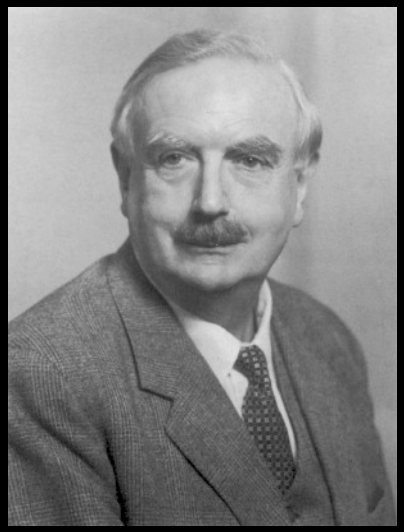
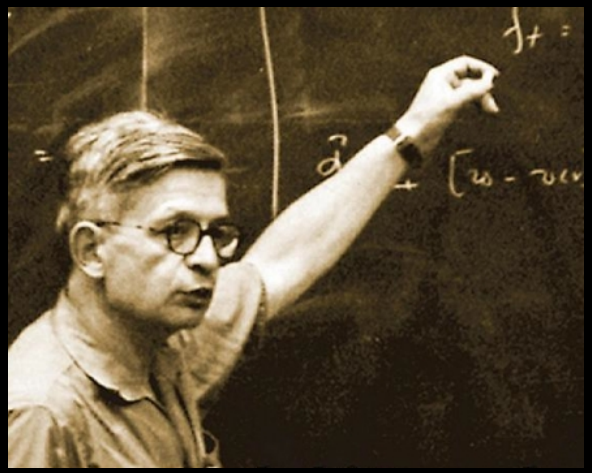
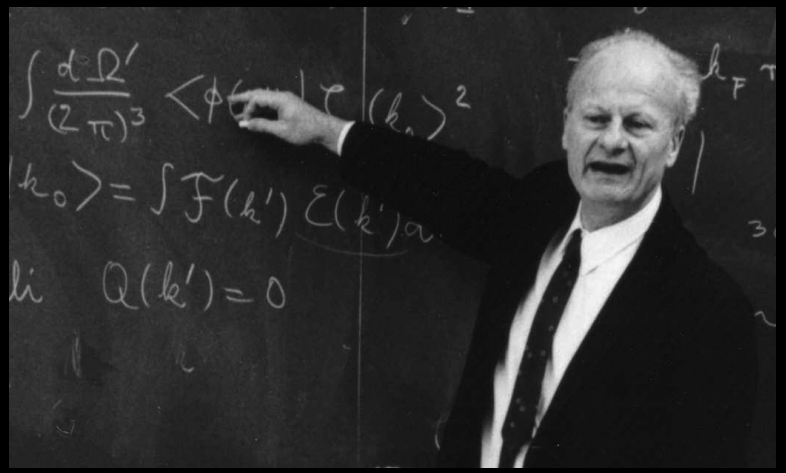
Early Neutrino History 1927-1987

Chris Polly, FNAL







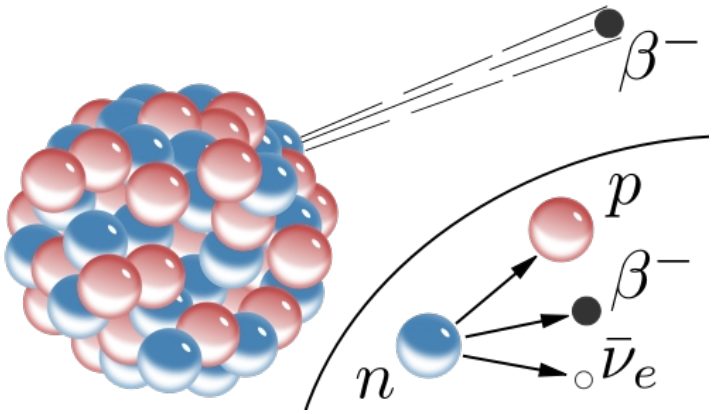
2010 Neutrino lectures

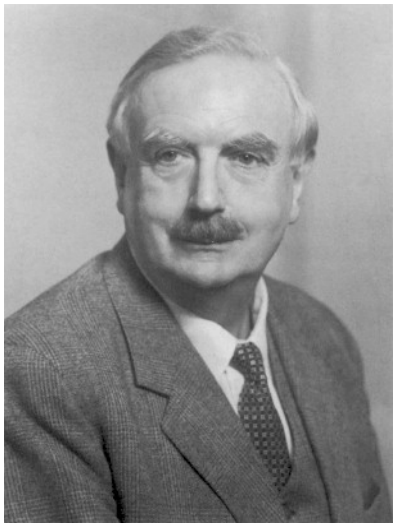
- June 17--Neutrinos from 1927 to 1987
- June 24--Neutrinos sources: beams et al.
- July 1--Neutrino cross sections
- July 8--Neutrino oscillations
- July 15--MiniBooNE
- July 22--MINOS
- July 29--Minerva
- Aug 5--NOvA
- Aug 12--ArgoNeut/MicroBooNE

This talk will cover early neutrino history, basically right up until the floodgates of neutrino oscillation data were opened

