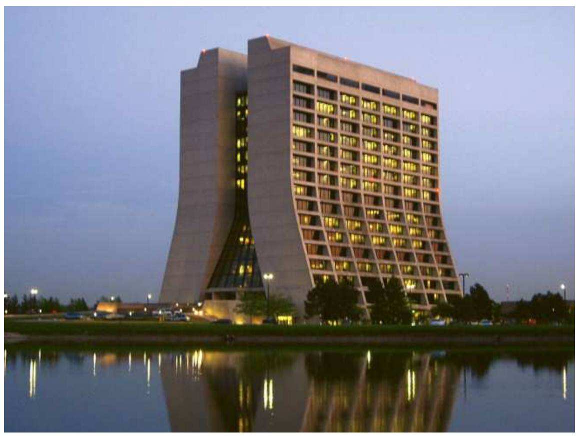
Fermilab Tour

Spangenberg

History of Fermi

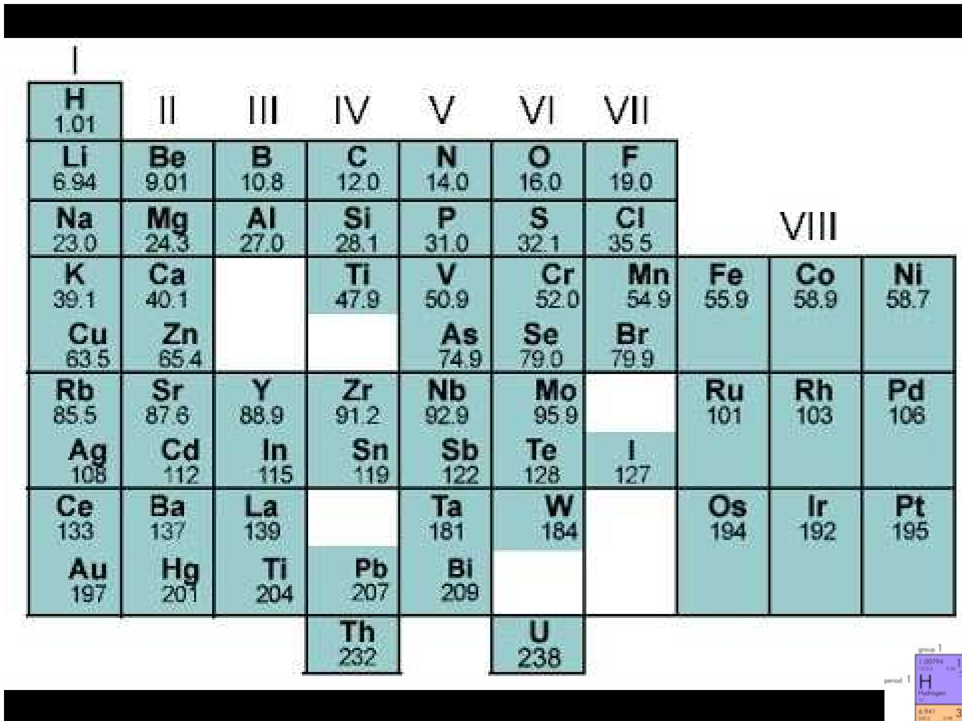


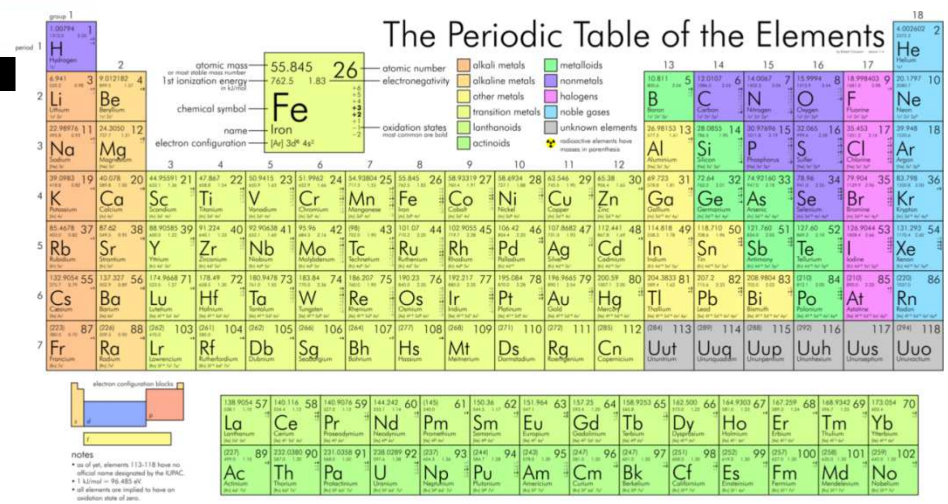
Location in Illinois

History

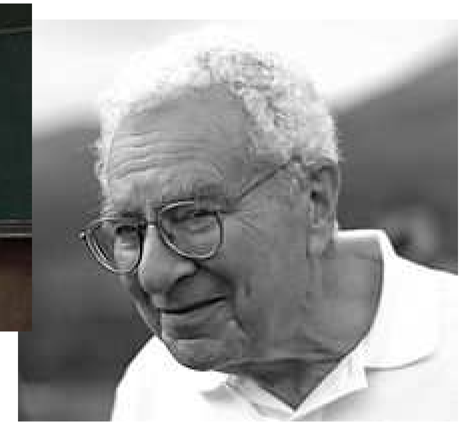
- Founded in 1967 as the National Accelerator Laboratory
  - 1st Director = Robert Wilson, opened ahead of schedule and under budget
  - Most of the sculptures you'll see are his
- Renamed in honor of Enrico Fermi in 1974
- Wilson stepped down in 1978 due to lack of funding
- Leon Lederman takes over and replaces the accelerator with the Tevatron – able to collide protons and antiprotons at energies of 1.96 TeV.

