Baryogenesis

Why We Need or Want Baryogenesis

Is There More Matter Than Anti-Matter?

- It is a matter of convention which particles are matter and which are anti-matter
- By convention, protons, neutrons, and electrons are all matter

- Neutrinos are tricky, because they are (probably) their own anti-particles
  - In the limit of massless neutrinos, you can sort them logically by their spin
- But neutrinos are basically impossible to count anyway
  - There could be a surplus of neutrinos or anti-neutrinos, no way to tell

- Photons are their own anti-particles, and hence they don’t count as matter or anti-matter

- We will focus on the baryons
- Looking locally, we discover that in our vicinity (Earth) there is much more matter (baryons) than anti-matter (anti-baryons)

The Scale of the Baryon Asymmetry (1)

- The Earth is made of matter; what else do we know?
- 99+% of our knowledge of the rest of the universe comes from e.m. waves
    - And these tell us nothing about matter vs. anti-matter

- We have sent probes to the Moon, Venus, Mars, Jupiter, Saturn, Titan (moon of Saturn), and several asteroids and comets
    - No boom
- The solar wind contains lots of protons, and no anti-protons
- The Solar system is all matter

- Modest energy cosmic rays come from throughout our galaxy
    - Overwhelmingly matter, not anti-matter
- We see nebulae colliding throughout our galaxy (and within other galaxies)
    - No boom
- Any given galaxy is almost certainly all matter or all anti-matter

The Scale of the Baryon Asymmetry (2)

- More powerful cosmic rays come from well outside our galaxy
- These are rare, and we don't normally see the primary
- We *do* see various galaxies colliding
  - And their gas clouds within them colliding
  - No boom
- *Almost certainly* galaxy groups and clusters are all matter or all anti-matter

- We have even seen galaxy clusters colliding with each other
  - No boom
- *Probably* galaxy superclusters are all matter or all anti-matter

- This suggests that baryon asymmetry exists at least on the ~100 Mpc scale
- Very difficult to imagine any mechanism that segregates it on this scale

- Best guess: The universe is made of matter, not anti-matter, on the scale of the entire visible universe

Magnitude of the Baryon Asymmetry (1)

- The baryon asymmetry is often given as a ratio of the number of baryons to photons:

$$\eta_0 \equiv \frac{n_B}{n_\gamma} = (6.2 \pm 0.2) \times 10^{-10}$$

- We should note that n_B actually represents the density of baryons minus anti-baryons
  - This quantity is conserved, since baryon number is conserved
- As the universe grows, both the density of baryons and photons scales as a^{-3}
  - So this ratio remains constant

$$\eta = \eta_0 \cdot \frac{g_{\text{eff}}}{3.91}$$

- Not exactly, since every time a particle annihilates, the photons get reheated
- Above around 150 MeV, you don't have baryons, you have quarks
- Every baryon just represents three quarks, so

$$n_q = 3n_B$$

- So we have
- Let's look around the electroweak scale, when g_{eff} = 106.75

$$\frac{n_q}{n_\gamma} = \frac{3g_{eff}}{3.91}\left(6.2 \times 10^{-10}\right) = 5.08 \times 10^{-8}$$

Magnitude of the Baryon Asymmetry (2)

- Recall, n_q is actually the difference between the number of quarks and anti-quarks

$$\frac{n_q - n_{\bar{q}}}{n_\gamma} \qquad \frac{n_q}{n_\gamma} \approx 5.08 \times 10^{-8}$$

- At the electroweak scale, all quarks are effectively massless
- If it weren't for the asymmetry, both photons and quarks would have a density proportional to T^3
  - Times some factors counting colors, spins, fermions vs. bosons, etc.

$$\frac{n_q}{n_\gamma} = \frac{n_{\bar{q}}}{n_\gamma} = \frac{27}{2} = 13.5$$

$$\frac{n_q - n_{\bar{q}}}{n_q} = 3.76 \times 10^{-9}$$

- Hence this is just a tiny asymmetry
  - But consistent throughout the universe
- For every 266 million anti-quarks, there are 266 million and 1 quarks
- As universe expanded, quarks annihilated anti-quarks
- The tiny surplus of quarks then organized themselves into baryons
- The matter we see is just the tiny remnant left over from this asymmetry

- Can we explain this asymmetry?