Long history of ν and data-driven mysteries

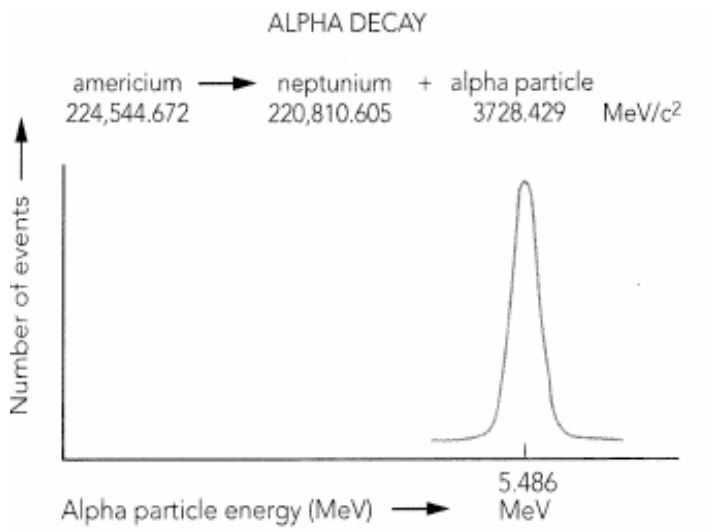
- Starting with the original mystery of the continuous nature of the β decay spectrum
  - Definitive experiment in 1927

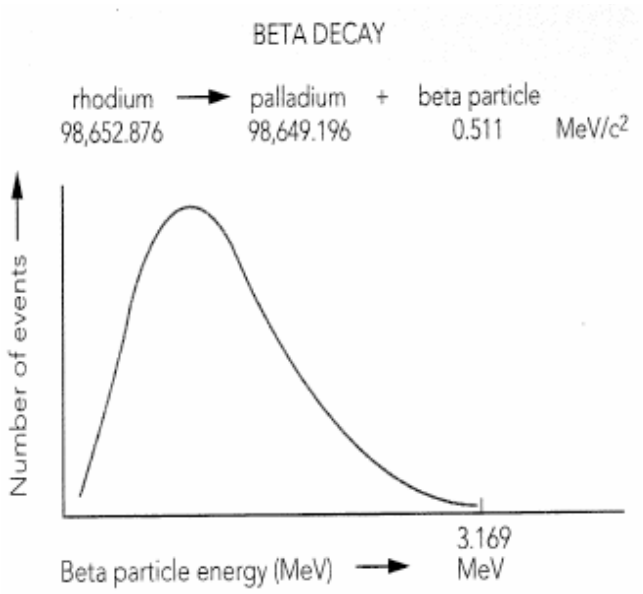




Ellis Drummond

James Chadwick





Detective Pauli to the rescue!

Detective Pauli

"I have done a terrible thing today by proposing a particle that cannot be detected; it is something no theorist should ever do."
W. Pauli 1930

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 ^{6}Li 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 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... From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately I will not be able to appear in Tübingen personally, because I am indispensable here due to a ball which will take place in Zürich during the night from December 6 to 7.....

Your humble servant, W. Pauli

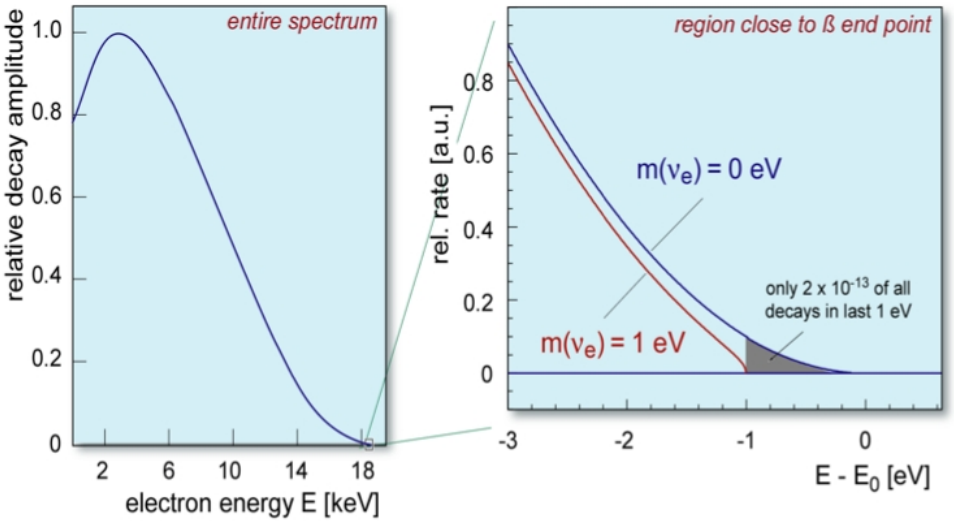
☆ And so the neutrino was 'discovered'!

1933--The first precision ν experiment

- Once again looking at the β decay spectrum, with a focus on resolving the endpoint

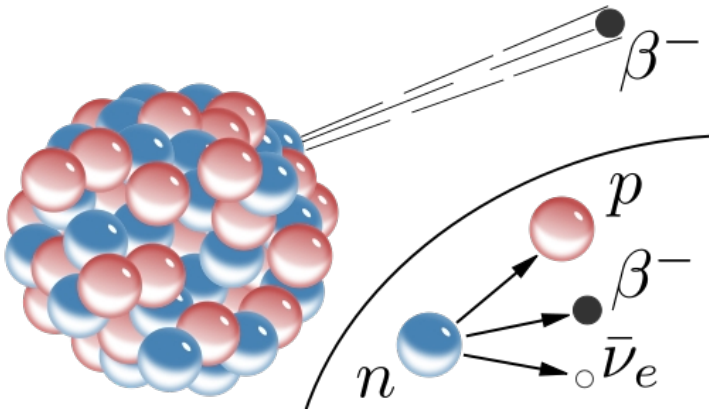
$$\frac{dN}{dE_\beta} \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m^2(\nu_e)c^4}$$

- Perrin also first to hypothesize that the neutrino is created in β decay and not just part of the nucleus



