Neutrinos on the Earth and from the Sky

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7th NeXT Workshop
Abingdon, UK

Plan of lectures

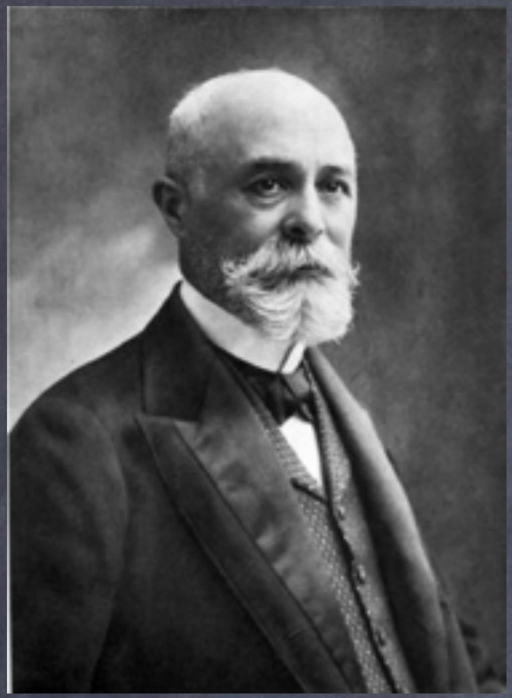
- I From the beginning...
- II Neutrino oscillations
- III High-energy neutrinos
- IV New physics with neutrino telescopes

HOW IT ALL STARTED...

1896: W. C. Röntgen
Discovery of X-rays

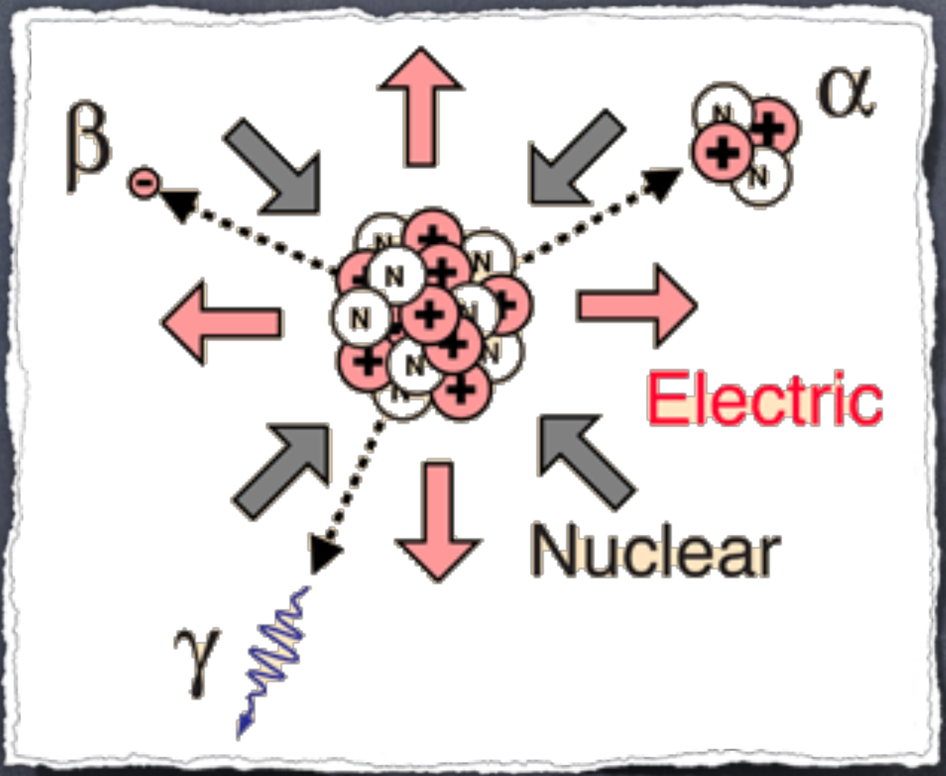
1901: W. C. Röntgen

HOW IT ALL STARTED...



1896: A. H. Becquerel
Discovery of natural radioactivity
1900: β^- is an electron

1899: E. Rutherford
Two types of radiation: β^- and α



1908:E. Rutherford (Chemistry)

1903: A. H. Becquerel, P. Curie and M. Curie

1900: P. Villard
Another type of radiation: γ

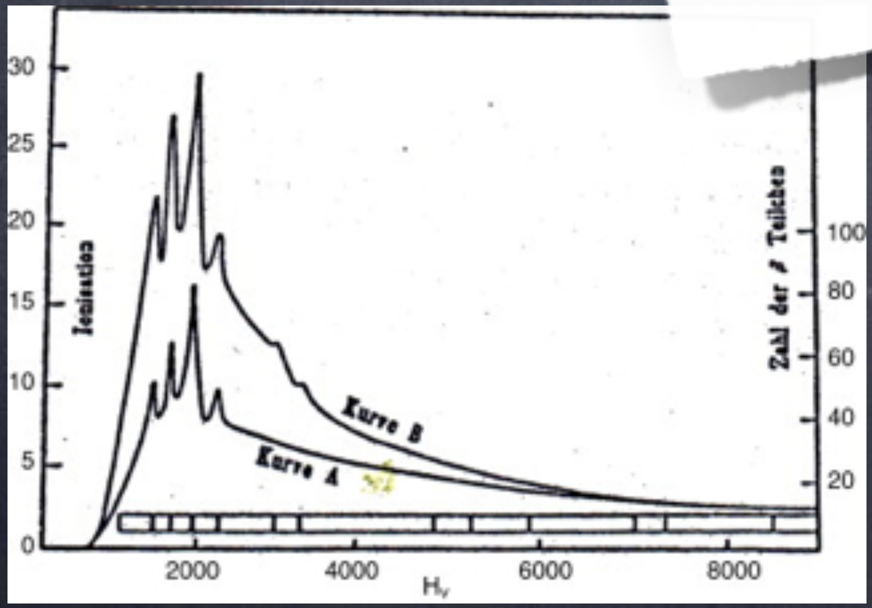
1898- 1902: P. Curie and M. Curie
Discovery of polonium, radium…

AND SOON... CONFUSION...

1914: J. Chadwick
Continuous β^- spectrum

If only electron emission...
two-body final state → single energy!

1922-1930: L. Meitner and others
No secondary process
No γ



J. Chadwick, Verh. Phys. Gesell. 16:383, 1914

1930: N. Bohr
Energy not conserved in β^- decays?

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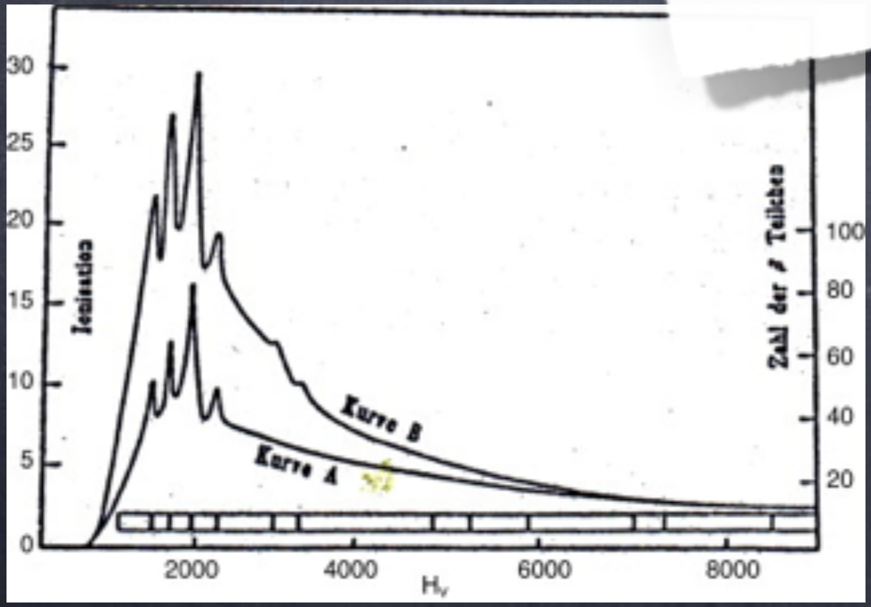


J. Chadwick, Verh. Phys. Gesell. 16:383, 1914

1930: N. Bohr
Energy not conserved in β^- decays?

Pauli to Bohr:
“let this note rest for a good long time and let the stars shine in peace!”

The desperate remedy

1945: W. Pauli
(exclusion principle)

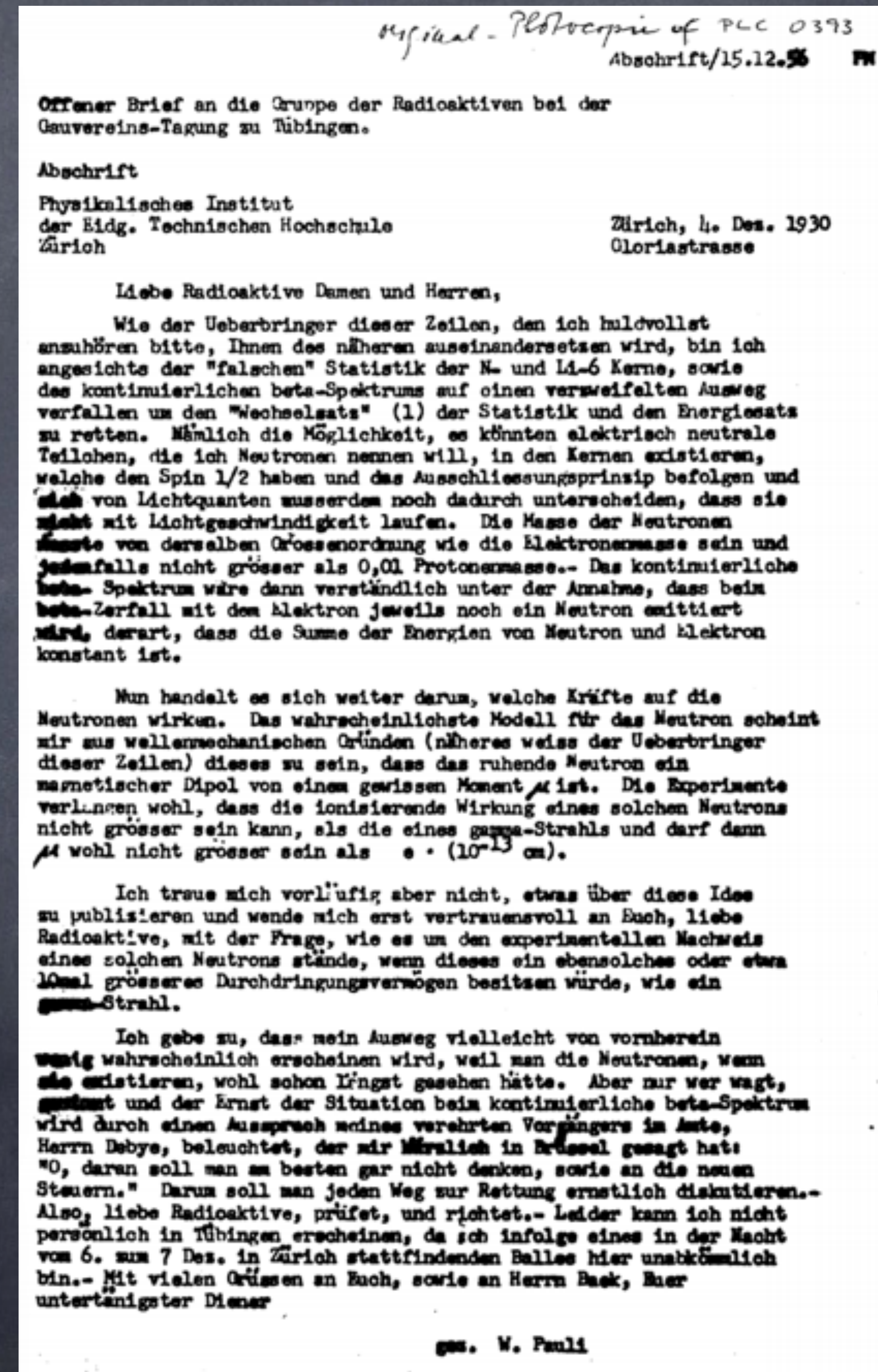
1930: W. Pauli
Proposal of the existence of the neutrino

"in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light"

"so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people"

"I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time"

Debye:
"Oh, It's better not to think about this at all, like new taxes"



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Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

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 Grössenordnung 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.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Neutron or neutrino?

