# What is mass?

# The origin of mass in the Standard Model

# What is mass?

- This grandiose question is actually many questions, because mass arises in many ways in physics, and it's not immediately clear why it's a "problem" or "question" at all.
- The first time we meet mass is in the context of Newton's 2nd Law: $F = m_{inertial}\ a$
- This defines inertial mass, in terms of the eminently measurable quantity, and The Force.
- What's force? Lots of different kinds (Hooke's Law for springs, pushes, tension, impulses…), all macroscopic, none fundamental.
- We can see this frustrating situation in history, where Aristotelian dynamics (things ultimately come to rest) did not give way to Newton's for a long time. Air friction is a hard force to even notice!
- We are defining a "fundamental" quantity in terms of a macroscopic, rather ill-defined quantity! It's only well defined in terms of Newton's 1st Law: If the net force is zero, there's no acceleration. Force is ultimately defined by its absence.
- In micro-physics, force is rarely (or never) mentioned; we work with the first integral (energy), and describe things as "interactions".
- Please read what Feynman has to say about force, in his Lectures.
- Please read what Wilczek has to say about force, in Physics Today, 10/04, 12/04, 7/05.

# Conservation of mass

- Is mass conserved?
- The masses of objects are constantly changing, as atoms are sloughed off or accreted.
- On the subatomic scale: Mass as "concentrated energy": $E=mc^2$.
- The mass of atoms changes as they absorb or emit radiation; nucleii fission or fuse; sub-atomic particles turn into each other.
- Really, $E^2 = (m_0c^2)^2 + (pc)^2$. The concept of "relativistic mass" is outdated; we stick with relativistically-invariant rest mass $m_0$. How is mass related to motion and kinetic energy?
- Quantum Mechanical description of a massive particle:
  - Mass and width / decay lifetime (see self-energy, later)
  - de Broglie waves:

$$\Psi \sim e^{iEt/\hbar} = e^{imc^2t/\hbar} \rightarrow e^{i(mc^2+i\Gamma/2)t/\hbar} = e^{imc^2t/\hbar}e^{-\Gamma t/2\hbar}$$

$$\left|\Psi\right|^2 \sim e^{-\Gamma t/\hbar} = e^{-t/\tau}, \quad \tau = \hbar/\Gamma$$

  - so… "imaginary" mass (self-energy) is related to lifetime! Mass has a "width", or fundmamental uncertainty in QM.
- And in QFT, we routinely talk about virtual particles, "off the mass shell".
  We allow for $E^2 = (m^*c^2)^2 + (pc)^2$, where $m^* \neq m_0$, so long as $(m^* - m_0) \sim< \Gamma$ for a time $\Delta t \sim< \hbar/\Gamma$.
- In the kinematics and dynamics of particle interactions, the equations are written so as to explicitly conserve energy and momentum (but not mass) at all times. But that's just bookkeeping!
- E-p conservation is a consequence of Poincare invariance, which is certainly an approximation; we can only apply it in an isolated system, or maybe the entire universe.
- But at the level of the entire universe, E-p are sourced by curved space!

