A brief introduction to neutrino physics

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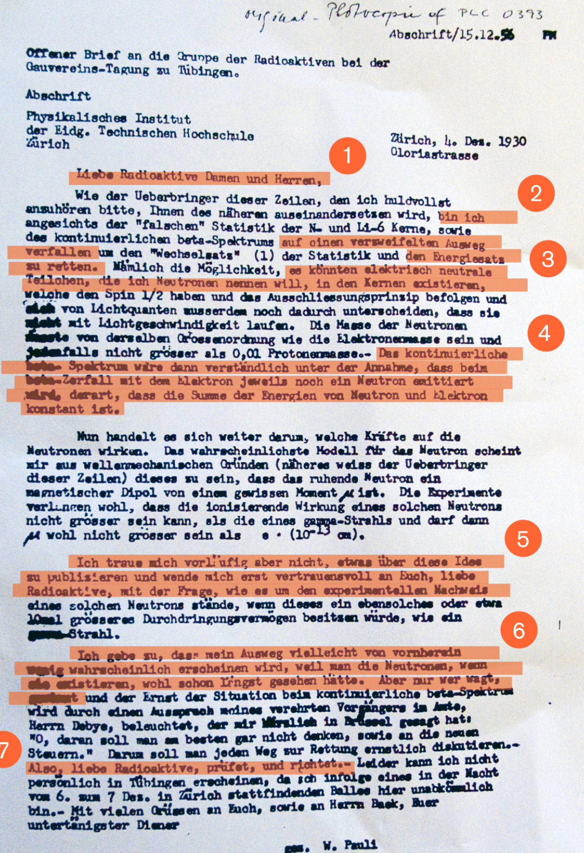
https://xunjiexu.github.io/

Neutrino history: a history of surprises

- 1930: Pauli's "desperate remedy" idea to explain why E_e in $A \to B + e^-$ is continuous
  - Pauli:"I do not dare to publish ... I admit that my remedy ... improbable".
- 1956: detected by Reines and Cowan (1995 Nobel)
- 1958: oscillation proposed by Pontecorvo, $\nu \leftrightarrow \overline{\nu}$, not $\nu_\alpha \leftrightarrow \overline{\nu}_\beta$
- 1960: muon neutrino (ν_μ) discovered (1988 Nobel)
- 1968: first solar neutrino observation (missing problem) } (2002 Nobel)
- 1987: supernova neutrino (unexpected) } (2002 Nobel)
- 1998-2002: first evidence of neutrino oscillations, SK and SNO (2015 Nobel):
- 2000-now: solar, reactor, accelerator neutrino exps ↑... established 3-ν mixing framework.
  - ν mixing angles unexpectedly large, even the smallest one
- 2014-now: IceCube (and more neutrino telescopes), new era=multimessenger astronomy.

See also https://neutrinos.fnal.gov/history/


Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

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 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.

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

1. Dear Radioactive Ladies and Gentlemen

2. I have hit upon a desperate remedy to save... the law of conservation of energy.

3. ... could exist electrically neutral particles, which I will call neutrons, in the nuclei...

4. The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

5. But so far I do not dare to publish anything about this idea, and trustfully turn first to you, ... how likely it is to find experimental evidence for such a neutron...

6. I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained...

7. ... dear radioactive ones, scrutinize and judge.

https://www.symmetrymagazine.org/article/march-2007/neutrino-invention

Outline

- The beginning of anomalies
  - solar neutrinos and ...
- The standard neutrino oscillation theory
  - in vacuum
  - in matter
    - why matter matters? the power of coherence
- Theories of neutrino masses
  - Seesaw, νMSM, ...
  - Majorana masses and $0\nu\beta\beta$
- Neutrino cosmology
  - $N_{\rm eff} = 3.045$
  - beyond $N_{\rm eff}$

Solar Neutrinos

gravitational contraction → solar energy?

— the contraction hypothesis, prevailing before 1920

14 *NATURE* [SEPTEMBER 2, 1920

The Internal Constitution of the Stars.*

By PROF. A. S. EDDINGTON, M.A., M.Sc., F.R.S.

LAST year at Bournemouth we listened to a proposal from the President of the Association to bore a hole in the crust of the | the ... there ... throu

If the contraction theory were proposed to-day as a novel hypothesis I do not think it would stand the smallest chance of acceptance. From all sides—biology, geology, physics, astronomy—it would be objected that the suggested source of energy was hopelessly inadequate to provide the heat spent during the necessary time of evolution; and, so far as it is possible to interpret observational evidence confidently, the theory would be held to be negatived definitely. Only the inertia of tradition keeps the contraction hypothesis alive—or, rather, not alive, but an unburied corpse. But if we decide to inter the corpse, let us frankly recognise the position in which we are left. A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the sub-atomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man will one day learn how to release it and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped. There is sufficient in the sun to maintain its output of heat for 15 billion years.