Possible Types of Explanations

- Can we explain this asymmetry?

$$\frac{n_q - n_{\bar{q}}}{n_q} = 3.76 \times 10^{-9}$$

- It could just be written into the initial conditions of the universe
- Though if there was inflation, this doesn't work
  - Rapid expansion of the universe would rapidly drop density to effectively zero
  - Then reheating at end of inflation would create loads of new quarks and anti-quarks
- The alternative is to *start* with no baryon asymmetry, and then have it created later
- This is strongly preferred by cosmologists

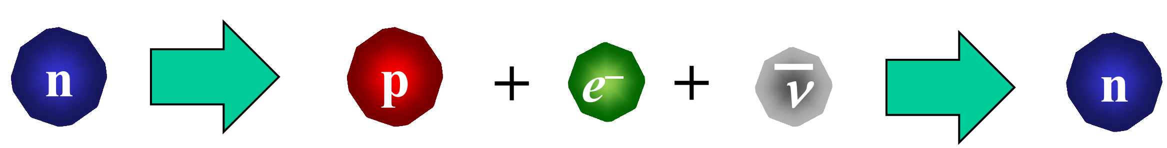
How to Create a Baryon Asymmetry

C, P, and T symmetry

- Three common symmetries of physics:
- Charge conjugation (C) says that anti-matter behaves the same way as matter

- Parity (P) says that mirror image processes work the same way

- Time reversal (T) says that any process can go in reverse



C, P, T and the CPT theorem

- *All* particle physics theory have to respect CPT
  - That is, if you do all three, the process goes just as fast
- *But* they don't have to respect them separately
- Strong and electromagnetic interactions are symmetric under C, P, and T
- Weak interactions maximally violate parity P
  - Neutrinos *always* spin a particular way
- Weak interactions in the quarks also *slightly* violate CP
- But they must satisfy CPT
  - And no evidence they don't

What Do We Need For Baryogenesis?

Three conditions are believed to be necessary for baryogenesis

- We need to have violation of baryon number
  - Obviously, otherwise you can't create something from nothing

- We need violation of C and CP symmetry
  - Otherwise you will make just as many anti-baryons as baryons

- We need to be out of thermal equilibrium
  - If you were in thermal equilibrium, then you'd be unmaking baryons about as fast as you are making them
  - You are in a time-symmetric state (T symmetry)
  - By the CPT theorem, you are then in a CP symmetric state
  - So you have as many baryons as anti-baryons

What Sorts of Processes Are Out of Equilibrium?

- Any process that is too slow to redistribute energy is out of equilibrium
- At present, for example, neutrinos are not in equilibrium with any other particles
  - Weak interactions are too slow to get it in equilibrium

There are two good ways to get a system far from equilibrium:

- Any decay that takes longer than the age of the universe (at that time) will be out of equilibrium
  - For example, neutron decay in the early universe

- Any sort of phase transition can be out of equilibrium
  - Has to be a first-order phase transition – there is a barrier
  - For example, supercooled water

Models for Baryogenesis

Three and a half ways to create the baryons:

- GUT scale baryogenesis
    - Decay of particles from the GUT scale

- Standard model baryogenesis
    - Caused at the electroweak scale
    - Probably too small to account for the effect