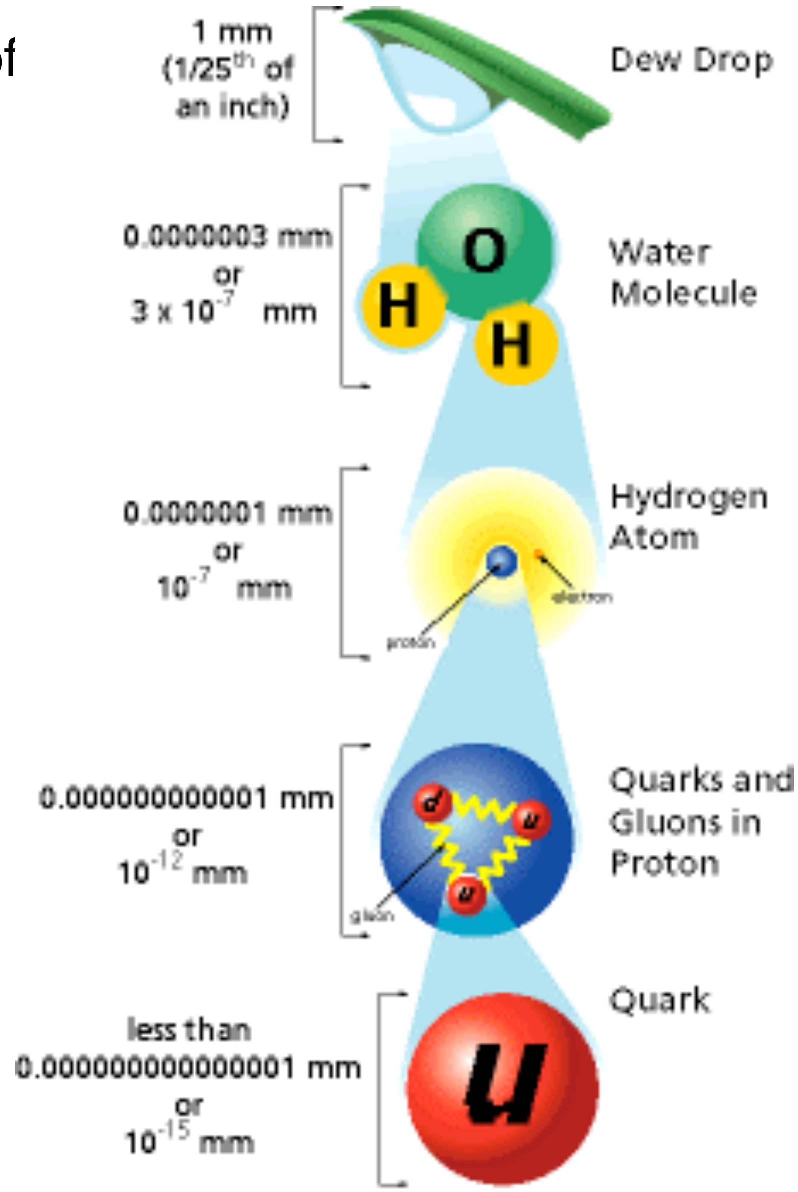
# Equivalence

- Inertial mass and gravitational mass:
  $F = m_{inertial}\ a = G\ m_{grav}\ m_{source} / r^2$
  If $m_{inertial} = m_{grav}$ for a “test particle” in a gravitational field generated by a source (eg, Earth in grav field of the sun), then
  $\Rightarrow a = G\ m_{source} / r^2$
  ie, the motion of the test particle (governed by acceleration) depends only on the location (relative to a source), and not on any of the properties of the test particle. This leads to the Principle of Equivalence (equivalence of gravitational and inertial mass, equivalence of gravitational acceleration and any other form of acceleration), and thence to the geometric theory of gravity: the General Theory of Relativity.
- Then, $m_{source}$ “generates space-time curvature”…
- Is $m_{inertial} = m_{grav}$ ? Much work has gone into answering this question in the 500 years since Galileo, and the work continues.
- If it is, why? GR “explains” it, or rather, trades it for a deeper question: why does mass/energy “source” curved space?
  $G = 8\ \pi\ T$.