Mendeleev and the Periodic Table





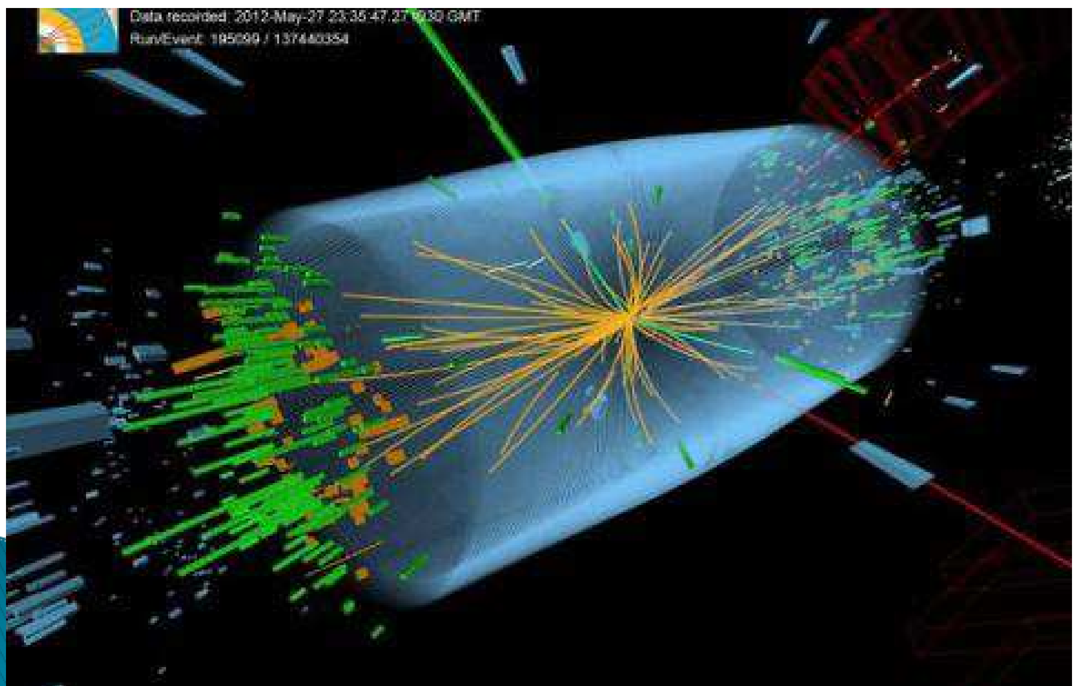
Particles in physics				
nentary	Fermions	Quarks		Up (quark · antiquark) · Down (quark · antiquark) · Charm (quark · antiquark) · Strange (quark · antiquark) · T Bottom (quark · antiquark)
		Leptons		Electron · Positron · Muon · Antimuon · Tau · Antitau · Electron neutrino · Electron antineutrino · Muon neutri Tau neutrino · Tau antineutrino
	Bosons	Gauge		Photon · Gluon · W and Z bosons
		Scalar		Higgs boson
	Ghost fields			Faddeev–Popov ghosts
	Hypothetical	Superpartners	Gauginos	Gluino · Gravitino · Photino
			Others	Axino · Chargino · Higgsino · Neutralino · Sfermion (Stop squark)
		Others		Axion · Dilaton · Dual graviton · Graviton · Leptoquark · Magnetic monopole · Majoron · Majorana fermi Sterile neutrino · Tachyon · W′ and Z′ bosons · X and Y bosons · X17 particle
nposite	Hadrons	Baryons / hyperons		Nucleon (Proton · Antiproton · Neutron · Antineutron) · Delta baryon · Lambda baryon · Sigma ba Omega baryon
		Mesons / quarkonia		Pion · Rho meson · Eta and eta prime mesons · Phi meson · J/psi meson · Omega meson · Upsil D meson
		Exotic hadrons		Tetraquark · Pentaquark
	Others			Atomic nuclei · Atoms · Exotic atoms (Positronium · Muonium · Tauonium · Onia) · Superatoms · Molecules
	Hypothetical	Hypothetical baryons		Hexaquark · Skyrmion
		Hypothetical mesons		Glueball · Theta meson · T meson
		Others		Mesonic molecule · Pomeron · Diquarks
iparticles				Davydov soliton · Dropleton · Exciton · Hole · Magnon · Phonon · Plasmaron · Plasmon · Polariton · Polaron · Roton · Trion
.ists				Baryons · Mesons · Particles · Quasiparticles · Timeline of particle discoveries
elated				History of subatomic physics (timeline) · Standard Model (mathematical formulation) · Subatomic particles · Particles · Antiparticles · Nuclear (Quark model) · Exotic matter · Massless particle · Relativistic particle · Virtual particle · Wave–particle duality · Particle chauvinism
dia books				Hadronic Matter · Particles of the Standard Model · Leptons · Quarks

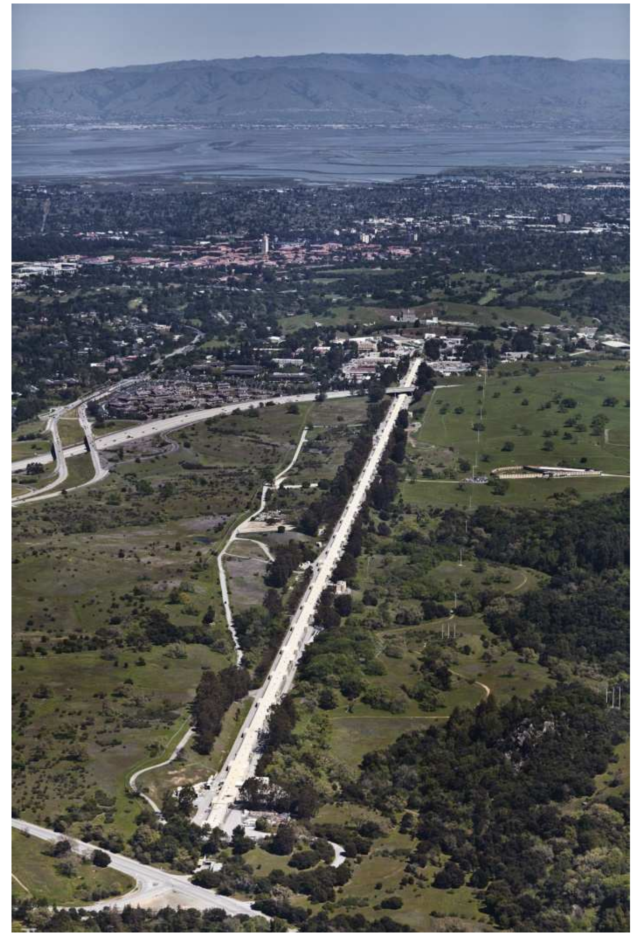


- Gell-Mann and Zweig said that all these particles were composed of combinations of quarks and antiquarks (more on that later)
- Reactions from the science community were mixed
- Is the quark an actual physical entity or a mere abstraction used to explain concepts that were not fully understood at the time
- They purported three quarks – up, down, and strange (called so because it has a strangley long lifetime before decay)

Linear accelerators

- Stanford Linear Accelerator
- Beams of protons, smash them together, see what comes out





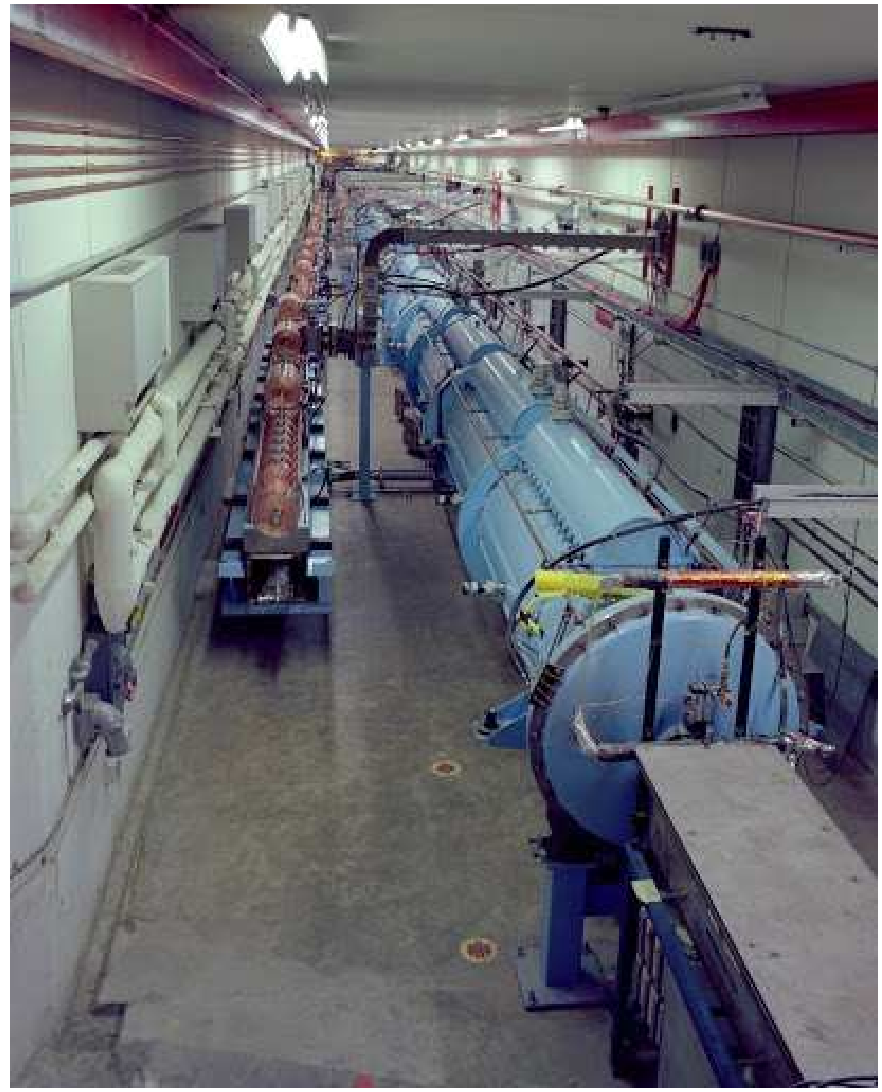
Stanford finds

- Up and down in 1968
- Charm in 1974

- They start finding patterns in the data (Mendeleev-esque), and predict the existence of other quarks

