energy
meter



The Standard Model

- What have we learned by experiments that collide particles at high energy?
  - A “new” periodic table.
  - Total of 12 **fundamental** particles





- Protons and neutrons are made of quarks
  - Proton (uud)
  - Neutron (udd)
- As with Lithium, all atoms are composed of u & d quarks and electrons!

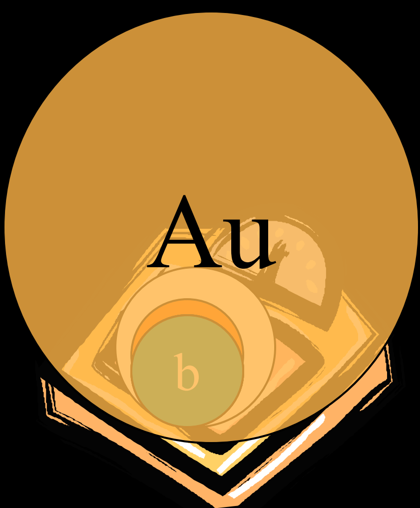
Why do “families II and III exist?

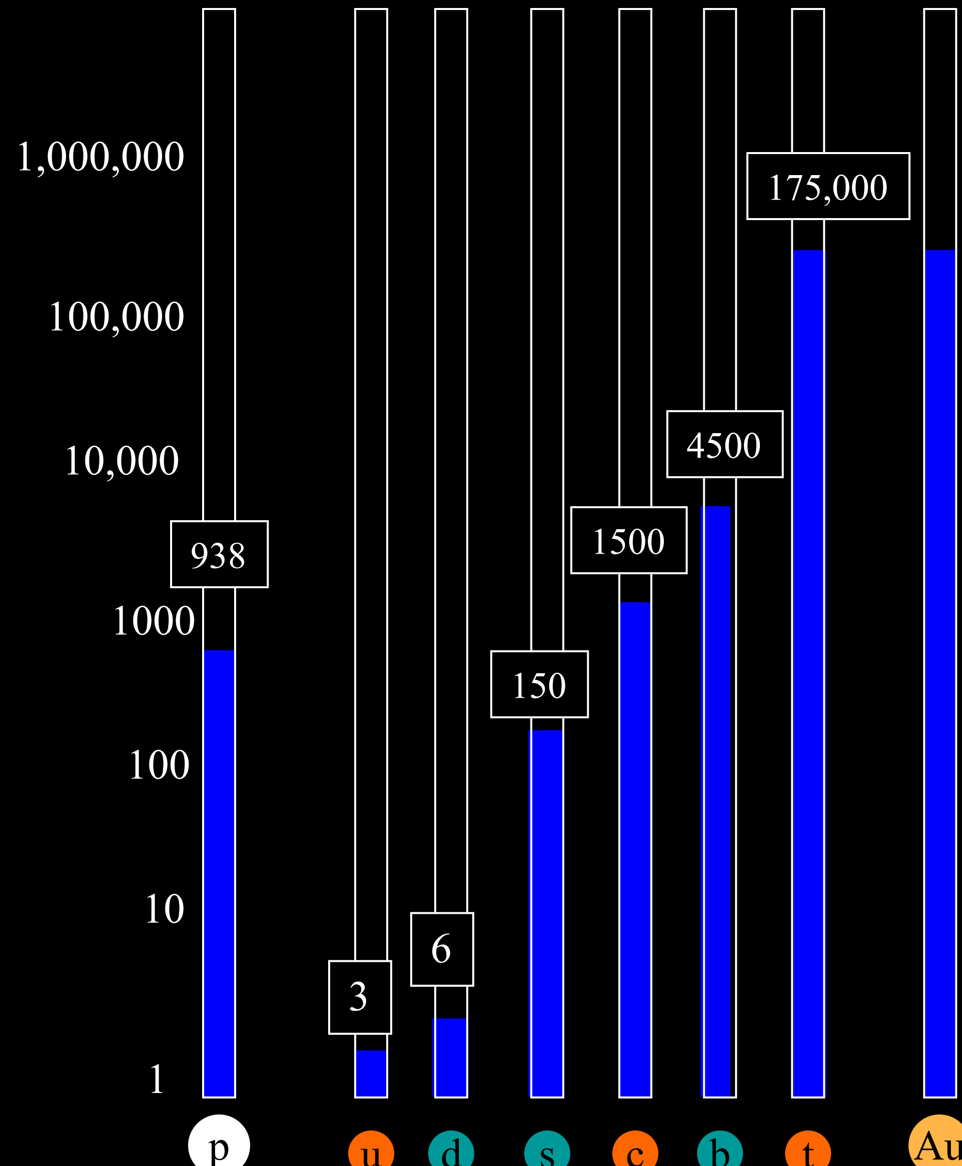
Quark Properties

- Charges?

I	II	III	
u	c	t	+2/3
d	s	b	-1/3

- Mass?
  - Let's weight them





Top quark is 60,000 times heavier than the up quark?

