Neutrino Mysteries

OLLI UC Irvine

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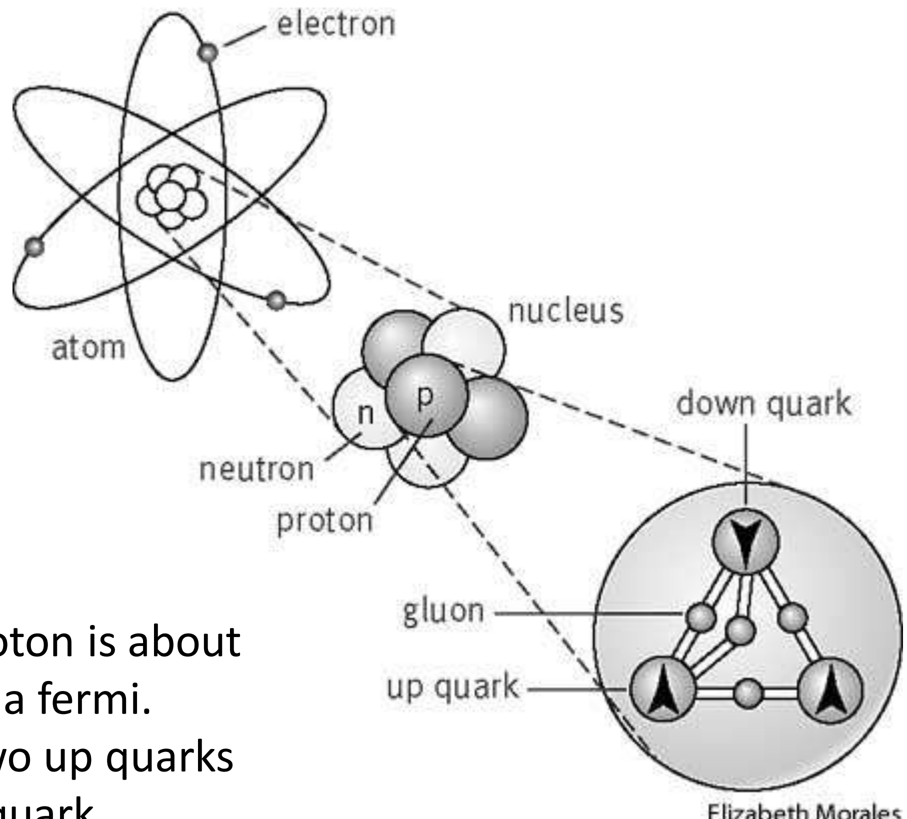
Neutrinos Around the Universe

- Neutrinos
- The Standard Model
- The Weak Interactions
- Neutrino Oscillations
- Solar Neutrinos
- Atmospheric Neutrinos
- Neutrino Masses
- Neutrino vs. Antineutrino
- Supernova Neutrinos

Introduction to the Standard Model

www.particleadventure.org

Over 100 Years of Subatomic Physics
Atoms to Electrons and Nuclei to Protons and Neutrons and to Quarks



The size of a proton is about 10^{-13} cm, called a fermi. Protons have two up quarks and one down quark. Neutrons have one up quark and two down quarks.

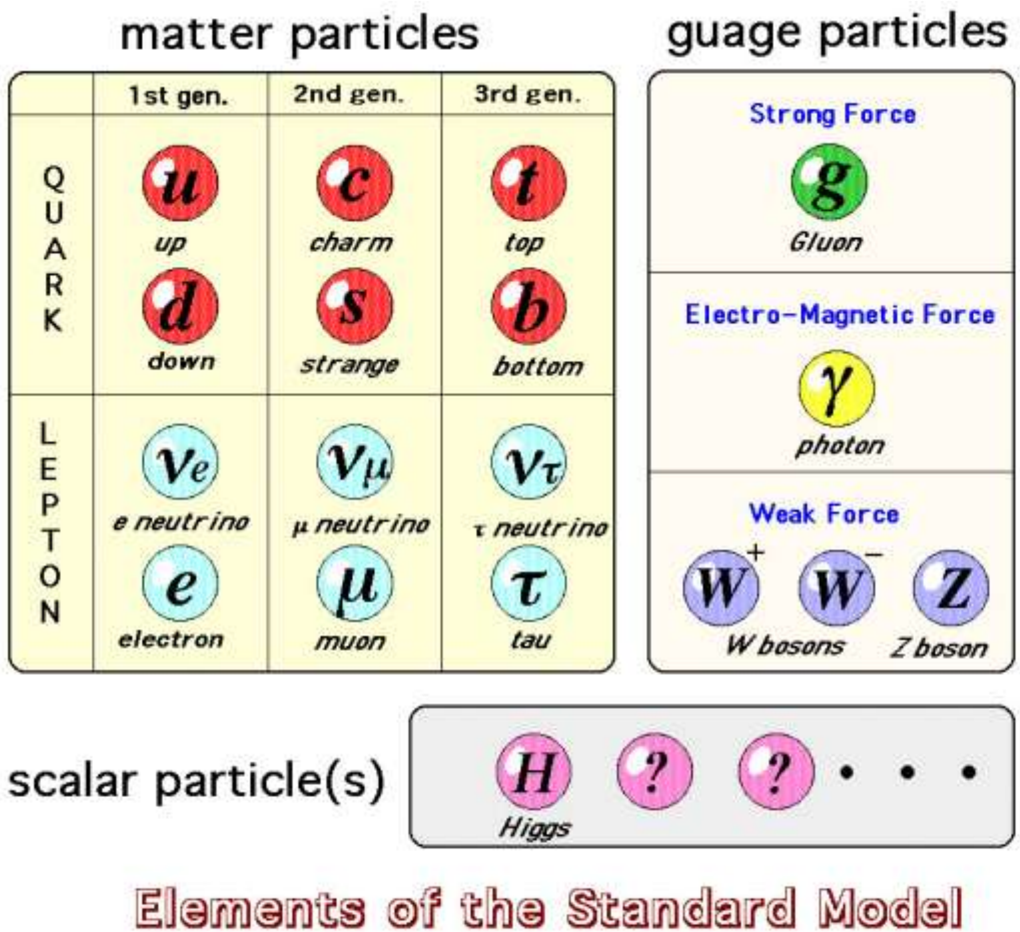
The Standard Model of Quarks and Leptons
Electromagnetic, Weak, and Strong Color Interactions

Q = +2/3 e

Q = -1/3 e

Q = 0

Q = - e



The Spin of Particles, Charges, and Anti-particles

- The quarks and leptons all have an intrinsic spin of ½ in units of hbar = $h/2\pi = \hbar$, a very small number. These are called fermions after Enrico Fermi. They have anti-particles with opposite charges.
- The up quarks have charge $+2/3$ of that of the electron's magnitude, and the bottom quarks have charge -1/3.
- The force particles have spin 1 times ħ, and are called bosons after S. N. Bose.
- The force particles are their own antiparticles like Z^0 and the photon, or in opposite pairs, like W^+ and W^-, and the colored gluons.

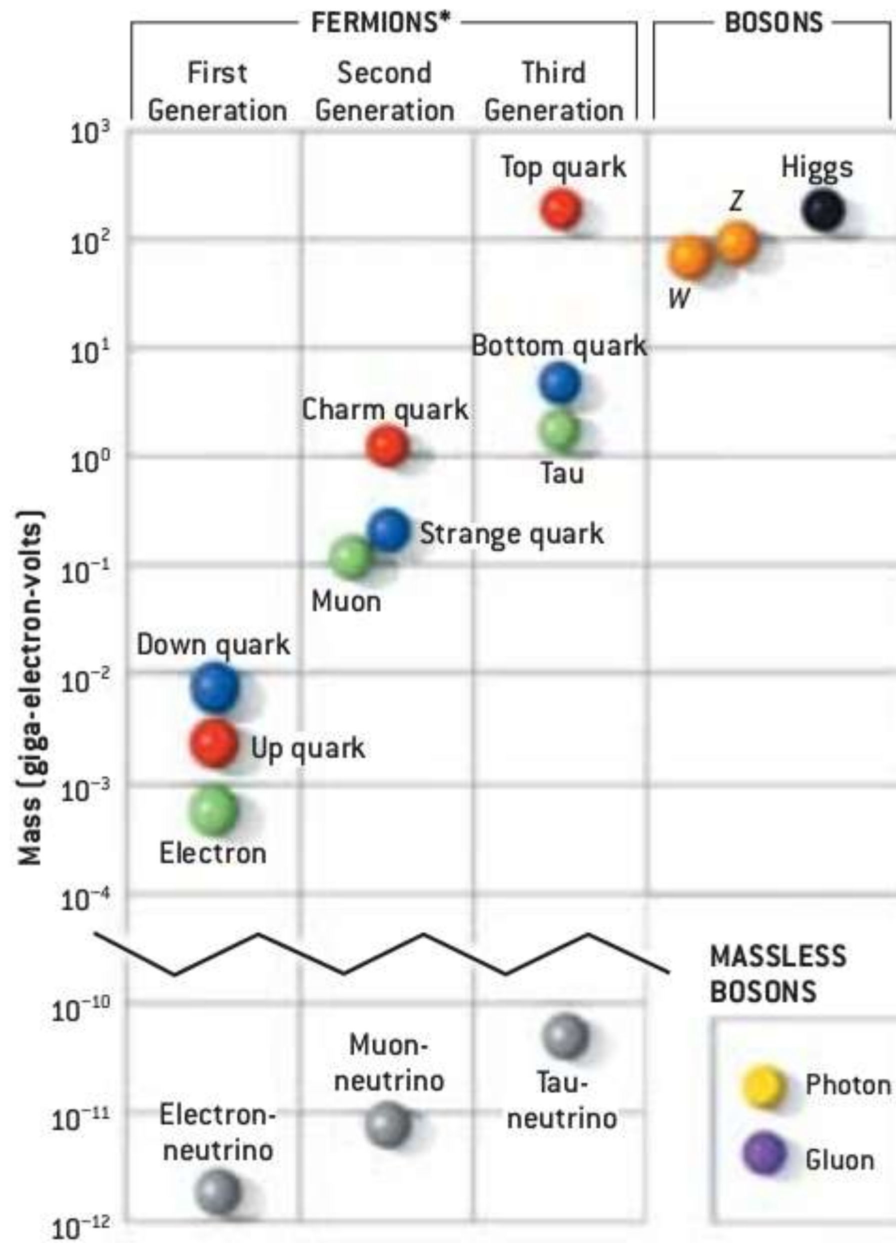
Masses of Elementary Particles

The Proton and Neutron are about 1 GeV →

A GeV is a giga electron volts in energy, or a billion electron volts

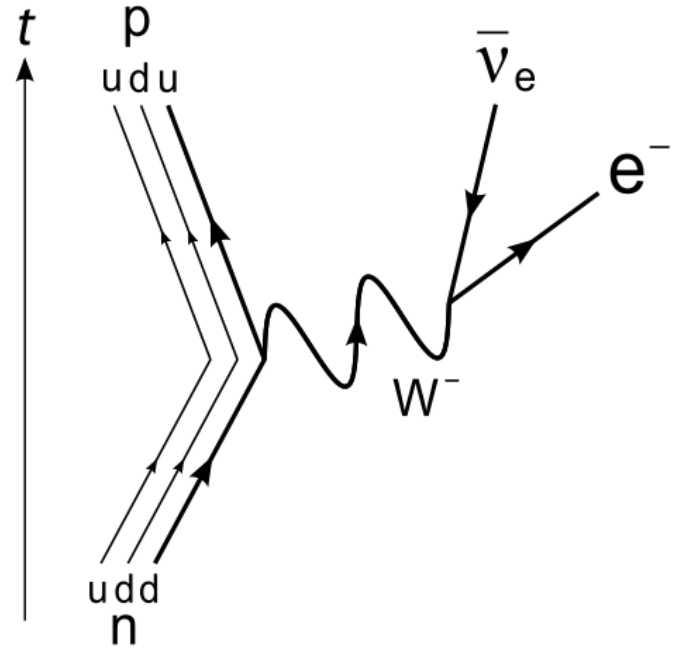
Diagram from Gordon Kane, Scientific American 2003

