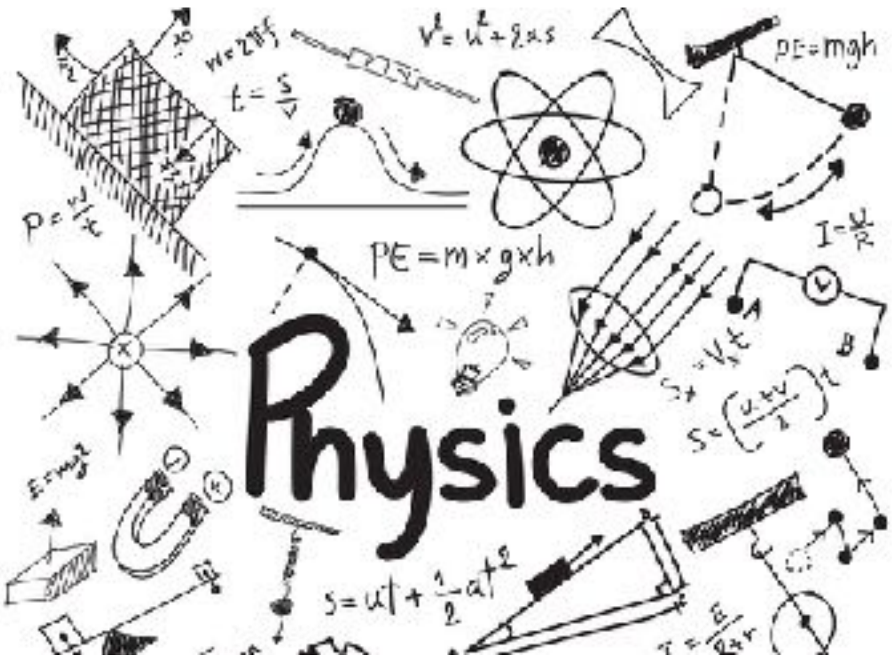
Frontiers in Physics and Astrophysics

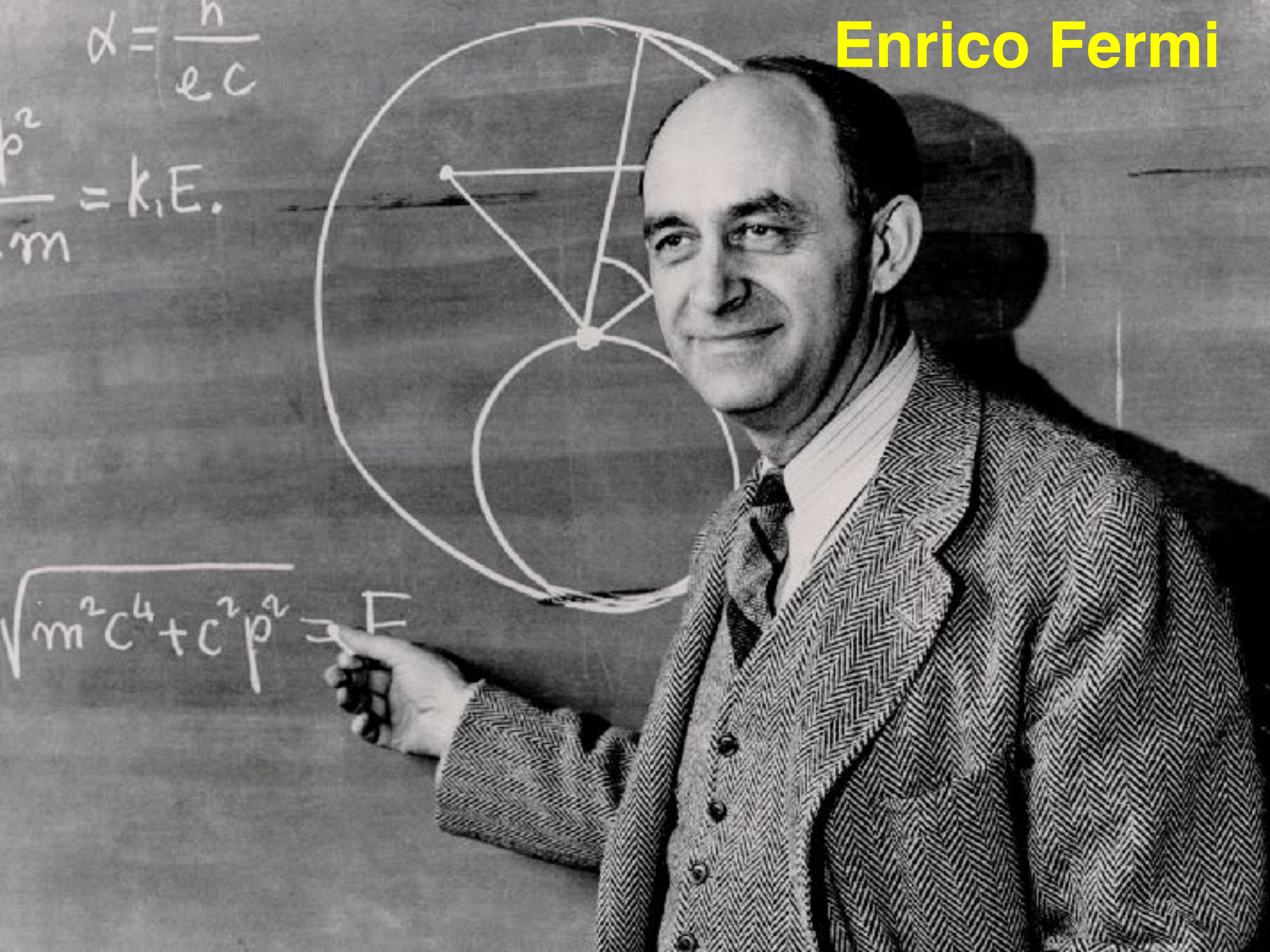
Fermi Lecture 8 – Introduction to Neutrinos



Barry C Barish

19-December-2019

Enrico Fermi



Enrico Fermi Lectures 2019-2020 Frontiers of Physics and Astrophysics

- Explore frontiers of Physics and Astrophysics from an Experimental Viewpoint
- Some History and Background for Each Frontier
- Emphasis on Large Facilities and Major Recent Discoveries
- Discuss Future Directions and Initiatives

- Thursdays   4-6 pm
- Oct 10,17,24,one week break, Nov 7
- Nov 28, Dec 5,12,19 Jan 9,16,23
- Feb 27, March 5,12,19

Frontiers

Fermi Lectures 2019-2020 - Barry C Barish

- Course Title: **Large Scale Facilities and the Frontiers of Physics**
- The Course will consist of 15 Lectures, which will be held **from 16:00 to 18:00** in **aula Amaldi**, Marconi building, according to the following schedule:
- 10 October 2019 - Introduction to Physics of the Universe
  17 October 2019 - Elementary Particles
  24 October 2019 - Quarks
  7 November 2019 – Particle Accelerators
  28 November 2019 – Big Discoveries and the Standard Model
  5 December 2019 – Force Carriers – Z, W
  12 December 2019 – Higgs Discovery, Supersymmetry?, Future??
  19 December 2019 – Introduction/History of Neutrinos
  9 January 2020 – Neutrino(2)
  16 January 2020 – Neutrinos(3)
  23 January 2020 – Neutrinos (4)
  27 February 2020 – Gravitational Waves (1)
  5 March 2020 – Gravitational Waves (2)
  12 March 2020 – Particle Astrophysics / Experimental Cosmology
  19 March 2020 – Future Perspectives
- All Lectures and the supporting teaching materials will be published by the Physics Department.

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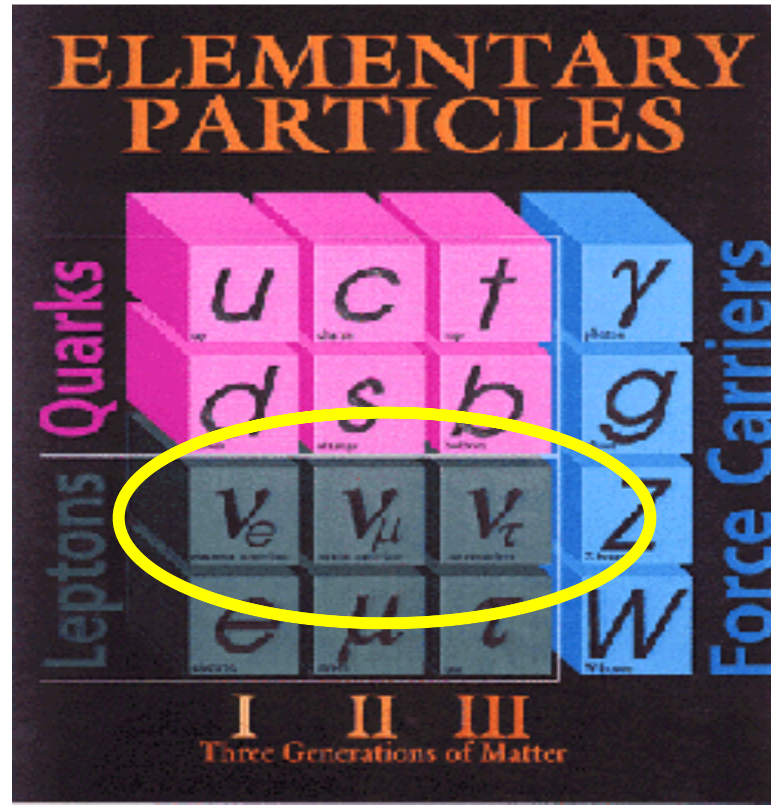
Neutrinos

- Chemistry tells us atoms are made up of electrons, protons and neutrons

- Particle physics probes deeper into the nucleus finding more fundamental particles: leptons and quarks
  - Leptons: electron, muon, tau and associated neutrinos, (all come in + and – varieties)
  - Quarks: up, down, charm, strange, top, bottom (all come in matter and anti-matter varieties)
  - Protons and neutrons are built out of 3 quarks (combo of up and down) with leptons waiting in the wings
  - Rules of interaction are complicated



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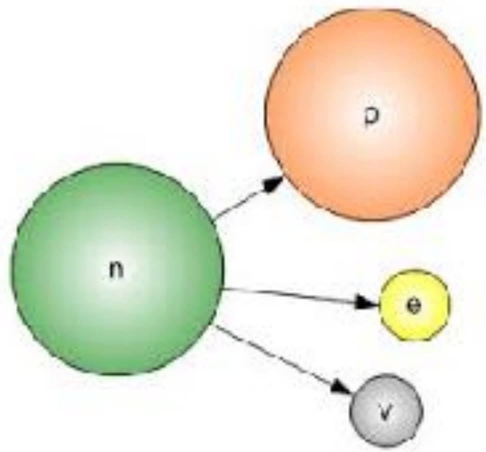
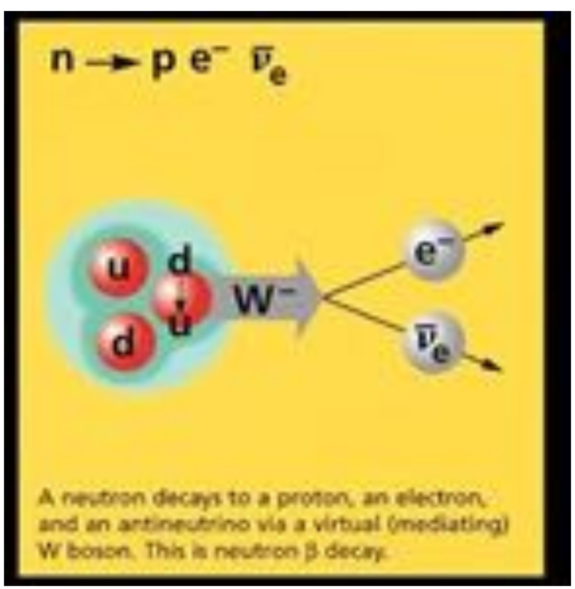
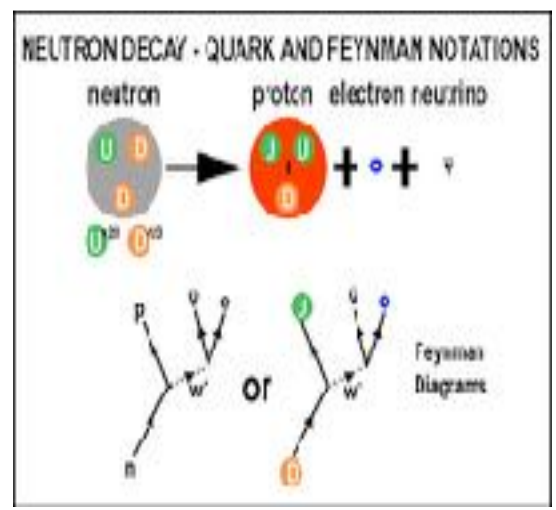
Neutrinos

The imagery is still accepted after nearly half a century. So, what could be wrong?



- Firstly, Up and Down quarks are supposed to be unique and singular. Thus, having a Down quark give an Up quark plus some other stuff is irrational.
- Secondly, why doesn't the Down quark of the proton decay? Unlike a neutron, which has a lifetime of ~880 seconds, a proton has a lifetime longer than 10^{34} years. A proton's lifetime is therefore about 7×10^{23} times longer than the universe's estimated age!
- Thirdly, many of the elements of the periodic table are quite stable, in spite of having many "neutrons".





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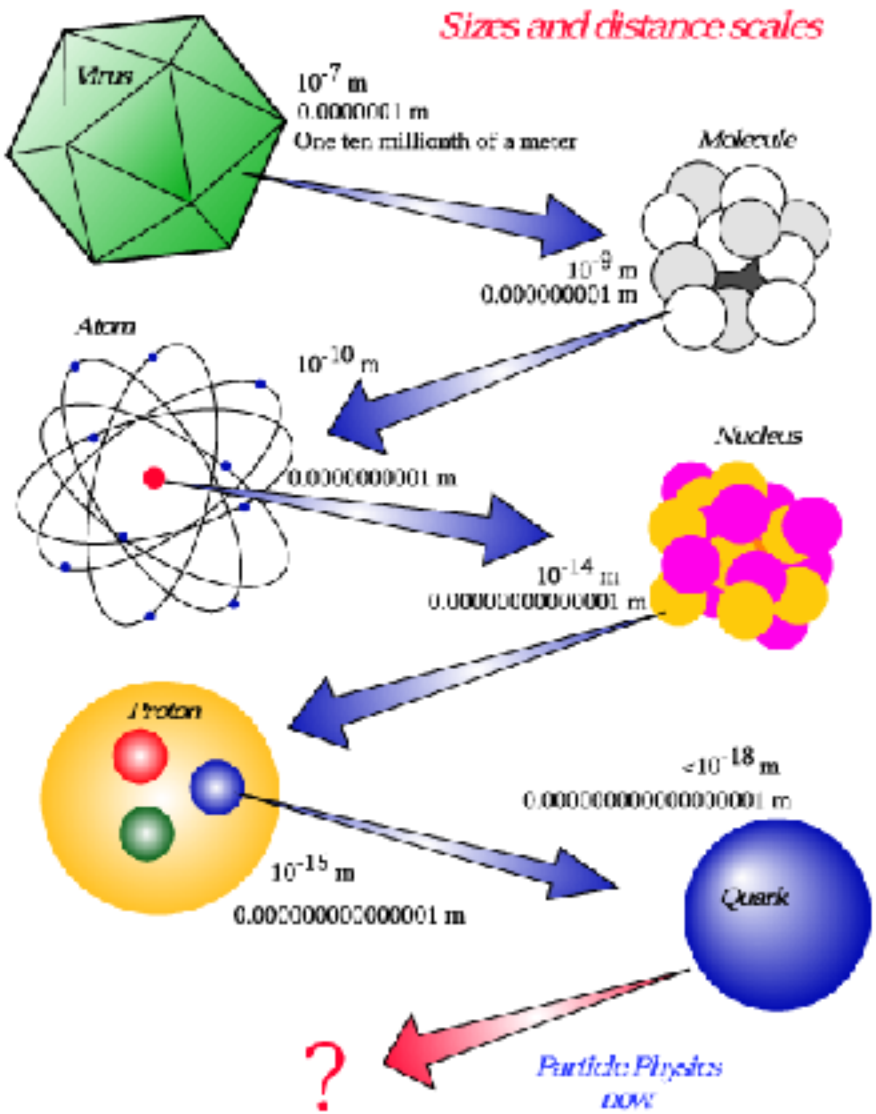
Neutrinos



Nature at shorter and shorter distances

Quarks and Electrons describe much of particle physics, but we also need neutrinos

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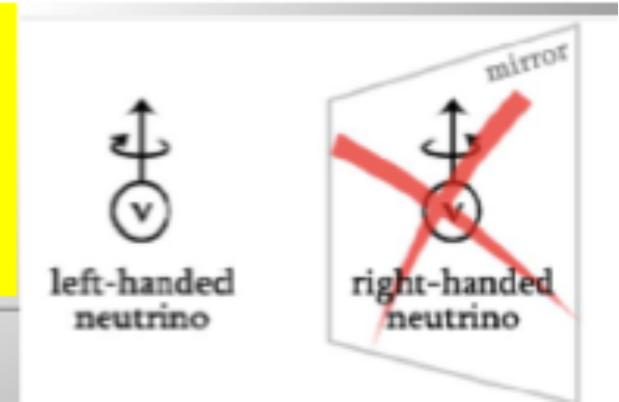
- Neutrinos are fundamental particles
- Neutrino are ghostly particles
- Trillions (10^{12}) of neutrinos pass per second through you for every second of your life! They come from the sun
- Neutrinos need a light year of lead ($\sim 10^{13}$ km) be stopped with 50% chance
- There are a billion neutrinos for each atom in the Universe. There are $\sim 3.10^{8}$ neutrinos per cubic meter- relic neutrinos
- Their sheer number must mean they are important
- Neutrinos have a fixed chirality ->



An (American) billion = 10^{9} = 1000000000

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Neutrinos are still mysterious particles

- Have only (left handed) weak interactions
- Are mass-less in the (minimal) Standard Model
- Are the only neutral fermions in the SM
- Could be Majorana or Dirac fermions
- Neutrinos come from everywhere
  - Solar neutrinos
  - Atmospheric neutrinos
  - Relic/supernova neutrinos
  - Nuclear reactor created neutrinos
  - Accelerator created neutrinos
  - Geoneutrinos, radioactive decay, even from your body

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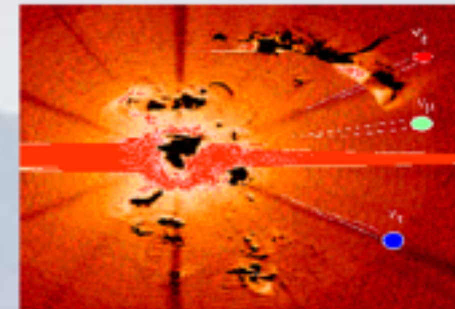
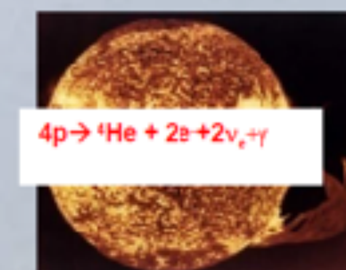
Where neutrinos come from?

- **Neutrinos from Big bang:**



330 ν/cm^3 ; $E_\nu \sim 4 \times 10^{-4}$eV
Decoupled about 1 min. after the Big bang

- **Neutrinos from Sun:**



Sun burns through nuclear Reaction
$E_\nu \sim 0.1 \sim 20$ MeV; Flux ~10^{12} /cm²/s

- **Explosion of Star:**

Most of the binding energy released When a neutron star is born is emitted in the form of neutrinos

$E_b \sim 10^{53}$ ergs, $E_\nu \sim 10$-30 MeV, T ~10 sec

Close Encounter with Neutrinos

- Every second Your body receives
  - About a trillion neutrinos from the sun
  - 50 billion neutrinos from the natural radioactivity of the earth
  - 10-100 billion neutrinos from nuclear plants all over the world

- Our body contains about 20 milligrams of ^{40}K which is β radioactive. We emit about 340 millions neutrinos/day. Which run from our body at the speed of light until the end of the universe.

Good news - Typically a neutrino has to zip through 10,000,000,000,000,000,000 people before doing anything.

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There are lots of neutrinos around – they are the second most abundant particle in the universe after microwave background photons. The problem is that they are very low energy and so very, very difficult (maybe impossible) to detect.