Sir Francis Perrin

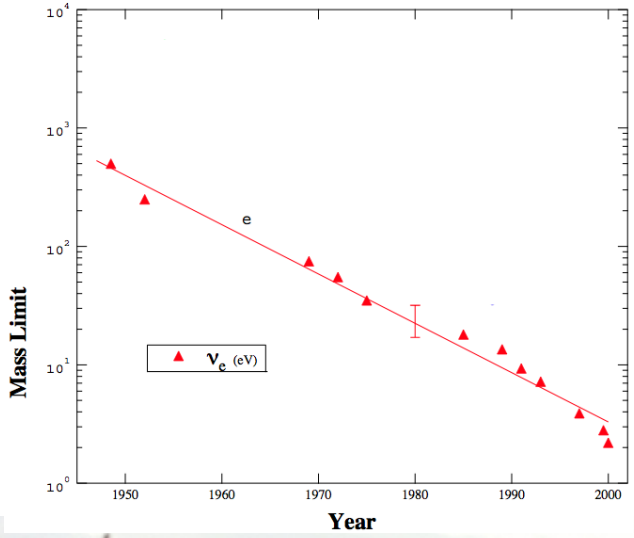
Enrico Fermi

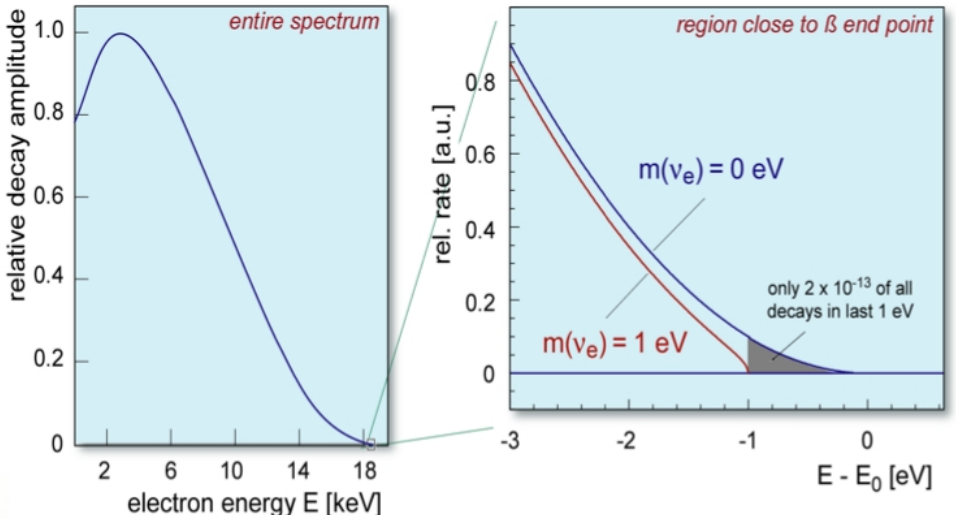


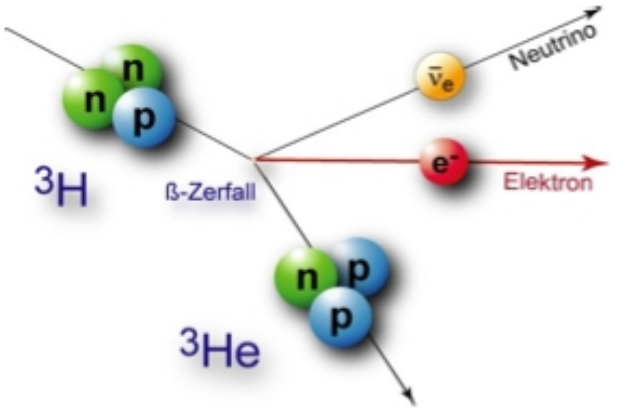
Fast forward to the modern version--Katrin

- KATRIN will weigh the neutrino from tritium β decay to 0.2 eV

$$\frac{dN}{dE_\beta} \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m^2(\nu_e)c^4}$$







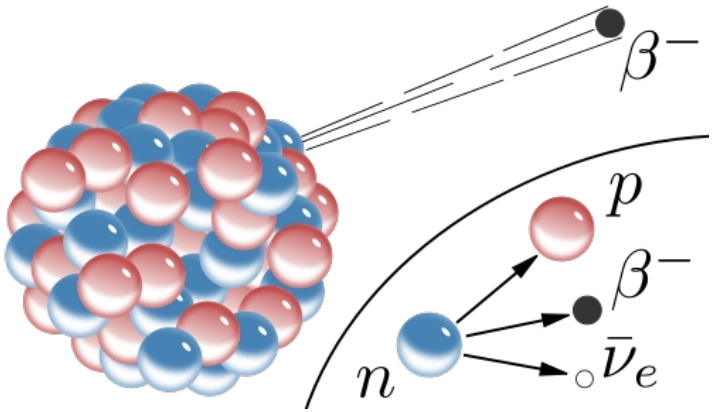
$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

Back to 1934 for the first theoretical treatment

- Incorporating theoretical ideas and experimental data, Fermi develops the basic description of β decay
  - Postulated the missing E was being carried away by a
  - Treated the as a generated quanta (like photons)
  - Derived lifetime and shape of decay spectrum
  - First successful description of creation/annihilation
  - Established what we now call “Fermi's Golden Rule”

Enrico Fermi

$$\lambda_{if} = | M_{if} |^2 \rho_f$$



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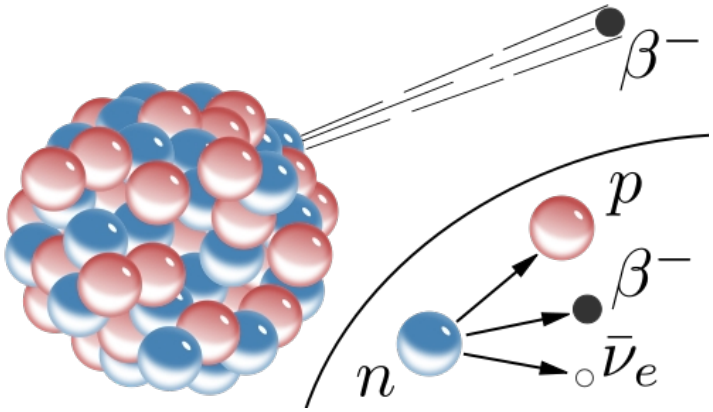
Enrico Fermi