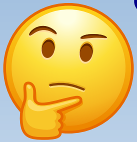
1920, Eddington:

- "hopelessly inadequate to provide the heat"
- "some unknown, vast reservoir of energy"
- "sub-atomic energy"
- [human] "controlling this power "
  - "well-being ... or ... suicide"?

If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfilment our dream of controlling this latent power for the well-being of the human race—or for its suicide.

- 1896, radioactivity discovered;
- 1911, Rutherford model (atmoic, not nuclear);
- 1915, $^{14}\mathrm{N} + \alpha \to {}^{17}\mathrm{O} + p$ by Rutherford;
- 1932, nuclear fusion achieved in lab;
- 1938, nuclear fission discovered;
- 1940s, Manhattan Project ...

How much did Eddington know about "sub-atomic energy" in 1920?



MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

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

(Received September 7, 1938)

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

integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

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

In 1938, Bethe computed ...

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

In 1938, Bethe computed ...

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

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

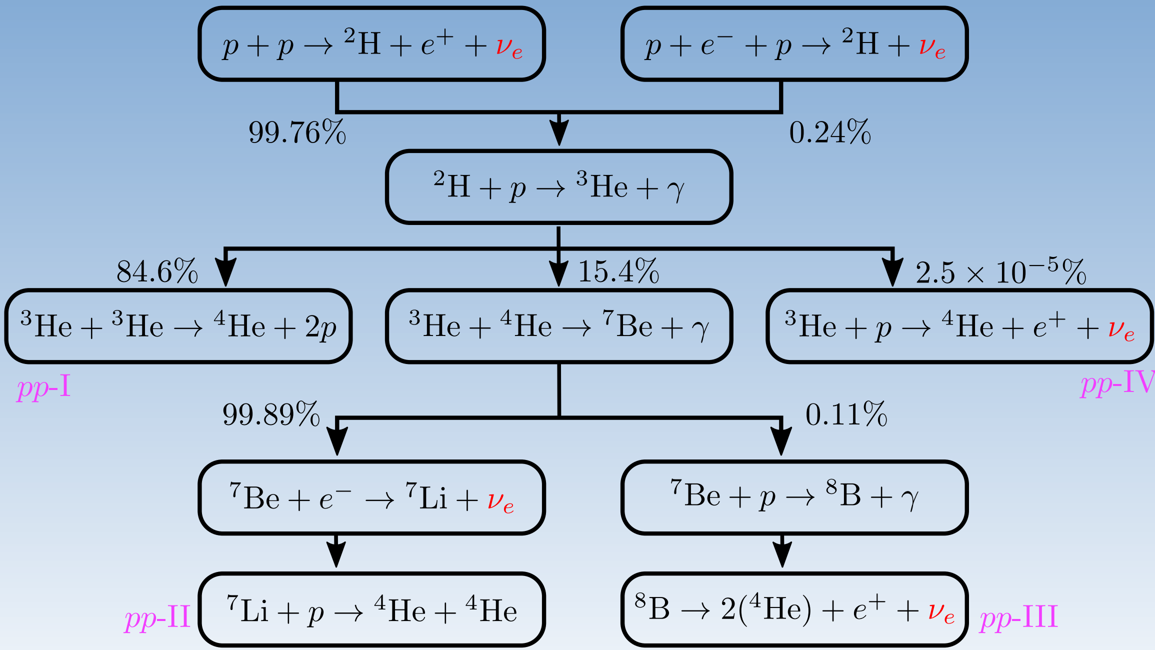
The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