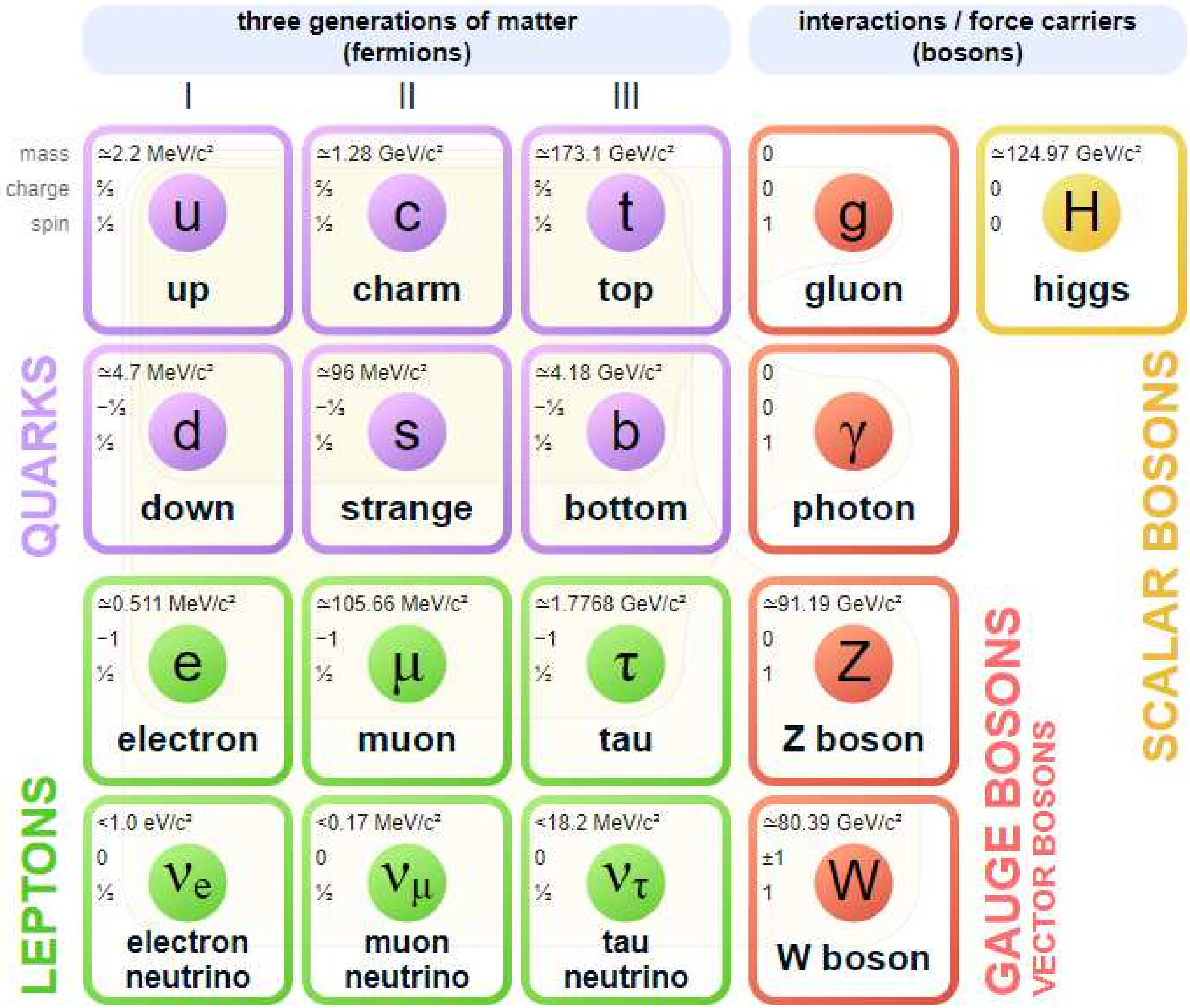
- Fermilab can achieve higher energy collisions than Stanford
  - Think about chemical bonds – there is a certain energy you need to put into the chemical bond in order to break it
  - You need to give protons enough kinetic energy in order to smash into each other hard enough in order to break the “quark bond”

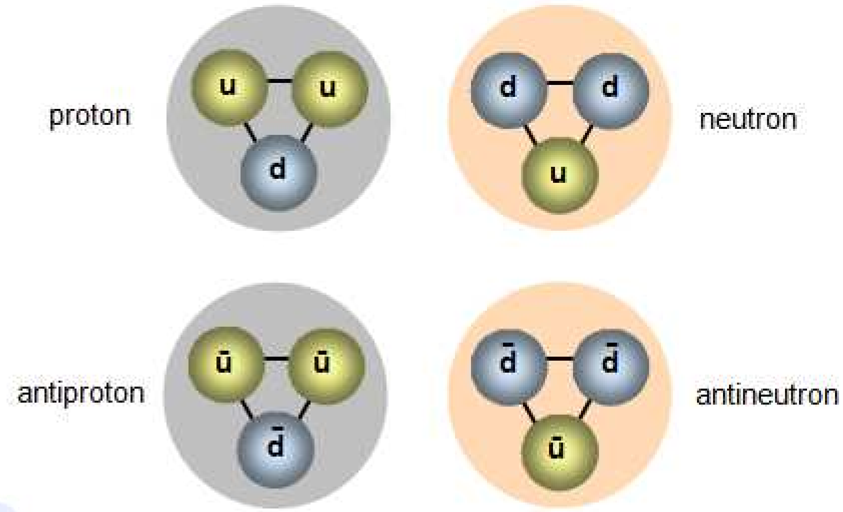
- Fermilab finds bottom quark in 1977 with its LINAC (linear accelerator)
  - Indicates existence of top quark (Mendeleev?) because bottom would need a partner



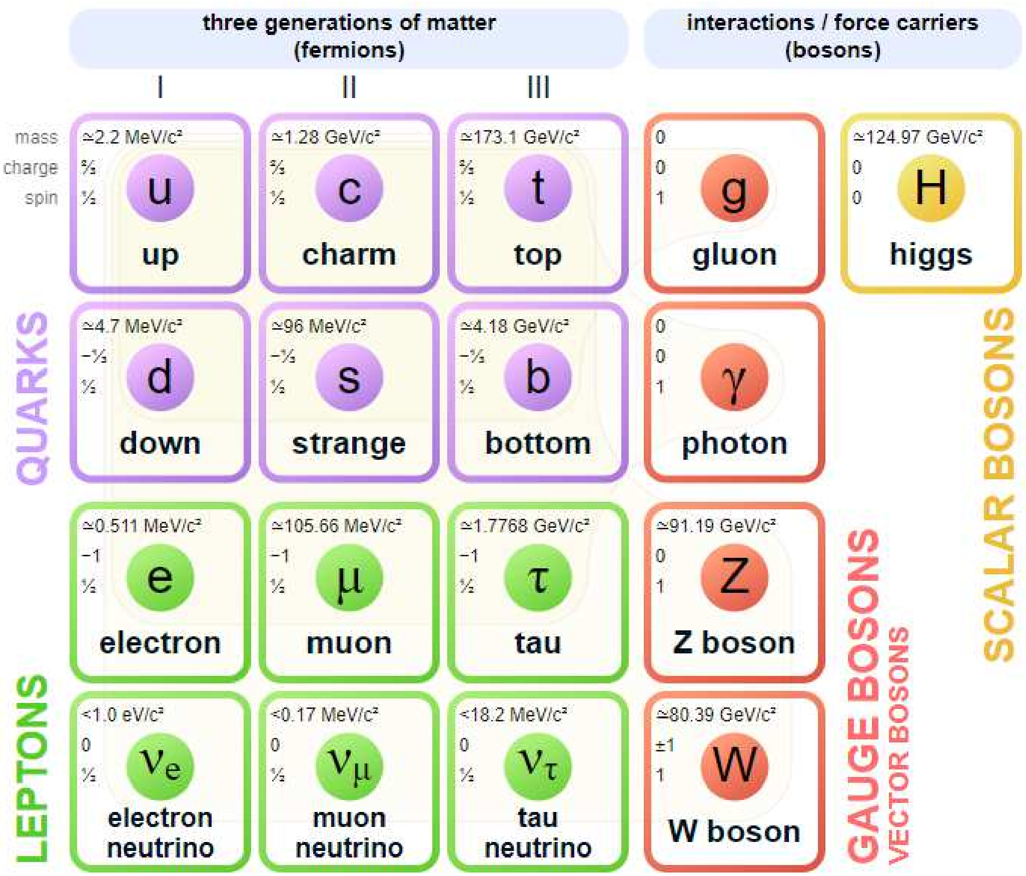
- The top quark is sooo much more massive that it took until 1992 to find it (and we had to switch to the Tevatron….the ring collider which could make protons move faster using superconducting magnets)