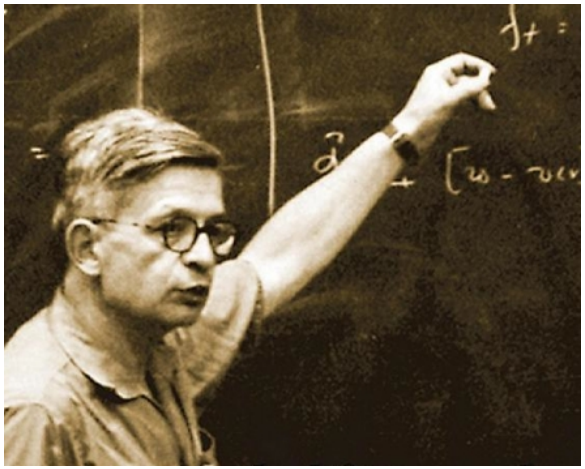
$$\lambda_{if} = | M_{if} |^2 \rho_f$$

Not bad! Integrated 30 years of confusion into one very simple theory.

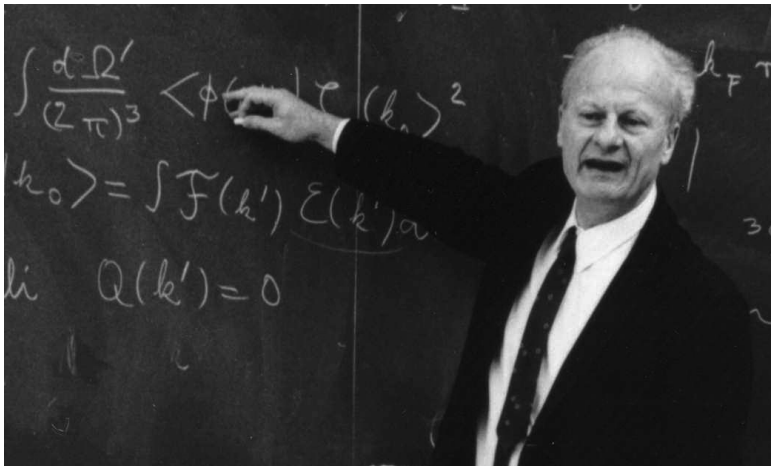
(but rejected by Nature)



With theory in place, let the calculations begin



Sir Rudolf Peierls



Hans Bethe

Bethe-Peierls (1934): calculation of first cross-section for inverse beta reaction using Fermi's theory for:

yields: $\bar{\nu}_e + p \rightarrow n + e^+$ or $\nu_e + n \rightarrow p + e^-$

$$\sigma \approx 10^{-44}\ cm^2 \quad \text{for} \quad E(\bar{\nu}) = 2\ MeV$$

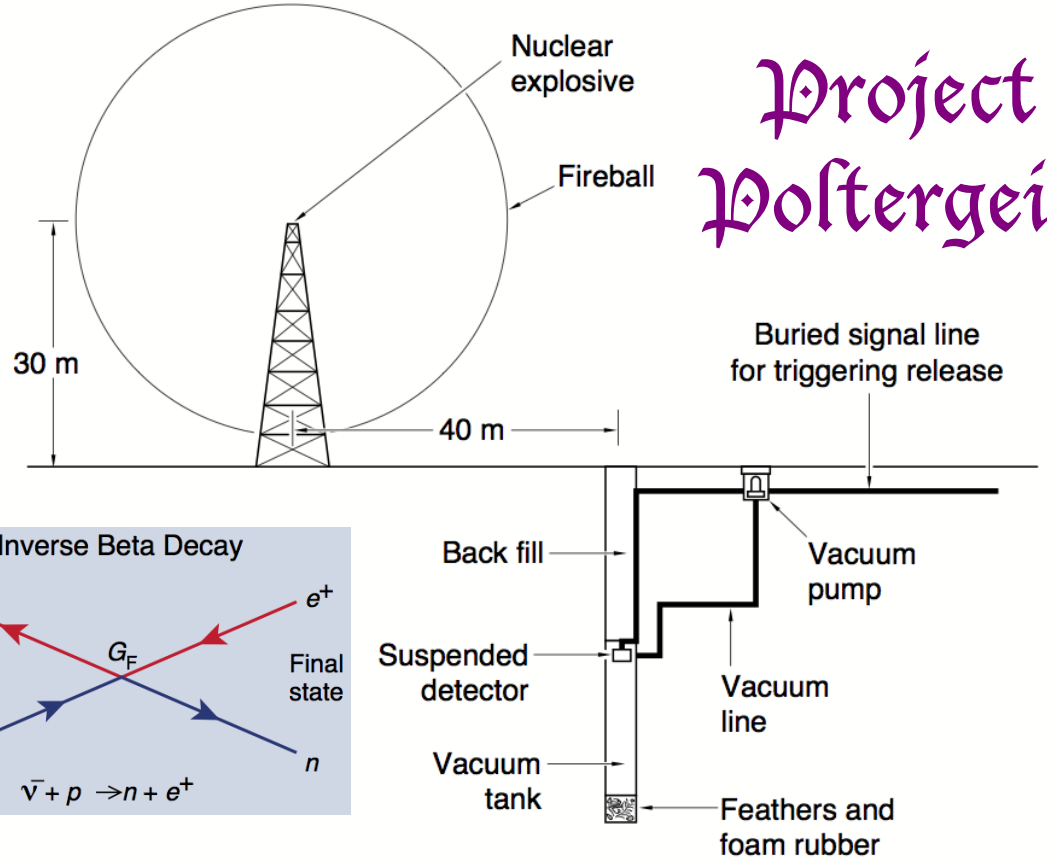
Not such great news for experimentalists anxious to directly observe ν's!