125 GeV →

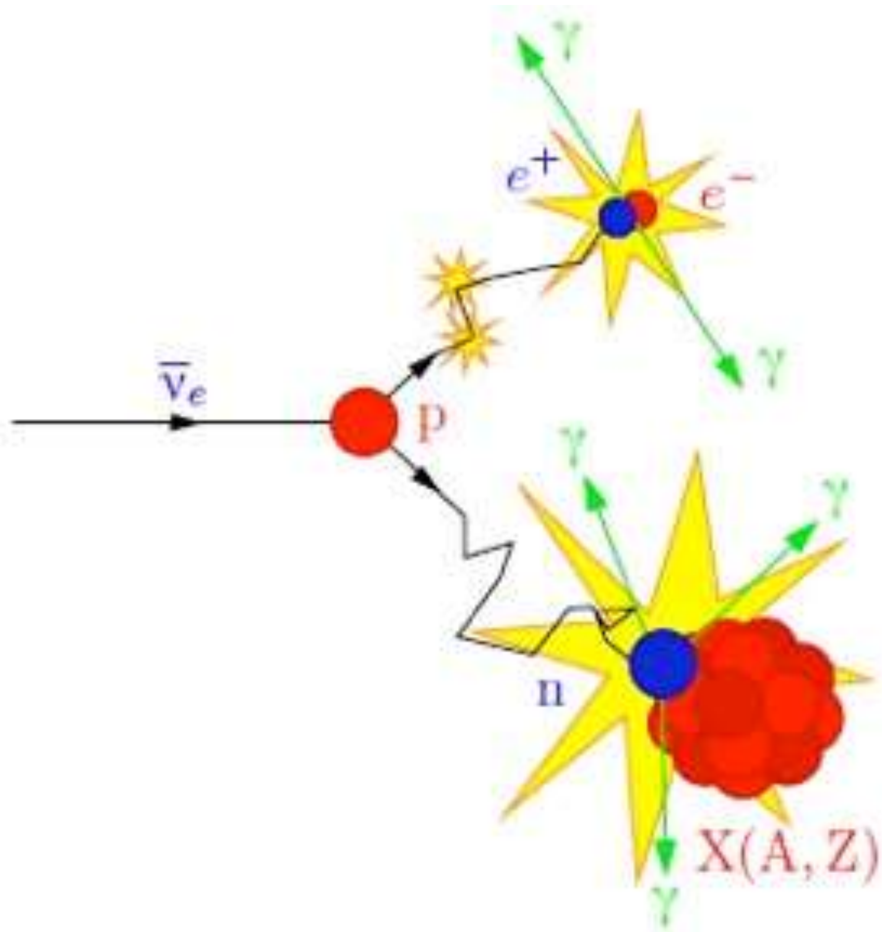


The Weak Interactions

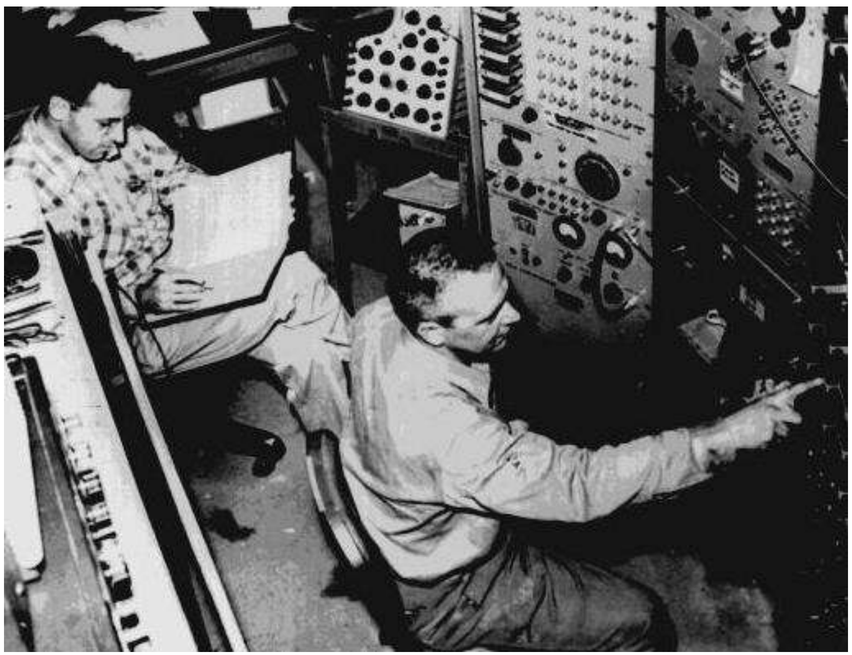
The Beta (electron) Decay of a neutron is really that of a down quark to an up quark with a virtual W^- creating an electron and an electron anti-neutrino. So the weak bosons W take us between up and down type quarks, and up and down type leptons in each generation. Nuclear reactors make a lot of neutrons and nuclei that decay like this.



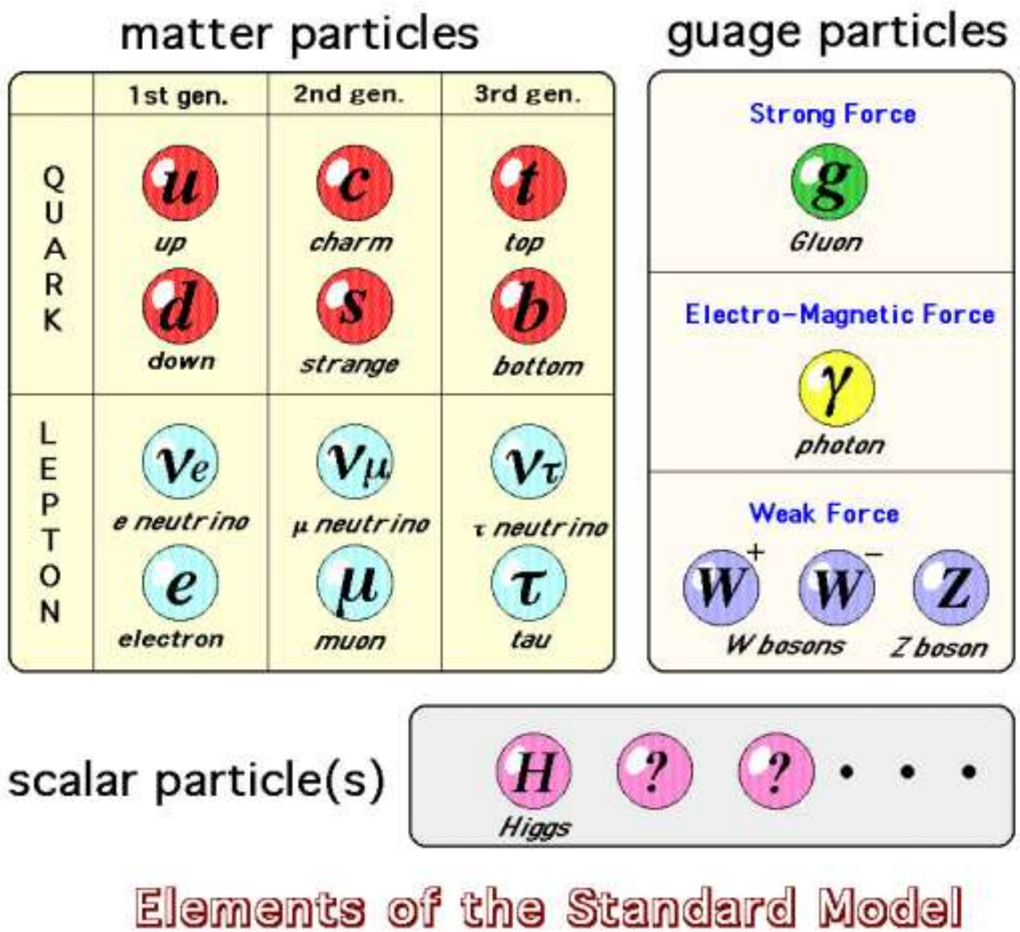
Detecting Reactor Anti-neutrinos Through Inverse Beta Decay



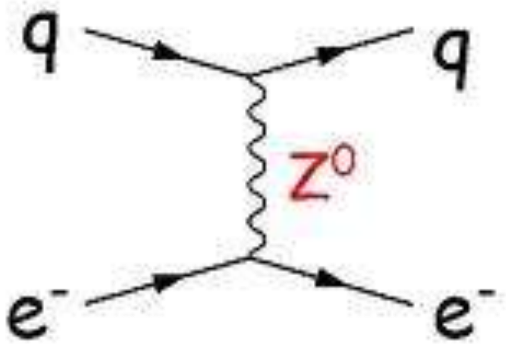
Discovery of the Neutrino by
Fred Reines and Clyde Cowan in 1956
Fred led the neutrino group at UC Irvine
Received Nobel Prize in 1995

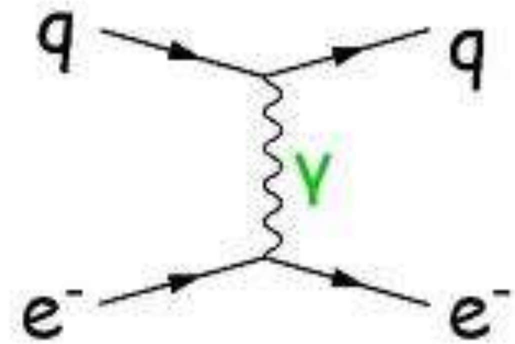


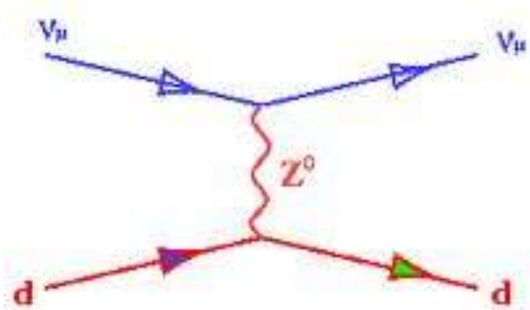
Charged Weak Interactions as Transitions between Up and Down Quarks or Up and Down Leptons

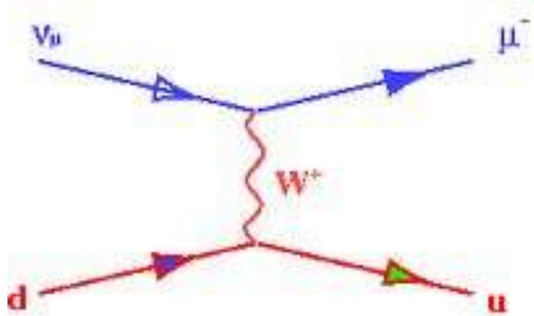


Charged W Bosons, Neutral Weak Interaction (Z^0) and Photon (γ) Exchanges









Photons couple with the charge.
Z^0 couples with $+1/2$ for up quarks or leptons, and $-1/2$ for down quarks or leptons, just like spin up or down with the magnetic field.
W^+ and W^- charged bosons change quarks and leptons between up and down.

Neutrinos in Interactions

- Neutrinos have three types of interactions:
- Creation: $e^- \rightarrow \nu_e + W^-$
- Disappearance: $\nu_e \rightarrow e^- + W^+$
- Scattering: $\nu_e \rightarrow \nu_e$ via exchange of a Z^o
- The ν_e is always associated with the electron
- There is also a ν_μ associated with the muon, and a ν_τ associated with the tau.
- These are called the flavor neutrino states.

Now Enters Quantum Mechanics

- The v_e , v_μ , and v_τ do not each have a definite rest mass, so they are not really fundamental particles.
- They are each quantum mechanical mixtures or superpositions of three neutrino particles of definite mass with the catchy names v_1 , v_2 , and v_3 . These are called the neutrino mass states. For example, v_e is a sum of v_1 , v_2 , v_3 :
- $V_e = U_{e1} v_1 + U_{e2} v_2 + U_{e3} v_3$

Probability is Conserved

- In quantum mechanics when there are mixed states, the probabilities of finding the system in all states must still add up to 1. U^2_{e1} is the probability of finding the mass state v_1 in the v_e , when it is just created.
- The amplitude of the three mass states in the flavor states is written in a table. The square of each element is the probability of finding the mass state in the flavor state.
- The Maki-Nakagawa-Sakata-Pontecorvo (MNSP) mixing matrix

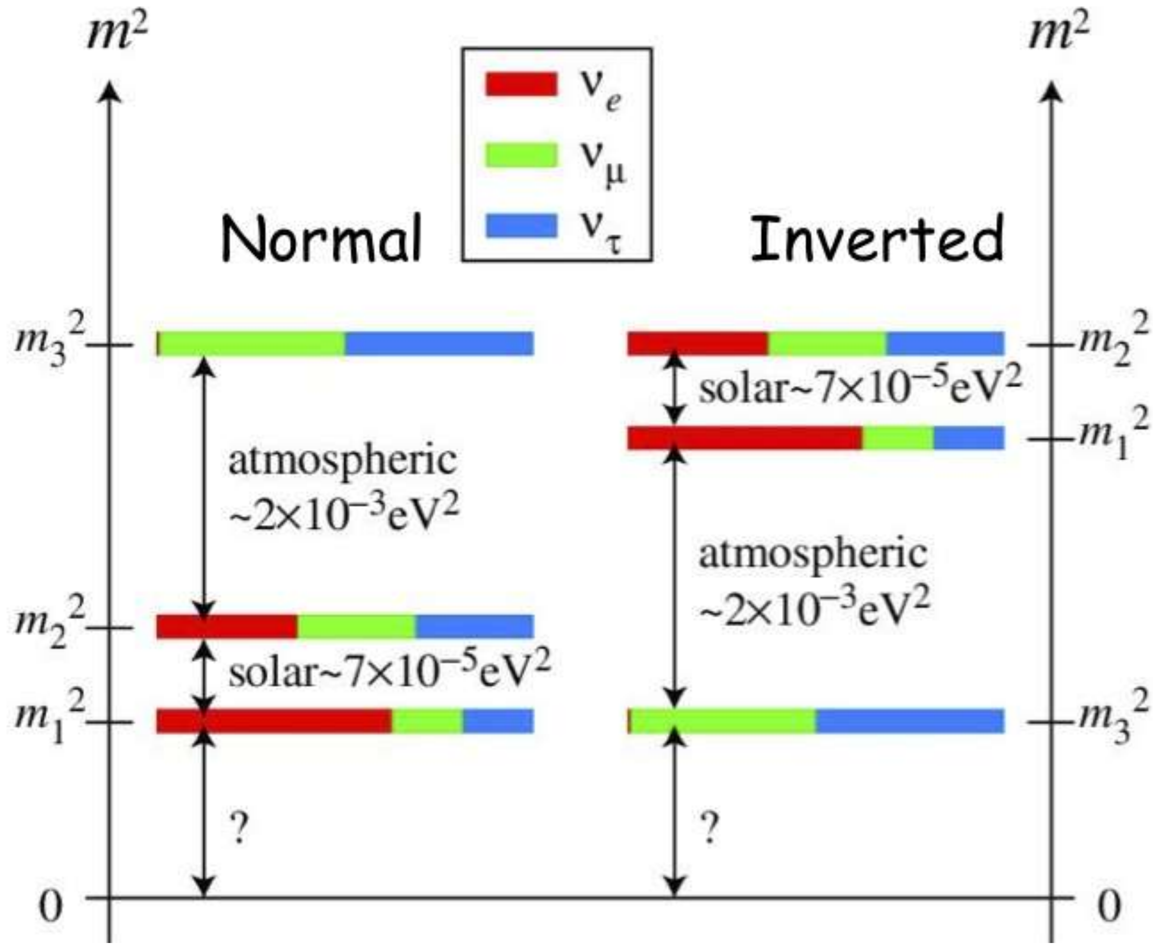
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