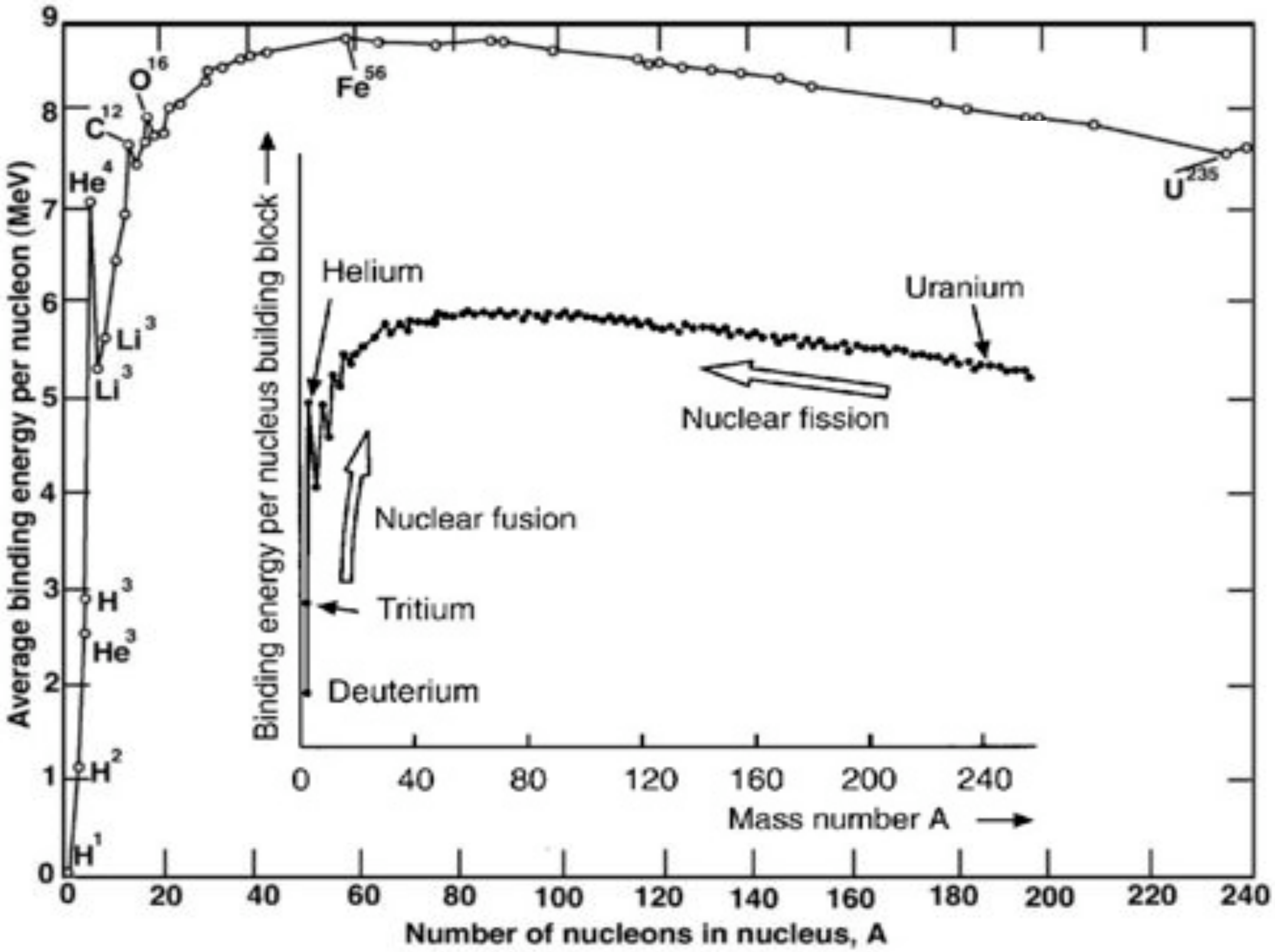
# The “origin of mass”

Mass of condensed objects (tables, etc) can be subdivided. Mass as the sum of the masses of the constituent parts

- true for all macroscopic objects
- not so true for atomic nuclei; the origin of nuclear energy in fission and fusion reactions
- completely untrue for the proton and the light mesons and baryons; most of the mass comes from binding energy, not the masses of the constituent quarks.
- Quarks are forever confined in the hadrons, and can’t be isolated. How can one even define the mass of a quark? Quark mass depends on the scale that you measure it, $m(\mu)$.
  - bare quark masses
  - constituent quark masses
  - current quark masses