1932: J. Chadwick
Discovery of the neutron

Not Pauli's neutron!

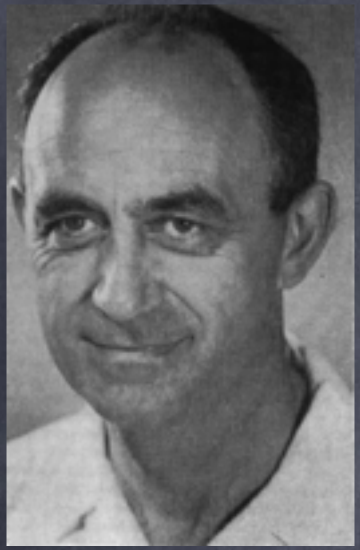
1935: J. Chadwick

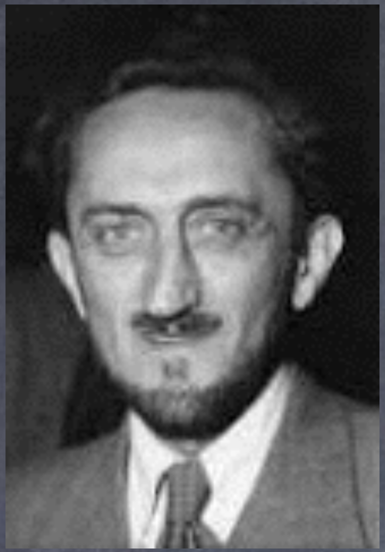
Pauli:
"... their mass cannot be much more than the electron mass. In order to distinguish them from heavy neutrons, Mr. Fermi has proposed to name them "neutrinos". It is possible that the proper mass of neutrinos be zero.... It seems to me plausible that neutrinos have spin 1/2... We know nothing about the interaction of neutrinos with the other particles of matter and with photons..."

1933: E. Fermi
Names the neutrino

or was it actually E. Amaldi?

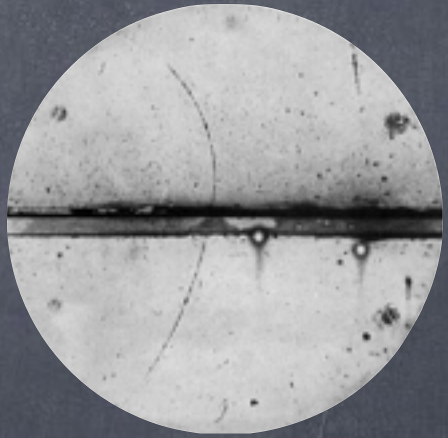
New discoveries





1933: E. Fermi and F. Perrin
Neutrino mass much
smaller than electron's

1933: C. D. Anderson
Discovery of the positron

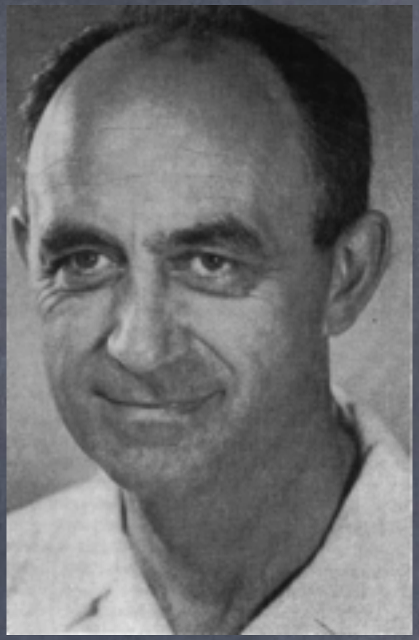


1936: V. F. Hess and C. D. Anderson

1934: F. Joliot and I. Joliot-Curie
Synthesis of radioactive materials
Discovery of β^{+} radiation

1935: F. Joliot and I. Joliot-Curie (Chemistry)

Fermi's theory



1934: E. Fermi
Vectorial theory of β decay

1938: E. Fermi
(discovery of radioactive elements after neutron irradiation)

"A quantitative theory of the emission of β rays is proposed in which **the existence of the "neutrino" is admitted** and the emission of electrons and neutrinos from a nucleus in a β decay is treated with a procedure similar to that followed in the theory of radiation in order to describe the emission of a quantum of light by an excited atom."

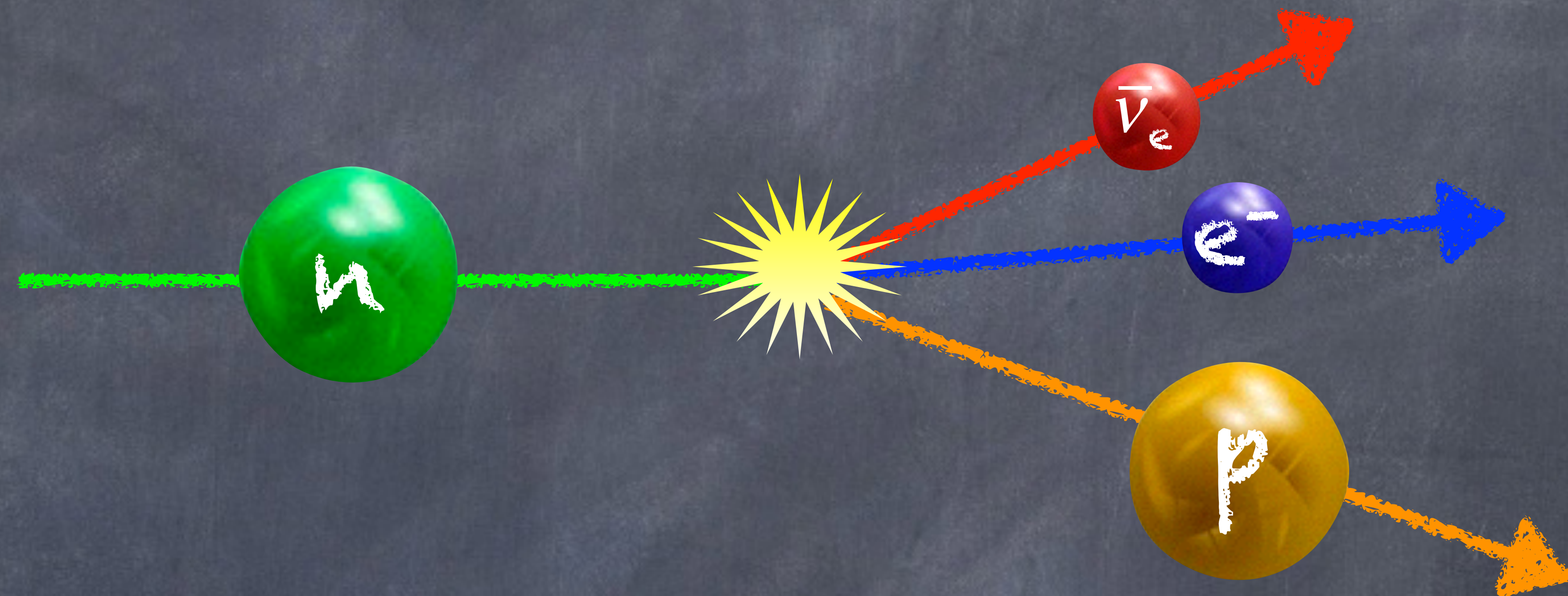
E. Fermi, Nuovo Cim. 11:1, 1934

$$\mathcal{L}_F = G_F \left(\bar{\Psi}_p \gamma_\mu \Psi_n\right)\left(\bar{\Psi}_e \gamma^\mu \Psi_\nu\right) + h.c.$$

Fermi's theory allowed to compute the rates of different processes

neutron decay

(in a nucleus: beta decay)



inverse β decay

(with a nucleus: DIS)

The undetectable neutrino

1967: H. Bethe
(theory of nuclear reactions)

1934: H. Bethe and R. Peierls
Calculation of the neutrino cross section

H. Bethe and R. Peierls,
Nature 133:532, 1934

They computed the neutrino cross section using Fermi theory

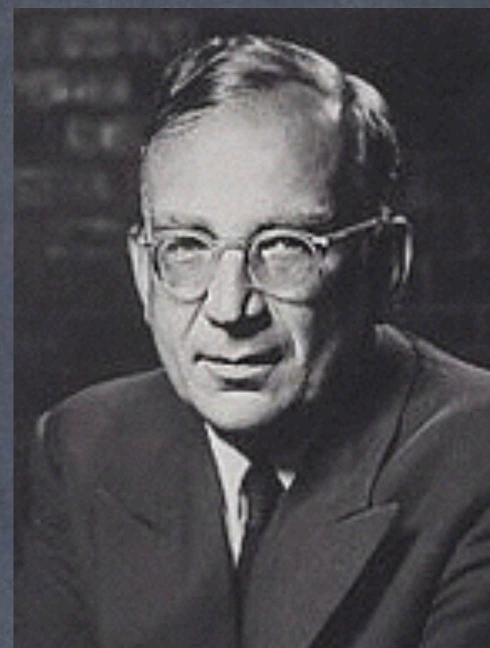
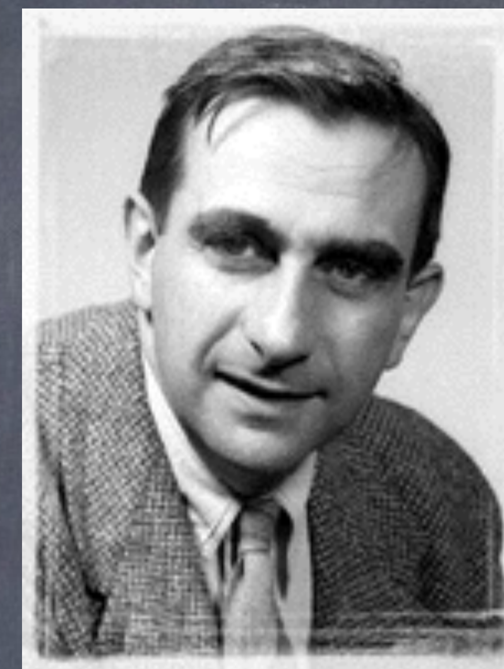
For MeV energies, $\sigma \sim 10^{-44}$ cm^2, which corresponds to a mean free path of ~1000 light years of equivalent hydrogen

"It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations."

"...one can conclude that there is no practically possible way of observing the neutrino."

Pauli: "I have done a terrible thing. I have postulated a particle that cannot be detected."

GENERALIZATION OF FERMI'S THEORY

1936: G. Gamow and E. Teller
Generalization of the Fermi contact theory

Most general Lagrangian invariant under Lorentz transformations and parity

axial vector current allows for different initial and final spins

$$\mathcal{L}_F = \sum_i G_i \left(\bar{\Psi}_p \mathcal{O}_i \Psi_n\right)\left(\bar{\Psi}_e \mathcal{O}^i \Psi_\nu\right) + h.c.$$

$$\mathcal{O}_i = \left\{1, \gamma_\mu, \gamma_\mu\gamma_5, \gamma_5, \sigma_{\mu\nu}\right\}$$

ONLY ONE NEUTRINO?