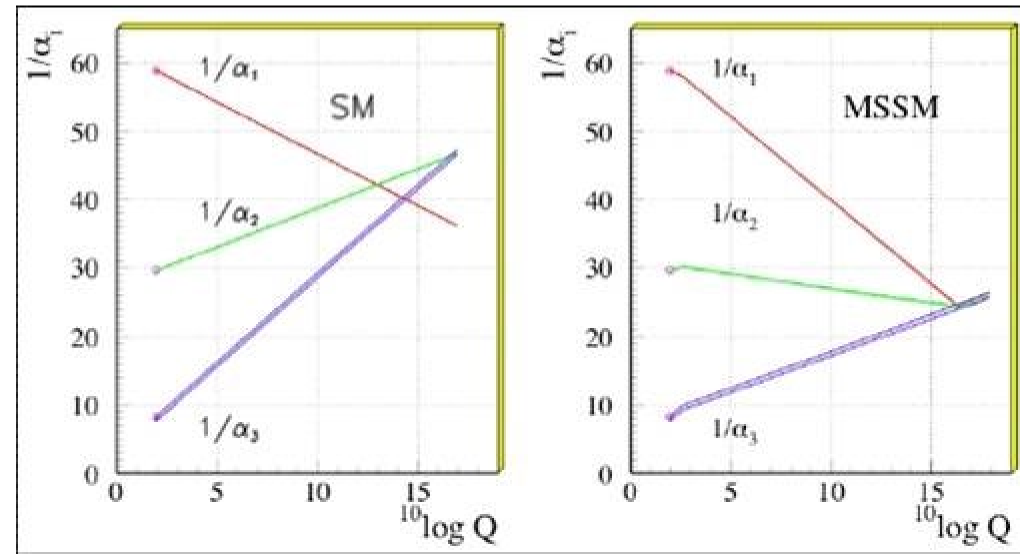
- Standard model plus supersymmetry

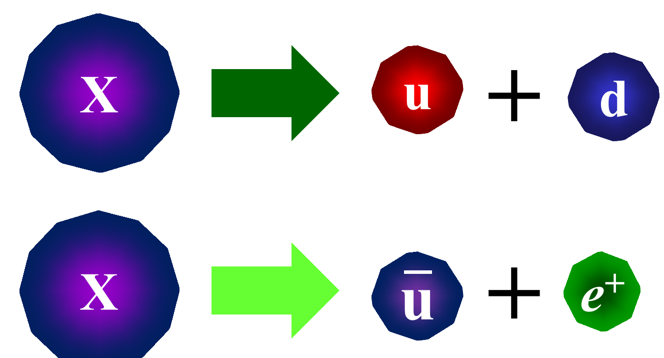
- Neutrino driven baryogenesis
    - Caused by decay of heavy sterile neutrinos

Grand Unification Baryogenesis

Grand Unification Revisited

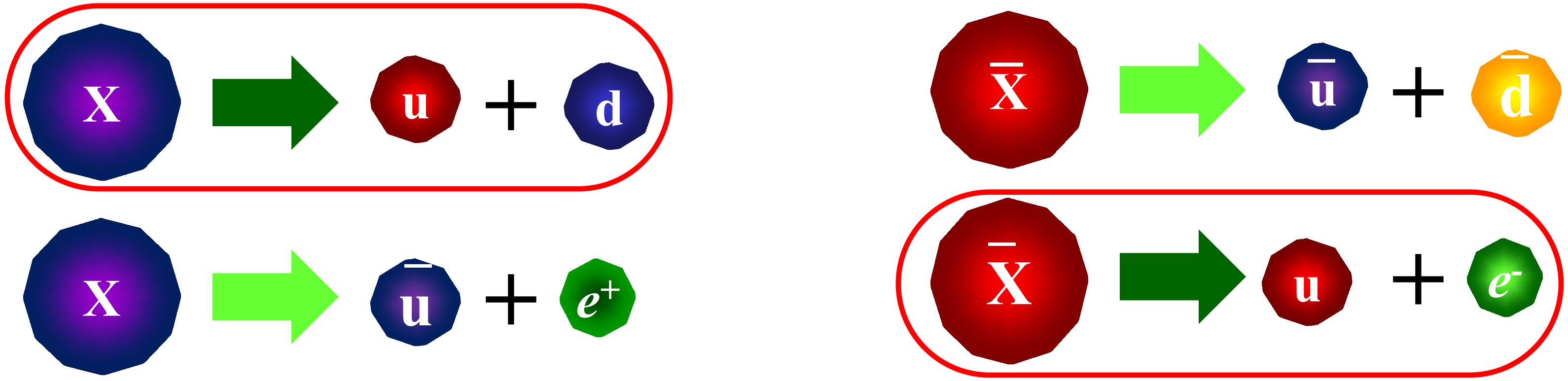
- Recall at the GUT scale, the strong, weak, and lectromagnetic forces all have about the same strength
- Many ideas on how to unify them into a single force
  - Simplest is the original SU(5) theory
- New force particles at the GUT scale
  - For example, *X* has charge +1/3
- These particles can decay slowly, taking longer than age of universe at this time
  - Out of equilibrium
- These particles also can violate conservation of baryon number
  - First decay creates two quarks
  - Second creates one anti-quark