Standard Model of Elementary Particles





Standard Model of Elementary Particles



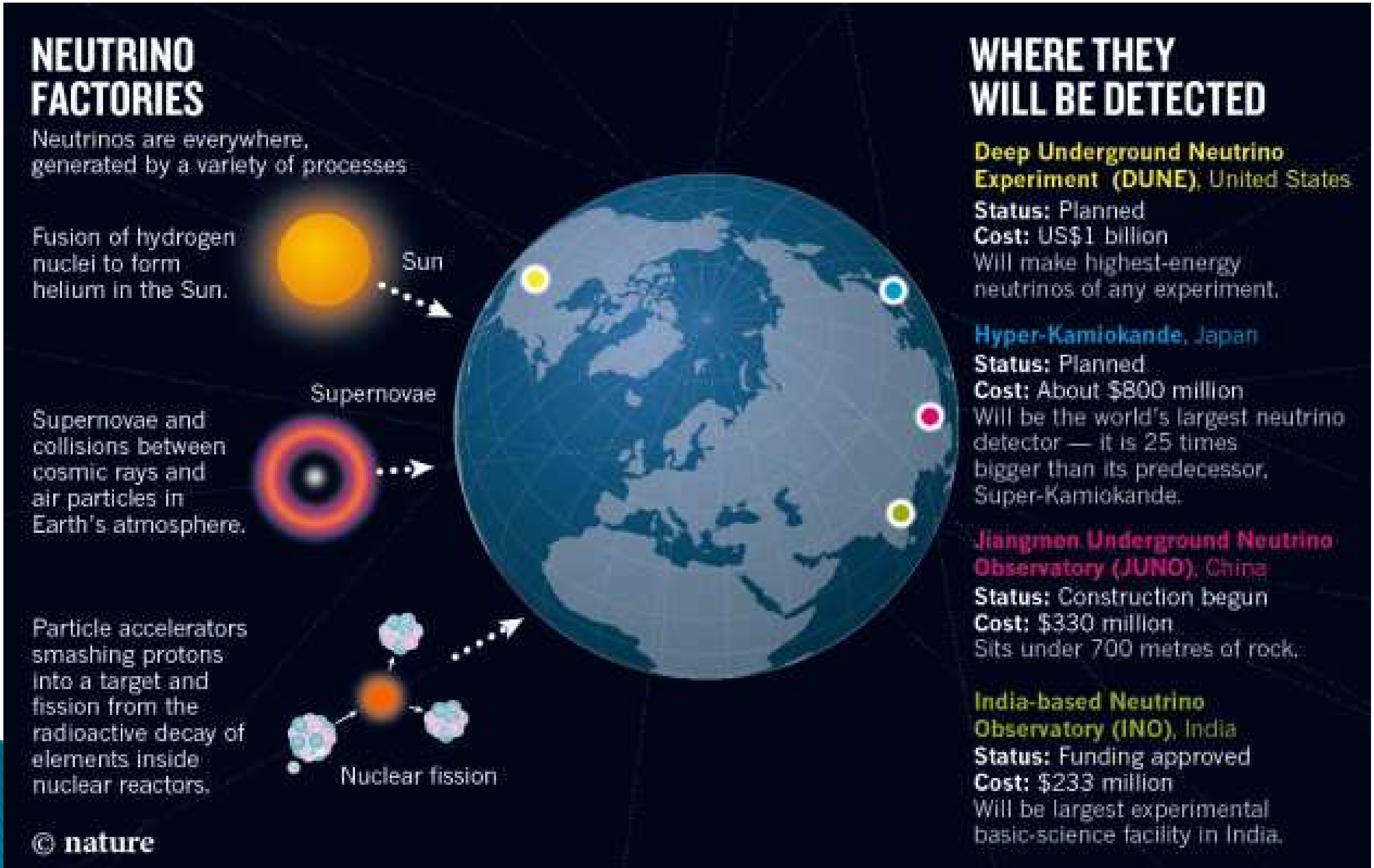
CERN and the LHC

- Nowadays, Fermilab's collider is shutdown. CERN (the one in Switzerland) can achieve so much higher energies that Fermilab can't compete.
- Fermilab's main ring is 3.9 miles (6.3 km) in circumference and (as of 2011) could produce energies of 1.6 TeV
  - Hence Tevatron
  - Tera electron volt ~ kinetic energy of a flying mosquito
- LHC has a circumference of 16.6 miles (26.7 km) can produce energies 13 TeV

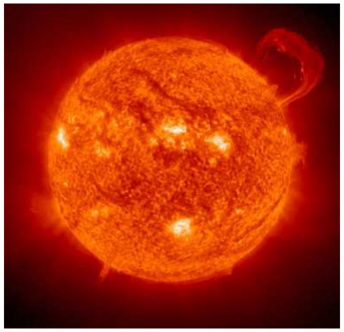

LHC
SWITZERLAND
FRANCE


Geneva
Future
Circular
Collider
PS
SPS
LHC
27 km
100 km

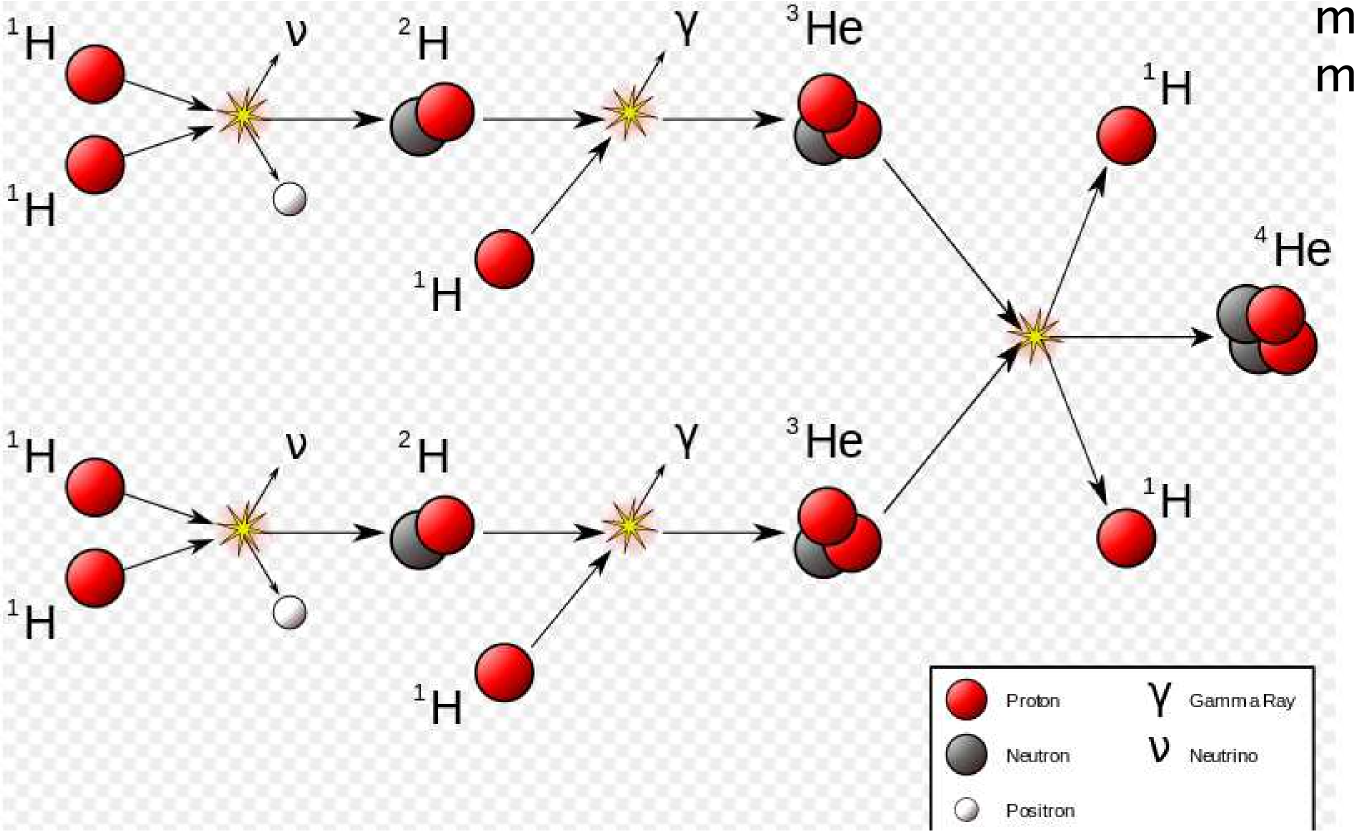
What is a neutrino?