This means that the mean free path of a neutrino in water is:

$$\lambda = \frac{1}{n\sigma} \approx 1.5 \times 10^{21}\ cm \approx 1600 \quad light - years$$

However, where there's a will...

However, where there's a will... there's a poltergeist?



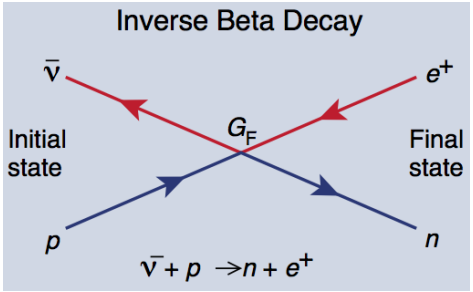
Project Poltergeist

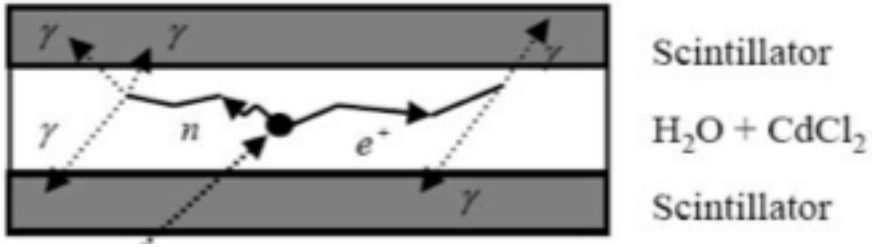
- 1951 Fred Reines (working in the nuclear program) realized an atomic explosion might just have the flux to allow observation of the neutrino
  - Planned to detect positrons from IBD
  - Needed 1 ton of the newly-developed organic scintillator
  - Unfortunately, never happened

Fred Reines

Nuclear reactors as a neutrino source

- With the work on Project Poltergeist it was realized there was an easier, if less dramatic, possibility
- Instead of just detecting positron, dope LS with Cadmium to see n capture coincidence
- Double coincidence gave enough background suppression to make reactor neutrinos competitive
- Constructed detector at Hanford in 1953





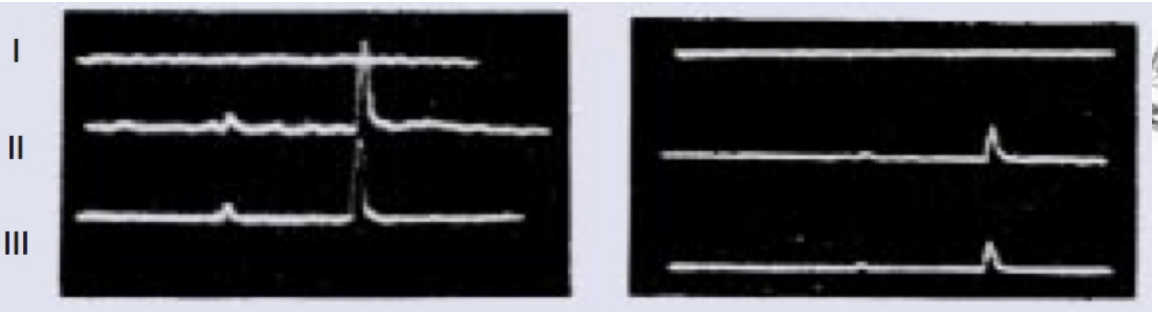
- Proved IBD process and technique
- Unfortunately, cosmic ray bkgds prevented a definitive signal

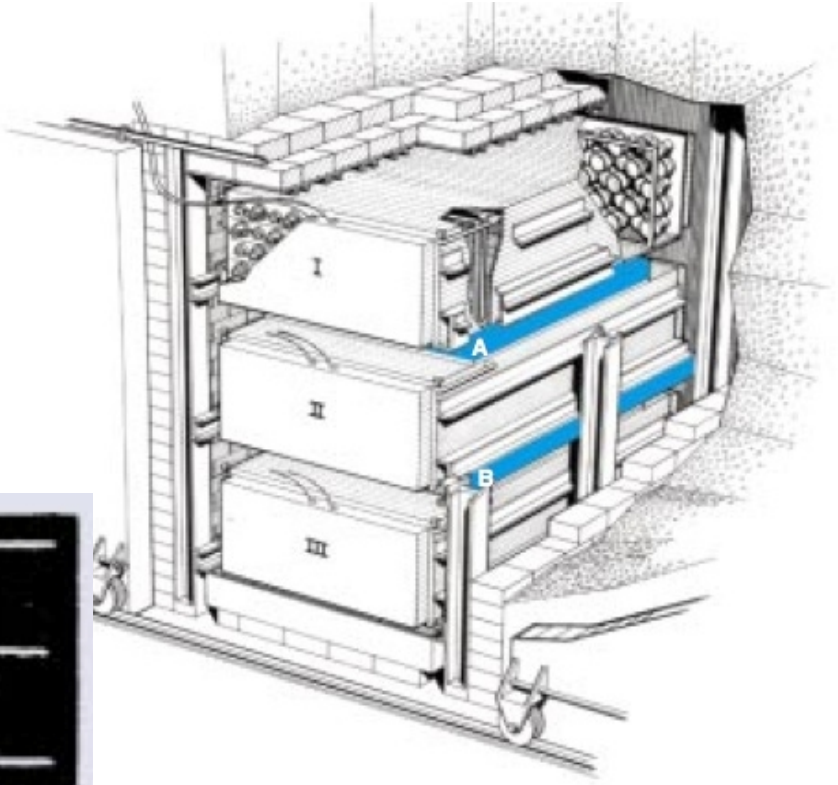
Fred Reines & Clyde Cowan at Hanford (1953)

