"There are more things in Heaven and Earth..."

Neutrinos in our Everyday World

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What are the BIG Questions?

Questions still out there...

- What is dark matter?
- What is the nature of dark energy?
- How did the universe begin?
- What are the masses of neutrinos and how have they shaped our universe?
- How do cosmic accelerators work?
- Do protons decay?
- How do particles acquire their masses?
- Are there greater symmetries or extra dimensions in our universe?
- How are we made of matter, as opposed to anti-matter?

Answers are out there too...

- Many of these questions are intertwined with our knowledge of neutrinos.
- Many of these questions are addressable experimentally.
- Underground physics plays a key role in addressing these questions.
- These are questions which are in experimental reach today...

The Lectures...

- Day One: Neutrinos in our World
- Day Two: The Quest for Neutrino Mass (Oscillations)
- Day Three: The Quest for Neutrino Mass (Other Methods)
- Day Four: Above and below ground...

What these lectures cover...

- I can't cover everything...

  this is just Joe's "blue plate special".

- I assume some exposure to particle physics and quantum mechanics.

- An overview of the field from an experimentalist's perspective.

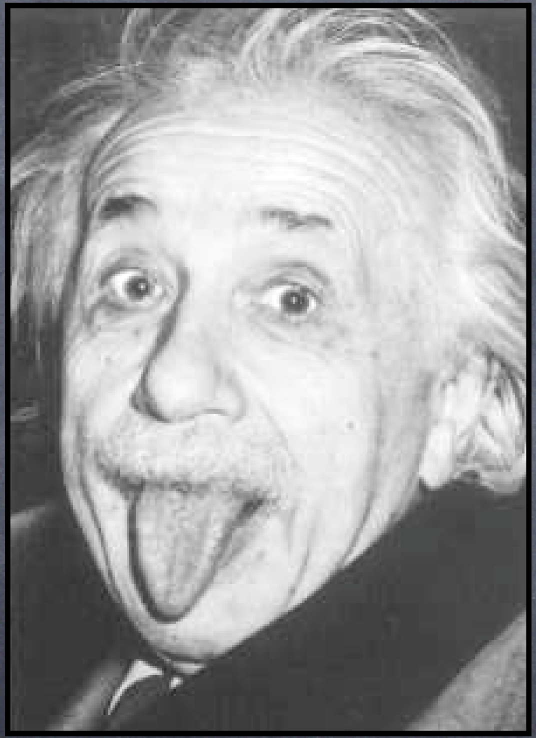
The Lectures...

- **Day One: Neutrinos in our World**
- Day Two: The Quest for Neutrino Mass (Oscillations)
- Day Three: The Quest for Neutrino Mass (Other Methods)
- Day Four: Above and below ground...

Lesson #1: Neutrinos in our world

"I have hit on a desperate remedy..."

A Wild Idea



- 101 years ago Einstein presents his paper on special relativity

A Wild Idea

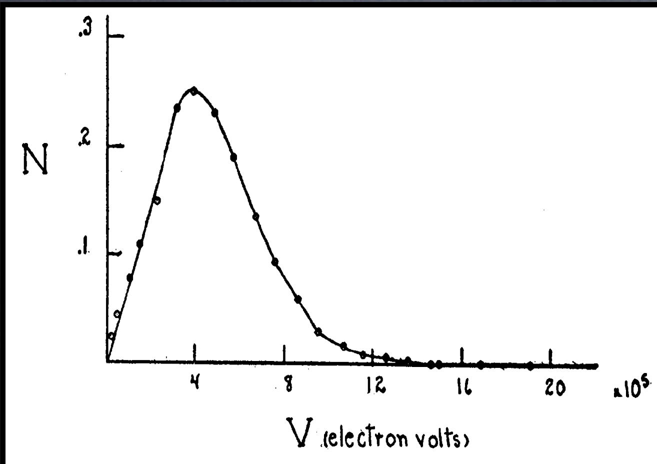
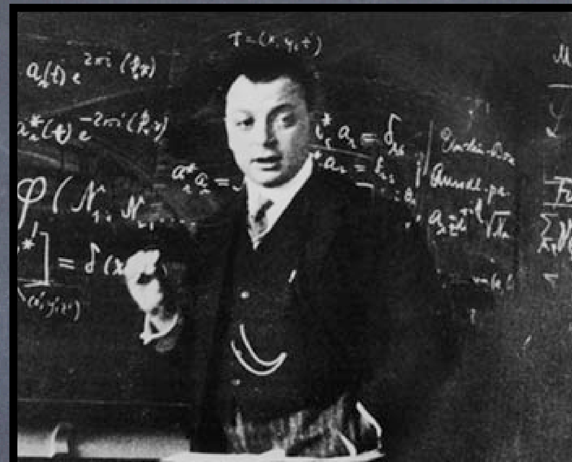


FIG. 5. Energy distribution curve of the beta-rays.



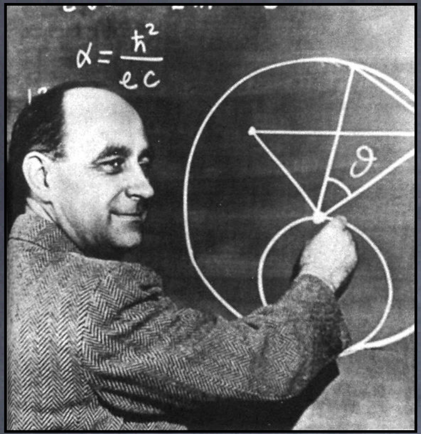
4th December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

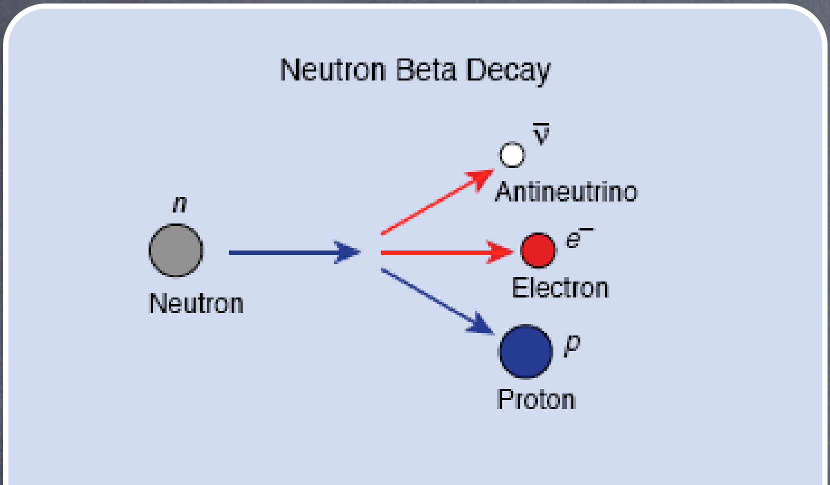
- 101 years ago Einstein presents his paper on special relativity and...
- 76 years ago, Pauli introduces the idea of neutrinos to help resolve the energy conservation crisis.
- The concept of the neutrino is born.

Path to Discovery

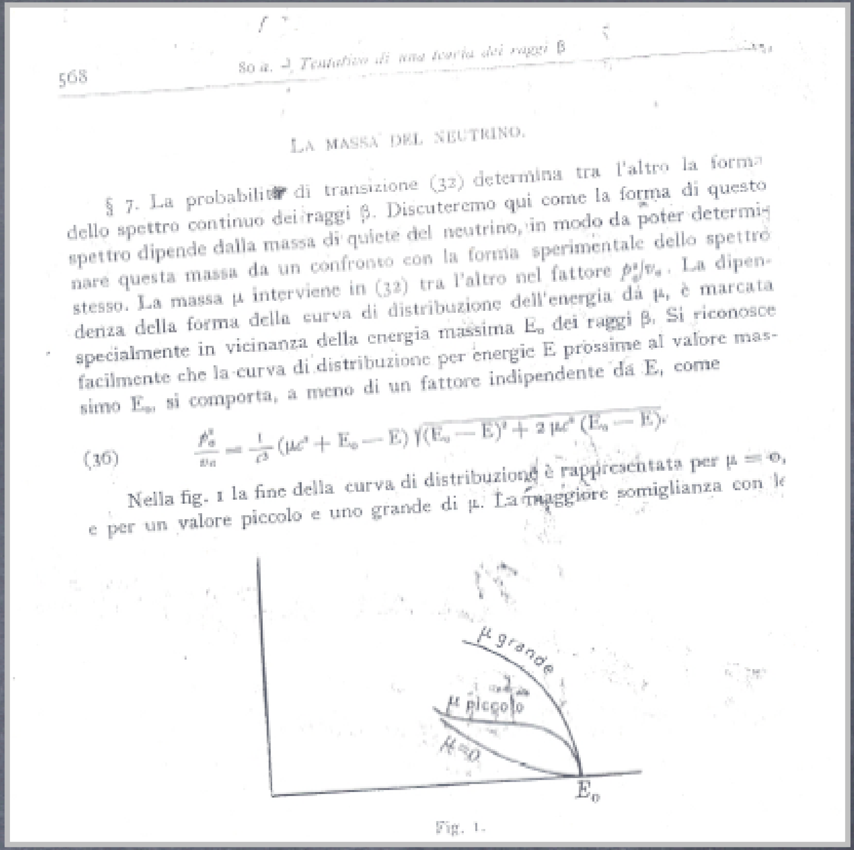


1934 Enrico Fermi establishes the theory of weak decay, providing a framework for neutrinos.

Fermi's "Neutrino"



$$\mathcal{H} = G_F(\bar{\Psi}_p \gamma_\mu \Psi_{\rm n})(\bar{\Psi}_e \gamma^\mu \Psi_\nu)...$$



568 80 a. – Tentativo di una teoria dei raggi β

La massa del neutrino.

§ 7. La probabilità di transizione (32) determina tra l'altro la forma dello spettro continuo dei raggi β. Discuteremo qui come la forma di questo spettro dipende dalla massa di quiete del neutrino, in modo da poter determinare questa massa da un confronto con la forma sperimentale dello spettro stesso. La massa μ interviene in (32) tra l'altro nel fattore p_σ^2/v_σ. La dipendenza della forma della curva di distribuzione dell'energia da μ, è marcata specialmente in vicinanza della energia massima E_0 dei raggi β. Si riconosce facilmente che la curva di distribuzione per energie E prossime al valore massimo E_0, si comporta, a meno di un fattore indipendente da E, come

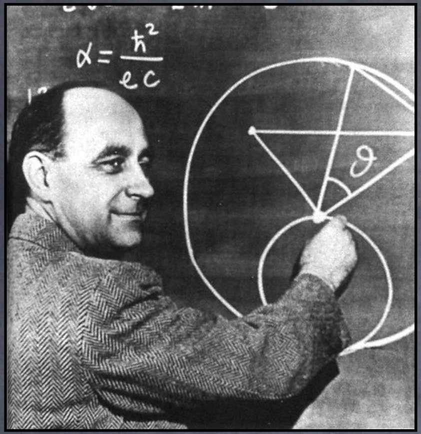
$$(36) \qquad \frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}.$$

Nella fig. 1 la fine della curva di distribuzione è rappresentata per μ = 0, e per un valore piccolo e uno grande di μ. La maggiore somiglianza con la

Fig. 1.

- Fermi formulates the theory of **weak decay**, describing the decay of neutrons inside nucleii *(March 25th letter to La Ricerca Scientifica)*.
- Uses 4-point interaction to describe this new force; remarkably accurate for modern day understanding of interaction...
- Fermi already appreciates the effect of neutrino masses (more on that later...)