1942: Y. Tanikawa
1943: S. Sakata and T. Inouë
1947: R. Marshak and H. Bethe
Suggested the existence of two type of mesons

Two types of mesons:
one type of meson (pion) interacts with nuclear matter and decays to form another type of meson (muon), which does not interact with nuclei

1947: C. F. Powell
Discovery of the pion

1950: C. F. Powell

1943: S. Sakata and T. Inouë
Suggested the possibility of more than one type of neutrinos

$$m \to e + n + \nu$$

$$n \neq \nu$$

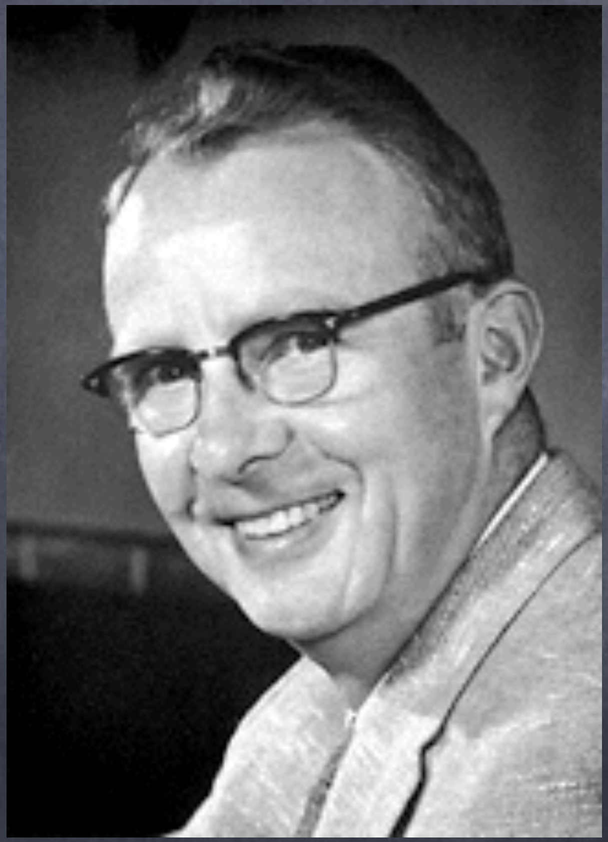
THE RACE FOR NEUTRINO DISCOVERY

Which reaction to use?

$$^{37}\mathrm{Cl} + \nu \rightarrow e^- + ^{37}\mathrm{Ar}\ ?$$

1946: B. Pontecorvo
Suggested the reaction $^{37}Cl(\nu,e^-)^{37}Ar$ to detect reactor neutrinos

Pontecorvo described in great detail how to do it



1949: L. W. Álvarez
Proposed to use that reaction to detect solar neutrinos

1968: L. W. Álvarez (hydrogen bubble chamber and discovery of resonances)

THE RACE FOR NEUTRINO DISCOVERY

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

- Liquid scintillator: detect e^{+}
- Big experimental improvement: liquid scintillators of up to 1 ton (up to about 1950, only 1 kg)

... but how to find an intense enough neutrino source?

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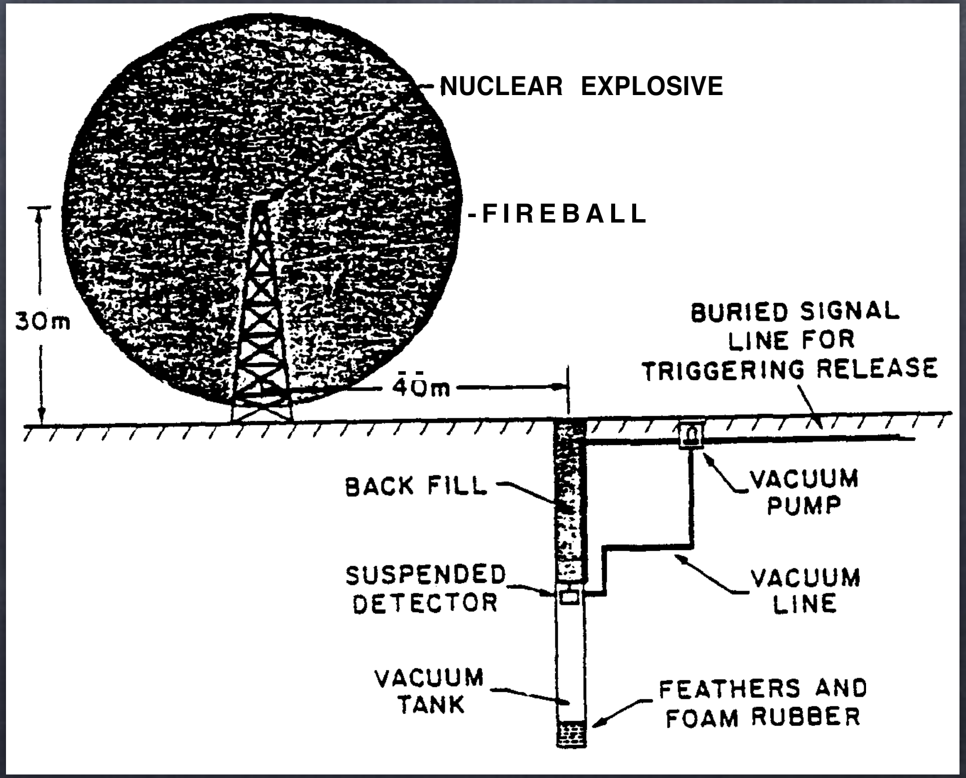
... but how to find an intense enough neutrino source?

1951: F. Reines and C. Cowan
The project got approved at Los Alamos

WHAT ABOUT A NUCLEAR BOMB?

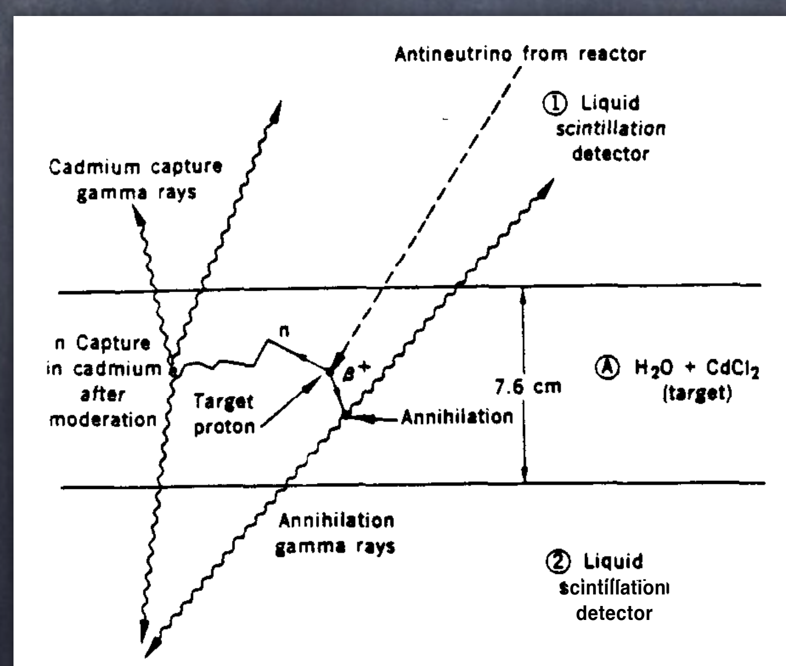


THE RACE FOR NEUTRINO DISCOVERY

1953: F. Reines and C. Cowan
First attempt at the Hanford reactors

1955: R. Davis
Used Pontecorvo reaction with no success

Also using neutron detection in coincidence

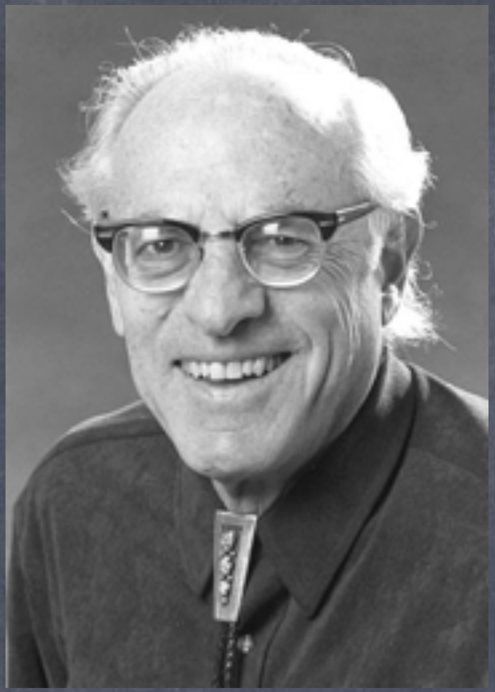


Why??

But too high cosmic-ray backgrounds

THE NEUTRINO DISCOVERY

1995: F. Reines and M. Perl
(Cowan died in 1974)



1956: F. Reines and C. Cowan
Discovery of the neutrino at Savannah River

THE NEUTRINO DISCOVERY

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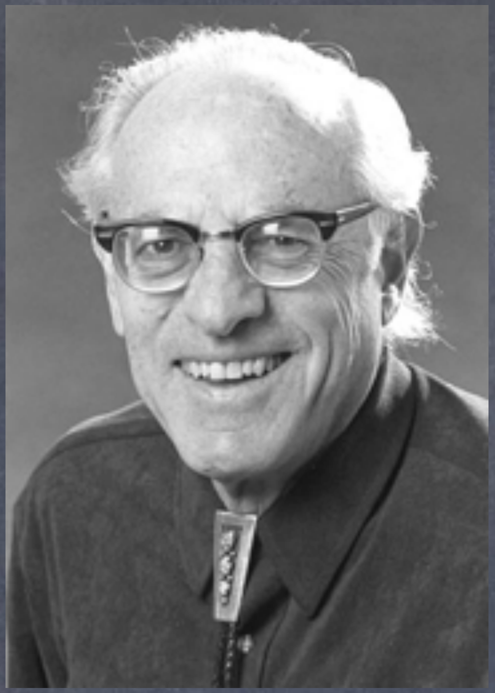

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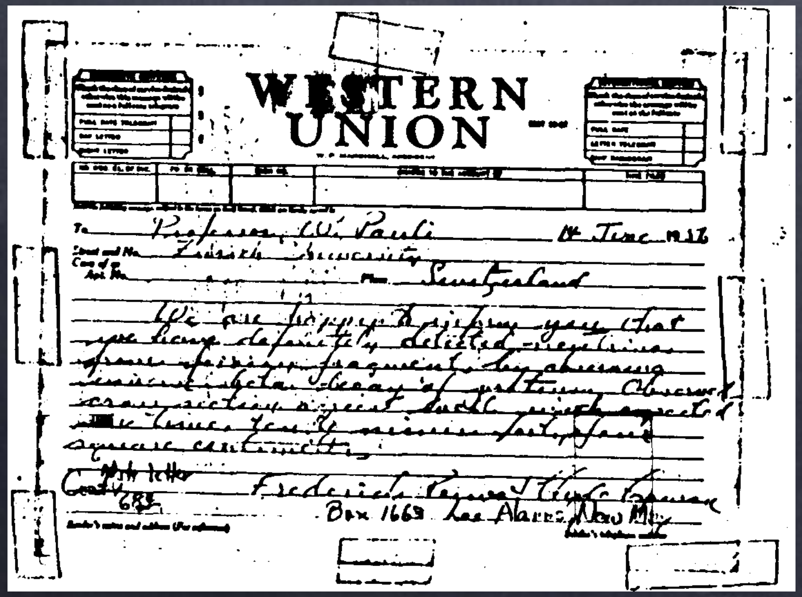
Telegram to Pauli:



WESTERN UNION

To Professor W. Pauli 14 June 1956
Zurich University
Switzerland

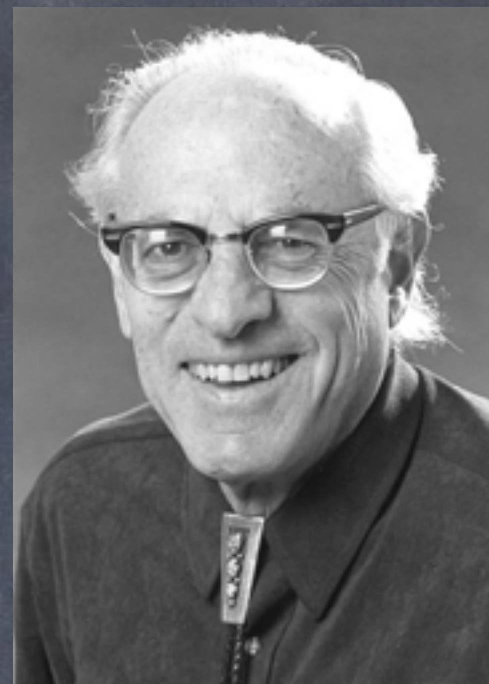
We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters.