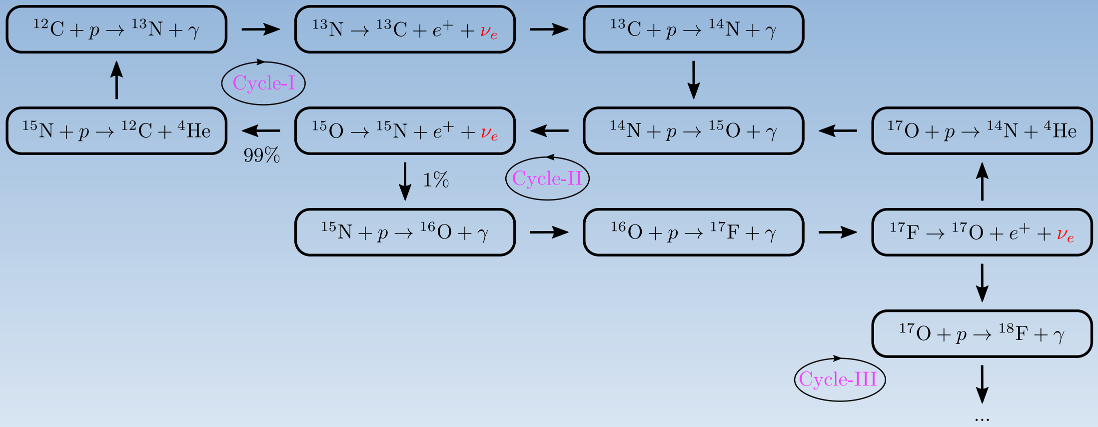
$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^+ \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^+ \\ N^{15}+H=C^{12}+He^4. & \end{array} \qquad (2)$$

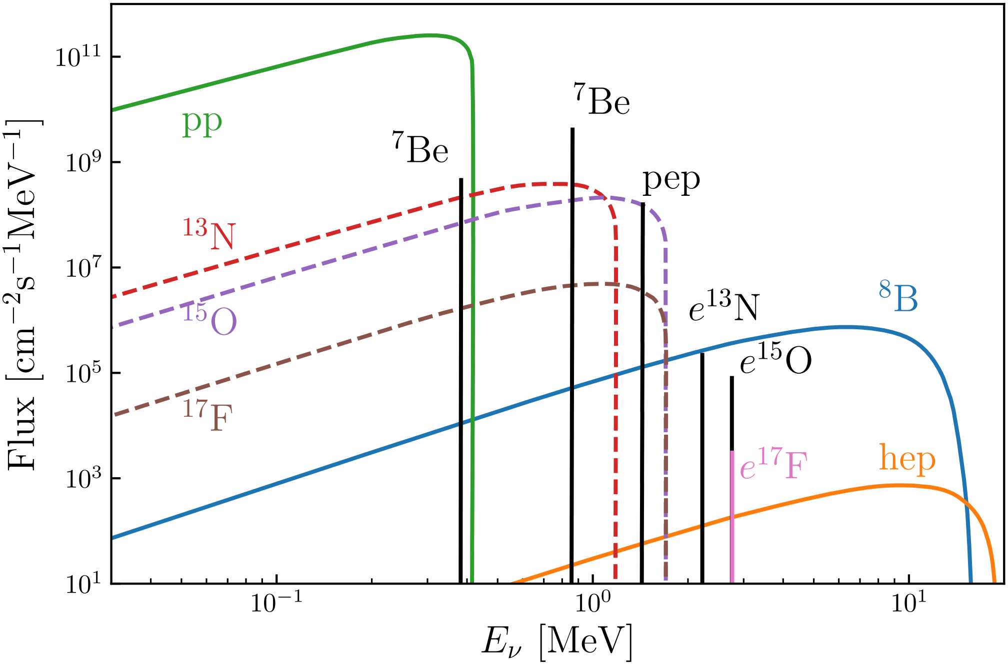
No neutrinos?

proposed in 1930
detected in 1956

see also:
neutrinos.fnal.gov/history/


$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$
$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$
99.76%
0.24%
${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$
84.6%
15.4%
$2.5 \times 10^{-5}\%$
${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$
${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$
${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$
pp-I
pp-IV
99.89%
0.11%
${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$
${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$
pp-II
${}^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$
${}^8\mathrm{B} \rightarrow 2({}^4\mathrm{He}) + e^+ + \nu_e$
pp-III


$^{12}\mathrm{C} + p \to {}^{13}\mathrm{N} + \gamma$
$^{13}\mathrm{N} \to {}^{13}\mathrm{C} + e^+ + \nu_e$
$^{13}\mathrm{C} + p \to {}^{14}\mathrm{N} + \gamma$
Cycle-I
$^{15}\mathrm{N} + p \to {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$
$^{15}\mathrm{O} \to {}^{15}\mathrm{N} + e^+ + \nu_e$
$^{14}\mathrm{N} + p \to {}^{15}\mathrm{O} + \gamma$
$^{17}\mathrm{O} + p \to {}^{14}\mathrm{N} + {}^{4}\mathrm{He}$
99%
1%
Cycle-II
$^{15}\mathrm{N} + p \to {}^{16}\mathrm{O} + \gamma$
$^{16}\mathrm{O} + p \to {}^{17}\mathrm{F} + \gamma$
$^{17}\mathrm{F} \to {}^{17}\mathrm{O} + e^+ + \nu_e$
$^{17}\mathrm{O} + p \to {}^{18}\mathrm{F} + \gamma$
Cycle-III
...