We didn't even know of their existence until 1930's prediction



- In nuclear reactions and nuclear decays
  - $E = mc^2$ → mass is converted to energy
  - For example, proton proton chain

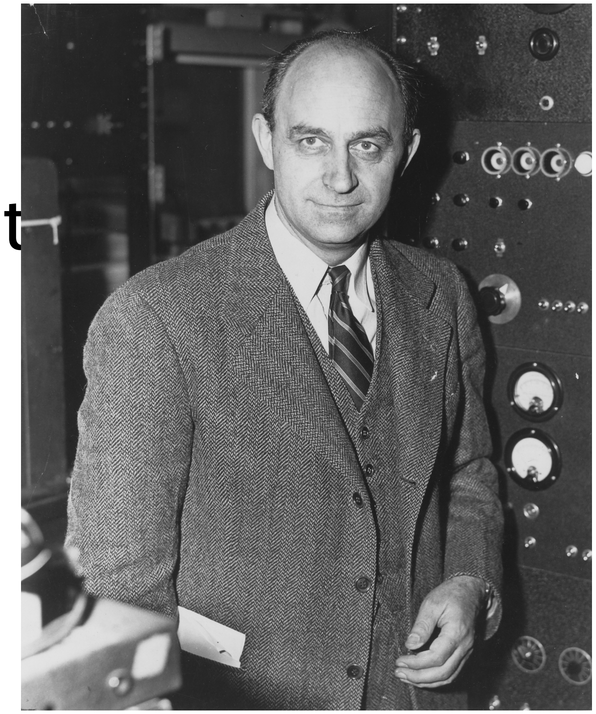


$m_{hydrogen} = 1.00784$ u
$m_{helium} = 4.002602$ u

Wolfgang Pauli, 1930

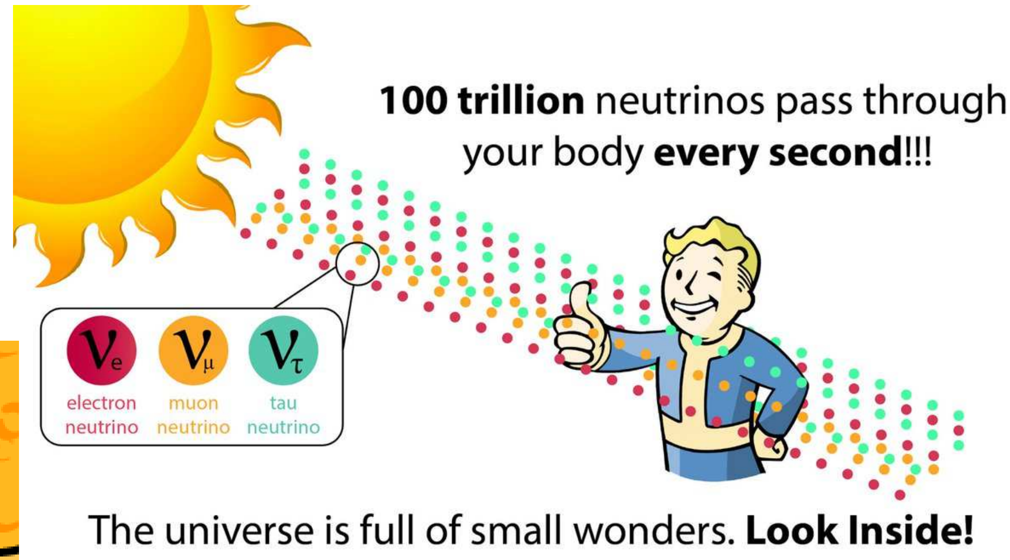
- The neutrino first mathematically predicted by Wolfgang Pauli in 1930 to explain how beta decay (nuclear reactions) could conserve energy
- Pauli called this previously undetected particle a "neutron"
  - using the same *-on* ending employed for naming both the proton and the electron.
- Said the particle was emitted from the nucleus
  - Also note the emission of the neutrino in the proton proton chain

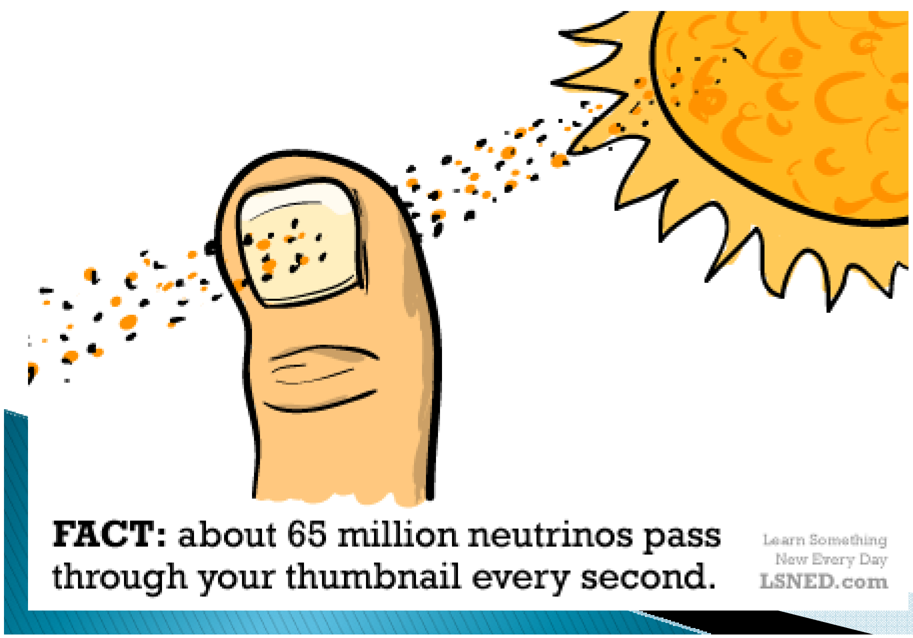
- James Chadwick discovered a much more massive neutral nuclear particle in 1932 and named it a neutron also, leaving two kinds of particles with the same name.
- The word "neutrino" comes from Enrico Fermi who jokingly used it during a conference in Paris in July 1932.
- The name means slangily means "lit neutral one" in Italian.
  - Distinguishes this light neutral particle from Chadwick's heavy neutron



Why had we never detected neutrinos before?