Grand Unification and Baryogenesis

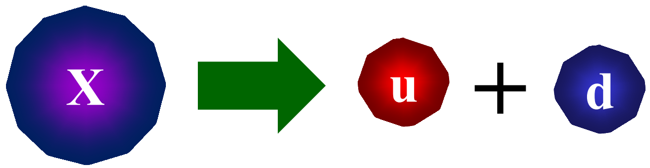
- Initially, there would probably be equal numbers of *X* and anti-*X* particles
- Any decay the *X* can do, the anti-*X*'s can anti-do:

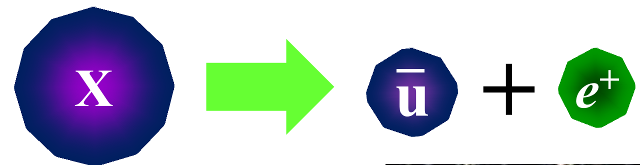


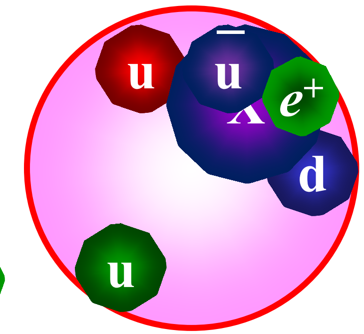
- However, most GUT theories have lots of C and CP-violation
- Under these circumstances, the decay rates may not be equal
- As the *X*'s decay, they would produce more quarks than anti-quarks
- Although the effects would probably be small, we don't *need* a big effect, since we are trying to get only about a 10^{-8} disparity
- Not hard to imagine this would work

Detecting Grand Unification

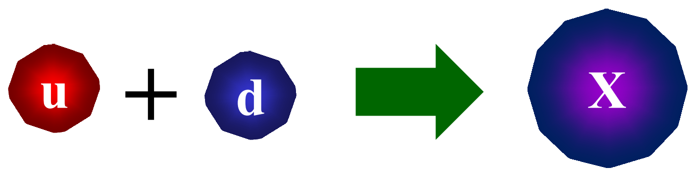
- If GUT scale baryogenesis is right, how do we detect it?
- Should be possible to see baryon violation directly







- Turn the first reaction around



- Combine them, and you have proton decay

$$p^{+} \rightarrow \pi^{0} + e^{+}$$

- Because the *X* is so heavy, you need to watch a *lot* of baryons
- Fortunately, baryons are cheap
- No decays seen so far
- Limit for this process:

$$\tau > 2.4 \times 10^{34} \ \text{yr}$$

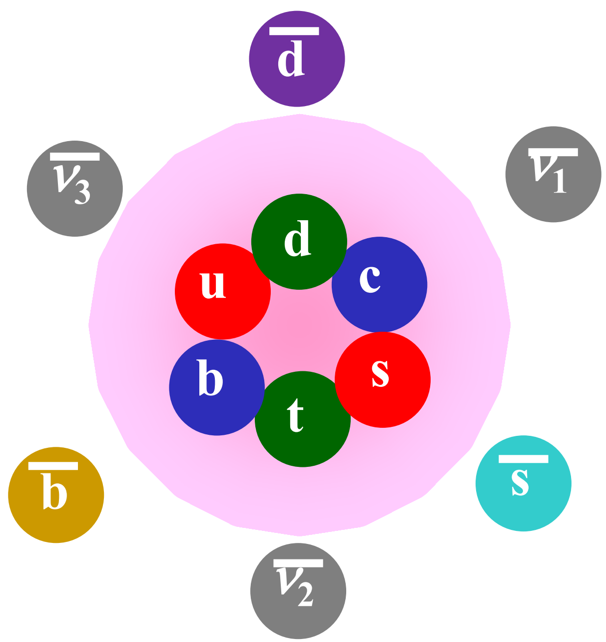
Electroweak Scale Baryogenesis

Baryon Violation in the Standard Model

- Most particle physics predictions are based on perturbation theory
- Perturbation theory says baryons number is conserved in the standard model
- And we have never seen such baryon violation
- But there are non-perturbative effects that are predicted to violate baryon number
- At low temperature, the probability of such effects is severely suppressed
  - You just aren't going to see it

$$P \propto e^{-4\pi/\alpha} \qquad \alpha = \tfrac{1}{137} \qquad P \sim 10^{-750}$$

- In the 90's (or so) it was realized that these effects can be large at high temperatures (above the electroweak transition)
- Objects called *sphalerons* allow these transitions to occur at these energies
- As particles pass through a sphaleron, they get transformed



- There is a net change in baryon number of ±3

Do We Have the Ingredients for Baryogenesis?

- We said before we need three ingredients:
  - Violation of baryon number
  - Out of thermal equilibrium
  - C and CP violation

- Sphalerons give you baryon number violation

- Consider the time of electroweak symmetry breaking

- If it is a first order phase transition (barrier to transition) you can get out of equilibrium
  - This is under dispute
  - Apparently it may *just barely* be first order

- C and CP violation exist in the quark sector for weak interactions
  - But it is very small

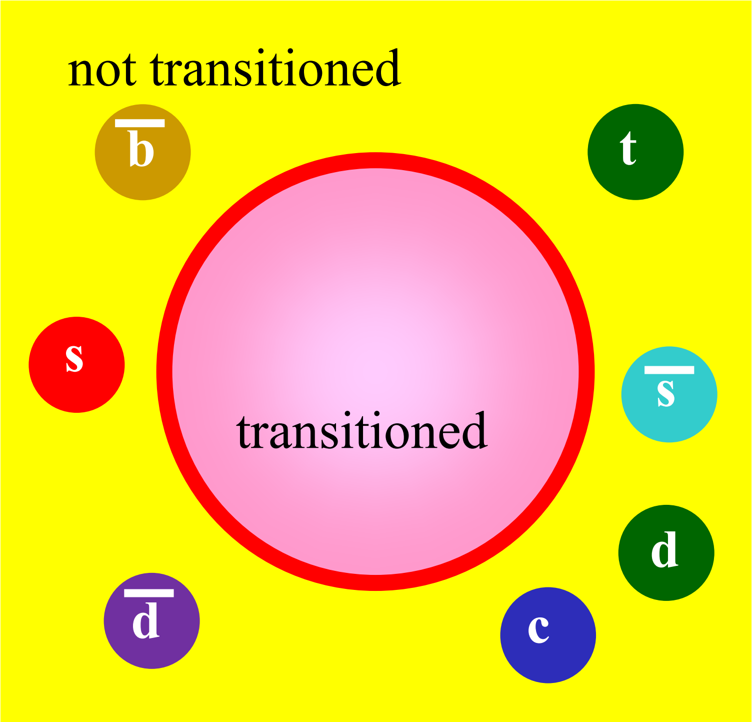
How You *Might* Get Some Baryogenesis

- As the temperature drops to the electroweak scale, electroweak transition starts
- If it is first order, it will appear as bubbles where the breaking occurs

- Quarks acquire mass as they cross the barrier
- The change in energy can cause them to reflect
- Because of the CP violation in the standard model, it is predicted that there will be more antiquarks reflected than quarks
- This leaves excess of quarks inside, anti-quarks outside

- Outside the bubble, an excess of anti-quarks can be wiped out by sphalerons
- In contrast, inside the bubble there are no sphalerons