Path to Discovery



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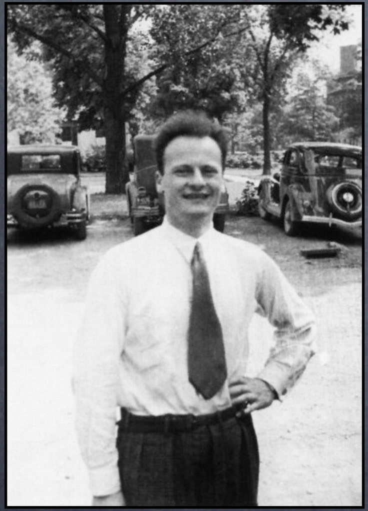
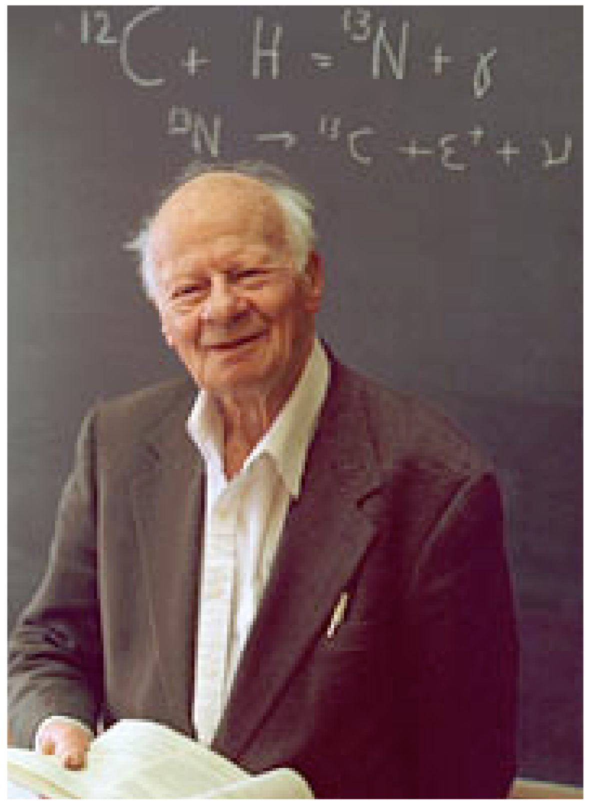


1935 Hans Bethe calculates the probability detecting a neutrino experimentally.

Detecting the Impossible...

$$\nu + n \rightarrow p + e^-$$

$$\bar{\nu} + p \rightarrow n + e^+$$

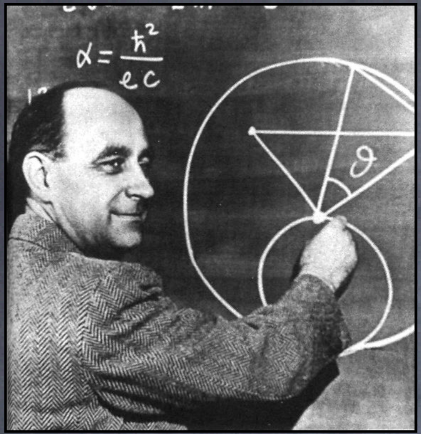


Hans Bethe (1906-2005)

- Bethe & Peirls use decay rates measured from nuclear decay and Fermi's formulation to calculate the inverse process (neutrino interacting with matter).
- Allows for neutrino detection from inverse beta decay
- Alas, the cross-section is a bit small...

$$\sigma_{\nu p} \sim 10^{-43} \text{ cm}^2 \text{ !}$$

Path to Discovery



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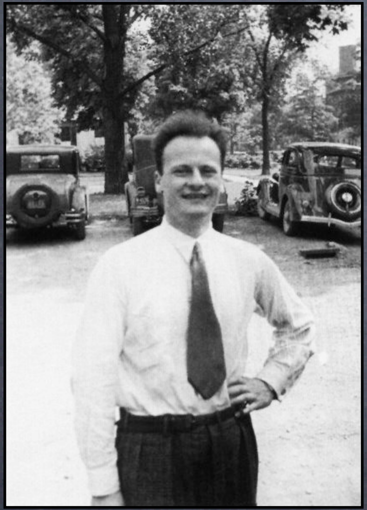

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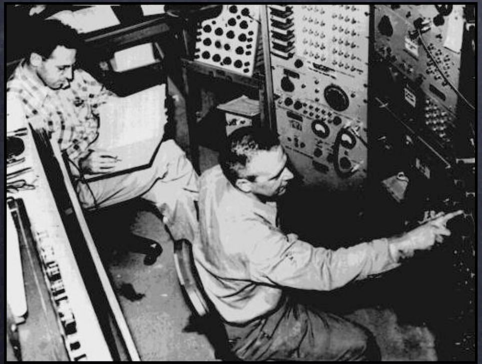


1956 Reines & Cowan use their Poltgergeist experiment to provide first detection of the neutrino.

Detecting the Ghost

- Reines and Cowen explore Bethe's hypothesis to use inverse beta decay to detect neutrinos.
- Original idea was to use neutrinos produced from a nuclear blast as a intense neutrino source.
- Moved to detecting neutrino and the neutron, allowing for a less-intense source to be used...
- Began with project Poltergeist...

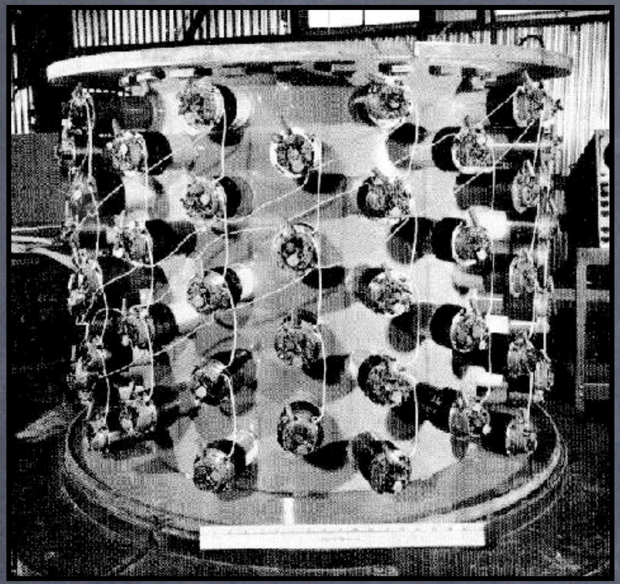
Searching for the Impossible

$$\bar{\nu} + p \rightarrow n + e^{+} \longrightarrow \text{signal here}$$

$$n + {}^{113}\mathrm{Cd} \rightarrow \gamma' s \searrow \text{and here!}$$

- Neutrino detection must battle the fact that the interaction rate is far smaller than with anything else.
- Reines and Cowen decided to use the coincidence of the primary anti-neutrino interaction (positron emission) and detection of the neutron.
- Coincidence signal allows for powerful background rejection.

Experimental Neutrino Physics Begins...



Project Poltergeist

W E S T E R N   U N I O N

June 14, 1956

Dear Professor Pauli,

We are happy to inform you that we have definitely detected neutrinos. . .

Fred Reines
Clyde Cowan

- Neutrinos finally detected (it took 26 years) !
- OK, now things get interesting...

Weird Fact #1:

Neutrinos only as left-handed particles...

C. S. Wu demonstrates parity violation in the weak force using ^{60}Co decay

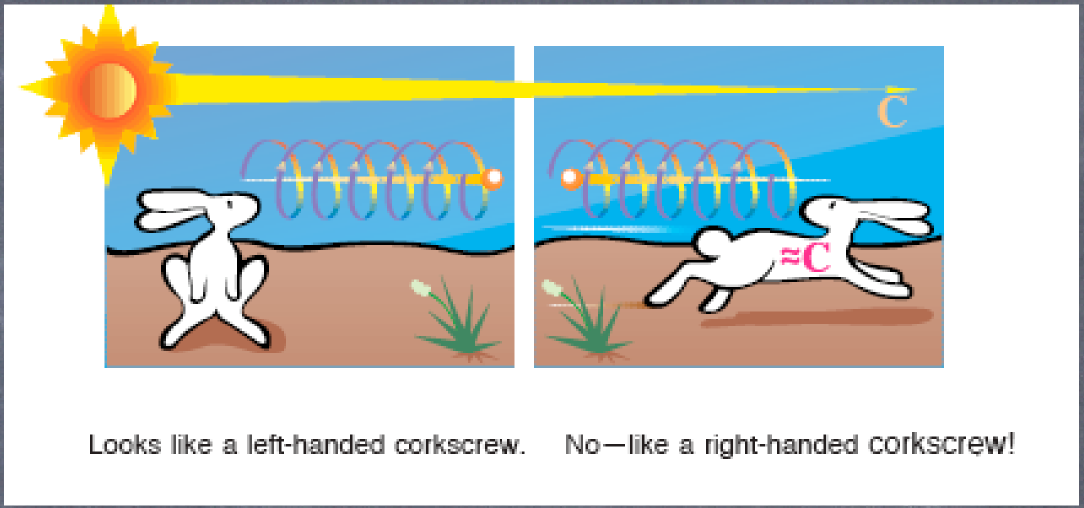
"Parity Violation"

- All other forces studied at the time (electromagnetism and the strong force) rigidly obeyed parity conservation. Naturally, so should the weak force/neutrinos.

...Nope. Violates it 100%

Weird Fact #1:

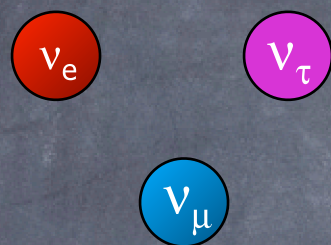
Neutrinos only as left-handed particles...

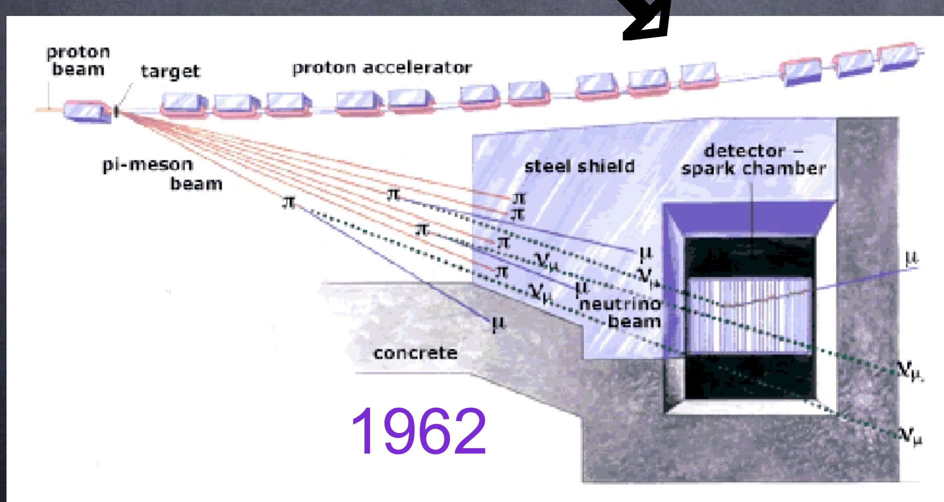


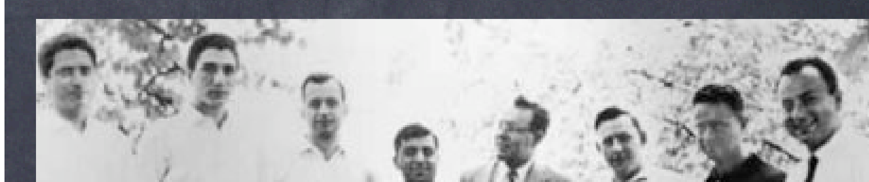
- Other interactions (e.m., strong) interact with particles (electrons, quarks) with both left-handed and right-handed components of spin.
- Only neutrinos (and the weak force) interacts as left-handed particles.
- There are no right-handed neutrinos!
  - (This fact has big consequences and will be explained later on...)

Weird Fact #2
Not 1 but 3...