Night letter
Govt
685

Frederick Reines Clyde Cowan
Box 1663 Los Alamos New Mex

THE NEUTRINO DISCOVERY

1995: F. Reines and M. Perl
(Cowan died in 1974)



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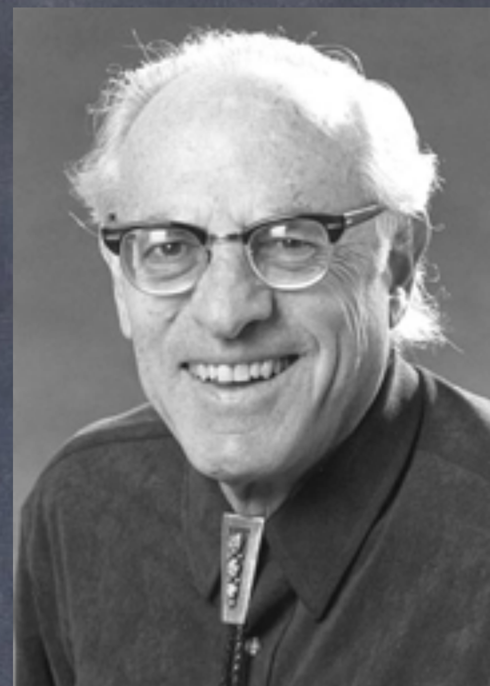

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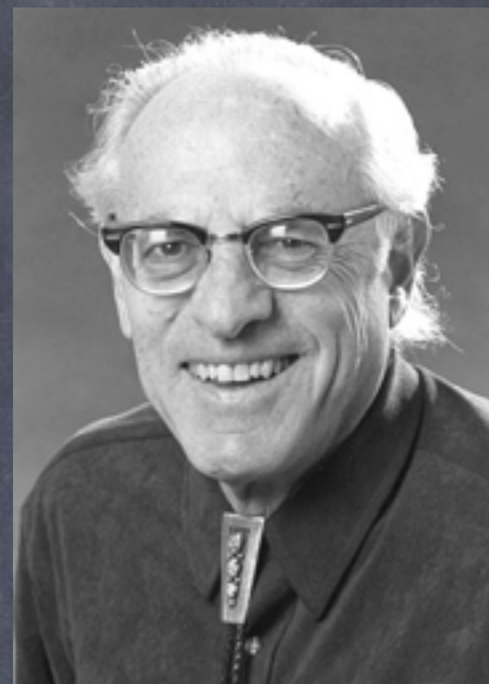
Pauli's reply:

Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who knows how to wait.
Pauli

THE NEUTRINO DISCOVERY

1995: F. Reines and M. Perl (Cowan died in 1974)



1956: F. Reines and C. Cowan
Discovery of the neutrino at Savannah River

Reines, confronting Bethe's 1934 statement after the discovery

Telegram to Pauli:

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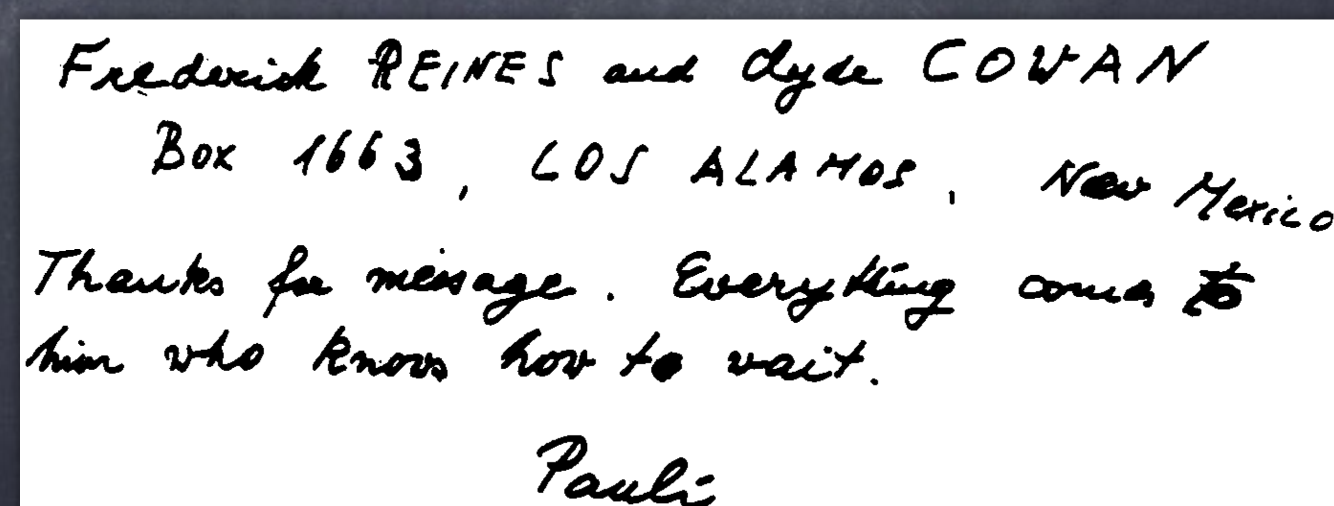

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PARITY VIOLATION

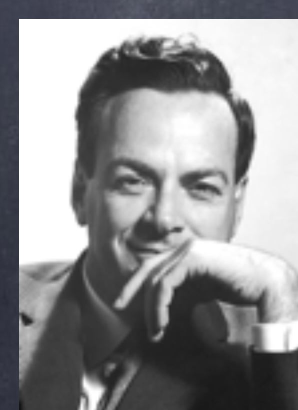
1957: T. D. Lee and C. N. Yang

1956: T. D. Lee and C. N. Yang
Suggested parity might be violated in weak interactions

1957: C. S. Wu (E. Ambler, R. W. Hayward, D. D. Hopps and R. P. Hudson)
Discovery of parity violation in β decays of Co

$$\mathcal{L}_{LY} = \sum_i \left(\bar{\Psi}_p \mathcal{O}_i (G_i + G'_i \gamma_5) \Psi_n\right)\left(\bar{\Psi}_e \mathcal{O}^i (G_i + G'_i \gamma_5) \Psi_\nu\right) + h.c.$$






1965: S. Tomonaga, J. Schwinger and R. P. Feynman (work on quantum electrodynamics)

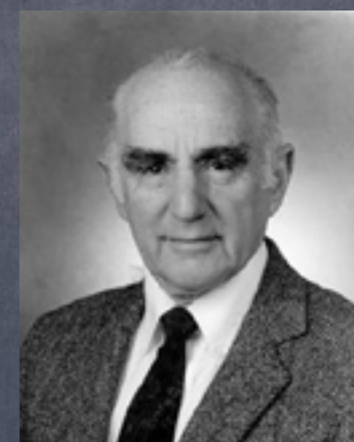
1969: M. Gell-Mann (classification of elementary particles)

1958: E. C. G. Sudarshan, R. E. Marshak, R. P. Feynman and M. Gell-Mann
Proposed a universal theory of parity violating V-A weak interactions, G=-G′

Chiral neutrinos: neutrino helicity

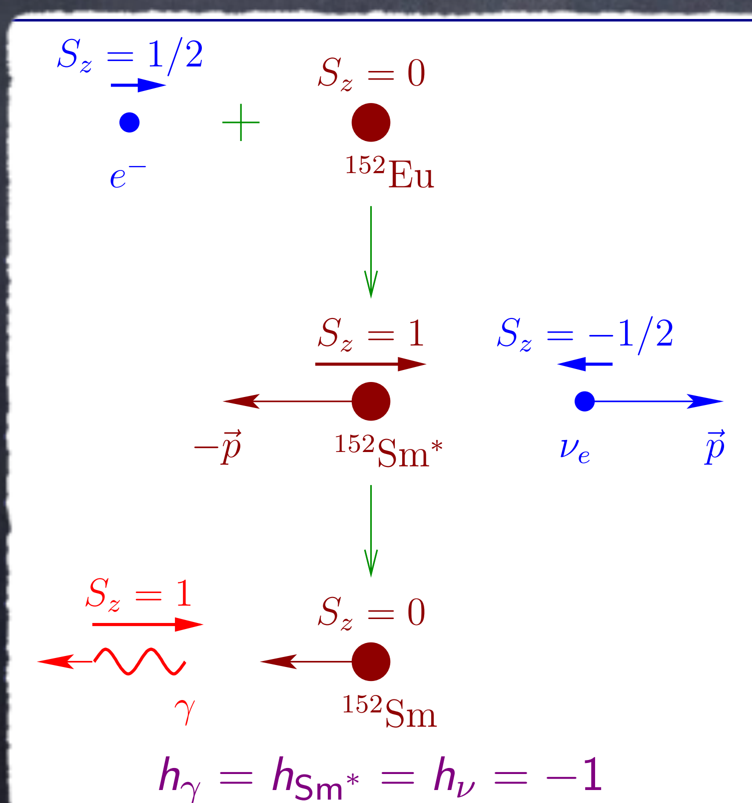
left-handed neutrinos and right-handed antineutrinos?

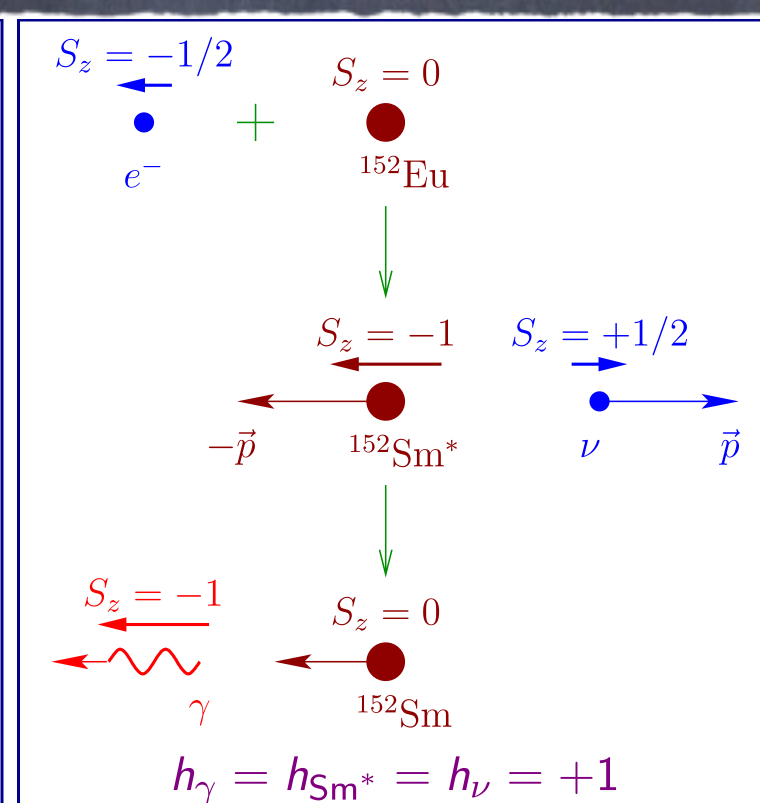
Possible if parity is violated and neutrinos are massless


1958: M. Goldhaber, L. Grodzins and A. W. Sunyar

Measurement of the neutrino helicity





$h_\gamma = -0.91 \pm 0.19 \Rightarrow$

neutrinos are left-handed

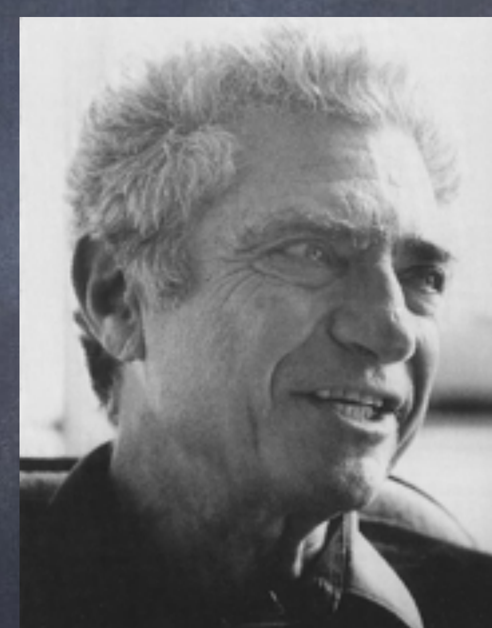
From C. Giunti

TWO NEUTRINO FLAVORS

1959: B. Pontecorvo
Suggested that neutrinos in beta decay and from pion decay might be different
Suggested a beam from pion decays

$$\pi^+ \rightarrow \mu^+ + \nu \quad \longrightarrow \quad \nu + n \rightarrow p + e^-$$

SOURCE — PROPAGATION — DETECTOR

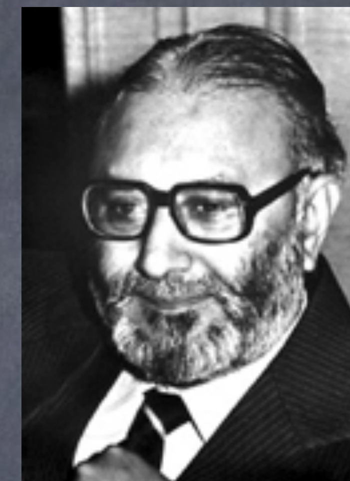


1962: L. Lederman, J. Steinberger and M. Schwartz
Discovery of muon neutrinos at BNL

1988: L. Lederman, J. Steinberger and M. Schwartz

THE STANDARD MODEL





1979: S. L. Glashow, S. Weinberg and A. Salam

1961: S. L. Glashow **1967: S. Weinberg** **1968: A. Salam**

Established electroweak unification within the V-A theory

assuming massless left-handed neutrinos and right-handed antineutrinos

$$\nu_L \xrightarrow{P} \cancel{\nu_R} \qquad \bar{\nu}_R \xrightarrow{P} \cancel{\bar{\nu}_L}$$