- We end with a net excess of quarks



Standard Model Baryogenesis

- In the standard model, all processes with CP violation involve all six quarks
  - Including some small masses and small angles
- Attempts to calculate the resulting baryon asymmetry indicate it would be too small
  - Much smaller than observed

- Pure standard model baryogenesis probably fails

Supersymmetric Baryogenesis

- Supersymmetry introduces a host of new particles
- Many of the couplings could have large CP violations
- Since the supersymmetry scale is right near the electroweak scale, we can use similar arguments

- Evidence indicates this *could* be the origin of the baryons

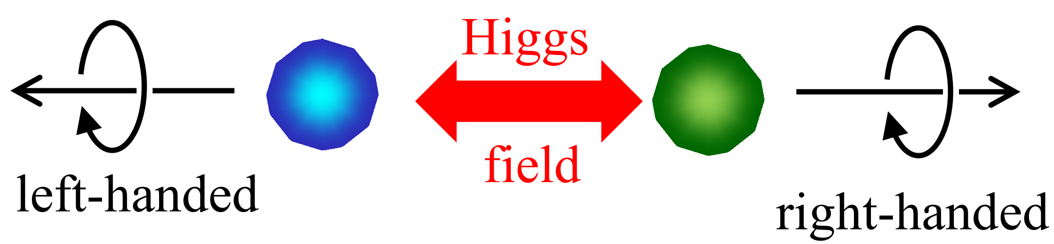
Neutrino Driven Baryogenesis

Masses in the Standard Model

- To understand neutrino-driven baryogenesis, you first have to understand how masses are made in the standard model

- A *massless* spin ½ particle always moves at *c*, and comes in two distinct spin types
- A right-handed particle spins clockwise as viewed along its direction of motion
- A left-handed particle spins counter-clockwise as along its direction of motion
- A *massive* particle must have both types

- Before the standard model was developed, weak interactions were a puzzle, because left-handed and right-handed particles acted differently
- In the standard model, the left- and right-handed fields are distinct, no connection



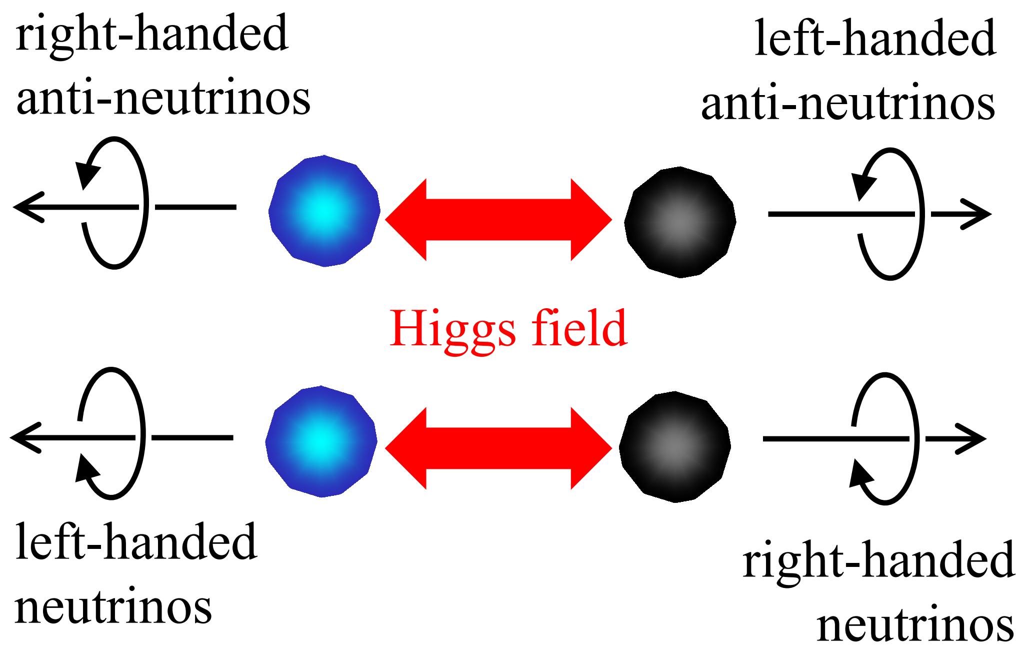
- But the Higgs field "marries" them, allowing them to be massive