- For every charged lepton, there is a chargeless neutrino partner.
- So, just like we have electrons, muons, and taus, we also have...
  - electron neutrinos
  - muon neutrinos
  - tau neutrinos



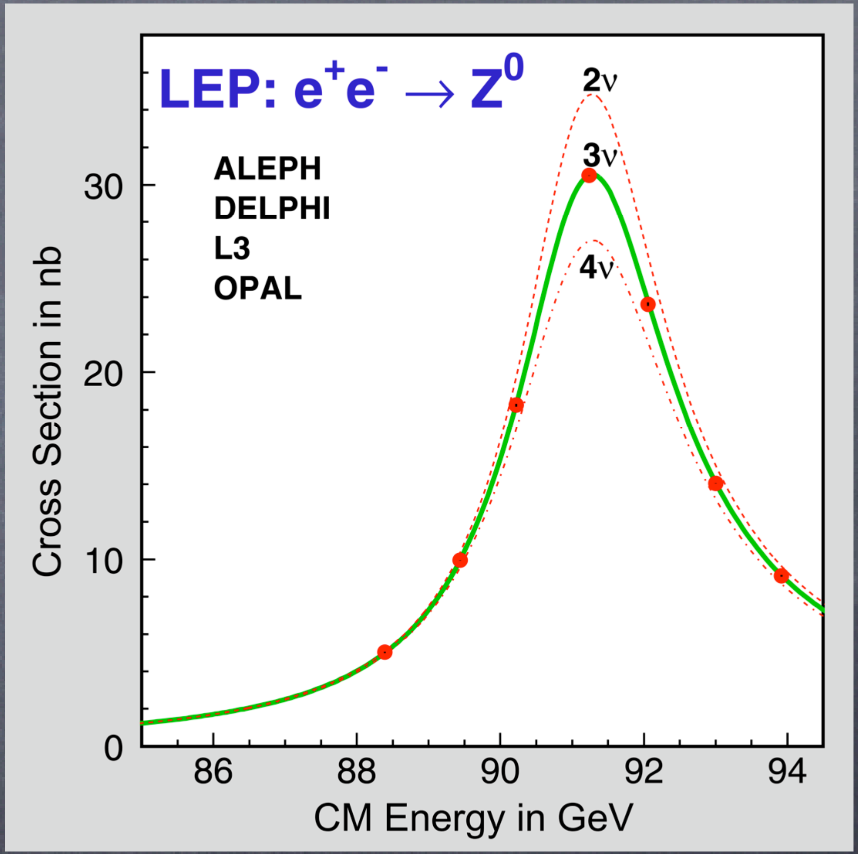


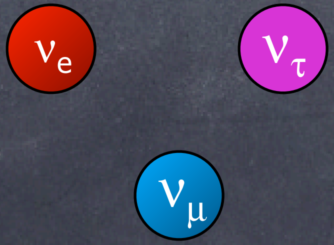


Why Not Four?

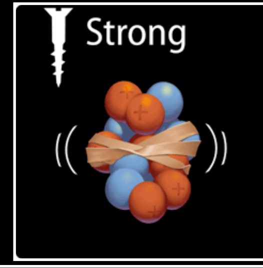
- Can look at "invisible" decays of Z^0 to determine the total number of ordinary, light neutrinos.
- Data from LEP experiments constrain number of neutrinos to...

N = 2.984 ± 0.008

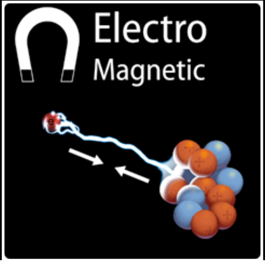




Within the Framework

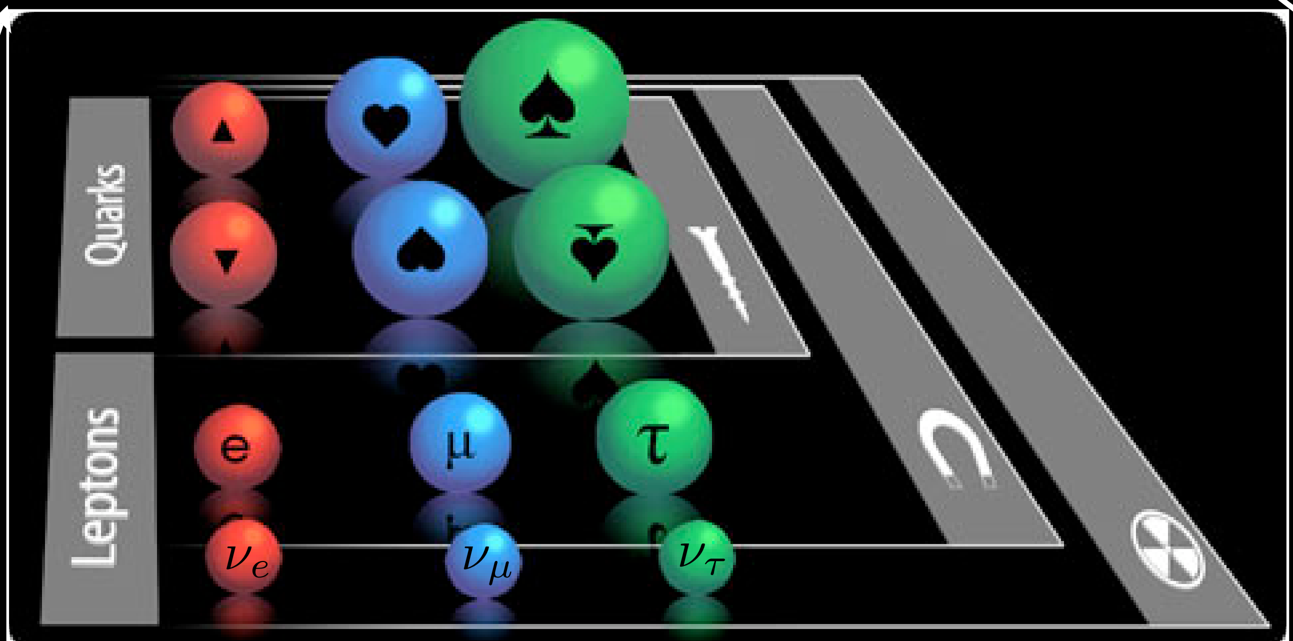


Binds nucleii;
mediated by gluons;
only couples to quarks



Couples to charge;
mediated by photons;
felt by quarks and leptons

Spin 1



Spin 1/2

Common to all particles;
mediated by the $W^{\pm}/Z^0$ bosons;
Neutrinos can only interact weakly

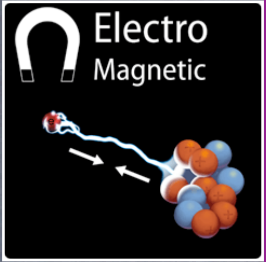
The Weak Force

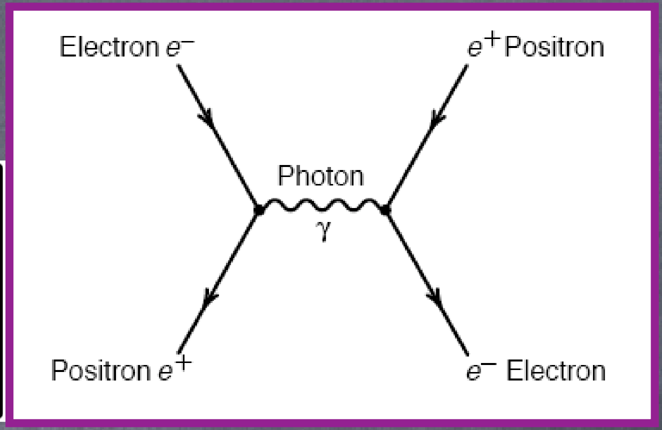
- Fermi got it almost right...
- Not a four-point interaction; but rather mediated through a heavy spin-1 boson ($W^{\pm}$,Z^{0})

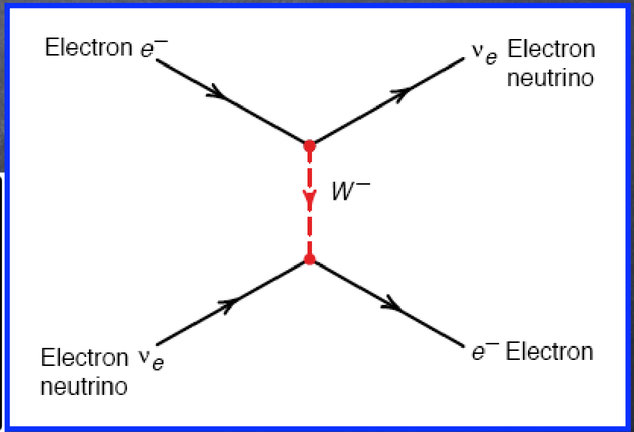
Mass of $W^{\pm}$: 80.425 GeV/c^2

Mass of Z^{0}: 91.188 GeV/c^2

- The boson mass is so large that it acts like a point-like exchange.
- Responsible for most of the radioactivity around our world.

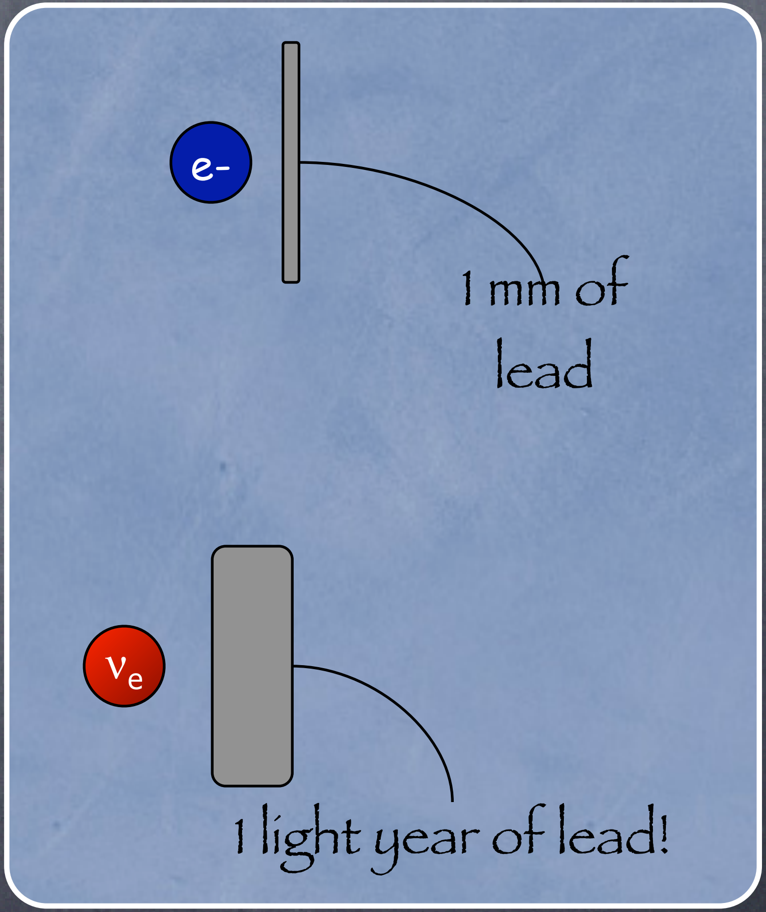






They are not very social...

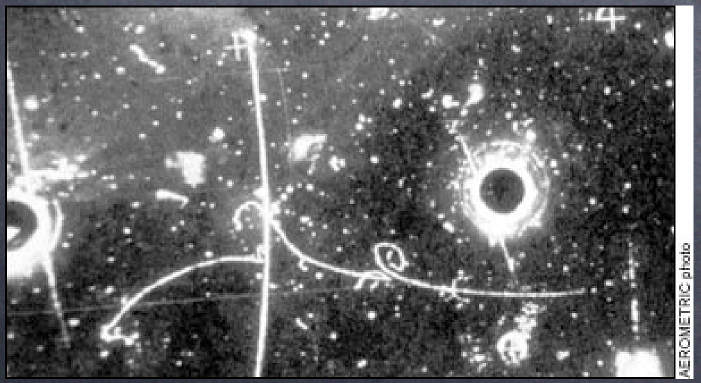
- They have no charge...
- They do not interact with quarks (because they are leptons)...
- In fact, they don't interact with much of anything (there are about ~1 million going through you every second, and they just pass by!)



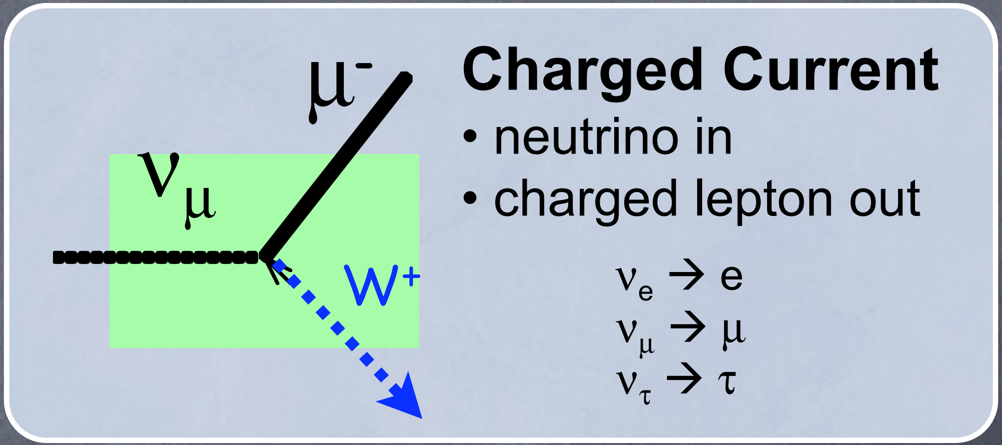
Note: Picture not to scale!