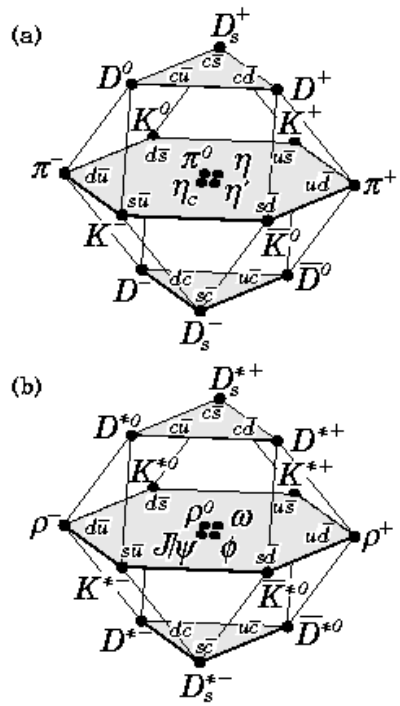
# Nuclear mass-energy

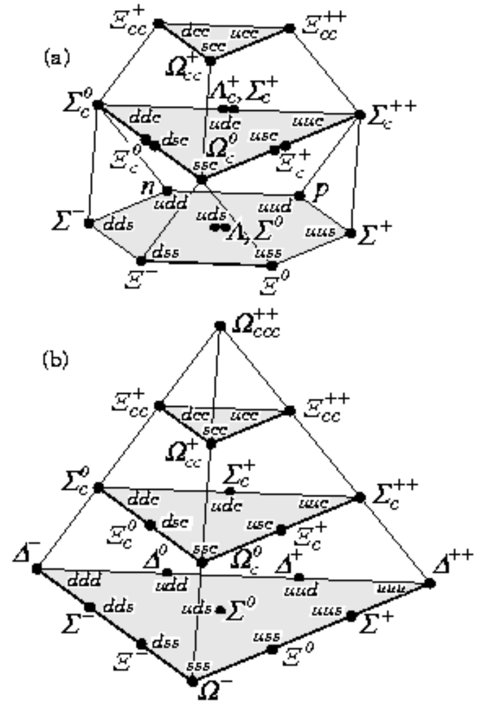


# Quarks to Mesons and Baryons: "Eightfold Way"

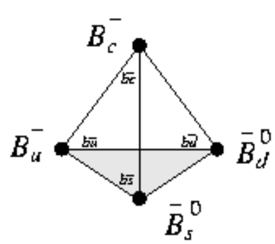
For first four quarks ($q = u, d, s, c$):

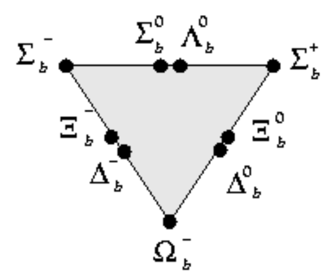
Mesons $= q\bar{q}$;   baryons $= qqq$ or $= \bar{q}\bar{q}\bar{q}$