Flux $[\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{MeV}^{-1}]$
10^{11}
10^{9}
10^{7}
10^{5}
10^{3}
10^{1}
10^{-1}
10^{0}
10^{1}
E_ν [MeV]
pp
^{7}Be
^{7}Be
pep
^{13}N
^{15}O
^{17}F
e^{13}N
e^{15}O
e^{17}F
^{8}B
hep

Solar neutrinos: the pioneering effort

VOLUME 20, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1968

SEARCH FOR NEUTRINOS FROM THE SUN*

Raymond Davis, Jr., Don S. Harmer,† and Kenneth C. Hoffman
Brookhaven National Laboratory, Upton, New York 11973
(Received 16 April 1968)

A search was made for solar neutrinos with a detector based upon the reaction $Cl^{37}(\nu, e^-)Ar^{37}$. The upper limit of the product of the neutrino flux and the cross sections for all sources of neutrinos was $3\times10^{-36}\ sec^{-1}$ per Cl^{37} atom. It was concluded specifically that the flux of neutrinos from B^8 decay in the sun was equal to or less than $2\times10^6\ cm^{-2}\ sec^{-1}$ at the earth, and that less than 9% of the sun's energy is produced by the carbon-nitrogen cycle.

Two papers, same volume:

Exp: PRL 20, 1205 (1968)
Th: PRL 20, 1209 (1968)

Result: $\Phi_\nu \lesssim 3$ SNU

many useful suggestions and direct assistance from the members of the staff of Brookhaven National Laboratory.

R. L. Chase and Mr. Lee Rogers of Brookhaven National Laboratory.

[13] J. N. Bahcall, N. A. Bahcall, and G. Shaviv, following Letter [Phys. Rev. Letters 20, 1209 (1968)].

cited each other

PRESENT STATUS OF THE THEORETICAL PREDICTIONS FOR THE ^{36}Cl SOLAR-NEUTRINO EXPERIMENT*

John N. Bahcall† and Neta A. Bahcall‡
California Institute of Technology, Pasadena, California

and

Giora Shaviv§
Cornell University, Ithaca, New York
(Received 8 April 1968)

The theoretical predictions for the ^{37}Cl solar-neutrino experiment are summarized and compared with the experimental results of Davis, Harmer, and Hoffman. Three important conclusions about the sun are shown to follow.

The experiment of Davis, Harmer, and Hoffman,[1,2] designed to detect solar neutrinos with a

tio of heavy elements to hydrogen recently obtained by Lambert and Warner.[9] We also discuss

Result: $\Phi_\nu \approx 11$ SNU

in fact, 5 models, $\Phi_\nu =$ 21, 11, 7.7, 4.4, 11 SNU

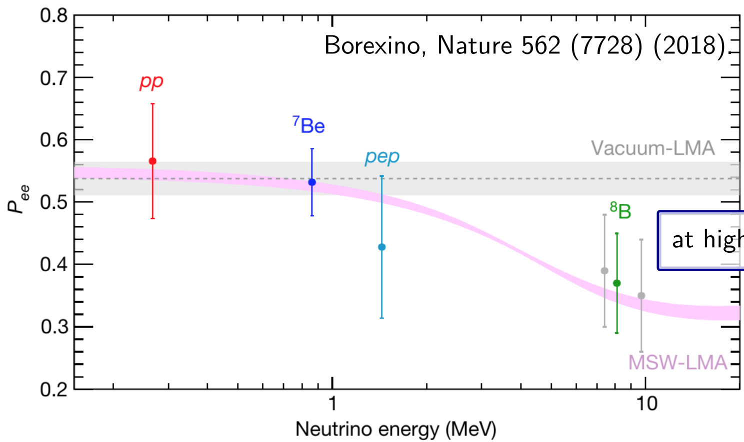
After decades of exp+th effort, ...

$$\Rightarrow \text{exp} \approx \frac{\text{th}}{3}$$

... the so-called "solar neutrino problem"

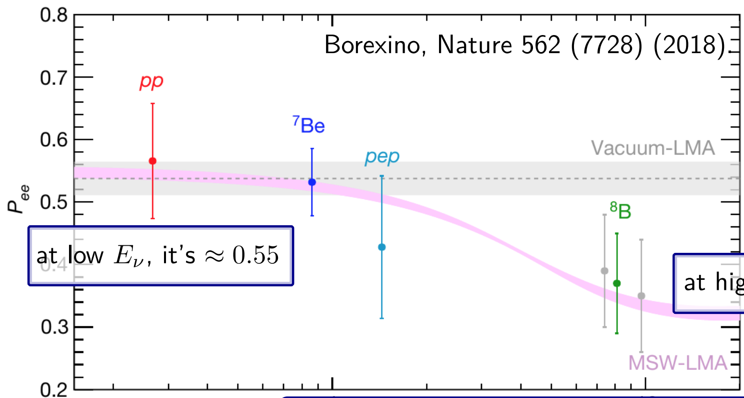
Various explanations: oscillation, decay, spin-flavor precession ...