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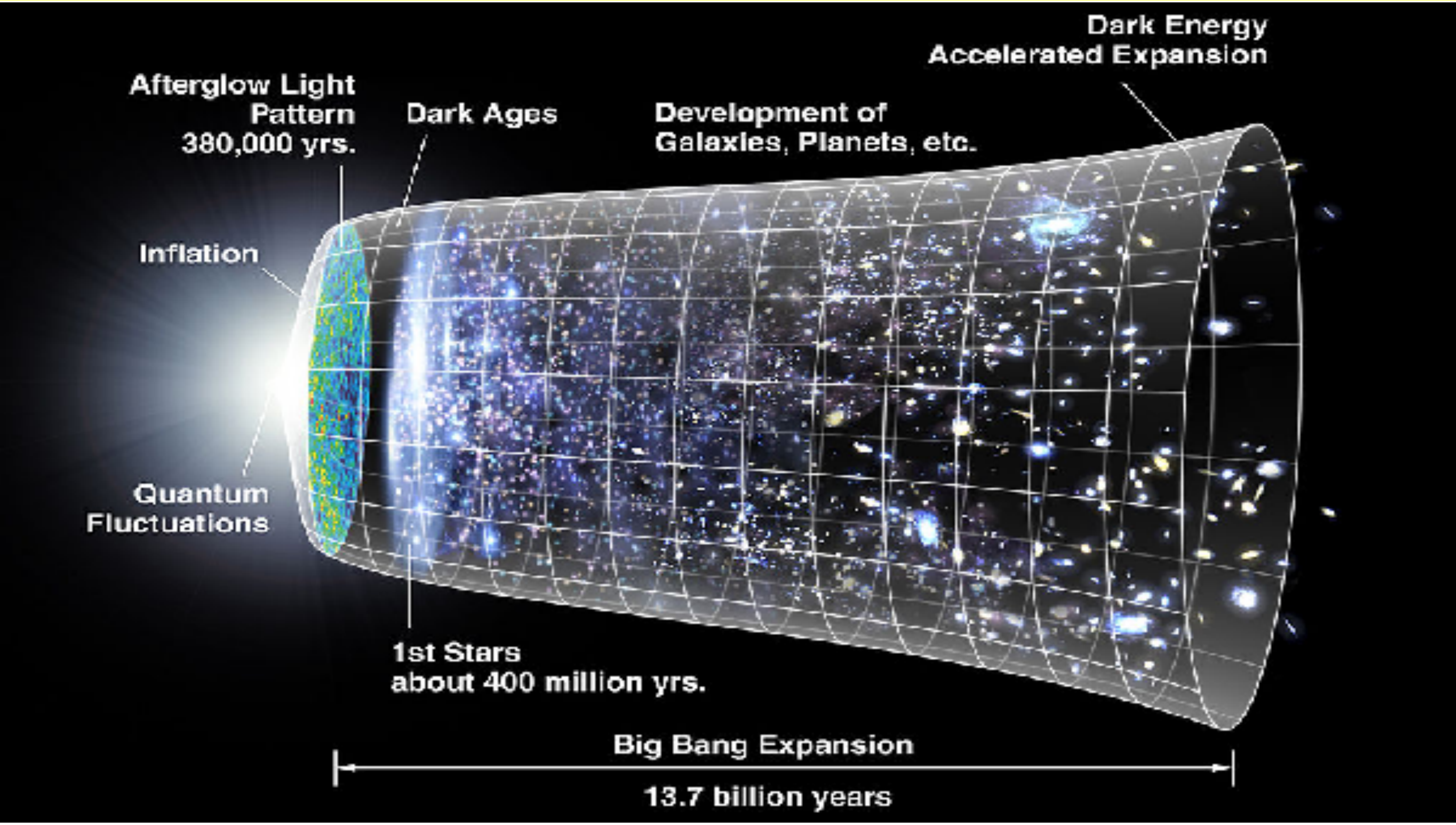

- There are photons still around from when the universe was 380,000 years old – the so-called Cosmic Microwave Background.
- There are neutrinos still around from when the universe was 1 SECOND old! These "Relic" neutrinos constitute the Cosmic Neutrino Background (CνB).

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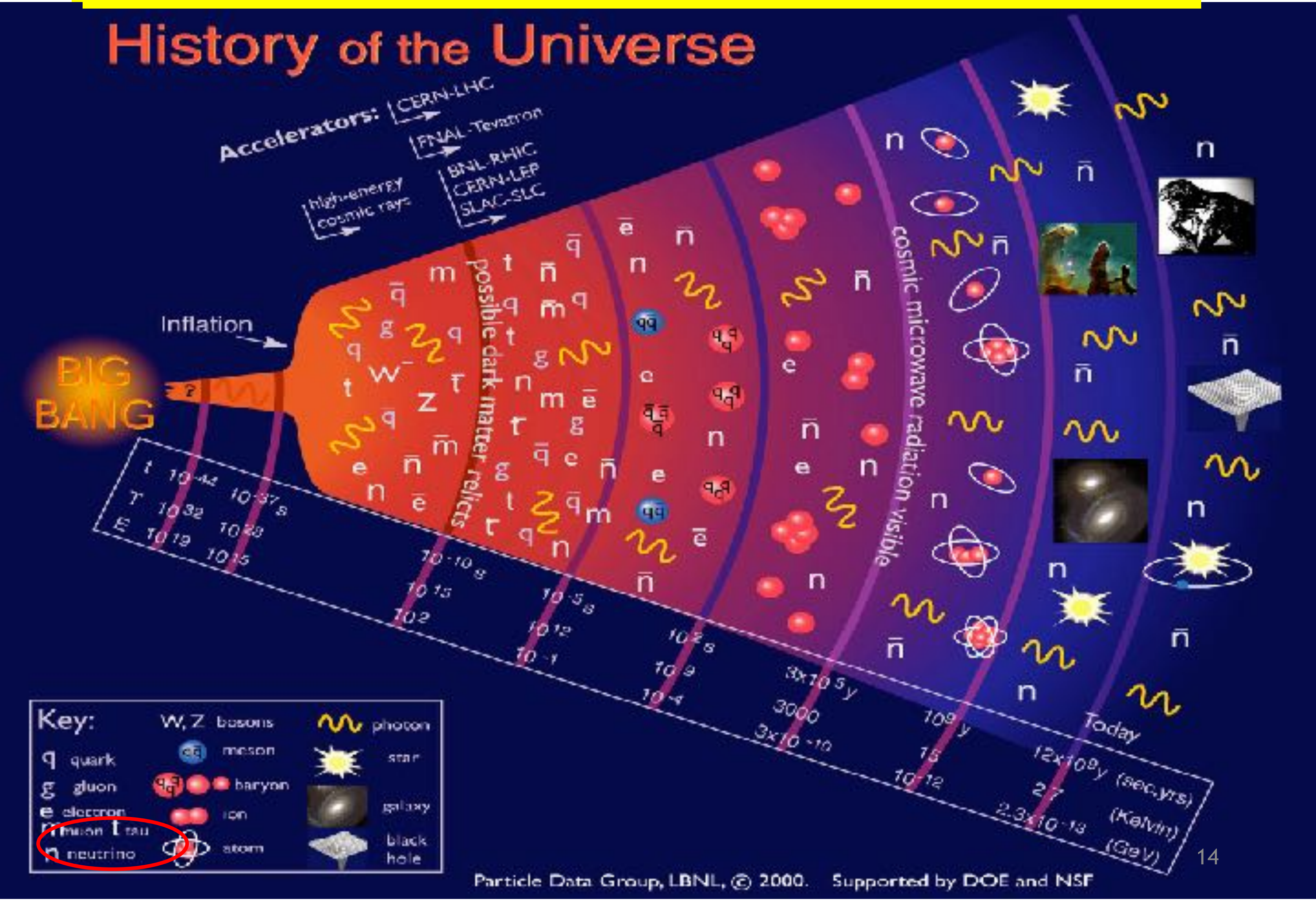
History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
(sec,yrs)
(Kelvin)
(GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

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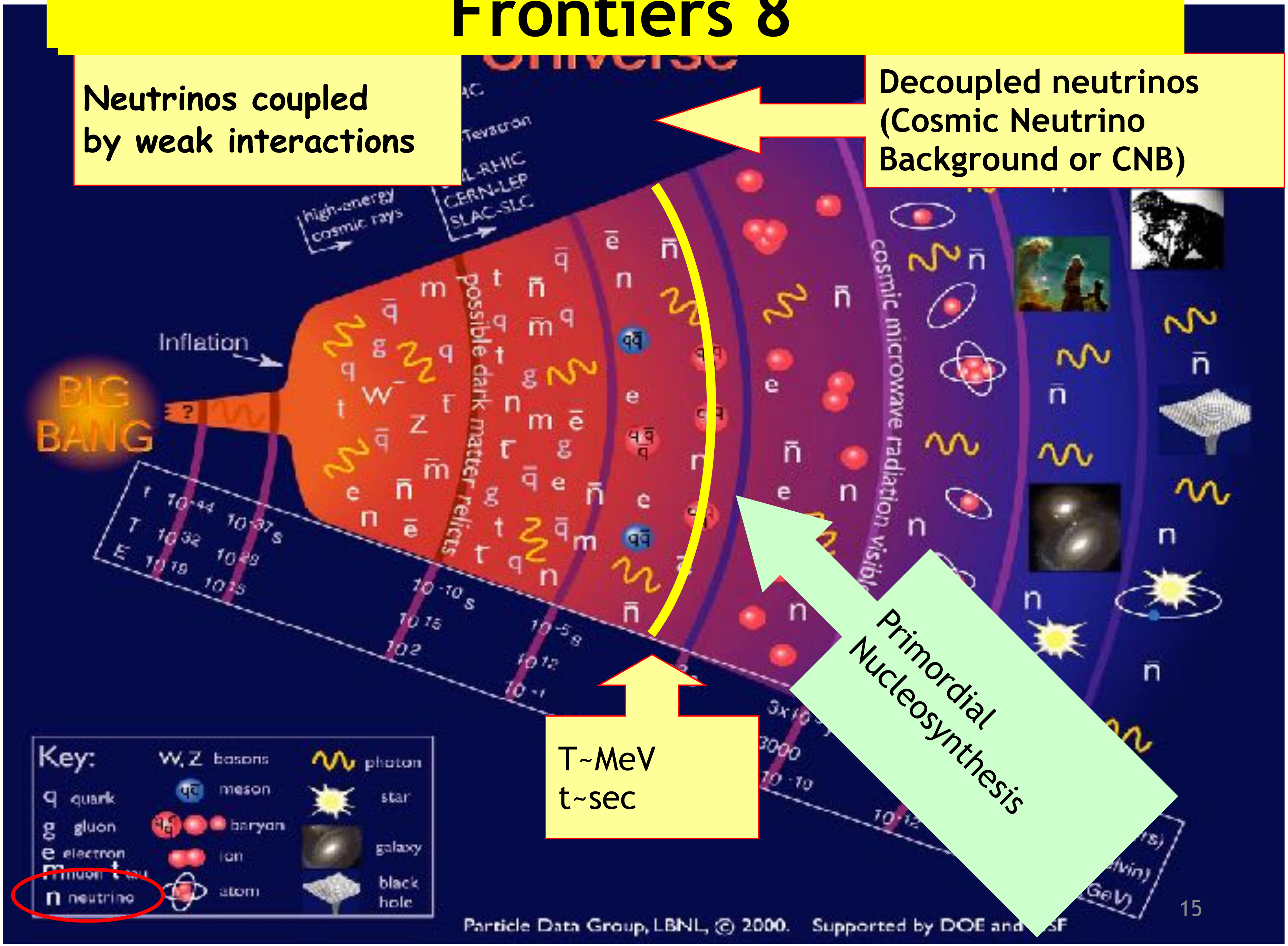

Neutrinos coupled by weak interactions
Decoupled neutrinos (Cosmic Neutrino Background or CNB)
T~MeV
t~sec
Primordial Nucleosynthesis
BIG BANG
Inflation
high-energy cosmic rays
CERN-LEP
SLAC-SLC
Tevatron
possible dark matter relicts
cosmic microwave radiation visible
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
galaxy
e electron
ion
atom
black hole
n neutrino
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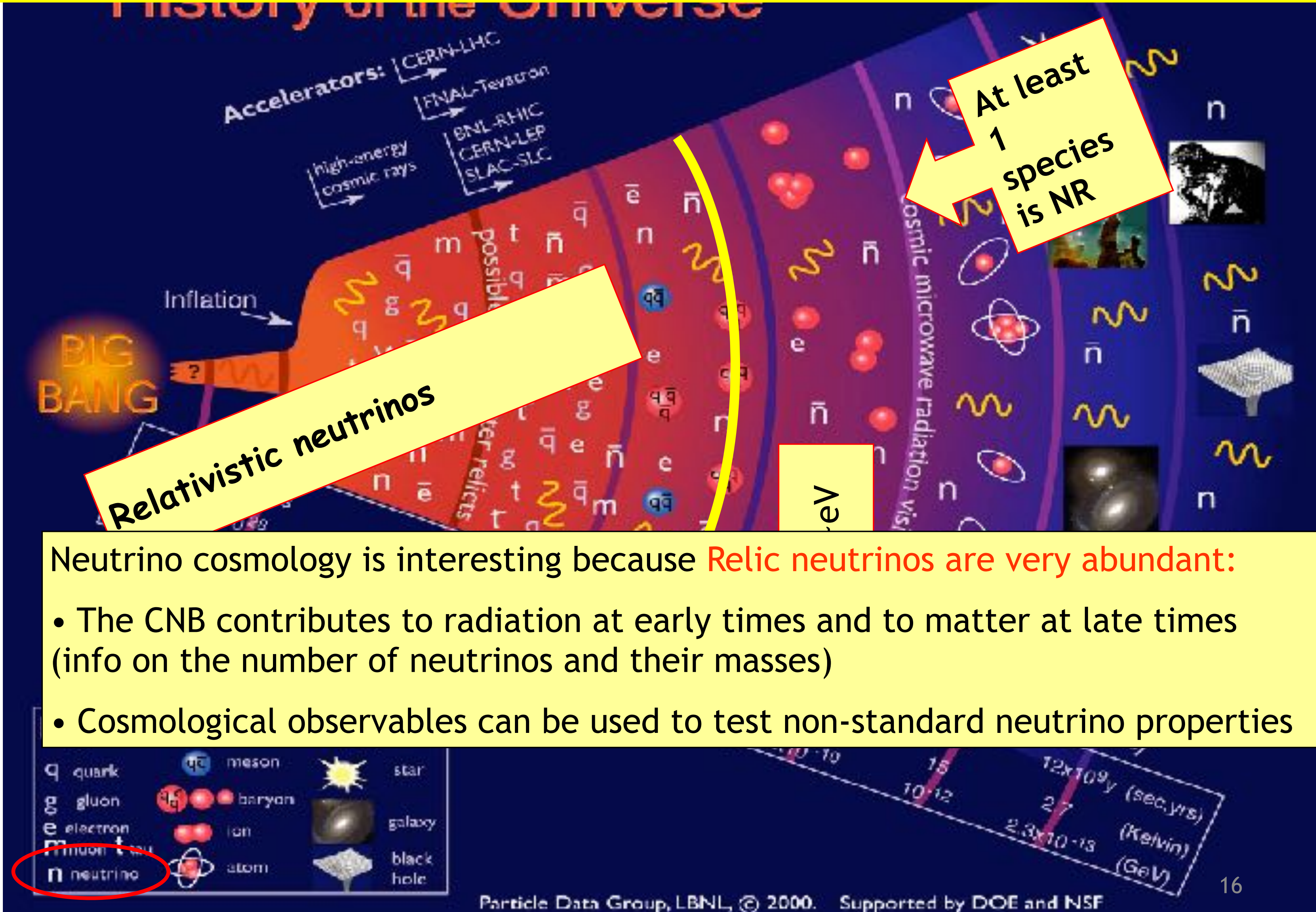

Neutrino cosmology is interesting because Relic neutrinos are very abundant:

- The CNB contributes to radiation at early times and to matter at late times (info on the number of neutrinos and their masses)
- Cosmological observables can be used to test non-standard neutrino properties

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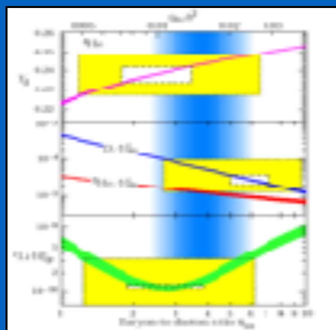
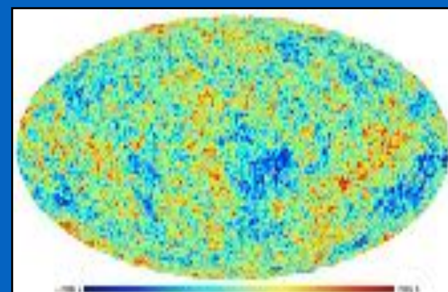
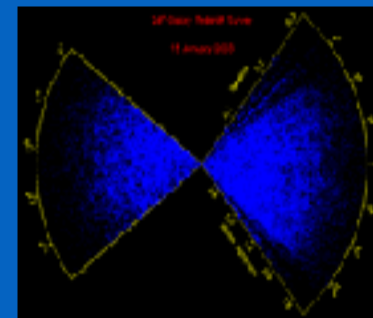
Relic neutrinos influence several cosmological epochs

		
Primordial Nucleosynthesis BBN	Cosmic Microwave Background CMB	Formation of Large Scale Structures LSS
T ~ MeV	T < eV	
ν_e vs $\nu_{\mu,\tau}$ N_{eff}	No flavour sensitivity N_{eff} & m_ν	

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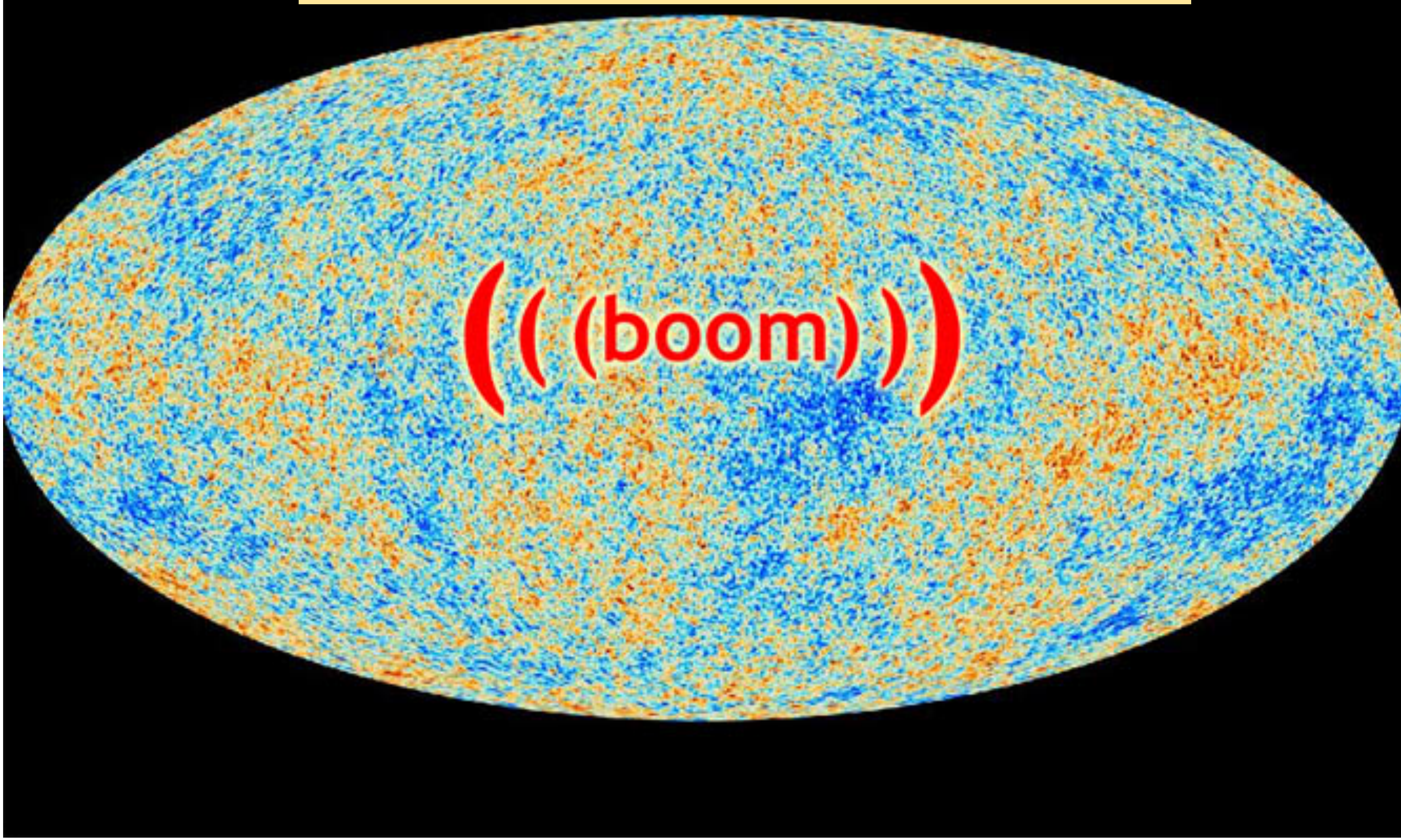
The Cosmic Microwave Background



"Listen" to the Big Bang at https://soundcloud.com/uw-today/bigbangsound100

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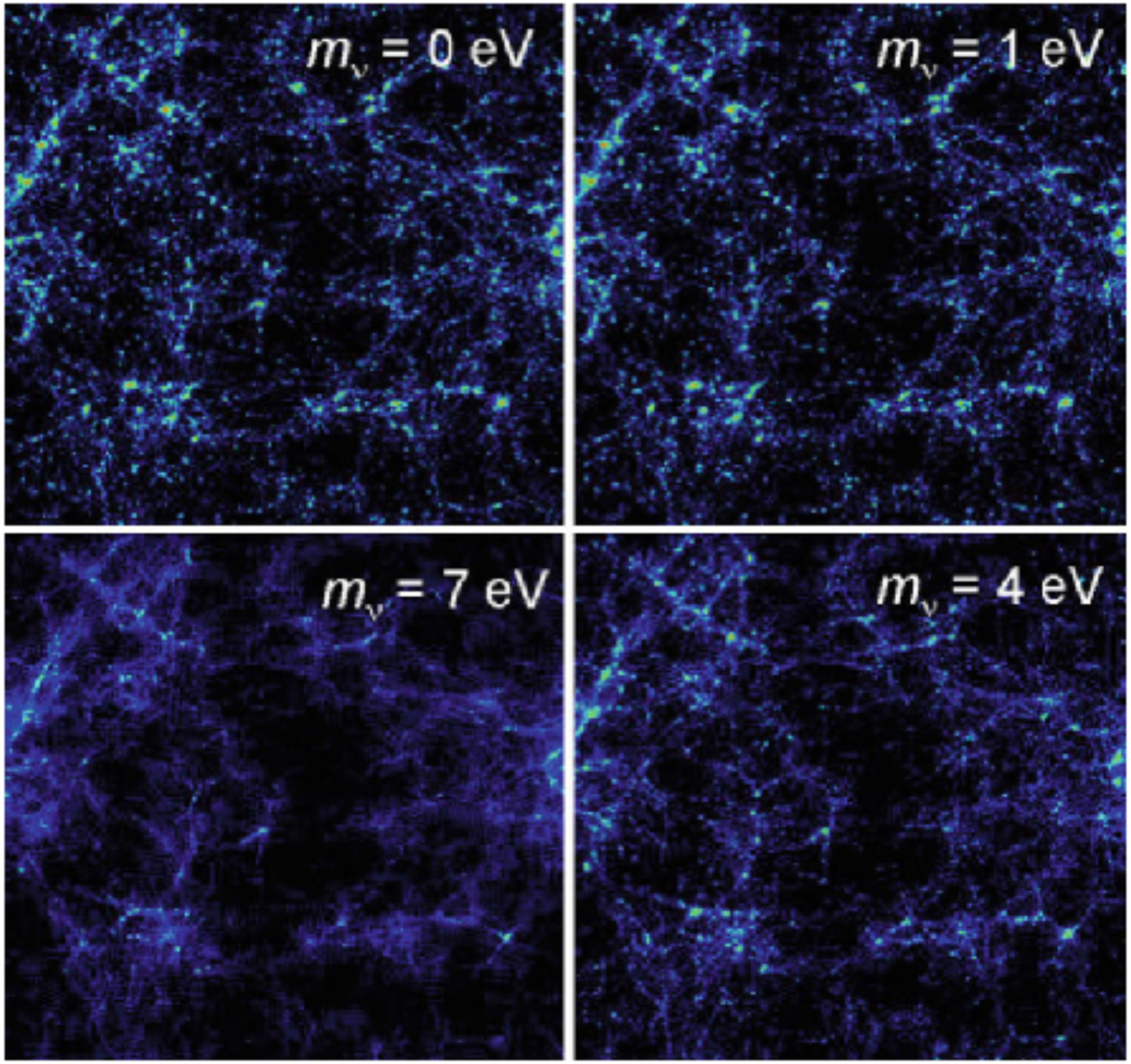