1956 Success at Savannah River

- Move to new more intense reactor at Savannah River with more overburden
- 11 m from reactor, 12 m underground
- 200L Cadmium loaded water, 1400L of liquid scintillator = 3 events/hour

Savannah River Event Display (scope trace)





Savannah River Detector

"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons."
Telegram from Reines and Cowan to Pauli

$$\sigma = (11 \pm 2.6) \times 10^{-44}\ \text{cm}^2 \text{ (within 5\% of expected)}$$

Pi's and Mu's and Parity

- Need to back up a bit and talk about other fantastic discoveries
  - Muon discovered in 1937 by Carl Anderson in cosmic radiations
  - Pions discovered in 1947 by Powell, Lattes, and Occhialini
- Yukawa predicted existence of pion, long period of confusion between observed muons and pions due to similar mass 106 MeV versus 140 MeV
- It was natural to presume the missing energy in pion decay was also being carried away by the same phantom particles…
- Parity violation experiments showed neutrinos to be left-handed

Pontecorvo first to point out possible ν mixing

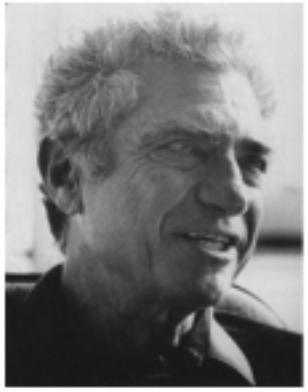
- Back in 1957, Pontecorvo noted that there could be a analogy between neutral kaon mixing and neutrinos
- In particular, in the same way neutral kaons mixed, neutrinos and their antiparticles might also oscillate
- This basic theory was eventually extended by Maki, Nakagawa, and Sakata, and into our modern version of mixing between flavor and mass eigenstates…see oscillation talk

Bruno Pontecorvo

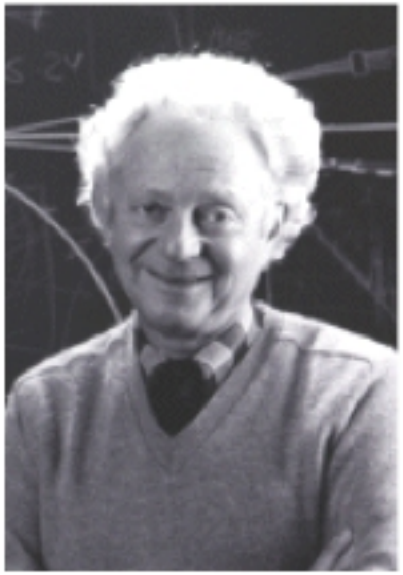
"At present this is highly speculative- there is no experimental evidence for neutrino oscillations…" D.J. Griffiths (1995), *Introduction to Quantum Mechanics*

1962 What, you mean there's two of them?

- Working with a beam of neutrinos from pions at BNL
  - Identified neutrino interactions in spark chamber
  - Found that the 34 events from muons and 11 events attributalbe to cosmics and neutron bkgs
- Concluded it was likely that there must be two varieties of neutrinos, those that makes electrons and those that makes muons



Jack Steinberger

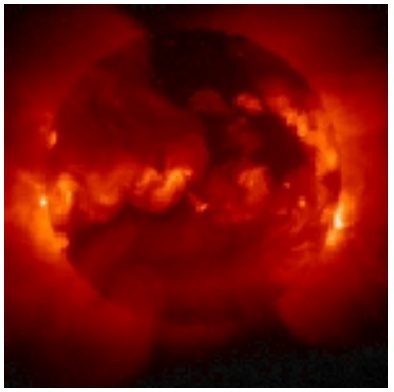


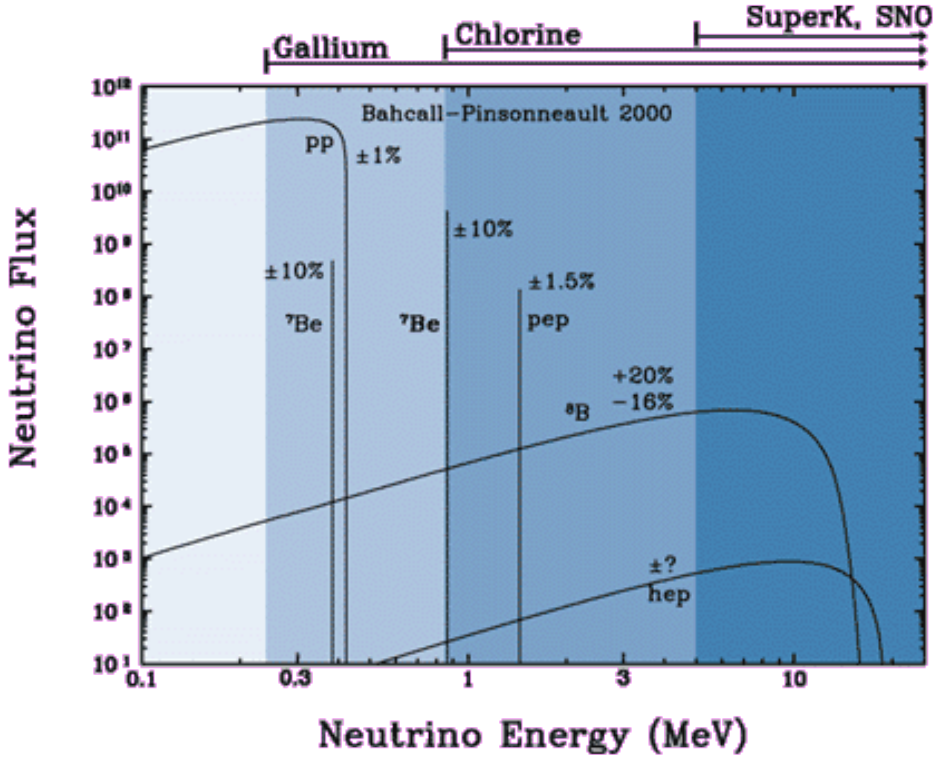
Leon Lederman

Melvin Schwartz

Starting in the 1960's solar ν mystery arises

- The sun is fueled by fusion reactions
  - $4\,^{1}H + 2e^{-} \rightarrow {}^{4}He + 2\nu_e + 6\gamma$
  - More reaction chains follow…
- Neutrinos are produced copiously
  - Note all ν_e have E_ν below ~10 MeV