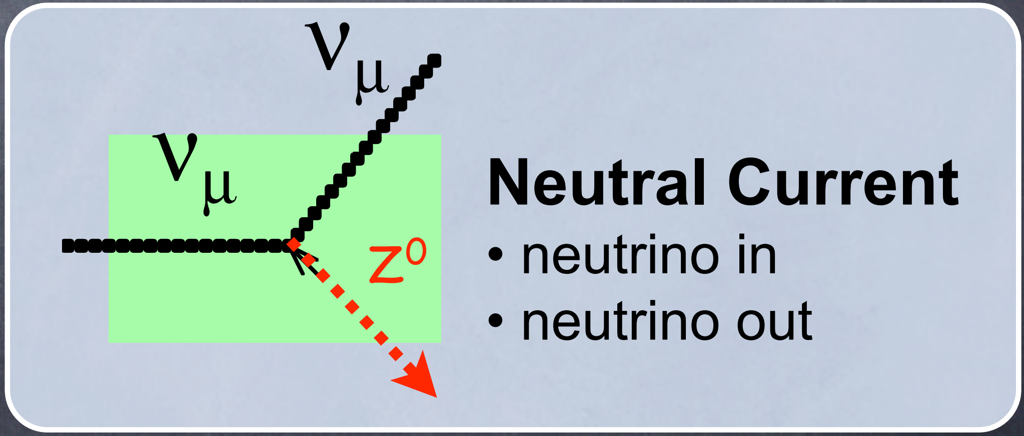
Two ways to interact...

- Charged current interactions allow us to tag the associated lepton.
- Neutral current interactions only leave a neutrino, but also deposit energy on their target.



Example of bubble chamber picture of neutral current event



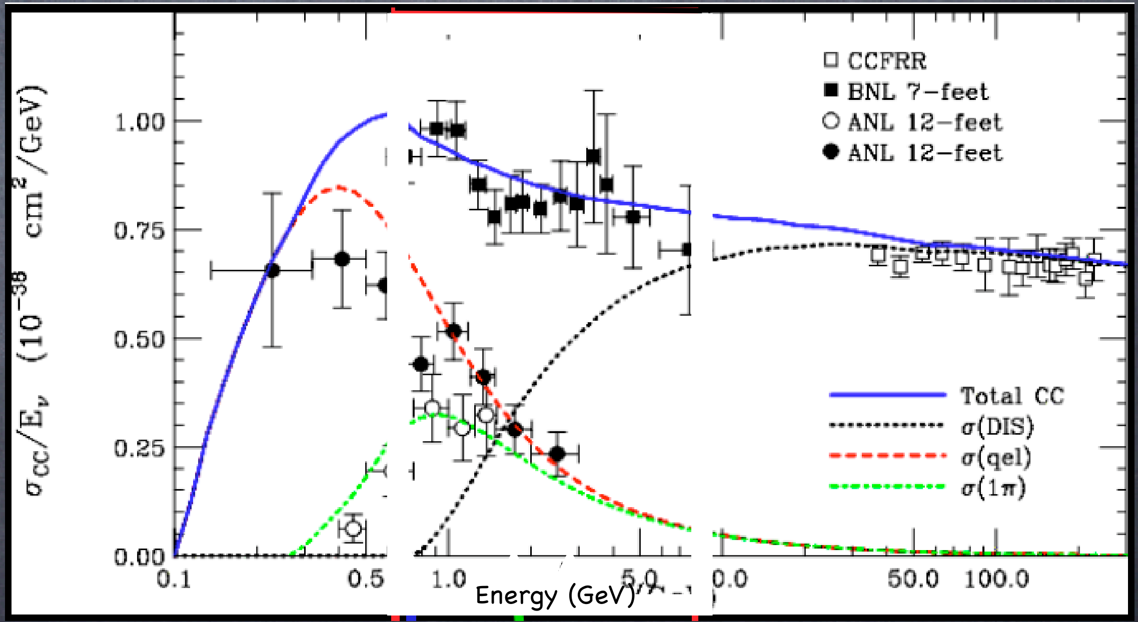


So, what happens when a neutrino does interact?

Elastic Scattering

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

- Experimental tag is single energetic electron.
- Reaction involves both charged current and neutral exchanges.
- Excellent probe into the nature of the weak current.



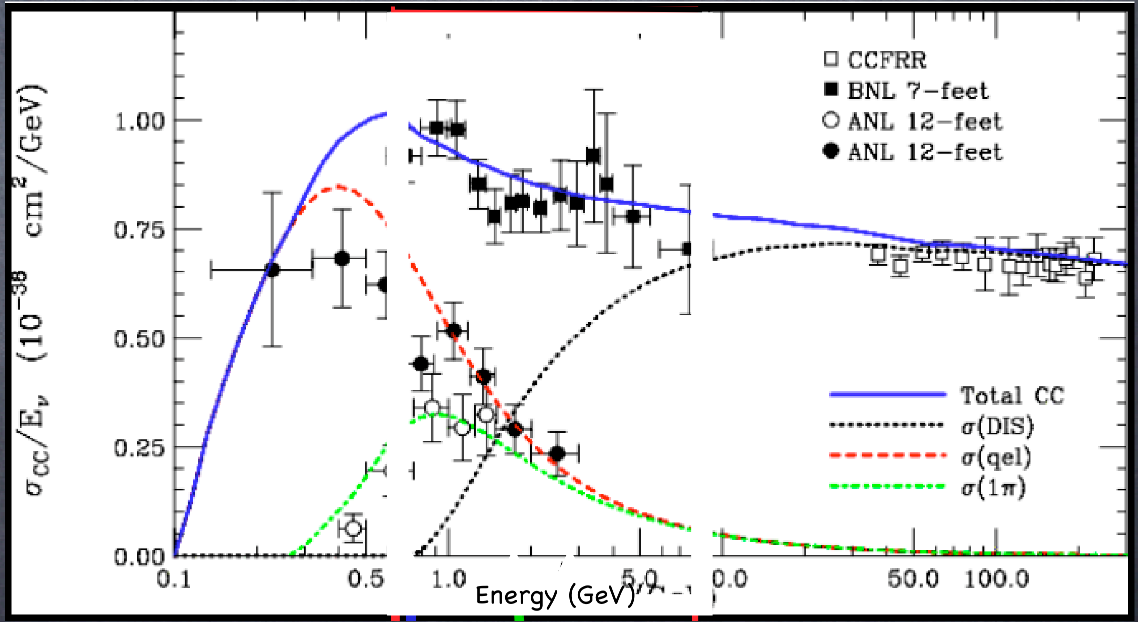
Neutrino cross-section as a function of energy.

So, what happens when a neutrino does interact?

Quasi-Elastic Scattering

$$\nu_l + N \rightarrow l + N'$$

- Experimental tag is lepton + proton or neutron.
- Reaction changes protons into neutrons (and vice versa).
- Dominates below 1 GeV



Neutrino cross-section as a function of energy.

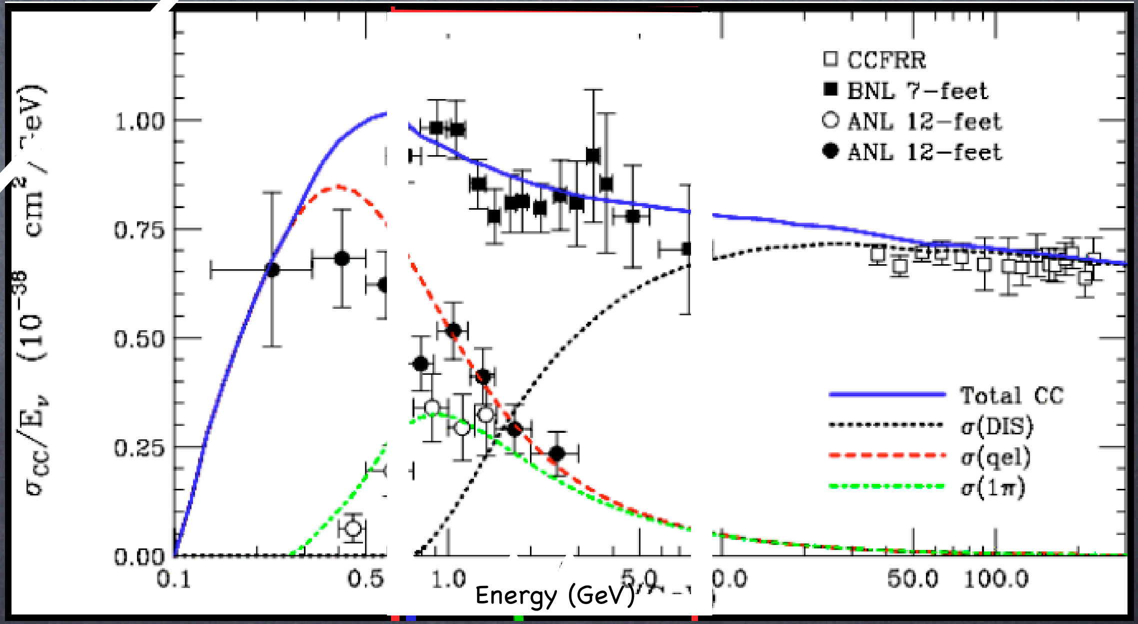
So, what happens when a neutrino does interact?

Pion Resonance

$\nu_l + N \rightarrow l + N' + \pi$

$$\nu_l + N \rightarrow \Delta^* + l \rightarrow l + N' + \pi$$

- Energetic enough to produce a delta resonance
- Reaction changes protons into neutrons (and vice versa).
- Dominates around 1 GeV; often a background for experiments



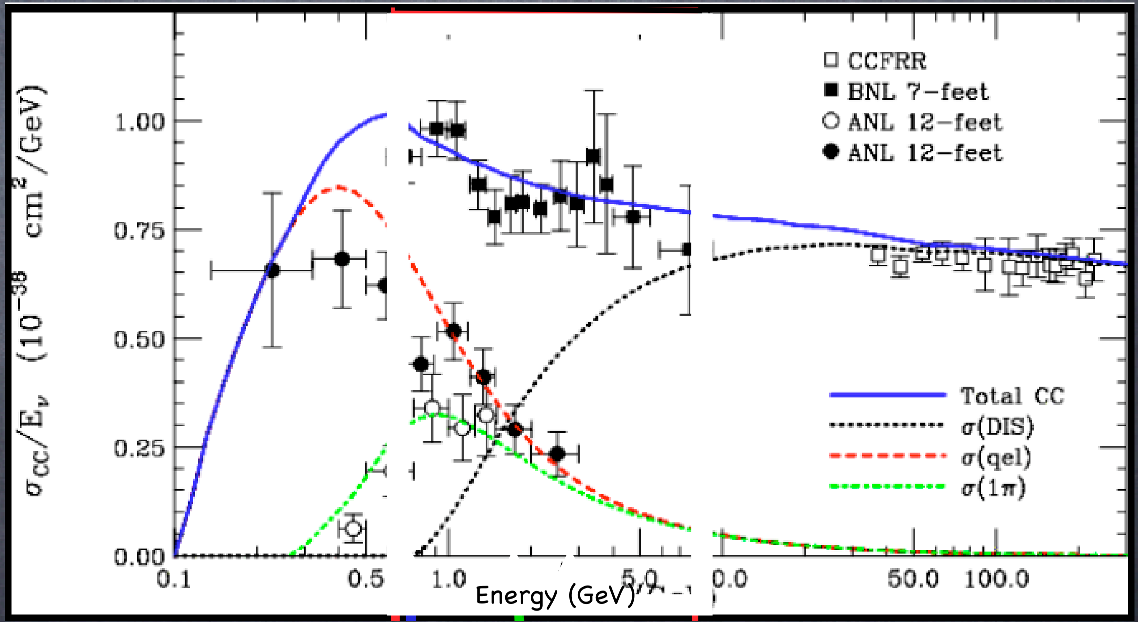
Neutrino cross-section as a function of energy.