The Simple Mixing Model and Probabilities
Flavor neutrinos from mass neutrinos.
Note the rows and columns of the probabilities sum to 1

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\frac{\sin\theta_{12}}{\sqrt{2}} & \frac{\cos\theta_{12}}{\sqrt{2}} & \sqrt{\frac{1}{2}} \\ \frac{\sin\theta_{12}}{\sqrt{2}} & -\frac{\cos\theta_{12}}{\sqrt{2}} & \sqrt{\frac{1}{2}} \end{pmatrix} \xrightarrow{\text{TBM}} \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}. \qquad (5)$$

$$\begin{bmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu 1}|^2 & |U_{\mu 2}|^2 & |U_{\mu 3}|^2 \\ |U_{\tau 1}|^2 & |U_{\tau 2}|^2 & |U_{\tau 3}|^2 \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \end{bmatrix}.$$

Neutrino Masses
Mixing of Mass Neutrinos into Flavor Neutrinos

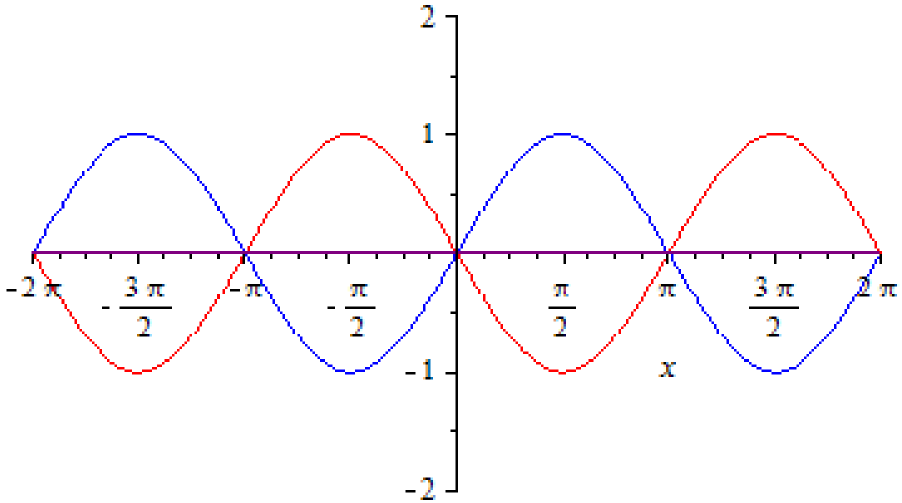


Neutrino Momentum

- The flavor neutrinos, when created, are a definite mixture of the mass neutrinos.
- If created at a definite energy, the momenta of the mass neutrinos will vary since (i=1,2,3)
- $P_i^2 = E^2 - m_i^2$. Solving for P_i gives
- $P_i = E - \frac{1}{2} m_i^2/E$

Particles Act Like Waves

- Louis de Broglie saw that on an atomic scale, particles behaved like waves with a wavelength $\lambda = h/p$ where p is the particle's momentum ($p = m\,v$), and h is Planck's atomic scale constant.
- Waves oscillate with an angular phase $\theta = 2\pi\, x/\lambda$ where x is the distance. As x goes 0 to λ, θ goes from 0 to 2π.
- So $\theta = p\,x / \hbar$, where $\hbar = h / 2\pi$.



Neutrino Oscillations

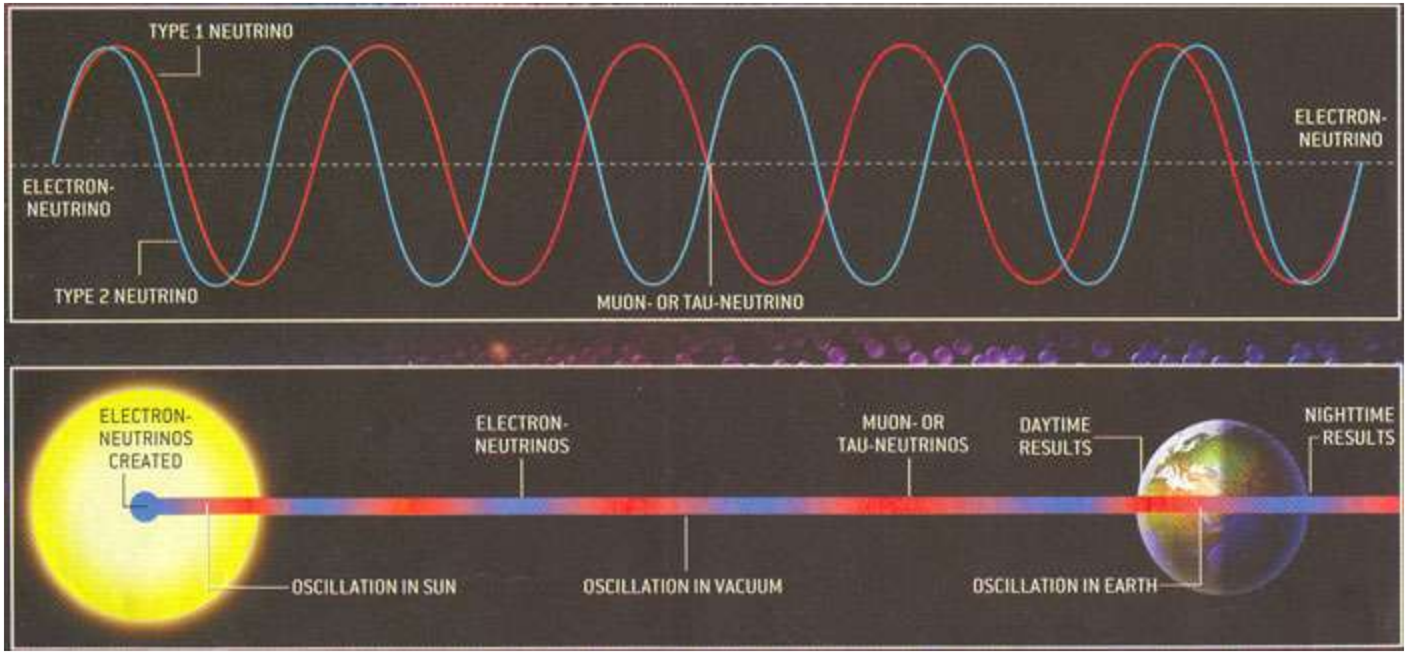
- As the mass neutrinos move by $x = L$, they change their wave phases by different angles:

  $P_i\, L/\hbar = E\, L/\hbar - \frac{1}{2}\, m_i^2\, L\, /E\, \hbar$

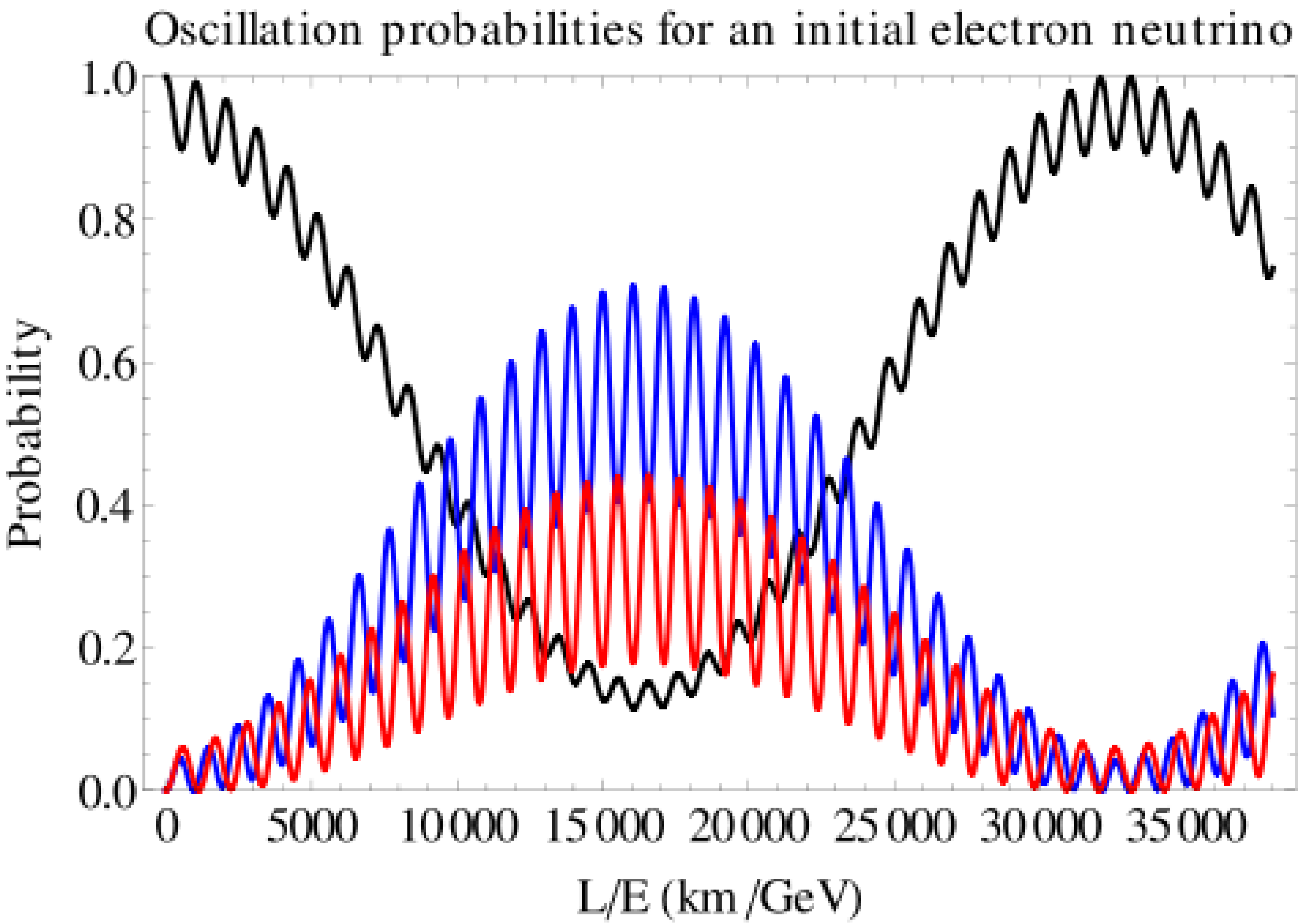
- The difference of the phases is the change that provides the oscillation, so this is proportional to the difference in m_i^2: $\Delta m^2_{21} = (m_2^2 - m_1^2)$, times $L/2E\hbar$.
- Then the mixture of mass neutrinos starts looking like other flavor neutrinos than the one that they started as, and can appear as other flavors in a flavor detecting creation experiment.

Solar Neutrino Oscillation

- Since Solar Neutrinos start out as ν_e , about an equal mix of ν_1 and ν_2 . As they move, they have different phases, which eventually make their amplitudes opposites, which looks more like ν_μ and ν_τ .



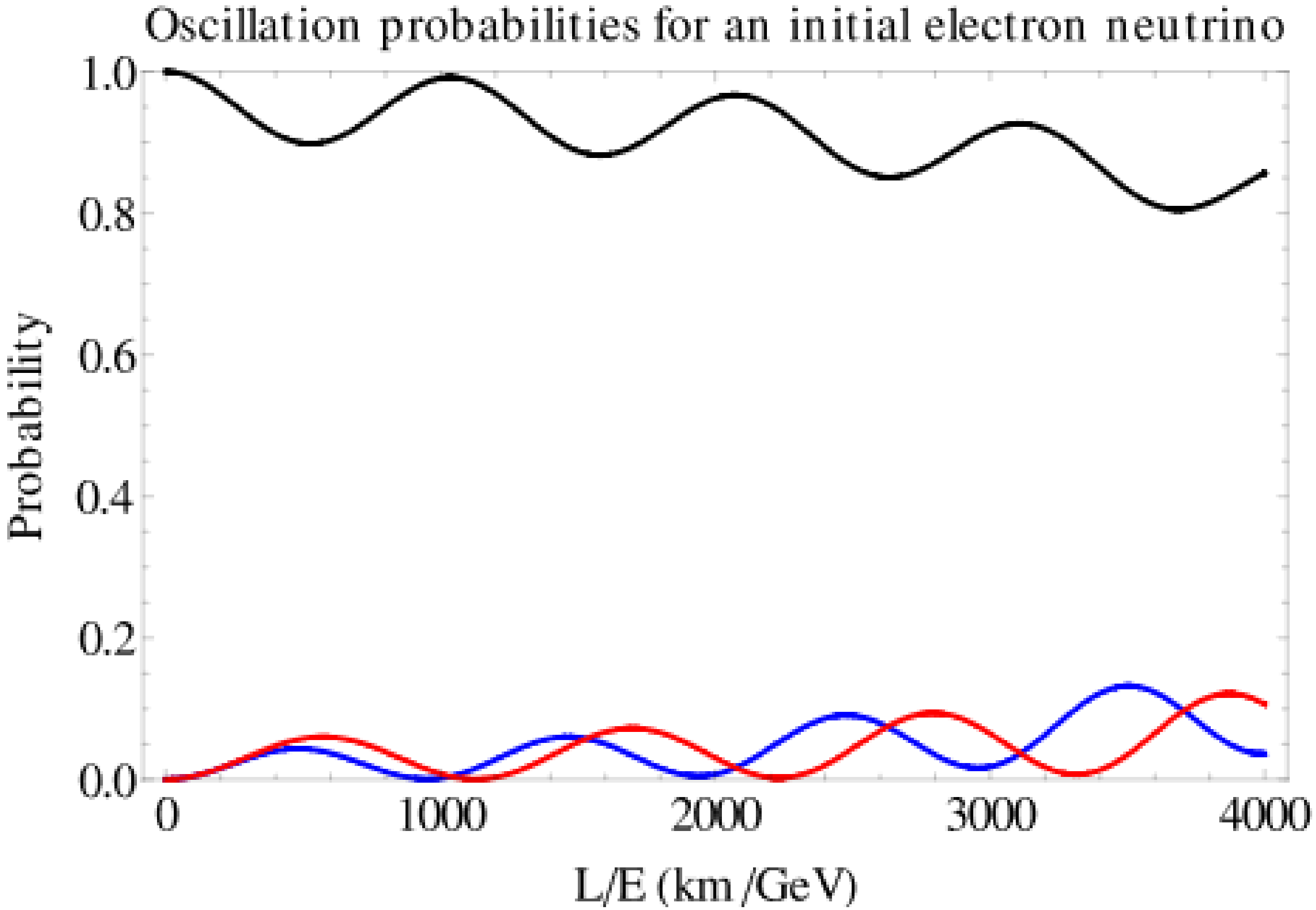
Electron Neutrino Oscillations (L in km, E in Gev)
Black is Electron ν_e, Blue is Muon ν_μ, Red is Tau ν_τ
For reactor neutrinos in MeV, divide base by 1,000