- Neutrinos don't interact with matter….basically ever





Why don't neutrinos interact?

- The atom is very tiny, having a diameter of about 10^{-10} meters. Keep in mind that's like saying 0.0000000001 meters, or about one-billionth of a meter across! But within this already extremely small atom is an even smaller region called the nucleus. The nucleus has a diameter of 10^{-14} m, so it is about 10,000 times smaller than the volume of the atom as a whole. One analogy is to imagine the atom is the size of a football stadium. In that gigantic stadium the nucleus would only be the size of a small marble sitting on the 50-yard line!

Atom

Nucleus

Mass Proton

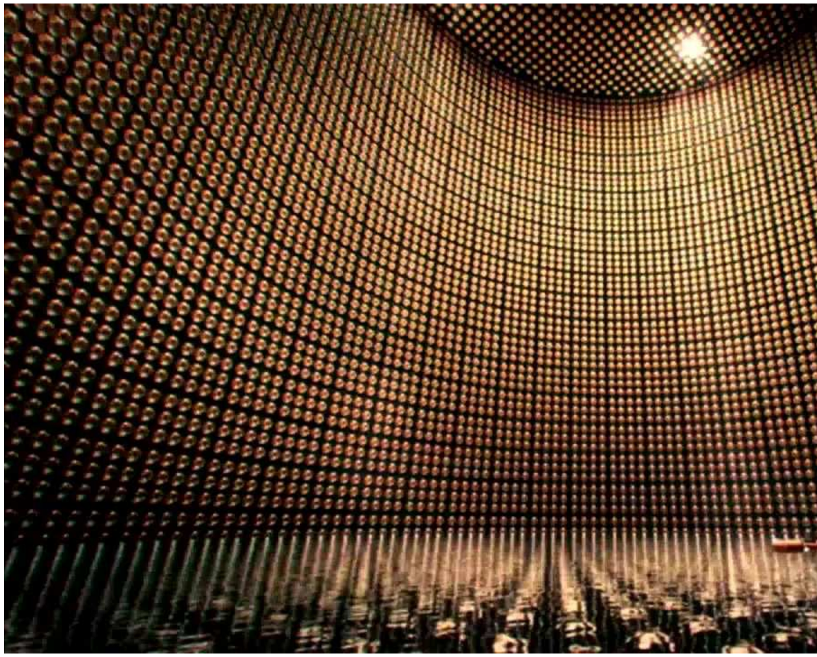
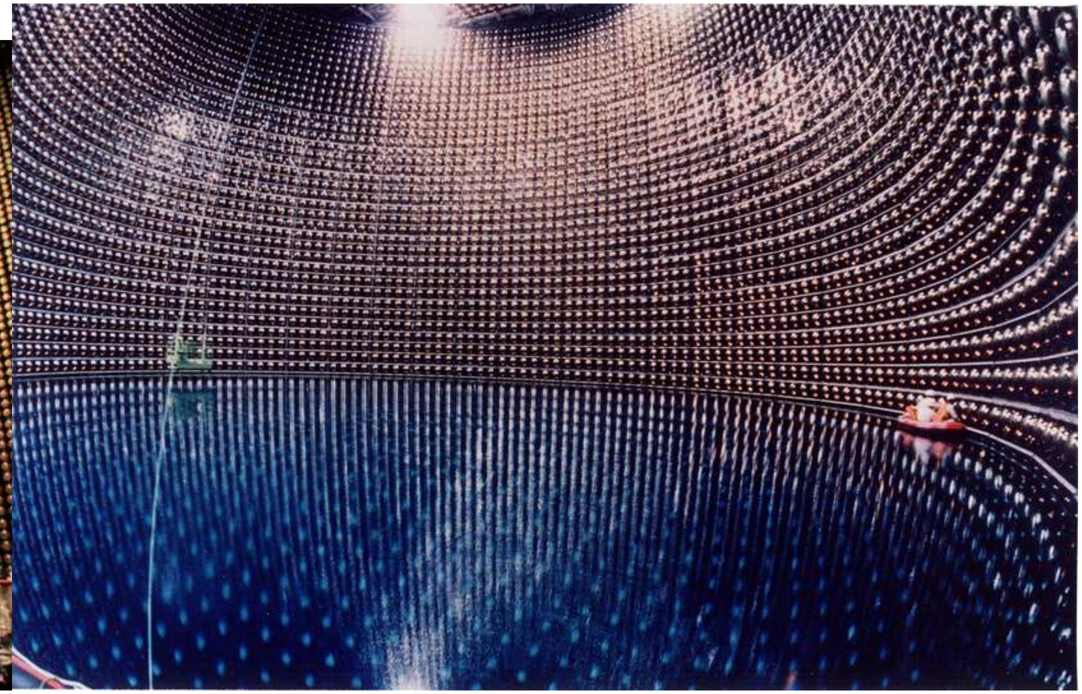
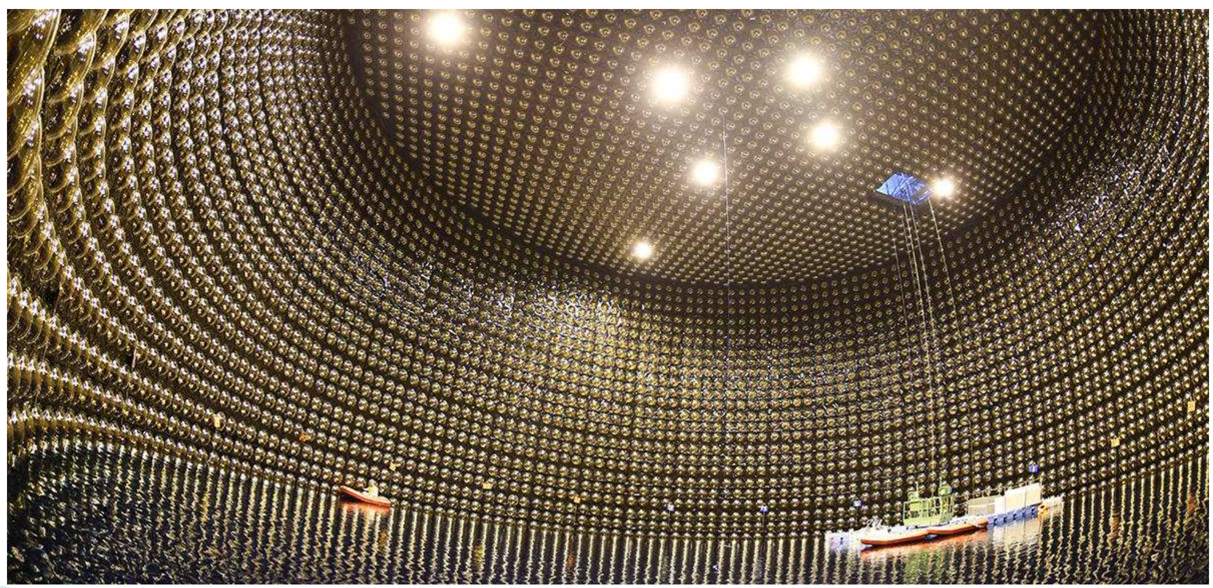
Mass Electron
(grain of rice)