P: left-right

$$\nu_L \xrightarrow{C} \cancel{\bar{\nu}_L} \qquad \bar{\nu}_R \xrightarrow{C} \cancel{\nu_R}$$

C: particle-antiparticle

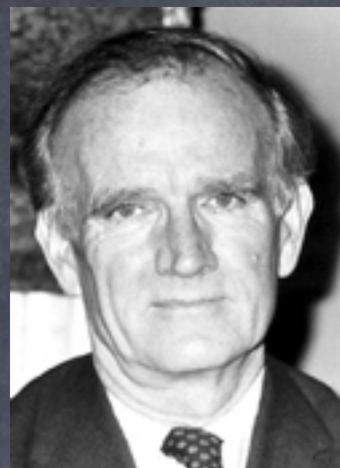


1970: S. L. Glashow, J. Iliopolus and L. Maiani
Predicted the existence of a fourth quark


1974: B. Richter and S. L. Ting
Discovery of the charm quark

1976: B. Richter and S. L. Ting

THE THIRD GENERATION

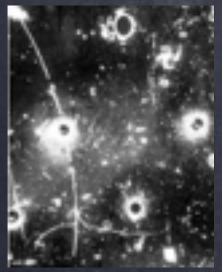



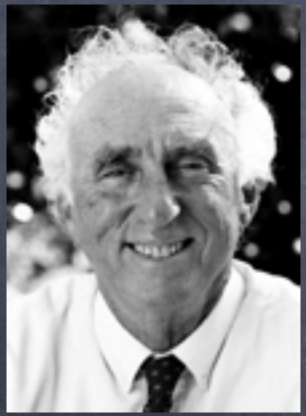
1964: J. W. Cronin, V. L. Fitch, J. H. Christenson and R. Turlay
Discovery of CP violation in the quark sector


1980: J. W. Cronin and V. L. Fitch


1973: M. Kobayashi and T. Maskawa
Understood three families are needed for CP violation


2008: Y. Nambu, M. Kobayashi and T. Maskawa


1973: Neutral currents are observed at CERN



1995: F. Reines and M. Perl

1975: M. Perl
Discovery of the tau lepton

2000: DONUT Collaboration
Discovery of the tau neutrino at Fermilab

1977: Discovery of the b quark at Fermilab
1989: Measurement of the Z width at LEP (three light neutrinos)
1995: Discovery of the t quark at Fermilab

NEUTRINOS IN THE STANDARD MODEL

SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_Q$$

	Left-handed		Right-handed		
	$(1,2)_{-1/2}$	$(3,2)_{1/6}$	$(1,1)_{-1}$	$(3,1)_{2/3}$	$(3,1)_{-1/3}$
	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^c \\ d^c \end{pmatrix}_L$	e_R	u_R	d_R
Leptons / Quarks	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^c \\ s^c \end{pmatrix}_L$	μ_R	c_R	s_R
	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^c \\ b^c \end{pmatrix}_L$	τ_R	t_R	s_R

No ν_R !

$$Q = I_3 + Y$$

NEUTRINOS IN THE STANDARD MODEL

Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau$

(gauge invariance and renormalizability)

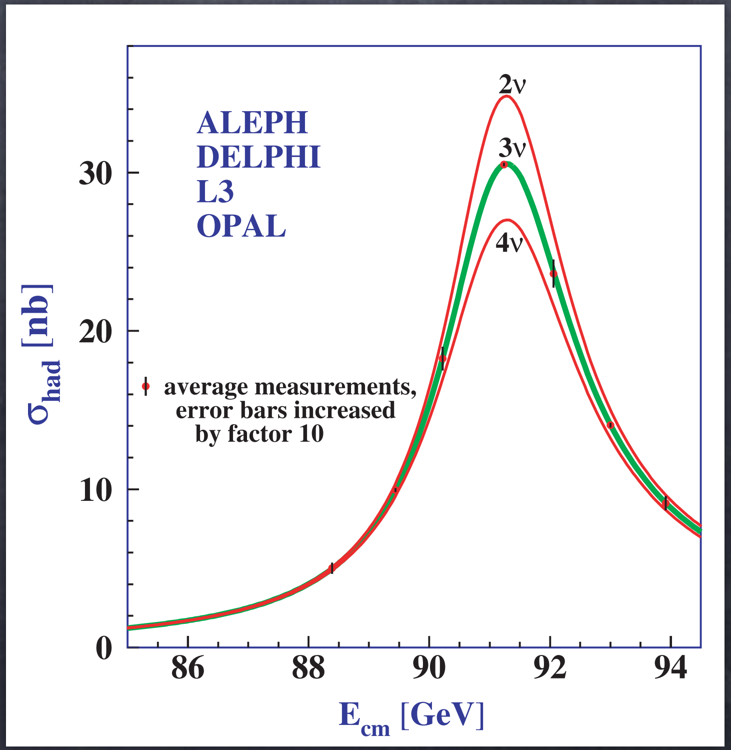
Lepton number ($L = L_e + L_\mu + L_\tau$) is conserved

Lepton flavor is conserved ⇔ Neutrinos are massless

Invisible Z decay

Only 3 (light & active) neutrinos

$N_\nu = 2.9840 \pm 0.0082$



[ALEPH, DELPHI, L3, OPAL, SLD, LEP Collaborations], Phys. Rept. 427:257, 2006

NEUTRINO MASSES

We have observed that neutrinos oscillate (next lecture)

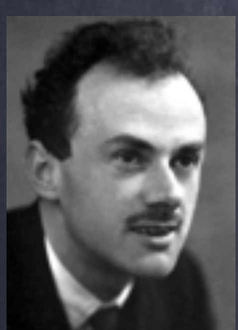
$\Downarrow$

Lepton flavor is violated

$\Downarrow$

add neutrino masses to SM

1933: E. Schrödinger and P. A. M. Dirac



introduce ν_R and conserve L		violate L (in two units)
Dirac: $\nu \neq \nu^C$	$\nu^C \equiv C\ \overline{\nu}^T$	**Majorana:** $\nu = \nu^C$
$M_\nu^D \overline{\nu}_L \nu_R$	$C = i\gamma_2\gamma_0$	$\frac{1}{2} M_\nu^M \overline{\nu}_L \nu_L^C$

Dirac spinor

Two 2-component Weyl spinors

$$\nu = P_L\nu + P_R\nu = \begin{pmatrix} \nu_L \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ \nu_R \end{pmatrix}$$

Majorana field

Only one 2-component Weyl spinor

$$\nu = \nu^c = P_L\nu + P_R\nu = \begin{pmatrix} \nu_L \\ 0 \end{pmatrix} + C\overline{\begin{pmatrix} \nu_L \\ 0 \end{pmatrix}}^T$$

$$(\nu_L)^c = (\nu^c)_R \qquad (\nu_R)^c = (\nu^c)_L$$

charge conjugation change chirality

Dirac mass term

$$-\mathcal{L}^D = \sum_{\alpha\beta} \bar{L}_\alpha \, Y_{\alpha\beta} \, \tilde{\Phi} \, (\nu_R)_\beta + h.c.$$

After Spontaneous Symmetry Breaking (Higgs acquires vev)

$$-\mathcal{L}^D = \sum_{\alpha\beta} (\bar{\nu}_L)_\alpha M^D_{\alpha\beta} (\nu_R)_\beta + h.c. = \sum_{\alpha\beta i} (\bar{\nu}_L)_i U^\dagger_{i\alpha} M^D_{\alpha\beta} V_{\beta i} (\nu_R)_i + h.c. = \sum_{\alpha\beta i} (\bar{\nu}_L)_i m_i (\nu_R)_i + h.c.$$

$$m_i = \sum_{\alpha\beta} U^\dagger_{i\alpha} \, M^D_{\alpha\beta} \, \mathrm{V}_{\beta i} = \sum_{\alpha\beta} U^\dagger_{i\alpha} \, \frac{v}{\sqrt{2}} Y_{\alpha\beta} \, \mathrm{V}_{\beta i} = \frac{v}{\sqrt{2}} Y_i$$

small masses = small Yukawas

$$(\nu_L)_\alpha = U_{\alpha i} (\nu_L)_i \qquad (\nu_R)_\alpha = V_{\alpha i} (\nu_R)_i$$

PMNS

unitary matrices

CC and NC terms

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W_\mu^+ \sum_{ij} \left(\bar{\ell}_{Li}\ \gamma^\mu (U)_{ij} \nu_{Lj} + \bar{U}_{Li}\ \gamma^\mu \left(U_{CKM}\right)_{ij} D_{Lj} \right) + h.c.$$

choosing diagonal charged lepton mass matrix

with 3 neutrino mass eigenstates

$$UU^\dagger \equiv U_{PMNS}\ U_{PMNS}^\dagger = 1_{3\times 3}$$

with 3+n neutrino mass eigenstates

$$UU^\dagger \neq 1_{(3+n)\times(3+n)}$$

flavor basis would not be orthonormal (at low energies)

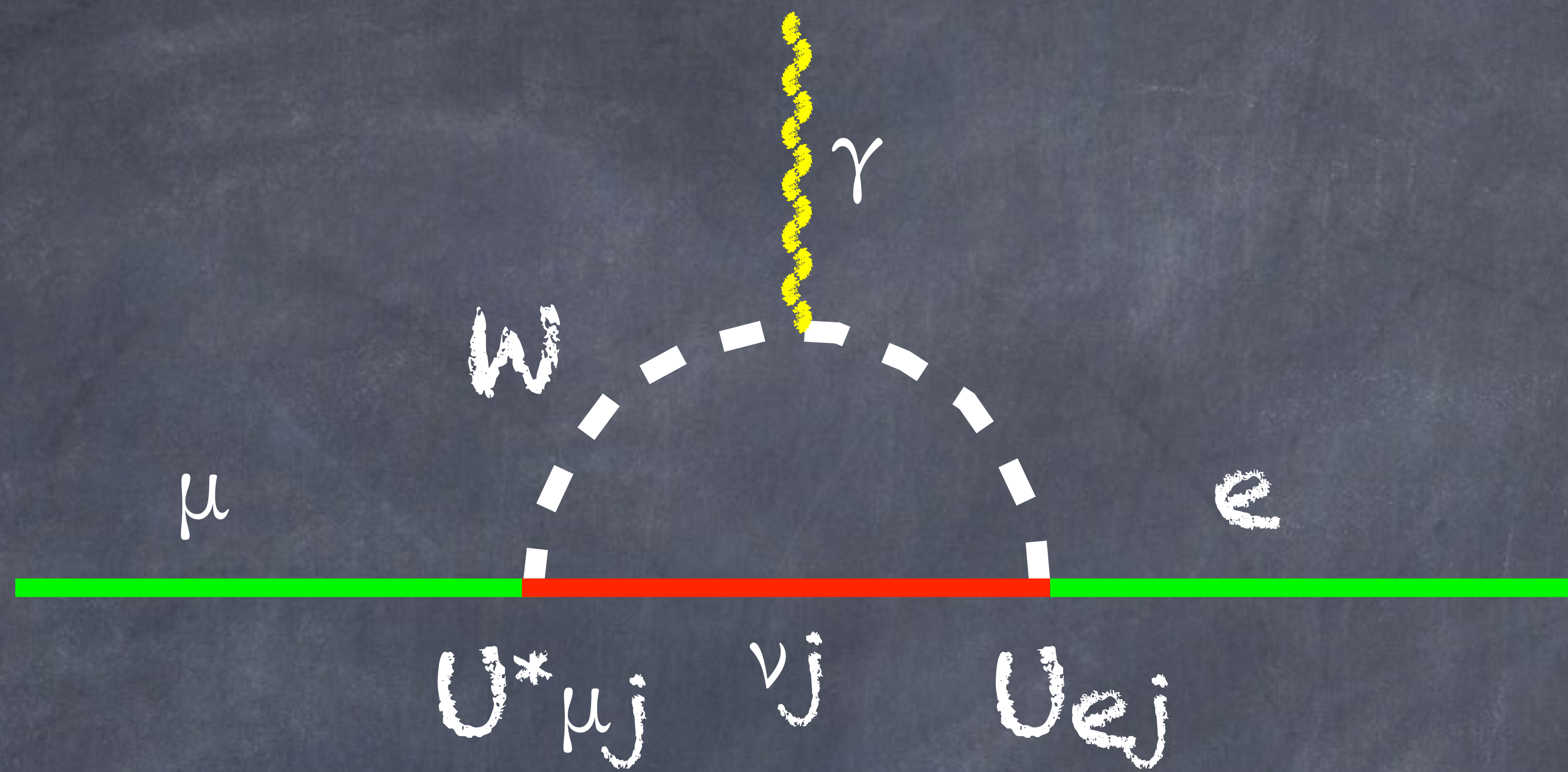
$$\mathcal{L}_{NC} = \frac{g}{2\cos\theta_W} Z_\mu \sum_{ij} \left(\bar{\nu}_{Li}\ \gamma^\mu \left(U^\dagger\right)_{ij} (U)_{ij} \nu_{Lj} + \bar{U}_{Li}\ \gamma^\mu \left(U_{CKM}\right)_{ij} \left(U_{CKM}^\dagger\right)_{ij} U_{Lj} \right) + h.c.$$

chiral flavor diagonal interaction

ν_R is sterile

with 3+n neutrino mass eigenstates,
it is convenient to redefine flavor states

Lepton Flavor violation



$$\Gamma \propto G_F^2 m_\mu^5 \alpha_{em} \left| \sum_j U^*_{\mu j} U_{ej} \frac{m_j^2}{M_W^2} \right|^2$$