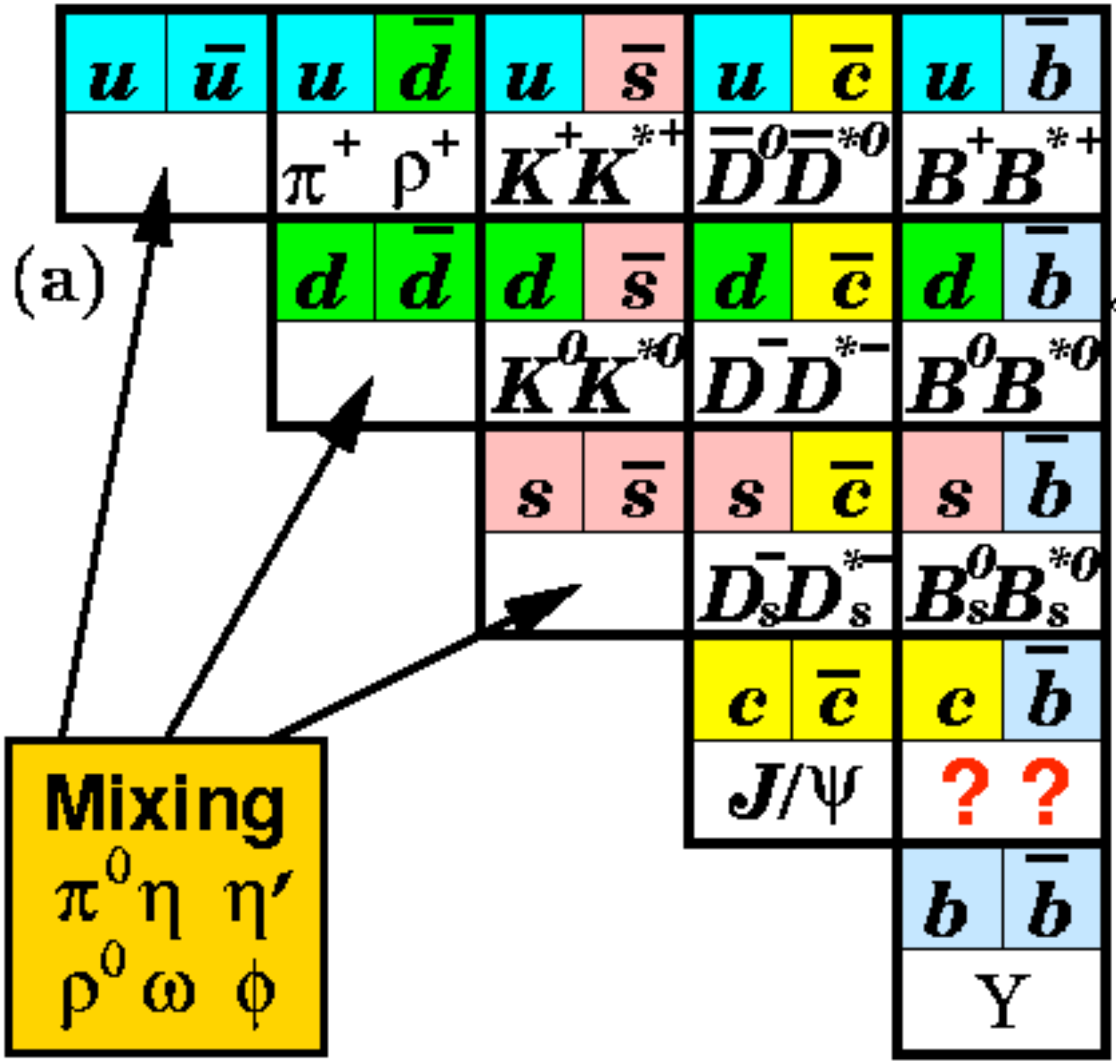

For the fifth quark ($q = b$):




Eightfold way

# Quarks to mesons



# Current quark masses

(MS renormal-ization scheme)