So, what happens when a neutrino does interact?

Deep Inelastic (DIS)

$$\nu_l + N \rightarrow l + X$$

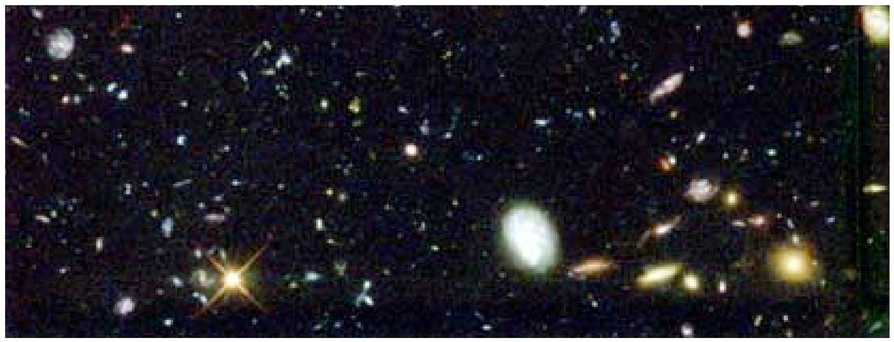
- After a few GeV, the nucleus begins to break apart as the neutrino strikes it and many, many final states are produced.
- This is known as deep inelastic scattering (DIS).
- Probes the interior of the nucleus.



Neutrino cross-section as a function of energy.

Neutrinos are Everywhere

Accelerators/Beams



Big bang

ν_e

The sun

Cosmic Rays & Geoneutrinos

Reactors

Neutrinos from the Cosmos

Neutrinos from the Cosmos

Most abundant particle in the universe aside from radiation (photons)

Produced from interactions of hot dense matter as universe expands from Big Bang (and at equilibrium).

$$\Gamma_{\text{interaction}} < H(t)_{\text{expansion}}$$

Eventually particles decoupling, or freeze-out, begins...

A hand-waving argument...

The rate of expansion is much faster.

$$\Gamma_{\text{int}} \simeq < \sigma_{\text{weak}} n_\nu v > \sim < (G_F^2 T^2)(T^3) >$$

Neutrinos decouple from matter when the universe temperature is about 1 MeV (or 10^{10} K)

$$H(t) \simeq g_\star^{\frac{1}{2}} \frac{T^2}{M_{\text{Plank}}}$$

The universe is 1 second old.

Neutrinos from the Cosmos

- Most abundant particle in the universe aside from radiation (photons)
- One can use the abundance of neutrinos in the universe to constrain the mass of the neutrino.

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{92.5\text{eV}}$$

$$n_\nu = 115\ \nu\text{'s cm}^{-3}$$

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

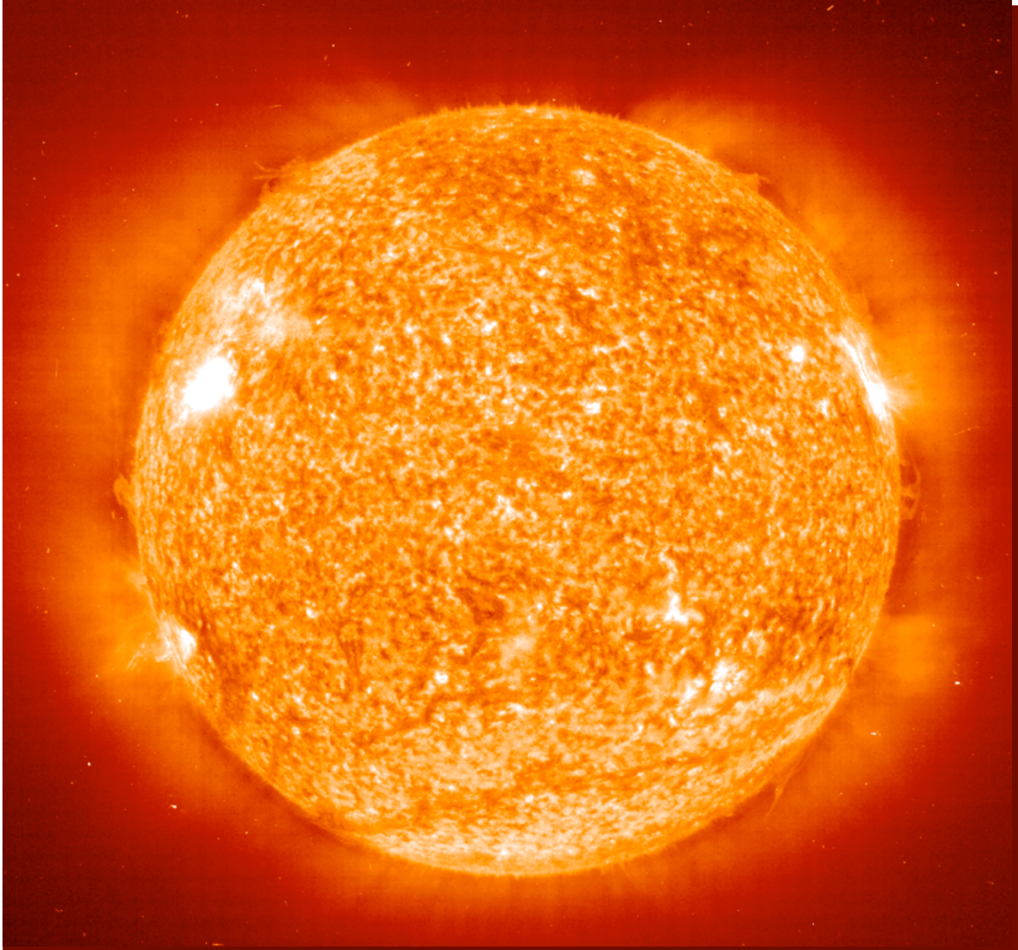
S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200$ eV/c^2 for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6$ eV/c^2 for the muonic neutrino.

Cosmological considerations connected with the hot model of the Universe [2] make it possible to strengthen greatly the second inequality. Just as in the paper by Ya. B. Zel'dovich and Ya. A. Smorodinskii [3], let us consider the gravitational effect of the neutrinos on the dynamics of the expanding Universe. The age of the known astronomical objects is not smaller than 5×10^9 years, and Hubble's constant H is not smaller than 75 km/sec-Mparsec $= (13 \times 10^9 \text{ years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time [1)]

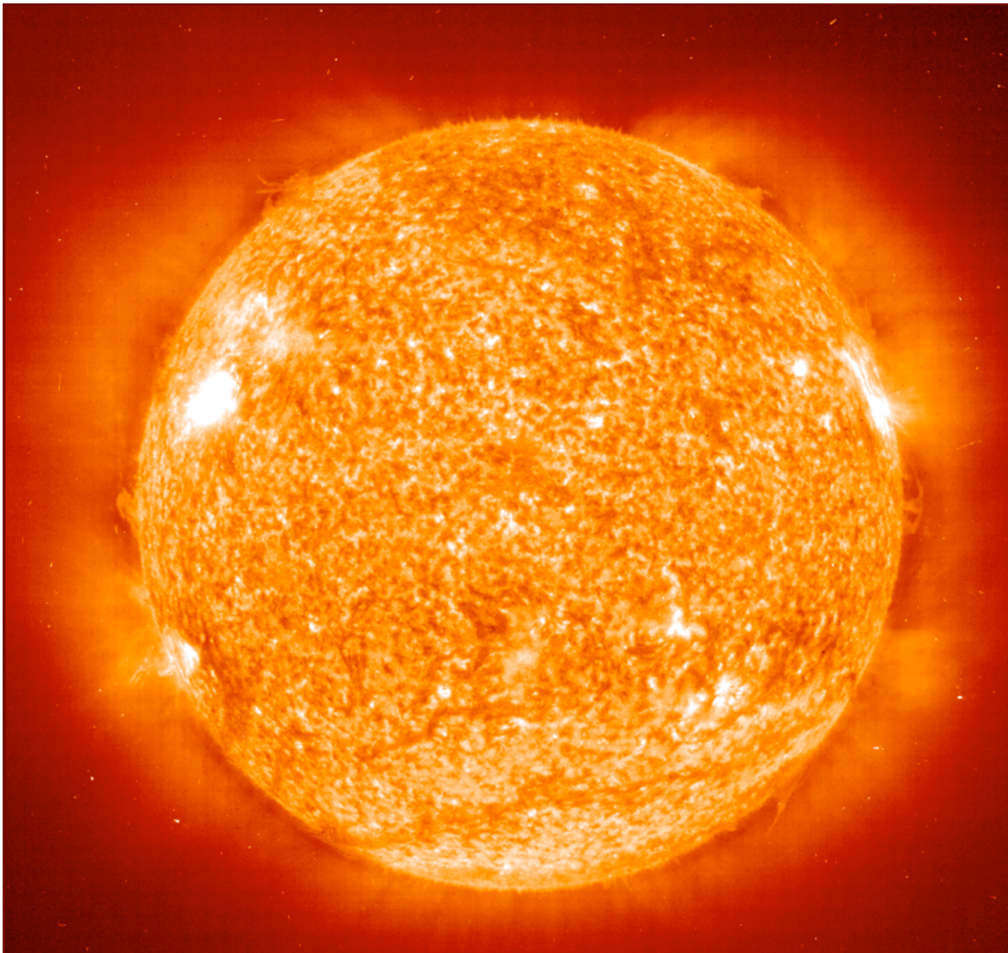
$$\rho < 2 \times 10^{-28} \text{ g/cm}^3.$$

Gershtein & Zeldovich
JETP Lett. 4 (1966) 120



Neutrinos from the Heavens....

...solar neutrinos



In 1854, von Helmholtz postulates that gravitational energy is responsible for solar burning.

In 1920, Eddington postulates that nuclear processes in the solar core may drive solar burning.

"We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place."

In 1938, Bethe and Critchfield calculate a solution...

In Bethe's original paper, neutrinos are not even in the picture.

(H. A. Bethe, Phys. Rev. 33, 1939)

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. Introduction

THE progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \qquad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, && N^{13}=C^{13}+\epsilon^+ \\ &C^{13}+H=N^{14}+\gamma, && \\ &N^{14}+H=O^{15}+\gamma, && O^{15}=N^{15}+\epsilon^+ \\ &N^{15}+H=C^{12}+He^4. && \end{aligned} \qquad (2)$$