Dirac Neutrino Masses

- In the standard model, there are only left-handed neutrinos
- And of course, their anti-neutrinos, which are right handed
- Because there is nothing for them to "marry" they would remain massless
- But there is now convincing evidence that neutrinos have masses

- Easiest way to modify the theory:
- Add right-handed neutrinos
  - Predicted by many GUTs
- These right-handed neutrinos would actually not have strong, weak or electromagnetic couplings

- The Higgs field then marries the particles in the usual way
- Leading to masses called Dirac masses, which we denote *m*



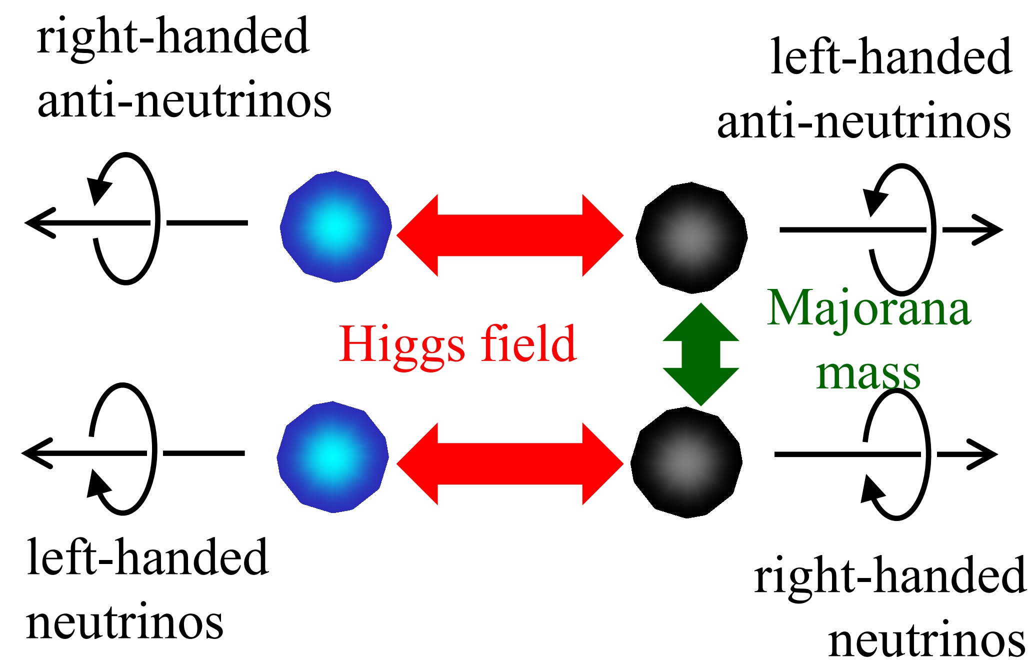
- It is then puzzling why the neutrinos are so ridiculously light

Majorana Masses and the See-Saw Mechanism

- There is a way to naturally get light neutrino masses

- Recall that the right-handed neutrinos have no strong, weak, electromagnetic couplings
- Even *without* the Higgs field, they can join together to make massive particles
  - This is called a *Majorana mass*, which we will denote by M
- Because it doesn't proceed via the Higgs mechanism, the masses can be much larger

- When the Higgs mechanism cuts in, it tries to create marriages as before
- But because the right-handed neutrinos resist, it isn't very effective