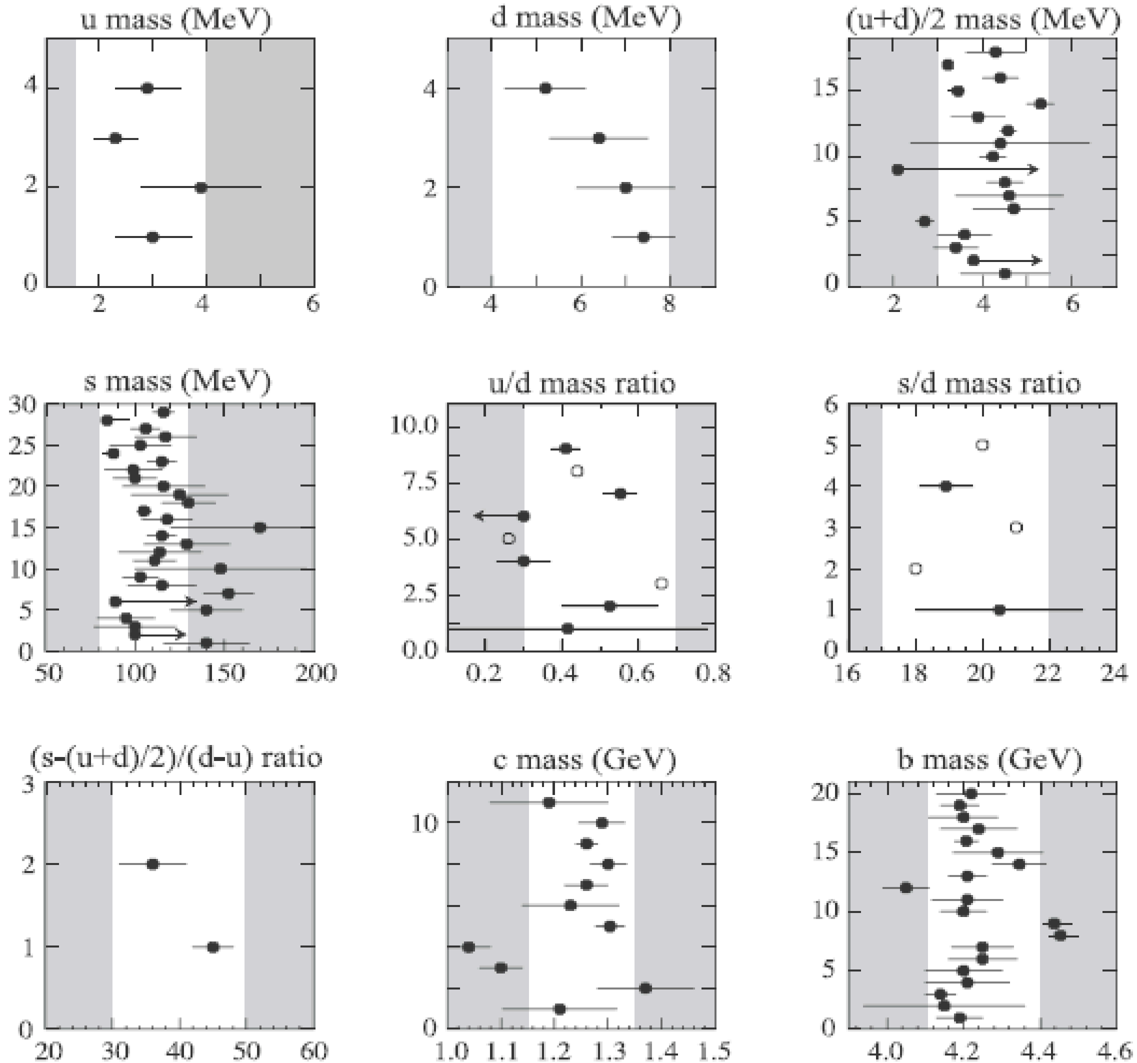



Figure 2. The values of each quark mass parameter taken from the 2004 Data Listings. The most recent data points are at the top of each plot. Points from papers reporting no error bars are open circles. Arrows indicate limits reported. The grey regions indicate values excluded by our evaluations; some regions were determined in part through examination of Fig. 1.

# Heavy fermions in the Standard Model

- The first 3 quarks ($u$, $d$, $s$) have $m_q \ll \Lambda_{QCD}$ - LIGHT
  mass can be neglected: $SU(3)_f$, "eightfold way"
  perturbation expansion in quark mass/momentum
  $\Longrightarrow$ chiral perturbation theory, $SU(3)_L \times SU(3)_R$

- the next 3 quarks ($c$, $b$, $t$) have $m_q \gg \Lambda_{QCD}$ - HEAVY
  bound state properties (mass, decay rates, ...)
  are independent of mass or spin of heavy quark;
  $\Longrightarrow$ $SU(2n_f)$ Heavy Quark Effective Theory
  (HQET, Isgur & Wise)
  perturbation expansion parameter: $1/m_q$

- Third generation quarks and leptons ($\tau$, $\nu_\tau$):
  highest sensitivity to interesting phenomena:
  CP violation, top, Higgs, 4th generation, ...