Fig. 2.9 Influence of the neutrino mass on small-scale structures of the universe. The plots show a simulation of the structure formation for different neutrino masses. For large neutrino masses the small scales are smeared out

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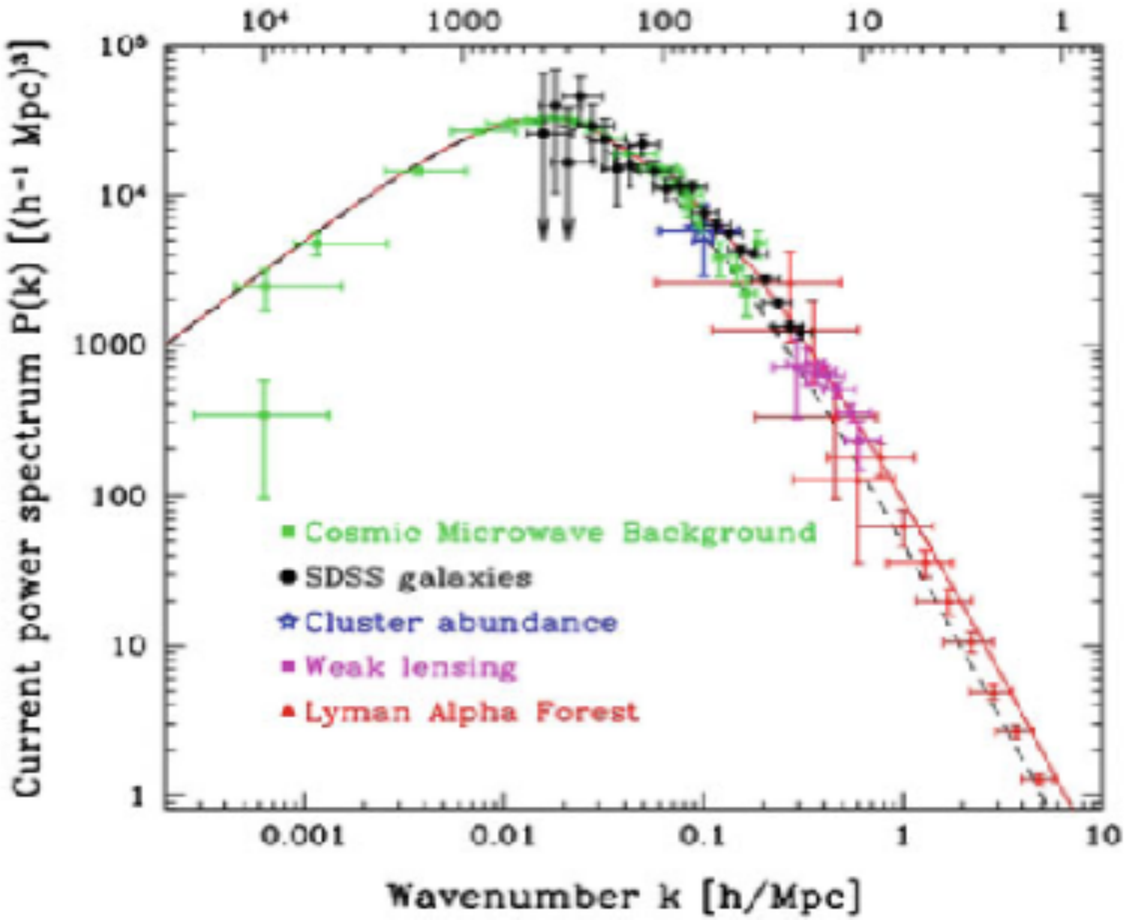

Fig. 2.10 Influence of the neutrino mass on the matter power spectrum. This plot shows the measurements and theoretical prediction of the matter power spectrum. The *solid line* represents a standard scenario, where the neutrino mass is assumed to be zero. The *dashed line* corresponds to where neutrinos contribute with 7 % to the dark matter in the universe, i.e. their mass is approximately 1 eV. The power spectrum is reduced by a factor of 2 for large wave numbers, i.e. small-scale structures [44]

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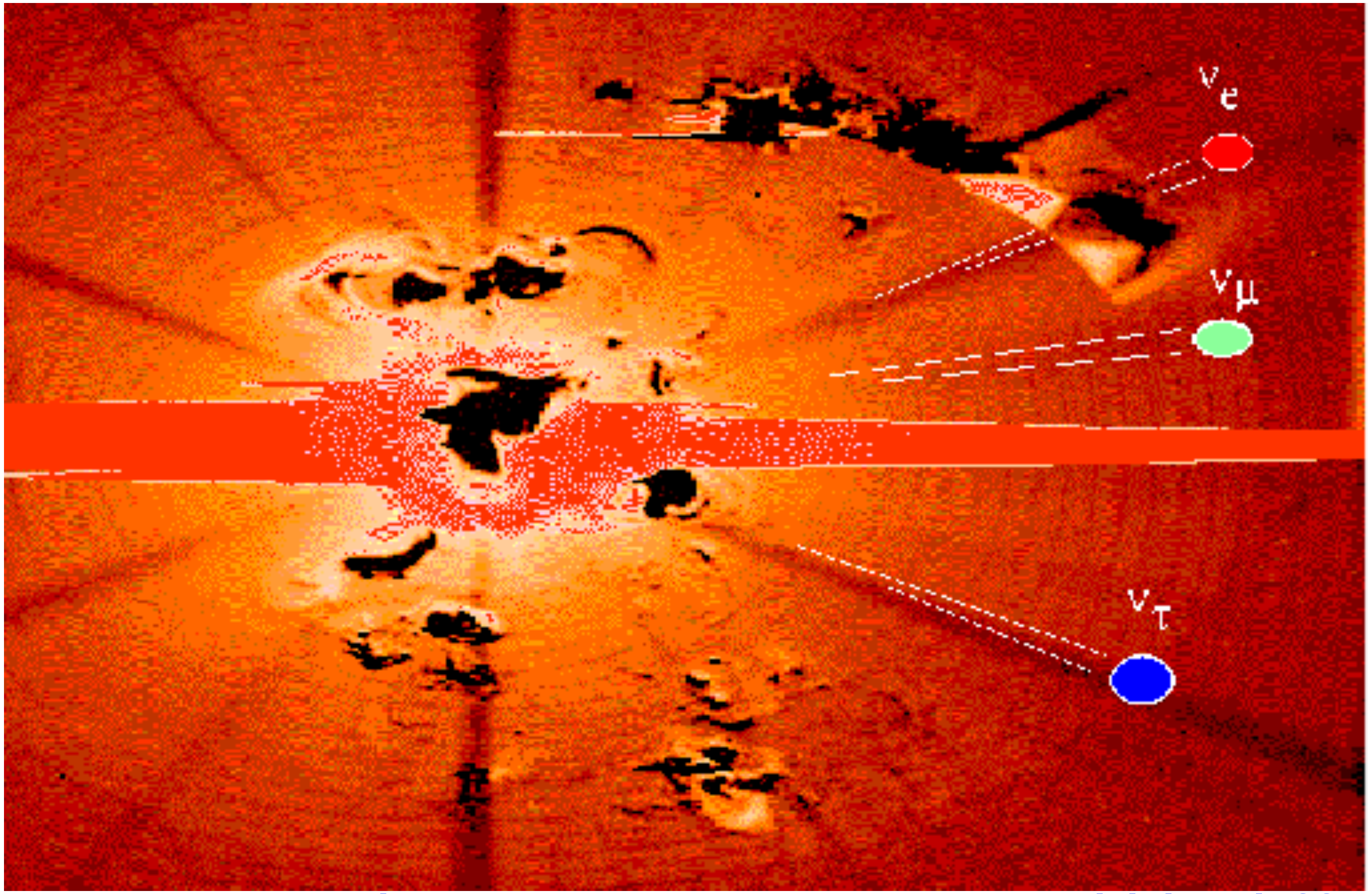
Why Not Just Measure the CνB (or CnB)?



We're trying! But these neutrinos are incredibly difficult to detect

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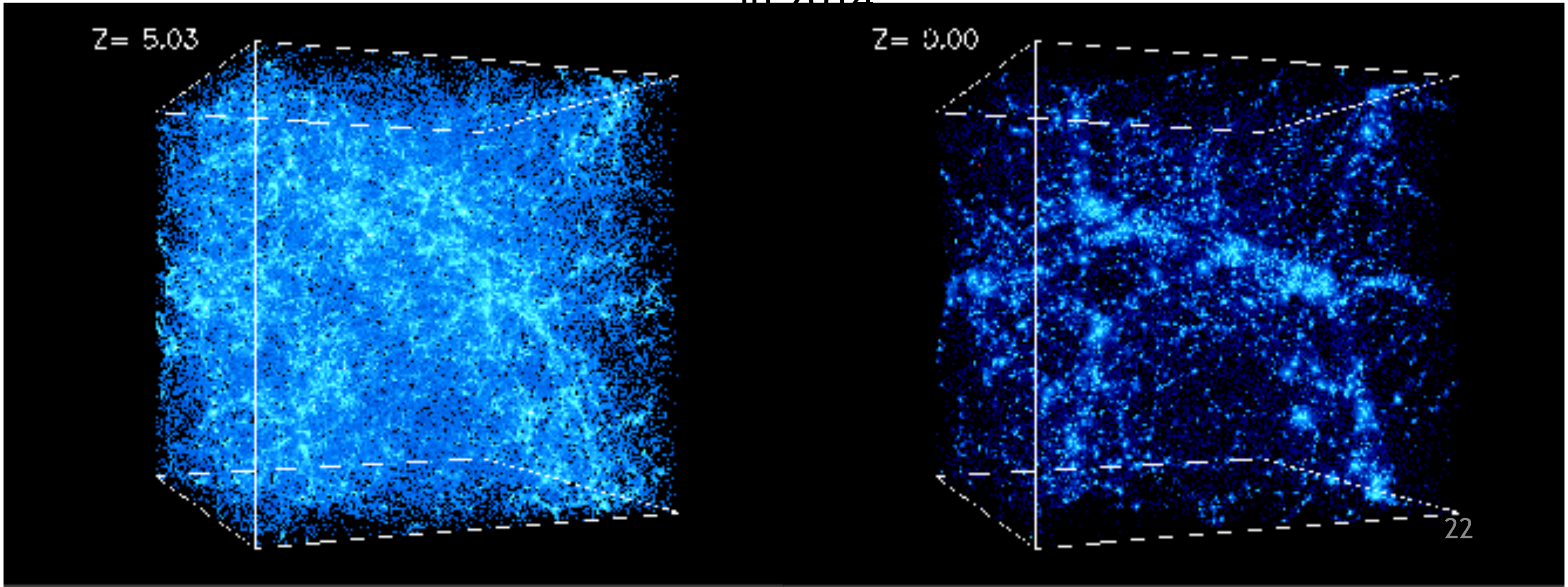
But relic neutrinos are slow enough ("non-relativistic") and they have mass (albeit tiny), so they can be trapped gravitationally by galaxies. Hence, they can be observed in how they affect the evolution of the large scale structure of the universe.

the 8.4-meter-diameter Large Synoptic Survey Telescope begins operating in Chile in 2014



Some History of our Understanding Neutrinos

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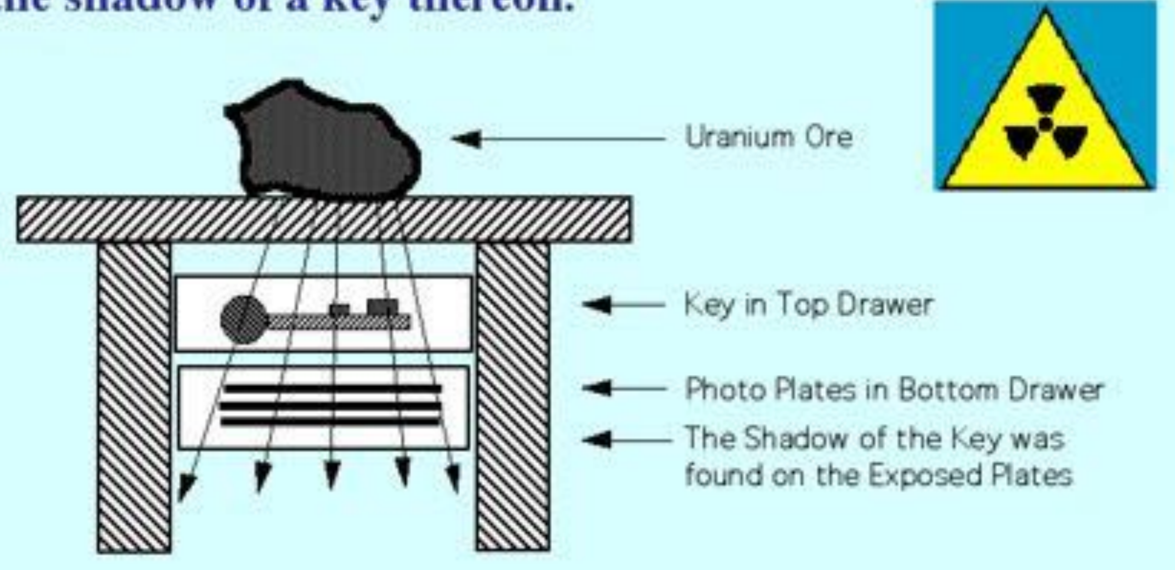
1. Some History

1886 Henri Becquerel radioactivity

Discovery of Radioactivity

Becquerel, experimenting with fluorescent minerals, found that Uranium ore on his desktop exposed film in the drawers below with the shadow of a key thereon.



Marie Curie analyzed Uranium ore and discovered new radioactive elements including Radium.

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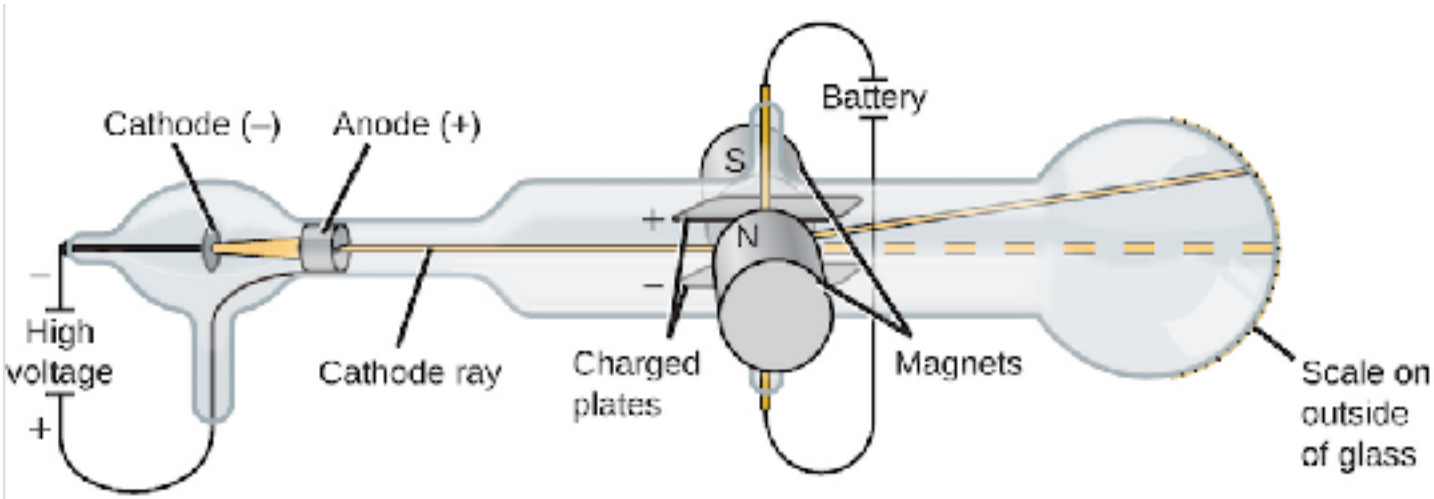
1. Some History

1897 JJ Thompson discovers the Electron



- In 1897, **J.J. Thomson discovered** the **electron** by experimenting with a Crookes, or cathode ray, tube. He demonstrated that cathode rays were negatively charged. In addition, he also studied positively charged particles in neon gas.

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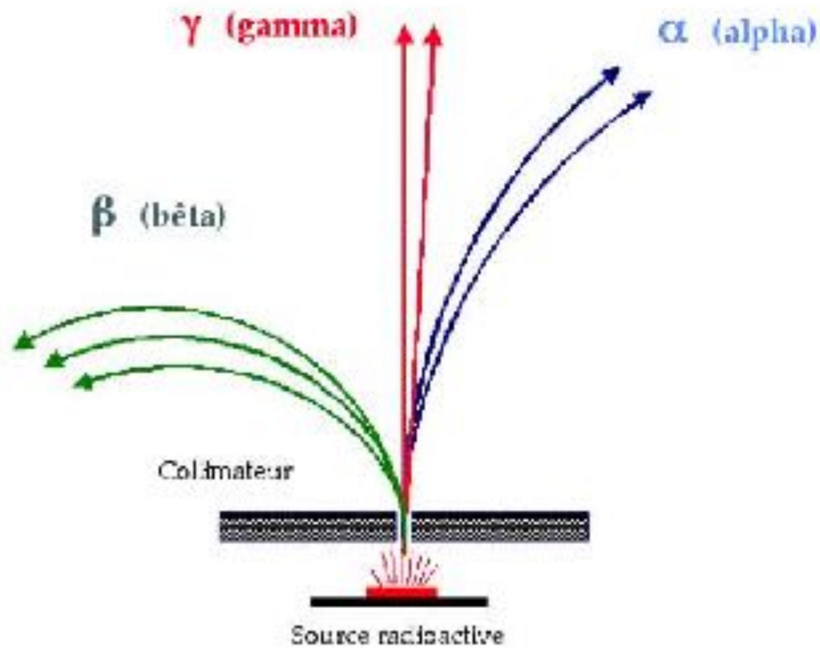
1. Some History

1902 Pierre and Marie Curie discover beta rays are electrons



- This diagram, copied from an original by Marie Curie, shows the effect a magnetic field can have on different types of radiation. Magnetic fields curve the trajectory of particles carrying an electric charge. Alpha rays, curving to the right, are positively charged, the beta rays curving to the left are negatively charged, and the unaffected gamma rays are electrically neutral. Years later, after 1932, beta particles were observed being curved to the right – this would herald the discovery of the positron, and beta-positive radiation.