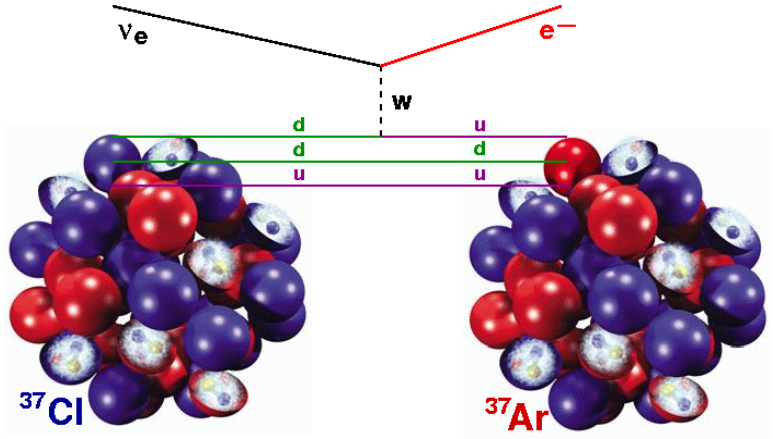




☆ Ray Davis sets out to measure solar ν's for the first time.

1968--Ray Davis starts a fight that lasts 30 years

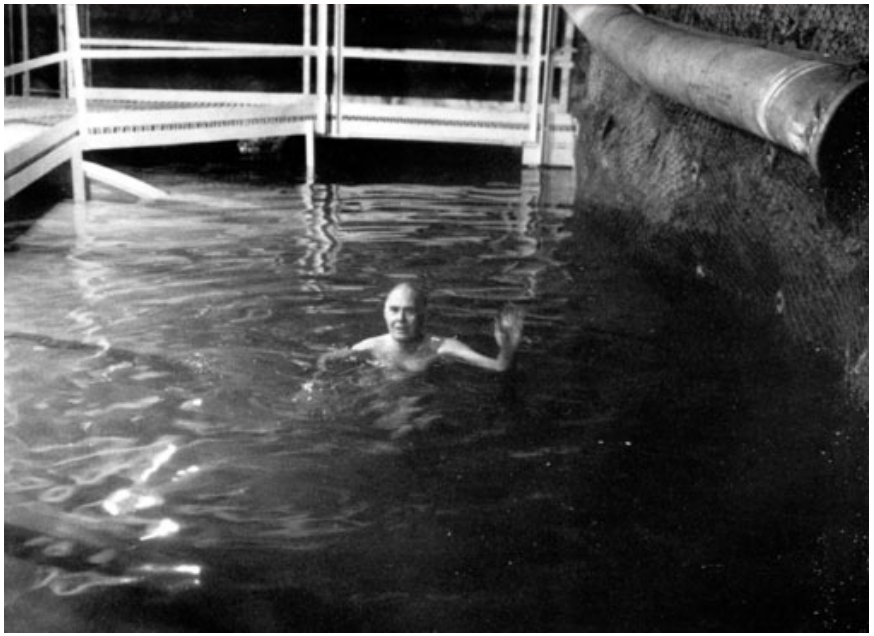
- Used a large vat of dry cleaning solution to look for Argon from inverse beta decay



36 Ar atoms per month.

$$\frac{\phi_{\nu_e}(\text{Homestake})}{\phi_{\nu_e}(\text{Theory})} = 0.34 \pm 0.06$$

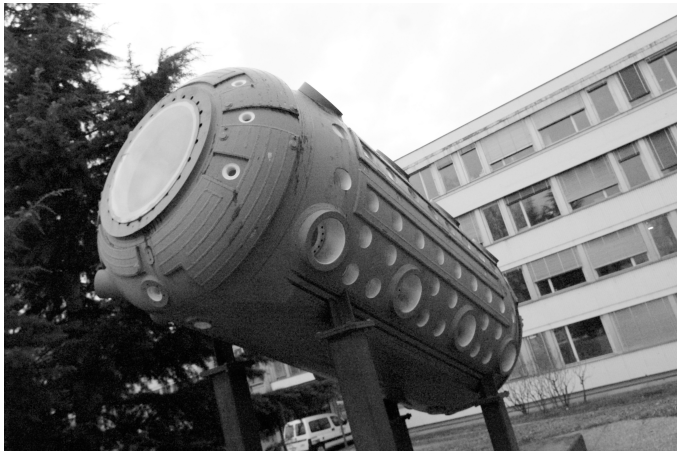
- Remained mired in controversy for 30 years. Do we understand fusion? Is the experiment correct? Could it be new physics, e.g. Pontecorvo's oscillations?