Neutrino Masses

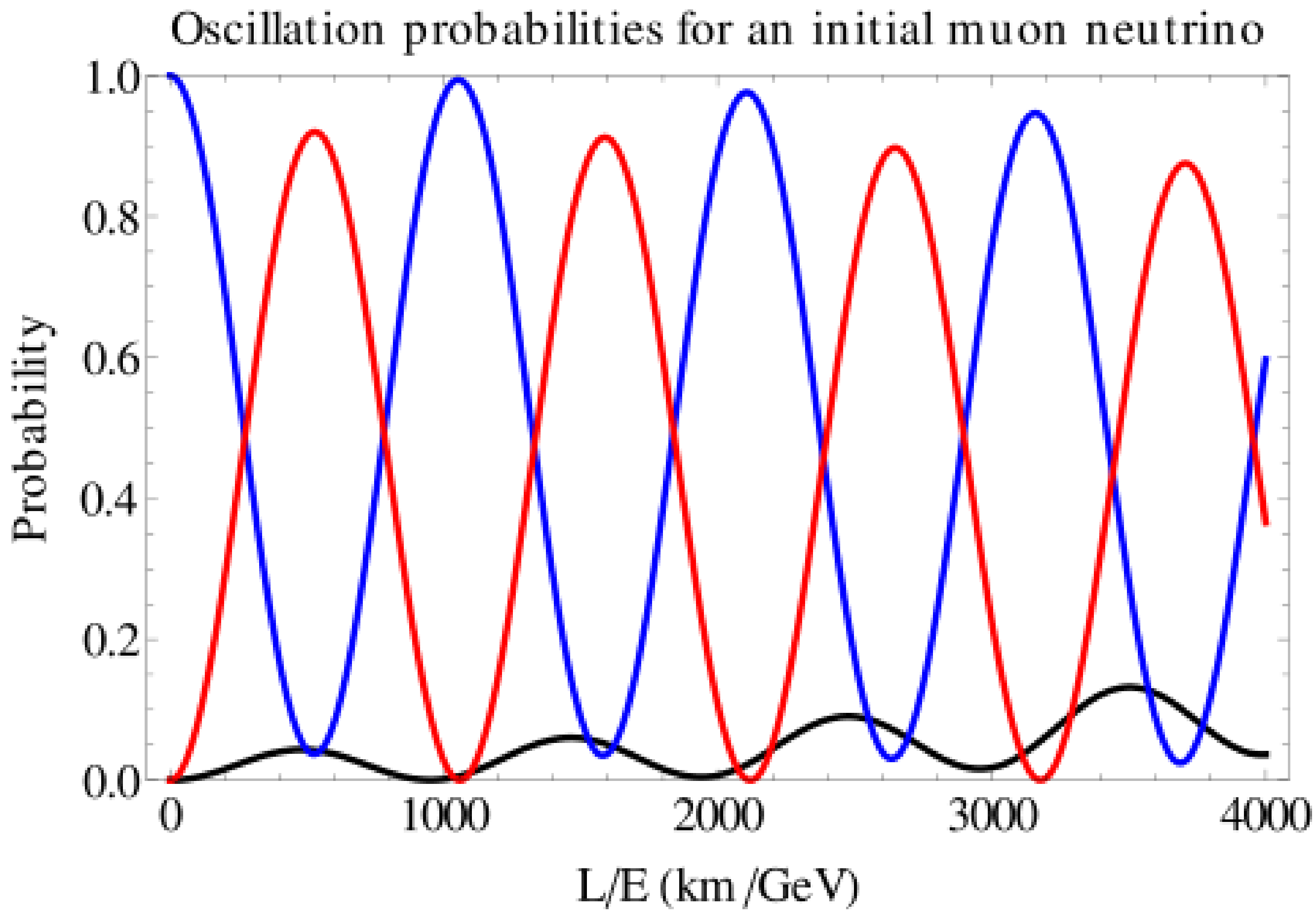
- The masses of the neutrinos are know to be less than 1 eV (electron volt) from the cosmic microwave background radiation and from the early synthesis of the nuclei. The electron mass, for comparison, is about 500,000 eV.
- The oscillations only give us differences of the squares of the masses, as in the previous formula.
- Oscillations increase with distance L, and occur more slowly if the neutrino energy E is large.

Electron Neutrino Oscillations (L in km, E in Gev)
Black is Electron ν_e, Blue is Muon ν_μ, Red is Tau ν_τ
For reactor neutrinos in MeV, divide base by 1,000



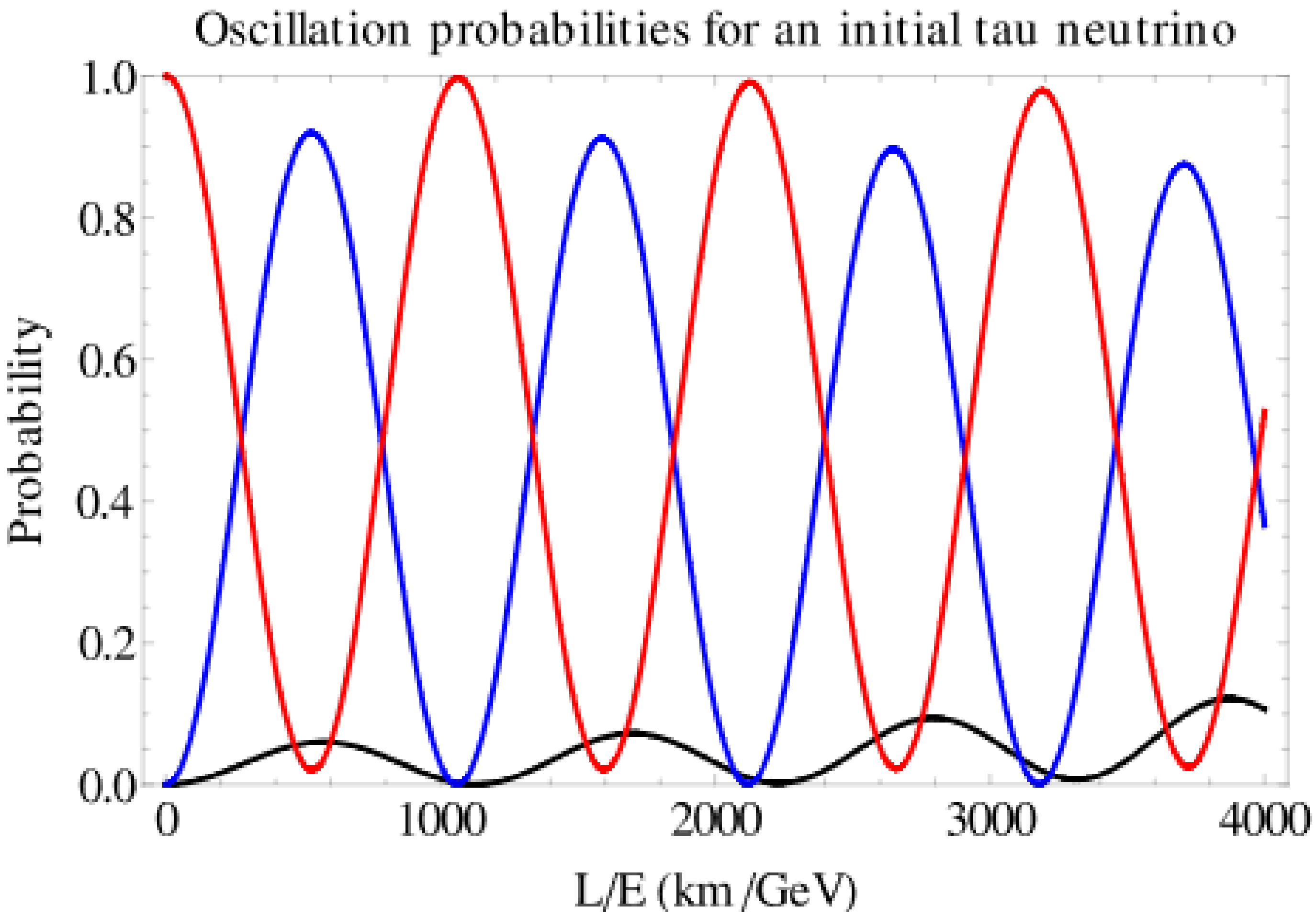
Muon Neutrino Oscillation

Blue is Muon, Red is Tau, Black is Electron



Tau Neutrino Oscillation

Red is Tau ν, Blue is Muon ν, Black is Electron ν



Neutrino Oscillation Experiments

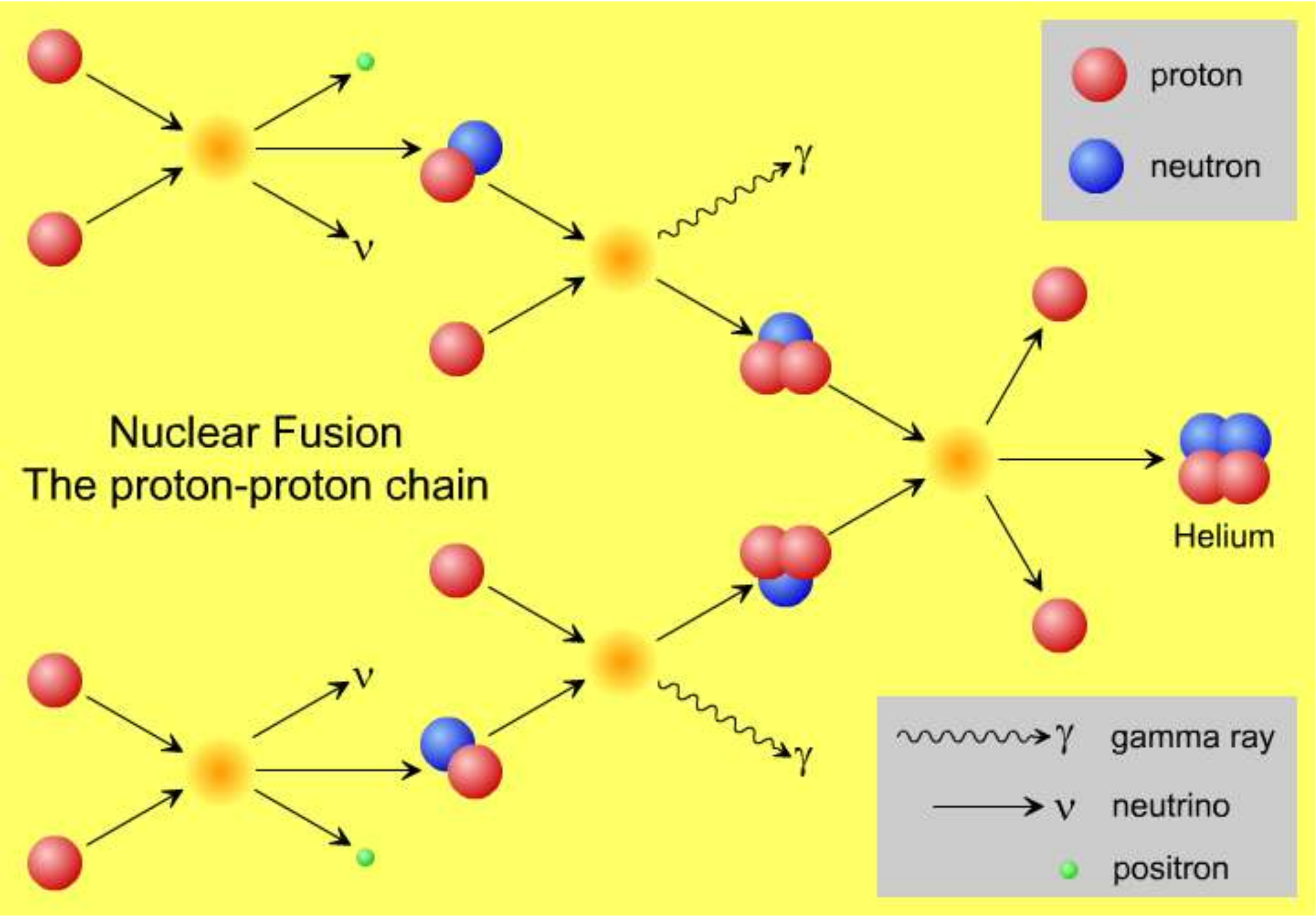
- An experiment in which an electron converts to a neutrino, and then recreates an electron is called a **disappearance experiment** because the electron probability has decreased due to oscillation to other neutrinos.
- An experiment in which an electron converts to a neutrino which then oscillates to another neutrino which then creates a muon or tau lepton is called an **appearance experiment**.