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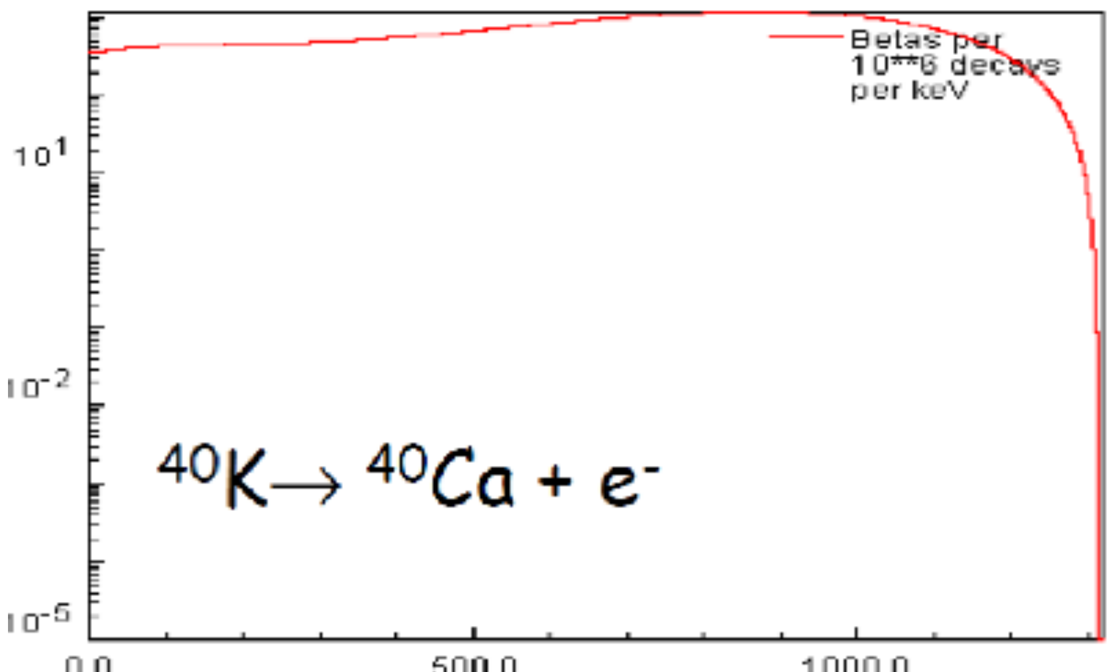
1. Some History

1914 Lise Maitner, Otto Hahn and James Chadwick measure the energy spectra of β-rays

Lise Maitner

Otto Hahn

James Chadwick



Energy in KeV

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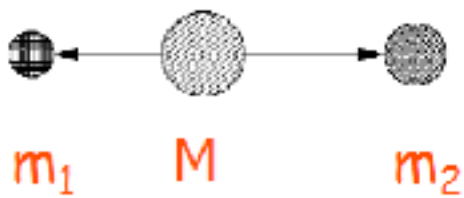
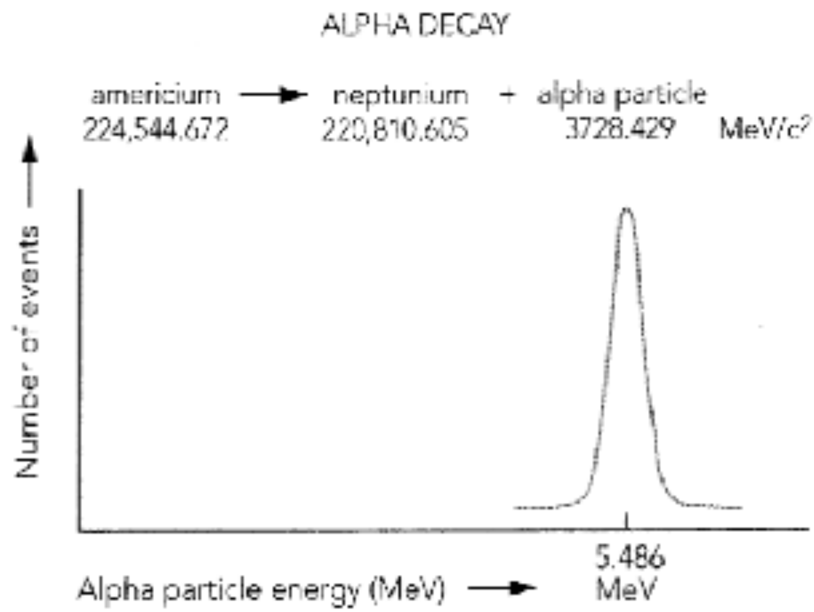
1. Some History

- Early Puzzle – Two Body Decay at rest



Energy-momentum conservation =>

$$E_2 = \sqrt{m_2^2 + p^2} = \frac{M^2 + m_2^2 - m_1^2}{2M}$$



- Energy of final products is unique within measuring errors

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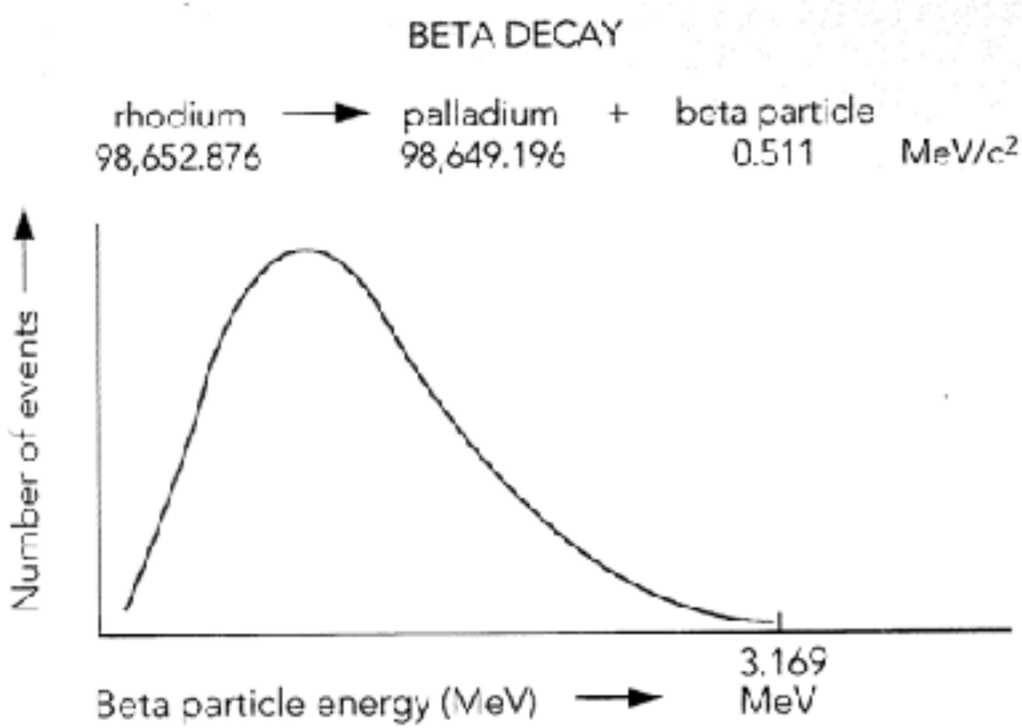
1. Some History

- During the period 1913 – 1930
- β beta decay spectrum was a big problem (puzzle).



- Continuous spectrum was observed for final state β spectrum

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Some History

- Physicists were divided !!!
  - Neils Bohr and others were willing to abandon the law of conservation of energy

Neils Bohr

  - Albert Einstein was a firm protectors of the law

Albert Einstein

1927: C.D.Ellis et W.A.Woobster 1930: L. Meitner et W. Orthman

calorimetric measurements in agreement with e^- spectra

$\rightarrow$ no γ ray emission

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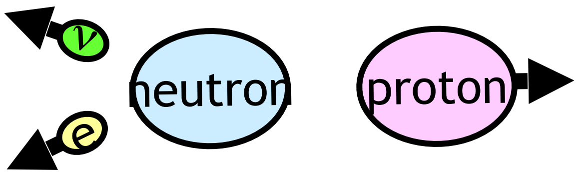
Wolfgang Pauli proposes a solution



Wolfgang Pauli

December 4, 1930

“Dear radioactive ladies and gentlemen,

...I have hit upon a ‘desperate remedy’ to save...the law of conservation of energy. Namely the possibility that there exists in the nuclei electrically neutral particles, that I call neutrons...I agree that my remedy could seem incredible...but only the one who dare can win...

Unfortunately I cannot appear in person, since I am indispensable at a ball here in Zurich.

Your humble servant
W. Pauli”

Note: this was before the discovery of the real neutron

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1. Some History

- 1930 Pauli's idea was that beta decay is really the **3 – body** decay:

Nucleus(i) → *Nucleus(f)* + *Electron* + ***"Neutron"***

The "neutron" carries away some of the energy released in the decay. The amount it takes away can vary. Also, angular momentum can now be conserved.

Inventing a new particle was not an accepted idea at that time

Sir Arthur Eddington said …

„In an ordinary way I might say that I do not believe in neutrinos. Dare I say that experimental physicists will not have sufficient ingenuity to make neutrinos."

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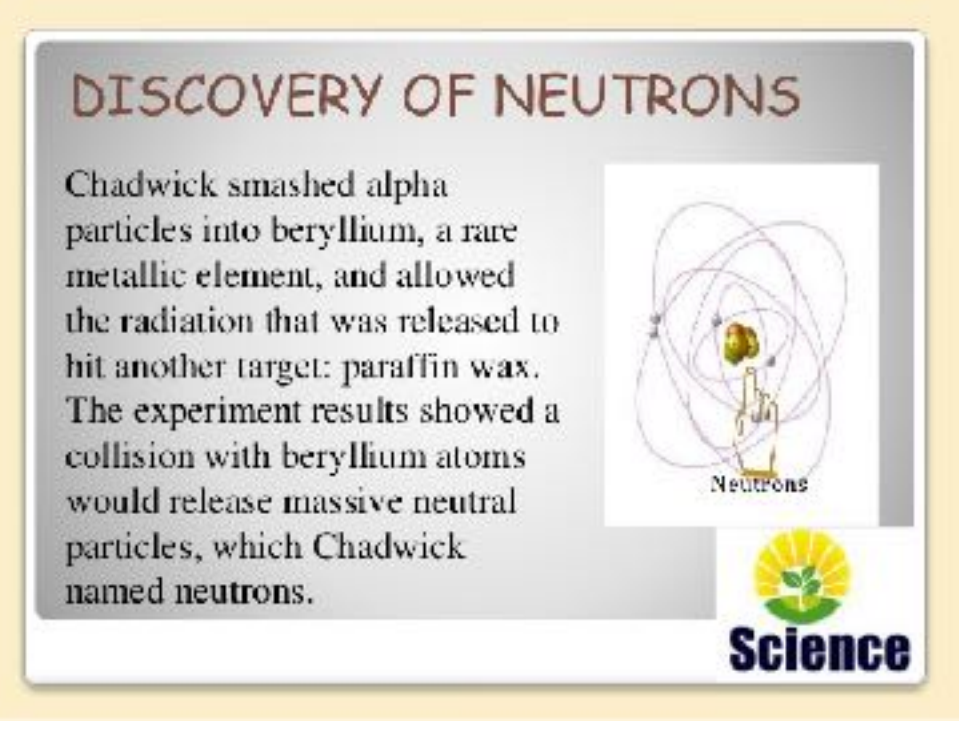
1. Some History

- **1932 – James Chadwick**

recognized existence of massive neutral particles which he called **h**
(Nobel prize in physics in 1935)

  - The atomic mass of an element is mainly determined by the total number of protons and neutrons in the nucleus
  - The atomic number of an element is determined by the total number of protons in the nucleus

James Chadwick



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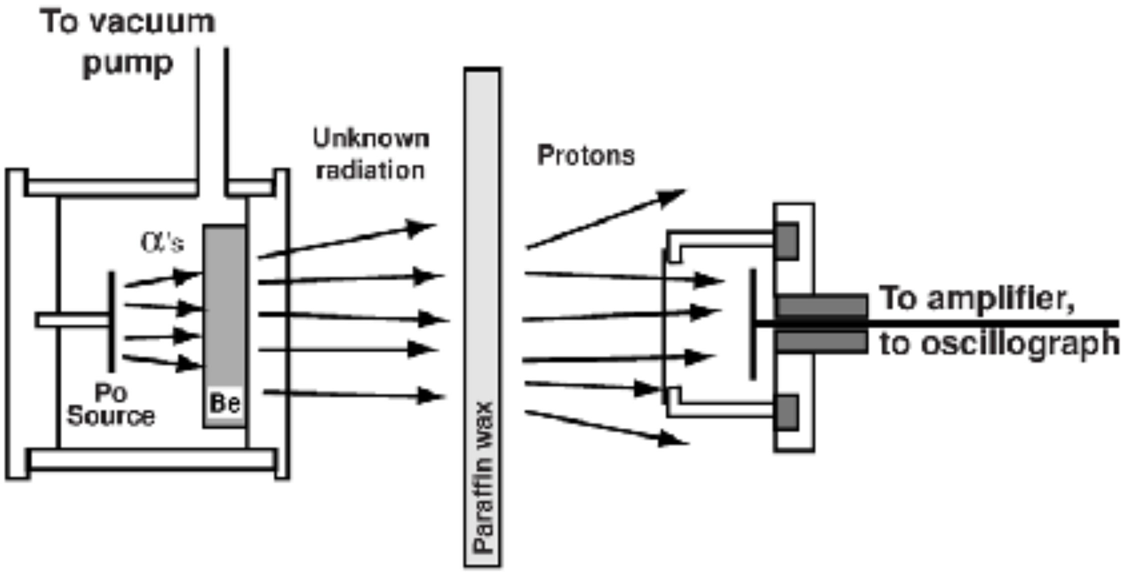
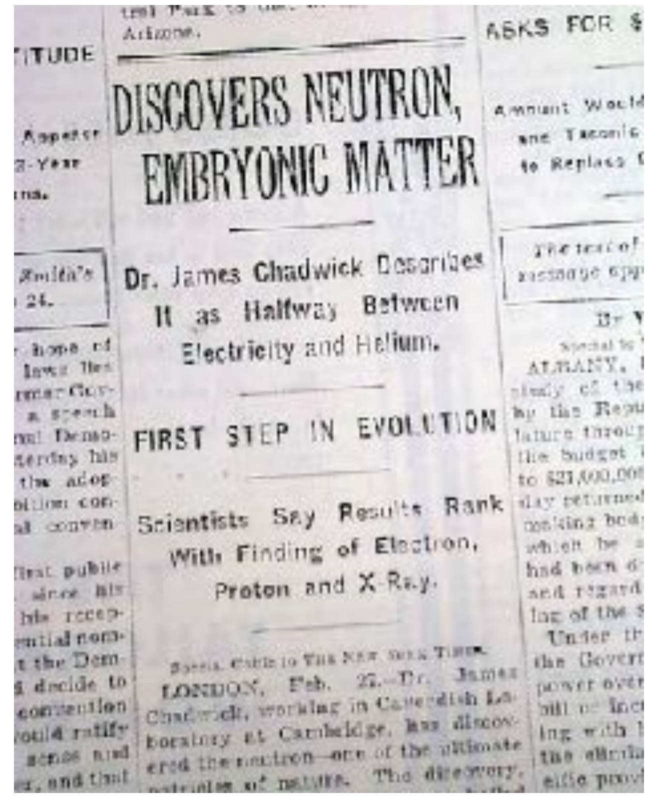
Chadwick Discovers the Neutron





DISCOVERS NEUTRON, EMBRYONIC MATTER

Dr. James Chadwick Describes It as Halfway Between Electricity and Helium.

FIRST STEP IN EVOLUTION

Scientists Say Results Rank With Finding of Electron, Proton and X-Ray.

LONDON, Feb. 27.—Dr. James Chadwick, working in Cavendish Laboratory at Cambridge, has discovered the neutron—one of the ultimate particles of nature. The discovery,

At left, a polonium source was used to irradiate beryllium with alpha particles, which induced an uncharged radiation. When this radiation struck paraffin wax, protons were ejected. The protons were observed using a small ionization chamber.

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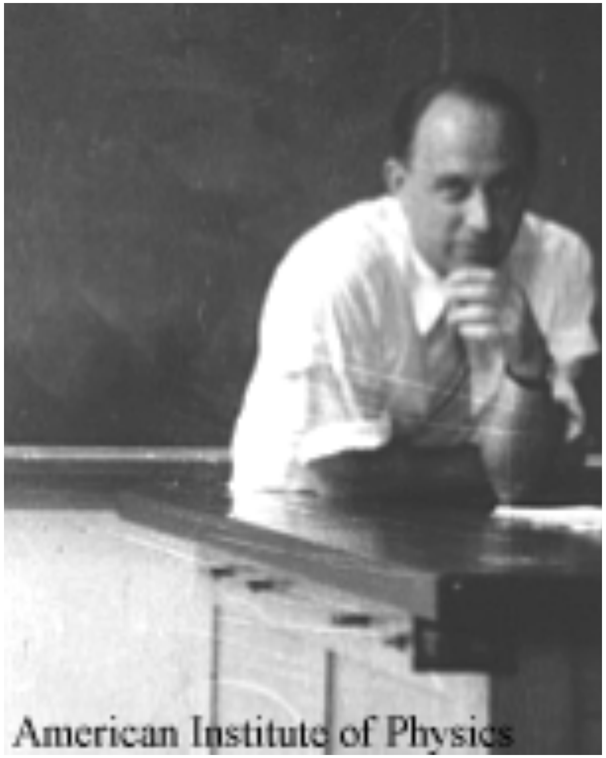
1. Some History

- **1933 Fermi's β-decay Model**
  - He accepted Pauli's "invisible" particle, renamed it ***"neutrino***" to distinguish from Chadwick's neutron
  - Proposed all β-decays were due to the same underlying process

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

  - The neutrino was treated as a ½ spin particle (conservation of angular momentum -→ neutrino is a fermion) and obeys Dirac equation.
  - Fermi developed formalism parallel to Dirac's equation for e/m interaction except intermediate propagator is G_F



Enrico Fermi

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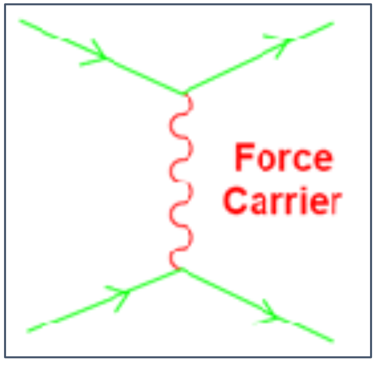
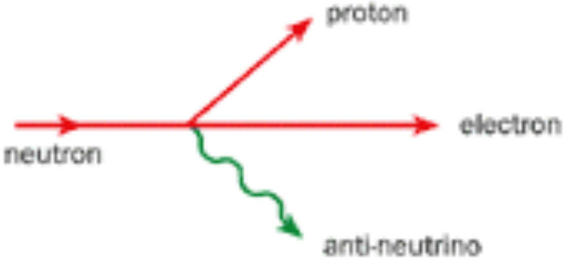
1. Some History

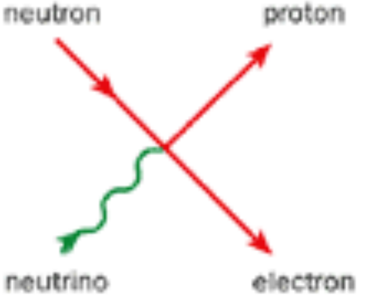
Theories of Forces

- Modern force description is quantum field theory…
  - often illustrated w/ its lowest order perturbative expansion…
- First theory of weak interactions (Fermi theory of beta decay, 1933)

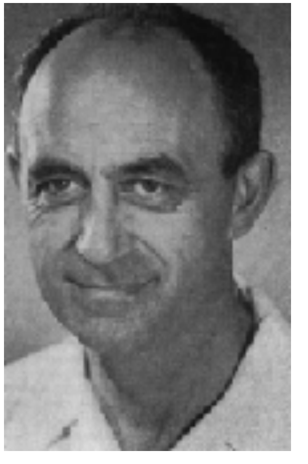




Neutron Beta Decay



Neutrino-Neutron "Quasi Elastic" Scattering



Enrico Fermi

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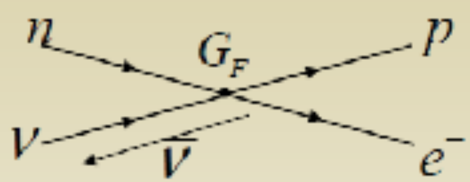
1. Some History

1933 Enrico Fermi develops the β-decay theory and names the "neutrino"

James Chadwick had discovered the neutral nucleon, the neutron, in 1932

Local 4-fermions current-current interaction based on the 4-spinor Dirac description of Fermions



$$H_{weak} \div G_F J^B_\mu J^{L\mu}$$

with $J^B_\mu = \bar{\psi}_p \; \gamma_\mu \; \psi_n$ baryonic (charged) current

$J^{L\mu} = \bar{\psi}_e \; \gamma^\mu \; \psi_\nu$ leptonic (charged) current

$$G_F \approx \frac{10^{-5}}{M_p^2} \approx 1.1 \cdot 10^{5} \; GeV^{2}$$ Fermi coupling constant

Note : the concept of current will be introduced in 1958 by Feynman and Gell-Mann

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1. Some History

Fermi Concluded

1) The difference in lifetimes of various elements was basically due to differences in phase space available for the final state electron and neutrino (proton balances the momenta of electron and neutrino and does not contribute to the available phase space).
2) The spectra of electrons were easily calculable from plain phase space considerations
3) The value of the constant $\mathbf{G_F = 1.166 \times 10^{-5}\ GeV^{-2}}$
4) elusiveness of neutrino detection: $\bar{\nu} + p \rightarrow n + e^+$

calculation showed right away why neutrinos were "invisible"

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} p_{cm}^2$$

$$\sigma = \frac{G^2}{\pi} p_{cm}^2$$

==> show that the energy threshold E_0 is 1.80 MeV (lab frame)

==> show that positrons momentum p_{cm}

equals to energy of an antineutrino above threshold ΔE (lab frame)

(assuming that antineutrino energy is << 1 GeV)

$\sim 10^{-48}\ \text{m}^2$ (at $\Delta E = 1$ MeV)

→ NEVERTHELESS, discovered by Cowan and Reines in 1956

1. Some History

5) Other β-decay related processes were possible and calculable:
   - β^+-decay: $p \rightarrow n + e^+ + \nu$

     possible in certain nuclei only (proton is lighter than neutron), e.g., $^{30}P \rightarrow {}^{30}Si + e^+ + \nu$

     → discovered by Joliot and Curie in 1933
   - K-capture: $p + e^- \rightarrow n + \nu$

     possible in certain nuclei only (proton and electron masses do not add up to neutron's mass)

     → to be discovered by Luis Alvarez in 1938
   - Relate the neutron β-decays to the muon decays and correctly describe muon lifetime…

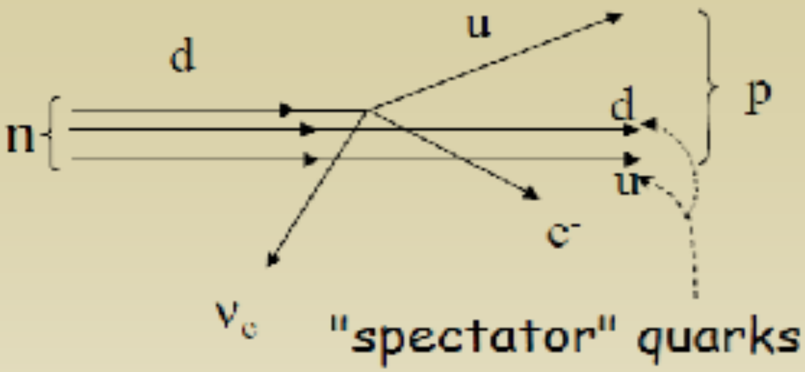
     → to be discovered later…

Note: Fermi's paper was rejected by *Nature* on the grounds of being "too speculative". The paper was later published in scientific journals in Italy and Germany. Meanwhile, Fermi went to do experiments and the same year discovered an artificial radioactivity induced by bombardment of nuclei with neutrons. In 1938 he was awarded the Nobel Prize "for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons".