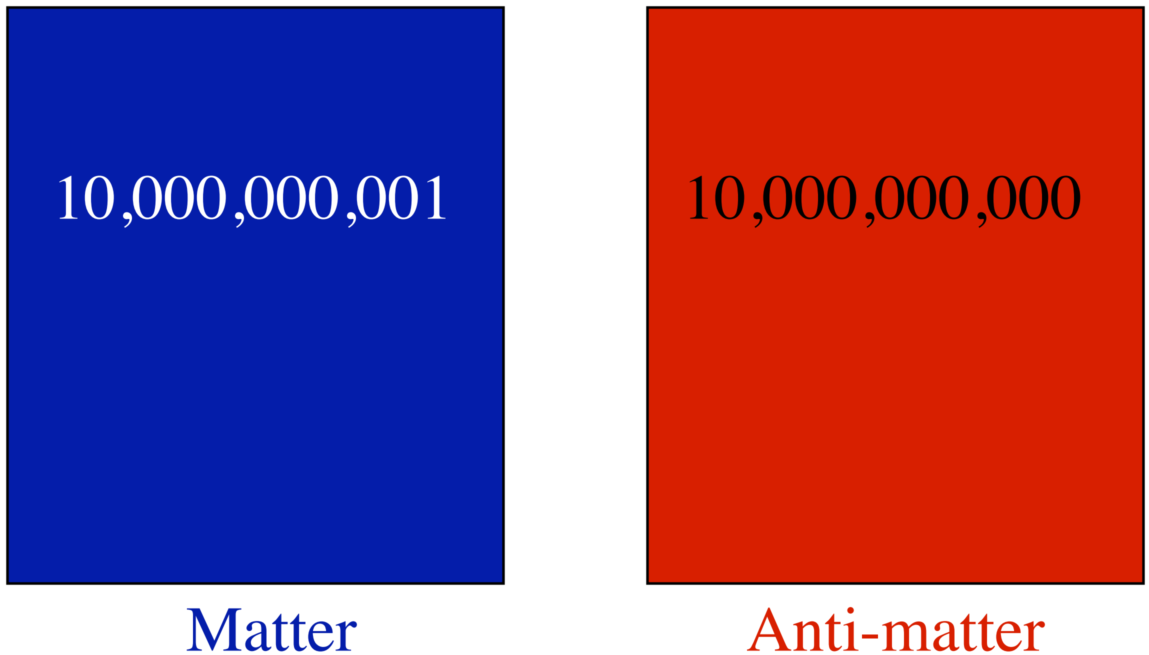
- UNIVERSALITY:
  Are all 12 quarks and leptons truly fundamental,
  pointlike objects, with identical couplings to the gauge
  bosons?


Why three families? Why the bizarre mass spectrum?