The Main Experimental Neutrino Sources

- Nuclear reactors are sources of electron anti-neutrinos through $n \rightarrow p + e^- + \text{anti-}\nu_e$, at a few MeV of energy.
- High energy accelerators and cosmic rays produce pions which decay to muon and electron neutrinos, from MeV to many GeV.
- Proton fusion in the sun and decay of nuclei there produce electron neutrinos in the few MeV range.
- About 100 trillion solar neutrinos pass through our bodies every second. 10^{23} in a lifetime.

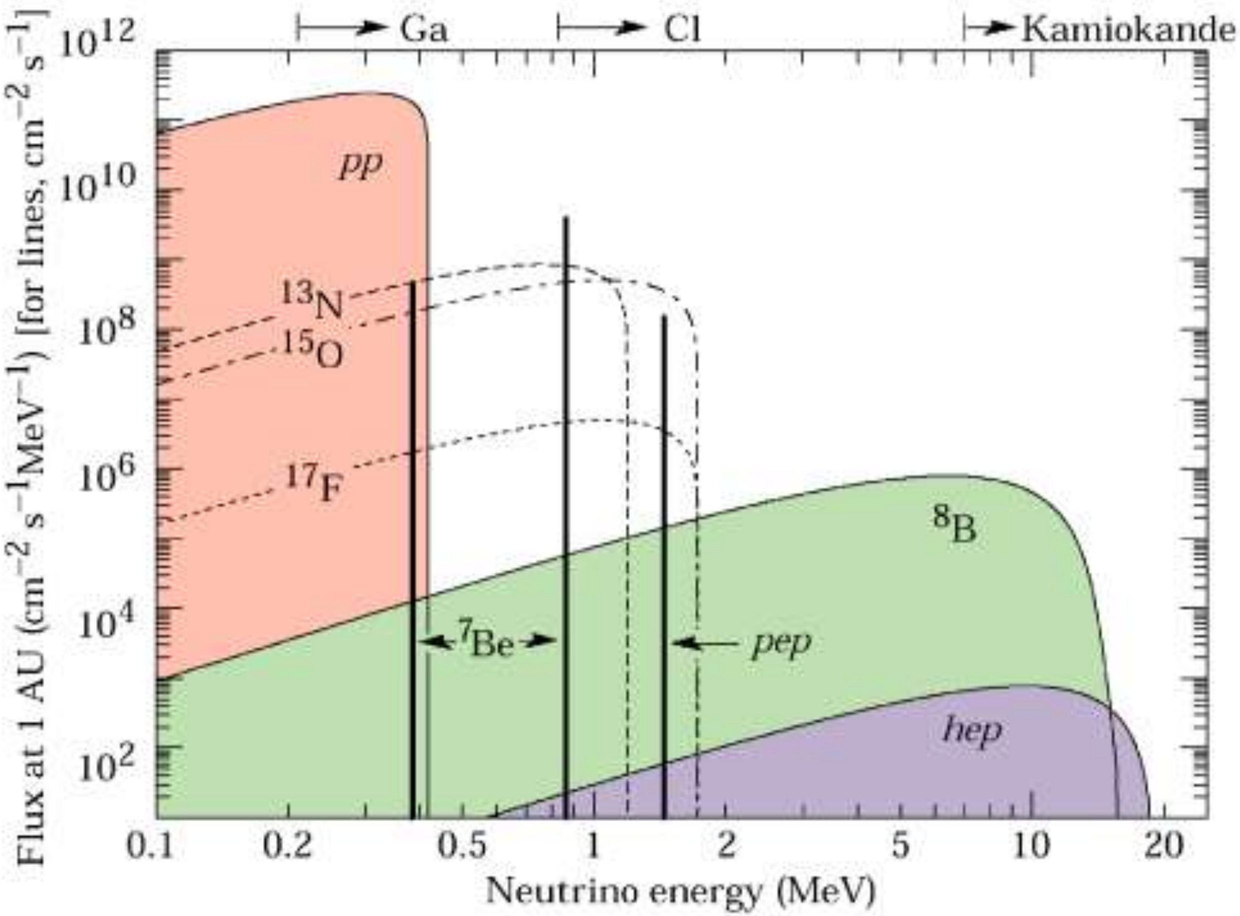
The Real Solar Power

Protons Fuse to deuterons via the Weak Interactions. Then they add another proton to form He^3. The two He^3 then combine to form He^4, shedding two protons back.



The Solar Neutrino Spectrum.

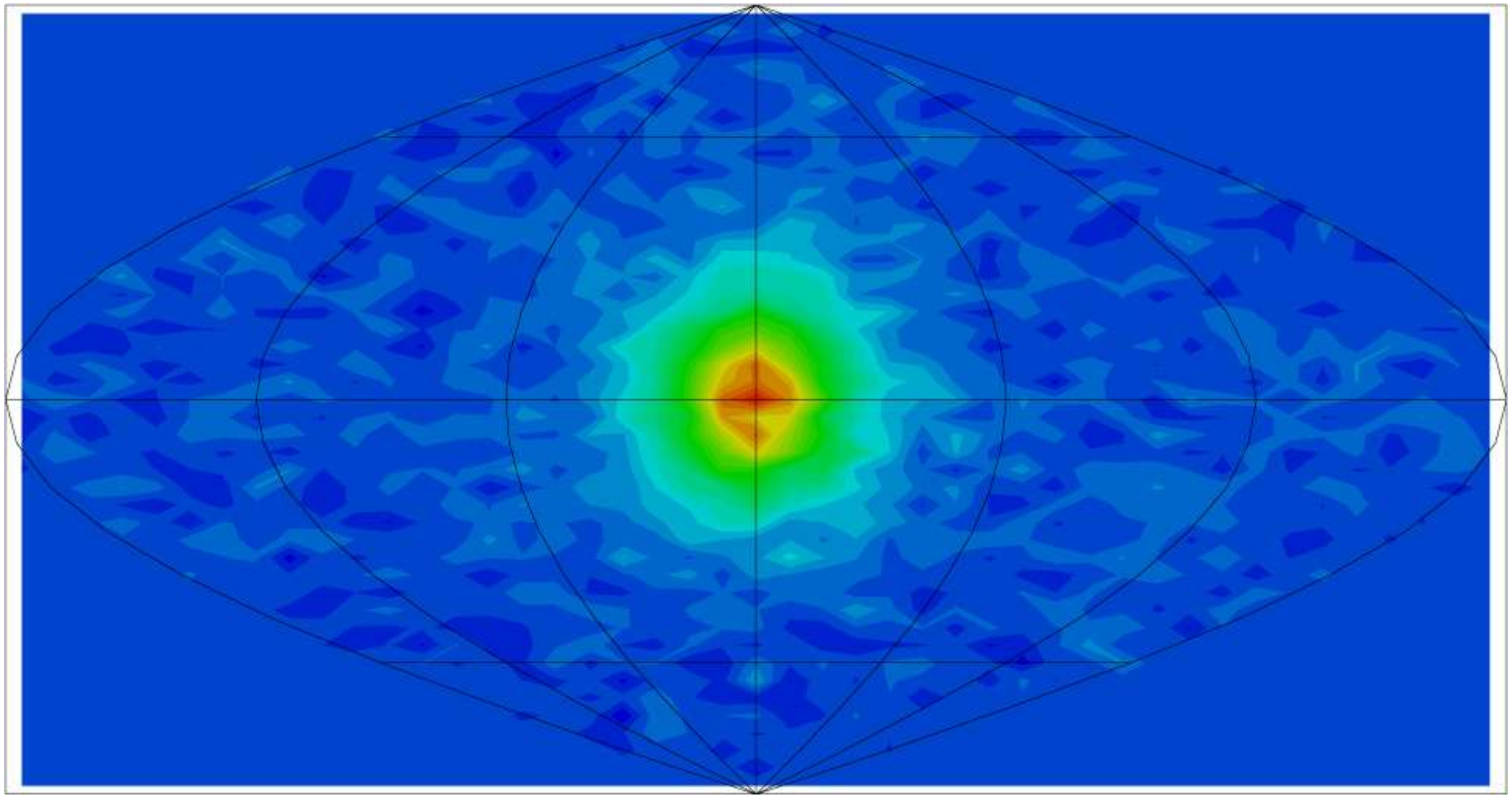
At the top are the energy thresholds for various detectors. The vertical lines are exact energies in simple decays to two particles. Note the energy scale is logarithmic.



Some Fun Facts About Fusion in the Sun

- The nuclear processes that occur in the sun were worked out by Hans Bethe in the 30's, after the neutron was discovered.
- The temperature at the center of the sun is 15 million °C. The temperature at the surface is 6,000 °C.
- It takes a million years for energy generated in the center to get to the surface. The core with fusion is about ¼ the radius of the sun.
- The sun generates 4×10^{26} watts, and burns 4×10^{38} protons per second.
- For every ^4He made, 27 MeV of energy is released. This is, however, only a conversion of 0.7% of matter into energy.

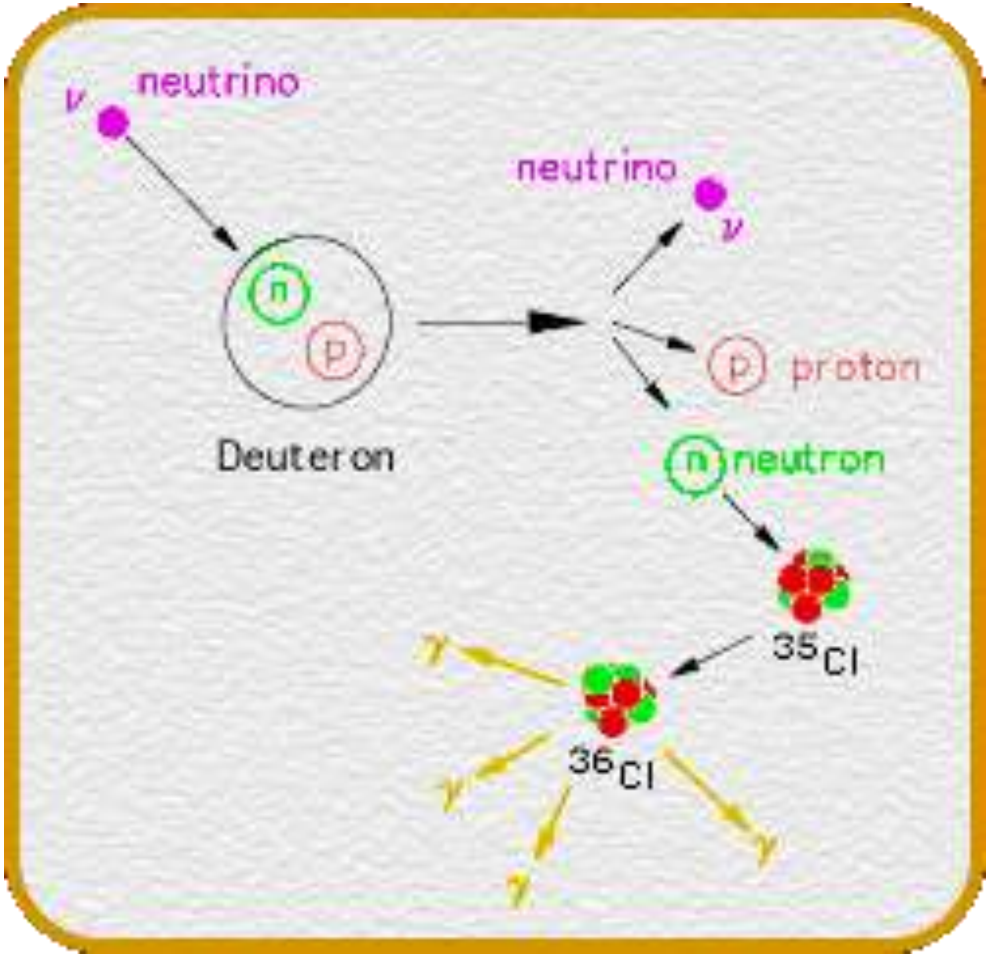
The Sun's Picture in Solar Neutrinos from $\nu_e\, e^-$ scattering, and electron re-scattering smearing The fusion core is about a quarter the size of the sun's radius or an eighth of a degree.