Frontiers 8

Some History

Modern quark version



$$H_{weak} = G_F J^Q_\mu J^{L\mu}$$

with $J^Q_\mu = \bar{\psi}_u \ \gamma_\mu \ \psi_d$

$J^{L\mu} = \bar{\psi}_e \ \gamma^\mu \ \psi_\nu$

1933 : Hans Bethe and Rudolf Peierls

$$\sigma_{\nu N} \approx 10^{-10} \sigma_{eN}$$

The beginning of a 23 year quest

Fermi: "I offer a case of champagne to whom will detect the first neutrino"

Frontiers 8

1. Some History

The Challenge of Detecting Neutrinos

- Making Neutrinos by β-decay ? e.g. **neutron decay**:

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

- Necessity of neutrino existence comes from the apparent energy and angular momentum non-conservation in observed reactions

- For the sake of lepton number conservation, electron must be accompanied by an anti-neutrino and not a neutrino!

- Mass limit for ν $\bar{\nu}_e$ can be estimated from the precise measurements of the β-decay: $m_e \leq E_e \leq \Delta M_N - m_{\bar{\nu}_e}$

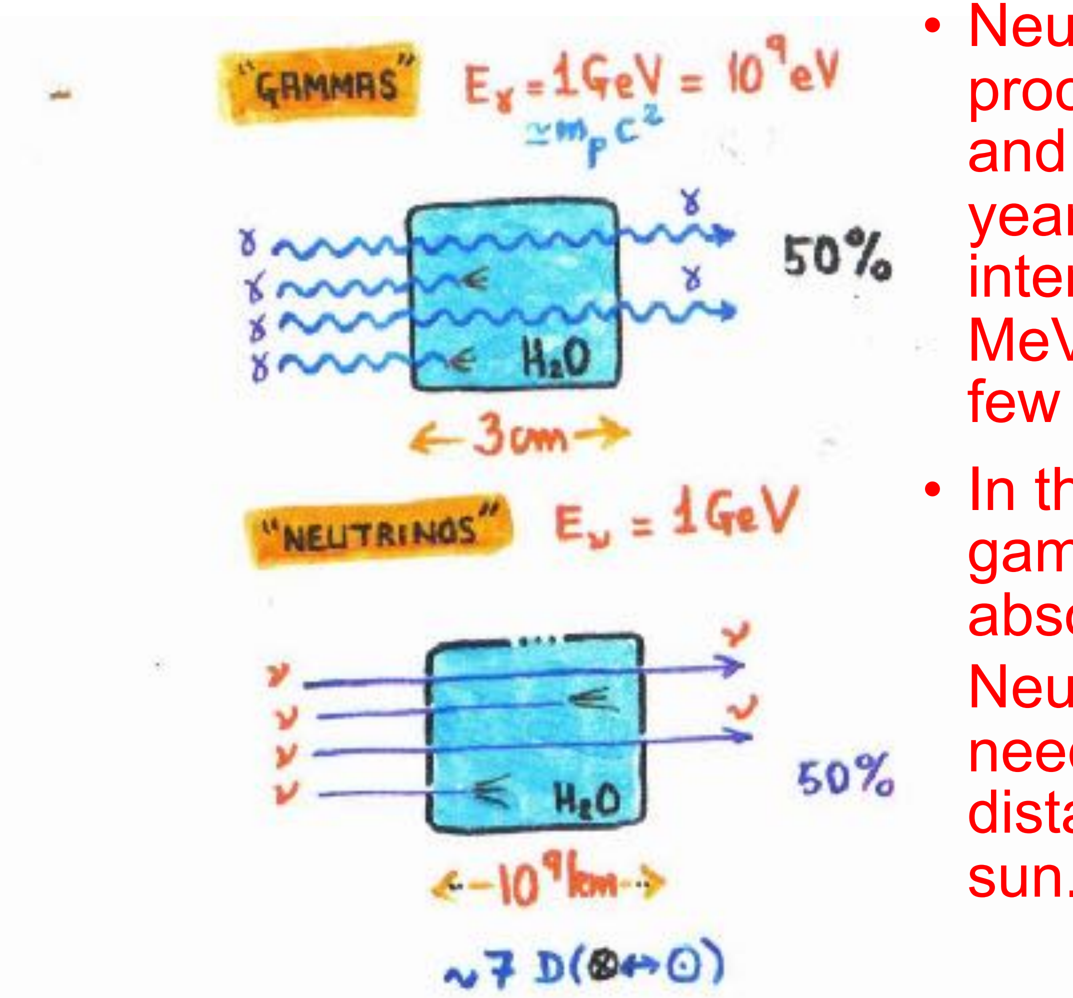
- Best results are obtained from tritium decay

$$^3H \longrightarrow {}^3He + e^- + \bar{\nu}_e$$

- it gives $m_{\bar{\nu}_e} \leq 2 \ \ eV/c^2$ (~ zero mass)

1. Some History

The Challenge of Detecting Neutrinos

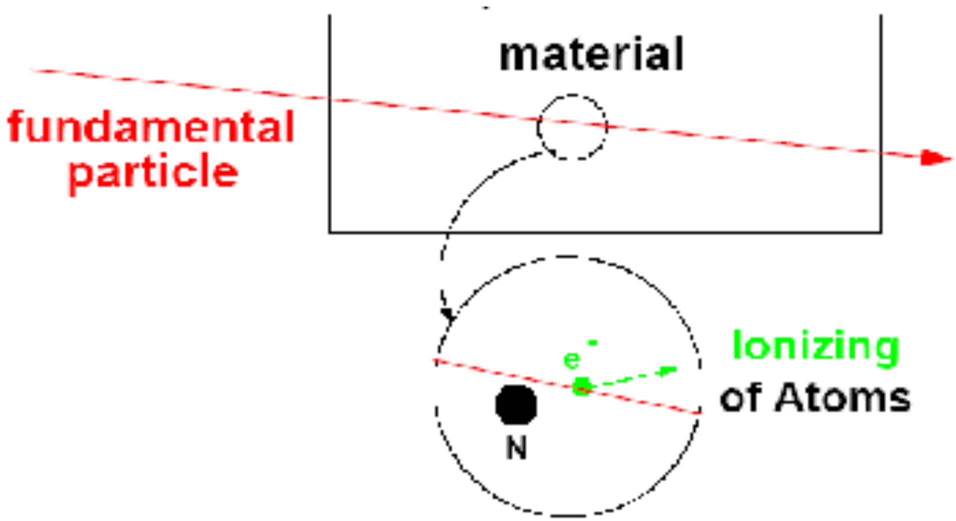


- Neutrinos from the fusion process in the sun are ~3 MeV and travel typically ~53 light-years in water before interacting. By comparison, a 3 MeV electron will travel only a few centimeters.
- In the sketch, for 1 GeV gamma rays, ~ 50% are absorbed in 3 cm of H_2O. For Neutrinos, the water pool would need to be seven times the distance from the earth to the sun.

Frontiers 8

1. Some History

- How can we detect neutrinos or any fundamental particle?
- Electromagnetic interactions in material kick electrons away from atoms where we can detect their deflection and the ionization.



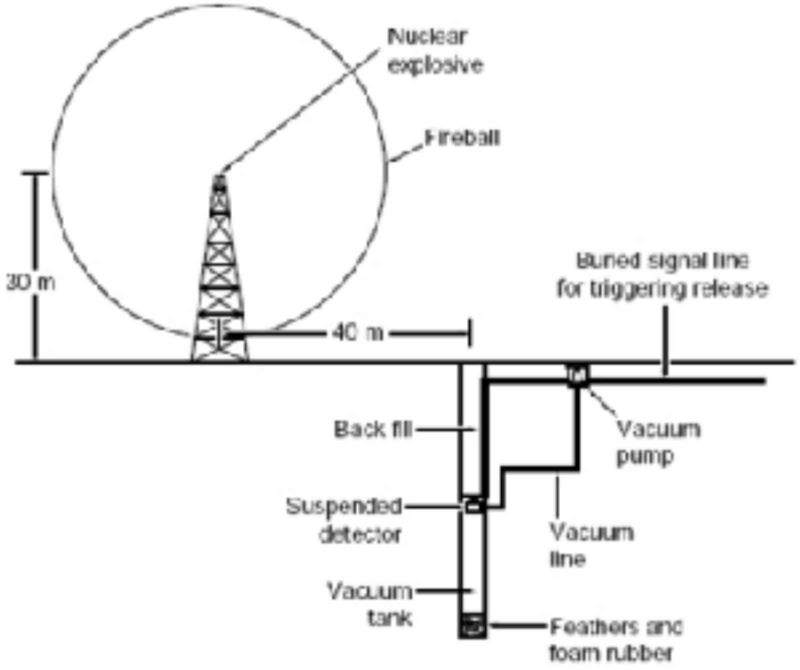
- Neutrinos do not have an electric charge and they only interact weakly, and we can only detect the by-products of their weak interactions

Frontiers 8

1. Some History

- The challenge : How to detect (discover) neutrinos???
- Clyde Cowan, Jr. and Frederick Reines, then at Los Alamos, conceived a plan to detect the neutrino experimentally. Their idea was to use the immense flux of neutrinos produced by H-bomb tests, and they even designed an apparatus that might have been capable of getting close enough to the test site to detect neutrinos, and yet be sufficiently well shielded from the other effects of the blast that it would remain intact.
- However, they were dissuaded from this slightly loony scheme by the suggestion of Los Alamos physics division head J. M. B. Kellogg, that they should use a nuclear reactor instead. Nuclear reactors were then in their early stages of commercial development, so this was not as obvious an idea as it might seem now.
- Cowan and Reines first conducted their experiment at the Hanford Site in Washington State, where they obtained some preliminary results. The definitive experiment, however, was conducted in early 1956 at P Reactor at the Savannah River Plant near Aiken, South Carolina, where they had better shielding against cosmic rays.
- *(from APS History Site)*

Reines and Cowan 1951



I. Explode bomb
II. At same time let detector fall in vacuum tank
III. Detect neutrinos
IV. Collect Nobel prize

OK – but repeatability is a bit of a problem

1. Some History

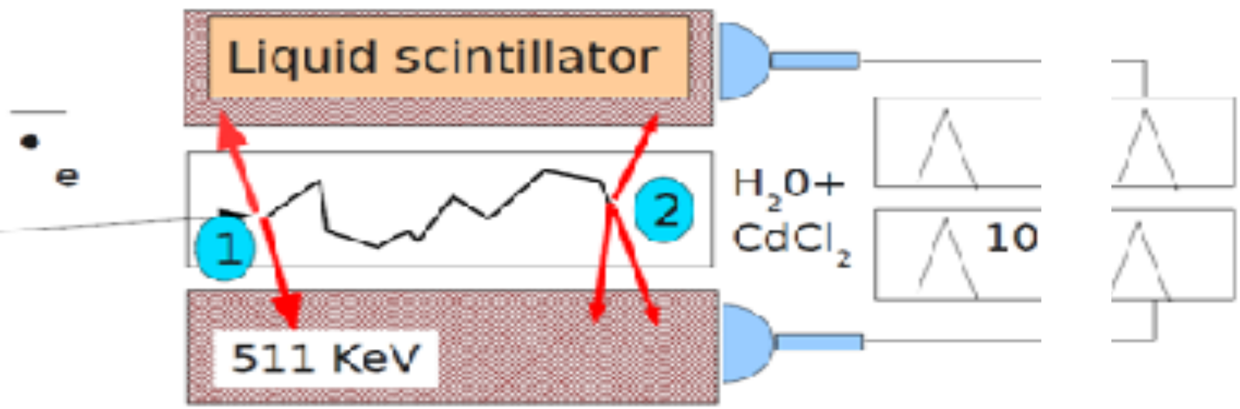
Idea Number 2 - 1956

A nuclear reactor is the next best thing

Fission of U^{235} produces a chain of • decay

Reactor on – Reactor off = 2.88 +/- 0.22 hr^{-1}
• = (11 +/- 2.6) x 10^{-44} cm^2
• (Pred) = (5 +/- 1) x 10^{-44} cm^2

Savannah River
(sort of)



•‾$_e$ +p • e^+ + n
2. Neutron capture
on Cd

From Zuber

Frontiers 8

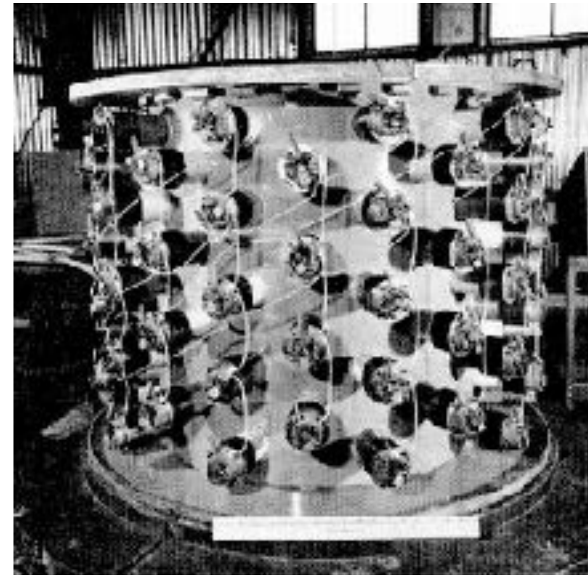
1. Some History

Project Poltergeist 1956

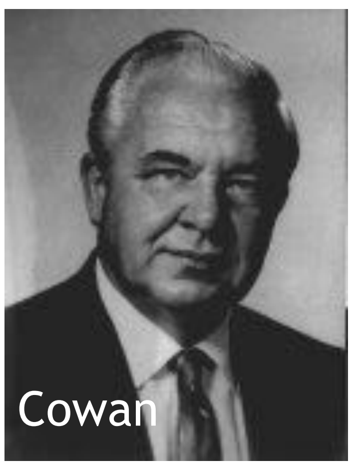
$$\nu + p^+ \rightarrow n^o + e^+$$

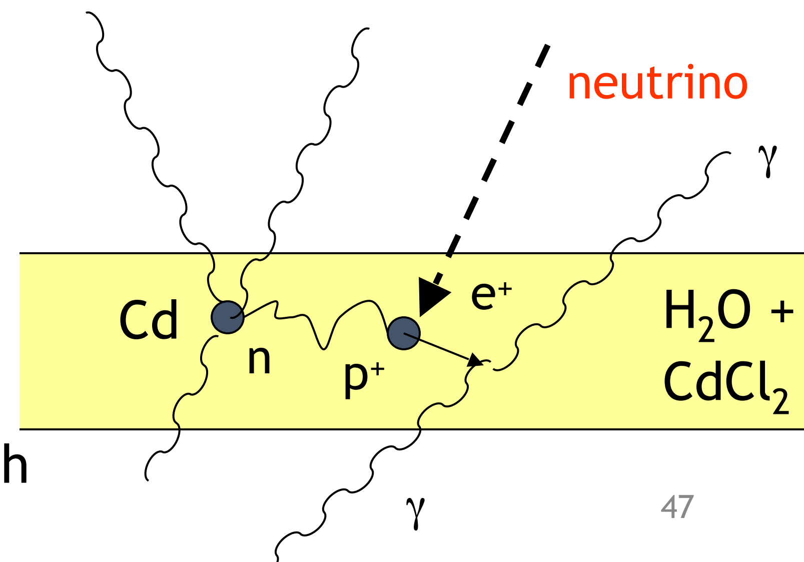
$$e^+ + e^- \rightarrow 2\gamma$$

$$n^o + \mathrm{Cd} \rightarrow (\mathrm{several})\gamma$$



Signal 2γ, then several γ ~few μs later





Experiment attempted at Hanford in 1953, too much background. Repeated at Savannah River in 1955. [Flux: 10^{13} neutrinos/(cm^2 s)]

Frontiers 8

1. Some History

- **β-decay**

$$n \to p + e^- + \bar{\nu}_e$$

•Also, **Inverse β-decay** takes place:

$$\nu_e + n \to e^- + p$$
$$or$$
$$\bar{\nu}_e + p \to e^+ + n$$

•The probability of these processes is very low. Therefore need a very intense flux of neutrinos

Reines and Cowan experiment (1956)

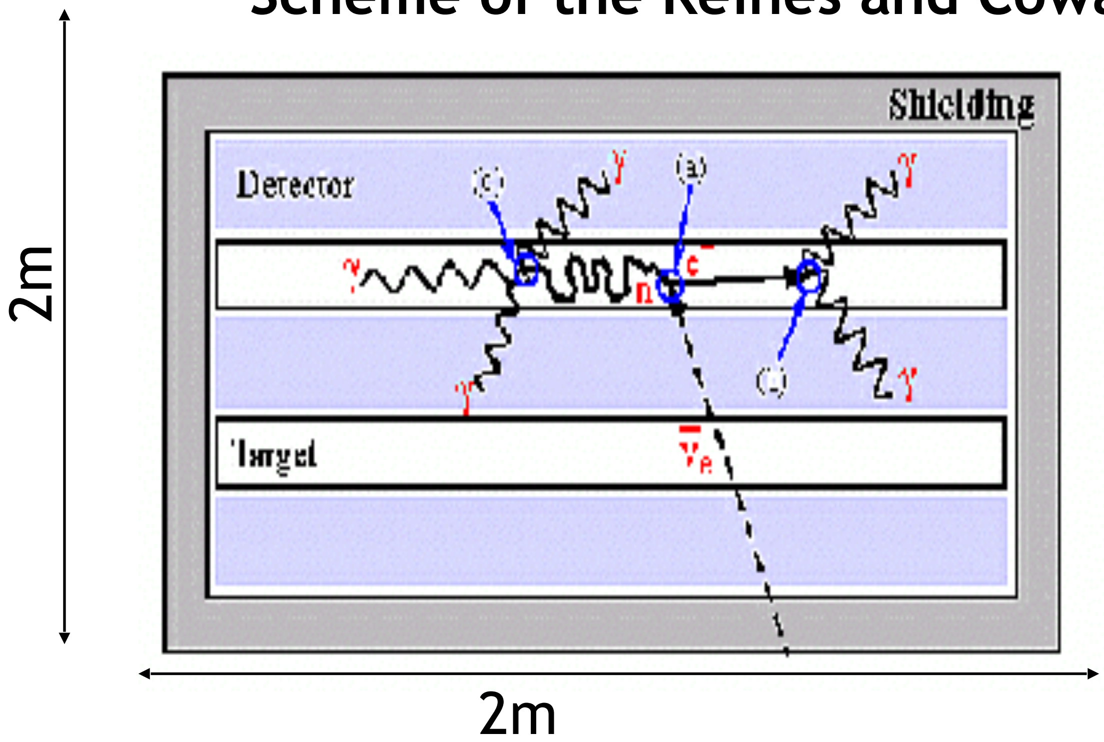
o Using antineutrinos produced in a nuclear reactor, possible to obtain around 2 evts/h

o Acqueous solution of $CdCl_2$ (200 l + 40 kg) used as target (Cd used to capture n)

o To separate the signal from background, “delayed coincidence” used: signal from neutron appears later than from electron

Frontiers 8

Scheme of the Reines and Cowan experiment



(a) Antineutrino interacts with p, producing n and e^+

(b) Positron annihilates with an atomic electron produces fast photon which give rise to softer photon through Compton effect

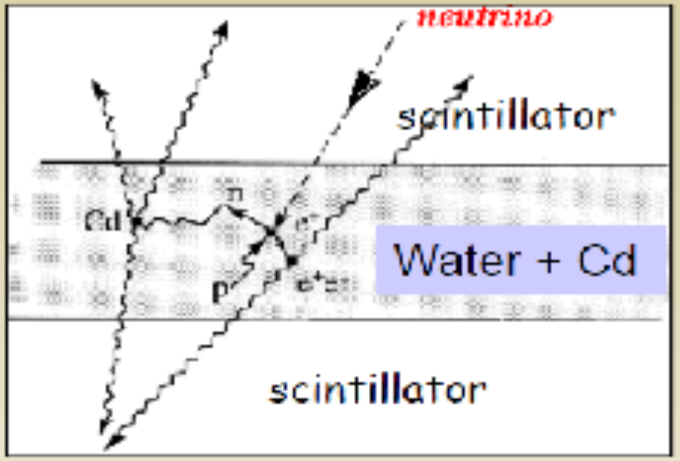
(c) Neutron captured by a Cd nucleus, releasing more photons

Frontiers 8

1. *Some History*

At the Savannah River nuclear power plant

Neutrino flux ~ 10^{13} /cm^2 s



"$\bar{\nu}$" + p → e^+ + n

Typical signal :

- prompt 2-γ coincidence from e^+ annhilation on e^-
- delayed γ's from n capture by neutrophage nuclei (Cadmium)

Results:

Run time	Reactor	Counting rate
900 hr	ON	~ 1 /hr
250 hr	OFF	0.25 /hr

Frontiers 8

Helicity states

For a massless fermion of positive energy, E = |p|

$$\frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}\chi = -\chi$$

helicity

$$H = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} = -1$$

H measures the sign of the component of the particle spin, in the direction of motion: $j_z = \pm 1/2$

H=+1 $\rightarrow$ right-handed (RH) H=-1 $\rightarrow$ left handed (LH)

$E\chi = -\vec{\sigma}\cdot\vec{p}\chi$ $\longrightarrow$ χ is a LH particle or a RH anti-particle

- Helicity is a Lorentz invariant for massless particles
- If extremely relativistic, also massive fermions can be described by Weyl equations

Anti-neutrino's

Nobel prize 2002

(Davis, Koshiba and Giacconi)

- Davis & Harmer
  - If the neutrino is same particle as anti-neutrino then close to power plant:

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

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

$$\nu_e + {}^{37}_{17}\mathrm{Cl} \rightarrow e^- + {}^{37}_{18}\mathrm{Ar}$$

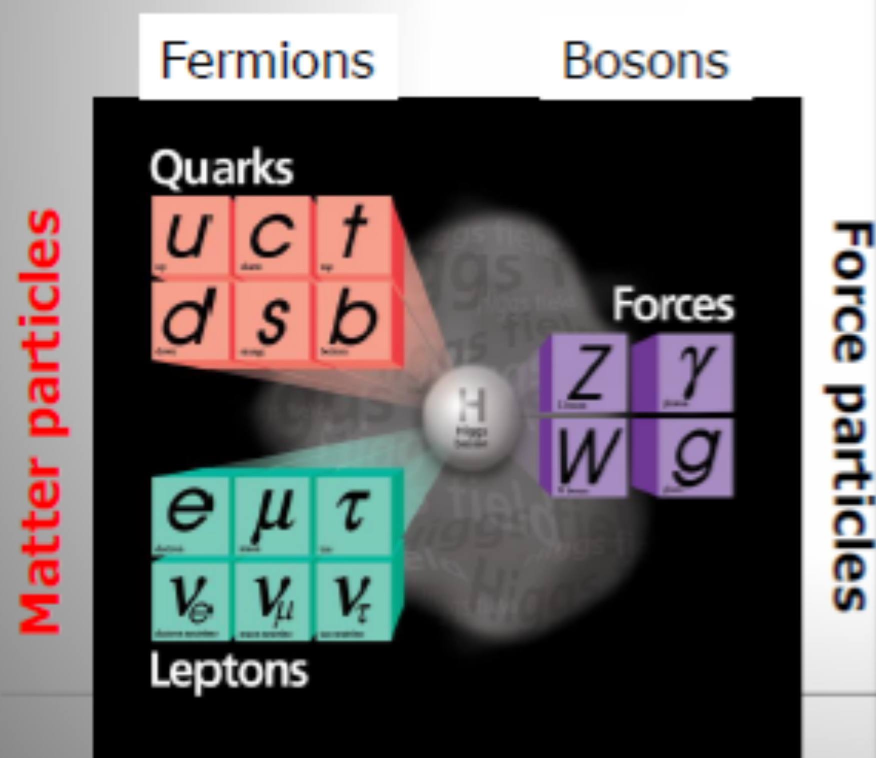
-615 tons kitchen cleaning liquid
-Typically one ^{37}Cl → ^{37}Ar per day
-Chemically isolate ^{37}Ar
-Count radio-active ^{37}Ar decay

- Reaction not observed:
  - Neutrino-anti neutrino not the same particle
  - Little bit of ^{37}Ar observed: neutrino's from cosmic origin (sun?)
  - Rumor spread in Dubna that reaction did occur: Pontecorvo hypothesis of neutrino oscillation

- Break

Frontiers 8

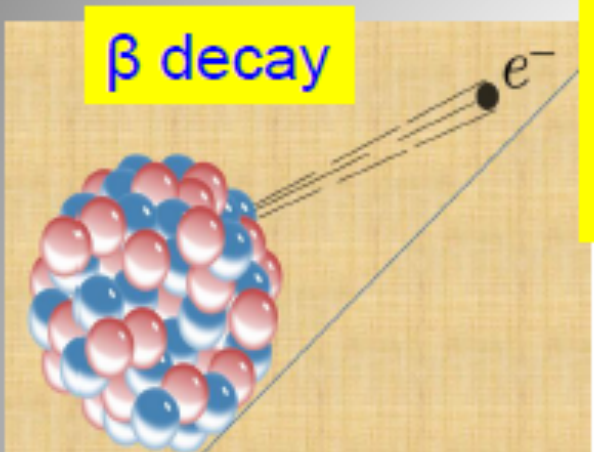
Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements:



Neutrinos are leptons that do not feel the strong force (no color) or the electromagnetic force (no charge). They interact only weakly.