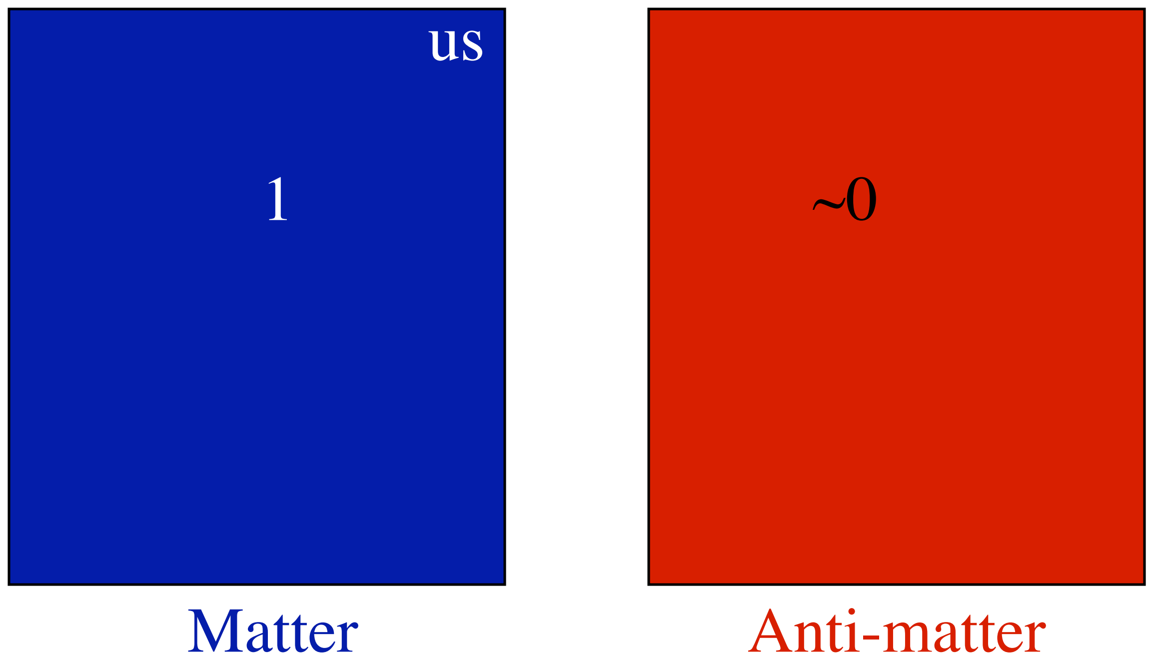
# Origin of mass on the cosmic scale

- **In the beginning (the Big Bang)**
  - the simplest initial conditions assume that there was nothing (no matter, anyway).
  - Well, there was an expanding universe, with an ~ infinite amount of gravitational self-energy.
  - As the universe expanded and had time to self-interact, the gravitational energy spilled into all the particle fields to which it could couple, filling the universe with a hot, dense sea of particle-antiparticle pairs.
  - "something from nothing"
- **The baryon asymmetry**
  - Sakharov's conditions for a baryon asymmetry where none existed:
    - Out-of-equilibrium conditions (we must invoke such an epoch somehow)
    - baryon number violation (exists even in the SM, and plenty of it in GUT theories)
    - CP violation (exists in the SM, but not enough in the quark sector…)
  - somehow, we ended up with net matter-over-antimatter, with one net baryon along with ~$10^9$ photons (from the annihilation of ~ $10^9$ quarks and antiquarks, leaving only a few left over!)

# Matter and Anti-Matter in the Early Universe



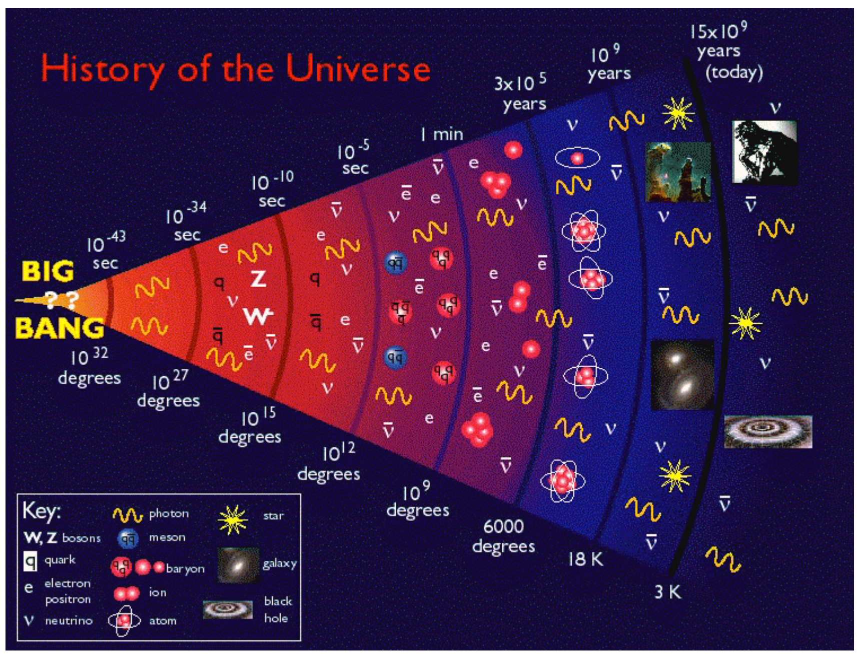
# Matter and Anti-Matter in the Current Universe




*The Great Annihilation*

# Cosmic nucleosynthesis

- **cosmic primordial baryogenesis and nucleosynthesis**
  - quark-gluon plasma cooled and condensed into protons and neutrons
  - Origin of the light elements, up to Li and Be
  - One of the great successes of the Hot Big Bang Model
  - "The cosmic freeze-out", leading to quantitative abundances of the light elements, and of any other (hypothetical) massive particles such as dark matter candidates
- All the heavier elements are consistent with being formed in the core of massive stars through nuclear fusion, then dispersed into interstellar space through supernova explosion
- Our sun and solar system are 2$^{nd}$ generation – **we are stardust**



# Time, size, density, energy, temperature during the Big Bang