Detecting All Solar Neutrinos

- The MeV energy solar neutrinos can only create an electron, not a muon at 106 MeV or a tau at 1.8 GeV, so only v_e is detected in charged current interactions.
- In 1984, Herb Chen of UC Irvine proposed an experiment that would count all solar neutrinos through their neutral current interactions, which are the same for all flavors.
- The neutral current on the deuteron is detected by breaking up the neutron, and catching the freed neutron in a Chlorine nucleus that decays with photons

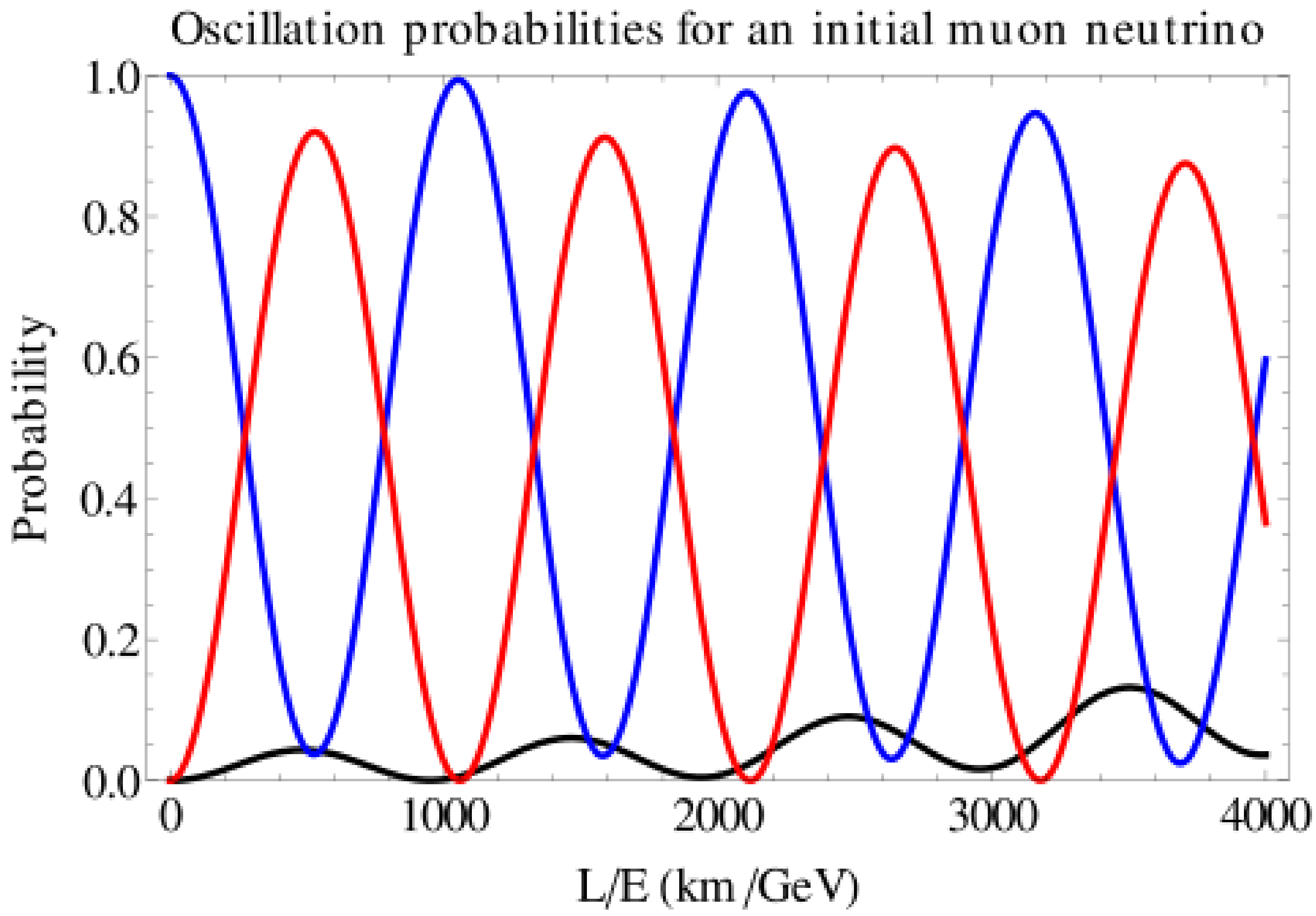
Neutral Current Breakup of the Deuteron in the Sudbury Neutrino Observatory (SNO)
Counting All Neutrinos Equally, the Data Give the Result of Solar Model Calculations, with Electron Neutrinos a Third of That.



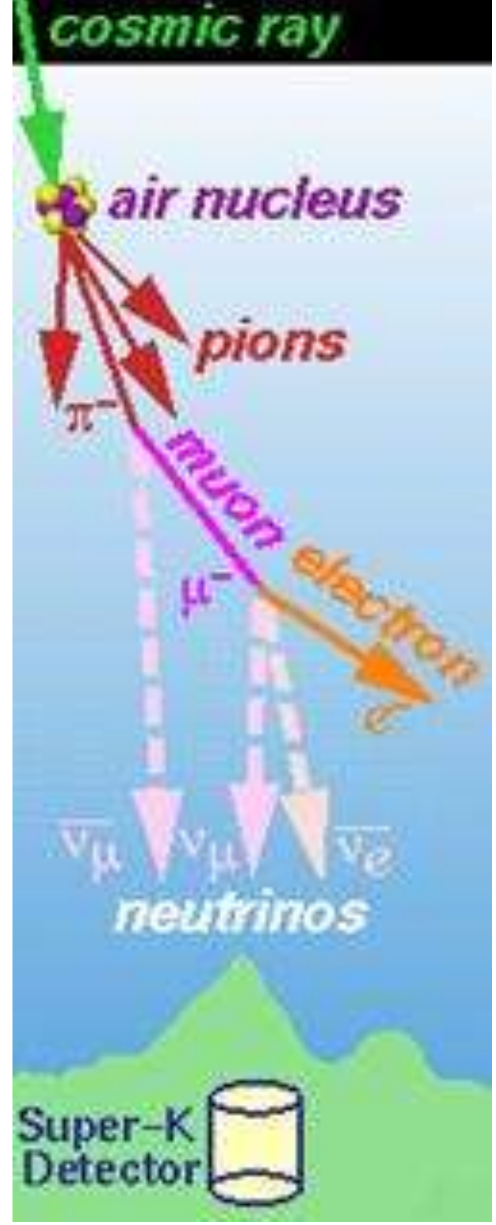
Atmospheric Neutrinos

- High energy cosmic ray protons strike the atmosphere and produce pions, mostly $\pi^+ \rightarrow \mu^+ + \nu_\mu$, and then the muon decays $\mu^+ \rightarrow e^+ + \text{anti-}\nu_\mu + \nu_e$.
- The neutrinos can have energy from hundreds of MeV through GeV.
- When created on the underside of the earth, the neutrinos can oscillate to the detector by up to 10,000 km.
- Since ν_μ are mainly ν_2 and ν_3 , which are also most of ν_τ , they oscillate to ν_τ , and reduce their signal to about ½.

Muon Neutrino Oscillation
Blue is Muon, Red is Tau, Black is Electron



Atmospheric Neutrinos
Here is a π^- and its neutrino decays



Neutrino Mass Differences

- From solar neutrino disappearance and reactor experiments, it has been determined that the smaller difference of squared masses is:

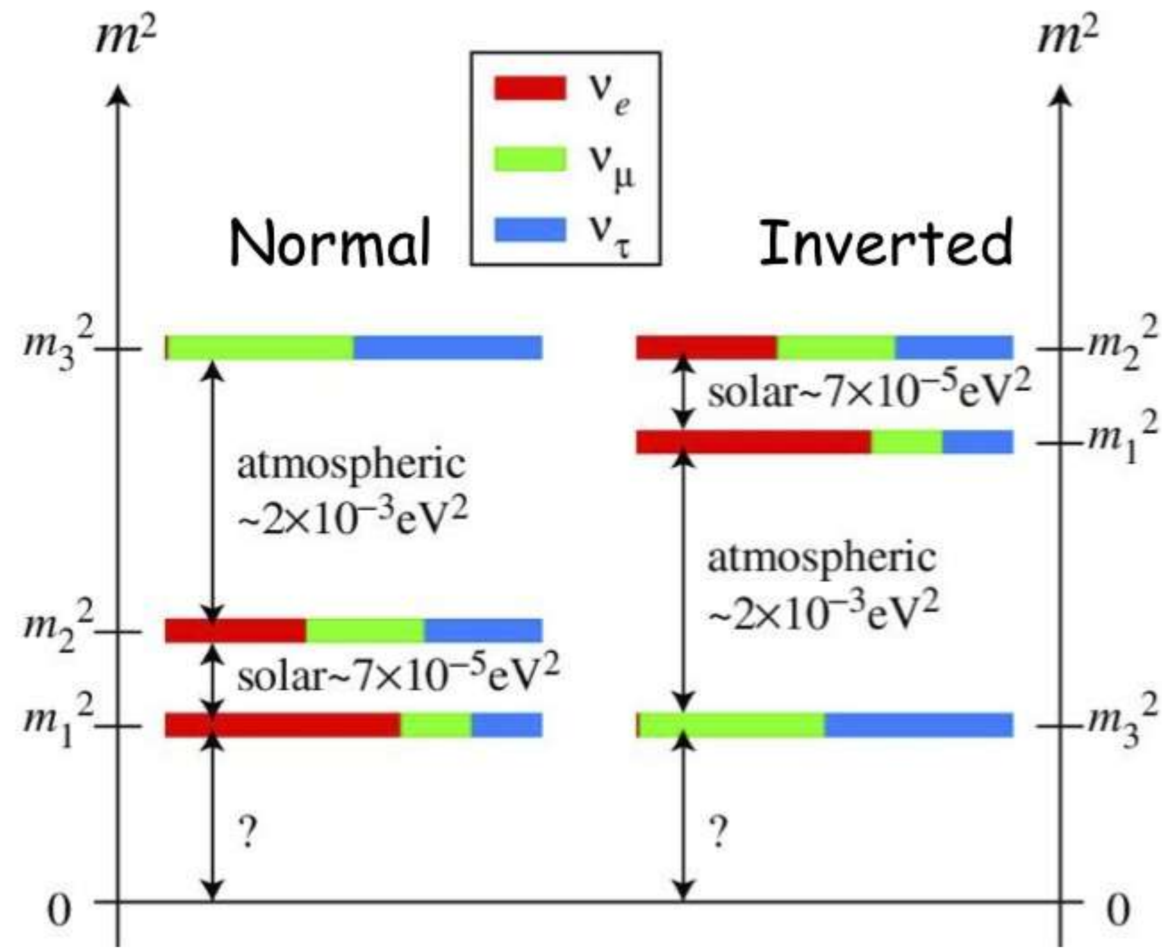
$$\Delta m^2_{21} = (0.750 \pm 0.020)\text{x}10^{-4}\ \text{eV}^2 \text{, also called } \Delta m^2_{sol}$$

- From atmospheric neutrinos and muon lab experiments, the larger squared mass difference is:

$$\Delta m^2_{32} = (23.2 \pm 1.2)\text{x}10^{-4}\ \text{eV}^2 \text{, also called } \Delta m^2_{atm}$$

- The **heirarchy** or ordering of the mass differences still has to be determined by experiments, as well as the difference of the lowest mass from zero.

Neutrino Masses
Mixing of Mass Neutrinos into Flavor Neutrinos



Minimal Masses
Just Playing with the Masses if m_1 is Near Zero.

- Then from $\Delta m^2{}_{21} = (0.750 \pm 0.020)\text{x}10^{-4}\ \text{eV}^2$

  we find $m_2 = 0.0087$ eV.

- And from $\Delta m^2{}_{32} = (23.2 \pm 1.2)\text{x}10^{-4}\ \text{eV}^2$

  we find $m_3 = 0.049$ eV, a factor of 5.6 times larger than m_2.

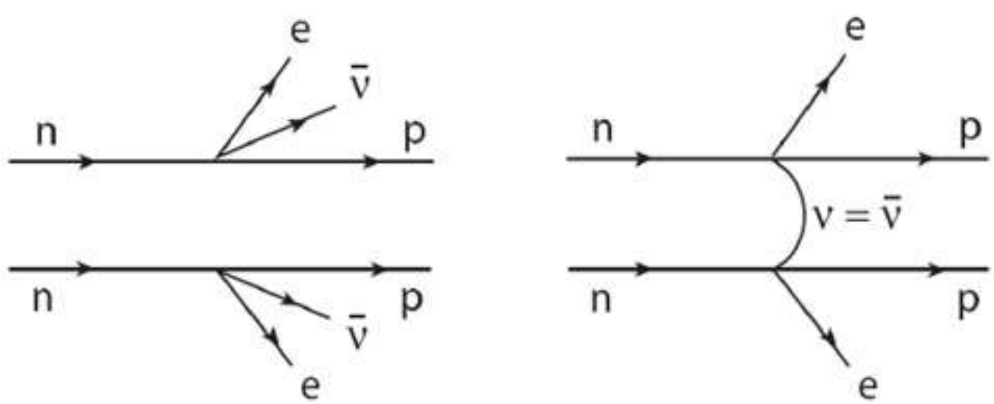
- These are as small as the masses can be with the experimental mass differences, and the normal heirarchy.

Do Anti-neutrinos Act Differently from Neutrinos?

- A more exact treatment of the neutrino mixing matrix has $U_{e3} = \sin(\theta_{13})\ e^{-i\delta} = \sin(\theta_{13})\ (\cos(\delta) - i \sin(\delta))$ instead of 0.
- The neutrino mixing matrix we have dealt with has been for neutrino oscillations. The one for anti-neutrinos has the sign of i changed, and gives different results.
- $\mathrm{Sin}^2(2\theta_{13}) = 0.090$ has recently been measured and is not zero.
- More oscillation experiments are in progress to find δ, which is roughly known to be negative and centered about -3π/2.

Are Neutrinos Different from Anti-Neutrinos?

- Ettore Majorana suggested in 1937 that the anti-neutrino might be the same particle as the neutrino.
- That would allow a process called neutrino-less double beta decay.
- Here it is shown along side a normal double beta decay, which occurs in nuclei where a single beta decay is not energetically allowed. Neutrino emitted, anti-neutrino absorbed.



Michael Moe, Steve Elliott, Alan Hahn Discover Double Beta Decay at UC Irvine

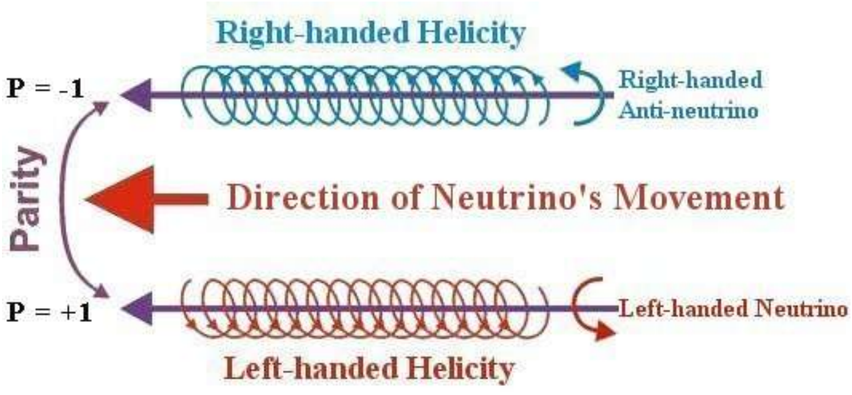
- In 1987, the above found the first double beta decay, from ^{82}Se at 10^{20} years half life.
- Current searches for neutrino-less double beta decay in ^{76}Ge exceed 2×10^{25} years.