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

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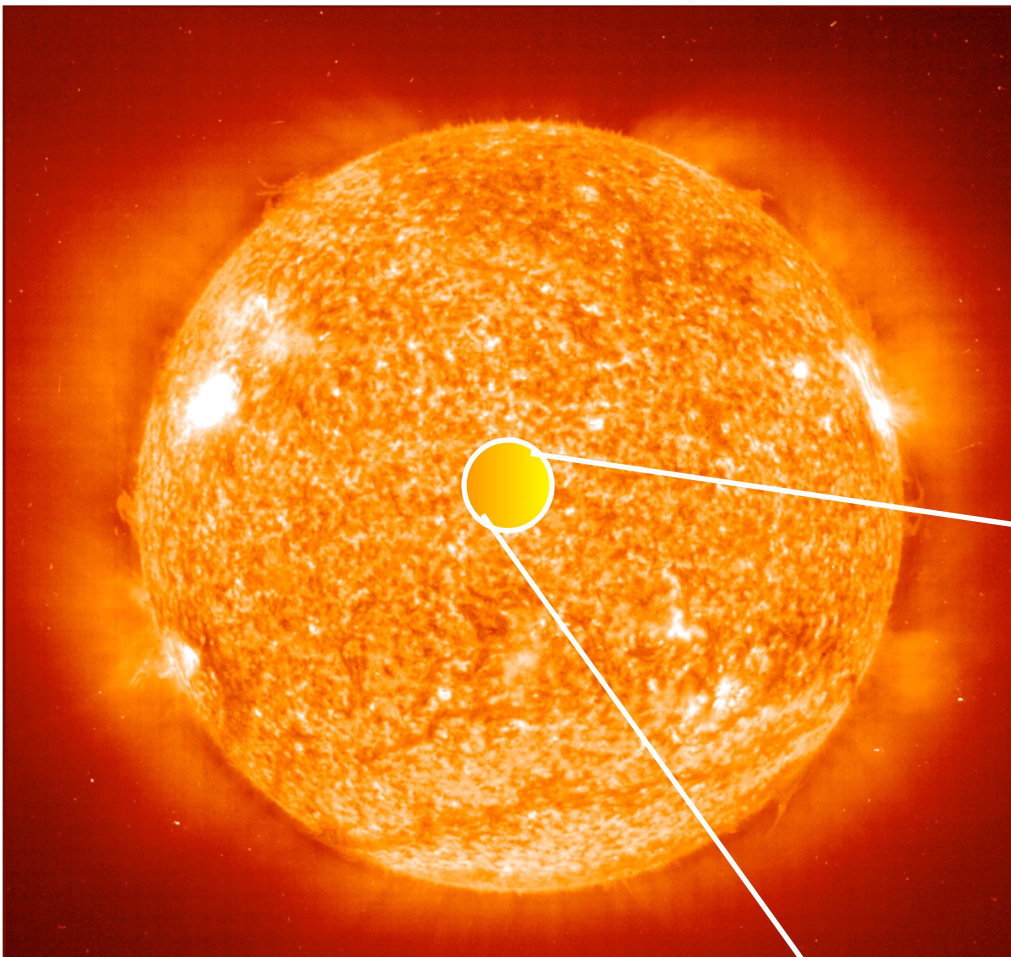
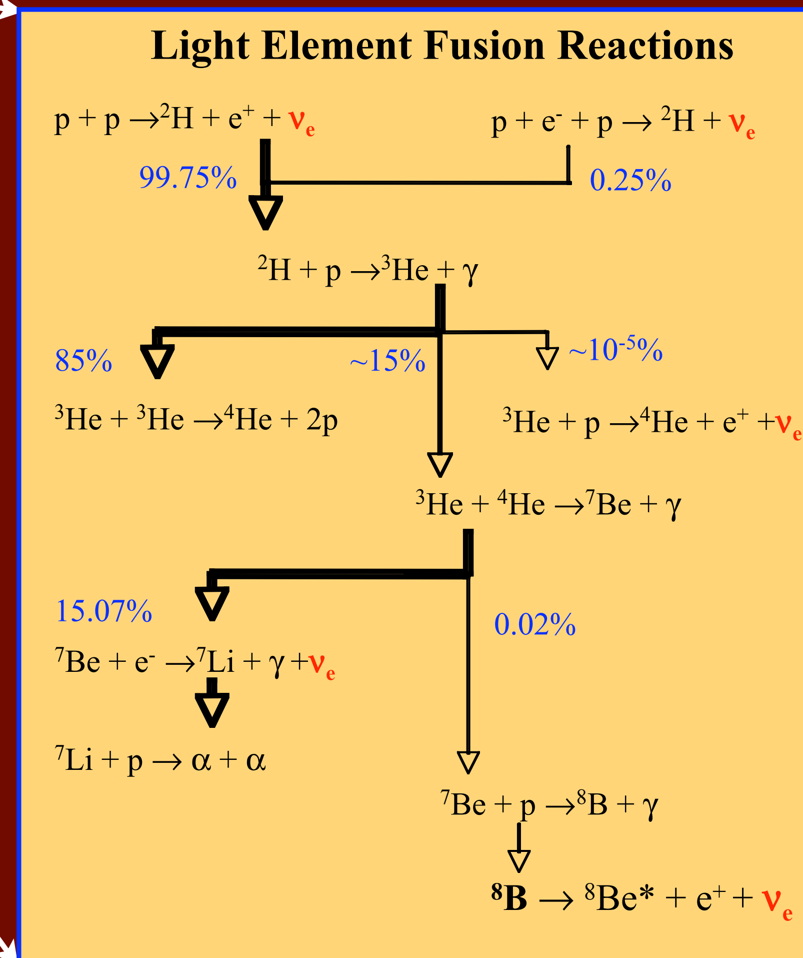


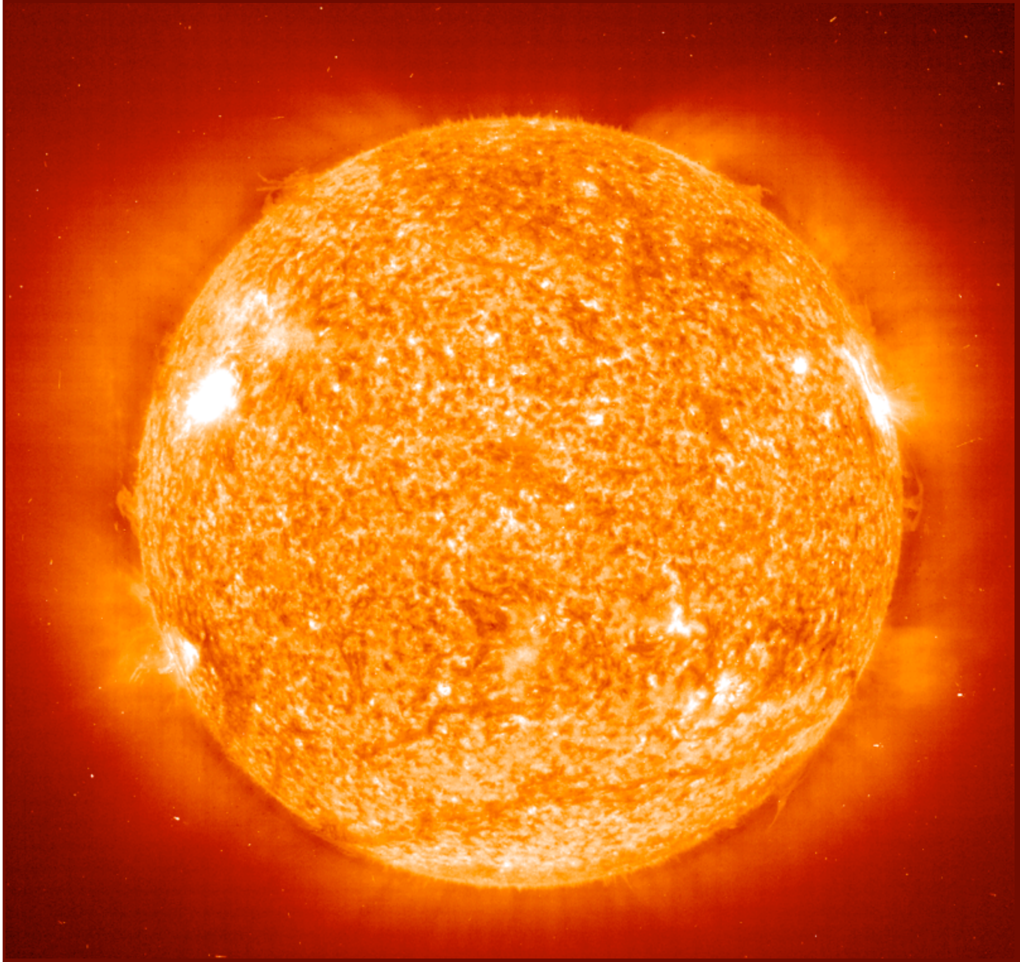
Basic Process:

$$4p + 2e^- \rightarrow He + 2\nu_e + 26.7\ \mathrm{MeV}$$



More detailed...

This is known as the pp fusion chain.



In the sixties, John Bahcall calculates the neutrino flux expected to be produced from the solar pp cycle.

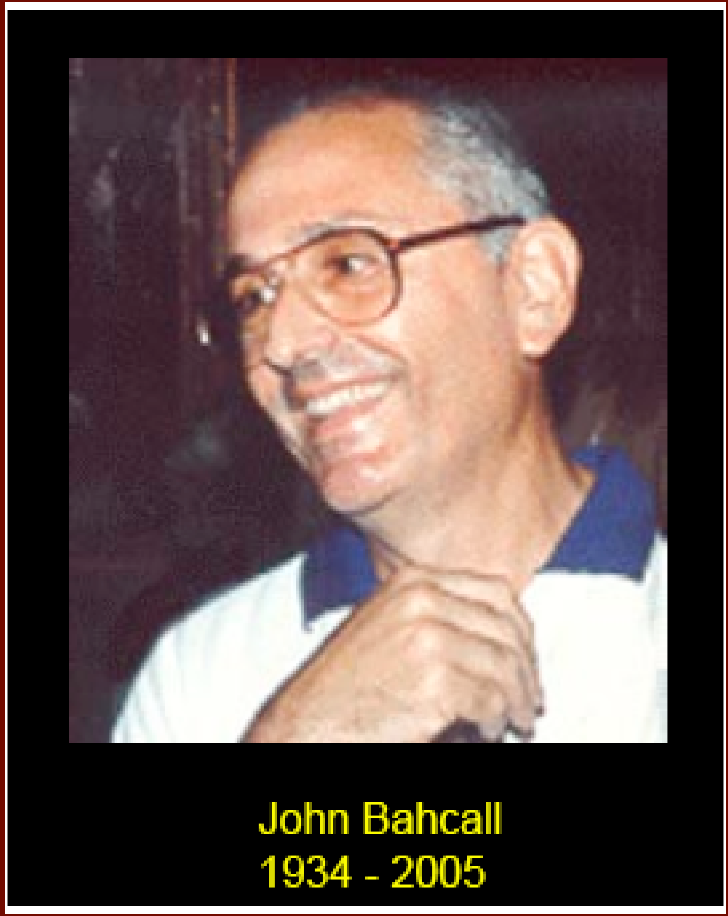
Basic assumptions of what is known as the Standard Solar Model...

(1) Sun is in hydrostatic equilibrium.

(2) Main energy transport is by photons.

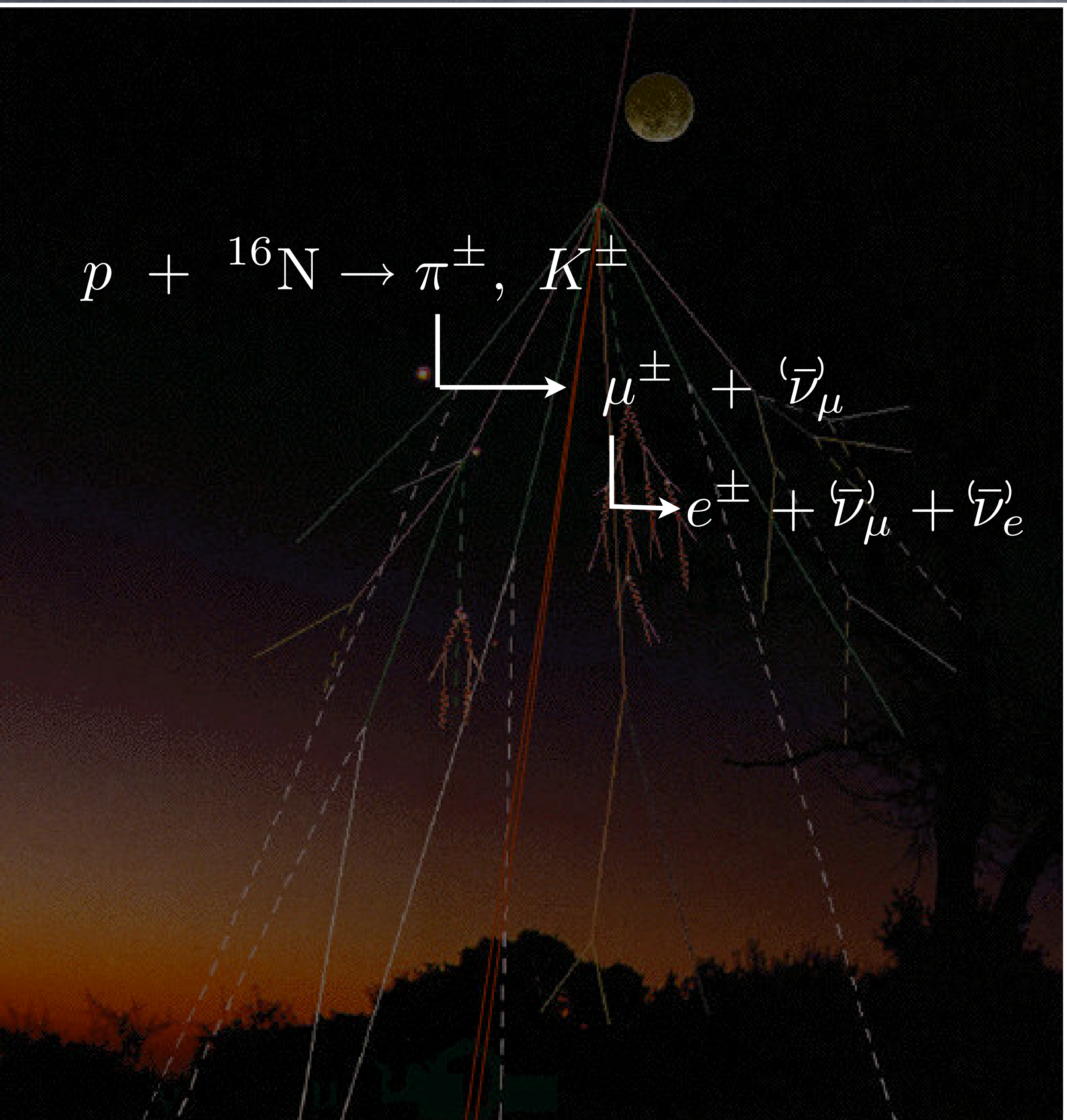
(3) Primary energy generation is nuclear fusion.