Today, we know it's osc.



at high E_ν, indeed it's $\sim 1/3$

Today, we know it's osc.



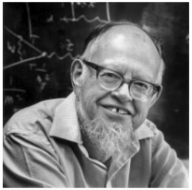
at low E_ν, it's ≈ 0.55

at high E_ν, it's ≈ 0.3

... not just osc, also MSW.

S. Mikheyev (1940-2011)

A. Smirnov (1951-)



L. Wolfenstein (1923-2015)

How are atmospheric neutrinos produced?

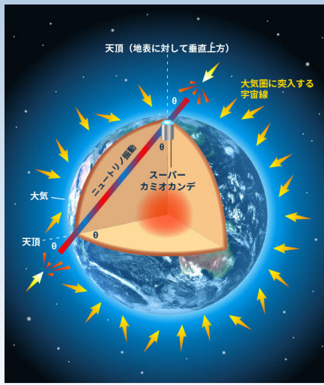
Cosmic ray scattering off nuclei in the atmosphere

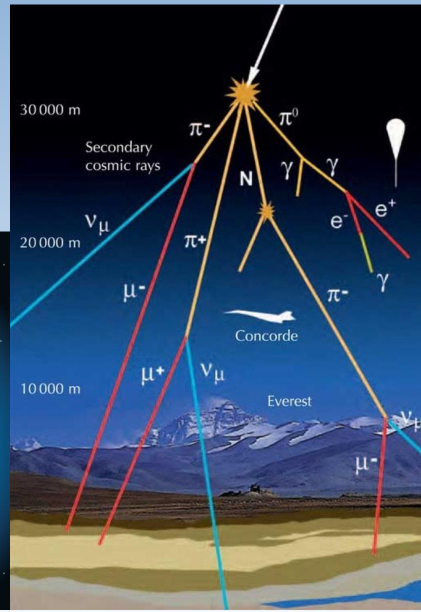
$\rightarrow$ a lot of pions ($\pi^{\pm}$, π^{0}) and ...

$\rightarrow$ $\pi^{\pm}$ dominantly decay to $\mu^{\pm}$ and ν_{μ} (or $\overline{\nu}_{\mu}$)

Question:

Both $\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$
and $\pi^{+} \rightarrow e^{+} + \nu_{e}$
are possible.
But the former is dominant:
99.988% vs 00.012%.
Why?

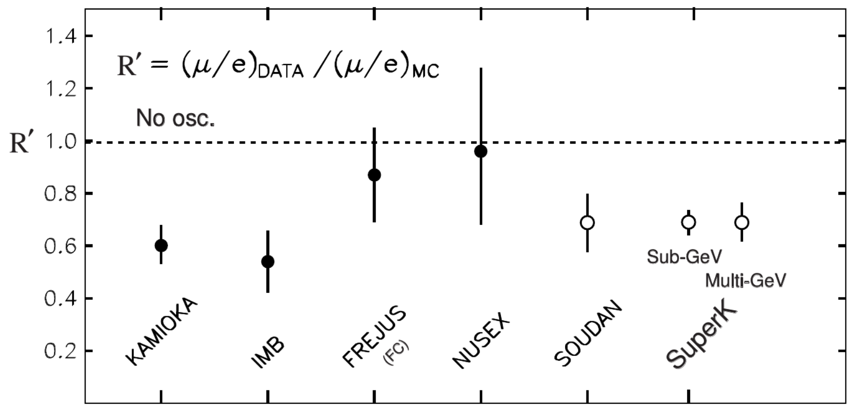




from Takaaki Kajita,
who shared 2015 Nobel with Arthur McDonald

Problem: deficit of muon neutrinos

from John Learned's review: hep-ex/0007056



First IMB (1986), then Kamiokande and SK... but some stories behind—see 1902.01757 from John Learned's review: hep-ex/0007056

Not only deficit...
you can even see the
dependence on L/E_ν