$BR_{SM} < 10^{-50}$

$BR_{exp} < 4 \times 10^{-13}$

A. M. Baldini [MEG Collaboration], Eur. Phys. J. C76:434, 2016

WINDOW TO NEW PHYSICS

Dirac mass term

- need to introduce singlet ν_R
- mass hierarchy problem with leptons
- Lepton Flavor (LF) is violated
- Lepton Number (LN) is conserved
- mixing among flavor states

Majorana mass term

$$\nu = \nu^C \equiv C\ \overline{\nu}^T$$

introduce ν_R

$$-\mathcal{L}_R^M = \frac{1}{2} m_R \overline{\nu}_R \nu_R^C + h.c.$$

invariant under SU(2)xU(1)

use ν_L

$$-\mathcal{L}_L^M = \frac{1}{2} m_L \overline{\nu}_L \nu_L^C + h.c.$$

not invariant under SU(2)xU(1)

needs extra fields

$$\overline{(\nu_L)^C} M_L^M \nu_L = -\left(\nu_L^T C^{-1} M_L^M \nu_L\right)^T = \nu_L^T \left(C^{-1}\right)^T \left(M_L^M\right)^T \nu_L = \overline{(\nu_L)^C} \left(M_L^M\right)^T \nu_L$$

symmetric mass matrix

Majorana mass term

- no need to introduce singlet ν_R (but extra fields) OR introduce singlet ν_R
- Lepton Flavor (LF) is violated
- Lepton Number (LN) is violated
- mixing among flavor states

Dirac-Majorana mass term

only adding right-handed neutrinos

$$M^{D+M} = \begin{pmatrix} 0 & (M^D)^T \\ M^D & M^R \end{pmatrix}$$

- mass eigenvalues of $M_R \gg v \Longrightarrow$ 3 light neutrinos and 3 heavy neutrinos (seesaw mechanism)

- mass eigenvalues of $M_R \lesssim v \Longrightarrow$ more than 3 light neutrinos (only 3 active!)

- mass eigenvalues of $M_R \ll v \Longrightarrow$ pseudo-Dirac neutrinos

Low-energy picture

- From oscillations (next lecture):
  - At least two massive neutrinos
  - Three non-zero mixings

- strong mass hierarchy with leptons
- Dirac or Majorana?
- 3 light states? but some anomalies (next lecture)

- UV complete models:
  - Why are neutrinos much lighter than leptons?

Origin of mass

  - Why is mixing so different from quarks'?

Flavor problem

SM as an Effective low energy theory

non-renormalizable higher-dimension operators
(invariant under SU(2)xU(1))

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \ldots = \mathcal{L}_{SM} + \sum_{n>4} \frac{c_n}{\Lambda_{NP}^{n-4}} \mathcal{O}_n$$

same particle content as SM
coefficients dependent on new physics scale Λ_{NP}

only 1 dim-5 operator

$$\delta\mathcal{L}^{d=5} = \frac{g_{ij}}{\Lambda_{NP}} \left(\bar{L}_{L,i}\tilde{\Phi}\right)\left(\tilde{\Phi}^T L_{L,j}^C\right) \xrightarrow{\text{SSB}} \delta\mathcal{L}^{d=5} = \left(\bar{\nu}_L\right)_i \frac{1}{2} \frac{g_{ij} v^2}{\Lambda_{NP}} \left(\nu_L^C\right)_j$$

S. Weinberg, Phys. Rev. Lett. 43:1566, 1979

Majorana mass

SM as Effective low energy theory

$$m_\nu \approx \frac{g\, v^2}{\Lambda_{NP}}$$

$m_\nu \ll m_{fermion} = y_{fermion}\, v$ if $\Lambda_{NP} \gg v$

$m_\nu \sim 0.1$ eV → $g \sim 10^{-5} - 1$ → $\Lambda_{NP} \sim (10^9 - 10^{14})$ GeV

Right scale for leptogenesis

... but if $g \sim (y_e)^2$ (or even smaller) → $\Lambda_{NP} \sim$ TeV

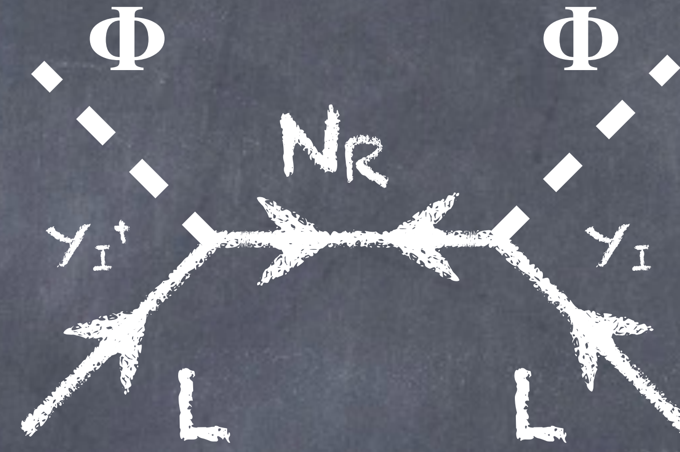
Colliders?

Tree-level realizations: See-saw

Type I: fermion singlet

$$-\mathcal{L}_{I} = \bar{L}\tilde{\Phi} Y_{I}^{\dagger} N_R + \frac{1}{2}\bar{N}_R M_R N_R^c + h.c.$$

$$M_\nu = -\frac{1}{2} Y_{I}^{T} M_R^{-1} Y_{I} v^2$$



minimal seesaw: only R neutrinos

Type II: scalar triplet

$$-\mathcal{L}_{II} = M_\Delta^2 |\Delta|^2 + \bar{\tilde{L}} Y_{II} \left(\vec{\sigma}\cdot\vec{\Delta}\right) L + \mu \Phi^\dagger \left(\vec{\sigma}\cdot\vec{\Delta}\right)^\dagger \Phi + h.c.$$

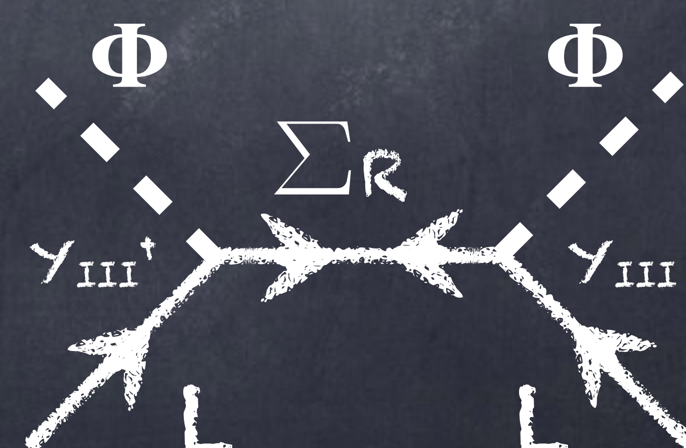
$$M_\nu = -2 Y_{II} \frac{\mu}{M_R^2} v^2$$

minimal seesaw without R neutrinos

Type III: fermion triplet

$$-\mathcal{L}_{III} = \bar{\vec{\Sigma}}_R Y_{III} \left(\tilde{\Phi}^\dagger \vec{\sigma} L\right) + \frac{1}{2}\bar{\vec{\Sigma}}_R M_R \vec{\Sigma}_R^c + h.c.$$

$$M_\nu = -\frac{1}{2} Y_{III}^{T} M_R^{-1} Y_{III} v^2$$



LFV & Colliders

- From oscillations we know Lepton Flavor is not conserved
  - However, if only dim=5 operators, LFV is very small
- dim=6 operator are LNC (e.g, $\bar{L}\bar{L}LL$), but LFV... can we decouple LFV and LNV?

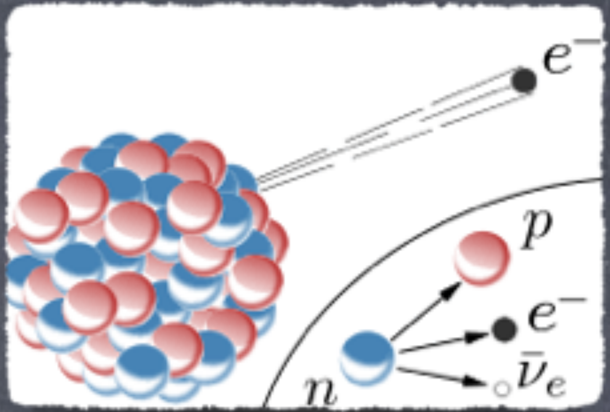
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_5}{\Lambda_{LN}} \mathcal{O}_5 + \sum_i \frac{c_{6,i}}{\Lambda_{LF}^2} \mathcal{O}_{6,i}$$

  - Scale Λ_{LN}: responsible for small neutrino masses
  - Scale Λ_{LF} ($\ll \Lambda_{LN}$): responsible for LFV processes
- Collider signatures?
  - If heavy state $M \sim \Lambda_{LF} \sim$ TeV (or $\Lambda_{LN} \sim$ TeV)
  - If c_5 related to c_6 $\Rightarrow$ LFV and collider signatures are related to m_ν

but what is the scale of m_ν?

BETA DECAY

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



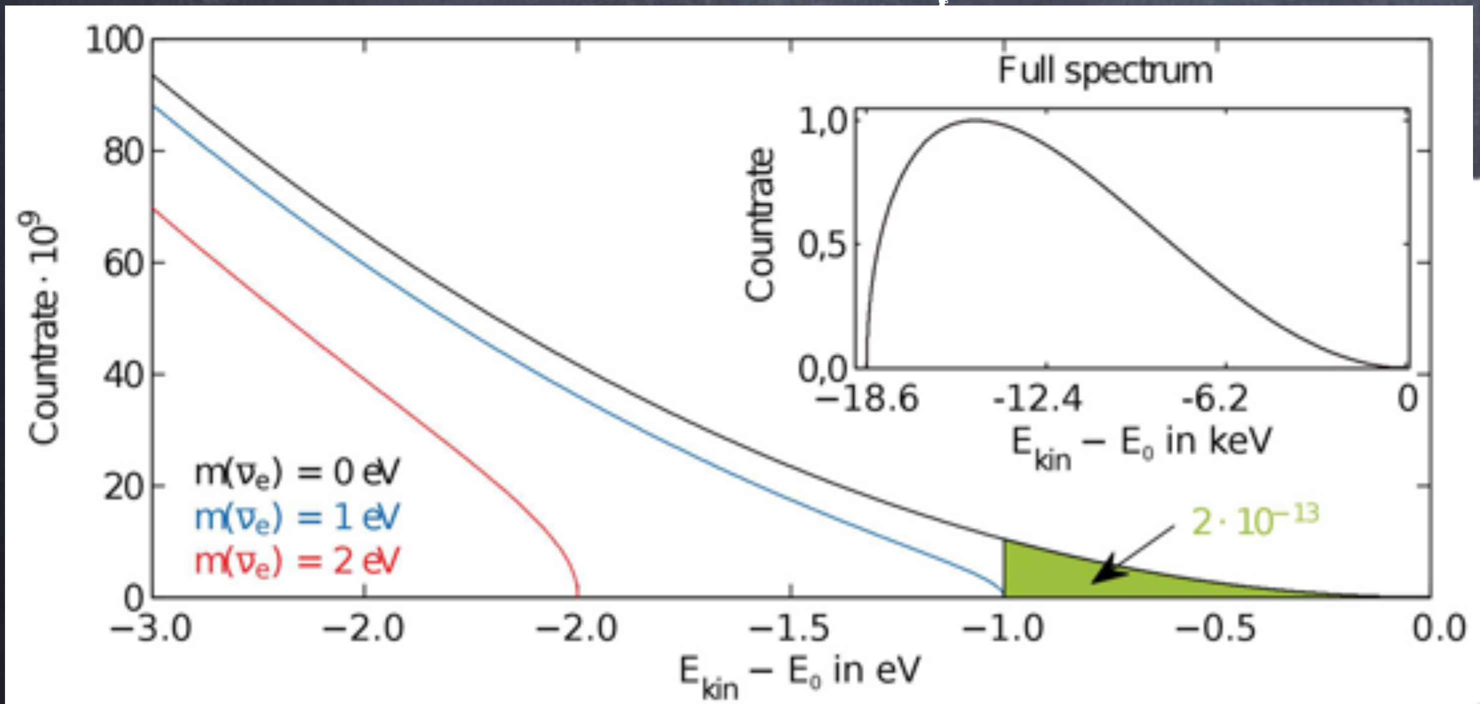
$$\frac{d\Gamma}{dT} \propto K^2(T)$$

$$Q = M_H - M_{He} - m_e = 18.58 \text{ keV}$$

$$K(T) = \sqrt{(Q-T)\sqrt{(Q-T)^2 - m_\beta^2}}$$

$$m_\beta^2 = \sum_j |U_{ej}|^2 m_j^2 = \begin{cases} NO: m_l^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 + \Delta m_{31}^2 s_{13}^2 \\ IO: m_l^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 - \Delta m_{31}^2 s_{13}^2 \end{cases}$$