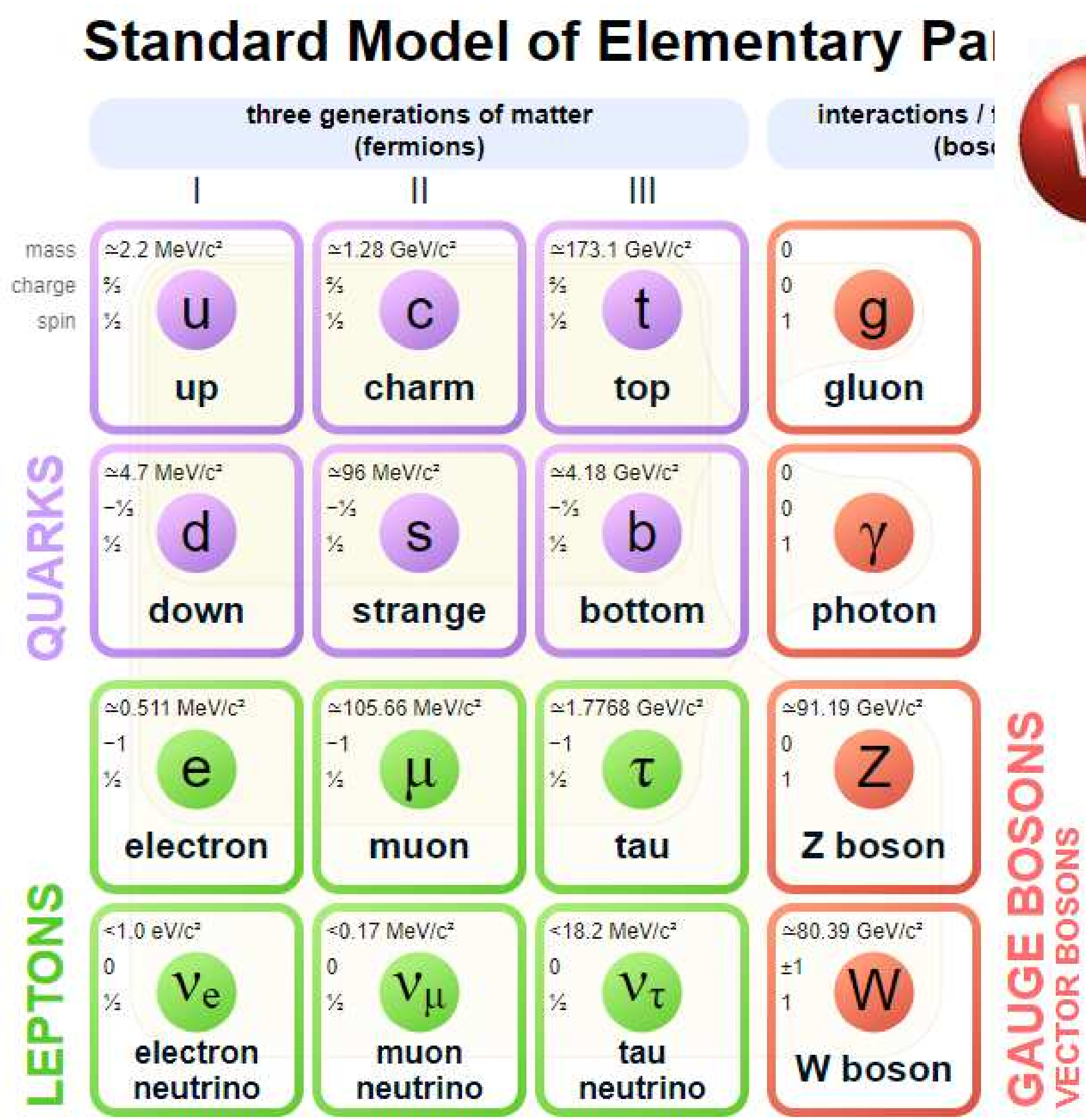
- Protons live in the nucleus, so 99.9% of an atom's mass is in the nucleus rather than being spread out across the entire atom.
- It is as if the entire mass of the football stadium were in the marble at the 50 yd line.
- The density of a nucleus is about 100,000,000,000,000 g/cm^3 (10^{14})
- You cannot fathom how dense that is.
- It is the density of about a billion cars (2.5 billion tons) in the size of a matchbox.
- Which is why the neutron is so important to keep the atom together.

- Neutrinos are around 10^{-37} m^2 (technically they don’t have a size, this is the size of their electroweak interaction – the size of the field they create)
- About an attometer (10^{-18} m) in diameter
- Or about 1 billionth the size of the uranium nucleus
- About a tenth the size of an electron
- About a tenth the size of an up quark
- About a tenth the size of a down quark

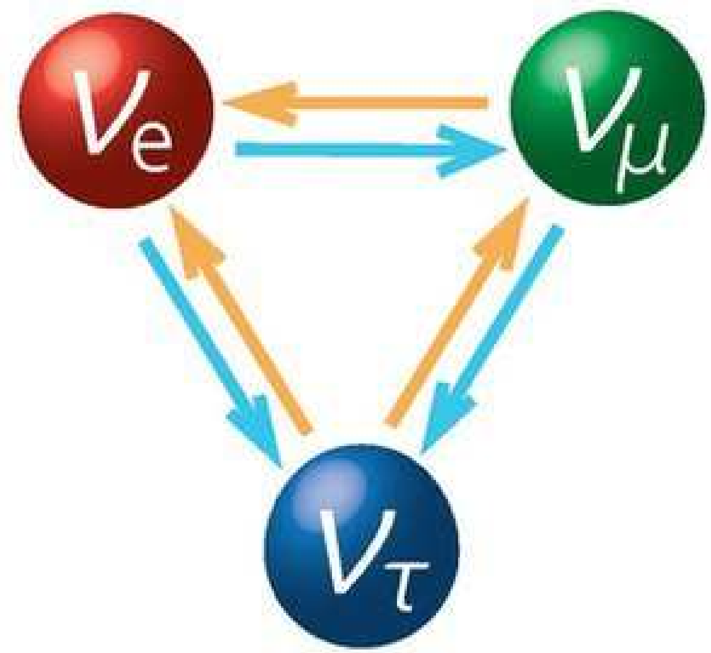
Solar Neutrino Problem

- Using math and science, we predicted how many neutrinos (electron neutrinos) we should be detecting coming from the sun.
- In the 1960's, we were only receiving half to two-thirds of the expected.
- How are we detecting them?



Standard Model of Elementary Pa
three generations of matter
(fermions)
interactions /
(bos
I
II
III
mass
charge
spin
≃2.2 MeV/c²
⅔
½
u
up
≃1.28 GeV/c²
⅔
½
c
charm
≃173.1 GeV/c²
⅔
½
t
top
0
0
1
g
gluon
≃4.7 MeV/c²
−⅓
½
d
down
≃96 MeV/c²
−⅓
½
s
strange
≃4.18 GeV/c²
−⅓
½
b
bottom
0
0
1
γ
photon
≃0.511 MeV/c²
−1
½
e
electron
≃105.66 MeV/c²
−1
½
μ
muon
≃1.7768 GeV/c²
−1
½
τ
tau
≃91.19 GeV/c²
0
1
Z
Z boson
<1.0 eV/c²
0
½
νe
electron neutrino
<0.17 MeV/c²
0
½
νμ
muon neutrino
<18.2 MeV/c²
0
½
ντ
tau neutrino
≃80.39 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR



νe
νμ
ντ

Neutrino Experiments

- LBNF/Dune
  - Long-Baseline Neutrino Facility/Deep Underground Neutrino Experiment