Neutrino-less Double Beta Proportional to Neutrino Masses

- Since it involves coupling the right handed anti-neutrino into the left handed neutrino it must involve the neutrino mass (even though neutrino and anti-neutrino are the same here).
- The process would tell us the sum of neutrino masses, being weighted by the known probability coefficients.

$$m_{\beta\beta} = \sum_{i=1}^{3} m_i U_{ei}^2.$$

Left and Right Handed Particles, and Mass



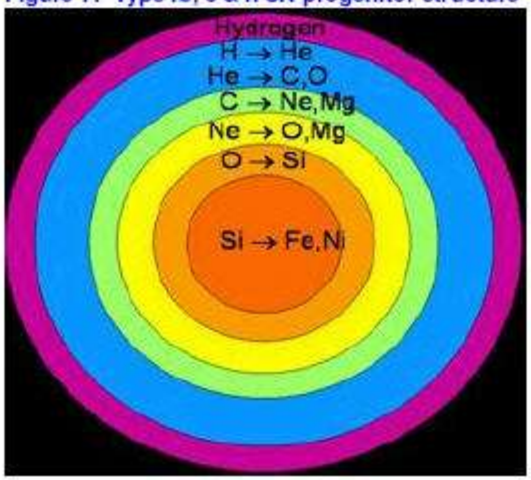
- To have mass from the Higgs, a particle must have a left and right handed part connected by the Higgs.
- However, weak interactions only involve the left handed part of the particle.
- Since neutrinos have only been seen in weak interactions, and have never been stopped to reverse their handedness, only the left handed neutrinos are known to exist.

The See-Saw Mechanism for Tiny Neutrino Masses

- The only neutrinos we know of are left handed from the weak interactions, and right handed anti-neutrinos. Handedness is the spin direction of the fingers, with our thumb along the direction of motion. Both handedness are needed to make mass.
- It is possible for an initial mass-less left handed neutrino to mix with energy m with a super-massive right handed neutrino N of much larger mass M. The resulting light neutrino of the mixture would have a mass m when it was mixed m/M of the time with the heavy neutrino.
- Its resulting average mass would be $(m \cdot m/M)$ or $m_v = m^2 / M$.
- With $m = 100$ GeV and $M = 10^{14}$ GeV, then $m_v = 0.1$ eV.

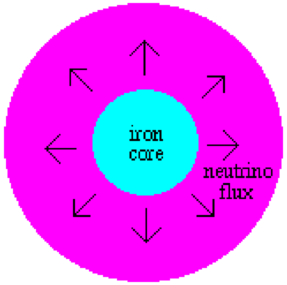
Supernova Explosion

Figure 7: Type Ib, c & II SN progenitor structure



Supernova Explosion

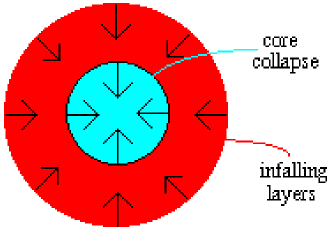
Inert iron core stops producing energy, but continues to produce neutrinos which release energy from core



Densities climb, protons and electrons combine to produce neutrons and more neutrinos

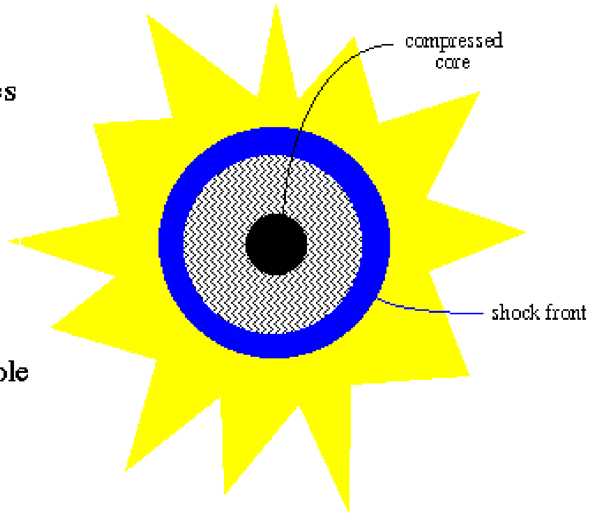
Sudden lost of energy causes core to collapse from lack of pressure support

Regions around core are unsupported and plunge onto core at speeds up to 15% the speed of light



Neutron densities are so high in core that it is incompressible and rigid. Infalling layers strike core and rebound.

In a fraction of a second, a wave of matter forms a shock front and moves outward towards stellar surface.



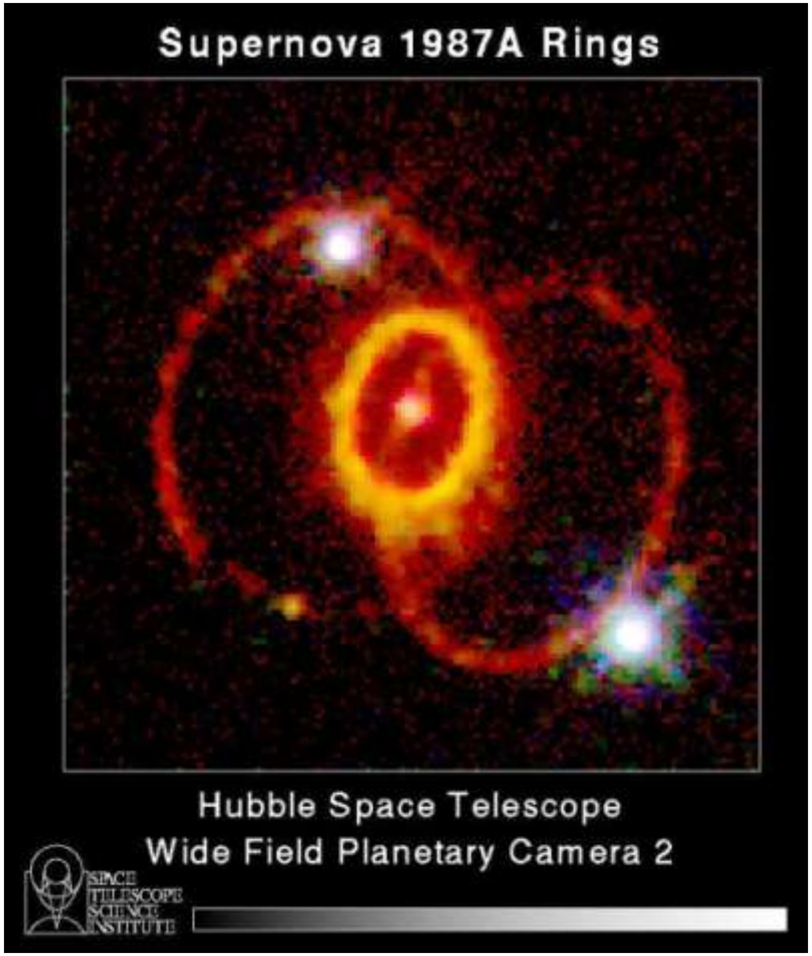
Shock wave hits surface of star and explodes

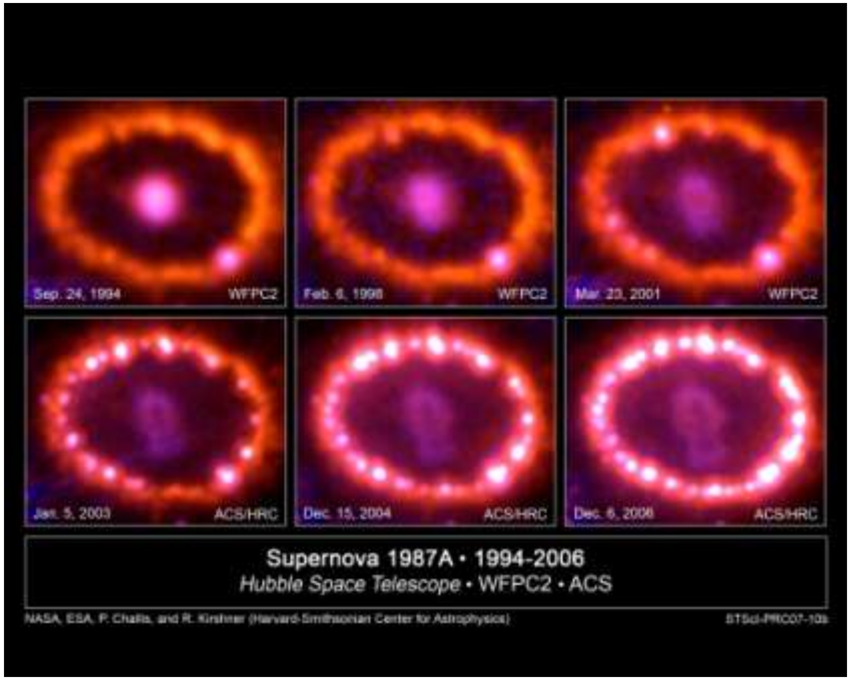
Inward shock compresses remaining stellar core into neutron star or black hole

Neutron Star Formation and Explosion of a Supernova

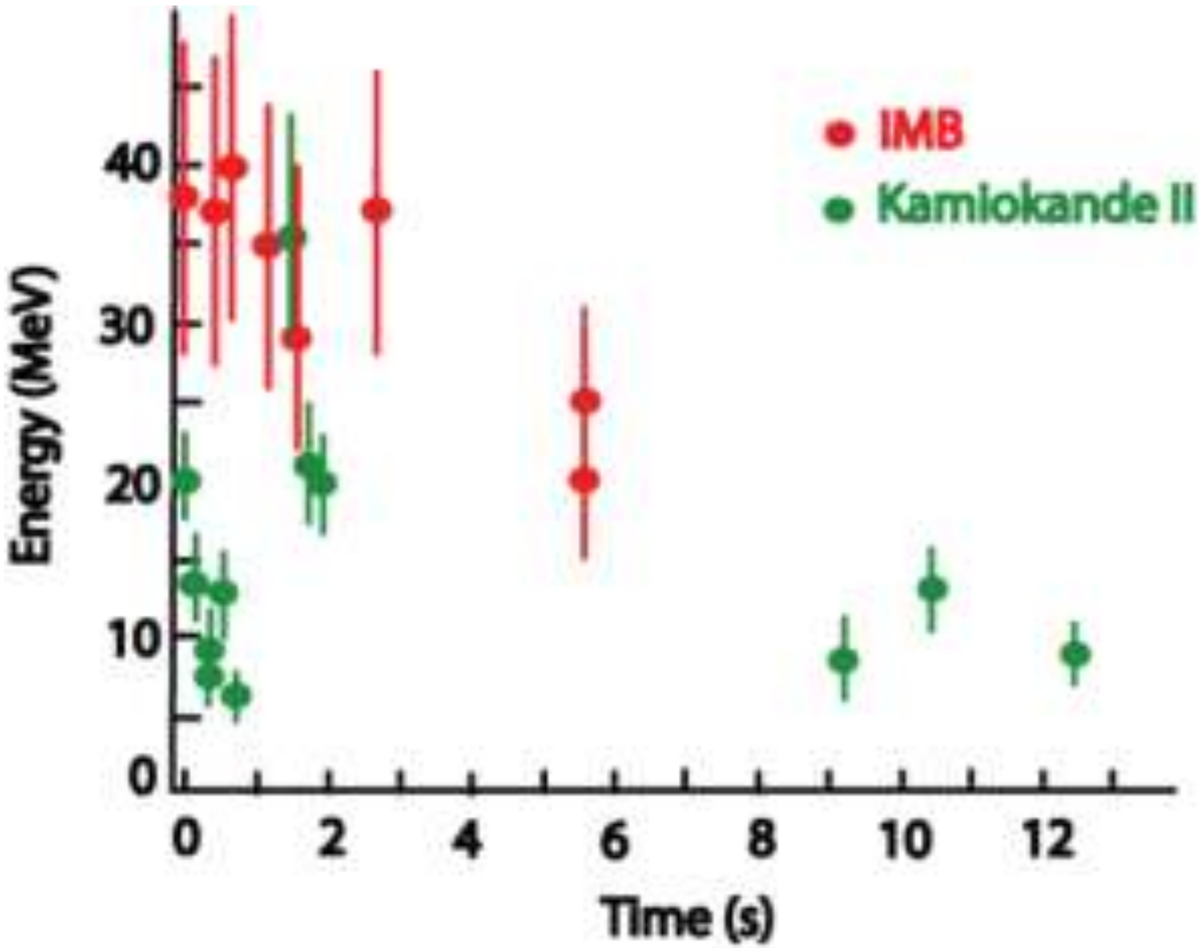
- Pressure of collapse forces electron and proton to make a neutron, with an escaping neutrino
- $e^- + p \rightarrow n + \nu_e$. This makes a neutron star, and releases a neutrino for every proton in the star.
- The collapse caused a shock wave bounce outward, and the ν_e collide with the shell to help blow it out. (This is still to be proven.)
- The neutron excess hits lead nuclei and produces heavier nuclei. This is the source of the heavy elements in the universe.
- Finally, a few hours later, the light of the supernova becomes visible.
- Stars more massive than 25 solar masses collapse to black holes.