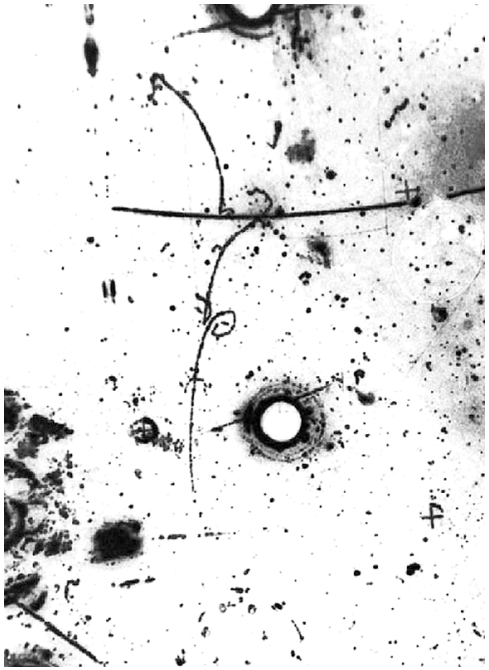
Ray Davis

1973 Almost 50 years after Fermi's desperate remedy, neutrinos become tools

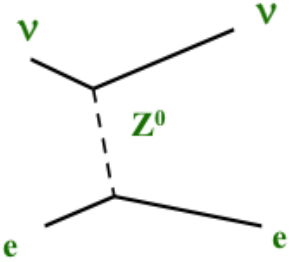
- Weinberg, Salam, and Glashow develop theory unifying weak and electromagnetic forces
  - Predicts the existence of neutral currents
- Race was on between CERN and Fermilab to try and discover the Z boson
- Neutrino the best probe, since other probes would be swamped by electromagnetic interactions



Gargamelle

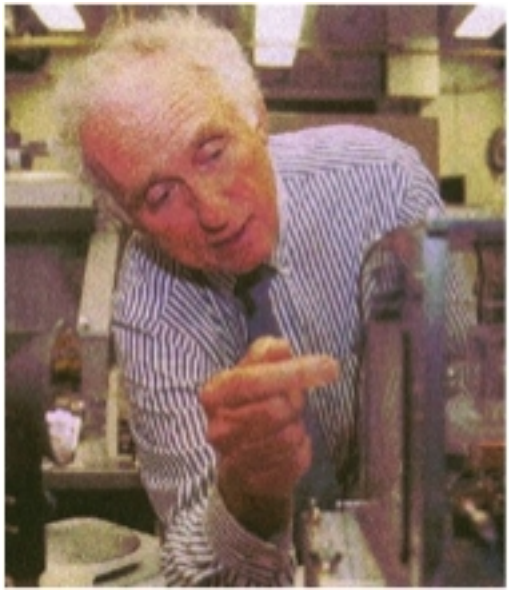


15 ft Bubble Chamber



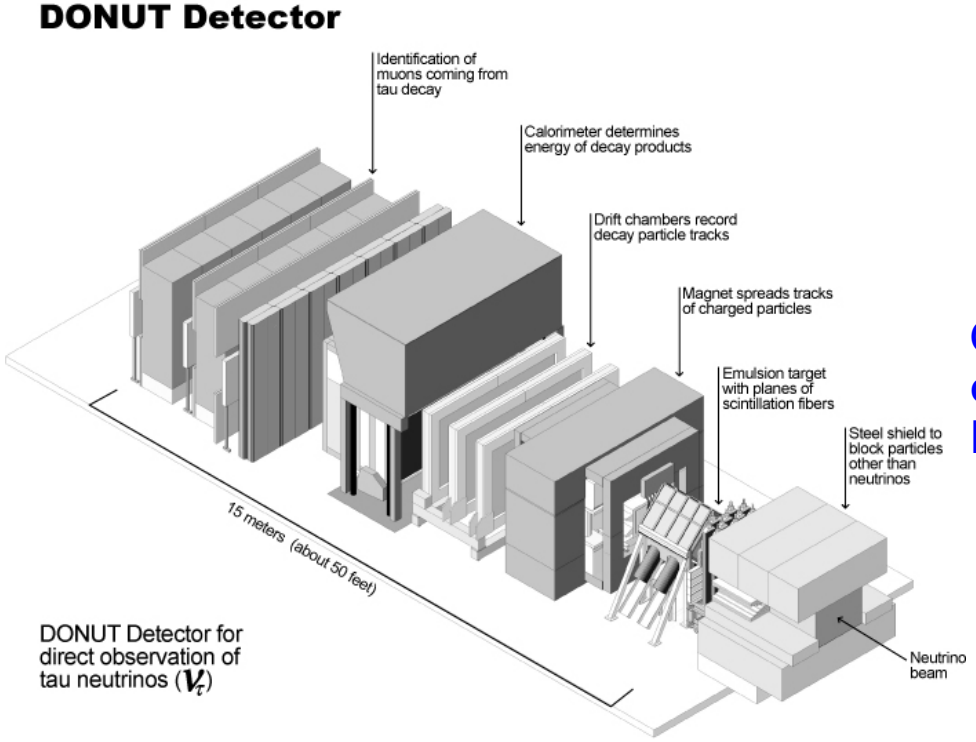
1978 tau lepton discovered by Marty Perl

- Tau lepton discovered at SLAC
  - Quickly realized this was a heavier version of the electron and muon
  - Natural to infer a tau neutrino



Marty Perl

- Direct detection of tau neutrino would have to wait until 2000, discovered by DONUT at the Tevatron



Observed 9 tau neutrino candidate events on a background of 1.5

Ending on a bang...supernova 1987A

- Only SN in our galaxy since we have had large neutrino/proton decay detectors in place
  - Kamiokande--11 events
  - IMB--8 events
  - Baksan--5 events
- IMB and Kamiokande observed a total of 11 neutrino interactions
- Like funding, we anxiously await more...

Fred Reines & Clyde Cowan at Hanford (1953)

Conclusion...

- Have not given nearly enough attention to many other experiments and theoretical work in the 60 year span
  - John Bahcall's work on solar nu theory
  - early solar/atmospheric nu experiments underground by Reines and Goku Menon
  - pi/mu puzzle with Shoichi Sakata Takesi Inoue
- Majority of neutrino work since 1987 has revolved around
  - using brighter sources--June 24 Debbie Harris
  - improving cross-section precision--July 1Kevin McFarland
  - neutrino oscillations--July 8 TBA
- Looking at the 60 year history presented here, it is clear we live in exciting times
  - many new experiments and results
  - theoretical puzzles to be explained