In the Standard Model they are massless, move with the speed of light and neutrinos are always left handed (opposite for ant-neutrinos)

Neutrinos are know to us since 1930!



If the process is A -> B + electron, the energy of the electron should be at a fixed value. This is not the case! Energy-momentum not conserved in Beta-decays?

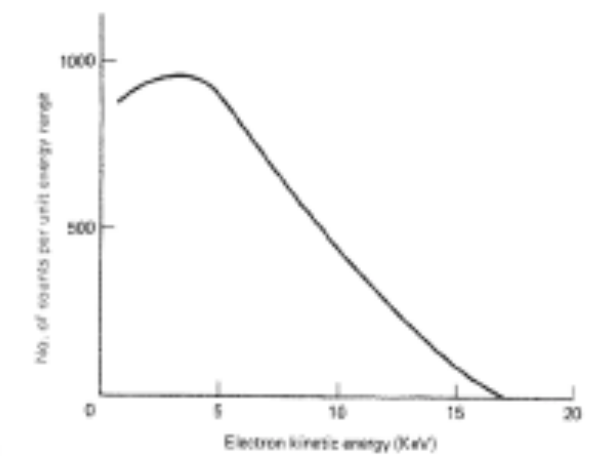


Fig. 1.5 The beta decay spectrum of tritium ($^3_1H \to ^3_2He$). (Source: Lewis, G. M. (1970) Neutrinos, Wykeham, London, p. 30.)

Pauli proposed instead the process:

$$\boxed{n \to p^+ + e^- + \bar{\nu}}$$

...At least in (controversial) theory

Neutrinos are know to us since 1930!

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Pauli Letter Collection, CERN

Pauli did not believe energy-momentum conservation was violated
He proposed a desperate way out: a new 'invisible' particle
He called it the neutron.
He also stayed away from the conference because of a ball in Zurich..

Neutrinos are know to us since 1934!

1934

Enrico Fermi, father of the world's first nuclear reactor, coined the term "neutrino" which is Italian for "little neutral"
The name neutron had meanwhile been claimed for the discovered nucleon partner of the proton

He proposed a theory for Beta-decay including the neutrino, a first formulation of the weak force...

Funny enough his paper got refused by Nature magazine
(criticism: nothing practical in this paper)

The Discovery of the Neutrino

1956: discovery of the neutrino

Savannah river reactor

It took 26 years to detect this particle.
Cowan and Reines put a detector close to the reactor in South Carolina and observed the inverse beta decay process (few events/hour)
Reactors give 10^{19} neutrinos/sec

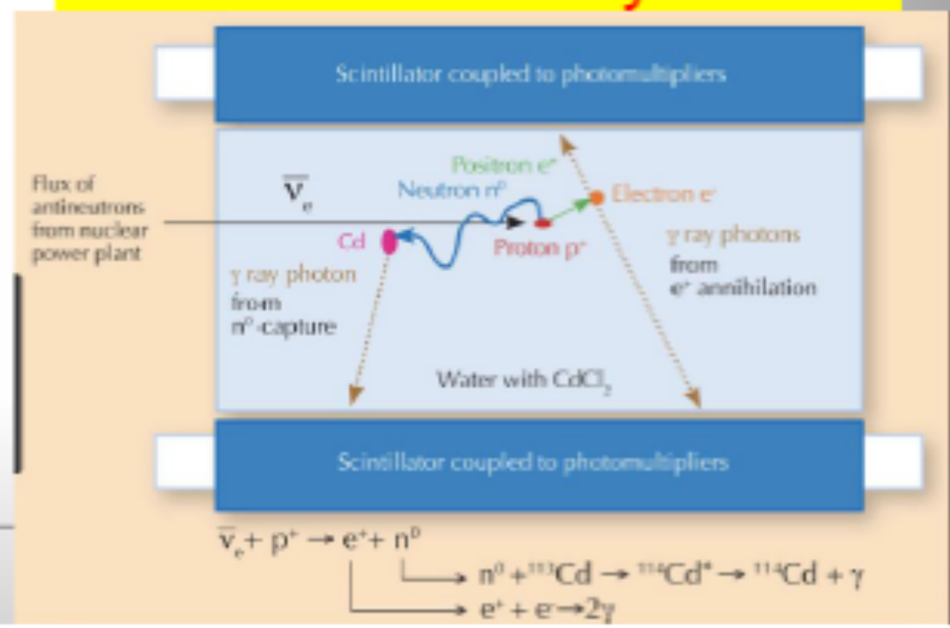
The neutrino really exists!

$$\bar{\nu}_e + p \Rightarrow n + e^+$$

5 μsecond delay

$$e^+ + e^- \Rightarrow \gamma + \gamma$$

n-capture by cadmium



The Discovery of the Neutrino

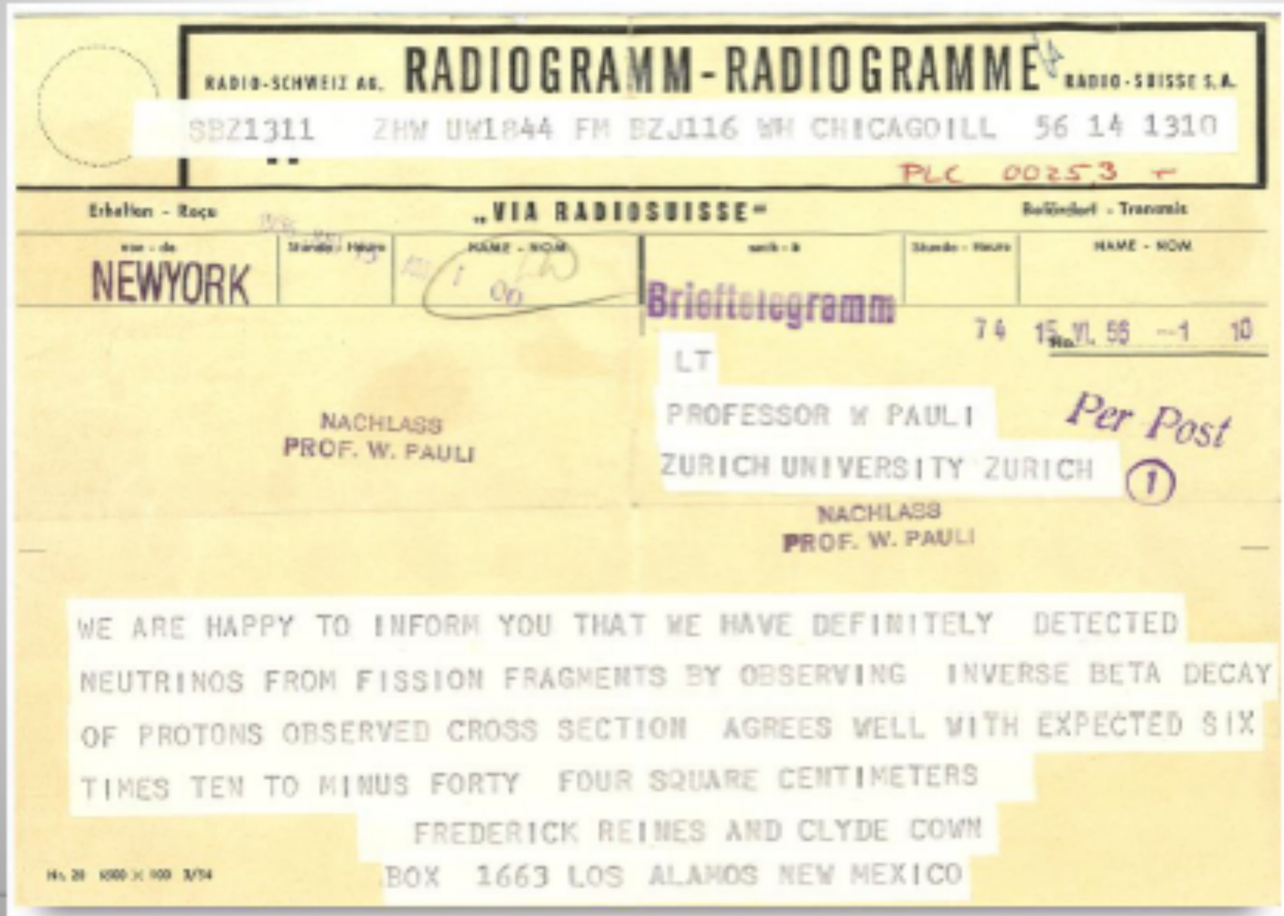
This was however not the first idea of Cowan and Reines.

They had originally proposed (and got approved for) putting an experiment close to an even more intense source of neutrinos nml 100m distance from an atomic blast!

They abandoned that idea when the realized there were certain 'practical problems' for the detector… (to survive)

The Discovery of the Neutrino

1956: the first experimental evidence from project "Poltergeist", informing Wolfgang Pauli..



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

More Neutrino Personalities

1937: Ettore Majorana
He postulated that neutrinos could be their own antiparticles. This special class of particles came to bear his name: Majorana particles

Majorana disappeared in 1938 on a boat trip from Sicily

1957: Bruno Pontecorvo
He hypothesized that neutrinos may oscillate, or change from one type to another and would go on to develop that theory over the years as more flavors were discovered.
He also predicted that supernovae, the giant explosion of a dying star, would release an enormous amount of energy in the form of neutrinos

Pontecorvo disappeared … to the east block in 1950

Frontiers 8

- Remember that the particle produced in β-decay is the antineutrino, not the neutrino.

$$n \to p + e^- + \bar{\nu}_e$$

- What is the difference between the neutrino and the antineutrino? Recall that the photon is its own antiparticle and the neutral pion is also its own antiparticle. On the other hand, the neutron is not its own antiparticle! What about the neutrino and antineutrino.
- Reines and Cowan detected

$$\nu_e + n \to e^- + p$$

$$or$$

$$\bar{\nu}_e + p \to e^+ + n$$

- Davis and Hammer looked for the analogous reaction for antineutrinos. $\bar{\nu}_e + n \to e^- + p$
- He did not observe and concluded the neutrino and antineutrino are distinct particles. LEPTON NUMBER

Frontiers 8

Lepton Number Conservation

• Anti-leptons are positron e+, positive muons and tauons and anti-neutrinos

$$\begin{pmatrix} e^{+} \\ \bar{\nu}_e \end{pmatrix} \quad \begin{pmatrix} \mu^{+} \\ \bar{\nu}_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^{+} \\ \bar{\nu}_\tau \end{pmatrix}$$

- Neutrinos and anti-neutrinos differ by the lepton number.
  For leptons $L_\alpha = 1$ ($\alpha = e, \mu$ or τ)
  For anti-leptons $L_\alpha = -1$

- **Lepton numbers are conserved in any reaction**

•So, what distinguishes neutrinos from antineutrinos? Best answer is Lepton Number. -1 for neutrinos and +1 for antineutrinos. (They also differ in Helicity or spin)

Frontiers 8

Another Puzzle as the story of the neutrino unfolds?

The reaction $\mu^- \neq e^- + \gamma$ **is never observed !!**

Lepton	*lepton – number*	*electron – number*	*muon – number*
e^-	1	1	0
ν_e	1	1	0
μ	1	0	1
ν_μ	1	0	1

Consequence of the lepton number conservation:
some processes are **not allowed**.....

$\nu_e + n \rightarrow p + e^-$	*Yes*
$\bar{\nu}_e + n \rightarrow p + e^-$	*No*
$\mu^- \rightarrow e^- + \gamma$	*No*
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$	*Yes*
$\bar{\nu}_\mu + p \rightarrow e^+ + n$	*No*

} Lederman, Schwartz, Steinberger

Frontiers 8

Two Neutrino Hypothesis

- Feynman declared that whatever is not expressly **forbidden** is **mandatory.**

- The absence of $\mu \rightarrow e + \gamma$ suggests conservation of mu-ness; BUT, then how can we explain observation of $\mu \rightarrow e + \nu + \_$
ν ?

- This problem led to several papers in the 1950s and 1960s proposing that there are two different kinds of neutrinos, one associated with the electron ν_e and one with the muon ν_μ

- If we define **muon number** L_μ = +1 to the μ^- and ν_μ
  and L_μ = -1 to the μ^+ and $\bar{\nu}_\mu$
- and define **electron number** L_e = +1 to the e^- and ν_e
  and L_e = -1 to the e^+ and ν_e

Change the conservation of Lepton number rule to conservation of electron number and conservation of muon number, we account for all the allowed and forbidden process

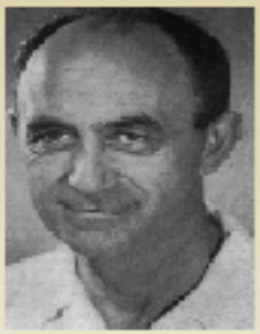
Frontiers 8

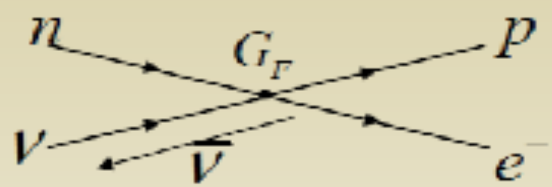
What is this four fermion weak interaction theory?

1933 Enrico Fermi develops the β-decay theory and names the "neutrino"

James Chadwick had discovered the neutral nucleon, the neutron, in 1932

Local 4-fermions current-current interaction based on the 4-spinor Dirac description of Fermions





$$H_{weak} \div G_F J^B_\mu J^{L\mu}$$

with $J^B_\mu = \bar{\psi}_p \; \gamma_\mu \; \psi_n$ baryonic (charged) current

$J^{L\mu} = \bar{\psi}_e \; \gamma^\mu \; \psi_\nu$ leptonic (charged) current

$G_F \approx \dfrac{10^{-5}}{M_p^2} \approx 1.1 \cdot 10^{-5} \; GeV^{-2}$ Fermi coupling constant

Note : the concept of current will be introduced in 1958 by Feynman and Gell-Mann

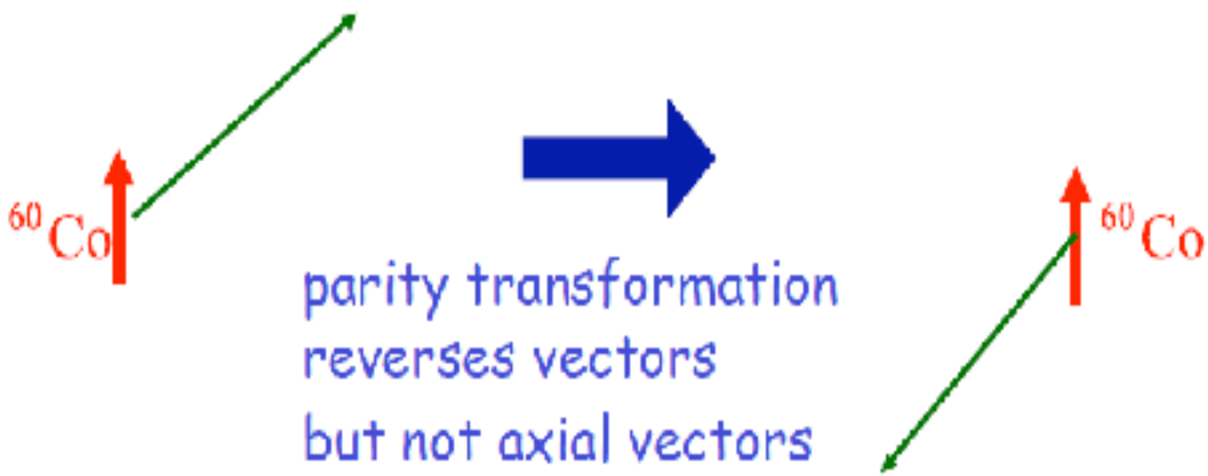
Frontiers 8

Parity Conservation?

Let's consider: $^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni}^{*} + e^{-} + \bar{\nu}_e$

and assume that cobalt nuclei are polarized
(by magnetic field at low temperatures)

If all laws of physics are symmetrical
under parity transformation then:



So **IF** parity
is conserved
then probab to
emit electrons
forward and
backward
should be equal

Frontiers 8

The τ-θ puzzle

The two particles were similar - their masses agreed within several MeV, and their lifetimes were roughly equal.
Thus they appeared to be related (the same particle?)

$\tau^+ \rightarrow \pi^+ \pi^+ \pi^-$

$\theta^+ \rightarrow \pi^+ \pi^0$

However, the decay products of the τ^+ have a parity of $(-1)(-1)^J$, while those of the θ^+ have a parity of $(-1)^J$, where J is the spin of the original K meson.

Thus, either τ^+ and θ^+ have opposite parity (and thus are different particles) or parity is not conserved in this decay.

Richard Dalitz - ***"I found myself unable to withstand the local pressures against any hypothesis of parity nonconservation. The argument against it was that parity violation was simply inconceivable and it was nonsensical even to mention this possibility."***

-Lee and Yang (1956) suggest that the particles are the same and parity is not conserved.
-Wu et. al. (1957) - Parity nonconservation in beta decay of cobalt nuclei.
Not inconceivable anymore!

τ^+ and θ^+ were then accepted as the same particle, called K^+

Frontiers 8

Parity Violation in the Weak Interactions

Madame Wu and collaborators proved Lee and Yang right

Chien-Shiung Wu Tsung-Dao Lee Chen-Ning Yang

T.D. Lee and Frank Yang solved a "kaon decay puzzle" and predicted weak interactions violated parity

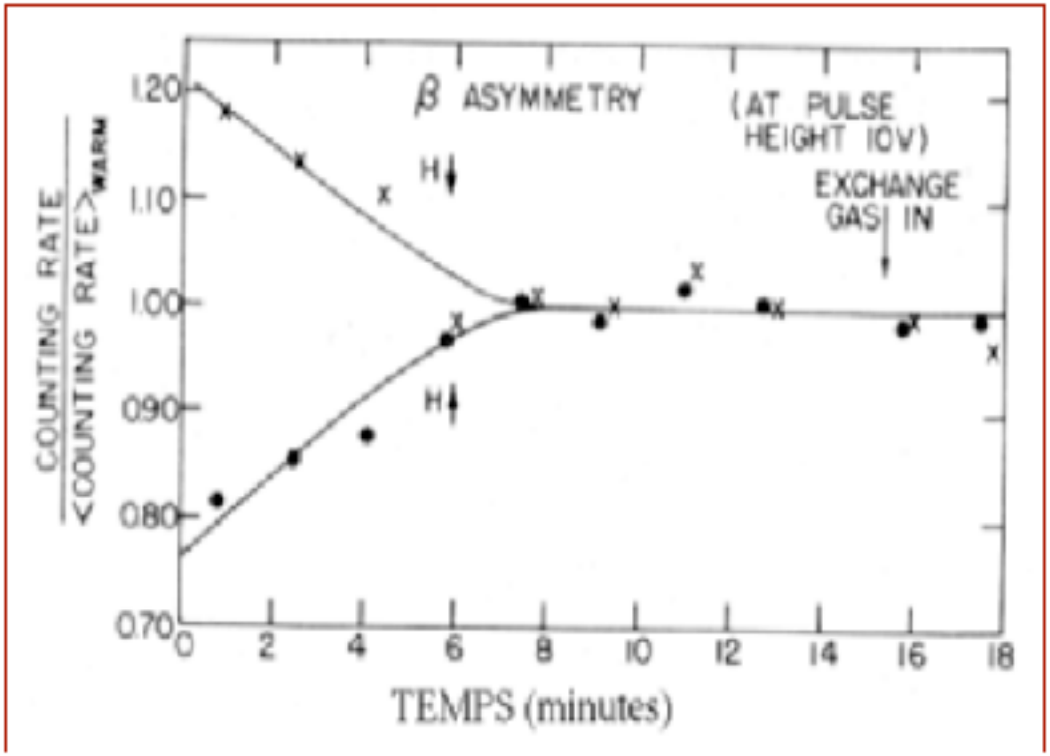
Mirror Image of Wu, Lee and Yang could function the same only, opposite handed

Same is true for the rest of the fundamental forces, they are ***parity conserving***,
BUT, the weak interactions are maximally ***parity violating***

Frontiers 8

Left – Right Asymmetry in β-Decay

1957:



Parity is NOT conserved in weak interactions

Mrs Wu et al. measured electrons from beta decays of Co^{60} nuclei whose spins were oriented (for a few minutes) in a magnetic field. It appeared that there were more electrons in the direction opposite to Co^{60} spins. Electrons are not symmetrically ejected over and under the plane perpendicular to the nuclear spins!