Supernova 1987A

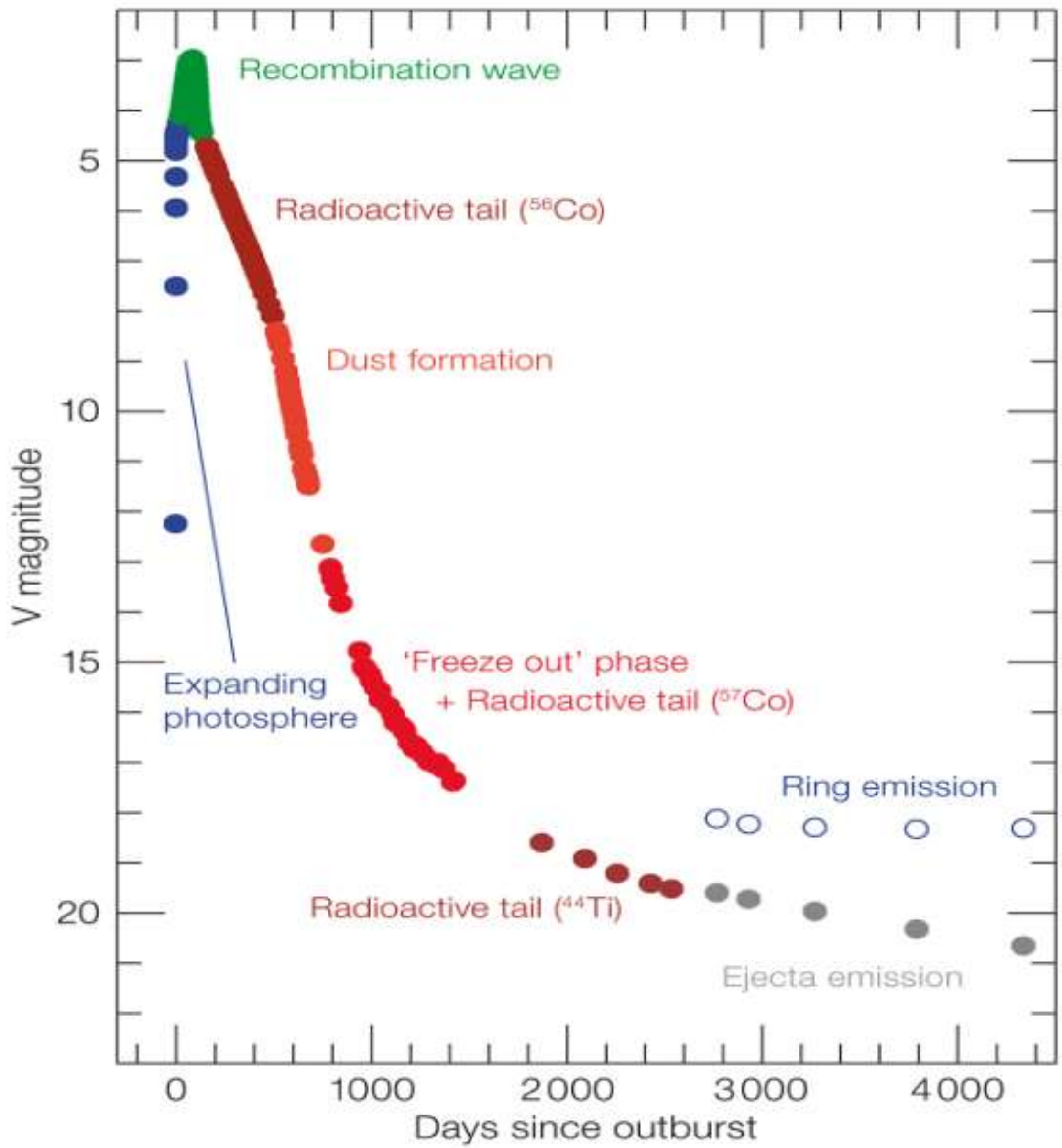




The Neutrinos from SN 1987A



Light Emission from SN 1987A



Neutrino Mysteries Galore

- We have seen that there are many neutrino mysteries by its occurrences throughout nature.
- Also, by its neutralness and lightness, it has many unusual properties like oscillations, and possible heavy partners, or being its own anti-particle.
- Many experiments are ongoing or being planned to discover its full nature.
- Hank Sobel will give the experimental talk at a **later date than in the catalog**, on May 12, 10 AM-12 PM, at Woodbridge.

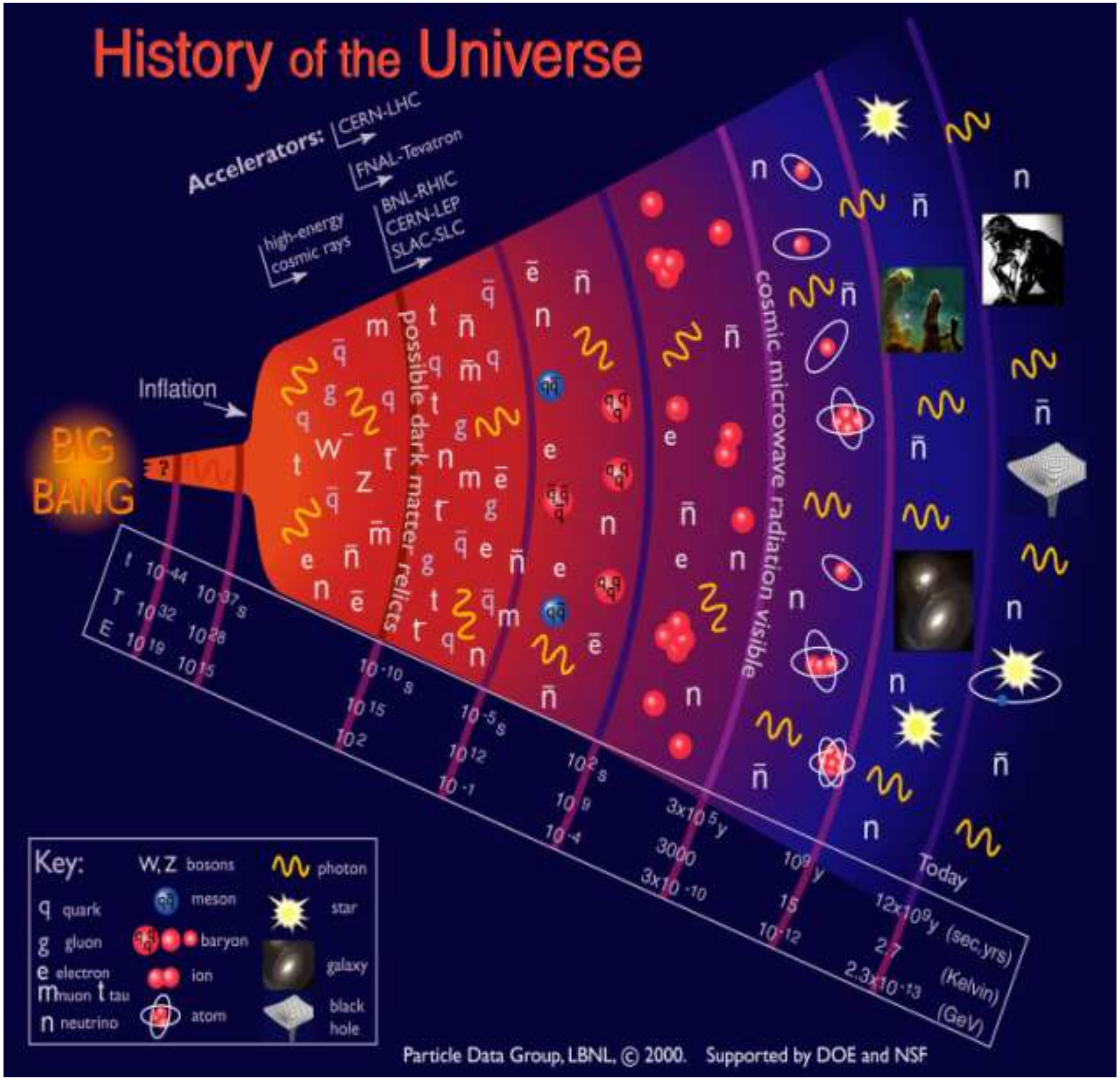
Particle Physics Blogs and Websites

- I have my particle lectures on my blog, where this lecture is posted.
  - My blog can be found by typing Dennis Silverman into Google search.
- An up to date particle physics blog is **Resonaances.**
- Matt Strassler has a comprehensive blog on particles: profmattstrassler.com
- The is a central list of all web articles in the press for particle physics at interactions.org
- An elementary introduction to particle physics at http://particleadventure.org

Extra Slides

The Existence of Matter

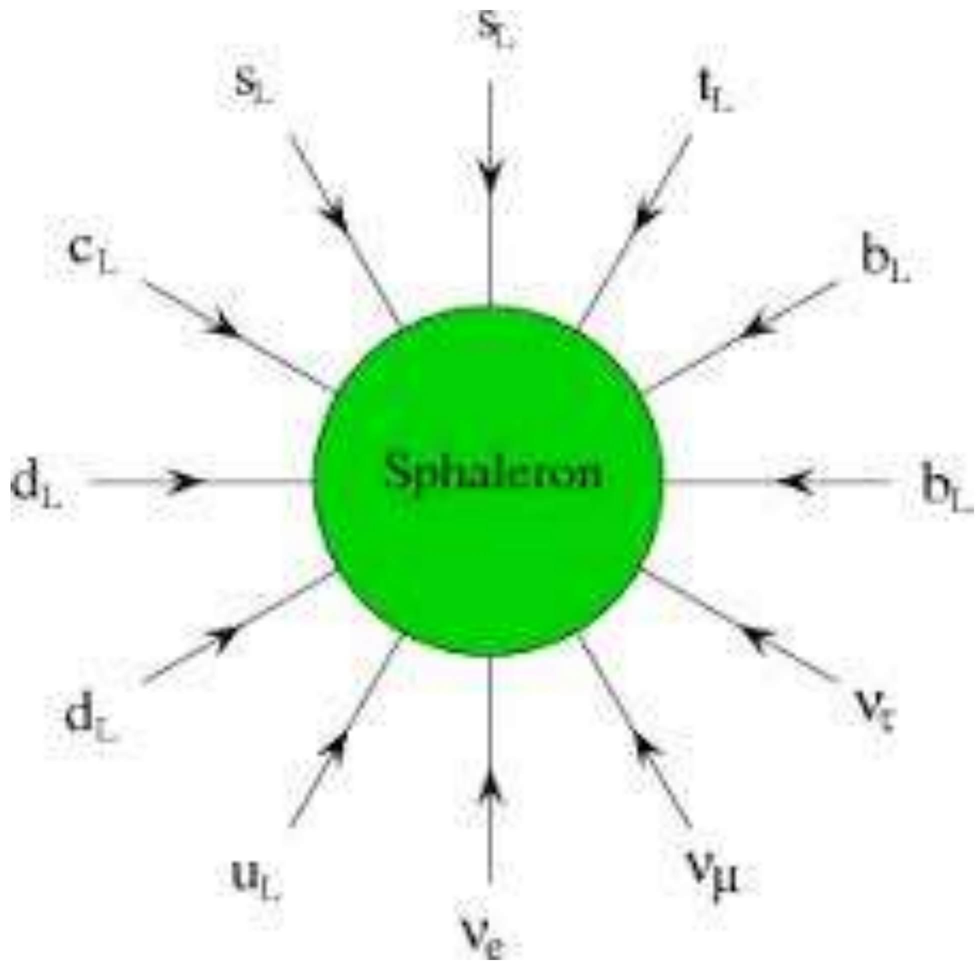
- In the beginning, at very high energy or temperature, there was a plasma of particles and anti-particles and radiation existed in about equal amounts.
- As the Universe cooled, the particles and anti-particles annihilated, except that about 1 part in 10^8 of particles or matter got left over to form the matter in our universe.
- This would have arisen from a tiny asymmetry between particles and anti-particles, such as that in neutrino mixing.
- In a Grand Unified Theory, where quarks are included with leptons and neutrinos, the excess in neutrinos could lead to the observed excess in quarks or protons.
- This is called Lepto-genesis


History of the Universe
Accelerators: CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
3×10^{5} y
3000
3×10^{-10}
10^{9} y
15
10^{-12}
Today
12×10^{9} y (sec, yrs)
2.7 (Kelvin)
2.3×10^{-13} (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Leptogenesis to Baryogenesis

- As in most accounts of the genesis of the excess of matter over antimatter, this one is complicated, and speculative.
- The heavy right handed neutrinos N in the see-saw have virtual Higgs in their decays that lead to excess creation of leptons over anti-leptons.
- High temperature over 100 GeV creates complex monsters in the theory called sphalerons or instantons, which convert the lepton excess to a baryon excess (protons and neutrons). This needs a Grand Unified Theory that has forces that can turn leptons into quarks.
- This must occur during a non equilibrium expansion phase that does not erase the excess.

Sphaleron Links Neutrinos to Quarks



Electroweak Founders

- The unified electroweak theory was founded by Steven Weinberg and Abdus Salam, shown below. In between them is Sheldon Glashow, a proposer of the generation or family structure. They received the Noble Prize for Physics in 1979.

Benefits of the Particle Physics Program

- The particle physics program cost about $750 million a year from DOE and $100 million from the NSF.
- This averages out to $3 per person per year in the US.
- It is a continuation of over 100 years of discoveries and technological development into the fundamental structure of matter, including atomic physics and nuclear physics.
- New technologies are created at the frontier of research, including nuclear power and medical detectors for X-rays, CAT scans, PET scans, high energy gammas for DNA scans.
- The internet and the World-Wide-Web were created to handle multi-country and institution collaborations sharing the data.

Local Benefits of Particle Physics

- The US participates in ATLAS, CMS, and most Neutrino Physics experiments.
- It also participates in dark matter detection experiments.
- Countries contribute in kind with new technological capabilities to make new devices
- Graduate students are trained with advanced new skills that will apply them in local businesses.
- In California, federal funding for research is a way to get back some of our federal tax payments.
- At UC Irvine, federal funding in all research fields, at 13% of our budget, now exceeds state funding.
- UC Irvine participates in ATLAS, in the SuperK neutrino experiment in Japan, in the ICECube neutrino detection in ice at the South Pole, in the Fermi gamma ray satellite, and in the Large Synoptic Space Telescope.
- UC Irvine also has a leading particle theory group and cosmology group.