(4) Elemental abundance determined solely from fusion reactions.




Neutrinos from the Heavens....
...atmospheric neutrinos

Atmospheric Neutrinos



- Neutrinos are also produced from cosmic ray interactions taking place in the upper atmosphere...
- Average energy near 1 GeV
- Note that there are two "muon neutrinos" for every "electron" neutrino.

Atmospheric Neutrinos

- Absolute atmospheric neutrino flux difficult to predict; depends on details of hadron shower propagation.
- Ratio ($R=e/\mu$), however relatively independent of absolute flux (some atmospheric depth dependence remains).
- For energies above 10 GeV, one can use the following approximation for the atmospheric neutrino flux.

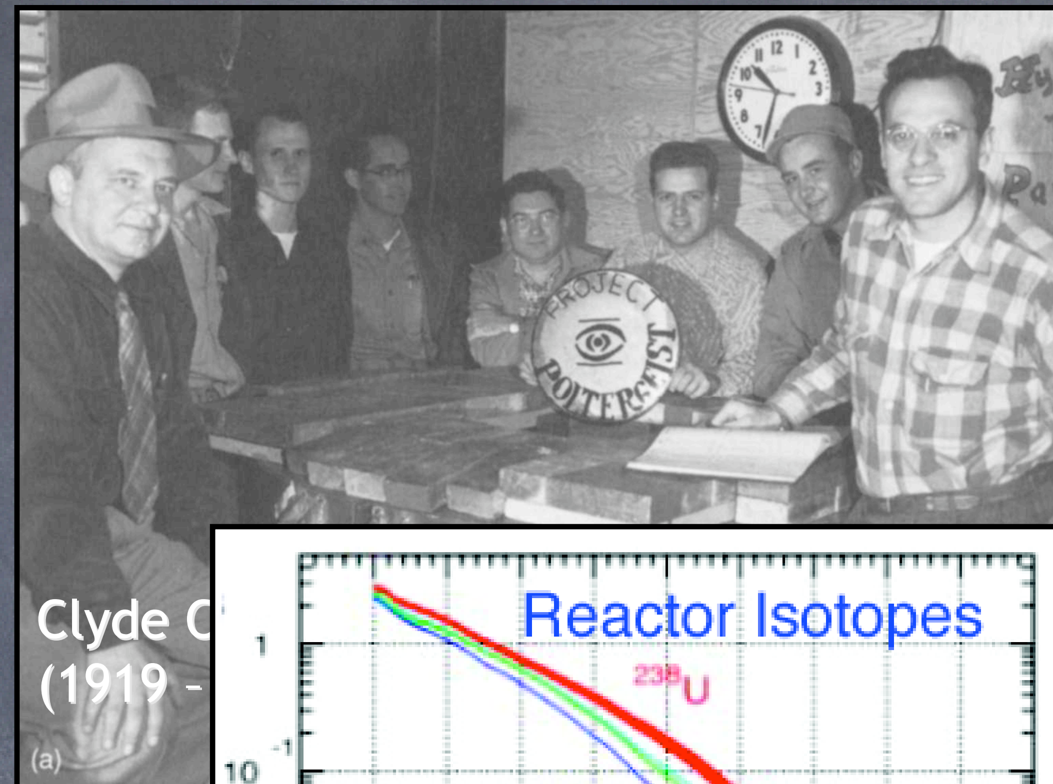
$$\frac{d^2\Phi_{\nu_\mu}}{dE_{\nu_\mu}d\Omega} \simeq 0.0286 E_\nu^{-2.7}\left(\frac{1}{1.0+\frac{6.0E_\nu\cos(\theta^*)}{115\ \mathrm{GeV}}}+\frac{0.213}{1+\frac{1.44E_\nu\cos(\theta^*)}{850\ \mathrm{GeV}}}\right)/\mathrm{cm}^2\,\mathrm{s\,sr\,GeV}$$

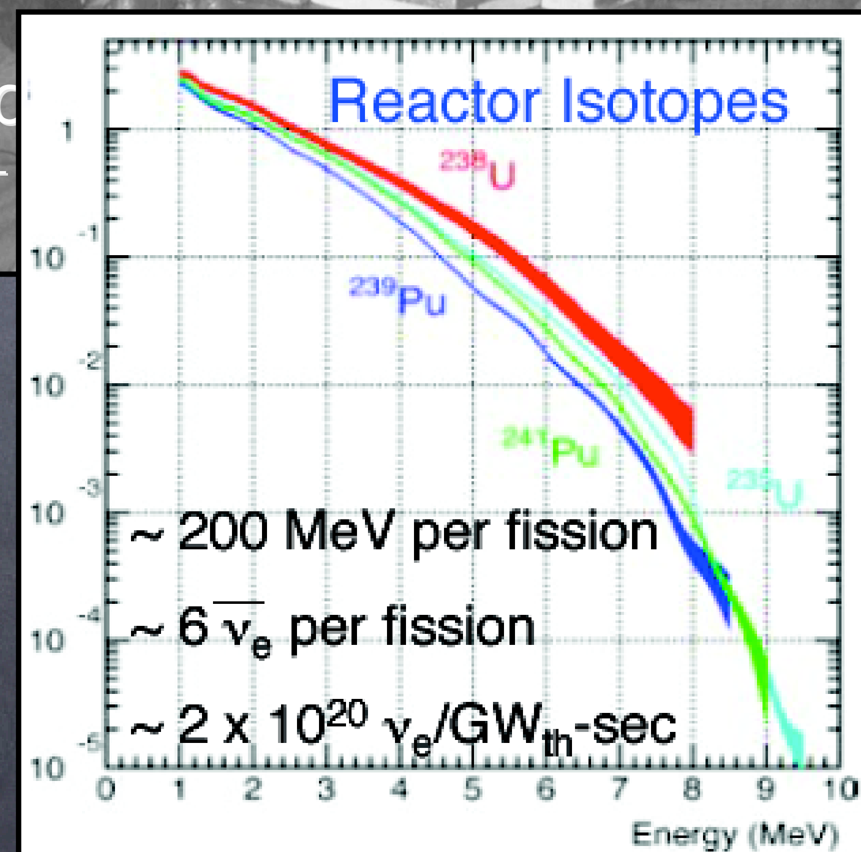
Neutrinos from the Earth...