As heavy as a gold atom!

Why is ordinary matter composed of only up & down quarks?

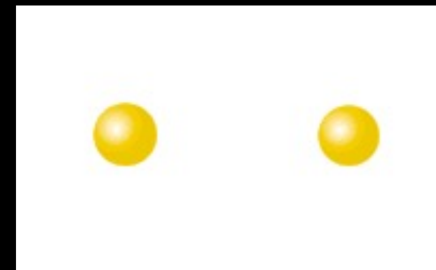
- s, c, b, t quarks are unstable, and decay to lighter quarks.
  - Once they reach the lightest ones (u,d), there are no lighter quarks. So after some time, only u,d quarks are left.

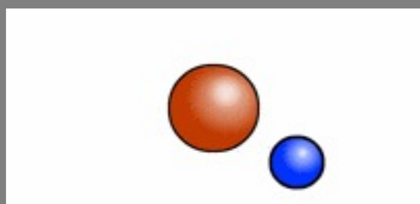
- Why do they decay?
  - Best answer: “Because they can!”
  - Fundamental postulate of physics (QM): “Unless nature strictly forbids something from happening, it WILL HAPPEN with some probability”

Laws of Nature

- Boils down to:
  - What are the fundamental particles ?
  - What are the **fundamental** forces in nature (that would govern the way the fundamental particles interact) ?

Forces





γ EM Force

There MUST be a stronger force present within the confines of the nucleus.

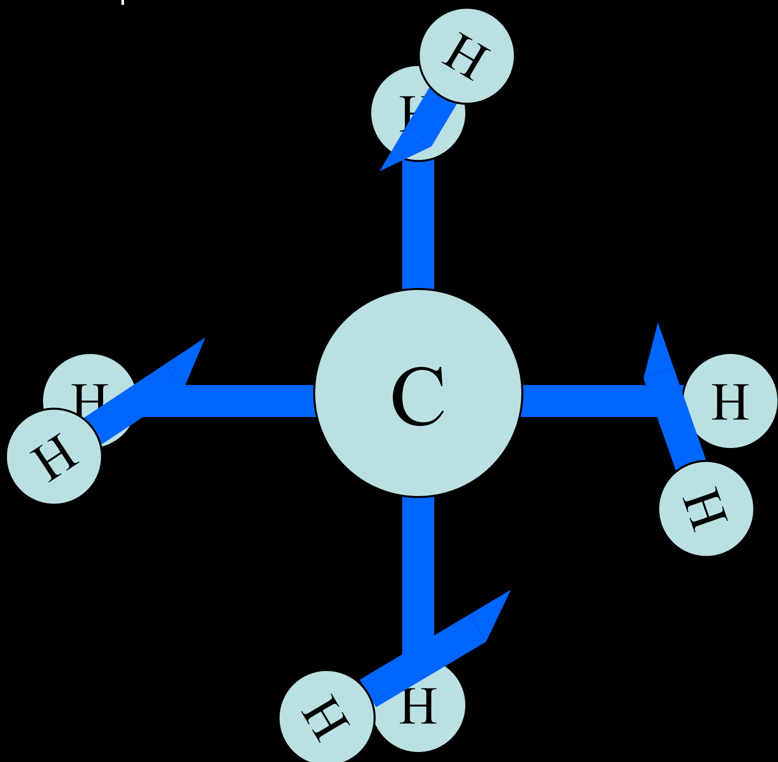
g Strong Force

$W^{\pm}$ Z^0 Weak Force

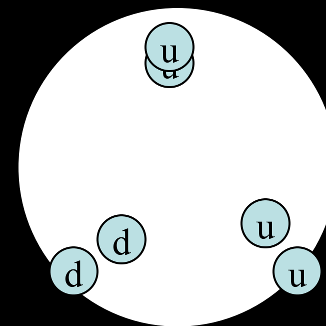
H^0 Higgs Boson

Binding and Heat

CH_4 covalent bonds



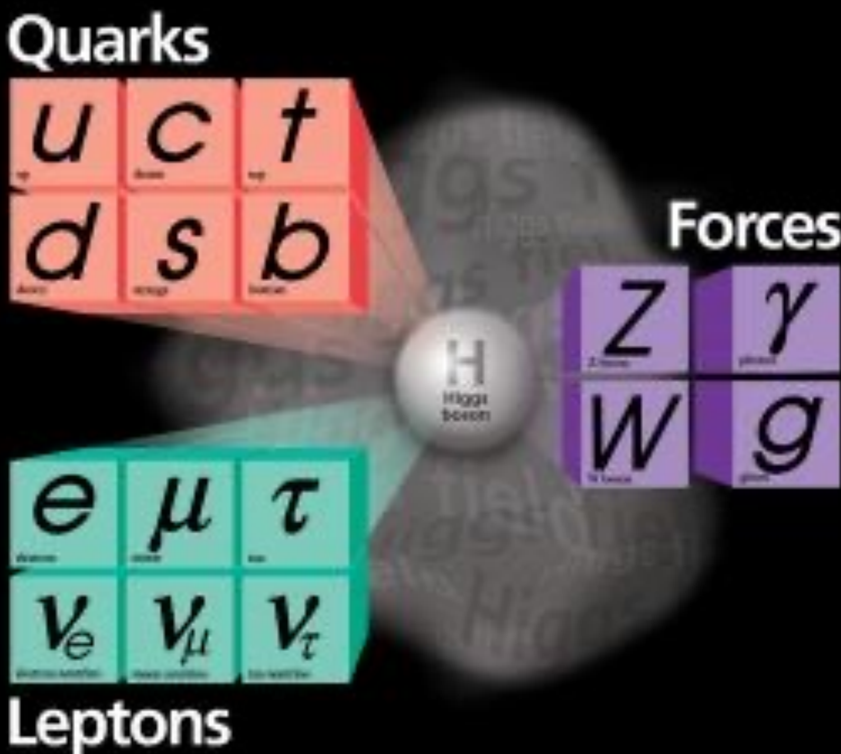
Strong Force binds quarks together to form a proton