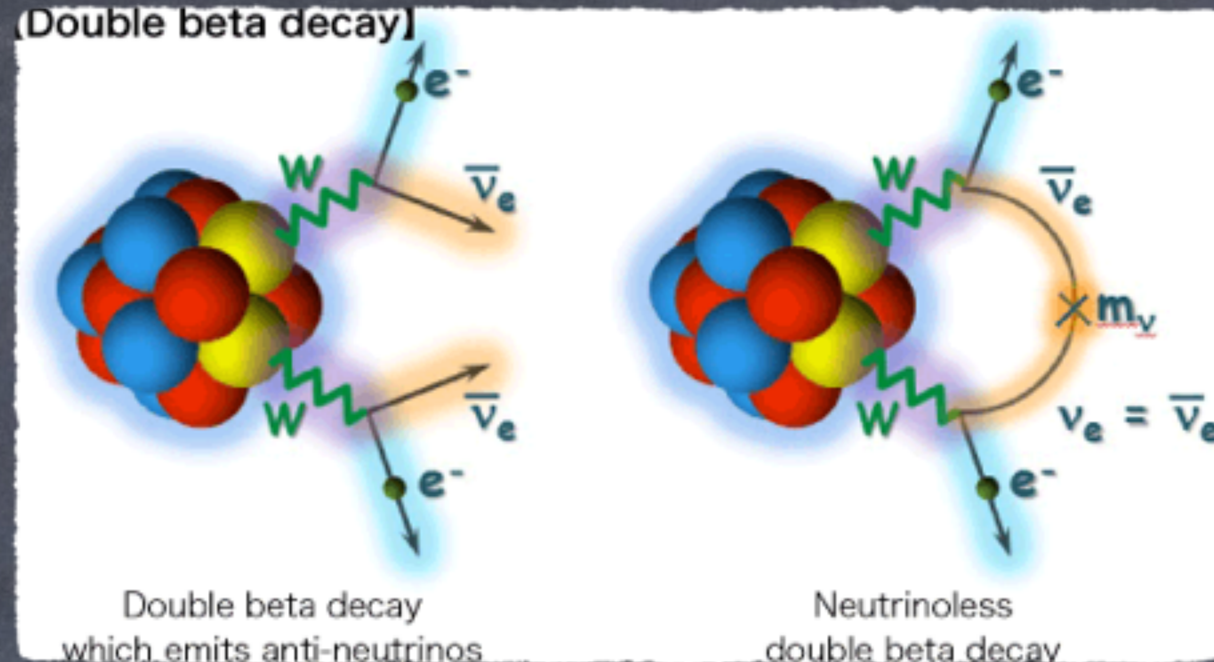
distortion of the Kurie plot



Present bound (Troitsk & Mainz):
$m_\beta < 2.2$ eV (95% CL)

Future sensitivity (KATRIN):
$m_\beta \sim 0.2$ eV

NEUTRINOLESS DOUBLE BETA DECAY



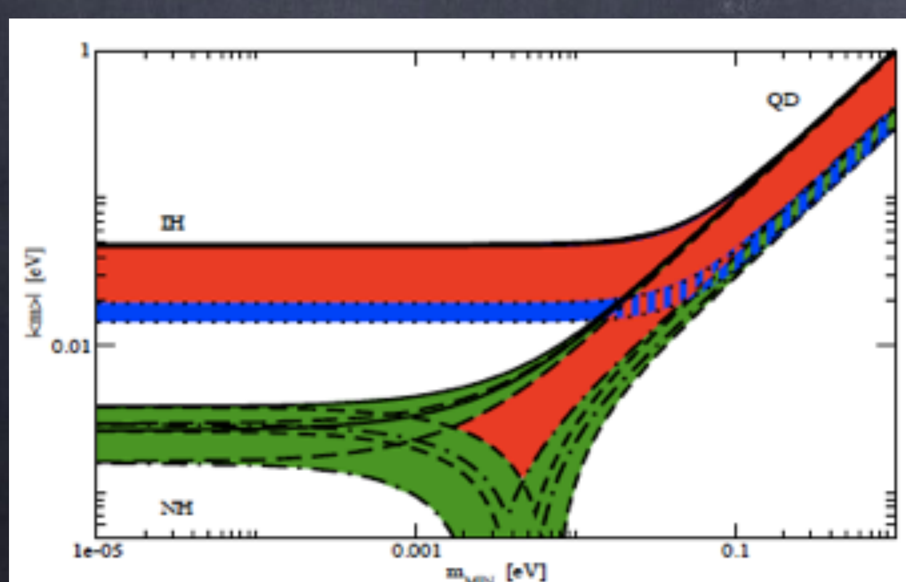
$\Delta L = 0$

$$(T_{1/2})^{2\nu} = (G_{2\nu}\ |M_{2\nu}|^2)^{-1}$$

$\Delta L = 2$

$$(T_{1/2})^{0\nu} = (G_{0\nu}\ |M_{0\nu}|^2\ |m_{\beta\beta}|^2)^{-1}$$

$$m_{\beta\beta} = \sum_j U_{ej}^2 m_j = \left| c_{13}^2 c_{12}^2 m_1 e^{i\eta_1} + c_{13}^2 s_{12}^2 m_2 e^{i\eta_2} + s_{13}^2 m_3 e^{-i\delta} \right|$$



Present bounds: $m_{\beta\beta} < 0.1\text{–}0.8$ eV

important nuclear uncertainties

Relic neutrinos affect cosmological observables

Number of neutrinos

modifies the relativistic energy density

$$\rho_r = \left(1 + \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)\rho_\gamma$$

Total mass

modifies the formation of the smallest structures (due to free streaming/ slower matter clustering)

$$\frac{\Delta P_{\rm matter}}{P_{\rm matter}} \approx -8\,\frac{\Omega_\nu}{\Omega_m} \propto \sum_i m_i$$

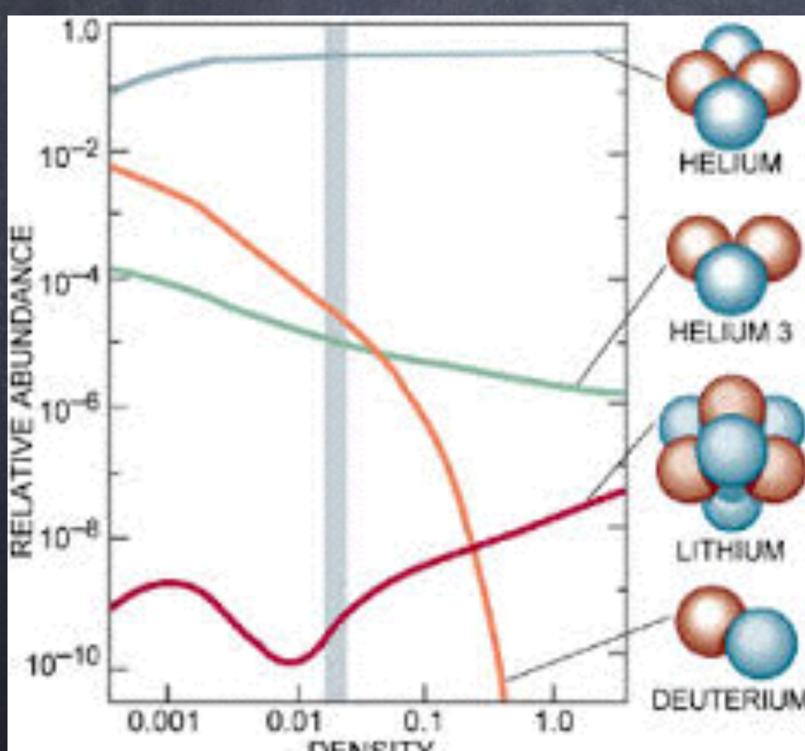
$$\sum_i m_i = \begin{cases} \text{NO}: \sqrt{m_l^2} + \sqrt{\Delta m_{21}^2 + m_l^2} + \sqrt{\Delta m_{31}^2 + m_l^2} \\ \text{IO}: \sqrt{m_l^2} + \sqrt{-\Delta m_{31}^2 - \Delta m_{21}^2 - m_l^2} + \sqrt{-\Delta m_{31}^2 - m_l^2} \end{cases}$$

Number of neutrinos

more light neutrinos (or large chemical potential) enhance the expansion rate ⇒ larger n/p ratio