Reactor Neutrinos

Double Chooz, France

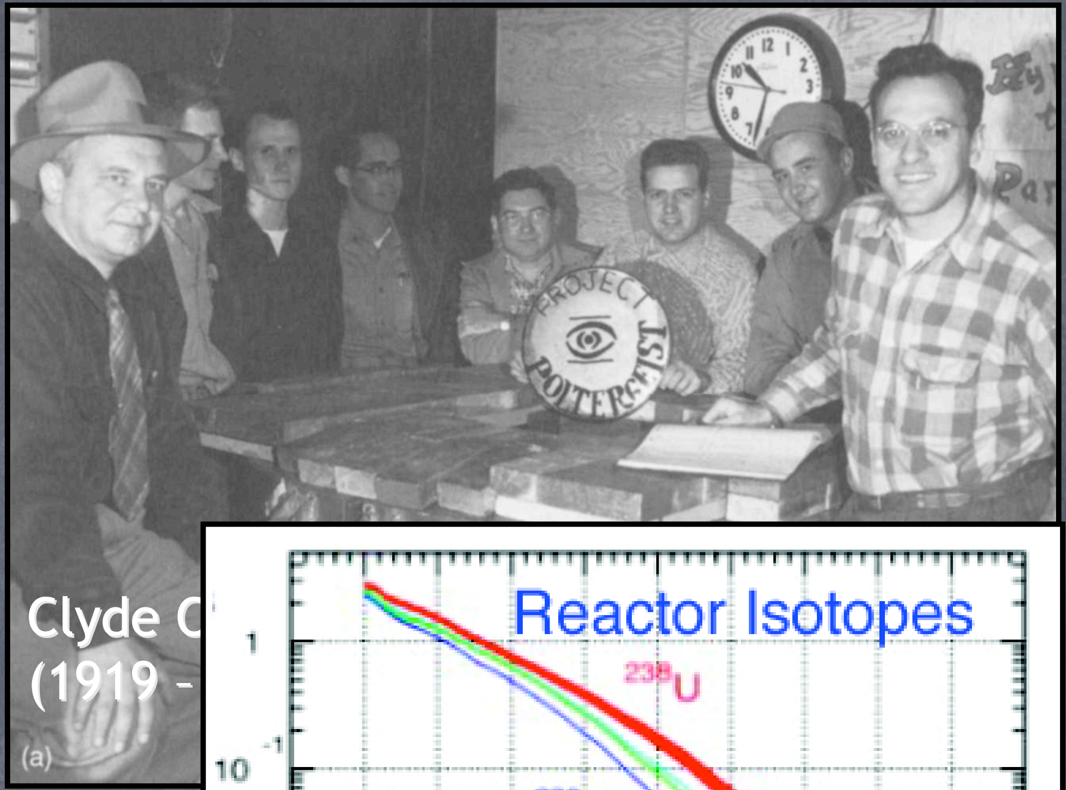
Neutrinos from Reactors

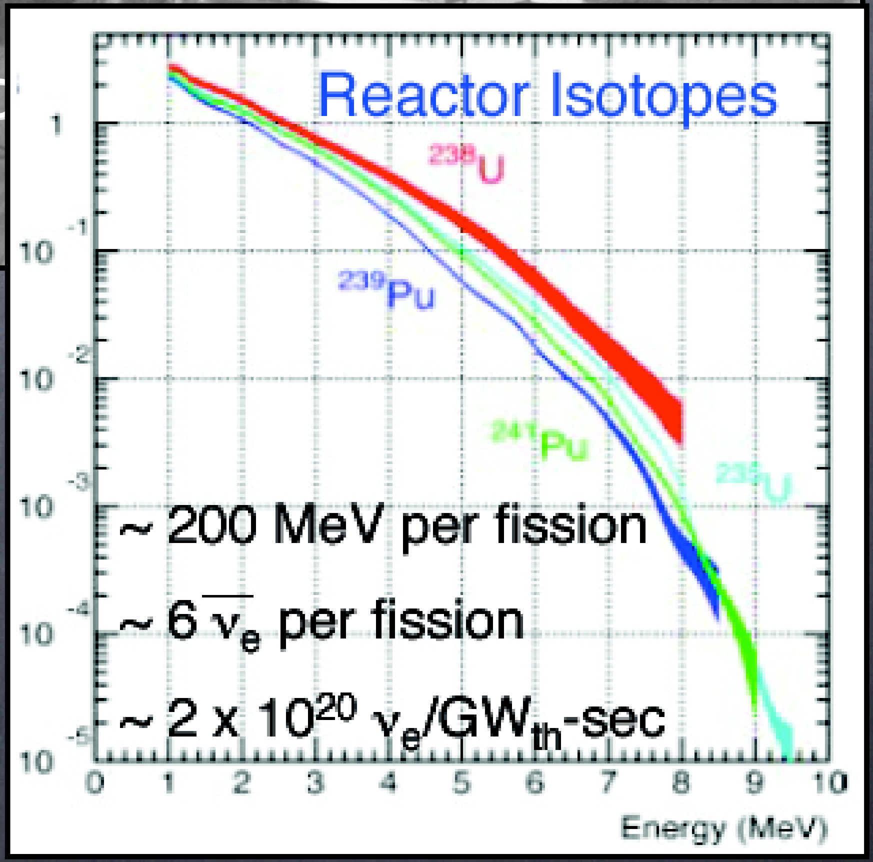




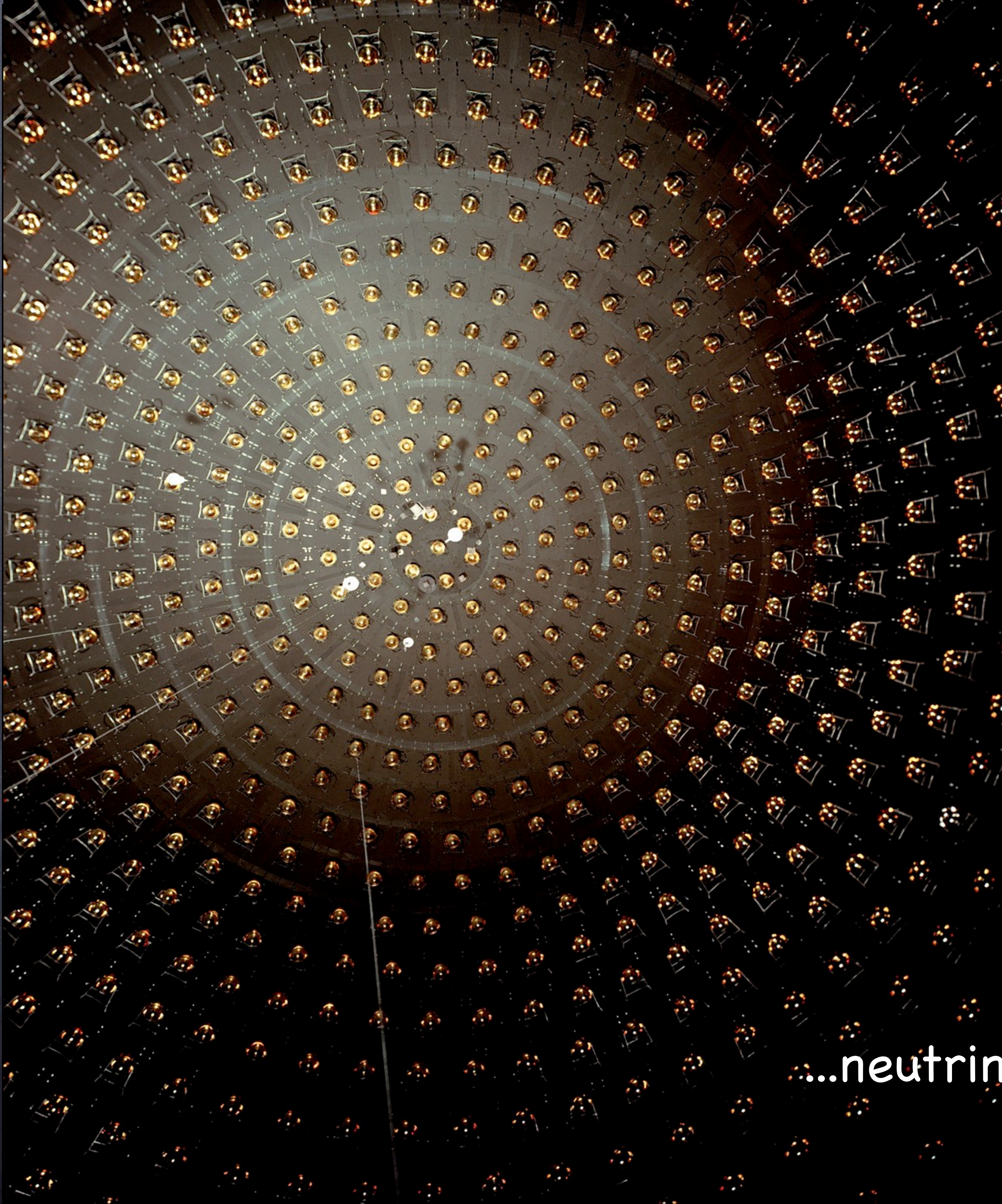
- Reactors allowed us to provide the first detection of neutrinos in 1956 (Cowen & Reines).
- Today remains an excellent source of electron anti-neutrinos at our disposal.
- Source from fission products of ^{238}U, ^{234}U, ^{239}Pu.

Neutrinos from Reactors



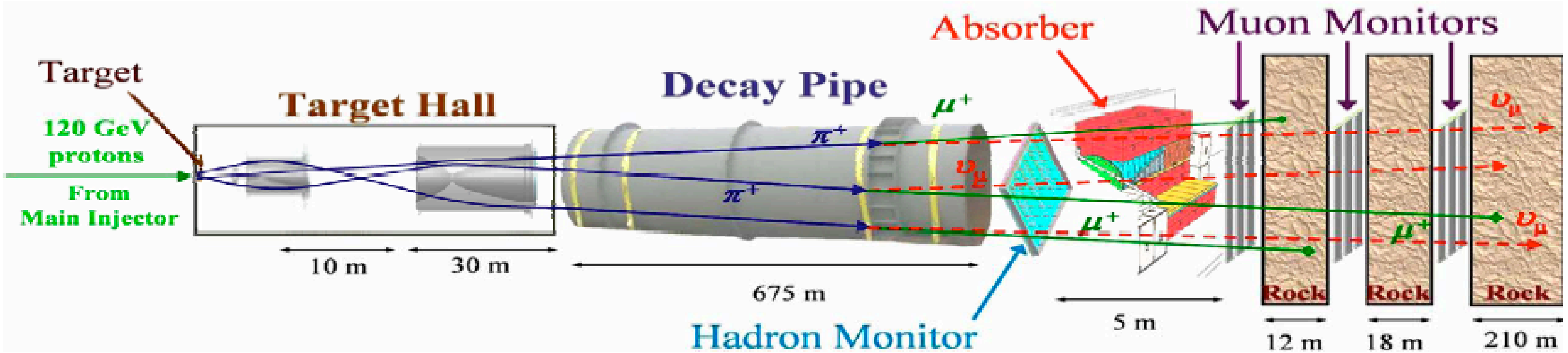


- Energy released through multiple fission reactions; each of which yields anti-neutrinos.
- An average of 6 neutrinos are released over each complete fission cascade.
- Proximity of source adds to accessibility to neutrinos to overcome cross-section.



Neutrinos from Earth

...neutrinos from accelerators

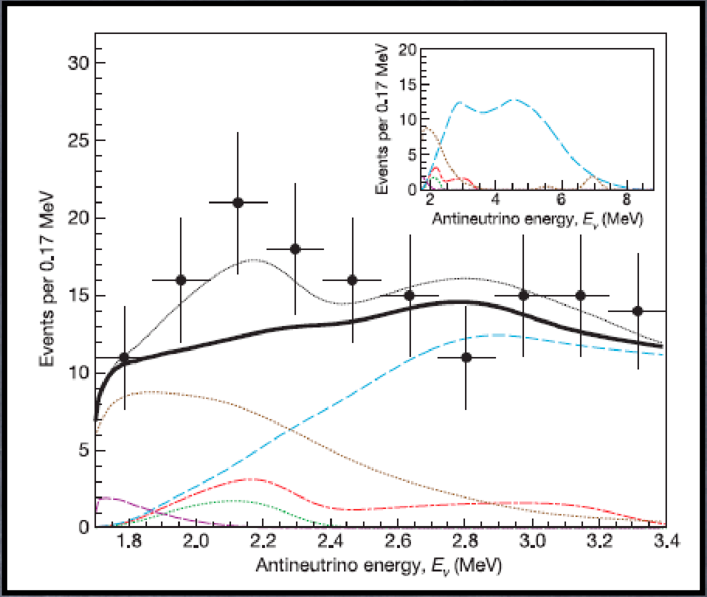


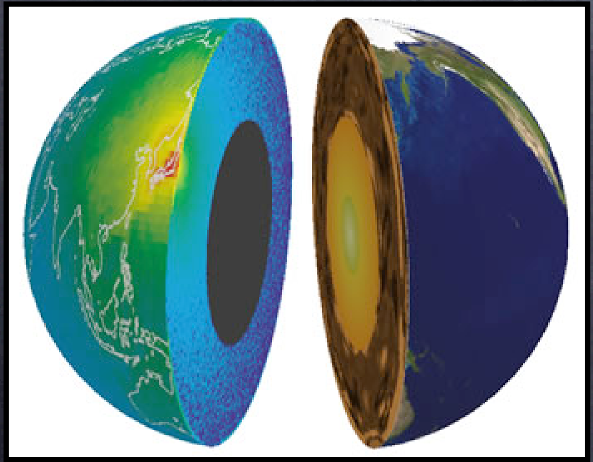
- Producing accelerator neutrinos...
  - Use accelerated proton beam to produce short-lived mesons (pions and kaons)
  - Focus mesons toward target detector.
  - Add dirt.
  - Gather neutrinos.

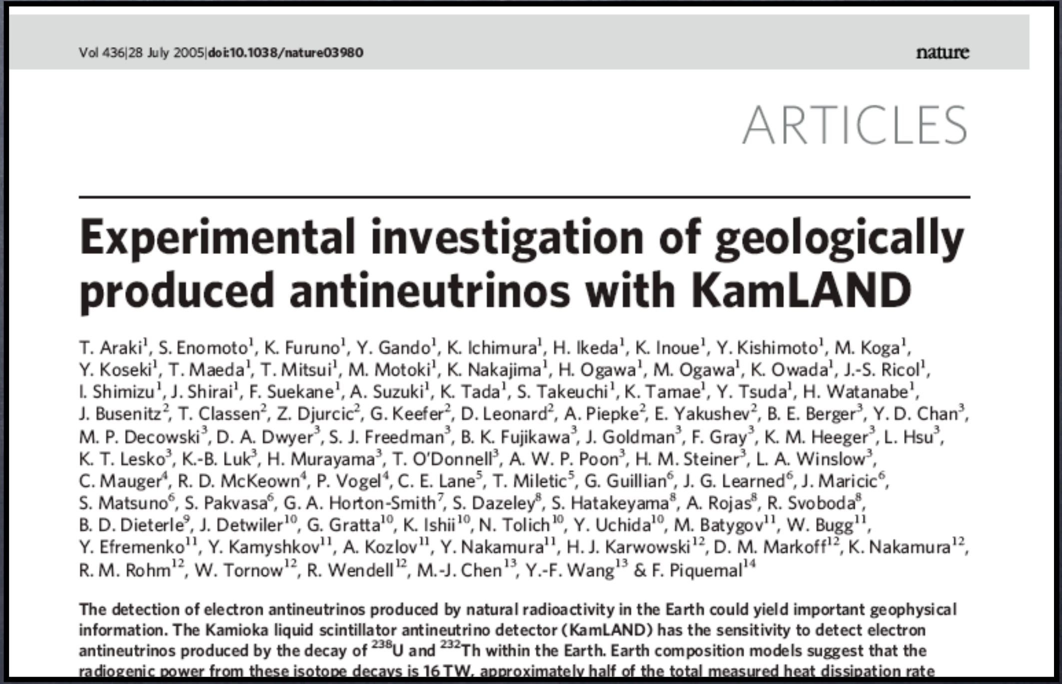

Neutrinos from Hell...
...literally!

Geoneutrinos

- Radiogenic heat (40-60% of 40 TW) from U and Th decays in the Earth's crust & mantle.
- Yields unique history of Earth's crust/core beyond what geological surveys can access.
- First observation of geoneutrinos from the KamLAND experiment.







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ARTICLES

Experimental investigation of geologically produced antineutrinos with KamLAND

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The detection of electron antineutrinos produced by natural radioactivity in the Earth could yield important geophysical information. The Kamioka liquid scintillator antineutrino detector (KamLAND) has the sensitivity to detect electron antineutrinos produced by the decay of ^{238}U and ^{232}Th within the Earth. Earth composition models suggest that the radiogenic power from these isotope decays is 16 TW, approximately half of the total measured heat dissipation rate

Part I: Summary

- In the past 76 years, we have gone from a desperate remedy to an essential component of our understanding of the Standard Model of particle and nuclear physics.

- Though in principle difficult to study, nature gives us plenty of sources of neutrinos to detect.

Next Week:

The Quest for Neutrino Mass