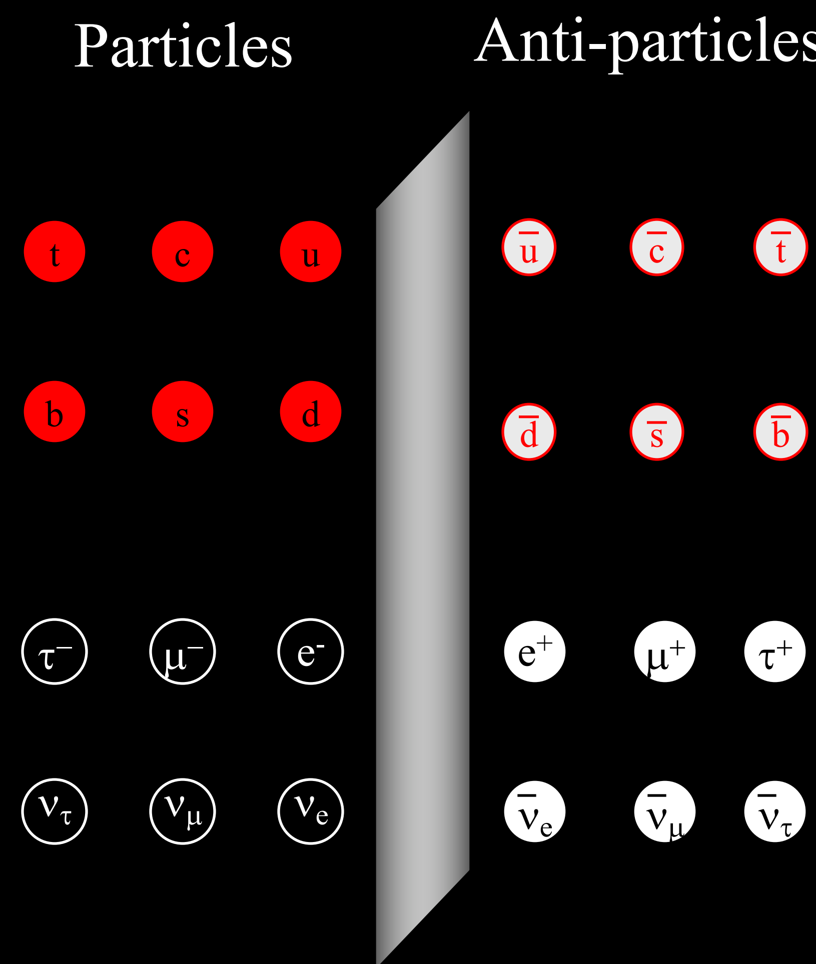


With enough heat, nothing can stay bound!

➔ Right after Big Bang T~10^{40}C ➔ Only elementary particles could exist (quarks, leptons?)

Standard Model of Particle Physics





Anti-particles have same mass but opposite charge wrt particle

Modern Physics is like an Onion

No, not because it makes you cry

- Goal of theory is to:

a) Explain existing data

b) Predict outcomes of future expt's.

- We seek the deepest possible explanation at any given time.
    - The Standard Model is almost certainly an "effective theory".
        - It describes data at today's reachable energies, but it almost certainly cannot fully describe physics 10^{-43} sec after the Big Bang!
    - There must be a more fundamental theory awaiting.
    - We're continually pulling off layers and getting a deeper picture.

Coming full circle

- Just after the Big Bang, $T=10^{40}$ means:
  - Only most fundamental particles around (all bonds broken)
- In collider experiments we study interactions of quarks and leptons.
  - The energies replicate conditions ~ 0.000000000001 seconds after the Big Bang
  - Potentially could reveal a "deeper layer" in the onion (new particles, new forces)
  - Many good reasons to expect that we will
    - Unanswered questions in the Standard Model (including "where's all the antimatter?")
    - Dark Matter – likely a new HEAVY particle (must be explained by a deeper theory)