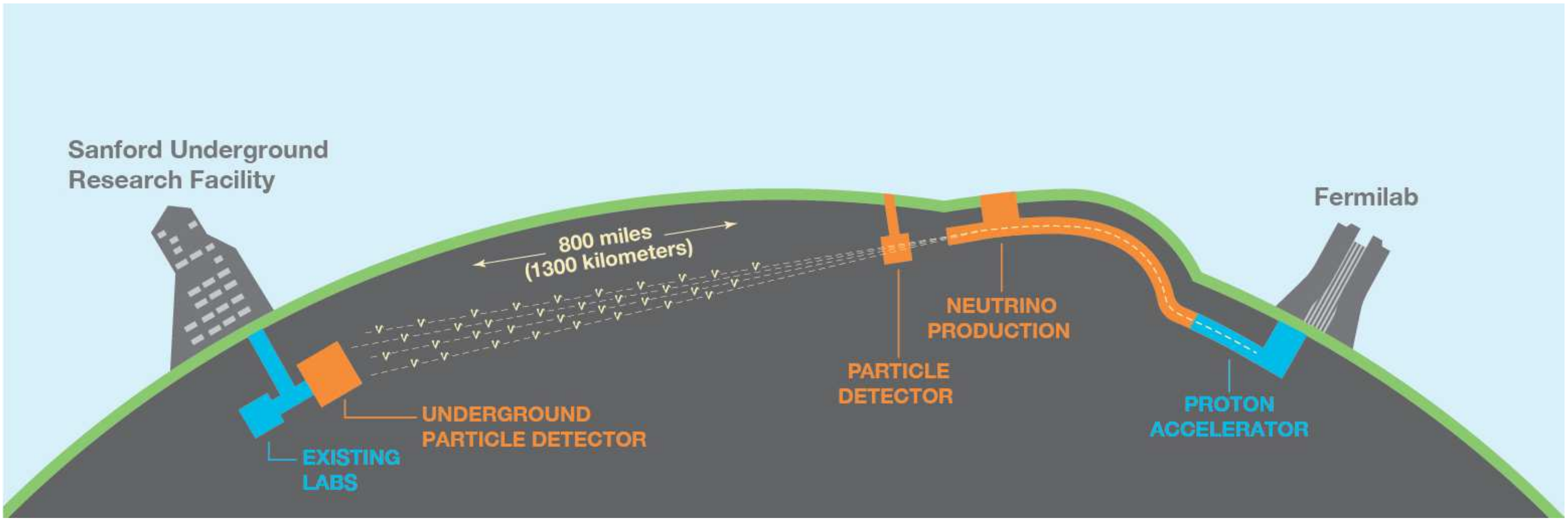
Science Goal #1 – Neutrino Oscillation and the Matter Issue

- We've discovered something called antimatter
- There really isn't much to say at this point
- A positron is just an electron with all of the same exact properties as an electron, it just has a positive charge.
- Antiproton, antihydrogen, antihelium – the exact same stuff – only has the exact opposite charges for their subatomic particles.
- The real question is why the universe seems to be dominated by matter and not antimatter (*which is the anti….?*)
  - They annihilate ($E=mc^2$) when they combine, so there must have been more matter after the big bang than antimatter – but why? Especially considering the law of conservation of charge!!!!! The very presence of matter seems to contradict it.

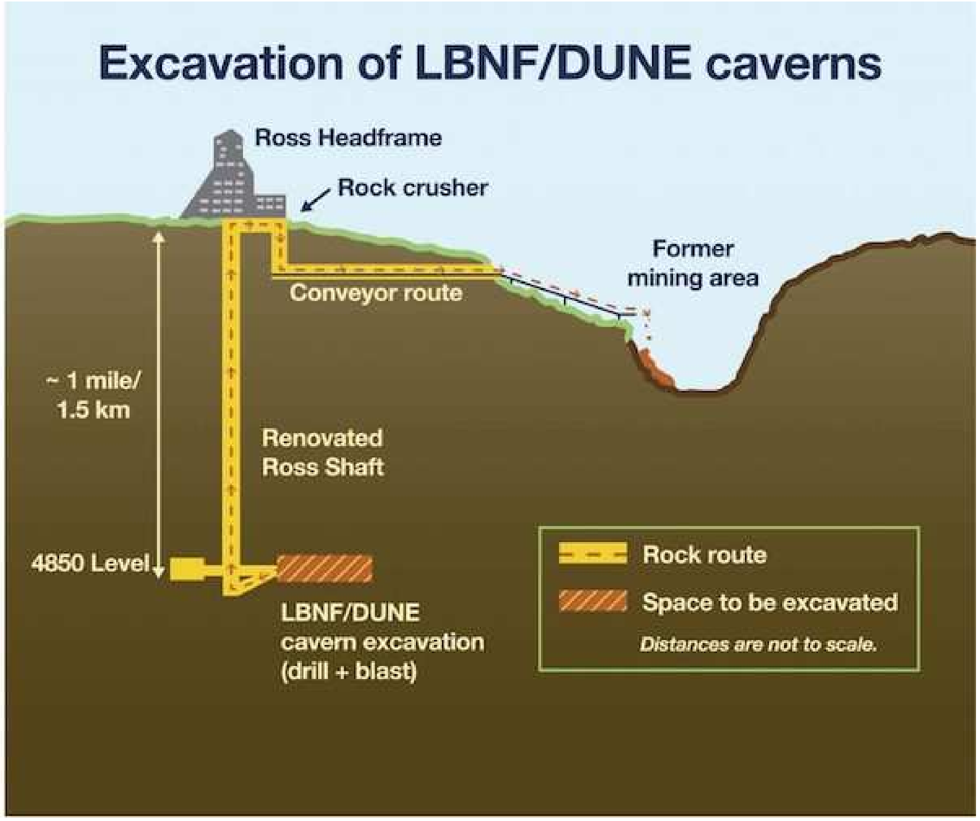
It also seems that neutrinos are their own antiparticle

- So, this is the leading hypothesis as to why we see much more matter than antimatter in the universe right now
- Like any radioactively energetic process, the Big Bang should've created equal amounts of matter and antimatter
- But the neutrinos can oscillate from one flavor to another (or from the matter properties to the antimatter properties)

Fermilab


Sanford Underground
Research Facility
800 miles
(1300 kilometers)
Fermilab
NEUTRINO
PRODUCTION
PARTICLE
DETECTOR
UNDERGROUND
PARTICLE DETECTOR
EXISTING
LABS
PROTON
ACCELERATOR

- Fermilab creates beams neutrinos (see video in a few slides), measures the statistics of beam constituents
- Sanford measures the statistics of which neutrinos they receive
- Statistics are done – does oscillation favor one transition more than others…?
  - Hypothesis – a certain type of transition is favored – one in which the matter particle is the end result more often
  - The matter we see is what was left over after all of the non-transitioned antimatter met an equivalent amount of matter



July 2017

Groundbreaking for LBNF/DUNE

Autumn 2018

ProtoDUNE detectors online at CERN

2019

Begin main cavern excavation in South Dakota

2022

Begin installing the first DUNE detector

2026

Fermilab's high-energy neutrino beam to South Dakota operational with two DUNE detectors online

- Show video on how you make neutrino beams at Fermilab
- http://www.fnal.gov/pub/science/lbnf-dune/photos-videos.html
- https://www.youtube.com/watch?v=U_xWDWKq1CM

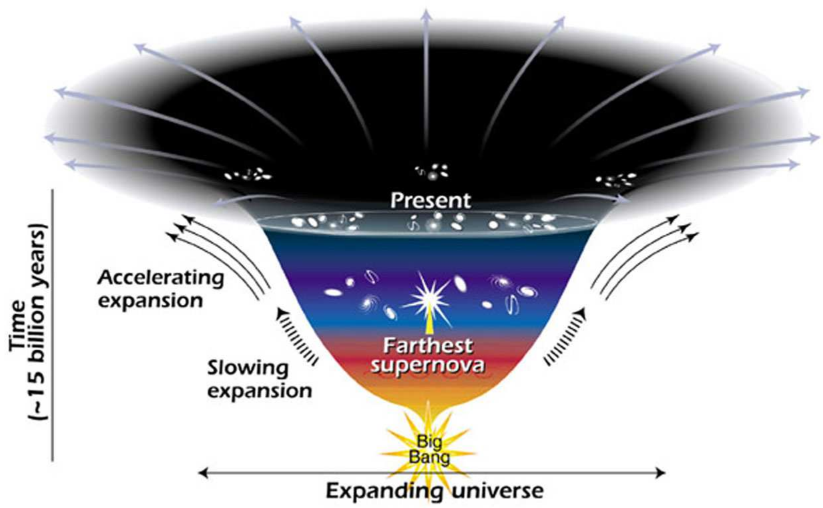
Other Science Goals

- Grand unification of the three or four forces
- Supernova explosions cause flurry of neutrinos – can we develop a “new type of telescope” that “sees” in the neutrino
- Also study black holes

Other stuff Fermi has done

- Neutron chemotherapy lab
- https://www-bd.fnal.gov/ntf/

d Dark Energy



This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.