- The right-handed fields end up having a mass $m_N \approx M$

- The left-handed fields end up having a mass $m_\nu \approx \dfrac{m^2}{M}$

- Note as M increases, m_ν decreases
  - The see-saw mechanism

Right-Handed Neutrinos and Neutrino Decay

- We have neutrinos ν_1, ν_2, and ν_3 that are almost exactly like standard model neutrinos
  - But they have mass
- We have neutrinos N_1, N_2, and N_3 that are very massive and don't have intrinsic strong, electromagnetic, or weak interactions
- But due to Higgs mechanism, they are *slightly* mixed with the regular neutrinos
- For this reason, they *can* decay, but it will be very slow, at least for the lightest N
  - Since slow, they can be out of equilibrium
- These decays can be either to left-handed particles (that act like neutrinos) or right-handed (that act like anti-neutrinos)
- Typical decays would be $N_1 \to \nu\nu\bar{\nu}$ or $N_1 \to \bar{\nu}\bar{\nu}\nu$
- If there is CP violation in neutrino sector, no reason these rates should be equal
- CP violation is *allowed* and *likely* to exist in the neutrino sector

Neutrinos and Baryogenesis

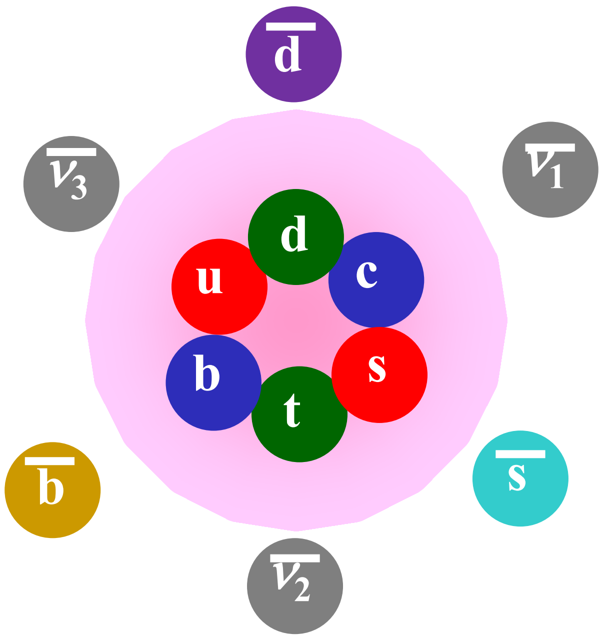
- Recall: we need three conditions for baryogenesis
- CP violation: Almost certainly present in neutrino interactions
- Out of equilibrium: Likely exists due to slow N_1 decay
- Baryon number violation: We are missing this!

- So far, we have explained why we could have an imbalance of neutrinos vs. anti-neutrinos

$$N_1 \to \nu\nu\bar{\nu} \quad \text{or} \quad N_1 \to \bar{\nu}\bar{\nu}\nu$$

- Assume anti-neutrinos dominate
- Recall, we still have sphalerons
- Sphalerons can convert anti-quarks to quarks and destroy anti-neutrinos in the process
  - And they can do the reverse

- But since there is an excess of anti-neutrinos, it is easier to go the direction that makes quarks
- Excess anti-neutrinos would lead to excess of quarks



Neutrino Baryogenesis: How To Test It

- If neutrino baryogenesis is right, then there should exist heavy right-handed neutrinos *N*
- The fact that the neutrinos are light suggests the *N*'s are probably really heavy
- We probably can't make them in the laboratory
- There should also be an excess of "anti-neutrinos" in the background neutrinos
  - We can't even *detect* these neutrinos yet
  - Good luck seeing a 1 ppb excess
- For this to work, must have CP violation in the neutrino sector
- We are already testing this, and should know soon
  - Already demonstrated with 95% confidence in 2017
  - Should be virtually certain soon
- Note: Just because we see CP violation in neutrinos doesn't mean this is the correct explanation

Baryogenesis - Summary

- We have strong evidence that the universe contains more matter than anti-matter
- Although it is possible that it was just primordial, it is more probable that it was created at some point

- We have three plausible mechanisms for making it:
- GUT scale violation of baryon number
- Weak scale sphaleron baryogenesis combined with a source of greater CP-violation
  - Such as supersymmetry
- Heavy right-handed neutrinos creating an excess of anti-neutrinos
  - Converted to baryons via sphalerons

- My opinion: Neutrino generated baryogenesis is the most probable
  - We already see neutrino masses
  - See-saw mechanism very likely explanation of small neutrino masses
  - CP violation very likely