Frontiers 8

Left – Right Asymmetry in β-Decay

Starting with the experiment by Wu et al. the measurements showed that the angular distribution of

electrons:

$$I(\theta) = 1 - \frac{v}{c}\cos\theta$$

positrons:

$$I(\theta) = 1 + \frac{v}{c}\cos\theta$$

where θ is the angle between the electron direction and its spin while v is the electron velocity

Thus:

electrons prefer backward positrons prefer forward emission with respect to their spins:

$\longrightarrow$ direction of motion $\longrightarrow$

$\longleftarrow$ direction of spin $\longrightarrow$

Electrons are mostly left-handed (LH) and positrons right-handed (RH)

Frontiers 8

Left – Right Asymmetry in β-Decay (continued)

We can define „Longitudinal polarization":

$$P = \frac{I(0) - I(\pi)}{I(0) + I(\pi)} = \alpha \frac{v}{c}$$

$\alpha = -1$ for e^-

$\alpha = +1$ for e^+

For massless neutrinos one can expect:

$I(\theta) = 1 - \cos\theta$ or $I(\theta) = 1 + \cos\theta$

i.e. neutrino polarization P is: $P = -1$ or $P = +1$

Left-handed or right-handed?

Frontiers 8

Measurement of the Neutrino Polarization (or helicity)

From Pauli hypothesis: **neutrino spin=1/2**
but what is its polarization ?

An experiment by Goldhaber et al. (1958)

Conclusion:
Neutrinos accompanying positrons are left-handed,
while those accompanying electrons are right-handed

Hence by convention:

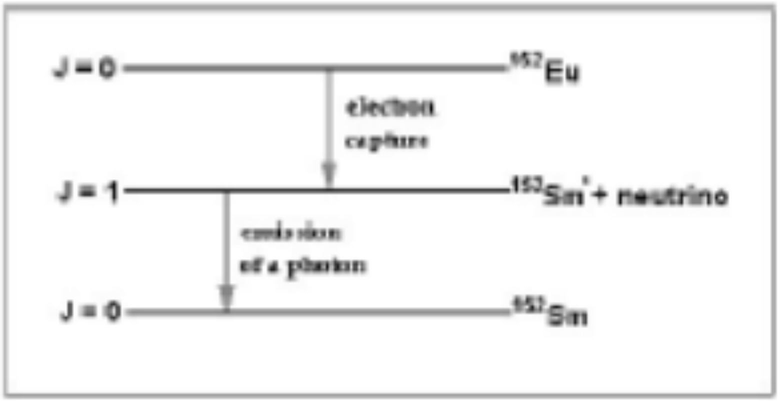
leptons are left-handed	anti-leptons are right-handed
electrons	positrons
neutrinos	anti-neutrinos

Frontiers 8

Goldhaber's Experiment

$$^{152}Eu(J=0)+e^- \rightarrow {}^{152}Sm^*(J=1)+\nu_e$$

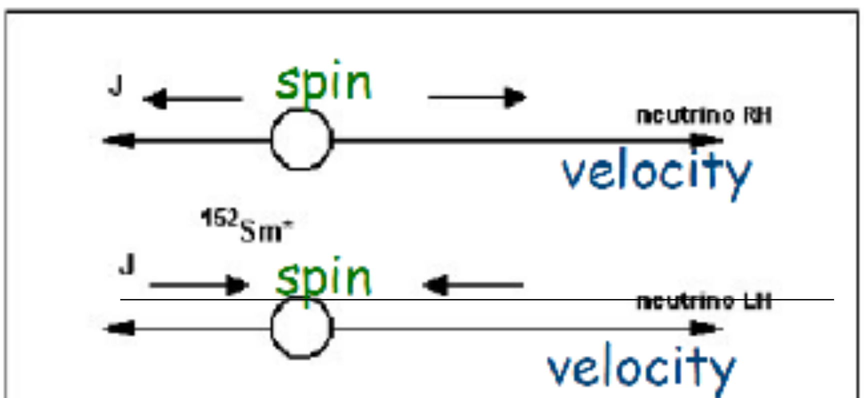
K orbit electron



Total angular momentum of the initial state is spin of a captured electron.

Final states:

i.e. spins are opposite

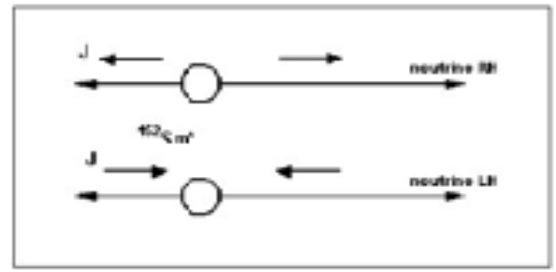


i.e. the recoiling nucleus has the same polarization sense (or handedness) as the neutrino - along or against velocity vector.

i.e. RH or LH

Frontiers 8

Goldhaber's Experiment



RH

LH

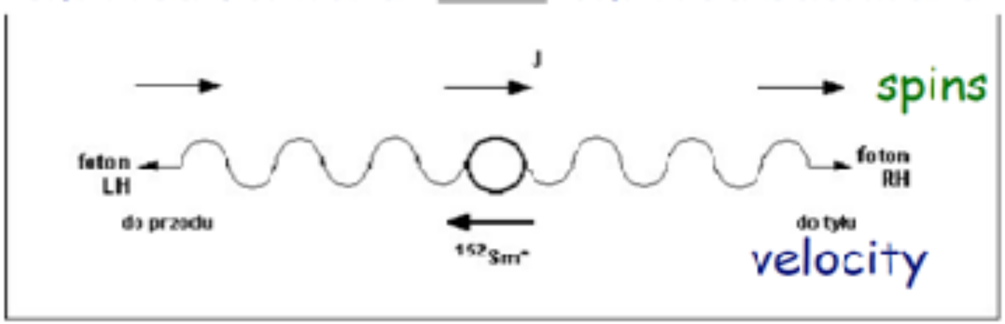
Next: $^{152}Sm^*(J=1) \rightarrow ^{152}Sm(J=0)+\gamma$

gamma has to carry away the angular momentum of the excited nucleus!

Let's consider the LH case – spins against velocities):

if photon emitted forward

if photon emitted backward



i.e. forward γ has to be LH

From neutrinos to cosmic sources, DK&ER

In the same way one can show that:

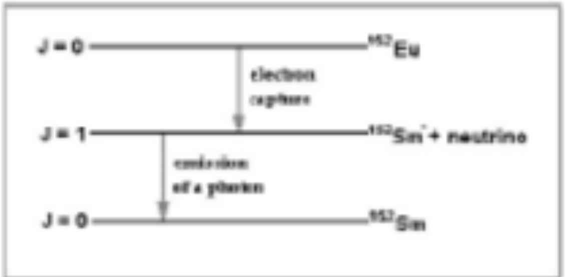
In RH case

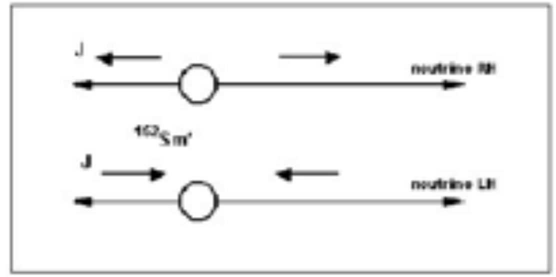
forward γ has to be RH

Hence: polarization of forward γ is the same as that of neutrinos!!

Frontiers 8

Goldhaber's Experiment





RH

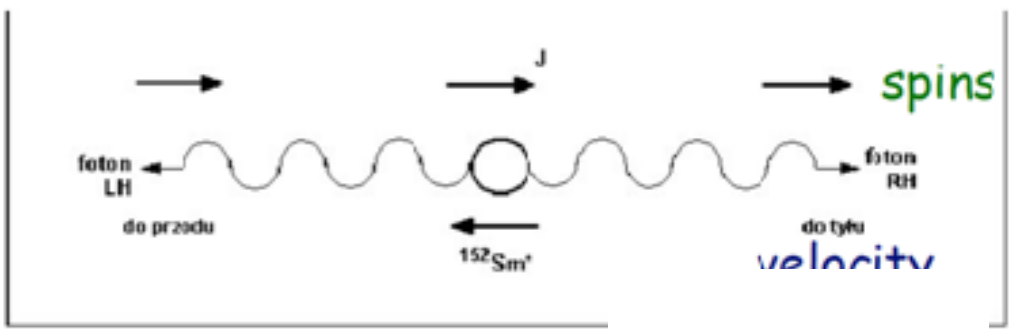
LH

Next: $^{152}Sm^*(J=1) \rightarrow {}^{152}Sm(J=0)+\gamma$

gamma has to carry away the angular momentum of the excited nucleus!

Let's consider the LH case – spins against velocities):

if photon emitted forward ____ if photon emitted backward



i.e. forward γ has to be LH

From neutrinos to cosmic sources, DK&ER

In the same way one can show that:

In RH case

forward γ has to be RH

Hence: polarization of forward γ is the same as that of neutrinos!!

Frontiers 8

Goldhaber's Experiment (cont.)

Hence we need to:

- select forward gammas
- measure their polarization

Another great idea: use resonant scattering:

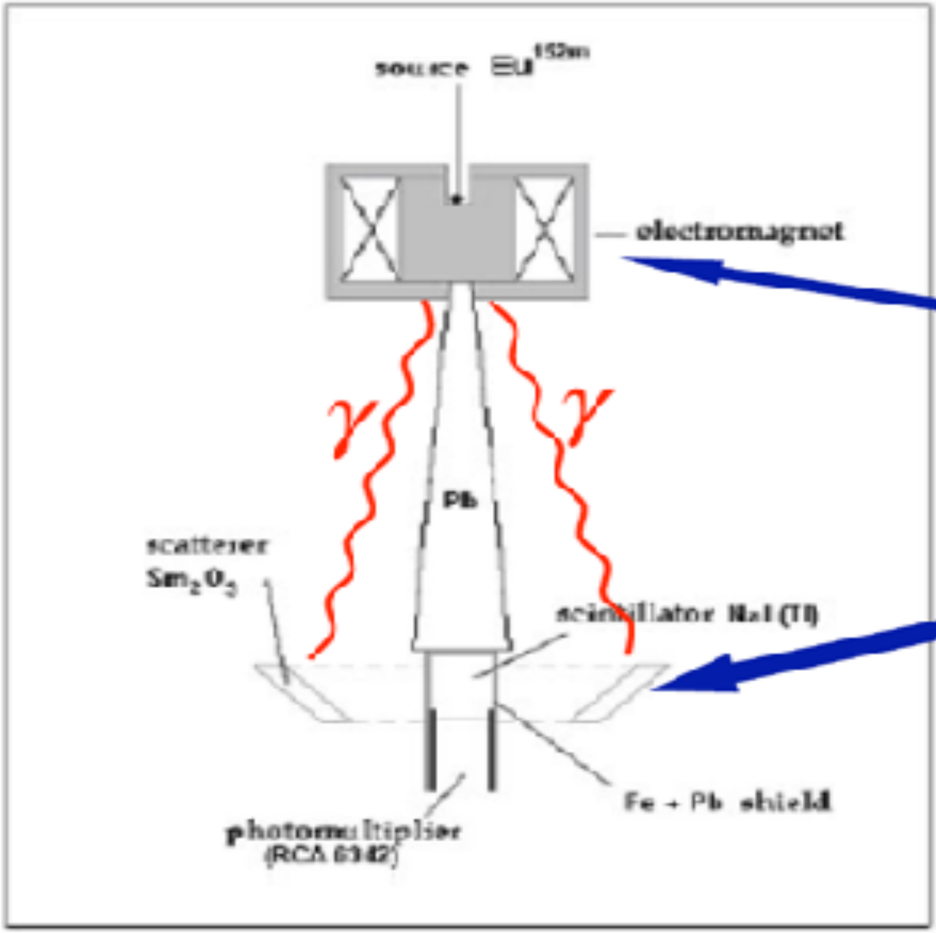
$$\gamma + {}^{152}\mathrm{Sm} \rightarrow {}^{152}\mathrm{Sm}^{*} \rightarrow \gamma + {}^{152}\mathrm{Sm}$$

possible only with a forward gamma because it has slightly higher energy than the excitation energy (thus allowing for some recoil energy of the nucleus)

Frontiers 8

Goldhaber's Experiment (cont.)

Schematic view of Goldhaber experiment



Experiment steps:

- Electron capture by ^{152}Eu
- Decay of $^{152}Sm^*$ with emission of gammas
- Measurement of gamma polarization by scattering on polarized electrons in iron (by mgt field)

$$P_\gamma = (68 \pm 15)\%$$

- Absorption and reemition of γ in ^{152}Sm selects only photons emitted forward
- Reemitted gammas measured by NaI

ic

K&ER

Frontiers 8

Goldhaber's Experiment (cont.)

Result of the experiment

$$\delta = \frac{(N_- - N_+)}{\frac{1}{2}(N_- + N_+)} = +0{,}017 \pm 0{,}003$$

- + or – is for magnetic field direction which polarizes spins of iron electrons which act as polarimeter for gamma polarization

- Compton scattering probability is bigger for opposite spin orientation of electron and photon

  → measured photons had preferentially the same spin orientation as electrons (because scattered photons are not„resonant" and do not get to NaI)

- As a result of this experiment the neutrino polarization was found to be: $P = -1.0 \pm 0.3$

Frontiers 8

Goldhaber's Experiment (cont.)

Neutrinos are Left-handed

i.e its spin projection on a direction of motion (helicity) is negative

Helicity of Neutrinos*

M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{\boldsymbol{p}}_\nu = -1$ (negative helicity).

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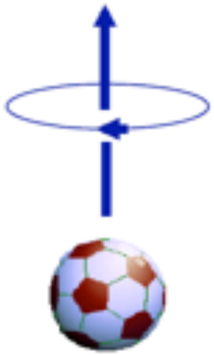
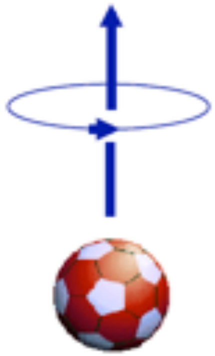
Goldhaber's Experiment (cont.)

Neutrino polarization

Massless neutrinos only rotate in one direction !



Neutrino



Anti Neutrino

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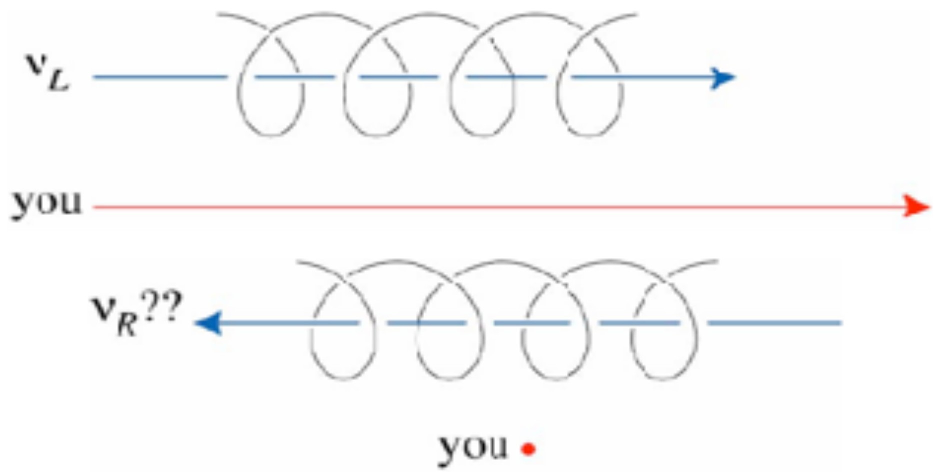
Goldhaber's Experiment (cont.)

Mass versus polarization

- All neutrinos left-handed ➡ massless
- If they have mass, can't go at speed of light.

  Because if an observer moves faster than neutrino:



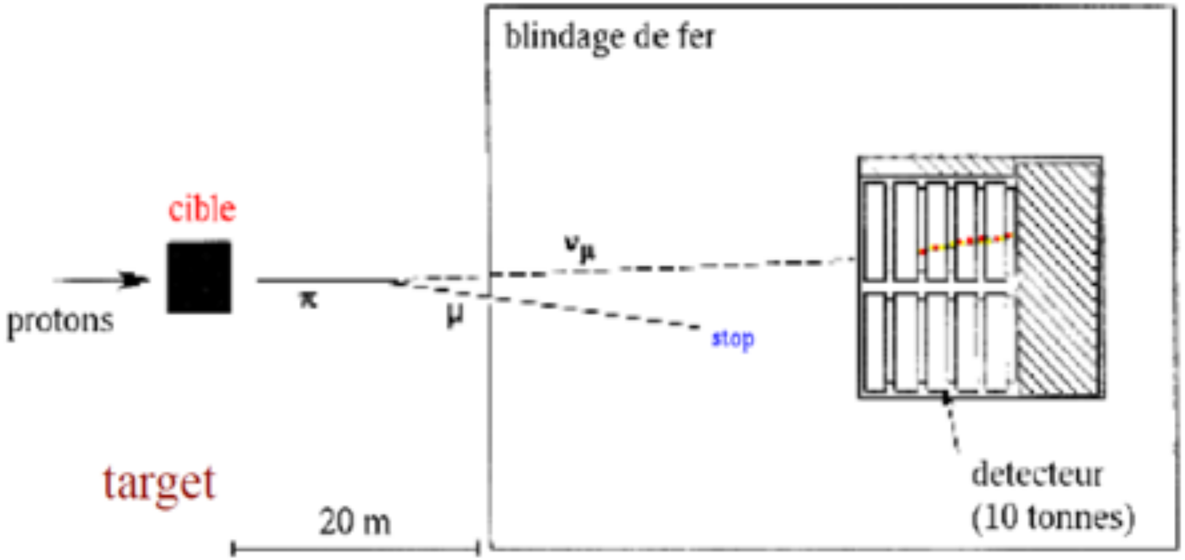
Now neutrino right-handed??

➡ contradiction ➡ can't be massive

Detection of the μ_ν

Experiment by Schwartz, Lederman and Steinberger in 1962:

Protons from an accelerator in Brookhaven (Long Island) interacted with target producing pions. Pions decayed producing muons and neutrinos. The experiment's goal was to study the nature of the neutrinos.



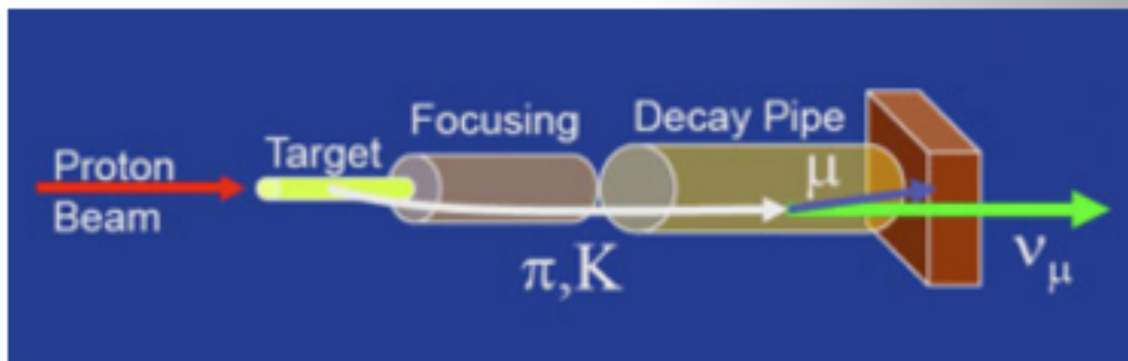
Detector:
iron plates interspersed
with spark chambers

----- sparks along
a muon track

Conclusion: the neutrinos accompanying μ from π decays produce in the detector muons and not electrons. They are different from neutrinos discovered by Reines and Cowan.