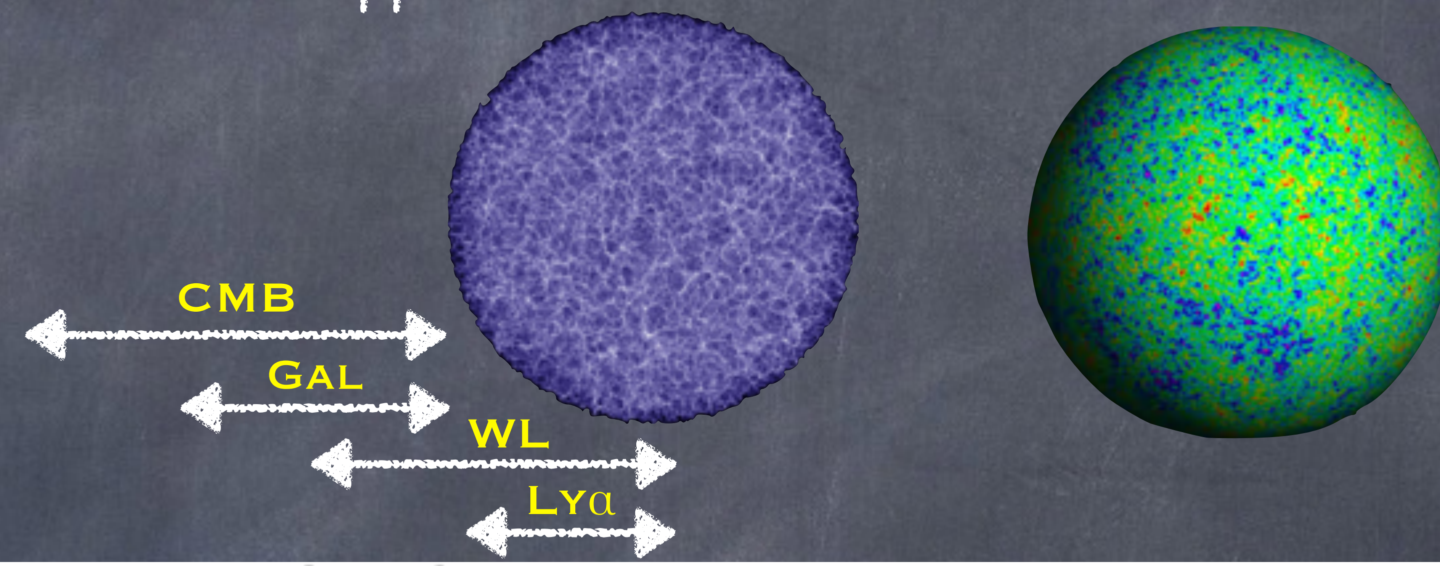
⇓

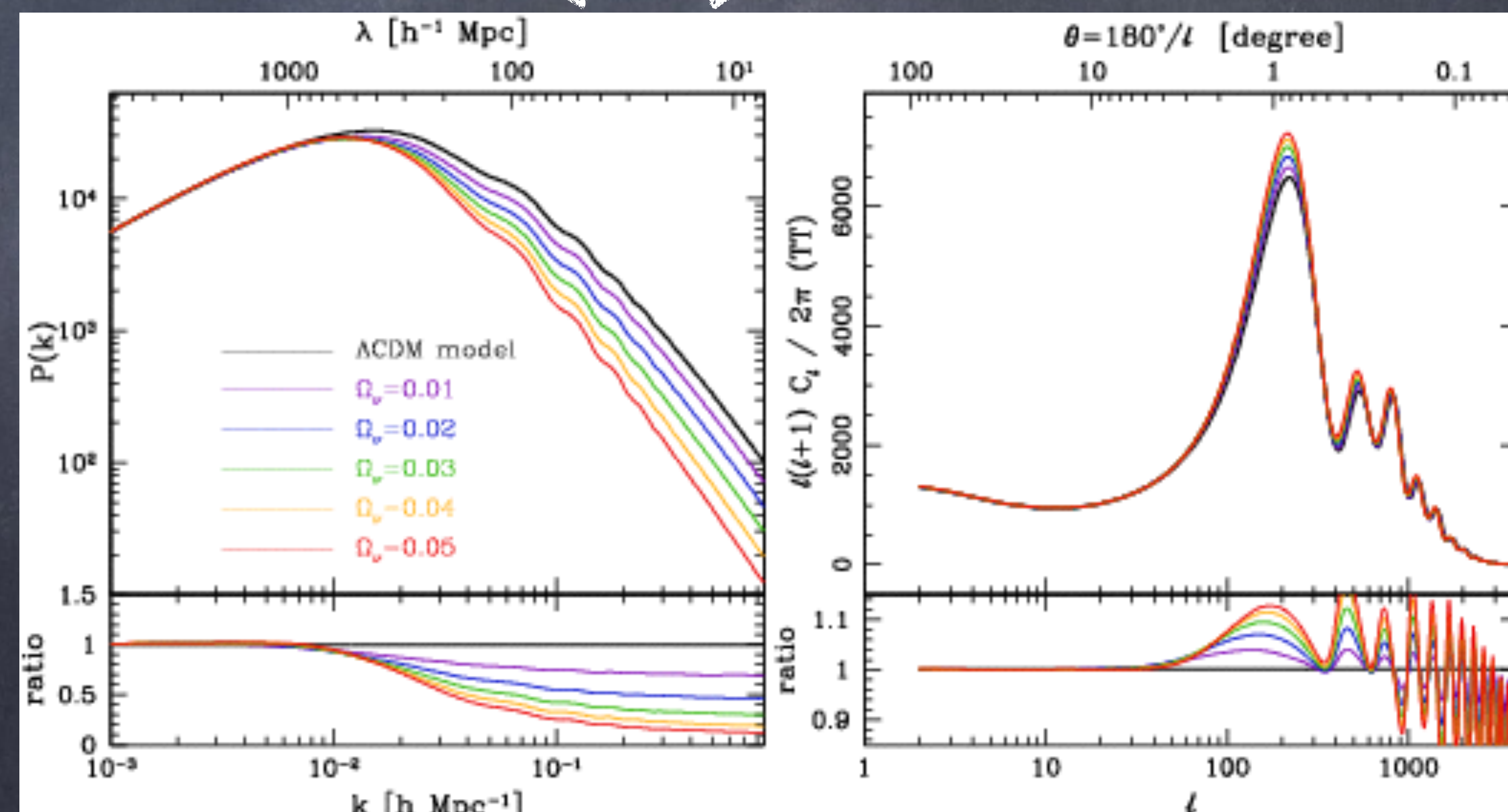
change the abundances of primordial elements



Total mass (and number of neutrinos)

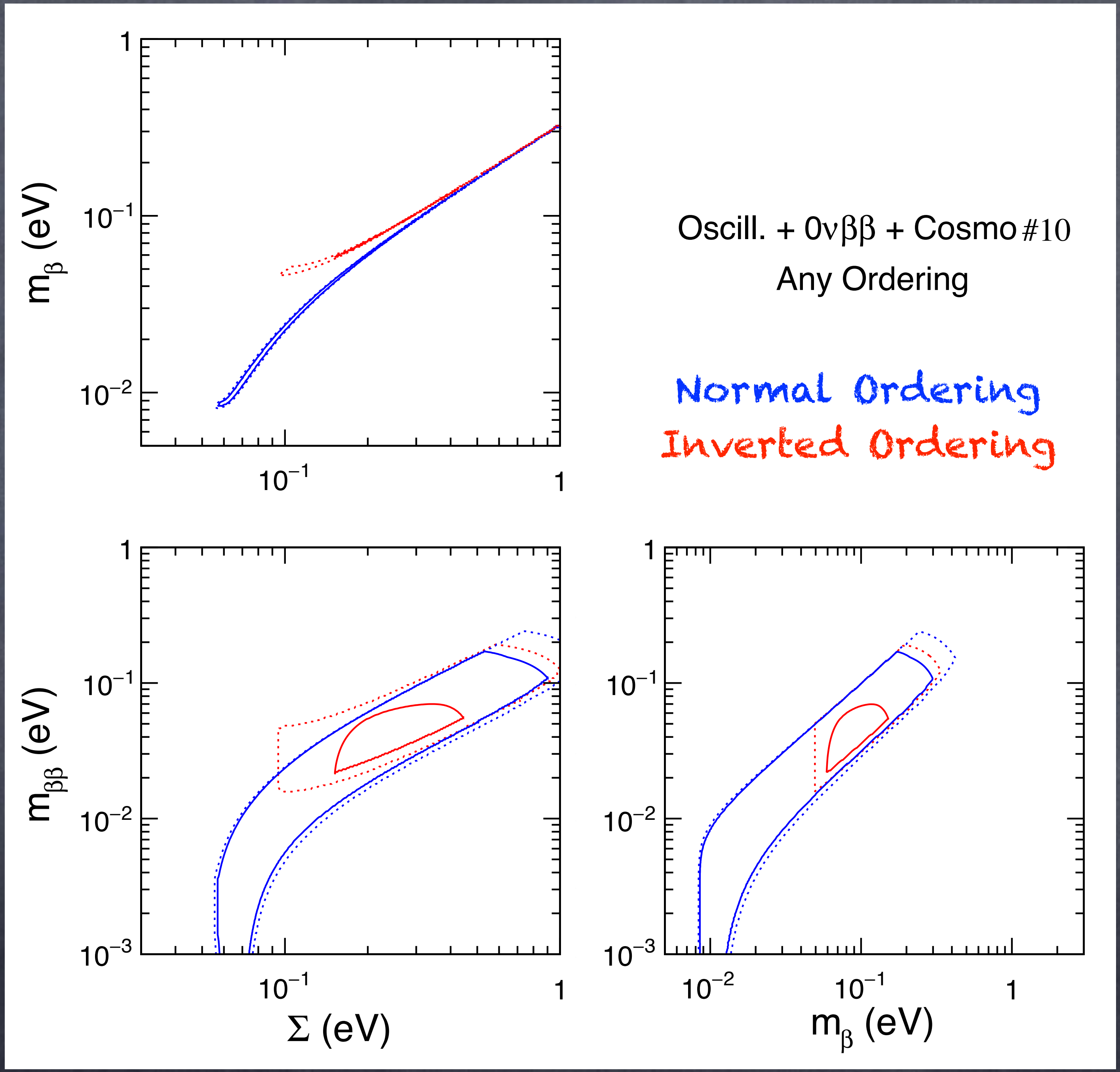
suppresses small-scale structure





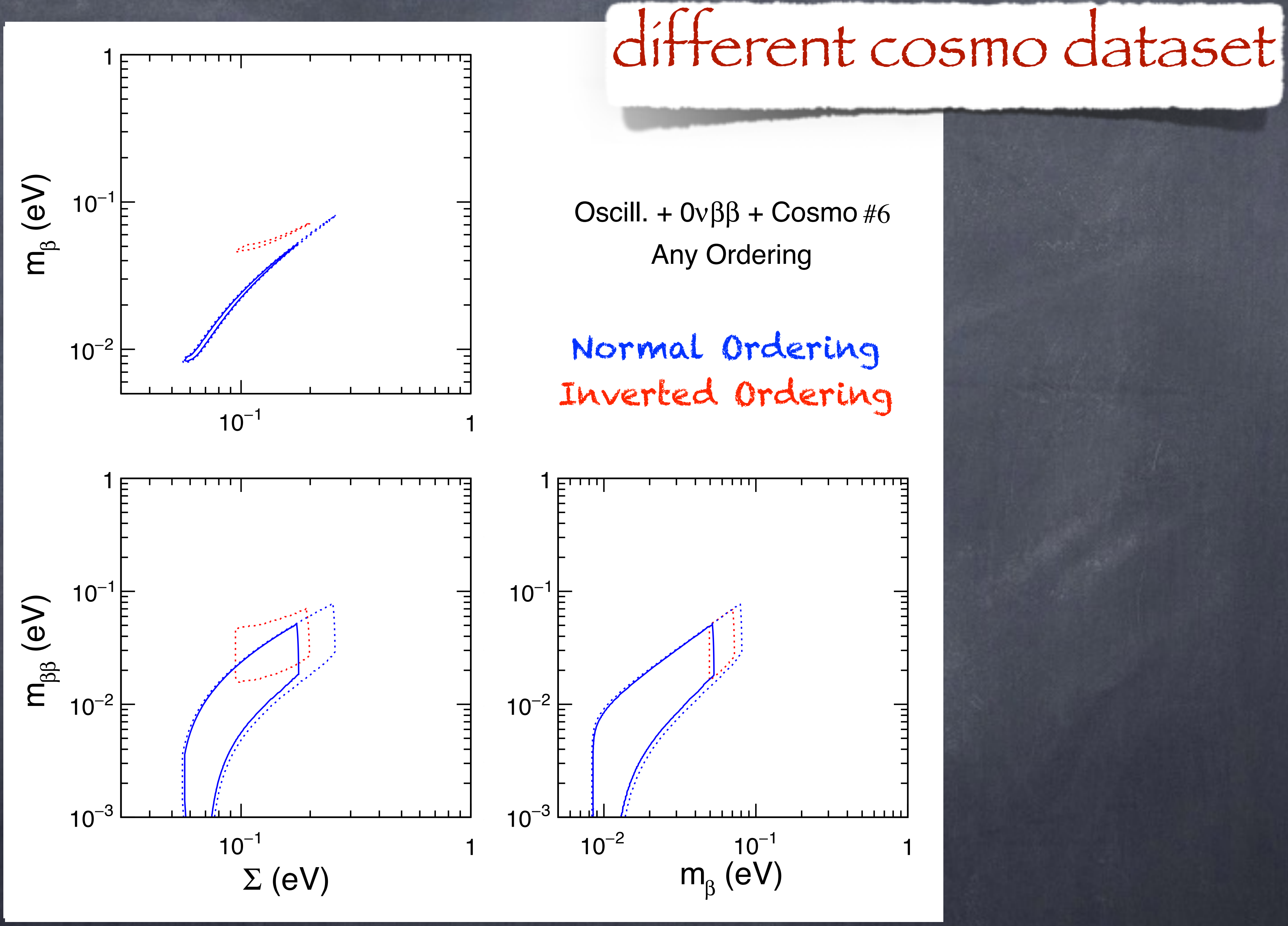
C.-G. Park, J-C. Hwang and H. Noh, Phys. Rev. D86:083535, 2012

Combining data



F. Capozzi et al., Phys. Rev. D95:09614, 2017

Combining data



F. Capozzi et al., Phys. Rev. D95:09614, 2017

Neutrino properties are fundamental ingredients of the Standard Model

... but neutrinos are also a powerful tool to search for physics beyond the Standard Model

Neutrinos helped us to build the Standard Model and may lead us, in the near future, beyond the Standard Model

Many Nobel Prizes along this road...
and probably several more to come...