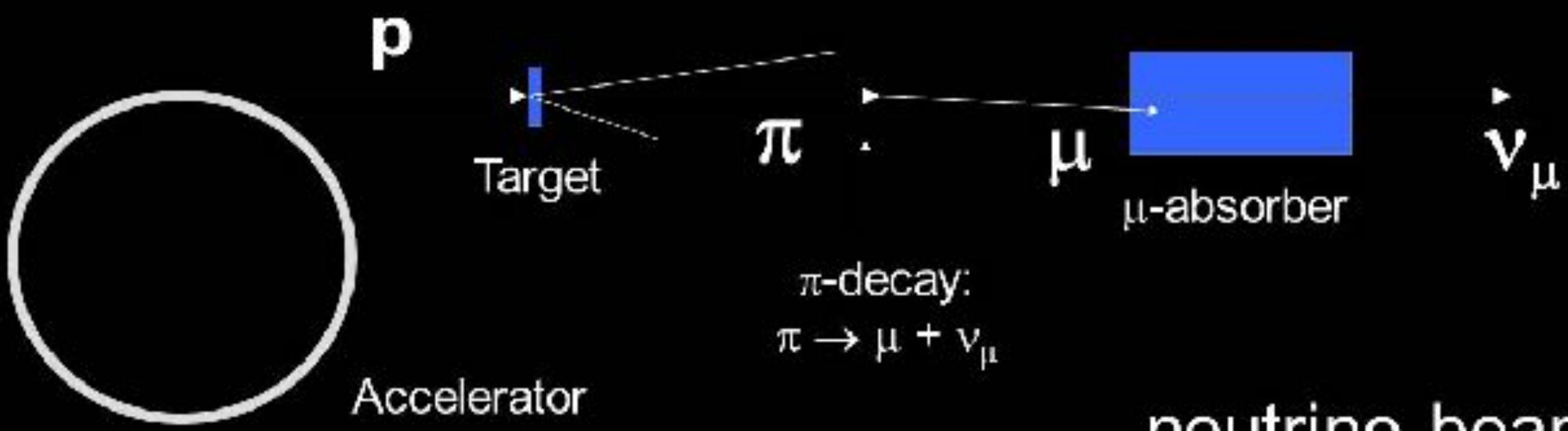
Neutrinos in the 1960s

1962: Lederman, Schwartz and Steinberger discovered the existence of second type of neutrino at the AGS in Brookhaven: the muon neutrino



1968: Davis and Bahcall and the solar neutrino problem. Only 1/3 of the expected (electron) neutrino rate was observed. What was wrong?

Leon Lederman, Melvin Schwartz,
Jack Steinberger (Brookhaven)



neutrino beam

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Two Neutrinos

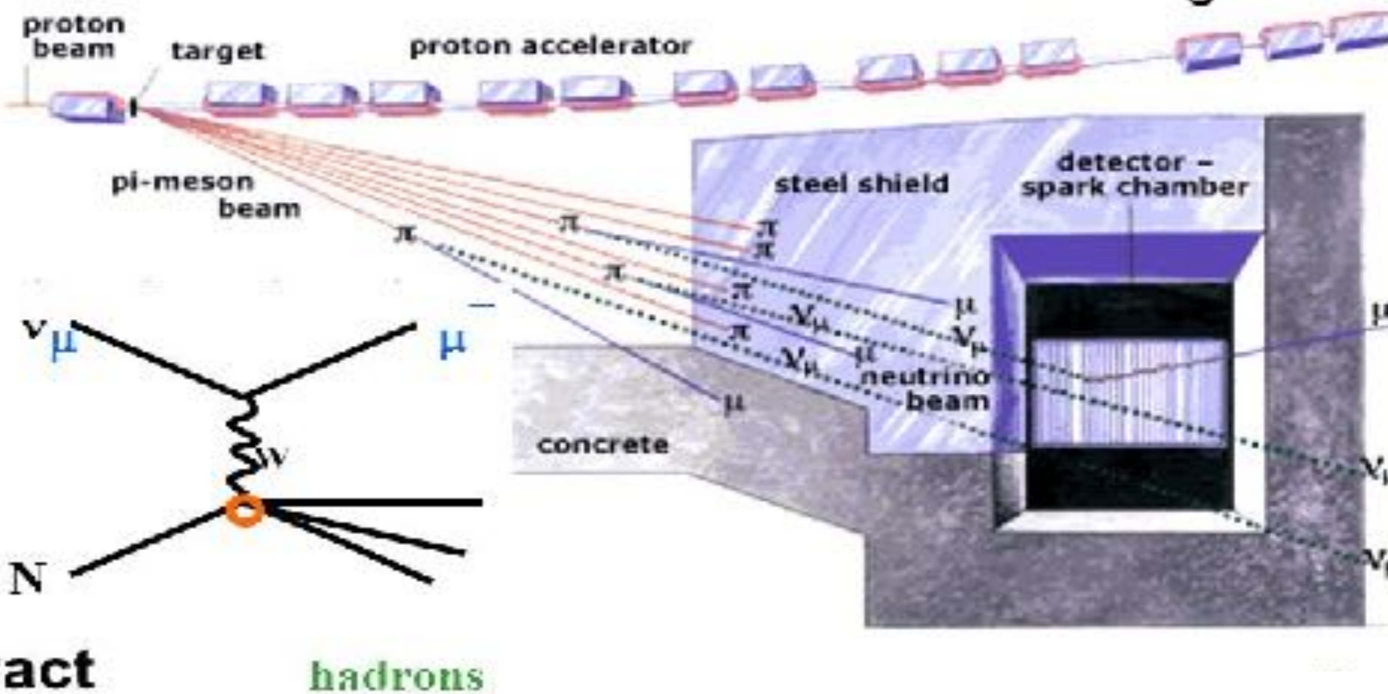
1962

Schwartz

Lederman

Steinberger

AGS Proton Beam



Neutrinos from π-decay only produce muons (not electrons)

when they interact in matter

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Detection of the μ_ν

The AGS Neutrino Experiment at Brookhaven

Spark Chamber to
detect neutrinos

Pions produced

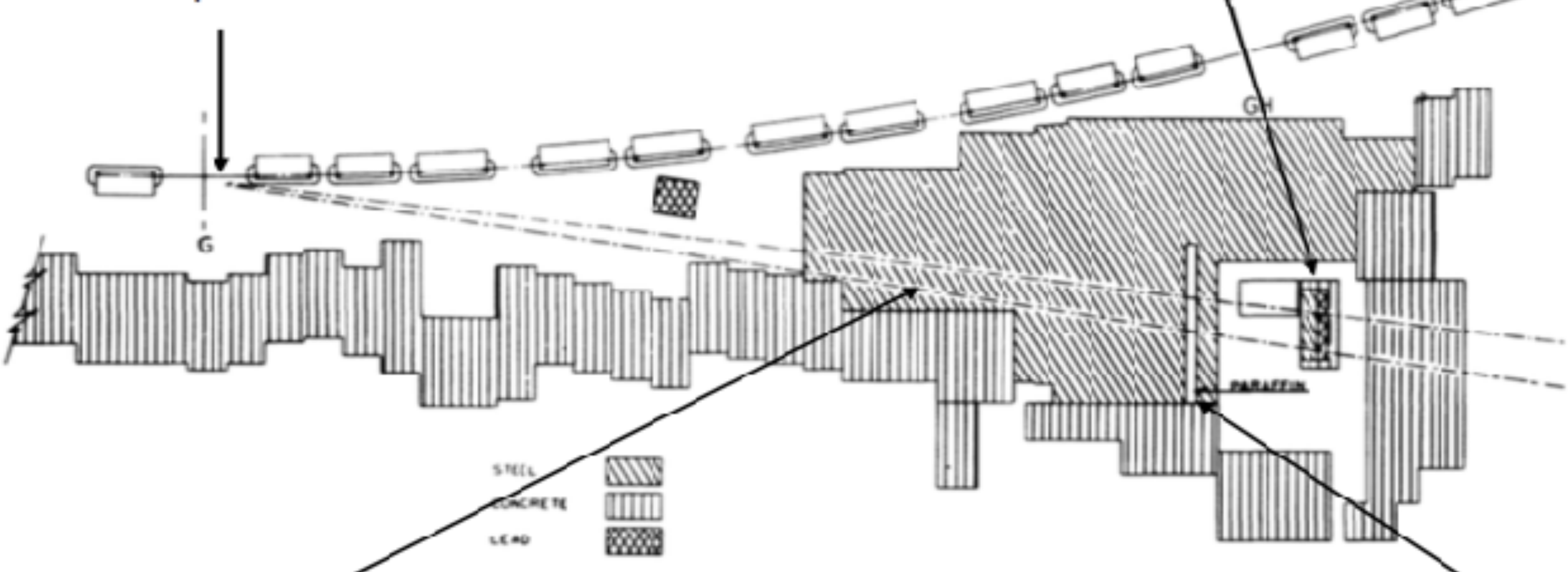

FIG. 1. Plan view of AGS neutrino experiment.

Steel shield stops strongly interacting particles

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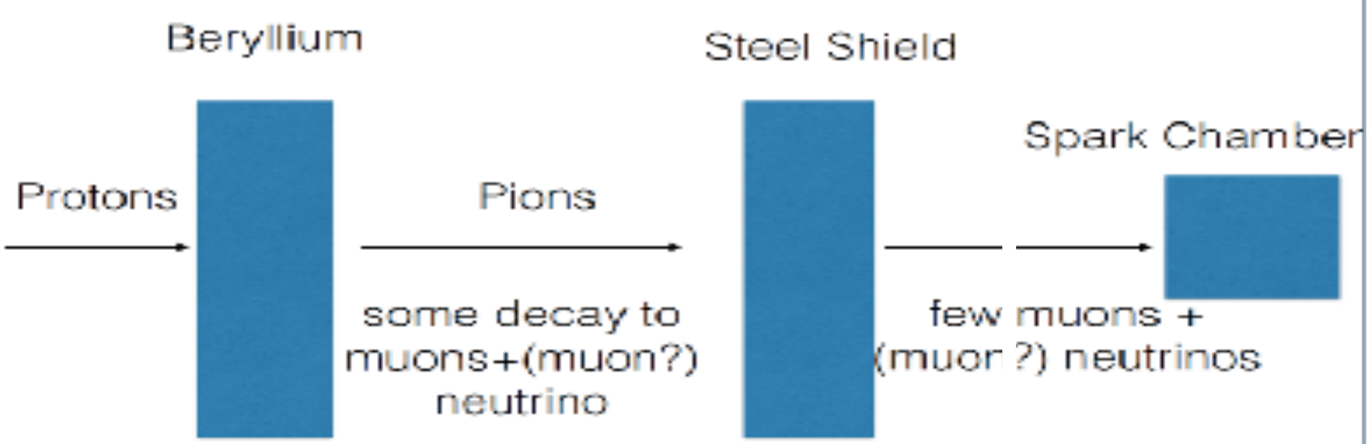
The Experiment

- 15GeV beam of protons strikes Beryllium target, producing pions
- Pions hit 13.5m think iron shield, 21m from the target
    - absorbs strongly interacting particles, attenuation of order 10^{-24}
- Some pions decay into muon + (muon?) neutrino



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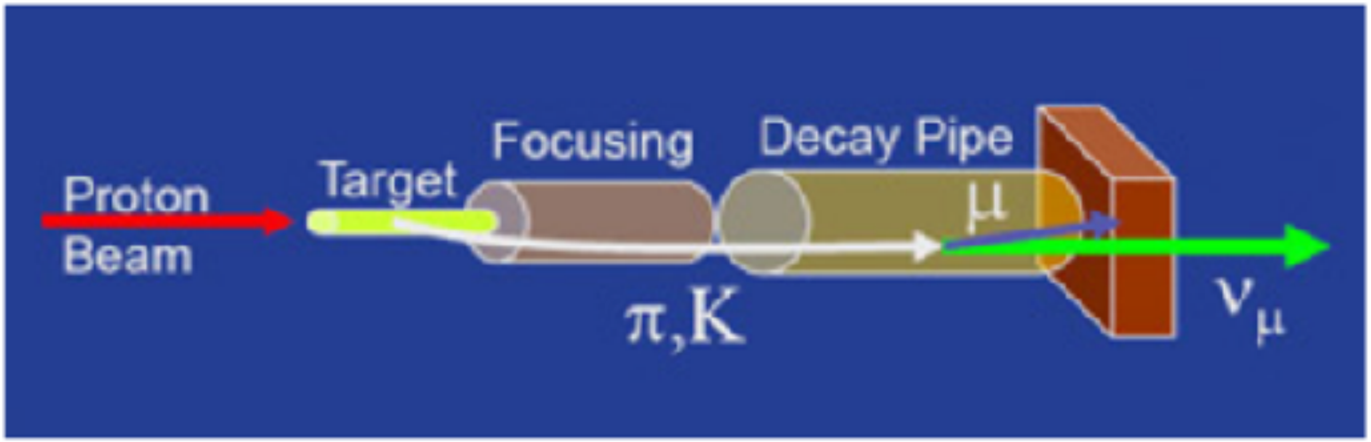
Neutrino Beam



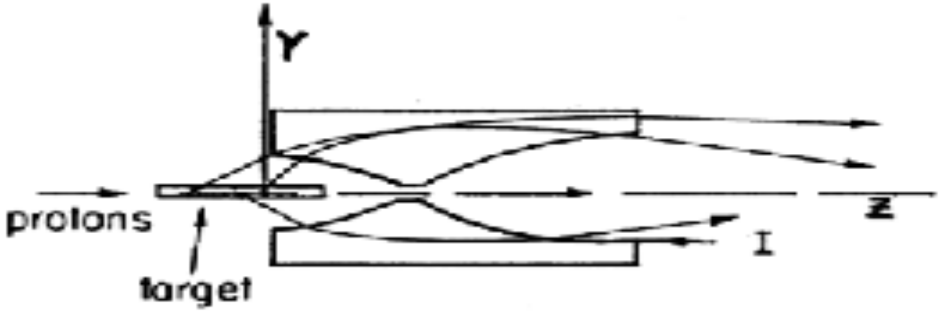


Fig. 4. Sketch of a parabolic horn

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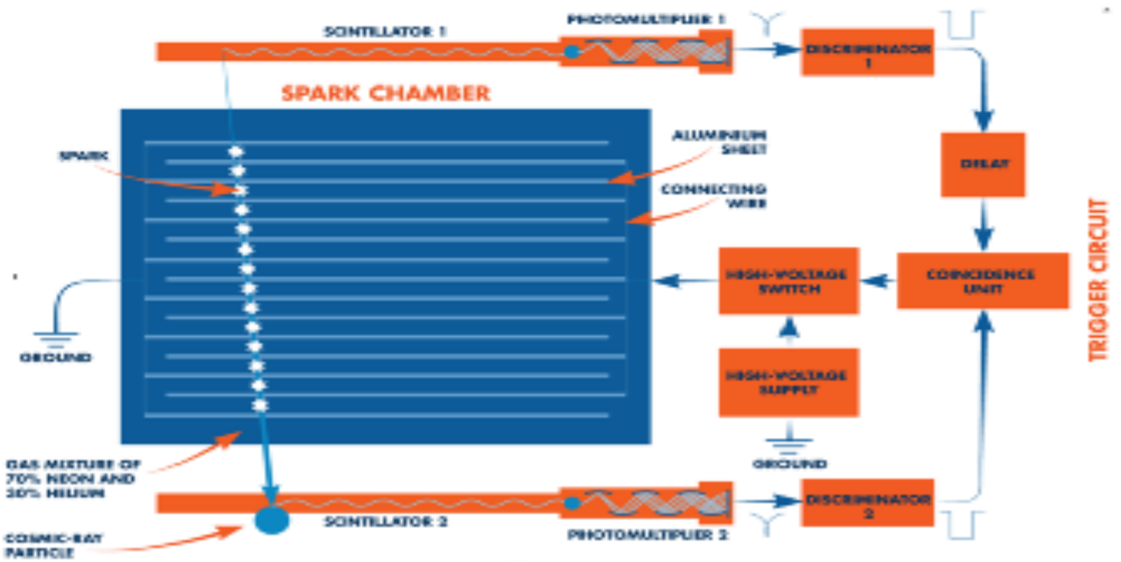
Spark Chambers: Cosmic Muons



- 5.5m of concrete on floor and roof to reduce cosmic muons
- Interactions observed in a 10-ton aluminum spark chamber behind steel shield
- If these neutrinos are muon neutrinos, they should only produce muons, not electrons
  - electrons produce distinct shower, muons produce nice tracks
- But how does spark chamber work?

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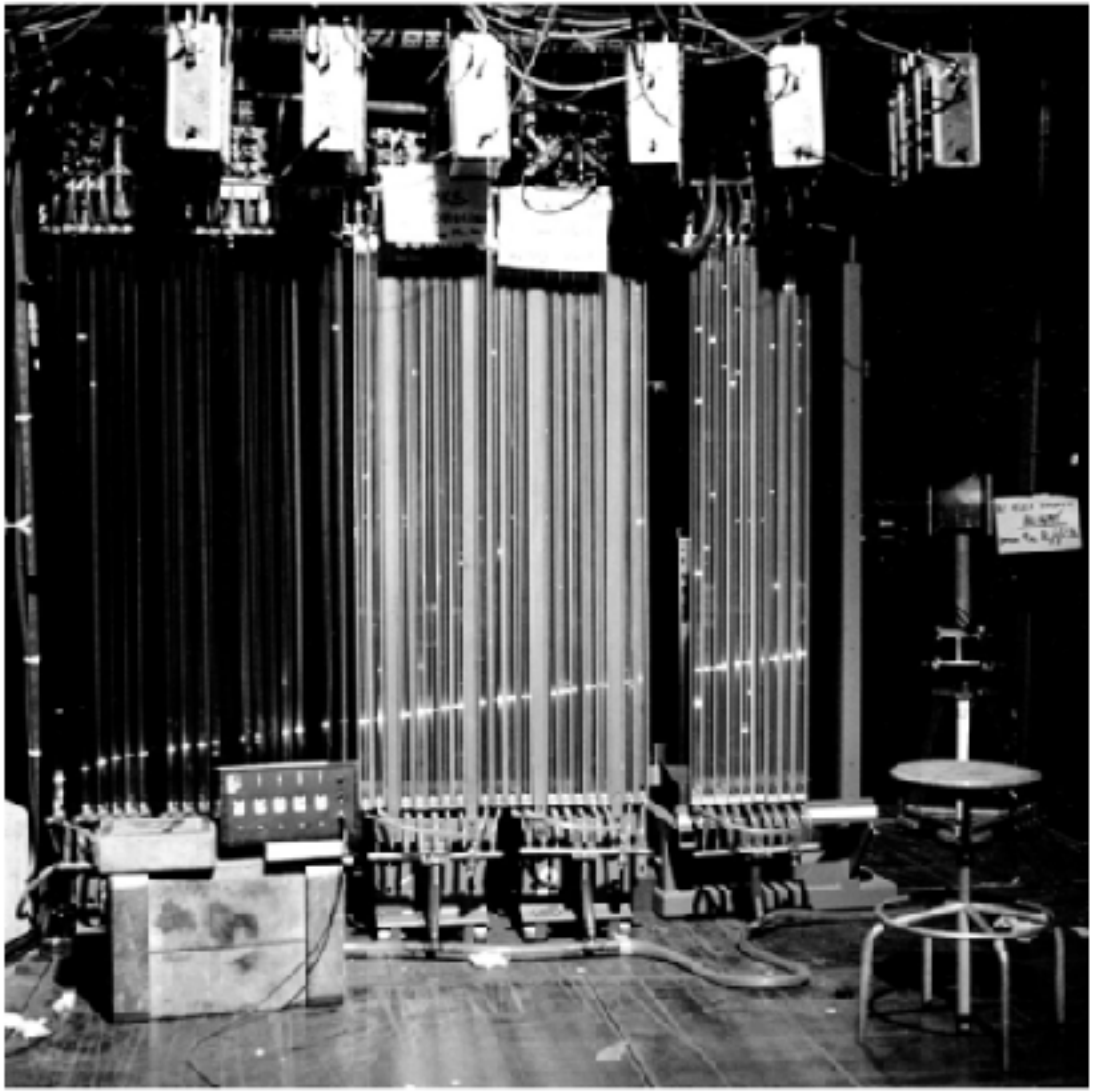

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Electron Showers

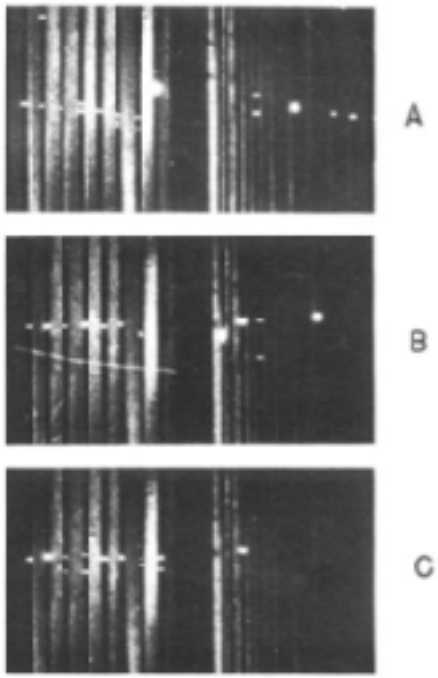

FIG. 8. 400-MeV electrons from the Cosmotron.

Muon Events

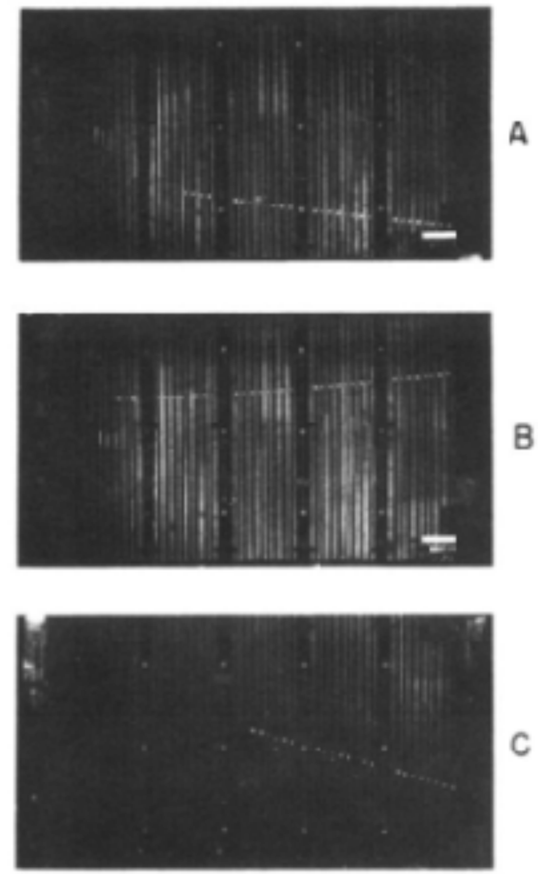

FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

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- The number of events found matching this criteria was 113 when 3.48×10^{17} protons were fired at the target
- Of these, 34 were single muon events (and originated inside the detector)
- If there was no difference between muon neutrinos and electron neutrinos, we would expect a similar number of electron showers
    - only 6 showers observed

Conclusion

- This experiment definitively showed that the neutrinos from beta decay and the neutrinos from muon decay were different
- First direct observation of muon neutrinos